Charm Physics

From Standard Model to New Physics

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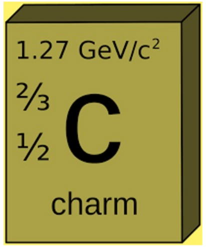
17–21 Jul 2023, Siegen

Outline



c-QUARK MASS	1.27 ± 0.02 GeV
m_c/m_s MASS RATIO	$11.76^{+0.05}_{-0.10}$
m_b/m_c MASS RATIO	4.58 ± 0.01
$m_b - m_c$ QUARK MASS DIFFERENCE	3.45 ± 0.05 GeV

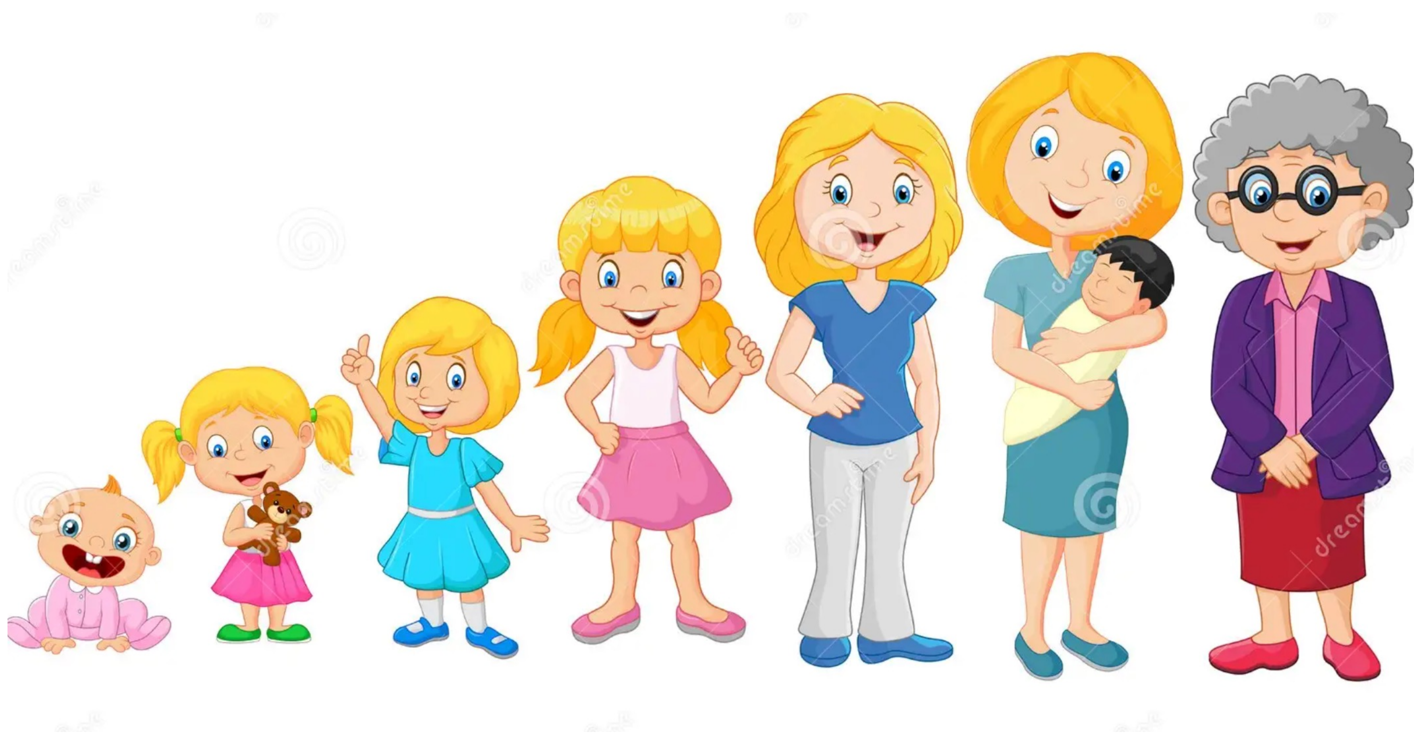
Introduction

SM interactions in CHARM PHYSICS →

- QCD (Spectroscopy, Lattice QCD)
- Electroweak interactions $SU(2)_L \times U(1)_Y$
- $\Delta C = 1$, $\Delta C = 2$ processes
- CP violation

Search for NP at low and high energies with charm

Introduction



1974

2023

Charm discovery

Not yet 50!

Charm - theory predictions

- 1964, James Bjorken and Sheldon Glashow speculated on "charm" as a new quantum number
- In 1970, Glashow, John Iliopoulos, and Luciano Maiani proposed a new quark classified by the charm quantum number. The charmed quark could provide a mechanism – **the GIM mechanism**

PHYSICAL REVIEW D VOLUME 2, NUMBER 7 1 OCTOBER 1970

Weak Interactions with Lepton-Hadron Symmetry*

S. L. Glashow, J. Iliopoulos, and L. Maiani†
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02139

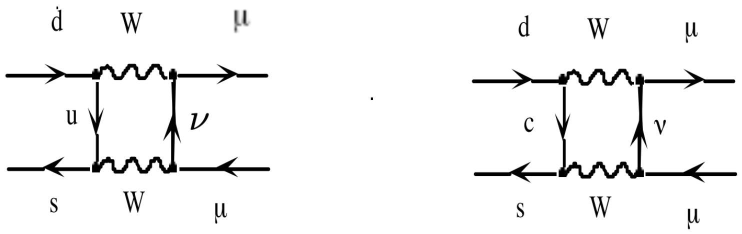
(Received 5 March 1970)

We propose a model of weak interactions in which the currents are constructed out of four basic quark fields and interact with a charged massive vector boson. We show, to all orders in perturbation theory, that the leading divergences do not violate any strong-interaction symmetry and the next to the leading divergences respect all observed weak-interaction selection rules. The model features a remarkable symmetry between leptons and quarks. The extension of our model to a complete Yang-Milis theory is discussed.

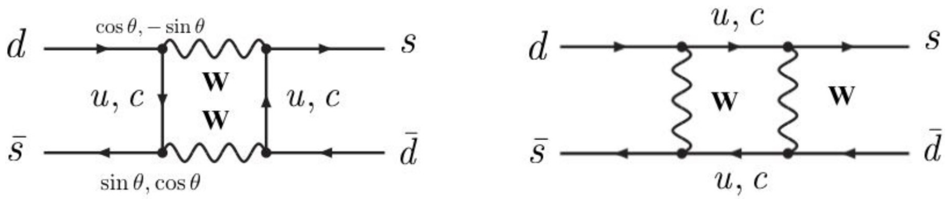
GIM mechanism

$K^0 \to \mu^+\mu^-$

1970:



$K^0 \leftrightarrow \bar{K}^0$



Why this decay amplitude is suppressed!

- vanishes for $m_c = m_u$
- finite amplitude of order $m^2_c - m^2_u \approx (3 - 4\ \mathrm{GeV})^2$ (Ioffe and Shabalin)
- prediction for charm quark mass $m_c \simeq 1.5\,\mathrm{GeV}$

Why important?

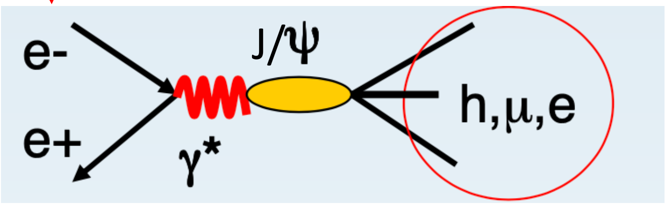
- Help to establish weak interactions quark left-handed doublets
- Quark-lepton symmetry
- Quark mixing matrix U is real, due to suitable redefinitions of the relative phases of the quarks makes U real and orthogonal (Cabibbo angle); no CP violation
- Charmed particles should be found!
- GIM: FCNC processes arise to order $\mathcal{O}(m_c^2)$

Experiment "November revolution" 1974

J/ψ discovery

BNL: J.J. Auber et al, PRL 33 (1974) 1404

SLAC: J.-E. Augustin et al, PRL (1974) 1406



$$m(J/\psi) = 3096.9 \pm 0.006\,\mathrm{MeV}$$

$$\Gamma(J/\psi) = 92.6 \pm 1.7\,\mathrm{keV}$$

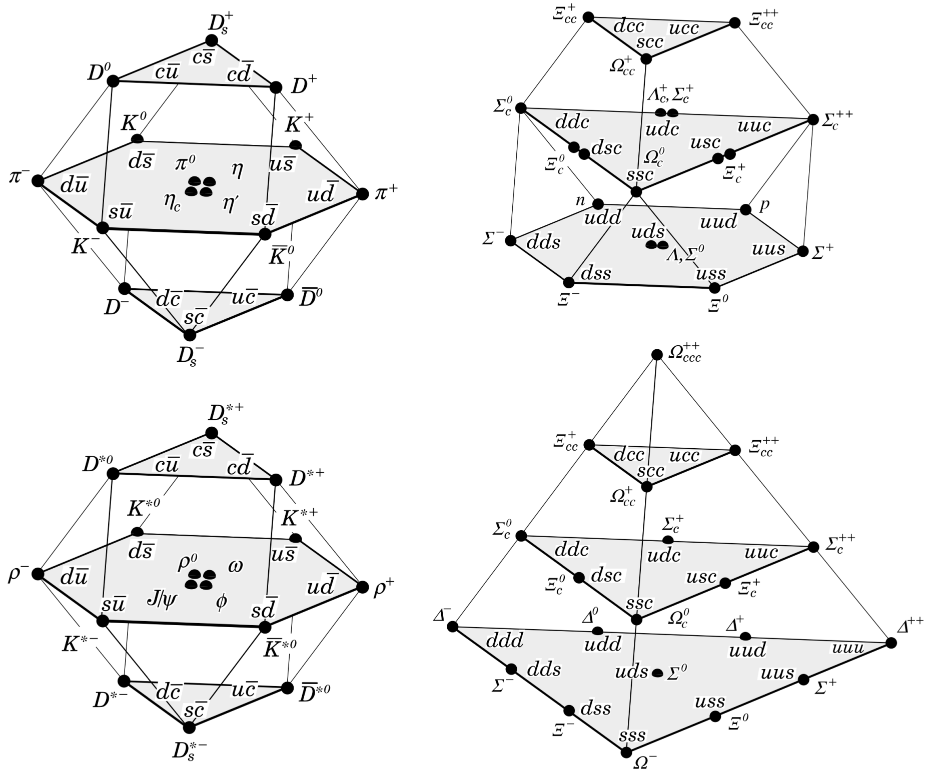
$$I^G(J^{PC}) = 0^-(1^{--})$$

1976 Nobel prize in Physics

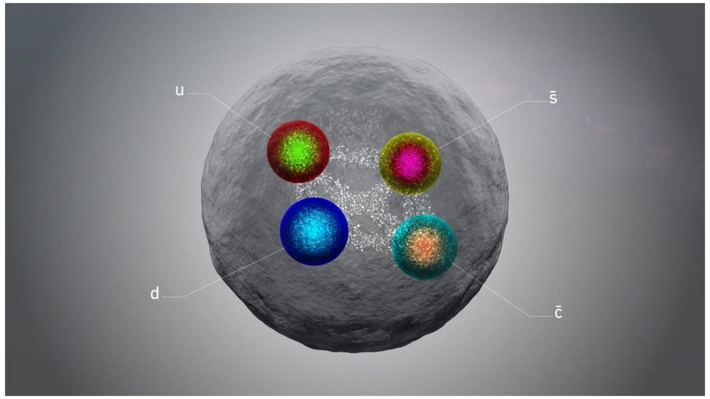
Burton Richter

Samuel Chao Chung Ting

After 1974 many charm hadrons



Exotic multi-quark states



X(3872), X(3915), Y(4220), Z_c(3900), Z_c(4020), Z(4430)…

From M. Petran et al, Computer Physics Communications 185, (2014), 2056

SM interactions in CHARM PHYSICS

QCD

- To understand spectra of hadronic states containing one, two charm quarks
- Processes with charm quarks, e.g. strong decays
  Charm quark presence in nucleons
  Charmed hadron lifetimes
- Charm quark in high energy processes (LHC and at future colliders)
- QCD contributions in weak processes, $\Delta C = 1$
  charm mesons, nonleptonic, semileptonic and leptonic decays,
  $\Delta C = 2$ in $D^0 - \bar{D}^0$ oscillations

From quark models to Lattice QCD

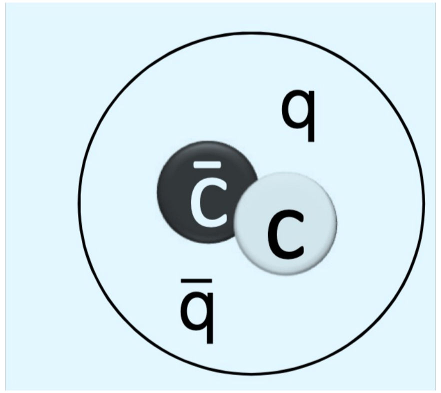
Hadronic spectra

Gell-Mann (1964)

The idea of quarks, with mesons as $\bar{q}q$ and baryons as qqq.
He also pointed out the possibility of multiquark states $\bar{q}\bar{q}qq$ mesons and $\bar{q}qqqq$ baryons.

R.R Jaffe (1977)

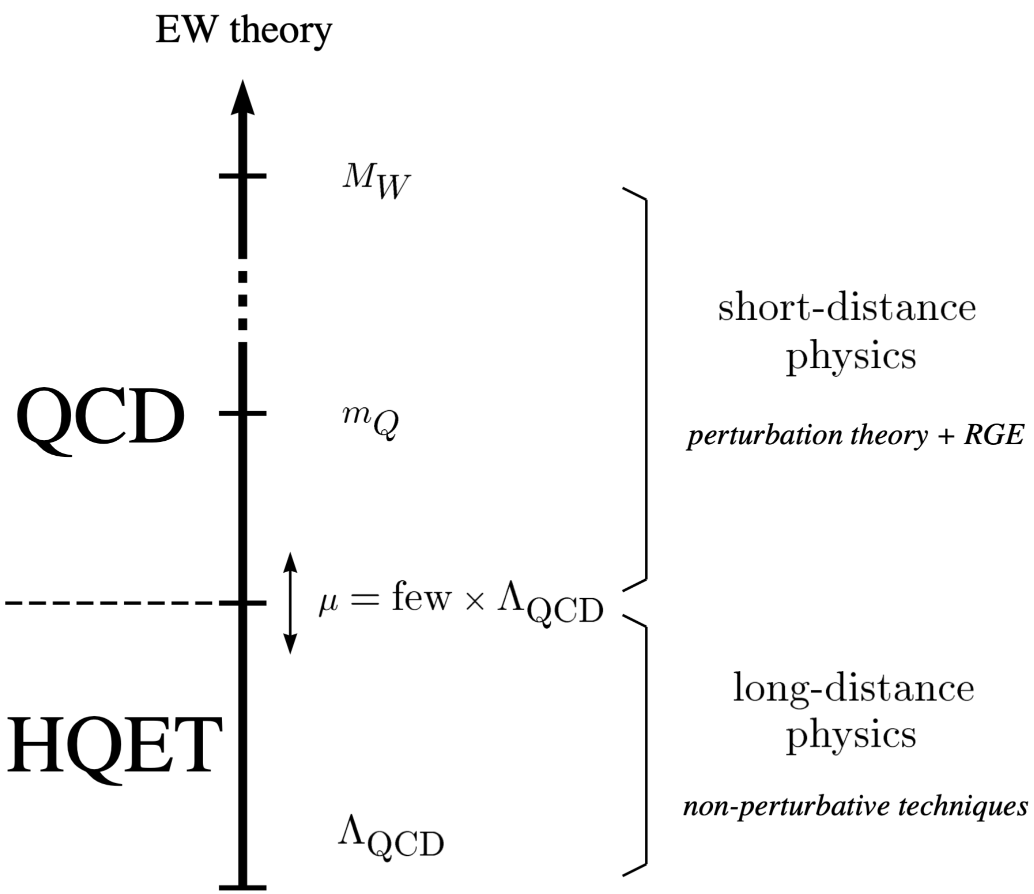
Multi-Hadrons – MIT bag model



“Multiquark states with heavy quarks are very different. This is where QCD dynamics enters. To paraphrase Orwell: all quarks are equal, but the heavy quarks are more equal then others.”
Brambilla et al., 2203.16583

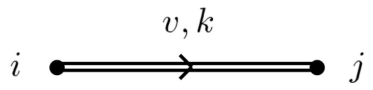
Snowmass 2021

See talks Polosa, Collins, Spradin, Ortega

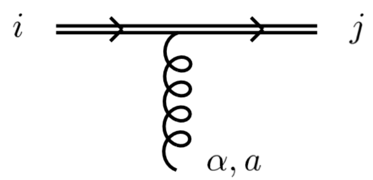


$$m_Q \to \infty$$

$$\mathcal{L}_\infty = \bar{h}_v \, iv\cdot D \, h_v$$



$$= \frac{i}{v\cdot k + i\eta} \frac{1+\not{v}}{2} \delta_{ji}$$



$$= i \; {}_s v^\alpha (t_a)_{ji}$$

WEAK TRANSITION FORM-FACTORS BETWEEN HEAVY MESONS #8
Nathan Isgur (Toronto U.), Mark B. Wise (Caltech) (Feb 5, 1990)
Published in: *Phys.Lett.B* 237 (1990) 527-530
DOI cite claim reference search 1,985 citations

Weak Decays of Heavy Mesons in the Static Quark Approximation #9
Nathan Isgur (Toronto U.), Mark B. Wise (Caltech) (Oct 30, 1989)
Published in: *Phys.Lett.B* 232 (1989) 113-117
DOI cite claim reference search 2,393 citations

Neubert, hep-ph/9610266

- theoretical frameworks for exotics rely in one way or another on $\Lambda_{QCD}/m_{b,c} \ll 1$

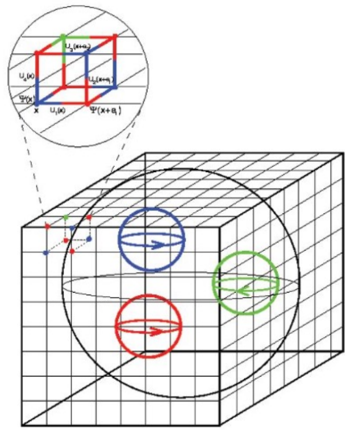
- Being heavy $m_{b,c}$ can be treated as nonrelativistic, (potential models, lattice calculations)

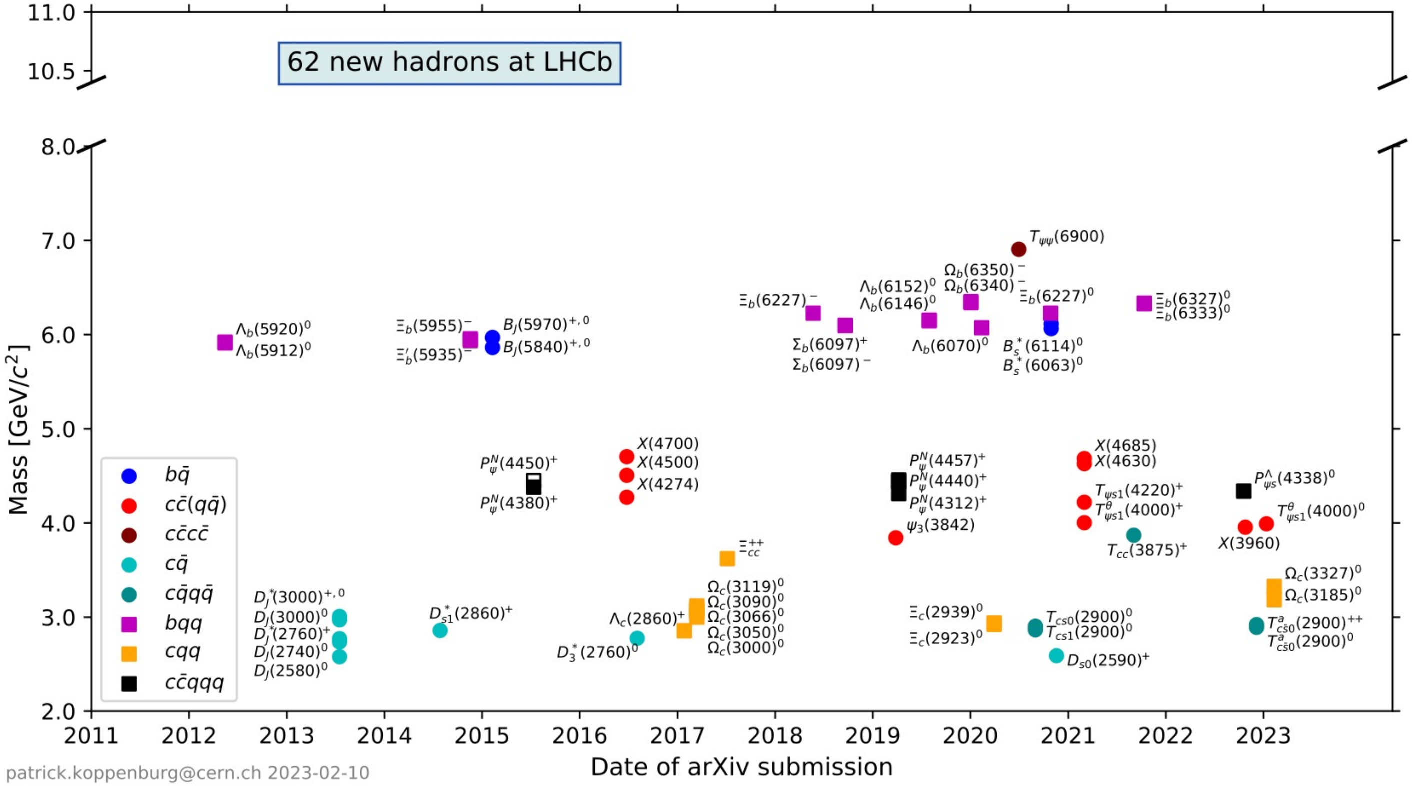
- The scale $m_{b,c}$ is heavy enough to belong to the asymptotic freedom region of QCD, allowing for an operator expansion in powers of $1/m_{b,c}$
(heavy-quark spin effective theory, QCD sum rules)

- the internal structure of many such heavy-light systems likely provides a natural mechanism resulting in a narrow width

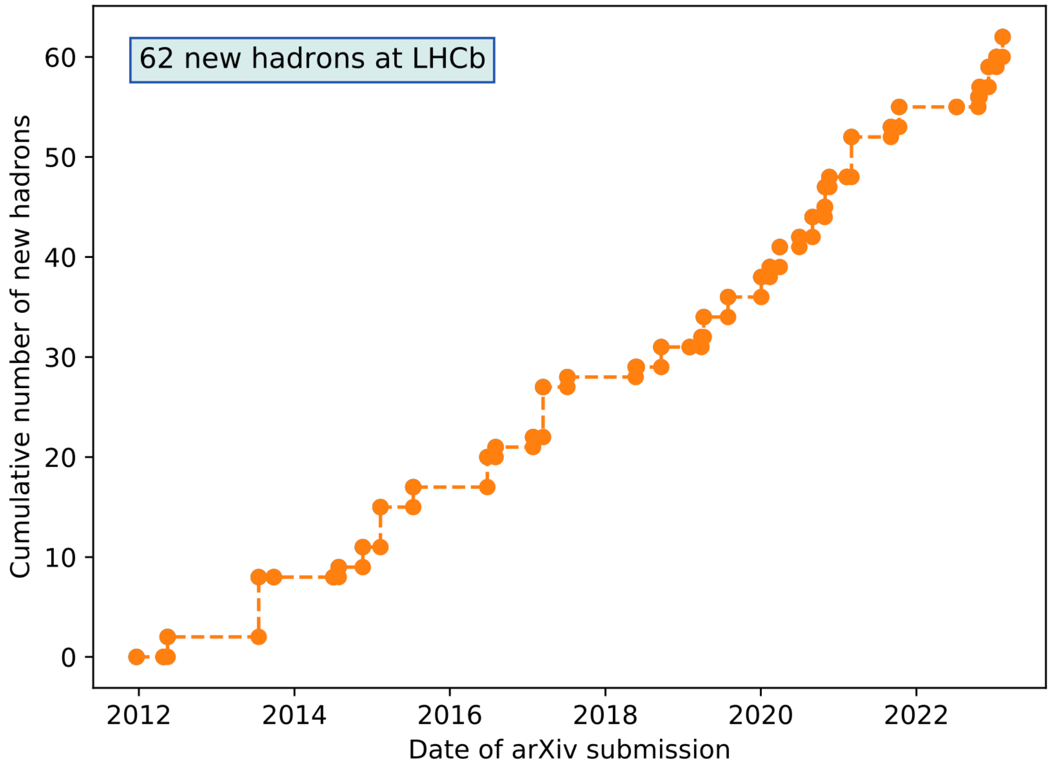
- the attraction between two heavy quarks scales like $\alpha_s^2 m_Q$, growing approximately linearly with the heavy quark mass

- advantage of having heavy quarks c and b in muliti-quark states:
the large mass of the heavy quarks greatly reduces their kinetic energy, making it easier for them to form multiquark clusters with the light quarks.



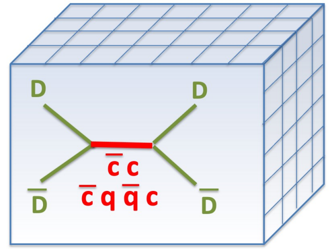


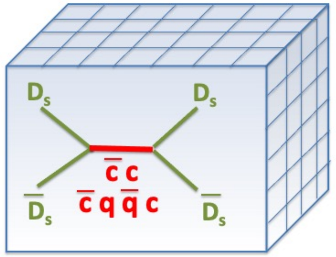
62 new hadrons at LHCb
Mass [GeV/c²]
Date of arXiv submission
bq̄
cc̄(qq̄)
cc̄cc̄
cq̄
cq̄qq̄
bqq
cqq
cc̄qqq
Λb(5920)⁰
Λb(5912)⁰
Ξb(5955)⁻
Ξ′b(5935)⁻
BJ(5970)+,0
BJ(5840)+,0
Ξb(6227)⁻
Σb(6097)+
Σb(6097)⁻
Λb(6152)⁰
Λb(6146)⁰
Λb(6070)⁰
Ωb(6350)⁻
Ωb(6340)⁻
Tψψ(6900)
Ξb(6227)⁰
B*s(6114)⁰
B*s(6063)⁰
Ξb(6327)⁰
Ξb(6333)⁰
X(4700)
X(4500)
X(4274)
X(4685)
X(4630)
X(3960)
ψ3(3842)
Ξcc++
DJ*(3000)+,0
DJ(3000)⁰
DJ*(2760)+
DJ(2740)⁰
DJ(2580)⁰
D*s1(2860)+
D*3(2760)⁰
Λc(2860)+
Ωc(3119)⁰
Ωc(3090)⁰
Ωc(3066)⁰
Ωc(3050)⁰
Ωc(3000)⁰
Ξc(2939)⁰
Ξc(2923)⁰
Tcs0(2900)⁰
Tcs1(2900)⁰
Ds0(2590)+
Tcc(3875)+
Ωc(3327)⁰
Ωc(3185)⁰
patrick.koppenburg@cern.ch 2023-02-10

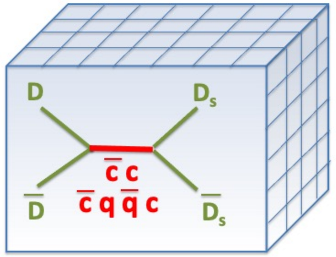


62 new hadrons at LHCb
Cumulative number of new hadrons
Date of arXiv submission

Charmonium(like) resonances and bound states







Lattice QCD: nonperturbative approach to QCD

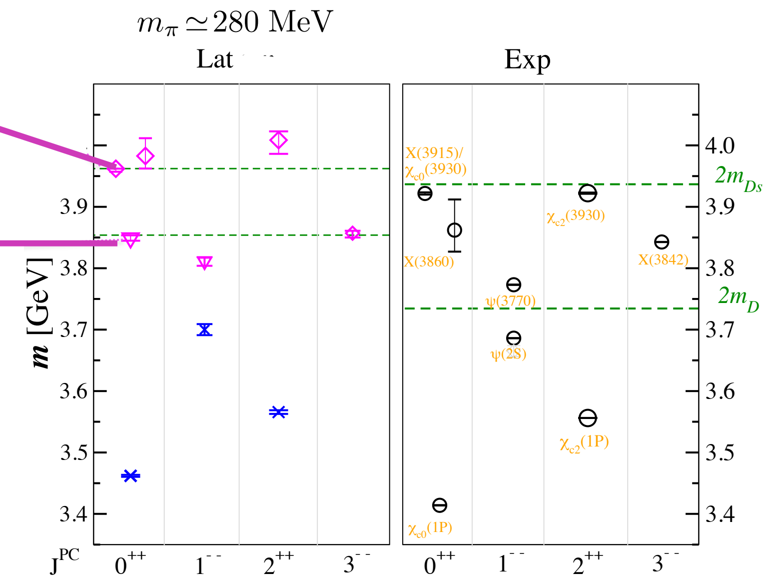
$$\bar{D}_s D_s \;\; J^P = 0^+$$

likely related to X(3915) / $\chi c0$ (3930) [BaBar, LHCb 2009.00026]; explaining why it has narrow width to DD. Predicted by Lebed, Polosa 1602.08421

$$\bar{D} D \;\; J^P = 0^+$$

predicted in models [Oset et al, 0612179 PRD, Hildago Duque et al 1305.4487, Baru et al 1605.09649 PLB]

seen in dispersive analysis of exp. data [Deineka, Danilkin et al 2111.15033]



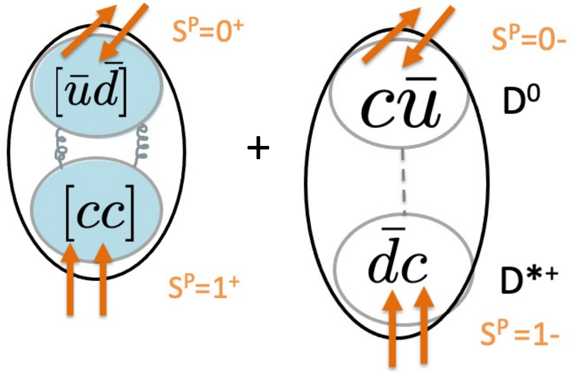
Prelovsek , Collins, Padmanath, Mohler, Piemonte 2011.02541 , 1905.03506 , 2111.02934

Courtesy of Saša Prelovsek

Doubly charm tetraquark T_{cc} from lattice QCD

Molecules or diquarks?

$cc\bar{d}\bar{u}$



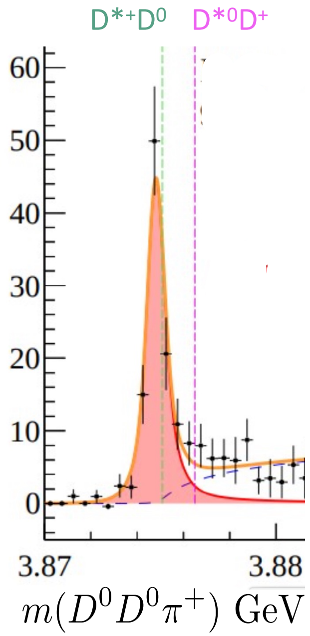
likely dominant

Padmanath, Prelovsek: 2202.101101

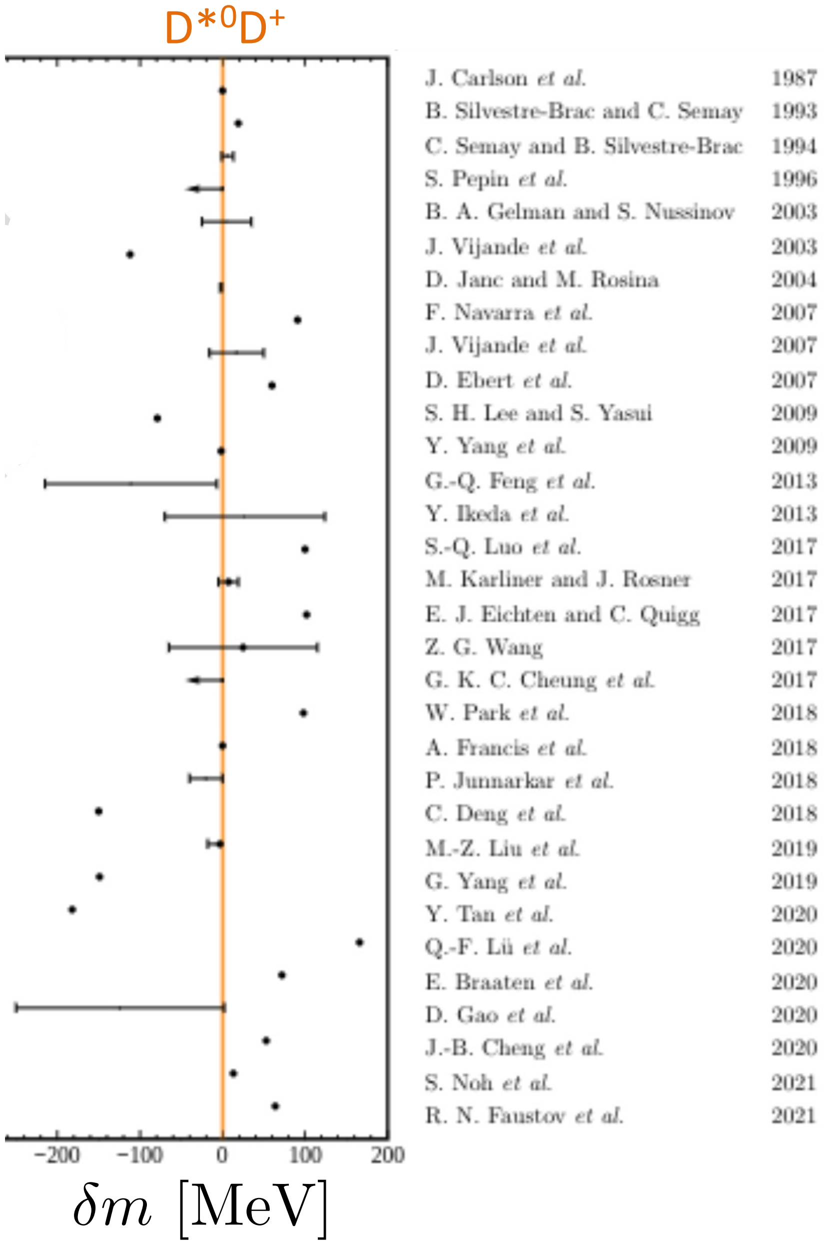
$$\delta m = m - (m_{D^{*+}} + m_{D^0})$$

$$\delta m_{pole} = -0.36 \pm 0.04 \text{ MeV}$$

LHCb 2109.01038, 2109.01056



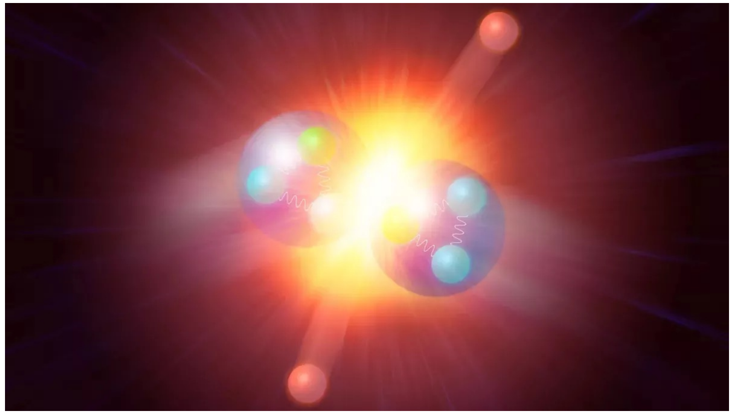
See talks He, Ortega



Theoretical predictions for T_{cc} mass ($I=0$, $J^P=1^+$)

Evidence for intrinsic charm quarks in the proton

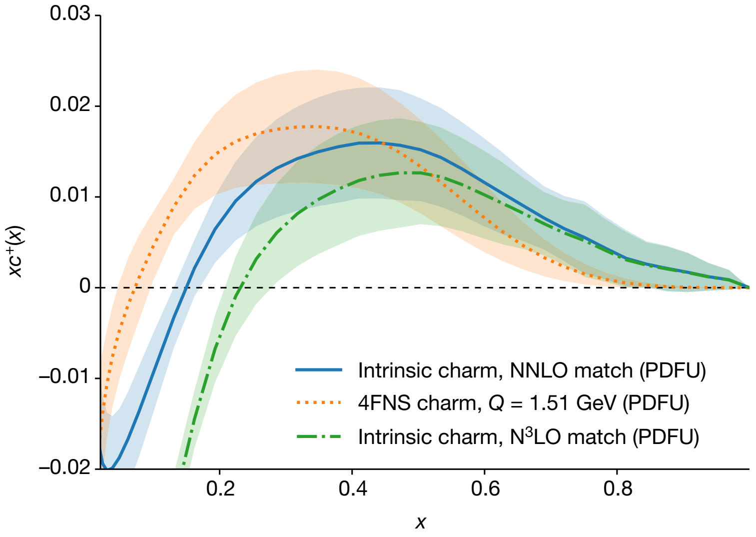
Nature **608**, pages 483–487 (2022)
NNPDF Collaboration

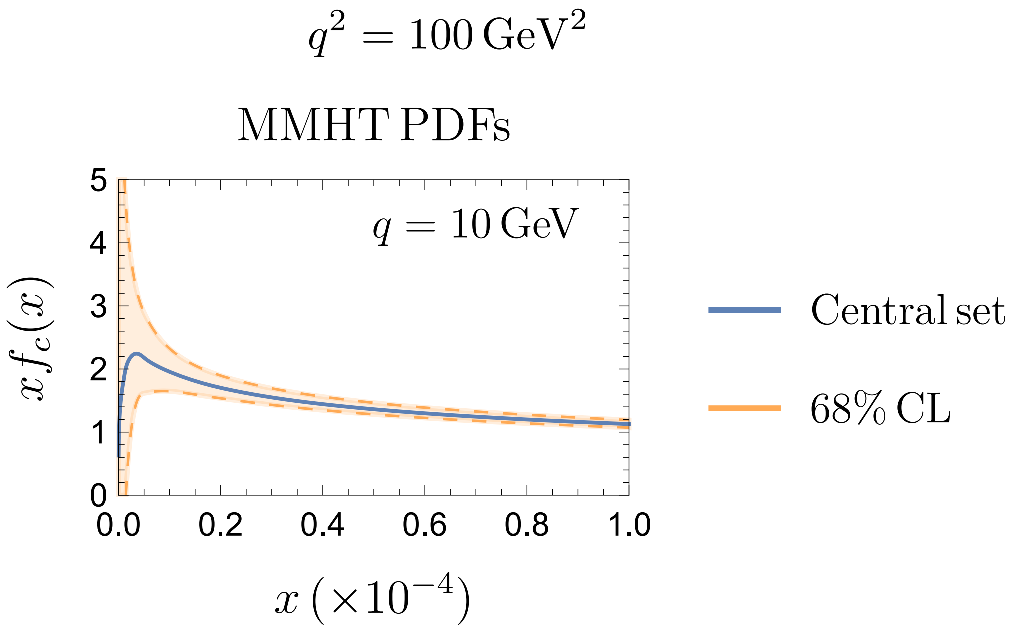


NNPDF:
Univ. Cambridge, Edinburgh,
Milan- INFN, Nikhef and VU Univ.
Amsterdam, Univ. Torino, NUS Singapore,
Univ. Wirzburg

- intrinsic charm content of proton by exploiting a high-precision determination of the quark–gluon content;
- remarkable agreement with model predictions (Brodsky et al., 1980, Hobbs et al.,2014);
- these findings are compared to very recent data on *Z*-boson production with charm jets from the Large Hadron Collider beauty (LHCb) experiment;
- charm PDF are obtained from hard-scattering global dataset, using perturbative QCD calculations, accommodating massive quarks inside the proton and machine learning techniques;
- next-to-next-to-leading order (NNLO) in an expansion in powers of the strong coupling, α_s, are performed

It is intrinsic to distinguish it from that computable in perturbation theory,which originates from QCD radiation





the PDFs of the 3FNS, only the three lightest quark flavours are radiatively corrected

$q \equiv |q^2|^{1/2}$

the purely intrinsic (3FNS) result (blue) with PDFU alone, compared to the 4FNS PDF, which includes both an intrinsic and a radiative component, at $Q = m_c = 1.51$ GeV (orange). The purely intrinsic (3FNS) result obtained using N3LO matching is also shown (green). (FNS – flavour number scheme)

Following Martin, Motylinski, Harland-Lang, Thorne (MMHT) 1704.00162

Courtesy of Arman Korajac

- charm PDF, by indirect constraints from high-precision LHC data, is consistent with direct constraints from both EMC charm production data (40 years ago), and recent Z + charm production data in the forward region from LHCb.
- local significance for intrinsic charm in the large-x region just above the 3σ level.

Charmed hadrons lifetimes

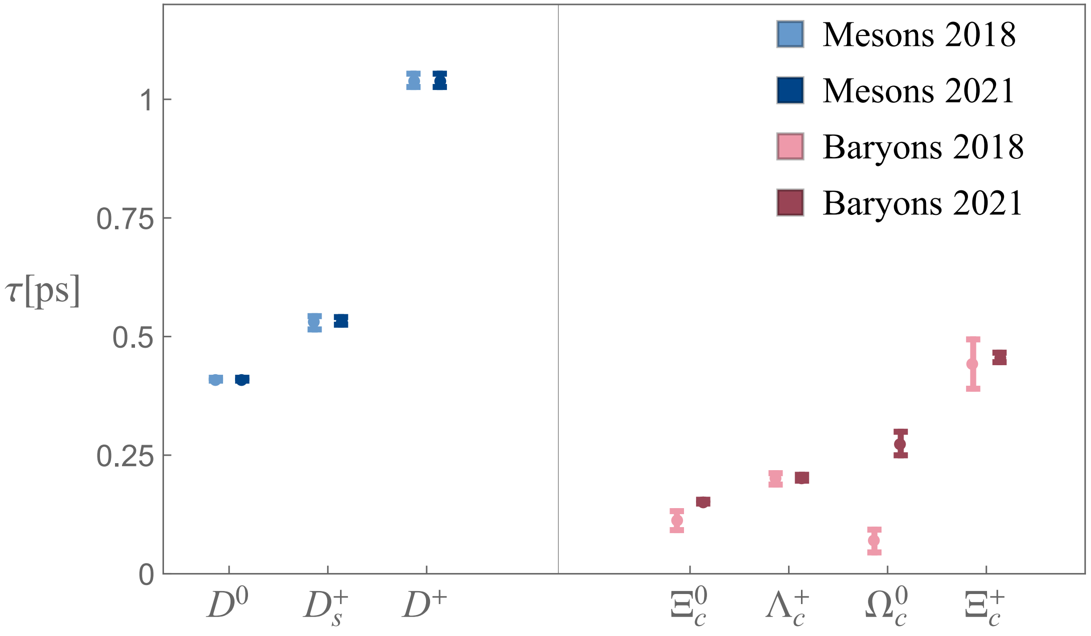
$$\frac{\tau(D^+)}{\tau(D^0)} = 2.54(2)$$

Heavy quark expansion

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

See King et al., 2109.13219

"The total decay rates of the D^0 and D^+ mesons are underestimated in our HQE approach and we suspect that this is due to missing higher-order QCD corrections to the free charm quark decay and the Pauli interference contribution."



Experimentally established hierarchy for charmed baryons

$$\tau(\Xi_c^0) < \tau(\Lambda_c^+) < \tau(\Omega_c^0) < \tau(\Xi_c^+)$$

Dulibic et al., 2305.02243

See talks Melic, Davis

See talk Hai-Yang Cheng

QCD in electroweak interactions of charm

- Charge current decays: leptonic and semileptonic
- FCNC processes, D mixing and rare decays
- Nonleptonic decays and CP asymmetry

QCD needed!

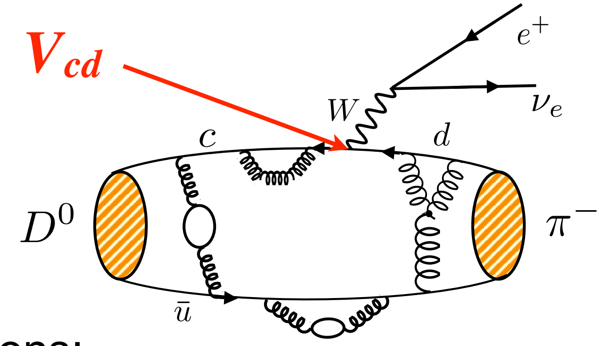
Short distance dynamics $m_c \gg \Lambda_{QCD}$,
$m_{u,d,s} < \Lambda_{QCD}$

Long distance dynamics

Lattice QCD, if applicable CχPT
HQET difficult to apply, m_c not heavy enough $1/m_c$
$(1/m_c)^2$,... corrections relevant!

Lattice QCD in leptonic and semileptonic

example: $D \to \pi \ell \nu$



Why important?

generic weak process involving hadrons:

(experiment) = (known) x (**CKM element**) x (had. matrix element)

$\Gamma_{K\ell 3}, \Gamma_{K\ell 2}, \ldots$ → (experiment)

Lattice QCD → (had. matrix element)

Lattice calculates
D meson's decay constants, D meson D→ P, V form factors, bag parameters for meson oscillations

See for review 2206.07501 and Jay's talk at this conference

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

PDG 2022

2206.07501 HFLAV

Mode	$\mathcal{B}$ (10^{-4})	$f_D|V_{cd}|$ (MeV)	Reference
$\mu^+\nu_\mu$	$3.95 \pm 0.35 \pm 0.09$	$47.2 \pm 2.1 \pm 0.5 \pm 0.2$	CLEO-c
	$3.71 \pm 0.19 \pm 0.06$	$45.7 \pm 1.2 \pm 0.4 \pm 0.2$	BESIII
	$\mathbf{3.77 \pm 0.17 \pm 0.05}$	$\mathbf{46.1 \pm 1.0 \pm 0.3 \pm 0.2}$	**Average**
$\tau^+\nu_\tau$	$12.0 \pm 2.4 \pm 1.2$	$50.4 \pm 5.0 \pm 2.5 \pm 0.2$	BESIII
$\boldsymbol{\mu^+\nu_\mu + \tau^+\nu_\tau}$		$\mathbf{46.2 \pm 1.0 \pm 0.3 \pm 0.2}$	**Average**
$e^+\nu_e$	< 0.088 at 90% C.L.		CLEO-c

Reference	Method	N_f	f_D(MeV)	f_{D_s}(MeV)	f_{D_s}/f_D
Fermilab/MILC 17 [31]	LQCD	2+1+1	212.1(0.3)(0.5)	249.9(0.3)(0.3)	1.1782(06)(15)*
ETM 14 [32]	LQCD	2+1+1	207.4(3.7)(0.9)	247.2(3.9)(1.4)	1.192(19)(11)
FLAG 21 average [2]	LQCD	2+1+1	212.0(0.7)	249.9(0.5)	1.1783(16)
χQCD 20A [73]	LQCD	2+1	213(5)	249(7)	1.16(3)
RBC/UKQCD 18A [74]†	LQCD	2+1	–	–	1.1740(51)(68)
RBC/UKQCD 17 [75]	LQCD	2+1	$208.7(2.8)(^{+2.1}_{-1.8})$	$246.4(1.3)(^{+1.3}_{-1.9})$	$1.1667(77)(^{+57}_{-43})$
χQCD 14 [76]	LQCD	2+1	–	254(2)(4)	–
HPQCD 12 [77]	LQCD	2+1	208.3(1.0)(3.3)	–	1.187(4)(12)
Fermilab/MILC 11 [78]	LQCD	2+1	218.9(9.2)(6.6)	260.1(8.9)(6.1)	1.188(14)(21)
HPQCD 10 [79]	LQCD	2+1	–	248.0(1.4)(2.1)	–
FLAG 21 average [2]	LQCD	2+1	209.0(2.4)	248.0(1.6)	1.174(7)
Pullin 21 [80]	QCD SR		190(15)	226(17)	1.19(7)
Wang 15 [81]‡	QCD SR		208(10)	240(10)	1.15(6)
Gelhausen 13 [82]	QCD SR		$201\left(^{+12}_{-13}\right)$	$238\left(^{+13}_{-23}\right)$	$1.15\left(^{+0.04}_{-0.05}\right)$
Narison 12 [83]	QCD SR		204(6)	246(6)	1.21(4)
Lucha 11 [84]	QCD SR		206.2(8.9)	245.3(16.3)	1.193(26)

$$f_{D^+} = 212.0(7)\ \text{MeV}\,, \quad f_{D_s} = 249.9(5)\ \text{MeV}\,, \quad \frac{f_{D_s}}{f_{D^+}} = 1.1783(16)\,.$$

Electromagnetic corrections are very important to achieve the precission.

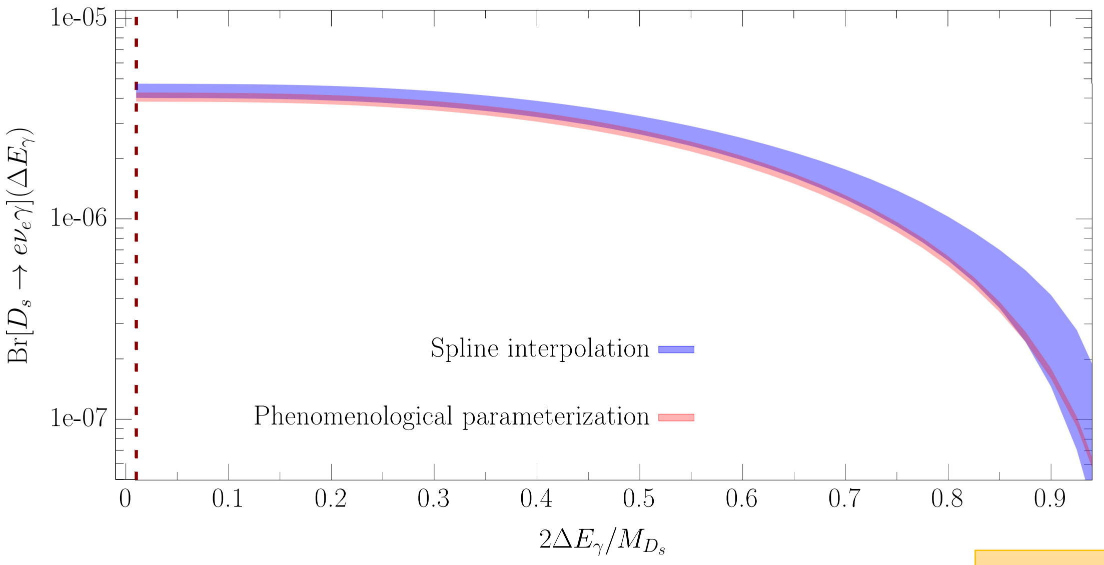
D_s meson radiative form factors

Lattice QCD contributed recently by the D_s meson radiative form factors over the full kinematical range
Frezzotti et al., (Rome& Southampton)
2306.05904

$$H_W^{r\nu}(k,\boldsymbol{p}) = \epsilon_\mu^r(k)\, H_W^{\mu\nu}(k,\boldsymbol{p}) = \epsilon_\mu^r(k) \int d^4y\, e^{ik\cdot y}\, \langle 0|\, \hat{\mathrm{T}}[\, j_W^\nu(0) j_{\mathrm{em}}^\mu(y)]\, |D_s^+(\boldsymbol{p})\rangle$$

$$j_W^\nu(x) = j_V^\nu(x) - j_A^\nu(x) = \bar\psi_s(x)\,(\gamma^\nu - \gamma^\nu\gamma_5)\,\psi_c(x)\,, \qquad j_{\mathrm{em}}^\mu(x) = \sum_f q_f \bar\psi_f(x)\gamma^\mu\psi_f(x)$$

$$\begin{aligned}
H_W^{\mu\nu}(k,\boldsymbol{p}) &= H_{\mathrm{SD}}^{\mu\nu}(k,\boldsymbol{p}) + H_{\mathrm{pt}}^{\mu\nu}(k,\boldsymbol{p}) \\
H_{\mathrm{SD}}^{\mu\nu}(k,\boldsymbol{p}) &= \frac{H_1(p\cdot k,k^2)}{M_{D_s}}\left[k^2 g^{\mu\nu} - k^\mu k^\nu\right] + \frac{H_2(p\cdot k,k^2)}{M_{D_s}}\frac{\left[(p\cdot k - k^2)k^\mu - k^2(p-k)^\mu\right]}{(p-k)^2 - M_{D_s}^2}(p-k)^\nu \\
&\quad - i\frac{F_V(p\cdot k,k^2)}{M_{D_s}}\varepsilon^{\mu\nu\gamma\beta}k_\gamma p_\beta + \frac{F_A(p\cdot k,k^2)}{M_{D_s}}\left[(p\cdot k - k^2)g^{\mu\nu} - (p-k)^\mu k^\nu\right] \\
H_{\mathrm{pt}}^{\mu\nu}(k,\boldsymbol{p}) &= f_{D_s}\left[g^{\mu\nu} + \frac{(2p-k)^\mu(p-k)^\nu}{2p\cdot k - k^2}\right],
\end{aligned}$$

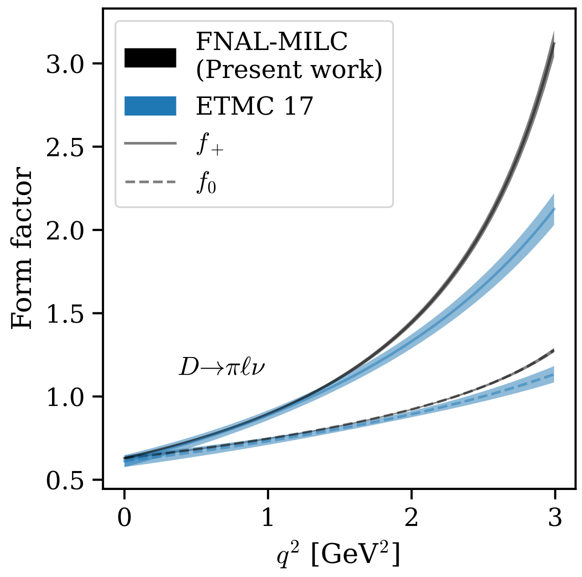


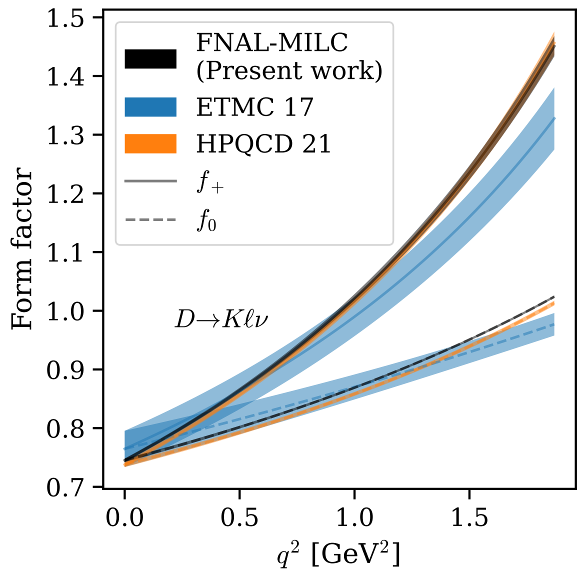
For a real photon (k^2=0) only $F_{V,A}$ contribute

$$\mathrm{Br}[D_s \to e\nu_e\gamma](\Delta E_\gamma) \equiv \frac{\Gamma_e(\Delta E_\gamma)}{\Gamma_{\mathrm{tot}}} < 1.3\times 10^{-4}, \qquad \Gamma_{\mathrm{tot}}^{-1} = (5.04\pm 0.04)\times 10^{-13}\ \mathrm{s}$$

$$E_\gamma > \Delta E_\gamma = 10\,\mathrm{MeV}$$

Br(Eγ > 10 MeV) = 4.4(3) × 10^{-6} is consistent with the upper bound from the BESIII experiment Br(Eγ > 10 MeV) < 1.3 × 10^{-4} at 90% confidence level





From Lytle talk at Beauty 2023

References:

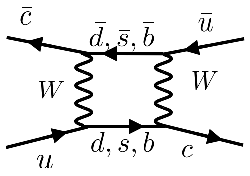
- FNAL-MILC 2212.12648
- HPQCD 21 2104.09883
- ETMC 17 1706.03017

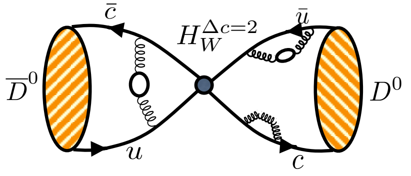
- Lattice errors roughly commensurate with experimental errors. In the next 5 years or so, these should continue to improve and lattice errors may become sub-dominant.

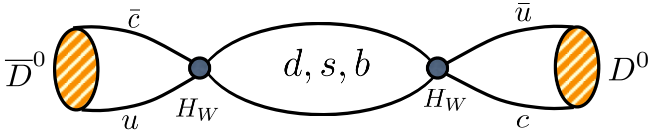
- To go beyond this requires adding EM and strong isospin breaking effects.

$D-\bar{D}$ mixing

$$M_{12}-\frac{i}{2}\Gamma_{12} \propto \langle D^0|H_W^{\Delta c=2}|\overline{D}^0\rangle + \sum_n \frac{\langle D^0|H_W^{\Delta c=1}|n\rangle\langle n|H_W^{\Delta c=1}|\overline{D}^0\rangle}{M_D-E_n+i\epsilon}$$







short distance

long distance

“Simple”

- can use the same methods as for *B* mixing
- BSMs with heavy new particles

can contribute here

“Difficult”

- large contribution

- intermediate state can include multiple (>2) hadrons: formalism for multi-hadron states still under development (Hansen & Sharpe, arXiv:1602.00324, 2016 PRD) mixing

$$D_1 = p|D^0\rangle - q|\overline{D}^0\rangle \quad \text{CP even}$$
$$D_2 = p|D^0\rangle + q|\overline{D}^0\rangle \quad \text{CP odd}$$

CPV parameters $|q/p|$ $\mathrm{Arg}(q/p) \equiv \phi.$

$$x = \frac{m_2 - m_1}{2\Gamma} \qquad y = \frac{\Gamma_2 - \Gamma_1}{2\Gamma}$$

HFLAV, 2206.07501

$$A_D \equiv \frac{\Gamma(D^0 \to K^+\pi^-) - \Gamma(\overline{D}^0 \to K^-\pi^+)}{\Gamma(D^0 \to K^+\pi^-) + \Gamma(\overline{D}^0 \to K^-\pi^+)}$$

$$A_K \equiv \frac{\Gamma(D^0 \to K^+K^-) - \Gamma(\overline{D}^0 \to K^-K^+)}{\Gamma(D^0 \to K^+K^-) + \Gamma(\overline{D}^0 \to K^-K^+)}$$

$$A_\pi \equiv \frac{\Gamma(D^0 \to \pi^+\pi^-) - \Gamma(\overline{D}^0 \to \pi^-\pi^+)}{\Gamma(D^0 \to \pi^+\pi^-) + \Gamma(\overline{D}^0 \to \pi^-\pi^+)},$$

$$R_D \equiv \frac{\Gamma(D^0 \to K^+\pi^-) + \Gamma(\overline{D}^0 \to K^-\pi^+)}{\Gamma(D^0 \to K^-\pi^+) + \Gamma(\overline{D}^0 \to K^+\pi^-)}$$

Decay Mode	Observables	Relationship
$D^0 \to K^+K^-/\pi^+\pi^-$	y_{CP} A_Γ	$2y_{CP} = (\lvert q/p\rvert + \lvert p/q\rvert)\, y\cos\phi - (\lvert q/p\rvert - \lvert p/q\rvert)\, x\sin\phi$ $2A_\Gamma = (\lvert q/p\rvert - \lvert p/q\rvert)\, y\cos\phi - (\lvert q/p\rvert + \lvert p/q\rvert)\, x\sin\phi$
$D^0 \to K^0_S\pi^+\pi^-$	x y $\lvert q/p\rvert$ ϕ	
$D^0 \to K^+\ell^-\overline{\nu}$	R_M	$R_M = \frac{x^2+y^2}{2}$

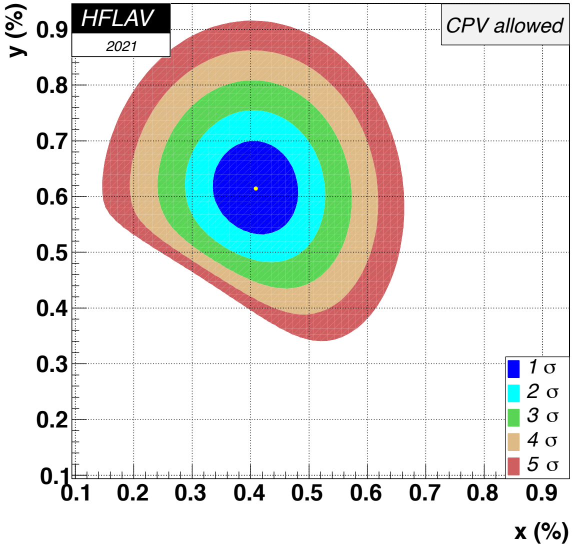
From all experiments, there are 61 measurements of 16 observables: y_{CP}, A_Γ, $(x, y, |q/p|, \phi)_{\text{Belle } K^0_S\pi^+\pi^-}$, $(x_{CP}, y_{CP}, \Delta x, \Delta y)_{\text{LHCb } K^0_S\pi^+\pi^-}$, $(x, y)_{\text{BaBar } K^0_S h^+h^-}$, $(x, y)_{\text{BaBar } \pi^0\pi^+\pi^-}$, $(R_M)/2_{\text{LHCb } K^+\pi^-\pi^+\pi^-}$, $(R_M)_{\text{semileptonic}}$, $(x'', y'')_{K^+\pi^-\pi^0}$, $(R_D, x^2, y, \cos\delta, \sin\delta)_{\psi(3770)}$, $(R_D, A_D, x'^{2\pm}, y'^{\pm})_{\text{BaBar}}$, $(R_D, A_D, x'^{2\pm}, y'^{\pm})_{\text{Belle}}$, $(R_D, x'^2, y')_{\text{CDF}}$, $(R_D^\pm, x'^{2\pm}, y'^{\pm})_{\text{LHCb}}$, $(A_{CP}^K, A_{CP}^\pi)_{\text{BaBar}}$, $(A_{CP}^K, A_{CP}^\pi)_{\text{Belle}}$, $(A_{CP}^K - A_{CP}^\pi)_{\text{CDF}}$, $(A_{CP}^K - A_{CP}^\pi)_{\text{LHCb}(D^*)}$, $(A_{CP}^K - A_{CP}^\pi)_{\text{LHCb}(B \to D^0\mu X)}$

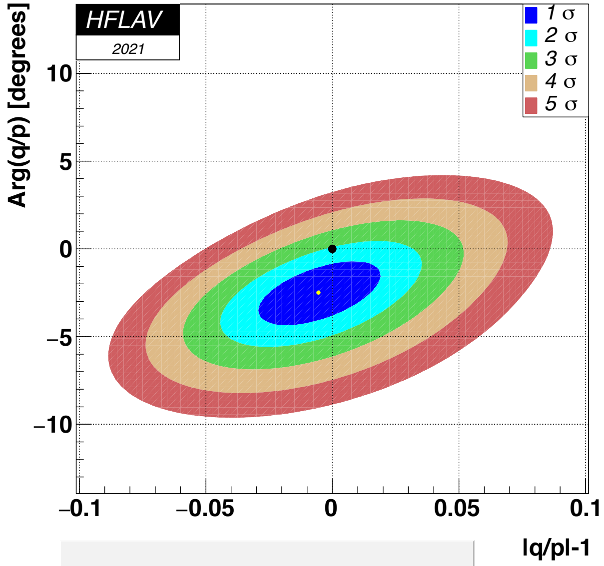
$$R_M = \frac{x^2+y^2}{2}$$

$$y_{CP} = \frac{1}{2}\left(\left|\frac{q}{p}\right|+\left|\frac{p}{q}\right|\right) y\cos\phi - \frac{1}{2}\left(\left|\frac{q}{p}\right|-\left|\frac{p}{q}\right|\right) x\sin\phi$$

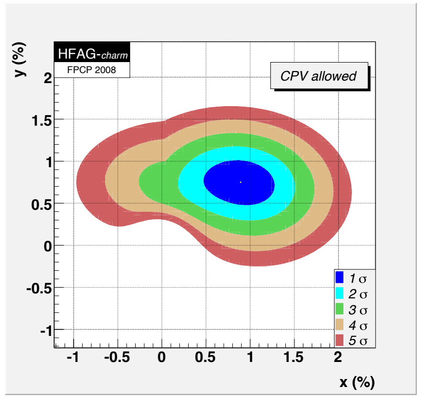
$$A_\Gamma = \frac{1}{2}\left(\left|\frac{q}{p}\right|-\left|\frac{p}{q}\right|\right) y\cos\phi - \frac{1}{2}\left(\left|\frac{q}{p}\right|+\left|\frac{p}{q}\right|\right) x\sin\phi$$

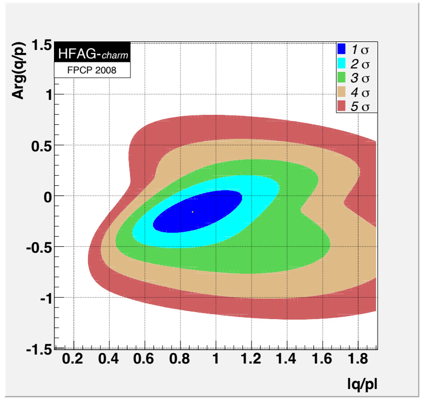
Mode	Observable	Values
$D^0 \to K^+K^-/\pi^+\pi^-$,	y_{CP}	$(0.719 \pm 0.113)\%$
ϕK^0_S	A_Γ	$(0.0089 \pm 0.0113)\%$
$D^0 \to K^0_S\pi^+\pi^-$ [1211]	x	$(0.56 \pm 0.19\,^{+0.067}_{-0.127})\%$
(Belle: no CPV)	y	$(0.30 \pm 0.15\,^{+0.050}_{-0.078})\%$





In 2008





The Direct CPV

$$|\mathcal{M}(D^0 \to f)| \neq |\bar{\mathcal{M}}|(D^0 \to \bar{f})|$$

$$\mathcal{M} = M_1 e^{i\delta_1} + M_2 e^{i\delta_2}$$

$$\bar{\mathcal{M}} = M_1^* e^{i\delta_1} + M_2^* e^{i\delta_2}$$

$$a_{CP}^{dir} = \frac{|\mathcal{M}|^2 - |\bar{\mathcal{M}}|^2}{|\mathcal{M}|^2 + |\bar{\mathcal{M}}|^2}$$

$$a_{CP}^{dir} = \frac{|\mathcal{M}|^2 - |\bar{\mathcal{M}}|^2}{|\mathcal{M}|^2 + |\bar{\mathcal{M}}|^2} = \frac{2\mathcal{I}(M_1^* M_2)\sin(\delta_1 - \delta_2)}{|M_1|^2 + |M_2|^2 + 2\mathcal{R}(M_1^* M_2)\cos(\delta_1 - \delta_2)}$$

Amplitude for D^0

$$\mathcal{M}^{SCS} = \frac{1}{2}(V_{cs}^* V_{us} - V_{cd}^* V_{ud}) M_T e^{i\delta} - \frac{1}{2}(V_{cb}^* V_{ub}) M_P e^{i\delta'}$$

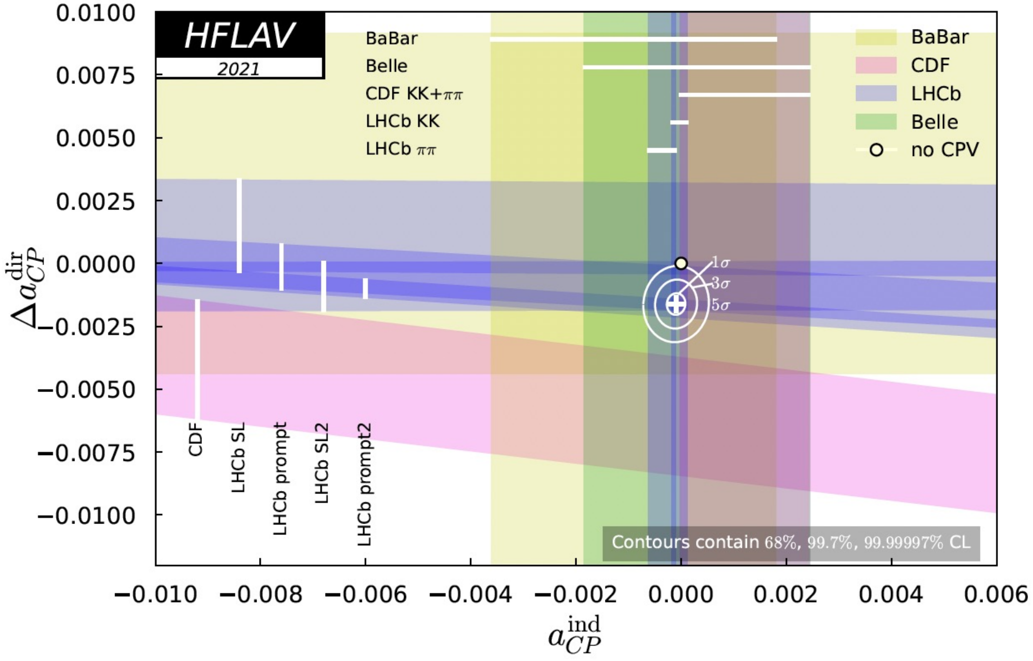
$$a_{CP}^{dir} \simeq (6 \times 10^{-4}) \sin(\delta - \delta') \left[\frac{M_P}{M_T}\right]$$

$$a_{CP}^{\rm dir} \equiv \frac{|\mathcal{A}_{D^0\to f}|^2 - |\mathcal{A}_{\overline{D}^0\to f}|^2}{|\mathcal{A}_{D^0\to f}|^2 + |\mathcal{A}_{\overline{D}^0\to f}|^2},$$

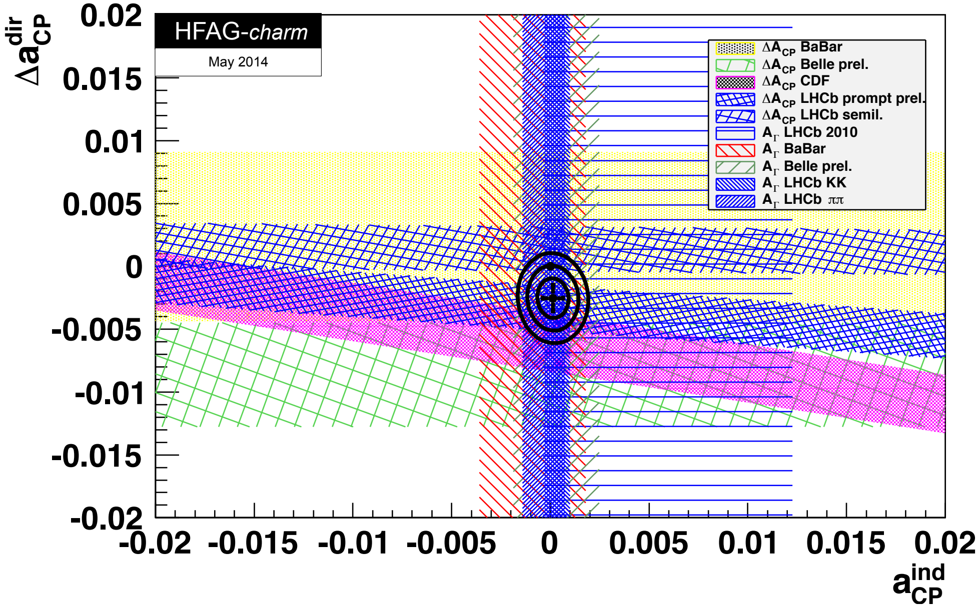
$$a_{CP}^{\rm ind} \equiv \frac{1}{2}\left[\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) x\sin\phi - \left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) y\cos\phi\right]$$

Year	Experiment	Results
2012	*BABAR*	$A_\Gamma = (+0.09 \pm 0.26 \pm 0.06)\%$
2021	LHCb	$\Delta Y(KK) = (-0.003 \pm 0.013 \pm 0.003)\%$
		$\Delta Y(\pi\pi) = (-0.036 \pm 0.024 \pm 0.004)\%$
2014	CDF	$A_\Gamma = (-0.12 \pm 0.12)\%$
2015	Belle	$A_\Gamma = (-0.03 \pm 0.20 \pm 0.07)\%$
2008	*BABAR*	$A_{CP}(KK) = (+0.00 \pm 0.34 \pm 0.13)\%$
		$A_{CP}(\pi\pi) = (-0.24 \pm 0.52 \pm 0.22)\%$
2012	CDF	$\Delta A_{CP} = (-0.62 \pm 0.21 \pm 0.10)\%$
2014	LHCb SL	$\Delta A_{CP} = (+0.14 \pm 0.16 \pm 0.08)\%$
2016	LHCb prompt	$\Delta A_{CP} = (-0.10 \pm 0.08 \pm 0.03)\%$
2019	LHCb SL2	$\Delta A_{CP} = (-0.09 \pm 0.08 \pm 0.05)\%$
2019	LHCb prompt2	$\Delta A_{CP} = (-0.18 \pm 0.03 \pm 0.09)\%$

$$a_{CP}^{\rm ind} = (-0.010 \pm 0.012)\%$$
$$\Delta a_{CP}^{\rm dir} = (-0.161 \pm 0.028)\%.$$



In 2014



$$a_{\rm CP}^{\rm ind} = (0.013 \pm 0.052)\%$$
$$\Delta a_{\rm CP}^{\rm dir} = (-0.253 \pm 0.104)\%$$

Year	Experiment	Results
2012	Belle prel.	$A_\Gamma = (-0.03 \pm 0.20 \pm 0.08)\%$
2012	*BABAR*	$A_\Gamma = (0.09 \pm 0.26 \pm 0.06)\%$
2013	LHCb	$A_\Gamma(KK) = (-0.035 \pm 0.062 \pm 0.012)\%$
		$A_\Gamma(\pi\pi) = (0.033 \pm 0.106 \pm 0.014)\%$
2008	*BABAR*	$A_{\rm CP}(KK) = (0.00 \pm 0.34 \pm 0.13)\%$
		$A_{\rm CP}(\pi\pi) = (-0.24 \pm 0.52 \pm 0.22)\%$
2012	Belle prel.	$\Delta A_{\rm CP} = (-0.87 \pm 0.41 \pm 0.06)\%$
2012	CDF	$\Delta A_{\rm CP} = (-0.62 \pm 0.21 \pm 0.10)\%$
2013	LHCb prel.	$\Delta A_{\rm CP} = (-0.34 \pm 0.15 \pm 0.10)\%$
2014	LHCb	$\Delta A_{\rm CP} = (0.14 \pm 0.16 \pm 0.08)\%$

$$\Delta A_{CP} = \mathcal{A}_{CP}(K^-K^+) - \mathcal{A}_{CP}(\pi^-\pi^+)$$

$$\mathcal{A}_{CP}(f) \approx a_f^d + \frac{\langle t \rangle_f}{\tau_D} \cdot \Delta Y_f$$

$a^d{}_f$ is the CP violation in the decay amplitude

ΔY_f is related to mixing-induced CP violation

$<t>_f$ is the mean decay lifetime of D^0

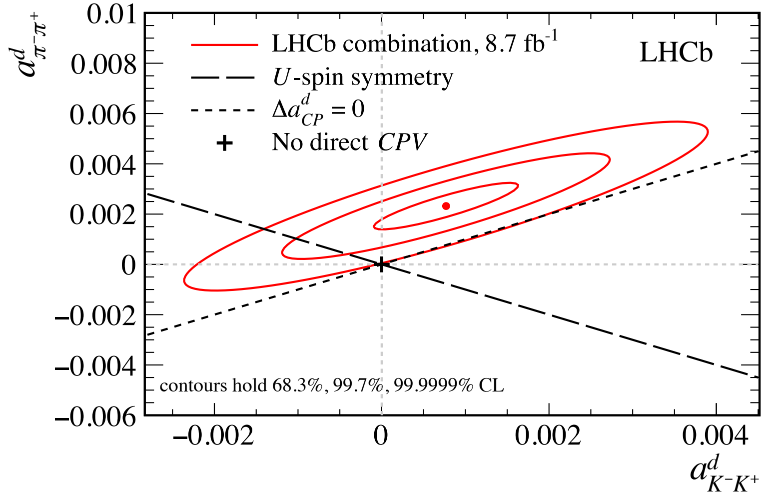
τ is the lifetime of D^0

LHCb 1903.08726

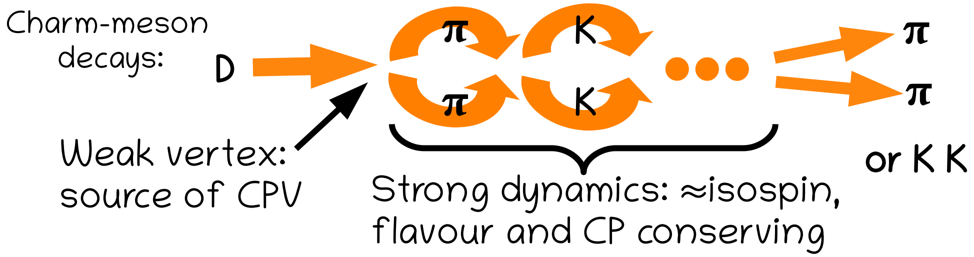
$$\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$$

$$a^d_{K^-K^+} = (\ 7.7 \pm 5.7) \times 10^{-4}$$
$$a^d_{\pi^-\pi^+} = (23.2 \pm 6.1) \times 10^{-4}$$

LHCb at PoS ICHEP2022 (2022) 732



U-spin CP anomaly
Bause et al., 2210.16330



(dispersive) (absorptive)

$$\mathrm{Re}[\Omega(s)] = \frac{1}{\pi}\int_{4M_\pi^2}^{\infty} \frac{\mathrm{Im}[\Omega(s')]}{s'-s} ds'$$

Dispersion Relation (DR) for Ω

Pich, Solomonidi, Vale Silva
2305.11951

Search for New Physics in Charm Processes

Why do we expect NP?

- origin of neutrino masses, dark matter, source of additional CP

- flavor anomalies in B mesons

If anomalies are in processes with the b quark, how to test up-quark sector?

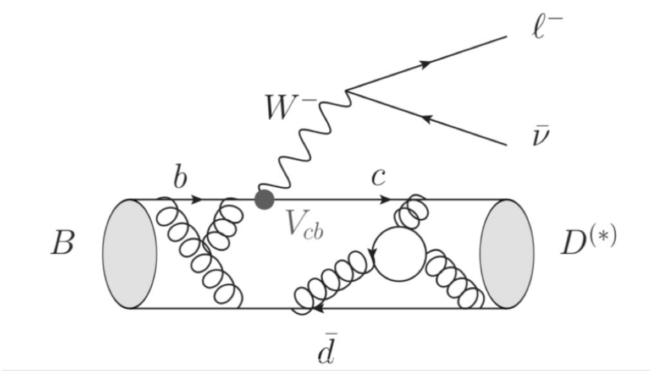
Experimental searches

- low energies
- high energies

Theoretical framework

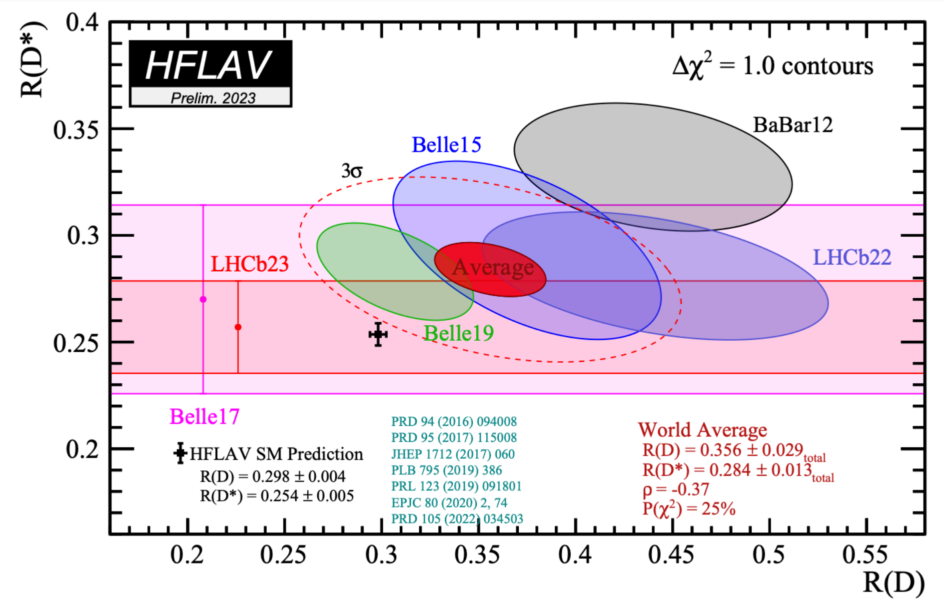
- Models (new gauge bosons, new scalars, new fermions,…)
- Model independent searches, e.g. SMEFT

Motivation from B anomaly:



$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\mu\nu)}$$

- R_D^{exp} and $R_{D^*}^{exp}$: dominated by BaBar!
- In $R_{J/\psi}^{exp}$ and $R_{\Lambda c}^{exp}$ limited precision.



Due to unitarity and perturbativity arguments e.g. di Luzio et al., 1604.05746 scale of New Physic below 10 TeV

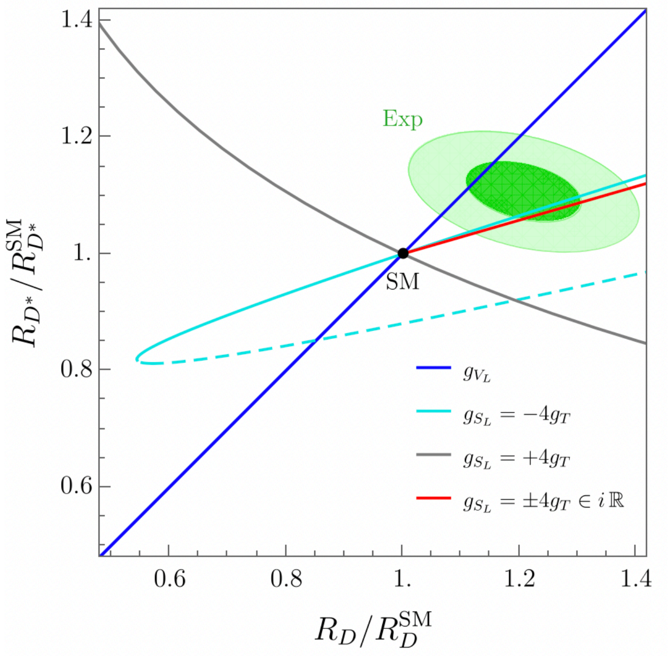
Solution for the puzzle New Physics!

New Belle-II and LHCb (run-2) data urgently needed!

$$\mathcal{L}_{\text{eff}} = -2\sqrt{2}G_F V_{cb}\Big[(1+g_{V_L})\big(\bar{c}_L\gamma_\mu b_L\big)\big(\bar{\ell}_L\gamma_\mu\nu_L\big) + g_{V_R}\big(\bar{c}_R\gamma_\mu b_R\big)\big(\bar{\ell}_L\gamma_\mu\nu_L\big)$$
$$+ g_{S_R}\big(\bar{c}_L b_R\big)\big(\bar{\ell}_R\nu_L\big) + g_{S_L}\big(\bar{c}_R b_L\big)\big(\bar{\ell}_R\nu_L\big) + g_T\big(\bar{c}_R\sigma_{\mu\nu} b_L\big)\big(\bar{\ell}_R\sigma_{\mu\nu}\nu_L\big)\Big] + \text{h.c.}$$

Angelescu et al., 2103.12504.

Eff. coeff.	1σ range	$\chi^2_{\text{min}}/\text{dof}$
$g_{V_L}(m_b)$	0.07 ± 0.02	$0.02/1$
$g_{S_R}(m_b)$	-0.31 ± 0.05	$5.3/1$
$g_{S_L}(m_b)$	0.12 ± 0.06	$8.8/1$
$g_T(m_b)$	-0.03 ± 0.01	$3.1/1$
$g_{S_L} = +4g_T \in \mathbb{R}$	-0.03 ± 0.07	$12.5/1$
$g_{S_L} = -4g_T \in \mathbb{R}$	0.16 ± 0.05	$2.0/1$
$g_{S_L} = \pm 4g_T \in i\,\mathbb{R}$	0.48 ± 0.08	$2.4/1$



Comment

If we assume that NP in $D_s \to \tau\nu$ can be estimated by CKM matrix element for g_V, this requires knowledge of f_{Ds}, and/or V_{cs} known at the level less than 1%!

Puzzles in b → s μμ transition

$$R_{K^{(*)}} = \frac{BR(B \to K^{(*)}\mu^+\mu^-)}{BR(B \to K^{(*)}e^+e^-)}$$

$$0.1 < q^2 < 1.1: \begin{cases} R_K & = 0.994\ ^{+0.090}_{-0.082}(\text{stat})^{+0.029}_{-0.027}(\text{syst}) \\ R_{K^*} & = 0.927\ ^{+0.093}_{-0.087}(\text{stat})^{+0.036}_{-0.035}(\text{syst}) \end{cases}$$

$$1.1 < q^2 < 6.0: \begin{cases} R_K & = 0.949\ ^{+0.042}_{-0.041}(\text{stat})^{+0.022}_{-0.022}(\text{syst}) \\ R_{K^*} & = 1.027\ ^{+0.072}_{-0.068}(\text{stat})^{+0.027}_{-0.026}(\text{syst}) \end{cases}$$

$$\mathcal{H}_{\text{eff}} = \mathcal{H}_{\text{eff}}^{\text{SM}} - \frac{4G_F}{\sqrt{2}}\frac{e^2}{16\pi^2}\sum_{q=s,d}\sum_{\ell=e,\mu}\sum_{i=9,10,S,P} V_{tb}V_{tq}^*(C_i^{bq\ell\ell}O_i^{bq\ell\ell} + C_i'^{bq\ell\ell}O_i'^{bq\ell\ell}) + \text{h.c.}\,.$$

$$O_9^{bq\ell\ell} = (\bar{q}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu\ell)\,, \qquad O_9'^{bq\ell\ell} = (\bar{q}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu\ell)\,,$$

$$O_{10}^{bq\ell\ell} = (\bar{q}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu\gamma_5\ell)\,, \qquad O_{10}'^{bq\ell\ell} = (\bar{q}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu\gamma_5\ell)\,,$$

$$O_S^{bq\ell\ell} = m_b(\bar{q}P_R b)(\bar{\ell}\ell)\,, \qquad O_S'^{bq\ell\ell} = m_b(\bar{q}P_L b)(\bar{\ell}\ell)\,,$$

$$O_P^{bq\ell\ell} = m_b(\bar{q}P_R b)(\bar{\ell}\gamma_5\ell)\,, \qquad O_P'^{bq\ell\ell} = m_b(\bar{q}P_L b)(\bar{\ell}\gamma_5\ell)\,.$$

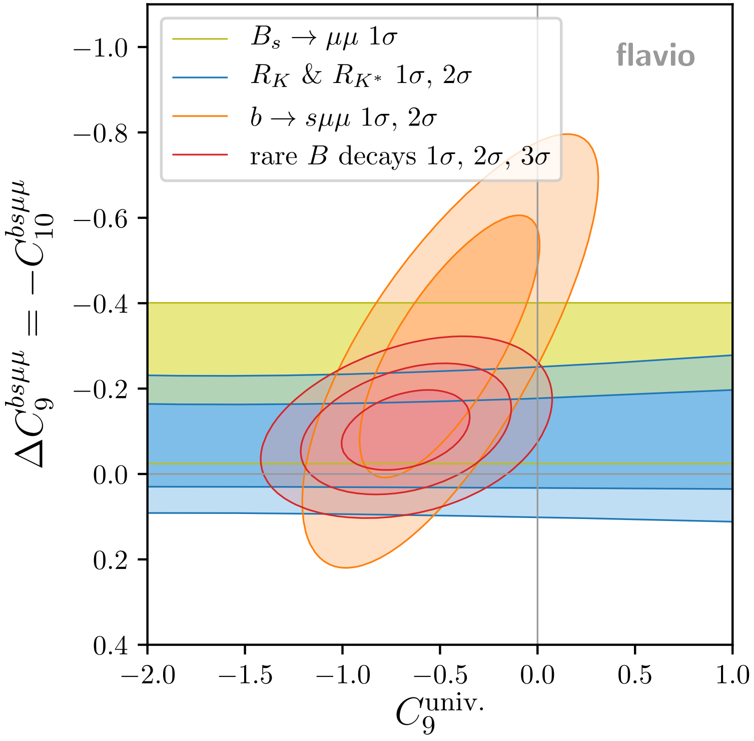
$$C_7^{SM} = 0.29;\ C_9^{SM} = 4.1;\ C_{10}^{SM} = -4.3;$$

Buras et al.,hep-ph/9311345;
Altmannshofer et al., 0811.1214;
Bobeth et al., hep-ph/9910220

$$C_9^{\text{univ.}} = -0.64 \pm 0.22$$

$$\Delta C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu} = -0.11 \pm 0.06$$

Greljo et al., 2212.10497



Angular observables, P_5' still remains.

How to search for New Physics?

Motivation: charged current weak processes with b quark

To rely on NP models resolving $R_{D(*)}$

Most favourable Leptoquarks

New vector-like fermions
New gauge bosons
New scalars (2THDM)

Motivation: FCNC processes

hopes for NP in $b \to s\, \mu\mu$

disappearance of $R_{K(*)}$ puzzle

Motivation $(g-2)_\mu$ unsettled HVP, …

Lepton flavour universality violation?

LHC did not find any evidence for NP particles

NP in CHARM processes?

Charm and top offer unique probes of NP in up sector

Leptoquarks can only accommodate $R_{D(*)}$ LQ= $(SU(3)_c, SU(2)_L, U(1)_Y)$
Dorsner, SF, Greljo, Kamenik,Kosnik 1603.04993

Models of NP

Scalar LQs they can modify Yukawa couplings (S_1(3,1,1/3) and R_2(3,2,7,6) for $R_{D(*)}$)
hopefully can help in understanding origin of flavour masses
and understanding flavour puzzle (why masses of quarks and leptons a so different)

Vector LQs prefarably should be gauge bosons, that requires full UV theory
Some GUTs, Pati-Salam-like theories (candidate to explain $R_{D(*)}$ U_1 (3,1,2/3)

Z' as a new gauge boson of additional U(1) gauge group (accompanied by 2HDM)
explanation of Charm CP violation, D meson mixing.

Charged current weak processes in LQ models which explain B anomalies marginally contriburte -% level.
In charm rare decays-FCNC efects are supressed ususally by V_{cb} V_{ub}^* leading to a small effect..

Standard model effective field theory SMEFT

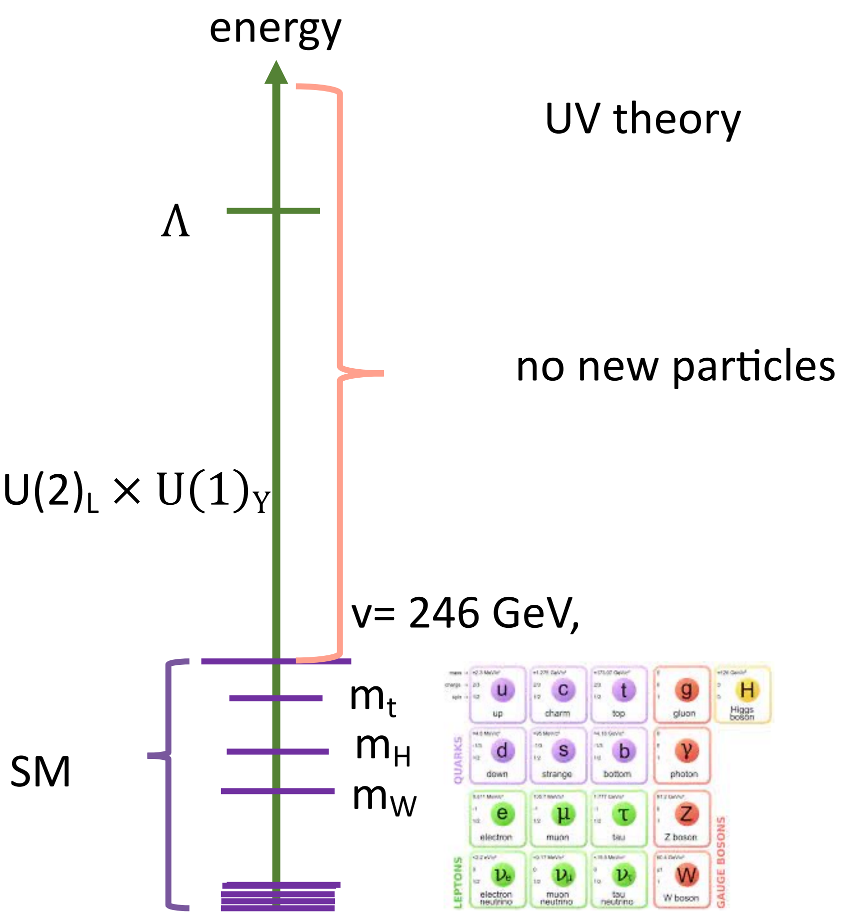
Weak interactions before SM

$$\mathcal{L}_{eff} = -\frac{G_F}{\sqrt{2}} J^{\dagger}_{\mu} J^{\mu}$$

However, we know that at low energies

$$\frac{g_2^2}{8\, m_W^2} = \frac{G_F}{\sqrt{2}} = \frac{1}{2\, v^2}$$

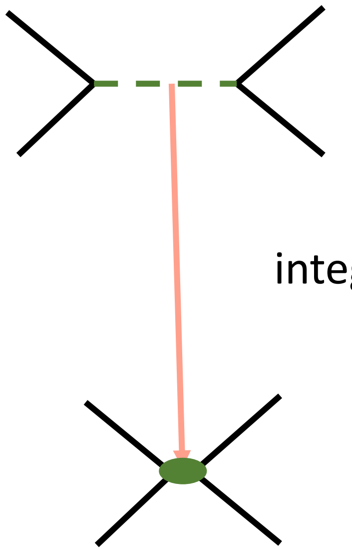
Energy scale of $SU(2)_L \times U(1)_Y$



- Expectation: NP appears on high energy scale Λ;
- No new degrees of freedom bellow this scale;
- New NP mediators create operators of dimension d≥ 5;
- Integrating out heavy degrees of freedom we create new operators not present in the SM

SMEFT

new heavy particle



integrate out heavy field

Effective operators 2499 possibilities

Important feature of the SMEFT approach:
running under SM gauge group

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \sum_{k,d} \frac{C_k^d}{\Lambda^{d-4}} \mathcal{O}_i^d$$

Gauge fields, Higgs   d$\geq$ 5

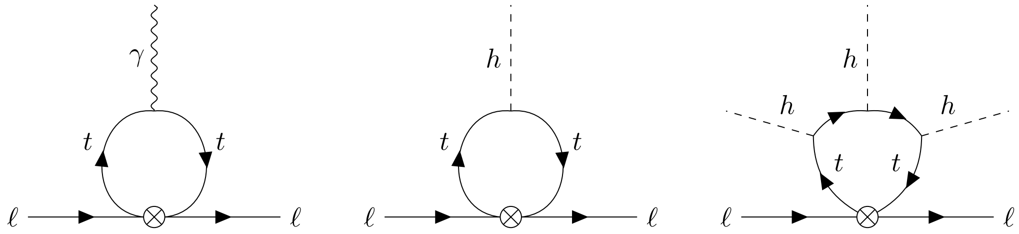
Warsaw basis, Grzadkowski et al, 1008.4884

SMEFT papers: Manohar et al., 1308.2627,
1309.0819, 1310,4838, 1312.2014

- There are 1350 CP-even and 1149 CP-odd parameters in the dimension-six Lagrangian for 3 generations, and our results give the entire 2499 × 2499 anomalous dimension matrix.

- Manohar et al. (1310.4838) , in three SMEFT papers calculated the complete order y^2 and y^4 terms of the 2499 × 2499 one-loop anomalous dimension matrix for the dimension-six operators of the SMEFT (y is a generic Yukawa coupling)

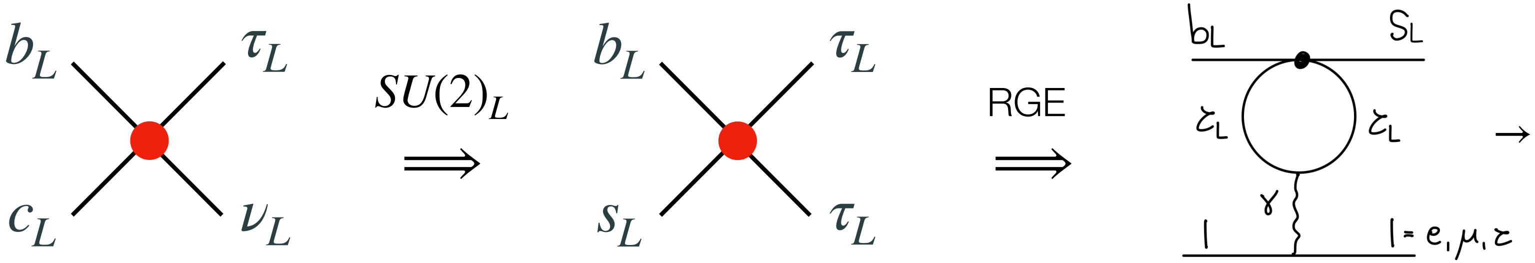
- Also they determined (1312.2014) the gauge terms of the one-loop anomalous dimension matrix for the dimension-six operators of the



It can help to that tree-level calculations in the UV model can reproduce the full theory two-loop calculations to remarkable accuracy.

e.g. 2HDM, SF et al., 2103.10859

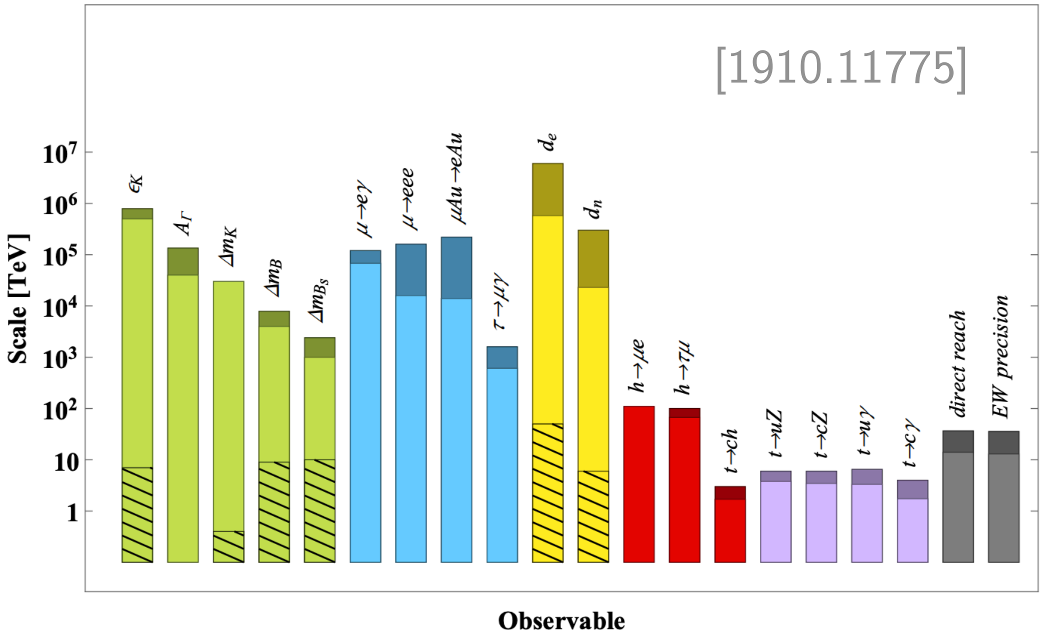
Universal contribution to C_9



$$\rightarrow \Delta C_9^U = C_9^U - C_9^{\rm SM}$$

Ben Stefanek, seminar IJS 4 May 2023

N = 2499 dim-6 operators that conserve B and L — rich flavor structure!



- The best probes of the SMEFT operators are rare/forbidden processes in the SM
(One has to be careful these processes can be suppressed in concrete scenarios)

- LHC processes can be useful to probe these types of scenarios (with lower values for Λ)!

High-p_T searches (CMS and ATLAS) can probe the same four-fermion operators constrained by flavor-physics experiments (NA62, KOTO, BES-III, LHCb, Belle-II...).

Too many operators!

The SM gauge-kinetic sector is invariant under a global flavour symmetry

$$G_F \equiv U(3)^5 = U(3)_q \times U(3)_u \times U(3)_d \times U(3)_l \times U(3)_e$$

$$U(3)_q \times U(3)_u \to U(1)_t \times U(2)_q \times U(2)_u$$

This works for the physics of the third generations.

How about charm quark? Above assumption means that the first and second generations are subjects of the U(2) symmetry. However,

$$m_c/m_u \sim 10^3$$

For the "charm" considerations one needs different framework than U(2) symmetry.

Correlating NP effects in D and K

SMEFT useful tool for the search of NP

- Need extra assumptions $U(2)^3$ symmetry
- Or Model of NP on high scale

U(2) flavor symmetry is not always applicable – only when the third generation is considered.

However, having only two generations one can correlate NP in K and D

PRL **102,** 211802 (2009) PHYSICAL REVIEW LETTERS week ending 29 MAY 2009

Combining K^0-$\bar{K}^0$ Mixing and D^0-$\bar{D}^0$ Mixing to Constrain the Flavor Structure of New Physics

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New physics at high energy scale often contributes to K^0-$\bar{K}^0$ and D^0-$\bar{D}^0$ mixings in an approximately $SU(2)_L$ invariant way. In such a case, the combination of measurements in these two systems is particularly powerful. The resulting constraints can be expressed in terms of misalignments and flavor splittings.

ΔS =2 and ΔC =2

$$\frac{1}{\Lambda_{\rm NP}^2}[z_1^K(\bar{d}_L\gamma_\mu s_L)(\bar{d}_L\gamma^\mu s_L)+z_1^D(\bar{u}_L\gamma_\mu c_L)(\bar{u}_L\gamma^\mu c_L)].$$

$$|z_1^K|\le z_{\rm exp}^K=8.8\times10^{-7}\left(\frac{\Lambda_{\rm NP}}{1\ {\rm TeV}}\right)^2 \qquad {\rm Im}(z_1^K)\le z_{\rm exp}^{IK}=3.3\times10^{-9}\left(\frac{\Lambda_{\rm NP}}{1\ {\rm TeV}}\right)^2$$

$$|z_1^D|\le z_{\rm exp}^D=5.9\times10^{-7}\left(\frac{\Lambda_{\rm NP}}{1\ {\rm TeV}}\right)^2 \qquad {\rm Im}(z_1^D)\le z_{\rm exp}^{ID}=1.0\times10^{-7}\left(\frac{\Lambda_{\rm NP}}{1\ {\rm TeV}}\right)^2$$

The above results can be derived by assuming

$$\frac{1}{\Lambda_{\rm NP}^2}(\bar{Q}_{Li}(X_Q)_{ij}\gamma_\mu Q_{Lj})(\bar{Q}_{Li}(X_Q)_{ij}\gamma^\mu Q_{Lj}),$$

X_Q Hermitian matrix, provides the source of flavor violation beyond the Yukawa matrices

K- mixing and D- mixing depend on the same Λ_{NP} two angles but differ in their alignment factors in such a way that depends on the Cabibbo angle. Thus, the combination of these measurements constrains, for TeV-scale new physics,

assuming ~~CP~~

$$z_1^K=\Lambda_{12}^2(\hat{v}_1-i\hat{v}_2)^2,$$

$$z_1^D=\Lambda_{12}^2(\cos2\theta_c\hat{v}_1-\sin2\theta_c\hat{v}_3-i\hat{v}_2)^2.$$

$$|z_1^K|=\Lambda_{12}^2[\cos^2\gamma\sin^2\alpha+\sin^2\gamma],$$

$$|z_1^D|=\Lambda_{12}^2[\cos^2\gamma\sin^2(\alpha-2\theta_c)+\sin^2\gamma]$$

$${\rm Im}(z_1^K)=-\Lambda_{12}^2\sin\alpha\sin2\gamma,$$

$${\rm Im}(z_1^D)=-\Lambda_{12}^2\sin(\alpha-2\theta_c)\sin2\gamma.$$

$$\Lambda_{12}\le3.8\times10^{-3}\left(\frac{\Lambda_{\rm NP}}{1\ {\rm TeV}}\right).$$

Correlating New Physics Effects in Semileptonic ΔC = 1 and ΔS = 1 Processes

$$\mathcal{L}_{\rm SMEFT} \supset \frac{X^{(3,\ell)}_{ij}}{\Lambda^2}(\bar{Q}_i\gamma_\mu\sigma^a Q_j)(\bar{L}_\ell\gamma^\mu\sigma_a L_\ell) + \frac{X^{(1,\ell)}_{ij}}{\Lambda^2}(\bar{Q}_i\gamma_\mu Q_j)(\bar{L}_\ell\gamma^\mu L_\ell)\,.$$

2305.13851, SF, JF Kamenik, N. Kosnik and a. Korajac

$$X^{(\pm)}_{ij} = \lambda^{(\pm)}\delta_{ij} + c^{(\pm)}_a(\sigma^a)_{ij}$$

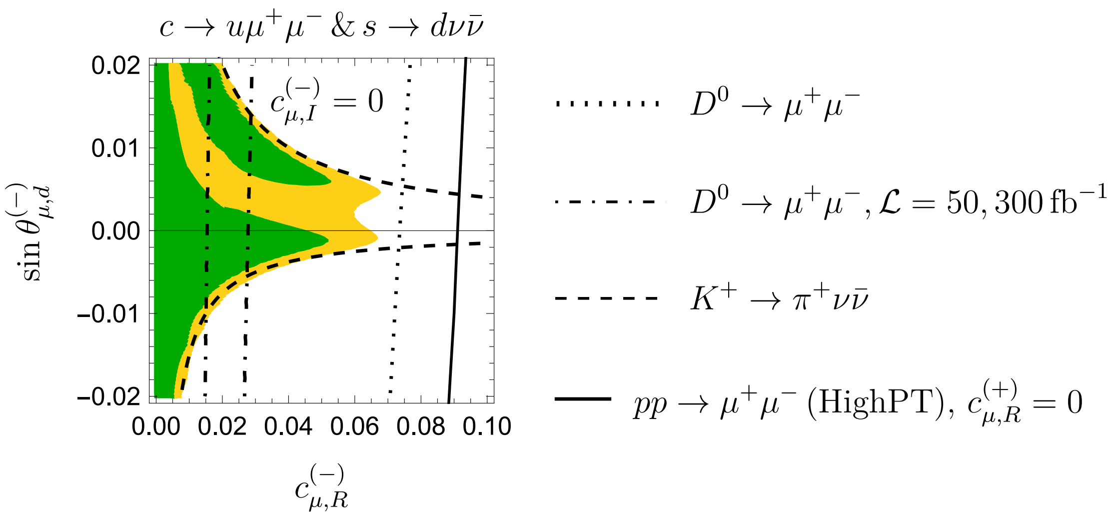
$$s\to d\nu\bar\nu: \quad C^{\Delta S=1,\,\rm NP}_{L,\nu} = \frac{2\pi}{\alpha_{\rm em}}\frac{v^2}{\Lambda^2}\left\{c^{(-)}_R\sin\theta^{(-)}_d - ic^{(-)}_I\right\},$$

$$c\to u\ell^+\ell^-: \quad C^{\Delta C=1,\rm NP}_9 = -C^{\Delta C=1,\rm NP}_{10} = \frac{\pi}{\alpha_{\rm em}}\frac{v^2}{\Lambda^2}\left\{c^{(-)}_R\sin(\theta^{(-)}_d - 2\theta_c) - ic^{(-)}_I\right\},$$

$$s\to d\ell^+\ell^-: \quad C^{\Delta S=1,\rm NP}_9 = -C^{\Delta S=1,\rm NP}_{10} = \frac{\pi}{\alpha_{\rm em}}\frac{v^2}{\Lambda^2}\left\{c^{(+)}_R\sin\theta^{(+)}_d - ic^{(+)}_I\right\}$$

$$c\to u\nu\bar\nu: \quad C^{\Delta C=1,\rm NP}_{L,\nu} = \frac{2\pi}{\alpha_{\rm em}}\frac{v^2}{\Lambda^2}\left\{c^{(+)}_R\sin(\theta^{(+)}_d - 2\theta_c) - ic^{(+)}_I\right\}.$$

$$|{\rm Im}[c^{(+)}_{\tau,I}]| \lesssim 0.15$$



universal ~~CP~~ phases

See talk by Korajac

Charm meson rare decays

On the quark level

$c \to u\ell^+\ell^-$

$c \to u\nu\bar{\nu}$

$c \to u\gamma$

Hadronic modes

$D \to \ell^+\ell^-$

$D \to P\ell^+\ell^-$

$D \to V\ell^+\ell^-$

$D \to P_1P_2\ell^+\ell^-$

$D \to \nu\bar{\nu}$

$D \to P\nu\bar{\nu}$

$D \to P_1P_2\nu\bar{\nu}$

$D \to V\gamma$

$D \to P_1P_2\gamma$

$D \to invisibles$

$D \to P\, invisibles$

For references see Gisbert et al, Mod.Phys.Lett.A 36 (2021) 04, 2130002, 2011.09478

Observables: Branching ratios
Angular observable
LU ratios & LFV CP asymmetries

See talks Suelmann, Plura, Korajac, Solomonidi, Khodjamirian

$$\mathcal{L}_{\text{eff}} = \frac{4G_F}{\sqrt{2}}\frac{\alpha_e}{4\pi}V_{ub}V_{cb}^*\left[\sum_{k=7,9,10}(C_k O_k + C_k' O_k') + \sum_{ij}(C_L^{ij}Q_L^{ij} + C_R^{ij}Q_R^{ij})\right]$$

$$\begin{aligned} O_7 &= \tfrac{m_c}{e}(\bar{u}_L\sigma_{\mu\nu}c_R)F^{\mu\nu}, & O_7' &= \tfrac{m_c}{e}(\bar{u}_R\sigma_{\mu\nu}c_L)F^{\mu\nu}, \\ O_9 &= (\bar{u}_L\gamma_\mu c_L)(\bar{l}\gamma^\mu\ell), & O_9' &= (\bar{u}_R\gamma_\mu c_R)(\bar{l}\gamma^\mu\ell), \\ O_{10} &= (\bar{u}_L\gamma_\mu c_L)(\bar{l}\gamma^\mu\gamma_5\ell), & O_{10}' &= (\bar{u}_R\gamma_\mu c_R)(\bar{l}\gamma^\mu\gamma_5\ell), \\ Q_L^{ij} &= (\bar{u}_L\gamma_\mu c_L)(\bar{\nu}_{Lj}\gamma^\mu\nu_{Li}), & Q_R^{ij} &= (\bar{q}_R\gamma_\mu c_R)(\bar{\nu}_{Lj}\gamma^\mu\nu_{Li}). \end{aligned}$$

$D^+ \to \pi^+\ell^+\ell^-$

$D \to P_1 P_2 \ell^+\ell^-$

See talk of Solomonidi

SF and Košnik 1510.00965
Bause et al 1909.11108,
see De Boer and Hiller, 1805.08516

- Branching ratios are insensitive to NP.
- Low q^2 a lot of resonances → sizable uncertainties.
- High q^2 might include NP

	SM	$\lvert C_9\rvert = 0.5$	$\lvert C_{10}\rvert = 0.5$	$\lvert C_9\rvert = \pm\lvert C_{10}\rvert = 0.5$
full q^2	$1.00 \pm \mathcal{O}(10^{-2})$	SM-like	SM-like	SM-like
low q^2	$0.95 \pm \mathcal{O}(10^{-2})$	$\mathcal{O}(100)$	$\mathcal{O}(100)$	$\mathcal{O}(100)$
high q^2	$1.00 \pm \mathcal{O}(10^{-2})$	$0.2 \ldots 11$	$3 \ldots 7$	$2 \ldots 17$

Dark Matter in charm decays

Belle collaboration 1611.09455
BR($D^0 \to$ invisible) $< 9.4 \times 10^{-5}$

SM: BR($D^0 \to \nu\nu$) = 1.1×10^{-30}

Badin & Petrov 1005.1277 suggested to search for processes with missing energy $\not{E}$ in

$$D^0 \to \gamma \not{E}$$ → could be SM neutrinos or DM!

Bhattacharya, Grant and Petrov 1809.04606

$$\mathcal{B}(D \to invisibles) = \mathcal{B}(D \to \nu\bar{\nu}) + \mathcal{B}(D \to \nu\bar{\nu} + \nu\bar{\nu}) + \ldots$$

The SM contributions to invisible widths of heavy mesons $\Gamma(D^0 \to$ missing energy) are completely dominated by the four-neutrino transitions $D^0 \to \nu\bar{\nu}\nu\bar{\nu}$.

$$BR(D \to \nu\bar{\nu}\bar{)} = (2.96 \pm 0.39) \times 10^{-27}$$

Bause et al., 2010.02225
SF and Novosel, 2101.10712

See talks Suelmann, Korajac

Could appear from these couplings of the scalar LQs

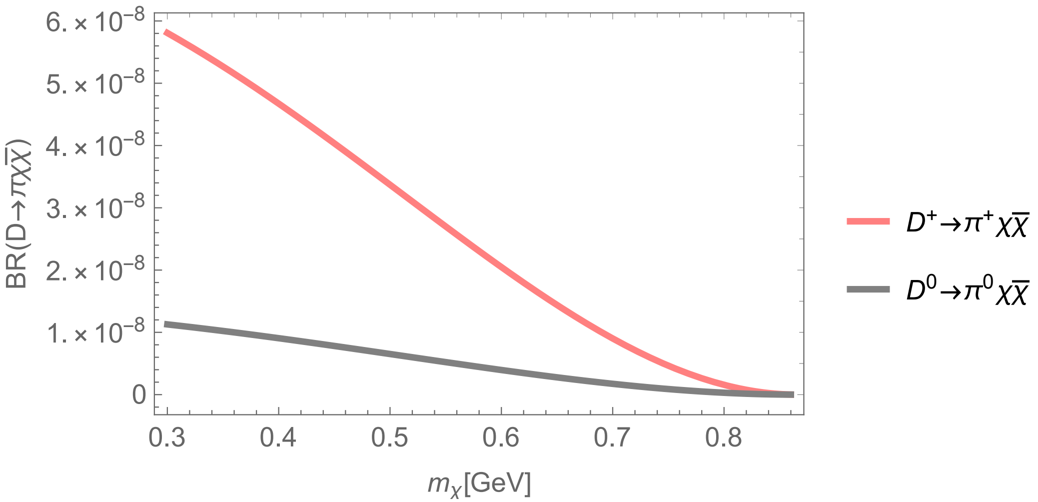
$$\mathcal{L}_{\text{eff}} = \sqrt{2}G_F\Big[c^{LL}(\overline{u}_L\gamma_\mu c_L)(\overline{\nu}_L\gamma^\mu\nu_L') + c^{RR}(\overline{u}_R\gamma_\mu c_R)(\overline{\nu}_R\gamma^\mu\nu_R')$$
$$+ c^{LR}(\overline{u}_L\gamma_\mu c_L)(\overline{\nu}_R\gamma^\mu\nu_R') + c^{RL}(\overline{u}_R\gamma_\mu c_R)(\overline{\nu}_L\gamma^\mu\nu_L') + g^{LL}(\overline{u}_L c_R)(\overline{\nu}_L\nu_R')$$
$$+ g^{RR}(\overline{u}_R c_L)(\overline{\nu}_R\nu_L') + g^{LR}(\overline{u}_L c_R)(\overline{\nu}_R\nu_L') + g^{RL}(\overline{u}_R c_L)(\overline{\nu}_L\nu_R')$$
$$+ h^{LL}(\overline{u}_L\sigma^{\mu\nu}c_R)(\overline{\nu}_L\sigma_{\mu\nu}\nu_R') + h^{RR}(\overline{u}_R\sigma^{\mu\nu}c_L)(\overline{\nu}_R\sigma_{\mu\nu}\nu_L')\Big] + \text{h. c.}.$$

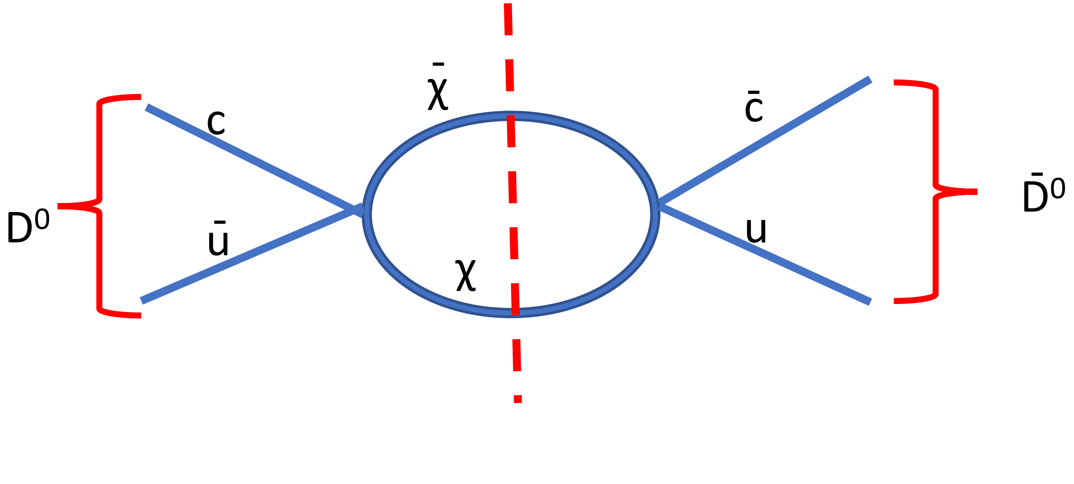
Cloured Scalar	Invisible fermion
$S_1 = (\bar{3}, 1, 1/3)$	$\bar{d}_R^{C\,i}\chi^j S_1$
$\bar{S}_1 = (\bar{3}, 1, -2/3)$	$\bar{u}_R^{C\,i}\chi^j \bar{S}_1$
$\tilde{R}_2 = (\bar{3}, 2, 1/6)$	$\bar{u}_L^i\chi^j \tilde{R}_2^{2/3}$
$\tilde{R}_2 = (\bar{3}, 2, 1/6)$	$\bar{d}_L^i\chi^j \tilde{R}_2^{-1/3}$

$$\mathcal{L}_{\text{eff}} = \sqrt{2}G_F\frac{v^2}{2M^2}\bar{y}^{RR}_{1\,c\chi}\bar{y}^{RR*}_{1\,u\chi}(\overline{u}_R\gamma_\mu c_R)(\overline{\chi}_R\gamma^\mu\chi_R)$$

m_χ (GeV)	$\mathcal{B}(D^0 \to \chi\bar{\chi})_{D-\bar{D}}$
0.18	$< 1.1 \times 10^{-9}$
0.50	$< 7.4 \times 10^{-9}$
0.80	$< 1.1 \times 10^{-8}$

m_χ (GeV)	$\mathcal{B}(D^0 \to \pi^0\chi\bar{\chi})_{D-\bar{D}}$	$\mathcal{B}(D^+ \to \pi^+\chi\bar{\chi})_{D-\bar{D}}$
0.18	$< 5.9 \times 10^{-9}$	$< 3.0 \times 10^{-8}$
0.50	$< 3.2 \times 10^{-9}$	$< 1.6 \times 10^{-8}$
0.80	$< 1.5 \times 10^{-10}$	$< 7.6 \times 10^{-10}$





$D^0 - \bar{D}^0$

SF and Novosel, 2101.10712

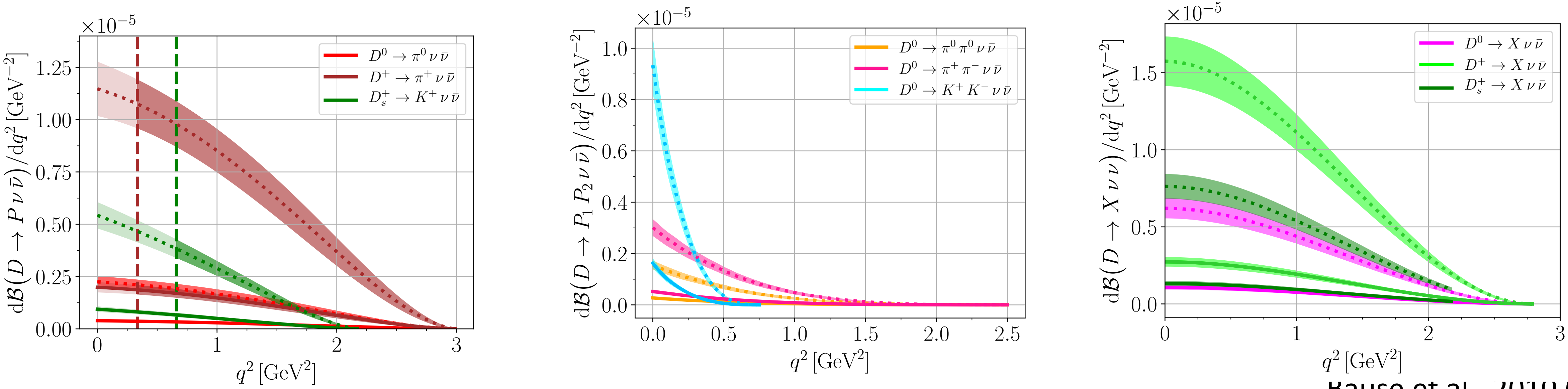
Bause et al., 2010.02225 provide model-independent upper limits on branching ratios reaching few 10^{-5} in the most general case of arbitrary lepton flavor structure, 10^{-5} for scenarios with charged lepton conservation and few 10^{-6} assuming lepton universality. We also give upper limits in Z′ and leptoquark models.

$$\mathcal{H}_{\text{eff}}^{\ell_i\ell_j} \supset -\frac{4\,G_{\text{F}}}{\sqrt{2}}\frac{\alpha_e}{4\pi}\left(\mathcal{K}_L^{Uij}O_L^{ij} + \mathcal{K}_R^{Uij}O_R^{ij}\right) + \text{H.c.}, \quad \mathcal{K}_{L,R}^U|_{\text{LU}} = \begin{pmatrix} k & 0 & 0 \\ 0 & k & 0 \\ 0 & 0 & k \end{pmatrix}, \; \mathcal{K}_{L,R}^U|_{\text{cLFC}} = \begin{pmatrix} k_e & 0 & 0 \\ 0 & k_\mu & 0 \\ 0 & 0 & k_\tau \end{pmatrix}$$

$$O_{L(R)}^{ij} = (\bar{u}_{L(R)}\gamma_\mu c_{L(R)})\,(\bar{\ell}_{jL}\gamma^\mu \ell_{iL})$$

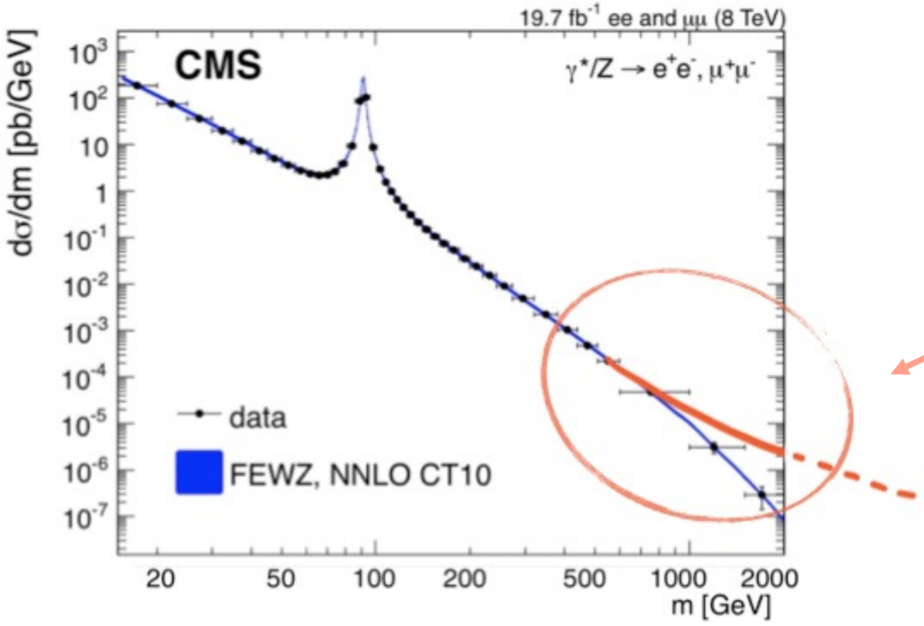
"general" - all entries in the coefficient matrix are arbitrarily filled,

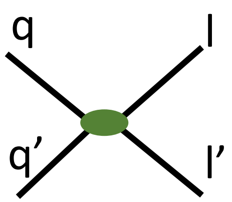
Relative statistical uncertainty of the branching ratio δB versus the branching ratio B for decays



Bause et al., 2010.02225

Indirect searches at the LHC





Allwicher et al., 2207.10756
HighPT software

$pp \to \tau\tau$	[arXiv:2002.12223]
$pp \to ee,\ \mu\mu$	CMS-PAS-EXO-19-019
$pp \to \tau\nu$	ATLAS-CONF-2021-025
$pp \to e\nu,\ \mu\nu$	[arXiv:1906.05609]
$pp \to e\mu,\ e\tau,\ \mu\tau$	[arXiv:2205.06709]

	$d=6$	ψ^4
Vector	$\mathcal{O}_{lq}^{(1)}$	$(\bar{l}_\alpha\gamma^\mu l_\beta)(\bar{q}_i\gamma_\mu q_j)$
	$\mathcal{O}_{lq}^{(3)}$	$(\bar{l}_\alpha\gamma^\mu\tau^I l_\beta)(\bar{q}_i\gamma_\mu\tau^I q_j)$
	$\mathcal{O}_{lu}$	$(\bar{l}_\alpha\gamma^\mu l_\beta)(\bar{u}_i\gamma_\mu u_j)$
	$\mathcal{O}_{ld}$	$(\bar{l}_\alpha\gamma^\mu l_\beta)(\bar{d}_i\gamma_\mu d_j)$
	$\mathcal{O}_{eq}$	$(\bar{e}_\alpha\gamma^\mu e_\beta)(\bar{q}_i\gamma_\mu q_j)$
	$\mathcal{O}_{eu}$	$(\bar{e}_\alpha\gamma^\mu e_\beta)(\bar{u}_i\gamma_\mu u_j)$
	$\mathcal{O}_{ed}$	$(\bar{e}_\alpha\gamma^\mu e_\beta)(\bar{d}_i\gamma_\mu d_j)$
Scalar	$\mathcal{O}_{ledq}$ + h.c.	$(\bar{l}_\alpha e_\beta)(\bar{d}_i q_j)$
	$\mathcal{O}_{lequ}^{(1)}$ + h.c.	$(\bar{l}_\alpha e_\beta)\varepsilon(\bar{q}_i u_j)$
Tensor	$\mathcal{O}_{lequ}^{(3)}$ + h.c.	$(\bar{l}_\alpha\sigma^{\mu\nu} e_\beta)\varepsilon(\bar{q}_i\sigma_{\mu\nu} u_j)$

Advantage: some processes are poorly constrained at low energies – but can be constrained at high energies
e.g., b → s $\tau\tau$, c→ d $\tau\nu$, c→ d $e\nu$ …

Procedure: Recast di-lepton searches and look for NP effects in the tails of the invariant- mass distributions

Charm leptonic and semileptpnic processes at LHC

Greljo et al., 2003.12421

$$\mathcal{L}_{\rm CC} = -\frac{4G_F}{\sqrt{2}} V_{ci} \left[\left(1+\epsilon_{V_L}^{\alpha\beta i}\right) \mathcal{O}_{V_L}^{\alpha\beta i} + \epsilon_{V_R}^{\alpha\beta i}\, \mathcal{O}_{V_R}^{\alpha\beta i} + \epsilon_{S_L}^{\alpha\beta i}\, \mathcal{O}_{S_L}^{\alpha\beta i} + \epsilon_{S_R}^{\alpha\beta i}\, \mathcal{O}_{S_R}^{\alpha\beta i} + \epsilon_{T}^{\alpha\beta i}\, \mathcal{O}_{T}^{\alpha\beta i} \right] + \text{h.c.}$$

$$\mathcal{O}_{V_L}^{\alpha\beta i} = (\bar{e}_L^\alpha \gamma_\mu \nu_L^\beta)(\bar{c}_L \gamma^\mu d_L^i)\,, \qquad \mathcal{O}_{V_R}^{\alpha\beta i} = (\bar{e}_L^\alpha \gamma_\mu \nu_L^\beta)(\bar{c}_R \gamma^\mu d_R^i)\,,$$

$$\mathcal{O}_{S_L}^{\alpha\beta i} = (\bar{e}_R^\alpha \nu_L^\beta)(\bar{c}_R\, d_L^i)\,, \qquad \mathcal{O}_{S_R}^{\alpha\beta i} = (\bar{e}_R^\alpha \nu_L^\beta)(\bar{c}_L\, d_R^i)\,,$$

$$\mathcal{O}_{T}^{\alpha\beta i} = (\bar{e}_R^\alpha \sigma_{\mu\nu} \nu_L^\beta)(\bar{c}_R \sigma^{\mu\nu} d_L^i)\,.$$

$$q_L^i = \begin{pmatrix} u_L^i \\ V_{ij}\, d_L^j \end{pmatrix} \qquad l_L^\alpha = \begin{pmatrix} \nu_L^\alpha \\ e_L^\alpha \end{pmatrix}$$

SMEFT running from μ =1 TeV to μ =2 GeV

$$\epsilon_{S_L}(2\,\text{GeV}) \approx 2.1\,\epsilon_{S_L}(\text{TeV}) - 0.3\,\epsilon_T(\text{TeV})\,, \qquad \epsilon_{S_R}(2\,\text{GeV}) \approx 2.0\,\epsilon_{S_R}(\text{TeV})$$

$$\epsilon_T(2\,\text{GeV}) \approx 0.8\,\epsilon_T(\text{TeV})\,.$$

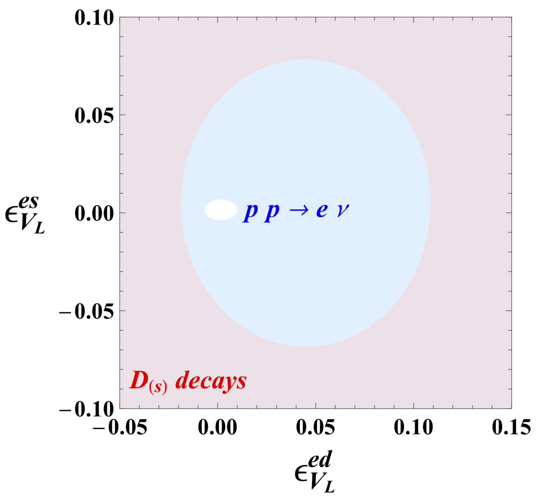
Using lattice input for decay constant/formfactors

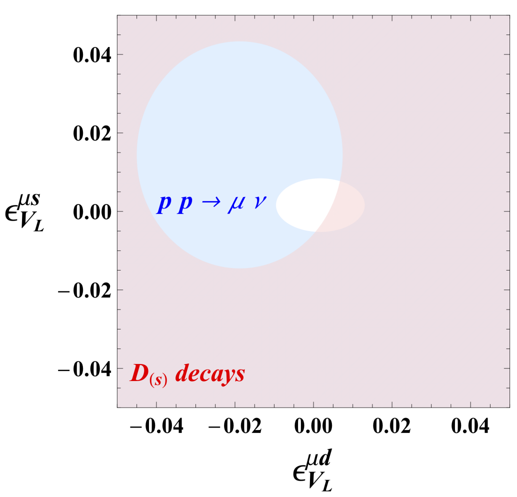
$$\text{BR}(D^+ \to \bar{e}^\alpha \nu^\alpha) = \tau_{D^+} \frac{m_{D^+} m_\alpha^2 f_D^2 G_F^2 |V_{cd}|^2 \beta_\alpha^4}{8\pi} \left| 1 - \epsilon_A^{\alpha d} + \frac{m_D^2}{m_\alpha (m_c + m_u)} \epsilon_P^{\alpha d} \right|^2$$

$$\frac{\text{BR}(D \to P_i\, \bar{\ell}^\alpha \nu^\alpha)}{\text{BR}_{\rm SM}} = \left|1 + \epsilon_V^{\alpha i}\right|^2 + 2\,\text{Re}\left[(1+\epsilon_V^{\alpha i})(x_S\, \epsilon_S^{\alpha i *} + x_T\, \epsilon_T^{\alpha i *})\right] + y_S\, |\epsilon_S^{\alpha i}|^2 + y_T\, |\epsilon_T^{\alpha i}|^2$$

$x_{S,T}$ and $y_{S,T}$ → the interference between NP and SM and the quadratic NP effects

i	α	$\epsilon_{V_L}^{\alpha\alpha i} \times 10^2$	$\lvert\epsilon_{V_L}^{\alpha\beta i}\rvert \times 10^2$	$\lvert\epsilon_{S_{L,R}}^{\alpha\beta i}(\mu)\rvert \times 10^2$		$\lvert\epsilon_{T}^{\alpha\beta i}(\mu)\rvert \times 10^3$	
			$(\alpha \neq \beta)$	$\mu = 1$ TeV	$\mu = 2$ GeV	$\mu = 1$ TeV	$\mu = 2$ GeV
d	e	$[-0.52, 0.86]$	0.67 (0.42)	0.72 (0.46)	1.5 (0.96)	4.3 (2.7)	3.4 (2.2)
	μ	$[-0.85, 1.2]$	1.0 (0.38)	1.1 (0.42)	2.3 (0.86)	6.6 (2.4)	5.2 (1.9)
	τ	$[-1.4, 1.8]$	1.6 (0.68)	1.5 (0.55)	3.1 (1.1)	8.7 (3.1)	6.9 (2.5)
s	e	$[-0.28, 0.59]$	0.42 (0.26)	0.43 (0.28)	0.91 (0.57)	2.8 (1.5)	2.2 (1.2)
	μ	$[-0.46, 0.78]$	0.63 (0.23)	0.68 (0.25)	1.4 (0.52)	4.0 (1.4)	3.1 (1.1)
	τ	$[-0.65, 1.2]$	0.93 (0.40)	0.87 (0.31)	1.8 (0.65)	5.2 (1.8)	4.1 (1.5)

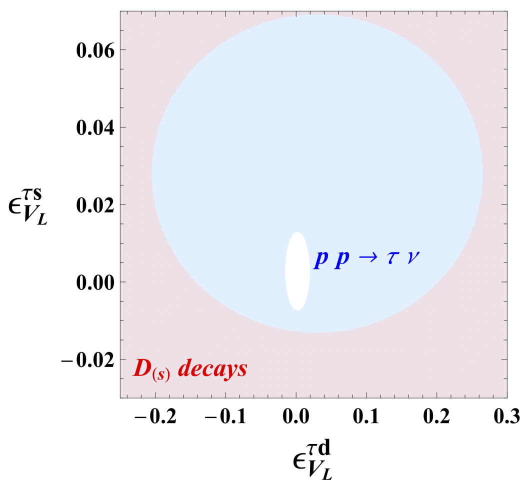




Exclusion limits at 95% CL on c → d(s)e⁻ ν transitions in (ϵ_{VL} , ϵ_{VL}) plane

pink region → excluded by D(s) meson decays

blue region → excluded by high-pT LHC



a striking illustration of the LHC potential to probe new flavor violating interactions at high-p_T

Summary and outlook

SM theoretical approaches make great progress in precision calculation of hadronic spectra, properties of charmed hadron, weak decays, rare decays within SM.

New Physics in charm processes are not expected to be significant.
Many studies established powerful constraints of the NP parameters.

New experimental results from Belle 2, BesIII, LHCb … will encourage theoretical studies!

A poem on the charm quark future

Charm quark, charm quark, What will you become?
A particle of the future, Or just a memory of some?
You're the third-most massive quark,
With a charge of +2/3 e.
You carry charm, a quantum number,
And you're found in various hadrons, you see.
You're an elementary particle,
Of the second generation.
You're part of the Standard Model,
And you're subject to speculation.
The future of charm quarks, Is still unknown to us.
But we'll keep on studying,
And we'll never lose our trust.

Created by AI!

AI generate charm quark in style

Ivana Kobilica

Picasso

Munch

Mucha

Dali