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"Jozef Stefan" Institute

ALSO WITH BELLE Belle II

2ND OPEN BELLE II PHYSICS WEEK
KEK
28TH OCT - 1ST NOV 2019

DISCLAIMER

CHOICE OF SUBJECTS, AND ESPECIALLY EXAMPLES, HAD TO BE MADE;

SPEAKER IS TO BE BLAMED FOR NOT SHOWING YOUR FAVORITE MEASUREMENT

FREQUENTLY USED REFERENCES:

PDG: M. TANABASHI ET AL. (PARTICLE DATA GROUP), PHYS. REV. D 98, 030001 (2018).

HFLAV: HEAVY FLAVOR AVERAGING GROUP, HTTPS://HFLAV.WEB.CERN.CH/

PBF : THE PHYSICS OF THE B FACTORIES, A. BEVAN, B. GOLOB, T. MANNEL. S. PRELL, B. YABSLEY EDS., EUR. PHYS. J. C 74 (2014) .

BIIPB: E. KOU, P. URQUIJO ETN AL. (BELLE II COLL.), ARXIV:1808.10567

Multi-body self conjugated states

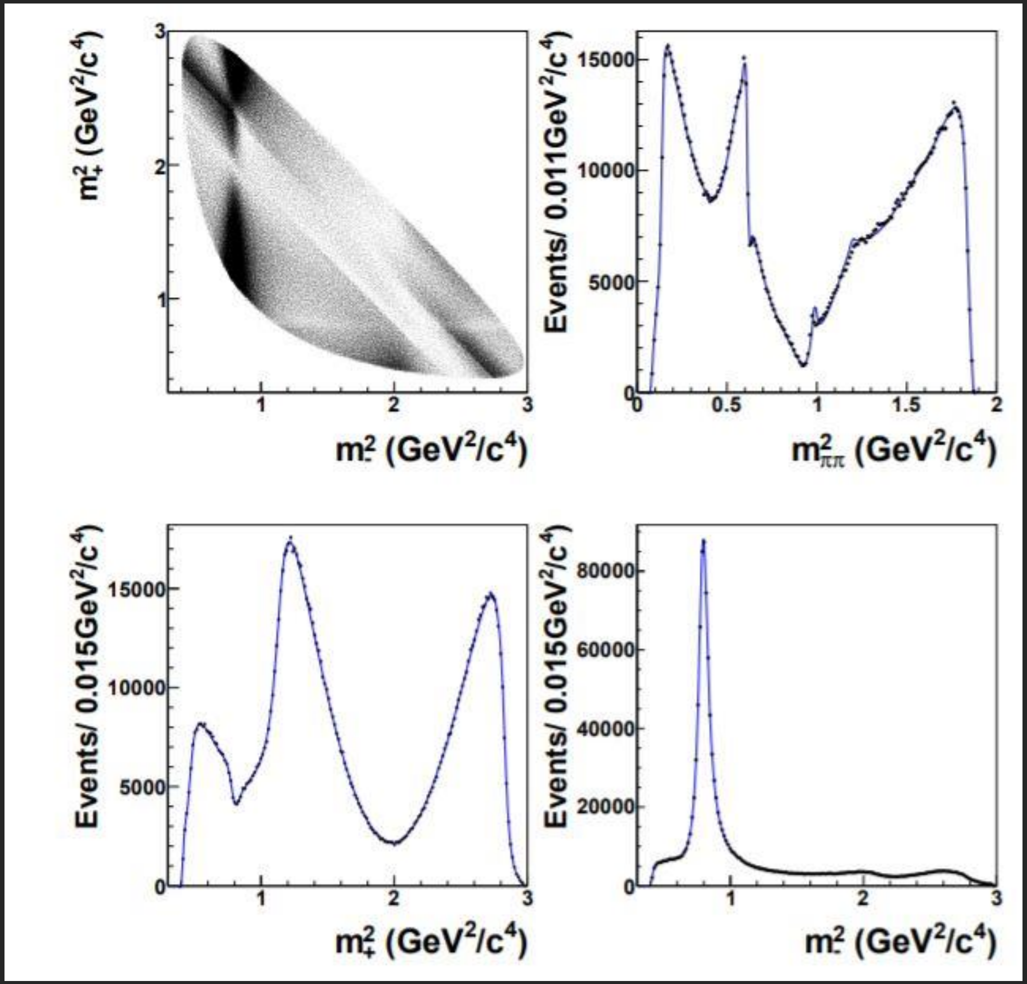
$D^0 \to K_S \pi^+ \pi^-$

no CPV result:

$$x = (0.56 \pm 0.19 \pm^{0.03}_{0.09} \pm^{0.06}_{0.09})\%$$

$$y = (0.30 \pm 0.15 \pm^{0.04}_{0.05} \pm^{0.03}_{0.06})\%$$

↑ uncertainty due to Dalitz model



T. Peng et al., (Belle Coll.), PRD 89, 091103 (2014)

MULTI-BODY SELF CONJUGATED STATES

BIIPB

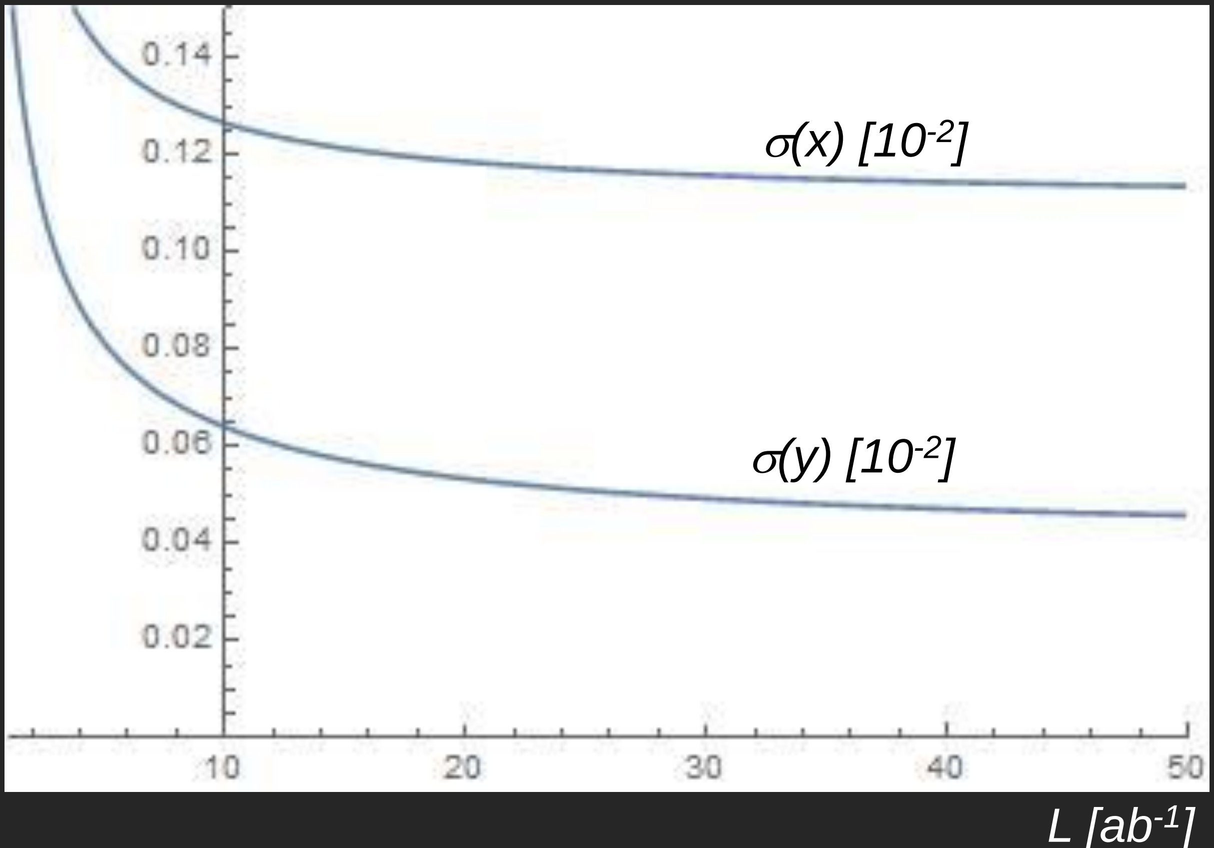
$D^0 \to K_S \pi^+ \pi^-$

BELLE II:
SYST. UNCERTAINTY DOMINATES @ FEW ab^{-1}

IN TURN, SYST. UNCERTAINTY DOMINATED BY THE MODEL UNCERTAINTY

CAN THIS BE EVADED?

BY MEASURING STRONG PHASE VARIATION ACROSS DALITZ PLANE USING COHERENT $D^0\bar{D}^0$ PAIRS (BES III)



MULTI-BODY SELF CONJUGATED STATES

$D^0 \to K_S \pi^+ \pi^-$

A. BONDAR, A. POLUEKTOV AND V. VOROBIEV, PRD 82, 034033 (2010)
A. GIRI, Y. GROSSMAN, A. SOFFER, AND J. ZUPAN, PR D 68, 054018 (2003)

MODEL INDEPENDENT METHOD

DALITZ- AND *t*- DEPENDENT AMPLITUDE UP TO $O(x^2, y^2)$

NOTATION: $\frac{q}{p} = r_{CP} e^{i\alpha_{CP}}$

$$\mathcal{P}_{D^0}(m_{12}^2, m_{13}^2, t) = \Gamma e^{-\Gamma t}\Big[a_{12,13}^2 + r_{CP}\, a_{12,13}\, a_{13,12}\, \Gamma t \,\{y_D \cos(\delta_{12,13} - \delta_{13,12} - \alpha_{CP}) + x_D \sin(\delta_{12,13} - \delta_{13,12} - \alpha_{CP})\}\Big]$$

C. THOMAS, G. WILKINSON, JHEP 2012:185

INTEGRATING OVER DALITZ- AND *t*-BIN

2N symmetric bins

$$\int_i \int_{t_a}^{t_b} \mathcal{P}_{D^0}(m_{12}^2, m_{13}^2, t)\, \mathrm{d}t\, \mathrm{d}m_{12}^2\, \mathrm{d}m_{13}^2 = n\Big\{(e^{-\Gamma t_a} - e^{-\Gamma t_b})T_i + [\Gamma(e^{-\Gamma t_a} t_a - e^{-\Gamma t_b} t_b) + (e^{-\Gamma t_a} - e^{-\Gamma t_b})] \times \{r_{CP}\sqrt{T_i T_{-i}}(y_D[c_i \cos(\alpha_{CP}) + s_i \sin(\alpha_{CP})] + x_D[s_i \cos(\alpha_{CP}) - c_i \sin(\alpha_{CP})])\}\Big\}$$

$$T_i \equiv \int_i a_{12,13}^2\, \mathrm{d}m_{12}^2\, \mathrm{d}m_{13}^2\,,$$

$$c_i \equiv \frac{1}{\sqrt{T_i T_{-i}}} \int_i a_{12,13}\, a_{13,12} \cos(\delta_{12,13} - \delta_{13,12})\, \mathrm{d}m_{12}^2\, \mathrm{d}m_{13}^2\,,$$

$$s_i \equiv \frac{1}{\sqrt{T_i T_{-i}}} \int_i a_{12,13}\, a_{13,12} \sin(\delta_{12,13} - \delta_{13,12})\, \mathrm{d}m_{12}^2\, \mathrm{d}m_{13}^2\,.$$

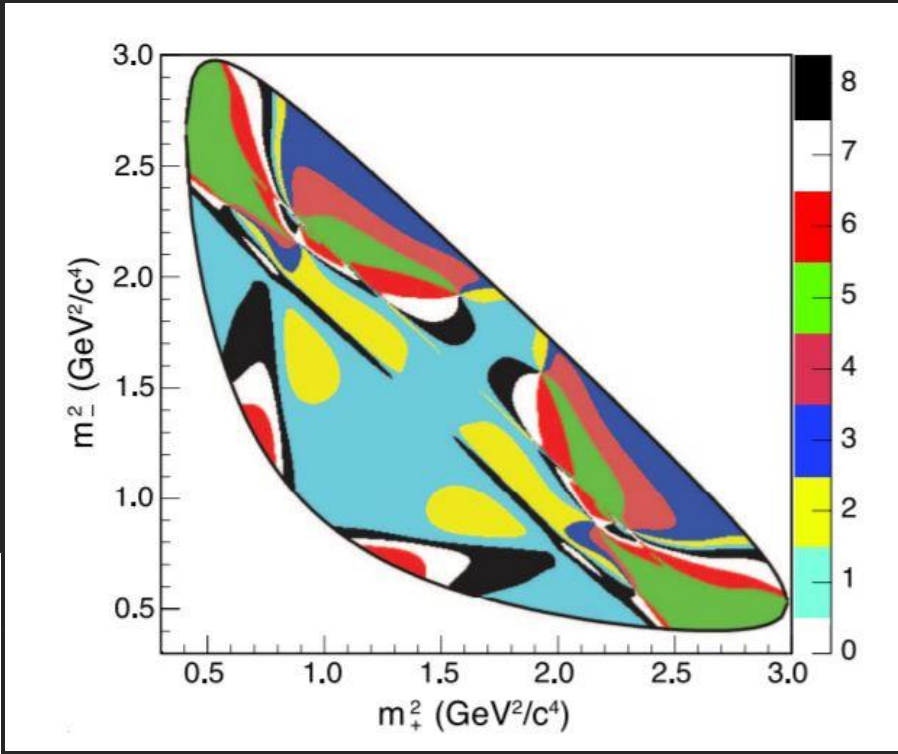
$c_{-i} = c_i$
$s_{-i} = -s_i$

IN LIMIT OF NO MIXING AND NO CPV
OF EVENTS FROM D^0 IN *i*-TH BIN
→ FREE PARAM. OF FIT
COSINE AND SINE OF AVERAGE STRONG PHASE DIFFERENCE $D^0/\bar{D}^0$ IN BIN *i* WEIGHTED BY RATE
→ QUANTUM CORR. $D^0\bar{D}^0$ PAIRS

MULTI-BODY SELF CONJUGATED STATES

$D^0 \to K_S\pi^+\pi^-$

J. LIBBY ET AL. (CLEO-C COLL.), PRD 82,112006 (2010)



MODEL INDEPENDENT METHOD

BINNING OF DALITZ PLANE BASED ON

A. POLUEKTOV ET AL. (BELLE COLL.), PR D 81, 112002 (2010)

($\Delta\delta \sim$ CONST. ACROSS BIN)

RESULTS USING L=0.8 FB^{-1}

i	c_i	s_i
	$\mathcal{N} = 4$ equal $\Delta\delta_D$ bins	
1	$0.858 \pm 0.059 \pm 0.034$	$0.309 \pm 0.248 \pm 0.180$
2	$0.176 \pm 0.223 \pm 0.091$	$0.992 \pm 0.473 \pm 0.403$
3	$-0.819 \pm 0.095 \pm 0.045$	$0.307 \pm 0.267 \pm 0.201$
4	$0.376 \pm 0.329 \pm 0.157$	$-0.133 \pm 0.659 \pm 0.323$

J. LIBBY ET AL. (CLEO-C COLL.), PRD 82,112006 (2010)

METHOD P. 42 DALTZ t-DEPENDENCE P. 44

UNCERTAINTIES ON c_i , s_i *PROPAGATE TO MEASURED VARIABLES (AS SYSTEMATIC UNCERTAINTY);*

STILL STATISTICS DOMINATED $\to$ BESIII HAS 3 FB^{-1} OF DATA, PLANNING TO RECORD 10 FB^{-1} MORE

MULTI-BODY SELF CONJUGATED STATES
$D^0 \to K_S \pi^+ \pi^-$

MODEL INDEPENDENT METHOD

T. PENG ET AL., (BELLE COLL.), PRD 89, 091103 (2014) : $1.33 \cdot 10^6$ D* TAGGED $D^0 \to K_S \pi^+ \pi^-$ / AB^{-1}

C. THOMAS, G. WILKINSON, JHEP 2012:185 : $100 \cdot 10^6$ D^* TAGGED $D^0 \to K_S \pi^+ \pi^-$:

$\sigma(x) = [\pm 0.017 \pm 0.076(c_i, s_i)]\ 10^{-2}$

$\sigma(y) = [\pm 0.019 \pm 0.087(c_i, s_i)]\ 10^{-2}$

CLEO-C (0.8 FB^{-1})

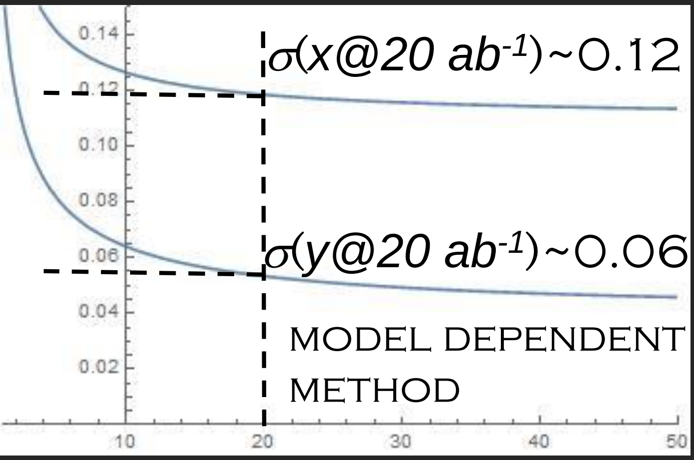
LHCB NEED ADDITIONAL ~1 FB^{-1} (IN ADDITION TO EXISTING 9 FB^{-1}) TO REACH THIS STAT. ACCURACY

$27 \cdot 10^6$ D^* TAGGED $D^0 \to K_S \pi^+ \pi^-$: (BELLE II @20 AB^{-1})

$\sigma(x) = [\pm 0.032 \pm 0.039(c_i, s_i)]\ 10^{-2}$

$\sigma(y) = [\pm 0.036 \pm 0.045(c_i, s_i)]\ 10^{-2}$

BESIII WITH 3 FB^{-1} (ONLY SIMPLE SCALING WITH L)



Where do we stand?

○ no mixing point

$$x = (0.50 \pm ^{0.13}_{0.14})\%$$

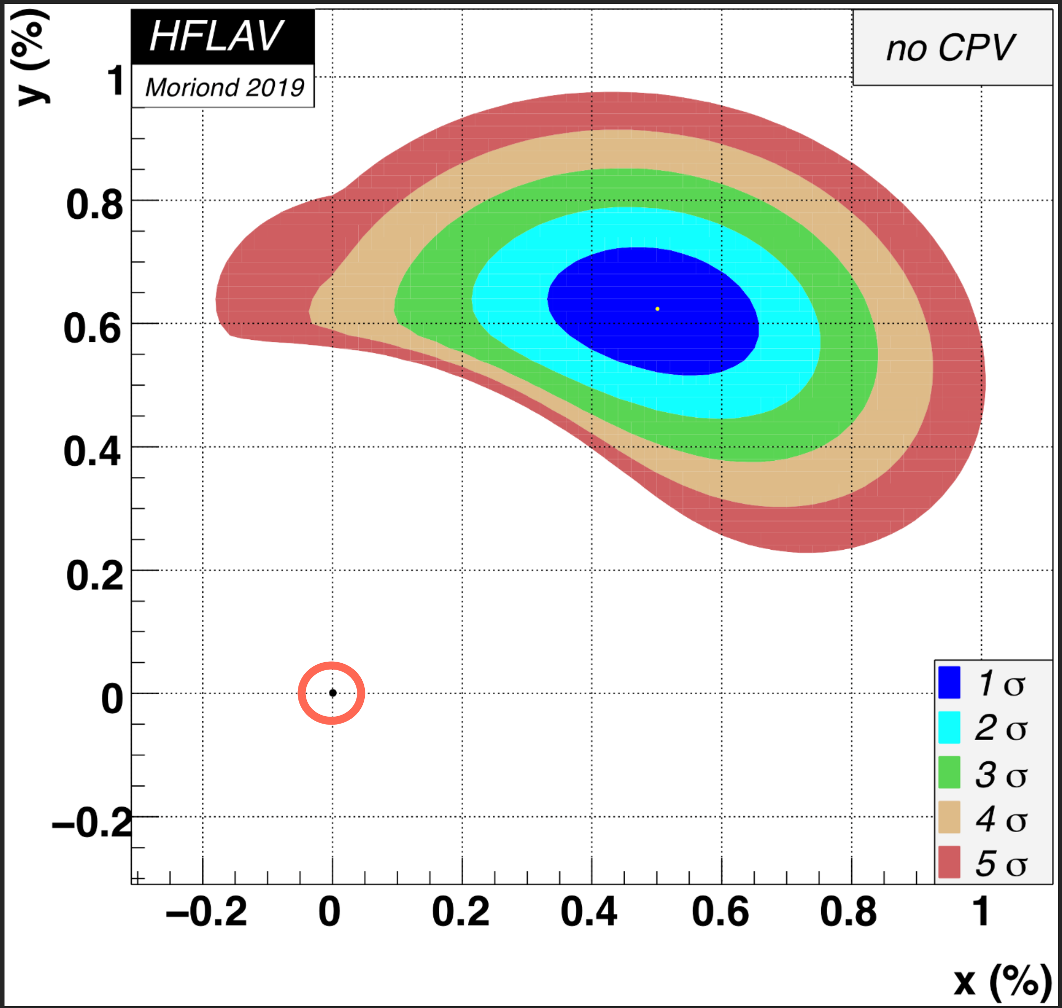
$$y = (0.62 \pm 0.07)\%$$

repeat from p. 29, w/o any disclaimer:

D^0 mesons, like other M^0, do mix, with the lowest probability of all

$P(D^0 \to \bar{D}^0) \sim 3 \cdot 10^{-5}$

HFLAV



D^0 mixing is data driven field (n.b. x, y needed for CPV predictions)

Charm CPV...

... is small

PBFB

CKM in Wolfenstein param. (to $O(\lambda^3)$)

$$\begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda+ & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3[1-(1-\lambda^2/2)(\rho+i\eta)] & -A\lambda^2+ & 1 \end{pmatrix} + O(\lambda^4)$$

elements related to charm are real

$\Rightarrow$ no complex phase, no CPV (in SM)

… IS SMALL

PBFB

CKM IN WOLFENSTEIN PARAM. (TO $O(\lambda^3)$)

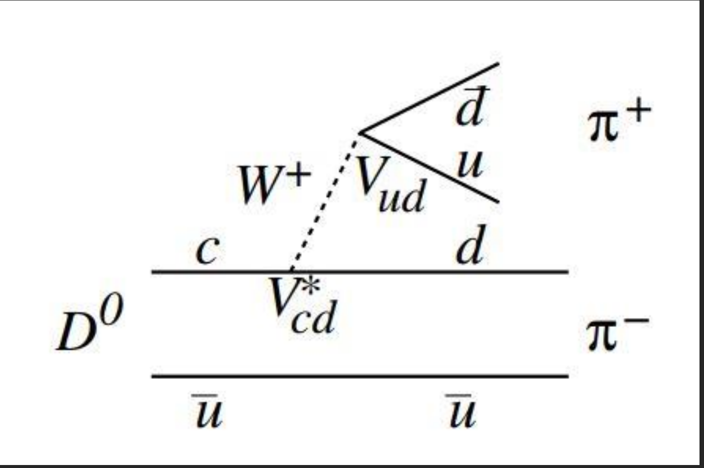
$$\begin{pmatrix} 1-\lambda^2/2-\lambda^4/8 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda+A^2\lambda^5[1-2(\rho+i\eta)]/2 & 1-\lambda^2/2-\lambda^4(1+4A^2)/8 & A\lambda^2 \\ A\lambda^3[1-(1-\lambda^2/2)(\rho+i\eta)] & -A\lambda^2+A\lambda^4[1-2(\rho+i\eta)]/2 & 1-A^2\lambda^4/2 \end{pmatrix} + O(\lambda^4)$$

ELEMENTS RELATED TO CHARM ARE REAL

$\Rightarrow$ NO COMPLEX PHASE, NO CPV (IN SM)

CKM IN WOLFENSTEIN PARAM. (TO $O(\lambda^5)$)

$$\arg\frac{\langle\pi^+\pi^-|D^0\rangle}{\langle\pi^+\pi^-|\overline{D}^0\rangle} = 2\ \arg(V_{cd}^* V_{ud}) \approx 2A^2\lambda^4\eta = 1.2\times 10^{-3}$$



CPV IN CHARM SECTOR IS SMALL, ASYMMETRIES ~ $O(10^{-3})$ IN SM.
POTENTIALLY GOOD PLACE TO LOOK FOR NP EFFECTS.

SOME REMINDERS

$f = \bar{f} = f_{CP}$

$$\frac{dN(D^0 \to f)}{dt} \propto e^{-\bar{\Gamma}t} |A_f|^2 \left[1 - y\,\mathrm{Re}(\lambda_f)\bar{\Gamma}t + x\,\mathrm{Im}(\lambda_f)\bar{\Gamma}t\right]$$

$$\frac{dN(\bar{D}^0 \to f)}{dt} \propto e^{-\bar{\Gamma}t} |\bar{A}_f|^2 \left[1 - y\frac{1}{|\lambda_f|^2}\mathrm{Re}(\lambda_f)\bar{\Gamma}t - x\frac{1}{|\lambda_f|^2}\mathrm{Im}(\lambda_f)\bar{\Gamma}t\right]$$

$$\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f}$$

1) $|\bar{A}_f| \neq |A_f|$

CPV IN DECAY (CPVDEC)

2) $|\lambda_f| \neq 1$, AND

TAKING INTO ACCOUNT 1), $\left|\frac{q}{p}\right| \neq 1$ CPV IN MIXING (CPVMIX)

3) $\mathrm{Im}(\lambda_f) \neq 1$ CPV IN INTERFERENCE BETWEEN DECAYS W/ AND W/O MIXING (CPVINT)

Some reminders

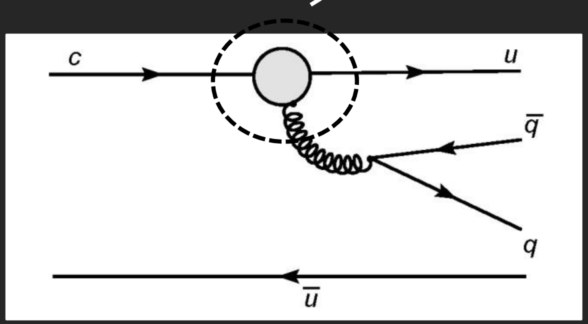
for CPV at least two processes with distinct weak and strong phase necessary (example of CPV in decay)

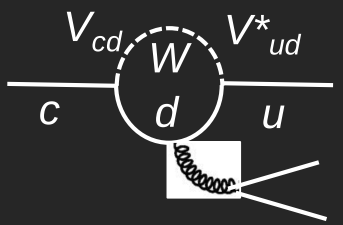
$$A_f = a_1 + a_2 = |a_1| e^{i(\delta_1+\varphi_1)} + |a_2| e^{i(\delta_2+\varphi_2)}$$

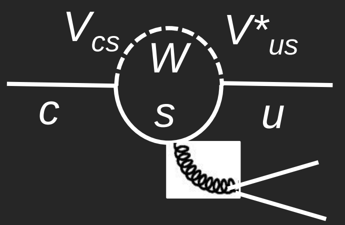
$$A_{CP} = \frac{\Gamma(M \to f) - \Gamma(\overline{M} \to \bar{f})}{\Gamma(M \to f) + \Gamma(\overline{M} \to \bar{f})} = \frac{|A_f / \overline{A}_{\bar{f}}|^2 - 1}{|A_f / \overline{A}_{\bar{f}}|^2 + 1} =$$

$$= \ldots = \frac{2|a_1 a_2| \sin(\delta_2 - \delta_1) \sin(\varphi_2 - \varphi_1)}{|a_1|^2 + |a_2|^2 + 2|a_1 a_2| \cos(\delta_2 - \delta_1) \cos(\varphi_2 - \varphi_1)}$$

in *D* meson decays this is only possible in SCS decays with contribution of penguin decays (beside tree contrib.)







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

WITH CPV PARAMETRIZATION MORE INVOLVED
(N.B. A_M, A_{dir}^f << 1)

$$\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f} = \left|\frac{q}{p}\right|\left|\frac{\bar{A}_f}{A_f}\right| e^{i\varphi} \qquad \eta_f = \begin{cases} +1 & f = CP+ \\ -1 & f = CP- \end{cases}$$

$$A_m = \left|\frac{q}{p}\right|^2 - 1 \qquad A_{dir}^f = \frac{\left|\bar{A}_f\right|^2}{\left|A_f\right|^2} - 1$$

A_M: CPVMIX
A_{dir}^f: CPVDEC

EXPRESSION FOR y_{CP} GETS MODIFIED BY KEEPING TERMS q/p IN „MASTER" FORMULAE ON P. 23:

$$y_{CP} = \eta_f \left[y\cos\phi - \frac{A_{dir}^f + A_m}{2} x \sin\phi \right]$$

IN LIMIT OF NO CPV $|q/p|=1$, $\phi=0 \Rightarrow y_{CP}=y$;

MOREOVER,

$$\frac{dN(D^0 \to f_{CP}^+)}{dt} \neq \frac{dN(\bar{D}^0 \to f_{CP}^+)}{dt}$$

Charm CPV CP eigenstates

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

neglecting CPV

$$\frac{1}{\tau_{eff}^{fCP}} = \frac{1}{\bar{\tau}_{eff}^{fCP}} = \frac{1+y_{CP}}{\tau}$$

assuming CPV

$$A_\Gamma = \frac{\bar{\tau}_{fCP}^{eff} - \tau_{fCP}^{eff}}{\bar{\tau}_{fCP}^{eff} + \tau_{fCP}^{eff}} \approx \left(\frac{A_{dir}^{fCP} + A_m}{2}\right) y\cos\phi - x\sin\phi$$

derivation

CPVDEC

CPVMIX

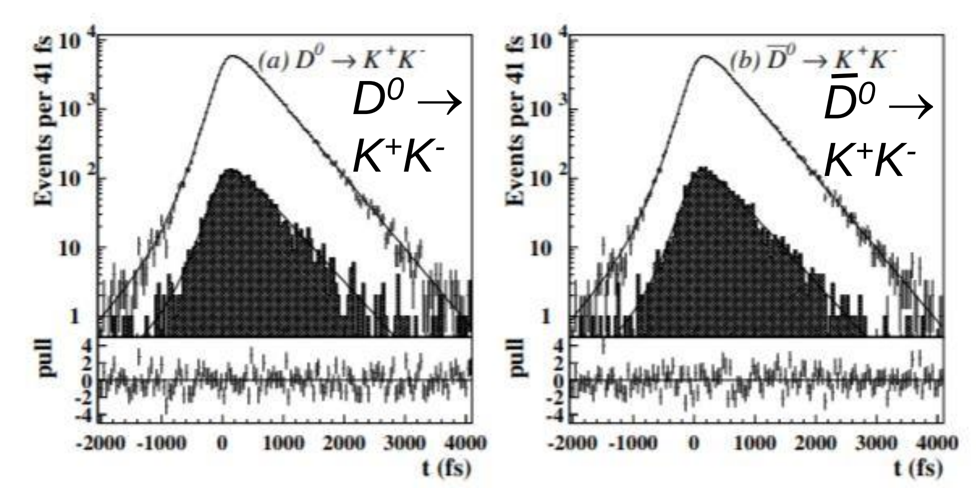
CPVINT

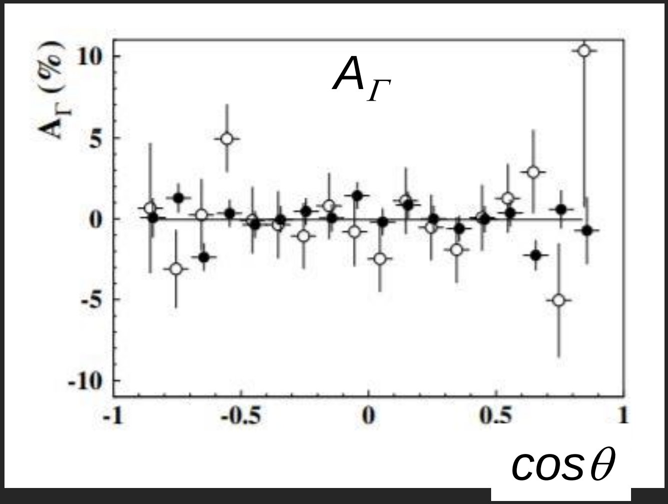
in limit of no CPV $|q/p|=1$, $\phi=0 \Rightarrow A_\Gamma = 0$

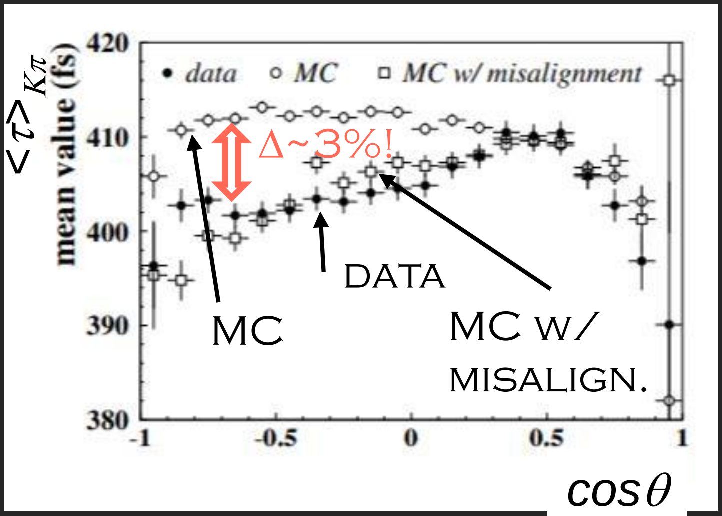
$D^0 \to K^+K^-$, $\pi^+\pi^-$

asymmetry A_Γ measured together with y_{CP} (just dividing the sample into D^0 / $\bar{D}^0$ tagged)

M. Staric et al. (Belle Coll.), PLB 753, 412 (2016)







$$A_\Gamma = (-0.03 \pm 0.20 \pm 0.07)\%$$

Subtle / important effects of SVD misalignment;
in τ measurements O(%) effects my be included in syst. uncertainty;
in determination of ‰ effects not

Charm CPV CP eigenstates

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

more p. 46

B Factories:

$$A_\Gamma = \frac{\bar{\tau}^{eff}_{fCP} - \tau^{eff}_{fCP}}{\bar{\tau}^{eff}_{fCP} + \tau^{eff}_{fCP}}$$

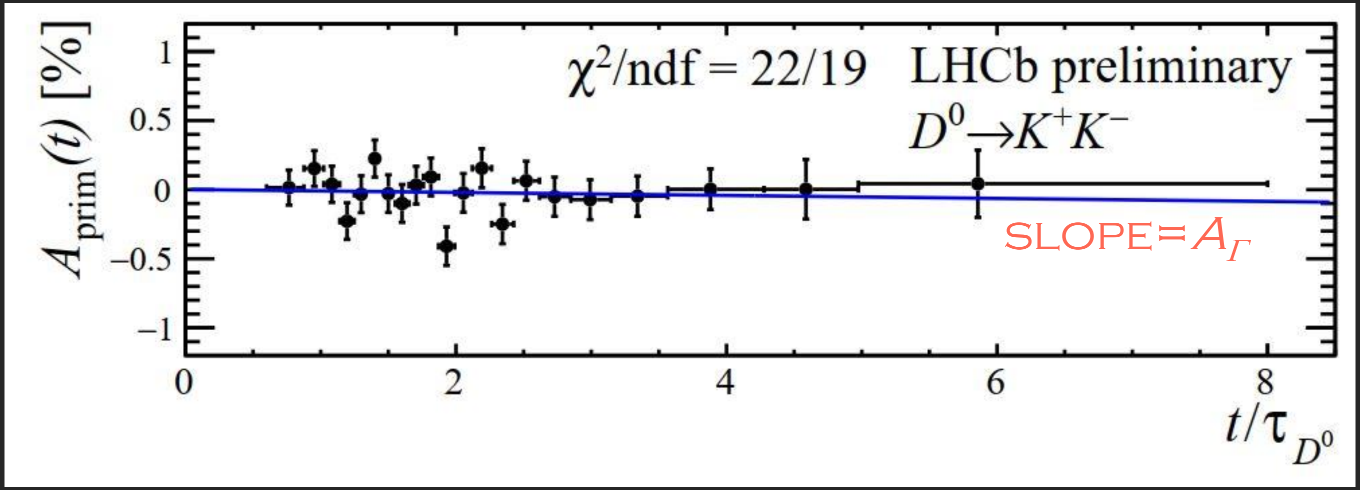
$$A_\Gamma = (1.3 \pm 3.5 \pm 0.07)\cdot 10^{-4}$$

LHCb:

$$\frac{\left(\frac{dN(D^0\to f)}{dt}\right) - \left(\frac{dN(\bar{D}^0\to f)}{dt}\right)}{\left(\frac{dN(D^0\to f)}{dt}\right) + \left(\frac{dN(\bar{D}^0\to f)}{dt}\right)} \approx A^f_{dir} - \tilde{A}_\Gamma \bar{\Gamma} t$$

R. Aaij et al. (LHCb Coll.), LHCb-PAPER-2019-032

using prompt D^*'s; similar result with $b \to c\mu X$



current combined exp. sensitivity O(10^{-4});
th. predictions for $A_\Gamma \sim$ O(10^{-5})   A. Cerri et al., arXiv:1812.07638

Charm CPV CP eigenstates

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

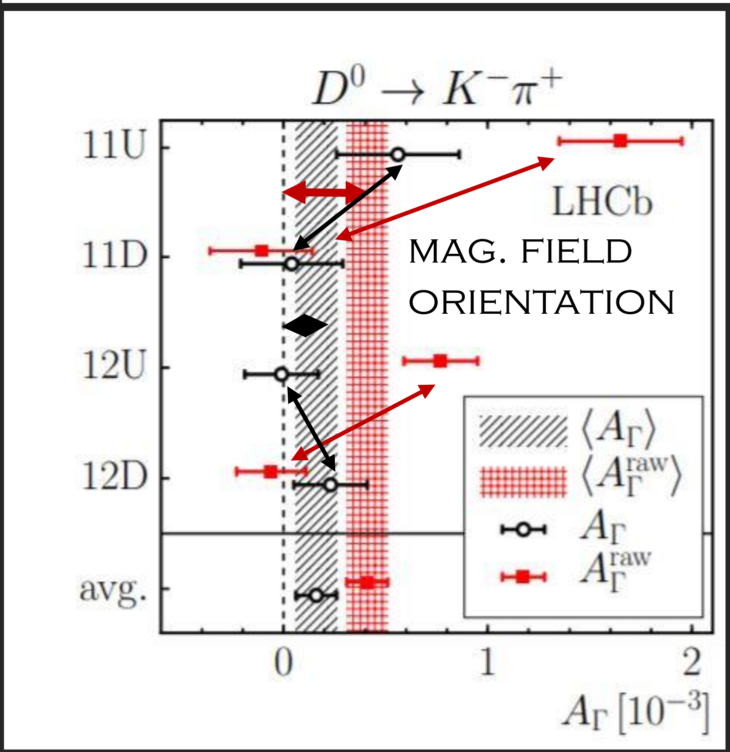
LHCb:

$$\frac{\left(\frac{1}{\varepsilon_+}\frac{dN^{meas}(D^0 \to f)}{dt}\right) - \left(\frac{1}{\varepsilon_-}\frac{dN^{meas}(\overline{D}^0 \to f)}{dt}\right)}{\left(\frac{1}{\varepsilon_+}\frac{dN^{meas}(D^0 \to f)}{dt}\right) + \left(\frac{1}{\varepsilon_-}\frac{dN^{meas}(\overline{D}^0 \to f)}{dt}\right)}$$

$$D^{*\pm} \to D^0(\overline{D}^0)\pi_s^\pm$$

$$\downarrow$$

$$\varepsilon_\pm$$



$$D^{*\pm} \to D^0(\overline{D}^0)\pi_s^\pm$$

$$\mapsto K^-\pi^+(K^+\pi^-)$$

No physics (CPV) asym. expected (CF decay) → correct $\varepsilon_\pm$ in bins of kinematic variables so that $N(D^{*+}) = N(D^{*-})$ in each bin

R. Aaij et al. (LHCb Coll.), PRL118 , 261803 (2017)

Charm CPV CP eigenstates

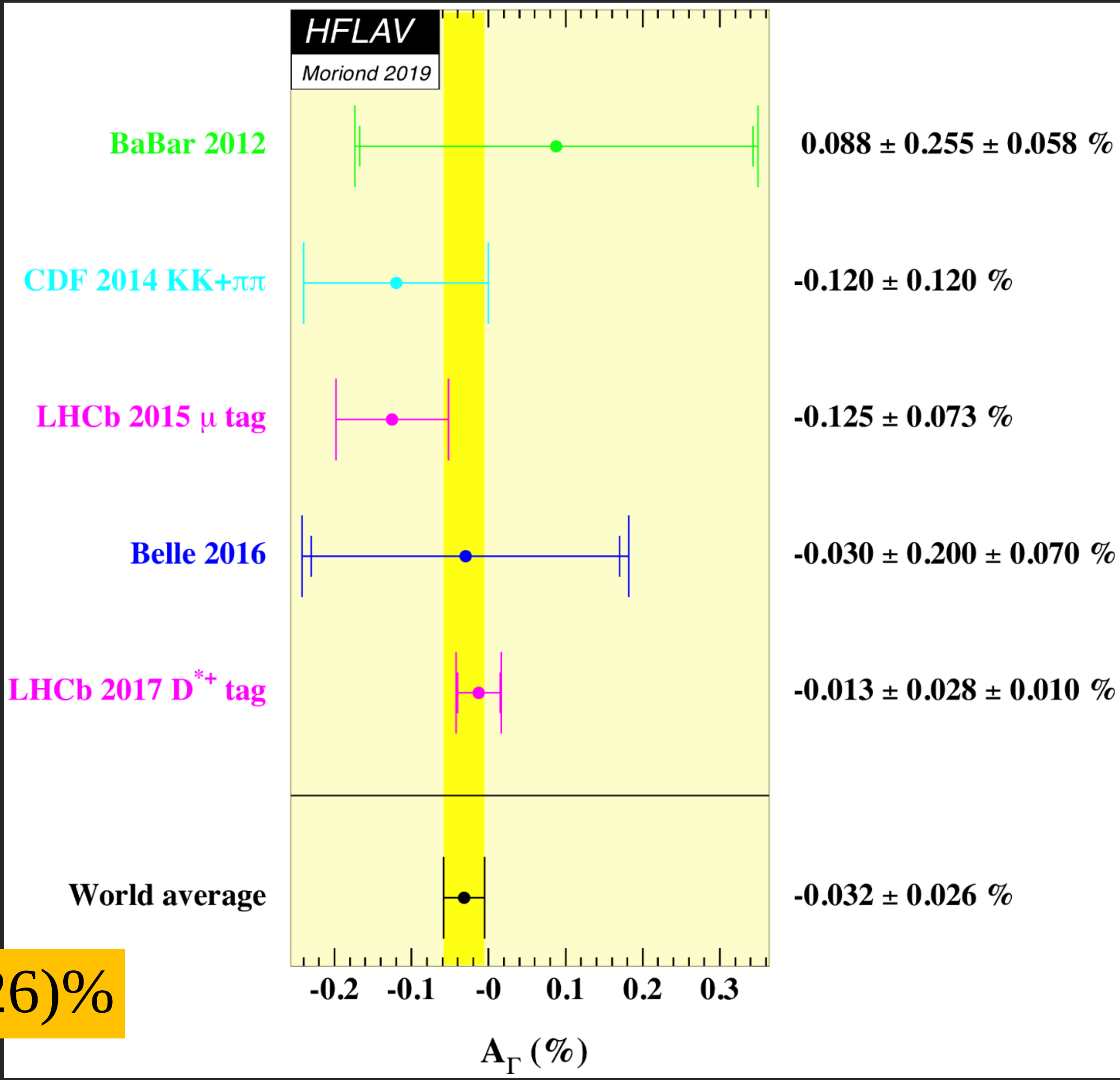
$D^0 \to K^+K^-,\ \pi^+\pi^-$

HFLAV

asymmetry A_Γ

LHCb using $b \to c$

LHCb using prompt D^*'s



$$A_\Gamma = (-0.032 \pm 0.026)\%$$

T-INDEPENDENT METHODS

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

t-integrated asymmetry A_{CP}

for general *f*: $A_{CP}^{f} \sim A_{dir}^{f} + C_1 y\cos\phi + C_2 x\sin\phi$

why? p. 48

$f=f_{CP}$

$$A_{CP}^{f} \approx A_{d}^{f} - y\frac{A_{d}^{f} + A_{m}}{2}\cos\varphi + x\sin\varphi$$

measurement includes detector induced asymmetries (example of D^+)

$$A_{\mathrm{rec}} = \frac{N(D^+ \to Xh^+) - N(D^- \to Xh^-)}{N(D^+ \to Xh^+) + N(D^- \to Xh^-)}$$

$|A_i| \ll 1$

$$A_{\mathrm{rec}} = A_{CP} + A_{FB} + A_{\epsilon}^{h^+}$$

physics asymm.

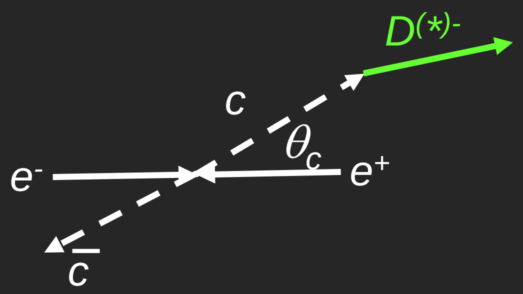
forward-backward asymm. in $e^+e^- \to c\overline{c}$; *vanishes if integrated over full polar angle*

difference in $h^{\pm}$ interactions on material

T-INDEPENDENT METHODS

FORWARD BACKWARD ASYMMETRY A_{fb}

$$\frac{N_c(\cos\theta_c) - N_{\bar{c}}(\cos\theta_c)}{N_c(\cos\theta_c) + N_{\bar{c}}(\cos\theta_c)} = \frac{8A^0_{FB}\cos\theta_c}{3(1+\cos^2\theta_c)}$$



$$A_{CP} = [A^{\rm corr}_{\rm rec}(\cos\theta^*) + A^{\rm corr}_{\rm rec}(-\cos\theta^*)]/2$$
$$A_{FB} = [A^{\rm corr}_{\rm rec}(\cos\theta^*) - A^{\rm corr}_{\rm rec}(-\cos\theta^*)]/2$$

$$A_{\rm rec} = A_{CP} + A_{FB} + A^{\pi_s}_{\epsilon}$$

ε ASYMMETRIES

EXAMPLE OF $D^{*+} \to D^0 (\to K^+K^-, \pi^+\pi^-) \pi_s^+$

$D^{*-} \to \bar{D}^0 (\to K^+K^-, \pi^+\pi^-) \pi_s^-$

NEED SAMPLE W/O PHYSICS ASYMM. TO CORRECT OR TWO SAMPLES TO SUBTRACT*

$\to$ CF DECAYS

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

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

$$A^{\rm tag}_{\rm rec} = A^{K\pi}_{CP} + A_{FB} + A^{K\pi}_{\epsilon} + A^{\pi_s}_{\epsilon}$$
$$A^{\rm untag}_{\rm rec} = A^{K\pi}_{CP} + A_{FB} + A^{K\pi}_{\epsilon}.$$

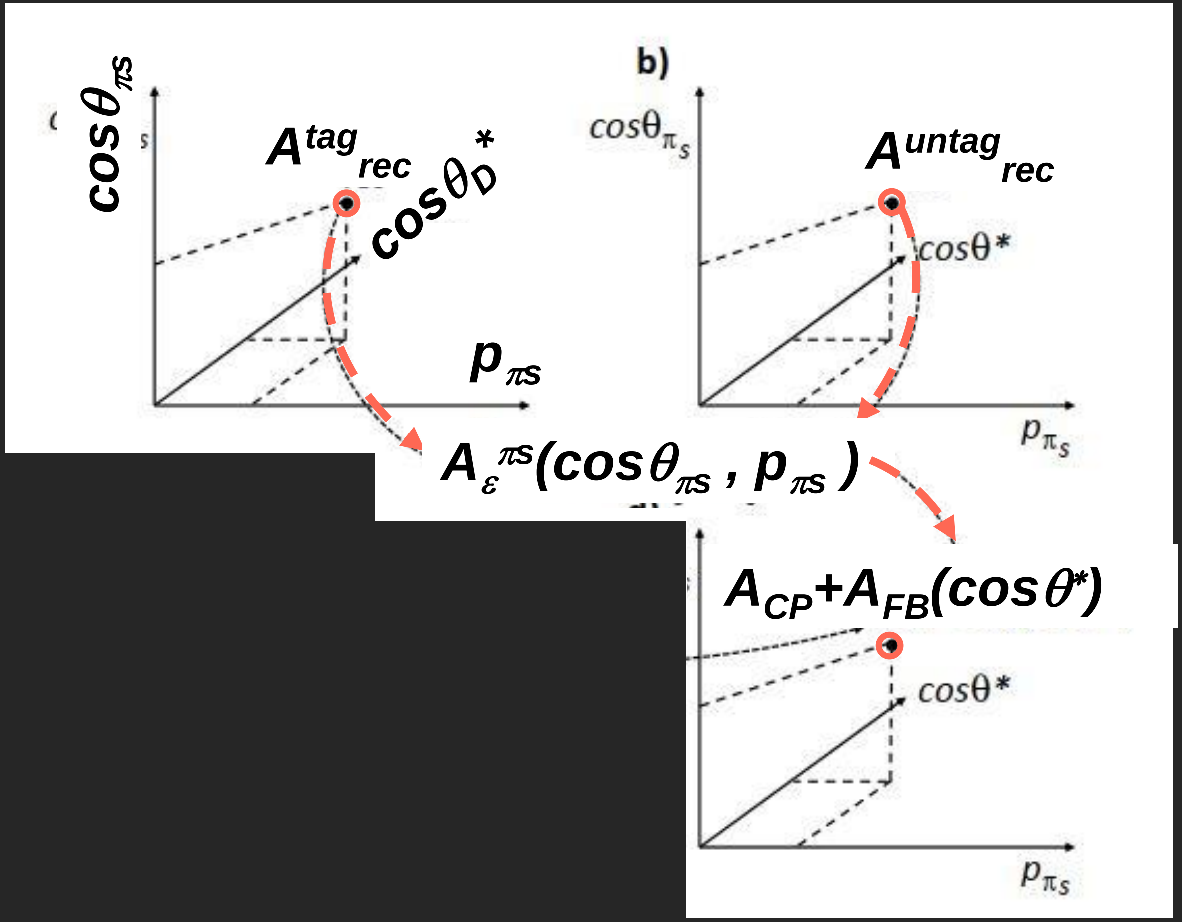
* *MC TYPICALLY NOT RELIABLE AT $\leq O(\%)$*

T-independent methods

asymmetry $A_{\varepsilon}^{\pi s}$ depends on π_s kinematics → binned in $p_{\pi s}$, $\cos\theta_{\pi s}$
... and in $\cos\theta_D$.... why?*

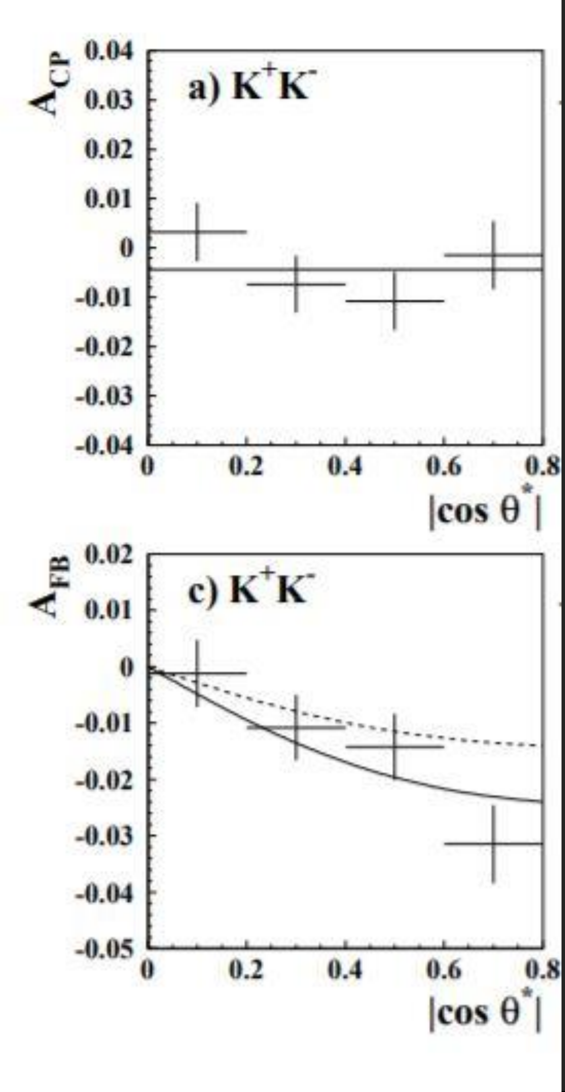
*because $\theta_{\pi s}$ correlated with θ_D**

integration over θ_D in a given bin of $\theta_{\pi s}$ does not cover full θ_D* interval ⇒ does not assure vanishing of A_{FB}*

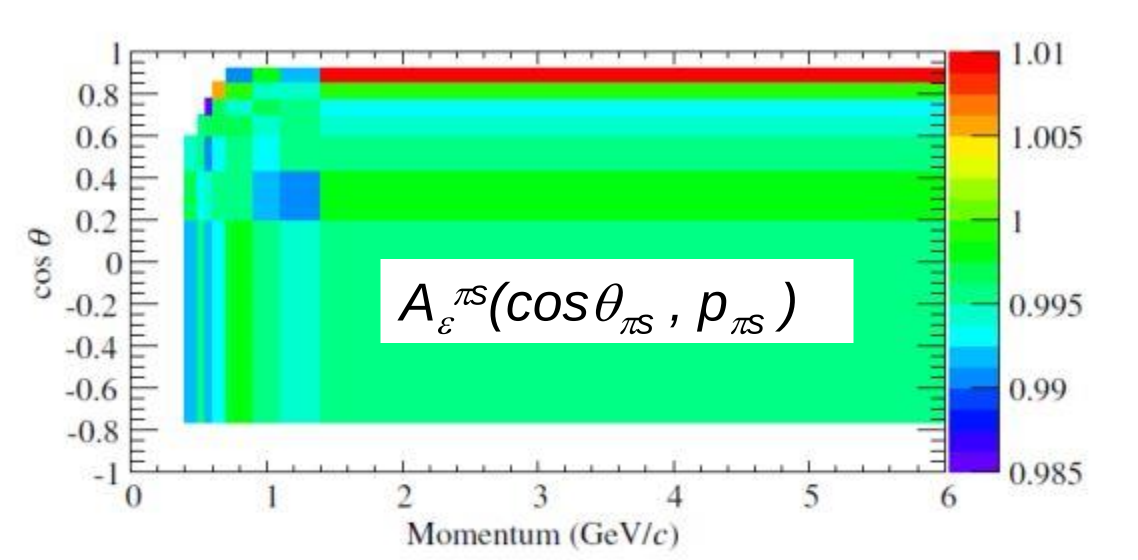


T-INDEPENDENT METHODS

ASYMMETRIES



B. AUBERT ET AL. (BABAR COLLAB.), PRL 100, 061803 (2008)



SLIGHT DEVIATION OF DATA FROM A_{FB} PREDICTION P. 50

$$A_{CP}^{KK} = (-0.43 \pm 0.30 \pm 0.11) \cdot 10^{-2}$$

M. STARIC ET AL. (BELLE COLLAB.), PLB 670, 190 (2008)

T-INDEPENDENT METHODS

$$A_{rec} = A_{CP} + A_{prod} + A_{\varepsilon}^{\pi_s}$$

OTHER INGENUINE METHODS TO DETERMINE UNWANTED ASYMMETRIES,
E.G. LHCB:

$$A_{rec}^{KK} = A_{CP}^{KK} + A_{prod} + A_{\varepsilon}^{\pi_s}$$

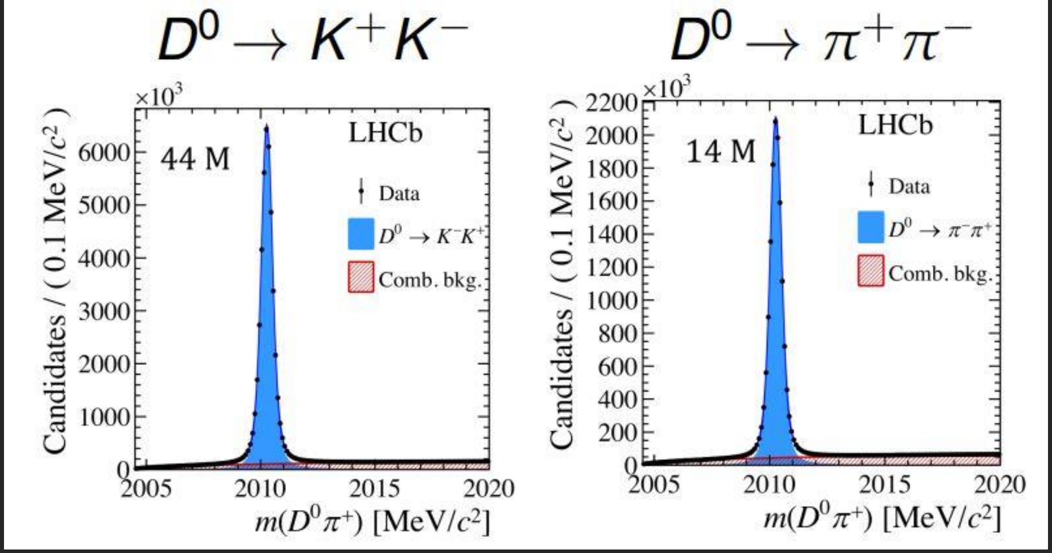
$$A_{rec}^{\pi\pi} = A_{CP}^{\pi\pi} + A_{prod} + A_{\varepsilon}^{\pi_s}$$

$$\Delta A_{rec} = A_{rec}^{KK} - A_{rec}^{\pi\pi} = A_{CP}^{KK} - A_{CP}^{\pi\pi}$$

$\Delta A_{CP} = A_{CP}^{f} - A_{CP}^{f'}$

M. Schubiger, Beauty 2019

$f = K^+K^-$, $f' = \pi^+\pi^-$



R. Aaij et al. (LHCb Collab.), PRL 122, 211803 (2019)

Charm CPV A_{CP}

T-independent methods

$$A_{rec} = A_{CP} + A_{prod} + A_{\varepsilon}^{\pi_s}$$

Other ingenuine methods to determine unwanted asymmetries,
e.g. LHCb:

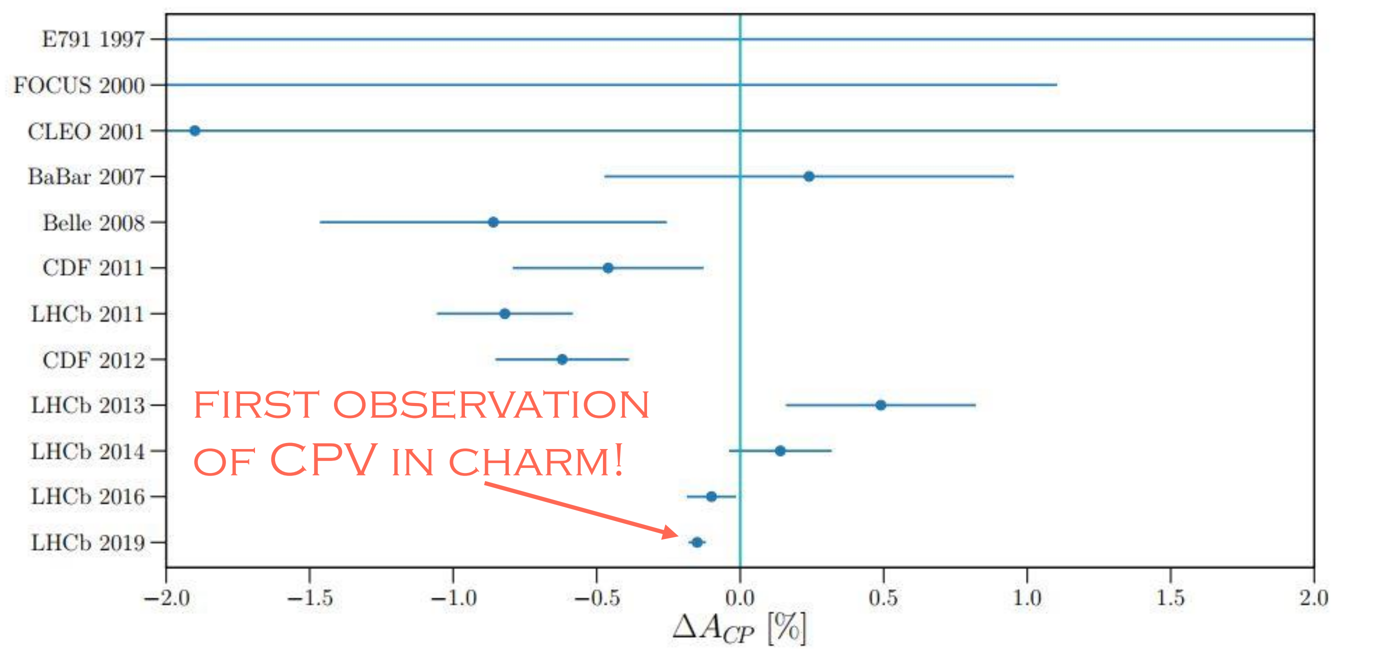
$$A_{rec}^{KK} = A_{CP}^{KK} + A_{prod} + A_{\varepsilon}^{\pi_s}$$

$$A_{rec}^{\pi\pi} = A_{CP}^{\pi\pi} + A_{prod} + A_{\varepsilon}^{\pi_s}$$

$$\Delta A_{rec} = A_{rec}^{KK} - A_{rec}^{\pi\pi} = A_{CP}^{KK} - A_{CP}^{\pi\pi}$$

$\Delta A_{CP} = A_{CP}^{f} - A_{CP}^{f'}$

M. Schubiger, Beauty 2019



R. Aaij et al. (LHCb Collab.), PRL 122, 211803 (2019)

First observation of CPV in charm

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

T-INDEPENDENT METHODS

$$A_{rec} = A_{CP} + \underbrace{A_{FB} + A_{\varepsilon}^{\pi^{\pm}} + A_{\varepsilon}^{\pi_s}}_{A_{\det}}$$

OTHER INGENUINE METHODS TO DETERMINE UNWANTED ASYMMETRIES,
E.G. BABAR IN $D^+ \to K_S \pi^+$:

P. DEL AMO SANCHEZ, ET AL. (BABAR COLLAB.), PRD 83, 071103 (2011)

$Y(4S) \to B\underline{B}$: STRONG INT. (NO CPV),
ISOTROPIC DISTR. OF TRACKS IN B SYSTEM

THE SAME DOES NOT HOLD FOR $e^+e^- \to q\underline{q}$!

USE INCLUSIVE SAMPLE OF TRACKS FROM $B\underline{B}$; DETERMINE ASYMMETRY OF $\pi^{\pm}$ IN KINEMATIC BINS;
USE INCLUSIVE SAMPLE OF TRACKS FROM CONTINUUM; DETERMINE ASYMMETRY OF $\pi^{\pm}$ IN KINEMATIC BINS;

DIFFERENCE IS $A_{\det}(\pi^{\pm} kinematics)$

$\to$ APPLY CORRECTION TO MEASURED ASYMM.

NEED TO BE CAREFUL NOT TO BIAS INCLUSIVNESS BY SELECTION

Comparison to predictions

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

R. Aaij et al. (LHCb Collab.), PRL 122, 211803 (2019)

difficult to calculate (ask Alexey/Alex/...)

within $SU(3)_{FLAVOR}$: $A_{CP}^{KK} \sim -A_{CP}^{\pi+\pi-}$

but then again, data show $SU(3)_{FLAVOR}$ violated at O(30%) in amplitudes

U. Nierste, Beauty 2019

CP asymmetries of hadronic charm decays ...

- ... are proportional to $\mathrm{Im}\,\frac{\lambda_b}{\lambda_{sd}} = -6 \cdot 10^{-4}$ in the Standard Model
  - ... and probe new physics in flavour transitions of up-type quarks,
- ... are very difficult to predict in the Standard Model.

$$\mathrm{Im}\left(\frac{2V_{cb}^{*}V_{ub}}{V_{cs}^{*}V_{us} - V_{cd}^{*}V_{ud}}\right) \sim -6 \cdot 10^{-4}$$

Comparison to predictions

sorry, need to do (repeat!) a kind joke:

U. Nierste, Beauty 2019

The theory community has delivered a perfect service to the experimental colleagues:
Every measurement hinting at some non-zero CP asymmetry was successfully postdicted offering interpretations both

- within the Standard Model
  and
- as evidence for new physics!

And we are not stubborn at all: After new measurements we eagerly change our opinions!

COMPARISON TO PREDICTIONS

U. NIERSTE, BEAUTY 2019

$$A_{CP}^{f} \propto \mathrm{Im}\left(\frac{2V_{cb}^{*}V_{ub}}{V_{cs}^{*}V_{us} - V_{cd}^{*}V_{ud}}\right) \sim -6\cdot 10^{-4}$$

SO.....

... BUT THE PREFACTOR??

USING QCD SUM RULES

A. KHODJAMIRIAN, A.A. PETROV, PLB 774, 235 (2017)

$$A_{CP}^{KK} \sim -A_{CP}^{\pi\pi}$$

$$\Delta A_{CP} \sim 2.0\cdot 10^{-4} \pm 0.3\cdot 10^{-4}$$

ACTUAL PREDICTION

SIGN??

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

R. AAIJ ET AL. (LHCB COLLAB.), PRL 122, 211803 (2019)

NEED FURTHER EXPERIMENTAL INFORMATION / CLARIFICATION

$$|a_{CP}^{\mathrm{dir}}(D^0 \to K_S K_S)| \leq 1.1\%$$

U. NIERSTE, ST. SCHACHT, PRD 92, 054036 (2015)

SEPARATE A_{CP}^{KK}, $A_{CP}^{\pi+\pi-}$

A_{CP} SUM RULES P. 52

$$|a_{CP}^{\mathrm{dir}}(D^0 \to \overline{K}^{*0} K_S)| \leq 0.003$$

U. NIERSTE, ST. SCHACHT, PRL 119, 251801 (2017)

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

t-DEPENDENT RATES FITTED SEPARATELY FOR D^0 AND $\overline{D}{}^0$

MANY PARAMETERS...

$$\frac{dN(D^0 \to f)}{dt} \propto e^{-\overline{\Gamma}t}\left[r^2 - ry'\overline{\Gamma}t + \frac{x'^2 + y'^2}{4}(\overline{\Gamma}t)^2\right]$$

$$\Downarrow$$

$$\frac{dN(D^0 \to f)}{dt} \propto e^{-\overline{\Gamma}t}\left[r_+^2 - r_+ y_+'\overline{\Gamma}t + \frac{x'^2_+ + y'^2_+}{4}(\overline{\Gamma}t)^2\right]$$

$$\frac{dN(\overline{D}{}^0 \to \bar{f})}{dt} \propto e^{-\overline{\Gamma}t}\left[r_-^{-2} - r_- y_-'\overline{\Gamma}t + \frac{x'^2_- + y'^2_-}{4}(\overline{\Gamma}t)^2\right]$$

$$x'^{\pm} = \left[\frac{1 \pm A_M}{1 \mp A_M}\right]^{1/4}(x'\cos\phi \pm y'\sin\phi)$$

$$y'^{\pm} = \left[\frac{1 \pm A_M}{1 \mp A_M}\right]^{1/4}(y'\cos\phi \mp x'\sin\phi).$$

$$A^f_{dir} = \frac{r_+ - r_-}{r_+ + r_-}$$

SIMILARLY IN $D^0 \to K_S\pi^+\pi^-$ WHERE $|q/p|$ AND ϕ ENTER DIRECTLY AS FIT PARAMETERS

$$\lambda_f = \frac{q}{p}\frac{\overline{A}_f}{A_f} = \left|\frac{q}{p}\right|\left|\frac{\overline{A}_f}{A_f}\right|e^{i\varphi}$$

Charm CPV Average

HFLAV

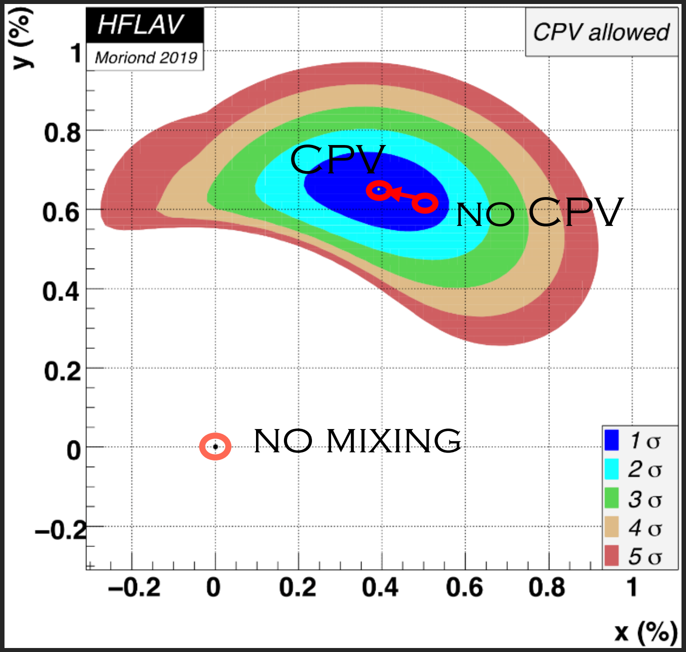
Averages

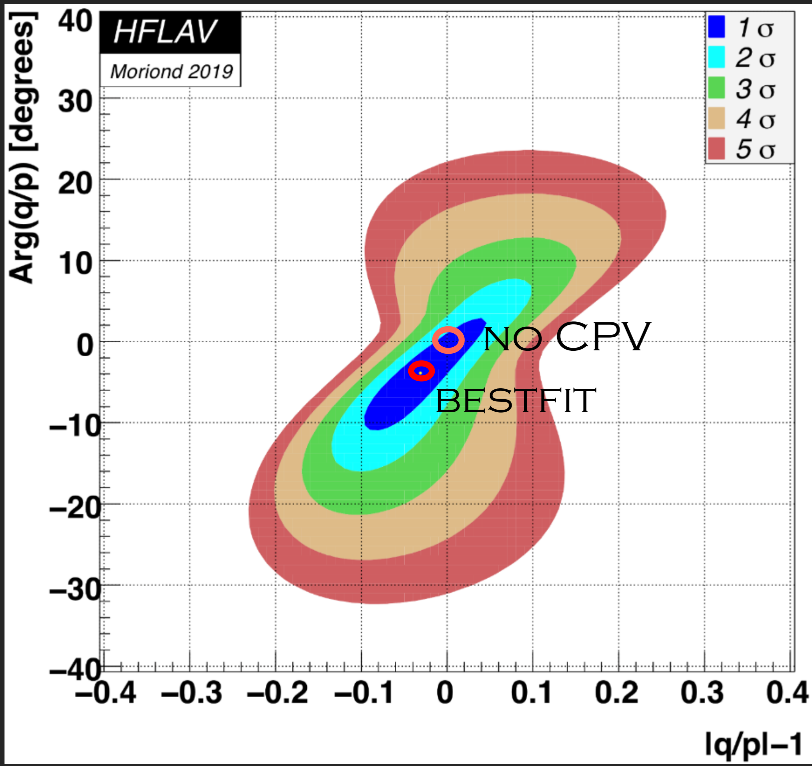
69 meas. of individual parameters enter the fit;

10 free param.

A_{dir}^{KK}, $A_{dir}^{\pi\pi}$ enter fit as individual free parameters;

χ^2/ndf ~ 1.5





mixing

$$x = (0.39 \pm {}^{0.11}_{0.12})\%$$

$$y = (0.65 \pm {}^{0.06}_{0.07})\%$$

no CPVmix, CPVint

$$\left|\frac{q}{p}\right| = 0.97 \pm 0.05$$

$$\phi = -3.9^o \pm {}^{4.5^o}_{4.6^o}$$

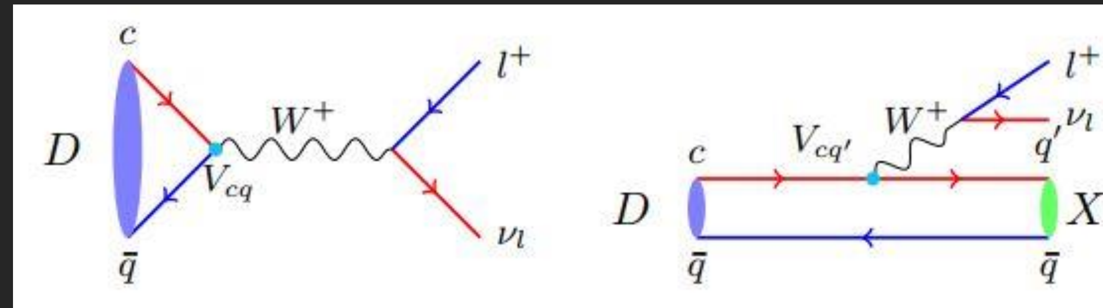
no CPVdec

details p. 54

$$A_{dir}^{KK} = -0.09 \pm 0.16 \qquad A_{dir}^{\pi\pi} = 0.06 \pm 0.16$$

$$\delta_{K\pi} = 26^o \pm {}^{23^o}_{24^o}$$

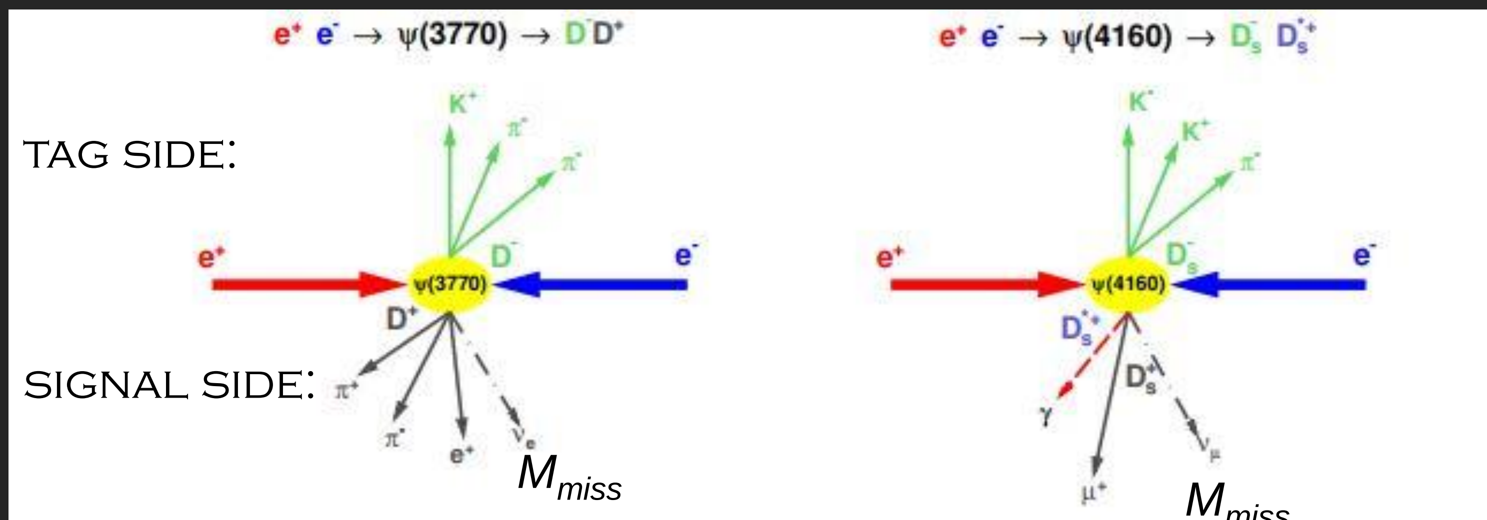
(Semi)leptonic decays



L. Zhang, Beauty 2019

BES III

Double tag method



$$@E_{cm} = 3.773\text{GeV} \Rightarrow \mathcal{B}_{sig} = \frac{N_{sig}}{\sum_\alpha N^\alpha_{tag}\epsilon^\alpha_{tag,sig}/\epsilon^\alpha_{tag}}$$

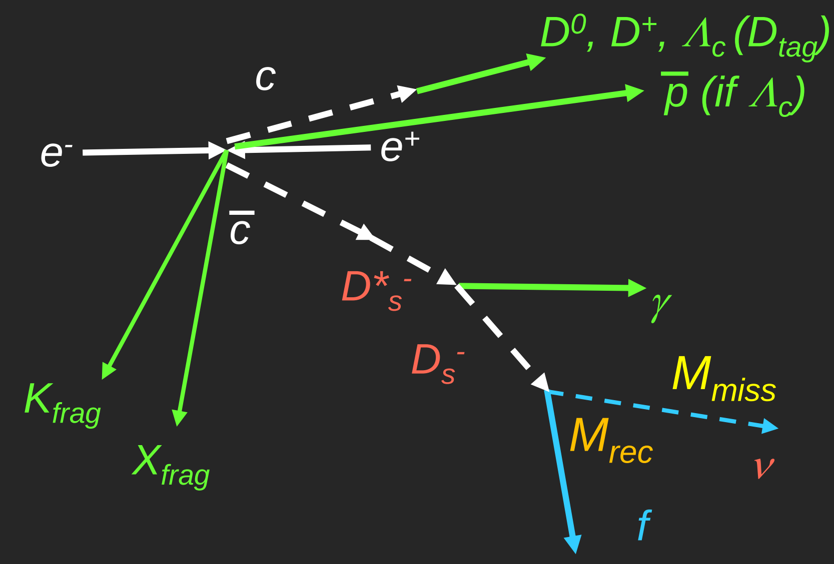
$$@E_{cm} = 4.178\text{GeV} \Rightarrow \mathcal{B}_{sig} = \frac{N_{sig}}{\mathcal{B}(D^*_s \to \gamma D_s)\sum_\alpha N^\alpha_{tag}\epsilon^\alpha_{tag,sig}/\epsilon^\alpha_{tag}}$$

(Semi)leptonic decays

A. Zupanc et al. (Belle Coll.), JHEP 09, 139 (2013)

B-Factory method

$N_{sig}(M_{miss}) \, / \, [\varepsilon(f) \, N_{sig}(M_{rec})] = Br(D_s \rightarrow f)$



(Semi)leptonic decays

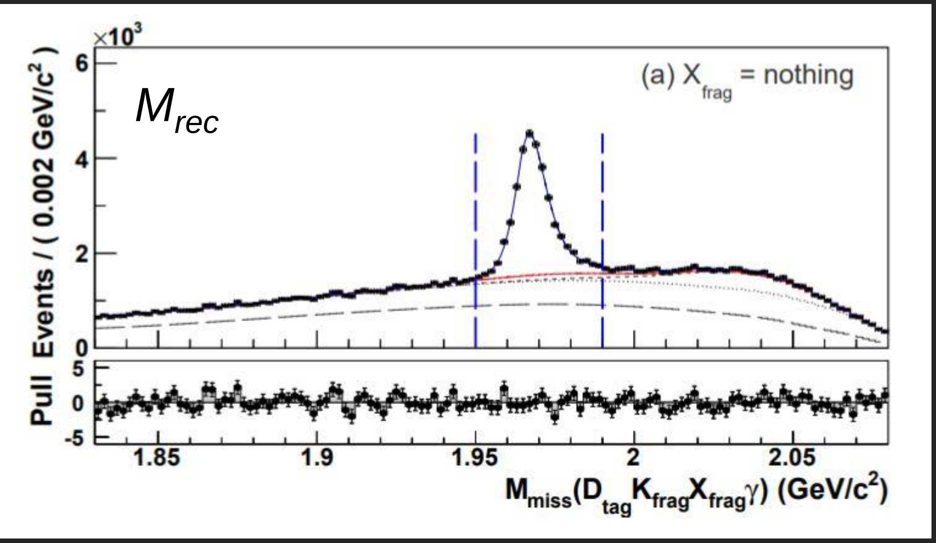
B-Factory method

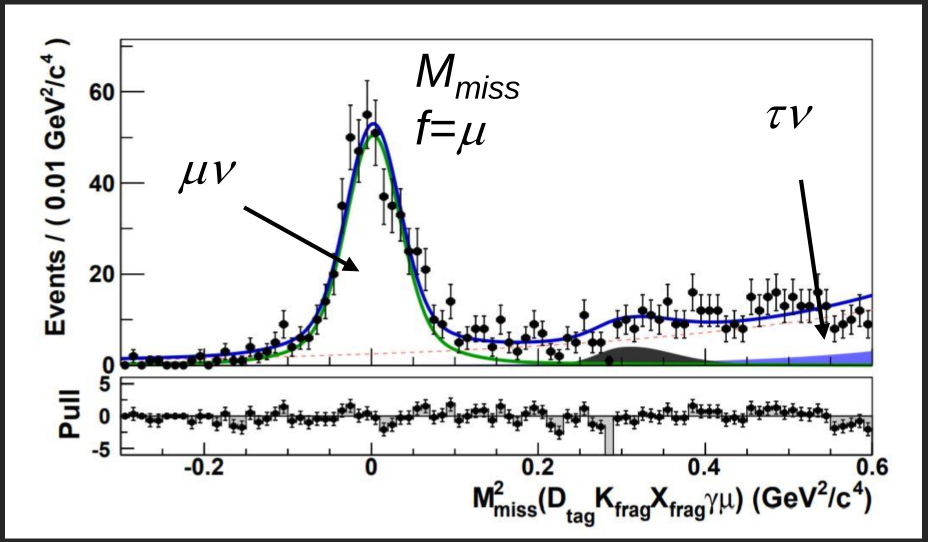
$$\mathcal{B}(D_s^+ \to \ell^+\nu_\ell) = \frac{\tau_{D_s} m_{D_s}}{8\pi} f_{D_s}^2 G_F^2 |V_{cs}|^2 m_\ell^2 \left(1 - \frac{m_\ell^2}{m_{D_s}^2}\right)^2$$

$N_{sig}(M_{miss}) / [\varepsilon(f)\, N_{sig}(M_{rec})] = Br(D_s \to f)$

leptonic decays:

A. Zupanc et al. (Belle Coll.), JHEP 09, 139 (2013)





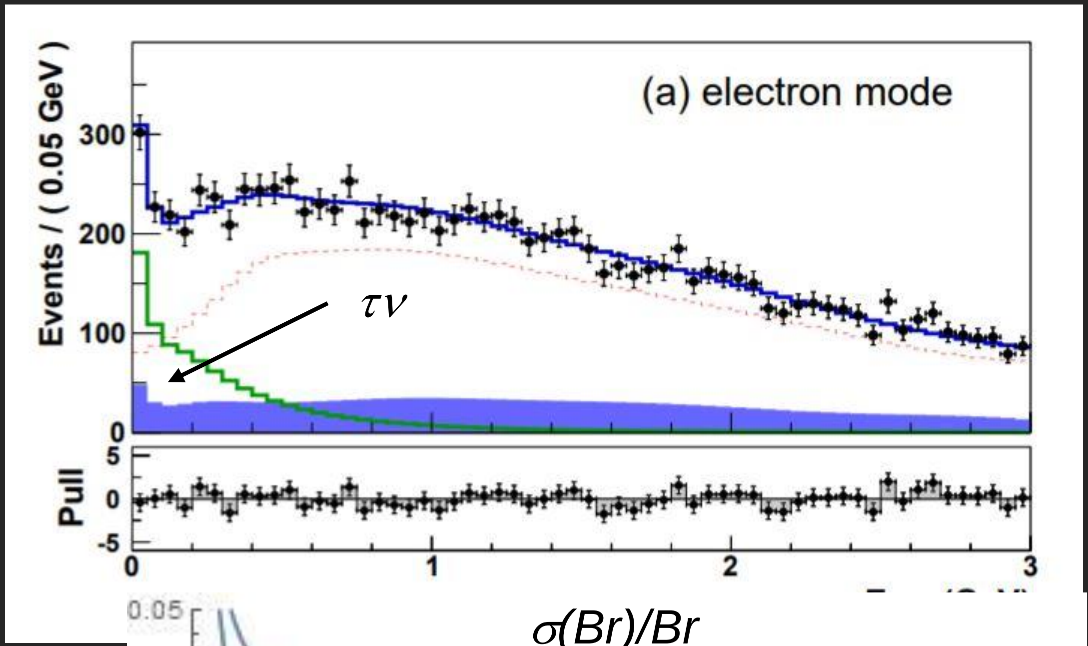
more p. 57

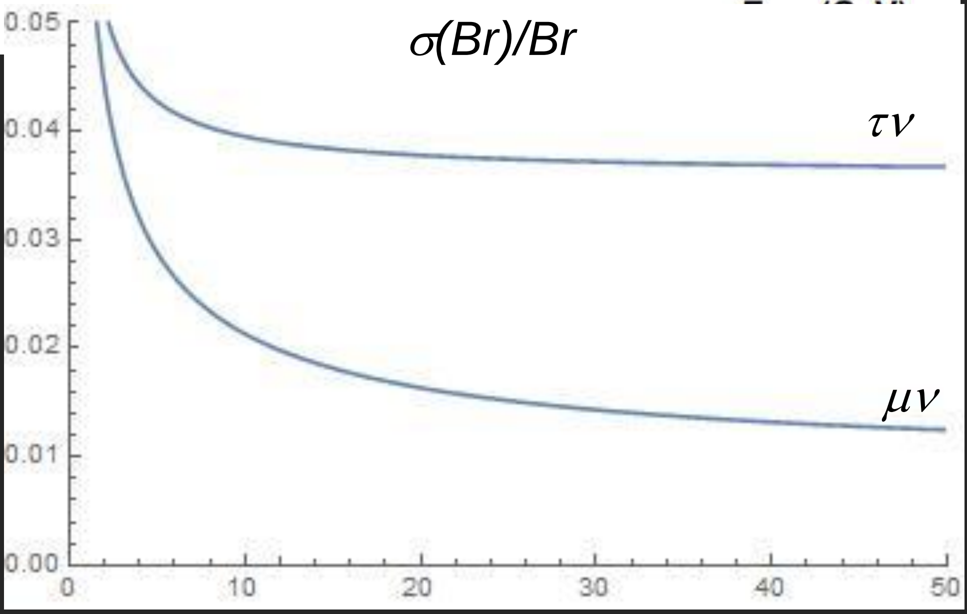
(SEMI)LEPTONIC DECAYS

A. ZUPANC ET AL. (BELLE COLL.), JHEP 09, 139 (2013)

B-FACTORY METHOD

FOR $\tau\nu$ BESIDE M_{MISS} ALSO E_{ECL} EXPLOITED





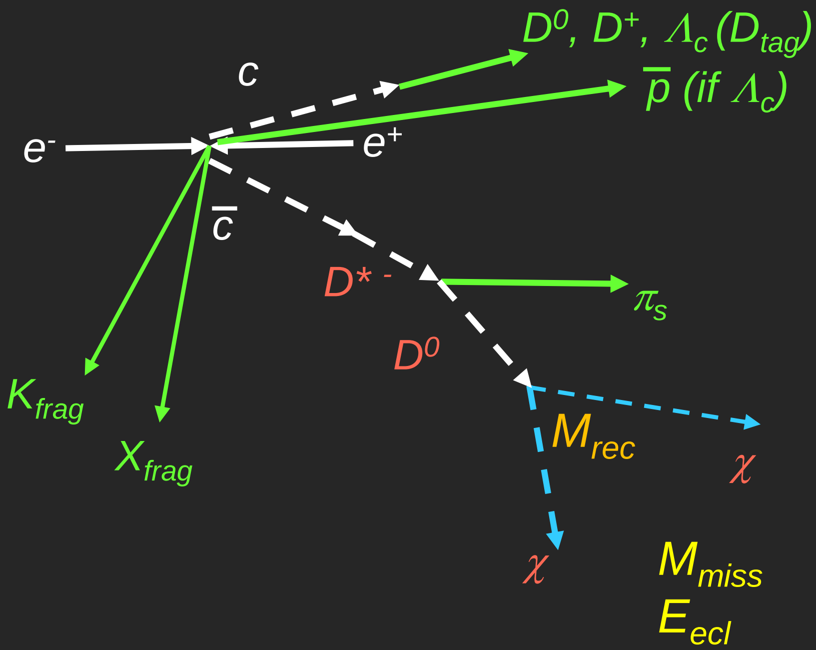
$$Br(D_s \to \mu\nu) = (0.531 \pm 0.028 \pm 0.020)\%$$

$$Br(D_s \to \tau\nu) = (5.70 \pm 0.21 \pm ^{0.31}_{0.30})\%$$

$$f_{D_s} = (255.5 \pm 4.2 \pm 5.1)\ \mathrm{MeV}$$

(Semi)leptonic decays

B-Factory
method can be used for D^0/D_s decays to invisible final state



sensitivity p. 59

BESIII LEPTONIC DECAYS

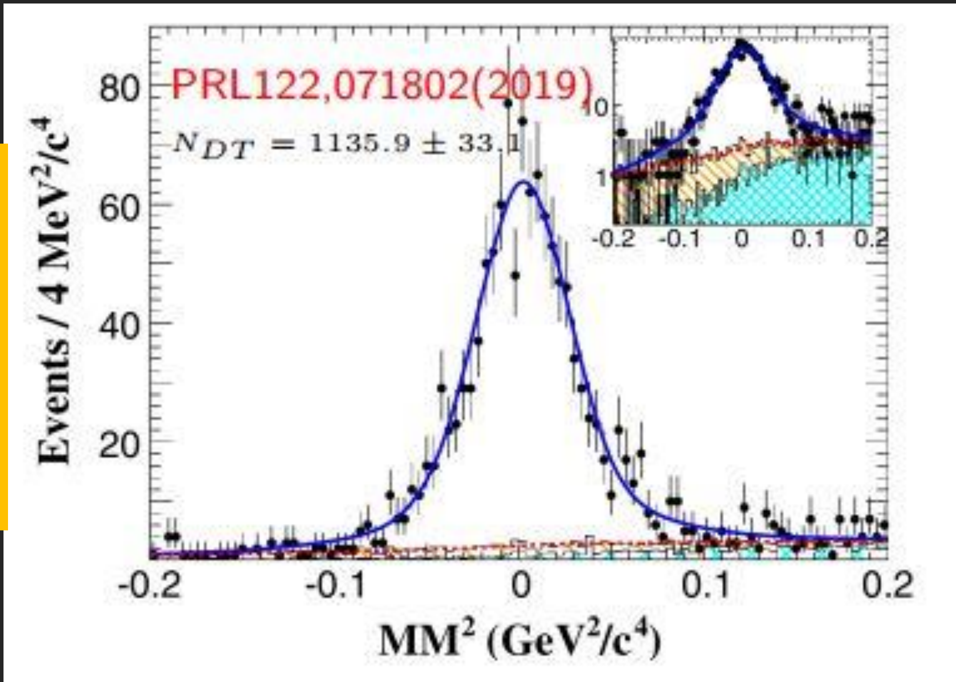
$D_s \to \mu\nu$

M. ABLIKIM ET AL. (BESIII COLL.), PRL 122, 071802 (2019)

$$Br(D_s \to \mu\nu) = (0.549 \pm 0.016 \pm 0.015)\%$$

$$R_{\tau/\mu} = \frac{Br^{PDG}(D_s \to \tau\nu)}{Br(D_s \to \mu\nu)} = 9.98 \pm 0.52$$

$$R^{SM}_{\tau/\mu} = 9.76 \pm 0.03$$



SEVERAL IMPORTANT SOURCES OF SYS. UNCERTAINTIES:

ε_γ ON SIGNAL SIDE ~ 1%

AMOUNT OF BKG. WITH UNMATCHED γ ON SIGNAL SIDE ~ 1%

CONTRIB. OF D_s RADIATIVE DECAYS ($D_s \to \mu\nu\gamma$) ~ 1%

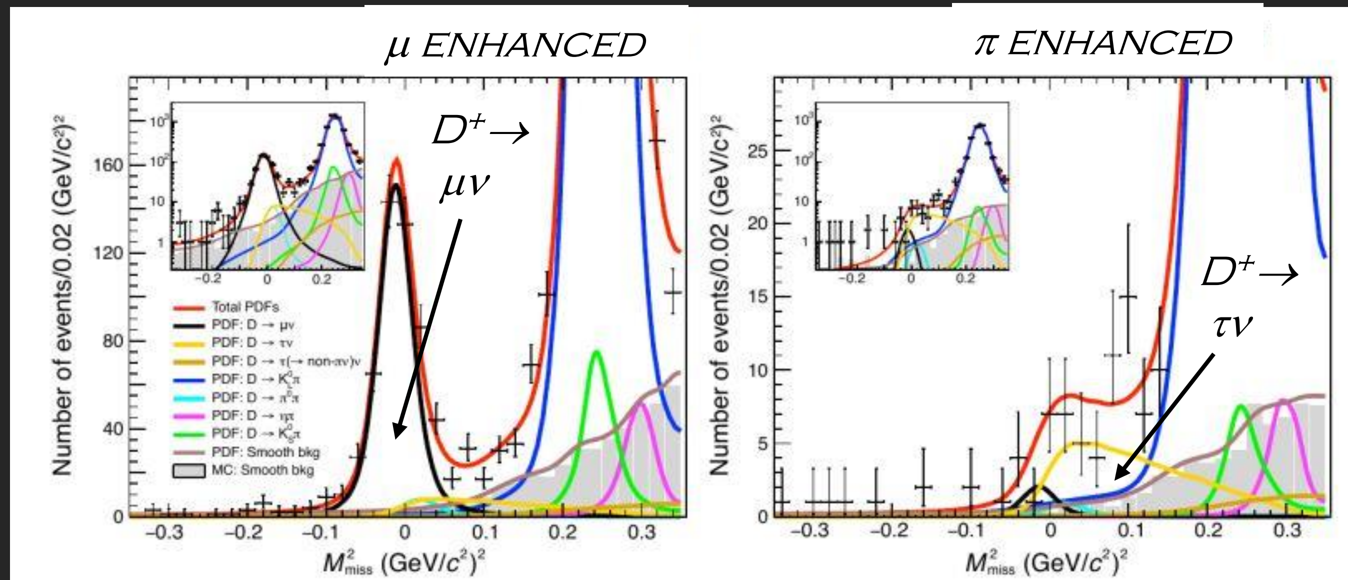
IF TOTAL UNCERTAINTY SCALABLE: $\sigma(Br)/Br$ ~ 0.024% WITH 10 fb^{-1}

SAME AS TOTAL UNCERTAINTY AT BELLE II @ 7 ab^{-1}

BESIII LEPTONIC DECAYS

$D^+ \to \tau(\to \pi\nu)\nu$

M. ABLIKIM ET AL. (BESIII COLL.) ARXIV:1908.08877



LARGEST SOURCES OF SYS. UNCERTAINTY:

$Br(D^+ \to \mu\nu) \sim 7\%$

BKG. SHAPE ~ 4%

FIRST OBSERVATION

$$Br(D^+ \to \tau\nu) = (0.120 \pm 0.024 \pm 0.012)\%$$

$$R_{\tau/\mu} = \frac{Br^{PDG}(D^+ \to \tau\nu)}{Br(D^+ \to \mu\nu)} = 3.21 \pm 0.64 \pm 0.43$$

$$R^{SM}_{\tau/\mu} = 2.67$$

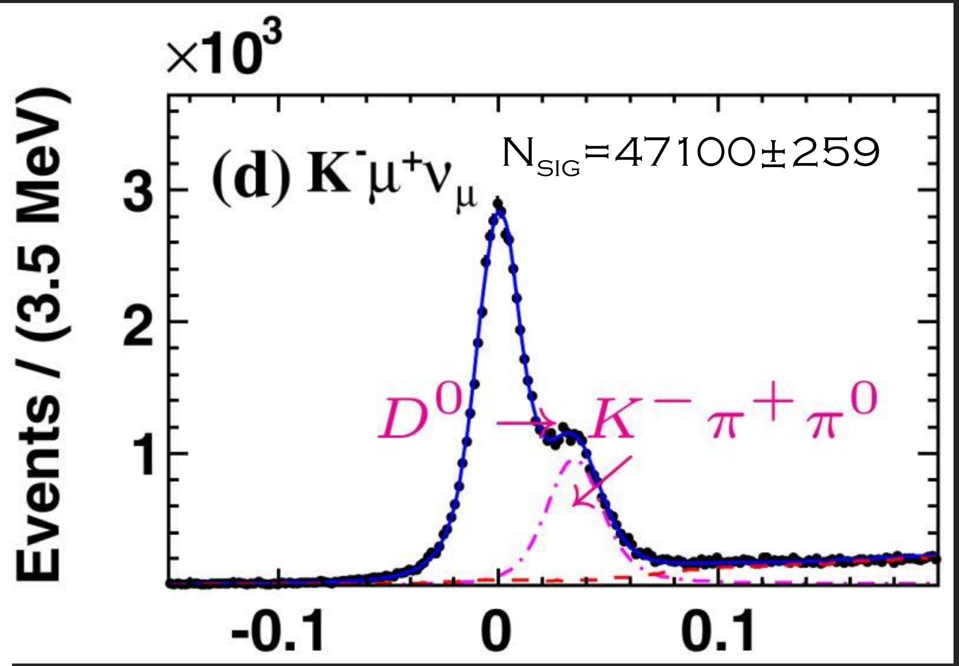
BESIII semileptonic decays

M. Ablikim et al. (BESIII Coll.) ,PRL122,011804 (2019)

$D^0 \to K^- \mu^+ \nu$

$$\frac{d\Gamma(D^0 \to P^- \ell^+ \nu_\ell)}{dq^2} = |V_{cQ}|^2 \frac{G_F^2}{24\pi^3} \frac{(q^2 - m_\ell^2)^2 \sqrt{E_P^2 - m_P^2}}{q^4 m_{D^0}^2}$$

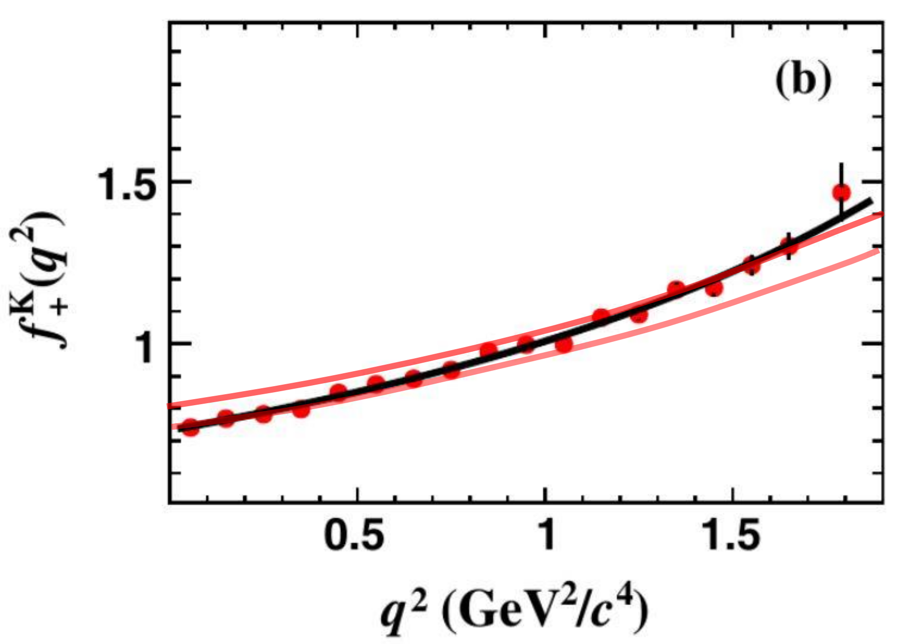
$$\left(1 + \frac{m_\ell^2}{2q^2}\right) m_{D^0} (E_P^2 - m_P^2) |f_+(q^2)|^2$$



$$U_{miss} \equiv E_{miss} - |\vec{p}_{miss}|$$

$$E_{miss} \equiv E_{beam} - E_{K^-} - E_{\mu^+}$$

form factor $f_+(q^2)$

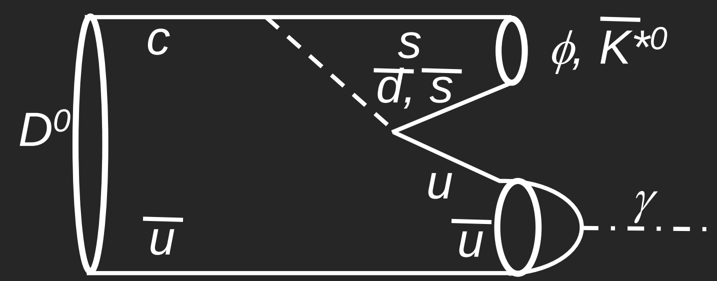


Belle II @ 50 ab^{-1} using method for $D_s \to \mu\nu$ probably lower statistics than BES III with 10 fb^{-1} p. 60

comparison to LQCD

V. Lubicz et al. (ETM Coll.) , PRD96, 054514 (2017)

$D^0 \to V\gamma$



RADIATIVE DECAYS $D^0 \to V\gamma$
$V=\rho^0, \phi, K^{*0}$

T. NANUT ET AL. (BELLE COLL.), PRL 118, 051801 (2017)

IMPROVED MEAS. OF BR'S, INCL. 1ST OBSERVATION OF $D^0 \to \rho^0\gamma$

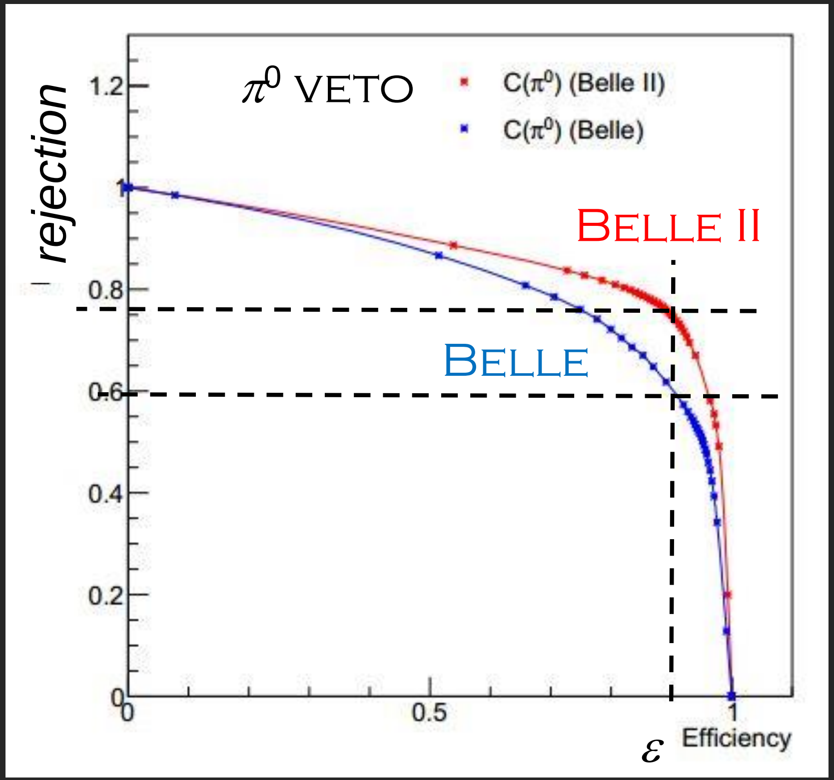
NP COULD ENHANCE $A_{CP}(D^0 \to V\gamma) \sim O(0.1)$

G. ISIDORI, J.F. KAMENIK, PRL 109, 171801 (2012)
J. LYON, R. ZWICKY, ARXIV:1210.6546
S. DE BOER, G. HILLER, JHEP08 (2017) 091

FIRST MEAS'S OF A_{CP}

MAIN BKG. $D^0 \to h^+h^-\pi^0(\to \gamma\gamma)$

IMPORTANT $\pi^0 (\to \gamma\gamma)$ VETO TO REDUCE BACKGROUNDS
NN VETO



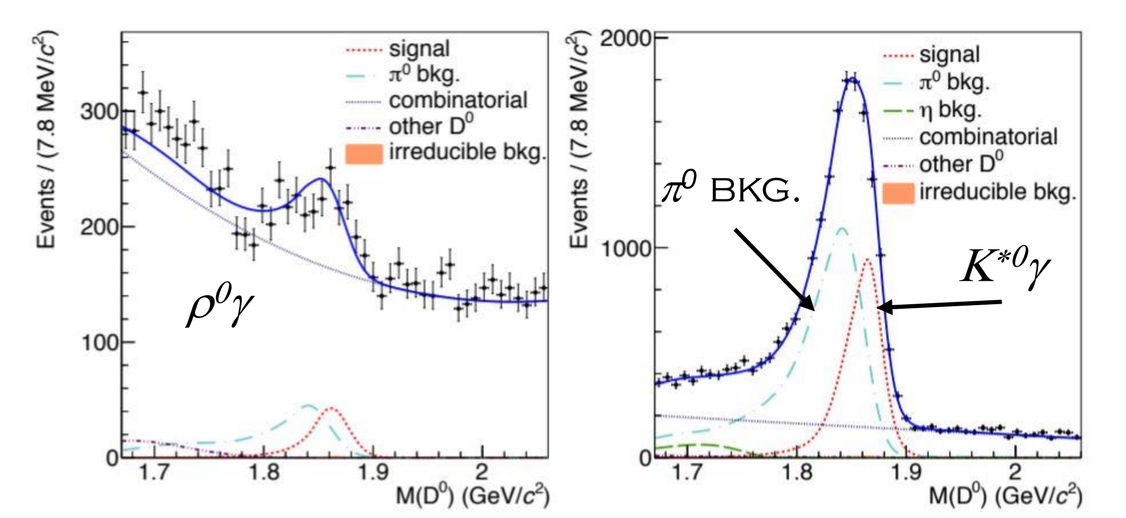
T. NANUT ET AL. (BELLE COLL.), PRL 118, 051801 (2017)

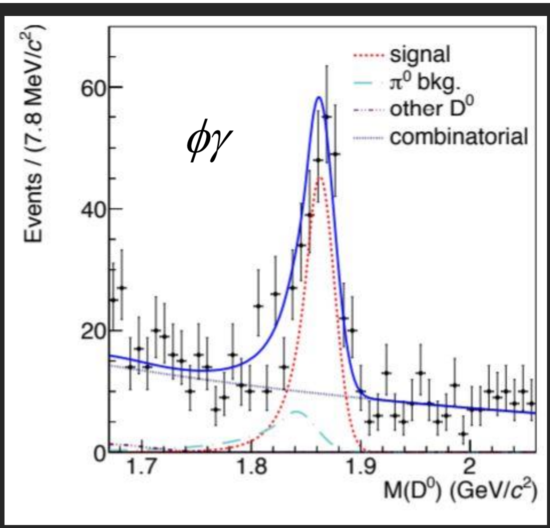
BR AND CPV

RADIATIVE DECAYS $D^0 \to V\gamma$
$V=\rho^0, \phi, K^{*0}$

HELICITY ANGLE AND $M(D^0)$
TO ISOLATE SIGNAL

BR (AND A_{CP}) DETERMINED
W.R.T. NORMALIZATION MODES
$\pi^+\pi^-$, K^+K^-, $K^-\pi^+$





$$\mathcal{B}\left(D^0 \to \rho^0\gamma\right) = (1.77 \pm 0.30 \pm 0.07) \times 10^{-5},$$
$$\mathcal{B}\left(D^0 \to \phi\gamma\right) = (2.76 \pm 0.19 \pm 0.10) \times 10^{-5},$$
$$\mathcal{B}\left(D^0 \to \overline{K}^{*0}\gamma\right) = (4.66 \pm 0.21 \pm 0.21) \times 10^{-4}.$$

CALCULATIONS $(0.1 - 1)\ 10^{-5}$ $\rho^0\gamma$
$(0.1\text{-}2)\ 10^{-5}$ $\phi\gamma$
$10 \times \phi\gamma$ $K^{*0}\gamma$

S. DE BOER, G. HILLER, JHEP08 (2017) 091

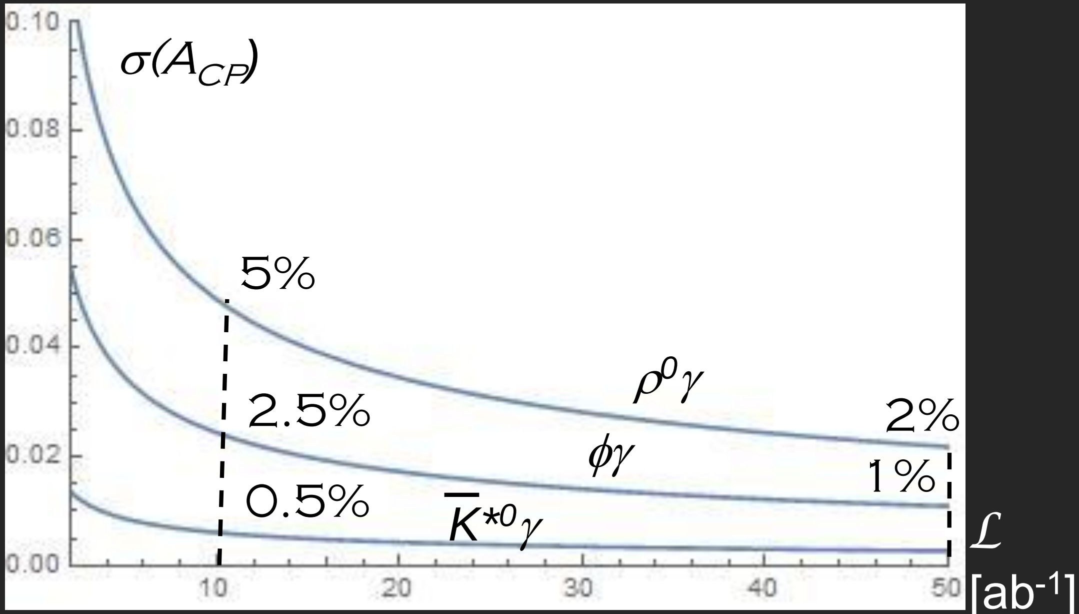
BR AND CPV

RADIATIVE DECAYS $D^0 \to V\gamma$
$V=\rho^0, \phi, K^{*0}$

ASYMMETRIES OTHER THAN A_{CP} CANCELED BY NORMALIZATION MODES

$$\mathcal{A}_{CP}^{\rm sig} = A_{\rm raw}^{\rm sig} - A_{\rm raw}^{\rm norm} + \mathcal{A}_{CP}^{\rm norm}$$

$$\mathcal{A}_{CP}\left(D^0 \to \rho^0\gamma\right) = +0.056 \pm 0.152 \pm 0.006,$$
$$\mathcal{A}_{CP}\left(D^0 \to \phi\gamma\right) = -0.094 \pm 0.066 \pm 0.001,$$
$$\mathcal{A}_{CP}\left(D^0 \to \overline{K}^{*0}\gamma\right) = -0.003 \pm 0.020 \pm 0.000,$$



u, d
1968 ISOSPIN VIOLATED (ENLARGED TO $SU(3)_{FLAVOR}$)
PREDICTED BY M. GELL-MANN, G. ZWEIG

s
1964 CP VIOLATED
NOT PREDICTED

b
2001 LARGE CP VIOLATION
PREDICTED BY M. KOBAYASHI, T. MASKAWA

c
????
NOT PREDICTED

REMEMBER THE WORDS BY KARIM: „CHARM IS THE NEW BEAUTY!“

Additional material

D^0 Mixing Dalitz

METHOD OF STRONG PHASE DIFFERENCE D^0 / $\bar{D}^0$ *DETERM.* USING COHERENT PRODUCTION OF *D* MESON PAIRS J. LIBBY ET AL. (CLEO-C COLL.), PRD 82,112006 (2010)

$\psi(3770)$ $(CP = +1) \rightarrow D_1\, D_2$;

if $D_1 \rightarrow CP+ \Rightarrow D_2$ is CP-; (CP-*TAGGED*)

$$CP = CP(D_1)CP(D_2)(-1)^{\ell=1}$$

if $D_1 \rightarrow D^0 \rightarrow f_{flav} \Rightarrow D_2$ is $\bar{D}^0$ (*FLAVOR-TAGGED*)

EVTS IN BIN *i* FOR FLAVOR TAGGED (D^0) DECAY:

$$K_i = A_D \int_i |f_D(m_+^2, m_-^2)|^2 dm_+^2 dm_-^2 = A_D F_i$$

(SAME FOR $\bar{D}^0$ WITH $m_+ \leftrightarrow m_-$)

D^0 MIXING DALITZ

J. LIBBY ET AL. (CLEO-C COLL.), PRD 82,112006 (2010)

DALITZ DIST. FOR CP TAGGED *(CP+, CP-)* DECAYS

$$f_{CP\pm}(m_+^2, m_-^2) = \frac{1}{\sqrt{2}}[f_D(m_+^2, m_-^2) \pm f_D(m_-^2, m_+^2)]$$

\# EVTS IN BIN *i*
FOR CP TAGGED *(CP+, CP-)* DECAY:

$$M_i^\pm = h_{CP\pm}(K_i \pm 2c_i\sqrt{K_iK_{-i}} + K_{-i})$$

FLAVOR-TAGGED:

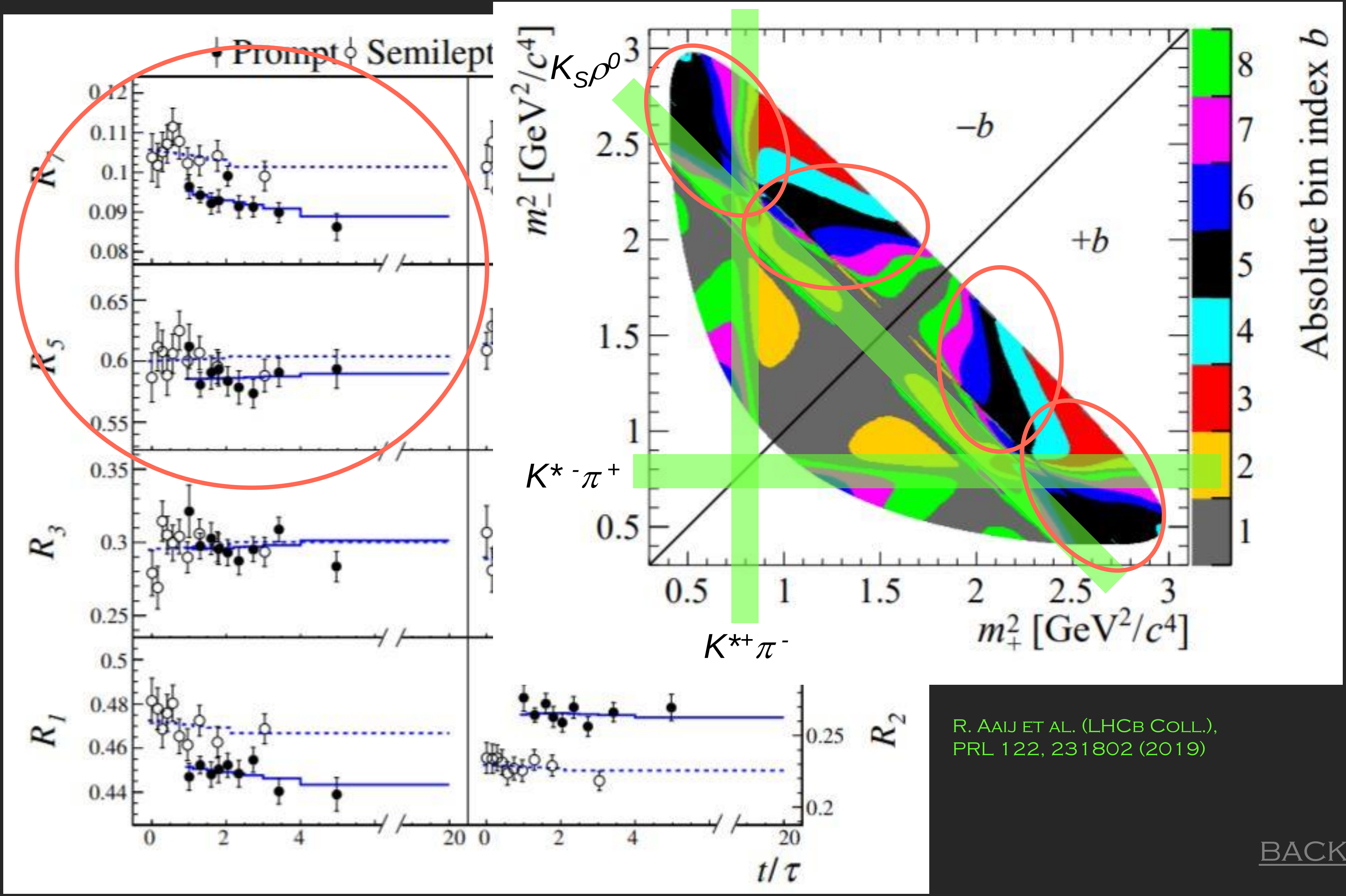
$$K_i = A_D \int_i |f_D(m_+^2, m_-^2)|^2 dm_+^2 dm_-^2 = A_D F_i$$

$$c_i \equiv \frac{1}{\sqrt{F_iF_{-i}}} \int_i |f_D(m_+^2, m_-^2)||f_D(m_-^2, m_+^2)| \cos[\Delta\delta_D(m_+^2, m_-^2)] dm_+^2 dm_-^2$$

$$s_i \equiv \frac{1}{\sqrt{F_iF_{-i}}} \int_i |f_D(m_+^2, m_-^2)||f_D(m_-^2, m_+^2)| \sin[\Delta\delta_D(m_+^2, m_-^2)] dm_+^2 dm_-^2$$

BACK

D^0 MIXING DALITZ



R. AAIJ ET AL. (LHCb COLL.), PRL 122, 231802 (2019)

BACK

Charm CPV CP eigenstates

CPV parametrization

$$\lambda_f = \frac{q}{p}\frac{\overline{A}_f}{A_f} = \left|\frac{q}{p}\right|\left|\frac{\overline{A}_f}{A_f}\right| e^{i\varphi}$$

$$A_m = \left|\frac{q}{p}\right|^2 - 1 \qquad A_{dir}^f = \frac{\left|\overline{A}_f\right|^2}{\left|A_f\right|^2} - 1$$

quantity measured by B Factories

$$\frac{dN(D^0 \to f)}{dt} \approx \left|A_f\right|^2 e^{-(1+y_D)\overline{\Gamma}t} \qquad y_D \approx \eta_f\left(1 + \frac{A_{dir}^f + A_m}{2}\right)(y\cos\varphi - x\sin\varphi)$$

$$\frac{dN(\overline{D}^0 \to f)}{dt} \approx \left|\overline{A}_f\right|^2 e^{-(1+y_{\overline{D}})\overline{\Gamma}t} \qquad y_{\overline{D}} \approx \eta_f\left(1 - \frac{A_{dir}^f + A_m}{2}\right)(y\cos\varphi + x\sin\varphi)$$

$$y_{CP} = \frac{y_D + y_{\overline{D}}}{2} \approx \eta_f\left[y\cos\varphi - \left(\frac{A_{dir}^f + A_m}{2}\right)x\sin\varphi\right]$$

$$A_\Gamma = \frac{\tau_{\overline{D}} - \tau_D}{\tau_{\overline{D}} + \tau_D} \approx \frac{y_D - y_{\overline{D}}}{2} \approx \eta_f\left[\left(\frac{A_{dir}^f + A_m}{2}\right)y\cos\varphi - x\sin\varphi\right]$$

BACK

CHARM CPV CP EIGENSTATES

CPV PARAMETRIZATION

$$\lambda_f = \frac{q}{p}\frac{\overline{A}_f}{A_f} = \left|\frac{q}{p}\right|\left|\frac{\overline{A}_f}{A_f}\right| e^{i\varphi}$$

$$A_m = \left|\frac{q}{p}\right|^2 - 1 \quad A_{dir}^f = \frac{\left|\overline{A}_f\right|^2}{\left|A_f\right|^2} - 1$$

QUANTITY MEASURED BY LHCB

$$\frac{\left(\frac{dN(D^0 \to f)}{dt}\right) - \left(\frac{dN(\overline{D}^0 \to f)}{dt}\right)}{\left(\frac{dN(D^0 \to f)}{dt}\right) + \left(\frac{dN(\overline{D}^0 \to f)}{dt}\right)} \approx A_{dir}^f - \tilde{A}_\Gamma \overline{\Gamma} t$$

$$\tilde{A}_\Gamma = \left(\frac{A_m - A_{dir}^f}{2}\right) y\cos\phi - x\sin\phi = A_\Gamma - A_{dir}^f\, y\cos\phi$$

BACK

CPV PARAMETRIZATION

$$\left(\frac{dN(D^0\to f)}{dt}\right)-\left(\frac{dN(\overline{D}^0\to f)}{dt}\right)=\left(A^f_{dir}-\tilde{A}_\Gamma\overline{\Gamma}t\right)\left[\left(\frac{dN(D^0\to f)}{dt}\right)+\left(\frac{dN(\overline{D}^0\to f)}{dt}\right)\right]$$

$$\int_0^\infty \frac{dN(D^0\to f)}{dt}dt=\int_0^\infty |A_f|^2 e^{-\overline{\Gamma}t}(1+y_D\overline{\Gamma}t)dt=|A_f|^2\overline{\tau}(1+y_D)$$

$$\int_0^\infty \frac{dN(\overline{D}^0\to f)}{dt}dt=\int_0^\infty |\overline{A}_f|^2 e^{-\overline{\Gamma}t}(1+y_{\overline{D}}\overline{\Gamma}t)dt=|\overline{A}_f|^2\overline{\tau}(1+y_{\overline{D}})$$

$$\int_0^\infty t\frac{dN(D^0\to f)}{dt}dt=\int_0^\infty |A_f|^2 e^{-\overline{\Gamma}t}(t+y_D\overline{\Gamma}t^2)dt=|A_f|^2\overline{\tau}^2(1+2y_D)$$

$$\int_0^\infty t\frac{dN(\overline{D}^0\to f)}{dt}dt=\int_0^\infty |\overline{A}_f|^2 e^{-\overline{\Gamma}t}(t+y_{\overline{D}}\overline{\Gamma}t^2)dt=|\overline{A}_f|^2\overline{\tau}^2(1+2y_{\overline{D}})$$

BACK

t-INTEGRATED CPV

$$A_{CP}^f \equiv \frac{\Gamma(D \to f) - \Gamma(\bar{D} \to \bar{f})}{\Gamma(D \to f) + \Gamma(\bar{D} \to \bar{f})}$$

FOR GENERAL *f*: $A_{CP}^f \sim A_{dir}^f + C_1 y\cos\phi + C_2 x\sin\phi$

$f=f_{CP}$

$$A_{CP}^f \approx A_d^f - y\frac{A_d^f + A_m}{2}\cos\varphi + x\sin\varphi$$

WHY IN CHARM SISTEM T-INTEGRATED ASYMMETRY (A_{CP}) BESIDE DIRECT RECEIVES CONTRIB. FROM INDIRECT CPV, WHILE IN B SYSTEM @ B-FACTORIES ONLY DIRECT CPV CONTRIBUTES?

NO y TERM BECAUSE $y \propto \Delta\Gamma$ NEGLIGIBLE IN B_d SYSTEM;

x TERM: IMPORTANT DIFFERENCE IN PRODUCTION OF $B\underline{B}$ AND $c\underline{c}$ PAIRS:
FORMER QUANTUM ENTANGLED ⇒ NOT *t*- BUT Δ*t*-DEPENDENCE OF RATES:

$$\frac{d\Gamma(P^0 \to f_{CP})}{d(\Delta t)} = \frac{1}{2}|A_f|^2(1+|\lambda|^2)\mathcal{N}e^{-\Gamma|\Delta t|}\left[1+\frac{1-|\lambda|^2}{1+|\lambda|^2}\cos(\Delta m\Delta t) - 2\frac{\mathrm{Im}(\lambda)}{1+|\lambda|^2}\sin(\Delta m\Delta t)\right]$$

$$\frac{d\Gamma(\bar{P}^0 \to f_{CP})}{d(\Delta t)} = \frac{1}{2}|A_f|^2(1+|\lambda|^2)\left|\frac{p}{q}\right|^2\mathcal{N}e^{-\Gamma|\Delta t|}\left[1-\frac{1-|\lambda|^2}{1+|\lambda|^2}\cos(\Delta m\Delta t) + +2\frac{\mathrm{Im}(\lambda)}{1+|\lambda|^2}\sin(\Delta m\Delta t)\right] . \quad (3.46)$$

t-integrated CPV

Charm hadrons produced in fragmentation, not entangled, *t*-dependent rate;
integration over Δt for *B* pairs [-∞, ∞]:

$$\int_{-\infty}^{\infty} e^{-\Gamma|\Delta t|}\cos(\Delta m \Delta t)\, d(\Delta t) = \frac{2\Gamma}{\Gamma^2+\Delta m^2}$$

$$\int_{-\infty}^{\infty} e^{-\Gamma|\Delta t|}\sin(\Delta m \Delta t)\, d(\Delta t) = 0$$

part $\propto Im(\lambda)$ vanishes!

For charm mesons integration over *t* [0, ∞]:

$$\int_{0}^{\infty} e^{-\Gamma|\Delta t|}\cos(\Delta m \Delta t)\, d(\Delta t) = \frac{\Gamma}{\Gamma^2+\Delta m^2}$$

$$\int_{0}^{\infty} e^{-\Gamma|\Delta t|}\sin(\Delta m \Delta t)\, d(\Delta t) = \frac{\Delta m}{\Gamma^2+\Delta m^2}$$

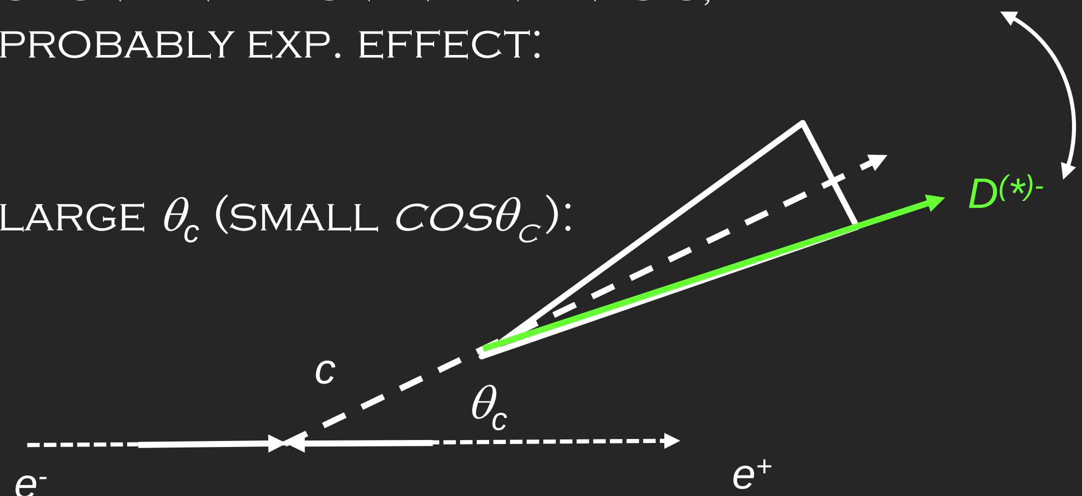
part $\propto Im(\lambda)$ is proportional to Δm (~x), does not vanish;
⇒ term with $x \sin\phi$ in A_{CP}!

Back

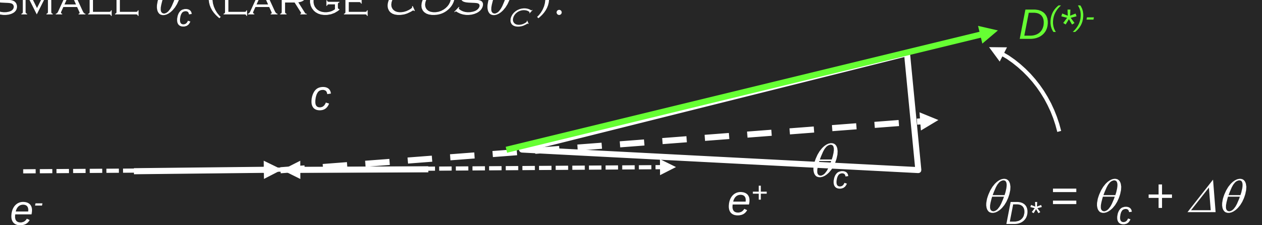
t-INTEGRATED CPV

SLIGHT DEVIATION OF DATA FROM AFB PREDICITION OBSERVED IN SEVERAL MEAS'S; PROBABLY EXP. EFFECT:

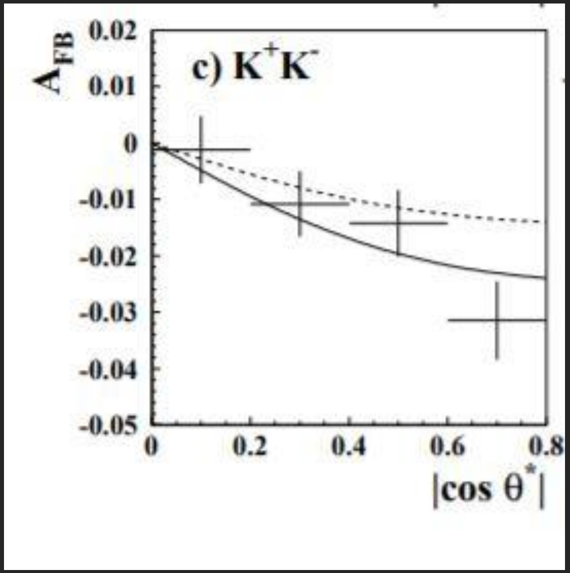
LARGE θ_c (SMALL $\cos\theta_c$):



SMALL θ_c (LARGE $\cos\theta_c$):



AT SMALL θ_c *ANY* DEVIATION OF θ_{D*} FROM θ_c CAN ONLY BE IN DIREVTION OF LARGER POLAR ANGLE



INTERESTING ASYMMETRIES

SUM RULES FOR A_{CP} RELATING — S. MÜLLER ET AL., PRL 115, 251802 (2015)

1) $D^0 \to K^+K^-,\ \pi^+\pi^-,\ \pi^0\pi^0$

2) $D^+ \to K^0K^+,\ D_s^+ \to K^0\pi^+,\ K^+\pi^0$

(W/O INCLUDING $SU(3)_F$ BREAKING OF PENGUIN CONTR., UP TO 0.3 A_{CP})

OTHER INTERESTING PREDICTIONS

$A_{CP}(D^0 \to K_sK_s) \leq \sim 0.01$ — U. NIERSTE, S. SCHACHT, PRD 92, 054036 (2015)

$A_{CP}(D^+ \to \pi^+\pi^0) \approx 0$ — F. BUCCELLA ET AL., PLB 302, 319 (1993)
(UP TO 10^{-2} A_{CP})

Charm CPV A_{CP}

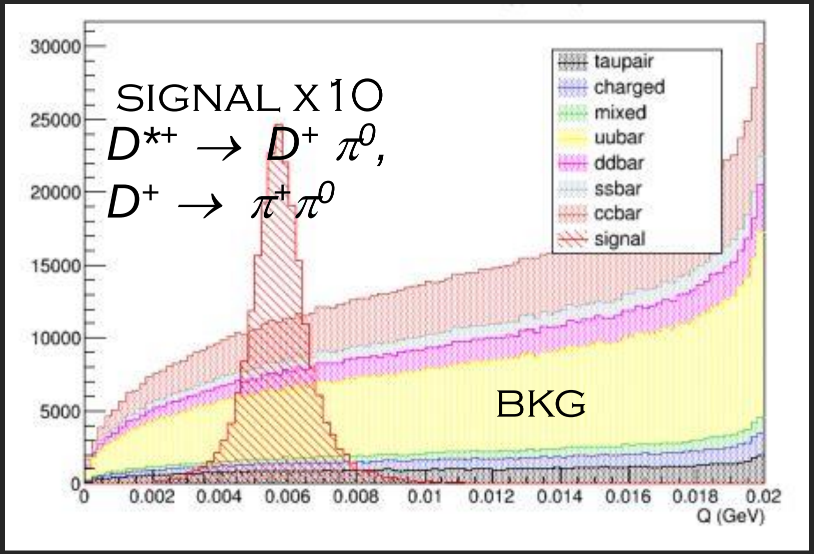
CPV in charm

$A_{CP}(D^+ \to \pi^+\pi^0) = 0$

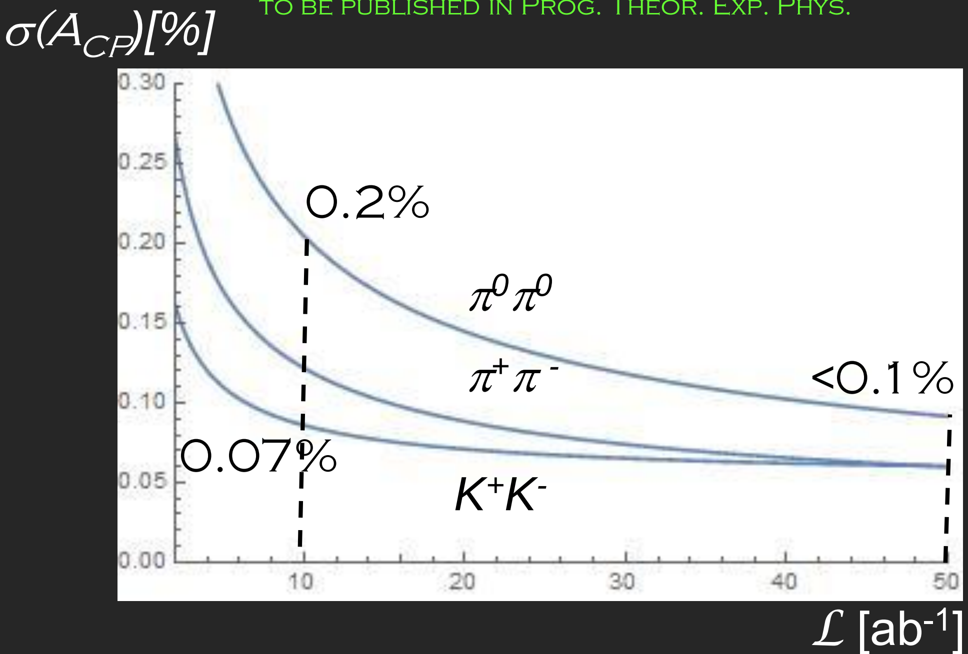
$D^{*+} \to D^+ \pi^0$, $D^+ \to \pi^+\pi^0$

$\sigma(A_{CP}(D^+ \to \pi^+\pi^0)) \sim 0.2\% - 0.4\%$ @ 50 ab^{-1}
$(A_{CP}^{SM}(D^+ \to \pi^+\pi^0) = 0)$

$\sigma(A_{CP}(D^+ \to K_sK_s)) \sim 0.25\%$ @ 50 ab^{-1}
$(A_{CP}^{SM}(D^+ \to K_sK_s) \sim 1\%)$



E. Kou, P. Urquijo eds., The Belle II Physics Book to be published in Prog. Theor. Exp. Phys.



A_{CP} in sum rules

back

AVERAGES

HFLAV

RESULTS

BACK

Parameter	No CPV	No direct CPV in DCS decays	CPV-allowed	CPV-allowed 95% CL Interval
x (%)	$0.50^{+0.13}_{-0.14}$	$0.43^{+0.10}_{-0.11}$	$0.39^{+0.11}_{-0.12}$	[0.16, 0.61]
y (%)	0.62 ± 0.07	0.63 ± 0.06	$0.651^{+0.063}_{-0.069}$	[0.51, 0.77]
$\delta_{K\pi}$ (°)	$8.9^{+8.2}_{-8.9}$	$9.3^{+8.3}_{-9.2}$	$12.1^{+8.6}_{-10.2}$	[−10.4, 28.2]
R_D (%)	0.344 ± 0.002	0.344 ± 0.002	0.344 ± 0.002	[0.339, 0.348]
A_D (%)	–	–	$-0.55^{+0.49}_{-0.51}$	[−1.5, 0.4]
$\lvert q/p \rvert$	–	0.998 ± 0.008	$0.969^{+0.050}_{-0.045}$	[0.89, 1.07]
ϕ (°)	–	0.08 ± 0.31	$-3.9^{+4.5}_{-4.6}$	[−13.2, 5.1]
$\delta_{K\pi\pi}$ (°)	$18.5^{+22.7}_{-23.4}$	$22.1^{+22.6}_{-23.4}$	$25.8^{+23.0}_{-23.8}$	[−21.3, 70.3]
A_π(%)	–	0.05 ± 0.16	0.06 ± 0.16	[−0.25, 0.38]
A_K(%)	–	-0.11 ± 0.16	-0.09 ± 0.16	[−0.40, 0.22]
x_{12} (%)	–	$0.43^{+0.10}_{-0.11}$		[0.22, 0.63]
y_{12} (%)	–	0.63 ± 0.06		[0.50, 0.75]
ϕ_{12}(°)	–	$-0.25^{+0.96}_{-0.99}$		[−2.5, 1.8]

AVERAGES

HFLAV

χ^2

BACK

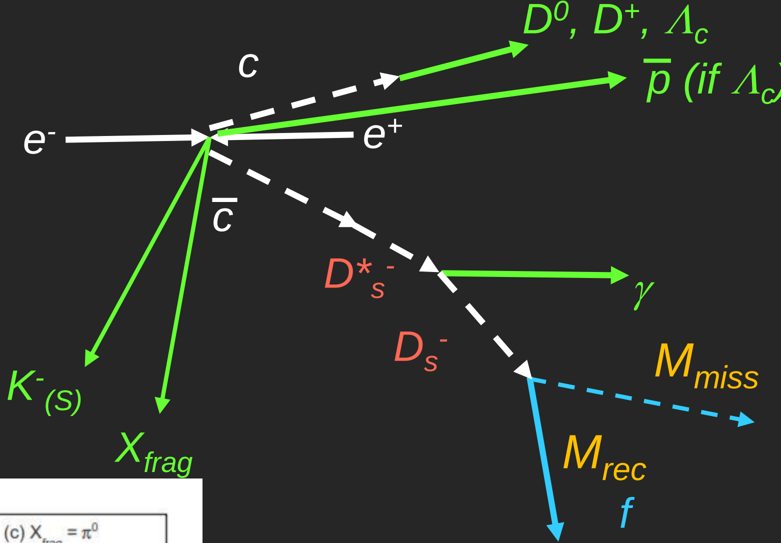
Observable	χ^2	$\sum\chi^2$
y_{CP} $(K^+K^-, \pi^+\pi^-)$ World Average	0.35	0.35
A_Γ World Average	2.07	2.41
$x_{K^0\pi^+\pi^-}$ Belle	0.71	3.12
$y_{K^0\pi^+\pi^-}$ Belle	4.42	7.54
$\lvert q/p\rvert_{K^0\pi^+\pi^-}$ Belle	0.48	8.02
$\phi_{K^0\pi^+\pi^-}$ Belle	0.53	8.55
x_{CP} $(K^0\pi^+\pi^-)$ LHCb	0.55	9.10
y_{CP} $(K^0\pi^+\pi^-)$ LHCb	0.06	9.16
Δx $(K^0\pi^+\pi^-)$ LHCb	0.00	9.16
Δy $(K^0\pi^+\pi^-)$ LHCb	0.09	9.26
$x_{K^0h^+h^-}$ Babar	0.73	9.98
$y_{K^0h^+h^-}$ Babar	0.08	10.06
$x_{\pi^0\pi^+\pi^-}$ Babar	0.68	10.74
$y_{\pi^0\pi^+\pi^-}$ Babar	0.19	10.93
$(x^2+y^2)_{K^+\ell^-\nu}$	0.14	11.07
$x_{K^+\pi^-\pi^0}$ Babar	7.10	18.17
$y_{K^+\pi^-\pi^0}$ Babar	3.91	22.08
CLEOc $(x/y/R_D/\cos\delta/\sin\delta)$	10.53	32.60
$R_D^+/x'^{2+}/y'^+$ Babar	8.69	41.30
$R_D^-/x'^{2-}/y'^-$ Babar	4.02	45.32
$R_D^+/x'^{2+}/y'^+$ Belle	1.88	47.20
$R_D^-/x'^{2-}/y'^-$ Belle	2.36	49.56
$R_D/x'^2/y'$ CDF	1.20	50.76
$R_D^+/x'^{2+}/y'^+$ LHCb	1.29	52.05
$R_D^-/x'^{2-}/y'^-$ LHCb	0.67	52.72
$A_{KK}/A_{\pi\pi}$ Babar	0.35	53.08
$A_{KK}/A_{\pi\pi}$ CDF	4.07	57.14
$A_{KK}-A_{\pi\pi}$ LHCb (D^*, $B^0\to D^0\mu X$ tags)	0.05	57.19
$(x^2+y^2)_{K^+\pi^-\pi^+\pi^-}$ LHCb	3.47	60.67

Charm Decays (semi)lepton.

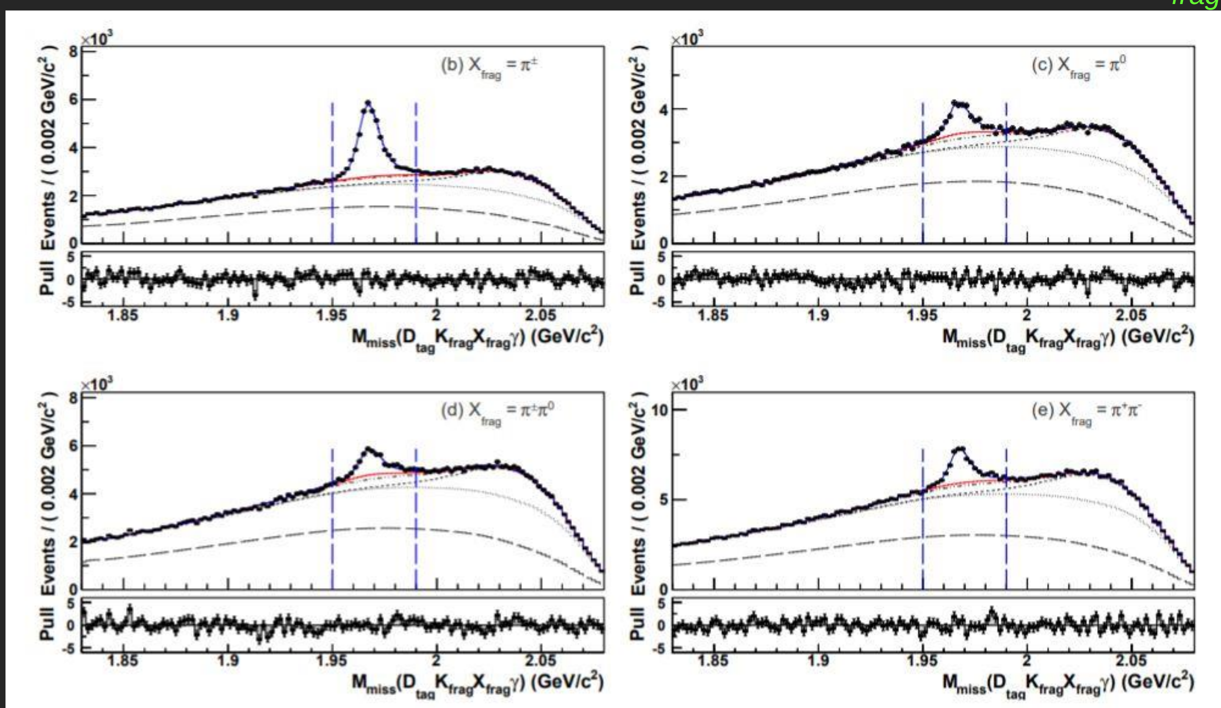
DECAYS
B-Factory
method

A. Zupanc et al. (Belle Coll.), JHEP 09, 139 (2013)

$N_{sig}(f) / [\varepsilon(f)\, N_{sig}(M_{rec})] = Br(D_s \to f)$

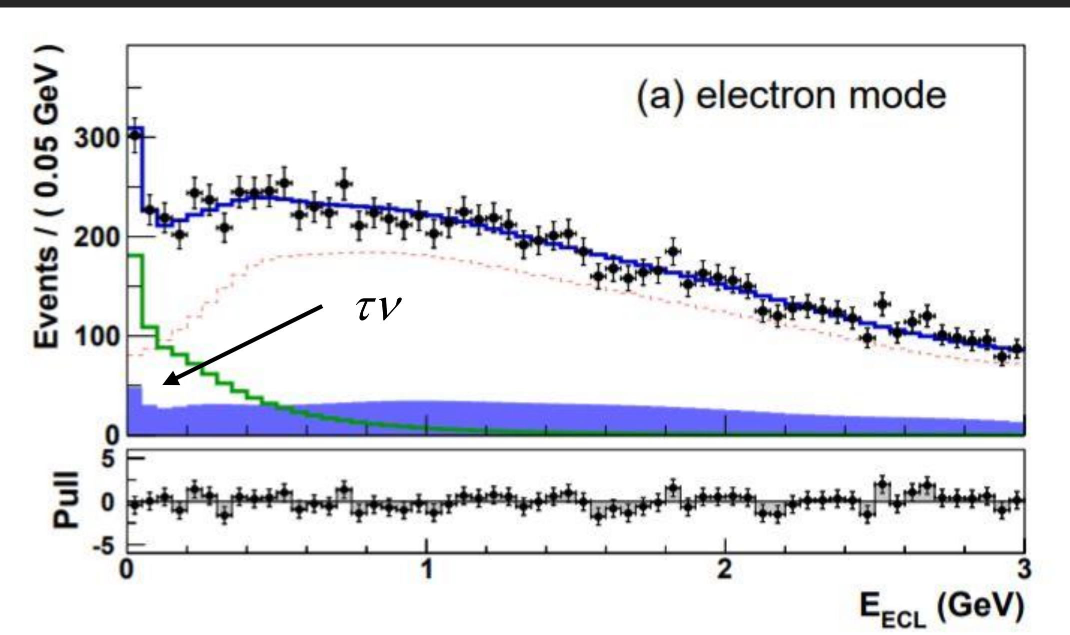


$$N_{Ds}^{inc} \approx (94.3 \pm 1.3) \cdot 10^3$$

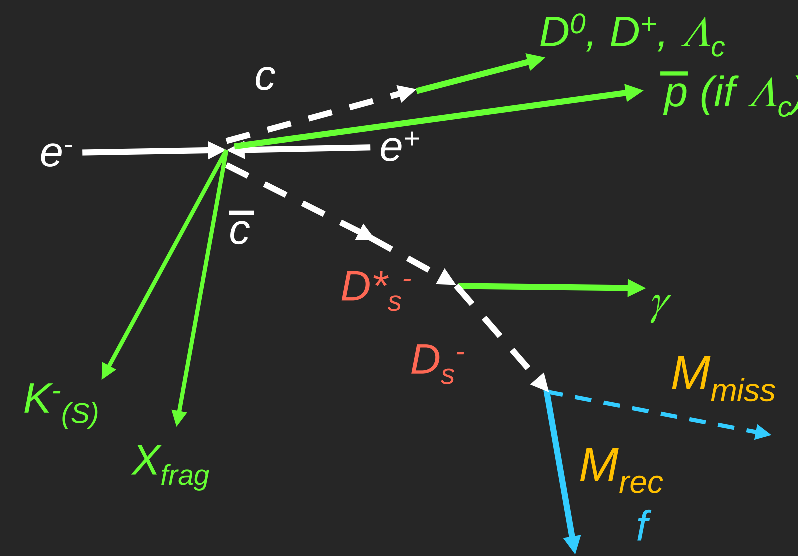


DECAYS
B-FACTORY METHOD

FOR $\tau\nu$ BESIDE M_{MISS} ALSO E_{ECL} EXPLOITED



A. ZUPANC ET AL. (BELLE COLL.), JHEP 09, 139 (2013)



BACK

DECAYS

B-FACTORY METHOD

SEARCH FOR INVISIBLE D DECAYS

$$N_{Ds}^{inc} \approx (94.3 \pm 1.3) \cdot 10^3$$

~ 10^5 N_{DS}^{INC} (1 ± 0.015) / AB-1

@ 20 AB^{-1} $2 \cdot 10^6$(1 ± 0.003)

~ $\sigma(N_{SIG}^{ECL})$ @ 1 AB^{-1} ~ 100

SENSITIVITY TO DECAYS TO INVISIBLE STATES

(IF BKG LIKE IN $\tau\nu$ CASE ?)

~ 20 · 100 / $2 \cdot 10^6$ ~ 10^{-3}

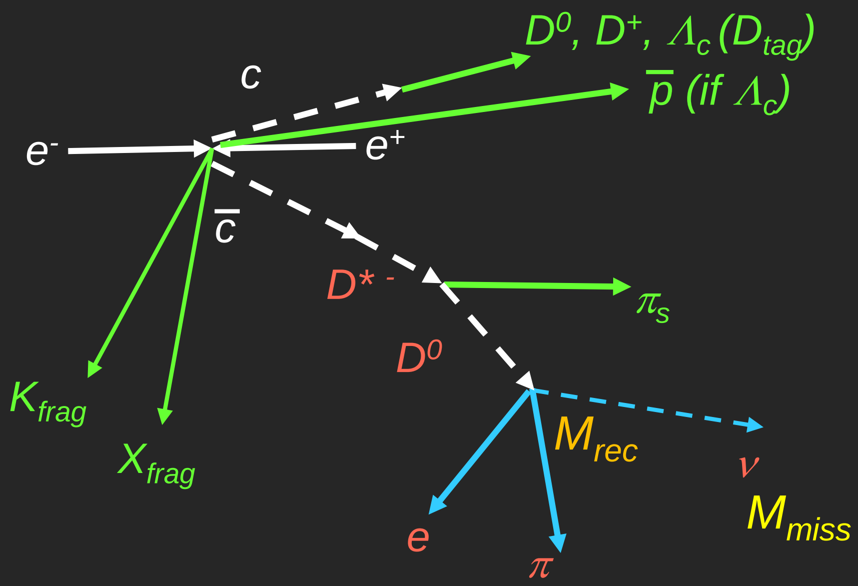
BACK

SEMILEPTONIC DECAYS

$D^0 \to K^- \mu^+ \nu$

BELLE: $N_{SIG}(D_s \to \mu^+ \nu)$ @ 1 AB^{-1} =492 ± 26

A. ZUPANC ET AL. (BELLE COLL.), JHEP 09, 139 (2013)



$$N_{sig}(D^0 \to K\mu\nu) \sim N_{sig}(D_s \to \mu\nu)\frac{\sigma(D^{*+})}{\sigma(D_s^*)}\frac{Br(D^* \to D^0\pi)}{Br(D_s^* \to D_s\gamma)}\frac{Br(D^0 \to K\mu\nu)}{Br(D_s \to \mu\nu)}\frac{\varepsilon_K\varepsilon_\pi}{\varepsilon_\gamma} \sim$$

$$\sim N_{sig}(D_s \to \mu\nu)\underbrace{\frac{\sigma(D^{*+})}{0.5\sigma(D_s)}}_{\sim 5}\underbrace{\frac{Br(D^* \to D^0\pi)}{Br(D_s^* \to D_s\gamma)}}_{\sim 0.7}\underbrace{\frac{Br(D^0 \to K\mu\nu)}{Br(D_s \to \mu\nu)}}_{\sim 6}\underbrace{\frac{\varepsilon_K\varepsilon_\pi}{\varepsilon_\gamma}}_{\sim 1} \sim 20 N_{sig}(D_s \to \mu\nu)$$

$\sigma(D^*)/\sigma(D)$

R. SEUSTER ET AL.. (BELLE COLL.), PHYS.REV. D73, 032002 (2006)

BELLE II: $N_{SIG}(D^0 \to K^- \mu^+ \nu)$ @ 20 AB^{-1} ~ $2 \cdot 10^4$

BACK