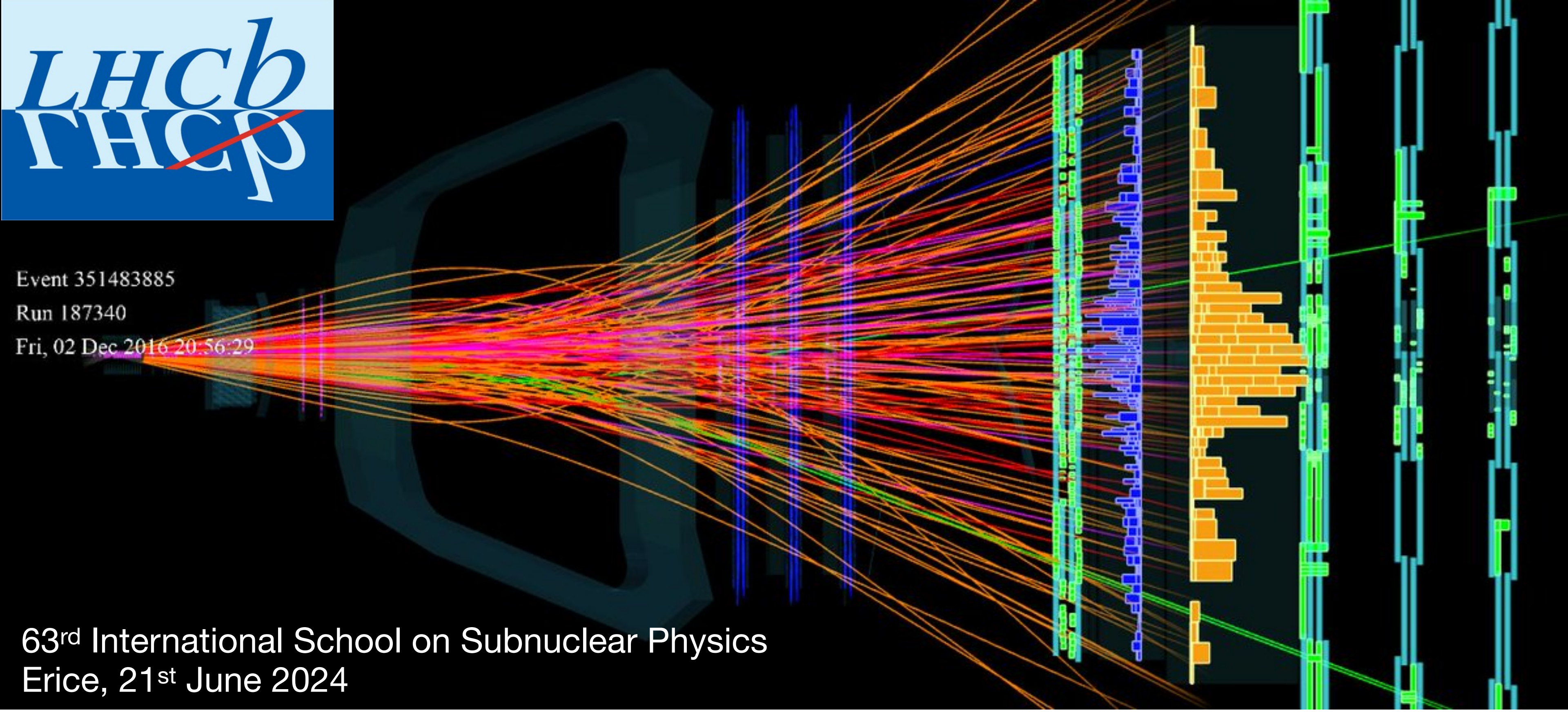
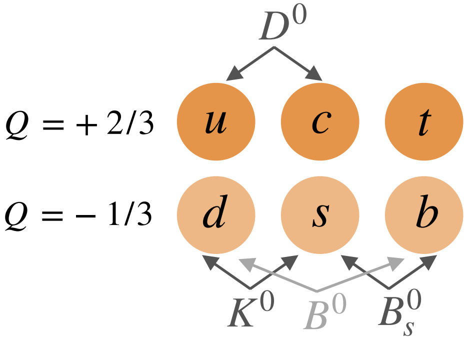


63rd International School on Subnuclear Physics
Erice, 21st June 2024

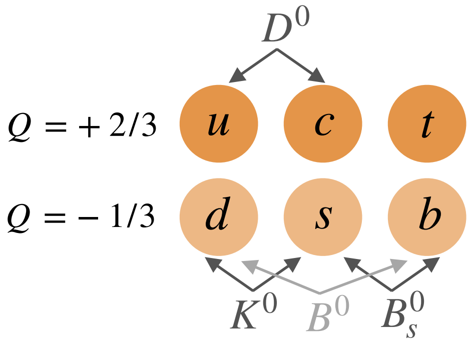
Mixing and CP violation in charm decays at LHCb

Tommaso Pajero
CERN

tommaso.pajero@cern.ch

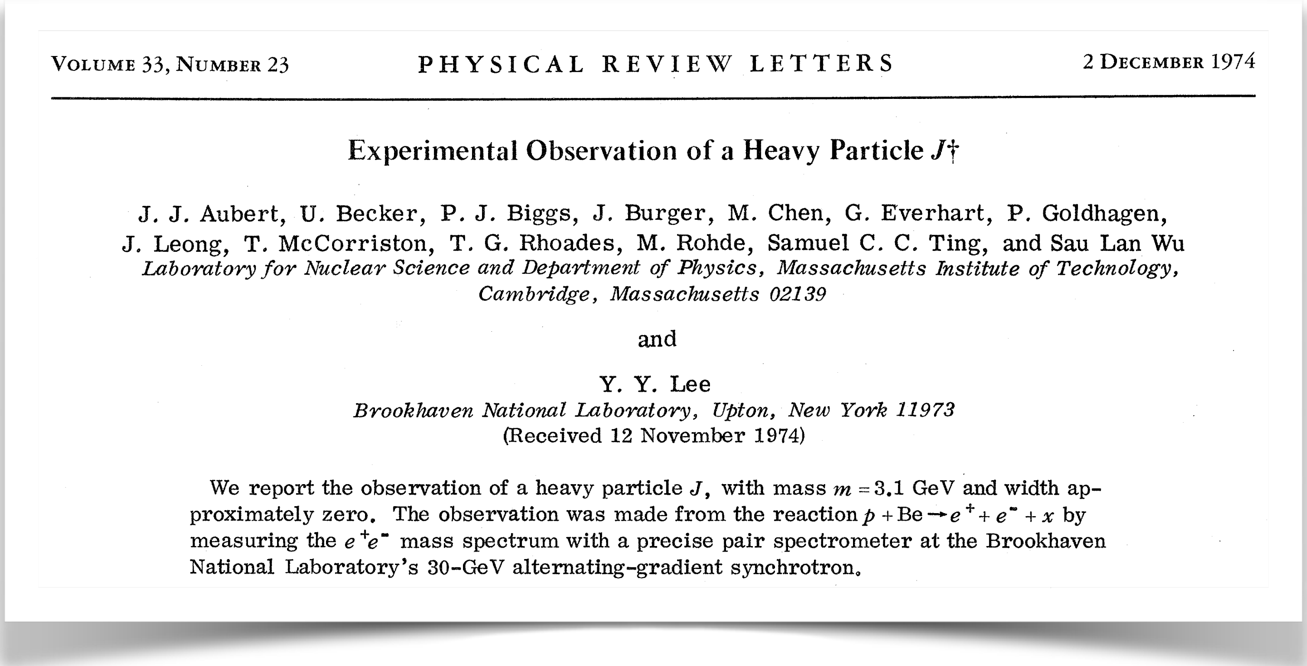


The only up-type quark which mixes and allows for precision *CP* violation (CPV) measurements



The only up-type quark which mixes and allows for precision *CP* violation (CPV) measurements

Happy 50TH Birthday


VOLUME 33, NUMBER 23 PHYSICAL REVIEW LETTERS 2 DECEMBER 1974

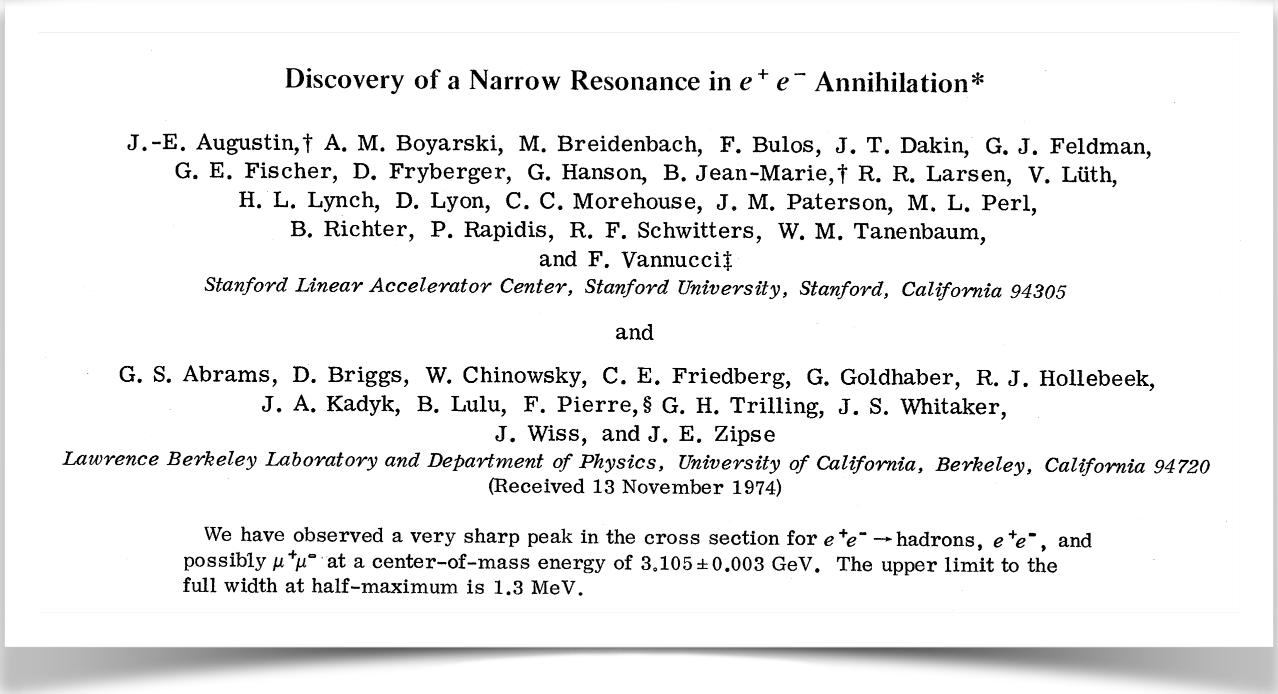
Experimental Observation of a Heavy Particle J†

J. J. Aubert, U. Becker, P. J. Biggs, J. Burger, M. Chen, G. Everhart, P. Goldhagen, J. Leong, T. McCorriston, T. G. Rhoades, M. Rohde, Samuel C. C. Ting, and Sau Lan Wu
Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

and

Y. Y. Lee
Brookhaven National Laboratory, Upton, New York 11973
(Received 12 November 1974)

We report the observation of a heavy particle J, with mass $m = 3.1$ GeV and width approximately zero. The observation was made from the reaction $p + \text{Be} \rightarrow e^+ + e^- + x$ by measuring the e^+e^- mass spectrum with a precise pair spectrometer at the Brookhaven National Laboratory's 30-GeV alternating-gradient synchrotron.


Discovery of a Narrow Resonance in $e^+ e^-$ Annihilation*

J.-E. Augustin,† A. M. Boyarski, M. Breidenbach, F. Bulos, J. T. Dakin, G. J. Feldman, G. E. Fischer, D. Fryberger, G. Hanson, B. Jean-Marie,† R. R. Larsen, V. Lüth, H. L. Lynch, D. Lyon, C. C. Morehouse, J. M. Paterson, M. L. Perl, B. Richter, P. Rapidis, R. F. Schwitters, W. M. Tanenbaum, and F. Vannucci‡
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

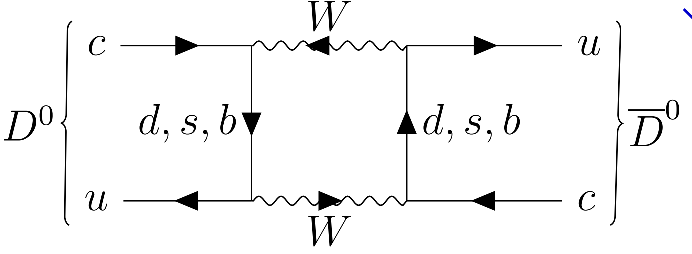
and

G. S. Abrams, D. Briggs, W. Chinowsky, C. E. Friedberg, G. Goldhaber, R. J. Hollebeek, J. A. Kadyk, B. Lulu, F. Pierre,§ G. H. Trilling, J. S. Whitaker, J. Wiss, and J. E. Zipse
Lawrence Berkeley Laboratory and Department of Physics, University of California, Berkeley, California 94720
(Received 13 November 1974)

We have observed a very sharp peak in the cross section for $e^+e^- \rightarrow$ hadrons, e^+e^-, and possibly $\mu^+\mu^-$ at a center-of-mass energy of 3.105 ± 0.003 GeV. The upper limit to the full width at half-maximum is 1.3 MeV.

A very peculiar phenomenology

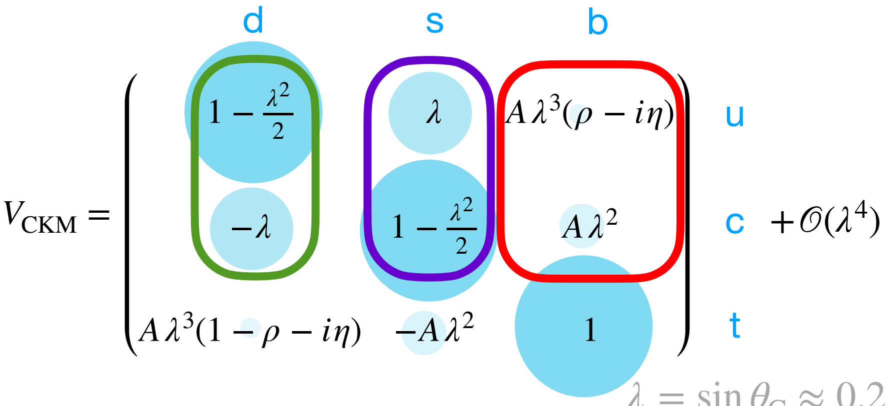
FCNC are extremely suppressed



mixing – short distance

GIM mechanism broken by m_b rather than m_t

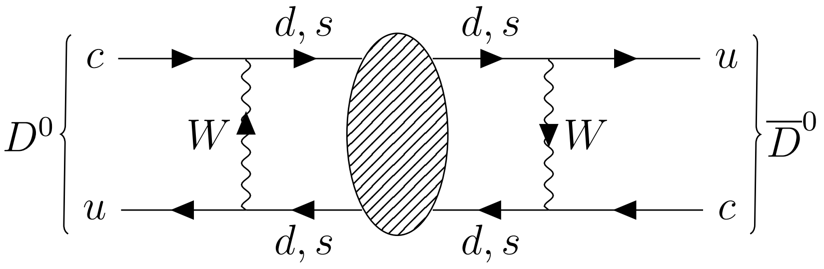
$$\propto \left(\frac{m_{d,s,b}}{m_W}\right)^2$$



$$V_{\text{CKM}} = \begin{array}{cccc} d & s & b & \\ \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} & & & \begin{matrix} u \\ c \\ t \end{matrix} \end{array} + \mathcal{O}(\lambda^4)$$

$\lambda = \sin\theta_C \approx 0.23$

- **CKM suppression** → third generation nearly decouples from the first two
- (**d** + **s** contribution) → 0 in the limit of U-spin symmetry, i.e. $m_s = m_d$



mixing – long distance

Main contributions from low-energy QCD. Charm is:

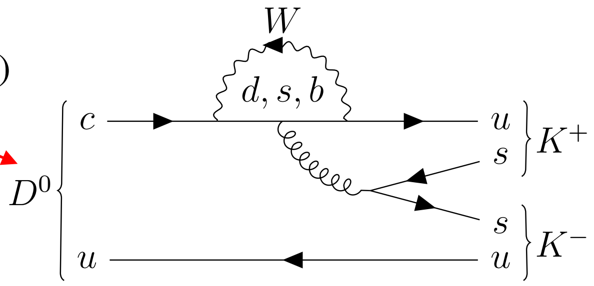
- too heavy for ChPT or exclusive analysis
- arguably too light for HQET $(\Lambda_{QCD}/m_c \approx 1)$

CPV in charm

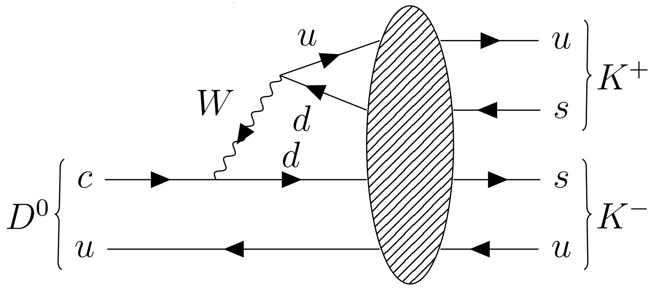
Detectable only in Cabibbo-suppressed decays

$$\mathit{CPV} \propto \mathrm{Im}\left(\frac{V_{cb}V_{bu}^{*}}{V_{cs}V_{su}^{*}}\right) \approx -6\times 10^{-4}$$

$$\begin{array}{rcl} & \begin{array}{ccc} \mathrm{d} & \qquad\qquad \mathrm{s} & \qquad\qquad \mathrm{b} \end{array} & \\ V_{\mathrm{CKM}} = & \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda \;\; -iA^2\lambda^5\eta & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} & \begin{array}{c} \mathrm{u} \\ \mathrm{c} \\ \mathrm{t} \end{array} \; +\mathcal{O}(\lambda^4) \end{array}$$

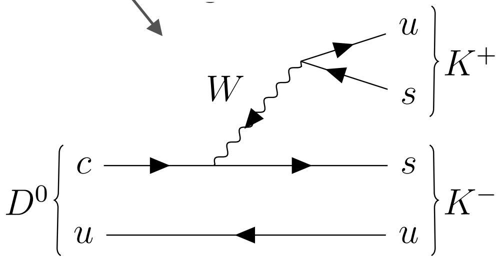


QCD penguin



Tree + rescattering (e.g. $D^0 \to \pi^+\pi^- \to K^+K^-$)

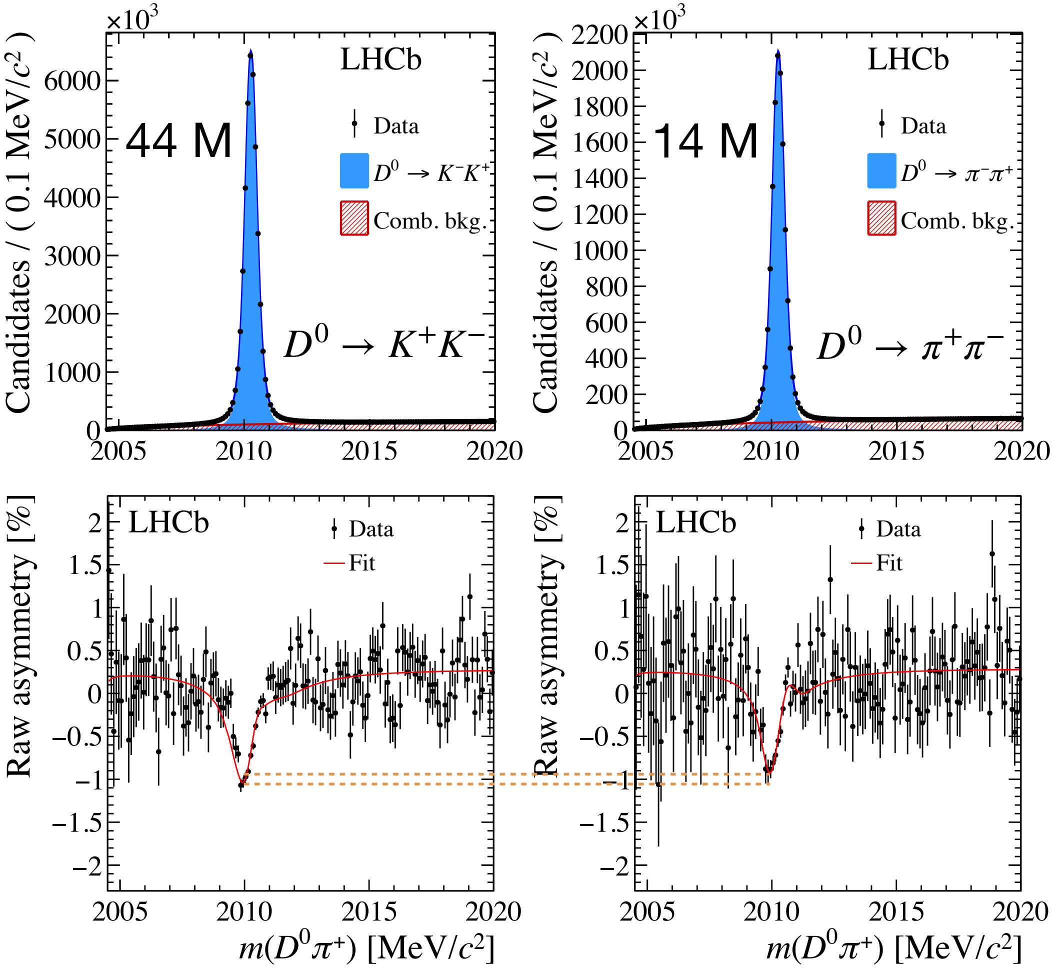
CPV from tiny nonunitarity of 2×2 CKM submatrix

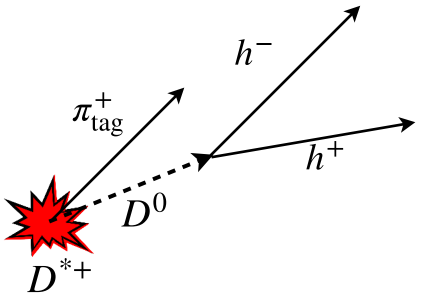


Tree

First observation of CPV

$D^*(2010)^+ \to D^0\pi^+$





$$\frac{N(D \to f) - N(\bar{D} \to \bar{f})}{N(D \to f) + N(\bar{D} \to \bar{f})}$$

production cross-section

$$A_{\mathrm{raw}}(f) \approx A_{CP}(f) + A_{\mathrm{det}}(\pi^+) + A_{\mathrm{prod}}(D^{*+})$$

a_f^d (CPV in decay)
+ small time-dependent contributions

detection of tagging π+

PRL 122 (2019) 211803
6 fb^{-1}, 2015–2018

$$\Delta A_{CP} = A_{\mathrm{raw}}(K^+K^-) - A_{\mathrm{raw}}(\pi^+\pi^-)$$
$$\approx a^d_{K^+K^-} - a^d_{\pi^+\pi^-} = (-1.54 \pm 0.29) \times 10^{-3} \quad (5.3\sigma)$$

$a^d_{K^+K^-} \approx -a^d_{\pi^+\pi^-}$ in the U-spin limit

First observation of CPV

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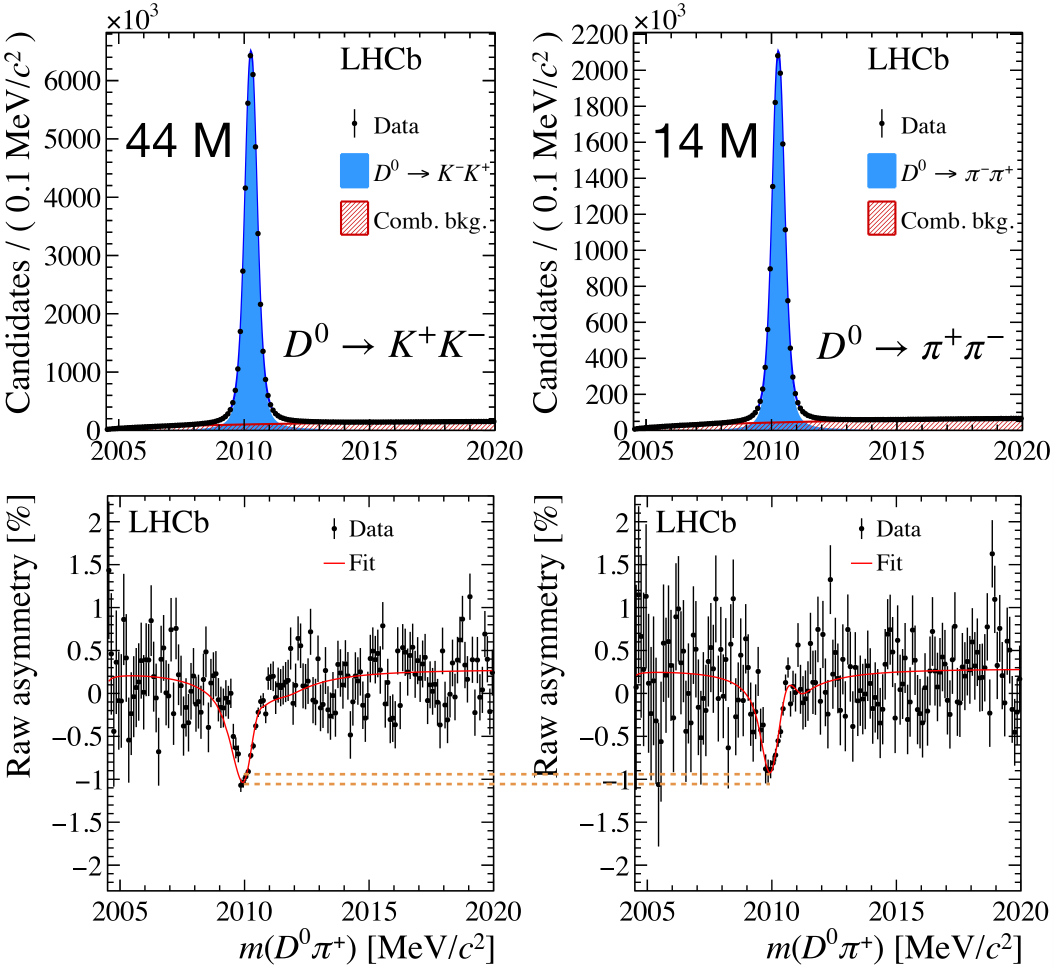
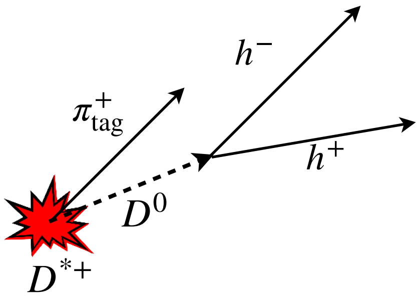




- Larger than most SM predictions
  Franco, Mishima & Silvestrini, JHEP 05 (2012) 140
  Li et al, Phys. Rev. D 86 (2012) 036012
  Cheng & Chiang, Phys. Rev. D 85 (2012) 034036
  Khodjamirian & Petrov, Phys. Lett. B 774 (2017) 235
  Pich, Solomonidi & Vale Silva, Phys. Rev. D 108 (2023) 3, 036026
  Lenz, Piscopo & Rusov, JHEP 03 (2024) 151
- O(1–10) enhancement of QCD rescattering or BSM?
  Chala et al, JHEP 07 (2019) 161
  Grossman & Schacht, JHEP 07 (2019) 020
  Buccella et al, Phys. Rev. D 99 (2019) 11, 113001
  Cheng & Chiang, Phys. Rev. D 100 (2019) 9, 093002
  Schacht & Soni, Phys. Lett. B 825 (2022) 136855
  Dery & Nir, JHEP 12 (2019) 104
  Wang et al, JHEP 09 (2021) 126
  Bause et al, Phys. Rev. D 101 (2020) 11, 115006
  Dery et al, JHEP 05 (2021) 179
  Cheng & Chiang, Phys. Rev. D 104 (2021) 7, 073003
  Gavrilova, Grossman & Schacht, Phys. Rev. D 109 (2024) 3, 033011

PRL 122 (2019) 211803
6 fb⁻¹, 2015–2018

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

$$\approx a^d_{K^+K^-} - a^d_{\pi^+\pi^-} = (-1.54 \pm 0.29) \times 10^{-3} \quad (5.3\sigma)$$

$a^d_{K^+K^-} \approx -a^d_{\pi^+\pi^-}$ in the U-spin limit

Measurement of $A_{CP}(D^0 \to K^+K^-)$

Nuisance asymmetries subtracted through Cabibbo-favoured ($c \to us\bar{d}$) decay channels

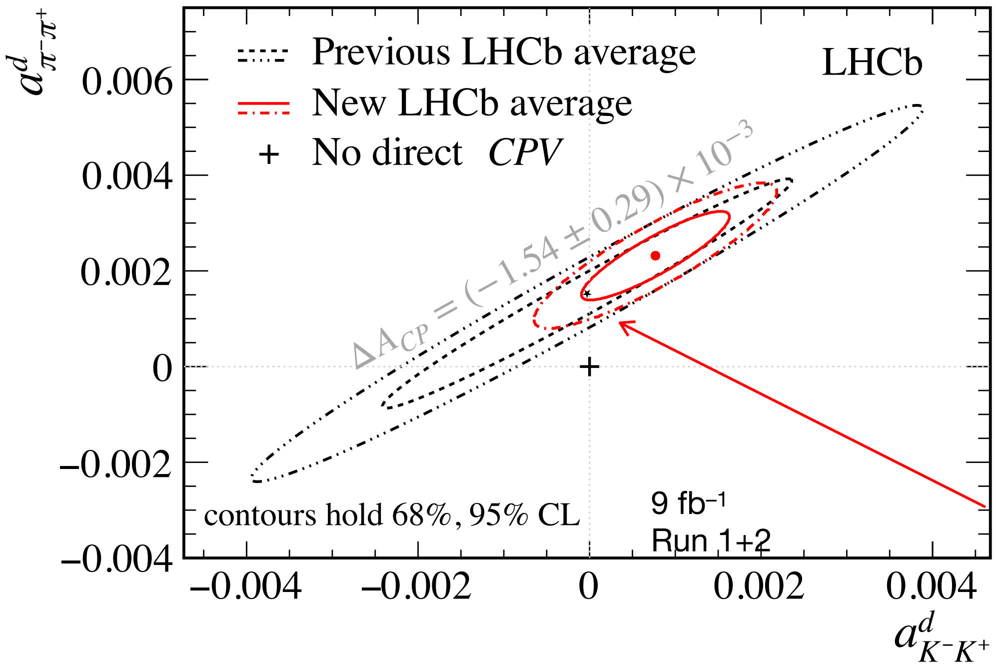
- no QCD penguin, no chromomagnetic dipole → negligible CPV

$$A_{CP}(D^0 \to K^+K^-) \approx A_{\rm raw}(D^{*+} \to D^0(\to K^+K^-)\pi^+) - A_{\rm raw}(D^{*+} \to D^0(\to K^-\pi^+)\pi^+)$$
$$+A_{\rm raw}(D_s^+ \to K^+K^-\pi^+) - A_{\rm raw}(D_s^+ \to K^+K_S^0) + A_{\rm det}(K^0)$$

bottleneck to final precision

regeneration and CPV in mixing explicitly calculated CERN-THESIS-2014-274

Phys. Rev. Lett. 131 (2023) 9, 091802



$$a^d_{K^-K^+} = (7.7 \pm 5.7) \times 10^{-4} \; 1.4\,\sigma$$
$$a^d_{\pi^-\pi^+} = (23.2 \pm 6.1) \times 10^{-4} \; 3.8\,\sigma$$

Kagan & Silvestrini, Phys. Rev. D 103 (2021) 5, 053008

The tortoise of flavour

$$i\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix}D^0(t)\\ \overline{D}^0(t)\end{pmatrix} = \left(\mathbf{M}-\tfrac{i}{2}\mathbf{\Gamma}\right)\begin{pmatrix}D^0(t)\\ \overline{D}^0(t)\end{pmatrix}$$

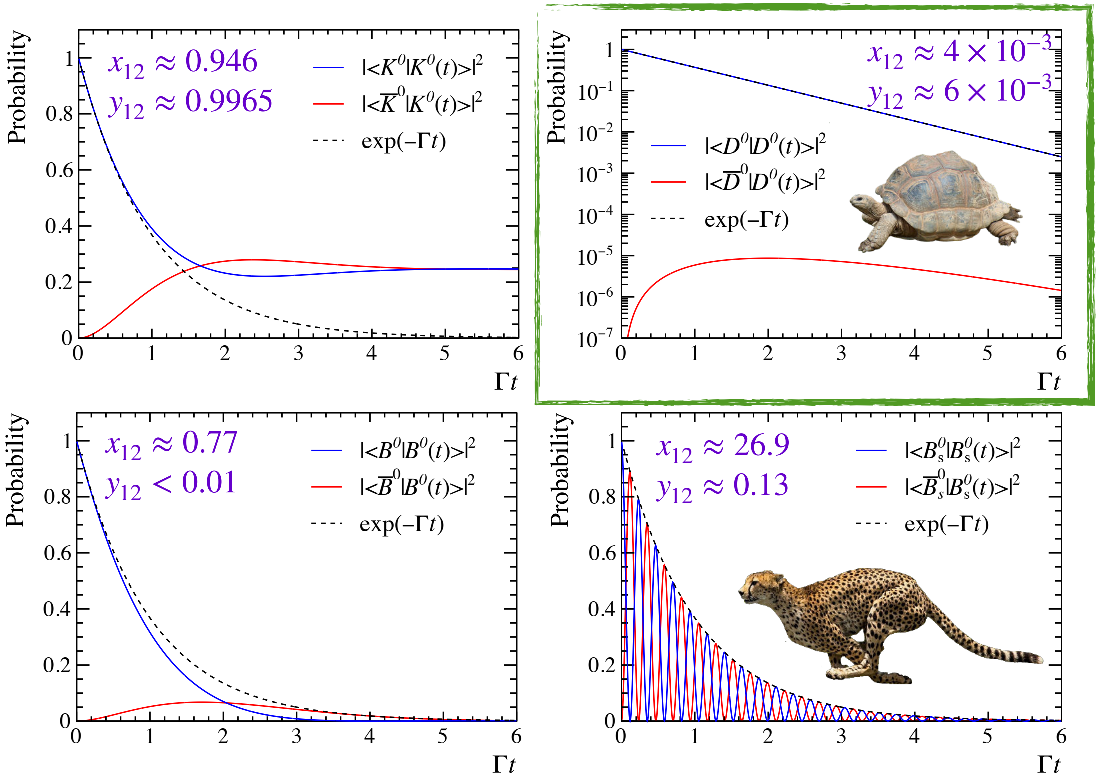
off-shell transitions. BSM?

on-shell transitions

Oscillation probability is determined by the size of the transition amplitudes:

$$\boxed{x_{12} \equiv \frac{2|M_{12}|}{\Gamma}, \qquad y_{12} \equiv \frac{|\Gamma_{12}|}{\Gamma}}$$

"mixing parameters"



Kagan & Silvestrini, Phys. Rev. D 103 (2021) 5, 053008

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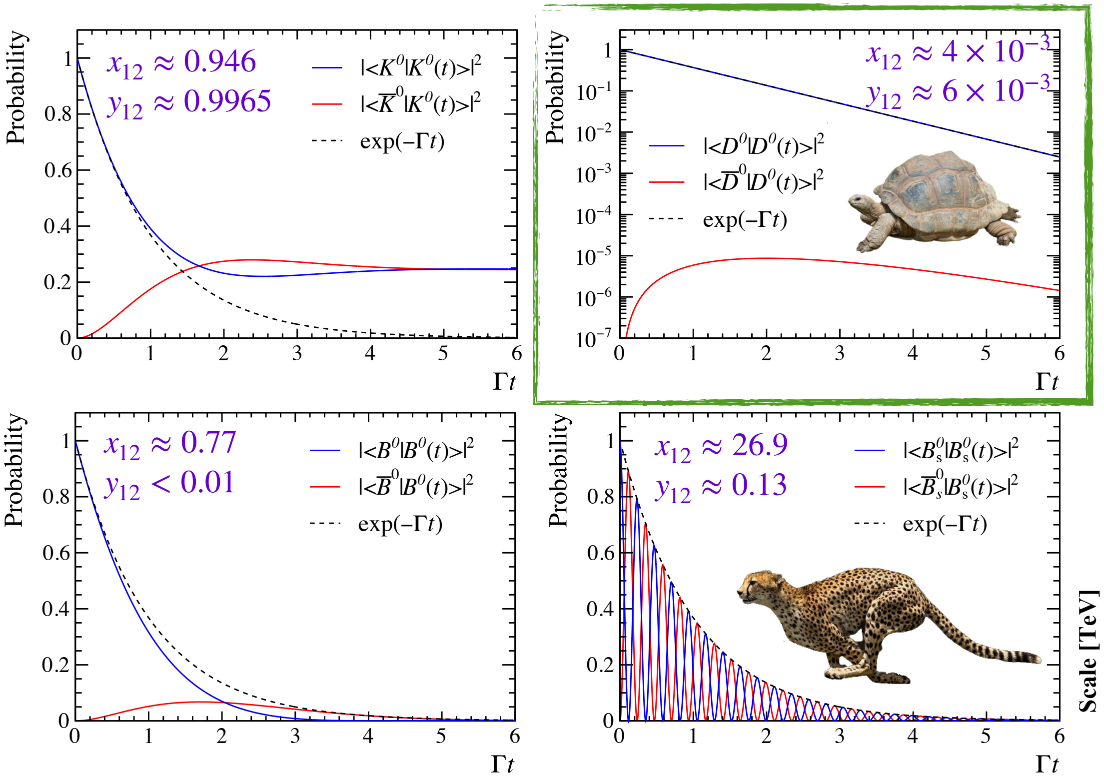
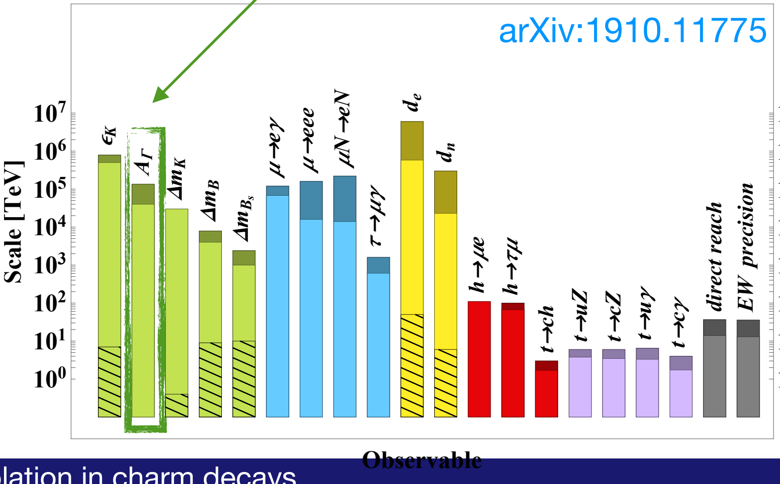


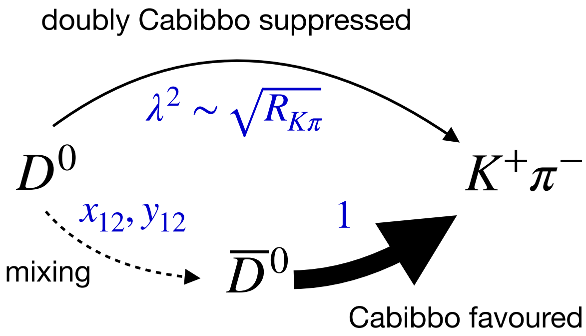
CPV in charm mixing

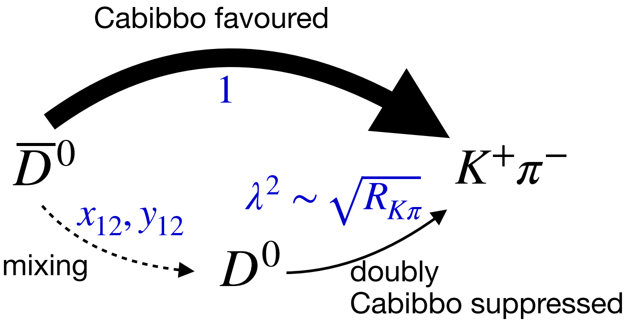


arXiv:1910.11775

Mixing and CPV with $D^0 \to K^+\pi^-$

LHC seminar 26.03.2024
LHCb-PAPER-2024-008
(in preparation)



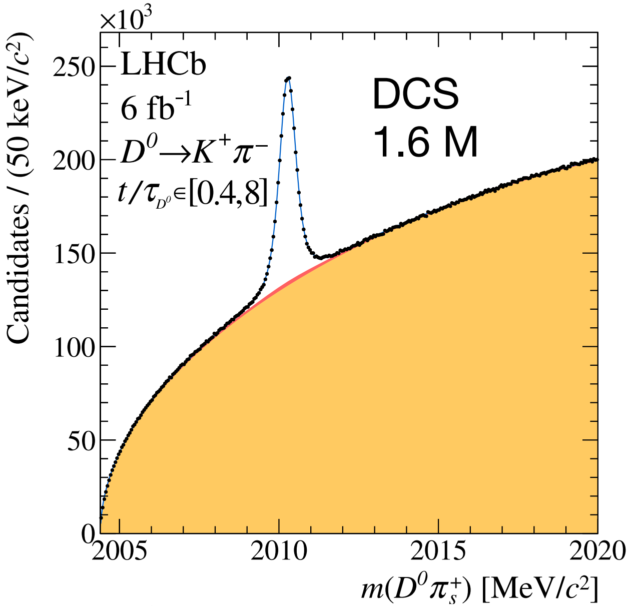


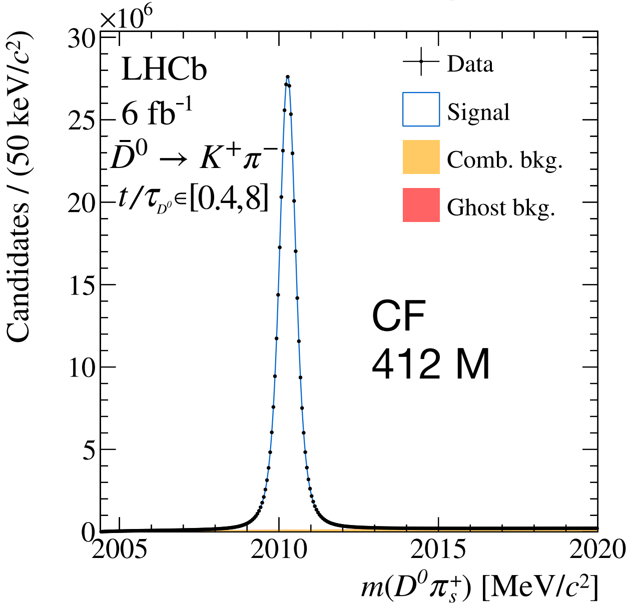
$$R(t) = \frac{\Gamma(D^0 \to K^+\pi^-;t)}{\Gamma(\bar{D}^0 \to K^+\pi^-;t)} = \overset{\text{DCS}}{\boxed{R_{K\pi}}} + \overset{\text{interference}}{\boxed{\sqrt{R_{K\pi}}\,c_{K\pi}\left(\frac{t}{\tau}\right)}} + \overset{\text{mixing + CF}}{\boxed{c'_{K\pi}\left(\frac{t}{\tau}\right)^2}}$$

$$y_{12}\cos\Delta_{K\pi} + x_{12}\sin\Delta_{K\pi}$$

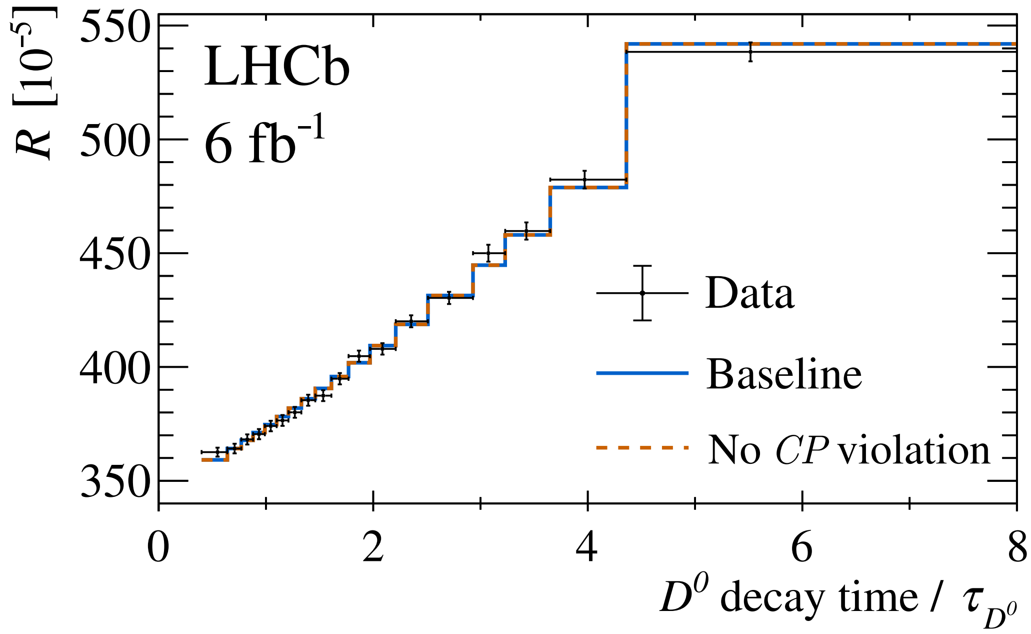
$$\frac{x_{12}^2 + y_{12}^2}{4}$$

$$\frac{A(D^0 \to K^+\pi^-)}{A(\bar{D}^0 \to K^+\pi^-)} \approx -\sqrt{R_{K\pi}}\,e^{i\Delta_{K\pi}}$$

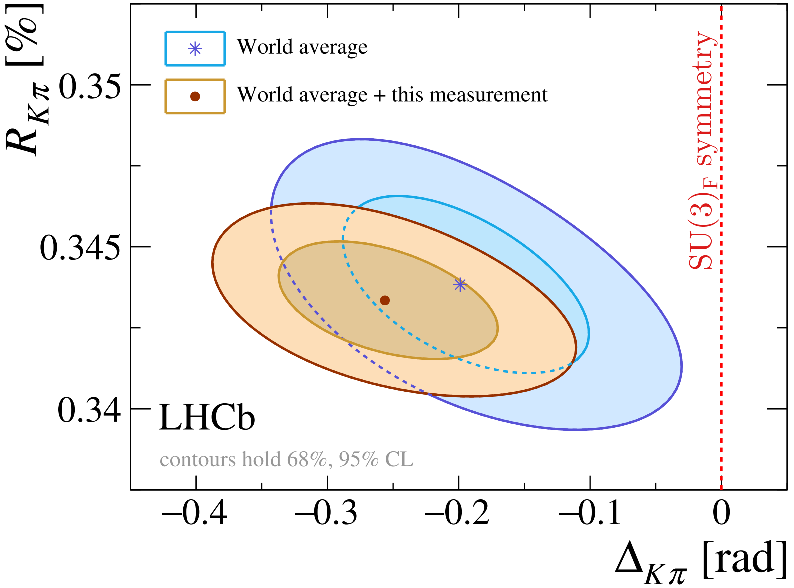




$D^0 \to K^+\pi^-$ results

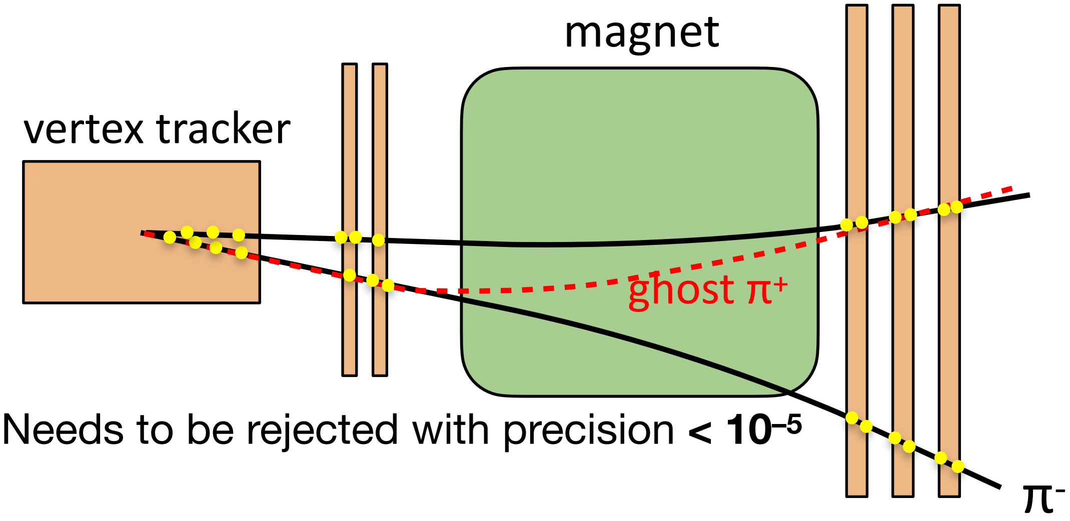


×2 improvement over previous determinations

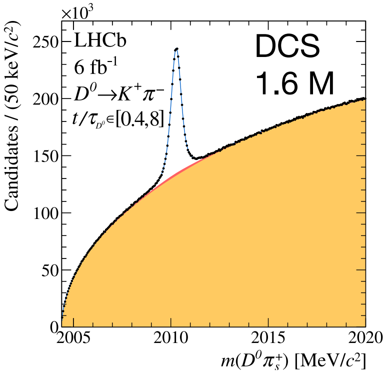


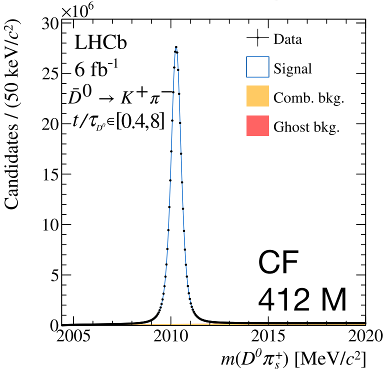
Background from ghost tracks

LHC seminar 26.03.2024
LHCb-PAPER-2024-008
(in preparation)



Needs to be rejected with precision **< 10^{-5}**



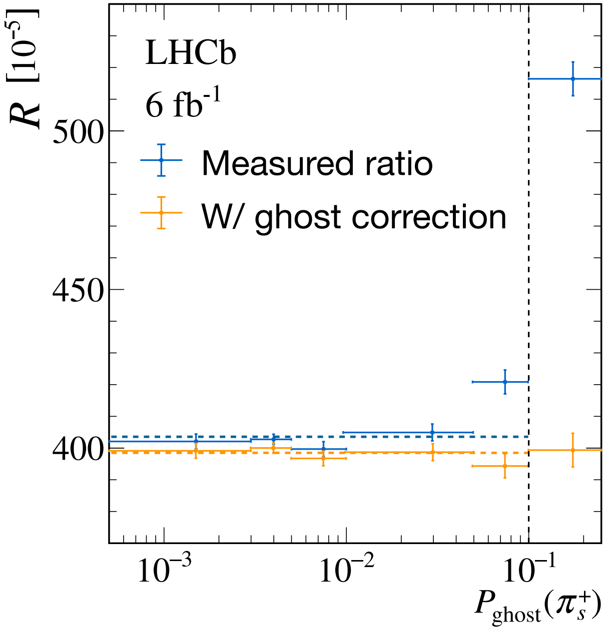


$$D^*(2010)^+ \rightarrow D^0(\rightarrow K^+\pi^-)\pi^+$$

$$D^*(2010)^+ \rightarrow D^0(\rightarrow K^+\pi^-)\pi^+$$

ghost

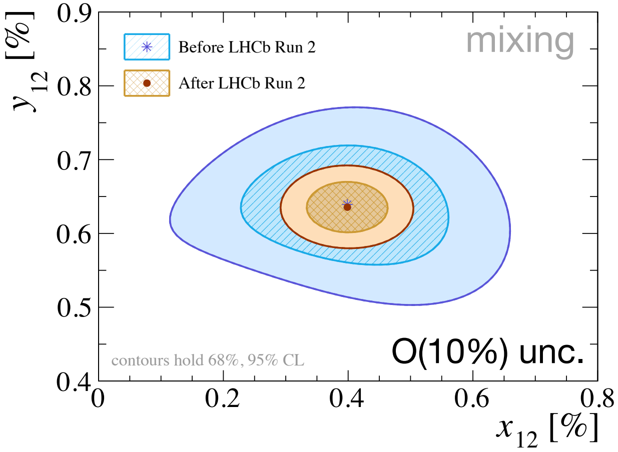
$$D^*(2010)^- \rightarrow \overline{D}^0(\rightarrow K^+\pi^-)\pi^-$$

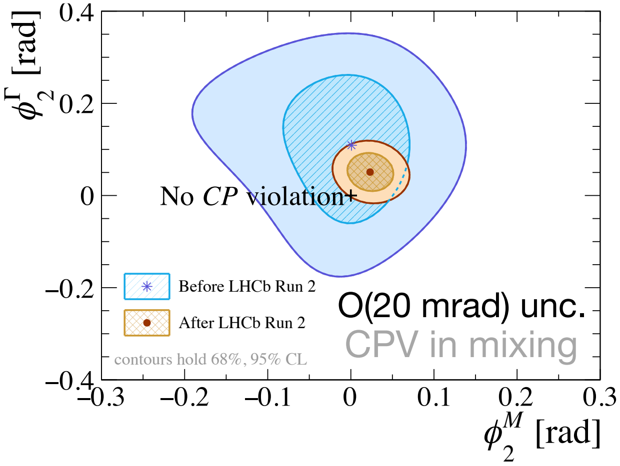


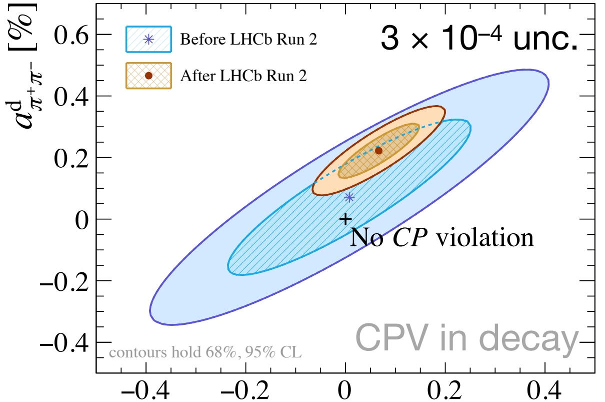
Conclusions

- After 50 years of life, charm looks more like a baby
    - mixing discovered in 2007
    - CPV in 2019

- CPV → BSM physics or unexpected QCD dynamics? More measurements and theoretical developments are needed
- Still waiting for observation of CPV in the mixing (LHCb Upgrade II please come soon…)







charm-fitter

To learn more:

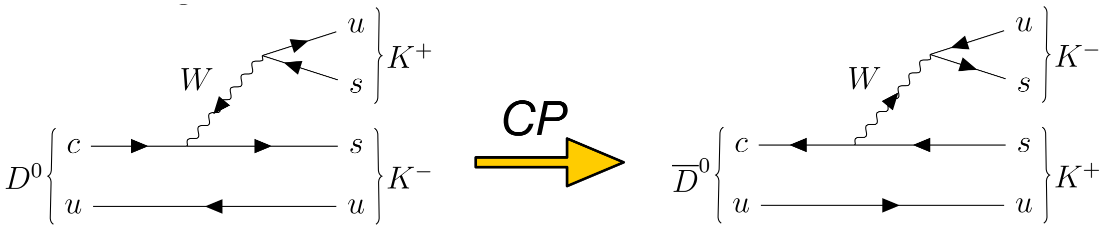
H. Gisbert, M. Golz and D. Mitzel, Mod. Phys. Lett. A 36 (2021) 04, 2130002
A. Lenz and G. Wilkinson, Ann. Rev. Nucl. Part. Sci. 71 (2021) 59-85
T. Pajero, Mod. Phys. Lett. A 37 (2022) 24, 2230012
A. Petrov, Eur. Phys. J. ST 233 (2024) 2, 439

Backup slides

Requirements to observe CPV

CP transformation:

- **strong phases** are invariant
- **weak phases** change sign



$A = |A|e^{i\delta}e^{i\phi}$

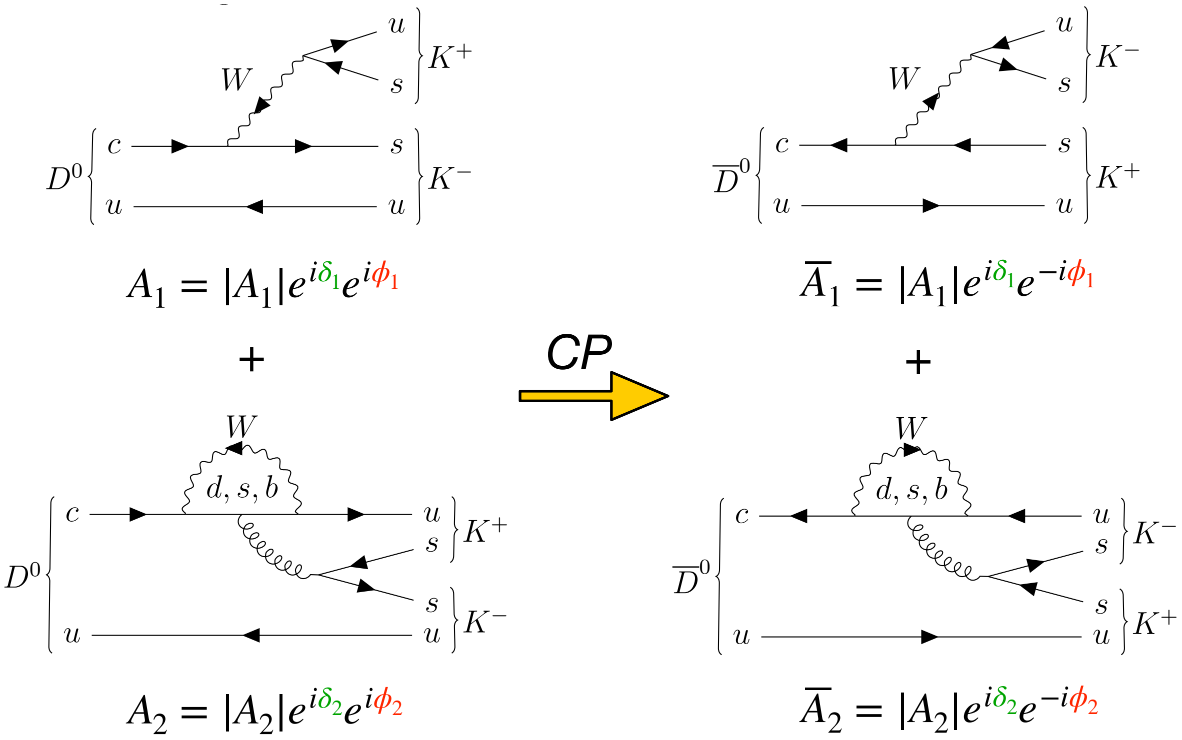
$\overline{A} = |A|e^{i\delta}e^{-i\phi}$

Only $|A|^2$ is observable
→ no *CP*V if only one amplitude contributes

Requirements to observe CPV

CP transformation:

- **strong phases** are invariant
- **weak phases** change sign



$$A_1 = |A_1| e^{i\delta_1} e^{i\phi_1}$$

$$\overline{A}_1 = |A_1| e^{i\delta_1} e^{-i\phi_1}$$

+

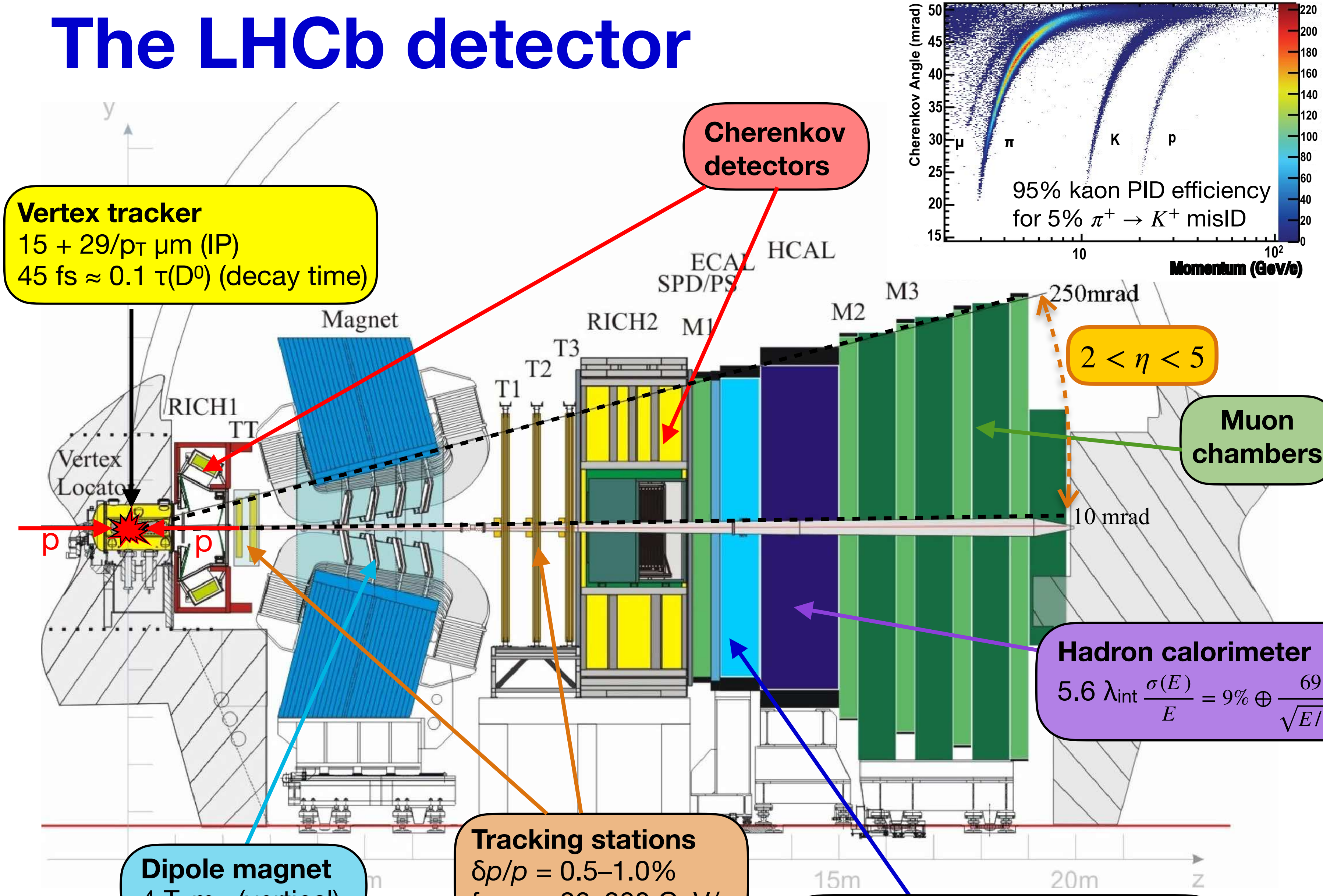
$$A_2 = |A_2| e^{i\delta_2} e^{i\phi_2}$$

$$\overline{A}_2 = |A_2| e^{i\delta_2} e^{-i\phi_2}$$

$$\boxed{|A_1 + A_2|^2 - |\overline{A}_1 + \overline{A}_2|^2 = -4|A_1||A_2| \sin(\delta_1 - \delta_2) \sin(\phi_1 - \phi_2)}$$

Need (at least) two interfering amplitudes with
– **different weak phases**
– **different strong phases**

The LHCb detector



95% kaon PID efficiency for 5% $\pi^+ \to K^+$ misID

Cherenkov detectors

Vertex tracker
15 + 29/p_T μm (IP)
45 fs ≈ 0.1 τ(D^0) (decay time)

$2 < \eta < 5$

Muon chambers

Hadron calorimeter
5.6 λ_{int} $\frac{\sigma(E)}{E} = 9\% \oplus \frac{69\,\%}{\sqrt{E/GeV}}$

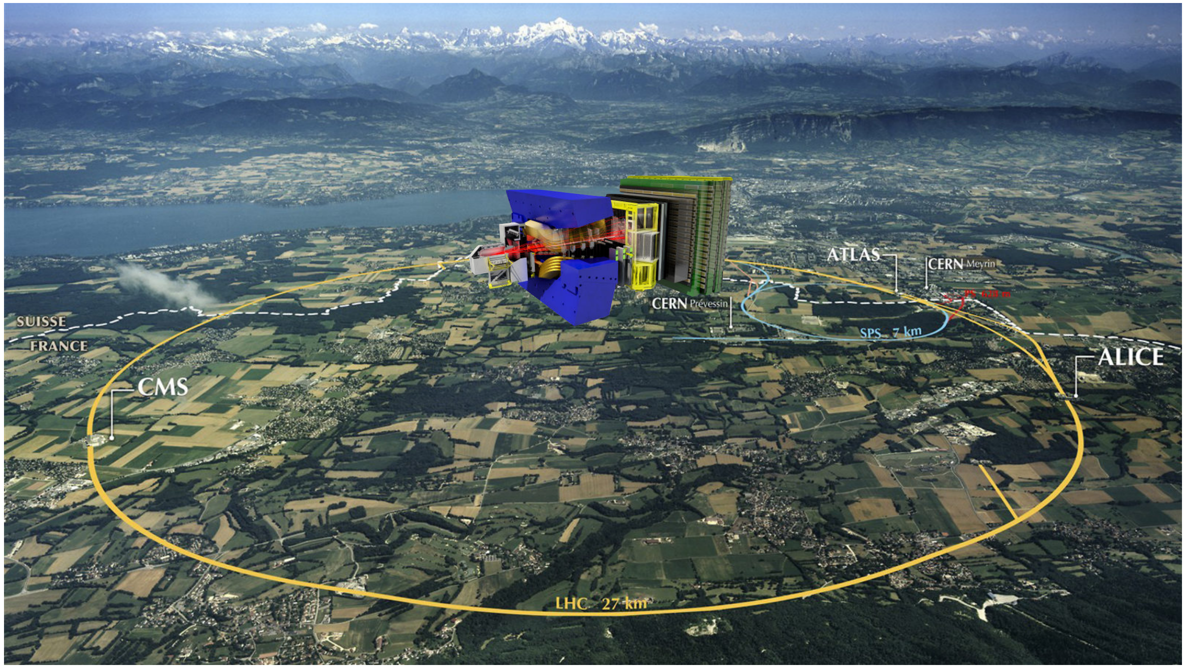
Dipole magnet
4 T·m (vertical)

Tracking stations
δp/p = 0.5–1.0%
for p = 20–200 GeV/c

Electromagnetic calorimeter
25 X_0, 1.2 λ_{int} $\frac{\sigma(E)}{E} = 1\% \oplus \frac{10\,\%}{\sqrt{E/GeV}}$

JINST 3 S08005 (2008)
Int. J. Mod. Phys. A 30 (2015) 7, 1530022

LHC as a charm factory



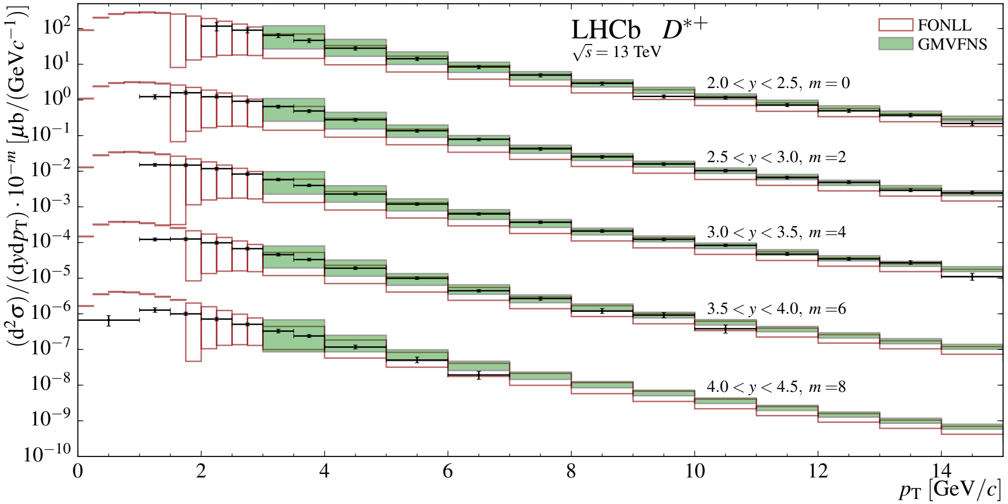
Largest number of $c\bar{c}$ pairs ever.
Mostly boosted at large η.

In the LHCb acceptance:

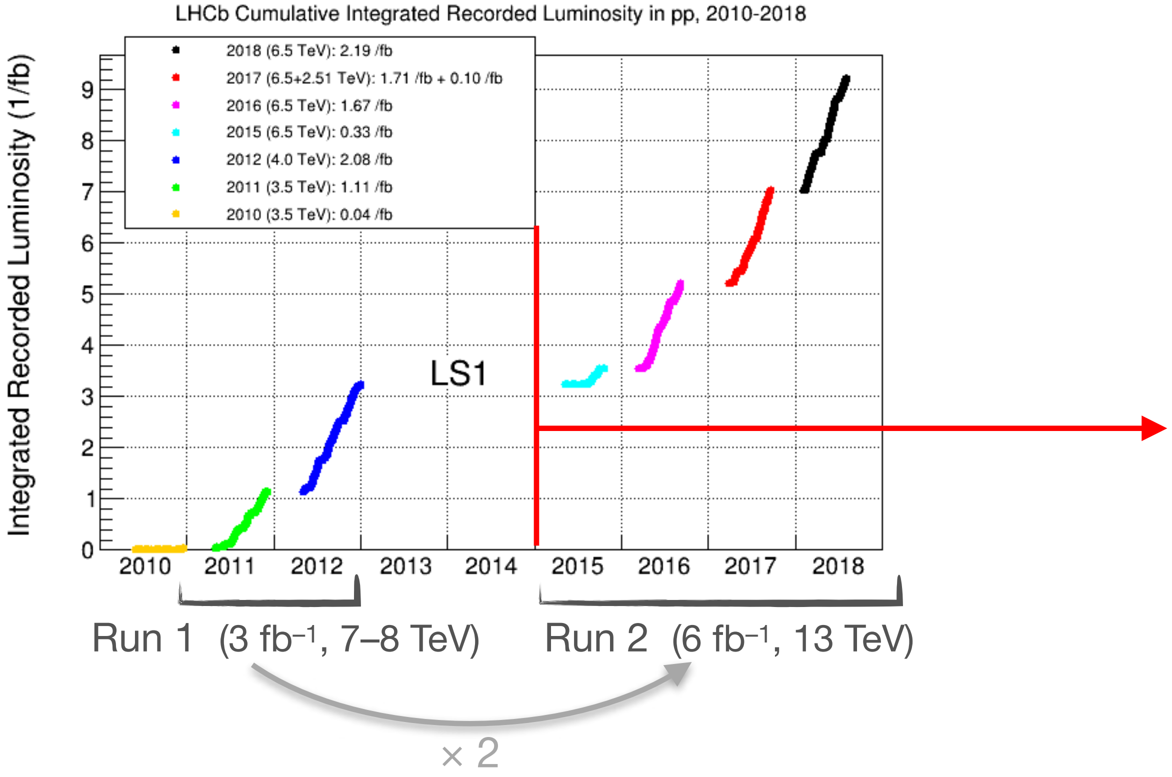
$$\sigma(pp \to c\bar{c}X) \approx \begin{array}{l} 1.4\text{ mb } \left(\sqrt{s} = 7\text{ TeV}\right) \\ 2.4\text{ mb } \left(\sqrt{s} = 13\text{ TeV}\right) \end{array}$$

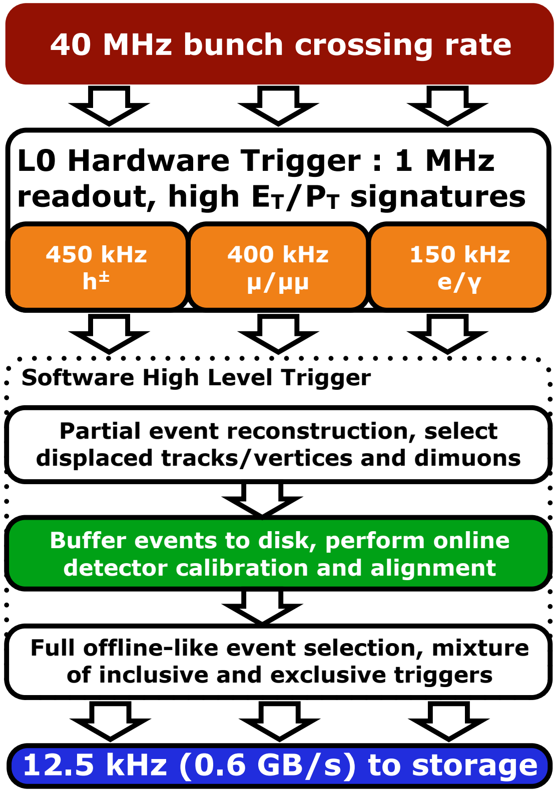
Nucl. Phys. B871 (2013) 1–20
JHEP 05 (2017) 074

1 MHz $c\bar{c}$ pairs



LHCb trigger and data-taking strategy





40 MHz bunch crossing rate

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

450 kHz $h^\pm$ | **400 kHz $\mu/\mu\mu$** | **150 kHz e/γ**

Software High Level Trigger

Partial event reconstruction, select displaced tracks/vertices and dimuons

Buffer events to disk, perform online detector calibration and alignment

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

12.5 kHz (0.6 GB/s) to storage

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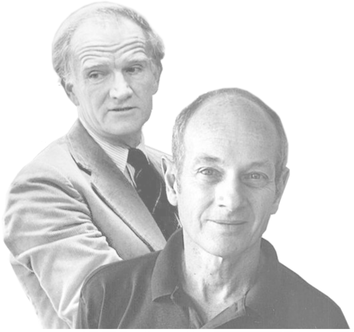
Yield has more than doubled between Run 1 and 2:

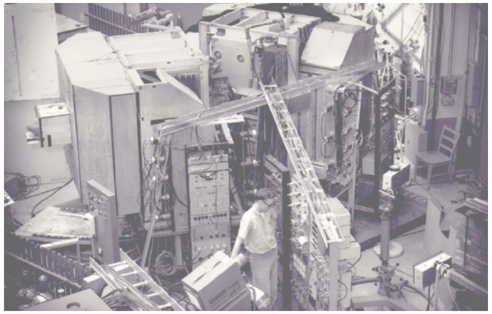
- × 1.7 increase in production cross-section;
- new “Turbo" data taking paradigm
  - only the signal candidates are recorded, rest of the event is discarded;
  - improved efficiency, higher rate recorded.

Pioneered by charm triggers

1964
Strange particles:
CP **violation in K^0 decays**

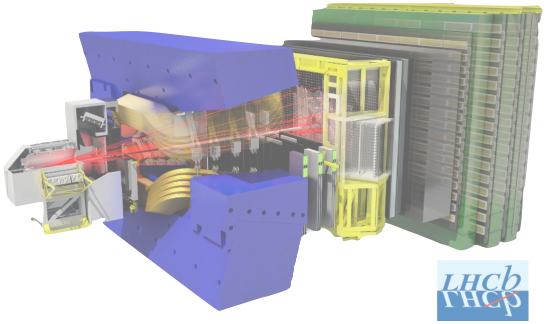


Cronin, Fitch et al.

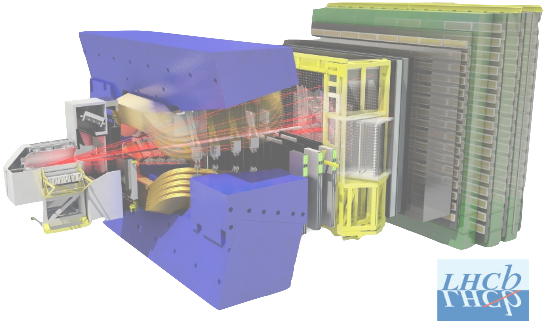


2001
Beauty particles:
CP **violation in B^0 decays**

2013
Beauty-strange particles:
CP **violation in B_s^0 decays**



2019
Charm particles:
CP **violation in D^0 decays**



$D^0 \rightarrow K^+\pi^-$ results

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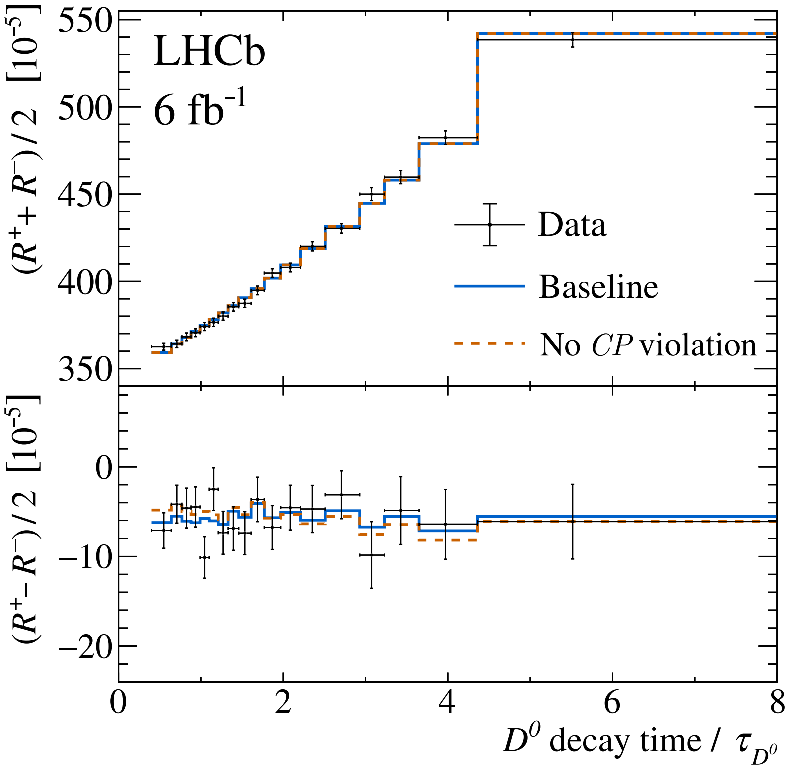


Parameters		Correlations [%]					
		$R_{K\pi}$	$c_{K\pi}$	$c'_{K\pi}$	$A_{K\pi}$	$\Delta c_{K\pi}$	$\Delta c'_{K\pi}$
$R_{K\pi}$	$(343.1 \pm 2.0) \times 10^{-5}$	100.0	−92.4	80.0	0.9	−0.8	0.1
$c_{K\pi}$	$(51.4 \pm 3.5) \times 10^{-4}$		100.0	−94.1	−1.4	1.4	−0.7
$c'_{K\pi}$	$(13.1 \pm 3.7) \times 10^{-6}$			100.0	0.7	−0.7	0.1
$A_{K\pi}$	$(-7.1 \pm 6.0) \times 10^{-3}$				100.0	−91.5	79.4
$\Delta c_{K\pi}$	$(3.0 \pm 3.6) \times 10^{-4}$					100.0	−94.1
$\Delta c'_{K\pi}$	$(-1.9 \pm 3.8) \times 10^{-6}$						100.0

$$R^{\pm}_{K\pi}(t) \approx R_{K\pi}(1 \pm A_{K\pi}) + \sqrt{R_{K\pi}(1 \pm A_{K\pi})}(c_{K\pi} \pm \Delta c_{K\pi})\frac{t}{\tau_{D0}} + (c'_{K\pi} \pm \Delta c'_{K\pi})\frac{t^2}{\tau^2_{D0}}$$

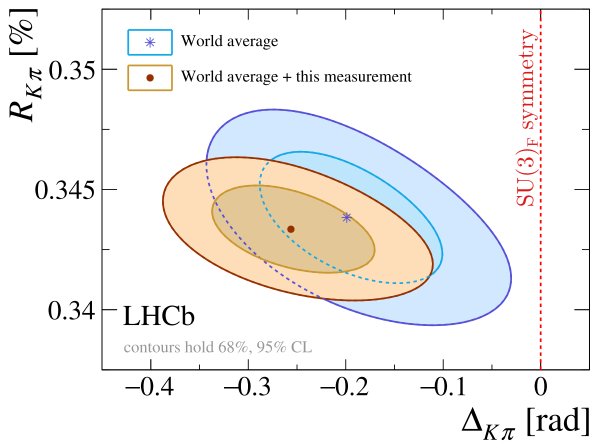
$$c_{K\pi} \approx y_{12}\cos\phi^{\Gamma}_f \cos\Delta_f + x_{12}\cos\phi^M_f \sin\Delta_f\,,$$

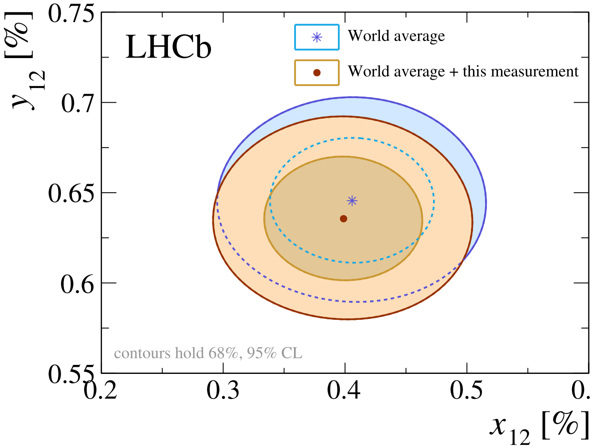
$$\Delta c_{K\pi} \approx x_{12}\sin\phi^M_f \cos\Delta_f - y_{12}\sin\phi^{\Gamma}_f \sin\Delta_f\,,$$

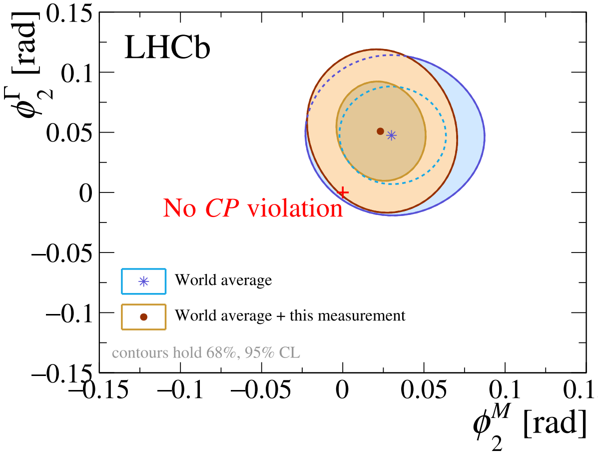
$$c'_{K\pi} \approx \frac{1}{4}\left(x^2_{12} + y^2_{12}\right)\,,$$

$$\Delta c'_{K\pi} \approx \frac{1}{2}x_{12}y_{12}\sin(\phi^M_f - \phi^{\Gamma}_f)\,.$$

×2 improvement over previous determinations



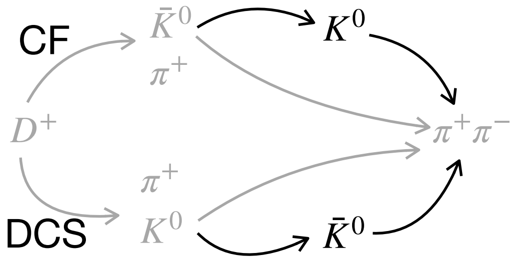




CPV from final-state KS

[PRL 119 (2017) 18180

- Consider the CF decay $D^+ \to K_S^0\pi^+$:
  - $A_{CP}(t) = A_{CP}^{\text{decay}} + A_{CP}^{\bar{K}^0}(t) + A_{CP}^{\text{int}}(t)$

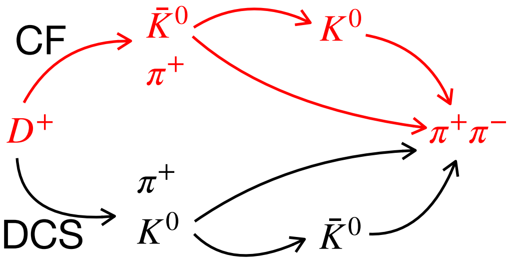


CPV in charm decay

$$\text{Im}\left(\frac{V_{cd}^* V_{us}}{V_{cs}^* V_{ud}}\right) \approx 10^{-5}$$

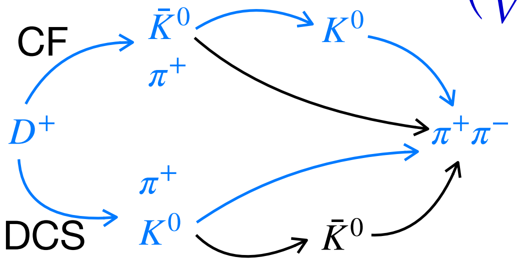
CPV in kaon mixing

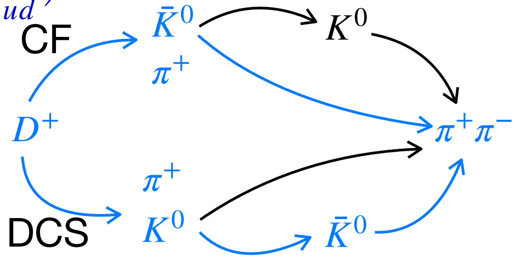
$\text{Re}(\epsilon) \approx 10^{-3}$

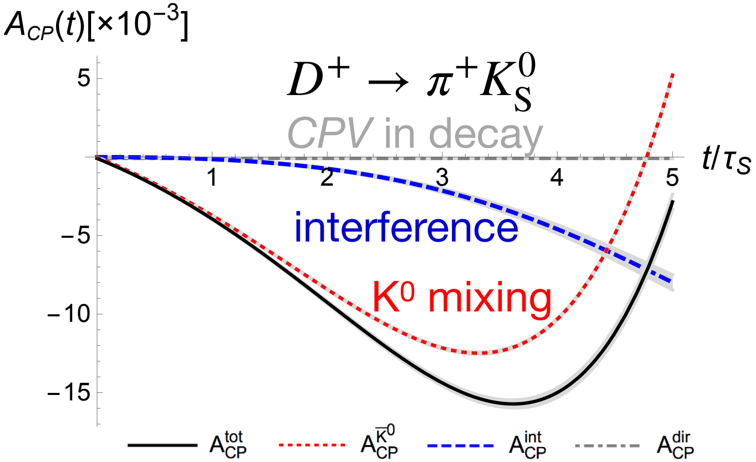


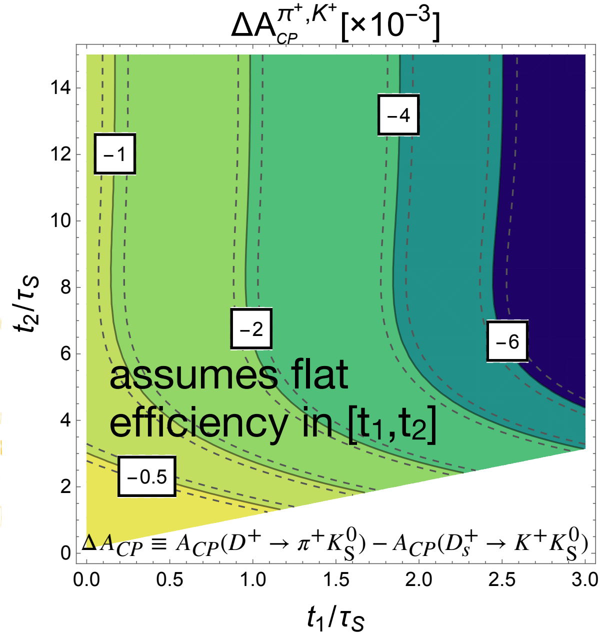
CPV in interference between D⁺ decay and kaon mixing

$$\text{Im}(\epsilon)\text{Re}\left(\frac{V_{cd}^* V_{us}}{V_{cs}^* V_{ud}}\right) \approx 10^{-3}$$









assumes flat efficiency in [t₁,t₂]

$\Delta A_{CP} \equiv A_{CP}(D^+ \to \pi^+ K_S^0) - A_{CP}(D_s^+ \to K^+ K_S^0)$

Only *CPV* in the interference survive in the difference

The tortoise of flavour

Kagan & Silvestrini, Phys. Rev. D 103 (2021) 5, 053008

$$i\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix} D^0(t) \\ \overline{D}^0(t) \end{pmatrix} = \left(\mathbf{M} - \frac{i}{2}\mathbf{\Gamma}\right)\begin{pmatrix} D^0(t) \\ \overline{D}^0(t) \end{pmatrix}$$

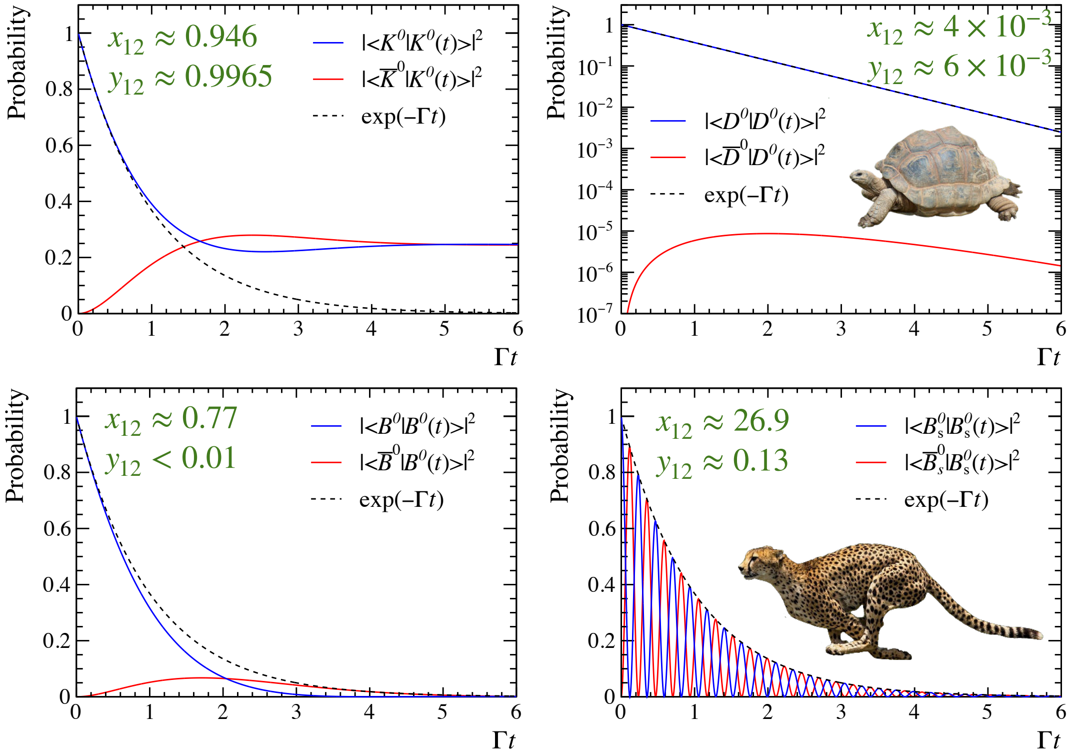
off-shell transitions. BSM?

on-shell transitions

Oscillation probability is determined by the size of the transition amplitudes:

$$\boxed{x_{12} \equiv \frac{2|M_{12}|}{\Gamma}, \qquad y_{12} \equiv \frac{|\Gamma_{12}|}{\Gamma}}$$

"mixing parameters"



The tortoise of flavour

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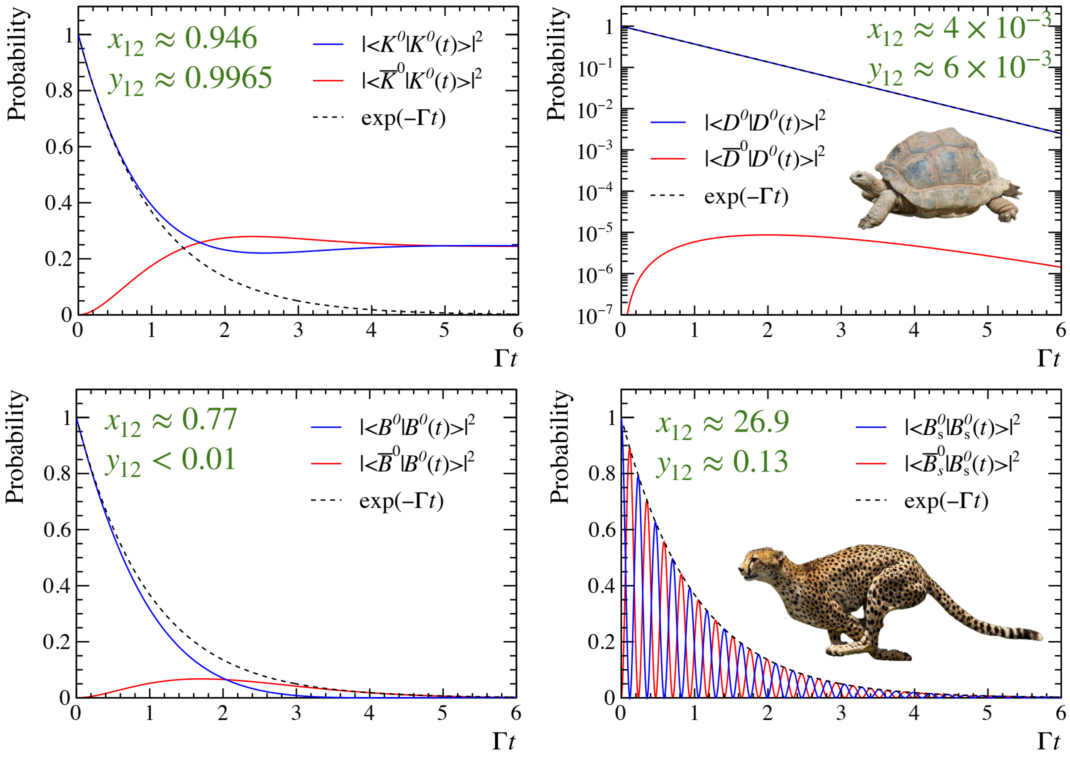
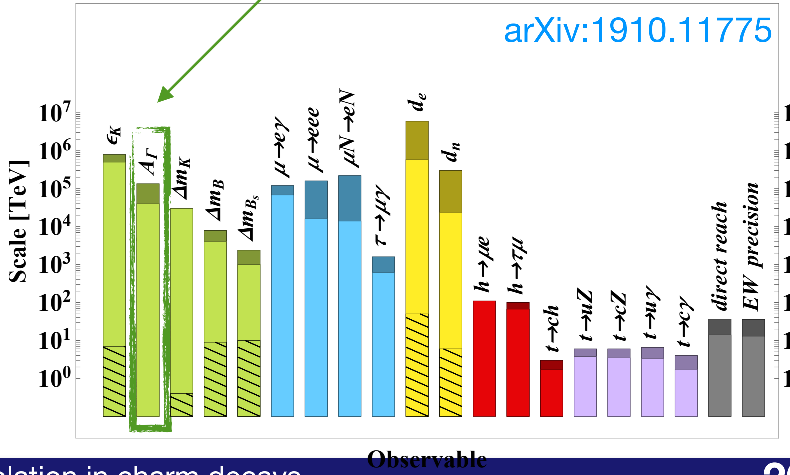


dispersive and absorptive CPV mixing phases

$$\boxed{\begin{aligned}\phi_2^M &\equiv \arg\left(\frac{M_{12}}{M_{12}^{\Delta U=2}}\right)\\ \phi_2^\Gamma &\equiv \arg\left(\frac{\Gamma_{12}}{\Gamma_{12}^{\Delta U=2}}\right)\end{aligned}}$$


arXiv:1910.11775

Background from ghost tracks

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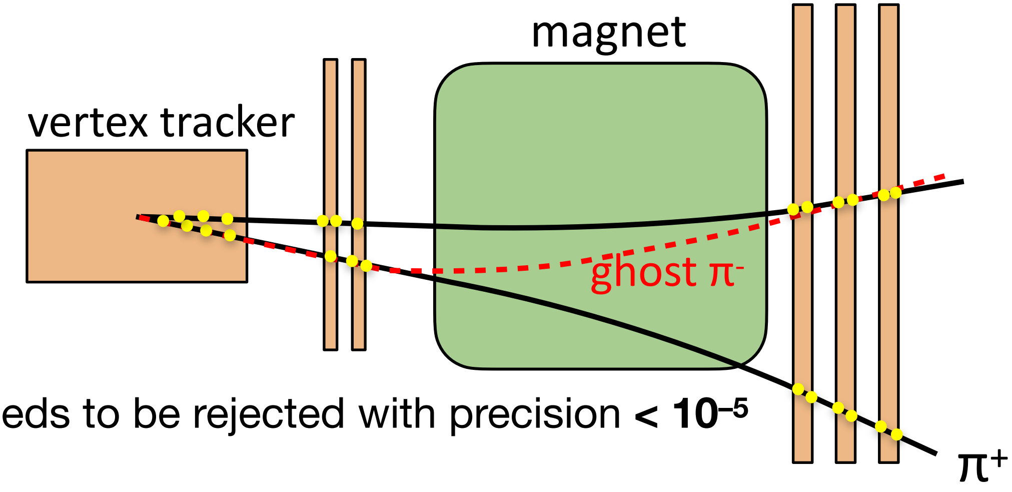
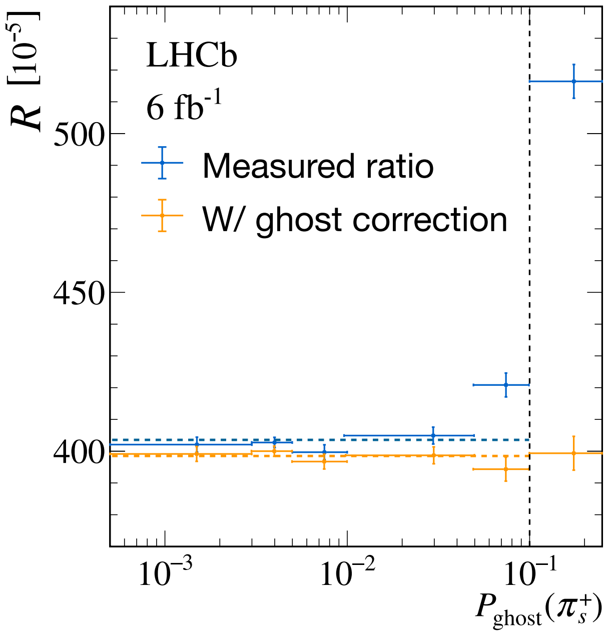
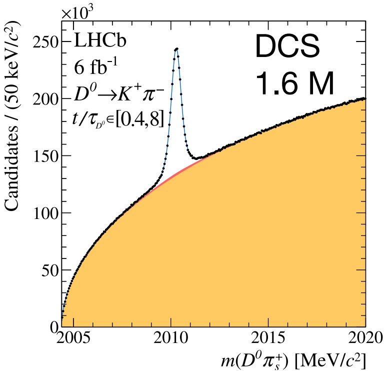
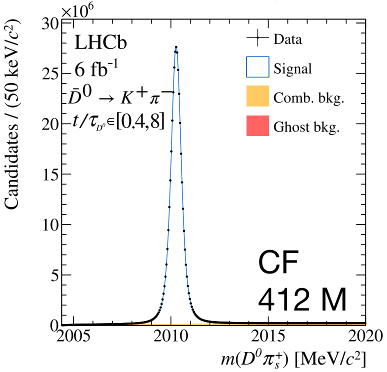


Needs to be rejected with precision **< 10⁻⁵**





$$D^*(2010)^+ \to D^0(\to K^+\pi^-)\pi^+$$



$$D^*(2010)^- \to \overline{D}^0(\to K^+\pi^-)\pi^-$$

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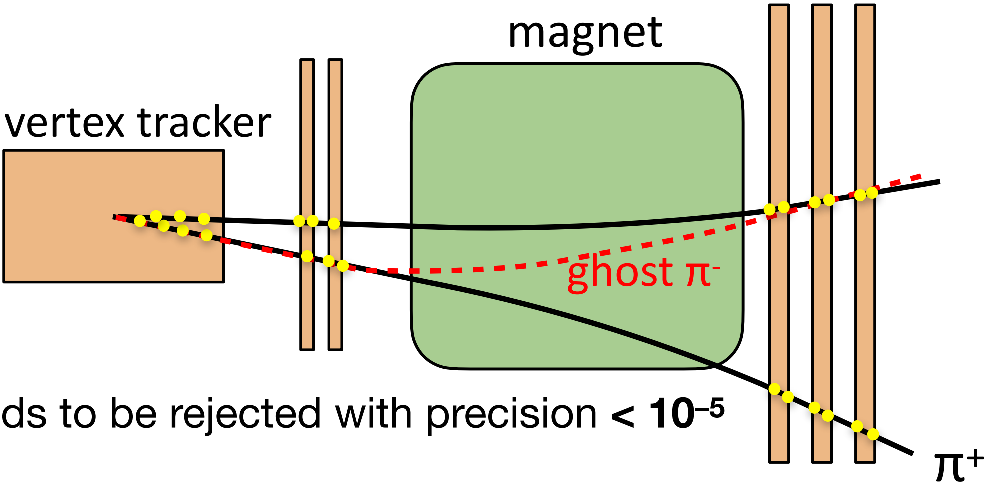
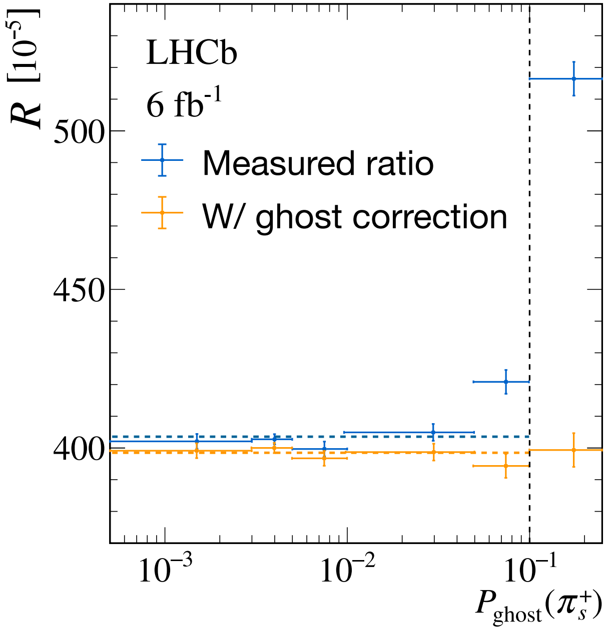
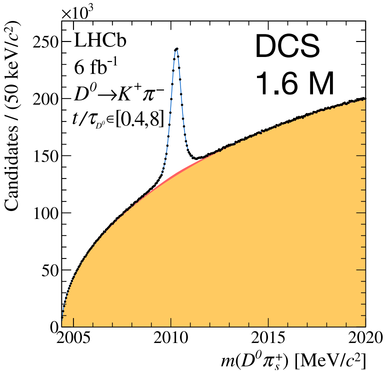
Background from ghost tracks



Needs to be rejected with precision **< 10–5**





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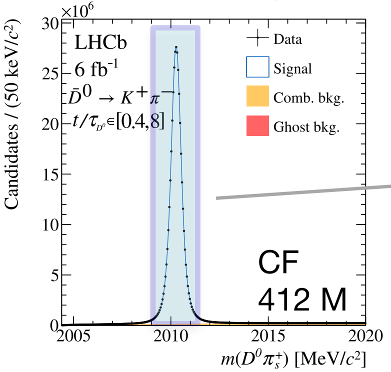

$$D^*(2010)^- \to \overline{D}^0(\to K^+\pi^-)\pi^-$$

doubly reconstructed π^+/π^-