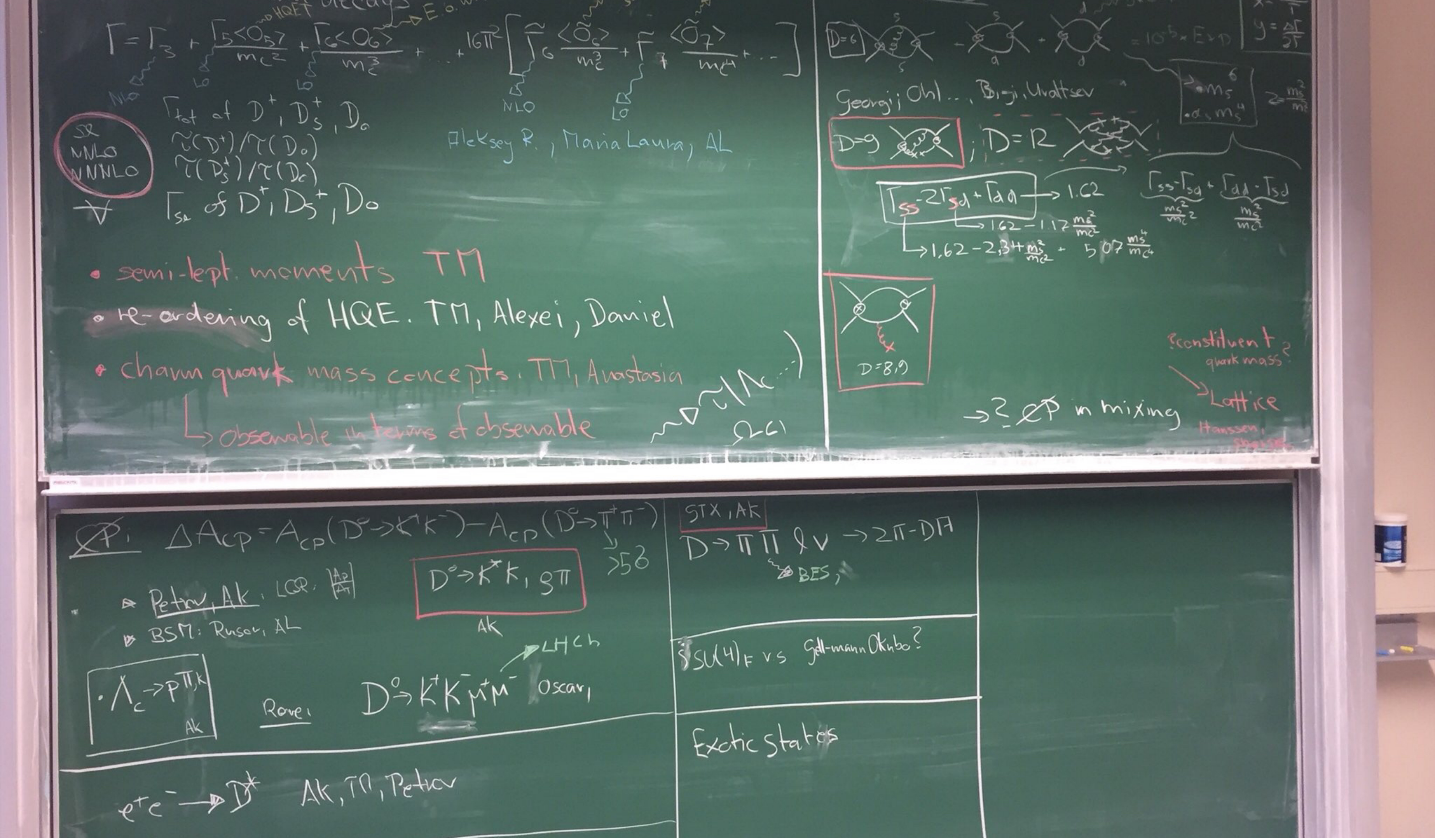
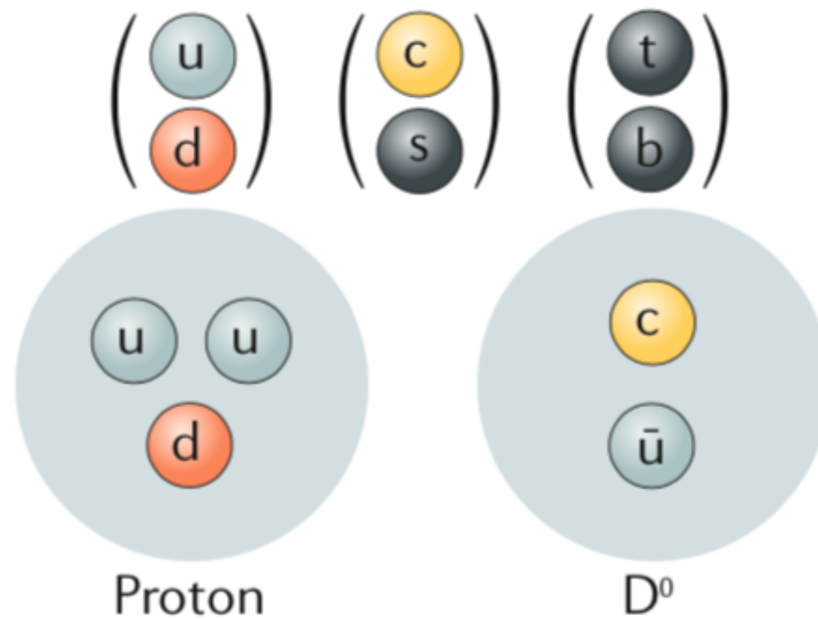


Charm Physics at a Super tau-charm factory

Alexander Lenz
Universität Siegen

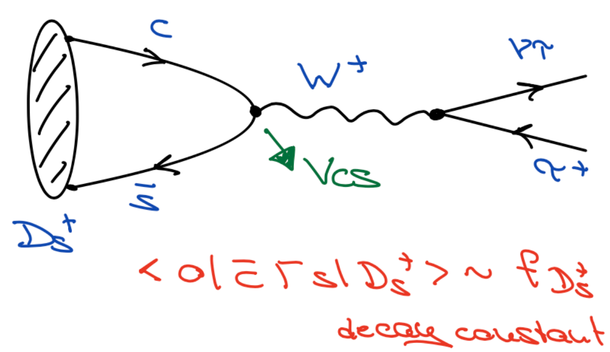
15.11.'21 Workshop on super $\tau - c$ factories

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

Charm Decays - Hadronic Difficulty

<table>
<tr><th></th><th>Leptonic</th><th>Semileptonic</th><th>Non-leptonic</th></tr>
<tr><td>Tree</td><td>


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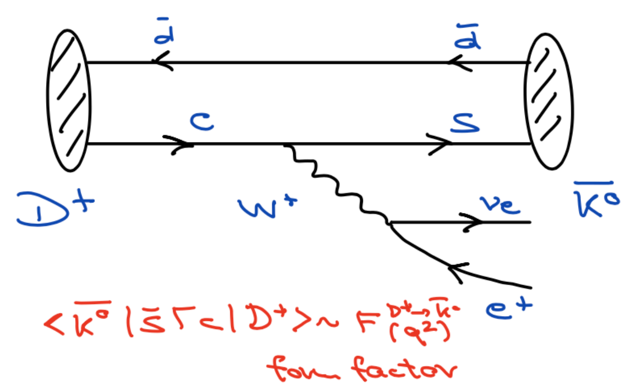

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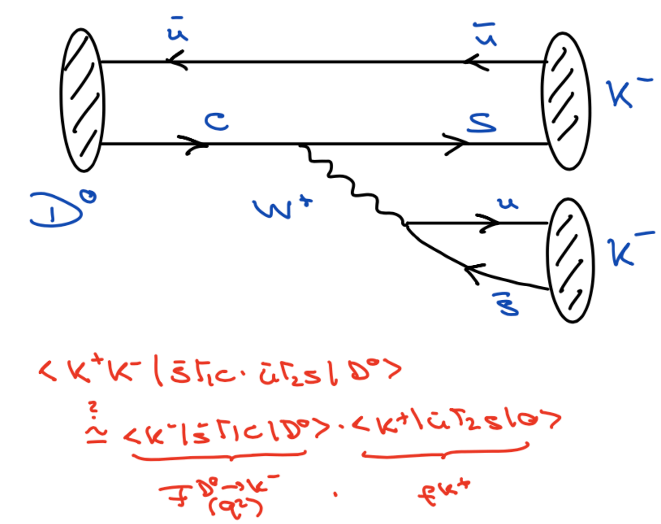

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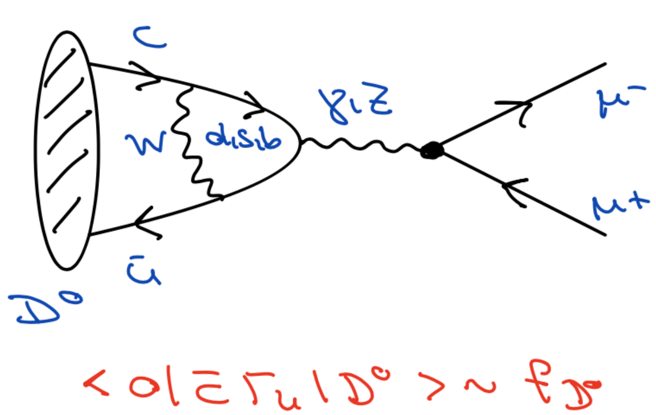
<tr><td>Loop</td><td>


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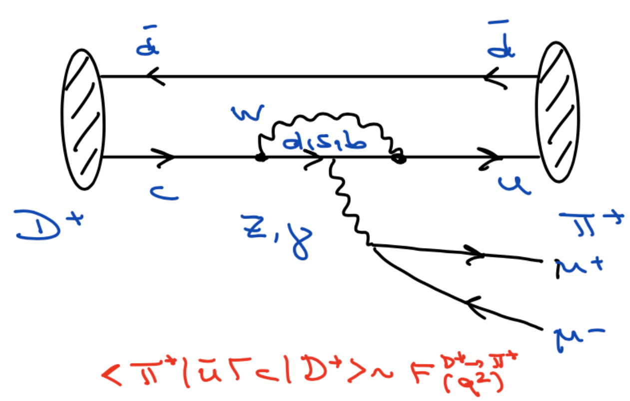

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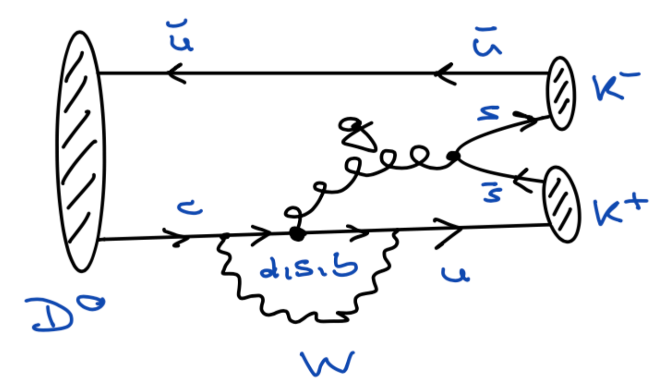
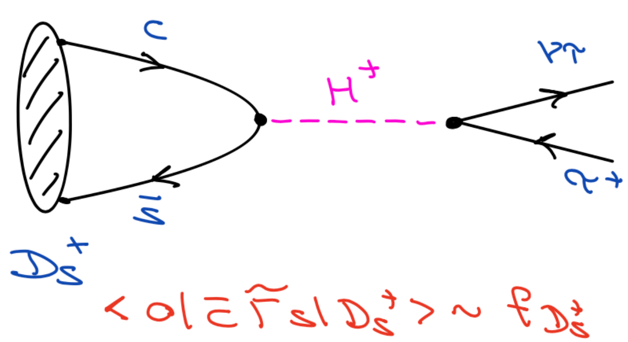


</td></tr>
</table>

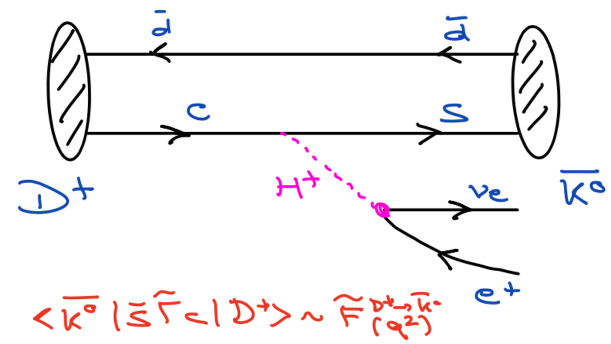
Charm Decays - BSM

	Leptonic	Semileptonic	Non-leptonic
Tree	see below	see below	see below
Loop	see below	see below	see below

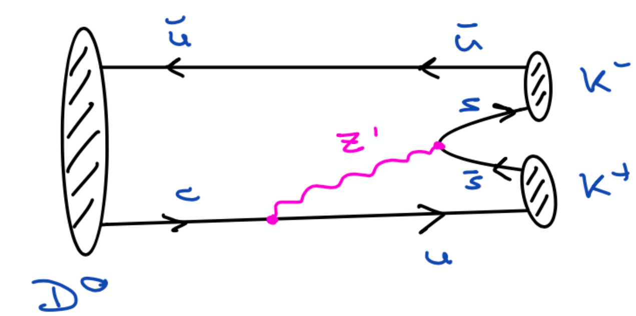
Tree — Leptonic



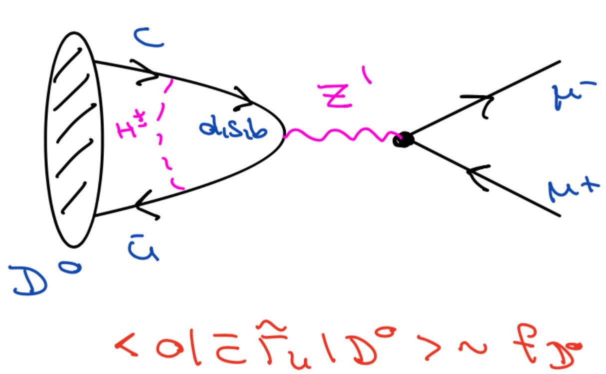
Tree — Semileptonic



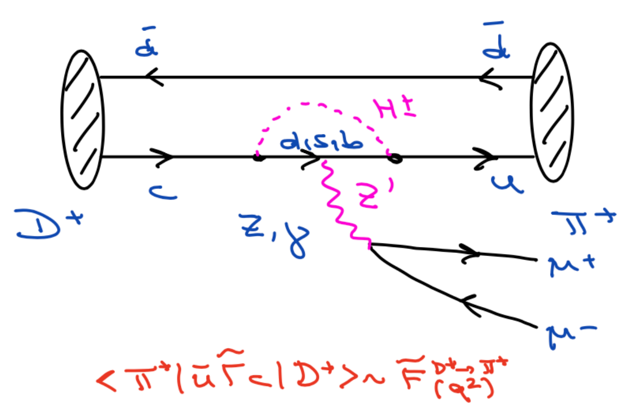
Tree — Non-leptonic



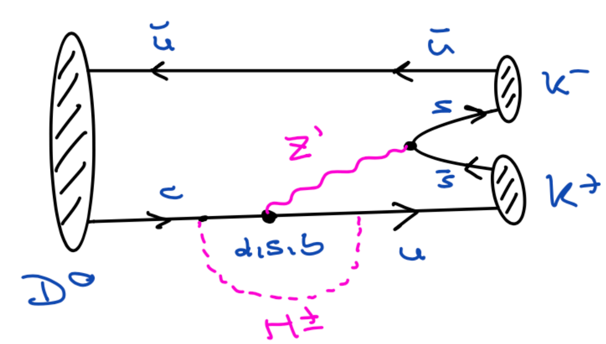
Loop — Leptonic



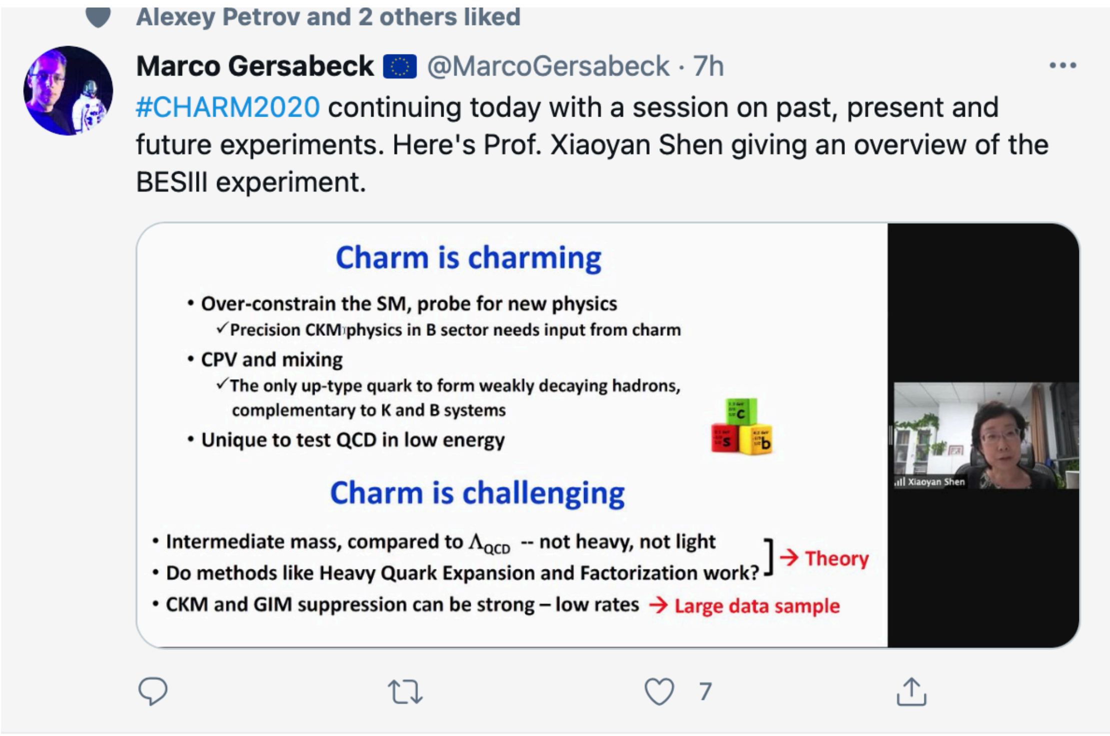
Loop — Semileptonic



Loop — Non-leptonic



Theoretical Peculiarities of Charm:



1. The strong coupling is strong

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

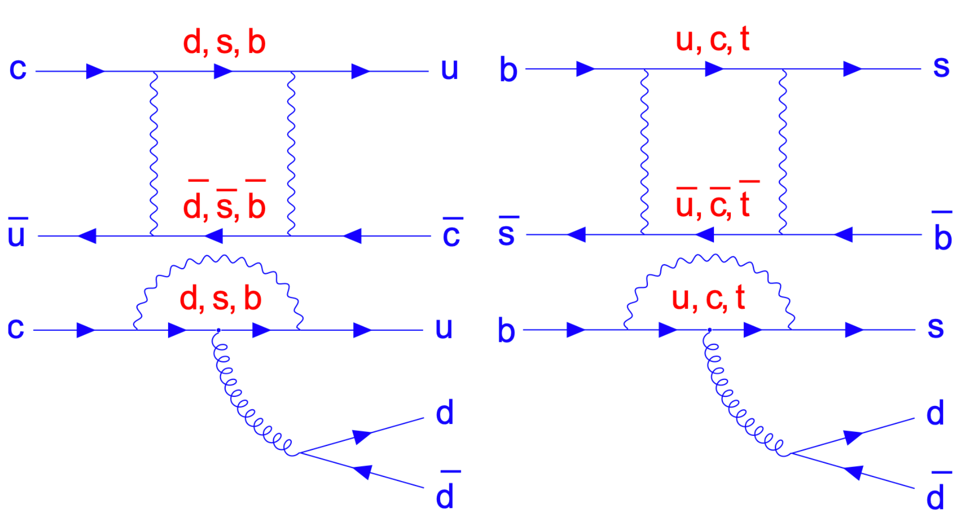
2. The charm quark is not really heavy

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

3. There is almost no CPV in charm

$$V_{\rm cd} = -0.2245 - 2.6 \cdot 10^{-5} I\ , \quad V_{\rm cs} = 0.97359 - 5.9 \cdot 10^{-6} I\ , \qquad V_{\rm cb} = 0.0416\ .$$

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

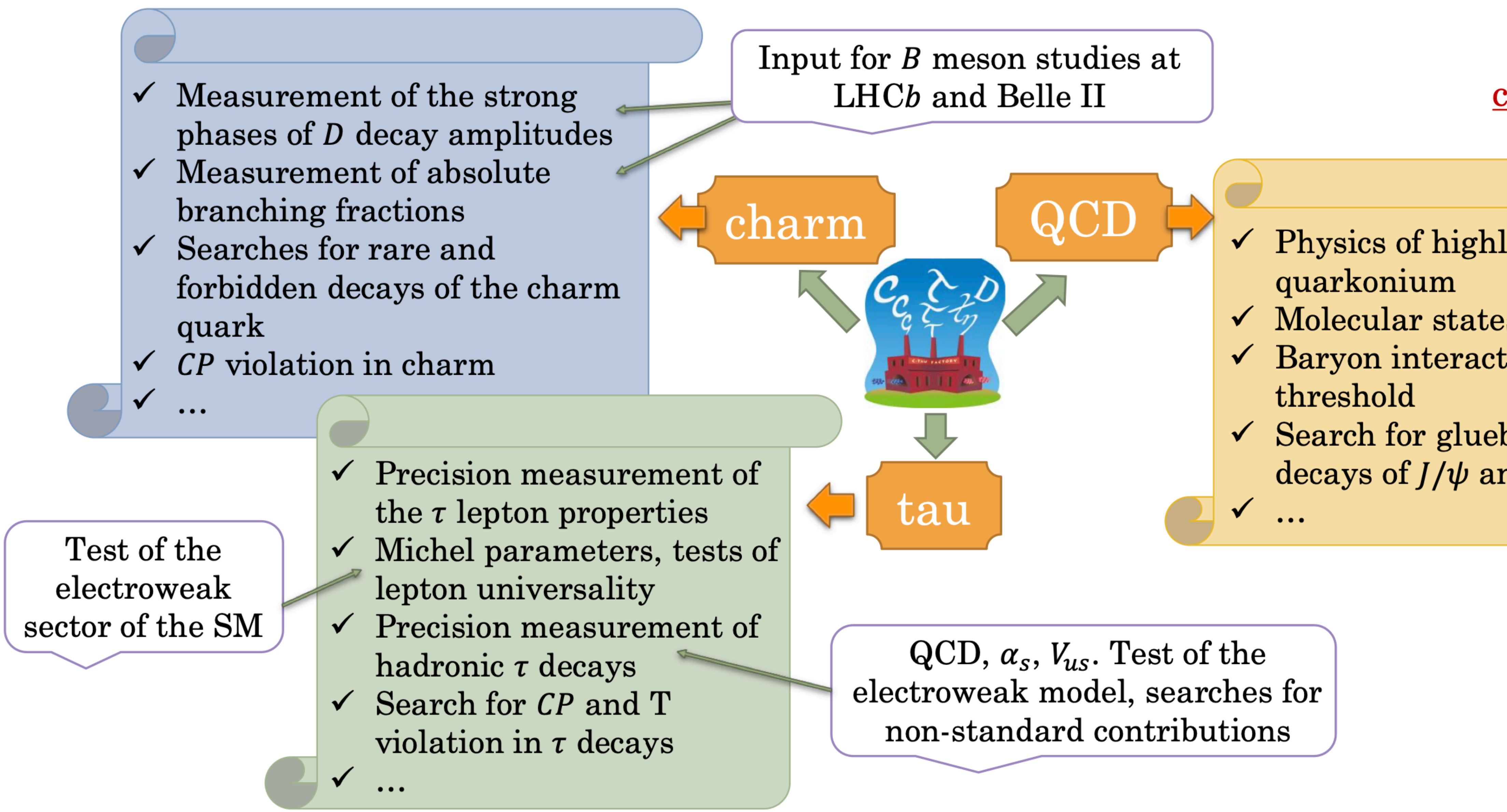


$$\left(\frac{m_d}{M_W}\right)^2 \approx 0\,, \qquad \left(\frac{m_u}{M_W}\right)^2 \approx 0\,,$$
$$\left(\frac{m_s}{M_W}\right)^2 \approx 1.3 \cdot 10^{-6}\,, \qquad \left(\frac{m_c}{M_W}\right)^2 \approx 2.5 \cdot 10^{-4}\,,$$
$$\left(\frac{m_b}{M_W}\right)^2 \approx 2.8 \cdot 10^{-3}\,, \qquad \left(\frac{m_t}{M_W}\right)^2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

**See e.g.
AL, G. Wilkinson
2011.04443**

STCF - Textbook Knowledge

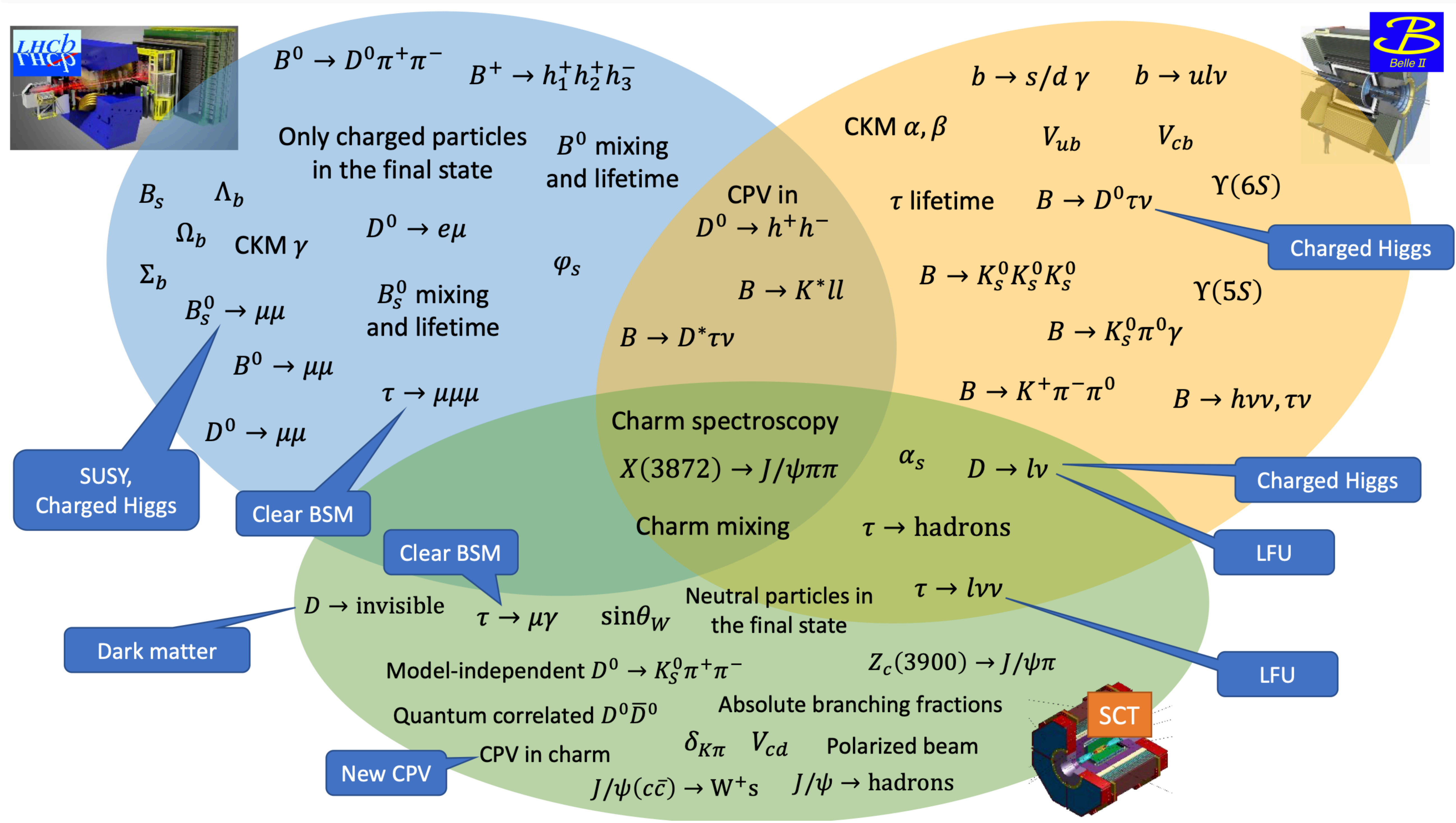
Physics program



ctd.inp.nsk.su

Vitaly Vorobyev, BINP

STCF - Textbook Knowledge



Vitaly Vorobyev, BINP

Charm Physics at a Super-tau-charm Factory

Try to be complementary to what is already known and what will be said at this workshop

But

Gudrun Hiller: **Rare charm decays to invisible final states**
Marcel Golz: **CP violating rare charm decays**
Alexey Nefediev: **On the nature of exotic Zcs states**
Sergei Trykov: **Prospects for dark matter search**
Vitaly Popov: **Strong phases in D-> K0(s) h decays**
Timofey Uglov: **Charmed baryons**
Huijin Li: **Leptonic decays of charm mesons**
Yulan Fan: **D0 -> K1 e nu**
Jiajun Liu: **CKM element Vcs and fDs in D_s^+ -> l nu**

So what is left?

Outline

1. CKM Unitarity

2. Inclusive Charm Decays

3. CP Violation

    A. Determination of γ^{CKM}
    B. D Meson Baryogengesis
    C. CPV in Charm Decays
    D. CPV in Charm Mixing

Cabibbo Anomaly

1. CKM Unitarity

See e.g. Crivellin et al. (6), Grossman, Passemar, Schacht 1911.07821, Kirk 20008.03261,…

$$\Delta_{\rm CKM} \equiv 1 - |V_{ud}|^2 - |V_{us}|^2 - |V_{ub}|^2 \qquad \Delta_{\rm CKM} = (1.12 \pm 0.28) \times 10^{-3} \, . \qquad 3.9\sigma$$

The CKM unitarity problem: A trace of new physics at the TeV scale? #1

Benedetta Belfatto (GSSI, Aquila and INFN, Aquila and L'Aquila U.), Revaz Beradze (Javakhishvili State U. and L'Aquila U.), Zurab Berezhiani (L'Aquila U. and INFN, Aquila) (Jun 6, 2019)

Published in: *Eur.Phys.J.C* 80 (2020) 2, 149 • e-Print: 1906.02714 [hep-ph]

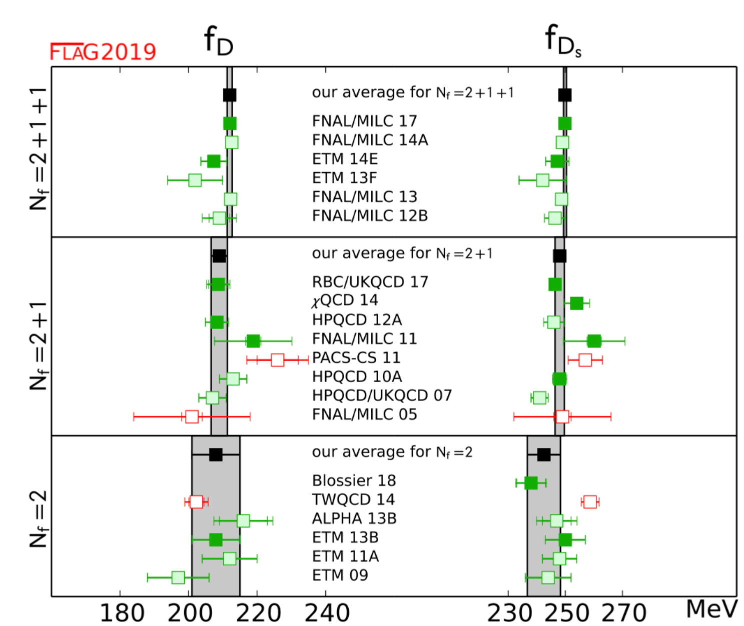
pdf DOI cite 69 citations

PDG: what about the second row?

$$|V_{ud}| = 0.97370 \pm 0.00014 \qquad |V_{us}| = 0.2245 \pm 0.0008 \qquad |V_{ub}| = (3.82 \pm 0.24) \times 10^{-3}$$

$$|V_{cd}| = 0.221 \pm 0.004 \qquad |V_{cs}| = 0.987 \pm 0.011 \qquad |V_{cb}| = (41.0 \pm 1.4) \times 10^{-3}$$

Leptonic D_s^+ and D^+ decays are theoretically very clean



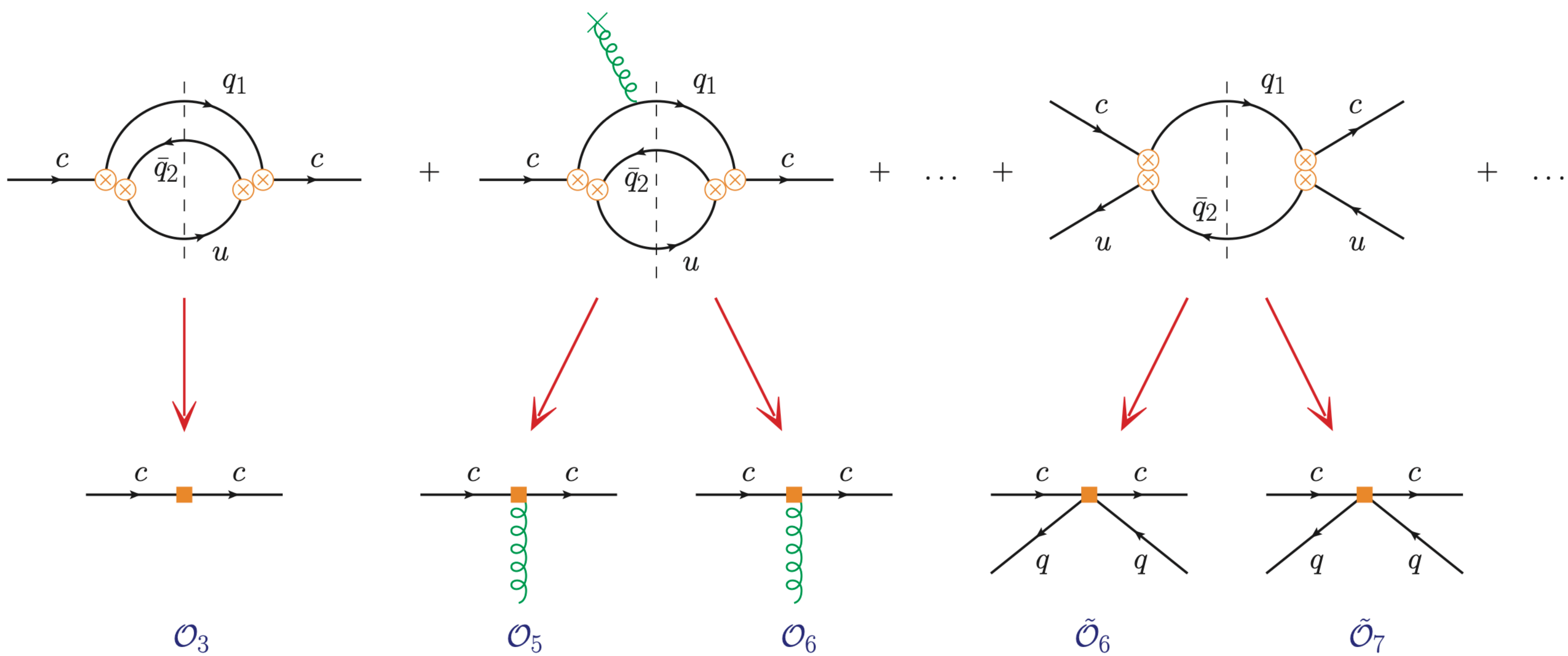
2. Inclusive Charm Decays

Test of theory tools in an “easy” system, without CPV and GIM

Inclusive decays - Sum over all exclusive channel = quark level description

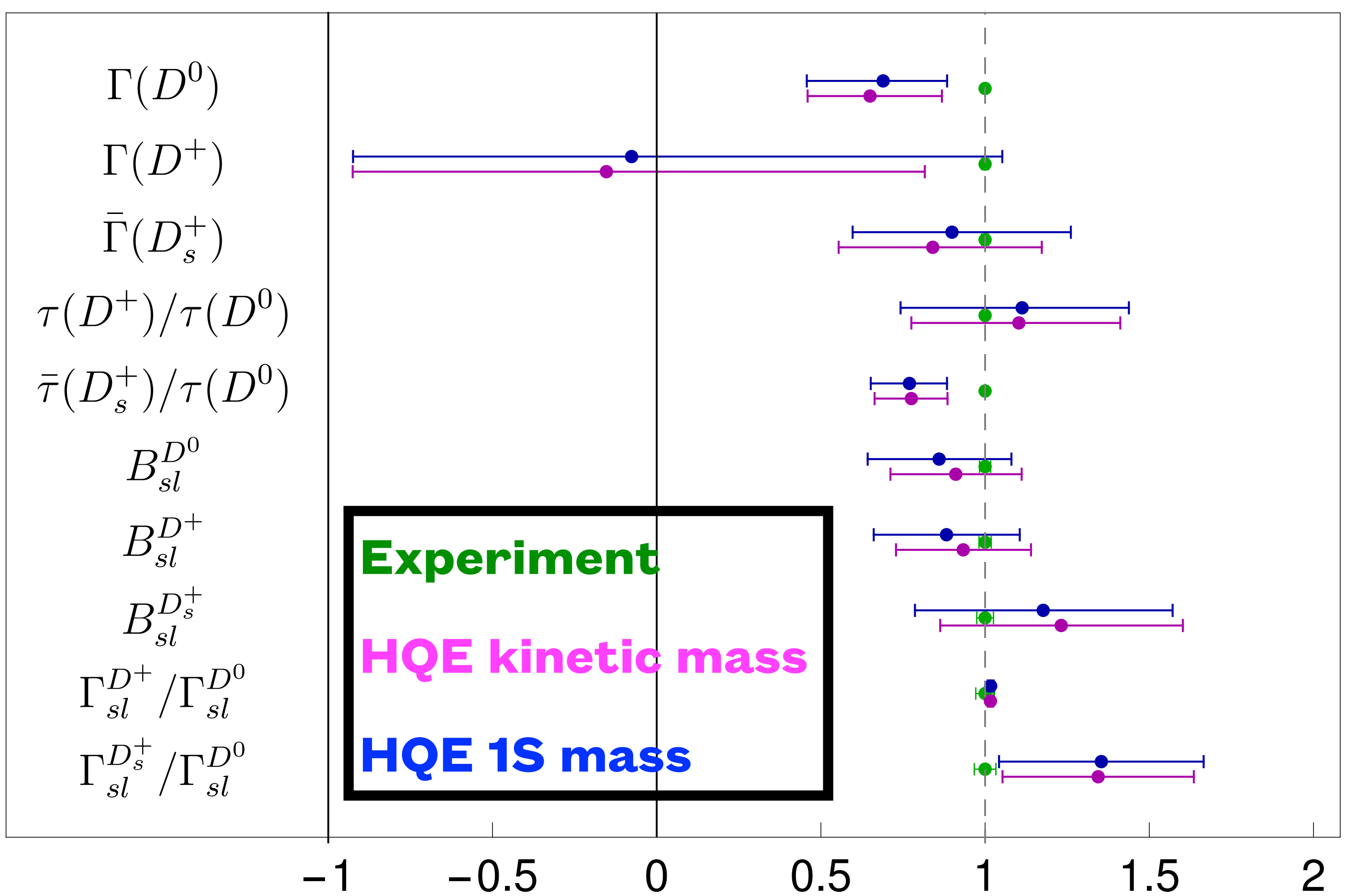
$$\Gamma(D) = \frac{1}{2m_D} \sum_X \int_{\text{PS}} (2\pi)^4 \delta^{(4)}(p_D - p_X) \, |\langle X(p_X)|\mathcal{H}_{\text{eff}}|D(p_D)\rangle|^2$$

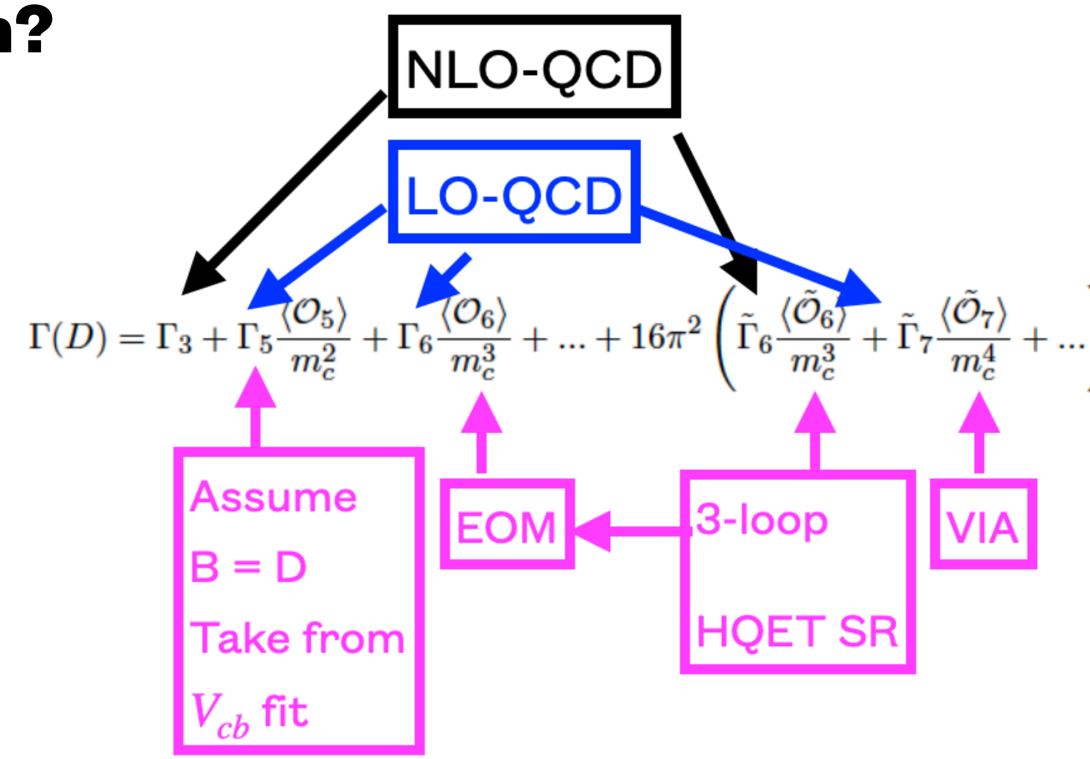
$$\Gamma(D) = \frac{1}{2m_D} \text{Im}\langle D|\mathcal{T}|D\rangle \qquad \mathcal{T} = i \int d^4x \, T\left\{\mathcal{H}_{\text{eff}}(x)\,,\mathcal{H}_{\text{eff}}(0)\right\}$$



2. Inclusive Charm Decays

Convergence of HQE in the charm system?





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

- **Huge uncertainties**
- **HQE covers experiment**
- $< 1\sigma$ **deviation for SU(3)F breaking in sl**

Charm Phenomenology: **King, AL, Piscopo, Rauh, Rusov, Vlahos 2109.13219**

Darwin Term: **AL, Piscopo, Rusov 2004.09527, Mannel, Moreno, Pivovarov 2004.09485, 2009.08756**

2. Inclusive Charm Decays

How to improve the precision of the HQE in the charm system?

$$\frac{\Gamma_{sl}^{D_s^+}}{\Gamma_{sl}^{D^0}} = 1 - 0.40\,[\mu_\pi^2(D_s) - \mu_\pi^2(D)] - 1.21\,[\mu_G^2(D_s) - \mu_G^2(D)] + 3.13\,[\rho_D^3(D_s) - \rho_D^3(D)]$$

$$- 8.84\,\tilde{B}_1^s + 8.84\,\tilde{B}_2^s - 3.02\,\tilde{\epsilon}_1^s + 2.79\,\tilde{\epsilon}_2^s \underbrace{+0.00}_{\text{dim}-7,\text{VIA}}$$

$$+0.35\,\tilde{\delta}_1^{qq} - 0.35\,\tilde{\delta}_2^{qq} + 6.60\,\tilde{\delta}_1^{qs} - 6.60\,\tilde{\delta}_2^{qs} - 0.52\,\tilde{\delta}_1^{sq} + 0.52\,\tilde{\delta}_2^{sq} + 9.68\,\tilde{\delta}_1^{ss} - 9.68\,\tilde{\delta}_2^{ss}$$

$$= 1 - 0.04\,\frac{\mu_\pi^2(D_s) - \mu_\pi^2(D)}{0.1\,\text{GeV}^2} - 0.02\,\frac{\mu_G^2(D_s) - \mu_G^2(D)}{0.02\,\text{GeV}^2} + 0.11\,\frac{\rho_D^3(D_s) - \rho_D^3(D)}{0.035\,\text{GeV}^2}$$

$$\underbrace{+0.00}_{\text{dim}-6,7,\text{VIA}} - 0.09\,\delta\tilde{B}_1^s + 0.09\,\delta\tilde{B}_2^s + 0.06\,\frac{\tilde{\epsilon}_1^s}{-0.02} - 0.06\,\frac{\tilde{\epsilon}_2^s}{-0.02}$$

$$+0.0009\,r_1^{qq} + 0.0006\,r_2^{qq} + 0.0112\,r_1^{qs} + 0.0079\,r_2^{qs}$$

$$- 0.0013\,r_1^{sq} - 0.0009\,r_2^{sq} + 0.0223\,r_1^{ss} + 0.0165\,r_2^{ss}$$

Could probably be extracted from momentum analysis of inclusive semileptonic D meson decays by BESIII, Belle II,... STCF

Bag parameter determined with 3-loop HQET sum rules:1711.02100
New: ms corrections King, AL, Rauh, to appear

New: first ever determination of eye-contractions King, AL, Rauh, to appear

Measurement of the absolute branching fraction of inclusive semielectronic D_s^+ decays #1
BESIII Collaboration • Medina Ablikim (Beijing, Inst. High Energy Phys.) et al. (Apr 15, 2021)
Published in: *Phys.Rev.D* 104 (2021) 1, 012003 • e-Print: 2104.07311 [hep-ex]
pdf DOI cite 6 citations

Lattice cross-check of HQET sum rules:
RBC-UKQCD, Oliver Witzel, Matthew Black

Moment analysis from B-factories: **Bordone, Capdevilla, Gambino 2107.00604**

$$\langle E_\ell^n \rangle = \frac{1}{\Gamma_{E_\ell > E_{\text{cut}}}} \int_{E_\ell > E_{\text{cut}}} E_\ell^n \frac{d\Gamma}{dE_\ell}\, dE_\ell \qquad \langle m_X^{2n} \rangle = \frac{1}{\Gamma_{E_\ell > E_{\text{cut}}}} \int_{E_\ell > E_{\text{cut}}} m_X^{2n} \frac{d\Gamma}{dm_X^2}\, dm_X^2$$

3A. Determination of γ^{CKM}

Determination of $\gamma = \arg(-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*)$ via $B^\pm \to DK^\pm$ decays (interference of $b \to c\bar{u}s$ and $b \to u\bar{c}s$ transitions)

Ultra-clean within the SM: 1308.5663

The ultimate theoretical error on γ from $B \to DK$ decays

Joachim Brod[1,*] and Jure Zupan[1,†]

[1]*Department of Physics, University of Cincinnati, Cincinnati, Ohio 45221, USA*

Abstract

The angle γ of the standard CKM unitarity triangle can be determined from $B \to DK$ decays with a very small irreducible theoretical error, which is only due to second-order electroweak corrections. We study these contributions and estimate that their impact on the γ determination is to introduce a shift $|\delta\gamma| \lesssim \mathcal{O}(10^{-7})$, well below any present or planned future experiment.

Mostly LHCb with BESIII input

$$\gamma = \left(65.4^{+3.8}_{-4.2}\right)^\circ$$

CKMfitter

$$\gamma = \left(65.66^{+0.90}_{-2.65}\right)^\circ$$

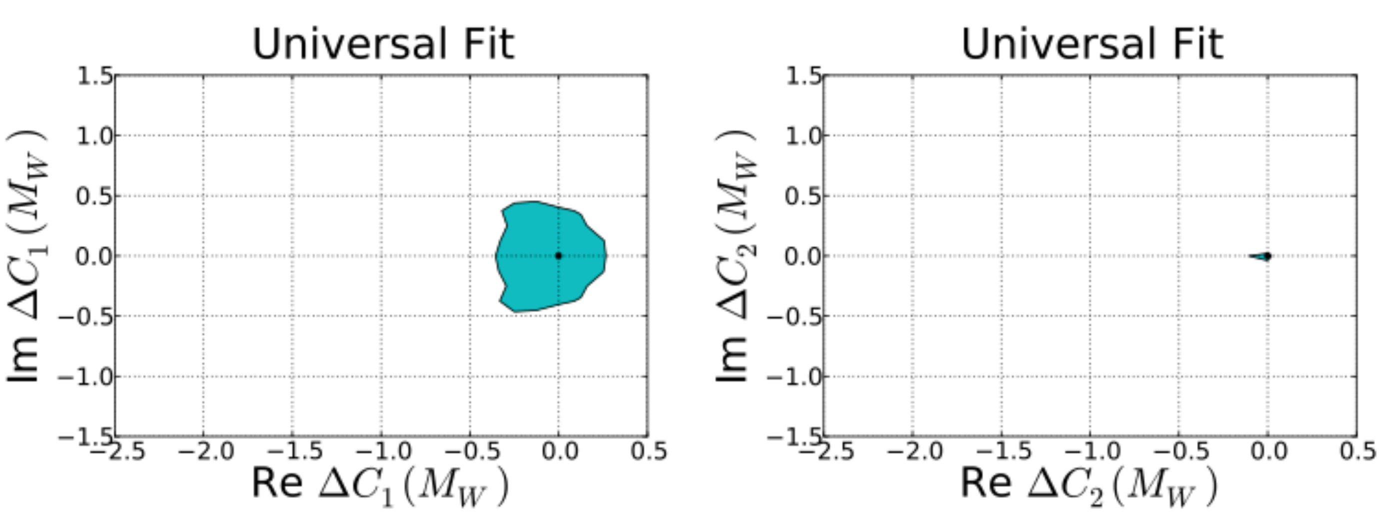
For experimental analysis strong phases needed

3A. Determination of γ^{CKM}

Can there be new physics effects in non-leptonic tree-level decays?

Constrain BSM effects in tree-level via

$$C_1(M_W) := C_1^{\rm SM}(M_W) + \Delta C_1(M_W),$$
$$C_2(M_W) := C_2^{\rm SM}(M_W) + \Delta C_2(M_W),$$



AL, Tetlamatzi-Xolocotzi 1912.07621

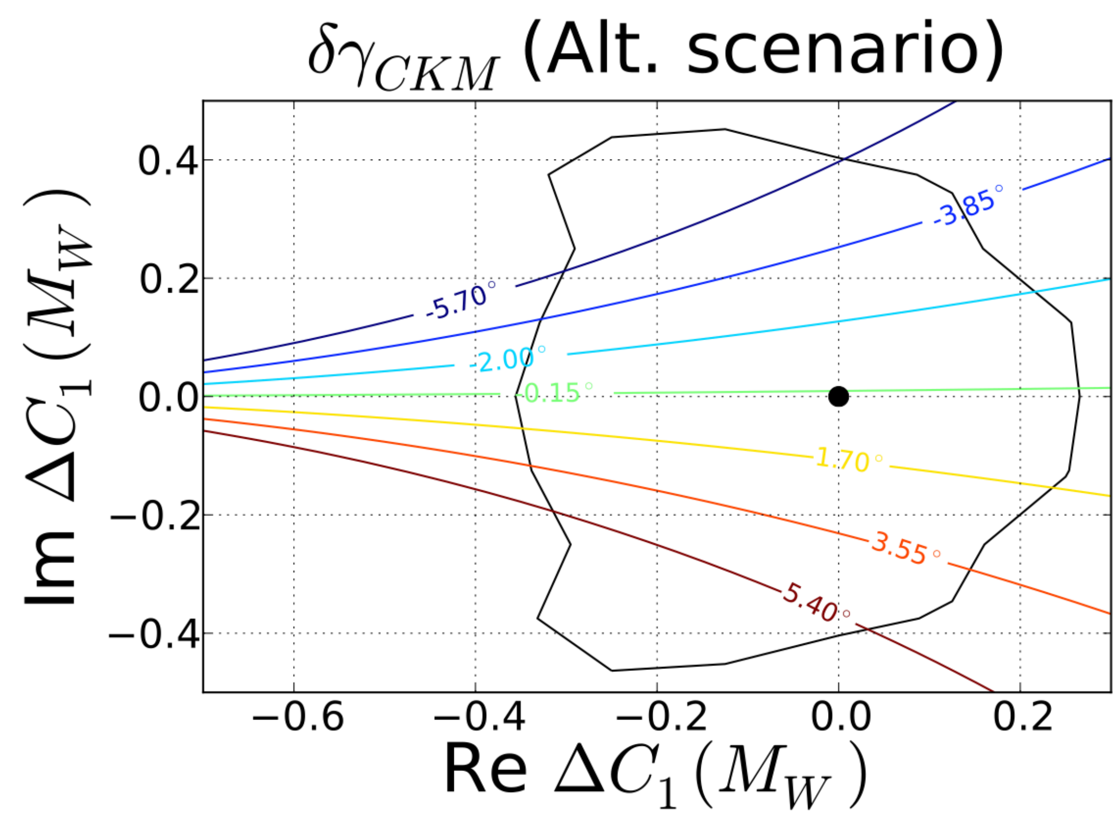
New physics effects in tree-level decays and the precision in the determination of the quark mixing angle γ

#27

Joachim Brod (Mainz U. and U. Mainz, PRISMA), Alexander Lenz (Durham U. and Durham U., IPPP), Gilberto Tetlalmatzi-Xolocotzi (Durham U. and Durham U., IPPP), Martin Wiebusch (Durham U. and Durham U., IPPP) (Dec 3, 2014)

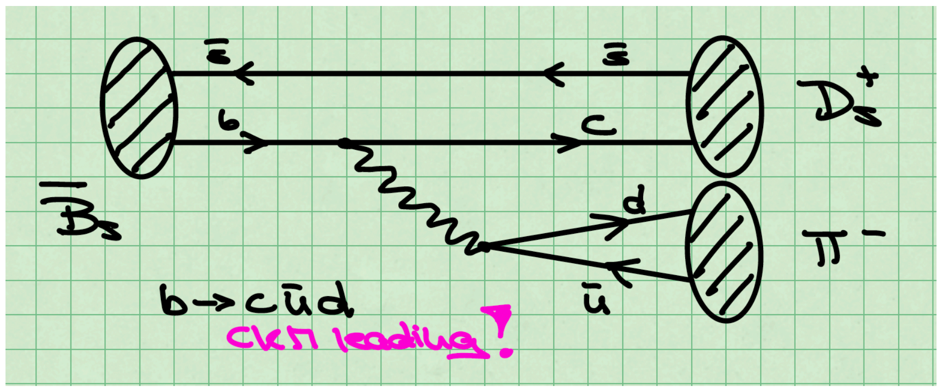
Published in: *Phys.Rev.D* 92 (2015) 3, 033002 • e-Print: 1412.1446 [hep-ph]

pdf DOI cite

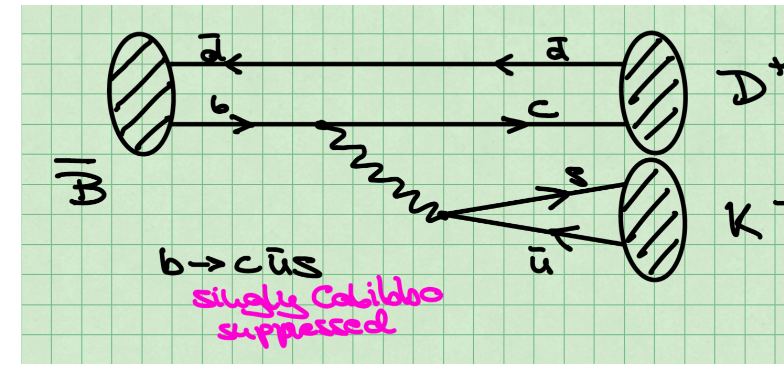


Deviations of several degrees Possible

3A. Determination of γ^{CKM}



Colour-allowed non-leptonic
tree-level decays
QCD factorisation should work best!



But: **Huber, Kränkl, Li 1606.02888, Bordone, Gubernari, Huber, Jung, van Dyk 2008´7.10338, Cai, Deng, Li, Yang 2103.0438**

Source	PDG	Our fits (w/o QCDF)		Our fit (w/ QCDF, no f_s/f_d)		QCDF prediction	
Scenario	–	No f_s/f_d	$(f_s/f_d)^{7\,\text{TeV}}_{\text{LHCb,sl}}$	Ratios only	~~SU(3)~~	–	
χ^2/dof	–	2.5/4	3.1/5	4.6/6	3.7/4	–	
$\mathcal{B}(\bar{B}_s^0 \to D_s^+\pi^-)$	3.00 ± 0.23	3.6 ± 0.7	3.11 ± 0.25	$3.11^{+0.21}_{-0.19}$	$3.20^{+0.20}_{-0.26}$ *	4.42 ± 0.21	4σ
$\mathcal{B}(\bar{B}^0 \to D^+K^-)$	0.186 ± 0.020	0.222 ± 0.012	0.224 ± 0.012	0.227 ± 0.012	0.226 ± 0.012	0.326 ± 0.015	>5σ
$\mathcal{B}(\bar{B}^0 \to D^+\pi^-)$	2.52 ± 0.13	2.71 ± 0.12	2.73 ± 0.12	2.74 ± 0.12	$2.73^{+0.12}_{-0.11}$	–	
$\mathcal{B}(\bar{B}_s^0 \to D_s^{*+}\pi^-)$	2.0 ± 0.5	2.4 ± 0.7	2.1 ± 0.5	$2.46^{+0.37}_{-0.32}$	$2.43^{+0.39}_{-0.32}$	$4.3^{+0.9}_{-0.8}$	2σ
$\mathcal{B}(\bar{B}^0 \to D^{*+}K^-)$	0.212 ± 0.015	0.216 ± 0.014	0.216 ± 0.014	$0.213^{+0.014}_{-0.013}$	$0.213^{+0.014}_{-0.013}$	$0.327^{+0.039}_{-0.034}$	3σ
$\mathcal{B}(\bar{B}^0 \to D^{*+}\pi^-)$	2.74 ± 0.13	2.78 ± 0.15	2.79 ± 0.15	$2.76^{+0.15}_{-0.14}$	$2.76^{+0.15}_{-0.14}$	–	

$B^0 \to D^+K^-$ $0.203(5)(7)(3) \cdot 10^{-3}$ 2111.04978 Belle II $\frac{(3.26-2.03)}{\sqrt{0.09^2+0.15^2}}$ naive 7σ
$B^0 \to D^+\pi^-$ $2.48(1)(9)(4) \cdot 10^{-3}$

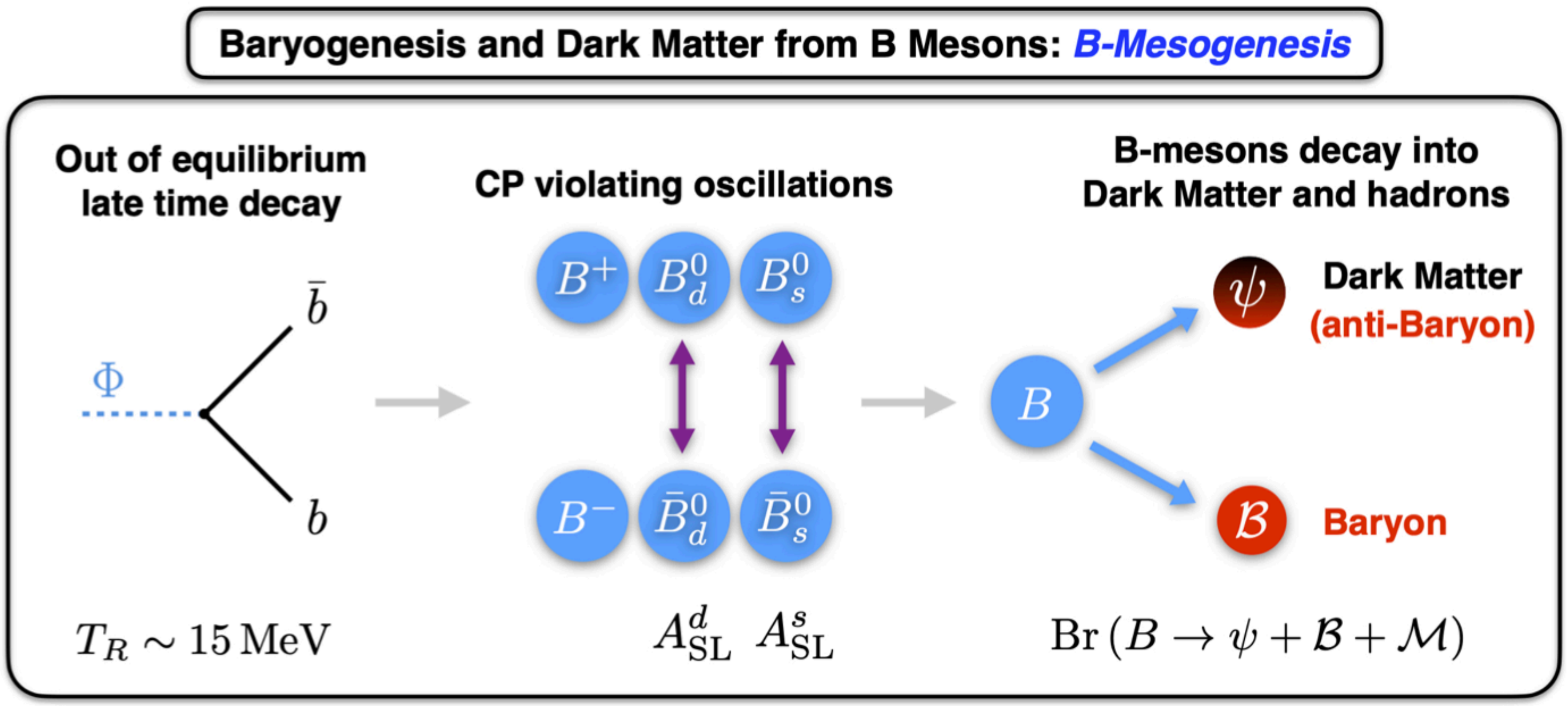
Either QCD factorisation fails significantly or BSM effects of the order of 15%

If BSM is CP violating => clean experimental proof possible

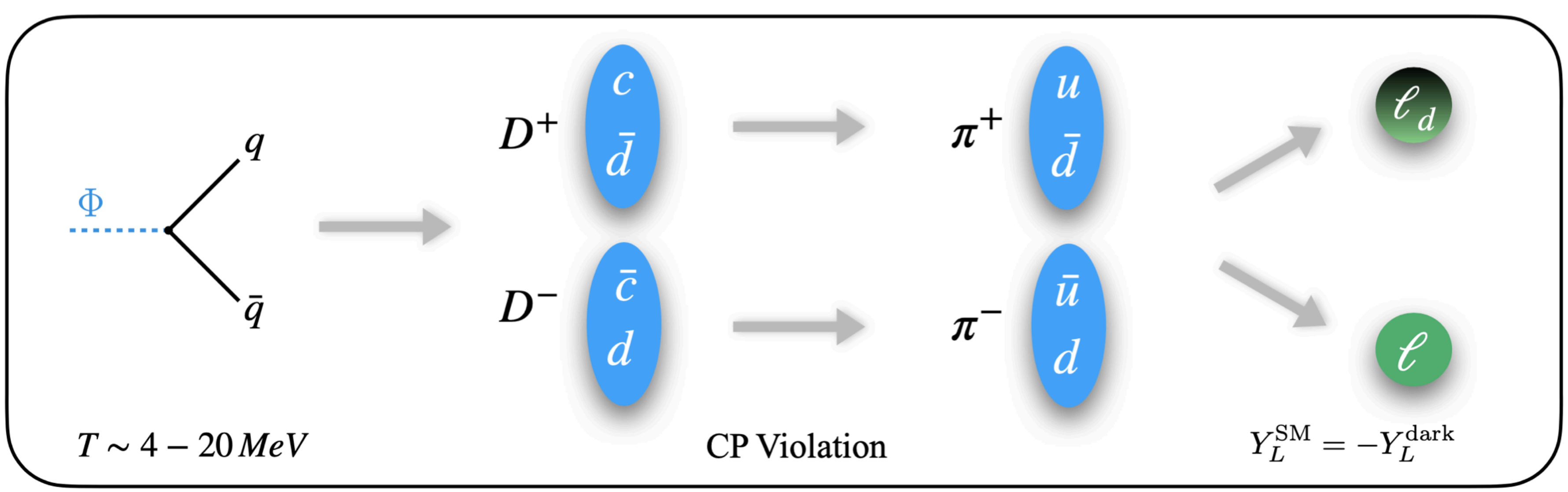
Gershon, AL, Rusov, Skidmore 2111.04478

3B. D Meson Baryogengesis

Baryogenesis plus Dark matter via B and D mesons: **Elor, Escudero, Nelson 1810.00880**



Alonso-Alvarez, Elor, Escudero 2101.02706



Elor, McGehee 2011.06115

Charged D meson into an odd number of charged pions

3B. CPV in Charm Decays

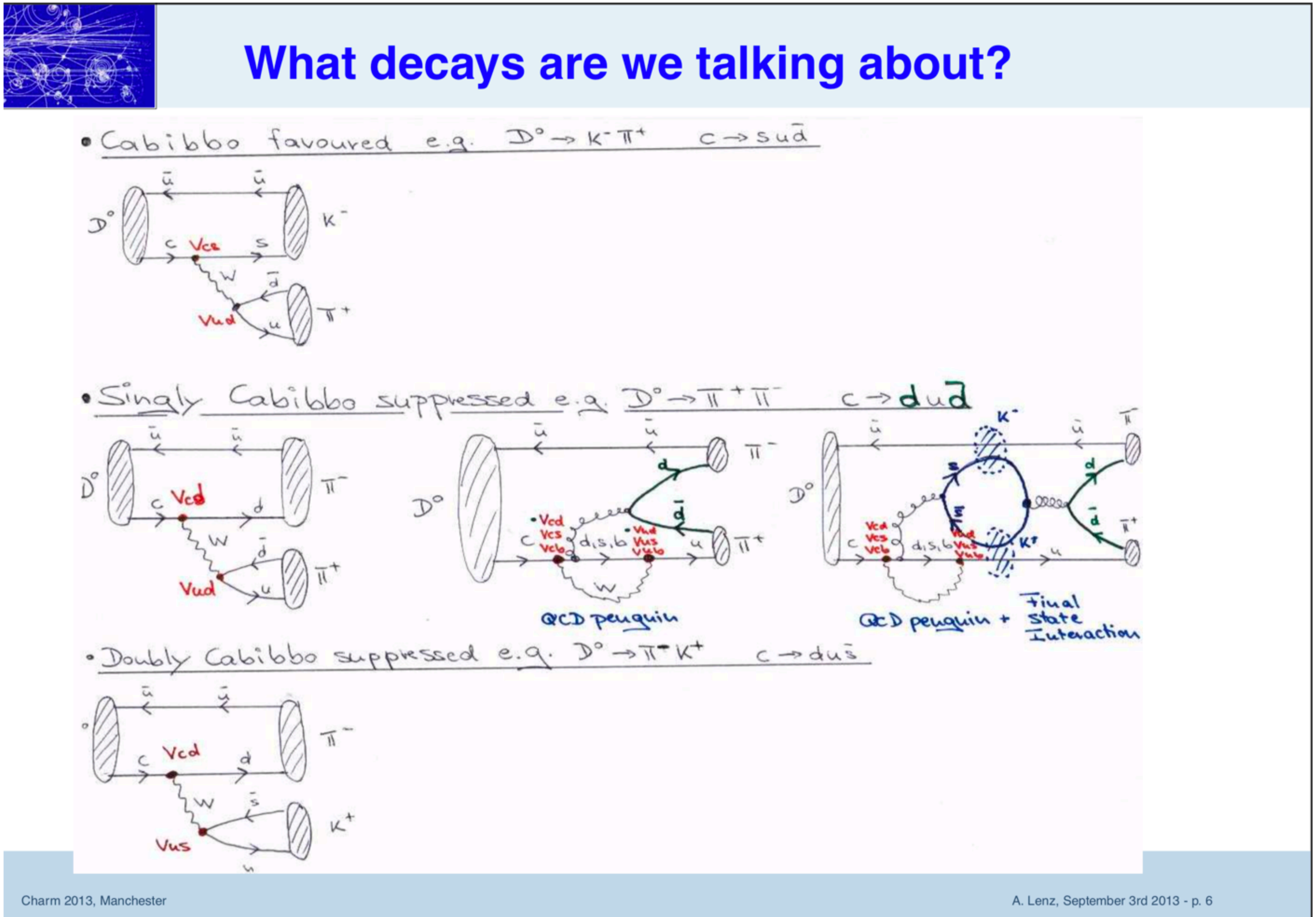
Spring 2019: $\Delta A_{CP}^{\text{Exp.}} = (-15.4 \pm 2.9) \times 10^{-4}$

$$\Delta A_{CP} = A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+)\,, \qquad A_{CP}(f,t) = \frac{\Gamma(D^0(t)\to f) - \Gamma(\overline{D}^0(t)\to f)}{\Gamma(D^0(t)\to f) + \Gamma(\overline{D}^0(t)\to f)}\,.$$

For the first time CPV in the up-quark sector with more than 5 sigma

Experiment	$\Delta A_{CP} \times 10^4$	Tag	arXiv
BaBar	$+24 \pm 62 \pm 26$	pion	0709.2715
LHCb	$-82 \pm 21 \pm 11$	pion	1112.0938
CDF	$-62 \pm 21 \pm 10$	pion	1207.2158
Belle	$-87 \pm 41 \pm 6$	pion	1212.1975
LHCb	$+49 \pm 30 \pm 14$	muon	1303.2614
LHCb	$+14 \pm 16 \pm 8$	muon	1405.2797
LHCb	$-10 \pm 8 \pm 3$	pion	1602.03160
LHCb	$-18.2 \pm 3.2 \pm 0.9$	pion	1903.08726
LHCb	$-9 \pm 8 \pm 5$	muon	1903.08726

3B. CPV in Charm Decays



3B. CPV in Charm Decays

SCS D-decay with $\mathcal{H}_{eff}$ III

$$
\begin{aligned}
\lambda_d &= -s_{12}c_{12}c_{23}c_{13} & -c_{12}^2 s_{23}s_{13}c_{13}e^{i\delta_{13}} \\
\lambda_s &= +s_{12}c_{12}c_{23}c_{13} & -s_{12}^2 s_{23}s_{13}c_{13}e^{i\delta_{13}} \\
\lambda_b &= & + \quad s_{23}s_{13}c_{13}e^{i\delta_{13}}
\end{aligned}
$$

Using unitarity of the CKM matrix - $\lambda_s = -\lambda_d - \lambda_b$ - we get

$$A = \frac{G_F}{\sqrt{2}}\lambda_d \left[\sum_{i=1,2} C_i \langle Q_i^d \rangle^{T+P+E} - \sum_{i=1,2} C_i \langle Q_i^s \rangle^{P+R} + \frac{\lambda_b}{\lambda_d} \left(\sum_{i=3}^{10} C_i \langle Q_i^b \rangle^{T} - \sum_{i=1,2} C_i \langle Q_i^s \rangle^{P+R} \right) \right]$$

We can write

$$A =: \frac{G_F}{\sqrt{2}}\lambda_d T \left[1 + \frac{\lambda_b}{\lambda_d}\frac{P}{T} \right] \Rightarrow \begin{cases} Br & \propto \frac{G_F^2}{2}|\lambda_d|^2 |T|^2 \\ a_{CP} & = 2\left|\frac{\lambda_b}{\lambda_d}\right| \sin\delta \left|\frac{P}{T}\right| \sin\phi = 0.0012 \left|\frac{P}{T}\right| \sin\phi \end{cases}$$

Problem: $|P/T|$ and the strong phase ϕ are unknown!

NAIVE EXPECTATION P/T = 0.1

Welcome to the SAGAland!

3B. CPV in Charm Decays

P/T can currently not be calculated from first principles

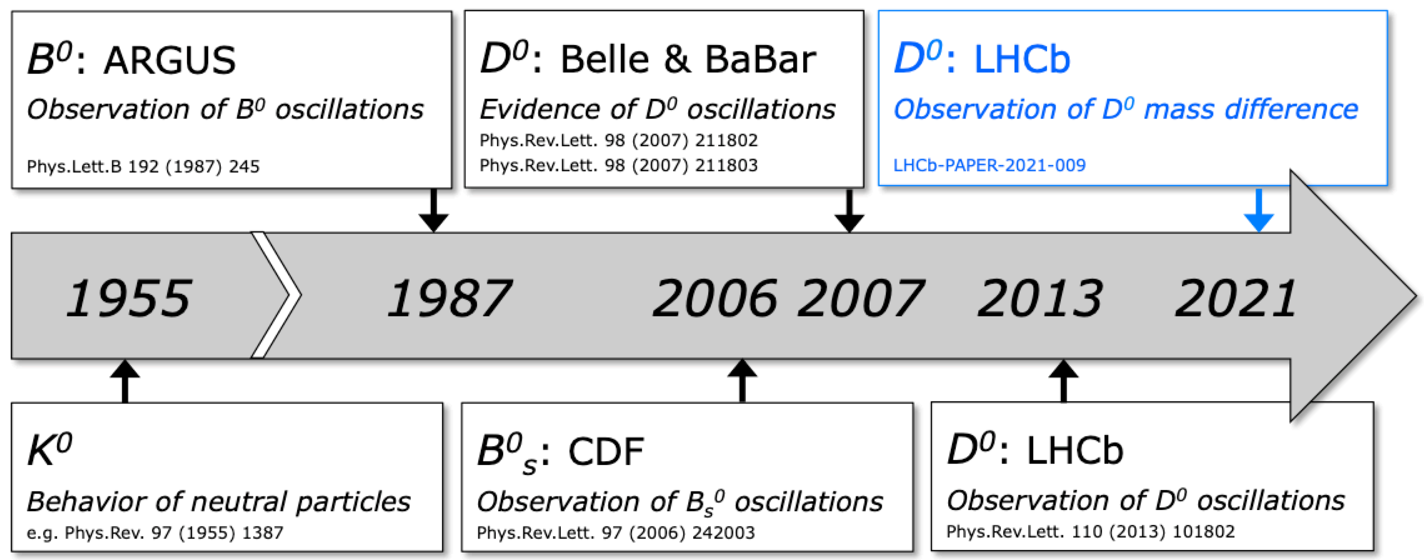
Additional assumptions (ideologies) needed - they might be wrong!

- **Ideology I:** NP = Non-perturbative physics
  - *"Non-perturbative effects are known to be huge"*
    Analogy to the $\Delta I = 1/2$ rule
  - Good starting point for arguing:
    $\sin\phi \approx 1 \Rightarrow P/T = 1.3$ sufficient for $\Delta a_{CP} = -0.00329$
- **Ideology II:** NP = New physics
  - *"Heavy quark expansion and factorisation are known to work well"*
    Analogy to the b-system
  - Good starting point for arguing:
    $\sin\phi \approx 1/10 \Rightarrow P/T = 13$ needed for $\Delta a_{CP} = -0.00329$

- **Direct CPV plus control measurement**
- **Baryonic analogue of $D \to \pi^+\pi^-, K^+K^-$**

Control hadronic contributions in charm system

3B. CPV in Charm Mixing

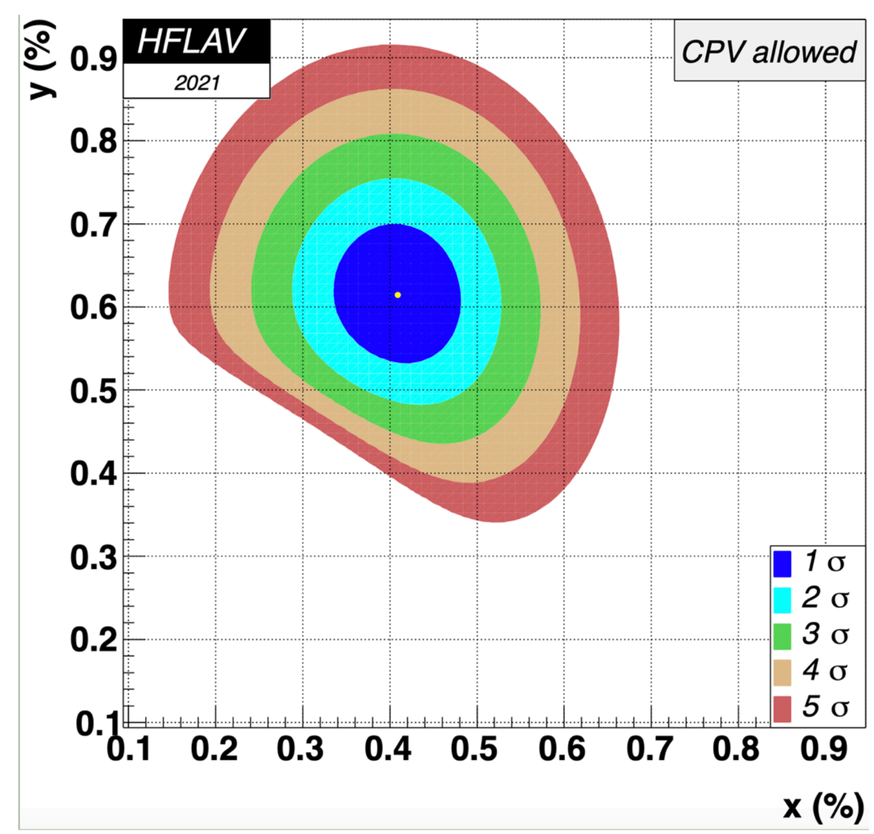


Experimental situation

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

$$y \equiv \frac{\Delta \Gamma_D}{2\Gamma_D} = 6.15^{+0.56}_{-0.55} \cdot 10^{-3}$$

HFLAV July 2021

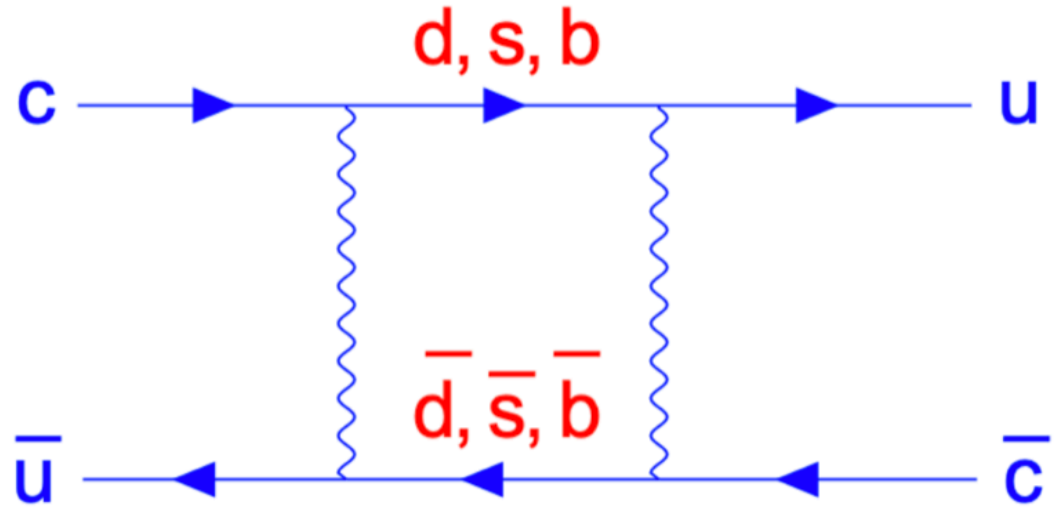


- Small values
- Finally non-vanishing x confirmed
- x and y are similar in size, no hierarchy

3B. CPV in Charm Mixing

CPV

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



survives in SU(3)F limit!

dominant fo[r] B mixing

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

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

3B. CPV in Charm Mixing

1. **Duality violations - break down of HQE**

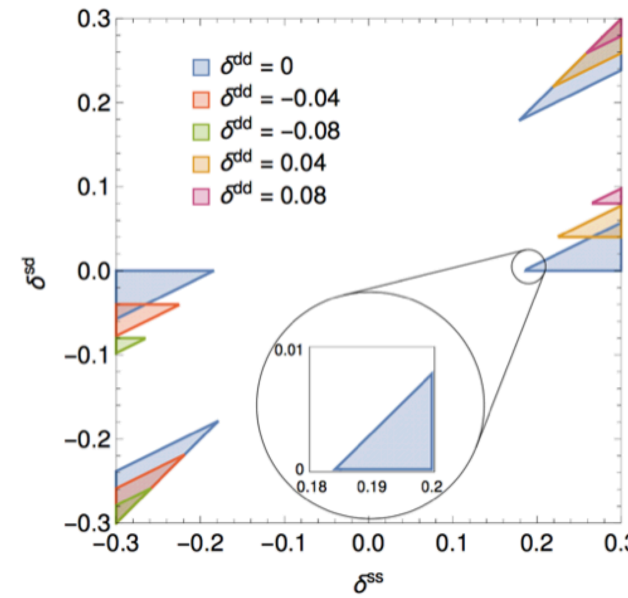
$$\Gamma_{12}^{ss} \rightarrow \Gamma_{12}^{ss}(1+\delta^{ss}) \,,$$

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

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

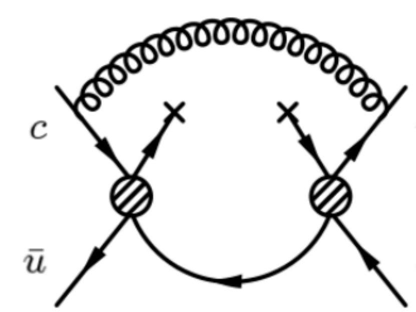
20% of duality violation is sufficient to explain experiment

Jubb, Kirk, AL, Tetlalmatzi-Xolocotzi 2016

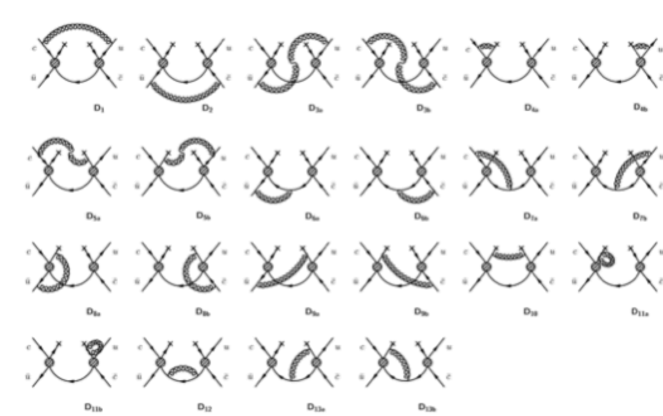


2. **Higher dimensions** Georgi 9209291; Ohl, Ricciardi,Simmons 9301212; Bigi, Uraltsev 0005089

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:-)**

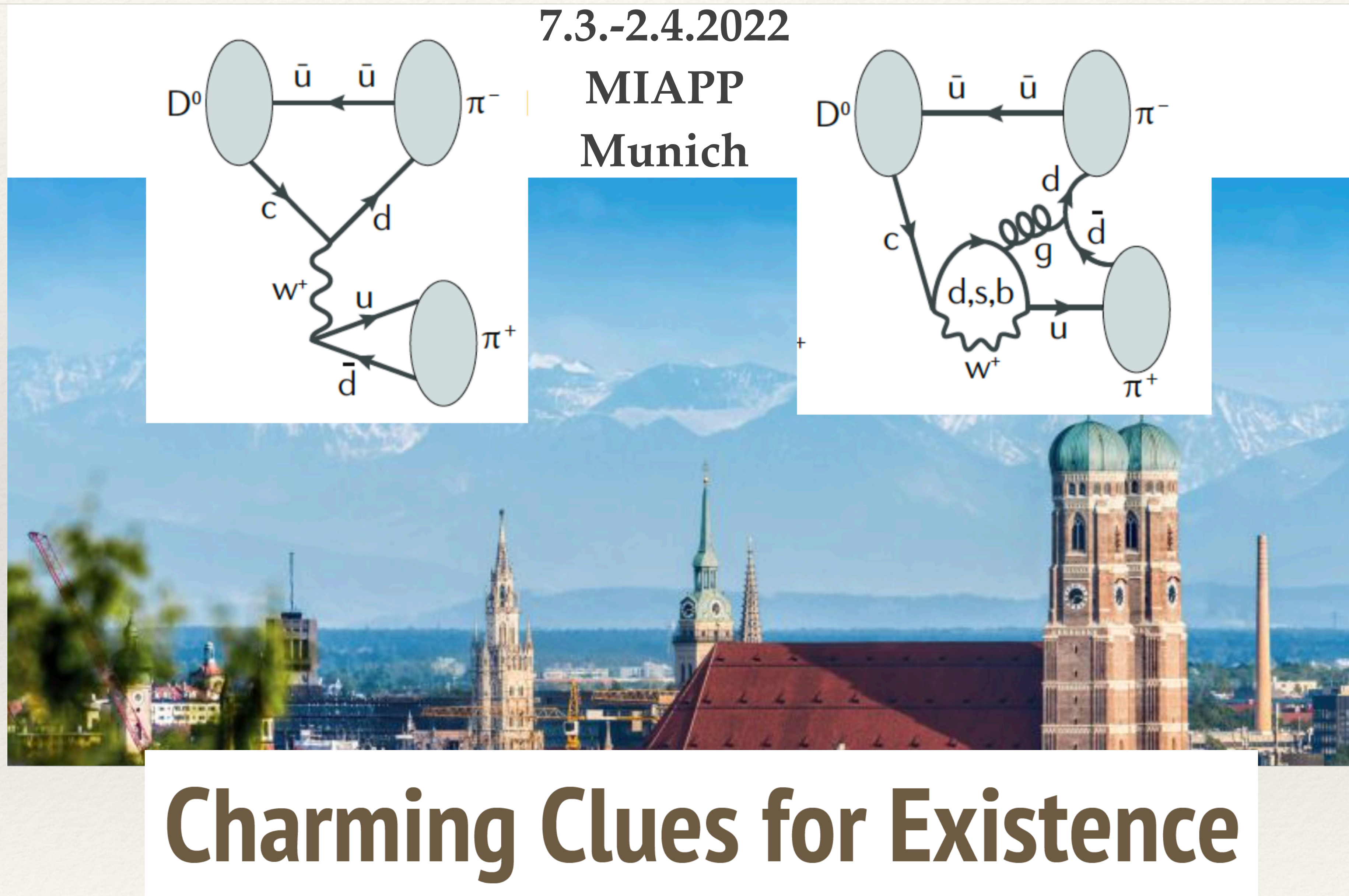
Conclusion: very rich Charm Physics Programme

Some highlights - additional motivation

- Precise Measurements of V_{cs} and V_{cd}
- Inclusive semi-leptonic decays - moment analysis - Precision of HQE in charm sector
- Input for precise determination of γ^{CKM} - BSM in tree-level B decays?
- Search for CPV in charm decays: Baryogengesis, CPV in charged D decays
- Search for CPV in charm decays: ΔA_{CP} is SM or BSM?
- CPV in charm mixing

- Rare Charm decays
- Exotics
- …

First ever Charm Physics event at MIAPP



Coordinators:
Eva Gersabeck
Marco Gersabeck
Alexander Lenz
Stephan Paul
Danny van Dyk
Guy Wilkinson

Charming Physics in Siegen

HQET decays → E.o.w. (?)

$$\Gamma = \Gamma_3 + \Gamma_5 \frac{\langle O_5 \rangle}{m_c^2} + \Gamma_6 \frac{\langle O_6 \rangle}{m_c^3} + \ldots + 16\pi^2 \left[\tilde{\Gamma}_6 \frac{\langle \tilde{O}_6 \rangle}{m_c^3} + \tilde{\Gamma}_7 \frac{\langle \tilde{O}_7 \rangle}{m_c^4} + \ldots \right]$$

NLO, LO, LO, NLO, LO

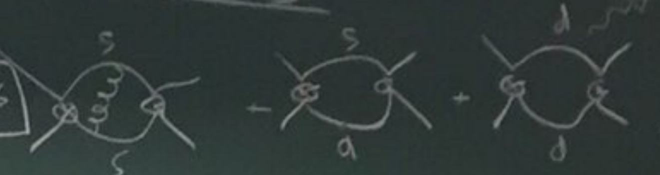
SR
NNLO
NNNLO
∀

Γ_{tot} of D^+, D_s^+, D_0
$\tau(D^+)/\tau(D_0)$
$\tau(D_s^+)/\tau(D_0)$
Γ_{sl} of D^+, D_s^+, D_0

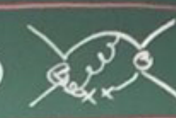
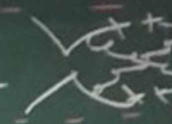
Aleksey R., Maria Laura, AL

- semi-lept. moments TM
- re-ordering of HQE. TM, Alexei, Daniel
- charm quark mass concepts. TM, Anastasia
  - → observable in terms of observable

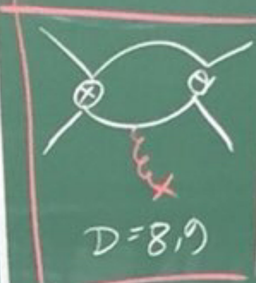
$\sim \tau(\Lambda_c \ldots)$ Ω_c

D=6 

Georgi; Ohl..., Bigi, Uraltsev

D=9  ; D=12 

$\Gamma_{ss} - 2\Gamma_{sd} + \Gamma_{dd} \to 1.62$
$\to 1.62 - 1.17 \frac{m_s^2}{m_c^2}$
$\to 1,62 - 2,34 \frac{m_s^2}{m_c^2} + 5.07$



→? CP in m

CP: $\Delta A_{CP} = A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-)$ → $>5\sigma$

- Petrov, AK: LCSR: $\left|\frac{A_P}{A_T}\right|$
- BSM: Rusov, AL

$D^0 \to K^* K, \rho\pi$ AK

$\cdot \Lambda_c \to p\pi, K$ AK

Rare: $D^0 \to K^+K^-\mu^+\mu^-$ Oscar, → LHCb

$e^+e^- \to D^*$ AK, TM, Petrov

STX, AK
$D \to \pi\pi \ell\nu \to 2\pi$-DA
→ BES,

$SU(4)_F$ vs Gell-mann Okubo?

Exotic states