Measuring CP asymmetry in $D^0 \to K^+K^-$ at LHCb

55th Recontres de Moriond EW
Young Scientist Forum
27/03/2024

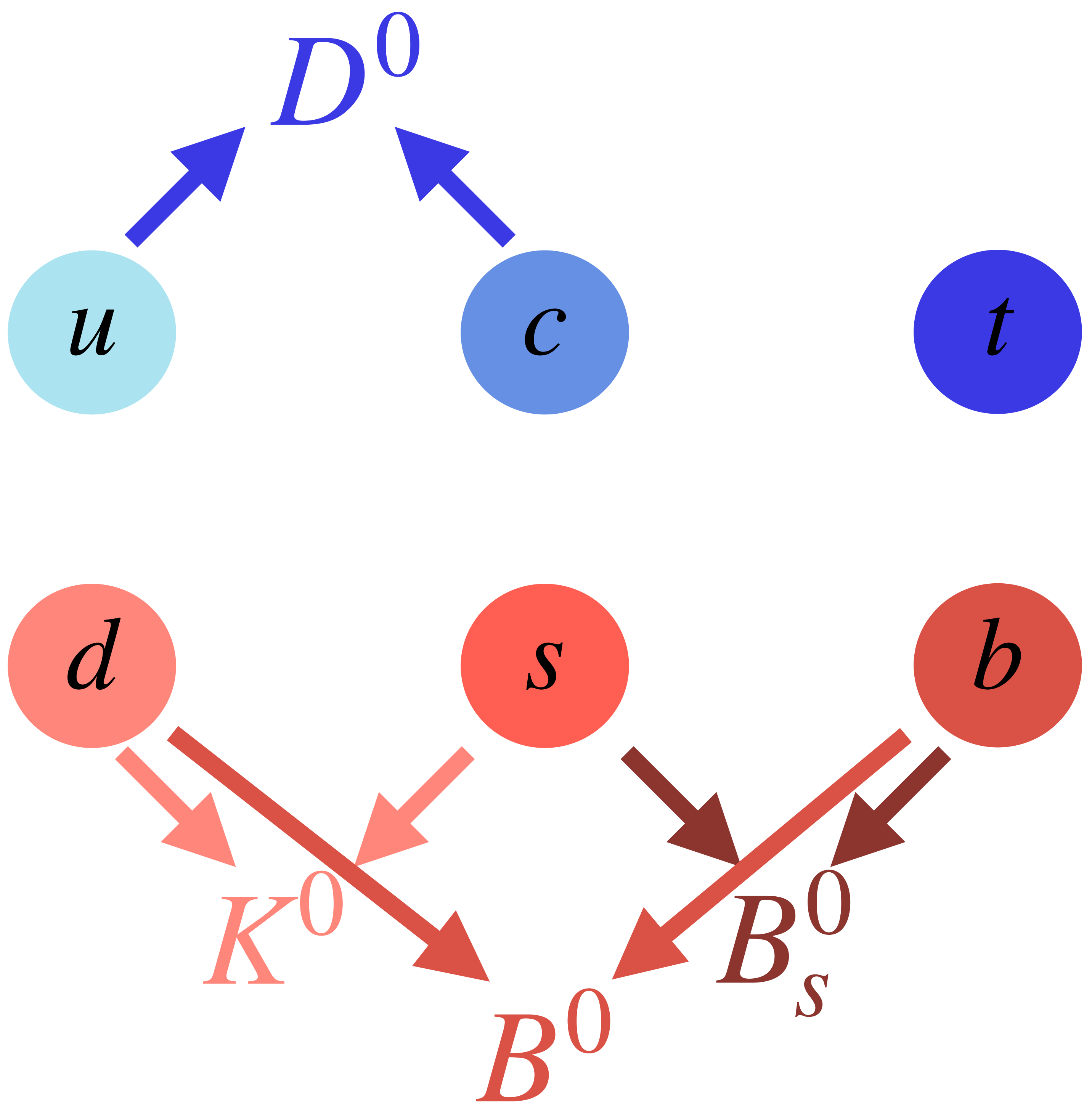
Nico Kleijne
nico.kleijne@cern.ch
on behalf of the LHCb collaboration

Why CP violation in Charm?

D^0 is the only flavoured neutral meson containing up-type quarks

- In SM due to CKM suppression CP violation is predicted to be small $\sim 10^{-3}$
- CP violation could be enhanced by BSM couplings which ignore down-type quarks

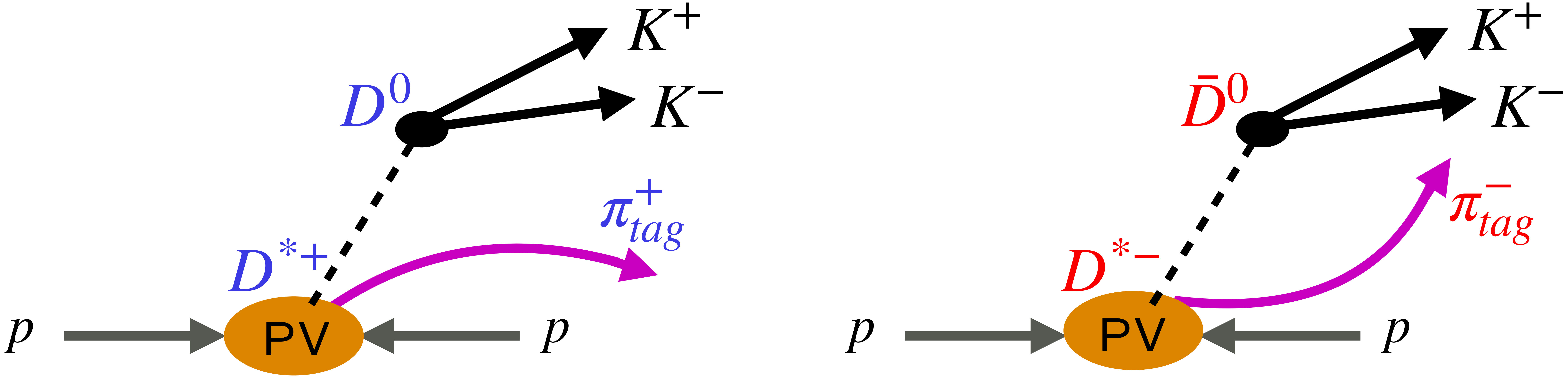
How can we measure this CP violation?



Experimental observables

Experimentally, we can only measure the asymmetry of yields

To assign the flavour of the neutral D^0 meson exploit $D^*(2010)$ decays

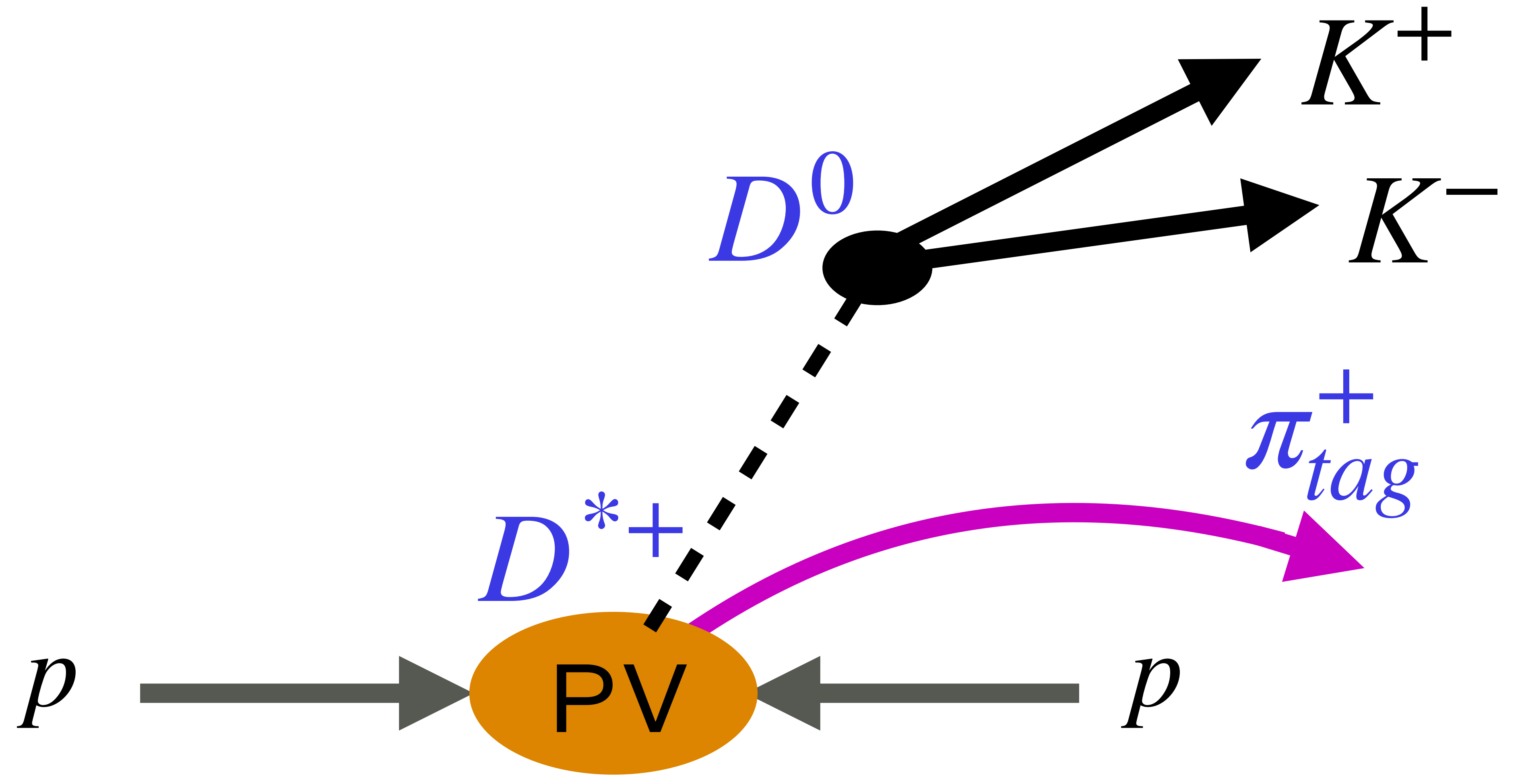


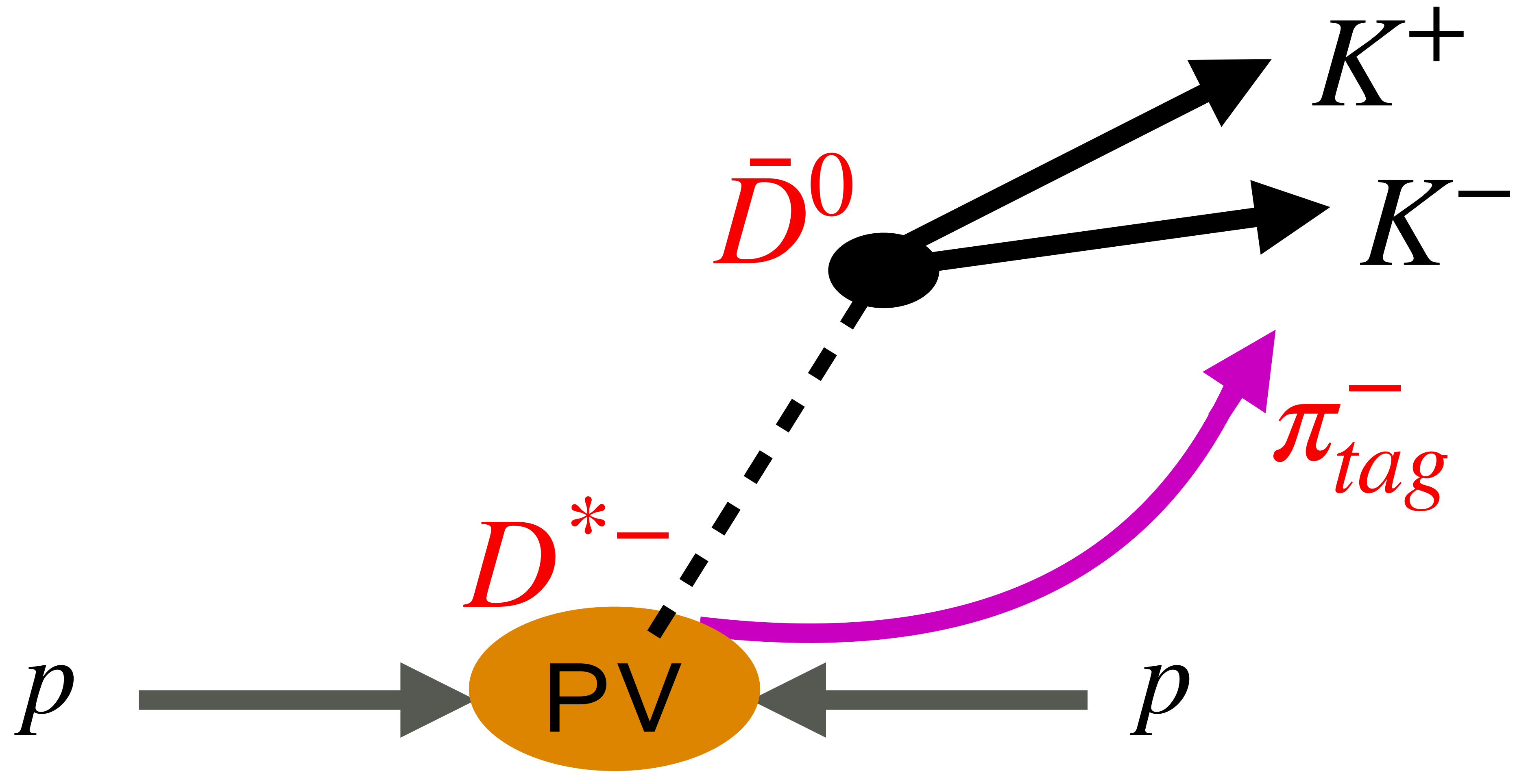
$$A_{obs}(D^0 \to K^+K^-) = \frac{N(D^0 \to K^+K^-) - N(\bar{D}^0 \to K^+K^-)}{N(D^0 \to K^+K^-) + N(\bar{D}^0 \to K^+K^-)} = A_{CP}(K^+K^-)$$

Experimental observables

Experimentally, we can only measure the asymmetry of yields

To assign the flavour of the neutral D^0 meson exploit $D^*(2010)$ decays





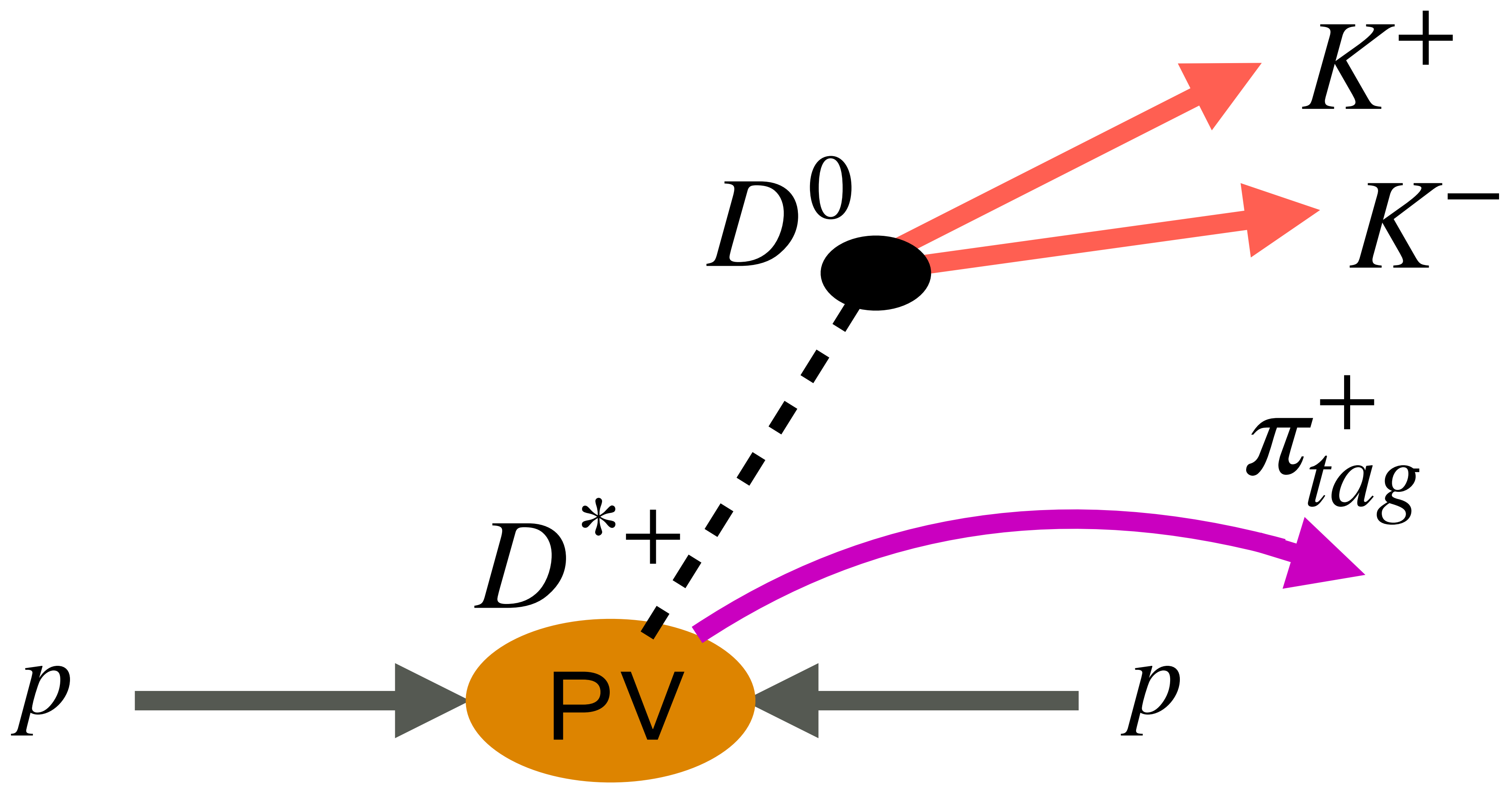
$$A_{obs}(D^0 \to K^+K^-) = \frac{N(D^0 \to K^+K^-) - N(\bar{D}^0 \to K^+K^-)}{N(D^0 \to K^+K^-) + N(\bar{D}^0 \to K^+K^-)} = A_{CP}(K^+K^-) + A_P(D^*) + A_D(\pi_{tag})$$

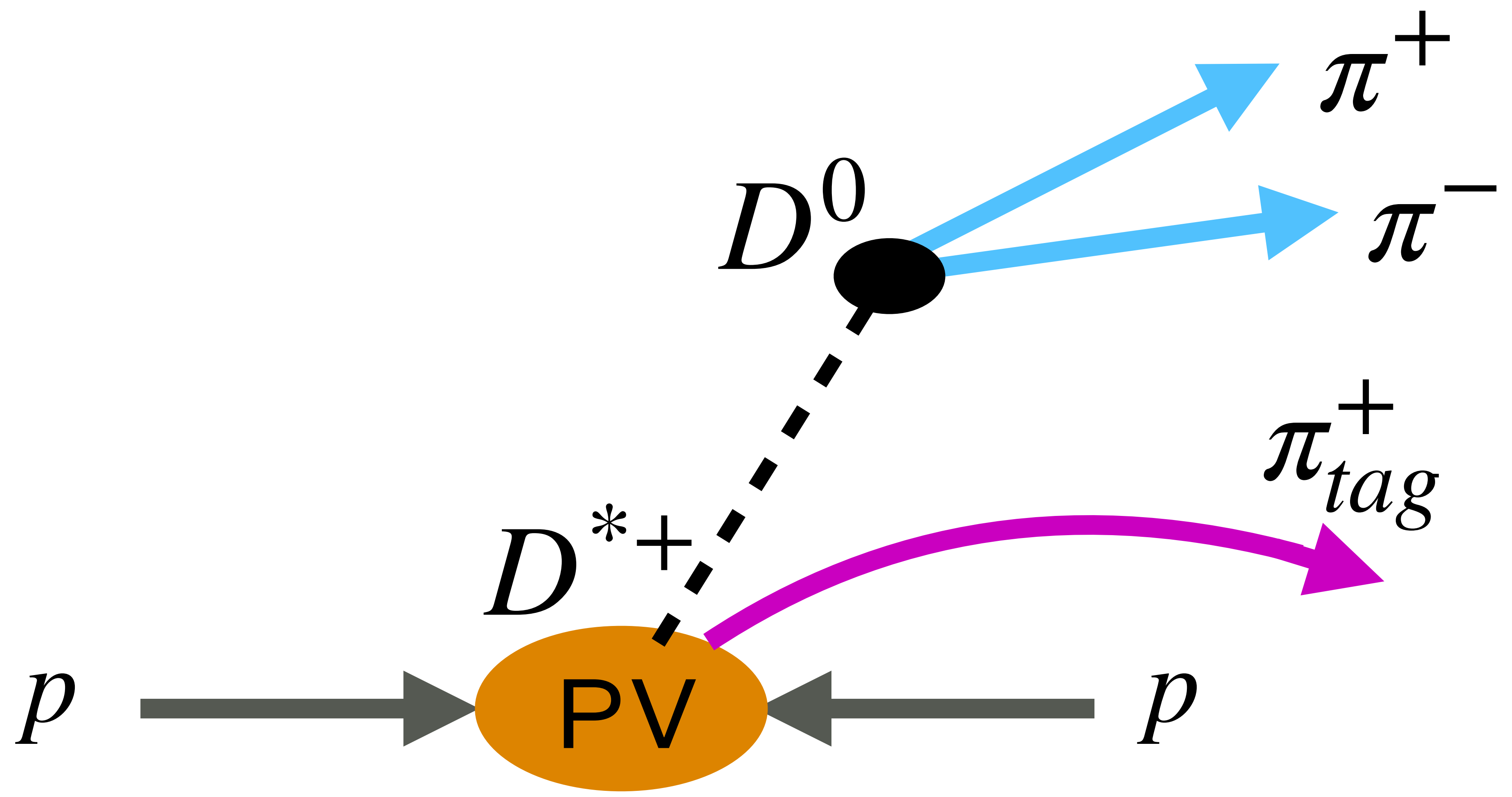
The tagging process introduces nuisance asymmetries $\sim 1\,\%$

$$A_P(D^*) = \frac{\sigma(D^{*+}) - \sigma(D^{*-})}{\sigma(D^{*+}) + \sigma(D^{*-})} \qquad A_D(\pi_{tag}) = \frac{\epsilon(\pi^+_{tag}) - \epsilon(\pi^-_{tag})}{\epsilon(\pi^+_{tag}) + \epsilon(\pi^-_{tag})}$$

The golden observable: ΔA_{CP} [PRL 122.211803]

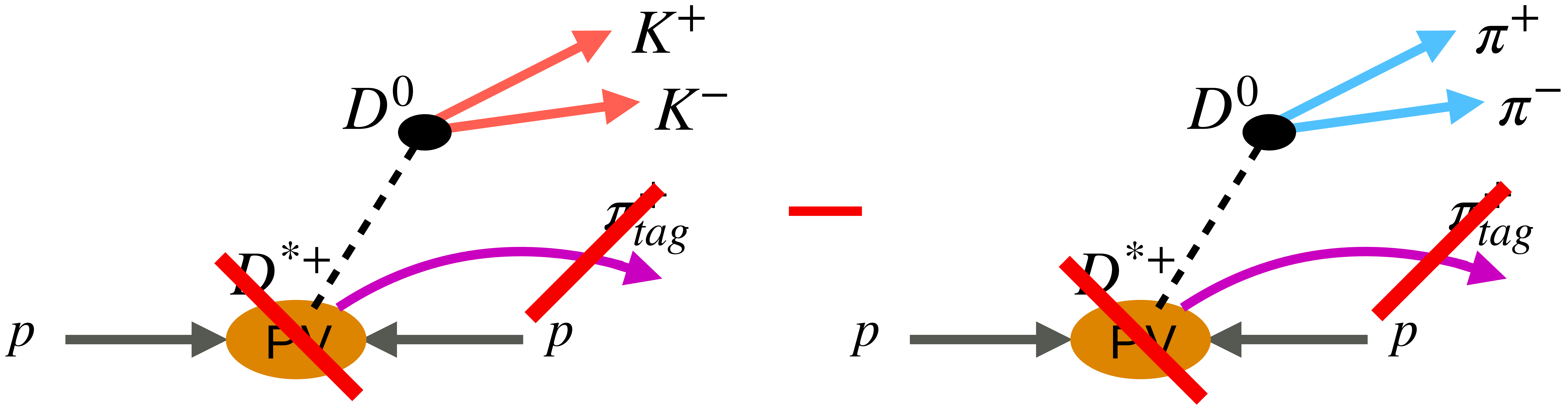
Consider two Cabibbo-suppressed CP-even D^0 decays (CPV $\neq 0$):





The golden observable: ΔA_{CP} [PRL 122.211803]

Consider two Cabibbo-suppressed CP-even D^0 decays (CPV $\neq 0$):

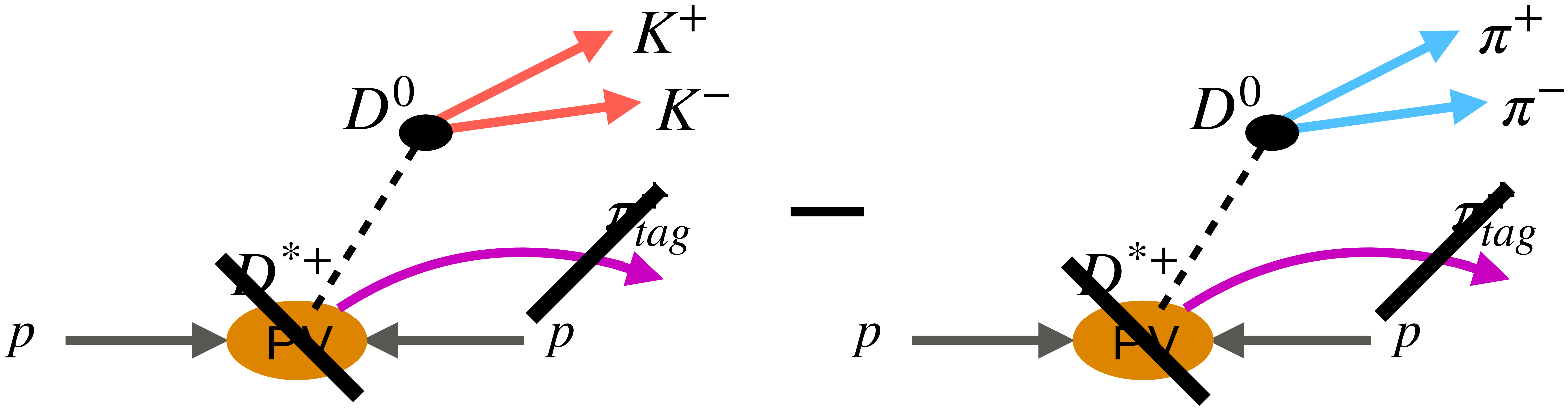


The difference of observed asymmetries cancels the nuisance asymmetries

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

The golden observable: ΔA_{CP} [PRL 122.211803]

Consider two Cabibbo-suppressed CP-even D^0 decays (CPV $\neq 0$):



The difference of observed asymmetries cancels the nuisance asymmetries

$$A_{obs}(K^+K^-) - A_{obs}(\pi^+\pi^-) = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) = \Delta A_{CP} = \Delta a^d_{CP} + \Delta Y \frac{\Delta\langle t\rangle}{\tau(D^0)}$$

CP violation in the decay

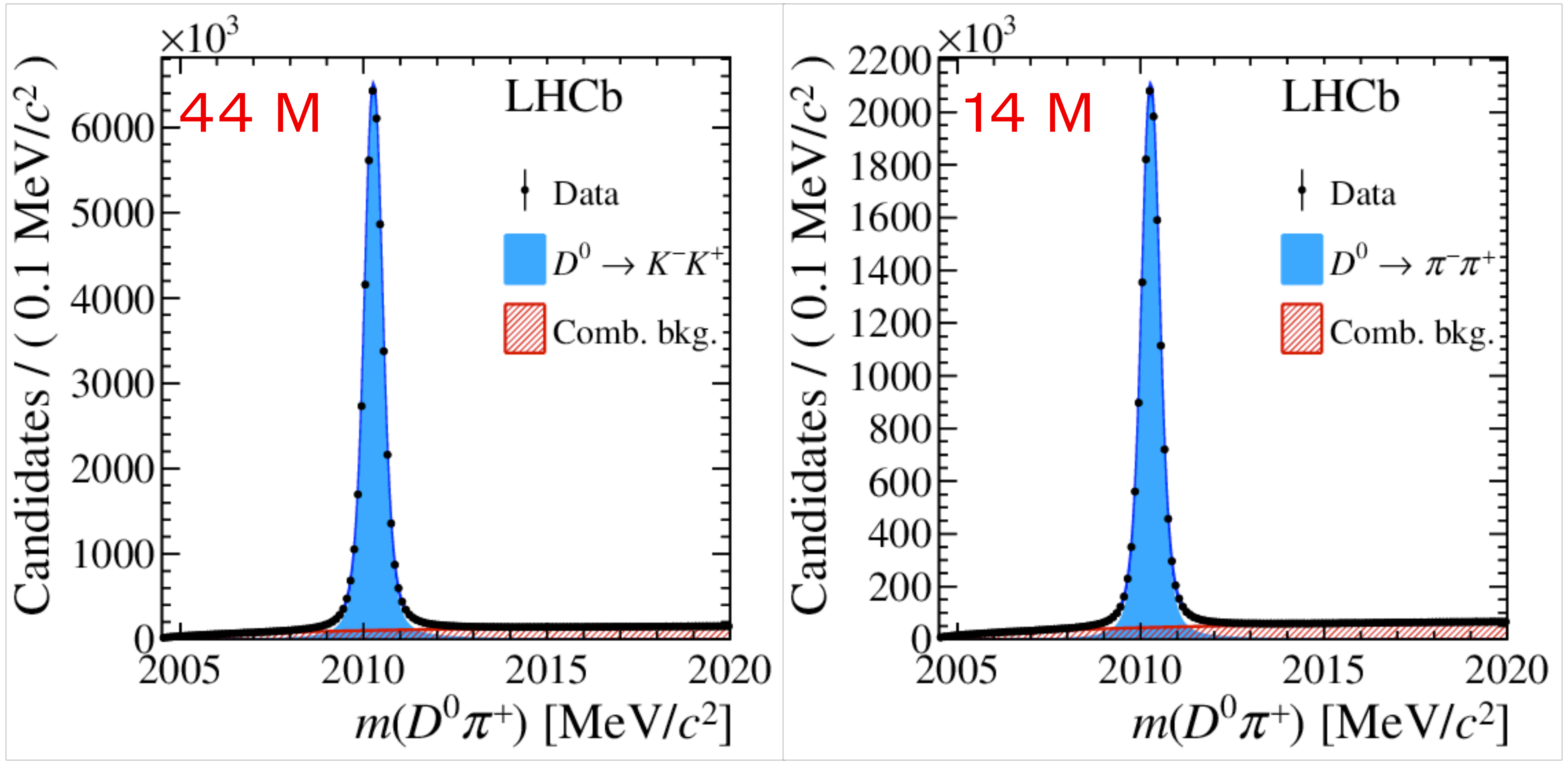
Time dependent CP violation

The golden observable: ΔA_{CP}

[PRL 122.211803]

Combining LHCb Run 1 + Run 2 data ($3\,\mathrm{fb}^{-1}$+$5.9\,\mathrm{fb}^{-1}$) and ΔY [PRD 104.072010]:

$$\Delta a^d_{CP} = a^d_{KK} - a^d_{\pi\pi} = (-15.7 \pm 2.9) \times 10^{-4}$$



First observation of CP violation in Charm sector in 2019!

Theory uncertainties do not allow to claim if this observation is SM or not

According to SU(3) flavour symmetry $a^d_{KK} = -a^d_{\pi\pi}$. How much is SU(3) violated? [PRD 75.036008, JHEP12(2019)104]

CP violation in a single decay channel: $A_{CP}(K^+K^-)$

To remove nuisance asymmetries use several Cabibbo-favoured decays as calibration channels (no CPV because no penguins)

[PRL 131.091802]

LHCb Run 2 data ($5.9\,\mathrm{fb}^{-1}$):

$$A_{CP}(K^+K^-) = (6.8 \pm \underset{\text{Stat}}{5.4} \pm \underset{\text{Syst}}{1.6}) \times 10^{-4}$$

CP violation in a single decay channel: $A_{CP}(K^+K^-)$

To remove nuisance asymmetries use several Cabibbo-favoured decays as calibration channels (no CPV because no penguins)

[PRL 131.091802]

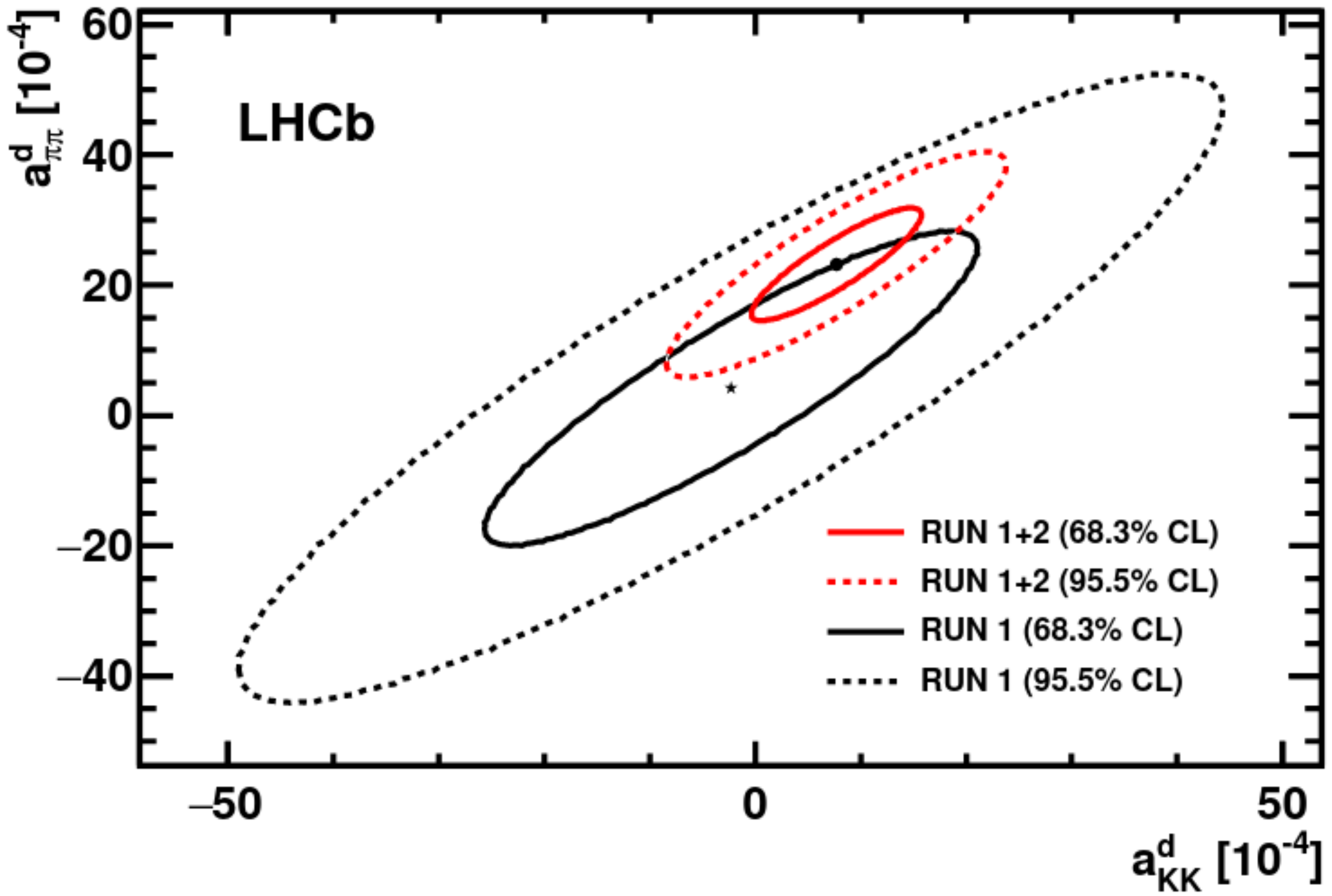
LHCb Run 2 data ($5.9\,\mathrm{fb}^{-1}$):

$$A_{CP}(K^+K^-) = (6.8 \pm \underset{\text{Stat}}{5.4} \pm \underset{\text{Syst}}{1.6}) \times 10^{-4}$$

Combining with Run 1 [PLB 2017.01.061], ΔA_{CP} [PRL 122.211803], and ΔY [PRD 104.072010]:

$$a^d_{KK} = (7.7 \pm 5.7) \times 10^{-4} \qquad a^d_{\pi\pi} = (23.6 \pm 6.1) \times 10^{-4}$$

First evidence of CP violation in a single decay channel at $3.8\,\sigma$!



CP violation in a single decay channel: $A_{CP}(K^+K^-)$

To remove nuisance asymmetries use several Cabibbo-favoured decays as calibration channels (no CPV because no penguins)

[PRL 131.091802]

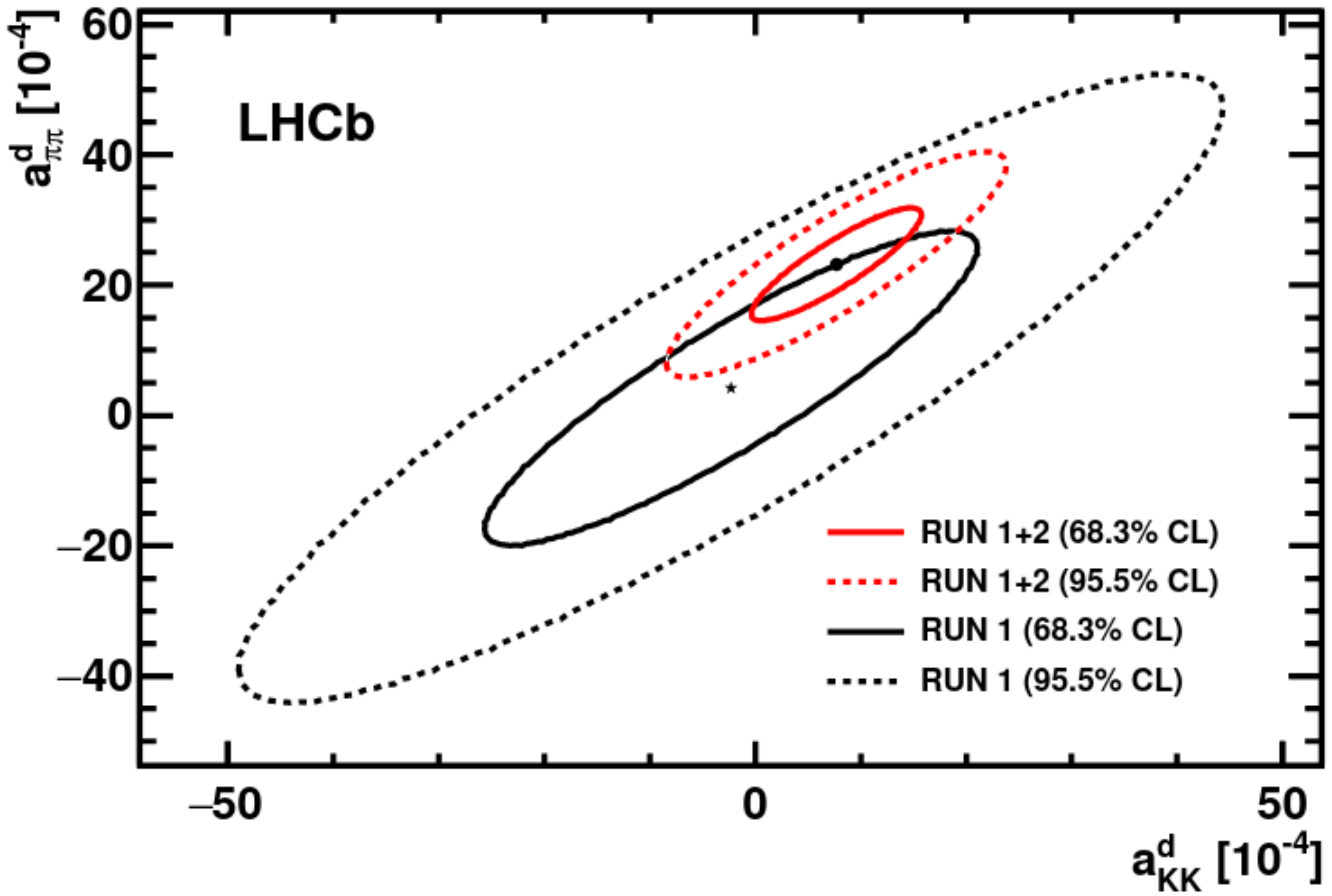
LHCb Run 2 data ($5.9\,\text{fb}^{-1}$):

$$A_{CP}(K^+K^-) = (6.8 \pm \underset{\text{Stat}}{5.4} \pm \underset{\text{Syst}}{1.6}) \times 10^{-4}$$

Combining with Run 1 [PLB 2017.01.061], ΔA_{CP} [PRL 122.211803], and ΔY [PRD 104.072010]:

$$a^d_{KK} = (7.7 \pm 5.7) \times 10^{-4}$$

$$a^d_{\pi\pi} = (23.6 \pm 6.1) \times 10^{-4}$$



First evidence of CP violation in a single decay channel at $3.8\,\sigma$!

The statistical uncertainty is dominated by the size of calibration samples

New method to measure $A_{CP}(K^+K^-)$

My PhD thesis

$$A_{obs}(D^{*+} \to D^0(\to K^+K^-)\,\pi^+_{tag}) = A_{CP}(K^+K^-) + A_P(D^{*+}) + A_D(\pi^+_{tag})$$

$$A_{obs}(D^{*+} \to D^0(\to \bar{K}^0\pi^+\pi^-)\,\pi^+_{tag}) = A_{CP}(\bar{K}^0\pi^+\pi^-) + A_P(D^{*+}) + A_D(\pi^+_{tag}) + A_D(\pi^+\pi^-) + A_D(\bar{K}^0)$$

New method to measure $A_{CP}(K^+K^-)$

My PhD thesis

$$A_{obs}(D^{*+} \to D^0(\to K^+K^-)\,\pi^+_{tag}) = A_{CP}(K^+K^-) + A_P(D^{*+}) + A_D(\pi^+_{tag})$$

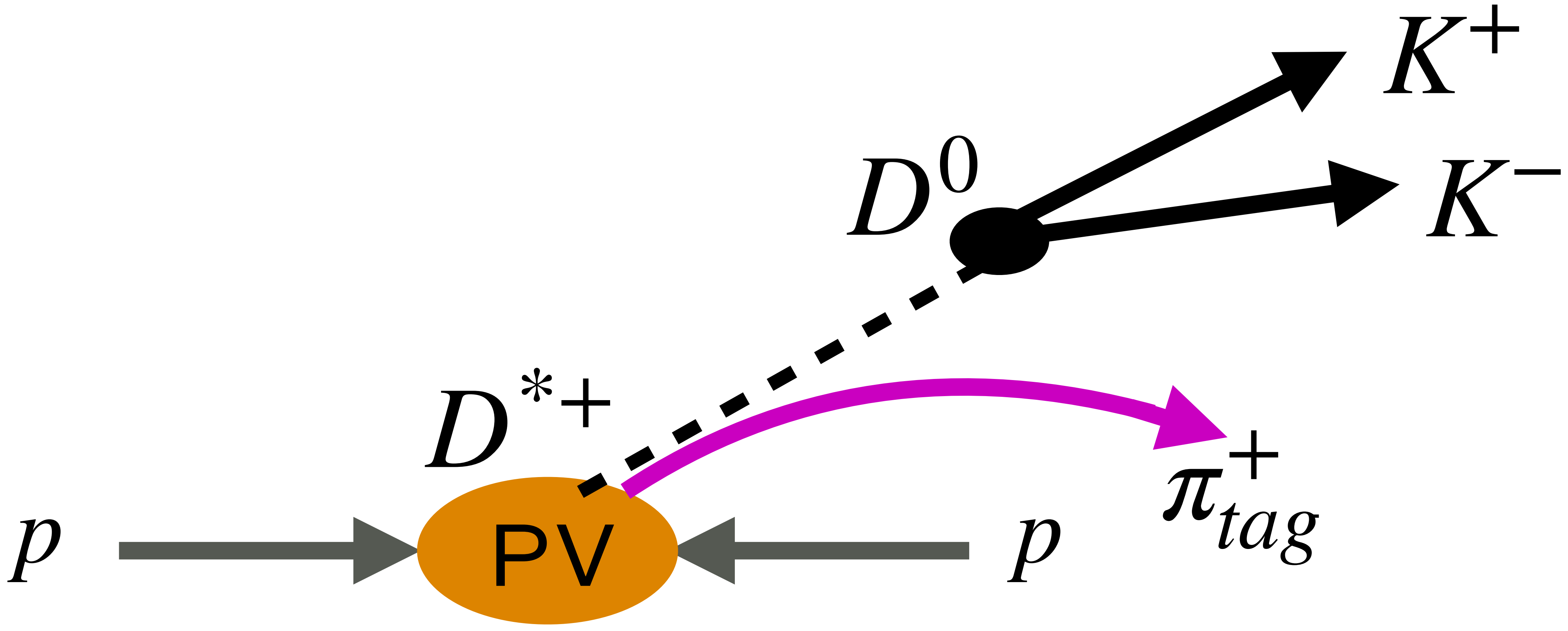
$$- \; A_{obs}(D^{*+} \to D^0(\to \bar{K}^0\pi^+\pi^-)\,\pi^+_{tag}) = A_{CP}(\bar{K}^0\pi^+\pi^-) + A_P(D^{*+}) + A_D(\pi^+_{tag}) + A_D(\pi^+\pi^-) + A_D(\bar{K}^0)$$

Usual cancellation of nuisance asymmetries

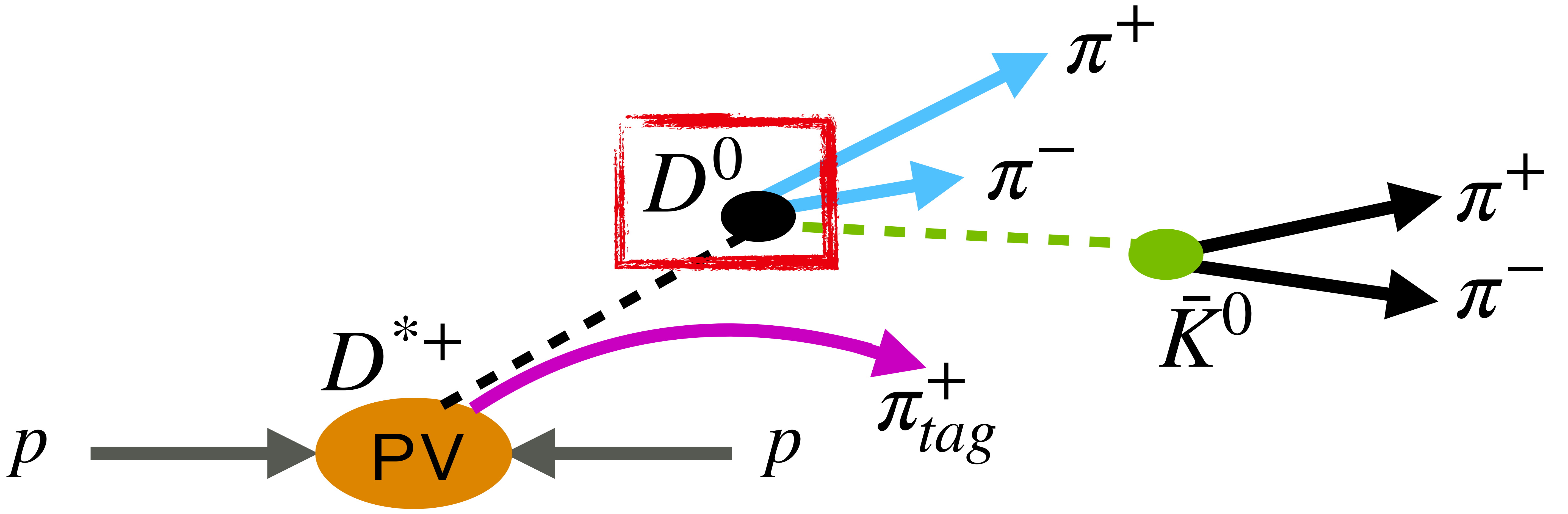
New method to measure $A_{CP}(K^+K^-)$

My PhD thesis

Signal decay



Calibration decay



$$A_{obs}(D^{*+} \to D^0(\to K^+K^-)\,\pi^+_{tag}) = A_{CP}(K^+K^-) + \cancel{A_P(D^{*+})} + \cancel{A_D(\pi^+_{tag})}$$

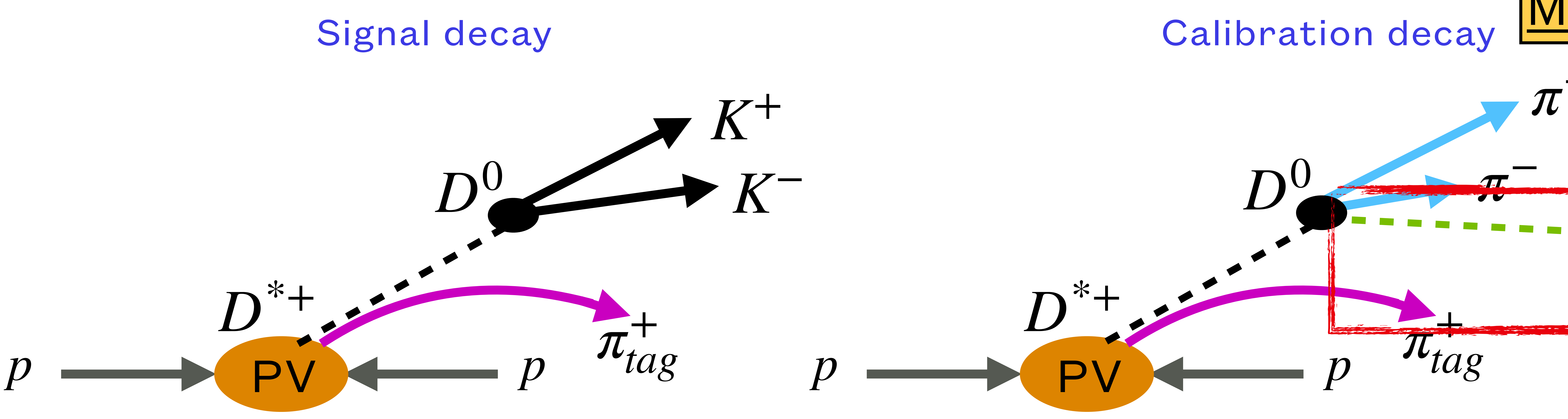
$$- \; A_{obs}(D^{*+} \to D^0(\to \bar{K}^0\pi^+\pi^-)\,\pi^+_{tag}) = \boxed{A_{CP}(\bar{K}^0\pi^+\pi^-)} + \cancel{A_P(D^{*+})} + \cancel{A_D(\pi^+_{tag})} + A_D(\pi^+\pi^-) + A_D(\bar{K}^0)$$

Cabibbo-favoured (or DCS) decay: - no CP violation in the decay

- time-dependent contribution $\lesssim 1 \times 10^{-4}$

New method to measure $A_{CP}(K^+K^-)$

My PhD thesis



$$A_{obs}(D^{*+} \to D^0(\to K^+K^-)\,\pi^+_{tag}) = A_{CP}(K^+K^-) + A_P(D^{*+}) + A_D(\pi^+_{tag})$$

$$- A_{obs}(D^{*+} \to D^0(\to \bar{K}^0\pi^+\pi^-)\,\pi^+_{tag}) = A_{CP}(\bar{K}^0\pi^+\pi^-) + A_P(D^{*+}) + A_D(\pi^+_{tag}) + A_D(\pi^+\pi^-) + A_D(\bar{K}^0)$$

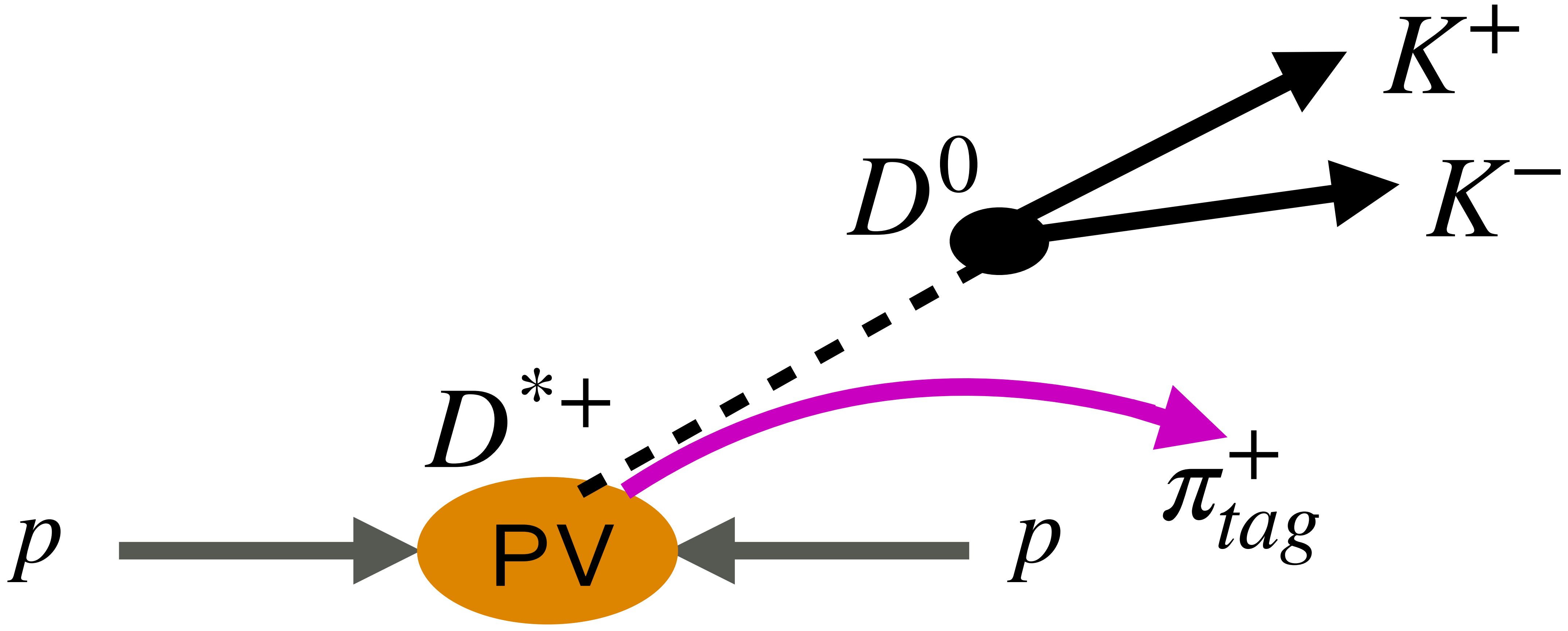
Generated by time dependent CP violation and material regeneration of neutral kaons

These physical effects are well understood and can be estimated as in previous analyses [PRL 131.091802]

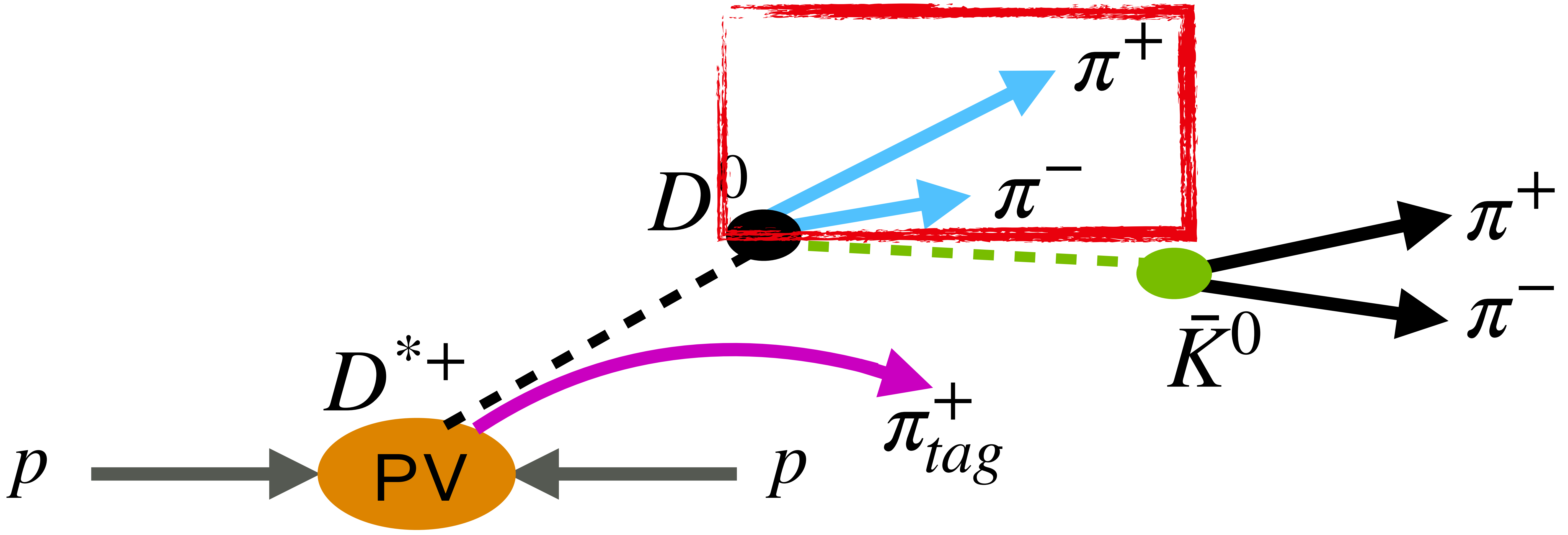
New method to measure $A_{CP}(K^+K^-)$

My PhD thesis

Signal decay



Calibration decay



$$A_{obs}(D^{*+} \to D^0(\to K^+K^-)\,\pi^+_{tag}) = A_{CP}(K^+K^-) + A_P(D^{*+}) + A_D(\pi^+_{tag})$$

$$-\; A_{obs}(D^{*+} \to D^0(\to \bar{K}^0\pi^+\pi^-)\,\pi^+_{tag}) = A_{CP}(\bar{K}^0\pi^+\pi^-) + A_P(D^{*+}) + A_D(\pi^+_{tag}) + A_D(\pi^+\pi^-) + A_D(\bar{K}^0)$$

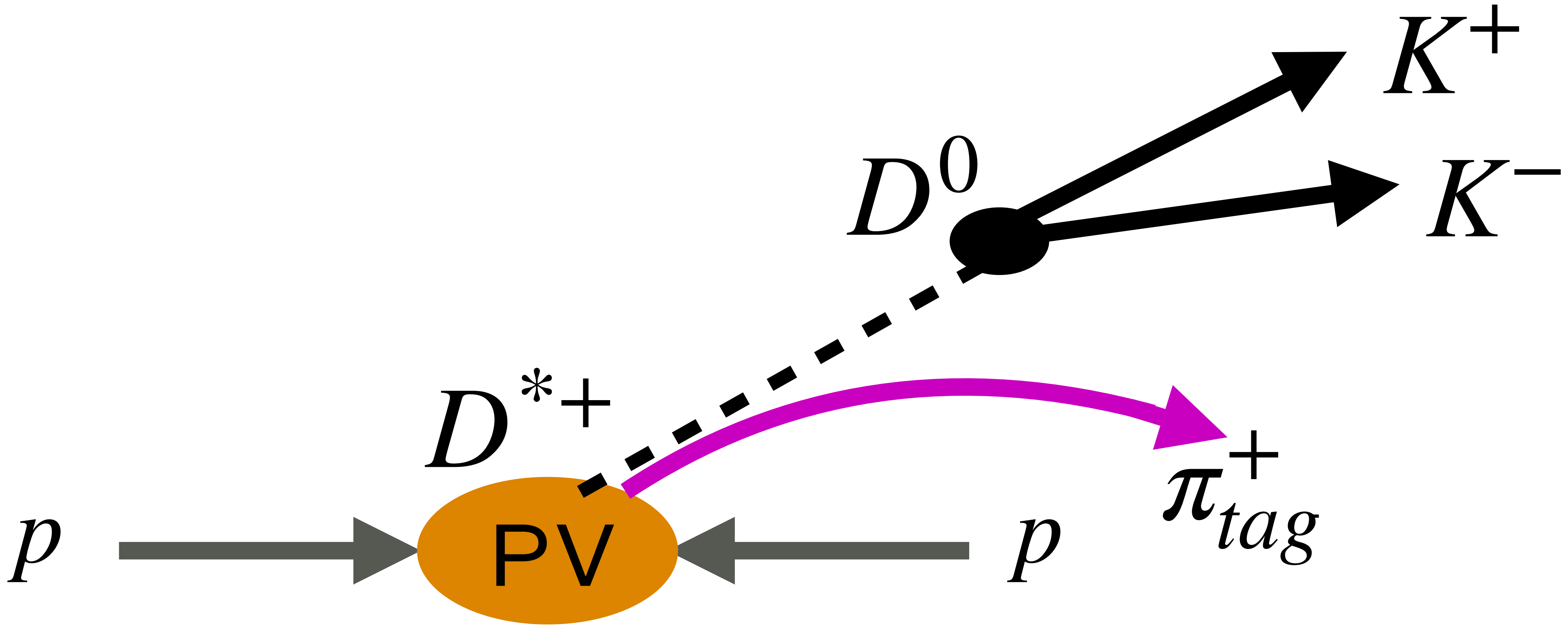
In $D^0 \to \bar{K}^0\pi^+\pi^-$ three-body decay the kinematics of the $\pi^+\pi^-$ pair is non symmetric

Weight candidates to make the kinematics symmetric under charge exchange

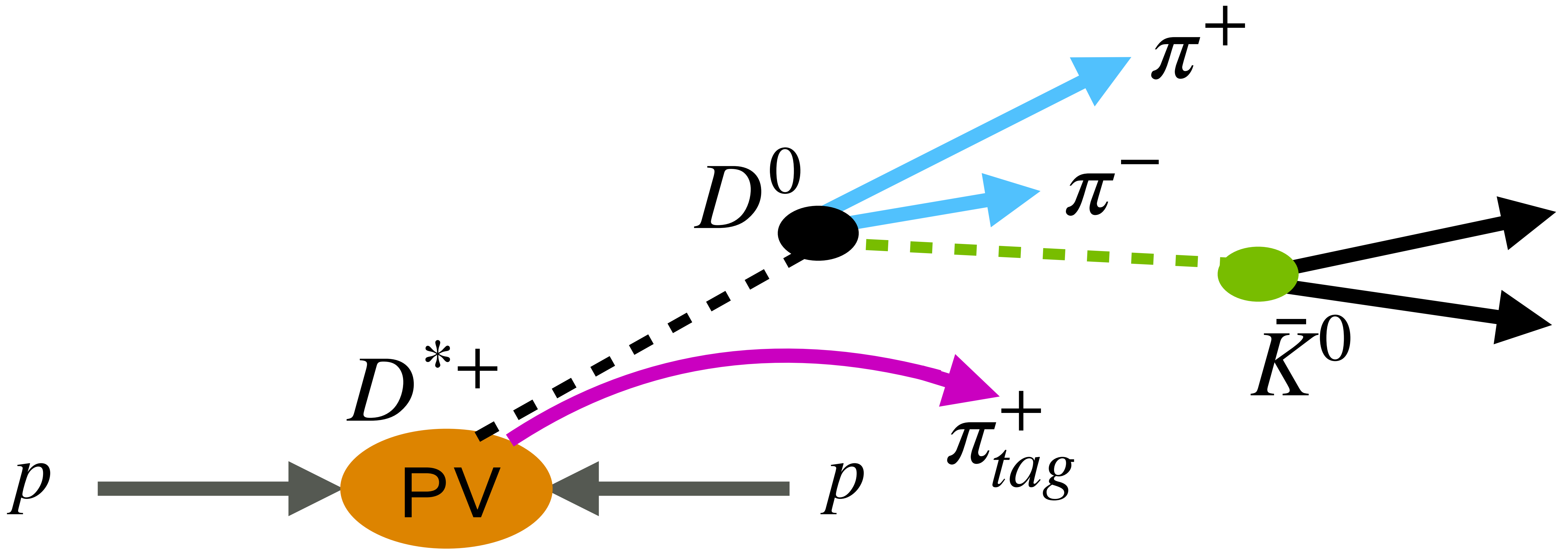
New method to measure $A_{CP}(K^+K^-)$

My PhD thesis

Signal decay



Calibration decay



$$A_{obs}(D^{*+} \to D^0(\to K^+K^-)\,\pi^+_{tag}) = \boxed{A_{CP}(K^+K^-)} + \cancel{A_P(D^{*+})} + \cancel{A_D(\pi^+_{tag})}$$

$$- \; A_{obs}(D^{*+} \to D^0(\to \bar{K}^0\pi^+\pi^-)\,\pi^+_{tag}) = \cancel{A_{CP}(\bar{K}^0\pi^+\pi^-)} + \cancel{A_P(D^{*+})} + \cancel{A_D(\pi^+_{tag})} + \cancel{A_D(\pi^+\pi^-)} + \cancel{A_D(\bar{K}^0)}$$

In the end only the quantity of interest is left!

What we expect for the near future

- The uncertainty on this Run 2 measurement should be dominated by the calibration sample:
  - Number of $D^0 \to K^+K^-$ candidates ~ 40 M [PRL 131.091802]
  - Number of $D^0 \to \bar{K}^0\pi^+\pi^-$ candidates $\lesssim 10$ M (only $\bar{K}^0$ with short flight distance) [PRL 127.111801]

What we expect for the near future

- The uncertainty on this Run 2 measurement should be dominated by the calibration sample:
  - Number of $D^0 \to K^+K^-$ candidates ~ 40 M [PRL 131.091802]
  - Number of $D^0 \to \bar{K}^0\pi^+\pi^-$ candidates $\lesssim 10$ M (only $\bar{K}^0$ with short flight distance) [PRL 127.111801]
- We expect an uncertainty almost independent and in the same ballpark of published methods:

Reminder of PRL 131.091802 : $a^d_{KK} = (7.7 \pm 5.7) \times 10^{-4}$ $a^d_{\pi\pi} = (23.6 \pm 6.1) \times 10^{-4}$

What we expect for the near future

- The uncertainty on this Run 2 measurement should be dominated by the calibration sample:
  - Number of $D^0 \to K^+K^-$ candidates $\sim 40\,$M [PRL 131.091802]
  - Number of $D^0 \to \bar{K}^0\pi^+\pi^-$ candidates $\lesssim 10\,$M (only $\bar{K}^0$ with short flight distance) [PRL 127.111801]
- We expect an uncertainty almost independent and in the same ballpark of published methods:

Reminder of PRL 131.091802 : $a^d_{KK} = (7.7 \pm 5.7) \times 10^{-4}$ $a^d_{\pi\pi} = (23.6 \pm 6.1) \times 10^{-4}$

If we are lucky, we could get closer to first observation of CP violation in a single decay channel $3.8\sigma \overset{?}{\to} 5\sigma$

Stay tuned!

Back up

Published strategy for $A_{CP}(K^+K^-)$

[PRL 131.091802]

Use $D^{*+} \to (D^0 \to K^-\pi^+)\pi^+_{tag}$ decays to cancel nuisance asymmetries

No CPV because they are Cabibbo-favoured (no penguins)

$$A_{CP}(K^+K^-) = A_{obs}(D^{*+} \to D^0(\to K^+K^-)\pi^+_{tag}) - A_{obs}(D^{*+} \to D^0(\to K^-\pi^+)\pi^+_{tag}) + A_D(K^-\pi^+)$$

New asymmetry due to non symmetric final state

Two methods to estimate it with other Cabibbo-favoured decays:

Method 1: $A_D(K^-\pi^+) = A_{obs}(D^+ \to K^-\pi^+\pi^+) - [A_{obs}(D^+ \to \bar{K}^0\pi^+) - A(\bar{K}^0)]$

Method 2: $A_D(K^-\pi^+) = A_{obs}(D_s^+ \to \phi\,\pi^+) - [A_{obs}(D_s^+ \to \bar{K}^0K^+) - A(\bar{K}^0)]$

Kinematic distributions of particles with the same color are equalised for an exact cancellation

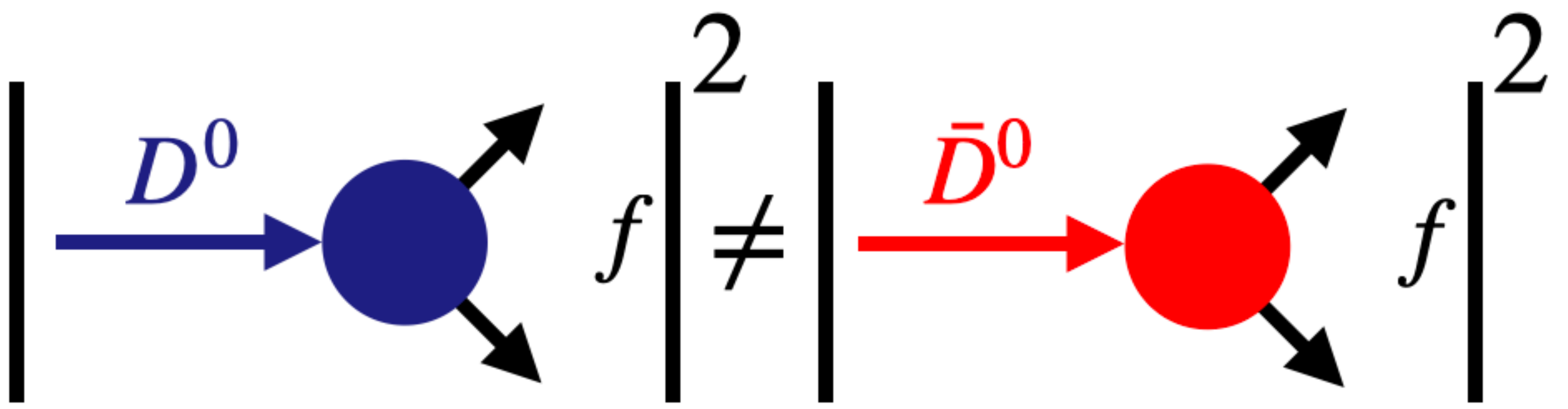
After the kinematic equalisation, statistical uncertainties are dominated by calibration channels:
the two methods are almost independent

CP violation in Charm

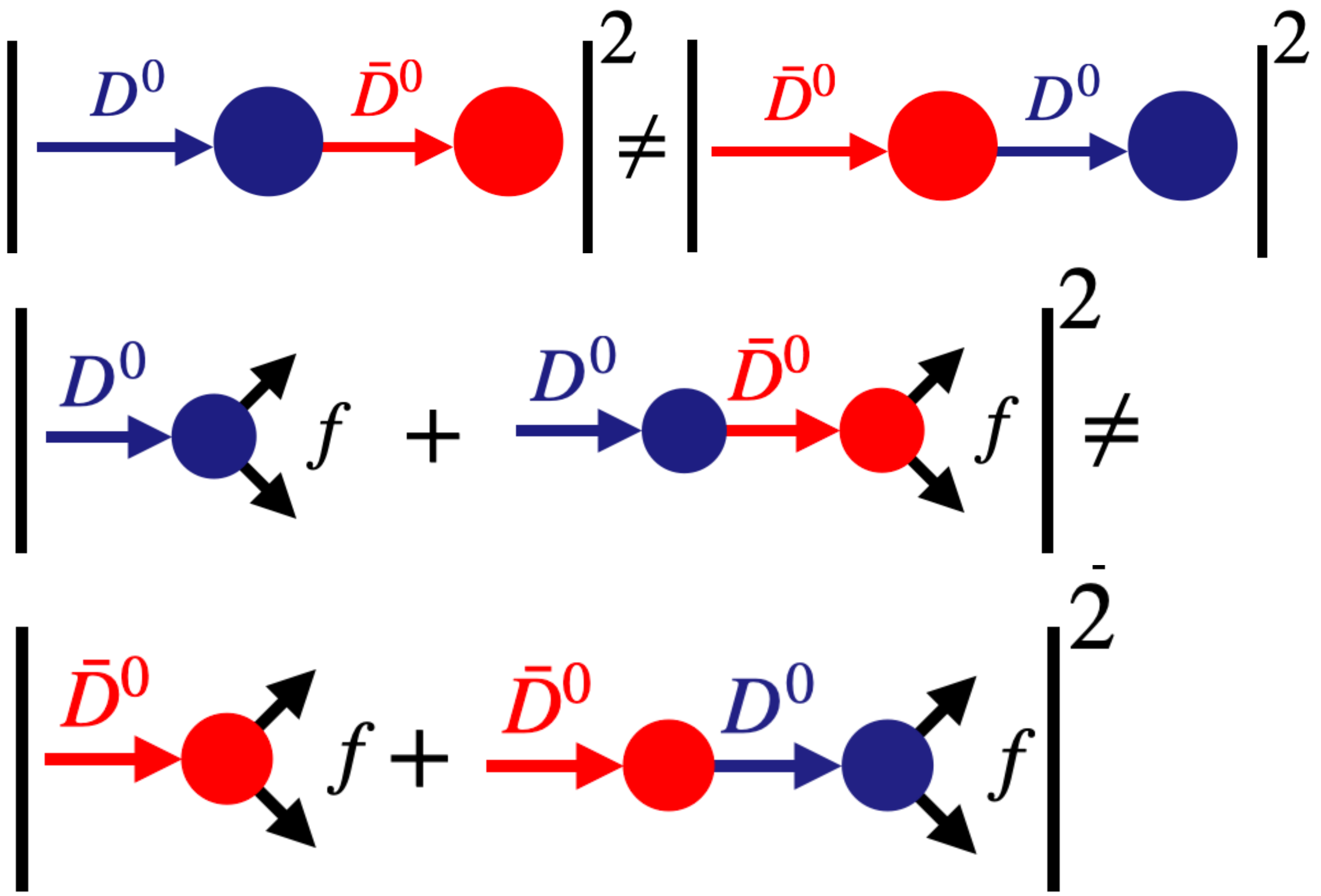
D^0 decays in $f = K^+K^-, \pi^+\pi^-$ (singly Cabibbo-suppressed CP-even):

$$A_{CP}(f,t) = \frac{\Gamma(D^0 \to f,t) - \Gamma(\bar{D}^0 \to f,t)}{\Gamma(D^0 \to f,t) + \Gamma(\bar{D}^0 \to f,t)} \approx a_f^d + \Delta Y \frac{t}{\tau_{D^0}}$$

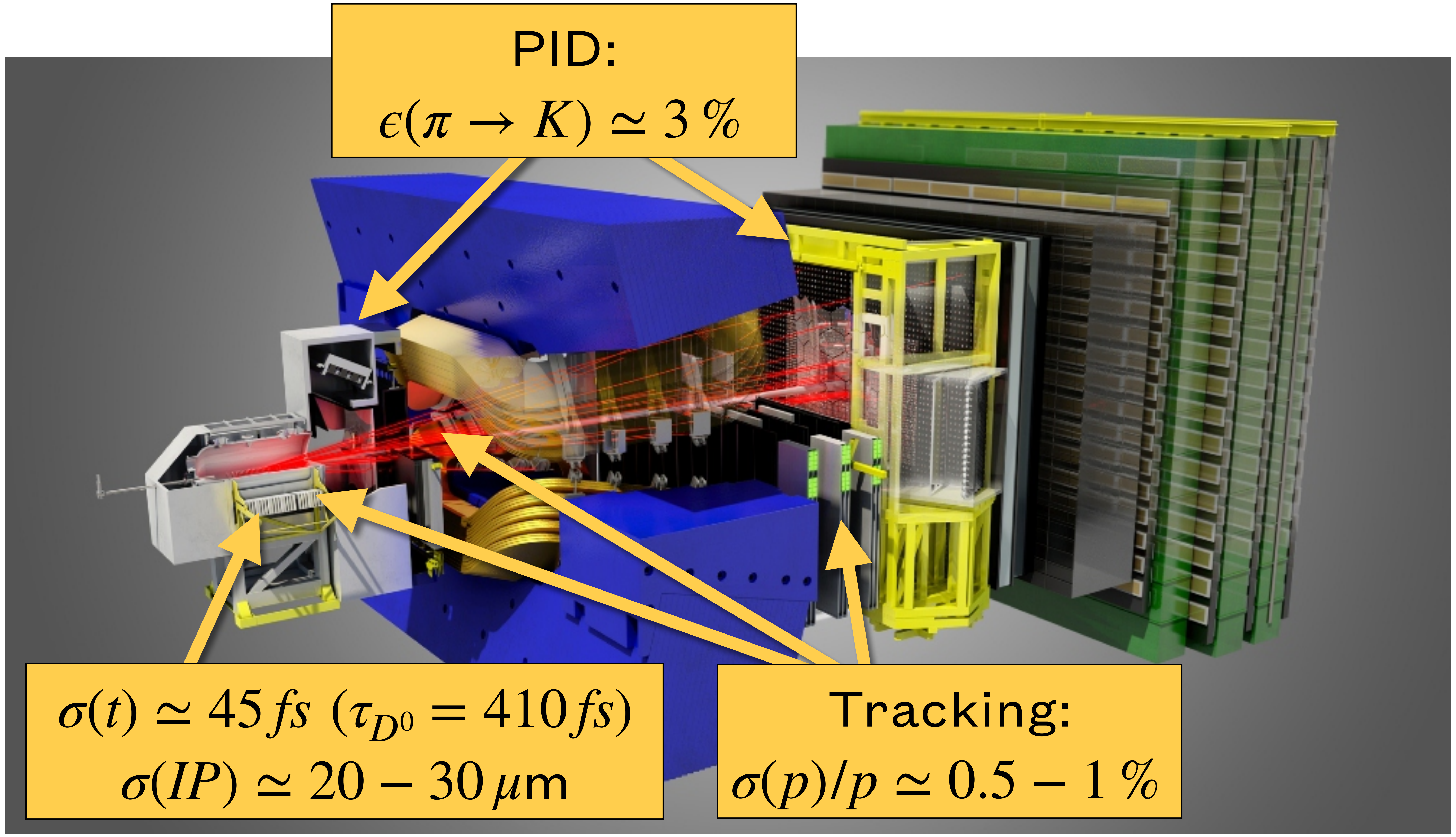
CPV in the decay

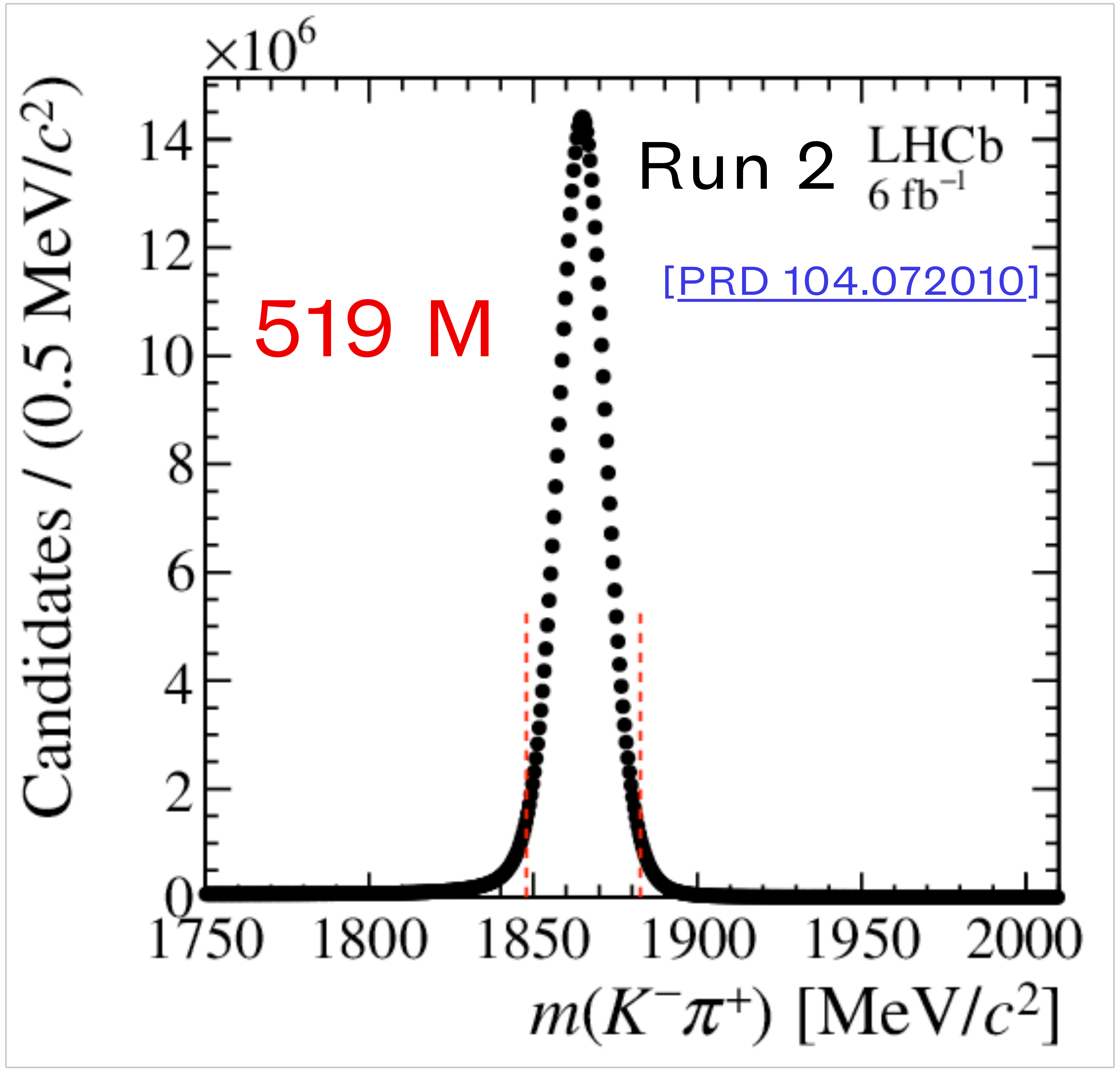


Time dependent CPV



LHCb, a Charm factory





$\sigma(pp \to c\bar{c}) \simeq 20\,\sigma(pp \to c\bar{c}) \simeq 2.4$ mb