Why flavor matters at the LHC

Recent developments and prospects in flavor physics

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Introduction

SM phenomenologically very successful theory

Strong theoretical arguments to consider it as effective theory

"Flavor physics"

one of arguments to consider SM not complete

key tool to investigate NP beyond SM

$$\mathcal{L}_{\nu\mathrm{SM}} = \mathcal{L}_{\mathrm{gauge}}(A_a, \psi_i) + D_\mu \phi^\dagger D^\mu \phi - V_{\mathrm{eff}}(\phi, A_a, \psi_i)$$

$$V_{\mathrm{eff}} = -\mu^2 \phi^\dagger \phi + \lambda(\phi^\dagger \phi)^2 + \boxed{Y^{ij}} \psi_L^i \psi_R^j \phi + \frac{\boxed{y^{ij}}}{\Lambda} \psi_L^{iT} \psi_L^j \phi^T \phi + \ldots$$

flavor content of model

Introduction

$$V_{\text{eff}} = -\mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2 + Y^{ij}\psi_L^i\psi_R^j\phi + \frac{y^{ij}}{\Lambda}\psi_L^{iT}\psi_L^j\phi^T\phi + \ldots$$

Beside direct searches for new d.o.f's at high energy colliders, main task is to understand/constrain size of <u>additional terms in series</u>

Higgs & Flavor physics

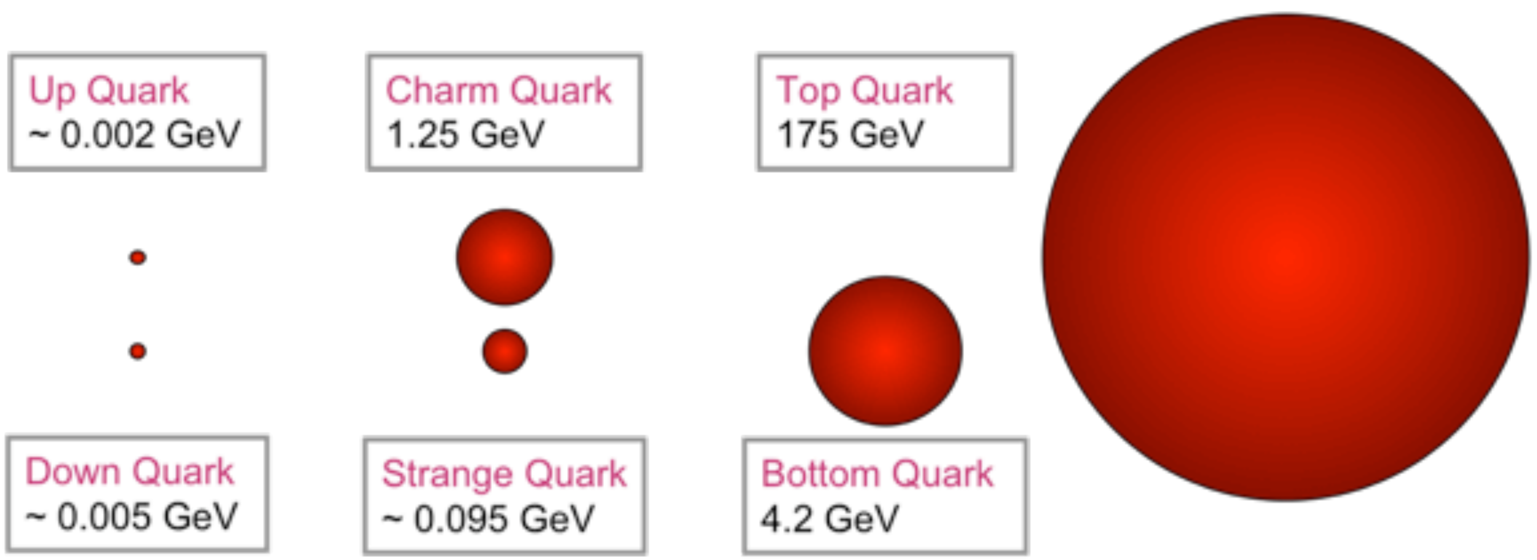
Given good agreement with SM predictions
- NP may exhibit considerable mass gap

Indirect searches of NP crucial - require high precision

The SM and NP flavor puzzles

The quark Yukawa sector of SM is very particular

$$m_u = v V_L^u Y^u V_R^{u\dagger}$$
$$m_d = v V_L^d Y^d V_R^{d\dagger}$$



$$V = V_L^u V_L^{d\dagger}$$

$$V \approx \begin{array}{cc} \begin{array}{ccc} d & s & b \end{array} & \\ \begin{pmatrix} 1 & \lambda & \lambda^3 \\ -\lambda & 1 & \lambda^2 \\ -\lambda^3 & -\lambda^2 & 1 \end{pmatrix} & \begin{array}{c} u \\ c \\ t \end{array} \end{array}$$

$\lambda \approx 0.22$: Cabibbo angle

hierarchical

aligned

"SM flavor puzzle"

The SM and NP flavor puzzles

Y^u, Y^d only source of global flavor symmetry breaking:

$$G_F = SU(3)_Q \times SU(3)_U \times SU(3)_D$$

10 physical parameters:

- 6 quark masses
- 3 CKM mixing angles
- 1 CP odd phase

Determine all flavor phenomena in quark sector!

The SM and NP flavor puzzles

Y^u, Y^d on … y breaking:

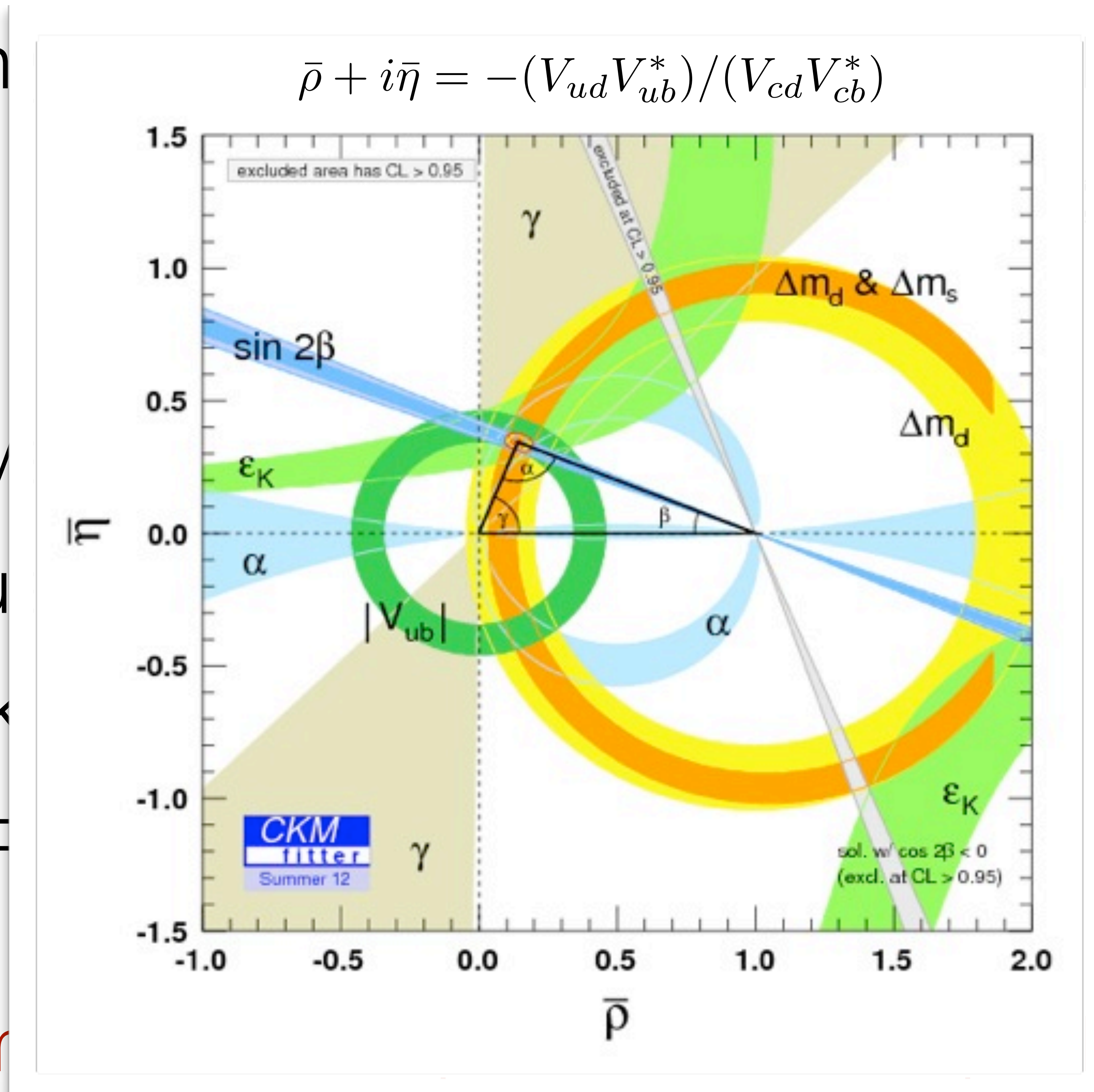
$)_D$

10 phy

6 qu

3 CK

1 CP



Determ … k sector!

Generally excellent consistency!

The SM and NP flavor puzzles

Severe constraints on NP sources of flavor

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum \frac{c_i^{(d)}}{\Lambda^{(d-4)}} O_i^{(d)}$$

Isidori, Nir & Perez, 1002.0900

Operator ($\Delta F = 2$)	Bounds on Λ in TeV ($c_{ij}=1$) Re	Im	Bounds on c_{ij} ($\Lambda = 1$ TeV) Re	Im	Observables
$(\bar{s}_L \gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	Δm_K; ϵ_K
$(\bar{s}_R\, d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	Δm_K; ϵ_K
$(\bar{c}_L \gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	Δm_D; $\lvert q/p\rvert, \phi_D$
$(\bar{c}_R\, u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	Δm_D; $\lvert q/p\rvert, \phi_D$
$(\bar{b}_L \gamma^\mu d_L)^2$	5.1×10^2	9.3×10^2	3.3×10^{-6}	1.0×10^{-6}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_R\, d_L)(\bar{b}_L d_R)$	1.9×10^3	3.6×10^3	5.6×10^{-7}	1.7×10^{-7}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_L \gamma^\mu s_L)^2$	1.1×10^2		7.6×10^{-5}		Δm_{B_s}
$(\bar{b}_R\, s_L)(\bar{b}_L s_R)$	3.7×10^2		1.3×10^{-5}		Δm_{B_s}

"NP flavor puzzle"

The SM and NP flavor puzzles

Severe constraints on NP sources of flavor

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum \frac{c_i^{(d)}}{\Lambda^{(d-4)}} O_i^{(d)}$$

NP at TeV scale has to be approximately flavor "aligned" with SM breaking

maximal alignment - Minimal Flavor Violation (Y^u, Y^d remain only sources)

d'Ambrosio et al., hep-ph/0207036

$$\mathcal{J}_\mu^{NP} = X_{ij} \bar{Q}^i \gamma_\mu Q^j \,, \quad X_{ij} = a_0 \mathbf{1} + a_1 Y^{u\dagger} Y^u + a_2 Y^{d\dagger} Y^d + \ldots$$

even in MFV, bounds on NP scale O (few TeV)!

Hurth, Isidori, J.F.K. & Mescia, 0807.5039
UTFit, 0707.0636

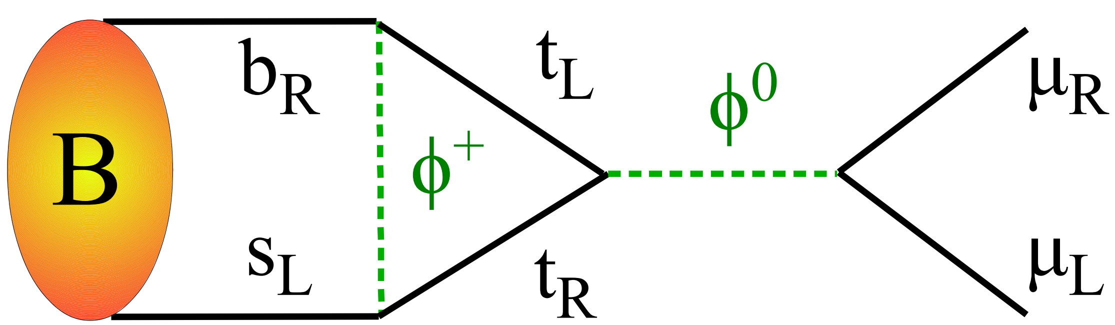
"NP flavor puzzle"

$B_{s,d} \to \mu^+\mu^-$ status and prospects

$B_{s,d} \to \mu^+\mu^-$ status and prospects

These modes are unique source of information about flavor physics beyond SM:

- theoretically very clean (virtually no long-distance contributions)
- particularly sensitive to FCNC scalar currents and FCNC Z penguins



(gaugeless limit - good approx. to full SM amplitude)

Clean probe of the Yukawa interaction
($\to$ Higgs sector) beyond tree level

$B_s \to \mu^+\mu^-$ recent developments

Updated SM prediction taking into account leading NLO EW (+ full NLO QCD)

Buras et al., 1208.0934

$$\mathcal{B}^{(0)}_{s,\mathrm{SM}} = 3.2348 \times 10^{-9} \times \left(\frac{M_t}{173.2\ \mathrm{GeV}}\right)^{3.07} \left(\frac{f_{B_s}}{227\ \mathrm{MeV}}\right)^{2} \left(\frac{\tau_{B_s}}{1.466\ \mathrm{ps}}\right) \left|\frac{V_{tb}^* V_{ts}}{4.05 \times 10^{-2}}\right|^2$$

~3% theory error.

systematic continuos improvement of f_{Bs} on Lattice (currently ~4%)

+ Correction factors in relating theory to experimentally accessible rate
 - Photon-energy cut → ~ -10% (already included in exp. eff.)
 - $\Delta\Gamma_s \neq 0$ → ~ +10% (not yet included in exp. results)

$$\overline{\mathcal{B}}_{s,SM} = (3.54 \pm 0.3) \times 10^{-9}$$

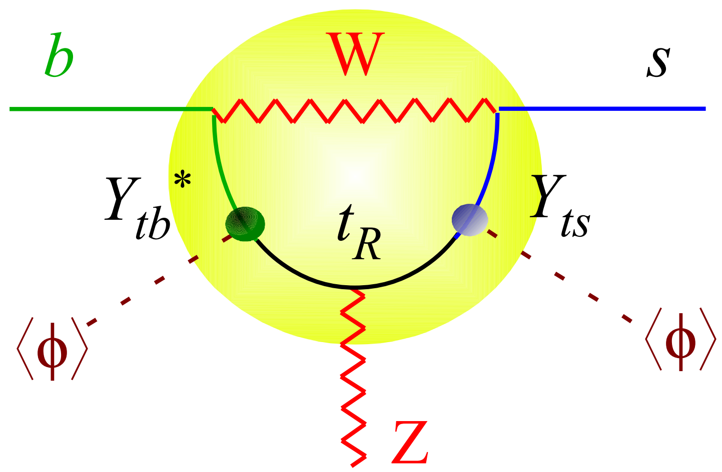
$$\overline{\mathcal{B}}_s^{(\mathrm{exp})} = (3.2^{+1.5}_{-1.2}) \times 10^{-9}$$ LHCb,1211.2674

At this stage there is perfect compatibility...

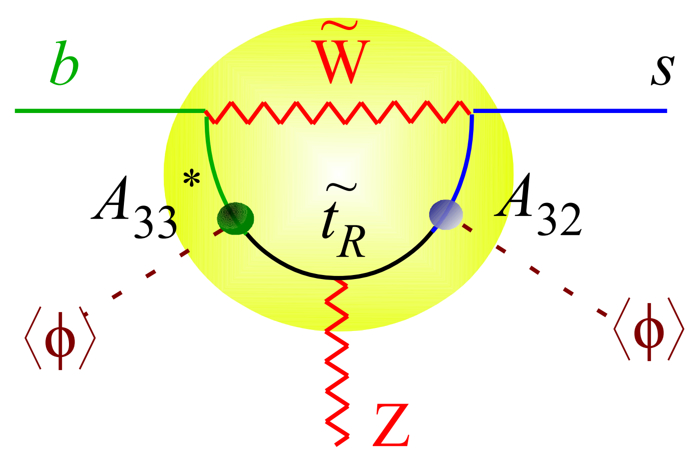
$B_s \to \mu^+\mu^-$ recent developments

...and good agreement with SM has important implications:

<u>Example</u>: Constraints on the structure of the A-terms in SUSY models



Leading contrib. in SM



Possible O(± 30%) corrections to Br for m_{tR} < 0.5 TeV

LR mixing term still largely unknown
(m_h ~125 GeV → large A_{33})

Measurement with σ(Br) ~ 30% provides first relevant constraint on such couplings below stability bounds ($|A_{33}\, A_{32}| < 3\, m_{tL}^2$) for m_{tL}<1 TeV

Puzzling CP violation in charm decays

Puzzling CP violation in charm decays

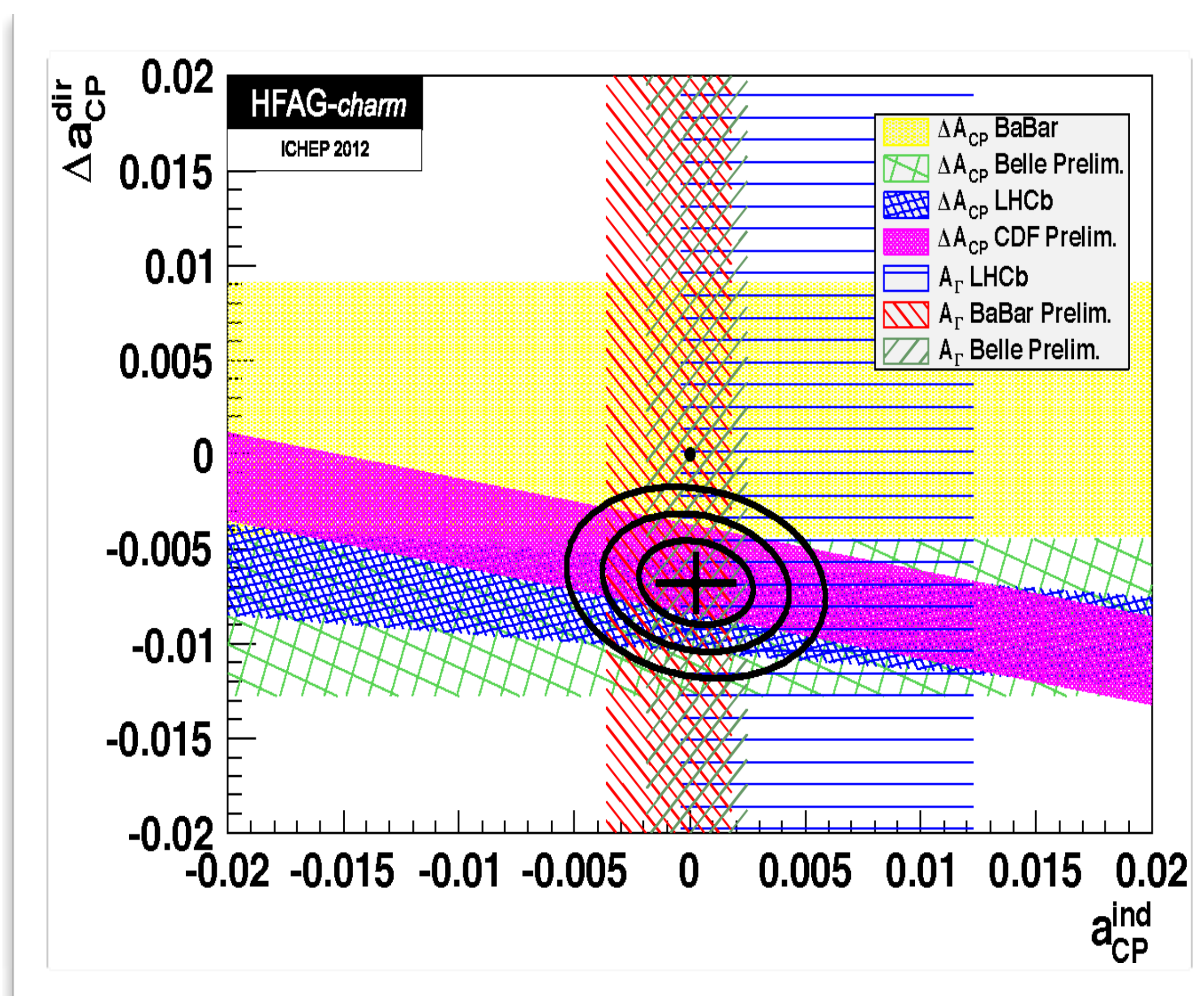
Year ago LHCb reported first evidence of CP violation in charm system, evidence soon after confirmed by CDF & Belle

$$\Delta a_{CP}^{\rm World} = -(0.68 \pm 0.15)\% \qquad (\sim 4.3\sigma \text{ from } 0)$$

Unambiguous evidence for direct CPV

$$a_f \equiv \frac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to f)}\,.$$

$$\Delta a_{CP} \equiv a_{K^+K^-} - a_{\pi^+\pi^-}$$



<u>Totally unexpected:</u> before LHCb result DCPV in charm above 0.1% often quoted as "clear signal of NP"...

Puzzling CP violation in charm decays

Observed Δa_{CP} is large compared to “natural” SM expectation

$$\boxed{\Delta a_{CP} \approx (0.13\%)\mathrm{Im}(\Delta R^{\mathrm{SM}})\,,}$$

CKM suppression

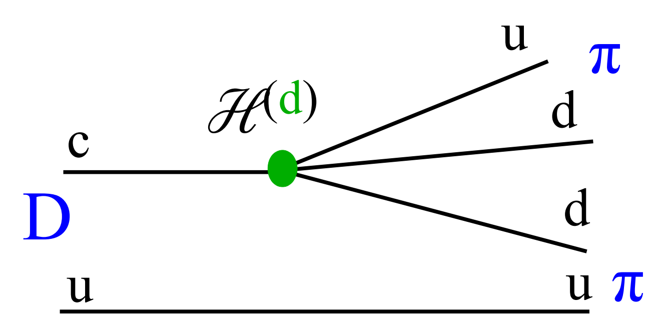
$$\arg\left(\frac{V_{cs}^* V_{us}}{V_{cd}^* V_{ud}}\right) = \mathcal{O}(\lambda^4)$$

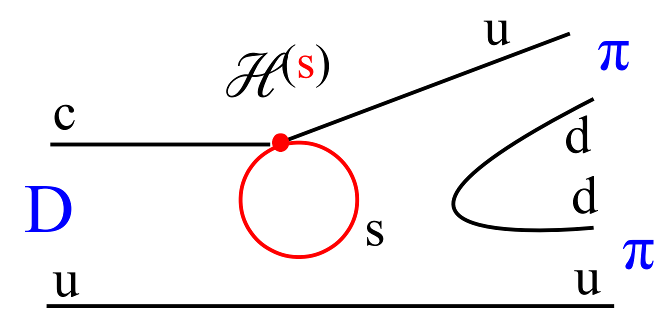
matrix element ratio:

$$\frac{\text{“disconnected”}}{\text{”connected”}}$$

naturally expected <1

c.f. Grossman et al., hep-ph/0609178

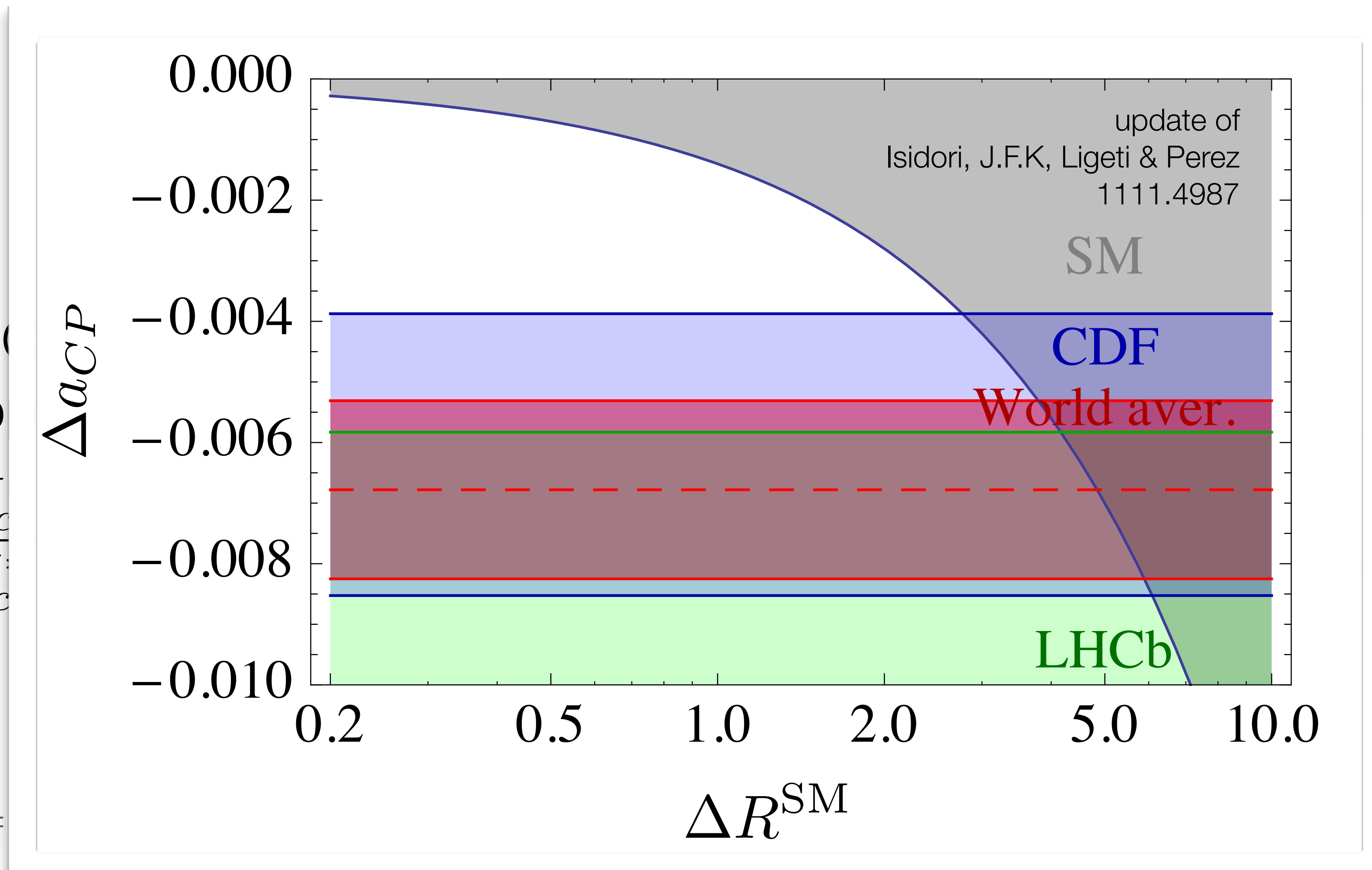


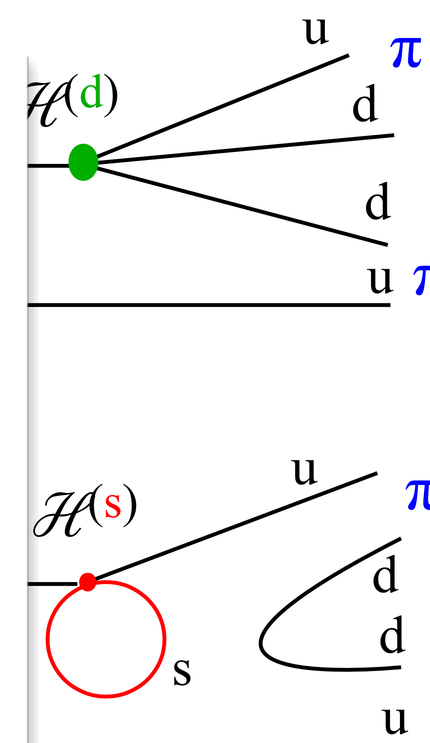


$$\mathcal{H}^{\mathrm{eff}}_{|\Delta c|=1} = \lambda_d \mathcal{H}^d_{|\Delta c|=1} + \lambda_s \mathcal{H}^s_{|\Delta c|=1} \quad \lambda_q \equiv V_{cq}^* V_{uq}$$

Puzzling CP violation in charm decays

Observed Δa_{CP} is large compared to “natural” SM expectation





O(4-6) values of $|\Delta R^{SM}|$ needed

Puzzling CP violation in charm decays

Observed Δa_{CP} is large compared to “natural” SM expectation

$$\boxed{\Delta a_{CP} \approx (0.13\%) \mathrm{Im}(\Delta R^{\mathrm{SM}}) \,,}$$

CKM suppression

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matrix element ratio:

$$\frac{\text{“disconnected”}}{\text{”connected”}}$$

naturally expected <1

c.f. Grossman et al., hep-ph/0609178

$\Delta R_{SM} > 1$ is not what we expect for $m_c >> \Lambda_{QCD}$, but is not impossible treating charm quark as light: possible connection with the $\Delta I=1/2$ rule in Kaons

Golden & Grinstein Phys. Lett. B 222 (1989)
Brod, Kagan & Zupan 1111.5000
Brod, Grossman, Kagan & Zupan 1203.6659

Puzzling CP violation in charm decays

Observed Δa_{CP} is large compared to "natural" SM expectation

...but not large enough, compared to SM uncertainties, to be considered clear signal of NP

Assuming SM does not saturate exp. value parametrize NP contributions normalized to effective SM scale

$$\Delta a_{CP} \approx (0.13\%)\mathrm{Im}(\Delta R^{\mathrm{SM}}) + 9\sum_i \mathrm{Im}(C_i^{\mathrm{NP}})\,\mathrm{Im}(\Delta R_i^{\mathrm{NP}})$$

- for $\mathrm{Im}(C_i^{\mathrm{NP}}) = \dfrac{v^2}{\Lambda^2}$: $\quad \dfrac{(10\ \mathrm{TeV})^2}{\Lambda^2} = \dfrac{(0.61 \pm 0.17) - 0.12\,\mathrm{Im}(\Delta R^{\mathrm{SM}})}{\mathrm{Im}(\Delta R^{\mathrm{NP}})}$

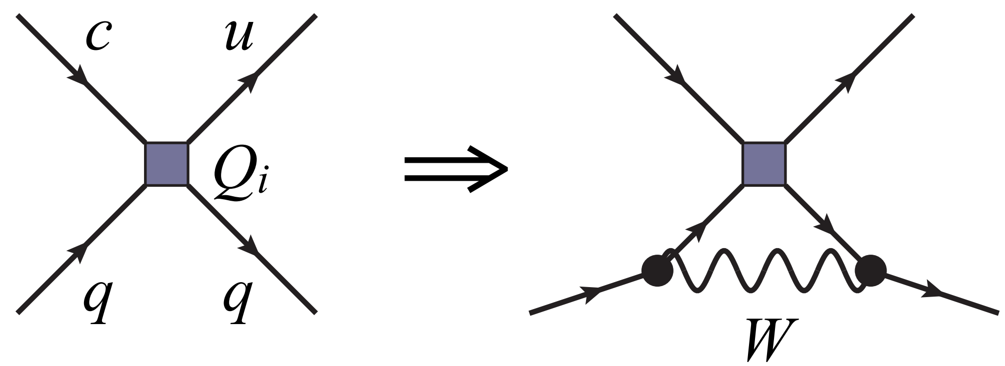
Are such contributions allowed by other flavor constraints?

Puzzling CP violation in charm decays

Isidori, J.F.K, Ligeti & Perez
1111.4987

In EFT can be estimated via “weak mixing” of operators

$$T\left\{\mathcal{H}^{\mathrm{eff-NP}}_{|\Delta c|=1}(0),\mathcal{H}^{\mathrm{SM}}(x)\right\}$$



Important constraints on most operators from D-D̄ mixing and direct CPV in $K^0\to\pi^+\pi^-$ (ε’/ε)

Gedalia, J.F.K, Ligeti & Perez
1202.5038

CPV chromo-magnetic operators only weakly constrained by EDMs

- Strict bounds from D meson mixing naturally satisfied
- Easily generated in various well-motivated models (SUSY, warped extra-dim.,....)

Giudice, Isidori & Paradisi,1201.6204
Keren-Zur et al., 1205.5803
Delaunay, J.F.K., Perez & Randall, 1207.0474

Puzzling CP violation in charm decays

Key question: how to distinguish NP vs. SM explanations?

NP explanation via chromo-magnetic operators:

Unavoidable large CPV also in the electric-dipole operators (model-independent connection via QCD)

Isidori & J.F.K., 1205.3164
Lyon & Zwicky, 1210.6546
Fajfer & Kosnik, 1208.0759

CPV in radiative D decays ($D \to (P^+P^-)_V \gamma$; also $D \to (P^+P^-)_V l^+l^-$)

CPV asymmetries above 3% would be a clear sign of NP in dipole operators

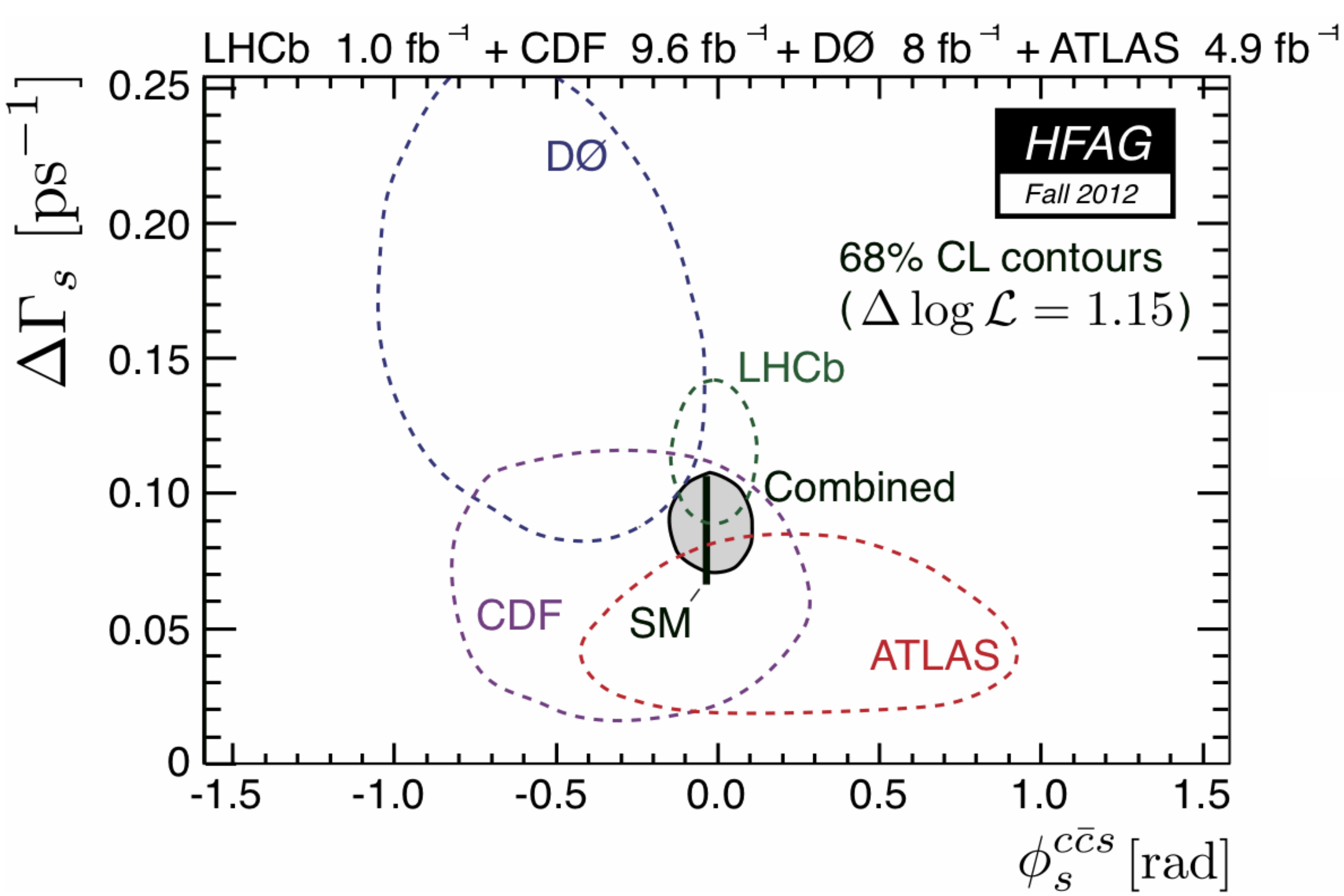
Neutron EDM and LFV in charged leptons are also expected to be close to present bounds, but connection is more model-dependent

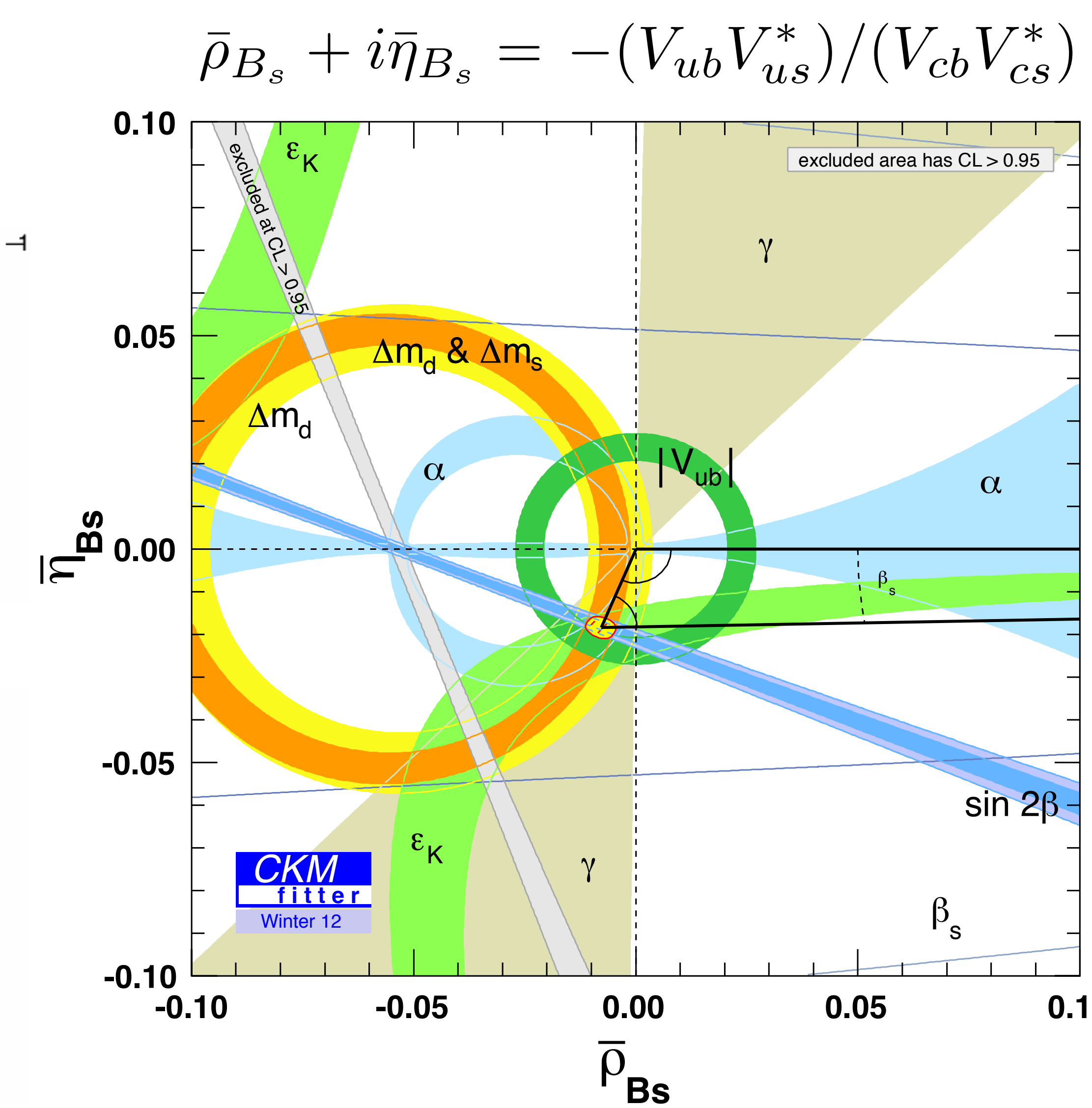
CP violation in B_s mixing?

CP violation in B_s mixing?

Given good consistency of global CKM fits, CPV in B_s mixing predicted precisely in SM

So far, no signs of deviations from the SM...

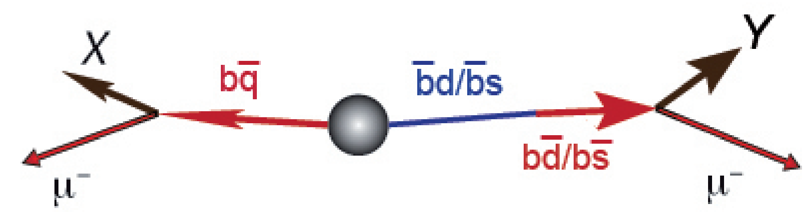




CP violation in B_s mixing?

...except persistent A_{sl} anomaly

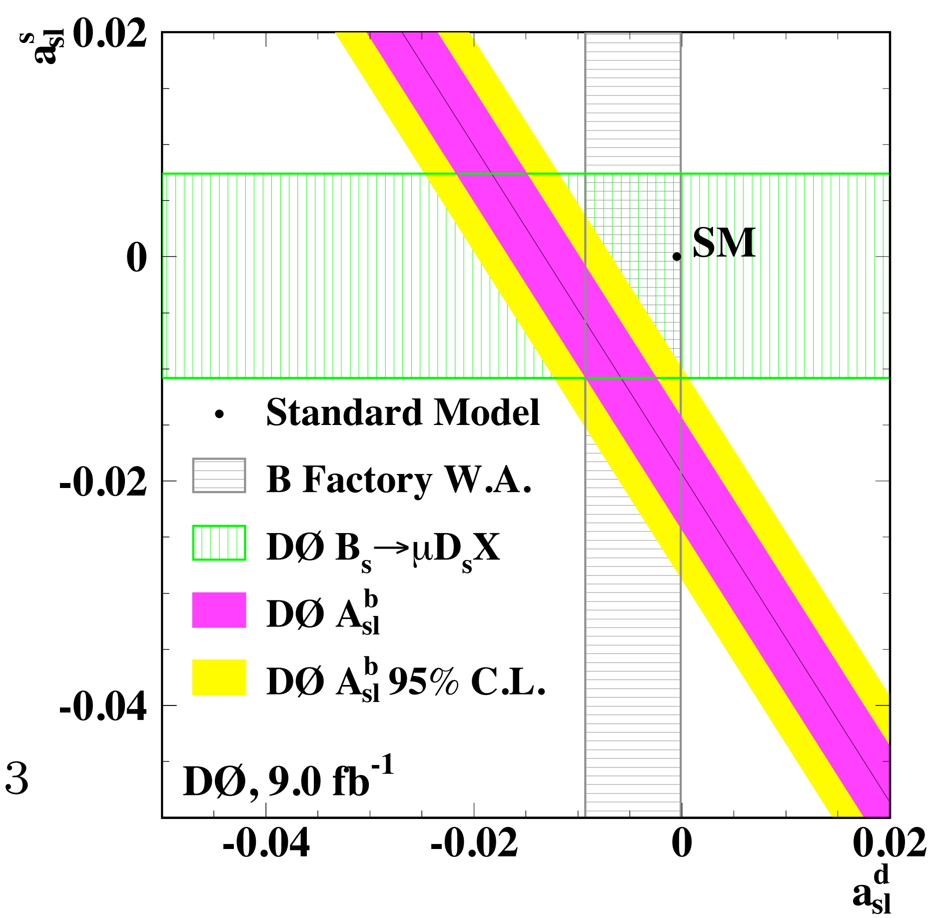
$$A = \frac{N^{++} - N^{--}}{N^{++} + N^{--}}$$



$$A \quad = (-0.787 \pm 0.172 \pm 0.093)\%$$

dimuon charge asymmetry by D0

D0, 1106.6308



If due to CPV in $B_{s,d}$ mixing

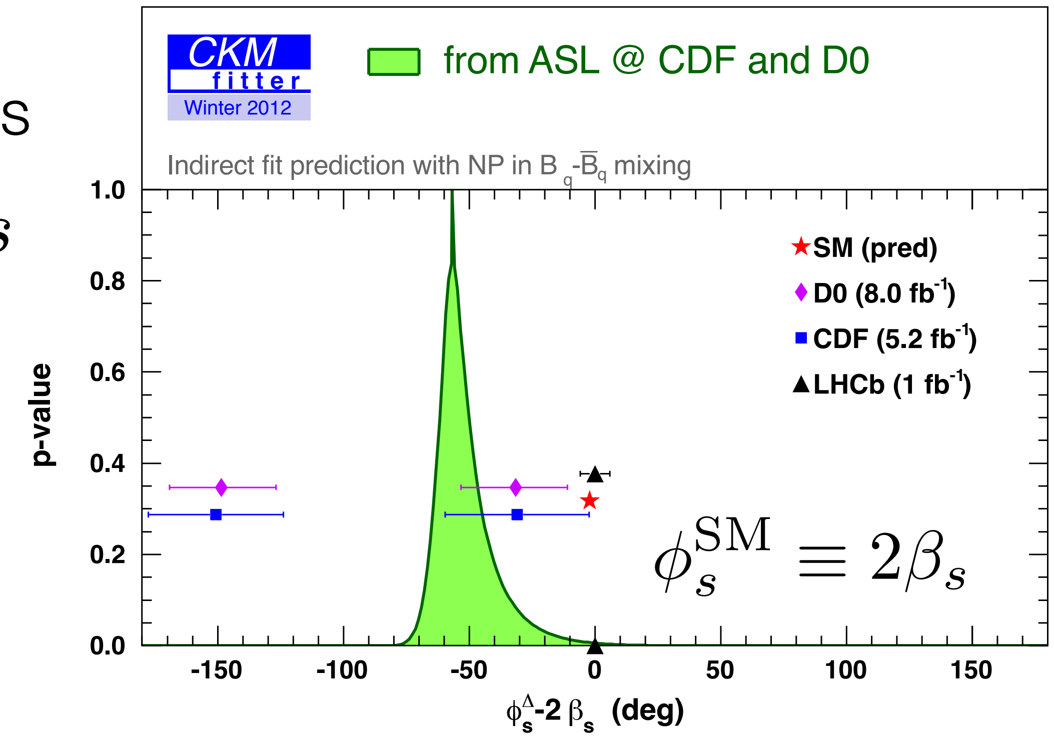
$$A_{\rm sl}^b = f_d a_{sl}^d + f_s a_{sl}^s$$

production (fragmentation) fractions

$$a_{sl}^q = \frac{\Gamma(\bar{B}_q \to \mu^+ X) - \Gamma(B_q \to \mu^- X)}{\Gamma(\bar{B}_q \to \mu^+ X) + \Gamma(B_q \to \mu^- X)}$$

SM prediction: $A_{\rm sl}^{b,\rm SM} = -(0.20 \pm 0.03) \times 10^{-3}$

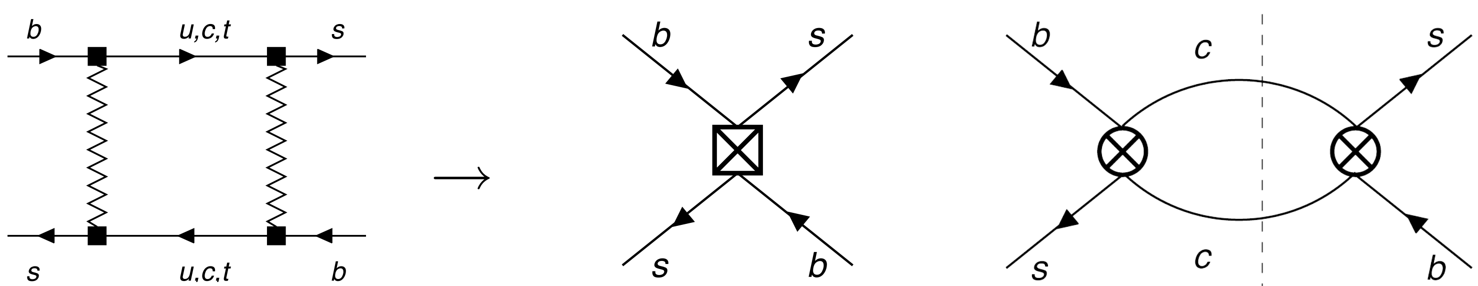
CP violation in B_s mixing?



If A would be due to NP phase in B_s mixing: in conflict with measured ϕ_s (similarly for B_d mixing)

Additional possibilities:

1. <u>NP in absorptive amplitudes</u>

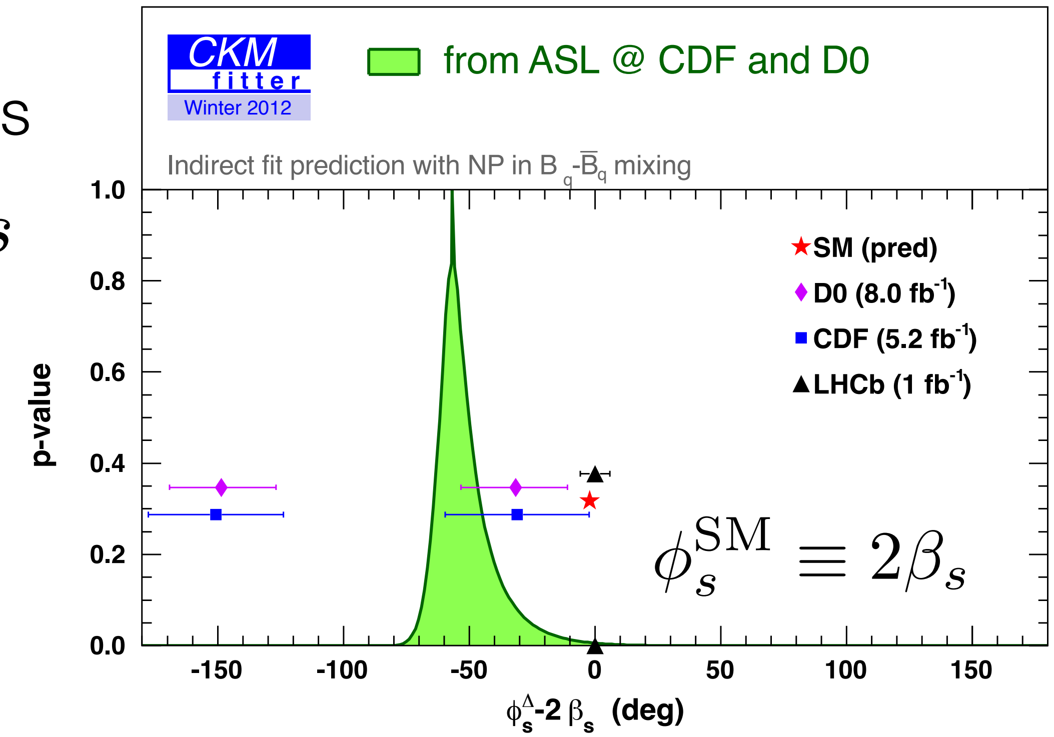


- in B_s system conflict with $\Delta\Gamma$, Δm_s
- in B_d system severe constraints from $\Delta F{=}1$, possibility remains

Bobeth & Haisch, 1109.1826

CP violation in B_s mixing?

If A would be due to NP phase in B_s mixing: in conflict with measured ϕ_s (similarly for B_d mixing)

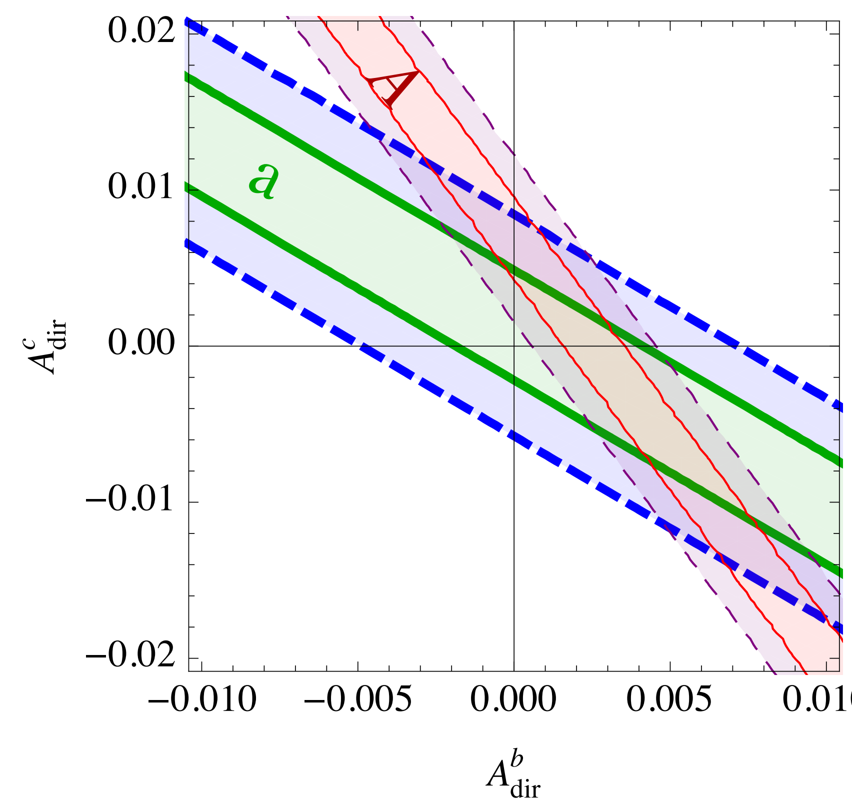


Additional possibilities:

1. <u>NP in absorptive amplitudes</u>
2. <u>NP in direct CP asymmetries</u>

(in semileptonic B_q or D_q decays)

Descotes-Genon & J.F.K., 1207.4483



- in B_q decays need O(0.1%) asym.
- in D_q decays need O(1%) asym.

Difficult to obtain in NP models

Violation of lepton flavor universality in B decays

LFU in (semi)leptonic B decays

In SM weak charged current interactions are lepton flavor universal

- Tested directly at colliders via W decays ~1%

Additional charged (scalar) interactions could induce LFU violation in processes at low energies

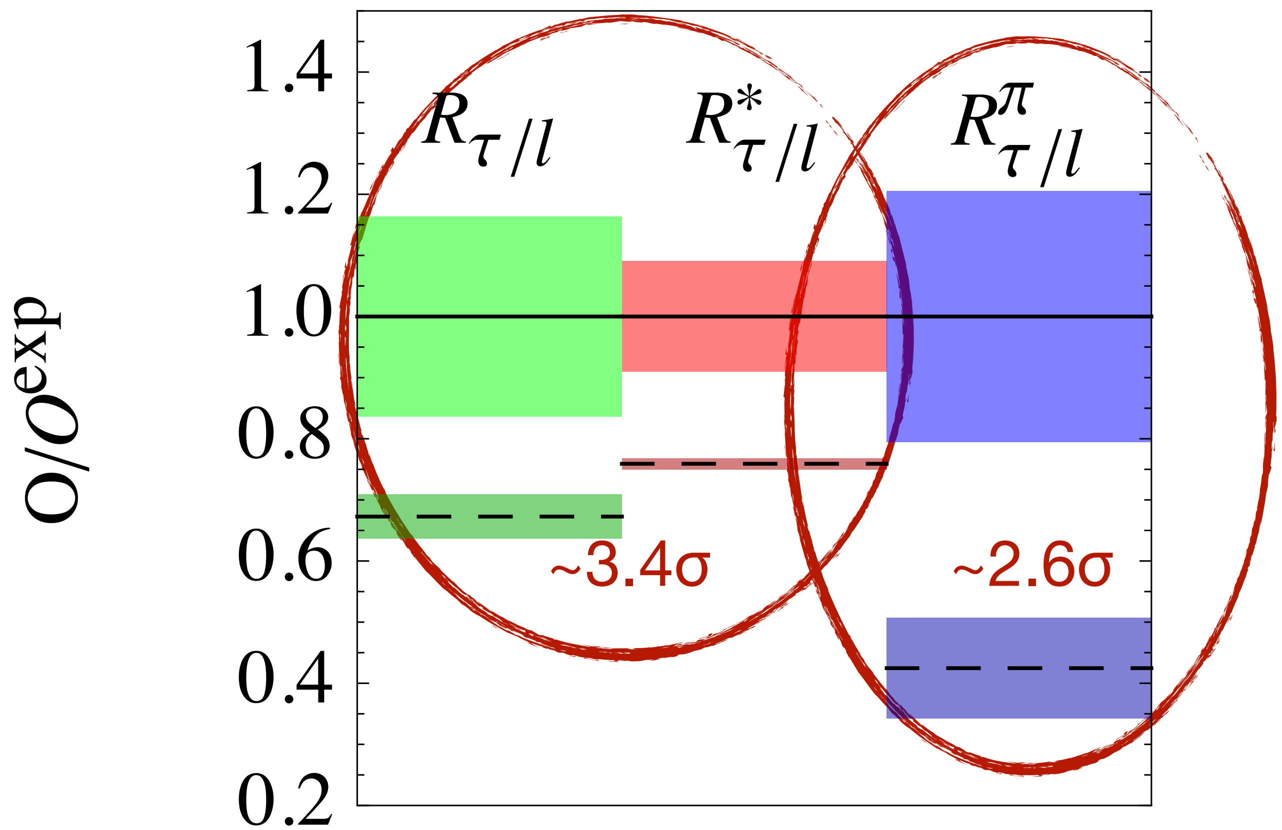
Can be predicted accurately even in hadronic processes, since most QCD uncertainties cancel in ratios

- Pion, kaon, D processes well consistent with LFU expectations ~(0.1-1)%
- In B sector tests only became feasible recently at B-factories...

c.f. HFAG, 1010.1589

LFU in (semi)leptonic B decays

Experimental situation



SM predictions

Fajfer, J.F.K., Nisandzic
1203.2654

J.F.K. & Mescia
0802.3790

Nierste, Trine & Westhoff
0801.4938

Tanaka & Watanabe
1005.4306

Laiho, Lunghi & Van de Water
0910.2928

BaBar, 1205.5442

$$\mathcal{R}^*_{\tau/\ell} \equiv \frac{\mathcal{B}(B \to D^* \tau\nu)}{\mathcal{B}(B \to D^* \ell\nu)} \qquad \mathcal{R}_{\tau/\ell} \equiv \frac{\mathcal{B}(B \to D\tau\nu)}{\mathcal{B}(B \to D\ell\nu)}$$

$$b \to c\tau\nu$$

HFAG
Belle, ICHEP2012

$$\mathcal{R}^\pi_{\tau/\ell} \equiv \frac{\tau(B^0)}{\tau(B^-)} \frac{\mathcal{B}(B^- \to \tau^-\bar{\nu})}{\mathcal{B}(\bar{B}^0 \to \pi^+\ell^-\bar{\nu})}$$

$$b \to u\tau\nu$$

LFU in (semi)leptonic B decays

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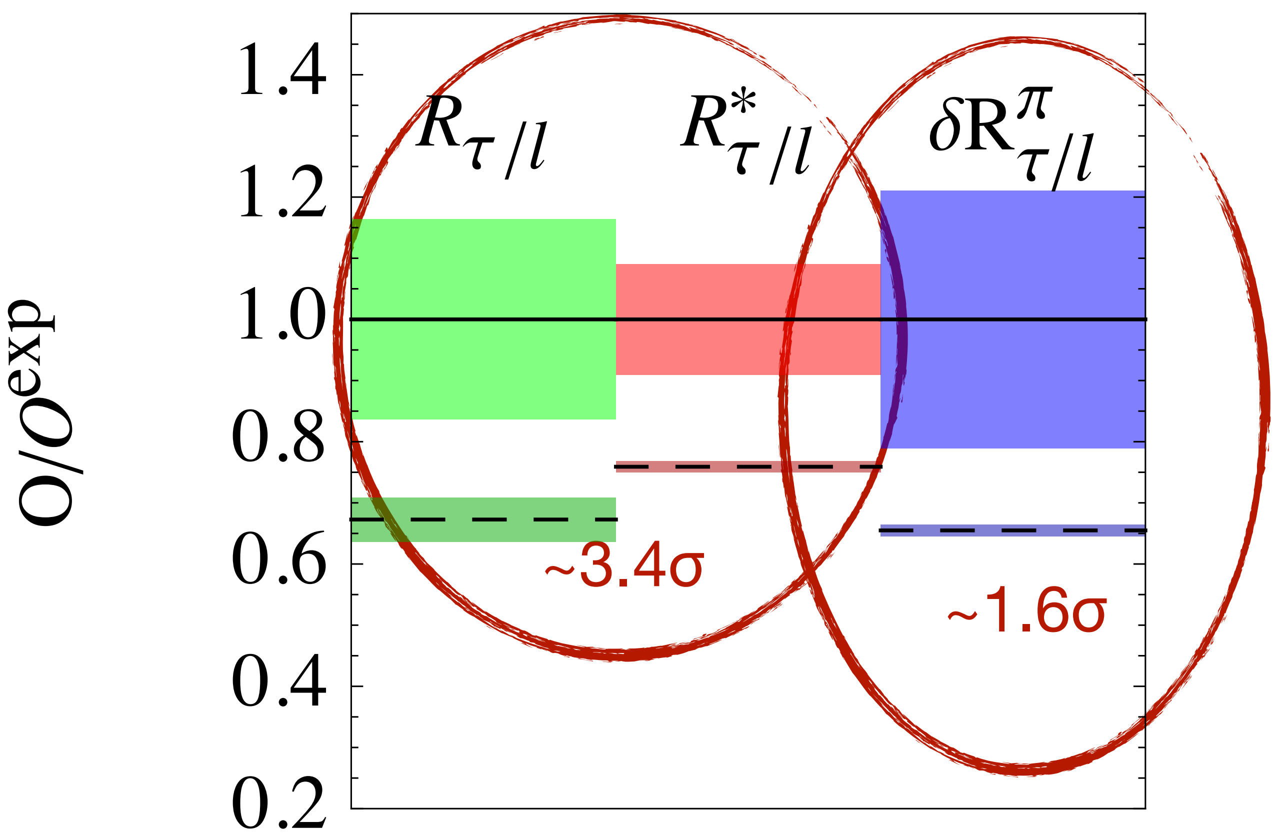

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HFAG
Belle, ICHEP2012

$$\Delta\mathcal{R}^\pi_{\tau/\ell} \equiv \frac{\tau(B^0)}{\tau(B^-)} \frac{\mathcal{B}(B^- \to \tau^-\bar{\nu})}{\Delta\mathcal{B}(\bar{B}^0 \to \pi^+\ell^-\bar{\nu})}$$

$$16 \text{ GeV}^2 < q^2 < 26.4 \text{ GeV}^2$$

$$b \to u\tau\nu$$

LFU in (semi)leptonic B decays

General requirements in EFT:

- no tree-level down quark / charged lepton FCNCs
- no LFU violations in pion, kaon sectors

} require flavor alignment

Fajfer, J.F.K., Nisandzic & Zupan, 1206.1872

A number of possibilities:

modification of left-hand current - preferred in MFV

Predict monotop signature at LHC

Andrea et al., 1106.6199
J.F.K. & Zupan, 1107.0623

chirality flipping scalar operators - require non-MFV

Example: generic 2HDM

see also Crivellin, Greub & Kokulu 1206.2634

severe bounds from FCNCs

Conclusions

Success of SM in describing flavor-changing processes implies that large new sources of flavor symmetry breaking at TeV scale are excluded.

However, there are sectors of the theory that are just starting to be tested

- Measurement of $B_{s,d} \to \mu^+\mu^-$ probes the Higgs Yukawa sector at loop level
- If due to NP, observed Δa_{CP} points towards new flavor sources in u_R sector
  - interesting implications for radiative charm decays
- D0 A_{sl} measurement inconsistent with LHCb measured CPV in B_s mixing
  - implications for (direct) semileptonic *B* (and *D*) asymmetries
- If confirmed, observed LFU violations in *B* decays point towards new charged current interactions of 3rd gen. matter fields
  - interesting top, tau physics at LHC

Backup

CPV in $|\Delta c|=2$

- **CPV in Mixing** $|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$

$$m \equiv \frac{m_1 + m_2}{2}\,, \qquad \Gamma \equiv \frac{\Gamma_1 + \Gamma_2}{2}\,,$$
$$x \equiv \frac{m_2 - m_1}{\Gamma}\,, \qquad y \equiv \frac{\Gamma_2 - \Gamma_1}{2\Gamma}\,.$$

- Experimentally accessible mixing quantities:
  - x,y (CP conserving)

    Cannot be estimated accurately within SM

    NP contributions are predictable
  - flavor specific time-dependent CPV decay asymmetries [sensitive to q/p]

$$a_f(t) \equiv \frac{\Gamma(D^0(t) \to f) - \Gamma(\bar{D}^0(t) \to f)}{\Gamma(D^0(t) \to f) + \Gamma(\bar{D}^0(t) \to f)}\,,$$

CPV in |Δc|=2

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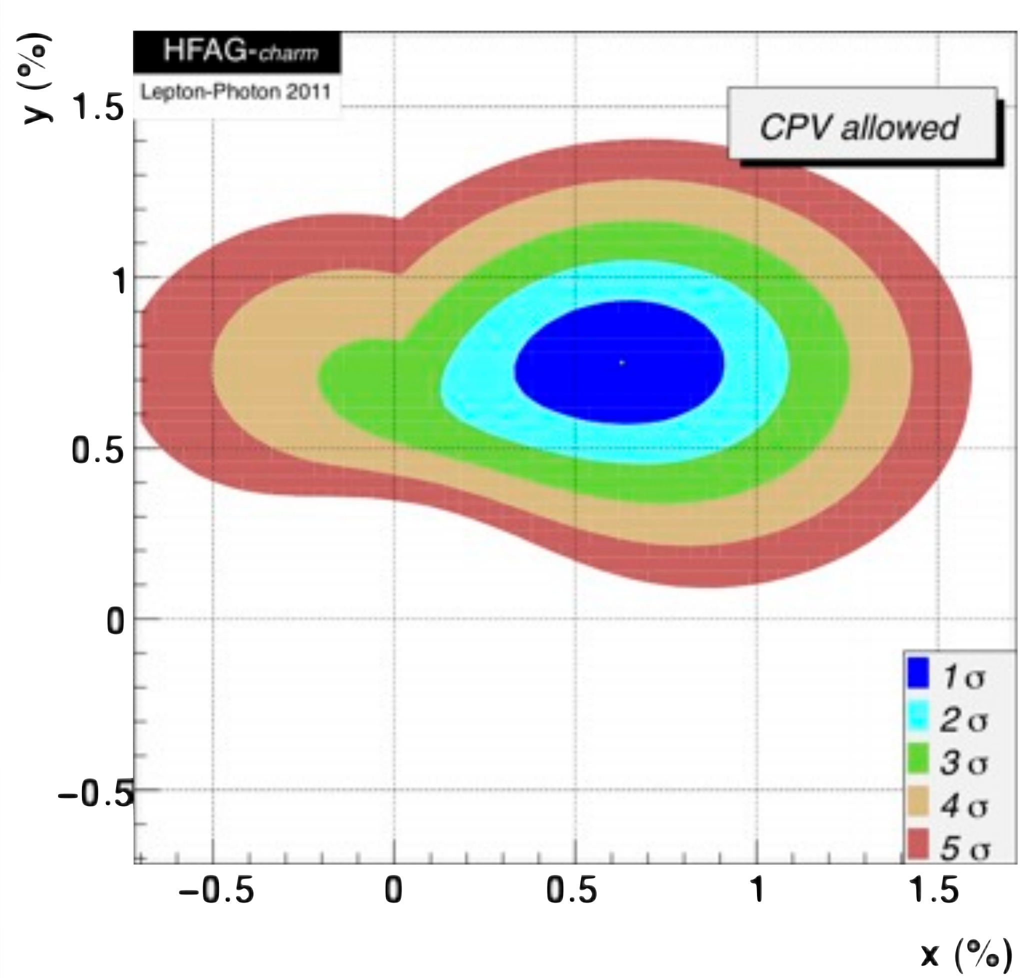
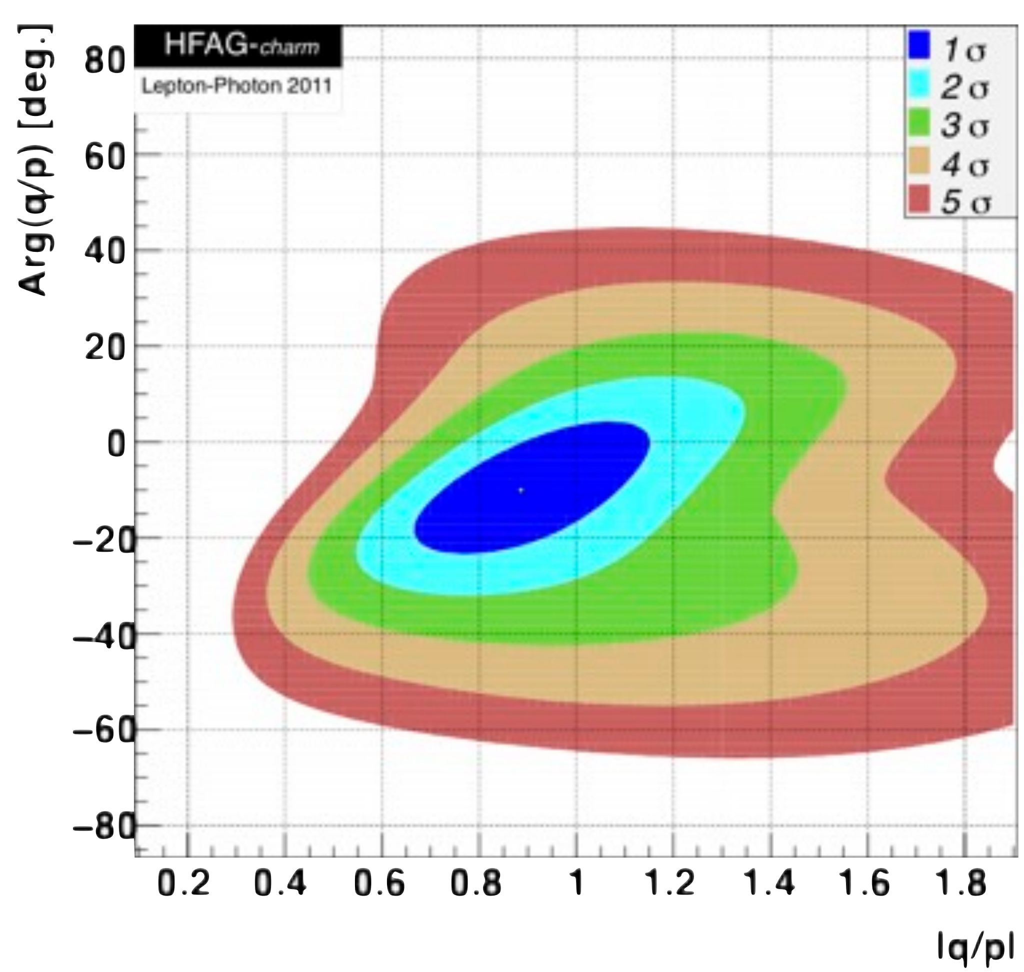
$$m \equiv \frac{m_1 + m_2}{2}\,, \qquad \Gamma \equiv \frac{\Gamma_1 + \Gamma_2}{2}\,,$$
$$x \equiv \frac{m_2 - m_1}{\Gamma}\,, \qquad y \equiv \frac{\Gamma_2 - \Gamma_1}{2\Gamma}\,.$$





CPV in |Δc|=2

- **CPV in Mixing** $|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$

$$m \equiv \frac{m_1 + m_2}{2}, \qquad \Gamma \equiv \frac{\Gamma_1 + \Gamma_2}{2},$$

$$x \equiv \frac{m_2 - m_1}{\Gamma}, \qquad y \equiv \frac{\Gamma_2 - \Gamma_1}{2\Gamma}.$$