



Flavor physics in the BSMs

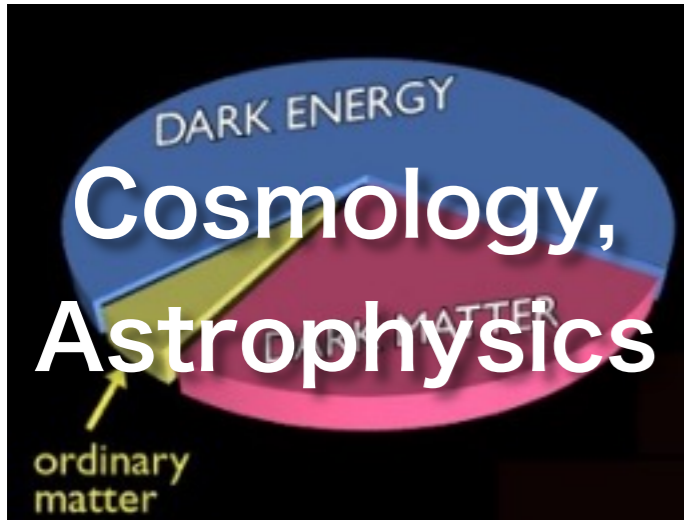
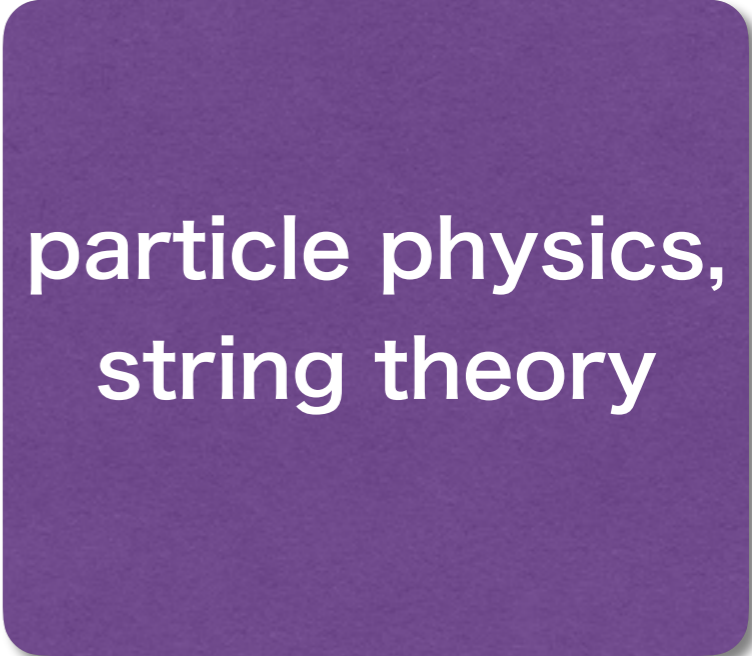
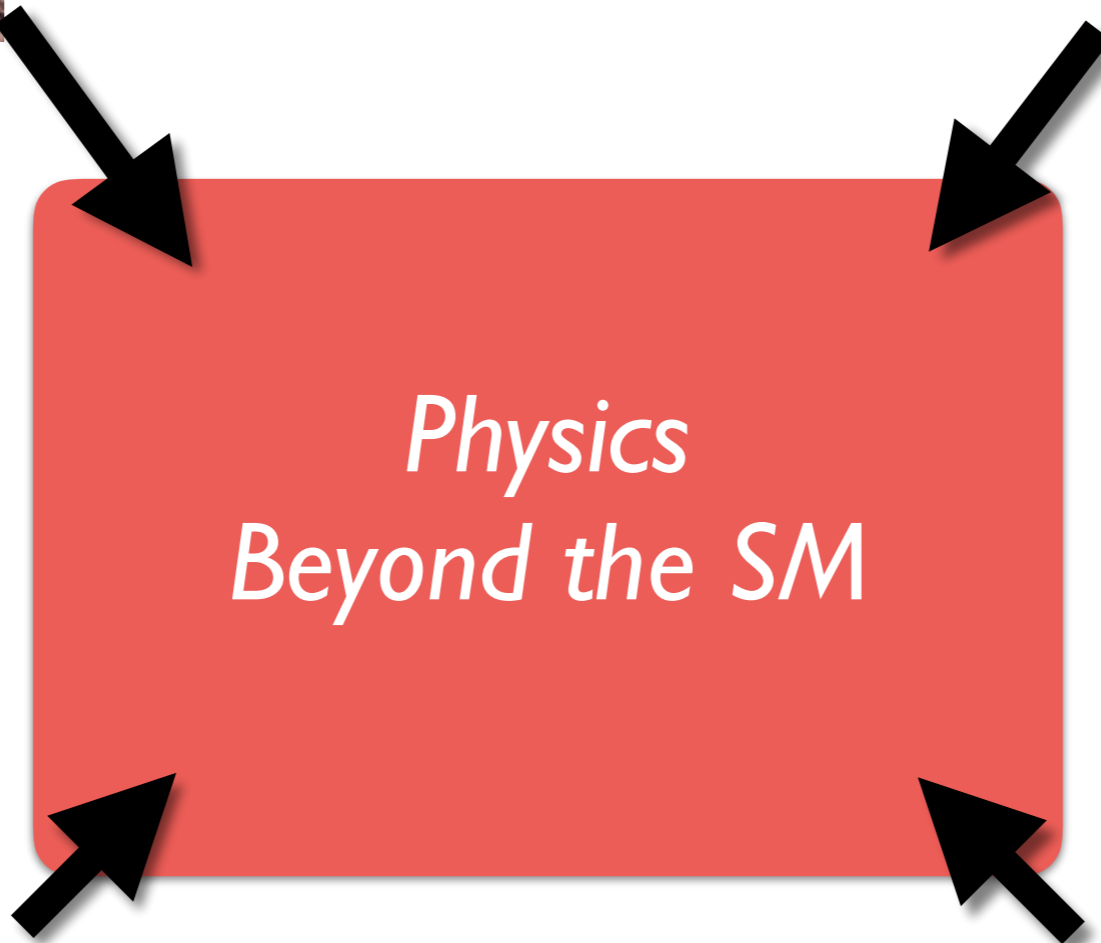
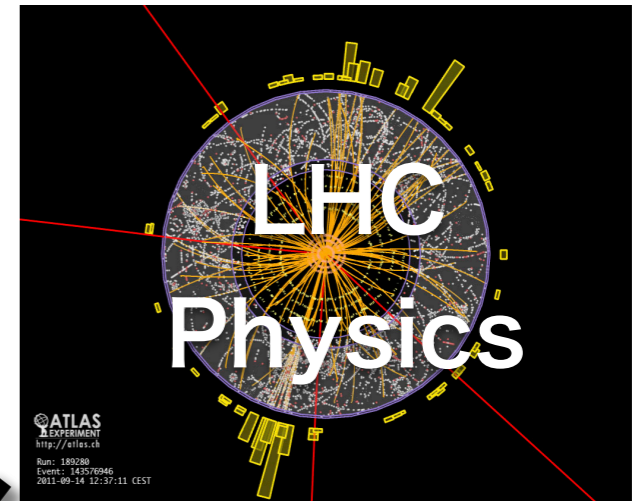
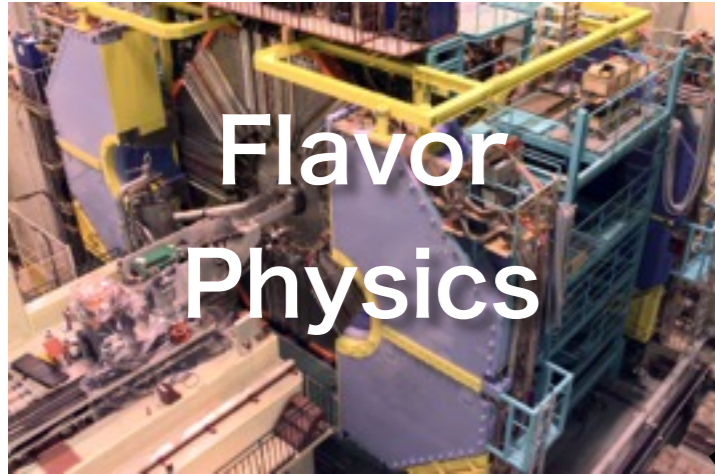
~SO(10) GUT~

Yuji Omura (KMI, Nagoya Univ.)

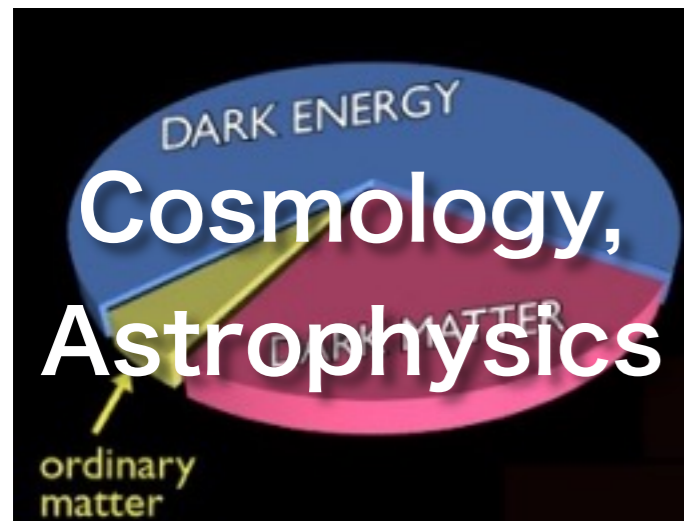
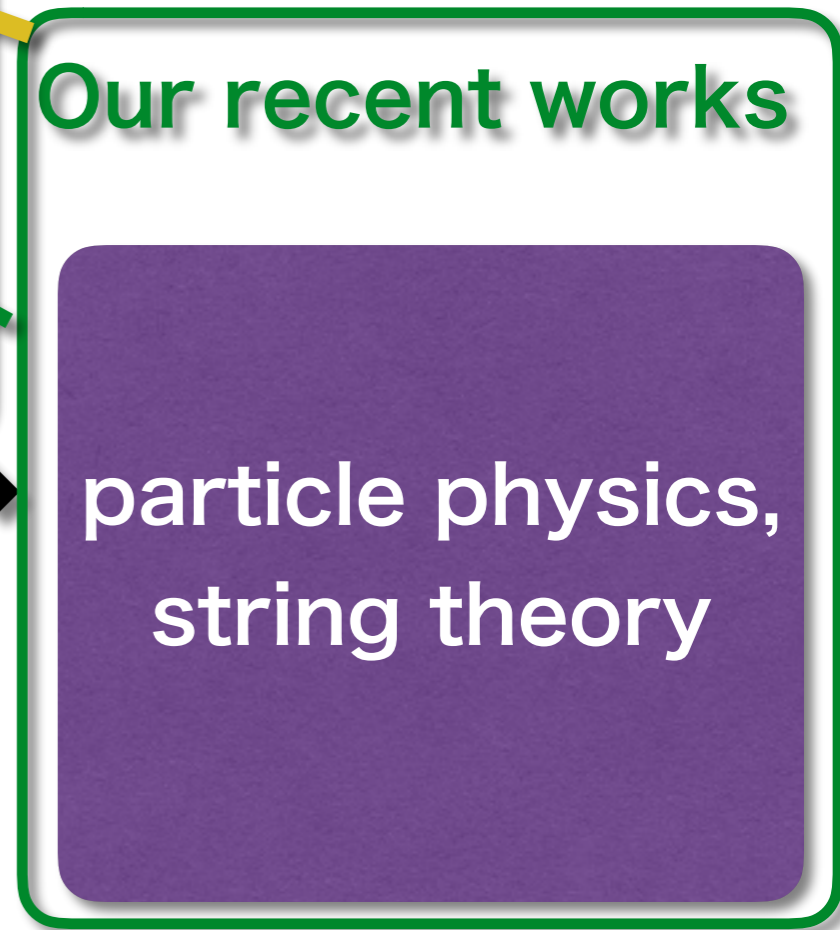
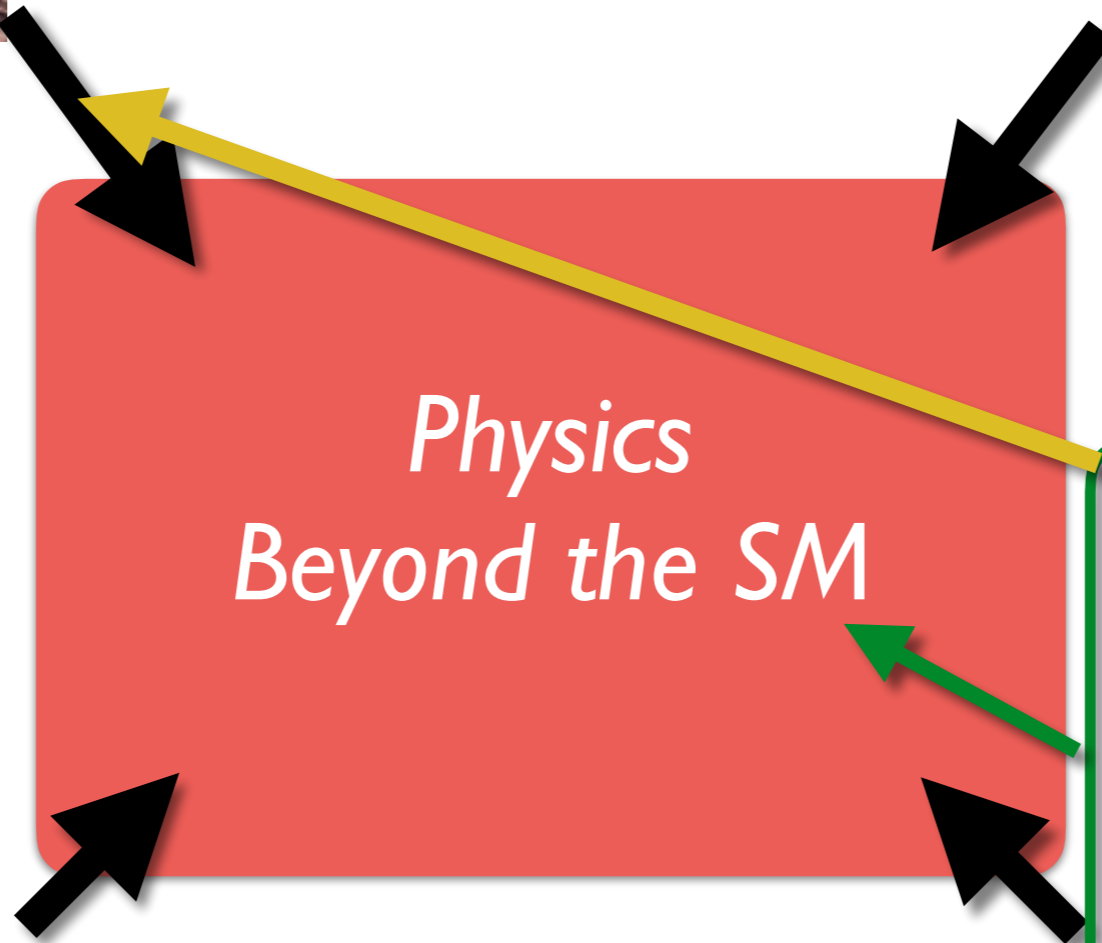
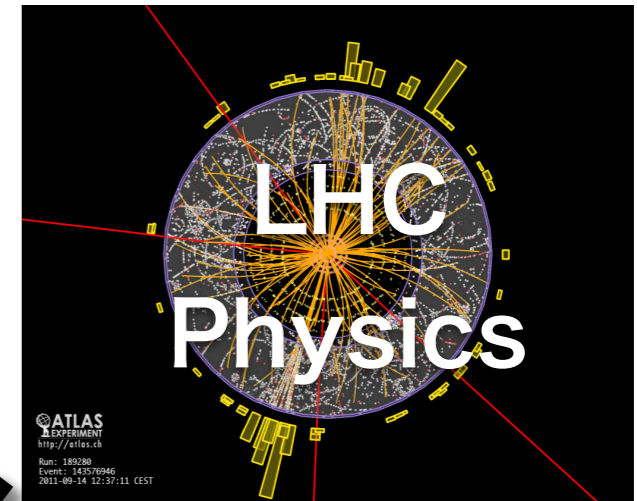
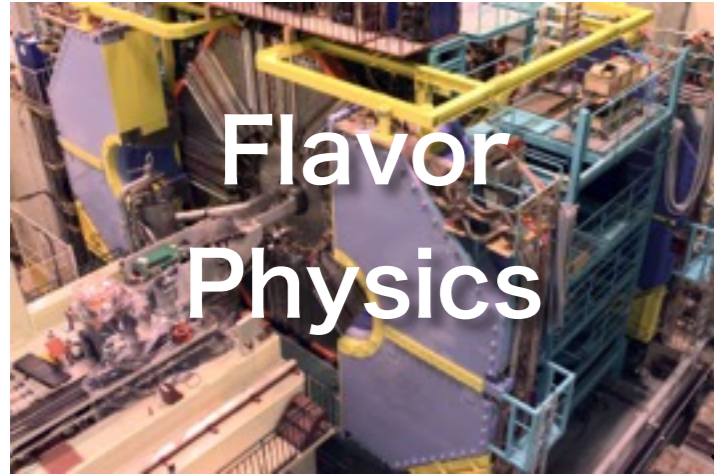
Based on PLB744 (2015) 395 (arXiv: 1503.06156),
JHEP1611(2016)018 (arXiv: 1607.05437);
arXiv: 1612.01643

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

Very exciting era!



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

1. Introduction

2. Setup

SO(10) GUT in high-scale SUSY scenario

Predictions for Z' interaction

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4. Summary and Discussion

(DM models)

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:

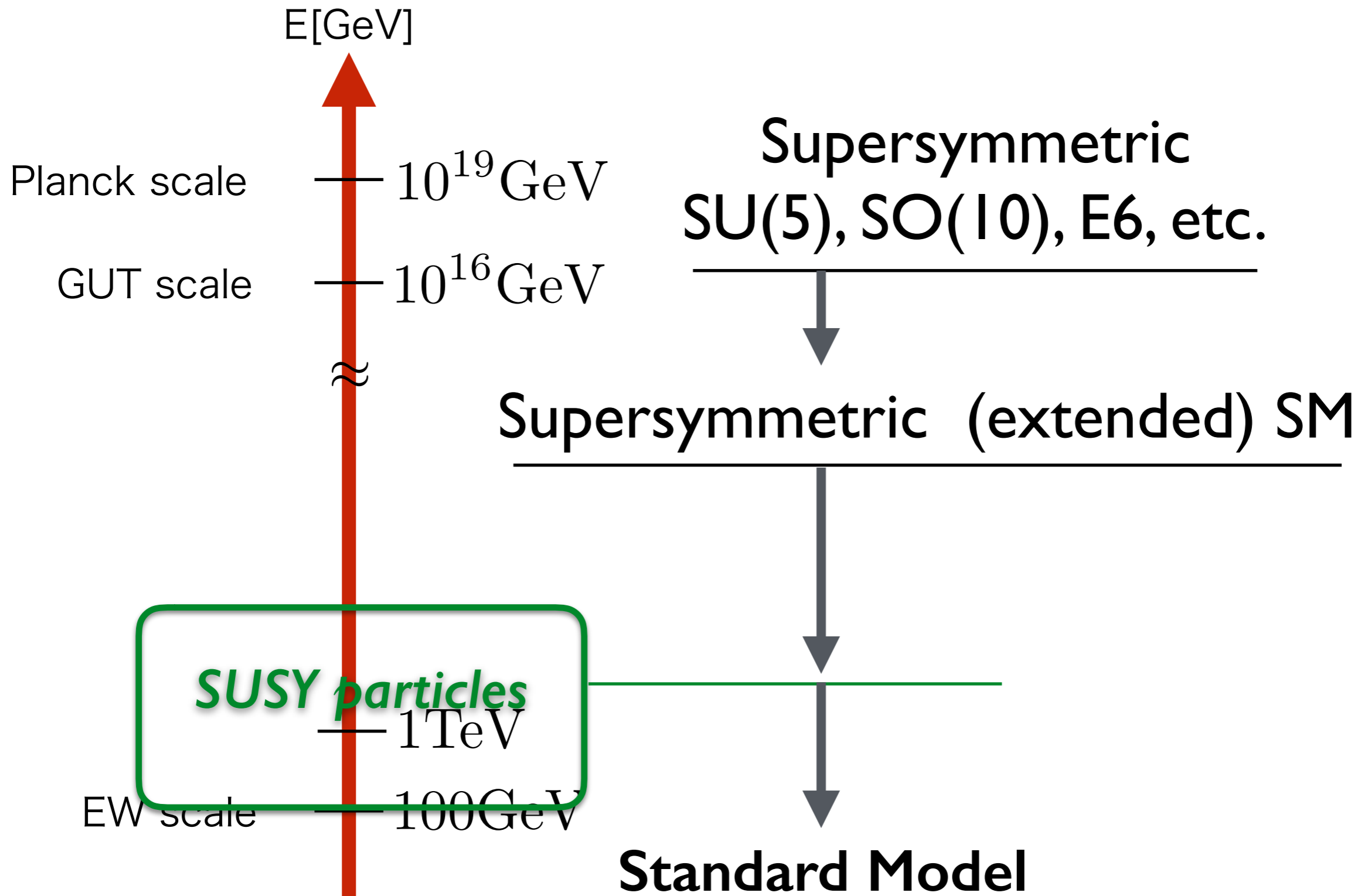
Origin of SM gauge groups

(Gauge coupling unification)

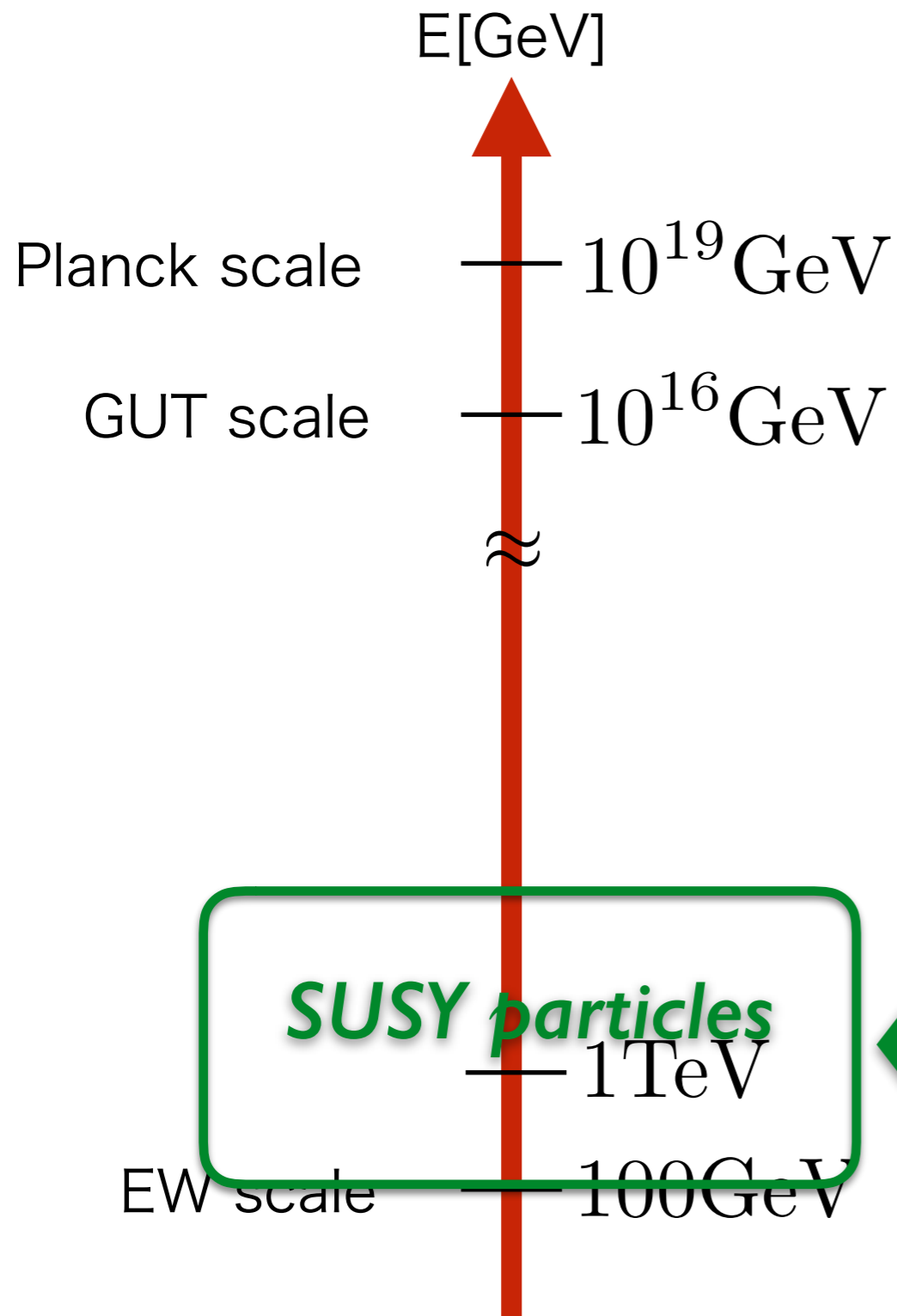
Origin of EW scale

Dark matter

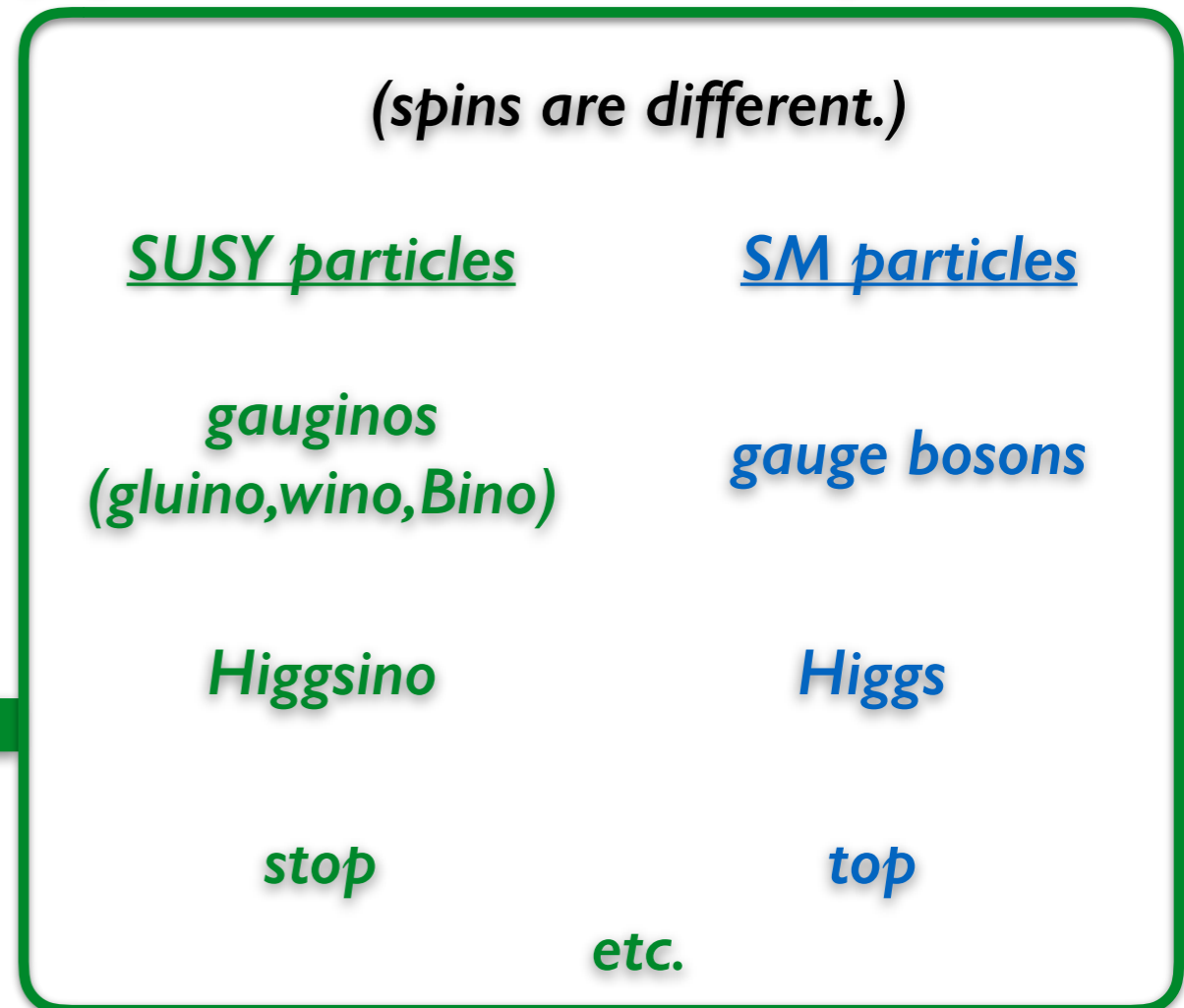
Typical scenario of SUSY GUT



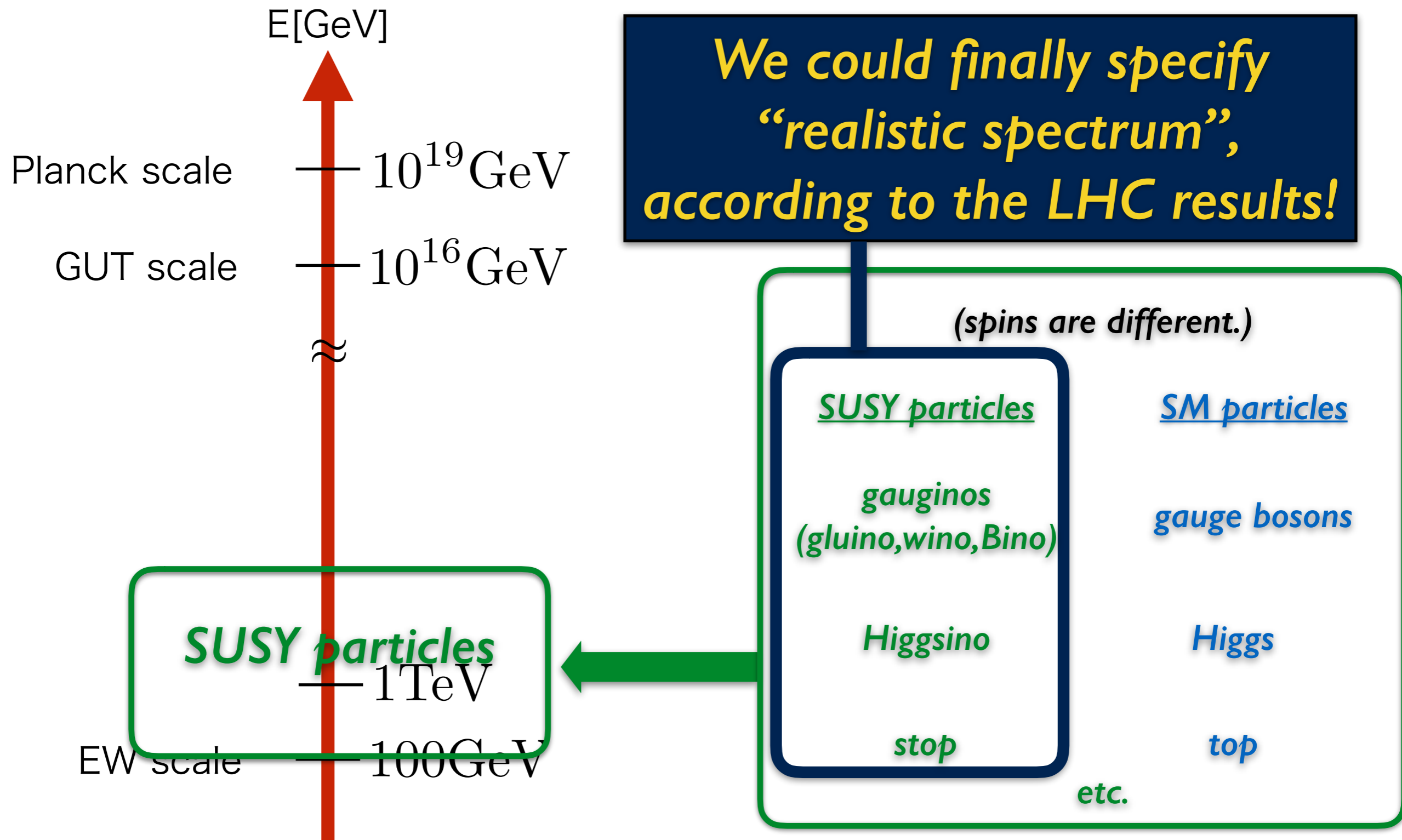
Typical scenario of SUSY GUT



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



Typical scenario of SUSY GUT



Relevant LHC results

Direct search at LHC

model-dependent but...

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

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

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

ATLAS SUSY Searches* - 95% CL Lower Limits
Status: Feb 2015

ATLAS Preliminary
 $\sqrt{s} = 7, 8 \text{ TeV}$

Model	$\epsilon, \mu, \tau, \gamma$	Jets	E_{T}^{miss}	$[L d](\text{fb}^{-1})$	Mass limit	Reference			
Include Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	\tilde{g}, \tilde{u}	$m(\tilde{g})=m(\tilde{u})$	1405.7875	
	$\tilde{g}, \tilde{q} \rightarrow q\tilde{q}^*$	0	2-6 jets	Yes	20.3	\tilde{g}, \tilde{q}	$m(\tilde{g}) > 0 \text{ GeV}, m(\tilde{q}) = m(\tilde{q}^*) = m(\tilde{q})$	1405.7875	
	$\tilde{g}, \tilde{q} \rightarrow q\tilde{q}^*$ (compressed)	1 γ	0-1 jet	Yes	20.3	\tilde{g}, \tilde{q}	$m(\tilde{g})=m(\tilde{q})=m(\tilde{q}^*)$	1411.1559	
	$\tilde{g}, \tilde{q} \rightarrow q\tilde{q}^*$	0	2-6 jets	Yes	20.3	\tilde{g}, \tilde{q}	$m(\tilde{g}) > 0 \text{ GeV}$	1405.7875	
	$\tilde{g}, \tilde{q} \rightarrow q\tilde{q}^*$	1 ϵ, μ	3-6 jets	Yes	20	\tilde{g}, \tilde{q}	$m(\tilde{g}) > 300 \text{ GeV}, m(\tilde{q}^*) = 0.5(m(\tilde{g}) + m(\tilde{q}))$	1501.03555	
	$\tilde{g}, \tilde{q} \rightarrow q\tilde{q}^*$	2 ϵ, μ	0-3 jets	Yes	20	\tilde{g}, \tilde{q}	$m(\tilde{g}) > 0 \text{ GeV}$	1501.03555	
	GMSB (\tilde{g} NLSP)	1.2 $\epsilon + 0.1 f$	0-2 jets	Yes	20.3	\tilde{g}, \tilde{q}	$\tan\beta > 20$	1407.0603	
	GGM (bino NLSP)	2 γ	-	Yes	20.3	\tilde{g}, \tilde{q}	$m(\tilde{g}) > 50 \text{ GeV}$	ATLAS-CONF-2012-001	
	GGM (wino NLSP)	1 $\epsilon, \mu + \gamma$	-	Yes	4.8	\tilde{g}, \tilde{q}	$m(\tilde{g}) > 50 \text{ GeV}$	ATLAS-CONF-2012-144	
	GGM (higgsino-bino NLSP)	7	1 b	Yes	4.8	\tilde{g}, \tilde{q}	$m(\tilde{g}) > 250 \text{ GeV}$	1211.1167	
$\tilde{g}, \tilde{q}, \tilde{q}^*$ ann. & prod.	GGM (higgsino NLSP)	2 $\epsilon, \mu (Z)$	0-3 jets	Yes	5.8	\tilde{g}, \tilde{q}	$m(\text{NLSP}) > 200 \text{ GeV}$	ATLAS-CONF-2012-152	
	Gravitino LSP	0	mono-jet	Yes	20.3	\tilde{g}, \tilde{q}	$m(\tilde{g}) > 1.8 \times 10^{-4} \text{ eV}, m(\tilde{q}) = m(\tilde{q}^*) = 1.5 \text{ TeV}$	1502.01518	
	$\tilde{g} \rightarrow \tilde{g}\tilde{g}^*$	0	3 b	Yes	20.1	\tilde{g}, \tilde{q}	$m(\tilde{g}) > 400 \text{ GeV}$	1407.0600	
	$\tilde{g} \rightarrow \tilde{g}\tilde{g}^*$	0	7-10 jets	Yes	20.3	\tilde{g}, \tilde{q}	$m(\tilde{g}) > 350 \text{ GeV}$	1308.1841	
	$\tilde{g} \rightarrow \tilde{g}\tilde{g}^*$	0-1 ϵ, μ	3 b	Yes	20.1	\tilde{g}, \tilde{q}	$m(\tilde{g}) > 400 \text{ GeV}$	1407.0600	
	$\tilde{g} \rightarrow \tilde{g}\tilde{g}^*$	0-1 ϵ, μ	3 b	Yes	20.1	\tilde{g}, \tilde{q}	$m(\tilde{g}) > 300 \text{ GeV}$	1407.0600	
	$\tilde{g}, \tilde{q}, \tilde{q}^*$ ann. & prod. direct	$\tilde{g}, \tilde{b}_1, \tilde{b}_1 \rightarrow \tilde{g}b\bar{b}$	0	2 b	Yes	20.1	\tilde{g}, \tilde{q}	$m(\tilde{g}) > 90 \text{ GeV}$	1308.2631
		$\tilde{g}, \tilde{b}_1, \tilde{b}_1 \rightarrow \tilde{g}b\bar{b}$	2 ϵ, μ (SS)	0-3 b	Yes	20.3	\tilde{g}, \tilde{q}	$m(\tilde{g}) > 2 m(\tilde{q})$	1404.2500
		$\tilde{g}, \tilde{b}_1, \tilde{b}_1 \rightarrow \tilde{g}b\bar{b}$	1.2 ϵ, μ	1-2 b	Yes	4.7	\tilde{g}, \tilde{q}	$m(\tilde{g}) > 2m(\tilde{q}), m(\tilde{q}) = 56 \text{ GeV}$	1209.2102, 1407.0583
		$\tilde{g}, \tilde{b}_1, \tilde{b}_1 \rightarrow W\tilde{b}\bar{b}$ or $\tilde{g}\tilde{b}\bar{b}$	2 ϵ, μ	0-2 jets	Yes	20.3	\tilde{g}, \tilde{q}	$m(\tilde{g}) > 1 \text{ GeV}$	1403.4853, 1412.4742
$\tilde{g}, \tilde{b}_1, \tilde{b}_1 \rightarrow \tilde{g}b\bar{b}$		0-1 ϵ, μ	1-2 b	Yes	20	\tilde{g}, \tilde{q}	$m(\tilde{g}) > 1 \text{ GeV}$	1407.0583, 1406.1122	
$\tilde{g}, \tilde{b}_1, \tilde{b}_1 \rightarrow \tilde{g}b\bar{b}$		0	mono-jet+tag	Yes	20.3	\tilde{g}, \tilde{q}	$m(\tilde{g}) = m(\tilde{q}) > 85 \text{ GeV}$	1407.0608	
$\tilde{g}, \tilde{b}_1, \tilde{b}_1 \rightarrow \tilde{g}b\bar{b}$		2 $\epsilon, \mu (Z)$	1 b	Yes	20.3	\tilde{g}, \tilde{q}	$m(\tilde{g}) > 150 \text{ GeV}$	1403.5222	
$\tilde{g}, \tilde{b}_1, \tilde{b}_1 \rightarrow \tilde{g}b\bar{b}$		3 $\epsilon, \mu (Z)$	1 b	Yes	20.3	\tilde{g}, \tilde{q}	$m(\tilde{g}) > 200 \text{ GeV}$	1403.5222	
EW direct		$\tilde{g}, \tilde{g}, \tilde{g} \rightarrow \tilde{g}\tilde{g}\tilde{g}$	2 ϵ, μ	0	Yes	20.3	\tilde{g}, \tilde{q}	$m(\tilde{g}) > 0 \text{ GeV}$	1403.5294
		$\tilde{g}, \tilde{g}, \tilde{g} \rightarrow \tilde{g}\tilde{g}\tilde{g}$	2 ϵ, μ	0	Yes	20.3	\tilde{g}, \tilde{q}	$m(\tilde{g}) > 0 \text{ GeV}, m(\tilde{q}) = 0.5(m(\tilde{g}) + m(\tilde{q}))$	1403.5294
	$\tilde{g}, \tilde{g}, \tilde{g} \rightarrow \tilde{g}\tilde{g}\tilde{g}$	2 τ	-	Yes	20.3	\tilde{g}, \tilde{q}	$m(\tilde{g}) > 0 \text{ GeV}, m(\tilde{q}) = 0.5(m(\tilde{g}) + m(\tilde{q}))$	1407.0350	
	$\tilde{g}, \tilde{g}, \tilde{g} \rightarrow \tilde{g}\tilde{g}\tilde{g}$	3 ϵ, μ	0	Yes	20.3	\tilde{g}, \tilde{q}	$m(\tilde{g}) > 0 \text{ GeV}, m(\tilde{q}) = 0.5(m(\tilde{g}) + m(\tilde{q}))$	1402.7029	
	$\tilde{g}, \tilde{g}, \tilde{g} \rightarrow W\tilde{g}\tilde{g}$	2-3 ϵ, μ	0-2 jets	Yes	20.3	\tilde{g}, \tilde{q}	$m(\tilde{g}) = m(\tilde{q}), m(\tilde{q}) > 0, \text{ sleptons decoupled}$	1403.5294, 1402.7029	
	$\tilde{g}, \tilde{g}, \tilde{g} \rightarrow W\tilde{g}\tilde{g}$	ϵ, μ, γ	0-2 b	Yes	20.3	\tilde{g}, \tilde{q}	$m(\tilde{g}) = m(\tilde{q}), m(\tilde{q}) > 0, \text{ sleptons decoupled}$	1501.07110	
	$\tilde{g}, \tilde{g}, \tilde{g} \rightarrow W\tilde{g}\tilde{g}$	4 ϵ, μ	0	Yes	20.3	\tilde{g}, \tilde{q}	$m(\tilde{g}) = m(\tilde{q}), m(\tilde{q}) > 0, m(\tilde{q}) = 0.5(m(\tilde{g}) + m(\tilde{q}))$	1405.5086	
	Long-lived particles	Direct $\tilde{g}, \tilde{g} \rightarrow \tilde{g}\tilde{g}$ prod., long-lived \tilde{g}	Disapp. trk	1 jet	Yes	20.3	\tilde{g}, \tilde{q}	$m(\tilde{g}) = m(\tilde{q}) = 160 \text{ MeV}, \tau(\tilde{g}) > 0.2 \text{ ns}$	1310.3675
		Stable \tilde{g} R-hadron	0	1-5 jets	Yes	27.9	\tilde{g}, \tilde{q}	$m(\tilde{g}) > 100 \text{ GeV}, 10 \mu\text{s} < \tau(\tilde{g}) < 1000 \text{ s}$	1310.6584
		GMSB, stable $\tilde{g}, \tilde{q} \rightarrow \tilde{g}\tilde{q}\tilde{q}^*$	1 $\mu, \text{ disp. vtx}$	-	-	19.1	\tilde{g}, \tilde{q}	$10^{-10} < \tau < 50$	1411.6795
GMSB, $\tilde{g}, \tilde{q} \rightarrow \tilde{g}\tilde{q}\tilde{q}^*$, long-lived \tilde{g}		2 γ	-	Yes	20.3	\tilde{g}, \tilde{q}	$2 \times 10^{-17} < \tau < 3 \text{ ns}, \text{ SPSB model}$	1409.5542	
$\tilde{g}, \tilde{q} \rightarrow \tilde{g}\tilde{q}\tilde{q}^*$ (RPV)		1 $\mu, \text{ disp. vtx}$	-	-	20.3	\tilde{g}, \tilde{q}	$1.5 \times 10^{-15} < \tau < 156 \text{ ns}, \text{ BR}(\tilde{g}) = 1, m(\tilde{g}) = 108 \text{ GeV}$	ATLAS-CONF-2013-092	
LFV $\tilde{g}\tilde{g} \rightarrow \tilde{g}\tilde{g} + X, \tilde{q}\tilde{q} \rightarrow \tilde{q}\tilde{q} + \mu$		2 ϵ, μ	-	-	4.6	\tilde{g}, \tilde{q}	$A_{111} = 0.10, A_{122} = 0.05$	1212.1272	
LFV $\tilde{g}\tilde{g} \rightarrow \tilde{g}\tilde{g} + X, \tilde{q}\tilde{q} \rightarrow \tilde{q}\tilde{q} + \tau$		1 $\epsilon, \mu + \tau$	-	-	4.6	\tilde{g}, \tilde{q}	$A_{111} = 0.10, A_{122} = 0.05$	1212.1272	
Bilinear RPV CMSSM		2 ϵ, μ (SS)	0-3 b	Yes	20.3	\tilde{g}, \tilde{q}	$m(\tilde{g}) = m(\tilde{q}), \tau_{\tilde{g}} > 1 \text{ mm}$	1404.2500	
$\tilde{g}, \tilde{g}, \tilde{g} \rightarrow W\tilde{g}\tilde{g}$		4 ϵ, μ	-	Yes	20.3	\tilde{g}, \tilde{q}	$m(\tilde{g}) > 2.2m(\tilde{q}), A_{111} = 0$	1405.5086	
$\tilde{g}, \tilde{g}, \tilde{g} \rightarrow W\tilde{g}\tilde{g}$		3 $\epsilon, \mu + \tau$	-	Yes	20.3	\tilde{g}, \tilde{q}	$m(\tilde{g}) > 0.2m(\tilde{q}), A_{111} = 0$	1405.5086	
RPV	$\tilde{g} \rightarrow \tilde{g}\tilde{g}$	0	6-7 jets	-	20.3	\tilde{g}, \tilde{q}	$\text{BR}(\tilde{g}) = \text{BR}(\tilde{q}) = \text{BR}(\tilde{q}^*) = 0\%$	ATLAS-CONF-2013-091	
	$\tilde{g} \rightarrow \tilde{g}\tilde{g}$	2 ϵ, μ (SS)	0-3 b	Yes	20.3	\tilde{g}, \tilde{q}	$m(\tilde{g}) > 200 \text{ GeV}$	1404.2500	
Other	Scalar charm, $\tilde{c} \rightarrow \tilde{c}\tilde{c}^*$	0	2 c	Yes	20.3	\tilde{g}, \tilde{q}	$m(\tilde{c}) > 200 \text{ GeV}$	1501.01325	

*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1 σ theoretical signal cross section uncertainty.

Relevant LHC results

Direct search at LHC

model-dependent but...

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

ATLAS SUSY Searches* - 95% CL Lower Limits
Status: Feb 2015

ATLAS Preliminary
 $\sqrt{s} = 7, 8 \text{ TeV}$

Model	e, μ, τ, γ	Jets	L_{miss}	$[L dt/dt^{-1}]$	Mass limit	Reference
MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	850 GeV	1405.7875
$\tilde{g}, \tilde{q} \rightarrow q\tilde{g}$	0	2-6 jets	Yes	20.3	250 GeV	1405.7875
$\tilde{g}, \tilde{q} \rightarrow q\tilde{g}$ (compressed)	1, \gamma	0-1 jet	Yes	20.3	1.33 TeV	1411.1559
$\tilde{g}, \tilde{q} \rightarrow q\tilde{g}$	0	2-6 jets	Yes	20.3	1.32 TeV	1405.7875
$\tilde{g}, \tilde{q} \rightarrow q\tilde{g}$	1, \mu, \tau	3-6 jets	Yes	20	1.2 TeV	1501.03555
$\tilde{g}, \tilde{q} \rightarrow q\tilde{g}$	2, \mu, \tau	0-3 jets	Yes	20	1.32 TeV	1501.03555
GMSB (\tilde{g} NLSP)	1, 2, \mu + 0, 1, \tau	0-2 jets	Yes	20.3	1.8 TeV	1407.0603
GGM (bino NLSP)	2, \gamma	-	Yes	20.3	1.28 TeV	1407.0603
GGM (wino NLSP)	1, \mu, \tau + \gamma	-	Yes	4.8	619 GeV	ATLAS-CONF-2014-001
GGM (higgsino-bino NLSP)	2, \mu, \tau	1, b	Yes	4.8	900 GeV	ATLAS-CONF-2012-144
GGM (higgsino NLSP)	2, \mu, \tau (Z)	0-3 jets	Yes	5.8	690 GeV	ATLAS-CONF-2012-152
Gravitino LSP	0	mono-jet	Yes	20.3	855 GeV	1502.01518
$\tilde{g} \rightarrow \tilde{g}\tilde{g}$	0	3, b	Yes	20.1	1.25 TeV	1407.0600
$\tilde{g} \rightarrow \tilde{g}\tilde{g}$	0	7-10 jets	Yes	20.3	1.1 TeV	1308.1841
$\tilde{g} \rightarrow \tilde{g}\tilde{g}$	0-1, \mu, \tau	3, b	Yes	20.1	1.34 TeV	1407.0600
$\tilde{g} \rightarrow \tilde{g}\tilde{g}$	0-1, \mu, \tau	3, b	Yes	20.1	1.3 TeV	1407.0600
$\tilde{t}_1, \tilde{b}_1 \rightarrow \tilde{t}_1\tilde{b}_1$	0	2, b	Yes	20.1	100-520 GeV	1308.2631
$\tilde{t}_1, \tilde{b}_1 \rightarrow \tilde{t}_1\tilde{b}_1$	2, \mu, \tau (SS)	0-3, b	Yes	20.3	275-440 GeV	1404.2500
$\tilde{t}_1, \tilde{b}_1 \rightarrow \tilde{t}_1\tilde{b}_1$	1, 2, \mu, \tau	1-2, b	Yes	4.7	110-167 GeV	1209.2100, 1407.0583
$\tilde{t}_1, \tilde{b}_1 \rightarrow W\tilde{t}_1^* \text{ or } \tilde{b}_1^*$	2, \mu, \tau	0-2 jets	Yes	20.3	90-191 GeV	1403.4853, 1412.4742
$\tilde{t}_1, \tilde{b}_1 \rightarrow \tilde{t}_1\tilde{b}_1$	1, 2, \mu, \tau	1-2, b	Yes	20	215-530 GeV	1407.0583, 1406.1122
$\tilde{t}_1, \tilde{b}_1 \rightarrow \tilde{t}_1\tilde{b}_1$	0-1, \mu, \tau	1-2, b	Yes	20	210-540 GeV	1407.0608
$\tilde{t}_1, \tilde{b}_1 \rightarrow \tilde{t}_1\tilde{b}_1$	0	mono-jet+tag	Yes	20.3	90-240 GeV	1407.0608
\tilde{t}_1, \tilde{b}_1 (natural GMSB)	2, \mu, \tau (Z)	1, b	Yes	20.3	150-580 GeV	1403.5222
$\tilde{t}_1, \tilde{b}_1 \rightarrow \tilde{t}_1\tilde{b}_1 + Z$	3, \mu, \tau (Z)	1, b	Yes	20.3	290-600 GeV	1403.5222
$\tilde{t}_1, \tilde{b}_1 \rightarrow \tilde{t}_1\tilde{b}_1$	2, \mu, \tau	0	Yes	20.3	90-325 GeV	1403.5294
$\tilde{t}_1, \tilde{b}_1 \rightarrow \tilde{t}_1\tilde{b}_1$	2, \mu, \tau	0	Yes	20.3	140-465 GeV	1403.5294
$\tilde{t}_1, \tilde{b}_1 \rightarrow \tilde{t}_1\tilde{b}_1$	2, \tau	-	Yes	20.3	100-350 GeV	1407.0350
$\tilde{t}_1, \tilde{b}_1 \rightarrow \tilde{t}_1\tilde{b}_1$	3, \mu, \tau	0	Yes	20.3	700 GeV	1402.7029
$\tilde{t}_1, \tilde{b}_1 \rightarrow W\tilde{t}_1^* \text{ or } \tilde{b}_1^*$	2, 3, \mu, \tau	0-2 jets	Yes	20.3	420 GeV	1403.5294, 1402.7029
$\tilde{t}_1, \tilde{b}_1 \rightarrow W\tilde{t}_1^* \text{ or } \tilde{b}_1^*$	\mu, \tau, \gamma	0-2, b	Yes	20.3	250 GeV	1501.07110
$\tilde{t}_1, \tilde{b}_1 \rightarrow W\tilde{t}_1^* \text{ or } \tilde{b}_1^*$	4, \mu, \tau	0	Yes	20.3	620 GeV	1501.07110
Direct \tilde{t}_1, \tilde{b}_1 prod., long-lived \tilde{t}_1	Disapp. trk	1 jet	Yes	20.3	270 GeV	1310.3675
Stable, stopped \tilde{g} R-hadron	0	1-5 jets	Yes	27.9	832 GeV	1310.6584
Stable \tilde{g} R-hadron	1, \mu, \tau	-	-	19.1	1.27 TeV	1411.6795
GMSB, stable $\tilde{t}_1, \tilde{b}_1 \rightarrow \tilde{t}_1\tilde{b}_1 + \mu, \tau$	1, 2, \mu, \tau	-	-	19.1	537 GeV	1411.6795
GMSB, \tilde{t}_1, \tilde{b}_1 long-lived \tilde{t}_1	2, \gamma	-	Yes	20.3	435 GeV	1409.5542
$\tilde{g}, \tilde{q} \rightarrow q\tilde{g}$ (RPV)	1, \mu, \tau, \nu\tau	-	-	20.3	1.0 TeV	ATLAS-CONF-2013-092
LFV $p\bar{p} \rightarrow \nu + X, \nu_i \rightarrow \nu_j + \mu$	2, \mu, \tau	-	-	4.6	1.61 TeV	1212.1272
LFV $p\bar{p} \rightarrow \nu + X, \nu_i \rightarrow \nu_j + \mu + \tau$	1, \mu, \tau	-	-	4.6	1.1 TeV	1212.1272
Bilinear RPV CMSSM	2, \mu, \tau (SS)	0-3, b	Yes	20.3	790 GeV	1404.2500
$\tilde{t}_1, \tilde{b}_1 \rightarrow \tilde{t}_1\tilde{b}_1$	4, \mu, \tau	-	Yes	20.3	450 GeV	1405.5086
$\tilde{t}_1, \tilde{b}_1 \rightarrow \tilde{t}_1\tilde{b}_1$	3, \mu, \tau	-	Yes	20.3	790 GeV	1405.5086
$\tilde{g} \rightarrow \tilde{g}\tilde{g}$	0	6-7 jets	-	20.3	916 GeV	ATLAS-CONF-2013-091
$\tilde{g} \rightarrow \tilde{g}\tilde{g}$	2, \mu, \tau (SS)	0-3, b	Yes	20.3	850 GeV	1404.2500
Scalar charm $\tilde{c} \rightarrow \tilde{c}\tilde{c}$	0	2, c	Yes	20.3	490 GeV	1501.01325

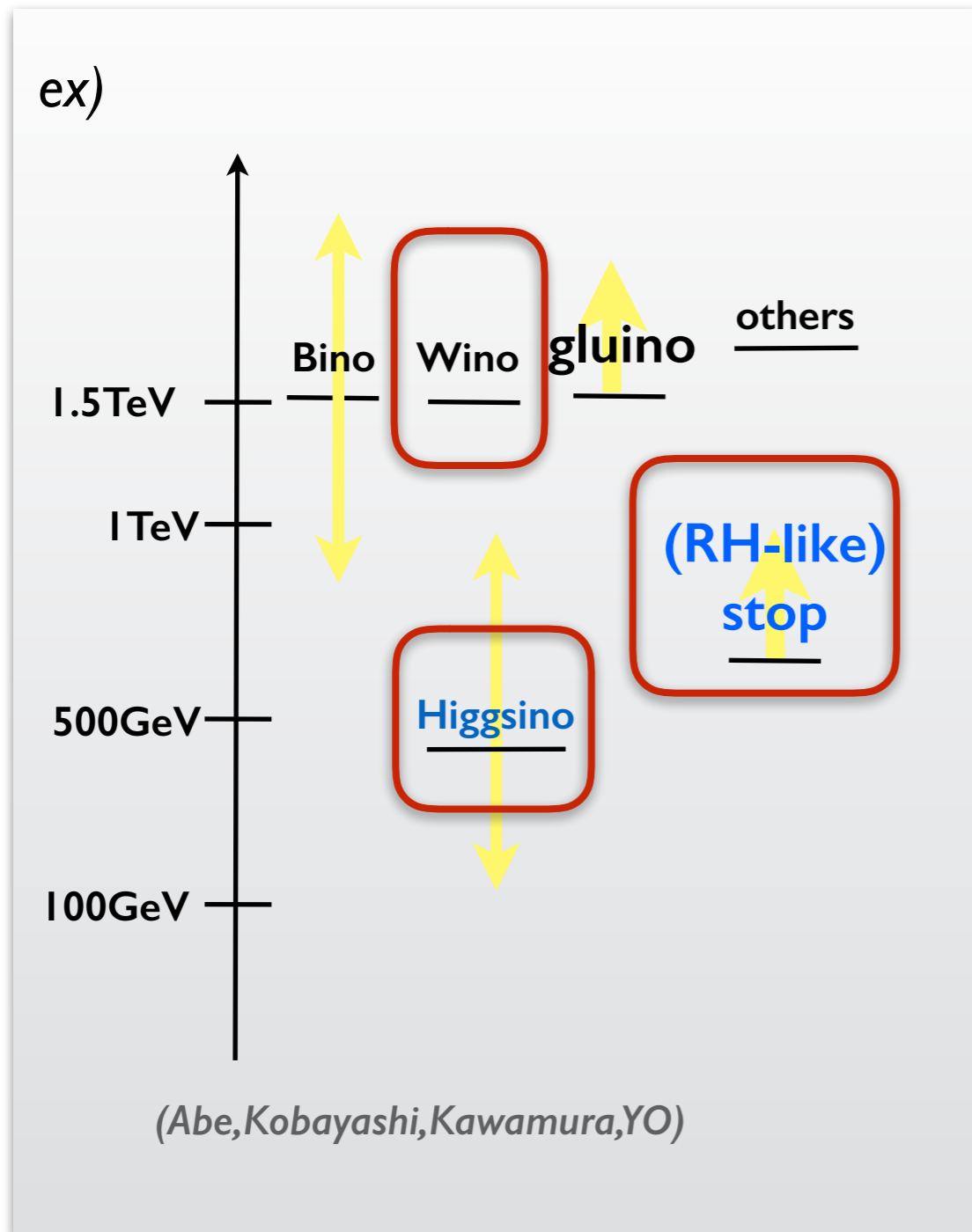
Many scenarios excluded!!

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.*

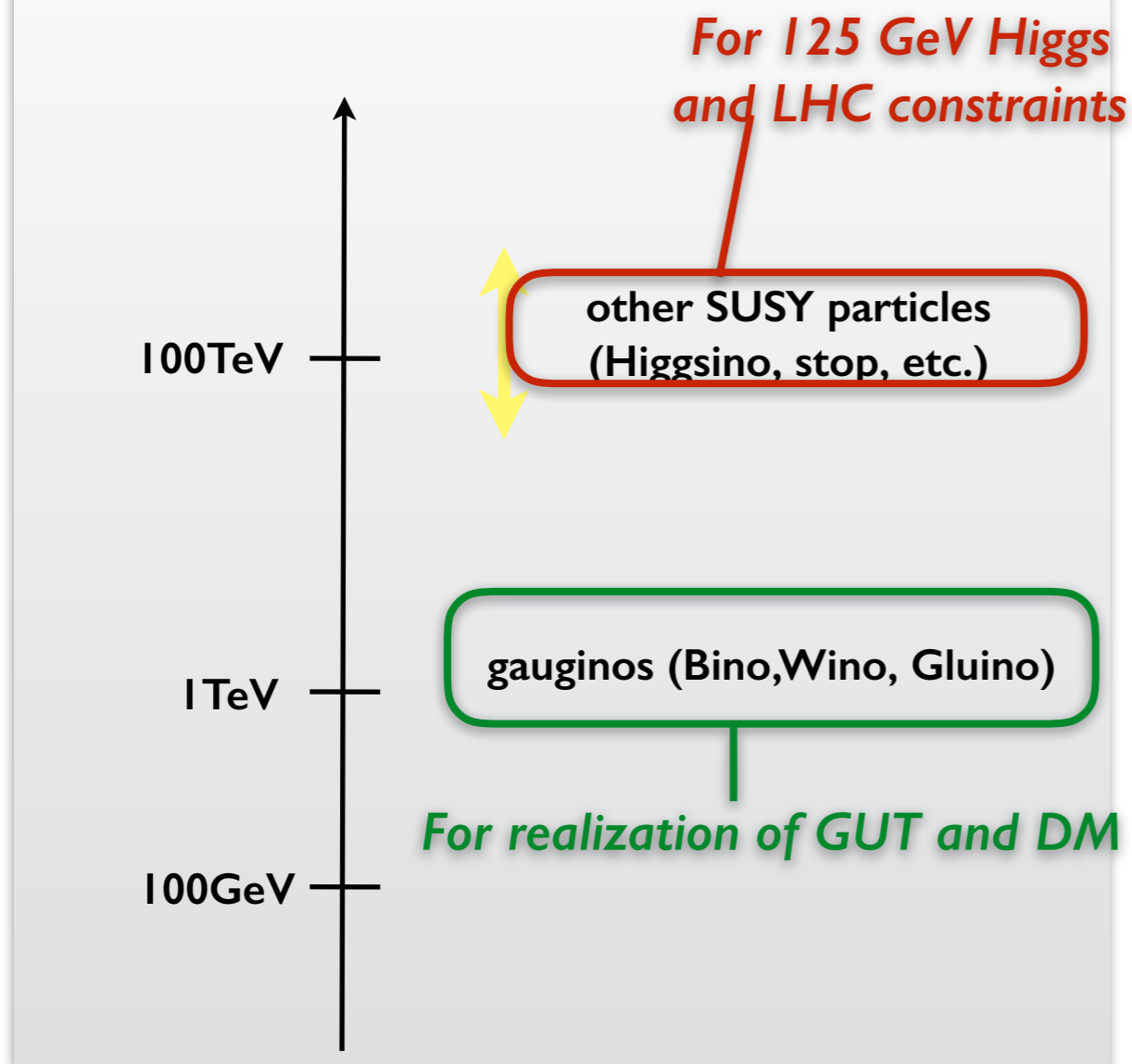
→ No fine-tuning in Higgs potential.

“Naturally EW scale is realized!”

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

Another possible spectrum is

High-scale SUSY (Split SUSY)



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

Big hierarchy between Higgsino and EW scale.

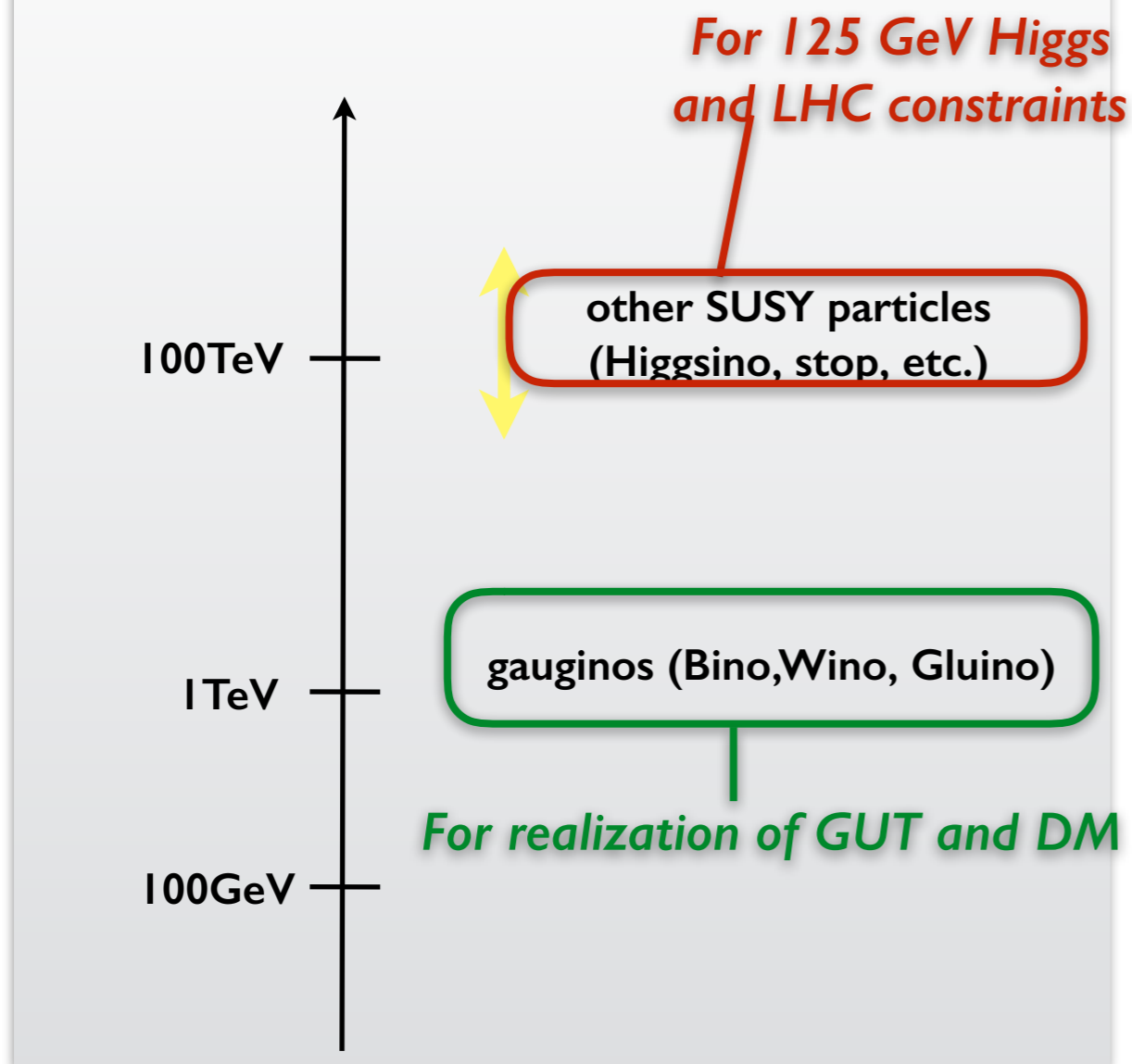
→ Require fine-tuning in Higgs potential

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

(Arkani-Hamed, Dimopoulos, 04'; Giudice, Romanino 04';
Cabrera, Casas, Delgado, 11'; Giudice, Strumia, 11'; Hall, Nomura, 11';
Arkani-Hamed, Gupta, et al, 12'; Ibe, Matsumoto, Yanagida, 12';
Hisano, Kuwahara, Nagata, 13';
Hisano, Muramatsu, Shigekami, YO, Yamanaka, 14', 16'; etc..)

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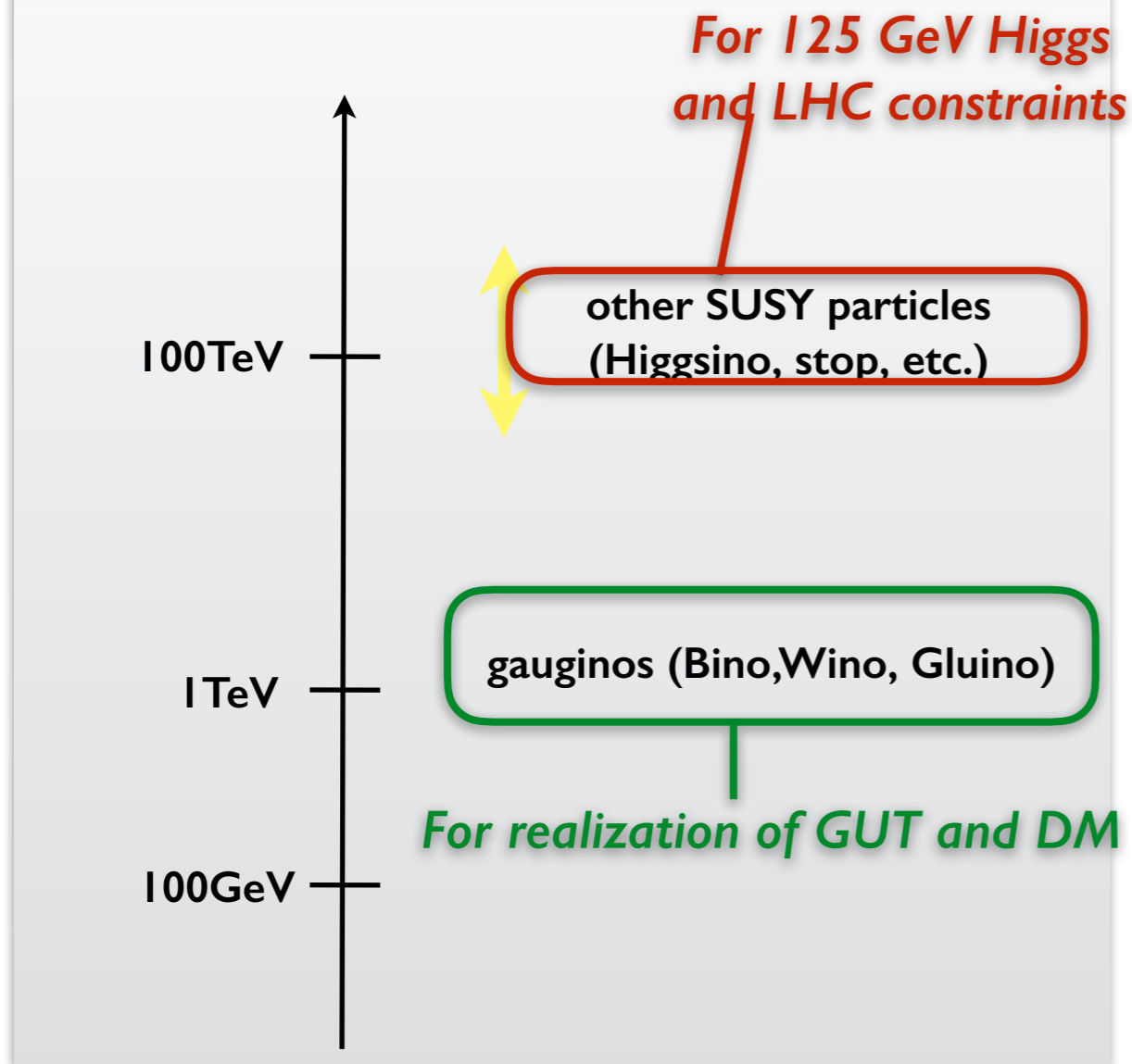
“The EW scale is given by the very fine-tuning!”

How can we prove this kind of scenario?

(Arkani-Hamed, Dimopoulos, 04'; Giudice, Romanino 04';
Cabrera, Casas, Delgado, 11'; Giudice, Strumia, 11'; Hall, Nomura, 11';
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→ Require *fine-tuning* in Higgs potential

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

How can we prove this kind of scenario?


→ We propose *flavor physics* in this talk!

(Arkani-Hamed, Dimopoulos, 04'; Giudice, Romanino 04';
Cabrera, Casas, Delgado, 11'; Giudice, Strumia, 11'; Hall, Nomura, 11';
Arkani-Hamed, Gupta, et al, 12'; Ibe, Matsumoto, Yanagida, 12';
Hisano, Kuwahara, Nagata, 13';
Hisano, Muramatsu, Shigekami, YO, Yamanaka, 14', 16'; etc..)

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!**

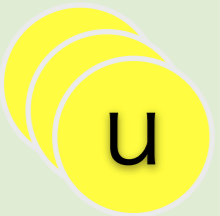
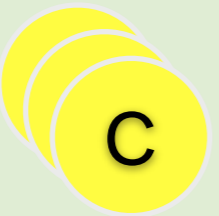
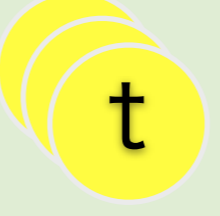
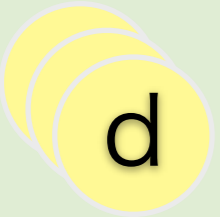
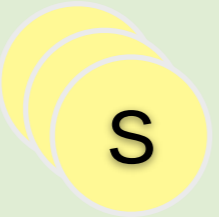
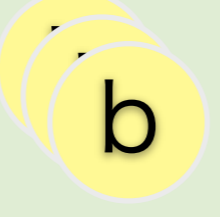
Setup

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

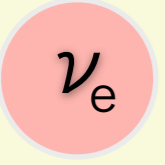
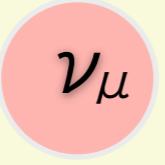



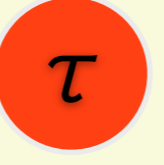
spin-1/2

quarks $SU(3)_c$ -charged

EM-charge


			$+2/3$
			$-1/3$

leptons


			0
			-1


spin-1

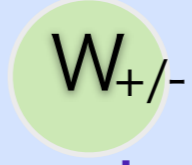
$SU(3)_c$ gauge

 gluon

$SU(2)_L \times U(1)_Y$

 massive


 photon

 massive

carry forces

spin-0

Higgs

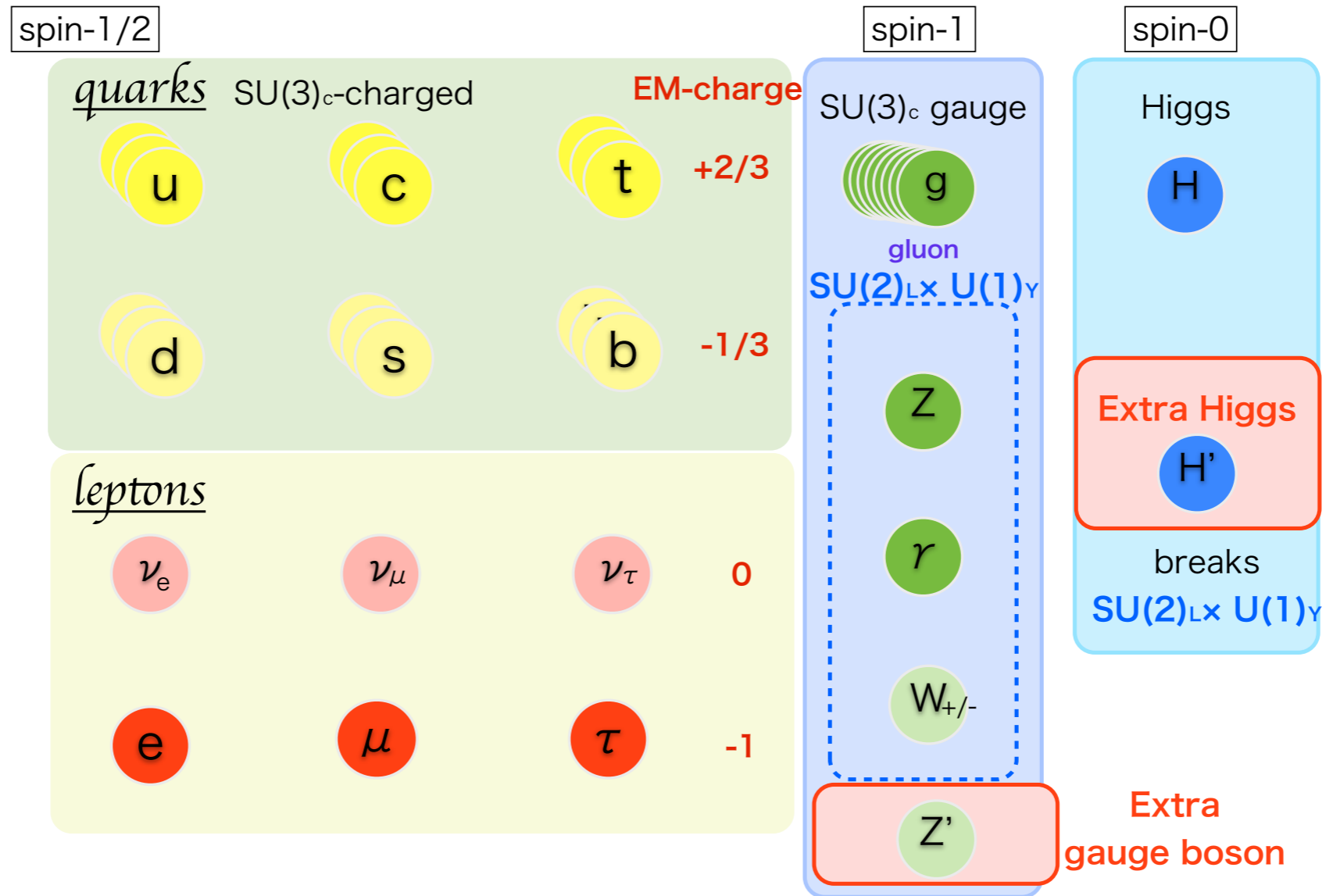


breaks $SU(2)_L \times U(1)_Y$

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

extra

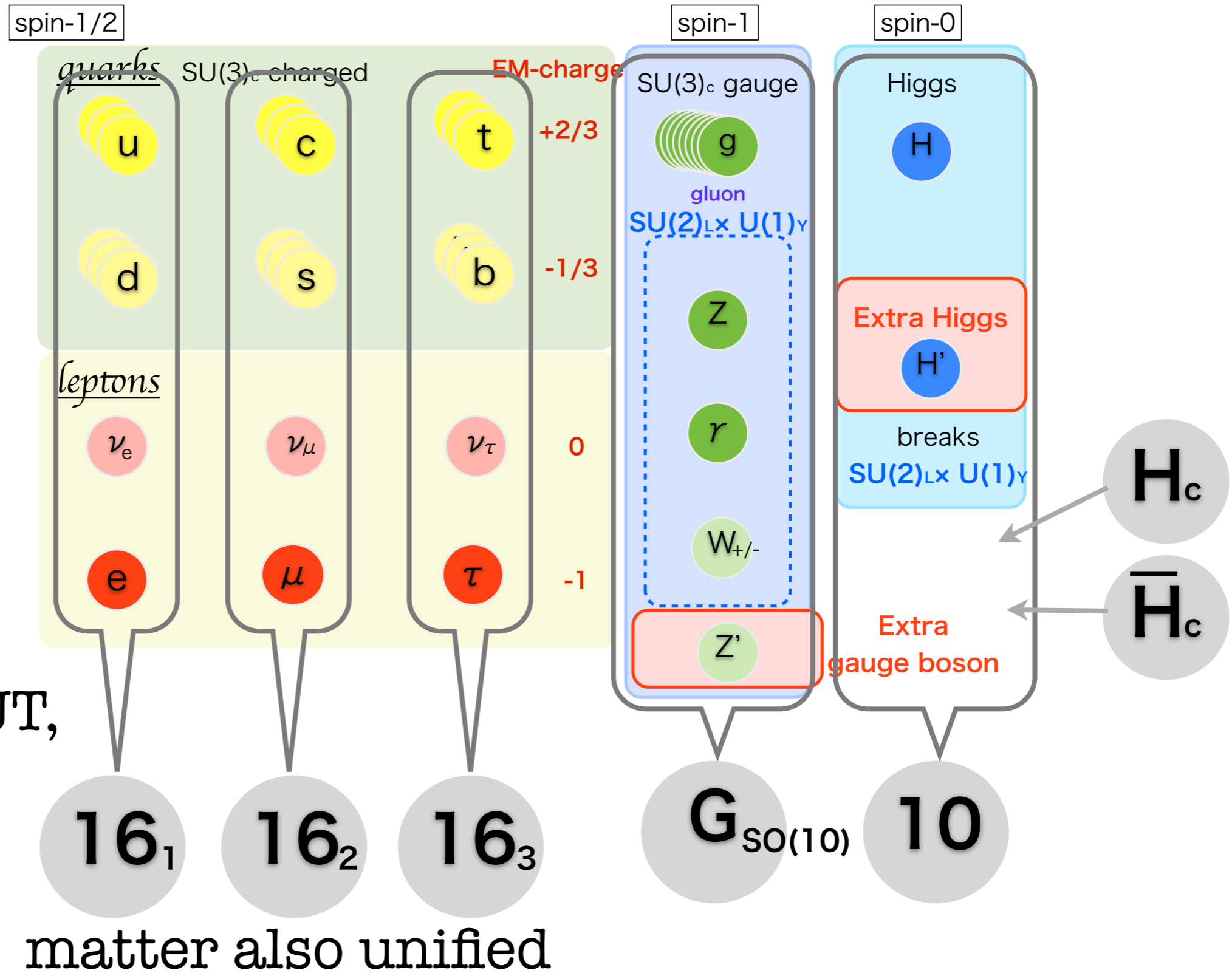
slightly extended SM



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

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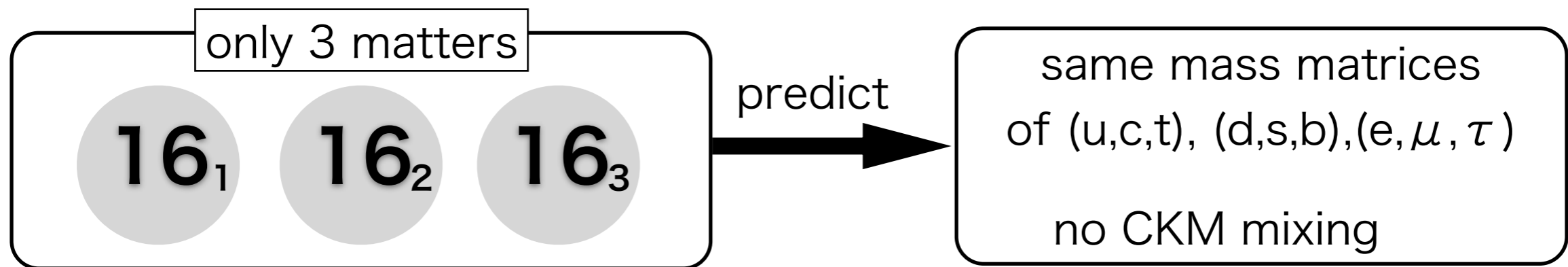
slightly extended SM



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.



Couplings for Mass matrices are

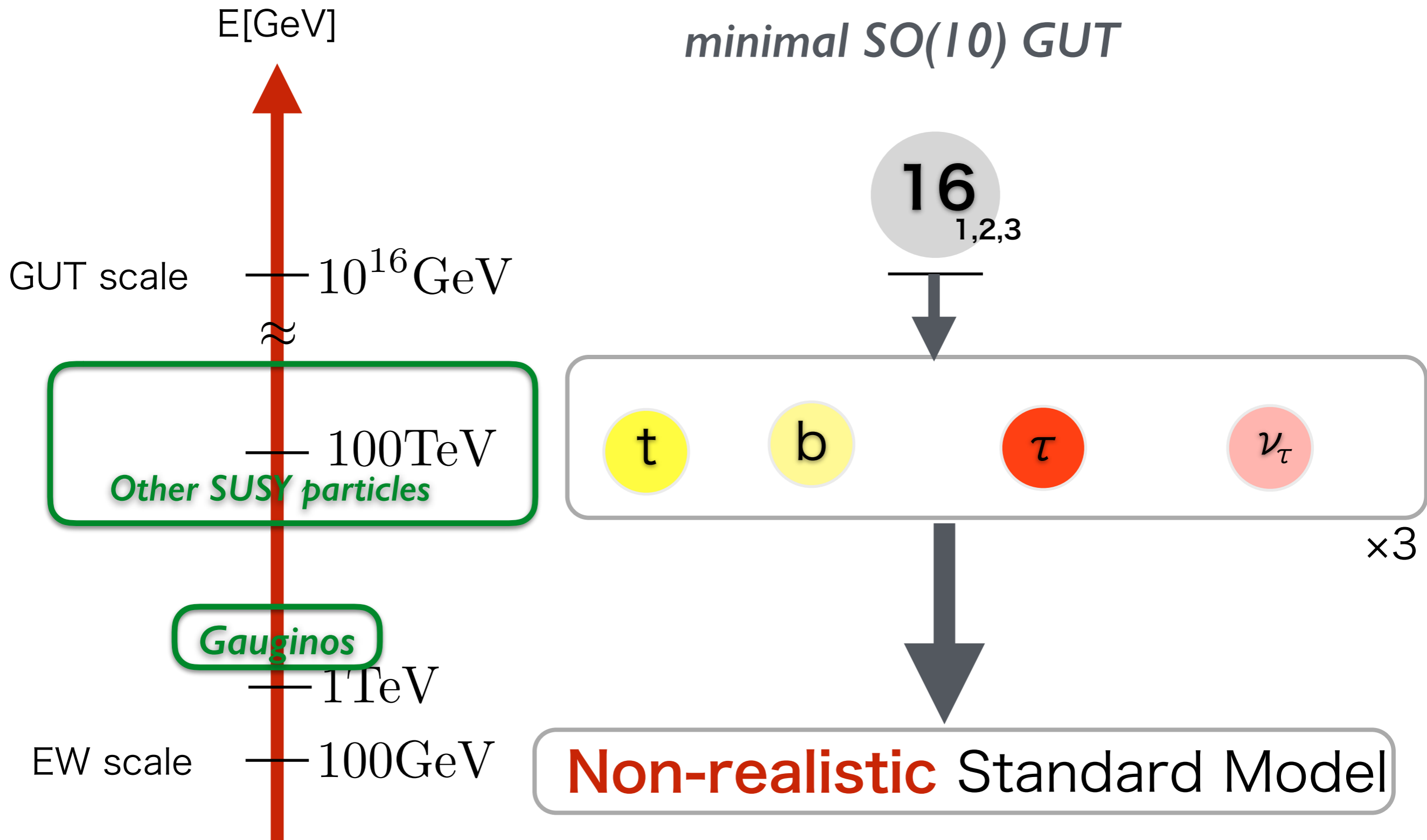
$$y_{ij} \mathbf{16}^i \mathbf{16}^j \mathbf{10}_H \quad \rightarrow \quad y_{ij}^u Q_L^i U_R^{c j} H_u + y_{ij}^d Q_L^i D_R^{c j} H_d + y_{ij}^l L^i E_R^{c j} H_d$$

can be diagonalized

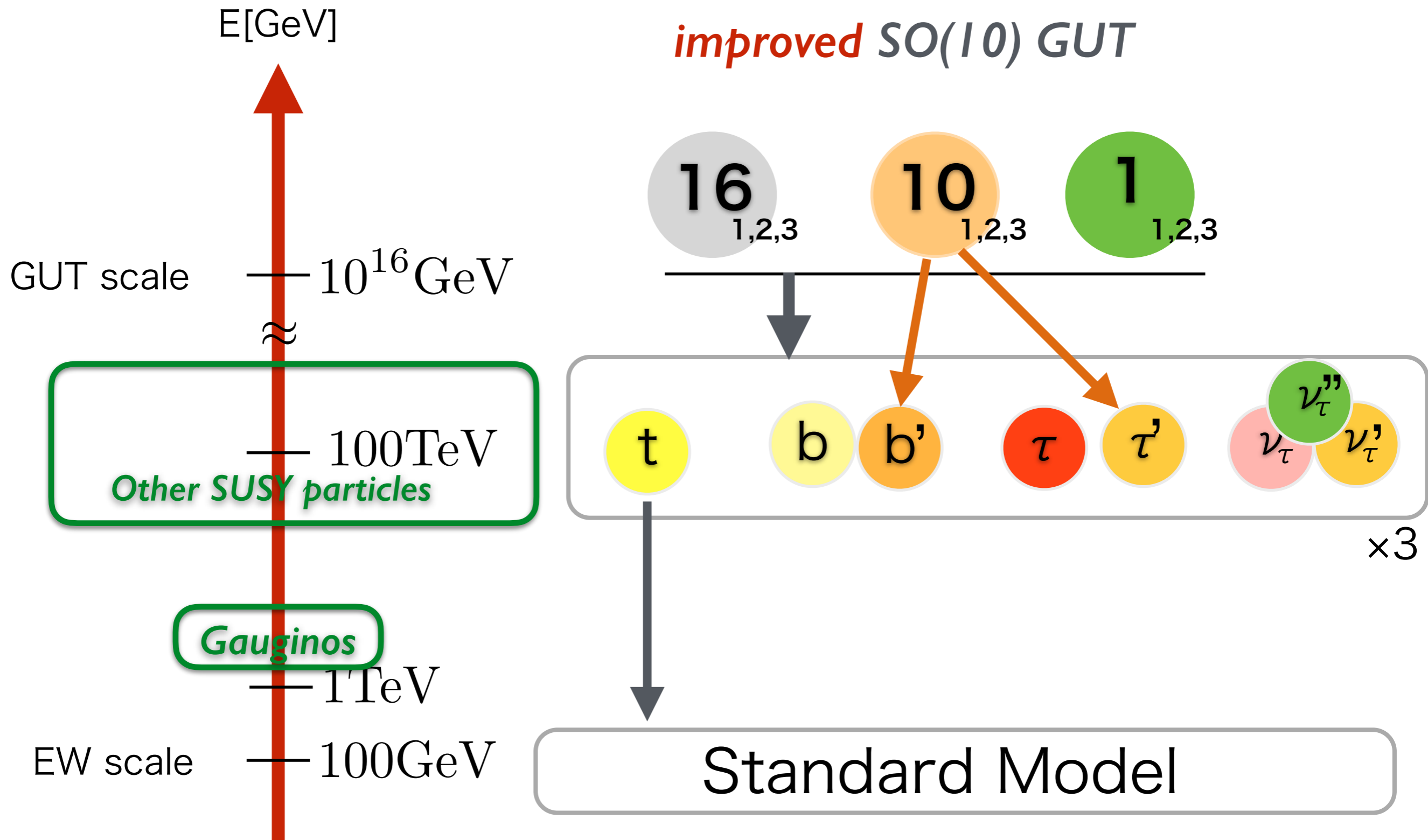
same structures of Yukawa (Mass matrices)

$$y_{ij}^u = \frac{m_i^u}{v \sin \beta} \delta_{ij} \approx y_{ij}^d \approx y_{ij}^l$$

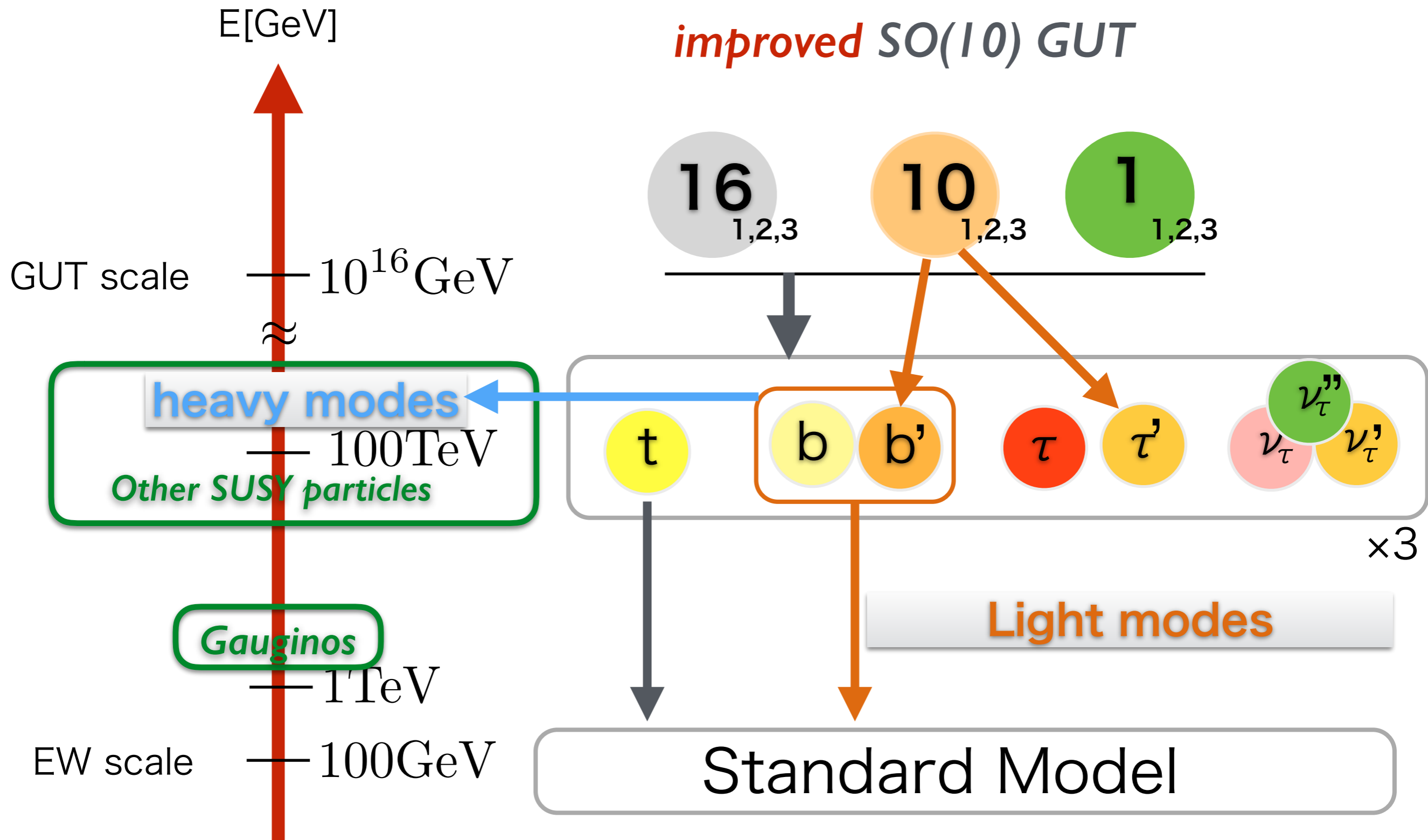
Rough sketch of our scenario



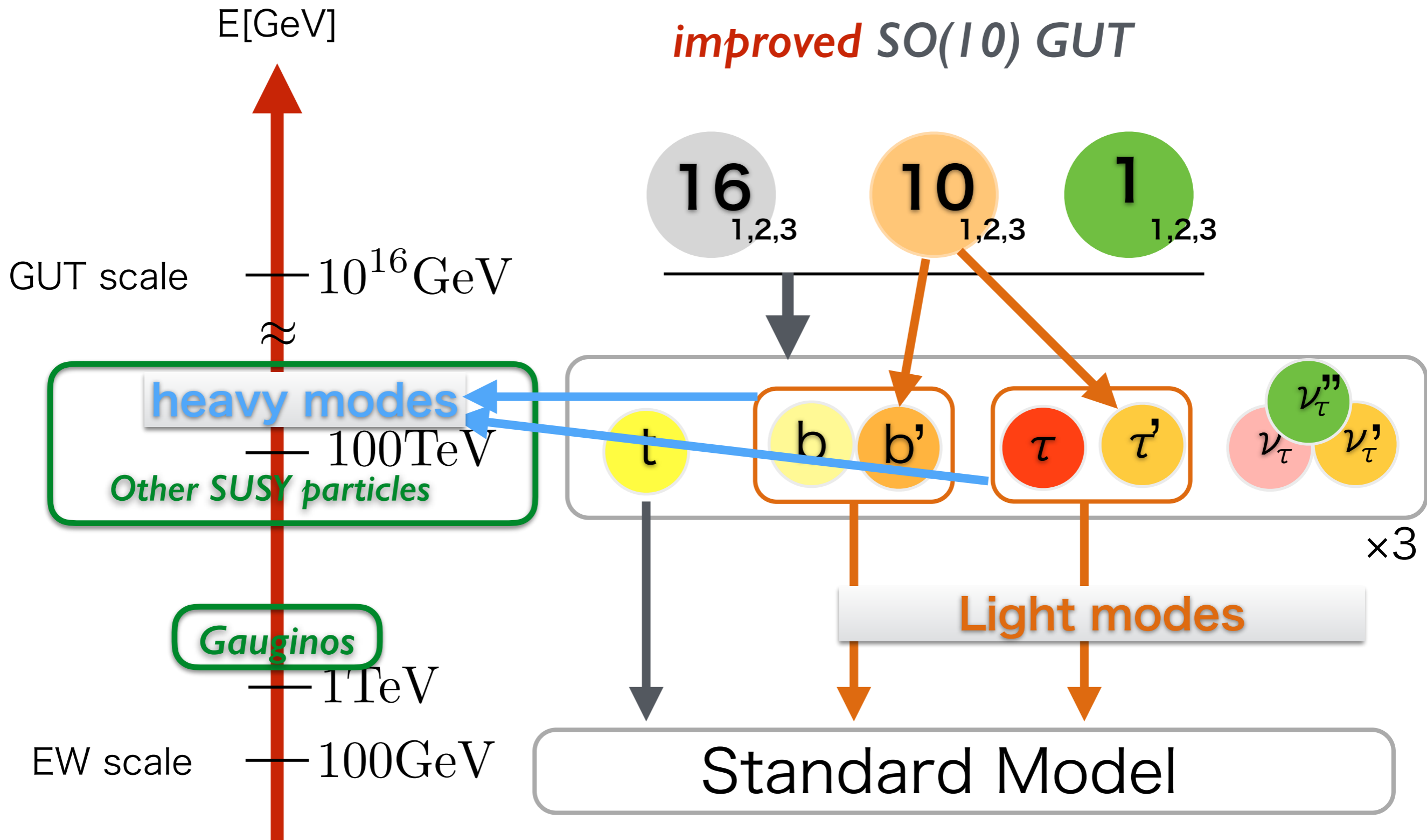
Rough sketch of our scenario



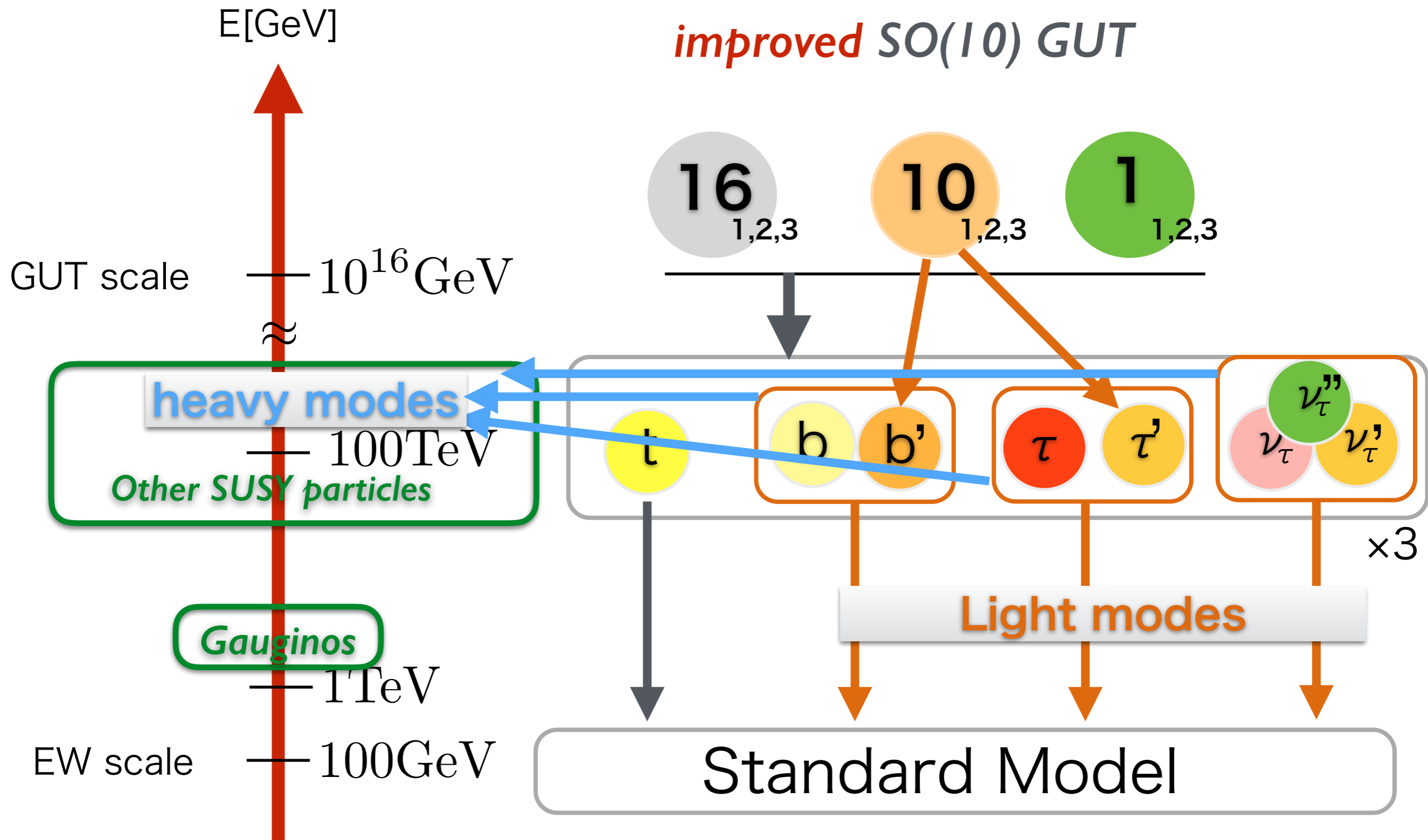
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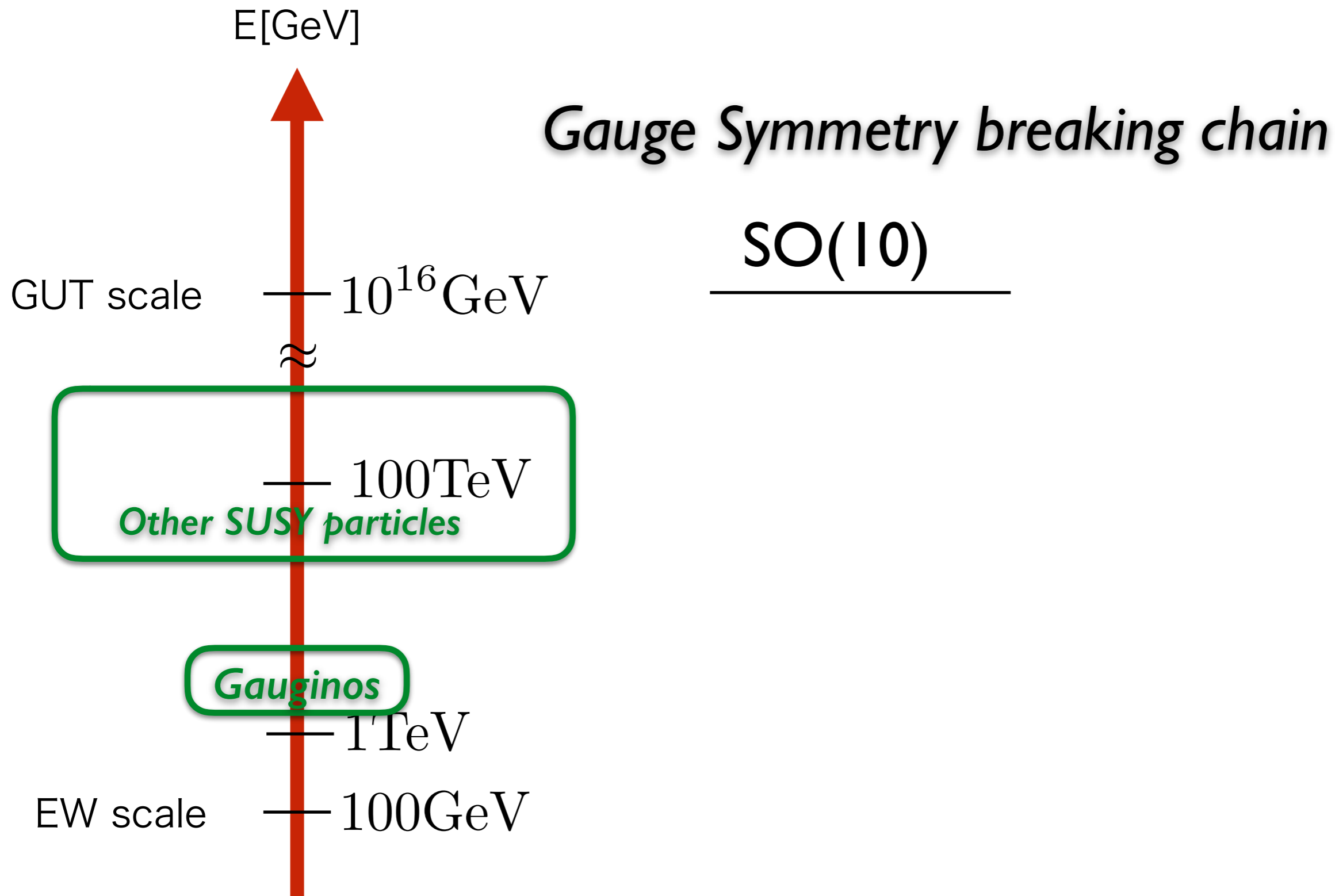
Rough sketch of our scenario



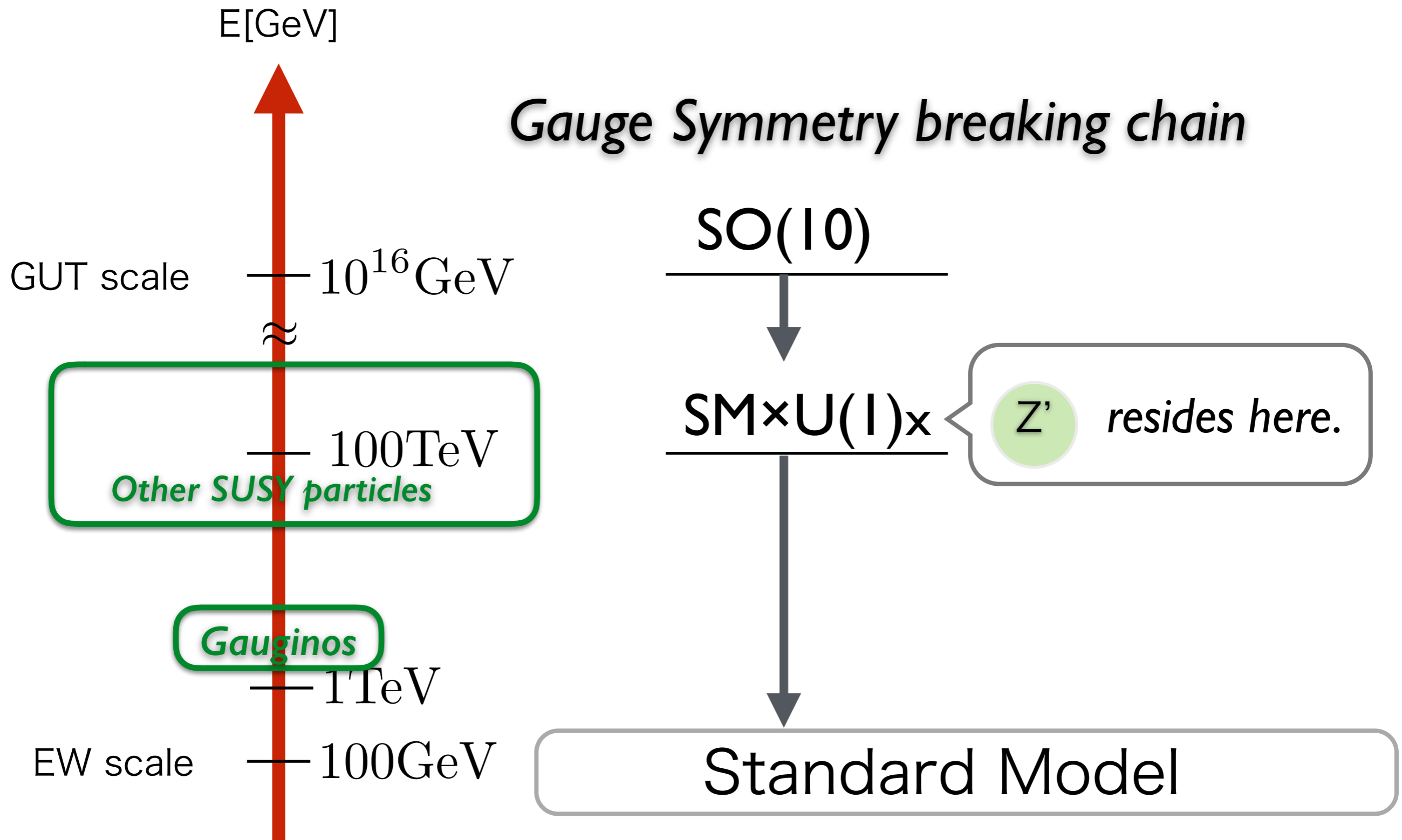
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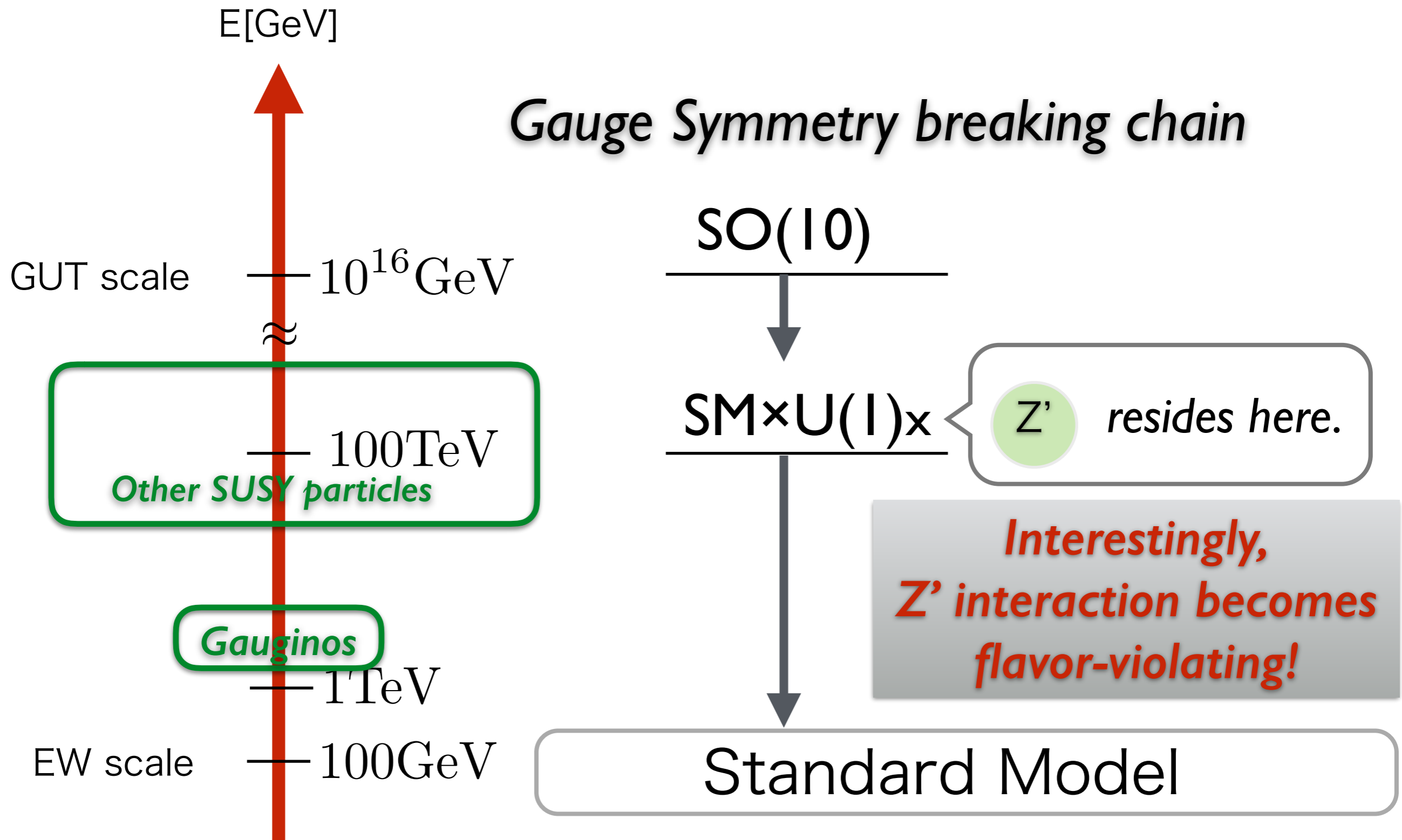
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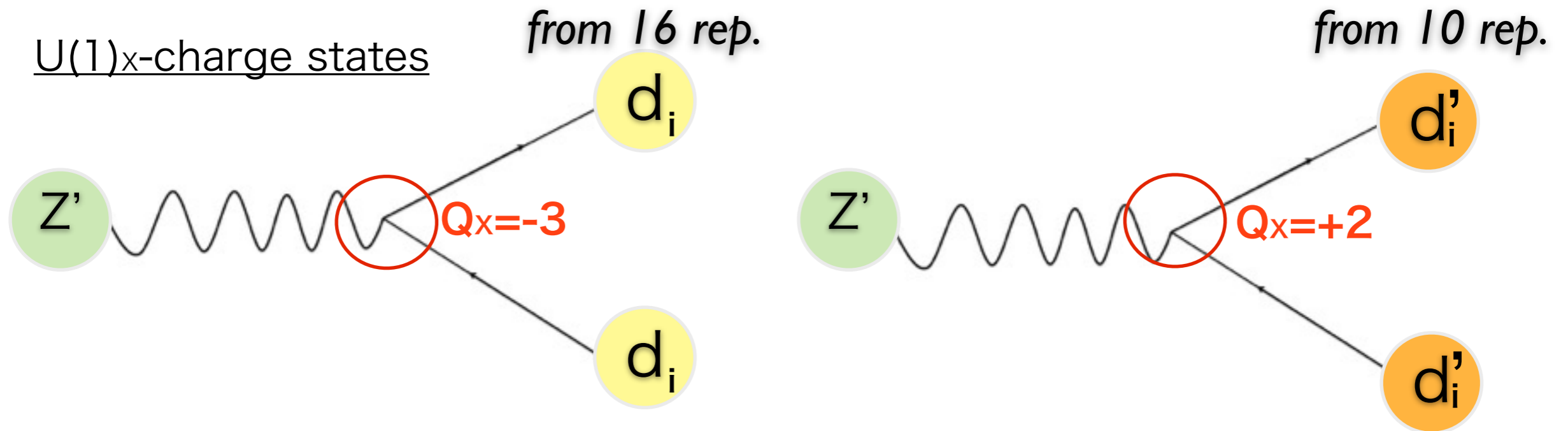


Rough sketch of our scenario



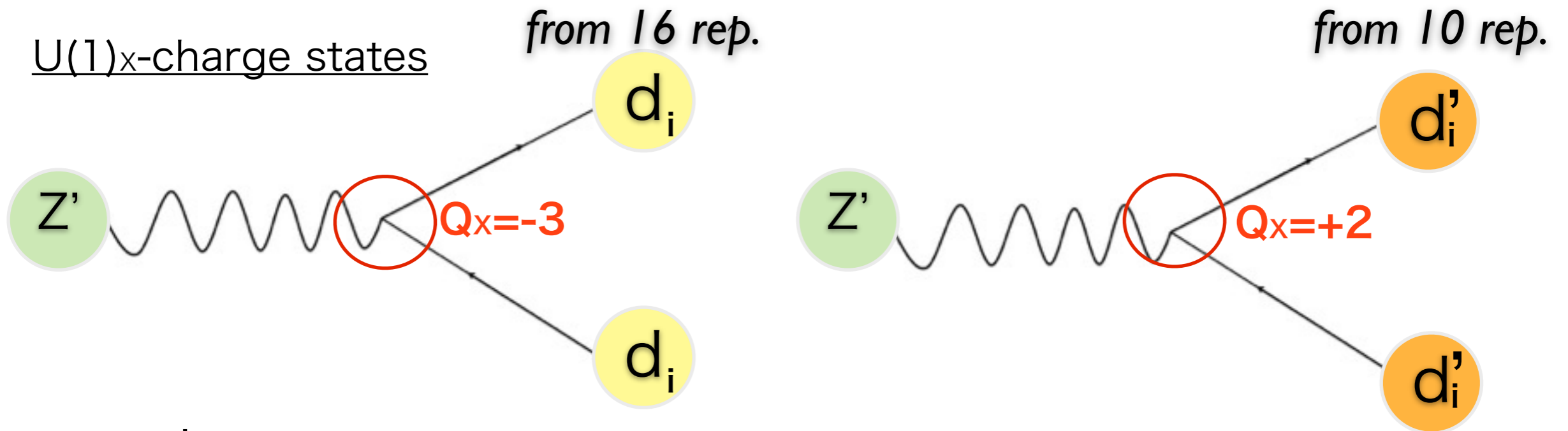
This is because

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



This is because

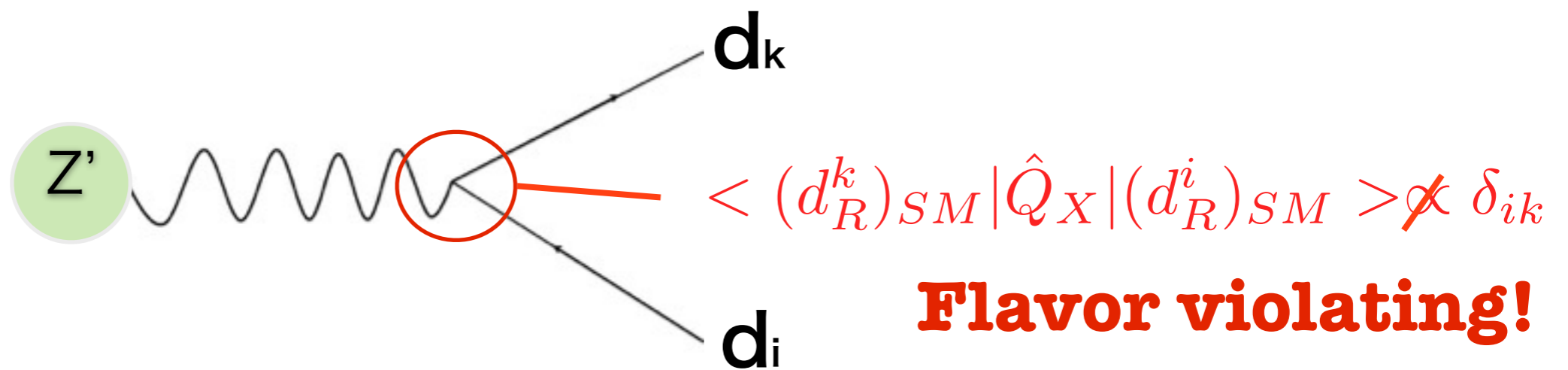
d_i and d'_i carry different $U(1)_X$ charges
extra



mass eigenstates

down-type quarks

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

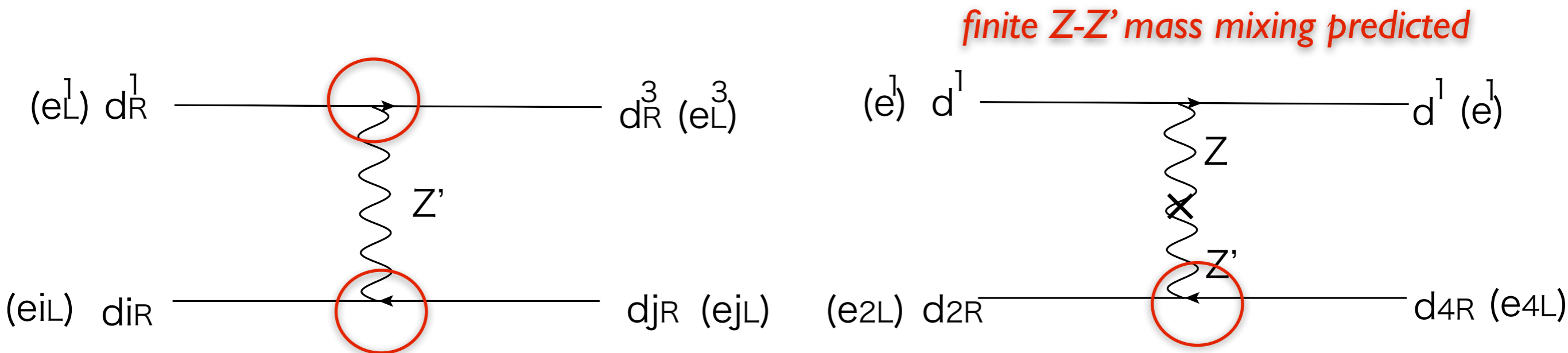


Flavor violating!

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.



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

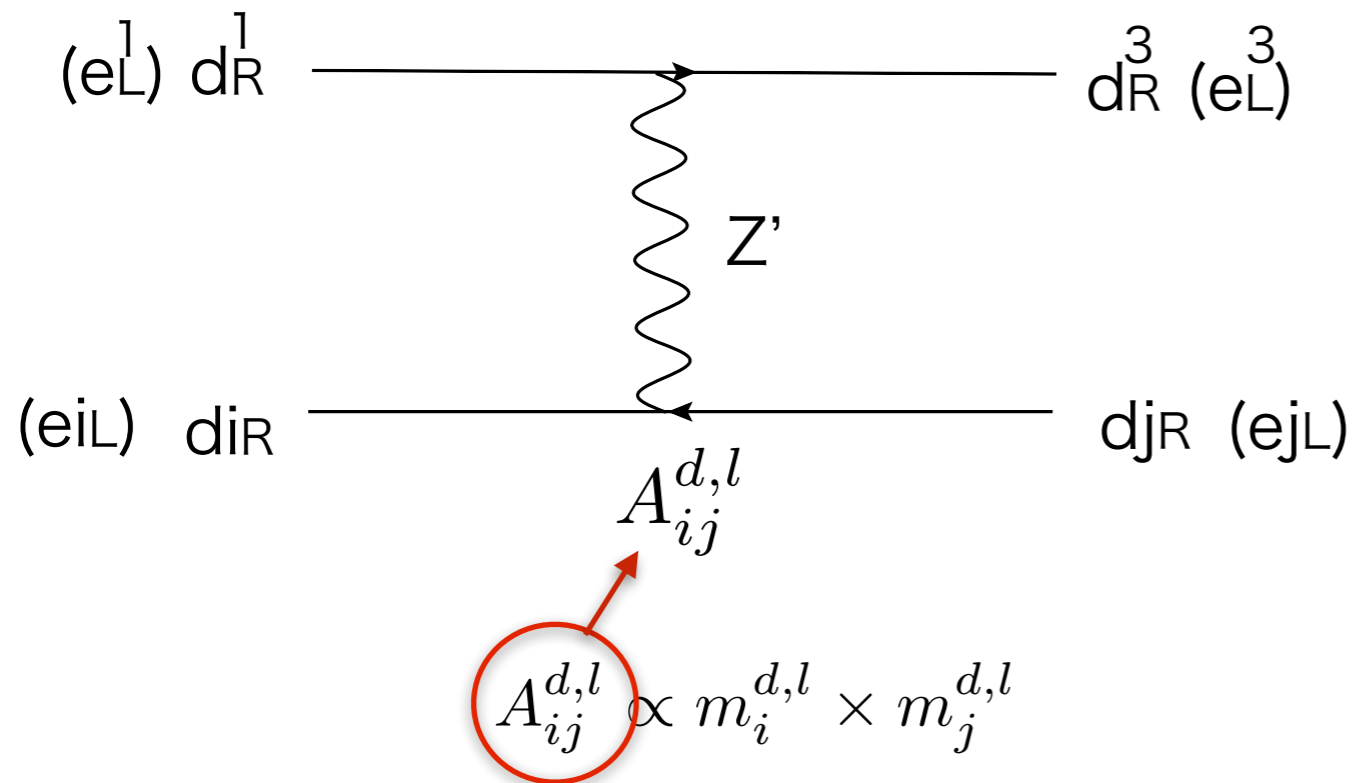
Roughly speaking, $A_{ij}^{d,l} \propto m_i^{d,l} \times m_j^{d,l}$

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

Flavor Physics

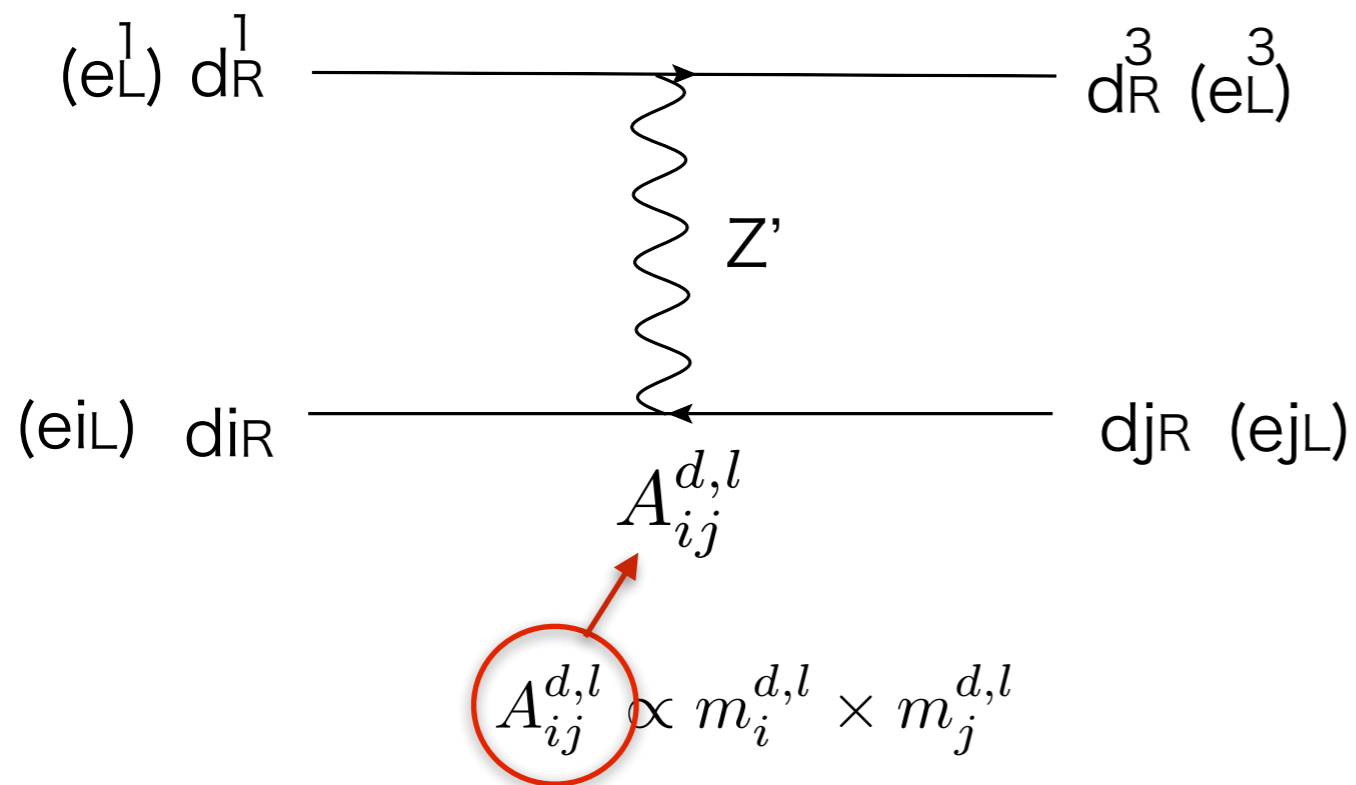
Relevant processes

(See Shigekami's poster)



Relevant processes

(See Shigekami's poster)



$\Delta F=2$ processes

ϵ_K is most sensitive.

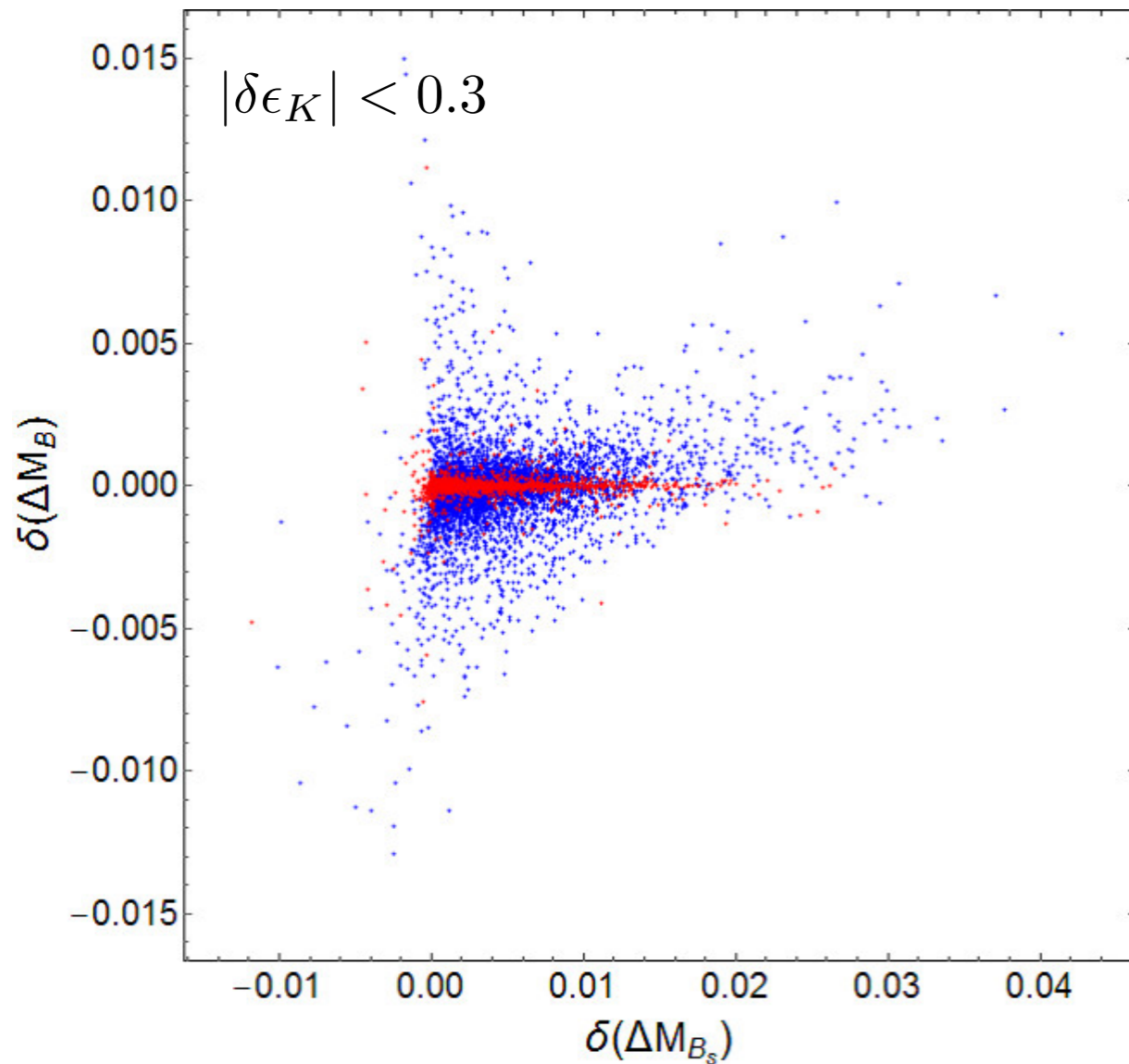
The deviation of B_s - \bar{B}_s mixing is also relatively large.

Deviations in $B_{(s)}-\bar{B}_{(s)}$

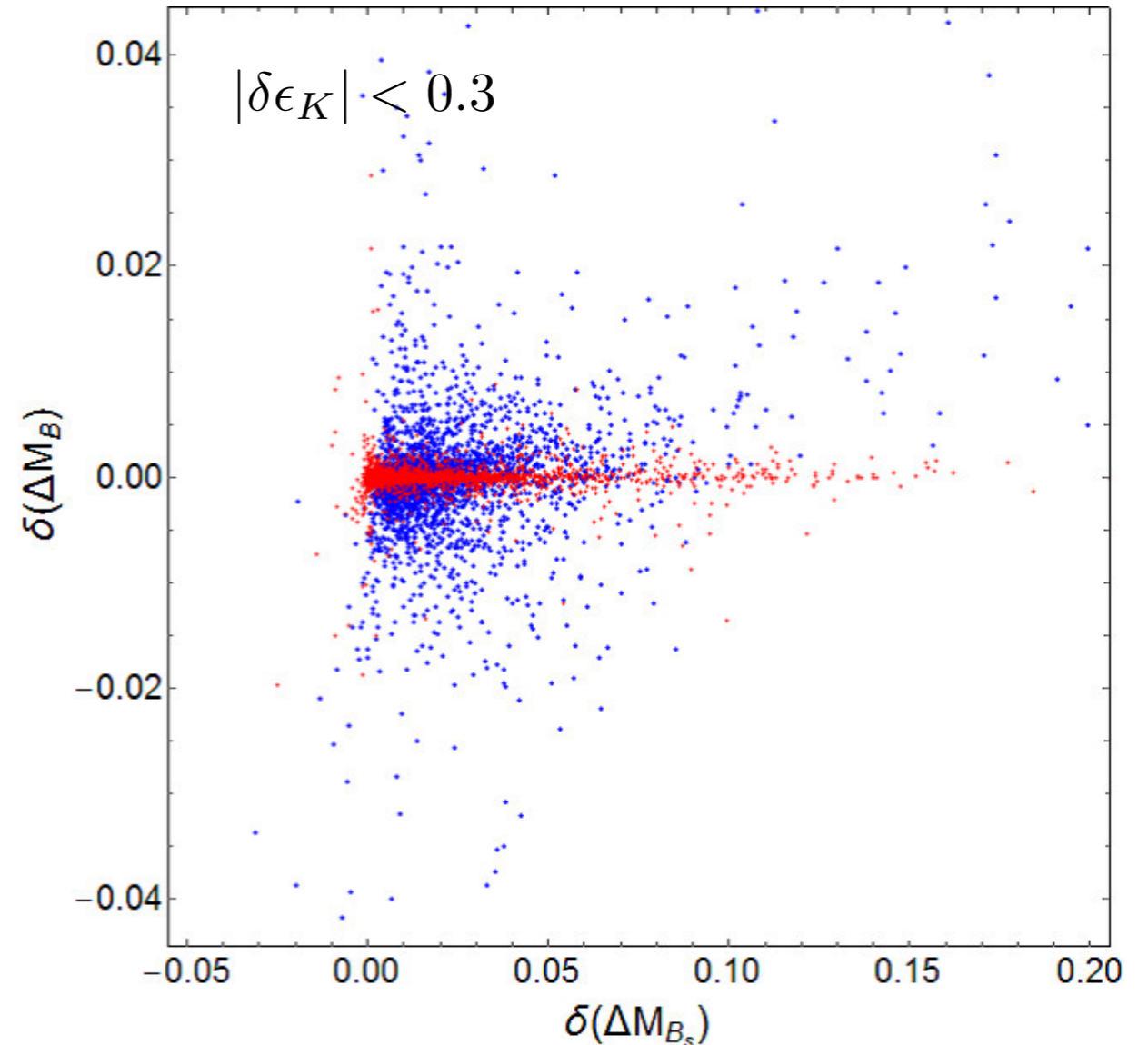
compared to the SM predictions

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

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



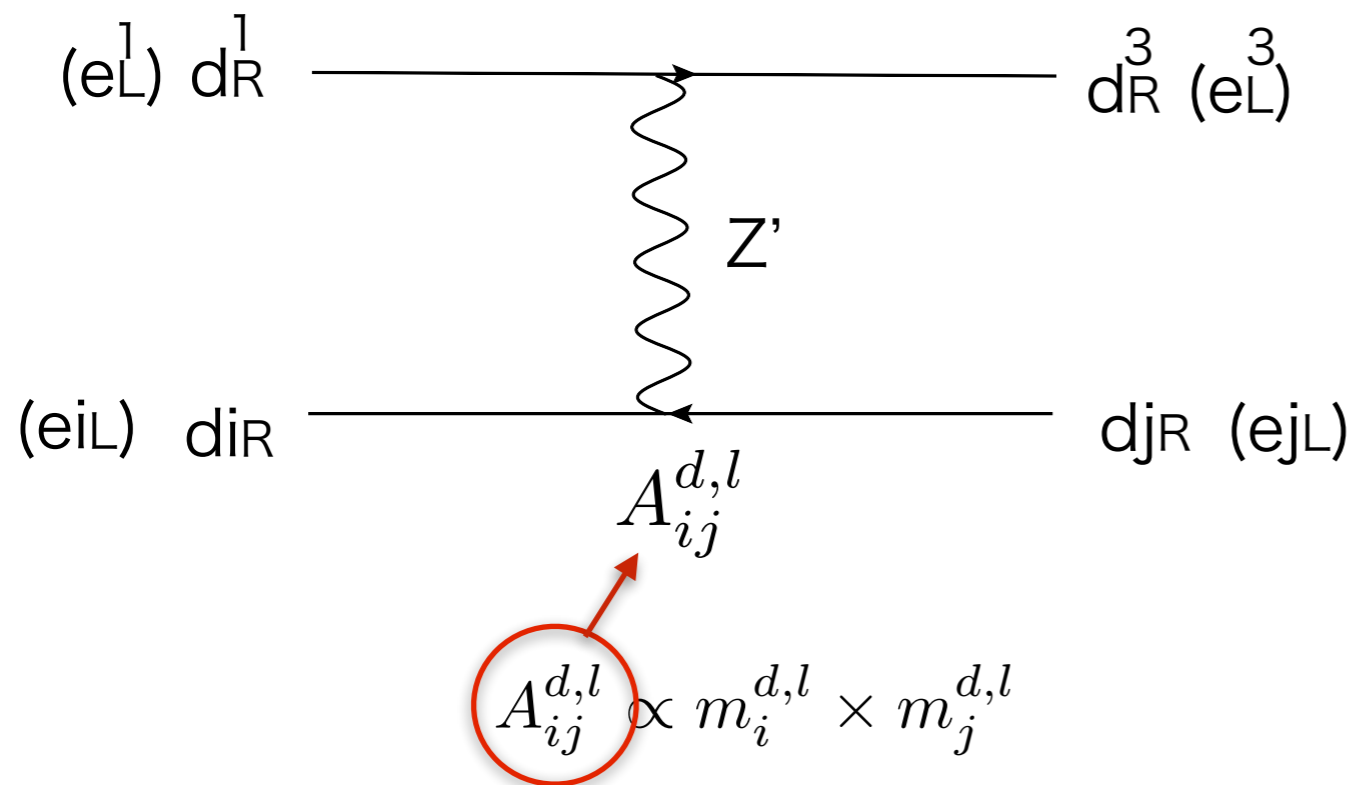
$M_{Z'} \approx 36\text{TeV}$



The deviation of $B_s-\bar{B}_s$ mixing reaches 10 % if Z' mass $O(10)$ TeV.

Relevant processes

(See Shigekami's poster)



$\Delta F=2$ processes

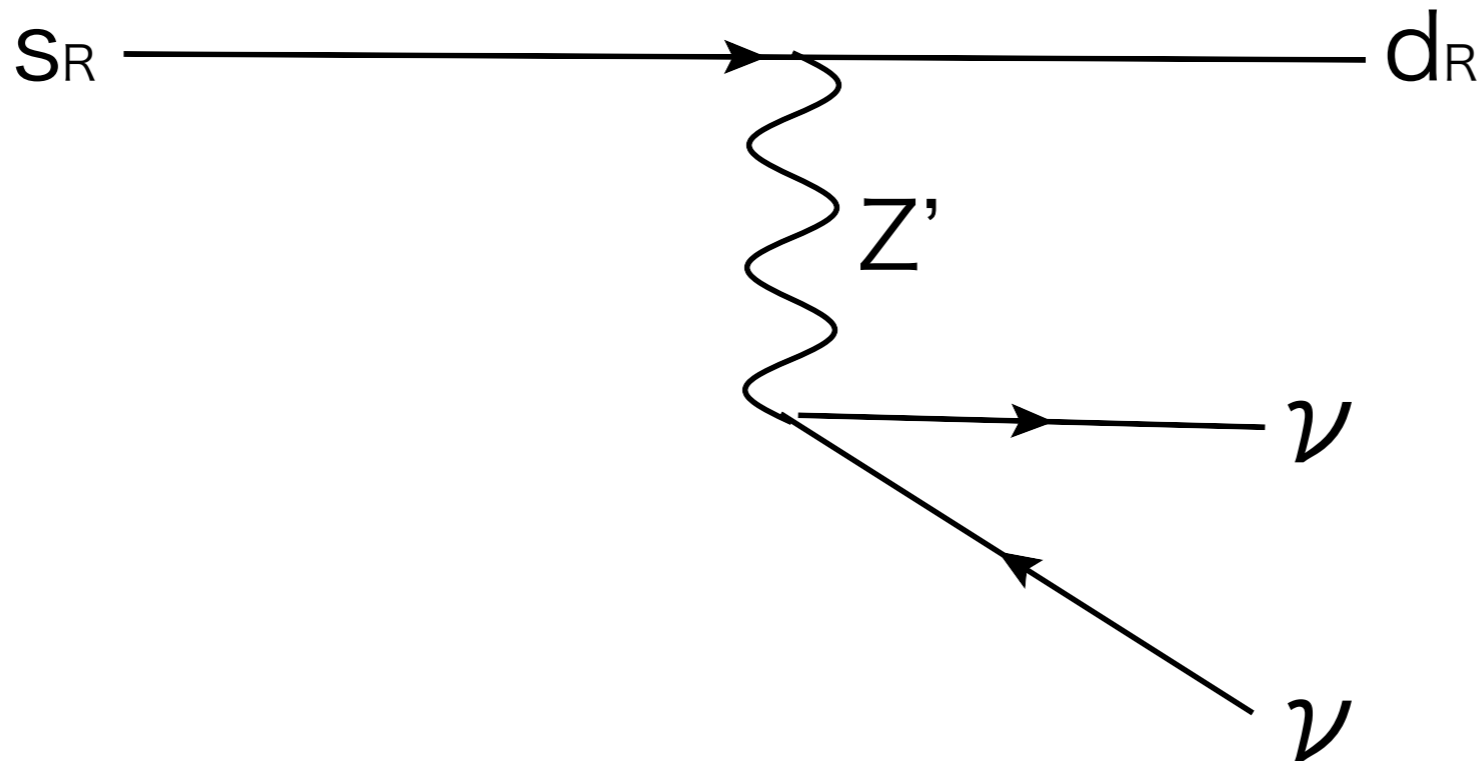
ϵ_K is most sensitive.

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

How about other processes?

Deviations in rare K decay

$K_L \rightarrow \pi^0 \nu \bar{\nu}$ will be measured by the KOTO experiment.



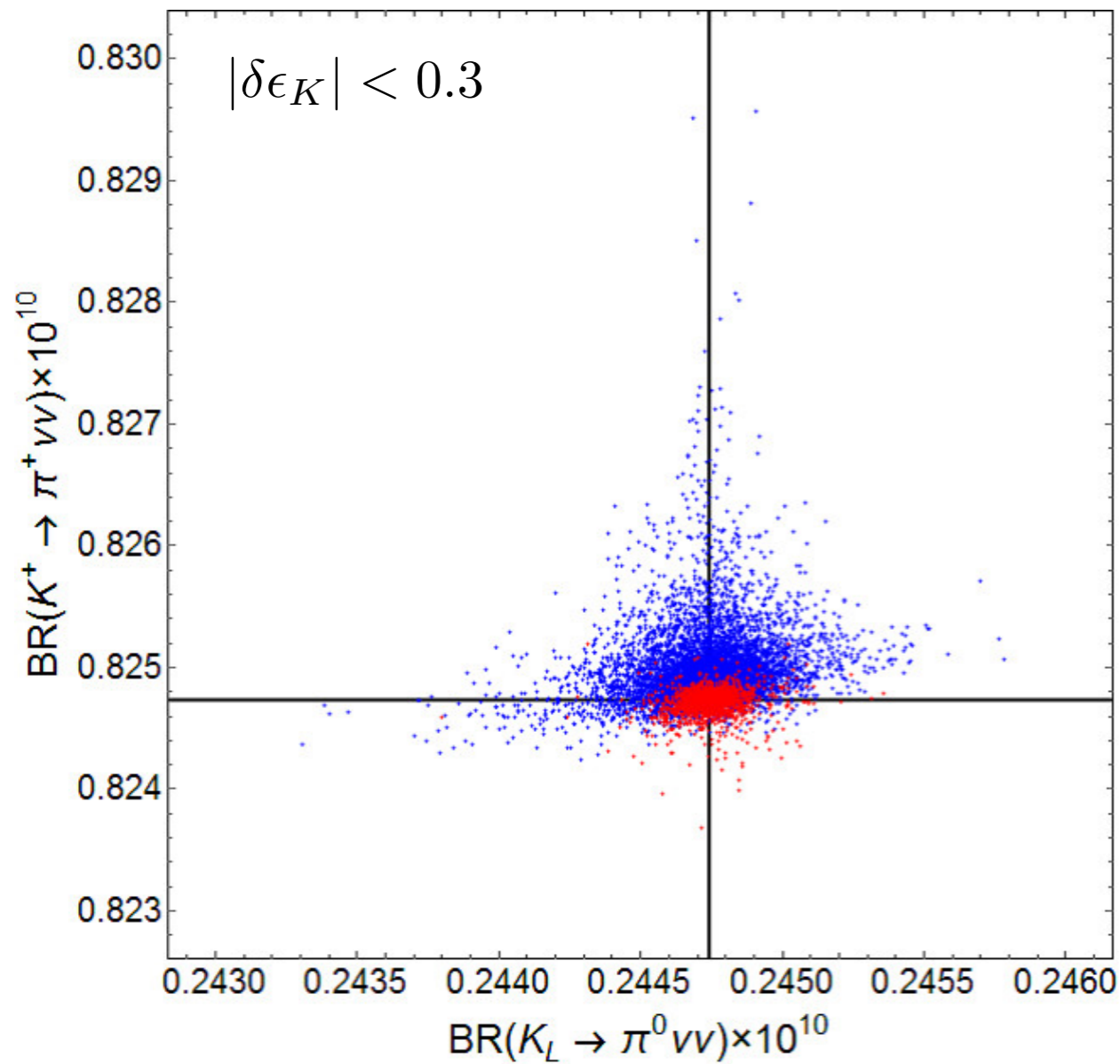
$$\text{BR}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = 1.73_{-1.05}^{+1.15} \times 10^{-10} \quad (\text{E949, 0903.0030})$$

$$\text{BR}(K_L \rightarrow \pi^0 \nu \bar{\nu}) < 2.6 \times 10^{-8} \quad (\text{E391a, 0911.4789})$$

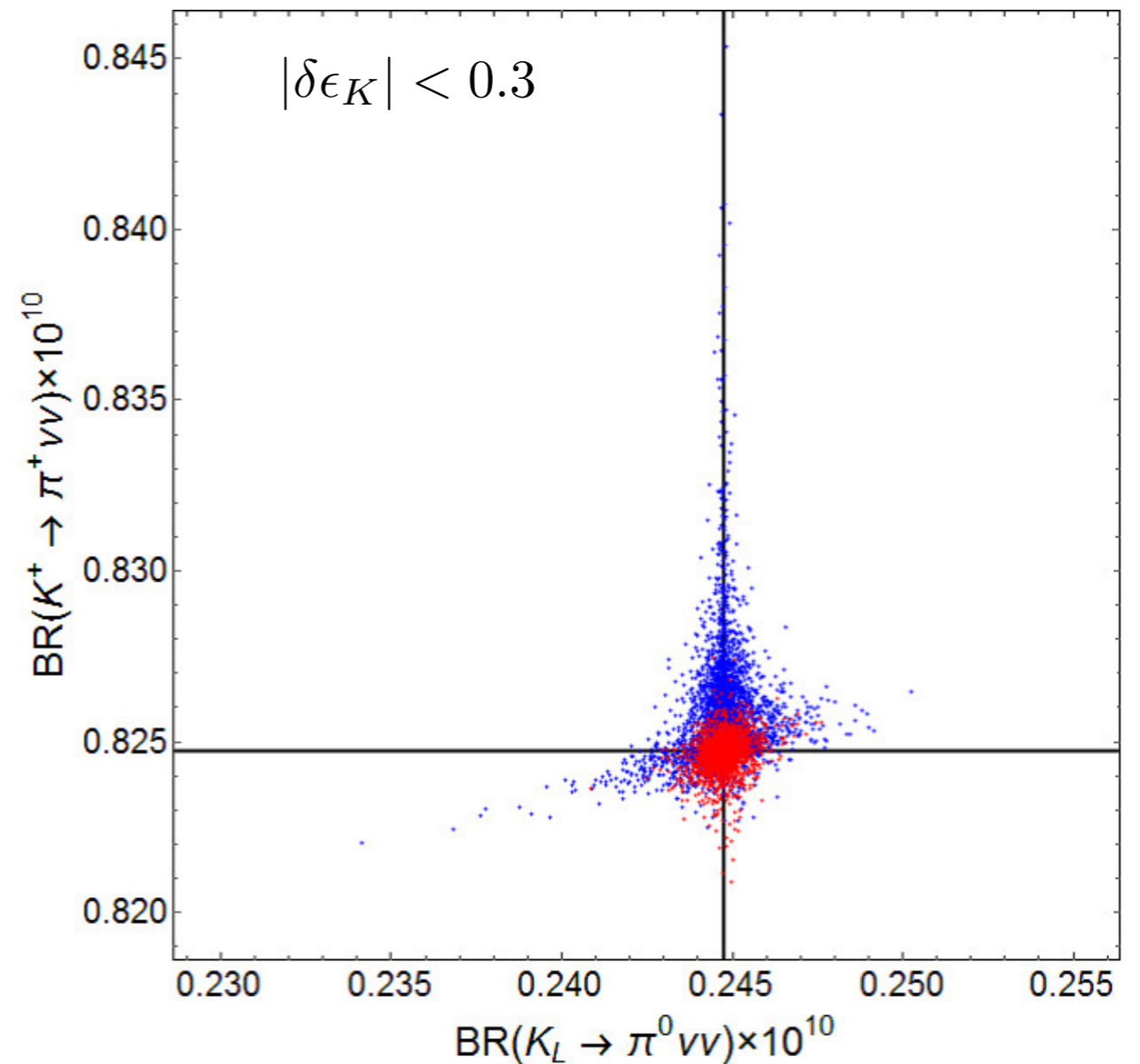
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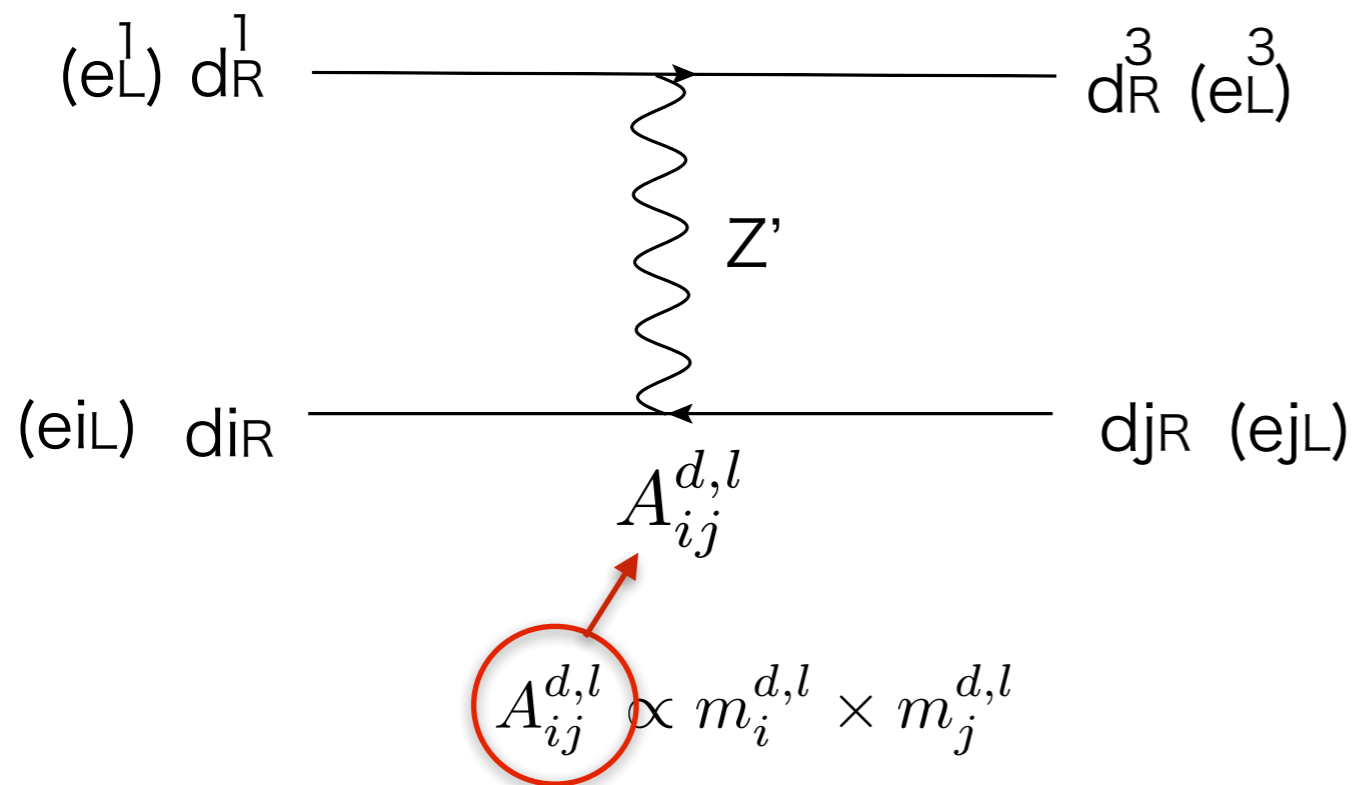
$M_{Z'} \approx 36 \text{ TeV}$



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

Relevant processes

(See Shigekami's poster)



$\Delta F=2$ processes

ϵ_K is most sensitive.

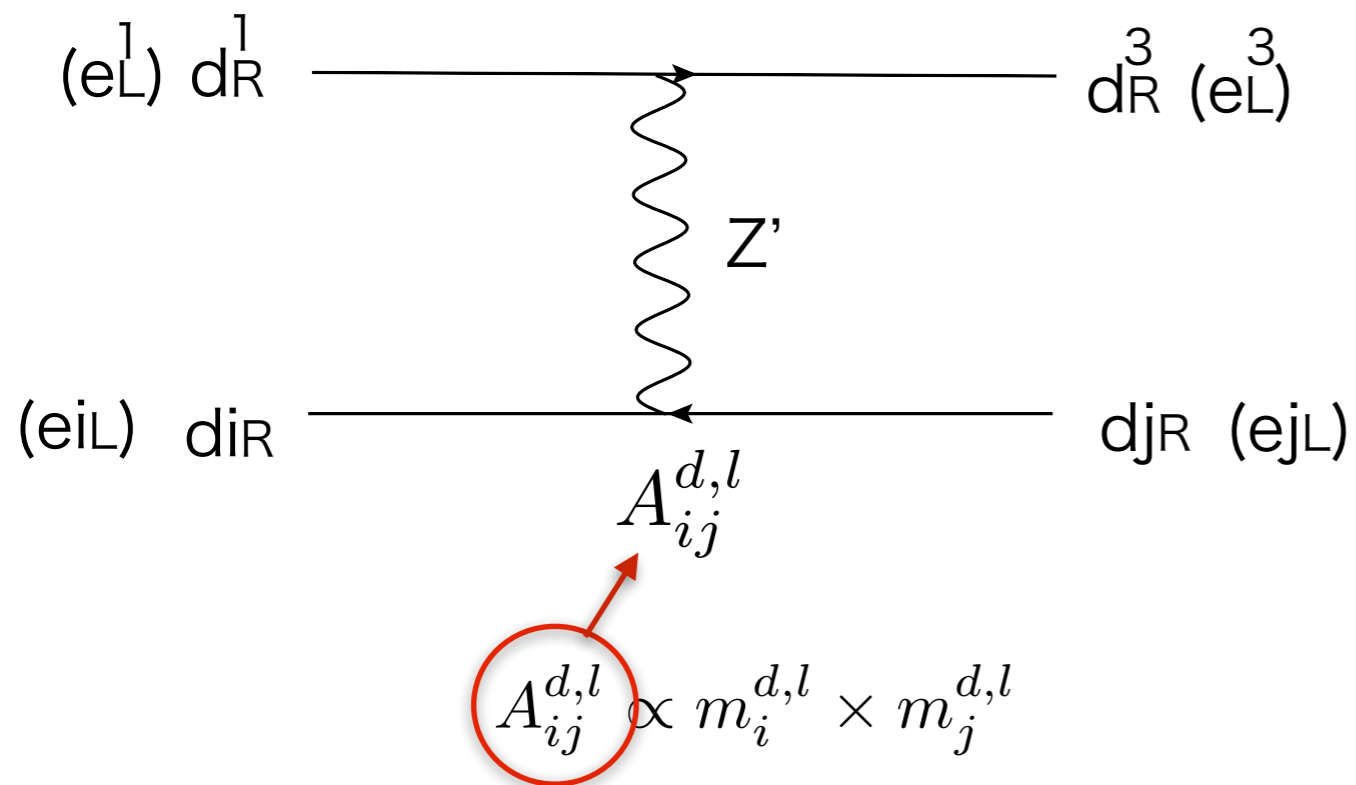
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How about other processes?

very small because of the constraint from ϵ_K .

Relevant processes

(See Shigekami's poster)



$\Delta F=2$ processes

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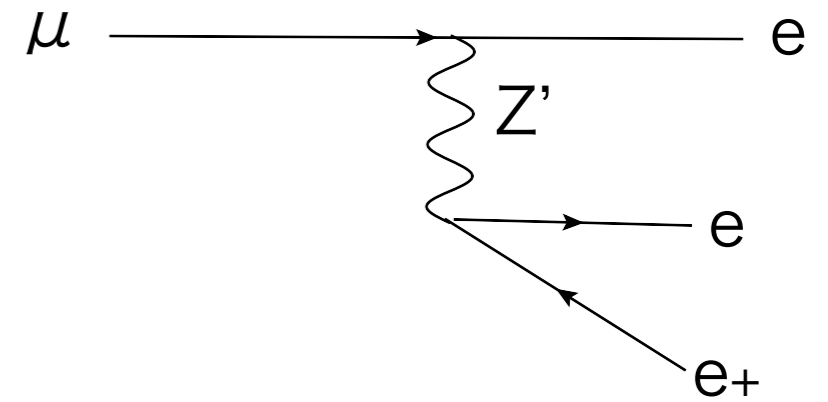
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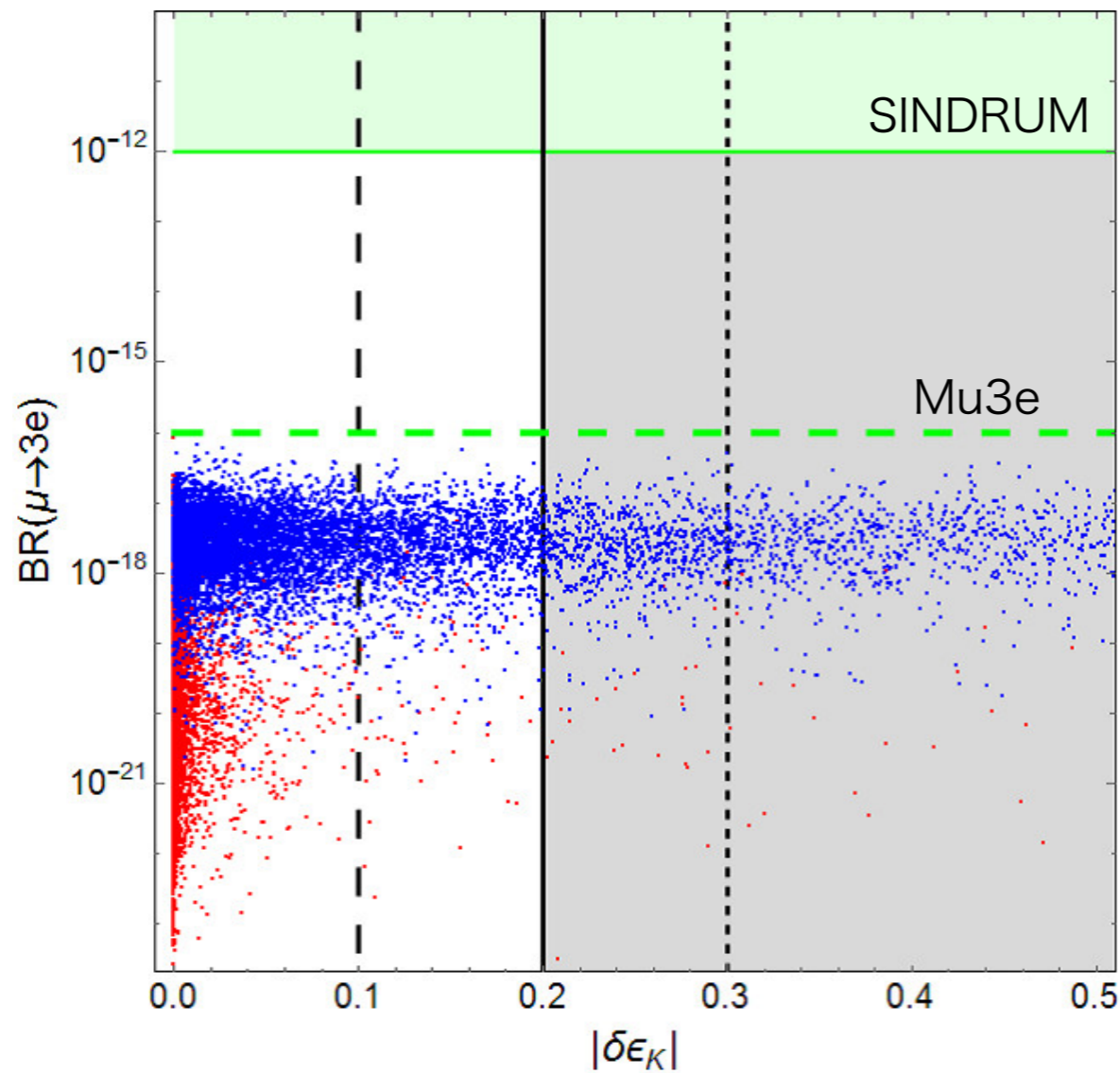
Lepton Flavor violation

$\mu \rightarrow 3e$, μ - e conversion are the most important.

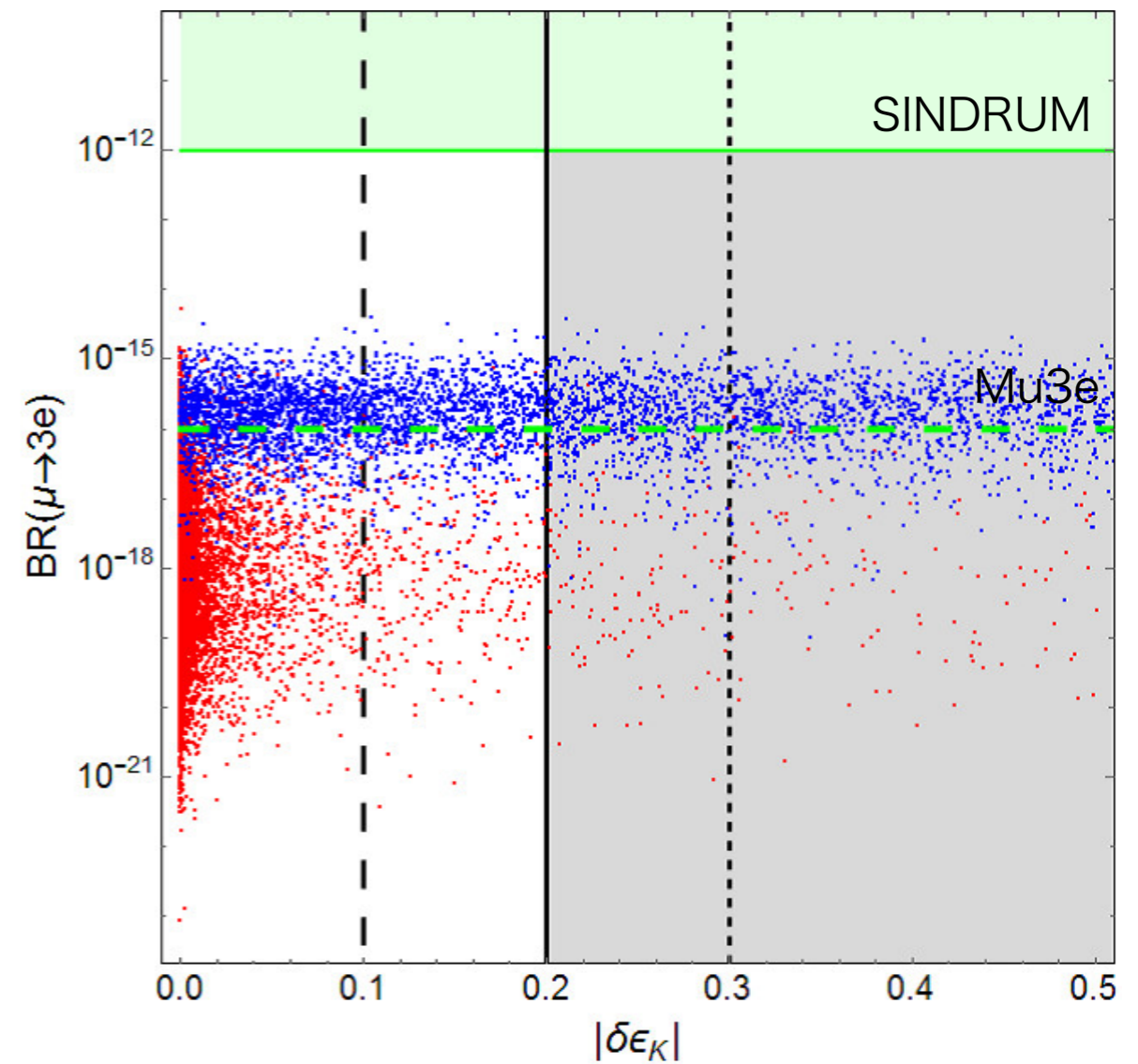
$$\underline{\mu \rightarrow 3e}$$



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

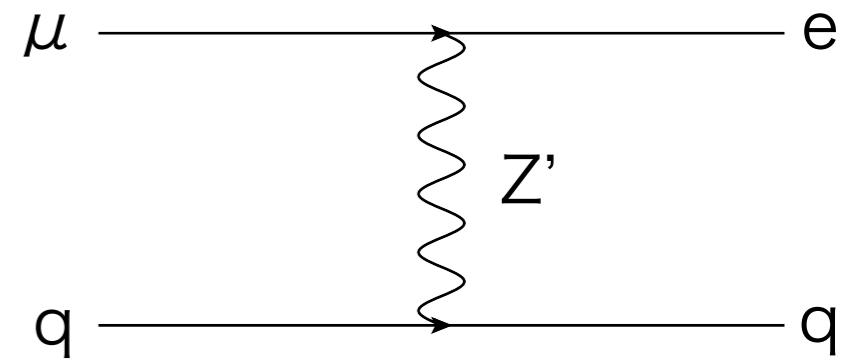


$$M_{Z'} \approx 36 \text{ TeV}$$

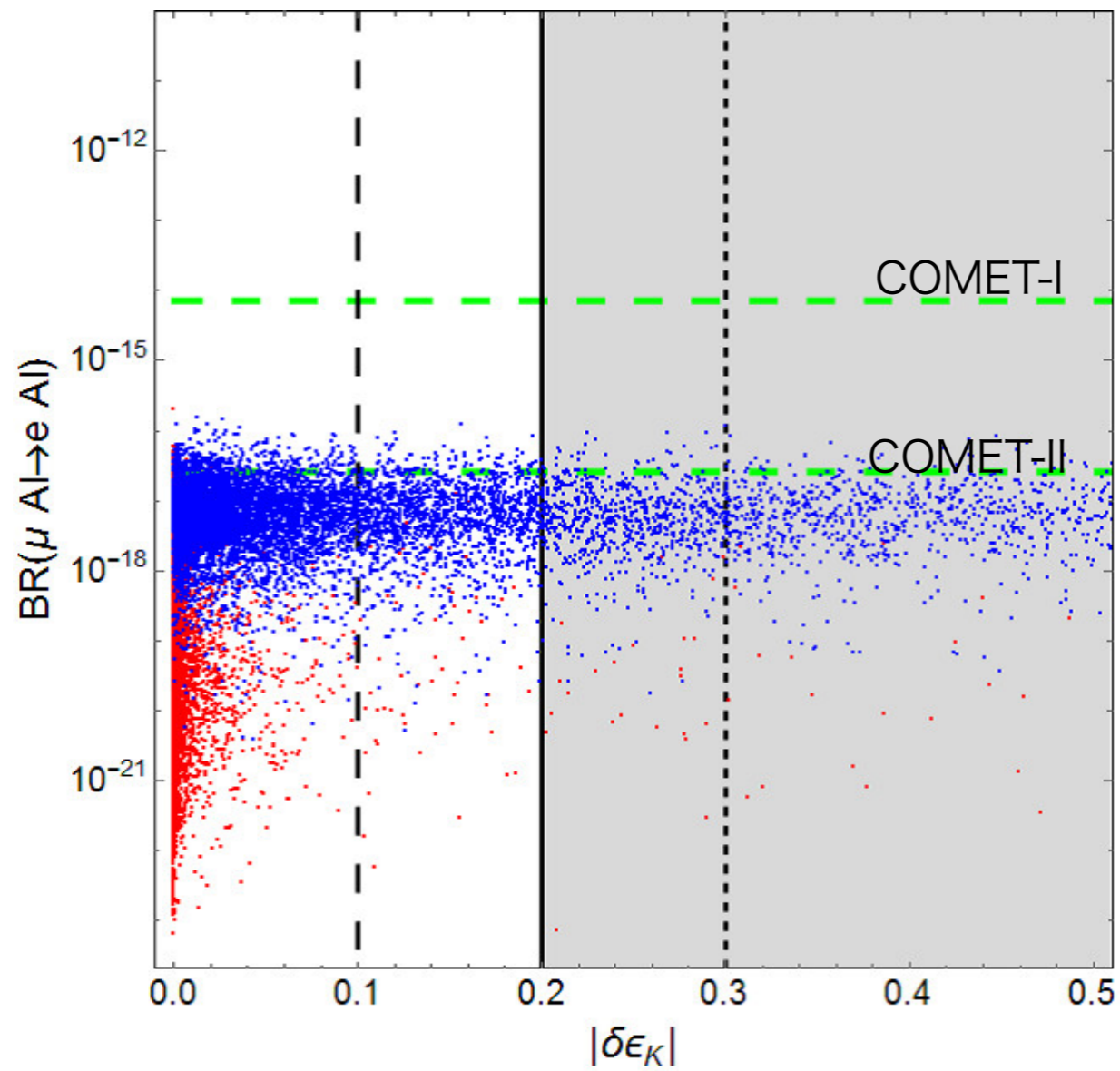


Future experiment (Mu3e) could reach our region!

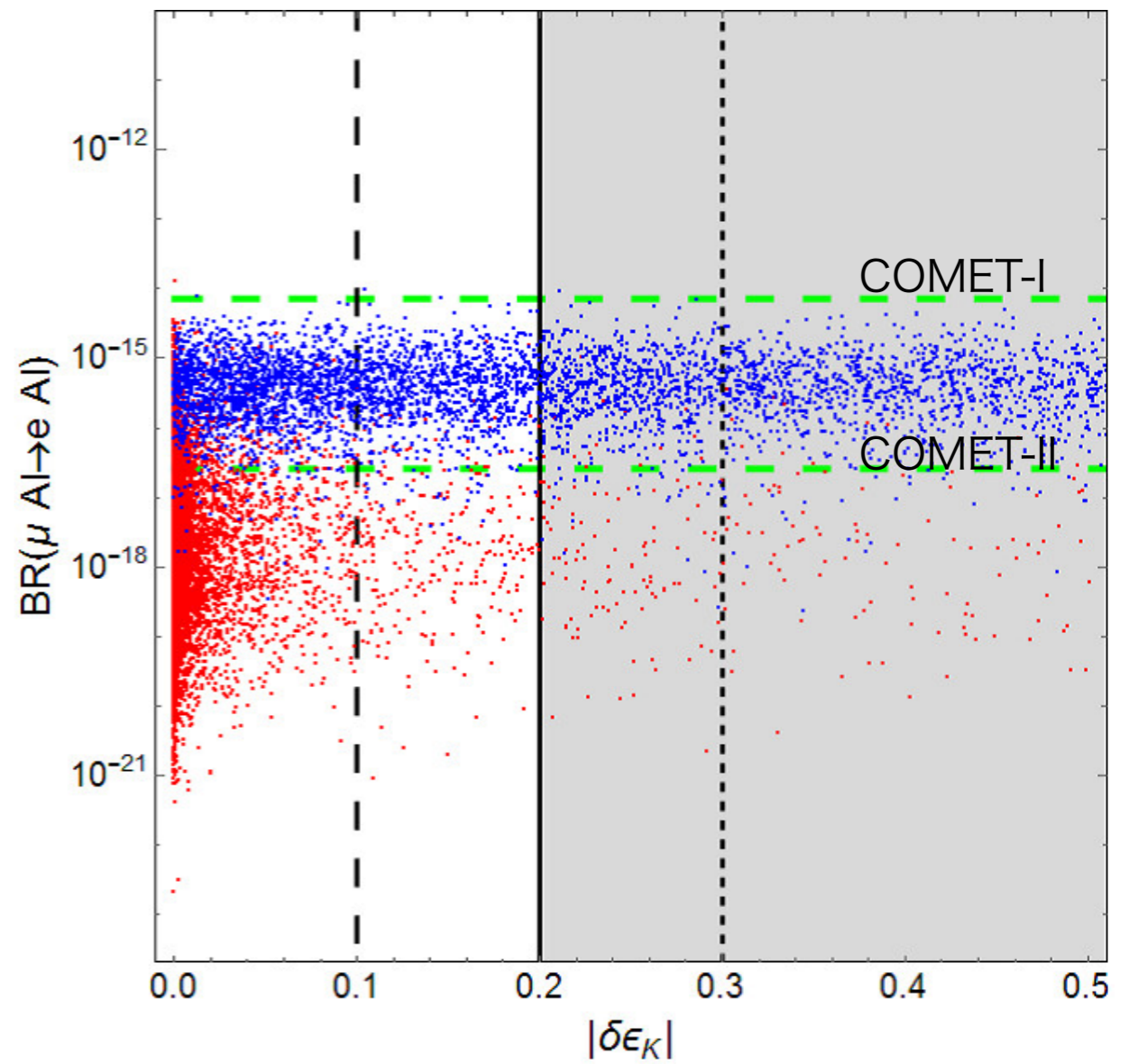
$\mu N \rightarrow e N$



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



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



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

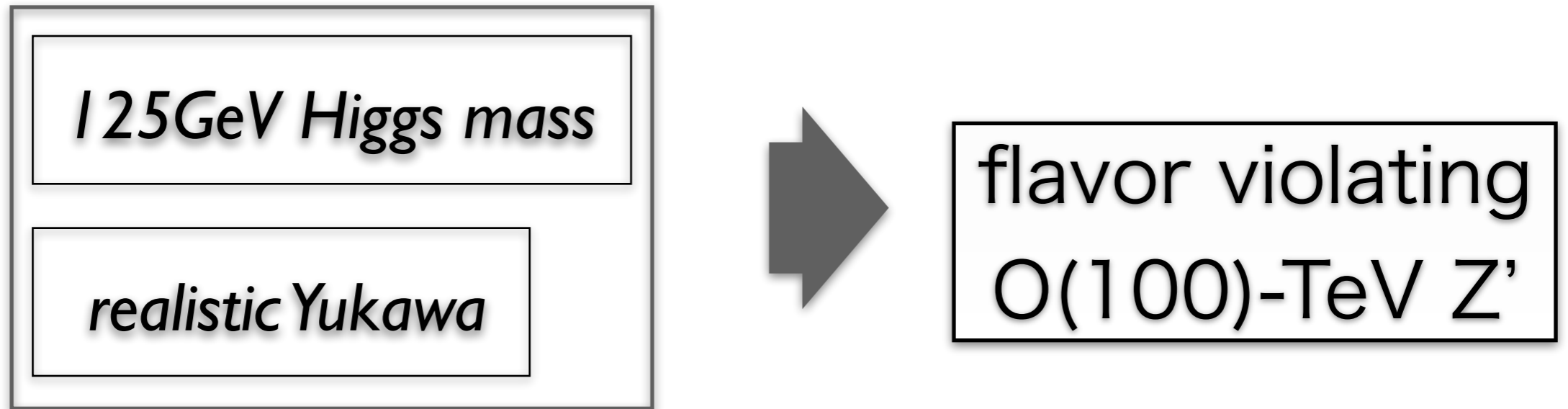
(T. Abe, J. Kawamura, S. Okawa, YO)

- 2HDM

K. Tobe's talk

(YO, E. Senaha, K. Tobe)

- In **SUSY SO(10) GUT**,



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

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

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

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

deviations of ΔM_{B_s} can reach 10% if $Z' \sim 30$ GeV, but ΔM_{B_d} less than 10%.

deviation of $B(s) \rightarrow \mu\mu$ 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

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

- 2HDM

K. Tobe's talk

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SUSY GUT (SO(10))

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dark matter models

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

2HDM

K. Tobe's talk

(YO, E. Senaha, K. Tobe)

Bottom-up approach:
Many free parameters.
Based on the experimental results,
we are studying how to prove the models.

SUSY GUT (SO(10))

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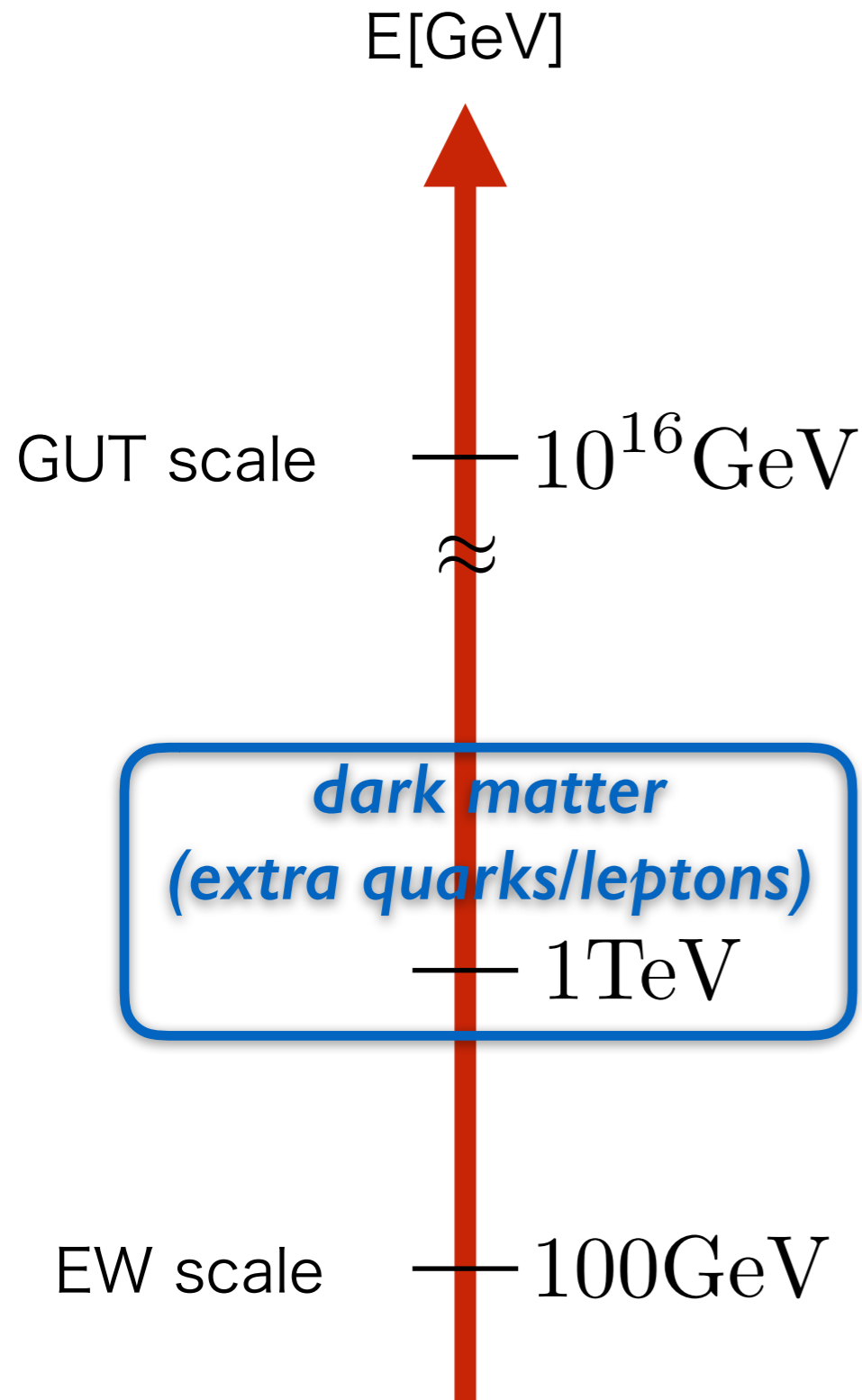
(YO, E. Senaha, K. Tobe)

Bottom-up approach:
Many free parameters.
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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.*

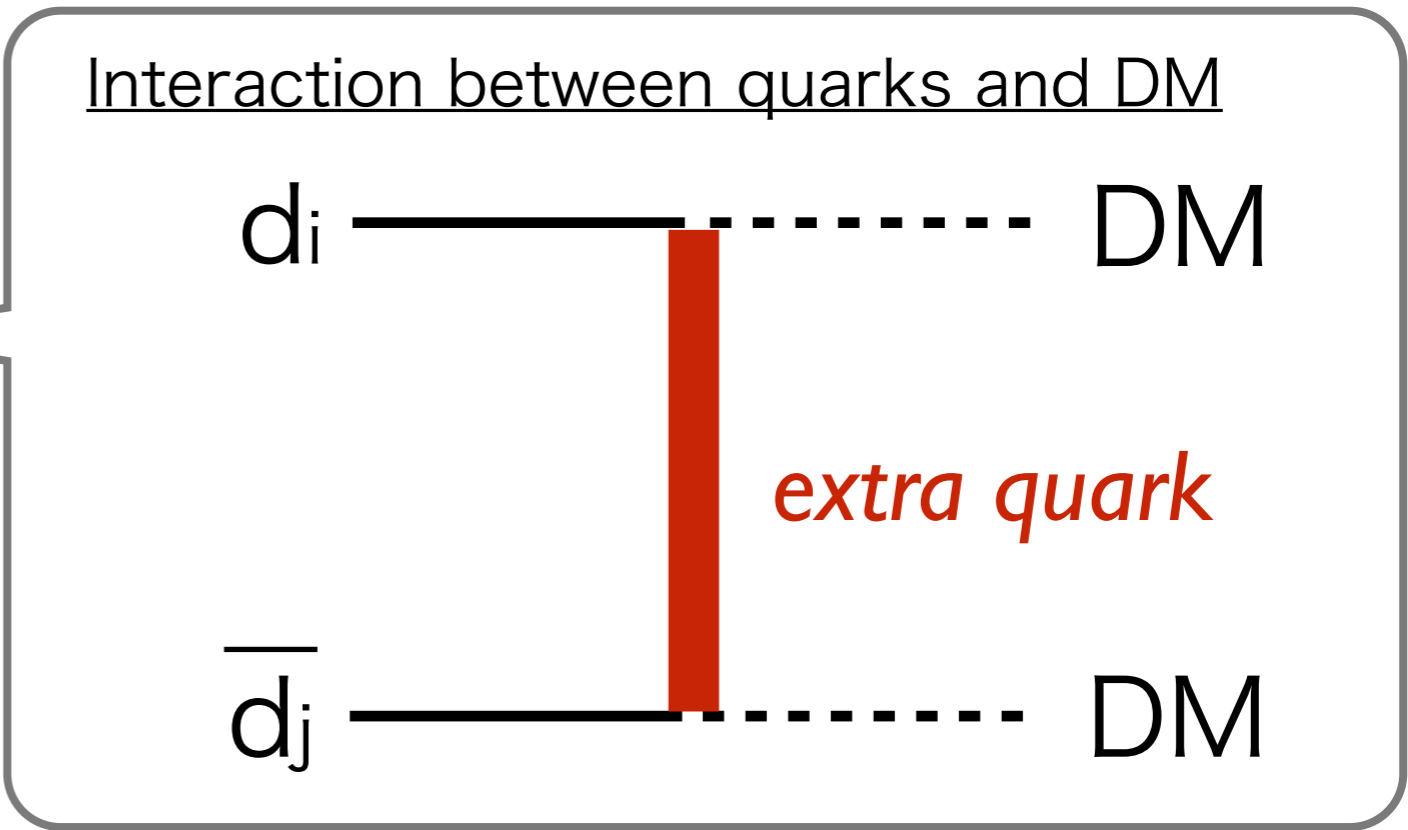
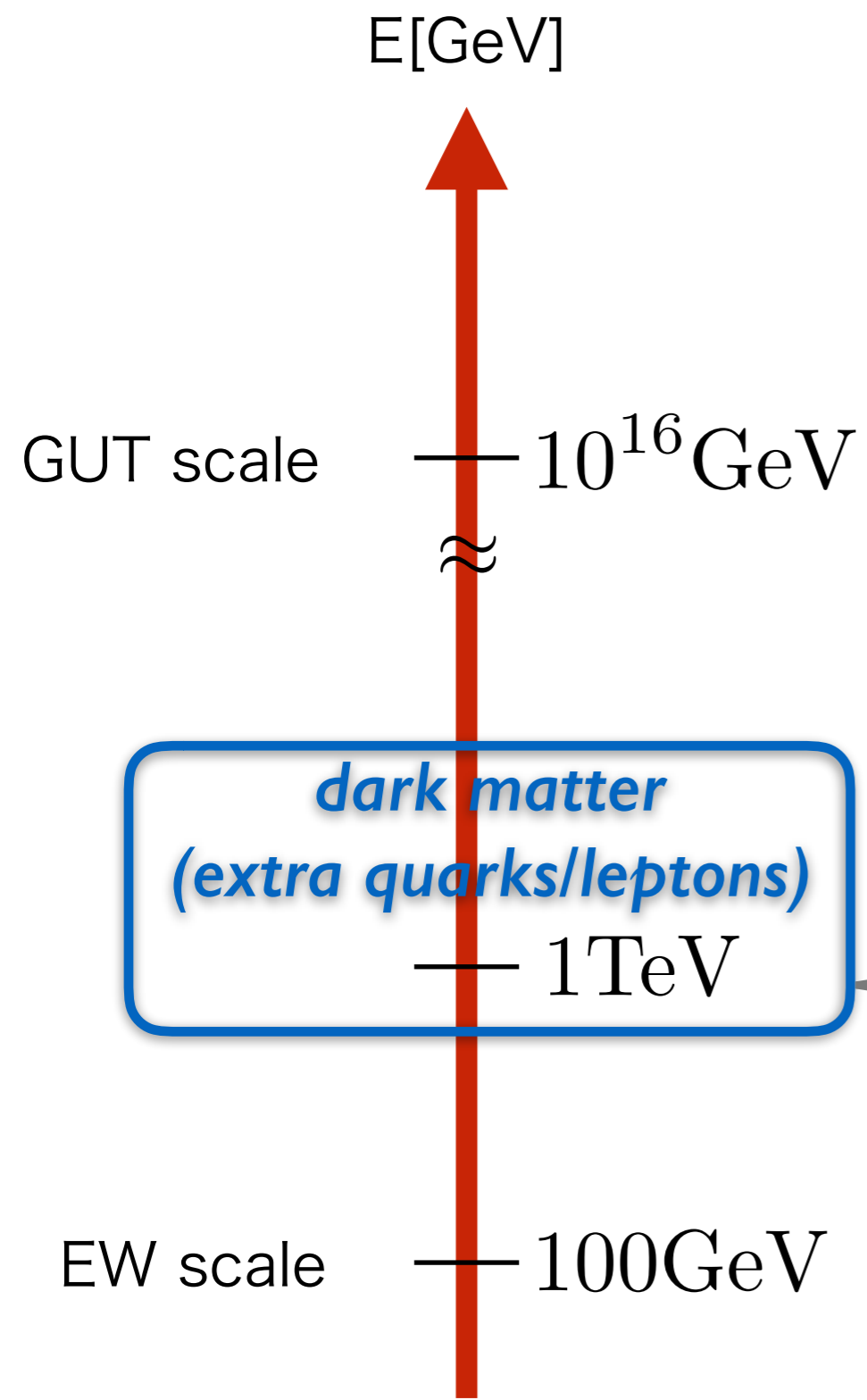
(T. Abe, J. Kawamura, S. Okawa, YO)



DM models in bottom-up approach

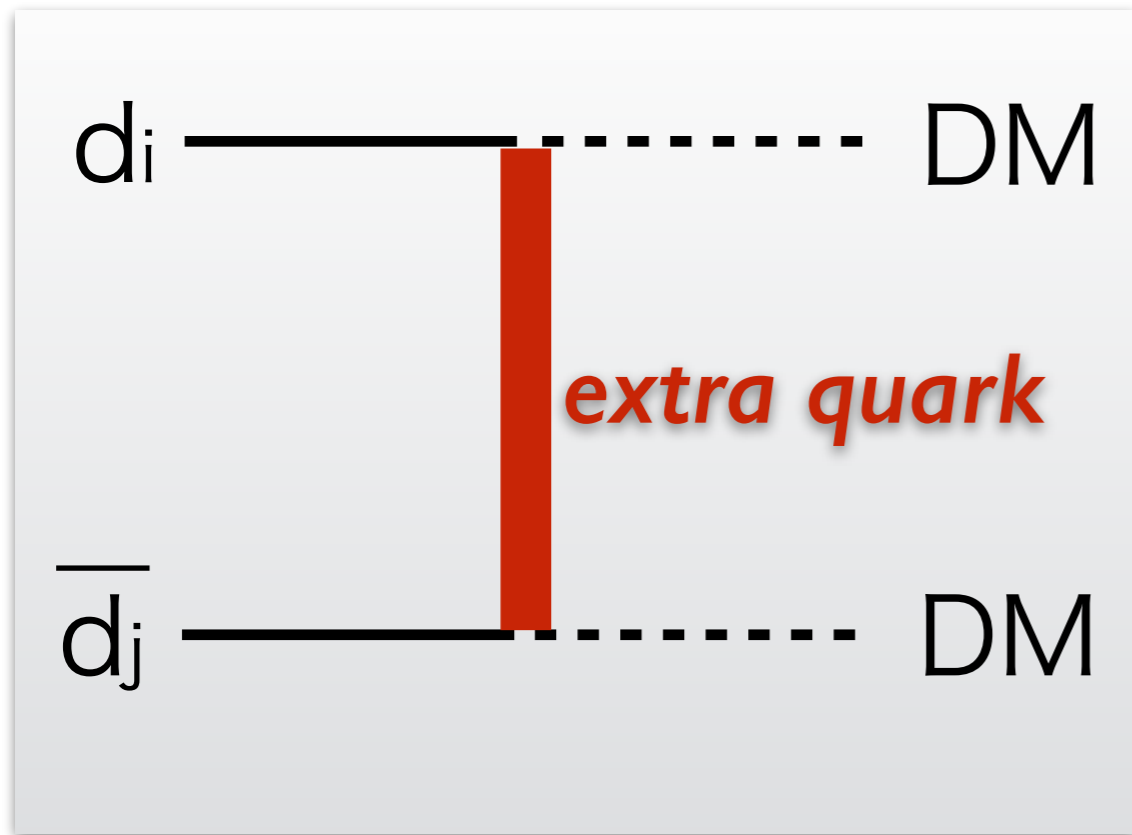
We build some simple BSMs with WIMP DMs, and find some correlations among direct search at the LHC, DM and flavor physics.

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



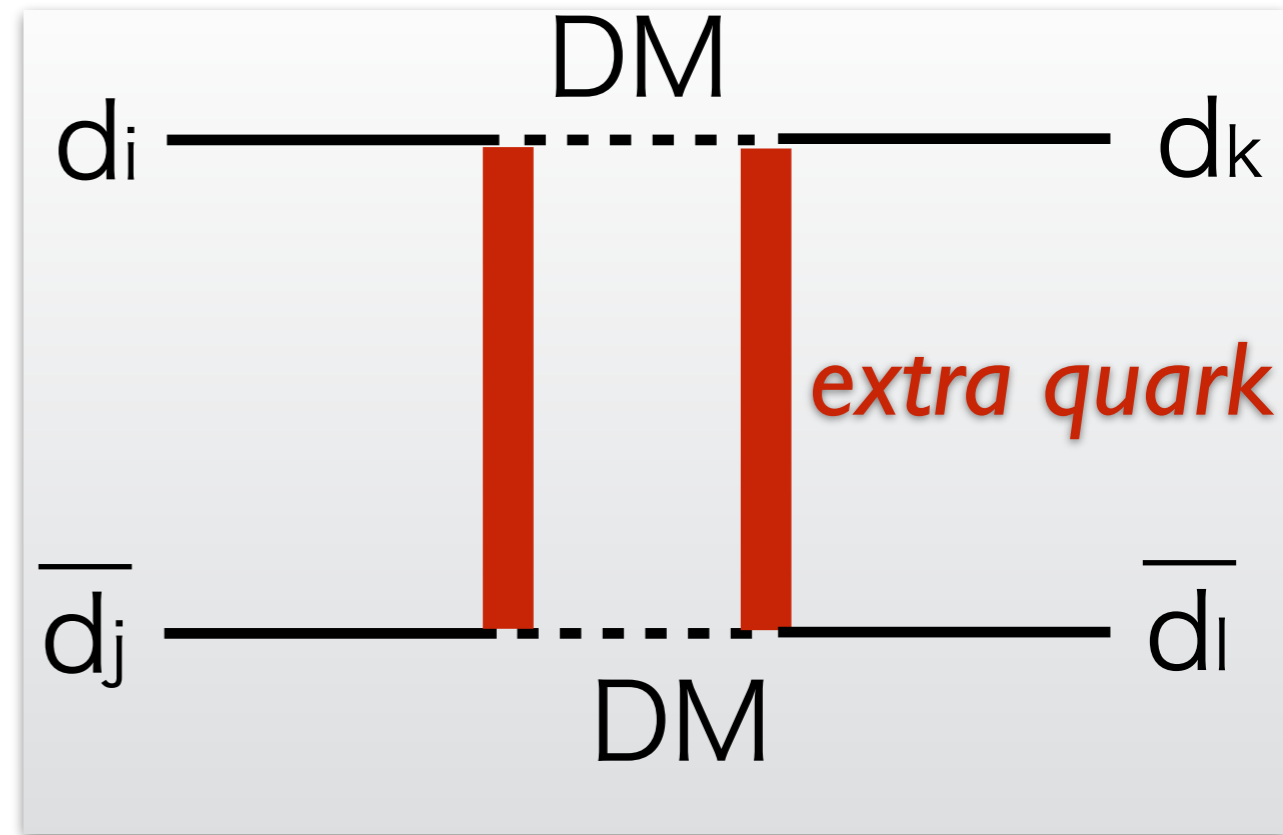
DM models in bottom-up approach

The same diagram contributes to DM and Flavor physics.



contribute to

**annihilation and
direct section of DMs.**



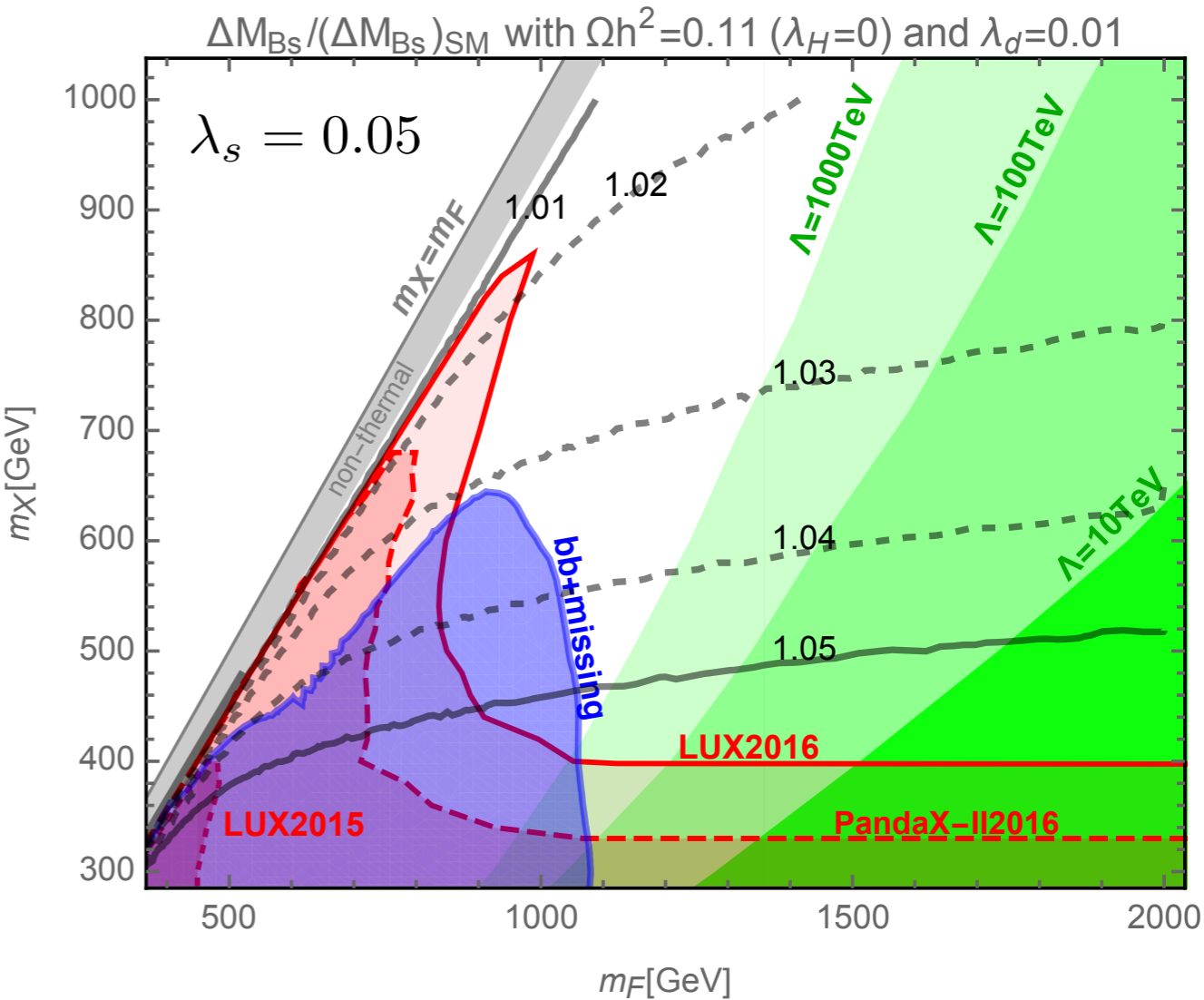
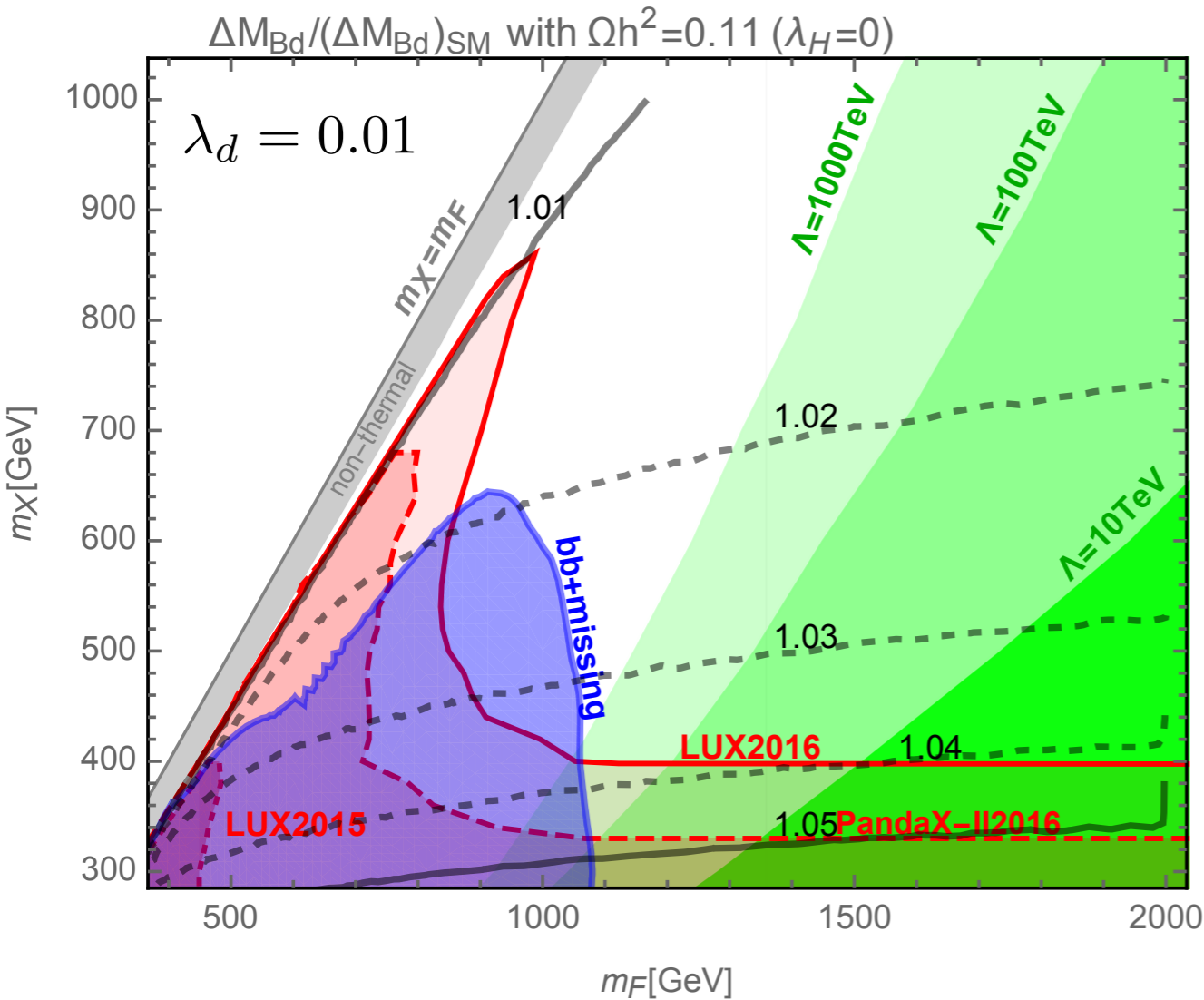
contribute to

**$\Delta F=2$ 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 $\Delta F=2$ processes are predicted!

- 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

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

There are correlations among LHC, DM, and flavor physics.

- 2HDM

K. Tobe's talk

(YO, E. Senaha, K. Tobe)

Bottom-up approach:

Many free parameters.

*Based on the experimental results,
we are studying how to prove the models.*

Thank you

Backup

Detail

In extended $SO(10)$ symmetric superpotential,

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

In effective superpotential ($SM \times U(1)_x$ symmetric superpotential),

quark sector

break extra $U(1)_x$ from $\mathbf{16}_H$

$$h^{ij} Q_{Li} U_{Rj}^c H_u + h^{ij} Q_{Li} \hat{D}_{Rj}^c H_d + g^{ij} \overline{D'_{Ri}{}^c} \hat{D}_{Rj}^c \langle \mathbf{1}_H \rangle + \mu_{10}^{ij} \overline{D'_{Ri}{}^c} D'_{Rj}{}^c$$

MSSM down-type

$$\hat{D}_{Ri}^c = (\hat{U}_D)_{ij} D_{Rj}^c + (\hat{U}'_D)_{ij} D''_{Rj}{}^c$$

$$h^{ij} Q_{Li} U_{Rj}^c H_u + (h \hat{U}_D)_{ij} Q_{Li} D_{Rj}^c H_d + \mu^{ij} \overline{D'_{Ri}{}^c} D''_{Rj}{}^c$$

Hierarchy is given by the mixing

Detail

In extended $SO(10)$ symmetric superpotential,

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

In effective superpotential ($SM \times U(1)_x$ symmetric superpotential),

lepton sector

break extra $U(1)_x$ from $\mathbf{16}_H$

$$h^{ij} \hat{L}_i N_{Rj}^c H_u + h^{ij} \hat{L}_i E_{Rj}^c H_d + g^{ij} \overline{L}'_i \hat{L}_j \langle \mathbf{1}_H \rangle + \mu_{10}^{ij} \overline{L}'_i L'_j$$

MSSM lepton

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

$$h^{ij} L_i N_{Rj}^c H_u + (\hat{U}_D^T h)_{ij} L_i E_{Rj}^c H_d + \mu^{ij} \overline{L}'_i L''_j$$

Hierarchy is given by the mixing