Flavor physics in the BSMs

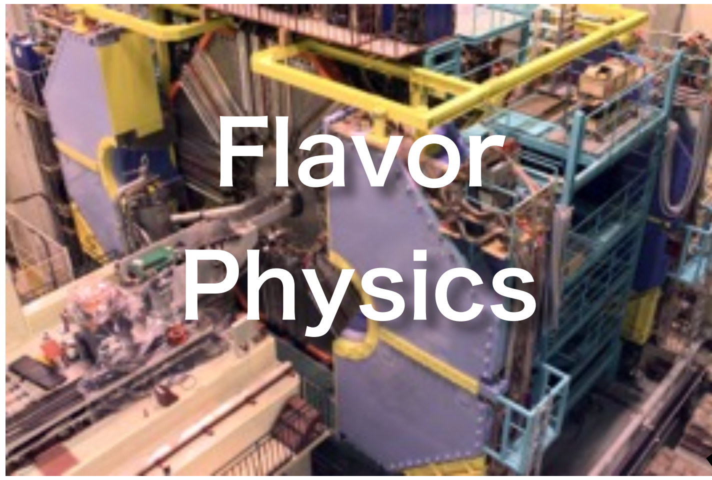
~SO(10) GUT~

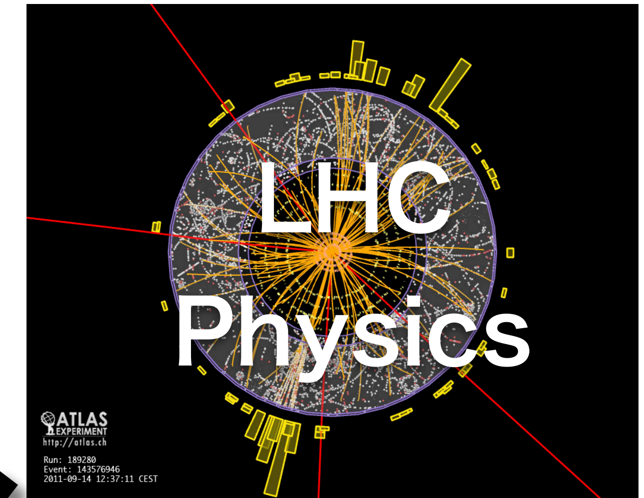
Yuji Omura (KMI, Nagoya Univ.)

Based on PLB744 (2015) 395 (arXiv: 1503.06156),
JHEP1611(2016)018 (arXiv: 1607.05437);
arXiv: 1612.01643

Collaborators: J. Hisano, Y. Muramatsu, Y. Shigekami, M. Yamanaka;
T. Abe, J. Kawamura, S. Okawa.

Very exciting era!

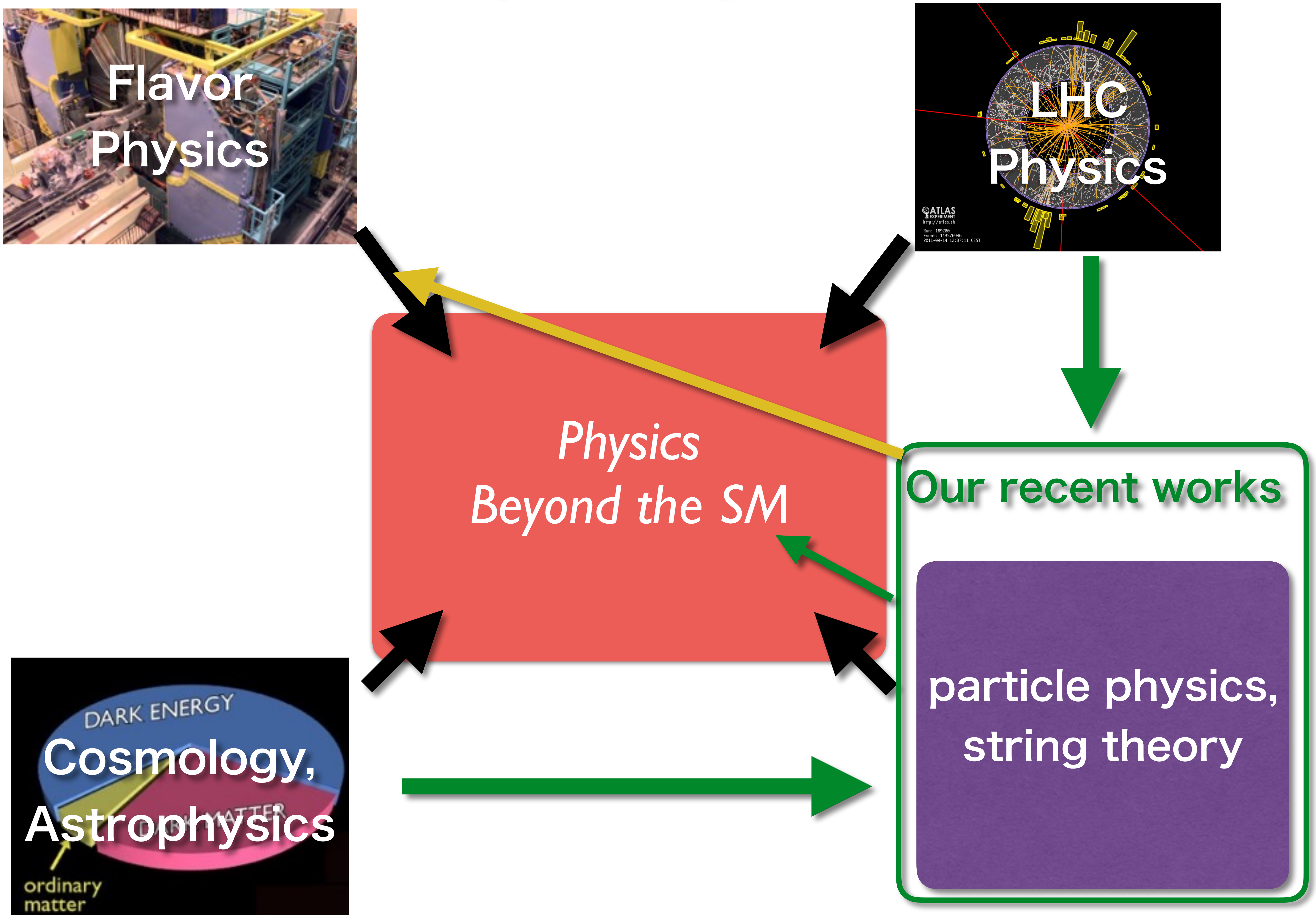




Physics
Beyond the SM

particle physics,
string theory

Very exciting era!



The BSMs I'm working on

- SUSY GUT (SO(10))
  (J. Hisano, Y. Muramatsu, YO, Y. Shigekami, M. Yamanaka)
- dark matter models
  (T. Abe, J. Kawamura, S. Okawa, YO)

  My talk
- 2HDM

  K. Tobe's talk

  (YO, E. Senaha, K. Tobe)

Contents

Introduction

There are many “evidences” of new physics:

anomaly-free conditions miraculously satisfied in the Standard Model (SM)

(Origin of SM gauge groups)

Big hierarchy between Planck scale and EW scale

(Origin of EW scale)

Dark matter

etc.

SUSY GUT can explain those mysteries:

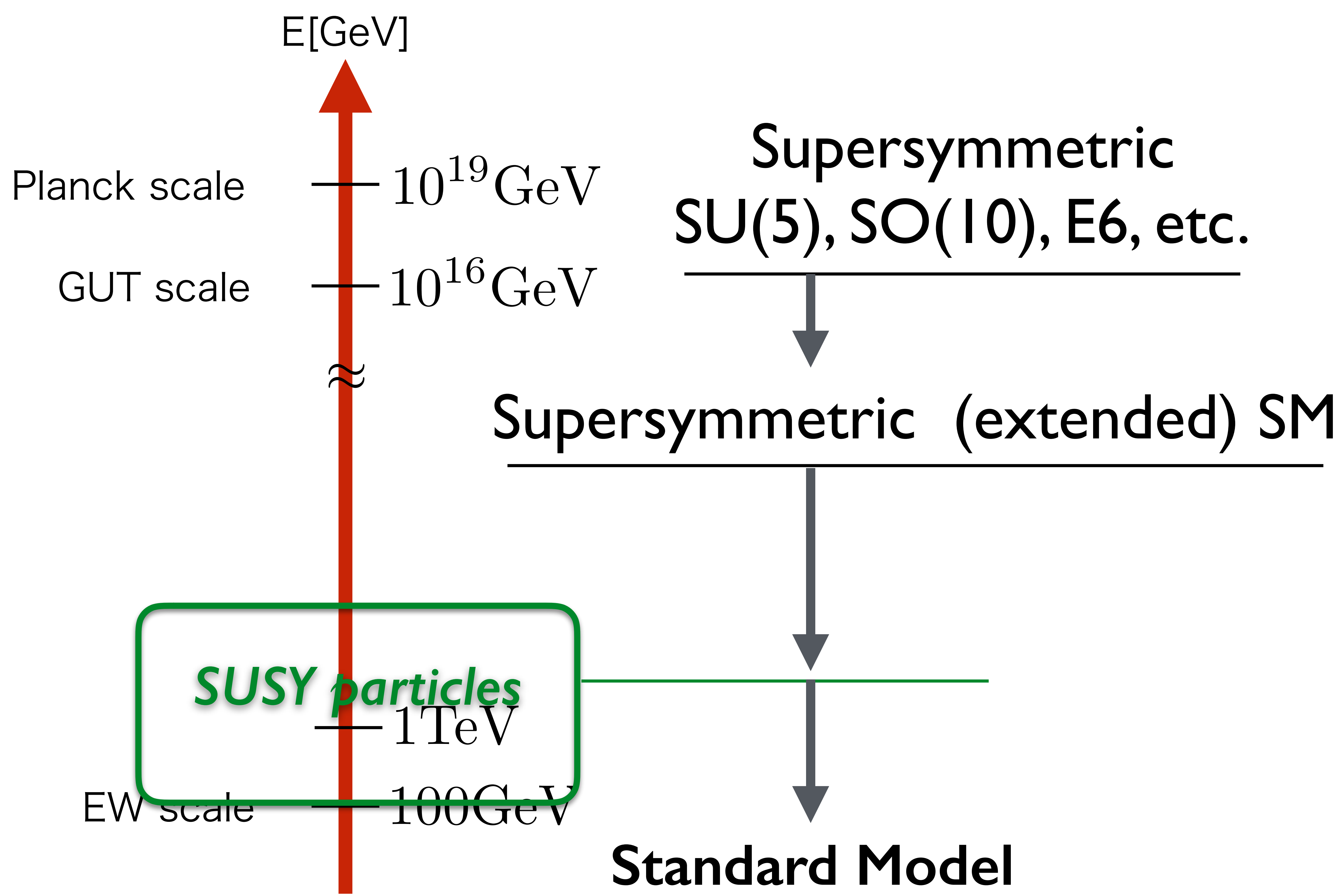
Origin of SM gauge groups

(Gauge coupling unification)

Origin of EW scale

Dark matter

Typical scenario of SUSY GUT



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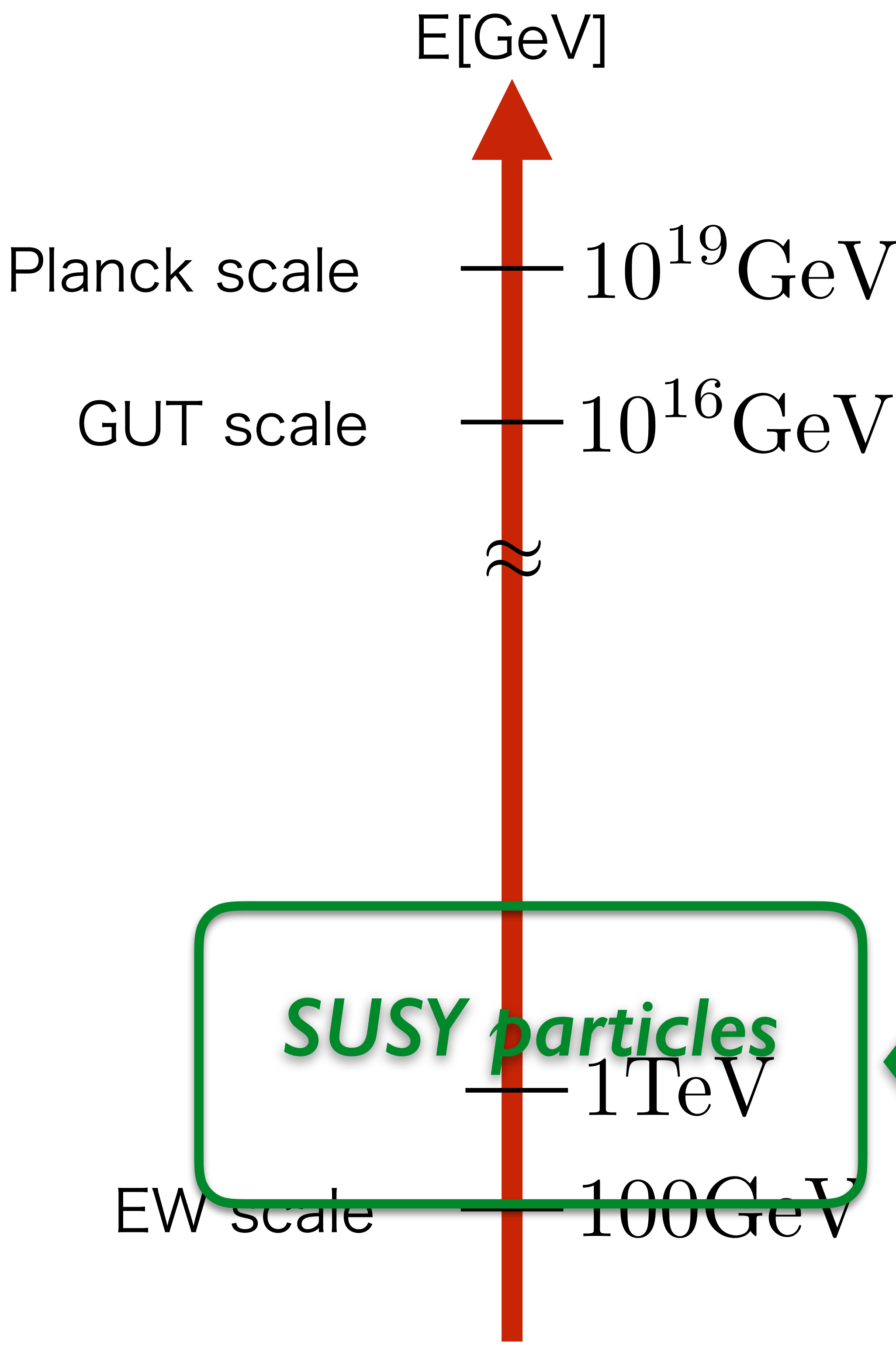


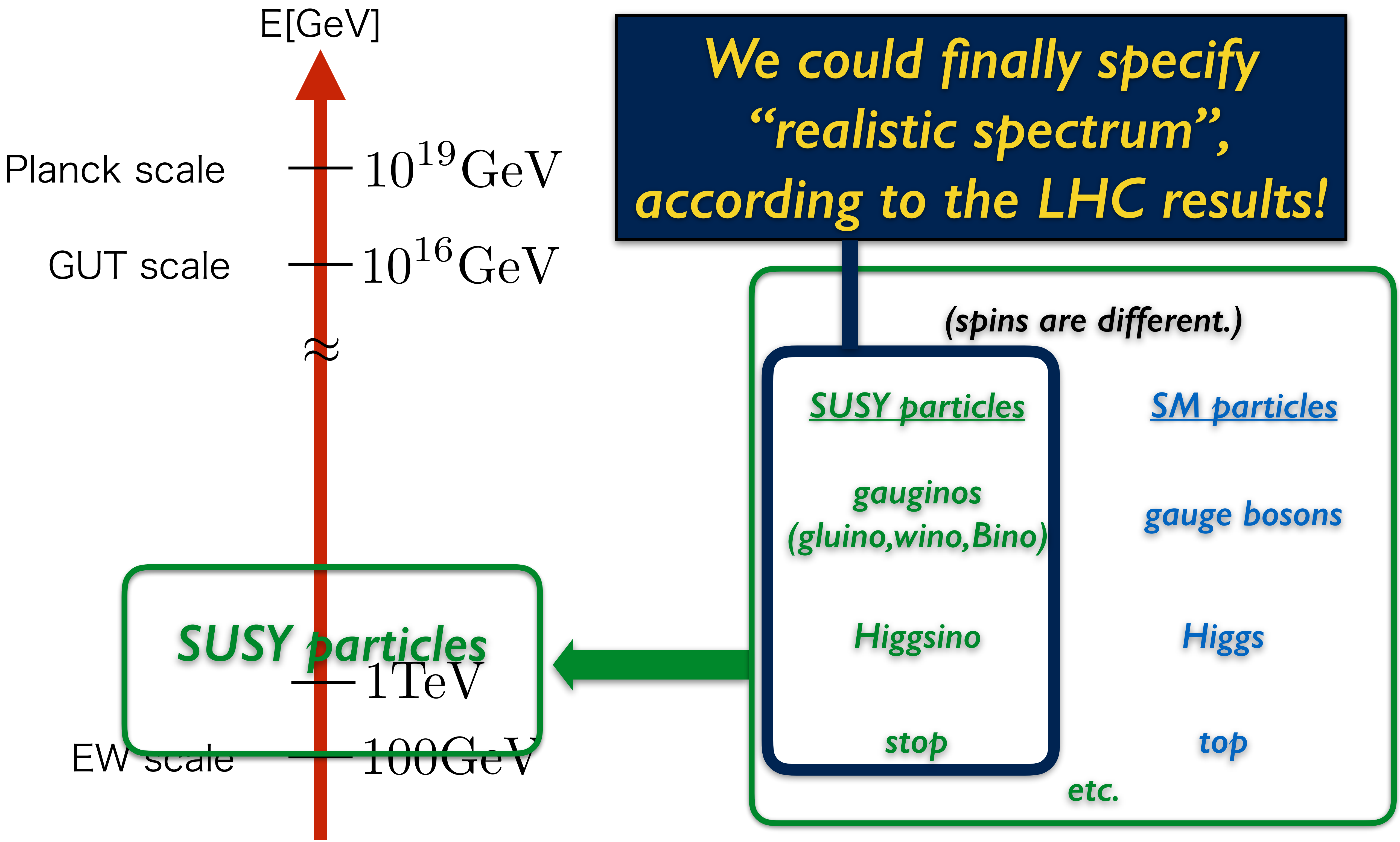
There are many SUSY particles, many possibilities of the spectrum.

(spins are different.)

SUSY particles	*SM particles*
gauginos (gluino,wino,Bino)	*gauge bosons*
Higgsino	*Higgs*
stop	*top*

etc.

Typical scenario of SUSY GUT



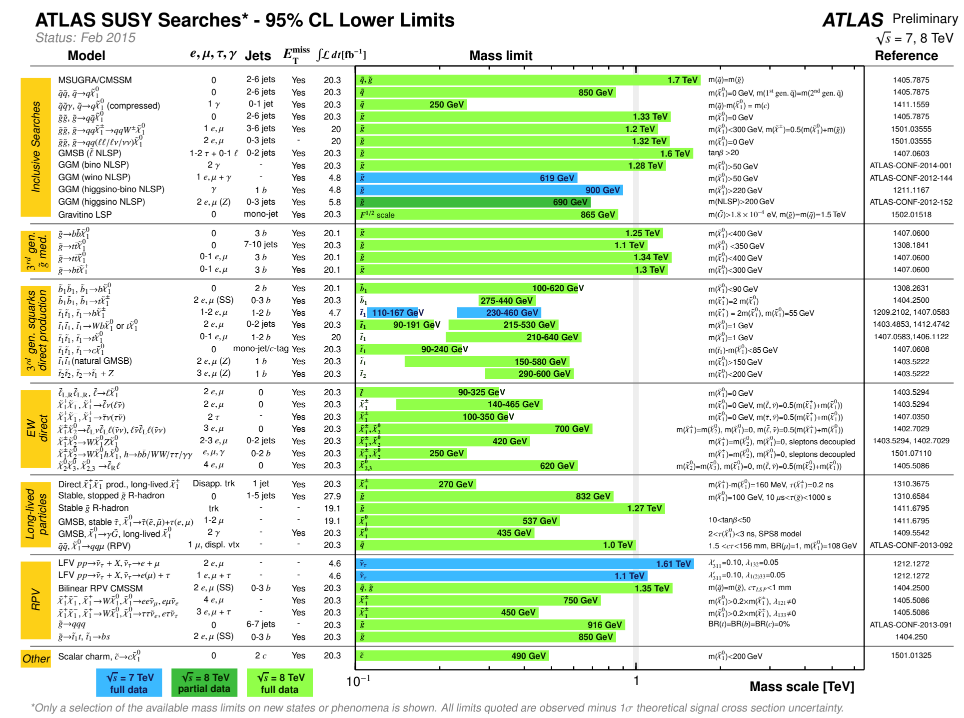
Relevant LHC results

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

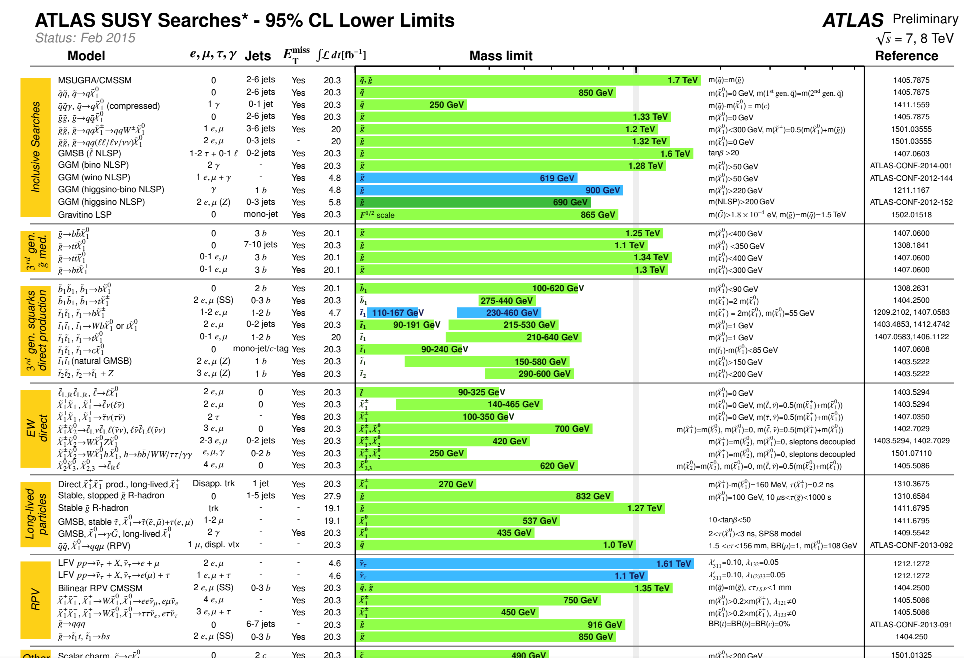
MSSM prediction

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

loop correction

Relevant LHC results

Direct search at LHC



model-dependent but…

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

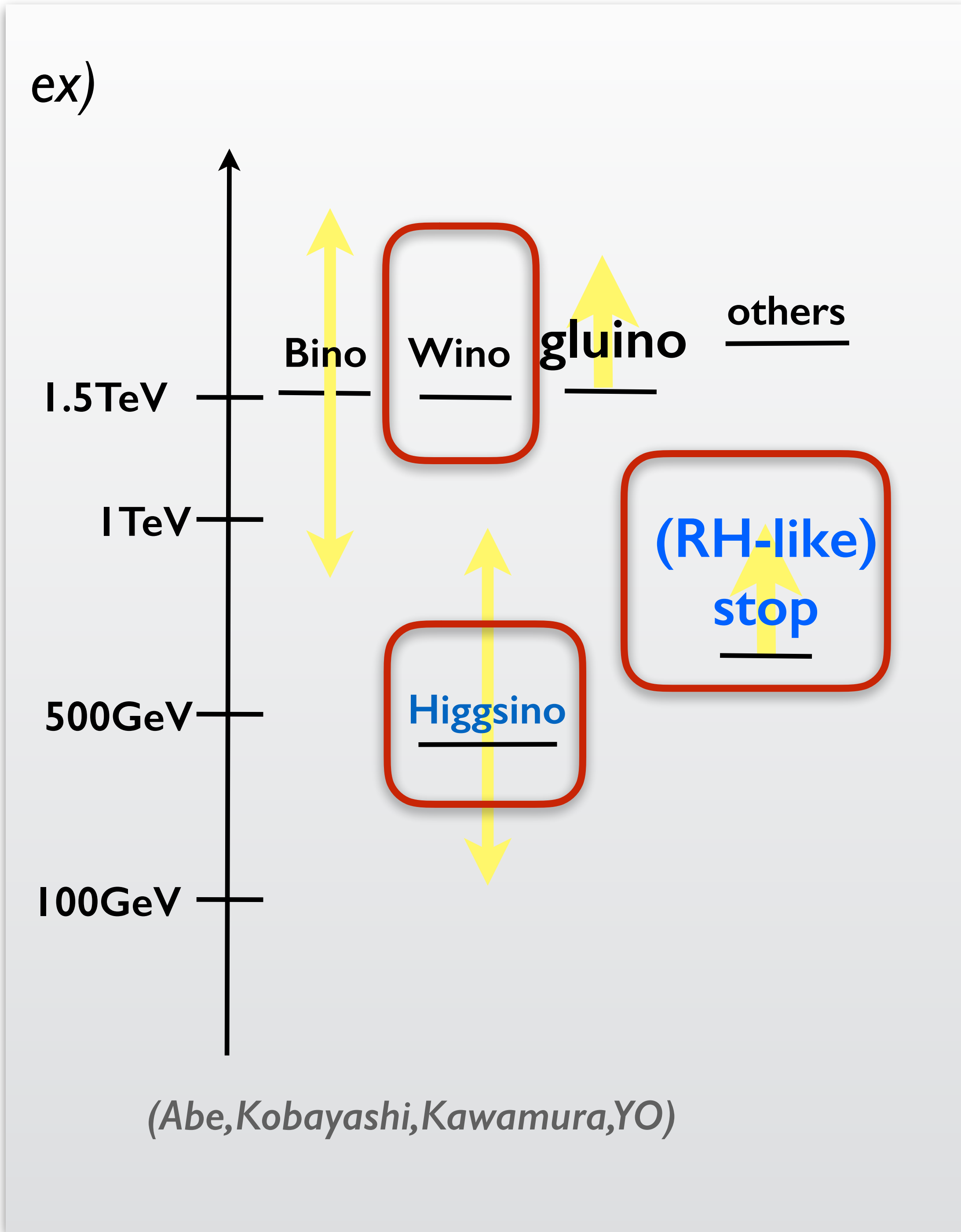
Many scenarios excluded!!

Especially, it is getting very difficult to realize the EW scale in SUSY!

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

loop correction

One possible spectrum is



Specific SUSY spectrum can realize 125 GeV Higgs mass and EW scale.

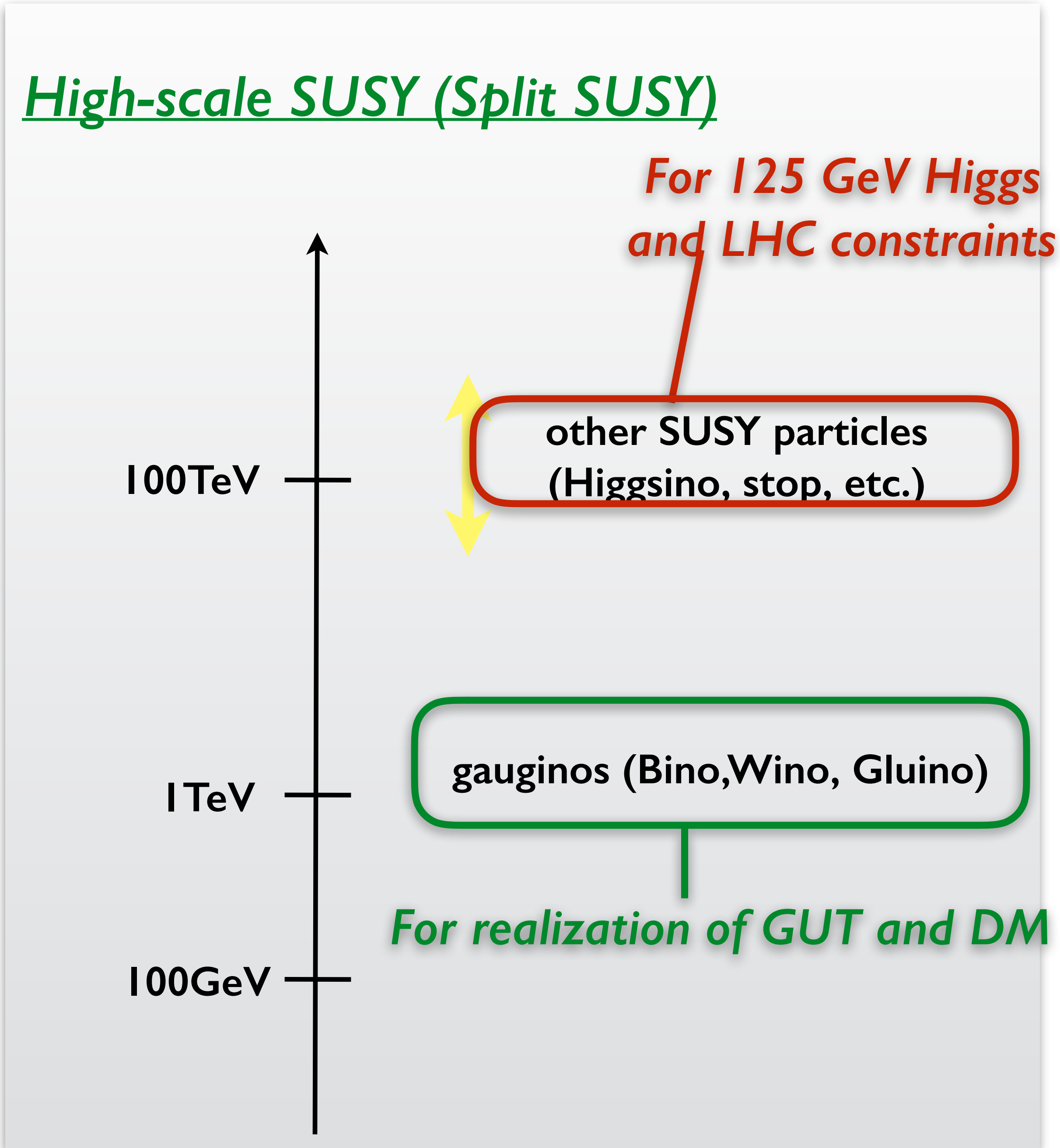
No hierarchy between Higgsino and EW scale.

→ No fine-tuning in Higgs potential.

"Naturally EW scale is realized!"

We can prove this kind of scenarios by direct stop/gluino searches at the LHC.

Another possible spectrum is



Simply very large SUSY scale can realize 125 GeV Higgs mass.

Big hierarchy between Higgsino and EW scale.

→ *Require fine-tuning in Higgs potential*

"The EW scale is given by the very fine-tuning!"

(Arkani-Hamed, Dimopoulos, 04';Giudice, Romanino 04';
Cabrera, Casas, Delgado, 11'; Guidice, Strumia, 11'; Hall, Nomura, 11';
Arkani-Hamed, Gupta,et.al,12'; Ibe, Matsumoto,Yanagida, 12';
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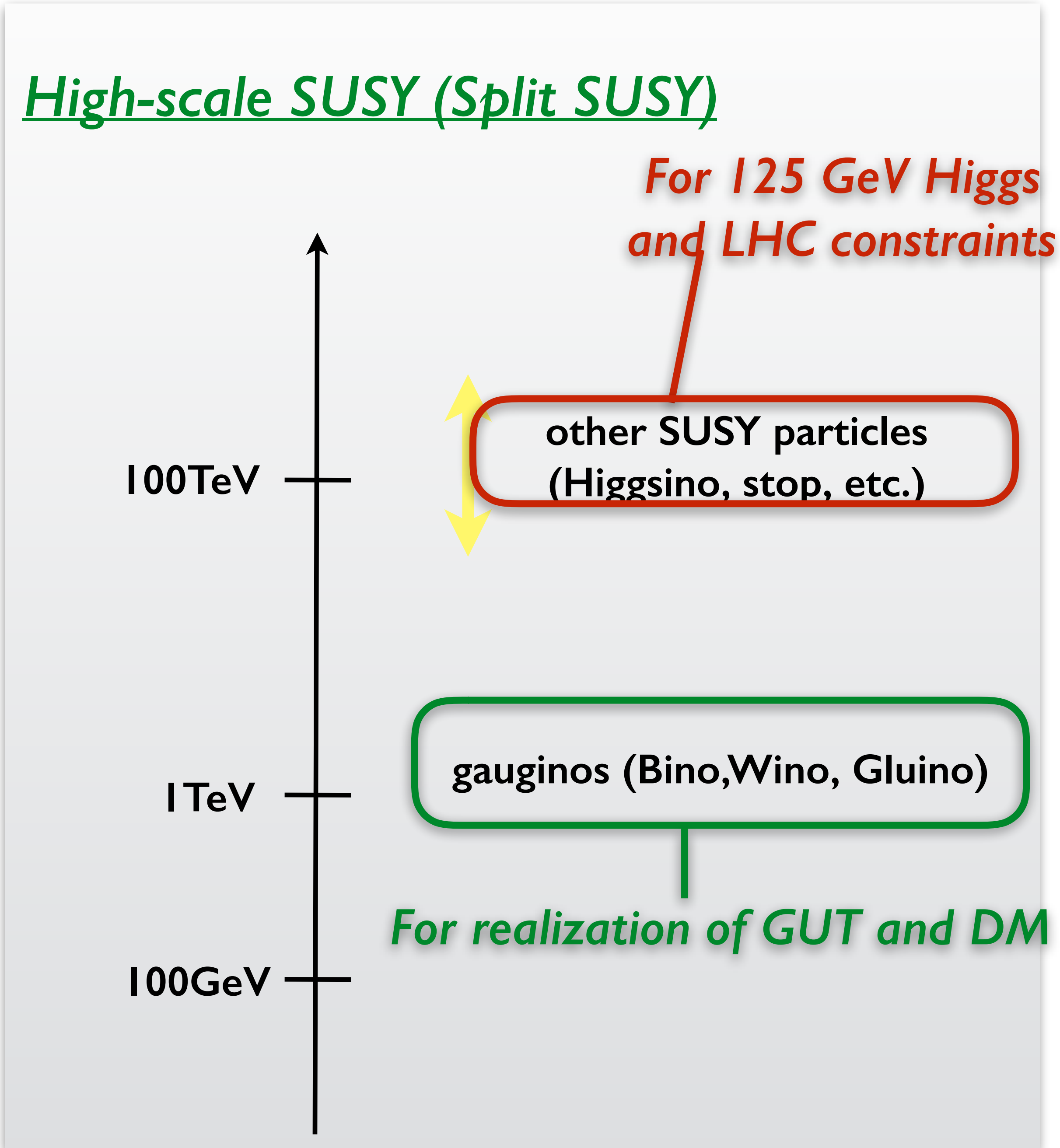

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How can we prove this kind of scenario?

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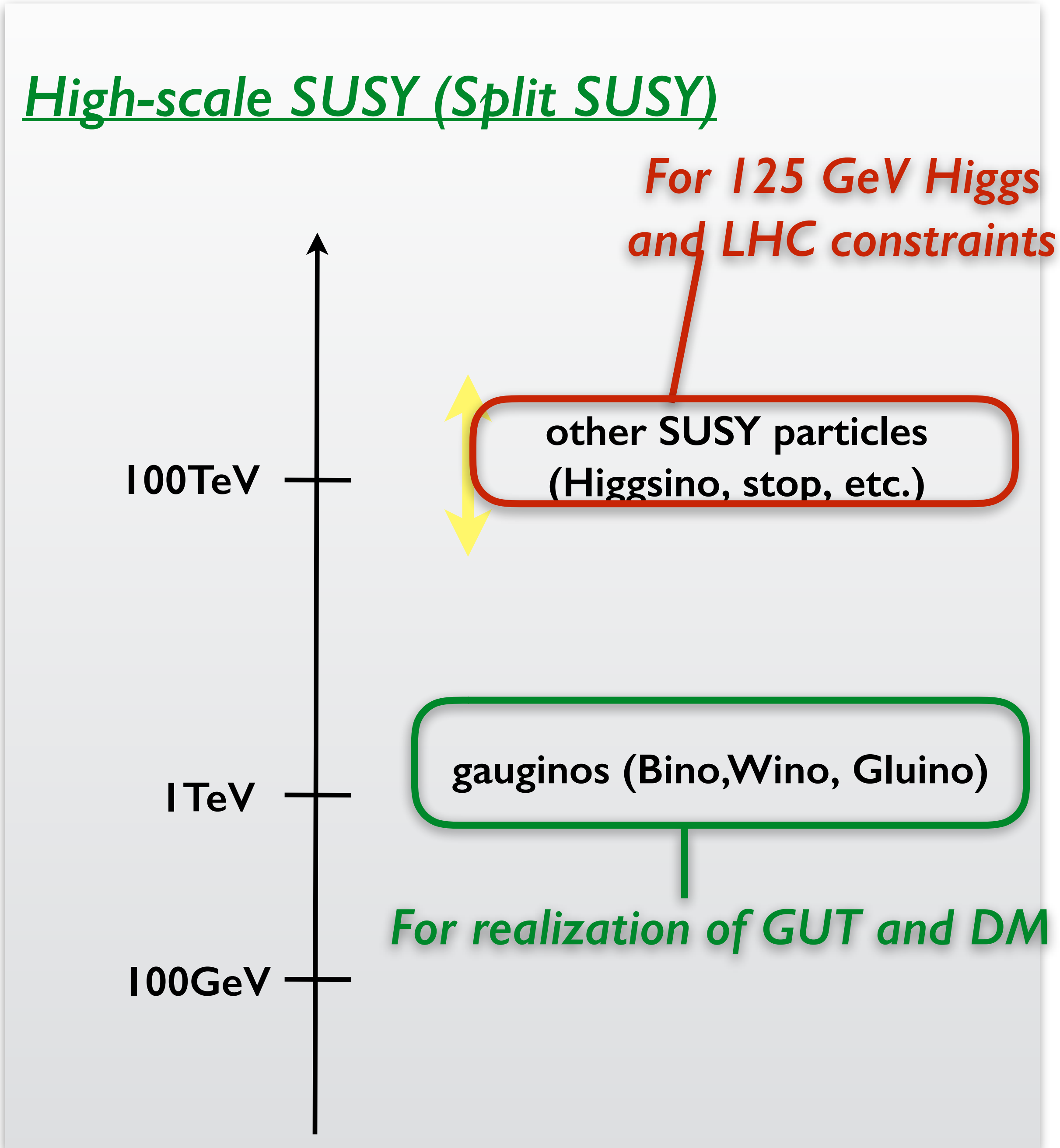

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How can we prove this kind of scenario?

→*We propose flavor physics in this talk!*

(Arkani-Hamed, Dimopoulos, 04';Giudice, Romanino 04';
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There are several hints in high-scale SUSY GUT:

Yukawa unification.

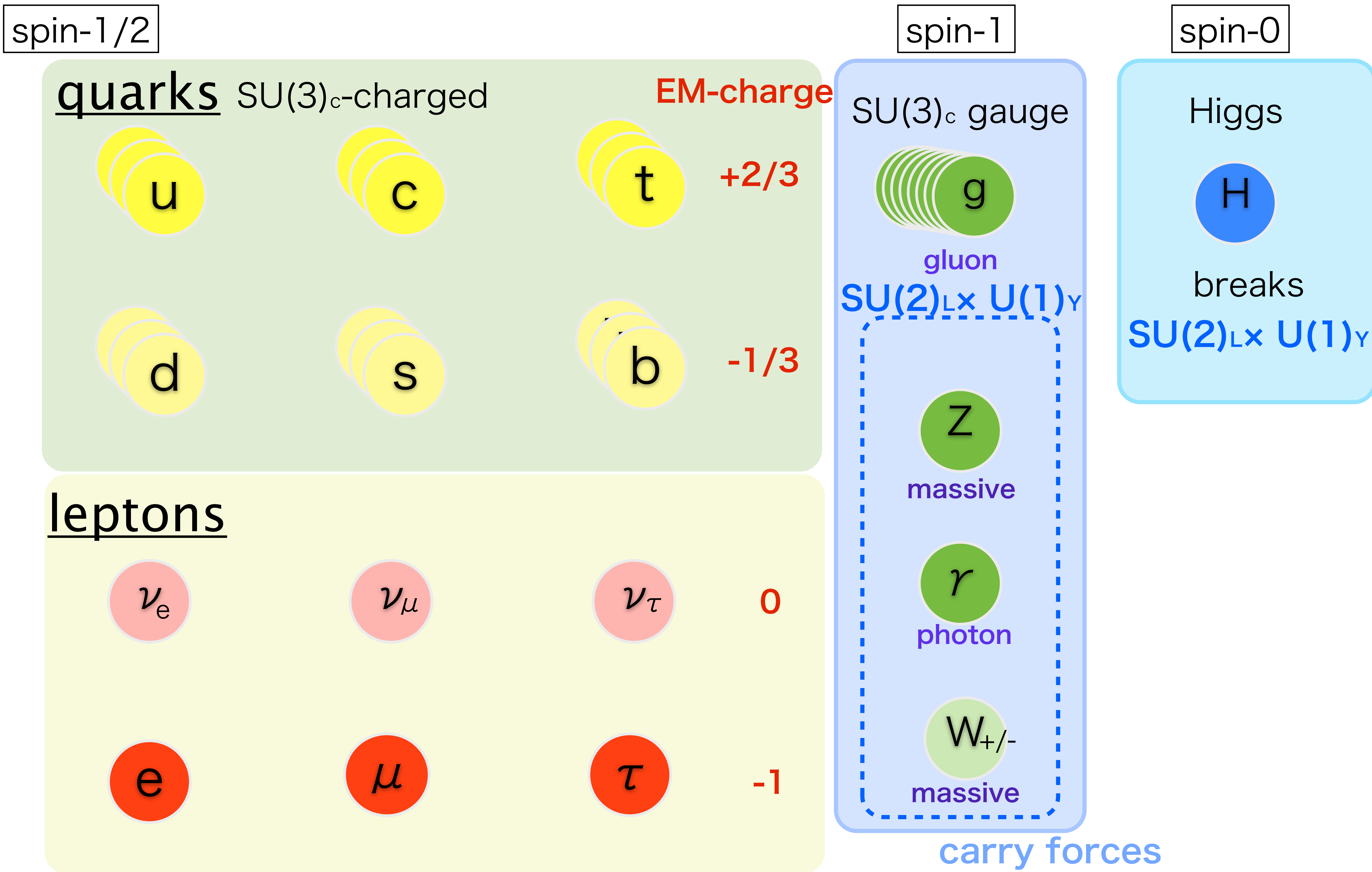
SO(10) and E6 GUTs predict extra gauge symmetry.

- We discuss the SO(10) GUT which realize the realistic Yukawa couplings.
- Z' interaction from SO(10) relates to the hierarchy, and **GUT could be tested by flavor physics**!

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

Setup

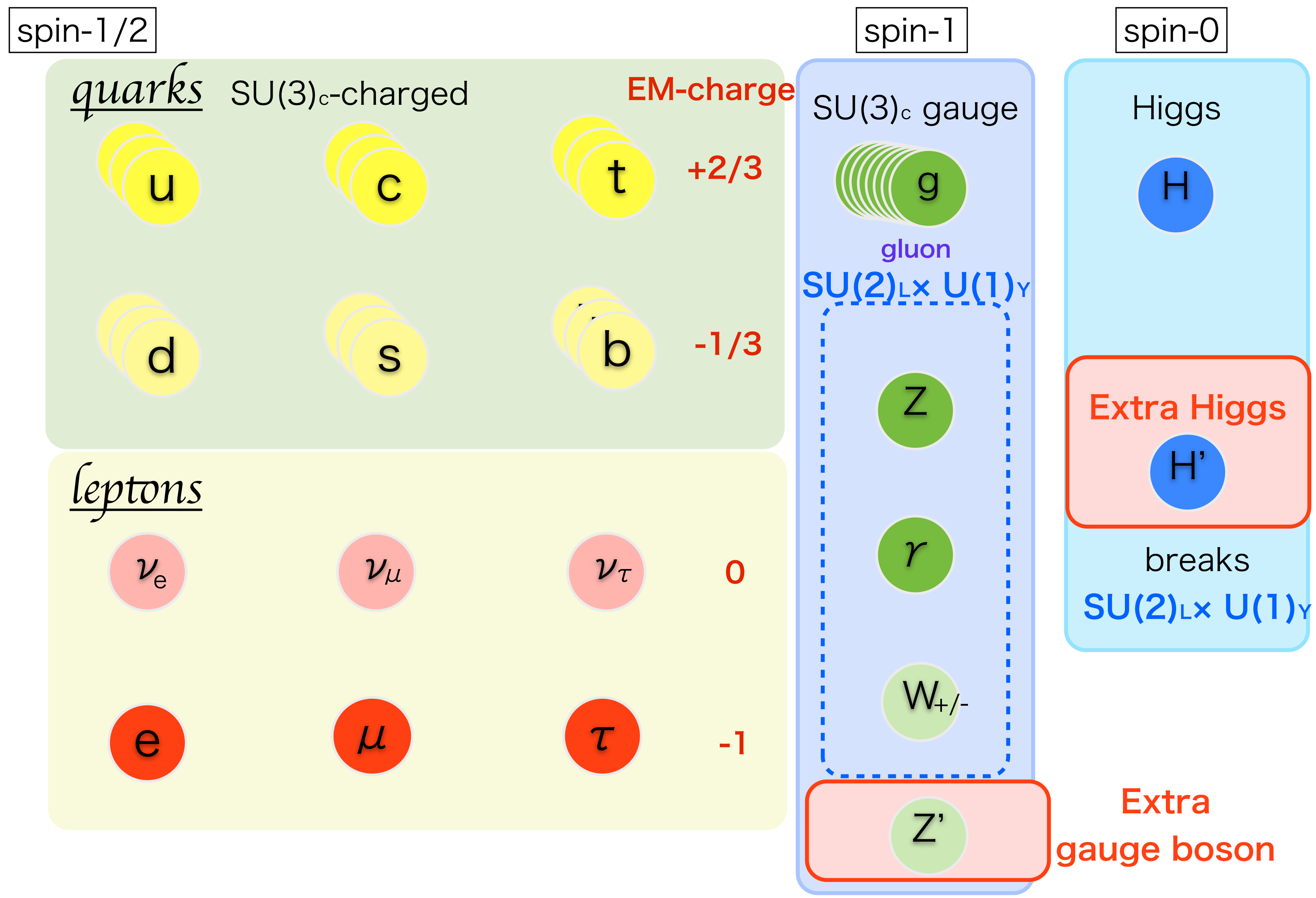
Standard Model $(SU(3)_c \times SU(2)_L \times U(1)_Y)$



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



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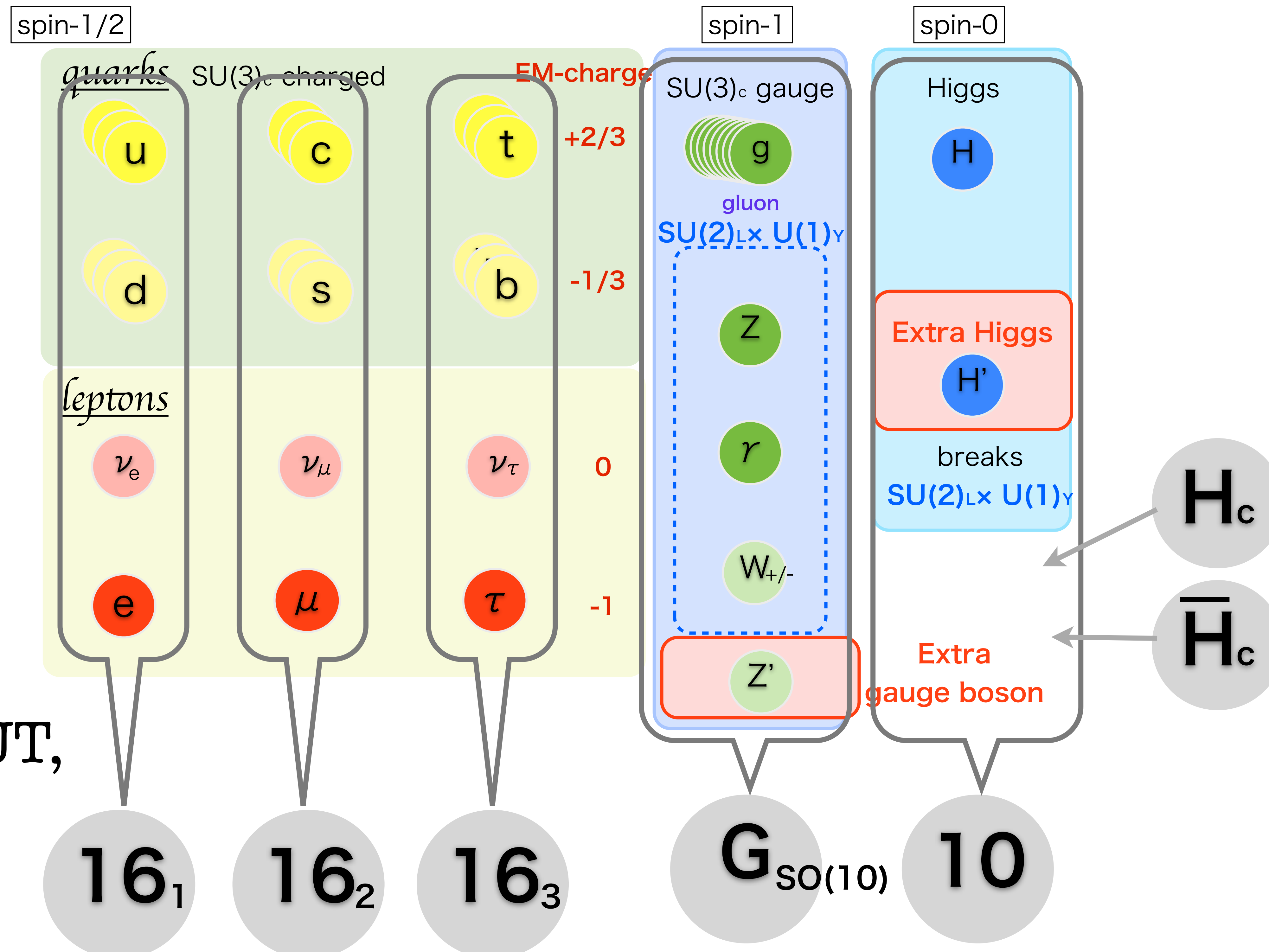


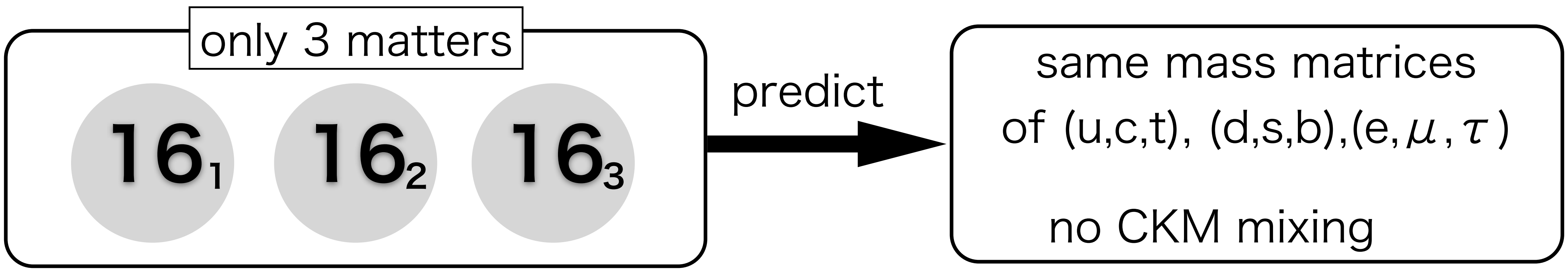
In SO(10) GUT,

matter also unified

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.



Couplings for Mass matrices are

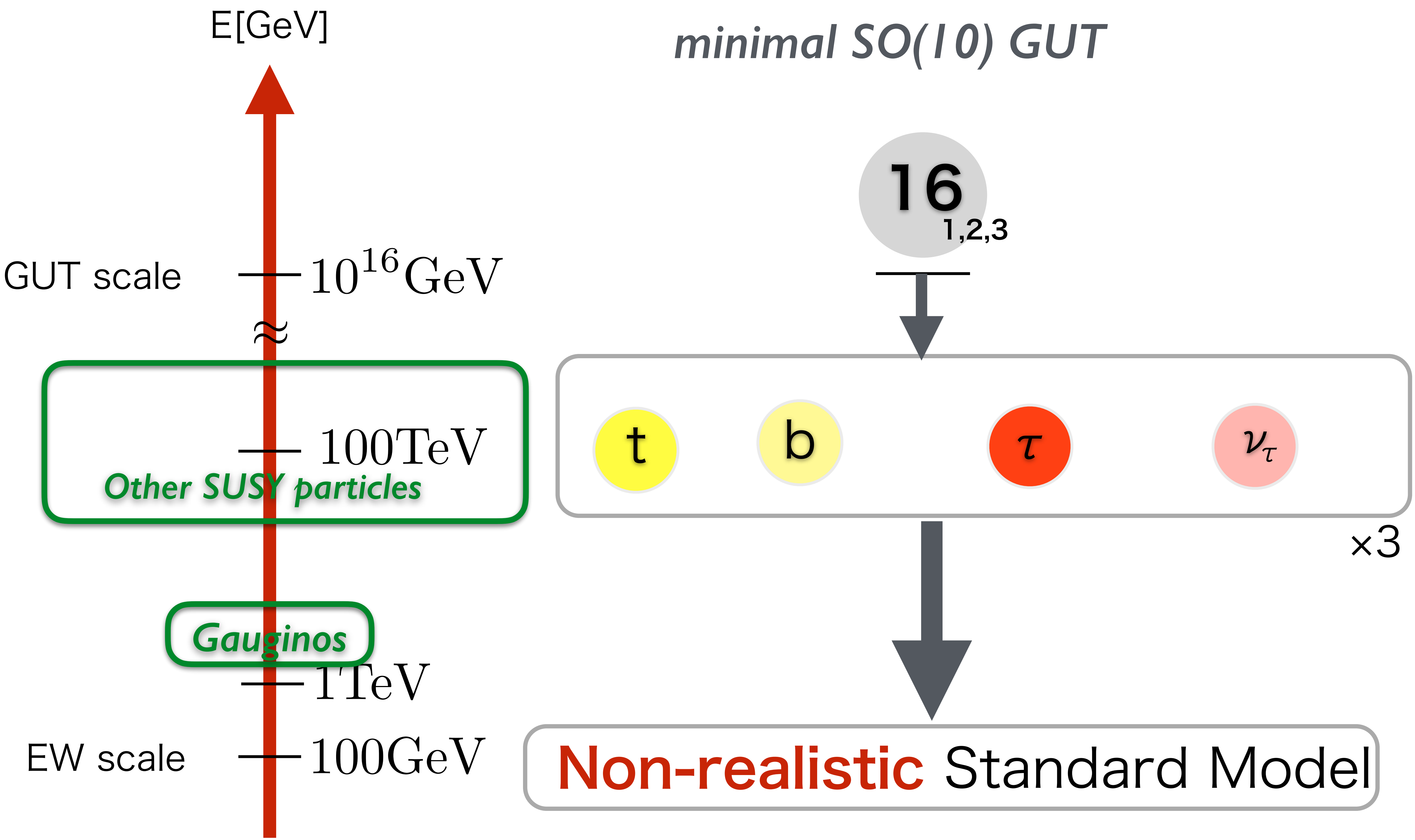
$$y_{ij}\mathbf{16}^i\mathbf{16}^j 10_H \quad \Rightarrow \quad y^u_{ij}Q^i_L U^{c\,j}_R H_u + y^d_{ij}Q^i_L D^{c\,j}_R H_d + y^l_{ij}L^i E^{c\,j}_R H_d$$

can be diagonalized

same structures of Yukawa (Mass matrices)

$$y^u_{ij} = \frac{m^u_i}{v\sin\beta}\delta_{ij} \approx y^d_{ij} \approx y^l_{ij}$$

Rough sketch of our scenario



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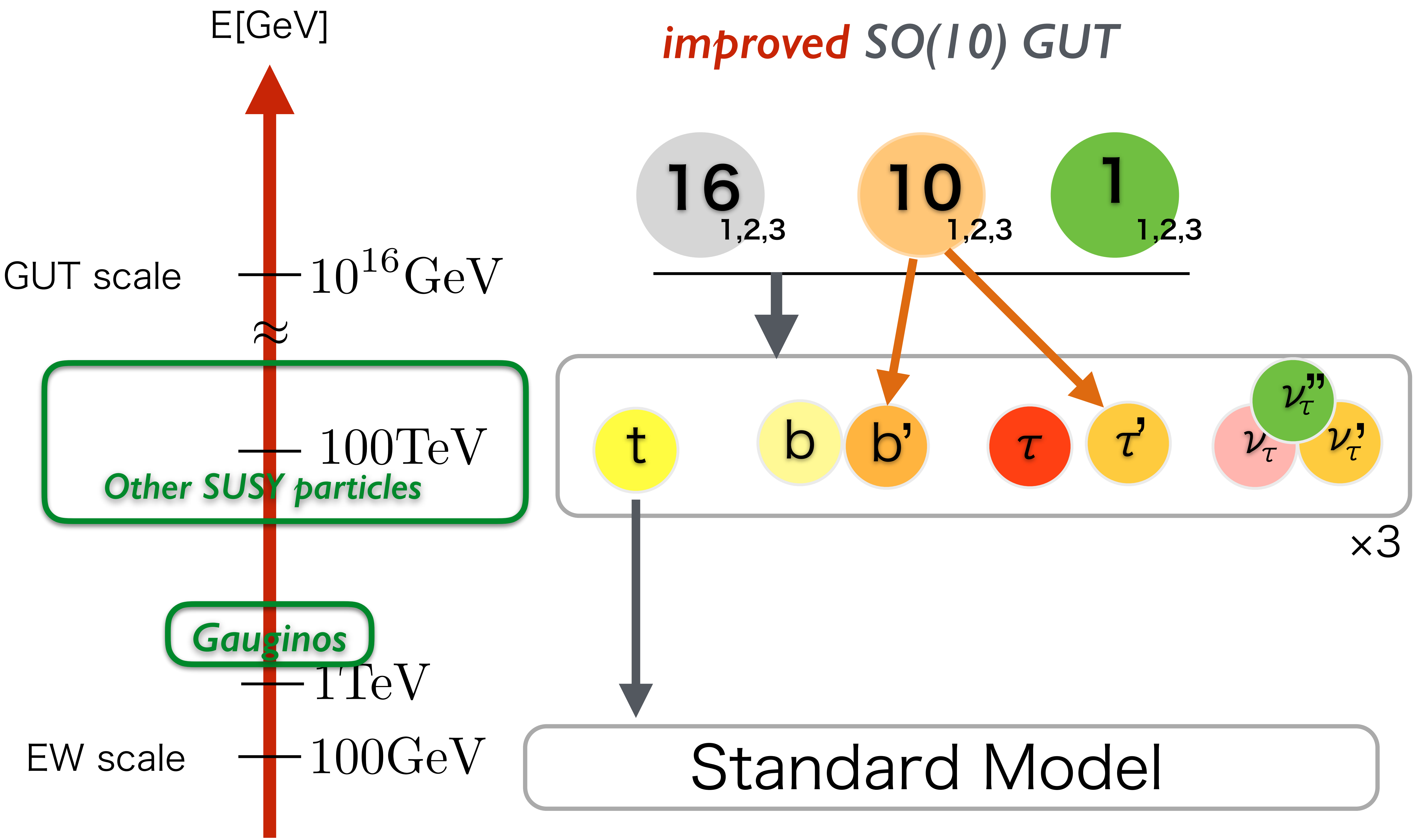

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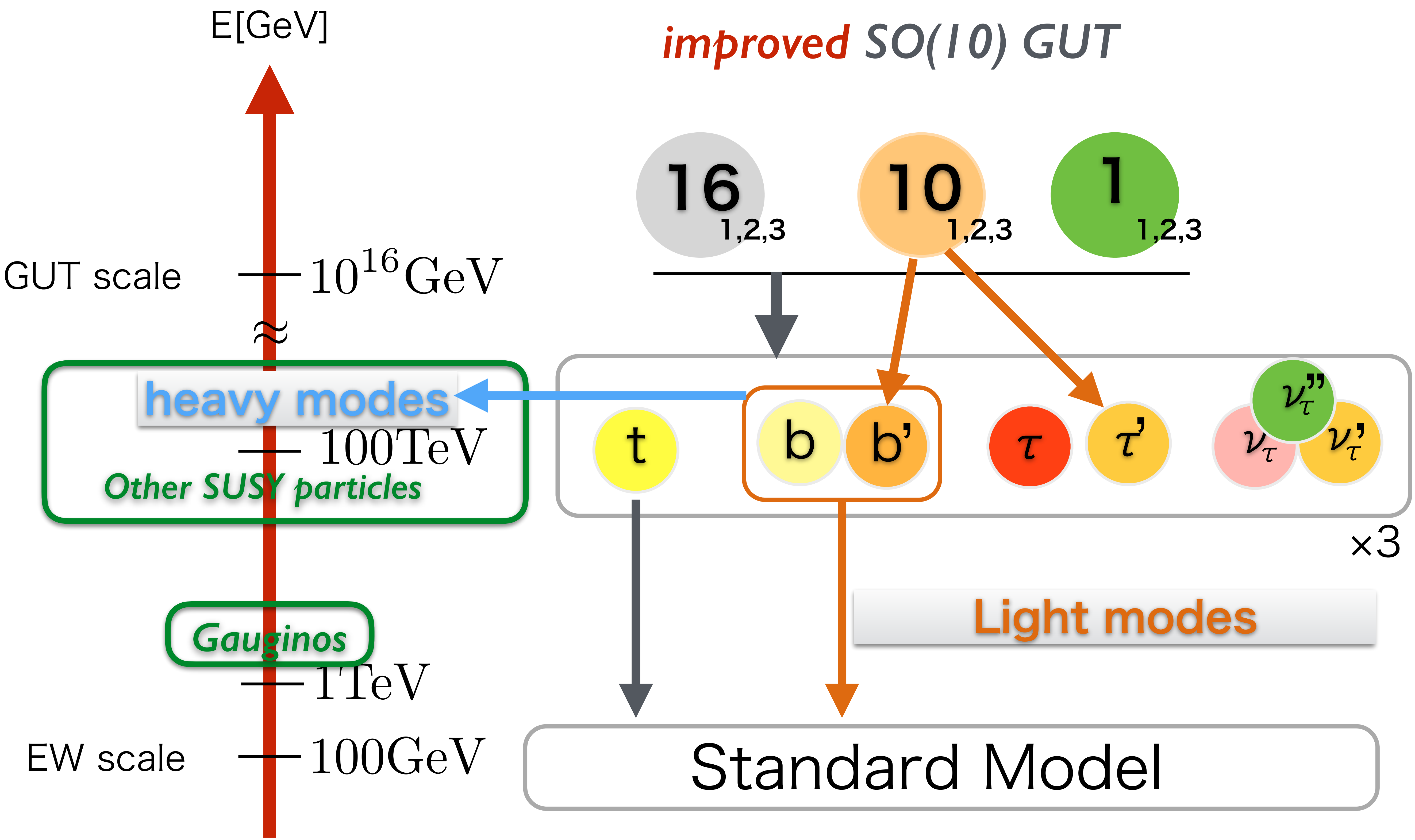

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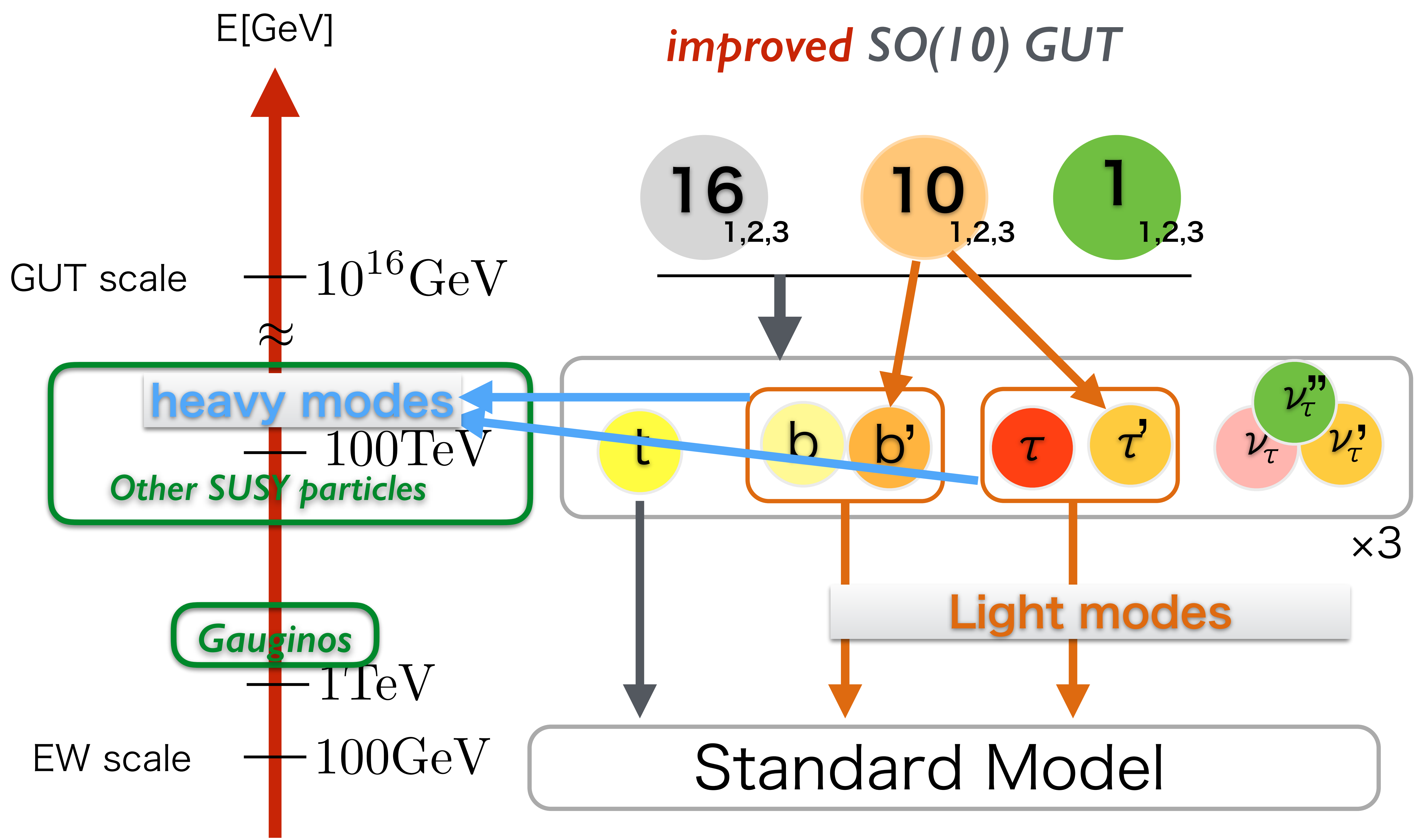

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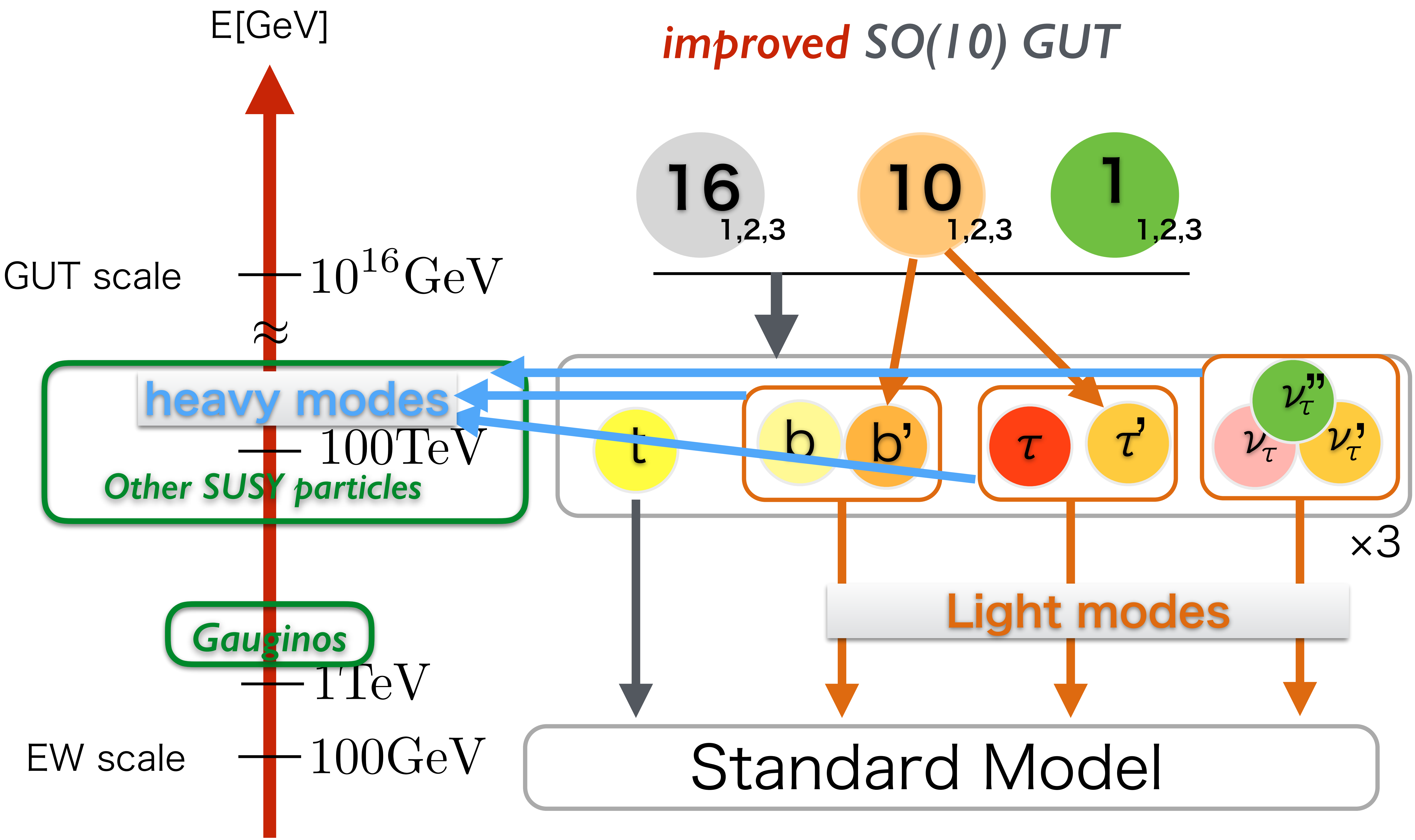

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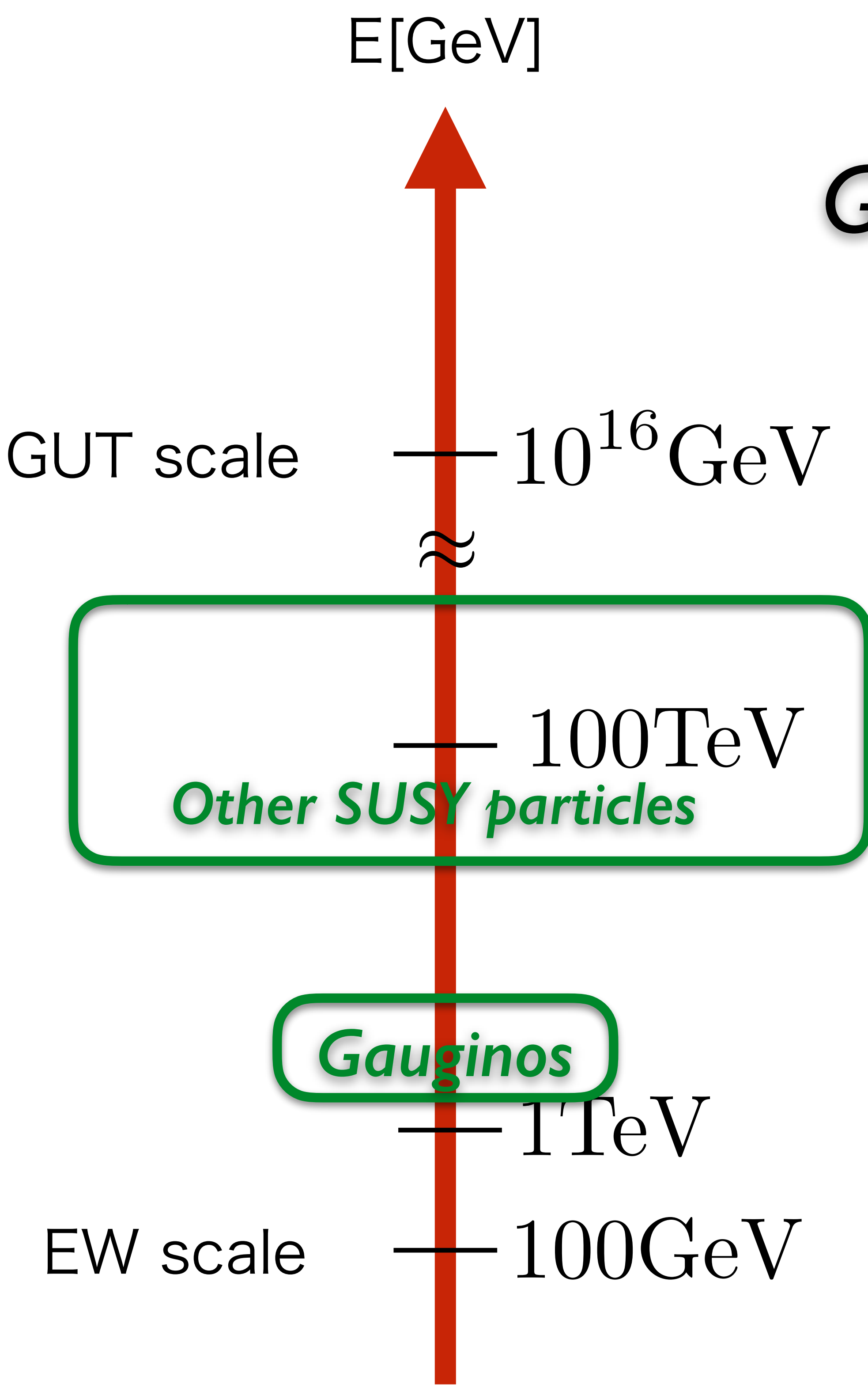
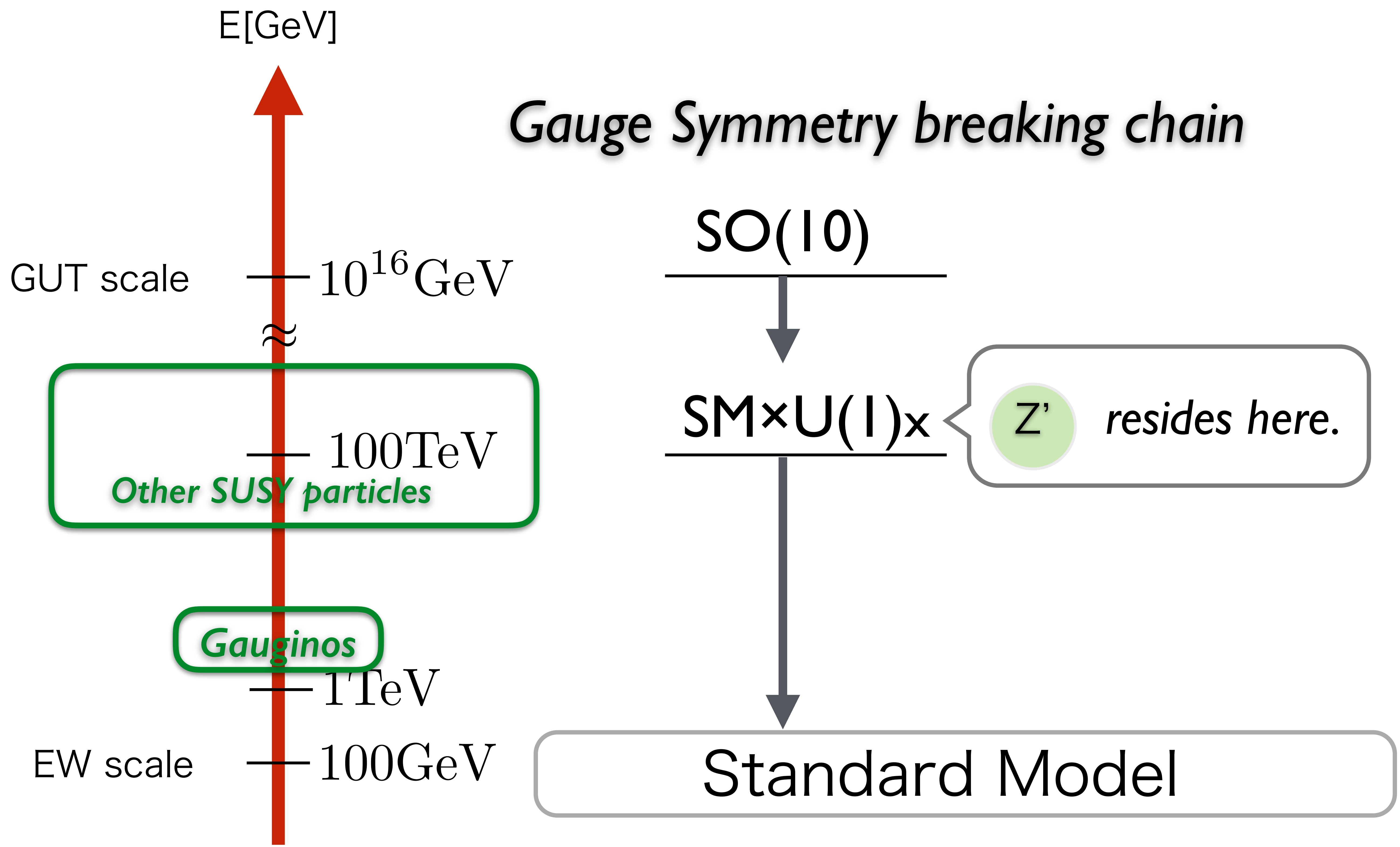


Gauge Symmetry breaking chain

SO(10)

Rough sketch of our scenario



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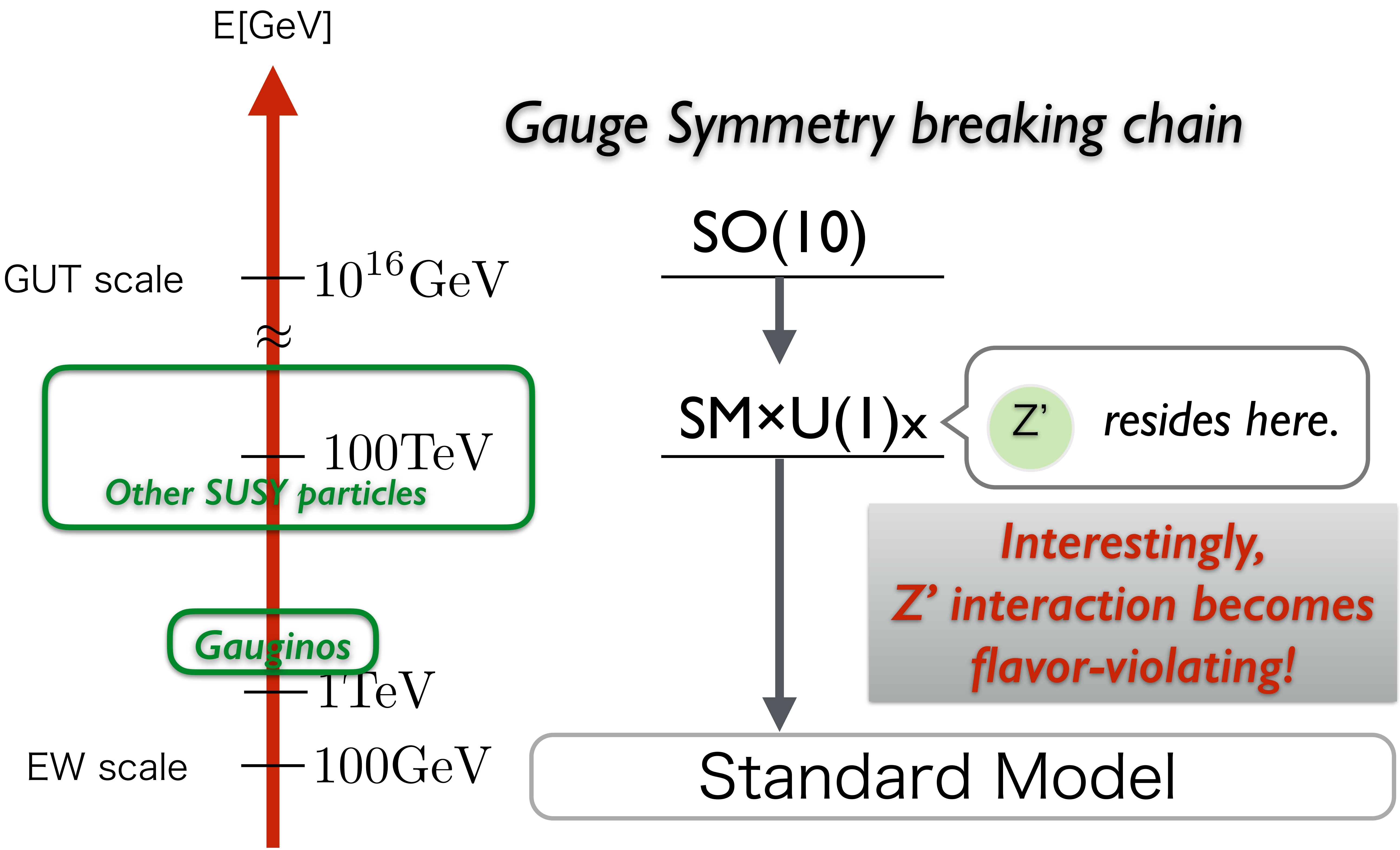
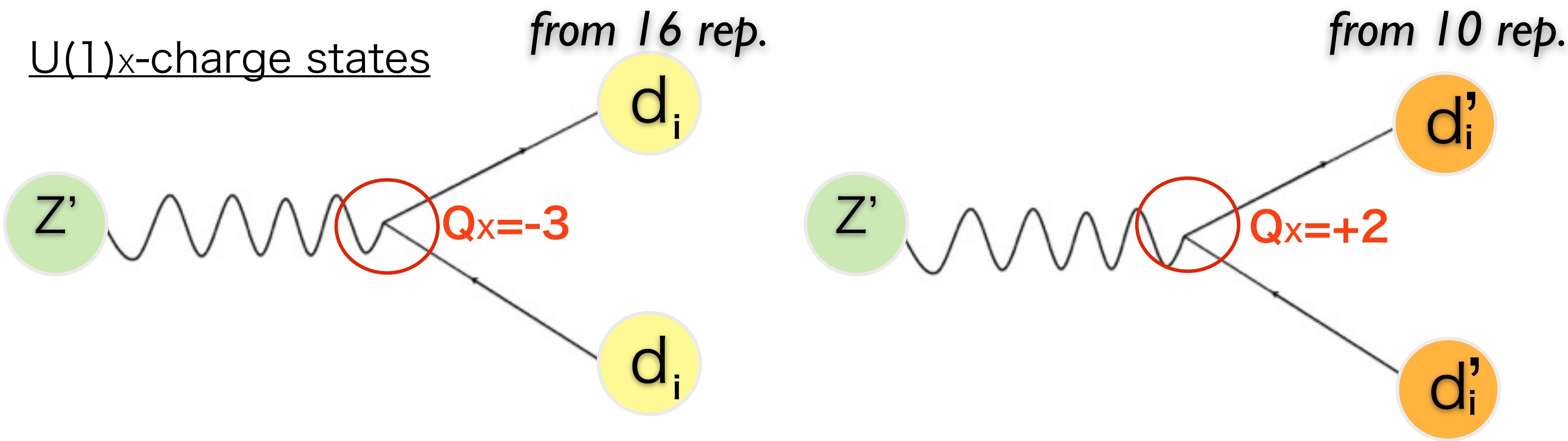


(YO, J. Hisano, Y. Muramatsu, Y. Shigekami,M. Yamanaka)

This is because

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

<u>$U(1)_X$-charge states</u>



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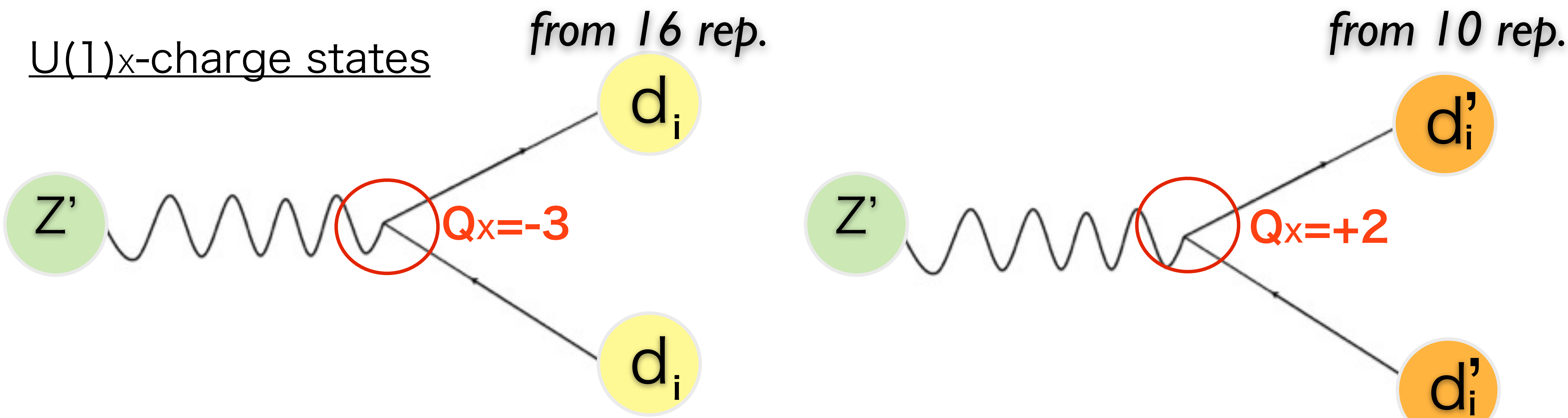
extra

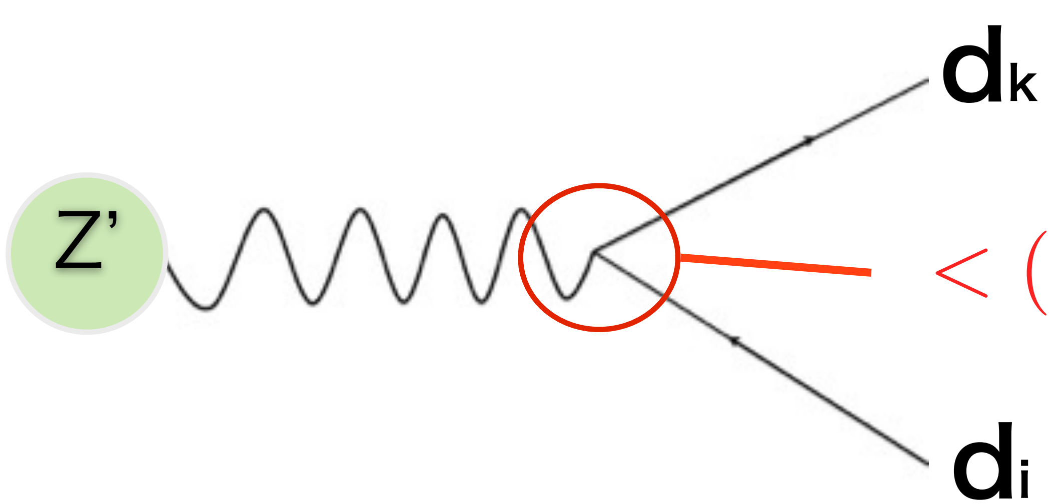
U(1)x-charge states



mass eigenstates

down-type quarks

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



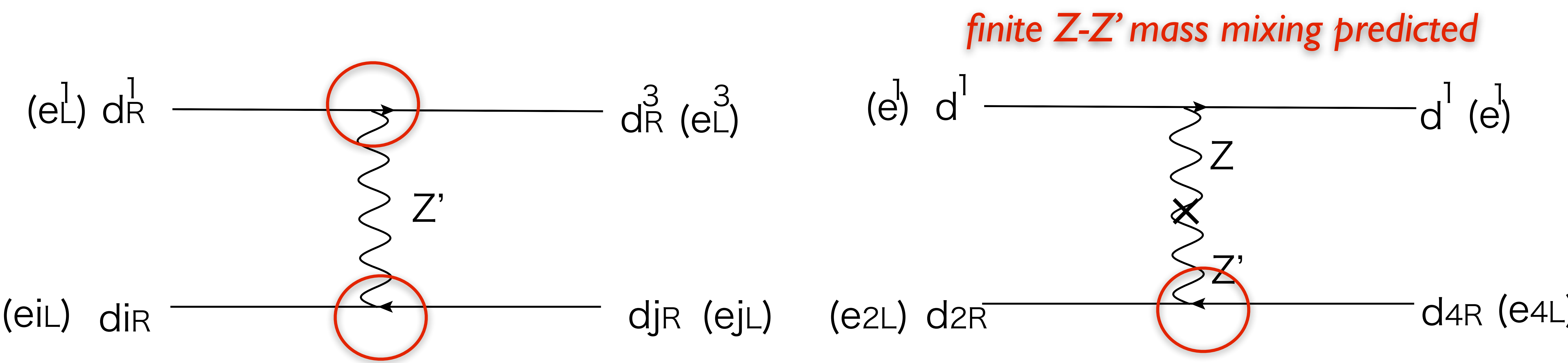
$$< (d_R^k)_{SM}|\hat{Q}_X|(d_R^i)_{SM} > \not\propto \delta_{ik}$$

Flavor violating!

Our Predictions

The detail shown in Shigekami's poster

Left-handed leptons and right-handed down-type quarks have FCNCs corresponding to the fermion mass hierarchy.



$A_{ij}^{d,l}$

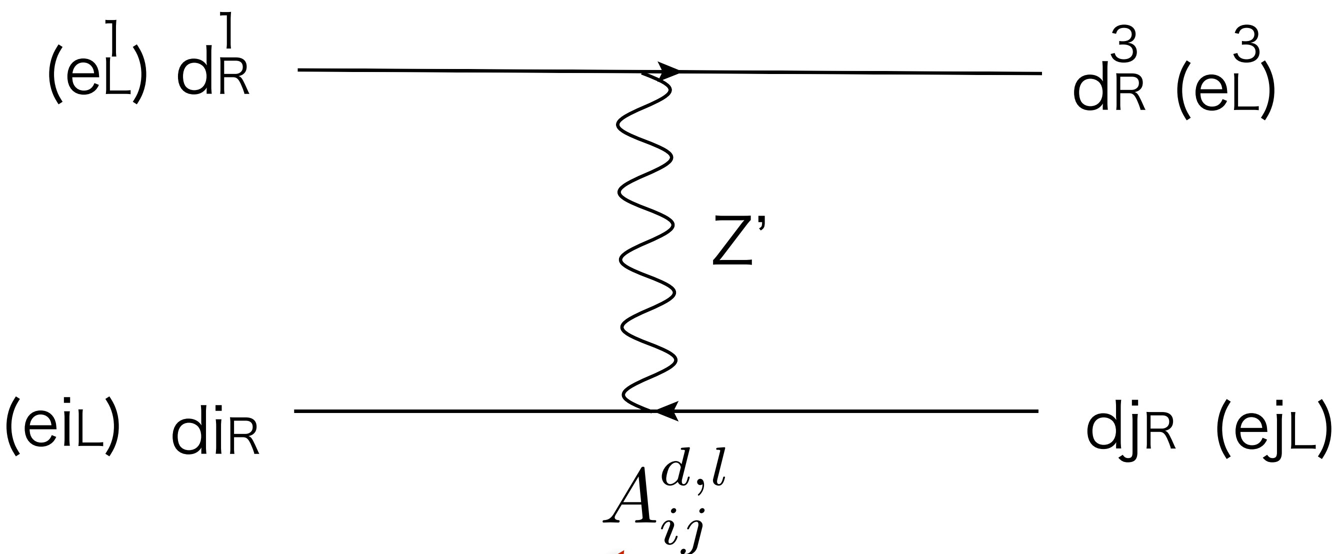
Roughly speaking, $A_{ij}^{d,l} \propto m_i^{d,l} \times m_j^{d,l}$

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

Flavor Physics

Relevant processes

(See Shigekami's poster)



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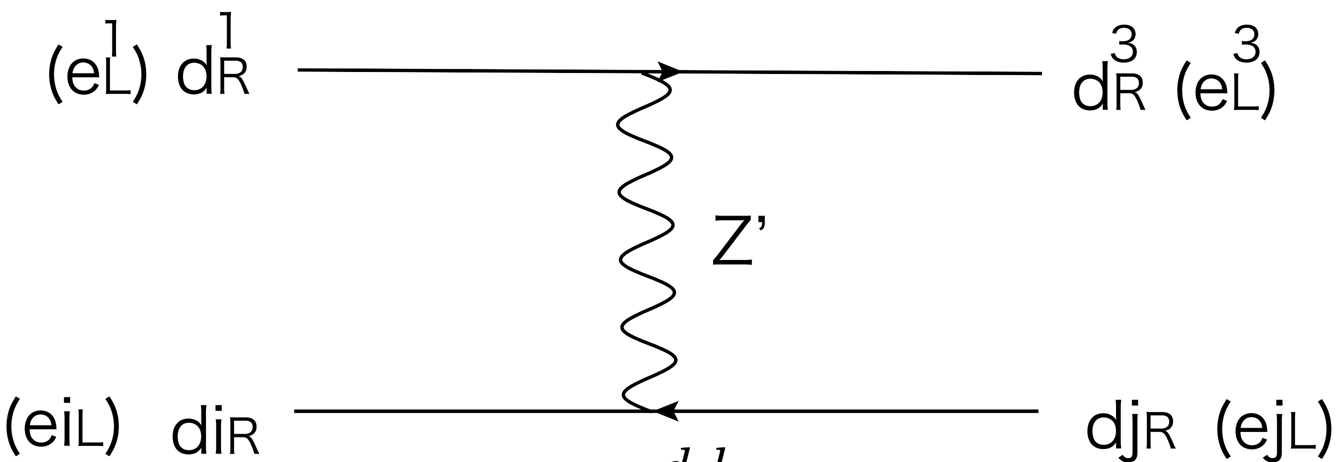


$A_{ij}^{d,l}$

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

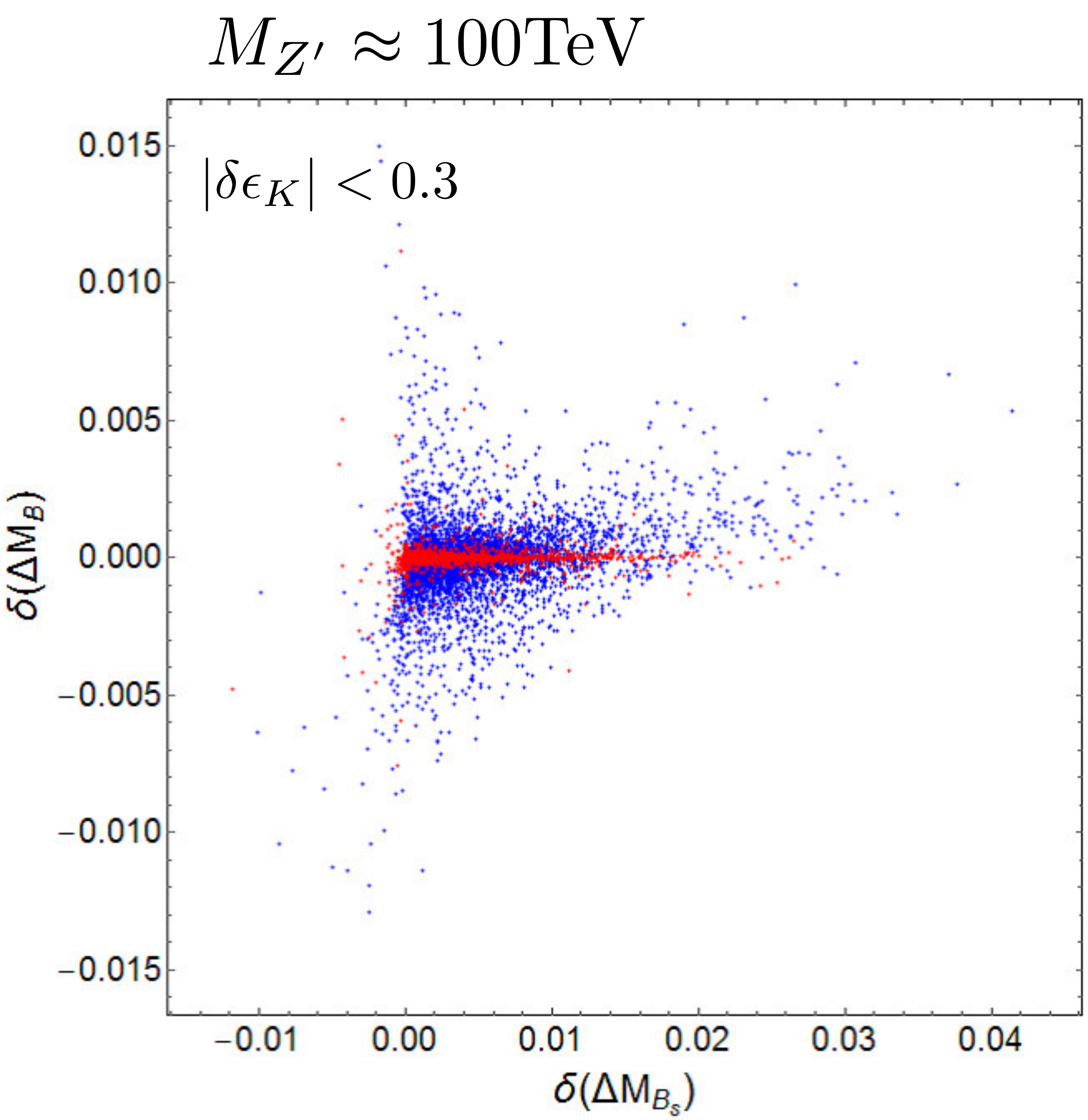
ΔF=2 processes

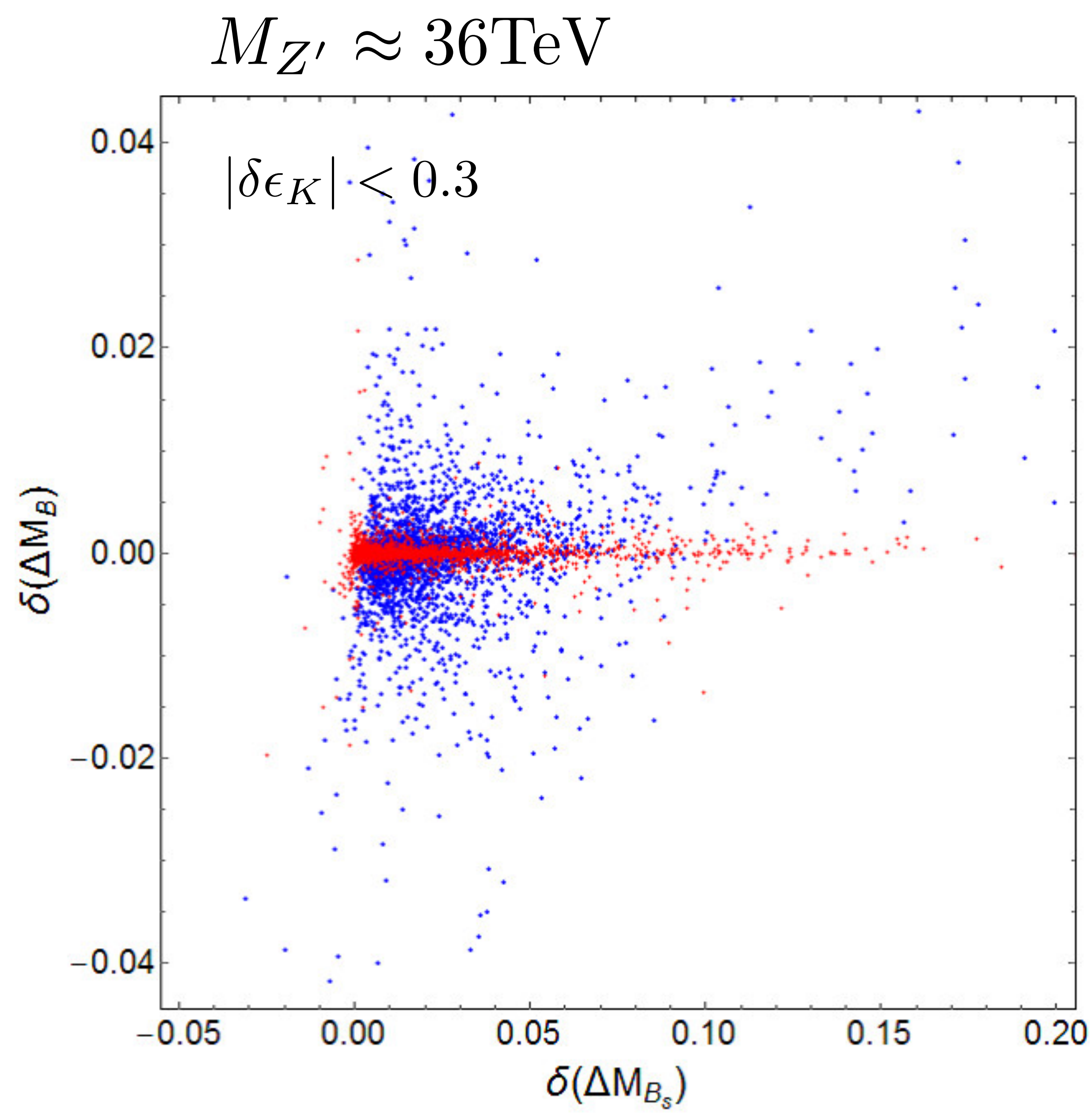
ε_K is most sensitive.

The deviation of B_s-$\overline{B}_s$ mixing is also relatively large.

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

Actually, there are free parameters to fit all experimental data.

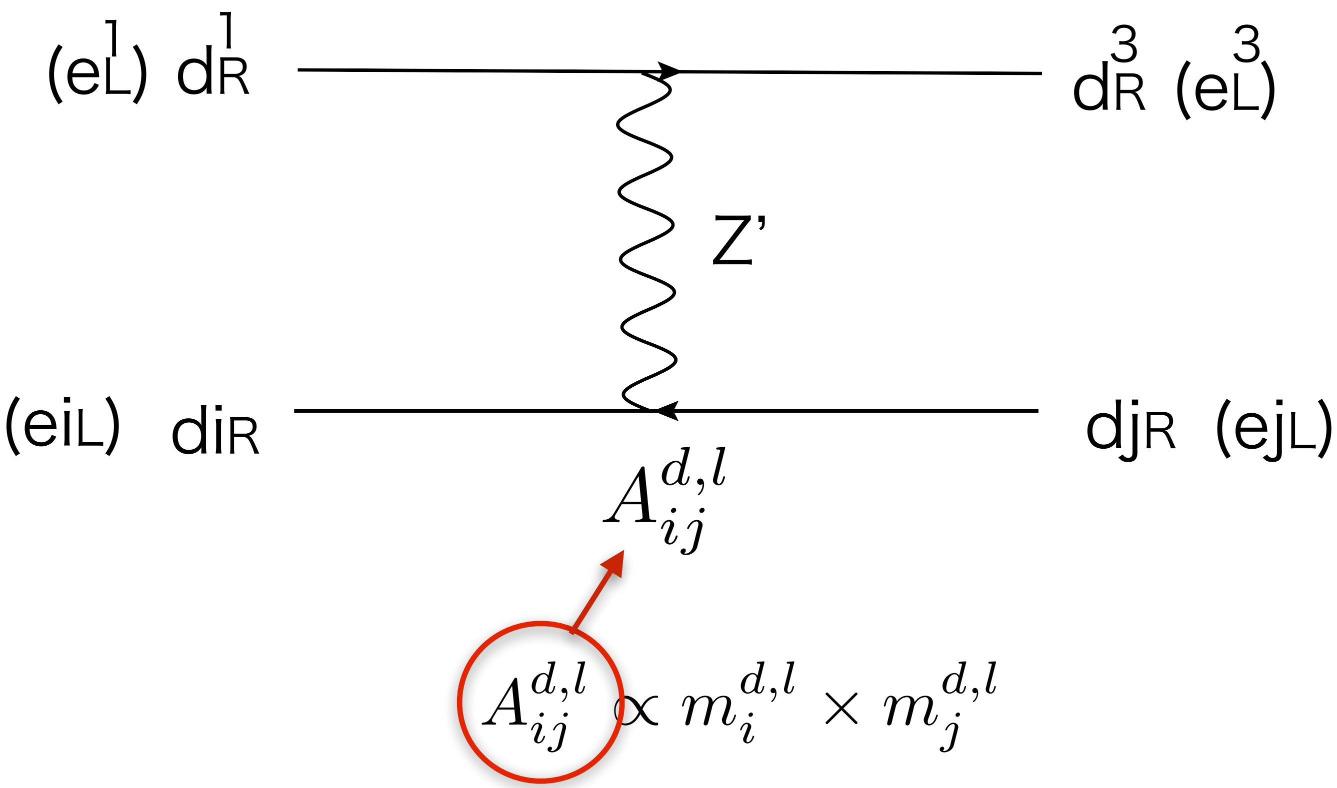




The deviation of Bs-$\overline{\text{B}}$s mixing reaches 10 % if Z' mass O(10) TeV.

Relevant processes

(See Shigekami's poster)



ΔF=2 processes

ε_K is most sensitive.

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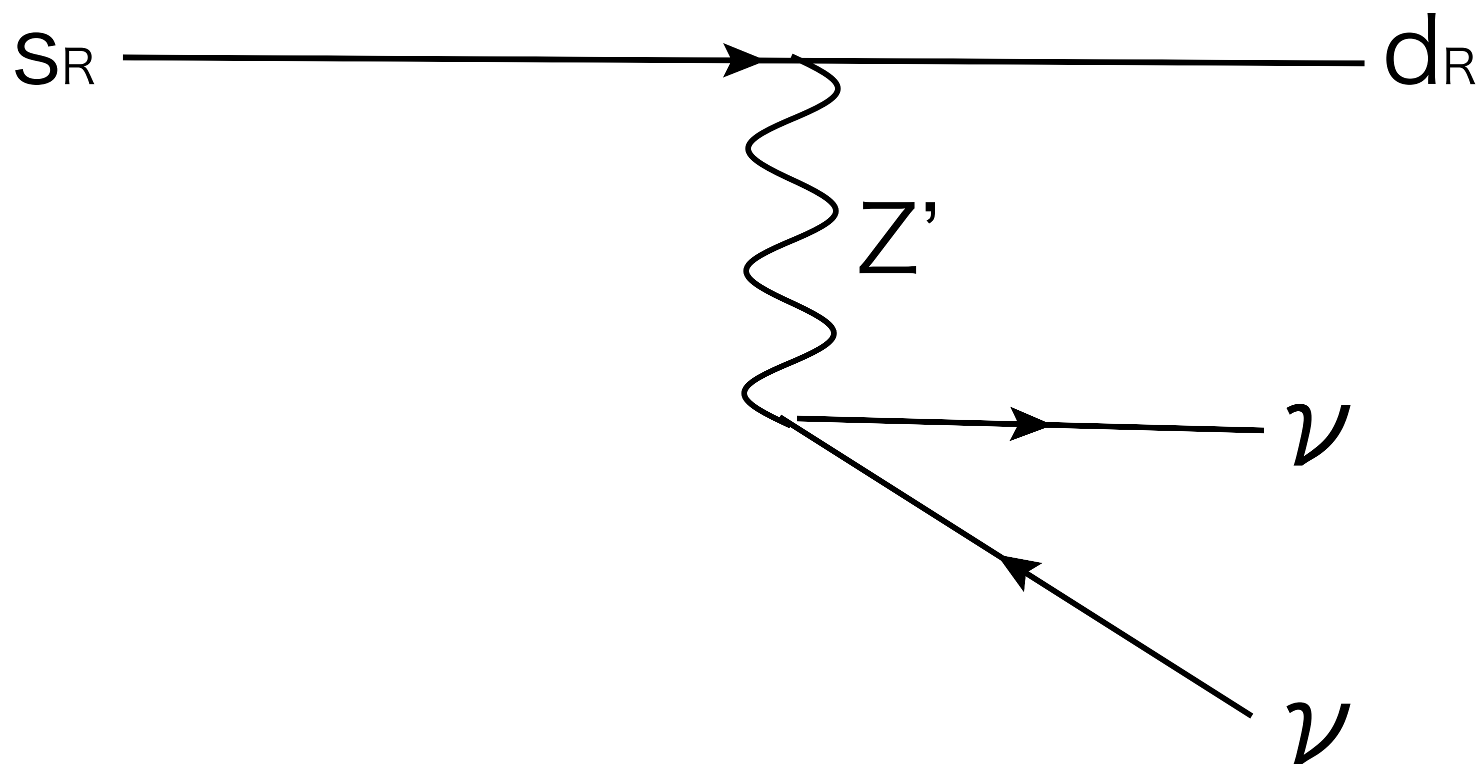
How about other processes?

Deviations in rare K decay

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



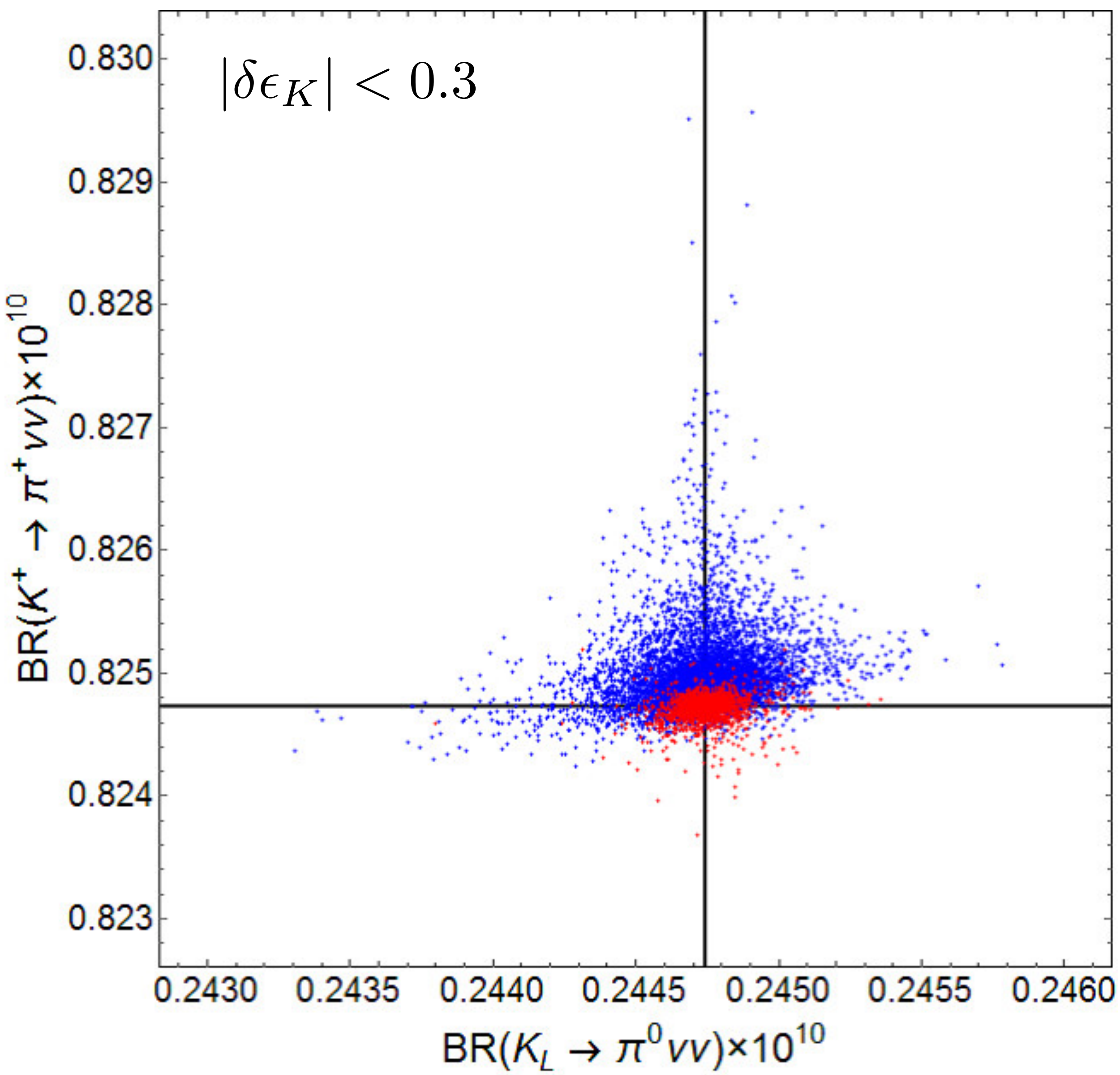
$$\mathrm{BR}(K^+ \to \pi^+ \nu\overline{\nu}) = 1.73^{+1.15}_{-1.05} \times 10^{-10}$$ (E949, 0903.0030)

$$\mathrm{BR}(K_L \to \pi^0 \nu\overline{\nu}) < 2.6 \times 10^{-8}$$ (E391a, 0911.4789)

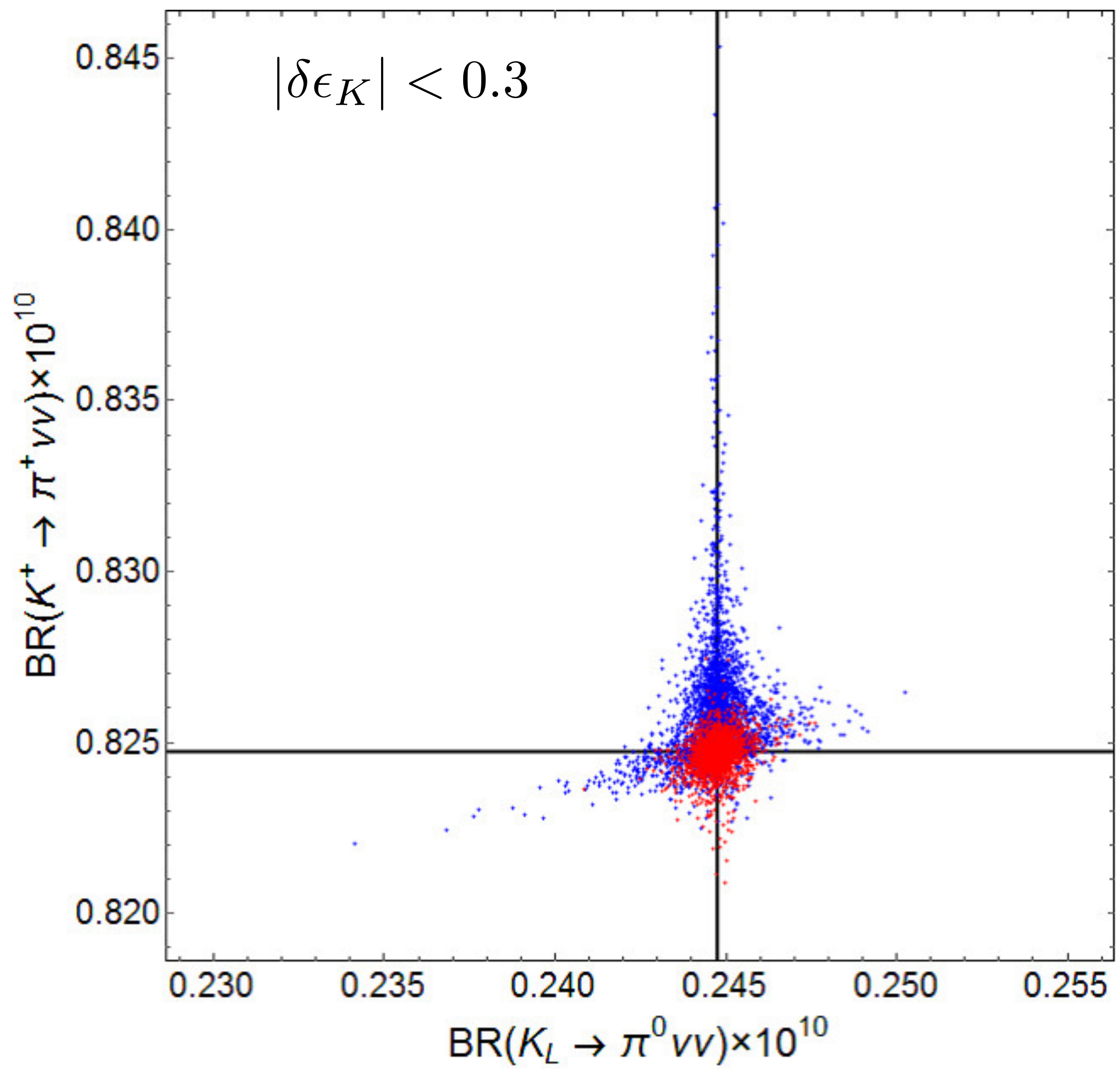
Deviations in rare K decay

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

$M_{Z'} \approx 100\text{TeV}$



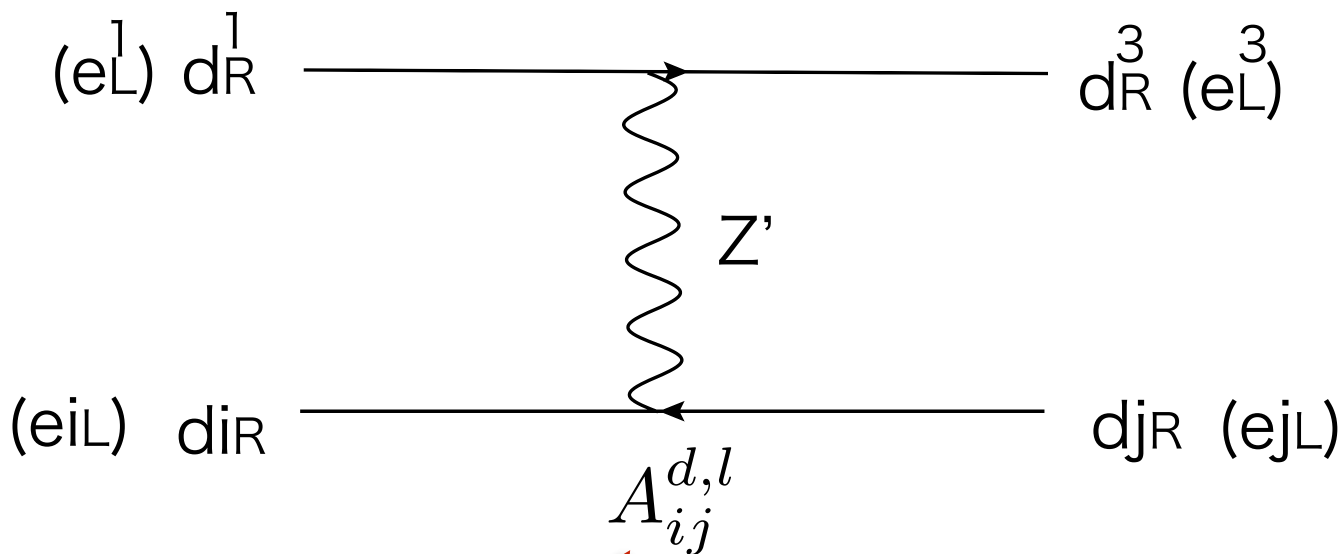
$M_{Z'} \approx 36\text{TeV}$



*deviations of KL→**μμ,μe**, K→**π0νν** are at most O(1)%.*

Relevant processes

(See Shigekami's poster)



$$A^{d,l}_{ij} \propto m^{d,l}_i \times m^{d,l}_j$$

ΔF=2 processes

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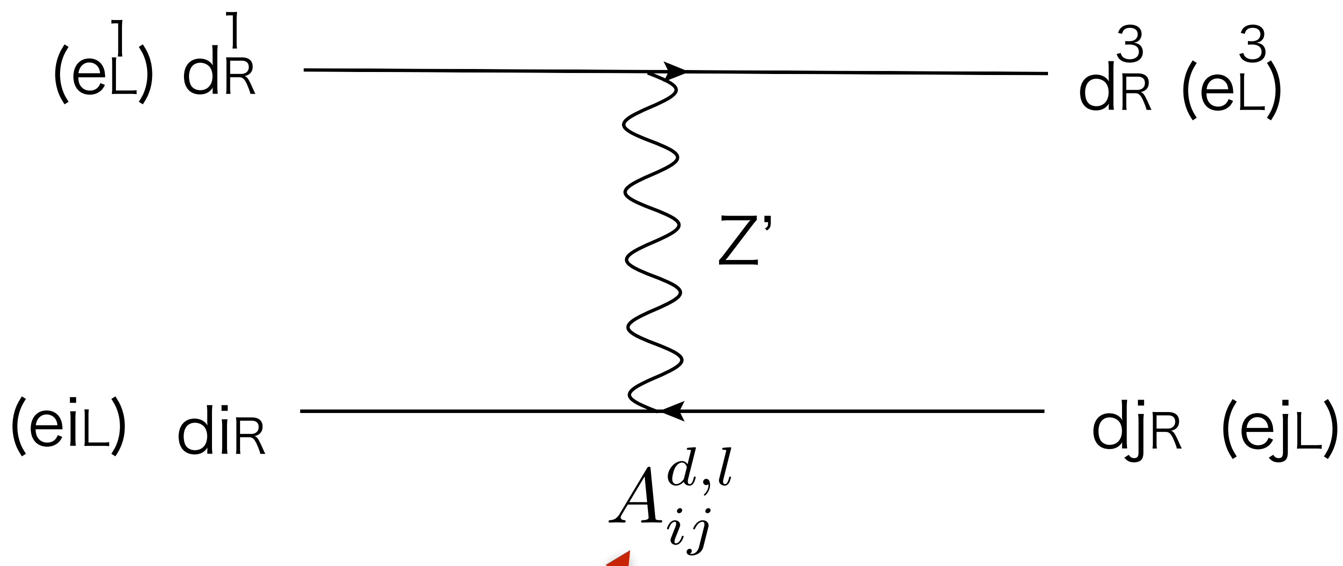
How about other processes?

very small because of the constraint from ε_K.

Relevant processes

(See Shigekami's poster)



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ΔF=2 processes

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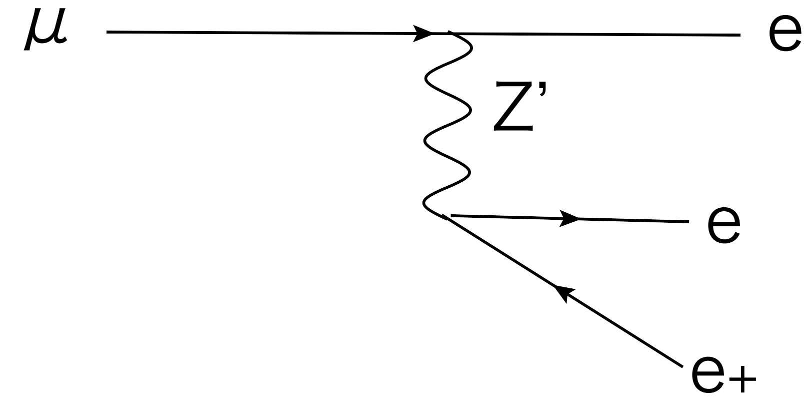
Lepton Flavor violation

μ→3e, μ-e conversion are the most important.

$\mu \to 3e$



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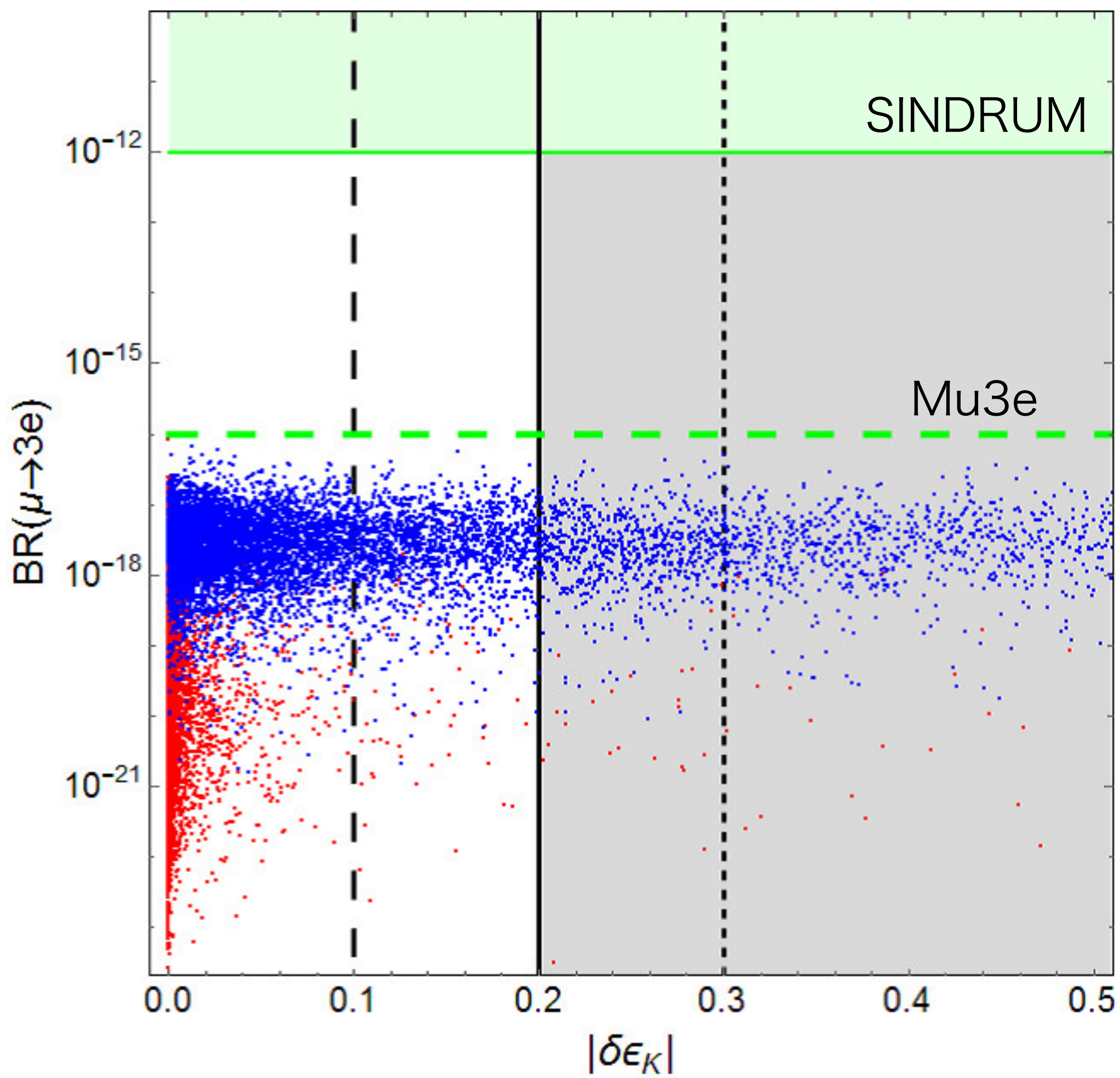

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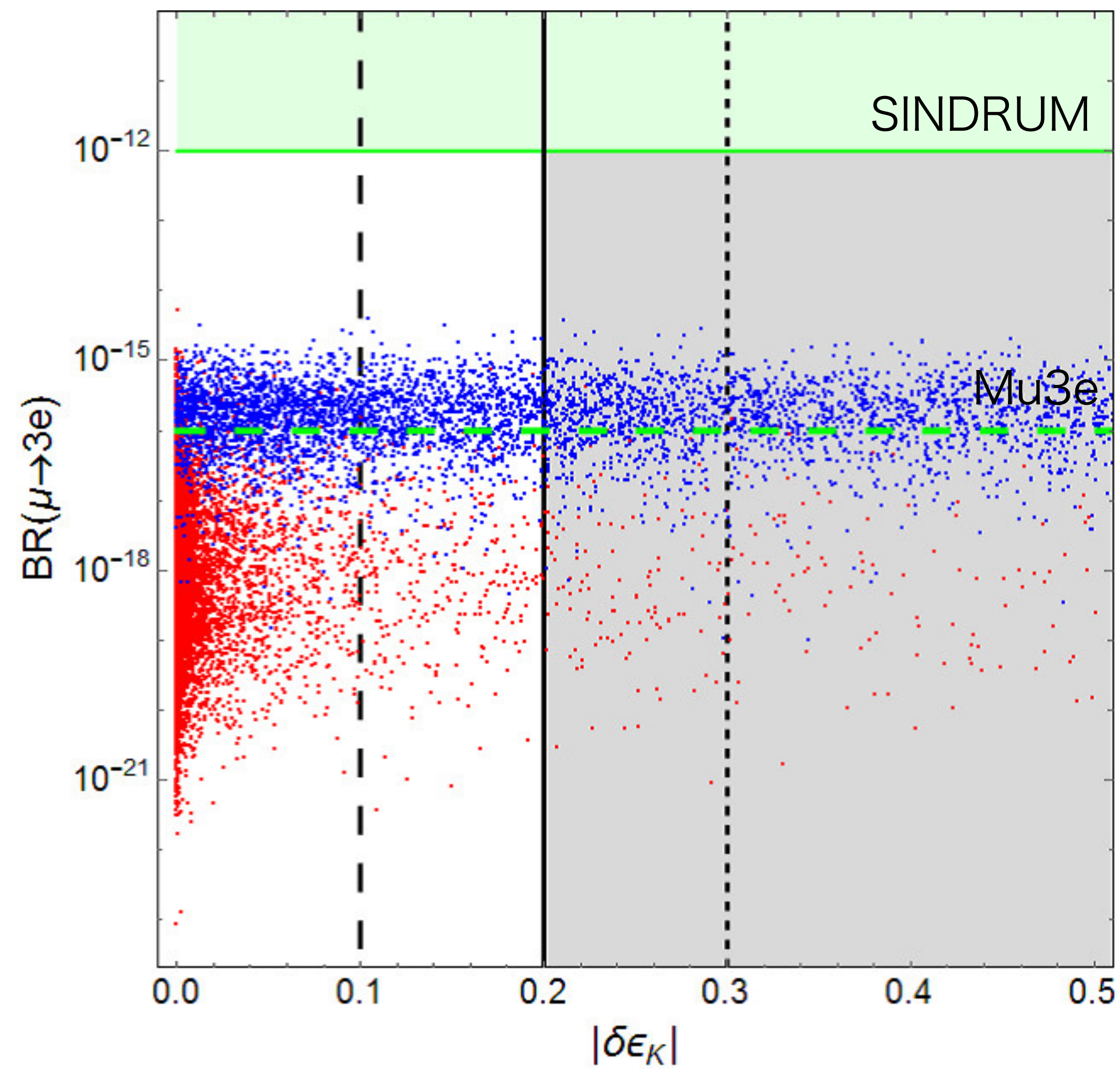
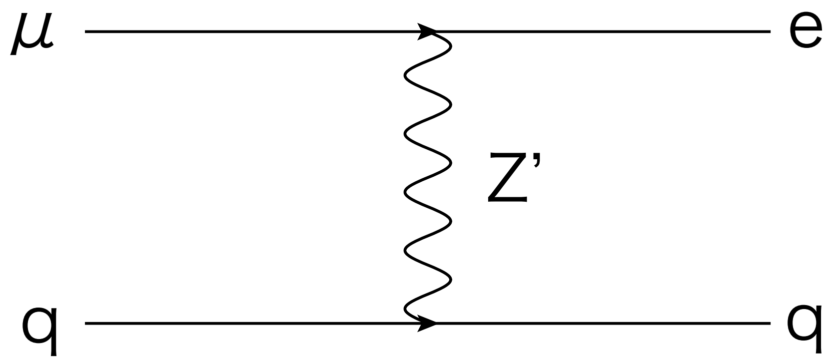
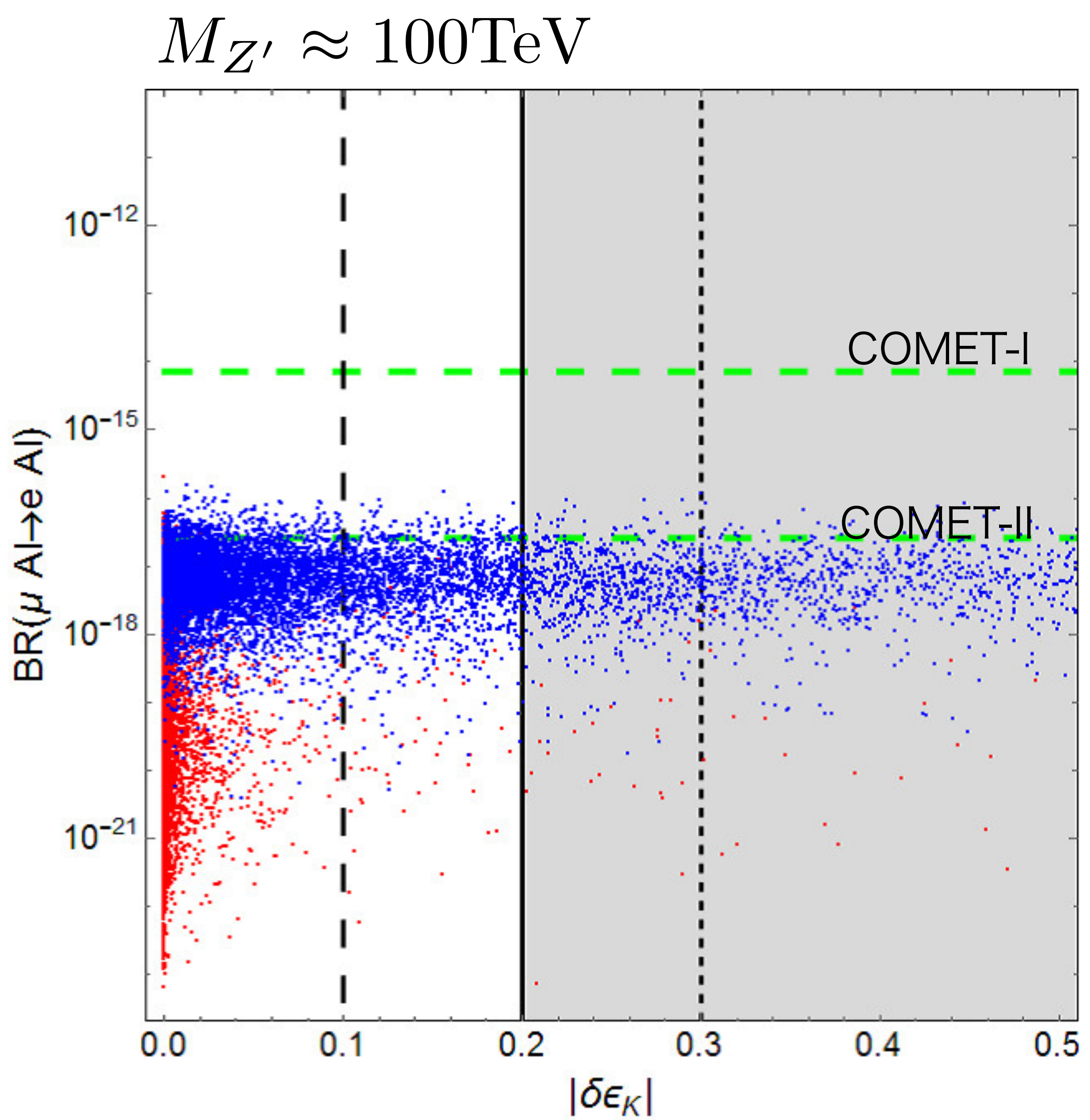
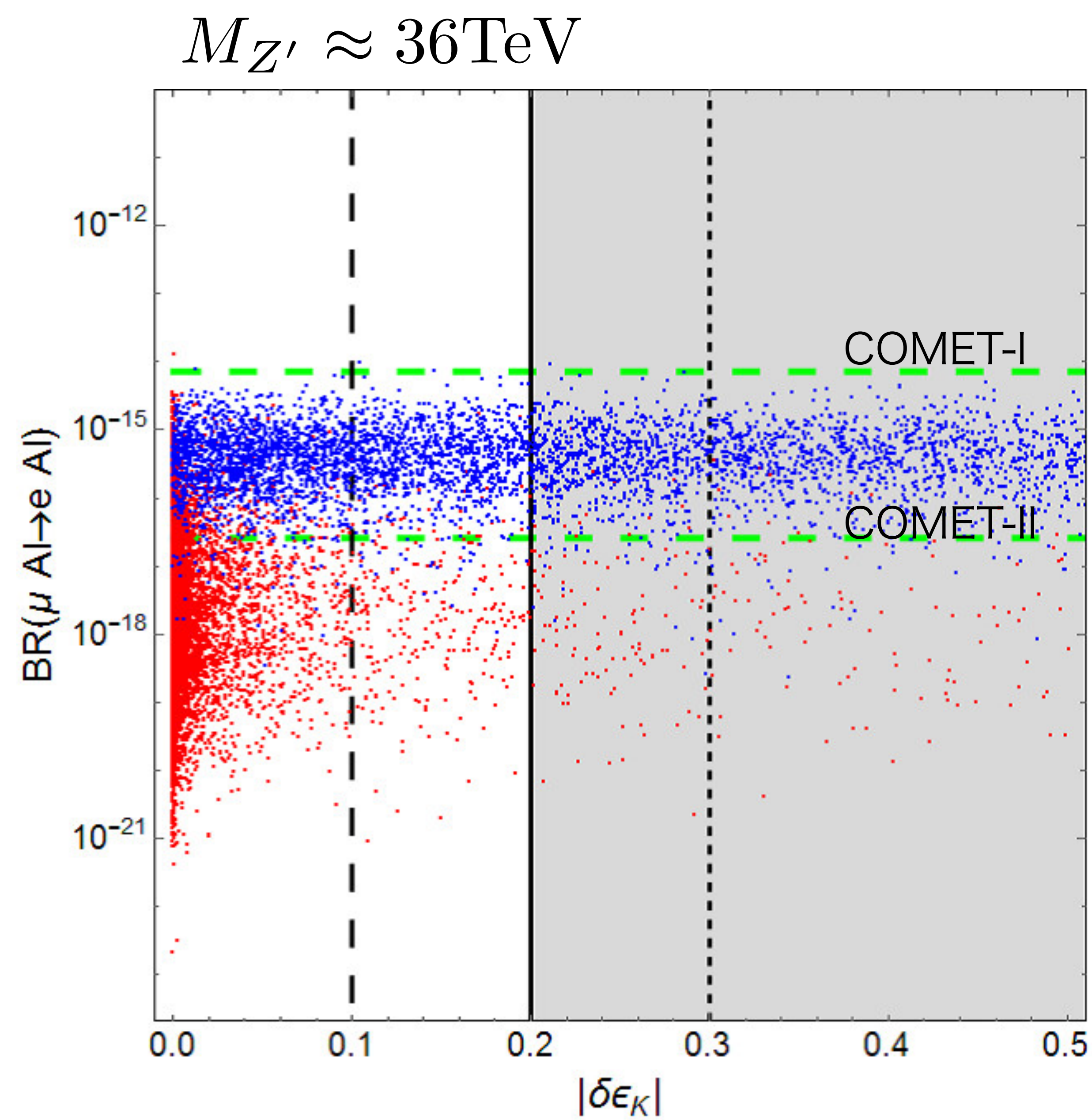


Future experiment (Mu3e) could reach our region!

μ N→e N







COMET experiment could reach our region!

Summary and Discussion

The BSMs I'm working on

- SUSY GUT (SO(10))

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

- dark matter models

  (T. Abe, J. Kawamura, S. Okawa, YO)

- 2HDM — *K. Tobe's talk*

  (YO, E. Senaha, K. Tobe)

The BSMs I'm working on

I introduced this work

- SUSY GUT (SO(10))

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

- dark matter models

  (T. Abe, J. Kawamura, S. Okawa, YO)

- 2HDM *K. Tobe's talk*

  (YO, E. Senaha, K. Tobe)

- In SUSY SO(10) GUT,

125GeV Higgs mass

realistic Yukawa

→ 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.

- SUSY GUT (SO(10)) **My talk**

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

  The setup predicts flavor violating processes.
  K and μ physics are the most important.

- dark matter models

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- 2HDM **K. Tobe's talk**

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- SUSY GUT (SO(10)) *My talk*

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***Bottom-up approach*:**
Many free parameters.
Based on the experimental results,
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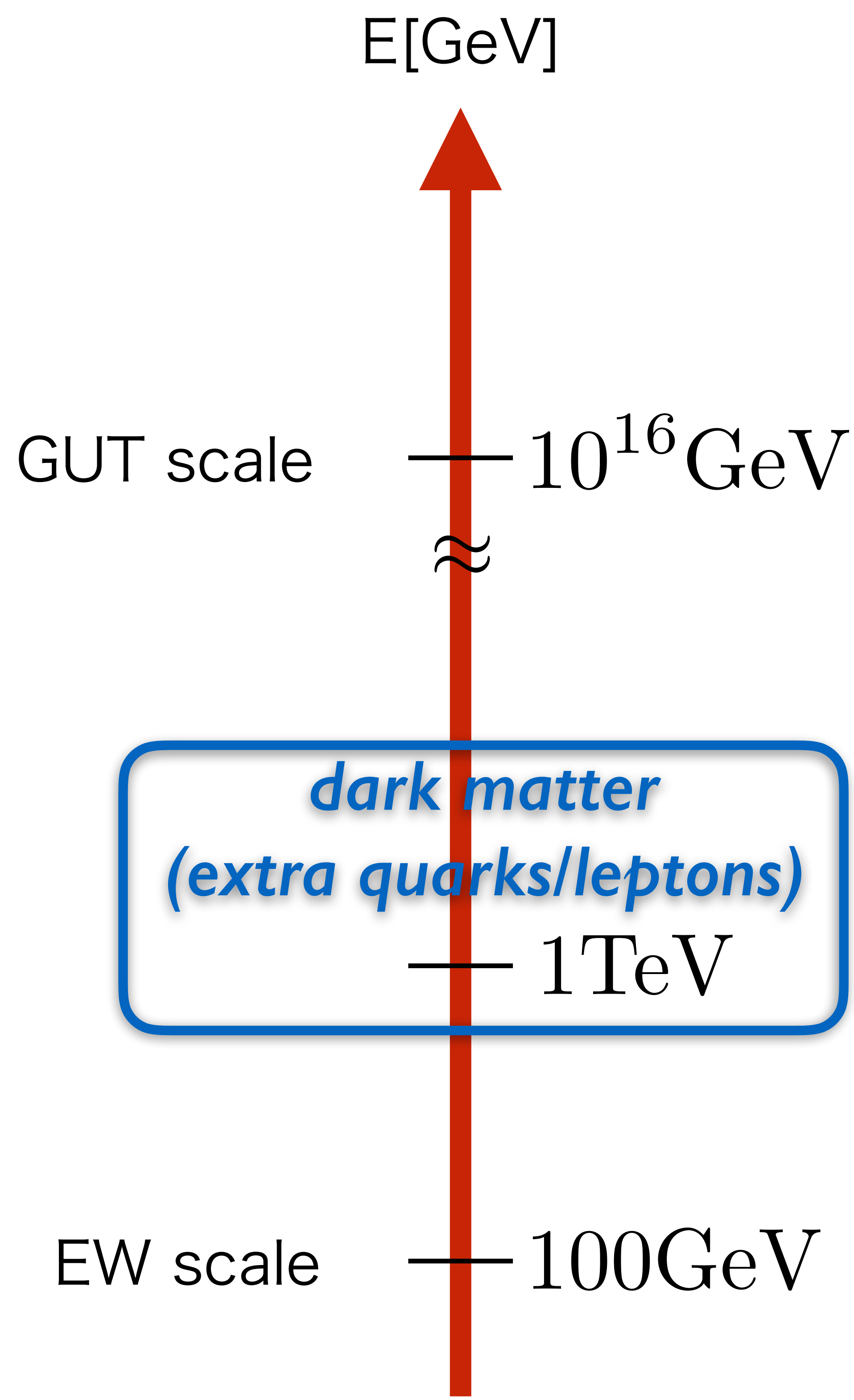
DM models in bottom-up approach



We build some simple BSMs with WIMP DMs,
and find some correlations among
direct search at the LHC, DM and flavor physics.

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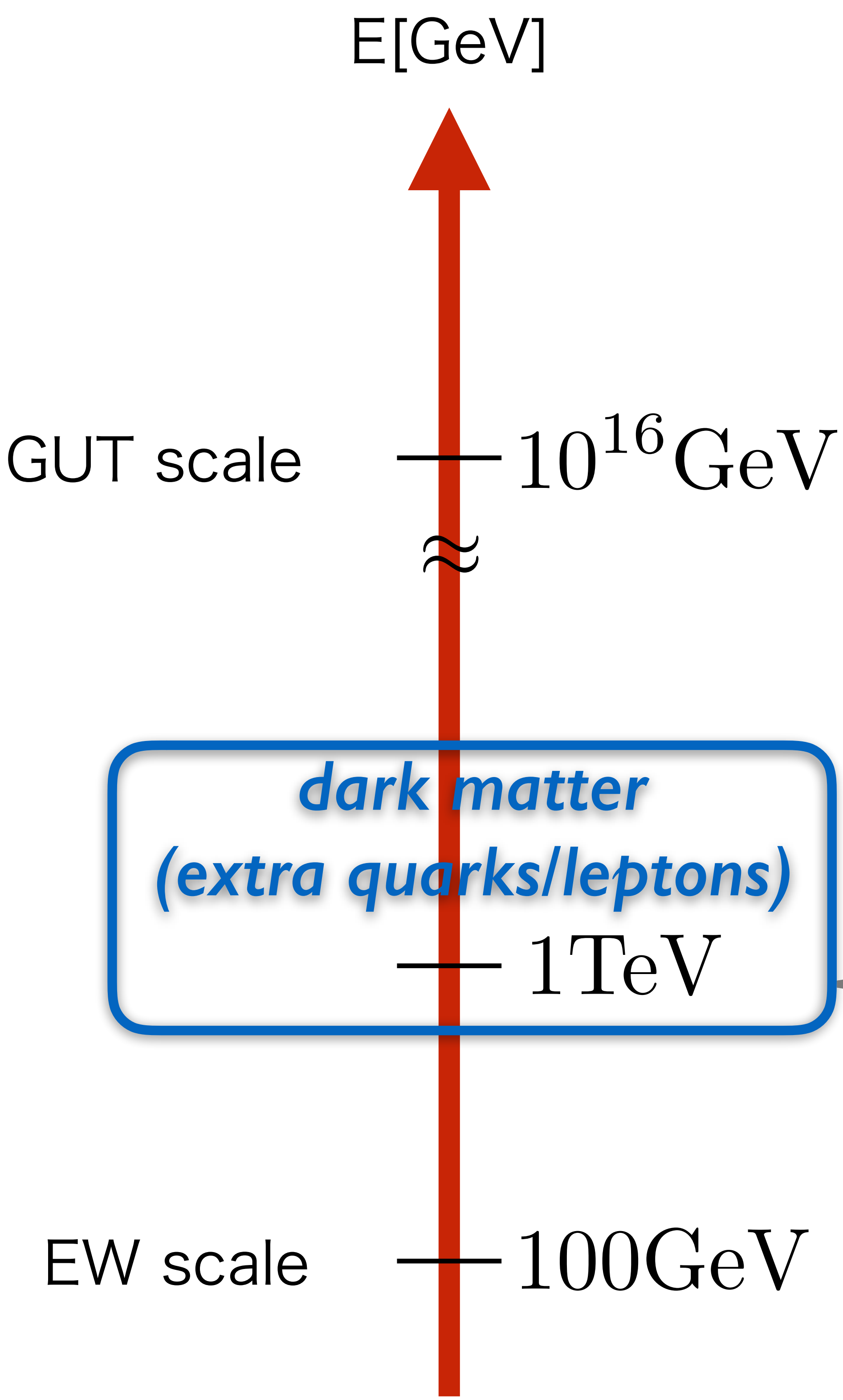
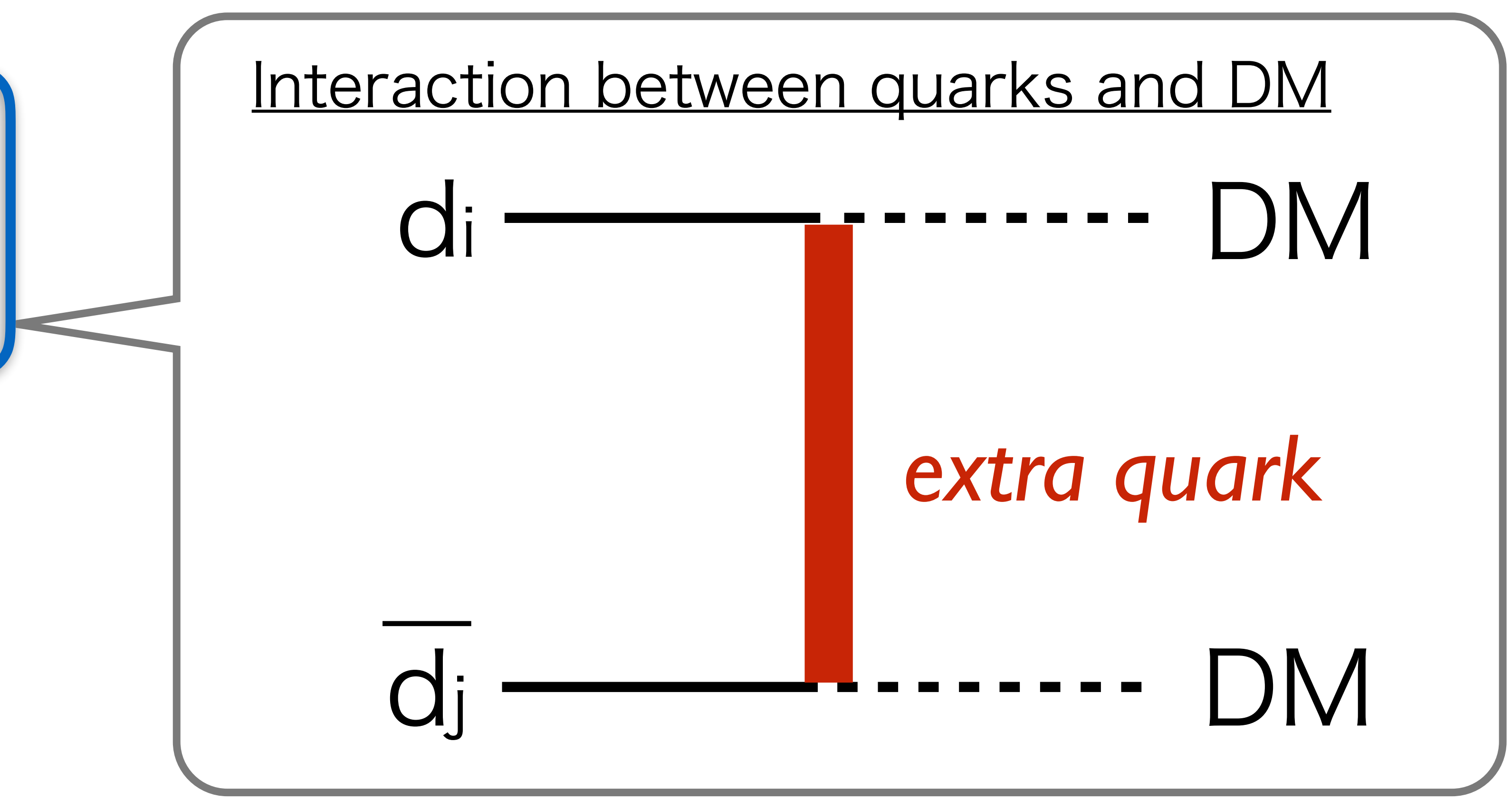
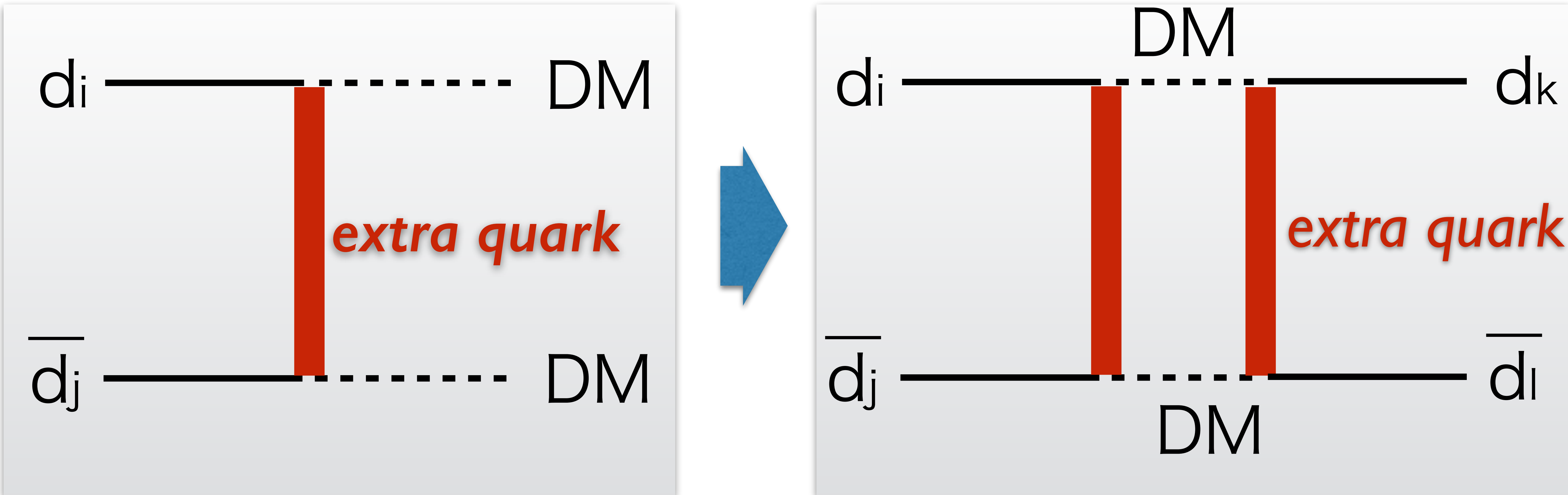




DM models in bottom-up approach

The same diagram contributes to DM and Flavor physics.



contribute to

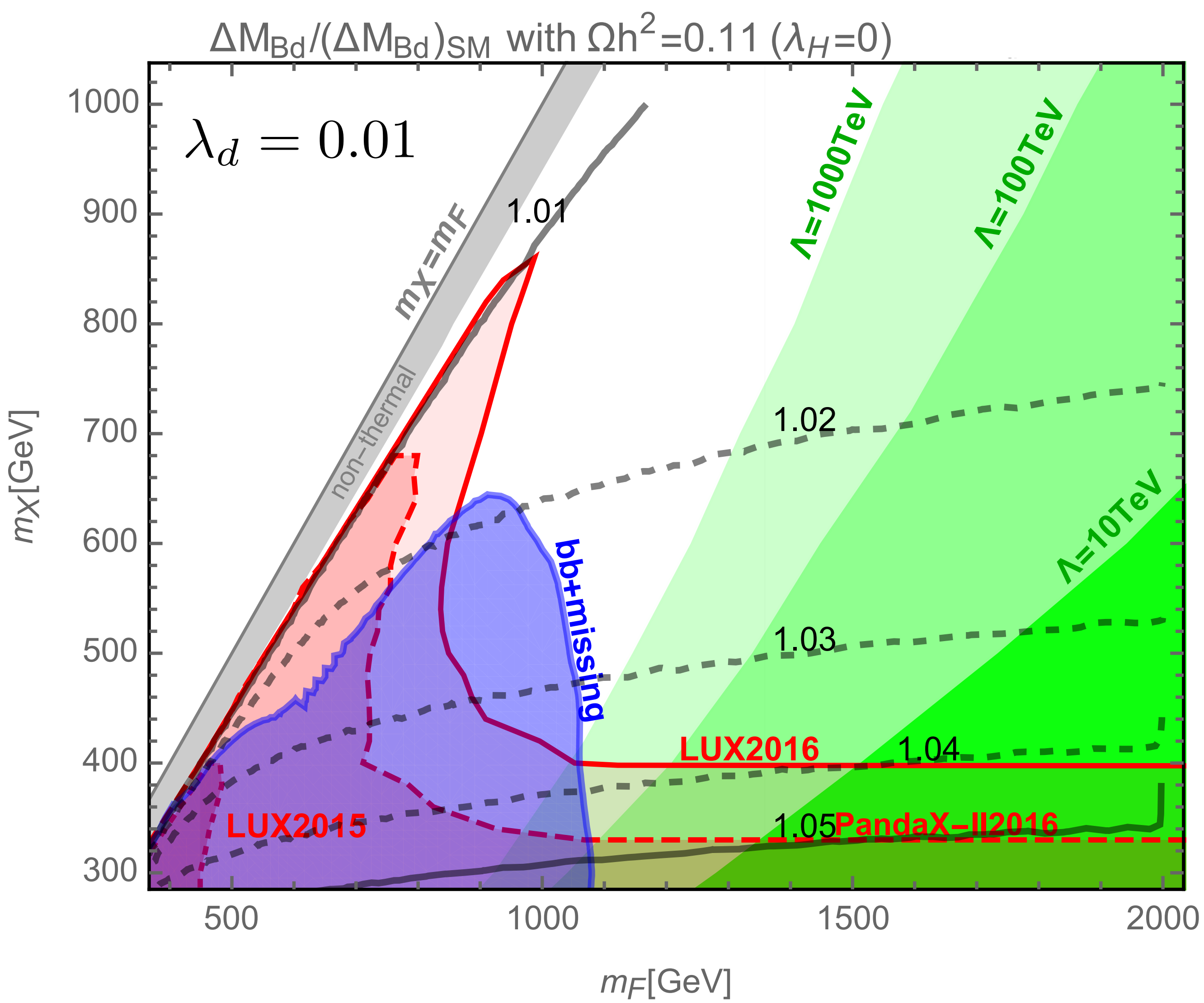
annihilation and
direct section of DMs.

contribute to

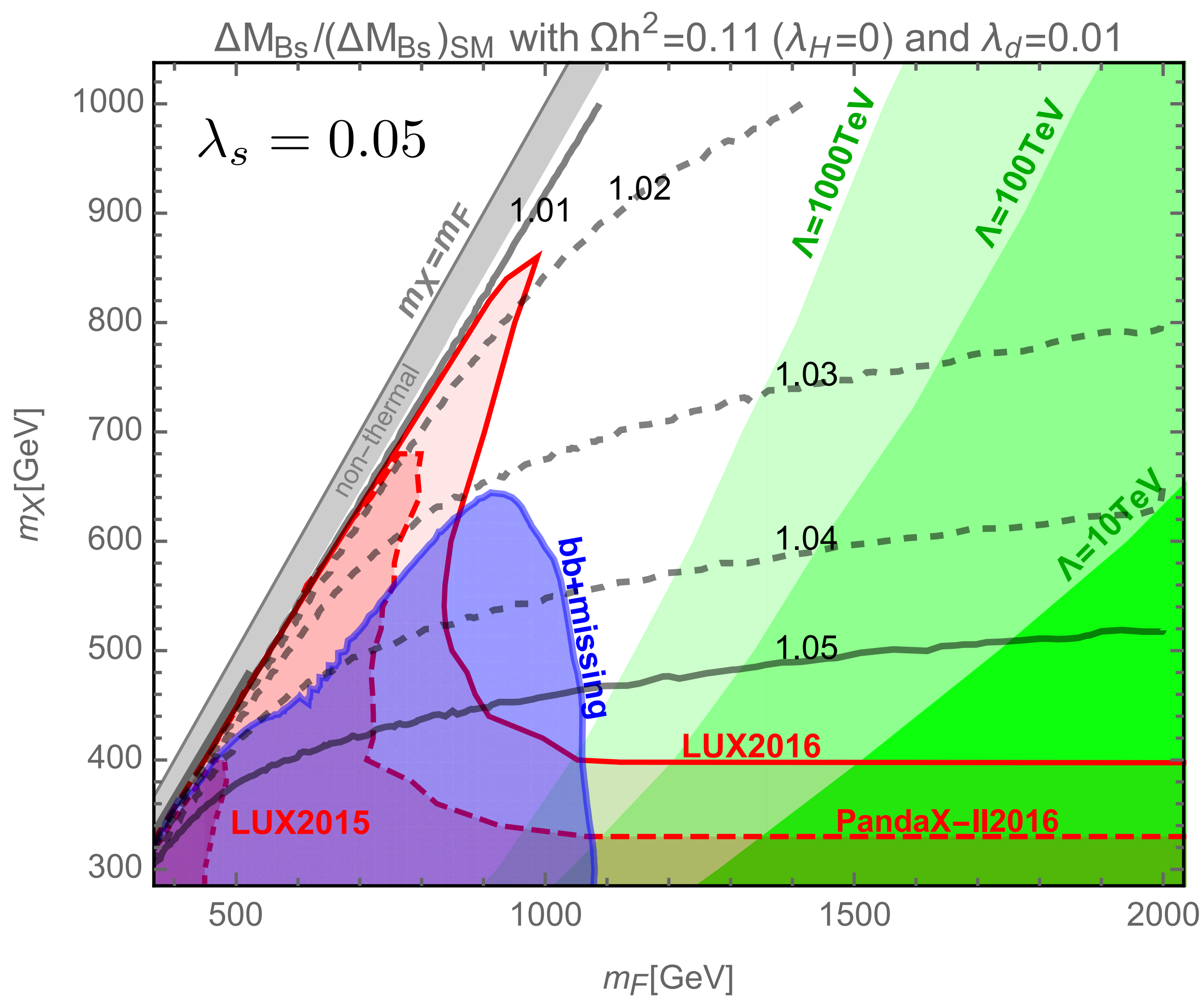
$\Delta F=2$ processes:
K-$\bar{K}$ and $B_{(s)}$-$\bar{B}_{(s)}$ mixing.

Correlations among the LHC, DM, flavor physics

$B_d - \overline{B_d}$ mixing



$B_s - \overline{B_s}$ mixing



O(1)-O(10)% Deviations of the ΔF=2 processes are predicted!

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The setup predicts flavor violating processes.
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There are correlations among LHC, DM, and flavor physics.

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Many free parameters.
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Thank you

Backup

Detail

In extended SO(10) symmetric superpotential,

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

In effective superpotential (SM×U(1)x symmetric superpotential),

quark sector

break extra U(1)x from 16H

$$h^{ij}Q_{L\,i}U^c_{R\,j}H_u + h^{ij}Q_{L\,i}\hat{D}^c_{R\,j}H_d + g^{ij}\overline{D'^c_{R\,i}}\hat{D}^c_{R\,j}\langle\mathbf{1}_H\rangle + \mu_{10}^{ij}\overline{D'^c_{R\,i}}D'^c_{R\,j}$$

MSSM down-type

$$\hat{D}^c_{R\,i} = (\hat{U}_D)_{ij}D^c_{R\,j} + (\hat{U}'_D)_{ij}D''^c_{R\,j}$$

$$h^{ij}Q_{L\,i}U^c_{R\,j}H_u + (h\hat{U}_D)_{ij}Q_{L\,i}D^c_{R\,j}H_d + \mu^{ij}\overline{D'^c_{R\,i}}D''^c_{R\,j}$$

Hierarchy is given by the mixing

Detail

In extended SO(10) symmetric superpotential,

$$h^{ij}\mathbf{16}_i\mathbf{16}_j\mathbf{10}_H + g^{ij}\mathbf{10}_i\mathbf{16}_j\mathbf{16}_H + \mu_{10}^{ij}10_i10_j$$

In effective superpotential (SM×U(1)x symmetric superpotential),

lepton sector

break extra U(1)x from 16H

$$h^{ij}\hat{L}_i N^c_{Rj} H_u + h^{ij}\hat{L}_i E^c_{Rj} H_d \quad + g^{ij}\overline{L'_i}\hat{L}_j \langle \mathbf{1}_H \rangle + \mu_{10}^{ij}\overline{L'_i}L'_j$$

MSSM lepton

$$\hat{L}_i = (\hat{U}_D)_{ij} L_j + (\hat{U}'_D)_{ij} L''_j$$

$$h^{ij} L_i N^c_{Rj} H_u + (\hat{U}_D^T h)_{ij} L_i E^c_{Rj} H_d \; + \mu^{ij}\overline{L'_i}L''_j$$

Hierarchy is given by the mixing