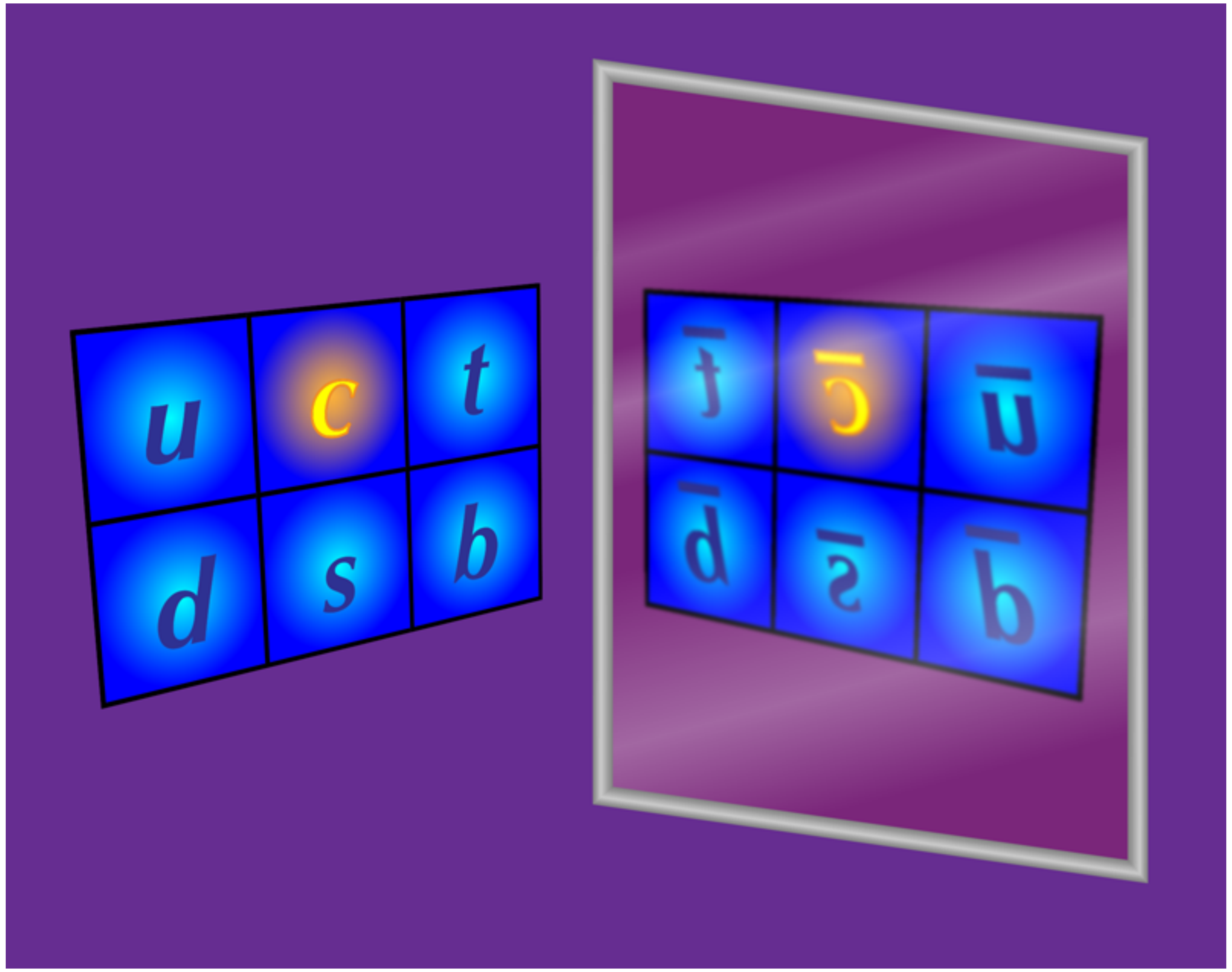
Charm quark mass & HQE



TRR 257 Mini Workshop on Quark Masses

Alexander Lenz, Siegen, 26.10.2020

Outline

- Peculiarities of Charm
- Lifetimes
- Charm Mixing
- Outlook

Disclaimer: Work in progress

Based on collaborations with

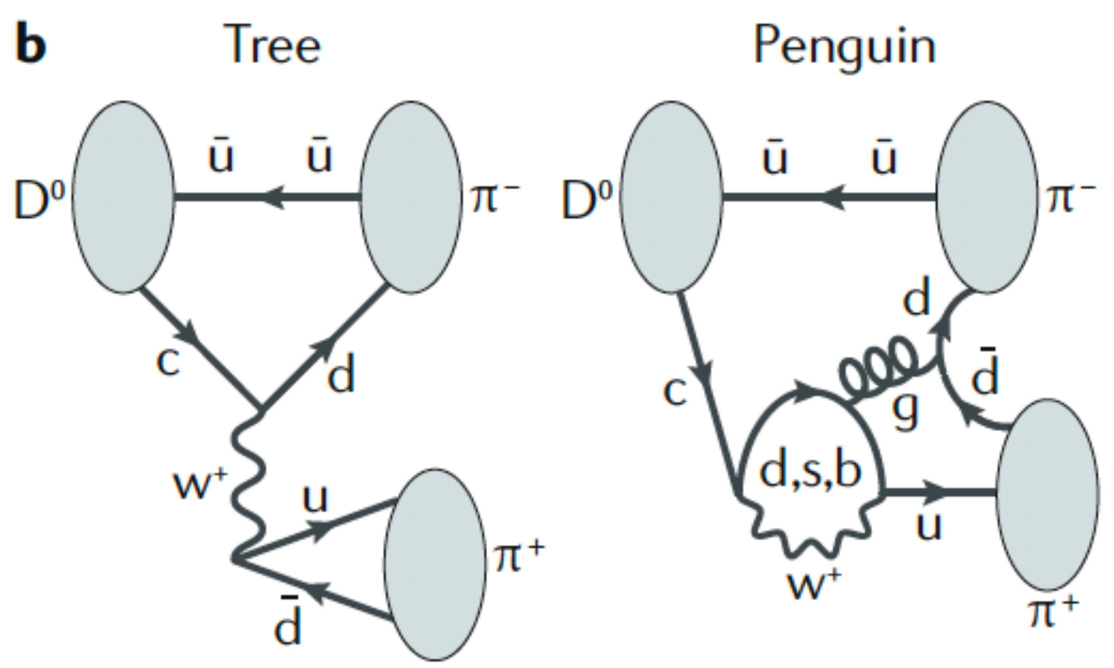
- Markus Bobrowski
- Mikael Chala
- Tom Jubb
- Daniel King
- Matthew Kirk
- Uli Nierste
- Maria Laura Piscopo
- Thomas Rauh
- Johann Riedl
- Jürgen Rohrwild
- Aleksey Rusov
- Jakub Scholtz
- Gilberto Tetlalmatzi-Xolocotzi
- Christos Vlahos
- Di Wang
- Guy Wilkinson

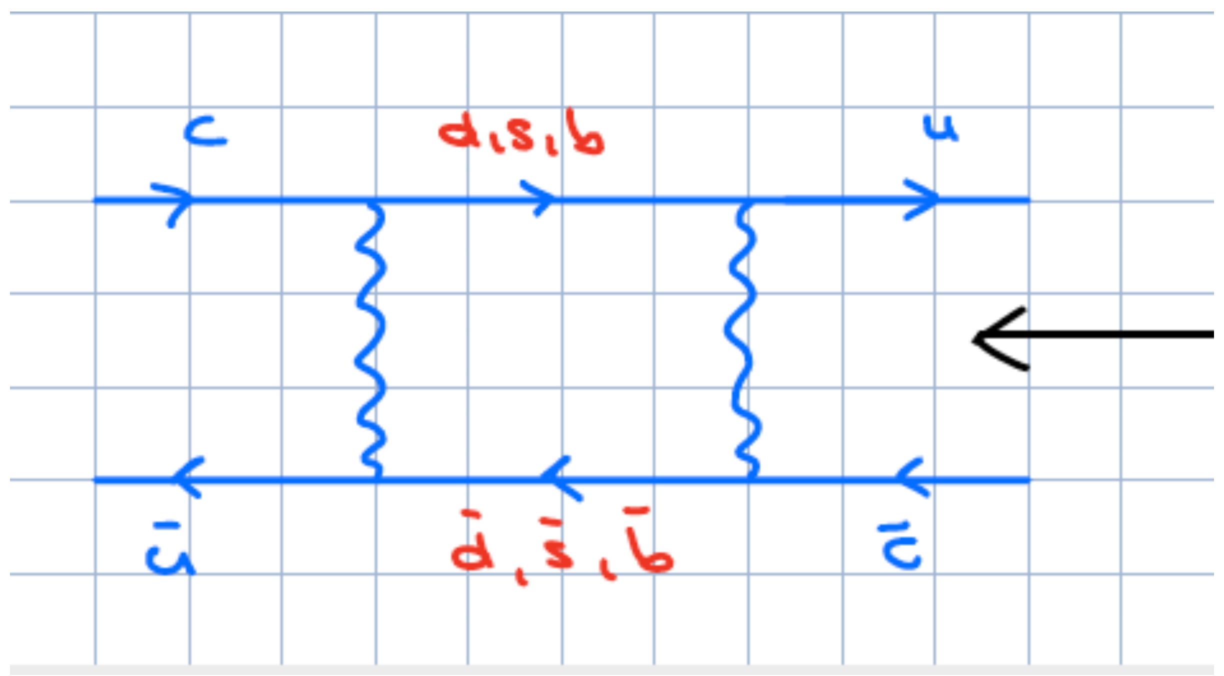
Peculiarities of the charm sector

- CKM Elelements

In singly Cabibbo-suppressed D-decays and in D-mixing the following CKM combination arises

$$\lambda_q = V_{cq} V_{uq}^*$$





$$\lambda_d = -0.21874 - 2.51 \cdot 10^{-5} I$$
$$\lambda_s = +0.21890 - 0.13 \cdot 10^{-5} I$$
$$\lambda_b = -1.5 \cdot 10^{-4} + 2.64 \cdot 10^{-5} I$$

Re>>Im => almost no CP violation

- GIM:

$$\lambda_d + \lambda_s + \lambda_b = 0$$

$$f_{Loop} = f_0 + f(m_q^2 / M_W^2)$$

$$\left(\frac{m_d}{M_W}\right)^2 \approx 0 \quad , \quad \left(\frac{m_u}{M_W}\right)^2 \approx 0 \, ,$$
$$\left(\frac{m_s}{M_W}\right)^2 \approx 1.3 \cdot 10^{-6} \, , \quad \left(\frac{m_c}{M_W}\right)^2 \approx 2.5 \cdot 10^{-4} \, ,$$
$$\left(\frac{m_b}{M_W}\right)^2 \approx 2.8 \cdot 10^{-3} \, , \quad \left(\frac{m_t}{M_W}\right)^2 \approx 4.5 \, .$$

Crazy GIM suppressed | Strongly GIM suppressed | No GIM suppression

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

CKM dominant | Strongly CKM suppressed | Crazy CKM suppressed

- Strong coupling $\alpha_s(m_c) = 0.33 \pm 0.01 \, .$

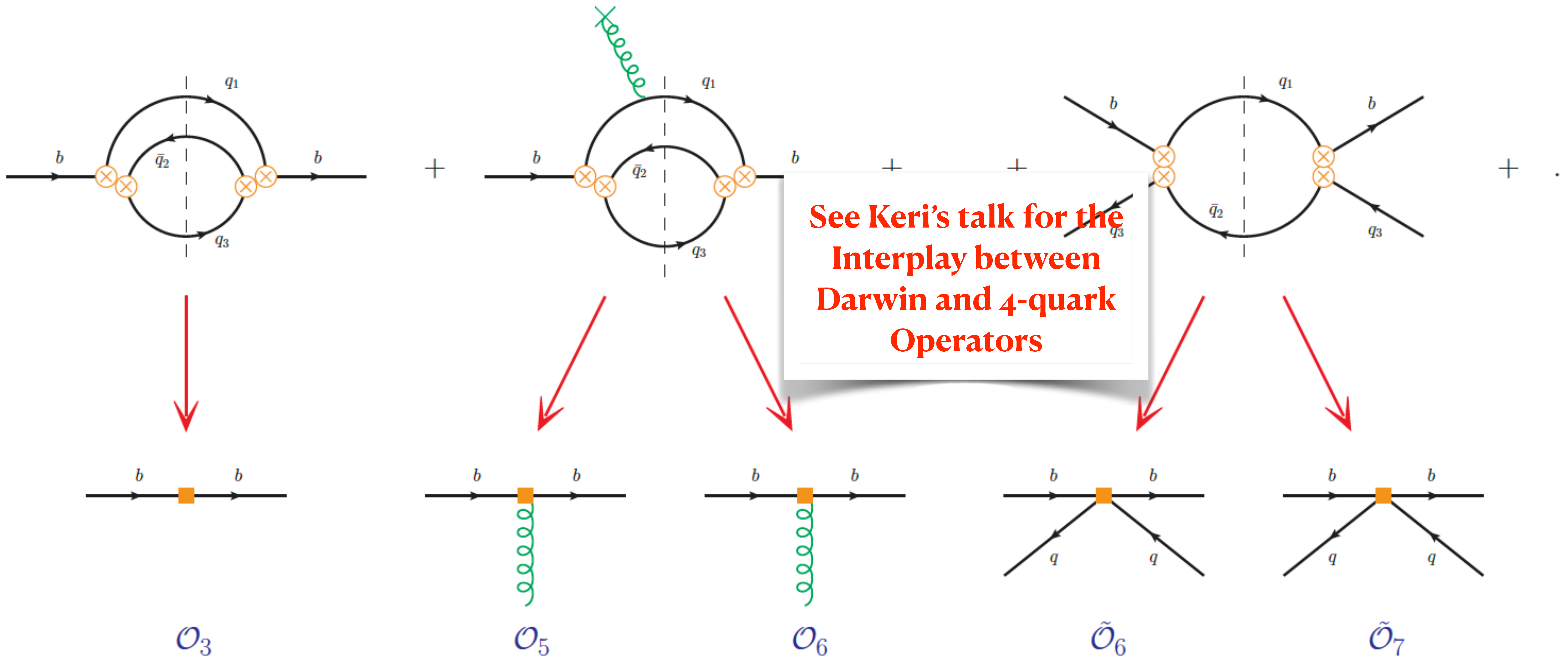
- Size of Λ / m_c

$$m_c^{\text{Pole}} = (1.67 \pm 0.07) \, \text{GeV} \qquad \overline{m}_c(\overline{m}_c) = (1.27 \pm 0.02) \, \text{GeV}$$

Lifetimes

No GIM cancellations are arising - pure test of expansion in α_s and Λ/m_c

$$\Gamma(H_c) = \Gamma_0 + \Gamma_2 \frac{\langle \mathcal{O}_5 \rangle}{m_c^2} + \Gamma_3 \frac{\langle \mathcal{O}_6 \rangle}{m_c^3} + \ldots + 16\pi^2 \left[\tilde{\Gamma}_3 \frac{\langle \tilde{\mathcal{O}}_6 \rangle}{m_c^3} + \tilde{\Gamma}_4 \frac{\langle \tilde{\mathcal{O}}_7 \rangle}{m_c^4} + \ldots \right]$$



Lifetimes

No GIM cancellations are arising - pure test of expansion in α_s and Λ/m_c

$$\Gamma(H_c) = \Gamma_0 + \Gamma_2 \frac{\langle \mathcal{O}_5 \rangle}{m_c^2} + \Gamma_3 \frac{\langle \mathcal{O}_6 \rangle}{m_c^3} + \ldots + 16\pi^2 \left[\tilde{\Gamma}_3 \frac{\langle \tilde{\mathcal{O}}_6 \rangle}{m_c^3} + \tilde{\Gamma}_4 \frac{\langle \tilde{\mathcal{O}}_7 \rangle}{m_c^4} + \ldots \right]$$

Perturbative Expansion of Wilson coefficients

$$\Gamma_i = \Gamma_i^{(0)} + \frac{\alpha_s(m_c)}{4\pi} \Gamma_i^{(1)} + \left(\frac{\alpha_s(m_c)}{4\pi} \right)^2 \Gamma_i^{(2)} + \ldots$$

Non-perturbative matrix elements

$$\langle \mathcal{O}_Y \rangle = \frac{\langle H_c(p_{H_c}) | \mathcal{O}_Y | H_c(p_{H_c}) \rangle}{2 M_{H_c}}$$

Lifetimes - State of the art

No GIM cancellations are arising - pure test of expansion in α_s and Λ/m_c

$$\Gamma(H_c) = \Gamma_0 + \Gamma_2 \frac{\langle \mathcal{O}_5 \rangle}{m_c^2} + \Gamma_3 \frac{\langle \mathcal{O}_6 \rangle}{m_c^3} + \ldots + 16\pi^2 \left[\tilde{\Gamma}_3 \frac{\langle \tilde{\mathcal{O}}_6 \rangle}{m_c^3} + \tilde{\Gamma}_4 \frac{\langle \tilde{\mathcal{O}}_7 \rangle}{m_c^4} + \ldots \right]$$

- $\Gamma_0^{(1)}$ **Ho-Kim, Pham, Altarelli, Petrarca, Voloshin, Bagan, Ball, Braun, Gosdzinsky, Fiol, AL, Nierste, Ostermaier, Krinner, Rauh; 1984 - 2013**
- $\Gamma_0^{(2)}$ **Czarnecki, Slusarcyk, Tkachov 2005** (m_c=0, not all color structures)
- $\Gamma_2^{(0)}$ **Bigi, Uraltsev, Vainshtein, Blok, Shifman 1992**
- $\Gamma_3^{(0)}$ **AL, Piscopo, Rusov, Mannel, Moreno, Pivovarov 2020**
- $\tilde{\Gamma}_3^{(1)}$ **Beneke, Buchalla, Greub, AL, Nieste, Franco, Lubicz, Mescia, Tarantino, Rauh 2002-13**
- $\tilde{\Gamma}_4^{(0)}$ *AL, Nierste*, **Gabbiani, Onishchenko, Petrov 2003-04**

Lifetimes - State of the art

No GIM cancellations are arising - pure test of expansion in α_s and Λ/m_c

$$\Gamma(H_c) = \Gamma_0 + \Gamma_2 \frac{\langle \mathcal{O}_5 \rangle}{m_c^2} + \Gamma_3 \frac{\langle \mathcal{O}_6 \rangle}{m_c^3} + \ldots + 16\pi^2 \left[\tilde{\Gamma}_3 \frac{\langle \tilde{\mathcal{O}}_6 \rangle}{m_c^3} + \tilde{\Gamma}_4 \frac{\langle \tilde{\mathcal{O}}_7 \rangle}{m_c^4} + \ldots \right]$$

$\langle \mathcal{O}_5 \rangle$ • Spectroscopy for chromomagnetic operator

$\langle \mathcal{O}_6 \rangle$ • E.o.M. for Darwin term: AL, Piscopo, Rusov in progress

$\langle \tilde{\mathcal{O}}_6 \rangle$ • HQET sum rules: Kirk, AL, Rauh 2017 - no lattice result

$\langle \tilde{\mathcal{O}}_7 \rangle$ • Vacuum insertion approximation

Lifetime Ratios

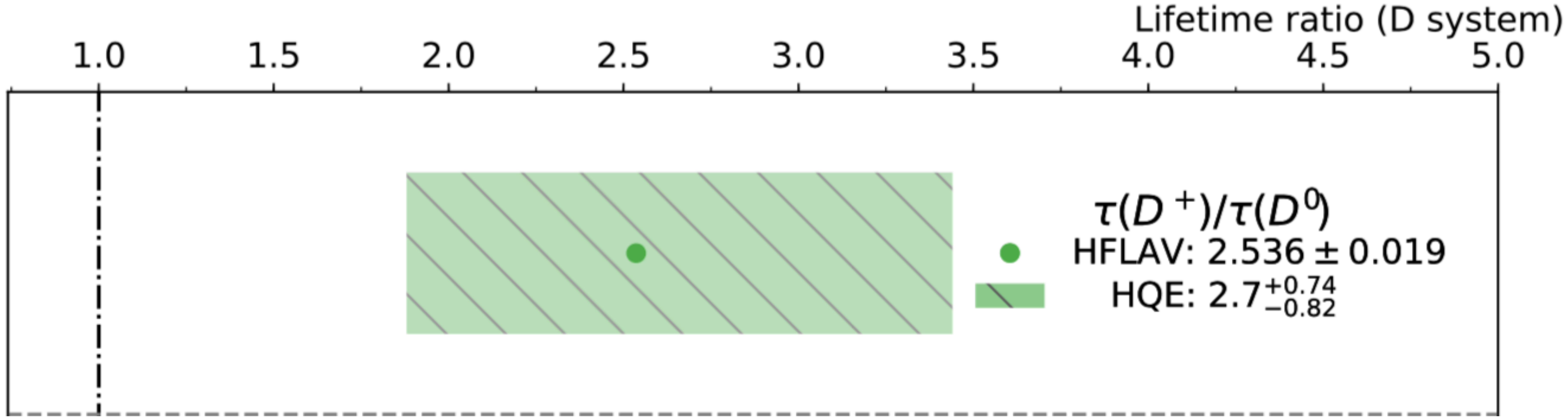
$$\frac{\tau(D^+)}{\tau(D^0)} = 1 + \left[\Gamma(D^0) - \Gamma(D^+)\right] \tau(D^+) = 1 + \left[\Gamma_2 \frac{\langle \mathcal{O}_5 \rangle_{D^0} - \langle \mathcal{O}_5 \rangle_{D^+}}{m_c^2} + \Gamma_3 \frac{\langle \mathcal{O}_6 \rangle_{D^0} - \langle \mathcal{O}_6 \rangle_{D^+}}{m_c^3} + \ldots + 16\pi^2 \left\{ \frac{\tilde{\Gamma}_3^{D^0} \langle \tilde{\mathcal{O}}_6 \rangle_{D^0} - \tilde{\Gamma}_3^{D^+} \langle \tilde{\mathcal{O}}_6 \rangle_{D^+}}{m_c^3} + \ldots \right\} \right] \tau(D^+)$$

Many terms cancel:

- No dependence on leading term
- Isospin symmetry: Matrix elements are equal
- Dominant contribution from Pauli interference
- Dimension 7 - 4 quark is crucial

Can the HQE reproduce the large experimental lifetime ratio?

Lifetime Ratio $\frac{\tau(D^+)}{\tau(D^0)}$



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

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

Lifetime Ratio $\frac{\tau(D^+)}{\tau(D^0)}$

Dependence on quark mass definition

$$\left.\frac{\tau(D^+)}{\tau(D^0)}\right|_{\overline{\rm MS}} = 2.61^{+0.72}_{-0.77} = 2.61\,^{+0.70}_{-0.66}\,(\text{had.})\,^{+0.12}_{-0.38}\,(\text{scale}) \pm 0.09\,(\text{param.}),$$

$$\left.\frac{\tau(D^+)}{\tau(D^0)}\right|_{\rm PS} = 2.70^{+0.74}_{-0.82} = 2.70\,^{+0.72}_{-0.68}\,(\text{had.})\,^{+0.11}_{-0.45}\,(\text{scale}) \pm 0.10\,(\text{param.}),$$

$$\left.\frac{\tau(D^+)}{\tau(D^0)}\right|_{\rm 1S} = 2.56^{+0.81}_{-0.99} = 2.56\,^{+0.78}_{-0.74}\,(\text{had.})\,^{+0.22}_{-0.65}\,(\text{scale}) \pm 0.10\,(\text{param.}),$$

$$\left.\frac{\tau(D^+)}{\tau(D^0)}\right|_{\rm kin} = 2.53^{+0.72}_{-0.76} = 2.53\,^{+0.70}_{-0.66}\,(\text{had.})\,^{+0.13}_{-0.37}\,(\text{scale}) \pm 0.10\,(\text{param.}),$$

Lifetime Ratios

$$\frac{\tau(D_s^+)}{\tau(D^0)} = 1 + \left[\Gamma_2 \frac{\langle \mathcal{O}_5 \rangle_{D^0} - \langle \mathcal{O}_5 \rangle_{D_s^+}}{m_c^2} + \Gamma_3 \frac{\langle \mathcal{O}_6 \rangle_{D^0} - \langle \mathcal{O}_6 \rangle_{D_s^+}}{m_c^3} + \ldots + 16\pi^2 \left\{ \frac{\tilde{\Gamma}_3^{D^0} \langle \tilde{\mathcal{O}}_6 \rangle_{D^0} - \tilde{\Gamma}_3^{D_s^+} \langle \tilde{\mathcal{O}}_6 \rangle_{D_s^+}}{m_c^3} + \ldots. \right\} \right] \tau(D^+)$$

Some terms cancel:

- No dependence on leading term
- SU(3)_F breaking can be large: Matrix elements are not equal
- Pauli interference less important due to CKM suppression
- Weak annihilation might become very large
- Dimension 7 - 4 quark is crucial

Work in progress:

1. **HQET sum rules for Bag parameter with ms corrections**
2. **Size of Darwin operator via E.o.M**
3. **Numerical analysis**

King, AL, Piscopo, Rauh, Rusov, Vlahos, Wang

Lifetime Ratios

Many more interesting experimental results for charmed baryons:

- But: Theory status much worse than in the meson sector
- Be aware of that when you find strong theory statements in the literature about charmed baryons
- Theory situation can be improved with current technology

Total decay rates

$$\Gamma(H_c) = \Gamma_0 + \Gamma_2 \frac{\langle \mathcal{O}_5 \rangle}{m_c^2} + \Gamma_3 \frac{\langle \mathcal{O}_6 \rangle}{m_c^3} + \ldots + 16\pi^2 \left[\tilde{\Gamma}_3 \frac{\langle \tilde{\mathcal{O}}_6 \rangle}{m_c^3} + \tilde{\Gamma}_4 \frac{\langle \tilde{\mathcal{O}}_7 \rangle}{m_c^4} + \ldots \right]$$

- Free quark decay shows a **huge dependence on the charm quark mass**

$$\frac{G_F^2 m_c^5}{192\pi^3} |V_{cs}|^2$$

Pole scheme

$$\begin{aligned} \Gamma_0^{LO} &= 2.63^{+0.46}_{-0.24}(scale)^{+0.61}_{-0.51}(m_c) \\ &= 2.63^{+0.75}_{-0.65} \\ \Gamma_0^{NLO} &= 2.72^{+0.46}_{-0.28}(scale)^{+0.6}_{-0.51}(m_c) \\ &= 2.72^{+0.76}_{-0.58} \end{aligned}$$

$\overline{MS}$ scheme

$$\begin{aligned} \Gamma_0^{LO} &= 0.7^{+0.07}_{-0.09}(scale)^{+0.058}_{-0.055}(m_c) \\ &= 0.7^{+0.09}_{-0.09} \\ \Gamma_0^{NLO} &= 1.37^{+0.006}_{-0.0002}(scale)^{+0.09}_{-0.09}(m_c) \\ &= 1.37^{+0.09}_{-0.09} \end{aligned}$$

- No pronounced cancellations among Wilson coefficients $C_1(1.5\text{GeV}) \approx -0.35,\ C_2(1.5\text{GeV}) \approx 1.2$

$$3C_1(\mu)^2 + 2C_1(\mu)C_2(\mu) + 3C_2^2(\mu)$$

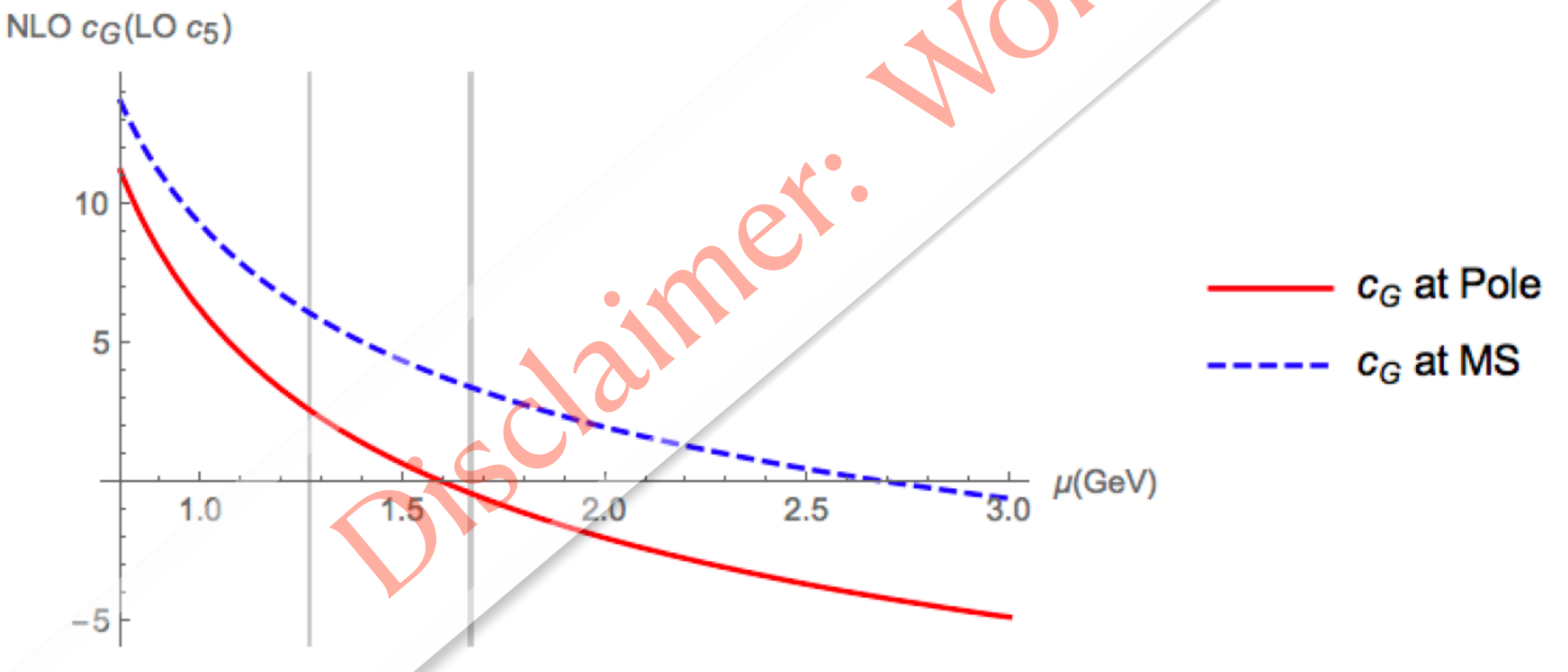
+0.37 -0.84 +4.32

- **To reduce dependence on scale and quark mass NNLO QCD corrections might be needed** $\Gamma_0^{(2)}$

Total decay rates

$$\Gamma(H_c) = \Gamma_0 + \Gamma_2 \frac{\langle \mathcal{O}_5 \rangle}{m_c^2} + \Gamma_3 \frac{\langle \mathcal{O}_6 \rangle}{m_c^3} + \ldots + 16\pi^2 \left[\tilde{\Gamma}_3 \frac{\langle \tilde{\mathcal{O}}_6 \rangle}{m_c^3} + \tilde{\Gamma}_4 \frac{\langle \tilde{\mathcal{O}}_7 \rangle}{m_c^4} + \ldots \right]$$

- 1/mc^2 corrections show a pronounced cancellations among Wilson coefficients $C_1(1.5\text{GeV}) \approx -0.35,\ C_2(1.5\text{GeV}) \approx 1.2$



- **The overall effect is small**

Pole scheme

$$\Gamma_2^{LO} = -0.21^{+0.21}_{-0.15}(scale)^{+0.025}_{-0.027}(m_c)$$
$$= -0.21^{+0.21}_{-0.15}$$

$\overline{MS}$ scheme

$$\Gamma_2^{LO} = -0.049^{+0.052}_{-0.085}(scale)^{+0.002}_{-0.002}(m_c)$$

Total decay rates

$$\Gamma(H_c) = \Gamma_0 + \Gamma_2 \frac{\langle \mathcal{O}_5 \rangle}{m_c^2} + \Gamma_3 \frac{\langle \mathcal{O}_6 \rangle}{m_c^3} + \ldots + 16\pi^2 \left[\tilde{\Gamma}_3 \frac{\langle \tilde{\mathcal{O}}_6 \rangle}{m_c^3} + \tilde{\Gamma}_4 \frac{\langle \tilde{\mathcal{O}}_7 \rangle}{m_c^4} + \ldots \right]$$

- Darwin term will probably give a sizeable positive contribution

Pole scheme

$$\Gamma_3^{LO} = 0.755^{+0.209}_{-0.122}(scale)^{+0.03}_{-0.003}(m_c)$$

$\overline{MS}$ **scheme**

$$\Gamma_3^{LO} = 0.61^{+0.085}_{-0.121}(scale)^{+0.012}_{-0.012}(m_c)$$

Total decay rates

$$\Gamma(H_c) = \Gamma_0 + \Gamma_2 \frac{\langle \mathcal{O}_5 \rangle}{m_c^2} + \Gamma_3 \frac{\langle \mathcal{O}_6 \rangle}{m_c^3} + \ldots + 16\pi^2 \left[\tilde{\Gamma}_3 \frac{\langle \tilde{\mathcal{O}}_6 \rangle}{m_c^3} + \tilde{\Gamma}_4 \frac{\langle \tilde{\mathcal{O}}_7 \rangle}{m_c^4} + \ldots \right]$$

- Pauli Interference is huge and negative, Weak exchange smaller an positive

$$\begin{aligned}
\tilde{\Gamma}_3^{LO}(D^0) &= 0.487^{+0.115}_{-0.068}(scale)^{+0.044}_{-0.042}(m_c) \\
&= 0.487^{+0.123}_{-0.08} \\
\tilde{\Gamma}_3^{NLO}(D^0) &= 0.433^{+0.003}_{-0.022}(scale)^{+0.006}_{-0.005}(m_c) \\
&= 0.433^{+0.007}_{-0.022} \\
\tilde{\Gamma}_3^{LO}(D^+) &= -3.484^{+1.361}_{-2.133}(scale)^{+0.315}_{-0.328}(m_c) \\
&= -3.484^{+1.4}_{-2.158} \\
\tilde{\Gamma}_3^{NLO}(D^+) &= -4.074^{+0.52}_{-0.0}(scale)^{+0.285}_{-0.293}(m_c) \\
&= -3.543^{+0.593}_{-0.293}
\end{aligned}$$

- Spectator corrections show a pronounced cancellations among Wilson coefficients $C_1(1.5\text{GeV}) \approx -0.35,\ C_2(1.5\text{GeV}) \approx 1.2$

$$\left(C_1^2 + 6C_1C_2 + C_2^2\right) B_1^{D^+} + 6\left(C_1^2 + C_2^2\right) \epsilon_1^{D^+}$$

+0.1225 -2.52 1.44 + 9.375

Enhancement of colour-octet operators

Total decay rates

$$\Gamma(H_c) = \Gamma_0 + \Gamma_2 \frac{\langle \mathcal{O}_5 \rangle}{m_c^2} + \Gamma_3 \frac{\langle \mathcal{O}_6 \rangle}{m_c^3} + \ldots + 16\pi^2 \left[\tilde{\Gamma}_3 \frac{\langle \tilde{\mathcal{O}}_6 \rangle}{m_c^3} + \tilde{\Gamma}_4 \frac{\langle \tilde{\mathcal{O}}_7 \rangle}{m_c^4} + \ldots \right]$$

- Dimension 7 is large and positive

$$\tilde{\Gamma}_4^{LO}(D^+) \quad = \quad 0.777^{+0.631}_{-0.417}(scale)^{+0.229}_{-0.252}(m_c)$$

- Overal results still suffers from huge uncertainties, but central values look promising! NNLO QCD for leading term and PI!!!

$$\Gamma(D^+) = (2.72 - 0.21 + 0.76 - 3.543 + 0.78)\text{ps}^{-1} = +0.507\text{ps}^{-1} \Rightarrow \tau(D^+) = 1.97\text{ ps vs.} 1.04\text{ ps}$$

$$\Gamma(D^0) = (2.72 - 0.21 + 0.76 + 0.433)\text{ps}^{-1} = +3.703\text{ps}^{-1} \Rightarrow \tau(D^0) = 0.27\text{ ps vs.} 0.41\text{ ps}$$

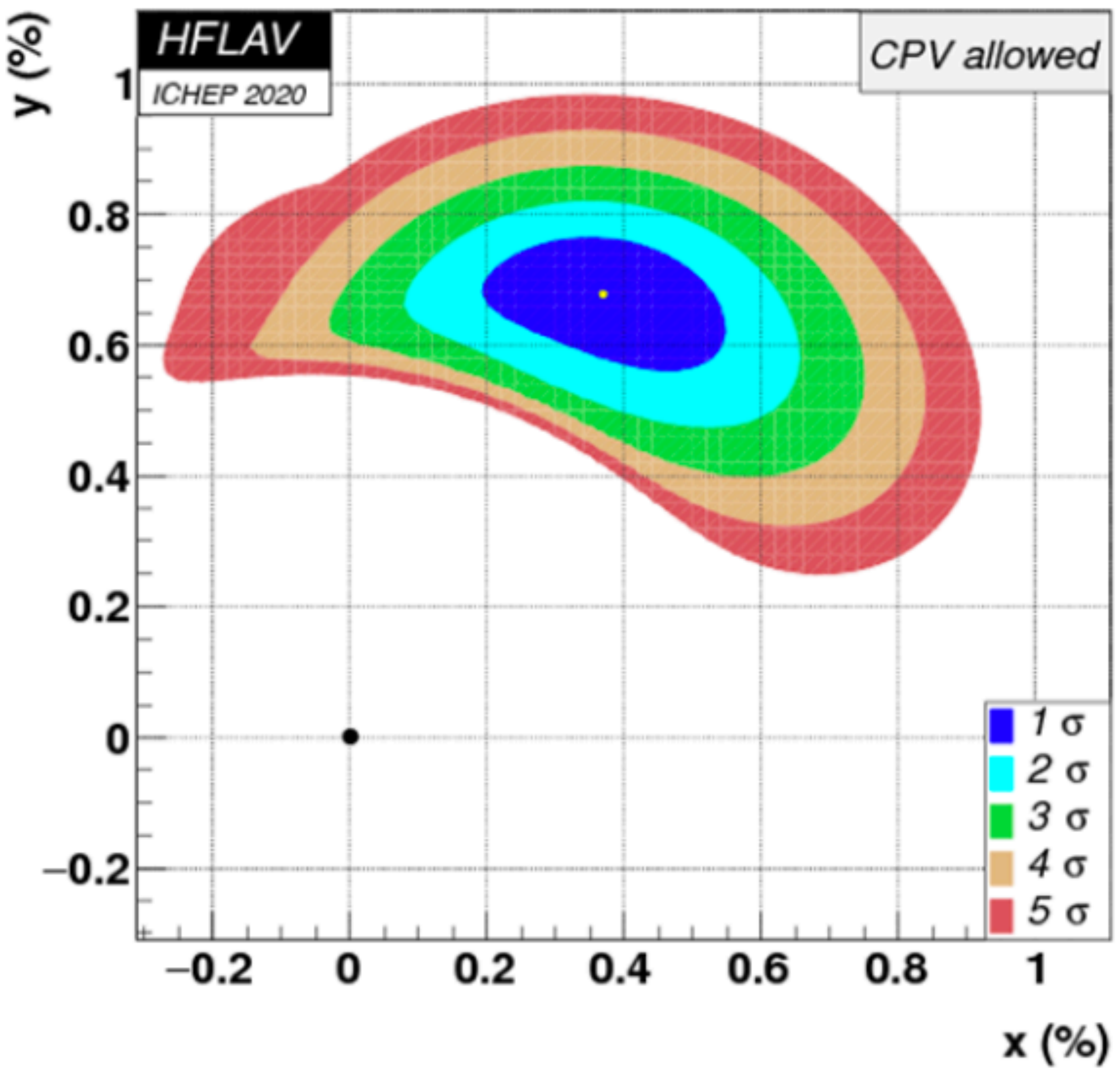
Disclaimer: Work in progress

See also talk by Daniel Moreno at annual SFB meeting in October in Siegen

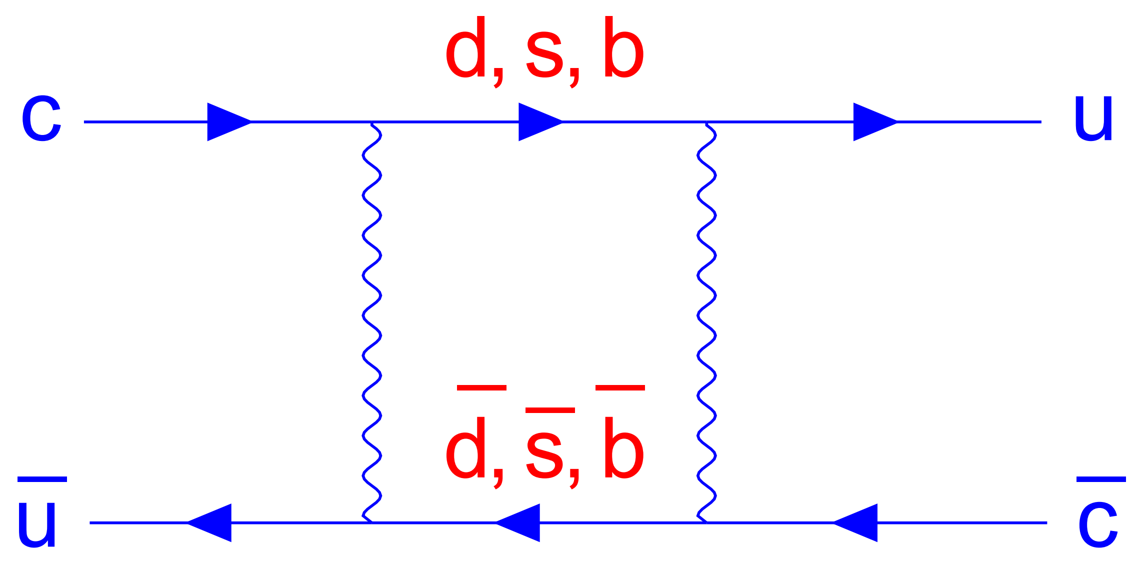
Charm Mixing

HFLAV 2020

$$x := \frac{\Delta M_D}{\Gamma_D} = (0.37 \pm 0.12)\%\,, \quad y := \frac{\Delta \Gamma_D}{2\Gamma_D} = 0.68^{+0.06}_{-0.07}\%\,,$$

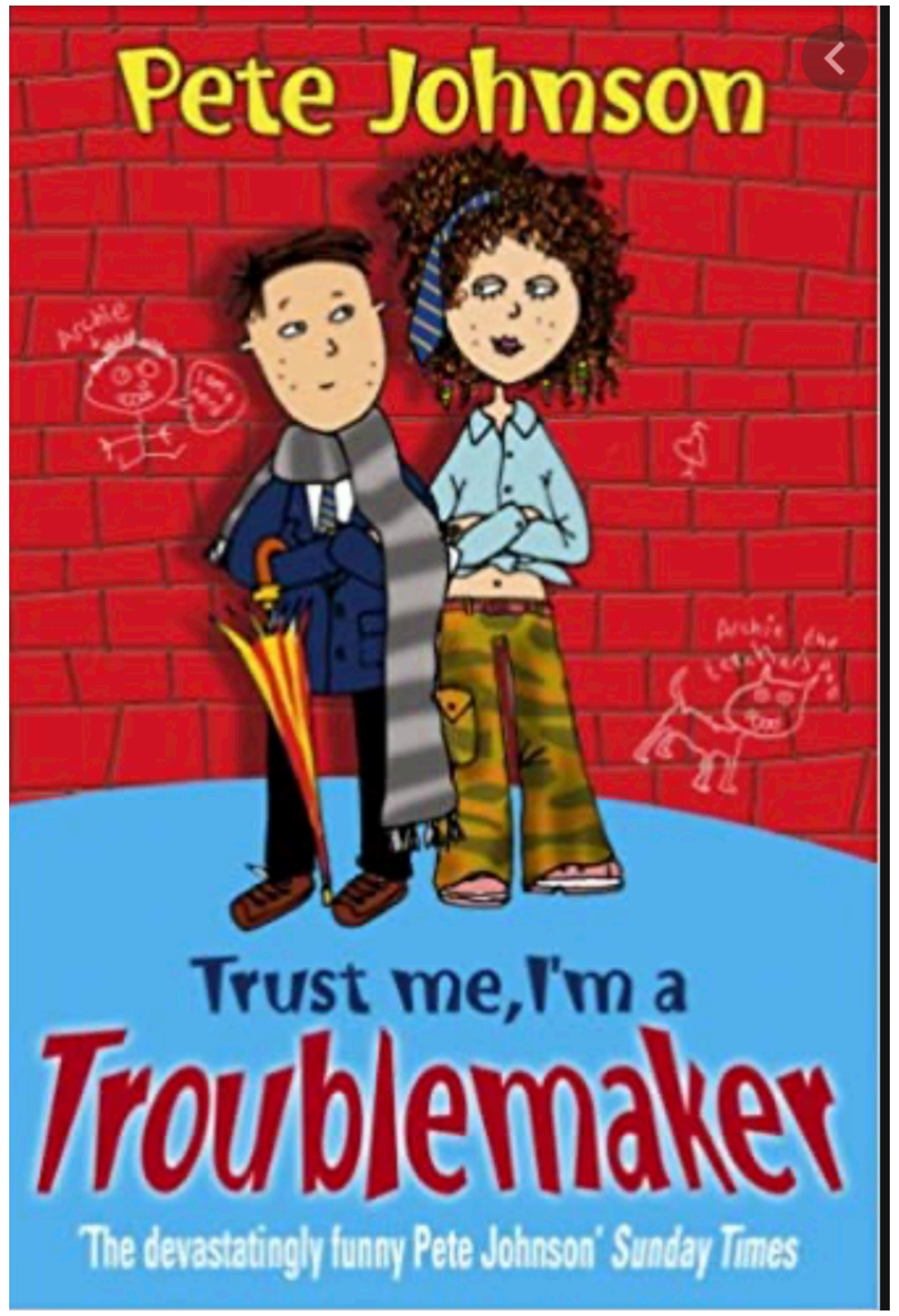


Charm Mixing



Γ_{12}^D On-shell part of box diagram

M_{12}^D Off-shell part of box diagram



Diagonalisation of the mixing matrix $\phi_{12}^D = \arg(-M_{12}^D/\Gamma_{12}^D)$

$$\Delta M_D^2 - \frac{\Delta\Gamma_D^2}{4} = 4\left|M_{12}^D\right|^2 - \left|\Gamma_{12}^D\right|^2 =: a\,, \quad \Delta M_D \Delta\Gamma_D = 4\left|M_{12}^D\right|\left|\Gamma_{12}^D\right|\cos(\phi_{12}^D) =: b$$

In the B-system one can expand in $\Gamma_{12}/M_{12} \approx 5 \cdot 10^{-3}$, to get simple formulae; in the D-system we have $\Gamma_{12}/M_{12} \approx 4$

$$\Delta\Gamma_D = \sqrt{2\left(\sqrt{a^2+b^2}-a\right)}\,, \qquad \Delta M_D = \sqrt{\frac{\sqrt{a^2+b^2}+a}{2}}\,.$$

Expansion in small phase yields

$$\Delta\Gamma_D = 2|\Gamma_{12}^D|\left[1 - \frac{4}{4+r}\frac{(\phi_{12}^D)^2}{2} + \mathcal{O}(\phi_{12}^D)^4\right],$$

$$\Delta M_D = 2|M_{12}^D|\left[1 - \frac{r}{4+r}\frac{(\phi_{12}^D)^2}{2} + \mathcal{O}(\phi_{12}^D)^4\right]$$

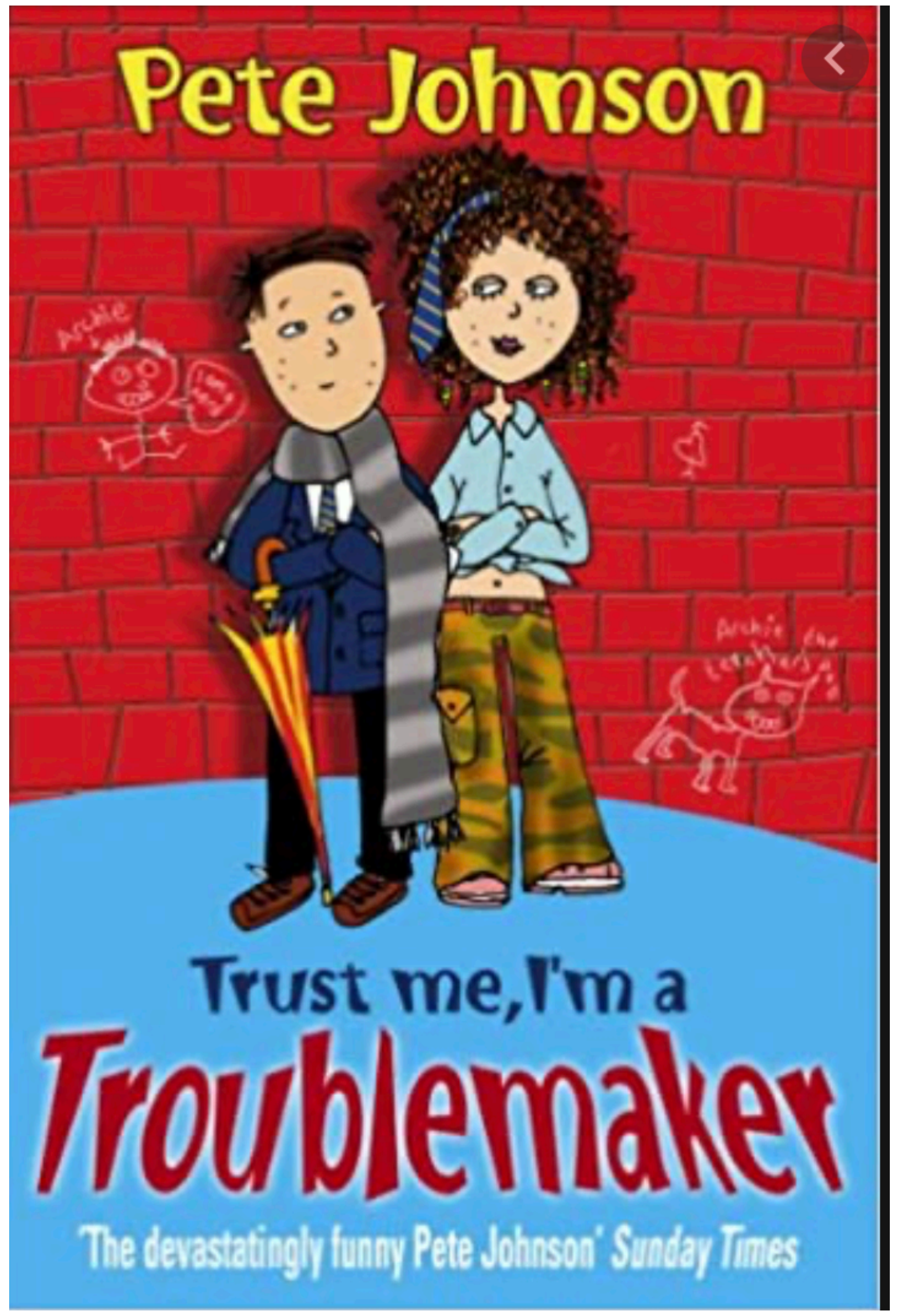
$$r = |\Gamma_{12}^D|^2/|M_{12}^D|^2$$

Charm Mixing

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

Taking only one diagram one gets: $-\lambda_s\Gamma_{ss}^{D} \approx 5\Gamma_{12}^{D,\mathrm{Exp.}}$

Taking all three diagram one gets: $-\lambda_s\left(\Gamma_{ss}^{D} - 2\Gamma_{sd}^{D} + \Gamma_{dd}^{D}\right) \approx 10^{-5}\Gamma_{12}^{D,\mathrm{Exp.}}$



Crazy GIM cancellations at work

Charm mixing

What could have gone wrong in D-mixing?

1. Duality violations - break down of HQE

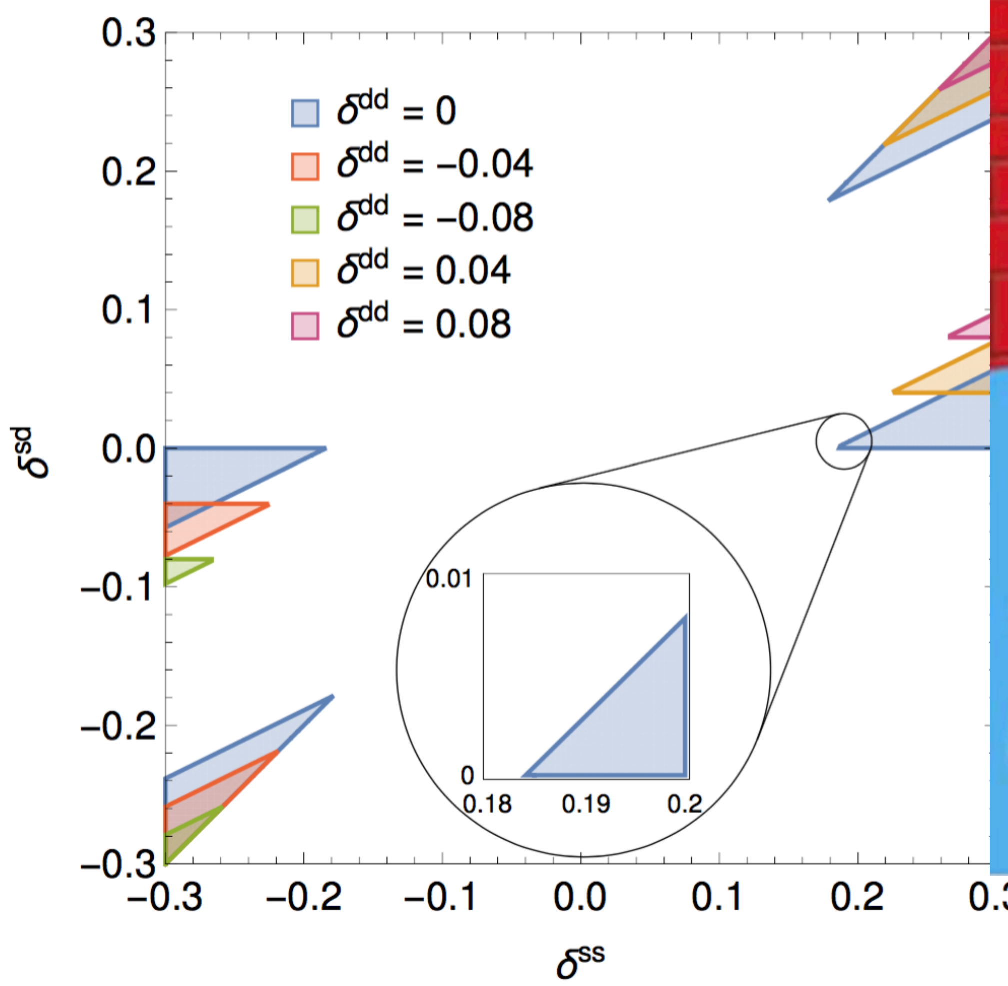
$$\Gamma_{12}^{ss} \to \Gamma_{12}^{ss}(1+\delta^{ss}) \; ,$$

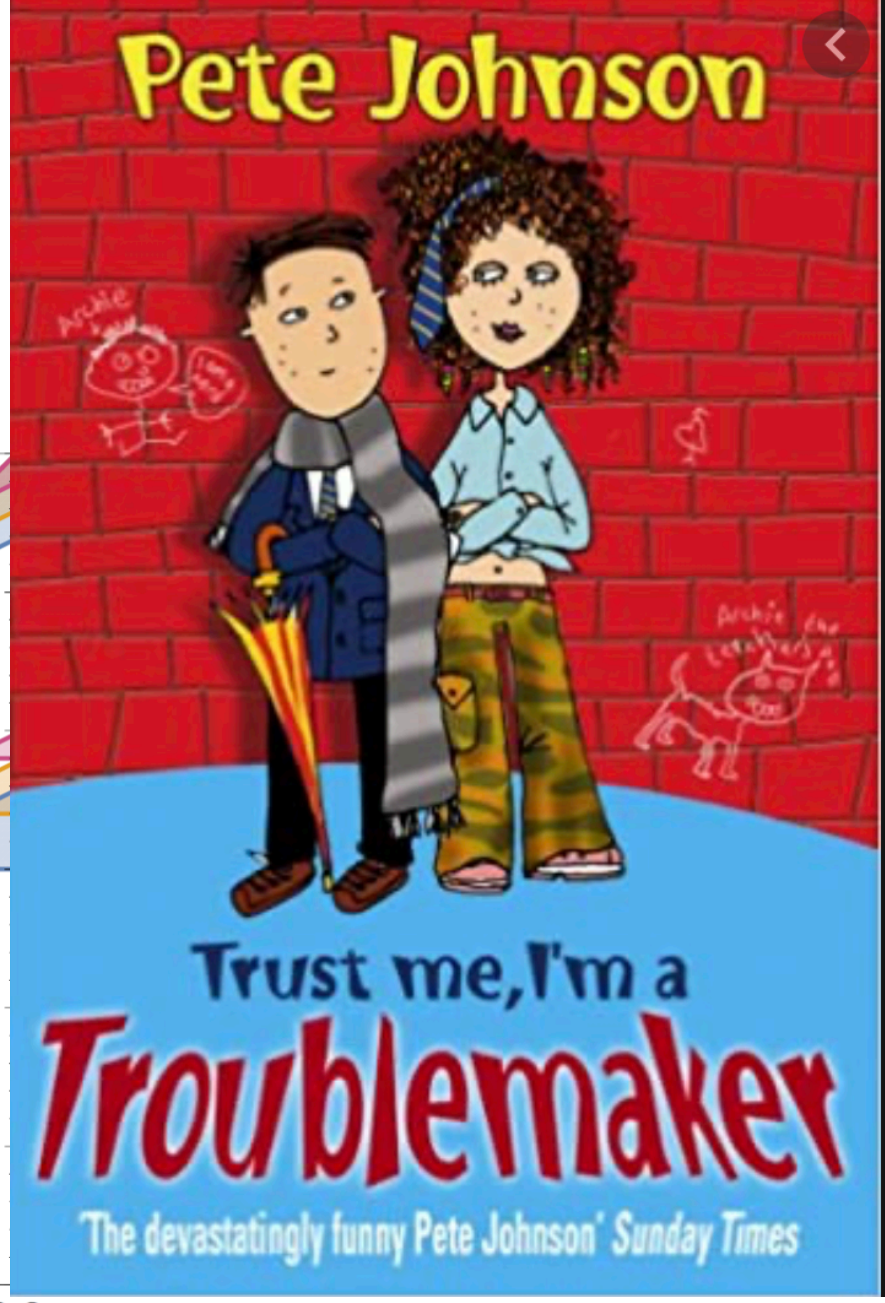
$$\Gamma_{12}^{sd} \to \Gamma_{12}^{sd}(1+\delta^{sd}) \; ,$$

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

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. Renormalisation scale setting:

AL, Piscopo, Vlahos 2020

$$\mu_x^{ss} = \mu_x^{sd} = \mu_x^{dd}$$

Implicitly assumes a precision of 10^-5!

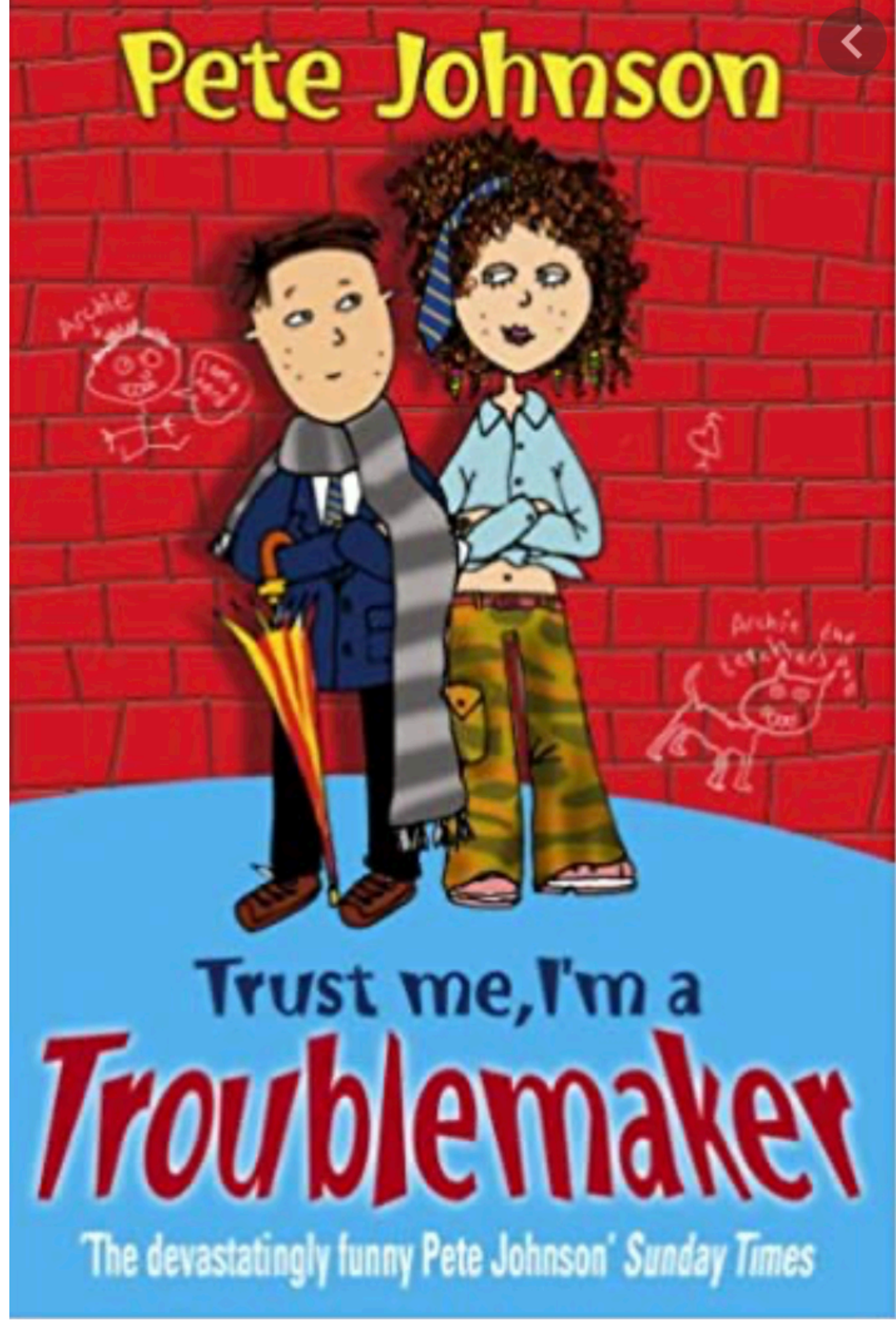
4. New Physics is present and we cannot prove it yet:-)

Exclusive approach

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

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

Cannot be calculated yet



Estimate phase space effects for y: Falk et al 0110317

- assume pert. SU(3)F breaking
- neglect 3rd family
- neglect SU(3)F breaking in matrix elements - no QCD calculation

$$y \approx 1\%$$

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

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

U-Spin sum rule Gronau, Rosner 2012

Factorisation-assisted topological amplitude approach
Jiang et al1705.07335 $\quad y \approx 0.2\%$

Direct lattice determination

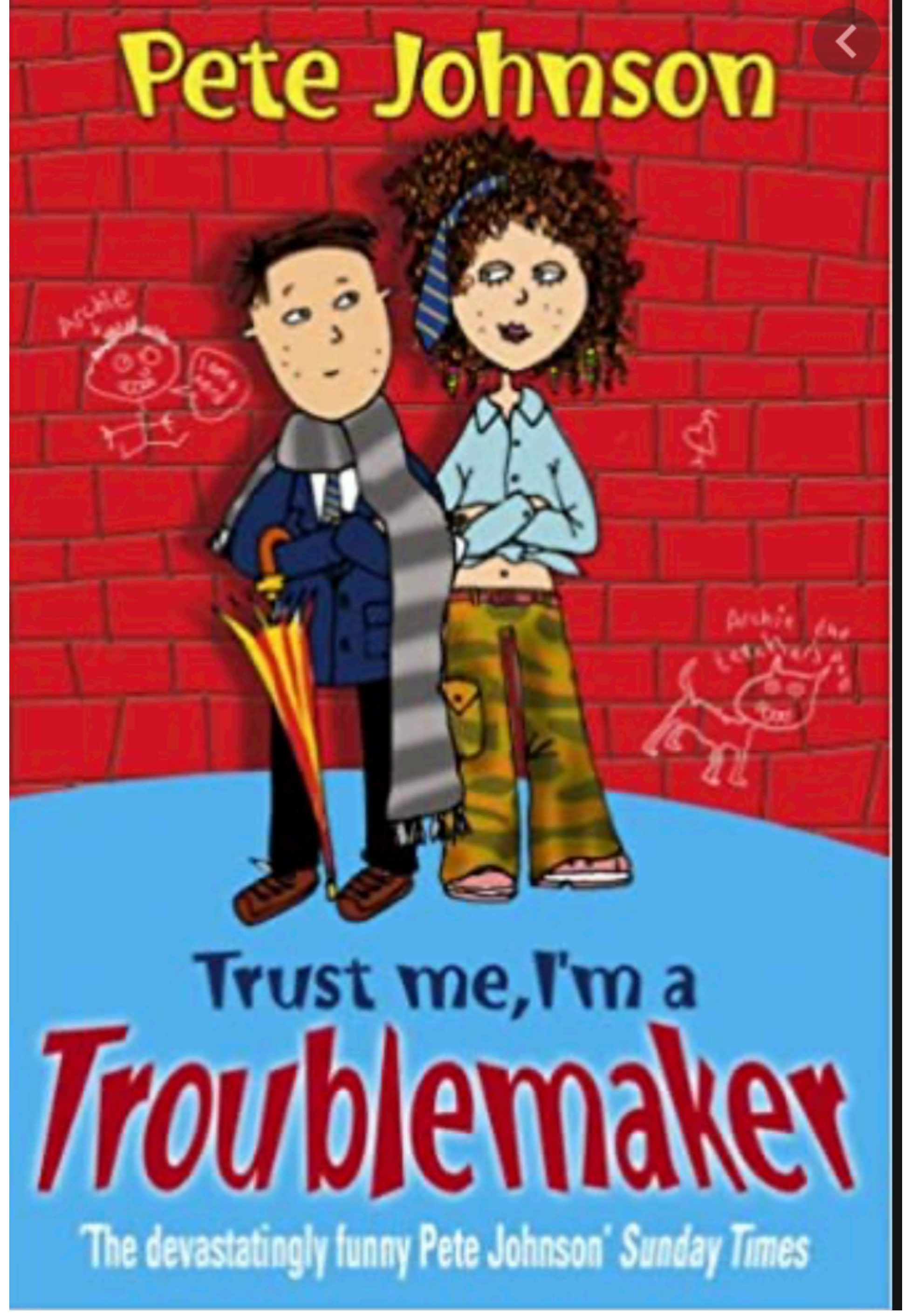
Still a very long way!
But not completely crazy anymore!

Multiple-channel generalization of Lellouch-Luscher formula #1

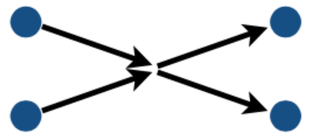
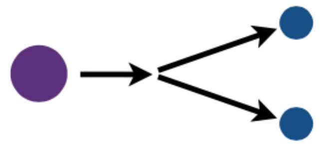
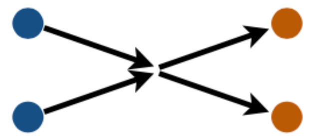
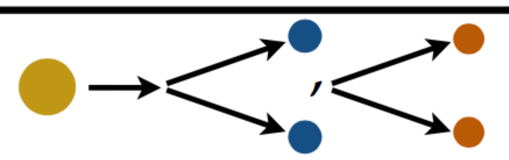
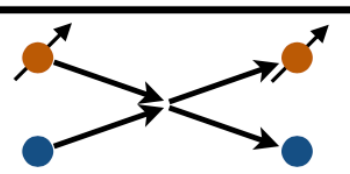
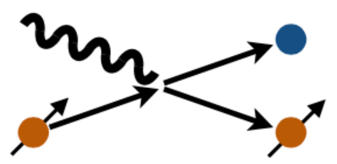
Maxwell T. Hansen (Washington U., Seattle), Stephen R. Sharpe (Washington U., Seattle) (Apr 4, 2012)

Published in: *Phys.Rev.D* 86 (2012) 016007 • e-Print: 1204.0826 [hep-lat]

pdf DOI cite 228 citations



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

Outlook

Lifetimes

Determine lifetime ratio D_s^+/D0

- ms corrections to Bag parameter
- Matrix elements of Darwin operator
- First lattice determinations

Determine lifetime ratio of charmed baryons

- Determine baryon matrix elements

Total decay rate

- NNLO QCD corrections to charm quark decay
- NNLO QCD corrections to Pauli interference
- Study different quark mass definitions

Mixing

Determine higher dimension contributions to Gamma_12

- D=9
- D=12

Determine NNLO-QCD to D=6

Determine M_12 in NNLO-QCD

Have a good idea for a model of duality violation

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$\Gamma_0^{(2)}$ Done by Kiril and friends for the semi leptonic case

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C1b: $B-\overline{B}$ mixing, CP violation, and Lifetimes

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