Nucleon Electric Dipole Moments in High-Scale Supersymmetric Models

Collaboration with J.Hisano, D.Kobayashi, and W.Kuramoto

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- Introduction
- High-scale SUSY Models
- Electric Dipole Moments in High-Scale SUSY
- Results
- Summary

Introduction

Discovery of the 126GeV Higgs boson @ LHC

→ significant implications for researches of particle physics.

- Success of the Standard Model (SM)
- Approach to the New Physics based on the SM (more realistic)

but there is no signature of the new physics @ LHC

SM must be an effective theory of a certain UV theory.

- No candidate of Dark Matter
- Why is our Universe the baryon asymmetric one?
- Neutrino mass/mixing
- Finely tuned or Natural Higgs mass

Phenomenological aspect

Theoretical aspect

- etc..

Supersymmetry (SUSY) is a promising way extending the SM

Symmetry between bosons and fermions

Advantage:

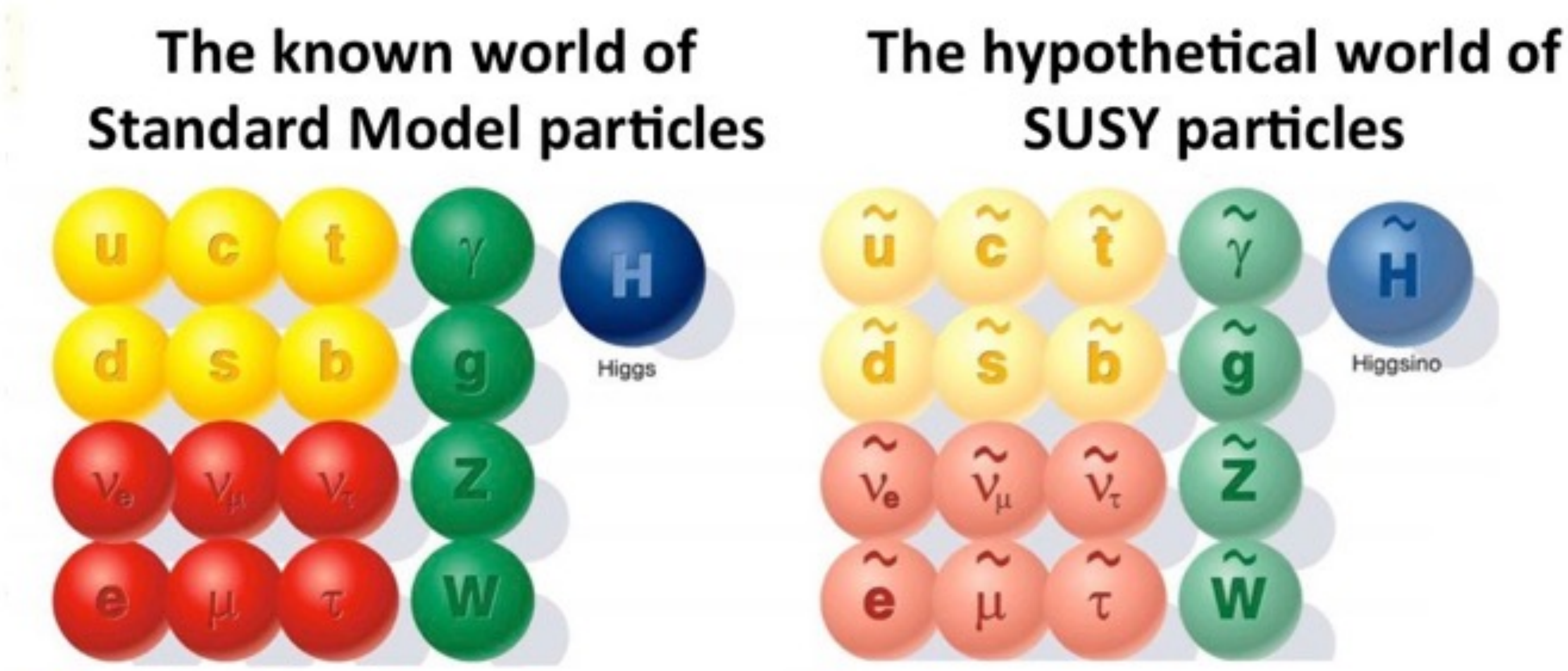
- Naturally solves the hierarchy problem (EW Scale-GUT/Planck Scale)
- Introduce a candidate of dark matter (R-parity)
- Gauge coupling unification works well

SUSY should be violated above EW scale

since SUSY partners are not observed

Minimal Supersymmetric Standard Model (MSSM)

is the minimal SUSY extension of the SM



- Introduce hypothetical particles which have opposite spin-statistics
  squarks and sleptons (bosons), higgsino and gauginos (fermions)
- Two-Higgs doublets (for gauge anomaly cancellation)

Higgs Mass vs SUSY Extension of SM

In the MSSM, 126 GeV Higgs is heavy

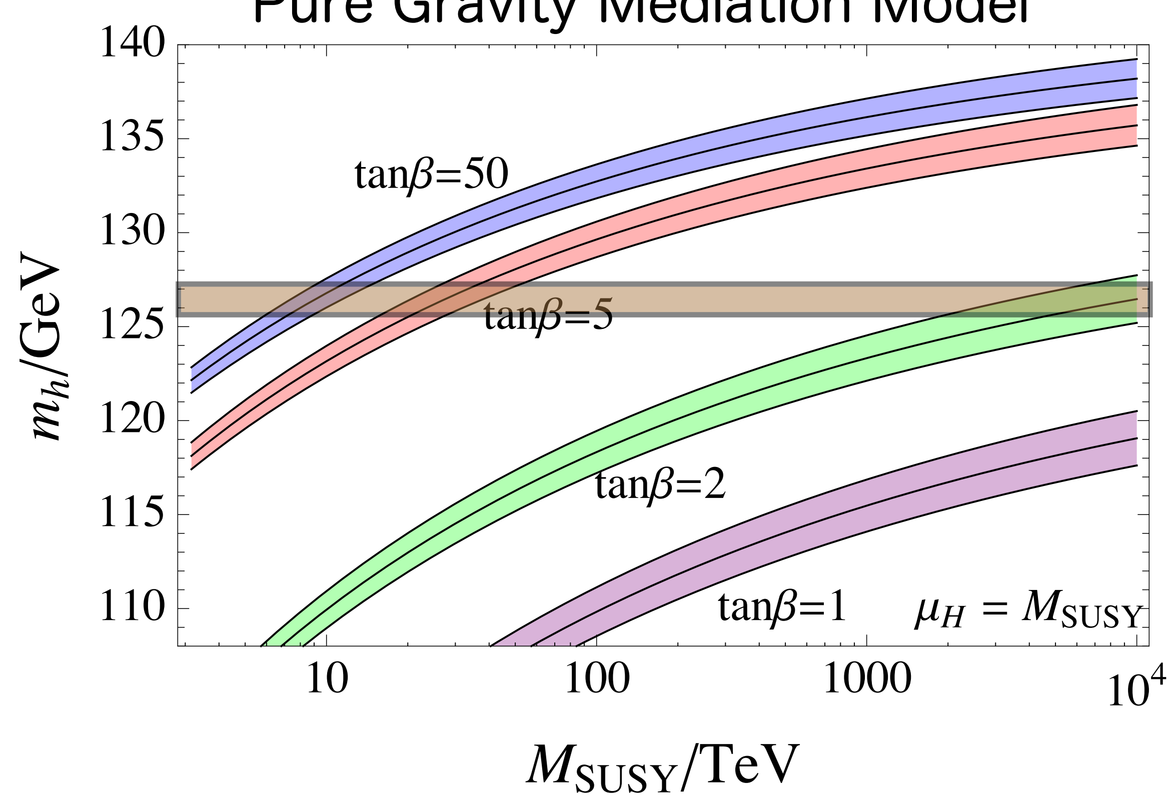
$$m_{h^0}^2 \approx m_Z^2 \cos^2 2\beta \qquad \text{tree level contribution}$$

$$+ \frac{3}{16\pi^2}\frac{m_t^4}{v^2}\left[\ln\frac{m_{\tilde{t}}^2}{m_t^2} + \frac{X_t^2}{m_{\tilde{t}}^2}\left(1 - \frac{X_t^2}{12 m_{\tilde{t}}^2}\right)\right]$$

$$X_t = A_t - \mu\cot\beta$$

Dominant one-loop contribution

Pure Gravity Mediation Model



M.Ibe and T.T.Yanagida (2011)

Models to explain 126GeV Higgs

Large quantum correction scenario

- Specific A-term
- Additional (Vector-Like) Matters
- High-scale (Split) SUSY

⋮

$\boxed{\text{High-scale (Split) SUSY scenario}}$

Advantage:

- ~~Naturally solves the hierarchy problem (EW Scale-GUT/Planck Scale)~~
- Introduce a candidate of dark matter (R-parity)
- Gauge coupling unification works well

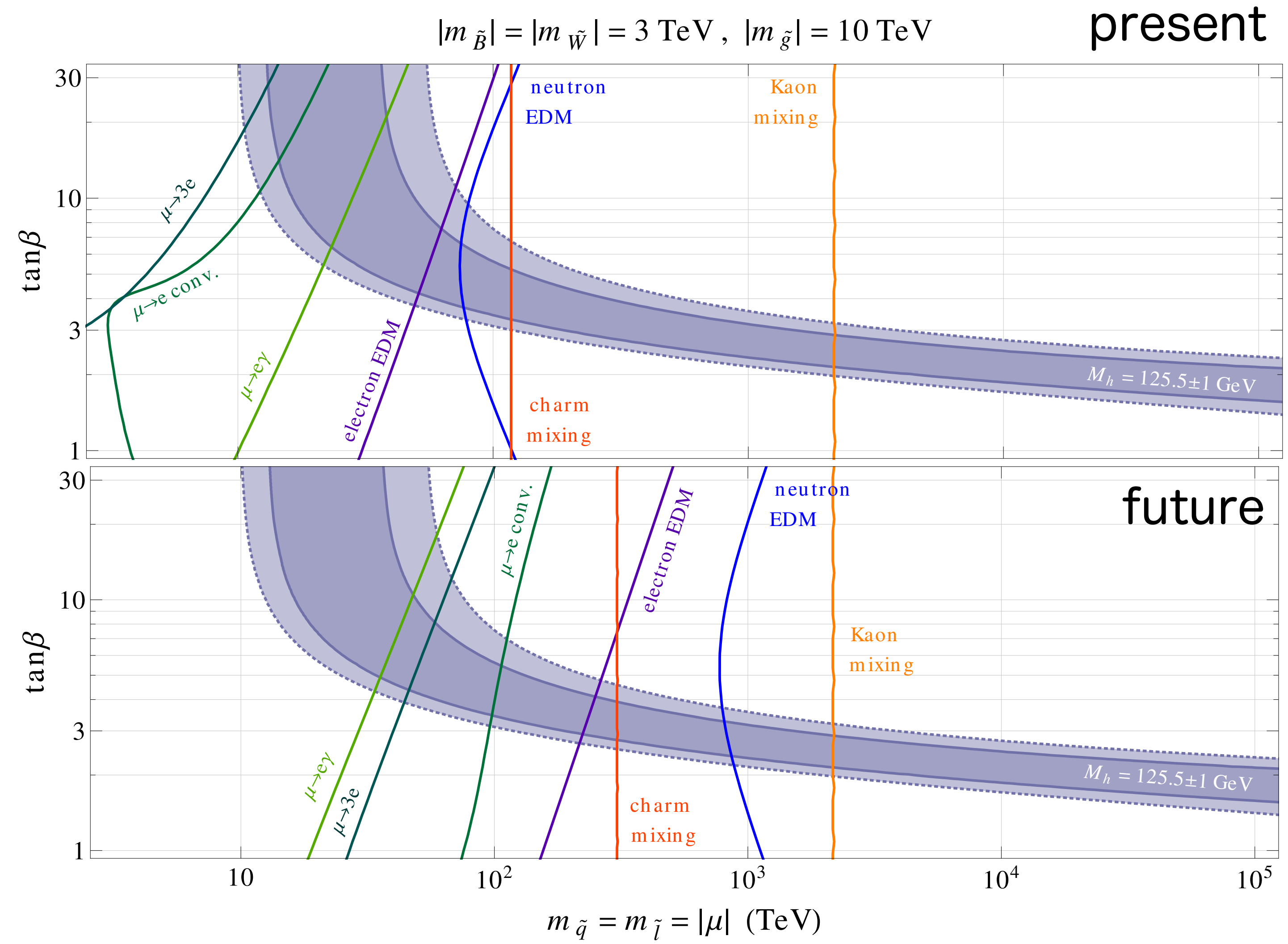
Motivation:

- Simple setup for phenomenological model building
- It can be accessible to check these scenario experimentally, by using non-collider experiments (constraints)

Experimental Check of High-scale SUSY

Sfermions are too heavy (outside of collider sensitivity)

- Rare Decay (K -> $\pi\,\nu\,\nu$)
- Rare Processes
- Electric Dipole Moment (EDM)



Altmannshofer, Harnik, Zupan (2013)

Electric Dipole Moment (EDM)

Relate to CP-violation (CPV)

Effective hamiltonian for a particle with spin S

$$H = -\mu \mathbf{B} \cdot \frac{\mathbf{S}}{S} - d\mathbf{E} \cdot \frac{\mathbf{S}}{S}$$

Under time reversal,

$$T(\mathbf{B} \cdot \mathbf{S}) = \mathbf{B} \cdot \mathbf{S}, \quad T(\mathbf{E} \cdot \mathbf{S}) = -\mathbf{E} \cdot \mathbf{S}$$

and CPT invariance → d violates CP invariance

In relativistic notation,

$$H = -d\mathbf{E} \cdot \frac{\mathbf{S}}{S} \quad \to \quad \mathcal{L} = -i\frac{d}{2}\bar{f}F^{\mu\nu}\sigma_{\mu\nu}\gamma_5 f$$

Electric Dipole Moment (EDM)

CPV in the SM = CKM phase

CPV observables are proportional to Jarlskog invariant

$$J_{\mathrm{CP}} = \mathrm{Im}(V_{cs}^* V_{us} V_{cd} V_{ud}^*) \sim 3 \times 10^{-5}$$

Neutron EDM in the SM

$$d_n^{\mathrm{SM}} \simeq 10^{-32} e\ \mathrm{cm}$$ @3-loop order

Electron EDM is more suppressed (due to CPV being in quark sector)

$$d_e^{\mathrm{SM}} \leq 10^{-38} e\ \mathrm{cm}$$ @4-loop order

EDMs have high sensitivity on the new physics

Electric Dipole Moment (EDM)

Experiments

Current constraint

$$|d_n| < 2.9 \times 10^{-26} [e\ \mathrm{cm}]$$

Ultra-Cold Neutron exp. @ Institut Laue-Langevin (2006)

$$|d_p| < 7.9 \times 10^{-25} [e\ \mathrm{cm}]$$ from Mercury (Hg^{199}) EDM (2009)

$$|d_e| < 8.7 \times 10^{-28} [e\ \mathrm{cm}]$$ ACME exp. (2013)

Future sensitivity

$$|d_n| \sim 10^{-28} [e\ \mathrm{cm}]$$ PSI, KEK-RCNP, TRIUNF, ⋯ (UCN exp.)

$$|d_p| \sim 10^{-29} [e\ \mathrm{cm}]$$ Storage ring exp. @ COSY, BNL

$$|d_e| = 3 \times 10^{-31} [e\ \mathrm{cm}]$$ Final goal of ACME exp.

High-scale SUSY Models

Models

Assumption: SUSY breaking chiral superfield X has any charge

$$\int d\theta^2 \frac{X}{M} \mathcal{W}^\alpha \mathcal{W}_\alpha \qquad \int d\theta^2 \frac{X}{M} U^C H_u Q$$

→ Forbidden by charge conservation

Gaugino masses, Scalar trilinear couplings = 0 @ tree-level

$$\int d\theta^4 \frac{X^\dagger X}{M^2} \Phi^\dagger \Phi$$

Scalar (non-holomorphic) masses are generated

$$m_S \simeq \left| \frac{F_X}{M} \right|$$

F_X: F-component VEV of X

Non-zero gaugino masses through Anomaly mediation

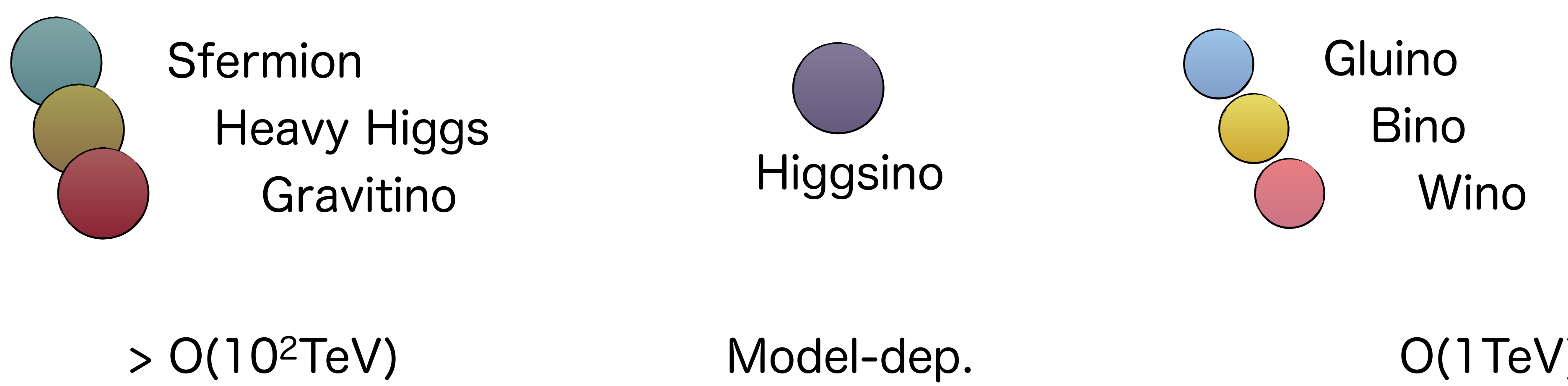
[Randall-Sundrum 98', Giudice-Luty-Murayama-Rattazzi 98']

$$M_a^{\mathrm{AMSB}} = \frac{\beta(g_a)}{g_a} m_{3/2}$$

Gravitino Mass

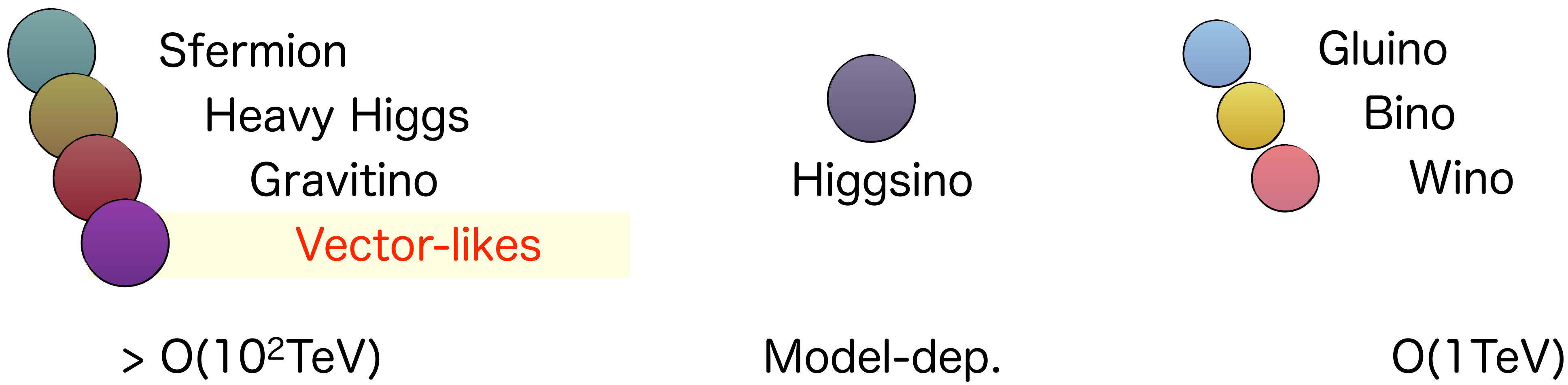
One-loop (beta-function) Suppressed gaugino masses realize Split-type SUSY Models

SUSY mass spectrum:



Now we extend the MSSM by introducing Vector-like Matters

[Olive-Evans 14']



Assumptions

- Vector-likes in SU(5) complete multiplets for maintaining coupling unification
- Especially, we introduce only a 5+5bar pair.

Characteristic

- Vector-like matters behave as messengers in gauge mediation
- Broadening allowed region for $\tan\beta$: $\tan\beta \lesssim 10$
- Bino-DM (Bino-other gaugino Co-annihilation)

Mass terms for Vector-Likes (Φ, $\overline{\Phi}$)

Φ: fundamental for SU(5)
$\overline{\Phi}$: anti-fundamental for SU(5)

Kähler Potential (supersymmetric kinetic term)

$$\mathcal{K} = \underbrace{|\overline{\Phi}|^2 + |\Phi|^2}_{\text{Canonical form}} + \underbrace{\left(c_\Phi \overline{\Phi}\Phi + \text{h.c.}\right)}_{\text{For Giudice-Masiero mechanism}}$$

Coupling with compensator field in AMSB

$$c_\Phi \overline{\Phi}\Phi \rightarrow c_\Phi \frac{S^\dagger}{S} \overline{\Phi}\Phi$$

$$\langle S \rangle = 1 + m_{3/2}\theta^2$$

Superpotential (supersymmetric mass and interaction terms)

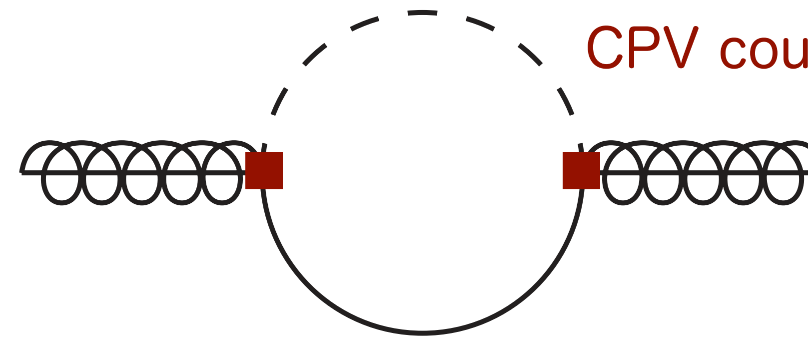
$$W(\Phi, \overline{\Phi}) = M_\Phi \overline{\Phi}\Phi$$

Squared Scalar Mass Matrix

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

Additional matters contribute gaugino masses

e.g.) Gluino mass term



CPV coupling

$$\mathcal{L} = \overline{\tilde{g}}\, M_{\tilde{g}}\, e^{i\theta\gamma_5}\, \tilde{g}$$

$$M_{\tilde{g}}\, e^{i\gamma_5\theta} = M_3^{\rm AMSB} + M_3^{\rm GMSB}$$

We take $M_3^{\rm AMSB}$ to be real

Additional contribution cf.) gauge mediation

x := $|F/M^2|$

$$M_3^{\rm GMSB} = \frac{g_3^2}{16\pi^2}(\cos\theta_F - i\sin\theta_F\gamma_5)n_3(\Phi)\left|\frac{F}{M}\right| g(x)$$

$n_3(\Phi)$: Sum of Dynkin index for Vector-likes (n_3 = 1 for fundamental)

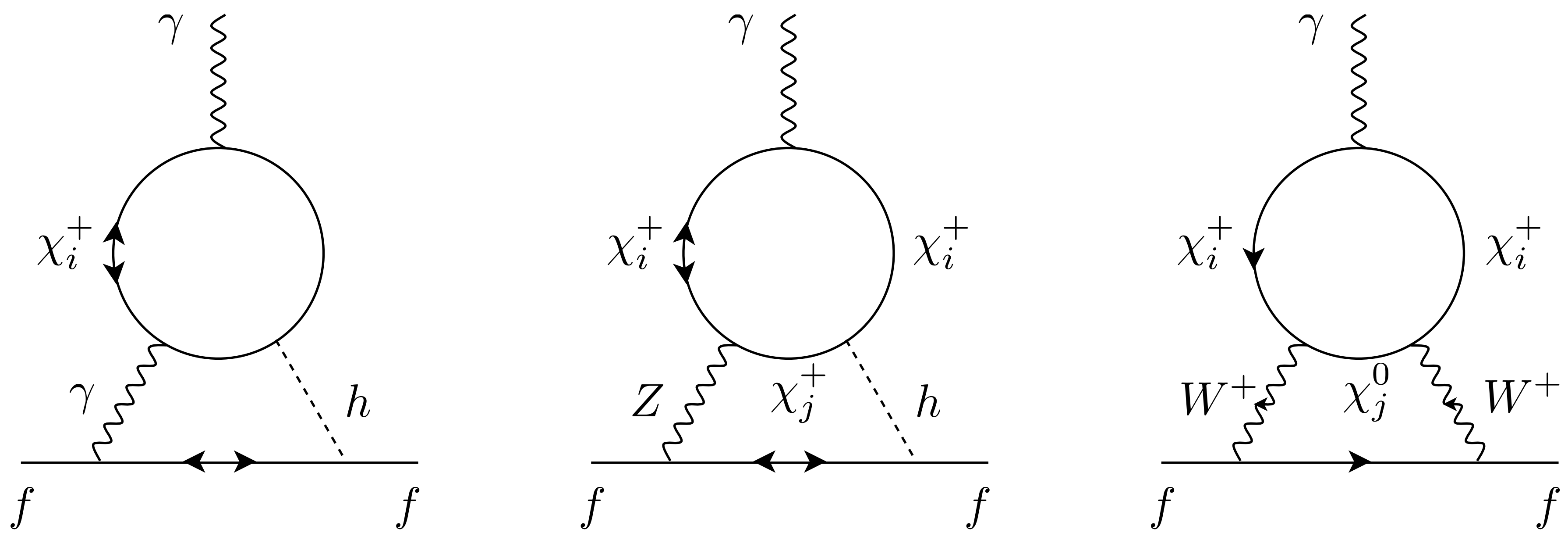
g(x): loop function

$$g(x) = \frac{(1+x)\ln(1+x) + (1-x)\ln(1-x)}{x^2}$$

Electric Dipole Moments
in
High-Scale SUSY Models

Barr-Zee EDMs in high-scale SUSY (MSSM)

Giudice, Romanino (2005)

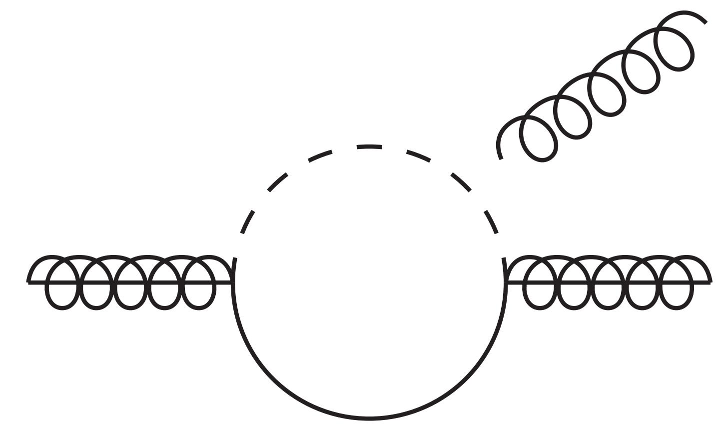


- Heavy scalars are decoupled
  Low-energy spectrum: SM + gauginos + higgsinos
- Charginos and Neutralinos only contribute to fermion EDMs (Barr-Zee Graph)

- Quark EDMs are dominant contribution to nucleon EDMs
- Predictive ratio of neutron and electron EDMs ($d_n/d_e \sim O(1)$)

After chiral rotation of gluino field

→ CP-violating vertex (Gluino-Vector-likes)



Gluino chromo-electric dipole moment (CEDM)

$$\mathcal{L}_{\tilde{g}\,\mathrm{CEDM}} = -\frac{i}{4}\tilde{d}_{\tilde{g}}\overline{\tilde{g}^b}\sigma^{\mu\nu}\gamma_5 G^a_{\mu\nu}[T^a]_{bc}\tilde{g}^c$$

after matching,

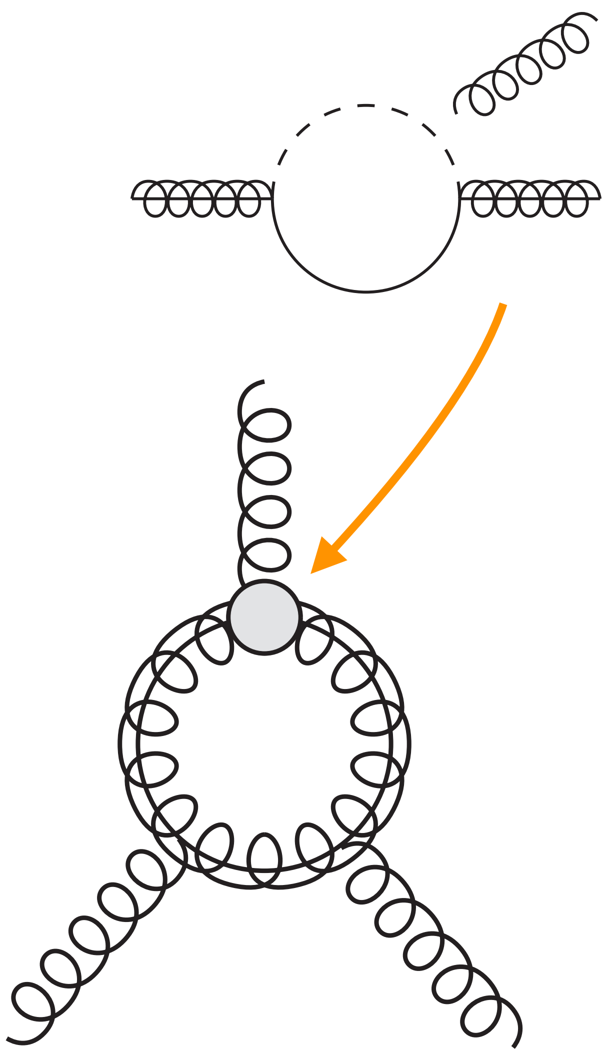
$$\tilde{d}_{\tilde{g}} = -\frac{g_3^3}{32\pi^2}\frac{M}{m_+^2}\sin(\theta+\theta_F)\,[A(r_+)+B(r_+)] - (m_+, r_+ \to m_-, r_-)$$

Loop Function

θ : gluino mass phase
θ_F: F-term phase

$$m_\pm^2 = |M|^2 \pm |F|, \quad r_\pm = |M|^2/m_\pm^2$$

CP-odd Weinberg operator induced by gluino CEDM



Lagrangian for CP-odd Weinberg operator

$$\mathcal{L}_W = \frac{1}{3} w f^{abc} \epsilon^{\mu\nu\rho\sigma} G^a_{\mu\lambda} G^{b\lambda}_{\nu} G^c_{\rho\sigma}$$

After integrating out gluino,

$$w = -\frac{3g_3^2}{16\pi^2}\frac{\widetilde{d}_{\widetilde{g}}}{M_{\widetilde{g}}}$$

typically $\propto g_3 \left(\frac{g_3^2}{16\pi^2}\right)^2 \frac{1}{MM_{\widetilde{g}}} \sin(\theta + \theta_F)$

θ : gluino mass phase

θ_F: F-term phase

two-loop

gluino & vector-like mass suppression

Comment on other contributions

After integrating out sfermions and vector-likes

Chirality flip

Quark (C)EDMs $\quad d_q(\tilde{d}_q) \simeq \frac{m_q}{M^2}$ $\quad$ @ three-loop level

Weinberg op. $\quad w \simeq \frac{1}{M^2}$ $\quad$ @ two-loop level

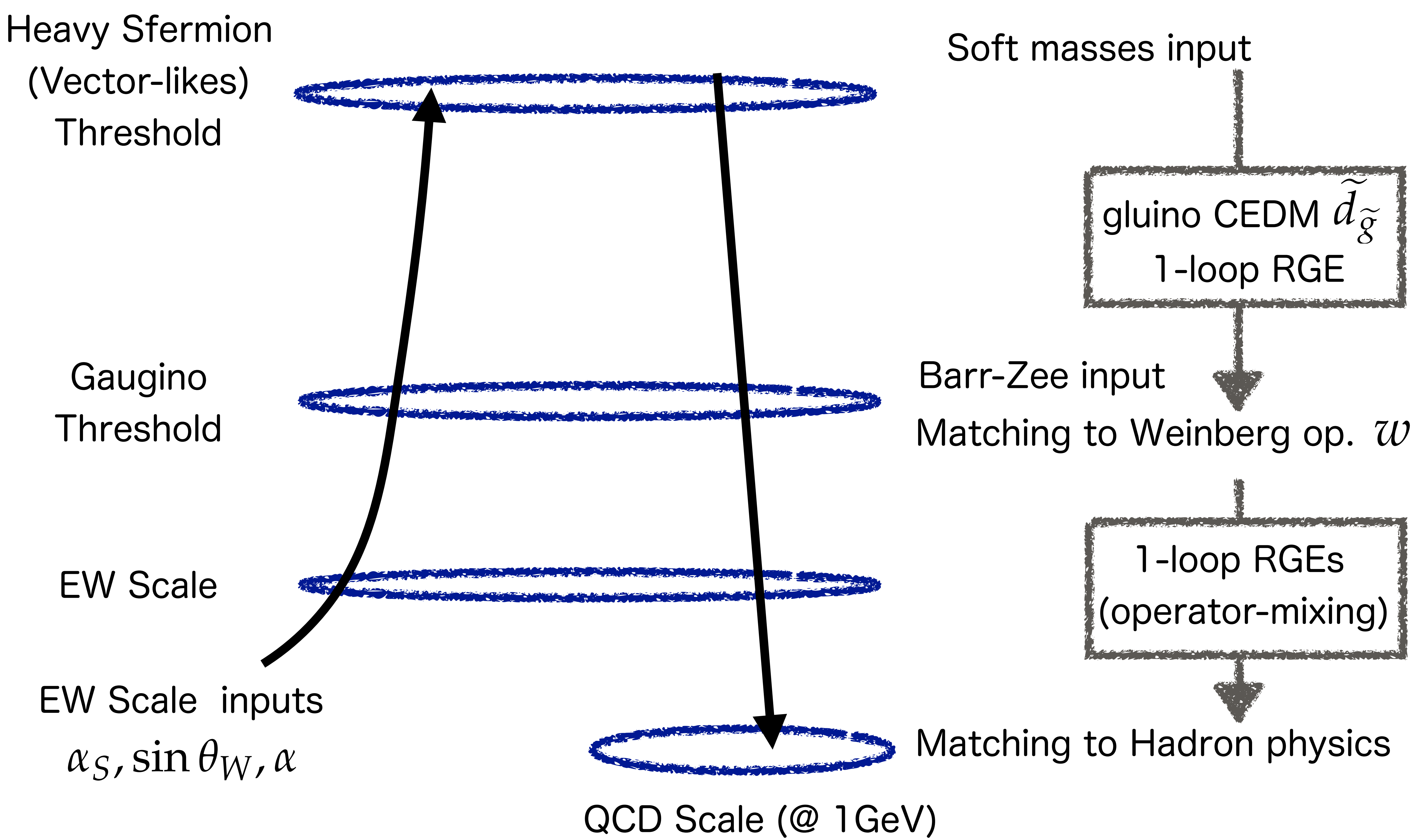
Each is suppressed by sfermion mass or vector-like mass.

From the sfermion and vector-like sector,

the gluino CEDM contribution dominates CPV

Results

Way to Estimate the Low-energy Observables



Nucleon EDMs from parton-level CP-odd parameters

CP-odd Lagrangian below EW scale (quark sector)

$$\mathcal{L}_{\text{CP-odd}} = \bar{\theta}\frac{g_3^2}{32\pi^2}G^a_{\mu\nu}\widetilde{G}^{a,\mu\nu} - \frac{i}{2}\sum_{q=u,d,s} d_q\bar{q}(F\cdot\sigma)\gamma_5 q - \frac{i}{2}\sum_{q=u,d,s}\tilde{d}_q g_3\bar{q}(G\cdot\sigma)\gamma_5 q + \frac{1}{3}w f^{abc}G^a_{\mu\nu}\widetilde{G}^{b,\nu\rho}G^c{}_\rho{}^\mu$$

- Renormalization group equations (RGEs) @1-loop level

Degrassi, Franco, Marchetti, and Silvestrini (2005)

- Connection between nucleon and parton-level CP-odd parameters
  - Naïve dimensional analysis
  - QCD sum rule

Nucleon EDMs from QCD sum rule @ 1GeV

$$d_p = -1.2 \times 10^{-16}[e\,\mathrm{cm}]\bar{\theta} + 0.78 d_u - 0.20 d_d + e(-0.28\tilde{d}_u + 0.28\tilde{d}_d + 0.021\tilde{d}_s),$$
$$d_n = \underbrace{8.2 \times 10^{-17}[e\,\mathrm{cm}]\bar{\theta}}_{\text{QCD theta}} \underbrace{- 0.20 d_u + 0.78 d_d}_{\text{quark EDMs}} + \underbrace{e(-0.30\tilde{d}_u + 0.30\tilde{d}_d - 0.014\tilde{d}_s)}_{\text{quark CEDMs}}.$$

Hisano, Lee, Nagata, Shimizu (2012)
Hisano, Kobayashi, Kuramoto, TK (2015)

If Peccei-Quinn symmetry is imposed,
QCD theta vanishes and coeff. of quark CEDMs will be changed.

But, the Barr-Zee contributes only to the fermion EDMs.

→ Main numerical result does not change even if PQ is imposed

Nucleon EDMs from Weinberg op. : Naïve dimensional analysis (NDA)

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

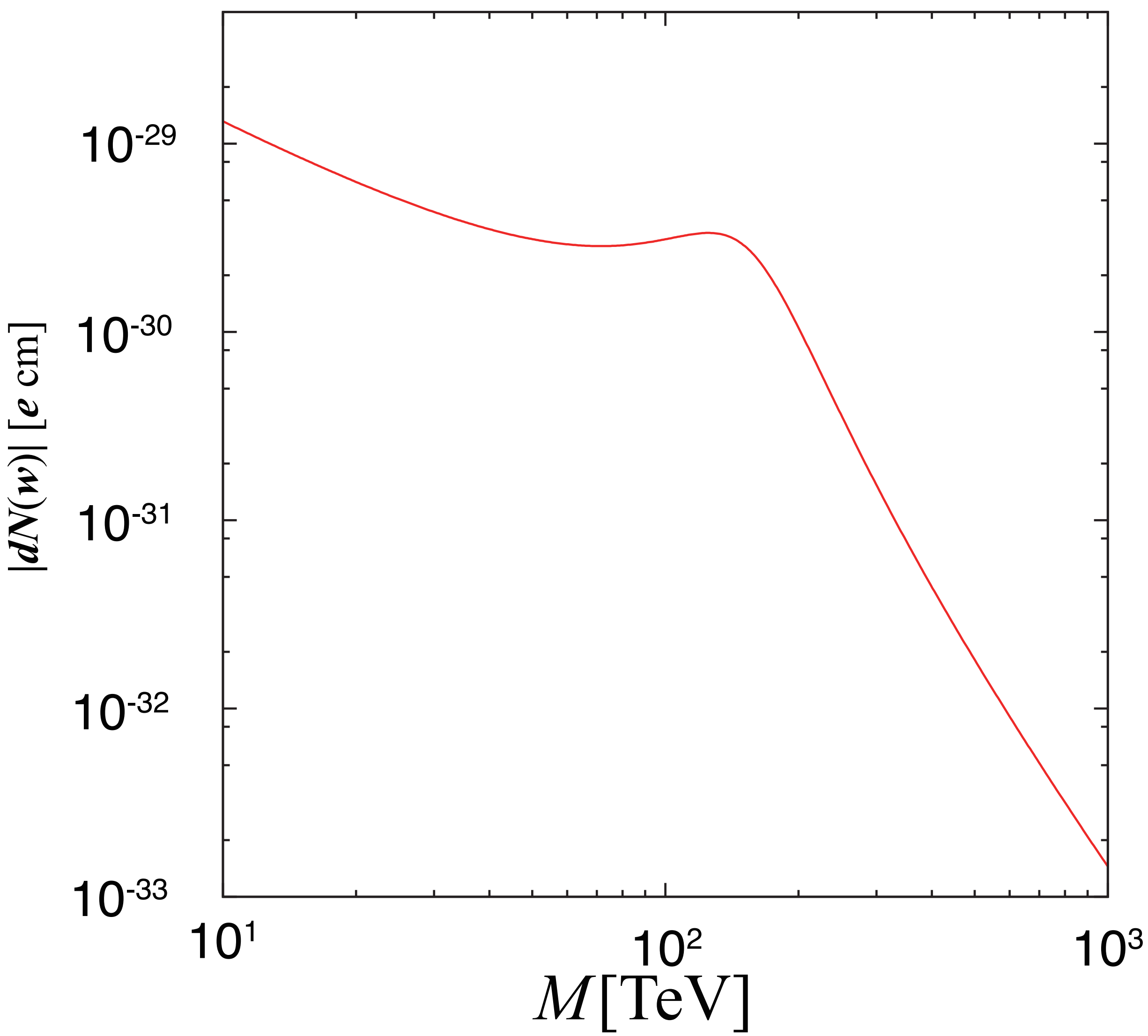
Demir, Pospelov, Ritz (2002)

Numerical results

Parameter dependence of Neutron EDM from gluino CEDM

New parameters: Scalar squared mass matrix for vector-likes

$$M,\ F,\ \theta_F \ \rightarrow \ M, x = |F/M^2|, \theta_F$$



- Squark masses: $M_S = m_{3/2} = 100\mathrm{TeV}$
- $M_3^{\mathrm{GMSB}} >> M_3^{\mathrm{AMSB}}$ @Large M
  and gluino mass phase $\theta \simeq -\theta_F$

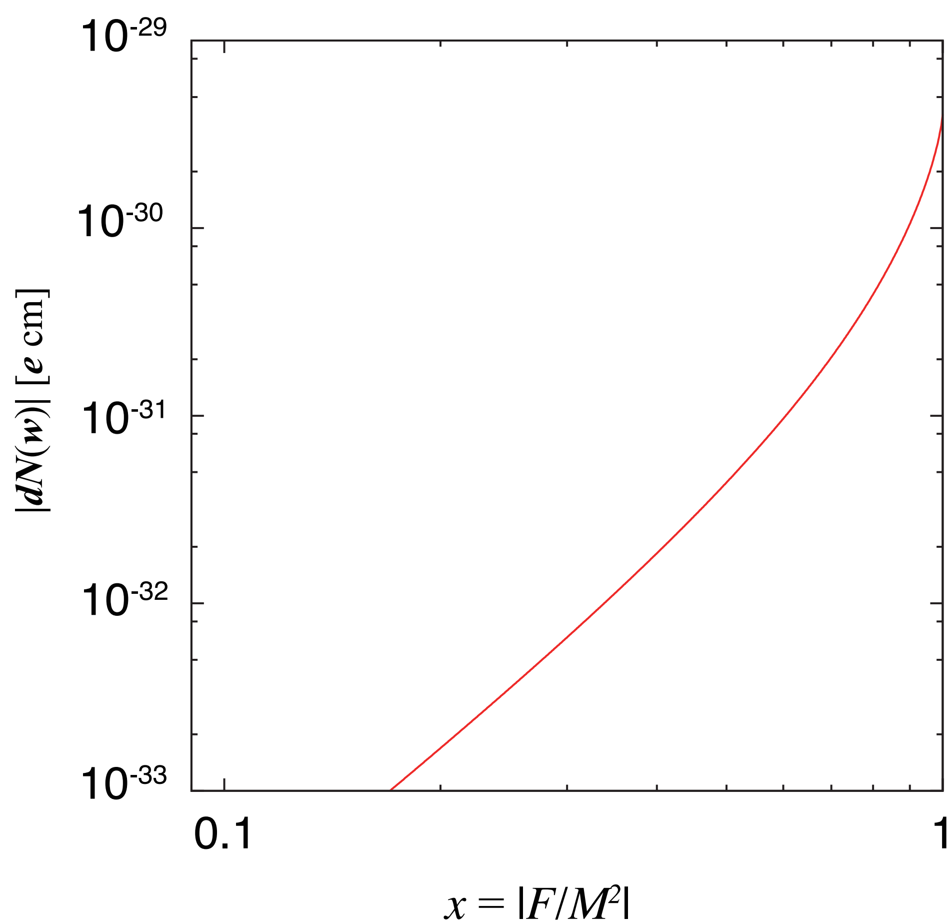
$$M_3 e^{i\theta\gamma_5} \simeq M_3^{\mathrm{GMSB}} = \frac{g_3^2}{16\pi^2} e^{-i\theta_F\gamma_5} n_3(\Phi) \left|\frac{F}{M}\right| g(x)$$

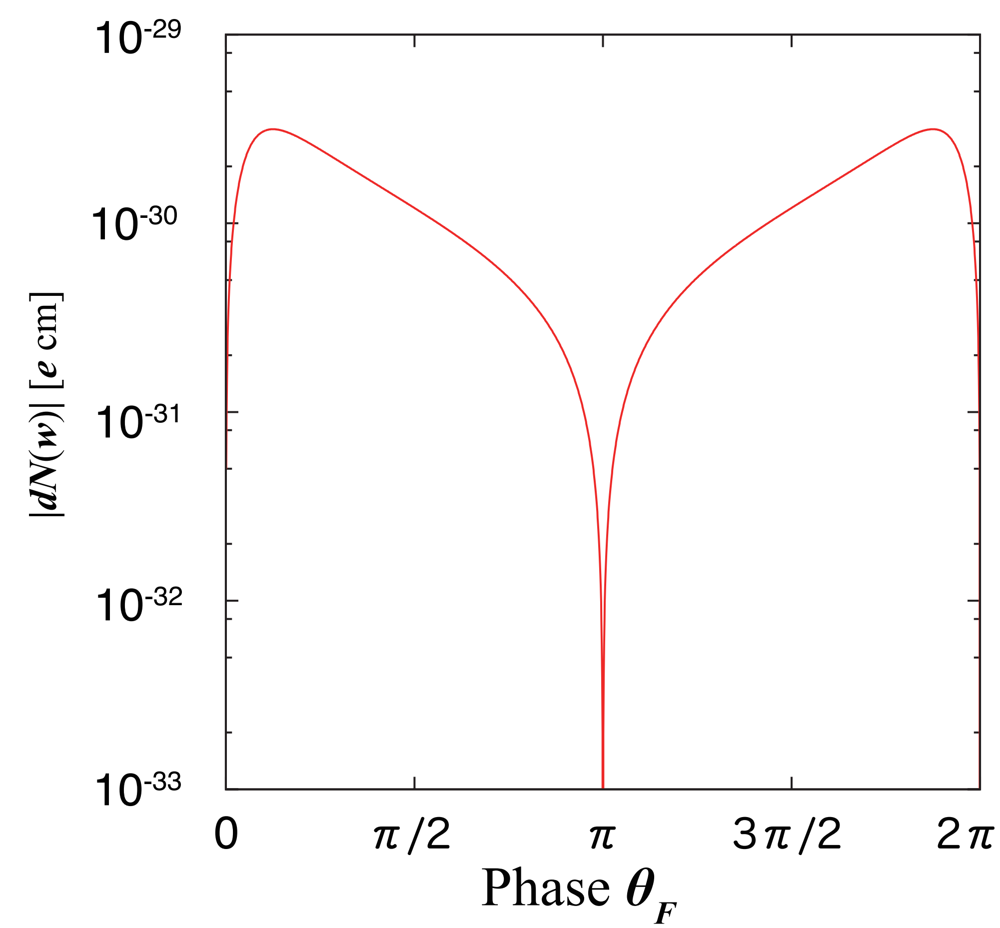
- $M_3^{\mathrm{GMSB}} << M_3^{\mathrm{AMSB}}$ @Small M
  and gluino mass phase $\theta \simeq 0$
- Slightly enhancement @ M ~ 100TeV
  (Cancellation of gluino mass)

Numerical results

New parameters: Scalar squared mass matrix for vector-likes

$$M,\ F,\ \theta_F \ \rightarrow\ M, x = |F/M^2|, \theta_F$$





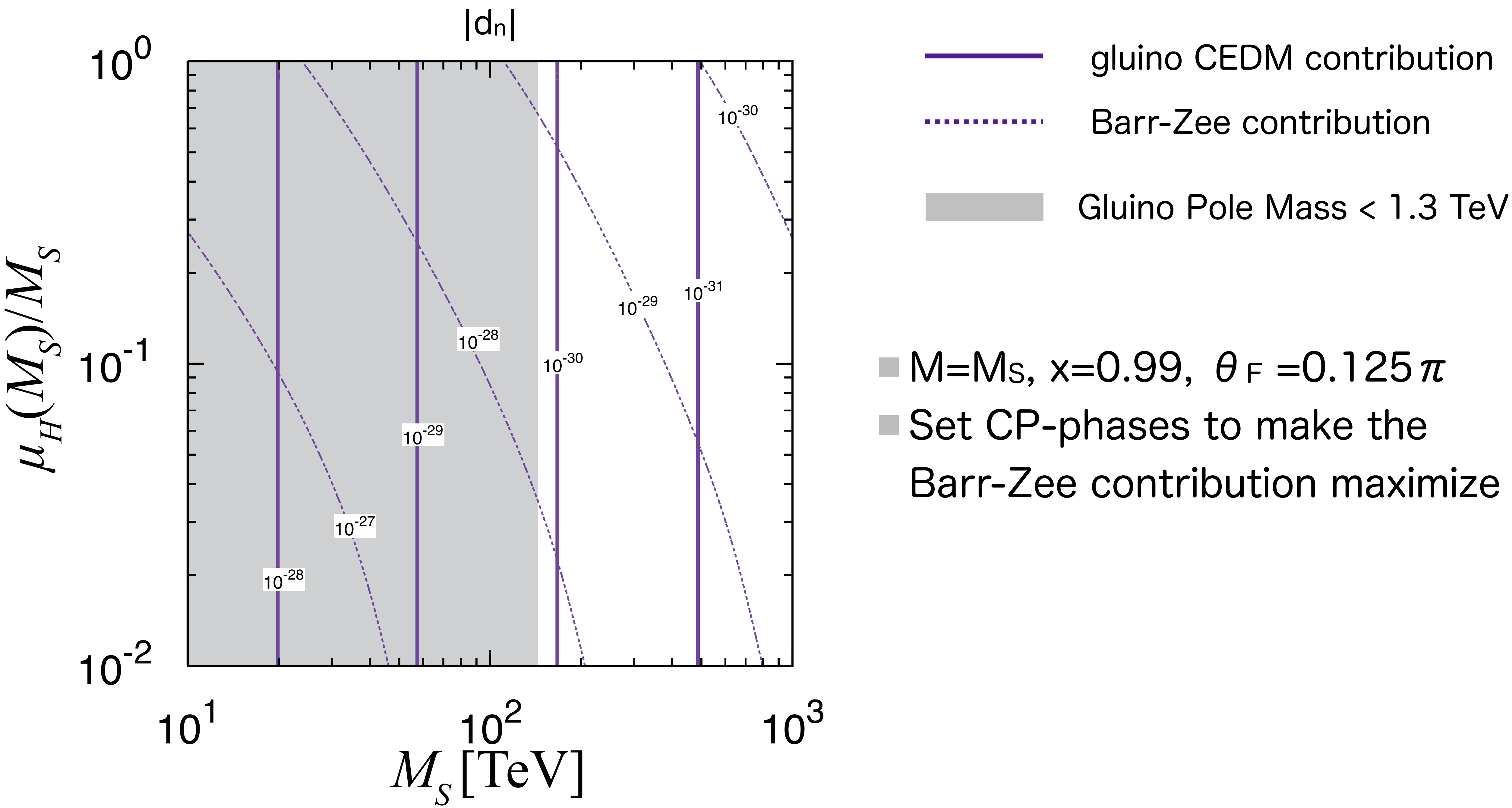
- $x \to 1$: massless scalar remains
- We take x=0.99

(Lightest scalar: 10TeV)

- $\theta_F = 0, \pi$: no phase in gluino mass
- We take $\theta_F = 0.125\pi$

(Maximal contribution)

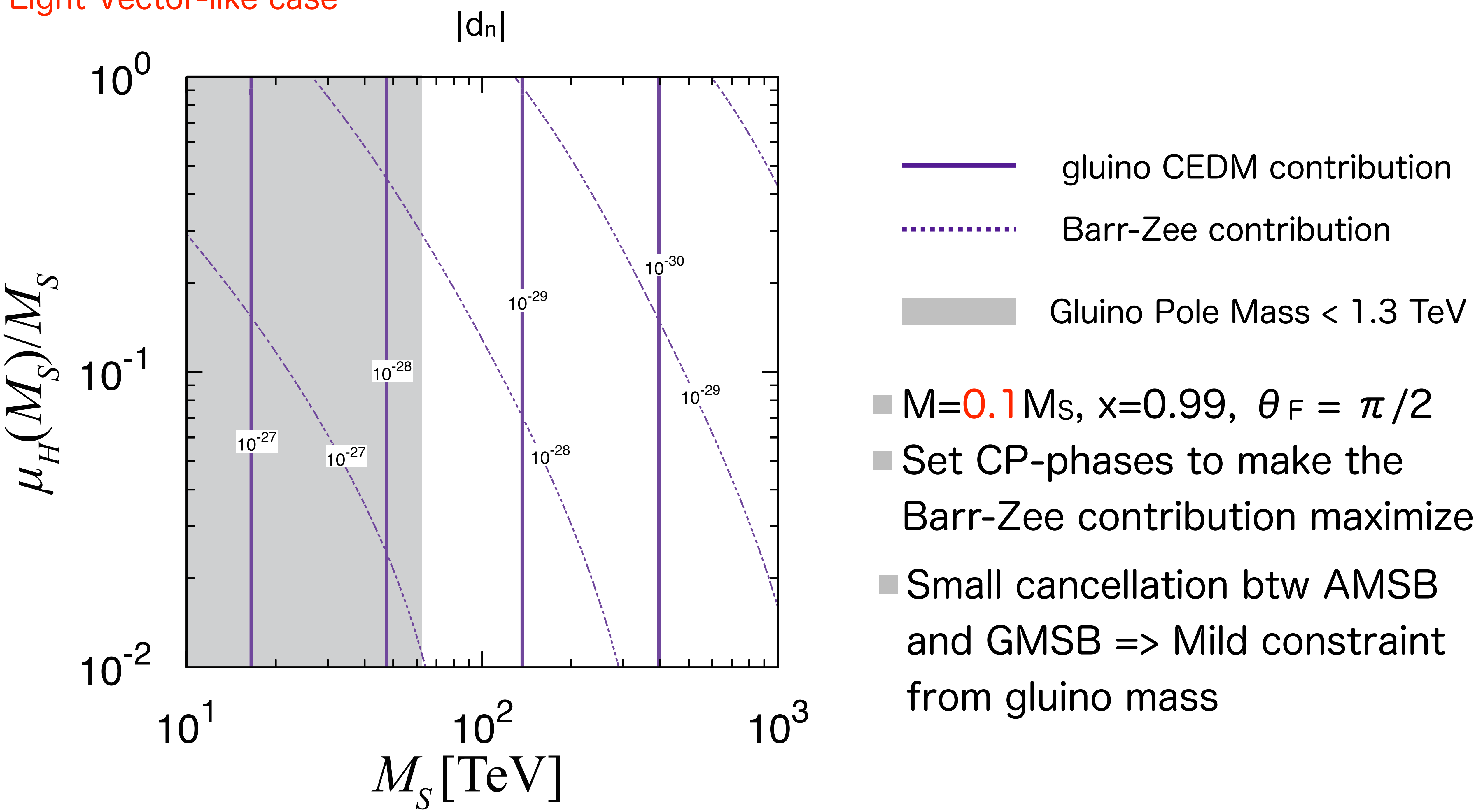
Barr-Zee contribution vs Gluino CEDM contribution



- M=Ms, x=0.99, $\theta_F = 0.125\pi$
- Set CP-phases to make the Barr-Zee contribution maximize

Barr-Zee contribution vs Gluino CEDM contribution

Light Vector-like case



- M=0.1Ms, x=0.99, $\theta_F = \pi/2$
- Set CP-phases to make the Barr-Zee contribution maximize
- Small cancellation btw AMSB and GMSB => Mild constraint from gluino mass

Comment on numerical analysis

- Proton EDM is similar as neutron EDM
  => We expect the discovery @ near future storage ring exp.

- Total nucleon EDMs cannot be estimated (due to NDA for Weinberg op.)
  => Relative sign ambiguity (between quark (C)EDMs contribution and Weinberg op.) etc..
  Also, sign of CPV in chargino-neutralino sector cannot be determined.

Anyway, Barr-Zee contributions to nucleon EDMs have opposite sign

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

$$d_n = 8.2 \times 10^{-17} [e\,\mathrm{cm}] \bar{\theta} - 0.20 d_u + 0.78 d_d + e(-0.30 \tilde{d}_u + 0.30 \tilde{d}_d - 0.014 \tilde{d}_s).$$

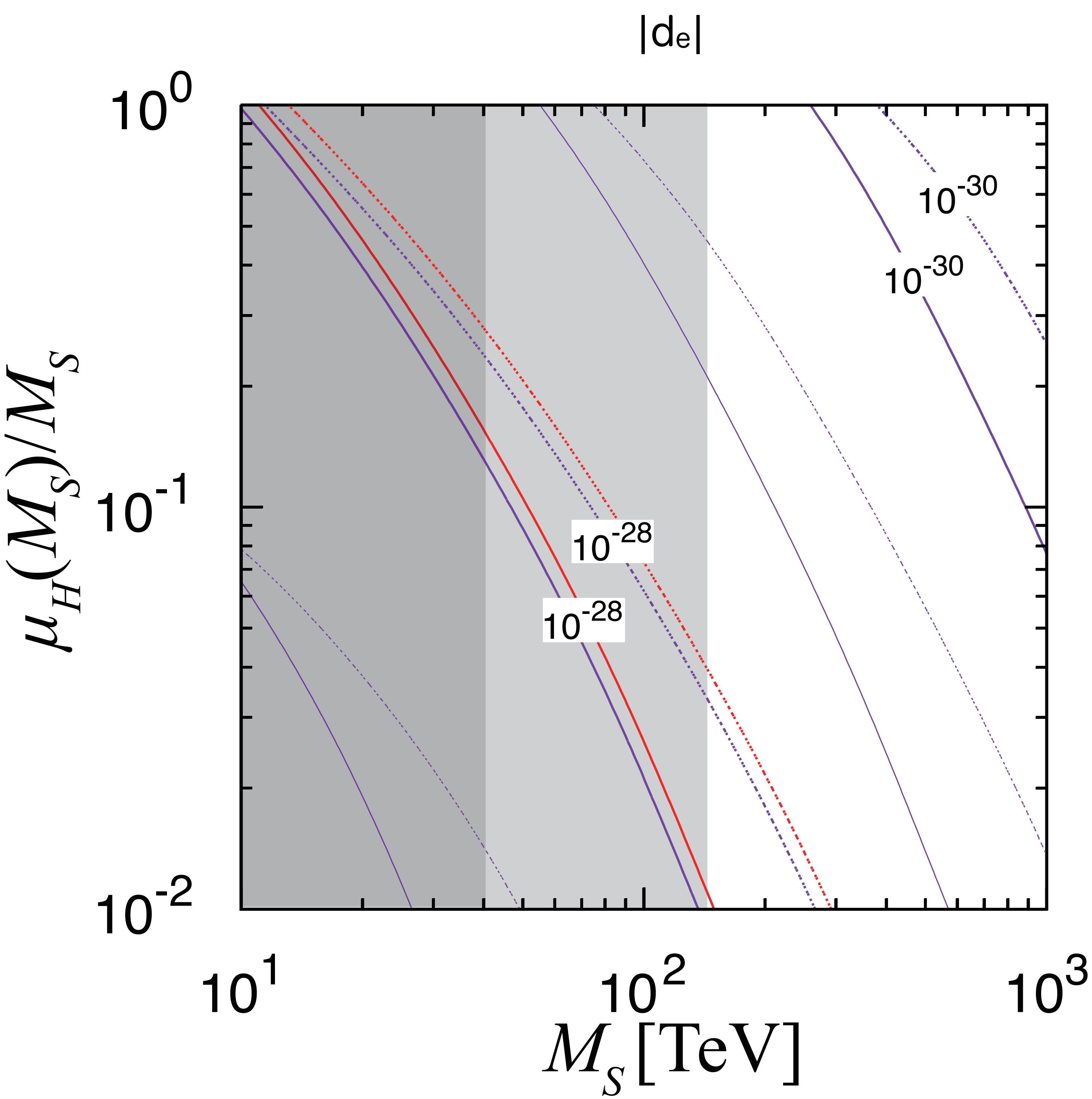
gluino CEDM contribution is expected that it affects to nucleon EDMs in a different way.

Summary

- We consider the High-scale SUSY models with vector-like multiplets and new contribution from gluino CEDM.
- Gluino contribution (gluino CEDM-> CP-odd Weinberg op.) is comparable to the standard contribution (Barr-Zee).
- But, qualitative estimation of total neutron EDM has ambiguity (from NDA of Weinberg op.)

Backups

Electron EDM in high-scale SUSY scenario



$N_5=1$

$N_5=0$

Gluino Pole Mass < 1.3 TeV

$N_5=1$

$N_5=0$

$M=M_S$

Red line: Current bound

$$|d_e| < 8.7 \times 10^{-28} [e\ \mathrm{cm}]$$

Ratio of Barr-Zee and gluino CEDM contributions