How much space is left for a new family

Alexander Lenz

University of Regensburg

Mixing with the 4th Family I

exploratory study in collaboration with
Markus Bobrowski, Johann Riedl, Jürgen Rohrwild; arXiv:0902.4883 , PRD
arXiv:0904.3971

As in any extension of the SM:
more parameters appear

Add a complete 4th family (b', t', l^-', ν') $\Rightarrow$ new parameters:

- Quark masses: 2
- Lepton masses: 2
- V_{CKM4}: 3 angles + 2 phases
- V_{PMNS4}: 3 angles + 2 phases + Majorana-phases

$\Rightarrow$ at least 14 new parameters

"Rome was not built in a day" : Start with flavor bounds on V_{CKM4}

Mixing with the 4th Family II

The general form of V_{CKM4} reads

$$V_{CKM4} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} & V_{ub'} \\ V_{cd} & V_{cs} & V_{cb} & V_{cb'} \\ V_{td} & V_{ts} & V_{tb} & V_{tb'} \\ V_{t'd} & V_{t's} & V_{t'b} & V_{t'b'} \end{pmatrix}$$

- What tree-level constraints do we have?
- What can we say about the mixing with the 4th family, if we assume V_{CKM4} to be unitary?

Mixing with the 4th Family III

Tree-level constraints

$$
\begin{array}{lllll}
V_{ud} & = & 0.97418 & \pm & 0.00027 \\
V_{us} & = & 0.2255 & \pm & 0.0019 \\
V_{ub} & = & 0.00393 & \pm & 0.00036 \\
V_{cd} & = & 0.230 & \pm & 0.011 \\
V_{cs} & = & 1.04 & \pm & 0.06 \\
V_{cb} & = & 0.0412 & \pm & 0.0011 \\
V_{tb} & > & 0.74 & &
\end{array}
$$

V_{ud}	$=$	0.97418	$\pm$	0.00027	Nuclear Beta decay
V_{us}	$=$	0.2255	$\pm$	0.0019	Semileptonic K-decay
V_{ub}	$=$	0.00393	$\pm$	0.00036	Semileptonic B-decay
V_{cd}	$=$	0.230	$\pm$	0.011	Semileptonic D-decay
V_{cs}	$=$	1.04	$\pm$	0.06	Semi- /Leptonic D-decay
V_{cb}	$=$	0.0412	$\pm$	0.0011	Semileptonic B-decay
V_{tb}	$>$	0.74			Single Top-production

Mixing with the 4th Family IV

From the unitarity of V_{CKM4} one gets ($\lambda := V_{us} = 0.2255$)

$$
\begin{aligned}
|V_{ub'}|^2 &= 0.0001 \pm 0.0014 \\
&\Rightarrow \text{Error: } 0.037 \approx 0.74 \cdot \lambda^2 \approx 3.3 \cdot \lambda^3 \\
|V_{td}|^2 + |V_{t'd}|^2 &= -0.0020 \pm 0.0055 \\
&\Rightarrow \text{Error: } 0.074 \propto 1.5 \cdot \lambda^2 \\
|V_{ts}|^2 + |V_{t's}|^2 &= -0.13 \pm 0.13 \\
&\Rightarrow \text{Error: } 0.36 \approx 1.6 \cdot \lambda^1 \\
|V_{cb'}|^2 &= -0.14 \pm 0.18 \\
&\Rightarrow \text{Error: } 0.42 \approx 1.9 \cdot \lambda^1 \\
|V_{t'b}|^2 &< 0.45 \\
&\Rightarrow |V_{t'b}| < 0.67 = 0.67 \cdot \lambda^0
\end{aligned}
$$

Mixing with the 4th Family V

There are many exact parametrizations of V_{CKM4} in the literature

We use the one by **Botella** and **Chau** / **Fritzsch** and **Plankl**

We have now the following parameters:

- The angles $\theta_{12}, \theta_{13}, \theta_{23}, \theta_{14}, \theta_{24}, \theta_{34}$ with $s_{ij} := \sin\theta_{ij}$, $c_{ij} := \cos\theta_{ij}$
- The CP-violating phases $\delta_{13}, \delta_{14}, \delta_{24}$

$$V_{CKM4} =$$

$$\begin{pmatrix}
c_{12}c_{13}c_{14} & c_{13}c_{14}s_{12} & c_{14}s_{13}e^{-i\delta_{13}} & s_{14}e^{-i\delta_{14}} \\
\begin{matrix} -c_{23}c_{24}s_{12} - c_{12}c_{24}s_{13}s_{23}e^{i\delta_{13}} \\ -c_{12}c_{13}s_{14}s_{24}e^{i(\delta_{14}-\delta_{24})} \end{matrix} & \begin{matrix} c_{12}c_{23}c_{24} - c_{24}s_{12}s_{13}s_{23}e^{i\delta_{13}} \\ -c_{13}s_{12}s_{14}s_{24}e^{i(\delta_{14}-\delta_{24})} \end{matrix} & \begin{matrix} c_{13}c_{24}s_{23} \\ -s_{13}s_{14}s_{24}e^{-i(\delta_{13}+\delta_{24}-\delta_{14})} \end{matrix} & c_{14}s_{24}e^{-i\delta_{24}} \\
\begin{matrix} -c_{12}c_{23}c_{34}s_{13}e^{i\delta_{13}} + c_{34}s_{12}s_{23} \\ -c_{12}c_{13}c_{24}s_{14}s_{34}e^{i\delta_{14}} \\ +c_{23}s_{12}s_{24}s_{34}e^{i\delta_{24}} \\ +c_{12}s_{13}s_{23}s_{24}s_{34}e^{i(\delta_{13}+\delta_{24})} \end{matrix} & \begin{matrix} -c_{12}c_{34}s_{23} - c_{23}c_{34}s_{12}s_{13}e^{i\delta_{13}} \\ -c_{12}c_{23}s_{24}s_{34}e^{i\delta_{24}} \\ -c_{13}c_{24}s_{12}s_{14}s_{34}e^{i\delta_{14}} \\ +s_{12}s_{13}s_{23}s_{24}s_{34}e^{i(\delta_{13}+\delta_{24})} \end{matrix} & \begin{matrix} c_{13}c_{23}c_{34} \\ -c_{13}s_{23}s_{24}s_{34}e^{i\delta_{24}} \\ -c_{24}s_{13}s_{14}s_{34}e^{i(\delta_{14}-\delta_{13})} \end{matrix} & c_{14}c_{24}s_{34} \\
\begin{matrix} -c_{12}c_{13}c_{24}c_{34}s_{14}e^{i\delta_{14}} \\ +c_{12}c_{23}s_{13}s_{34}e^{i\delta_{13}} \\ +c_{23}c_{34}s_{12}s_{24}e^{i\delta_{24}} - s_{12}s_{23}s_{34} \\ +c_{12}c_{34}s_{13}s_{23}s_{24}e^{i(\delta_{13}+\delta_{24})} \end{matrix} & \begin{matrix} -c_{12}c_{23}c_{34}s_{24}e^{i\delta_{24}} + c_{12}s_{23}s_{34} \\ -c_{13}c_{24}c_{34}s_{12}s_{14}e^{i\delta_{14}} \\ +c_{23}s_{12}s_{13}s_{34}e^{i\delta_{13}} \\ +c_{34}s_{12}s_{13}s_{23}s_{24}e^{i(\delta_{13}+\delta_{24})} \end{matrix} & \begin{matrix} -c_{13}c_{23}s_{34} \\ -c_{13}c_{34}s_{23}s_{24}e^{i\delta_{24}} \\ -c_{24}c_{34}s_{13}s_{14}e^{i(\delta_{14}-\delta_{13})} \end{matrix} & c_{14}c_{24}c_{34}
\end{pmatrix}$$

Mixing with the 4th Family VI

Strategy

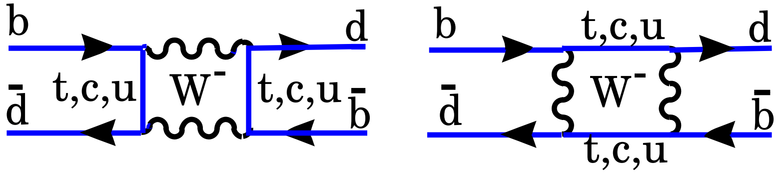
1. Create randomly 10^{10} data points for
   - The angles $\theta_{12}, \theta_{13}, \theta_{23}, \theta_{14}, \theta_{24}, \theta_{34}$
   - The CP-violating phases $\delta_{13}, \delta_{14}, \delta_{24}$
   - The mass m_t' (set $m_b' = m_t' - 55$ GeV)

   Calculate elements of all V_{CKM4} elements exactly!
2. Check if tree level constraints are full-filled
3. Check if FCNC constraints are full-filled

$\Rightarrow 10^7 (10^5)$ data points survive

Mixing with the 4th Family VII

Bounds from FCNC:

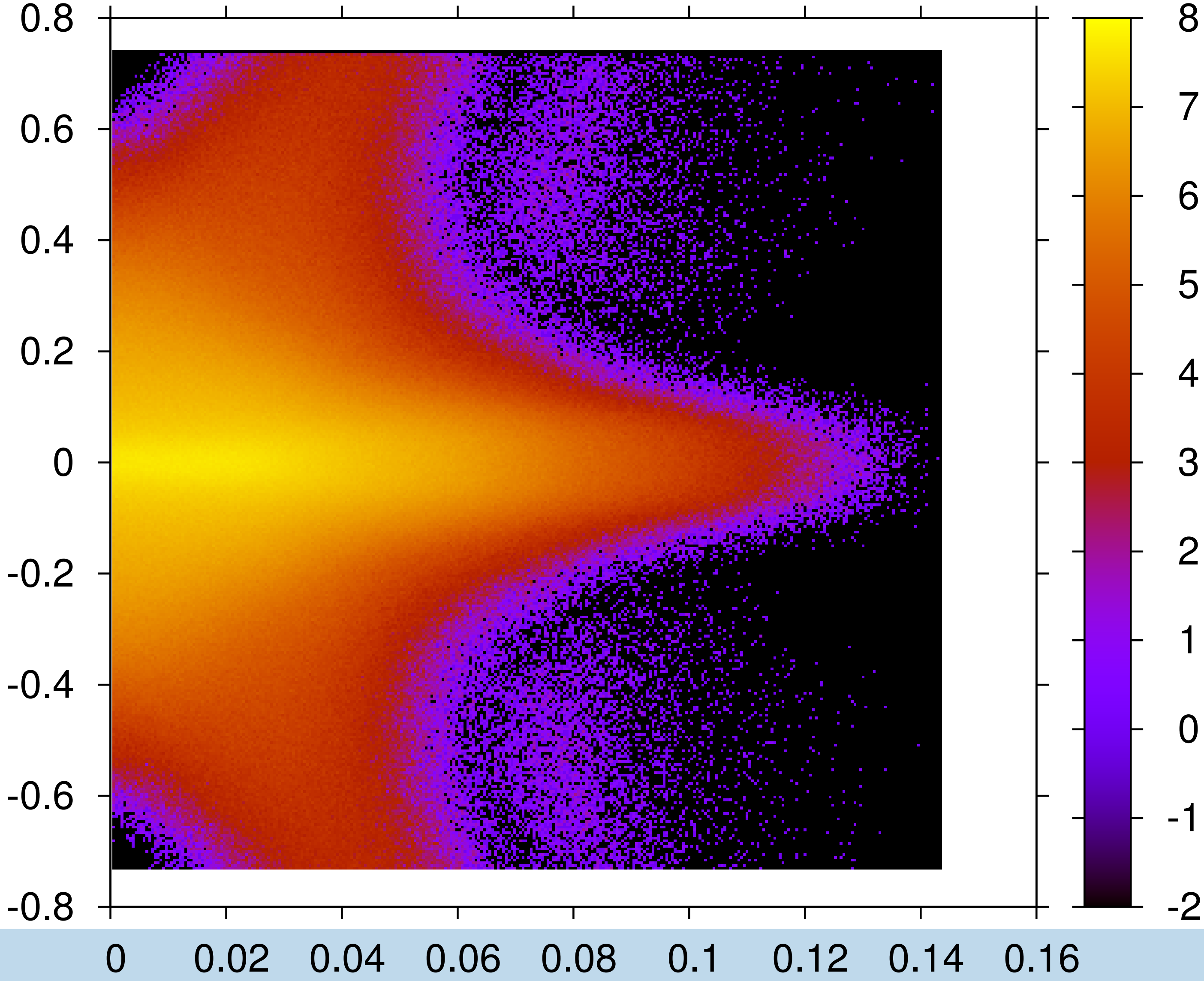


$$\Delta_X := \frac{X_{SM4}}{X_{SM3}}$$

- K-Mixing: $Re(\Delta_K) = 1 \pm 0.5\,(0.25)$ $\quad Im(\Delta_K) = 0 \pm 0.3\,(0.15)$
- B_d-Mixing: $|\Delta_{B_d}| = 1 \pm 0.3\,(0.1)$ $\quad Arg(\Delta_{B_d}) = 0 \pm 10^\circ\,(5^\circ)$
- B_s-Mixing: $|\Delta_{B_s}| = 1 \pm 0.3\,(0.1)$ $\quad Arg(\Delta_{B_s}) =$ free
- $b \to s\gamma$ $\quad \Delta_{b\to s\gamma} = 1 \pm 0.15\,(0.07)$

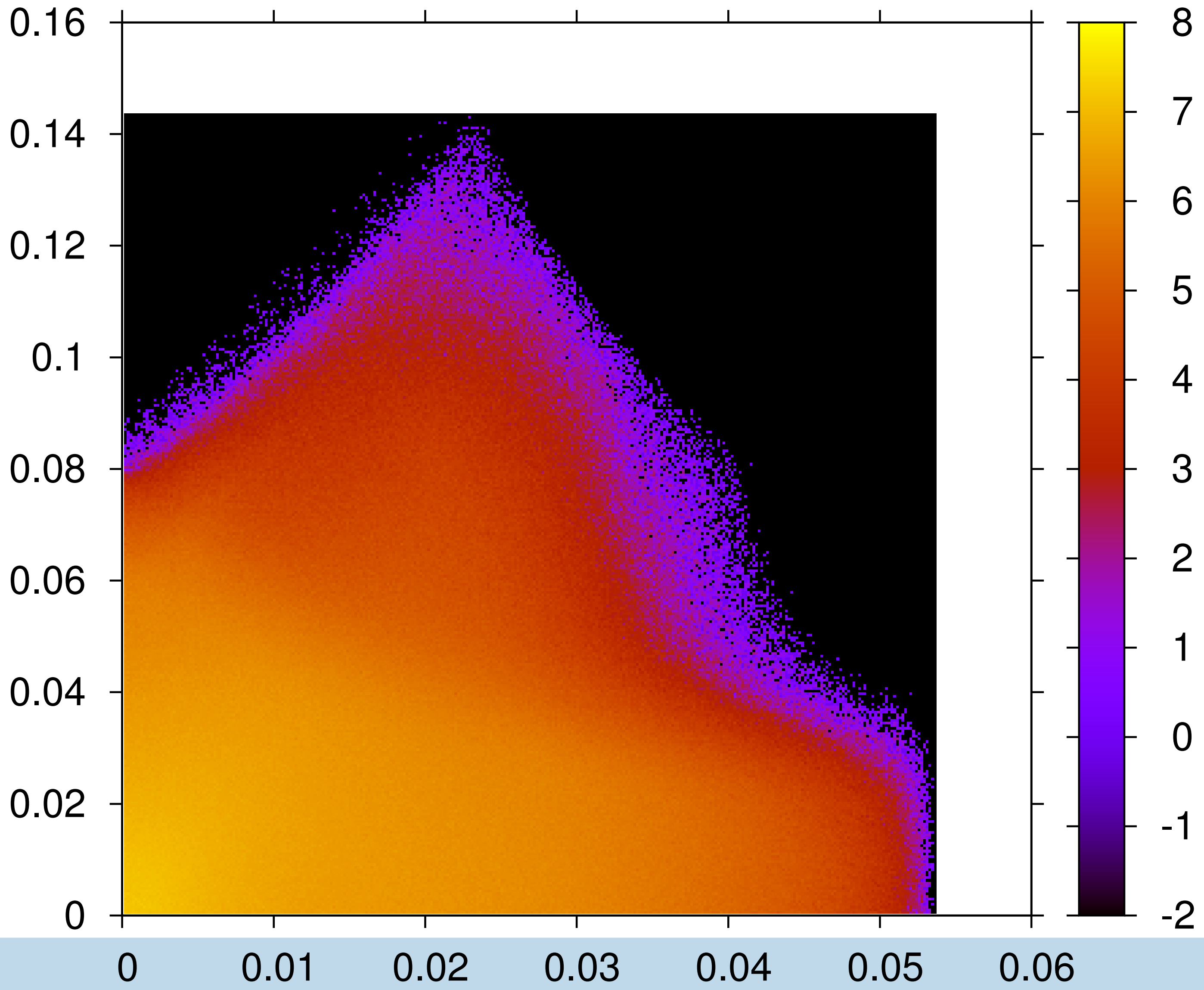
Mixing with the 4th Family VIII

Allowed Parameters: θ_{34} vs. θ_{24}



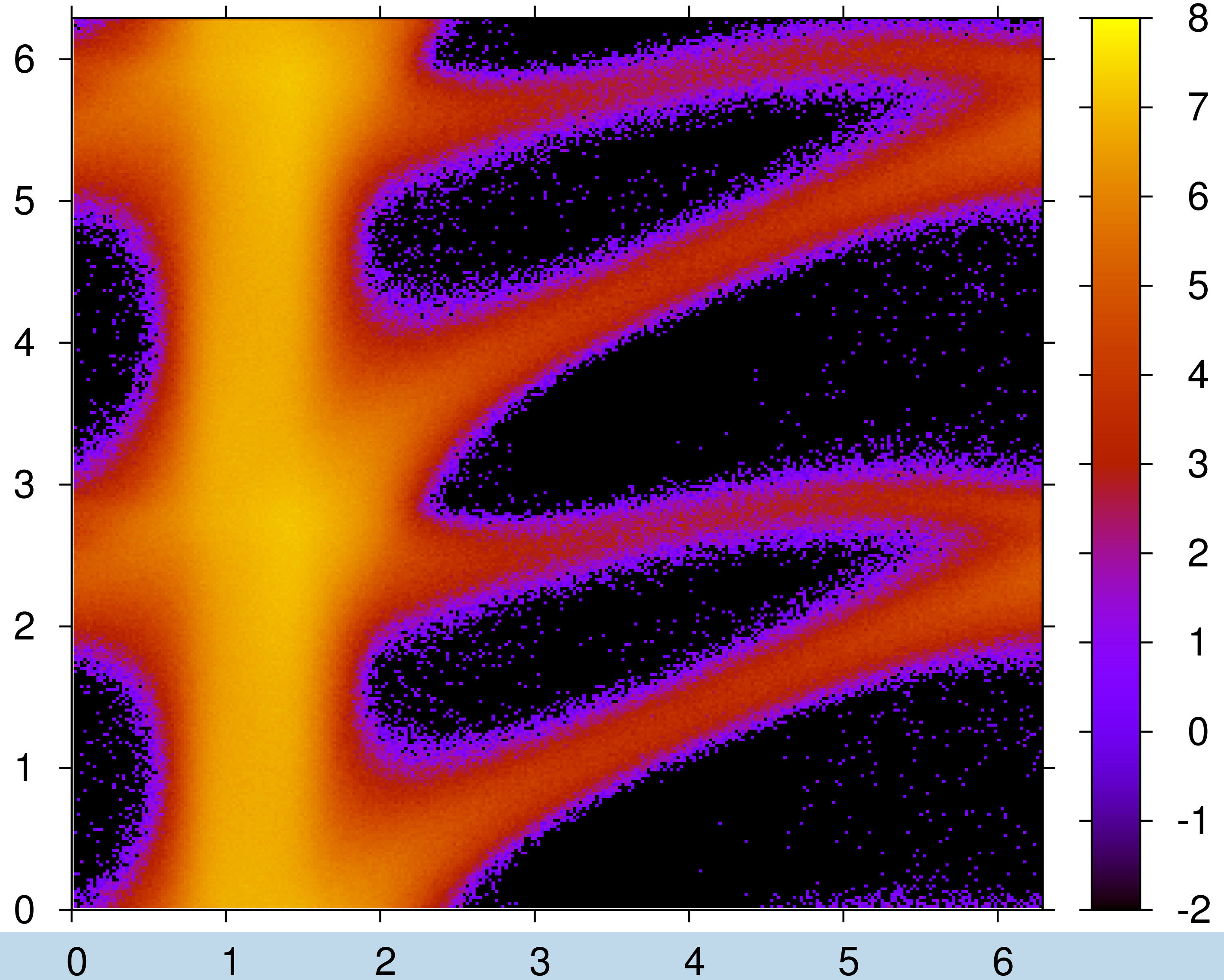
Mixing with the 4th Family IX

Allowed Parameters: θ_{24} vs. θ_{14}



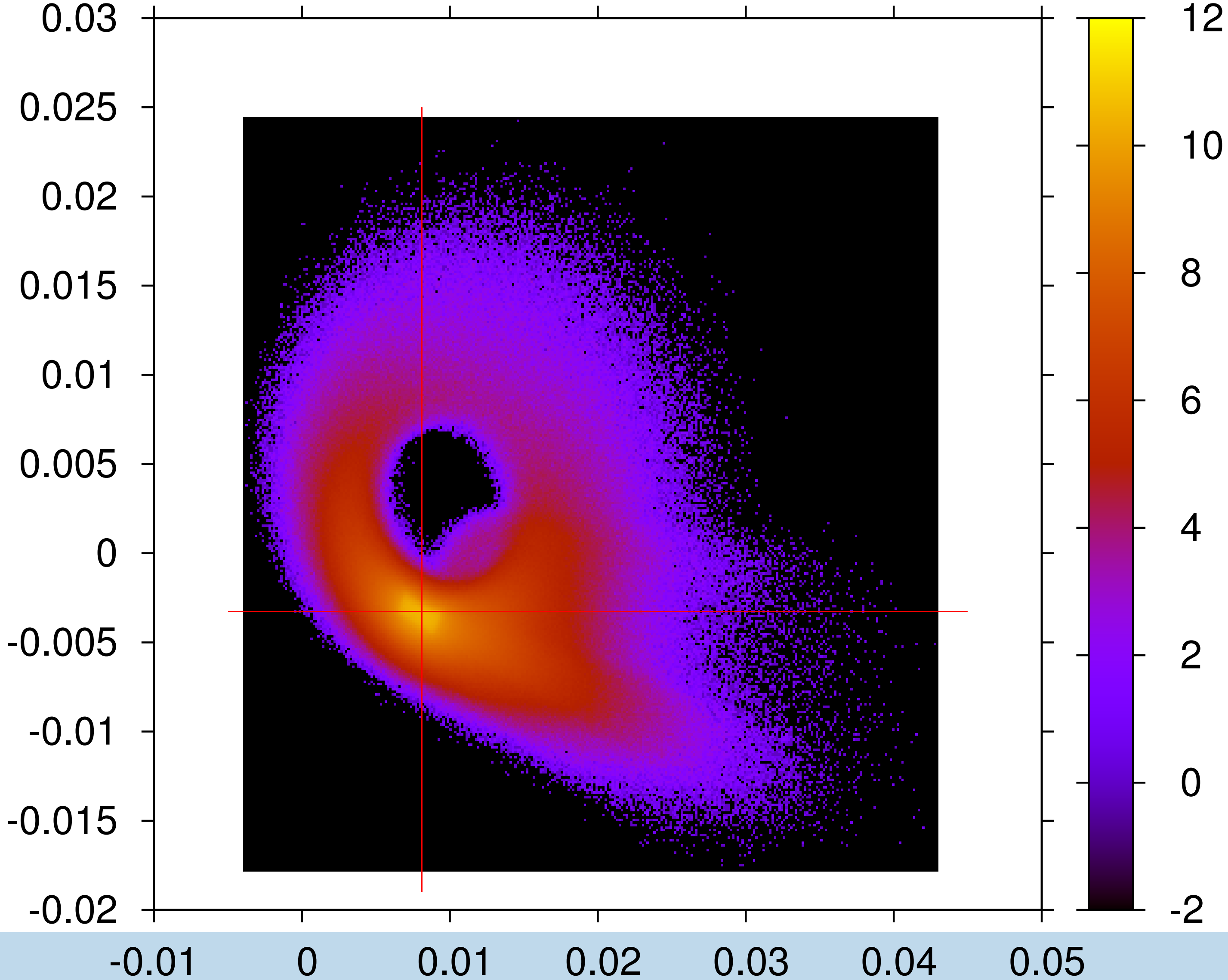
Mixing with the 4th Family X

Allowed Parameters: δ_{14} vs. δ_{13}



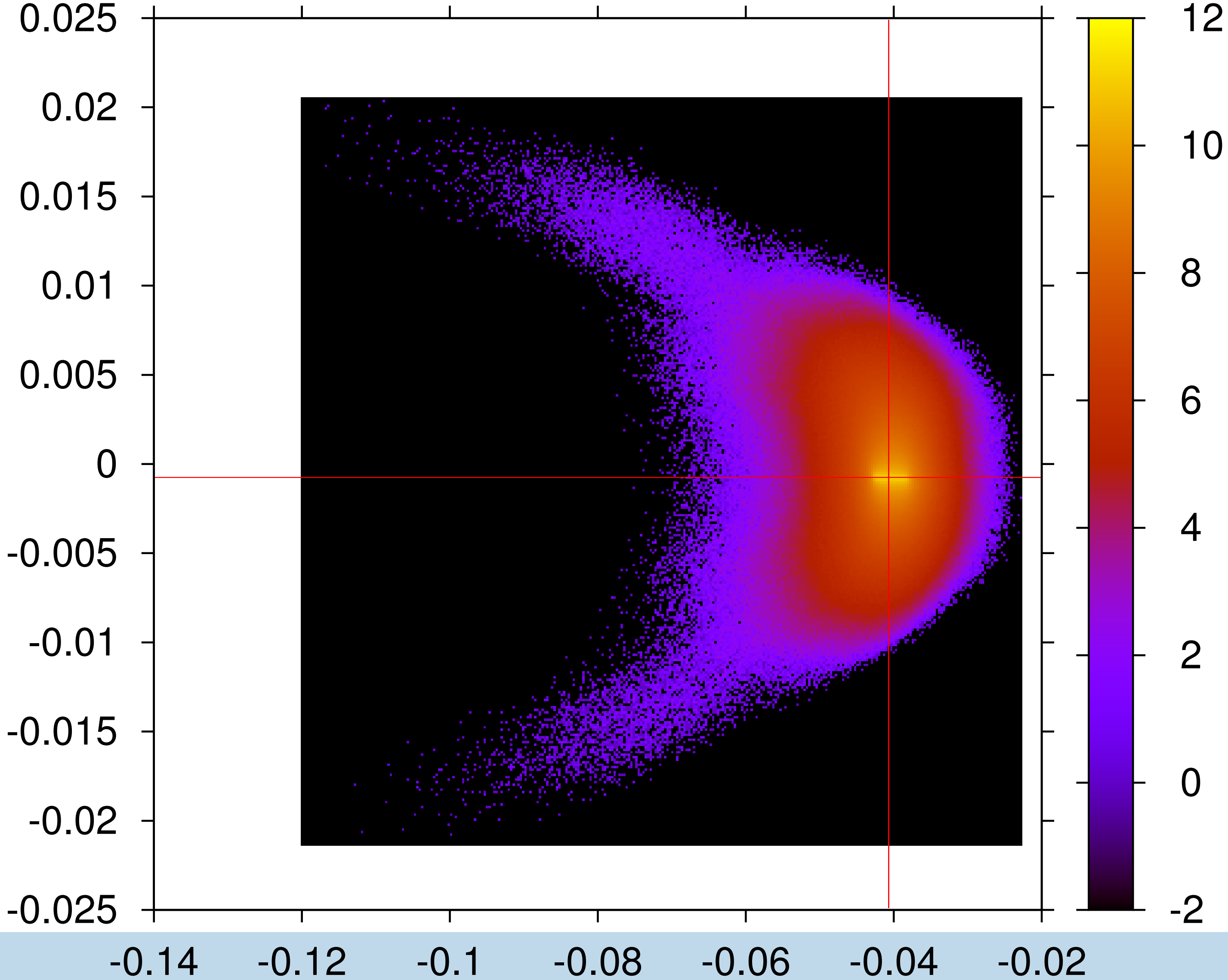
Mixing with the 4th Family XI

Allowed Parameters: Im V_{td} vs. Re V_{td}



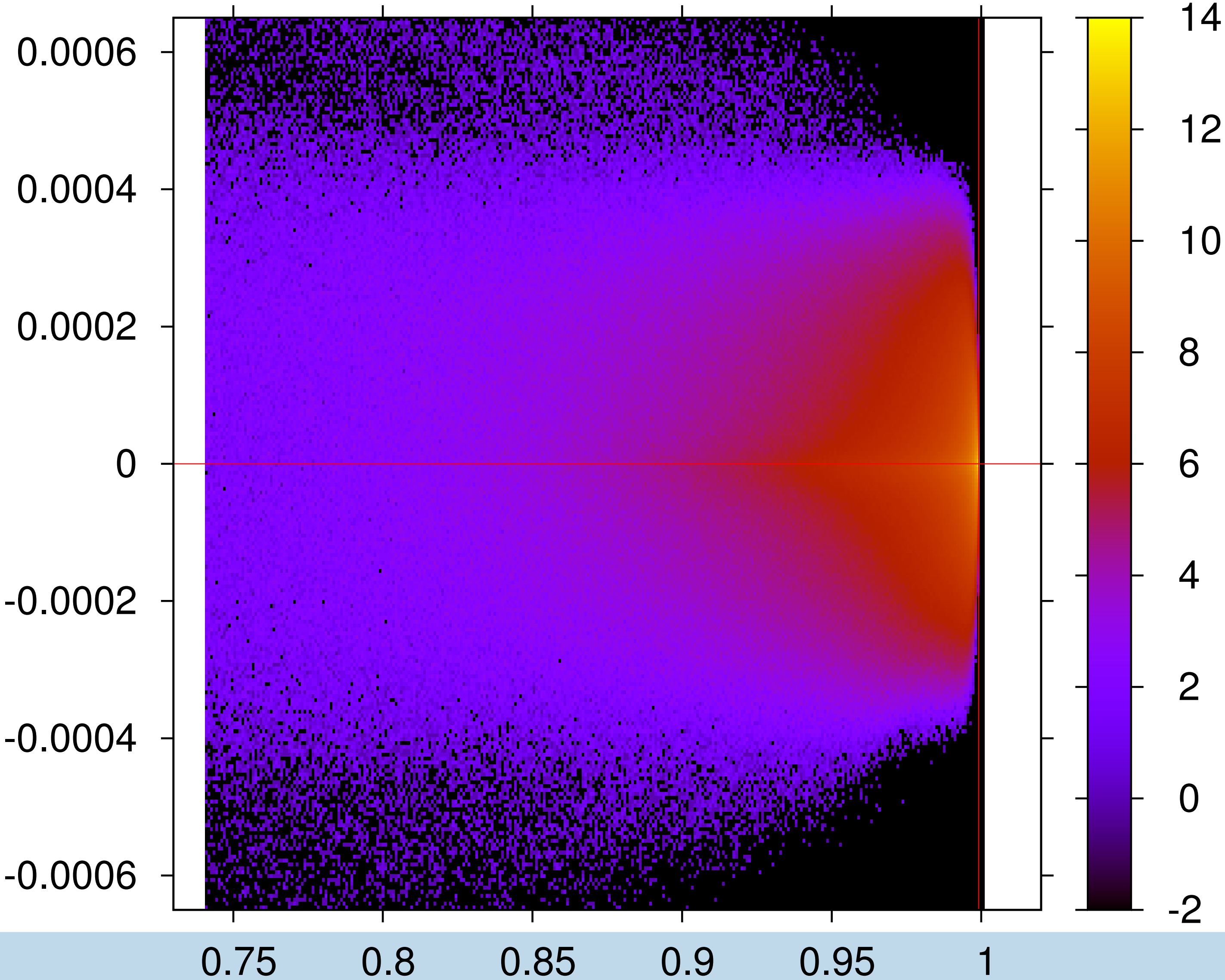
Mixing with the 4th Family XII

Allowed Parameters: Im V_{ts} vs. Re V_{ts}



Mixing with the 4th Family XIII

Allowed Parameters: Im V_{tb} vs. Re V_{tb}



Mixing with the 4th Family XIV

Result:

- **As expected:** most points belong to SM3 like parameters
- **Unexpected:** large mixing not yet excluded
  V_{td}, V_{ts}, V_{tb} can differ considerably from SM3-fit values

Ultraconservative allowed ranges

$$\begin{aligned}
\theta_{14} &\leq 0.04 \approx 1.27\lambda^2 \\
\theta_{24} &\leq 0.25 \approx 0.9\lambda^1 \\
\theta_{34} &\leq 0.8 \approx 0.8\lambda^0 \\
\delta_{14}, \delta_{24} &\leq 2\pi
\end{aligned}$$

No “nice” Wolfenstein expansion possible

Mixing with the 4th Family XV

Unexpected regions in the allowed parameter space

$$x_{14} = 0.8617, \qquad y_{14} = 0.8838$$
$$\theta_{24} = 0.08367, \qquad \theta_{34} = 0.5574, \quad \delta_{24} = 0.3149,$$
$$m_t = 160 \text{ GeV}, \qquad m_{t'} = 503.3 \text{ GeV}, \quad m_c = 1.2 \text{ GeV}$$

leads to

$$\begin{aligned}
\Delta_K &= 1.012 + 0.139i \\
\Delta_{B_d} &= 0.718 - 0.040i = 0.72\, e^{i3.2^\circ} \\
\Delta_{B_s} &= 0.6393 - 0.5353i = 0.834\, e^{-i39.9^\circ} \\
\Delta_{b \to s\gamma} &= 1.041
\end{aligned}$$

and

$$\begin{aligned}
|V_{td}| &= 0.012 \quad \text{vs.} \quad 0.00874 \pm 0.0004 \\
|V_{ts}| &= 0.08 \quad \text{vs.} \quad 0.0407 \pm 0.0010 \\
|V_{tb}| &= 0.84 \quad \text{vs.} \quad 0.99913 \pm 0.0004
\end{aligned}$$

Mixing with the 4th Family XVI

Why is this not seen in CKM-Fits?

Mixing with the 4th Family XVII

Why is this not seen in CKM-Fits?

Nature might be nasty
Large Effects cancel and imitate the SM3 result

Mixing with the 4th Family XVIII

Why is this not seen in CKM-Fits?

Split up the contributions as

$$\frac{M_{12}^{SM4}}{M_{12}^{SM3}} = 1 + \left(\frac{M_{12}^{t,VCKM4}}{M_{12}^{t,VCKM3}} - 1 \right) + \frac{M_{12}^{t',VCKM4}}{M_{12}^{t,VCKM3}}$$

With our previous example we obtain

$$\begin{aligned} \frac{M_{B_s,12}^{SM4}}{M_{B_s 12}^{SM3}} &= 1 + (1.48304 - 0.986885 I) + (-1.84369 + 0.451341 I) \\ &= 0.6393 - 0.5353 i = 0.834\, e^{-i 39.9^\circ} \end{aligned}$$

Nature might be nasty
Large Effects cancel and imitate the SM3 result

New Physics in B_s mixing? I

A.L., Nierste, hep-ph/0612167

$$\Gamma_{12,s} = \Gamma_{12,s}^{\rm SM}\,, \qquad M_{12,s} = M_{12,s}^{\rm SM} \cdot \Delta_s\,; \qquad \Delta_s = |\Delta_s| e^{i\phi_s^\Delta}$$

$$\Delta M_s = 2|M_{12,s}^{\rm SM}| \cdot |\Delta_s|$$

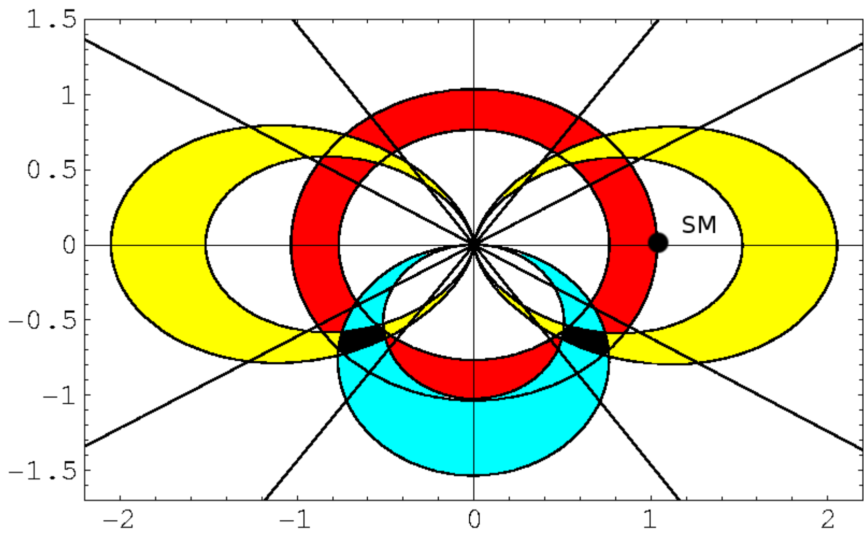
$$\Delta \Gamma_s = 2|\Gamma_{12,s}| \cdot \cos\left(\phi_s^{\rm SM} + \phi_s^\Delta\right)$$

$$\frac{\Delta \Gamma_s}{\Delta M_s} = \frac{|\Gamma_{12,s}|}{|M_{12,s}^{\rm SM}|} \cdot \frac{\cos\left(\phi_s^{\rm SM} + \phi_s^\Delta\right)}{|\Delta_s|}$$

$$a_{fs}^s = \frac{|\Gamma_{12,s}|}{|M_{12,s}^{\rm SM}|} \cdot \frac{\sin\left(\phi_s^{\rm SM} + \phi_s^\Delta\right)}{|\Delta_s|}$$

$$\sin(\phi_s^{\rm SM}) \approx 1/240$$

For $|\Delta_s| = 0.9$ and $\phi_s^\Delta = -\pi/4$ one gets the following bounds in the **complex Δ-plane**:



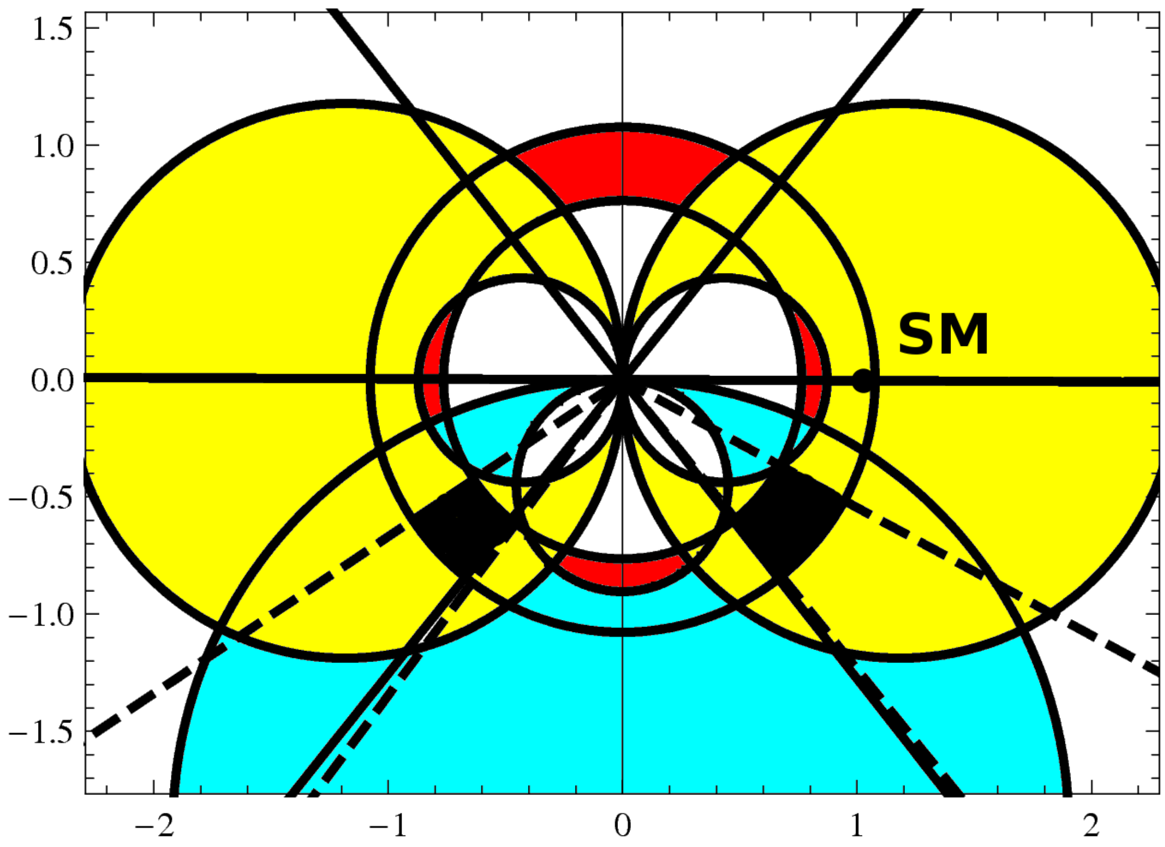
New Physics in B_s Mixing II

Current exp. bounds:

- ΔM_s
- Dimuonasymmetry
- A_{sl}^s direct
- $\Delta\Gamma, \Phi_s$ $(B_s \to J/\Psi\Phi)$ combined tagged number in progress

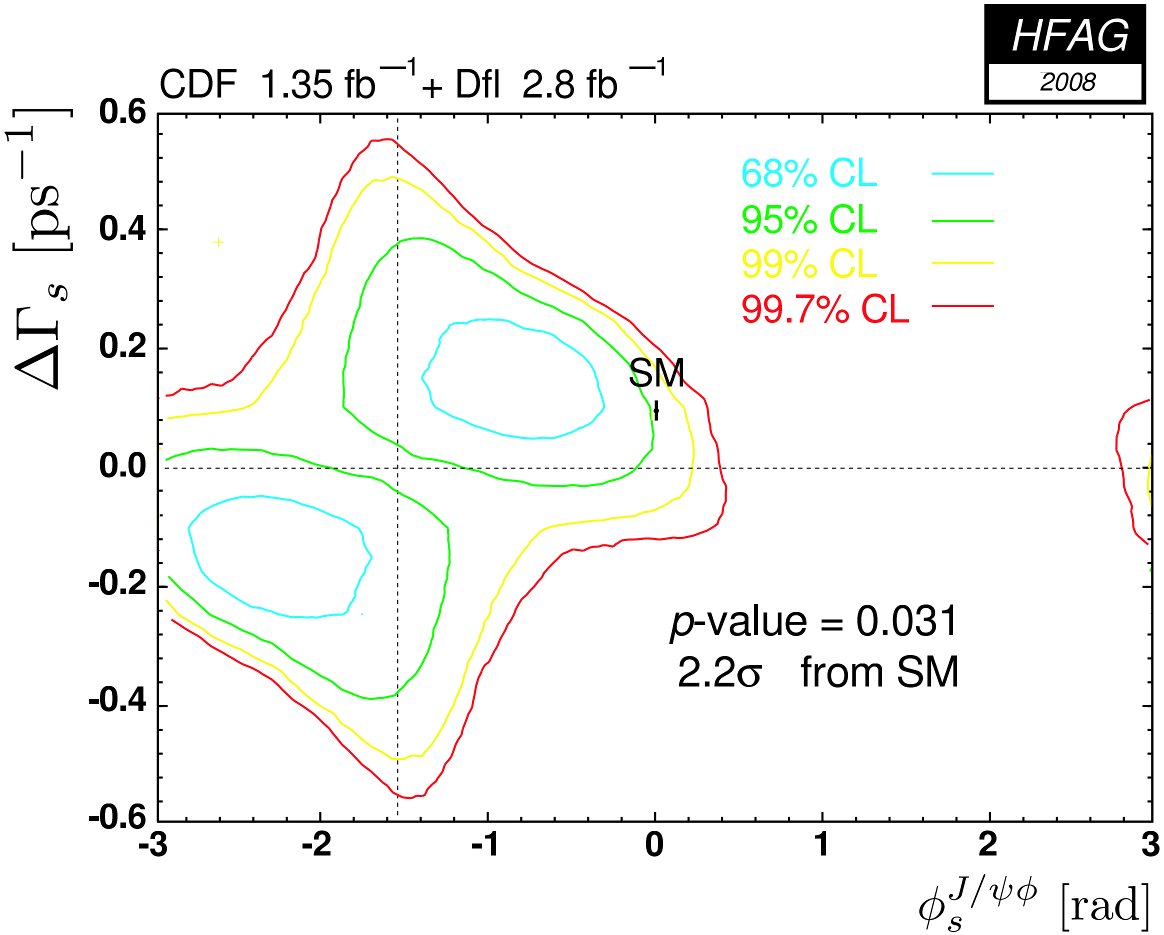
Analyses

- A. L., U. Nierste, CKMfitter in preparation
- UT-Fit, arXiv:0803.0659, 3.7 σ deviation



New Physics in B_s Mixing III

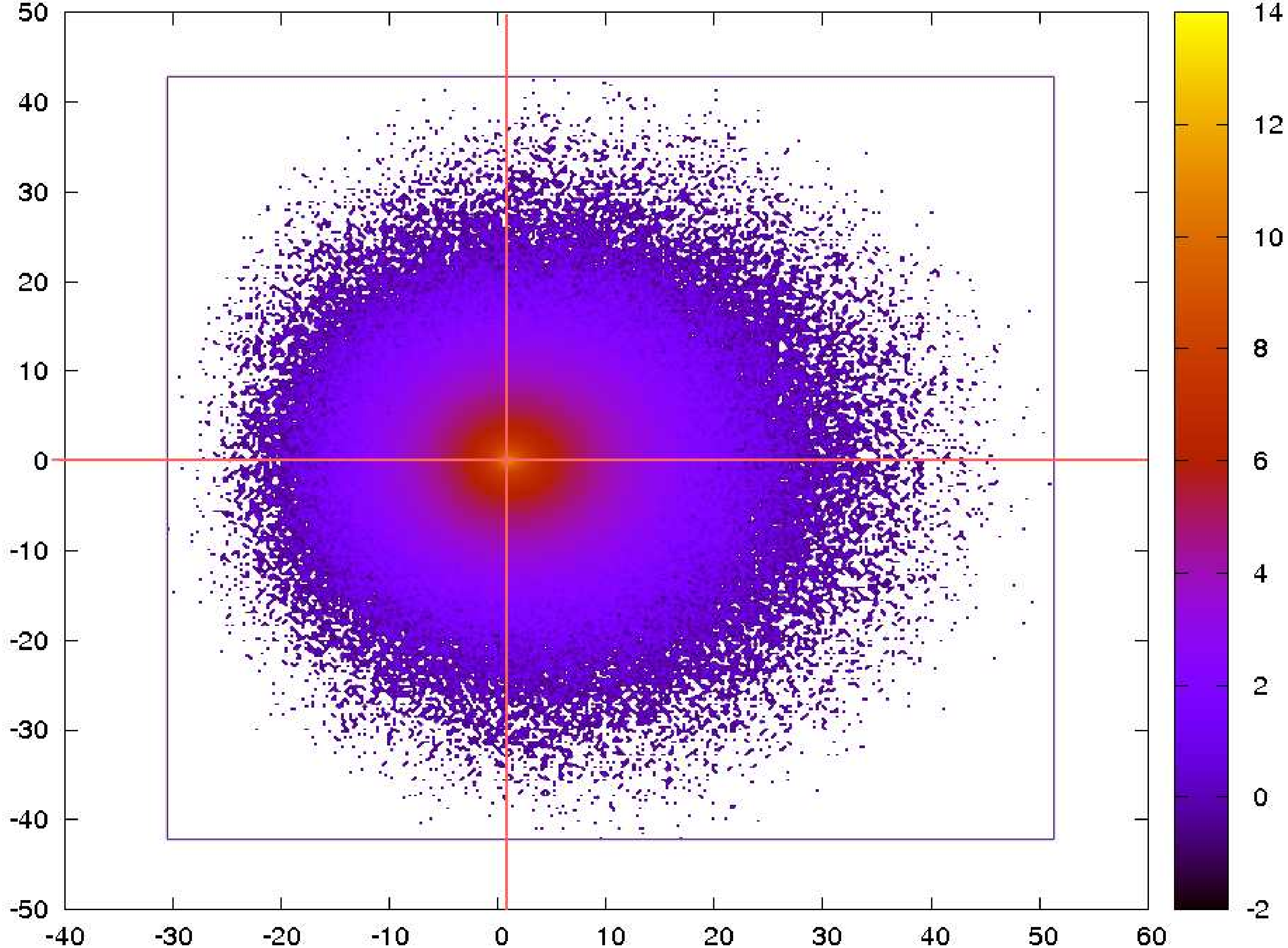
TeVatron is trying hard to find new physics before LHC: see talk by D. Zieminska



Current consensus: 2.2-2.9 σ deviation from SM: CKMfitter, HFAG, UTfit

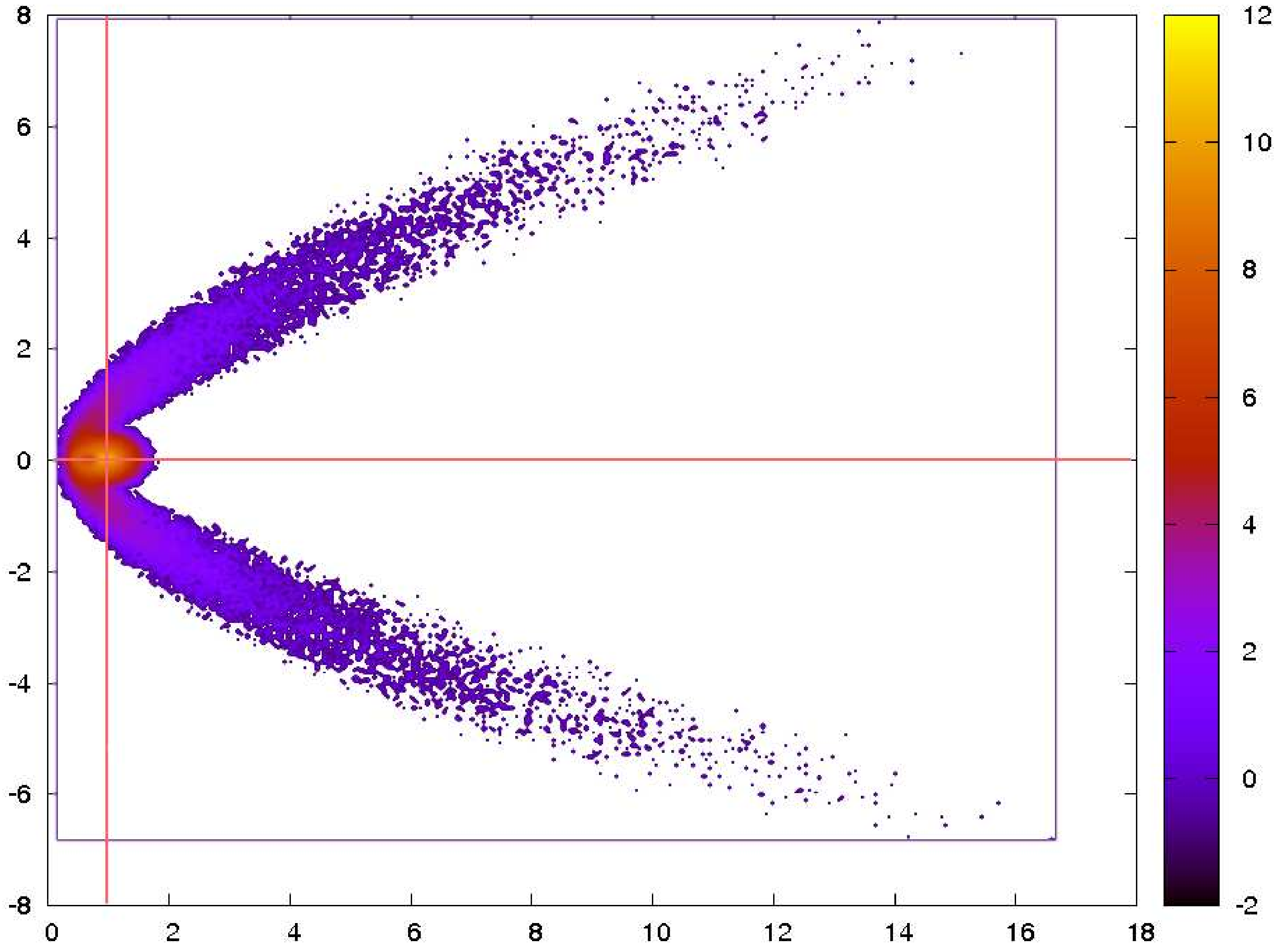
New Physics in B_s mixing = 4th family? I

Only Tree-level Bounds: Im Δ_{B_s} vs. Re Δ_{B_s}



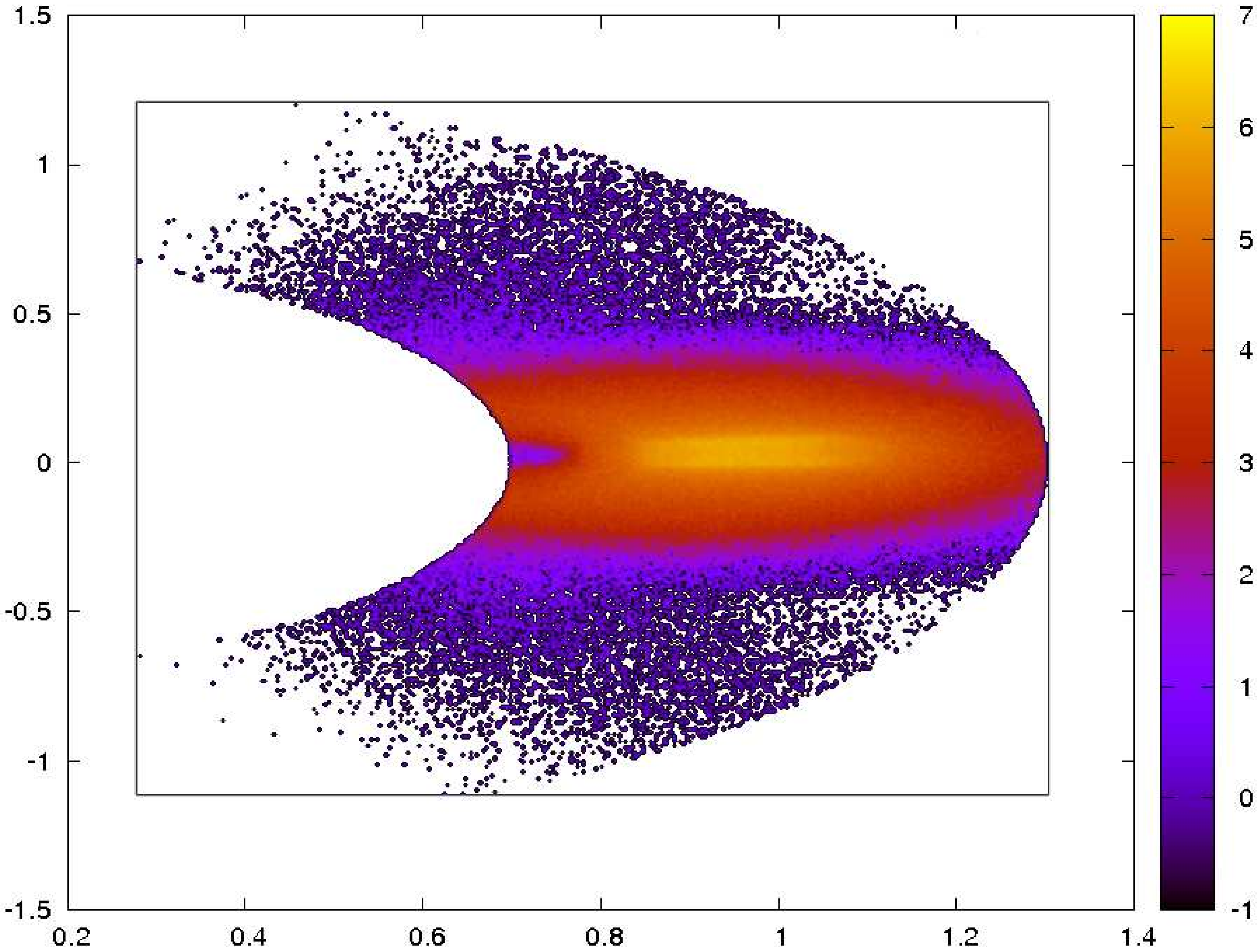
New Physics in B_s mixing = 4th family? II

Tree-level+ $b \to s\gamma$: Im Δ_{B_s} vs. Re Δ_{B_s}



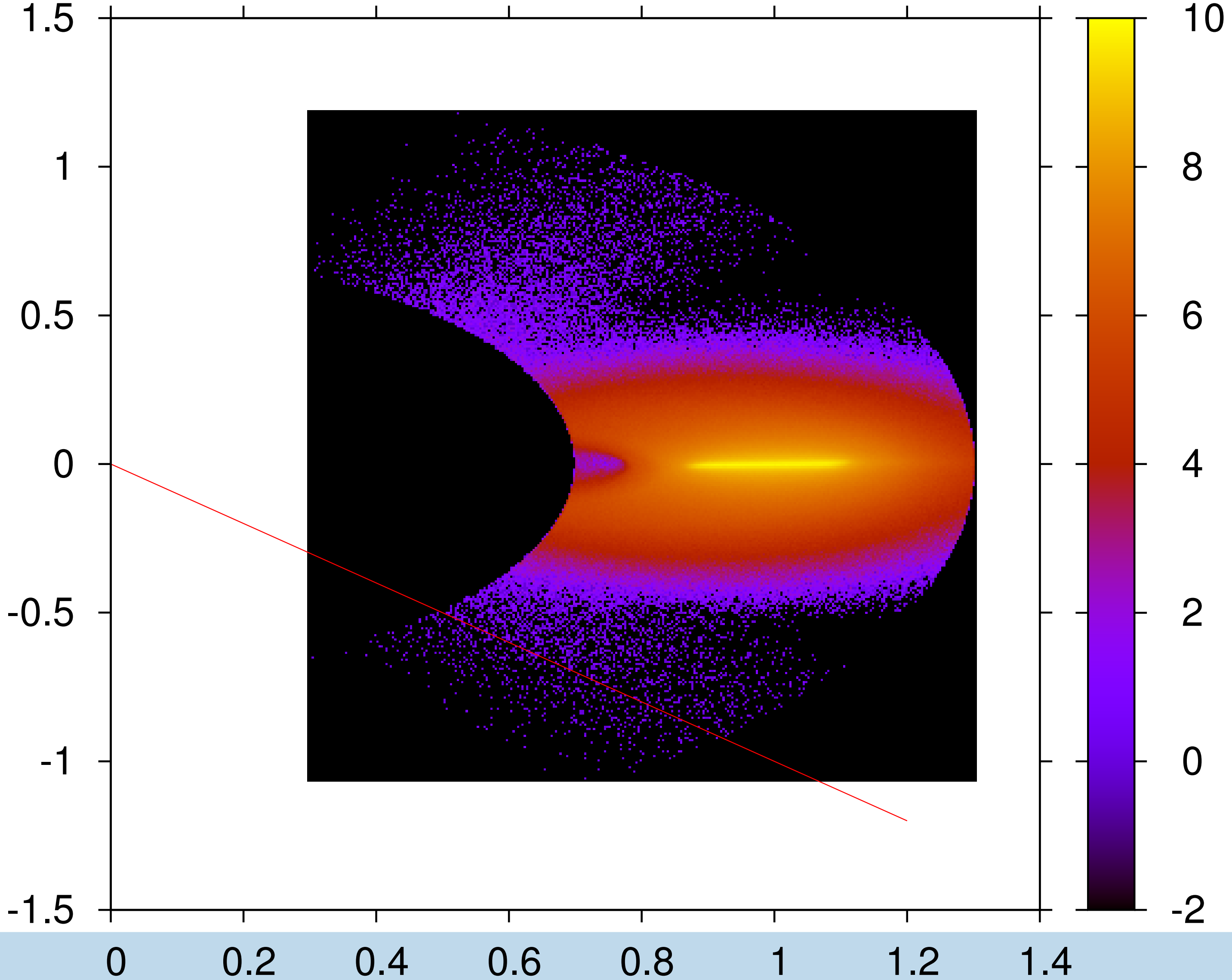
New Physics in B_s mixing = 4th family? III

Tree-level+ $b \to s\gamma$ + ΔM_s: Im Δ_{B_s} vs. Re Δ_{B_s}



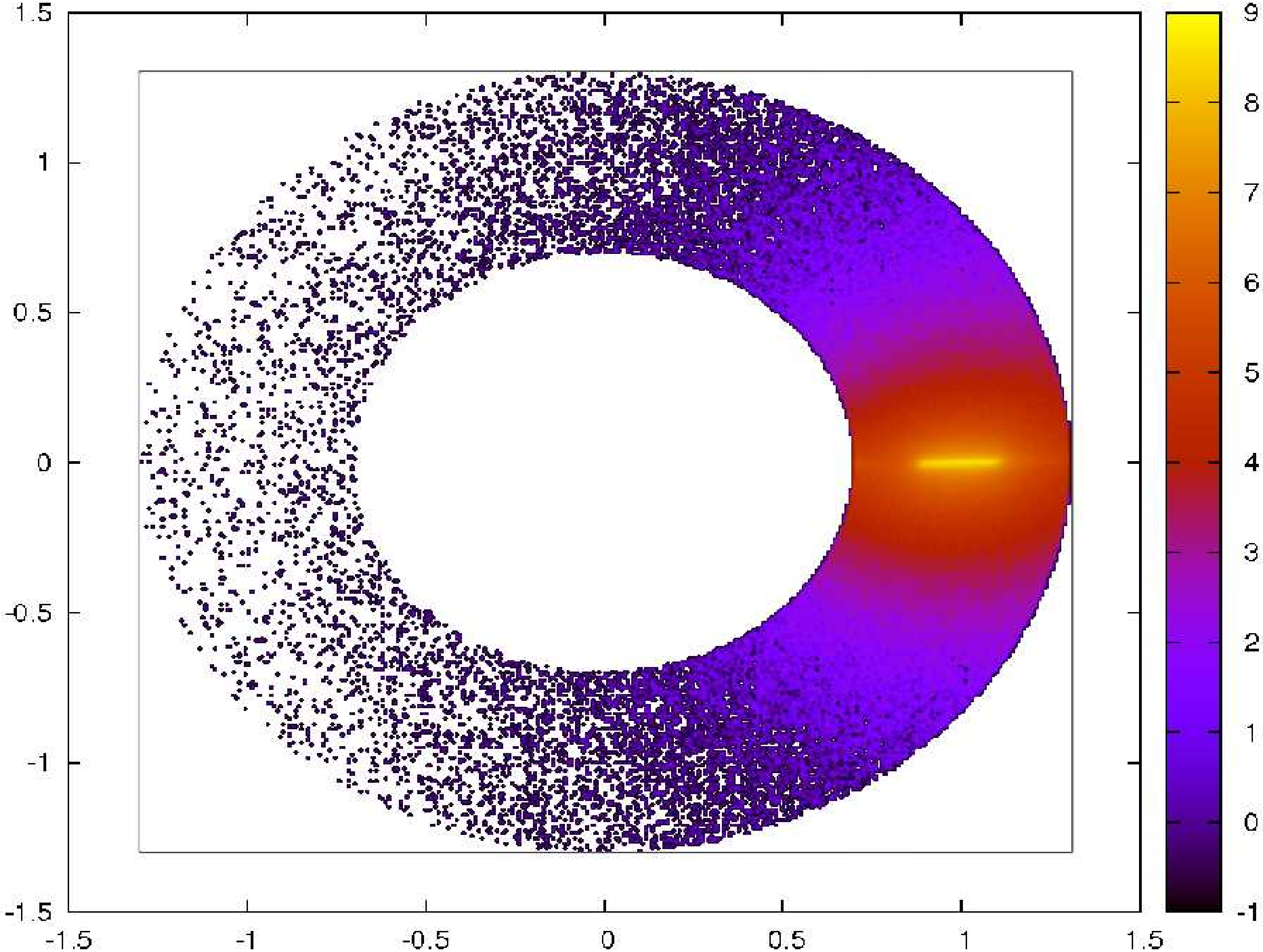
New Physics in B_s mixing = 4th family? IV

All bounds: Im Δ_{B_s} vs. Re Δ_{B_s}



New Physics in B_s mixing = 4th family? V

All bounds but $b \to s\gamma$: Im Δ_{B_s} vs. Re Δ_{B_s}



Why exploratory?

- QCD in $b \to s\gamma$ naive - only CKM times Inami-Lim
  Determine full $\mathcal{H}_{eff}$ for SM4
- Many Flavor observables missing
  Include more flavor observables, e.g. $B_s \to \mu\mu$, ...
- No electro-weak observable included
  Include S,T,U — R_b
  Include full dependence on V_{CKM} (typically $V_{tb} = 1$)
  Chanowitz excluded 3 of our numerous unexpected data points

Work in progress with M. Bobrowski, J. Rohrwild, J. Riedl, O. Eberhardt
thanks to J. Erler for many explanations

- Our approach has no statistical meaning yet
  Make a fit - like the CKMfit

Collaboration with H. Lacker and U. Nierste

Wishlist

What do we need to constrain V_{CKM4} further?

- More precise determination of V_{cd} and V_{cs} — Need e.g. f_{D_s}, $D \to K$ form factor
- More precise determination of V_{tb} — Single top production at TeVatron
- Tree level determination of V_{td} and V_{ts} possible?
- Precise determination of all mixing quantities

Final Experimental work

- Find fourth family

SM predictions for Γ_{12} in D-mixing I

in collaboration with M. Bobrowski, J. Riedl, J. Rohrwild; arXiv:0904.3971

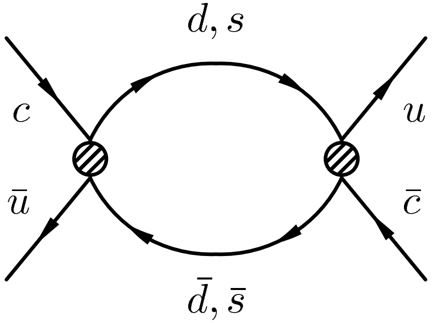
$$\Gamma_{12} = -\lambda_s^2 \Gamma_{ss} - \lambda_s \lambda_d \Gamma_{sd} - \lambda_d^2 \Gamma_{dd}$$

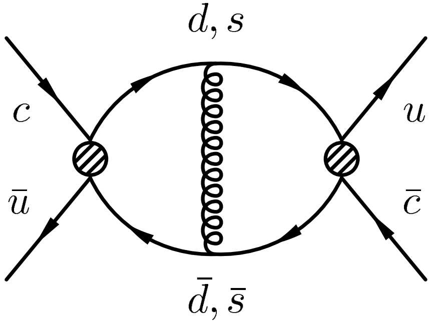
with $\lambda_d + \lambda_s + \lambda_b = 0$ and $\lambda_x = V_{cx} V_{ux}^*$.

If $\lambda_b \approx 0 \Rightarrow \Gamma_{12}$ real and vanishes in the SU(3)$_F$ limit

$$GIM cancellations : \Gamma_{12} = -\lambda_s^2 \left(\Gamma_{ss} - 2\Gamma_{sd} + \Gamma_{dd}\right) + 2\lambda_s \lambda_b \left(\Gamma_{sd} - \Gamma_{dd}\right) - \lambda_b^2 \Gamma_{dd}$$

- not zero in SU(3)$_F$ limit

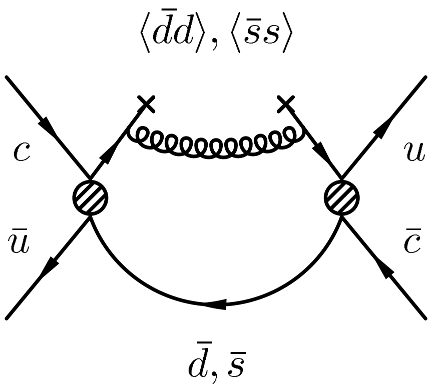


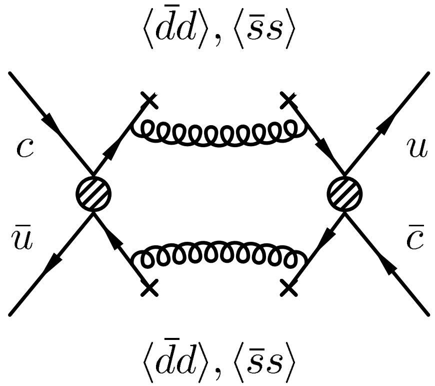


- $\Gamma_{12} \propto \lambda_s^2 m_s^6/m_c^6 + 2\lambda_s \lambda_b m_s^2/m_c^2 - \lambda_b^2 \; 1$
- $y_D \in [0.3, 1.5] \cdot 10^{-6} \Rightarrow$ much smaller than experiment ($7 \cdot 10^{-3}$), but large phase ($\mathcal{O}(1)$) possible

SM predictions for Γ_{12} in D-mixing II

Idea: higher orders in HQE might be dominant if GIM is less pronounced





naive expectation for a single diagram:

y_D	no GIM	with GIM
$D = 6, 7$	$2 \cdot 10^{-2}$	$5 \cdot 10^{-7}$
$D = 9$	$5 \cdot 10^{-4}$	???
$D = 12$	$2 \cdot 10^{-5}$	???

? Can one obtain $y_D^{Exp.}$?

?How big can ϕ be?

SM4 predictions for Γ_{12} in D-mixing

Overseen: Large Effects in Γ_{12} in D-mixing due to NP possible!

$$\Gamma_{12} = -\lambda_s^2 \left(\Gamma_{ss} - 2\Gamma_{sd} + \Gamma_{dd}\right) + 2\lambda_s(\lambda_b + \lambda_{b'}) \left(\Gamma_{sd} - \Gamma_{dd}\right) - (\lambda_b + \lambda_{b'})^2 \Gamma_{dd}$$

$\lambda_b \propto \lambda^{5\ldots6}$ - still possible $\lambda_{b'} \propto \lambda^3$