The 10th Annual
Large Hadron Collider Physics Conference
May 16-21, 2022

LHCP TAIPEI ONLINE

0th Edition of the Large Hadron Collider Physics Conference

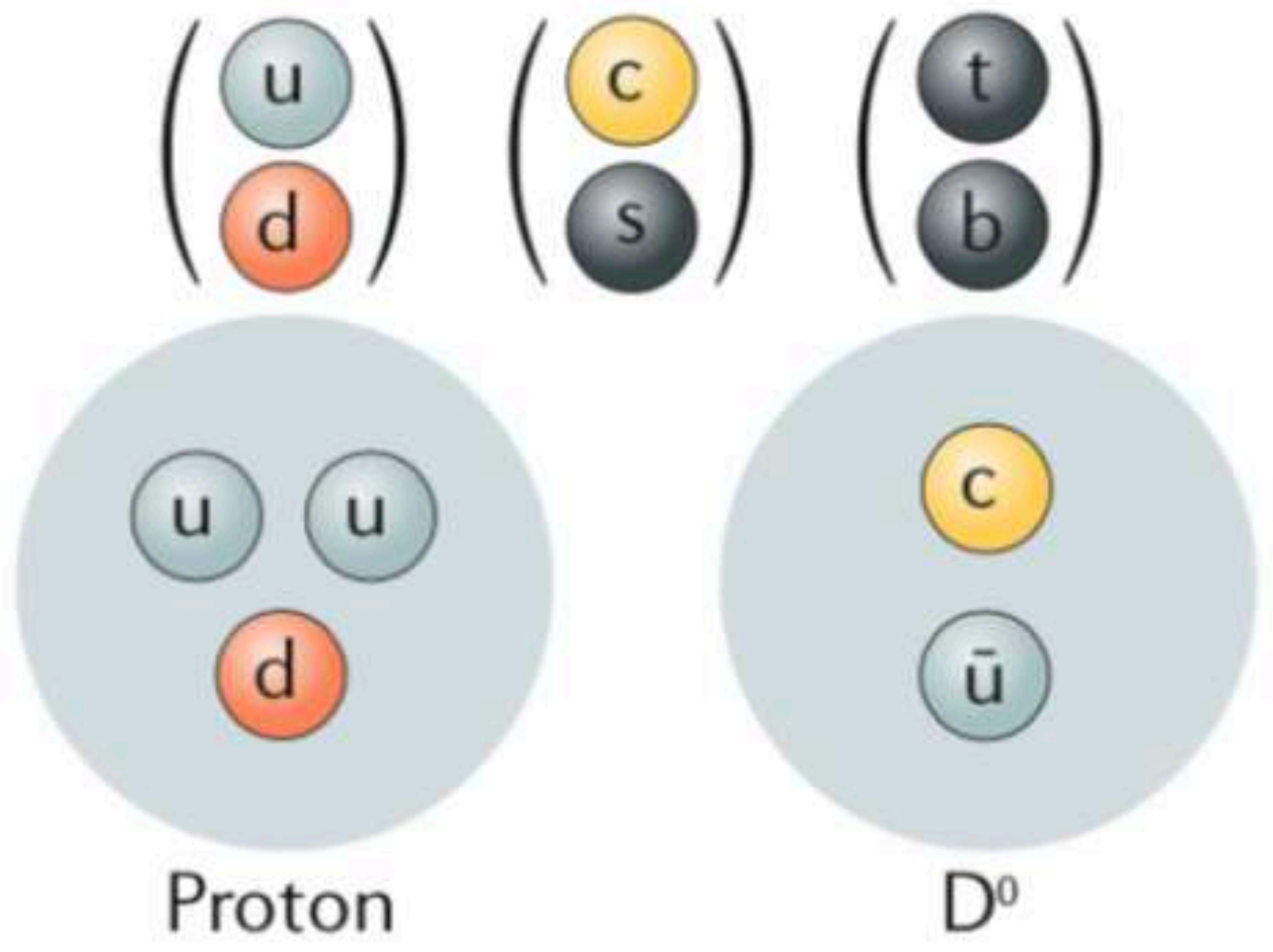
CPV and Mixing in the Charm Sector: Theory Overview

2022 LHCP TAIPEI

16.5.2022

Alexander Lenz

Charm Physics



	$D^0 = (\bar{u}c)$	$D^+ = (\bar{d}c)$	$D_s^+ = (\bar{s}c)$	$\Lambda_c = (udc)$
Mass (GeV)	1.86486	1.86962	1.96850	2.28646
Lifetime (ps)	0.4101	1.040	0.500	0.200

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Charm Physics

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Theoretical Peculiarities of Charm:

Thanks Tommaso and Patricia!

1. The strong coupling is strong

$$\alpha_s(m_c) = 0.33 \pm 0.01$$

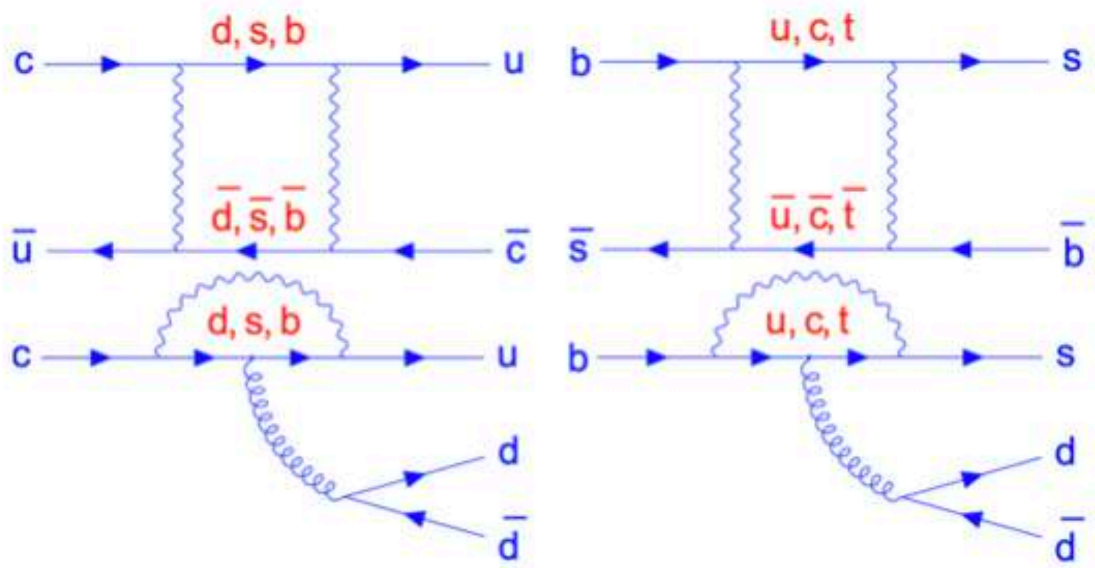
2. The charm quark is not really heavy

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

3. There is almost no CPV in charm

$$V_{cd} = -0.2247 - 1.4 \cdot 10^{-4} I\,,\ V_{cs} = 0.97354 - 3.1 \cdot 10^{-5} I\,,\ V_{cb} = 0.0416$$

4. There are extremely pronounced GIM cancellations in the charm sector



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

See e.g.
AL, G. Wilkinson
2011.04443

Cancellations

The charm system is theoretically more difficult than the b system since

$$\alpha_s(m_c) \approx 0.33 \quad \text{and} \quad \frac{\Lambda_{QCD}}{m_c} \approx 3\frac{\Lambda_{QCD}}{m_b}$$

Nevertheless the **Heavy Quark Expansion** might still converge

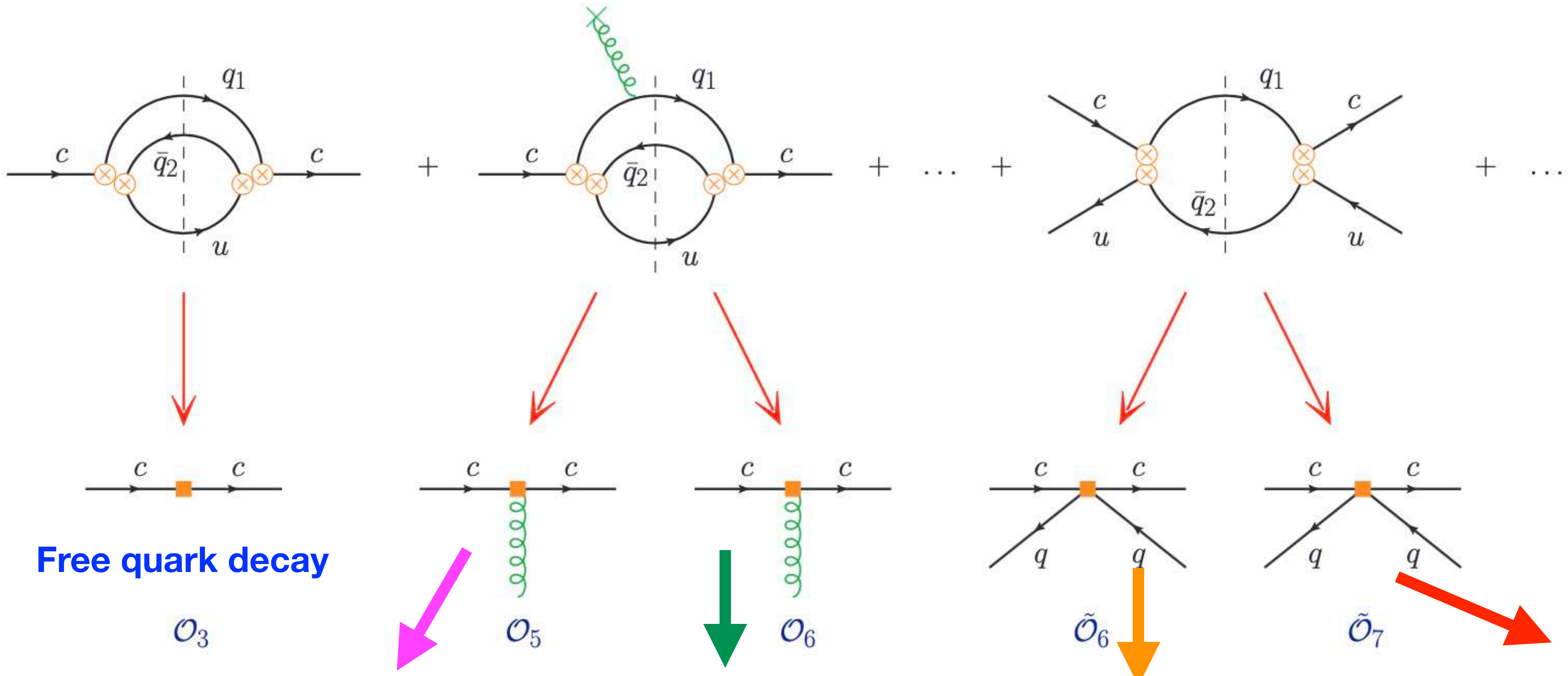
But things will become very ugly, if in addition cancellations arising

A. No cancellations, e.g. $\Gamma(D^0)$
B. Strong cancellations, e.g. $\Gamma(D^+)$
C. Crazy cancellations, e.g. D-mixing

A. No Cancellations

$$\Gamma(D) = \Gamma_3 + \Gamma_5 \frac{\langle \mathcal{O}_5 \rangle}{m_c^2} + \Gamma_6 \frac{\langle \mathcal{O}_6 \rangle}{m_c^3} + ... + 16\pi^2 \left(\tilde{\Gamma}_6 \frac{\langle \tilde{\mathcal{O}}_6 \rangle}{m_c^3} + \tilde{\Gamma}_7 \frac{\langle \tilde{\mathcal{O}}_7 \rangle}{m_c^4} + ... \right),$$

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



Kinetic operator μ_π^2

Chromomagnetic operator μ_G^2

Darwin operator μ_π^2

4-quark operator B_i, ϵ_i

Eye contractions r

Dimension 7 operators

Vacuum insertion approximation

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A. No Cancellations

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$$\Gamma(D^0) = 6.15\,\Gamma_0\Big[1 + 0.48 - 0.13\,\frac{\mu_\pi^2(D)}{0.48\,\mathrm{GeV}^2} + 0.01\,\frac{\mu_G^2(D)}{0.34\,\mathrm{GeV}^2} + 0.31\,\frac{\rho_D^3(D)}{0.082\,\mathrm{GeV}^3}$$

$$- \underbrace{0.01}_{\mathrm{dim-6,VIA}} - 0.005\,\frac{\delta\tilde{B}_1^q}{0.02} + 0.005\,\frac{\delta\tilde{B}_2^q}{0.02} + 0.137\,\frac{\tilde{\epsilon}_1^q}{-0.04} - 0.125\,\frac{\tilde{\epsilon}_2^q}{-0.04} + \underbrace{0.00}_{\mathrm{dim-7,VIA}}$$

$$- 0.0045\,r_1^{qq} - 0.0004\,r_2^{qq} - 0.0035\,r_3^{qq} + 0.0000\,r_4^{qq}$$

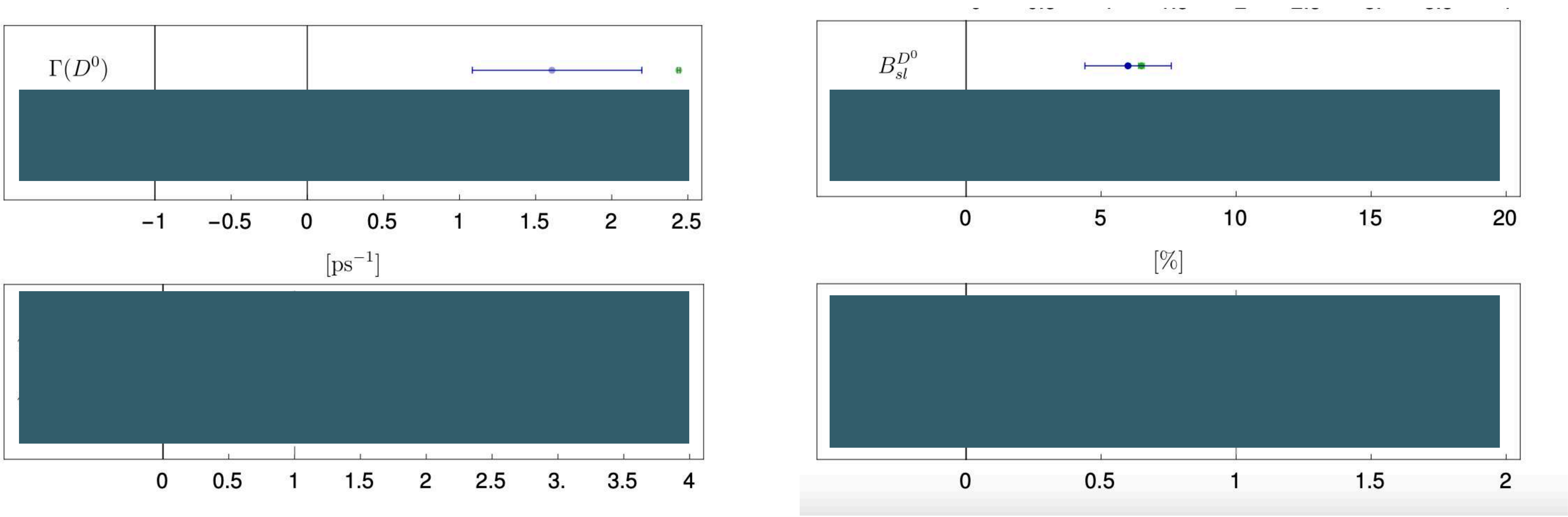
$$- 0.0109\,r_1^{sq} - 0.0079\,r_2^{sq} - 0.0000\,r_3^{sq} + 0.0001\,r_4^{sq}\Big].$$

Revisiting Inclusive Decay Widths of Charmed Mesons #5

Daniel King (Durham U., IPPP and Durham U.), Alexander Lenz (Siegen U.), Maria Laura Piscopo (Siegen U.), Thomas Rauh (U. Bern, AEC), Aleksey V. Rusov (Siegen U.) et al. (Sep 27, 2021)

e-Print: 2109.13219 [hep-ph]

A. No Cancellations



- Values of $\mu_\pi^2, \mu_G^2, \rho_D^3$ almost unknown
- NNLO-QCD corrections to free quark decay in progress

Fael, Steinhauser,...

- NNLO-QCD corrections to spectator effects in progress

Nierste, Steinhauser,...

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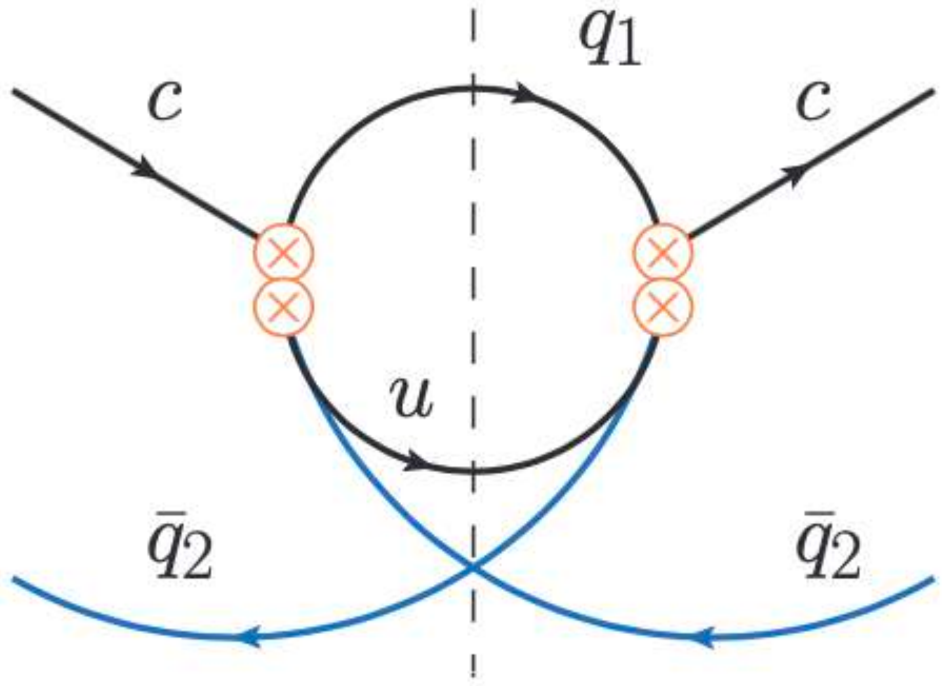
B. Strong Cancellations

$$\Gamma(D^+) = 6.15\,\Gamma_0 \Big[1 + 0.48 - 0.13\,\frac{\mu_\pi^2(D)}{0.48\,\text{GeV}^2} + 0.01\,\frac{\mu_G^2(D)}{0.34\,\text{GeV}^2} + 0.31\,\frac{\rho_D^3(D)}{0.082\,\text{GeV}^3}$$

$$- \underbrace{2.66}_{\text{dim}-6,\text{VIA}} - 0.055\,\frac{\delta\tilde{B}_1^q}{0.02} + 0.002\,\frac{\delta\tilde{B}_2^q}{0.02} - 0.546\,\frac{\tilde{\epsilon}_1^q}{-0.04} + 0.009\,\frac{\tilde{\epsilon}_2^q}{-0.04} + \underbrace{1.10}_{\text{dim}-7,\text{VIA}}$$

$$- 0.0000\, r_1^{qq} - 0.0000\, r_2^{qq} + 0.0011\, r_3^{qq} + 0.0008\, r_4^{qq}$$

$$- 0.0109\, r_1^{sq} - 0.0080\, r_2^{sq} - 0.0000\, r_3^{sq} + 0.0001\, r_4^{sq} \Big],$$



Huge effects due to Pauli interference

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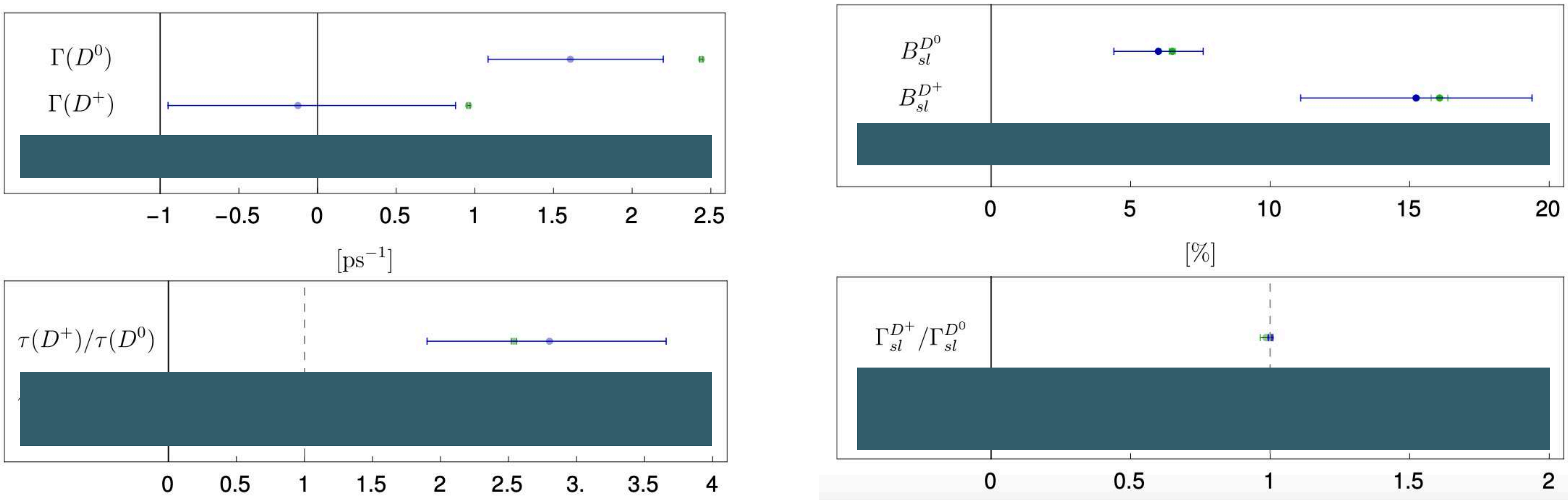

- Values of $\mu_\pi^2, \mu_G^2, \rho_D^3$ almost unknown
- NNLO-QCD corrections to free quark decay in progress

Fael, Steinhauser,…

- NNLO-QCD corrections to spectator effects in progress

Nierste, Steinhauser,…

- Check of HQET sum rule results with lattice

Black, Witzel,…RBC-UK

- First non-perturbative determination of dimension 7

Revisiting Inclusive Decay Widths of Charmed Mesons #5

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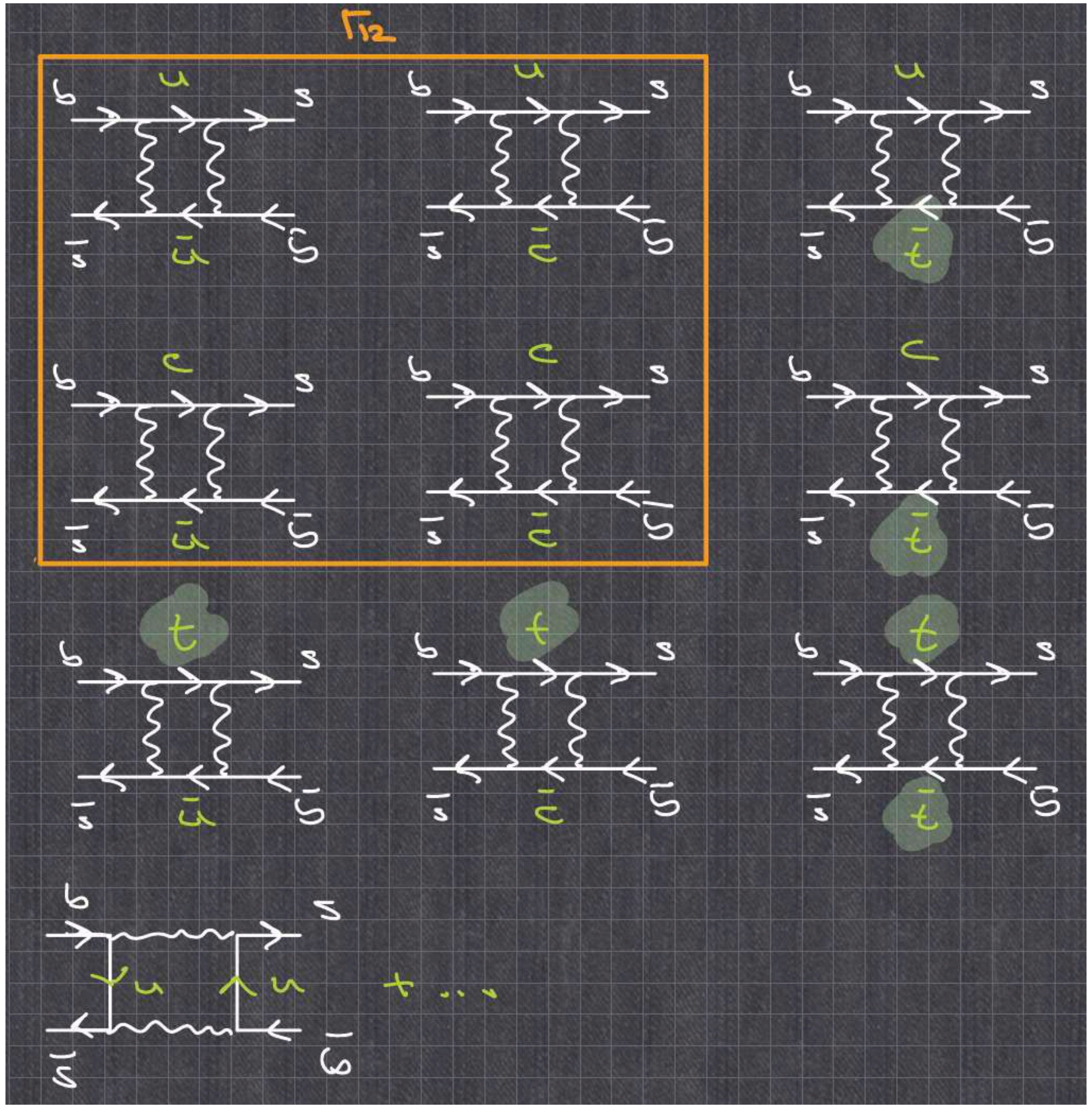
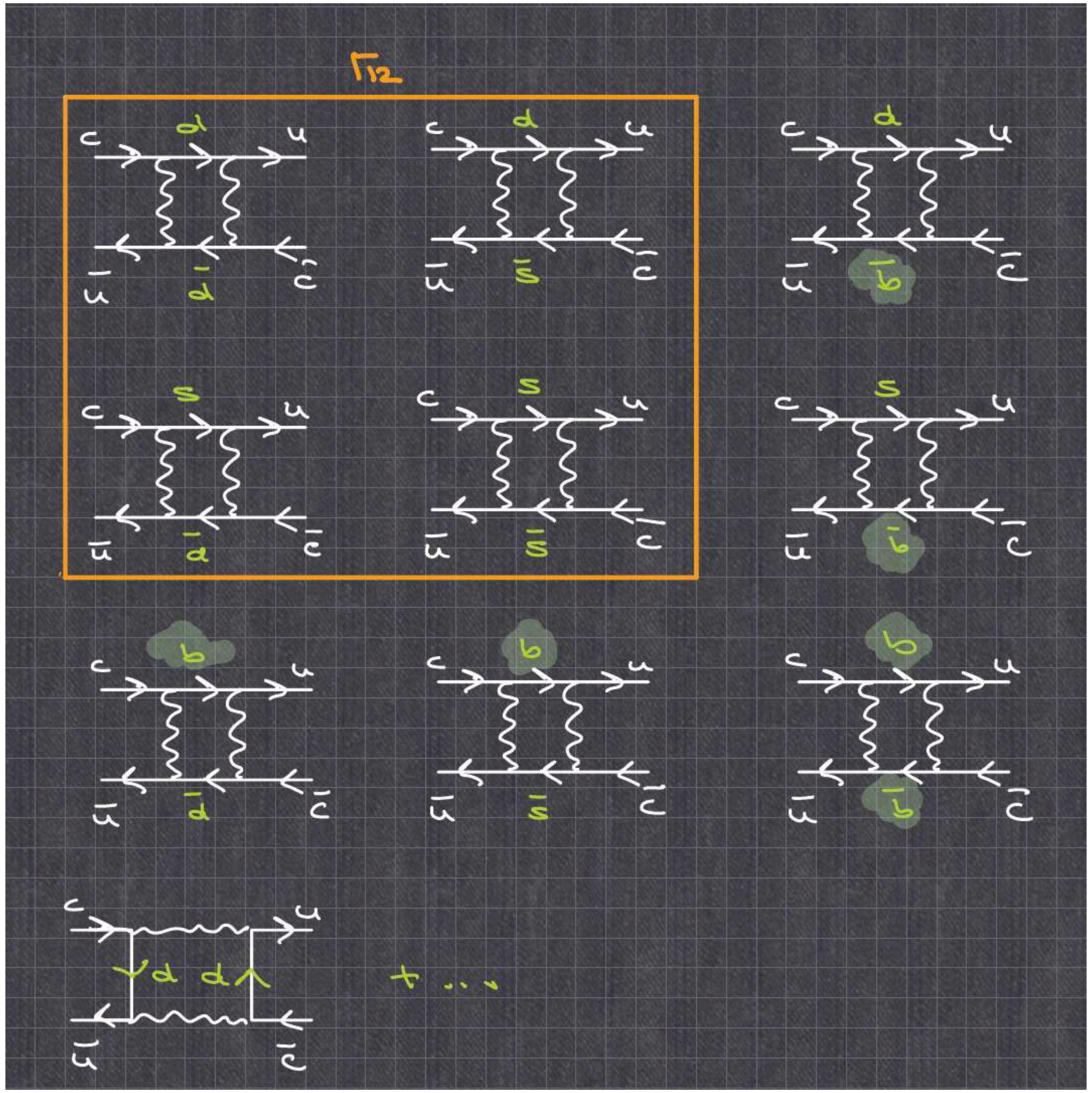
C: Crazy Cancellations

B-mixing



D-mixing



C: Crazy Cancellations

B-mixing

$$M_{12} = \lambda_u^2 F(u,u) + \lambda_u\lambda_c F(u,c) + \lambda_u\lambda_t F(u,t) + \lambda_c\lambda_u F(c,u) + \lambda_c^2 F(c,c) + \lambda_c\lambda_t F(c,t) + \lambda_t\lambda_u F(t,u) + \lambda_t\lambda_c F(t,c) + \lambda_t^2 F(t,t)$$

$\lambda_u + \lambda_c + \lambda_t = 0$

$$= \lambda_u^2 \left[F(c,c) - 2F(u,c) + F(u,u)\right] + 2\lambda_u\lambda_t\left[F(c,c) - F(u,c) + F(u,t) - F(c,t)\right] + \lambda_t^2\left[F(c,c) - 2F(c,t) + F(t,t)\right]$$

	B_d	B_s
λ_u	$\lambda^{3.8}$	$\lambda^{4.8}$
λ_c	λ^3	λ^2
λ_t	λ^3	λ^2

$m_u^2/M_W^2 \simeq 0$

$m_c^2/M_W^2 \simeq 2.5\cdot 10^{-4}$

$m_t^2/M_W^2 \simeq 4.5$

CKM dominant ≡ GIM dominant

CKM suppressed ≡ GIM suppressed

D-mixing

$$M_{12} = \lambda_d^2 F(d,d) + \lambda_d\lambda_s F(d,s) + \lambda_d\lambda_b F(d,b) + \lambda_s\lambda_d F(s,d) + \lambda_s^2 F(s,s) + \lambda_s\lambda_b F(s,b) + \lambda_b\lambda_d F(b,d) + \lambda_b\lambda_s F(b,s) + \lambda_b^2 F(b,b)$$

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

$$= \lambda_d^2 \left[F(d,d) - 2F(d,s) + F(s,s)\right] + 2\lambda_s\lambda_b\left[F(s,s) - F(d,s) + F(d,b) - F(s,b)\right] + \lambda_b^2\left[F(s,s) - 2F(s,b) + F(b,b)\right]$$

	D
λ_d	λ^1
λ_s	λ^1
λ_b	$\lambda^{5.8}$

$m_d^2/M_W^2 \simeq 0$

$m_s^2/M_W^2 \simeq 1.3\cdot 10^{-6}$

$m_b^2/M_W^2 \simeq 2.8\cdot 10^{-3}$

CKM suppressed ≡ GIM dominant

CKM dominant ≡ GIM suppressed

C: Crazy Cancellations

$$x \equiv \frac{\Delta M_D}{\Gamma_D} = 4.09^{+0.48}_{-0.49} \cdot 10^{-3}$$

HFLAV

$$\frac{\Delta \Gamma_D}{2\Gamma_D} = 6.15^{+0.56}_{-0.55} \cdot 10^{-3} \qquad \frac{\Delta \Gamma_D^{\text{naive HQE}}}{\Delta \Gamma_D^{\text{EXp.}}} \approx 10^{-5} \ldots 10^{-4}$$

AL, Piscopo, Vlahos
2007.03022

B^0: ARGUS
Observation of B^0 oscillations
Phys.Lett.B 192 (1987) 245

D^0: Belle & BaBar
Evidence of D^0 oscillations
Phys.Rev.Lett. 98 (2007) 211802
Phys.Rev.Lett. 98 (2007) 211803

D^0: LHCb
Observation of D^0 mass difference
LHCb-PAPER-2021-009

1955 — 1987 — 2006 2007 — 2013 — 2021

K^0
Behavior of neutral particles
e.g. Phys.Rev. 97 (1955) 1387

B^0_s: CDF
Observation of B_s^0 oscillations
Phys.Rev.Lett. 97 (2006) 242003

D^0: LHCb
Observation of D^0 oscillations
Phys.Rev.Lett. 110 (2013) 101802

2012: $\Delta\Gamma_s$ by LHCb

8 June 2021: First observation of the mass difference between neutral charm mesons.

$x = (3.98^{+0.56}_{-0.54}) \times 10^{-3}$

$m_1 - m_2 = 6.4 \times 10^{-6}$ eV = 0.00000000000000000000000000000000000001 grams (1×10^{-38} g)

$(m_1 - m_2)/(D^0 \text{mass}) = 3 \times 10^{-15}$

Today, the LHCb Collaboration submitted a paper for publication that reports the first observation of the mass difference between neutral charm mesons (or rather their mass eigenstates for experts). The result is also presented today at the CERN seminar and was reported last week at the 10th International Workshop on CHARM Physics. This mass difference determines the

Exclusive approaches

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 $x \approx y$
Exp. data Cheng, Chiang 1005.1106 $x \propto \mathcal{O}(0.1\%)$ $y \propto \mathcal{O}(few\ 0.1\%)$
U-Spin sum rule Gronau, Rosner 2012
Factorisation-assisted topological amplitude approach
Jiang et al. 1705.07335 $y \approx 0.2\%$

C: Crazy Cancellations

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

=> apply it for D-mixing

$$y_D^{\rm HQE} \approx \lambda_s^2 \left(\Gamma_{12}^{ss} - 2\Gamma_{12}^{sd} + \Gamma_{12}^{dd}\right) \approx 10^{-5} y_D^{\rm Exp.}$$

How can this be?

Look only at a single diagram:

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

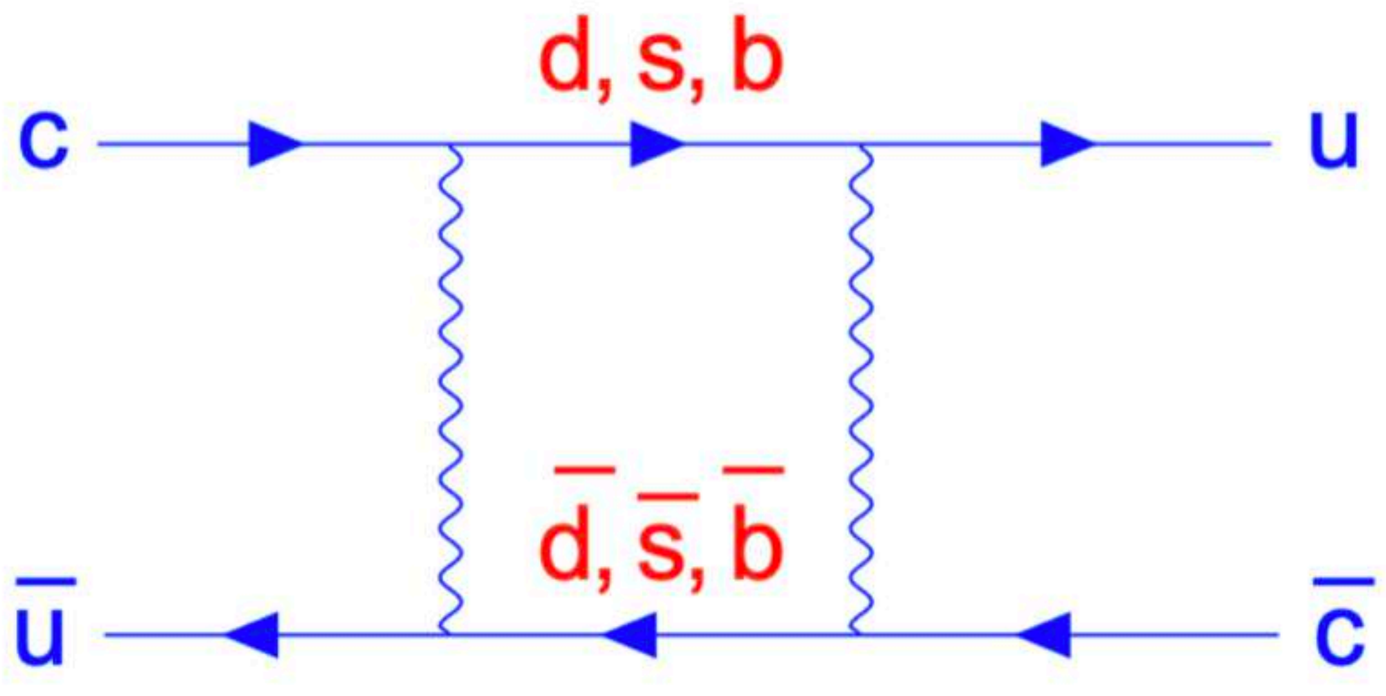
pert. calculation: Bobrowski et al 1002.4794
lattice input: ETM 1403.7302; 1505.06639; FNAL/MILC 1706.04622
HQET sum rules: Kirk, AL, Rauh 1711.02100

The problem seems to originate in the extreme GIM cancellations

C: Crazy Cancellations

CPV

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



survives in SU(3)F limit!

dominant for B mixing

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

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

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C: Crazy Cancellations

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1. Duality violations - break down of HQE

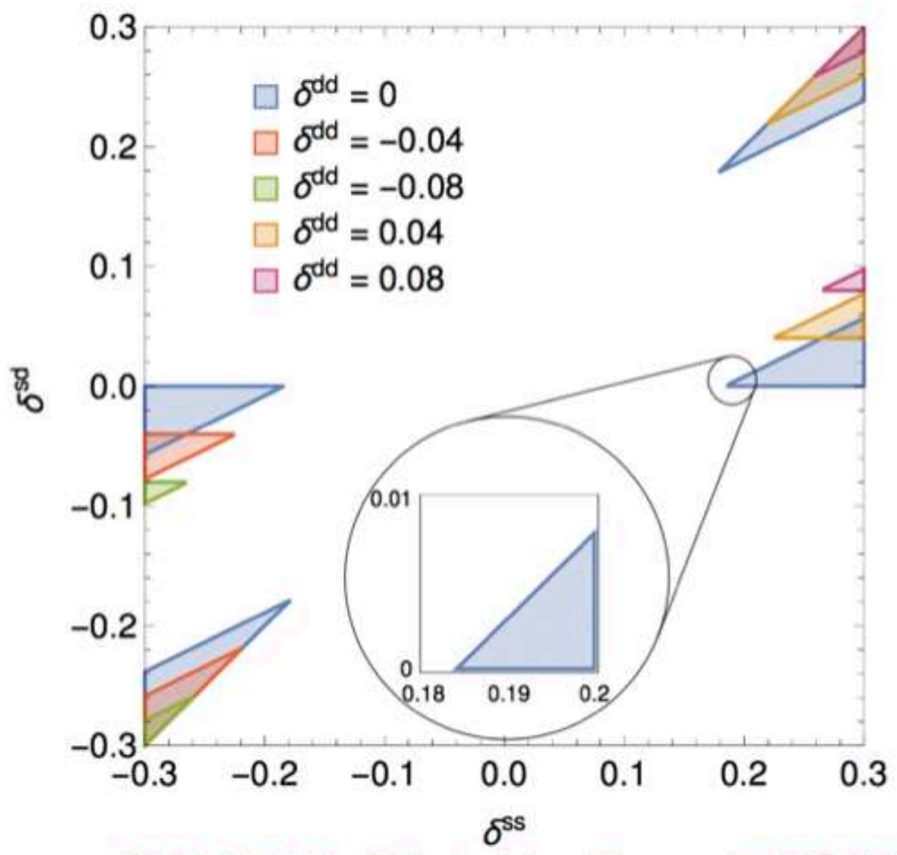
$$\Gamma_{12}^{ss} \to \Gamma_{12}^{ss}(1+\delta^{ss}) \,,$$

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

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

20% of duality violation is sufficient to explain experiment

Jubb, Kirk, AL, Tetlalmatzi-Xolocotzi 2016

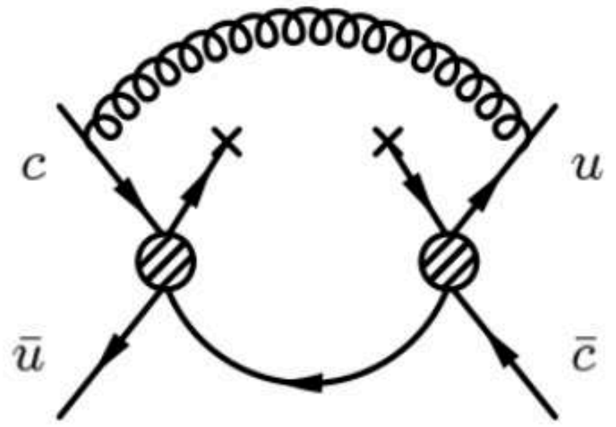


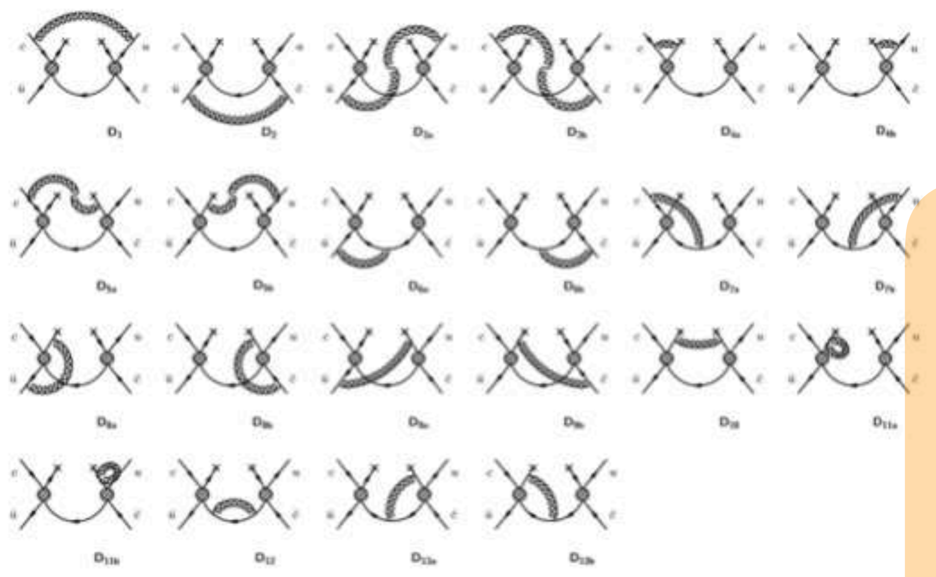
2. Higher dimensions

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:-)

1) Vary $\mu^{ss,dd}$ and μ^{ds} independently between 1 GeV and 2 m_c
   $\Rightarrow$ uncertainty increases and exp. value is covered

2) Choose scales somehow phase space inspired as

$$\mu^{ss} = m_c - 2\epsilon$$
$$\mu^{sd} = m_c - \epsilon$$
$$\mu^{dd} = m_c$$

$\Rightarrow$ exp. value is covered

Exclusive and inclusive approaches can over the experimental regions

No precision determination possible

C: Crazy Cancellations

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

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C: Crazy Cancellations

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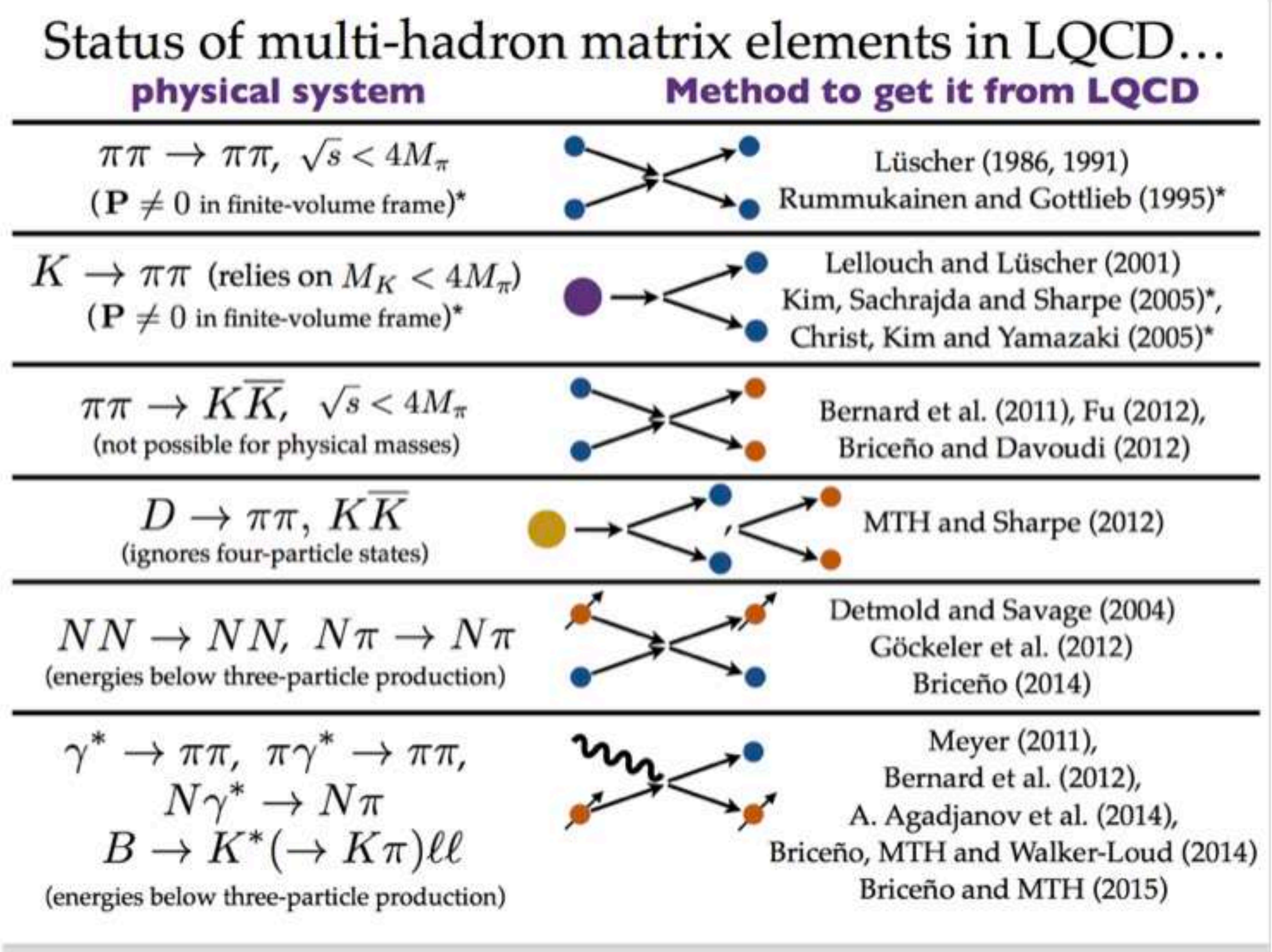
Direct lattice determination

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

Multiple-channel generalization of Lellouch-Luscher formula
Maxwell T. Hansen (Washington U., Seattle), Stephen R. Sharpe (Washington U., Seattle) (Apr, 2012)
Published in: *Phys.Rev.D* 86 (2012) 016007 • e-Print: 1204.0826 [hep-lat]
pdf DOI cite



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

CP Violation

1. **CP violation in Mixing**: Consider a **flavour specific (** $\mathcal{A}_{\bar f} = 0 = \bar{\mathcal{A}}_f$**) decay** $B \to f$

$$A^q_{\rm fs} = \frac{\Gamma\left(\bar B_q(t) \to f\right) - \Gamma\left(B_q(t) \to \bar f\right)}{\Gamma\left(\bar B_q(t) \to f\right) + \Gamma\left(B_q(t) \to \bar f\right)}$$

$\boxed{\bar{\mathcal{A}}_{\bar f} = \mathcal{A}_f}$ = No direct CP violation

$$a^q_{\rm fs} \approx \frac{|\Gamma^q_{12}|}{|M^q_{12}|} \sin \phi^q_{12}$$

e.g. $B \to X l \nu$
or $\bar B_s \to D_s^+ \pi^-$
or $\bar B_d \to D^+ K^-$

2. **CP violation in interference of mixing and decay**

$$A^q_{\rm ind} = \frac{\Gamma\left(\bar B_q(t) \to f\right) - \Gamma\left(B_q(t) \to f\right)}{\Gamma\left(\bar B_q(t) \to f\right) + \Gamma\left(B_q(t) \to f\right)}$$

e.g. $B_s \to J/\Psi \phi$
or $B_d \to J/\Psi K_s$

See also 1511.09466, hep-ph/0201071

3. **CP violation in decay**

$$A^q_{\rm dir} = \frac{\Gamma\left(\bar B_q(t) \to \bar f\right) - \Gamma\left(B_q(t) \to f\right)}{\Gamma\left(\bar B_q(t) \to \bar f\right) + \Gamma\left(B_q(t) \to f\right)} = \frac{|\bar{\mathcal{A}}_{\bar f}|^2 - |\mathcal{A}_f|^2}{|\bar{\mathcal{A}}_{\bar f}|^2 + |\mathcal{A}_f|^2}$$

e.g. ΔA_{CP}
or $D^0 \to \pi^-\pi^+, K^-K^+$

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Status Quo: CPV in Interference

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$$A_{CP,f}(t) = \frac{\Gamma\left(\bar{B}_s^0(t) \to f\right) - \Gamma\left(B_s^0(t) \to f\right)}{\Gamma\left(\bar{B}_s^0(t) \to f\right) + \Gamma\left(B_s^0(t) \to f\right)} = -\frac{A_{CP}^{dir}\cos(\Delta M_s t) + A_{CP}^{mix}\sin(\Delta M_s t)}{\cosh(\frac{\Delta\Gamma_s t}{2}) + A_{\Delta\Gamma}\sinh(\frac{\Delta\Gamma_s t}{2})}$$

$$A_{CP}^{dir} = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}, \quad A_{CP}^{mix} = -\frac{2\Im(\lambda_f)}{1+|\lambda_f|^2}, \quad A_{\Delta\Gamma} = -\frac{2\Re(\lambda_f)}{1+|\lambda_f|^2}.$$

$$\lambda_f \approx -\frac{V_{ts}V_{tb}^*}{V_{ts}^*V_{tb}}\frac{\bar{A}_f}{A_f}\left[1 - \frac{a_{fs}^s}{2}\right]$$

$$A_f = \langle f|\mathcal{H}_{eff}|B_s^0\rangle$$
$$\bar{A}_f = \langle f|\mathcal{H}_{eff}|\bar{B}_s^0\rangle$$

CP violation in the B_s^0 system
Marina Artuso (Syracuse U.), Guennadi Borissov (Lancaster U.), Alexander Lenz (Durham U., IPPP) (Nov 30, 2015)
Published in: *Rev.Mod.Phys.* 88 (2016) 4, 045002, *Rev.Mod.Phys.* 91 (2019) 4, 049901 (addendum) • e-Print: 1511.09466 [hep-ph]

If there is **only one decay topology** contributing to the decay

$$A_f = |A_f^{Tree}|\, e^{i\left[\phi_{Tree}^{QCD} + \arg(\lambda_c)\right]}$$

$$\bar{A}_{\bar{f}} = |A_f^{Tree}|\, e^{i\left[\phi_{Tree}^{QCD} - \arg(\lambda_c)\right]}$$

$$\frac{\bar{A}_{f_{CP}}}{A_{f_{CP}}} = -\eta_{CP}\, e^{-2i\phi_j^{CKM}}$$

All hadronic uncertainties are cancelling exactly in the CP asymmetry!

Gold-plated modes

Status Quo: CPV in Interference

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If there are **two decay topologies** contributing to the decay

$$\mathcal{A}_f = \left|\mathcal{A}_f^{\rm Tree}\right| e^{i\left[\phi^{\rm QCD}_{\rm Tree} + \arg(\lambda_c)\right]} + \left|\mathcal{A}_f^{\rm Peng}\right| e^{i\left[\phi^{\rm QCD}_{\rm Peng} + \arg(\lambda_u)\right]}$$

$$\bar{\mathcal{A}}_{\bar f} = \left|\mathcal{A}_f^{\rm Tree}\right| e^{i\left[\phi^{\rm QCD}_{\rm Tree} - \arg(\lambda_c)\right]} + \left|\mathcal{A}_f^{\rm Peng}\right| e^{i\left[\phi^{\rm QCD}_{\rm Peng} - \arg(\lambda_u)\right]}$$

Could also be BSM if there is only one SM amplitude

Then the CP asymmetry depends on

$$\frac{\bar{\mathcal{A}}_{\bar f}}{\mathcal{A}_f} = -e^{-2i\arg(\lambda_c)}\left[\frac{1 + r e^{-i\arg\left(\frac{\lambda_u}{\lambda_c}\right)}}{1 + r e^{+i\arg\left(\frac{\lambda_u}{\lambda_c}\right)}}\right]$$

with $r = |\mathcal{A}_f^{\rm Peng}|/|\mathcal{A}_f^{\rm Tree}|$

The Golden Modes B0 ---> J/psi K(S,L) in the Era of Precision Flavour Physics #7
Sven Faller (CERN and Siegen U.), Martin Jung (Siegen U.), Robert Fleischer (CERN), Thomas Mannel (CERN and Siegen U.) (Sep, 2008)
Published in: *Phys.Rev.D* 79 (2009) 014030 • e-Print: 0809.0842 [hep-ph]
pdf DOI cite 97 citations

For a review see e.g.:

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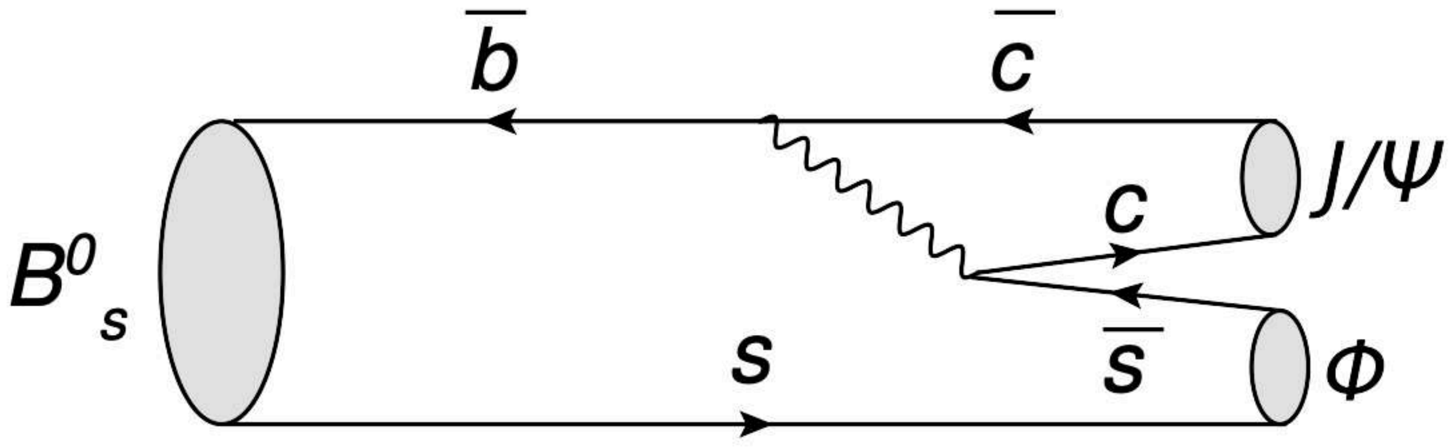
If penguins are small compared to tree-level, the hadronic corrections are cancelling to leading order and there is a correction proportional to r

Penguin pollution

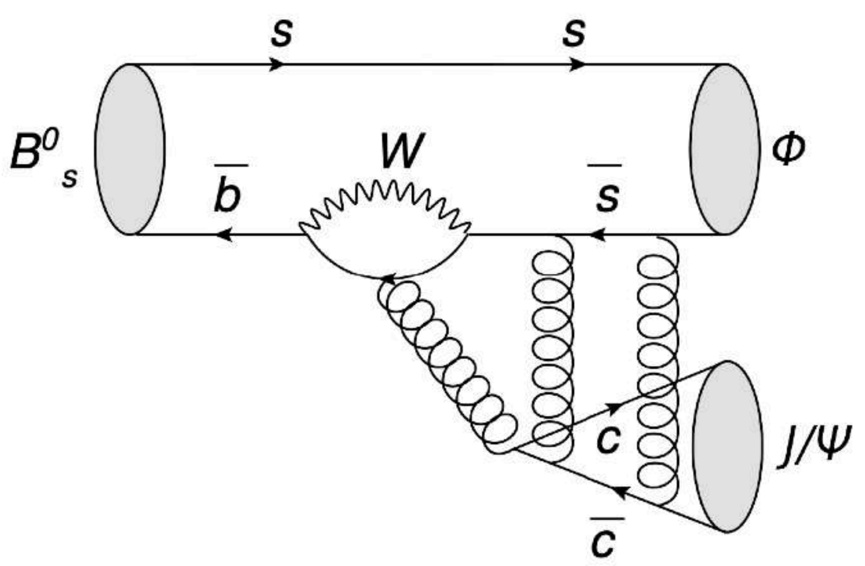
Status Quo: CPV in Interference

Golden plated modes: $B_s \to J/\Psi\phi$ and $B_d \to J/\Psi K_s$

$$\mathcal{A}_f = \sum_j \mathcal{A}_j e^{i(\phi_j^{\text{strong}} + \phi_j^{\text{CKM}})} =$$



$+$



This is not the SM prediction for ϕ_s!

Neglect penguins:

CP asymmetry in $B_s \to J/\Psi\phi$ is directly proportional to sin $(2\beta_s)$ with $\phi_s = -2\beta_s^{\text{CKMFitter}} = -0.0370^{+0.0007}_{-0.0008}$

CP asymmetry in $B_d \to J/\Psi K_s$ is directly proportional to sin (2β)

Bigi, Sanda 1981,…

Since there is only one amplitude, all hadronic effects cancel exactly!

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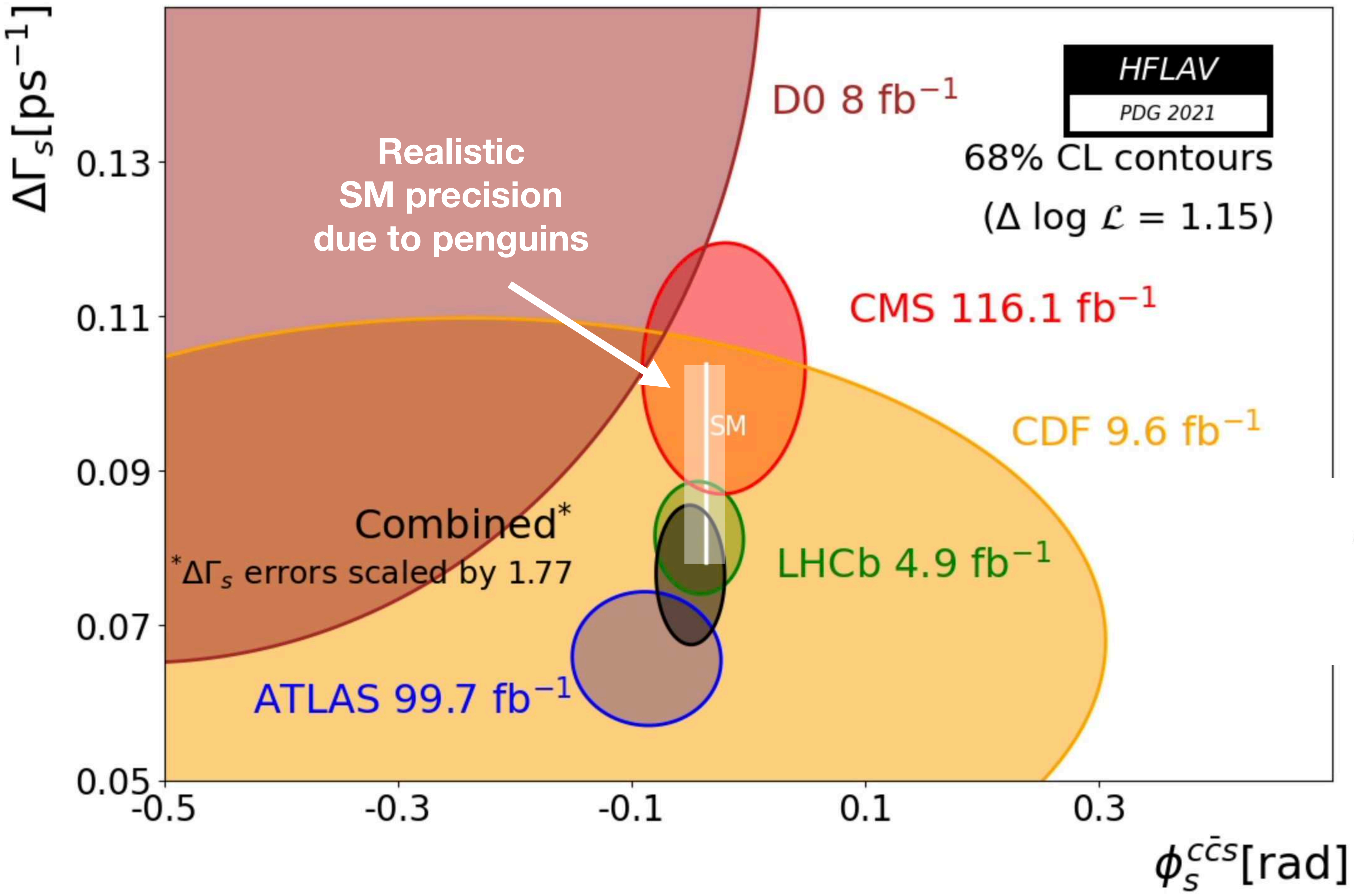
Within the SM penguins are expected to give contributions of the order of $\pm 1^\circ \approx \pm 0.017$

Now the hadronic ratio of penguin/tree has to be known - extremely challenging

Fleischer,… (2010.14423), Ciuchini et al, Faller et al, Jung, Ligeti et al, Frings, Nierste and Wiebusch,…

Status Quo: CPV in Interference

Golden plated modes: $B_s \to J/\Psi\phi$



Modification due to **New Physics**

$$M_{12}^s = M_{12}^{s,\mathrm{SM}} |\Delta_s| e^{i\phi_s^\Delta}$$

$$\Gamma_{12}^s = \Gamma_{12}^{s,\mathrm{SM}} \left|\tilde{\Delta}\right| e^{-i\phi_s^{\tilde{\Delta}}}$$

$B_s \to J/\Psi\phi$

$$-2\beta_s^{\mathrm{Exp}} = -2\beta_{s,\mathrm{Tree}}^{\mathrm{SM}} + \phi_s^\Delta + \beta_{s,\mathrm{Peng}}^{\mathrm{SM}} + \beta_{s,\mathrm{Peng}}^{\mathrm{BSM}},$$

$$\phi_{12}^{s,\mathrm{Exp}} = \phi_{12}^{s,\mathrm{SM}} + \phi_s^\Delta + \tilde{\phi}_s^\Delta,$$

a_{fs}^s

not really constrained by $\phi_s^{c\bar{c}s}$

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Status Quo: CPV in Decay

$$A_{\mathrm{dir.CP},f}(t)=\frac{\Gamma\left(\bar{B}_s^0(t)\to\bar{f}\right)-\Gamma\left(B_s^0(t)\to f\right)}{\Gamma\left(\bar{B}_s^0(t)\to\bar{f}\right)+\Gamma\left(B_s^0(t)\to f\right)}=\frac{\left|\bar{\mathcal{A}}_{\bar{f}}\right|^2-\left|\mathcal{A}_f\right|^2}{\left|\bar{\mathcal{A}}_{\bar{f}}\right|^2+\left|\mathcal{A}_f\right|^2}=\frac{2|r|\sin\left(\phi_{\mathrm{Peng}}^{\mathrm{QCD}}-\phi_{\mathrm{Tree}}^{\mathrm{QCD}}\right)\sin\left[\arg(\lambda_u)-\arg(\lambda_c)\right]}{1+|r|^2+2|r|\cos\left(\phi_{\mathrm{Peng}}^{\mathrm{QCD}}-\phi_{\mathrm{Tree}}^{\mathrm{QCD}}\right)\cos\left[\arg(\lambda_u)-\arg(\lambda_c)\right]}$$

$$\mathcal{A}_f=\left|\mathcal{A}_f^{\mathrm{Tree}}\right|e^{i\left[\phi_{\mathrm{Tree}}^{\mathrm{QCD}}+\arg(\lambda_c)\right]}+\left|\mathcal{A}_f^{\mathrm{Peng}}\right|e^{i\left[\phi_{\mathrm{Peng}}^{\mathrm{QCD}}+\arg(\lambda_u)\right]}$$

$$\bar{\mathcal{A}}_{\bar{f}}=\left|\mathcal{A}_f^{\mathrm{Tree}}\right|e^{i\left[\phi_{\mathrm{Tree}}^{\mathrm{QCD}}-\arg(\lambda_c)\right]}+\left|\mathcal{A}_f^{\mathrm{Peng}}\right|e^{i\left[\phi_{\mathrm{Peng}}^{\mathrm{QCD}}-\arg(\lambda_u)\right]}$$

The **leading contribution to the CP asymmetry is proportional to** $r=|\mathscr{A}_f^{\mathrm{Peng}}|/|\mathscr{A}_f^{\mathrm{Tree}}|$

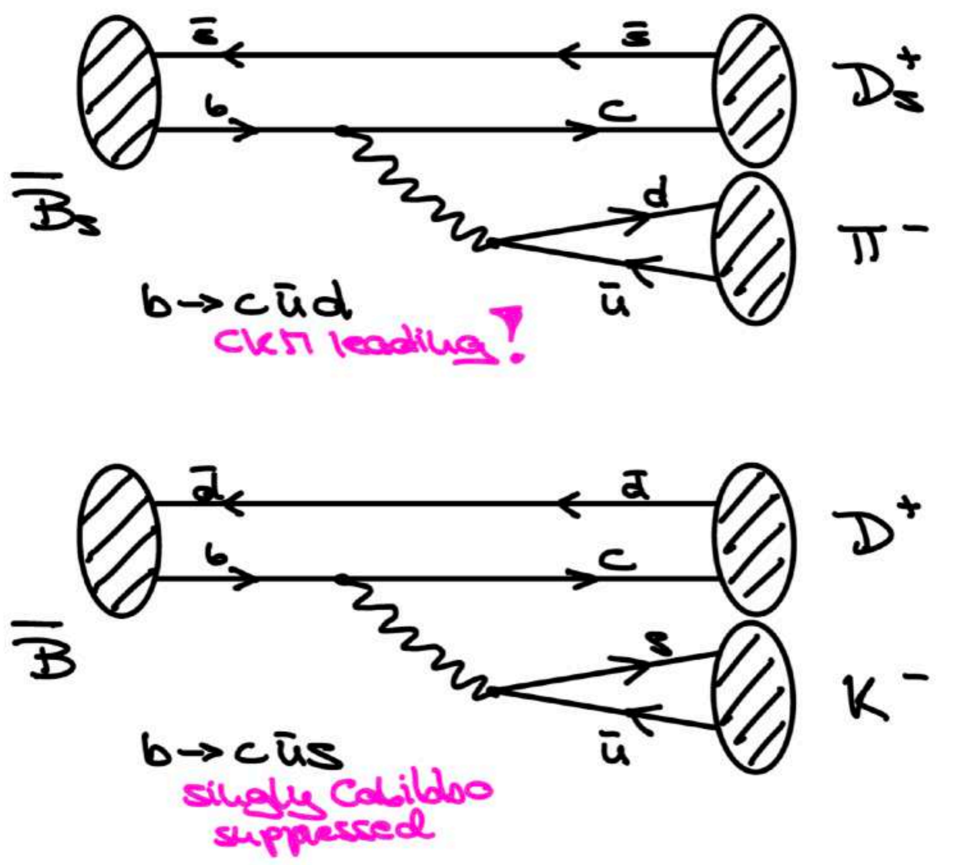
Extremely hard to predict!

(In the case of CPV in interference the leading term was free of hadronic uncertainties and only the penguin corrections depended on r)

Status Quo: Non-leptonic decays

3 σ to 9 σ deviation of experiment from QCDf predictions with standard error estimates

Colour-allowed Tree-level Decays

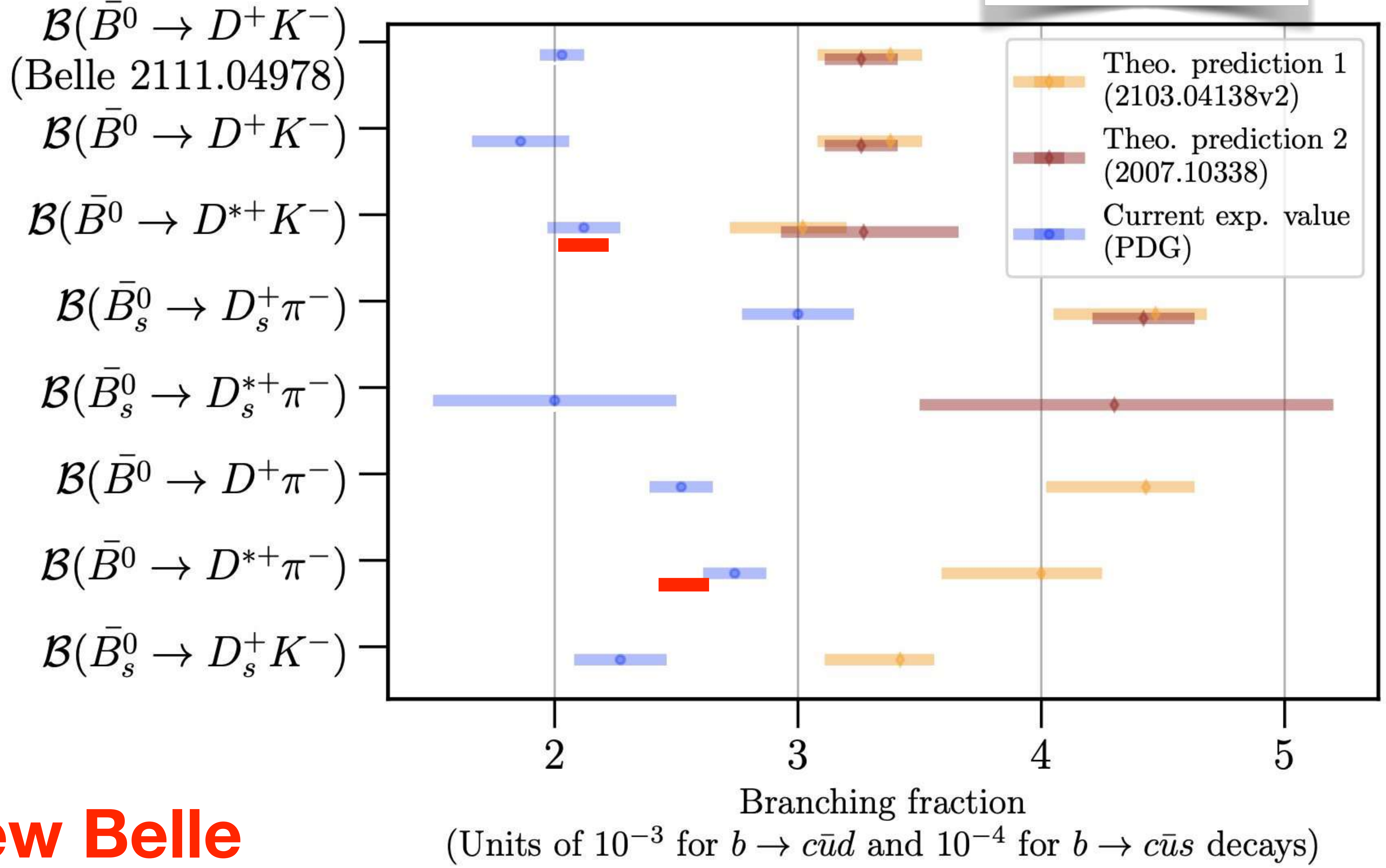


- CKM leading decays
- The are no annihilation, penguins,…
- QCDf should work at its best!

Beneke, Buchalla, Neubert, Sachrajda 1999...

$$\langle D_q^{(*)+} L^- | \mathcal{Q}_i | \bar{B}_q^0 \rangle = \sum_j F_j^{\bar{B}_q \to D_q^{(*)}}(M_L^2) \times \int_0^1 du\, T_{ij}(u)\phi_L(u) + \mathcal{O}\left(\frac{\Lambda_{QCD}}{m_b}\right)$$

N. Skidmore



— New Belle

Direct CP asymmetries

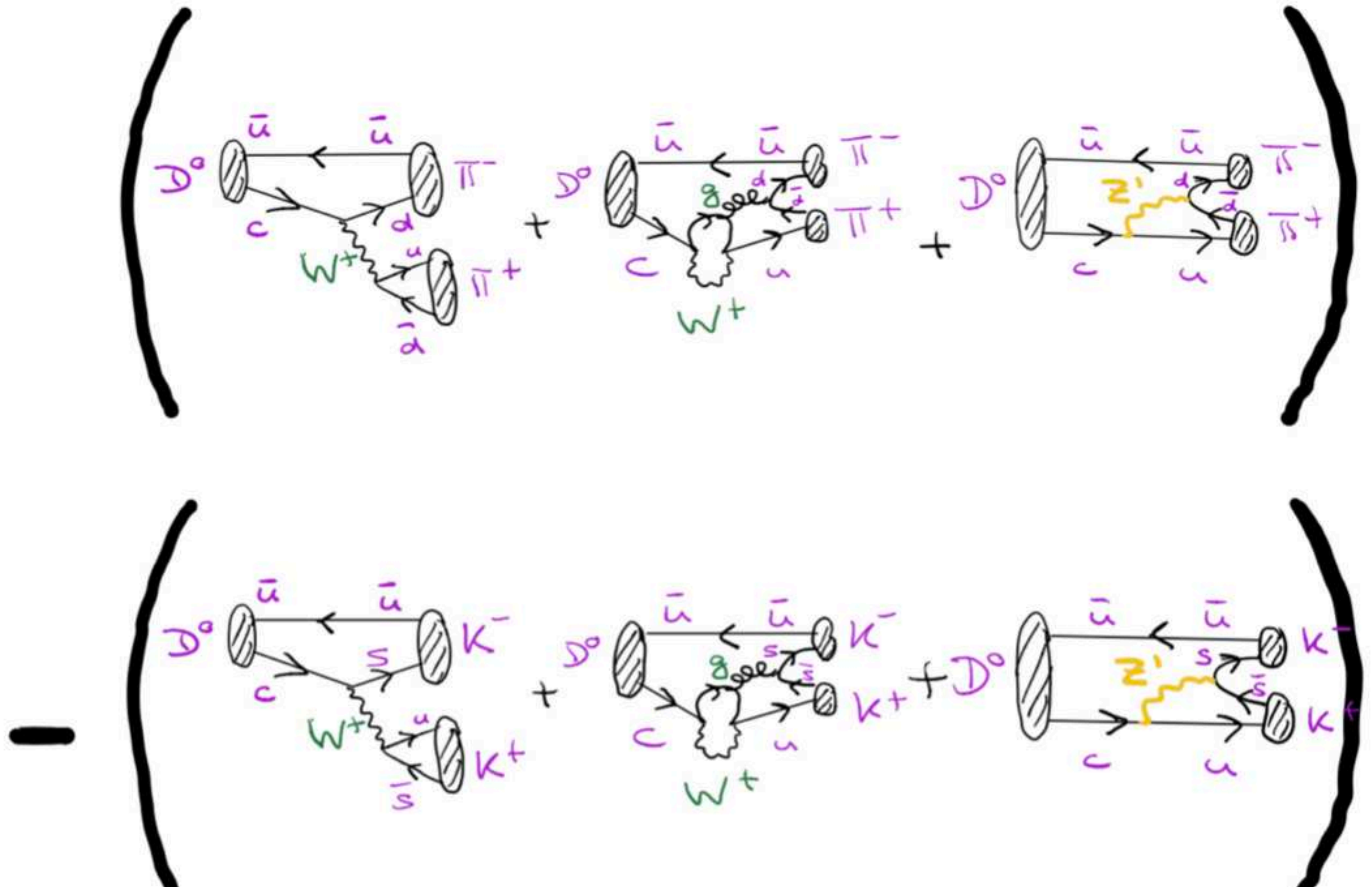
- $B \to K\pi$ puzzle still present, see. e.g. 1507.03700

  Updates: **2002.03262** complete 2-loop penguins
  2107.03819 QED corrections
  2104.14871 $A_{CP}(B^0 \to \pi^0 \bar{K}^0)$ Belle II
  SU(3) symmetry e.g. **1806.08783, 2111.06418,…**
  comprehensive phenomenological study missing

We need $r = |\mathscr{A}_f^{\text{Peng}}| / |\mathscr{A}_f^{\text{Tree}}|$

- ΔA_{CP}: direct CP violation in the charm system $D^0 \to K^+K^-$ vs. $D^0 \to \pi^+\pi^-$

  Experiment: LHCb 03/2019



Theory: SM or not SM?
E.g. 1903.10952,1909.03063 vs. 1903.10490, 1909.11242

We need $r = |\mathscr{A}_f^{\text{Peng}}| / |\mathscr{A}_f^{\text{Tree}}|$

Theory for Charm

Theory for Charm Observable ≠ Theory for Charm Observable

Theory for Charm

Theory for Charm Observable $\neq$ Theory for Charm Observable

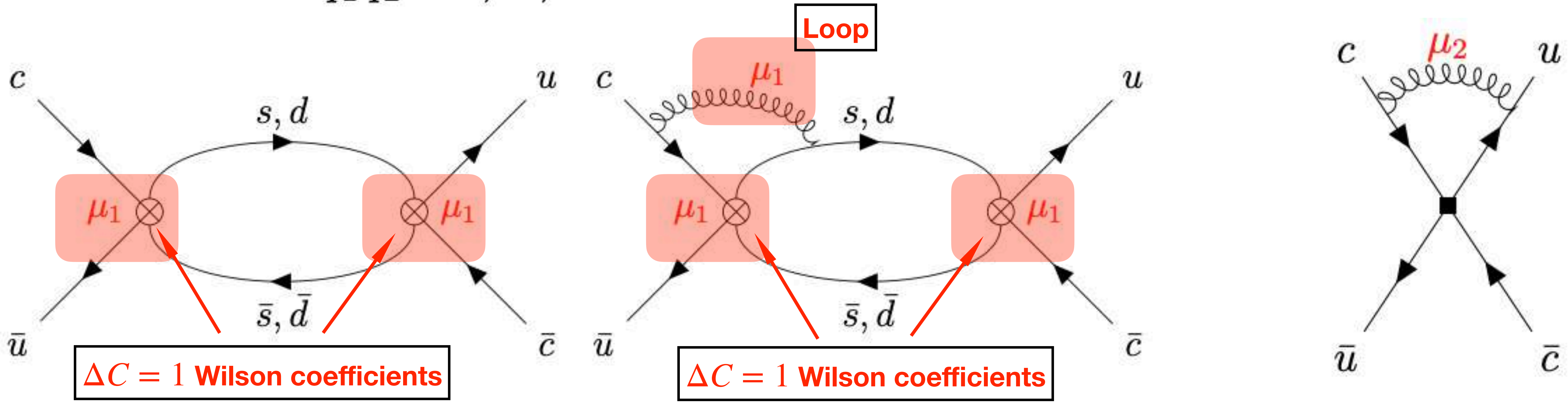
- No cancellations, e.g. Lifetime of D^0 can be predicted, $1/m_c$ **works**
- Cancellations, e.g. Lifetime of D^+ lies in the right ball park, $1/m_c$ **might work**
- Crazy cancellations, e.g. Mixing of D^0 HQE might overlap with exp., $1/m_c$ **not excluded**
- Hadronic decays: **we have to first understand the B-system!**

THANKS

Charm mixing - Theory

Renormalisation scale setting?

$$\Gamma_{12} = \sum_{q_1q_2=ss,sd,dd} \Gamma_3^{q_1q_2}(\mu_1^{q_1q_2}, \mu_2^{q_1q_2})\langle Q\rangle(\mu_2^{q_1q_2})\frac{1}{m_c^3} + \dots$$



μ_1 and μ_2 cancel within the ss, sd and dd contributions independently

Is there any requirement to set exactly $\mu_1^{ss} = \mu_1^{sd} = \mu_1^{dd}$ (also during scale variation)?

ss and dd might be related via re-scattering, but sd is physically different from ss!

Charm mixing - Theory

Renormalisation scale setting?

$\Delta\Gamma_D > 0.028\text{ps}^{-1} \Rightarrow \Omega \equiv \frac{2|\Gamma_{12}|^{\text{SM}}}{0.028\text{ps}^{-1}} \Rightarrow \Omega \approx 1$ **means HQE can describe Experiment**

Two scenarios:

1. Vary $\mu^{ss}, \mu^{sd}, \mu^{dd}$ independently around m_c between 1GeV and 2 m_c:

$$\Omega \in [4.6 \cdot 10^{-5}, 1.3]$$

2. Phase space inspired scale choice

$$\mu^{ss} = m_c - 2\epsilon$$
$$\mu^{sd} = m_c - \epsilon$$
$$\mu^{dd} = m_c$$