Theory Overview

Alexander Lenz, IPPP Durham

CHARM 2016, Bologna

5th September 2016

Thanks to the organisers for choosing the great venue!

- Dominicans (Dominikus 1170 -1221) have a long intellectual tradition, e.g. Alberts Magnus, Thomas from Aquin, Meister Eckart, …
- A real teaching"CHAIR" can be seen at a Dominican church in Regensburg
- They are a medicant order - reminds to beging for money from politicians, writing fund applications,…

We might take over some of their experience in treating people with different opinions…

Referees

Esteemed colleagues

Idea of outlook

- No presentation of results that will be shown later
  we will have many interesting talks and a theory summary
- Show results from groups not present at CHARM 2016
- Systematic, brief overview of our field and its aims
- Try to point out some directions, that might be important for the future development of our field

Sessions@ CHARM2016

- Heavy Ions
- Multi-body hadronic decays and amplitude analysis
- Leptonic, semi-leptonic and rare decays (CKM elements)
- Charm Baryon decays
- Charmonium and Exotics, production and spectroscopy
- CP violation, Mixing and non-leptonic decays
- Open Charm production and spectroscopy
- Future Prospects

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 (HQE) work?

Summary

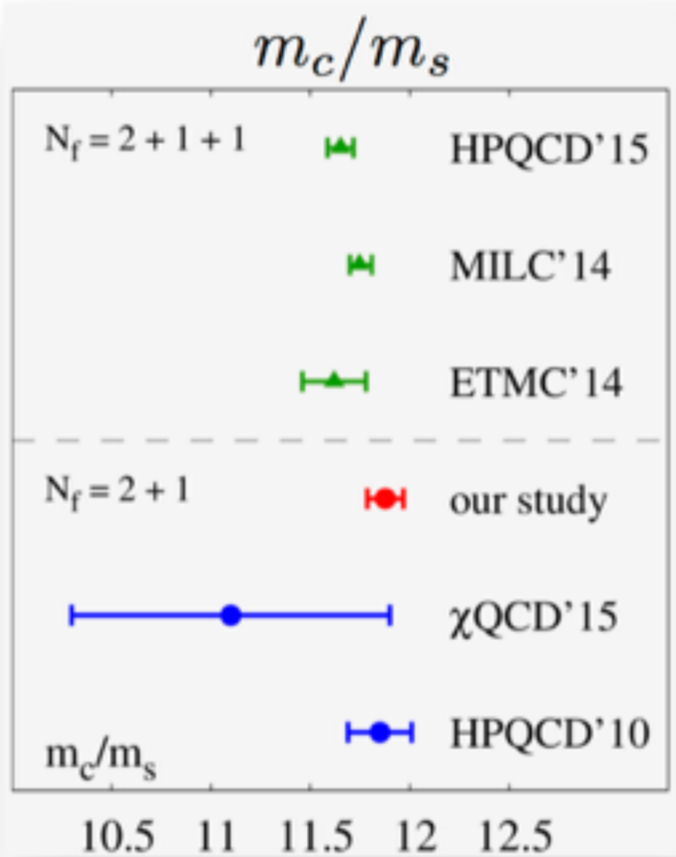
arXiv:1606.08798

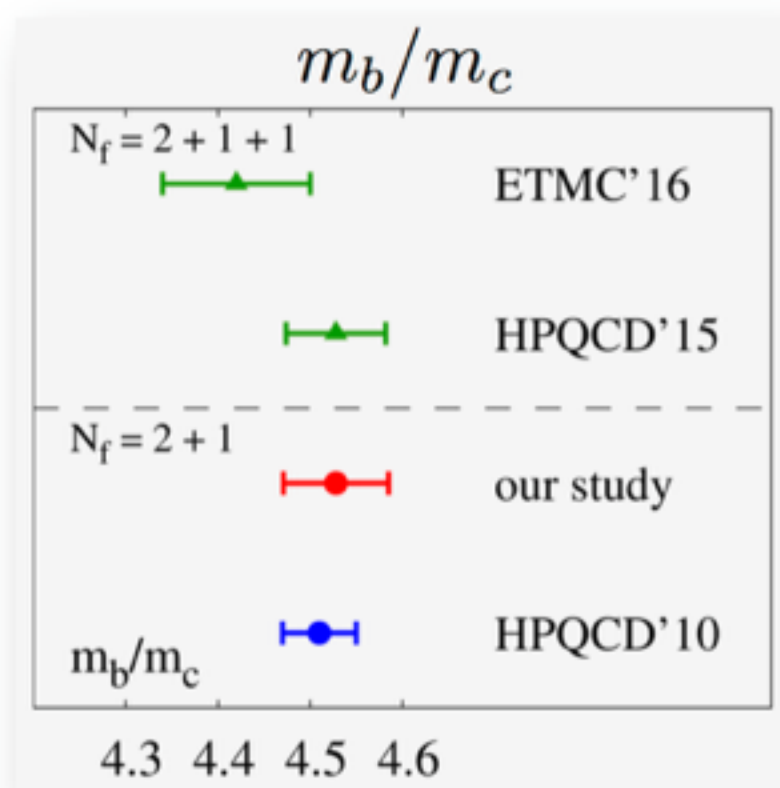
via meson masses: $m_c/m_s = 11.877(91)\,, \quad m_b/m_c = 4.528(57)$

via moments: $\alpha_s(\mu = m_c, n_f = 3) = 0.3945(75)\,, \quad m_c(\mu = m_c, n_f = 3) = 1.267(11)$ GeV

evolving with 4-loops PT in $\overline{\text{MS}}$ scheme:
RunDeC package

$$\begin{cases} \alpha_s(M_Z, n_f = 5) = 0.11622(75) \\ m_s(\mu = 2\,\text{GeV}, n_f = 3) = 92.0(1.5)\ \text{MeV} \\ m_b(\mu = m_b, n_f = 5) = 4.184(83)\ \text{GeV} \end{cases}$$





Maezawa
Lattice 2016

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

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

- 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?

Very strong GIM cancellations in mixing and rare decays

Mixing:

$$x_D^{\text{Exp.}} = (0.37 \pm 0.16) \cdot 10^{-2} \quad y_D^{\text{Exp.}} = 0.66^{+0.07}_{-0.10} \cdot 10^{-2}$$

Try to calculate like in the B_s^0 system:

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

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

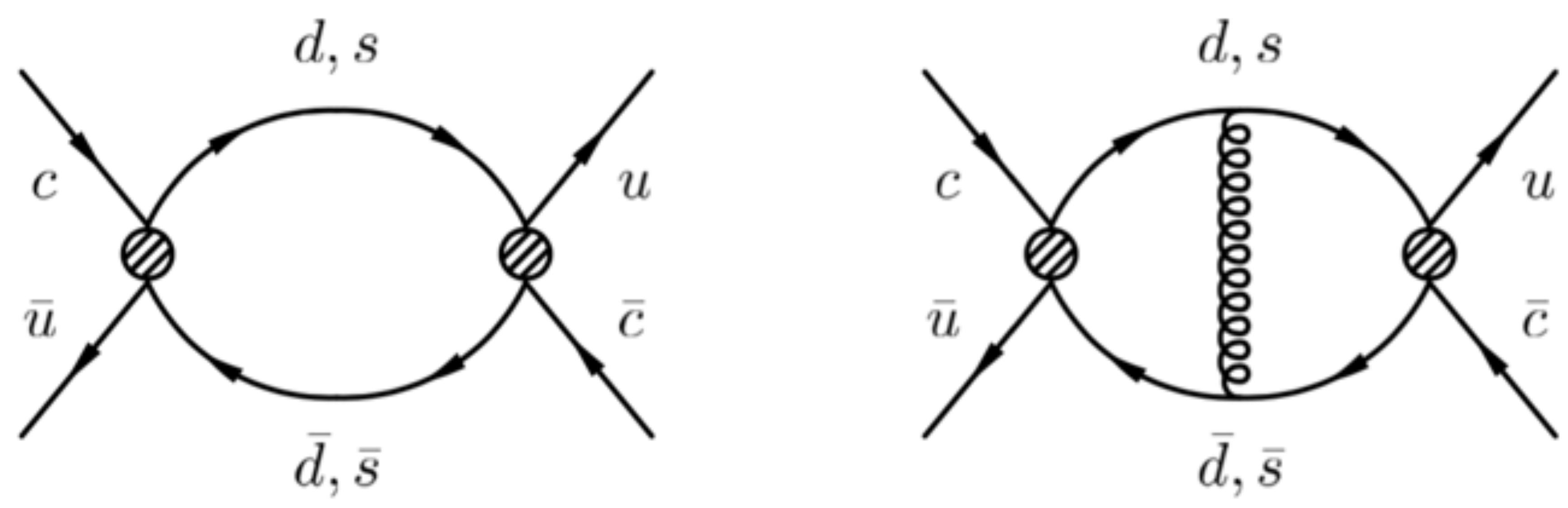


Figure 1: Contributions to Γ_{12} from operators of dimension 6 ($D = 6$). The leading order QCD diagram is shown in the left panel, an example for α_s corrections is shown in the right panel.

What is special about Charm?

Very strong GIM cancellations in mixing and rare decays

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

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 $H \to c\bar{c}$

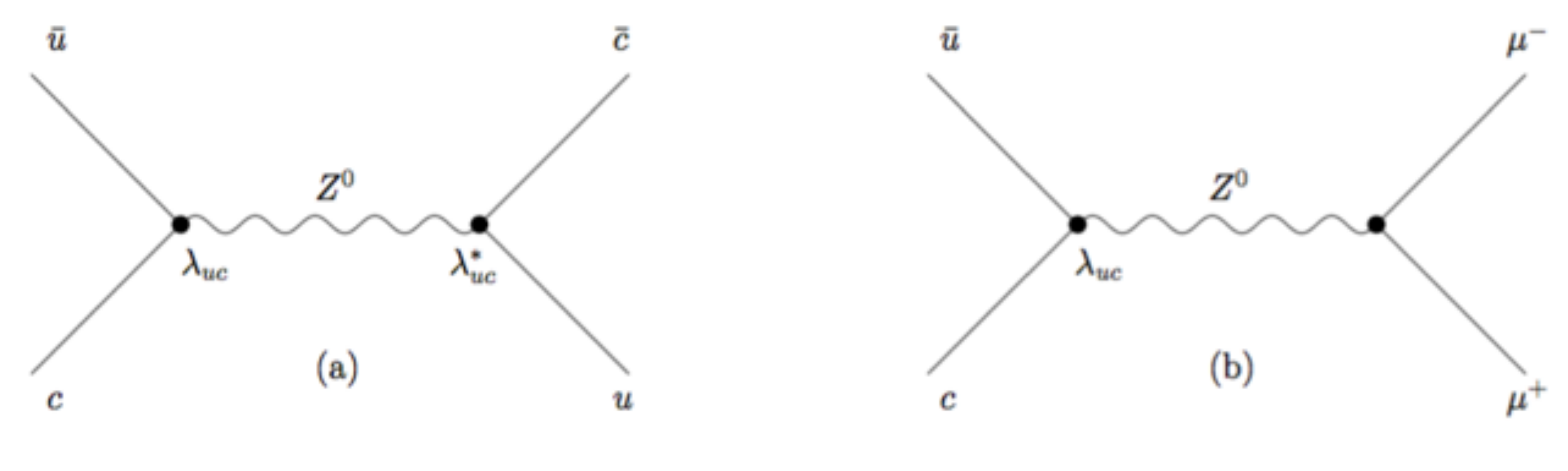


FIG. 1: (a) D^0-$\bar{D}^0$ Mixing, (b) $D^0 \to \mu^+\mu^-$.

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

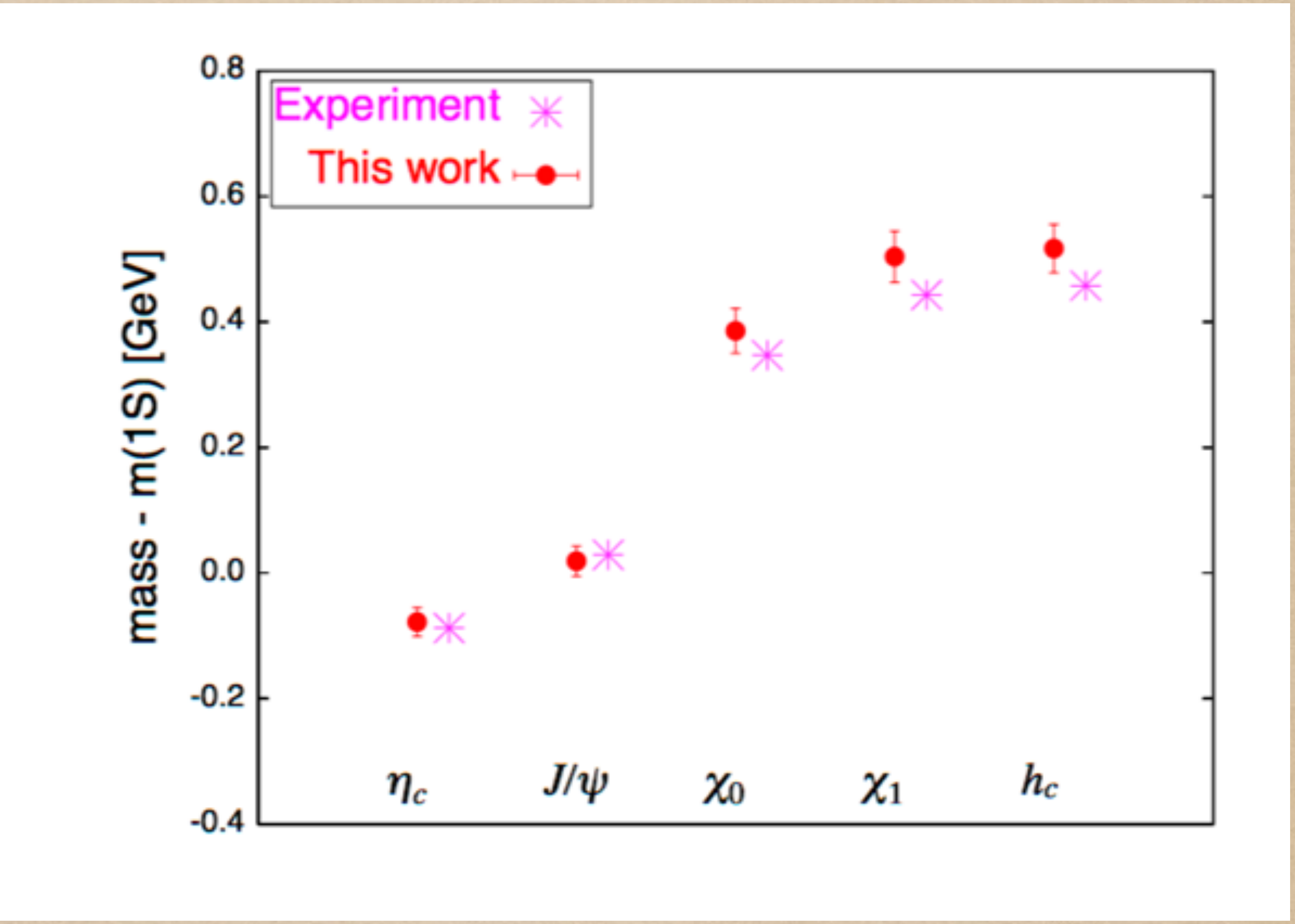
Understanding QCD

- 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!

Spectroscopy

- Mesons
- Baryons
- Exotics

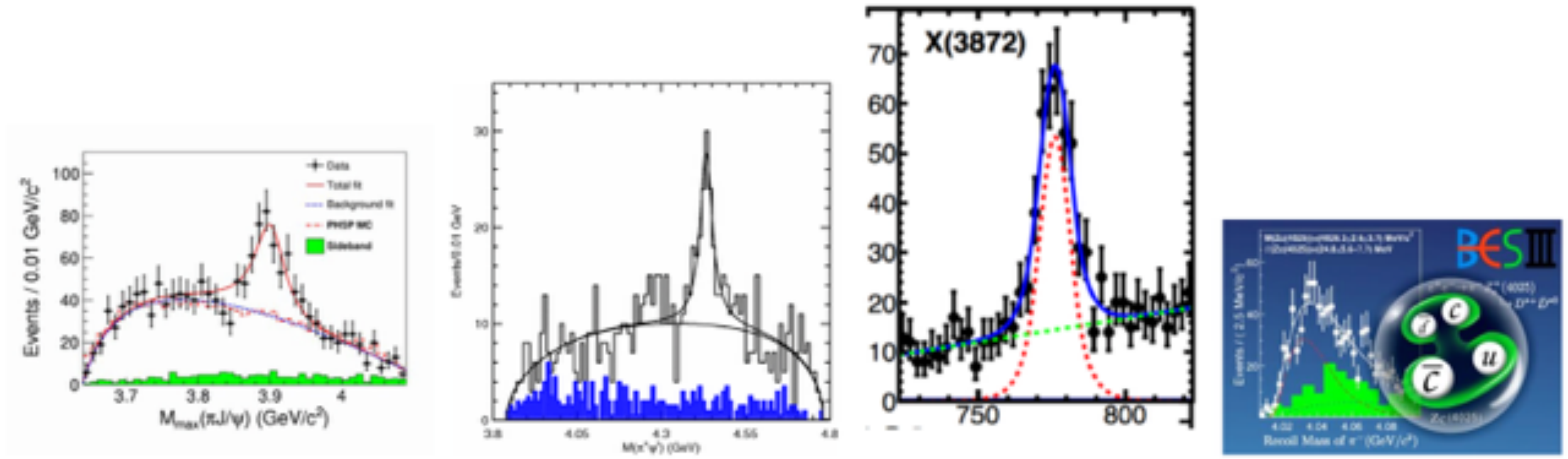
PACS@Lattice2016



Some problems:

- D* s0(2317)± and Ds1(2460)± are lighter and narrower than expected from phenomenological models.
- Nature of exotics: hybrid states, meson molecules, tetra quarks, hadro-quarkonium, pentaquark,...

Spectroscopy- Exotics



$Z_c(3900)$ $Z(4430)$ $X(3872)$ $Z_c(4025)$

- quarkonium-like states: valence quark structure $Q\bar{Q}q'\bar{q}$
- Neutral ones, $q = q'$, e.g. $X(3872)$, $Y(4260)$, etc.
- Charged ones, $q \neq q'$, $Z_c(3900)$, $Z_c(4025)$, $Z(4430)$, etc.
- Close to thresholds of mesons: $Q\bar{q}$ and $\bar{Q}q'$

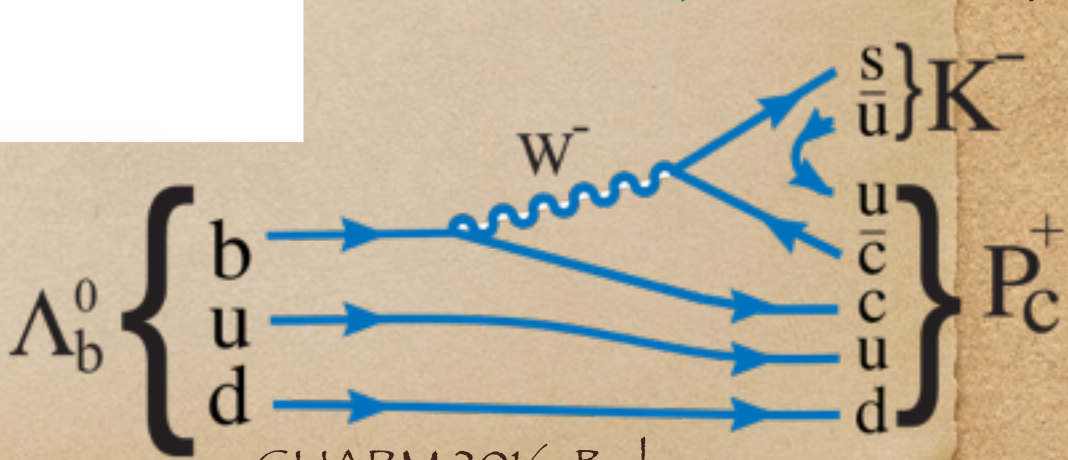
Plus the newly discovered pentaquark states: P_c^+, etc.

Liu, Lattice2016

$Z^-(4430) = c\bar{c}d\bar{u}$

LHCb:1606.07895
X(4140) (CDF, CMS, D0), X(4274), X(4500) and X(4700)

LHCb: PRL 117(082002/3),



$$\Lambda_b \to P_c^+(4380, 4450) \to J/\Psi\ p\ (\pi^-, K^-)$$

Spectroscopy

Playground for QCD models

- Lattice (e.g. 1608.06537)
- one pion exchange: (e.g. 1608.06535)
- color-magnetic IA model (1608.07900)
- solitonic baryons
- instantons
- Quarkmodels
- effective theories
- QCD sum rules
- …

Hadro-quarkonium from Lattice QCD

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[2] *Institut für Theoretische Physik, Universität Regensburg, Universitätsstraße 31, 93053 Regensburg, Germany*
[3] *Department of Theoretical Physics, Tata Institute of Fundamental Research, Homi Bhabha Road, Mumbai 40000*
[4] *Department of Applied Mathematics and Theoretical Physics, Centre for Mathematical Sciences, University of Cambridge, Wilberforce Road, Cambridge, CB3 0WA, UK*

The hadro-quarkonium picture [1] provides one possible interpretation for the pentaquark candidates with hidden charm, recently reported by the LHCb Collaboration, as well as for some of the charmonium-like "X, Y, Z" states. In this model, a heavy quarkonium core resides within a light hadron giving rise to four- and five-quark/antiquark bound states. We test this scenario in the heavy quark limit by investigating the modification of the potential between a static quark-antiquark pair induced by the presence of a hadron. Our lattice QCD simulations are performed on a CLS ensemble with $N_f = 2+1$ flavours of non-perturbatively improved Wilson quarks at a pion mass of about 223 MeV and a lattice spacing of about $a = 0.0854$ fm. We study the static potential in the presence of a variety of light mesons as well as of octet and decuplet baryons. In all these cases, the resulting configurations are favoured energetically, however, the associated binding energies between the quarkonium in the heavy quark limit and the light hadron are found to be smaller than a few MeV, similar in strength to deuterium binding.

The $X(4140)$, $X(4270)$, $X(4500)$ and $X(4700)$ and their $cs\bar{c}\bar{s}$ tetraquark partners

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[2] *School of Physical Science and Technology, Lanzhou University, Lanzhou 730000, China*
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Shi-Lin Zhu[4,5,6‡]
[4] *School of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China*
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[6] *Center of High Energy Physics, Peking University, Beijing 100871, China*
(Dated: August 30, 2016)

In the simple color-magnetic interaction model, we investigate possible ground $cs\bar{c}\bar{s}$ tetraquark states in the diquark-antidiquark basis. We use several methods to estimate the mass spectrum and discuss possible assignment for the X states observed in the $J/\psi\phi$ channel. We find that assigning the Belle $X(4350)$ as a 0^{++} tetraquark is consistent with the tetraquark interpretation for the $X(4140)$ and $X(4270)$ while the interpretation of the $X(4500)$ and $X(4700)$ needs orbital or radial excitation. There probably exist several tetraquarks around 4.3 GeV which decay into $J/\psi\phi$ or $\eta_c\phi$.

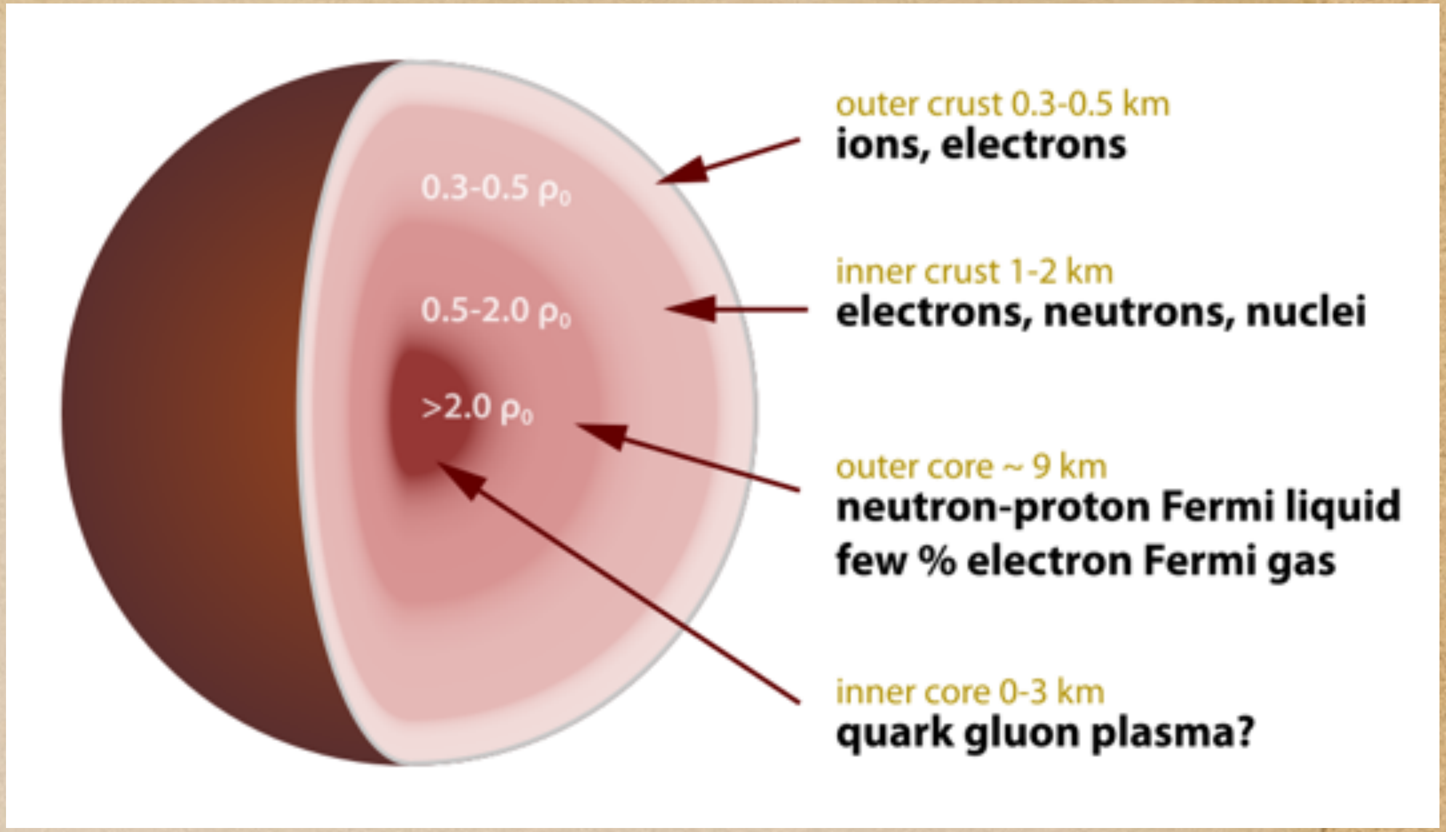
Heavy Exotic Molecules with Charm and Bottom

Yizhuang Liu[*] and Ismail Zahed[†]
Department of Physics and Astronomy, Stony Brook University, Stony Brook, New York 11794-3800, USA
(Dated: August 24, 2016)

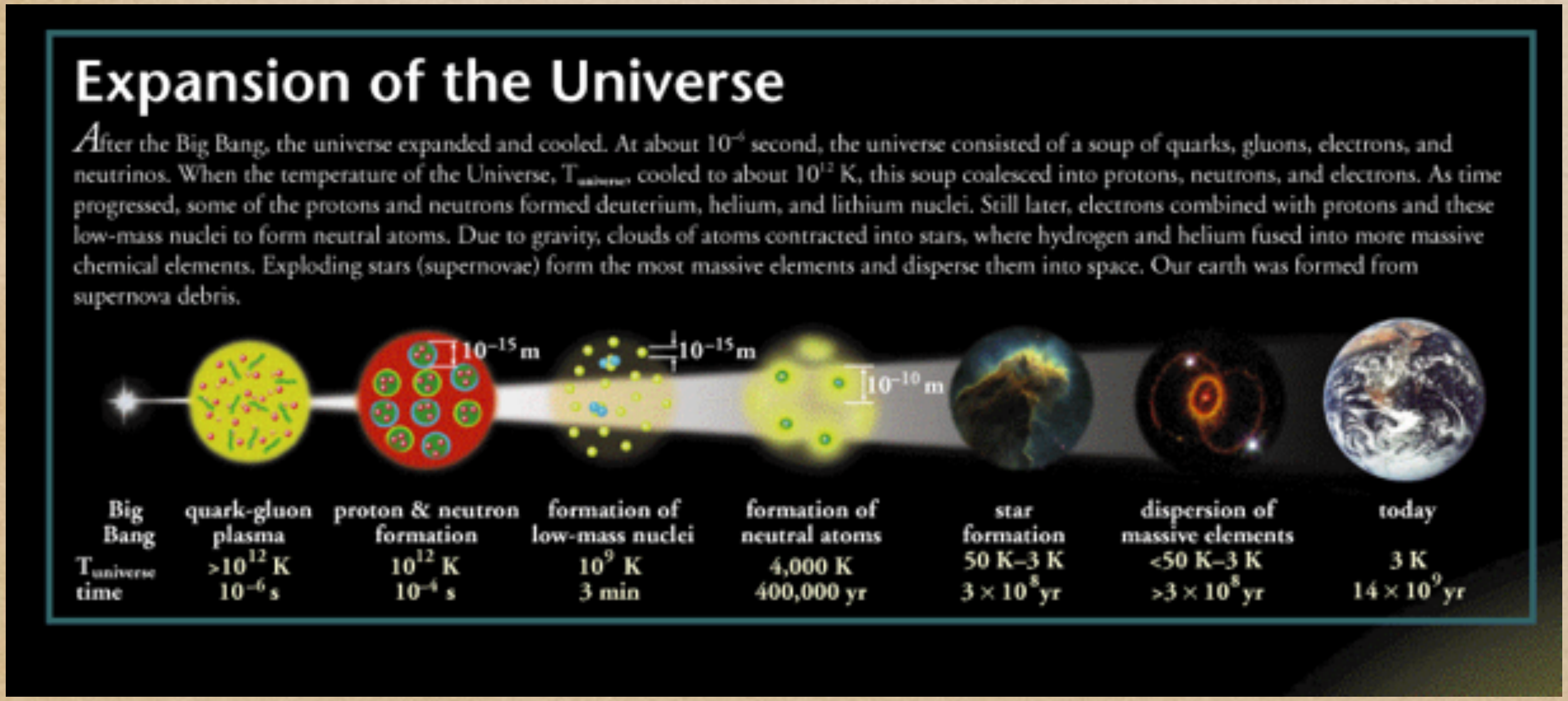
We revisit the formation of pion-mediated heavy-light exotic molecules with both charm and bottom and their chiral partners under the general strictures of both heavy-quark and chiral symmetry. The chiral exotic partners with good parity formed using the $(0^+, 1^+)$ multiplet are about twice more bound than their primary exotic partners formed using the $(0^-, 1^-)$ multiplet. The chiral couplings across the multiplets $(0^\pm, 1^\pm)$ cause the chiral exotic partners to unbind, and the primary exotic molecules to be about twice more bound, for $J \leq 1$. Our multi-channel coupling results show that only the charm isosinglet exotic molecules with $J^{PC} = 1^{++}$ binds, which we identify as the reported neutral $X(3872)$. Also, the bottom isotriplet exotic with $J^{PC} = 1^{+-}$ binds, which we identify as a mixture of the reported charged exotics $Z_b^+(10610)$ and $Z_b^+(10650)$. The bound isosinglet with $J^{PC} = 1^{++}$ is suggested as a possible neutral $X_b(10532)$ not yet reported.

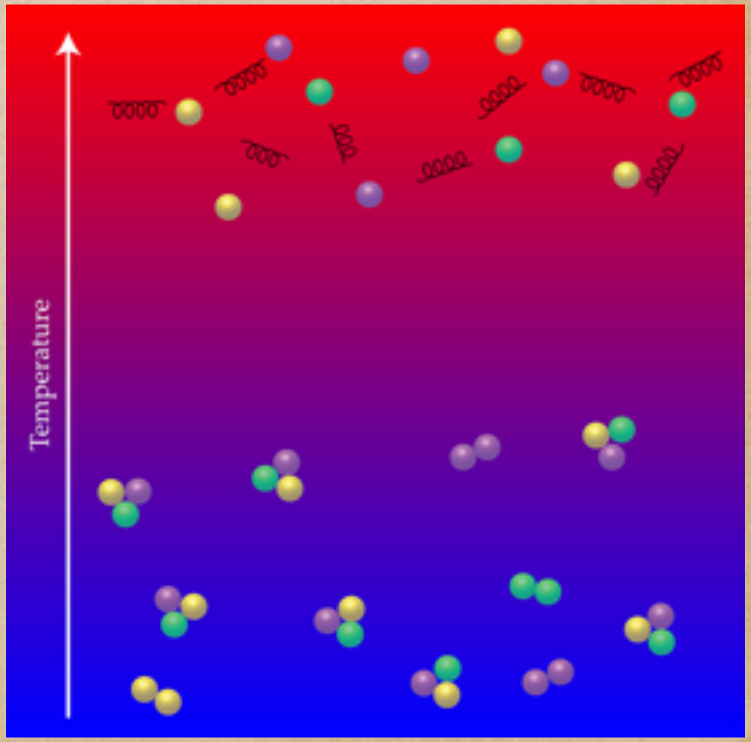
Heavy Ions

- Quark Gluon plasma
- use also charm quarks, to identify properties of the QGP



see afternoon session





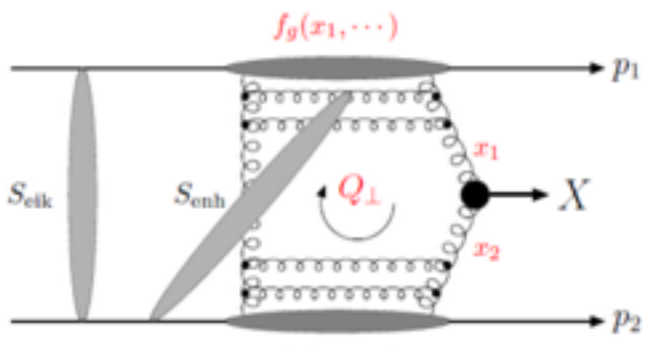
Charm production

'Durham Model' of Central Exclusive Production

- Model via diagram shown: two gluons exchange in the t-channel. Use of pQCD justified by hard scale $\sim M_X$. IR stable result due to Sudakov factor: probability of no additional hard radiation.
- However must also include probability of no additional soft secondary particle production, independent of hard process: the soft survival factor S^2, discussed before.

$\longrightarrow$ Both soft and hard QCD must be included.

- $J_z^{PC} = 0^{++}$ selection rule: these quantum numbers are dominantly preferred, i.e. only certain $gg \to X$ helicity amplitudes contribute, not the usual inclusive sum.



Non-CHARM2016 examples

Intrinsic charm content of p

Brodsky, Lipatov, Ball et. al

Valerie Khoze, 1405.0018

Beauty-quark and charm-quark pair production asymmetries at LHCb

Rhorry Gauld,[1,*] Ulrich Haisch,[2,3,†] Ben D. Pecjak,[1,‡] and Emanuele Re[2,§]

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[2] *Rudolf Peierls Centre for Theoretical Physics, University of Oxford, OX1 3PN Oxford, United Kingdom*
[3] *CERN Theory Division, CH-1211 Geneva 23, Switzerland*

(Dated: May 12, 2015)

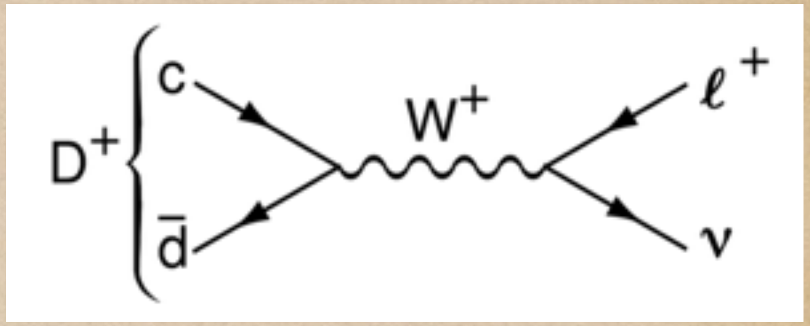
The LHCb collaboration has recently performed a first measurement of the angular production asymmetry in the distribution of beauty quarks and anti-quarks at a hadron collider. We calculate the corresponding standard model prediction for this asymmetry at fixed-order in perturbation theory. Our results show good agreement with the data, which is provided differentially for three bins in the invariant mass of the $b\bar{b}$ system. We also present similar predictions for both beauty-quark and charm-quark final states within the LHCb acceptance for a collision energy of $\sqrt{s} = 13\,\mathrm{TeV}$. We finally point out that a measurement of the ratio of the $b\bar{b}$ and $c\bar{c}$ cross sections may be useful for experimentally validating charm-tagging efficiencies.

$H \to c\bar{c}$

1505.02429

Decay Constants

- leptonic decays have the simplest possible hadronic structure of all meson decays



$$\mathcal{B}(D_{(s)} \to \ell \nu_\ell) = \frac{G_F^2 |V_{cq}|^2 \tau_{D_{(s)}}}{8\pi} f_{D_{(s)}}^2 m_\ell^2 m_{D_{(s)}} \left(1 - \frac{m_\ell^2}{m_{D_{(s)}}^2}\right)^2$$

- all hadronic physics is encoded in the decay constant

Rosner, Stone, PDG

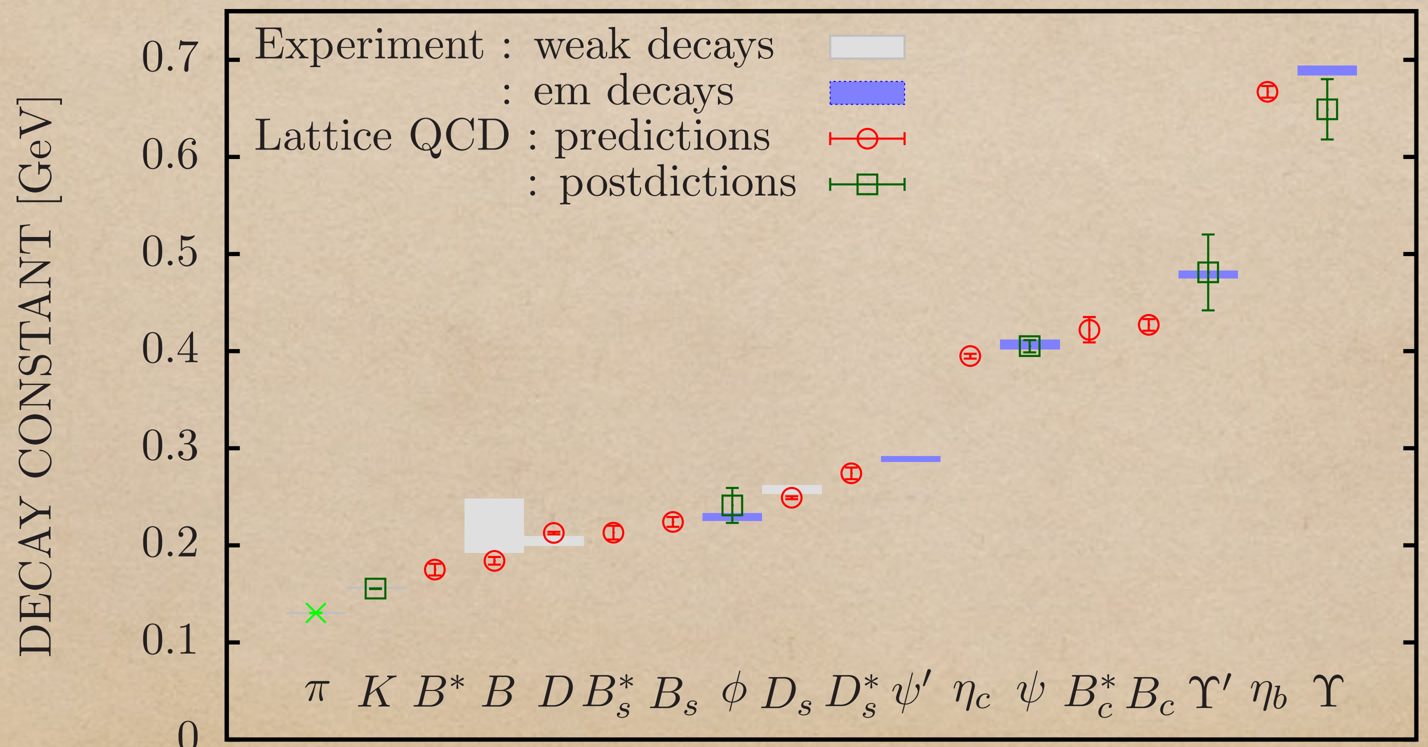
$$\langle 0 | \bar{c} \gamma_\mu \gamma_5 q | D_q(p) \rangle = f_{D_q} p_{D_q}^\mu$$

- Decay constants are determined via LATTICE-QCD, sum rules,...

Decay Constants

Model	$f_{D_s^+}$(MeV)	f_{D^+}(MeV)	$f_{D_s^+}/f_{D^+}$
Experiment (our averages)	257.5 ± 4.6	204.6 ± 5.0	1.258 ± 0.038
Lattice (HPQCD) [22]	$246.0 \pm 0.7 \pm 3.5$	$208.3 \pm 1.0 \pm 3.3$	$1.187 \pm 0.004 \pm 0.012$
Lattice (FNAL+MILC) [23]	$246.4 \pm 0.5 \pm 3.6$	$209.2 \pm 3.0 \pm 3.6$	1.175 ± 0.019
PQL [24]	244 ± 8	197 ± 9	1.24 ± 0.03
QCD sum rules [25]	205 ± 22	177 ± 21	$1.16 \pm 0.01 \pm 0.03$
QCD sum rules [26]	$245.3 \pm 15.7 \pm 4.5$	$206.2 \pm 7.3 \pm 5.1$	$1.193 \pm 0.025 \pm 0.007$
QCD sum rules [27]	246 ± 6	204 ± 6	1.21 ± 0.04
QCD sum rules [28](I)	241 ± 12	208 ± 11	1.16 ± 0.07
QCD sum rules [28](II)	258 ± 13	211 ± 14	1.22 ± 0.08
QCD sum rules [29]	238^{+13}_{-23}	201^{+12}_{-13}	$1.15^{+0.04}_{-0.05}$
Field correlators [30]	260 ± 10	210 ± 10	1.24 ± 0.03
Light front [31]	268.3 ± 19.1	206 (fixed)	1.30 ± 0.04

Rosner, Stone, PDG

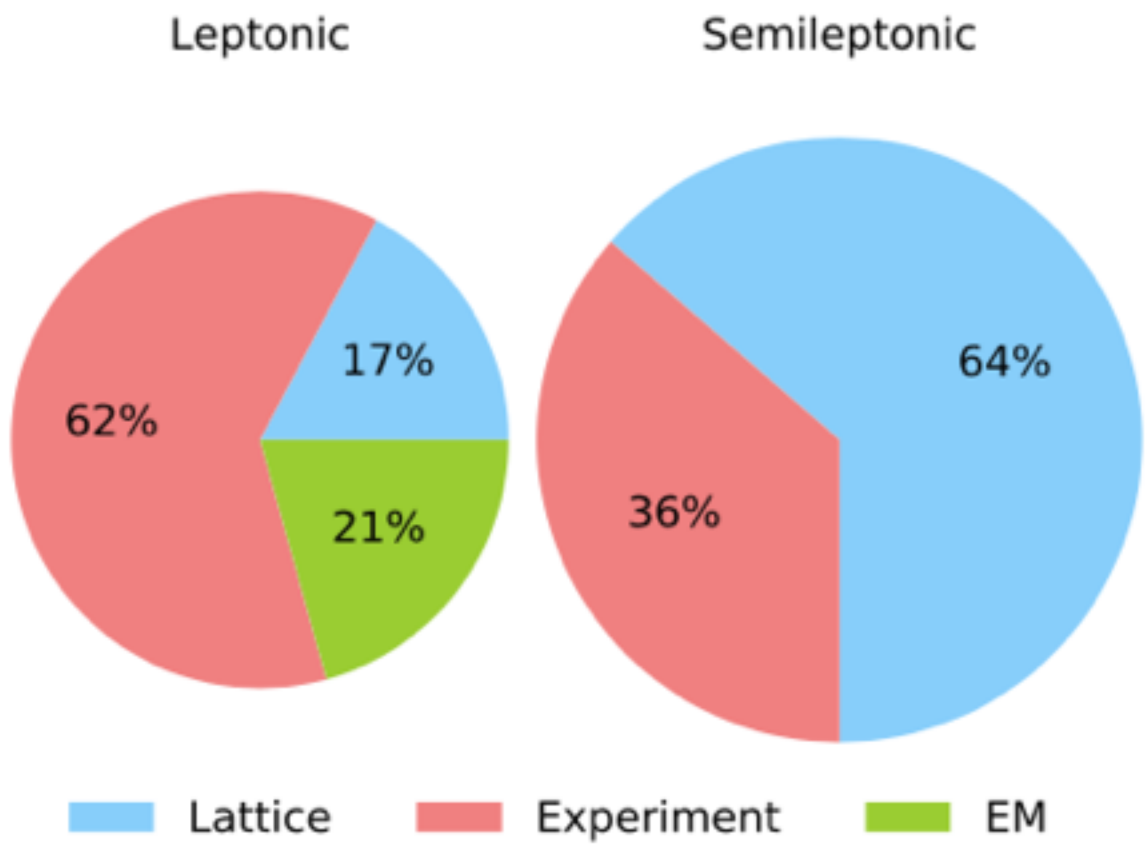


Thanks to C. Davies
1503.05762

Form factors

- semi-leptonic decays: form factors (LATTICE, sum rules)

$$\langle K|V^\mu|D\rangle = f_+(q^2)\left[p_D^\mu + p_K^\mu - \frac{M_D^2 - M_K^2}{q^2}q^\mu\right] + f_0(q^2)\frac{M_D^2 - M_K^2}{q^2}q^\mu$$



Comparison of contributions to $|V_{cs}|$ errors from the leading leptonic decay[1] and semileptonic decay[2] determinations. Radius is proportional to total error.

Gottlieb @LATTICE2016

Hadronic decays

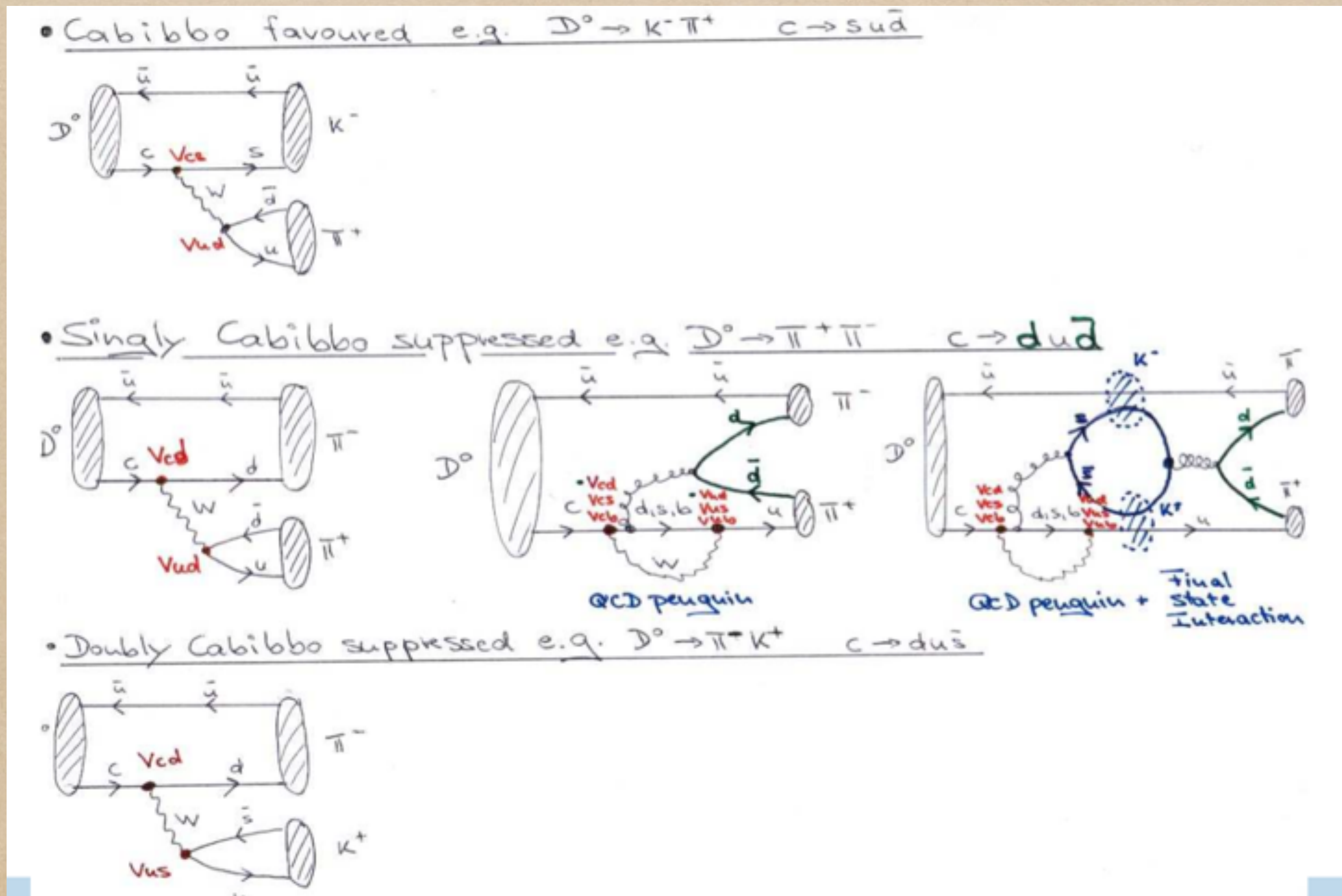
What have we learnt in theory from the ΔA_{CP}

Alexander Lenz

IPPP Durham

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

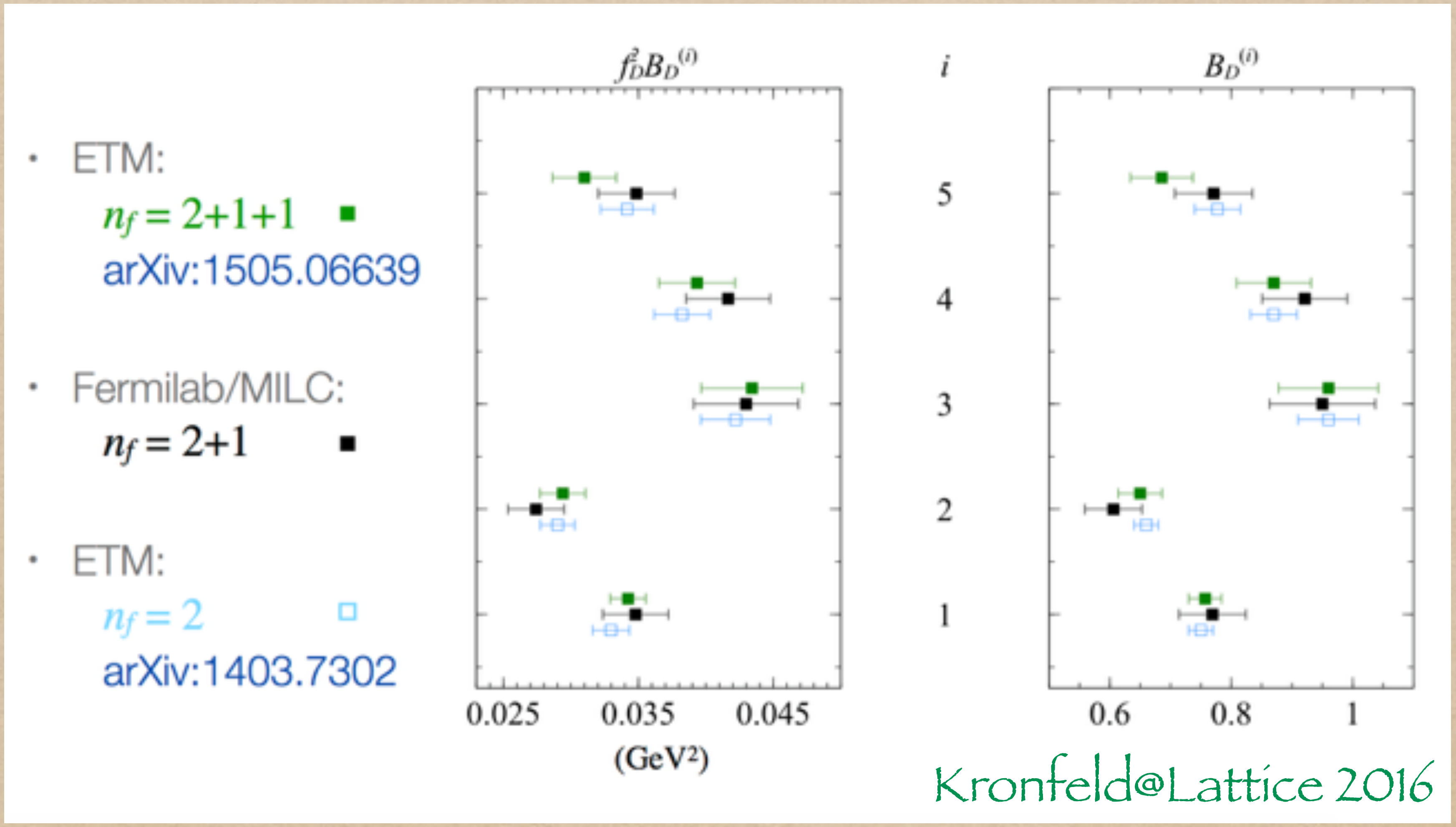
do any of our theory tools work? Heavy Quark Expansion?

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

- 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



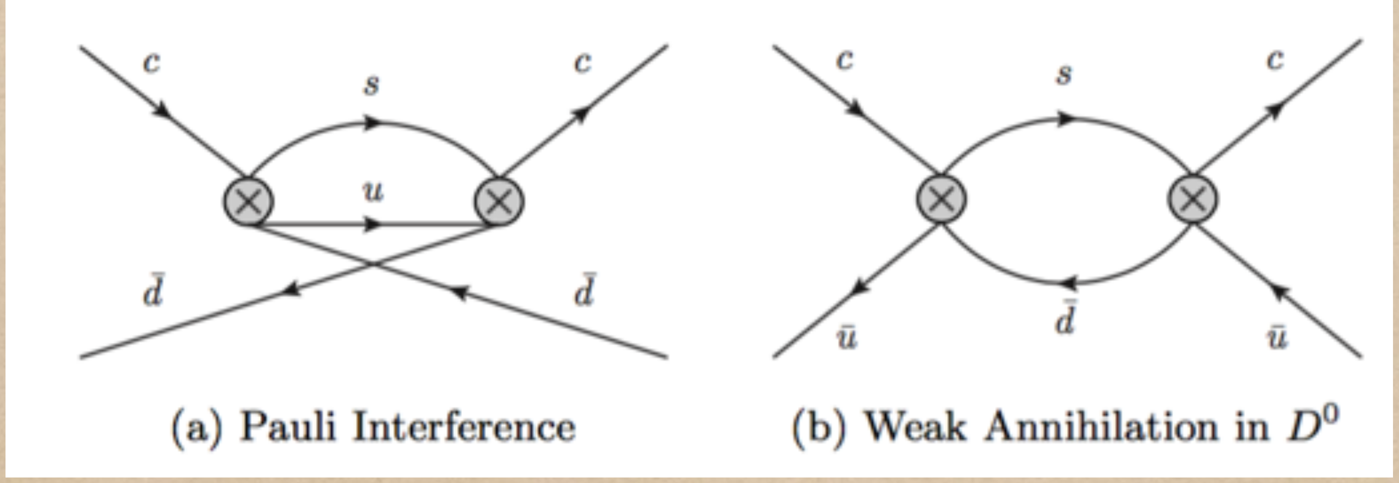
Test of validity of HQE in the charm system

- 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



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

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

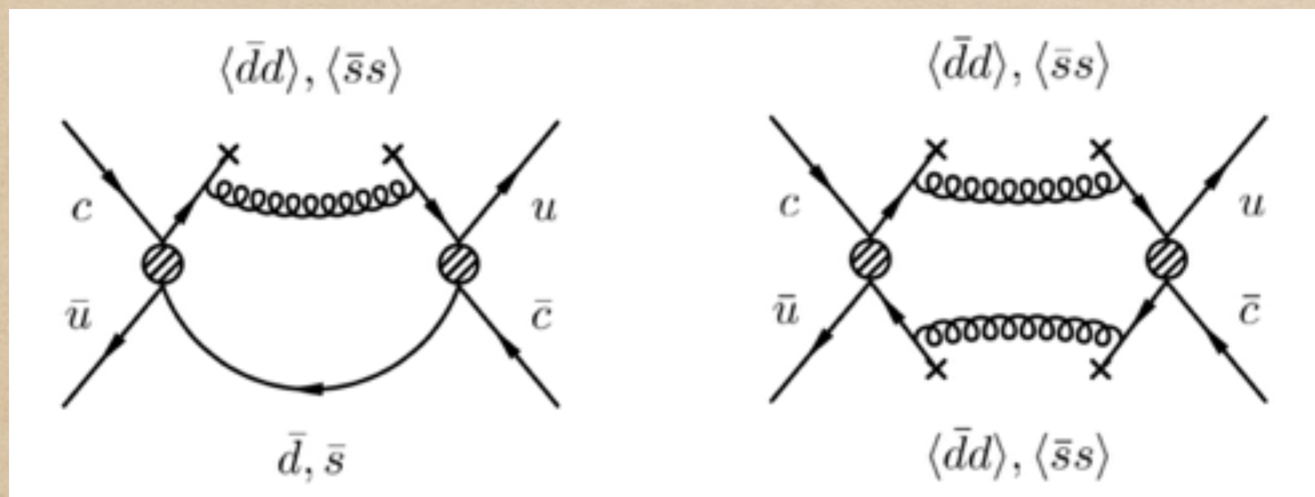
AL, Rauh 1305.3588

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

Please calculate the matrix elements on the lattice!!!

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

- GIM mechanism less effective in higher orders in the HQE



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

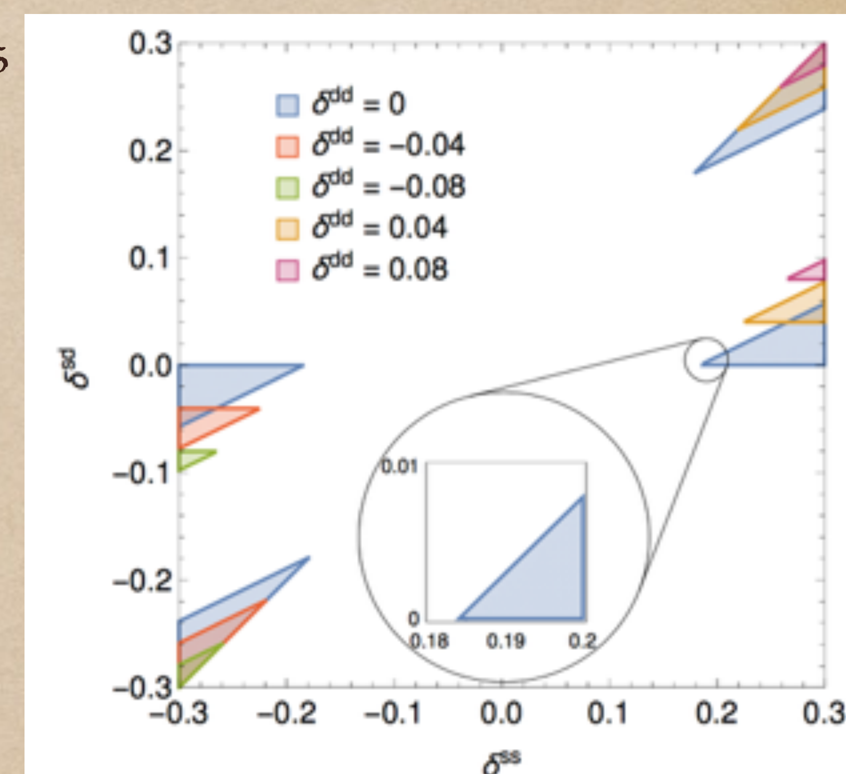
- Duality violations that have no/tiny GIM cancellations

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

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

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

Jubb, Kirk, AL,
Tetlalmatzi-Xolocotzi
2016



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

- HQE simply does not converge at all in the Charm-system

Determination of Standard Model parameters

- CKM elements

$$|V_{cd}| = 0.225 \pm 0.008$$

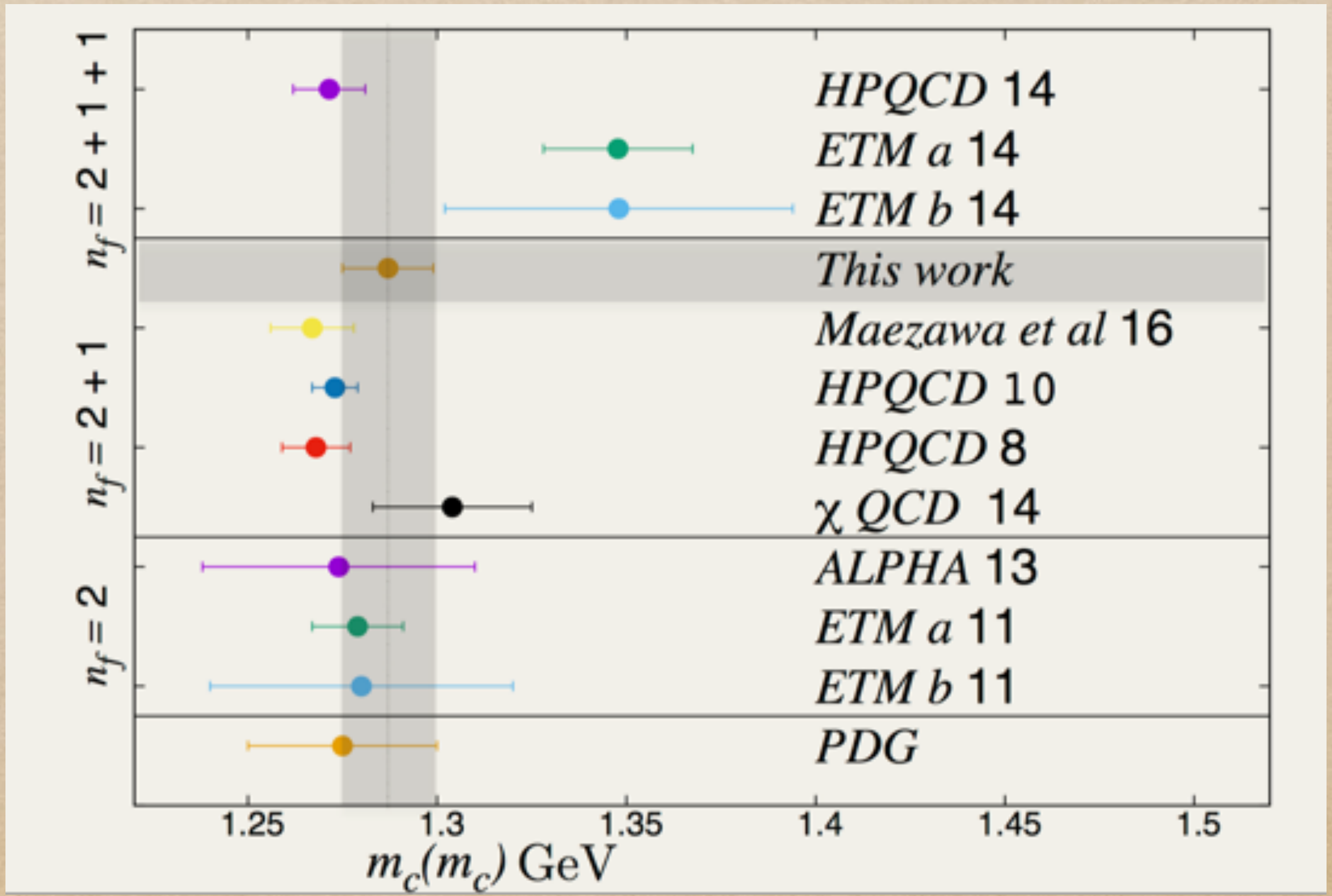
$$|V_{cs}| = 0.986 \pm 0.016$$

$$|V_{cb}| = 0.0411 \pm 0.0013$$

$$|V_{cd}|^2 + |V_{cs}|^2 + |V_{cb}|^2 = 1.024 \pm 0.032$$

PDG online

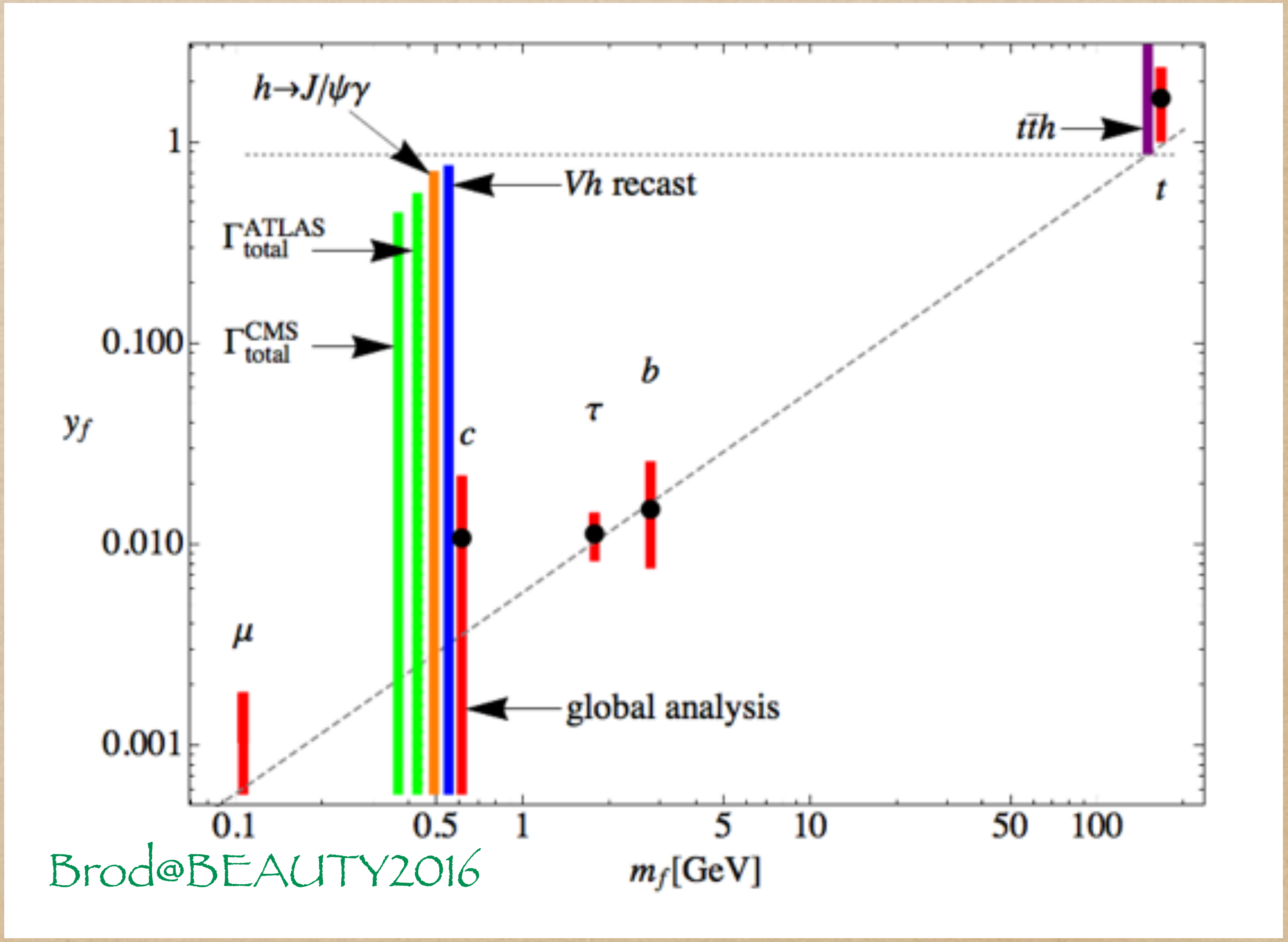
- Quark mass mc



Katsuma, JLQCD, Lattice 2016

Search for new physics?

- New physics might be heavy and theory tools could work - the only problem is to assume a value for the SM contribution
  - Meson decays (leptonic, semi-leptonic, hadronic ones, including rare decays)
  - $H \to c\bar{c}$
  - D-mixing
  - indirect contributions to g-2, epsilon_K,….



Conclusion

- Charm is complementary to many ongoing studies!
- Have a great conference!
- Hope for many new charming results
- Hope we will also experience many of the specialities from Emilia Romagna

Evening Prayer?

I believe in the HQE, the almighty series,
creator of true predictions.
I believe in its convergence also in the charm sector…