CP violation in quark flavor physics

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University of Cincinnati

Testing CP-violation for baryogengesis
University of Massachusetts, Amherst,

March 29, 2018

Outline and aim of the talk

Outline

1. Phases of the CKM unitary triangle
2. Meson mixing
3. Kaon rare decays

Aims

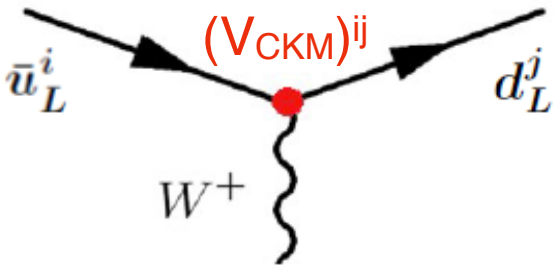
- Overview
- Latest updates on the experimental measurements
- Implications on NP theories

CP violation in:

B mesons b→s, b→d	D mesons c→u	Kaons s→d

During the rest of the workshop,
we will learn its connection to baryogengesis

Standard Model flavor & CP



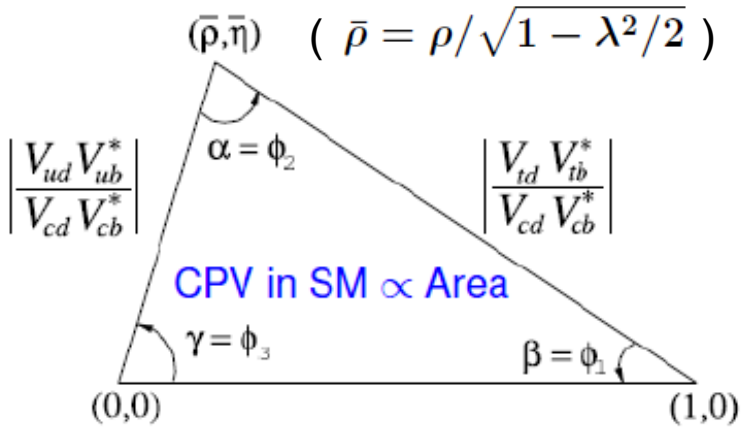
Flavor and CP-violation arising from the CKM matrix (V_{CKM})

$$V_{CKM} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

$$\sim \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\varrho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\varrho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

(λ = Cabibbo angle)

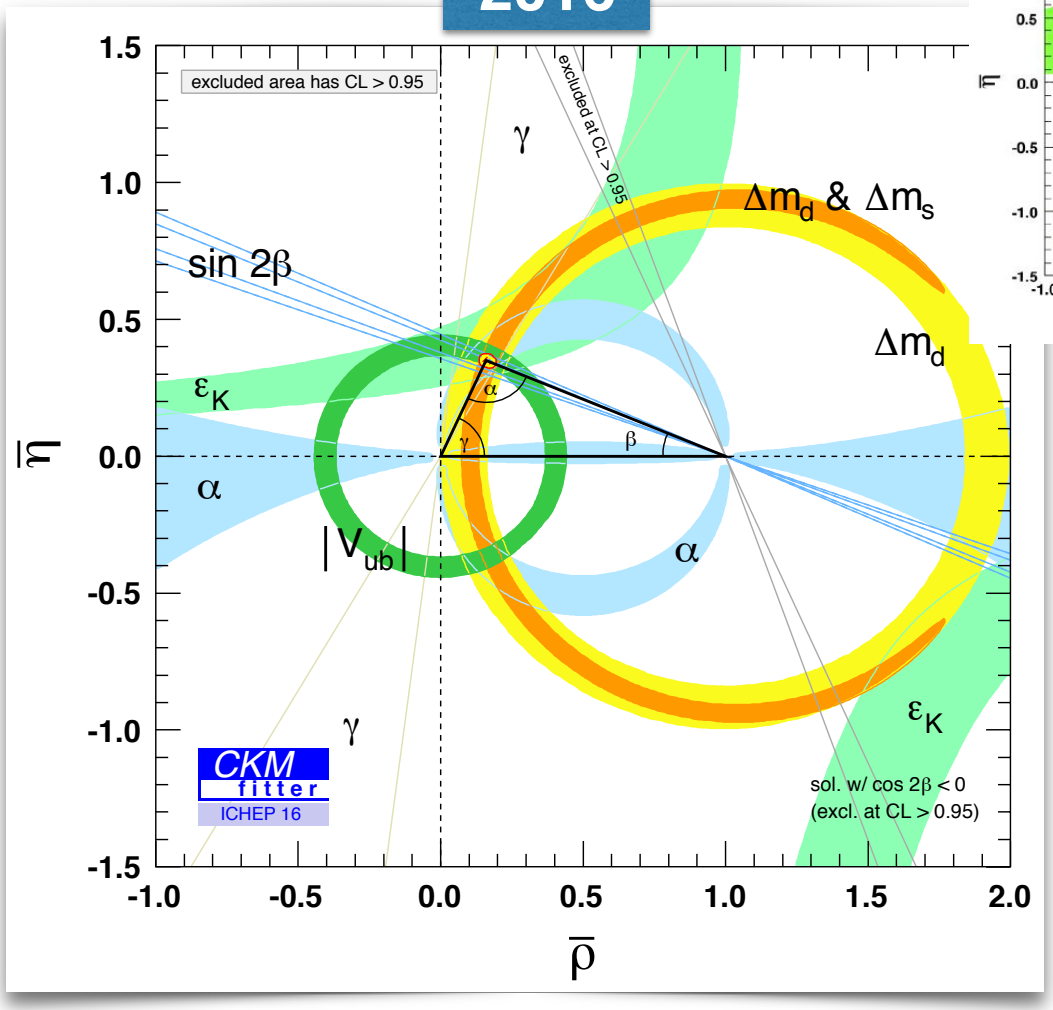
Free parameters:
3 real rotation angles and
one (CP-violating) phase



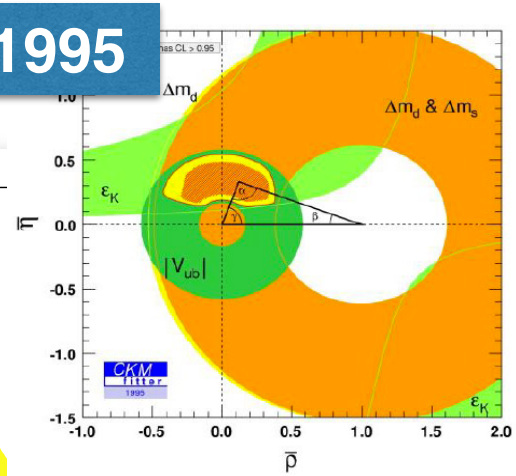
Goal:
over-constrain sides and angles
by many measurements sensitive
to different short distance physics

Its success

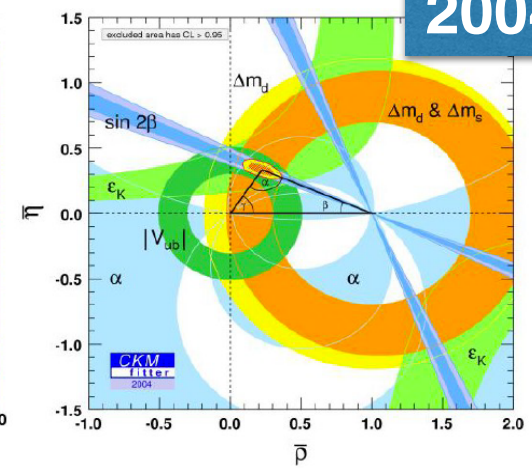
2016



1995



2004



$$A = 0.8250^{+0.0071}_{-0.0111}$$
$$\lambda = 0.22509^{+0.00029}_{-0.00028}$$
$$\bar{\rho} = 0.1598^{+0.0076}_{-0.0072}$$
$$\bar{\eta} = 0.3499^{+0.0063}_{-0.0061}$$

(68% CL)

See also
http://www.utfit.org/UTfit/

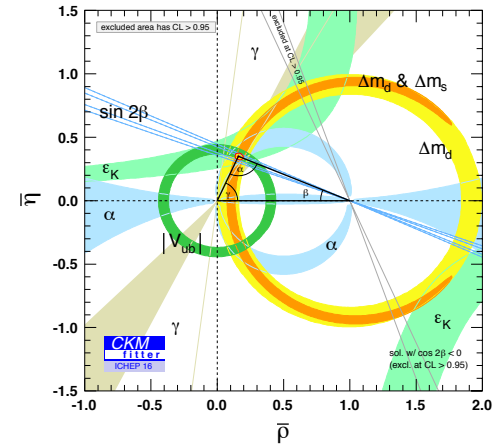
Remarkable success of the CKM picture!

Measurement of the γ angle

$$\gamma = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right) \sim \arg(-V_{ub})$$

The CKM angle γ is the least known constraint:

Direct γ measurement	Indirect γ extrapolation
$(73.5^{+4.3}_{-5.0})^\circ$	$(65.3^{+1.0}_{-2.5})^\circ$



LHCb expected precision by 2029 (end of Run 4) < 0.4°

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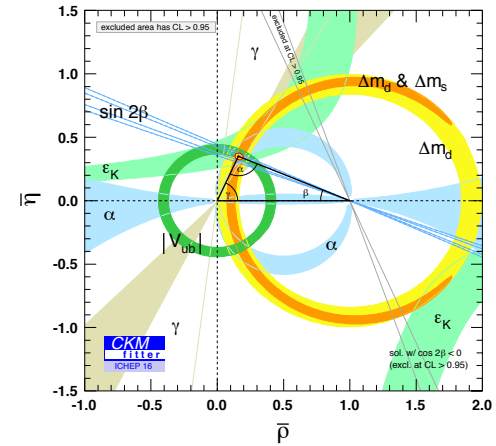

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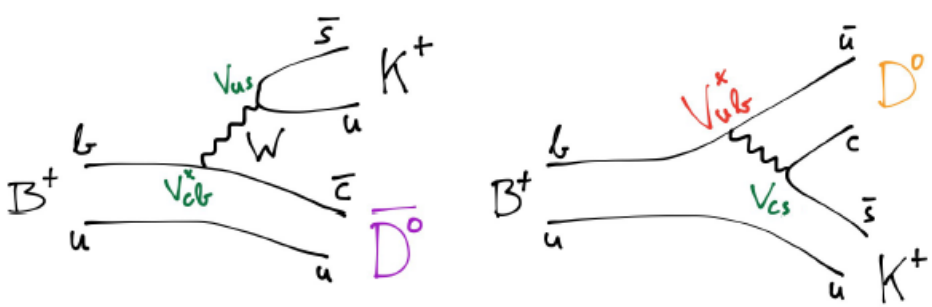
γ can be measured using tree level B decays

(only CKM angle accessible at tree level)

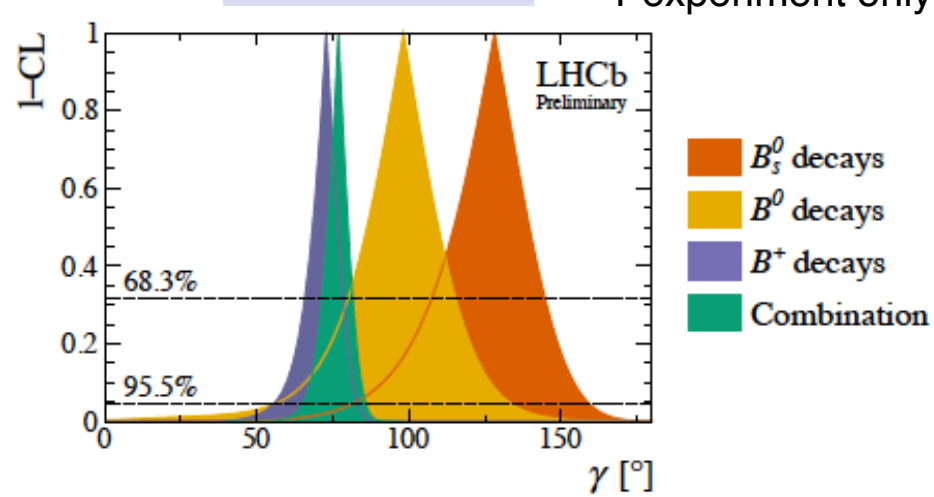
Require interference between
b → cW and b → uW to access it:



LHCb-CONF-2017-004

$\gamma = (76.8^{+5.1}_{-5.7})^\circ$

Most precise measurement from 1 experiment only



M. Kenzie

Theory for the γ angle

* γ is known very well in the SM

$$|\delta\gamma| \lesssim \mathcal{O}(10^{-7})$$

second-order electroweak corrections
(other theory errors can eliminated using data)
Brod, Zupan, 1308.5663

* γ is an good probe of new physics

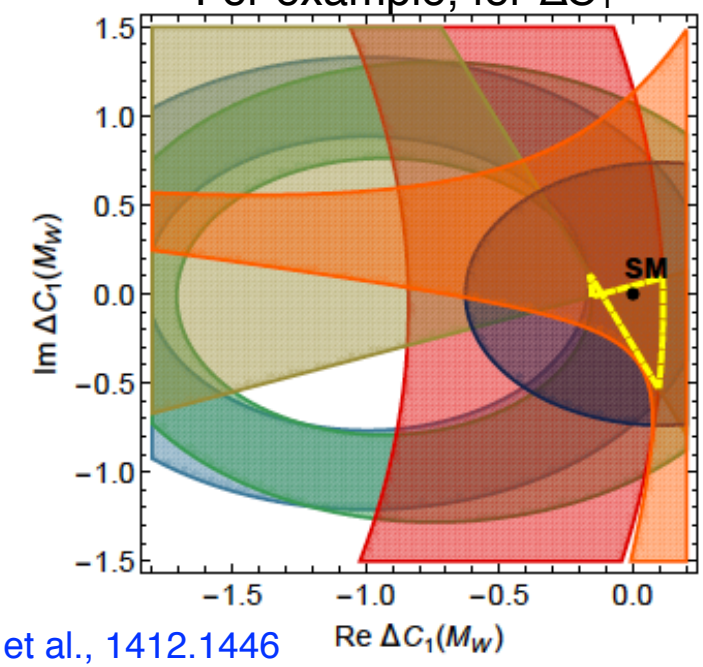
$$Q_1^{\bar{u}_1 u_2 d_1} = (\bar{u}_1^\alpha b^\beta)_{V-A}(\bar{d}_1^\beta u_2^\alpha)_{V-A}\ , \quad Q_2^{\bar{u}_1 u_2 d_1} = (\bar{u}_1^\alpha b^\alpha)_{V-A}(\bar{d}_1^\beta u_2^\beta)_{V-A}$$

Im(ΔC_1) and Im(ΔC_2) can be of order ±10% without violating any constraints from data

(constraints from $B \to D\pi$ and $B \to D^{(*)0}h^0$ decays, $b \to d\gamma$, $B \to \pi\pi$, $\rho\pi$, $\rho\rho$-decays).

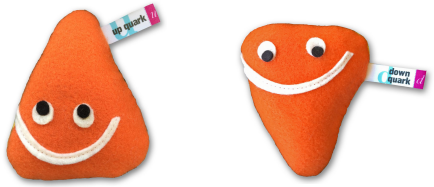
New physics in $C_{1,2}$ can cause sizeable shifts in γ ($|\delta\gamma| \approx 4°$)

For example, for ΔC_1



Brod et al., 1412.1446

2. The physics of meson mixing



CP violation in the meson system

Let us consider a meson (M) decay.

We define the decay amplitudes to the final state f

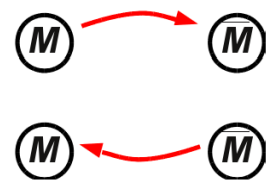
$$\mathcal{A}_f = \langle f|\mathcal{H}|M\rangle, \quad \bar{\mathcal{A}}_f = \langle f|\mathcal{H}|\bar{M}\rangle$$

The mass eigenstates are

$$|M_{H,L}\rangle = p|M\rangle \mp q|\bar{M}\rangle$$

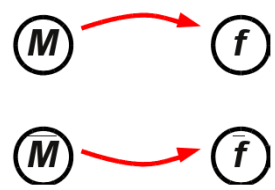
In general, there are 3 types of CP violation:

* CP violation in mixing,
  when the two neutral mass eigenstate admixtures cannot be chosen to be CP-eigenstates



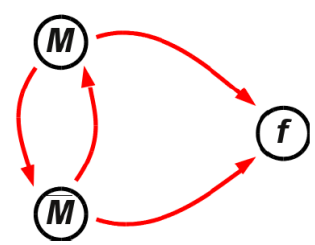
$$|q/p| \neq 1$$

* CP violation in decay,
  when the amplitude for a decay and its CP-conjugate process have different magnitudes



$$|A_f/\bar{A}_{\bar{f}}| \neq 1$$

* CP violation in the interference
  of decays with and without mixing, which occurs in decays into final states that are common to M and $\bar{M}$



$$\mathrm{Im}\left(\frac{q}{p}\frac{\bar{A}_{\bar{f}}}{A_f}\right) \neq 0$$

Example for the B_s meson system

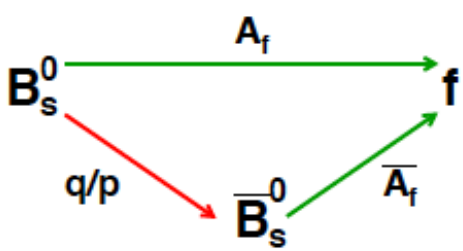
$$\mathrm{CP}(B) = \bar{B}$$
$$\mathrm{CP}(\bar{B}) = B$$

Flavor eigenstates

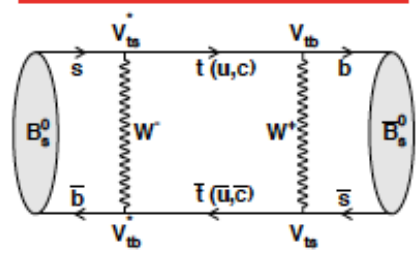
$$|B_{H,L}\rangle = p|B\rangle \mp q|\bar{B}\rangle$$

Mass eigenstates

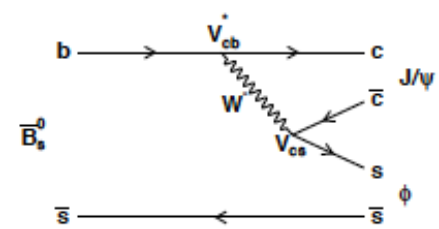
B mesons
b→s, b→d



$\phi_M^{SM} = 2\arg(V_{ts}V_{tb}^*)$



$\phi_D = \arg(V_{cs}V_{cb}^*)$



$\bar{B}_s \to J/\Psi\phi$

$$\phi_s = \phi_M^{\mathrm{SM}} - 2\phi_D = -2\arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right) \equiv -2\beta_s$$

can be affected by NP

small number in the SM

Interference between mixing and decay

Latest measurements, B mesons

B mesons
b→s, b→d

B_s

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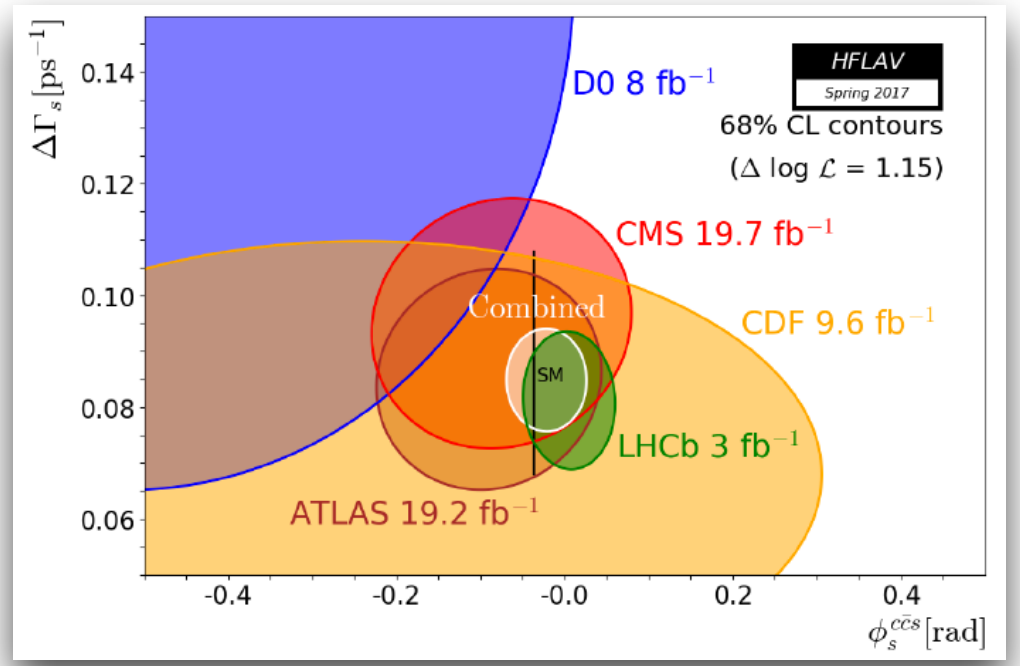
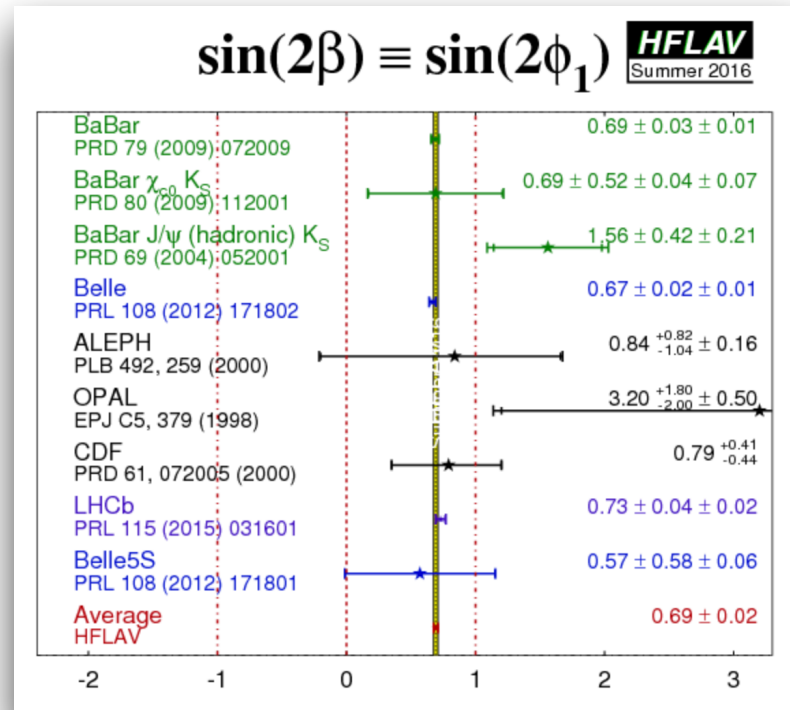


LHCb dominates this world average

$$\arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right) \equiv \beta$$

B_d



LHCb is comparable to Belle & Babar

(latest LHCb (2017): 0.760 ± 0.034)

Latest measurements, D mesons

D mesons
c→u

In the SM,

- CP violating effects in the $D - \bar{D}$ system are expected to be small, O(10^{-3})
- sizeable uncertainties on hadronic form factors

cc production ~ 20 bb production at LHCb!

Latest determination: LHCb, 5.0 fb^{-1} recorded in 2011-2016 PHYSICAL REVIEW D 97, 031101

- through the decays $D, \bar{D} \to K^+\pi^-$ $D \to K^-\pi^+$

  Cabibbo-suppressed Cabibbo-favored that follows from the oscillation (“wrong sign” (WS) decay)

  Cabibbo-favored (“right sign” (RS) decay)

- (also past determination through the decays to Kaons and pions)

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$$R_D^+ \equiv \frac{N(D \to K^+\pi^-)}{N(D \to K^-\pi^+)}, \quad R_D^- \equiv \frac{N(\bar{D} \to K^-\pi^+)}{N(\bar{D} \to K^+\pi^-)}$$

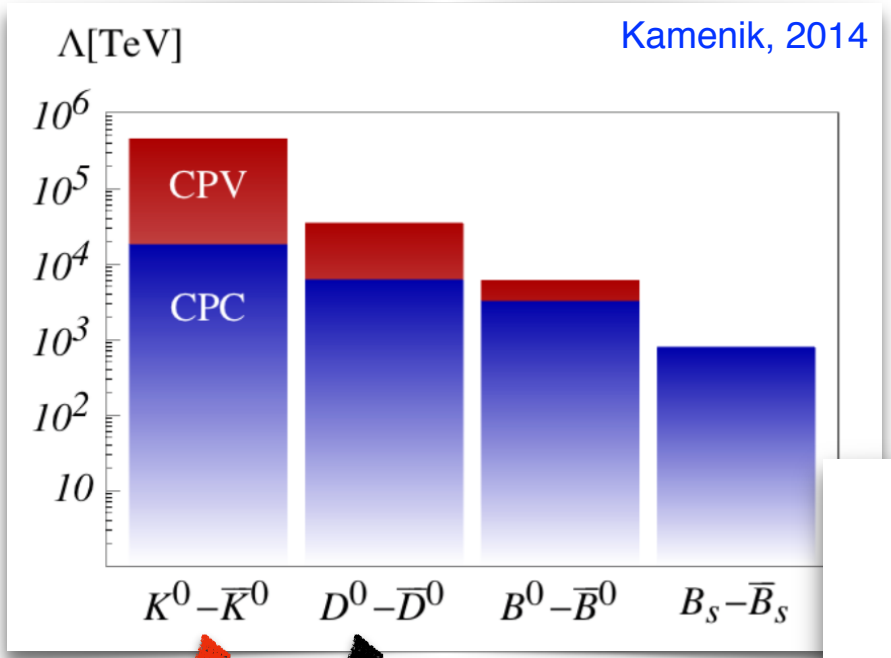
non-vanishing difference between R_{D^+} and R_{D^-} would imply CP violation

No evidence for CP violation in charm mixing is yet observed

$$\begin{cases} 1.00 < |q/p| < 1.35 \\ A_D \equiv \dfrac{R_D^+ - R_D^-}{R_D^+ + R_D^-} = (-0.1 \pm 9.1) \times 10^{-3} \end{cases}$$

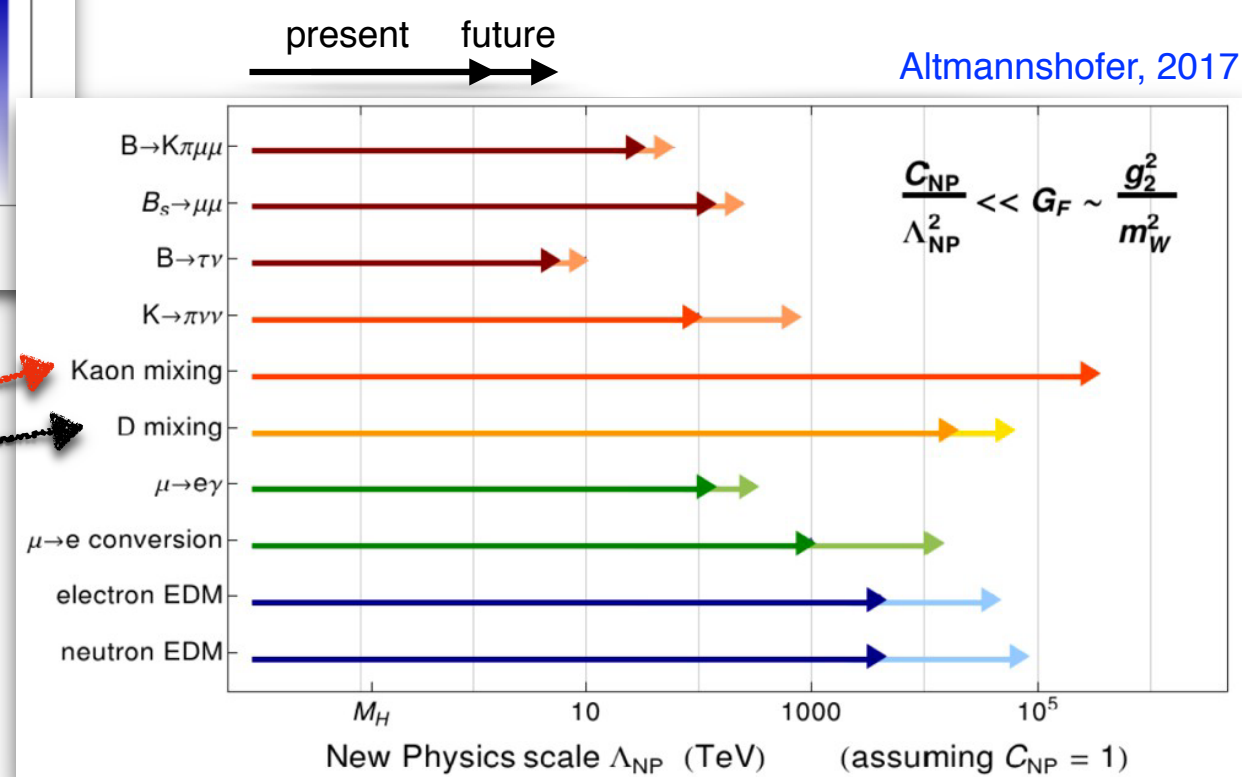
(68.3% CL.)

Probing high New Physics scales



In the framework of effective field theories…

$$\mathcal{L}_{\rm BSM} \to \mathcal{L}_{\nu\rm SM} + \sum_{d>4} \frac{\mathcal{Q}_i^{(d)}}{\Lambda^{d-4}}$$



CP violation in D mixing gives the best bound after ε_K (Kaon mixing)

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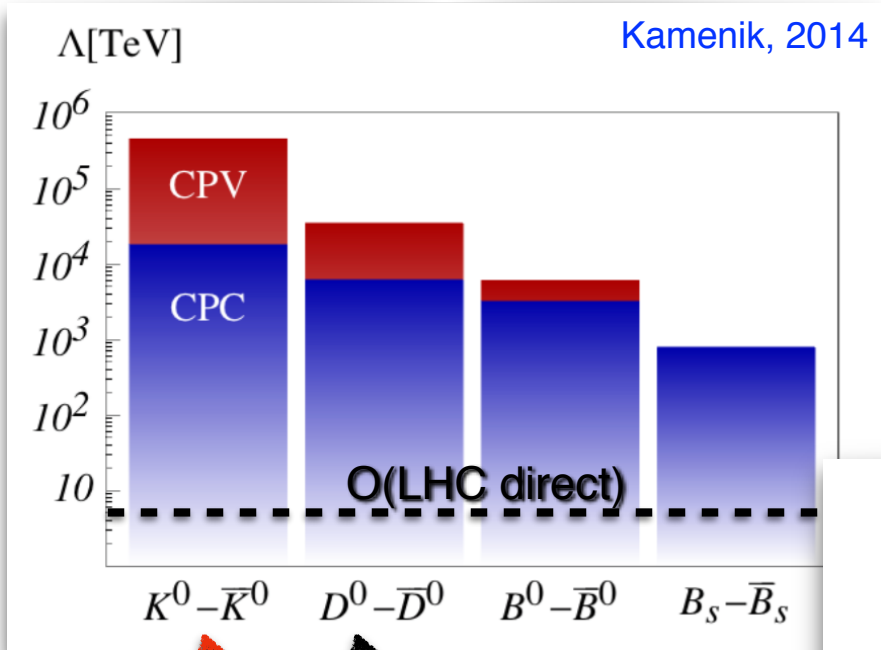

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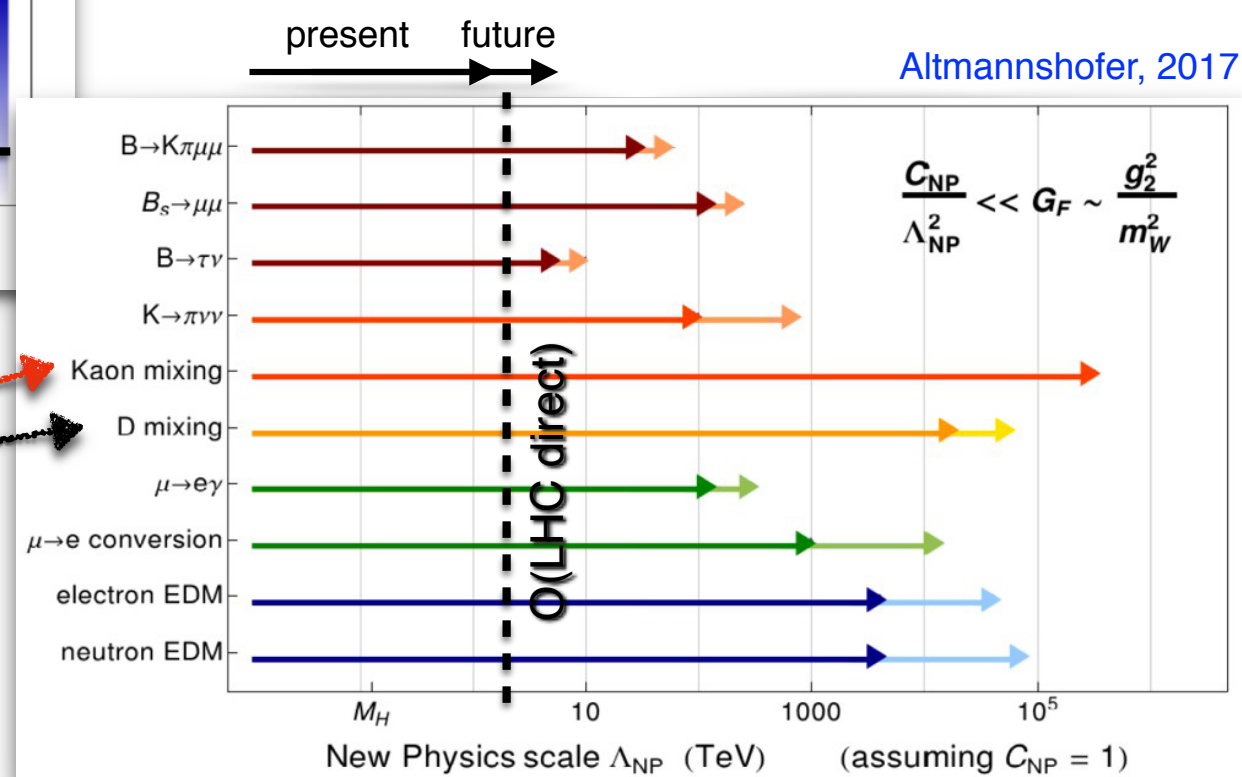

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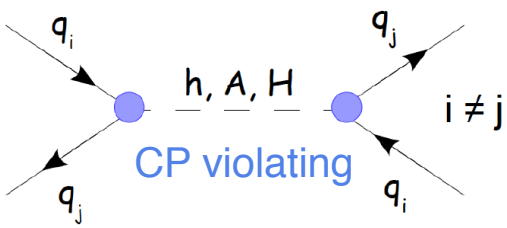
New CPV Higgs bosons (MFV 2HDM)

Beyond EFTs, one can set constraints on the (flavor and) CP structure of NP models containing new (~ light) degrees of freedom

Example: **a 2HDM with Minimal Flavor Violation (MFV)**

$$\mathcal{H}_Y^{\rm gen} = \bar{Q}_L X_{d1} D_R H_1 + \bar{Q}_L X_{u1} U_R H_1^c + \bar{Q}_L X_{d2} D_R H_2^c + \bar{Q}_L X_{u2} U_R H_2 + \text{h.c.}$$

$$\begin{cases} X_{d1} &= Y_d \ \ \text{(definition)} \\ X_{u1} &= a_u Y_u + \epsilon_1' Y_u^\dagger Y_u Y_u + \epsilon_2' Y_d^\dagger Y_d Y_u + \cdots \\ X_{d2} &= a_d Y_d + \epsilon_1 Y_d^\dagger Y_d Y_d + \epsilon_2 Y_u^\dagger Y_u Y_d + \cdots \\ X_{u2} &= Y_u \ \ \text{(definition)} \end{cases}$$



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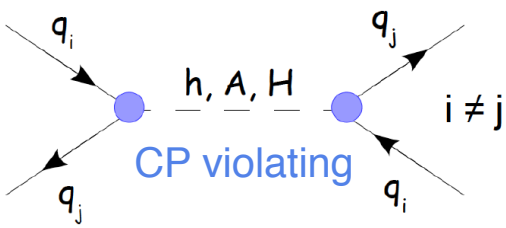
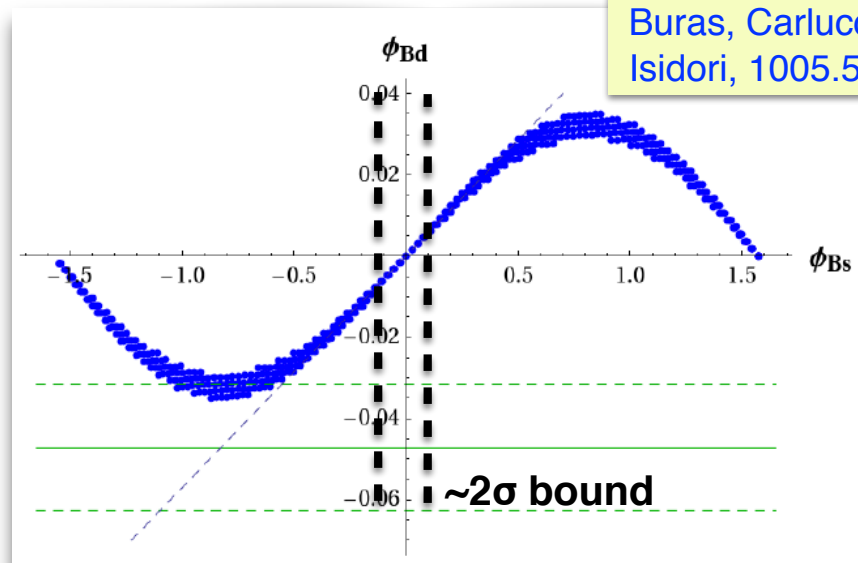
Generically,
O(1) complex coefficients



Matrix element for meson mixing:

$$M_{12}^{B_q} \propto \frac{F(\epsilon_i)}{m_H^2}\, y_b y_q\, [y_t^2 V_{tb} V_{tq}^*]^2$$

Buras, Carlucci, SG, Isidori, 1005.5310



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MFV is not the full story for 2HDMs → **A "flavorful" 2HDM**

Altmannshofer, SG, Kagan, Silvestrini, Zupan, 1507.07927

$$\mathcal{L} = \bar{f} Y f H + \bar{f} Y' f H' \rightarrow \mathcal{M} = vY + v'Y'$$

$$(\mathcal{M}_0 + \Delta\mathcal{M})$$

125 Higgs (h) — Additional Higgses (H, A, H±)

$$\mathcal{M}_0 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & m_t \end{pmatrix}, \quad \Delta\mathcal{M} = \begin{pmatrix} m_u & \mathcal{O}(m_u) & \mathcal{O}(m_u) \\ \mathcal{O}(m_u) & m_c & \mathcal{O}(m_c) \\ \mathcal{O}(m_u) & \mathcal{O}(m_c) & \mathcal{O}(m_c) \end{pmatrix}$$

(analogous structure in the down-quark sector)

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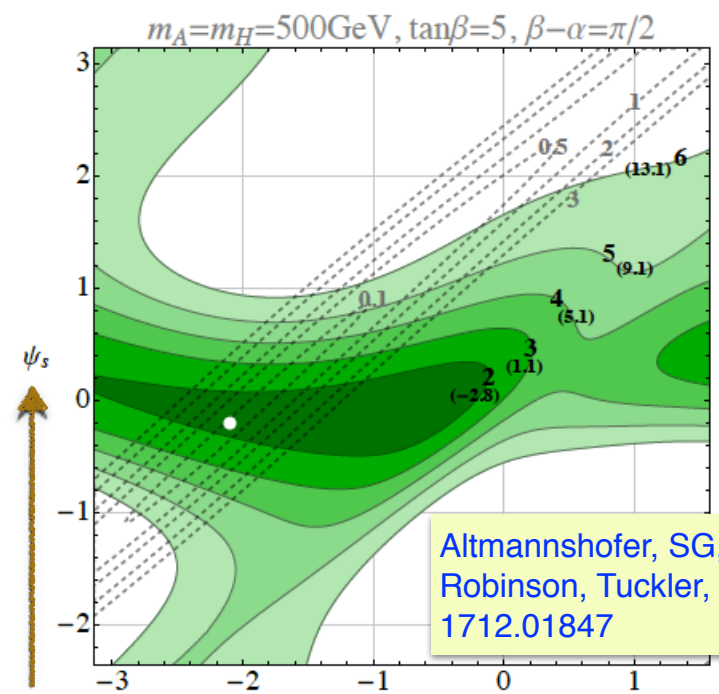
O(1) complex coefficients

(analogous structure in the down-quark sector)

Approximate U(2) symmetry in each sector



2 of the phases

Complementarity with LHC searches

Broad program for searches for new Higgs bosons

Most searches (and interpretation of searches) are performed
in the context of “type-II-like” 2Higgs doublet models.

The typical golden channel is $H \to \tau\tau$. This is not necessarily true in these new models

The LHC tests the absolute value of the free parameters of the theory

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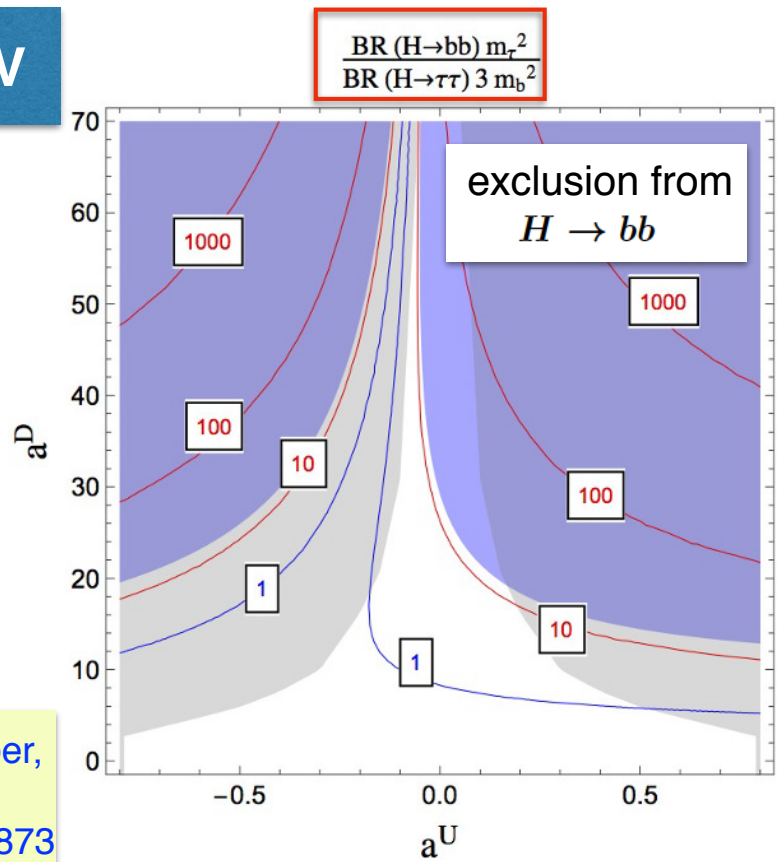
MFV



SG, Haber, Santos, 1703.05873

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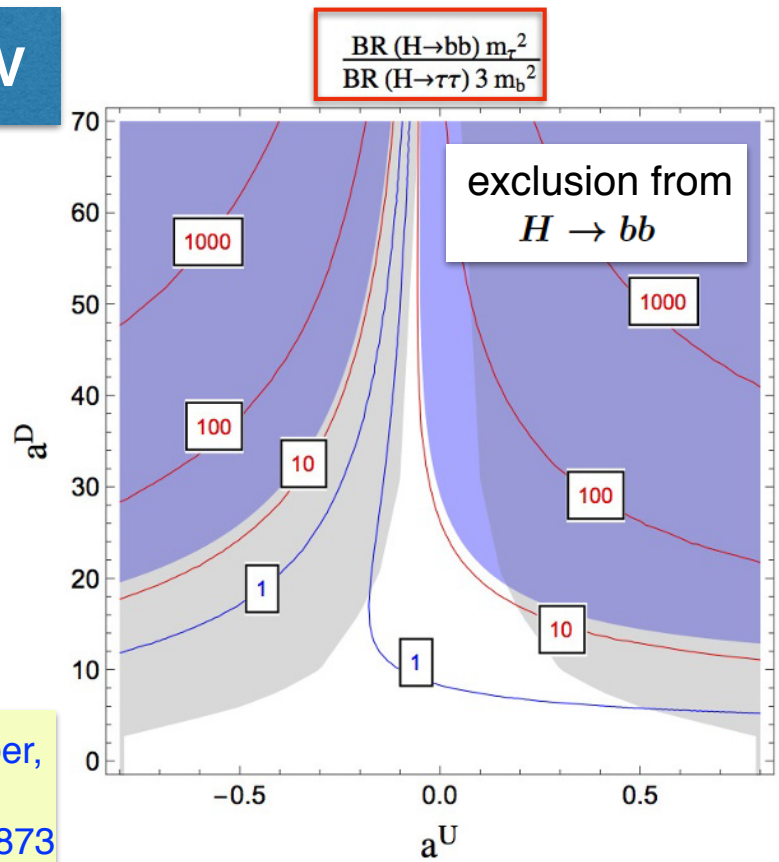
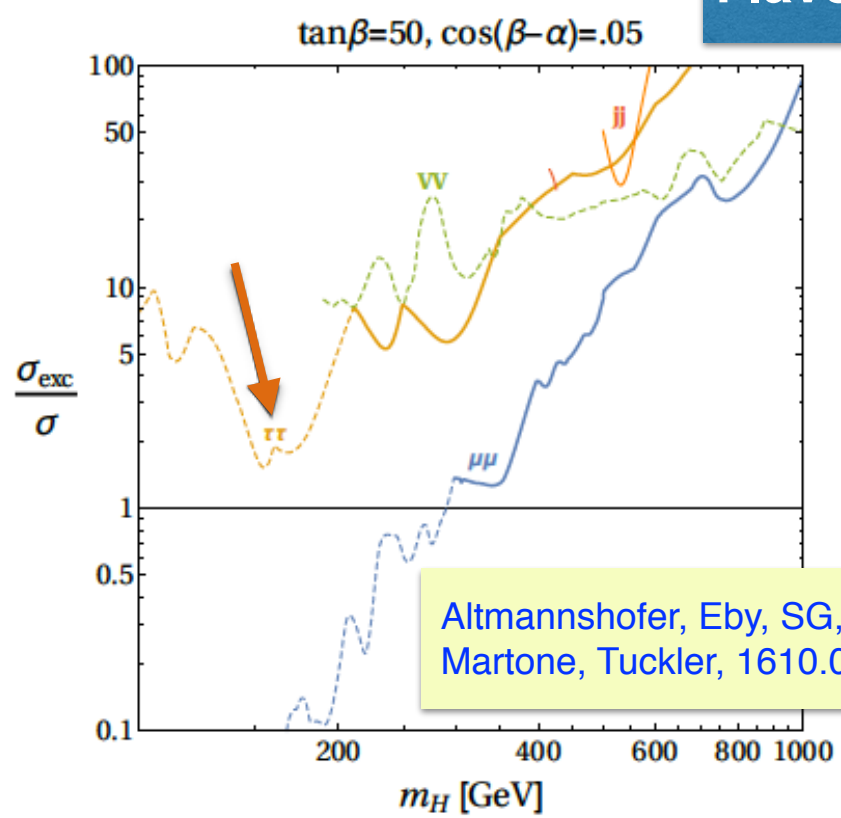
MFV



SG, Haber, Santos, 1703.05873

Flavorful



Altmannshofer, Eby, SG, Lotito, Martone, Tuckler, 1610.02398

The LHC tests the absolute value of the free parameters of the theory

New CPV Higgs bosons (SUSY)

SUSY Higgs sectors do not bring new sources of flavor violation at the tree level.

Nevertheless, many new (Higgs) sources of flavor and CP violation
(soft masses, trilinear terms)

For example in the squark down sector:

$$\begin{cases} \mathcal{M}_D^2 = \mathrm{diag}(\tilde{m}^2) + \tilde{m}^2 \delta_d \\ \delta_d = \begin{pmatrix} \delta_d^{LL} & \delta_d^{LR} \\ \delta_d^{RL} & \delta_d^{RR} \end{pmatrix} \end{cases}$$

off-diagonal soft masses & trilinear terms

6X6 matrix

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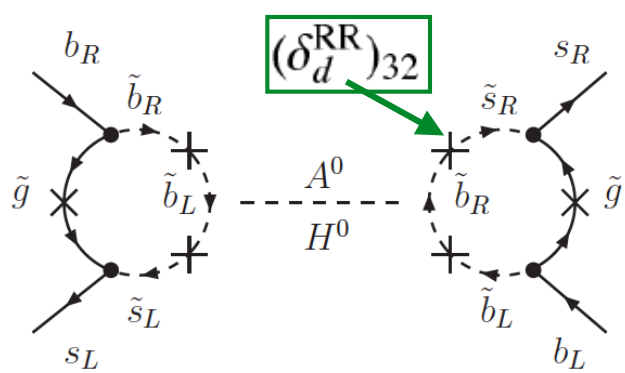
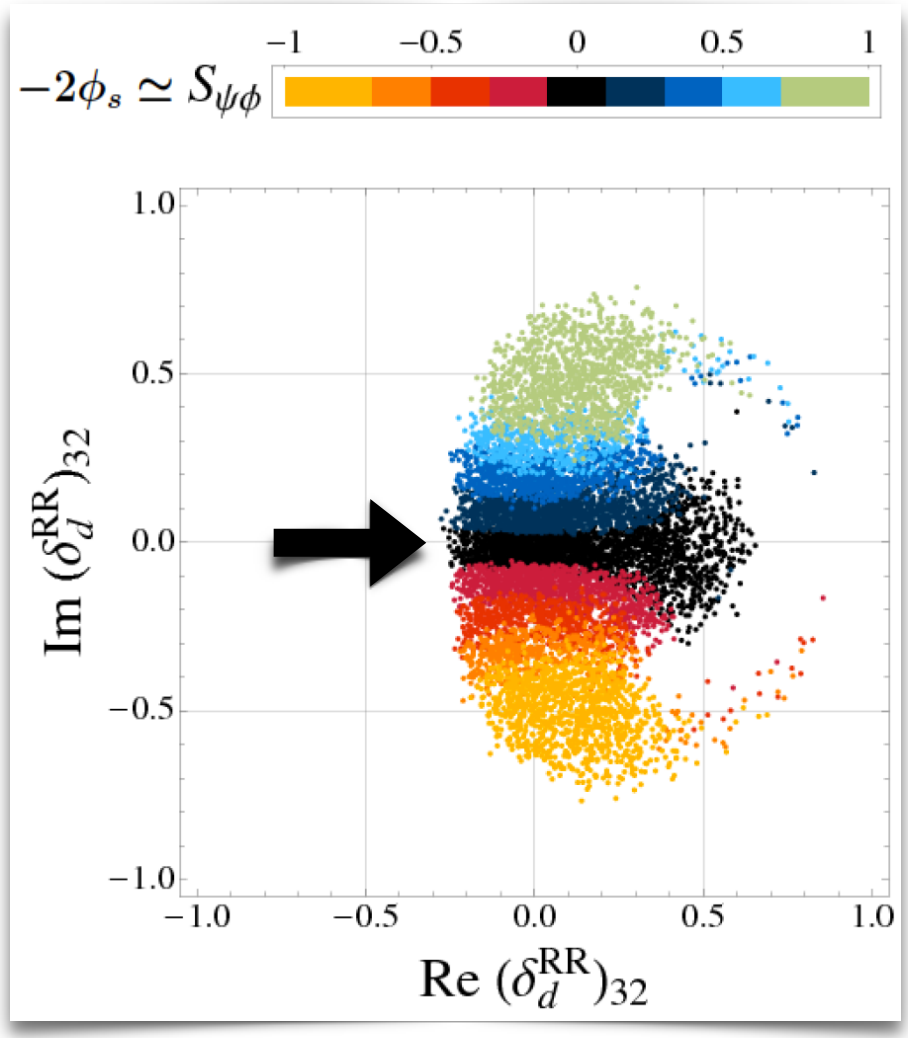
Example diagram:

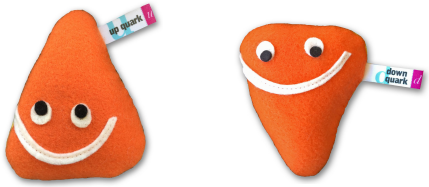




Altmannshofer, Buras, SG, Paradisi, Straub, 0909.1333

3. Kaon rare decays

$$K^+ \to \pi^+ \nu\bar{\nu},\ K_L \to \pi^0 \nu\bar{\nu}$$



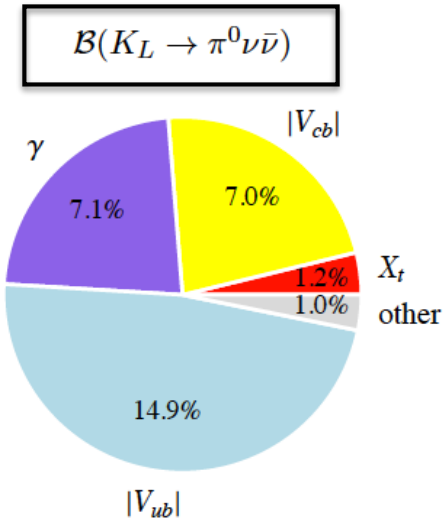
Kaons
s→d

Kaon rare decays in the SM

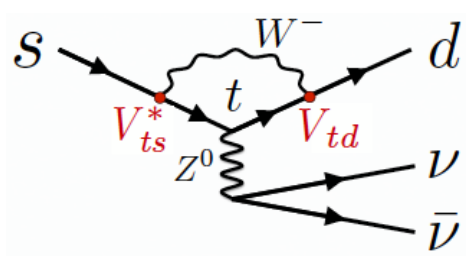
Very clean decays (mainly short distance contribution)

Dominant uncertainties originate from the CKM parameters $|V_{cb}|$, $|V_{ub}|$ and γ.

$$\mathcal{H}_{\rm SM} = g_{\rm SM}^2 \sum_{\ell=e,\mu,\tau} \left[V_{cs}^* V_{cd} X(x_c) + V_{ts}^* V_{td} X(x_t)\right] \underbrace{(\bar{s}_L \gamma_\mu d_L)(\bar{\nu}_\ell \gamma^\mu \nu_\ell)}_{\text{Only operator in the SM}}$$



Buras, Buttazzo, Girbach-Noe, Knegjens, 1503.02693



+ box diagrams

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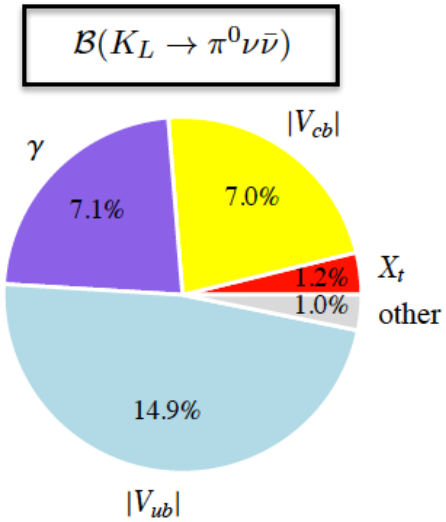
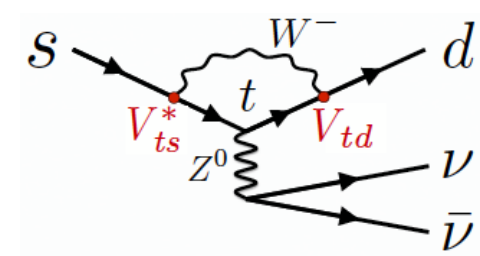


$$\begin{cases} \mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) \simeq \kappa_+ \left| \dfrac{V_{ts}^* V_{td}}{\lambda^5} X(x_t) + \dfrac{V_{cs}^* V_{cd}}{\lambda} \left(\dfrac{X(x_c)}{\lambda^4} + \delta P \right) \right|^2 \\ \text{CP-conserving} \\ \mathcal{B}(K_L \to \pi^0 \nu\bar{\nu}) \simeq \kappa_L \, \mathrm{Im} \left(\dfrac{V_{ts}^* V_{td}}{\lambda^5} X(x_t) \right)^2 \\ \text{CP-violating} \end{cases}$$

Long-distance contributions

Buras, Buttazzo, Girbach-Noe, Knegjens, 1503.02693



+ box diagrams

$$\begin{cases} \mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) = (9.11 \pm 0.72) \times 10^{-11} \\ \mathcal{B}(K_L \to \pi^0 \nu\bar{\nu}) = (3.00 \pm 0.30) \times 10^{-11} \end{cases}$$

Brod, Gorbahn, Stamou 1009.0947; Buras, Buttazzo, Girbach-Noe, Knegjens, 1503.02693

Very rare!
⟶ Access to NP

NA62 and KOTO are beginning their experimental program…

Kaons
s→d

News from NA62 (K^+)

Predecessor:

$$BR(K^+ \to \pi^+ \nu\bar{\nu}) = (17.3^{+11.5}_{-10.5}) \times 10^{-11}$$

BNL measurement, 2009
(4 event @ BNL-949; 3 events @ BNL-787)

NEW!

Moriond 2018

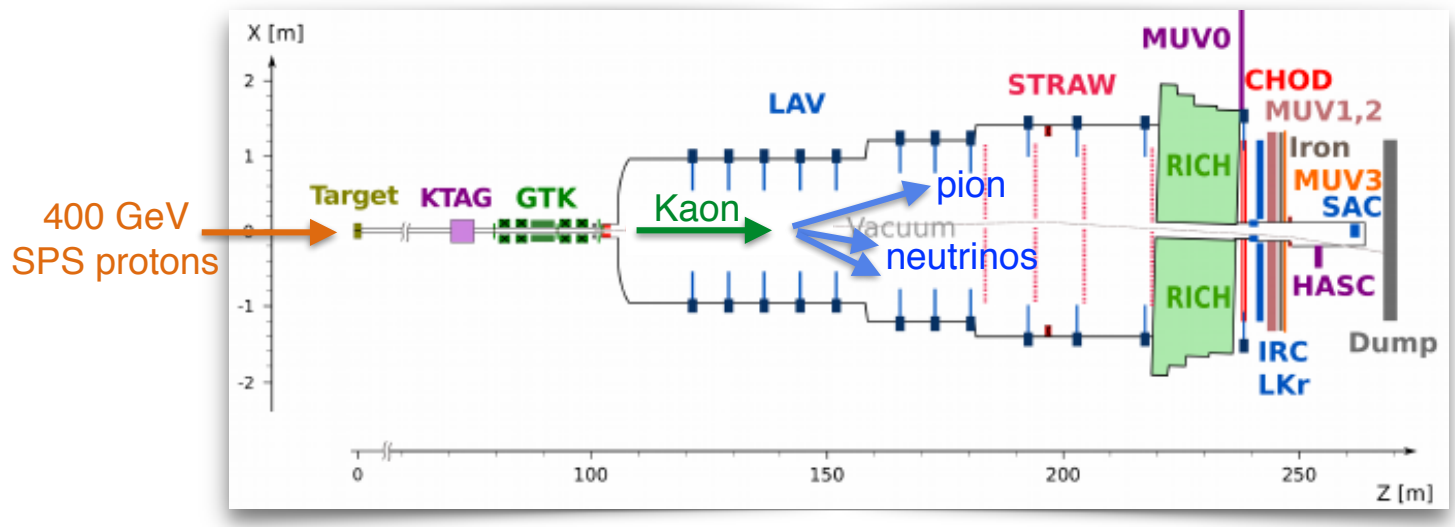
Talk by Marchevski

- NA62 has started data taking in Sept. 2016

CERN-SPSC-2017-013

- Exploratory analysis with 5% of 2016 data set

0 signal event found



Kaons
s→d

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CERN-SPSC-2017-013

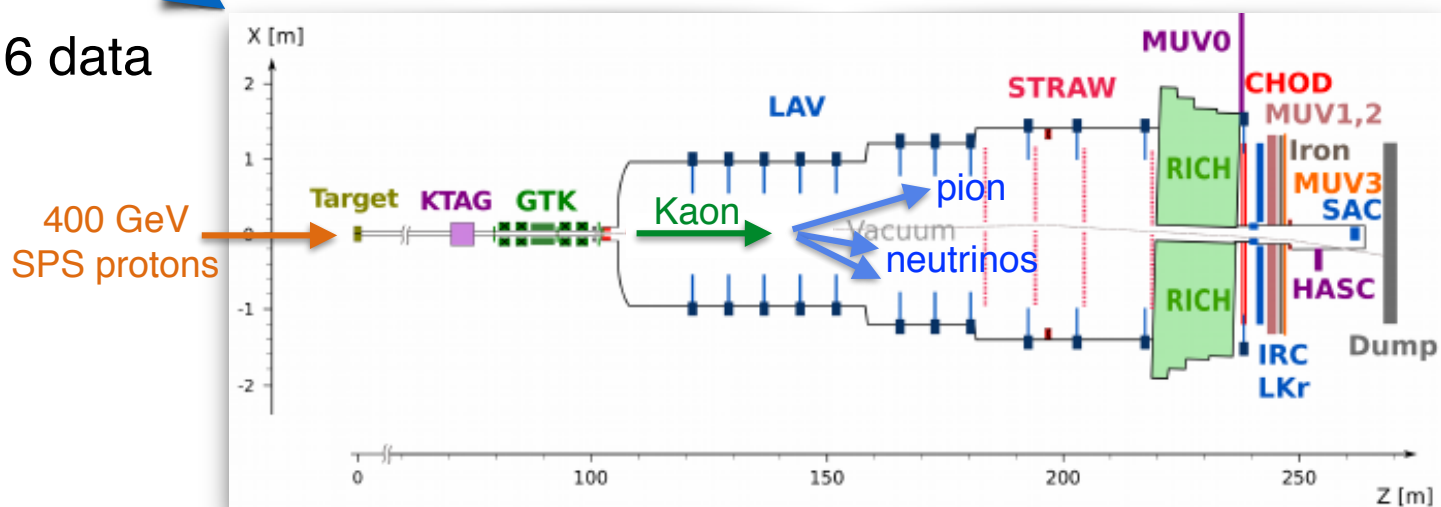
- NA62 has started data taking in Sept. 2016
- Exploratory analysis with 5% of 2016 data set
  0 signal event found
- Analysis of the full 2016 data announced at Moriond

Optimized to suppress backgrounds from leading Kaon decay modes

$$15 < P_{\pi^+} < 35 \text{ GeV/c}$$

$$m^2_{miss} = (P_K - P_{\pi^+})^2$$

1 event seen! (0.3 expected)



Data taking until the end of 2018
Running after 2018 is approved
Aim: Measurement of the SM BR at the **~10%** level

Kaons
s→d

News from KOTO (K_L)

Predecessor: $\mathrm{BR}(K_L \to \pi^0 \nu\bar{\nu}) < 2.6 \times 10^{-8}$

KEK E391a bound, 2010

(0 events seen)

Indirect bound:
(using Grossmann-Nir) $\mathrm{BR}(K_L \to \pi^0 \nu\bar{\nu})_{\mathrm{GN}} < 1.46 \times 10^{-9}$

Moriond 2018

Talk by Marchevski

Grossman-Nir bound (model independent): $\dfrac{\mathrm{BR}(K_L \to \pi^0 \nu\bar{\nu})}{\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu})} < 4.4$

9701313

Experimental challenges associated to the signature (2 photons+nothing)

Kaons
s→d

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9701313

Experimental challenges associated to the signature (2 photons+nothing)

- initial physics data taken in 2013 (1609.03637)

  1 event observed (0.34 expected)

  $\mathrm{BR}(K_L \to \pi^0 \nu\bar{\nu})_{\mathrm{KOTO}} < 5.1 \times 10^{-8}$

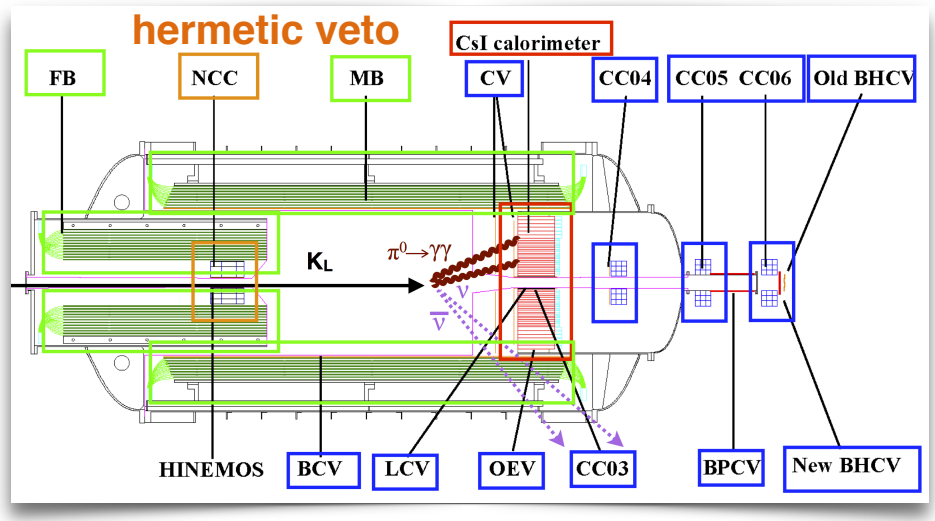
- 2015 run: ~ 20 times more data

Preliminary analysis discussed at Moriond

(still to be optimized)

expectation:

improvement on the bound by a factor of ~10



Final Aim:

10% measurement of the BR

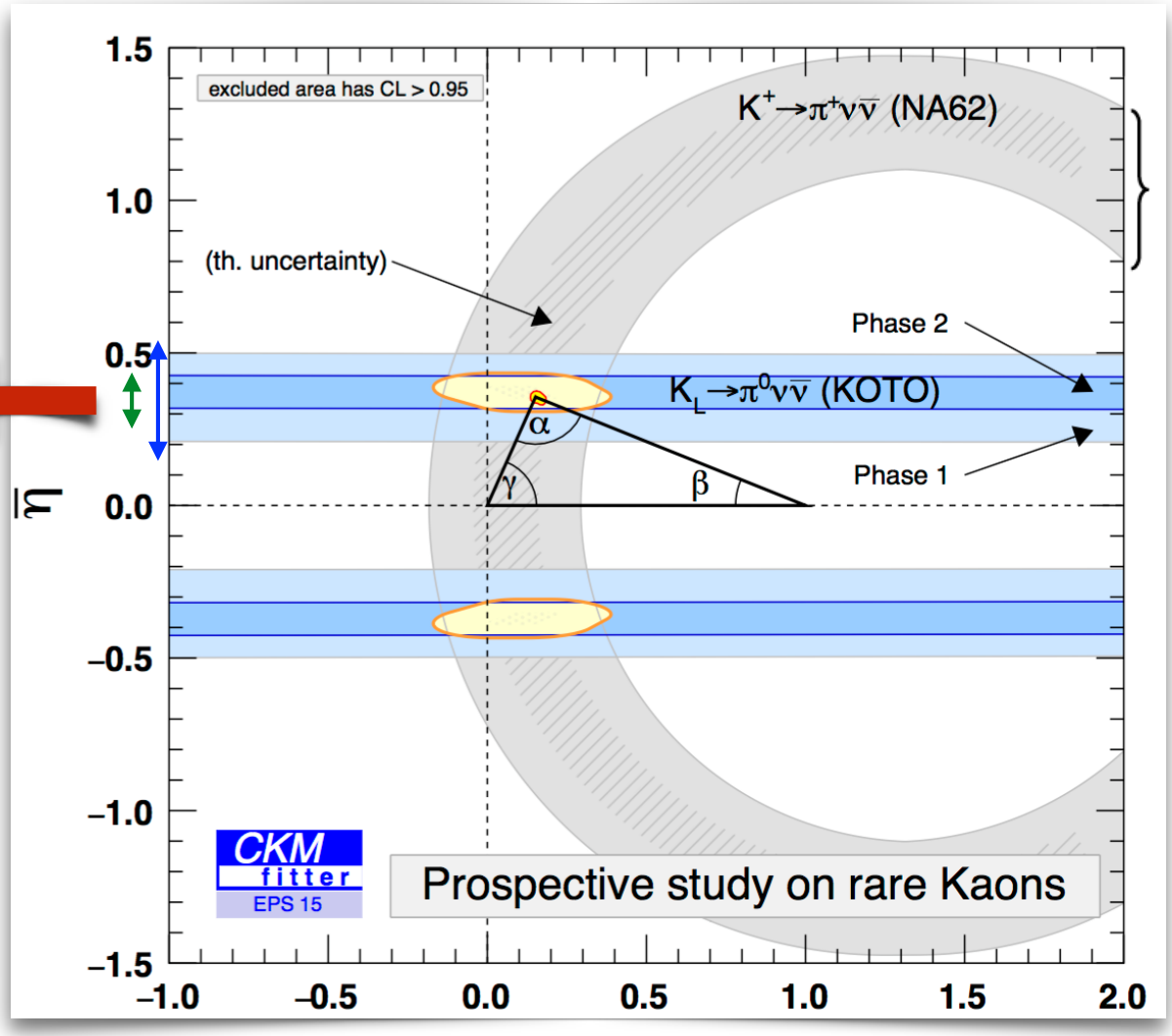
CKM fit from Kaon measurements!

Kaons
s→d

Putting together future NA62 and KOTO analyses, one can reconstruct the unitary triangle (just using Kaon physics)

3σ constraint on the BR

10% measurement



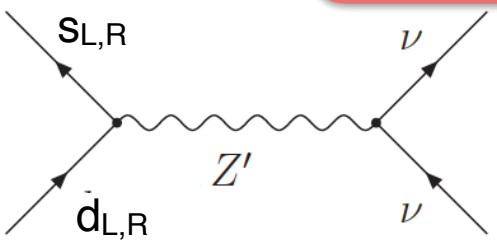
with 10% measurement

Implications on New Physics theories

Kaons
s→d

- Many NP models induce sizable NP effects in the BRs:

Custodial Randall-Sundrum [Blanke, Buras, Duling, Gemmler, SG, 0812.3803]
Simplified Z, Z' models [Buras, Buttazzo, Knegjens, 1507.08672]
Lepton flavor universality violation models [Bordone, et al., 1705.10729]
…



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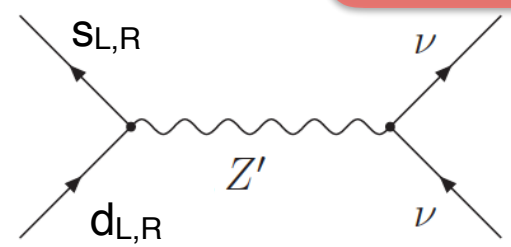
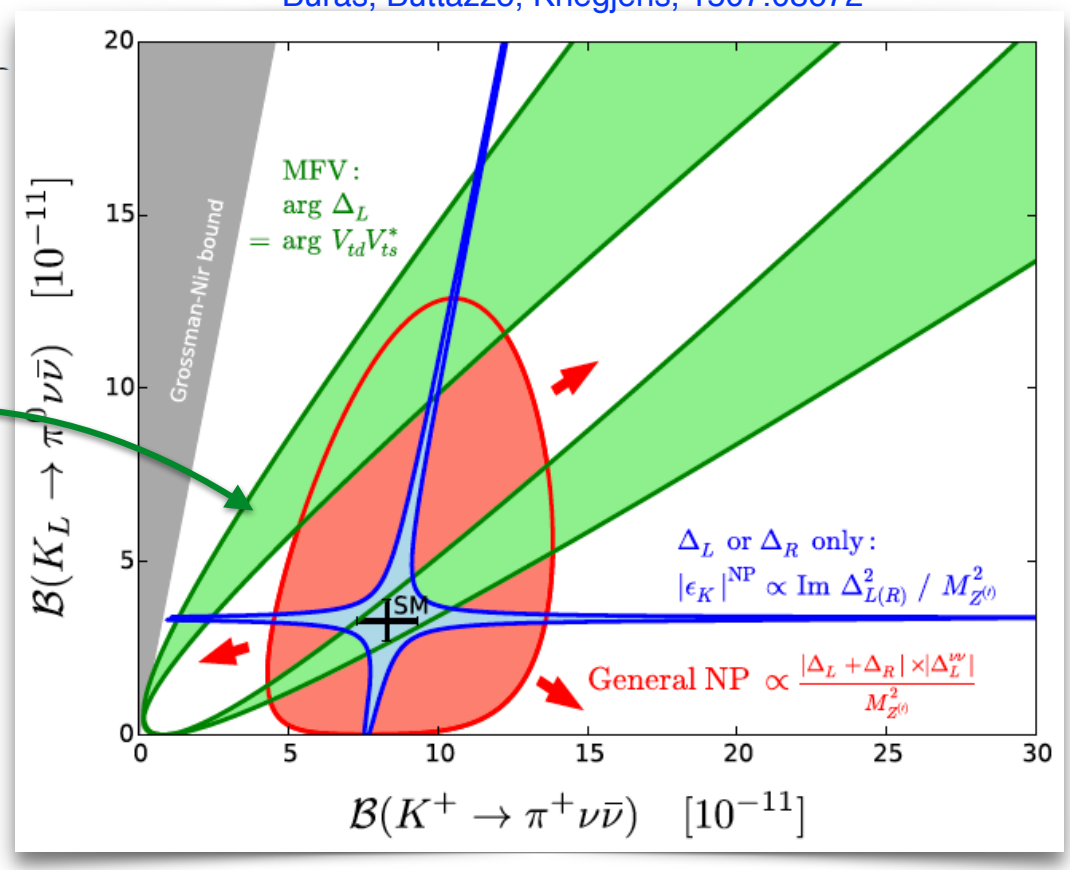


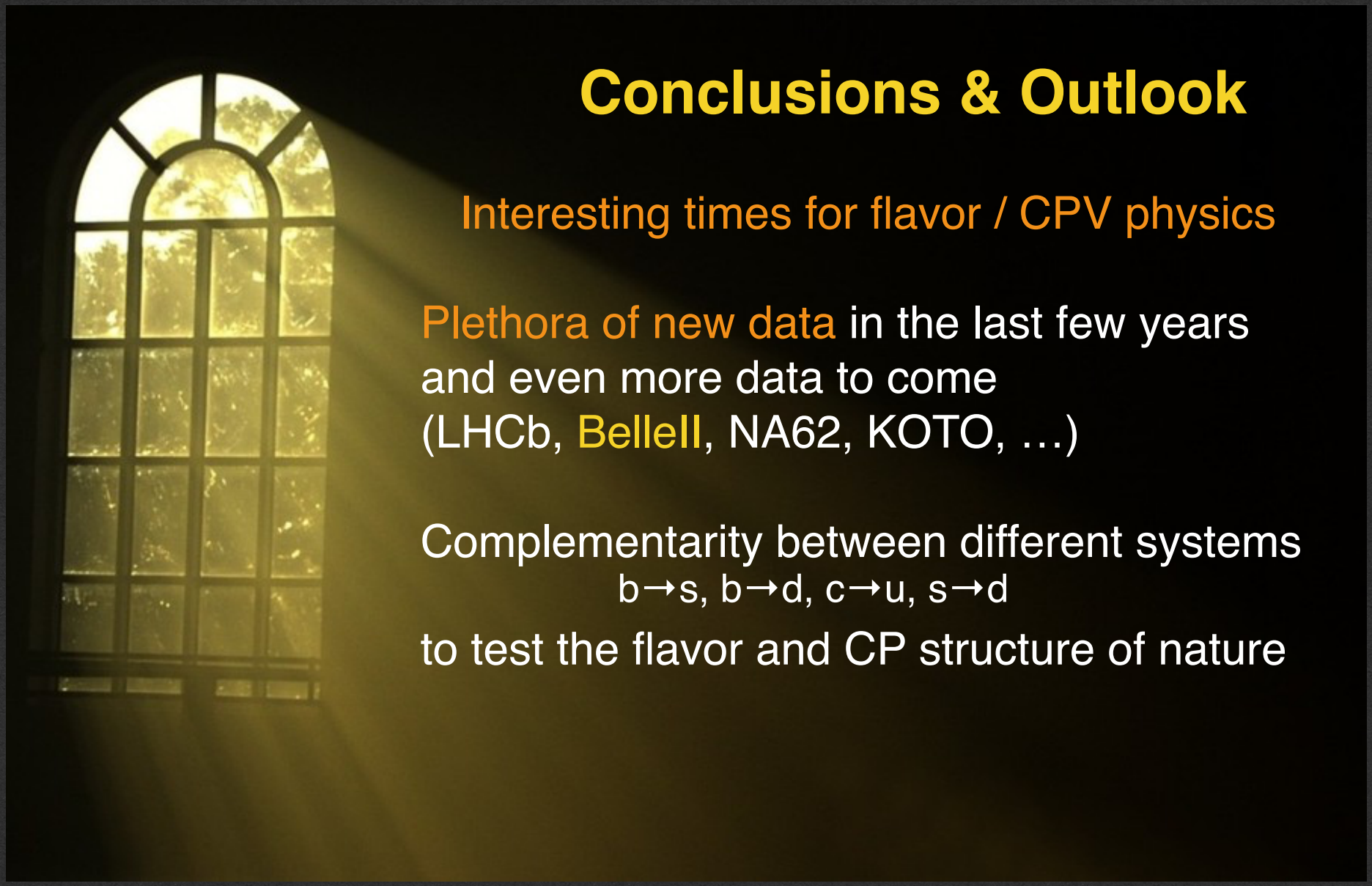
- At the operator level:

$$\mathcal{H}_{\rm eff} = \frac{c_1}{\Lambda^2}\underbrace{(\bar{s}_L\gamma_\mu d_L)(\bar{\nu}_\ell\gamma^\mu\nu_\ell)}_{\text{SM operator}} + \frac{c_2}{\Lambda^2}(\bar{s}_R\gamma_\mu d_R)(\bar{\nu}_\ell\gamma^\mu\nu_\ell)$$

Region for Minimal
Flavor Violating models

Buras, Buttazzo, Knegjens, 1507.08672





Conclusions & Outlook

Interesting times for flavor / CPV physics

Plethora of new data in the last few years
and even more data to come
(LHCb, BelleII, NA62, KOTO, …)

Complementarity between different systems
$b \to s$, $b \to d$, $c \to u$, $s \to d$
to test the flavor and CP structure of nature