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B&K mixing and CP asymmetries in SUSY at NLO

M.Ciuchini, E.Franco, D.Guadagnoli, V.Lubicz, V.P., L.Silvestrini

We derive bounds on the squark mass splittings comparing the full NLO computation of gluino-mediated contributions to $\Delta B=2$ and $\Delta S=2$ processes with the measured values of

$$\Delta M_K \qquad \varepsilon_K \qquad a_{J/\psi K_s} \qquad \Delta M_d \qquad \Delta M_s$$

analysis in progress…

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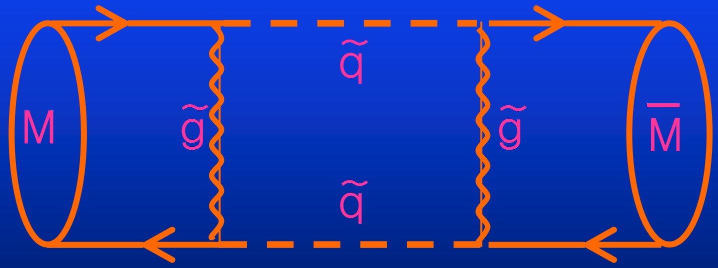
α_s^2



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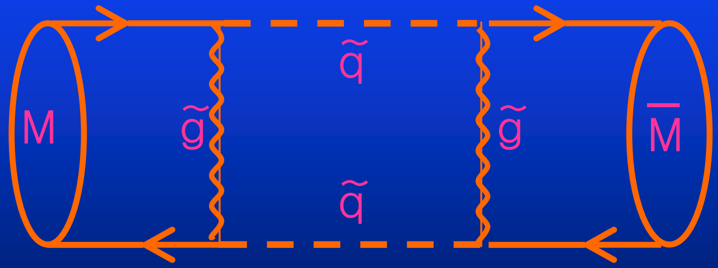

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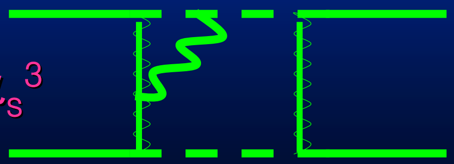

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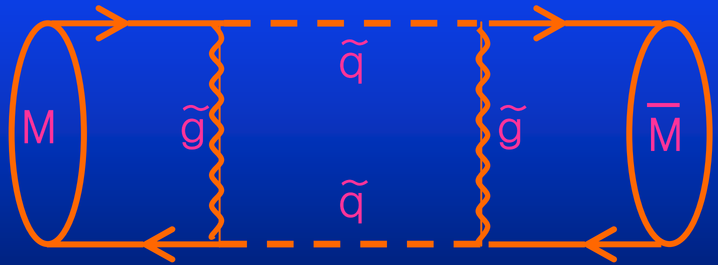

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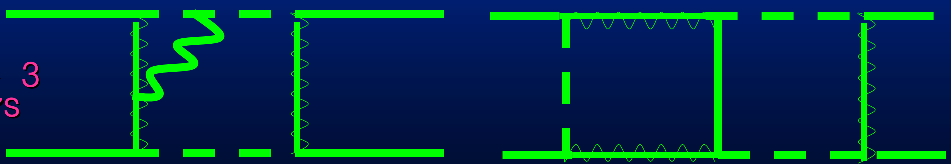

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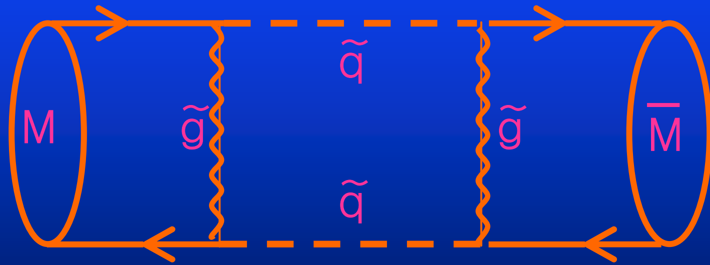

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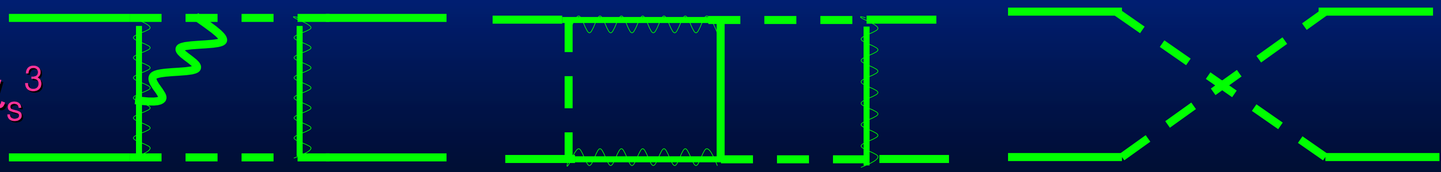

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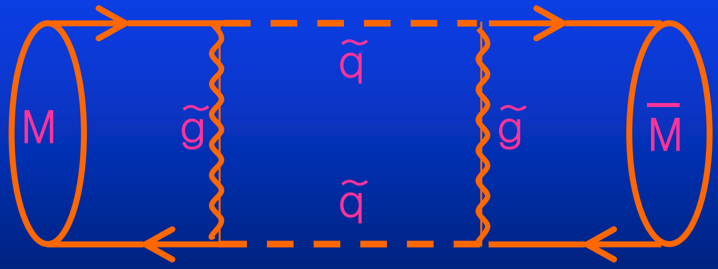

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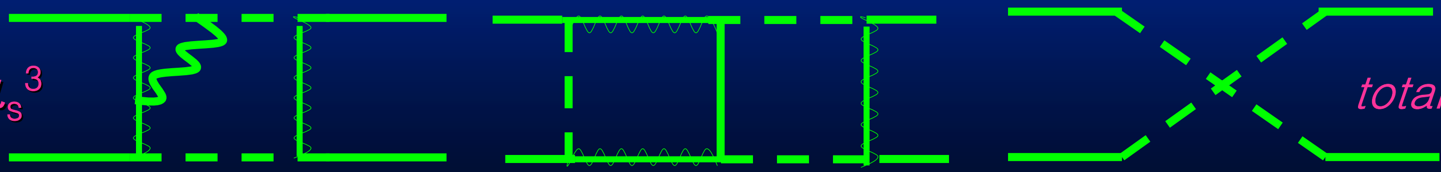

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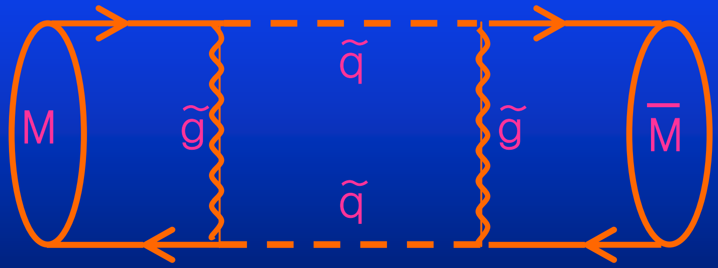

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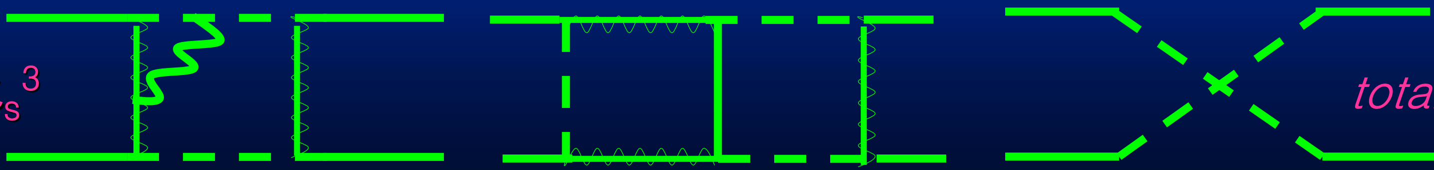

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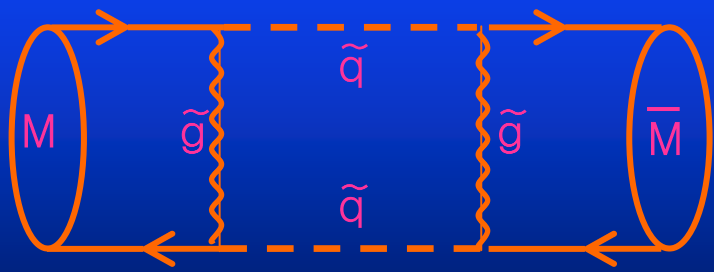

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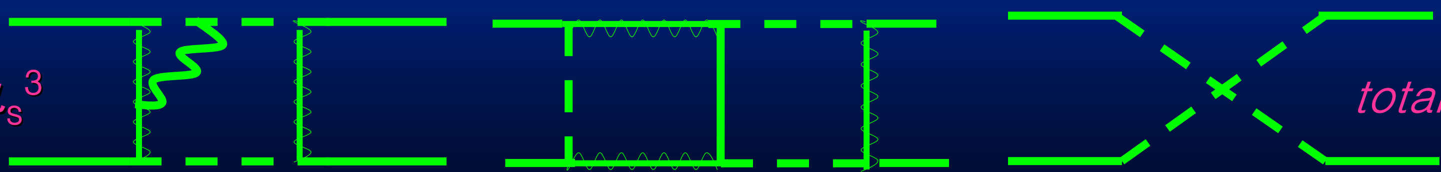

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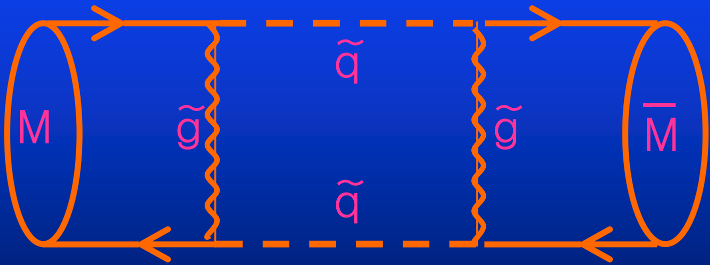

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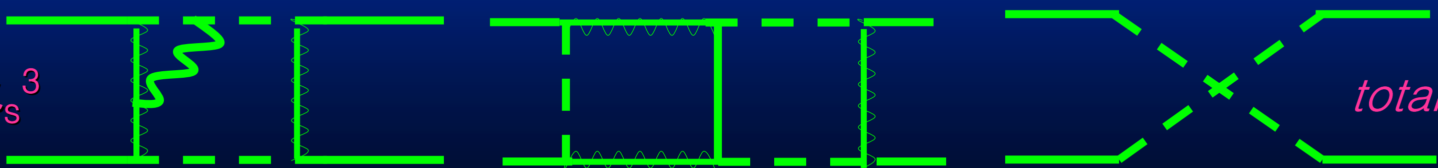

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And what is (still) missing

– global analysis including also charginos, neutralinos, charged Higgs exchange

– unquenched $B_{3,4,5}$ parameters

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It is an unexpected experimental fact that in charged current weak interactions the mass eigenstates are mixed.

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we use FCNC and CP violating processes to constrain the huge SUSY parameter space

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Squared mass matrix for the squarks $(\tilde{d}_L, \tilde{s}_L, \tilde{b}_L, \tilde{d}_R^*, \tilde{s}_R^*, \tilde{b}_R^*)$ in the basis where the quark mass matrices $m_{u,d}$ are diagonal

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Every block is 3x3 in flavour space

$$\begin{pmatrix} m_1^2 & \Delta^{12} & \Delta^{13} \\ \Delta^{21} & m_2^2 & \Delta^{23} \\ \Delta^{31} & \Delta^{32} & m_3^2 \end{pmatrix}_{LR}$$

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In order to properly account for the scheme and scale dependence in the physical result *2 loop diagrams are needed*

Low energy part

Integrating out squarks and gluinos gives the operators (SUSY basis)

$$Q_1 = \bar{d}_L^{\alpha} \gamma_\mu b_L^{\alpha} \bar{d}_L^{\beta} \gamma_\mu b_L^{\beta} \qquad Q_4 = \bar{d}_R^{\alpha} b_L^{\alpha} \bar{d}_L^{\beta} b_R^{\beta}$$

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The matrix elements of the operators between the mesons M are given in the Vacuum Insertion Approximation (VIA) as functions of the quark and the meson masses and decay constant.
The effect of non-factorizable corrections is contained in the B parameters

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important: $Q_{2,3,4,5}$ can be enhanced with respect to Q_1 by $m_M^2/(m_{q_1}+m_{q_2})^2$

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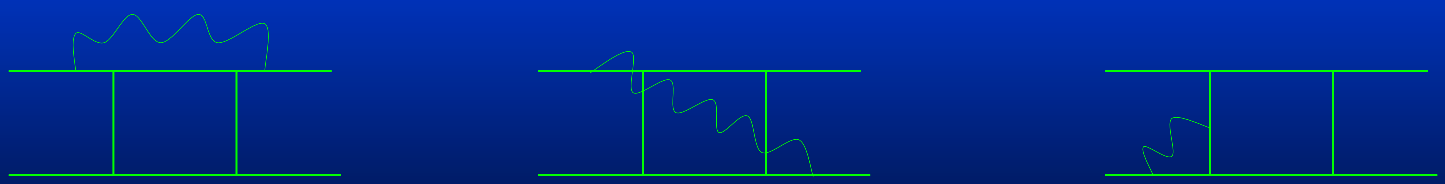

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Solutions

- avoid IR div: we gave mass to the gluon (done NDR and DRED)
- do the matching in d-dim keeping also EO's (checked in DRED where EO's arise when a $g_{\mu\nu}$ in 4-dim from γ algebra meets a $g_{\mu\nu}$ in d-dim from impulses)

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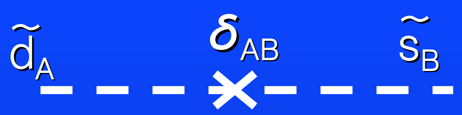

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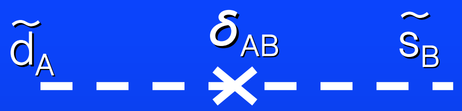

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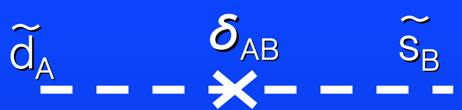

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But you are assuming that

↓ the off diagonal entries in M_D are small quantities

↓ the diagonal entries are nearly degenerate

↓ no interference effects occur

self-service analysis

CASE 1

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Compare with the bounds we give on the δ's.

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Because of possible interference/cancellation effects you might decide to trust only the order of magnitude of the bounds on the **δ's.** We give also the exact result: you can fill in directly the exact parameters of your model in our Wilson coefficients.

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In cases 2–3 to get the physical amplitude you still have to

1) evolve the Wilson coefficients to the low energy scale μ

We give the evolution equation (with NLO ADM) in the ready–to–use form

$$C_r(\mu) = \sum_i \sum_s \left(b_i^{(r,s)} + \eta\, c_i^{(r,s)}\right) \eta^{a_i}\, C_s(M_{high})$$

$b_i^{(r,s)}$, $c_i^{(r,s)}$, a_i magic numbers $\qquad \eta = \alpha_s(M_{high})/\alpha_s(m_t)$

2) multiply for the matrix elements of the operators computed at the scale μ

We list their analytic formulae and the numerical values of the parameters contained: quark and meson masses, decay constants, B–parameters.

CP Violation and FCNC in SUSY

Overview of the Calculation

Framework for a Model Independent Analysis

Numerical Analysis

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Contact Experiment–Theory

$K^o\bar{K}^o$ system $\rightarrow \delta^d_{12}$

$$\Delta M_K = 2\,\mathrm{Re}\langle \bar{K} | \mathcal{H}^{\Delta S=2} | K \rangle$$

$$\varepsilon_K = \frac{\mathrm{Im}\langle \bar{K} | \mathcal{H}^{\Delta S=2} | K \rangle}{\sqrt{2}\;\Delta M_K}$$

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$B_d\overline{B}_d$ system $\rightarrow \delta^d_{13}$

$$\Delta m_d = 2\,|\langle \overline{B}_d | \mathcal{H}^{\Delta B=2} | B_d \rangle|$$

$$a_{J/\psi K_S} = \sin 2\beta_{eff} \sin(\Delta m_d t)$$

New physics can enter !

$2\beta_{eff} \rightarrow \mathrm{Arg}\langle \overline{B}_d | \mathcal{H}^{\Delta B=2} | B_d \rangle$

measured ← → calculated NLO in terms of $m_{\tilde{q}}$, $m_{\tilde{g}}$, δ's

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$B_s\bar{B}_s$ system $\rightarrow \delta^d_{23}$

interesting but only bounded:

- The SM amplitude is real
- $\left(\frac{\Delta m_d}{\Delta m_d}\right)_{SM} \sim \left(\frac{\Delta m_d}{\Delta m_s}\right)_{MSSM}$

The method

$$\langle \bar{M} | \mathcal{H}^{\Delta S=2} | M \rangle =$$

$$\mathrm{Re}\, A_{SM} + i\, \mathrm{Im}\, A_{SM} + A_{SUSY}\, \mathrm{Re}(\delta^d_{ij})^2_{AB} + i\, A_{SUSY}\, \mathrm{Im}(\delta^d_{ij})^2_{AB}$$

The constraints are obtained imposing that the sum of SUSY contributions is proportional to a single δ and the SM contribution reproduce the measured value of the observable. The d's appear quadratically in the Wilson coefficients in the combinations

$$\delta_{LL}^2 \quad \delta_{RL}^2 \quad \delta_{LL}\delta_{RR} \quad \delta_{LR}\delta_{RL} \quad \delta_{RR}^2 \quad \delta_{LR}^2$$

the mixed products are bounded setting $\delta_{ij}=\delta_{kl}$

This is the main limit of the analysis → intereference effects possible order of magnitude bounds

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The parameters x_i are extracted from flat distribution in $[x_i - \sigma_i,\ x_i + \sigma_i]$

The average observables O are calculated with the weighting factor

$$e^{-\frac{(O(x_i) - O_{exp})^2}{\sigma_{exp}^2}}$$

[if σ_{exp} <<, not efficient → we solve in the less constrained parameter]

Main input parameters used in the preliminary analysis

$\sin 2\beta = 0.726 \pm 0.037$

$\Delta m_d \ (ps^{-1}) = 0.502 \pm 0.006$

CKM parameters from the UTfit (www.utfit.org)

only measures New Physics free

$\bar{\rho} = 0.21 \pm 0.10$

$\bar{\eta} = 0.36 \pm 0.06$

$\lambda_c = 0.2258 \pm 0.0014$

$V_{cb} = 0.0416 \pm 0.0007$

B–parameters

from hep–lat/0110091 in RI–MOM

$B_1(m_b) = 0.87(4)^{+5}_{-4}$

$B_2(m_b) = 0.82(3)(4)$

$B_3(m_b) = 1.02(6)(9)$

$B_4(m_b) = 1.16(3)^{+5}_{-7}$

$B_5(m_b) = 1.91(4)^{+22}_{-7}$

The plots shown here are at fixed values of the squark and gluino masses:

$$m_{\tilde{q}} = m_{\tilde{g}} = 350 \text{ GeV}$$
$$x = m_{\tilde{g}}/m_{\tilde{q}} = 1$$

How do the constraints on the δ's vary with x and $m_{\tilde{g},\tilde{q}}$?

- The results of the analysis are reliable for $x \leq \mathcal{O}(1)$. However
  $x > 1$ disfavoured by the evolution from M_{PL} to M_W: $\quad x_W = \dfrac{9\, x_{PL}}{1 + 7\, x_{PL}}$
  $x << 1$ only in specific models
- If $m_{\tilde{q},\tilde{g}}$ or $x \to \infty$, the bounds on the δ's become loose
  consequence of decoupling

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consequence of decoupling

The constraints on the δ's don't solve to the flavour problem:

very high scale for new physics

$m_{\tilde{g},\tilde{q}}$ >> and loose δ's

or flavour symmetries + new physics at lower scale

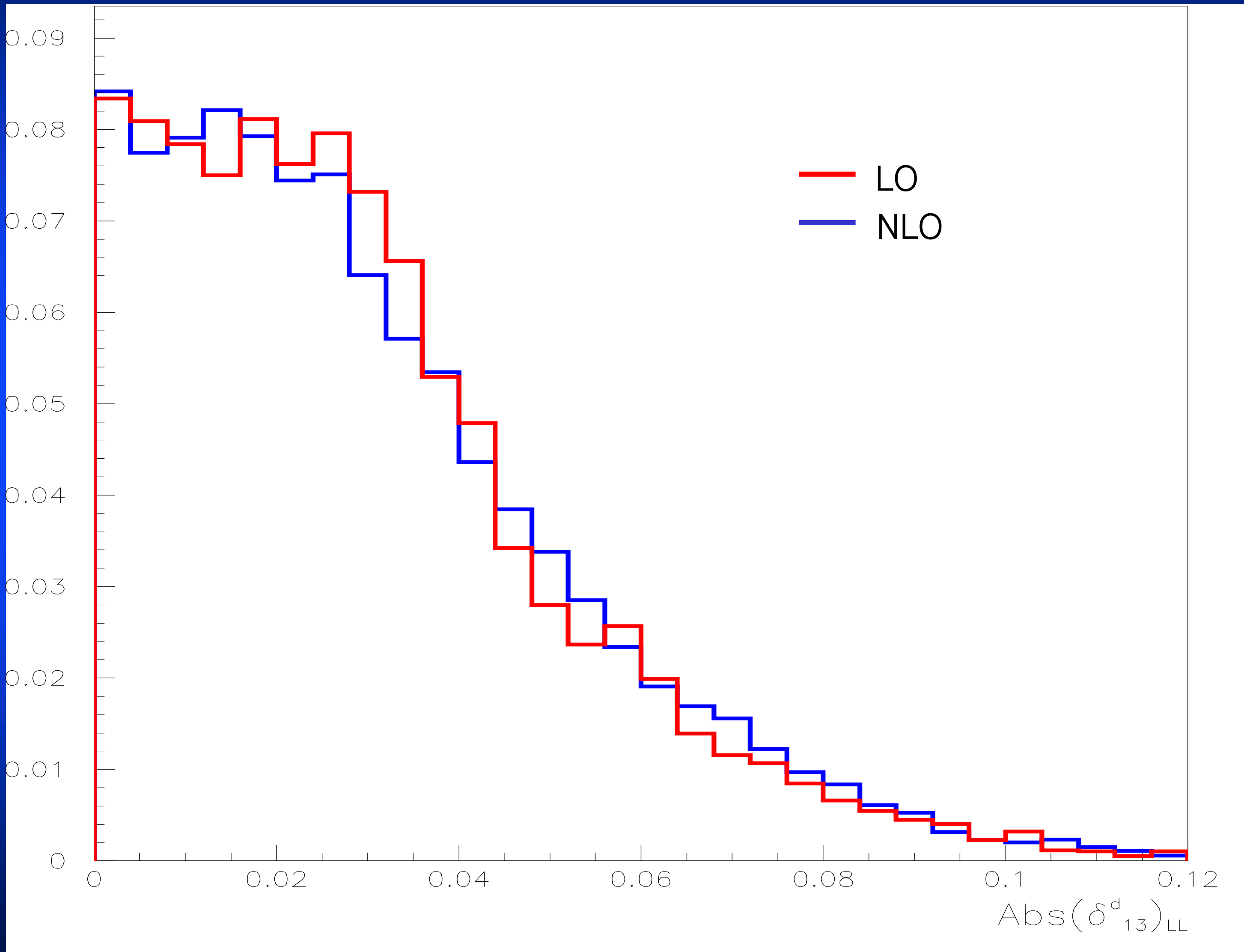
lower $m_{\tilde{g},\tilde{q}}$ and stringent δ's

are both possible

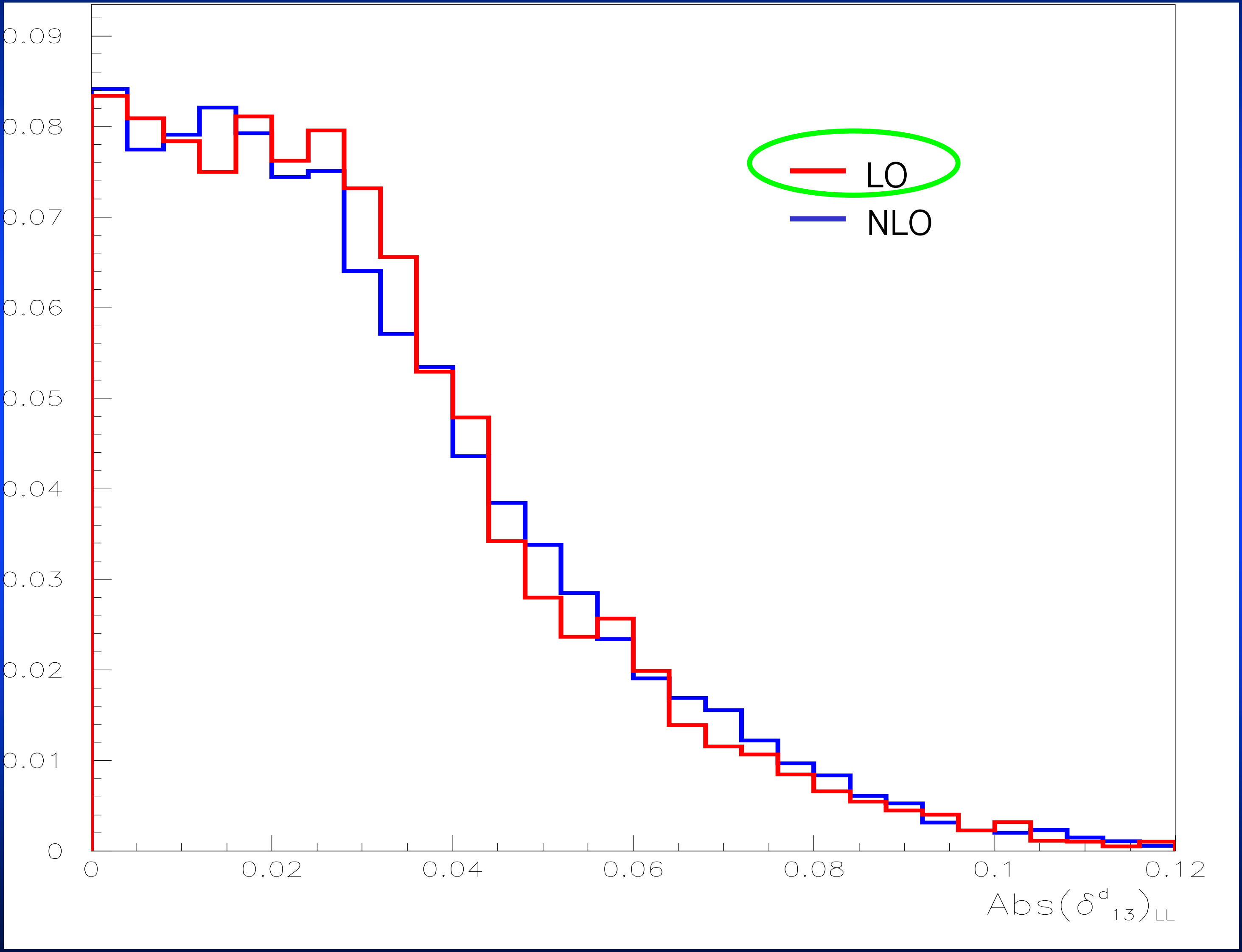
What is the effect of the NLO coefficients ?

- Depends on the mass insertion considered
- Doesn't alter the order of magnitude
- A direct comparison with previous analysises is not possible, but the improvements on the bounds appears mainly due to the higher precision of the recent measures.
- A major effect is due to the NLO evolution with respect to the LO evolution
- Weakens the dependence on the matching scale

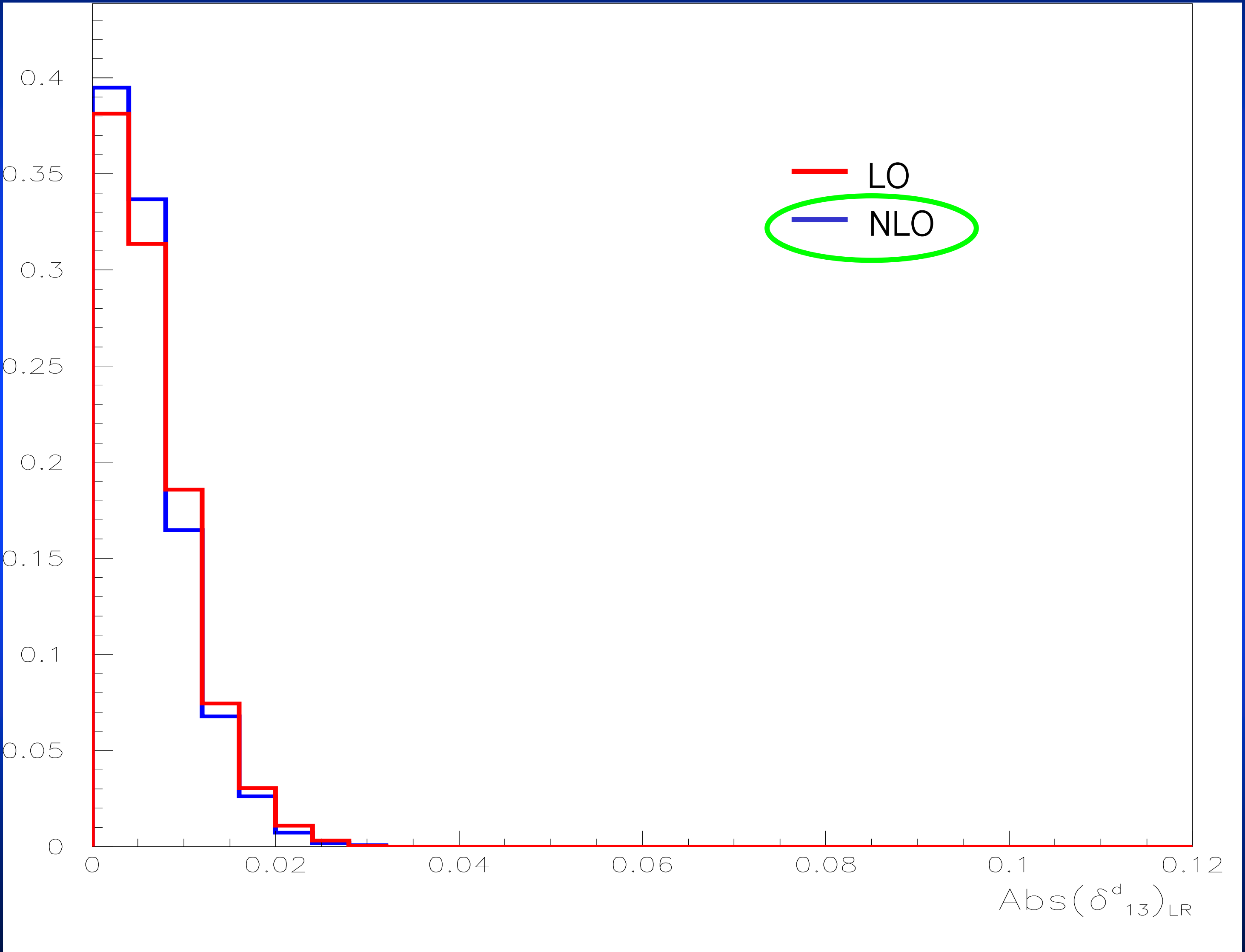
$\left|(\delta^d_{13})_{LL}\right|$



$$\left|(\delta^d{}_{13})_{LL}\right|$$

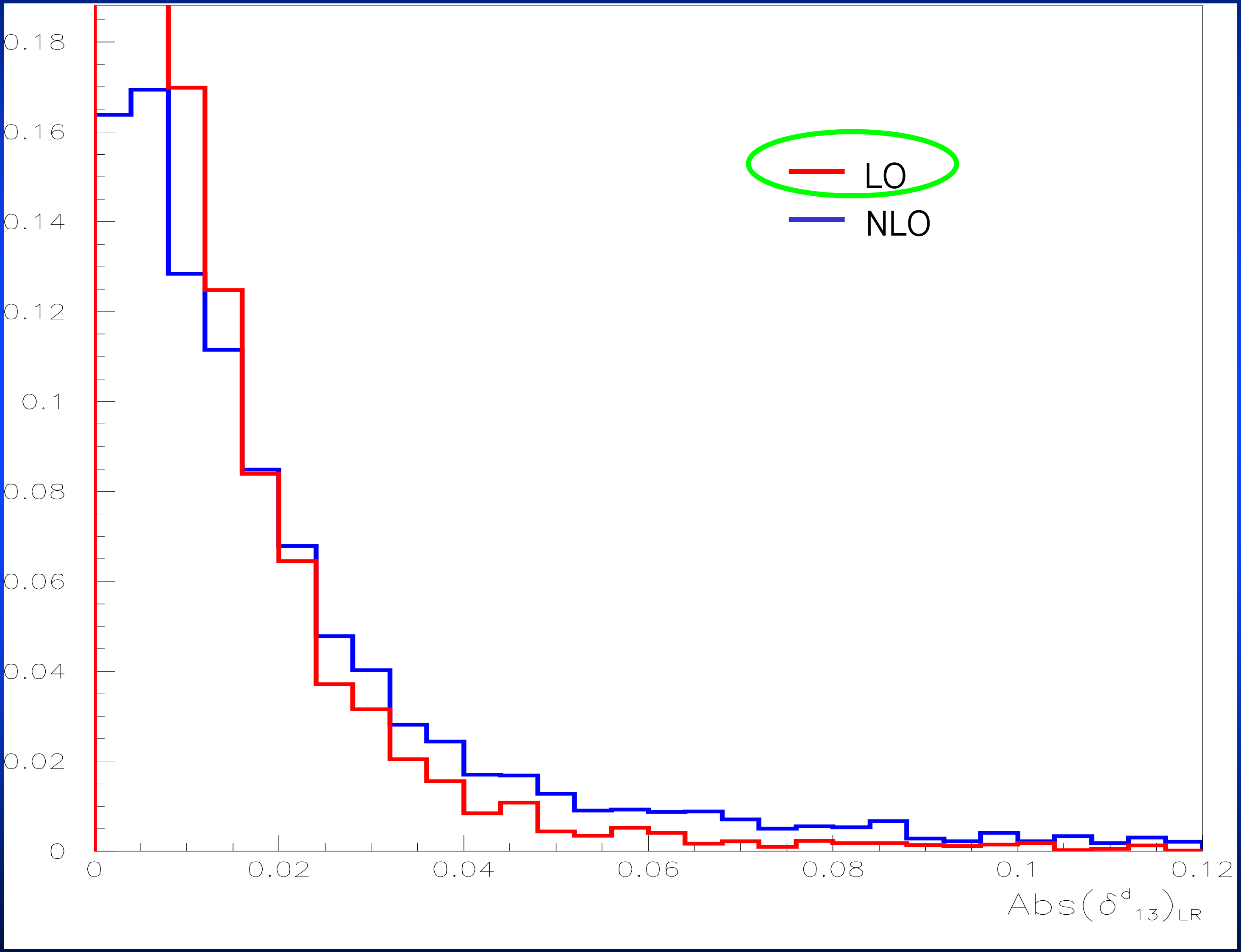


$|(\delta^d_{13})_{LR}|$



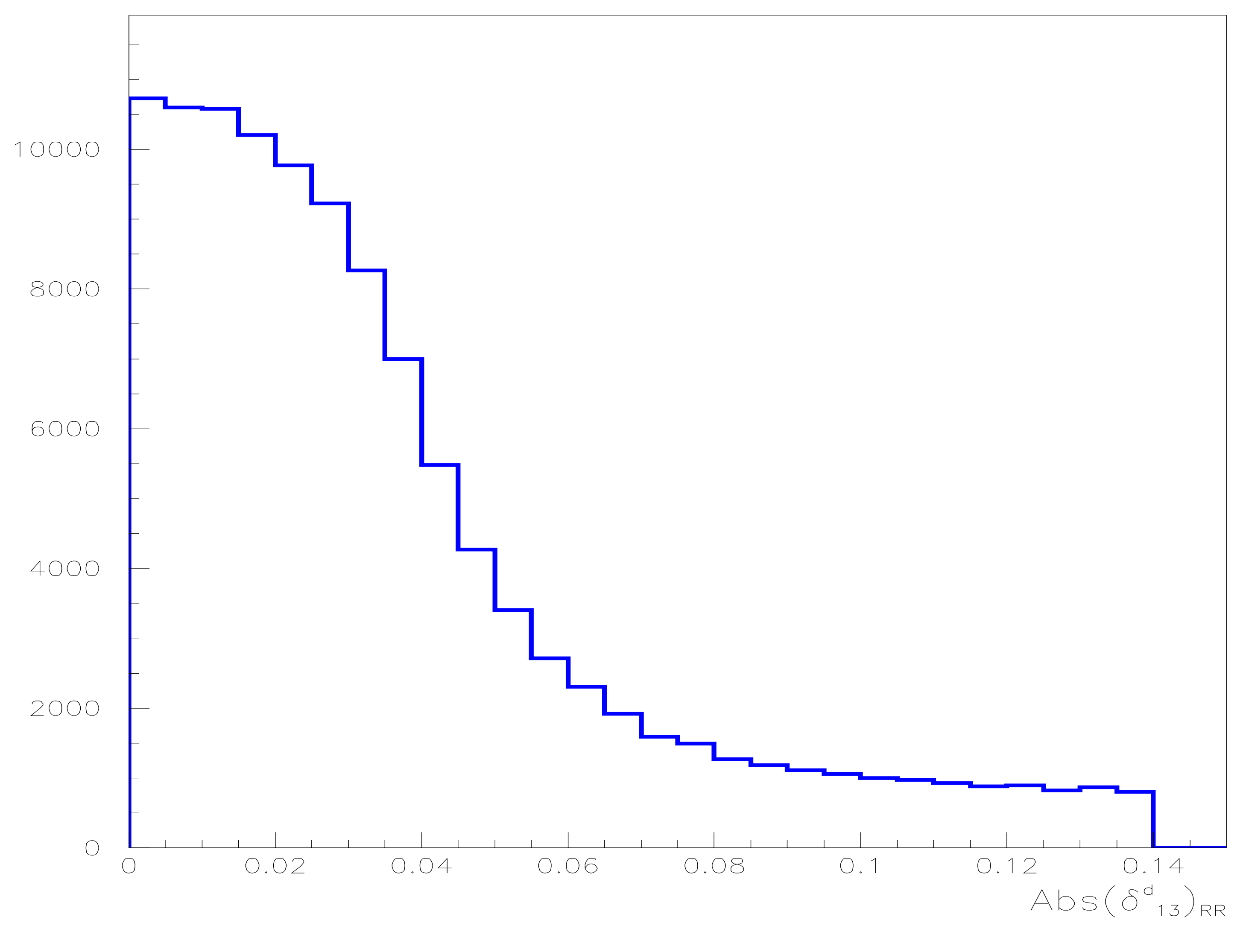
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
0.02
0.04
0.06
0.08
0.1
0.12
Abs(δ^d_{13})$_{LR}$
LO
NLO

$$\left| (\delta^d_{13})_{LR=RL} \right|$$

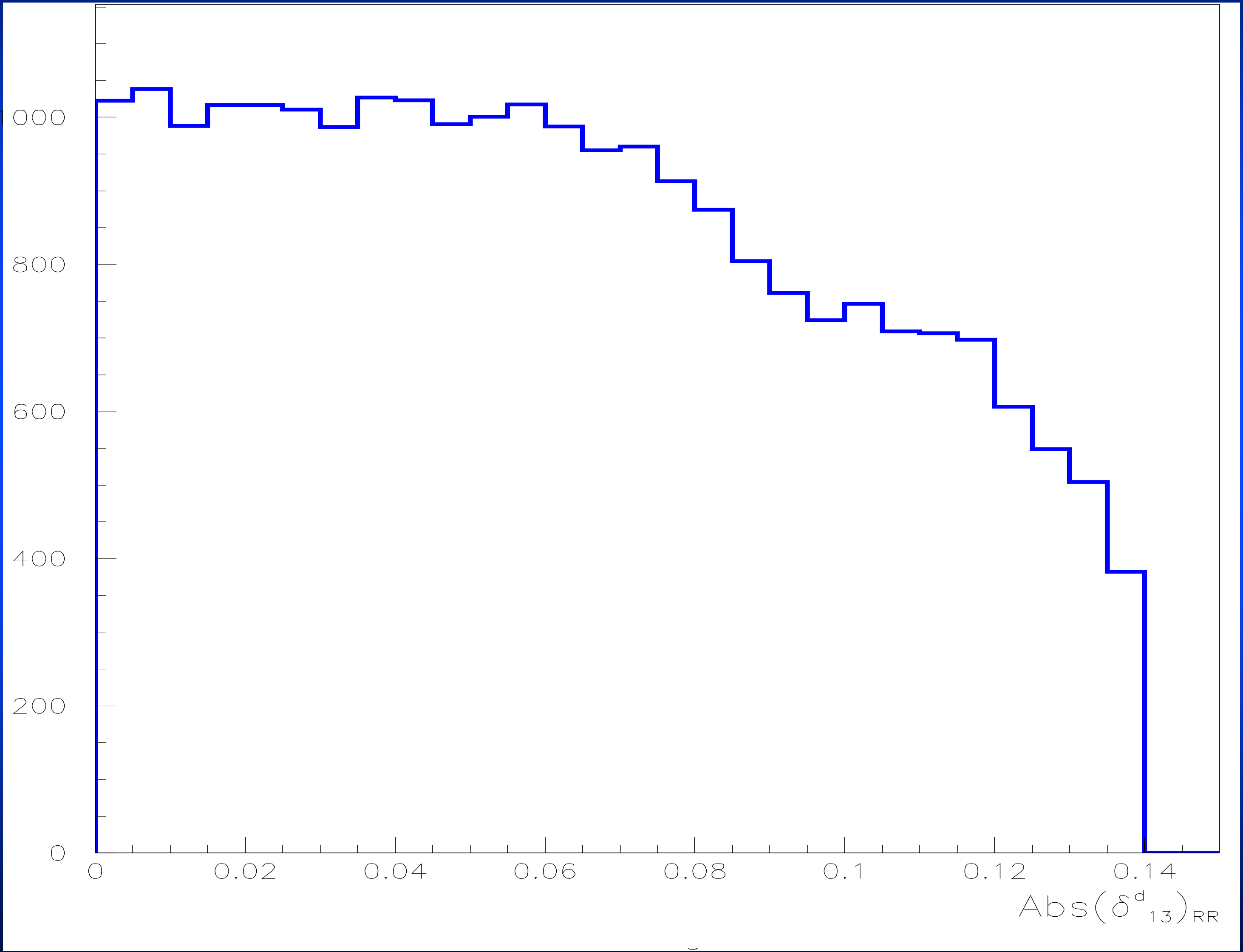


What is the effect of every experimental bound on the δ's?

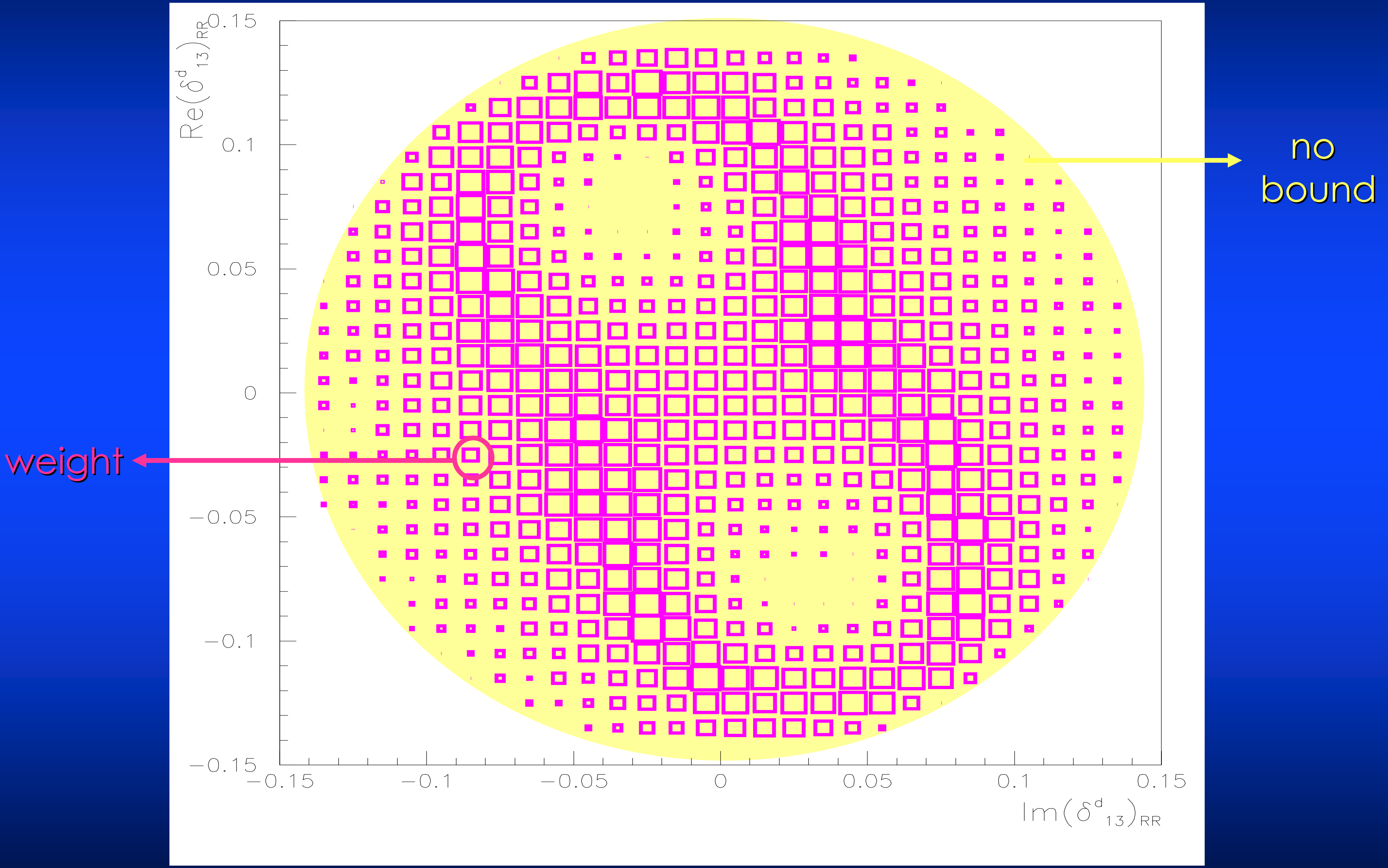
sin 2β on $|(\delta^d_{13})_{RR}|$



Δm_d on $\left|(\delta^d_{13})_{RR}\right|$



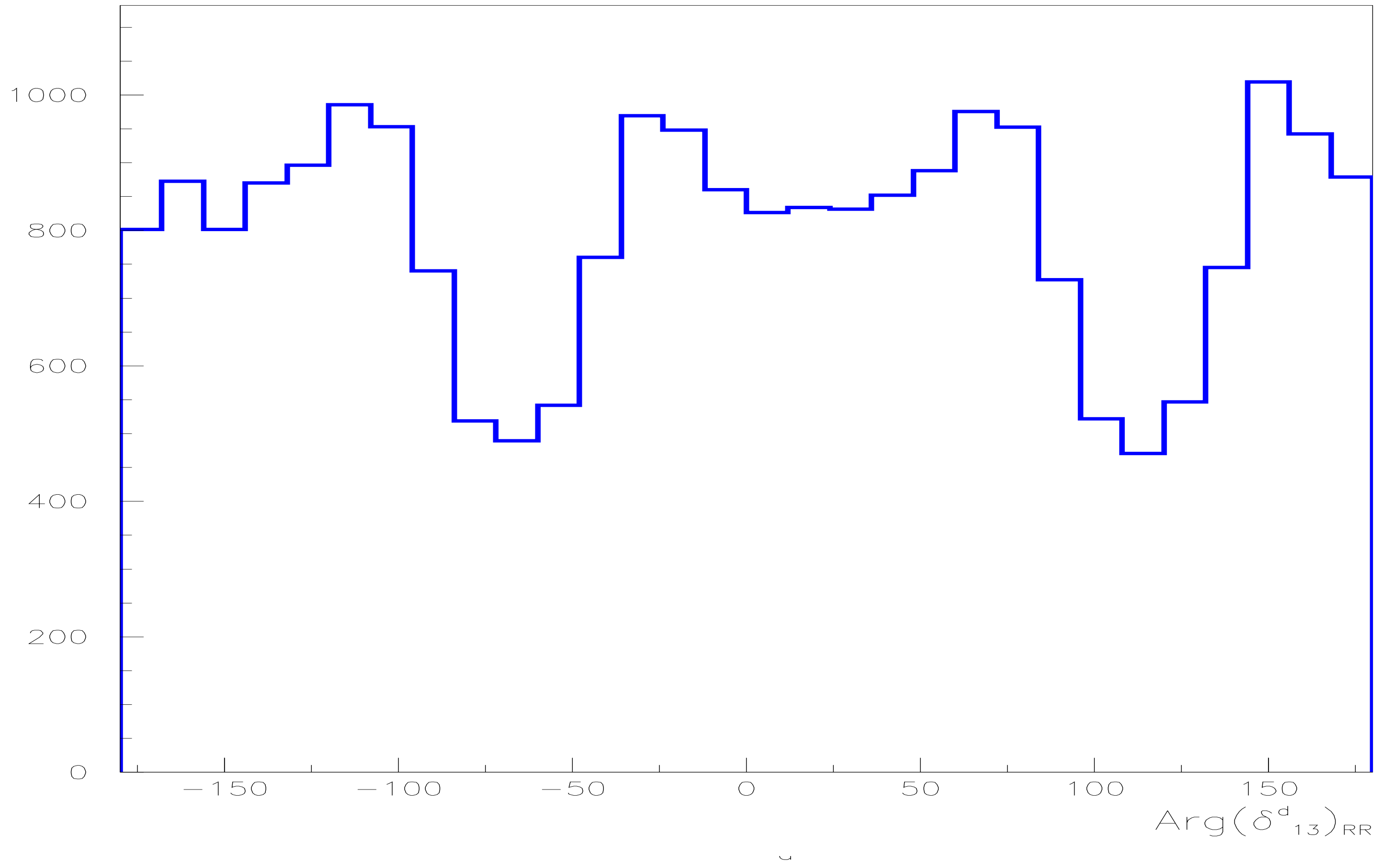
Δm_d



no bound
weight
0.15
0.1
0.05
0
−0.05
−0.1
−0.15
Re(δ^d_13)_RR
−0.15
−0.1
−0.05
0
0.05
0.1
0.15
Im(δ^d_13)_RR

projected on Arg $(\delta^d_{13})_{RR}$

$$\Delta m_d = 2|\langle \bar{B}_d|\mathcal{H}^{\Delta B=2}|B_d\rangle| = 2|A_{SM}\, e^{i2\beta} + A_{SUSY}\, e^{i2\phi}|$$



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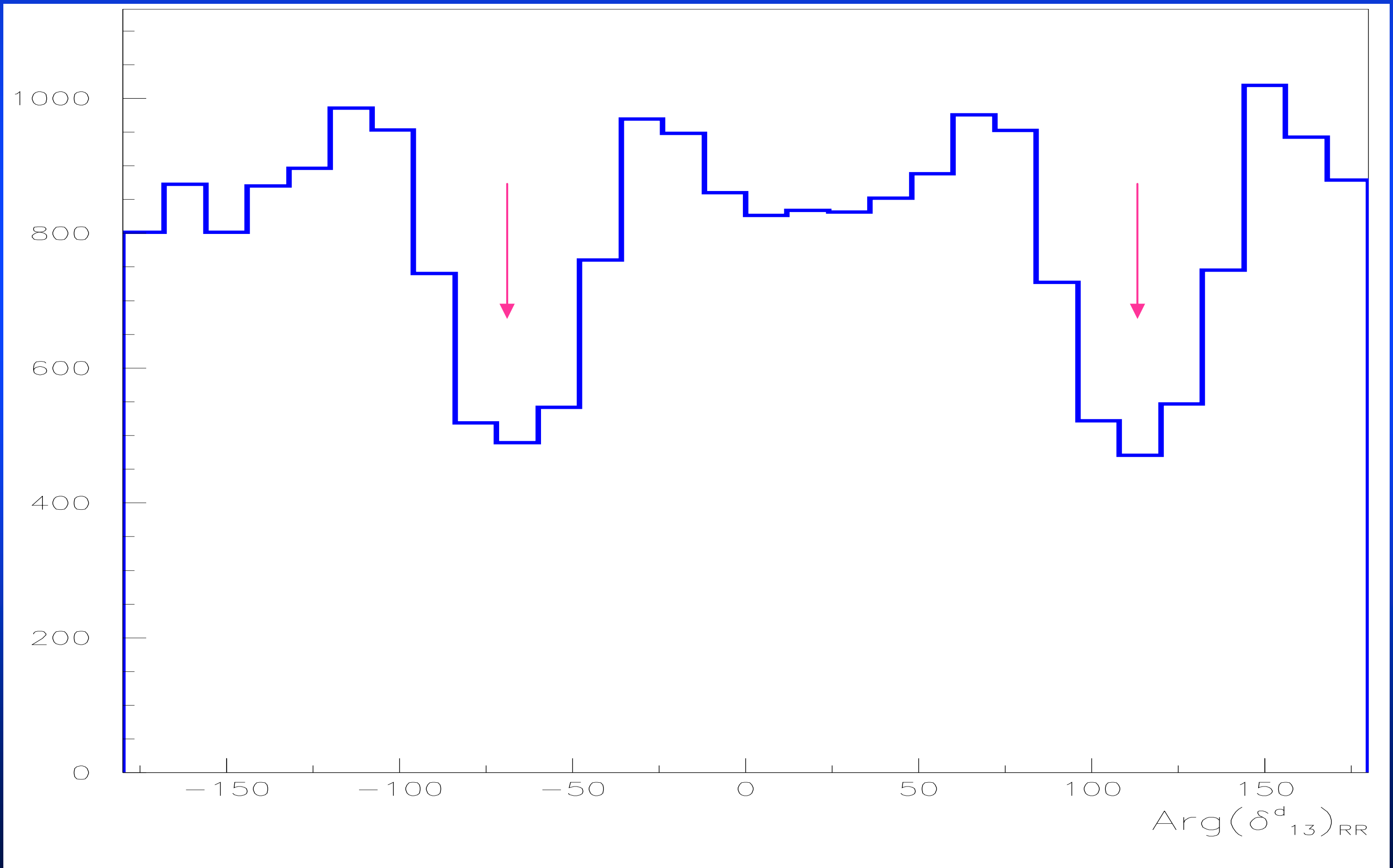
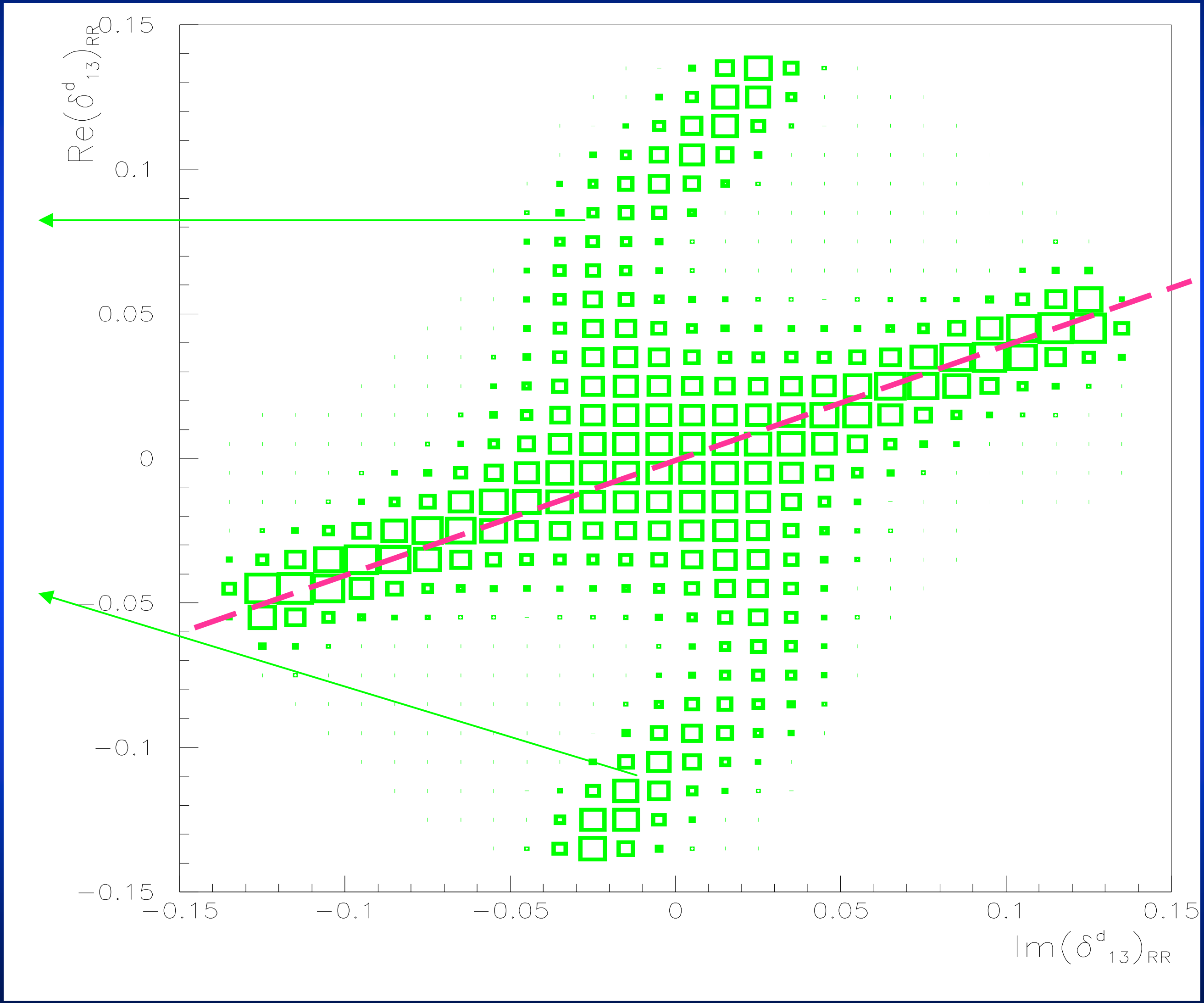
if $\varphi = \pm\, \beta$ SUSY contribution is quadratic, otherwise linear



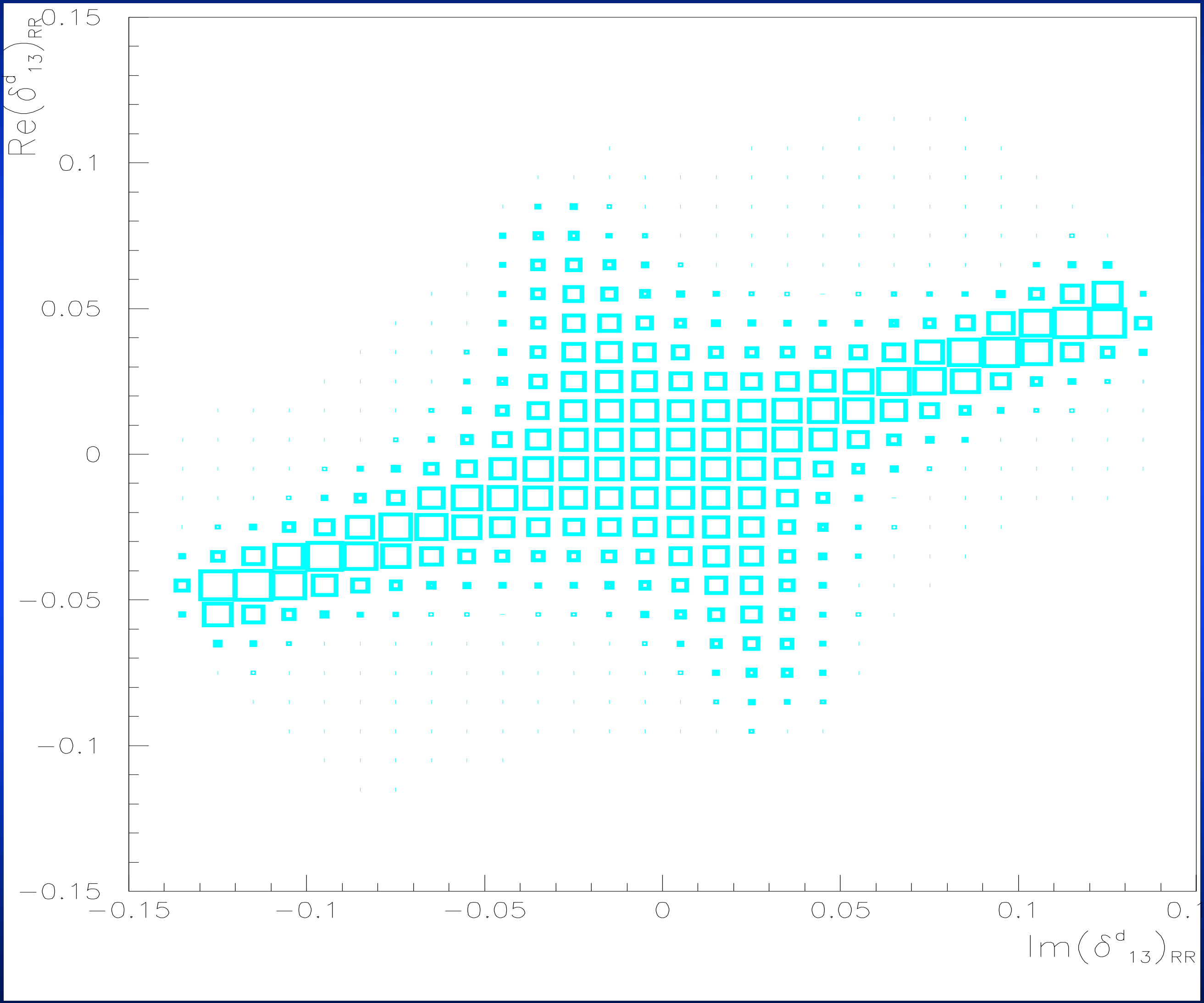
sin 2β

Wrong sign branches

Note the non uniform weights

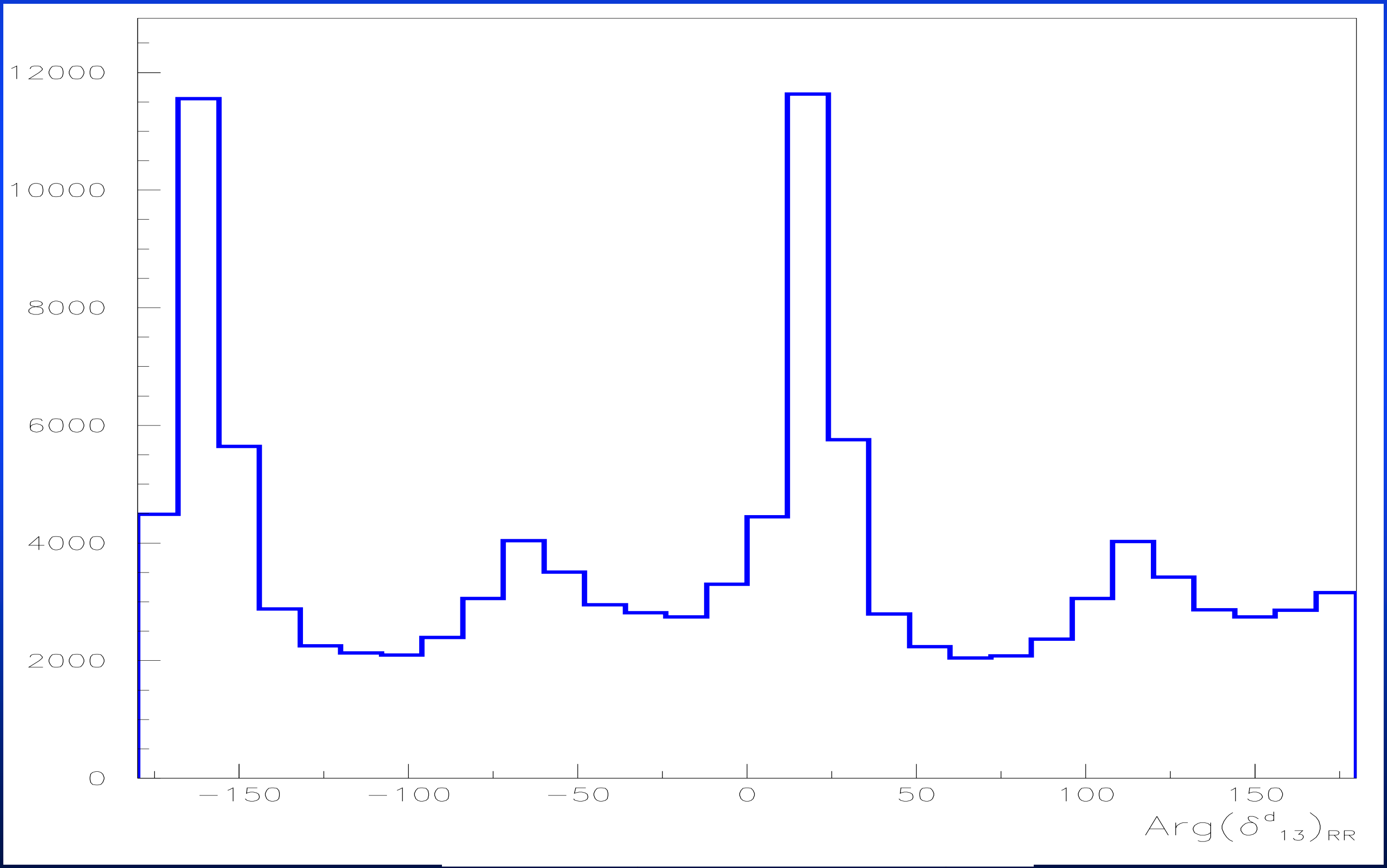


sin 2β and cos 2β



projected on $Arg\,(\delta^{d}_{13})_{RR}$

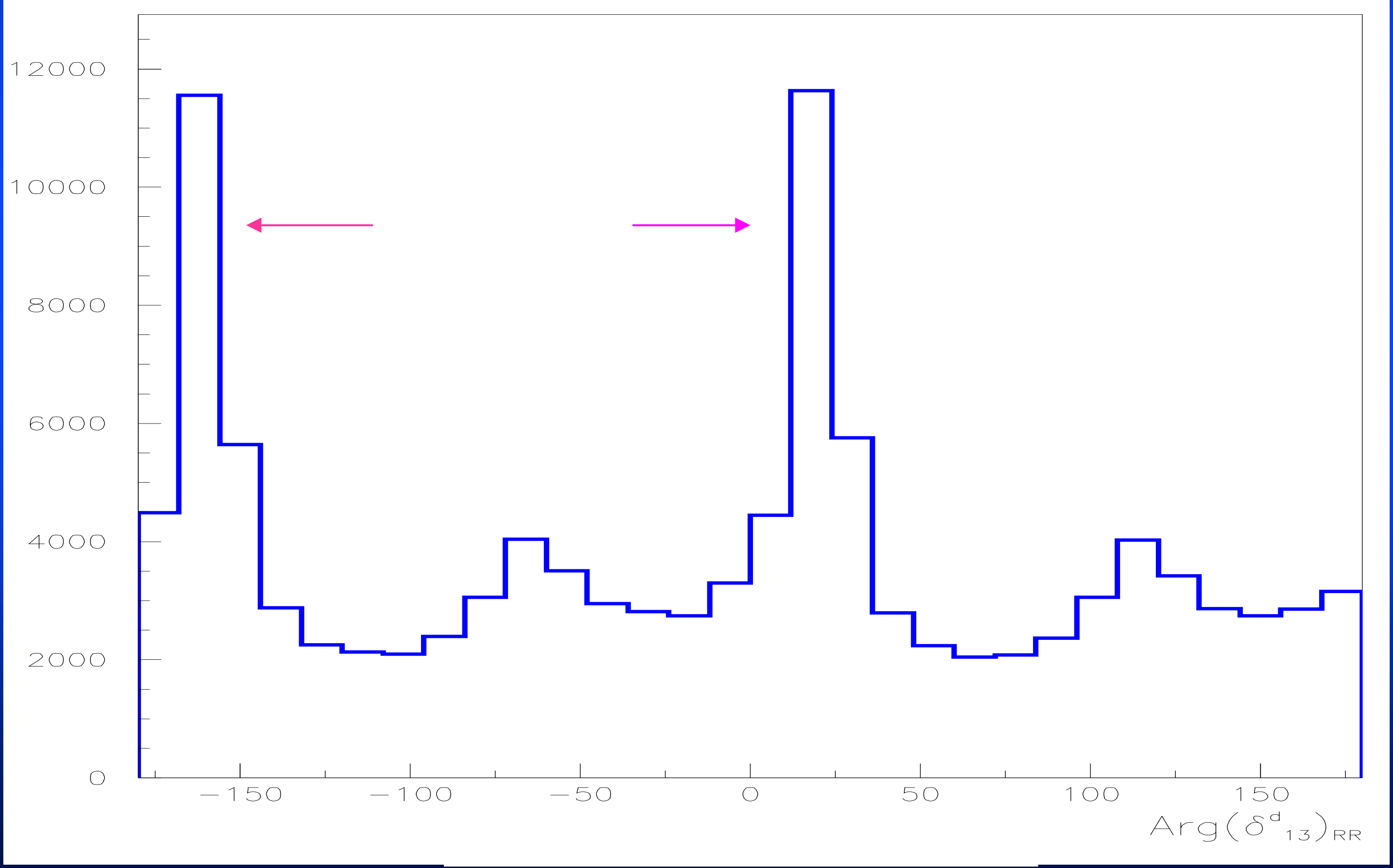
$$2\beta = \mathrm{Arg}\,|\langle \bar{B}_d|\mathcal{H}^{\Delta B=2}|B_d\rangle| = \mathrm{Arg}\,|A_{SM}\,e^{i2\beta} + A_{SUSY}\,e^{i2\phi}|$$



projected on Arg $(\delta^d_{13})_{RR}$

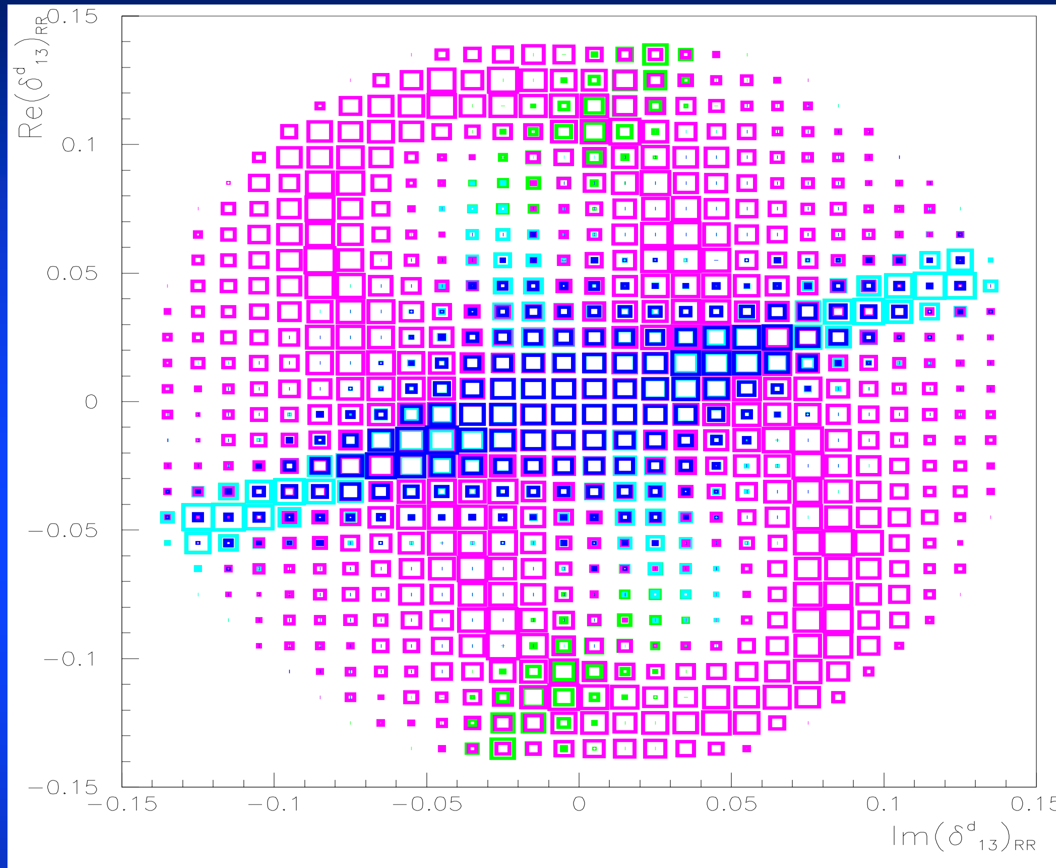
$$2\beta = \text{Arg}|\langle \bar{B}_d|\mathcal{H}^{\Delta B=2}|B_d\rangle| = \text{Arg}|A_{SM}\, e^{i2\beta} + A_{SUSY}\, e^{i2\phi}|$$

if $\phi = \beta$ the bound is satisfied for every A_{SUSY}

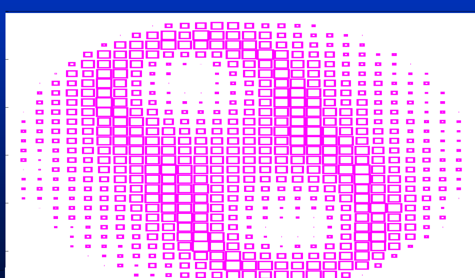


All the bounds together:

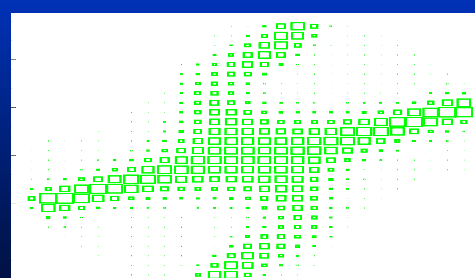
allowed region: dark blue squares



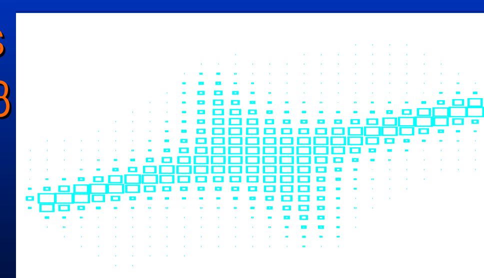
Δm_d



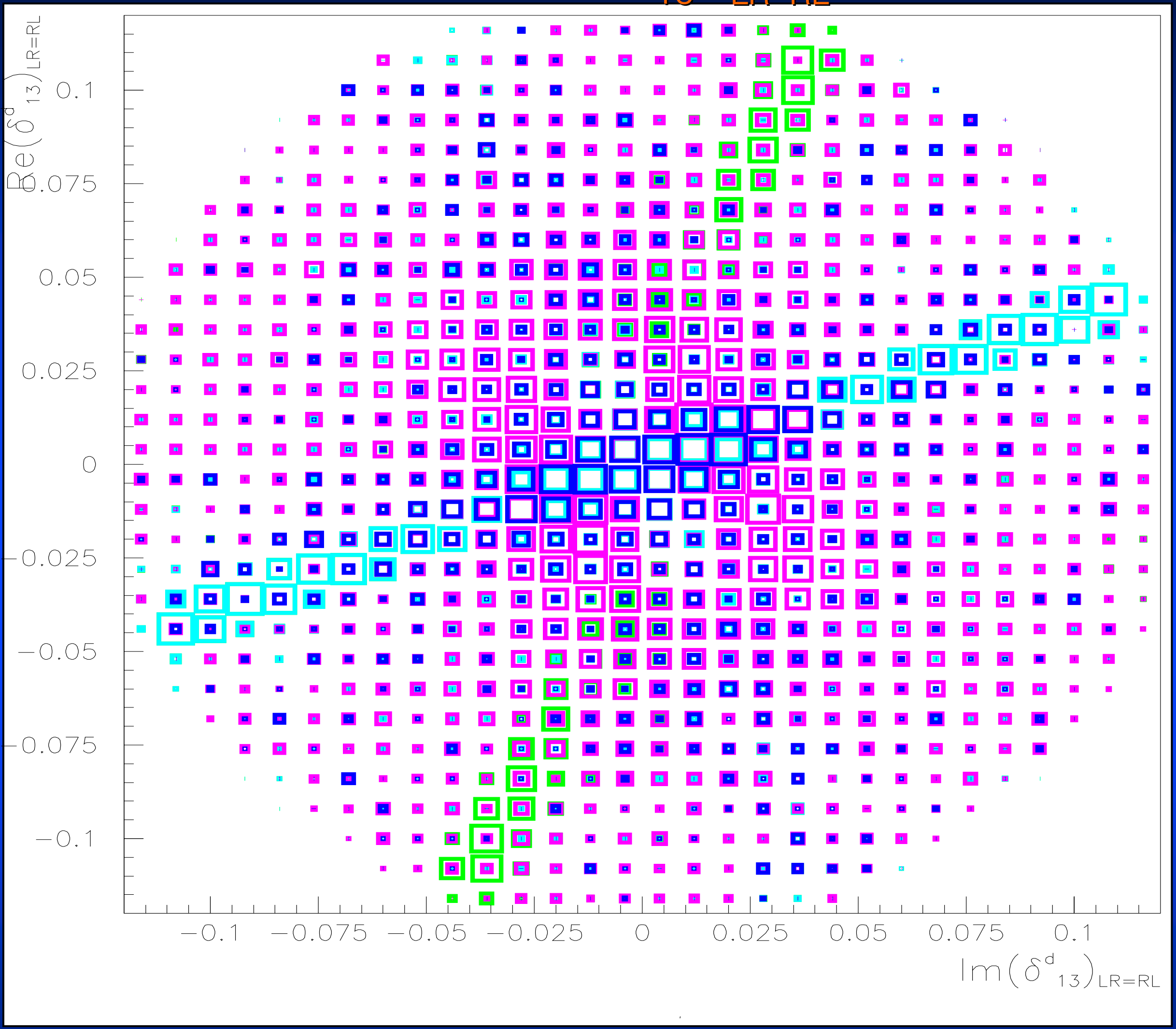
sin 2β



cos 2β

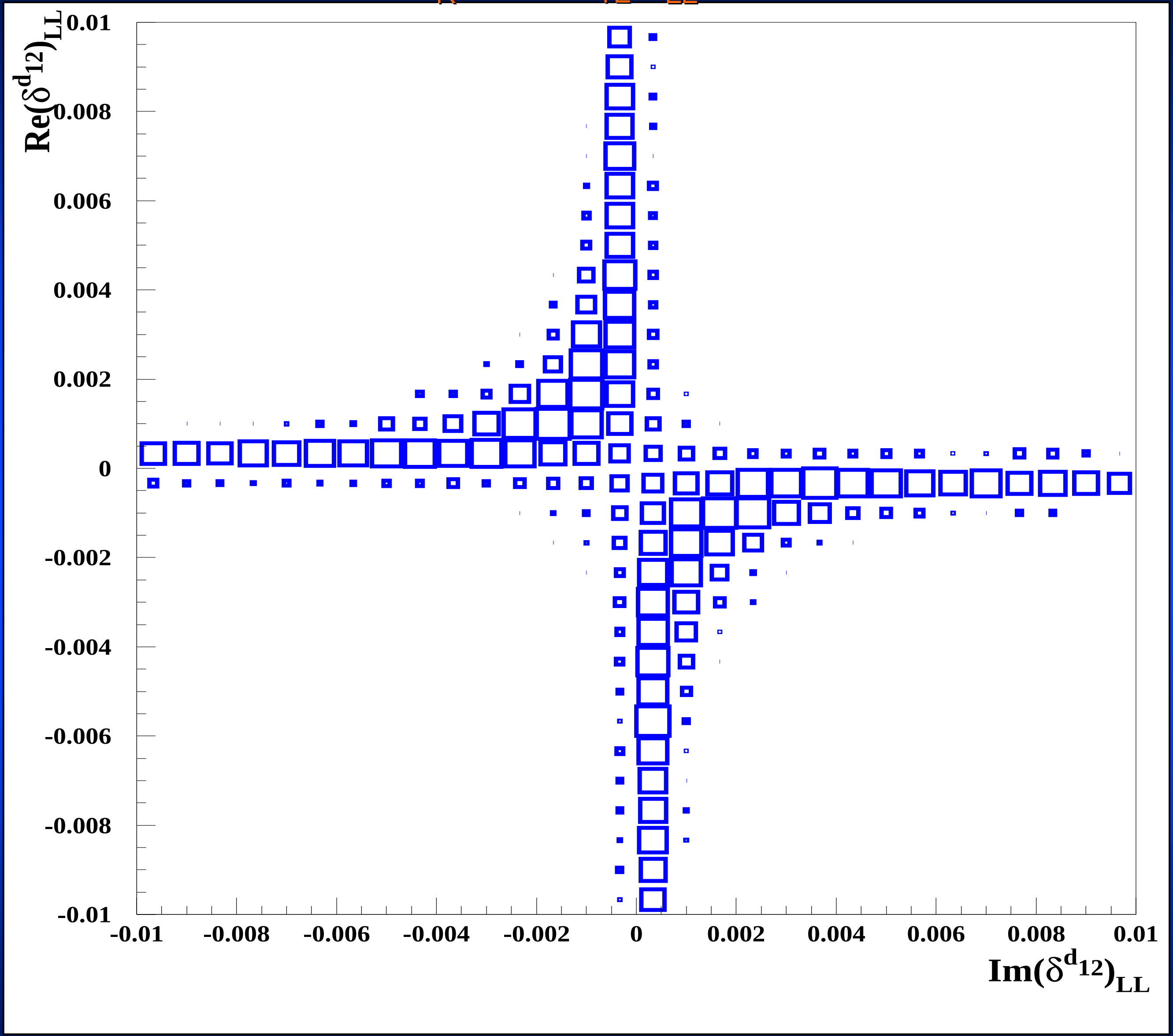


The same for $(\delta^d_{13})_{LR=RL}$

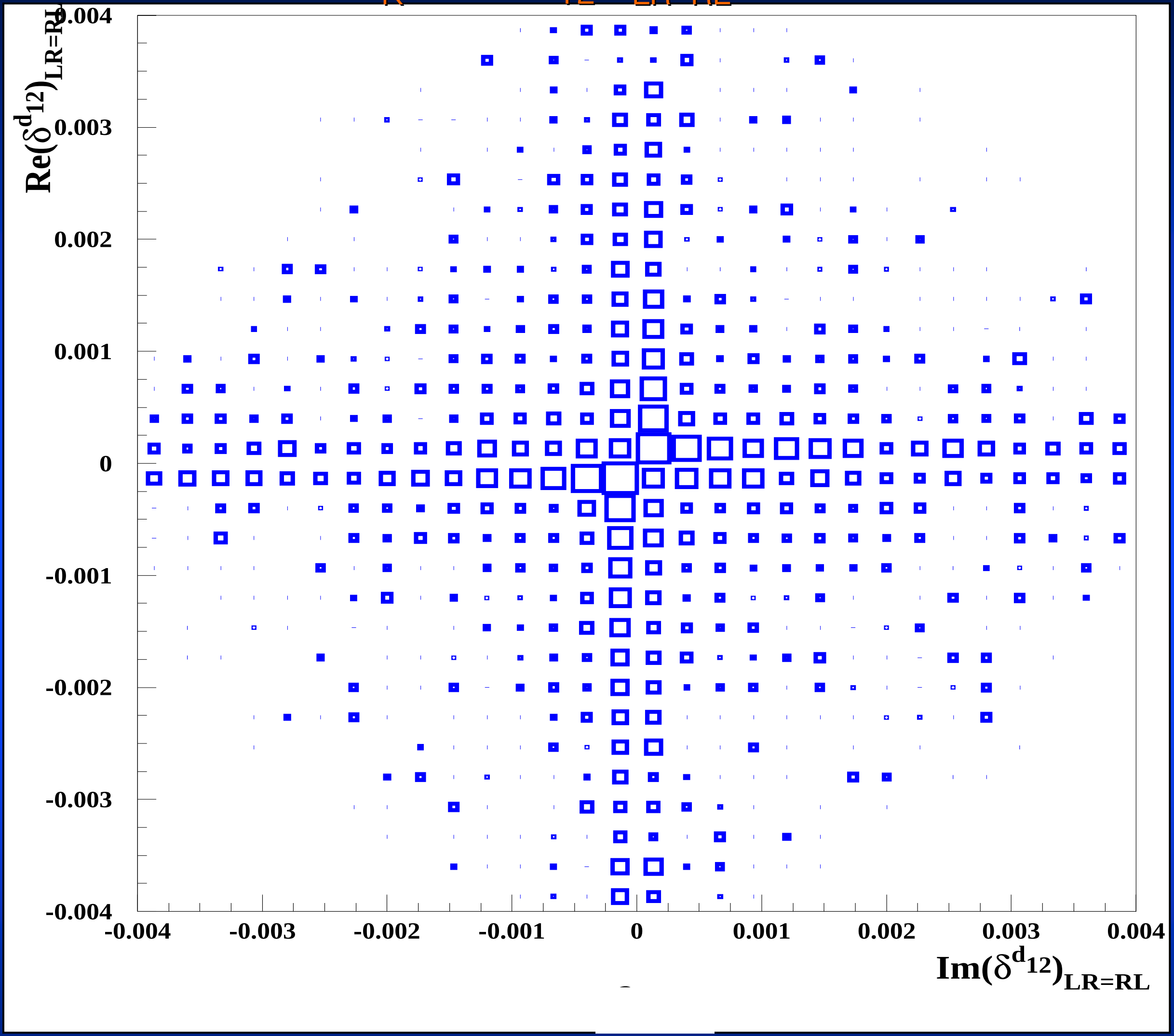


A partial cancellation in the Wilson coefficients occurs: the bounds are less effective, the plot is more scattered

ε_K on $(\delta^d_{12})_{LL}$



ε_K on $(\delta^d_{12})_{LR=RL}$



Again an interference effect . Usually SUSY models with dominant LR/RL mass insertions can contribute more to ε'_K