The status and long-term prospects of CP violation in beauty and charm (with a focus on charm)

Alexander Lenz, IPPP Durham

Annecy

22nd March 2018

Introduction

On behalf of the organising committee we would like to invite you to give a talk on the status and long-term prospects of **CP violation in beauty and charm** (**with a focus on charm**), assuming that LHCb would increase the statistics by a factor 100 with respect to Run-1. = 300/fb,

This can easily fill a many year research programme for several people

Previous editions

- http://www.hep.manchester.ac.uk/theatre-of-dreams/index.html
- https://agenda.infn.it/conferenceDisplay.py?confId=12253

CP violation

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

CP violation in the B_s^0 system

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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 $B_s^0 \to Xl\nu$	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

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

***CP* violation in the B_s^0 system**

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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!!!

Heavy Quark Expansion for B mesons

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

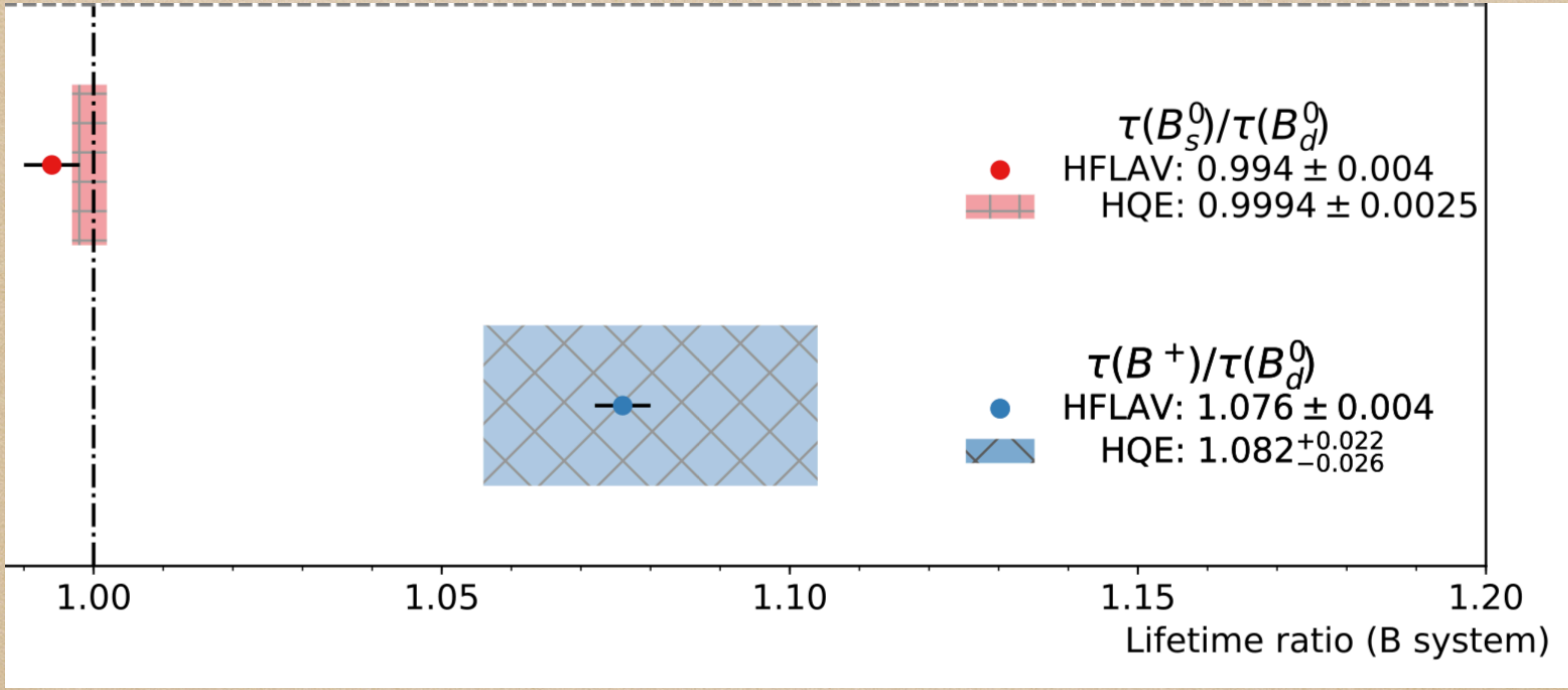
$$\Gamma_{12}^q = \left(\frac{\Lambda}{m_b}\right)^3 \Gamma_3 + \left(\frac{\Lambda}{m_b}\right)^4 \Gamma_4 + \ldots$$

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

HQE for B mesons - lifetimes

- no lattice results since 2001
- 3-loop HQET sum rules

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



1. HQE works well!
2. Lattice confirmation urgently needed
3. Still higher experimental accuracy for Bs lifetime needed

HQE for B mesons - Mixing

- Most recent lattice results

Bs-mixing matrix elements from lattice QCD for the Standard Model and beyond
Fermilab Lattice and MILC Collaborations (A. Bazavov (Iowa U.) *et al.*).
Phys.Rev. D93 (2016) no.11, 113016 arXiv:1602.03560 [hep-lat] |

- HQET sum rules agree

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]

- First steps towards NNLO

Towards next-to-next-to-leading-log accuracy for the width difference in the B s − system:
H.M. Asatrian, Artyom Hovhannisyan (Yerevan Phys. Inst.), Ulrich Nierste (Karlsruhe), Arsen Yeghiazaryan
JHEP 1710 (2017) 191 arXiv:1709.02160 [hep-ph] |

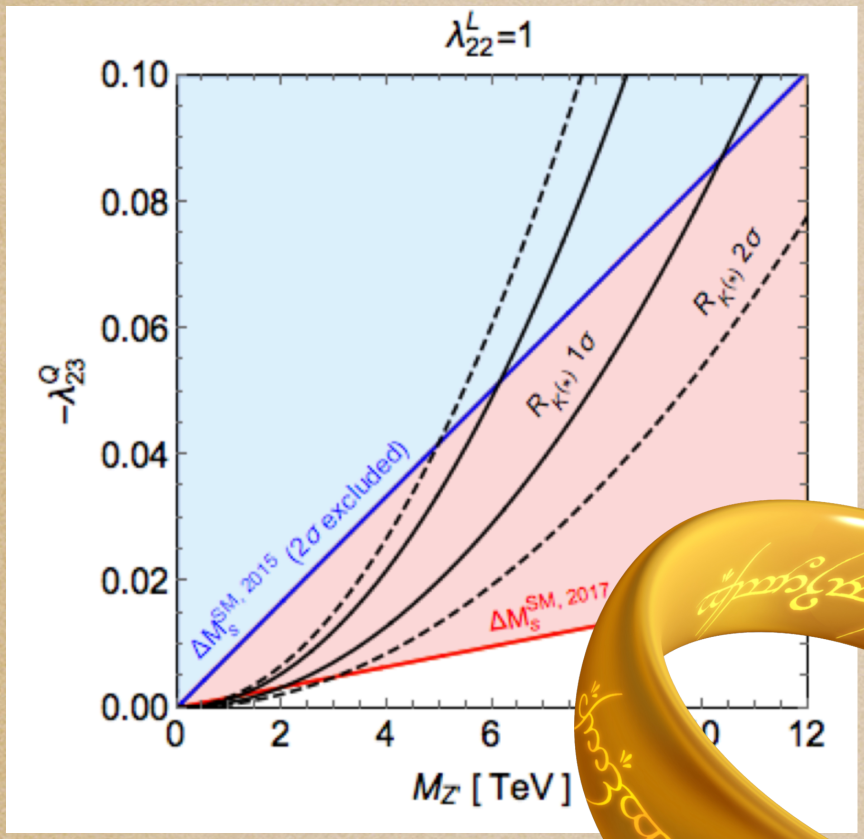
Observable	Exp.	Theory
ΔM_s	$(17.757 \pm 0.021)\text{ps}^{-1}$	$(20.01 \pm 1.25)\text{ps}^{-1}$
$\Delta \Gamma_s$	$(0.090 \pm 0.005)\text{ps}^{-1}$	$(0.100 \pm 0.013)\text{ps}^{-1}$
a_{sl}^s	$(-60 \pm 280) \cdot 10^{-5}$	$(2.27 \pm 0.25) \cdot 10^{-5}$

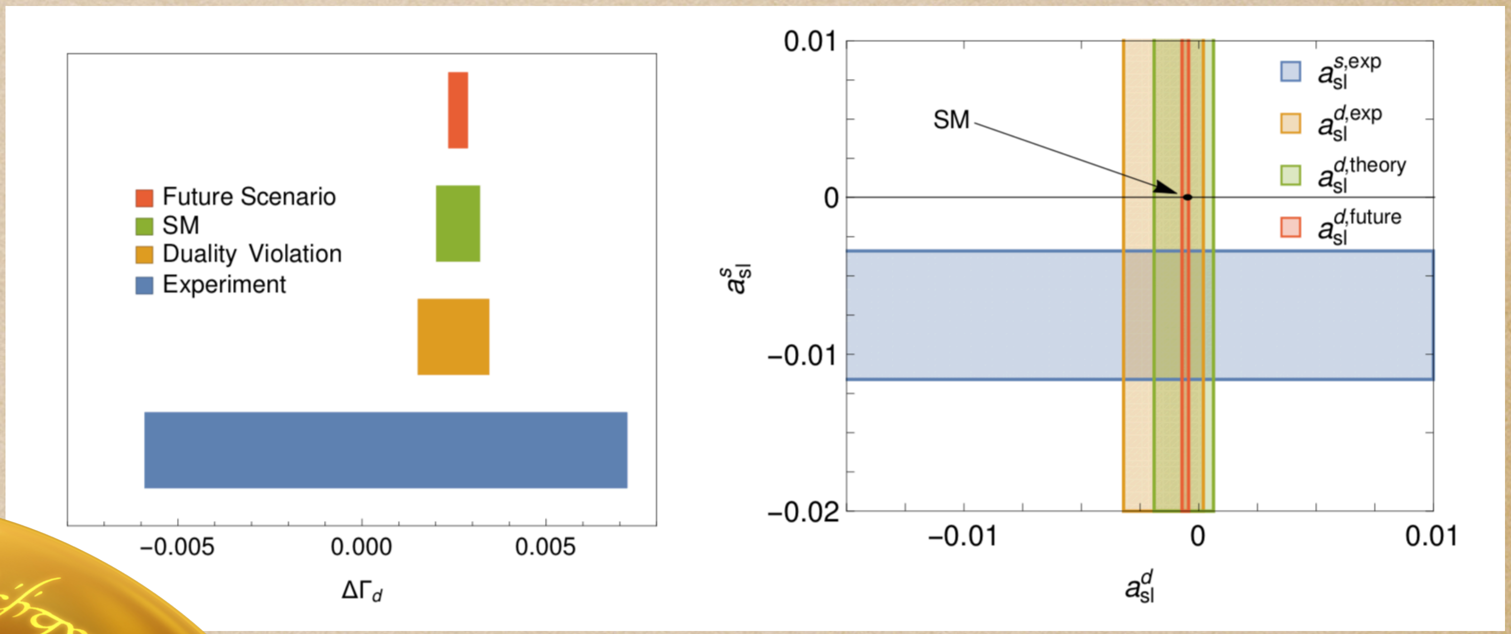
Observable	Exp.	Theory
ΔM_d	$(0.5065 \pm 0.019)\text{ps}^{-1}$	$(0.615 \pm 0.053)\text{ps}^{-1}$
$\Delta \Gamma_d$	$(-2 \pm 10) \cdot 10^{-3}\text{ps}^{-1}$	$(3.1 \pm 0.5) \cdot 10^{-3}\text{ps}^{-1}$
a_{sl}^d	$(-210 \pm 170) \cdot 10^{-5}$	$(-48.8 \pm 5.4) \cdot 10^{-5}$

One constraint to kill them all?
Luca Di Luzio, Matthew Kirk, AL
(Durham U., IPPP).
arXiv:1712.06572 [hep-ph]

On the ultimate precision of meson mixing observables
Thomas Jubb, Matthew Kirk, AL, Gilberto Tetlalmatzi-Xolocotzi (Durham U., IPPP
Nucl.Phys. B915 (2017) 431-453
arXiv:1603.07770 [hep-ph]

HQE for B mesons - BSM/Duality bounds





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One constraint to kill them all?
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- **Confirm Fermilab lattice results! - serious consequences**
- **Measure Delta Gamma_d**
- **Improve precision on Delta Gamma_s (Exp.+Theory)**
- **Measure semi-leptonic CP asymmetries more precisely**

Semileptonic decays of B mesons

more complicated than HQE, but simpler than hadronic decays

one needs **form factors as non-perturbative input**

CP asymmetries in b -> s mu mu, e.g.

Symmetries and Asymmetries of B→ K ∗ μ + μ − B → K ∗ μ + μ − Decays in the Standard Model and Beyond
Wolfgang Altmannshofer (Munich, Tech. U.), Patricia Ball (Munich, Tech. U. & Durham U., IPPP & Durham U.), Aoife Bharucha (Durham U., IPPP & Du
Andrzej J. Buras, David M. Straub, Michael Wick (Munich, Tech. U.)
JHEP 0901 (2009) 019 arXiv:0811.1214 [hep-ph]

CP asymmetries in b -> s gamma, e.g.

Time-dependent CP Asymmetry in B ---> K* gamma as a (Quasi) Null Test of the Standard Model
Patricia Ball, Roman Zwicky (Durham U., IPPP).
Phys.Lett. B642 (2006) 478-486 hep-ph/0609037

Next step: b -> d gamma, b -> d mu mu, e.g.

Hadronic effects and observables in B→π ℓ + ℓ − B → π ℓ + ℓ − decay at large recoil
Christian Hambrock, Alexander Khodjamirian, Aleksey Rusov (Siegen U.).
Phys.Rev. D92 (2015) no.7, 074020 arXiv:1506.07760 [hep-ph]

Hadronic decays of B mesons

Theoretical description of exclusive hadronic decays is much more complicated - no quark hadron duality available

Promising: QCD-factorisation approach

$$\langle \pi(p')\pi(q)|Q_i|\bar{B}(p)\rangle = f^{B\to\pi}(q^2)\int_0^1 dx\, T_i^I(x)\Phi_\pi(x)$$
$$+\int_0^1 d\xi dx dy\, T_i^{II}(\xi,x,y)\Phi_B(\xi)\Phi_\pi(x)\Phi_\pi(y), \qquad (3) \quad +\mathcal{O}\left(\frac{\Lambda}{m_b}\right)?$$

QCD factorization for B -> pi pi decays: Strong phases and CP violation in the heavy quark limit
M. Beneke, G. Buchalla (CERN), M. Neubert (SLAC), Christopher T. Sachrajda (Southampton U.)
Phys.Rev.Lett. 83 (1999) 1914-1917
hep-ph/9905312 I PDF
Cited by 1198 records

- NNLO QCD analysis underway
- 1/mb might be sizeable, so far not calculable

Hadronic decays of B mesons

We need the penguin over tree ratio

$$\langle \pi(p')\pi(q)| \quad\text{[penguin]}\quad |\bar{B}(p)\rangle$$

$$\overline{}$$

$$\langle \pi(p')\pi(q)| \quad\text{[tree]}\quad |\bar{B}(p)\rangle$$

as {
- a correction for mixing induced CPV
- dominant term for direct CPV

SU(3)F clearly not exact

$$f_{B_s}/f_B = 1.205(7)$$

How to estimate the size of penguins:

- Penguins via SU(3): **Fleischer, Jung, Ciuchini, Mannel,….**
- Penguins via QCD factorisation: **Nierste**

$$+\mathcal{O}\left(\frac{\Lambda}{m_b}\right)?$$

current theory precision O(1 deg) - **difficult to increase!!!**

Evidence for CP violation in time-integrated $D^0 \to h^- h^+$ decay rates
LHCb Collaboration (R. Aaij (NIKHEF, Amsterdam) *et al.*). Dec 2011. 8 pp.
Published in **Phys.Rev.Lett. 108 (2012) 111602**
LHCB-PAPER-2011-023, CERN-PH-EP-2011-208
DOI: 10.1103/PhysRevLett.108.111602, 10.1103/PhysRevLett.108.129903
e-Print: **arXiv:1112.0938** **[hep-ex]** | **PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
CERN Document Server; ADS Abstract Service
Detailed record - Cited by 340 records 250+

charm

/tʃɑːm/

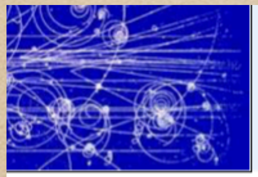
noun

1. the power or quality of delighting, attracting, or fascinating others.
   "he was captivated by her youthful charm"
   synonyms: attractiveness, beauty, glamour, prettiness, loveliness; More
2. a small ornament worn on a necklace or bracelet.
   "the trinkets were charms from his wife's bracelet"
   synonyms: ornament, trinket, bauble; *archaic* bijou
   "he took the charms from his wife's bracelet"

verb

1. delight greatly.
   "the books have charmed children the world over"
   synonyms: delight, please, win, win over, appeal to, attract, captivate, allure, lure, draw, dazzle, fascinate, bewitch, beguile, enchant, enthral, enrapture, enamour, seduce, ravish, hypnotize, mesmerize, spellbind, transfix, rivet, grip; *rare* rapture
   "he charmed thousands with his singing"
2. control or achieve by or as if by magic.
   "a gesticulating figure endeavouring to charm a cobra"

What can theory tell about charm?



Try to save work: poll among worthy colleagues

Q:"What did we learn from the ΔA_{CP}-Saga?"

- ...one should not jump on every 3σ-effect...
- ...it is very difficult for me to say what happens in D-decays...
- ...we need a deeper understanding of QCD ...
- ...ΔA_{CP} in SM bigger than 0.1% is a stretch... ...original justification for considering enhanced penguins in D decays is somewhat weakened...
- ...I don't really know what we can learn from ΔA_{CP} at this moment...
- ...since ΔA_{CP} seems now significantly smaller, we believe that this is really a confirmation of our arguments for the SM origin...
- ...penguins are still very large and currently one cannot not decide if this can be of SM origin without additional assumptions...
- ...ΔA_{CP} should be at most a few times 10^{-3} in the SM...
- ...making (reliable) theoretical predictions about ΔA_{CP} is hard, but so is measuring it...
- ...a value close to 1% is very unlikely in the SM...
- ...the most important thing I (re) learned (over $\&$ over again) is that 3σ experimental results are not really reliable! But LHCb did a great job in focusing on D decays
- ...preliminary data can change a lot... we have to probe 3- and 4-body FS...

Bigi, Brod, Feldmann, Hiller, Isidori, Kagan, Kamenik, Li, Nierste, Silvestrini, Soni, Zupan

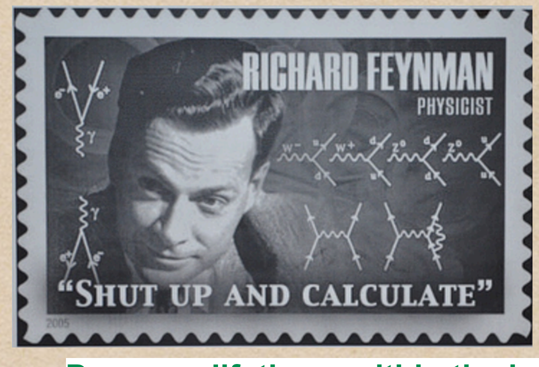
Charm 2013, Manchester A. Lenz, September 3rd 2013 - p. 3

Heavy Quark Expansion for D mesons

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:

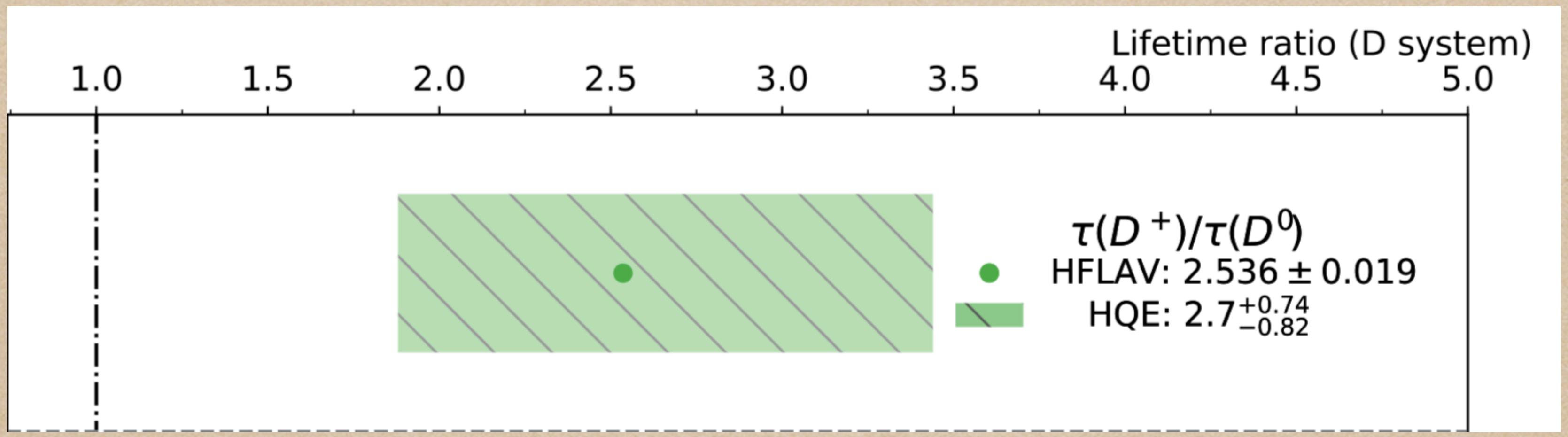


NLO -QCD

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**

HQE for Charm mixing?

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:

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

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

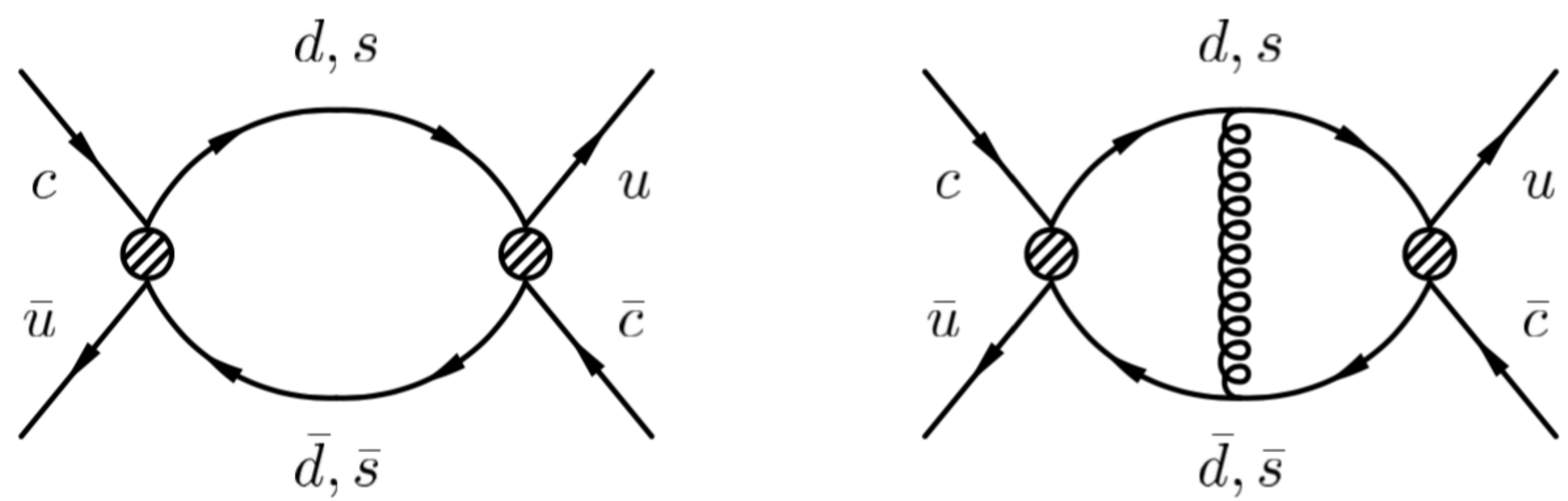


Figure 1: Contributions to Γ_{12} from operators of dimension 6 ($D = 6$). The leading order QCD diagram is shown in the left panel, an example for α_s corrections is shown in the right panel.

What is special about Charm?

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

Consider only the first term:

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

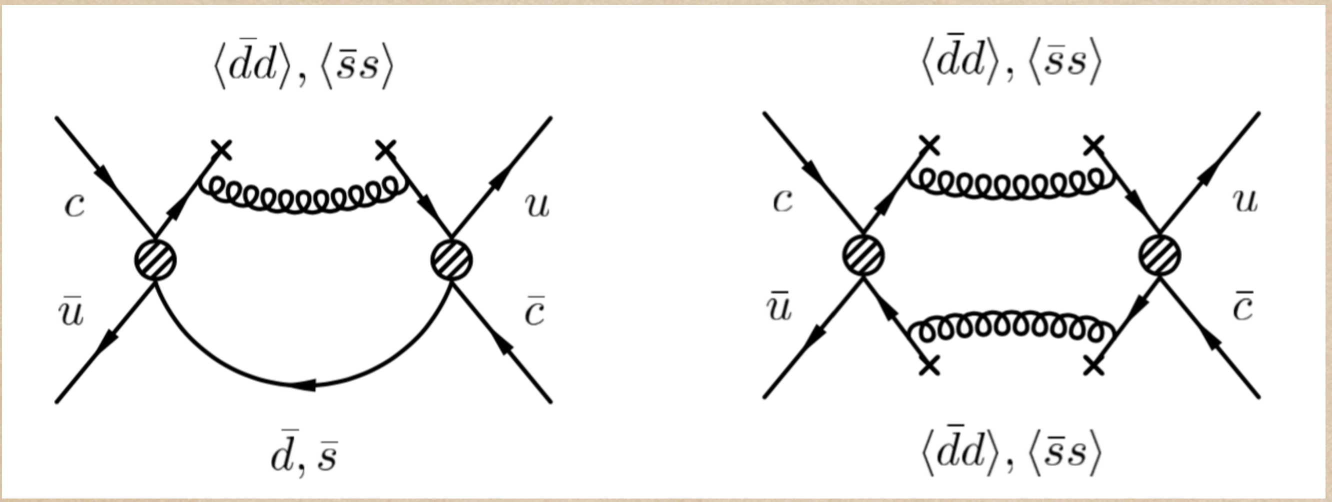
Do the full expression (use CKM unitarity)

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

HQE itself gives not small numbers, but extremely effective GIM cancellation
similar effects in penguin induced charm decays

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

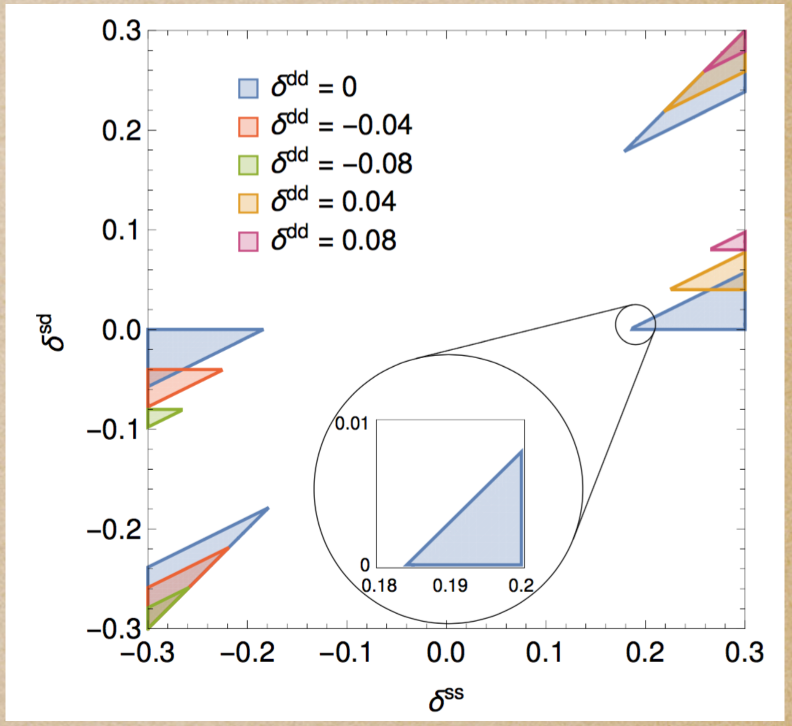
2. Duality violations that have no/tiny GIM cancellations

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

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

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

Jubb, Kirk, AL, Tetlalmatzi-Xolocotzi 2016



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

3. HQE simply does not converge at all in the Charm-system -> BUT: lifetimes

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 D0 Mixing Be?
M. Bobrowski (Regensburg U.), AL (Dortmund U. & Regensburg U.), J. Riedl (Regensburg U.), J. Rohrwild (Regensburg U. & RWTH Aachen U.)
JHEP 1003 (2010) 009 arXiv:1002.4794 [hep-ph]

Im (Gamma_12/M_12) up to 0.01!

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

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+

ad 3. **Confirm other charm lifetimes, in particular charmed baryons**

Semileptonic decays of D mesons

more complicated than HQE, but simpler than hadronic decays

one needs **form factors as non-perturbative input**

- D -> P+P- gamma, omega gamma, rho gamma
  including CP asymmetries

Shedding light on CP violation in the charm system via D to V gamma decays
Gino Isidori (CERN & Frascati), Jernej F. Kamenik (Stefan Inst., Ljubljana & Lju
Phys.Rev.Lett. 109 (2012) 171801 arXiv:1205.3164 [hep-ph]

"Enhanced matrix elements of the electromagnetic dipole operators can partly compensate the long distance dominance in these decays, leading to CP asymmetries of the order of several percent. If observed at this level, these would provide a clean signal of physics beyond the SM

- D -> P l l , P = K, pi
  including CP asymmetries
  non-factorisable terms neglected

Flavor and new physics opportunities with rare charm decays into leptons
Stefan de Boer, Gudrun Hiller (Tech. U., Dortmund)
Published in Phys.Rev. D93 (2016) no.7, 074001 arXiv:1510.00311 [hep-ph]

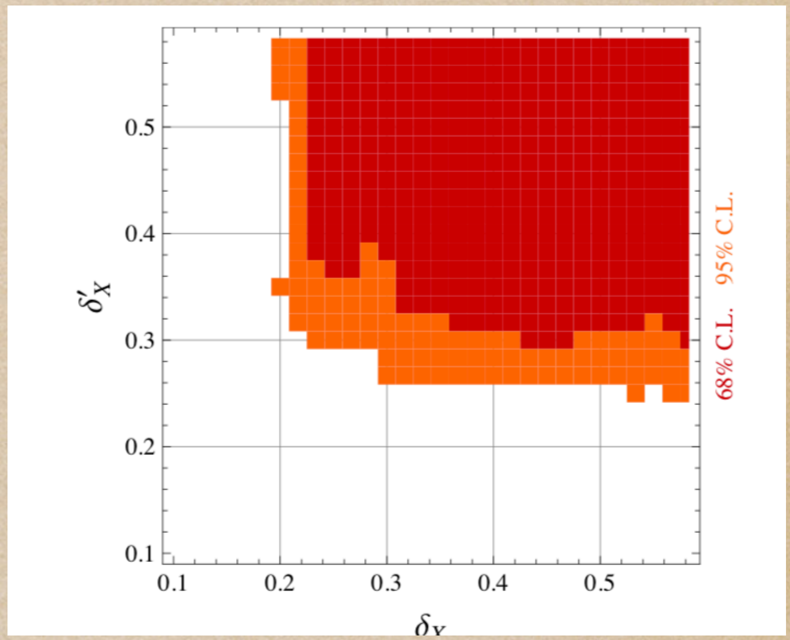
$D \to \rho \ell^+ \ell^-$ $D \to \rho \ell^+ \ell^-$ decays in the QCD factorization approach
Thorsten Feldmann, Bastian Müller, Dirk Seidel (Siegen U.).
JHEP 1708 (2017) 105 arXiv:1705.05891 [hep-ph]

- more field theoretical
  "we have found that in general the contributions from non-factorizable effects dominate "
  "we have found that reliable theoretical predictions for the differential decay widths in $D \to \rho\, l^+ l^-$ within the QCDF approach are almost impossible."

Hadronic decays of D mesons

SU(3)_F analysis seems to be the best one can do - QCD factorisation seems to be very questionable

- SU(3) breaking can be as low as 30%, **but might also be larger**



- Asymmetries suggested e.g. by **Schacht, Nierste**

CP Violation in $D^0 \to K_S K_S$

Ulrich Nierste[a*] and Stefan Schacht[a†]
[a] *Institut für Theoretische Teilchenphysik, Karlsruher Institut für Technologie, 76128 Karlsruhe, Germany*

The direct CP asymmetry $a_{CP}^{\mathrm{dir}}(D^0 \to K_S K_S)$ involves exchange diagrams which are induced at tree level in the Standard Model. Since the corresponding topological amplitude E_{KK} can be large, $D^0 \to K_S K_S$ is a promising discovery channel for charm CP v penguin annihilation amplitude with a perturbative calculation and extra E_{KK} from a global fit to D branching ratios. Our results are further mixing-induced CP violation. We obtain $|a_{CP}^{\mathrm{dir}}(D^0 \to K_S K_S)| \leq 1.1\%$ (9 applies to the nonuniversal part of the phase between the $D-\overline{D}$ mixin future data exceed our predictions, this will point to new physics or an e annihilation amplitude by QCD dynamics. We briefly discuss the implic for other CP asymmetries.

Neutral $D \to KK^*$ decays as discovery channels for charm CP violation

Ulrich Nierste[a*] and Stefan Schacht[b†]
[a] *Institut für Theoretische Teilchenphysik, Karlsruher Institut für Technologie, 76128 Karlsruhe, Germany*
[b] *Dipartimento di Fisica, Università di Torino & INFN, Sezione di Torino, I-10125 Torino, Italy*

We point out that the CP asymmetries in the decays $D^0 \to K_S K^{*0}$ and $D^0 \to K_S \overline{K}^{*0}$ are potential discovery channels for charm CP violation in the Standard Model. We stress that no flavor tagging is necessary, the untagged CP asymmetry $a_{CP}^{\mathrm{dir}}(\overset{(-)}{D} \to K_S K^{*0})$ is essentially equal to the tagged one, so that the untagged measurement comes with a significant statistical gain. Depending on the relevant strong phase, $|a_{CP}^{\mathrm{dir,\ untag}}|$ can be as large as 0.003. The CP asymmetry is dominantly generated by exchange diagrams and does not require non-vanishing penguin amplitudes. While the CP asymmetry is smaller than in the case of $D^0 \to K_S K_S$, the experimental analysis is more efficient due to the prompt decay $K^{*0} \to K^+ \pi^-$. One may further search for favourable strong phases in the Dalitz plot in the vicinity of the K^{*0} peak.

Sum Rules of Charm CP Asymmetries beyond the $SU(3)_F$ Limit*

Sarah Müller[a,b,†] Ulrich Nierste[b,‡] and Stefan Schacht[b§]
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[b] *Institut für Theoretische Teilchenphysik, Karlsruher Institut für Technologie, 76128 Karlsruhe, Germany*

d new sum rules between direct CP asymmetries in D meson decays with coefficients that etermined from a global fit to branching ratio data. Our sum rules eliminate the penguin s P and PA, which cannot be determined from branching ratios. In this way we can make ns about direct CP asymmetries in the standard model without *ad hoc* assumptions on the penguin diagrams. We consistently include first-order $SU(3)_F$ breaking in the topological les extracted from the branching ratios. By confronting our sum rules with future precise m LHCb and Belle II one will identify or constrain new-physics contributions to P or e first sum rule correlates the CP asymmetries a_{CP}^{dir} in $D^0 \to K^+K^-$, $D^0 \to \pi^+\pi^-$, and $^0\pi^0$. We study the region of the $a_{CP}^{\mathrm{dir}}(D^0 \to \pi^+\pi^-)$–$a_{CP}^{\mathrm{dir}}(D^0 \to \pi^0\pi^0)$ plane allowed by lata and find that our sum rule excludes more than half of the allowed region at 95% C.L. nd sum rule correlates the direct CP asymmetries in $D^+ \to \bar{K}^0 K^+$, $D_s^+ \to K^0\pi^+$, and $^+\pi^0$.

Hadronic decays of D mesons

Interesting new route to follow

Physics Letters B 774 (2017) 235–242

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Direct CP asymmetry in $D \to \pi^-\pi^+$ and $D \to K^-K^+$ in QCD-based approach

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ABSTRACT

We present the first QCD-based calculation of hadronic matrix elements with penguin topology determining direct CP-violating asymmetries in $D^0 \to \pi^-\pi^+$ and $D^0 \to K^-K^+$ nonleptonic decays. The method is based on the QCD light-cone sum rules and does not rely on any model-inspired amplitude decomposition, instead leaning heavily on quark–hadron duality. We provide a Standard Model estimate of the direct CP-violating asymmetries in both pion and kaon modes and their difference and comment on further improvements of the presented computation.

$$r_\pi = \frac{|\mathcal{P}^s_{\pi\pi}|}{|\mathcal{A}_{\pi\pi}|} = 0.093 \pm 0.011\,,$$

$$r_K = \frac{|\mathcal{P}^d_{KK}|}{|\mathcal{A}_{KK}|} = 0.075 \pm 0.015\,.$$

What-to-do

- Lattice confirmation of mixing results from Fermilab/MILC
- Lattice determination of lifetime matrix elements
- Investigation of baryon lifetimes (bottom and charm)
- Non-perturbative determination of form factors
- NNLO-QCD precision
- Alternatives to QCD factorisation (sum rules) and 1/mb in QCDF
- Lattice determination of hadronic D decays…

- More precise values of Delta Gamma_s,d; a_sl^s,d; tau Bs/tau Bd
- More precise lifetimes of charm baryons
- CPV in semi-leptonic decays like b -> s mu mu, but also b -> d …
- CPV in charmed semi-leptonic decays
- Hadronic control channels for penguin pollution in B system
- CPV in hadronic charm channels - based on SU(3)

END

Outline: Why Charm-physics?

- What is special about charm?

  - Mass: charm is neither heavy nor light; do theory tools (e.g. HQE, factorisation,..) work?

  - very strong GIM cancellations

  - lots of data for up-type quarks and B- and K-mesons are already very well studied

- Understanding of QCD:

  -Spectroscopy, exotics: Cheung, Cleven, Burns,Fernandez, Gonzalez, Pilloni, Ryan, Brambilla

  - heavy ions: quark-gluon plasma Geurts, Arleo, Berardo, Vairo

  - Charm production: perturbative QCD Haidenbauer, Zhao, Wang

  - leptonic, semi-leptonic decays: decay constants, form factors (Lattice, sum rules) El-Khadra

  - hadronic decays: $SU(3)_F$ Santorelli, Lattice Moir, Dalitz Loiseau, Nakamura Magalhaes

  - mixing: do any of our theory tools work? Martinelli, Ciuchini HQE? Compare to lifetimes!

  Determination of Standard model parameters:

  - CKM elements, mostly V_{cs} and V_{cd} Derkach

  - Quark mass m_c

- Search for new physics: New physics might be heavy and theory tools could work

  - D-meson decays (leptonic, semi-leptonic, hadronic ones) Kosnik, Paul, de Boer

  - $H \to c\bar{c}$, DM coupled to up-type quark sector, …

  - indirect charm contributions (g-2 on the lattice, epsilon_K on the lattice,…)

- Understanding of Quantum Mechanics Briere

What is special about Charm?

- Mass of charm: charm is neither heavy nor light; do theory tools like HQE work?
- HQE works very nicely in B-physics

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

- Comparison with Experiment (HFAG=ATLAS, CMS, LHCb, CDF, D0 vs. ABL 2015)

$$\left(\frac{\Delta\Gamma}{\Gamma}\right)_{B_s^0}^{\text{Exp.}} = 0.083 \pm 0.006\text{ps}^{-1} \qquad \left(\frac{\Delta\Gamma}{\Gamma}\right)_{B_s^0}^{\text{SM.}} = 0.088 \pm 0.020\text{ps}^{-1}$$

- Does this also work in the charm system?

$$m_b/m_c \approx 3.3$$

What is special about Charm?

- LHC and BESIII are charm factories
- up-type quark, B- and K-mesons are already very well studied

- Possibility to study complementary NP scenarios,
  e.g. coupling of new particles (Z', SUSY, KK,DM,...) to up-type quarks or anomalous Higgs coupling $H \to c\bar{c}$

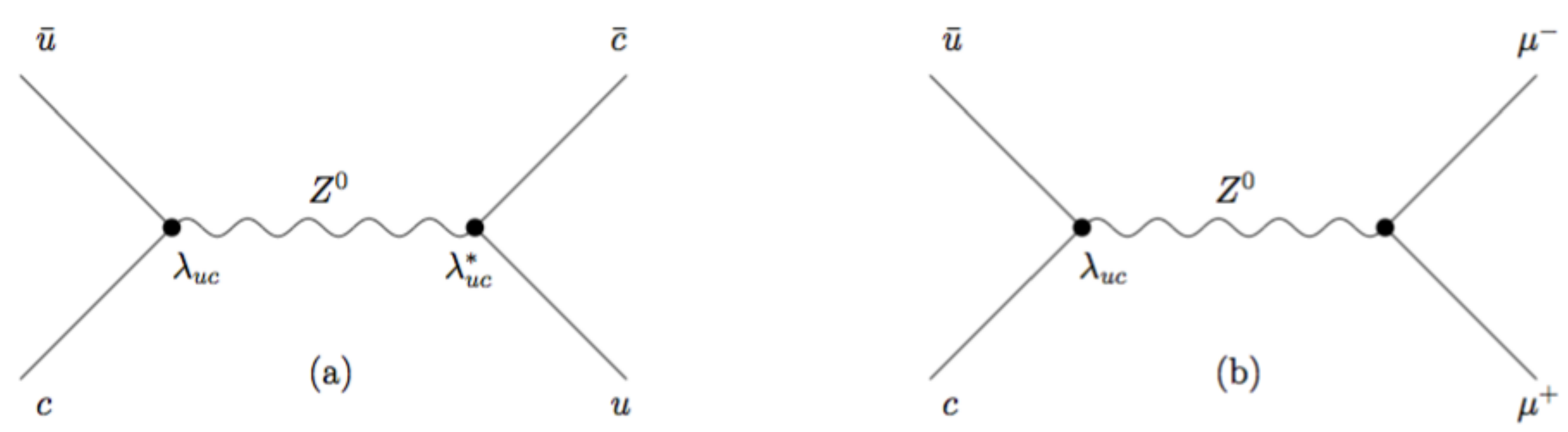


FIG. 1: (a) D^0-$\bar{D}^0$ Mixing, (b) $D^0 \to \mu^+\mu^-$.

e.g. Golowich, Hewett, Pakwasa, Petrov 0903.2830

Understanding QCD

- Spectroscopy, exotics: Cheung, Cleven, Burns,Fernandez, Gonzalez, Pilloni, Ryan, Brambilla
- Heavy ions: quark-gluon plasma Geurts, Arleo, Berardo, Vairo
- Charm production: perturbative QCD Haidenbauer, Zhao, Wang
- leptonic, semi-leptonic decays: decay constants, form factors (Lattice, sum rules) El-Khadra
- hadronic decays: Santorelli, Lattice Moir, Dalitz Loiseau, Nakamura Magalhaes
- mixing: do any of our theory tools work? Martinelli, Ciuchini HQE? Compare to lifetimes!

Hadronic decays

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

Alexander Lenz

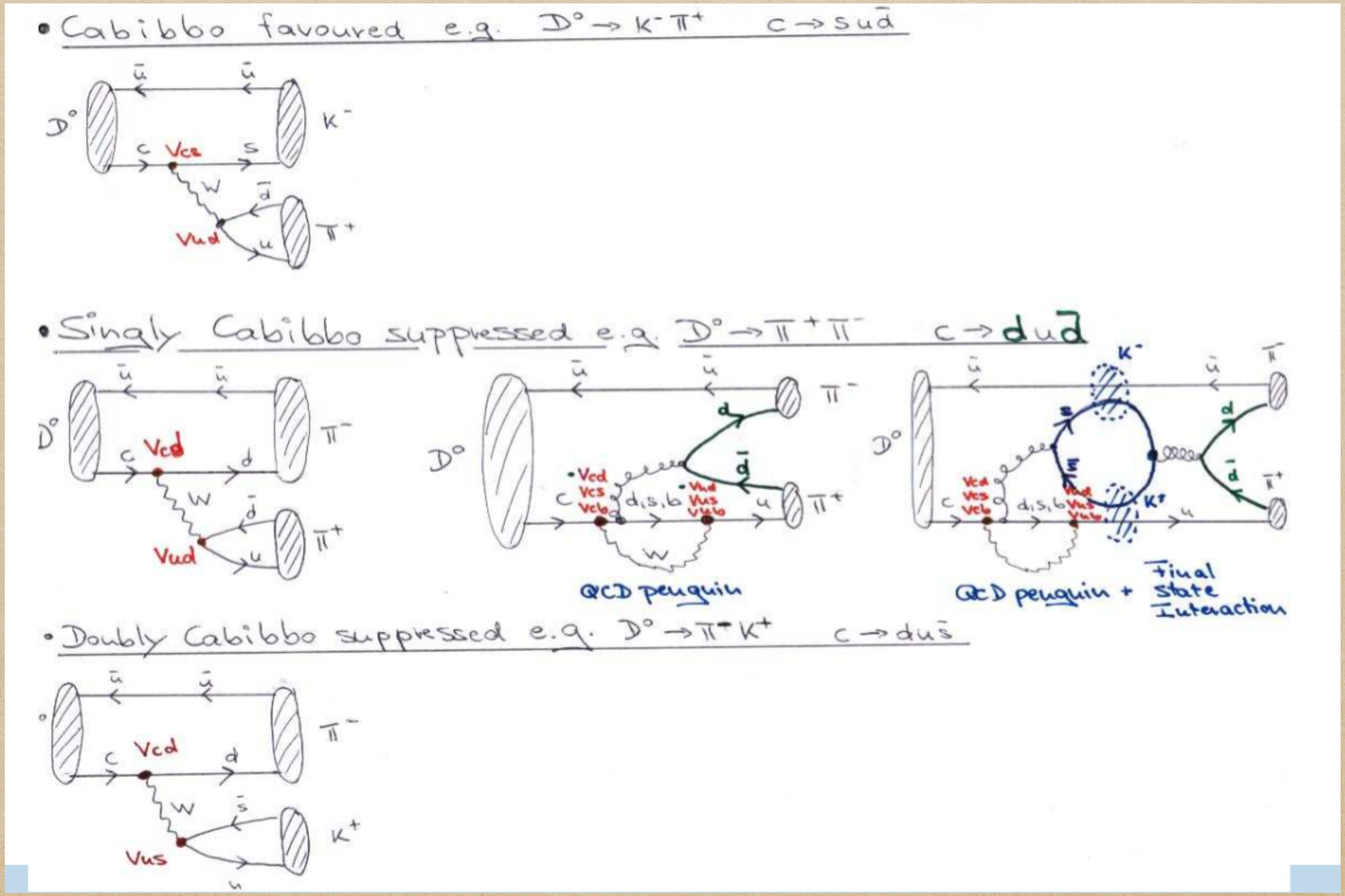
IPPP Durham

Charm 2013, Manchester

A. Lenz, September 3rd 2013 - p. 1

Hadronic decays

- Non-leptonic decays have the most complicated hadronic structure



Hadronic decays

How to treat hadronic decays in theory?

- Factorisation like in B-decays is unlikely to work - but test!
- Try to use symmetries, like SU(3)_F -> experimental test channels!
- Can lattice say something?

1. **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
   Detailed record - Cited by 125 records 100+

Generalisation to

- multi-body decays
- baryonic decays

D-mixing

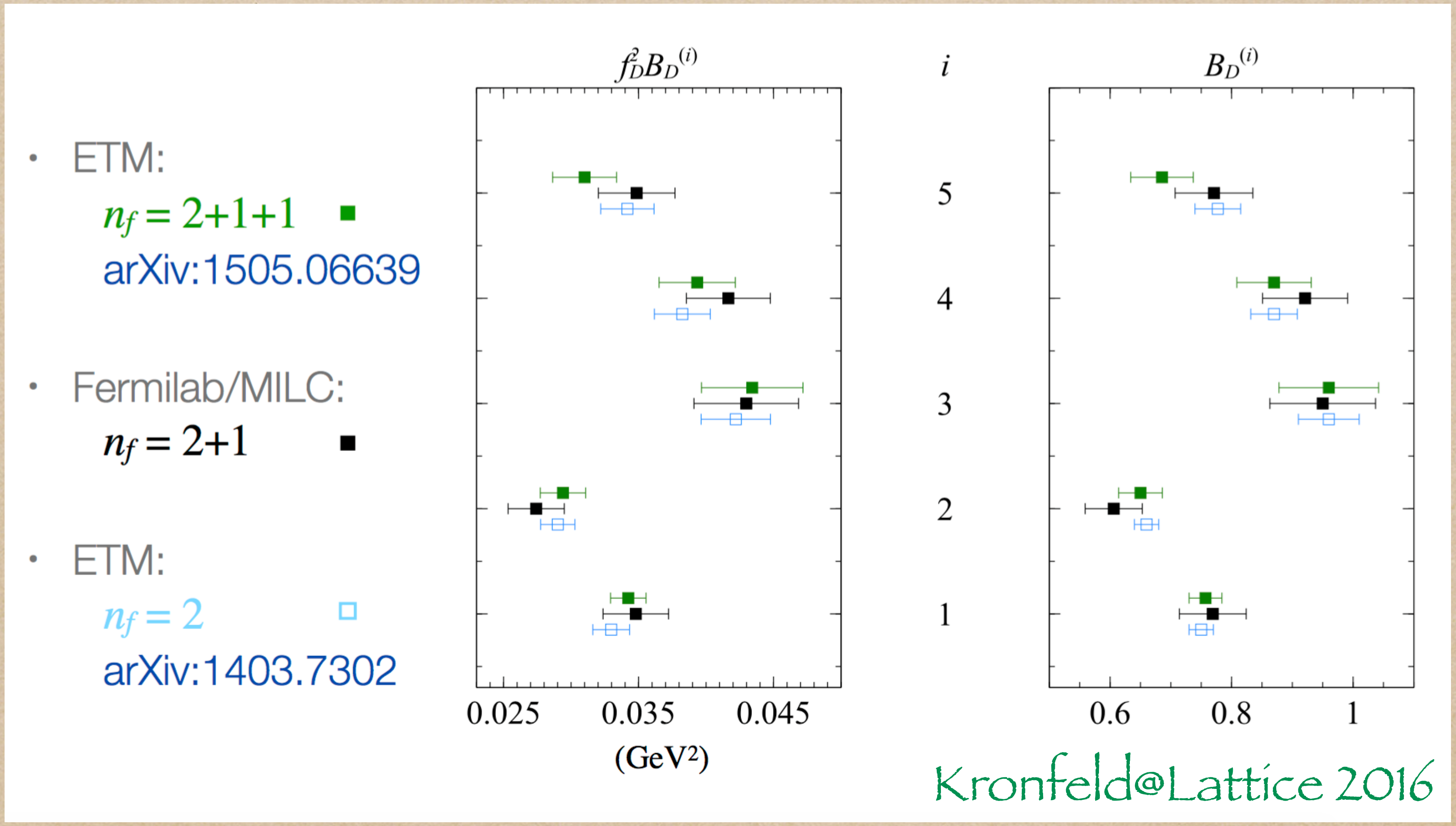
do any of our theory tools work? Heavy Quark Expansion?

$$\left(M - \frac{i}{2}\Gamma\right)_{21} = \frac{1}{2M_D}\langle \overline{D}^0 | H_w^{|\Delta C|=2} | D^0 \rangle + \frac{1}{2M_D}\sum_n \frac{\langle \overline{D}^0 | H_w^{|\Delta C|=1} | n \rangle \langle n | H_w^{|\Delta C|=1} | D^0 \rangle}{M_D - E_n + i\epsilon}$$

- the first term is short-distance, it can be treated like in the B-system
  - need matrix elements of 4-quark operators
  currently done on the lattice e.g. Fermilab-MILC , ETMC
  - heavy new physics contributes here!
- the second term looks like long-distance
  - try to determine with models, symmetries,.... e.g. Falk, Grossman, Ligeti, Petrov hep-ph/0110317; Falk, Grossman, Ligeti, Nir, Petrov hep-ph/0402204 numerical size of experiment is reproduced, but not a first principle calculation
  - try to determine on the lattice: very difficult! Hansen, Sharpe?
  - try HQE (maybe failure of HQE is mimicked by extreme GIM cancellation), e.g. Bigi, Uraltsev can be "tested via charm lifetimes"

D-mixing

- Lattice results for the dimension 6 matrix elements contributing to the short-distance part of D-mixing.
- This is crucial for heavy new physics contributions to D-mixing and it might be crucial for the SM contributions, if the HQE would work



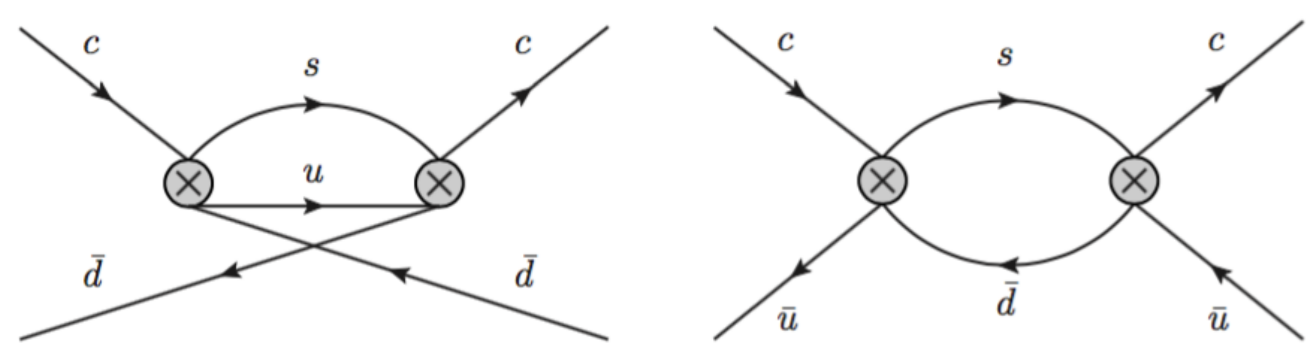
Test of validity of HQE in the charm system

- Charmed meson lifetime ratios are very well measured

$$\frac{\tau(D^+)}{\tau(D^0)} = 2.536 \pm 0.019$$

looks like 150% correction in the HQE, but it could be only 40%: (1+0.4)/(1-0.4) = 2.33!

- The corresponding theory prediction is not affected by GIM cancellations



(a) Pauli Interference (b) Weak Annihilation in D^0

Test of validity of HQE in the charm system

- Problem: non-perturbative matrix elements of dimension 6 operators are not known

$$Q^q = \bar{c}\gamma_\mu(1-\gamma_5)q\;\bar{q}\gamma^\mu(1-\gamma_5)c, \qquad Q_S^q = \bar{c}(1-\gamma_5)q\;\bar{q}(1+\gamma_5)c,$$
$$T^q = \bar{c}\gamma_\mu(1-\gamma_5)T^a q\;\bar{q}\gamma^\mu(1-\gamma_5)T^a c, \qquad T_S^q = \bar{c}(1-\gamma_5)T^a q\;\bar{q}(1+\gamma_5)T^a c.$$

Do naive assumptions for the matrix elements plus very conservative uncertainties

$$\left(\frac{\tau(D^+)}{\tau(D^0)}\right)_{\overline{\rm MS},\rm VSA} = 2.2 \pm 1.7^{(\rm hadronic)}\;{}^{+0.3}_{-0.7}{}^{(\rm scale)} \pm 0.1^{(\rm parametric)}.$$

AL, Rauh 1305.3588

It is not excluded that the HQE works reasonably well in the charm sector

Please calculate the matrix elements on the lattice!!!