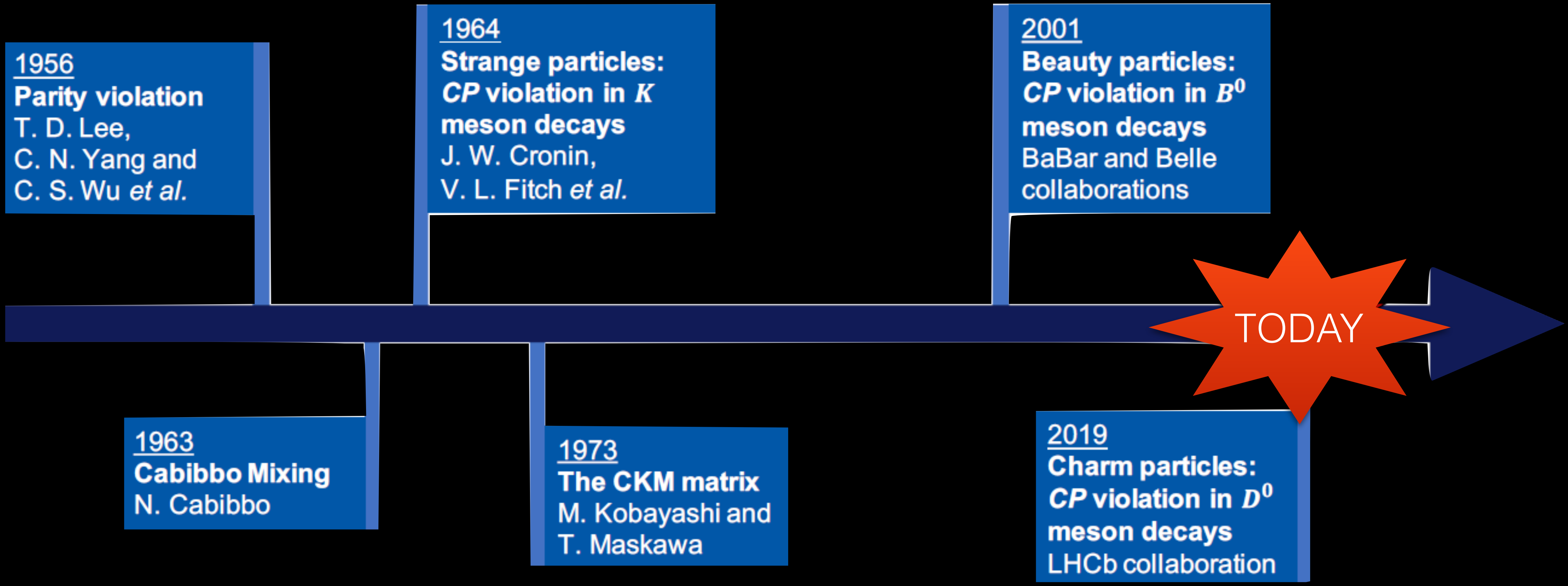
~~CP~~ in charm at Upgrade II

In the context of recent developments in (my understanding of) charm physics

Upgrade 2 workshop, Amsterdam April 9, 2019
Laurent Dufour
Thanks to Angelo Di Canto, Tim Evans, Maurizio Martinelli and Mark Williams

A change of scenery



1956
Parity violation
T. D. Lee,
C. N. Yang and
C. S. Wu *et al.*

1963
Cabibbo Mixing
N. Cabibbo

1964
Strange particles:
CP violation in K
meson decays
J. W. Cronin,
V. L. Fitch *et al.*

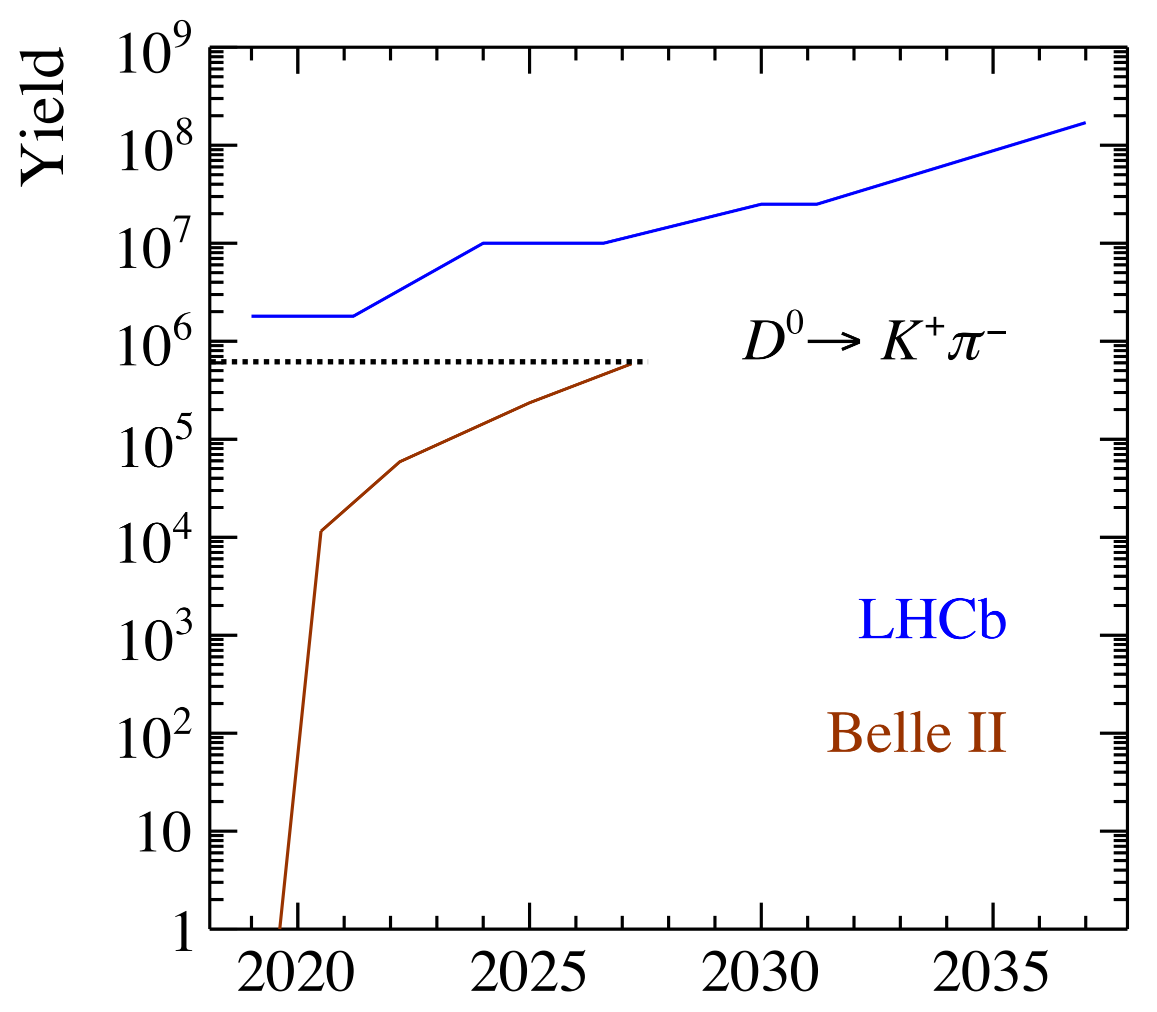
1973
The CKM matrix
M. Kobayashi and
T. Maskawa

2001
Beauty particles:
CP violation in B^0
meson decays
BaBar and Belle
collaborations

2019
Charm particles:
CP violation in D^0
meson decays
LHCb collaboration

This talk Key LHCb contributions w/Upgrade II

Another change of scenery



[Belle II physics book]

Expect a strong contribution from BELLE for modes with neutrals

Exploring the landscape of charm CPV

THEORY

Theory handle on CPV expectations limited. Hard to estimate and relate strong phases.

SU(3) breaking is there, but it might be not *that* broken!

$$\frac{\mathcal{B}(D^0 \to K^+K^-)}{\mathcal{B}(D^0 \to \pi^+\pi^-)} \approx 3$$

EXPERIMENT

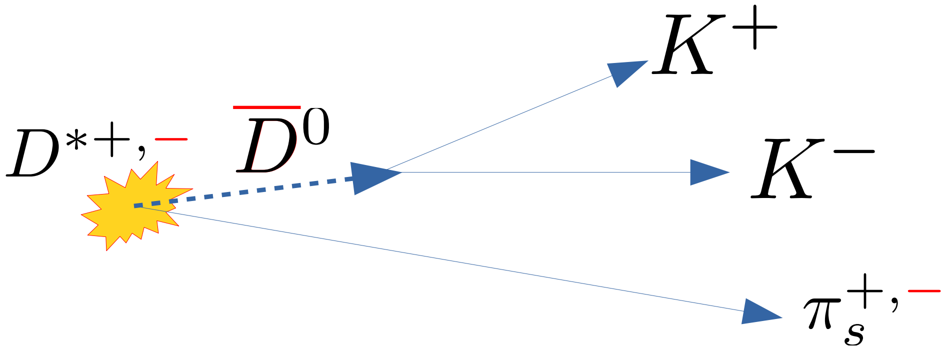
Our mission: measure CP asymmetries and branching fractions in as many SU(3) related decays as possible, different diagrams, *including neutrals and pseudo 2-body*!

DIRECT CPV

Direct CPV in charm

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

Need: flavour tagging of D⁰



Now also dependent on Production +
Detection asymmetries

Two approaches

1. Avoid the problem

Discovery channel

Measure quantities which are "safe" from production and detection asymmetries: perfect cancellation of both production and detection asymmetries.

$$\Delta A_{\mathrm{CP}} = A_{\mathrm{CP}}(D^0 \to K^+K^-) - A_{\mathrm{CP}}(D^0 \to \pi^+\pi^-)$$

2. Apply corrections

Inevitable to complete the picture

Dependent on excellent detector calibration, simulation and Cabibbo-favoured normalisation channels.

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

LHCb-PUB-2014-006, M. Vesterinen

Measuring $A_{CP}(K^+K^-)$

$$A_{\mathrm{CP}}(D^0 \to K^+K^-) = A_{\mathrm{meas}}(D^0 \to K^+K^-) - A_{\mathrm{meas}}(D^0 \to K^-\pi^+) \\ - A_{\mathrm{det}}(K^-\pi^+)$$

Cancel A_{prod}

Cancel A_{det} just introduced

LHCb-PUB-2014-006, M. Vesterinen

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Cancel A_{prod}

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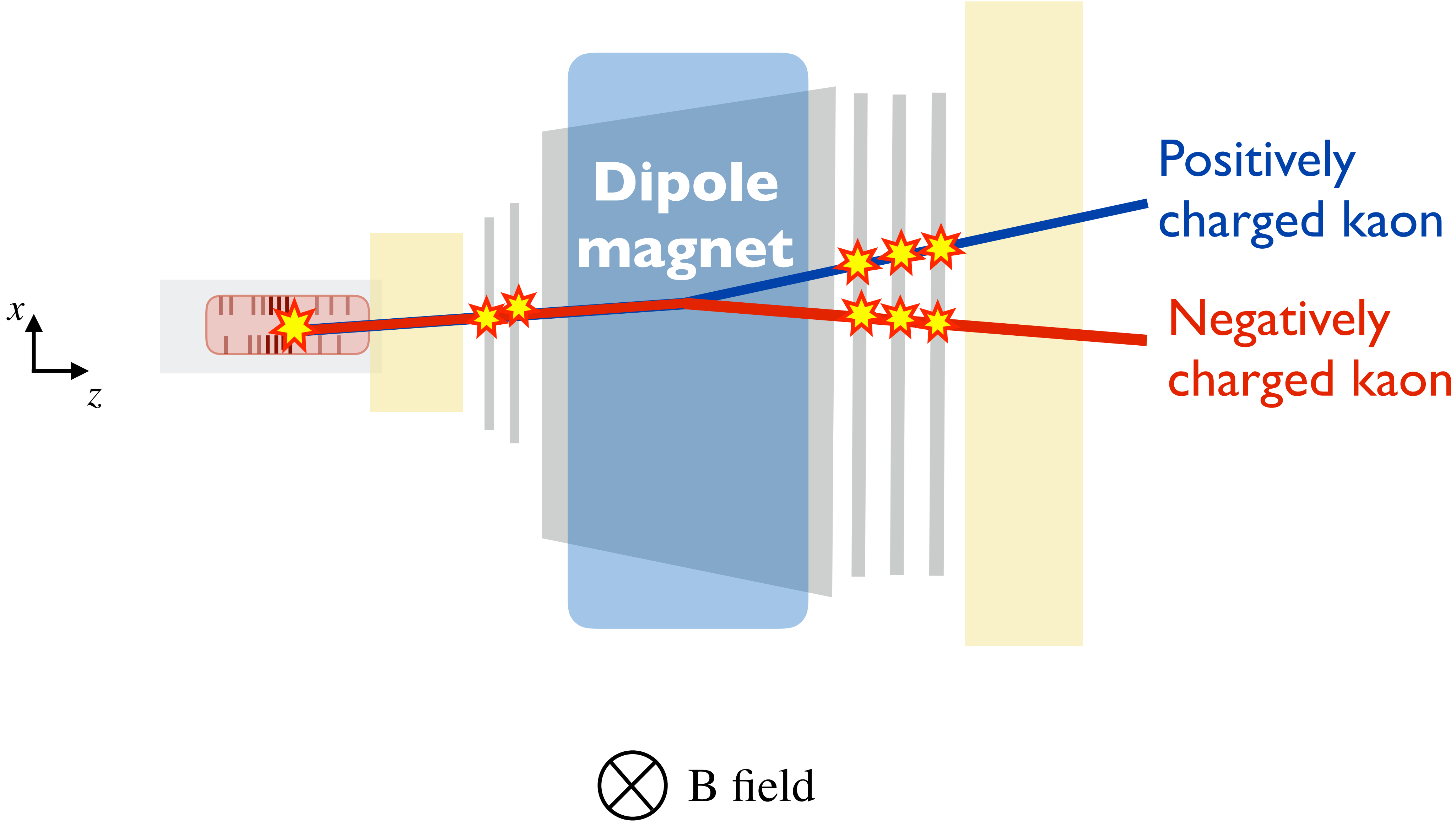


LHCb-PUB-2014-006, M. Vesterinen

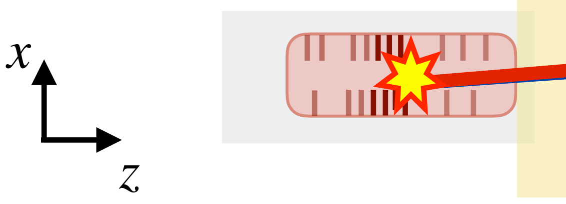
Measuring $A_{CP}(K^+K^-)$

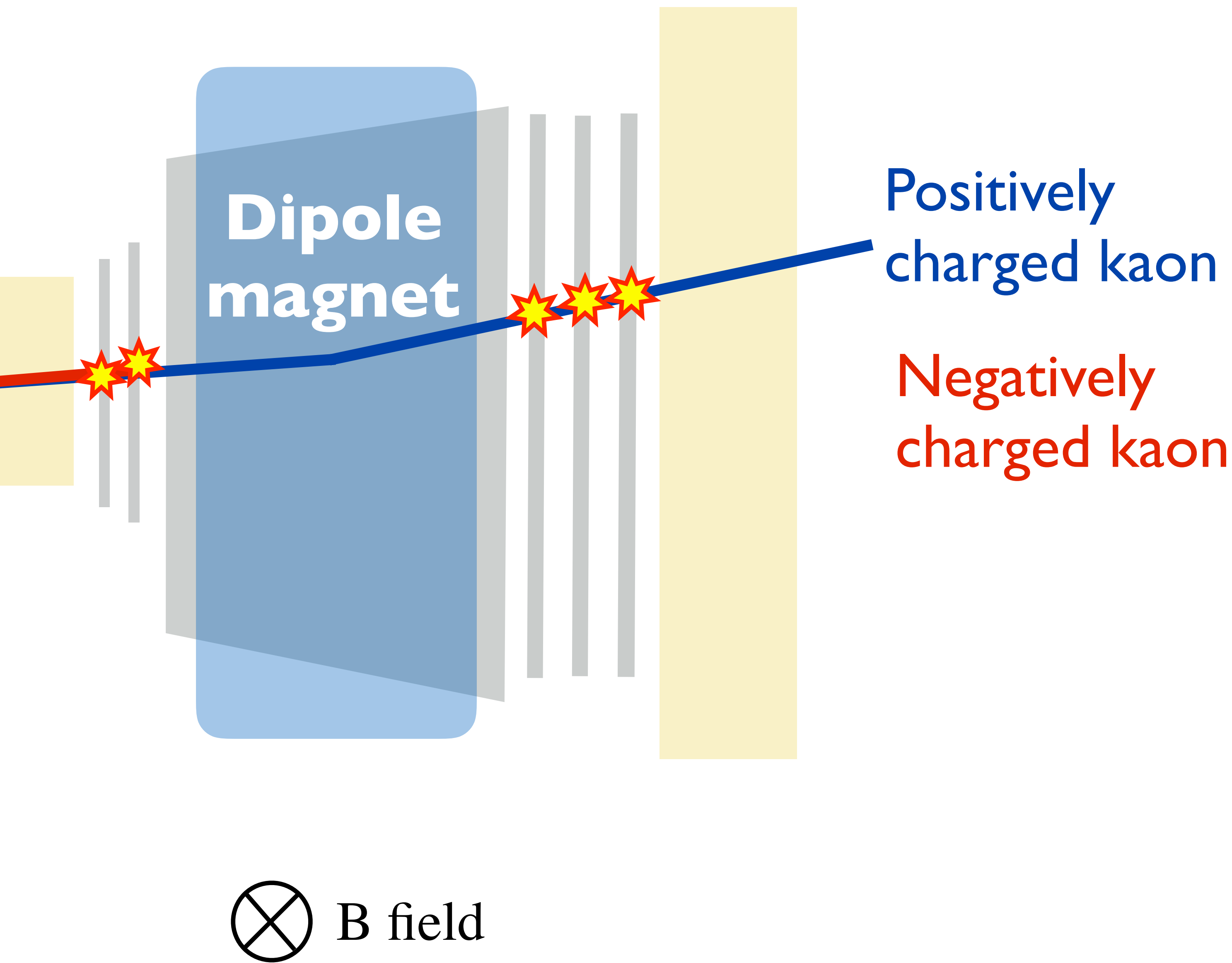
$$A_{\mathrm{CP}}(D^0 \to K^+K^-) = A_{\mathrm{meas}}(D^0 \to K^+K^-) - A_{\mathrm{meas}}(D^0 \to K^-\pi^+) - A_{\mathrm{det}}(K^-\pi^+)$$

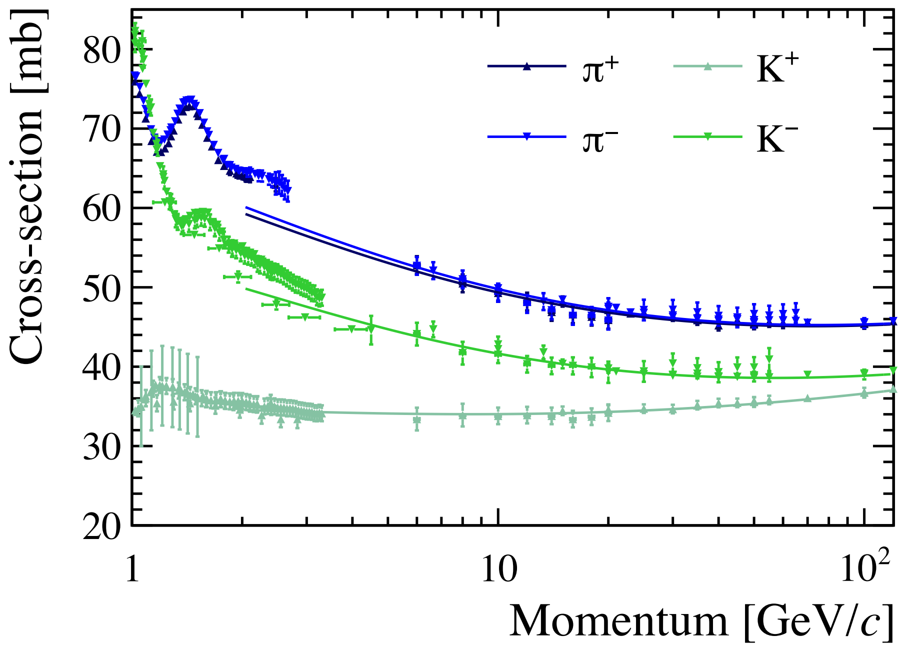
$\mathcal{O}(1\%)$ for LHCb

Cancel A_{prod}

Cancel A_{det} just introduced







LHCb-PUB-2018-009

Measuring $A_{CP}(K^+K^-)$

In the SU(3) limit: $2|A_{CP}(KK)| = |\Delta A_{CP}|$.

Would need to resolve a $\mathcal{O}(0.07\%)$ CP asymmetry

Luminosity scaling only

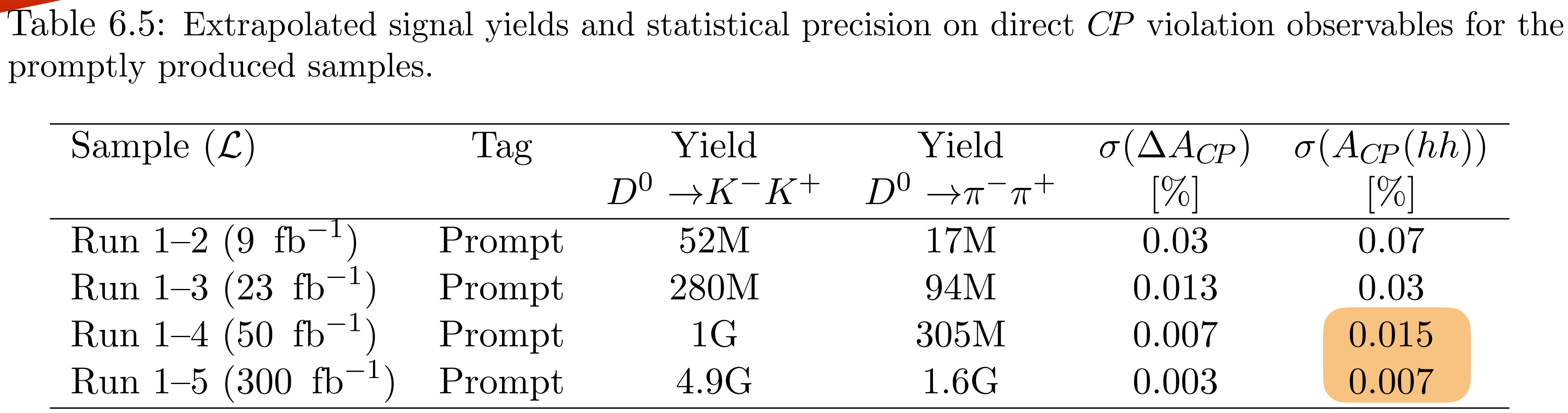
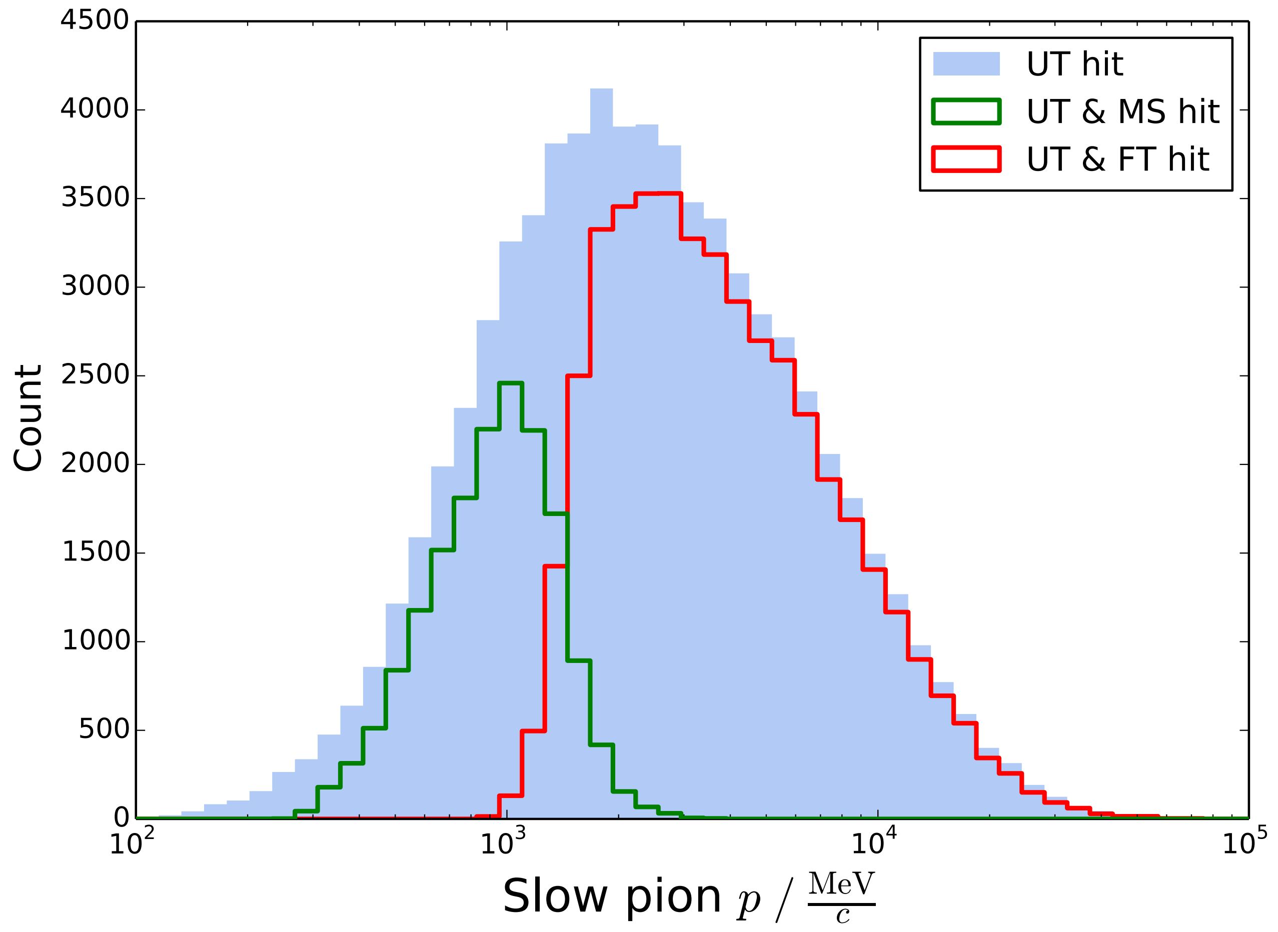


Table 6.5: Extrapolated signal yields and statistical precision on direct *CP* violation observables for the promptly produced samples.

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	0.007	0.015
Run 1–5 (300 fb^{-1})	Prompt	4.9G	1.6G	0.003	0.007

Development in detector calibration essential

Magnet side-stations

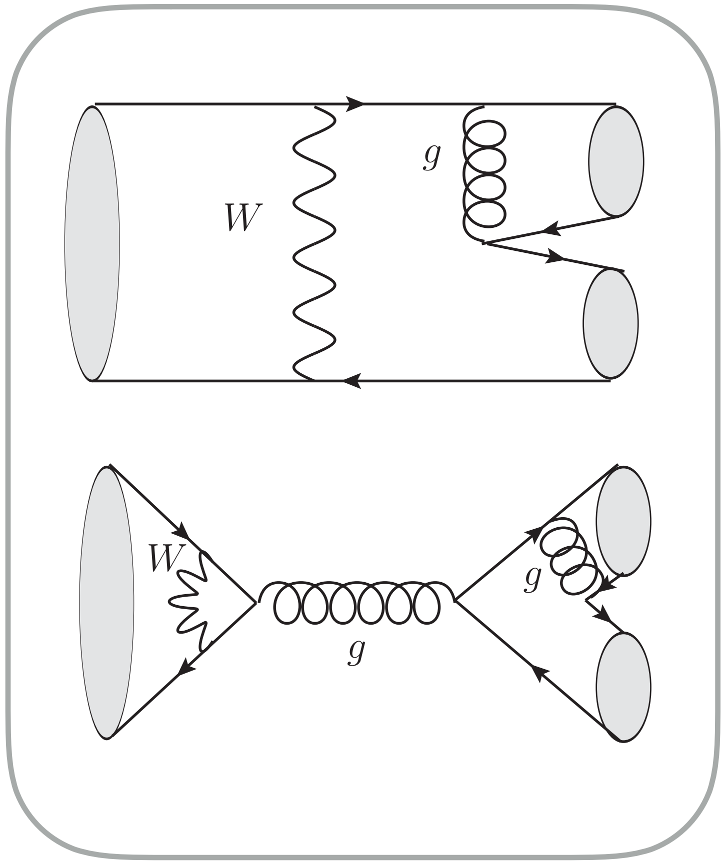


Control of "wrong-charge ghosts" critical!

Moving closer to our competition

Beyond $A_{CP}(K^+K^-)$: K_SK_S

Significant theory interest in $A_{CP}(D^0 \to K_SK_S)$
Estimations vary from ≤ 1% to $\mathcal{O}(3/2\ \Delta A_{CP})$



	Uncertainty [%]
Belle I	± 1.53 ± 0.17
LHCb '12-'16	± 2.8 ± 0.9
LHCb Run 2	± 1.5
Belle II	± 0.23
LHCb Upgrade-II	± 0.12 - 0.23*

Upgrade-II essential!
Main challenge: event trigger

[1]: Nierste, Schacht '15
[2]: Hiller, Jung, Schacht '13
[2]: Cheng, Chaing '12

*: Unofficial extrapolation based on presented improvements

Outlook on 2-body CPV

[A. Di Canto, LHCb-PUB-2018-009]

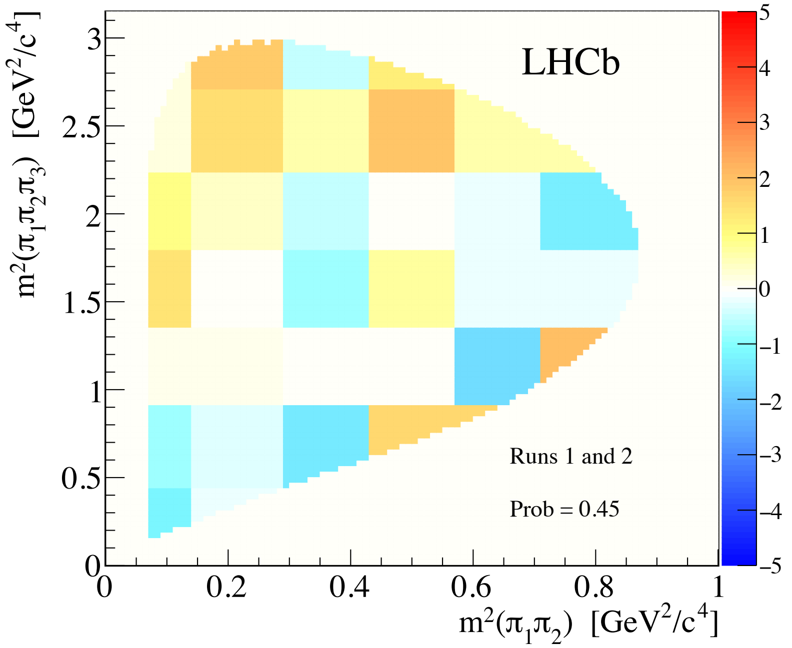
Decay mode	Current best sensitivity (stat + syst) [10^{-3}]		LHCb 300/fb (stat only) [10^{-3}]	Belle II 50/ab (stat+syst) [10^{-3}]
ΔA_{CP}	0.29	LHCb (9/fb)	0.03	(0.6)
$D^0 \to K^+K^-$	1.8	LHCb (3/fb)	0.07	0.3
$D^0 \to \pi^+\pi^-$	1.8	LHCb (3/fb)	0.07	0.5
$D^0 \to K^+\pi^-$	9.1	LHCb (5/fb)	0.5	(4.0)
$D^0 \to K_S K_S$	15	Belle (1/ab)	.12-.23	2.3
$D_s \to K_S \pi^+$	18	LHCb (6.8/fb)	0.32	2.9
$D^+ \to K_S K^+$	0.76	LHCb (6.8/fb)	0.12	0.4
$D^0 \to K_S \bar{K}^{*0}$	3.0	LHCb (3/fb)	(0.06)	(?)
$D^0 \to K_S K^{*0}$	4.0	LHCb (3/fb)	(0.08)	(?)
$D^+ \to \phi\pi^+$	0.49	LHCb (4.8/fb)	0.06	0.4

Direct CPV beyond 2-body

Interest in quasi two-body modes, such as $D^0 \rightarrow K^*K$, $D_s \rightarrow \rho$ K. Tend to spread over phase-space. Usually overlapping amplitudes in D → hhh decays, widely varying strong phase.

- ✳ Strong phase can change sign

- Both model-dependent and model-independent approaches pursued.
  - E.g. Energy test (unbinned), S_{CP} (binned).
- Model-dependent needed to interpret results.



INDIRECT CPV

Charm mixing

$$\begin{tikzcd}D^0 \arrow[rr, bend left] & & \overline{D}^0 \arrow[ll, bend left]\end{tikzcd}$$

Like all other neutral mesons, also D^0 mesons mix.

$$\langle D^0_{1,2}| = p\,\langle D^0| \mp q\,\langle \overline{D^0}|$$

$$P(D^0 \to \overline{D^0}) \propto \left|\frac{p}{q}\right|^2 e^{-\Gamma t}\left(\cosh(\frac{1}{2}\Delta\Gamma t) - \cos(\Delta m t)\right)$$

Charm mixing

$$\begin{tikzcd} D^0 \arrow[r, bend left] & \bar{D}^0 \arrow[l, bend left] \end{tikzcd}$$

Like all other neutral mesons, also D⁰ mesons mix…
but rarely!

$$\langle D^0_{1,2}| = p\,\langle D^0| \mp q\,\langle \overline{D^0}|$$

$$P(D^0 \to \overline{D^0}) \approx \left|\frac{p}{q}\right|^2 e^{-\Gamma t}\frac{x^2+y^2}{2}(\Gamma t)^2$$

Observables

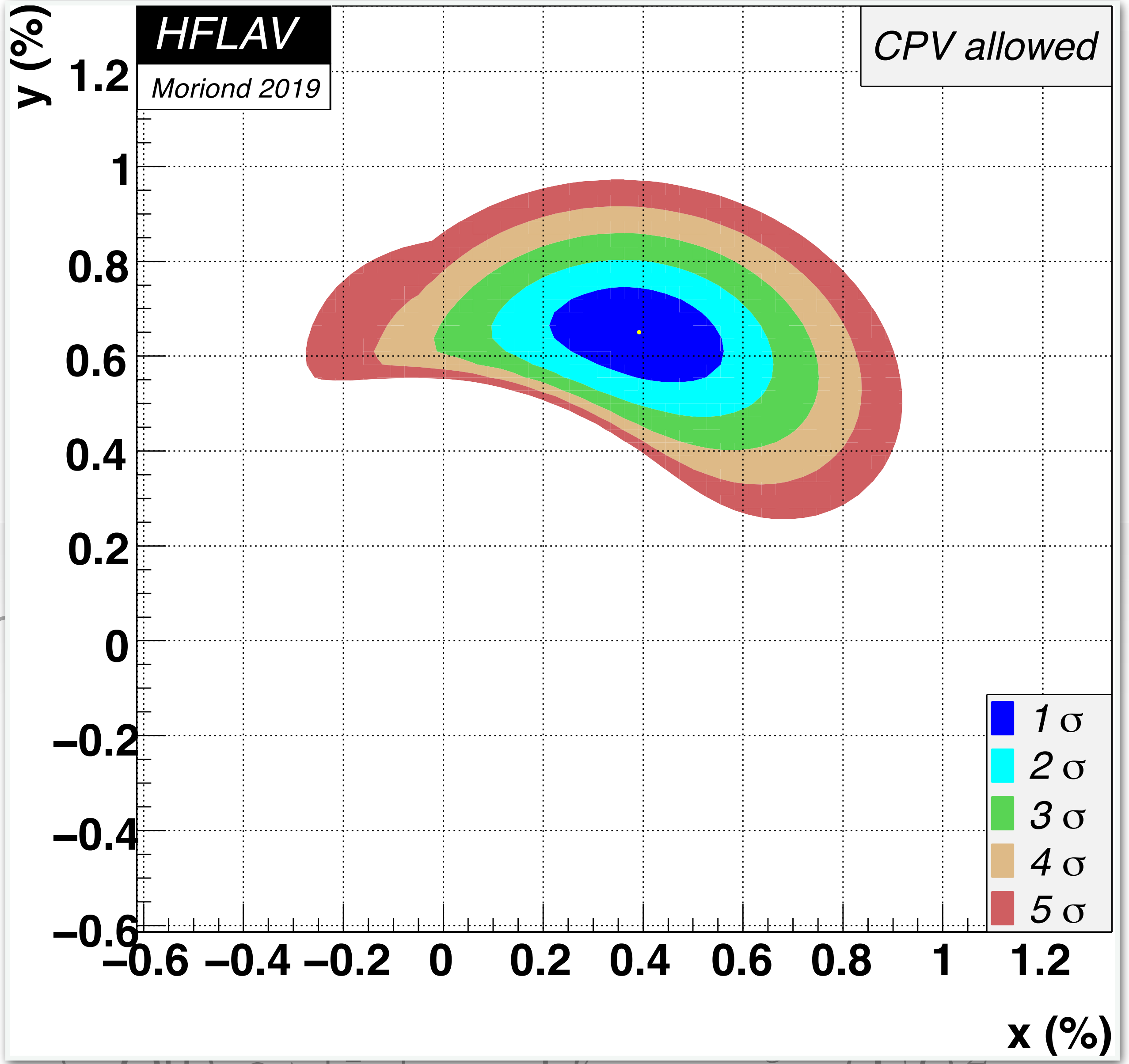
CPV in mixing	$\lvert q/p \rvert$
Mixing phase	φ_D
#diffraction	x
#absorption	y

[HFLAV]

Charm mixing

Like all other neutr
but rarely!

$\langle D^0_{1,2}$



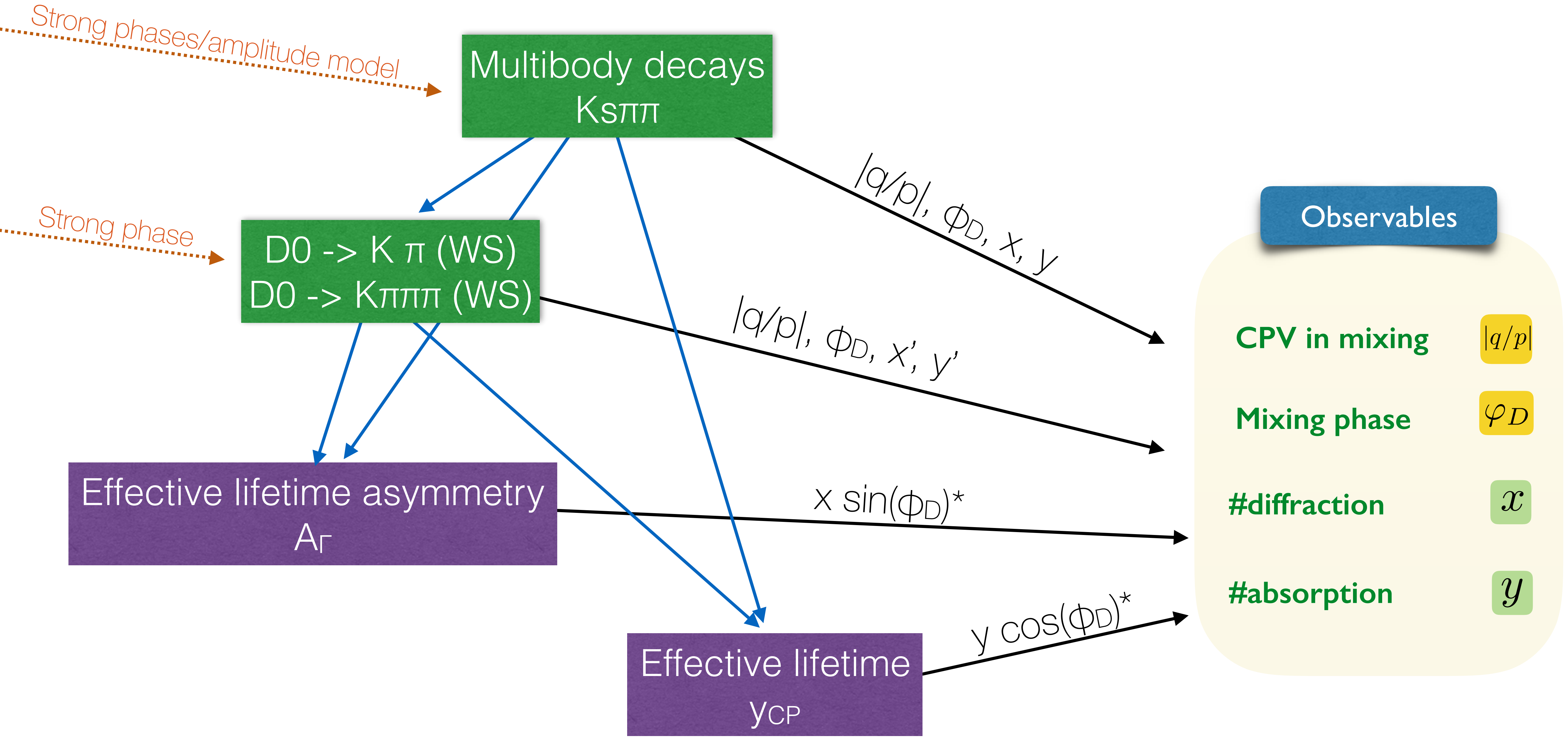
$P(D^0 \to D^0) \approx \left|\frac{}{q}\right| e \quad \frac{}{2} (\Gamma t)^2$

Most often, the D0 did not change flavour before decay

Observables

CPV in mixing	$\lvert q/p \rvert$
Mixing phase	φ_D
#diffraction	x
#absorption	y

Charm mixing



Strong phases/amplitude model

Multibody decays
$K_S\pi\pi$

Strong phase

D0 -> K π (WS)
D0 -> Kπππ (WS)

Effective lifetime asymmetry
A_Γ

Effective lifetime
y_{CP}

$|q/p|$, ϕ_D, x, y

$|q/p|$, ϕ_D, x', y'

$x \sin(\phi_D)^*$

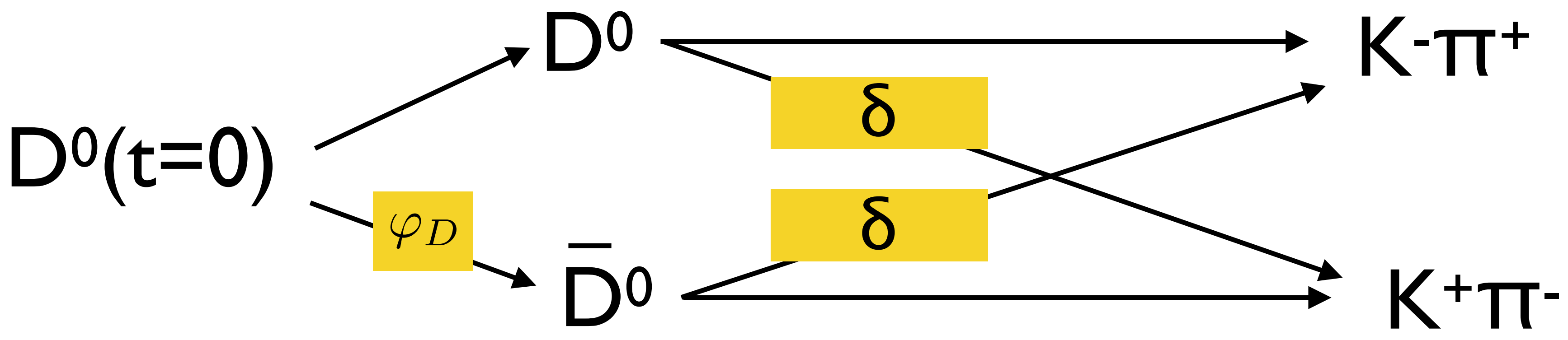
$y \cos(\phi_D)^*$

Observables

CPV in mixing	$\lvert q/p \rvert$
Mixing phase	φ_D
#diffraction	x
#absorption	y

*: if $|q/p| \neq 1$, then more complex

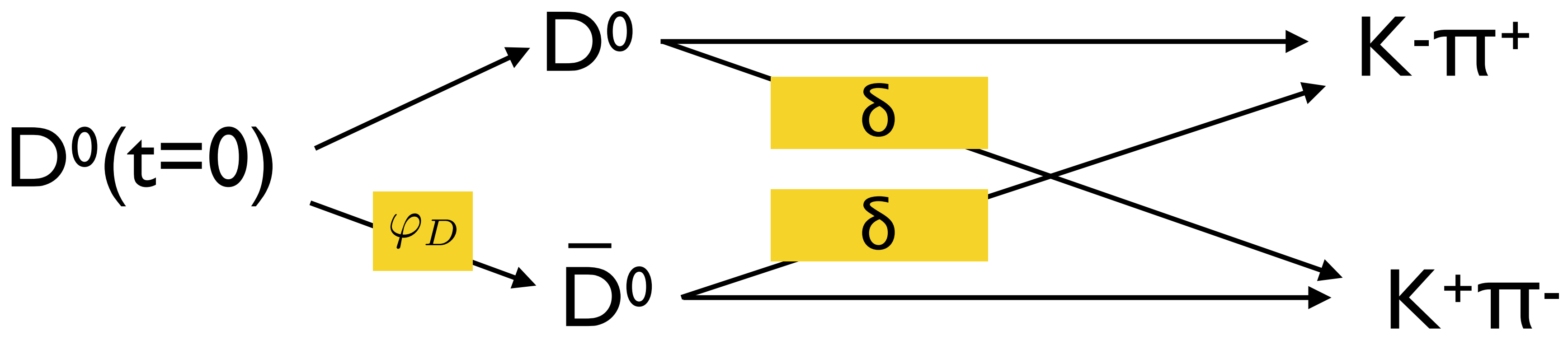
CPV in mixing: the classic WS



Goal: CPV in mixing, but start simple.

Mixing: tiny
DCS: tiny

CPV in mixing: the classic WS



Naive idea: x, y mixing due to diffraction (Im) and absorption (Re).
An additional phase shift, **δ**, rotates the two contributions to x' and y'.
But common to both D0 and D~0

Measure 2, solve for 2 unknowns: |q/p|, **φ**D (assume no direct CPV)

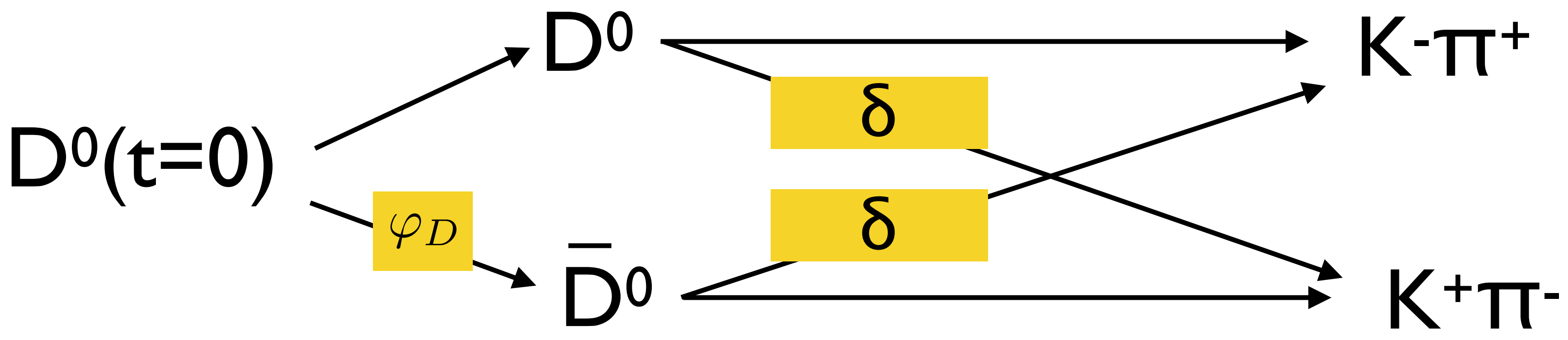
$$R(t) = \frac{\Gamma(D^0 \to K^+\pi^-|t)}{\Gamma(D^0 \to K^-\pi^+|t)} \approx R_D + \sqrt{R_D}y'\left(\frac{t}{\tau}\right) + \frac{x'^2 + y'^2}{4}\left(\frac{t}{\tau}\right)^2$$

Interference

Purely mixing

Measure this for D0 and D0 separately,
to measure asymmetry in mixing

CPV in mixing: the classic WS

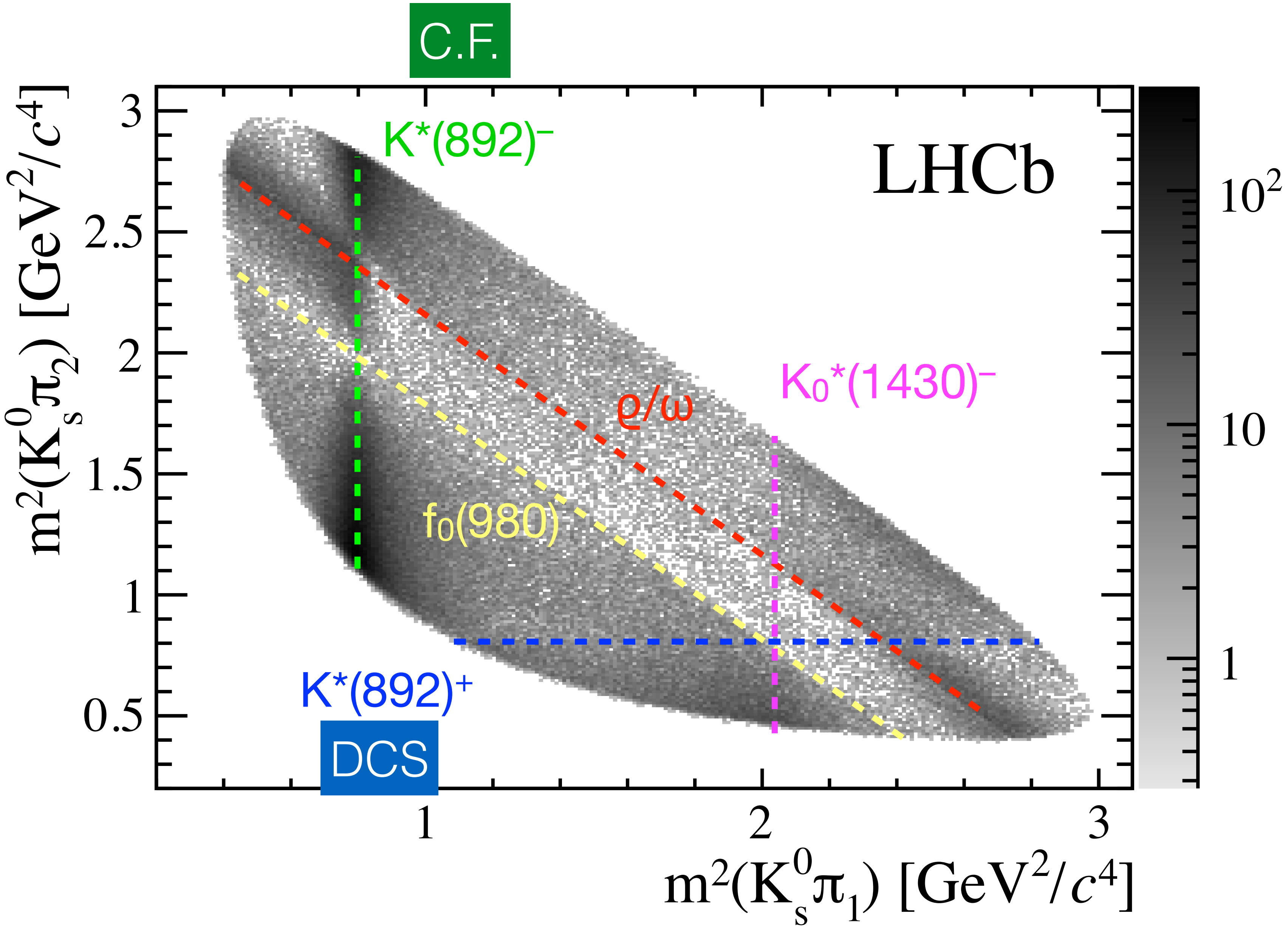


$$\delta \sim 180^\circ$$

$$y' \equiv y \cos\delta - x \sin\delta \sim y$$

$$R(t) = \frac{\Gamma(D^0 \to K^+\pi^-|t)}{\Gamma(D^0 \to K^-\pi^+|t)} \approx R_D + \sqrt{R_D}y' \left(\frac{t}{\tau}\right) + \frac{x'^2 + y'^2}{4} \left(\frac{t}{\tau}\right)^2$$

A “golden mode”: $K_S\ \pi^+\ \pi^-$

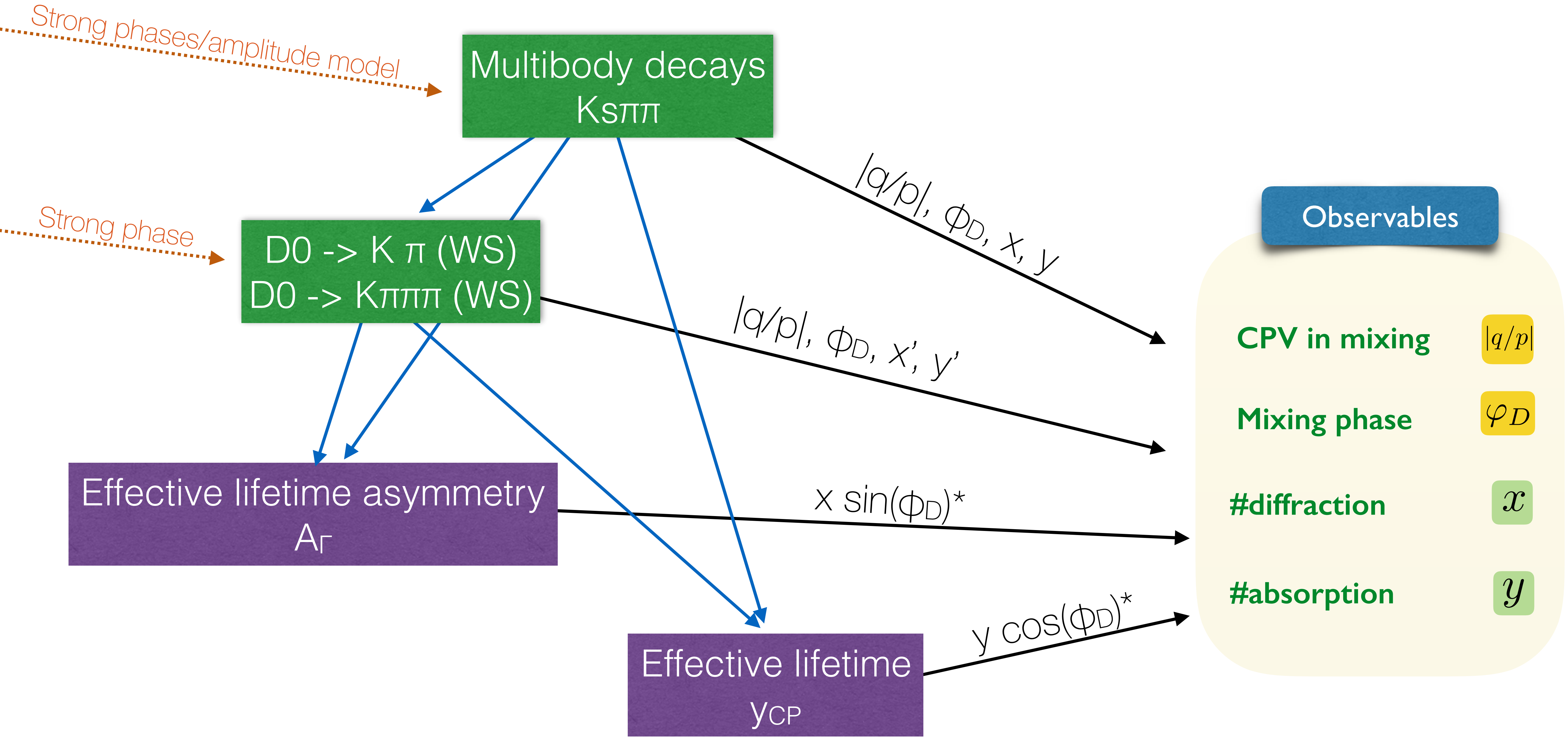


A “golden mode”: $K_S\ \pi^+\ \pi^-$

- Use the strong phase to our advantage: look at multibody decays with a *varying* strong phase across phase space
  - Exploiting this requires a phase-space dependent analysis
- If the phases are known (either by an amplitude analysis + global phase external input or external input completely), can resolve |q/p|, ϕ_D, x and y with a high precision from all local measurements.

Charm mixing

Complete programme



Strong phases/amplitude model

Multibody decays $K_S\pi\pi$

Strong phase

D0 -> K π (WS)
D0 -> $K\pi\pi\pi$ (WS)

Effective lifetime asymmetry A_Γ

Effective lifetime y_{CP}

$|q/p|$, ϕ_D, x, y

$|q/p|$, ϕ_D, x', y'

$x \sin(\phi_D)^*$

$y \cos(\phi_D)^*$

Observables

CPV in mixing $|q/p|$

Mixing phase φ_D

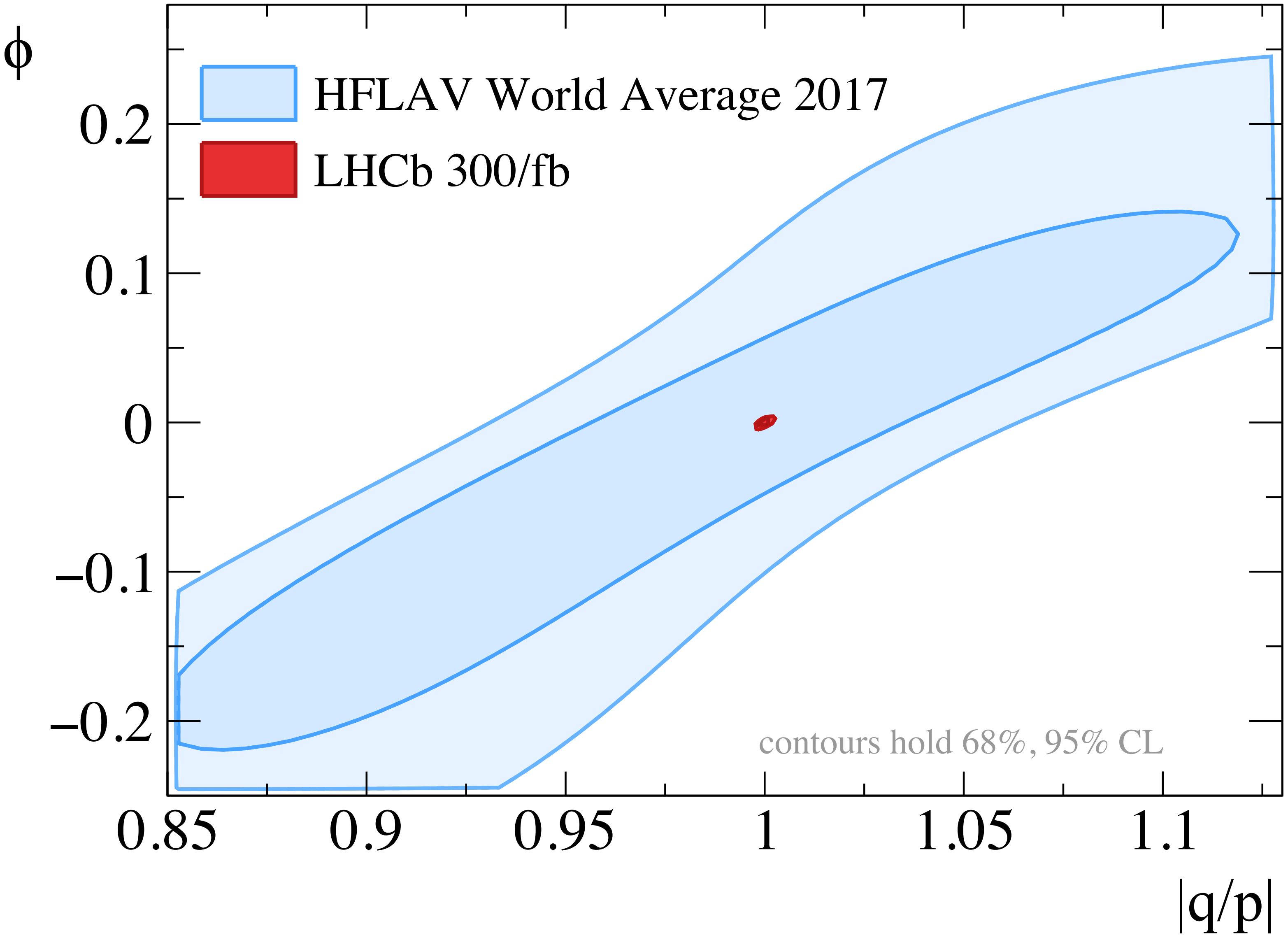
#diffraction x

#absorption y

*: if |q/p|≠1, then more complex

Outlook to charm mixing CPV

Mixing phase



CPV in mixing

Conclusion

- After the discovery of direct CPV in charm, the goal is to measure CPV in as many modes as possible: expect LHCb to stay the strongest player for charged final states, and BELLE-II having this honour for final states with neutrals.
- Role for multi-body decays, both for mixing parameters and direct CPV in quasi two-body modes
  - ➡ Great potential for LHCb
  - ➡ Will benefit greatly from external measurements of strong phases
- Could benefit from magnet side-stations, require good ghost rejection
- Programme requires a close collaboration with the trigger group

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In the context of recent developments in (my understanding of) charm physics

Upgrade 2 workshop, Amsterdam April 9, 2019
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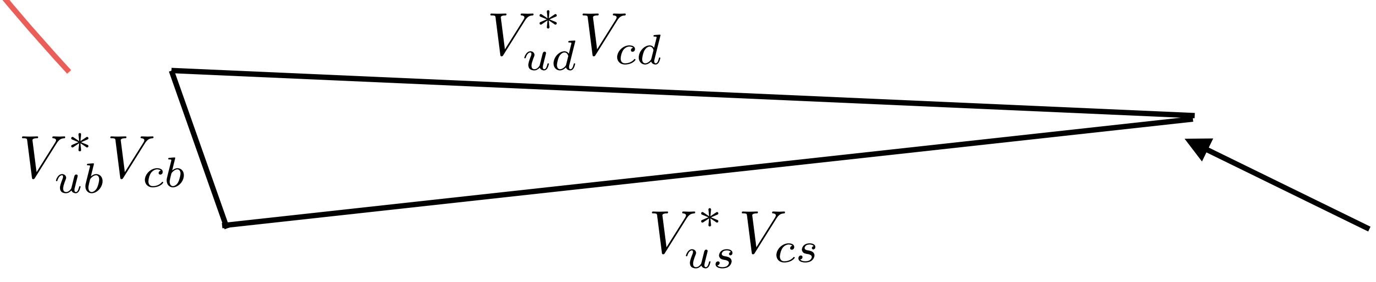
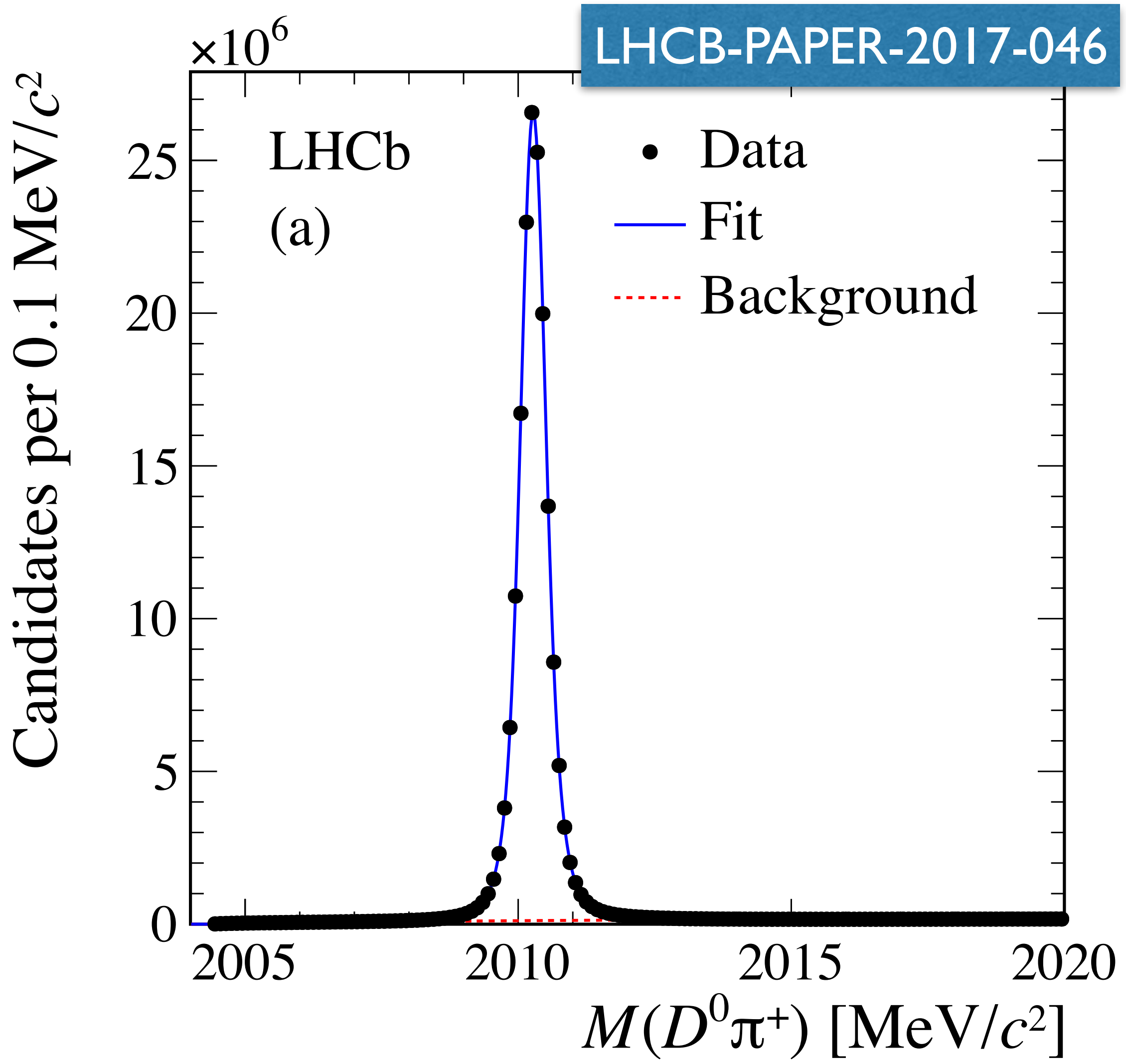
CP violation in the charm sector

- Long-distance physics effects
- Expectation: little CP violation.
- ✓ Enormous production at the LHC



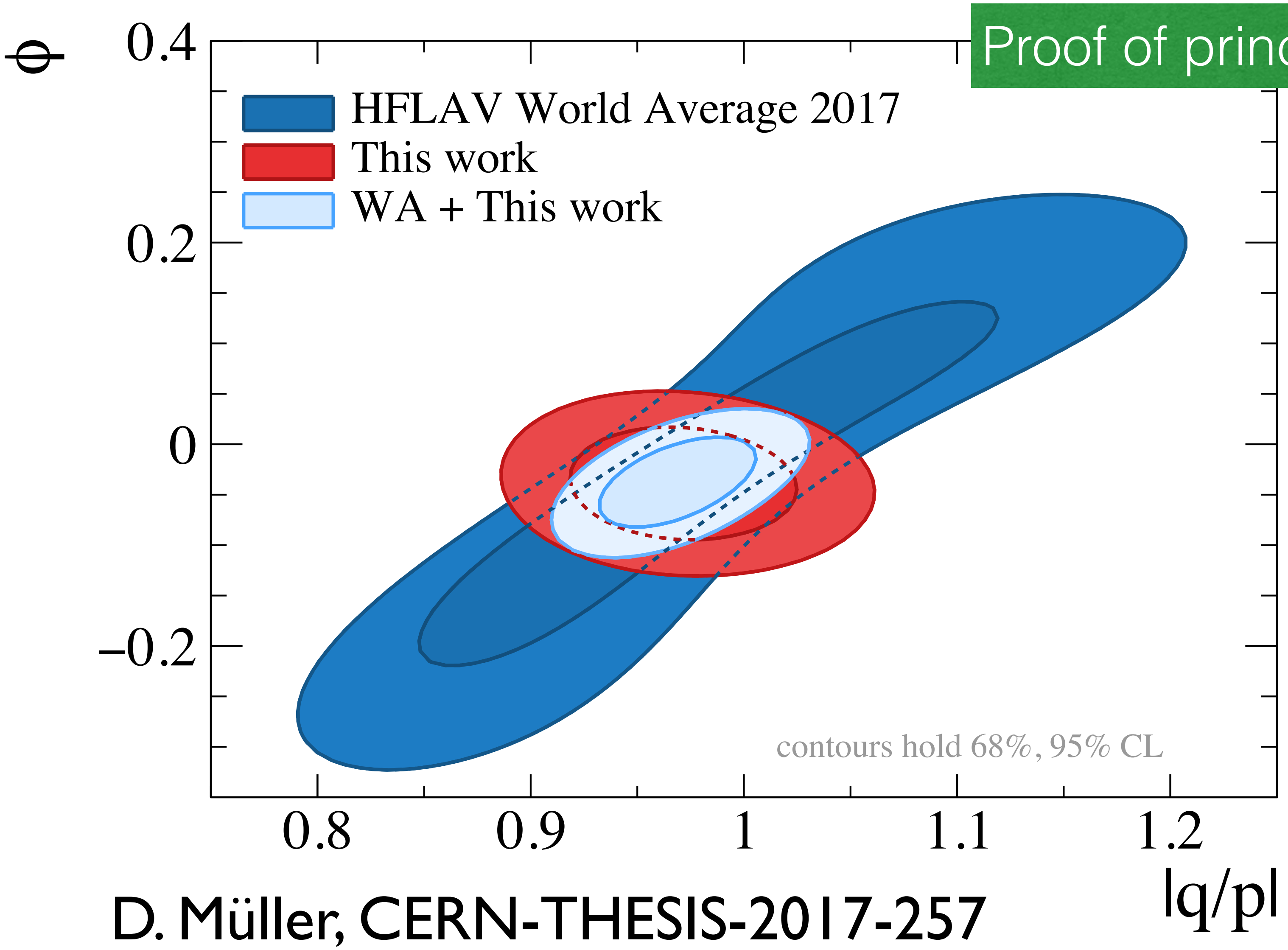
(absolutely not to scale)



More golden modes

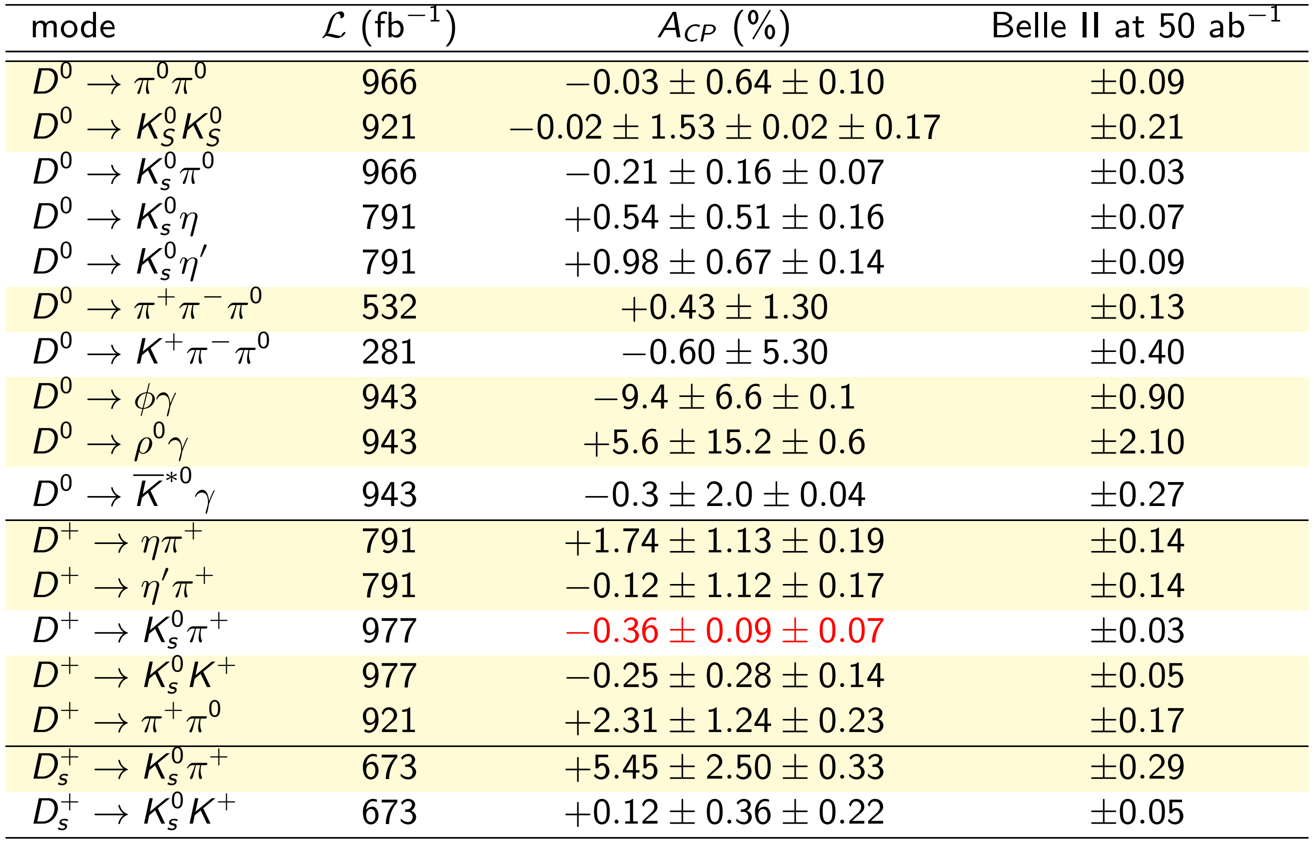
Can do a similar trick for $D^0 \to K^+ \pi \pi \pi$ decays (but require external input)!

Proof of principle



D. Müller, CERN-THESIS-2017-257

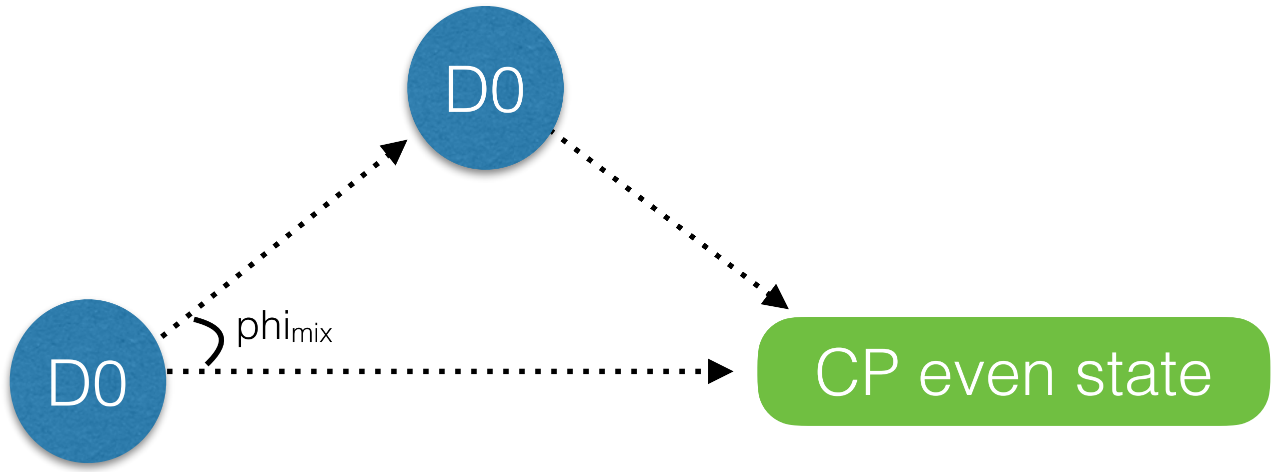
Belle II prospects



mode	$\mathcal{L}$ (fb^{-1})	A_{CP} (%)	Belle II at 50 ab^{-1}
$D^0 \to \pi^0\pi^0$	966	$-0.03 \pm 0.64 \pm 0.10$	± 0.09
$D^0 \to K_S^0 K_S^0$	921	$-0.02 \pm 1.53 \pm 0.02 \pm 0.17$	± 0.21
$D^0 \to K_s^0 \pi^0$	966	$-0.21 \pm 0.16 \pm 0.07$	± 0.03
$D^0 \to K_s^0 \eta$	791	$+0.54 \pm 0.51 \pm 0.16$	± 0.07
$D^0 \to K_s^0 \eta'$	791	$+0.98 \pm 0.67 \pm 0.14$	± 0.09
$D^0 \to \pi^+\pi^-\pi^0$	532	$+0.43 \pm 1.30$	± 0.13
$D^0 \to K^+\pi^-\pi^0$	281	-0.60 ± 5.30	± 0.40
$D^0 \to \phi\gamma$	943	$-9.4 \pm 6.6 \pm 0.1$	± 0.90
$D^0 \to \rho^0\gamma$	943	$+5.6 \pm 15.2 \pm 0.6$	± 2.10
$D^0 \to \overline{K}^{*0}\gamma$	943	$-0.3 \pm 2.0 \pm 0.04$	± 0.27
$D^+ \to \eta\pi^+$	791	$+1.74 \pm 1.13 \pm 0.19$	± 0.14
$D^+ \to \eta'\pi^+$	791	$-0.12 \pm 1.12 \pm 0.17$	± 0.14
$D^+ \to K_s^0\pi^+$	977	$-0.36 \pm 0.09 \pm 0.07$	± 0.03
$D^+ \to K_s^0 K^+$	977	$-0.25 \pm 0.28 \pm 0.14$	± 0.05
$D^+ \to \pi^+\pi^0$	921	$+2.31 \pm 1.24 \pm 0.23$	± 0.17
$D_s^+ \to K_s^0\pi^+$	673	$+5.45 \pm 2.50 \pm 0.33$	± 0.29
$D_s^+ \to K_s^0 K^+$	673	$+0.12 \pm 0.36 \pm 0.22$	± 0.05

https://indico.cern.ch/event/760368/contributions/3316190/attachments/1822851/2982255/staric_charmCPV-neutrals.pdf

Effective decay width



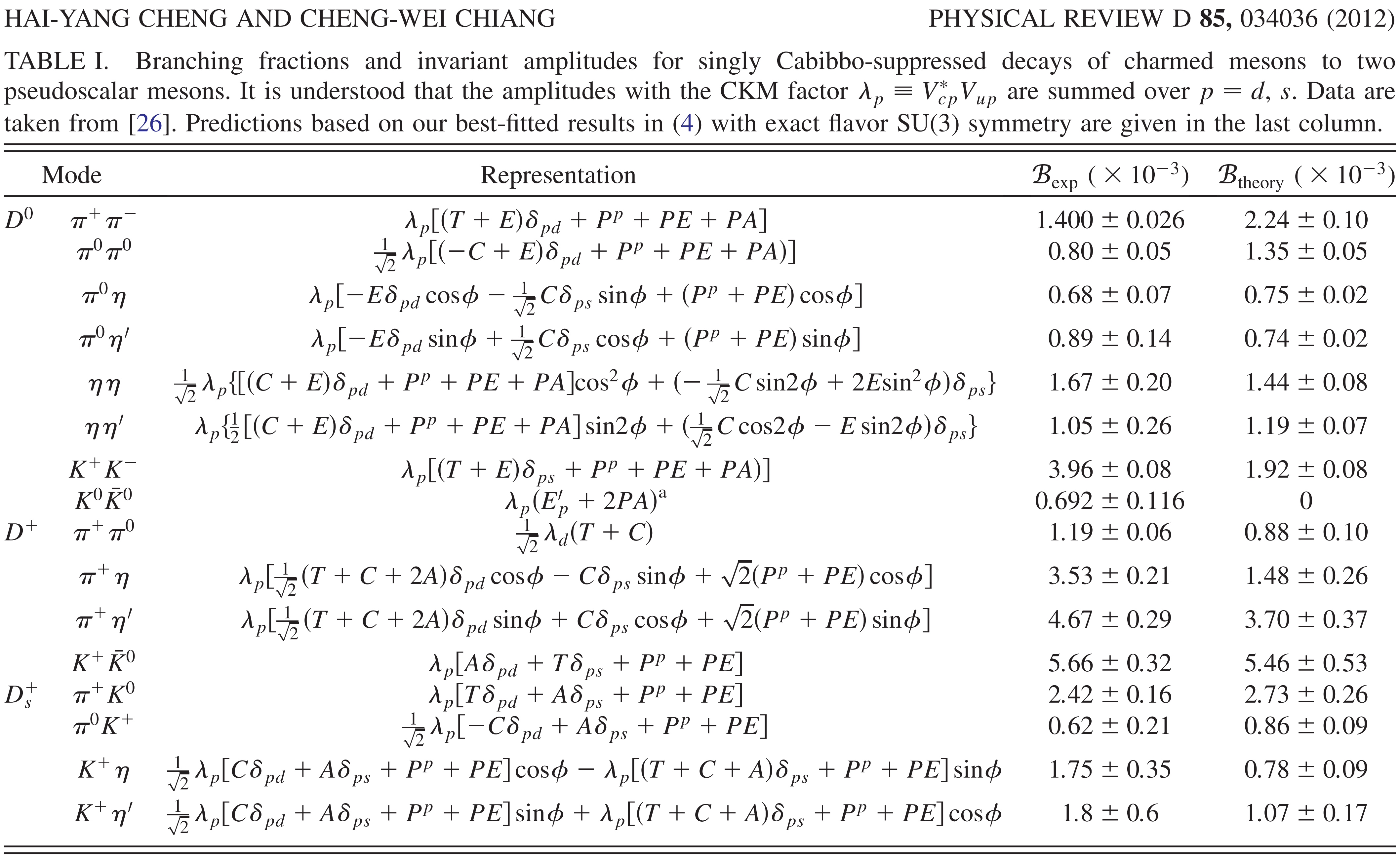
Measure the time-dependence CPV of D⁰ -> K⁺K⁻. Two terms:

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

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

Good knowledge of the CPV in mixing requires good knowledge of x

D -> P P



HAI-YANG CHENG AND CHENG-WEI CHIANG PHYSICAL REVIEW D **85,** 034036 (2012)

TABLE I. Branching fractions and invariant amplitudes for singly Cabibbo-suppressed decays of charmed mesons to two pseudoscalar mesons. It is understood that the amplitudes with the CKM factor $\lambda_p \equiv V_{cp}^* V_{up}$ are summed over $p = d, s$. Data are taken from [26]. Predictions based on our best-fitted results in (4) with exact flavor SU(3) symmetry are given in the last column.

Mode		Representation	$\mathcal{B}_{\text{exp}}$ $(\times 10^{-3})$	$\mathcal{B}_{\text{theory}}$ $(\times 10^{-3})$
D^0	$\pi^+\pi^-$	$\lambda_p[(T+E)\delta_{pd} + P^p + PE + PA]$	1.400 ± 0.026	2.24 ± 0.10
	$\pi^0\pi^0$	$\frac{1}{\sqrt{2}}\lambda_p[(-C+E)\delta_{pd} + P^p + PE + PA)]$	0.80 ± 0.05	1.35 ± 0.05
	$\pi^0\eta$	$\lambda_p[-E\delta_{pd}\cos\phi - \frac{1}{\sqrt{2}}C\delta_{ps}\sin\phi + (P^p + PE)\cos\phi]$	0.68 ± 0.07	0.75 ± 0.02
	$\pi^0\eta'$	$\lambda_p[-E\delta_{pd}\sin\phi + \frac{1}{\sqrt{2}}C\delta_{ps}\cos\phi + (P^p + PE)\sin\phi]$	0.89 ± 0.14	0.74 ± 0.02
	$\eta\eta$	$\frac{1}{\sqrt{2}}\lambda_p\{[(C+E)\delta_{pd} + P^p + PE + PA]\cos^2\phi + (-\frac{1}{\sqrt{2}}C\sin 2\phi + 2E\sin^2\phi)\delta_{ps}\}$	1.67 ± 0.20	1.44 ± 0.08
	$\eta\eta'$	$\lambda_p\{\frac{1}{2}[(C+E)\delta_{pd} + P^p + PE + PA]\sin 2\phi + (\frac{1}{\sqrt{2}}C\cos 2\phi - E\sin 2\phi)\delta_{ps}\}$	1.05 ± 0.26	1.19 ± 0.07
	K^+K^-	$\lambda_p[(T+E)\delta_{ps} + P^p + PE + PA)]$	3.96 ± 0.08	1.92 ± 0.08
	$K^0\bar{K}^0$	$\lambda_p(E'_p + 2PA)^{\text{a}}$	0.692 ± 0.116	0
D^+	$\pi^+\pi^0$	$\frac{1}{\sqrt{2}}\lambda_d(T+C)$	1.19 ± 0.06	0.88 ± 0.10
	$\pi^+\eta$	$\lambda_p[\frac{1}{\sqrt{2}}(T+C+2A)\delta_{pd}\cos\phi - C\delta_{ps}\sin\phi + \sqrt{2}(P^p + PE)\cos\phi]$	3.53 ± 0.21	1.48 ± 0.26
	$\pi^+\eta'$	$\lambda_p[\frac{1}{\sqrt{2}}(T+C+2A)\delta_{pd}\sin\phi + C\delta_{ps}\cos\phi + \sqrt{2}(P^p + PE)\sin\phi]$	4.67 ± 0.29	3.70 ± 0.37
	$K^+\bar{K}^0$	$\lambda_p[A\delta_{pd} + T\delta_{ps} + P^p + PE]$	5.66 ± 0.32	5.46 ± 0.53
D_s^+	π^+K^0	$\lambda_p[T\delta_{pd} + A\delta_{ps} + P^p + PE]$	2.42 ± 0.16	2.73 ± 0.26
	π^0K^+	$\frac{1}{\sqrt{2}}\lambda_p[-C\delta_{pd} + A\delta_{ps} + P^p + PE]$	0.62 ± 0.21	0.86 ± 0.09
	$K^+\eta$	$\frac{1}{\sqrt{2}}\lambda_p[C\delta_{pd} + A\delta_{ps} + P^p + PE]\cos\phi - \lambda_p[(T+C+A)\delta_{ps} + P^p + PE]\sin\phi$	1.75 ± 0.35	0.78 ± 0.09
	$K^+\eta'$	$\frac{1}{\sqrt{2}}\lambda_p[C\delta_{pd} + A\delta_{ps} + P^p + PE]\sin\phi + \lambda_p[(T+C+A)\delta_{ps} + P^p + PE]\cos\phi$	1.8 ± 0.6	1.07 ± 0.17