高スケール超対称模型における核子の電気双極子能率

Nucleon electric dipole moments in high-scale supersymmetric models

JHEP11(2015)085

共同研究者:久野 純治，小林 大輝，桑原 拓巳

名古屋大学 理学研究科 E研

M2 倉本 渉

@松江素粒子物理学研究会 2016 3/27

Plan

I. Introduction

- ・高スケール超対称模型
- ・電気双極子能率

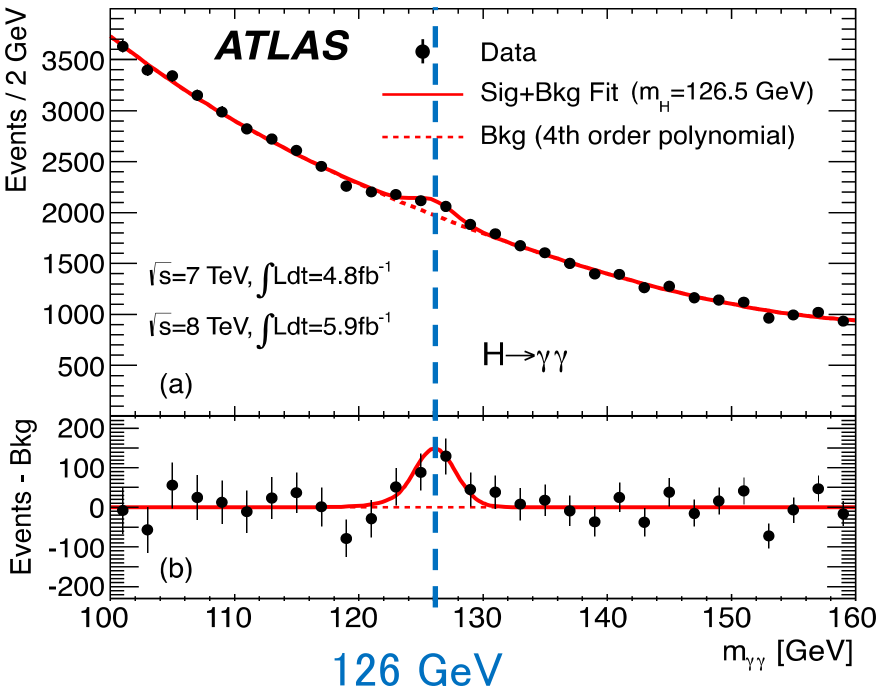
II. グルイーノCEDMによる核子のEDMへの寄与

III. まとめ

Introduction

標準模型

ヒッグス粒子の発見（LHC run 1）　標準模型の完成



標準模型の問題点

- ゲージ階層性問題
- 暗黒物質候補の不在
- アノマリー相殺の理由
- 電荷の量子化の理由

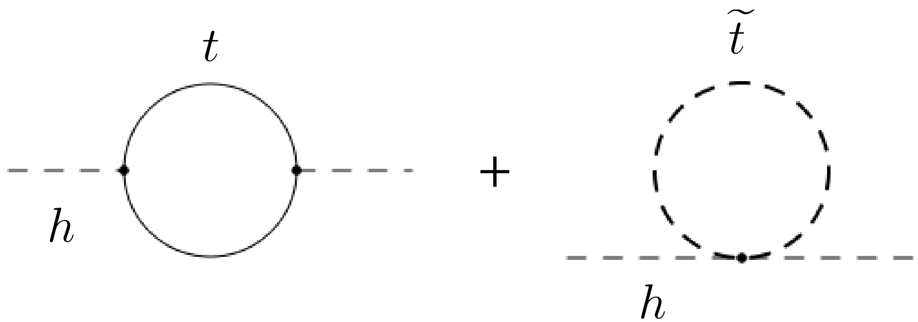
etc.

標準模型は拡張を要する

超対称標準模型

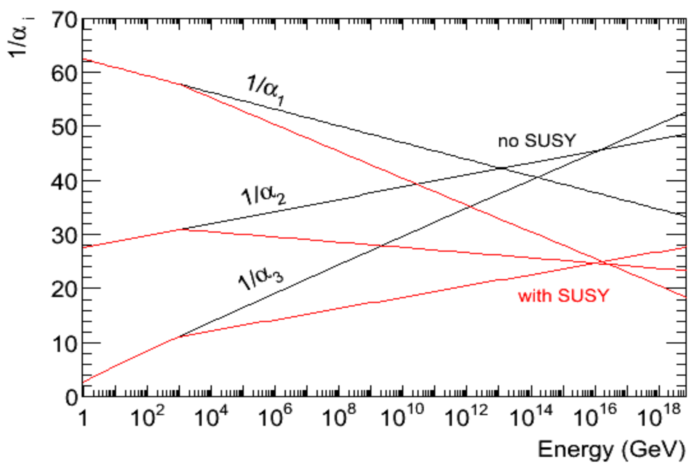
標準模型を超える物理の最有力候補

◆二次発散の相殺



統計性の違いにより
ヒッグス粒子の質量
の二次発散が相殺

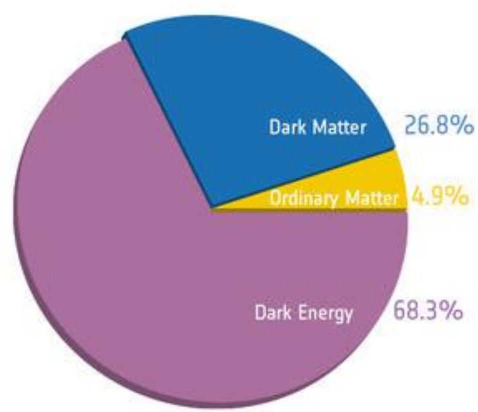
◆ゲージ結合定数の統一



大統一理論を支持

電荷の量子化
アノマリー相殺

◆暗黒物質の候補



最も軽い中性の
超対称性粒子が
暗黒物質の候補に

問題点

- MSSMはツリーレベルで軽いヒッグス粒子を予言　$m_h^2 \leq m_Z^2 \cos^2 2\beta$

⇒ 125 GeV を再現すべく,
ヒッグス粒子の質量を量子補正などで重くする必要性

$$\delta m_h^2 = \frac{3g^2 m_t^4}{8\pi^2 m_W^2}\left[\ln\left(\frac{m_{\tilde{t}}^2}{m_t^2}\right) + \frac{X_t^2}{m_{\tilde{t}}^2}\left(1 - \frac{X_t^2}{12m_{\tilde{t}}^2}\right)\right] \qquad X_t = A_t - \frac{\mu}{\tan\beta}$$

MSSMにおいて超対称性粒子がTeVスケール以下の質量を持つ場合,
量子補正を考慮しても125 GeV の質量は容易に説明出来ない

- 理論のパラメーターが多く, 一般の値を仮定するとCP・FCNCの実験に抵触する
- 超対称性の兆候は未だに発見されていない

⇓

スフェルミオンが現代の加速器実験では到達出来ない程重いという可能性を示唆

高スケール超対称模型

スフェルミオンの質量が 10^{2-3} T程度であれば, 上記の問題を解決出来る

問題点

宇宙論的にも…

- グラヴィティーノ問題

  グラヴィティーノが軽すぎると，グラヴィティーノの崩壊により
  ビッグバン元素合成で作られた元素が壊されてしまう

$$\tau \simeq \frac{M_P^2}{m_{3/2}^3} \simeq 9.8 \times 10^{13} \left(\frac{1\ \mathrm{GeV}}{m_{3/2}}\right)^3 \mathrm{sec}$$

  グラヴィティーノ問題を回避するためには，100 TeV以上の質量が必要

- 暗黒物質の残存量の説明

  WIMP miracle?

  ウィーノで残存量を説明するためには，数TeV程度の質量が望ましい
  (“高スケール”だけれど，そこまで重くなれない)

高スケール超対称模型

このような模型は，アノマリー媒介機構を用いれば実現可能

$$M_a = \frac{b_a g_a^2}{(4\pi)^2} m_{3/2} \qquad b_a = \left(\frac{33}{5}, 1, -3\right)$$

ウィーノLSP

G. F. Giudice, M. A. Luty, H. Murayama & R. Rattazzi, JHEP 9812, 027 (1998)
L. Randall & R. Sundrum, Nucl.Phys. B557, 79 (1999)

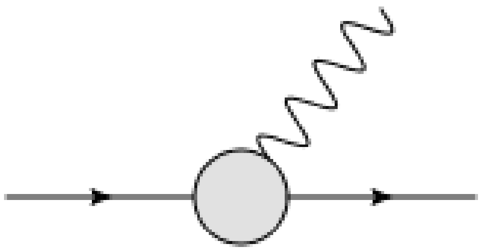
スフェルミオンが重いため，加速器による直接探索は困難

⇒ **電気双極子能率(EDM)に着目**

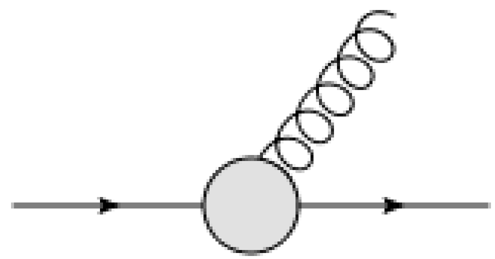
電気双極子能率(EDM)

$$\mathscr{L}_{\not{CP}} = -d_q \frac{i}{2}\bar{q}\sigma^{\mu\nu}\gamma_5 q F_{\mu\nu} - \tilde{d}_q \frac{i g_s}{2}\bar{q}\sigma^{\mu\nu}T^a\gamma_5 q G^a_{\mu\nu} - w\frac{1}{3} f^{abc} G^a_{\mu\sigma} G^{b,\sigma}_{\nu} \tilde{G}^{c,\mu\nu}$$

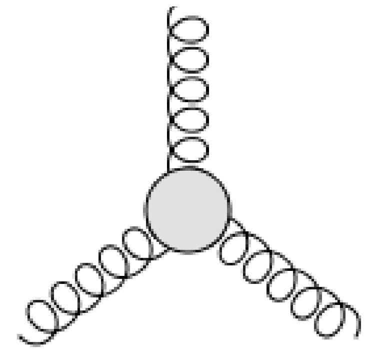
クォークEDM



クォークCEDM



Weinberg演算子



QCD和則 （quark EDM,CEDMによる核子のEDMへの寄与）

$$d_p = -1.2\times 10^{-16}\ [e\ \mathrm{cm}]\ \bar{\theta} + 0.78 d_u - 0.20 d_d + e(-0.28\tilde{d}_u + 0.28\tilde{d}_d + 0.021\tilde{d}_s)$$

$$d_n = +8.2\times 10^{-17}\ [e\ \mathrm{cm}]\ \bar{\theta} - 0.12 d_u + 0.78 d_d + e(-0.30\tilde{d}_u + 0.30\tilde{d}_d - 0.014\tilde{d}_s)$$

J. Hisano, J. Y. Lee, N. Nagata & Y. Shimizu, Phys.Rev. D85, 114044 (2012)

Naïve dimensional analysis （Weinberg operatorによる核子のEDMへの寄与）

$$d_N(w) \sim e\ (10-30)\ \mathrm{MeV}\ w(1\mathrm{GeV})$$

D. A. Demir, M. Pospelov & A. Ritz, Phys.Rev. D67, 015007 (2003)

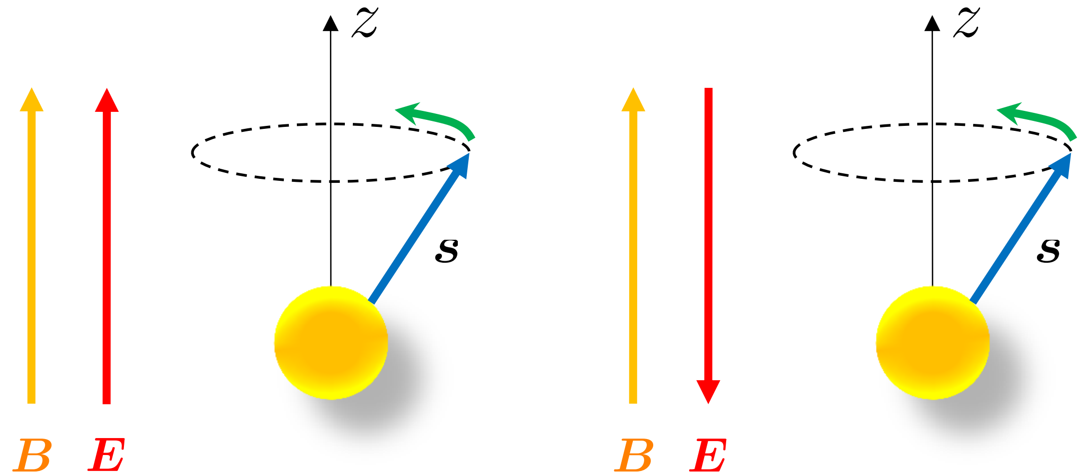
電気双極子能率(EDM)

<u>測定原理</u>

電磁場中のLarmor歳差運動の周波数を測定

$$H = -\boldsymbol{\mu}\cdot\boldsymbol{B} - \boldsymbol{d}\cdot\boldsymbol{E}$$

$$\omega_+ - \omega_- = 4dE$$



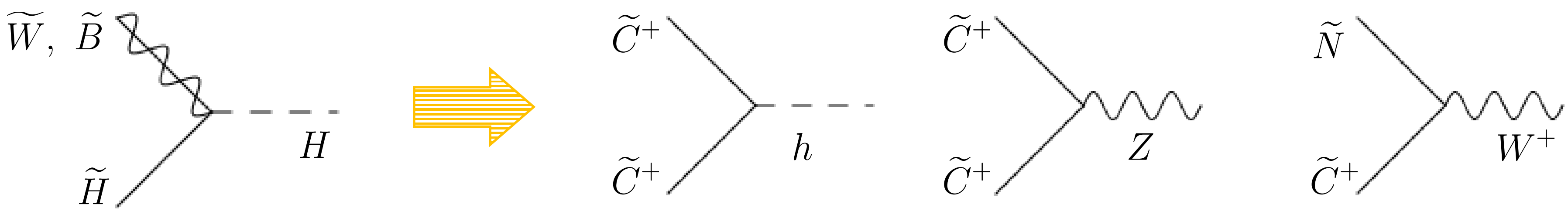
$$\omega_+ = 2\mu B + 2dE \qquad \omega_- = 2\mu B - 2dE$$

	現在の制限 [e cm]	測定対象	参照文献	将来実験の到達目標[e cm]	標準模型の予言値[e cm]
$\lvert d_e \rvert$	$< 8.7 \times 10^{-29}$	ThO	ACME, J. Baron *et al.*, Science 343, 269 (2014)	$\sim 3 \times 10^{-31}$	$\sim 10^{-38}$
$\lvert d_p \rvert$	$< 7.9 \times 10^{-25}$	Hg	W. Griffith *et al.*, Phys.Rev. Lett. 102, 101601 (2009)	$\sim 10^{-29}$	$\sim 10^{-31}$
$\lvert d_n \rvert$	$< 2.9 \times 10^{-26}$	UCN	C. Baker *et al.*, Phys.Rev. Lett.97, 131801 (2006)	$\sim 10^{-28}$	$\sim 10^{-33}$

電気双極子能率(EDM)

高スケール超対称模型ではスフェルミオン関連のCPは重い質量で抑制される

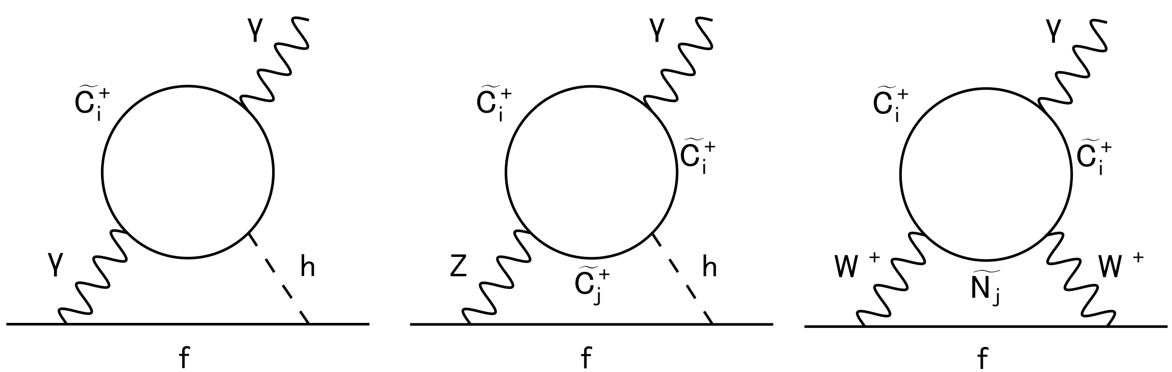
EDMへの主要な寄与はヒッグス–ヒッグシーノ–ゲージーノの結合から



標準模型のフェルミオンと直接結合しない

チャージーノ・ニュートラリーノをループに含む
Barr–ZeeダイアグラムがEDMへの主要な寄与となる

G.F. Giudice & A. Romanino,
Phys. Lett. B 634 (2006) 307



$$M_2 \sim \frac{\alpha_2}{4\pi} M_s$$

$$\sim e\frac{\alpha\alpha_2}{(4\pi)^2}\frac{m_f}{\mu_H M_2} \sim e\frac{\alpha}{4\pi}\frac{m_f}{\mu_H M_s}$$

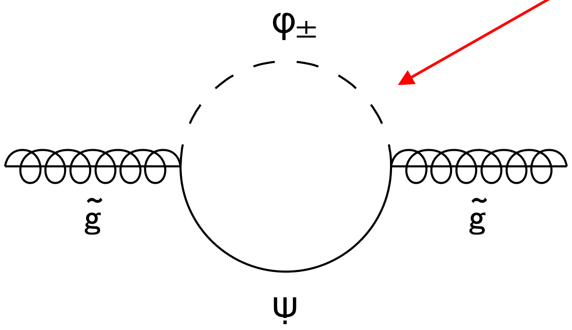
グルイーノCEDMによる
核子のEDMへの寄与

拡張模型

高スケール超対称模型はCPやフレーバーからの実験的な制限が緩い

⇒ 模型が含む粒子はMSSMと同一である必要は無い

高スケール超対称模型 (minimal)	高スケール超対称模型 (extended)
MSSM	MSSM + vector-like matter



vector-like matterのループにより，ゲージーノに追加の質量が生じる

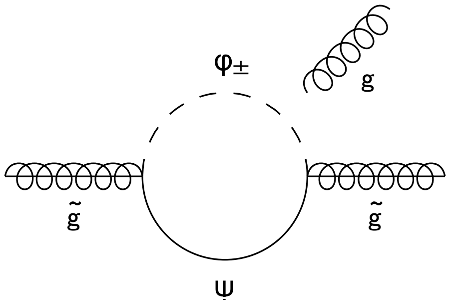
ゲージ媒介機構

ゲージーノの質量 = アノマリー媒介機構の寄与 + ゲージ媒介機構の寄与

相対的な位相差が新たなCP位相となり，核子のEDMに寄与

拡張模型

メッセンジャーの積分でグルイーノCEDMが1ループで生じる



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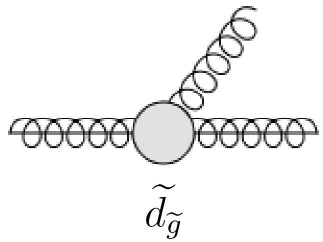
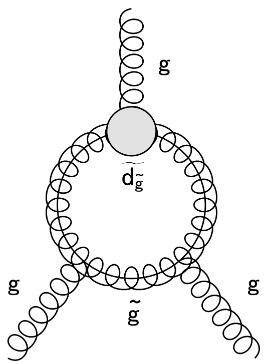


$$\sim \frac{\alpha_s}{4\pi}\frac{1}{M_{\rm mess}}$$

グルイーノを積分してWeinberg演算子が2ループのオーダーで生じる



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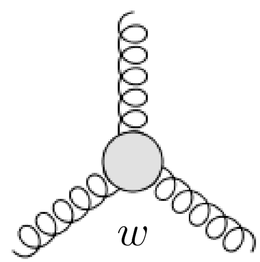


$$\sim \left(\frac{\alpha_s}{4\pi}\right)^2 \frac{1}{M_{\rm mess}M_{\tilde{g}}}$$

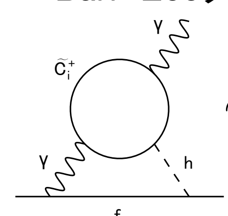
$$M_{\tilde{g}} \sim \frac{\alpha_s}{4\pi}M_s$$

NDAより，核子のEDMが求まる

$$d_N(w) \sim e\ (10-30)\ {\rm MeV}\ w(1{\rm GeV})$$

$$d_N \sim e\left(\frac{\alpha_s}{4\pi}\right)^2 \frac{\Lambda}{M_{\rm mess}M_{\tilde{g}}} \sim e\frac{\alpha_s}{4\pi}\frac{\Lambda}{M_{\rm mess}M_s}$$

Barr–Zeeダイアグラム



$$\sim e\frac{\alpha}{4\pi}\frac{m_f}{\mu_H M_s}$$

計算結果

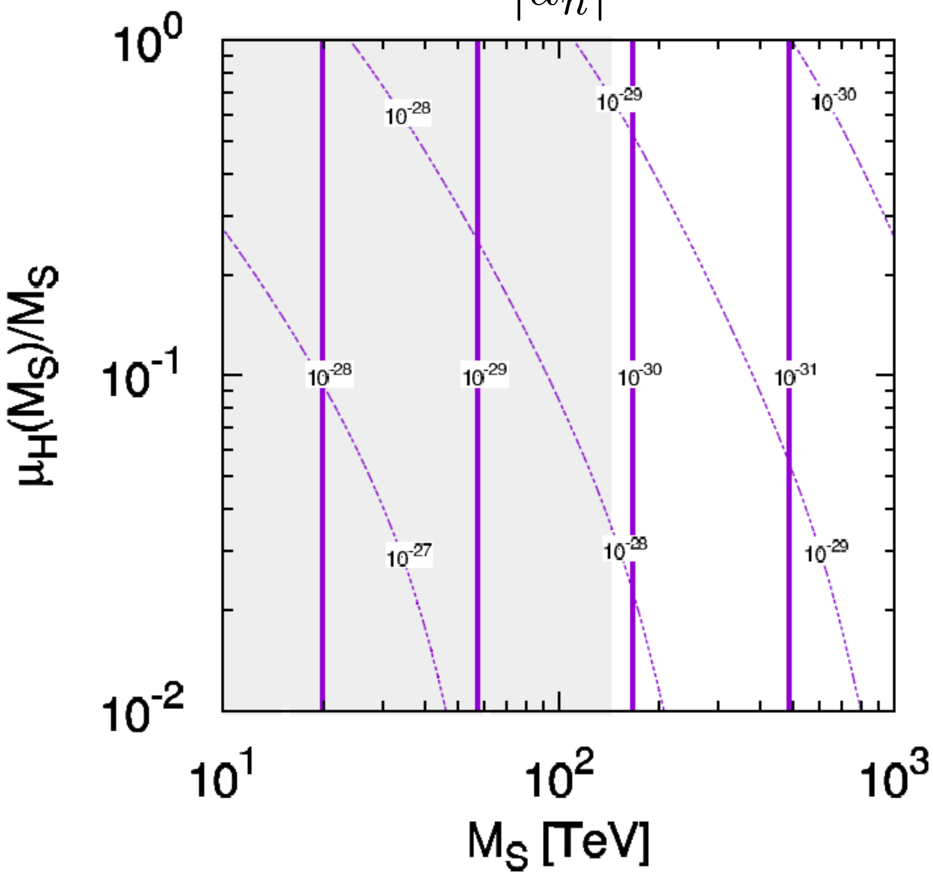
グルイーノCEDMの寄与と，Barr-Zeeダイアグラムの寄与を比較

スフェルミオン，重いヒッグス，グラヴィティーノは
全て M_s に縮退していると仮定
ヒッグシーノ質量 μ_H をフリーパラメーターとしてプロット

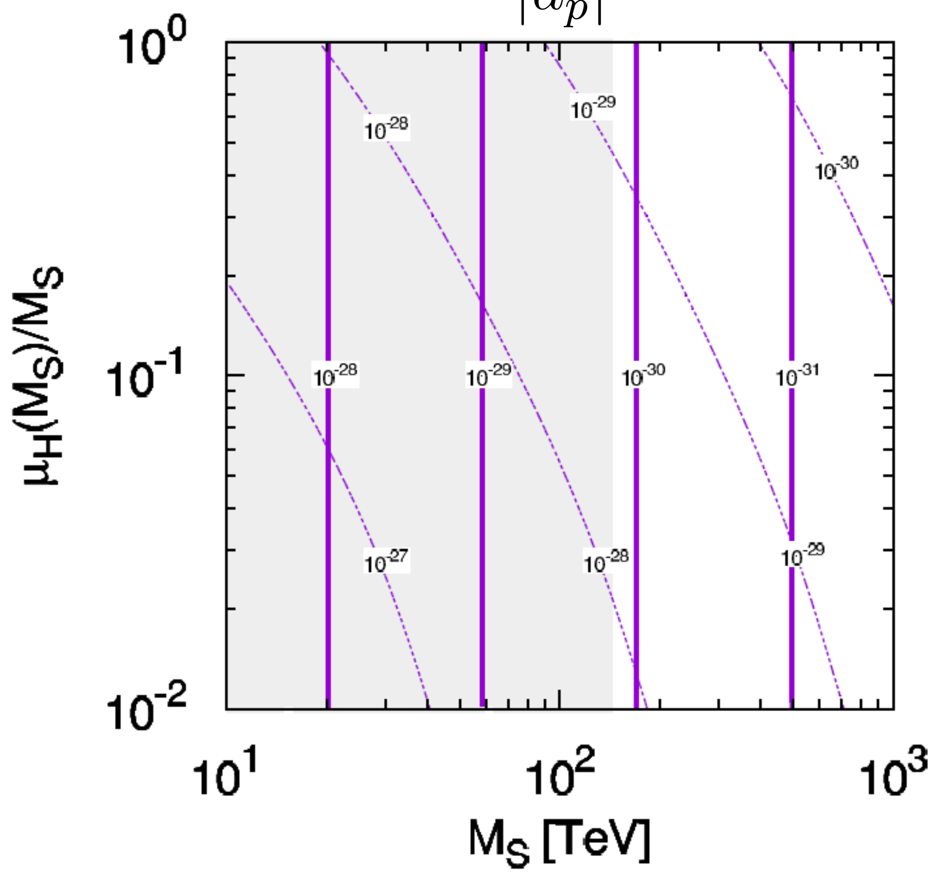
$\tan\beta = 3$

メッセンジャー質量
$M_{\rm mess} = M_s$

$|d_n|$



$|d_p|$



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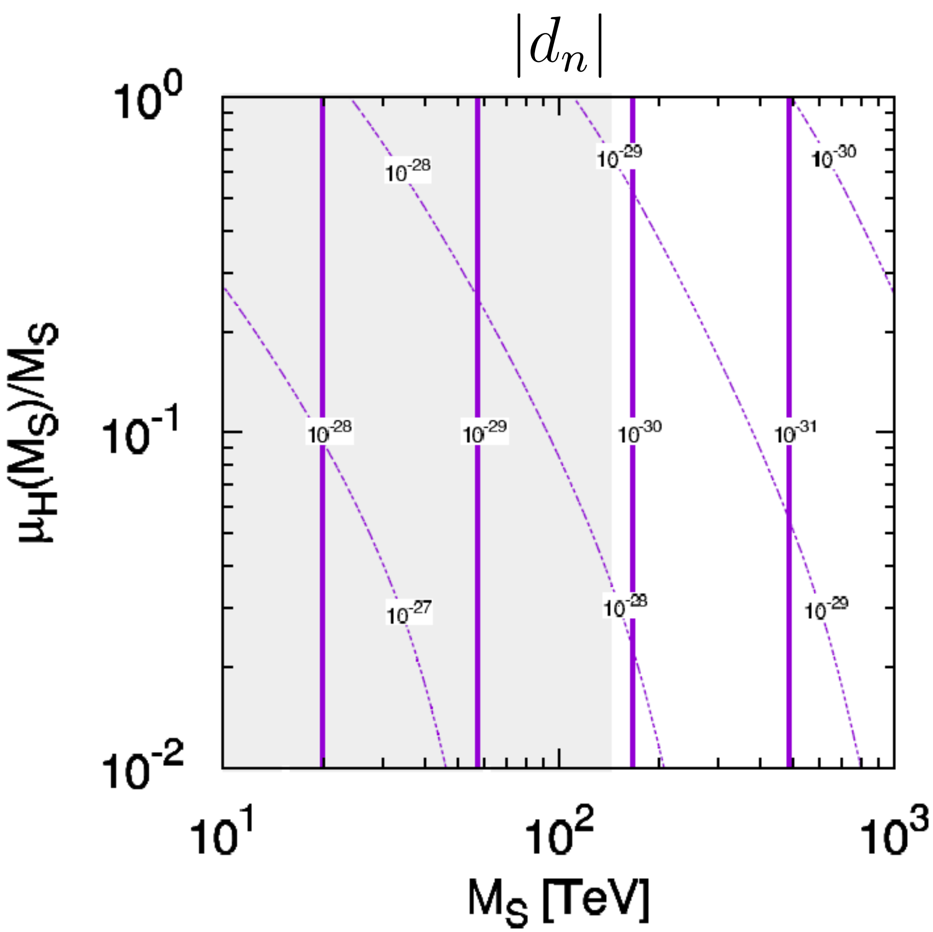

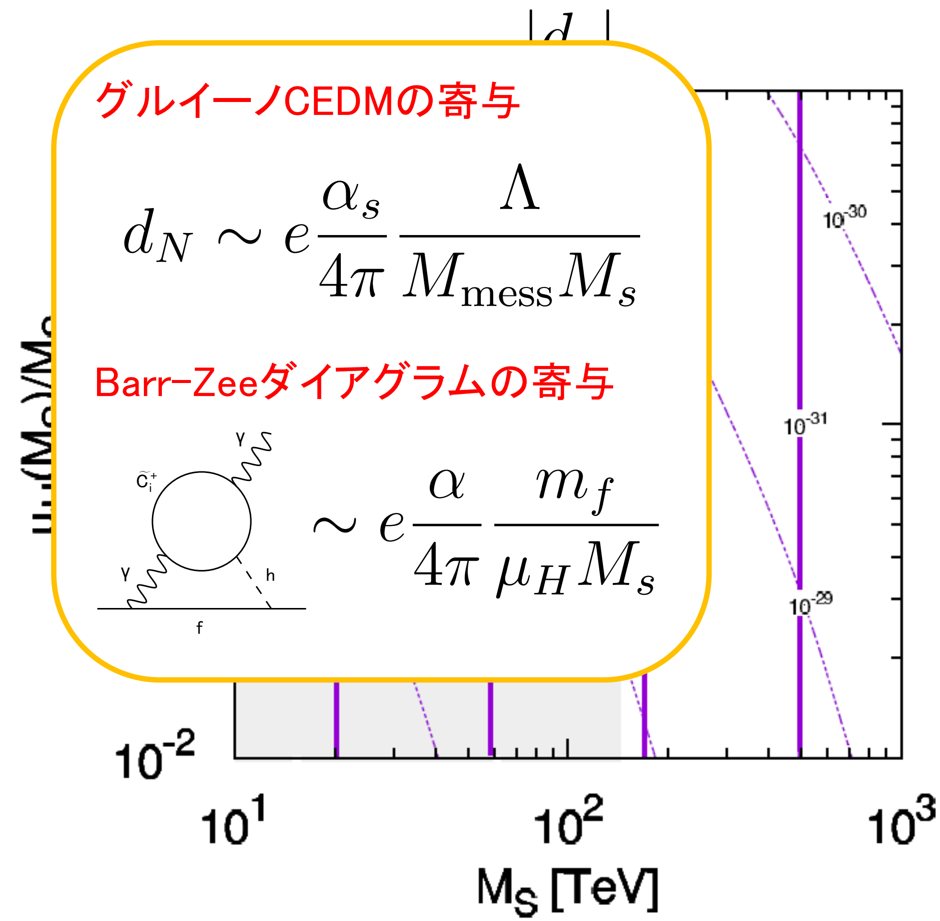

グルイーノCEDMの寄与

$$d_N \sim e\frac{\alpha_s}{4\pi}\frac{\Lambda}{M_{\rm mess}M_s}$$

Barr−Zeeダイアグラムの寄与

$$\sim e\frac{\alpha}{4\pi}\frac{m_f}{\mu_H M_s}$$

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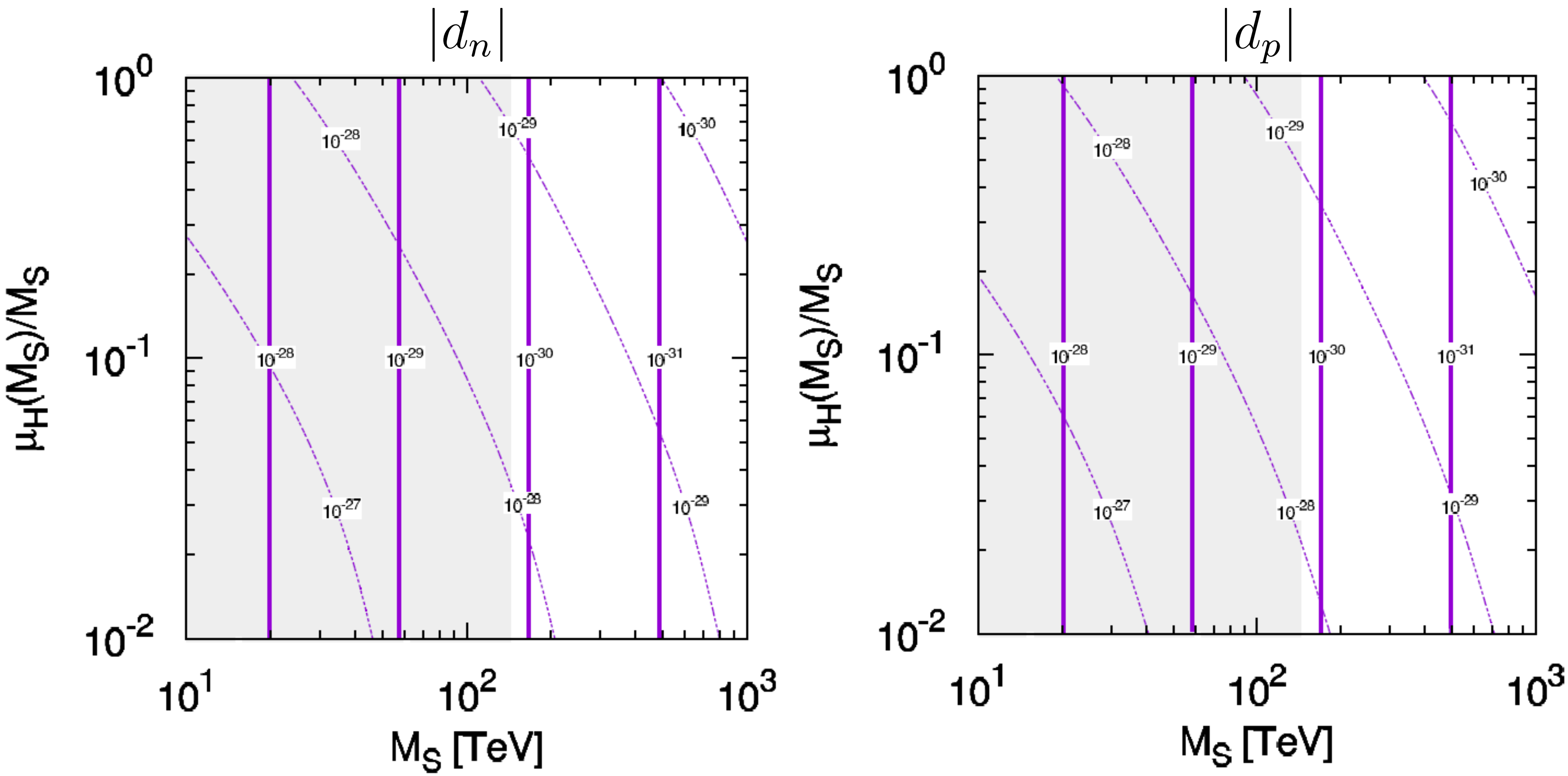

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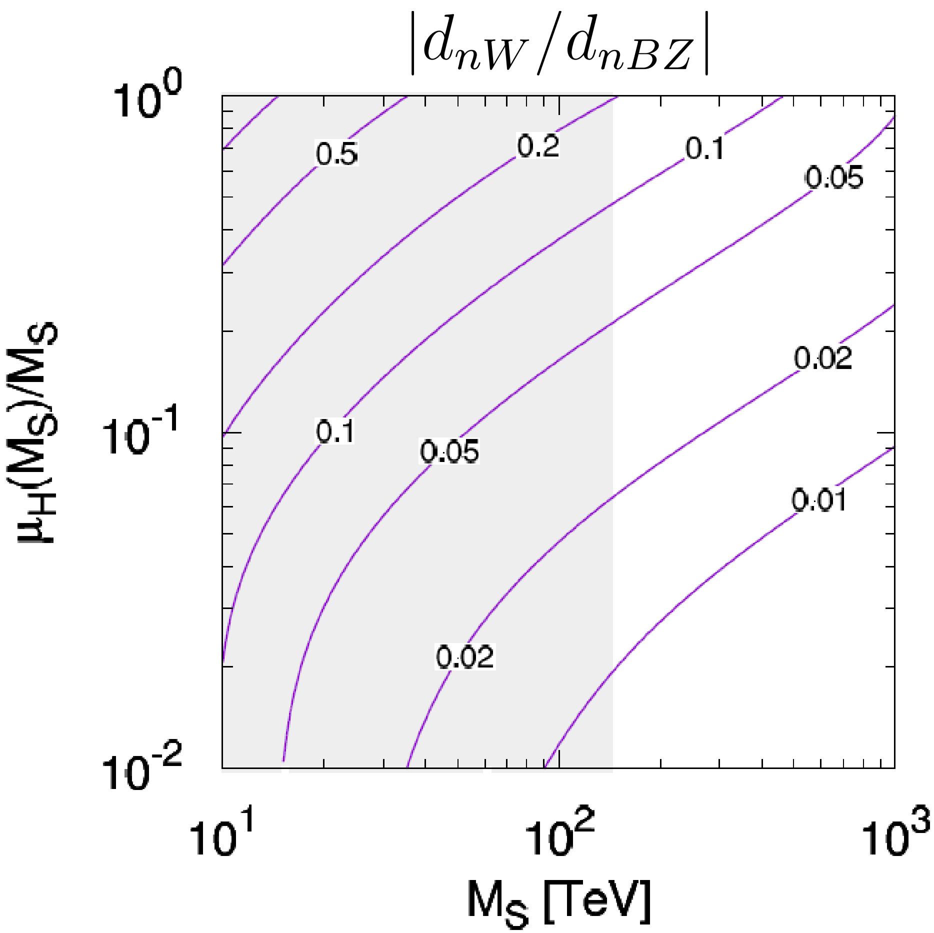
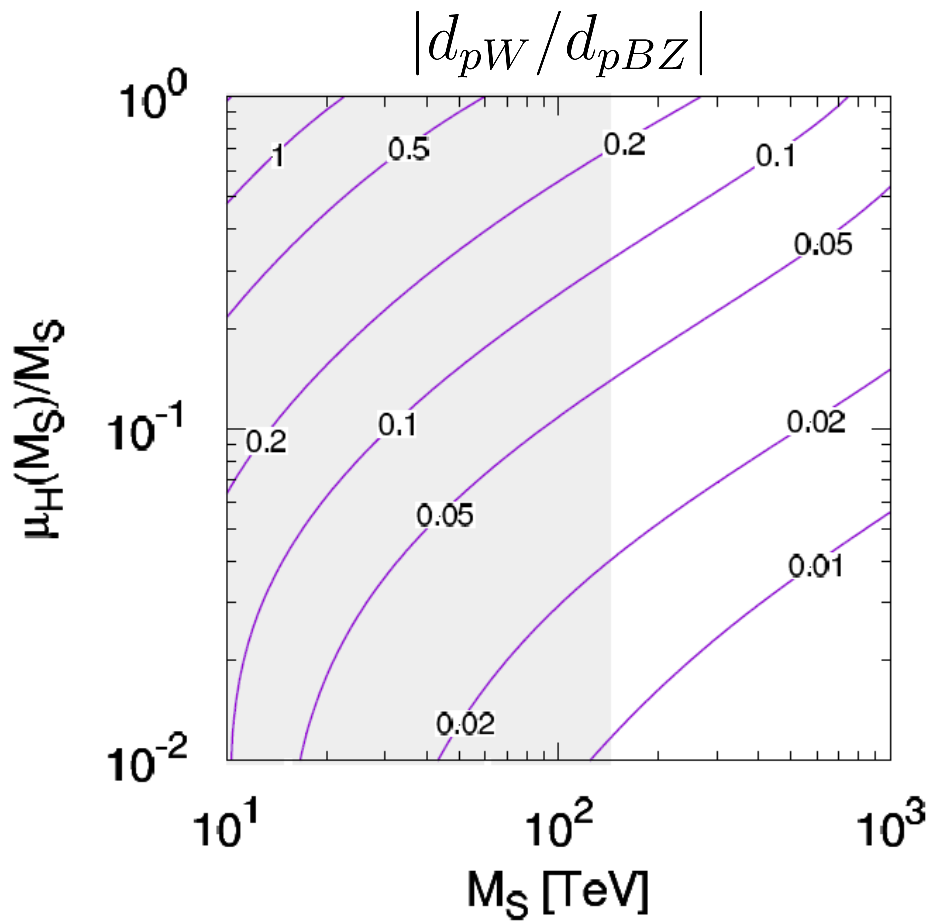




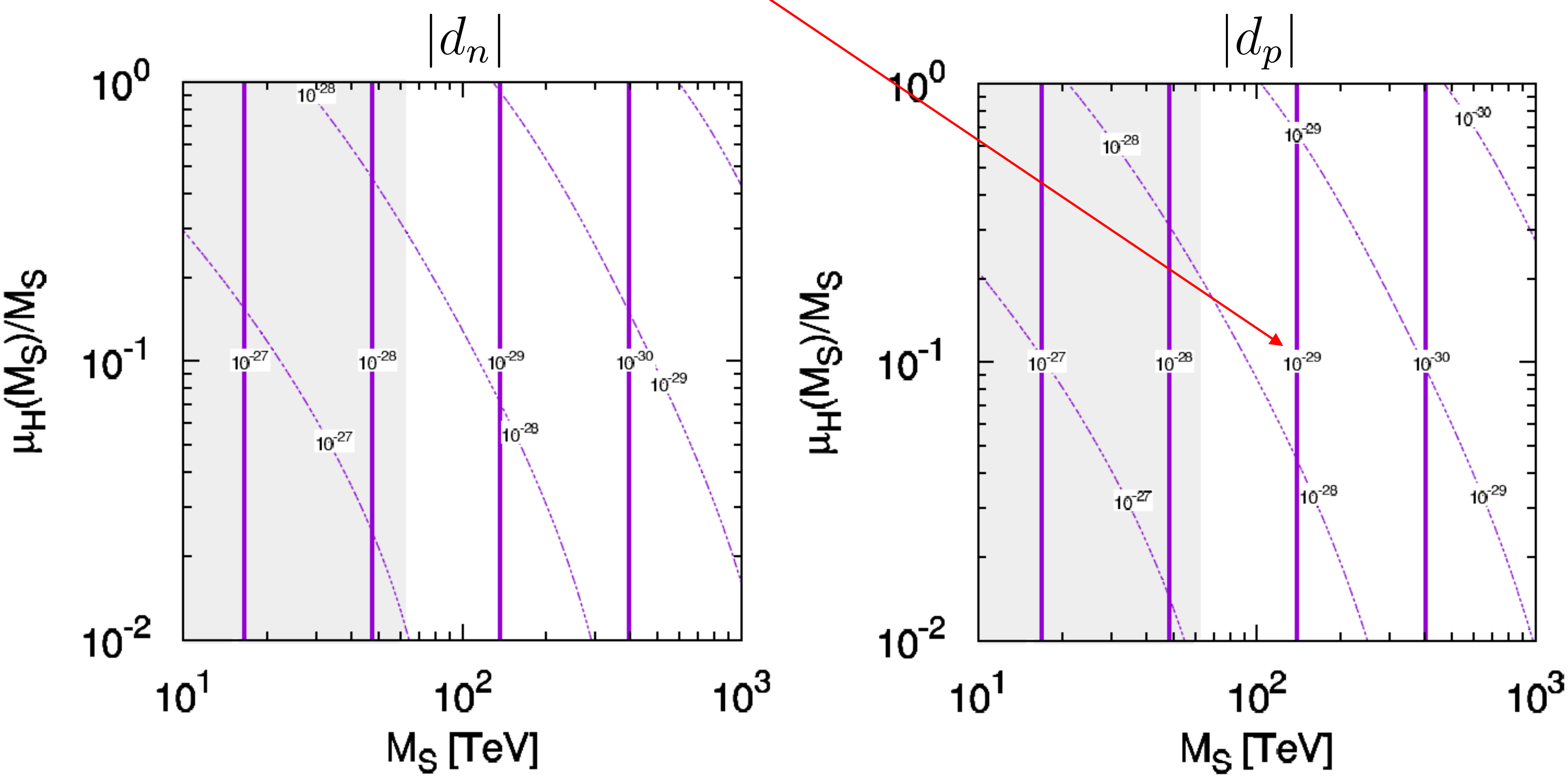
計算結果

軽いメッセンジャーの場合

$M_{\rm mess} = 0.1 M_s$

グルイーノCEDMの寄与が
将来実験における陽子のEDMの
精度を超え得る

⇒ グルイーノCEDMの効果が
観測される可能性



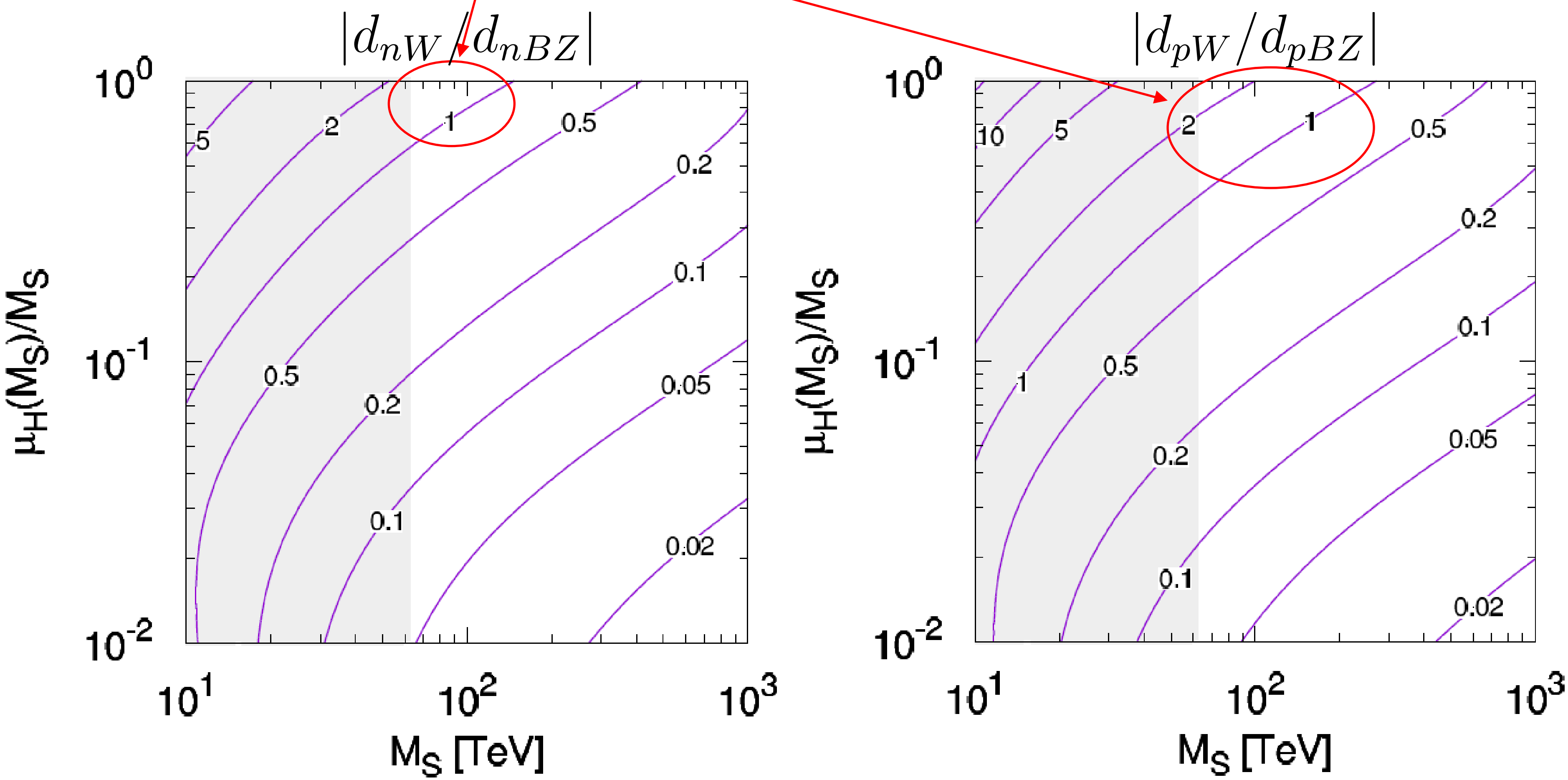
計算結果

軽いメッセンジャーの場合

$M_{\rm mess} = 0.1 M_s$

グルイーノCEDMの寄与が
Barr-Zeeの寄与を超える
領域が存在

⇒ 高スケール超対称模型の
模型の判別に有用



まとめ

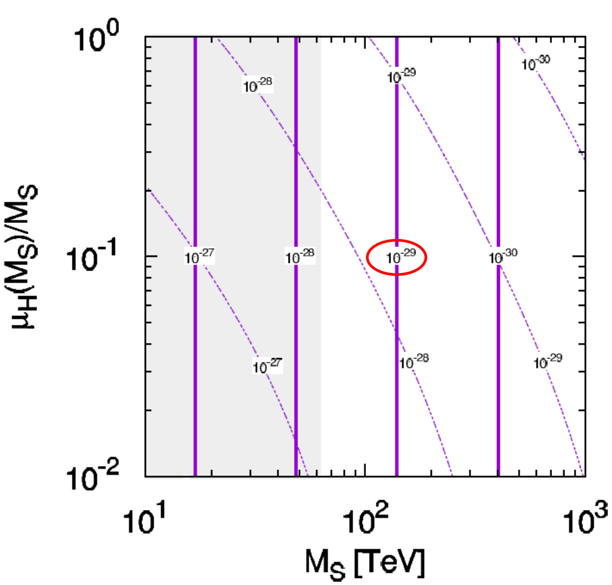
高スケール超対称模型は現象論的に非常に魅力的な模型である.

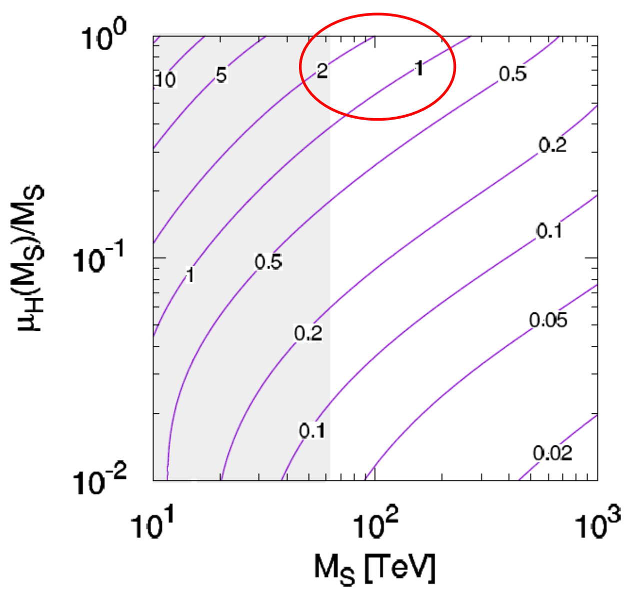
本研究では，グルイーノCEDMという新たな寄与が存在することを指摘した.

⇒ 高スケール超対称模型における核子のEDMの予言に影響する.

高スケール超対称模型がメッセンジャーを含むかどうかの
判断を下せる可能性を示唆.

グルイーノCEDMの寄与は，将来的に陽子のEDMの測定で観測される可能性がある.





将来実験の到達目標

$$|d_p| \sim 10^{-29}\ [e\ \mathrm{cm}]$$

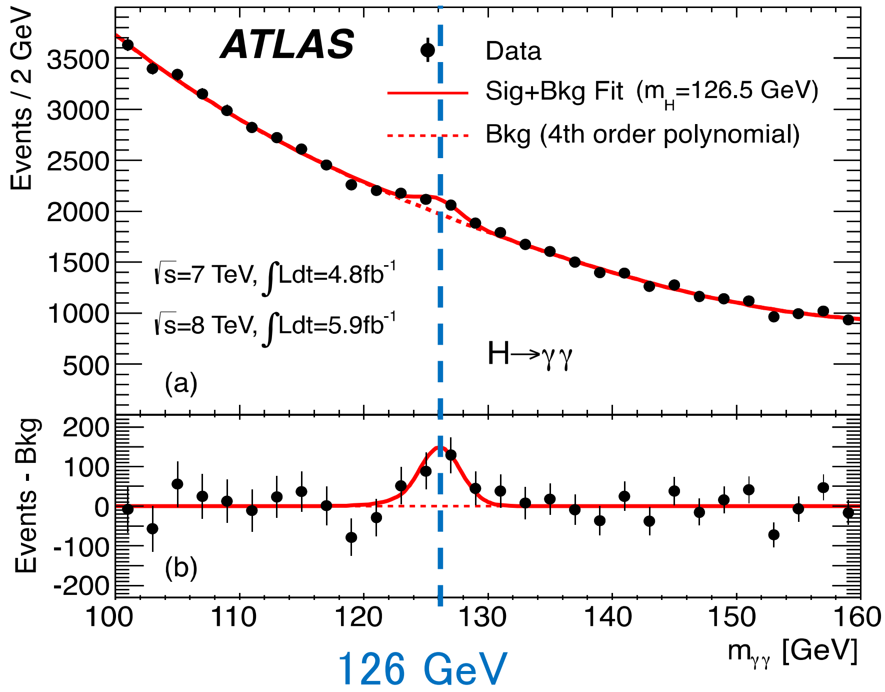
Back up

Introduction

High-scale SUSY

Discovery of Higgs boson
(LHC run 1)

completion of SM



Problems of SM

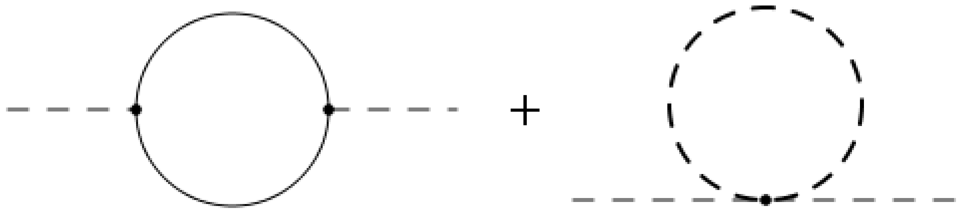
- Gauge hierarchy problem
- Absence of dark matter
- Reason for anomaly cancellation
- Reason for charge quantization

etc.

SM must be extended.

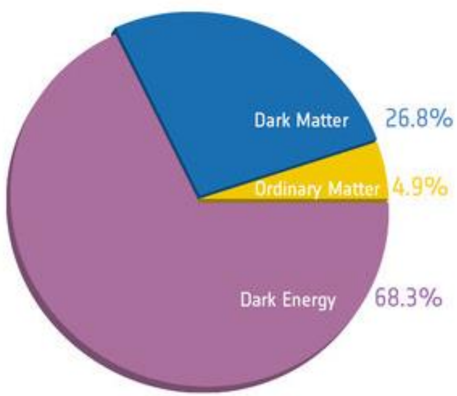
Supersymmetry – One of the most attractive candidate for BSM

◆Cancellation of quadratic divergence



Quadratic divergence of Higgs mass cancels.

◆Candidate for dark matter



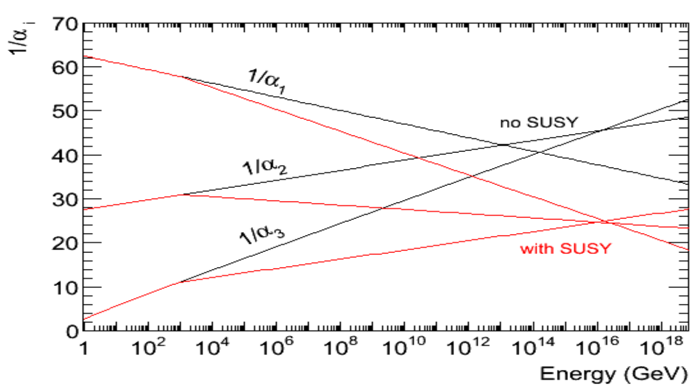
LSP become stable.

◆Unification of gauge couplings

Support of GUT

anomaly cancellation

charge quantization



Problems of SUSY SM

- At tree level, MSSM predicts light Higgs boson. $m_h^2 \leq m_Z^2 \cos^2 2\beta$

To realize 125GeV Higgs,
We must take into account radiative correction, and so on.

$$\delta m_h^2 = \frac{3g^2 m_t^4}{8\pi^2 m_W^2}\left[\ln\left(\frac{m_{\tilde{t}}^2}{m_t^2}\right) + \frac{X_t^2}{m_{\tilde{t}}^2}\left(1 - \frac{X_t^2}{12 m_{\tilde{t}}^2}\right)\right] \qquad X_t = A_t - \frac{\mu}{\tan\beta}$$

When MSSM haves sfermions lighter than TeV,
it is difficult to explain 125 GeV even if radiative correction is considered.

- MSSM haves large number of parameters. When general value is supposed, it immediately conflict with CP・~~FC~~NC experiment.

- Signal of supersymmetry hasn't been observed yet.

These status suggest a possibility that sfermions are very heavy.

High-scale SUSY

Cosmological problems

- Gravitino problem

If gravitino is too light, decay of gravitino destroys nucleus created by BBN.

lifetime $$\tau \simeq \frac{M_P^2}{m_{3/2}^3} \simeq 9.8 \times 10^{13} \left(\frac{1\ \mathrm{GeV}}{m_{3/2}}\right)^3 \mathrm{sec}$$

To avoid the gravitino problem, more than 100 TeV of mass is needed.

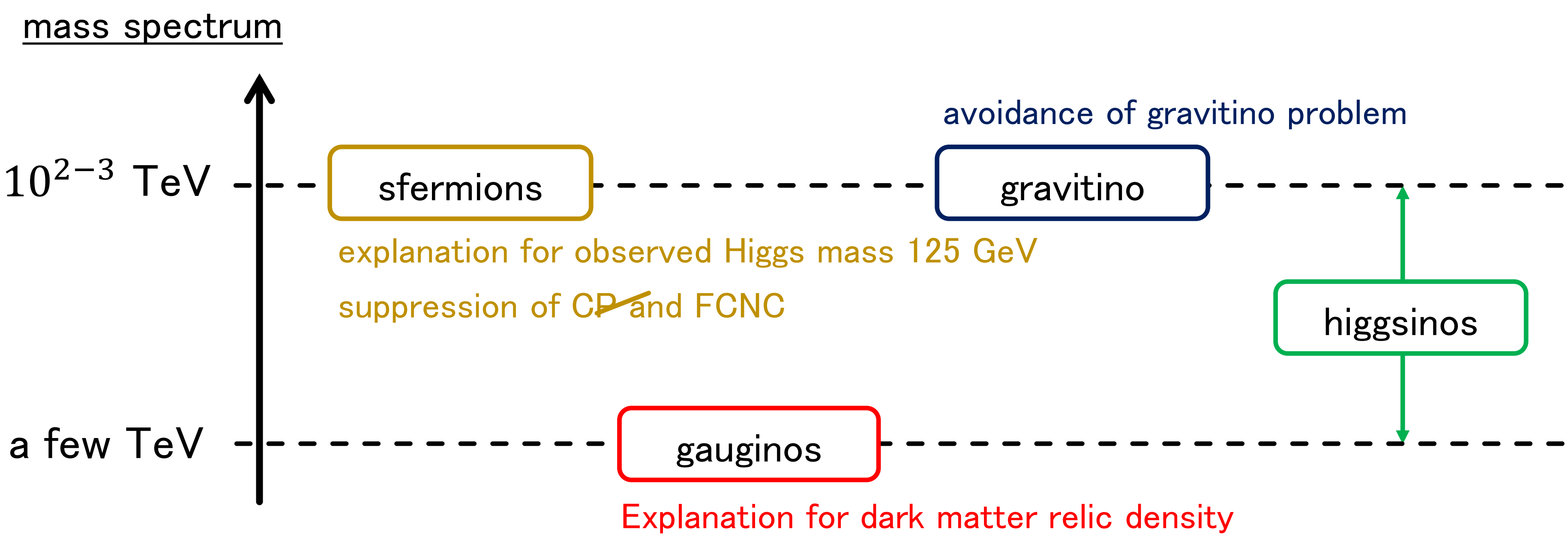
- Explanation for dark matter relic density

WIMP miracle?

If LSP is Wino, a few TeV Wino mass is desired.
In spite of "high-scale", LSP can't be too heavy.

High-scale SUSY

From these reason, following mass spectrum is favored.



Such model can be made when no gauge singlet in hidden sector is assumed and using anomaly mediation.

Gravity–mediated contribution to soft terms

Assuming that there are no gauge singlet in hidden sector.

superpotential
$$W = W_{\text{MSSM}} - \frac{1}{M_P}\left(\frac{1}{6}y^{Xijk}X\Phi_i\Phi_j\Phi_k + \frac{1}{2}\mu^{Xij}X\Phi_i\Phi_j\right) + \cdots$$

Kähler potential
$$\mathcal{K} = \Phi^{*i}\Phi_i + \frac{1}{M_P}(n_i^j X + \bar{n}_i^j X^*)\Phi^{*i}\Phi_j - \frac{1}{M_P^2}k_i^j X X^* \Phi^{*i}\Phi_j + \cdots$$

gauge kinetic function
$$f_{ab} = \frac{\delta_{ab}}{g_a^2}\left(1 - \frac{2}{M_P}f_a X + \cdots\right)$$

$$F = \langle F_X \rangle$$

gaugino mass
$$M_a = \frac{F}{M_P}f_a$$

A–term
$$a^{ijk} = \frac{F}{M_P}(y^{Xijk} + n_p^i y^{pjk} + n_p^j y^{pik} + n_p^k y^{pij})$$

B–term
$$b^{ij} = \frac{F}{M_P}(\mu^{Xij} + n_p^i \mu^{pj} + n_p^j \mu^{pi})$$

squared–mass
$$(m^2)_j^i = \frac{|F|^2}{M_P^2}(k_j^i + n_p^i \bar{n}_j^p)$$

$$\mu_{\text{SUSY}} \sim 10^{12}\ \text{GeV}$$

sfermion mass

$$M_s \sim \frac{|F|}{M_P}$$

$$\sim 10^{2-3}\ \text{TeV}$$

Gravity mediation won't be main contribution of gaugino mass.

Anomaly–mediated contribution

Due to anomalous breaking of superconformal symmetry,
soft terms are arise through scale dependence.

Especially, this will be main contribution of gaugino mass.

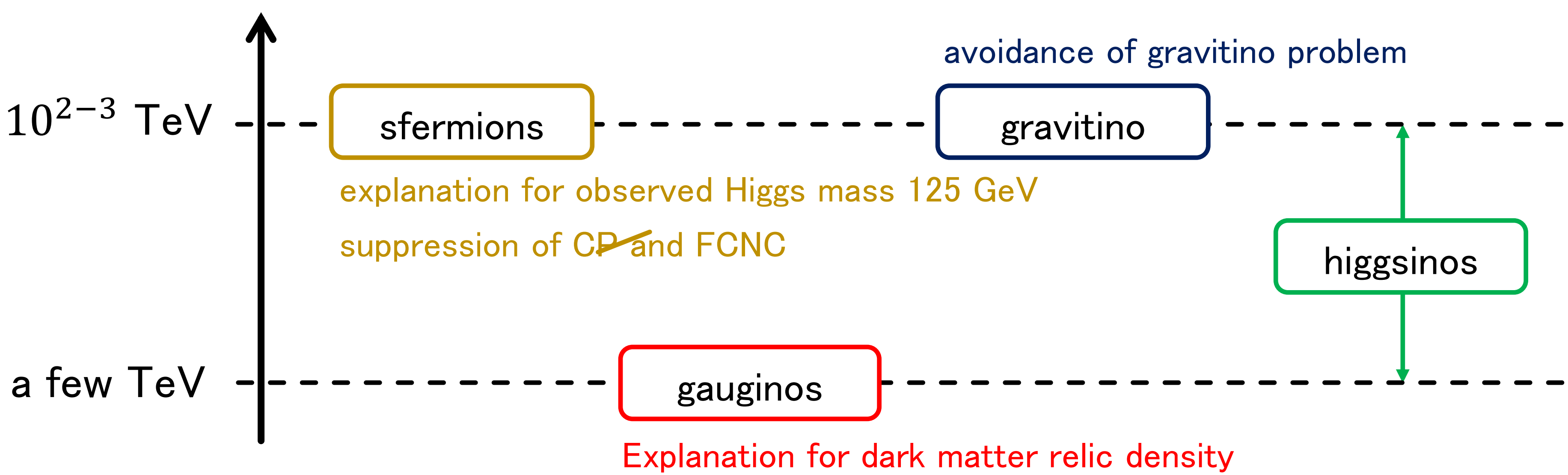
$$M_a^{\mathrm{AMSB}} = \frac{b_a g_a^2}{(4\pi)^2} m_{3/2} \qquad b_a = \left(\frac{33}{5}, 1, -3\right)$$

Wino becomes LSP.

G. F. Giudice, M. A. Luty, H. Murayama & R. Rattazzi, JHEP 9812, 027 (1998)

L. Randall & R. Sundrum, Nucl.Phys. B557, 79 (1999)

Using anomaly mediation, we can easily make this mass spectrum.



High-scale SUSY model is very attractive phenomenologically because this model can solve many problems.

However, sfermions are so heavy that
It is difficult to search directly at collider experiment.

To search a such model,
What physical observable should we focus on?

⇒ We focus on electric dipole moments(EDM),
observable based on CP violation.

Introduction

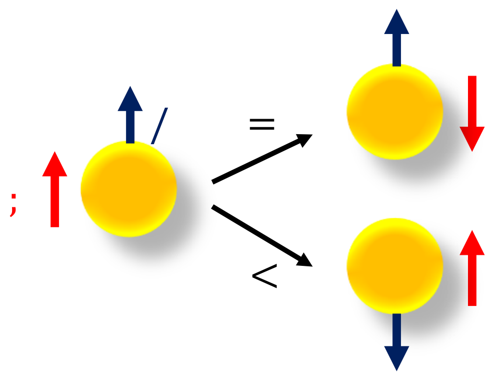
Electric Dipole Moment

Electric Dipole Moment

The only vectorial quantum numbers associated with a point-like particle are its momentum $\boldsymbol{p}$ and spin $\boldsymbol{s}$.

For a particle at rest, EDM must be proportional to the spin.

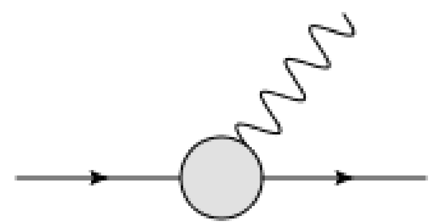
$$\boldsymbol{d}_f = d_f \frac{\boldsymbol{s}}{|\boldsymbol{s}|} \qquad H_{\rm EDM} = -\boldsymbol{d}_f \cdot \boldsymbol{E} = -d_f \frac{\boldsymbol{s} \cdot \boldsymbol{E}}{|\boldsymbol{s}|}$$



$\boldsymbol{s} \cdot \boldsymbol{E}$ is odd under P, T.

CPT theorem

EDM is odd under CP.

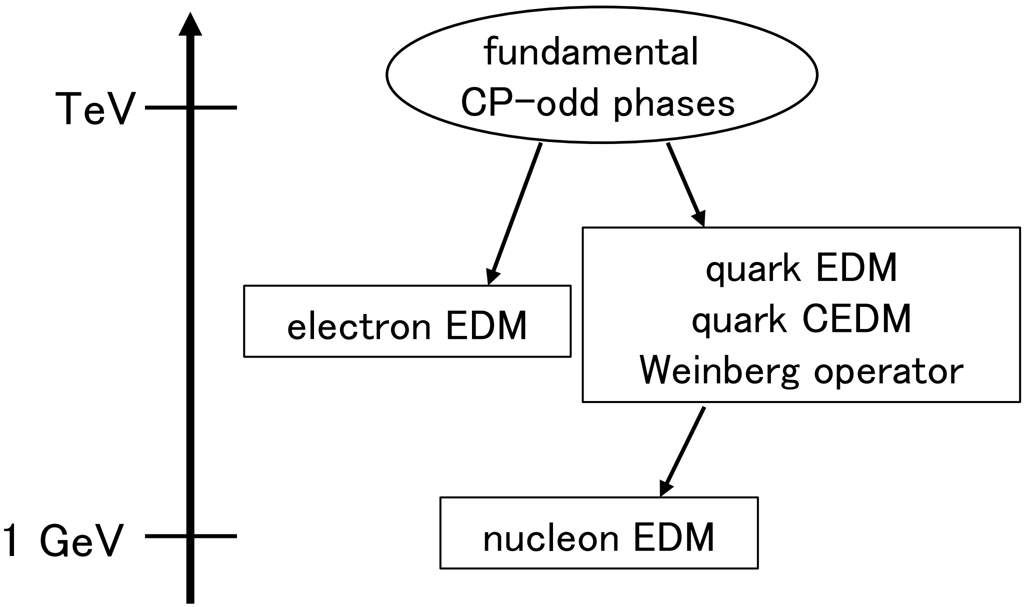


$$H_{\rm EDM} = -d_f \frac{\boldsymbol{s} \cdot \boldsymbol{E}}{|\boldsymbol{s}|} \quad \Rightarrow \quad \mathscr{L}_{\rm EDM} = -d_f \frac{i}{2} \bar{f} \sigma^{\mu\nu} \gamma_5 f F_{\mu\nu}$$

dimension 5, CP-odd operator

SM predictions of EDMs are small, so EDMs are sensitive to TeV scale physics.

Nucleon EDM

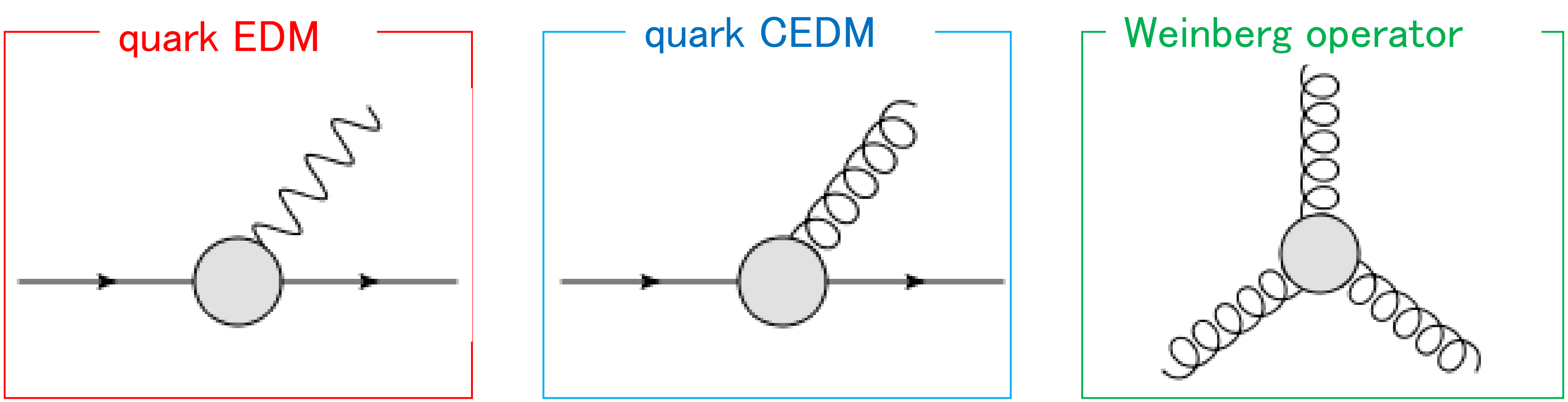


Usually, new physics contains CP phases.

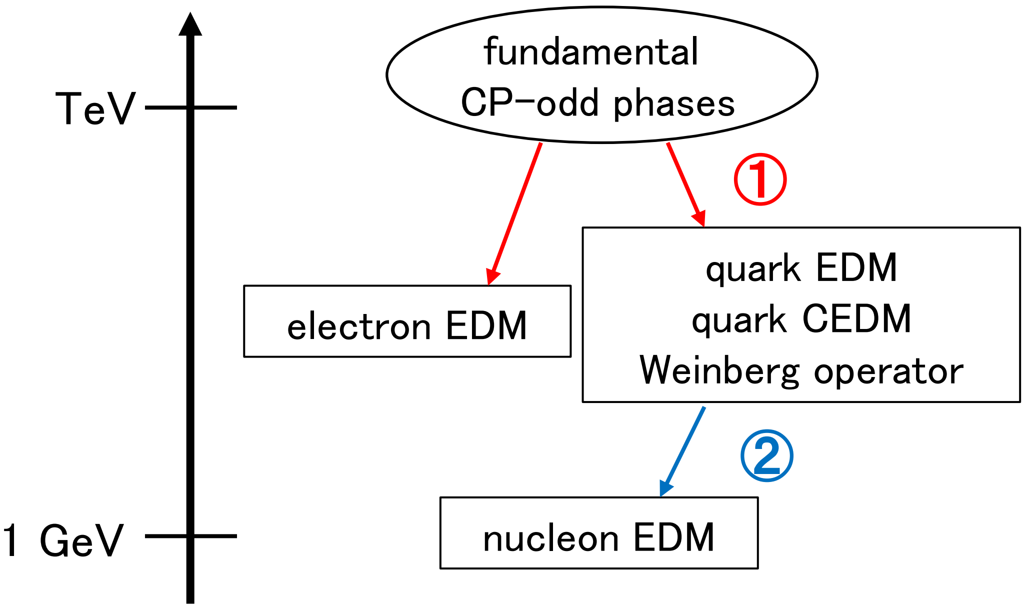
Integrating out heavy degree of freedom induces CP-odd operators.

Nucleon EDMs are deduced from these operators.

$$\mathscr{L}_{\not{CP}} = -d_q \frac{i}{2}\bar{q}\sigma^{\mu\nu}\gamma_5 q F_{\mu\nu} - \tilde{d}_q \frac{ig_s}{2}\bar{q}\sigma^{\mu\nu}T^a\gamma_5 q G^a_{\mu\nu} - w\frac{1}{3} f^{abc} G^a_{\mu\sigma} G^{b,\sigma}_{\nu} \tilde{G}^{c,\mu\nu}$$



Nucleon EDM



①RG evolution

$$\mu \frac{d}{d\mu}\begin{pmatrix} C_1^q \\ C_2^q \\ C_W \end{pmatrix} = \frac{\alpha_s}{4\pi}\begin{pmatrix} 8C_F & 8C_F & 0 \\ 0 & 16C_F - 4N & 2N \\ 0 & 0 & N + 2n_f + \beta_0 \end{pmatrix}\begin{pmatrix} C_1^q \\ C_2^q \\ C_W \end{pmatrix}$$

G. Degrassi, E. Franco, S. Marchetti & L. Silvestrini, JHEP 0511, 044 (2005)

②QCD sum rule (contribution from quark EDM and CEDM)

$$d_p = -1.2 \times 10^{-16}\ [e\ \mathrm{cm}]\ \bar{\theta} + 0.78 d_u - 0.20 d_d + e(-0.28\tilde{d}_u + 0.28\tilde{d}_d + 0.021\tilde{d}_s)$$

$$d_n = +8.2 \times 10^{-17}\ [e\ \mathrm{cm}]\ \bar{\theta} - 0.12 d_u + 0.78 d_d + e(-0.30\tilde{d}_u + 0.30\tilde{d}_d - 0.014\tilde{d}_s)$$

J. Hisano, J. Y. Lee, N. Nagata & Y. Shimizu, Phys.Rev. D85, 114044 (2012)

Naïve dimensional analysis (contribution from Weinberg op.)

$$d_N(w) \sim e\ (10 - 30)\ \mathrm{MeV}\ w(1\mathrm{GeV})$$

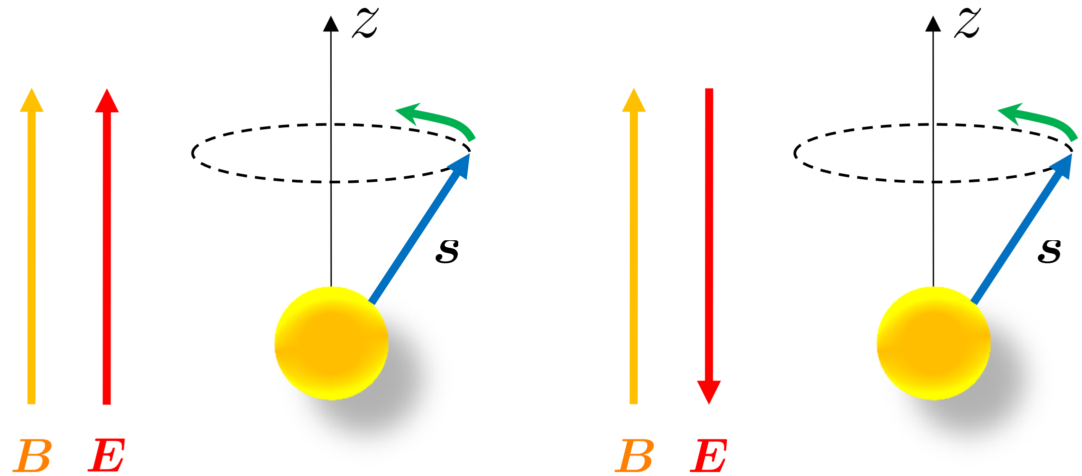
D. A. Demir, M. Pospelov & A. Ritz, Phys.Rev. D67, 015007 (2003)

Experimental bounds

The frequency of the Larmor precession in electromagnetic field is measured.

$$H = -\boldsymbol{\mu}\cdot\boldsymbol{B} - \boldsymbol{d}\cdot\boldsymbol{E}$$

$$\omega_+ - \omega_- = 4dE$$



$$\omega_+ = 2\mu B + 2dE \qquad \omega_- = 2\mu B - 2dE$$

	Current bounds [e cm]	Target	ref.	sensitivity of the future exp. [e cm]	SM value [e cm]
$\lvert d_e \rvert$	$< 8.7\times10^{-29}$	ThO	ACME, J. Baron *et al.*, Science 343, 269 (2014)	$\sim 3\times10^{-31}$	$\sim 10^{-38}$
$\lvert d_p \rvert$	$< 7.9\times10^{-25}$	Hg	W. Griffith *et al.*, Phys.Rev. Lett. 102, 101601 (2009)	$\sim 10^{-29}$	$\sim 10^{-31}$
$\lvert d_n \rvert$	$< 2.9\times10^{-26}$	UCN	C. Baker *et al.*, Phys.Rev. Lett.97, 131801 (2006)	$\sim 10^{-28}$	$\sim 10^{-33}$

Barr-Zee contribution

to EDM

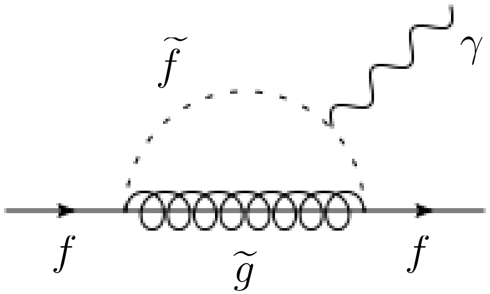
EDM prediction in high-scale SUSY

MSSM haves large number of CP phase.
Therefore, there are many contribution to EDM.

I'll see what kind of contribution dominates in high-scale SUSY model.

Typical 1-loop diagram

$$M_a \simeq \frac{\alpha_a}{4\pi} M_s$$



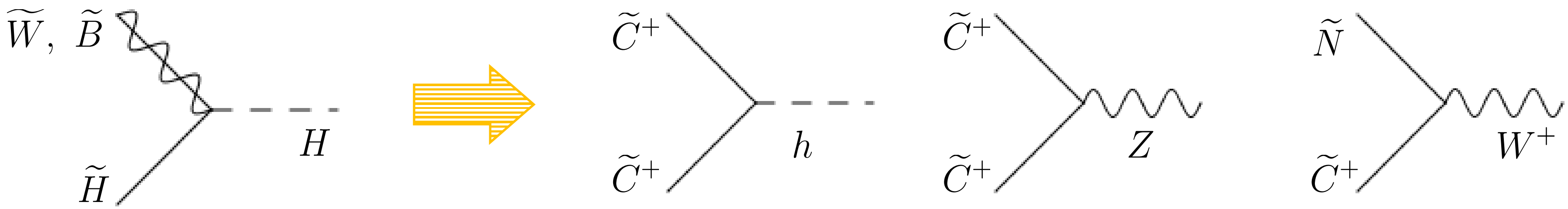
$$\sim \frac{e\alpha_s}{4\pi} \frac{m_f \mu_H \tan\beta \; M_{\widetilde{g}}}{M_s^4} \sim e \left(\frac{\alpha_s}{4\pi}\right)^2 \frac{m_f \mu_H \tan\beta}{M_s^3}$$

- CP violations rerated to sfermions are sufficiently suppress due to heavy sfermion mass.

- Fermion EDM calculated from this diagram looks like 2-loop contribution due to relatively light gaugino mass.

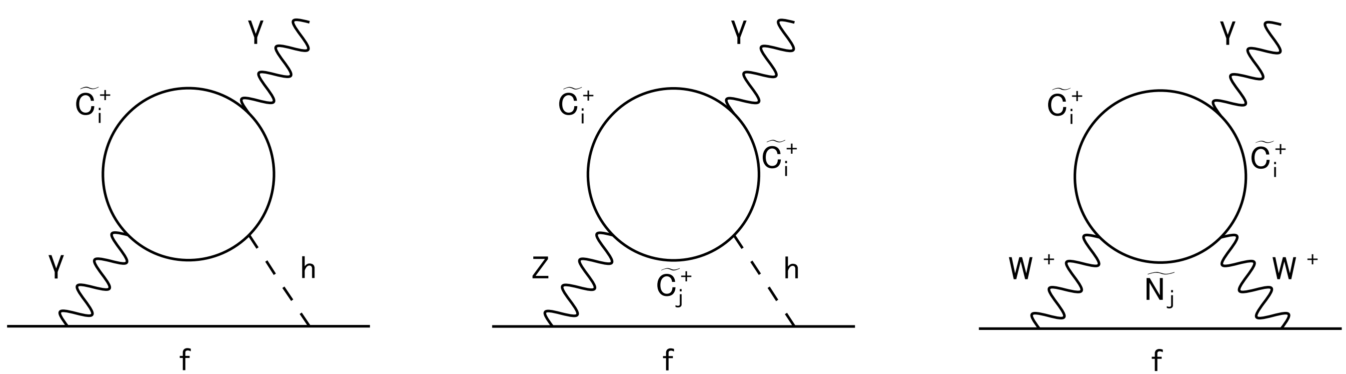
- CP violations rerated to sfermions are sufficiently suppress due to heavy sfermion mass.

How about a gaugino-higgsino sector?



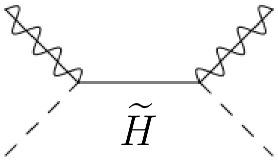
Which doesn't couple to SM fermions directly.

Dominant contribution to EDM from these coupling are arize at 2-loop level, called Barr-Zee diagrams with chargino/neutralino loop.

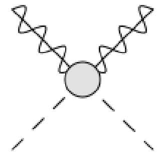


Barr–Zee diagram

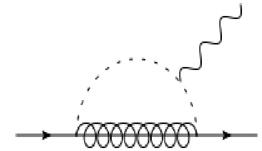
dim. 5



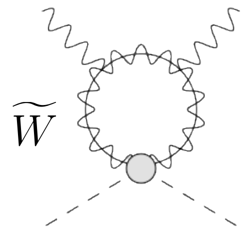
integrating out higgsino



$$\sim \frac{g_2^2}{\mu_H}$$

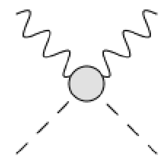


$$\sim e \left(\frac{\alpha_s}{4\pi}\right)^2 \frac{m_f \mu_H \tan\beta}{M_s^3}$$



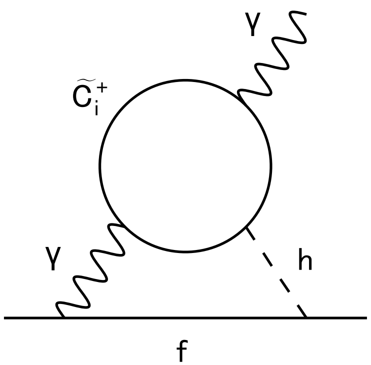
integrating out wino

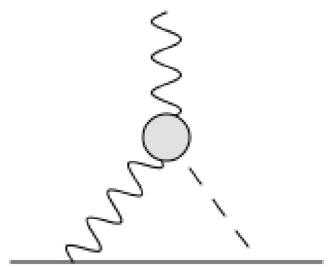
dim. 6



$$\sim \frac{g_2^2}{\mu_H} \cdot \frac{\alpha}{4\pi}\frac{1}{M_2} = \frac{\alpha\alpha_2}{\mu_H M_2}$$

$$M_a \simeq \frac{\alpha_a}{4\pi} M_s$$



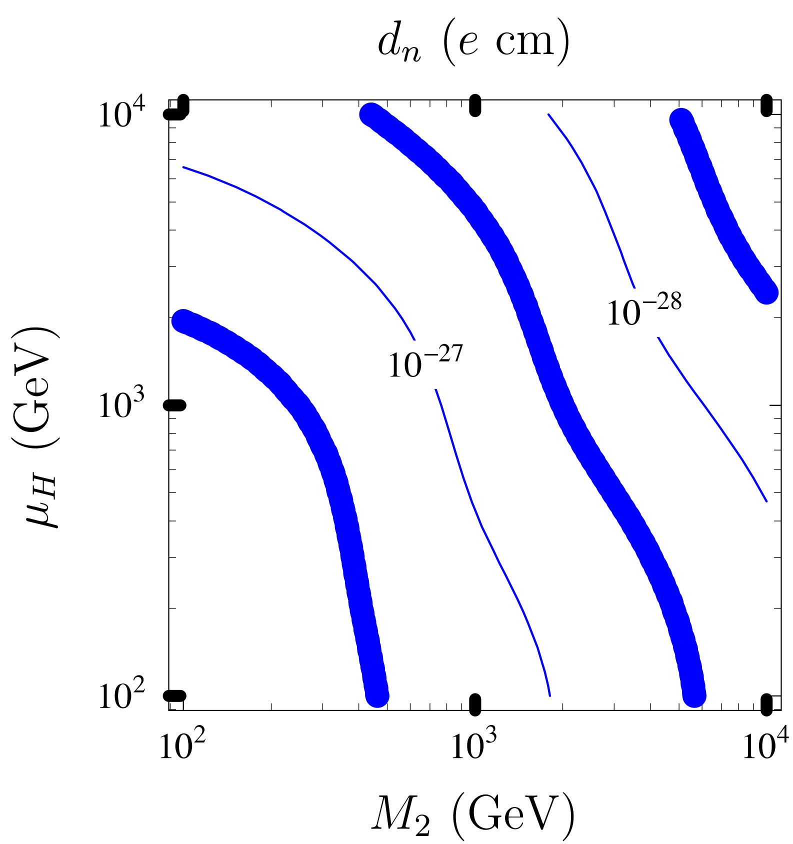


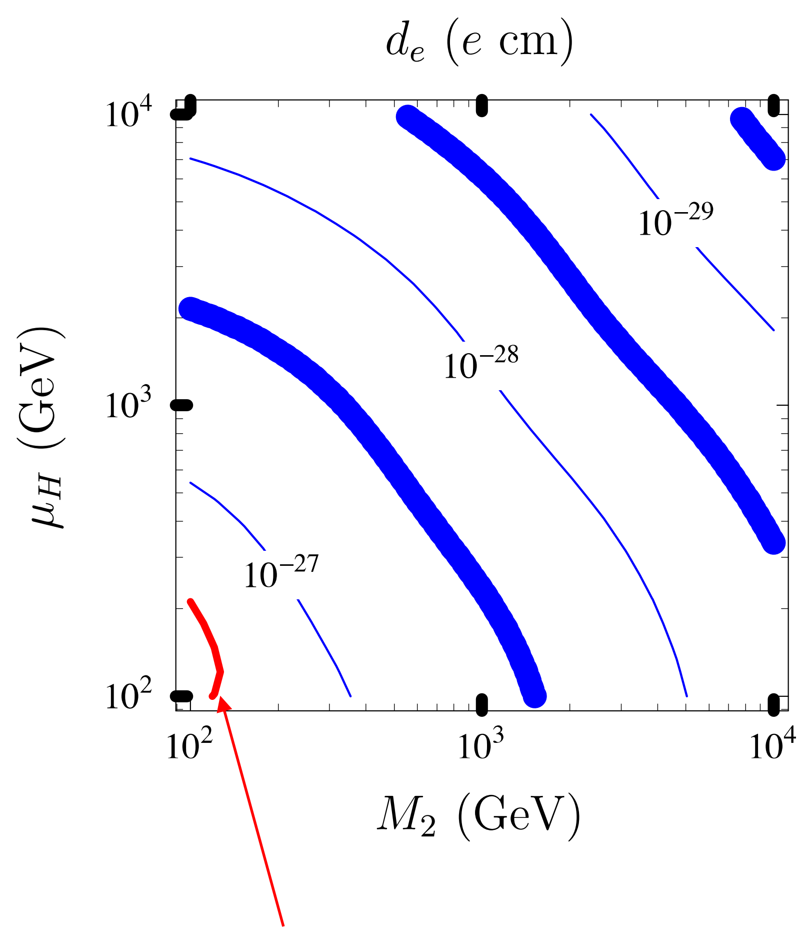
$$\sim \frac{\alpha\alpha_2}{\mu_H M_2} \cdot \frac{e m_f}{(4\pi)^2} = e\frac{\alpha}{4\pi}\frac{m_f}{\mu_H M_s}$$

- Barr–Zee contribution to EDM looks like 1–loop level due to gaugino mass.
- Barr–Zee diagrams become dominant contribution to EDM in high-scale SUSY.

Numerical values

G.F. Giudice & A. Romanino, Phys. Lett. B 634 (2006) 307





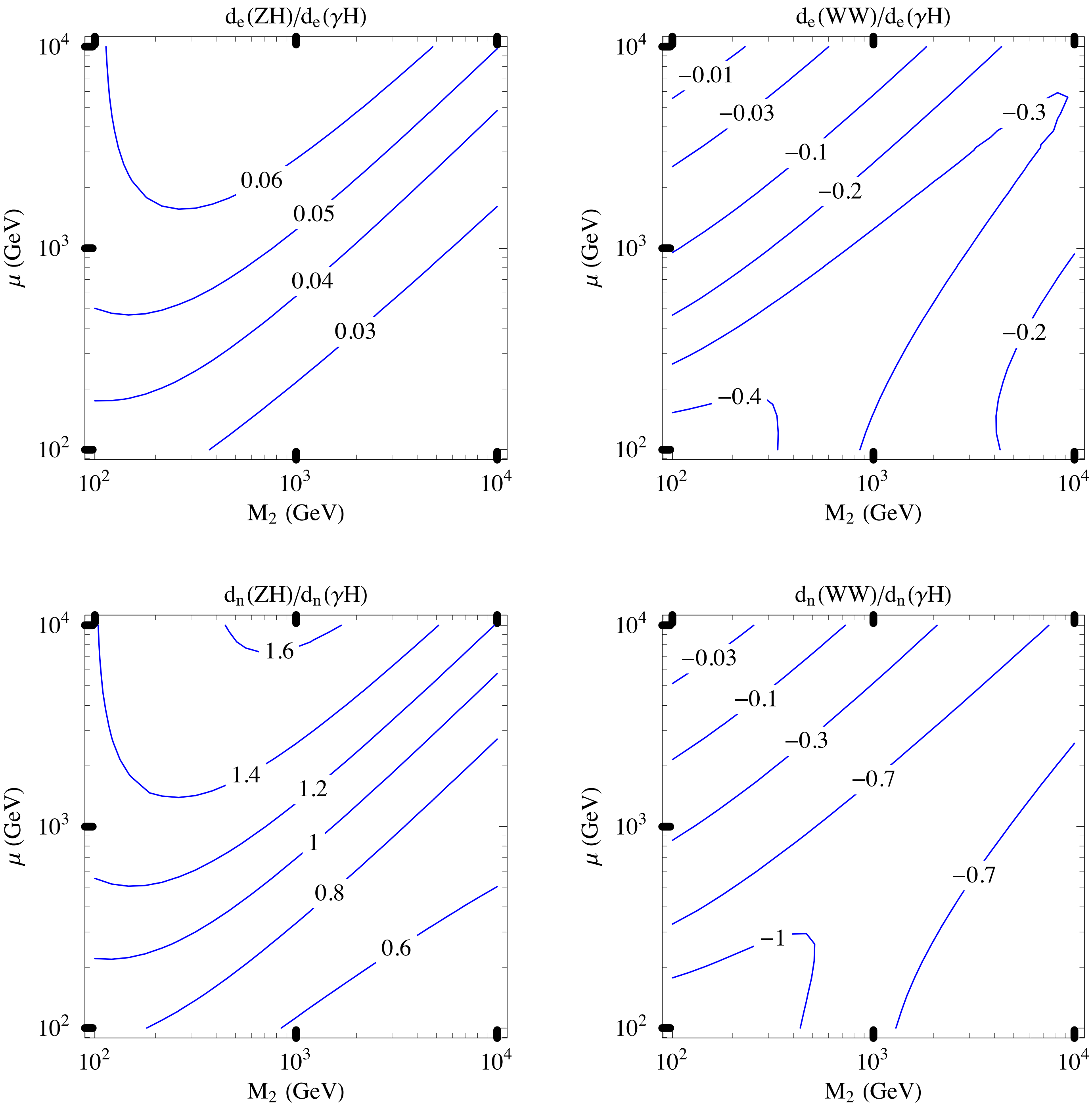
$d_e < 1.6 \times 10^{-27} e$ cm

(bound of ten years ago)

Current bounds

$$d_n < 2.9 \times 10^{-26} e \text{ cm}$$

$$d_e < 8.7 \times 10^{-29} e \text{ cm}$$



d_e(ZH)/d_e(γH)
0.06
0.05
0.04
0.03
μ (GeV)
M_2 (GeV)
10^2
10^3
10^4
d_e(WW)/d_e(γH)
−0.01
−0.03
−0.1
−0.2
−0.3
−0.2
−0.4
d_n(ZH)/d_n(γH)
1.6
1.4
1.2
1
0.8
0.6
d_n(WW)/d_n(γH)
−0.03
−0.1
−0.3
−0.7
−0.7
−1

Gluino CEDM contribution

to EDM

Extemded models

In high-scale SUSY model,
experimental bounds from CP violation and FCNC are quite loose.

It is unnecessary that particle contents in high-scale SUSY model are equivalent to MSSM.

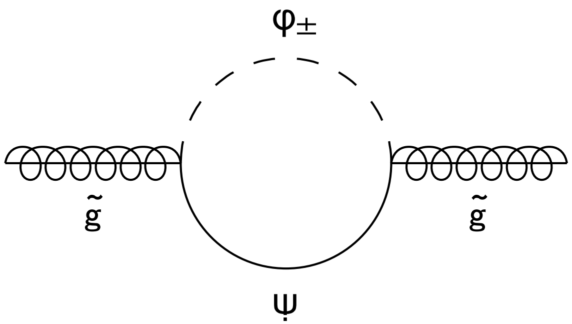
High-scale SUSY model (minimal)	High-scale SUSY model (extended)
MSSM	MSSM + vector-like matter

We assumed these additional superfields in $\mathbf{5}+\bar{\mathbf{5}}$ representation.

$$\Phi = (\phi \quad \psi_\phi \quad F_\phi)$$

How can we distinguish these models?

Vector like matters play the role of messengers in terms of gauge mediation.



Gluino acquires additional mass from gauge-mediated contribution.

Total mass of gluino is the sum of anomaly- and gauge-mediated contributions.

$$M_{\tilde{g}} e^{i\gamma_5 \theta} \equiv M_3^{\mathrm{AMSB}} + M_3^{\mathrm{GMSB}}$$

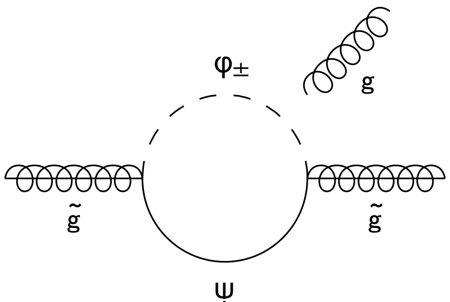
Relative phase difference of M_3^{AMSB} and M_3^{GMSB} is new physical CP phase.

If this new CP phase contributes to EDM enormously,
We can distinguish whether the model contains additional vector matters or not.

Gluino CEDM contribution

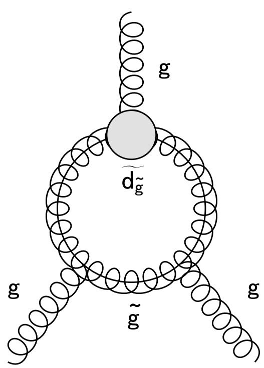
New CP phase contributes to nucleon EDM as follows;

- Integrating out messengers induces gluino CEDM at 1-loop level.



$$= \quad \tilde{d}_{\tilde{g}} \sim \frac{\alpha_s}{4\pi}\frac{1}{M_{\rm mess}}$$

- Then, Integrating out gluino induces Weinberg operator at 2-loop level.



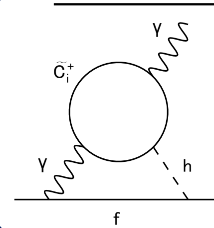
$$= \quad w \sim \left(\frac{\alpha_s}{4\pi}\right)^2 \frac{1}{M_{\rm mess}M_{\tilde{g}}}$$

- Using NDA, we finally obtain the nucleon EDM.

$$d_N(w) \sim e\ (10-30)\ \mathrm{MeV}\ w(1\mathrm{GeV})$$

$$d_N \sim e\left(\frac{\alpha_s}{4\pi}\right)^2 \frac{\Lambda}{M_{\rm mess}M_{\tilde{g}}} \sim e\frac{\alpha_s}{4\pi}\frac{\Lambda}{M_{\rm mess}M_s}$$

Barr-Zee contribution



$$\sim e\frac{\alpha}{4\pi}\frac{m_f}{\mu_H M_s}$$

Messenger scalar mass matrix

superpotential $W = M_\Phi \overline{\Phi}\Phi$

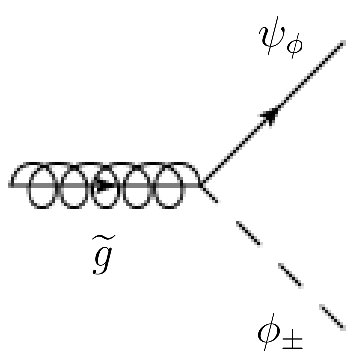
Kähler potential $\mathcal{K} = |\overline{\Phi}|^2 + |\Phi|^2 + (c_\Phi \overline{\Phi}\Phi + \mathrm{h.c.})$

$$\Rightarrow \quad \mathrm{m}_\phi^2 = \begin{pmatrix} |M_\Phi + c_\Phi m_{3/2}|^2 & c_\Phi^* m_{3/2}^* \\ c_\Phi m_{3/2}^2 & |M_\Phi + c_\Phi m_{3/2}|^2 \end{pmatrix} \equiv \begin{pmatrix} |M_{\mathrm{mess}}|^2 & -|F|e^{-i\theta_F} \\ -|F|e^{i\theta_F} & |M_{\mathrm{mess}}|^2 \end{pmatrix}$$

(The terms proportional to $m_{3/2}$ arises from the Giudice–Masiero mechanism.)

G. Giudice & A. Masiero, Phys.Lett. B206, 480 (1988)

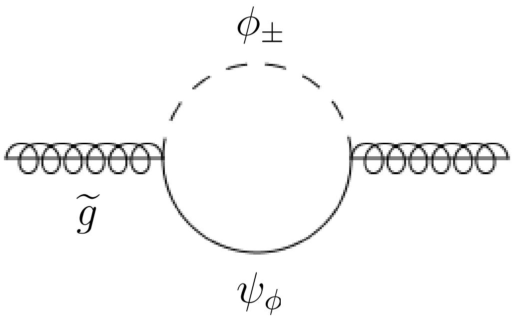
mass eigenstates : $\phi_\pm$ eigenvalue : $|M_{\mathrm{mess}}| \pm |F|$



$$= \begin{cases} -ig_s e^{i\theta_F/2} T^a \gamma_5 e^{-i\gamma_5 \theta_F/2} \\ -ig_s e^{i\theta_F/2} T^a e^{-i\gamma_5 \theta_F/2} \end{cases}$$

Gluino mass

$$g(x) = \frac{1}{x^2}[(1-x)\log(1-x) + (1+x)\log(1+x)]$$

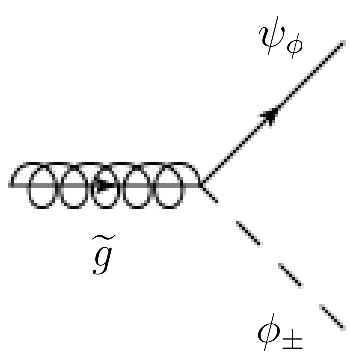


$$M_3^{\mathrm{GMSB}} = \frac{\alpha_s}{4\pi} e^{-i\gamma_5\theta_F} \left|\frac{F}{M_{\mathrm{mess}}}\right| g(x) \qquad x = \left|\frac{F}{M_{\mathrm{mess}}^2}\right|$$

$$M_{\tilde{g}} = \frac{g_3^2}{16\pi^2}\sqrt{b_3^2 m_{3/2}^2 + 2b_3 m_{3/2}\left|\frac{F}{M}\right| g(x)\cos\theta_F + \left|\frac{F}{M}\right|^2 \{g(x)\}^2}$$

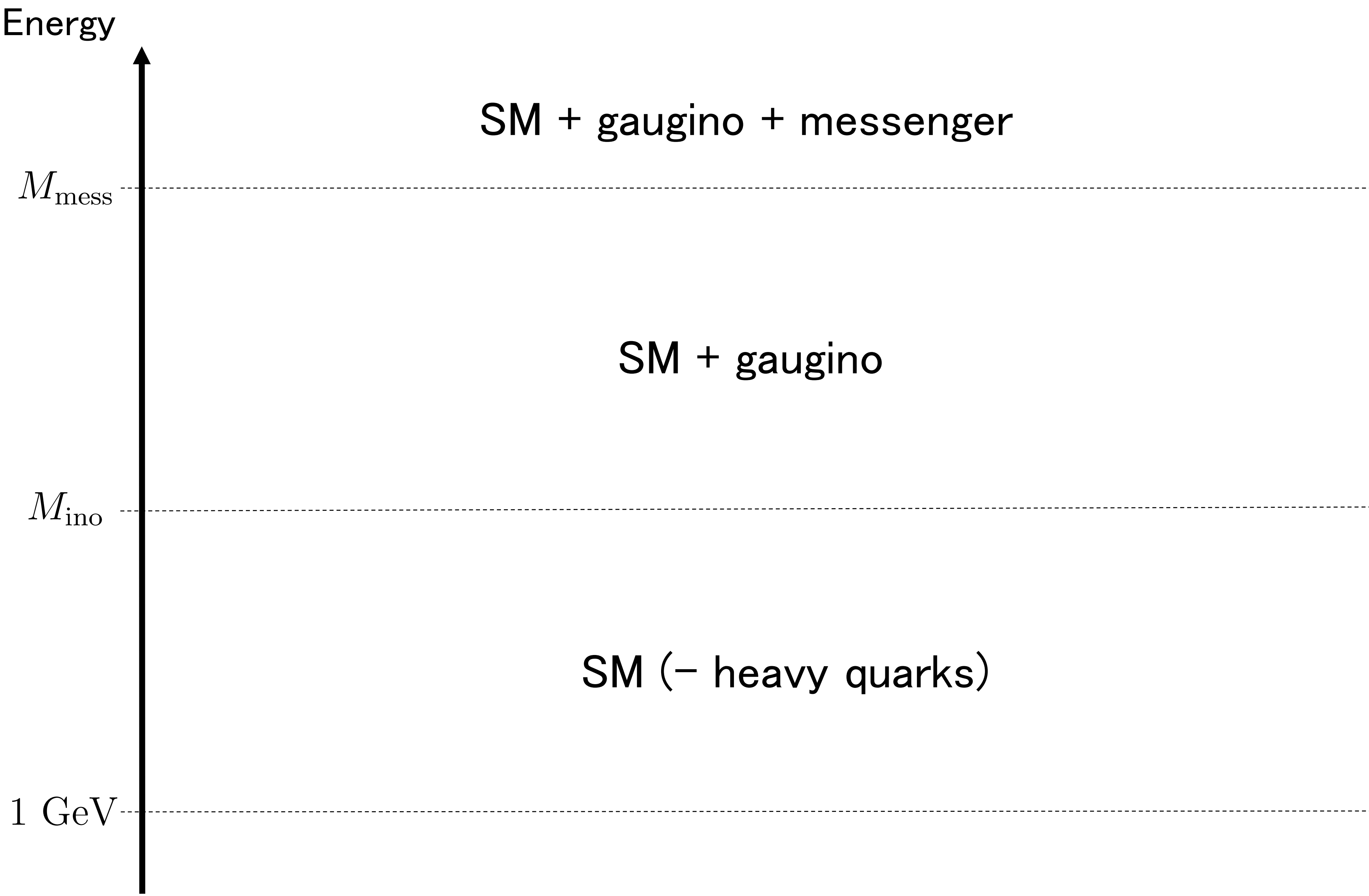
$$\tan\theta = \frac{\sin\theta_F \left|\frac{F}{M}\right| g(x)}{b_3 m_{3/2} + \cos\theta_F \left|\frac{F}{M}\right| g(x)} \qquad M_{\tilde{g}} e^{i\gamma_5\theta} \equiv M_3^{\mathrm{AMSB}} + M_3^{\mathrm{GMSB}}$$

After chiral rotation to take gluino mass to be real,



$$= \begin{cases} -ig_s e^{i\theta_F/2} T^a \gamma_5 e^{i\gamma_5 \frac{\theta-\theta_F}{2}} \\ -ig_s e^{i\theta_F/2} T^a e^{i\gamma_5 \frac{\theta-\theta_F}{2}} \end{cases}$$

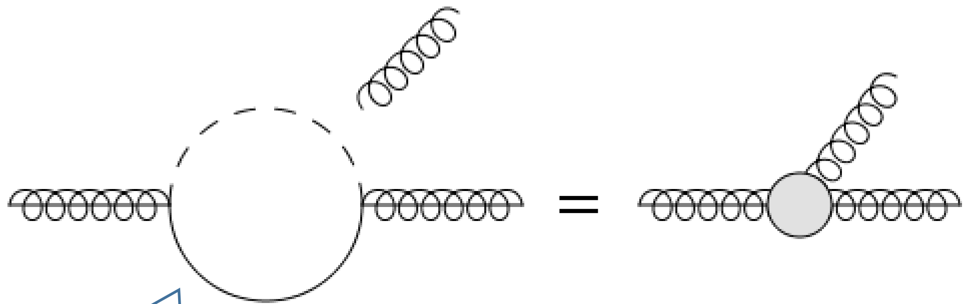
Calculations of the nucleon EDM



Calculations of the nucleon EDM

Energy

$M_{\rm mess}$ $\widetilde{d}_{\tilde{g}}(M_{\rm mess})$



SM + gaugino

$M_{\rm in}$

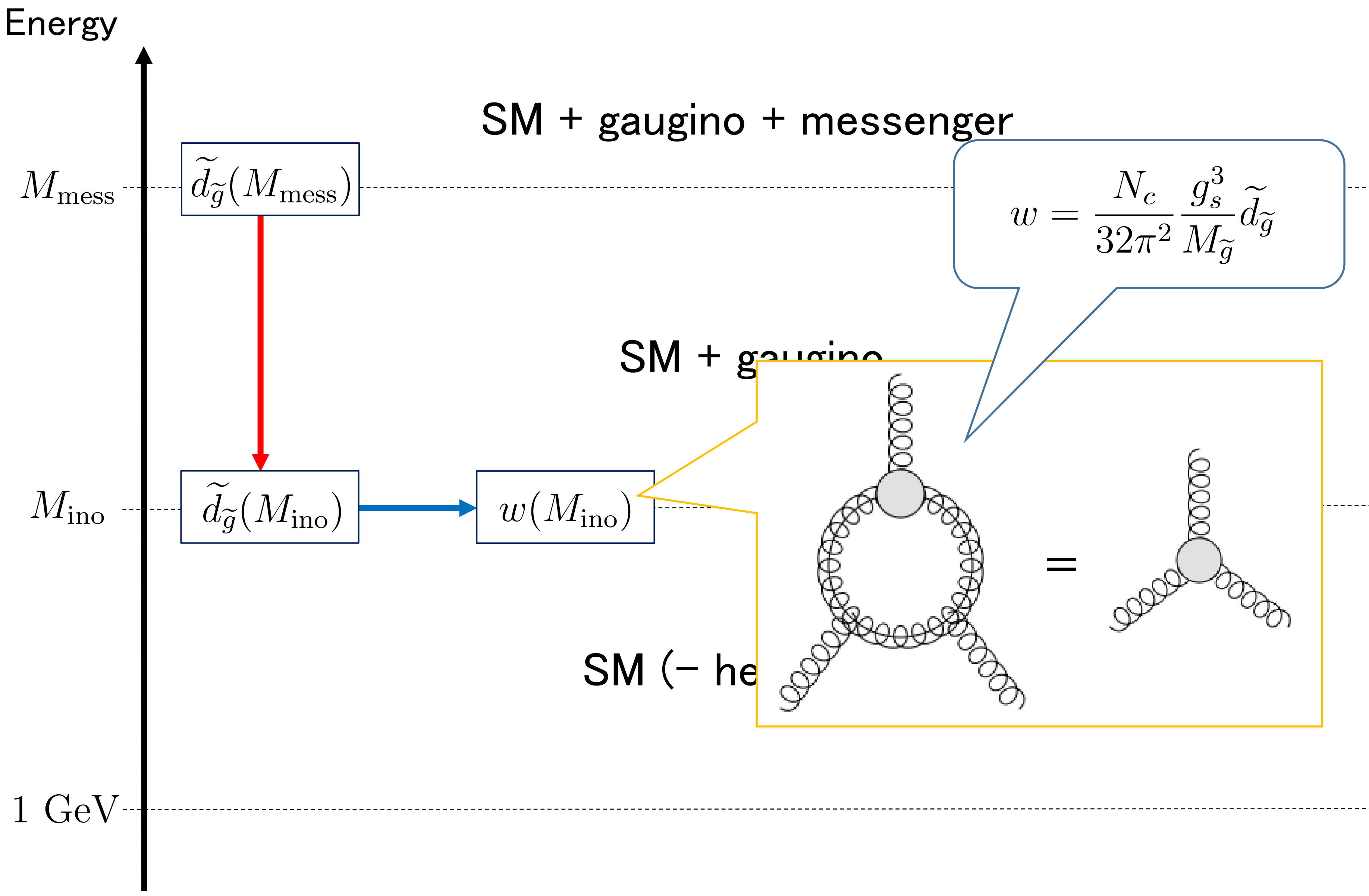
$$\widetilde{d}_{\tilde{g}} = -\frac{\alpha_s}{8\pi} M_{\rm mess} \sin(\theta + \theta_F) \left\{ \frac{1}{m_+^2}[A(r_+) + B(r_+)] - \frac{1}{m_-^2}[A(r_-) + B(r_-)] \right\}$$

$$A(r) \equiv \frac{1}{2(1-r)^2}\left(3 - r + \frac{2\log r}{1-r}\right) \qquad m_\pm^2 = |M_{\rm mess}|^2 \pm |F|$$

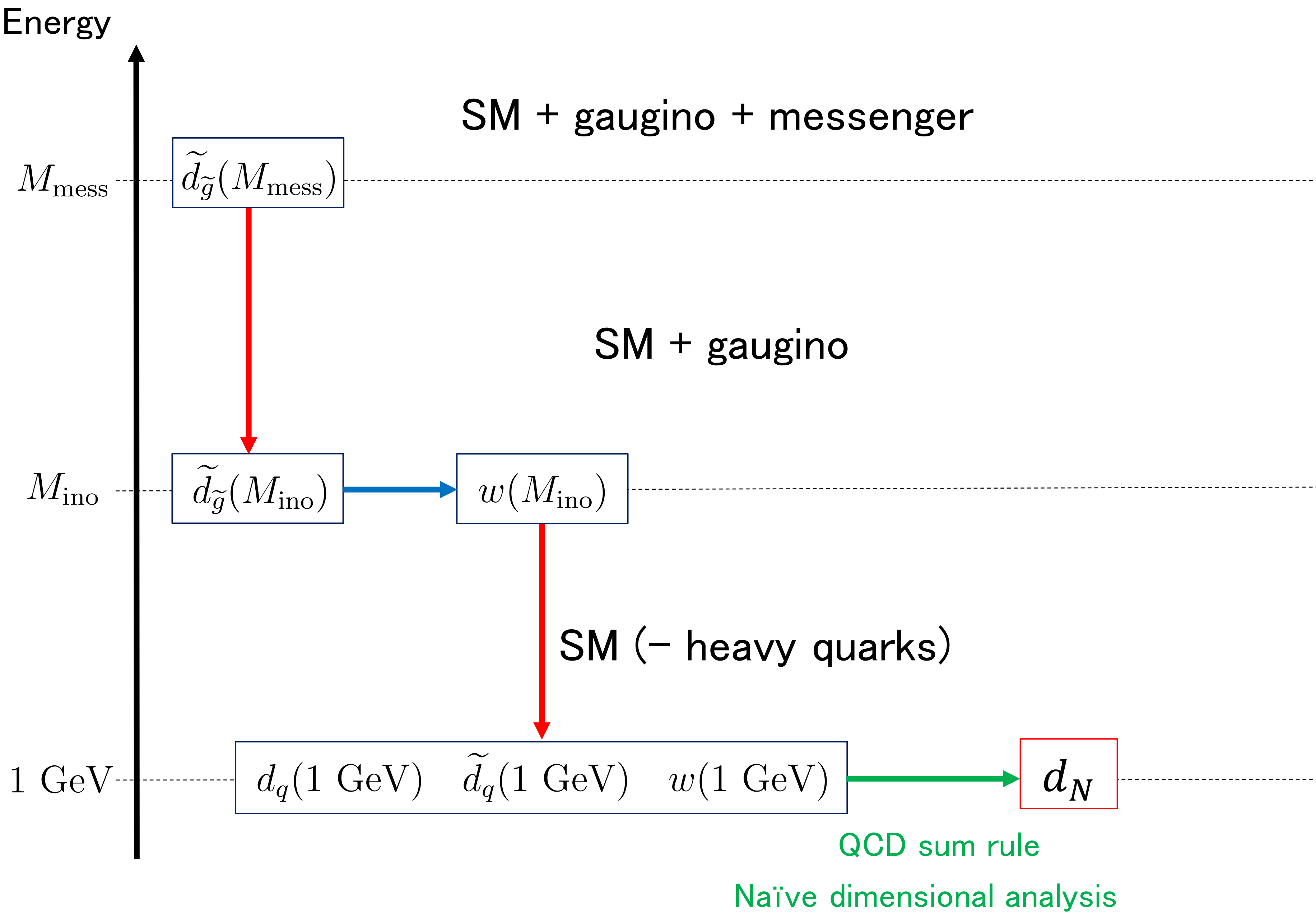
$$B(r) \equiv \frac{1}{2(1-r)^2}\left(1 + r + \frac{2r\log r}{1-r}\right) \qquad r_\pm = \frac{|M_{\rm mess}|^2}{m_\pm^2}$$

1 GeV

Calculations of the nucleon EDM



Calculations of the nucleon EDM



Numerical results

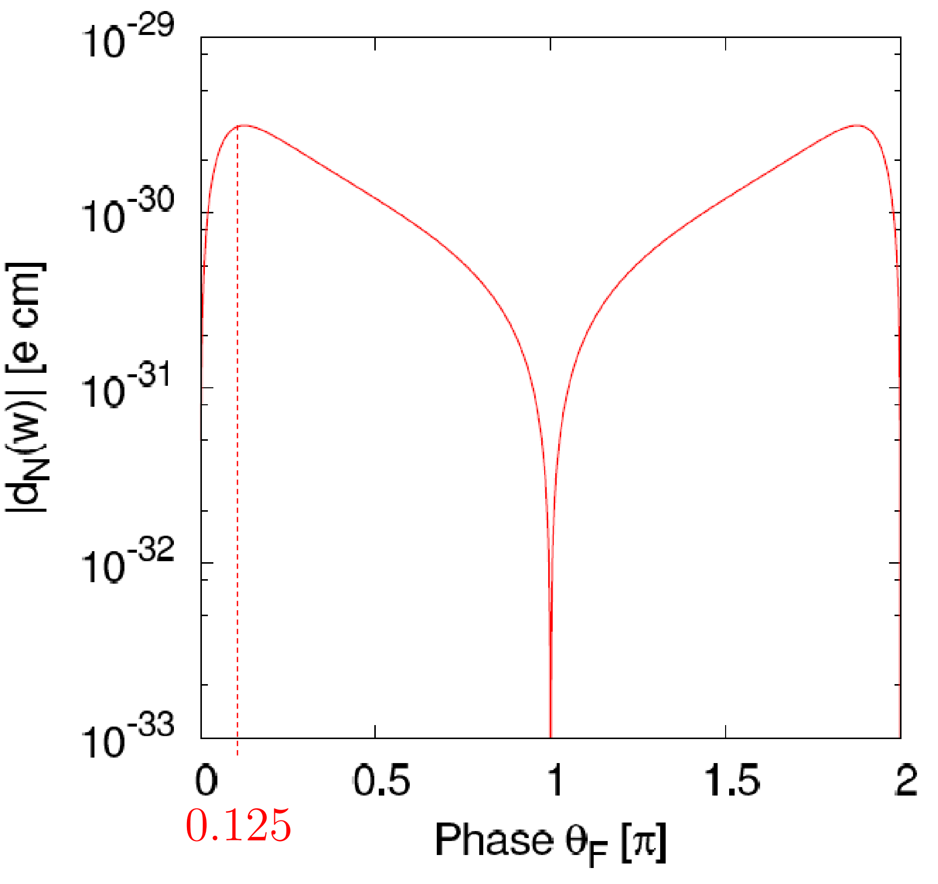
Gluino CEDM contribution to the nucleon EDM

We assume that
sfermions, heavy Higgs and gravitino
are degenerate in $M_S = 100$ TeV

remaining parameters : $M_{\rm mess},\ |F|,\ \theta_F$

We choose three independent parameters as

$$M_{\rm mess},\ \theta_F, x = \left|\frac{F}{M_{\rm mess}^2}\right| .$$

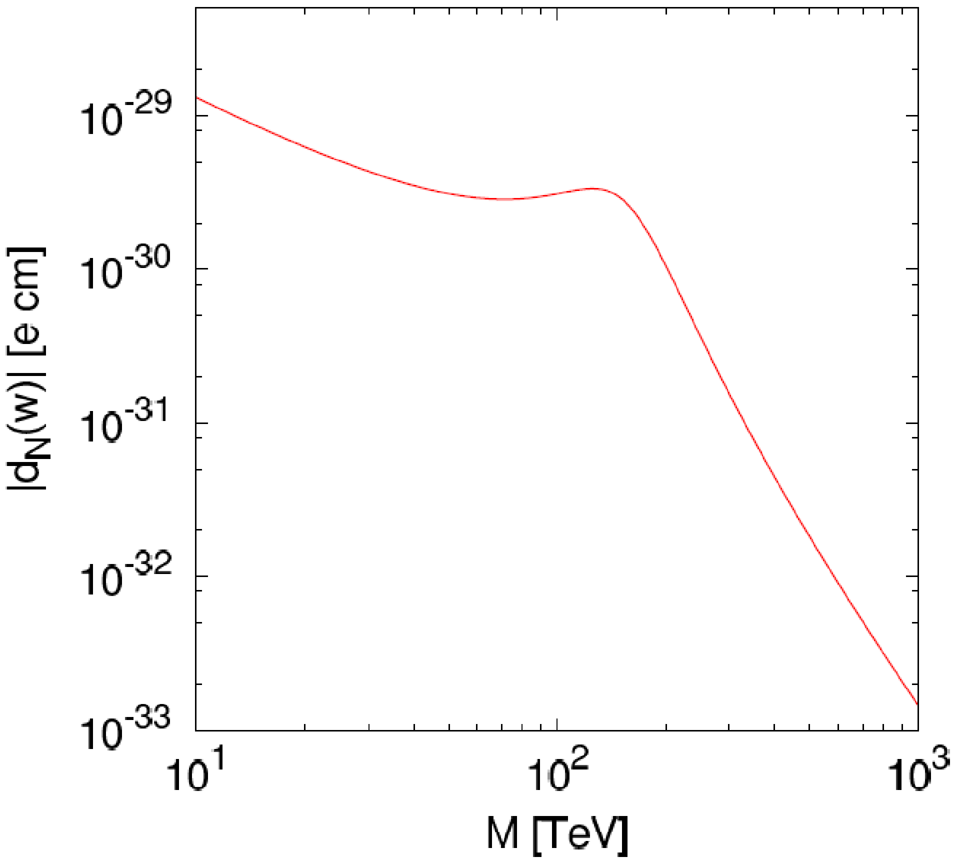


$M_{\rm mess} = 100$ TeV $\quad x = 0.99$

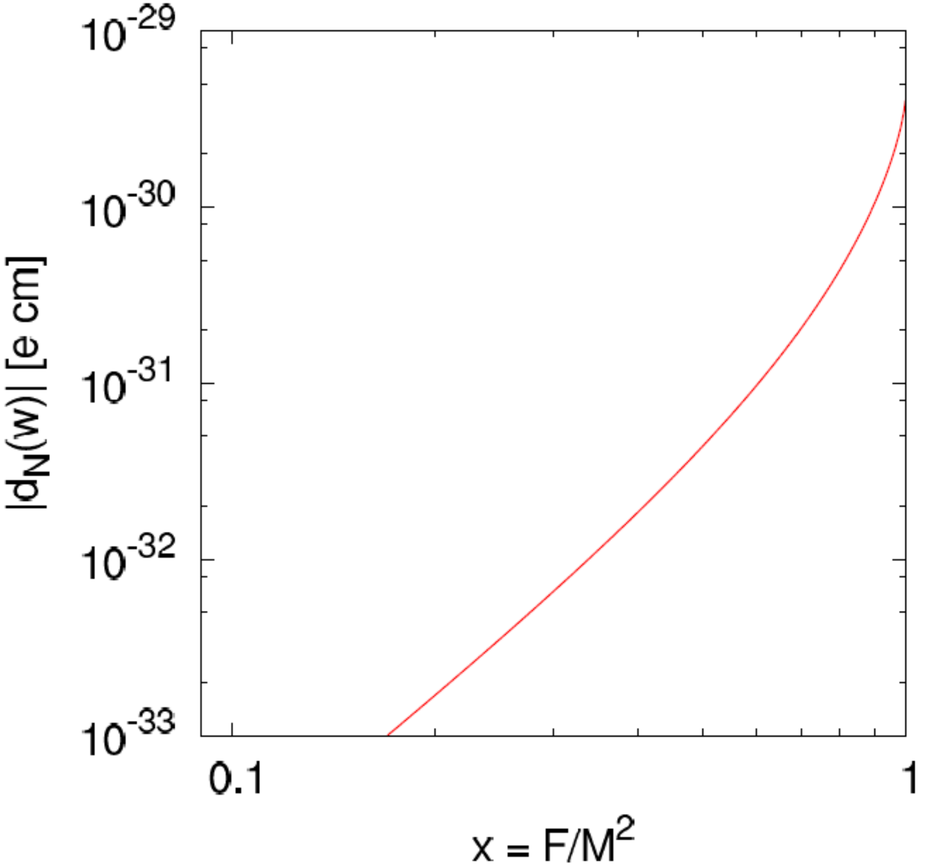
Numerical results

Gluino CEDM contribution to the nucleon EDM

We set $\theta_F = 0.125\pi$



$x = 0.99$



$M_{\mathrm{mess}} = 100\ \mathrm{TeV}$

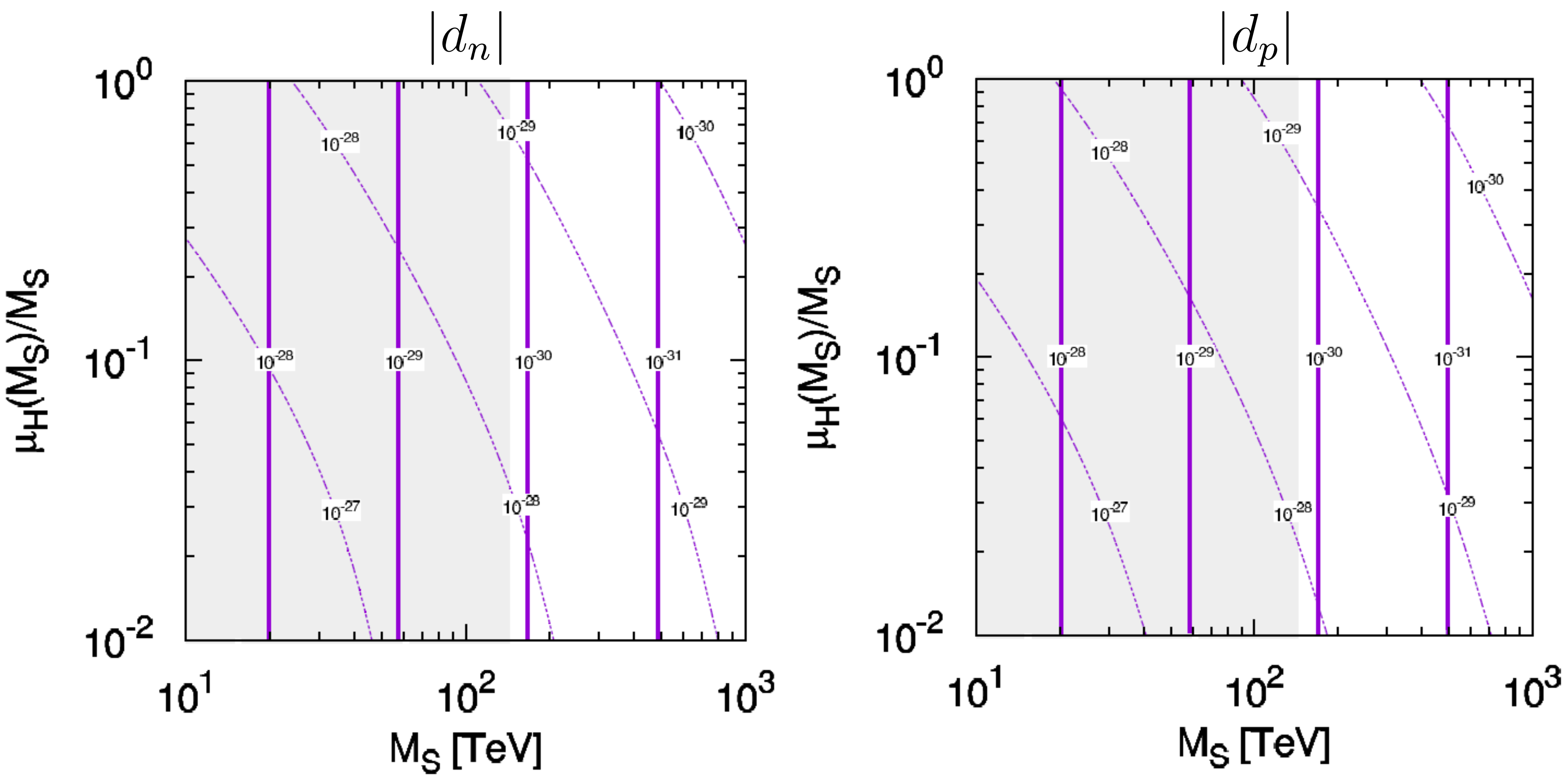
Numerical results

Comparison with the Barr-Zee contribution

$M_{\rm mess} = M_s$
$\theta_F = 0.125\pi$
$x = 0.99$
$\tan\beta = 3$

Higgsino mass μ_H is taken as a free parameter.

Phase of μ_H is determined to maximize the Barr-Zee contribution.



Numerical results

Comparison with the Barr–Zee contribution

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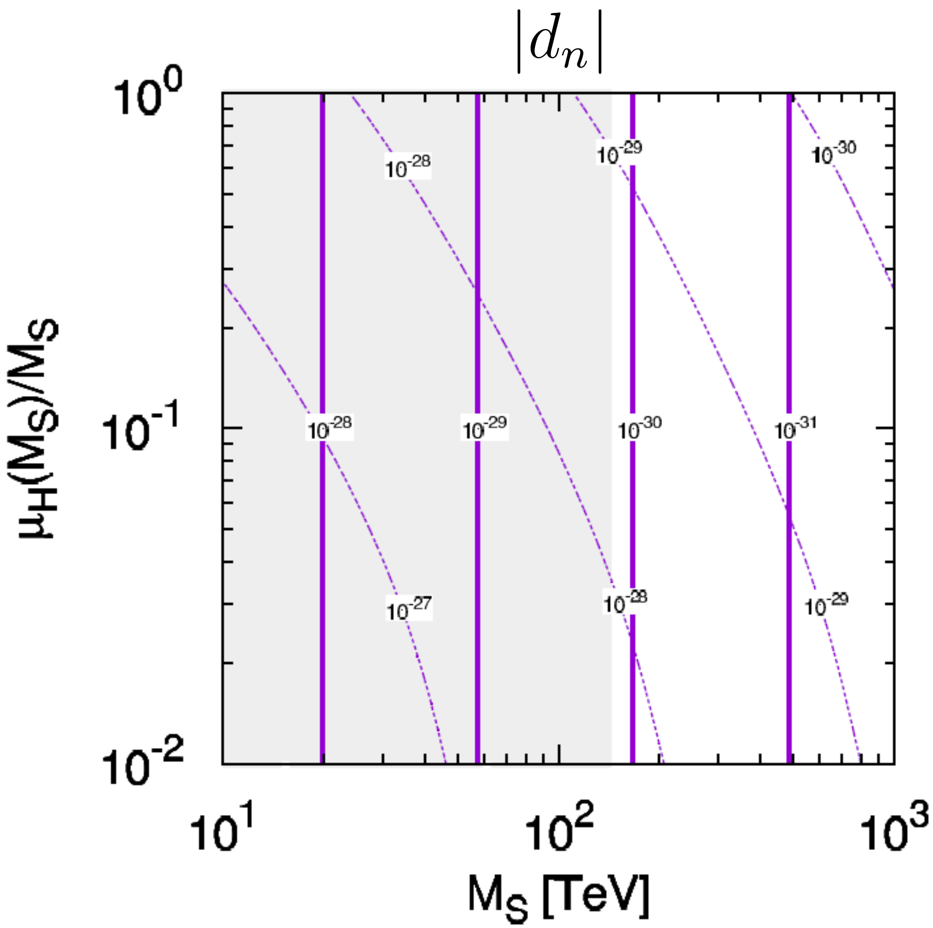
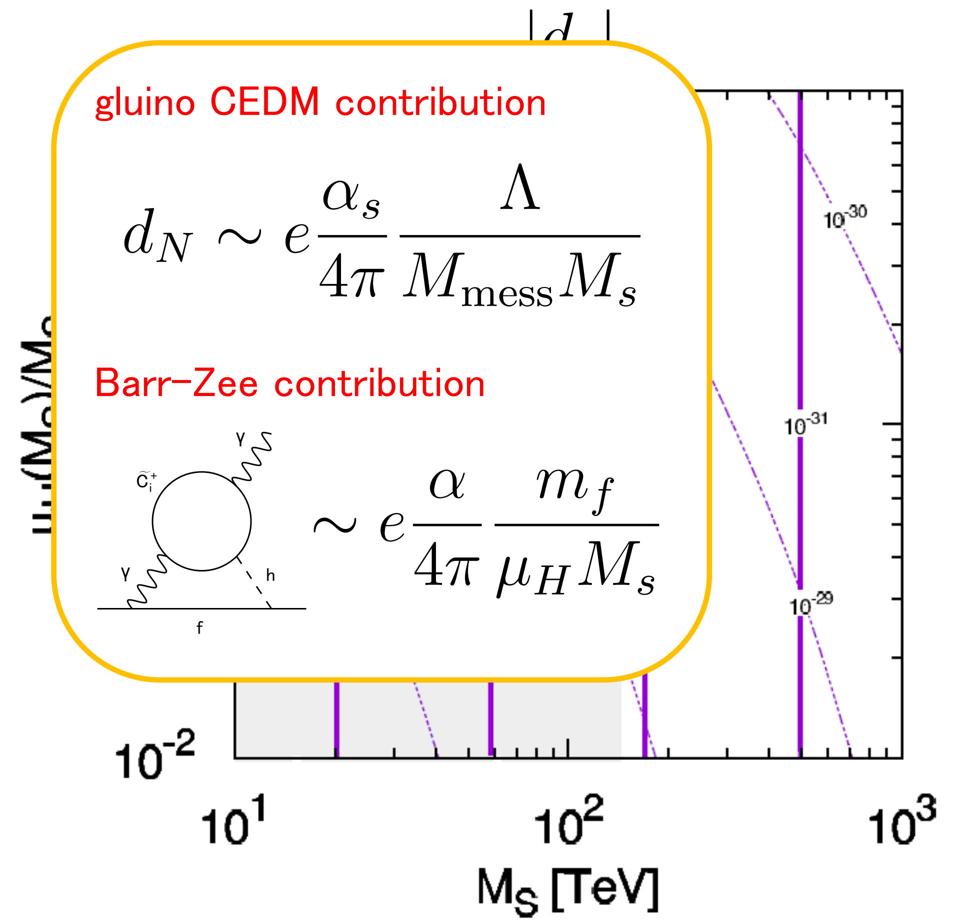




gluino CEDM contribution

$$d_N \sim e\frac{\alpha_s}{4\pi}\frac{\Lambda}{M_{\rm mess}M_s}$$

Barr–Zee contribution

$$\sim e\frac{\alpha}{4\pi}\frac{m_f}{\mu_H M_s}$$

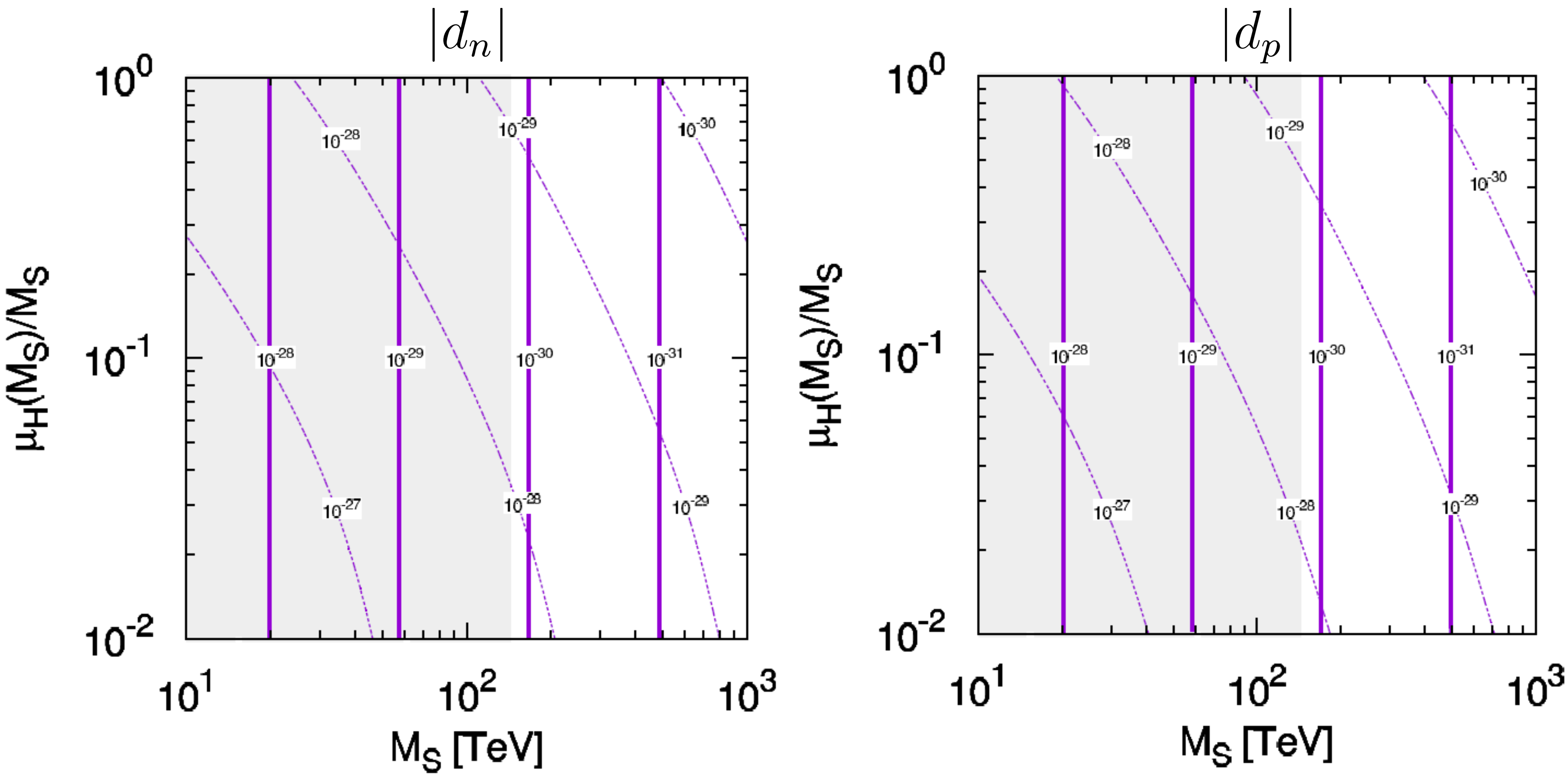
Numerical results

Comparison with the Barr–Zee contribution

Higgsino mass μ_H is taken as a free parameter.

Phase of μ_H is determined to maximize the Barr–Zee contribution.

$M_{\rm mess} = M_s$
$\theta_F = 0.125\pi$
$x = 0.99$
$\tan\beta = 3$



Numerical results

Comparison with the Barr-Zee contribution

$M_{\rm mess} = M_s$
$\theta_F = 0.125\pi$
$x = 0.99$
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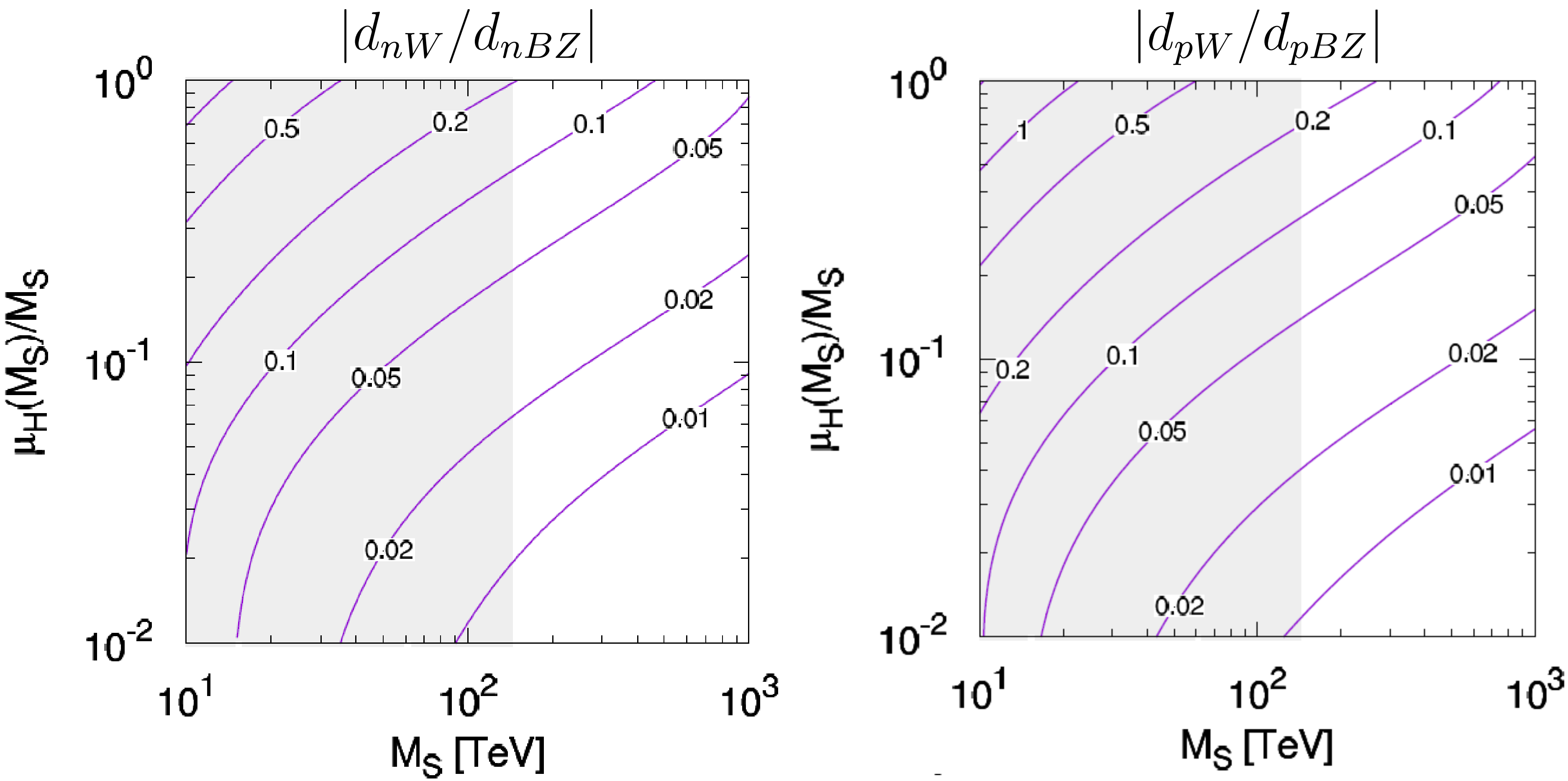
Phase of μ_H is determined to maximize the Barr-Zee contribution.



Numerical results

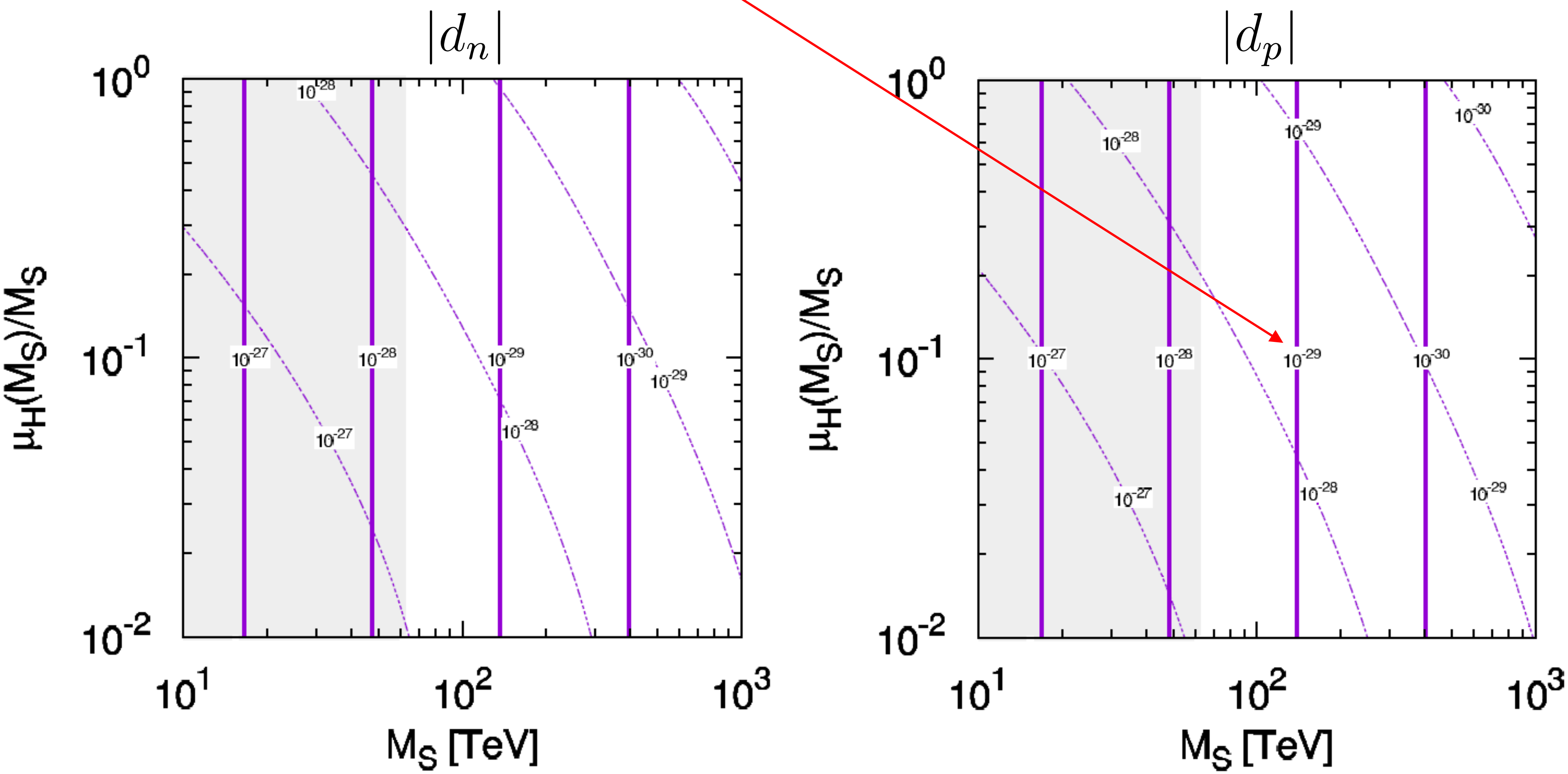
case of light messenger

$$M_{\text{mess}} = 0.1 M_s$$

Comparison with the Barr–Zee contribution

Gluino CEDM contribution may exceed the sensitivity of future proton EDM experiment.

There is a possibility that gluino CEDM effect will be found in the future.



Numerical results

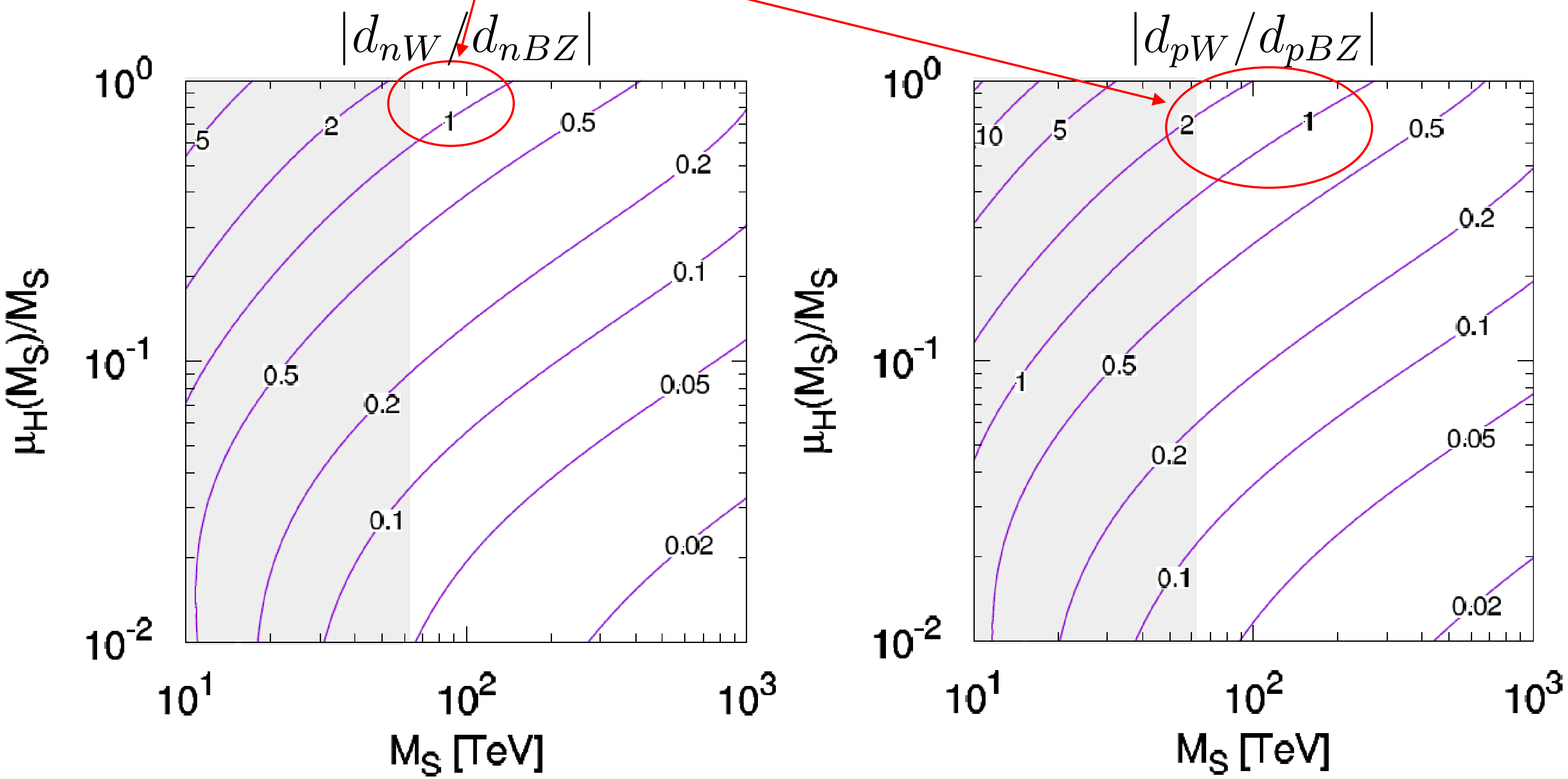
case of light messenger

$M_{\rm mess} = 0.1 M_s$

Comparison with the Barr-Zee contribution

In some region, gluino CEDM contribution exceeds Barr-Zee one.

It can be used to distinguish the model.



Summary

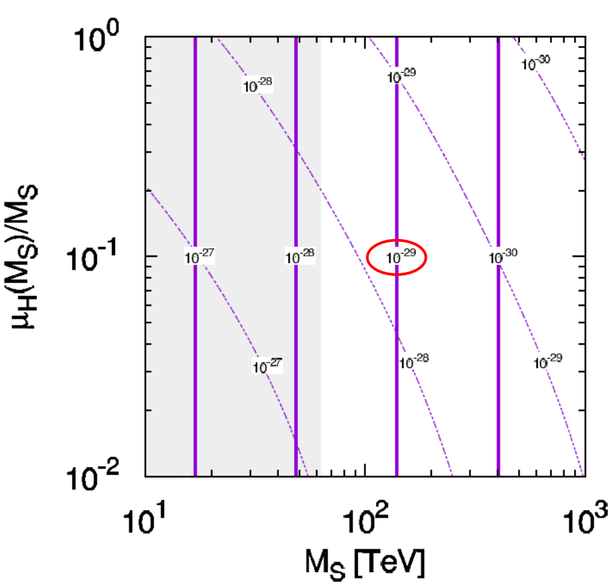
High-scale SUSY model is very attractive phenomenologically.

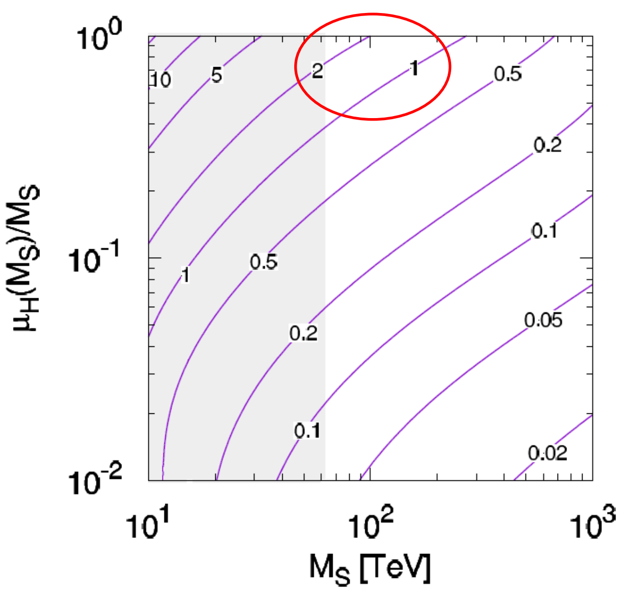
In this work, we pointed out there exists a new contribution from gluino CEDM.

⇒ It affect on the prediction of nucleon EDM in the high-scale SUSY model.

It may be useful to distinguish whether high-scale SUSY model includes messengers or not.

There is a possibility that gluino CEDM effect will be found in the future through the proton EDM.





sensitivity of the future experiment

$$|d_p| \sim 10^{-29}\ [e\ \mathrm{cm}]$$

繰り込み群方程式

$$\mathcal{L}_{\not{CP}} = \sum_{i=1}^{2} \sum_{q=u,d,s} C_i^q \mathcal{O}_i^q + C_W \mathcal{O}_W$$

Wilson係数

$$C_1^q \equiv \frac{d_q}{m_q e e_q} \qquad C_2^q \equiv \frac{\tilde{d}_q}{m_q} \qquad C_W \equiv \frac{w}{g_S}$$

$$\mu \frac{d}{d\mu} \begin{pmatrix} C_1^q \\ C_2^q \\ C_W \end{pmatrix} = \frac{\alpha_S}{4\pi} \begin{pmatrix} \gamma_e & \gamma_{qe} & 0 \\ 0 & \gamma_q & \gamma_{Gq} \\ 0 & 0 & \gamma_G \end{pmatrix} \begin{pmatrix} C_1^q \\ C_2^q \\ C_W \end{pmatrix} = \frac{\alpha_S}{4\pi} \begin{pmatrix} 8C_F & 8C_F & 0 \\ 0 & 16C_F - 4N_C & 2N_C \\ 0 & 0 & N_C + 2n_f - b_3 \end{pmatrix} \begin{pmatrix} C_1^q \\ C_2^q \\ C_W \end{pmatrix}$$

G. Degrassi, E. Franco, S. Marchetti & L. Silvestrini, JHEP 0511, 044 (2005)

$$C_1^q(\mu) = \eta^{\kappa_e} C_1^q(M) + \frac{\gamma_{qe}}{\gamma_e - \gamma_q}(\eta^{\kappa_e} - \eta^{\kappa_q}) C_2^q(M)$$
$$+ \left[\frac{\gamma_{Gq}\gamma_{qe}\eta^{\kappa_e}}{(\gamma_q - \gamma_e)(\gamma_G - \gamma_e)} + \frac{\gamma_{Gq}\gamma_{qe}\eta^{\kappa_q}}{(\gamma_e - \gamma_q)(\gamma_G - \gamma_q)} + \frac{\gamma_{Gq}\gamma_{qe}\eta^{\kappa_G}}{(\gamma_e - \gamma_G)(\gamma_q - \gamma_G)} \right] C_3(M)$$

$$C_2^q(\mu) = \eta^{\kappa_q} C_2^q(M) + \frac{\gamma_{Gq}}{\gamma_q - \gamma_G}(\eta^{\kappa_q} - \eta^{\kappa_G}) C_3^q(M) \qquad \eta = \frac{\alpha_S(\mu)}{\alpha_S(M)} \qquad \kappa_i = -\frac{\gamma_i}{2b_3}$$

$$C_3(\mu) = \eta^{\kappa_G} C_3(M)$$