Is the CP violation observed in D decays a signal of new Physics?

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To be submitted shortly
arXiv:2410.xxxxx

LHCb observation of CP violation in D mesons

14th Nov 2011:

LHCb presents first evidence of CP violation in D decays.

$$\Delta A_{CP} \equiv A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) = (-0.82 \pm 0.21 \pm 0.11)\%$$

21st Mar 2019:

$$\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4} > 5\sigma$$

13th July 2022:

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

$$a_{+-}^{\pi\pi} = (23.2 \pm 6.1) \times 10^{-4}$$

arXiv:1404.1266 [hep-ex] Belle:

$$a_{00}^{\pi\pi} = (-3 \pm 64) \times 10^{-4}$$

$$B_{+-} = (1.454 \pm 0.024) \times 10^{-3} \qquad B_{00} = (8.26 \pm 0.25)10^{-4}$$

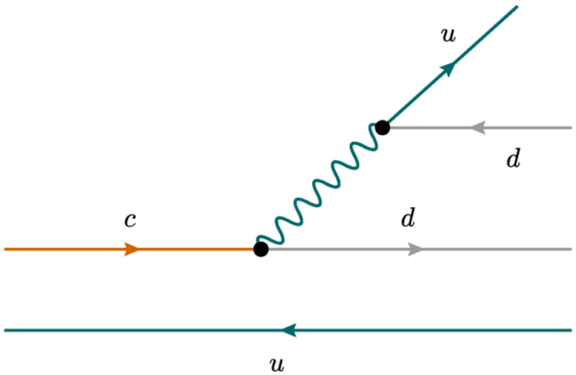
$$B_{+0} = (1.247 \pm 0.033) \times 10^{-3}$$

PDG

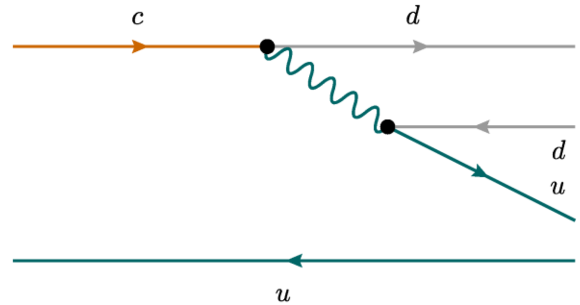
For a long time, it was believed that any CP violation seen in D-decays is a smoking gun signal of New Physics.

- *Evidence of CP violation in $D \to \pi\pi$ and $D \to KK$ has raised a debate whether the observed CPV can be regarded as a signal of NP.*
- *Confusion stems from the difficultly in reliably estimating long distance contributions & establishing that the penguin contribution is too large to be acceptable in SM.*
- *Several studies have examined the issues. No clear indications.*
- *We estimate the size of the penguin contributions directly from experimental data.*
- *Examine final-state interactions in a model independent way based only on unitarity.*

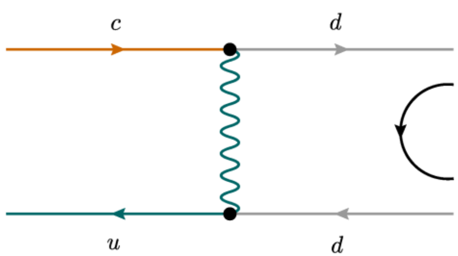
Penguin topologies



T



C



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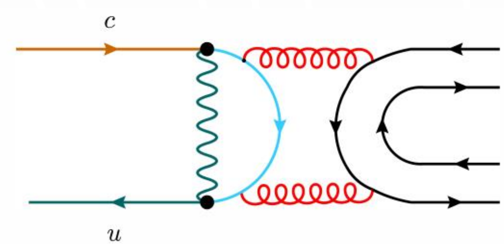
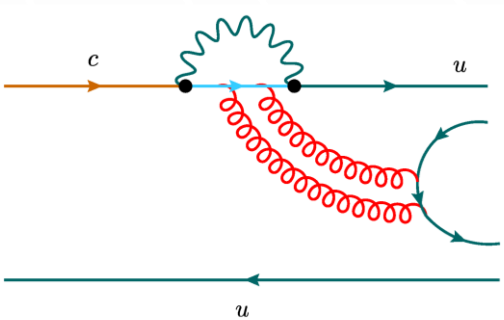
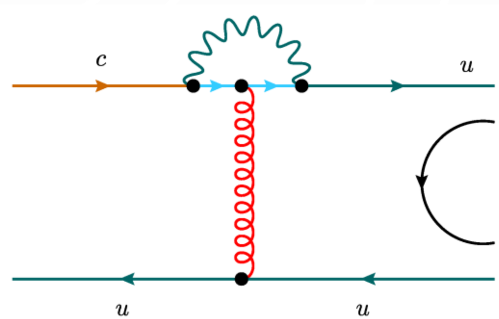


PA



P



PE

The amplitude for $D \to \pi\pi$

$$A(D^0 \to \pi^+\pi^-) = \sqrt{2}\left(\lambda_d(T+E^d)+\lambda_p(P^p+PE^p+PA^p)\right)$$

$$A(D^0 \to \pi^0\pi^0) = \left(\lambda_d(C-E^d)-\lambda_p(P^p+PE^p+PA^p)\right)$$

$$A(D^+ \to \pi^+\pi^0) = \lambda_d(T+C)$$

$$\lambda_d = V_{cd}^* V_{ud}$$

$$\lambda_s = V_{cs}^* V_{us}$$

$$\lambda_b = V_{cb}^* V_{ub}$$

Unitarity of CKM

$$\lambda_d + \lambda_s + \lambda_b = 0$$

$$\Rightarrow \lambda_b = -\lambda_d - \lambda_s$$

$$A(D^0 \to \pi^+\pi^-) \equiv A^{+-} = \sqrt{2}(t + e^{i\phi} p)$$

$$A(D^0 \to \pi^0\pi^0) \equiv A^{00} = c - e^{i\phi} p$$

$$A(D^+ \to \pi^+\pi^0) \equiv A^{+0} = (t + c),$$

$$t = |\lambda_d|\,(T + E^d + P^{db} + PE^{db} + PA^{db}),$$

$$c = |\lambda_d|\,(C - E^d - P^{db} - PE^{db} - PA^{db}),$$

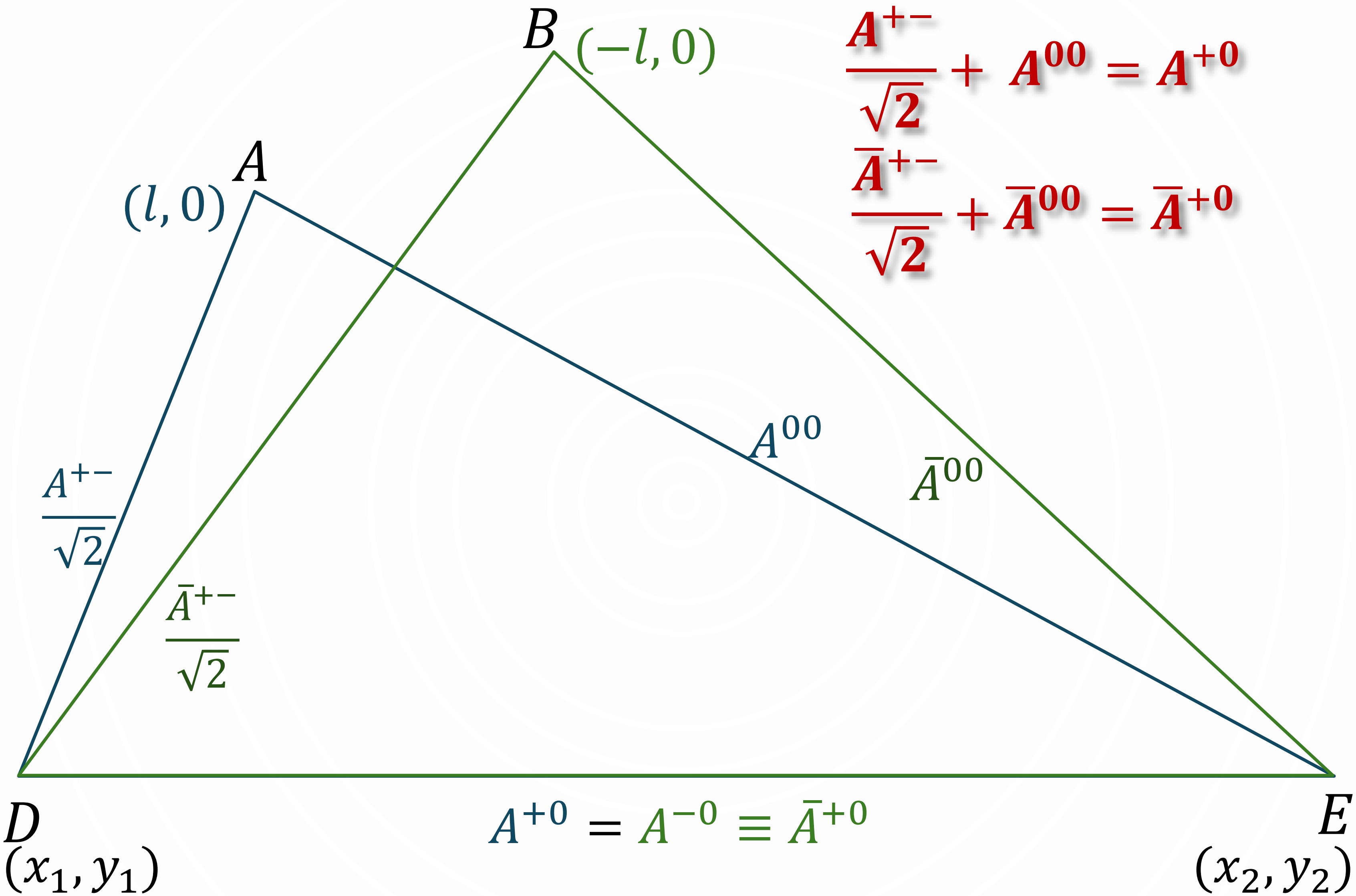
$$p = |\lambda_s|\,(P^{sb} + PE^{sb} + PA^{sb}),$$

$$X^{ij} = X^i - X^j \quad i = \{d, s\} \; j = b$$

$$\frac{1}{\sqrt{2}} A^{+-} + A^{00} = A^{+0}$$

$$\frac{A^{+-}}{\sqrt{2}} + A^{00} = A^{+0}$$

$$\frac{\bar{A}^{+-}}{\sqrt{2}} + \bar{A}^{00} = \bar{A}^{+0}$$

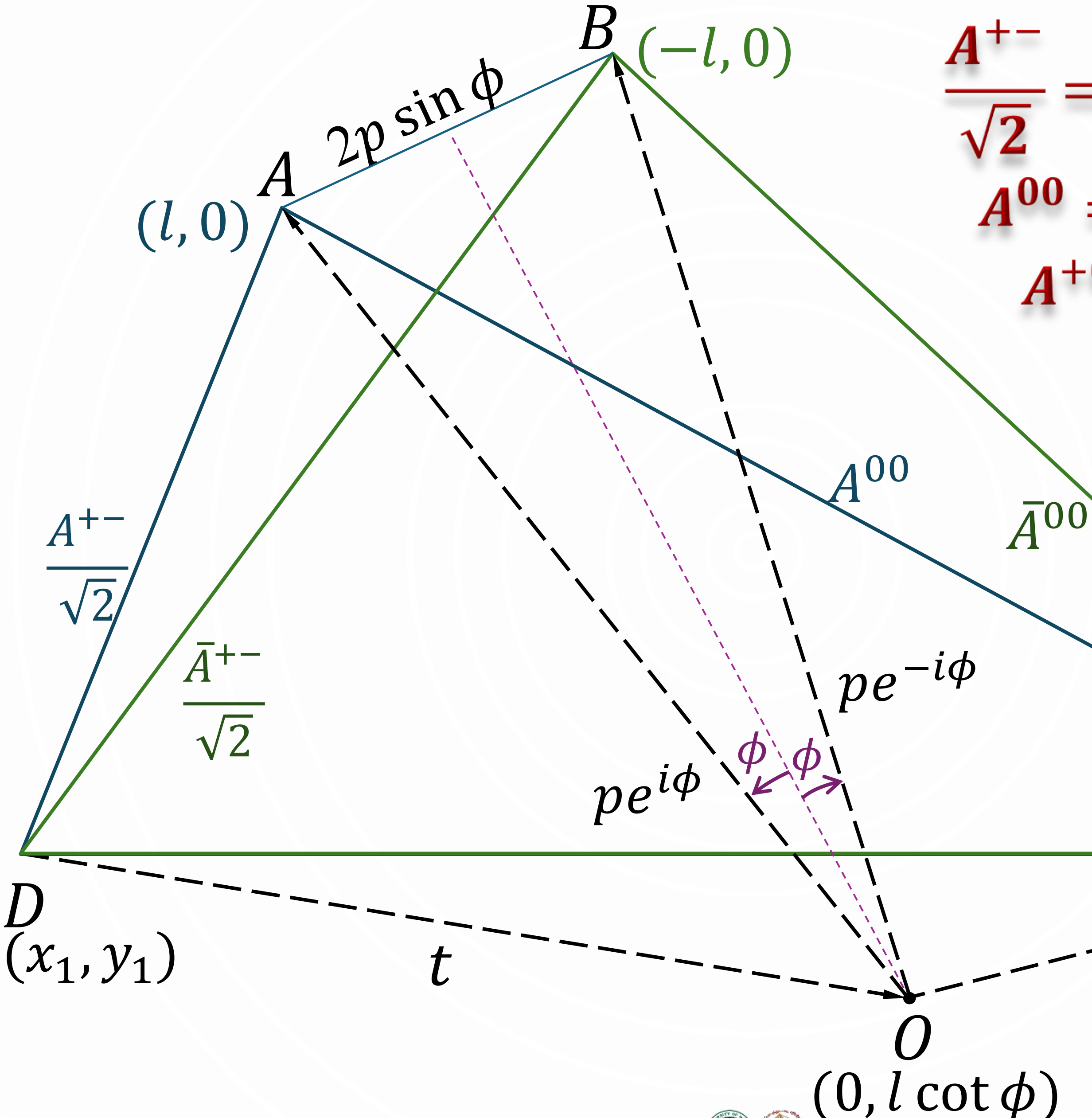


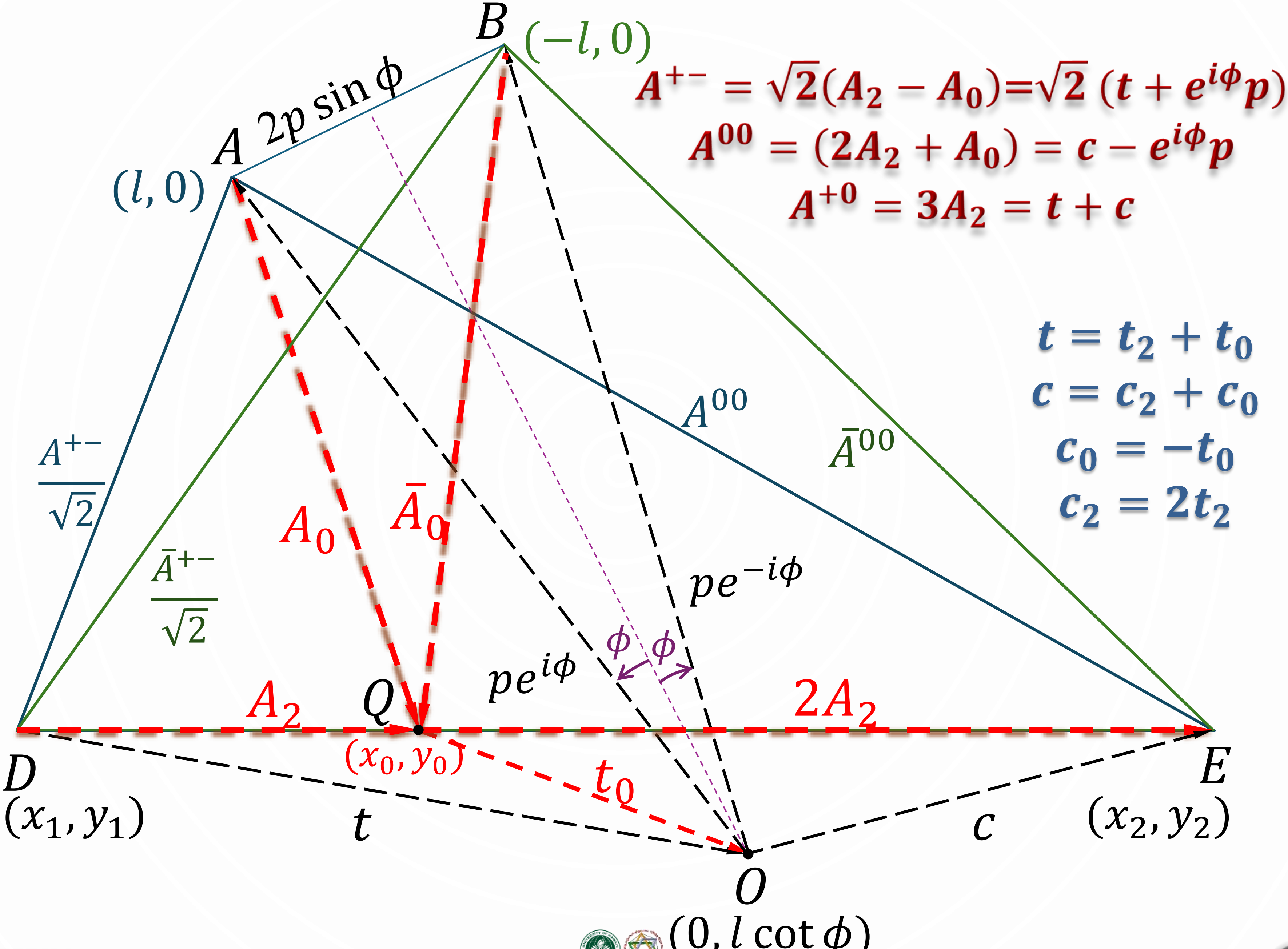
The isospin triangles for $D \rightarrow \pi\pi$ modes

$$\frac{A^{+-}}{\sqrt{2}} = (t + e^{i\phi} p)$$

$$A^{00} = c - e^{i\phi} p$$

$$A^{+0} = t + c$$





$$A^{+-} = \sqrt{2}(A_2 - A_0) = \sqrt{2}\,(t + e^{i\phi}p)$$

$$A^{00} = (2A_2 + A_0) = c - e^{i\phi}p$$

$$A^{+0} = 3A_2 = t + c$$

$$t = t_2 + t_0$$

$$c = c_2 + c_0$$

$$c_0 = -t_0$$

$$c_2 = 2t_2$$

CKM parameters

Evaluate λ_d, λ_s *in Wolfenstein parametrization up to* $\mathcal{O}(\lambda^6)$ *where* $\lambda \equiv \sin\theta_c$.

$$\lambda_d = \left(-\lambda + \tfrac{1}{2}A^2\lambda^5\left(1 - 2(\rho + i\,\eta)\right)\right)\left(1 - \tfrac{1}{2}\lambda^2 - \tfrac{1}{8}\lambda^4\right)$$
$$= (0.219113 \pm 0.000625)e^{i(-0.00063 \pm 0.000026)}$$

$$\lambda_s = \lambda\left(1 - \tfrac{1}{2}\lambda^2 - \tfrac{1}{8}\lambda^4\left(1 + 4A^2\right)\right) = 0.219045 \pm 0.000624$$

$$\lambda = 0.22501 \pm 0.00068 \qquad A = 0.826^{+0.016}_{-0.015}$$

$$\bar{\rho} = 1.591 \pm 0.0091 \qquad \bar{\eta} = 0.3523^{+0.0073}_{-0.0071}$$

SM weak phase $\phi \equiv \arg(-\lambda_s/\lambda_d)$
$$= (0.000633 \pm 0.000026)$$
$$= (0.0363 \pm 0.0015)^{\mathrm{o}}$$

Smallest weak phase & most accurately determined phase

In terms of the coordinates the observables are derived to be

$$B_{+-} = 2(x_1^2 + y_1^2) + 2\,l^2, \qquad B_{00} = (x_2^2 + y_2^2) + l^2$$

$$B_{+0} = (x_1^2 + y_1^2) + (x_2^2 + y_2^2) - 2\,x_1 x_2 - 2\,y_1 y_2,$$

$$a_{+-} = -\frac{4 x_1 p \sin\phi}{B_{+-}} \qquad a_{00} = -\frac{2 x_2 p \sin\phi}{B_{00}}$$

x_1, y_1, x_2, y_2 and l that define the coordinates can be solved in terms of the five observables

$$x_1 = -\frac{a_{+-} B_{+-}}{4\,l}, \qquad x_2 = -\frac{a_{00} B_{00}}{2\,l},$$

$$y_1 = \pm\frac{\sqrt{a_{+-}^2 B_{+-}^2 + 8 B_{+-}\,l^2 + 16\,l^4}}{4\,l},$$

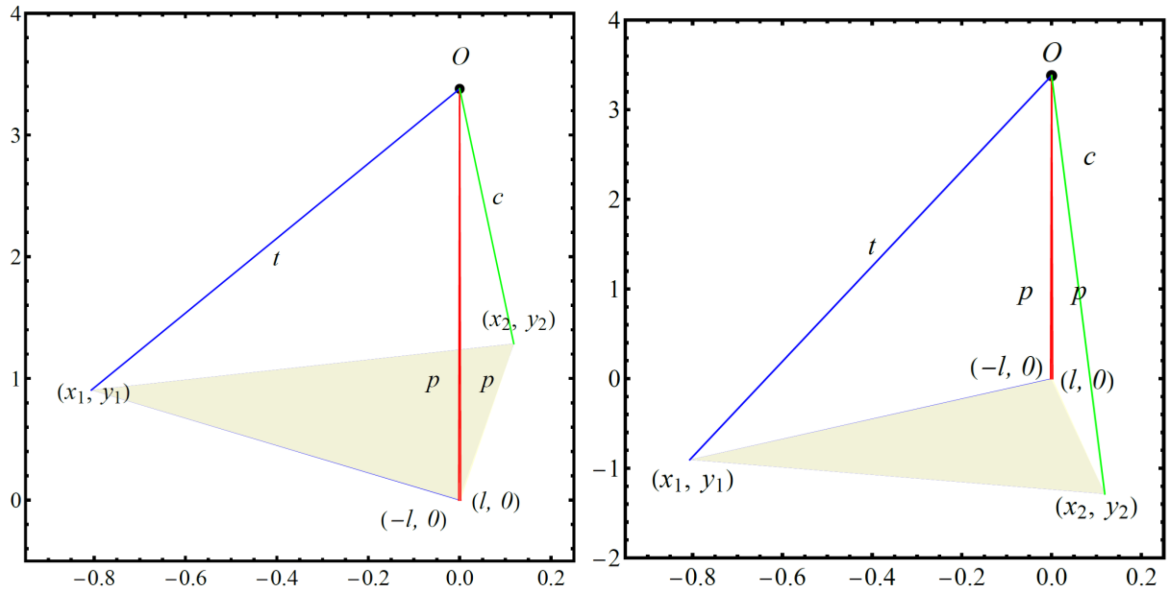
$$y_2 = \pm\frac{\sqrt{a_{00}^2 B_{00}^2 + 4 B_{00}\,l^2 + 4\,l^4}}{2\,l},$$

l^2 can be solved up to a quadratic ambiguity using the expression for B^{+0}

The amplitudes and strong phases of t, c, p, A_2, A_0, $\bar{A}_0$ and t_0 can be determined purely in terms of experimental data. write the amplitudes in terms of complex coordinate system as follows:

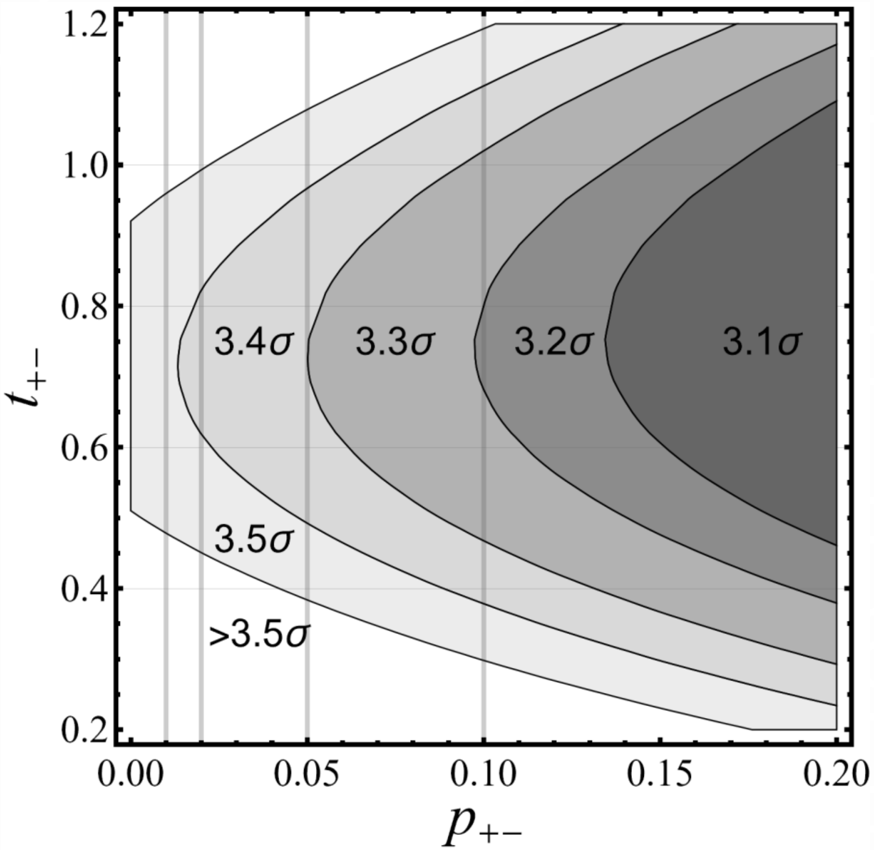
$$
\begin{aligned}
t =& -x_1 + i(l\cot\phi - y_1),\\
c =& \quad x_2 + i(y_2 - l\cot\phi),\\
p =& \qquad -i\, l\csc\phi,\\
A_0 =&(2x_1 + x_2)/3 - l + i(2y_1 + y_2)/3,\\
\bar{A}_0 =&(2x_1 + x_2)/3 + l + i(2y_1 + y_2)/3,\\
A_2 =&(-x_1 + x_2)/3 + i(-y_1 + y_2)/3,\\
t_0 =&(2x_1 + x_2)/3 + i(l\cot\phi - (2y_1 + y_2)/3)
\end{aligned}
$$

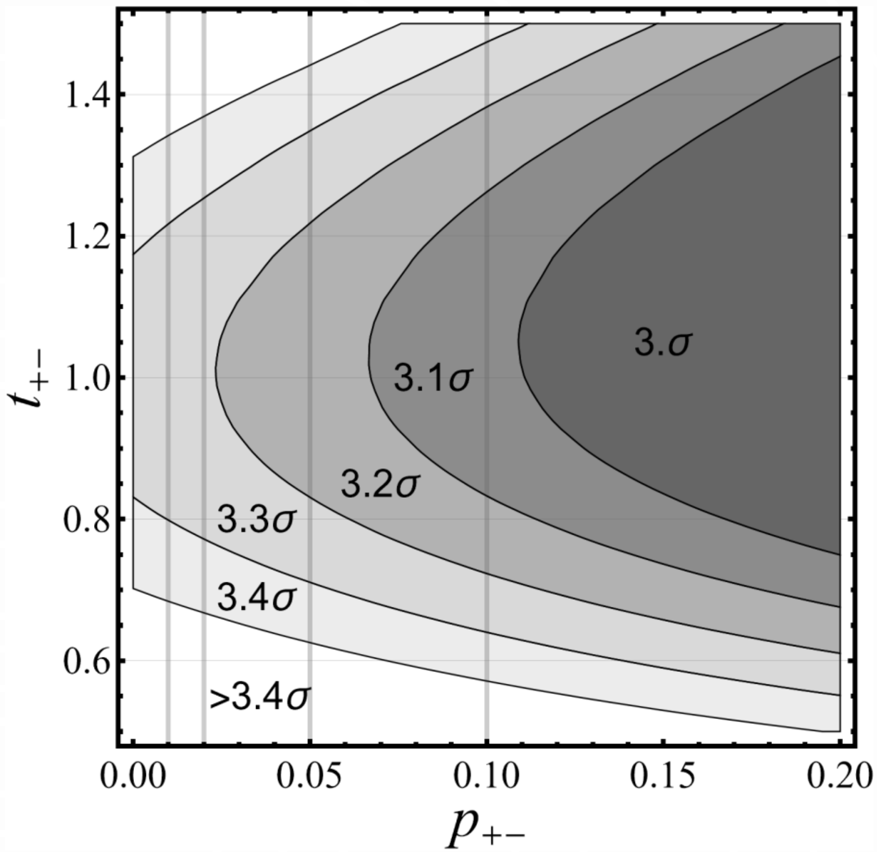
Well known that solutions have four-fold ambiguities which correspond to the relative orientation of the triangles.



Triangles representing the central values of the measured observables. Note that the triangles corresponding to mode and conjugate mode almost overlap. Only 2 triangles which have smaller penguin shown .

The amplitudes of t, c, p, A_2, A_0 and t_0 as-well-as their phases are evaluated using 200,000 points simulated data set of B_{+-}, B_{00}, B_{+0}, a_{+-}, a_{00} and ϕ.





(4.74,4.18)

(4.74,5.40)

Best fit values for (p_{+-}, t_{+-})

$p_{+-} = 4.74^{+3.72}_{-2.83}$ 1σ

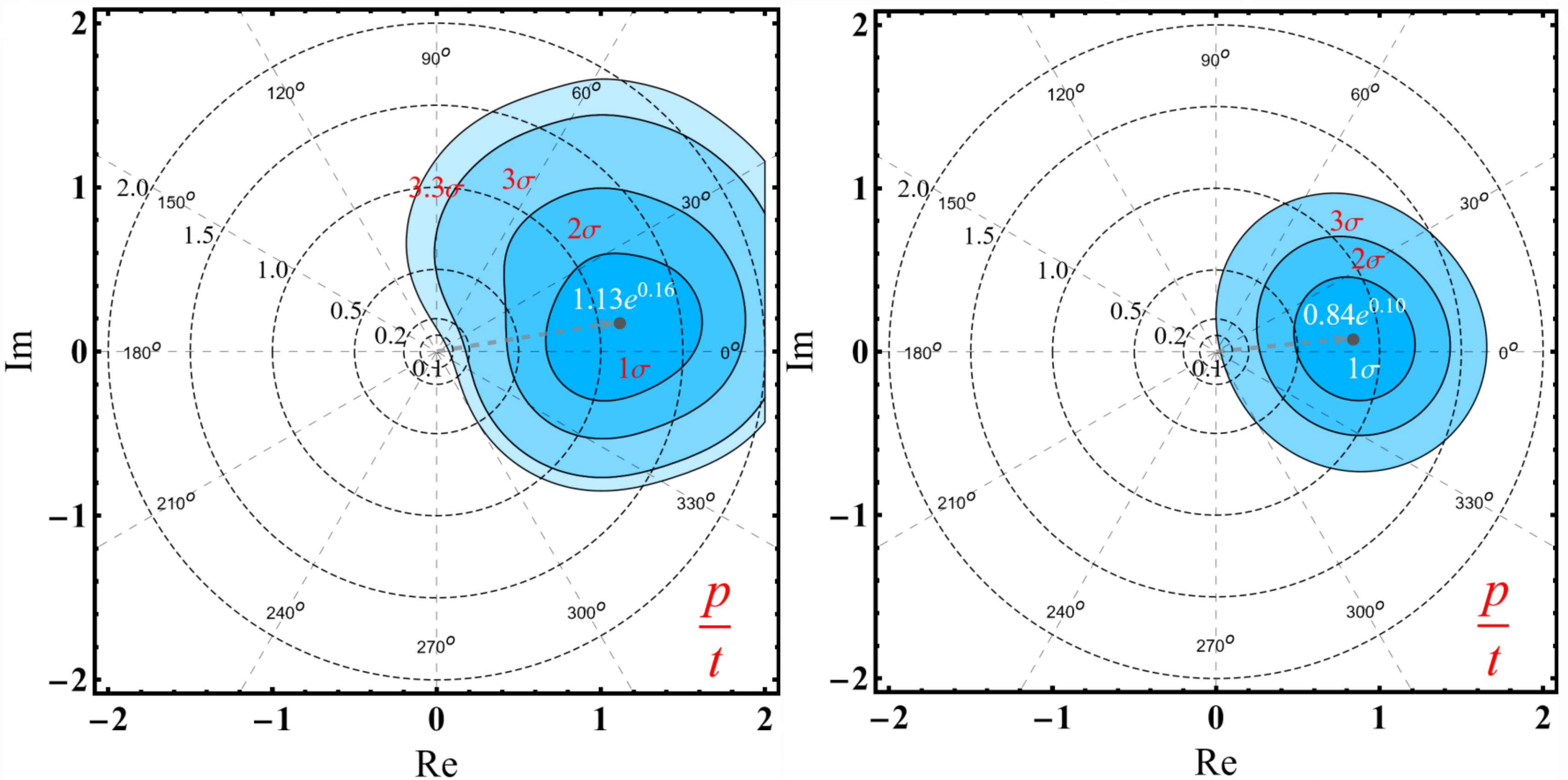
$p_{+-} = 4.74^{+5.56}_{-3.25}$ 2σ

$$p_{+-} = \frac{p}{\sqrt{B_{+-}}}$$

$$t_{+-} = \frac{t}{\sqrt{B_{+-}}}$$

$p_{+-} = 4.74^{+3.75}_{-2.84}$ 1σ

$p_{+-} = 4.74^{+5.58}_{-3.26}$ 2σ



$\frac{p}{t}$ *corresponding to the two triangle orientations are shown.*
Note that small values of $\frac{p}{t} = 0.1$ *are possible only at* $\sim 3\sigma$.

Khodjamirian & Petrov: Estimate $p_{+-} = (0.09 \pm 0.01)$, *using light cone sum rule technique.*

- *Since momentum flowing through the penguin loop are of order* $1GeV$ *or larger perturbative calculation of loop is reasonable.*
- *Convincing arguments on the broad reliability of these estimates have been made in literature.*

Final state interactions might alter size of the penguin contributions. Examine effects of final state interactions in a model independent way and draw general conclusions.

In two-body scattering of n-coupled channels a convenient parametrization of a unitary S-matrix is in terms of the K-matrix.

$$S(s) = \left(1 - iK(s)\right)^{-1}(1 + iK(s))$$

$K(s)$ *is a* $n \times n$ *hermitian matrix and* $s = m_D^2$.

A set of "n" un-unitarized weak decay amplitudes $A^O(s)$ are unitarized into a set $A^U(s)$ through multichannel final state interactions via matrix equation,

$$A^U(s) = \left(1 - iK(s)\right)^{-1} A^O(s)$$

Since strong interactions conserve isospin, has to be written for each isospin

Let U be a unitary matrix that diagonalizes the hermitian matrix K with real eigenvalues λ_i $(i = 1, \ldots, n)$.

$$\Rightarrow \sum_i^n A_i^{U\dagger} A_i^U(s) = \sum_i^n (UA^O)_i^\dagger \left(1 + \lambda_i^2\right)^{-1} (UA^O)_i$$

$$\Rightarrow \sum_i^n \left|A_i^U\right|^2 \leq \sum_i^n \left|A_i^O\right|^2 \qquad \because \lambda_i \text{ are real}$$

The sum of transition probabilities after interchannel mixing cannot exceed the sum before mixing.

- *Penguin amplitudes "p" has a weak phase ⇒ cannot receive contributions from amplitudes that do not have a weak phase.*

$$\Rightarrow \sum_{i}^{n} |p_i^U|^2 \leq \sum_{i}^{n} |p_i^O|^2$$

Unitarity condition applies separately to the p amplitudes.

- *If anomaly of large penguin contributions arises from within the SM, one must generate large penguin contributions in at least one of the channels that re-scatters to produce the observed asymmetries. This is a far cry within the SM.*

Impossible therefore that re-scattering could account for the large penguins and the observed CP asymmetries.

Including NP contributions

- *Justifiable in SM to ignore electroweak penguins* (p_{EW}).
- *In the presence of NP,* p_{EW} *can be sizable. In such a case we cannot solve for all the parameters.*
- *Direct CP asymmetry measured in the* $D^+ \to \pi^+\pi^0$ *mode* $a_{+0} = (4.0 \pm 8.0) \times 10^{-3}$.
- *Since* A^{+0} *and* $\bar{A}^{+0}$ *can differ maximum by* 0.012 *at* 1σ, *two triangles may not in principle share a common base.*
- *However, this difference is a small given the estimate of penguin contributions.*
- *To a very good approximation we can assume that p includes* p_{EW} *contributions if any in all our estimations.*

NP amplitude $Ne^{i\phi_{NP}}$ *can be rewritten such that*

$$Ne^{i\phi_{NP}} \equiv N_1 + N_2 e^{i\phi}$$

$$\Longrightarrow N_1 = N\cos\phi_{NP} - N\cot\phi\sin\phi_{NP}$$

$$N_2 = N\csc\phi\sin\phi_{NP}$$

N_1 *must be clubbed with* t *and* N_2 *with* p *so that the weak phases are aligned.* $\Rightarrow$ *both* t *and* p *get altered by NP.*

Relative strong phase

$$p_{+-}^{\rm obs} = (p_{+-}^{\rm SM} + N_{+-}e^{i\delta_{NP}}\csc\phi\sin\phi_{NP})e^{i\phi},$$

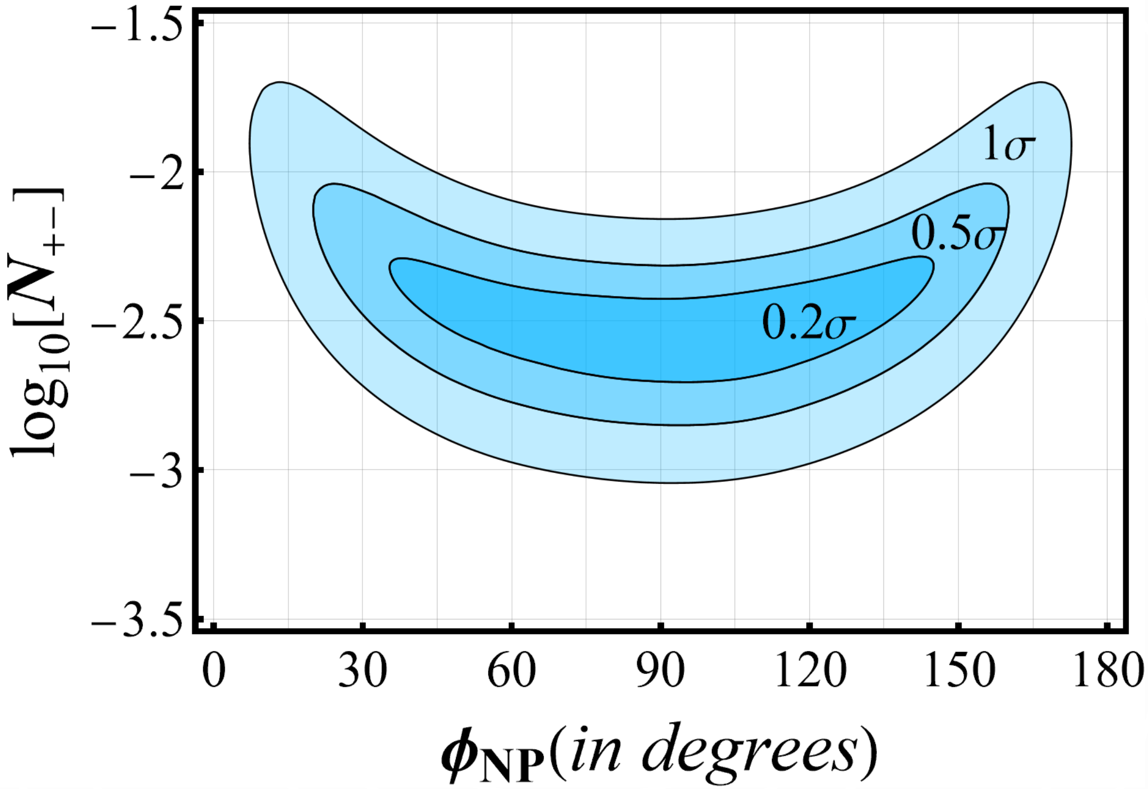
Normalized to $\sqrt{B_{+-}}$

$$(p_{+-}^{\rm obs})^2 = (p_{+-}^{\rm SM})^2 + 2N_{+-}p_{+-}^{\rm SM}\cos\delta_{NP}\csc\phi\sin\phi_{NP} + N_{+-}^2\csc^2\phi\sin^2\phi_{NP}$$

Obtained from data

Estimated to be 0.09 ± 0.01

Solve for N_{+-}

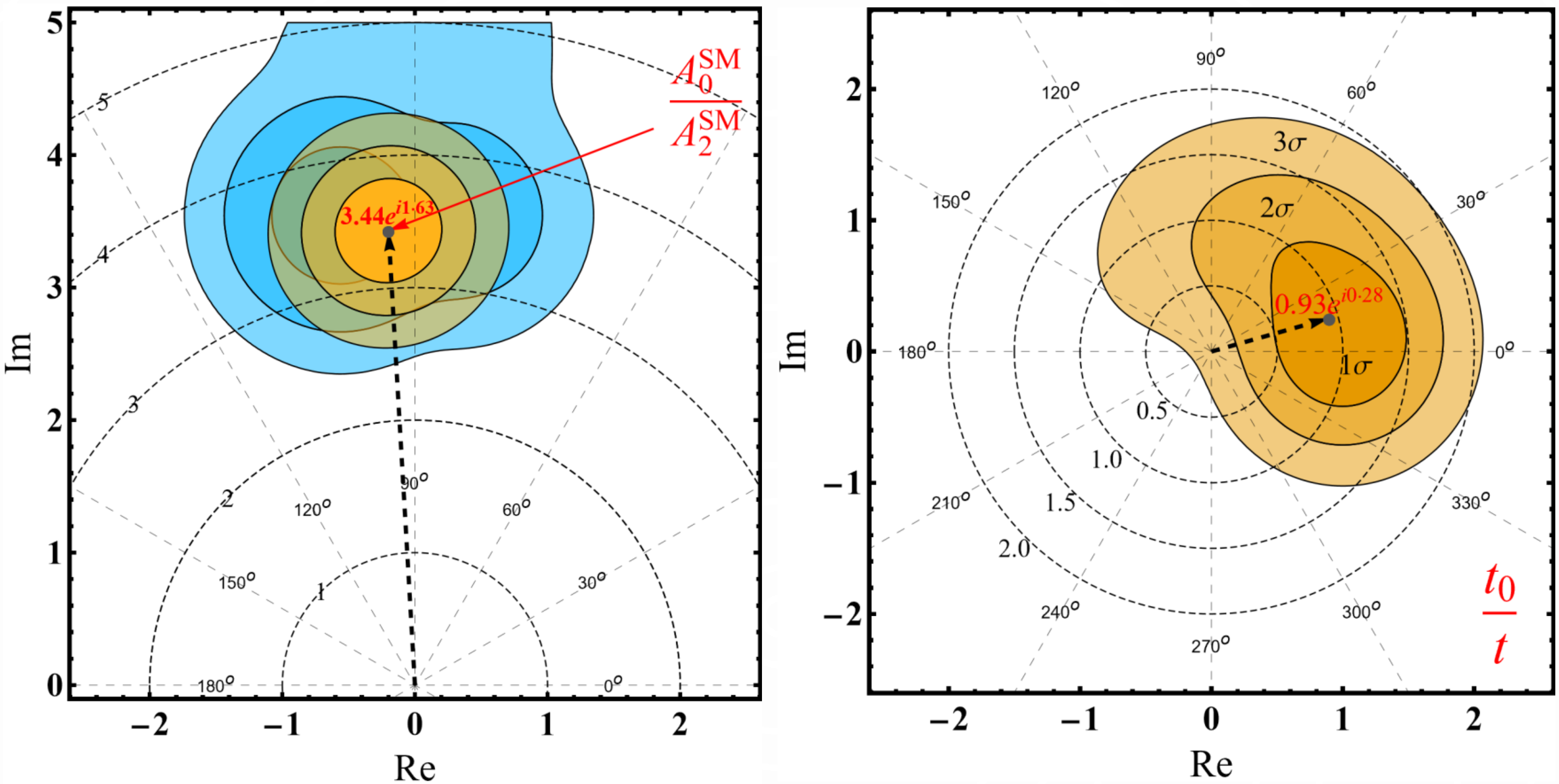


Contours for $\log_{10}[N_{+-}]$ versus ϕ_{NP} (in degrees). It is easy to see that reasonable value of N_{+-} smaller than p_{+-} can result in large observed penguin and CP violation.

Conclusions

- *Data indicates that* $p_{+-} \approx 0.1$ *is at least* 3σ *away from the estimated value indicating an unacceptably large penguin contribution.*
- *Reasonable value of* N_{+-} *smaller than* p_{+-} *can result in large observed penguin and CP violation.*
- *If central values of* $D \to \pi\pi$ *observables do not change, we have a clear evidence of NP.*

Thanks



$\frac{A_0^{SM}}{A_2^{SM}}$
$3.44e^{i1.63}$
Im
Re
3σ
2σ
1σ
$0.93e^{i0.28}$
$\frac{t_0}{t}$