DISCRETE 2022
Kongresshaus Baden-Baden

Study of New Physics in $B_q^0 - \bar{B}_q^0$ Mixing: Challenges, Prospects and Implications for Leptonic Decays

arXiv:2208.14910

Kristof De Bruyn, Robert Fleischer, E.M., Philine van Vliet

Eleftheria Malami

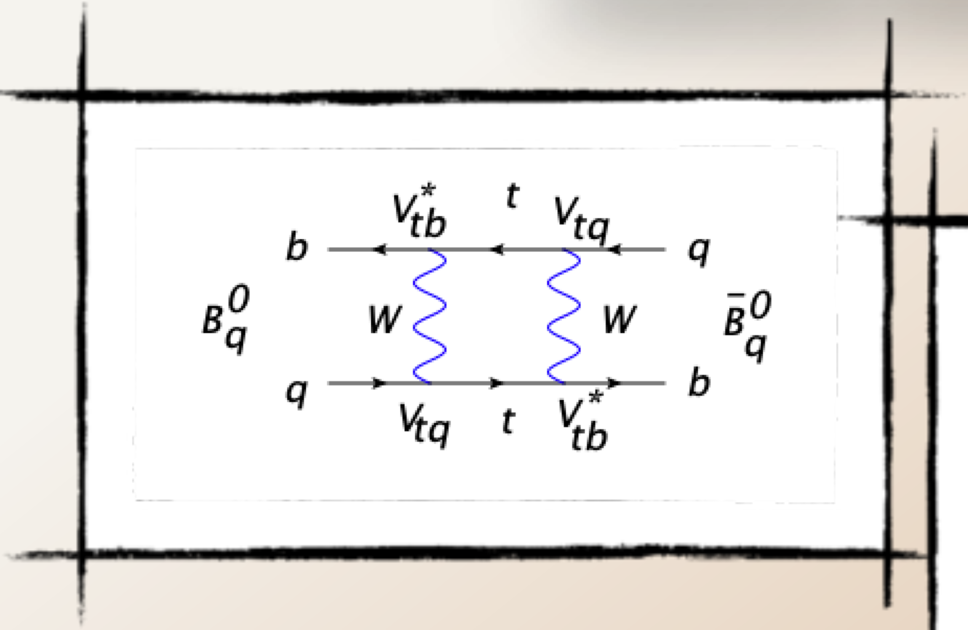
Theoretical Particle Physics Group

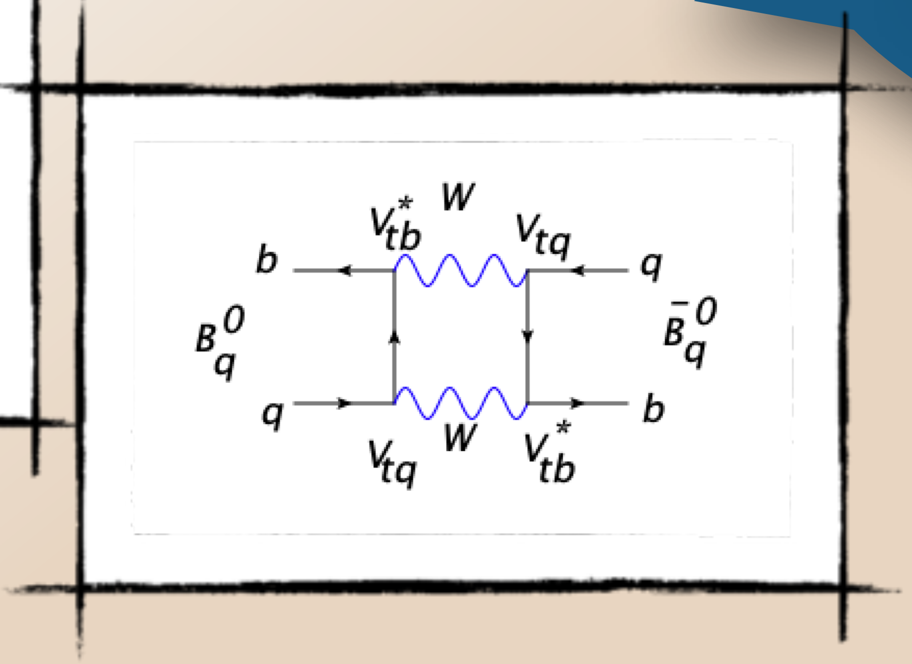
Nikhef UNIVERSITÄT SIEGEN

Wednesday November 9th 2022

Introduction

Neutral Meson Mixing





ϕ_d and ϕ_s mixing phases

$$|B_q(t)\rangle = a(t)|B_q^0\rangle + b(t)|\overline{B_q^0}\rangle$$

Schrödinger equation → Mass eigenstates

Time-dependent decay rates: characterised by mass difference ΔM_q

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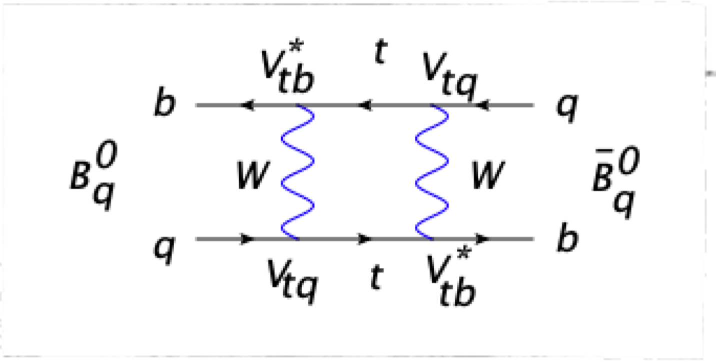

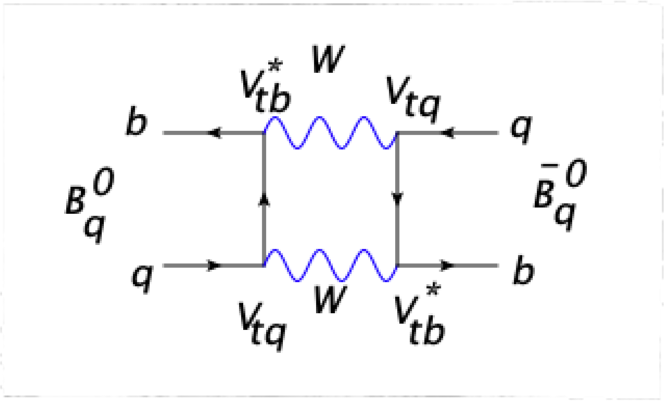

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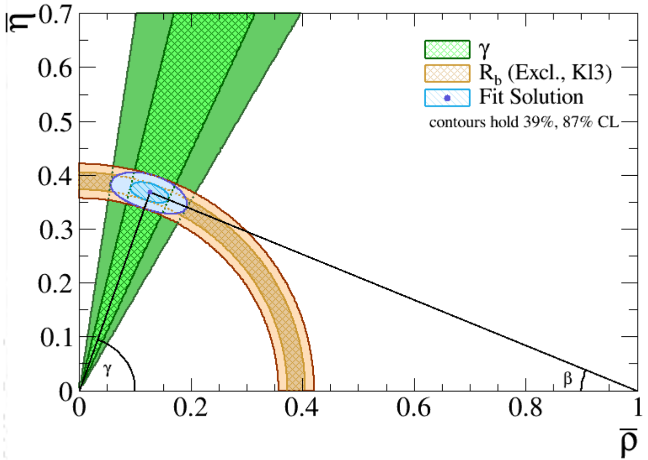
Unitarity Triangle

$$\boxed{\bar{\rho} \equiv \left(1 - \frac{\lambda^2}{2}\right)\rho}$$

$$\boxed{\bar{\eta} \equiv \left(1 - \frac{\lambda^2}{2}\right)\eta}$$

Wolfenstein parameters



[M.Z. Barel, K. De Bruyn, R. Fleischer, & E.M. (2020)]

Following PDG parametrisation, the UT coordinates are given by:

$$\boxed{R_b\, e^{i\gamma} = \bar{\rho} + i\bar{\eta}}$$

$$\left.\begin{matrix} R_b \\ \gamma \end{matrix}\right\}$$ determined from decays that proceed only via tree topologies

Unitarity Triangle Apex Determination

▹ Utilising γ and R_b

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- **Decay-time-independent $B \to DK$**

sensitivity to γ → from direct CP violation

$\gamma_{B\to DK} = (64.9^{+3.9}_{-4.5})^\circ$

[LHCb Collaboration(2021)]

assume
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determined with $B_s^0 \rightarrow J/\psi\phi$
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HFLAV(2022)

We calculate the UT side R_b :

$R_{b,\text{incl},K\ell3} = 0.434 \pm 0.018$

$R_{b,\text{excl},K\ell3} = 0.392 \pm 0.014$

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HFLAV(2022), arXiv:2107.00604 arXiv:0707.2493

3.9σ

$$|V_{ub}|_{\text{incl}} = (4.19 \pm 0.17) \times 10^{-3}$$

$$|V_{ub}|_{\text{excl}} = (3.51 \pm 0.12) \times 10^{-3}$$

HFLAV(2022)

HFLAV(2022), arXiv:2107.00604

4.3σ

$$|V_{cb}|_{\text{incl}} = (42.16 \pm 0.50) \times 10^{-3}$$

$$|V_{cb}|_{\text{excl}} = (39.10 \pm 0.50) \times 10^{-3}$$

HFLAV(2022)

We calculate the UT side R_b :

$$R_{b,\text{incl},K\ell3} = 0.434 \pm 0.018$$

$$R_{b,\text{excl},K\ell3} = 0.392 \pm 0.014$$

2.4σ

Unitarity Triangle Apex Determination

▶ Utilising γ and R_b →

tensions between various theoretical & experimental approaches

✱ Decay-time-independent $B \to DK$

sensitivity to γ → from direct CP violation

$\gamma_{B\to DK} = (64.9^{+3.9}_{-4.5})^\circ$

assume free from NP

[LHCb Collaboration(2021)]

✱ Decay-time-dependent $B_s^0 \to D_s^\mp K^\pm$

Through interference effects with the $B_s^0 - \bar{B}_s^0$ mixing the CP asymmetry parameters allow determination of

[M.Z. Barel, K. De Bruyn, R. Fleischer, & E.M. (2020)]

$(-4.2 \pm 1.4)^\circ$ ← $\phi_s + \gamma$

Theoretically clean

determined with $B_s^0 \to J/\psi\phi$
- penguin effects included

sensitivity to γ
↓
from mixing-induced CP violation

[R. Fleischer and E.M. (2021)]

$\gamma_{B_s\to D_sK} = (131^{+17}_{-22})^\circ$

✱ Isospin analysis of $B \to \pi\pi,\ \rho\pi,\ \rho\rho$

[M.Z. Barel, K. De Bruyn, R. Fleischer, & E.M. (2020)]

$\phi_d = (44.4^{+1.6}_{-1.5})^\circ$

penguin effects included

$\gamma_{\text{iso}} = (72.6^{+4.3}_{-4.9})^\circ$

possible NP at the amplitudes through penguin

✱ Average

$\gamma_{\text{avg}} = (68.4 \pm 3.4)^\circ$

$$R_b \equiv \left(1 - \frac{\lambda^2}{2}\right)\frac{1}{\lambda}\left|\frac{V_{ub}}{V_{cb}}\right| = \sqrt{\bar{\rho}^{\,2} + \bar{\eta}^{\,2}}$$

$\lambda \equiv |V_{us}|, |V_{ub}|$ and $|V_{cb}|$

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HFLAV(2022), arXiv:2107.00604 arXiv:0707.2493

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4.3σ

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2.4σ

Third possibility: hybrid combination of exclusive $|V_{ub}|$ with inclusive $|V_{cb}|$

$R_{b,\text{hybrid},K\ell3} = 0.364 \pm 0.013$

Unitarity Triangle Apex Determination

▹ Utilising γ and R_b ⟶

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$\phi_s + \gamma$

Theoretically clean

[M.Z. Barel, K. De Bruyn, R. Fleischer, & E.M. (2020)]

$(-4.2 \pm 1.4)^\circ$

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$|V_{us}| = 0.22309 \pm 0.00056$

HFLAV(2022), arXiv:2107.00604 arXiv:0707.2493

3.9σ

$|V_{ub}|_{\rm incl} = (4.19 \pm 0.17) \times 10^{-3}$

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HFLAV(2022)

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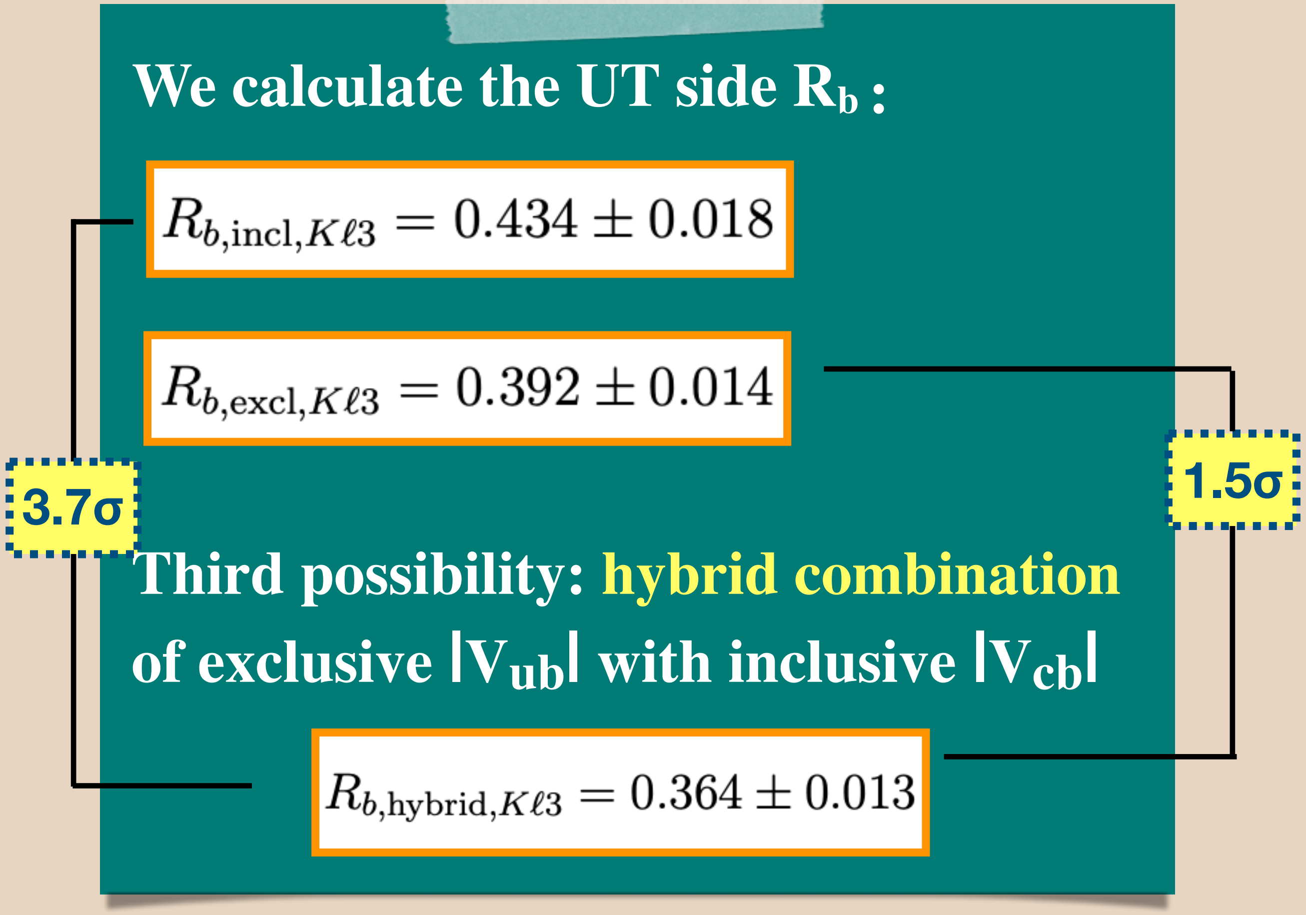
HFLAV(2022)



We calculate the UT side R$_b$:

$R_{b,\rm incl,K\ell3} = 0.434 \pm 0.018$

$R_{b,\rm excl,K\ell3} = 0.392 \pm 0.014$

3.7σ

1.5σ

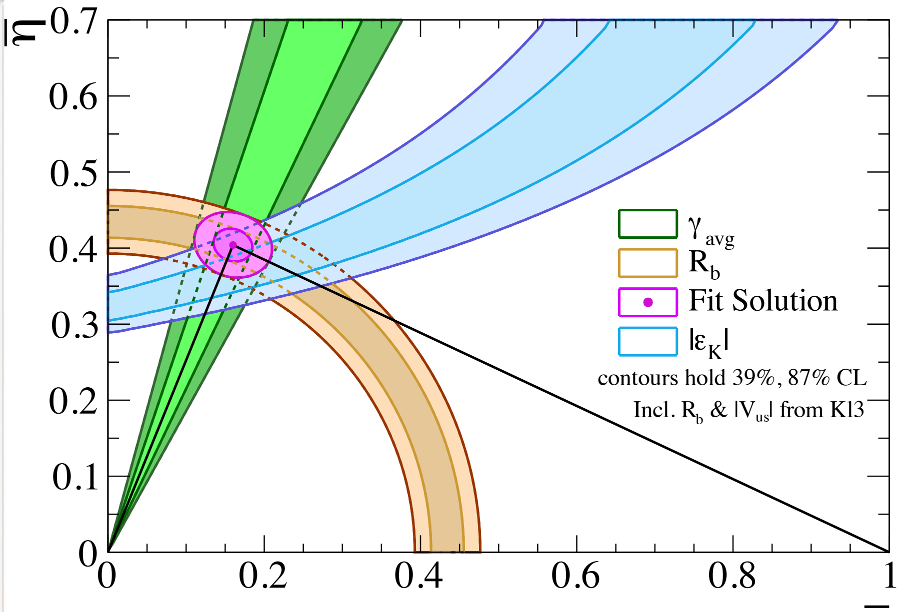
Third possibility: hybrid combination of exclusive |V$_{ub}$| with inclusive |V$_{cb}$|

$R_{b,\rm hybrid,K\ell3} = 0.364 \pm 0.013$

Unitarity Triangle Apex Determination

Utilising γ and R_b

	Inclusive	Exclusive	Hybrid
α	$(85.2^{+4.8}_{-4.3})^\circ$		
ϕ_d	$(44.4^{+1.6}_{-1.5})^\circ$		
$\gamma_{B\to DK}$	$(64.9^{+3.9}_{-4.5})^\circ$		
γ_{iso}	$(72.6^{+4.3}_{-4.9})^\circ$		
γ_{avg}	$(68.4 \pm 3.3)^\circ$		
$\lvert V_{us}\rvert$	0.22309 ± 0.00056		
$\lvert V_{ub}\rvert \times 10^3$	4.19 ± 0.17	3.51 ± 0.12	3.51 ± 0.12
$\lvert V_{cb}\rvert \times 10^3$	42.16 ± 0.50	39.10 ± 0.50	42.16 ± 0.50
R_b	0.434 ± 0.018	0.392 ± 0.014	0.364 ± 0.013
$\bar\rho$	0.160 ± 0.025	0.144 ± 0.022	0.134 ± 0.021
$\bar\eta$	0.404 ± 0.022	0.365 ± 0.018	0.338 ± 0.017



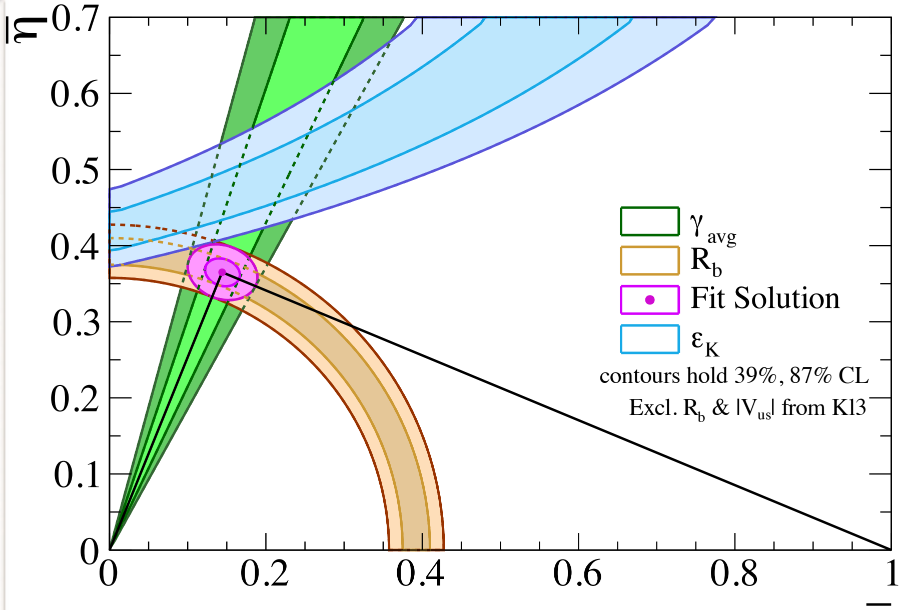
Inclusive case

Making a fit to R_b and γ

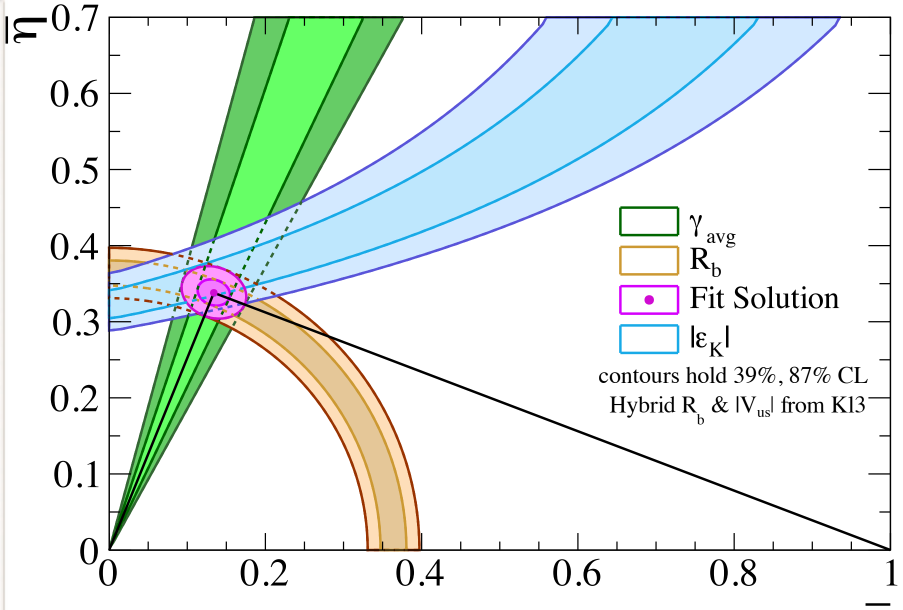
Incl, $K\ell3$ $\bar\rho = 0.160 \pm 0.025$, $\bar\eta = 0.404 \pm 0.022$

Excl, $K\ell3$ $\bar\rho = 0.144 \pm 0.022$, $\bar\eta = 0.365 \pm 0.018$

Hybrid, $K\ell3$ $\bar\rho = 0.134 \pm 0.021$, $\bar\eta = 0.338 \pm 0.017$



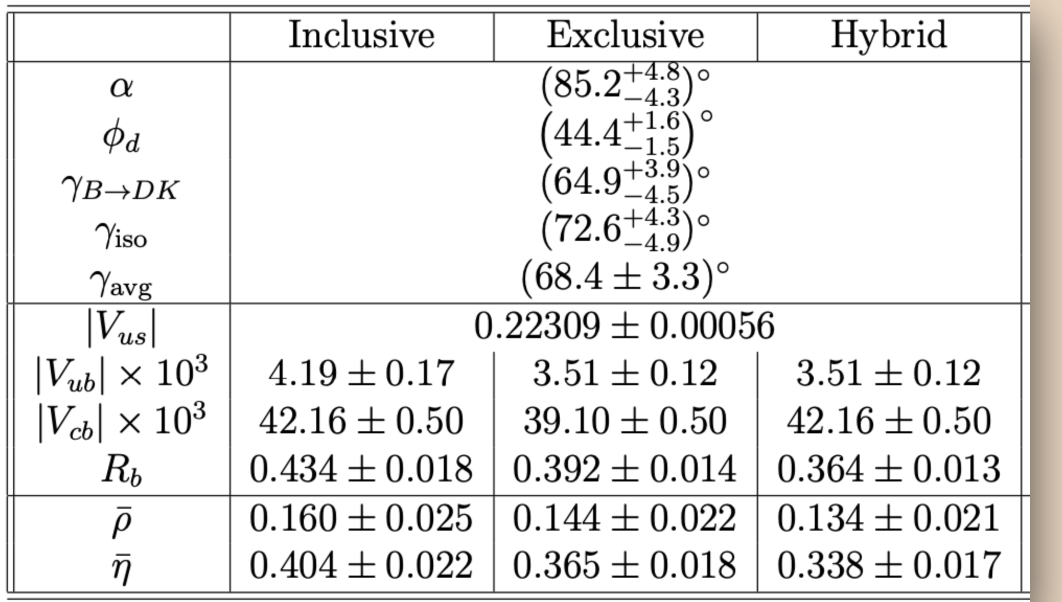
Exclusive case



Hybrid case

Unitarity Triangle Apex Determination

Utilising γ and R_b



	Inclusive	Exclusive	Hybrid
α	$(85.2^{+4.8}_{-4.3})^\circ$		
ϕ_d	$(44.4^{+1.6}_{-1.5})^\circ$		
$\gamma_{B\to DK}$	$(64.9^{+3.9}_{-4.5})^\circ$		
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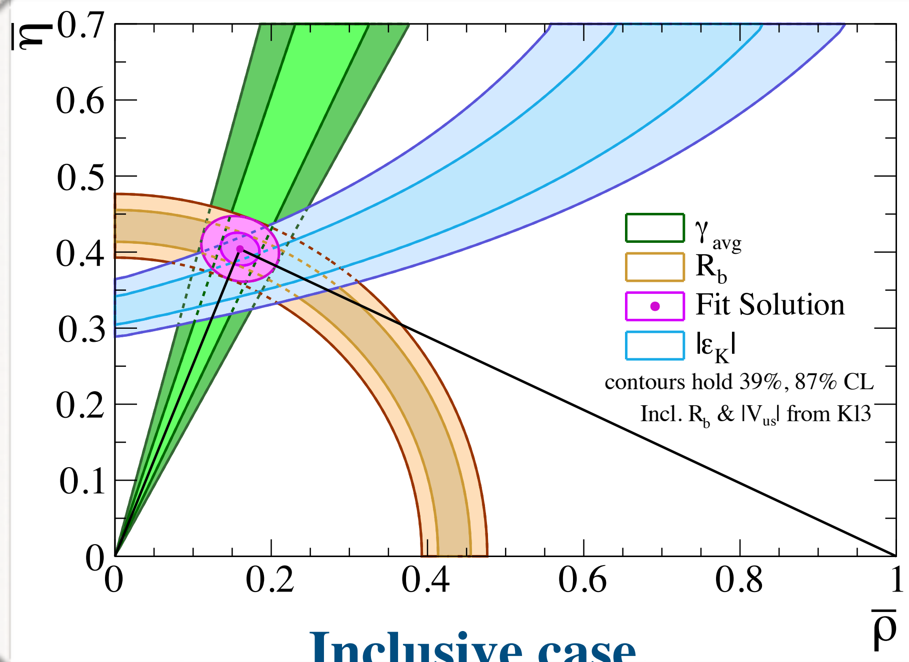
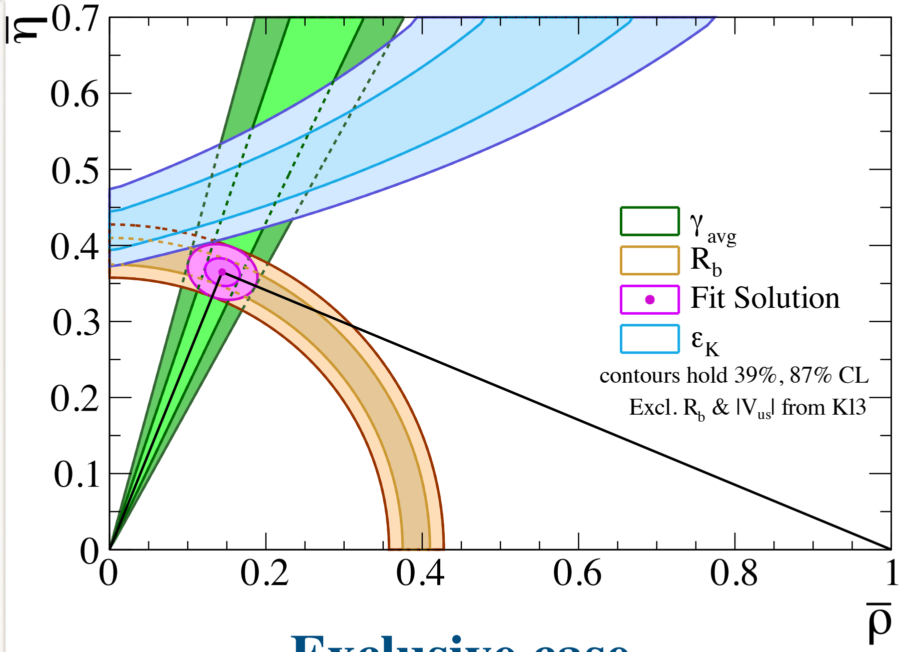
$\bar\rho$	0.160 ± 0.025	0.144 ± 0.022	0.134 ± 0.021
$\bar\eta$	0.404 ± 0.022	0.365 ± 0.018	0.338 ± 0.017

arXiv:1911.06822

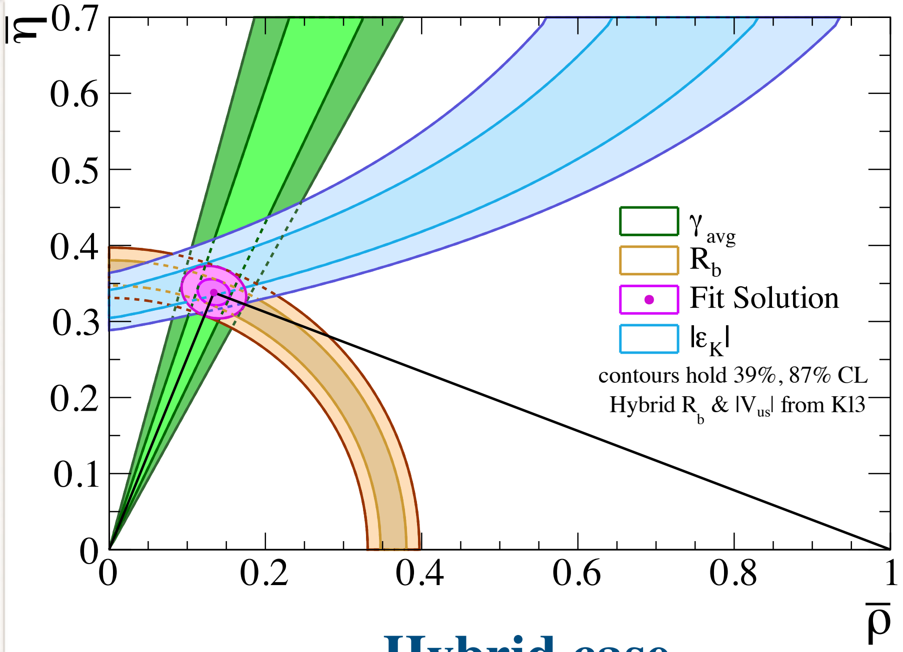
$$|\varepsilon_K| = \frac{G_F^2 m_W^2 m_K f_K^2}{6\sqrt{2}\pi^2 \Delta m_K} \kappa_\varepsilon \hat{B}_K |V_{cb}|^2 \lambda^2 \bar\eta \left[|V_{cb}|^2 (1-\bar\rho)\, \eta_{tt}^{\rm EW} \eta_{tt}\, \mathcal{S}(x_t) - \eta_{ut}\, \mathcal{S}(x_c, x_t) \right]$$



Inclusive case



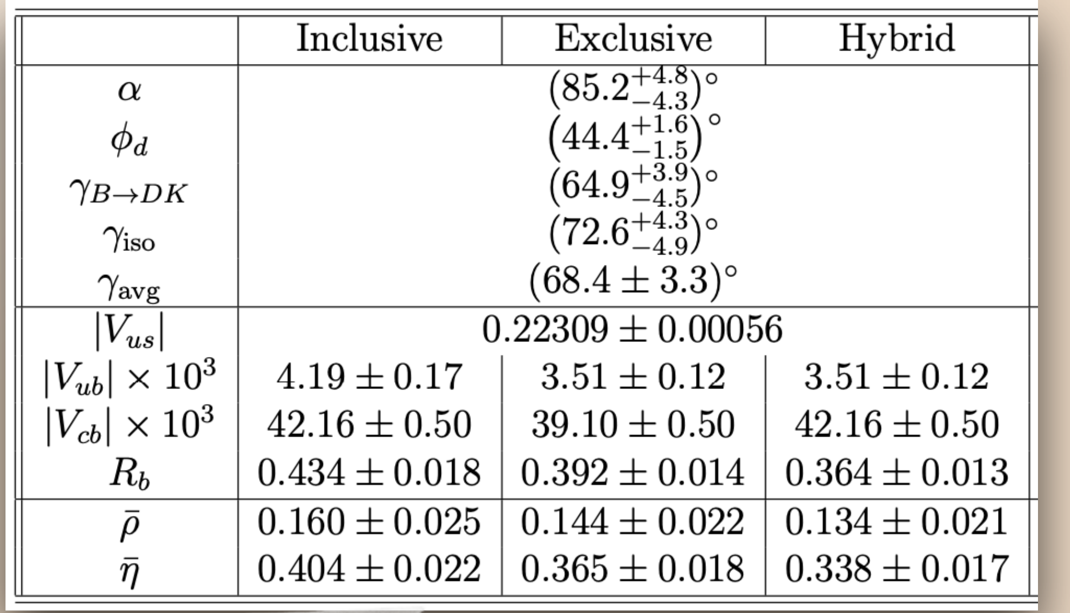
Exclusive case



Hybrid case

Unitarity Triangle Apex Determination

▷ Utilising γ and R_b



	Inclusive	Exclusive	Hybrid
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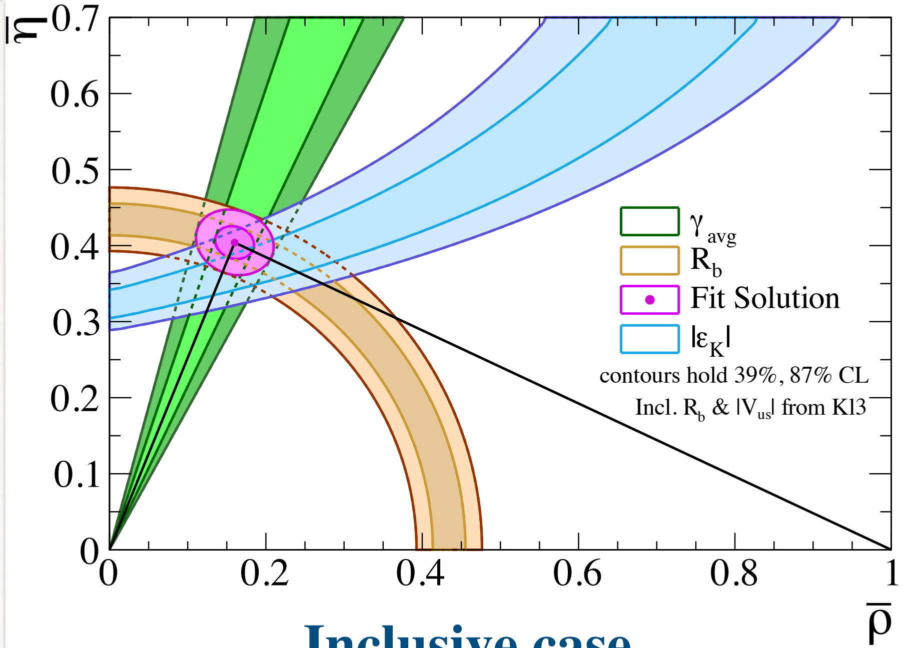
$\bar\eta$	0.404 ± 0.022	0.365 ± 0.018	0.338 ± 0.017

arXiv:1911.06822

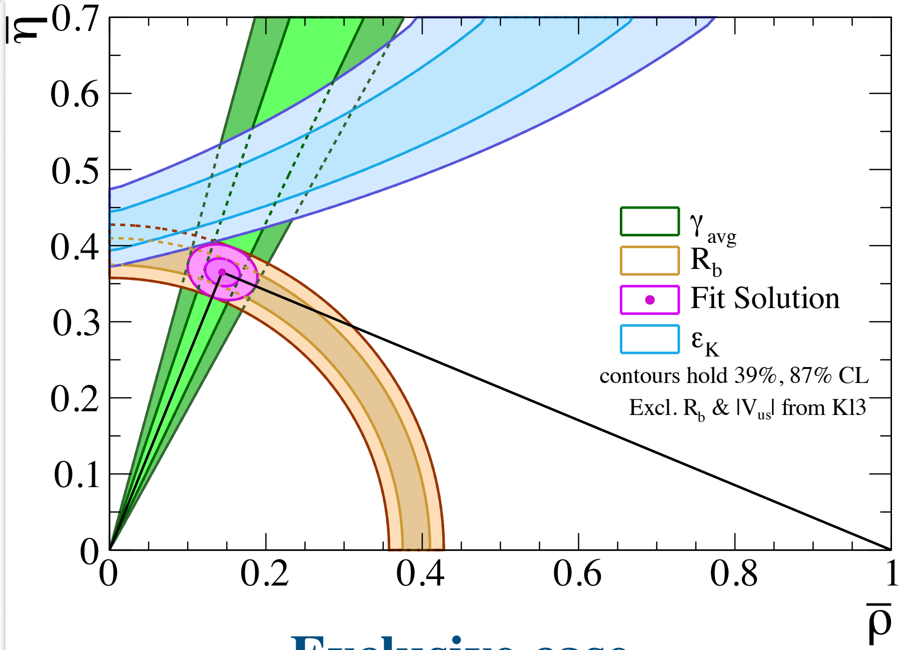
$|\varepsilon_K| =$ … $\eta_{ut}\,\mathcal{S}(x_c, x_t)]$

Strong dependence of value of $|V_{cb}|$

In the future: it could help to understand the inclusive-exclusive puzzle, if NP in kaon can be controlled/ignored

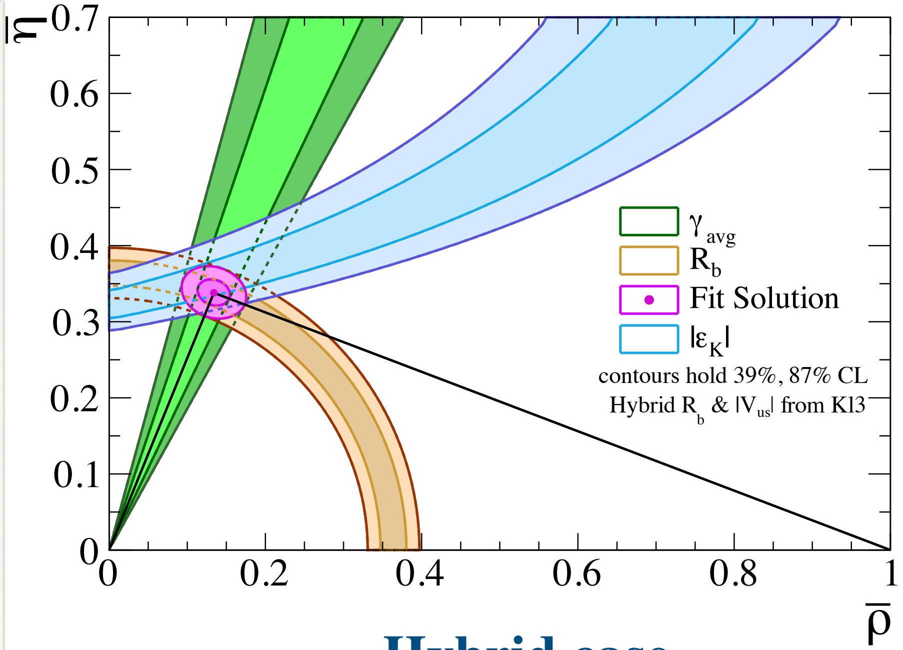


Inclusive case



Exclusive case

Most consistent picture of UT apex



Hybrid case

SM expressions for the Mixing Parameters

The SM prediction of ϕ_d

$$\phi_d^{\mathrm{SM}} = 2\beta = 2\mathrm{arg}\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right) = 2\tan^{-1}\left(\frac{\bar{\eta}}{1-\bar{\rho}}\right)$$

Incl, $K\ell3$	$\phi_d^{\mathrm{SM}} = (51.4 \pm 2.8)^\circ$
Excl, $K\ell3$	$\phi_d^{\mathrm{SM}} = (46.2 \pm 2.3)^\circ$
Hybrid, $K\ell3$	$\phi_d^{\mathrm{SM}} = (42.6 \pm 2.2)^\circ$

The SM expression of ϕ_s

$$\phi_s^{\mathrm{SM}} = -2\delta\gamma = -2\lambda^2\bar{\eta} + \mathcal{O}(\lambda^4)$$

Dependence on UT apex: doubly Cabibbo-suppressed

Incl, $K\ell3$	$\phi_s^{\mathrm{SM}} = (-2.30 \pm 0.13)^\circ$
Excl, $K\ell3$	$\phi_s^{\mathrm{SM}} = (-2.08 \pm 0.10)^\circ$
Hybrid, $K\ell3$	$\phi_s^{\mathrm{SM}} = (-1.93 \pm 0.10)^\circ$

Global fit of UT $\phi_s^{\mathrm{SM}} = \left(-2.110^{+0.049}_{-0.034}\right)^\circ$ **rely on info from neutral B mixing without accounting for possible NP contributions**

SM expressions for the Mixing Parameters

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Global fit of UT $\phi_s^{\rm SM} = \left(-2.110^{+0.049}_{-0.034}\right)^\circ$ **rely on info from neutral B mixing without accounting for possible NP contributions**

- **We introduce the mass difference** $\Delta m_q = 2|M_{12}^q| + \mathcal{O}\left(\left|\frac{\Gamma_{12}^q}{M_{12}^q}\right|^2\right)$ **and in SM** $|M_{12}^q|_{\rm SM} = \frac{G_{\rm F}^2 m_W^2}{12\pi^2} m_{B_q} |V_{tq}V_{tb}|^2 \; S_0(x_t)\, \eta_{2B} \hat{B}_{B_q} f_{B_q}^2$

We obtain the predictions

Incl, $K\ell3$ $\quad \Delta m_d^{\rm SM} = (0.513 \pm 0.040)\ {\rm ps}^{-1}, \quad \Delta m_s^{\rm SM} = (17.23 \pm 0.87)\ {\rm ps}^{-1}$

Excl, $K\ell3$ $\quad \Delta m_d^{\rm SM} = (0.439 \pm 0.033)\ {\rm ps}^{-1}, \quad \Delta m_s^{\rm SM} = (14.80 \pm 0.76)\ {\rm ps}^{-1}$

Hybrid, $K\ell3$ $\quad \Delta m_d^{\rm SM} = (0.510 \pm 0.037)\ {\rm ps}^{-1}, \quad \Delta m_s^{\rm SM} = (17.19 \pm 0.87)\ {\rm ps}^{-1}$

We compare with experimental values $\Delta m_d = (0.5065 \pm 0.0019)\ {\rm ps}^{-1} \quad \Delta m_s = (17.7656 \pm 0.0057)\ {\rm ps}^{-1}$ **one to two orders of magnitude more precise**

Unitarity Triangle Apex Determination

- Utilising Mixing and R_b - without γ

assume $\dfrac{\Delta m_s^{\mathrm{SM}}}{\Delta m_d^{\mathrm{SM}}}$

Unitarity Triangle Apex Determination

Utilising Mixing and R_b - without γ

- **The UT side R_t is defined as:**

$$R_t \equiv \left|\frac{V_{td}V_{tb}}{V_{cd}V_{cb}}\right| = \sqrt{(1-\bar{\rho})^2+\bar{\eta}^{\,2}} = \frac{1}{\lambda}\left|\frac{V_{td}}{V_{ts}}\right|\left[1-\frac{\lambda^2}{2}(1-2\bar{\rho})\right] + \mathcal{O}\left(\lambda^4\right)$$

fit to the sides R_b and R_t

Incl, $K\ell3$	$\bar{\rho} = 0.180 \pm 0.014\,,$	$\bar{\eta} = 0.395 \pm 0.020$
Excl, $K\ell3$	$\bar{\rho} = 0.163 \pm 0.013\,,$	$\bar{\eta} = 0.357 \pm 0.017$
Hybrid, $K\ell3$	$\bar{\rho} = 0.153 \pm 0.013\,,$	$\bar{\eta} = 0.330 \pm 0.016$

scenarios <u>with γ</u> are a factor 2 less precise than the scenarios without γ

assume $\Delta m_s^{\rm SM}$ $\Delta m_d^{\rm SM}$

$$\left|\frac{V_{td}}{V_{ts}}\right| = \xi\sqrt{\frac{m_{B_s}\Delta m_d^{\rm SM}}{m_{B_d}\Delta m_s^{\rm SM}}}$$

lattice

$$\xi \equiv \frac{f_{B_s}\sqrt{\hat{B}_{B_s}}}{f_{B_d}\sqrt{\hat{B}_{B_d}}}$$

FLAG(2021), arXiv:1907.01025

$\xi = 1.212 \pm 0.016$

$$\left|\frac{V_{td}}{V_{ts}}\right| = 0.2063 \pm 0.0004 \pm 0.0027$$

due to lattice input

due to experiment

Unitarity Triangle Apex Determination

Utilising Mixing and R_b - without γ

assume $\Delta m_s^{\rm SM}$ $\Delta m_d^{\rm SM}$

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lattice

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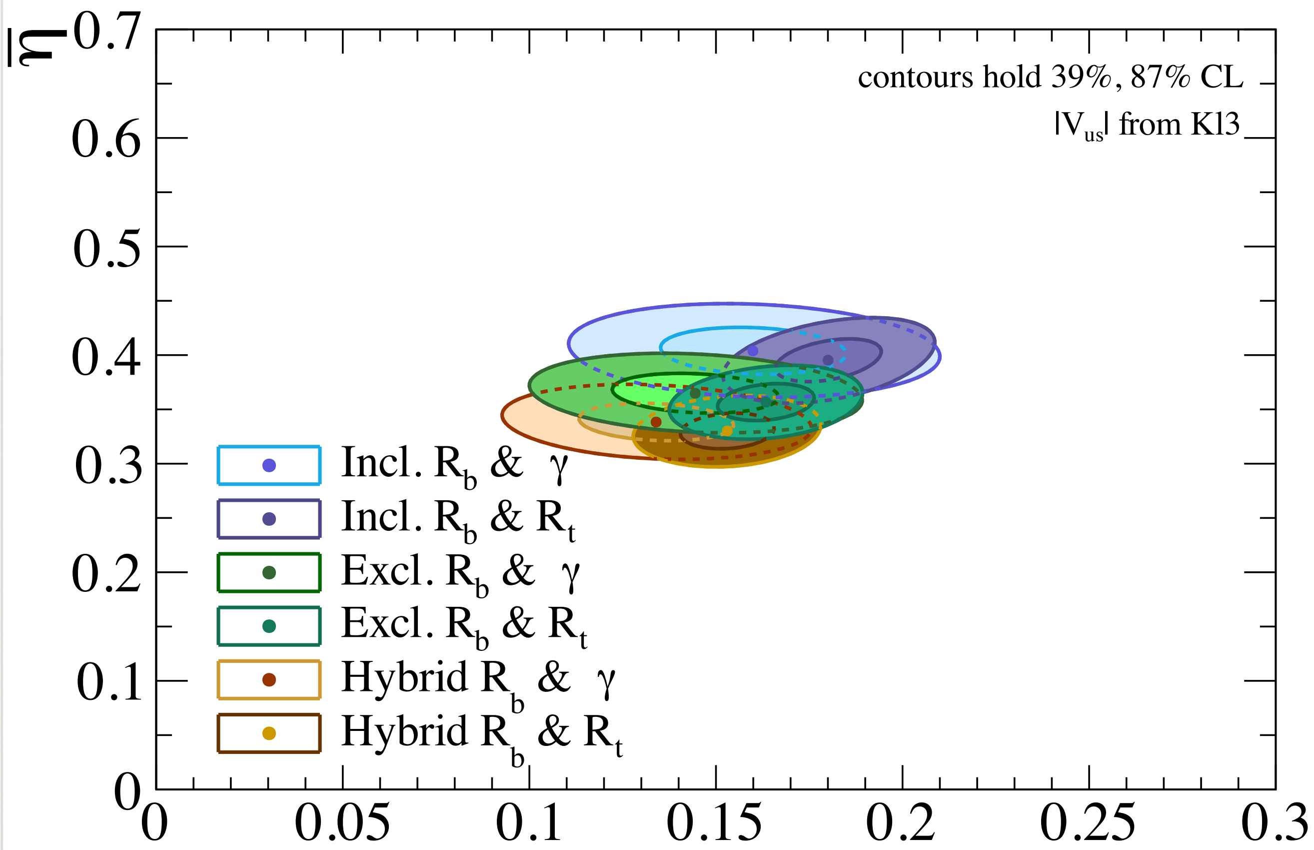
scenarios with γ are a factor 2 less precise than the scenarios without γ



Comparison of the UT apex determination through γ and R_b and through R_b and R_t

Unitarity Triangle Apex Determination

▶ Utilising Mixing and R_b - without γ

assume $\Delta m_s^{\rm SM}$ $\Delta m_d^{\rm SM}$

- **The UT side R_t is defined as:**

$$R_t \equiv \left|\frac{V_{td}V_{tb}}{V_{cd}V_{cb}}\right| = \sqrt{(1-\bar\rho)^2+\bar\eta^{\,2}} = \frac{1}{\lambda}\left|\frac{V_{td}}{V_{ts}}\right|\left[1-\frac{\lambda^2}{2}(1-2\bar\rho)\right]+\mathcal{O}\left(\lambda^4\right)$$

$$\left|\frac{V_{td}}{V_{ts}}\right| = \xi\sqrt{\frac{m_{B_s}\Delta m_d^{\rm SM}}{m_{B_d}\Delta m_s^{\rm SM}}}$$

lattice

$$\xi \equiv \frac{f_{B_s}\sqrt{\hat B_{B_s}}}{f_{B_d}\sqrt{\hat B_{B_d}}}$$

FLAG(2021), arXiv:1907.01025

$$\xi = 1.212 \pm 0.016$$

$$\left|\frac{V_{td}}{V_{ts}}\right| = 0.2063 \pm \underbrace{0.0004}_{\text{due to experiment}} \pm 0.0027 \xrightarrow{} \text{due to lattice input}$$

fit to the sides R_b and R_t

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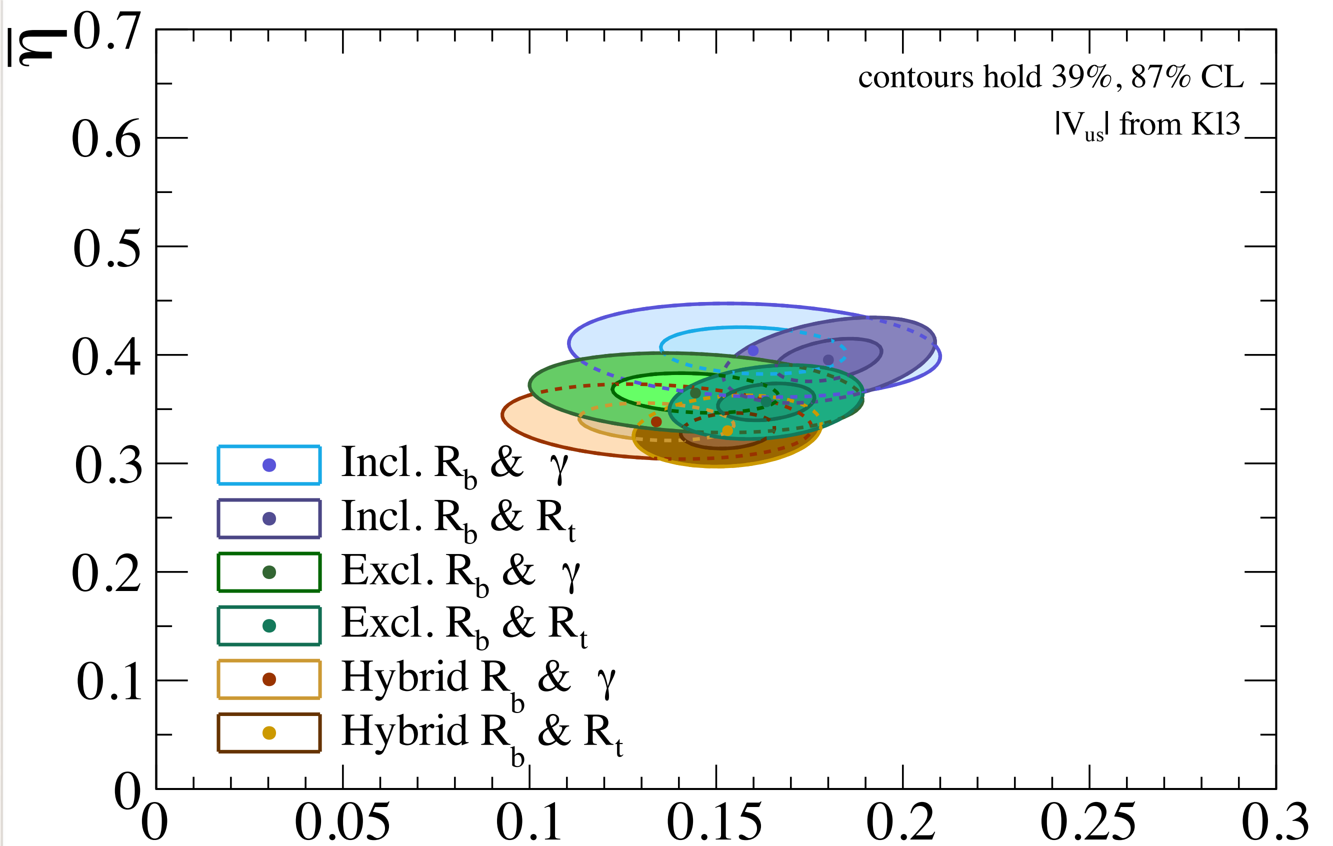
→ scenarios <u>with γ</u> are a factor 2 less precise than the scenarios without γ

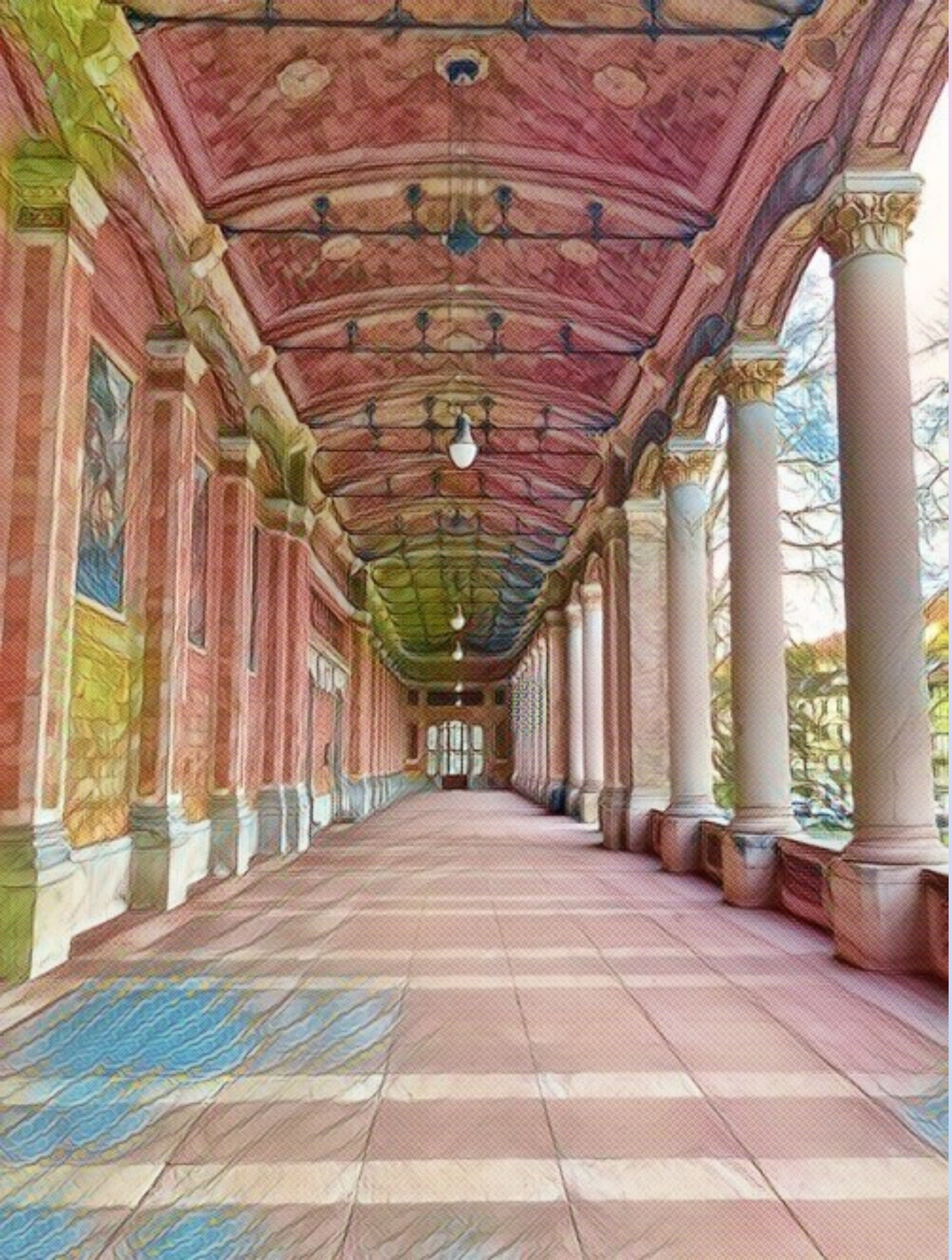


Comparison of the UT apex determination through γ and R_b and through R_b and R_t

- ✱ **UT apex determination through R_b and R_t is more precise**
- ✱ **R_t determined assuming SM Δm_d and Δm_s**

  ↓

  ignores possible NP in $B_q^0 - \bar B_q^0$ mixing
  - **NP will contaminate R_t determination**
    - **Special case: FUNP**
- ✱ **To determine NP in $B_q^0 - \bar B_q^0$ mixing in a general scenario: UT apex determination through R_b and γ**



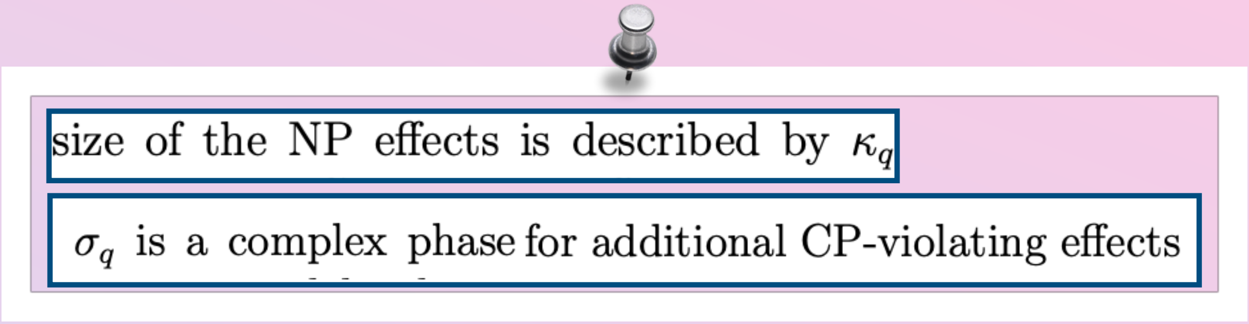
New Physics in $B_q^0 - \bar{B}_q^0$ Mixing

Introducing NP Parameters

$$\Delta m_q = \Delta m_q^{\mathrm{SM}} \left(1 + \kappa_q e^{i\sigma_q}\right)$$

$$\phi_q = \phi_q^{\mathrm{SM}} + \phi_q^{\mathrm{NP}} = \phi_q^{\mathrm{SM}} + \arg\left(1 + \kappa_q e^{i\sigma_q}\right)$$

Model independent parametrization



size of the NP effects is described by κ_q

σ_q is a complex phase for additional CP-violating effects

Introducing NP Parameters

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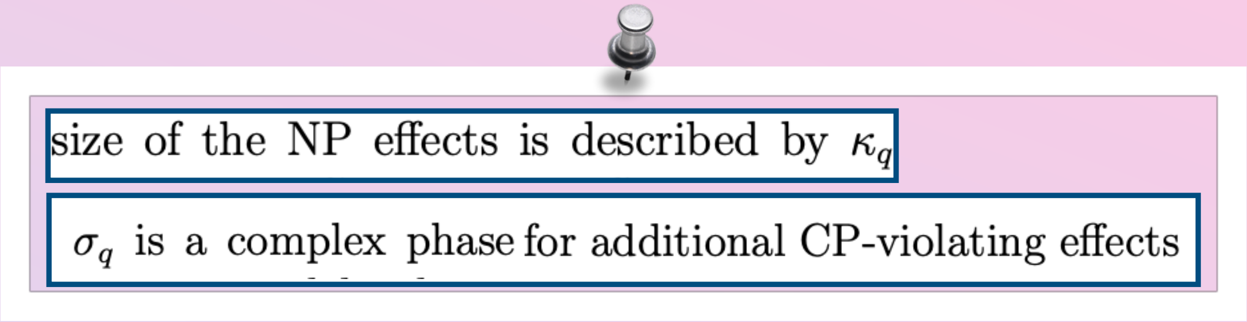

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We explore 3 different NP scenarios

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We explore 3 different NP scenarios

Scenario I → most general case

utilise UT apex determination for the SM predictions of Δm_q and ϕ_q

↓

NP parameters (κ_d, σ_d) and (κ_s, σ_s) independently from each other

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Scenario II

we consider NP contributions are equal in the B_d and the B_s systems

FUNP

↓

UT apex determination that only relies on R_b and mixing parameters without information on γ.

↓

NP in γ will not affect the results

Introducing NP Parameters

$$\Delta m_q = \Delta m_q^{\mathrm{SM}} \left(1 + \kappa_q e^{i\sigma_q}\right)$$

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Comparing FUNP with Scenario I

test of FUNP assumption

Impact of the assumptions on the constraints on parameters space of NP in mixing

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Scenario III → interpolation between Scenario I and II

assume FUNP to determine the UT apex.

only information from R_b and mixing parameters

but will relax this assumption when determining (κ_d, σ_d) and (κ_s, σ_s)

less strong assumption than full FUNP

Introducing NP Parameters

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Comparing Scenario III with Scenario I & II shows impact of:

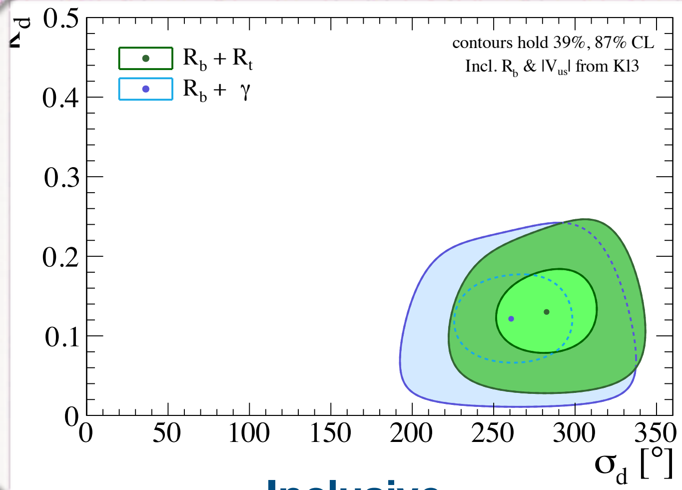
FUNP on fit to NP parameters

different UT apex determinations

SM predictions and experimental inputs for NP fit in B_s :
Identical for Scenario I & III

This is not the case for B_d

Similarly, comparing Scenario I & II:
B_d and B_s statistically compatible but don't look the same



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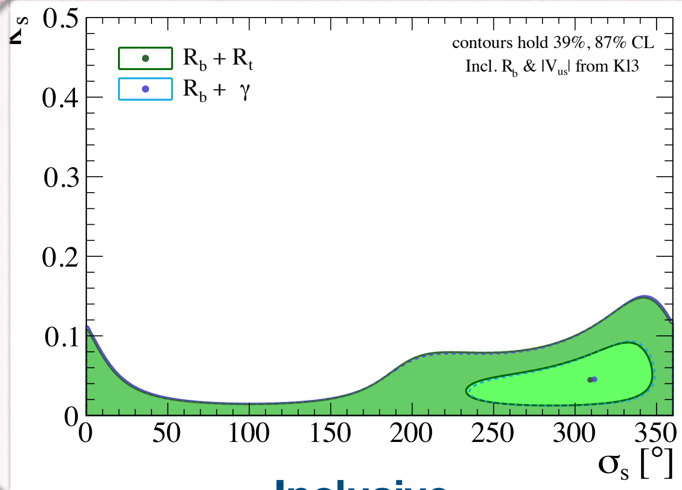

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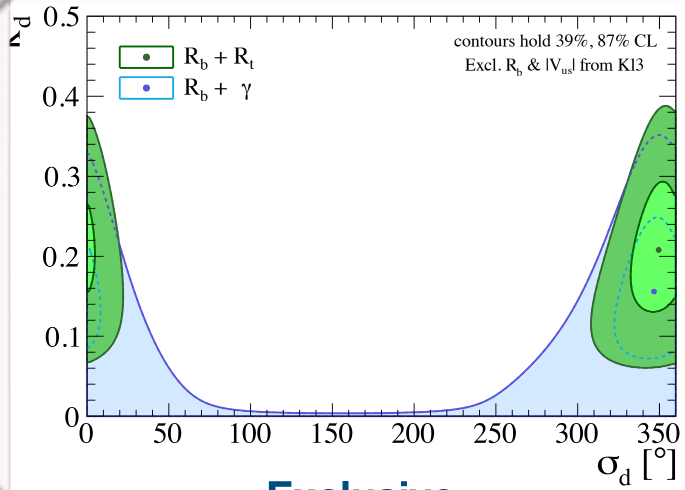

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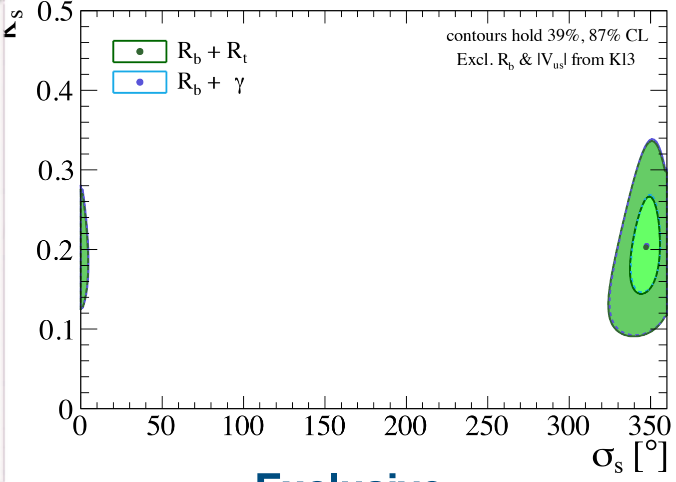

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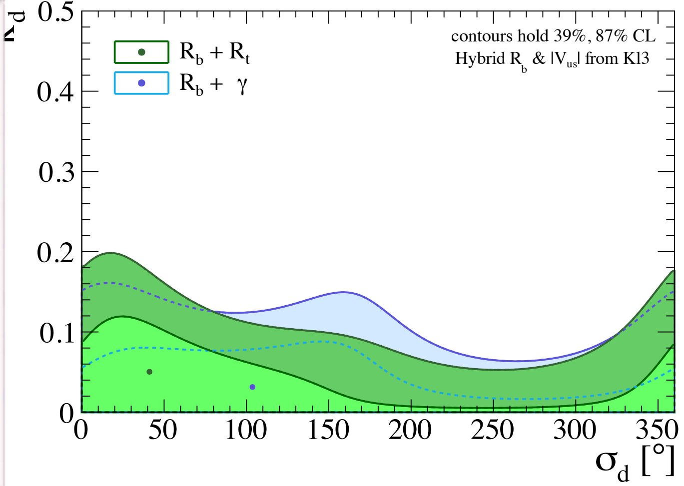
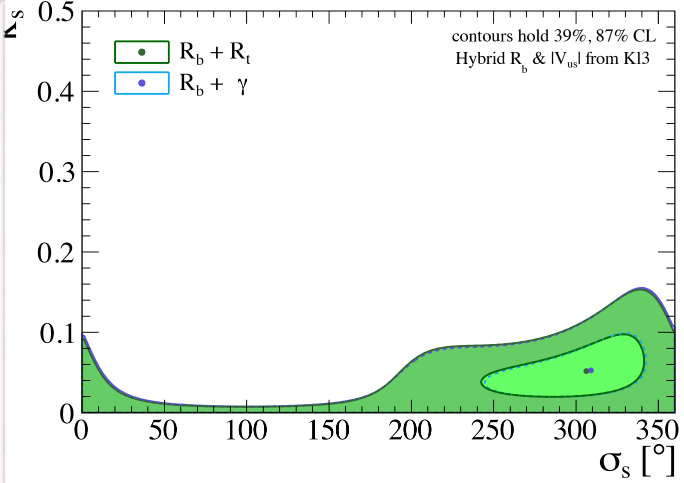


Hybrid



Hybrid

Applications for Leptonic Rare Decays

Determining NP in $B_s^0 \rightarrow \mu^+\mu^-$

NP can modify its branching ratio

(Pseudo-)Scalar

$B_s^0 - \bar{B}_s^0$ mixing

The measured branching ratio:

$$\bar{\mathcal{B}}(B_s \to \mu^+\mu^-) = \bar{\mathcal{B}}(B_s \to \mu^+\mu^-)^{\rm SM} \times \frac{1 + \mathcal{A}^{\mu\mu}_{\Delta\Gamma_s} y_s}{1 + y_s} \left(|P^s_{\mu\mu}|^2 + |S^s_{\mu\mu}|^2\right)$$

$\mathcal{A}^{\mu\mu}_{\Delta\Gamma_s}$ depends on $P^s_{\mu\mu} \equiv |P^s_{\mu\mu}|e^{i\varphi_P}$, $S^s_{\mu\mu} \equiv |S^s_{\mu\mu}|e^{i\varphi_S}$ and $\phi_s^{\rm NP}$

$$\mathcal{A}^{\mu\mu}_{\Delta\Gamma} = \frac{|P^s_{\mu\mu}|^2 \cos(2\varphi_P - \phi_s^{\rm NP}) - |S^s_{\mu\mu}|^2 \cos(2\varphi_S - \phi_s^{\rm NP})}{|P^s_{\mu\mu}|^2 + |S^s_{\mu\mu}|^2}$$

In SM

$$P^{s,\rm SM}_{\mu\mu} = 1$$

$$S^{s,\rm SM}_{\mu\mu} = 0$$

Determining NP in $B_s^0 \to \mu^+\mu^-$

NP can modify its branching ratio

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$B_s^0 - \bar{B}_s^0$ **mixing**

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Comparing

Incl, $K\ell 3$	$\bar{\mathcal{B}}(B_s \to \mu^+\mu^-) = (3.81 \pm 0.11) \times 10^{-9}$,
Excl, $K\ell 3$	$\bar{\mathcal{B}}(B_s \to \mu^+\mu^-) = (3.27 \pm 0.10) \times 10^{-9}$,
Hybrid, $K\ell 3$	$\bar{\mathcal{B}}(B_s \to \mu^+\mu^-) = (3.80 \pm 0.10) \times 10^{-9}$.

with

$$\bar{\mathcal{B}}(B_s \to \mu^+\mu^-) = (2.85^{+0.34}_{-0.31}) \times 10^{-9}$$

We constrain the parameters $|P^s|$ and $|S^s|$ arXiv:1204.1737

Here we assume NP phases for the pseudo-scalar and scalar contributions are zero $\varphi_P = \varphi_S = 0$

Determining NP in $B_s^0 \to \mu^+\mu^-$

NP can modify its branching ratio

(Pseudo-)Scalar

$B_s^0 - \bar{B}_s^0$ mixing

The measured branching ratio:

$$\bar{\mathcal{B}}(B_s \to \mu^+\mu^-) = \bar{\mathcal{B}}(B_s \to \mu^+\mu^-)^{\mathrm{SM}} \times \frac{1+\mathcal{A}^{\mu\mu}_{\Delta\Gamma_s} y_s}{1+y_s}\left(|P^s_{\mu\mu}|^2+|S^s_{\mu\mu}|^2\right)$$

$\mathcal{A}^{\mu\mu}_{\Delta\Gamma_s}$ depends on $P^s_{\mu\mu} \equiv |P^s_{\mu\mu}|e^{i\varphi_P}$, $S^s_{\mu\mu} \equiv |S^s_{\mu\mu}|e^{i\varphi_S}$ and ϕ_s^{NP}

$$\mathcal{A}^{\mu\mu}_{\Delta\Gamma} = \frac{|P^s_{\mu\mu}|^2\cos(2\varphi_P - \phi_s^{\mathrm{NP}}) - |S^s_{\mu\mu}|^2\cos(2\varphi_S - \phi_s^{\mathrm{NP}})}{|P^s_{\mu\mu}|^2 + |S^s_{\mu\mu}|^2}$$

In SM

$P^{s,\mathrm{SM}}_{\mu\mu} = 1$

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Incl, $K\ell3$	$\bar{\mathcal{B}}(B_s \to \mu^+\mu^-) = (3.81 \pm 0.11) \times 10^{-9}$,
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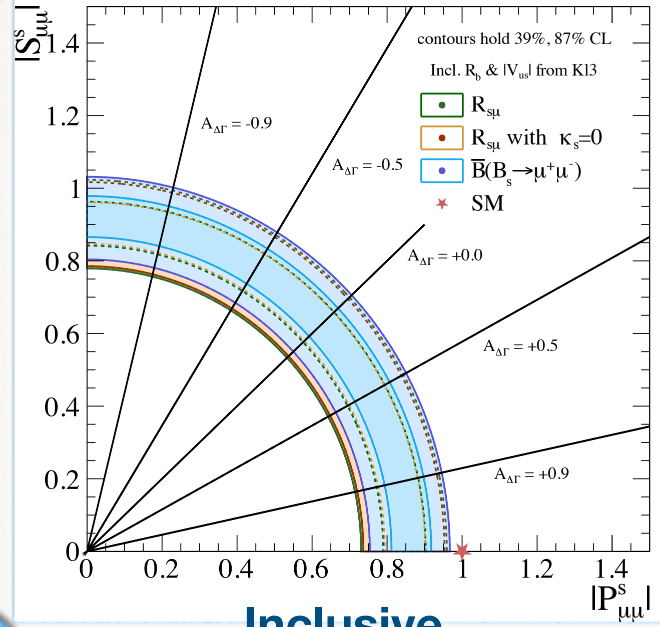

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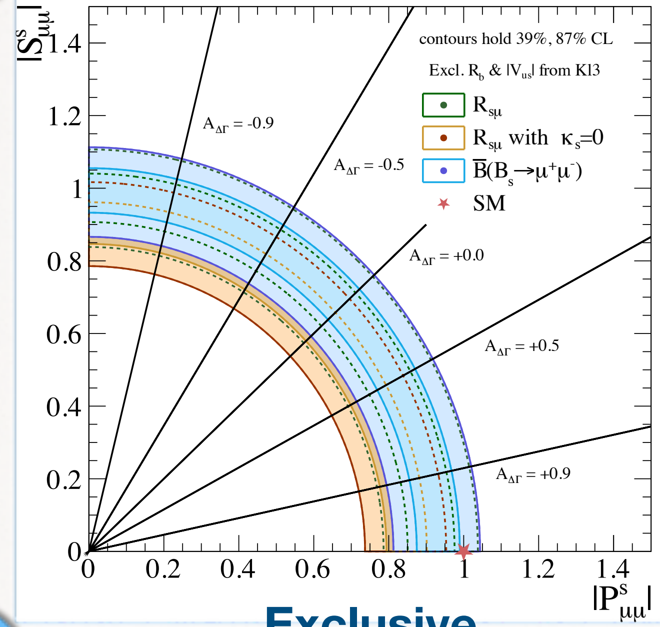

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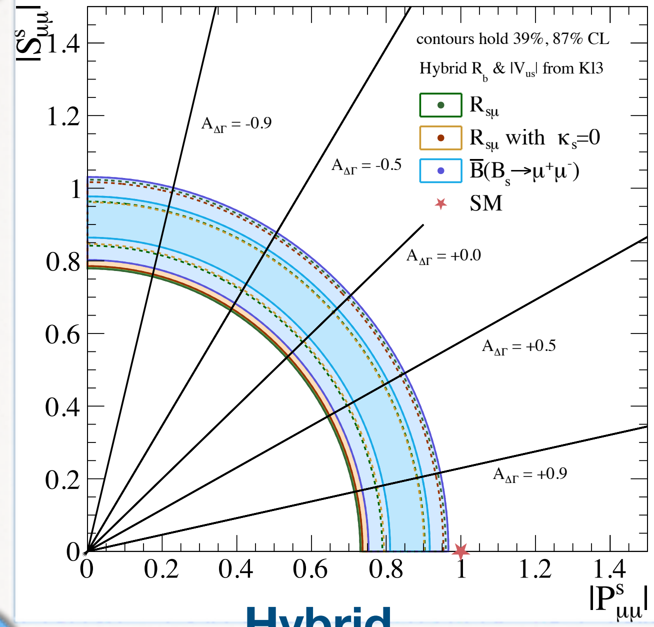


Hybrid

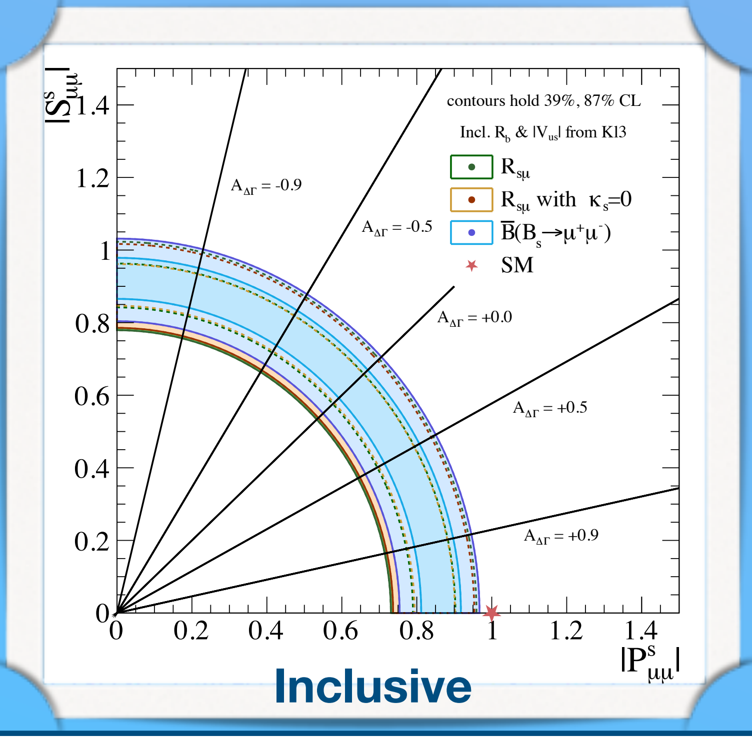
Comparing blue contours:
dependence of the NP searches with $B(B_s \to \mu^+\mu^-)$ on the CKM matrix element $|V_{cb}|$ and the UT apex

Determining NP in $B_s^0 \to \mu^+\mu^-$

NP can modify its branching ratio

(Pseudo-)Scalar

$B_s^0 - \bar{B}_s^0$ **mixing**



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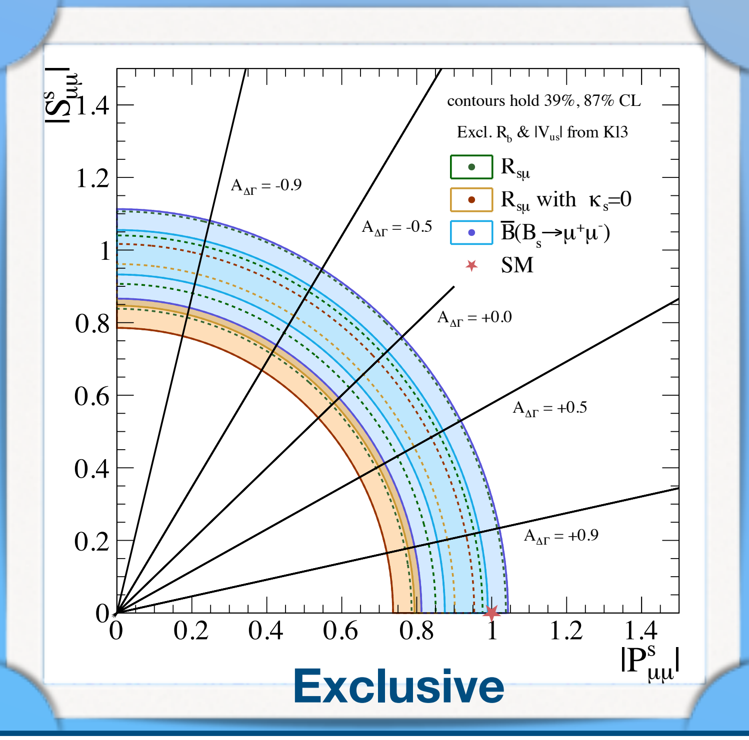

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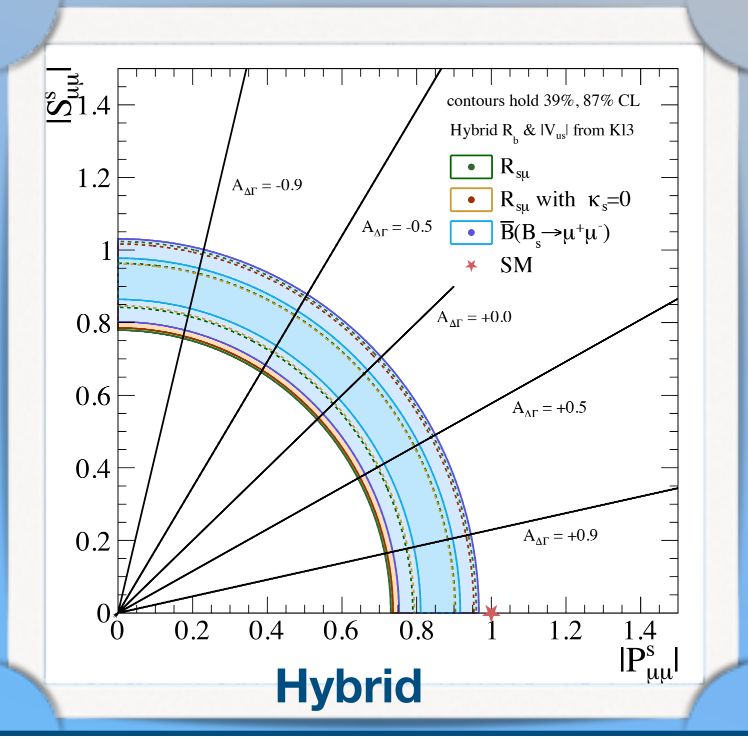


Hybrid

We can minimise this dependence, creating the following ratio $R_{s\mu}$

Determining NP in $B_s^0 \to \mu^+\mu^-$

arXiv:hep-ph/0303060
arXiv:2104.09521
arXiv:2109.11032

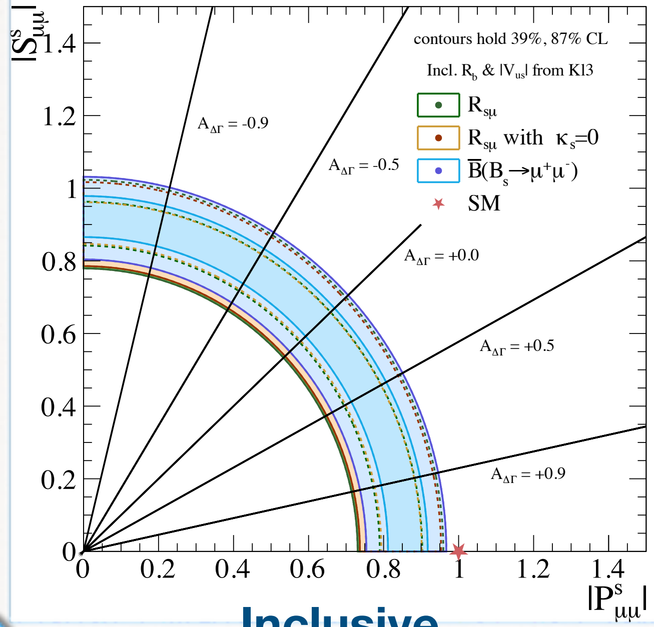
$$\mathcal{R}_{s\mu} \equiv \left|\frac{\bar{\mathcal{B}}(B_s \to \mu^+\mu^-)}{\Delta m_s}\right|$$

CKM elements drop out in the SM ratio

NP can modify its branching ratio

(Pseudo-)Scalar

$B_s^0 - \bar{B}_s^0$ **mixing**



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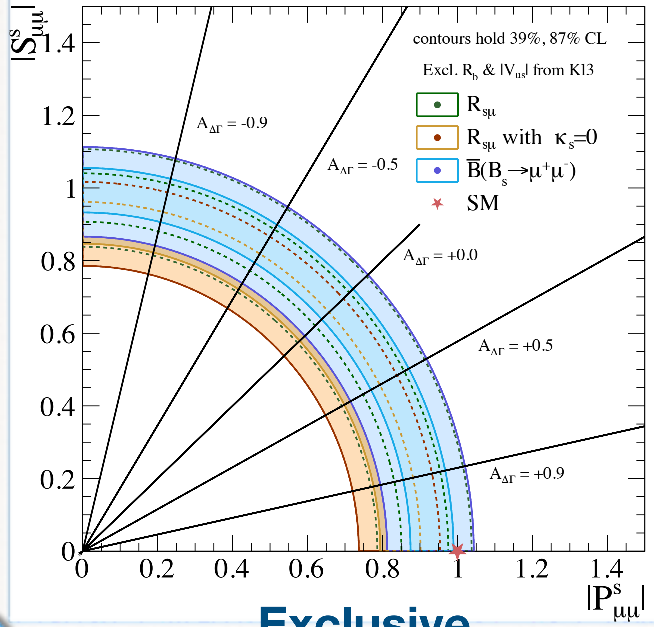

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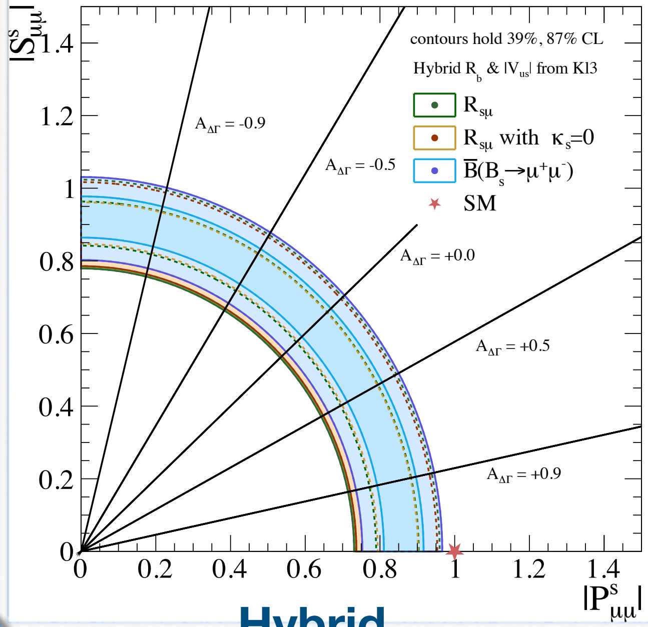

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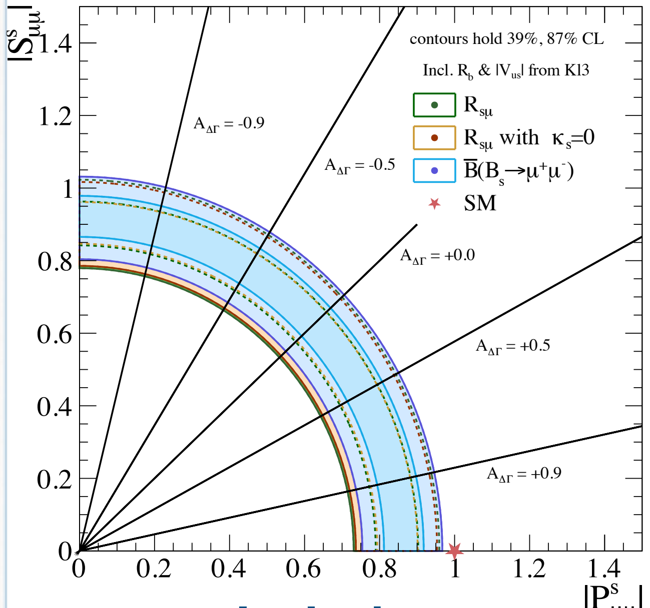
Including NP effects in both $B(B_s \to \mu^+\mu^-)$ and Δm_s we get the generalised expression

$$\mathcal{R}_{s\mu} = \mathcal{R}_{s\mu}^{\rm SM} \times \frac{1 + \mathcal{A}_{\Delta\Gamma_s}^{\mu\mu} y_s}{1 + y_s} \frac{|P_{\mu\mu}^s|^2 + |S_{\mu\mu}^s|^2}{\sqrt{1 + 2\kappa_s \cos\sigma_s + \kappa_s^2}} \, .$$

$$\mathcal{R}_{s\mu}^{\rm SM} = \frac{\tau_{B_s}}{1 - y_s} \frac{3 G_{\rm F}^2 m_W^2 \sin^4\theta_W}{4\pi^3} \frac{|C_{10}^{\rm SM}|^2}{S_0(x_t)\eta_{2B}\hat{B}_{B_s}} m_\mu^2 \sqrt{1 - 4\frac{m_\mu^2}{m_{B_s}^2}}$$

introduces a dependence on the CKM matrix elements through the NP parameters ($\varkappa_S$, σ_S)



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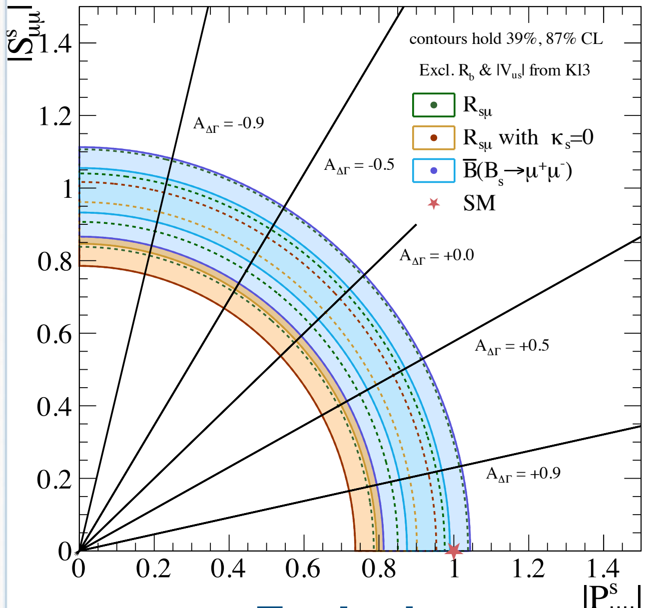

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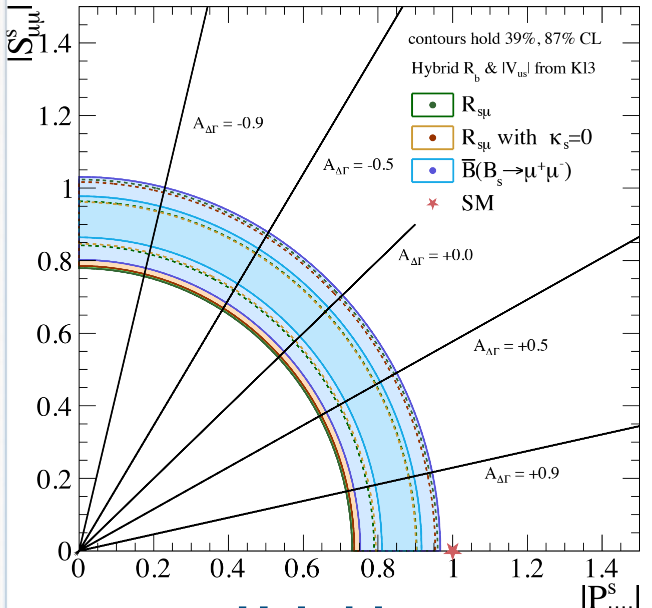

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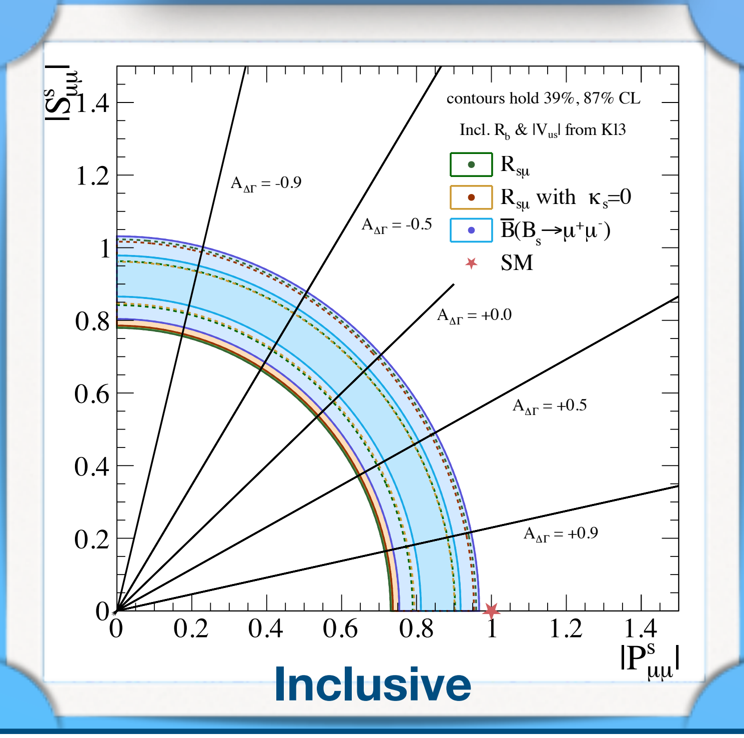
$$\mathcal{R}_{s\mu}^{\rm SM} = (2.22 \pm 0.10) \times 10^{-10}\ \rm ps$$

introduces a dependence on the CKM matrix elements through the NP parameters ($\varkappa_S$, σ_S)

$$\mathcal{R}_{s\mu} = (1.60 \pm 0.19) \times 10^{-10}$$

Comparing with the SM, we obtain extra contours



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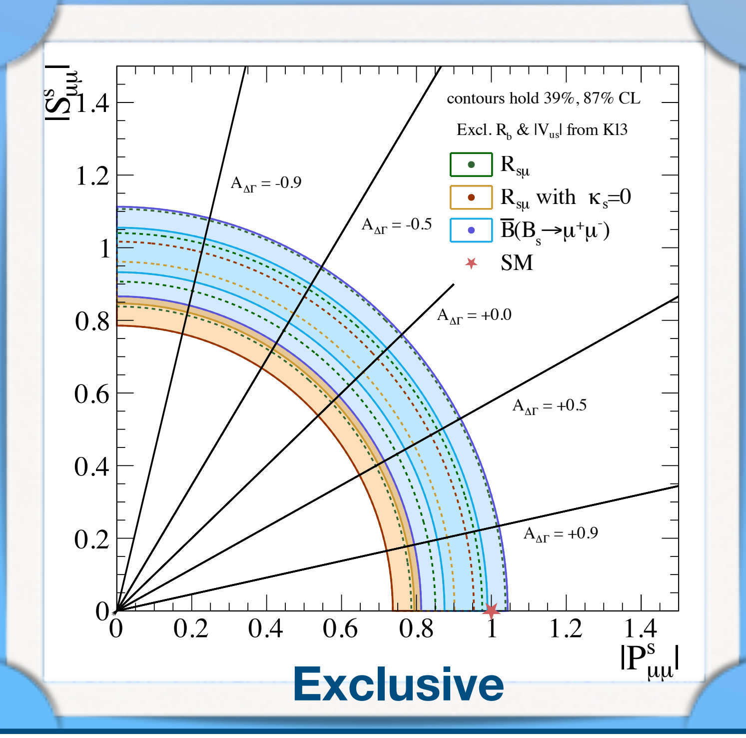

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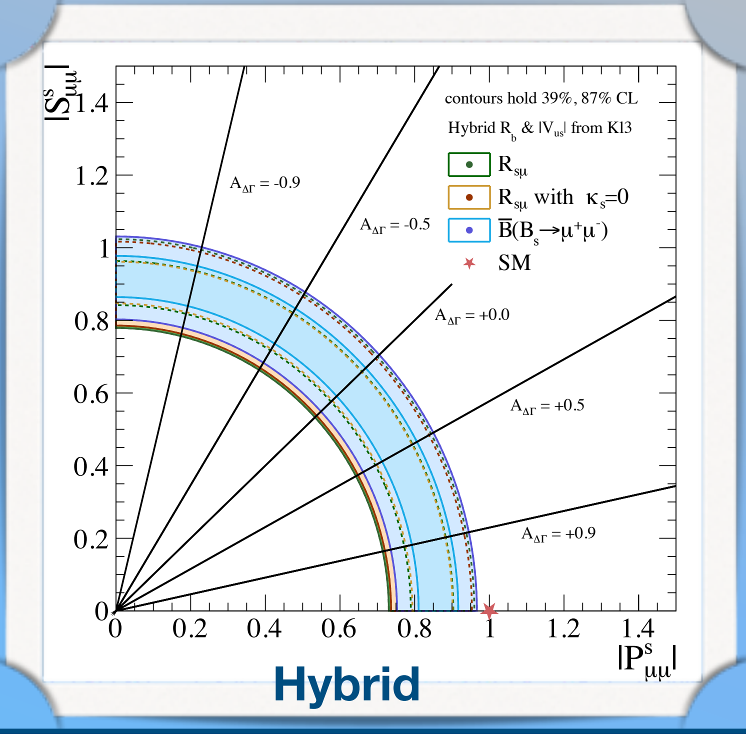

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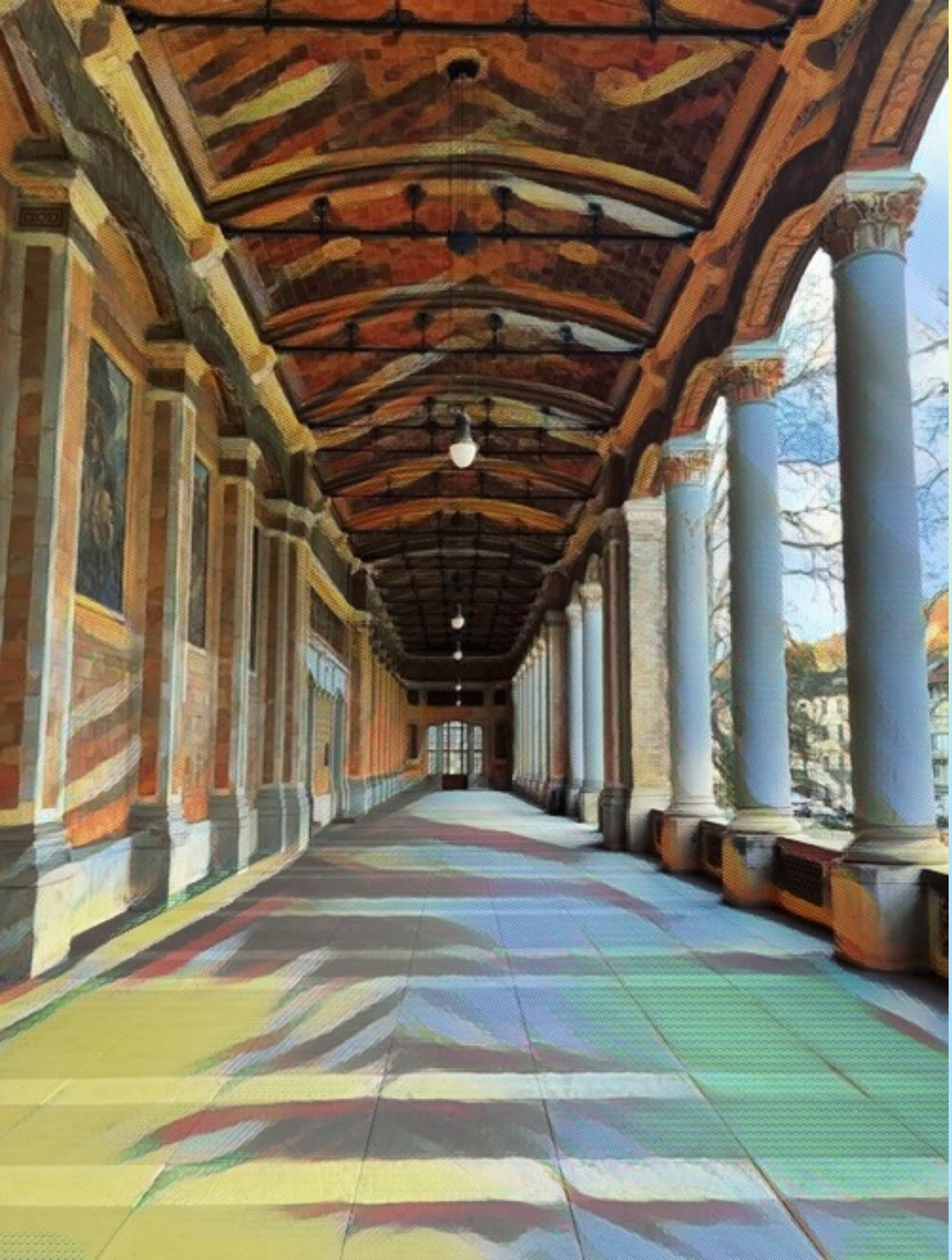

Future Prospects

∗Improved Precision on $\varkappa_q$ and σ_q

Assuming a hypothetical reduction of 50% in the uncertainty on the CKM matrix element $|V_{cb}|$, the lattice calculations, or the UT apex:

B_s-meson system:limited precision on $\varkappa_s$ and σ_s by lattice uncertainty

impact from improvements on the UT apex is negligible (especially for ϕ_s)

NP in the B_s-meson system are highly dependent on the assumptions made

exclusive scenario assuming a 50% improvement from lattice appears most exciting

B_d-meson system: improvements in UT apex & lattice: equally big impact

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*NP in γ

Improved precision on the input measurements: <u>discrepancies</u> between the two γ determinations

Averaging over both results would then no longer be justified - UT should be revisited

Independent info from additional observables: necessary to resolve the situation
Exciting new opportunities to search for NP,
both in γ itself and in $B_q^0 - \bar{B}_q^0$ mixing:strongly correlated with the coordinates of the UT apex.

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Hints of NP in $B_d^0 - \bar{B}_d^0$ mixing: less promising than the B_s-meson due to small $\varkappa_d$ we find with current data

∗NP in γ

Improved precision on the input measurements: discrepancies between the two γ determinations

Averaging over both results would then no longer be justified - UT should be revisited

Independent info from additional observables: necessary to resolve the situation
Exciting new opportunities to search for NP,
both in γ itself and in $B_q^0 - \bar{B}_q^0$ mixing:strongly correlated with the coordinates of the UT apex.

∗Opportunities for $B(B_q \rightarrow \mu^+\mu^-)$

1) Ratio of branching fractions between $B_d^0 \rightarrow \mu^+\mu^-$ and $B_s^0 \rightarrow \mu^+\mu^-$:alternative way to determine the UT side R_t
2) Another useful application for the ratio of branching fractions between $B_d^0 \rightarrow \mu^+\mu^-$ and $B_s^0 \rightarrow \mu^+\mu^-$

∗Improved Precision on $\varkappa_q$ and σ_q

Assuming a hypothetical reduction of 50% in the uncertainty on the CKM matrix element $|V_{cb}|$, the lattice calculations, or the UT apex:

B_s-meson system:limited precision on $\varkappa_s$ and σ_s by lattice uncertainty

impact from improvements on the UT apex is negligible (especially for ϕ_s)

NP in the B_s-meson system are highly dependent on the assumptions made

exclusive scenario assuming a 50% improvement from lattice appears most exciting

B_d-meson system: improvements in UT apex & lattice: equally big impact

NP in the B_d-meson system are highly dependent on the assumptions made

inclusive scenario assuming 50% improvement on UT apex stands out

Hints of NP in $B_d^0-\bar{B}_d^0$ mixing: less promising than the B_s-meson due to small $\varkappa_d$ we find with current data

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∗Opportunities for $B(B_q \to \mu^+\mu^-)$

1) Ratio of branching fractions between $B_d^0 \to \mu^+\mu$

2) Another useful application for the ratio of bran

$$U^{ds}_{\mu\mu} \equiv \sqrt{\frac{|P^d_{\mu\mu}|^2+|S^d_{\mu\mu}|^2}{|P^s_{\mu\mu}|^2+|S^s_{\mu\mu}|^2}},$$

$$= \left[\frac{\tau_{B_s}}{\tau_{B_d}}\frac{1-y_d^2}{1-y_s^2}\frac{1+\mathcal{A}^d_{\Delta\Gamma}y_d}{1+\mathcal{A}^s_{\Delta\Gamma}y_s}\frac{\sqrt{m^2_{B_s}-4m^2_\mu}}{\sqrt{m^2_{B_d}-4m^2_\mu}}\left(\frac{f_{B_s}}{f_{B_d}}\right)^2\left|\frac{V_{ts}}{V_{td}}\right|^2\frac{\bar{\mathcal{B}}(B_d\to\mu^+\mu^-)}{\bar{\mathcal{B}}(B_s\to\mu^+\mu^-)}\right]^{1/2}.$$

more powerful test of the SM, where $U^{ds}_{\mu\mu}=1$

Thank you!

Backup Slides

Scenario I

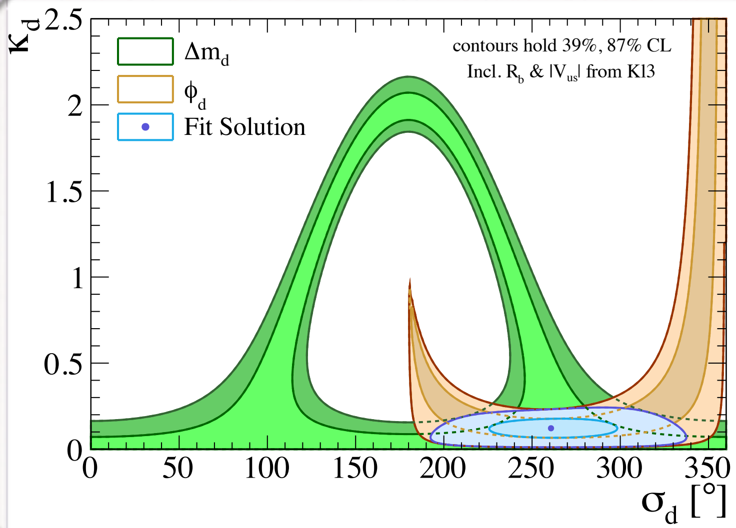
No NP in γ

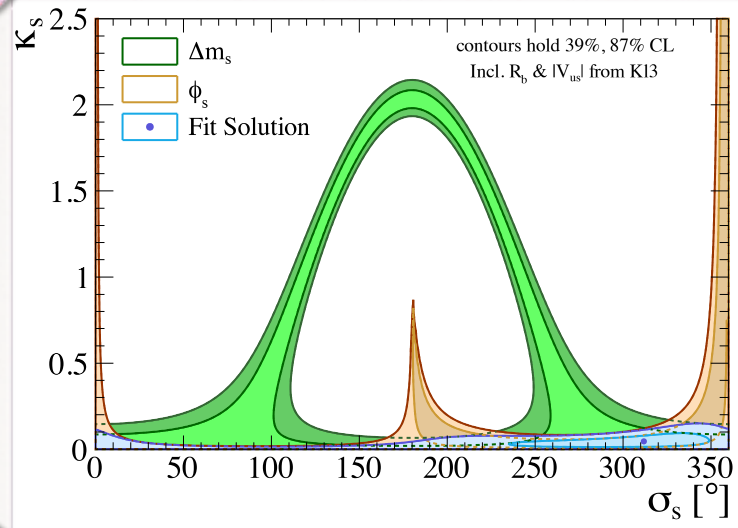
UT apex fit
R_b and γ

* Inclusive

$\kappa_d = 0.121^{+0.056}_{-0.055}$
$\kappa_s = 0.045^{+0.048}_{-0.033}$

$\sigma_d = \left(261^{+37}_{-35}\right)^{\circ}$
$\sigma_s = \left(312^{+37}_{-77}\right)^{\circ}$

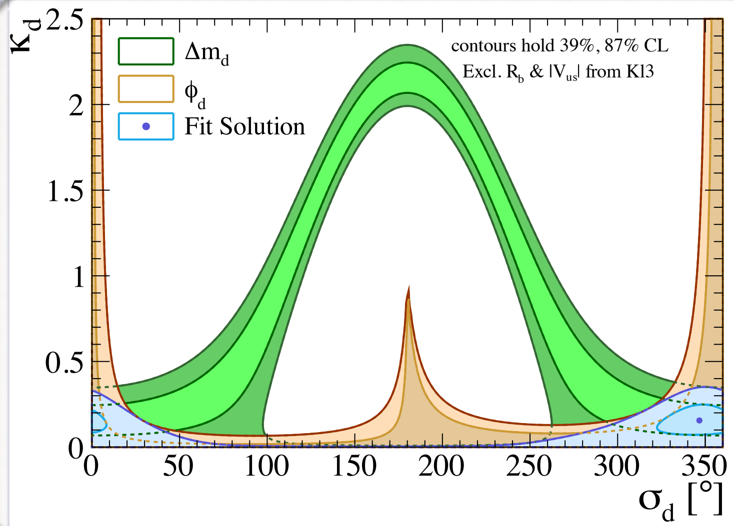


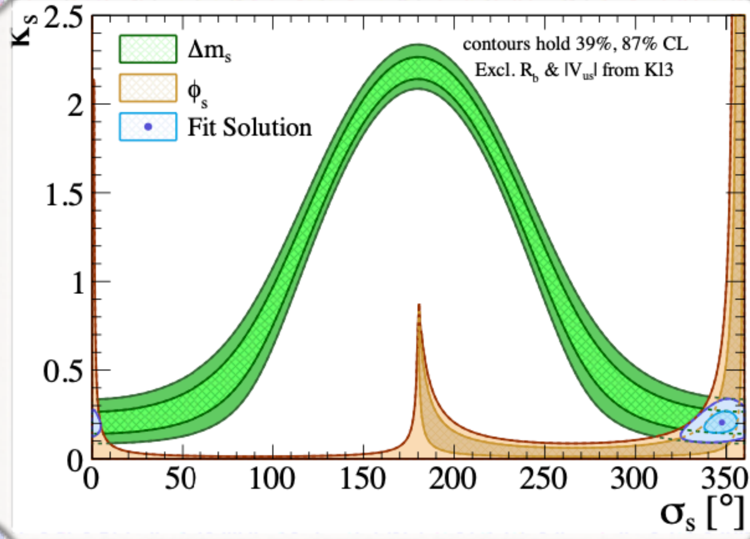


* Exclusive

$\kappa_d = 0.156^{+0.093}_{-0.084}$
$\kappa_s = 0.205^{+0.064}_{-0.059}$

$\sigma_d = \left(347^{+21}_{-25}\right)^{\circ}$,
$\sigma_s = \left(347.6^{+8.5}_{-9.8}\right)^{\circ}$

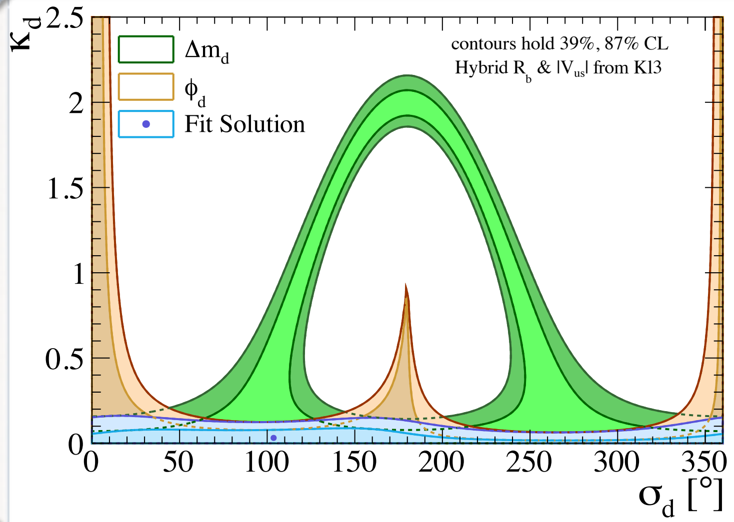


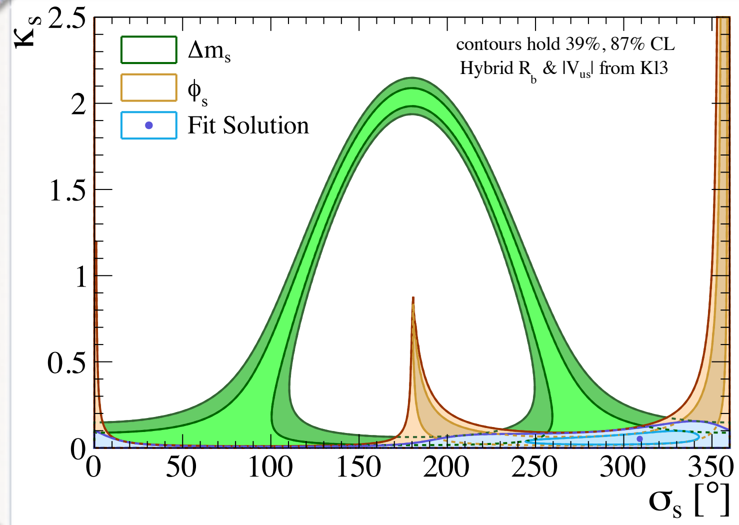


* Hybrid

$\kappa_d = 0.031^{+0.057}_{-0.031}$
$\kappa_s = 0.053^{+0.046}_{-0.034}$

$\sigma_d = \left(104^{+256}_{-104}\right)^{\circ}$
$\sigma_s = \left(309^{+34}_{-65}\right)^{\circ}$





Scenario II

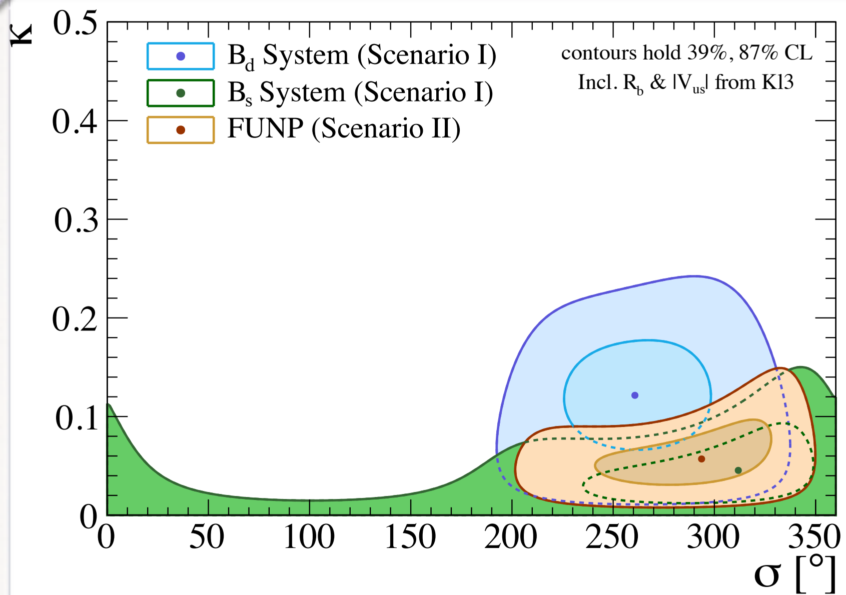
FUNP

UT apex fit
R_b and R_t

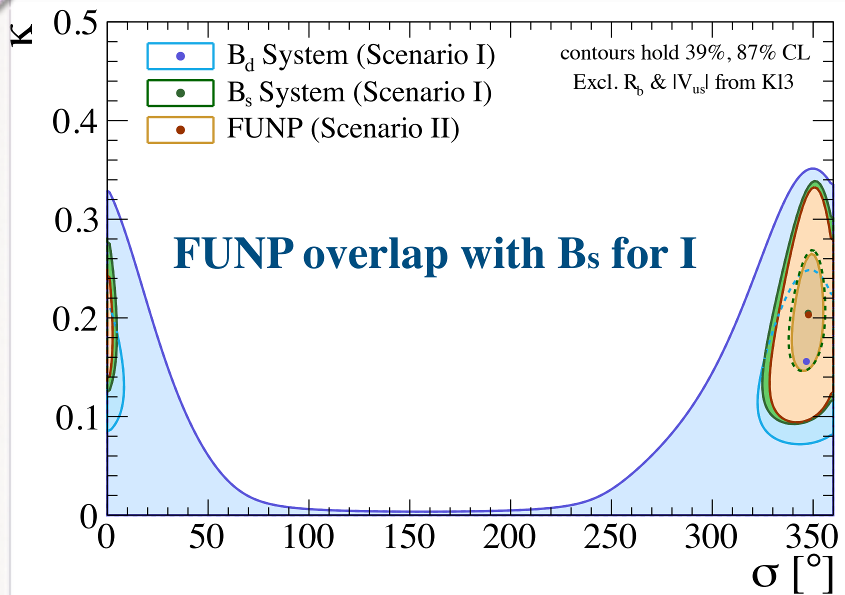
$$\kappa_d = \kappa_s \equiv \kappa$$
$$\sigma_d = \sigma_s \equiv \sigma$$

Incl, $K\ell 3$	$\kappa = 0.057^{+0.040}_{-0.026}$,	$\sigma = \left(294^{+34}_{-53}\right)^{\circ}$,
Excl, $K\ell 3$	$\kappa = 0.203^{+0.062}_{-0.057}$,	$\sigma = \left(347.7^{+7.4}_{-8.3}\right)^{\circ}$
Hybrid, $K\ell 3$	$\kappa = 0.043^{+0.049}_{-0.036}$,	$\sigma = \left(326^{+32}_{-90}\right)^{\circ}$.

NP effects drop out in the ratio $\Delta m_d/\Delta m_s$



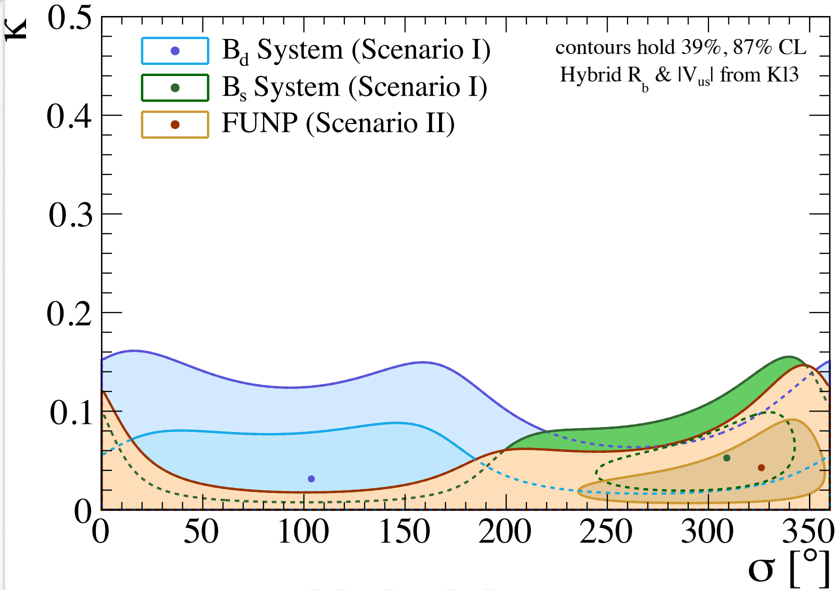
Inclusive



FUNP overlap with Bs for I

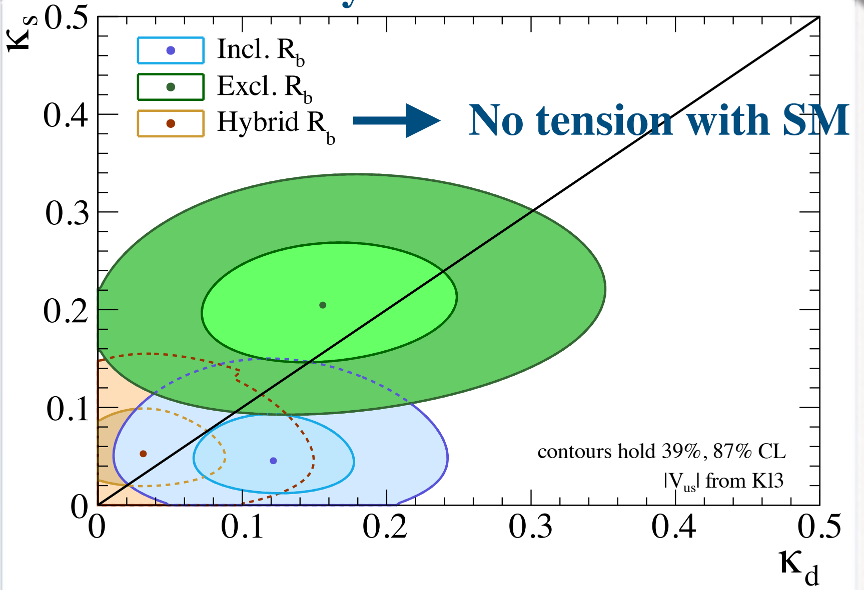
Exclusive

FUNP might not be a correct assumption but the solutions still overlap within the error margin



Hybrid

Comparison between the inclusive, exclusive and hybrid scenarios



No tension with SM

Scenario III

Partial FUNP

UT apex fit
R_b and R_t

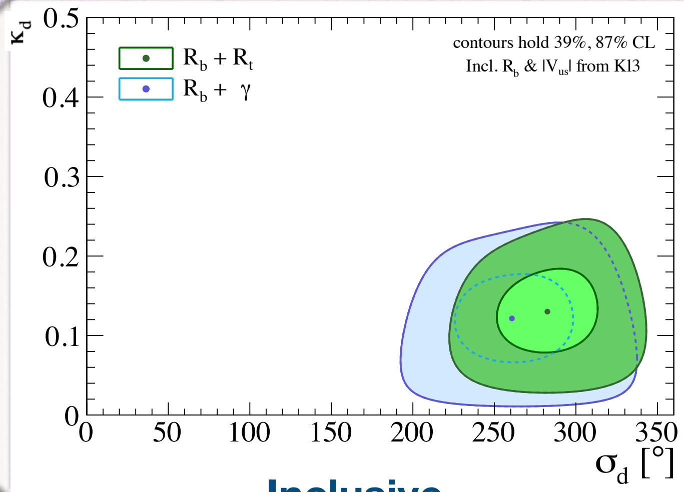
$(\kappa_d,\ \sigma_d)$ and $(\kappa_s,\ \sigma_s)$ separately utilising individual measurements of $\Delta m_d, \Delta m_s, \phi_d$ and ϕ_s.

✱ Inclusive

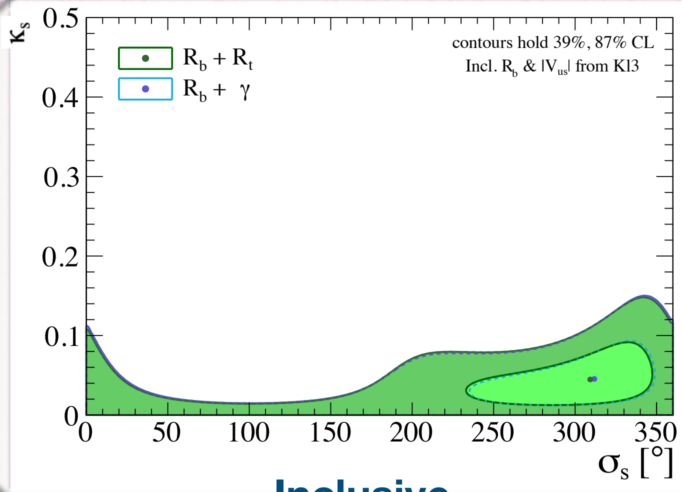
$\kappa_d = 0.130^{+0.054}_{-0.051}$
$\kappa_s = 0.045^{+0.047}_{-0.033}$

$\sigma_d = (282^{+31}_{-30})^\circ$
$\sigma_s = (309^{+38}_{-76})^\circ$

SM predictions and experimental inputs for NP fit in B_s : are identical for Scenario I & III
This is not the case for B_d



Inclusive



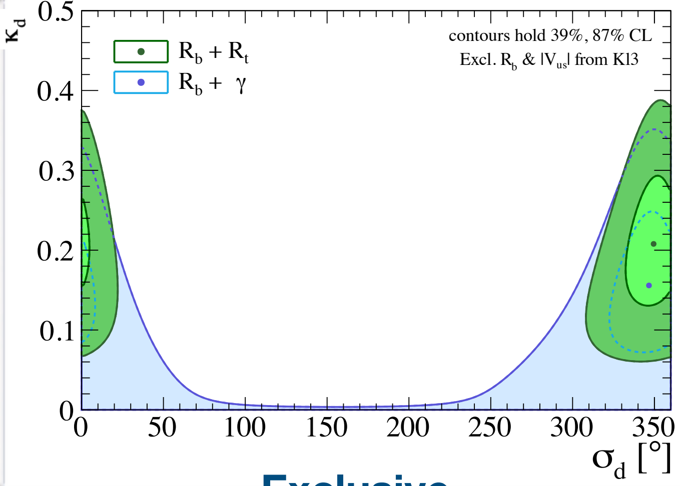
Inclusive

✱ Exclusive

$\kappa_d = 0.208^{+0.085}_{-0.078}$
$\kappa_s = 0.203^{+0.063}_{-0.059}$

$\sigma_d = (350^{+10}_{-18})^\circ$,
$\sigma_s = (347.2^{+8.6}_{-9.9})^\circ$

Similarly, comparing Scenario I & II: B_d and B_s statistically compatible but don't look the same



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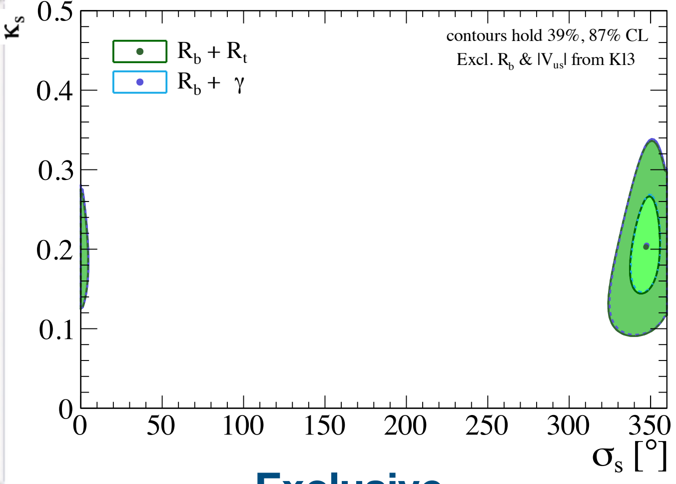
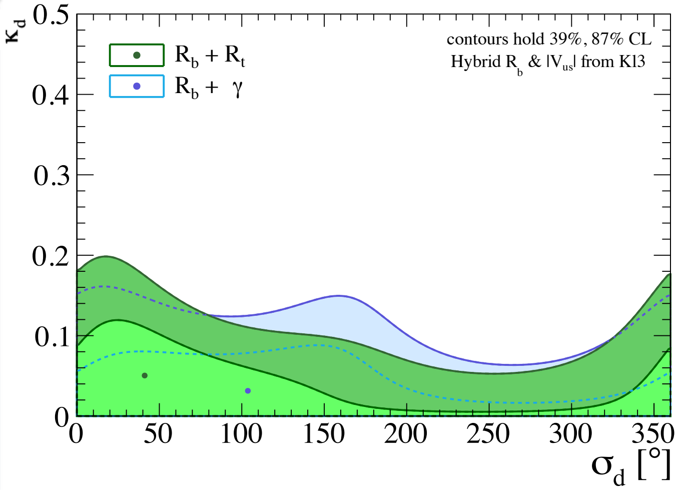


Exclusive

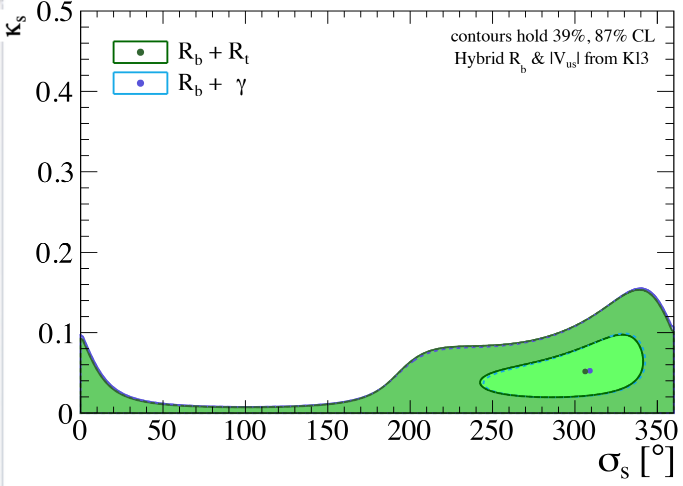
✱ Hybrid

$\kappa_d = 0.050^{+0.069}_{-0.050}$
$\kappa_s = 0.052^{+0.046}_{-0.032}$

$\sigma_d = (41^{+319}_{-41})^\circ$
$\sigma_s = (307^{+34}_{-65})^\circ$



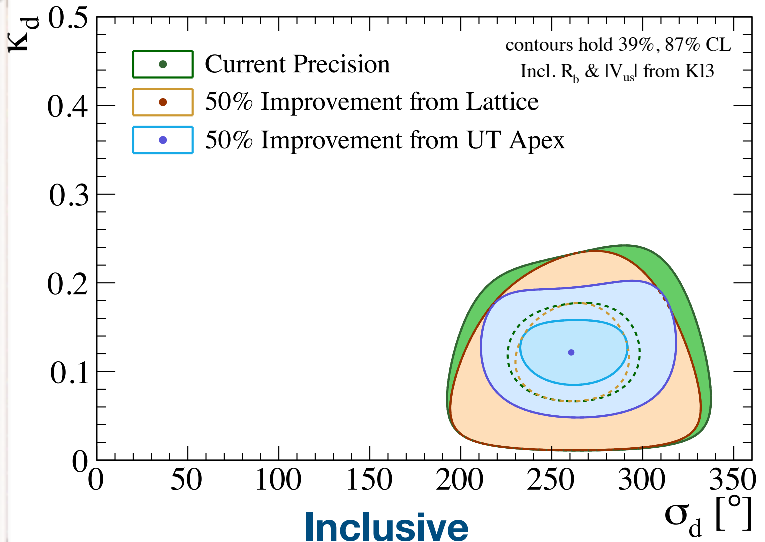
Hybrid



Hybrid

Improved Precision on $\varkappa_q$ and σ_q

Assuming a hypothetical reduction of 50% in the uncertainty on the CKM matrix element $|V_{cb}|$, the lattice calculations, or the UT apex



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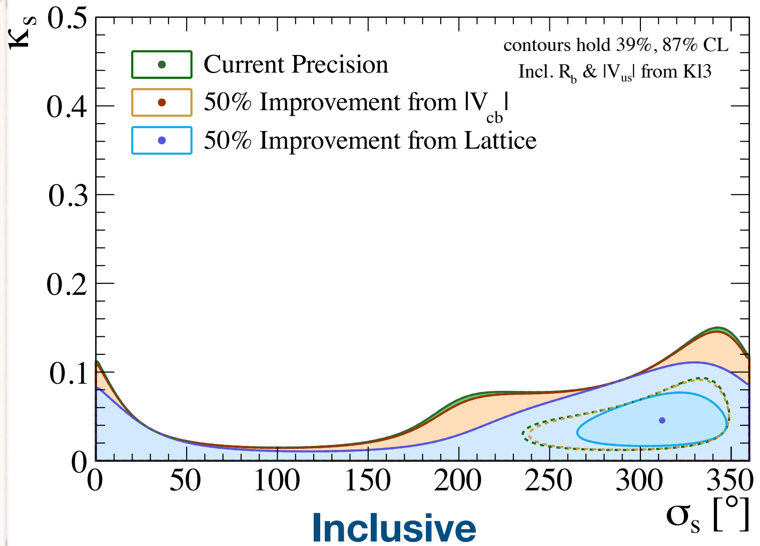

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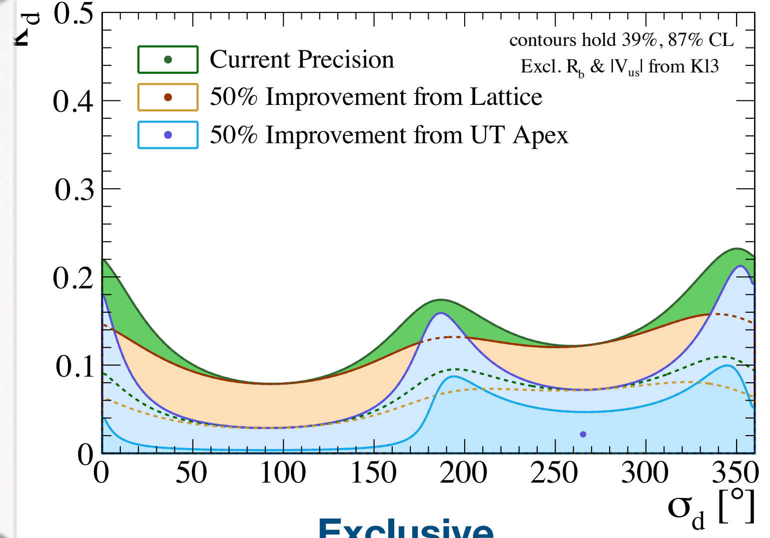

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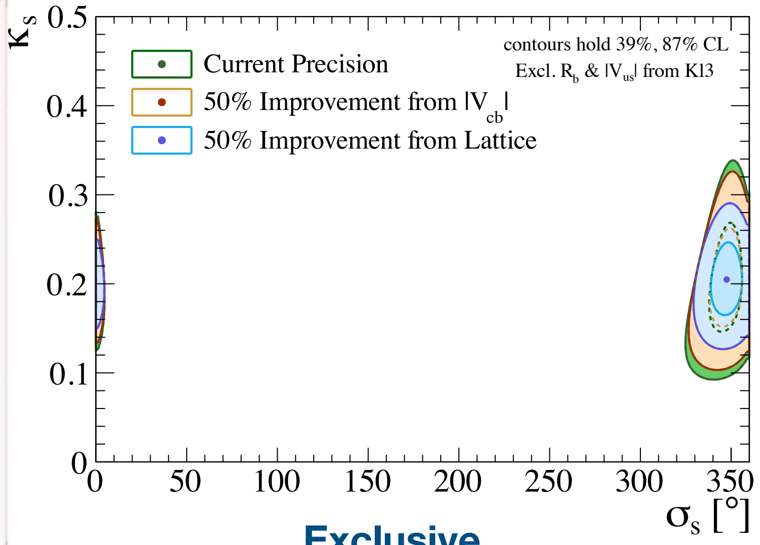

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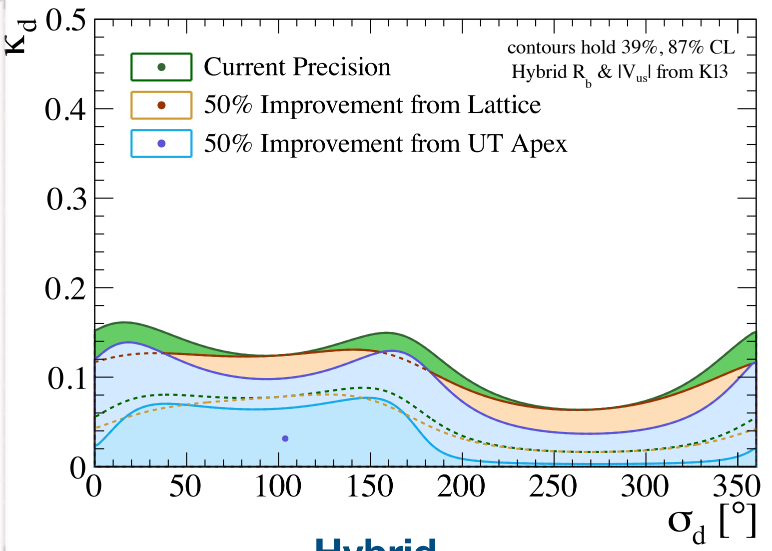

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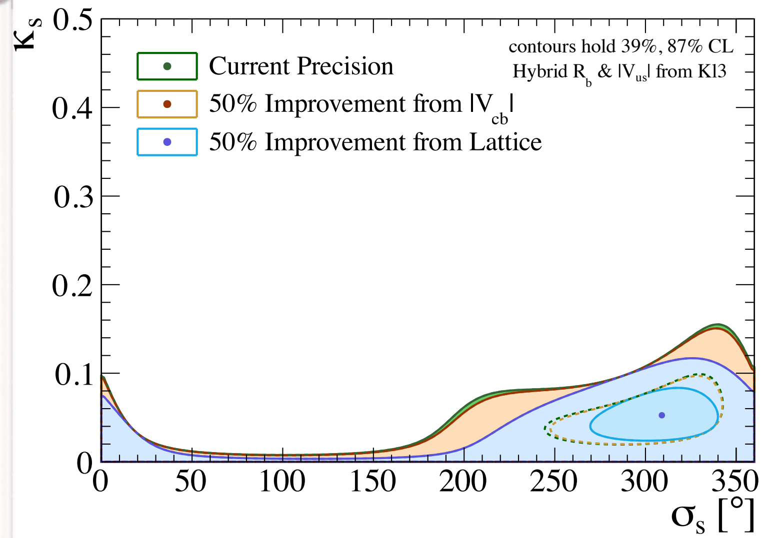

Hybrid

B_s-meson system:limited precision on $\varkappa_s$ and σ_s by lattice uncertainty

impact from improvements on the UT apex is negligible (especially for ϕ_s)

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B_d-meson system: improvements in UT apex & lattice: equally big impact

NP in the B_d-meson system are highly dependent on the assumptions made

inclusive scenario assuming 50% improvement on UT apex stands out

Hints of NP in $B_d^0 - \bar{B}_d^0$ mixing: with significance of more than 3σ

less promising than the B_s-meson due to small $\varkappa d$ we find with current data