# Theoretical Implications of Flavor-Physics Measurements

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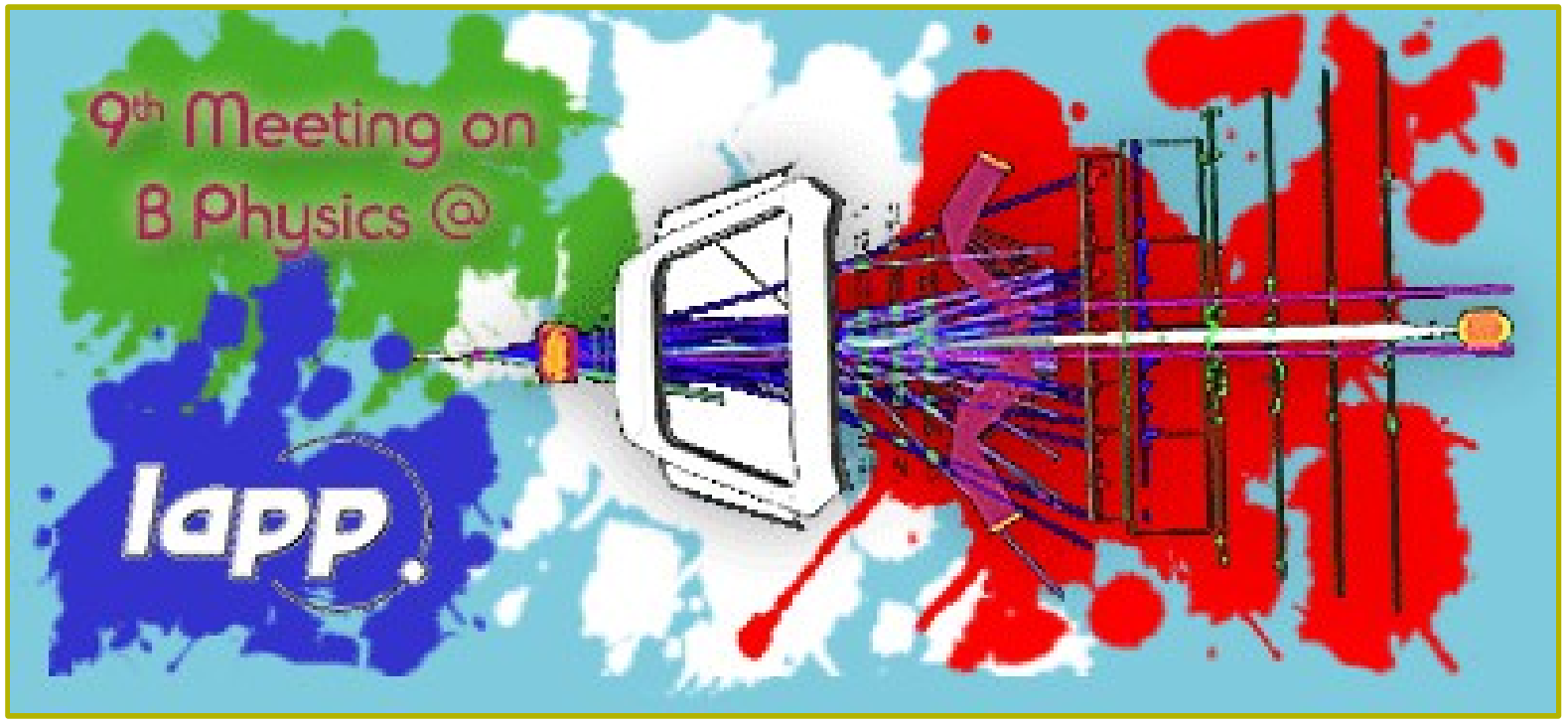
CNRS, LAPTh Annecy



**LHCb (plus some B-factories' updates) has already produced results on a multitude of important flavor-physics observables:**

See e.g. recent talks by Tim Gershon

## CPV effects

- sin 2ß from $B^0 \to J/\psi\, K_s$ (CPV in mixing/decay interf.)
- $B^0 \to KKK, K\pi\pi, [\pi K]_D\, K$ (direct CPV)
- Semilep. asymmetries in $B_d$, $B_s$ (CPV in B-mixing)
- $\Delta A_{CP}(D \to h^+ h^-)$ (direct CPV)

## CKM angles' / sides' knowledge

- ß : many more modes besides $J/\psi\, K_s$
- α : $B \to \pi\pi, \rho\pi, \rho\rho, a_1\pi$
- γ : tree-level $B \to DK$
- $ß_s$ : $B_s \to J/\psi\, \varphi$ & $J/\psi\, \pi\pi$ (by-product: $\Delta\Gamma_s$ established)
- progress on $|V_{ub}|, |V_{cb}|, |V_{td}|, |V_{ts}|$

## Selected B-decays

- $B \to \tau\nu$ , $B \to D(*)\tau\nu$
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offers two 'prototype' examples of how progress is made (and even more can be made)

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☞ So I'll concentrate on these two topics

$B_s \rightarrow \mu^+\mu^-$

## The $B_s \to \mu\mu$ decay within the SM: structure

See: Buchalla, Buras '93; Misiak, Urban '99

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$$BR[B_s \to \mu^+\mu^-] \simeq \frac{1}{\Gamma_s} \times \left( \frac{G_F^2 \alpha_{\text{e.m.}}^2}{16\pi^3 s_W^4} \right) \cdot \left| V_{tb}^* V_{ts} \right|^2 \cdot f_{B_s}^2 \; m_{B_s} \cdot m_\mu^2 \cdot Y^2(m_t^2/M_W^2)$$

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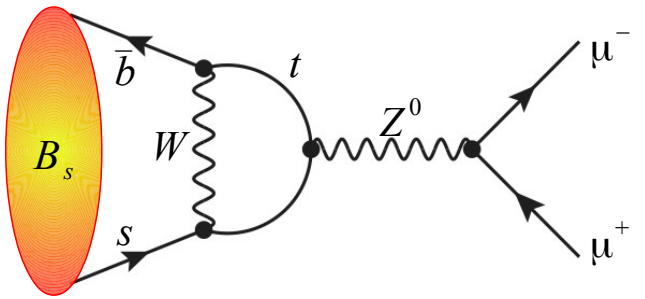
### Some Comments

**Example of diagram**

**The $Z^0$-penguin (contribution: ~ 80%)**

**couplings and Y-function:**




- The relevant CKM structure is $V^*_{tb} V_{ts}$
- top-mass dependence from the loop

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**hadronic matrix element**

Recall: the final state is purely leptonic

The only non-null matrix elem' is:

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Within the SM, only one operator contributing:

$$O_A \equiv (\bar{b}\gamma_L^\alpha s)(\bar{\mu}\gamma_\alpha\gamma_5\mu)$$

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Chiral suppression && purely leptonic nature of the decay

⇩

Extremely rare && very clean decay at the same time

One of the best available probes of physics at and (well) above the LHC reach

## $BR[B_s \to \mu\mu]$: parametric dependence

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☞ Thus, one can write the following phenomenological expression for the BR

top "pole" mass here

$$BR[B_s \to \mu^+\mu^-] = 3.23 \cdot 10^{-9} \cdot \left( \frac{\tau_{B_s}}{1.466\,\text{ps}} \right) \cdot \left( \frac{\text{Re}(V_{tb}^* V_{ts})}{4.05 \cdot 10^{-2}} \right)^2 \cdot \left( \frac{f_{B_s}}{227\,\text{MeV}} \right)^2 \cdot \left( \frac{M_t}{173.2\,\text{GeV}} \right)^{3.07}$$

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$$BR[B_s \to \mu^+\mu^-] = 3.23 \cdot 10^{-9} \cdot \left( \frac{\tau_{B_s}}{1.466\,\text{ps}} \right) \cdot \left( \frac{\text{Re}(V_{tb}^* V_{ts})}{4.05 \cdot 10^{-2}} \right)^2 \cdot \left( \frac{f_{B_s}}{227\,\text{MeV}} \right)^2 \cdot \left( \frac{M_t}{173.2\,\text{GeV}} \right)^{3.07}$$

☑ Thence one can easily work out the main error components as follows

| | pdgLive | CKMfitter or UTfit | LQCD average (central value from C. Davies) |
|---|---|---|---|
| **Input** | $\tau_{B_s} = 1.466(31)\,\text{ps}$ | $\text{Re}(V_{tb}^* V_{ts}) = 4.05(8) \cdot 10^{-2}$ | $f_{B_s} = 227(8)\,\text{MeV}$ |
| **Contribution to BR relative error** | 2% | 4% | 7% |

## BR[$B_s \to \mu\mu$]: parametric dependence

**Note:** I'll skip here the (more technical) issue of the residual systematic errors. On this, see: Buras, Girrbach, DG, Isidori, EPJC 12

☑ The main sources of error within the BR formula are:

$$BR[B_s \to \mu^+\mu^-] \simeq \frac{1}{\Gamma_s} \times \left( \frac{G_F^2 \alpha_{\text{e.m.}}^2}{16\pi^3 s_W^4} \right) \cdot \left| V_{tb}^* V_{ts} \right|^2 \cdot f_{B_s}^2 m_{B_s} \cdot m_\mu^2 \cdot Y^2(m_t^2/M_W^2)$$

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| **Contribution to BR relative error** | 2% | 4% | 7% | 1.6% |

Total relative error expected for BR[$B_s \to \mu\mu$]: **about 8.5%**

## BR[$B_s \to \mu^+\mu^-$] beyond the SM

☑ **Model-independent approach:** effective operators

Beyond the SM,
a total of 6 operators can contribute:

**SM operator**

$$O_A \equiv (\bar{b}\gamma_L^\alpha s)(\bar{\mu}\gamma_\alpha\gamma_5\mu) \qquad O'_A \equiv (\bar{b}\gamma_R^\alpha s)(\bar{\mu}\gamma_\alpha\gamma_5\mu)$$

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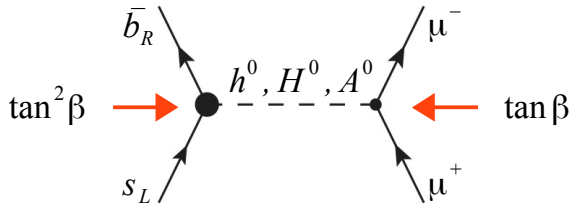
*One famous example:*
*the MSSM with large tanß*




Effectively tree-level diagrams:
Enhancement going as:

$$BR[B_s\to\mu^+\mu^-] \propto A_t^2 \frac{\tan^6\beta}{M_A^4}$$

## BR[$B_s \to \mu\mu$] as an EW precision test

DG, Isidori, to appear (tomorrow)

- ☑ $B_s \to \mu\mu$ is more than 'just' a probe of new scalars mediating FCNCs

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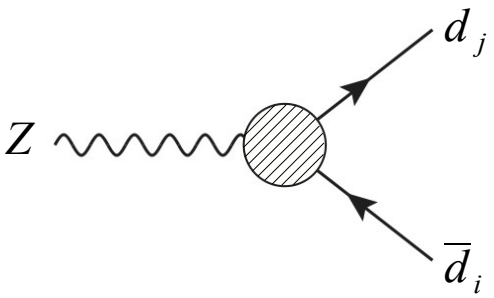

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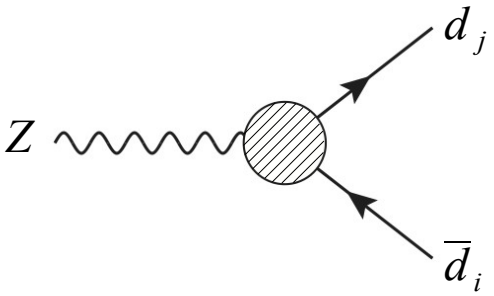


**Flavor-diag:** $i = j\ (= 3)$

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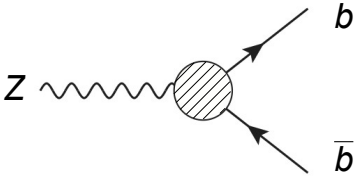

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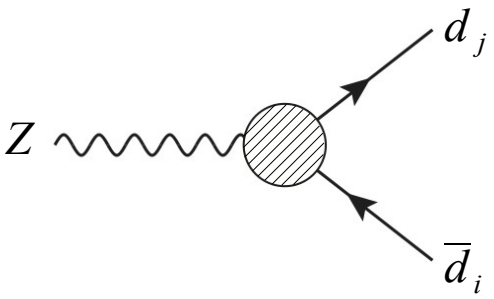


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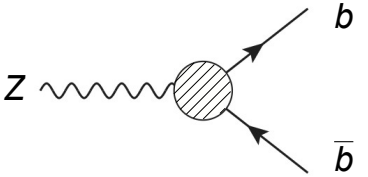


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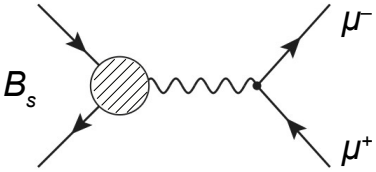

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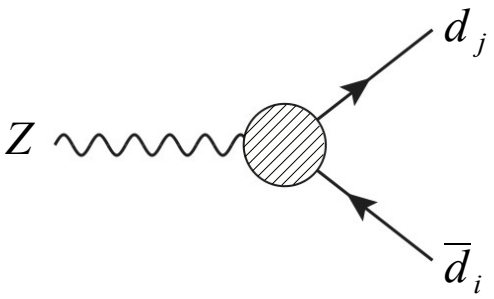


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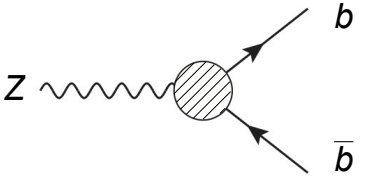


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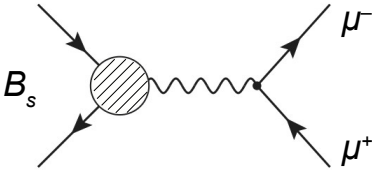


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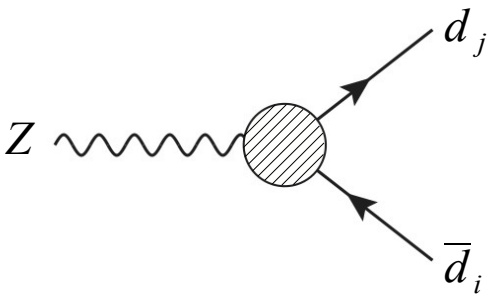


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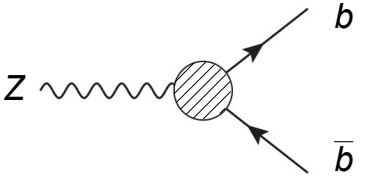


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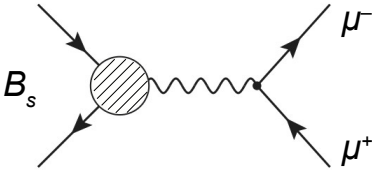


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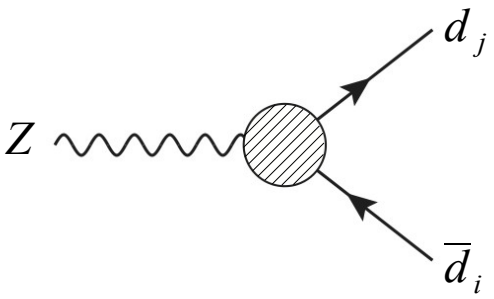


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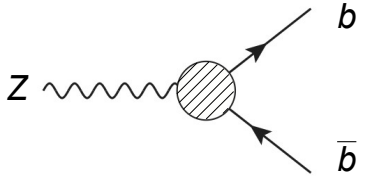


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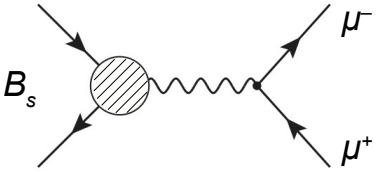


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**Comments**

- Three such structures compatible with the SM gauge group
- Other operators yield negligible effects in either $Z$-peak obs or in $B_s \to \mu\mu$

## **BR[$B_s \to \mu\mu$] as an EWPT:** continued

- In this approach, there is a correlation between $Z \to b\,\bar{b}$ and $B_s \to \mu\mu$.

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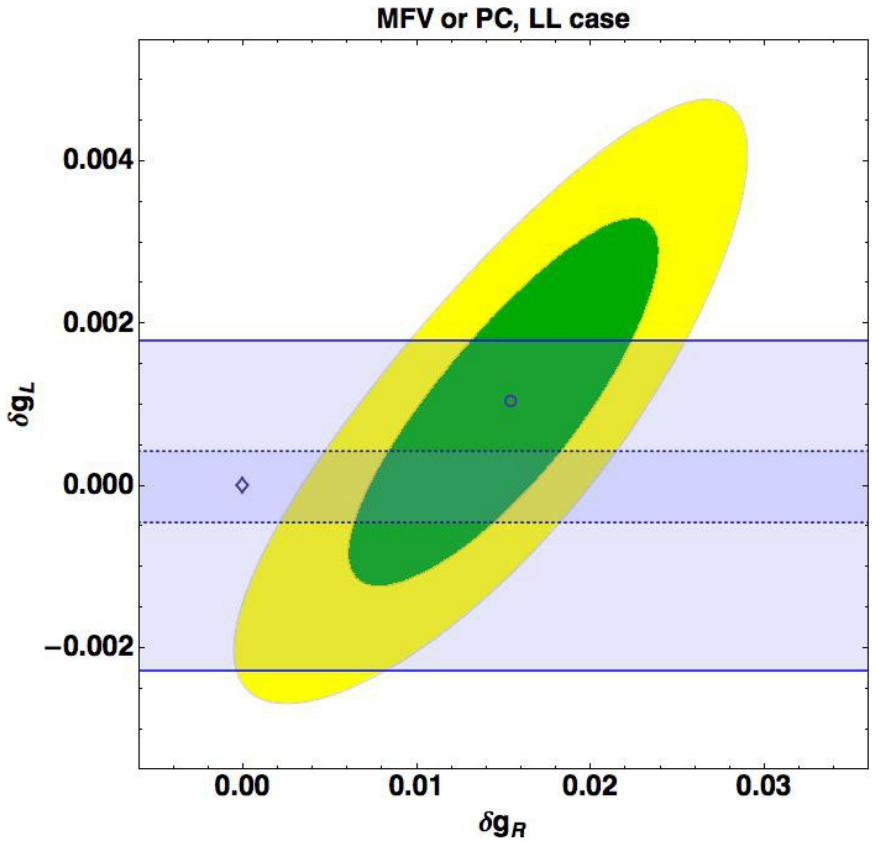

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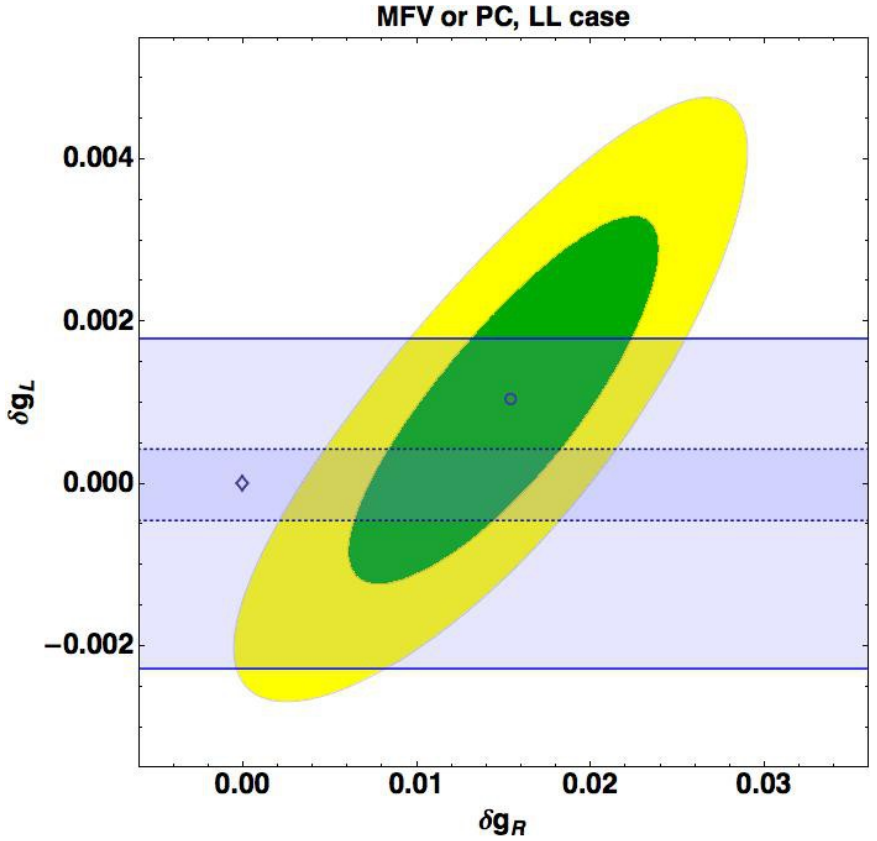


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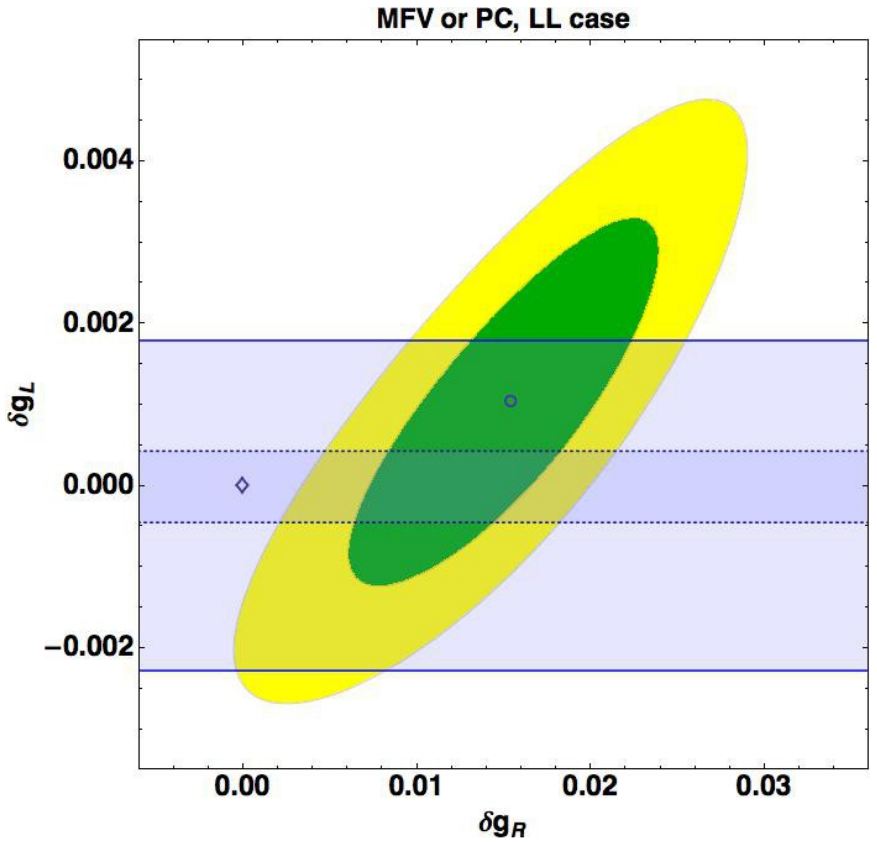


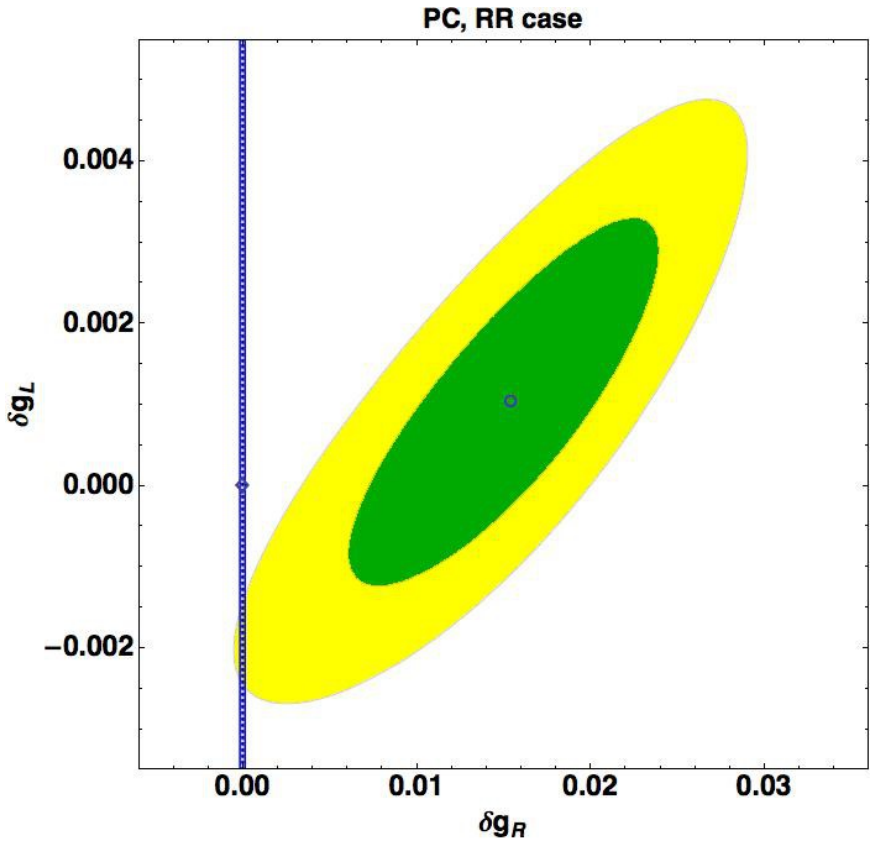


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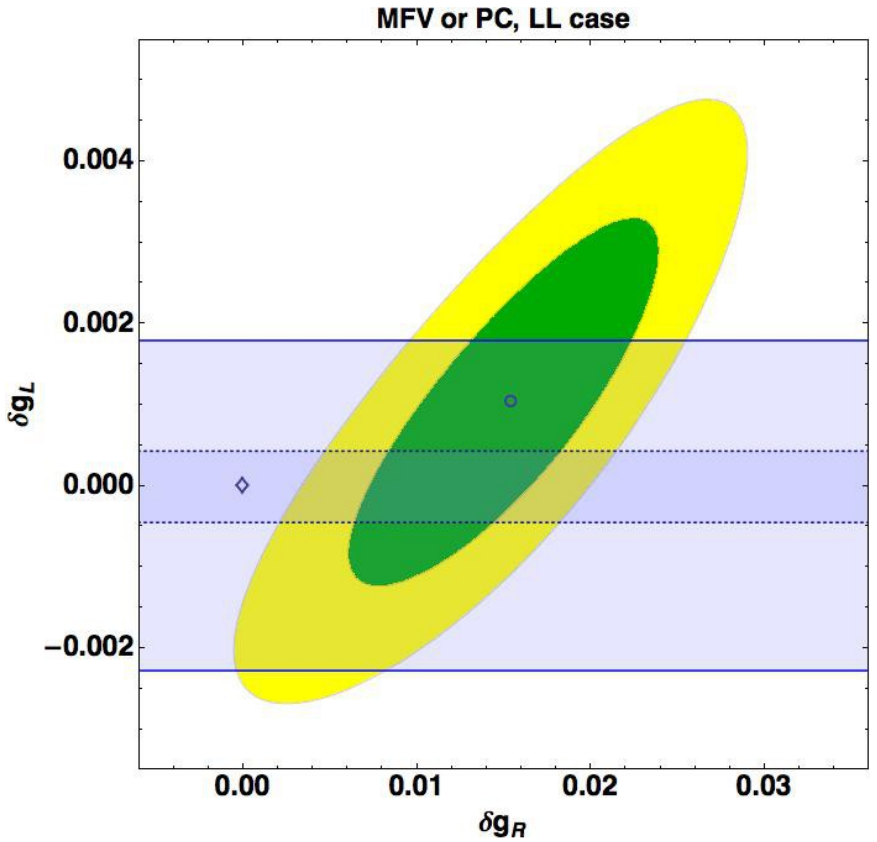


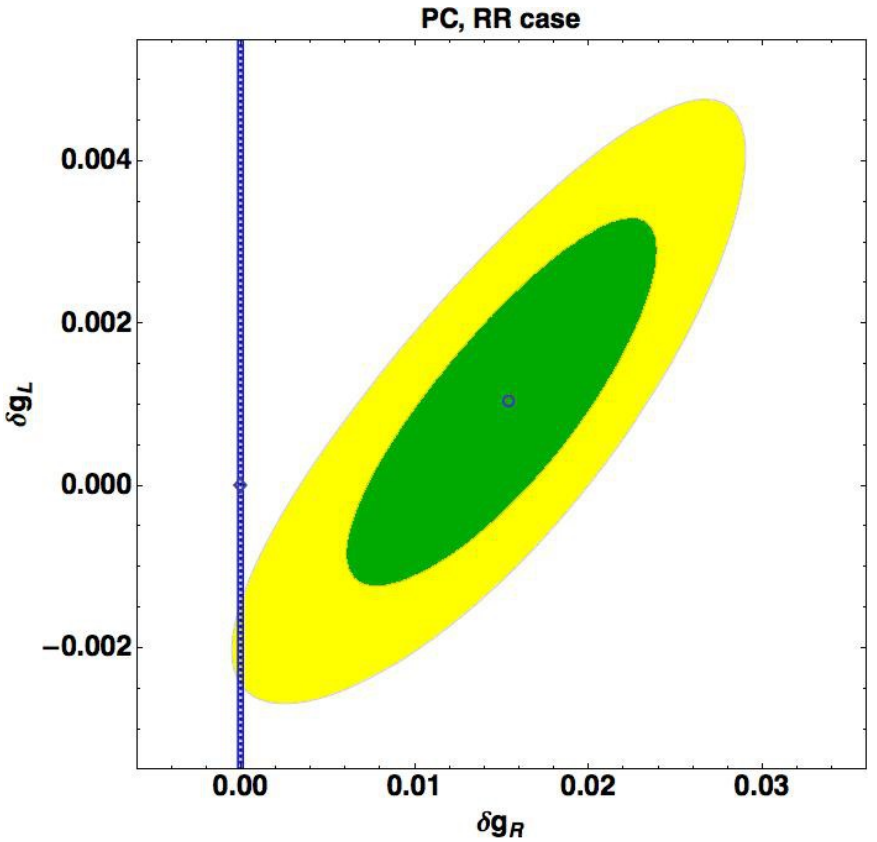


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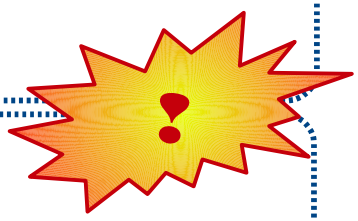

# Direct CPV in charm

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**Main point**

All the asymmetry components other than cancel to high accuracy in the difference between the K K and the π π channel.

Hence the LHCb measurement is the first evidence of direct CPV in charm

*… and it's larger than expected...*

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For large phases, the asymmetry goes down as the magnitude of the sub-leading / leading amplitude ratio.

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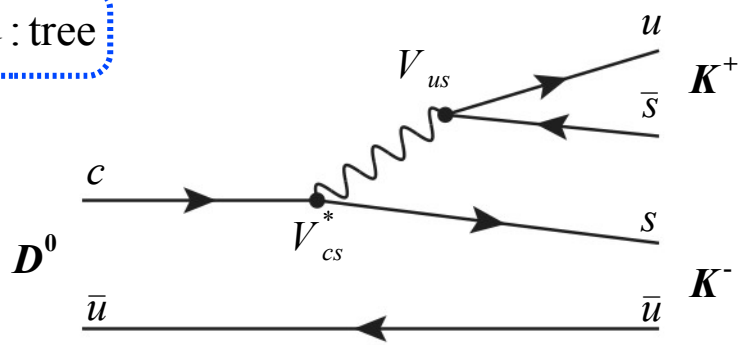


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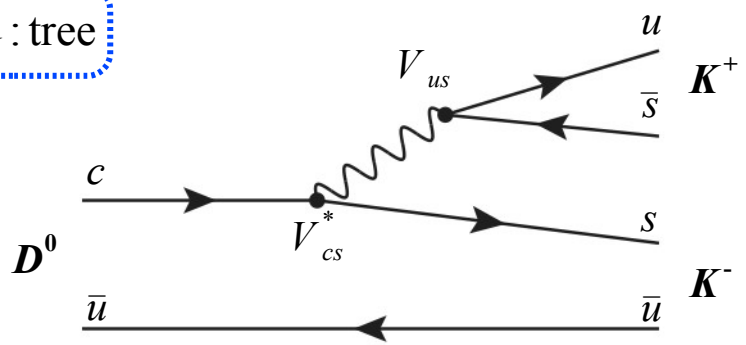


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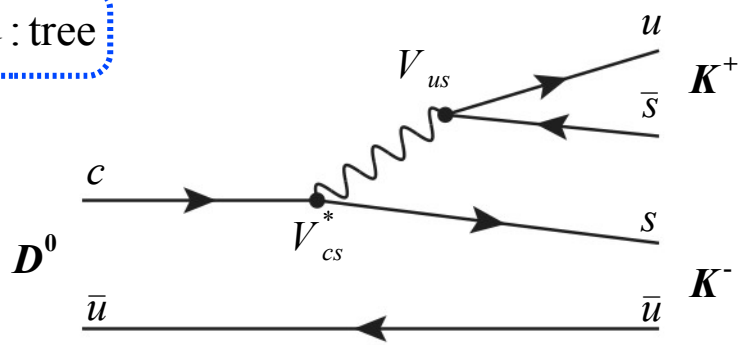


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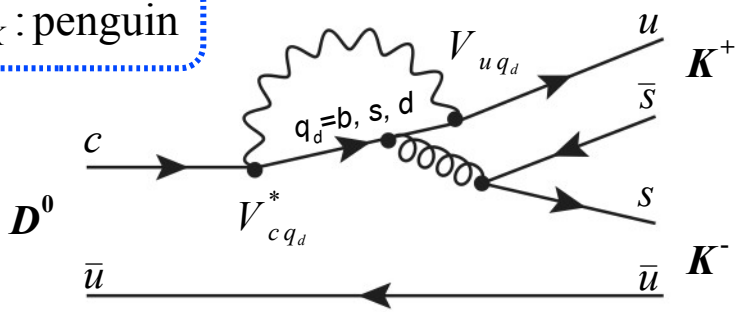


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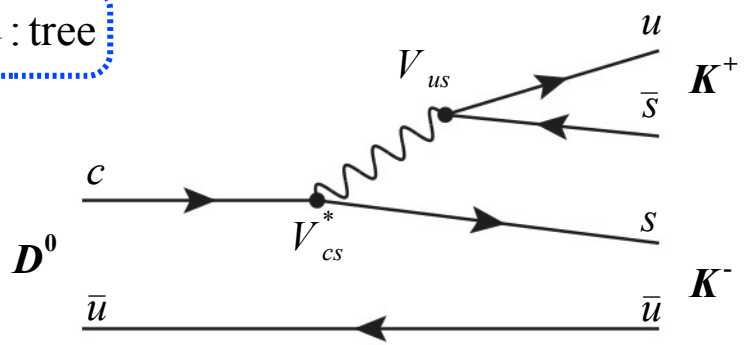


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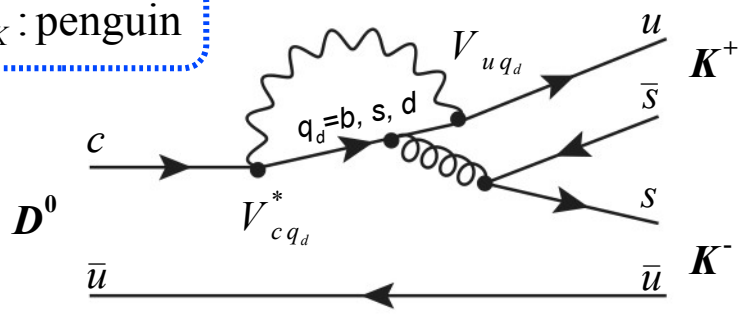


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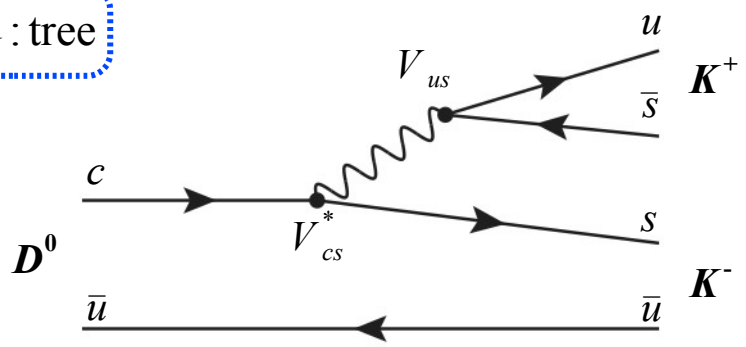


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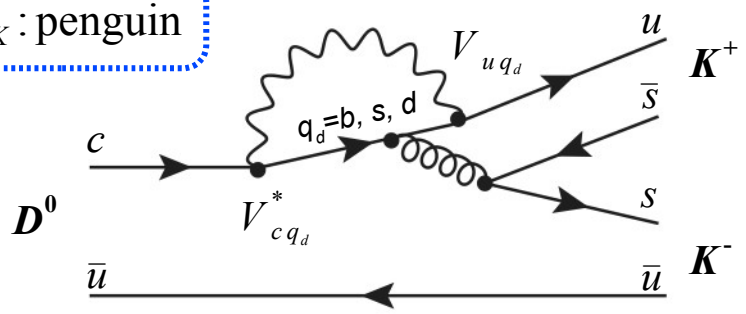


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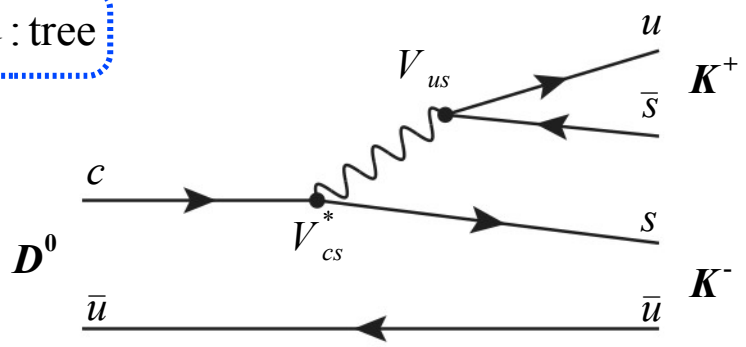


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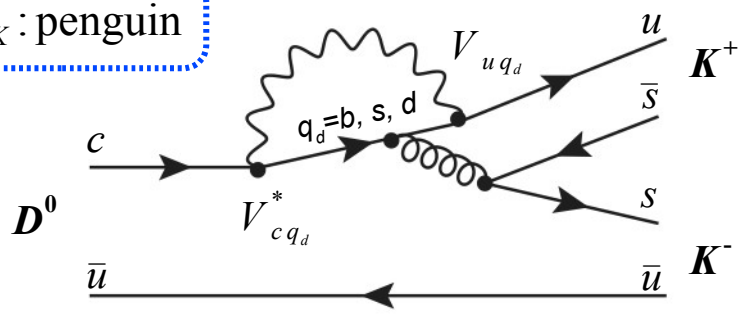


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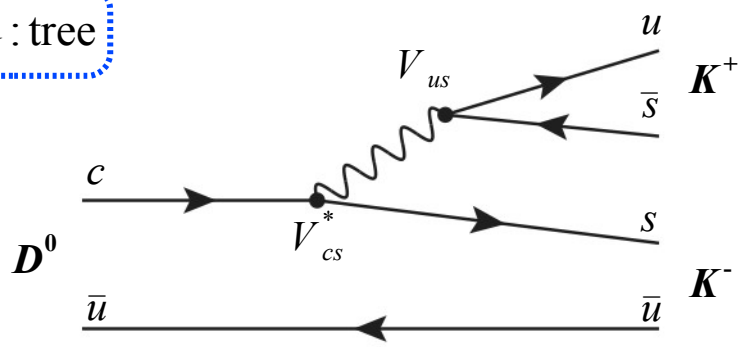


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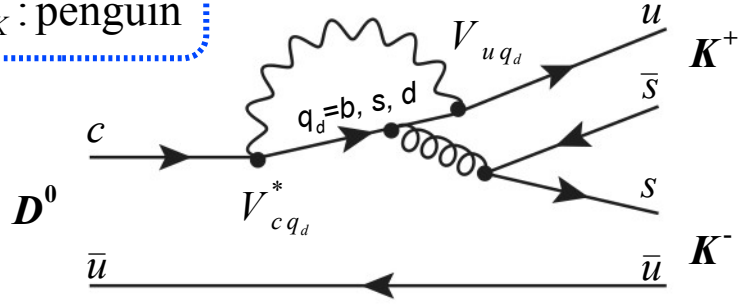


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Hence the amplitude ratio estimate: $r_f \sim A^P_{KK} / A^T_{KK} \sim \lambda_C^4 \, \alpha_S(m_c)/\pi \sim 10^{-4}$

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**Two main questions arise:**

**(a)** Can this estimate be missing the actual SM order of magnitude? What enhancements are possible?

**(b)** How plausibly can non-SM physics explain this signal?

## $\Delta A_{CP}$ : suppose it's pure SM dynamics

**ENHANCED *CP* VIOLATIONS IN HADRONIC CHARM DECAYS**

Michell GOLDEN and Benjamin GRINSTEIN
*Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, IL 60510, USA*

Received 6 March 1989

☑ **Observation:**

*The CKM structure responsible for large CPV in the $|\Delta C| = 1$ Hamiltonian ( $V_{cb}^* \; V_{ub}$ ) multiplies certain operators ( transforming as triplets under $SU(3)_{flavor}$ ) whose matrix elements may be enhanced with respect to naïve expectations.*

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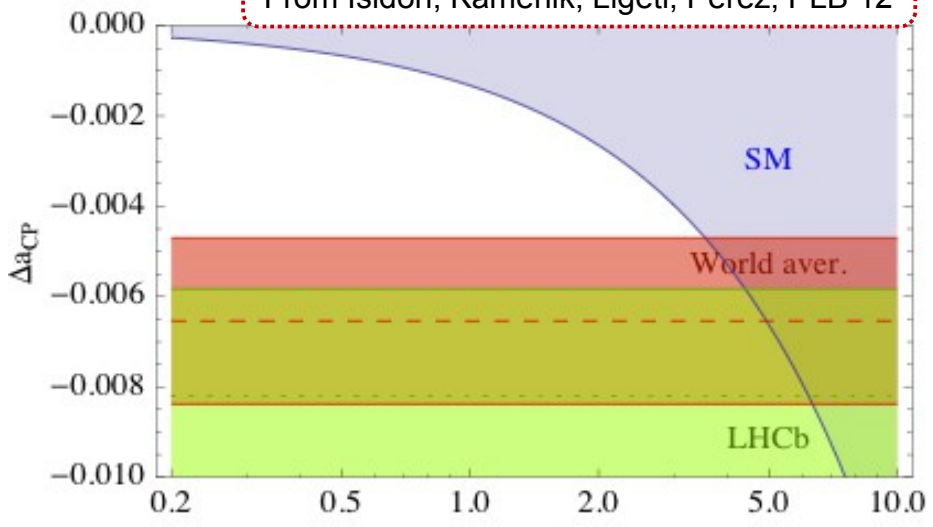


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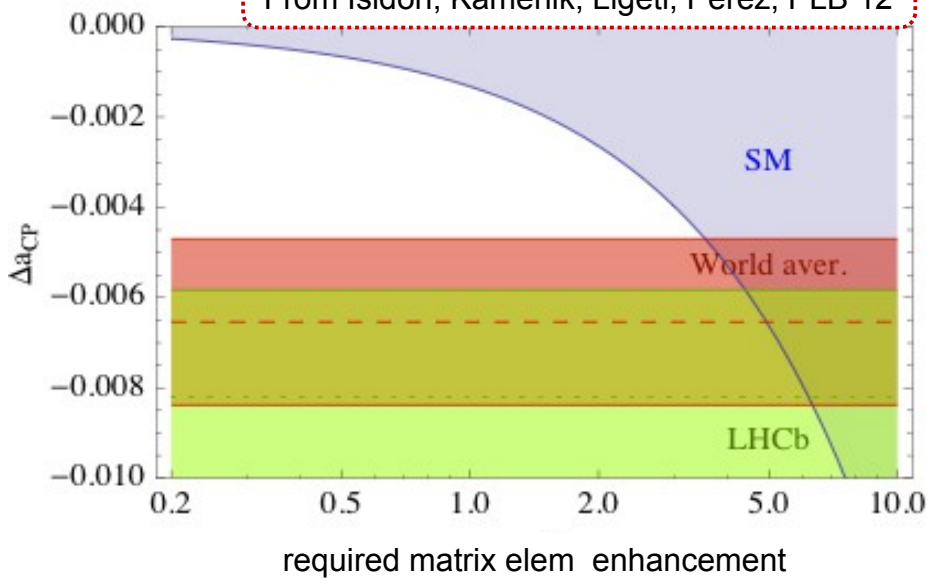


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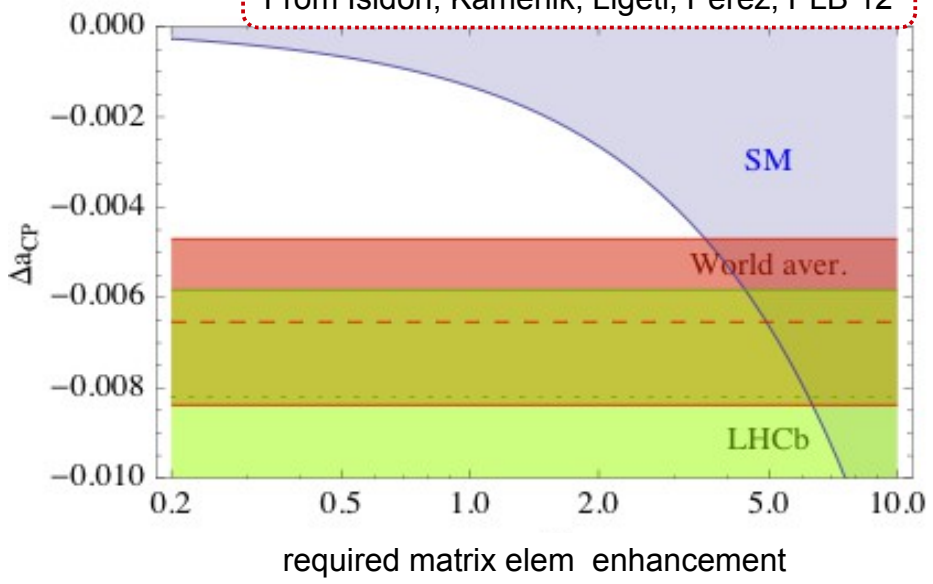


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**Main messages**

- An explanation of $\Delta A_{CP}$ as "another $\Delta I = ½$ rule" remains a possibility
- But an explanation in terms of new dynamics is not less plausible.

Given its potential implications, pursuing this possibility is of utmost importance

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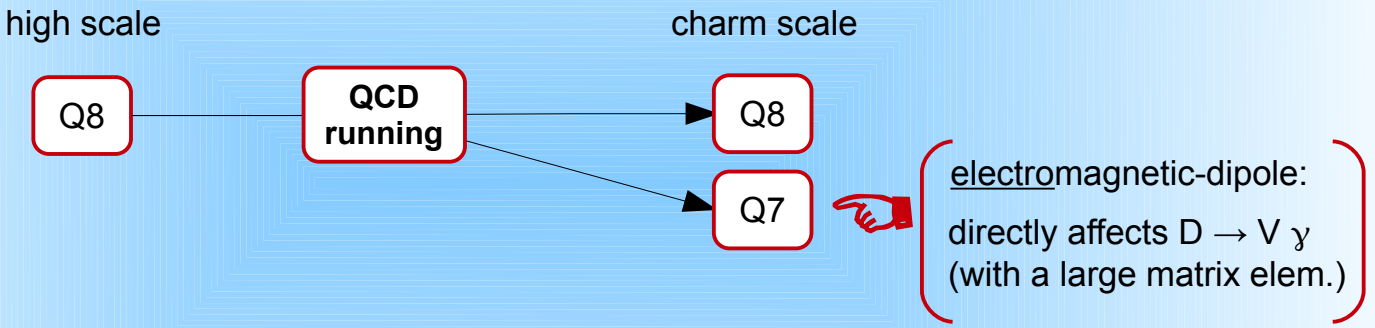

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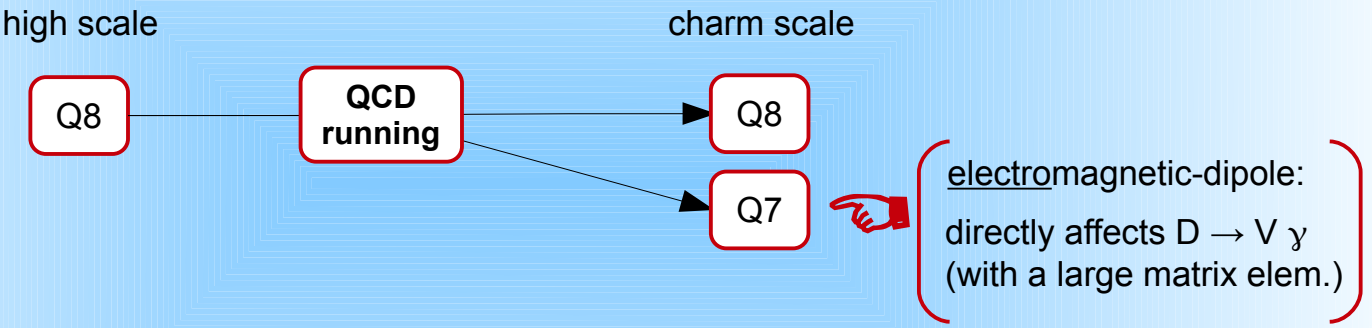


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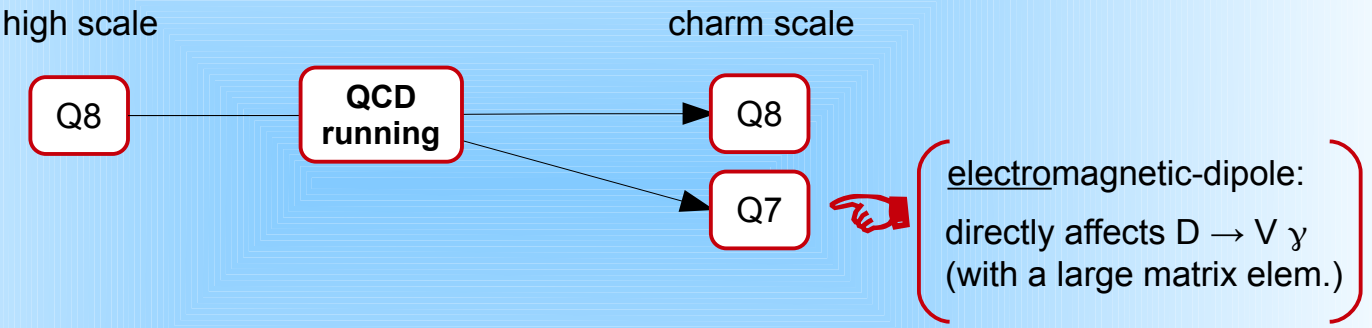


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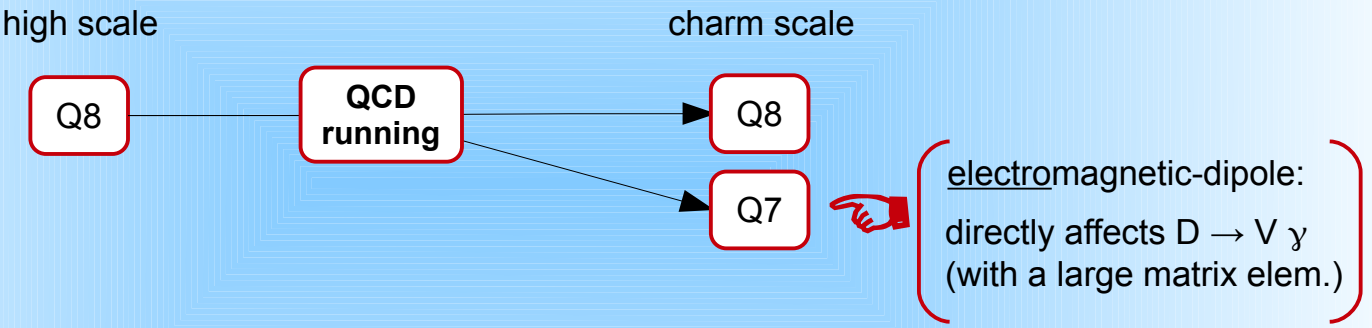


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**Main message**

*An observation of $|A_{CP}(D \to V\gamma)| \sim$ few $\times 10^{-2}$ would be a clear indication of new physics and even of its nature.*

## How to exclude or discover new physics in $\Delta A_{CP}$ :
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☑ **Concluding remark / disclaimer**

Other, interesting, proposals for new measurements exist.

For example, $\Delta I = 3/2$ new physics can be tested via the decays

$D \to \pi\,\pi$

$D \to \rho\,\pi$

$D \to \rho\,\rho$

$D \to K\,\bar{K}\,\pi$

$D_s \to K^*\,\pi$

See:
Grossman, Kagan, Zupan
PRD 12

*Unfortunately, no time for a comprehensive coverage*

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  *E.g. $O(10^{-5})$ deviations in couplings to RH down-quarks: way more stringent than EWPO*

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- *(Go for the $B_d$ channel as well. E.g. it will be a stringent test of MFV)*

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- *Theory (SM) ready to match expected experimental accuracy*
- *One example of $B_s \to \mu\mu$ constraining power:*
  *able to test even tiny deviations in Z-down-quark couplings.*
  *E.g. $O(10^{-5})$ deviations in couplings to RH down-quarks: way more stringent than EWPO*
- *(Go for the $B_d$ channel as well. E.g. it will be a stringent test of MFV)*

☑ **$\Delta A_{CP}$ : direct CPV in charm**

- *Ultimate proof that exciting physics can come from where you didn't expect it*

## Conclusions

*The LHCb program is proceeding even better than we (theoreticians) expected.*

*Among the already many interesting measurements reported, two stand out (personal opinion):*

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☑ **$\Delta A_{CP}$ : direct CPV in charm**

- *Ultimate proof that exciting physics can come from where you didn't expect it*
- *The jury is out on whether $\Delta A_{CP}$ is a signal of new physics or not*
- *For a robust answer, we need more measurements.*
  *A few sensible proposals have been put forward. Go for them!*