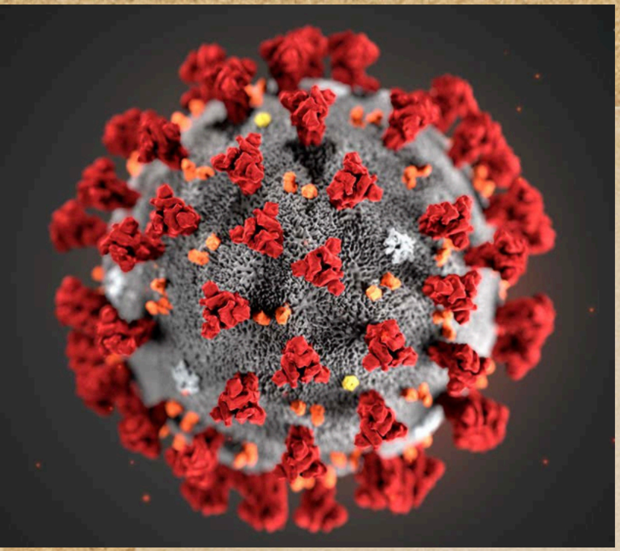
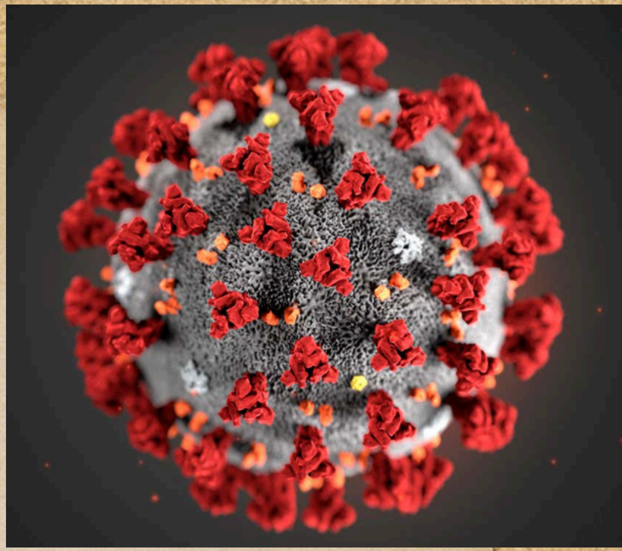
CP violation at Upgrade II

Alexander Lenz, IPPP Durham

Barcelona/Witton Gilbert

1st April 2020





We are living in troubled times

I strongly hope all of you and your families and friends are still fine

Nevertheless/Because of that we should keep up the good mood, keep things going and make the best out of these times

Here the situation is still ok

For me the most troublesome development so far was

For me the most troublesome development so far was

So I was immediately checking my former PhD student Matthew Kirk who is now post-doc in Rome

And I got this reply

Relief from Rome

May your supermarkets look like that!

My Tasks

1. Highly precise request: Dear Alex,
   we would like to invite you to give a talk about
   "CP violation at Upgrade II"

2. Many of my theory colleagues are now even
   more socially distanced than usually

My Tasks

1. Highly prec
we would li   bout
"CP violati
2. Many of m   even
more soci   )

=> Make a poll among my theory colleagues

Dear xxx,

I was asked to present a talk about
"CP violation in Beauty and Charm" at the LHCb Upgrade II
on April 1st (no joke!)
at the now virtual Barcelona workshop.

Therefore I would like to ask several experts on what they consider to be the (up to 3) most important future topics related to CP violation in beauty and charm.

14 Replies from: Andrzej Buras, Sebastian Jäger, Yuval Grosman, Uli Nierste, Marco Ciuchini, Jure Zupan, Gudrun Hiller, Thorsten Feldmann, Zoltan Ligeti, Thomas Mannel, Danny van Dyk, Svjetlana Fajfer, Gino Isidori, Luca Silvestrini

- Mixing induced CPV in charm IIIII II
- B -> K(*) mu mu and friends: IIII
- Gamma below 1% IIII
- A_CP (D_0-> K+K-), A_CP (D_0-> pi +pi-) IIII
- Sort out penguin pollution for beta, beta_s II
- B-> 3 bodies II
- epsilon'/epsilon -> relation to charm due to SU(2)_L II
- A_CP (D_0-> K_S K_S), A_CP (D_0-> K* K_S) II
- A_CP in rare charm decays D-> pi (pi) mu mu…. II
- b-> c \bar{c} s -> non-leptonic (lifetimes)
- A_CP in c-> u gamma, Lambda_c -> p gamma
- S_f in b->s qq transitions
- A_SL

REVIEWS OF MODERN PHYSICS, VOLUME 88, OCTOBER–DECEMBER 2016

CP violation in the B_s^0 system

Marina Artuso
Department of Physics, Syracuse University, Syracuse, New York 13244, USA

Guennadi Borissov
Physics Department, Lancaster University, Lancaster LA1 4YB, United Kingdom

Alexander Lenz
Institute for Particle Physics Phenomenology, Durham University, South Road, Durham DH1 3LE, United Kingdom

CP violation

Theoretical control	CPV in	Formulae	Example	Problems
***	Mixing	$a_{\rm fs}^s = \frac{\Gamma(\bar{B}_s^0(t) \to f) - \Gamma(B_s^0(t) \to \bar{f})}{\Gamma(\bar{B}_s^0(t) \to f) + \Gamma(B_s^0(t) \to \bar{f})} \equiv a_{\rm sl}^s.$	$B_s^0 \to D_s^- \pi^+$ or $B_s^0 \to X l \nu$	Convergence of HQE
**	Interference	$A_{CP,f}(t) = \frac{\Gamma(\bar{B}_s^0(t) \to f) - \Gamma(B_s^0(t) \to f)}{\Gamma(\bar{B}_s^0(t) \to f) + \Gamma(B_s^0(t) \to f)}.$	$B_s \to J/\psi\phi$	Penguin pollution
*	Decay	$A_{{\rm dir}.CP,f}(t) = \frac{\Gamma(\bar{B}_s^0(t) \to \bar{f}) - \Gamma(B_s^0(t) \to f)}{\Gamma(\bar{B}_s^0(t) \to \bar{f}) + \Gamma(B_s^0(t) \to f)}$	$B_s^0 \to K^- \pi^+$	Strong phases+ penguin/tree

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CP violation

Theoretical control	CPV in		Problems
***	Mixing	$= \left\| \frac{\Gamma_{12}^s}{M_{12}^s} \right\| \sin \phi_{12}^s .$	Convergence of HQE
**	Interference	$\frac{\bar{A}_{\bar{f}}}{A_f} \approx -e^{-2i\arg(\lambda_c)} \left\{ 1 - 2ir \sin\left[\arg\left(\frac{\lambda_u}{\lambda_c}\right)\right]\right\}$	$r = \left\|\frac{\lambda_u}{\lambda_c}\right\| \left\|\frac{\tilde{A}_f^{\text{Peng}}}{\tilde{A}_f^{\text{Tree}}}\right\| e^{i(\phi_{\text{Peng}}^{\text{QCD}} - \phi_{\text{Tree}}^{\text{QCD}})}$
*	Decay	$A_{\text{dir}CP,f}(t) = \frac{2\|r\| \sin(\phi_{\text{Peng}}^{\text{QCD}} - \phi_{\text{Tree}}^{\text{QCD}}) \sin\gamma}{1 + \|r\|^2 - 2\|r\| \cos(\phi_{\text{Peng}}^{\text{QCD}} - \phi_{\text{Tree}}^{\text{QCD}}) \cos\gamma}$	proportional to penguins!!! not only pollution!!!

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CP violation in mixing and gamma

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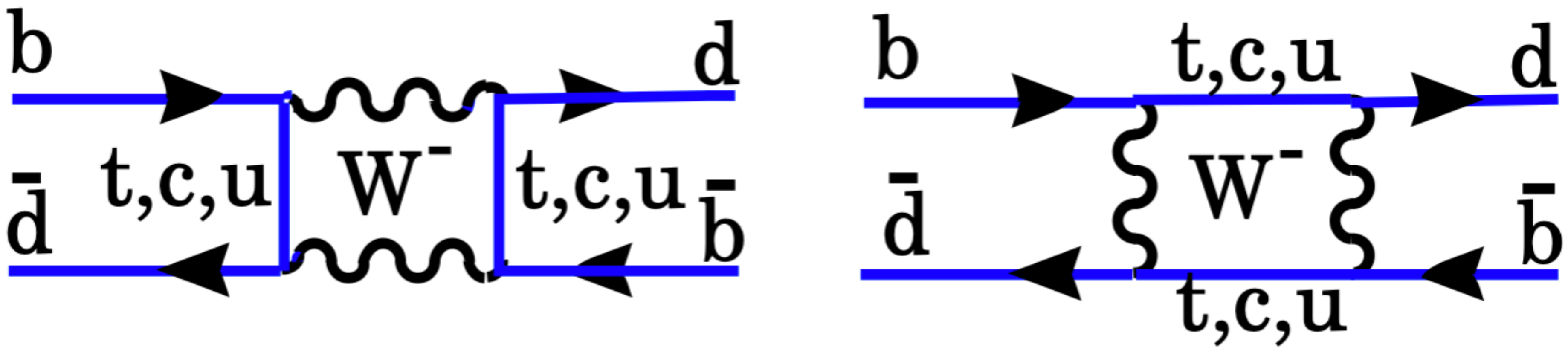
CP violation in mixing and gamma



$|M_{12}|$, $|\Gamma_{12}|$ and $\phi = \arg(-M_{12}/\Gamma_{12})$ can be related to three observables:

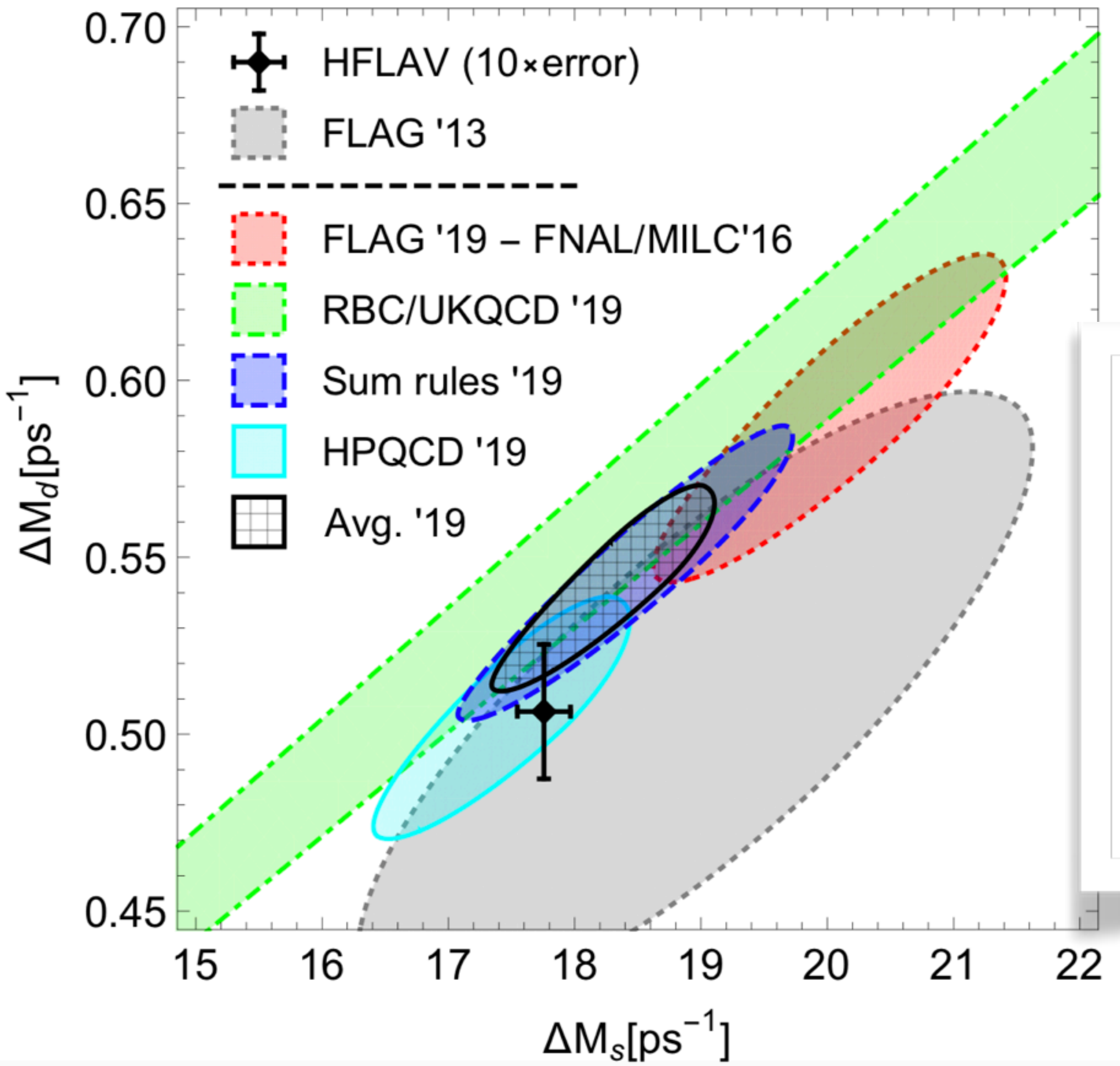
- **Mass difference:** $\Delta M := M_H - M_L \approx 2|M_{12}|$ **(off-shell)**
  $|M_{12}|$: heavy internal particles: t, SUSY, ...
- **Decay rate difference:** $\Delta\Gamma := \Gamma_L - \Gamma_H \approx 2|\Gamma_{12}|\cos\phi$ **(on-shell)**
  $|\Gamma_{12}|$: light internal particles: u, c, ... (almost) no NP!!!
- **Flavor specific/semi-leptonic CP asymmetries:** e.g. $B_q \to Xl\nu$ (*semi-leptonic*)

$$a_{sl} \equiv a_{fs} = \frac{\Gamma(\overline{B}_q(t) \to f) - \Gamma(B_q(t) \to \overline{f})}{\Gamma(\overline{B}_q(t) \to f) + \Gamma(B_q(t) \to \overline{f})} = \left|\frac{\Gamma_{12}}{M_{12}}\right| \sin\phi$$

CP violation in mixing and gamma

Mass difference ΔM_q

Huge progress in sum rules and lattice



Very active field:

- **Flag 19: mostly FNAL-MILC (2/16)**
- **RBC-UK: 12-18**
- **Sum rules: Durham 4/19 (based on Siegen 16-18, Durham 17)**
- **HPQCD: 07/19**

Sum rules determine
B-1 approx 0.1

Thus a 20% uncertainty
in B-1 can transform into
a 2% uncertainty of B=O(1)

1/m_b corrections
are estimated to be small

New averages of lattice and sum rules
Di Luzio, Kirk, AL, Rauh
1909.11087 JHEP

CP violation in mixing and gamma

ΔM_s^{SM}	This work	ABL 2015	LN 2011	LN 2006
Central Value	$18.77\,\mathrm{ps}^{-1}$	$18.3\,\mathrm{ps}^{-1}$	$17.3\,\mathrm{ps}^{-1}$	$19.3\,\mathrm{ps}^{-1}$
$\delta(f_{B_s}\sqrt{B_1})$	3.1%	13.9%	13.5%	34.1%
$\delta(V_{cb})$	3.4%	4.9%	3.4%	4.9%
$\delta(m_t)$	0.3%	0.7%	1.1%	1.8%
$\delta(\alpha_s)$	0.2%	0.1%	0.4%	2.0%
$\delta(\gamma)$	0.1%	0.1%	0.3%	1.0%
$\delta(\lvert V_{ub}/V_{cb}\rvert)$	$< 0.1\%$	0.1%	0.2%	0.5%
$\delta(\overline{m}_b)$	$< 0.1\%$	$< 0.1\%$	0.1%	$- - -$
$\sum \delta$	4.6%	14.8%	14.0%	34.6%

AL, 2019

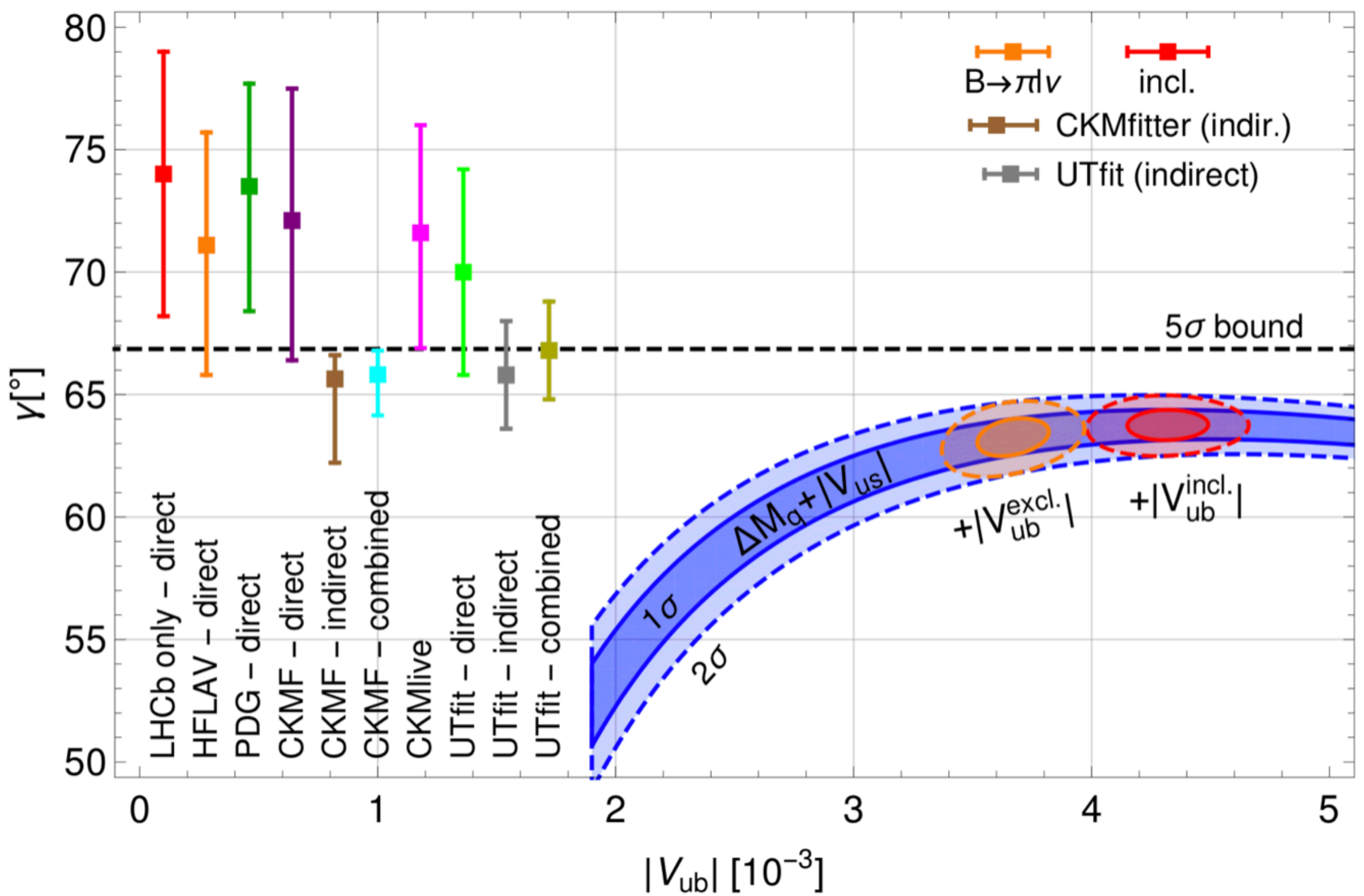
Thanks to
Lattice,
Sum rules

Fix V_us and try to use B_s and B_d mixing (independent of V_ub) to determine V_cb & gamma,….

CP violation in mixing and gamma

Within the SM we get

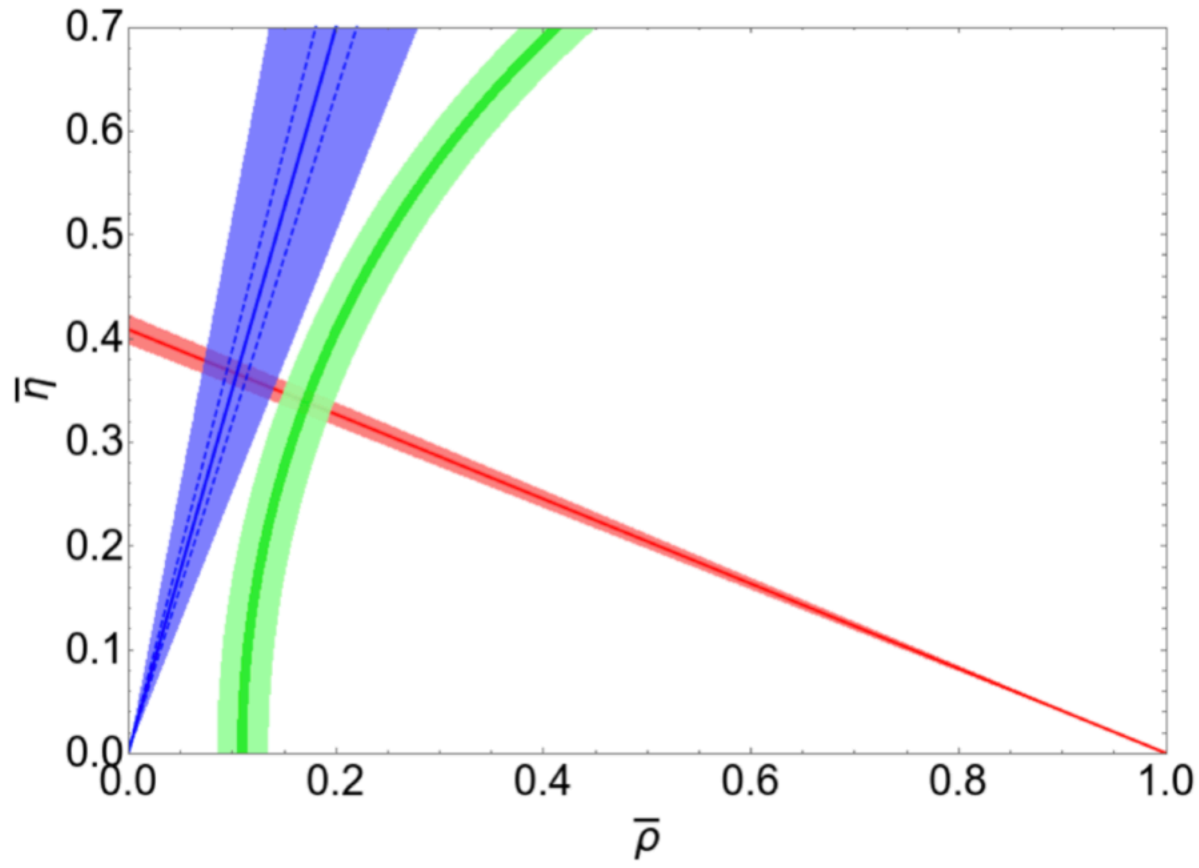
King, Kirk, AL, Rauh
1911.07856



Vub unconstrained, upper limit on gamma?

CP violation in mixing and gamma

Upper limit on gamma?



King, Kirk, AL, Rauh
1911.07856

$$\gamma \leq 66.9^\circ \qquad [5\sigma]$$

or

- **BSM in mixing**
- **BSM in non-leptonic tree-level decays**

Brod, AL, Tetlalmatzi-Xolocotzi 1412.1446, PRD
AL, Tetlalmatzi-Xolocotzi 1912.07621

CP violation in mixing and gamma

The amazing cleanliness of gamma is based on assuming no BSM effects in non-leptonic tree-level decays

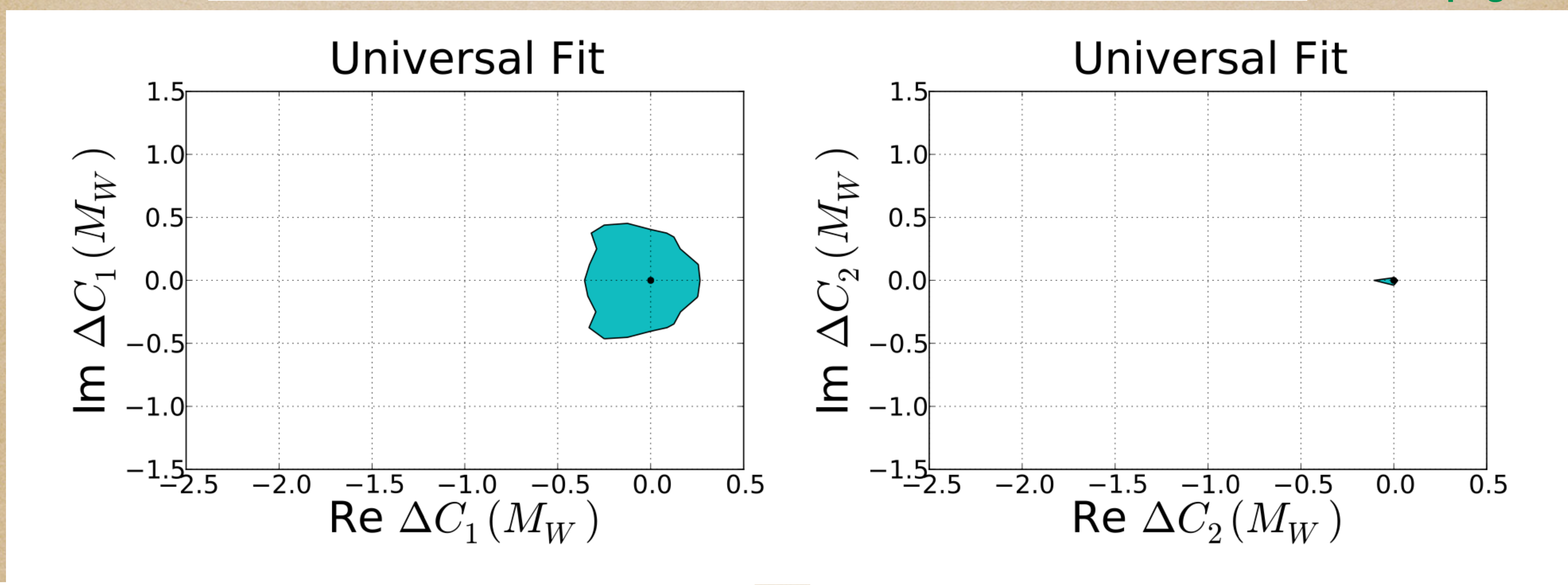
The ultimate theoretical error on γ from $B \to DK$ decays
Joachim Brod (Cincinnati U.), Jure Zupan (Cincinnati U.) (Aug 26, 2013)
Published in: *JHEP* 01 (2014) 051 • e-Print: 1308.5663 [hep-ph]

In view of an ever increasing experimental precision, how well is this assumption justified?

Look at observables, that are reasonably well known in theory and experiment and try to identify the potential space for BSM effects in the Wilson coefficients C_1 and C_2 for non-leptonic tree-level decays

Model-independent bounds on new physics effects in non-leptonic tree-level decays of B-mesons
Alexander Lenz (Durham U., IPPP), Gilberto Tetlalmatzi-Xolocotzi (Siegen U. and Nikhef, Amsterdam) (Dec 16, 2019)
e-Print: 1912.07621 [hep-ph]

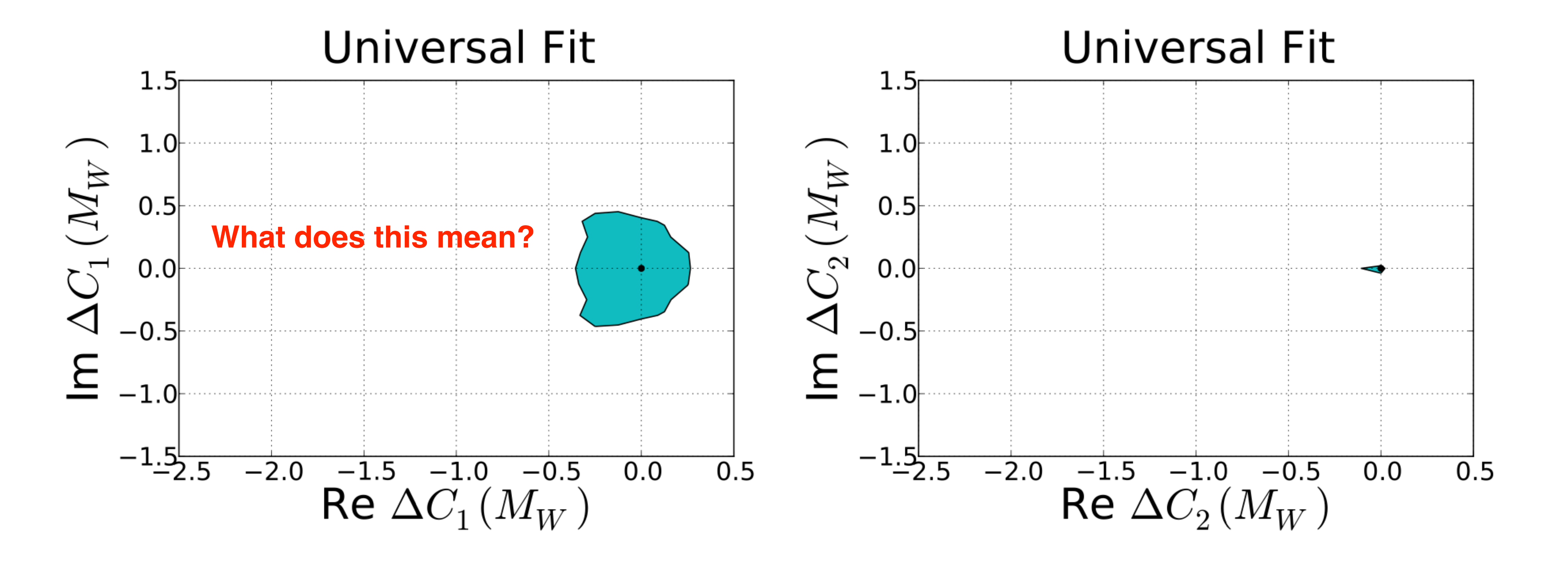
Perfect self-isolation reading material: 100 pages!!!



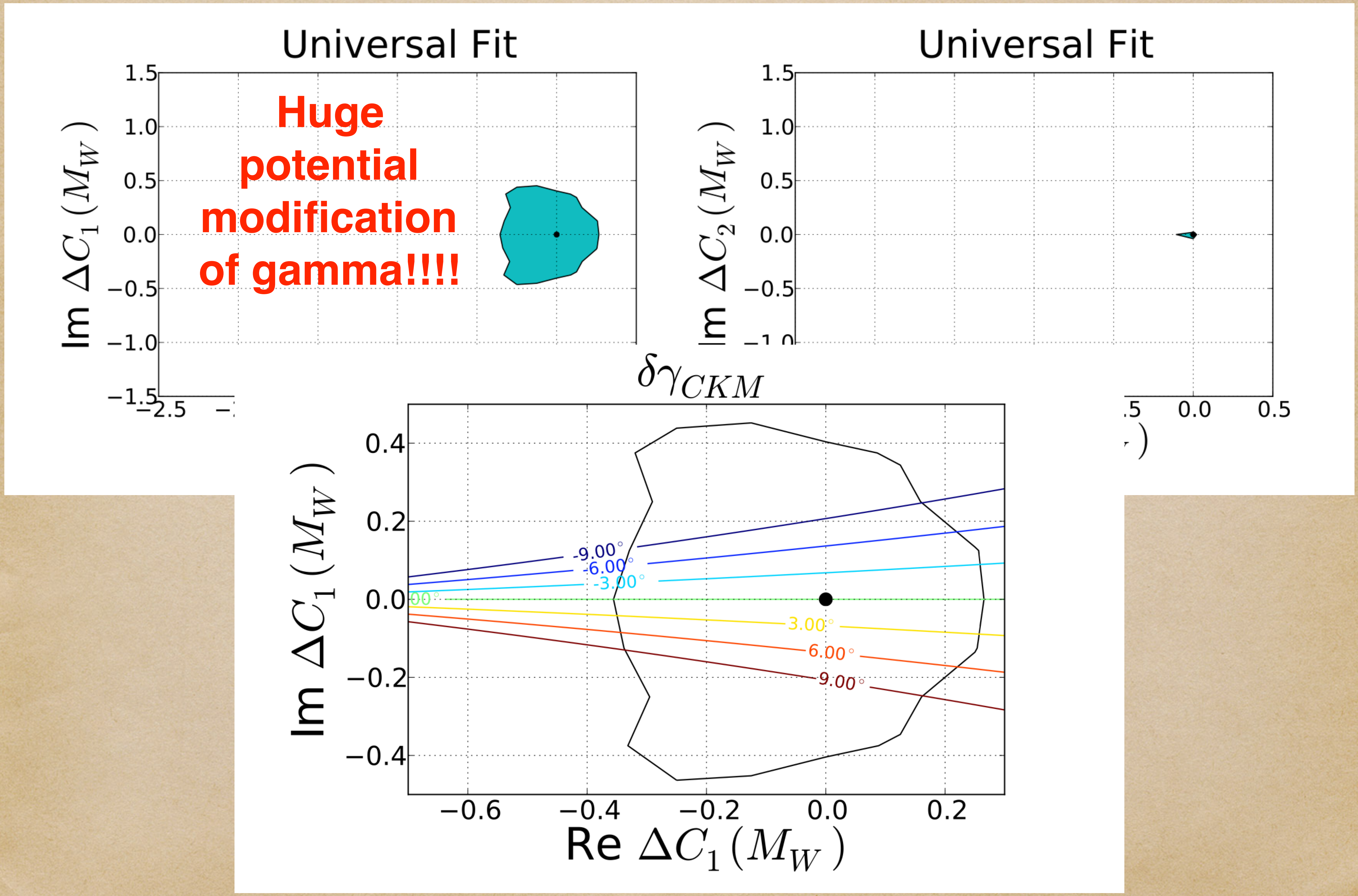
New physics effects in tree-level decays and the precision in the determination of the quark mixing angle γ
Joachim Brod (Mainz U. and U. Mainz, PRISMA), Alexander Lenz (Durham U. and Durham U., IPPP), Gilberto Tetlalmatzi-Xolocotzi (Durham U. and Durham U., IPPP), Martin Wiebusch (Durham U. and Durham U., IPPP) (Dec 3, 2014)
Published in: *Phys.Rev.D* 92 (2015) 3, 033002 • e-Print: 1412.1446 [hep-ph]

On new physics in $\Delta\Gamma_d$ #14
Christoph Bobeth (TUM-IAS, Munich), Ulrich Haisch (Oxford U., Theor. Phys. and CERN), Alexander Lenz (Durham U., IPPP), Ben Pecjak (Durham U., IPPP), Gilberto Tetlalmatzi-Xolocotzi (Durham U., IPPP) (Apr 9, 2014)
Published in: *JHEP* 06 (2014) 040 • e-Print: 1404.2531 [hep-ph]

CP violation in mixing and gamma

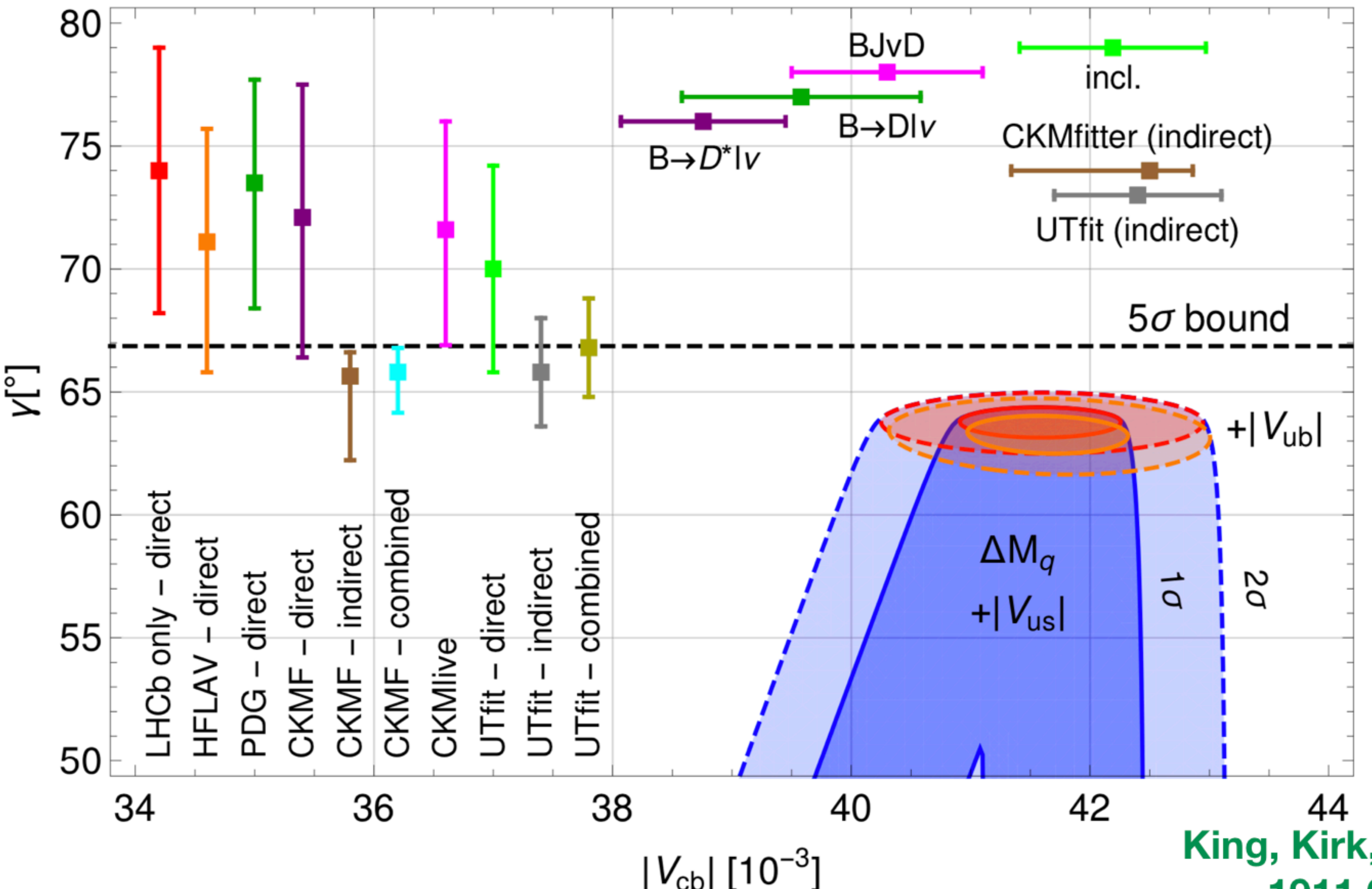


CP violation in mixing and gamma



CP violation in mixing and gamma

Within the SM we get $\gamma = (63.4 \pm 0.9)^\circ$ $|V_{cb}| = (41.6 \pm 0.7) \cdot 10^{-3}$



King, Kirk, AL, Rauh
1911.07856

Competitive precision for Vcb - favours inclusive value, upper limit on gamma

CP violation in mixing and gamma

For predicting CPV in mixing we need Gamma_12 besides M_12

Total decay rate can be expanded in inverse powers of mb

$$\Gamma = \Gamma_0 + \frac{\Lambda^2}{m_b^2}\Gamma_2 + \frac{\Lambda^3}{m_b^3}\Gamma_3 + \frac{\Lambda^4}{m_b^4}\Gamma_4 + \ldots$$

Each term in the series can be further expanded in the strong coupling

$$\Gamma_j = \Gamma_j^{(0)} + \frac{\alpha_s(\mu)}{4\pi}\Gamma_j^{(1)} + \frac{\alpha_s^2(\mu)}{(4\pi)^2}\Gamma_j^{(2)} + \ldots$$

Each term is a product of a perturbative function and the matrix element of **Delta B = 0 operators** **(lattice , sum rules)**

Mixing obeys a similar HQE

$$\Gamma_{12}^q = \left(\frac{\Lambda}{m_b}\right)^3 \Gamma_3 + \left(\frac{\Lambda}{m_b}\right)^4 \Gamma_4 + \ldots$$

Now **Delta B = 2 operators appear** **(lattice , sum rules)**

CP violation in mixing and gamma

$$\Re\left(\frac{\Gamma_{12}^q}{M_{12}^q}\right) = -\frac{\Delta\Gamma_s}{\Delta M_q}$$

$$\Im\left(\frac{\Gamma_{12}^q}{M_{12}^q}\right) = a_{sl}^q$$

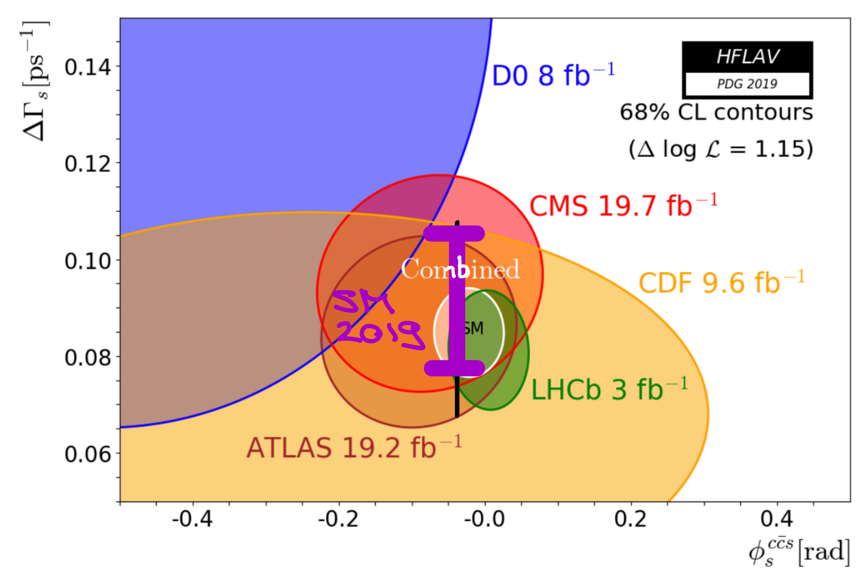
- **Decay constants cancel completely**
- **Bag parameter cancel largely**

$$\Delta\Gamma_s^{\mathrm{SM\,2019}} = (0.091 \pm 0.013)\,\mathrm{ps}^{-1}$$

$$\Delta\Gamma_s^{\mathrm{HFLAV\,2019}} = (0.088 \pm 0.006)\,\mathrm{ps}^{-1}$$

$$\Delta\Gamma_d^{\mathrm{SM\,2019}} = (2.6 \pm 0.4) \cdot 10^{-3}\,\mathrm{ps}^{-1}$$

$$\Delta\Gamma_d^{\mathrm{HFLAV\,2019}} = (-1.3 \pm 6.6) \cdot 10^{-3}\,\mathrm{ps}^{-1}$$



- **Strong test of HQE**
- **Violation of Quark hadron duality must be small**

CP violation in mixing and gamma

$$\Re\left(\frac{\Gamma_{12}^q}{M_{12}^q}\right) = -\frac{\Delta\Gamma_s}{\Delta M_q}$$

$$\Im\left(\frac{\Gamma_{12}^q}{M_{12}^q}\right) = a_{sl}^q$$

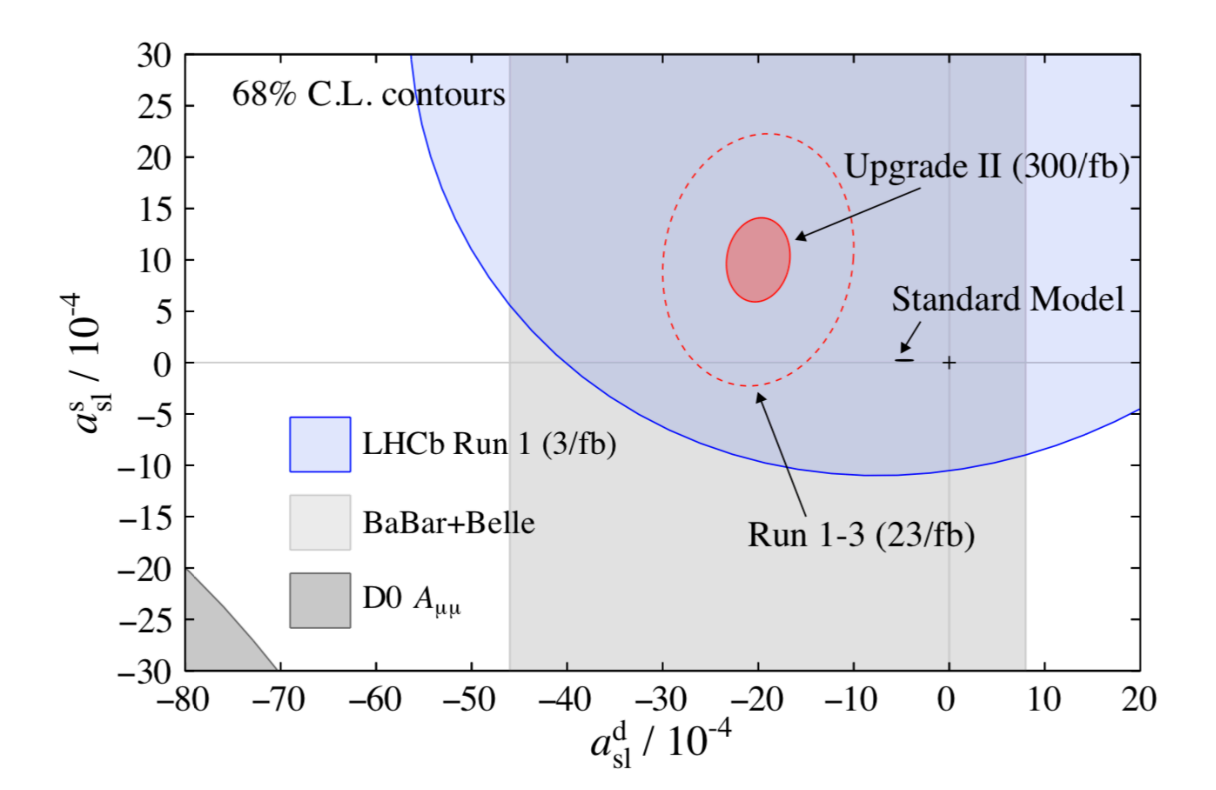
- **Decay constants cancel completely**
- **Bag parameter cancel largely**

$$a_{fs}^{s,\,\mathrm{SM}\,2019} = (2.06 \pm 0.18)\cdot 10^{-5}$$

$$a_{fs}^{s,\,\mathrm{HFLAV}\,2019} = (-60 \pm 280)\cdot 10^{-5}$$

$$a_{fs}^{d,\,\mathrm{SM}\,2019} = -(4.73 \pm 0.42)\cdot 10^{-4}$$

$$a_{fs}^{d,\,\mathrm{HFLAV}\,2019} = (-21 \pm 17)\cdot 10^{-4}$$

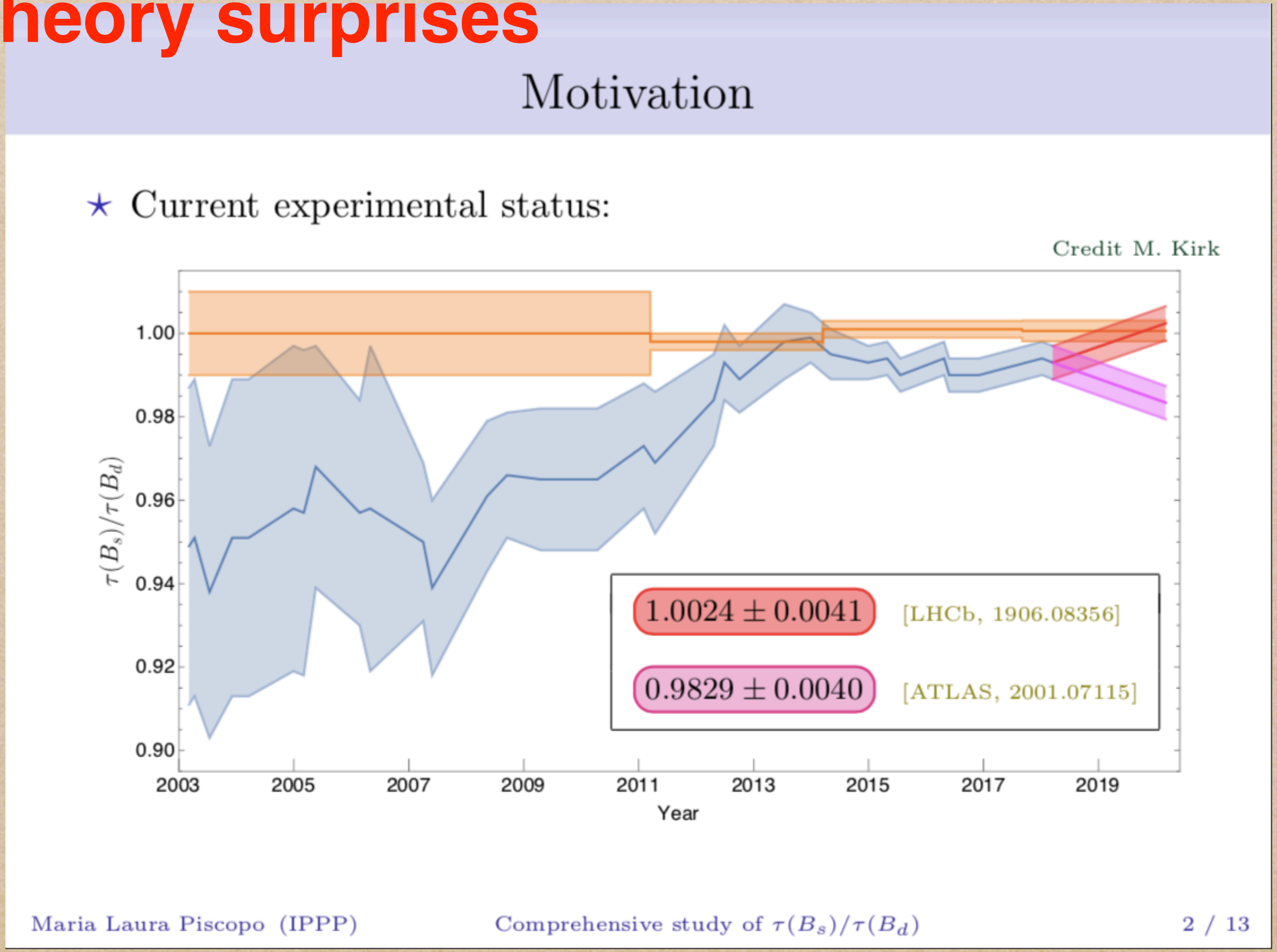


- **Very sensitive to BSM effects!**
- **In particular to CPV BSM effects in tree-level decays**
- **Experimental number needed**

CP violation in mixing and gamma

Further HQE tests from study of hadron lifetimes

1. HQE with Bag parameter from HQET sum rules works well!
2. Lattice confirmation urgently needed
3. Still higher experimental accuracy for Bs lifetime needed
4. Soon some theory surprises



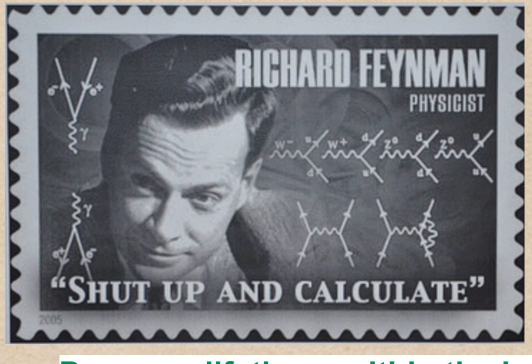
Bs/Bd lifetime ratios gives strong constraints on BSM effects in C_1,2

CP violation in mixing and gamma

Lifetimes of charmed mesons deviate hugely from each other and charm is not really heavy

=> does it make any sense to apply the HQE?

Our approach:

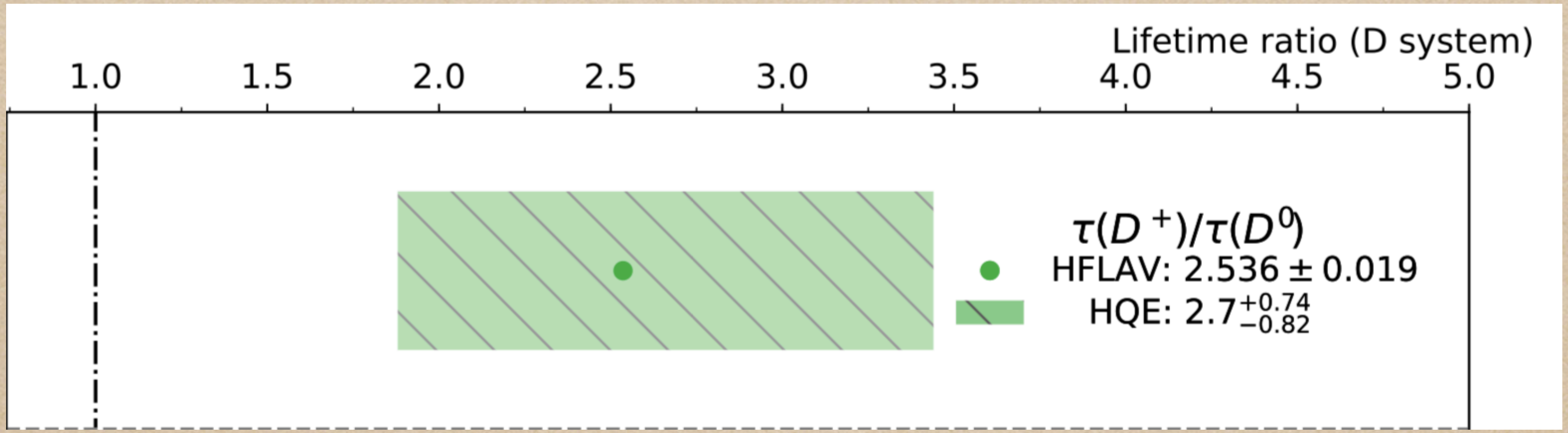


NLO -QCD

D-meson lifetimes within the heavy quark expansion
AL(Durham U., IPPP), Thomas Rauh (Munich, Tech. U.)
Phys.Rev. D88 (2013) 034004 arXiv:1305.3588 [hep-ph]

Matrix elements

Dimension-six matrix elements for meson mixing and lifetimes from sum rules
M. Kirk, AL, T. Rauh (Durham U. & Durham U., IPPP)
JHEP 1712 (2017) 068 arXiv:1711.02100 [hep-ph]



- **HQE seems also to work for lifetimes of charmed mesons!**
- **Confirm sum rule results with lattice/ do higher orders in HQE**
- **Investigate charmed baryon lifetimes**

CP violation in mixing and gamma

Mixing: $x_D^{\text{Exp.}} = (0.32 \pm 0.14) \cdot 10^{-2}$ $y_D^{\text{Exp.}} = 0.69^{+0.06}_{-0.07} \cdot 10^{-2}$

Try to calculate like in the B_s^0 system:

$$y_D^{\text{HQE}} \leq |\Gamma_{12}^D| \tau_D$$

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

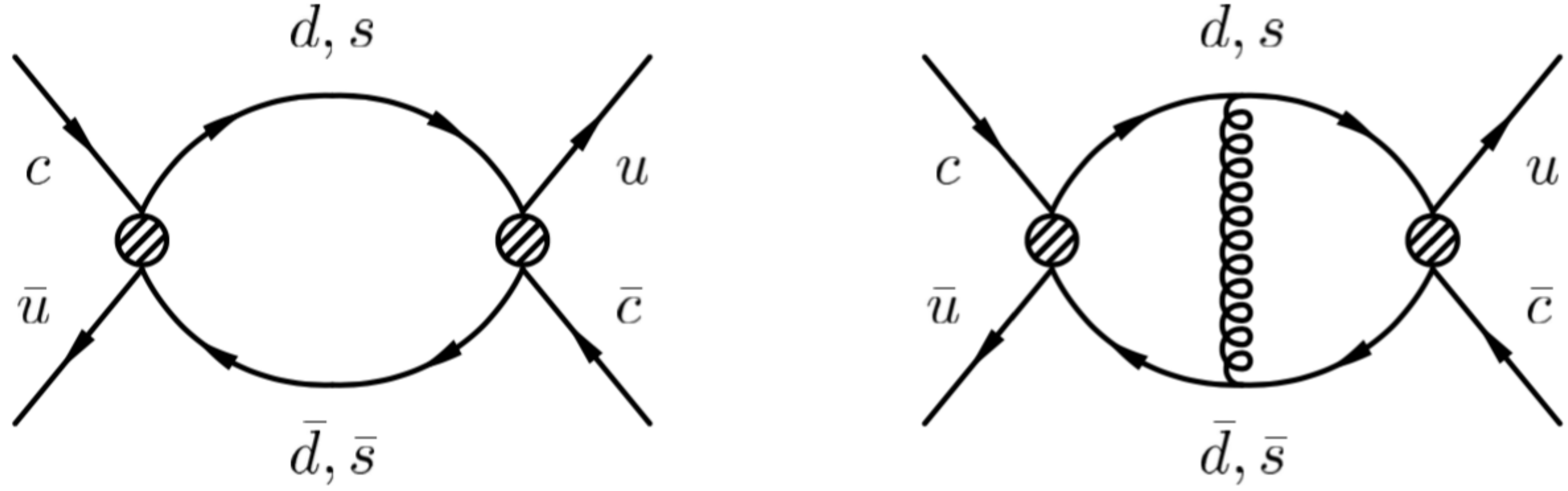


Figure 1: Contributions to Γ_{12} from operators of dimension 6 ($D = 6$). The leading order QCD diagram is shown in the left panel, an example for α_s corrections is shown in the right panel.

CP violation in mixing and gamma

Huge GIM cancellations in mixing and rare decays - not in lifetimes!

Consider only the first term:

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

Do the full expression (use CKM unitarity)

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

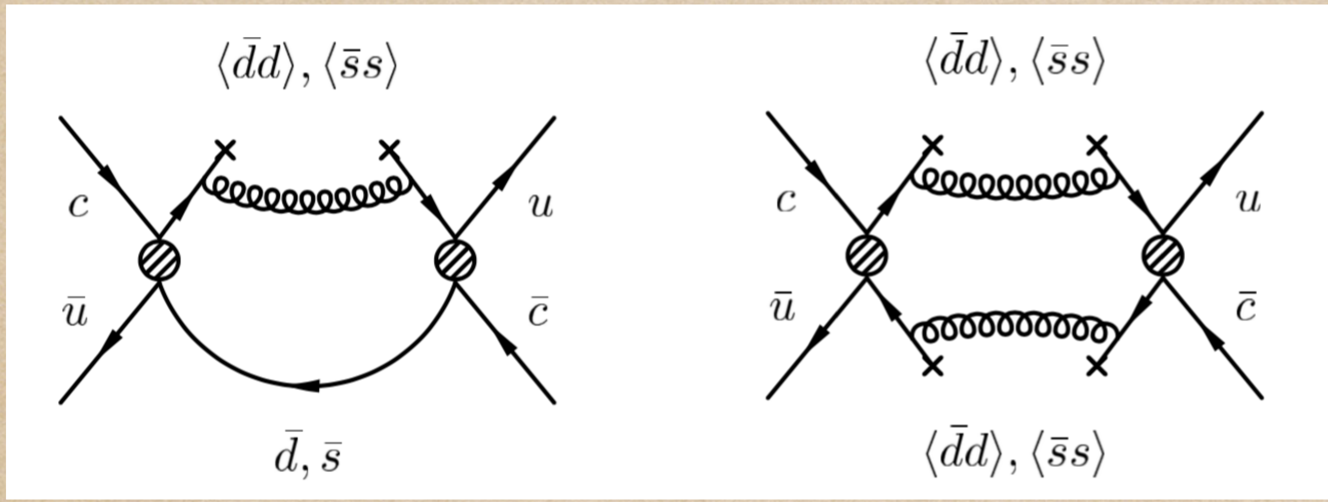
HQE itself gives not small numbers, but extremely effective GIM cancellation

similar effects in penguin induced charm decays

GIM is overshadowing everything

What could have gone wrong in the HQE for D-mixing?

1. GIM mechanism less effective in higher orders in the HQE



Georgi 1992
Ohl, Ricciardi, Simmons 1993
Bigi, Uraltsev 2000
Bobrowski, Riedl, Rohrwild, AL 2010

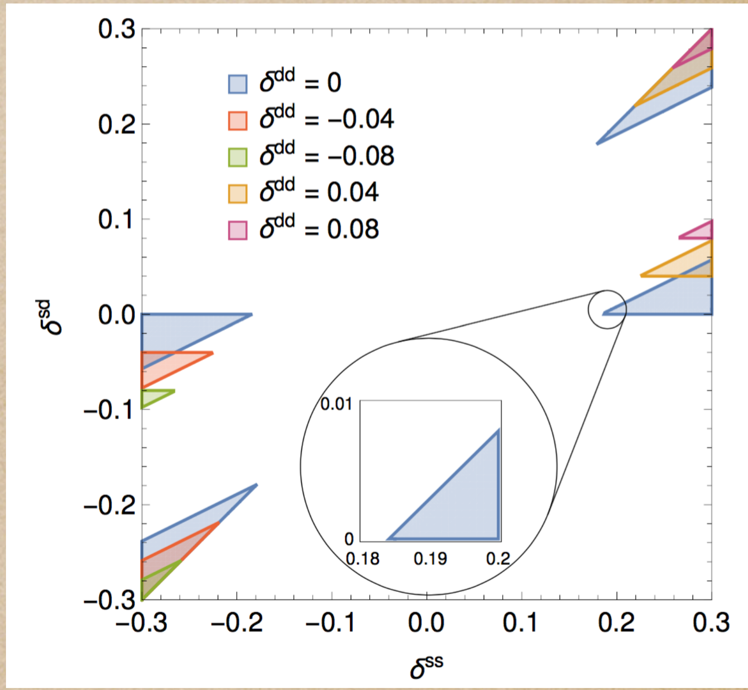
2. Small (20%) duality violations that have no/tiny GIM cancellations

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

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

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

Jubb, Kirk, AL, Tetlalmatzi-Xolocotzi 2016



20% of duality violation is sufficient to explain D-mixing!

3. ?Consider different scales for the 3 different contributions? Partial lifting of GIM

4. HQE simply does not converge at all in the Charm-system -> BUT: lifetimes one has to use different approaches

Heavy Quark Expansion for D mesons

ad 1. **Do D=9 and D=12 calculation**

How Large Can the SM Contribution to CP Violation in $D^0 - \bar{D}^0$ Mixing Be?
M. Bobrowski (Regensburg U.), A. Lenz (Dortmund U. & Regensburg U.), J. Riedl (Regensburg U.), J. Rohrwild (Regensburg U. & RWTH Aachen U.).
Published in **JHEP 1003 (2010) 009**
DO-TH-10-04, TTK-10-2
DOI: 10.1007/JHEP03(2010)009
e-Print: **arXiv:1002.4794 [hep-ph]** | **PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service
Detailed record - Cited by 112 records 100+

Im (Gamma_12/M_12) up to 0.01!

ad 2. **Try other approaches/to do a non-perturbative calculation**

Falk, Grossman, Ligeti, Petrov
Phys.Rev. D65 (2002) 054034 Cited by 276 records

Falk, Grossman, Ligeti, Nir, Petrov
Phys.Rev. D69 (2004) 114021 Cited by 231 records

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 165 records 100+

D meson mixing as an inverse problem
Hsiang-Nan Li, Hiroyuki Umeeda (Taiwan, Inst. Phys.), Fanrong Xu (Jinan U.), Fu-Sheng Yu (Lanzhou U.).
e-Print: **arXiv:2001.04079 [hep-ph]** | **PDF**

Dispersive and Absorptive CP Violation in $D^0 - D^0$ Mixing
Alexander L. Kagan (Cincinnati U.), Luca Silvestrini (CERN & INFN, Rome). Ja
CERN-TH-2020-011
e-Print: **arXiv:2001.07207 [hep-ph]** | **PDF**

ad 3. **Analysis in progress**

ad 4. **Confirm other charm lifetimes, in particular charmed baryons**

13 Replies from: Andrzej Buras, Sebastian Jäger, Yuval Grosman, Uli Nierste, Marco Ciuchini, Jure Zupan, Gudrun Hiller, Thorsten Feldmann, Zoltan Ligeti, Thomas Mannel, Danny van Dyk, Svetlana Fajfer, Gino Isidori

Delta A_CP and friends

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- B-> 3 bodies II
- epsilon'/epsilon -> relation to charm due to SU(2)_L II
- A_CP (D_0-> K_S K_S), A_CP (D_0-> K* K_S) II
- A_CP in rare charm decays D-> pi (pi) mu mu…. II
- b-> c \bar{c} s -> non-leptonic (lifetimes)
- A_CP in c-> u gamma, Lambda_c -> p gamma
- S_f in b->s qq transitions
- A_SL

Delta A_CP and friends

Due to lack of time, just three comments:

1) Experiment ≈ 10 times naive SM

e.g. nice overview + references in Nierste 2003.01788

2) BSM explanations difficult because of strong D-mixing constraints, but not impossible

e.g.

ΔA_{CP} within the Standard Model and beyond
Mikael Chala, Alexander Lenz, Aleksey V. Rusov, Jakub Scholtz (Durham U., IPPP).
Published in **JHEP 1907 (2019) 161**
IPPP/19/25
DOI: 10.1007/JHEP07(2019)161
e-Print: **arXiv:1903.10490 [hep-ph] | PDF**

and many more

Implications of the LHCb discovery of CP violation in charm decays
Avital Dery (Cornell U., LEPP), Yosef Nir (Weizmann Inst.). Sep 24, 2019. 12 pp.
Published in **JHEP 1912 (2019) 104**
DOI: 10.1007/JHEP12(2019)104
e-Print: **arXiv:1909.11242 [hep-ph] | PDF**

3) Try to measure more precise and control channels

What-to-do

- **Stay healthy and in good mood!**
- **Continue to improve precision in gamma, beta, beta_s, Delta A_CP, (including control channels)**
- **Try to measure CPV in mixing: D_0, B_d, B_s**
- **Continue to improve precision in tau(B_s), charm lifetimes, Delta Gamma_d**
- **Study also CPV observables in b -> s ll and b-> dll**
- **Study CPV in rare charm decays**

END