Recent Results on Flavour Physics

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- *Outline*

✓ What is Flavour Physics?:

➲ CKM, Higgs → Flavour Physics

✓ What do we understand about New Physics so far?

➲ *Results from Babar, Belle, Tevatron & LHC*

✓ Future perspectives for New Physics via the Flavour Window

➲ $\Delta F=2$ processes: ϵ_K, ΔM_s → ***3σ tension sinβ vs*** $\boldsymbol{\epsilon_K}$

➲ $\Delta F=1$ processes: b → s modes from LHCb → ***4σ tension B → K(*)μμ,ee***

ConfXI, September 9th 2014 St Petersburg

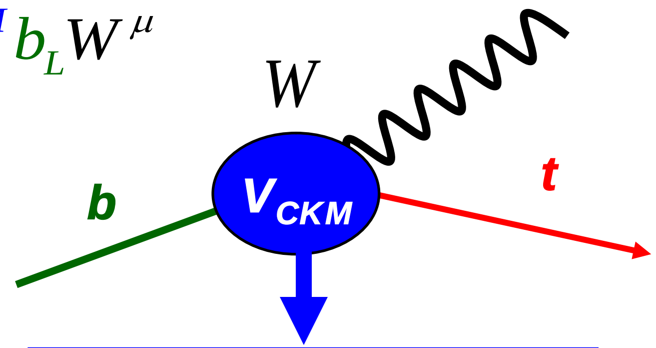
Introduction: *What is Flavour Physics?*

- **<u>Flavour Transitions</u>:**

  - **W interactions violate Flavour and CP: *complex 3x3 matrix* (CKM)**

$$\mathcal{L}_{int} = \bar{t}_L \gamma_\mu V^{CKM} b_L W^\mu$$

…



1937

β *decay:* $n \rightarrow p\, e^- \nu$

1964

$K \leftrightarrow \bar{K}$ *mixing*

$$V^{CKM} = \boxed{\begin{pmatrix} \begin{array}{c} V_{ud} \\ \pi \to l\nu \end{array} & \begin{array}{c} V_{us} \\ K \to \pi l\nu \end{array} & \begin{array}{c} V_{ub} \\ B \to \pi l\nu \end{array} \\ \begin{array}{c} V_{cd} \\ D \to \pi l\nu \\ D \to l\nu \end{array} & \begin{array}{c} V_{cs} \\ D \to K l\nu \\ D_s \to l\nu \end{array} & \begin{array}{c} V_{cb} \\ B \to D^{(*)} l\nu \\ \end{array} \\ \begin{array}{c} V_{td} \\ \langle B_d | \bar{B}_d \rangle \end{array} & \begin{array}{c} V_{ts} \\ \langle B_s | \bar{B}_s \rangle \end{array} & \begin{array}{c} V_{tb} \\ \end{array} \end{pmatrix}} \quad \textbf{(unitarity)}$$

$\rightarrow$ **3 angles and 1 Phase**

  - **Z interactions conserve Flavour and CP.**

Introduction: *What is Flavour Physics?*

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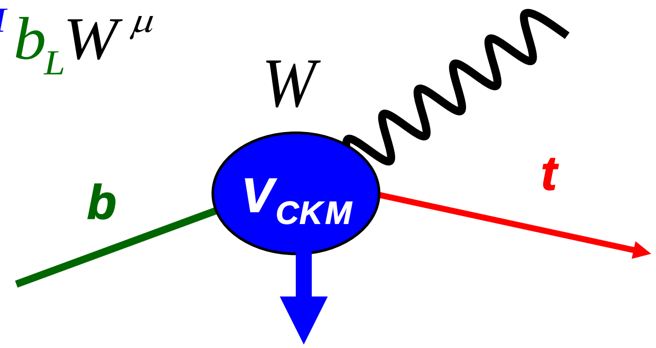
$$\ldots$$



But this is only macroscopic picture (phenomenogical couplings at low scales)

Introduction: *What is Flavour Physics?*

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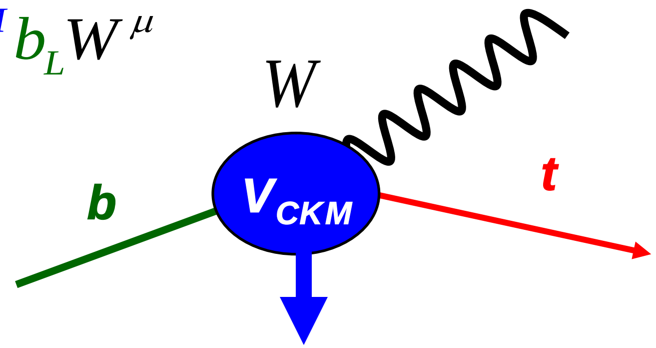


Microscopic picture ↔ Higgs mediator

1973

$$\mathcal{L}_{\text{int}} = \mathcal{L}_{gauge}(A_i, Q_i) + \bar{Q}_L Y_U U_R H + \bar{Q}_L Y_D D_R \tilde{H}$$

Higgs gives rise to CKM and Masses by Yukawa interactions

$$Y_U = V_{CKM}^\dagger \hat{M}_u \qquad V_{CKM}^\dagger V_{CKM} = 1 \qquad Y_D = \hat{M}_d$$

Flavour Physics Today

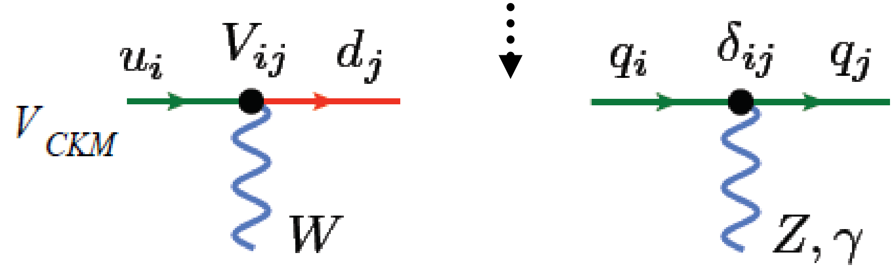
Thanks to modern experiments (*Babar, Belle, KLOE, NA48, Tevatron & LHC*) ,
the Yukawa interaction has been confirmed with high accuracy
as the dominant source of Flavour and CP violation at low energy.

$$\mathcal{L}_{SM} = \mathcal{L}_{gauge}(A_i, Q_i) + \overline{Q}_L Y_U U_R H + \overline{Q}_L Y_D D_R \tilde{H}$$

✓ Two of 9 unitarity relations of CKM, tested at percent level

1) $\boxed{|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1}$

2) $\boxed{V_{cd}V_{cb}^* + V_{ud}V_{ub}^* + V_{td}V_{tb}^* = 0}$



V: CKM matrix

δ: unit matrix

$$V_{CKM} = \begin{array}{c} \\ \\ \end{array} \begin{array}{cc} & \begin{array}{ccc} d & s & b \end{array} \\ & \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\bar{\rho}-i\bar{\eta}) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\bar{\rho}-i\bar{\eta}) & -A\lambda^2 & 1 \end{pmatrix} \begin{array}{c} u \\ c \\ t \end{array} \end{array}$$

$V_{us} = \lambda, \quad V_{cb} = A\lambda^2$

✓ Only 4 parameters V_{us}, V_{cb}, ρ and η, control a large set of Flavour observables to a high accuracy!

✓ Only 1 parameter η controls CP violation!

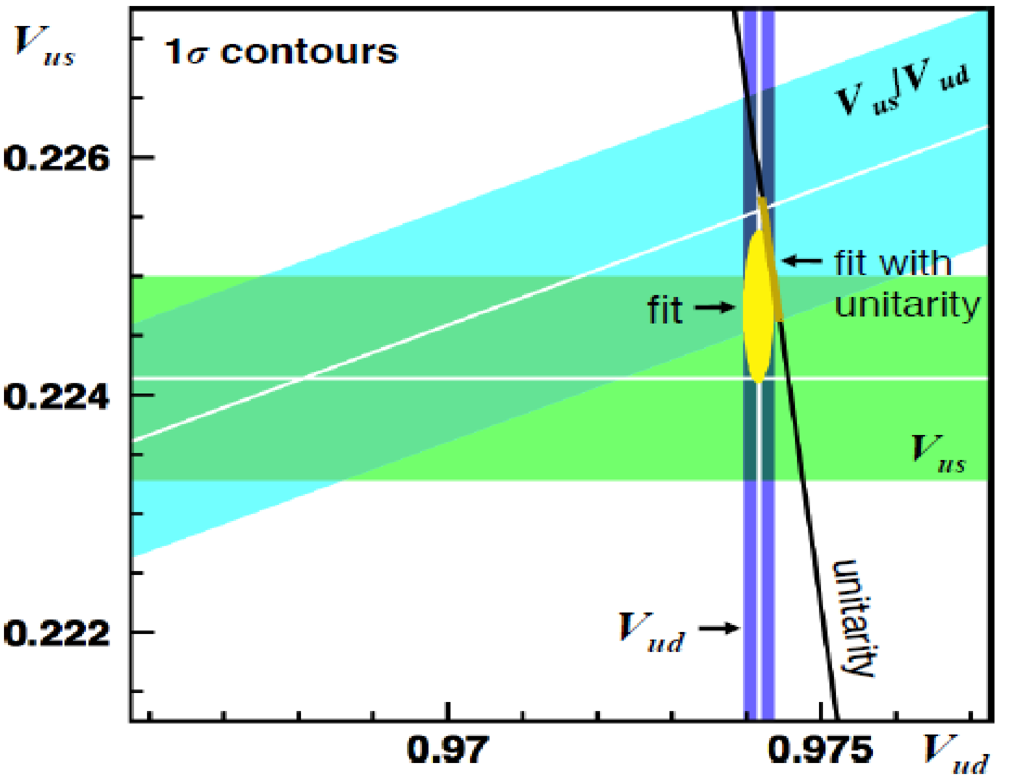
V_{us} and V_{ud} - unitarity test $\left(V_{CKM}^{\dagger}V_{CKM}\right)_{uu} \equiv |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$

$$\boxed{|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 - 1 = -0.0005(5)}$$

- $|V_{ud}|$ from β nuclear decays
- $|V_{us}|$ from $K \to \pi l \nu$ decays
- $|V_{us}|/|V_{ud}|$ from $K \to \mu\nu$ decays

❖ 1 angle to fit 3 measurements

❖ lattice inputs, f_K/f_π & $f_+(0)$, @0.4%



Fit results, no constraint:

$|V_{ud}|$= 0.97416(21)
$|V_{us}|$= 0.2248(7)
Δ_{CKM} = -0.0005(5)

Fit results, unitarity constraint:

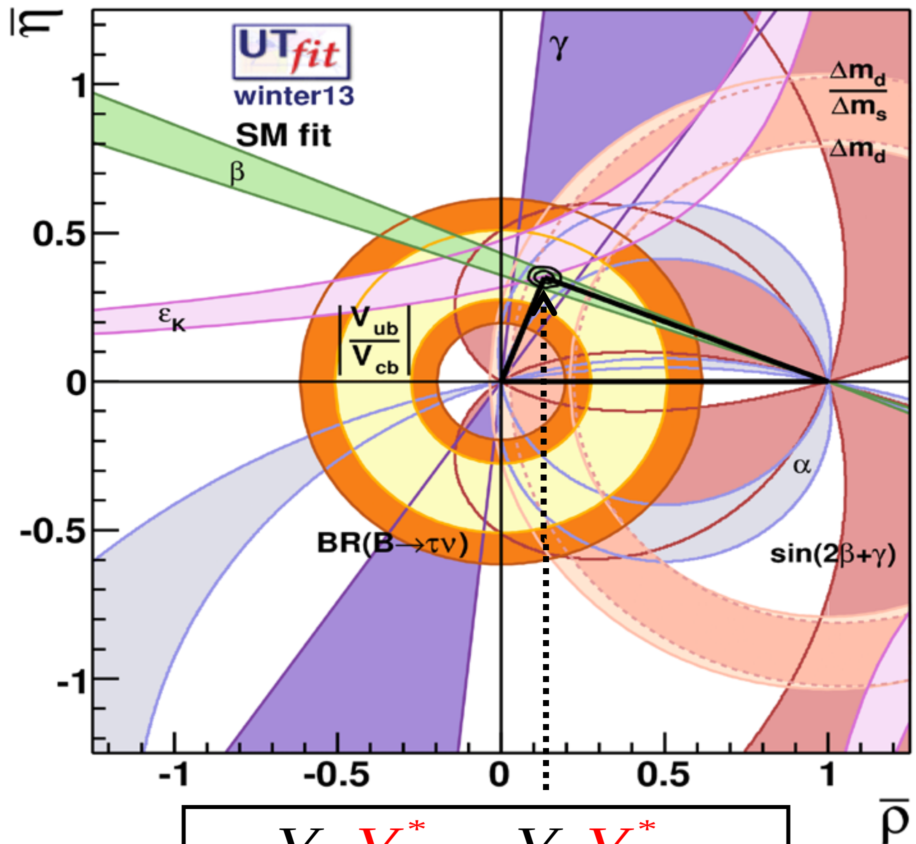
$|V_{ud}| = \cos\theta_c$ =0.97432(12)
$|V_{us}| = \sin\theta_c$ = 0.2251(5)

Yesterday @PII-LQ, em corr. by Martinelli & Szabo

See FLAG13, 1310.8555, for last results

Unitarity triangle Analysis: $\left(V_{CKM}V_{CKM}^{\dagger}\right)_{db} \equiv V_{cd}V_{cb}^{*}+V_{ud}V_{ub}^{*}+V_{td}V_{tb}^{*}=0$

see also results by CKMfiter and Laiho, E. Lunghi & R. Van de Water



$$1+\frac{V_{ud}V_{ub}^{*}}{V_{cd}V_{cb}^{*}}+\frac{V_{td}V_{tb}^{*}}{V_{cd}V_{cb}^{*}}=0$$

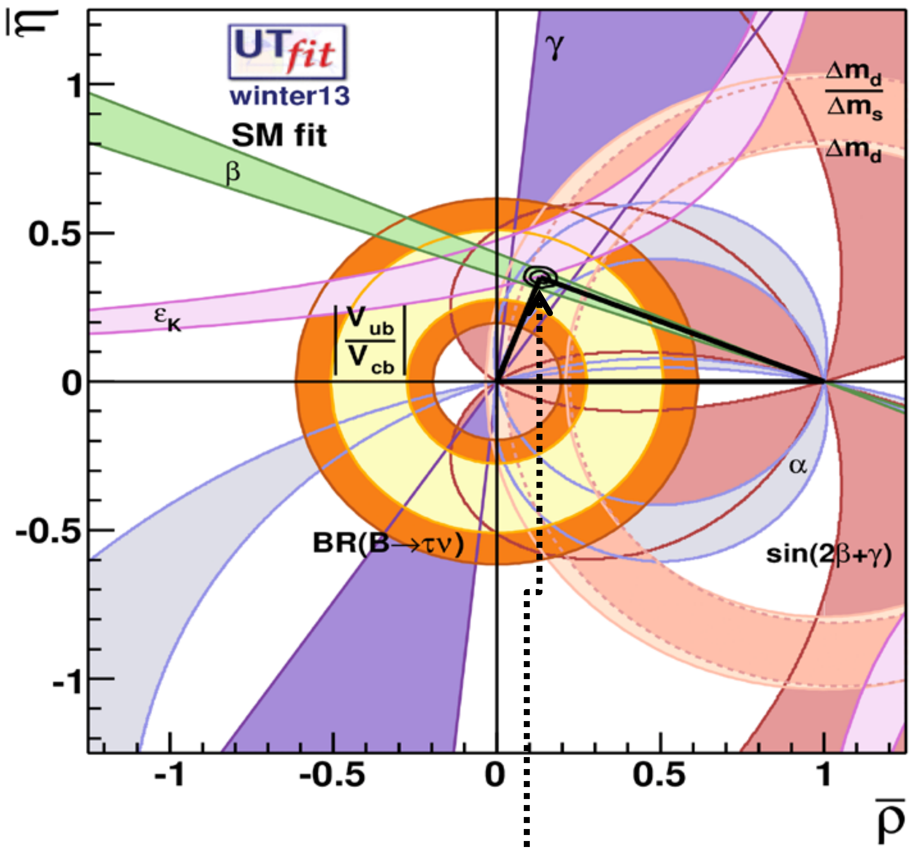
$$V_{cd}V_{cb}^{*}+V_{ud}V_{ub}^{*}+V_{td}V_{tb}^{*}=0$$

All exp. band overlap in a common area

$$\frac{V_{ud}V_{ub}^{*}}{V_{cd}V_{cb}^{*}} \approx \sqrt{\bar{\rho}^2+\bar{\eta}^2}$$

$$\frac{V_{td}V_{tb}^{*}}{V_{cd}V_{cb}^{*}} \approx \sqrt{\left(1-\bar{\rho}\right)^2+\bar{\eta}^2}$$

Unitarity triangle Analysis: $\left(V_{CKM}V_{CKM}^{\dagger}\right)_{db} \equiv V_{cd}V_{cb}^{*} + V_{ud}V_{ub}^{*} + V_{td}V_{tb}^{*} = 0$



$\bar{\rho} = 0.139 \pm 0.021 \rightarrow 15\%$

$\bar{\eta} = 0.352 \pm 0.016 \rightarrow 4.5\%$

4 CKM parameters to fit more than 11 measurements

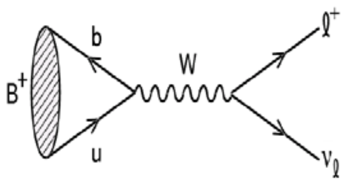
$|V_{ud}|, \ |V_{us}|, \ |V_{cb}|, \ |V_{ub}|_{SL} \quad B \to \tau\nu$

$\Delta m_d, \Delta m_s, \epsilon_K$

$\alpha, \sin 2\beta, \gamma$

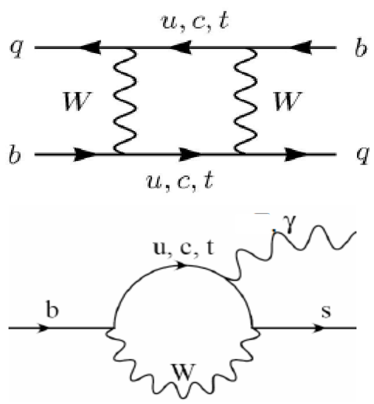
Unitarity triangle Analysis: closer look

I. *Remarkable consistency between tree-level processes*

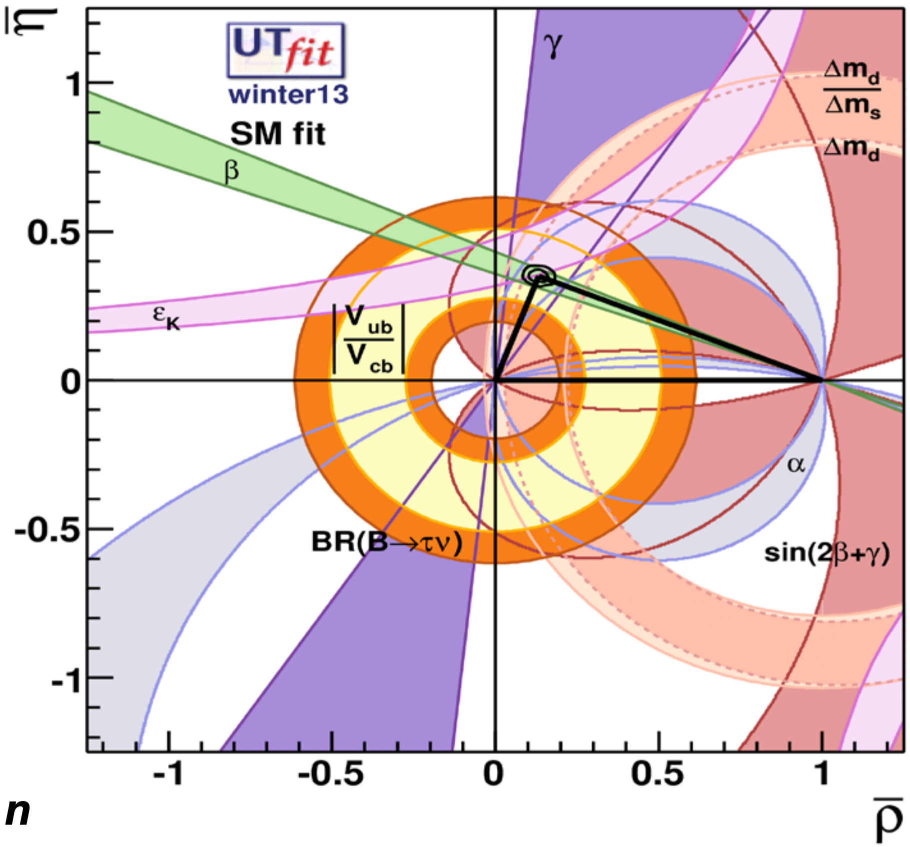


γ, α, V_{ub}, V_{cb}

and loop induced observables (FCNC)



$\sin(2\beta)$, Δm_{ds}, ε_K, b->sγ …

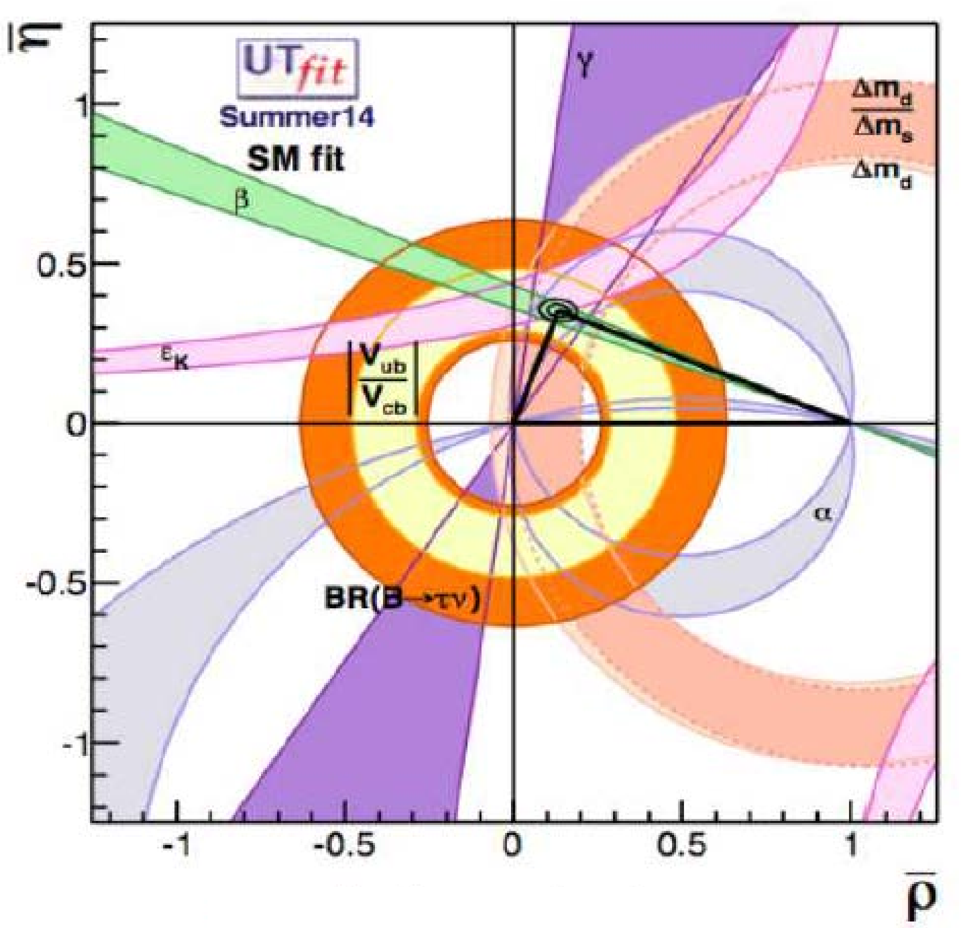


II. *Remarkable consistency between CPC and CPV observables*

Δm_{ds}, ε_K

$$\boxed{V_{cd}V_{cb}^{*} + V_{ud}V_{ub}^{*} + V_{td}V_{tb}^{*} = 0}$$

What's Next?



❖ *Despite all its successes, the SM is likely to be an effective theory,*
the low-energy limit of a more fundamental theory, with new degrees of freedom above the electroweak scale

What's Next?

❖ *Despite all its successes, the SM is likely to be an effective theory,* the low-energy limit of a more fundamental theory, with new degrees of freedom above the electroweak scale.

Already many hints for physics beyond SM:

☹ gravity, 😐neutrino oscillations,

☺dark matter, ☺matter/anti-matter asymmetries

no clear clues to NP model ***but n.o.f at high scale looks necessary!***

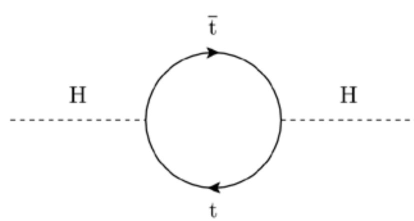
Moreover, open questions within Flavour dynamics itself

➢ What is the origin of Yukawa couplings in the SM?

→ new degrees of freedom at unification scale 10^{15} TeV, M_{planck}?

Yukawa int.: *large loop corrections to the higgs mass* → **NP** *at O(***1** TeV*)*?

$$m_H^2 \propto$$

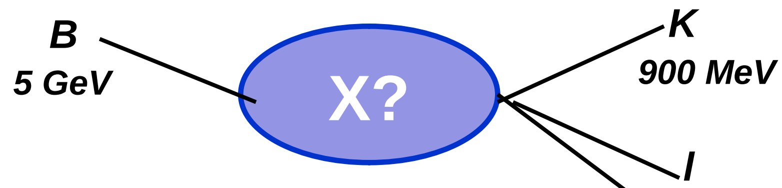


$$= y_{top} \frac{\Lambda^2_{cutoff}}{16\pi^2} \log \frac{\Lambda^2_{cutoff}}{m^2_{top}}$$

What's Next?

❖ *Despite all its successes, the SM is likely to be an effective theory,* the low-energy limit of a more fundamental theory, with new degrees of freedom above the electroweak scale

Potential new degrees of freedom can modify Flavour decays through quantum fluctuations



Quantum Fluctuation

(sensitive to Λ>>5 GeV)

twofold role of Flavour physics in the LHC era

Identify BSM mechanism of Flavour-breaking

Probe physics at energy scale not accessible at LHC

Are the Yukawa couplings the only source of Flavour?

Twofold role of Flavour for BSM - Example ϵ_K and SUSY

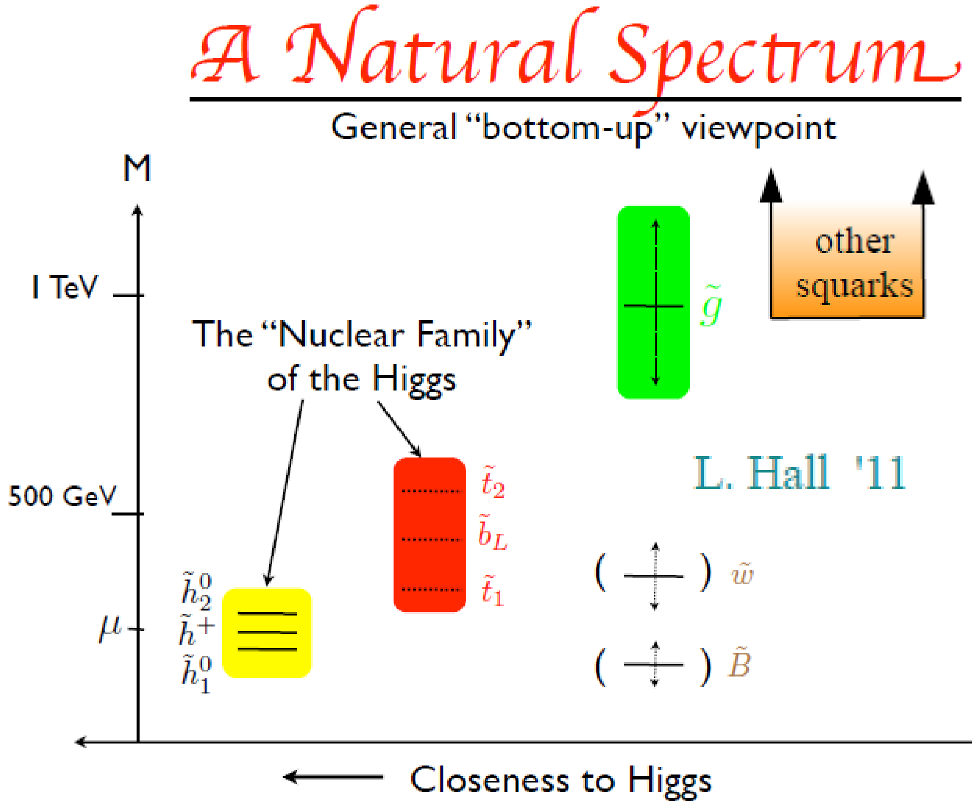
- **NATURAL SUSY Constraints from ϵ_K:** **[Mescia, Virto, 1208.0533]**

i. *1^{st} & 2^{nd} gen. squarks has to be heavy to escape current LHC bounds*

ii. *But stop, sbottom and Higgsinos need to be light to avoid tuning in m_h*

NATURAL SUSY:

- *non-trivial flavour spectrum: 3^{rd} gen. of squarks lighter than others*



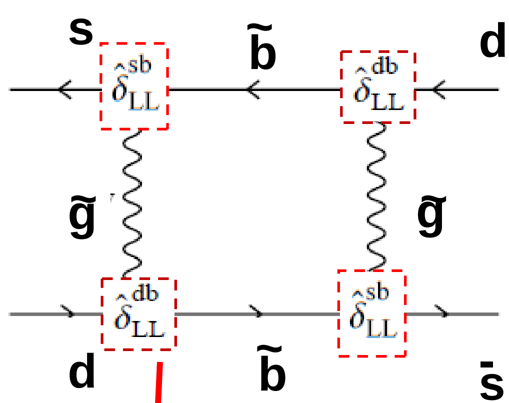
Dimopulos, Giudice 95
Cohen, Kaplan, Nelson 96'

ϵ_K mediated by 3^{rd} generations of squarks!!

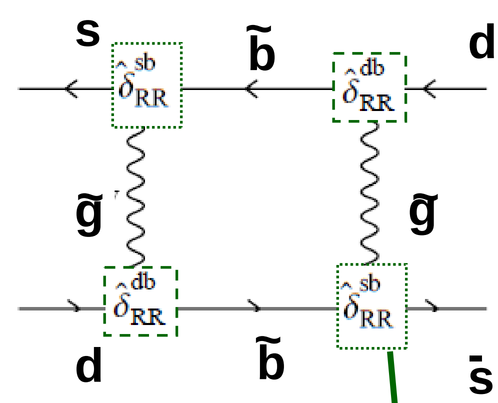
Twofold role of Flavour for BSM - Example ϵ_K and SUSY

- **NATURAL SUSY Constraints from ϵ_K:** **[Mescia, Virto, 1208.0533]**

$\epsilon_K \sim \epsilon_K^{SM}$ +



+



$\boxed{\hat{\delta}_{LL}} \rightarrow$ *New sources of Flavour-breaking on SUSY* $\leftarrow \boxed{\hat{\delta}_{RR}}$

Two scenarios and the twofold role of Flavour:

$\hat{\delta}_{LL} = \hat{\delta}_{RR} \sim$ CKM **1**

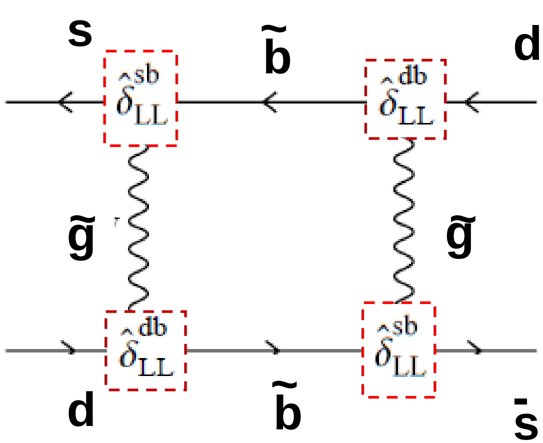
$\hat{\delta}_{LL} \sim$ CKM, $\hat{\delta}_{RR} = 0$ **2**

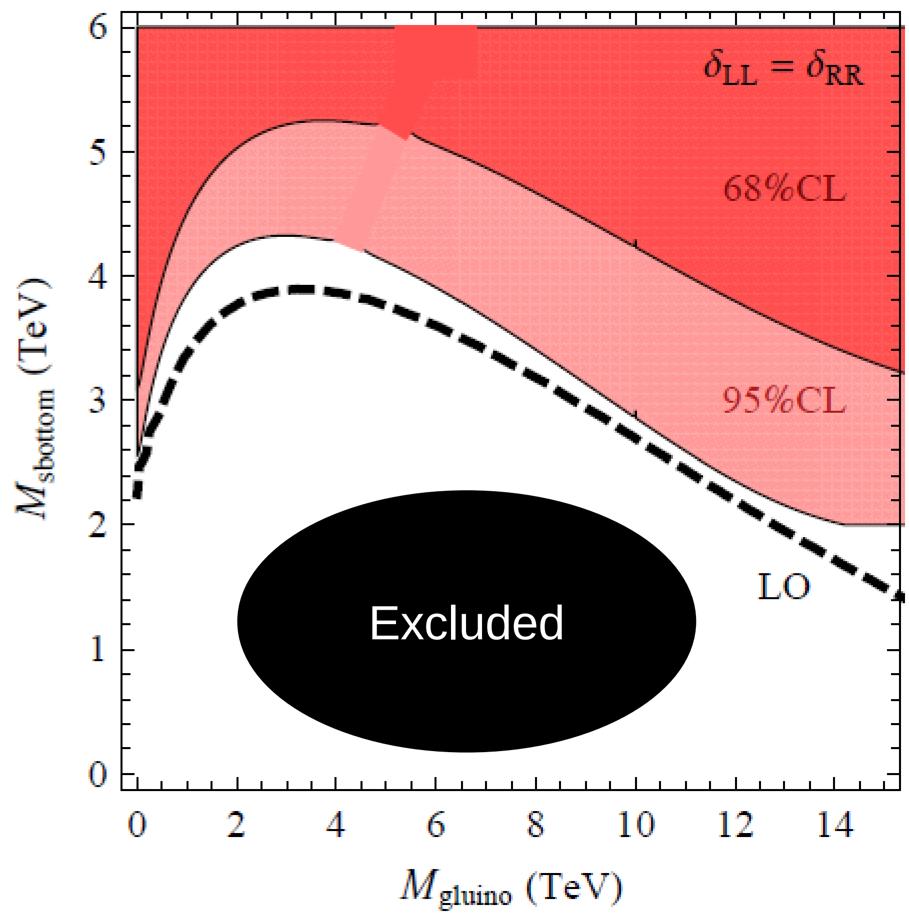
Twofold role of Flavour for BSM - Example ϵ_K and SUSY

- **NATURAL SUSY Constraints from ϵ_K:** **[Mescia, Virto, 1208.0533]**

$$\boxed{\hat{\delta}_{LL} = \hat{\delta}_{RR} \sim \text{CKM}}$$

$\epsilon_K \sim$





The twofold role of Flavour

1

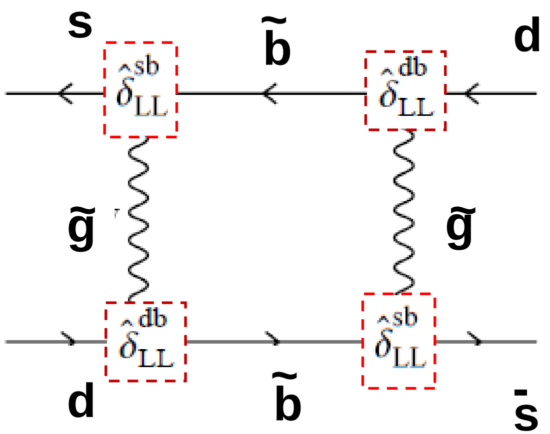
Natural SUSY hypothesis ($m_{sbottom}$<1 TeV) ?
built in to pass LHC searches excluded by Flavour breaking 1

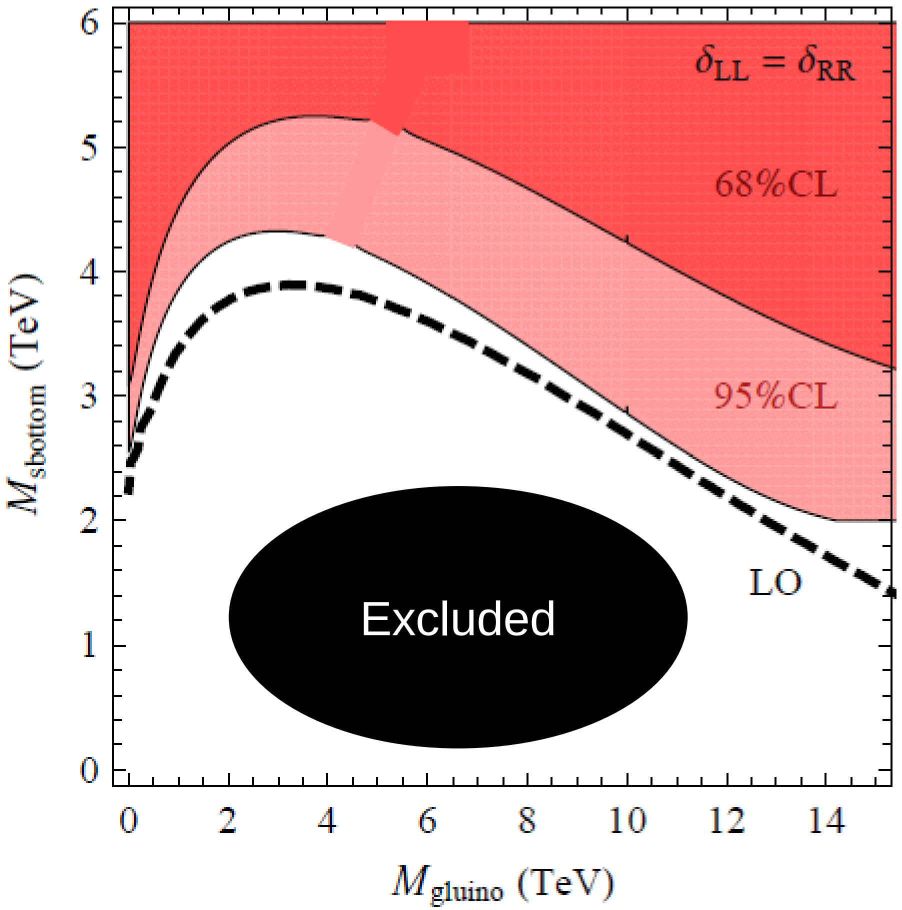
Twofold role of Flavour for BSM - Example ϵ_K and SUSY

- **NATURAL SUSY Constraints from ϵ_K:** **[Mescia, Virto, 1208.0533]**

$$\boxed{\hat{\delta}_{LL} = \hat{\delta}_{RR} \sim \text{CKM}}$$

ϵ_K ~





Powerful role of Flavour

1

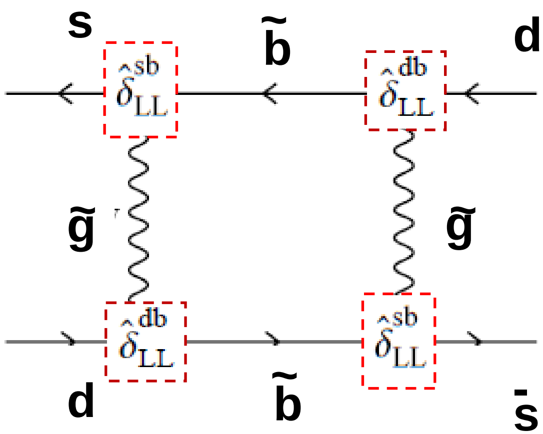
NP too heavy and not directly accessible at LHC: $m_{sbottom}$>3 TeV
– but still accessible by Flavour observables through loops –

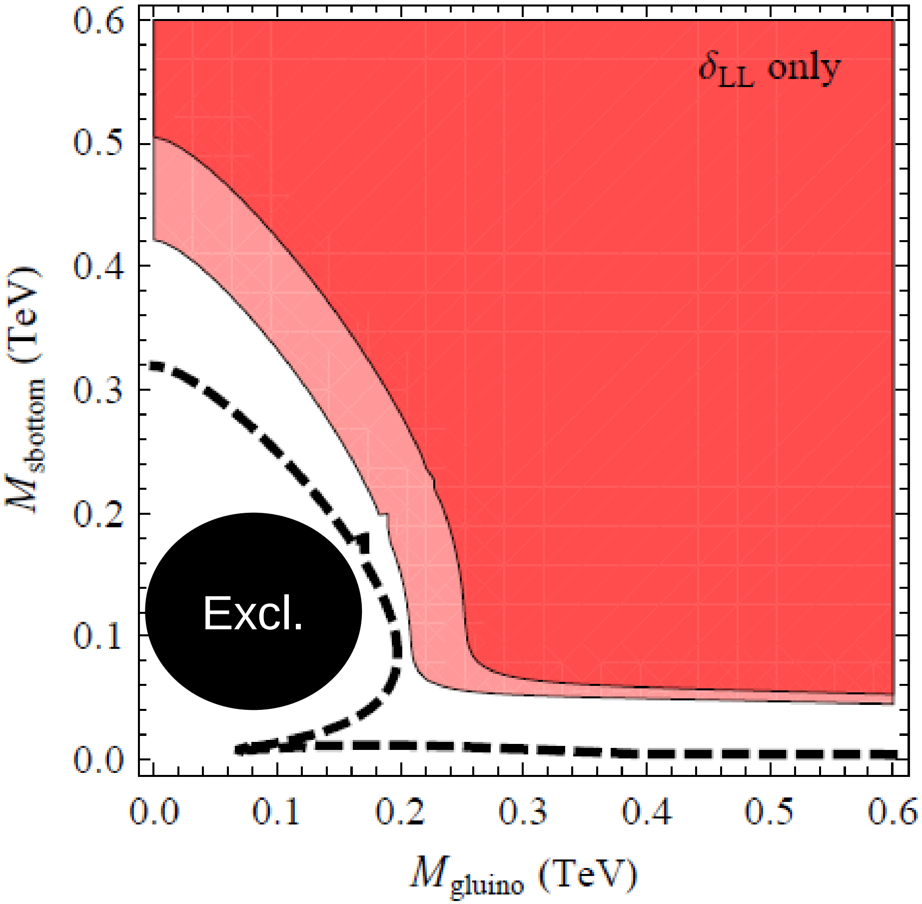
Twofold role of Flavour for BSM - Example ϵ_K and SUSY

- **NATURAL SUSY Constraints from ϵ_K:** **[Mescia, Virto, 1208.0533]**

$\boxed{\hat{\delta}_{LL} \sim \text{CKM}, \ \hat{\delta}'_{RR} = 0}$

$\epsilon_K \sim$





Powerful role of Flavour

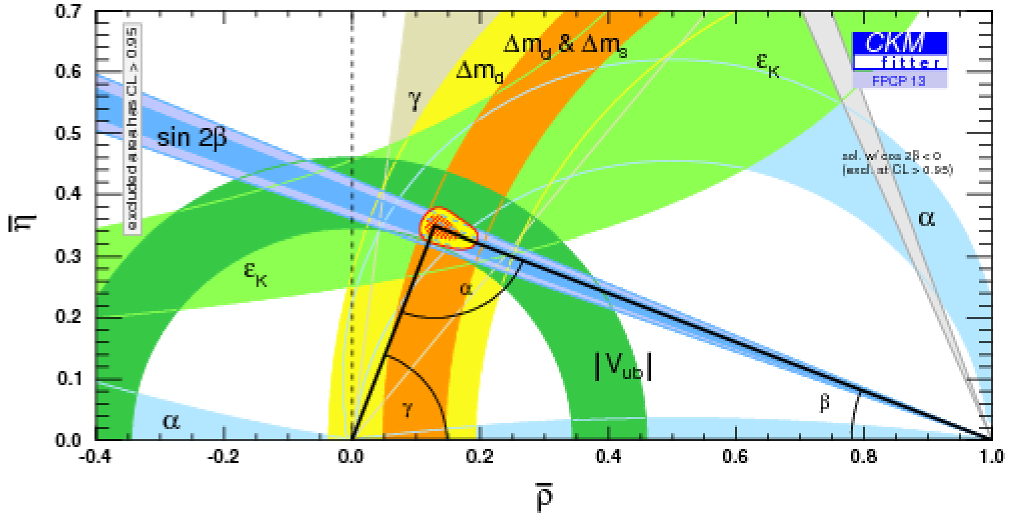
2

OK Natural SUSY spectrum ($m_{sbottom}$<1 TeV)!
- Flavour helpful to fix BSM symmetries.

$\hat{\delta}^{db}_{RR} = 0$

Future perspective for New Physics via Flavour Window

- *What is the origin of Yukawa couplings in the SM?*
- Are the Yukawa couplings the only source of Flavour?



- In many observables theoretical errors still larger than exp. ones

1. *Refined CKM fits to* 1% by Belle II and LHCb*:*
→ new physics in B_d, B_s and K mixing! **2020**

- Past studies on FCNC mainly involve b→d (and s→d) transitions

2. *b→s transitions: possible "rich" ground for surprises!*
→ already some anomalies in $B_d \to K^* \mu\mu$! NOW LHCb

3. *Rare Kaon decays: s→d penguins* >2020,NA62, JPARC..

1. CKM fits to 1% by tree-level modes (2020)

Experimental errors on *B* and *K* mixings are already below 1%

ϵ_K: K^0-$\bar{K}^0$ *mixing*	ΔM_d: B^0_d-$\bar{B}^0_d$ *mixing*	ΔM_s: B^0_s-$\bar{B}^0_s$ *mixing*
exp. err 0.5%	exp. err 0.7%	exp. err 0.1%
th.err 10%	th.err 6%	th.err 6%

By reducing the theory errors we become more sensitive to NP:

2 sources of th. error: hadronic + parametrical (CKM, masses) ones

2 sources of theory error: hadronic + parametrical uncertainties (CKM, masses)

$$A_{\Delta F=2}\left(P_{ij}\to\overline{P}_{ij}\right)\sim\underbrace{\left(V_{ti}V_{tj}^{*}\right)^{2}}_{4\%}\times\underbrace{m_t^2}_{2\%}\times m_P^2\,\underbrace{f_P^{\,2}}_{6\%}\,\underbrace{B_P}_{3\%}$$

parametrical uncertainties

hadronic uncertainties

1. CKM fits to 1% by tree-level modes (2020)

Experimental errors on *B* and *K* mixings are already below 1%

ϵ_K: K^0-$\bar{K}^0$ *mixing*	ΔM_d: B^0_d-$\bar{B}^0_d$ *mixing*	ΔM_s: B^0_s-$\bar{B}^0_s$ *mixing*
exp. err 0.5%	exp. err 0.7%	exp. err 0.1%
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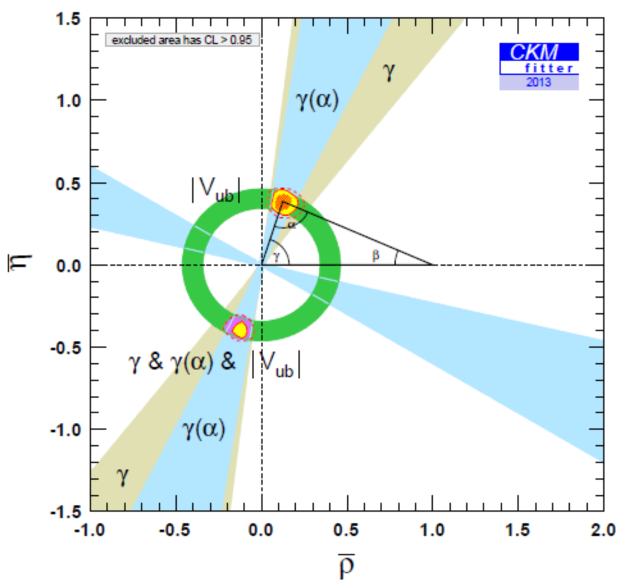
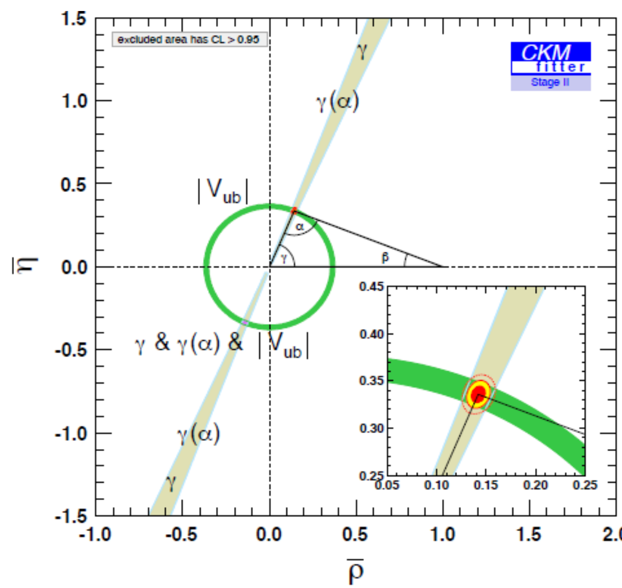
2014

$\bar{\rho}\sim 15\%$

$\bar{\eta}\sim 10\%$





2020

$\bar{\rho}\sim 1\%$

$\bar{\eta}\sim 1\%$

Belle II @ 50ab^{-1}

LHCb @ 50fb^{-1}

Drastic reduction of CKM parametrical uncertainties by improving V_{ub} and γ

Tension in CKM fits: ϵ_K-$\sin(2\beta)$, V_{ub}

Parameter	Input value	SM Prediction	
$\sin(2\beta)$	$S_{\psi K_s} = 0.680 \pm 0.023$ →	0.755 ± 0.044	-
$\lvert\epsilon_k\rvert$	0.002228 ± 0.000013 →	0.00188 ± 0.0002	+

UTfit Collaboration

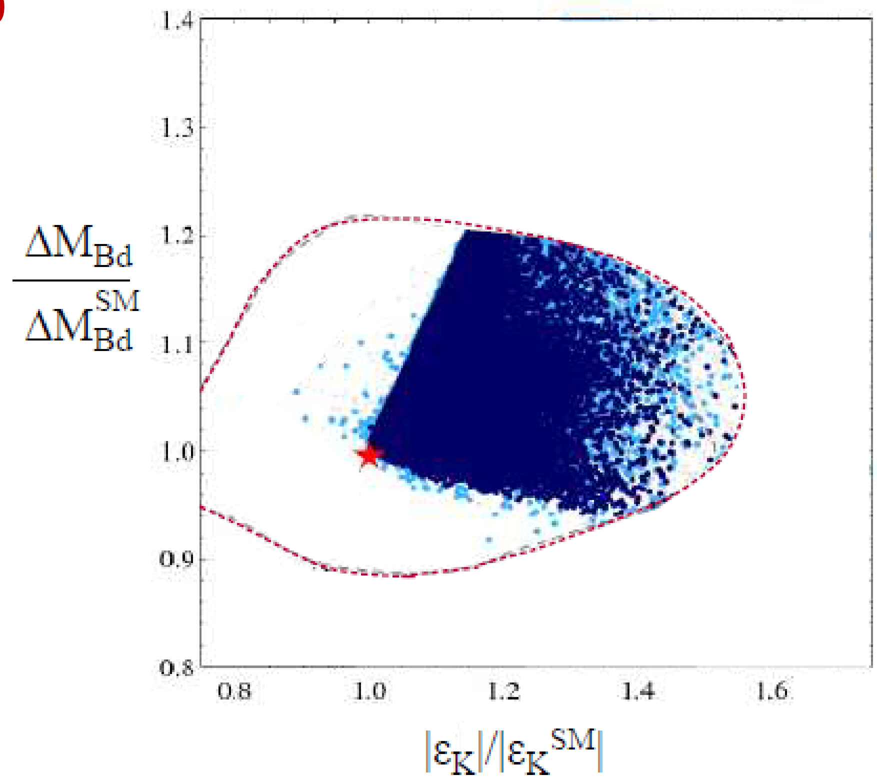
fit vs. exp ≈ 2.4σ

Weak evidence of $|\epsilon_K^{Exp}| - |\epsilon_K^{SM}| > 0$

A positive contribution to ϵ_K is common to MFV-like (SUSY) models

Barbieri, Buttazzo, Sala, Straub '13

In order to clarify the picture we need a more clean determination of $|V_{ub}|$ & γ



Points allowed by present CMS/ATLAS data + present flavor data

2. b→s transitions: possible "rich" ground for surprises!

✓Large amount of observables: a rich anatomy of b → s couplings

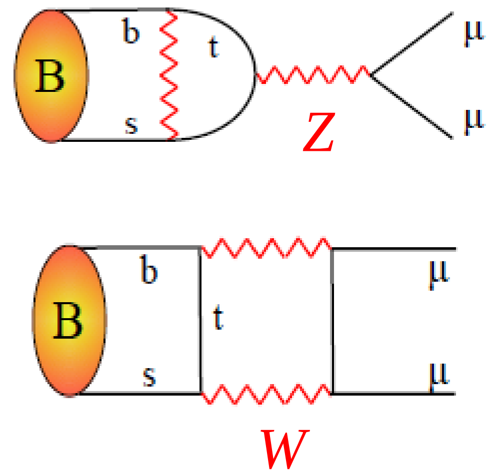
LHCb TASK

$b \to s$ transitions: $B_s \to \mu\mu$

SM operators

$$O_7 = \bar{b}_R \sigma^{\mu\nu} s_L F_{\mu\nu}, O_9 = \left(\bar{b}\gamma_L^\mu s\right)\bar{\ell}\gamma^\mu \ell$$

$$O_{10} = \left(\bar{b}\gamma_L^\mu s\right)\bar{\ell}\gamma^\mu \gamma_5 \ell$$



$$\Gamma\left(B_s^0 \to \mu^+\mu^-\right) \sim \frac{G_F^2 \alpha^2}{64\pi^3} m_{Bs}^2 f_{Bs}^2 \left|V_{tb} V_{ts}\right|^2 \left|2 m_\mu C_{10}\right|^2$$

Special Mode

❖double suppressed!

→ No SM tree-level contributions (FCNC)

→ Helicity suppression

❖hadronic uncertainties under control

Only one hadronic parameter: f_{Bs}

$$\langle 0 | \bar{b}\gamma^\mu \gamma_5 s | B_s^0 \rangle = i q^\mu f_{Bs}$$

$$f_{Bs} = \left(228 \pm 5\right) \mathrm{MeV}$$

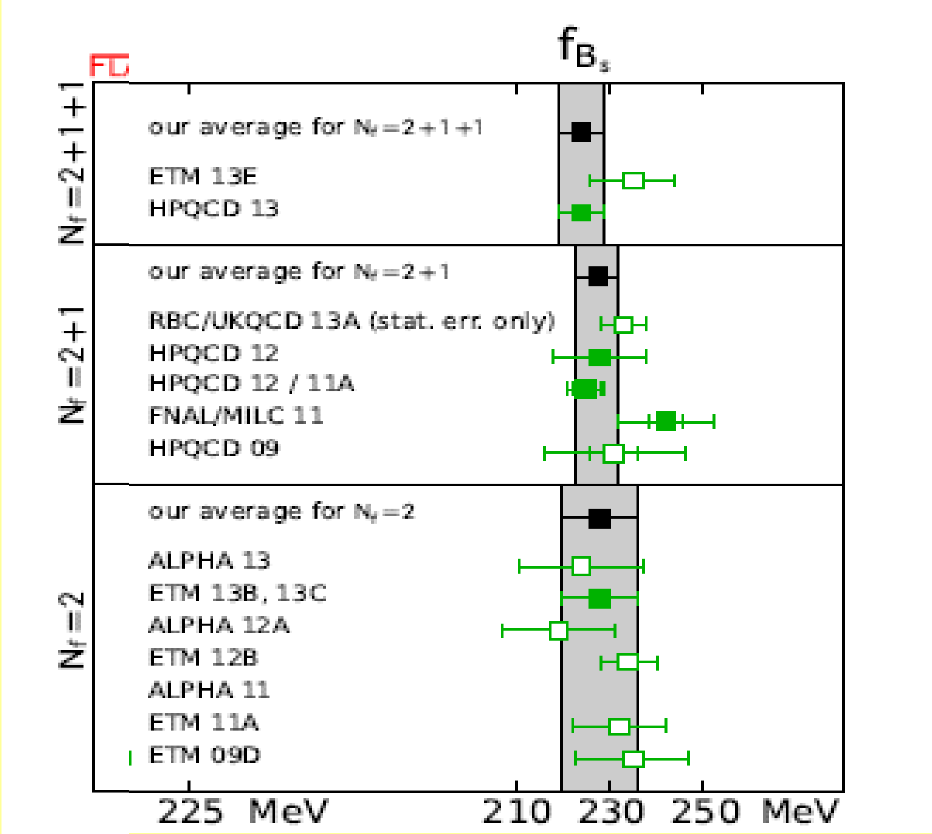
3% hadronic uncertainty

Lattice from many groups

Theory: Hadronic Uncertainties

$B_s \to \mu\mu$

f_{Bs}



See FLAG13, 1310.8555, for last results

Only one hadronic parameter: f_{Bs}

$$f_{Bs} = (228 \pm 5)\,\mathrm{MeV}$$

$B_s \to \mu\mu$

$$\langle 0 | \bar{b}\gamma^{\mu}\gamma_5 s | B_s^0 \rangle = ip^{\mu} f_{Bs}$$

3% hadronic uncertainty

Lattice from many groups

$Br(B_s \to \mu\mu)^{SM} = (3.3 \pm 0.3) \times 10^{-9}$ (8%)

$b\to s$ transitions: $B_s\to\mu\mu$

SM operators

$$O_7 = \bar{b}_R \sigma^{\mu\nu} s_L F_{\mu\nu}, O_9 = \left(\bar{b}\gamma_L^\mu s\right)\bar{\ell}\gamma^\mu \ell$$

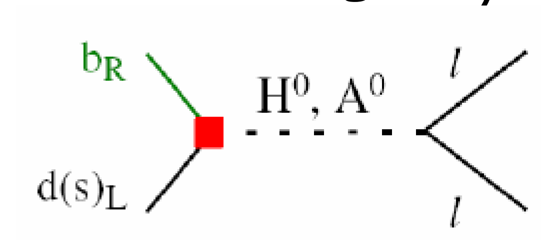
$$O_{10} = \left(\bar{b}\gamma_L^\mu s\right)\bar{\ell}\gamma^\mu\gamma_5\ell$$

BSM operators

$$O_{S(P)} = \left(\bar{b}_R s_L\right)\bar{\ell}\ell_{S(P)}, O_T = \left(\bar{b}_R\sigma^{\mu\nu} s_L\right)\bar{\ell}\sigma^{\mu\nu}\ell$$

$$O'_{7,9,10,S,P} = O_{7,9,10,S,P}\left(L \leftrightarrow R\right)$$

SUSY at large tanβ



$$A(B\to ll)_H \sim \frac{m_b m_l}{M_A^2}\,\frac{\mu A_U}{\tilde{M}_q^2}\,\tan^3\beta$$

GOLDEN MODE at LHCb
enhanced $C_{S(P)}$ ~$\tan^3\beta$

$$\Gamma\left(B_s^0 \to \mu^+\mu^-\right) \sim \frac{G_F^2\alpha^2}{64\pi^3} m_{Bs}^2 f_{Bs}^2 \left|V_{tb}V_{ts}\right|^2$$
$$\times\left[\left|2m_\mu\left(C_{10}-C'_{10}\right)+m_{Bs}\left(C_P-C'_P\right)\right|^2 + m_{Bs}\left|\left(C_S-C'_S\right)\right|^2\right]$$

Only one hadronic parameter: f_{Bs}

$$\langle 0|\bar{b}\gamma^\mu\gamma_5 s|B_s^0\rangle = iq^\mu f_{Bs}$$

$$\langle 0|\bar{b}\gamma_5 s|B_s^0\rangle = -if_{Bs}M_{Bs}^2/m_b$$

(PCAC Ward Identity)

$b \to s$ transitions: $B_s \to \mu\mu$

SM operators

$$O_7 = \bar{b}_R \sigma^{\mu\nu} s_L F_{\mu\nu}, O_9 = (\bar{b}\gamma^\mu_L s)\bar{\ell}\gamma^\mu \ell$$

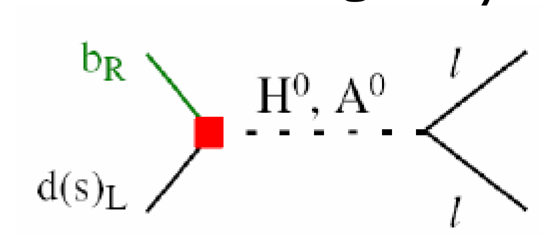
$$O_{10} = (\bar{b}\gamma^\mu_L s)\bar{\ell}\gamma^\mu \gamma_5 \ell$$

BSM operators

$$O_{S(P)} = (\bar{b}_R s_L)\bar{\ell}\ell_{S(P)}, O_T = (\bar{b}_R \sigma^{\mu\nu} s_L)\bar{\ell}\sigma^{\mu\nu}\ell$$

$$O'_{7,9,10,S,P} = O_{7,9,10,S,P}(L \leftrightarrow R)$$

SUSY at large tanβ



$$A(B \to ll)_H \sim \frac{m_b m_l}{M_A^2} \frac{\mu A_U}{\tilde{M}_q^2} \tan^3\beta$$

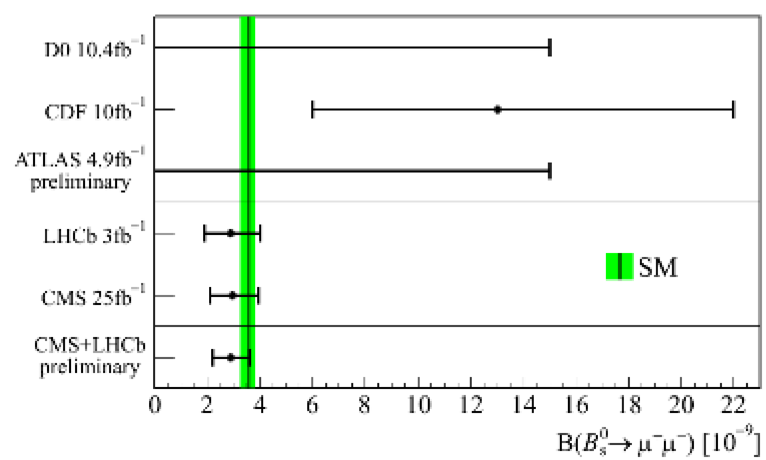
GOLDEN MODE at LHCb
enhanced $C_{S(P)} \sim \tan^3\beta$

BIG News:

✓*Nov. 2012, first evidence of $B_s \to \mu^+\mu^-$ from* LHCb

✓*July 2013, LHCb-CMS world average*

➲*PANIC:* $Br^{exp}(B_s \to \mu\mu) = (2.9 \pm 0.7)10^{-9}$ (25%)
$Br^{SM}(B_s \to \mu\mu) = (3.3 \pm 0.3)10^{-9}$ (8%)



$b \to s$ transitions: $B_s \to \mu\mu$

SM operators

$$O_7 = \bar{b}_R \sigma^{\mu\nu} s_L F_{\mu\nu}, O_9 = \left(\bar{b}\gamma_L^{\mu} s\right)\bar{\ell}\gamma^{\mu}\ell$$

$$O_{10} = \left(\bar{b}\gamma_L^{\mu} s\right)\bar{\ell}\gamma^{\mu}\gamma_5\ell$$

BSM operators

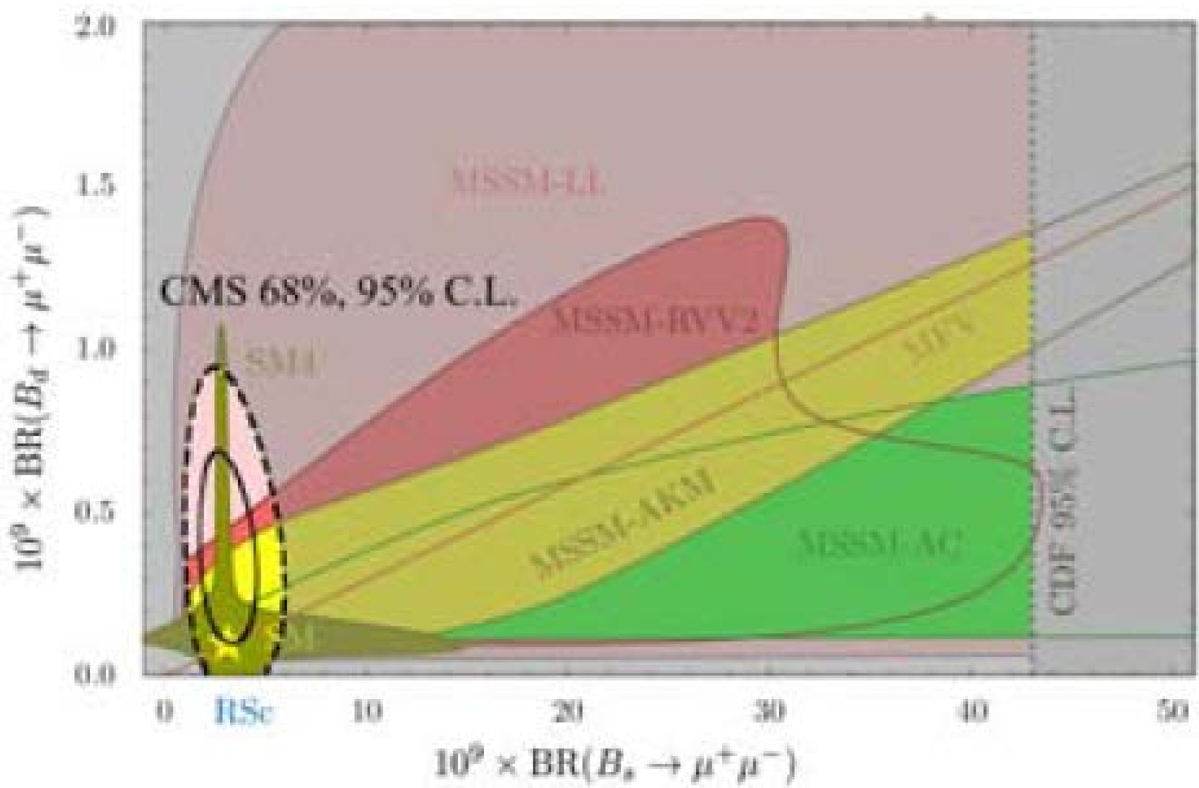
$$O_{S(P)} = \left(\bar{b}_R s_L\right)\bar{\ell}\ell_{S(P)}, O_T = \left(\bar{b}_R \sigma^{\mu\nu} s_L\right)\bar{\ell}\sigma^{\mu\nu}\ell$$

$$O'_{7,9,10,S,P} = O_{7,9,10,S,P}\left(L \leftrightarrow R\right)$$

➲ PANIC:

Br^{exp}($B_s \to \mu\mu$) = (2.9 ± 0.7)10^{-9}

Br^{SM}($B_s \to \mu\mu$) = (3.3 ± 0.3)10^{-9}



update of D. Straub 12

$b \to s$ transitions: $B_s \to \mu\mu$

SM operators

$$O_7 = \bar{b}_R \sigma^{\mu\nu} s_L F_{\mu\nu}, O_9 = \left(\bar{b}\gamma_L^{\mu} s\right)\bar{\ell}\gamma^{\mu}\ell$$

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BSM operators

$$O_{S(P)} = \left(\bar{b}_R s_L\right)\bar{\ell}\ell_{S(P)}, O_T = \left(\bar{b}_R \sigma^{\mu\nu} s_L\right)\bar{\ell}\sigma^{\mu\nu}\ell$$

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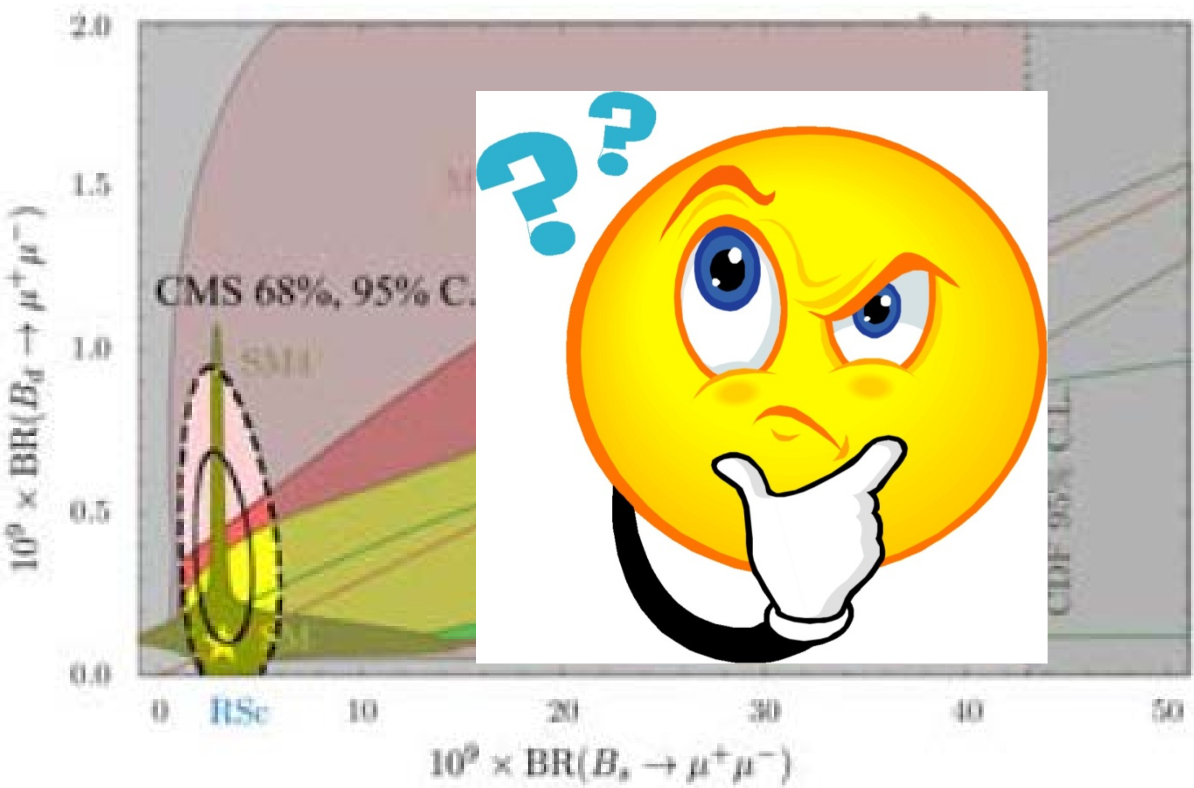
Br^{exp}($B_s \to \mu\mu$) = (2.9 ± 0.7)10^{-9}

Br^{SM}($B_s \to \mu\mu$) = (3.3 ± 0.3)10^{-9}

➲ NO NEW PHYISICS?



update of D. Straub 12

$b \to s$ transitions: $B_s \to \mu\mu$ + $B \to K^{(*)}\mu\mu$ + $B_s \to \tau\tau$

SM operators

$$O_7 = \bar{b}_R \sigma^{\mu\nu} s_L F_{\mu\nu}, O_9 = \left(\bar{b}\gamma_L^{\mu} s\right)\bar{\ell}\gamma^{\mu}\ell$$

$$O_{10} = \left(\bar{b}\gamma_L^{\mu} s\right)\bar{\ell}\gamma^{\mu}\gamma_5\ell$$

BSM operators

$$O_{S(P)} = \left(\bar{b}_R s_L\right)\bar{\ell}\ell_{S(P)}, O_T = \left(\bar{b}_R \sigma^{\mu\nu} s_L\right)\bar{\ell}\sigma^{\mu\nu}\ell$$

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$\mathrm{Br}^{\mathrm{exp}}(B_s \to \mu\mu) = (2.9 \pm 0.7)10^{-9}$

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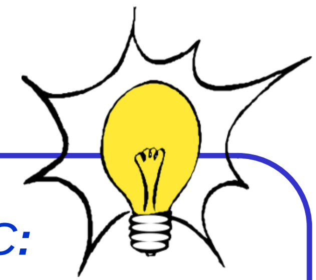
➲ NO NEW PHYISICS?



➲ NO PANIC:

$B \to K^{*}\mu\mu$, $B \to K\mu\mu$ & $B \to \tau\tau$

sensitive to different "$b \to s$ couplings"

3 ways out to overcome the $B_s \to \mu\mu$ constraints

$b \to s$ transitions: $B_s \to \mu\mu$ + $B \to K^{(*)}\mu\mu$ 1

SM operators

$$O_7 = \bar{b}_R \sigma^{\mu\nu} s_L F_{\mu\nu}, \; O_9 = \left(\bar{b}\gamma_L^{\mu} s\right)\bar{\ell}\gamma^{\mu}\ell$$

$$O_{10} = \left(\bar{b}\gamma_L^{\mu} s\right)\bar{\ell}\gamma^{\mu}\gamma_5\ell$$

BSM operators

$$O_{S(P)} = \left(\bar{b}_R s_L\right)\bar{\ell}\ell_{S(P)}, \; O_T = \left(\bar{b}_R \sigma^{\mu\nu} s_L\right)\bar{\ell}\sigma^{\mu\nu}\ell$$

$$O'_{7,9,10,S,P} = O_{7,9,10,S,P}\left(L \leftrightarrow R\right)$$

$$\Gamma\left(B_s^0 \to \mu^+\mu^-\right) \sim \frac{G_F^2\alpha^2}{64\pi^3} m_{Bs}^2 f_{Bs}^2 \left|V_{tb}V_{ts}\right|^2$$
$$\times\left[\left|2m_\mu\left(C_{10}-C'_{10}\right)+m_{Bs}\left(C_P-C'_P\right)\right|^2\right.$$
$$\left.+m_{Bs}\left|\left(C_S-C'_S\right)\right|^2\right]$$

☺ **No contribution from O_9**

☺ **C_9 couplings unconstrained by $B_s \to \mu\mu$**

J. Matias, S Descotes-Genon, J. Virto '13

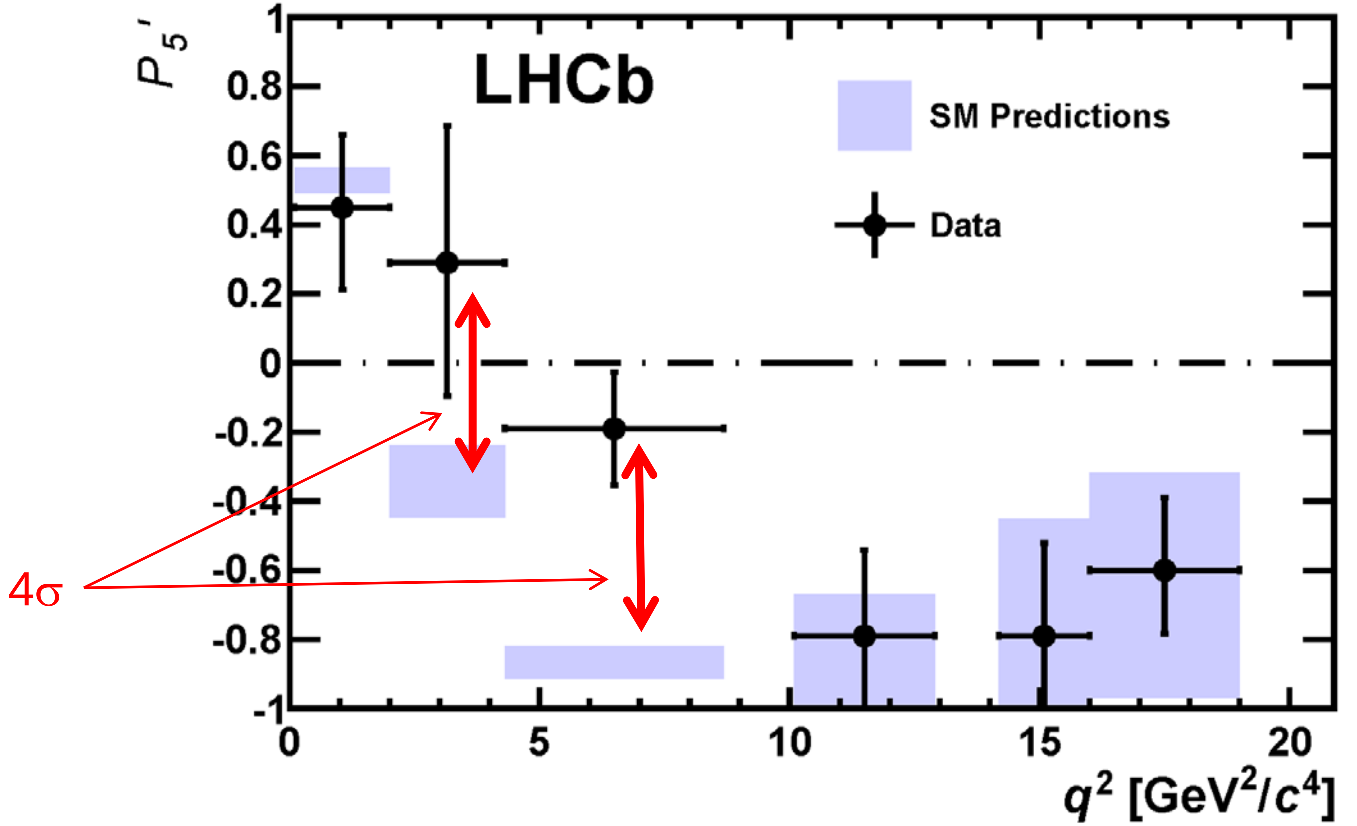
1

However, O_9 gives contribution to $B \to K^* \mu\mu$, $B \to K\mu\mu$, and non-SM effects can be possible

$$\langle B(p)|\bar{b}\gamma^\mu s|K(k)\rangle = (p^\mu + k^\mu - \cancel{\frac{m_B^2 - m_K^2}{q^2}} q^\mu) f_+(q^2) + \cancel{\frac{m_B^2 - m_K^2}{q^2}} q^\mu f_0(q^2)$$

$b \to s$ transitions: Anomaly on $B \to K^{(*)}\mu\mu$

July 2013, **LHCb found a deviation of about 4σ w.r.t the SM in the P_5' observable, one of the coefficients of the $B \to K^*\mu\mu$ angular distribution**

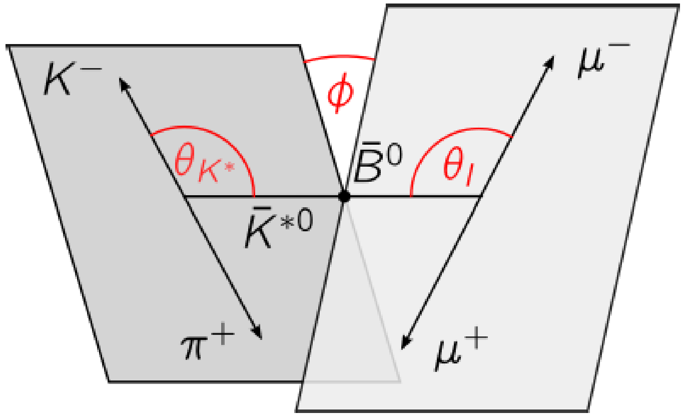


July 2013

Warning: LHCb analysis low statistics -- about 800 events $B \to K^*\mu\mu$

$b\to s$ transitions: Anomaly on $B\to K^{(*)}\mu\mu$

$$\bar{B}^0 \to \bar{K}^{*0}(\to K^-\pi^+)\mu^+\mu^-$$



$$\frac{1}{\mathrm{d}\Gamma/dq^2}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi\,\mathrm{d}q^2} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K + \frac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_{\mathrm{L}}\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi$$
$$+ S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi$$
$$+ S_6\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$
$$+ S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big],$$

11 angular coefficients to measure from $\boxed{\bar{B}^0 \to \bar{K}^{*0}(\to K^-\pi^+)\mu^+\mu^-}$

$$\boxed{P_5' = \frac{S_5}{\sqrt{F_L\left(1-F_L\right)}}}$$

$b \to s$ transitions: Anomaly on $B \to K^{(*)}\mu\mu$

SM operators

$$O_7 = \bar{b}_R \sigma^{\mu\nu} s_L F_{\mu\nu}, O_9 = \left(\bar{b}\gamma_L^{\mu} s\right)\bar{\ell}\gamma^{\mu}\ell$$

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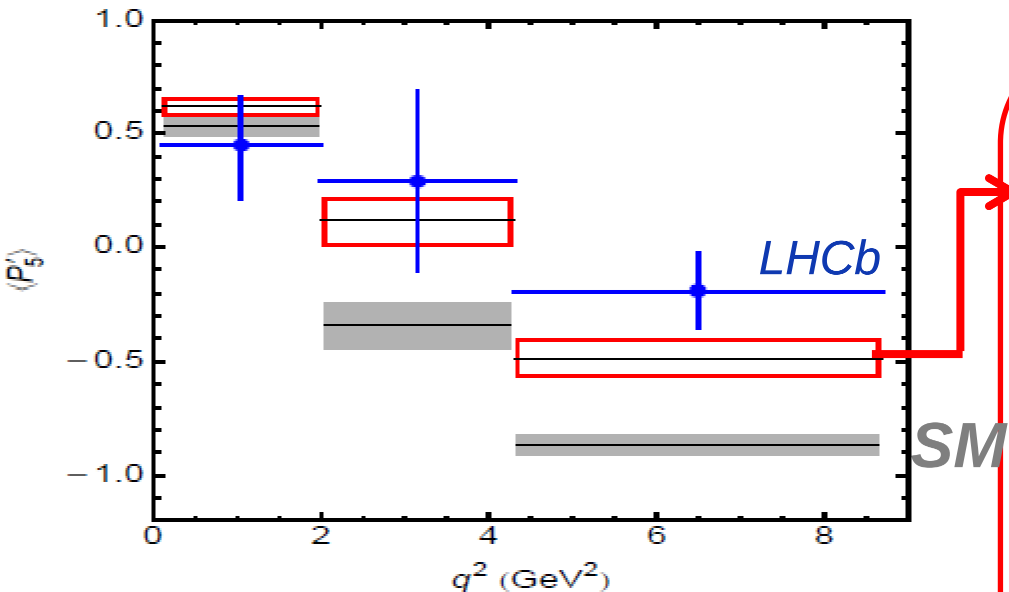
BSM operators

$$O_{S(P)} = \left(\bar{b}_R s_L\right)\bar{\ell}\ell_{S(P)}, O_T = \left(\bar{b}_R \sigma^{\mu\nu} s_L\right)\bar{\ell}\sigma^{\mu\nu}\ell$$

$$O'_{7,9,10,S,P} = O_{7,9,10,S,P}\left(L \leftrightarrow R\right)$$



A negative contribution to $C_9 = C_9^{SM}$-1.5 improves the agreement between LHCb and SM (**4σ–>1.8σ**)

J. Matias, S Descotes-Genon, J. Virto '13

Warning: still some *controversial!*

Are hadronic effects?

J. Lyon, R. Zwicky '14,

S. Jäger, J. M. Camalich '12

NP ruled out by other modes?

Straub et al '14

Experimental fluctuacions?

Warning: LHCb analysis low statistics -- about 800 events $B \to K^{*}\mu\mu$

$b \to s$ transitions: Anomaly on $B \to K^{(*)} \mu\mu$

SM operators

$$O_7 = \bar{b}_R \sigma^{\mu\nu} s_L F_{\mu\nu}, \quad O_9 = \left(\bar{b}\gamma_L^{\mu} s\right)\bar{\ell}\gamma^{\mu}\ell$$

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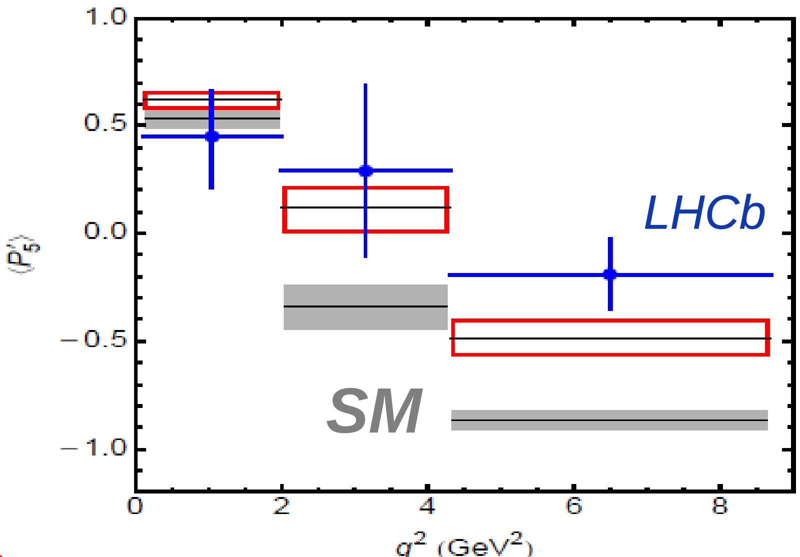
2013 - Anomaly on $B \to K^{*} \mu\mu$



2014 - Tension on $B \to K\mu\mu / B \to Kee$

$$\left(\frac{Br(B \to K\mu\mu)}{Br(B \to Kee)}\right)^{SM} = 1.0003 \pm 0.0001$$

~2.6σ

$$\left(\frac{Br(B \to K\mu\mu)}{Br(B \to Kee)}\right)^{LHCb} = 0.745 \pm 0.096$$

at large recoil region:
$1\,\mathrm{GeV}^2 < q^2 < 6\,\mathrm{GeV}^2$

A negative contribution to *the $b \to s\mu\mu$ C_9 couplings* improves the agreement between LHCb and SM in both cases

R. Alonso '14, G. Hiller '14, D. Ghosch '14

$b \to s$ transitions: Anomaly on $B \to K^{(*)}\mu\mu$

SM operators

$$O_7 = \bar{b}_R \sigma^{\mu\nu} s_L F_{\mu\nu}, \quad O_9 = \left(\bar{b}\gamma_L^\mu s\right)\bar{\ell}\gamma^\mu \ell$$

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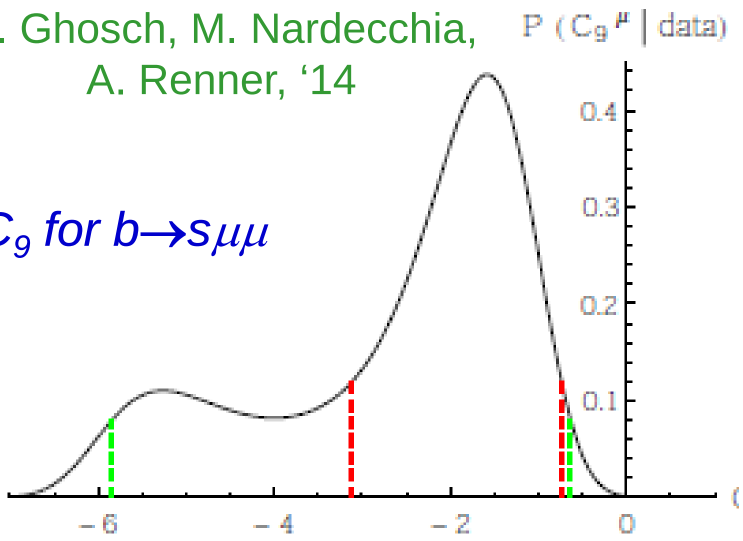
BSM operators

$$O_{S(P)} = \left(\bar{b}_R s_L\right)\bar{\ell}\ell_{S(P)}, \quad O_T = \left(\bar{b}_R \sigma^{\mu\nu} s_L\right)\bar{\ell}\sigma^{\mu\nu}\ell$$

$$O'_{7,9,10,S,P} = O_{7,9,10,S,P}\left(L \leftrightarrow R\right)$$

D. Ghosch, M. Nardecchia, A. Renner, '14

C_9 for $b \to s\mu\mu$



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R. Alonso '14, G. Hiller '14, D. Ghosch '14

Theory: Hadronic Uncertainties

Detour on hadronic uncertainties
of $B \to K^{(*)}\mu\mu$

$b \to s$ transitions: Anomaly on $B \to K^{(*)}\mu\mu$

1

Theory: Hadronic Uncertainties

GOAL: calculate Matrix elements of 2-quark operators between hadrons (decay constants & Form factors)

SM operators

$$O_7 = \bar{b}_R \sigma^{\mu\nu} s_L F_{\mu\nu}$$

$$O_9 = \left(\bar{b}\gamma_L^{\mu} s\right)\bar{\ell}\gamma^{\mu}\ell$$

$$O_{10} = \left(\bar{b}\gamma_L^{\mu} s\right)\bar{\ell}\gamma^{\mu}\gamma_5\ell$$

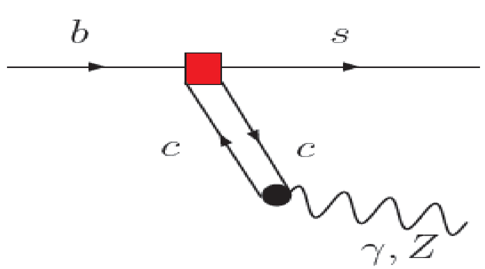
$$O_2 = \left(\bar{b}\gamma_L^{\mu} c\right)\left(\bar{c}\gamma_L^{\mu} s\right)$$

BSM operators

$$O_{S(P)} = \left(\bar{b}_R s_L\right)\bar{\ell}\ell_{S(P)},\ O_T = \left(\bar{b}_R \sigma^{\mu\nu} s_L\right)\bar{\ell}\sigma^{\mu\nu}\ell$$

$$+L \leftrightarrow R$$

Charm Loops



Under control (to some extent)
at low and large q^2, *out of resonance region*

$b \to s$ transitions: Anomaly on $B \to K^{(*)}\mu\mu$

$$\langle V(p',\varepsilon)|\bar{q}\hat{\gamma}^{\mu}b|B(p)\rangle = \frac{2iV(q^2)}{m_B+m_V}\epsilon^{\mu\nu\rho\sigma}\varepsilon^*_{\nu}p'_{\rho}p_{\sigma}$$

Form Factor Definition for $B \to K^*\gamma$, $B \to K^*ll$

$$\begin{aligned}\langle V(p',\varepsilon)|\bar{q}\hat{\gamma}^{\mu}\hat{\gamma}^5 b|B(p)\rangle = \; & 2m_V A_0(q^2)\frac{\varepsilon^*\cdot q}{q^2}q^{\mu} \\ & +(m_B+m_V)A_1(q^2)\left(\varepsilon^{*\mu}-\frac{\varepsilon^*\cdot q}{q^2}q^{\mu}\right) \\ & -A_2(q^2)\frac{\varepsilon^*\cdot q}{m_B+m_V}\left((p+p')^{\mu}-\frac{m_B^2-m_V^2}{q^2}q^{\mu}\right)\end{aligned}$$

$$q^{\nu}\langle V(p',\varepsilon)|\bar{q}\hat{\sigma}_{\mu\nu}b|B(p)\rangle = 2T_1(q^2)\epsilon_{\mu\rho\tau\sigma}\varepsilon^{*\rho}p^{\tau}p'^{\sigma} \longrightarrow$$

$Br(B \to K^*\gamma)$
one ff. at $q^2=0$

$$\begin{aligned}q^{\nu}\langle V(p',\varepsilon)|\bar{q}\hat{\sigma}_{\mu\nu}\hat{\gamma}^5 b|B(p)\rangle = \; & iT_2(q^2)[\varepsilon^*_{\mu}(m_B^2-m_V^2)-(\varepsilon^*\cdot q)(p+p')_{\mu}] \\ & +iT_3(q^2)(\varepsilon^*\cdot q)\left[q_{\mu}-\frac{q^2}{m_B^2-m_V^2}(p+p')_{\mu}\right]\end{aligned}$$

$Br(B \to K^*ll)$: 7 form factors in QCD

Form Factor Definition for B→Kll

$$\langle B(p)|\bar{b}\gamma^\mu s|K(k)\rangle = \left(p^\mu + k^\mu - \frac{m_B^2 - m_K^2}{q^2}q^\mu\right) f_+(q^2) + \frac{m_B^2 - m_K^2}{q^2}q^\mu f_0(q^2)$$

$$\langle B(p)|\bar{b}\sigma^{\mu\nu} s|K(k)\rangle = \frac{i f_T}{m_B + m_K}\left[(p^\mu + k^\mu)q^\nu - (p^\nu + k^\nu)q^\mu\right]$$

Br(B→Kll): 3 form factors in QCD

Studies of form-factor calculations on the Lattice:

$B \to Kll$

❖ HPQCD 2013 -> mature calculation

N_F=2+1 stag. fermions: **NRQCD**, m_π>250 MeV, a^{-1}~2GeV->0

relative form-factor error @5%

N_F=0: Wilson fermions: **relativistic fermions**

❖ D. Becirevic, N. Kosnik, F. M., E. Schneider, 2012

$\boxed{f_{+,0,T}(q^2)}$

$B \to K^* ll$

❖ R. Horgan et al. 2013

N_F=2+1 stag. fermions: **NRQCD** , m_π>300 MeV, a^{-1}~2GeV

still an exploratory stage:
K* stable?

see Horgan'talk on PIII-HQ, 11/09 at 16:00

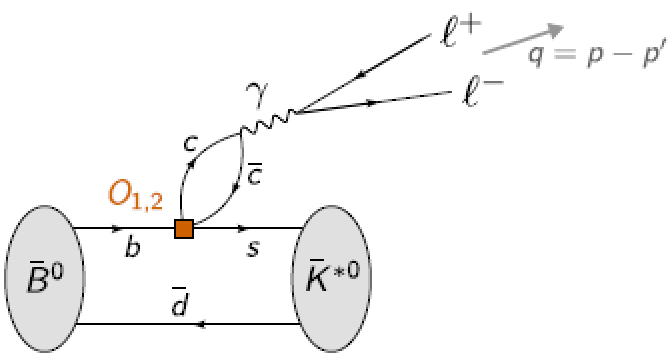
$T_{12}(q^2)$
$V(q^2)$, $A_{012}(q^2)$

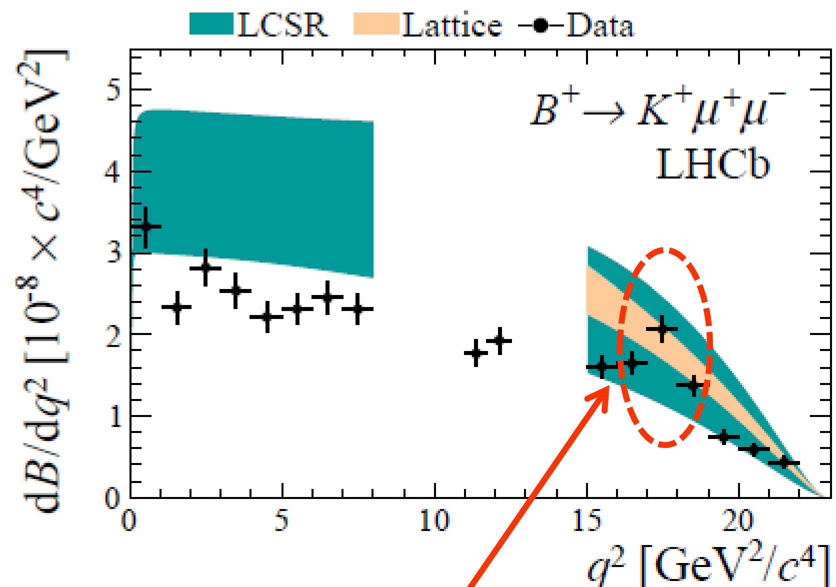
N_F=0: Wilson fermions: **relativistic fermions**

❖ D. Becirevic, V. Lubicz & F. M. 2007 $\longrightarrow$ $\boxed{T_{12}(q^2)}$

Studies of form-factor calculations on the Lattice:

- NRQCD method
  -> automatically gives form factors at zero recoil: q^2>16 GeV^2





New LHCb results with 3 fb^{-1} [arXiv:1403.8044]:

Large contribution from $\psi(4160)$ at high q^2

See yesterday talk @PII-LQ by AGADJANOV

$b \to s$ transitions: Anomaly on $B \to K^{(*)}\mu\mu$

$$\bar{B}^0 \to \bar{K}^{*0}(\to K^-\pi^+)\mu^+\mu^-$$

$$\begin{aligned}\frac{1}{\mathrm{d}\Gamma/dq^2}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi\,\mathrm{d}q^2} = \frac{9}{32\pi}\Big[&\frac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K + \frac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_\ell \\ &- F_{\mathrm{L}}\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi \\ &+ S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi \\ &+ S_6\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi \\ &+ S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big],\end{aligned}$$

F_l and S_i coefficients are plagued by large hadronic uncertainties.

KEY STRATEGY: *by using appropriate normalization, we can define observables, P_i, theoretically clean*

$$P_5' = \frac{S_5}{\sqrt{F_L\left(1-F_L\right)}}$$

J. Matias, F.M., J. Virto & M. Ramon in '12.

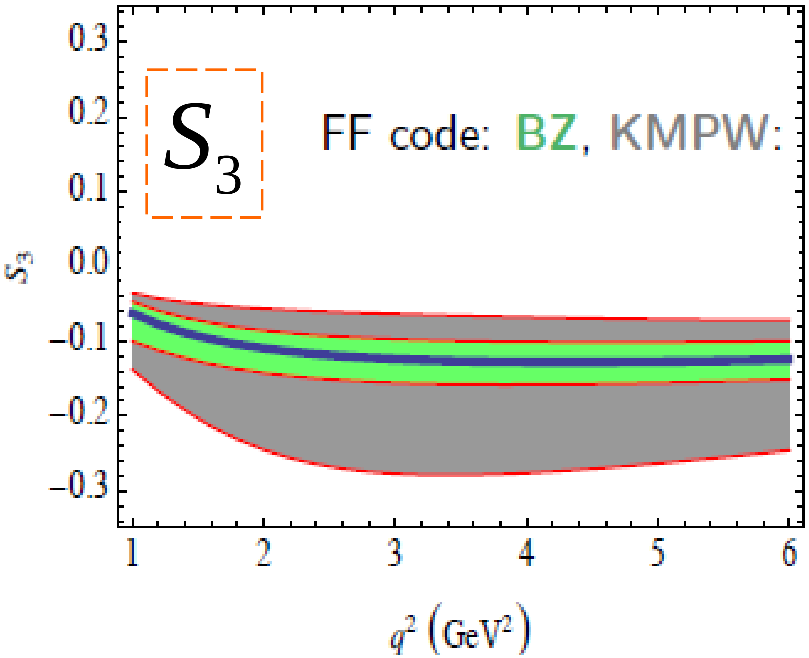
F.Kruger, J.Matias '05; D.Becirevic, E. Schneider '12: C.Bobeth, G. Hiller & D. Van Dvk '12

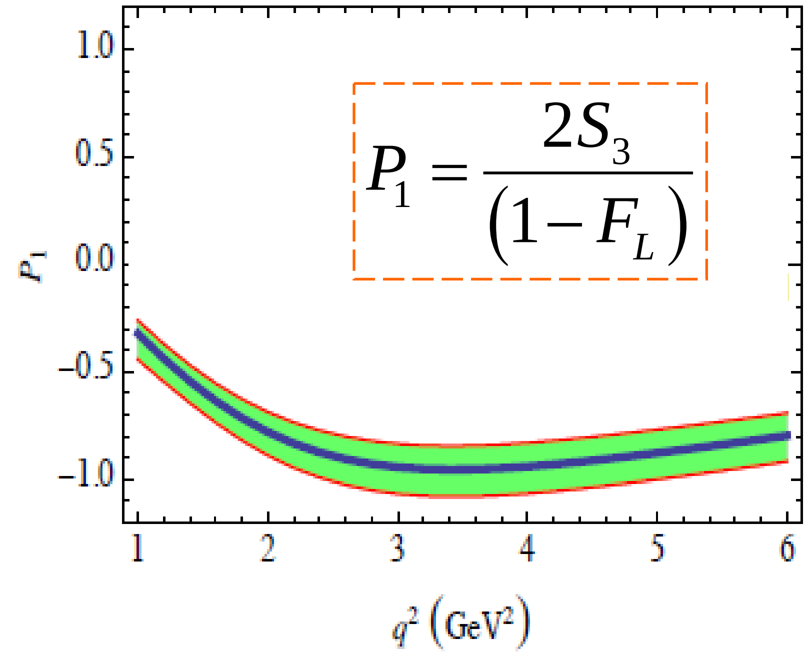
$b \to s$ transitions: Anomaly on $B \to K^{(*)}\mu\mu$

1

F_L and S_i coefficients are plagued by large hadronic uncertainties.

By using appropriate normalization, we defined observables, P_i, theoretically clean





The green/gray bands are the hadronic uncertainties for 2 different determinations of QCD form factors

Large hadronic uncertainties reduced: clean gain on New Physics search

J. Matias, F.M., J. Virto & M. Ramon in ’12

$b \to s$ transitions: $B_s \to \mu\mu$ + $B \to K^{(*)}\mu\mu$

SM operators

$$O_7 = \bar{b}_R \sigma^{\mu\nu} s_L F_{\mu\nu}, O_9 = \left(\bar{b}\gamma_L^\mu s\right)\bar{\ell}\gamma^\mu \ell$$

$$O_{10} = \left(\bar{b}\gamma_L^\mu s\right)\bar{\ell}\gamma^\mu \gamma_5 \ell$$

BSM operators

$$O_{S(P)} = \left(\bar{b}_R s_L\right)\bar{\ell}\ell_{S(P)}, O_T = \left(\bar{b}_R \sigma^{\mu\nu} s_L\right)\bar{\ell}\sigma^{\mu\nu}\ell$$

$$O'_{7,9,10,S,P} = O_{7,9,10,S,P}\left(L \leftrightarrow R\right)$$

$$\Gamma\left(B_s^0 \to \mu^+\mu^-\right) \sim \frac{G_F^2\alpha^2}{64\pi^3} m_{Bs}^2 f_{Bs}^2 \left|V_{tb}V_{ts}\right|^2 \times\left[\left|2m_\mu\left(C_{10}-C'_{10}\right)+m_{Bs}\left(C_P-C'_P\right)\right|^2 + m_{Bs}\left|\left(C_S-C'_S\right)\right|^2\right]$$

$B_s \to \mu\mu$ **(P=-1)**

2) Only contributions from axial combinations

D. Becirevic, N. Kosnik, F. M, E. Scheider '12

However, orthogonal combinations of couplings enters $B \to K^*\mu\mu$, $B \to K\mu\mu$

2

$B \to K\, ll$ **(P=1)**

$$\langle K|\bar{b}\gamma^\mu\gamma_5 s|B_s^0\rangle = \langle K|\bar{b}\gamma_5 s|B_s^0\rangle = 0$$

$$\mathrm{Br} \propto \left(C_9+C'_9\right),\left(C_{10}+C'_{10}\right),\left(C_P+C'_P\right),\left(C_S+C'_S\right)$$

$b \to s$ transitions: $B_s \to \mu\mu$ + $B_s \to \tau\tau$

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$$\times\left[\left|2m_\mu\left(C_{10} - C'_{10}\right) + m_{Bs}\left(C_P - C'_P\right)\right|^2 + m_{Bs}\left|\left(C_S - C'_S\right)\right|^2\right]$$

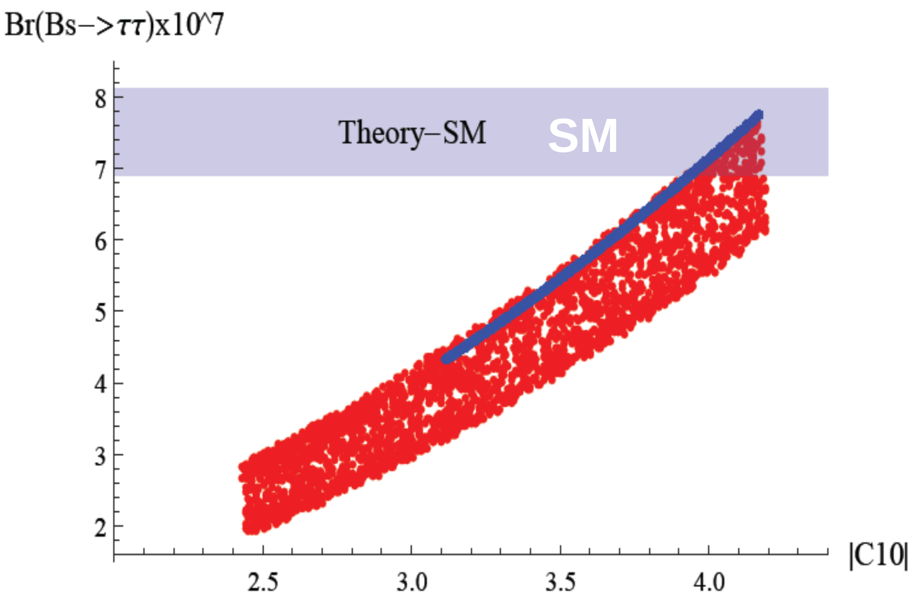
1) Helicity suppression is not fully working for **B->$\tau\tau$**

3

Smallish contributions to $B \to \mu\mu$ can still give sizeable deviations of the rate for $B \to \tau\tau$

D. Becirevic, N. Kosnik, F. M, A. Tayduganov, A. Renau in progress ‘14

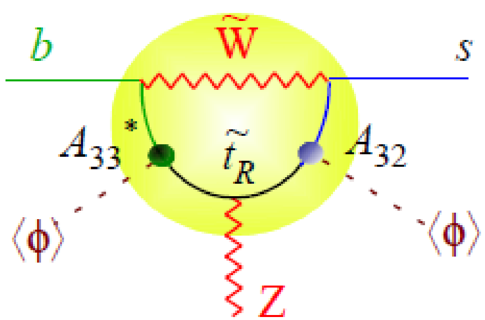
$b \to s$ transitions: $B_s \to \mu\mu + B_s \to \tau\tau$



- All the points compatible with present constraints
  - Blue Line with only C_{10} not-vanishing
  - Red points C_{10}, C_S, C_P free

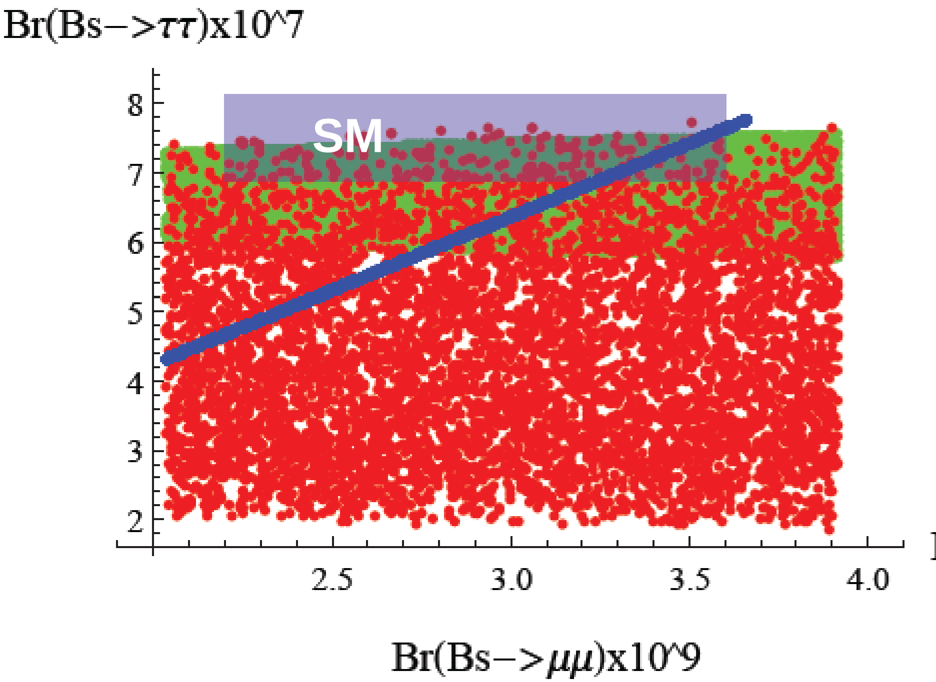
3

Non-SM contributions to C_{10} easily expected in SUSY



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

$b \to s$ transitions: $B_s \to \mu\mu + B_s \to \tau\tau$ 3



- All the points compatible with present constraints
  - Blue Line with only C_{10} not-vanishing
  - Red points C_{10}, C_S, C_P free
  - Green points C_S, C_P free and $C_{10} = C_{10}^{SM}$

3 ***However, smallish contributions to $B \to \mu\mu$ can still give sizeable deviations of the rate for $B \to \tau\tau$***

D. Becirevic, N. Kosnik, F. M, A. Tayduganov, A. Renau in progress '13

$b \to s$ transitions: Resum

Br($B_s \to \mu\mu$) is genuinely sensitive to (pseudo)scalar operators

$$O'_S = \left(\bar{b}P_{R,L}s\right)\bar{\ell}\ell, \text{ and } O_P = \left(\bar{b}P_{R,L}s\right)\bar{\ell}\gamma_5\ell$$

- Only one hadronic parameter enters, ***f_{Bs} -> small th. error***

Br($B \to K ll$) & Br($B \to K^* ll$) are sensitive to scalar + vector operators (+ tensors)

- hadronic uncertainties **->** ***still large th. error***
- **With respect to $B_s \to \mu\mu$ & $B_s \to X_s \gamma$, they probe the effective Hamiltonian in an "orthogonal" direction!**
- **Improvement of form factors calculation** would make the observables a high resolution probe of scalar operators

Conclusions

What about BSM effects?

- *We learned a lot about Flavour physics during last years:*
- *<u>Disentangling New Physics, it is mainly a question of precision and new modes</u>*
- *Potential n.d.f at the TeV scale must have a rather sophisticated Flavour structure … which we have not clearly understood yet*
- *Some tension emerging in several modes: B->K*, sin(2β) vs ϵ_K*

- ***Multiple probes! Almost all channels are sensitive at NP at well motivated levels!***

d-quarks	Probe
s-d	K-K
b-d	B-B
b-s	B_s-B_s

Higgs couplings
Rare *K* decays
Rare *B* decays

Leptons	Probe
μ-e	muons
τ-e	eEDM
τ-μ	LHC

THANKS VERY MUCH

$$\frac{m^2_{Higgs}}{2} = -\boxed{|\mu|^2} + \ldots + \boxed{\delta m^2_H}$$

Higgsinos

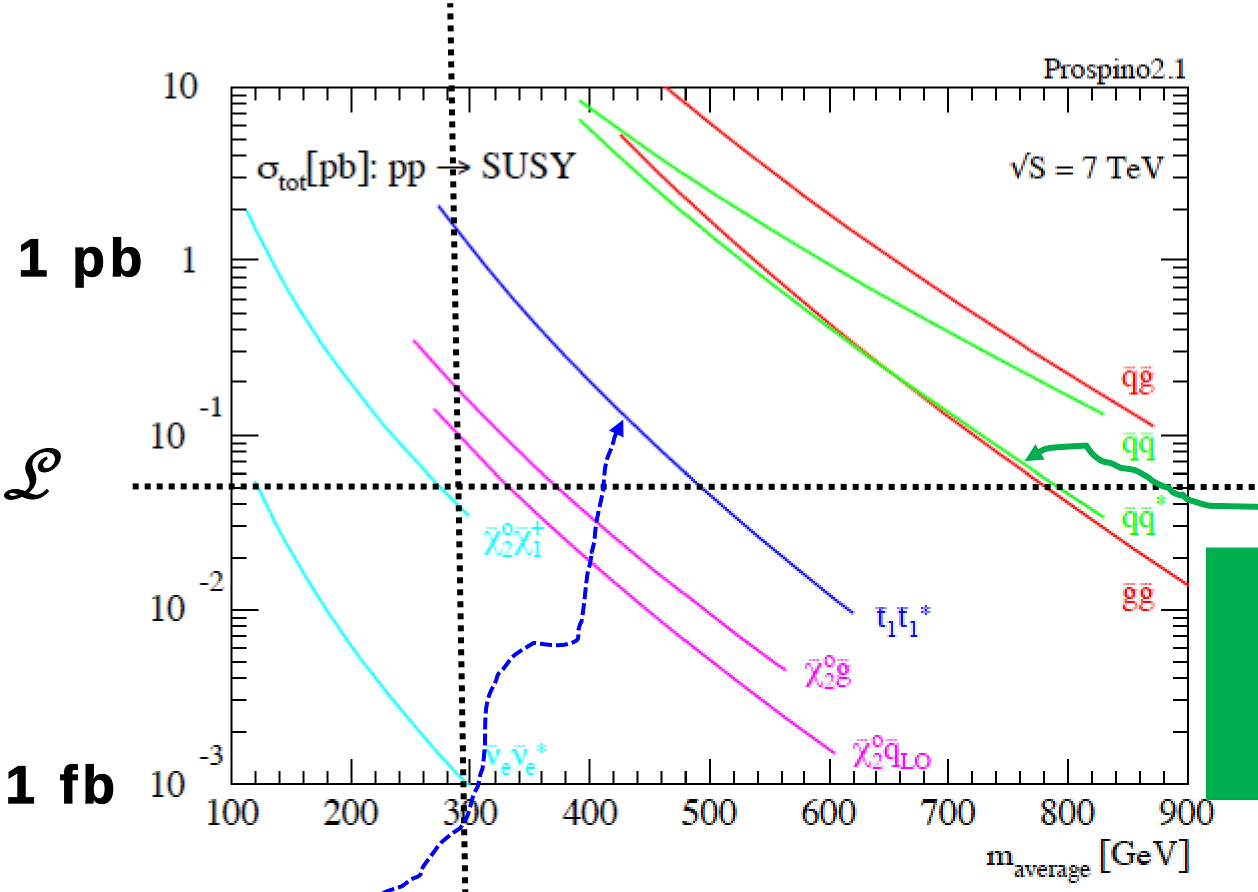
1loop $$\boxed{\delta m^2_H|_{stop}} = -\frac{3}{8\pi^2} y_t^2 \left(\underline{m^2_{U_3} + m^2_{Q_3} + |A_t|^2} \right) \log\left(\frac{\Lambda}{\text{TeV}}\right)$$

stops, sbottom$_L$

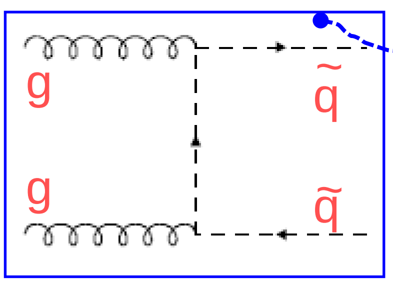
2loop $$\boxed{\delta m^2_H|_{gluino}} = -\frac{2}{\pi^2} y_t^2 \left(\frac{\alpha_s}{\pi}\right) \underline{|M_3|^2} \log^2\left(\frac{\Lambda}{\text{TeV}}\right)$$

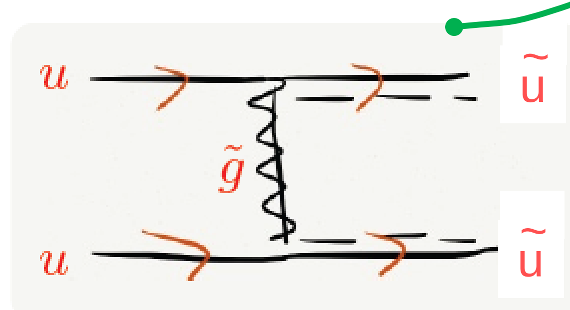
gluino

Natural SUSY:
no fine tuning on the the Higgs mass:
stops, sbottomL and gluinos lights



stronger constraint for light squarks





squarks

σ~pb (300 GeV/*m*)⁶

Flavour Independent

$\sigma \sim$ **(TeV/$m_{\tilde{g}}$)²**

Flavour Dependent:U/D PDF large