MIXING AND CP VIOLATION IN D DECAYS

Seema Bahinipati
IIT Bhubaneswar

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OUTLINE

- Motivation
- Charm Mixing & CPV
- Mixing Results
- Direct CPV in K+K-
- Time-integrated CPV in D0 to π+π-, K+K-, D0 to KsKs
- New flavour tagging technique at Belle II
- Outlook and Summary

WHY CHARM IS CHARMING ?

- Charm is an up-type quark: charm physics is an interesting area of flavour physics: complementary to bottom and strange, but different from top
- Charm is neither too heavy nor too light: ideal situation for interesting QCD physics
- Charm physics offers unique test bed for New Physics

WHY CHARM PHYSICS?

- In SM, FCNC's are suppressed by GIM mechanism

$$\text{GIM} \propto \frac{1}{16\pi^2}\frac{m_t^2 - m_u^2}{M_W^2}$$

bottom and strange: GIM is weakened due to large top mass

$$\text{GIM} \propto \frac{1}{16\pi^2}\frac{m_b^2 - m_d^2}{M_W^2}$$

charm and top: GIM is much more efficient ($m_b < m_t$)

$$\left(\frac{\text{NP Signal}}{\text{SM noise}}\right)_{\text{up-type}} > \left(\frac{\text{NP Signal}}{\text{SM noise}}\right)_{\text{down-type}}$$

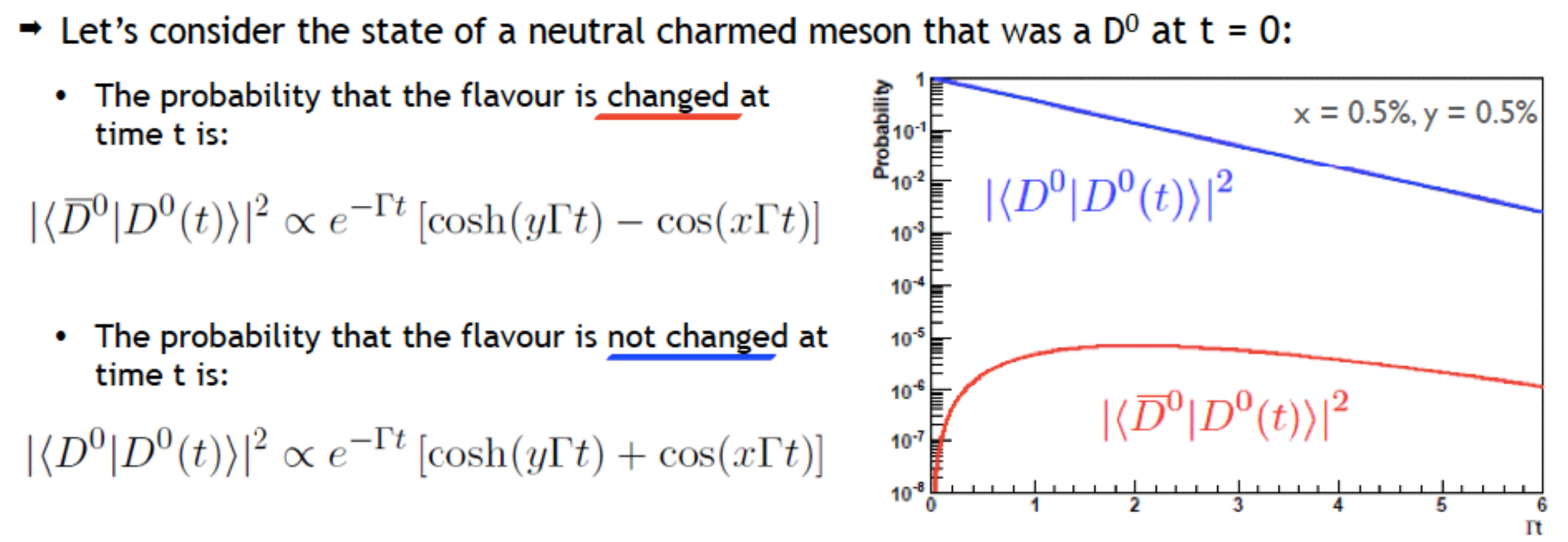
Cleaner signals of NP

CHARM MIXING

D0 can mix with D0-bar and vice-versa

M1,2 = $|D_{1,2}\rangle = p|D^0\rangle \pm q|\overline{D}^0\rangle$ $\quad |p|^2 + |q|^2 = 1$ Two mass eigenstates

$x = \frac{m_1 - m_2}{\Gamma} \quad y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma}$ with $\Gamma = \frac{1}{2}(\Gamma_1 + \Gamma_2)$ Mixing parameters



➡ Let's consider the state of a neutral charmed meson that was a D^0 at $t = 0$:

- The probability that the flavour is changed at time t is:

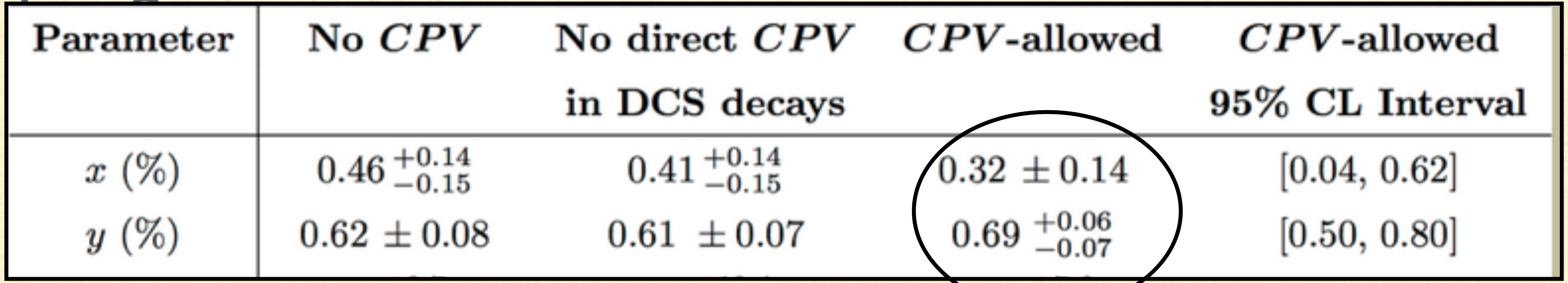
$$|\langle \overline{D}^0 | D^0(t)\rangle|^2 \propto e^{-\Gamma t}\left[\cosh(y\Gamma t) - \cos(x\Gamma t)\right]$$

- The probability that the flavour is not changed at time t is:

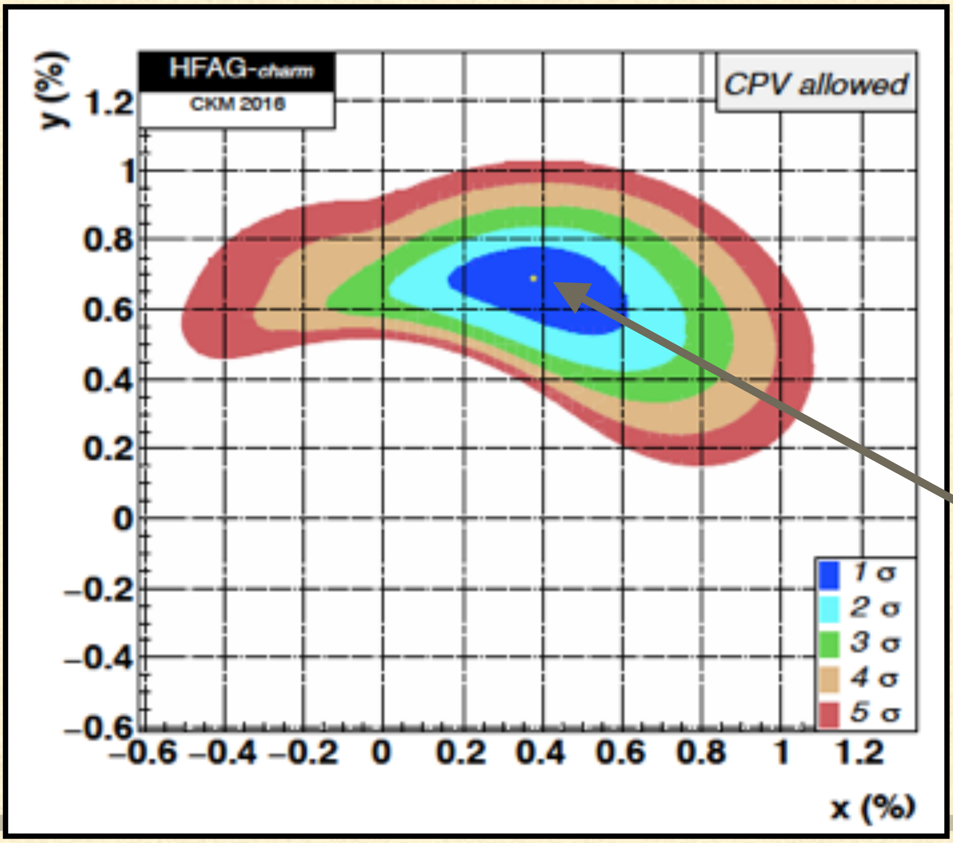
$$|\langle D^0 | D^0(t)\rangle|^2 \propto e^{-\Gamma t}\left[\cosh(y\Gamma t) + \cos(x\Gamma t)\right]$$

CHARM MIXING STATUS

- D^0 mixing firmly established experimentally, though with still relatively large errors for x



Parameter	No *CPV*	No direct *CPV* in DCS decays	*CPV*-allowed	*CPV*-allowed 95% CL Interval
x (%)	$0.46^{+0.14}_{-0.15}$	$0.41^{+0.14}_{-0.15}$	0.32 ± 0.14	[0.04, 0.62]
y (%)	0.62 ± 0.08	0.61 ± 0.07	$0.69^{+0.06}_{-0.07}$	[0.50, 0.80]



No mixing scenario: x = 0, y, 0

Mixing constraint in D0-D0bar system

D0 SYSTEM

- Only heavy, neutral up-type system - unique test bed for CPV
- In SM, CPV in charm is highly suppressed

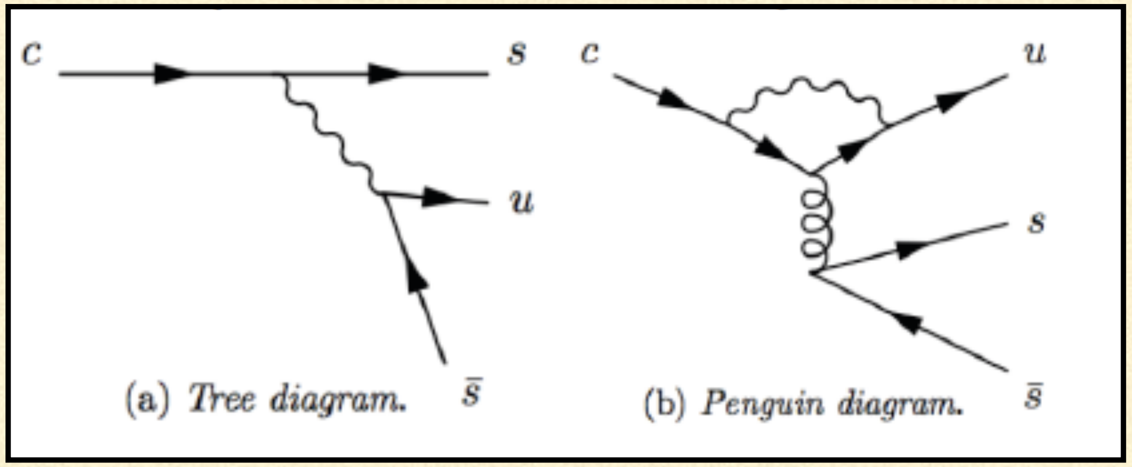
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

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

$$\lambda \simeq 0.23, \quad A \simeq 0.81, \quad \rho - i\eta \simeq 0.14 - 0.35i.$$

CPV IN CHARM

- SM picture: Expected CPV in charm sector is small
- Couplings to the third generation is small: Effectively “two-family” physics
- Presence of weak phases in CS decays, not in CA and DCS decays



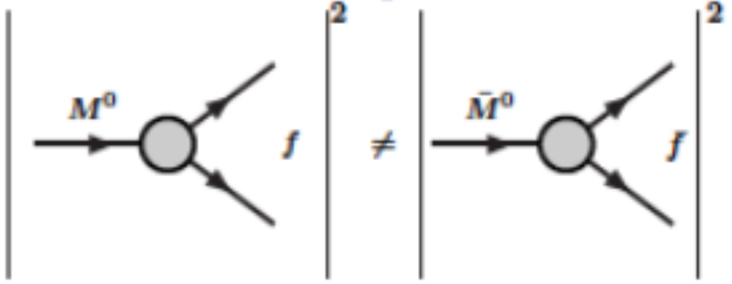
(a) *Tree diagram.* (b) *Penguin diagram.*

The direct CPV

Grossman, Kagan, Nir Phys.Rev.D75
Guadagnoli@FPLH

CPV in decay occurs when the absolute value of the decay rate $M \to f$ differs from the decay rate involving the CP-conjugate states

$$|A(M^0 \to f)| \neq |A(\bar{M}^0 \to \bar{f})|$$



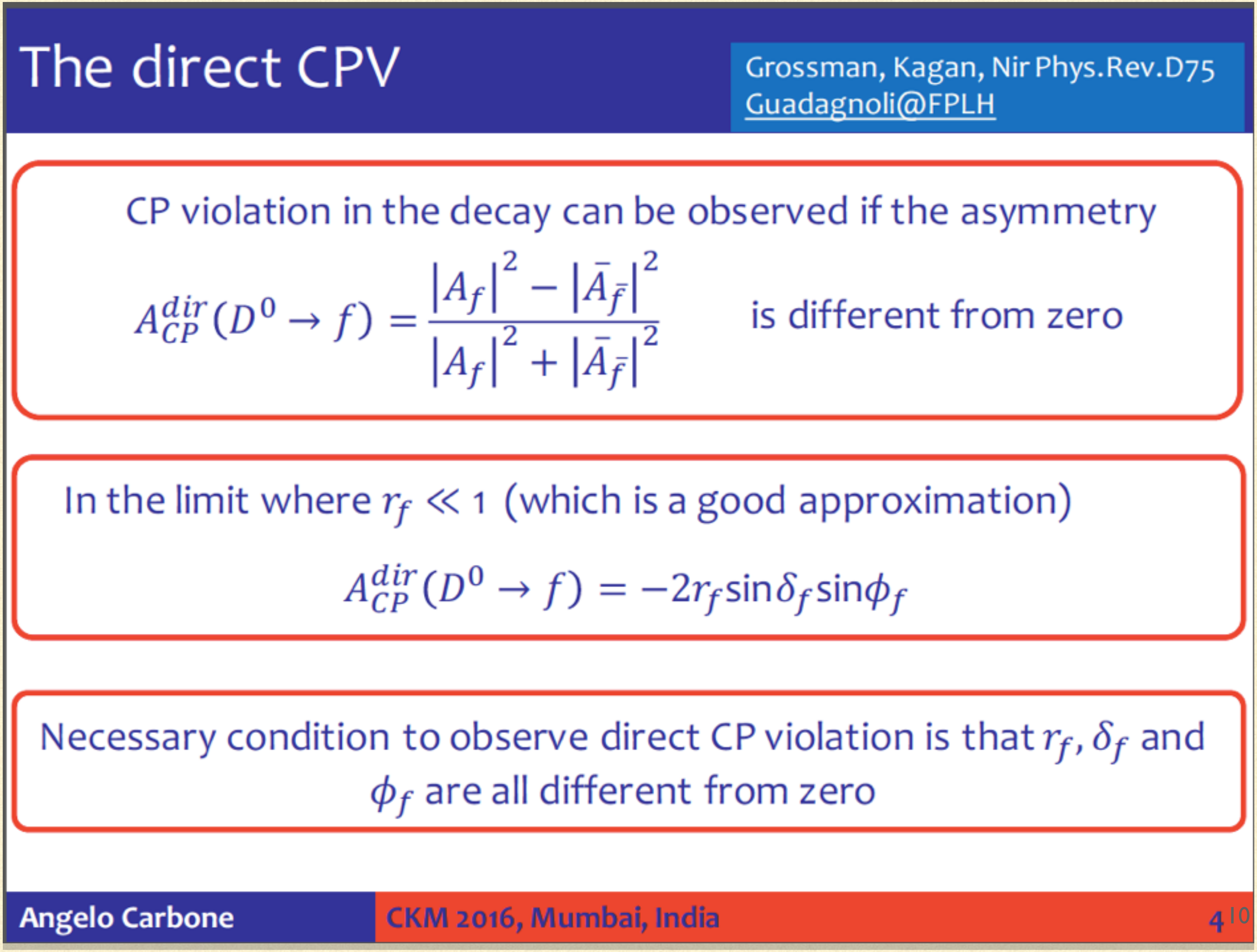
CPV can happens if the final state can be reached at least with two different path

The amplitude of a CP eingenstate, i.e. $D^0 \to f$ with $f = K^-K^+$ or $f = \pi^-\pi^+$, it can be written with a leading term and a sub-leading as follows

Sub-leading amplitude: with relative strong (δ_f) and weak (ϕ_f) phases

$$A_f = \boxed{A_f^T}\left(1 + \boxed{r_f e^{i(\delta_f+\phi_f)}}\right)$$

Leading amplitude: its phase is taken to be zero



The direct CPV

Grossman, Kagan, Nir Phys.Rev.D75
Guadagnoli@FPLH

CP violation in the decay can be observed if the asymmetry

$$A_{CP}^{dir}(D^0 \to f) = \frac{|A_f|^2 - |\bar{A}_{\bar{f}}|^2}{|A_f|^2 + |\bar{A}_{\bar{f}}|^2}$$

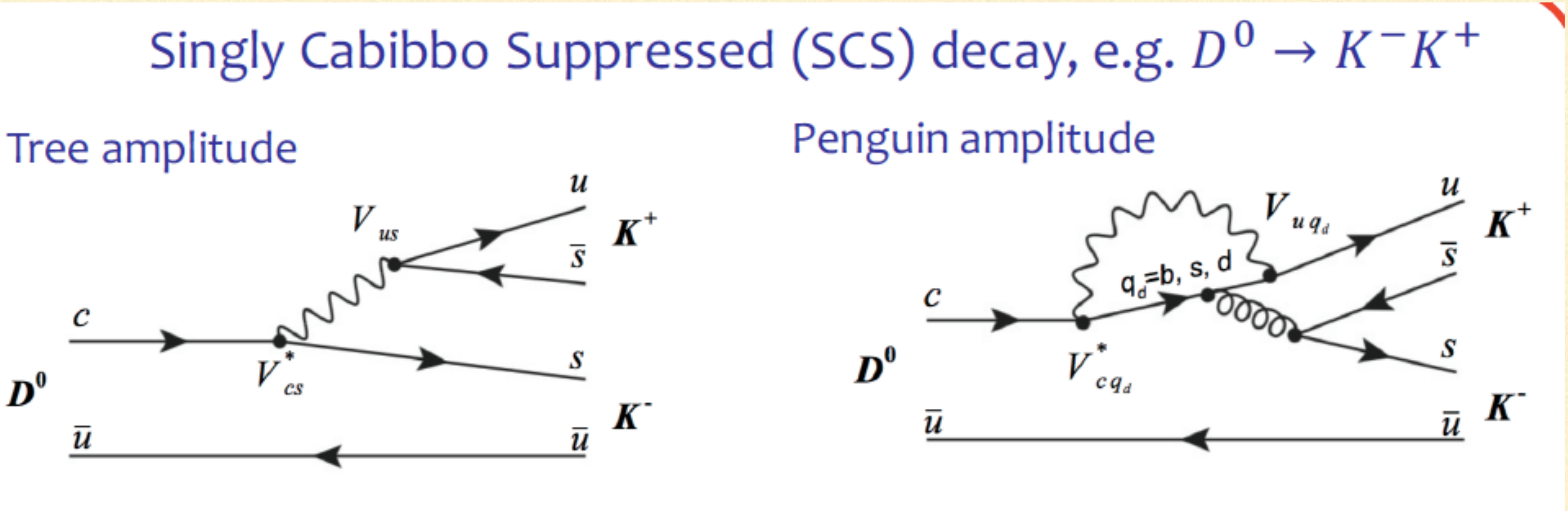
is different from zero

In the limit where $r_f \ll 1$ (which is a good approximation)

$$A_{CP}^{dir}(D^0 \to f) = -2 r_f \sin\delta_f \sin\phi_f$$

Necessary condition to observe direct CP violation is that r_f, δ_f and ϕ_f are all different from zero

SCS DECAYS



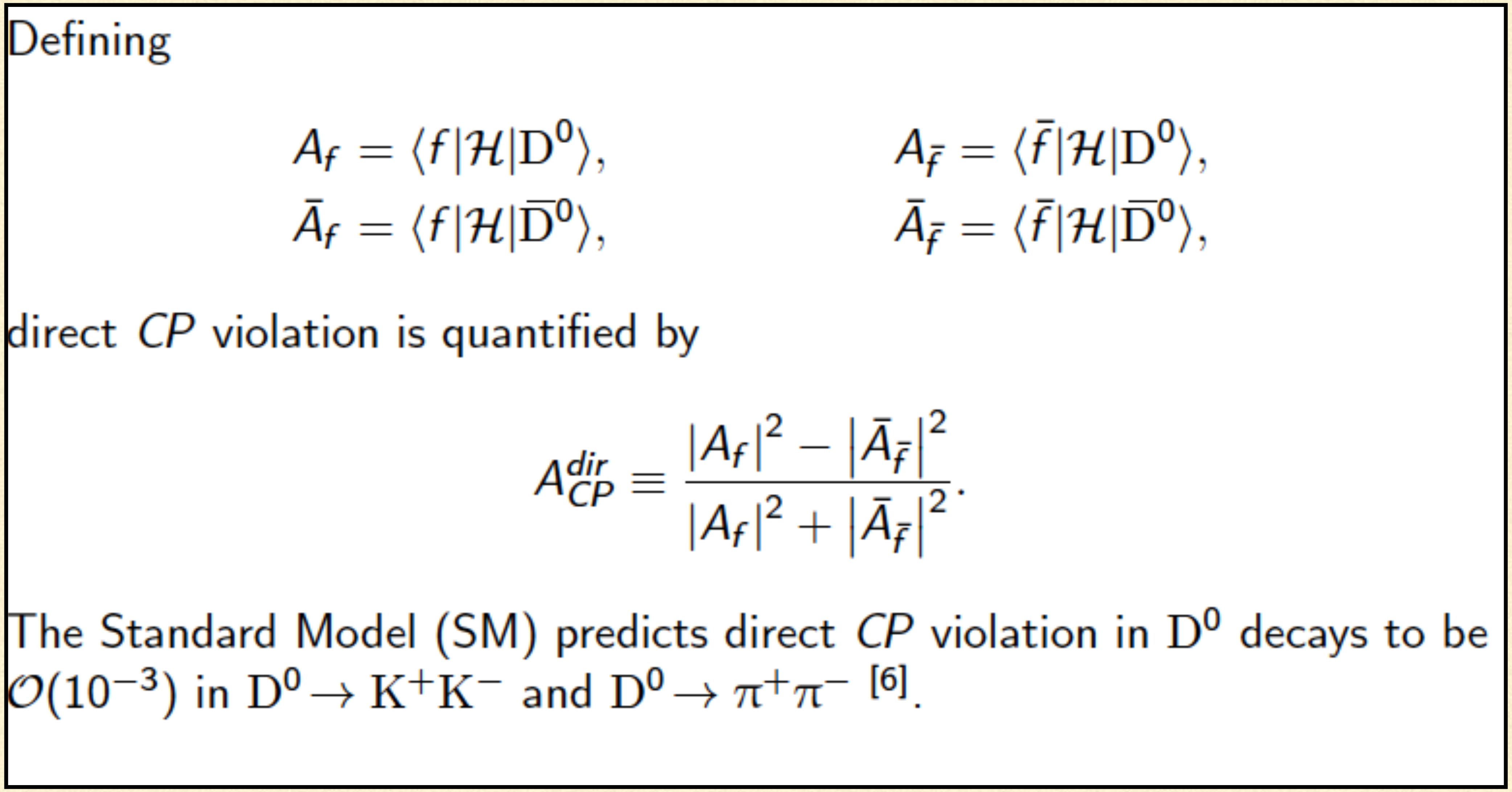
Singly Cabibbo Suppressed (SCS) decay, e.g. $D^0 \to K^- K^+$

Tree amplitude

Penguin amplitude

Of Special interest:
possible interference with NP amplitude could lead to larger nonzero CPV

DCPV



Defining

$$A_f = \langle f|\mathcal{H}|\mathrm{D}^0\rangle, \qquad A_{\bar{f}} = \langle \bar{f}|\mathcal{H}|\mathrm{D}^0\rangle,$$

$$\bar{A}_f = \langle f|\mathcal{H}|\overline{\mathrm{D}}^0\rangle, \qquad \bar{A}_{\bar{f}} = \langle \bar{f}|\mathcal{H}|\overline{\mathrm{D}}^0\rangle,$$

direct *CP* violation is quantified by

$$A_{CP}^{dir} \equiv \frac{|A_f|^2 - |\bar{A}_{\bar{f}}|^2}{|A_f|^2 + |\bar{A}_{\bar{f}}|^2}.$$

The Standard Model (SM) predicts direct *CP* violation in D^0 decays to be $\mathcal{O}(10^{-3})$ in $\mathrm{D}^0 \to \mathrm{K}^+\mathrm{K}^-$ and $\mathrm{D}^0 \to \pi^+\pi^-$ [6].

The single asymmetry $A_{CP}(KK)$

In order to measure the single asymmetry it is necessary to know the pion detection asymmetry $A_D(\pi_s^+)$ and the D^{*+} production asymmetry $A_P(D^{*+})$

$$A_{raw}(KK) = A_{CP}(KK) + A_P(D^{*+}) + A_D(\pi_s^+)$$

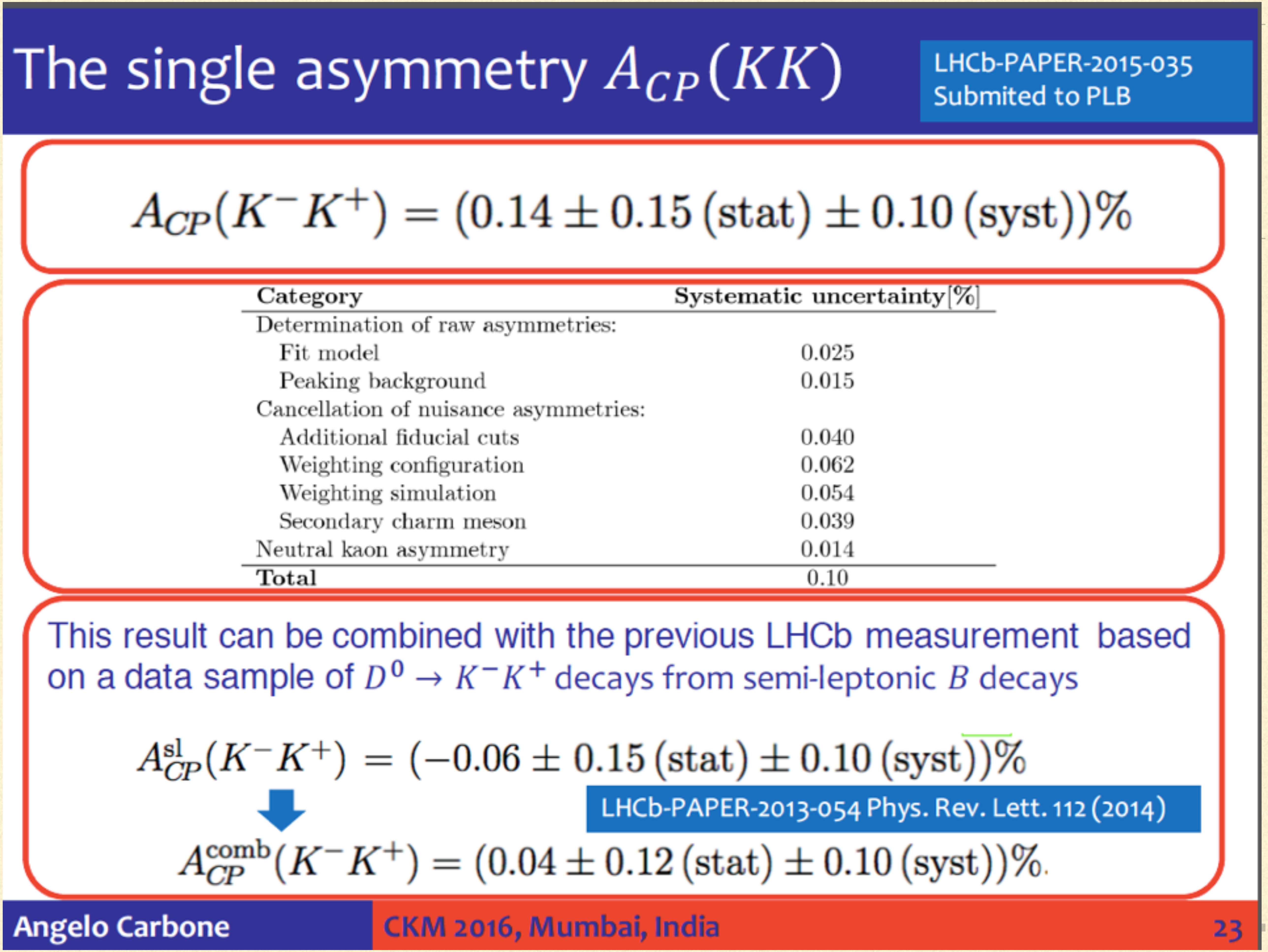
The raw asymmetry for $D^{*+} \to D^0(K^-\pi^+)\pi^+$, $A_D(\pi_s^+)$ cancel

$$A^*_{raw}(K\pi) = A_{CP}(K\pi) + A_D(K\pi) + A_P\,(D^{*+}) + A_D(\pi_s^+)$$

In the difference between the two A_{raw}, $A_P(D^{*+})$ and $A_D(K\pi)$ cancel

$$A_{raw}(KK) - A^*_{raw}(K\pi) = A_{CP}(KK) - A_D(K\pi)$$

It is still necessary to measure $A_D(K\pi)$



The single asymmetry $A_{CP}(KK)$

LHCb-PAPER-2015-035
Submited to PLB

$$A_{CP}(K^-K^+) = (0.14 \pm 0.15\,(\text{stat}) \pm 0.10\,(\text{syst}))\%$$

Category	Systematic uncertainty[%]
Determination of raw asymmetries:	
Fit model	0.025
Peaking background	0.015
Cancellation of nuisance asymmetries:	
Additional fiducial cuts	0.040
Weighting configuration	0.062
Weighting simulation	0.054
Secondary charm meson	0.039
Neutral kaon asymmetry	0.014
Total	0.10

This result can be combined with the previous LHCb measurement based on a data sample of $D^0 \to K^-K^+$ decays from semi-leptonic B decays

$$A^{\text{sl}}_{CP}(K^-K^+) = (-0.06 \pm 0.15\,(\text{stat}) \pm 0.10\,(\text{syst}))\%$$

LHCb-PAPER-2013-054 Phys. Rev. Lett. 112 (2014)

$$A^{\text{comb}}_{CP}(K^-K^+) = (0.04 \pm 0.12\,(\text{stat}) \pm 0.10\,(\text{syst}))\%.$$

Combination with previous LHCb measurements

LHCb-PAPER-2015-035, Submited to PLB

From the previous ΔA_{CP} mesurement, is possible to measure $A_{CP}(\pi\pi)$

$$A_{CP}(\pi^+\pi^-) = A_{CP}(K^+K^-) - \Delta A_{CP} = (0.24 \pm 0.15\,(\mathrm{stat}) \pm 0.11\,(\mathrm{syst}))\%$$

with a correlation between the two mesurements

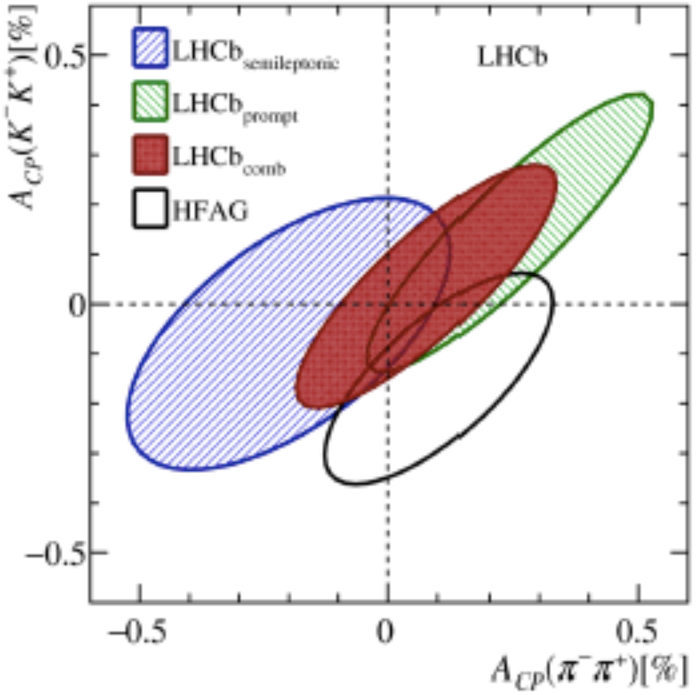
$$\rho\big(A_{CP}(KK), A_{CP}(\pi\pi)\big) = 0.24$$

This result can be combined with the previous LHCb measurement based on a data sample of $D^0 \to \pi^-\pi^+$ decays from semi-leptonic B decays

$$A_{CP}^{\mathrm{sl}}(\pi^-\pi^+) = (-0.19 \pm 0.20\,(\mathrm{stat}) \pm 0.10\,(\mathrm{syst}))\%$$

LHCb-PAPER-2013-054 Phys. Rev. Lett. 112 (2014)

$$A_{CP}^{\mathrm{comb}}(\pi^-\pi^+) = (0.07 \pm 0.14\,(\mathrm{stat}) \pm 0.11\,(\mathrm{syst}))\%$$



Time-integrated CP asymmetry

CP asymmetry is defined as

$$A_{CP}(f) = \frac{\Gamma(D^0 \to f) - \Gamma(\overline{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\overline{D}^0 \to f)}$$

with $f = K^-K^+$ and $f = \pi^-\pi^+$

The flavour of the initial state (D^0 or $\overline{D}^0$) is tagged by the charge of the slow pion from, $D^{*\pm} \to D^0\pi^\pm$

The raw asymmetry for tagged D^0 decays to a final state f is given by

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

where N refers to the number of reconstructed events of decay after background subtraction

Production and detection asymmetries

What we measure is the physical asymmetry plus asymmetries due to production and detector effects

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

CP asymmetry

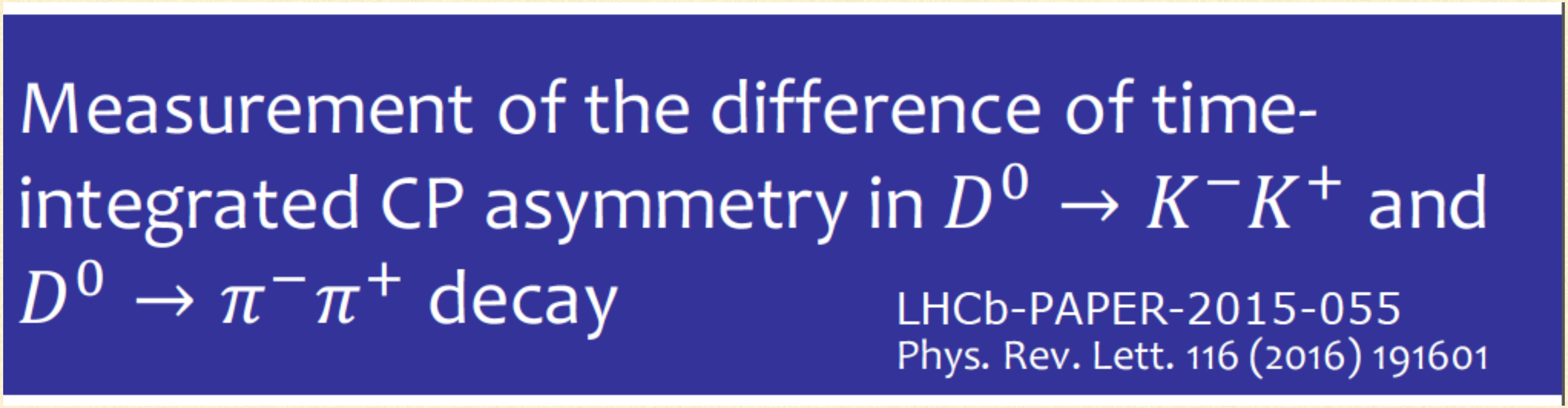
Any charge-dependent asymmetry in slow pion reconstruction

$D^{*\pm}$ production asymmetry

- No detection asymmetry for D^0 decays to K^-K^+ or $\pi^-\pi^+$
- … if we take the raw asymmetry difference

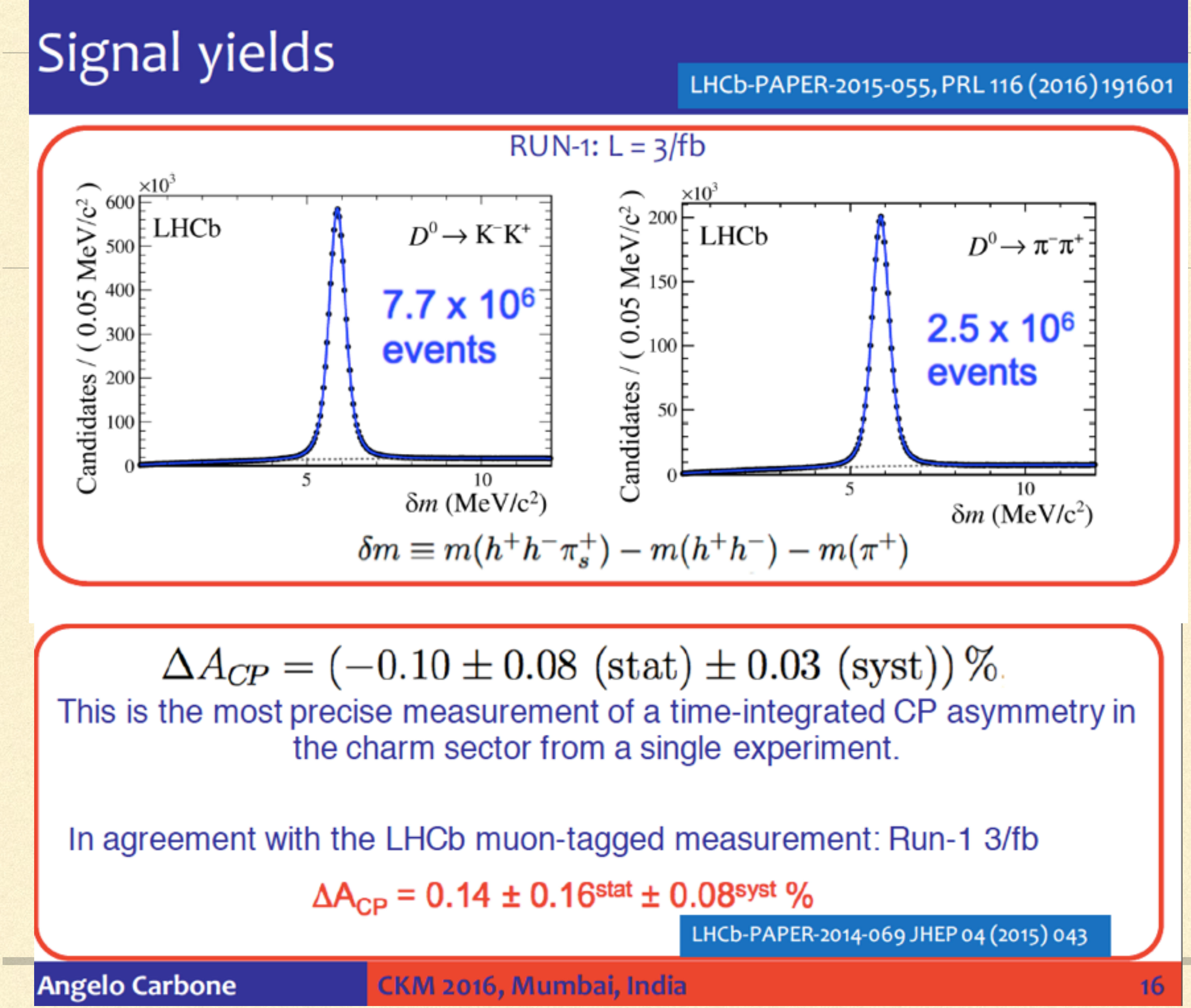
$$\boxed{\Delta A_{CP} \equiv A_{raw}(KK) - A_{raw}(\pi\pi) = A_{CP}(KK) - A_{CP}(\pi\pi)}$$

- the D^{*+} production and the slow pion detection asymmetries will cancel



Measurement of the difference of time-integrated CP asymmetry in $D^0 \rightarrow K^-K^+$ and $D^0 \rightarrow \pi^-\pi^+$ decay

LHCb-PAPER-2015-055
Phys. Rev. Lett. 116 (2016) 191601



Signal yields

LHCb-PAPER-2015-055, PRL 116 (2016) 191601

RUN-1: L = 3/fb

$$\delta m \equiv m(h^+h^-\pi_s^+) - m(h^+h^-) - m(\pi^+)$$

$$\Delta A_{CP} = (-0.10 \pm 0.08\ (\mathrm{stat}) \pm 0.03\ (\mathrm{syst}))\ \%$$

This is the most precise measurement of a time-integrated CP asymmetry in the charm sector from a single experiment.

In agreement with the LHCb muon-tagged measurement: Run-1 3/fb

$\Delta A_{CP} = 0.14 \pm 0.16^{\mathrm{stat}} \pm 0.08^{\mathrm{syst}}\ \%$

LHCb-PAPER-2014-069 JHEP 04 (2015) 043

Angelo Carbone CKM 2016, Mumbai, India 16

Results

LHCb-PAPER-2015-055, PRL 116 (2016) 191601

The observable ΔA_{CP} is mostly sensitive to direct CP asymmetry, Δa^{dir}_{CP}, but with a small contribution also to indirect CP asymmetry, a^{ind}_{CP}

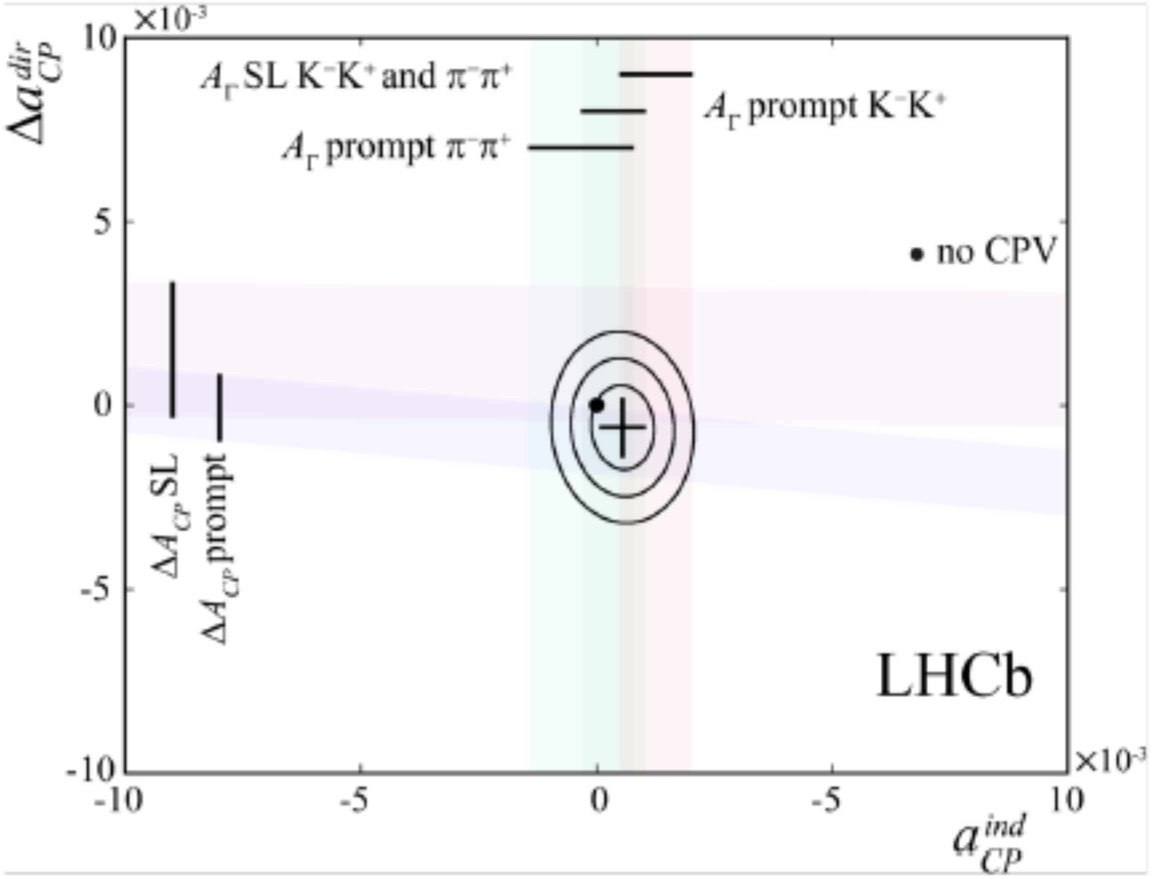
$$\begin{aligned}\Delta A_{CP} &\equiv A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+)\\ &\approx \Delta a^{\rm dir}_{CP}\left(1+\underbrace{\frac{\overline{\langle t\rangle}}{\tau}y_{CP}}_{\sim 2 \times 10^{-4}}\right)+\underbrace{\frac{\Delta\langle t\rangle}{\tau}}_{\sim 0.12}a^{\rm ind}_{CP}\end{aligned}$$

Combination with LHCb measurements

$$\Delta a^{dir}_{CP}\,(-0.061 \pm 0.076)\%$$

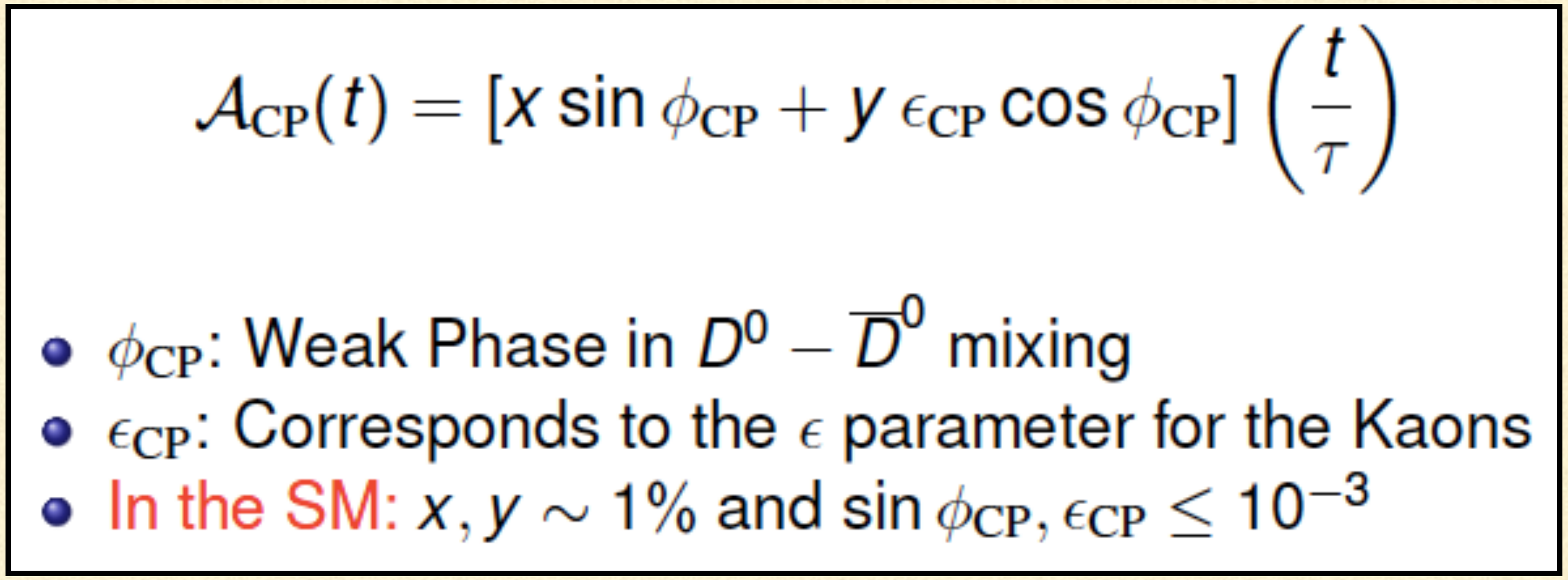
$$a^{ind}_{CP}\,(0.058 \pm 0.044)\%$$

The result is consistent with the hypothesis of CP symmetry with a p-value of 0.32



CPV IN CHARM

Neutral D mixing opens up additional avenues for CPV in charm



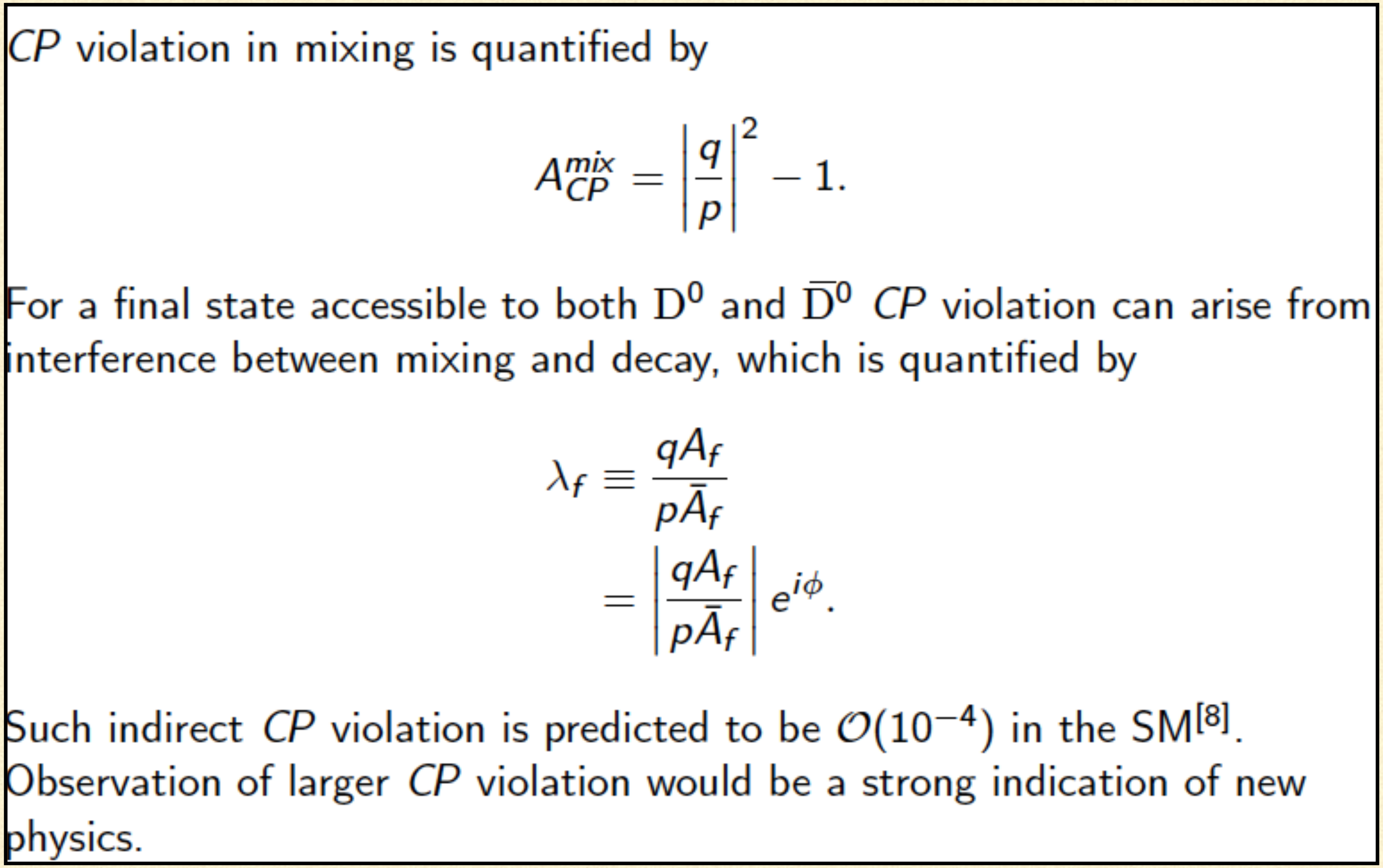
$$\mathcal{A}_{\mathrm{CP}}(t) = [x \sin\phi_{\mathrm{CP}} + y\, \epsilon_{\mathrm{CP}} \cos\phi_{\mathrm{CP}}] \left(\frac{t}{\tau}\right)$$

- ϕ_{CP}: Weak Phase in $D^0 - \overline{D}^0$ mixing
- ϵ_{CP}: Corresponds to the ϵ parameter for the Kaons
- In the SM: $x, y \sim 1\%$ and $\sin\phi_{\mathrm{CP}}, \epsilon_{\mathrm{CP}} \leq 10^{-3}$

CPV in charm could be indication of NP:
$A_{CP}(t) \sim 10^{-3}$ in some NP models

Final state distributions carry large CP sensitivity

CPV IN MIXING



CP violation in mixing is quantified by

$$A_{CP}^{mix} = \left|\frac{q}{p}\right|^2 - 1.$$

For a final state accessible to both D^0 and $\overline{\mathrm{D}}^0$ *CP* violation can arise from interference between mixing and decay, which is quantified by

$$\begin{aligned}\lambda_f &\equiv \frac{qA_f}{p\bar{A}_f} \\ &= \left|\frac{qA_f}{p\bar{A}_f}\right| e^{i\phi}.\end{aligned}$$

Such indirect *CP* violation is predicted to be $\mathcal{O}(10^{-4})$ in the SM[8]. Observation of larger *CP* violation would be a strong indication of new physics.

CP eigenstates decays $D^0 \rightarrow K^+K^- / \pi^+\pi^-$

Mixing in D^0 decays to CP eigenstates, give rise to an effective lifetime τ that differs from that in the decays to flavor eigenstates such as $D \rightarrow K^+\pi^-$.

Observables

$$y_{CP} = \frac{\tau(D^0 \to K^-\pi^+)}{\tau(D^0 \to K^-K^+)} - 1$$

PLB 486, 418 (2000)

y_{CP} is equal to the mixing parameter y if CP is conserved.

Otherwise, effective lifetimes of $\bar{D}^0$ and D^0 decaying to the same CP eigenstate differ and the asymmetry

$$A_\Gamma = \frac{\tau(\bar{D}^0 \to K^-K^+) - \tau(D^0 \to K^+K^-)}{\tau(\bar{D}^0 \to K^-K^+) + \tau(D^0 \to K^+K^-)} \neq 0$$

In absence of direct CP violation, y_{CP} and A_Γ are related to x and y as

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

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

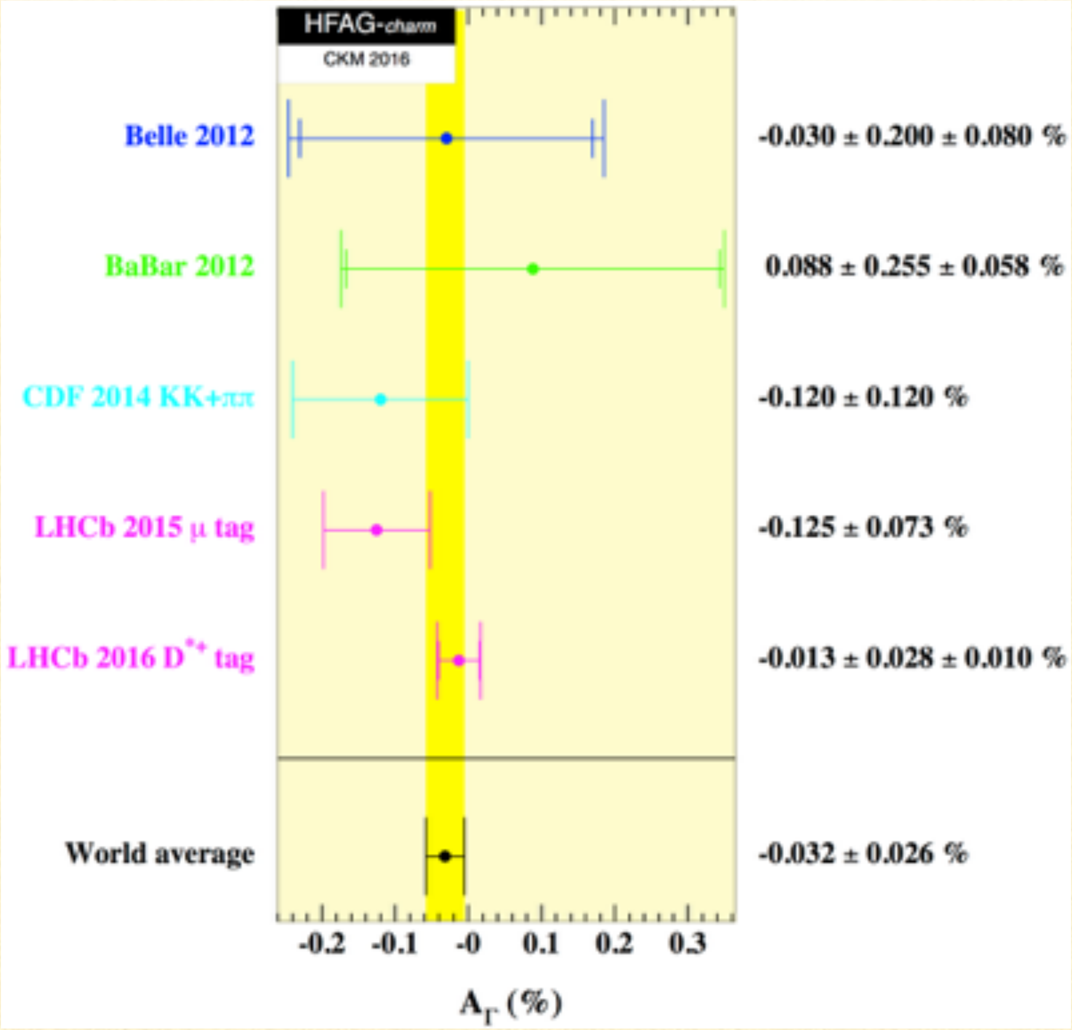
where $\phi = \arg(\frac{q}{p})$

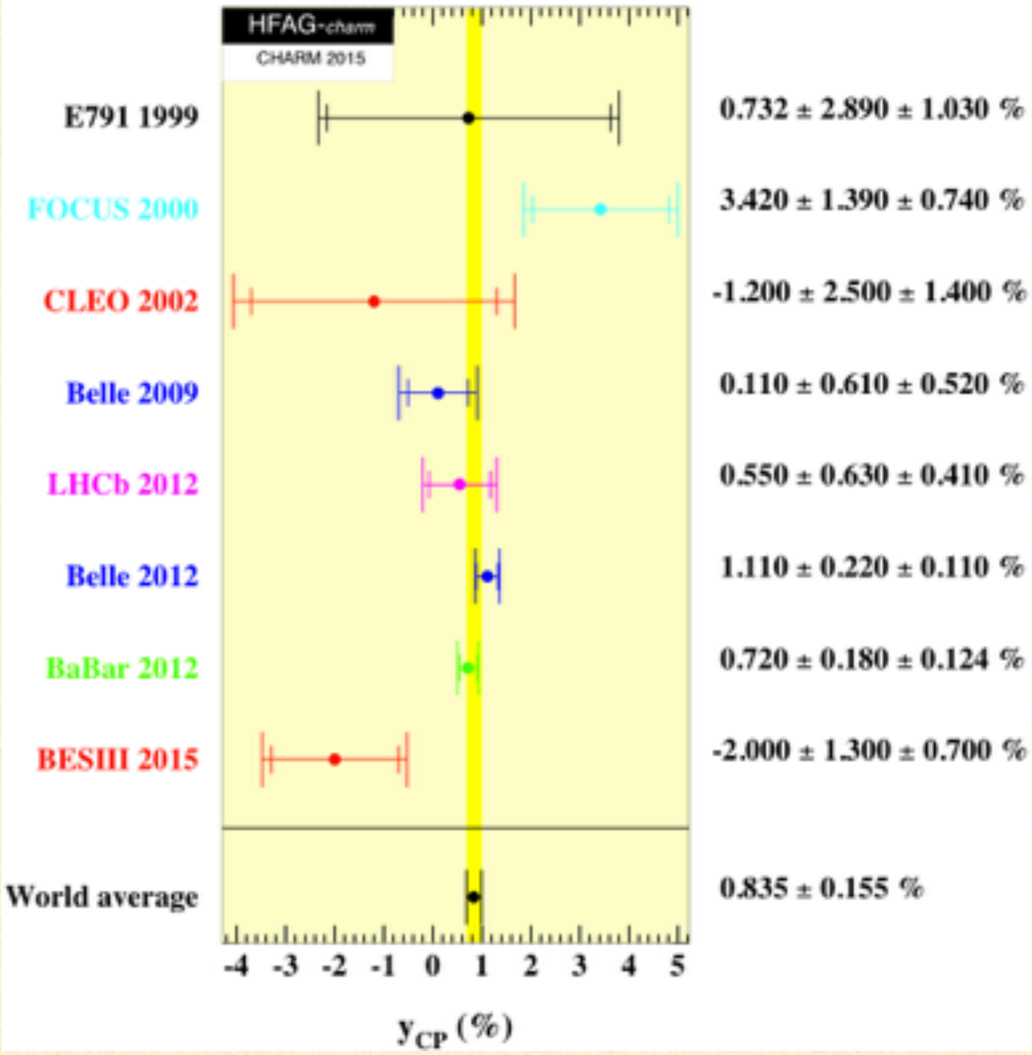
PLB 486, 418 (2000)
JHEP 0705, 102 (2007)

We measure:

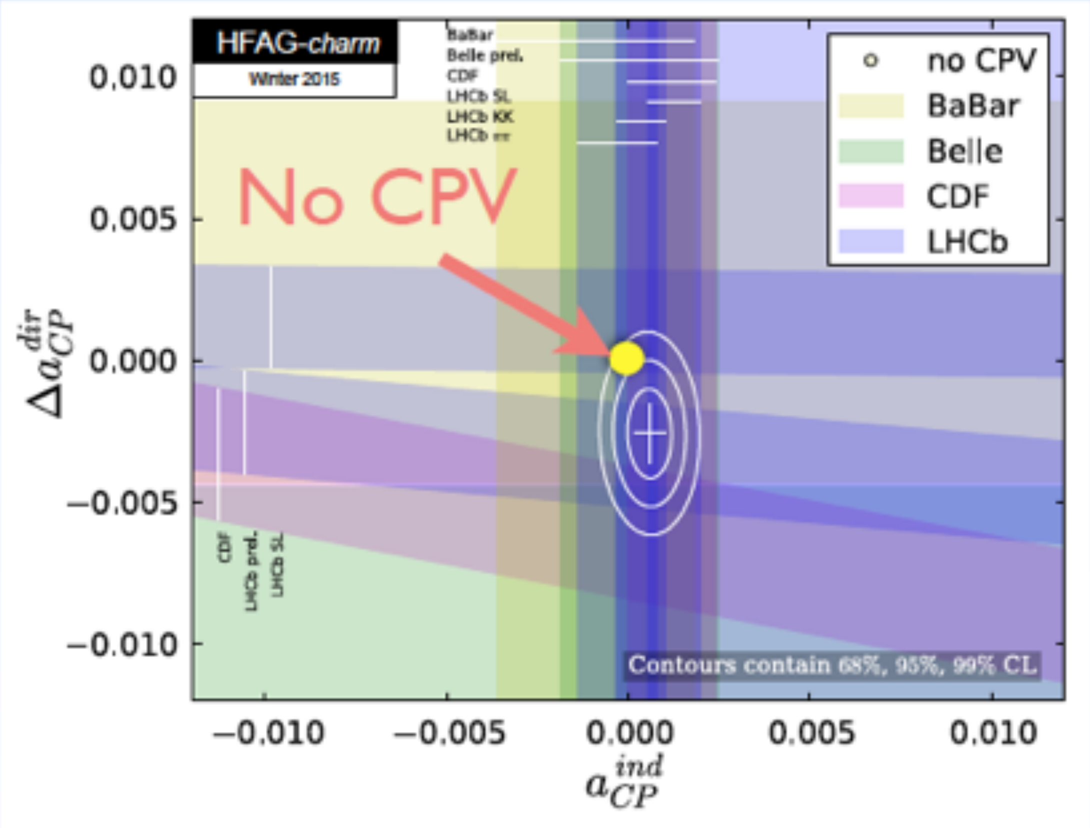
Difference in proper decay time distributions of $D^0 \rightarrow f$ and $\bar{D}^0 \rightarrow \bar{f}$

RESULTS


HFAG-charm
CKM 2016
Belle 2012
-0.030 ± 0.200 ± 0.080 %
BaBar 2012
0.088 ± 0.255 ± 0.058 %
CDF 2014 KK+ππ
-0.120 ± 0.120 %
LHCb 2015 μ tag
-0.125 ± 0.073 %
LHCb 2016 D*+ tag
-0.013 ± 0.028 ± 0.010 %
World average
-0.032 ± 0.026 %
-0.2
-0.1
-0
0.1
0.2
0.3
A_Γ (%)


HFAG-charm
CHARM 2015
E791 1999
0.732 ± 2.890 ± 1.030 %
FOCUS 2000
3.420 ± 1.390 ± 0.740 %
CLEO 2002
-1.200 ± 2.500 ± 1.400 %
Belle 2009
0.110 ± 0.610 ± 0.520 %
LHCb 2012
0.550 ± 0.630 ± 0.410 %
Belle 2012
1.110 ± 0.220 ± 0.110 %
BaBar 2012
0.720 ± 0.180 ± 0.124 %
BESIII 2015
-2.000 ± 1.300 ± 0.700 %
World average
0.835 ± 0.155 %
-4
-3
-2
-1
0
1
2
3
4
5
y_CP (%)

CHARM CPV STATUS

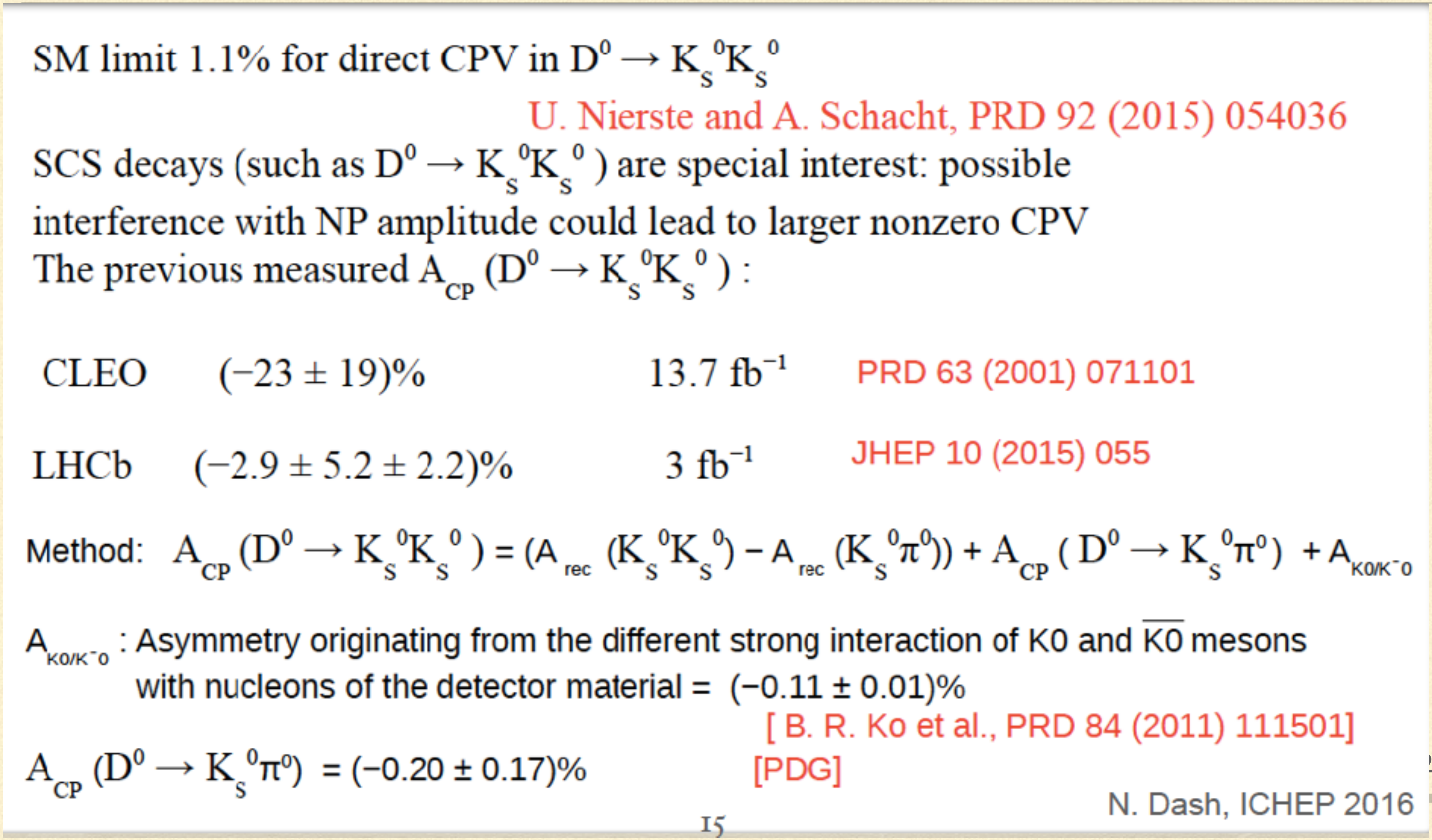


$a_{CP}^{ind} = 0.00058 \pm 0.00040$

$\Delta a_{CP}^{dir} = -0.00257 \pm 0.00104$

No evidence for CPV in the charm sector at 1.8% CL

D0 TO KSKS



SM limit 1.1% for direct CPV in $D^0 \rightarrow K_S^0 K_S^0$

U. Nierste and A. Schacht, PRD 92 (2015) 054036

SCS decays (such as $D^0 \rightarrow K_S^0 K_S^0$) are special interest: possible interference with NP amplitude could lead to larger nonzero CPV

The previous measured $A_{CP}(D^0 \rightarrow K_S^0 K_S^0)$:

CLEO	$(-23 \pm 19)\%$	$13.7\ fb^{-1}$	PRD 63 (2001) 071101
LHCb	$(-2.9 \pm 5.2 \pm 2.2)\%$	$3\ fb^{-1}$	JHEP 10 (2015) 055

Method: $A_{CP}(D^0 \rightarrow K_S^0 K_S^0) = (A_{rec}(K_S^0 K_S^0) - A_{rec}(K_S^0 \pi^0)) + A_{CP}(D^0 \rightarrow K_S^0 \pi^0) + A_{K0/\bar{K}0}$

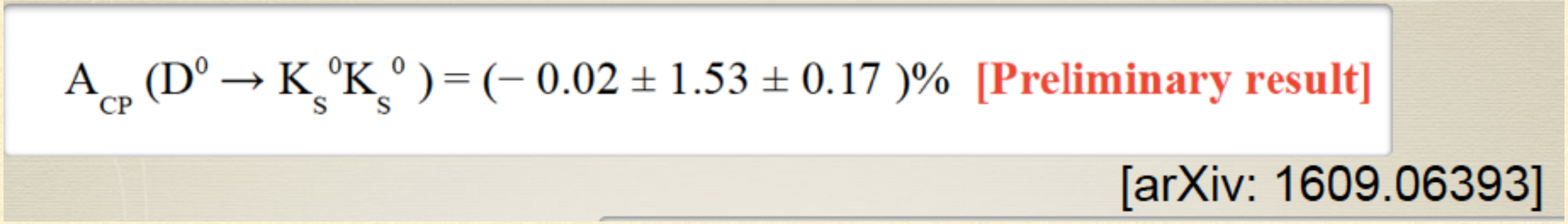
$A_{K0/\bar{K}0}$: Asymmetry originating from the different strong interaction of K0 and $\overline{K0}$ mesons with nucleons of the detector material = $(-0.11 \pm 0.01)\%$

[B. R. Ko et al., PRD 84 (2011) 111501]

$A_{CP}(D^0 \rightarrow K_S^0 \pi^0) = (-0.20 \pm 0.17)\%$ [PDG]

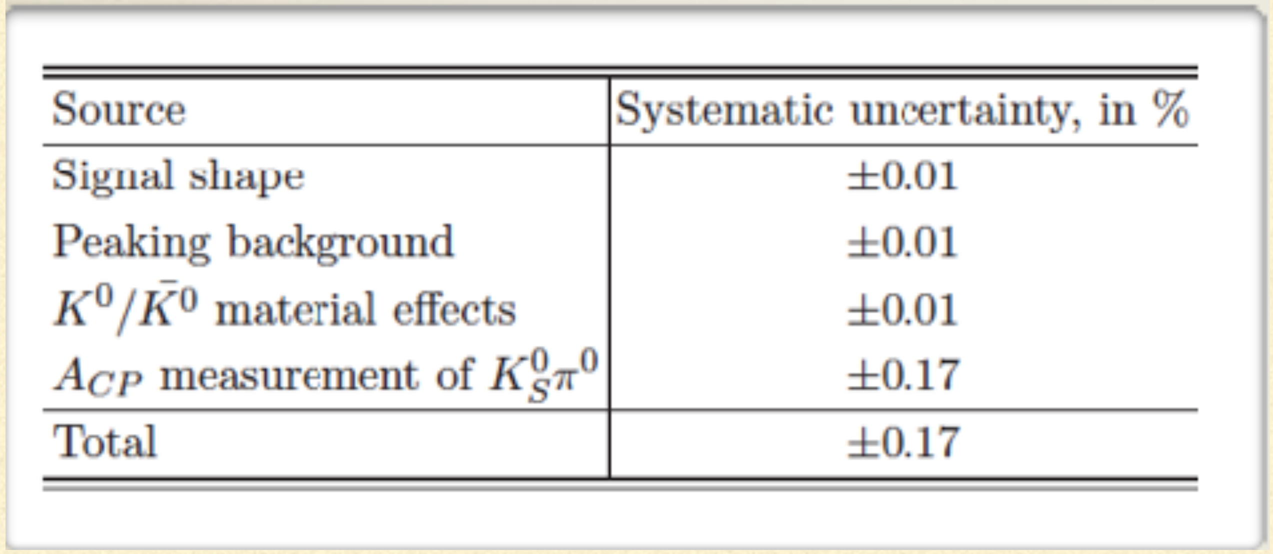
N. Dash, ICHEP 2016

D0 TO KSKS



$A_{CP}(D^0 \to K_S^0 K_S^0) = (-0.02 \pm 1.53 \pm 0.17)\%$ **[Preliminary result]**

[arXiv: 1609.06393]



Source	Systematic uncertainty, in %
Signal shape	±0.01
Peaking background	±0.01
$K^0/\bar{K}^0$ material effects	±0.01
A_{CP} measurement of $K_S^0\pi^0$	±0.17
Total	±0.17

With 50 ab-1 at Belle II, expect a precision of ~ 0.2 % on ACP

REQUIREMENT FOR CHARM FACTORIES

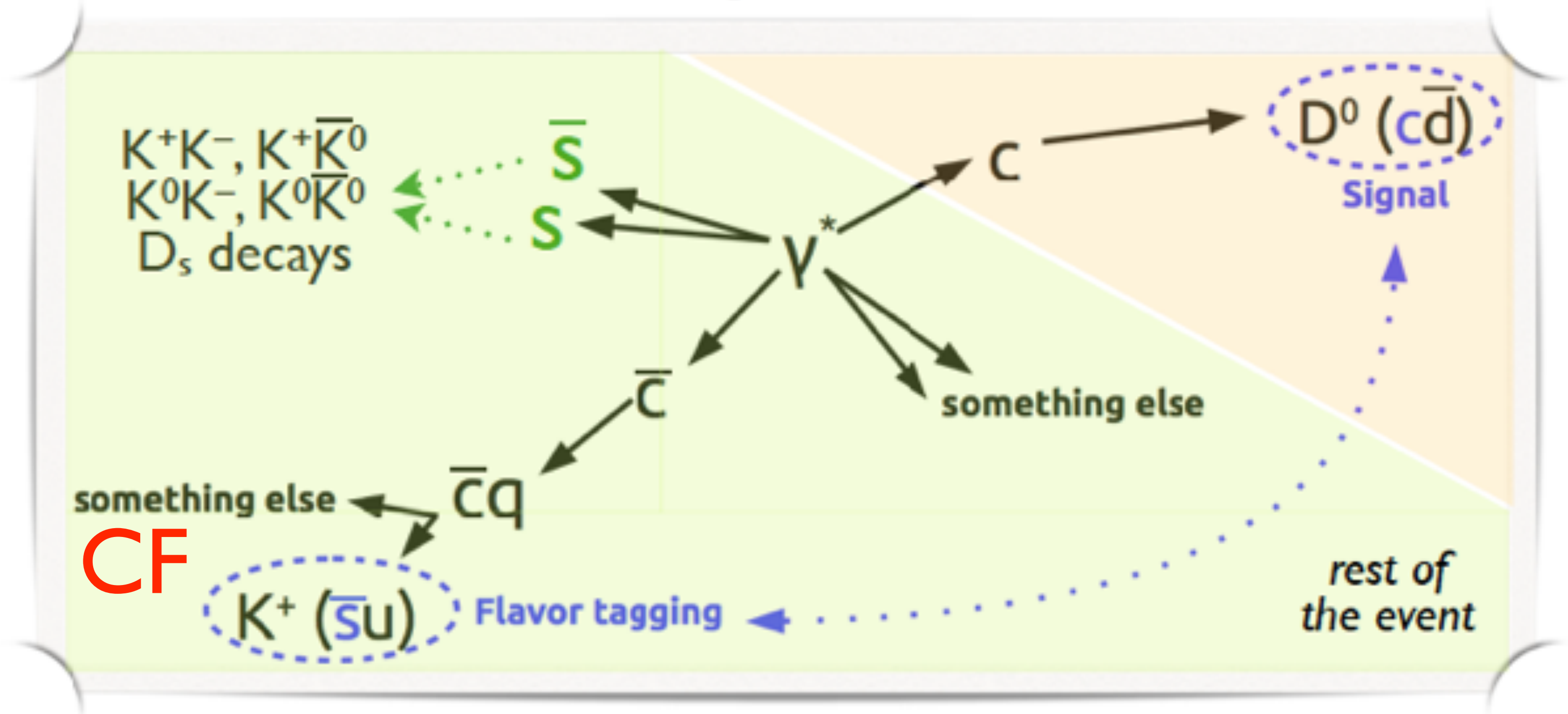
- Large samples of charm
- High signal efficiency and good background rejection
- Large boost (displaced vertex), hermetic detector, excellent PID, γ and π0

NEW FLAVOUR TAGGING TECHNIQUE AT BELLE II

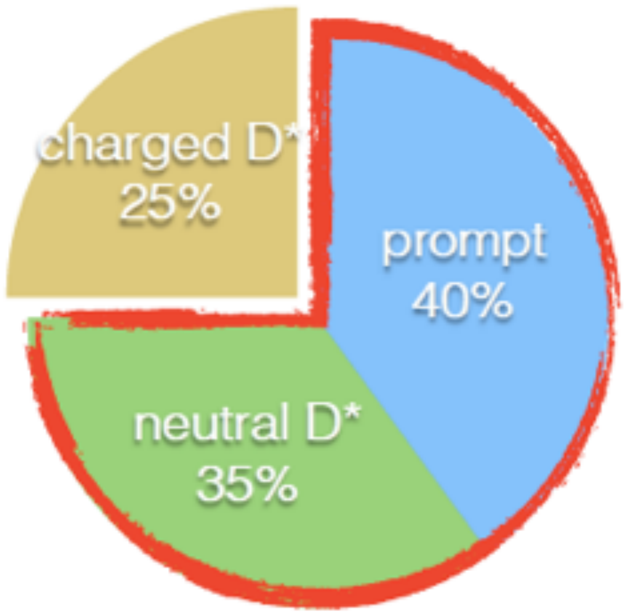
Belle II

Prompt D^0 Flavour Tagging

- Can we recover at least a fraction of the 75% produced D^0 not coming from a charged D^* decay?
  - reconstruct the D^0 in the signal channel and define the rest of the event (ROE) as all the reconstructed particles that are not coming from the signal D^0 decay
  - select events with one single K in the ROE



D⁰ mothers in $c\bar{c}$ events



Typical Correctly Tagging Events

$cc \rightarrow D^0 D^- X$, $D^0 \rightarrow$ signal ch

$D^- \rightarrow K^{*0} e^- \nu$; $K^{*0} \rightarrow K^+\pi^-$

$cc \rightarrow D^0 \Lambda_c^- X$, $D^0 \rightarrow$ signal ch

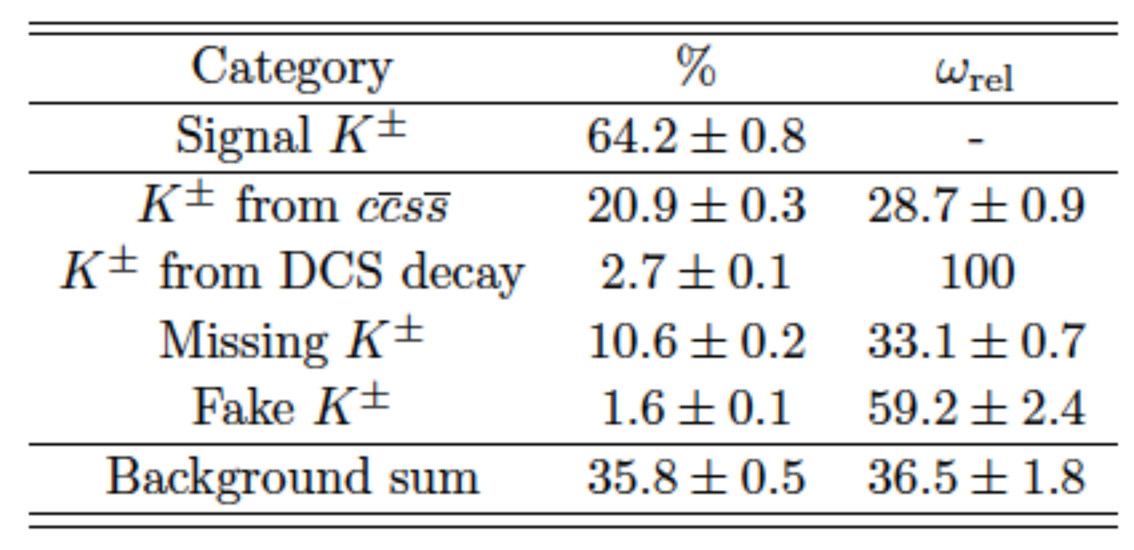
$\Lambda_c^- \rightarrow \Delta^{--} K^{*+}$; $K^{*+} \rightarrow K^+\pi^0$

- flavour mis-tagging due to $c\bar{c}s\bar{s}$ when a K escapes reconstruction: these events introduce un-correlated charged kaons into the rest of the event
- irreducible mistag due to DCS decays of the rest of the event charmed meson or baryon

G. Casarosa[2], A. Kagan[1], A. Petrov[3], A. Schwartz[1]

[1] *Cincinnati*, [2] *Pisa*, [3] *Wayne*

Signal & Background contributions



Category	%	$\omega_{\rm rel}$
Signal $K^\pm$	64.2 ± 0.8	-
$K^\pm$ from $c\bar{c}s\bar{s}$	20.9 ± 0.3	28.7 ± 0.9
$K^\pm$ from DCS decay	2.7 ± 0.1	100
Missing $K^\pm$	10.6 ± 0.2	33.1 ± 0.7
Fake $K^\pm$	1.6 ± 0.1	59.2 ± 2.4
Background sum	35.8 ± 0.5	36.5 ± 1.8

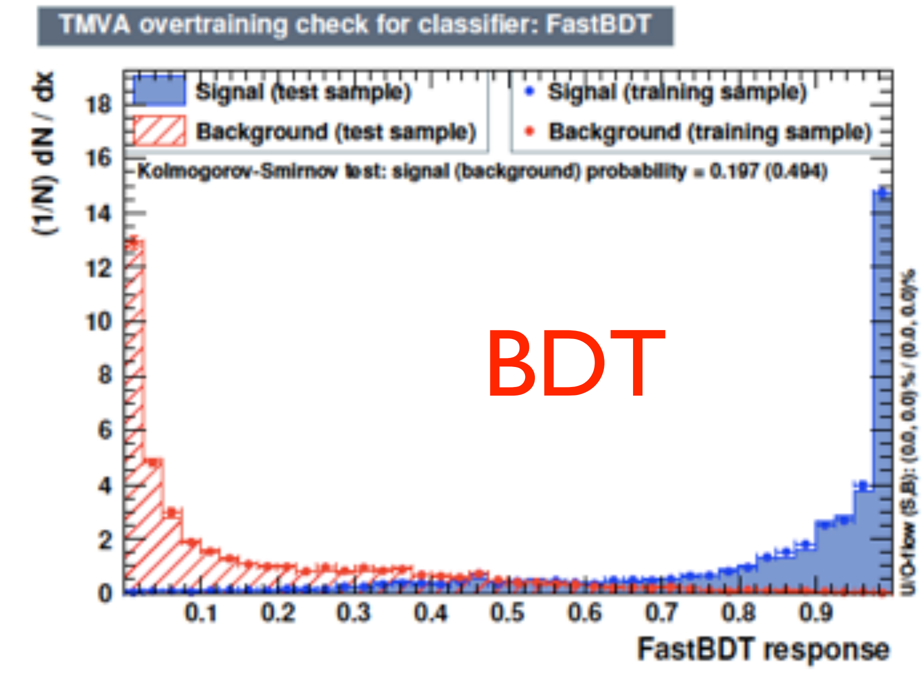


Figure 1.3: Performance of the multivariate classification for the selection of charged tracks generated by $K^\pm$.

BDT

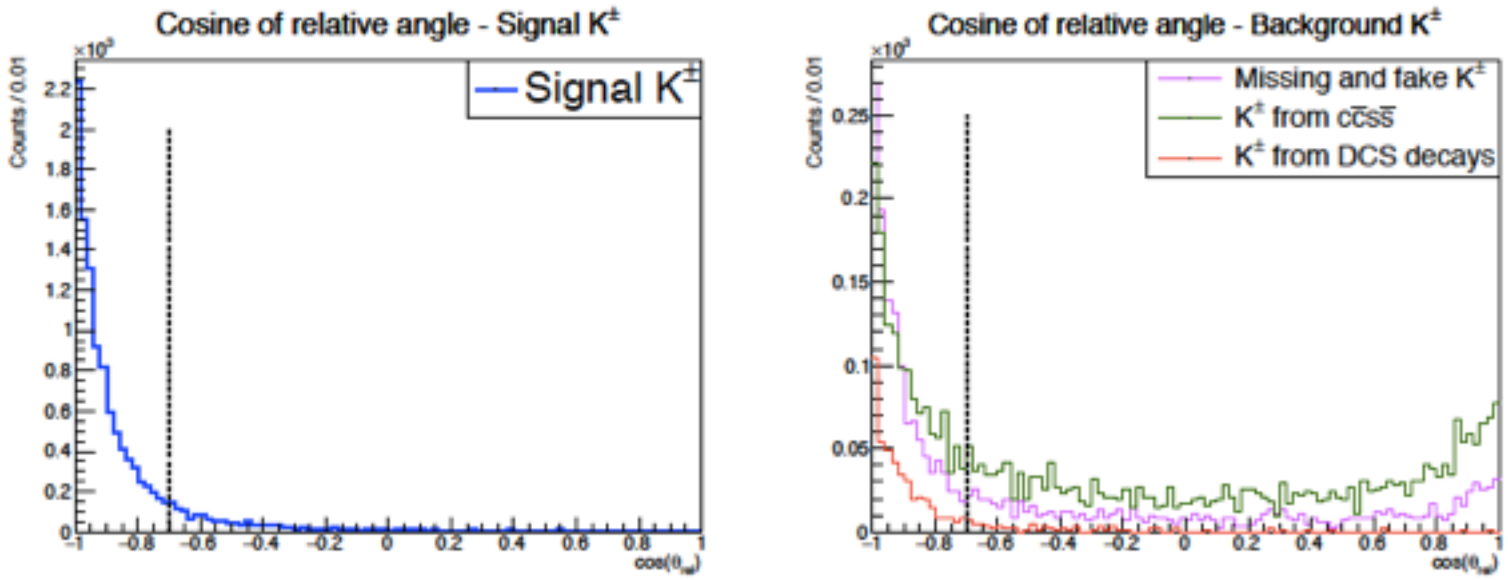
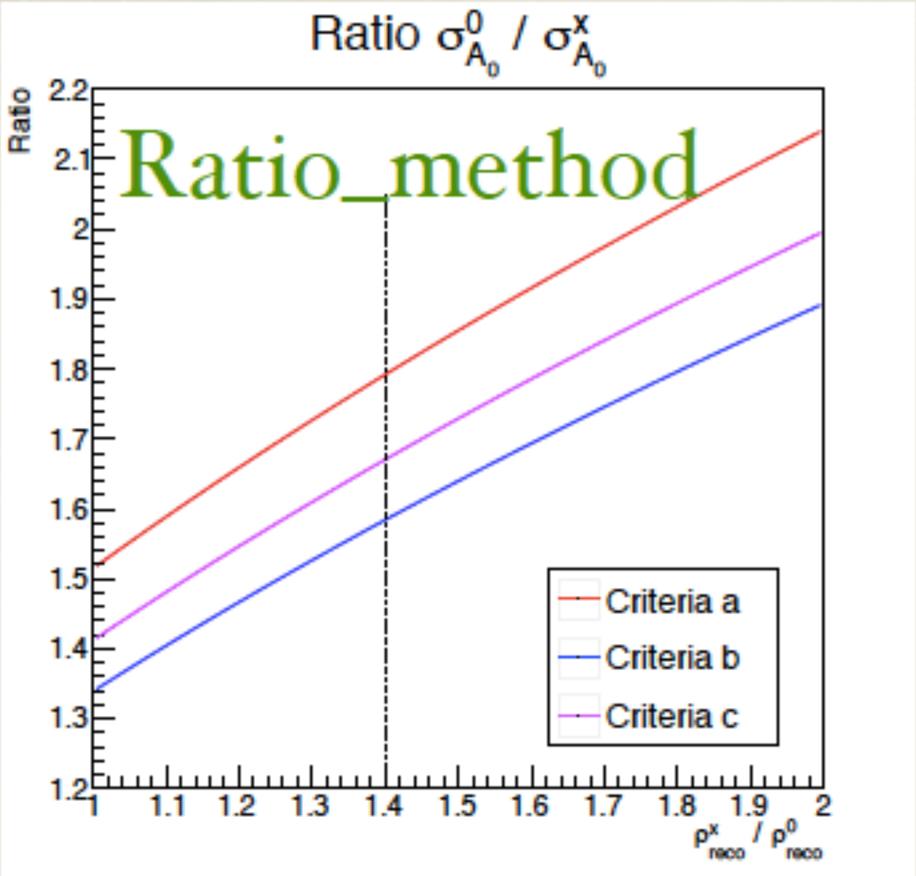


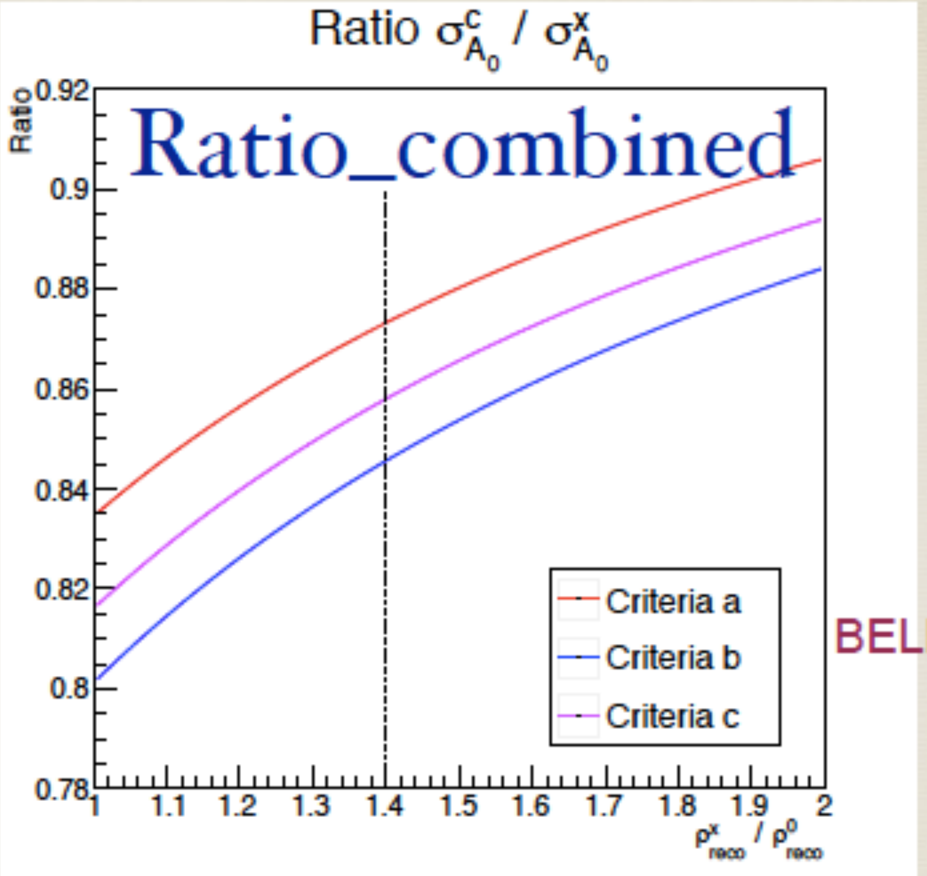
Figure 1.4: Distribution of $\theta^*_{\rm rel}$ for signal $K^\pm$ (left) and all of the background $K^\pm$ (right). The dotted vertical line is at the value $\cos(\theta^*_{\rm rel}) = -0.7$.

cos(theta*_rel)

Since the two charm quarks are produced back-to-back, a signal K in the ROE tends to be produced to the opposite direction respect to the neutral D meson.

New flavour tagging method





case I: only BDT selection
case II: BDT + veto K_s + cos(θ)
case III: BDT + veto MC K^0 + cos(θ)

BELLE2-MTHESIS-2016-007;
To be published

- Left plot: Ratio between the statistical error on a A_{CP} measurement using the two different flavour tagging methods (D* and ROE, given by σ^X and σ^0) as a function of the purity of D^0 samples.
- Right plot: Ratio between the combined statistical error (σ^C) and the statistical error from the D* method.
- Reference point for the ratio of the purity of D^0 samples: 1.4* [PhysRevD.87.012004]
- In the best case, assuming the value 1.4 for Belle II, we can expect a reduction of ~15% of the statistical error on a A_{CP} measurement.

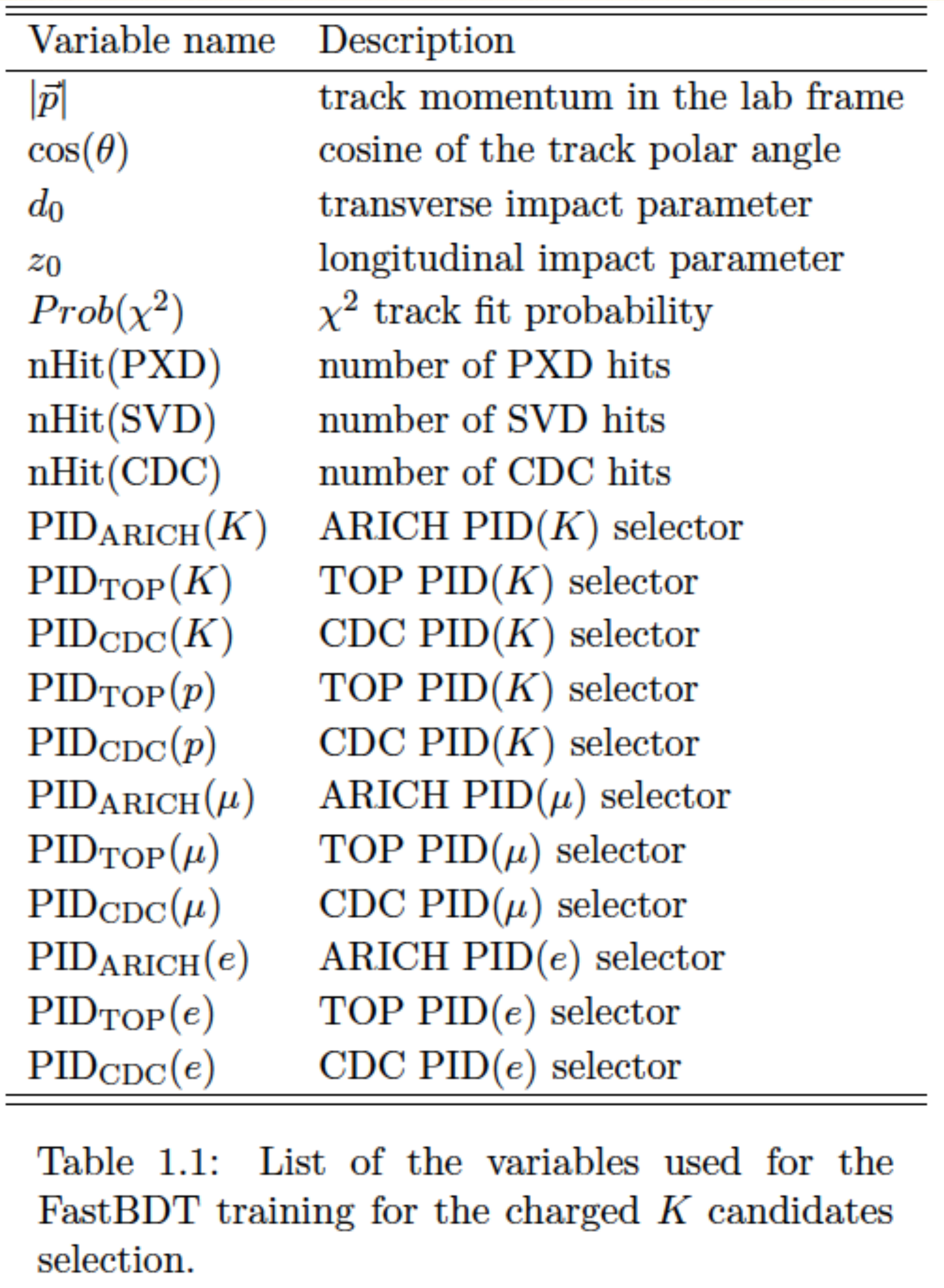
---

* ratio between the purity of the untagged D0 sample and the purity of the tagged (with D*) sample

FUTURE PROSPECTS

- Sensitivity needs to be improved
- Mixing in charm is well-established
- Yet to observe CPV in charm decays: D0 to Ks Ks is an interesting channel to hunt for it
- Belle II, LHCb, BESIII collaborations expected to be major players

BACK-UP

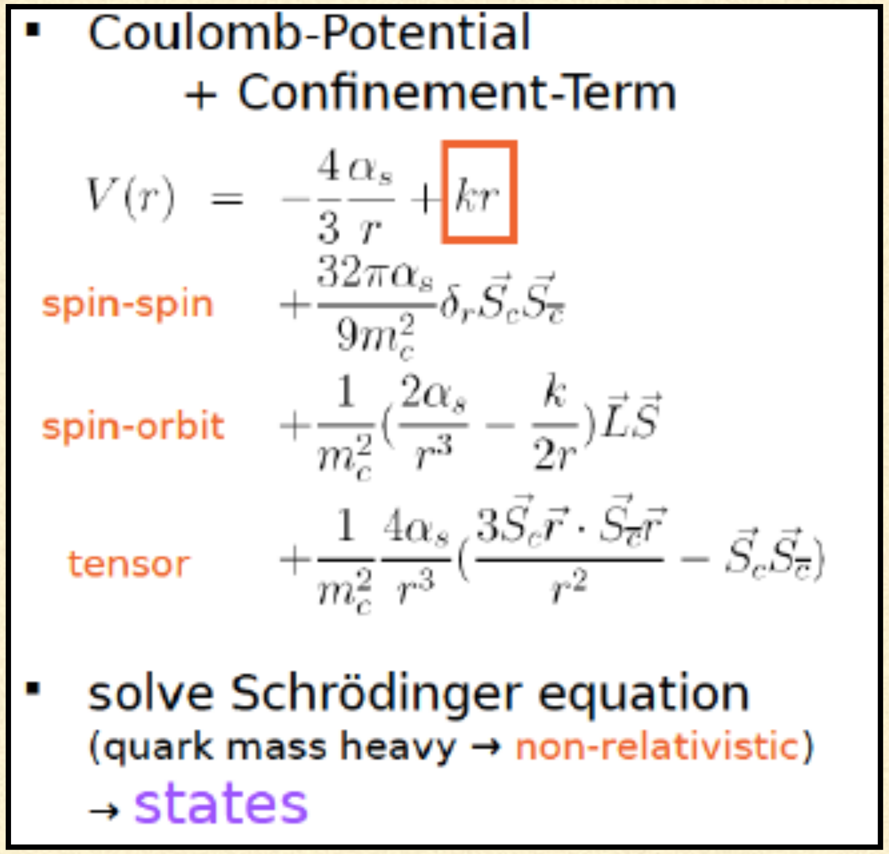


Variable name	Description
$\lvert\vec{p}\rvert$	track momentum in the lab frame
$\cos(\theta)$	cosine of the track polar angle
d_0	transverse impact parameter
z_0	longitudinal impact parameter
$Prob(\chi^2)$	χ^2 track fit probability
nHit(PXD)	number of PXD hits
nHit(SVD)	number of SVD hits
nHit(CDC)	number of CDC hits
$\mathrm{PID}_{\mathrm{ARICH}}(K)$	ARICH PID(K) selector
$\mathrm{PID}_{\mathrm{TOP}}(K)$	TOP PID(K) selector
$\mathrm{PID}_{\mathrm{CDC}}(K)$	CDC PID(K) selector
$\mathrm{PID}_{\mathrm{TOP}}(p)$	TOP PID(K) selector
$\mathrm{PID}_{\mathrm{CDC}}(p)$	CDC PID(K) selector
$\mathrm{PID}_{\mathrm{ARICH}}(\mu)$	ARICH PID(μ) selector
$\mathrm{PID}_{\mathrm{TOP}}(\mu)$	TOP PID(μ) selector
$\mathrm{PID}_{\mathrm{CDC}}(\mu)$	CDC PID(μ) selector
$\mathrm{PID}_{\mathrm{ARICH}}(e)$	ARICH PID(e) selector
$\mathrm{PID}_{\mathrm{TOP}}(e)$	TOP PID(e) selector
$\mathrm{PID}_{\mathrm{CDC}}(e)$	CDC PID(e) selector

Table 1.1: List of the variables used for the FastBDT training for the charged K candidates selection.

CHARM SPECTROSCOPY

- Non-relativistic frame-work with “Cornell Potential”



- Coulomb-Potential
  + Confinement-Term

$$V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + \boxed{kr}$$

spin-spin $$+\frac{32\pi\alpha_s}{9m_c^2}\delta_r\vec{S}_c\vec{S}_{\bar{c}}$$

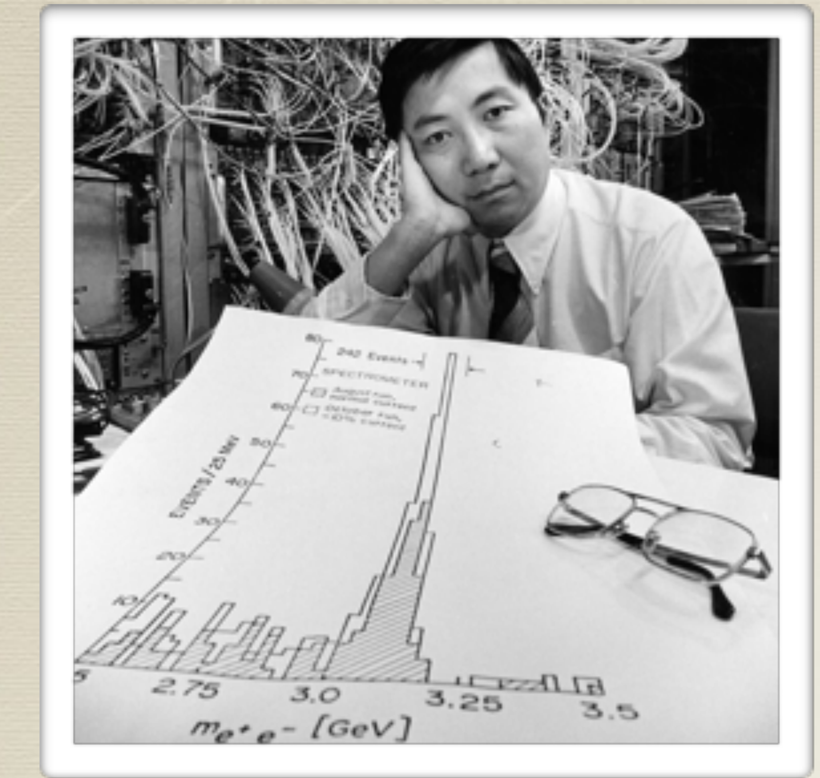
spin-orbit $$+\frac{1}{m_c^2}\left(\frac{2\alpha_s}{r^3} - \frac{k}{2r}\right)\vec{L}\vec{S}$$

tensor $$+\frac{1}{m_c^2}\frac{4\alpha_s}{r^3}\left(\frac{3\vec{S}_c\vec{r}\cdot\vec{S}_{\bar{c}}\vec{r}}{r^2} - \vec{S}_c\vec{S}_{\bar{c}}\right)$$

- solve Schrödinger equation
  (quark mass heavy → non-relativistic)
  → states

Alternate method: Lattice Calculation

Charming debut of “charm” quark in 1974
“The November Revolution”



Brookhaven National Lab via AIP Emilio Segre Visual Archives

http://www.slac.stanford.edu/spires/

Burt Richter (L),
Sam Ting (R)

“Charming Socialites”

First evidence of charm mixing in 2007 by BaBar, Belle, later by CDF

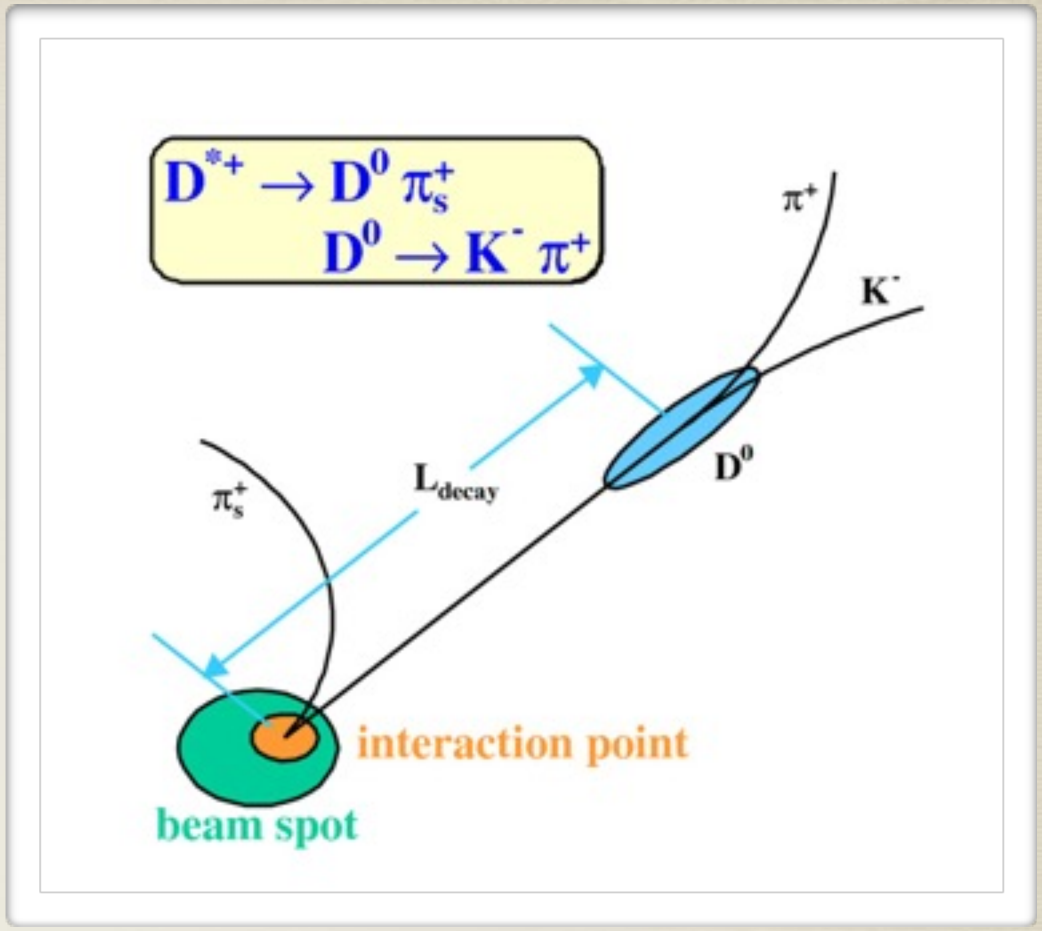
http://www.fnal.gov/pub/today/archive/archive_2013/today13-07-11.html

Charm mixing: Experimental Techniques

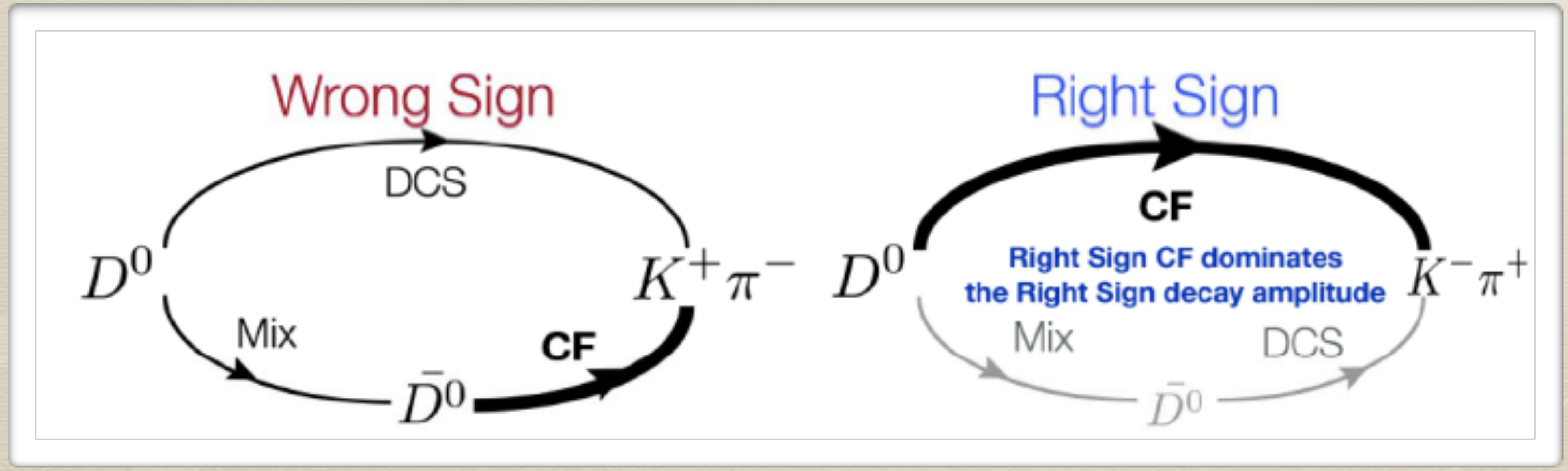
- D^{*+} to $D^0\pi^+_{slow}$: Flavor tagging using π^+_{slow}
- Data used is usually Upsilon (4S) data: p_{D^*} in CMS frame > 2.5 GeV to suppress D^{*+} coming from B decays
- Kinematic variables looked at: D^0 invariant mass (M_{D^0}), Mass difference $M_{D^*} - M_{D^0}$

Charm mixing

D^* decays to D° and a soft π
D° decays to $K^- \pi^+$ (Right sign decay)



http://www.fnal.gov/pub/today/archive/archive_2013/today13-07-11.html



Impact on the charm physics @ Belle II (II)

It's also possible to evaluate size of the stastical uncertainty of a CP asimmetry measured with the new sample.

If A_0 is the "true" asimmetry we want to measure, the statistical error σ_A will be:

$$\sigma_A \sim 1 / Q^{1/2} \qquad Q = \varepsilon_{tag}\,(1 - 2\omega)$$

If σ^0_A is the error measured with the new tecnhique, σ^*_A is the error with D^{*+} techinque and σ^c_A is the combined error, we have:

$$\frac{\sigma^0_{A_0}}{\sigma^*_{A_0}} = \sqrt{\frac{Q^*}{Q^0}} \cdot \sqrt{\frac{\rho^*_{reco}}{\rho^0_{reco}}} \cdot \sqrt{\frac{S^*_{gen}}{S^0_{gen}}} \equiv \alpha$$

$$\frac{\sigma^c_{A_0}}{\sigma^*_{A_0}} = \frac{\alpha}{\sqrt{1 + \alpha^2}}$$

Purity of reconstructed sample

Number of generated D^0 = 0.24/0.76

[Slide from Giacomo De Pietro]