Flavor physics induced by light Z' from SO(10) GUT

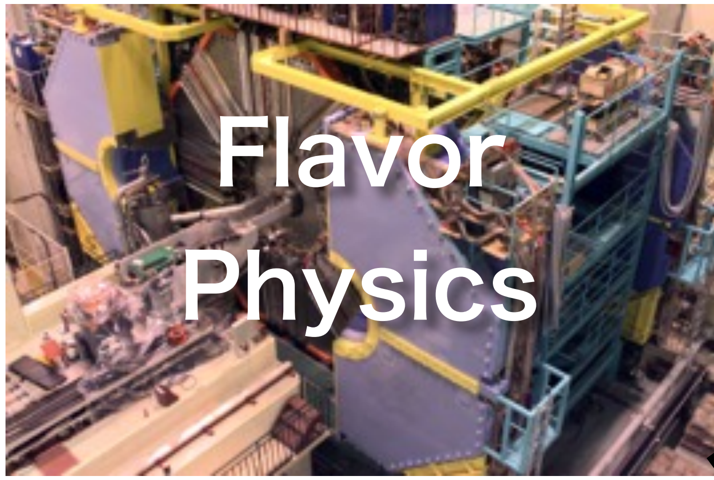
Yuji Omura (KMI, Nagoya Univ.)

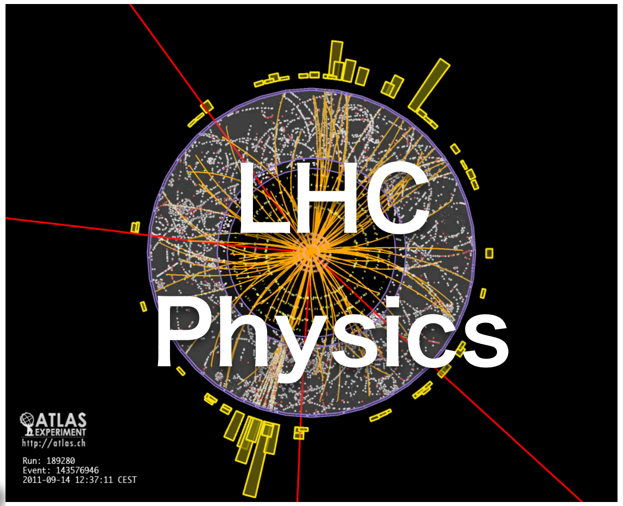
Based on PLB744 (2015) 395 (arXiv: 1503.06156)
and JHEP1611(2016)018 (arXiv: 1607.05437)

Collaborators: J. Hisano, Y. Muramatsu, Y. Shigekami, M. Yamanaka

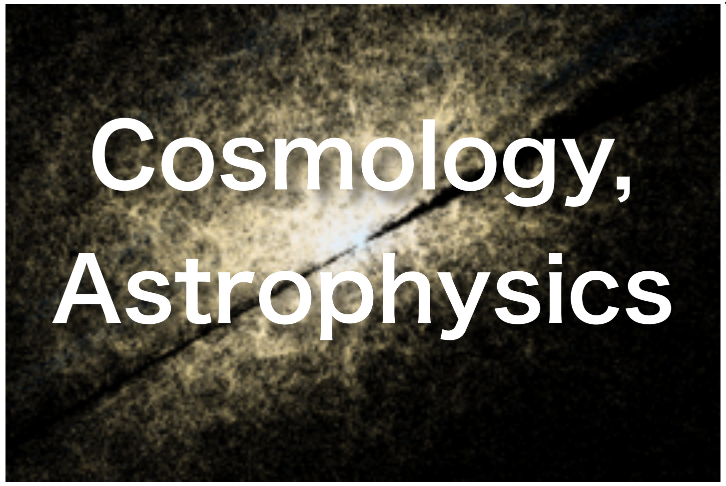
Introduction

Very exciting era!



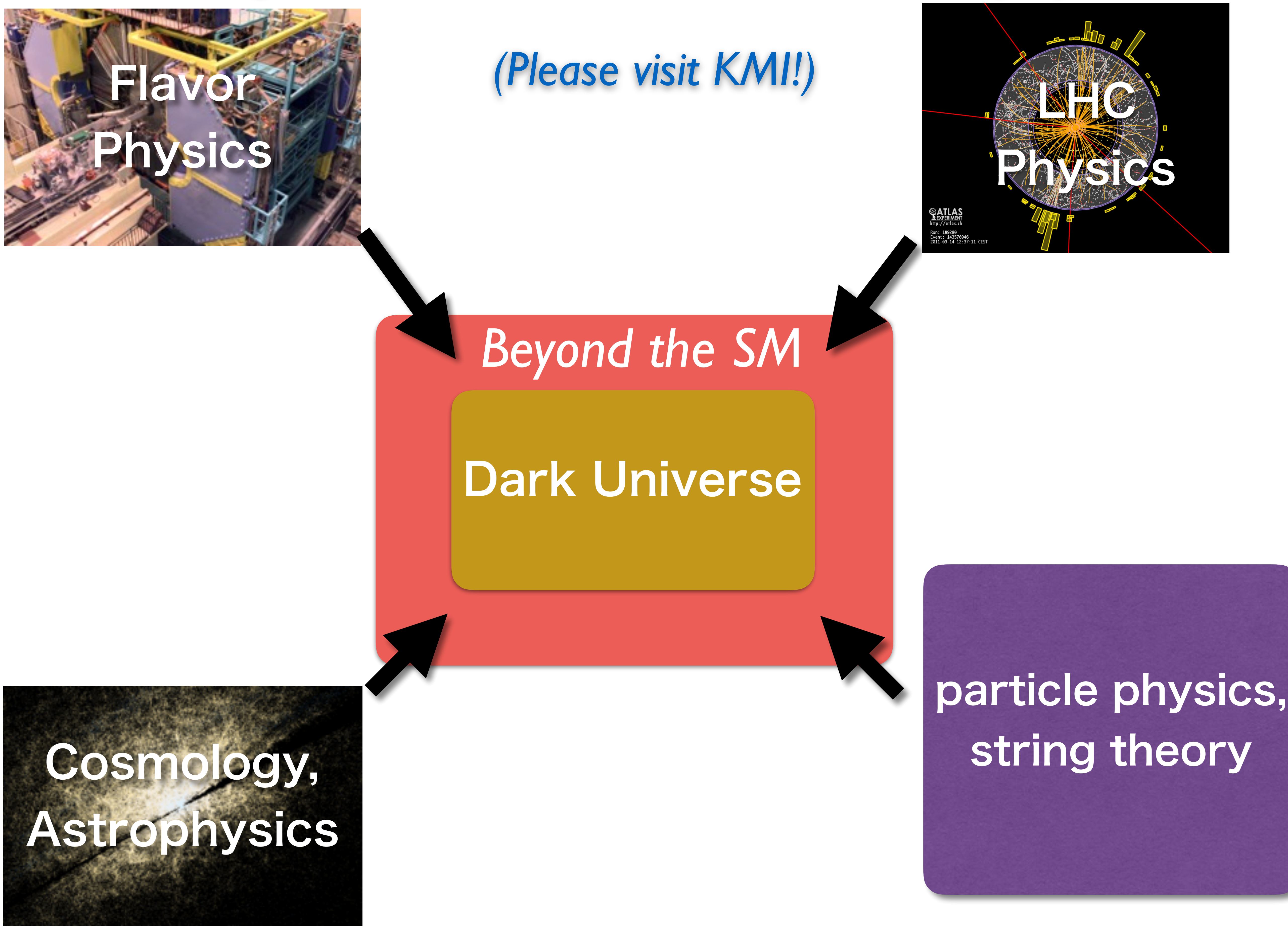


Physics
Beyond the SM



particle physics,
string theory

Integrated Research at KMI (Nagoya)



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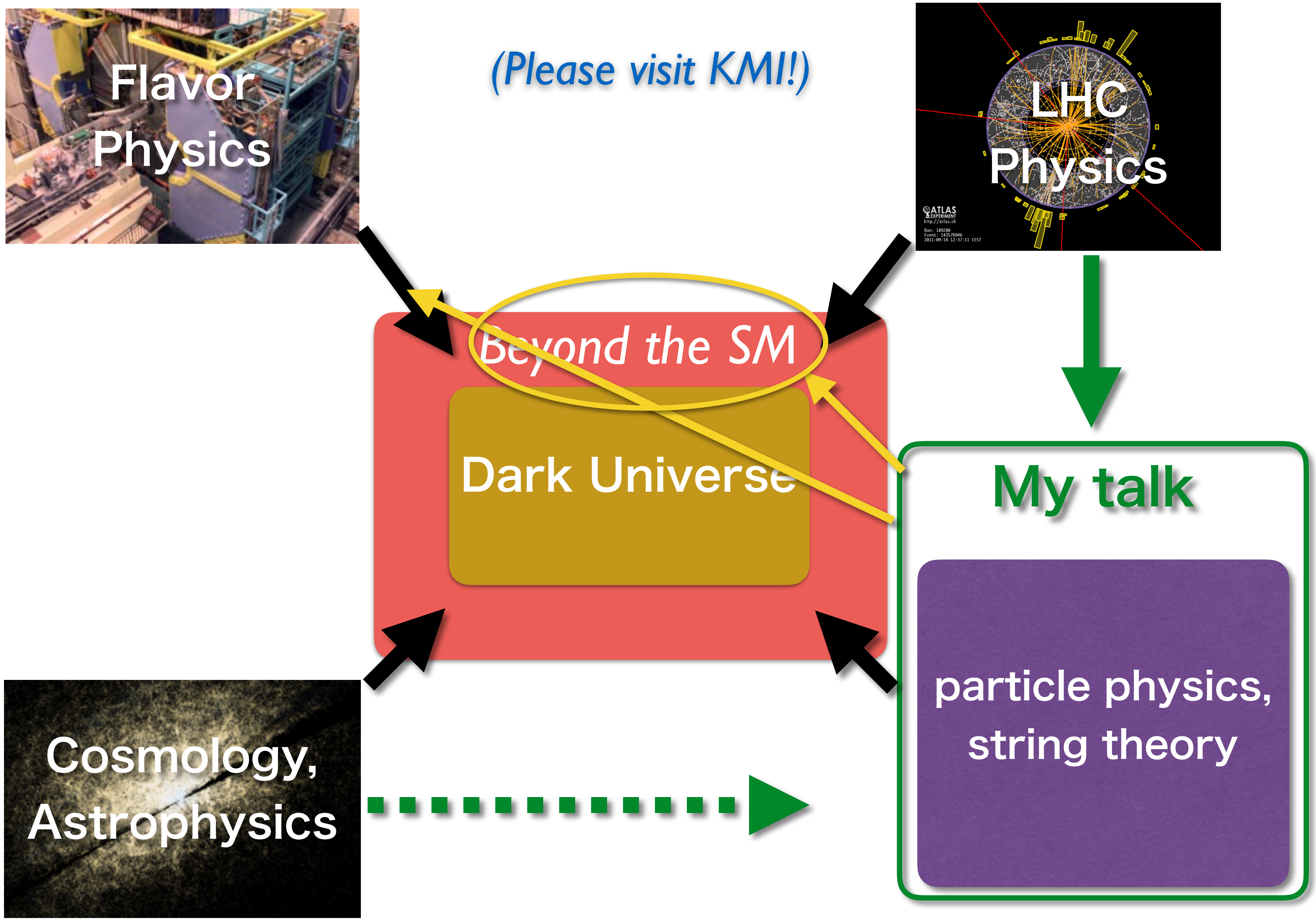

As a candiate for BSM,

we discuss SUSY GUT.

(SUSY is still a attractive BSM.)

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The (original) motivations are

Origin of EW scale

Gauge coupling unification (GUT)

(Origin of SM gauge groups)

Dark matter

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Really??

Gauge coupling unification (GUT)

(Origin of SM gauge groups)

Dark matter

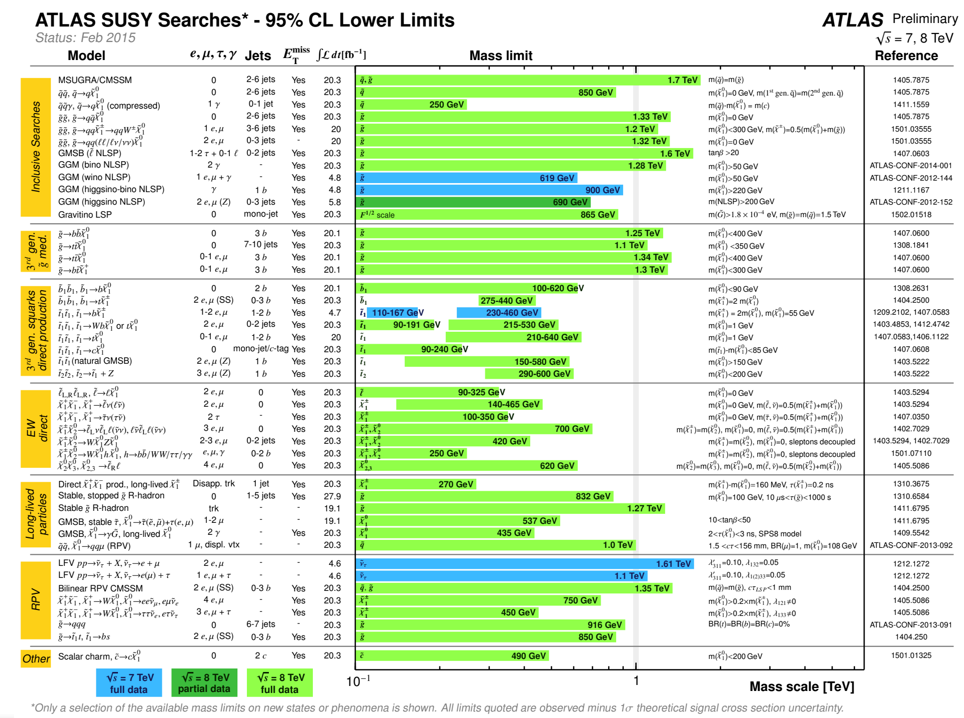
Experimental constraints

Direct search at LHC

model-dependent but…

$$m_{gluino} \gtrsim 1.5\,\mathrm{TeV},\ m_{squark} \gtrsim 1.3\,\mathrm{TeV}$$

$$m_{stop} \gtrsim 700\mathrm{GeV}$$

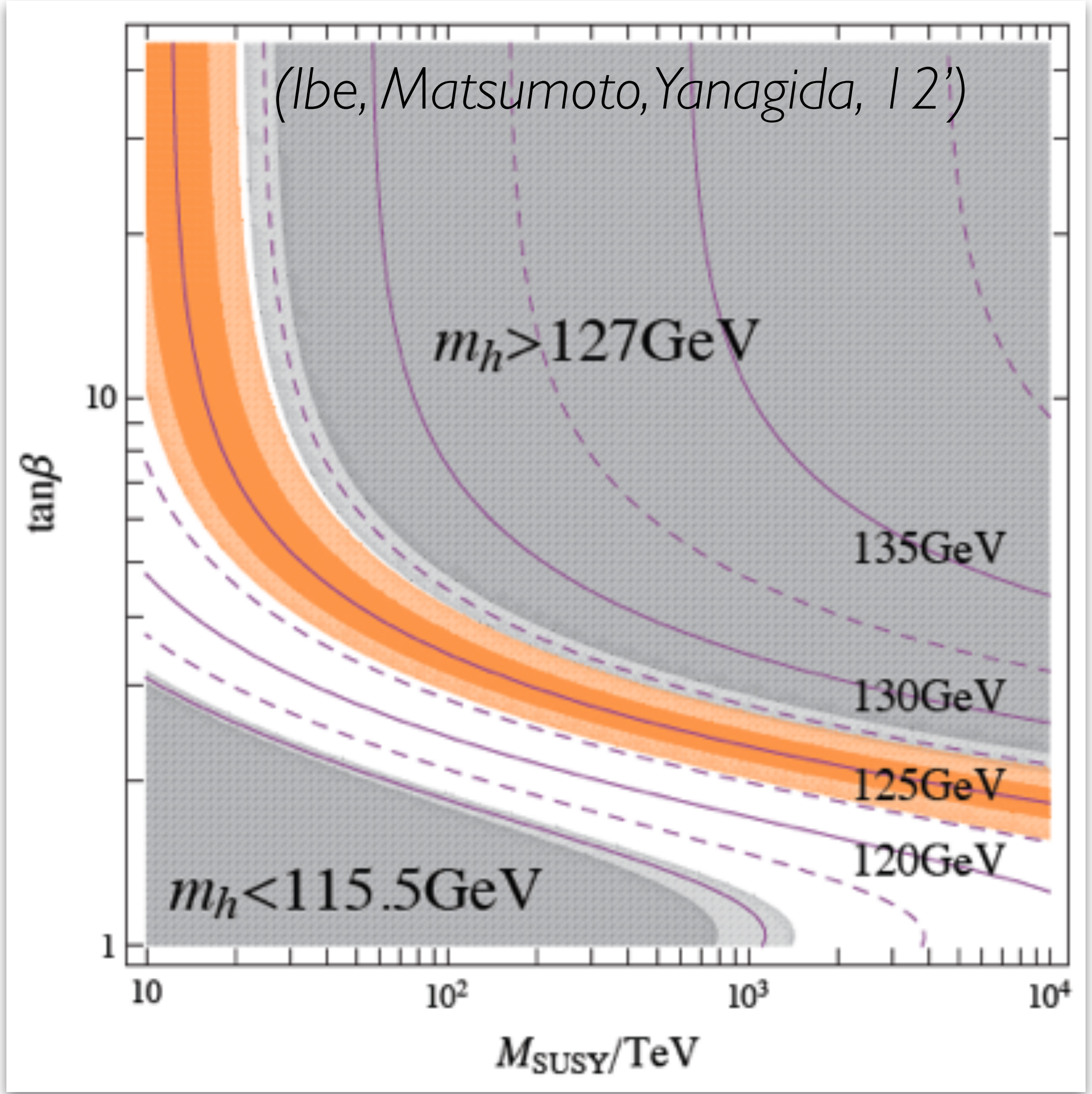


Higgs mass is around 125 GeV

MSSM prediction

$$m_h^2 \leq M_Z^2 \cos^2 2\beta + \boxed{\Delta m_h^2(m_{stop}^2, A_t - \mu/\tan\beta)}$$

loop correction



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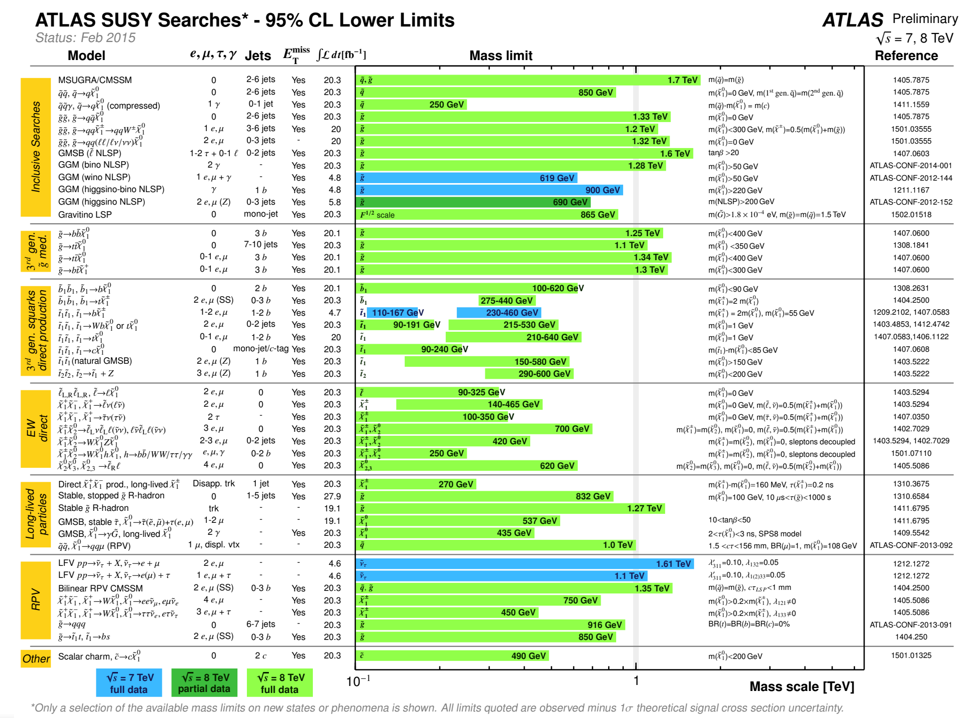

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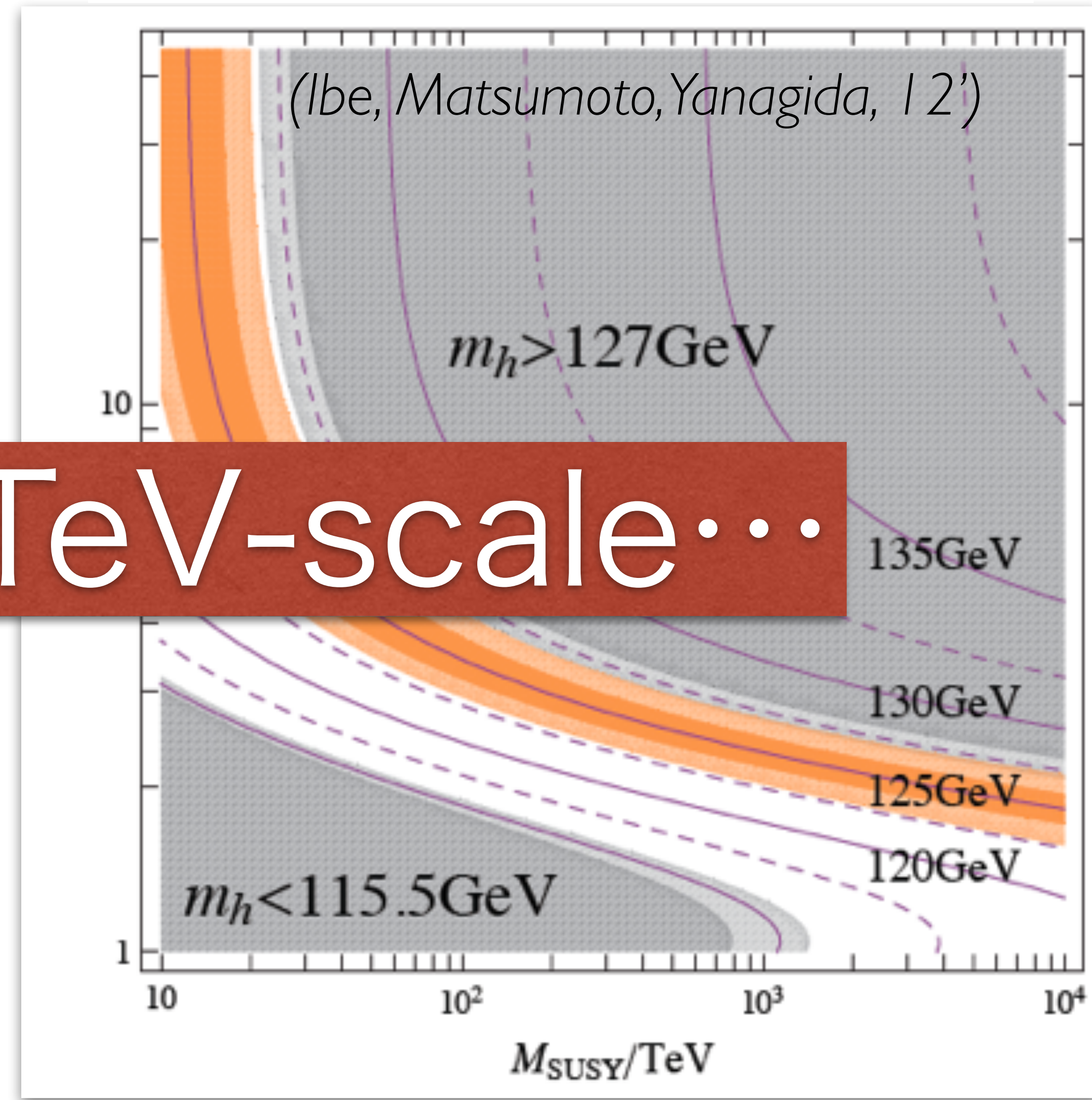


MSSM prediction

$$m_h^2 < M_Z^2 \cos^2 2\beta + \boxed{\Delta m^2(m^2 \ldots A \ldots \mu/\tan\beta)}$$

loop correction

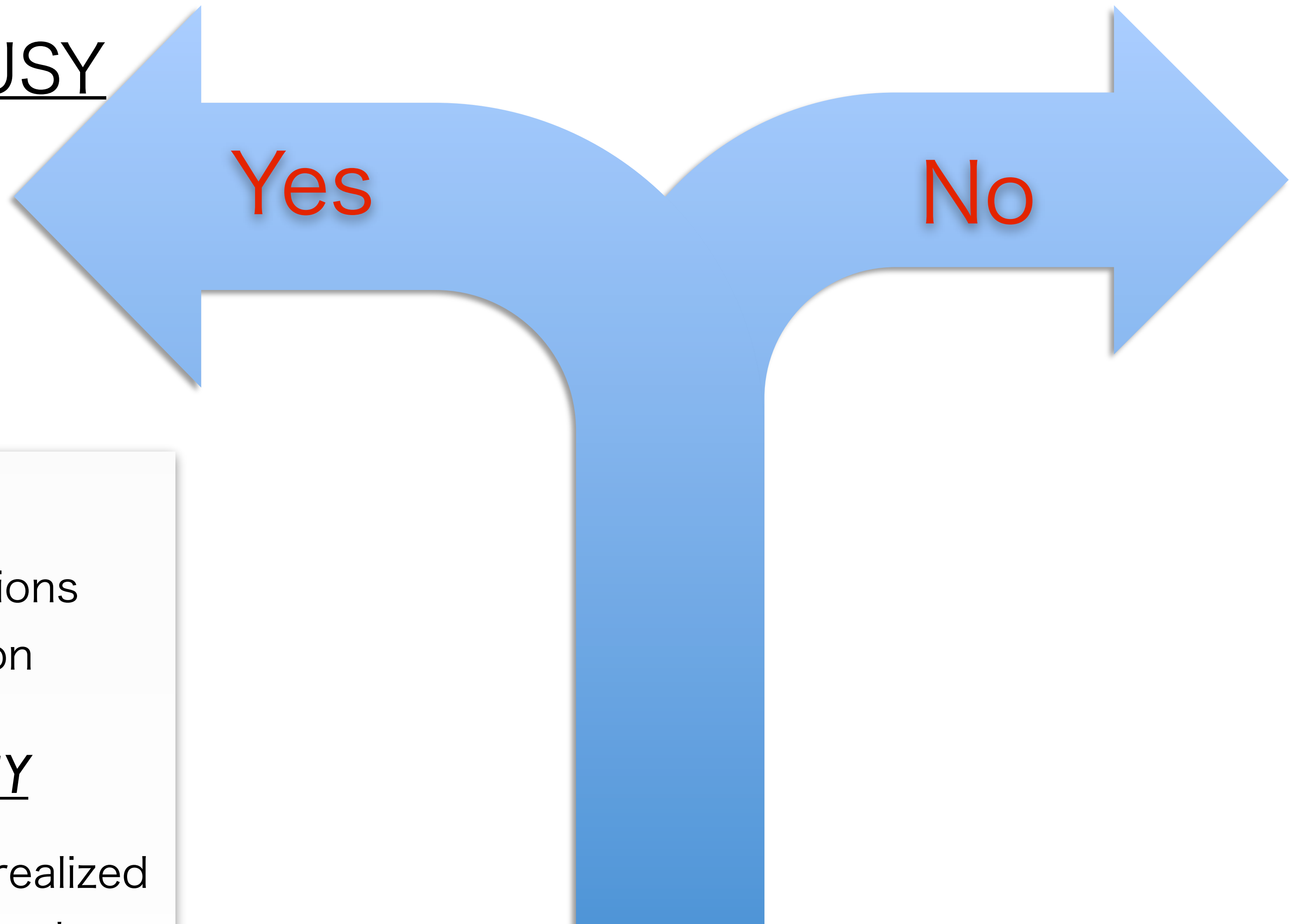
no SUSY around TeV-scale…

Is SUSY really the origin of the EW scale?

<u>low-scale SUSY</u>

not easy

but possible



effective SUSY

heavy 1,2 generations

light 3 generation

focus-point SUSY

EW scale naturally realized by specific mass spectrum

extended MSSM

NMSSM

MSSM with U(1)

Higgs discovery

and

severe constraints

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Yes

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heavy 1,2 generations

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focus-point SUSY

EW scale naturally realized

by specific mass spectrum

extended MSSM

NMSSM

MSSM with U(1)

<u>high-scale SUSY</u>

<u>(split SUSY)</u>

respect only

unification,

DM

my talk

Higgs discovery

and

severe constraints

In high-scale SUSY scenario,

gauginos: a few TeV

sfermions: O(100)TeV

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gauginos: a few TeV
sfermions: O(100)TeV

- 125-GeV Higgs mass is realized by small tan β.

(Cabrera, Casas, Delgado, 11'; Guidice, Strumia, 11'; Hall, Nomura, 11'; Arkani-Hamed, Gupta,et.al,12'; Ibe, Matsumoto,Yanagida, 12'; etc.)

- gauge coupling unification has been studied well.

(Arkani-Hamed, Dimopoulos, 04';Giudice, Romanino 04'; Hisano,Kuwahara,Nagata, 13'; etc.)

- DM may be wino.

- Constraints from flavor physics are relaxed.

In high-scale SUSY scenario,

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how to realize the fermion mass hierarchy from Yukawa unification (GUT),

how to prove such a high-scale physics,

doublet-triplet splitting (proton decay),

how to generate baryon asymmetry,

and so on.

In high-scale SUSY scenario,

there are still some issues:

Motivation of our model

how to realize the fermion mass hierarchy from Yukawa unification (GUT),

how to prove such a high-scale physics,

doublet-triplet splitting (proton decay),

how to generate baryon asymmetry,

and so on.

In minimal SO(10) GUT, all SM fermions are from 16

I introduce extra matters to realize top-bottom hierarchy:

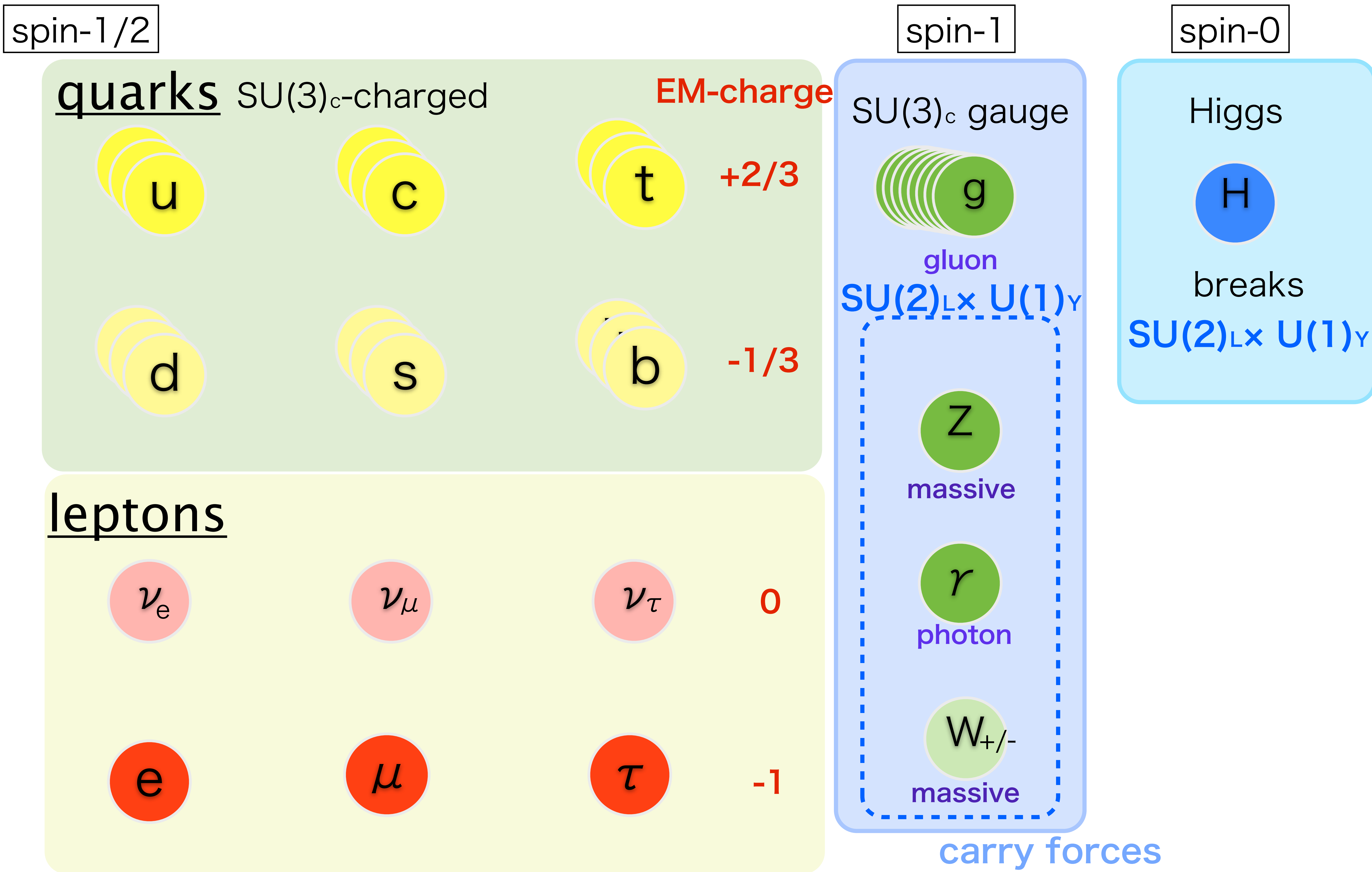
16 10

SM particles are the linear combinations of these 2 fields.

- Hierarchy between top and bottom quarks are realized.
- Z' interaction from SO(10) relates to the hierarchy, and **GUT could be tested by flavor physics**!

Setup

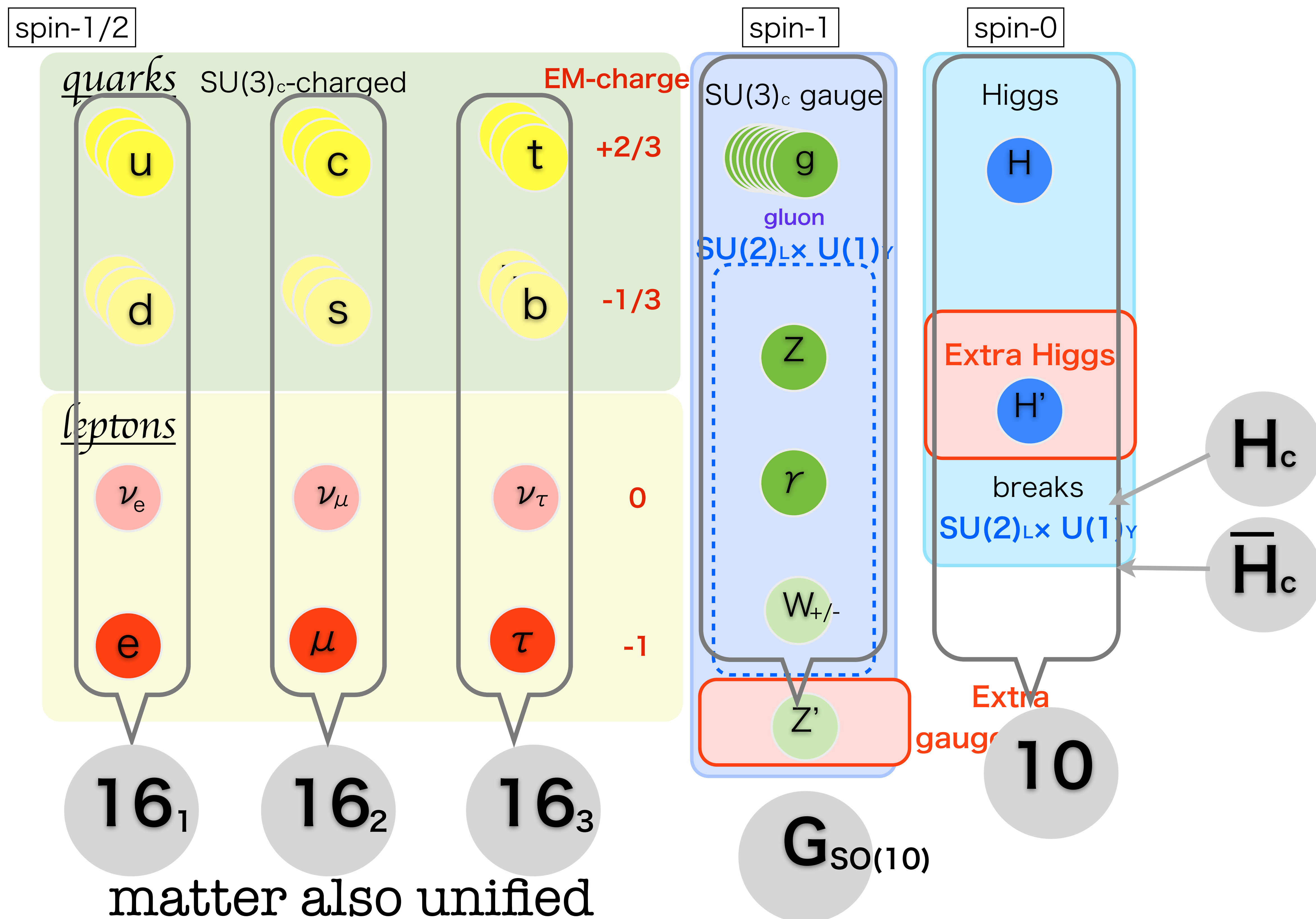
Standard Model $(SU(3)_c \times SU(2)_L \times U(1)_Y)$



SO(10) Embedding: $SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_X \rightarrow SO(10)$

extra

slightly extended SM



This looks elegant and we expect the GUT exists at the high scale.

But we can easily notice that

it is not simple to realize the realistic Yukawa couplings in the GUT.

only 3 matters

$\mathbf{16}_1$ $\mathbf{16}_2$ $\mathbf{16}_3$

predict

same mass matrices of (u,c,t), (d,s,b),(e,μ,τ)

no CKM mixing

$$y_{ij}\mathbf{16}^i\mathbf{16}^j 10_H \quad \Rightarrow \quad y_{ij}\overline{Q^i_L}u^j_R H_u + y_{ij}\overline{Q^i_L}d^j_R H_d + y_{ij}\overline{l^i_L}e^j_R H_d$$

can be diagonalized

same mass spectrum

$$m_t \approx m_b \, (\tan\beta \approx 1)$$

There are several ways to solve this problem:

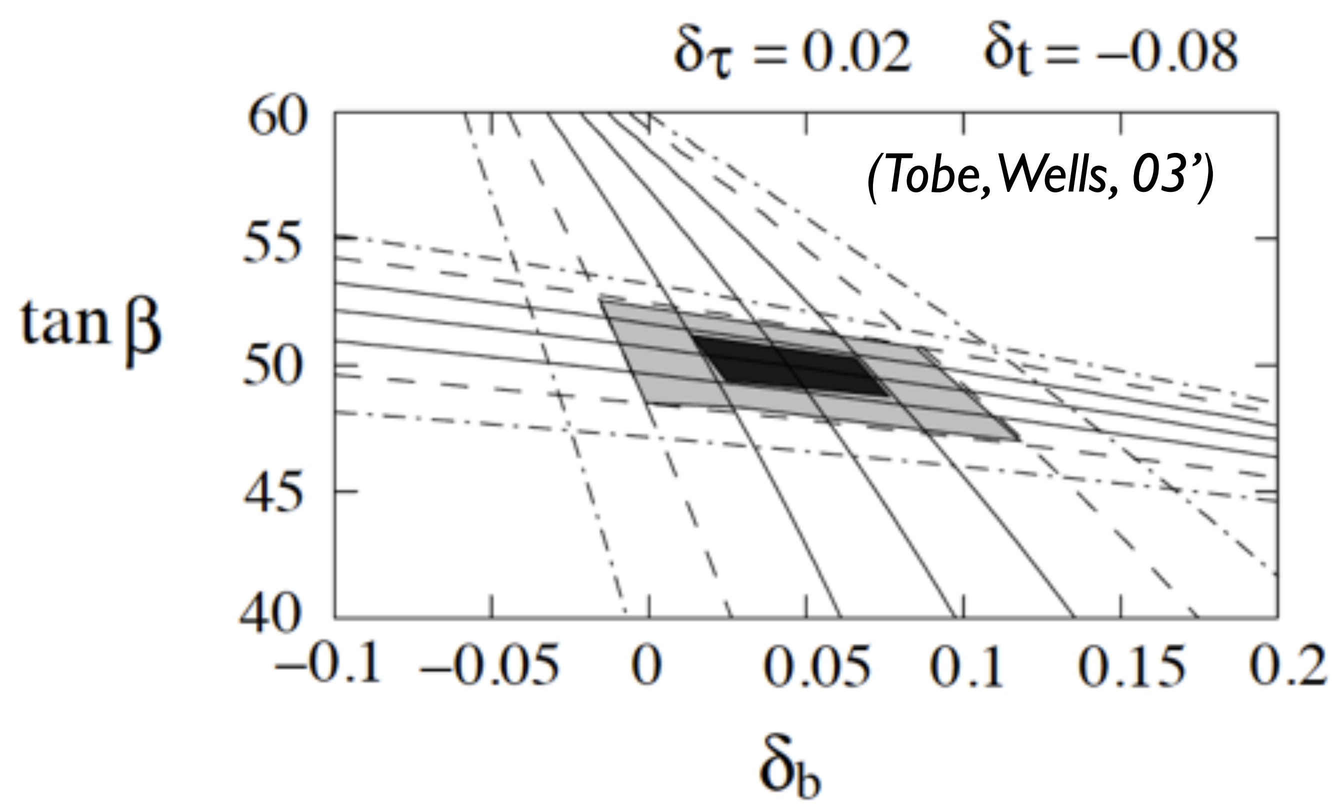
Introduce higher dimensional operators

(Georgi, Jarlskog, 79', etc.)

Introduce extra matters(quark/lepton), Higgs fields

(Ellis, Gaillard, 79'; Lazarides, Shafi, Wetterich, 81'; Barr 81', etc.)

Consider large tanβ *(Banks, 88'; Olechowski, Pokorski, 81'; etc..)*



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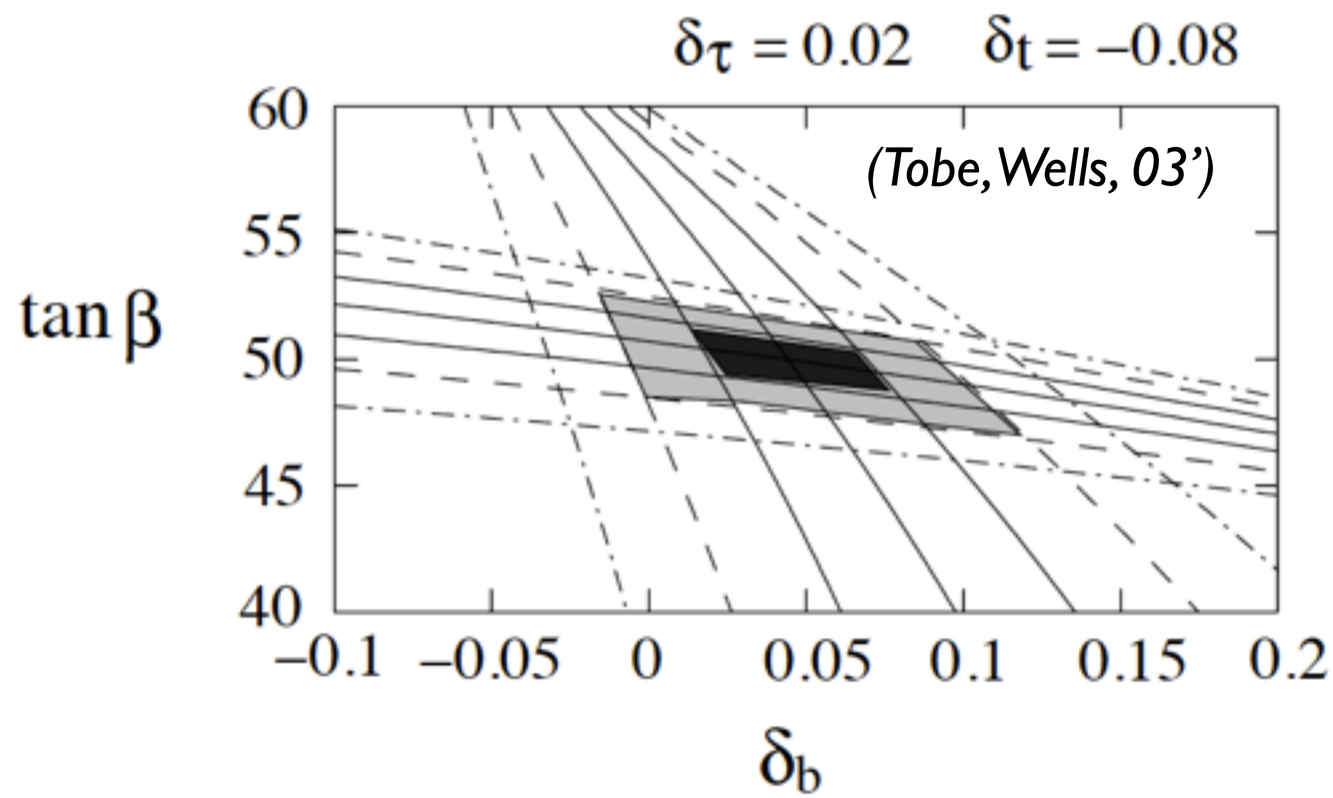
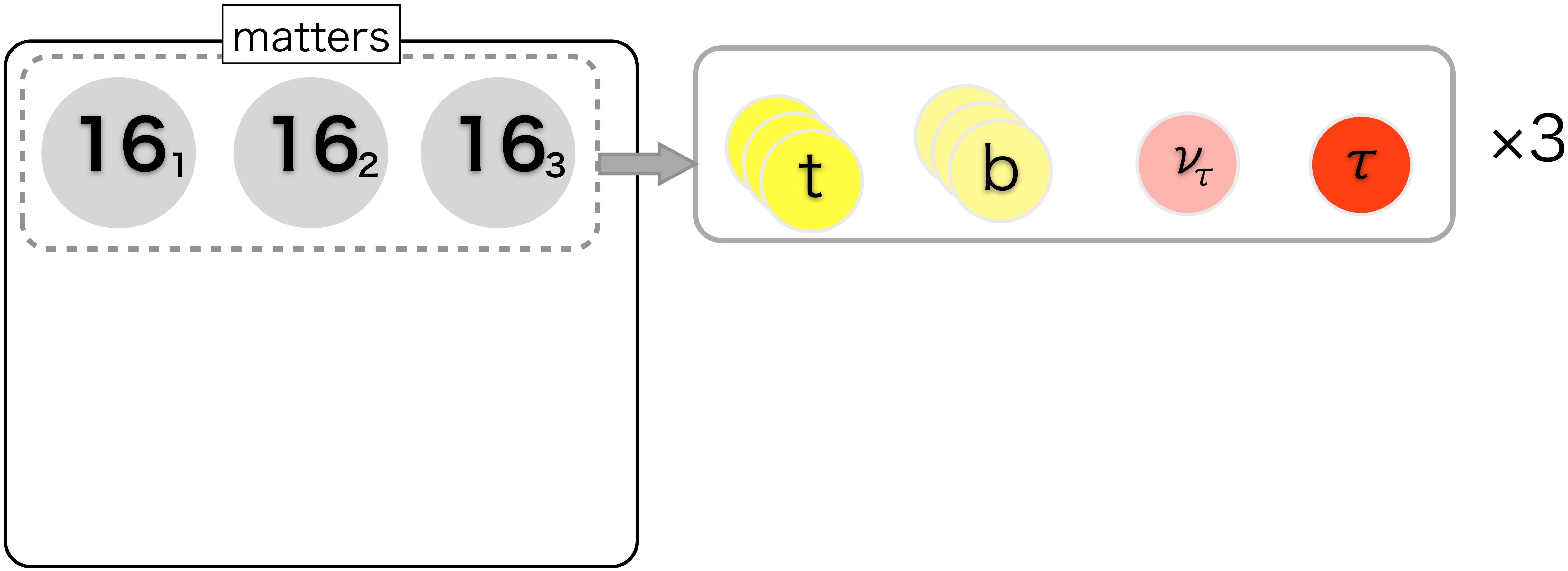
Consider $\boxed{\text{large } \tan\beta}$

disfavored by 125-GeV Higgs

(Banks, 88'; Olechowski,Pokorski, 81';etc..)

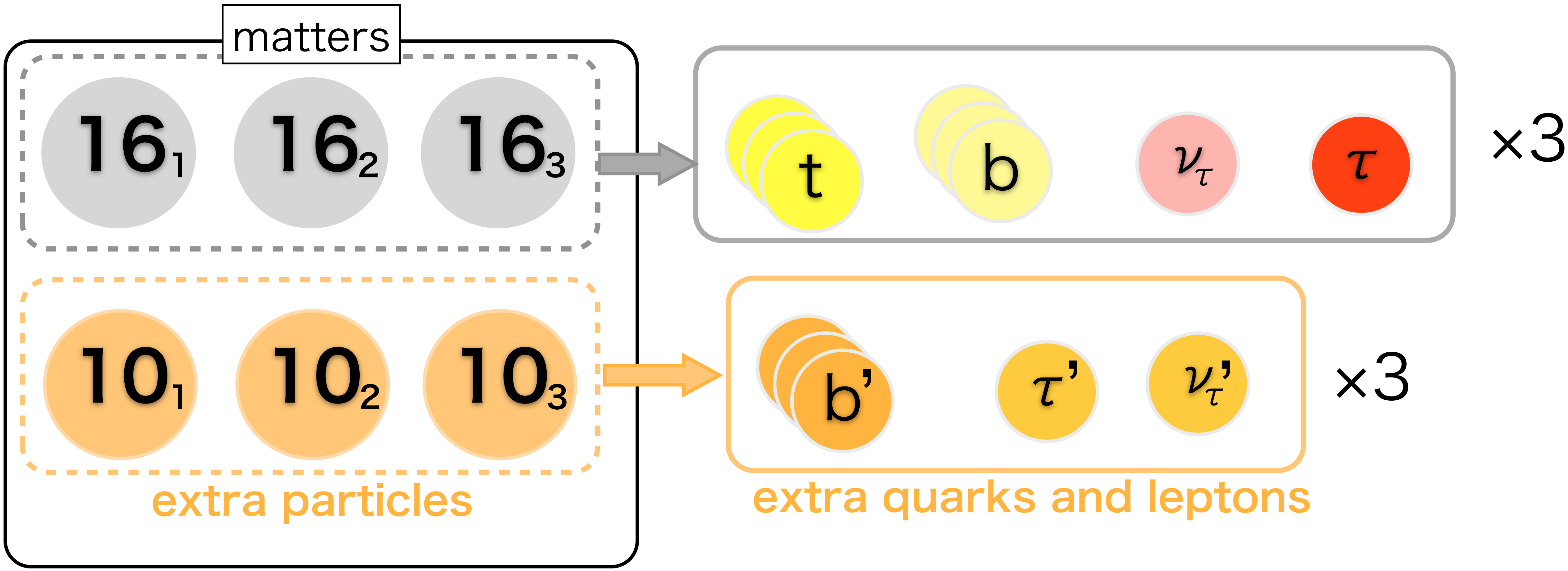


minimal setup



Let me add extra matters ($\mathbf{10}_1$, $\mathbf{10}_2$, $\mathbf{10}_3$)

(YO, J. Hisano, Y. Muramatsu, M. Yamanaka)



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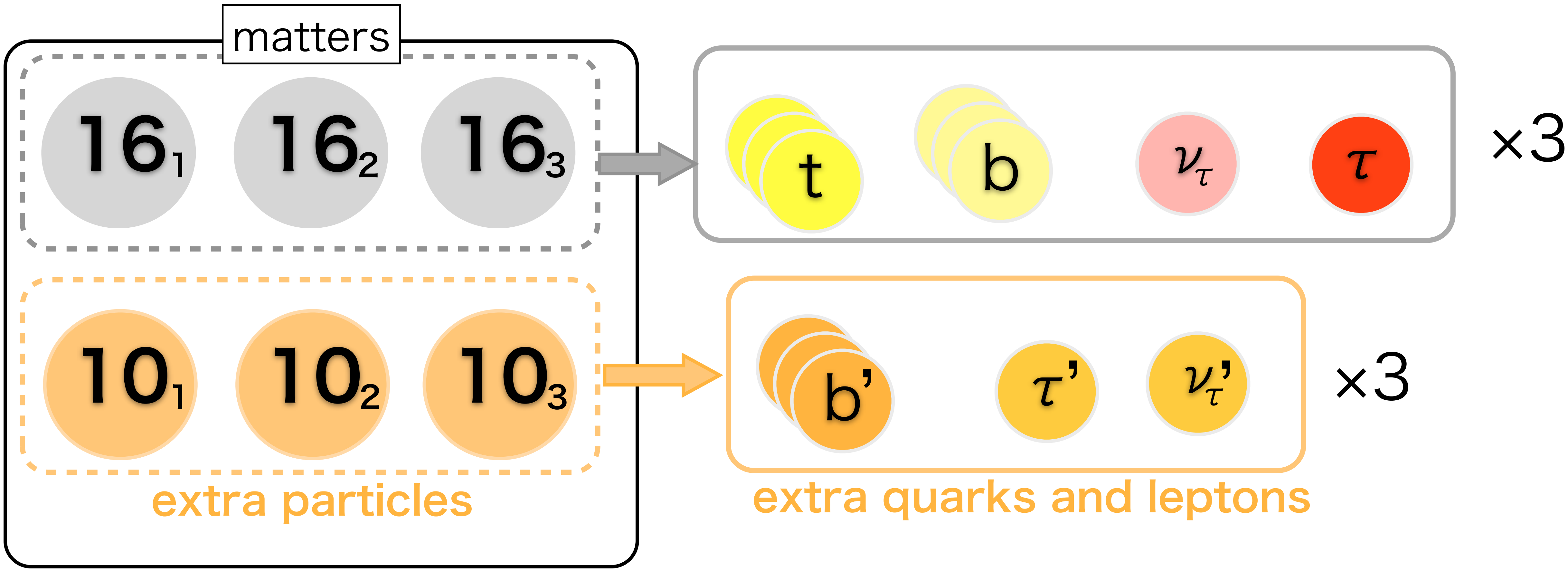

Then SM particles are given by the linear combinations:

ex)

minimal

$$|(b_R^c)_{SM}>=|b_R^c>$$

extended

$$|(b_R^c)_{SM}>=(\cos\theta_b)|b_R^c>+(\sin\theta_b)|b_R'^c>$$

"The GUT relation" is broken.

Ex) 3rd generation

In minimal SO(10) GUT, $m_t \approx m_b \, (\tan\beta \approx 1)$

Observed value: $\boxed{m_b \approx m_t \times (1/60)}$

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Improved prediction:

$$|(b_R^c)_{SM} >= (\cos\theta_b)|b_R^c> +(\sin\theta_b)|b_R^{\prime c}>$$

$$\boxed{m_b = \quad m_t \quad \times \left(\cos\theta_b \right) \quad \text{small } \cos\theta_b \text{ required}}$$

The detail of the mass mixing

top: $m_t \, t_L t_R^c$

bottom: $m_t \, b_L \hat{b}_R^c$ $+ M' \overline{b'_R}^c \hat{b}_R^c + \mu_{10} \overline{b'_R}^c b'^c_R$

"extra" quarks

mass mixing

from

$$g^{ij} \mathbf{16}_i \mathbf{10}_j \mathbf{16}_H + \mu_{10}^{ij} 10_i 10_j$$

develop nonzero VEV

Diagonalizing this mass matrix, we get the bottom quark mass.

How test this GUT?

Usually, proton decay.

Hints

There is Z' from SO(10).

Z' interaction is flavor-dependent because of the fermion mass hierarchy.

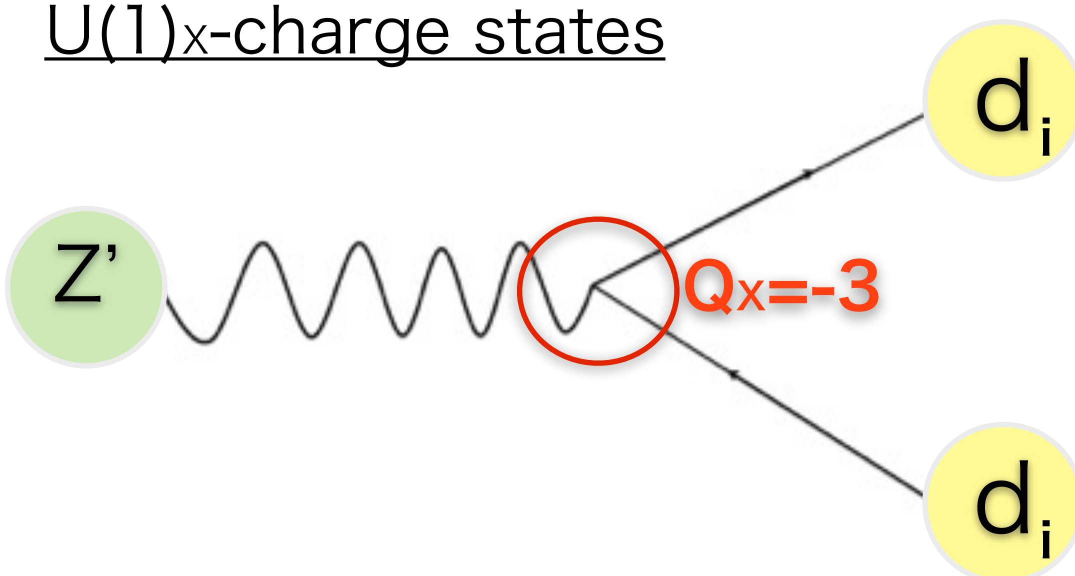
This is because

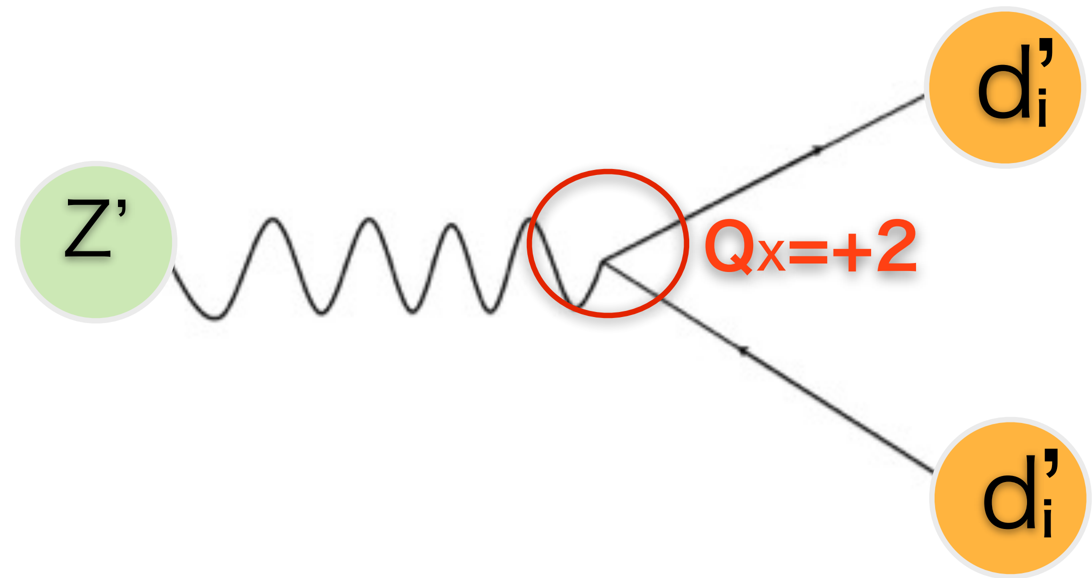
(YO, J. Hisano, Y. Muramatsu, M. Yamanaka)

d_i and d'_i carry different U(1)$_X$ charges

extra

U(1)$_X$-charge states





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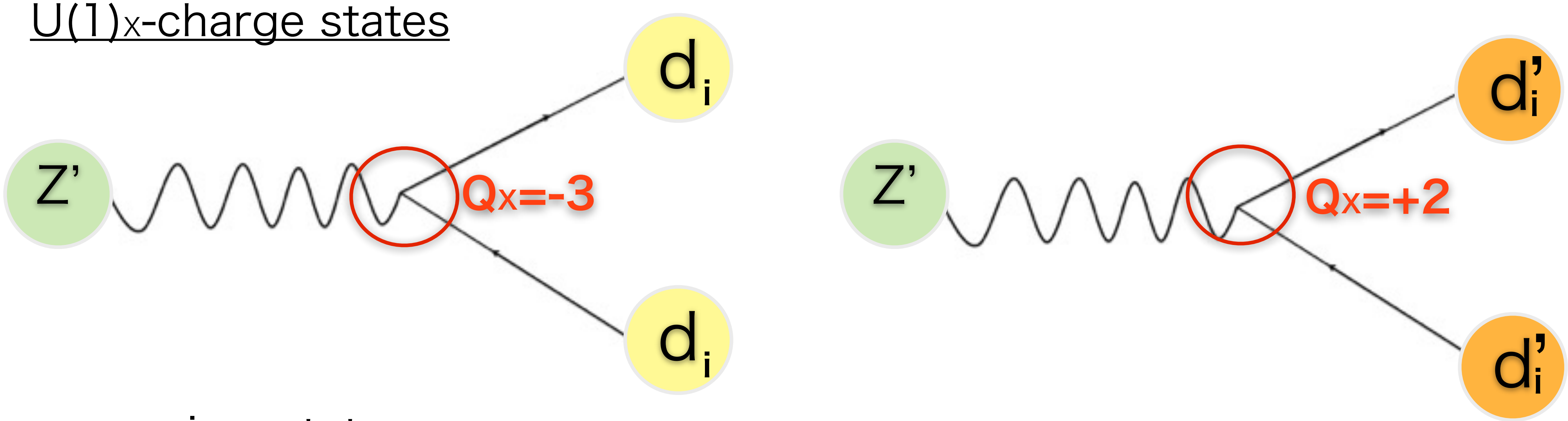
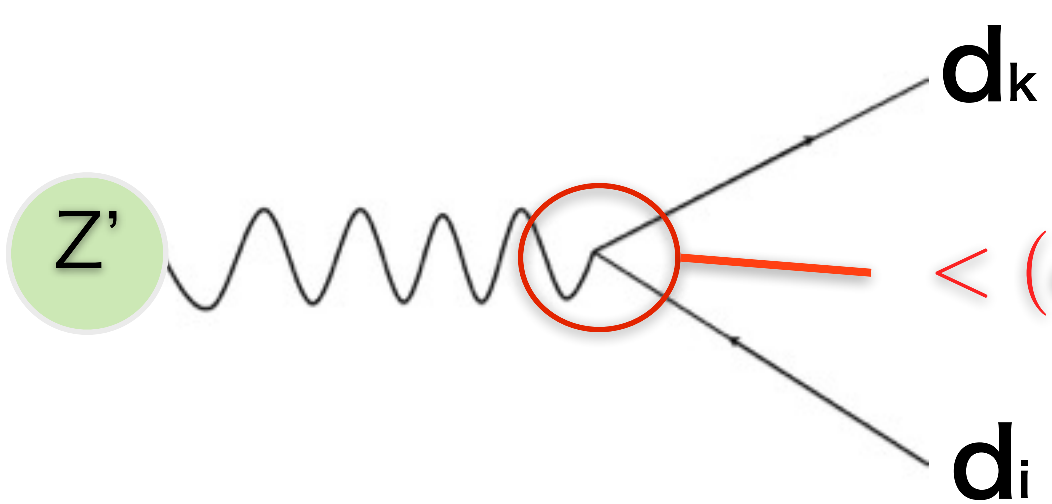


mass eigenstates

down-type quarks

$$|(d_R^i)_{SM} >= U_{ij}|d_R^j(-3) > +U'_{ij}|d'^j_R(+2) >$$



$$< (d_R^k)_{SM}|\hat{Q}_X|(d_R^i)_{SM} > \not\propto \delta_{ik}$$

Flavor violating!

How test this GUT?

Usually, proton decay.

Hints

There is Z' from SO(10).

Z' interaction is flavor-dependent because of the fermion mass hierarchy.

If Z' resides around SUSY scale (~100TeV),
We can test the SO(10) GUT by flavor physics!

Our Predictions

Left-handed leptons and right-handed down-type quarks have FCNCs.

FCNCs relate to the fermion mass hierarchy and CKM.

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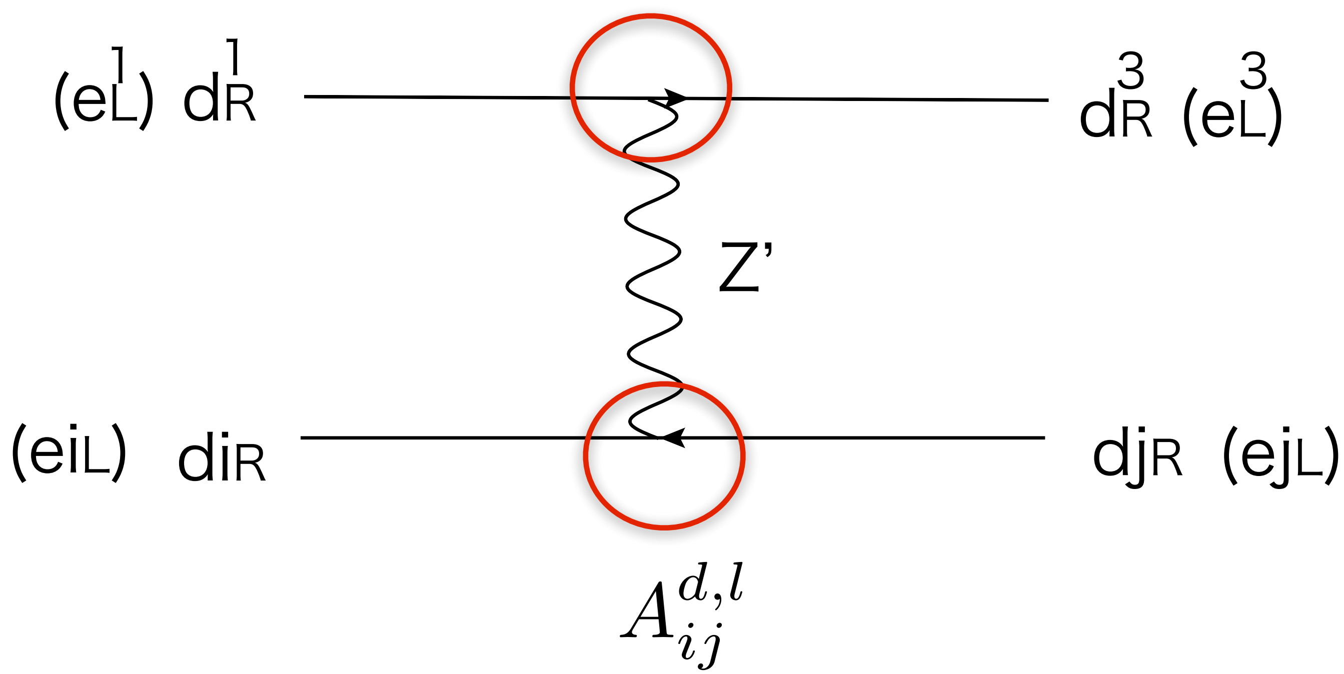
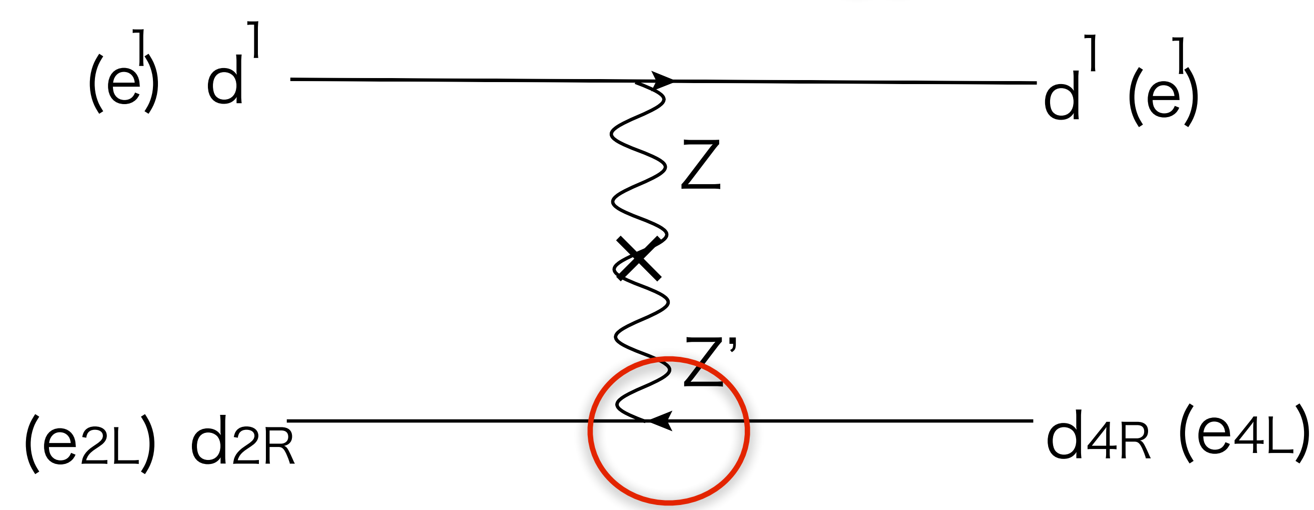


finite Z-Z' mass mixing predicted



Roughly speaking, $A_{ij}^{d,l} \propto m_i^{d,l} \times m_j^{d,l}$

For instance, (b,s) element is relatively large

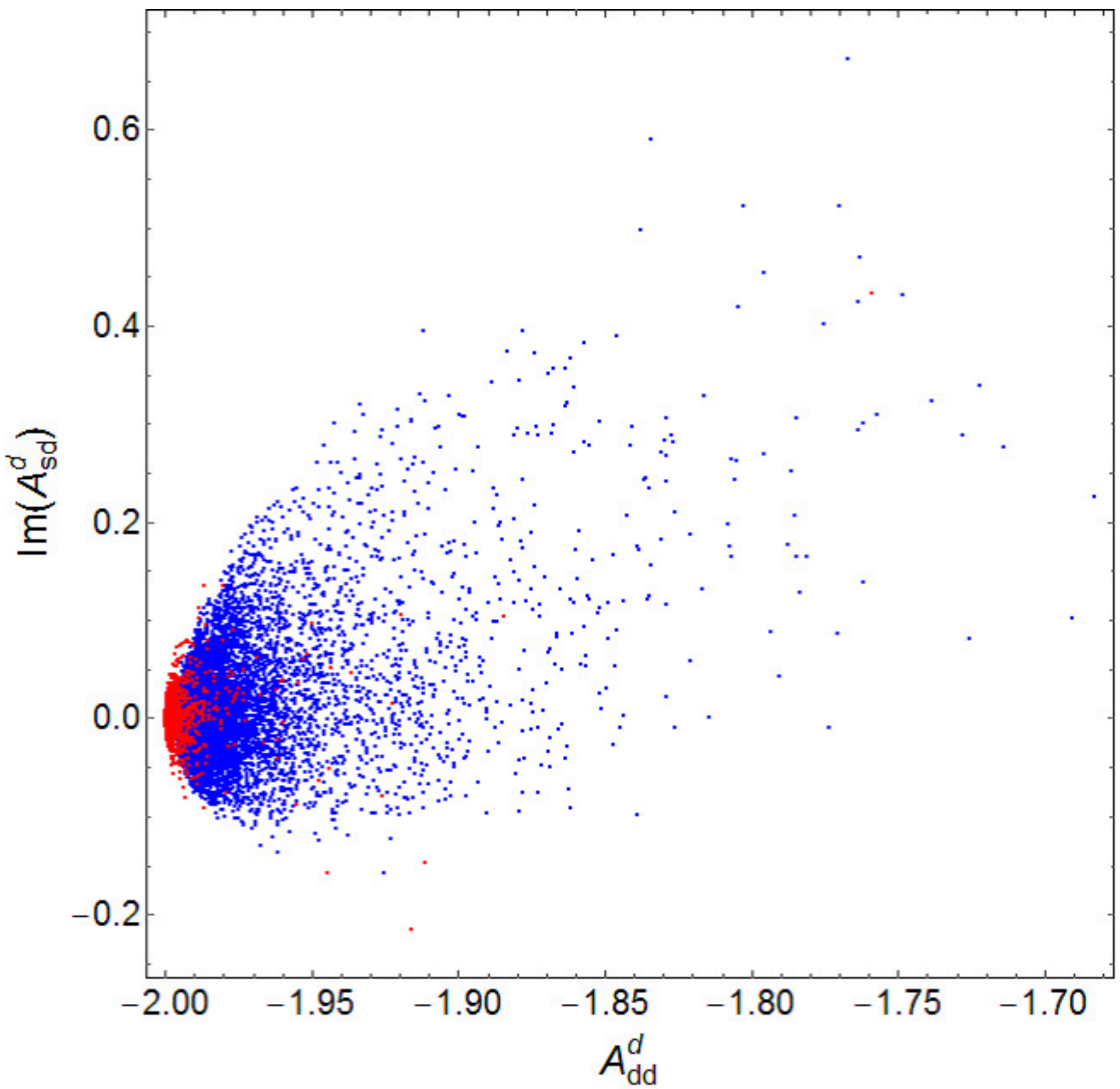
Our Predictions for $A_{ij}^{d,l}$

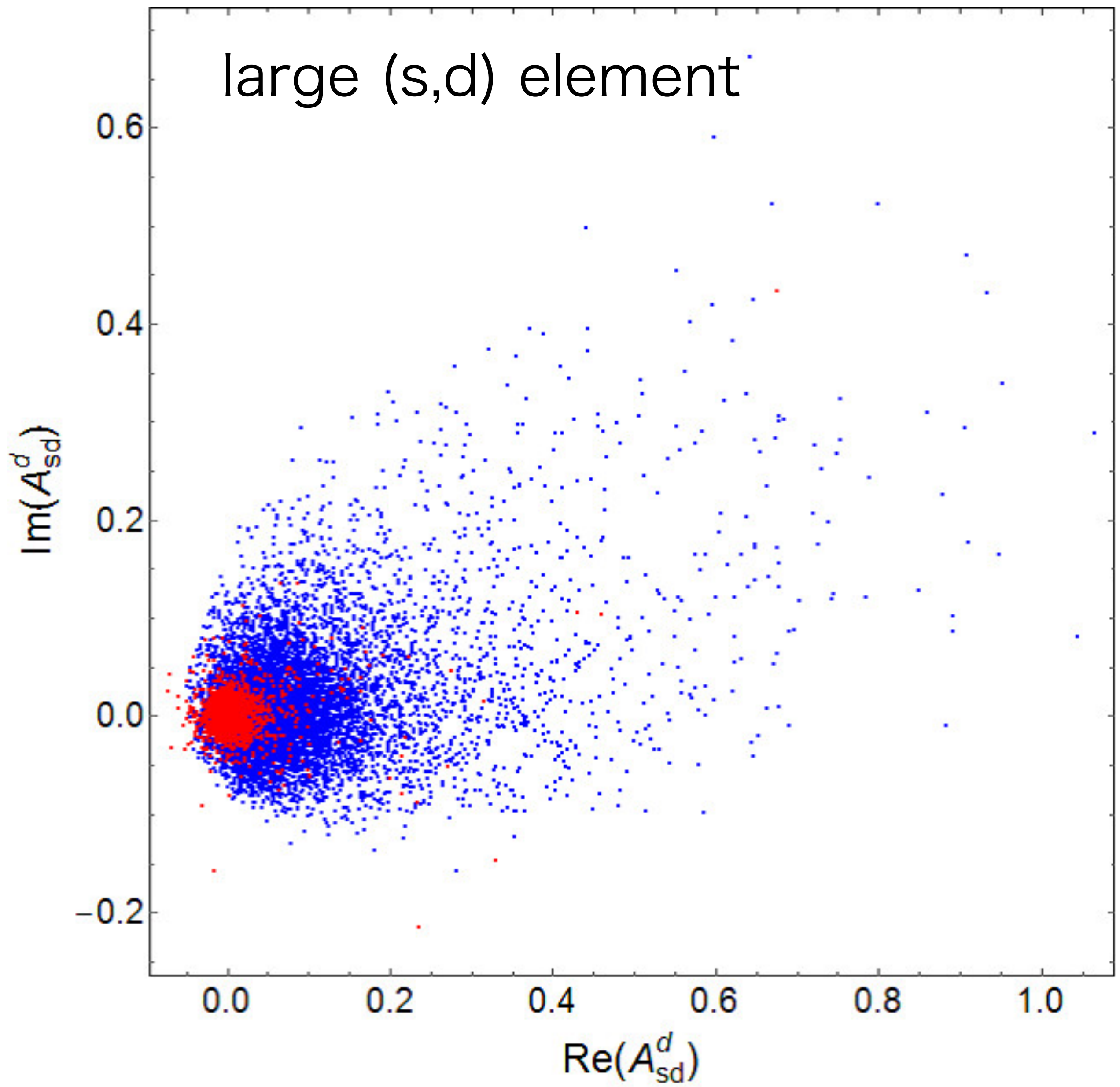
(s,d) vs. (d,d)

Blue points: higher-dim. ope. < 0.001

Red points: higher-dim. ope. < 0.01

We need extra contributions to be realist





down quark is mainly from 10 representation !

Our Predictions for $A^{d,l}_{ij}$

(b,d) element

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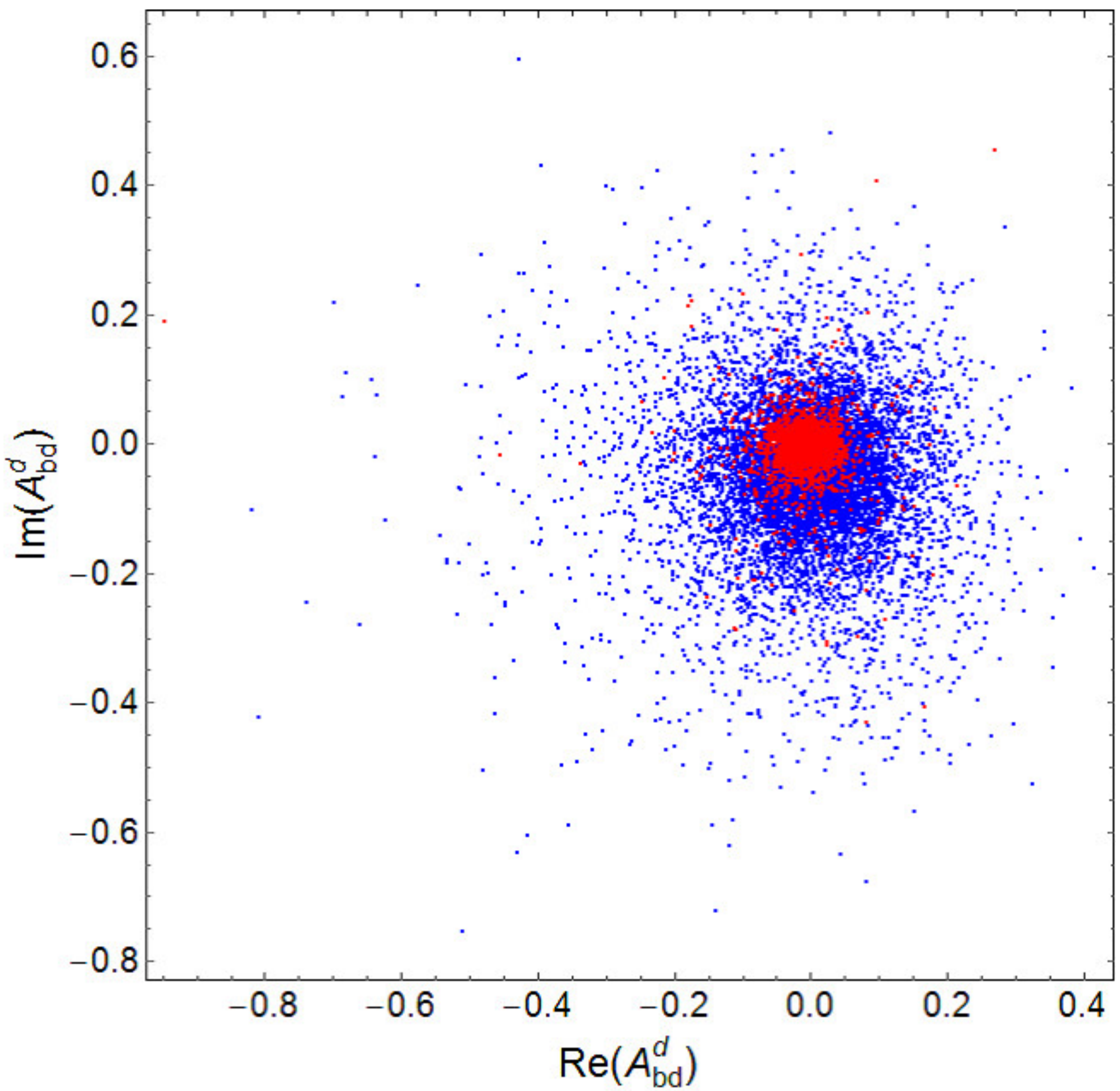
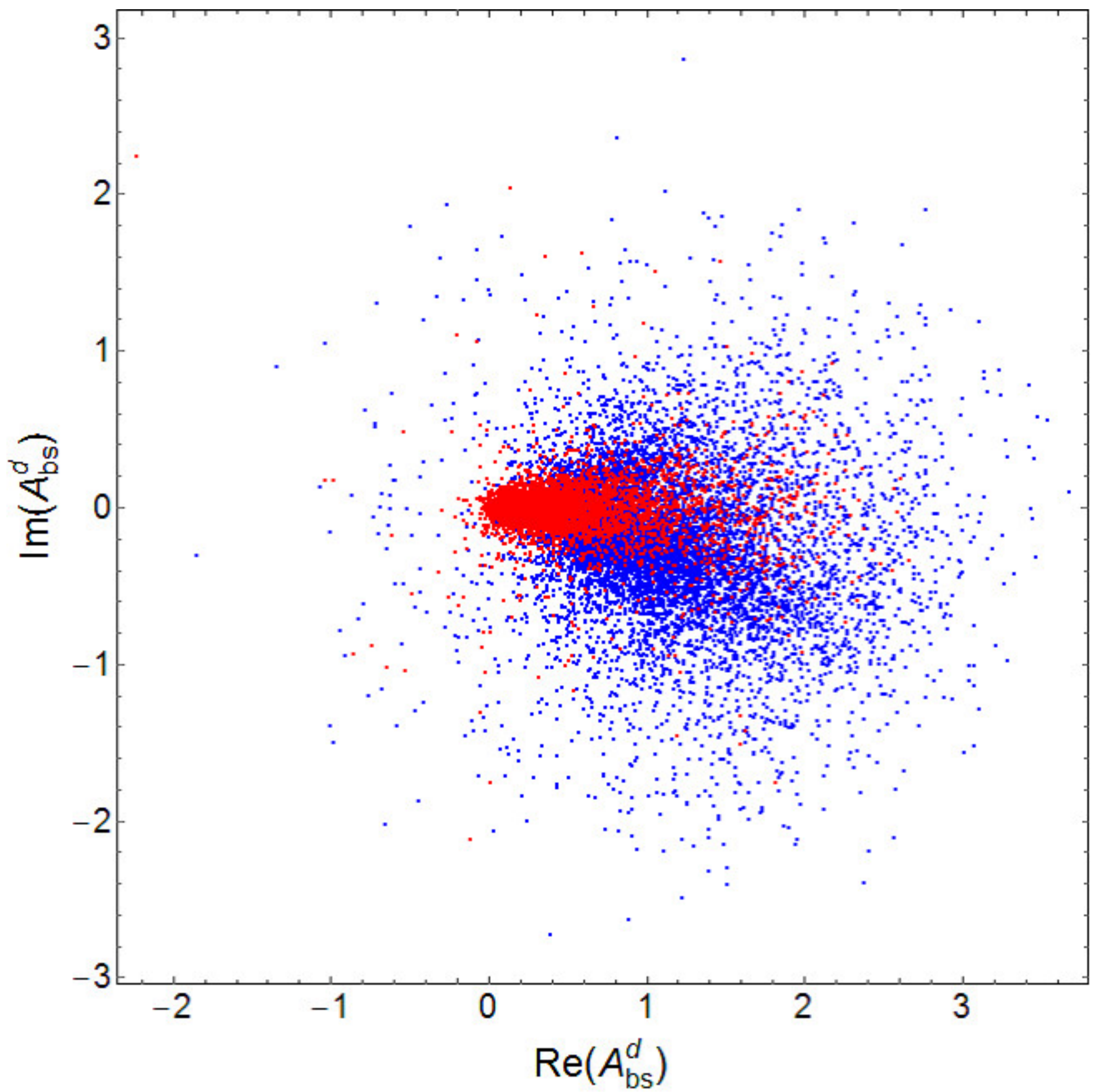


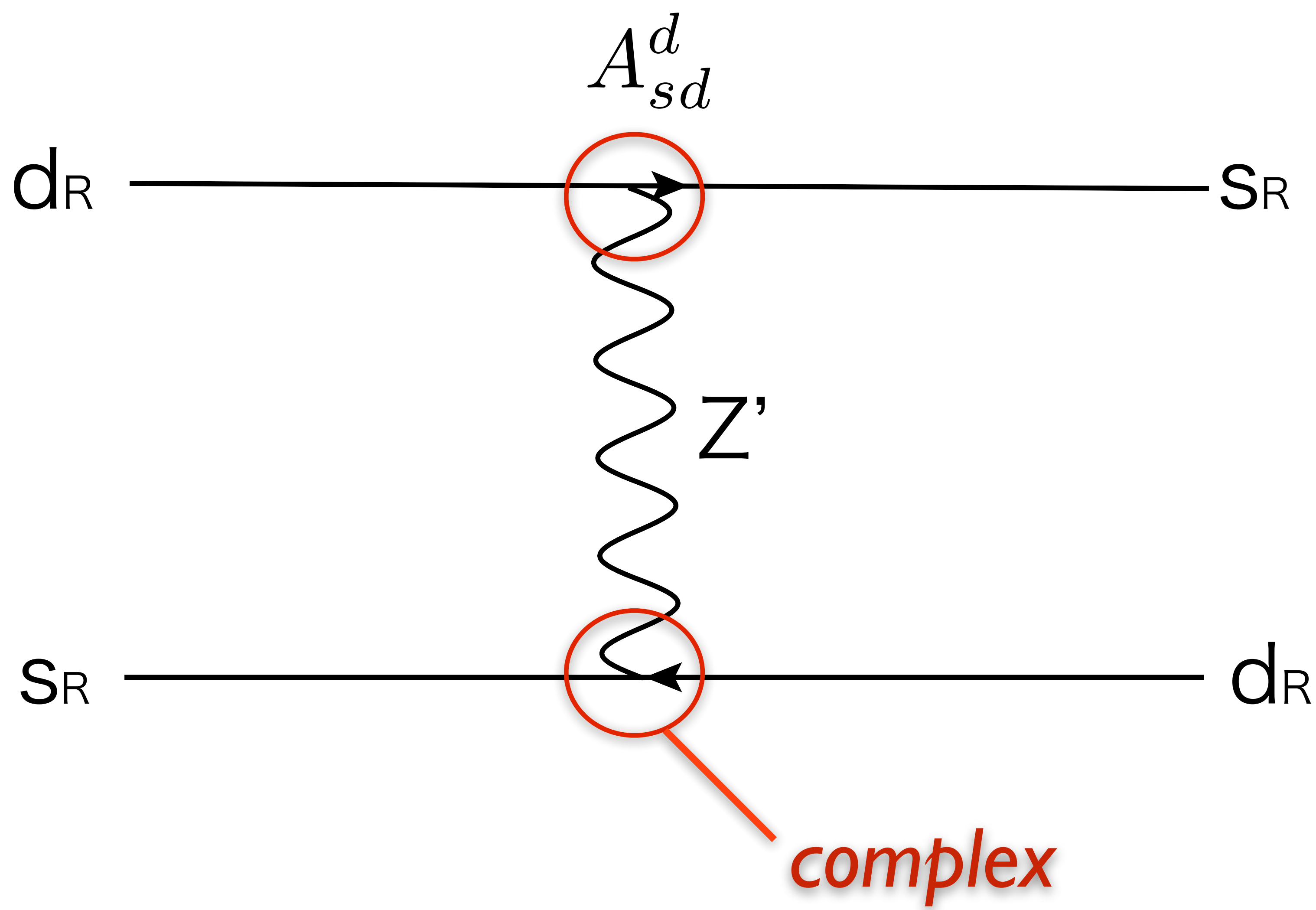
(b,s) element

very large because of m_b and m_s!



Flavor Physics

Deviations in K-$\overline{\text{K}}$ compared to the SM predictions



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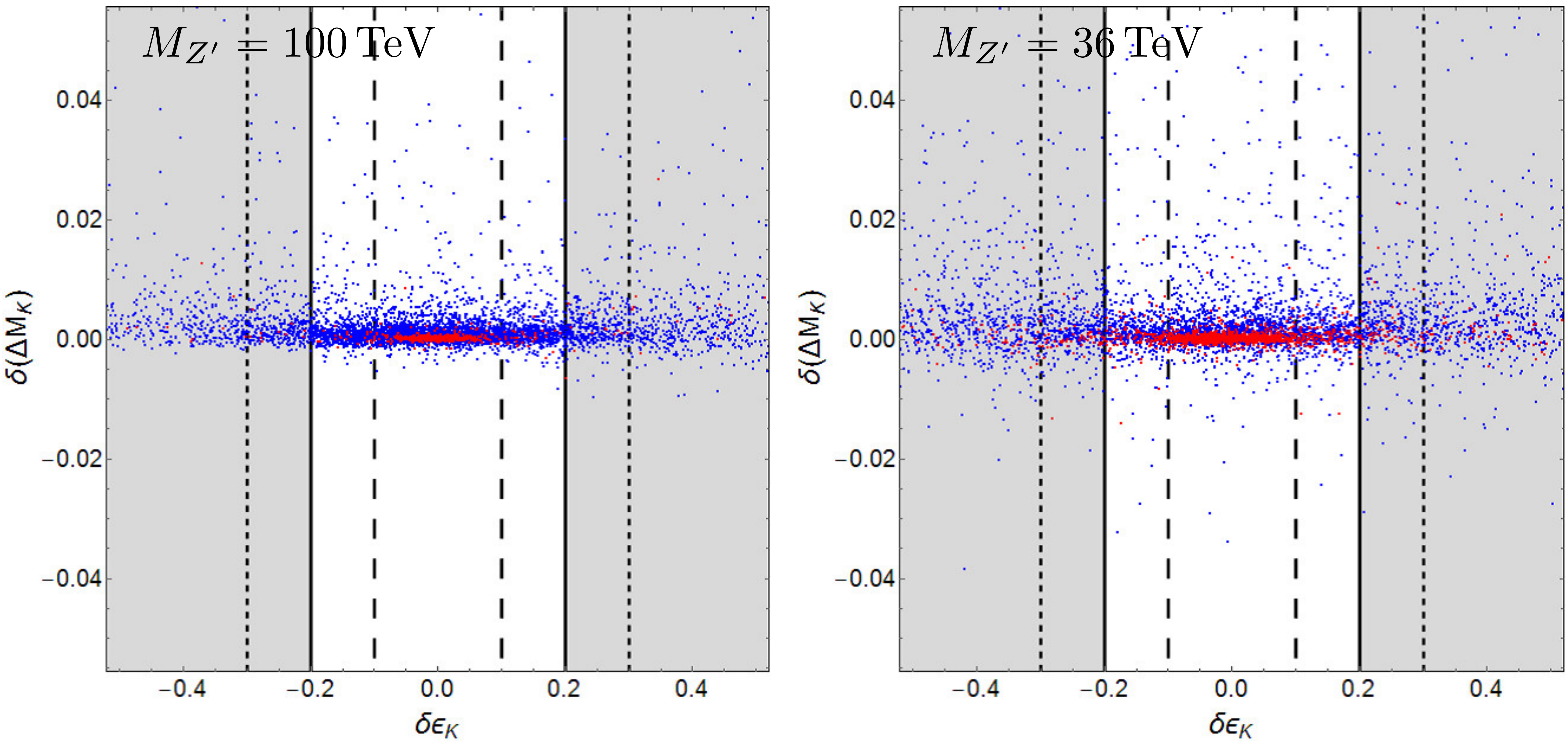
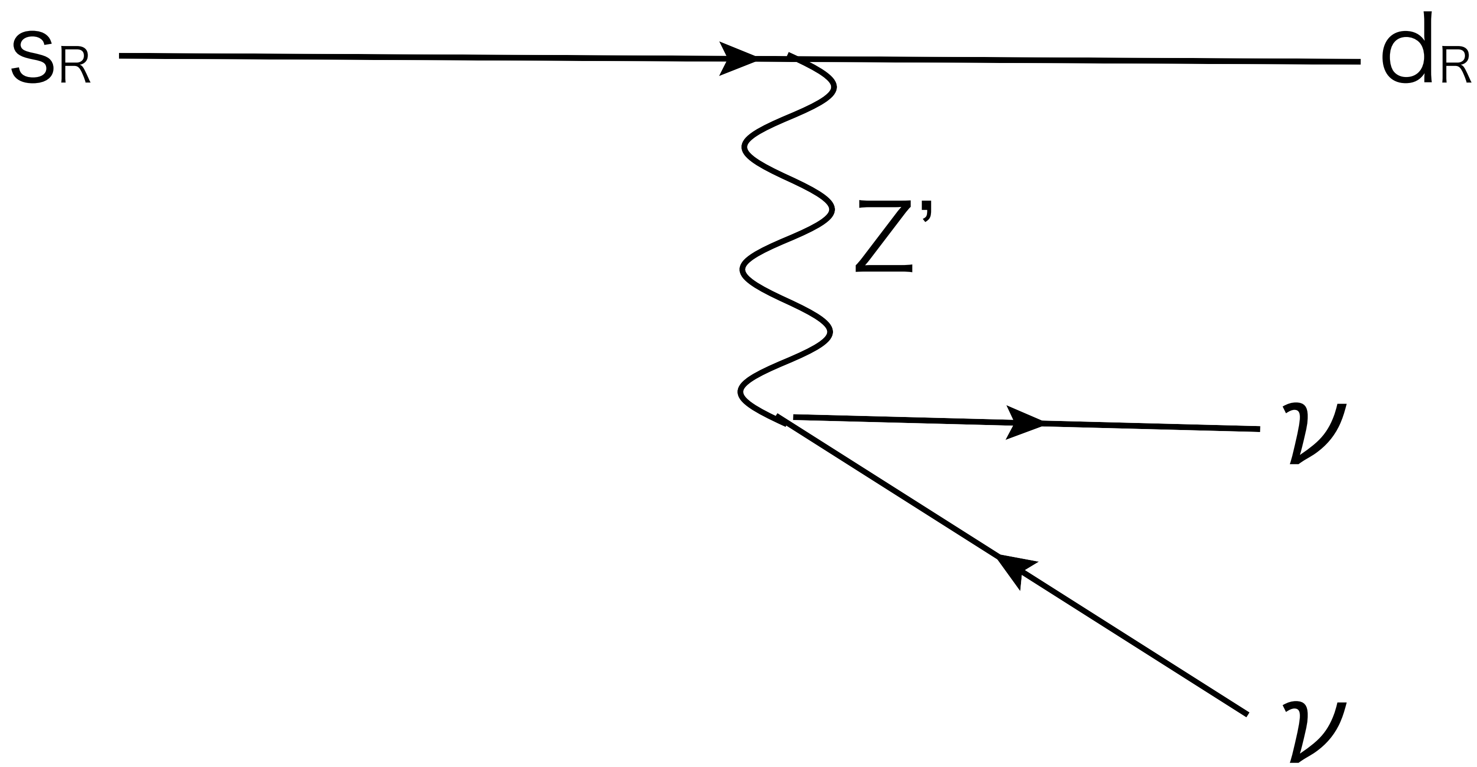


For example, CKM fitter collaboration suggest $|\delta\epsilon_K| \lesssim 0.3$

(arXiv: 1309.2293)

Deviations in rare K decay

$K_L \to \pi^0 \nu \nu$ will be measured by the KOTO experiment.



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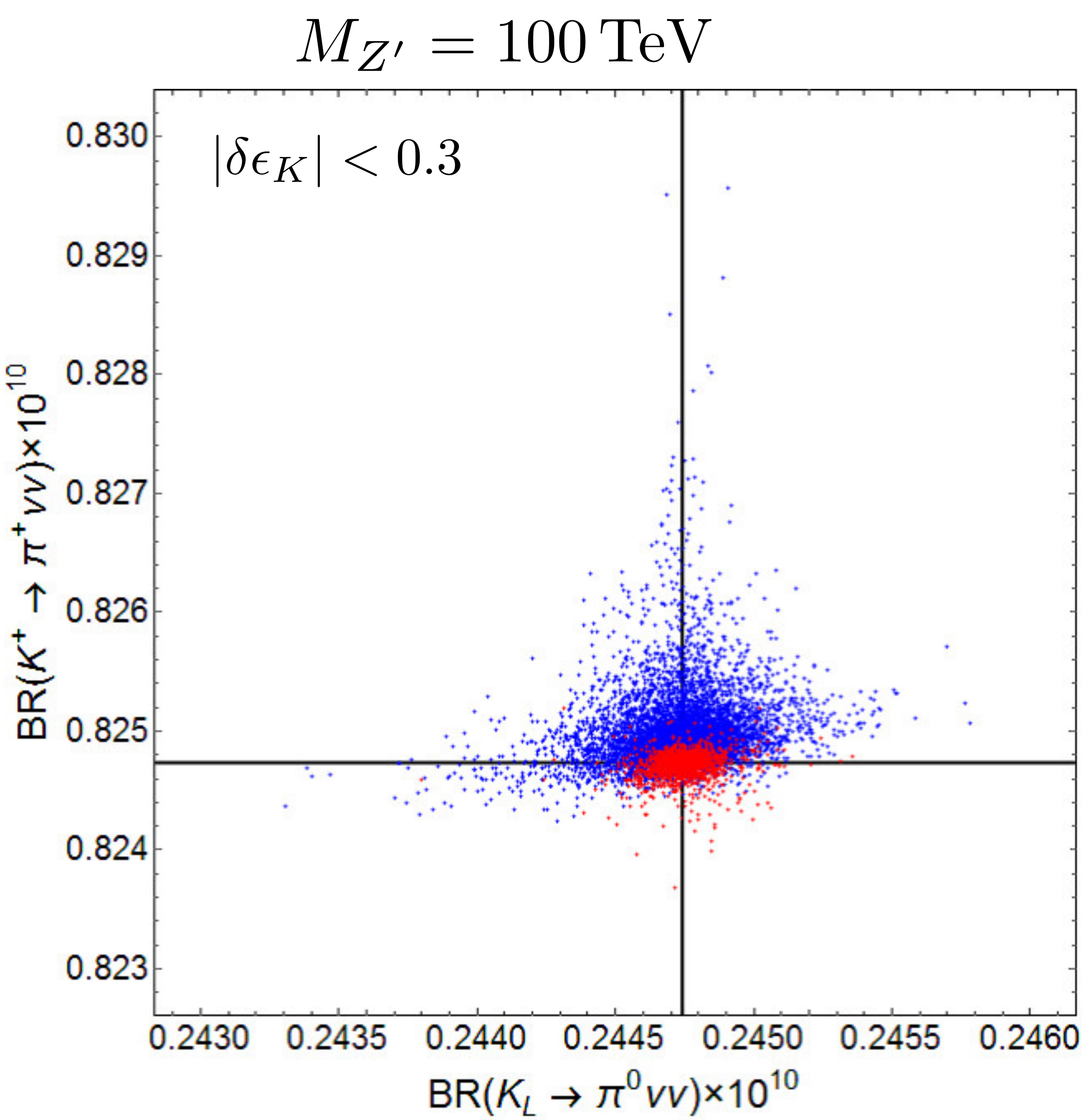
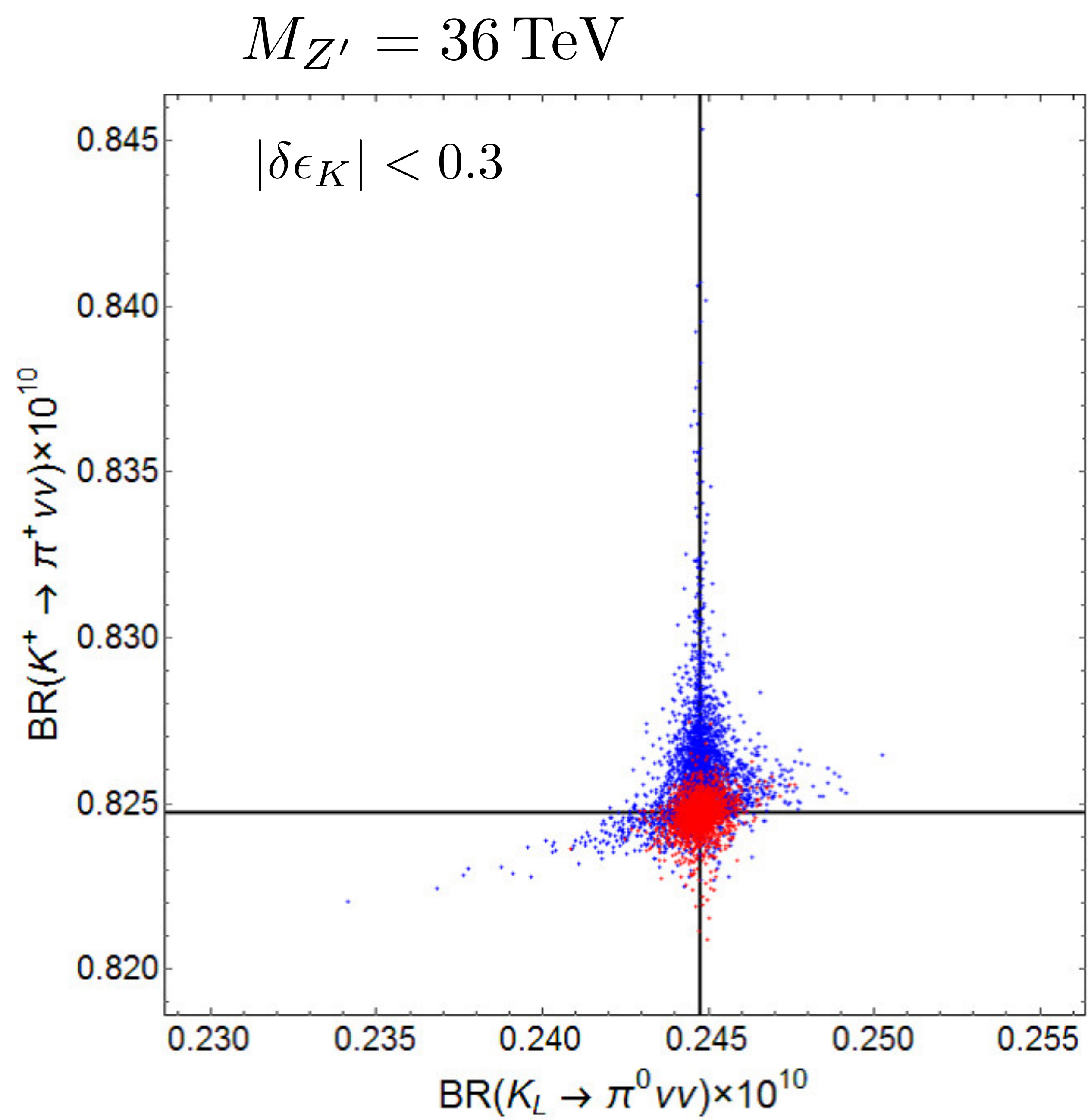
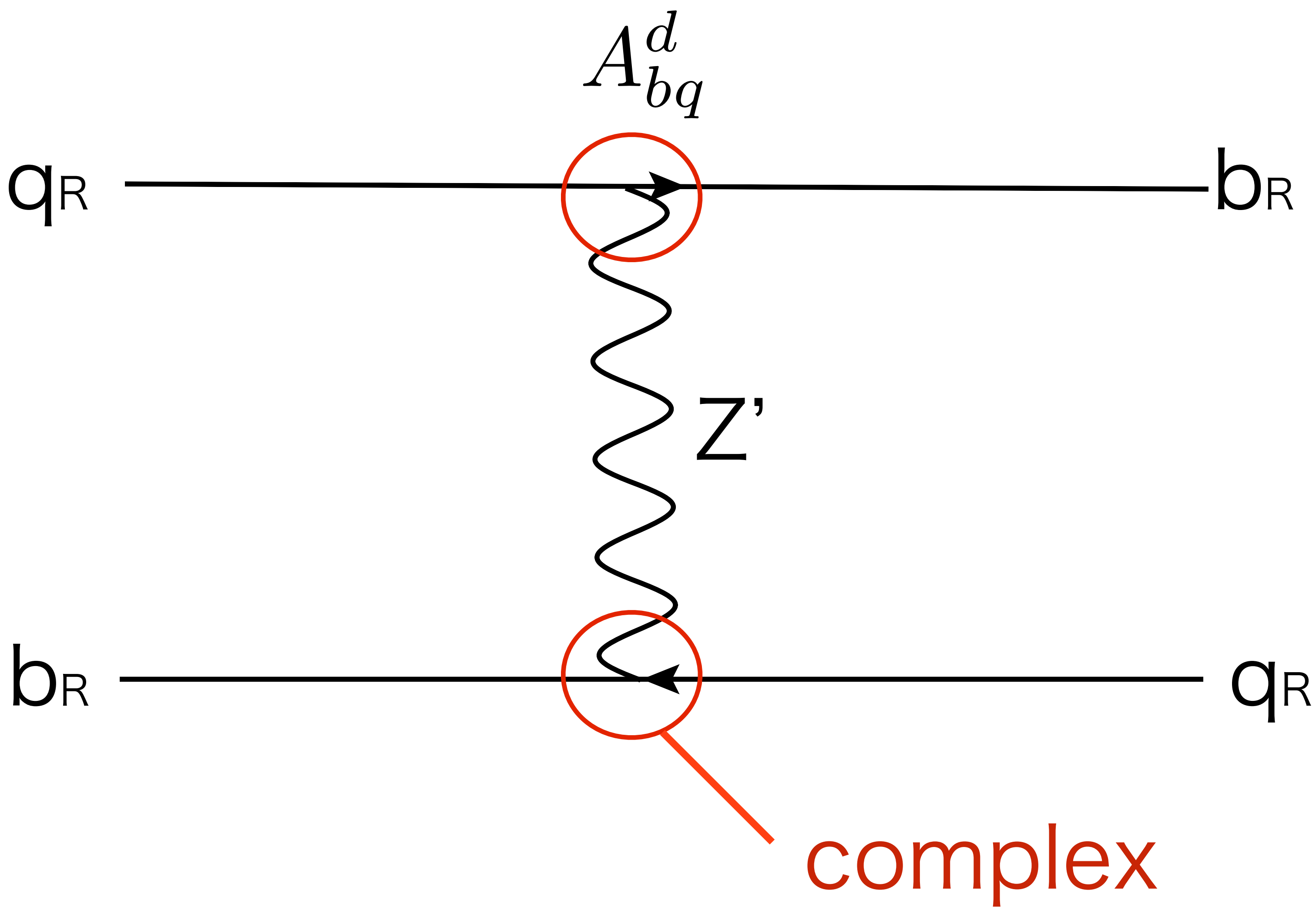




deviations of $K_L \to \mu\mu, \mu e$, $K \to \pi^0 \nu\nu$ are at most O(1)%.

Deviations in $B_{(s)}$-$\overline{B}_{(s)}$ compared to the SM predictions



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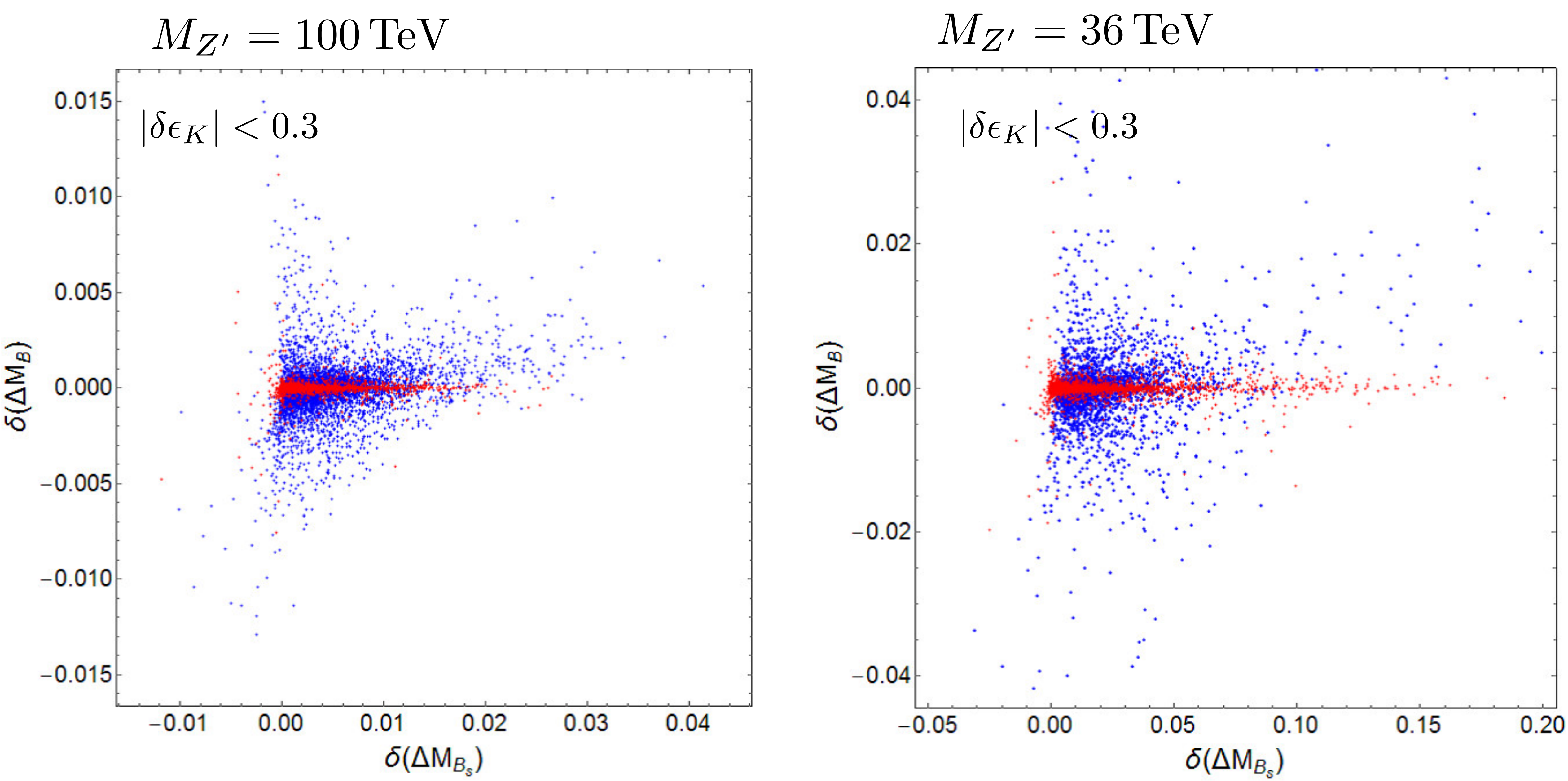


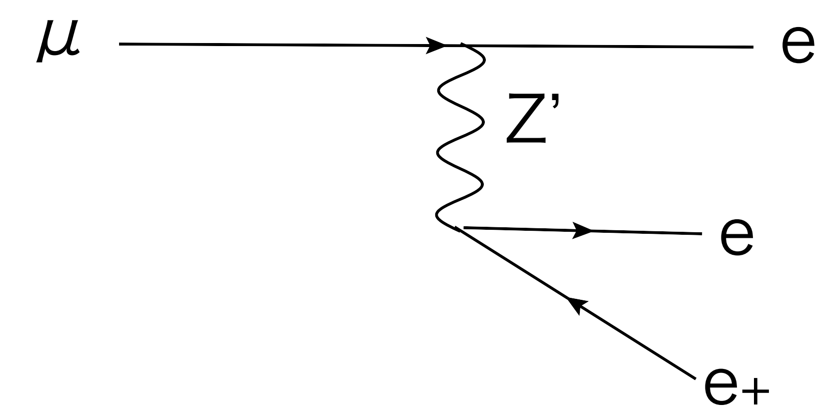
The deviation of Bs-$\overline{\text{B}}$s mixing reaches 10 % if Z' mass O(10) TeV.

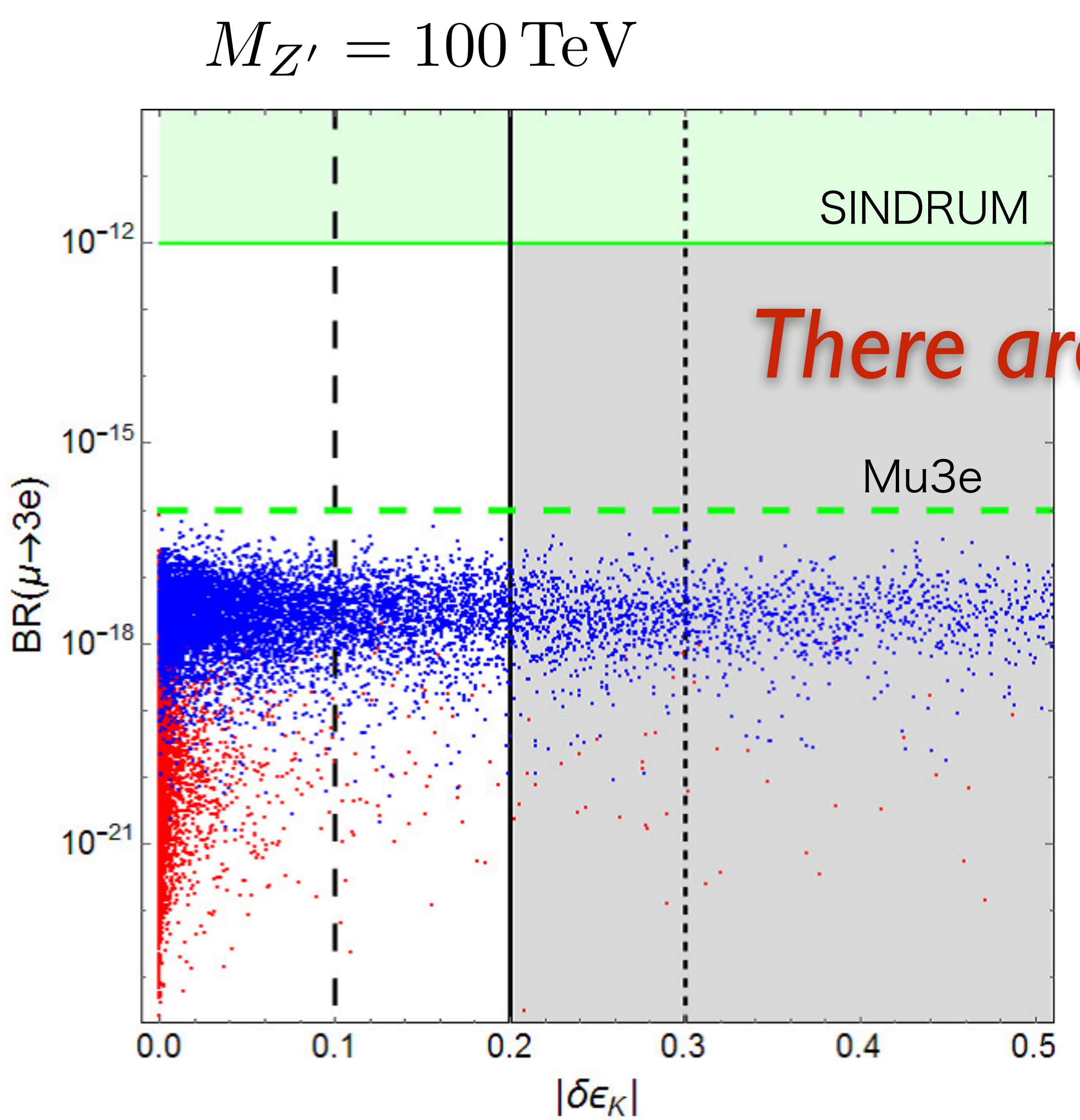
Lepton Flavor Violations

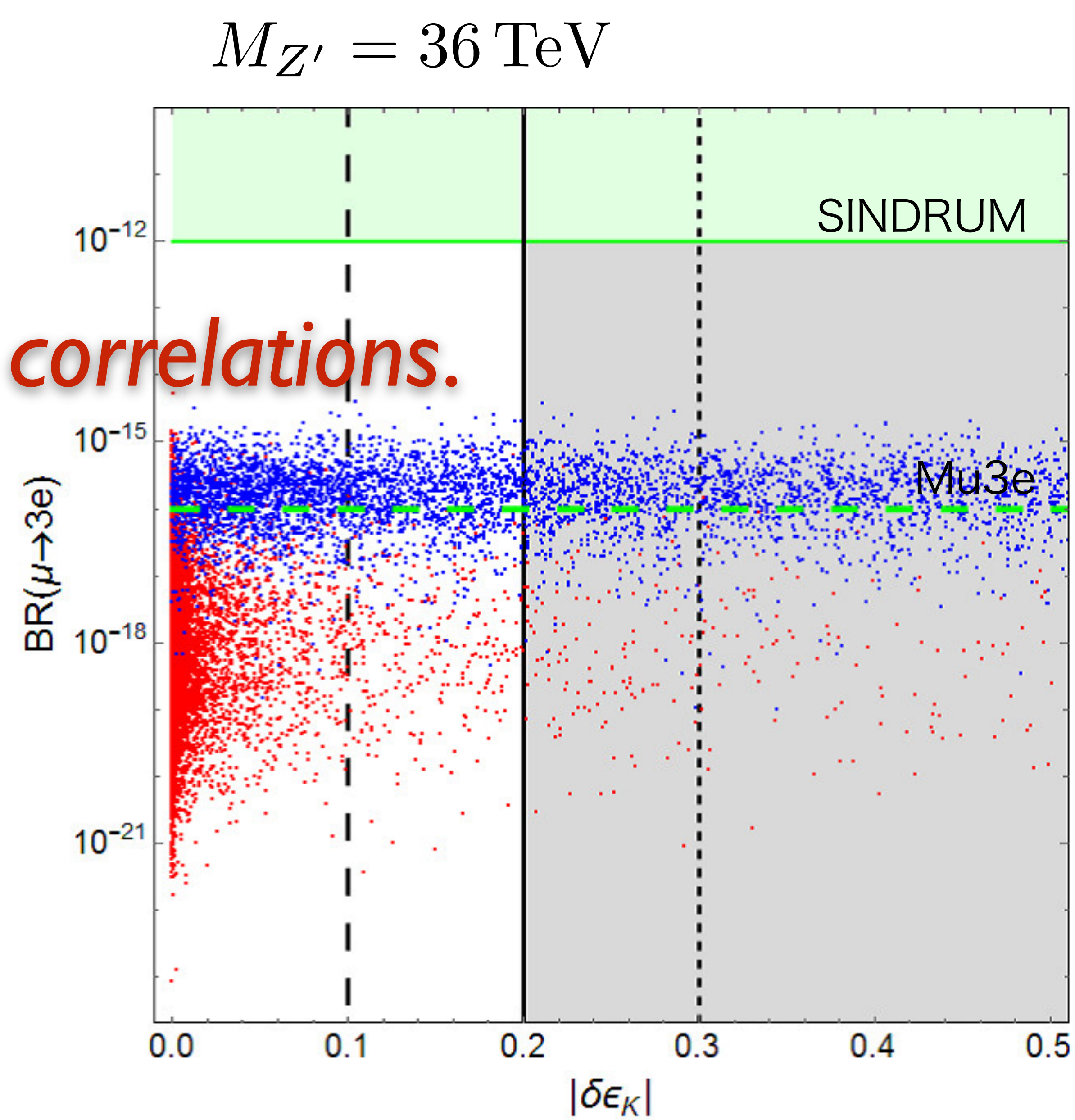
$\mu \to 3e$

Blue points: higher-dim. ope. < 0.001

Red points: higher-dim. ope. < 0.01





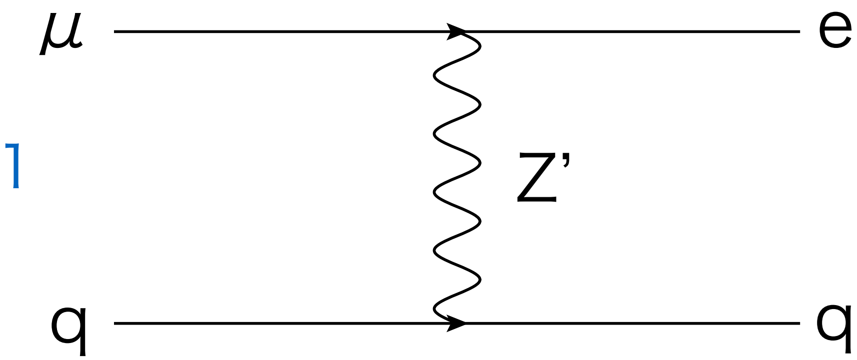


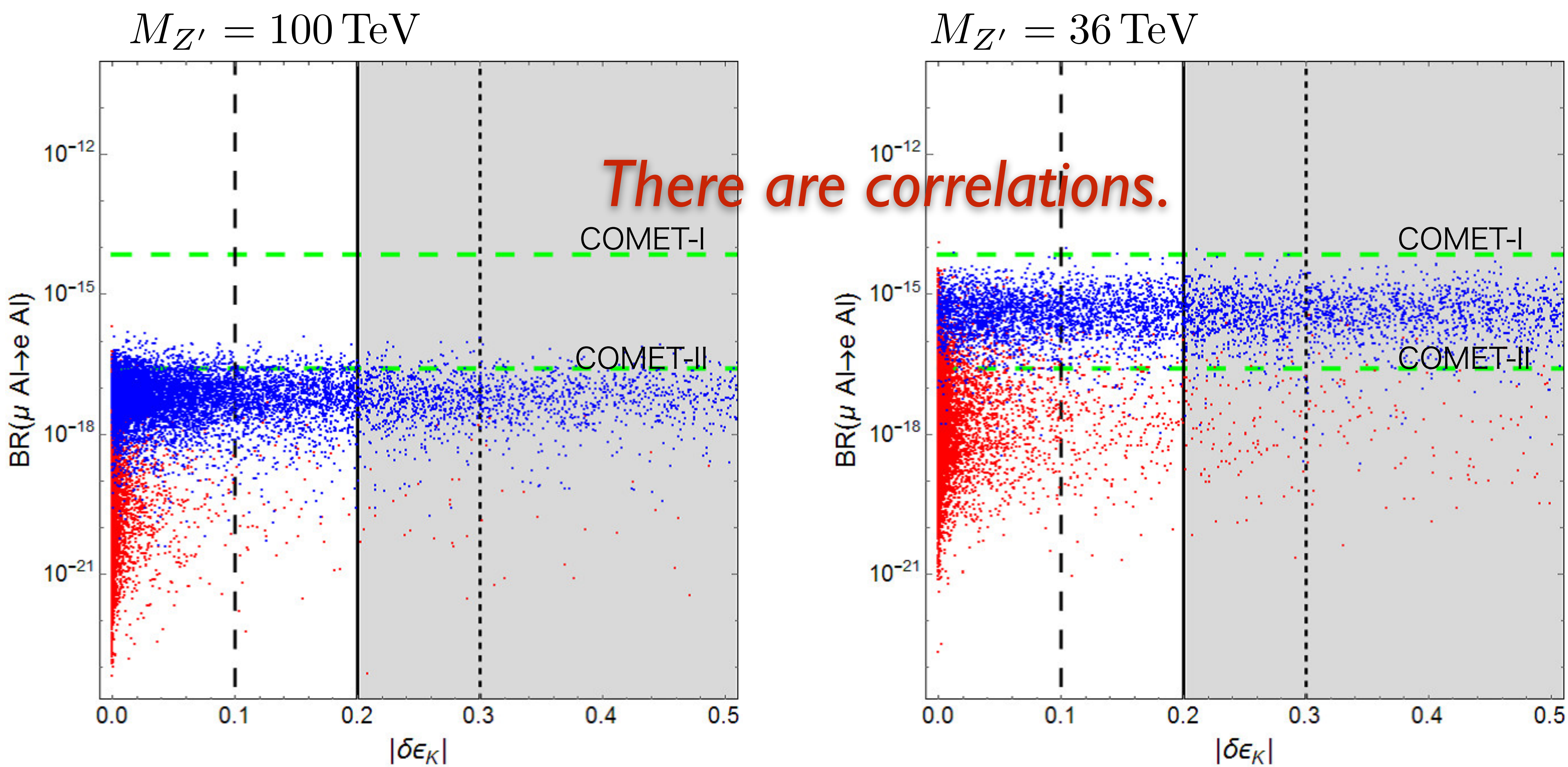
There are correlations.

Future experiment (Mu3e) could reach our region!

$\mu N \to e N$

Blue points: higher-dim. ope. < 0.001
Red points: higher-dim. ope. < 0.01





There are correlations.

COMET experiment could reach our region!

Summary

- I discussed SUSY SO(10) GUT.

125GeV Higgs mass

realistic Yukawa

$\Rightarrow$

flavor violating O(100)-TeV Z'

- This setup can be tested via K and μ physics.

ε_K, $\mu \to 3e$ and μ-e conversion are relevant.
(Mu3e and COMET experiments may discover.)

deviations of $K_L \to \mu\mu, \mu e$, $K \to \pi_0 \nu\nu$ are at most O(1)%.

- If Z' has lower mass, B and τ become important.

deviations of ΔM_{Bs} can reach 10% if Z' ~30 GeV, but ΔM_{Bd} less than 10%.

deviation of $B(s) \to \mu\mu$ is a few percent.

Thank you

Backup

Note

The mixing between 10 and 16 can realize the hierarchy between top and bottom.

(High-scale SUSY predict small tan β)

But it is difficult for only the mixing to achieve the all elements of realistic Yukawa coupling.

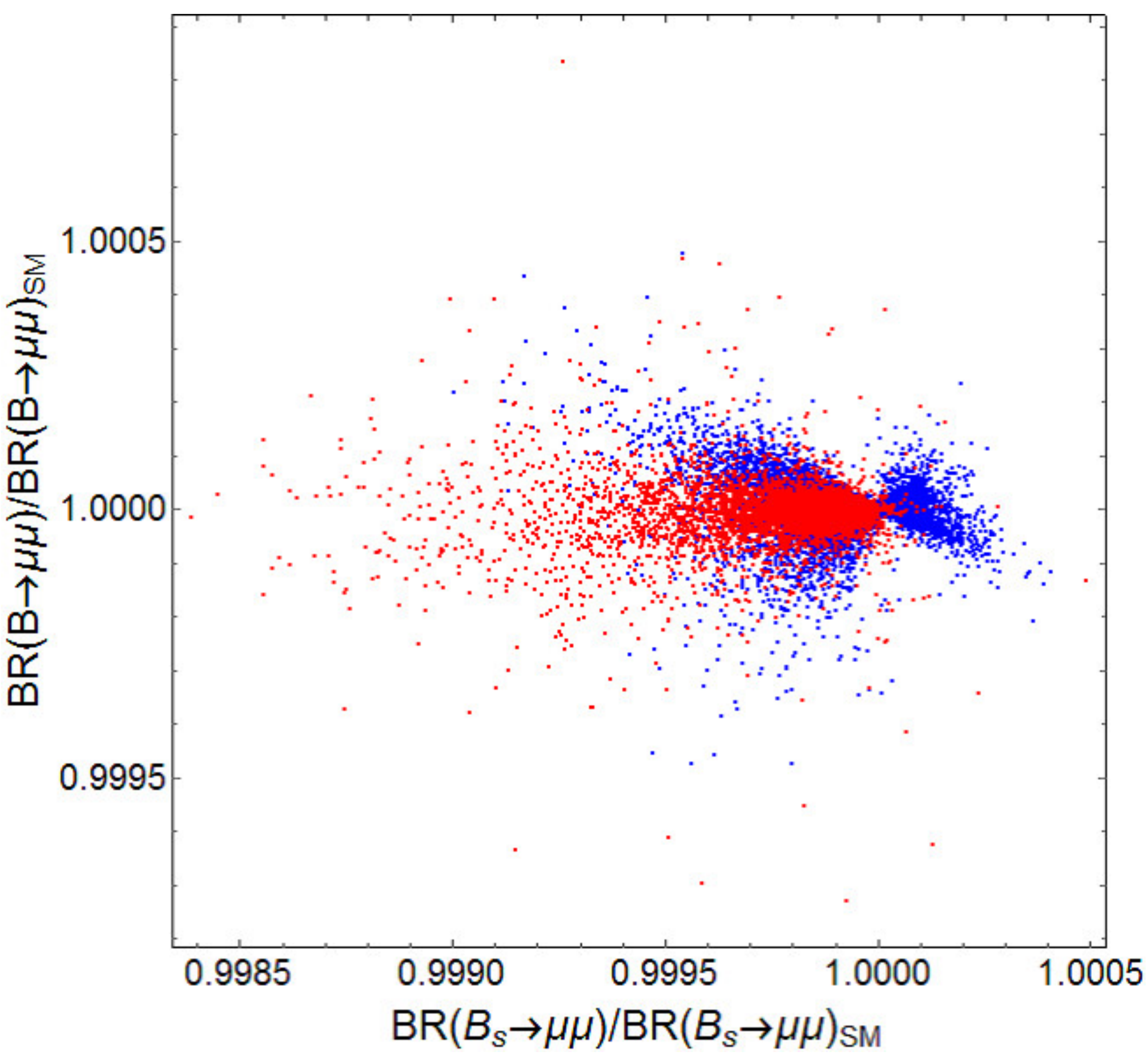
$$(mixing) = \tan\beta (V_{CKM})_{ub} \frac{m_b}{m_u} > 1$$

We are adding Higher-dim. operators

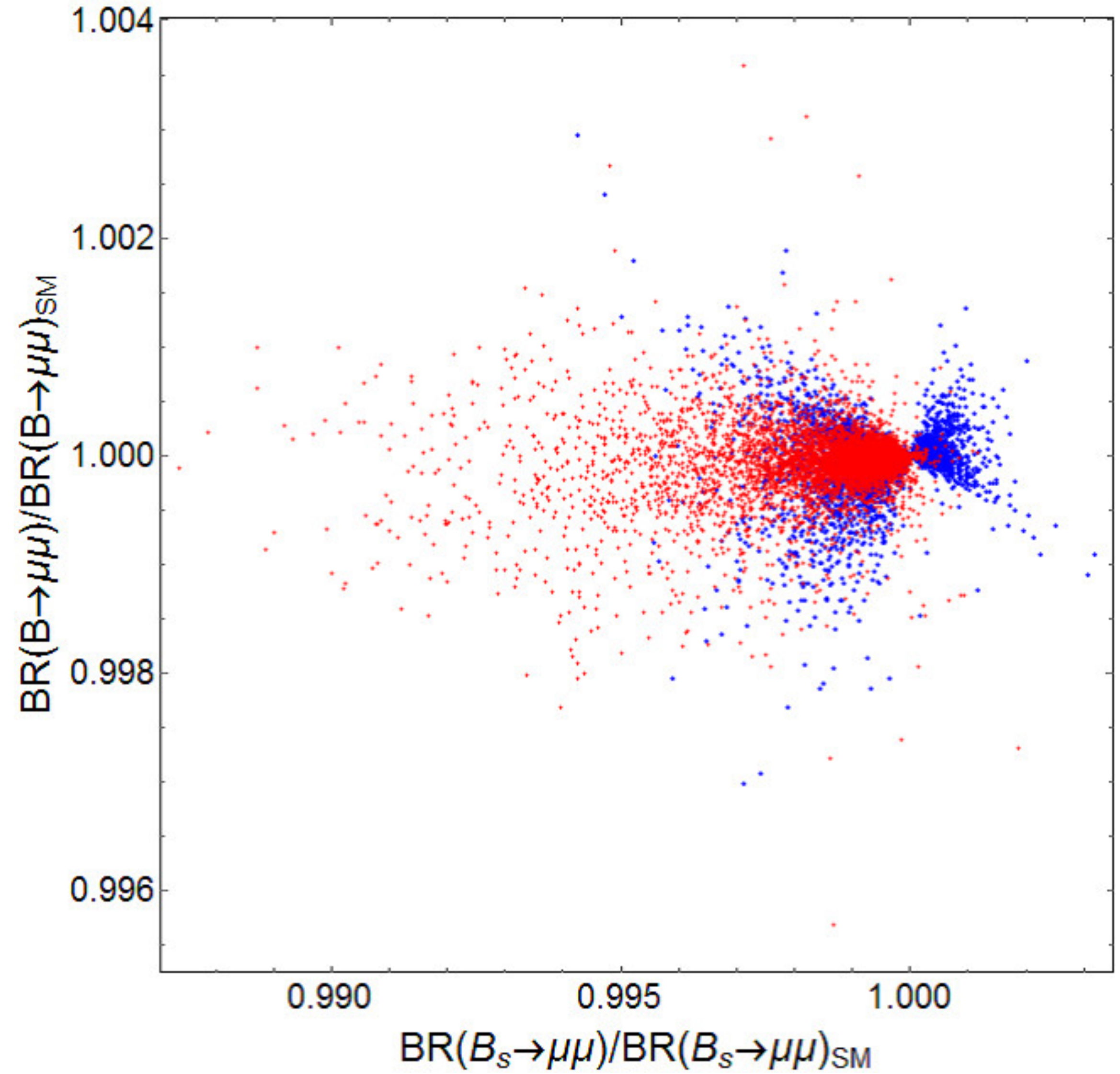
$$(h_{u\,ij} + \epsilon_{d\,ij}) Q_{L\,i} \hat{D}^c_{R\,j} H_d + (h_{u\,ij} + \epsilon_{e\,ij}) \hat{L}_{L\,i} E^c_{R\,j} H_d$$

B(s)→μμ

$M_{Z'} = 100\,\mathrm{TeV}$



$M_{Z'} = 36\,\mathrm{TeV}$



The deviation of B(s)→μμ is a few percent.