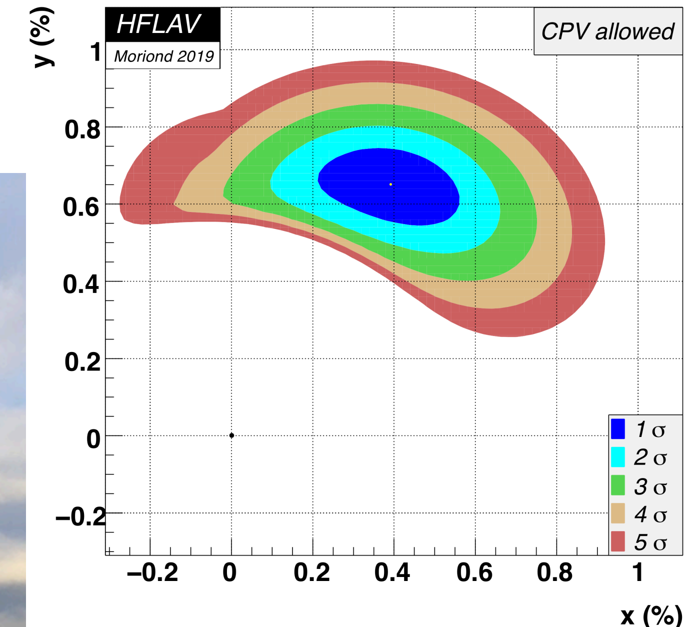
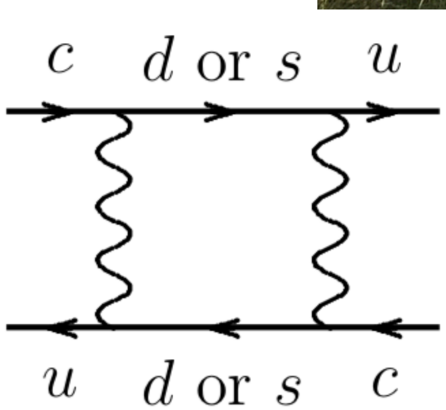
Roadmap towards SM predictions for CPV in mixing





Alexander Lenz, IPPP Durham

4. April 2019

Towards the Ultimate Precision in Flavour Physics II

Content

Charm theory is notoriously difficult
- **Nelson plot**
- **Delta I = 1/2**

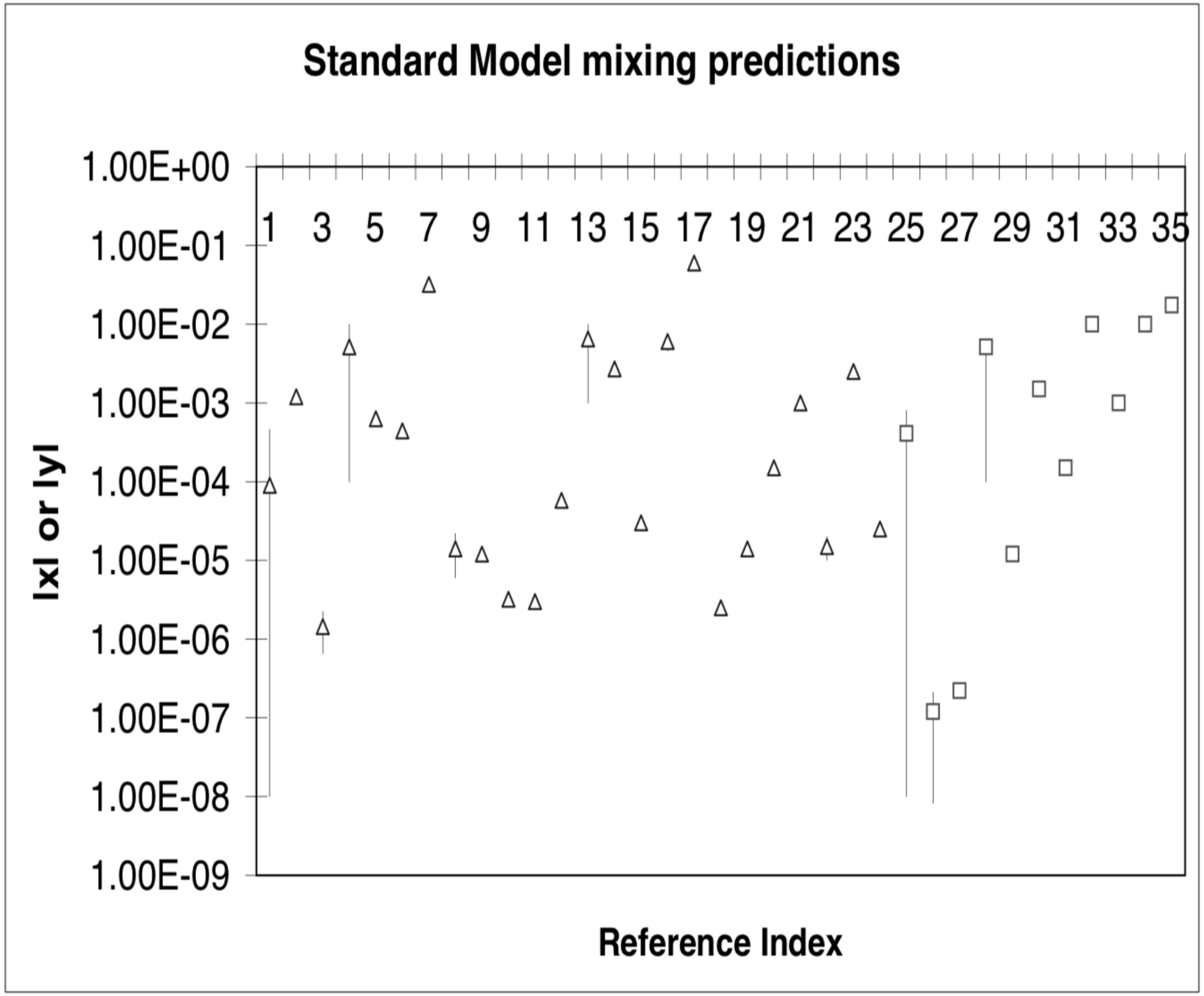
Charm Lifetimes

Charm Mixing
- **Inclusive**
- **Exclusive**
- **Lattice**

Delta A_CP
- **LCSR**

Prediction for TUPIFP 2022

Charm theory is notoriously difficult

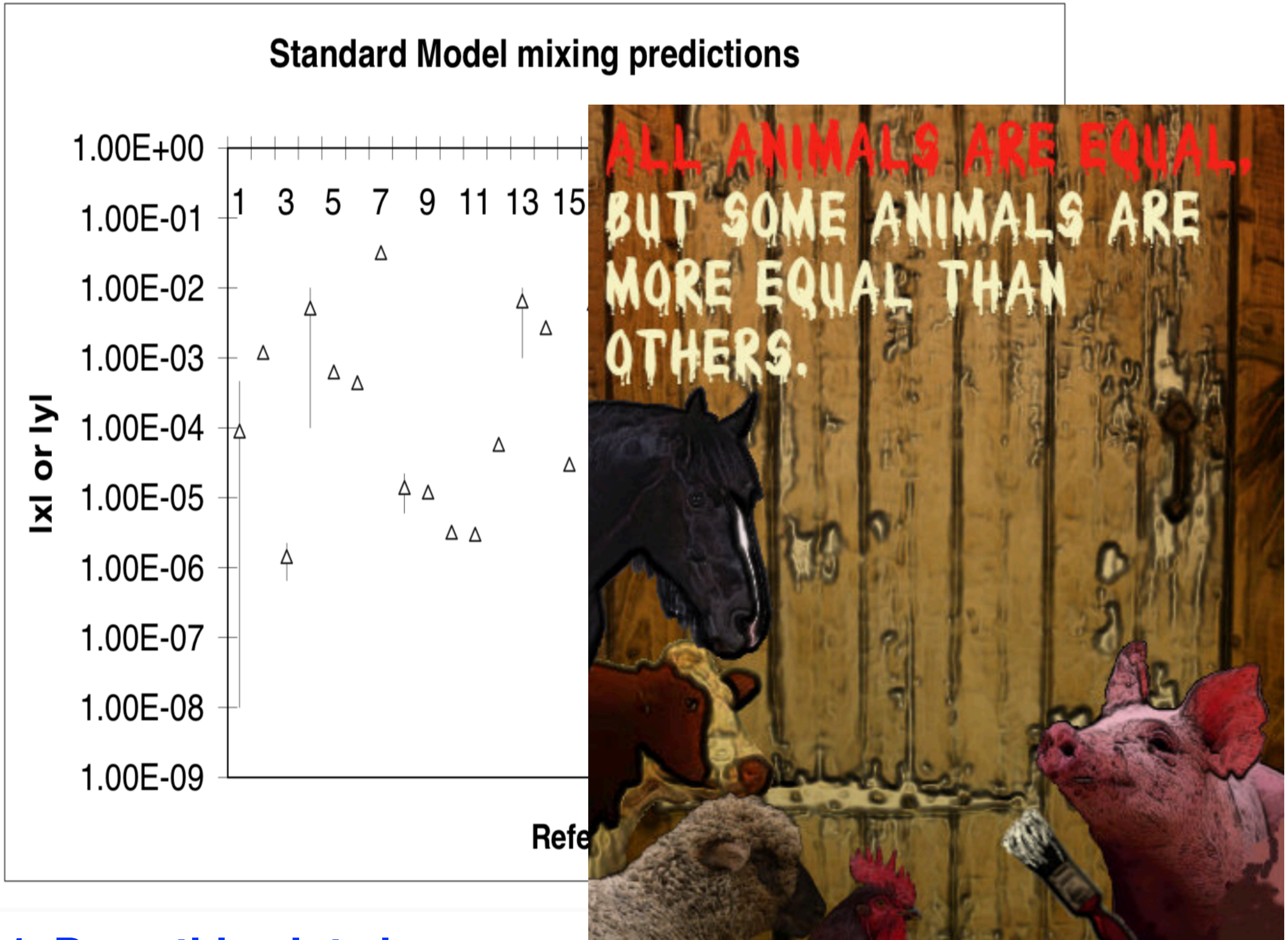


modified Nelson plot from A. Petrov hep-ph/0311371

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

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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**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service; ADS Abstract Service; OSTI.gov Server

Charm theory is notoriously difficult

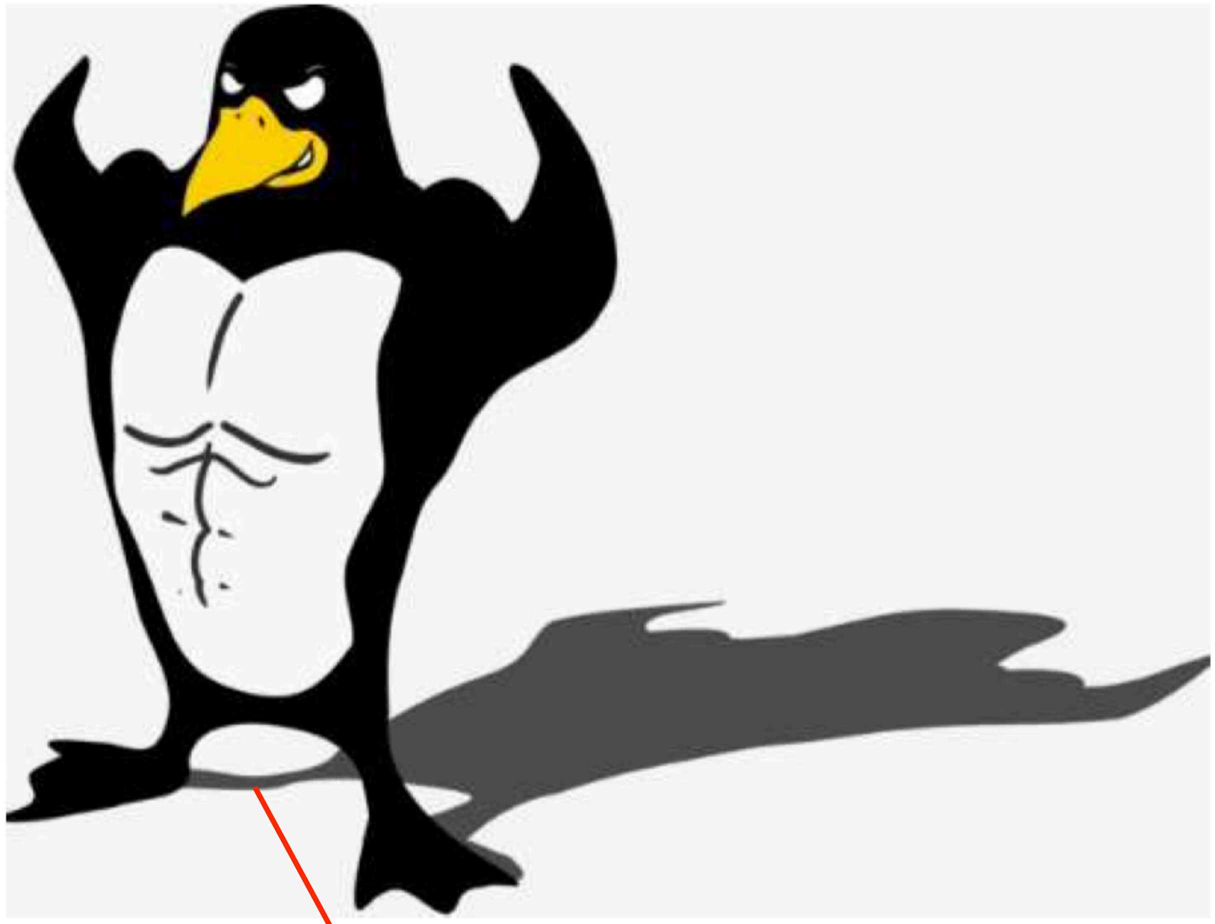
Delta I =1/2 rule

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

See Chris Sachrajda's talk

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

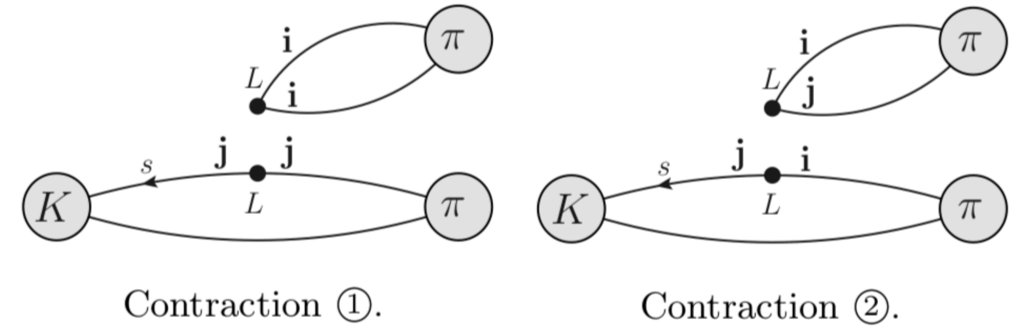


FIG. 1: The two contractions contributing to ReA_2. They are distinguished by the color summation ($\mathbf{i}, \mathbf{j}$ denote color). s denotes the strange quark and L that the currents are left-handed.

See Max Hansen's talk

1505.7863

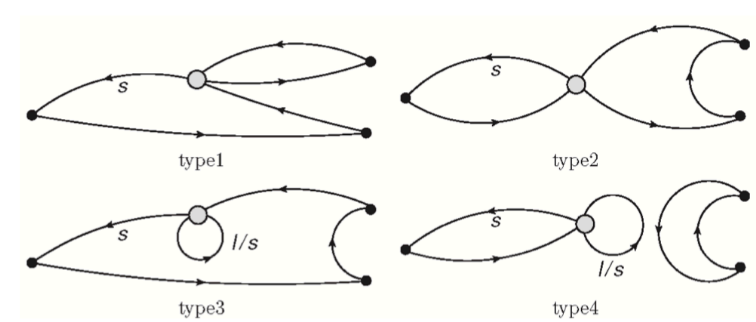


FIG. 1. Examples of the four types of diagram contributing to the $\Delta I = 1/2$, $K \to \pi\pi$ decay. Lines labeled ℓ or s represent light or strange quarks. Unlabeled lines are light quarks.

See this talk

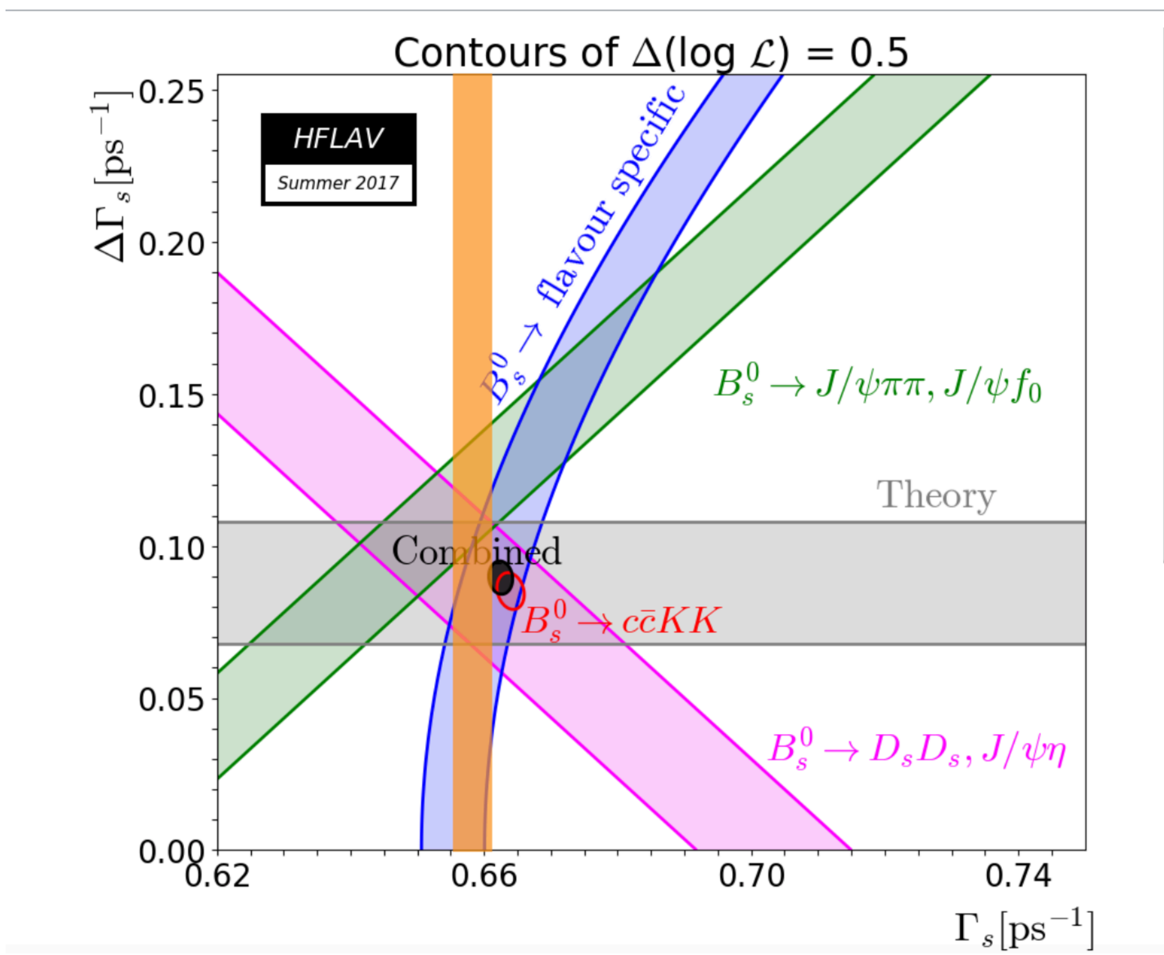
Charm Theory 1

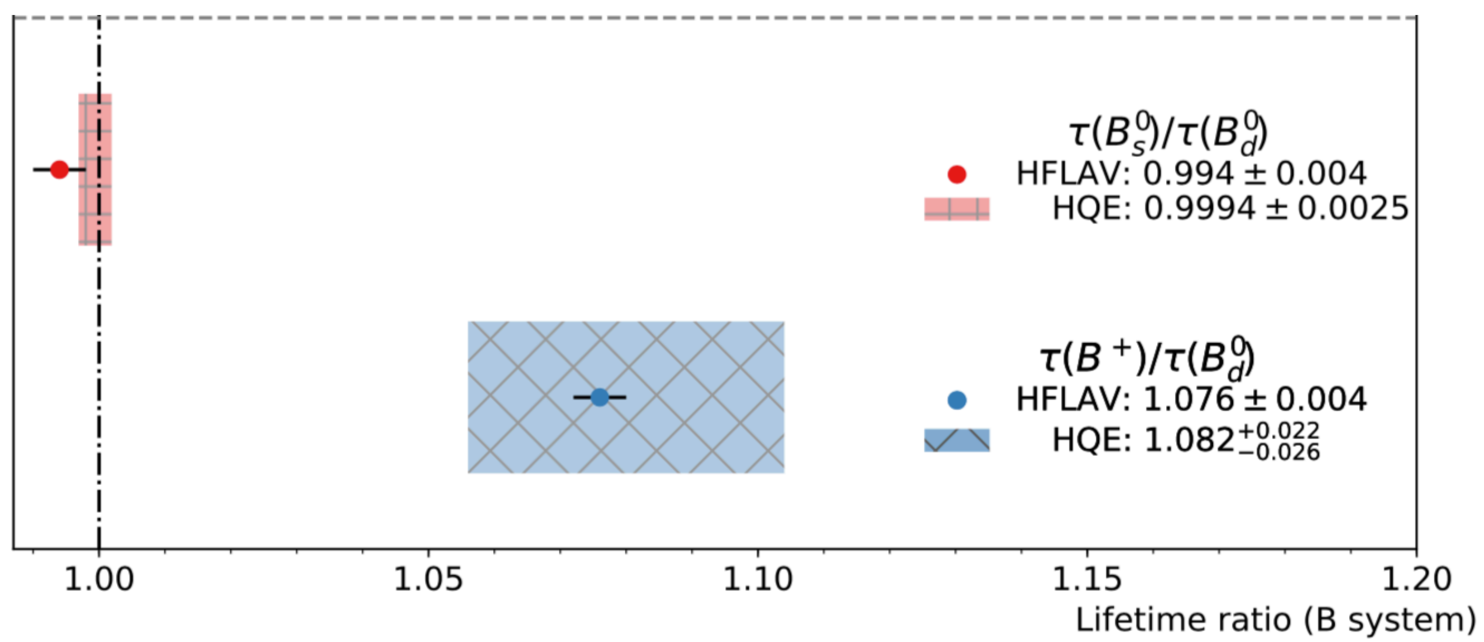
The Heavy Quark Expansion

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

Expansion in Λ / m_Q

The HQE works well in the B-system



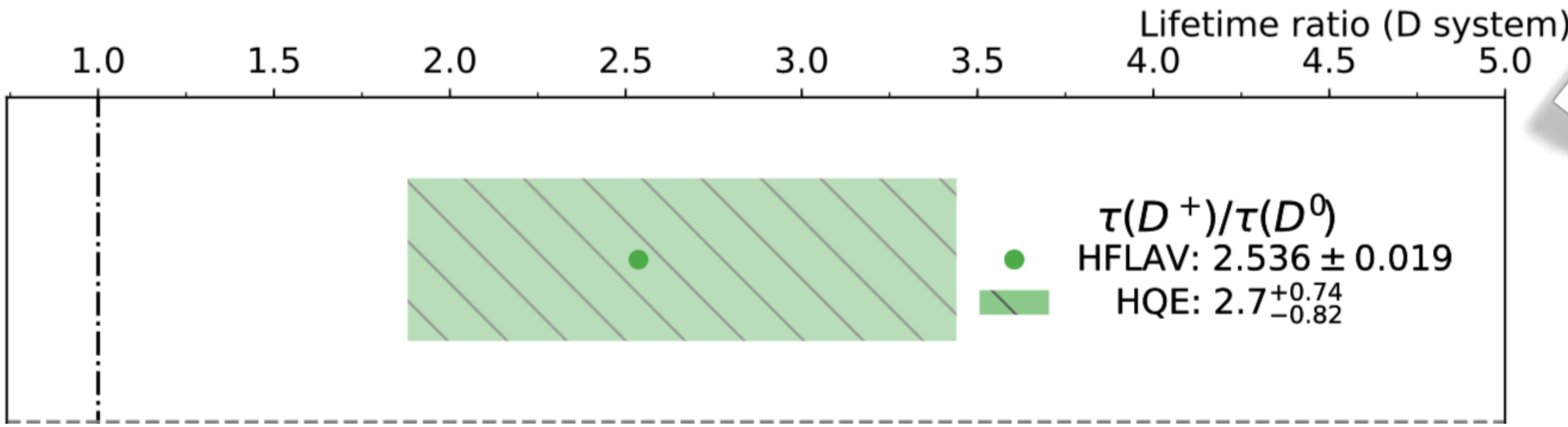


Kirk, AL, Rauh 1711.02100

Charm Theory 2

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

Look in systems without GIM cancellation: D-lifetimes



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

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 3

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 4

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+)

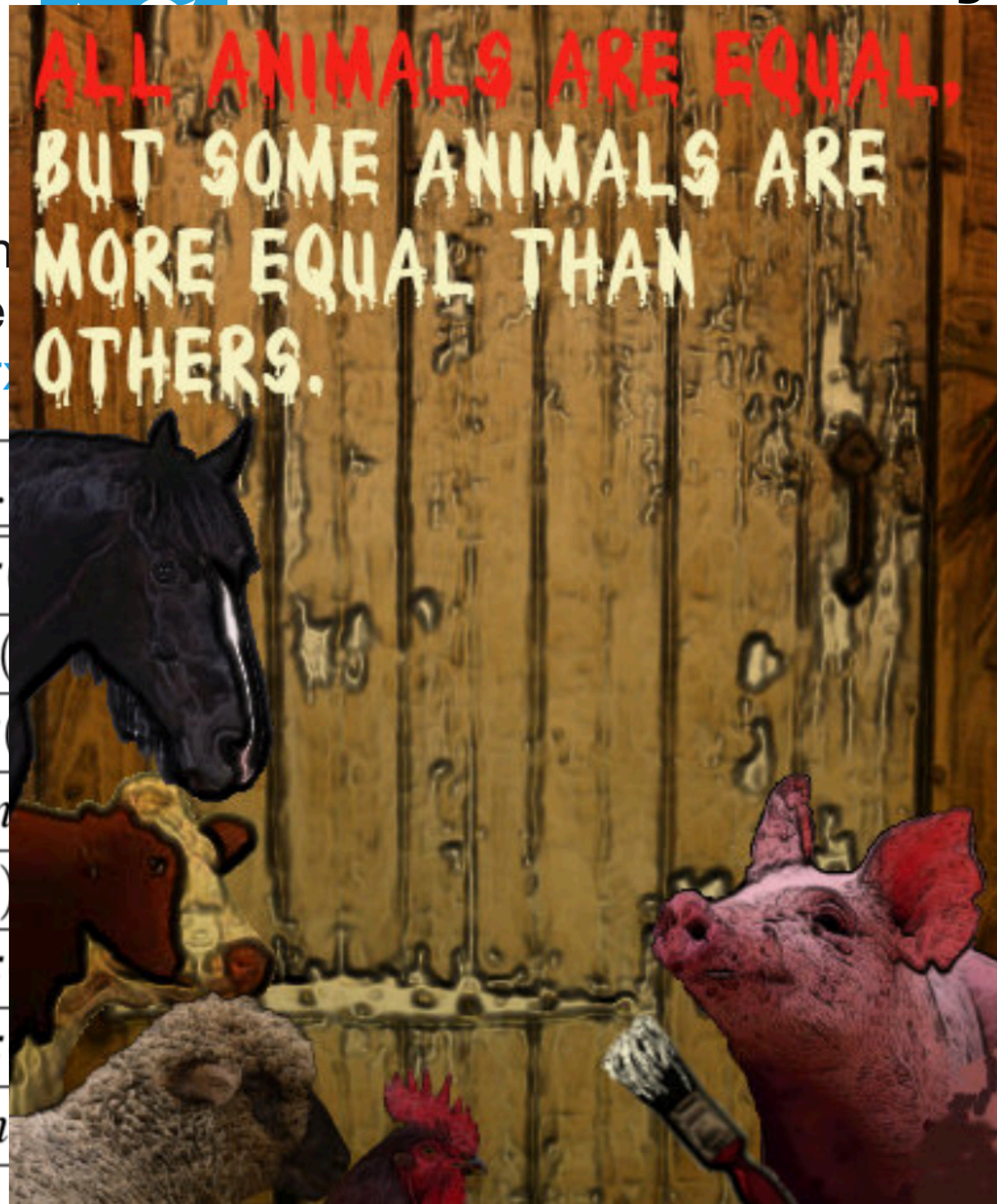
Hai-Yang Cheng

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

Charm Theory 4

Mark Williams
@QuarkWilliams

How much can
predictions? Fi
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

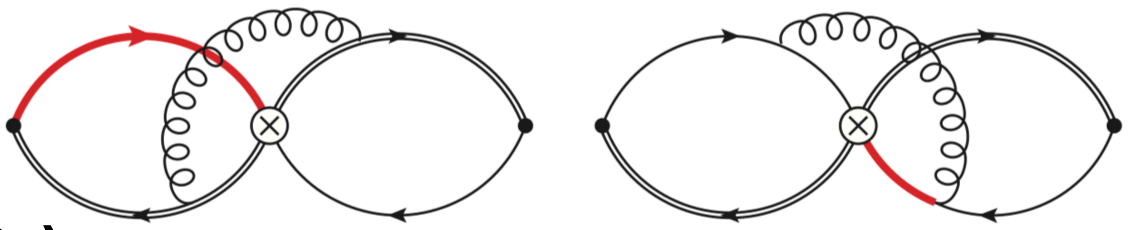
****: 12-15 *** 8 -11.5 **: 4-7.5 *: 2-3.5

Charm Theory 5

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 1904.00940lattice)

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)

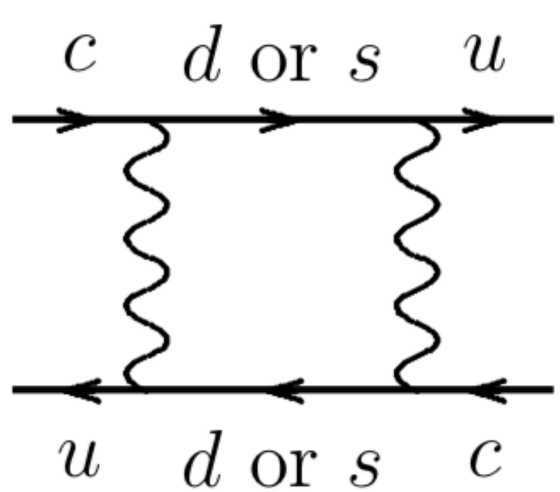
Confirm/disprove the applicability of the HQE in the charm sector for inclusive quantities

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

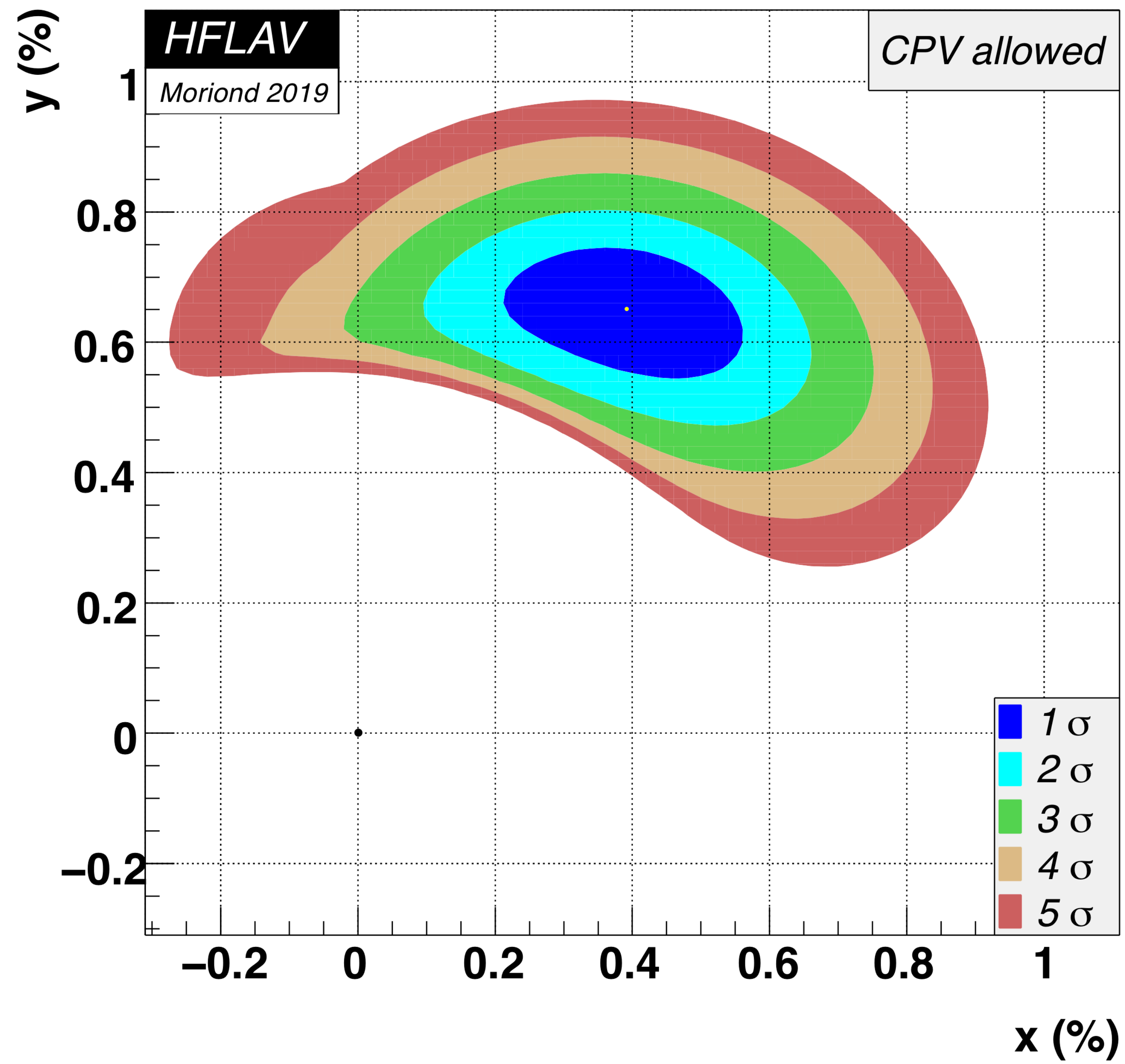
Charm mixing - Experiment

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,
see Marco Gersabeck's talk



- 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!!!

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

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

Charm mixing - Theory 3

Crucial differences compared to B mixing

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

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survives in SU(3)F limit!

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

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

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

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 $\Delta\Gamma_D \leq 2|\Gamma_{12}^D|$

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

CPV

survives in SU(3)F limit!

dominant for B mixing

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

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

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 7

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

=> apply it for D-mixing

Charm mixing - Theory 7

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 7

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 7

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

=> apply it for D-mixing

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

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

Bobrowski et al 1002.4794

Important observation for CPV

Charm mixing - Theory 8

What could have gone wrong in D-mixing?

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

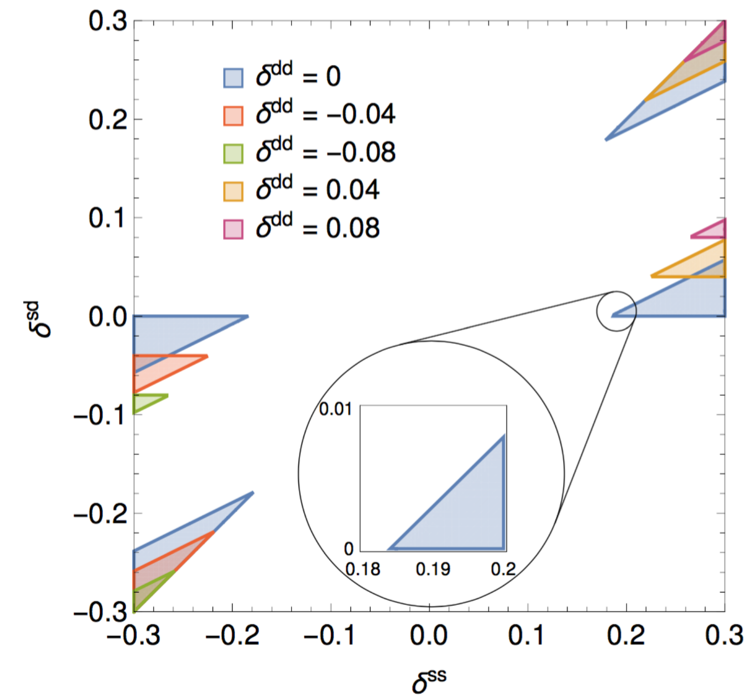
$$\Gamma_{12}^{ss} \to \Gamma_{12}^{ss}(1+\delta^{ss}) \, ,$$

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

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

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 proof it :-)**

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 $x \propto \mathcal{O}(0.1\%)$ $y \propto \mathcal{O}(few\ 0.1\%)$

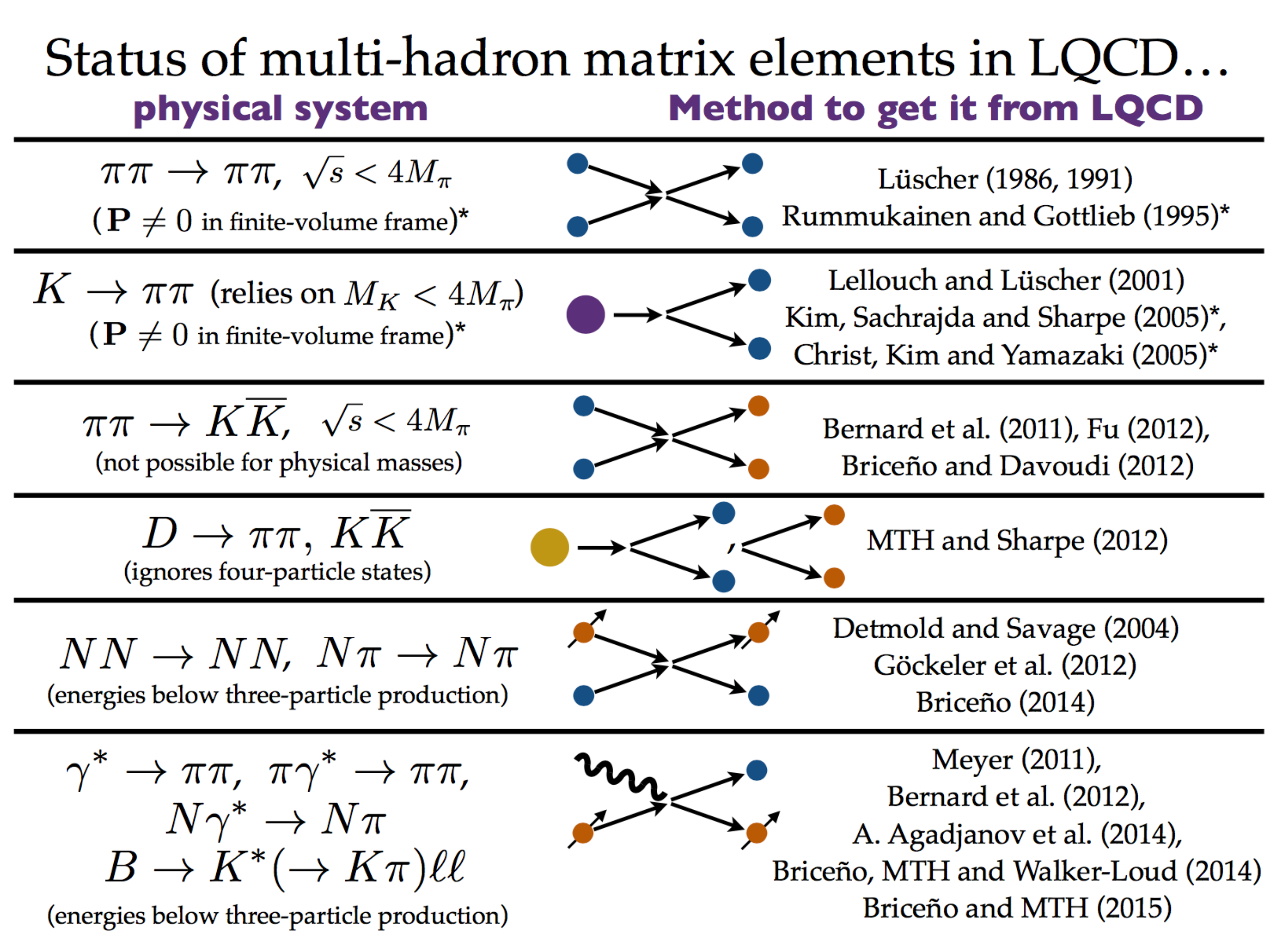
U-Spin sum rule Gronau, Rosner 2012

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

COMMENTS ON DELTA A_CP

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… (see also Keri Vos)

   Can /will be improved

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

Can /will be improved

COMMENTS ON DELTA A_CP

ΔA_{CP} within the Standard Model and beyond

Mikael Chala, Alexander Lenz, Aleksey V. Rusov and Jakub Scholtz

Institute for Particle Physics Phenomenology, Durham University,
DH1 3LE Durham, United Kingdom

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 ΔA_{CP}. We get as an upper bound in the SM $|\Delta A_{CP}^{\mathrm{SM}}| \leq 3 \times 10^{-4}$, which can be compared to the measurement of $\Delta A_{CP}^{\mathrm{LHCb2019}} = (-15.4 \pm 2.9) \times 10^{-4}$. We discuss resolving this tension

Maybe 4 but not the slightest indication for 15!

Conclusion

1) Yes, charm SM predictions are notoriously difficult

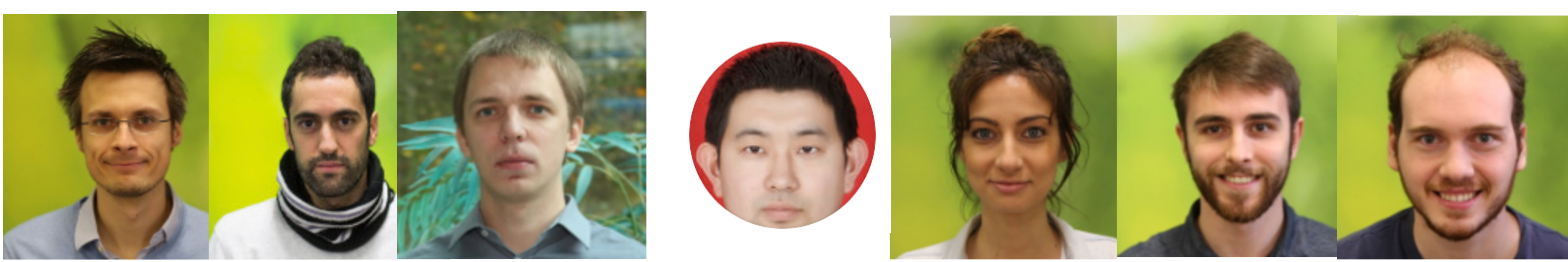
Be aware of cancellations:
- GIM in Mixing
- Wilson coefficients in lifetimes
- …

2) No, not all animals are equal

3) No, charm SM predictions are not arbitrary

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

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



Outlook

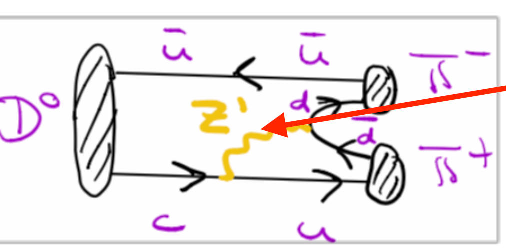
My prediction:

Yuval will meet the lady on the train again when travelling to TUPIFP 2022 and will have to say:

When half way through the journey of our life
I found that I was in a gloomy wood,
because the path which led aright was lost.
And ah, how hard it is to say just what
this wild and rough and stubborn woodland was,
the very thought of which renews my fear!
So bitter 't is, that death is little worse;
but of the good to treat which there I found,
I 'll speak of what I else discovered there.

First trip to Durham in 2019

QCD based theory tools for charm HQE, LCSR,…



I cannot well say how I entered it,
so full of slumber was I at the moment
when I forsook the pathway of the truth;