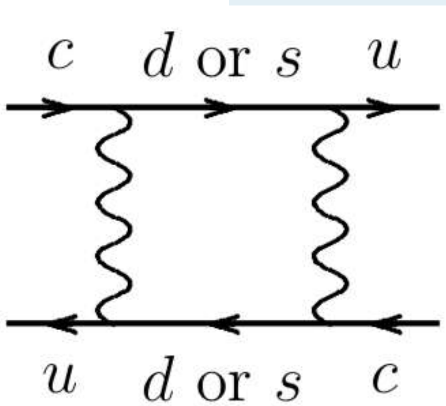
The ΔA_{CP} saga continues

What have we learnt in theory from the ΔA_{CP}

Alexander Lenz

IPPP Durham

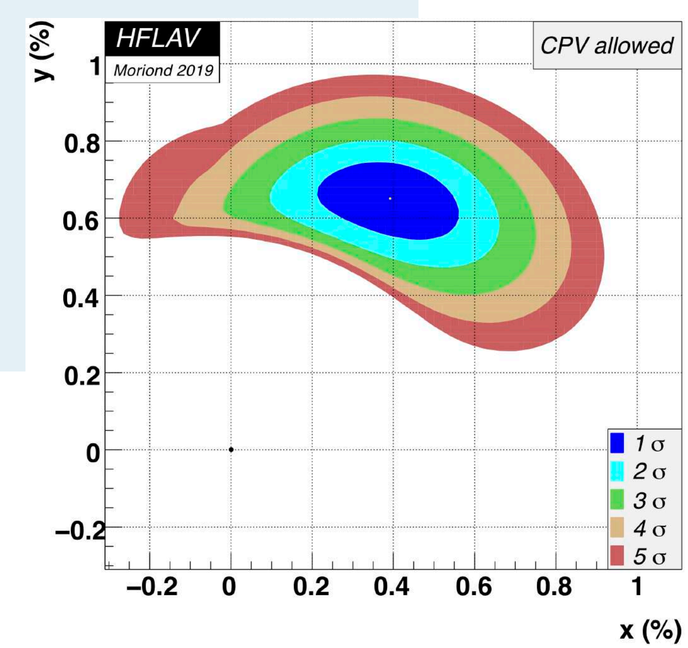


Alexander Lenz, IPPP Durham

17th September 2019

NP at lowE precision frontier

Orsay



Content

Charm Physics for pedestrians

SAGALAND

Charm Theory is notoriously difficult

Nelson plot

Delta I = 1/2

THE REAL WORLD

Charm Lifetimes

Charm Mixing

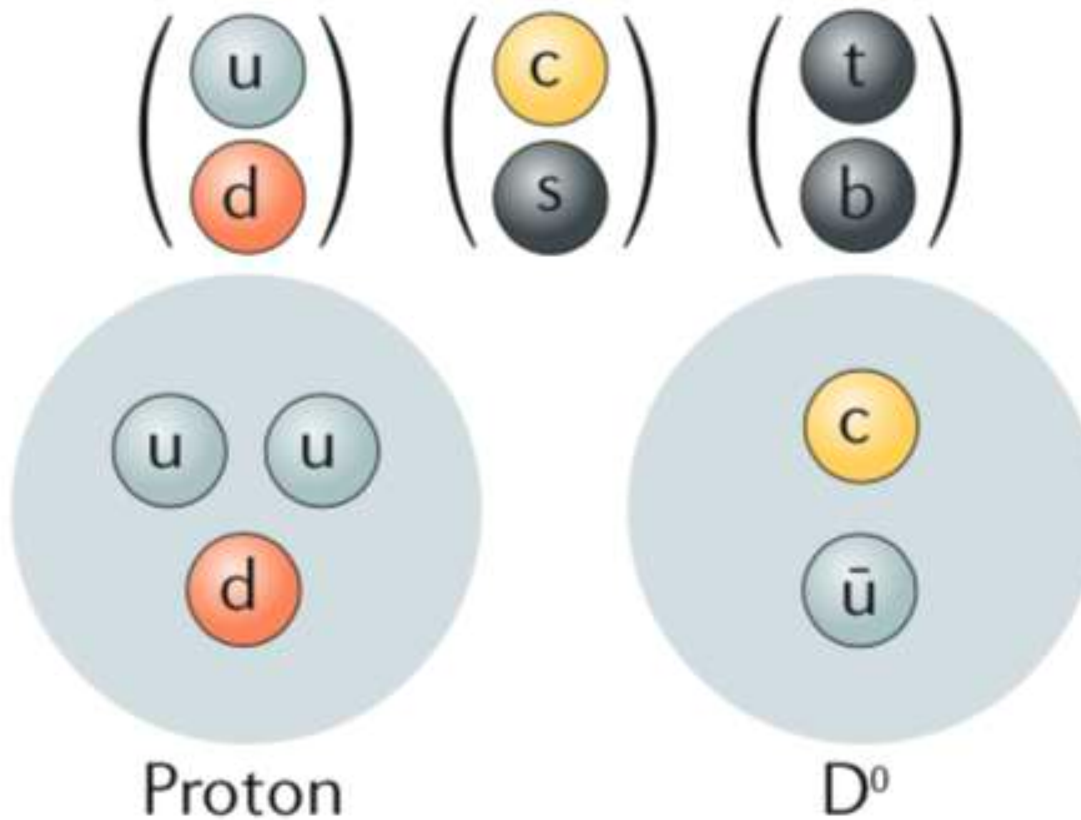
Delta A_CP - LCSR

Outlook

Short summary

- I do not claim that I can proof a BSM origin of Delta A_CP
- I claim theory predictions in the charm system have an unjustified bad reputation - but they are much harder than theory predictions in the beauty sector
- I claim there is no evidence for assuming generally order 10 non-perturbative effects in the charm system
- There are many ways in order to improve the reliability of charm predictions
- It is worthwhile considering BSM explanations of Delta A_CP

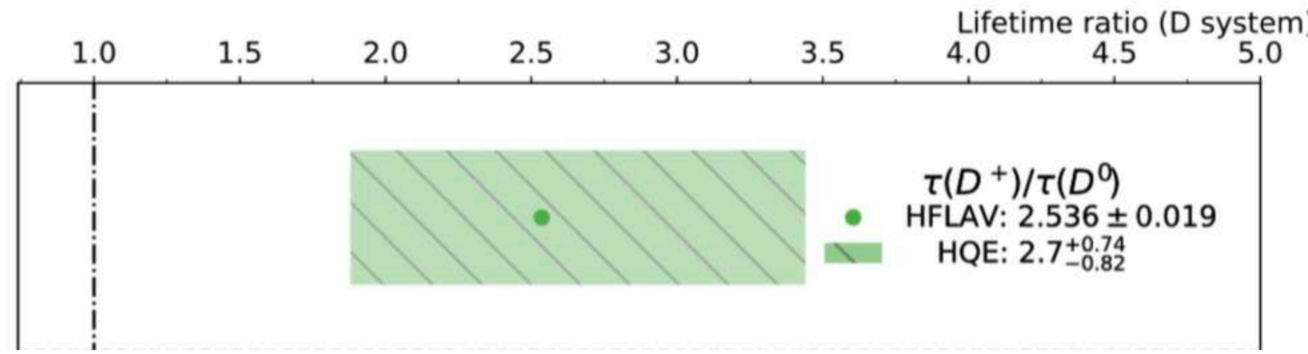
Charm physics



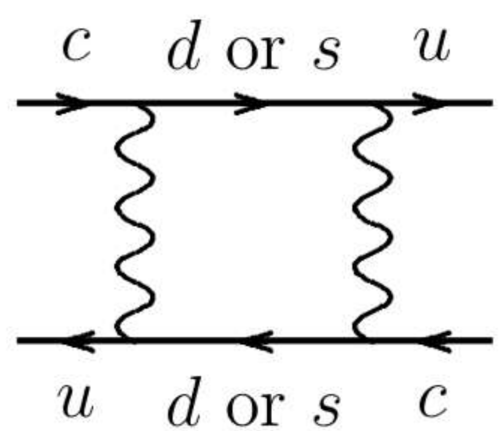
	$D^0 = (\bar{u}c)$	$D^+ = (\bar{d}c)$	$D_s^+ = (\bar{s}c)$	$\Lambda_c = (udc)$
Mass (GeV)	1.86486	1.86962	1.96850	2.28646
Lifetime (ps)	0.4101	1.040	0.500	0.200

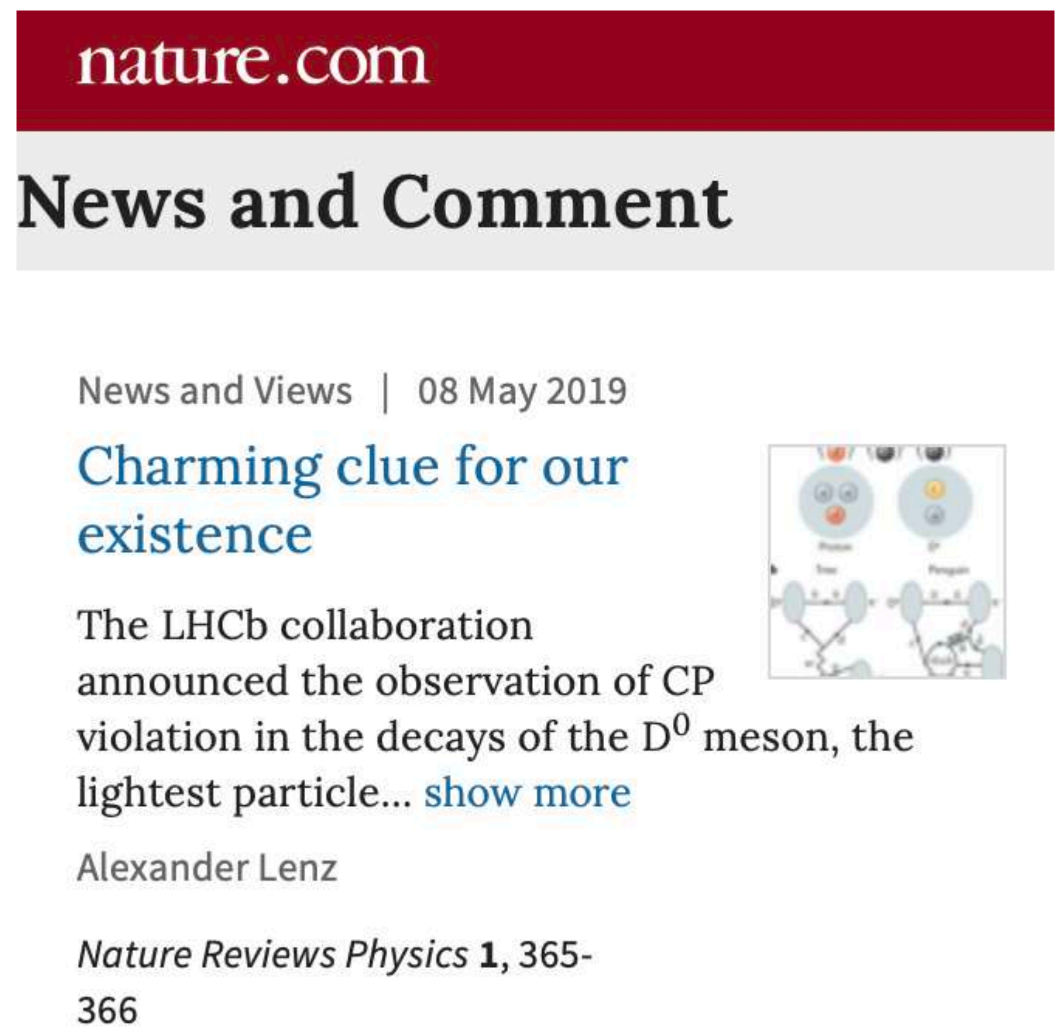
Charm physics

Charm lifetimes



Charm Mixing




nature.com

News and Comment

News and Views | 08 May 2019

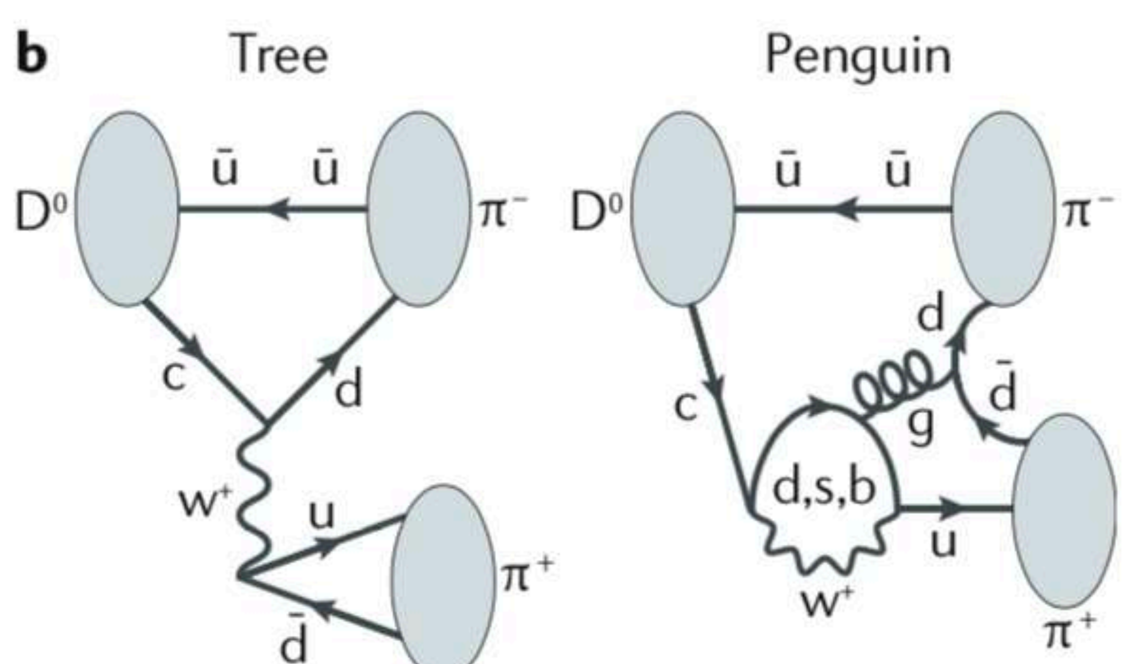
Charming clue for our existence

The LHCb collaboration announced the observation of CP violation in the decays of the D^0 meson, the lightest particle... show more

Alexander Lenz

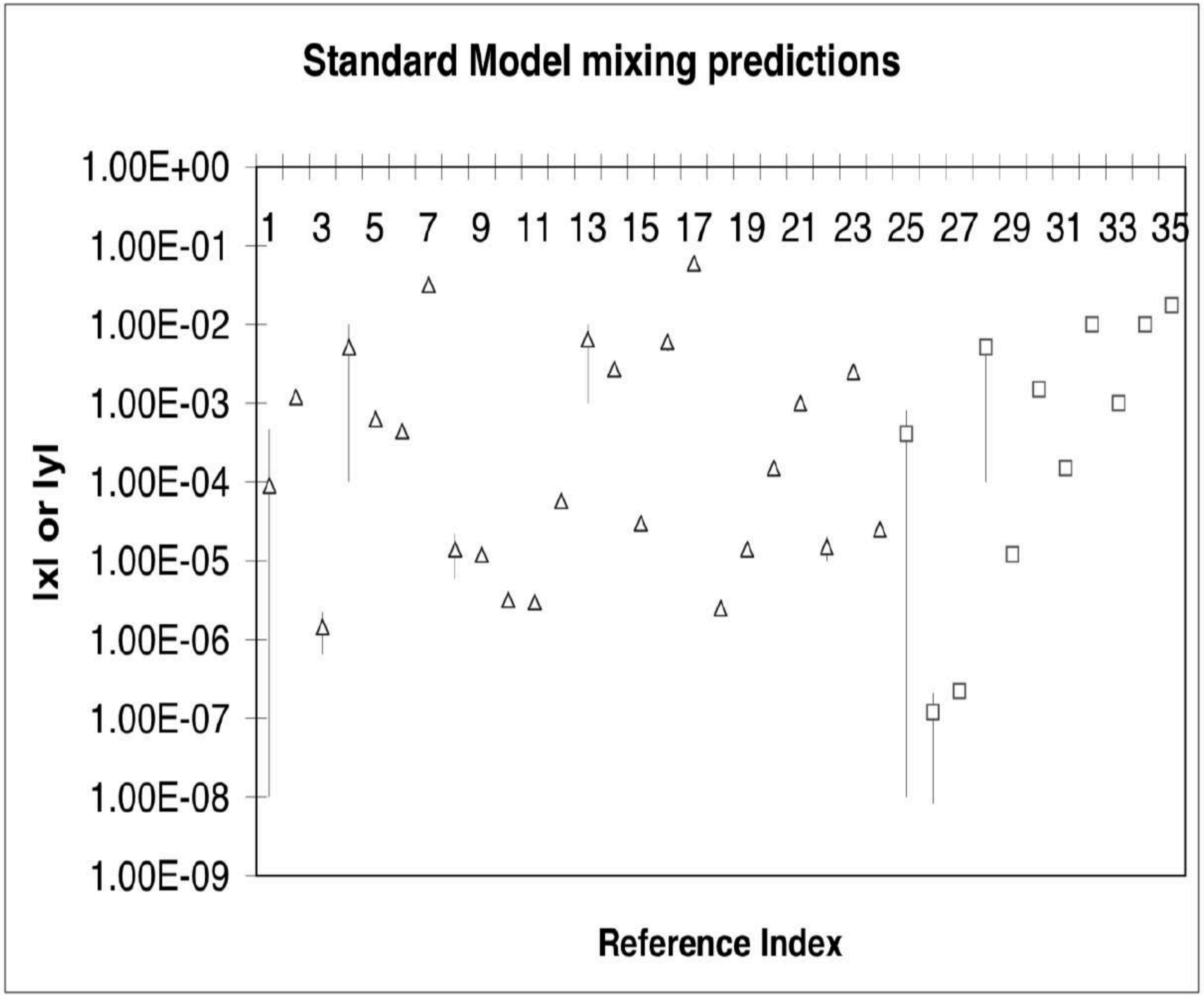
Nature Reviews Physics **1**, 365-366

Delta A_CP



Welcome to Sagaland

Charm theory is notoriously difficult

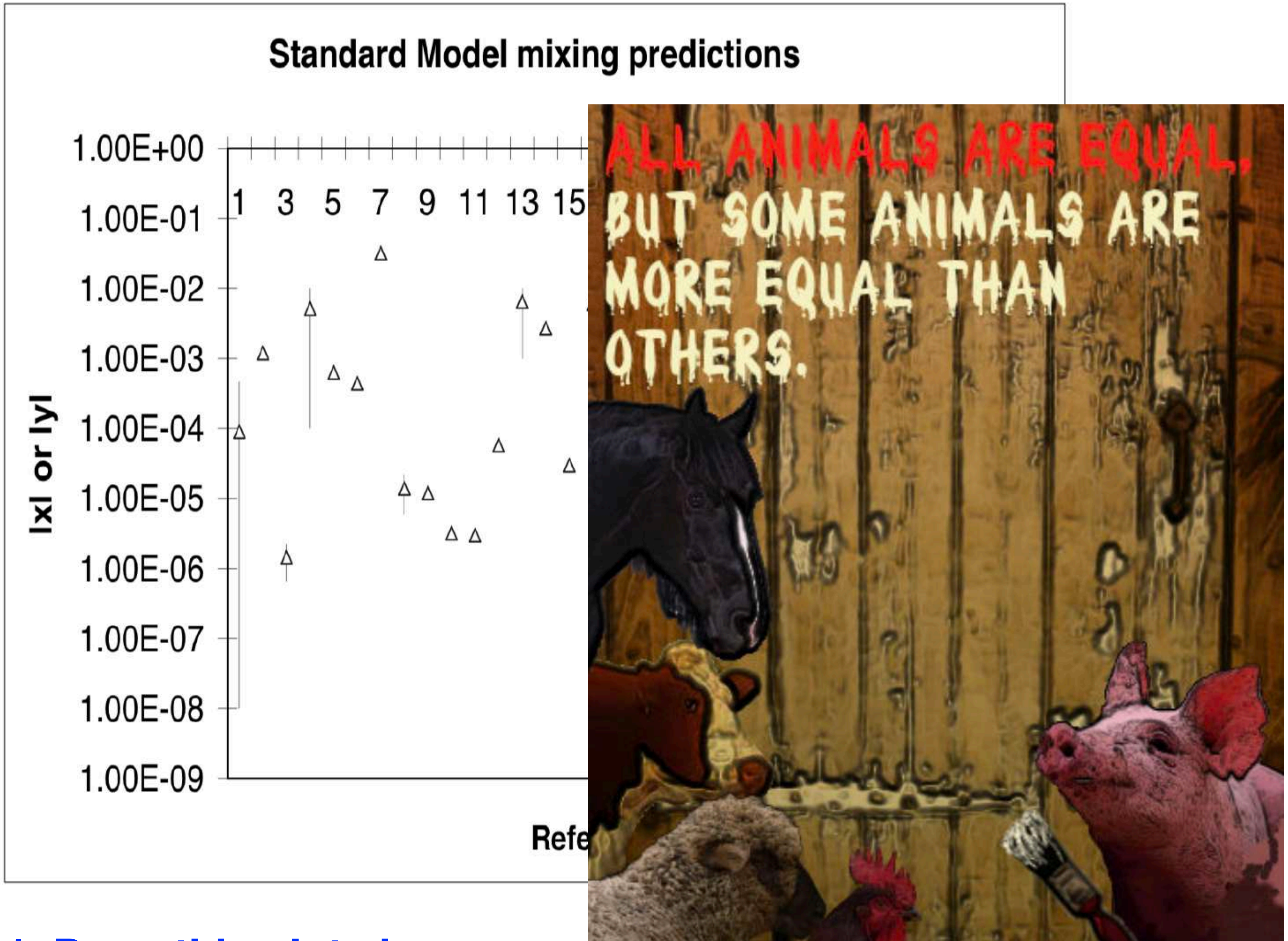


modified
Nelson plot
from A. Petrov
hep-ph/0311371

Q1: Does this plot show

a) the ignorance of the theorists trying to calculate D mixing within the SM
b) the ignorance of the person showing this plot
c) or is just for entertainment?

Charm theory is notoriously difficult



modified Nelson plot from A. Petrov hep-ph/0311371

Q1: Does this plot show

a) the ignorance of the theorists trying to calculate D mixing within the SM
b) the ignorance of the person showing this plot
c) or is just for entertainment?

Charm theory is notoriously difficult

Delta I =1/2 rule

top quark mass. Following an early suggestion [4] that the penguin amplitude in D decays

1

may be enhanced by nonperturbative effects in analogy to the $s \to d$ penguin amplitude in $K \to \pi\pi$, recent studies [2, 3, 5] indicate that an order of magnitude enhancement is not impossible.

CP asymmetries in singly-Cabibbo-suppressed D decays to two pseudoscalar mesons

Bhubanjyoti Bhattacharya (Montreal U.), Michael Gronau (Technion), Jonathan L. Rosner (Chicago U., EFI & Chicago U.). Jan 2012. 13 pp.

Published in **Phys.Rev. D85 (2012) 054014, Phys.Rev. D85 (2012) no.7, 079901**
UDEM-GPP-TH-12-205, TECHNION-PH-12-1, EFI-12-1
DOI: 10.1103/PhysRevD.85.079901, 10.1103/PhysRevD.85.054014
e-Print: **arXiv:1201.2351 [hep-ph] | PDF**

Charm theory is notoriously difficult

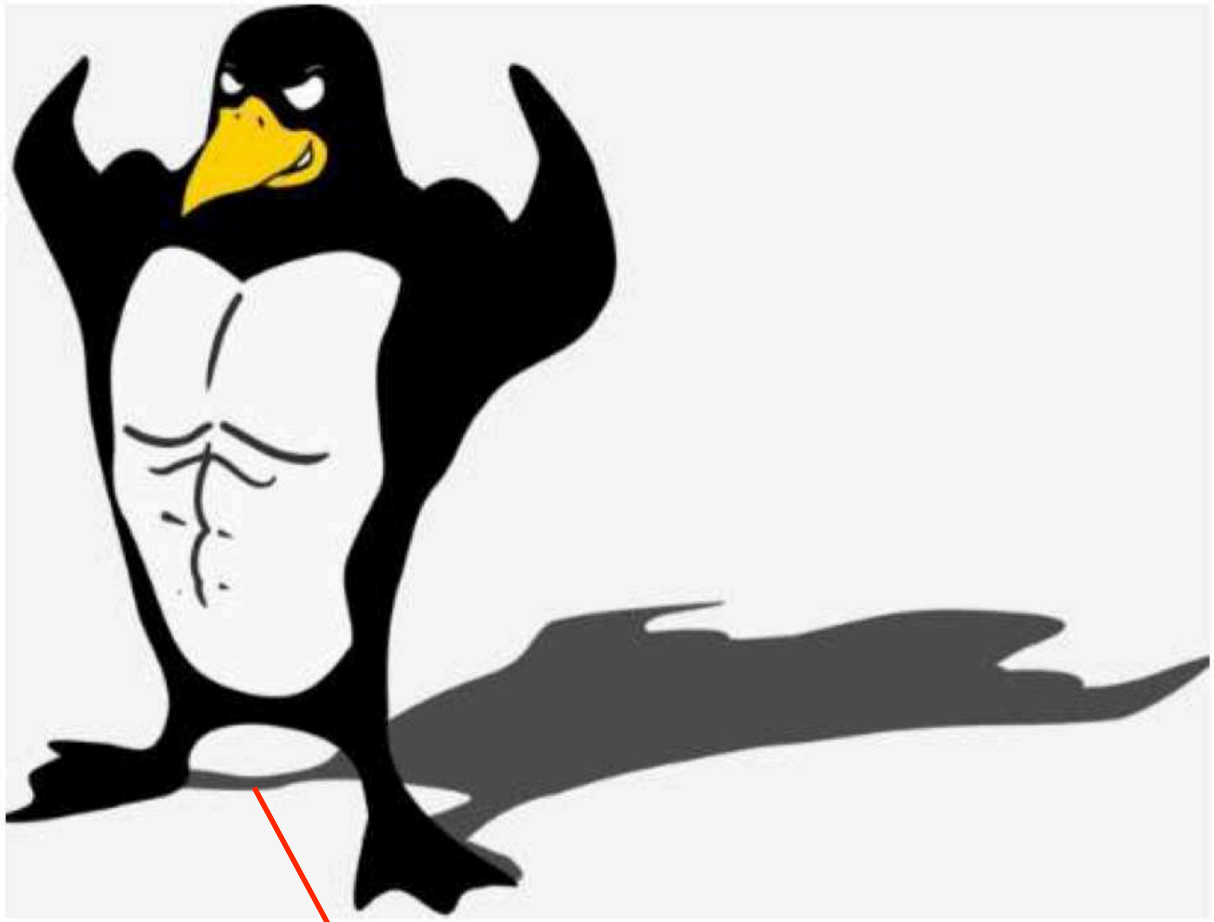
Delta I =1/2 rule

For the decay of a neutral kaon into two pions, the CP-conserving amplitude with a final $I = 0$ state ($\Delta I = 1/2$) is measured to be [2]

$$\text{Re } A_0(K^0 \to 2\pi) = 3.33 \times 10^{-7}\,\text{GeV}\,, \tag{1.1}$$

and it is approximately 22 times larger than that with the pions in the $I = 2$ state ($\Delta I = 3/2$):

$$\text{Re } A_2(K^0 \to 2\pi) = 1.50 \times 10^{-8}\,\text{GeV}\,. \tag{1.2}$$



About a factor of ten larger compared to perturbative estimates

Maybe penguins in the charm system are also a factor of 10 larger than naive expectations

Charm theory is notoriously difficult?

Delta I =1/2 rule

Lattice: Enhancement seems to come from cancellation of tree level contributions in Re A_2 and not from enhancements of penguins In Re A_0

Seems not to tell anything about about the possible size of non-perturbative contributions in the charm system

What can tell us anything about about the possible size of non-perturbative contributions in the charm system?

1212.1474

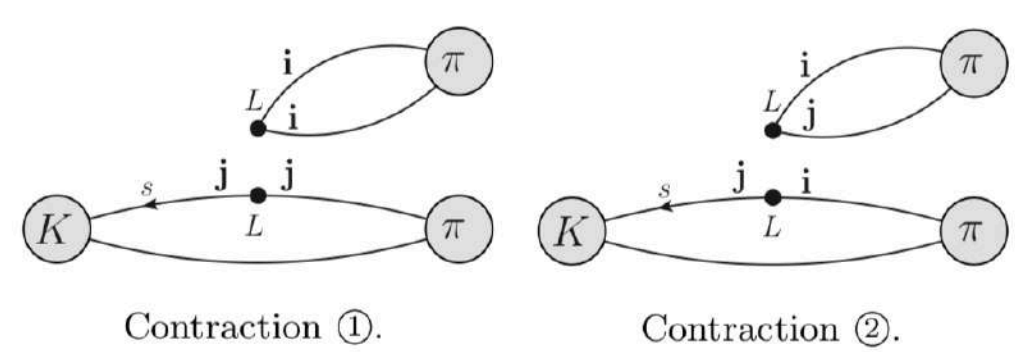


FIG. 1: The two contractions contributing to ReA_2. They are distinguished by the color summation ($\mathbf{i}, \mathbf{j}$ denote color). s denotes the strange quark and L that the currents are left-handed.

1505.7863

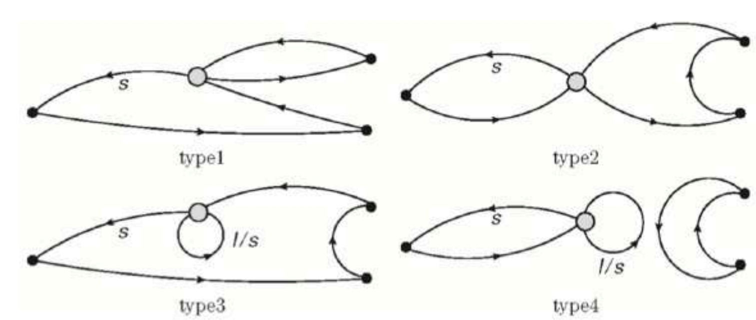


FIG. 1. Examples of the four types of diagram contributing to the $\Delta I = 1/2$, $K \to \pi\pi$ decay. Lines labeled ℓ or s represent light or strange quarks. Unlabeled lines are light quarks.

Welcome to the real world

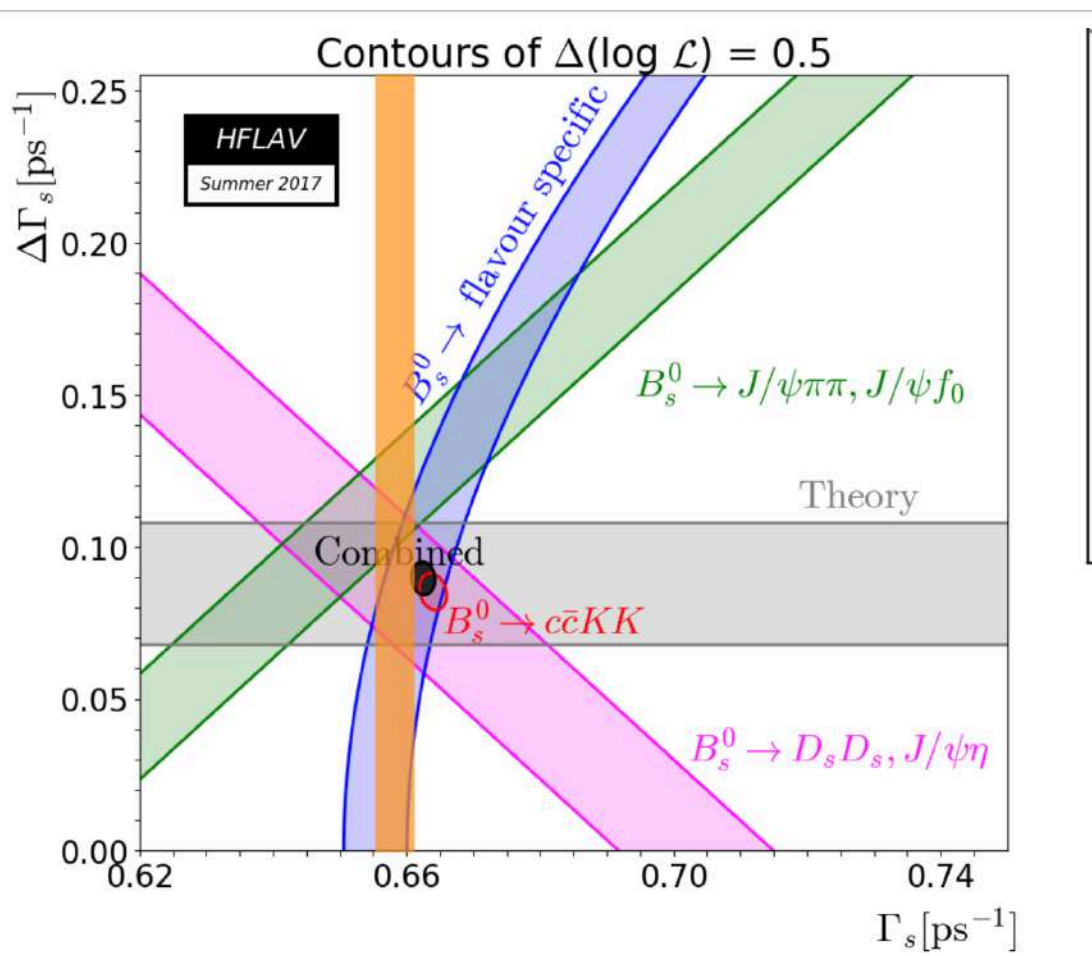
Charm Theory 1

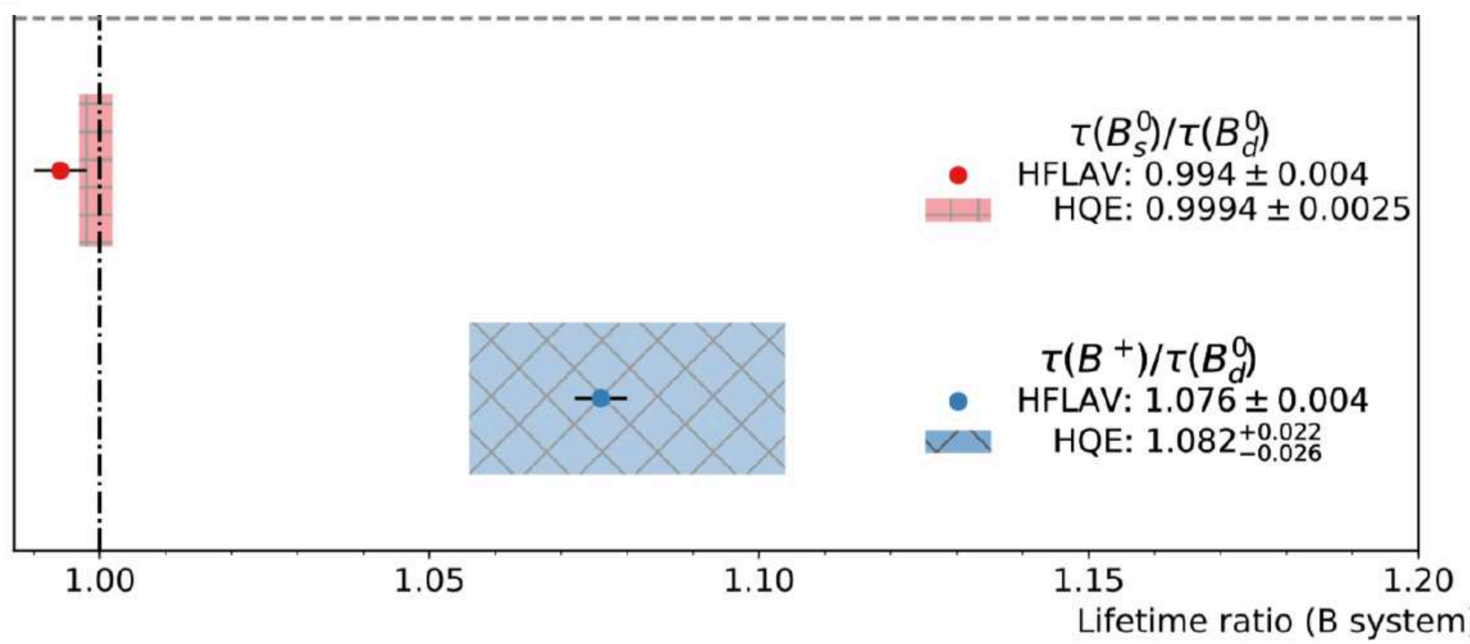
Voloshin, Shifman 1983, 1985
Bigi, Uraltsev 1992
Bigi, Uraltsev, Vainshtein 1992
Blok, Shifman 1992

The Heavy Quark Expansion

Expansion of inclusive decay rates in Λ/m_Q

The HQE works well in the B-system





Kirk, AL, Rauh 1711.02100

Charm Theory 1

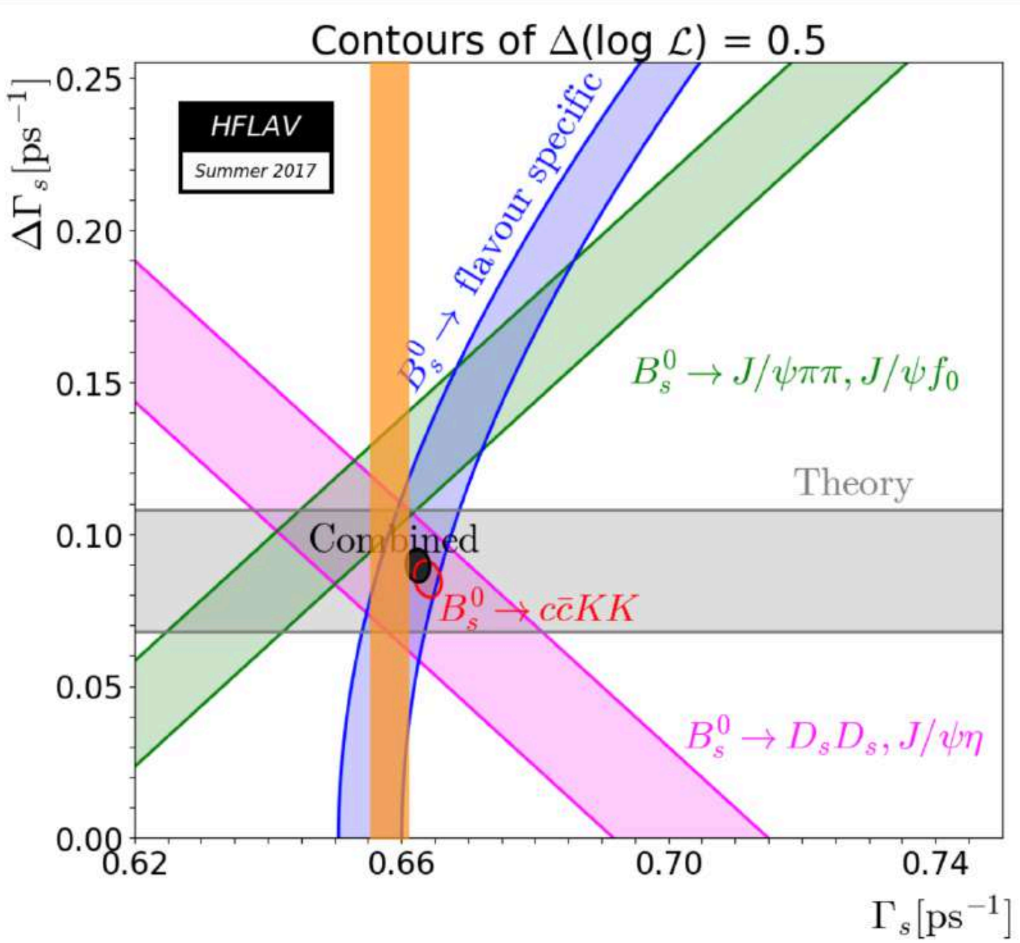
The Heavy Quark Expansion

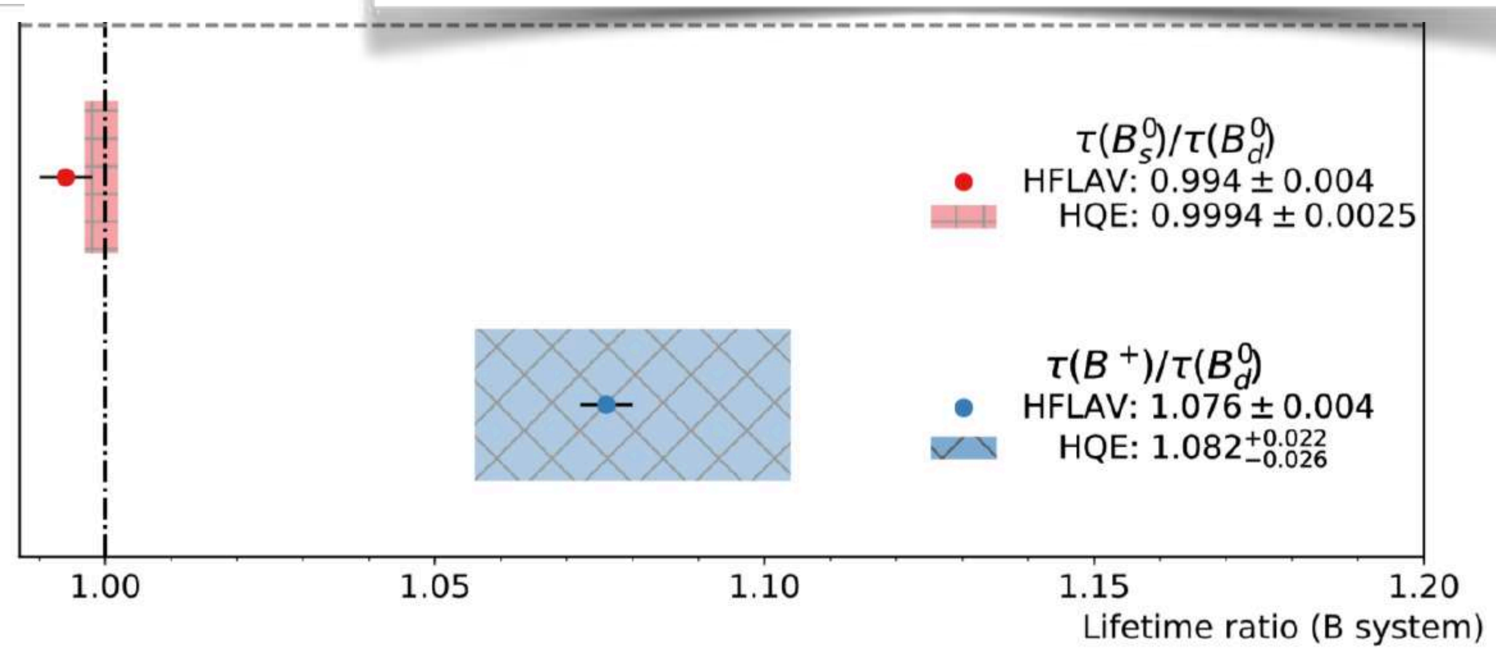
Voloshin, Shifman 1983, 1985
Bigi, Uraltsev 1992
Bigi, Uraltsev, Vainshtein 1992
Blok, Shifman 1992

Expansion of inclusive decay rates in Λ/m_Q

The HQE works well in the B-system

$$\frac{\Lambda}{m_b} \propto \mathcal{O}(0.1) \quad \overset{m_b \approx 3m_c}{\Longrightarrow} \quad \frac{\Lambda}{m_c} \propto \mathcal{O}(0.15)$$





Kirk, AL, Rauh 1711.02100

Charm Theory 2

HQE $$\frac{1}{\tau} = \Gamma = \Gamma_0 + \frac{\Lambda^2}{m_c^2}\Gamma_2 + \frac{\Lambda^3}{m_c^3}\Gamma_3 + \frac{\Lambda^4}{m_c^4}\Gamma_4 + \ldots$$

Each term can be split up into
a perturbative Wilson coefficient and a non-perturbative matrix element

$$\Gamma_i = \left[\Gamma_i^{(0)} + \frac{\alpha_S}{4\pi}\Gamma_i^{(1)} + \frac{\alpha_S^2}{(4\pi)^2}\Gamma_i^{(2)} + \ldots,\right]\langle O^{d=i+3}\rangle$$

For mixing a similar expansion holds - starting at the third order

$$\Gamma_{12} = \frac{\Lambda^3}{m_c^3}\tilde{\Gamma}_3 + \frac{\Lambda^4}{m_c^4}\tilde{\Gamma}_4 + \ldots$$

Charm Theory 3

Mark Williams
@QuarkWilliams

Following

How much can I trust theoretical predictions? Finally the star-based rating system I've been waiting for! Thanks @alexlenz42! arxiv.org/pdf/1809.09452…

A + for each independent calculation
At most ++
At most +++ for <>: 2 lattice, 1 sum rule
Punishment: A - - for no <Q6>
A 0 for quark model et al for <Q6>

Obs.	$\Gamma_3^{(0)}$	$\Gamma_3^{(1)}$	$\Gamma_3^{(2)}$	$\langle O^{d=6} \rangle$	$\Gamma_4^{(0)}$	$\Gamma_4^{(1)}$	$\langle O^{d=7} \rangle$	Σ
$\tau(B^+)/\tau(B_d)$	++	++	0	+	++	0	0	** (7+)
$\tau(B_s)/\tau(B_d)$	++	++	0	$\frac{+}{2}$	++	0	0	** (6.5+)
$\tau(\Lambda_b)/\tau(B_d)$	++	$\frac{+}{2}$	0	$\frac{+}{2}$	+	0	0	** (4+)
$\tau(b-baryon)/\tau(B_d)$	++	0	0	0	+	0	0	* (3+)
$\tau(B_c)$	+	0	0	+	0	0	0	* (2+)
$\tau(D^+)/\tau(D^0)$	++	++	0	+	++	0	0	** (7+)
$\tau(D_s^+)/\tau(D^0)$	++	++	0	$\frac{+}{2}$	++	0	0	** (6.5+)
$\tau(c-baryon)/\tau(D^0)$	++	0	0	0	+	0	0	* (3+)

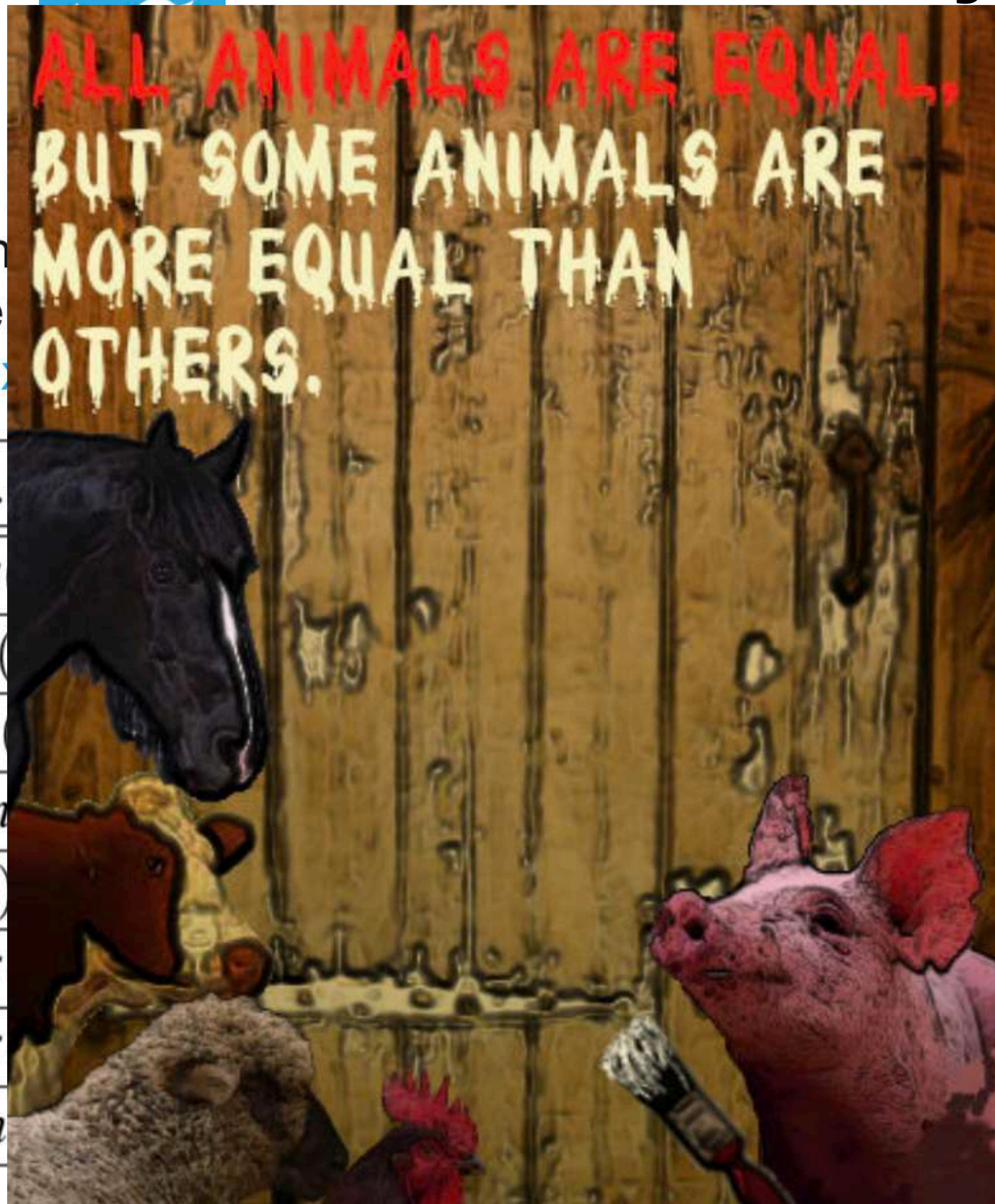
Hai-Yang Cheng 1807.00916

****: 12-15 ***: 8 -11.5 **: 4-7.5 *: 2-3.5

Charm Theory 4

Mark Williams
@QuarkWilliams

How much can
predictions? Fin
system I've bee
@alexlenz42! ar



ndependent calculation

for <>: 2 lattice, 1 sum rule
A - - for no <Q6>
k model et al for <Q6>

Obs.	$\langle O^{d=7}\rangle$	Σ
$\tau(B^+)/\tau$	0	** (7+)
$\tau(B_s)/\tau$	0	** (6.5+)
$\tau(\Lambda_b)/\tau$	0	** (4+)
$\tau(b-baryon$	0	* (3+)
$\tau(B_c)$	0	* (2+)
$\tau(D^+)/\tau$	0	** (7+)
$\tau(D_s^+)/\tau$	0	** (6.5+)
$\tau(c-baryon$	0	* (3+)

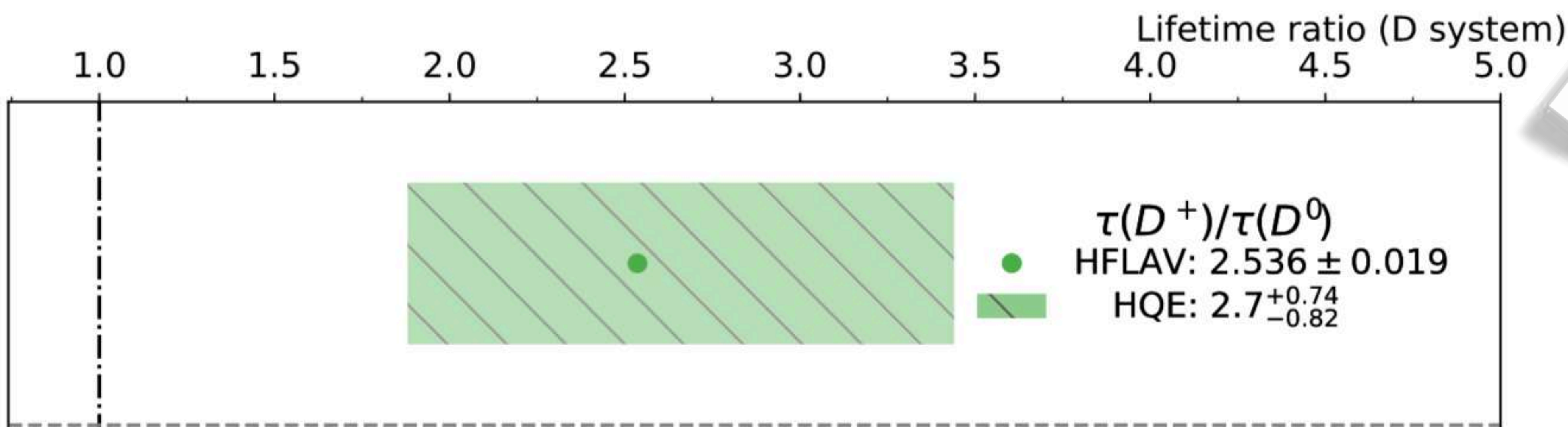
Hai-Yang Cheng

****: 12-15 *** 8 -11.5 **: 4-7.5 *: 2-3.5

Charm Theory 5

$\Lambda/m_c \approx 3\Lambda/m_b$ - could still give some reasonable estimates!

Look in systems without GIM cancellation: D-lifetimes



NEW 3-loop sum rules

$$\frac{\tau(D^+)}{\tau(D^0)} = 2.7 = 1 + 16\pi^2\,(0.25)^3\,(1 - 0.34)$$

Kirk, AL, Rauh 1711.02100

pert. NLO-QCD:

AL, Rauh 1305.3588

Expansion parameter for HQE in charm = 0.3
not a back of envelope statement, but real calculations

d=6 calculated with sum rules
lattice confirmation urgently needed

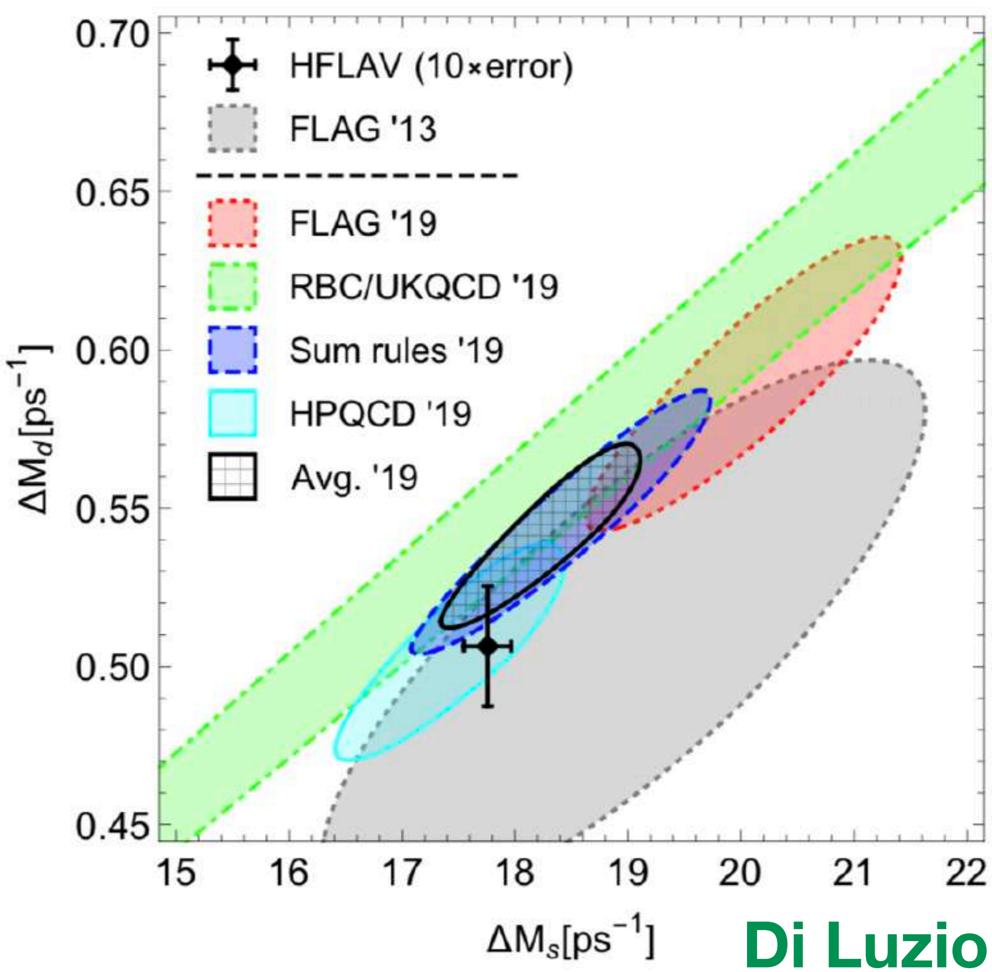
d=7 estimated in vacuum insertion approximation
do sum rule/lattice

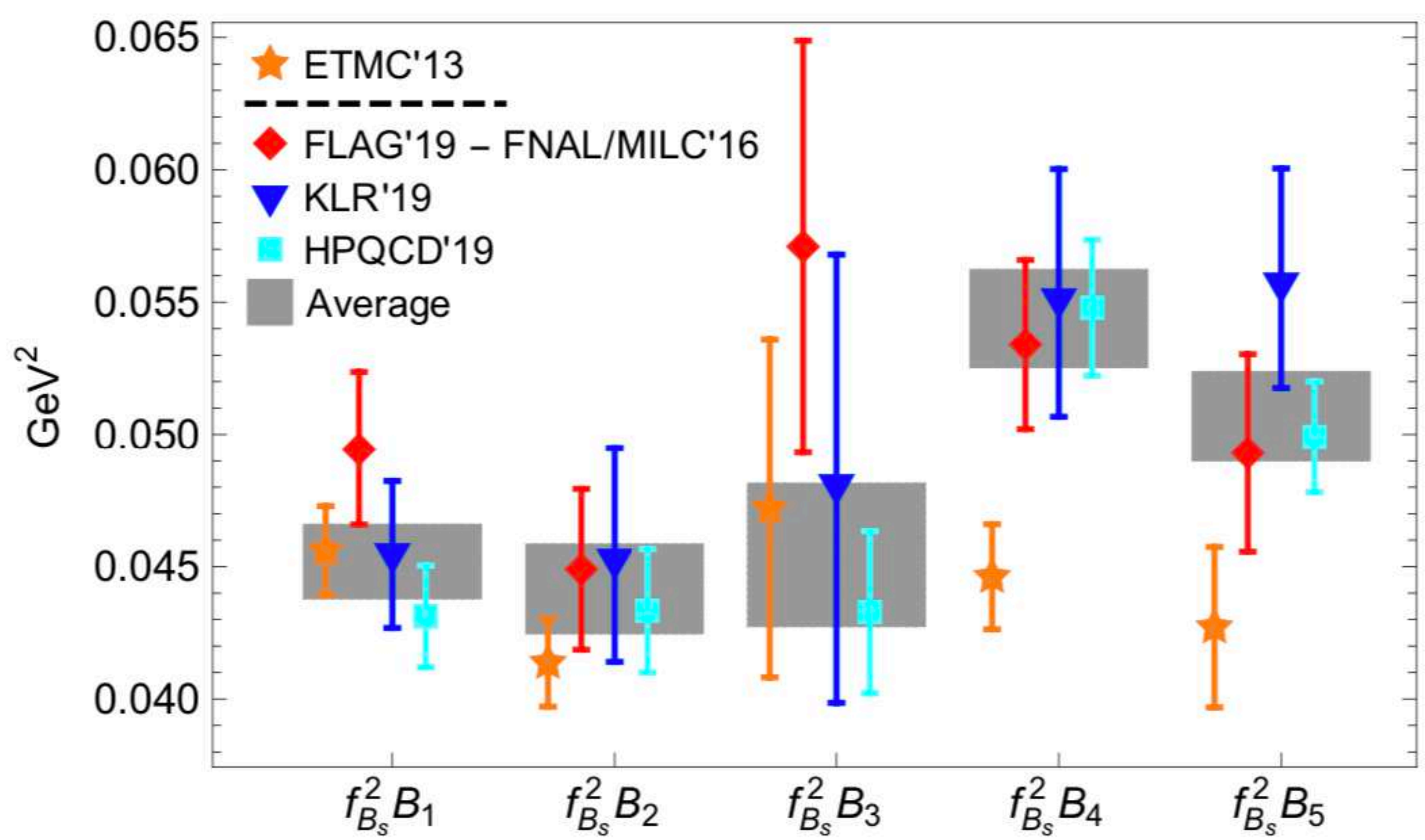
Charm Theory 6

Impressive confirmation of HQET sum rules by lattice:

The same methods can be used for B mixing

- **pre 2016: Delta Ms SM like, large uncertainties**
- **FNAL/MILC (1602.03560): Delta Ms 2 sigma above experiment; dramatic consequences for BSM models (One constraint to kill them all, 1712/06572)**
- **HQET sum rules (1606.06054, 1711.02100, 1904.00940) do not confirm the large FNAL/MILC values**
- **Average with most recent lattice (HQPCD 1907.01025) confirms sum rules**





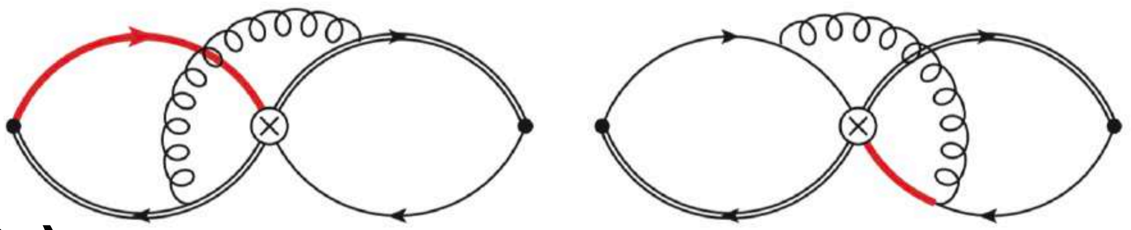
Di Luzio, Kirk, AL, Rauh 1909.xxxxx

Charm Theory 7

How to improve charm lifetime predictions?

a) Improve precision for D+/D0
- NNLO matching for HQET SR (see Grozin, Mannel, Pivovarov 1806.00253)
- lattice determination of matrix elements
- determine the D=7 matrix elements (HQET SR/lattice)
  (see Wingate et al for Bs mixing)

b) Do different meson systems Ds+/D0
- HQET sum rules for Ds+
  (ms corrections as in Bs mixing, also tau Bs)
- lattice determination of matrix elements
- determine the D=7 matrix elements (HQET SR/lattice)

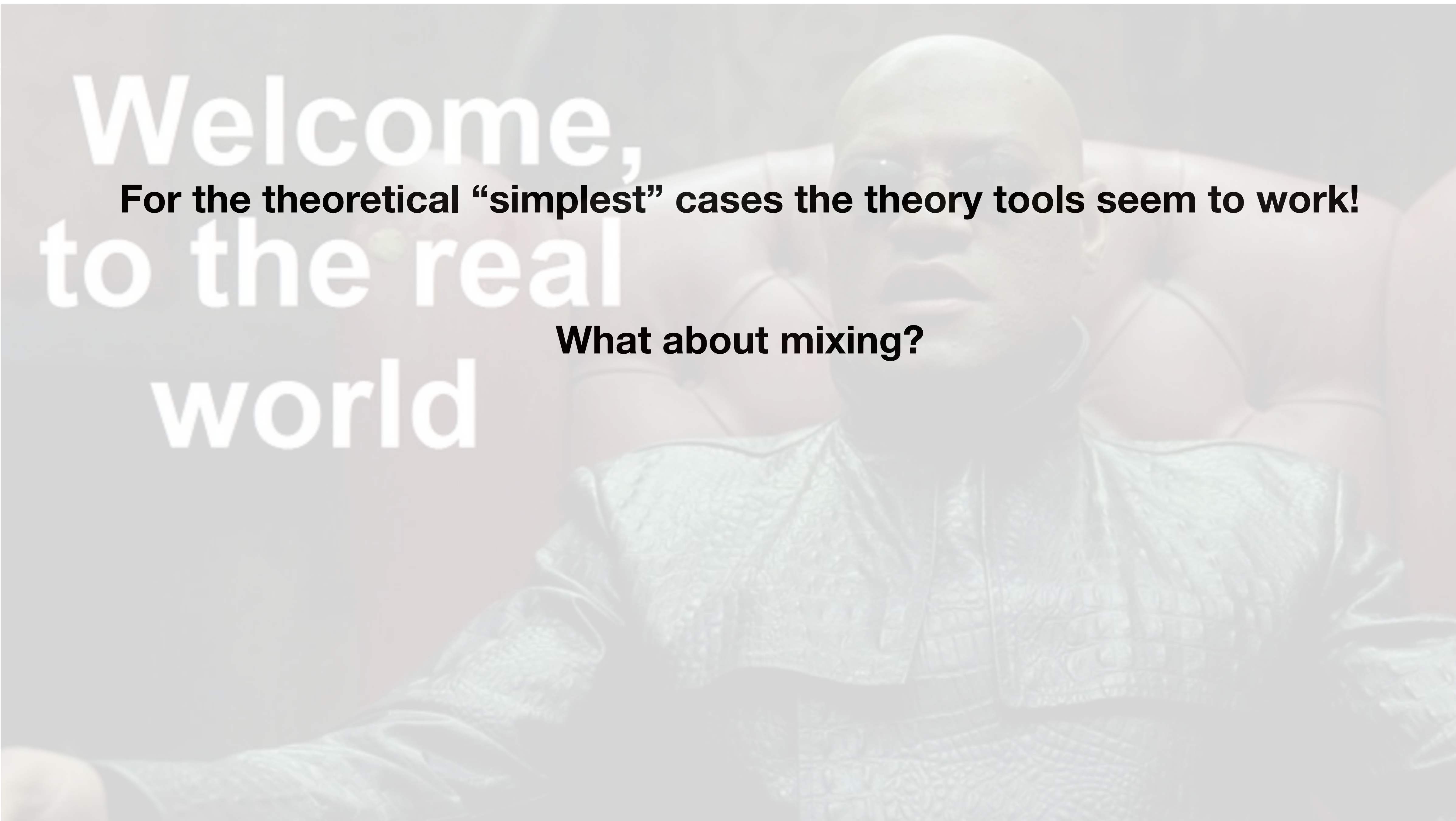


(see King, AL, Rauh 1904.00940)

c) Improve on charm baryon lifetimes
- perturbative NLO-QCD corrections
- D=6 matrix elements with HQET sum rules
- D=6 matrix elements with lattice
- determine the D=7 matrix elements (HQET SR/lattice)

Confirm/disprove the applicability of the HQE in the charm sector for inclusive quantities

Welcome to the real world



For the theoretical “simplest” cases the theory tools seem to work!

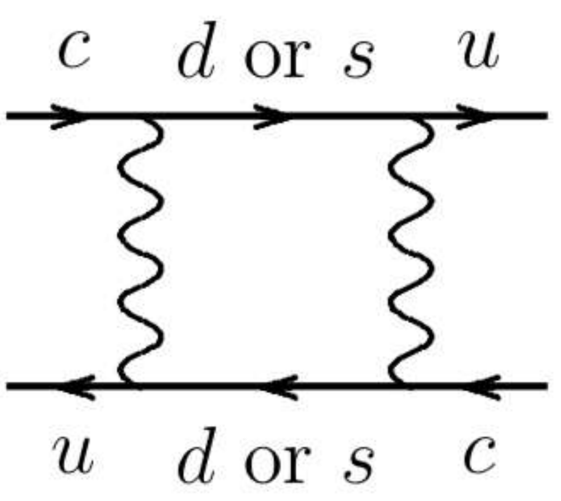
What about mixing?

for details see spare slides

Charm mixing - Summary

Naive HQE estimate deviates by 10^4 from Exp

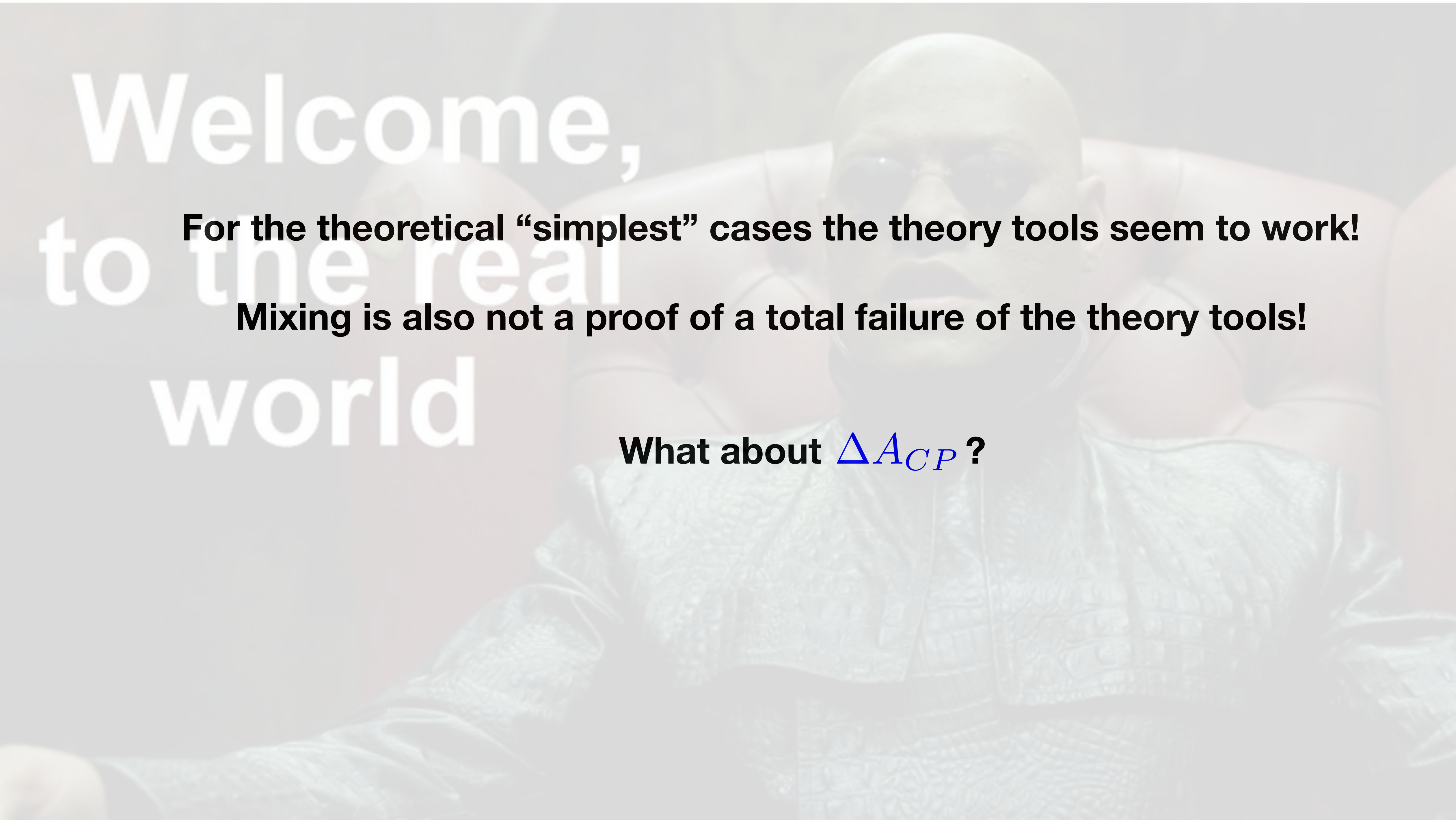
due to severe GIM cancellation of 3 contributions that are individually 5 times larger than experiment



20% of deviation from HQE expectation sufficient to explain experiment! Not 1000000%

So far no proof for this possibility, but many doable ideas around to test that idea

Welcome to the real world



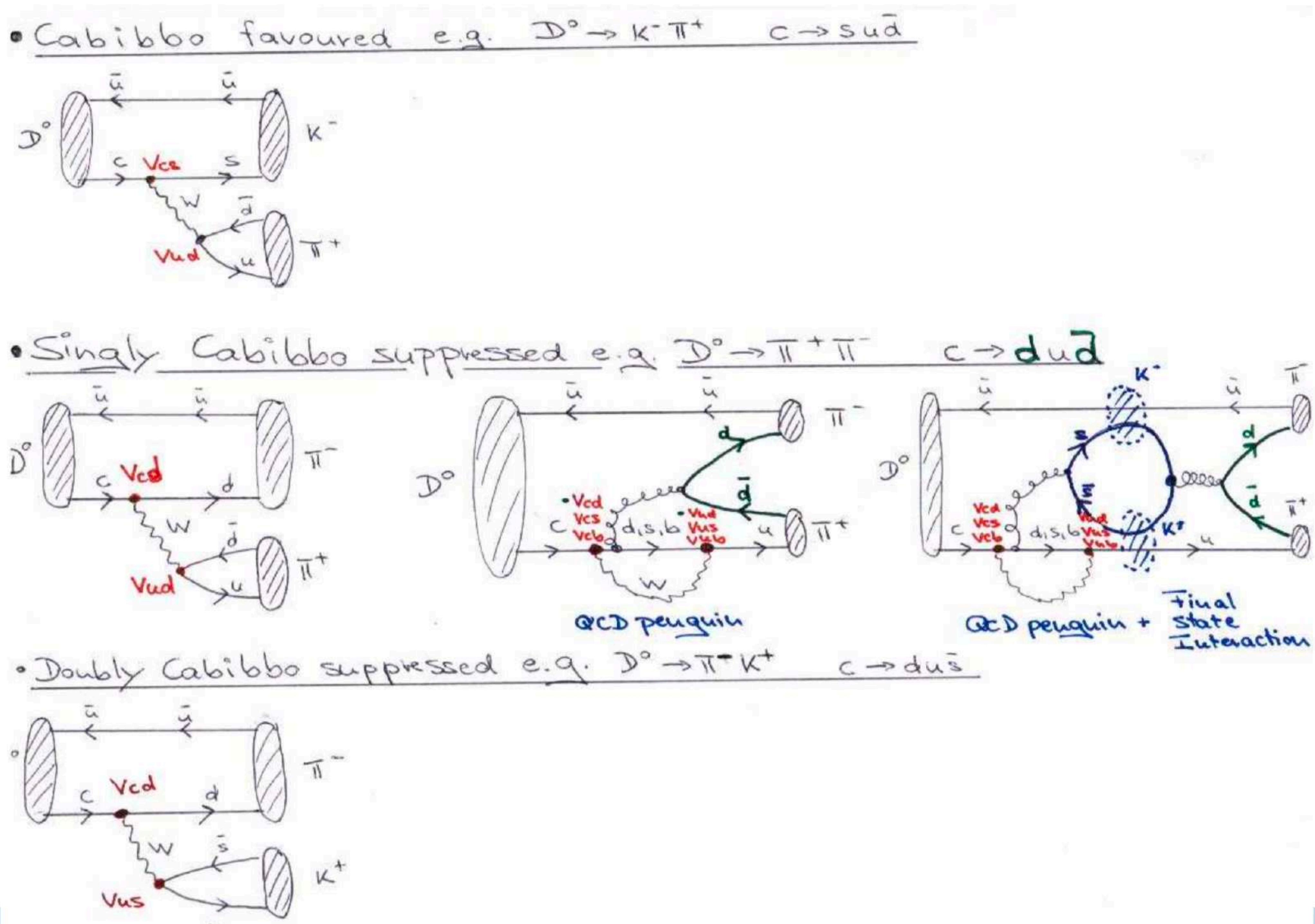
For the theoretical “simplest” cases the theory tools seem to work!

Mixing is also not a proof of a total failure of the theory tools!

What about ΔA_{CP} ?

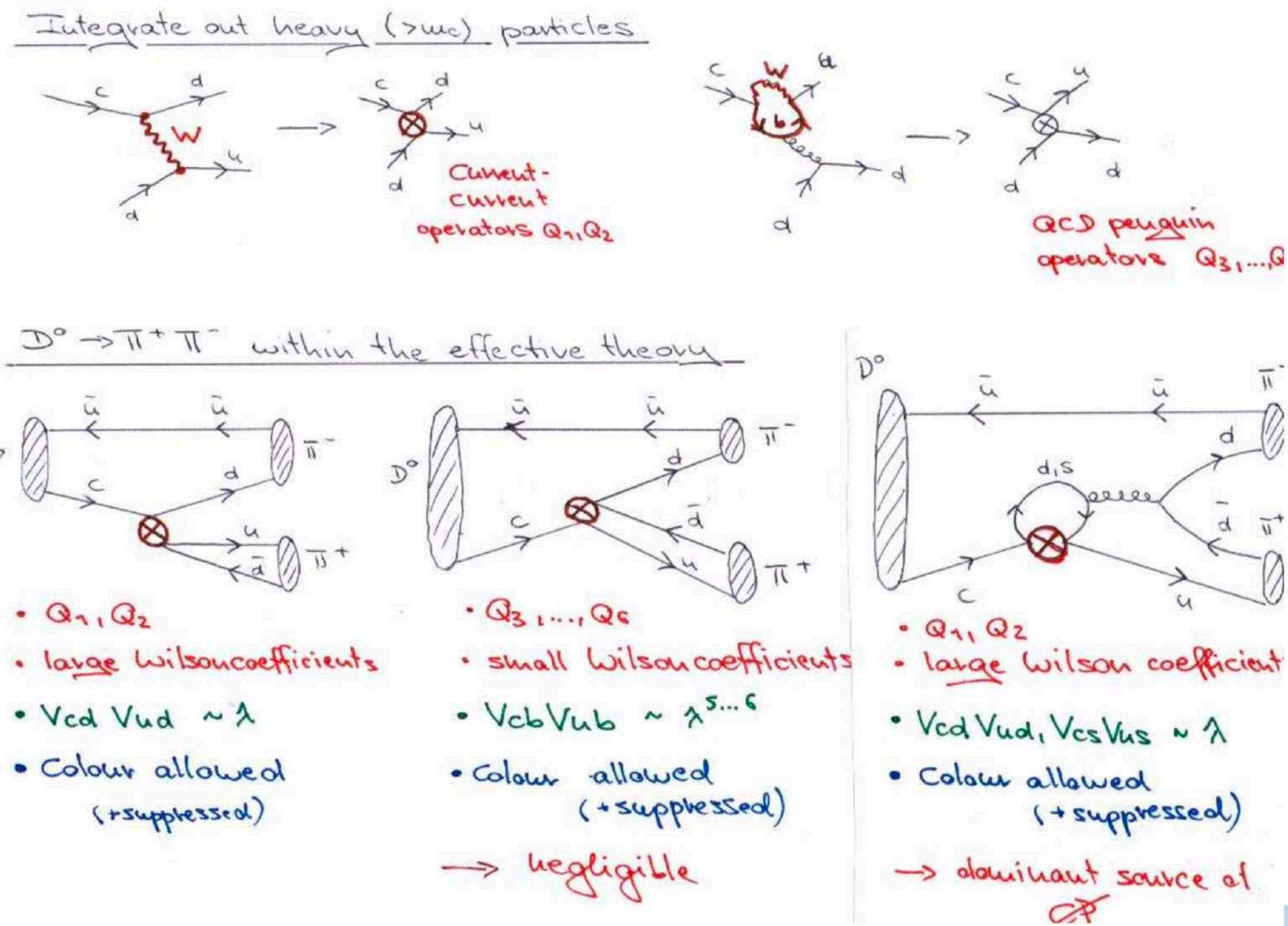
ΔA_{CP}

What decays are we talking about?



ΔA_{CP}

SCS D-decay with $\mathcal{H}_{eff}$ I



ΔA_{CP}

SCS D-decay with $\mathcal{H}_{eff}$ II

The amplitude is given by

$$A\left(D^0 \longrightarrow \pi^+\pi^-\right) = \langle D^0 | \mathcal{H}_{eff} | \pi^+\pi^- \rangle \, ,$$

with the effective Hamiltonian

$$\mathcal{H}_{eff.} = \frac{G_F}{\sqrt{2}} \left[\lambda_d \left(C_1 Q_1^d + C_2 Q_2^d \right) + \lambda_s \left(C_1 Q_1^s + C_2 Q_2^s \right) + \lambda_b \sum_{i=3}^{10} C_i Q_i \right] \, .$$

and the CKM structure $\lambda_x := V_{cx}^* V_{ux}$. Thus the amplitude reads

$$A \;=\; \frac{G_F}{\sqrt{2}} \left[\lambda_d \sum_{i=1,2} C_i \langle Q_i^d \rangle^{T+P+E} + \lambda_s \sum_{i=1,2} C_i \langle Q_i^s \rangle^{P+R} + \lambda_b \sum_{i=3}^{10} C_i \langle Q_i^b \rangle^{T} \right]$$

- $\langle Q \rangle^T$: tree-level insertion of the operator Q,
- $\langle Q \rangle^E$: insertion of the operator Q in weak exchange diagram,
- $\langle Q \rangle^P$: insertion of the operator Q in a penguin diagram.
- $\langle Q \rangle^R$: insertion of the operator Q in rescattering diagram,

ΔA_{CP}

SCS D-decay with $\mathcal{H}_{eff}$ III

$$\begin{aligned} \lambda_d &= -s_{12}c_{12}c_{23}c_{13} \quad -c_{12}^2 s_{23}s_{13}c_{13}e^{i\delta_{13}} \\ \lambda_s &= +s_{12}c_{12}c_{23}c_{13} \quad -s_{12}^2 s_{23}s_{13}c_{13}e^{i\delta_{13}} \\ \lambda_b &= \qquad\qquad\qquad\quad + \quad s_{23}s_{13}c_{13}e^{i\delta_{13}} \end{aligned}$$

Using unitarity of the CKM matrix - $\lambda_s = -\lambda_d - \lambda_b$ - we get

$$A = \frac{G_F}{\sqrt{2}}\lambda_d \left[\sum_{i=1,2} C_i \langle Q_i^d \rangle^{T+P+E} - \sum_{i=1,2} C_i \langle Q_i^s \rangle^{P+R} + \frac{\lambda_b}{\lambda_d} \left(\sum_{i=3}^{10} C_i \langle Q_i^b \rangle^{T} - \sum_{i=1,2} C_i \langle Q_i^s \rangle^{P+R} \right) \right]$$

We can write

$$A =: \frac{G_F}{\sqrt{2}}\lambda_d T \left[1 + \frac{\lambda_b}{\lambda_d}\frac{P}{T} \right] \Rightarrow \begin{cases} Br & \propto \frac{G_F^2}{2} |\lambda_d|^2 |T|^2 \\ a_{CP} & = 2 \left| \frac{\lambda_b}{\lambda_d} \right| \sin\delta \left| \frac{P}{T} \right| \sin\phi = 0.0012 \left| \frac{P}{T} \right| \sin\phi \end{cases}$$

Problem: $|P/T|$ and the strong phase ϕ are unknown!

NAIVE EXPECTATION
P/T = 0.1

Welcome to the SAGAland!

What can we do?

P/T **can currently not be calculated from first principles**

Additional assumptions (ideologies) needed - they might be wrong!

- **Ideology I:** NP = Non-perturbative physics
  - *"Non-perturbative effects are known to be huge"*
    Analogy to the $\Delta I = 1/2$ rule
  - Good starting point for arguing:
    $\sin\phi \approx 1 \Rightarrow P/T = 1.3$ sufficient for $\Delta a_{CP} = -0.00329$
- **Ideology II:** NP = New physics
  - *"Heavy quark expansion and factorisation are known to work well"*
    Analogy to the b-system
  - Good starting point for arguing:
    $\sin\phi \approx 1/10 \Rightarrow P/T = 13$ needed for $\Delta a_{CP} = -0.00329$
- **Less ideological:** Symmetry rules
  in particular $SU(3)_F$ and U-spin
- **Find experimental cross-checks for different ideologies...**

WHAT HAPPENED IN THEORY SINCE 2013?

1. Convergence of HQE for tau D+/tau D - expansion parameter = 0.30
   Can /will be improved

2. Delta I = 1/2 in Kaon gives no indication for large penguins in D decays

3. Failure of HQE for mixing might be due to a phase space dependent LD effect as small as 20%
   Can /will be improved

4. Expansion works very well in the b-sector, the expansion parameter should only be around 3 times worse…
   Can /will be improved

=> do not assume O(10) enhancements of penguins,
=> rely on QCD based approaches like LCSR (see Khodjamirian, Petrov)

Can /will be improved

COMMENTS ON ΔA_{CP}

$\Delta A_{\rm CP}$ within the Standard Model and beyond

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ABSTRACT: In light of the recent LHCb observation of CP violation in the charm sector, we review standard model (SM) predictions in the charm sector and in particular for $\Delta A_{\rm CP}$. We get as an upper bound in the SM $|\Delta A_{\rm CP}^{\rm SM}| \leq 3.6 \times 10^{-4}$, which can be compared to the measurement of $\Delta A_{\rm CP}^{\rm LHCb2019} = (-15.4 \pm 2.9) \times 10^{-4}$. We discuss resolving this tension within an extension of the SM that includes a flavour violating Z' that couples only to $\bar{s}s$ and $\bar{c}u$. We show that for masses below 80 GeV and flavour violating coupling of the order of 10^{-4}, this model can successfully resolve the tension and avoid constraints from dijet searches, $D^0 - \overline{D}^0$ mixing and measurements of the Z width.

KEYWORDS: CP violation, Heavy Quark Physics

ARXIV EPRINT: 1903.10490

JHEP07(2019)161

COMMENTS ON ΔA_{CP}

Petrov, Khodjamirian 2017: LCSR determination

Re-run B-> pi pi calculation (Khodjamirian 2000, Khodjamirian, Mannel , Melic 2003)

Determine T from experiment

$$\begin{aligned} \mathrm{Br}(D^0 \to K^+K^-) &= (3.97 \pm 0.07) \times 10^{-3}, \\ \mathrm{Br}(D^0 \to \pi^+\pi^-) &= (1.407 \pm 0.025) \times 10^{-3}, \end{aligned}$$

Determine P from LCSR based estimate (update after LHCb measurement)

$$\begin{aligned} \left|\frac{P}{T}\right|_{\pi^+\pi^-} &= 0.093 \pm 0.056\,, \\ \left|\frac{P}{T}\right|_{K^+K^-} &= 0.075 \pm 0.048\,, \end{aligned}$$

Only strong phase of P is determined,
but not strong phase of P/T

$$|\Delta A_{CP}| \leq (2.2 \pm 1.4) \times 10^{-4} \leq 3.6 \times 10^{-4}.$$

COMMENTS ON ΔA_{CP}

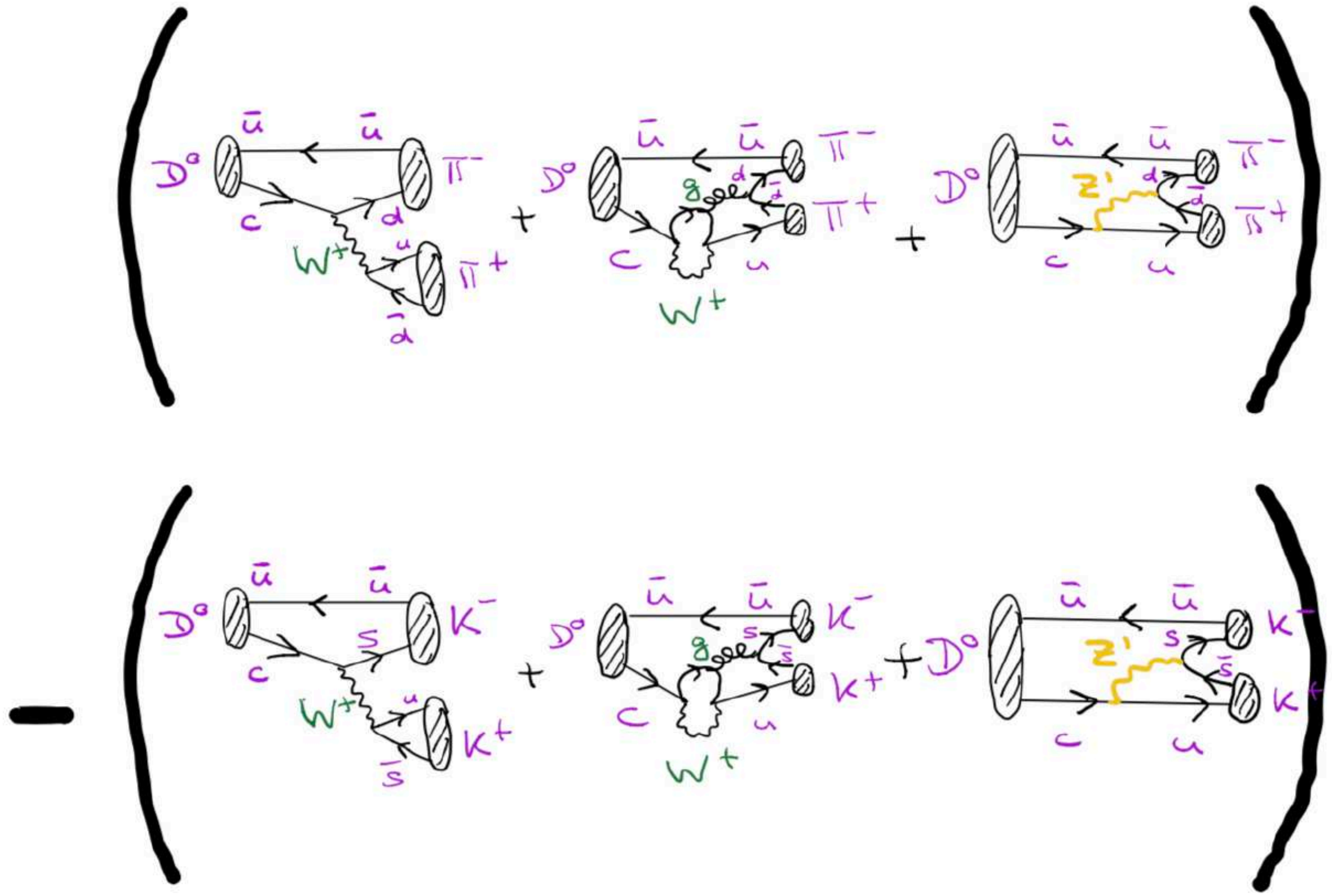
How to improve on LCSR determination?

1. **Include Pengiun operators in the penguin contribution**
   relatively easy

2. **Include Higher twist corrections in the penguins**
   less easy

3. **Determine also T - many topologies will contribute, also penguins and determine also branching ratios**
   Much more complicated than calculating P alone
   If Br agrees then this will be a huge boost for the SM theory predictions

COMMENTS ON ΔA_{CP}

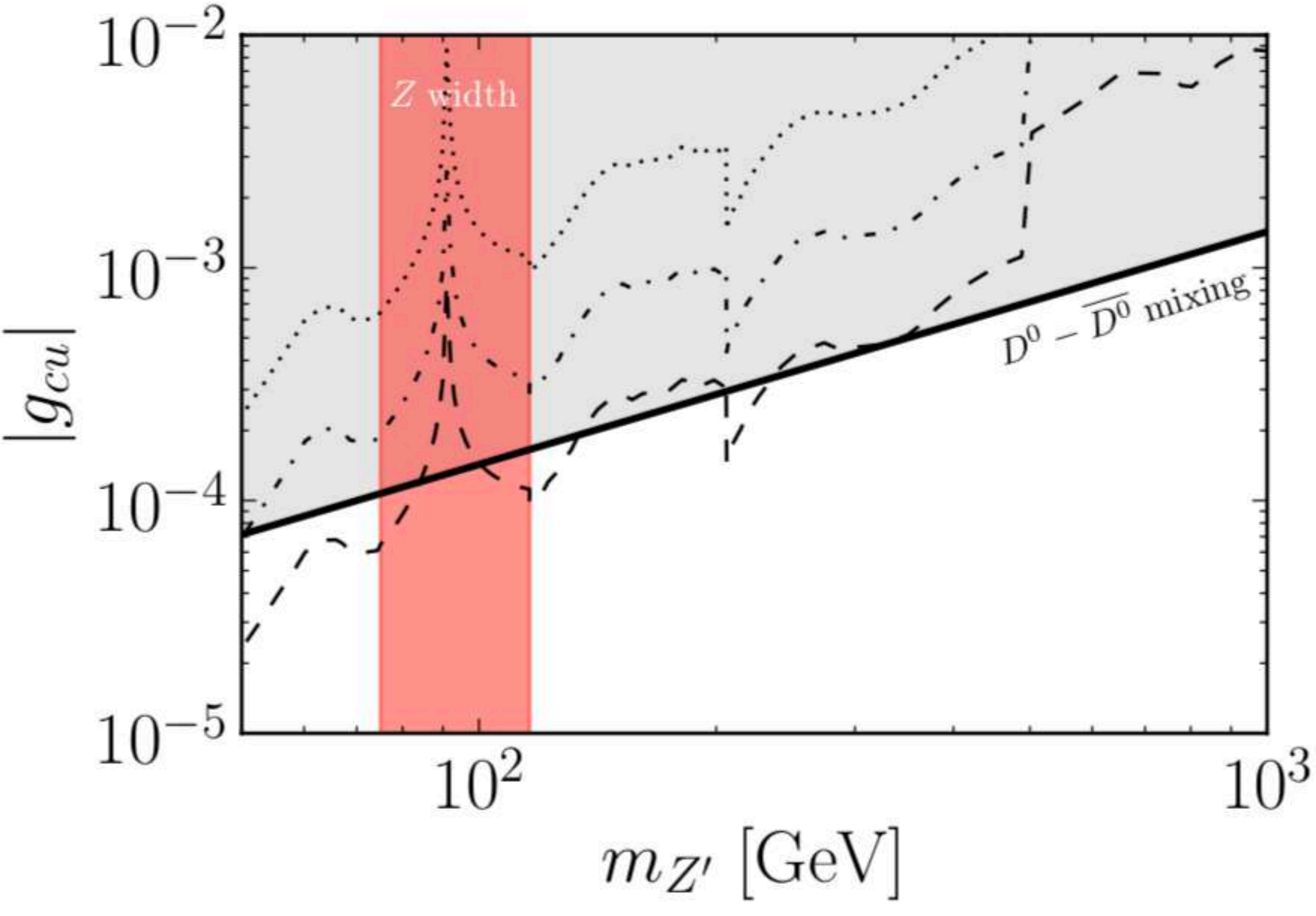


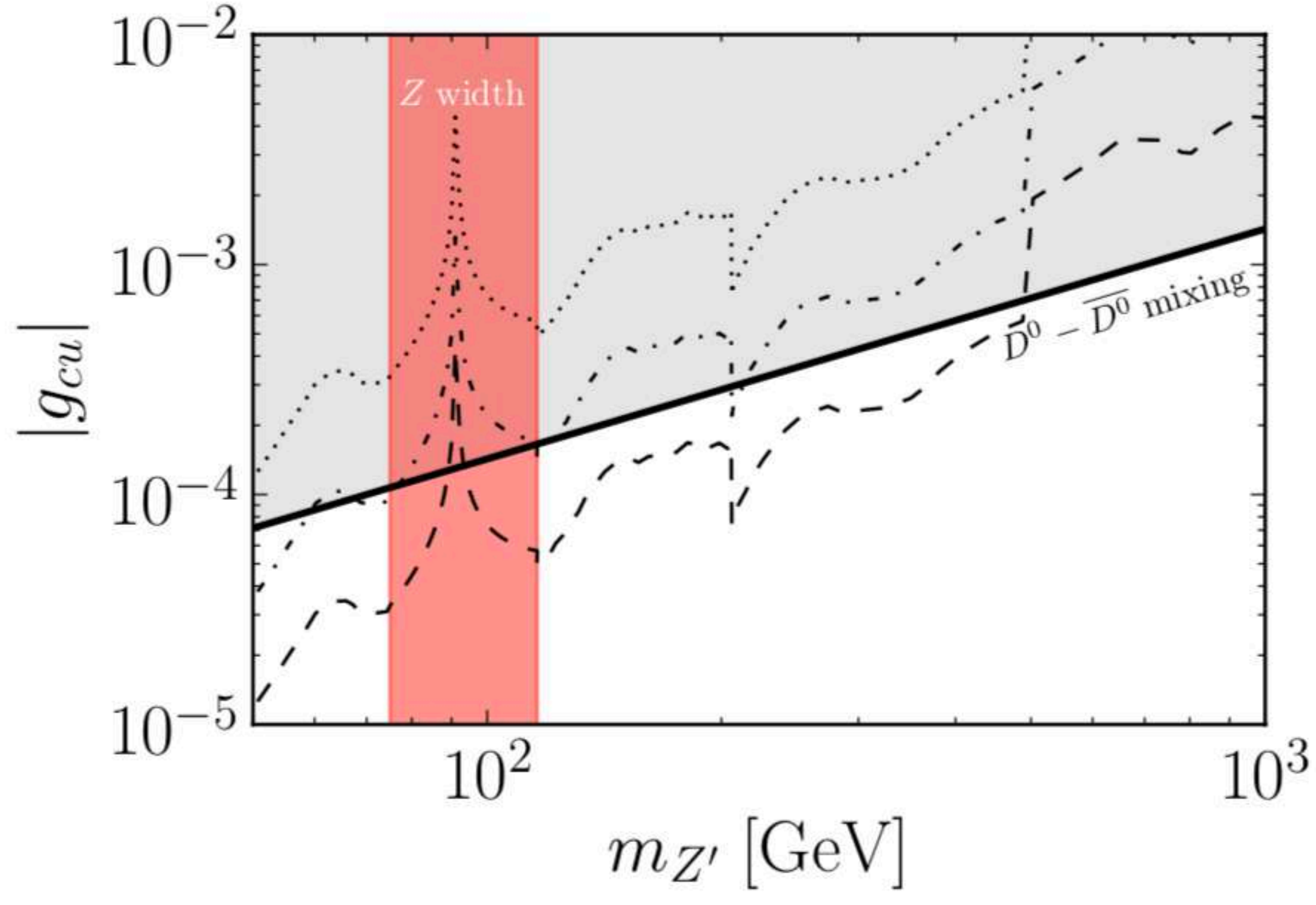
= Experiment!

⇒ look for new Z, W

COMMENTS ON ΔA_{CP}

BSM explanations are strongly constrained, but not impossible





COMMENTS ON ΔA_{CP}

Compare disagreeing literature: e.g. Grossman, Schacht 1903.10952

- Assume: P/T cannot be calculated from first principles
- Use symmetries like SU(3)_F or U-spin
- Find a consistent picture if you assume large values of P/T

Be aware: this does by no means proof the SM origin of large P/T

Large of P/T due to NP

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- **Assume: P/T cannot be calculated from first principles**
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Be aware: this does by no means proof the SM origin of large P/T

Large of P/T due to NP

NP = non-perturbative or NP = new physics?

COMMENTS ON ΔA_{CP}

Compare disagreeing literature: e.g. Grossman, Schacht 1903.10952

Now the question is: what is C? As at this time no method is available in order to calculate C with a well-defined theoretical uncertainty, we do not employ here a dynamical calculation in order to provide a SM prediction for C and $\Delta a_{CP}^{\text{dir}}$. We rather show the different principal possibilities and how to interpret them in view of the current data. In order to do so we measure the order of magnitude of the QCD correction term C relative to the "no QCD" limit $\tilde{p}_0 = 1$. Relative to that limit, we differentiate between three cases

1. $C = \mathcal{O}(\alpha_s/\pi)$: perturbative corrections to $\tilde{p}_0$.
2. $C = \mathcal{O}(1)$: non-perturbative corrections that produce strong phases from rescattering but do not significantly change the magnitude of $\tilde{p}_0$.
3. $C \gg \mathcal{O}(1)$: large non-perturbative effects with significant magnitude changes and strong phases from rescattering to $\tilde{p}_0$.

COMMENTS ON ΔA_{CP}

Compare disagreeing literature: e.g. Grossman, Schacht 1903.10952

Some perturbative results concluded that $C = \mathcal{O}(\alpha_s/\pi)$, leading to $\Delta a_{CP}^{\rm dir} \sim 10^{-4}$ [40, 77]. Note that the value $\Delta a_{CP}^{\rm dir} = 1 \times 10^{-4}$, assuming $O(1)$ strong phase, would correspond numerically to $C \sim 0.04$. We conclude that if there is a good argument that C is of category (1), the measurement of $\Delta a_{CP}^{\rm dir}$ would be a sign of beyond the SM (BSM) physics, because it would indicate a relative $\mathcal{O}(10)$ enhancement.

The current data, eq. (5.3), is consistent with category (2). In the SM pi
measurement of $\Delta a_{CP}^{\rm dir}$ proves the non-perturbative nature of the $\Delta U = 0$ matri
with a mild enhancement from $\mathcal{O}(1)$ rescattering effects. This is the $\Delta U = 0$ rule
Note that the predictions for $\Delta a_{CP}^{\rm dir}$ of category (i) and (ii) differ by $\mathcal{O}(10)$
category (ii) contains only an $\mathcal{O}(1)$ nonperturbative enhancement with respect
QCD" limit $\tilde{p}_0 = 1$. We emphasize that a measure for a QCD enhancement is
sarily its impact on an observable, but the amplitude level comparison with the

COMMENTS ON ΔA_{CP}

Compare disagreeing literature: e.g. Grossman, Schacht 1903.10952

So far, I agree with Stefan and Yuval

Here I disagree, please Check the quoted lattice Papers by your self

ABSTRACT: We discuss the implications of the recent discovery of CP violation in two-body SCS D decays by LHCb. We show that the result can be explained within the SM without the need for any large SU(3) breaking effects. It further enables the determination of the imaginary part of the ratio of the $\Delta U = 0$ over $\Delta U = 1$ matrix elements in charm decays, which we find to be (0.65 ± 0.12). Within the standard model, the result proves the non-perturbative nature of the penguin contraction of tree operators in charm decays, similar to the known non-perturbative enhancement of $\Delta I = 1/2$ over $\Delta I = 3/2$ matrix elements in kaon decays, that is, the $\Delta I = 1/2$ rule. As a guideline for future measurements, we show how to completely solve the most general parametrization of the $D \to P^+P^-$ system.

Conclusion

1) Yes, charm SM predictions are notoriously difficult

   Be aware of cancellations:
   - GIM in Mixing
   - Wilson coefficients in lifetimes
   - ...

2) No, not all animals are equal

3) HQET sum rules are competitive to most recent lattice evaluations of bag parameter

4) No, charm SM predictions are not arbitrary

   I see no justification for order 10 non-perturbative effects maybe 20% - 100%? Depending on observable

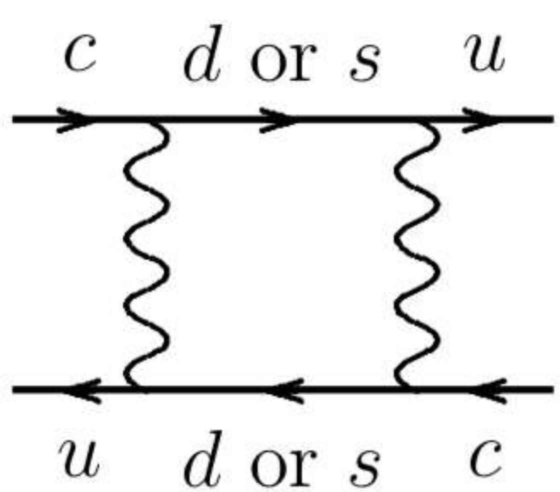
5) A lot of work has still to be done - but it can be done!

Charm mixing - Theory 1

Flavour Eigenstates

$$|D^0\rangle = |c\bar{u}\rangle \qquad |\bar{D}^0\rangle = |\bar{c}u\rangle$$

Mixing due to box diagrams



Mass Eigenstates

$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$$

Charm mixing - Theory 2

Diagonalise mass and decay rate matrix

$$\Delta M_D^2 - \frac{1}{4}\Delta\Gamma_D^2 = 4\left|M_{12}^D\right|^2 - \left|\Gamma_{12}^D\right|^2 \,,$$

$$\Delta M_D \Delta\Gamma_D = 4\left|M_{12}^D\right|\left|\Gamma_{12}^D\right|\cos(\phi_{12}^D)\,,$$

mass difference $\Delta M_D = M_1 - M_2$

decorate difference $\Delta\Gamma_D = \Gamma_2 - \Gamma_1$

absorptive part of box diagram (on-shell) Γ_{12}^D

dispersive part of box diagram (off-shell) M_{12}^D

relative phase $\phi_{12}^D = -\arg(-M_{12}^D/\Gamma_{12}^D)$

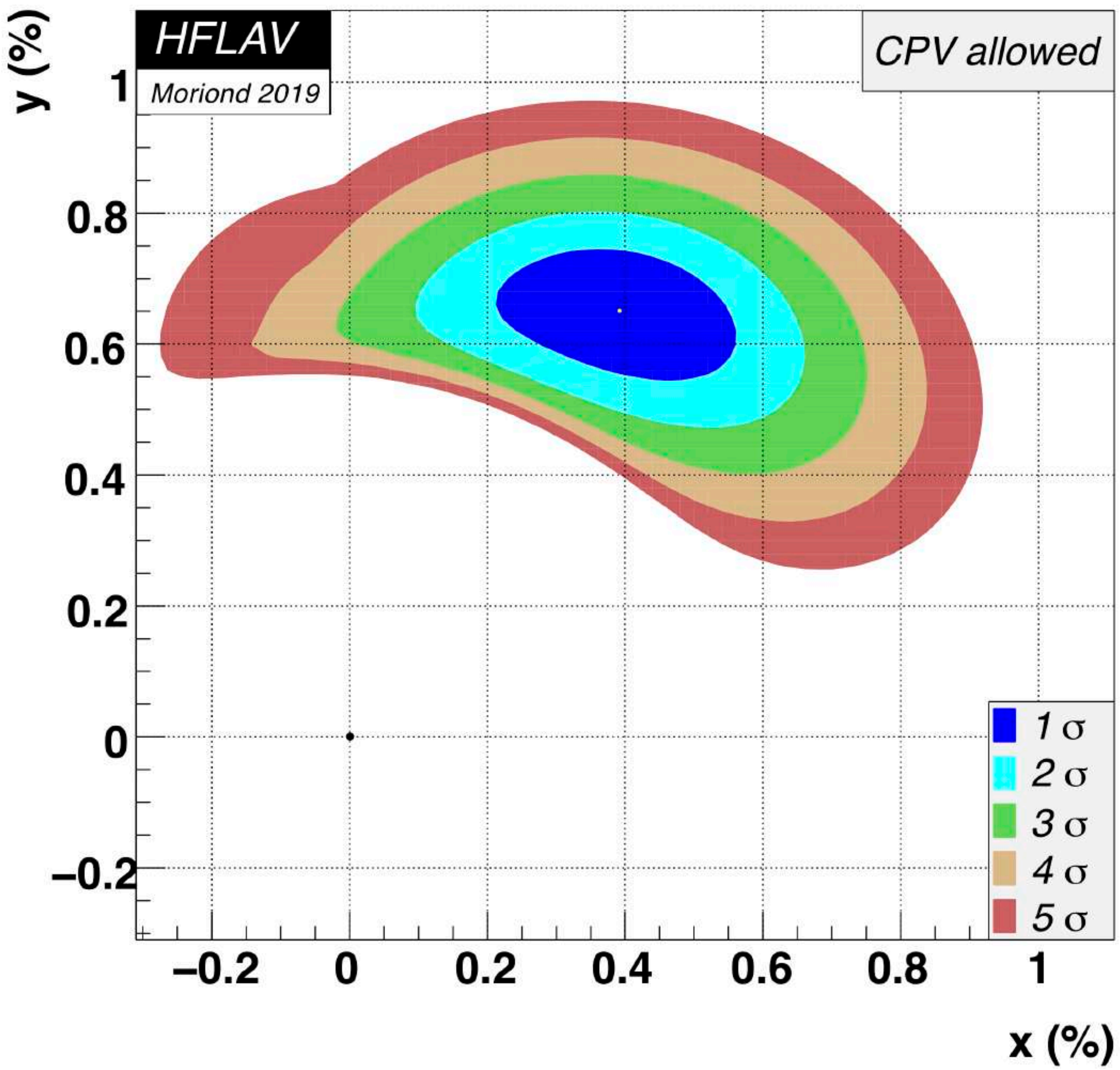
Charm mixing - Experiment

Experimental situation

$$x := \frac{\Delta M_D}{\Gamma_D} = 0.39\%^{+0.11\%}_{-0.12\%}$$

$$y := \frac{\Delta \Gamma_D}{2\Gamma_D} = 0.651\%^{+0.063\%}_{-0.069\%}$$

HFLAV 2019



- Small values
- non-vanishing x not yet confirmed

Charm mixing - Theory 3

Crucial differences compared to B mixing

1) No simple formulae like $\Delta M_{B_S} = 2|M_{12}^{B_s}|$

both Γ_{12}^D and M_{12}^D have to be known!

but there is a bound $\Delta\Gamma_D \leq 2|\Gamma_{12}^D|$

Nierste 0904.1869
Jubb et al. 1603.07770

2) GIM cancellation vs CKM hierarchy: $|\lambda_b| \ll |\lambda_s|$, but complex!!!

$$\Gamma_{12}^D = \quad -\lambda_s^2\left(\Gamma_{ss}^D - 2\Gamma_{sd}^D + \Gamma_{dd}^D\right) + 2\lambda_s\lambda_b\left(\Gamma_{sd}^D - \Gamma_{dd}^D\right) - \lambda_b^2\Gamma_{dd}^D\,,$$

$$M_{12}^D = \lambda_s^2\left[M_{ss}^D - 2M_{sd}^D + M_{dd}^D\right] + 2\lambda_s\lambda_b\left[M_{bs}^D - M_{bd}^D - M_{sd}^D + M_{dd}^D\right] + \lambda_b^2\left[M_{bb}^D - 2M_{bd}^D + M_{dd}^D\right]\,.$$

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survives in SU(3)F limit!

dominant for B mixing

CPV

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Charm mixing - Theory 4

Two theory approaches for calculating D mixing

1) **Inclusive** approach

calculate on **quark level**

Georgi 9209291
Ohl, Ricciardi,Simmons 9301212
Bigi, Uraltsev 0005089
Bobrowski et al 1002.4794

2) **Exclusive** approach

calculate on **hadron level**

Falk, Grossman, Ligeti, Petrov 0110317
Falk, Grossman, Ligeti, Nir, Petrov 0402204
Cheng, Chiang 1005.1106
Jiang et al1705.07335

Due to extreme GIM cancellation very high precision necessary!!!

Charm mixing - Theory 5

The HQE is successful in the B system and for D meson lifetimes

=> apply it for D-mixing

Charm mixing - Theory 5

The HQE is successful in the B system and for D meson lifetimes

=> apply it for D-mixing

$$y_D^{\mathrm{HQE}} \approx \lambda_s^2 \left(\Gamma_{12}^{ss} - 2\Gamma_{12}^{sd} - \Gamma_{12}^{dd} \right) \approx 1.7 \cdot 10^{-4} y_D^{\mathrm{Exp.}}$$

How can this be?

Charm mixing - Theory 5

The HQE is successful in the B system and for D meson lifetimes

=> apply it for D-mixing

$$y_D^{\text{HQE}} \approx \lambda_s^2 \left(\Gamma_{12}^{ss} - 2\Gamma_{12}^{sd} - \Gamma_{12}^{dd}\right) \approx 1.7 \cdot 10^{-4} y_D^{\text{Exp.}}$$

How can this be?

Look only at a single diagram:

$$y_D^{\text{HQE}} \neq \lambda_s^2 \Gamma_{12}^{ss} \tau_D = 3.7 \cdot 10^{-2} \approx 5.6 y_D^{\text{Exp.}}$$

pert. calculation: **Bobrowski et al 1002.4794**
latice input: **ETM 1403.7302; 1505.06639; FNAL/MILC 1706.04622**

The problem seems to originate in the extreme GIM cancellations

Charm mixing - Theory 5

The HQE is successful in the B system and for D meson lifetimes

=> apply it for D-mixing

$$\Gamma_{12}^D = -\lambda_s^2 \left(\Gamma_{ss}^D - 2\Gamma_{sd}^D + \Gamma_{dd}^D\right) + 2\lambda_s\lambda_b \left(\Gamma_{sd}^D - \Gamma_{dd}^D\right) - \lambda_b^2 \Gamma_{dd}^D \,,$$

$$\begin{aligned} 10^7 \Gamma_{12}^{D=6,7} = & -14.6409 + 0.0009i && (1^{\rm st} \text{ term}) \\ & -6.68 - 15.8i && (2^{\rm nd} \text{ term}) \\ & +0.27 - 0.28i && (3^{\rm rd} \text{ term}) \end{aligned}$$

Bobrowski et al 1002.4794

Important observation for CPV

Charm mixing - Theory 6

What could have gone wrong in D-mixing?

1. **Duality violations - break down of HQE**

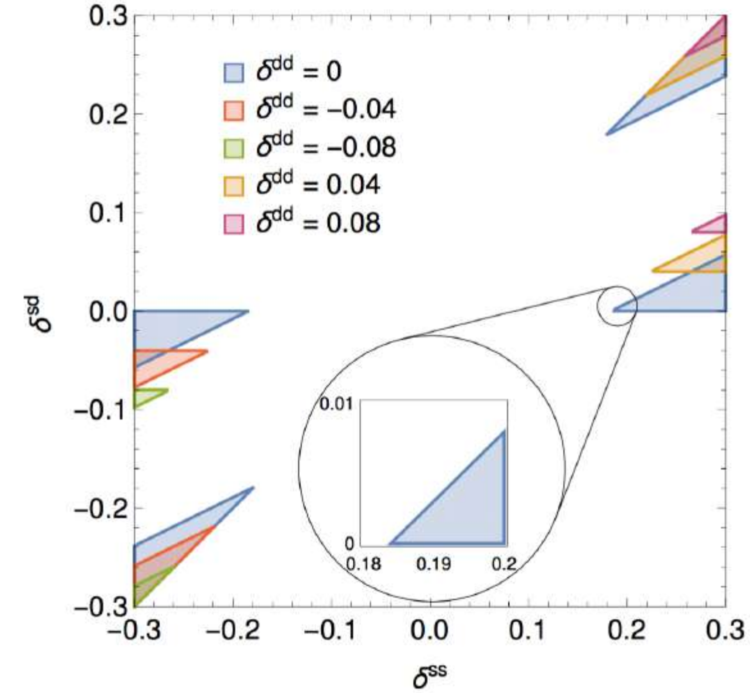
$$\Gamma_{12}^{ss} \to \Gamma_{12}^{ss}(1+\delta^{ss}) \,,$$

$$\Gamma_{12}^{sd} \to \Gamma_{12}^{sd}(1+\delta^{sd}) \,,$$

$$\Gamma_{12}^{dd} \to \Gamma_{12}^{dd}(1+\delta^{dd}) \,,$$

20% of duality violation is sufficient to explain experiment

Jubb, Kirk, AL, Tetlalmatzi-Xolocotzi 2016



2. **Higher dimensions** Georgi 9209291; Ohl, Ricciardi,Simmons 9301212; Bigi, Uraltsev 0005089

Idea: GIM cancellation is lifted by higher orders in the HQE - overcompensating the 1/mc suppression.

Partial calculation of D=9 yields an enhancement - but not to the experimental value Bobrowski, AL, Rauh 2012

3. **New Physics is present and we cannot prove it yet:-)**

Exclusive approach

$$\Gamma_{12}^D = \sum_n \rho_n \langle \bar{D}^0 | \mathcal{H}_{eff.}^{\Delta C=1} | n \rangle \langle n | \mathcal{H}_{eff.}^{\Delta C=1} | D^0 \rangle ,$$

$$M_{12}^D = \sum_n \langle \bar{D}^0 | \mathcal{H}_{eff.}^{\Delta C=2} | D^0 \rangle + P \sum_n \frac{\langle \bar{D}^0 | \mathcal{H}_{eff.}^{\Delta C=1} | n \rangle \langle n | \mathcal{H}_{eff.}^{\Delta C=1} | D^0 \rangle}{m_D^2 - E_n^2} ,$$

Cannot be calculated yet

Estimate phase space effects for y: Falk et al 0110317

- **assume pert. SU(3)F breaking** $y \approx 1\%$
- **neglect 3 family**
- **neglect SU(3)F breaking in matrix elements**

Mass difference from a dispersion relation Falk et al 0402204 $x \approx y$

Exp. data Cheng, Chiang 1005.1106 $x \propto \mathcal{O}(0.1\%)$ $y \propto \mathcal{O}(few\ 0.1\%)$

U-Spin sum rule Gronau, Rosner 2012

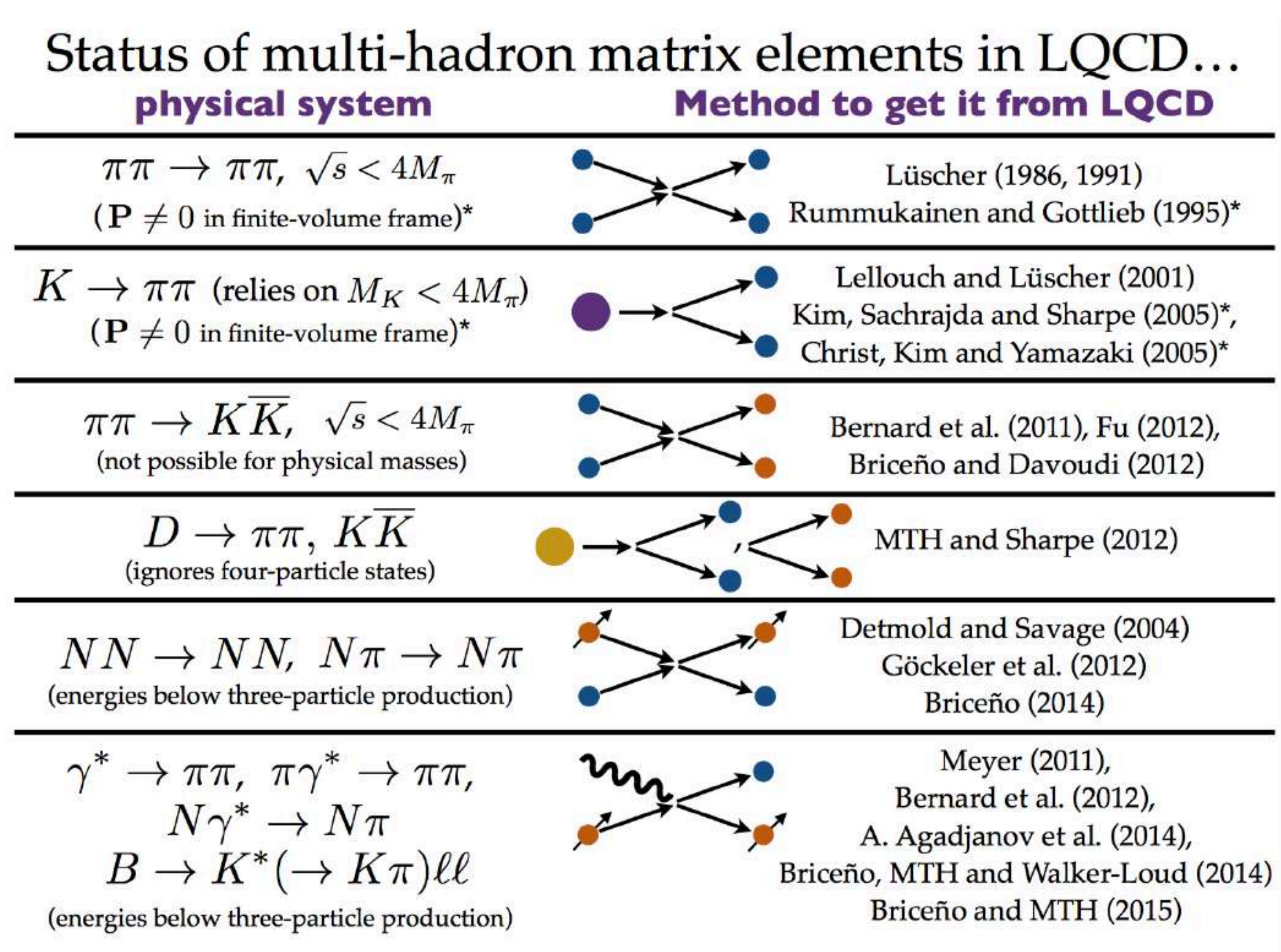
Factorisation-assisted topological amplitude approach

Jiang et al1705.07335 $y \approx 0.2\%$

Direct lattice determination

Still a very long way!
But not completely crazy anymore!

Multiple-channel generalization of Lellouch-Luscher formula
Maxwell T. Hansen, Stephen R. Sharpe (Washington U., Seattle). Apr 2012. 15 pp.
Published in **Phys.Rev. D86 (2012) 016007**
DOI: 10.1103/PhysRevD.86.016007
e-Print: **arXiv:1204.0826 [hep-lat] | PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service; OSTI.gov Server
Detailed record - Cited by 186 records 100+



Status of multi-hadron matrix elements in LQCD…

physical system	Method to get it from LQCD
$\pi\pi \to \pi\pi$, $\sqrt{s} < 4M_\pi$ ($\mathbf{P} \neq 0$ in finite-volume frame)*	Lüscher (1986, 1991) Rummukainen and Gottlieb (1995)*
$K \to \pi\pi$ (relies on $M_K < 4M_\pi$) ($\mathbf{P} \neq 0$ in finite-volume frame)*	Lellouch and Lüscher (2001) Kim, Sachrajda and Sharpe (2005)*, Christ, Kim and Yamazaki (2005)*
$\pi\pi \to K\overline{K}$, $\sqrt{s} < 4M_\pi$ (not possible for physical masses)	Bernard et al. (2011), Fu (2012), Briceño and Davoudi (2012)
$D \to \pi\pi, K\overline{K}$ (ignores four-particle states)	MTH and Sharpe (2012)
$NN \to NN$, $N\pi \to N\pi$ (energies below three-particle production)	Detmold and Savage (2004) Göckeler et al. (2012) Briceño (2014)
$\gamma^* \to \pi\pi$, $\pi\gamma^* \to \pi\pi$, $N\gamma^* \to N\pi$ $B \to K^*(\to K\pi)\ell\ell$ (energies below three-particle production)	Meyer (2011), Bernard et al. (2012), A. Agadjanov et al. (2014), Briceño, MTH and Walker-Loud (2014) Briceño and MTH (2015)

slide by Max Hansen

Theory to-do-list

Determine higher dimension contributions to Gamma_12

- **D=9**
- **D=12**

Determine M_12

Have a good idea for a model of duality violation

Have a good idea for improving exclusive approaches

Continue lattice studies for D-mixing

Charm Theory 6

Impressive confirmation of HQET sum rules by lattice:

The same methods can be used for B mixing

- **pre 2016: Delta Ms SM like, large uncertainties**
- **FNAL/MILC (1602.03560): Delta Ms 2 sigma above experiment; dramatic consequences for BSM models (One constraint to kill them all, 1712/06572)**
- **HQET sum rules (1606.06054, 1711.02100, 1904.00940) do not confirm the large FNAL/MILC values**
- **Most recent lattice (HQPCD 1907.01025) impressively confirm sum rules**