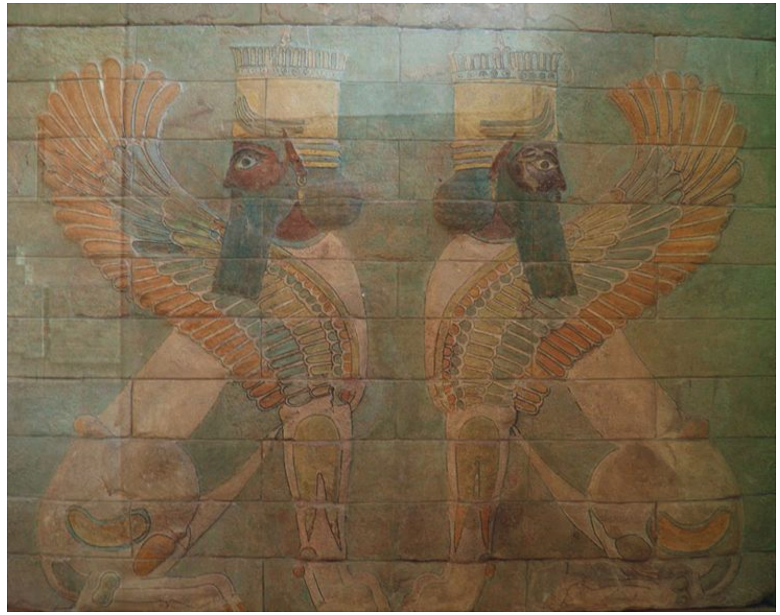


Observation of CP violation in charm: what should we study next ?

Wojciech Krzemień

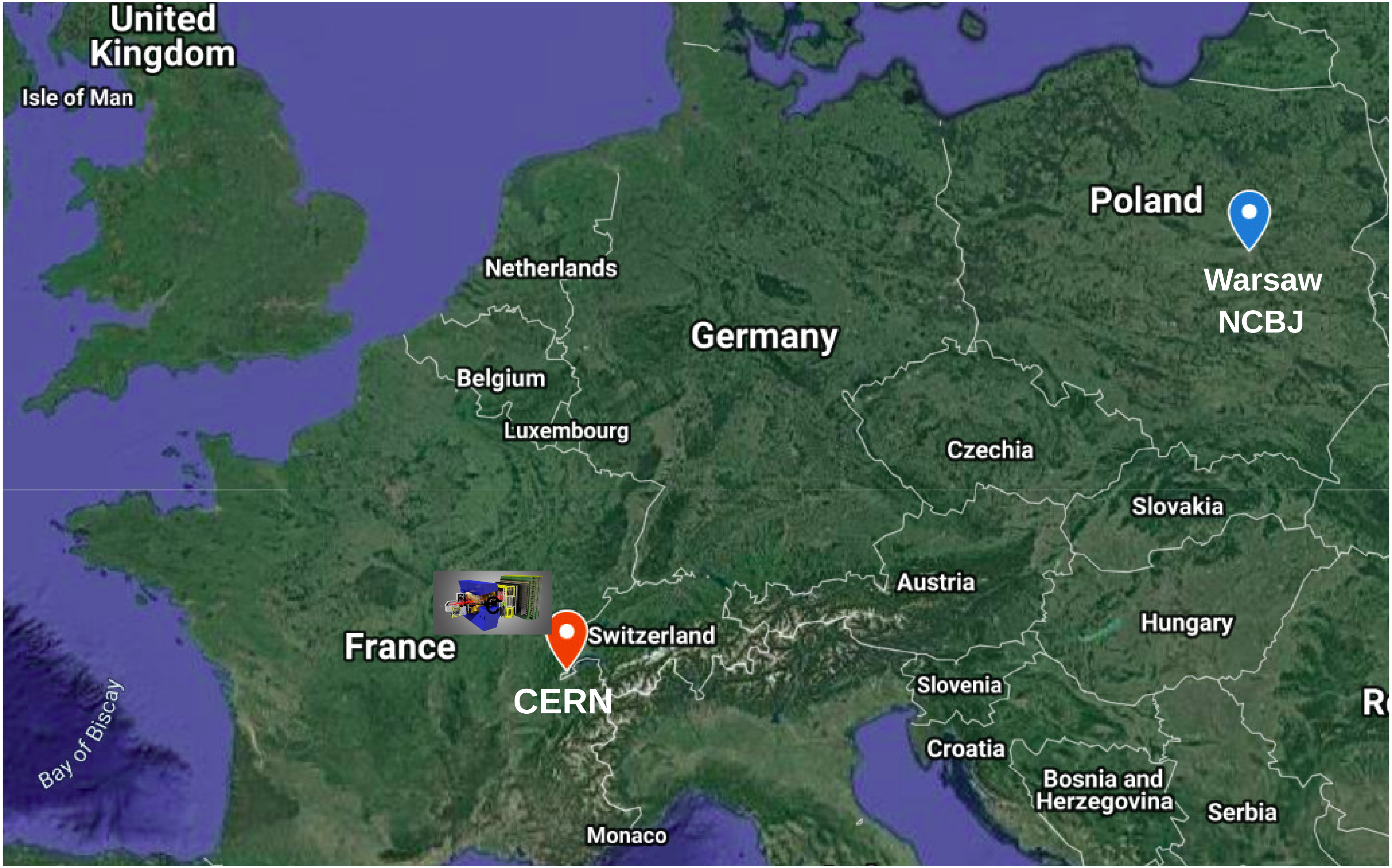
on behalf of the LHCb collaboration

Workshop on High Energy Physics Phenomenology XVI

IIT Guwahati 06. 12. 2019

Outline

- ➔ Flavour mixing and CP violation (in charm)
- ➔ Experiments
- ➔ CP symmetry violation discovery (CP in decay)
- ➔ Indirect CPV searches
- ➔ Future perspectives
- ➔ Summary & Outlook


United Kingdom
Isle of Man
Netherlands
Belgium
Luxembourg
Germany
Poland
Warsaw
NCBJ
Czechia
Slovakia
Austria
Hungary
Switzerland
France
CERN
Slovenia
Croatia
Bosnia and Herzegovina
Serbia
Monaco
Bay of Biscay

Scales:
Warsaw – CERN: ~1002 km
Warsaw – Guwahati: ~6573 km

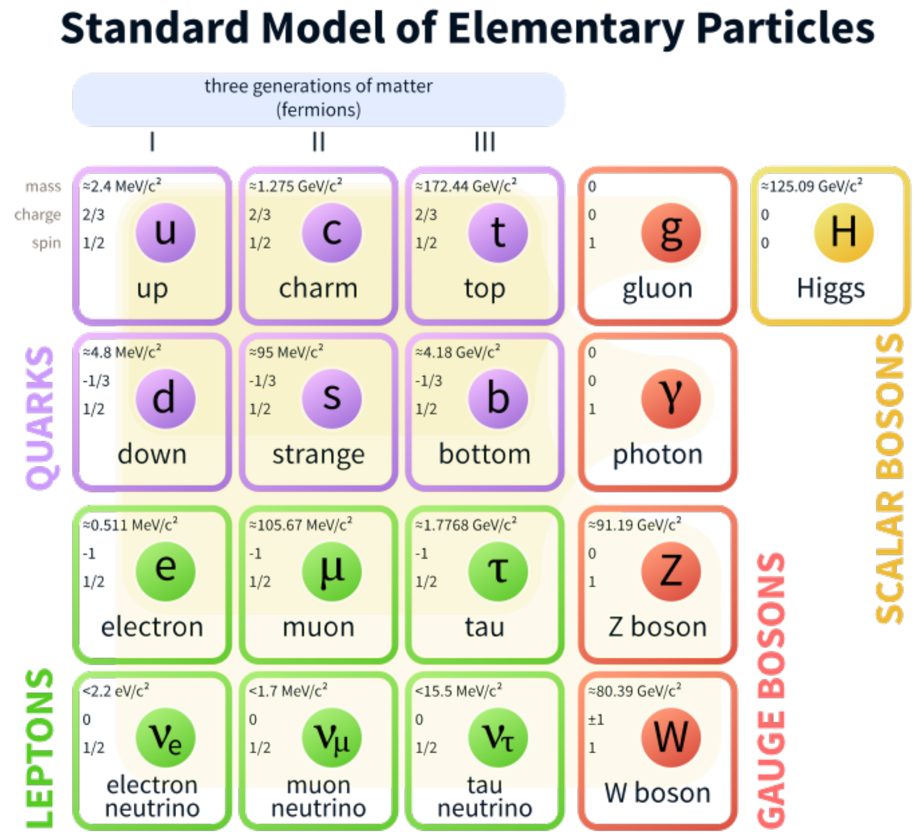
Predicted by SM:

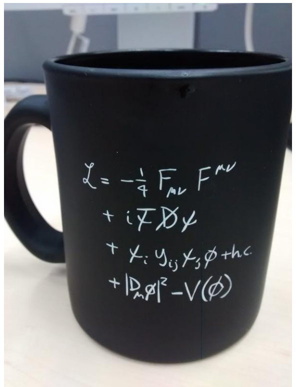
- W, Z boson
- gluon
- c and t quarks
- Higgs boson

However several unresolved questions:

- Quark mass hierarchy problem
- Matter-antimatter asymmetry
- Dark matter / dark energy
- Neutrino mass

- ...
- How to incorporate gravity forces





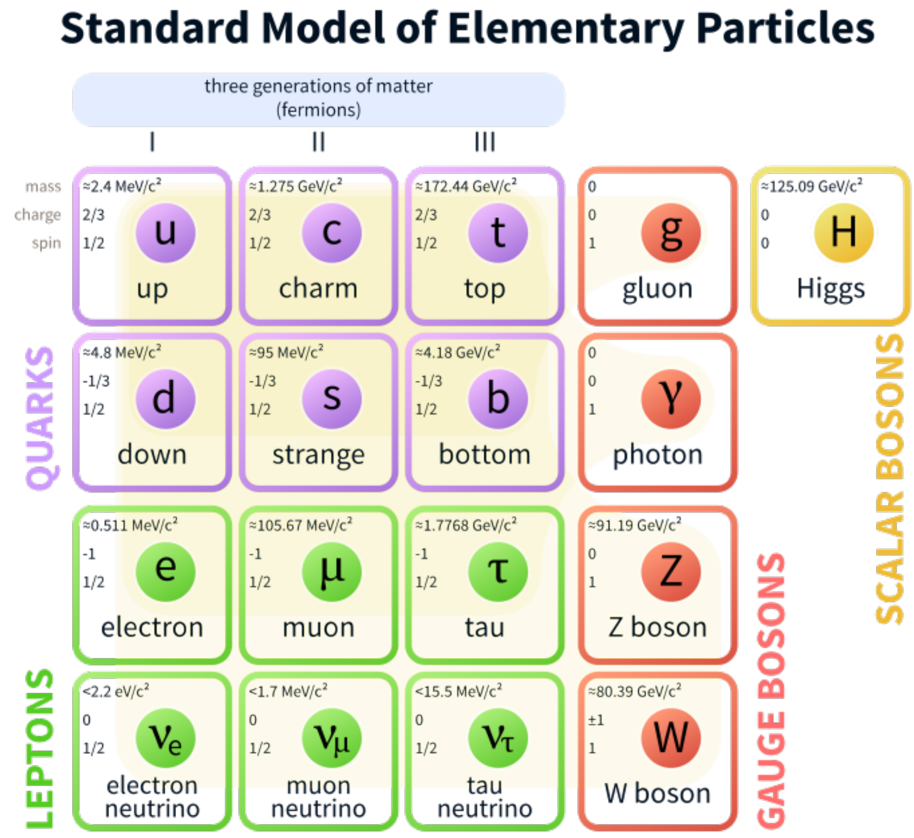
Predicted by SM:

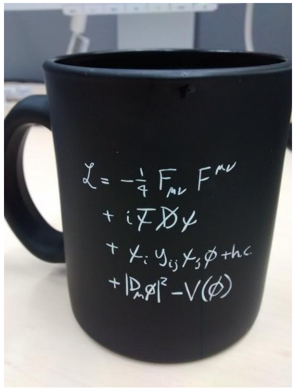
- W, Z boson
- gluon
- c and t quarks
- Higgs boson

However several unresolved questions:

- Quark mass hierarchy problem
- Matter-antimatter asymmetry
- Dark matter / dark energy
- Neutrino mass

- ...
- How to incorporate gravity forces

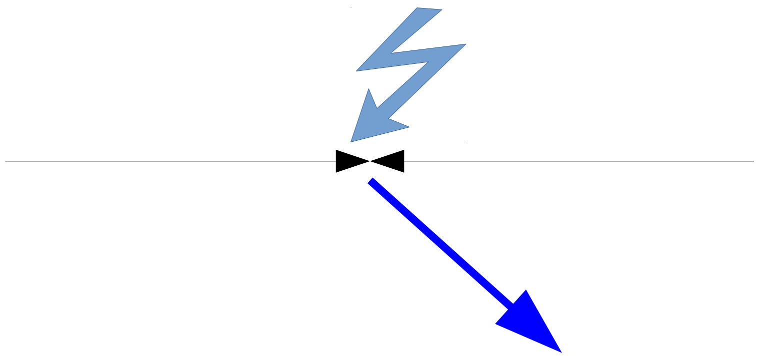




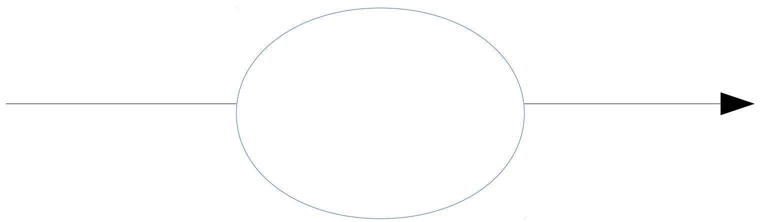
Looking for SM “holes” to reveal “hidden” New Physics phenomena

Towards New Physics

Direct searches



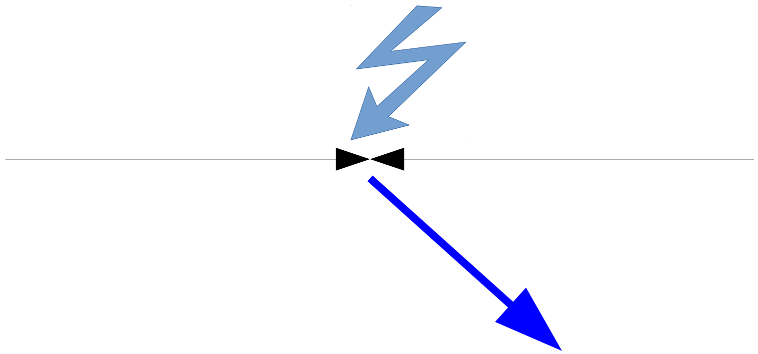
Indirect searches (precise measurements)



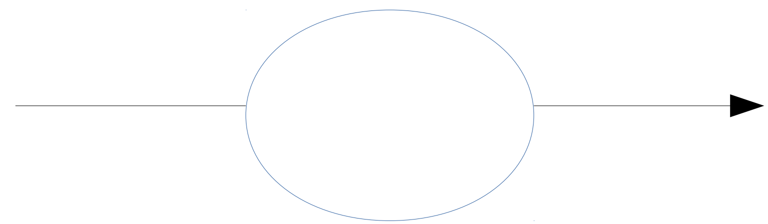
Loops → virtual particles

Towards New Physics

Direct searches



Indirect searches (precise measurements)



Loops → virtual particles

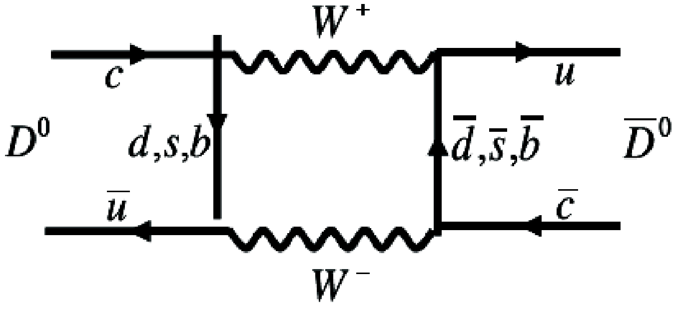
Flavour physics → sensitivity to particles much heavier than produced directly

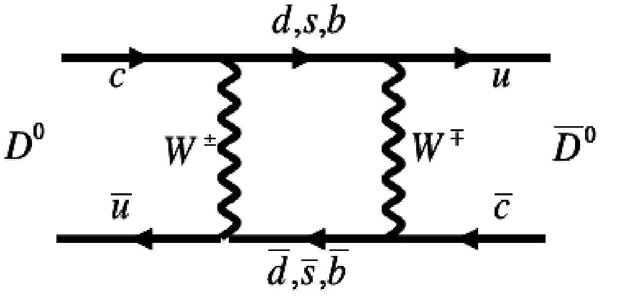
In the past:
- charm quark prediction (suppression of FCNC)
- bottom/top quark prediction (observation of CP violation)

Flavour mixing

Neutral flavour mesons mixing

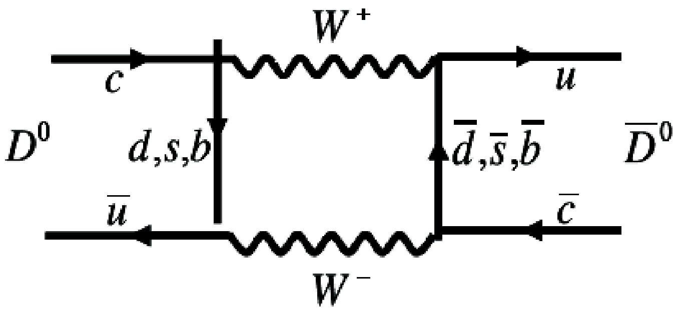
Weak interactions do not conserve the flavour

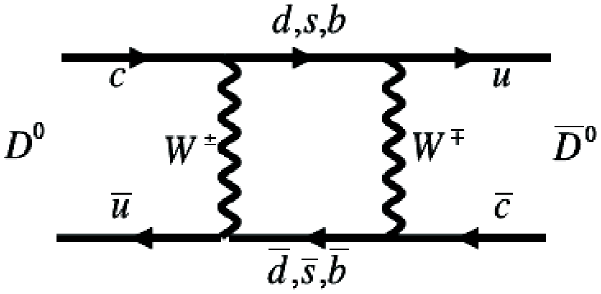




Neutral flavour mesons mixing

Weak interactions do not conserve the flavour



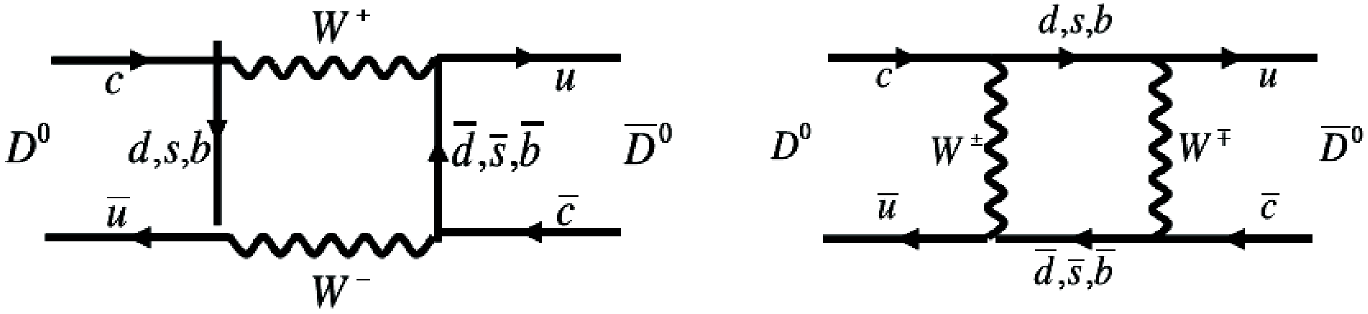


Flavour states are not eigenvectors of the full Hamiltonian

$$\frac{\partial}{\partial t}|\Phi> = H|\Phi>$$

Neutral flavour mesons mixing

Weak interactions do not conserve the flavour



Flavour states are not eigenvectors of the full Hamiltonian

$$\frac{\partial}{\partial t}|\Phi >= H|\Phi >$$

Mass eigenstates expressed as a superposition of flavour eigenstates :

$$|D_{1,2}\rangle = p|\mathrm{D}^0\rangle \pm q|\bar{\mathrm{D}}^0\rangle \qquad |p|^2 + |q|^2 = 1$$

p, q are complex

Neutral flavour mesons mixing II

Probabilities of mixing:

$\Pr[P^0 \rightarrow P^0] \sim e^{-\Gamma t} (\cosh(y\Gamma t) + \cos(x\Gamma t))$

$\Pr[P^0 \rightarrow \overline{P}^0] \sim e^{-\Gamma t} |q/p|^2 (\cosh(y\Gamma t) - \cos(x\Gamma t))$

Mixing parameters:

$$x = \frac{\Delta m}{\Gamma} \qquad \Delta\Gamma = \Gamma_1 - \Gamma_2$$

$$y = \frac{\Delta\Gamma}{2\Gamma} \qquad \Delta m = m_1 - m_2$$

Neutral flavour mesons mixing II

Probabilities of mixing:

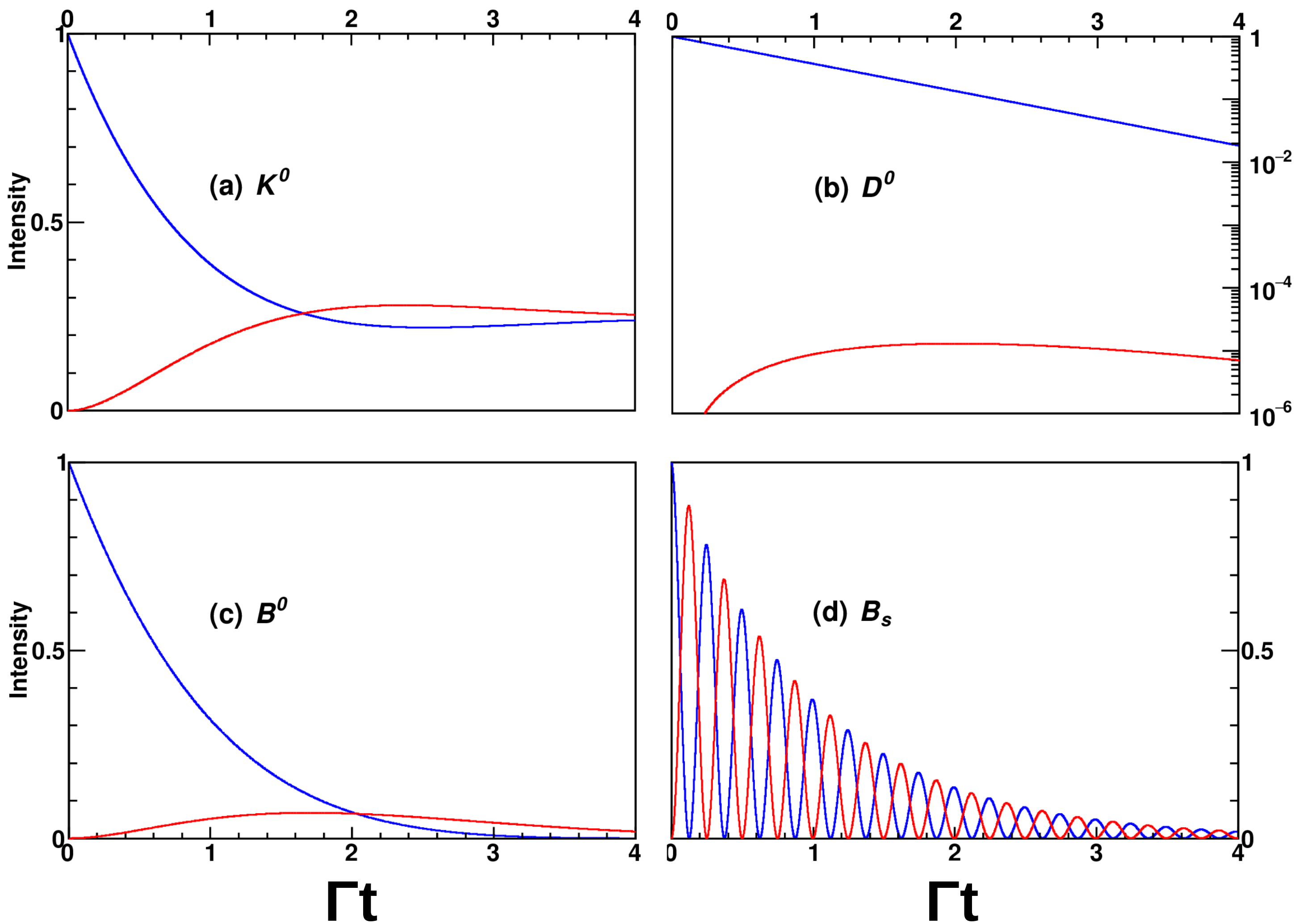
$Pr[P^0 \rightarrow P^0] \sim e^{-\Gamma t} (\cosh(y\Gamma t) + \cos(x\Gamma t))$

$Pr[P^0 \rightarrow \overline{P}^0] \sim e^{-\Gamma t} |q/p|^2 (\cosh(y\Gamma t) - \cos(x\Gamma t))$

Mixing parameters:

$$x = \frac{\Delta m}{\Gamma} \qquad \Delta\Gamma = \Gamma_1 - \Gamma_2$$

$$y = \frac{\Delta\Gamma}{2\Gamma} \qquad \Delta m = m_1 - m_2$$



D^0 very slow:
x ≈0.001, y≈0.001

K^0 slow:
X≈-0.95, y=0.99

B^0 fast:
x≈0.78, y<0.01

B^0_s the fastest:
x≈26.1, y≈0.15

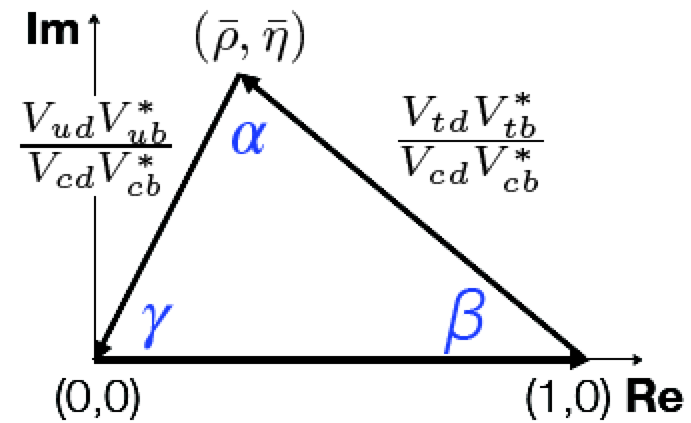
CP symmetry

CP violation in Standard Model

- In SM, CPV is accommodated in weak interactions

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

$$\cong \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$



Unitarity Triangle

(1st and 3rd CKM columns)

- The η is the only source of CPV in the SM.

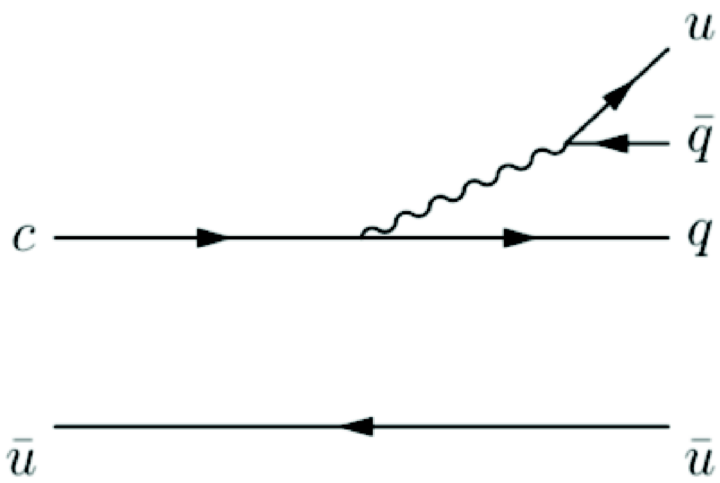
$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

Over-constrain unitarity triangle apex coordinates for a stringent test of SM:

- CP violation measurements give angles
- CP conserving measurements give sides

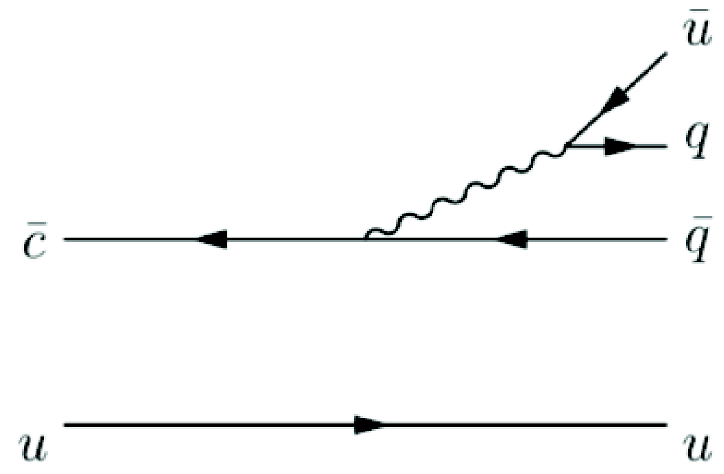
CP violation in decay

$A = |A|\, e^{i\theta}\, e^{i\delta}$



CP

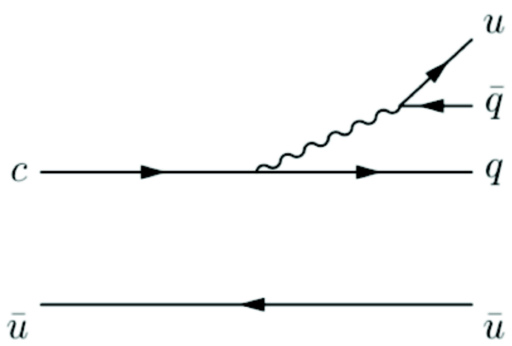
$\bar{A} = |A|\, e^{i\theta}\, e^{-i\delta}$



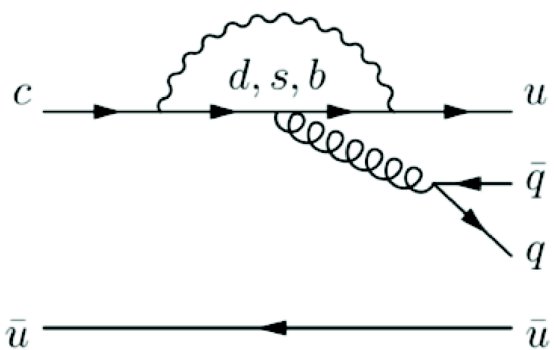
- θ – strong (CP-conserving) phase
- δ – weak phase

$|\bar{A}|^2 - |A|^2 = 0$ → We cannot observe CP violation

CP violation in decay

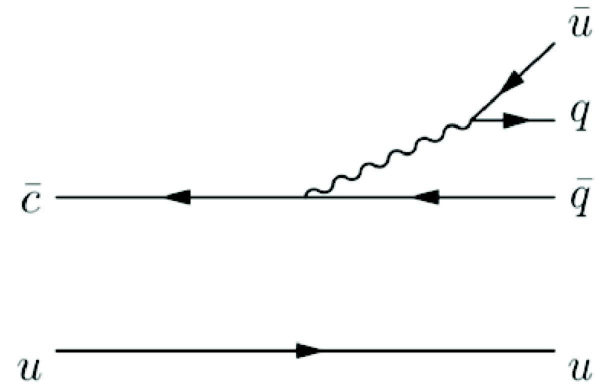


$A_1 = |A_1|\, e^{i\theta 1}\, e^{i\delta 1}$

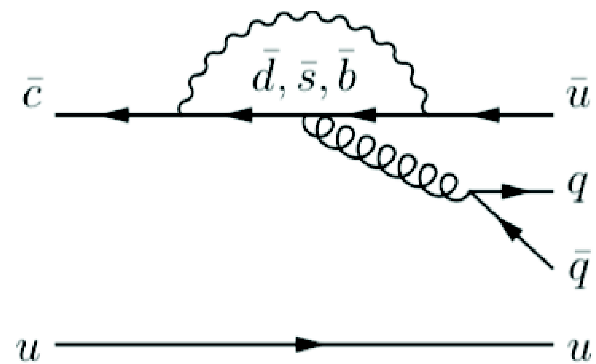


$A_2 = |A_2|\, e^{i\theta 2}\, e^{i\delta 2}$

CP

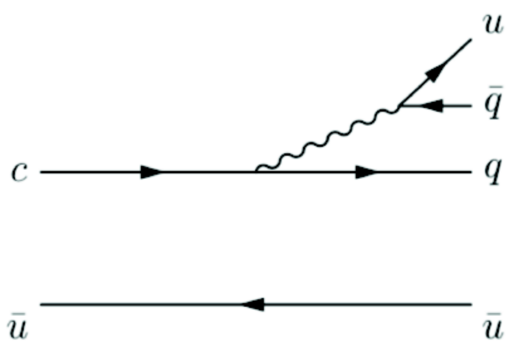


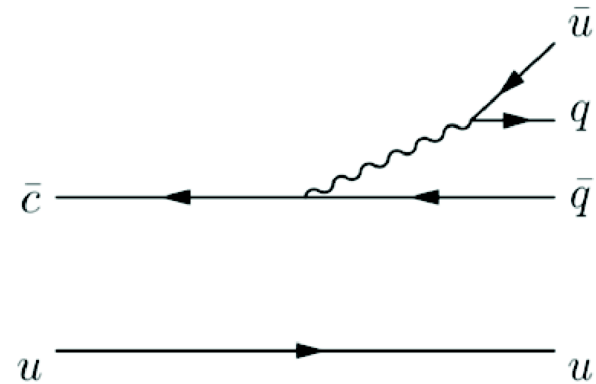
$\overline{A}_1 = |A_1|\, e^{i\theta 1}\, e^{-i\delta 1}$



$\overline{A}_2 = |A_2|\, e^{i\theta 2}\, e^{-i\delta 2}$

CP violation in decay

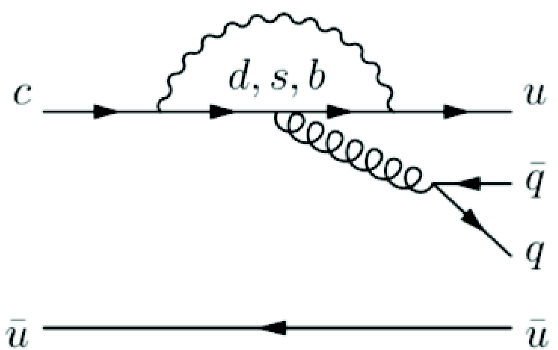


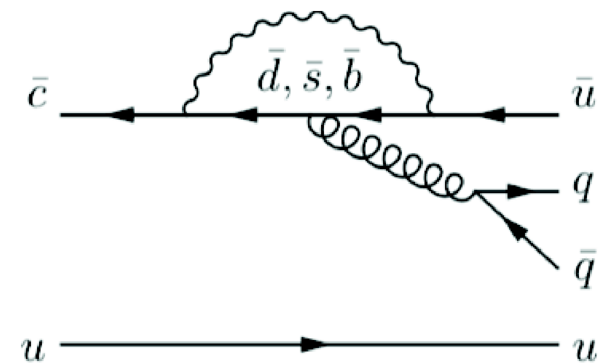


$A_1 = |A_1|\, e^{i\theta 1}\, e^{i\delta 1}$

CP

$\overline{A}_1 = |A_1|\, e^{i\theta 1}\, e^{-i\delta 1}$





$A_2 = |A_2|\, e^{i\theta 2}\, e^{i\delta 2}$

$\overline{A}_2 = |A_2|\, e^{i\theta 2}\, e^{-i\delta 2}$

$$|\overline{A}_1 + \overline{A}_2|^2 - |A_1 + A_2|^2 = 4\,|A_1|\,|A_2|\,\sin(\theta_1 - \theta_2)\ \sin(\delta_1 - \delta_2)$$

CP violation in mixing

$$\Gamma(P^0 \rightarrow \bar{P}^0) \neq \Gamma(\bar{P}^0 \rightarrow P^0)$$

$|q/p| \neq 1$

CP violation in interference between mixing and decays

$$\Gamma(P^0 \rightarrow \bar{P}^0 \rightarrow f_{CP}) \neq$$
$$\Gamma(\bar{P}^0 \rightarrow P^0 \rightarrow f_{CP})$$

$\Updownarrow$

Relative phase $\delta \neq 0$

$$\lambda_f \equiv q/p\ \bar{A}_{\bar{f}}\ /A_f = |q/p\ \bar{A}_{\bar{f}}\ /A_f|\ e^{i\theta}\ e^{i\delta}$$

CP violation and its types

C – charge conjugation (particle → antiparticle) $\hat{C}|\vec{r}, t, q >= e^{i\alpha_1}|\vec{r}, t, -q >$

P – parity (spatial reflection) $\hat{P}|\vec{r}, t, q >= e^{i\alpha_2}|-\vec{r}, t, q >$

The CP discrete symmetry is broken if: $\lambda_f \equiv q/p\ \bar{A}_{\bar{f}}/A_f \neq 1$

CP violation in decay

$$\Gamma(P^0 \rightarrow f) \neq \Gamma(\bar{P}^0 \rightarrow \bar{f})$$

$$|\bar{A}_{\bar{f}}/A_f| \neq 1$$

- Depends on decay mode

CP violation in mixing

$$\Gamma(P^0 \rightarrow \bar{P}^0) \neq \Gamma(\bar{P}^0 \rightarrow P^0)$$

$$|q/p| \neq 1$$

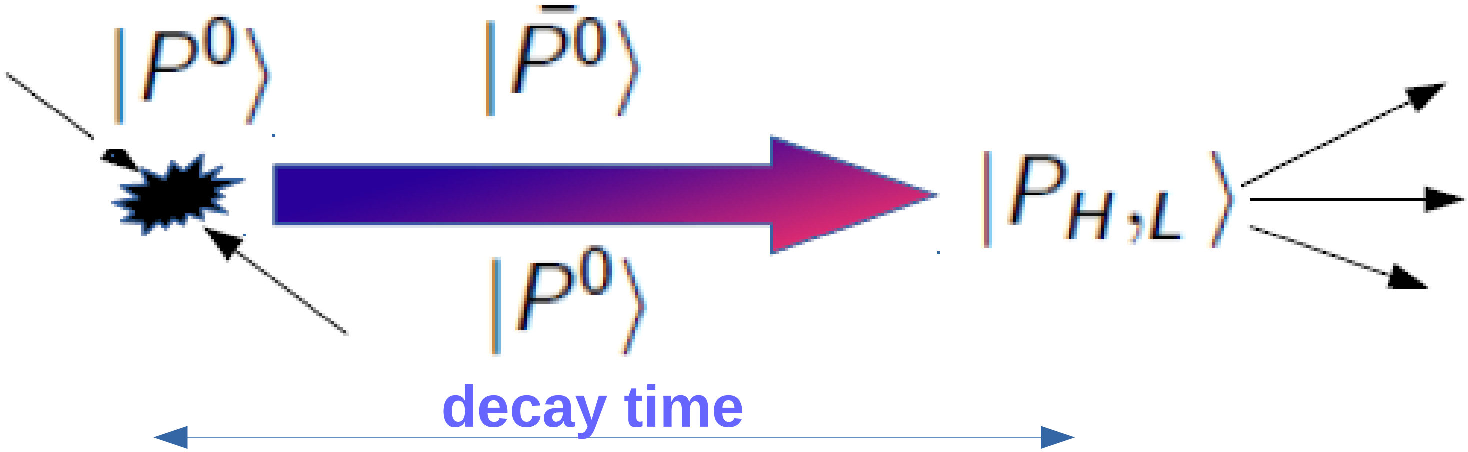
CP violation in interference between mixing and decay

$$\Gamma(P^0 \rightarrow \bar{P}^0 \rightarrow f_{CP}) \neq \Gamma(\bar{P}^0 \rightarrow P^0 \rightarrow f_{CP})$$

$$\arg(q/p\ \bar{A}_{\bar{f}}/A_f) \neq 0$$

- Not depends on decay mode
- only for neutral mesons

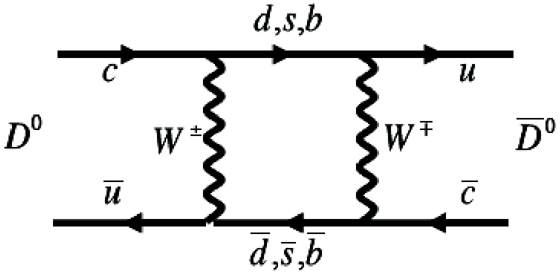
General experimental idea

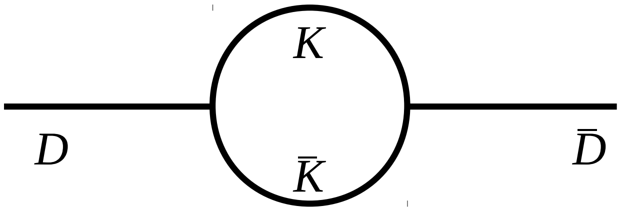


1. determine flavour in the initial state
2. determine decay time
3. determine flavour in the final state
4. construct (time-dependent) asymmetry A (A(t))
5. extract (mixing/CP) parameters from the fit

Mixing and CPV in charm

- In charm mixing and CPV in the up-type quark system (complementarity to s and b)



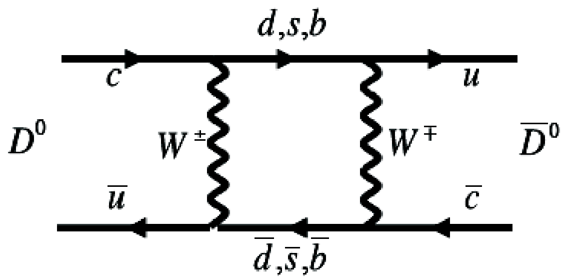


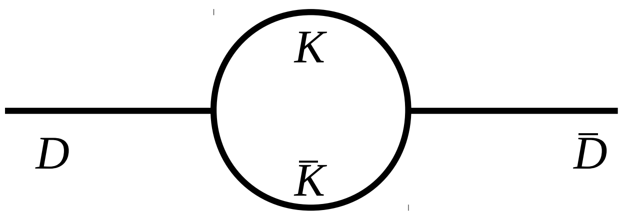
long-range contributions dominates – hard to calculate

- Perturbative QCD valid for >> 1GeV
- Chiral perturbation theory valid: 0.1 to 1 GeV
- m(D^0) ≈ 1.864 GeV

Mixing and CPV in charm

- In charm mixing and CPV in the up-type quark system (complementarity to s and b)



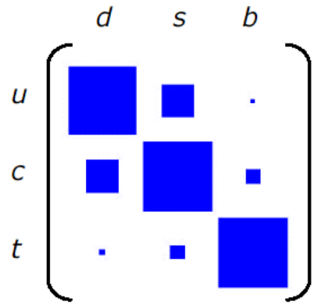


long-range contributions dominates – hard to calculate

- Perturbative QCD valid for >> 1GeV
- Chiral perturbation theory valid: 0.1 to 1 GeV
- $m(D^0) \approx 1.864$ GeV

Standard Model predictions: tiny effects

- Flavor-Changing Neutral Currents suppressed with respect to s and b (GIM mechanism slightly broken by the b mass (but smaller effect that for t))
- CP violation effects suppressed by the CKM hierarchy



- **CPV in decays ~ $O(10^{-3})$**
- **in mixing/interference < $O(10^{-4})$**

I.I Bigi PoS ICHEP2016 (2016)

L. Silvestrini CHARM2015 theory summary [1510.05797]

M. Bobrowski, A. Lenz, J. Riedl, J. Rohrwild JHEP 03(2010) 009

Mixing and CPV in charm

beauty

$$\beta = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right) \sim 23^\circ$$

$$\beta_s = \arg\left(-\frac{V_{cs}V_{cb}^*}{V_{ts}V_{tb}^*}\right) \sim 1^\circ$$

Precise tests of SM

charm

$$\beta_c = \arg\left(-\frac{V_{cd}V_{ud}^*}{V_{cs}V_{us}^*}\right) \sim 0.03^\circ$$

Search for New Physics effects

since SM effects suppressed

Experimental challenge:

- High statistics needed
- Keep systematics very small (<0.1%)

Mixing and CPV in charm

SM predictions:

- **CPV in decay ~ $O(10^{-3})$**
  (but different predictions "on the market"):
  ~ $O(10^{-3})$ - $O(10^{-4})$
  - **in mixing/interference < $O(10^{-4})$**

I.I Bigi PoS ICHEP2016 (2016)

L. Silvestrini CHARM2015 theory summary [1510.05797]

M. Bobrowski, A. Lenz, J. Riedl, J. Rohrwild JHEP 03(2010) 009

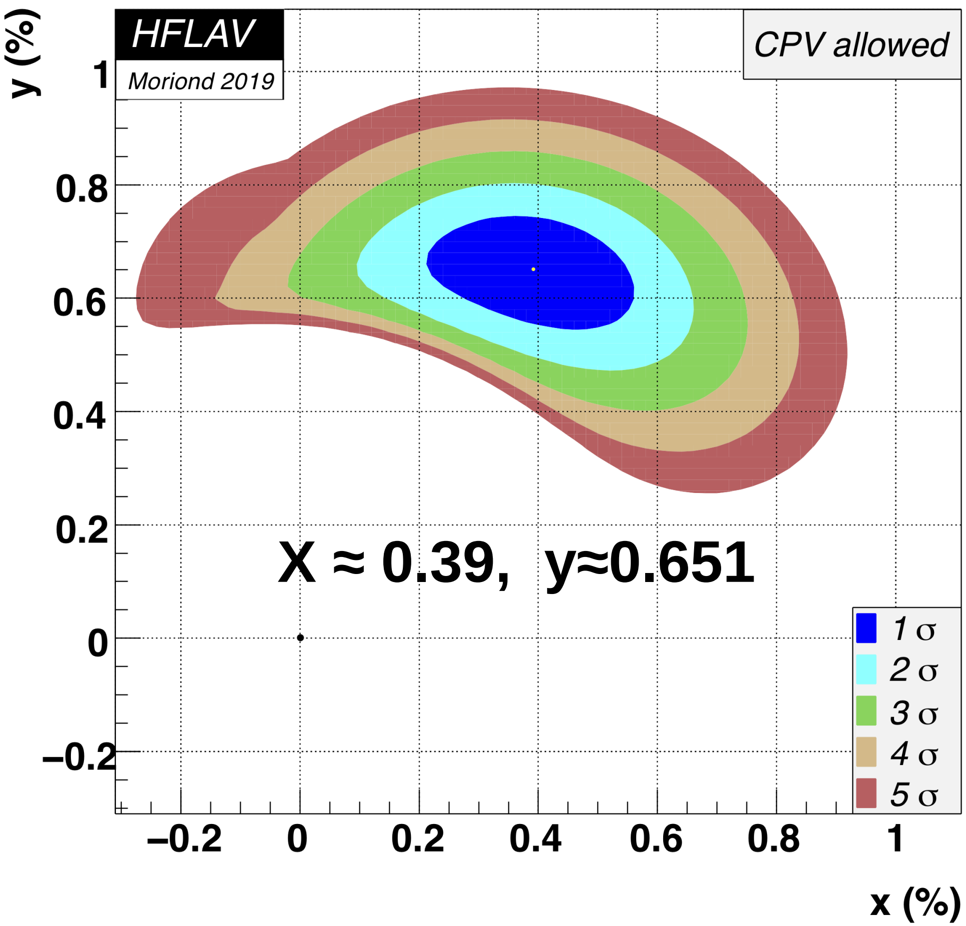
Experimental status:

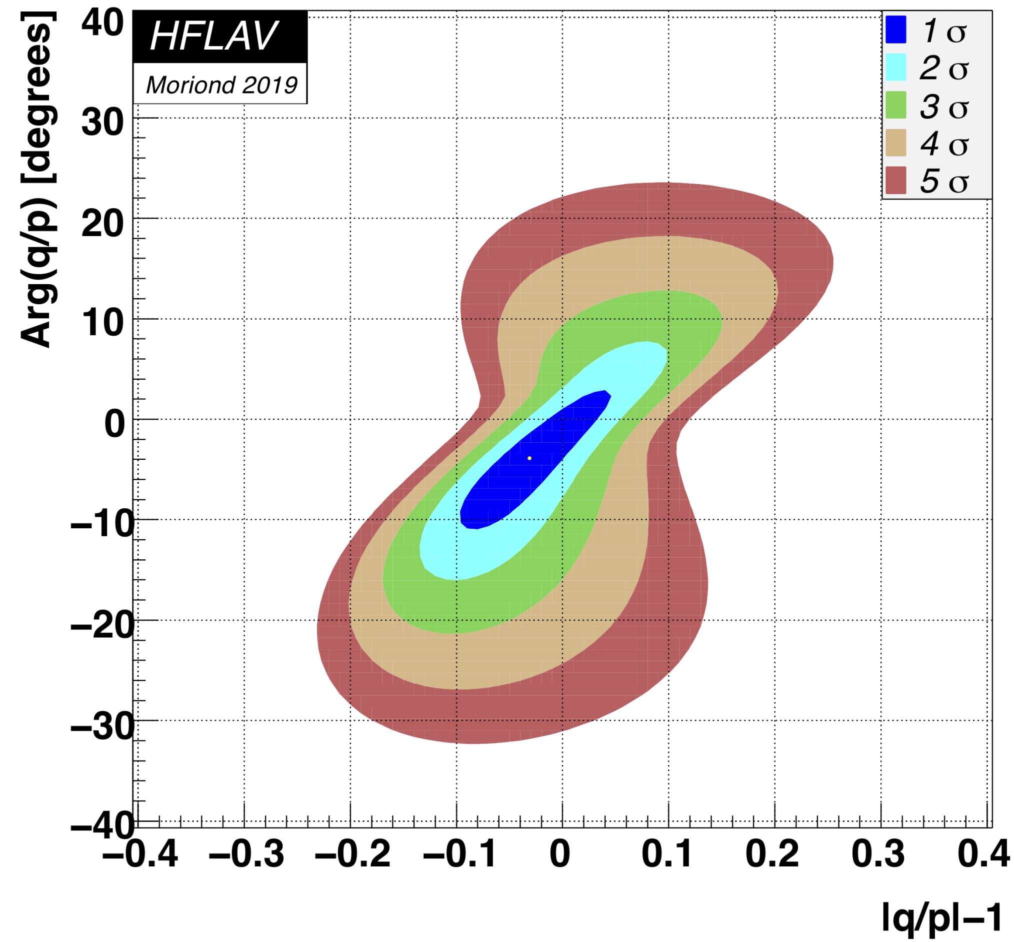
- **Mixing established (> 11 σ effect)**
  - First evidence Babar, Belle, CDF: PRL 98 (2007) 211802, PRL 98 (2007) 211803, PRL 100 (2008) 121802
  - LHCb measurements: PRL 113 (2013) 231802, PRD 95 (2017) 052004 PRD 96 (2017) 099907, PRD97 (2018) 031101, **PRL 122, 231802 (2019)**
- **CPV discovery (in decay) announced this year (5,3 σ effect)**

Mixing and CPV in charm

$x = \frac{\Delta m}{\Gamma}$ $y = \frac{\Delta\Gamma}{2\Gamma}$

$|D_{1,2}\rangle = p|\mathrm{D}^0\rangle \pm q|\overline{\mathrm{D}}^0\rangle$





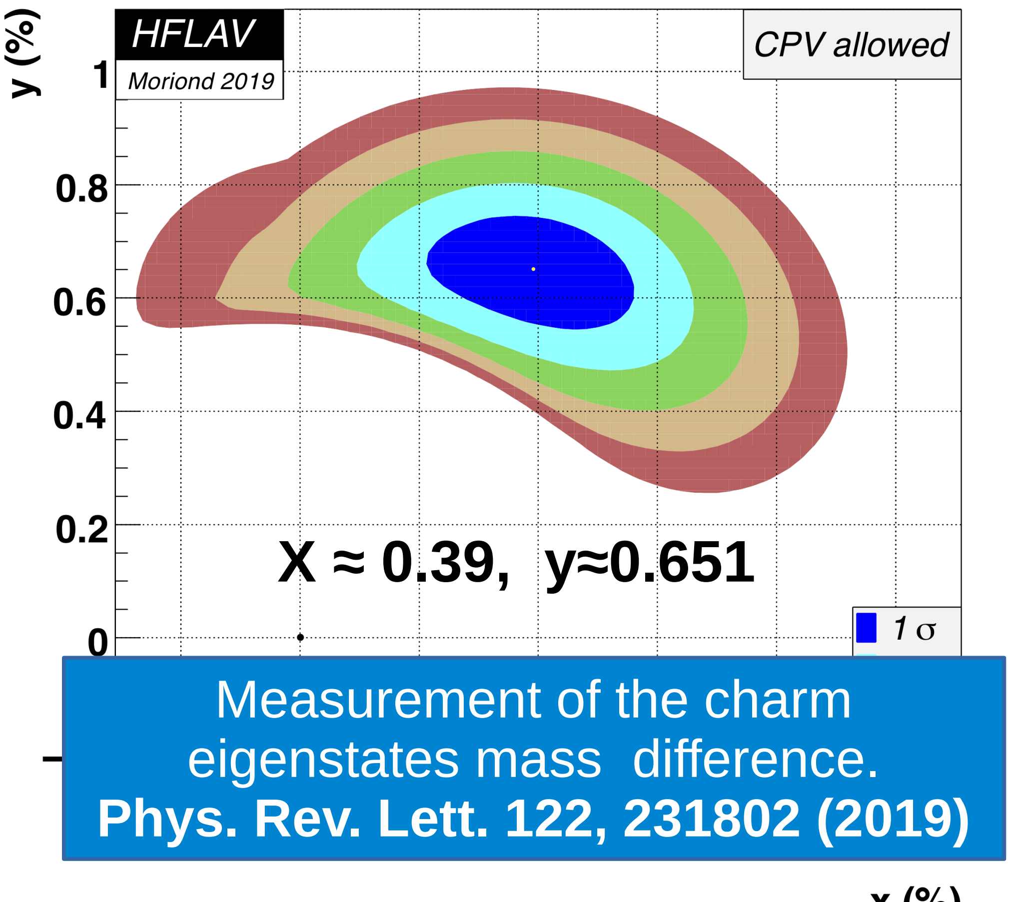
x or y ≠ 0 → mixing

|q/p|≠ 1 → CPV in mixing

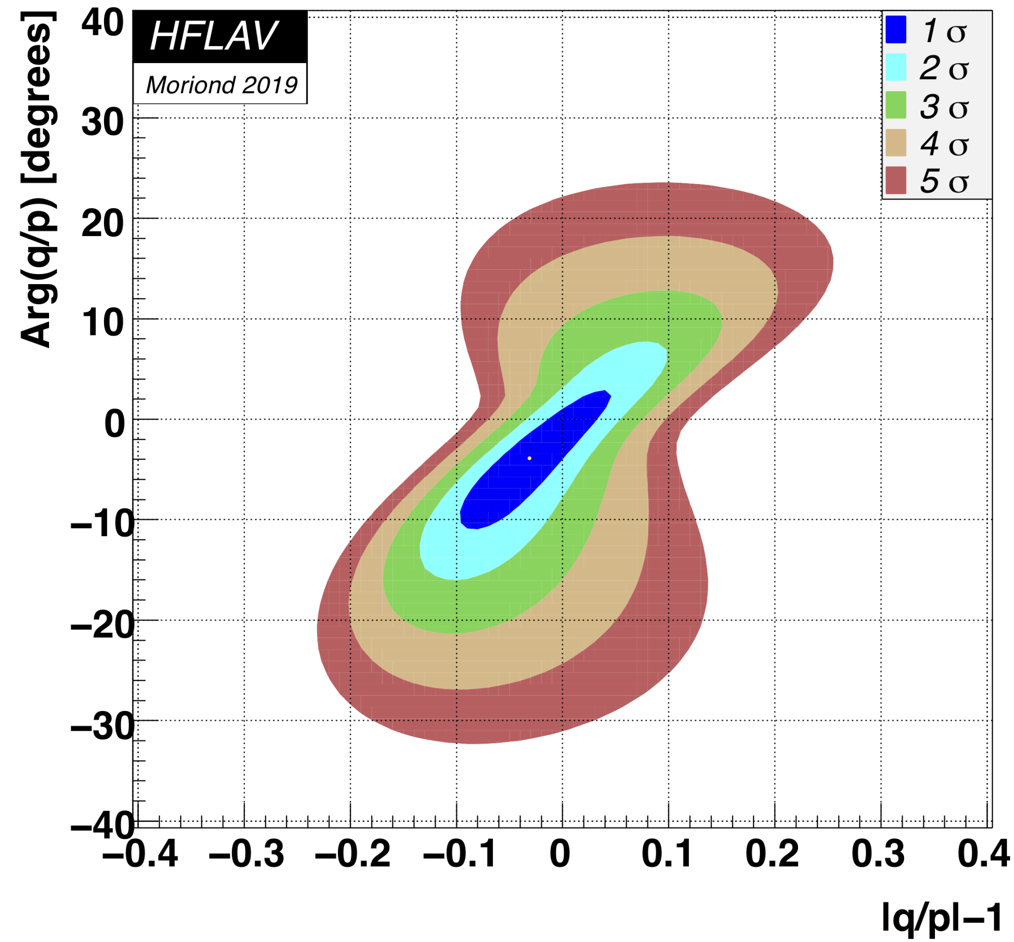
Mixing and CPV in charm

$x = \frac{\Delta m}{\Gamma}$ $y = \frac{\Delta\Gamma}{2\Gamma}$

$|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$



Measurement of the charm eigenstates mass difference.
Phys. Rev. Lett. 122, 231802 (2019)

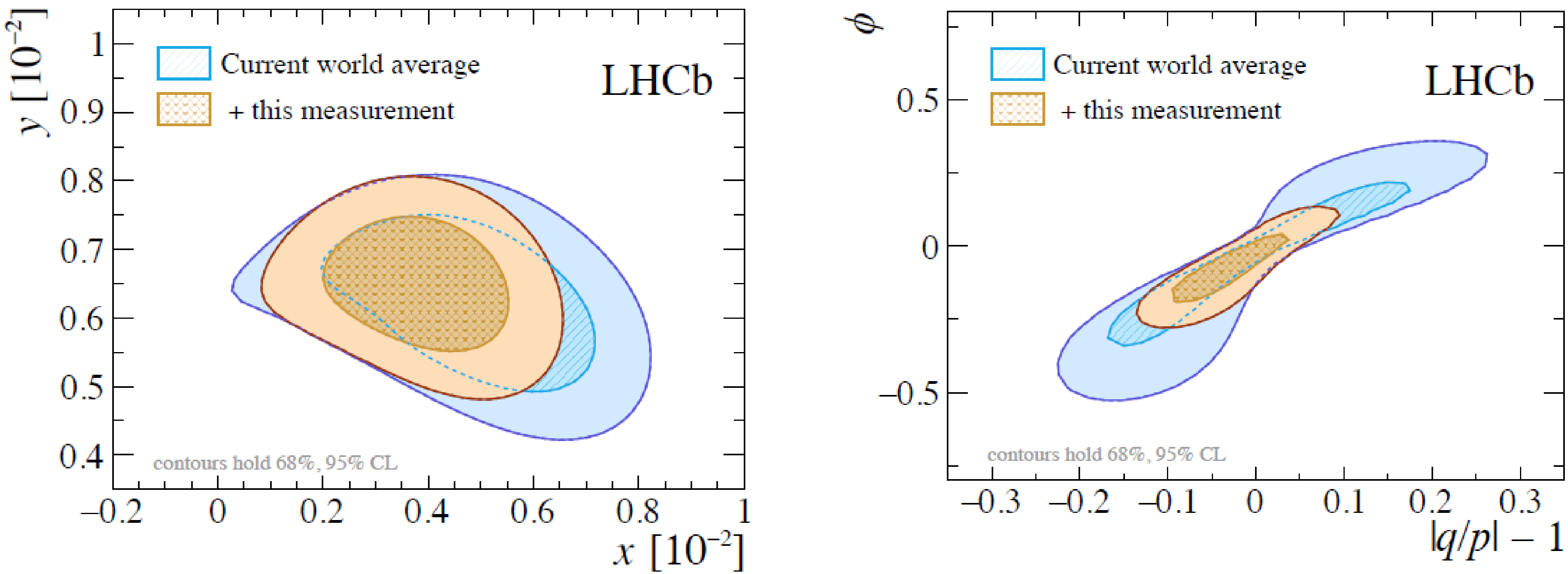


x or y ≠ 0 → mixing

|q/p|≠ 1 → CPV in mixing

Phys. Rev. Lett. 122, 231802 (2019)

Measurement of the charm eigenstates mass difference with $D^0 \to K_s \pi^+ \pi^-$ (Run I 3 fb^{-1})



- **Consistent with CP symmetry conservation.**
- **Combined with world average x > 0, more than 3 σ effect**

The first evidence of charm eigenstates mass difference

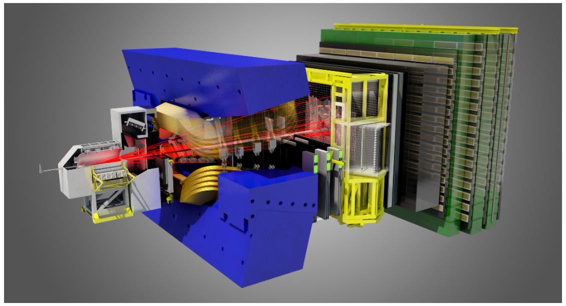
Charming players

Charming players

Sachin Tendulkar

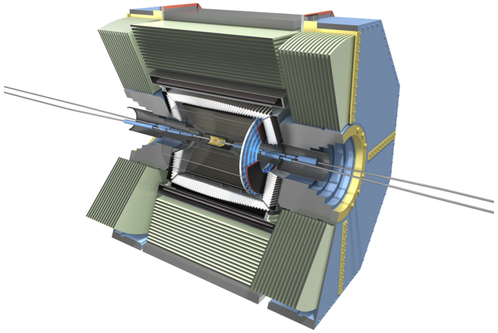
Charming players

LHCb



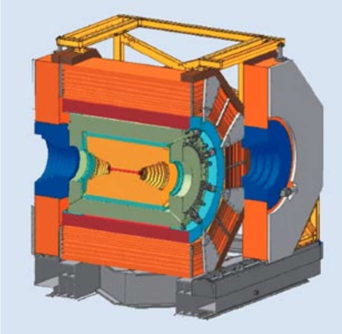
- High cross-sections:
  - Decays in charged final states yield of 9 fb^{-1} @LHCb corresponds to 50 ab^{-1}@Belle-2
  - baryon production (e.g. Λ_c)
- Good decay-time resolution (~45 fs ~ 0.1 $\tau(D^0)$)
- Busy environment
  - non-trivial triggers
  - non-trivial efficiency corrections

Belle-2



- Good reconstruction for neutral particles
- Known initial state:
  - Better separation from prompt and secondaries production (from B decays)
- Clean environment:
  - Milder efficiency variation
  - Easier control of systematics
  - Absolute asymmetry measurement possible

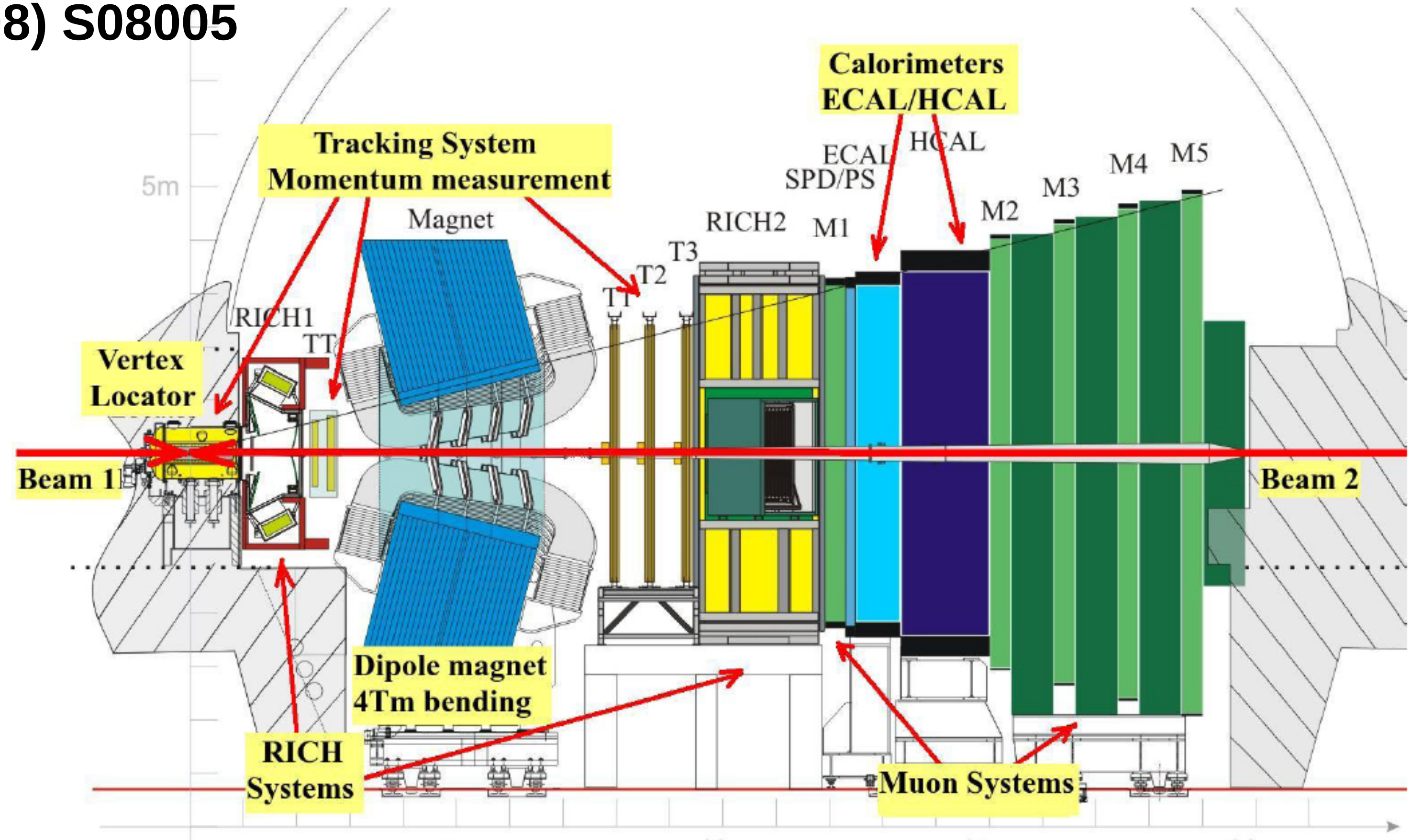
BES-3



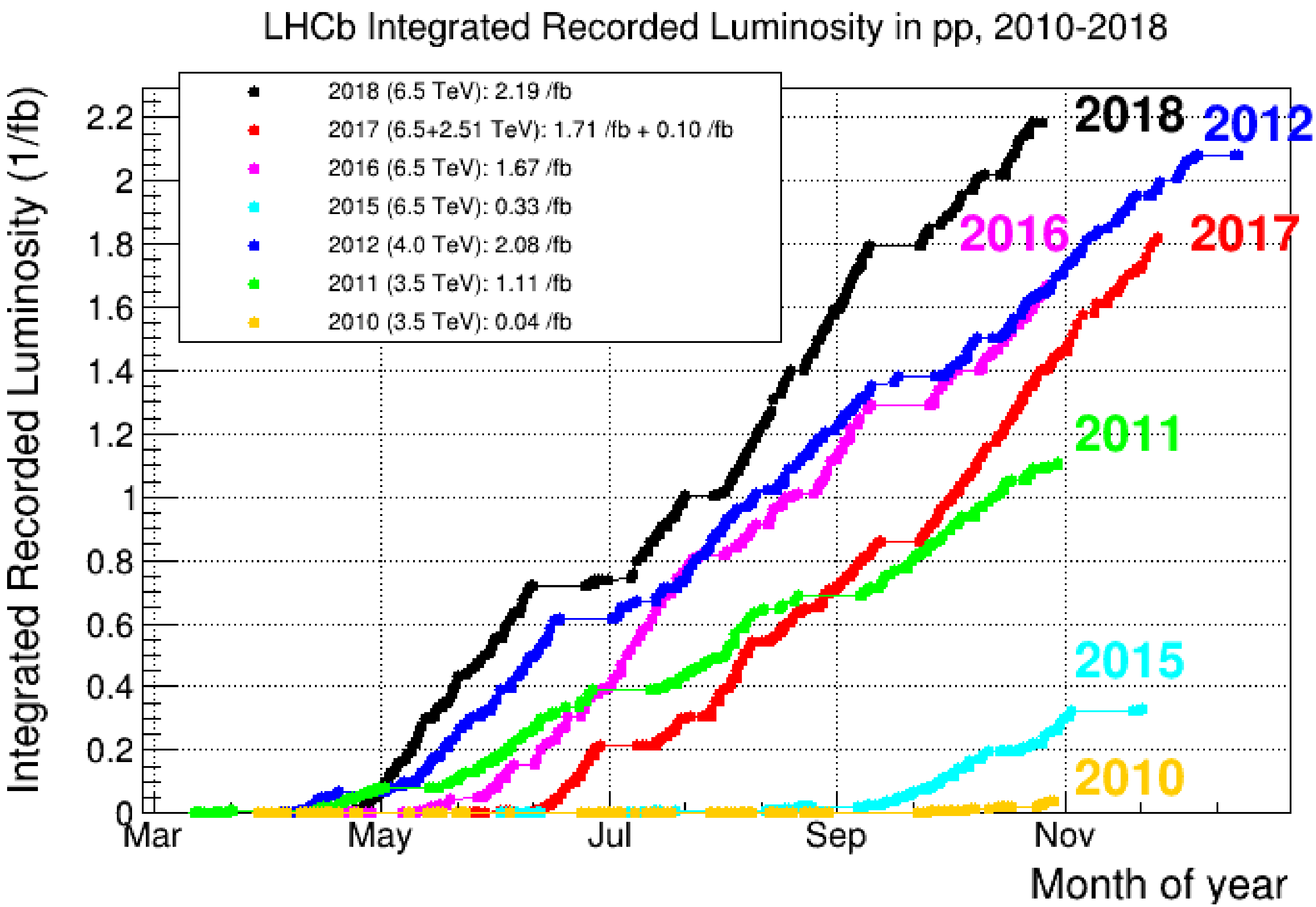
- Background-free charm
- No time measurement since charm not boosted
- Quantum entangled pairs $\Psi(3370) \rightarrow D\overline{D}$
- Complementary measurements to LHCb and Belle-2 e.g. measurement of strong phases

Large Hadron Collider beauty detector

JINST 3 (2008) S08005



- Single-arm forward spectrometer covering range $2 < \eta < 5$ ($10 < \theta < 300$ mrad)
- Momentum resolution $\Delta p/p = 0.4 - 0.6$ % @ 5 GeV/c to @ 100 GeV/c
  (**~8 MeV/c^2 mass resolution** for two-body charm decay)
- Impact parameter resolution: 20 μm from high p_T tracks (**decay lifetime ~45 fs ~ 0.1 $\tau(D^0)$**)



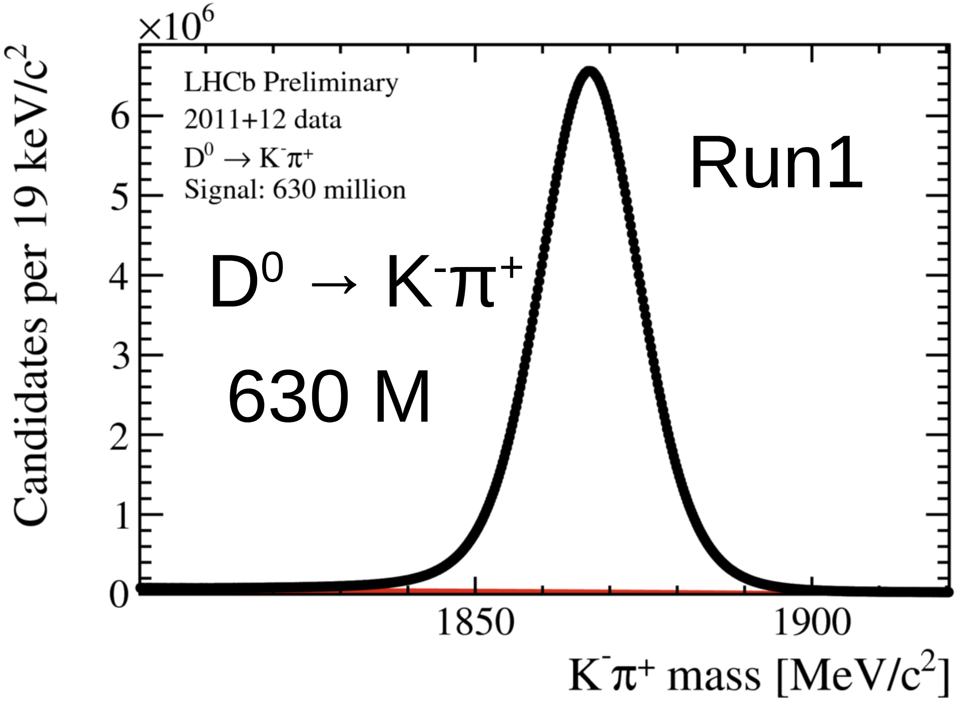
Run I (2011-2012): 3 fb^{-1} @7 and @8 TeV

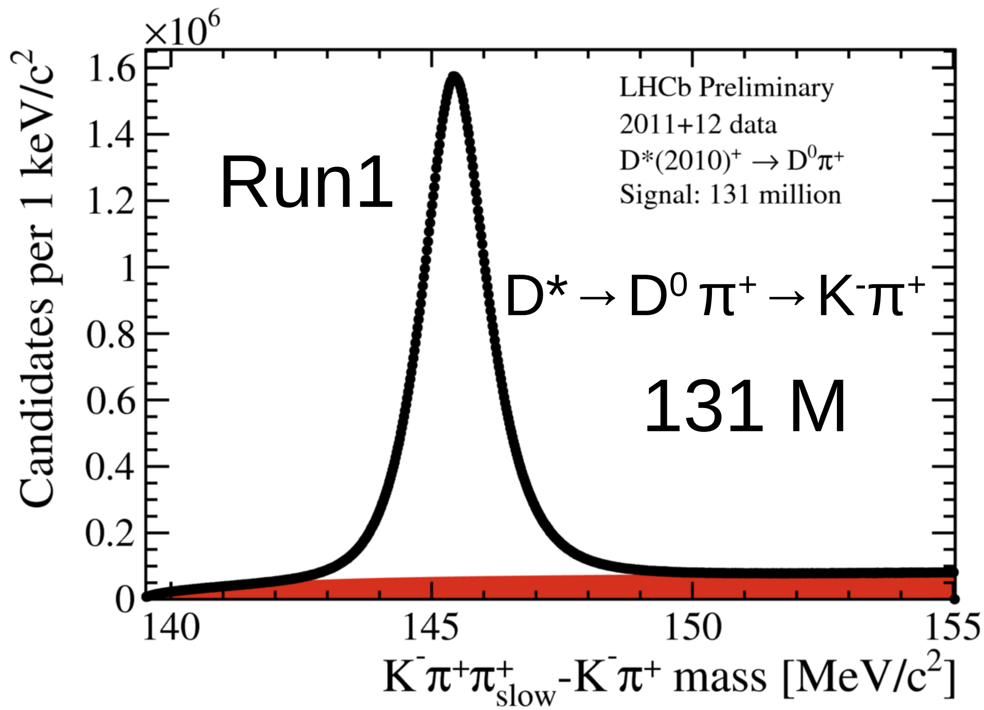
Run II (2015-2018): 6 fb^{-1} @13 TeV

Total sample collected: 9 fb^{-1}

LHCb is also charming...

LHCb-CONF-2016-005





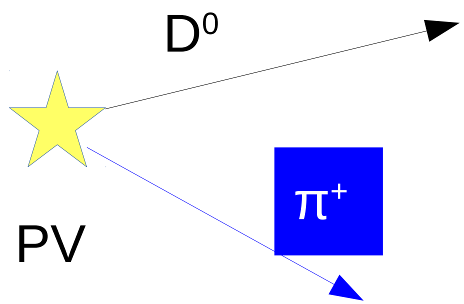
Charm produced copiously in the pp collisions:

- $\sigma(pp \rightarrow c\bar{c}) \sim 1419\ \mu b$ @ 7 TeV **Nucl.Phys.B871(2016) 1**
- $\sigma(pp \rightarrow c\bar{c}) \sim 2840\ \mu b$ @ 13 TeV **JHEP03(2017) 74**

More than one billion of $D^0 \rightarrow K^-\pi^+$ events reconstructed from the collected sample.

Tagging of initial flavour

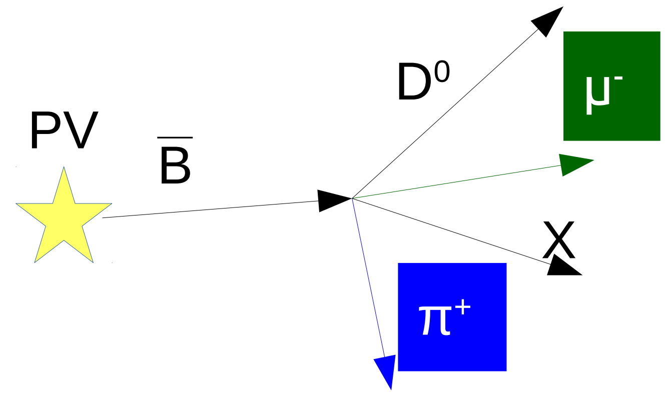
Prompt charm



$D^{*+} \rightarrow D^0\pi^+$

Decay time acceptance limits

(Double-tagged) secondary charm



$\overline{B} \rightarrow D^{*+}\mu^- X$

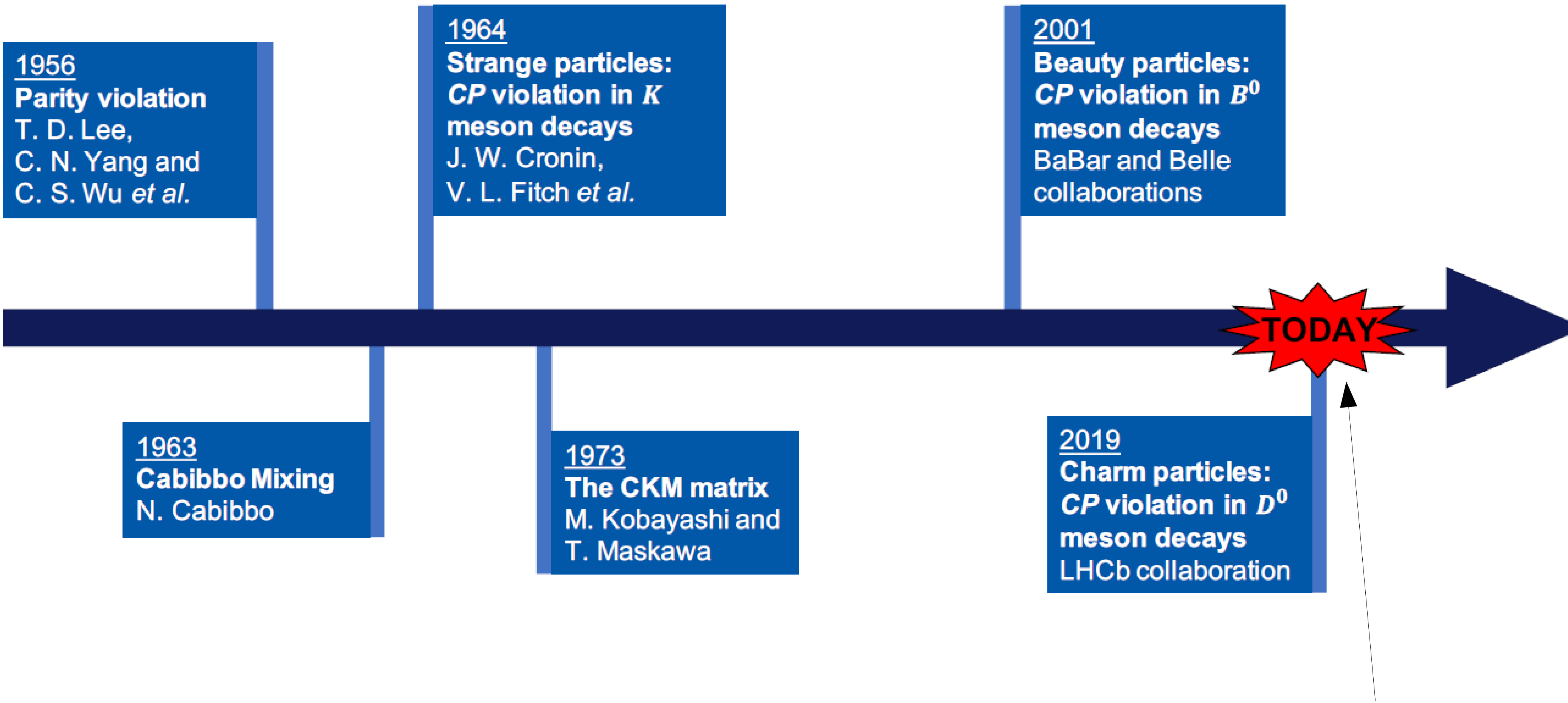
$D^{*+} \rightarrow D^0\pi^+$

All decay time available

- **$D^{*+} \rightarrow D^0\pi^+$** (largest yield, high purity, $\sigma(t) \approx 0.1\,\tau$)
- **$\overline{B} \rightarrow D^{*+}\mu^- X$** (1/6 * yield, lower purity, $\sigma(t) \approx 0.3\,\tau$)
- **$\overline{B} \rightarrow D^{*+}\mu^- X$ $D^{*+} \rightarrow D^0\pi^+$** (1/40 * yield, highest purity $\sigma(t) \approx 0.3\,\tau$)

Observation of CP violation in charm decays

History of CP violation discoveries



“Today” = presented 21. 03. 2019 at Moriond conference.

Observation of CP violation in charm decays

- $D^0 \to \pi^+\pi^-$ (K^+K^-)
- Run II, L = 6 fb^{-1} @13 TeV
- Initial charm tagged with π (μ) sign

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

Phys. Rev. Lett. 122, 211803 (2019)

Observation of CP violation in charm decays

- $D^0 \rightarrow \pi^+\pi^-$ (K^+K^-)
- Run II, L = 6 fb^{-1} @13 TeV
- Initial charm tagged with π (μ) sign

$$A_{\rm raw}(f) = \frac{N(D^0 \rightarrow f) - N(\overline{D}^0 \rightarrow f)}{N(D^0 \rightarrow f) + N(\overline{D}^0 \rightarrow f)}$$

$$A_{\rm raw}(f) = \boxed{A_{CP}(f)} + \cancel{A_D(f)} + \boxed{A_D(\pi_s^+)} + \boxed{A_P(D^{*+})}$$

Symmetric final state

Should be same for $\pi^+\pi^-$ and K^+K^- if kinematics the same

Phys. Rev. Lett. 122, 211803 (2019)

Observation of CP violation in charm decays

- $D^0 \to \pi^+\pi^-$ (K^+K^-)
- Run II, L = 6 fb^{-1} @13 TeV
- Initial charm tagged with π (μ) sign

$$A_{\rm raw}(f) = \frac{N(D^0 \to f) - N(\bar{D}^0 \to f)}{N(D^0 \to f) + N(\bar{D}^0 \to f)}$$

$$A_{\rm raw}(f) = \boxed{A_{CP}(f)} + \cancel{A_D(f)} + \boxed{A_D(\pi_s^+)} + \boxed{A_P(D^{*+})}$$

Symmetric final state

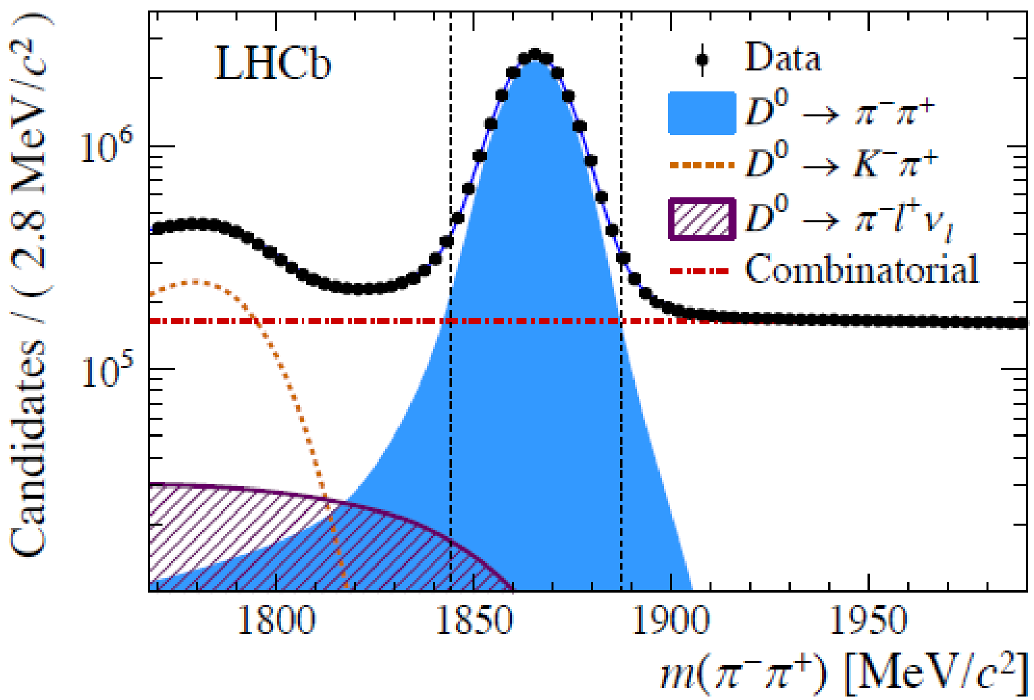
Should be same for $\pi^+\pi^-$ and K^+K^- if kinematics the same

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

Phys. Rev. Lett. 122, 211803 (2019)

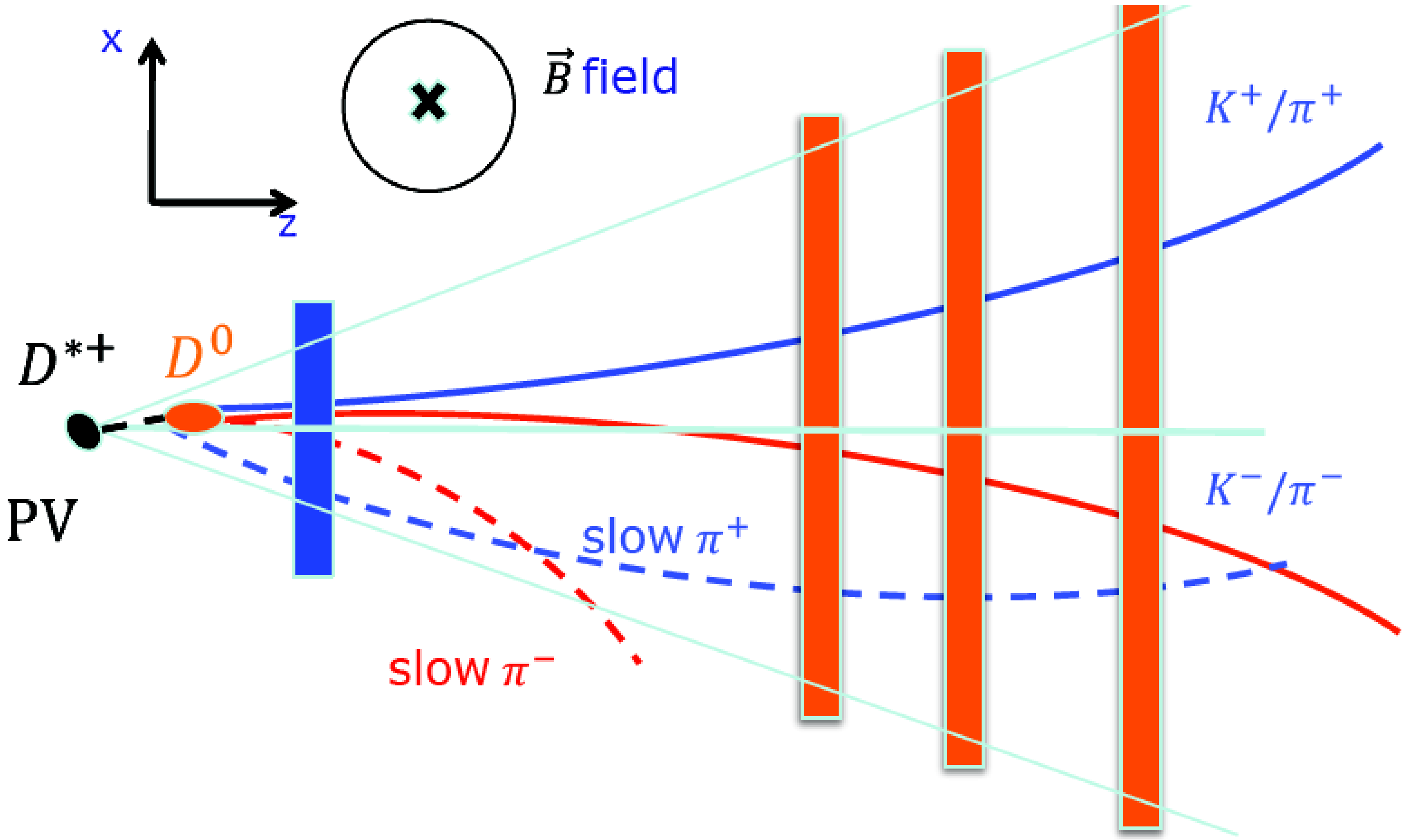
Data selection

- Full reconstruction online (Turbo stream) Comput. Phys. Commun. 208 (2016) 35
- Requirements on:
  - Quality and particle identification information of tracks
  - D_0 vertex quality
  - P_T of tracks and D_0
  - Interaction point of D_0



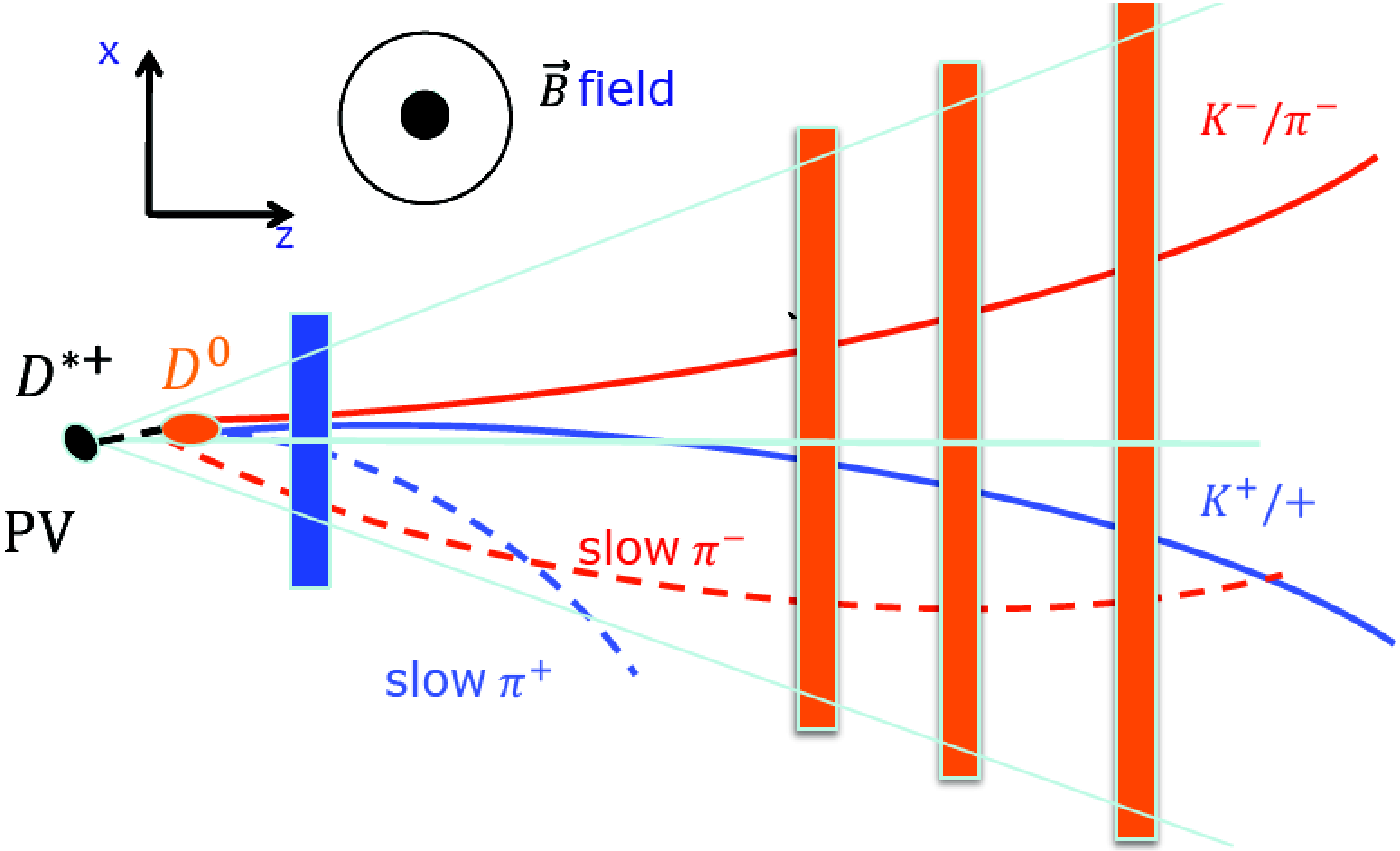
Fiducial selection I

- Remove regions when assumption about small reconstruction asymmetry is not true – π_s (μ) not in acceptance



Fiducial selection I

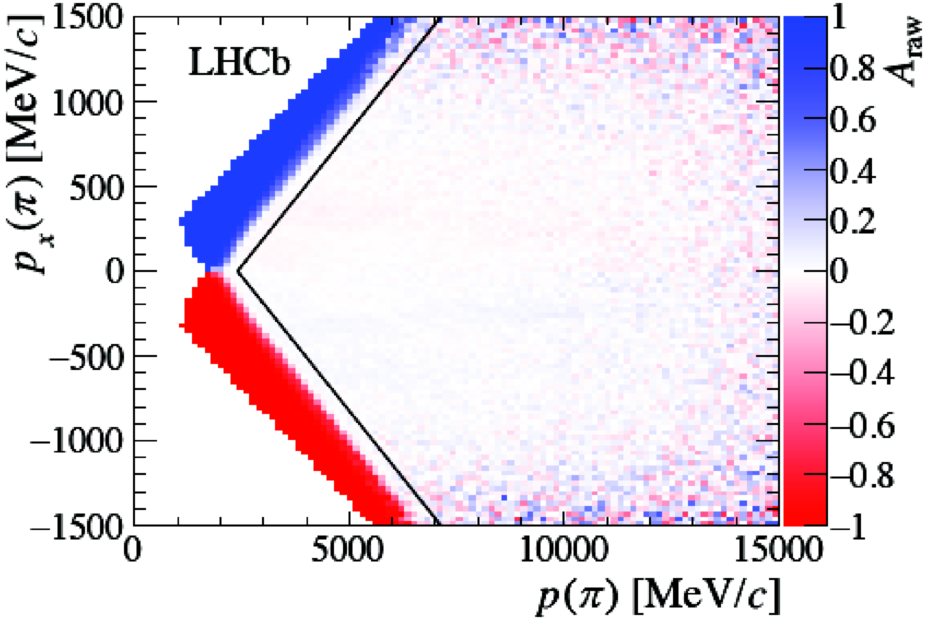
- Remove regions when assumption about small reconstruction asymmetry is not true – π_s (μ) not in acceptance

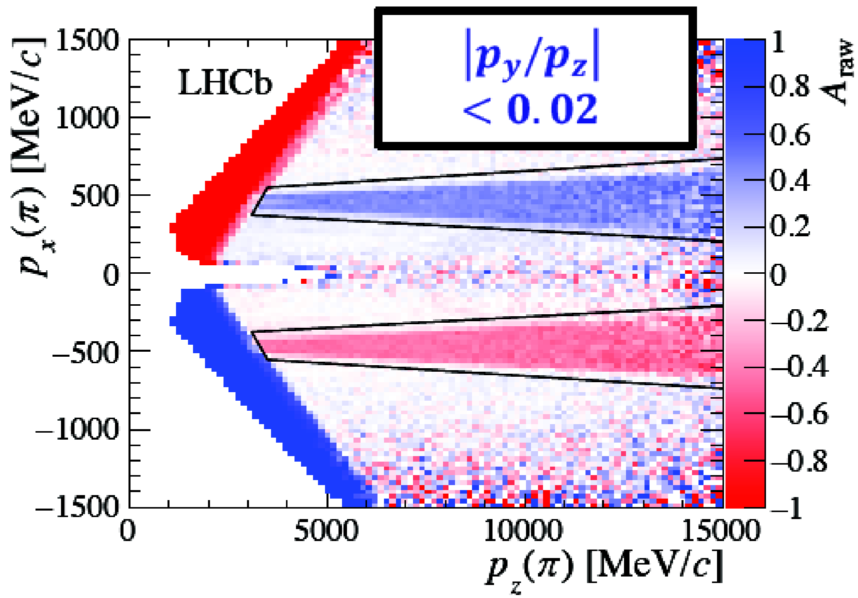


Phys. Rev. Lett. 122, 211803 (2019)

Fiducial selection II

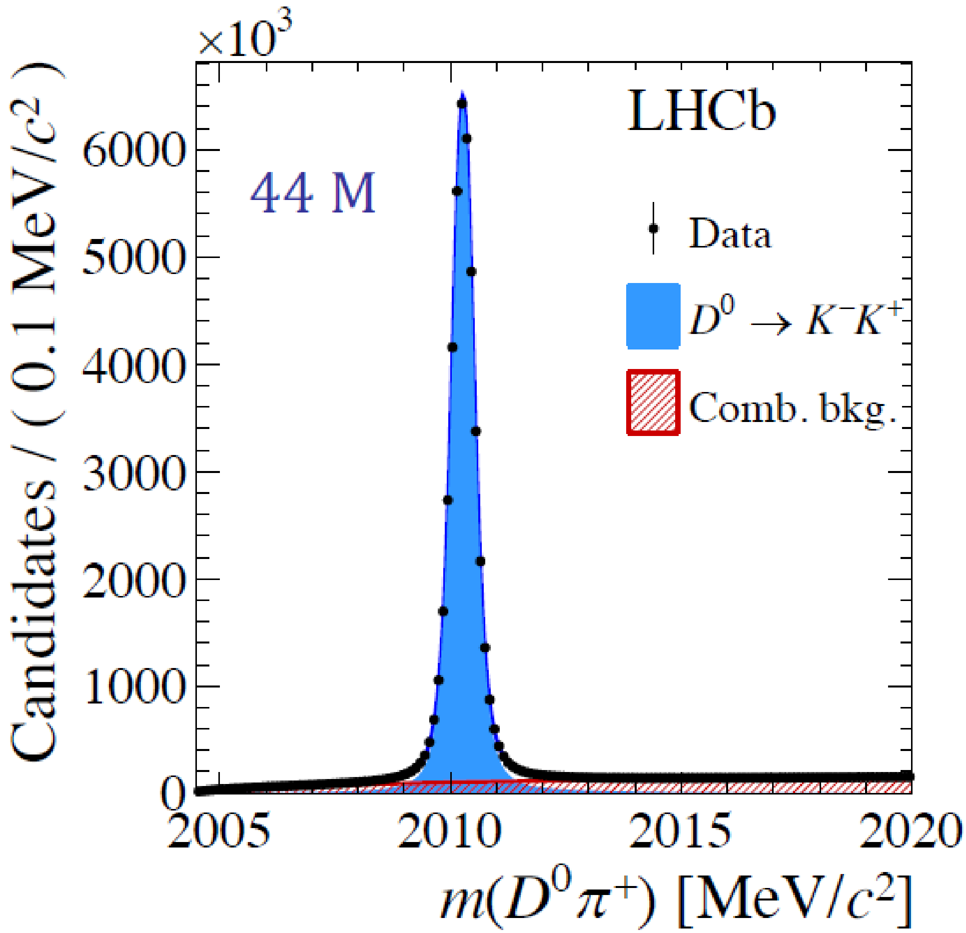
- Remove regions when assumption about small reconstruction asymmetry is not true – regions of phasespace where only D^{*+} (D^{*-}) are kinematically possible.

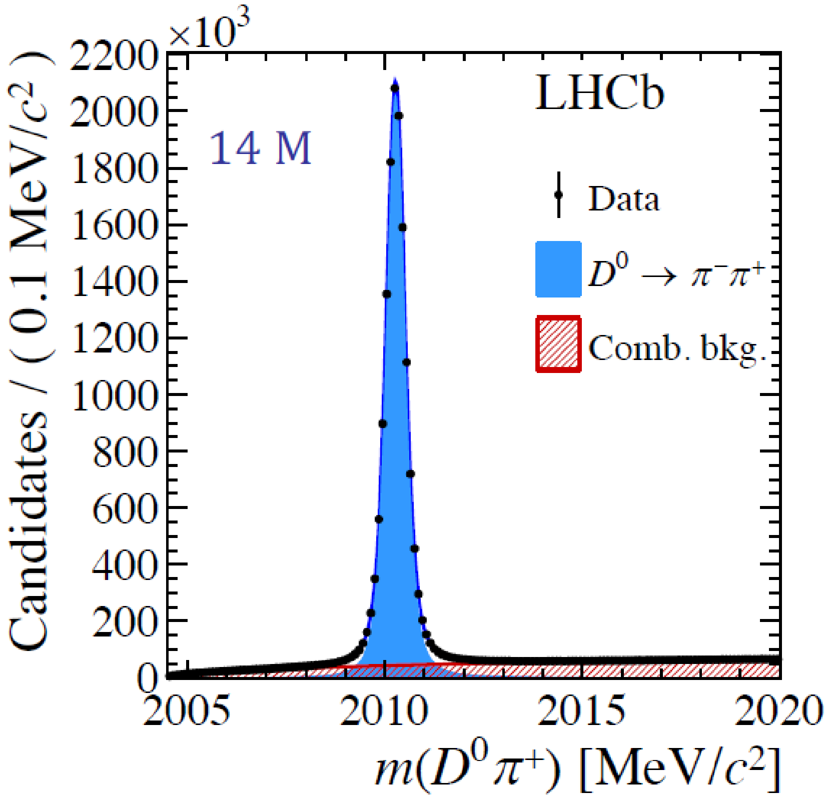




A_{raw} measurement (π-tagged)

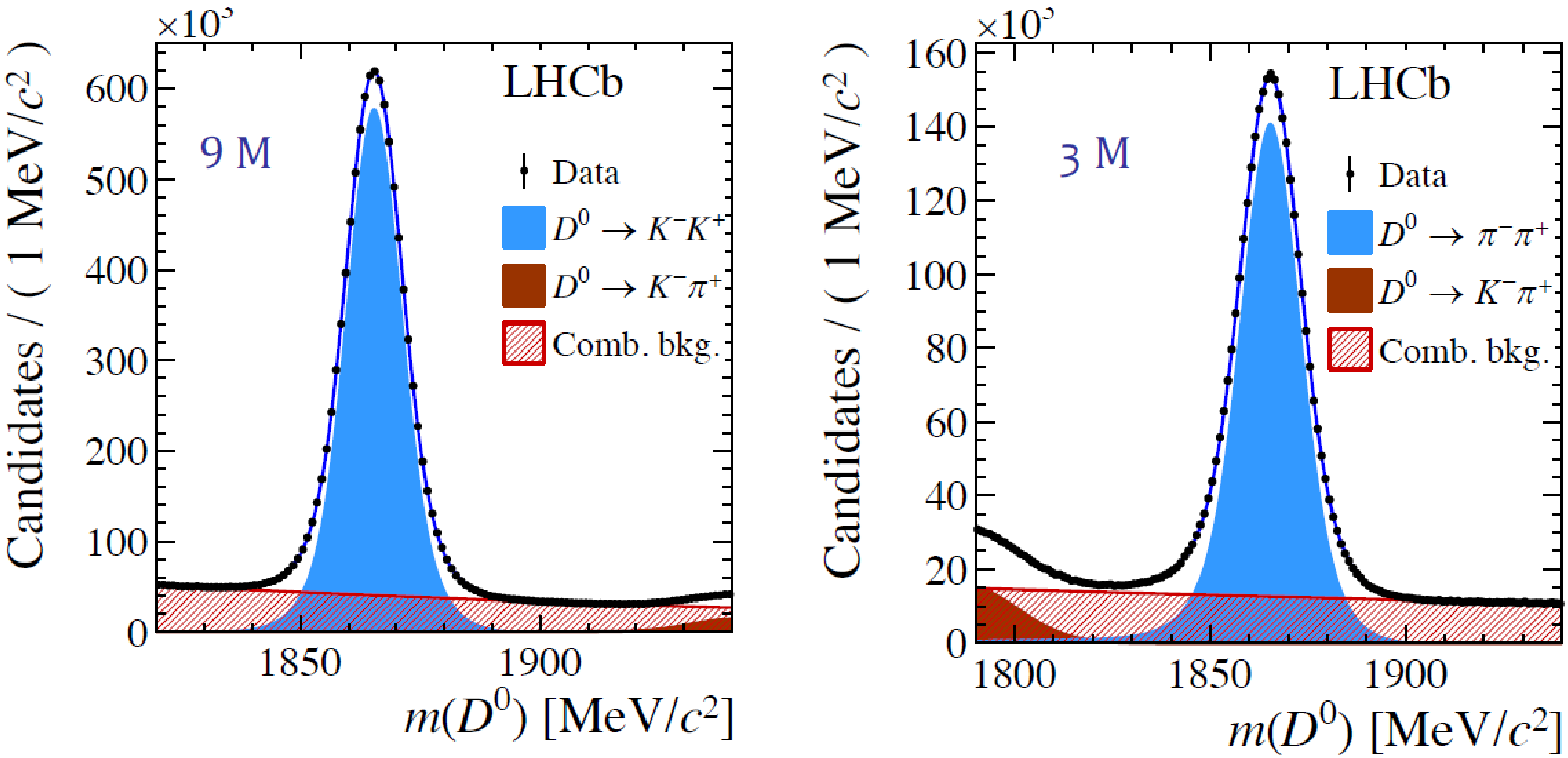
- Fit m(D^0 π) distribution
- Asymmetry from simultaneous fit between D^{*+} and D^{*-}





A_{raw} measurement (μ-tagged)

- Fit $m(D^0)$ distribution
- Asymmetry measured from simultaneous fit between D^0 and $\overline{D^0}$



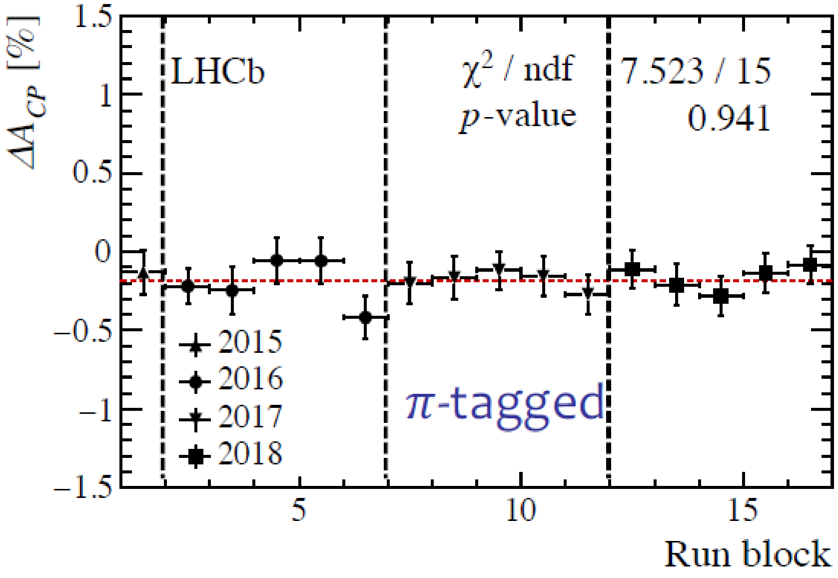
Systematics

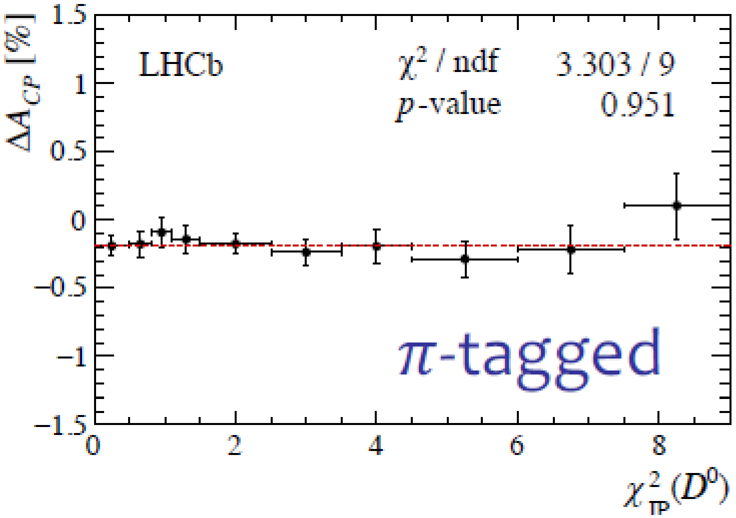
Source	π-tagged $[10^{-4}]$	μ-tagged $[10^{-4}]$
Fit model	0.6	2
Mistag	–	4
Weighting	0.2	1
Secondary decays	0.3	–
B^0 fraction	–	1
B reco. efficiency	–	2
Peaking background	0.5	–
Total	0.9	5

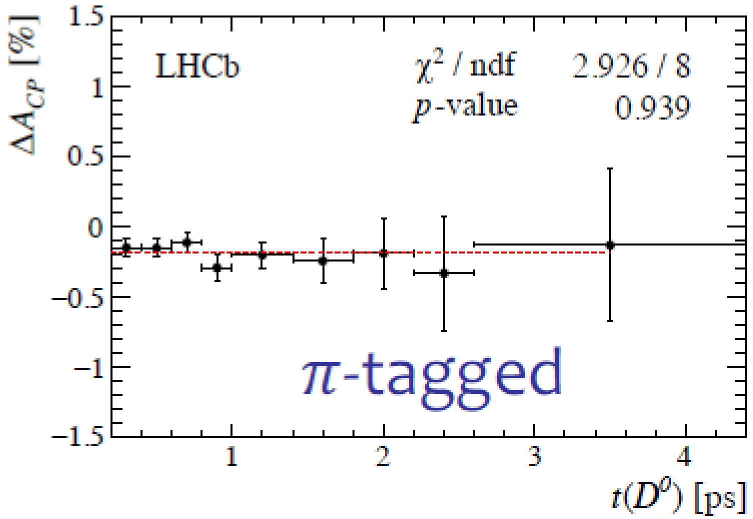
π-tagged systematic uncertainty below 10^{-4}!

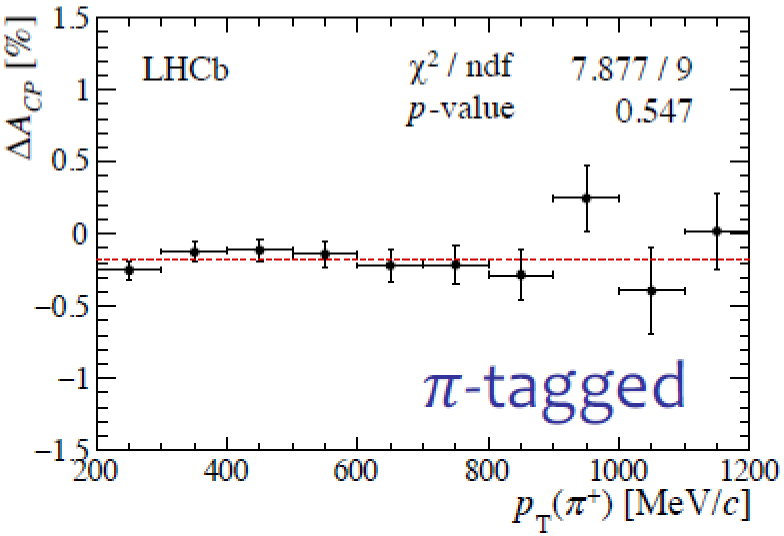
- π-tagged systematica dominated by the fit model
- μ-tagged systematica dominated by mistag (wrong muon sign)

Robustness checks









Run II results (6 fb^{-1})

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

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

$$\Delta A_{CP} = (+14 \pm 16(\text{stat}) \pm 8\,(\text{syst}))\times 10^{-4}$$

μ-tagged Run 1 (3 fb^{-1})

Phys. Rev. Lett. 116 (2016)

$$\Delta A_{CP} = (-10 \pm 8\,(\text{stat}) \pm 3\,(\text{syst}))\times 10^{-4}$$

π-tagged Run 1 (3 fb^{-1})

JHEP 07 041 (2014)

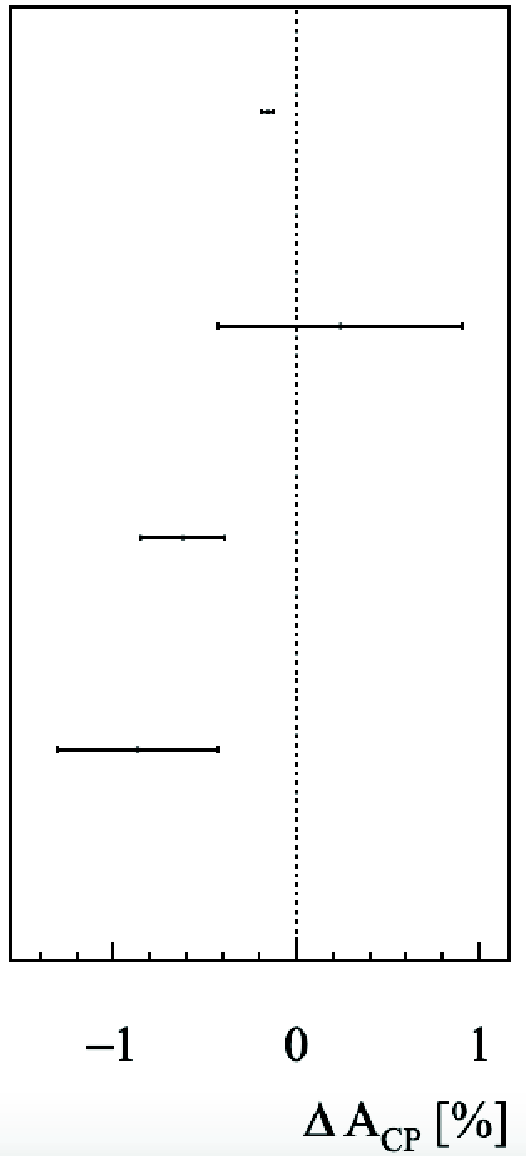
Combined Run I and Run II (9 fb^{-1})

Phys. Rev. Lett. 122, 211803 (2019)

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

5.3 σ effect

First observation of CP violation in the decays of charm mesons



$9\ \mathrm{fb}^{-1}$ at $\sqrt{s} = 7, 13$ TeV pp — LHCb, Phys. Rev. Lett. 122 (2019) 211803

$385.8\ \mathrm{fb}^{-1}$ at $\Upsilon(4S)$ — BaBar, Phys. Rev. Lett. 100 (2008) 061803

$9.7\ \mathrm{fb}^{-1}$ at $\sqrt{s} = 1.96$ TeV $p\bar{p}$ — CDF, Phys. Rev. Lett. 109 (2012) 111801

$976\ \mathrm{fb}^{-1}$ at $\Upsilon(4S)$ — Belle Preliminary [arXiv:1212.1975]

ΔA_{CP} interpretation

$$\Delta A_{CP} \simeq \Delta a_{CP}^{\mathrm{dir}} \left(1 + \frac{\overline{\langle t \rangle}}{\tau(D^0)} y_{CP}\right) + \frac{\Delta \langle t \rangle}{\tau(D^0)} a_{CP}^{\mathrm{ind}}$$

reconstructed event decay time

$$\overline{\langle t \rangle} = \frac{\langle t \rangle_{KK} - \langle t \rangle_{\pi\pi}}{2}$$

ΔA_{CP} interpretation

For the full LHCb data set (9 fb^{-1}):

$$\Delta\langle t\rangle/\tau(D^0) = 0.115 \pm 0.002$$

$$\overline{\langle t\rangle}/\tau(D^0) = 1.71 \pm 0.10$$

$$y_{CP} = (5.7 \pm 1.5)\times 10^{-3}$$

$$A_\Gamma = (-2.8 \pm 2.8)\times 10^{-4} \simeq -a_{CP}^{\mathrm{ind}}$$

JHEP 04 (2012) 129
Phys. Rev. Lett. 122 (2019) 011802

JHEP 04 (2015) 043
Phys. Rev. Lett. 118 (2017) 261803

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

ΔA_{CP} mostly sensitive to direct part

Experiment vs theory (SM interpretations)

- Some (slight) tension with theoretical SM estimates (10^{-4} to 10^{-3}) → hard to calculate precisely due to low-energy strong interactions effects

A. Soni [1905.00907] (see also A. Soni's talk in the same session)

F. Buccella, A. Paul, P. Santorelli [PRD 99 (2019) 113001],

H. Li, C. Lü, F. Yu [1903.10638],

H. Cheng, C. Chiang [PRD 100 (2019) 093002]

[JHEP 1907 (2019) 020],

Experiment vs theory (BSM)

- Predictions based on the QCD sum rules

  A. Khodjamirian and A. Petrov [Phys. Lett. B774 (2017) 235]

  $$|\Delta A_{CP}| \leq (2.0 \pm 0.3) \times 10^{-4}$$

  QCD sum rules does not work for D physics?

- Light Z'

  M. Chala, A. Lenz, A. V. Rusov, J. Scholtz [JHEP 1907 (2019) 161]

- Several scenario with new heavy particles

  A. Dery, Y. Nir [1909.11242]

Experiment vs theory (BSM)

- Predictions based on the QCD sum rules

  A. Khodjamirian and A. Petrov [Phys. Lett. B774 (2017) 235]

  $$|\Delta A_{CP}| \leq (2.0 \pm 0.3) \times 10^{-4}$$

  QCD sum rules does not work for D physics?

- Light Z'

  M. Chala, A. Lenz, A. V. Rusov, J. Scholtz [JHEP 1907 (2019) 161]

- Several scenario with new heavy particles

  A. Dery, Y. Nir [1909.11242]

Further measurements and theoretical input needed to clarify the situation

Further experimental checks

- Confirm CP violation effects in other channels

  e.g. $D^0 \rightarrow K_s^0 K_s^0$, $D^0 \rightarrow K_s^0 K_s^*$

  ([PRD 92 (2015) 054036] → expected enhancement of CPV to 1%)

- Disentangle ΔA_{CP} into $A_{CP}(\pi^+\pi^-)$ $A_{CP}(K^+K^-)$

  From Run1 data (3 fb^{-1}):

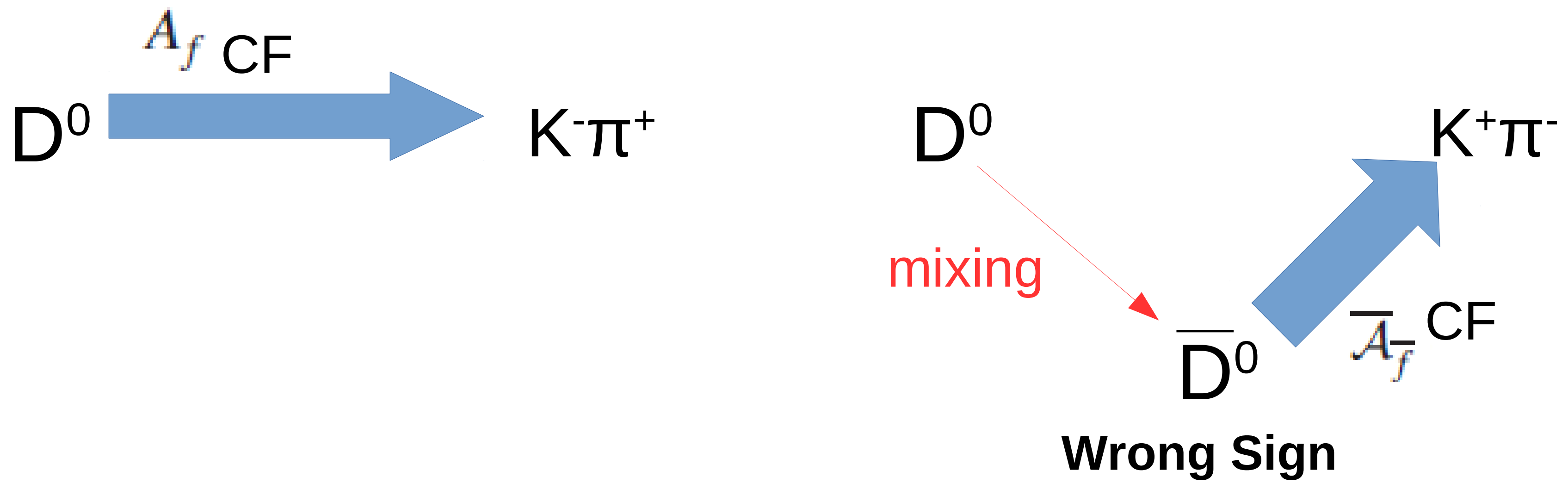
  $$A_{CP}(K^-K^+) = (0.04 \pm 0.12\,(\mathrm{stat}) \pm 0.10\,(\mathrm{syst}))\%$$

  [JHEP 1407 (2014) 041]
  [PLB 767 (2017) 177]

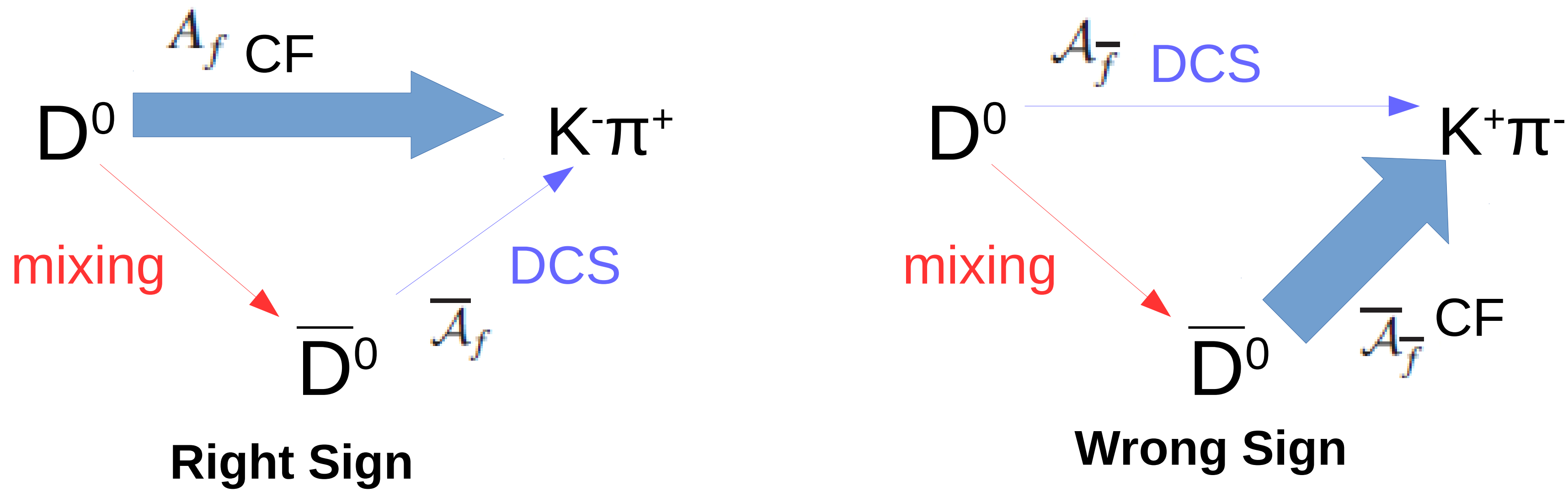
- Null test of $A_{CP}(D^+ \rightarrow \pi^+\pi^0) < 10^{-5}$ (isospin symmetry)
- Search for time-dependent CPV (SM predictions: $O(10^{-4})$)

CPV in mixing

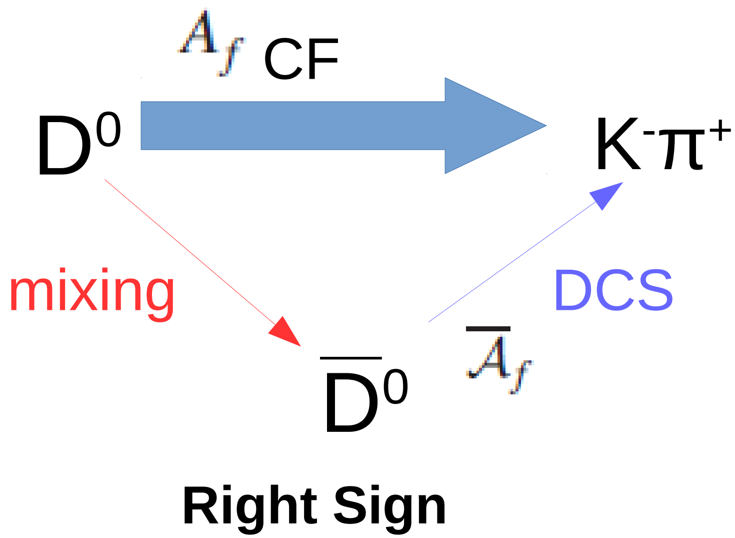
Mixing and CP studies in $D^0 \rightarrow K^+\pi^-$ decays

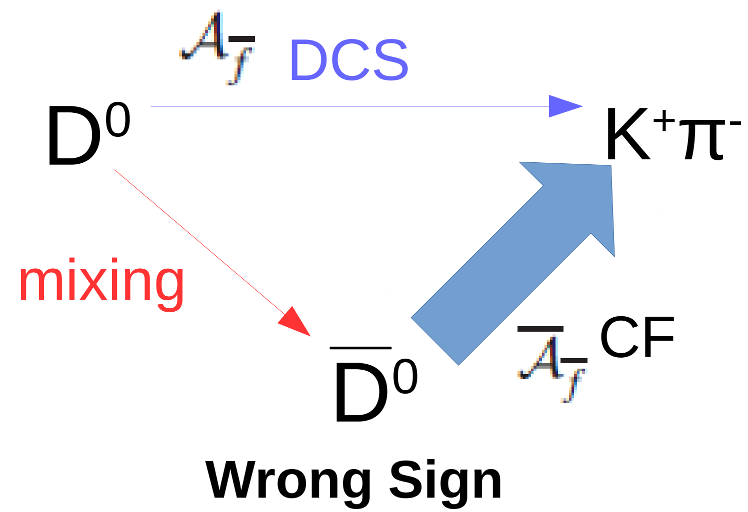


Mixing and CP studies in $D^0 \to K^+\pi^-$ decays



Mixing and CP studies in $D^0 \rightarrow K^+\pi^-$ decays





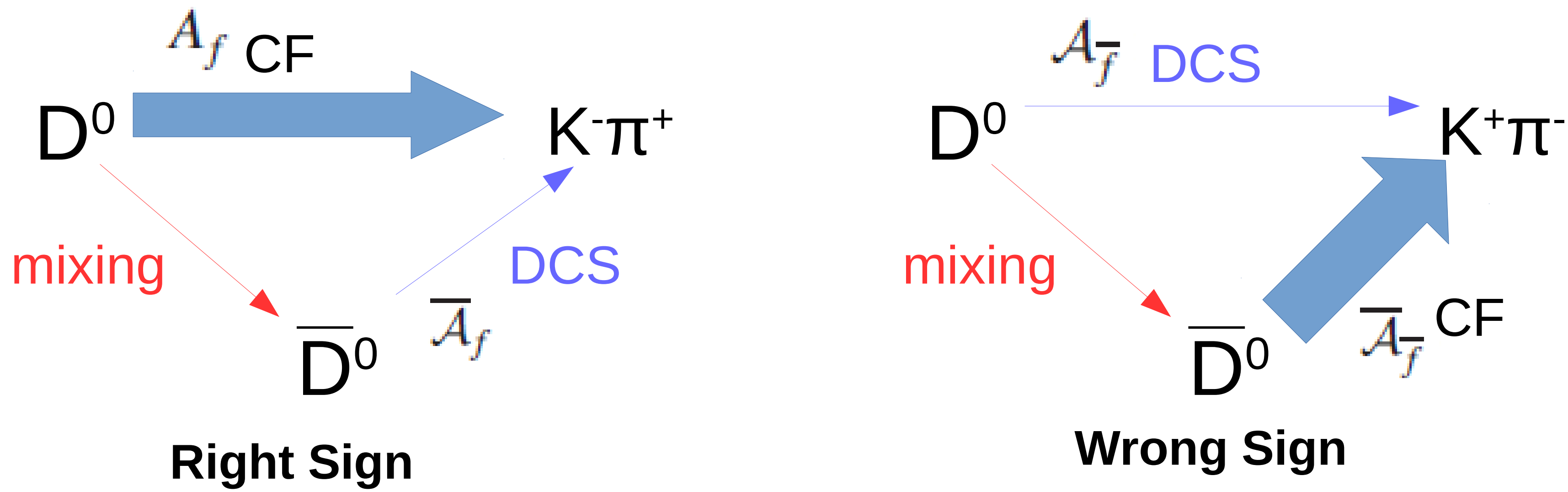
Assuming small values of x and y parameters the ratio R(t) = WS/RS (t):

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

$$R_D^+ = |\mathcal{A}_{\bar{f}} / \mathcal{A}_f|^2$$

$$R_D^- = |\overline{\mathcal{A}}_f / \overline{\mathcal{A}}_{\bar{f}}|^2$$

Mixing and CP studies in $D^0 \rightarrow K^+\pi^-$ decays



Assuming small values of x and y parameters the ratio R(t) = WS/RS (t):

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

$$R_D^+ = |A_{\overline{f}}/A_f|^2$$

$$R_D^- = |\overline{A}_f/\overline{A}_{\overline{f}}|^2$$

If $R^+(t) \neq R^-(t)$ then CP is violated:

- $R^+_D \neq R^-_D$ direct CPV
- $x'^+ \neq x'^-$ or $y'^+ \neq y'^-$ indirect CPV

- $x' = x\cos(\delta) + y\sin(\delta)$
- $y' = y\cos(\delta) + x\sin(\delta)$

SM expectation for CPV in mixing ~O(10^{-4})

Phys. Rev. D 97, 031101 (2018)

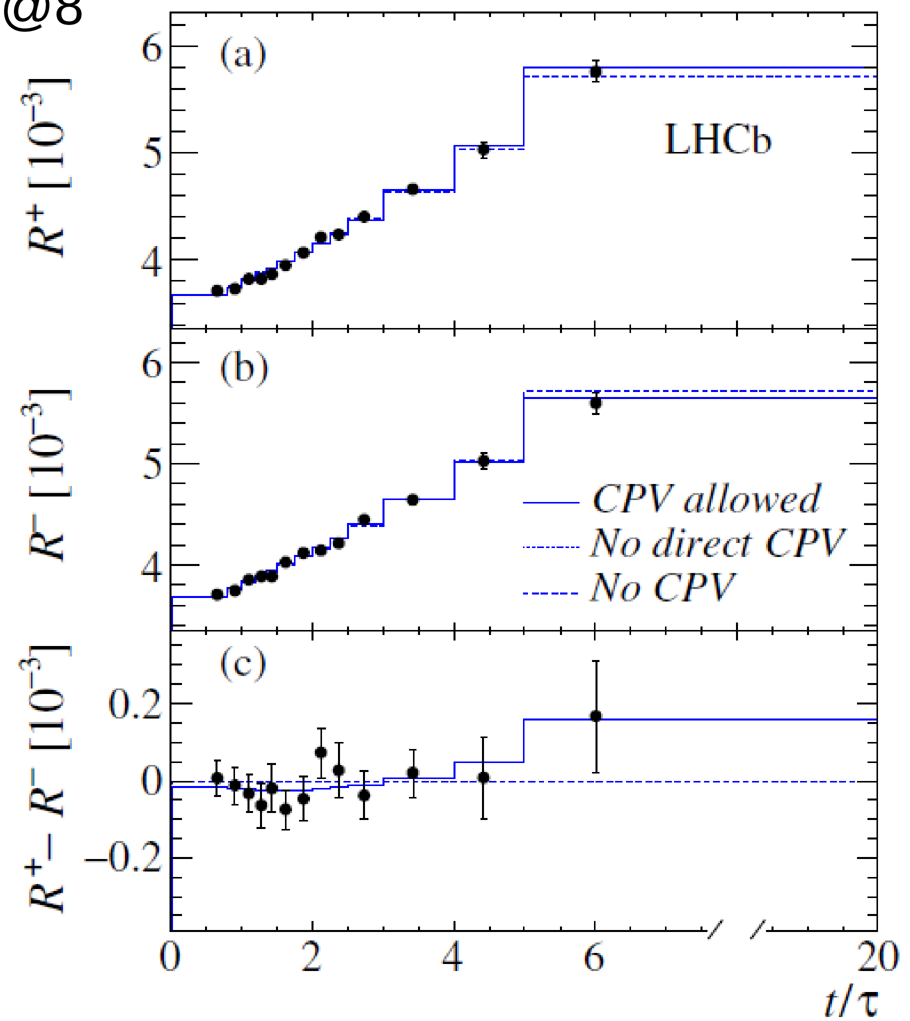
Mixing and CP studies in $D^0 \rightarrow K^+\pi^-$ decays

- Run I and II data sample (3 fb^{-1} pp @7 TeV and @8 TeV and 2 fb^{-1} @13 TeV)
- Time-dependent asymmetry R(t)
- Prompt charm
- Fit D^* mass to extract D^0 in five time bins
- Correct for time-dependent detector effects

Phys. Rev. D 97, 031101 (2018)

Mixing and CP studies in $D^0 \rightarrow K^+\pi^-$ decays

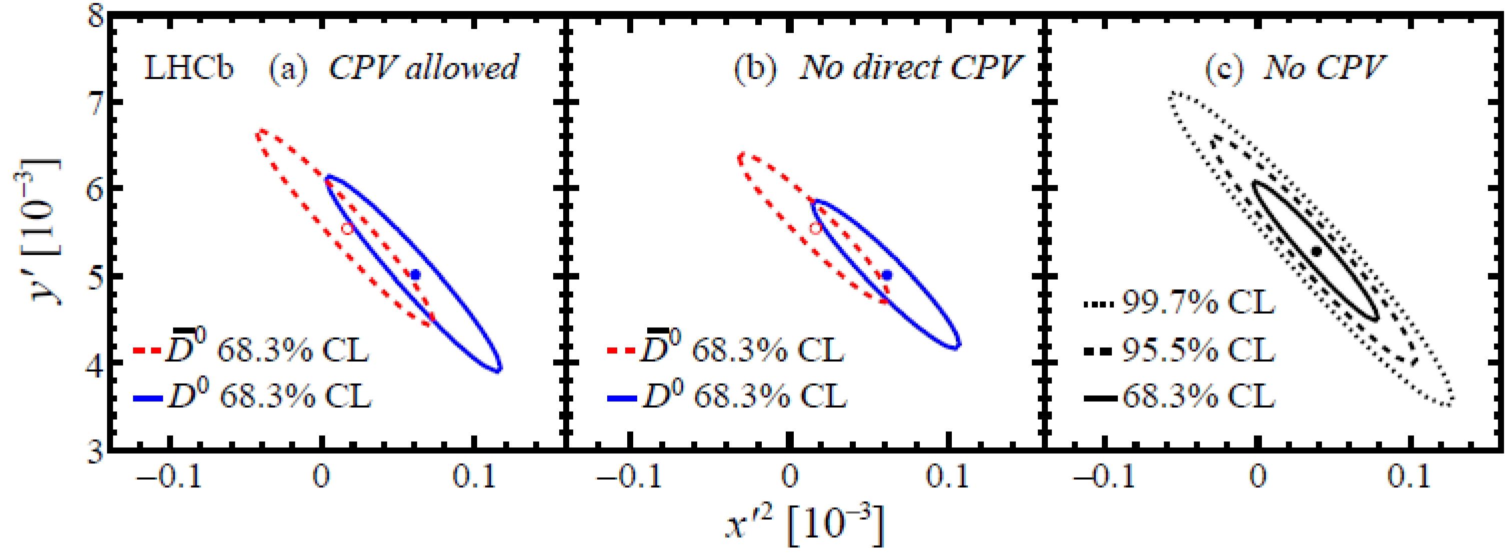
- Run I and II data sample (3 fb^{-1} pp @7 TeV and @8 TeV and 2 fb^{-1} @13 TeV)
- Time-dependent asymmetry R(t)
- Prompt charm
- Fit D^* mass to extract D^0 in five time bins
- Correct for time-dependent detector effects
- Three fit scenario considered:
  - All CPV allowed
  - No direct CPV allowed
  - **No CPV allowed**



Consistent with non-CPV hypothesis

Phys. Rev. D 97, 031101 (2018)

Mixing and CP studies in $D^0 \to K^+\pi^-$ decays



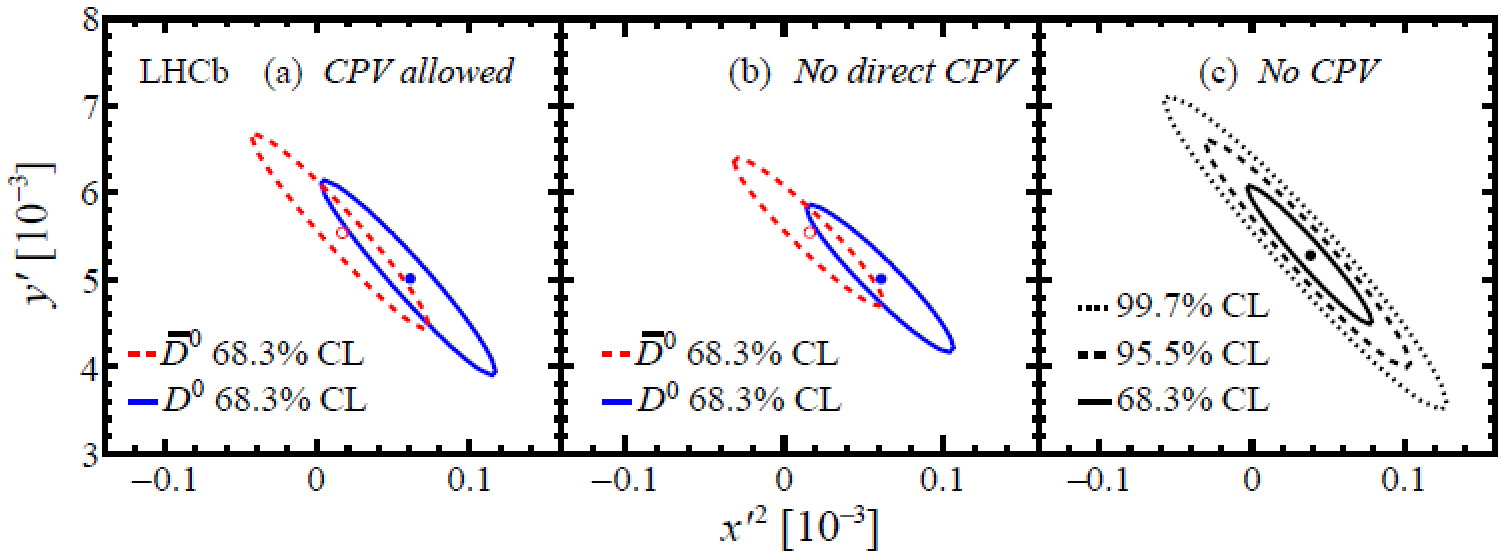
$A_D = (-0.1 \pm 9.1) \times 10^{-3}$ **@ 68% C.L.**

$1.00 < |q/p| < 1.35$ **@ 68% C.L.**

Consistent with non-CPV hypothesis

Phys. Rev. D 97, 031101 (2018)

Mixing and CP studies in $D^0 \to K^+\pi^-$ decays



$$A_D = (-0.1 \pm 9.1) \times 10^{-3}$$ @ 68% C.L.

$$1.00 < |q/p| < 1.35$$ @ 68% C.L.

Analogical analysis can be performed with:
$D^0 \to K^+\pi^- \pi^+\pi^-$ $D^0 \to K^-\pi^+\pi^+\pi^-$

Indirect CPV

$$A_{CP}(t) = \frac{\Gamma(D^0(t) \to f) - \Gamma(\overline{D}^0(t) \to f)}{\Gamma(D^0(t) \to f) + \Gamma(\overline{D}^0(t) \to f)} = A_{CP}^{\text{dir}} + \frac{t}{\tau_D} A_{CP}^{\text{indir}} + \mathcal{O}\left(\left(\frac{t}{\tau_D}\right)^2\right) \simeq A_{CP}^{\text{dir}} - \frac{t}{\tau_D} A_\Gamma$$

$f = \pi^+\pi^-$ or $\mathrm{K}^+\mathrm{K}^-$

average D^0 lifetime

Neglecting sub-leading amplitudes: $A_{CP}^{dir} = 0$

A_Γ becomes universal

(not depended on decay mode)

If no CPV asymmetry in mixing:

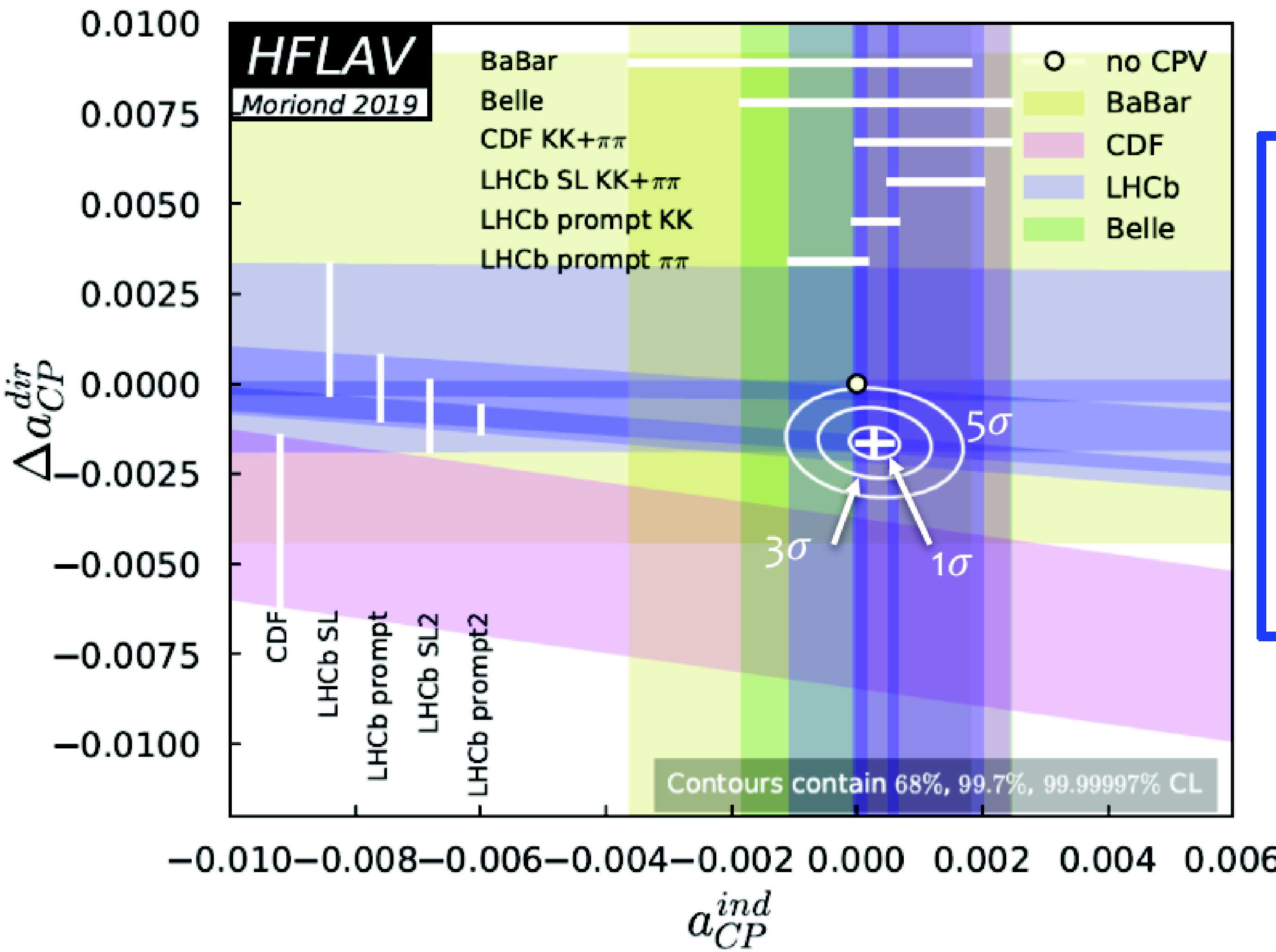
$$A_\Gamma = -x \sin\phi \to |A_\Gamma| < |x| \lesssim 5 \times 10^{-3} \qquad \phi = \arg\left((q\overline{A}_f)/(pA_f)\right)$$

Phys. Rev. Lett. 118 (2017) 261803

Average from Run1 : $A_{\Gamma} = (-0.13 \pm 0.28 \pm 0.10) \times 10^{-3}$

Submitted to PRD [1911.01114]

Average from Run1 +Run2 : $A_{\Gamma} = (-2.9 \pm 2.0 \pm 0.6) \times 10^{-4}$



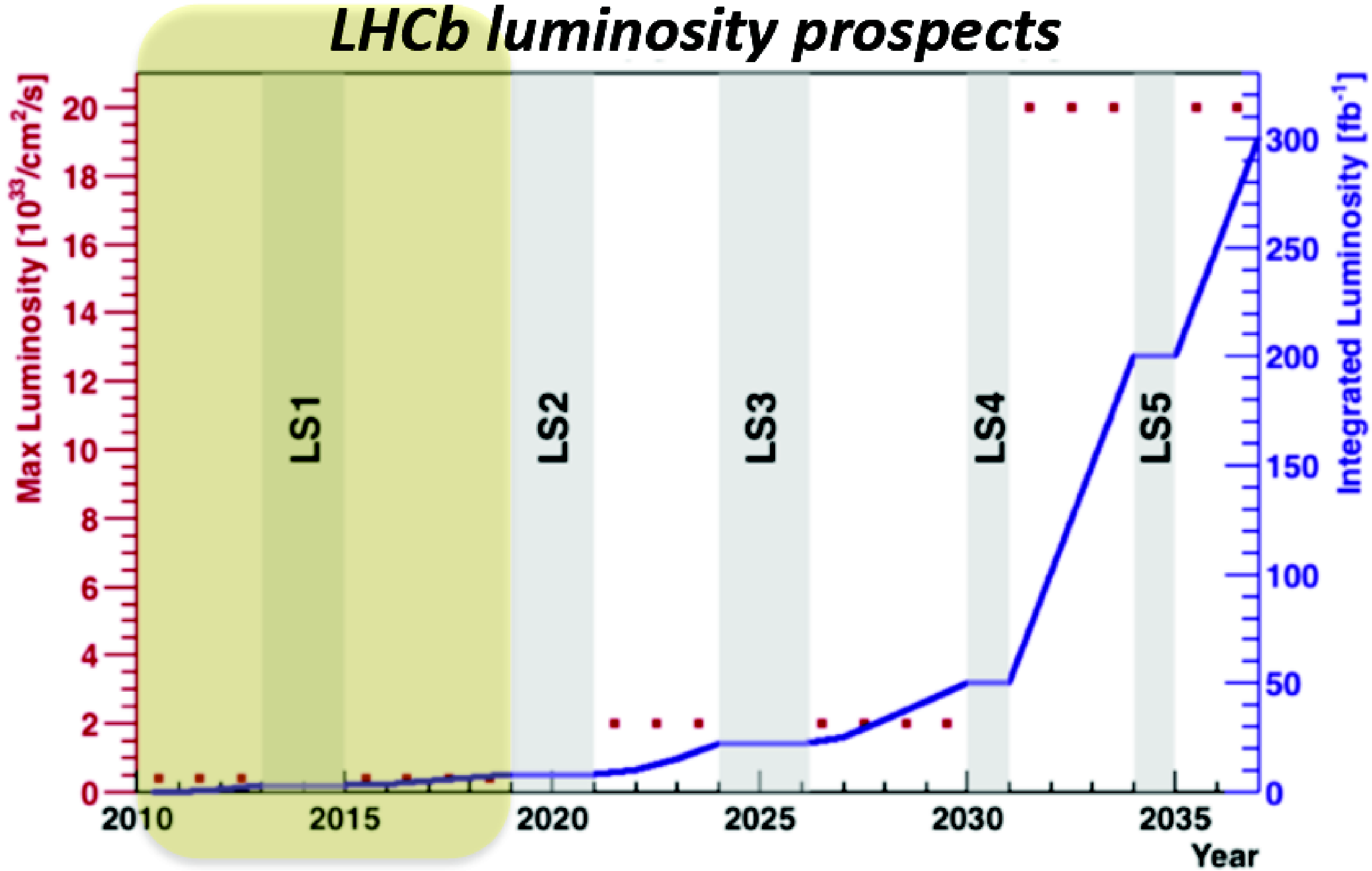
HFLAV combination

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

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

Consistency with NO CPV hypothesis: $5{\times}10^{-8}$

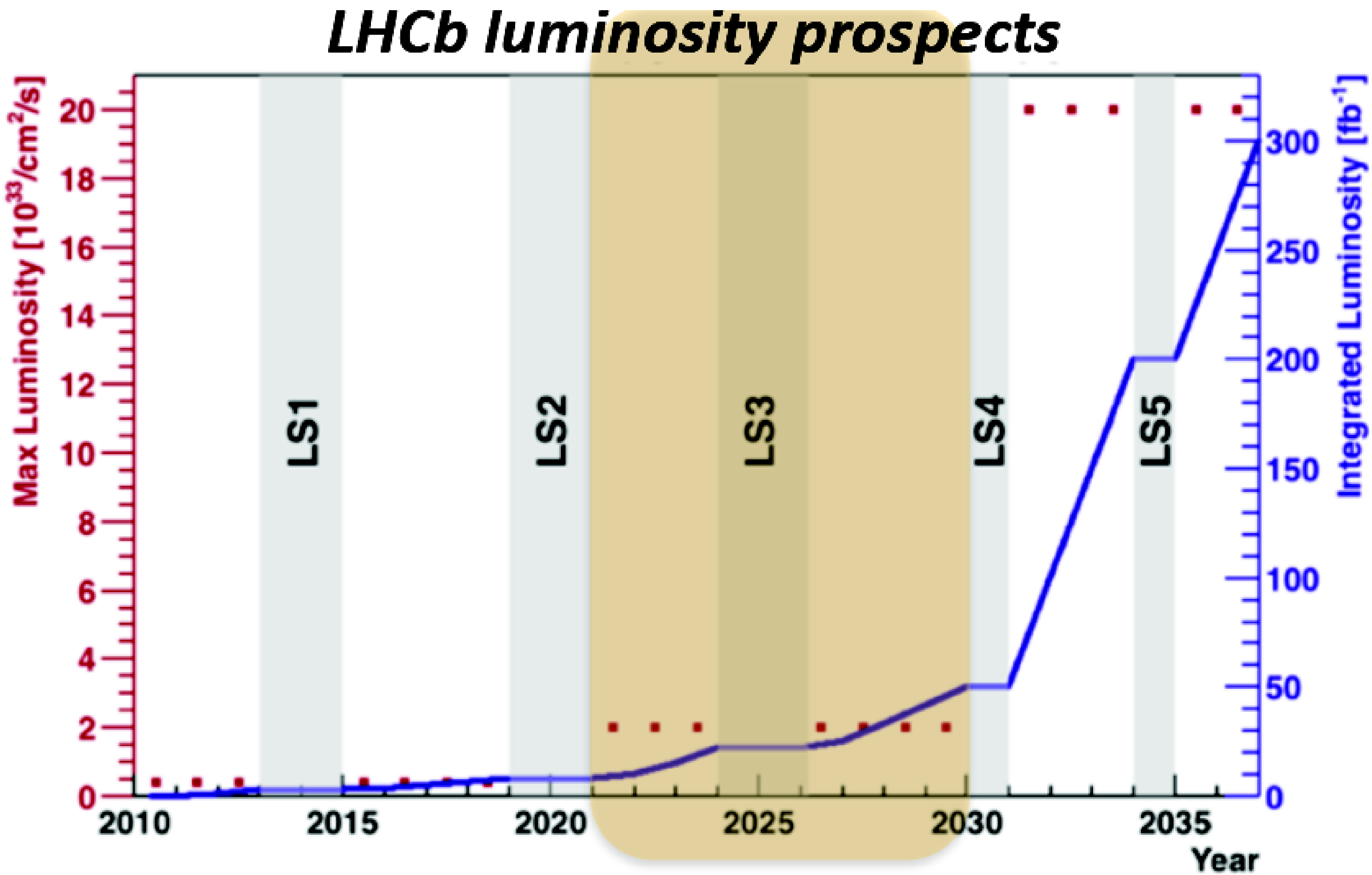
Future prospects



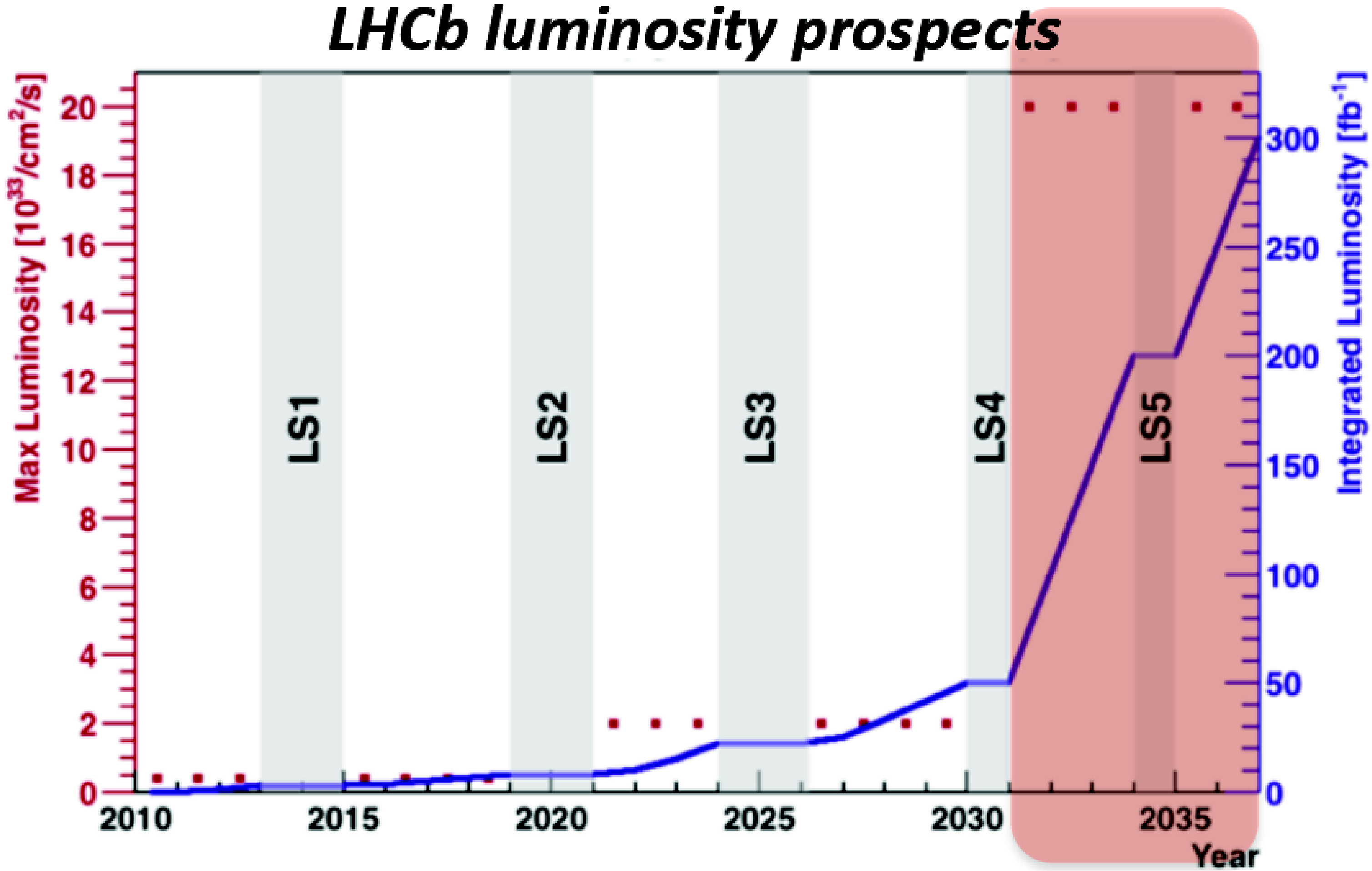
2011-2018 LHCb has collected 9 fb^{-1} of data

Run I (2011-2012): 3 fb^{-1} @7 and @8 TeV

Run II (2015-2018): 6 fb^{-1} @13 TeV



- In 2021 LHCb will resume the operation to run up to 2030 → 50 fb^{-1} of data expected
- Belle-2 is taking data from 2019 with the goal to collect 50 ab^{-1} integrated luminosity at Y(4S) up to 2027



LHCb has proposed the new upgrade for 2030 to reach the instantaneous luminosity of 2 * 10^{34} cm^{-2} s^{-1} and collect at least **300 fb^{-1}** till the end of the program.

LHCb-PUB-2018-009

Prospects for ΔA_{CP}

Sample ($\mathcal{L}$)	Tag	Yield $D^0 \to K^- K^+$	Yield $D^0 \to \pi^- \pi^+$	$\sigma(\Delta A_{CP})$ [%]	$\sigma(A_{CP}(hh))$ [%]
Run 1–2 (9 fb^{-1})	Prompt	52M	17M	0.03	0.07
Run 1–3 (23 fb^{-1})	Prompt	280M	94M	0.013	0.03
Run 1–4 (50 fb^{-1})	Prompt	1G	305M	0.01	0.03
Run 1–5 (300 fb^{-1})	Prompt	4.9G	1.6G	0.003	0.007

- LHCb Upgrade-I phase: $\sigma_{stat}(\Delta A_{CP})$ expected to be **$O(10^{-4})$**
- LHCb upgrade-II phase: $\sigma_{stat}(\Delta A_{CP})$ expected to be **3×10^{-5}**

Phys. Rev. Lett. 118 (2017) 261803

Average from Run1 : $A_\Gamma = (-0.13 \pm 0.28 \pm 0.10) \times 10^{-3}$

Submitted to PRD [1911.01114]

Average from Run1 +Run2 : $A_\Gamma = (-2.9 \pm 2.0 \pm 0.6) \times 10^{-4}$

Phys. Rev. Lett. 118 (2017) 261803

Average from Run1 : $A_\Gamma = (-0.13 \pm 0.28 \pm 0.10) \times 10^{-3}$

Submitted to PRD [1911.01114]

Average from Run1 +Run2 : $A_\Gamma = (-2.9 \pm 2.0 \pm 0.6) \times 10^{-4}$

LHCb-PUB-2018-009

Prospects for A_Γ

Sample ($\mathcal{L}$)	Tag	Yield K^+K^-	$\sigma(A_\Gamma)$	Yield $\pi^+\pi^-$	$\sigma(A_\Gamma)$
Run 1–2 (9 fb^{-1})	Prompt	60M	0.013%	18M	0.024%
Run 1–3 (23 fb^{-1})	Prompt	310M	0.0056%	92M	0.0104 %
Run 1–4 (50 fb^{-1})	Prompt	793M	0.0035%	236M	0.0065 %
Run 1–5 (300 fb^{-1})	Prompt	5.3G	0.0014%	1.6G	0.0025 %

Aiming at precision: ~$\mathbf{10^{-5}}$

compared to the SM bound: $\mathbf{A_\Gamma < 5 * 10^{-3}}$

Summary

- Mixing and CP violation studies in charm as tests of SM and probes of New Physics effects,
- LHCb observed CP violation in charm decays with a significance 5.3 standard deviations
- Several other searches for CP violation are carried in different channels
- The LHCb run 3 (and further runs) together with input from Belle-2 will provide much larger statistics available

	LHC era			HL-LHC era	
	Run 1 (2010-12)	Run 2 (2015-18)	Run 3 (2021-24)	Run 4 (2027-30)	Run 5+ (2031+)
ATLAS, CMS	25 fb^{-1}	100 fb^{-1}	300 fb^{-1}	⟶	3000 fb^{-1}
LHCb	3 fb^{-1}	6 fb^{-1}	25 fb^{-1}	50 fb^{-1}	*300 fb^{-1}

* assumes a future LHCb upgrade to raise the instantaneous luminosity to 2×10^{34} cm^{-2}


Thank you for your attention