Implications of EDM constraints in SUSY scenarios

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EDM Workshop, CERN, March 26th 2018

MSSM scenarios

Minimal Supersymmetric extension of the Standard Model (MSSM)

- More than 100 free parameters
- Not every parameter relevant for different studies
- EDMs relevant for CP violation

CPV-CMSSM: 10 parameters

GUT-universal parameters: m_0, $m_{1/2}$, A_0, $\tan\beta$

+ 6 phases: ϕ_{M_1}, ϕ_{M_2}, ϕ_{M_3}, ϕ_{A_b}, ϕ_{A_t}, ϕ_{A_τ}

CPX: 9 parameters

1 unified sfermion mass: M_S

with $\mu = 4M_S$, $|A_{U,D,\ell}| = 2M_S$, $|M_1| = |M_2| = 1$ TeV, $|M_3| = 3$ TeV

+ 2 Higgs parameters $\tan\beta$, m_{H^+}

+ 6 phases: ϕ_{M_1}, ϕ_{M_2}, ϕ_{M_3}, ϕ_{A_b}, ϕ_{A_t}, ϕ_{A_τ}

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CP violating pMSSM

CP violating phenomenological MSSM (CPV-pMSSM)

$\rightarrow$ 19 pMSSM parameters + 6 phases = 25 parameters

10 sfermion masses: $M_{\tilde{e}_L} = M_{\tilde{\mu}_L}$, $M_{\tilde{e}_R} = M_{\tilde{\mu}_R}$, $M_{\tilde{\tau}_L}$, $M_{\tilde{\tau}_R}$, $M_{\tilde{q}_{1L}} = M_{\tilde{q}_{2L}}$, $M_{\tilde{q}_{3L}}$, $M_{\tilde{u}_R} = M_{\tilde{c}_R}$, $M_{\tilde{t}_R}$, $M_{\tilde{d}_R} = M_{\tilde{s}_R}$, $M_{\tilde{b}_R}$

3 gaugino masses: $|M_1|$, $|M_2|$, $|M_3|$

+ 3 gaugino phases: ϕ_{M_1}, ϕ_{M_2}, ϕ_{M_3}

3 trilinear couplings: $A_d = A_s = |A_b|$, $A_u = A_c = |A_t|$, $A_e = A_\mu = |A_\tau|$

+ 3 trilinear coupling phases for the third generation fermions: ϕ_{A_b}, ϕ_{A_t}, ϕ_{A_τ}

3 Higgs/Higgsino parameters: M_{H^+}, $\tan\beta$, μ

A. Arbey, J. Ellis, R. Godbole, FM, Eur. Phys. J. C75 (2015), 85

$$M_\alpha = |M_\alpha| e^{i\phi_\alpha} \qquad A_\beta = |A_\beta| e^{i\phi_\beta}$$

The CP phases can take values between -180 and 180 degrees, and modify the mixing matrices and couplings

3 neutral Higgs bosons h_1, h_2, h_3 with scalar and pseudoscalar components

In the following, we consider only the case of neutralino LSP (= dark matter)

EDM constraints

Convention used thereafter:

$$\mathcal{L}_{\text{EDM}} = -\frac{i}{2} d_f F^{\mu\nu} \bar{f} \sigma_{\mu\nu} \gamma_5 f$$

Current limits at 95% C.L.

EDM	Upper limit (e.cm)	Equivalent limit (e.cm)	Reference
Thallium	1.3×10^{-24}	$d_e : 2.1 \times 10^{-27}$	PRL 88 (2002) 071805
Thorium monoxide	-	$d_e : 1.1 \times 10^{-28}$	Science 343 (2014) 269
Muon	1.9×10^{-19}	$d_\mu : 1.9 \times 10^{-19}$	PRD 80 (2009) 052008
Mercury	7.4×10^{-30}	$d_n : 1.6 \times 10^{-26}$ $d_p : 2.0 \times 10^{-25}$	PRL 116 (2016) 161601
Neutron	4.2×10^{-26}	$d_n : 4.2 \times 10^{-26}$	PRL 97 (2006) 131801

Prospective values for proton EDM

	(e.cm)
Case 1	$\lvert d_p \rvert < 2 \times 10^{-29}$
Case 2	$d_p = (1.00 \pm 0.01) \times 10^{-27}$

Nucleon EDMs

Different possible parametrizations for the nucleon EDMs
$\rightarrow$ EDM values can be changed by a factor of a few.

For simplicity, we use here the parton quark model parametrization:

$$d_N = \eta^E(\Delta_d^N d_d + \Delta_u^N d_u + \Delta_s^N d_s)$$

where $\eta^E = 1.53$ and the Δ's are the quark polarisations in the nucleon.

For the neutron, the Δ's are precisely known:

$$\Delta_d^n = 0.746 \ , \ \Delta_u^n = -0.508 \ , \ \Delta_s^n = -0.226$$

For the proton, the spin structure of the proton is not well-known, and we consider the simplest isospin symmetric model:

$$\Delta_u^p = 4/3 \ , \ \Delta_d^p = -1/3 \ , \ \Delta_s^p = 0$$

Regardless of the chosen parameters, the neutron and proton EDMs are expected to be of the same order of magnitude.

EDM in the MSSM

$$d_f = d_f^{\tilde{\chi}^\pm} + d_f^{\tilde{\chi}^0} + d_f^{\tilde{g}} + d_f^H \text{ where } f = e, \mu, u, d, s.$$

Chargino-mediated one-loop EDMs

$$\begin{aligned}
d_l^{\tilde{\chi}^\pm} &= -\frac{e}{16\pi^2} \sum_i \frac{m_{\tilde{\chi}_i^\pm}}{m^2_{\tilde{\nu}_l}} \mathrm{Im}\left(g_{Ri}^{\tilde{\chi}^\pm l\tilde{\nu}*} g_{Li}^{\tilde{\chi}^\pm l\tilde{\nu}}\right) f(m^2_{\tilde{\chi}_i^\pm}/m^2_{\tilde{\nu}_l}) \\
d_u^{\tilde{\chi}^\pm} &= \frac{e}{16\pi^2} \sum_{i,j} \frac{m_{\tilde{\chi}_i^\pm}}{m^2_{\tilde{d}_j}} \mathrm{Im}\left(g_{Rij}^{\tilde{\chi}^\pm u\tilde{d}*} g_{Lij}^{\tilde{\chi}^\pm u\tilde{d}}\right) \left[f(m^2_{\tilde{\chi}_i^\pm}/m^2_{\tilde{d}_j}) - \frac{1}{3} g(m^2_{\tilde{\chi}_i^\pm}/m^2_{\tilde{d}_j})\right] \\
d_d^{\tilde{\chi}^\pm} &= \frac{e}{16\pi^2} \sum_{i,j} \frac{m_{\tilde{\chi}_i^\pm}}{m^2_{\tilde{u}_j}} \mathrm{Im}\left(g_{Rij}^{\tilde{\chi}^\pm d\tilde{u}*} g_{Lij}^{\tilde{\chi}^\pm d\tilde{u}}\right) \left[-f(m^2_{\tilde{\chi}_i^\pm}/m^2_{\tilde{u}_j}) + \frac{2}{3} g(m^2_{\tilde{\chi}_i^\pm}/m^2_{\tilde{u}_j})\right]
\end{aligned}$$

Neutralino-mediated one-loop EDMs

$$d_f^{\tilde{\chi}^0} = \frac{e}{16\pi^2} \sum_{i,j} \frac{m_{\tilde{\chi}_i^0}}{m^2_{\tilde{f}_j}} \mathrm{Im}\left(g_{Rij}^{\tilde{\chi}^0 f\tilde{f}*} g_{Lij}^{\tilde{\chi}^0 f\tilde{f}}\right) Q_{\tilde{f}}\, g(m^2_{\tilde{\chi}_i^0}/m^2_{\tilde{f}_j})$$

The $g^{\tilde{\chi} ff'}$ contains the chargino/neutralino/squark mixing matrices, $Q_{\tilde{f}}$ is the charge of $\tilde{f}$.

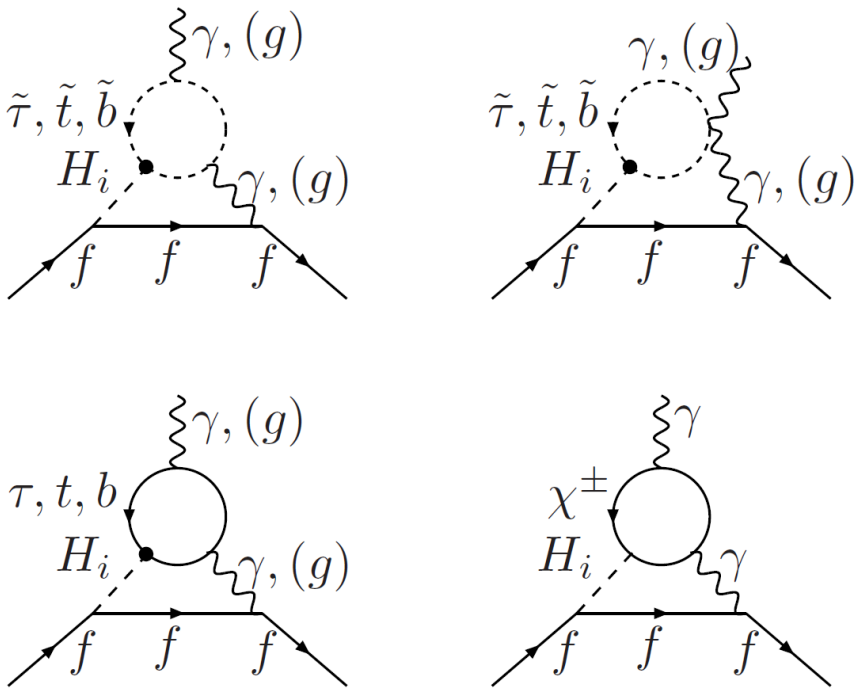
EDM in the MSSM

$$d_f = d_f^{\tilde{\chi}^\pm} + d_f^{\tilde{\chi}^0} + d_f^{\tilde{g}} + d_f^H \text{ where } f = e, \mu, u, d, s.$$

Gluino-mediated one-loop EDMs

$$d_q^{\tilde{g}} = \frac{e}{3\pi^2} \sum_i \frac{m_{\tilde{g}}}{m^2_{\tilde{q}_i}} \mathrm{Im}\left(g_{Ri}^{\tilde{g}q\tilde{q}*} g_{Li}^{\tilde{g}q\tilde{q}}\right) Q_{\tilde{f}}\, g(m^2_{\tilde{g}}/m^2_{\tilde{q}_i})$$

(Higher order) Higgs-mediated Barr-Zee diagrams:



MSSM scans and constraints

Methodology

Random scans in the CP violating pMSSM scenario

(Codes involved: CPsuperH, SuperIso Relic, micrOMEGAs, ...)

A. Arbey, J. Ellis, R. Godbole, FM, Eur. Phys. J. C75 (2015), 85

imposing many constraints:

- LEP and Tevatron direct search limits
- Light Higgs mass range
- Flavour physics limits, in particular from $\mathrm{BR}(B \to X_s\gamma)$, $\mathrm{BR}(B_s \to \mu^+\mu^-)$, $\mathrm{BR}(B \to \tau\nu)$, ΔM_{B_s}
- Muon anomalous magnetic moment, $(g-2)_\mu$
- Dark matter relic density
- Dark matter direct search limits
- Heavy Higgs mass limits
- Higgs production and decay rates
- LHC SUSY direct search limits
- Electric dipole moments (EDMs)

Problem: the EDMs impose so strong constraints that only zero phases are allowed, apart in some very restricted regions of the parameter space!

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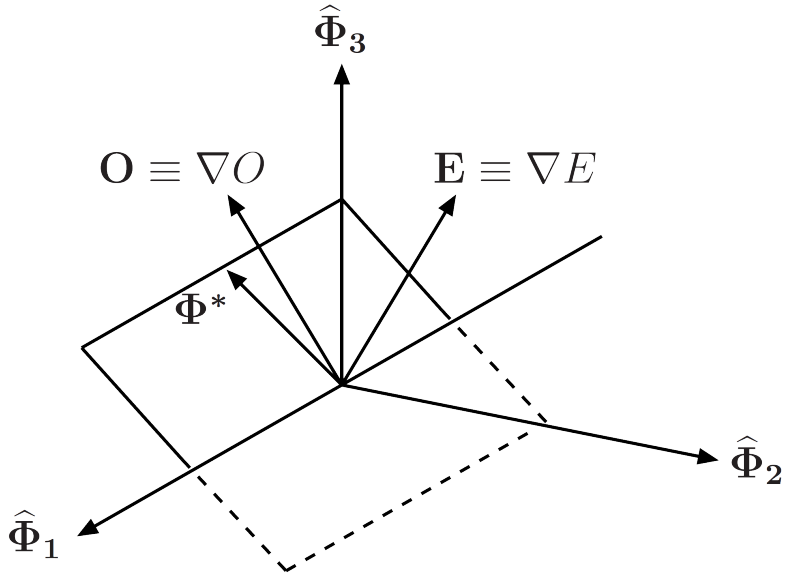
Geometric approach

Method inspired by J. Ellis, J.S. Lee, A. Pilaftsis, JHEP 1010 (2010) 049

How to determine the direction in the phase parameter space minimizing the EDMs and maximizing other CP violating observables?

Let us consider a simple example: how to minimize the EDM E while maximizing the observable O in the 3 phases parameter space (ϕ_1, ϕ_2, ϕ_3)?



$\vec{\nabla} O$: direction corresponding to the maximal increase of $|O|$

$\vec{\nabla} E$: direction corresponding to the maximal increase of $|E|$

Optimal direction $\vec{\phi}^*$
= intersection of the plane perpendicular to $\vec{\nabla} E$ with the plane defined by $\vec{\nabla} O$ and $\vec{\nabla} E$
= direction minimizing $|E|$ and allowing for an increase in $|O|$

Works well in the limit of small phases...

Improved geometric approach

In our study, we want to minimize the four strongest EDM constraints (E^i)

and maximize the CP asymmetry of $b \to s\gamma$ (O) over the six phases ϕ_i.

The optimal direction, computed for each choice of the 19 CP conserving pMSSM parameters, is given by:

$$\phi^*_\alpha = \epsilon_{\alpha\beta\gamma\delta\mu\eta}\, \epsilon_{\eta\nu\lambda\rho\sigma\tau}\, E^a_\beta\, E^b_\gamma\, E^c_\delta\, E^d_\mu\, O_\nu\, E^a_\lambda\, E^b_\rho\, E^c_\sigma\, E^d_\tau$$

with $\phi_\alpha = \phi_{1,2,3,t,b,\tau}$, $E^i_\alpha \equiv \partial E^i/\partial\phi_\alpha$ and $O_\alpha \equiv \partial O/\partial\phi_\alpha$

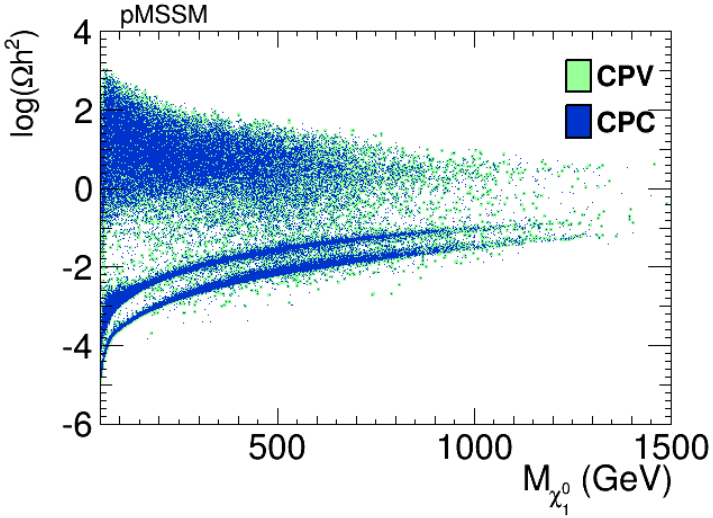
Iterative approach still necessary:

To go beyond the limit of small phases, we start with phases at 0, determine the optimal direction, move by at most 20 degrees, and iterate to determine the optimal direction at the new position.

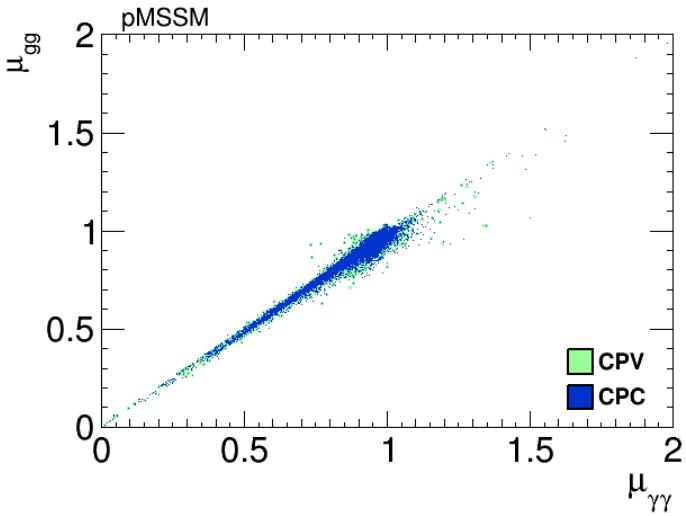
Sectors weakly affected by CP violation

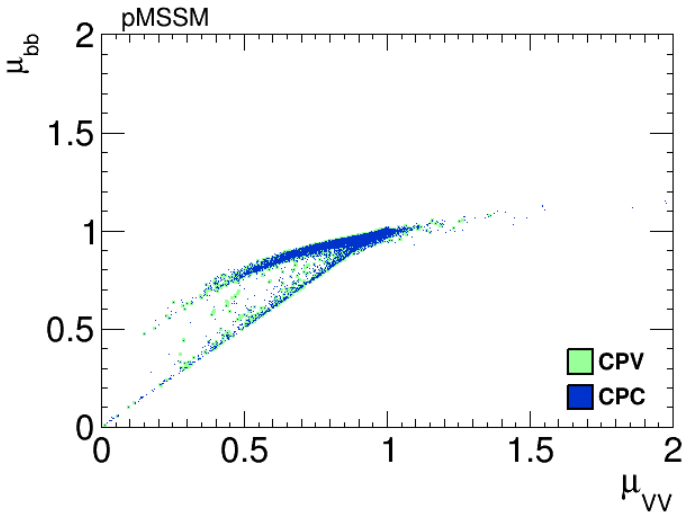
Relic density

Planck: $\Omega h^2 \sim 0.1$



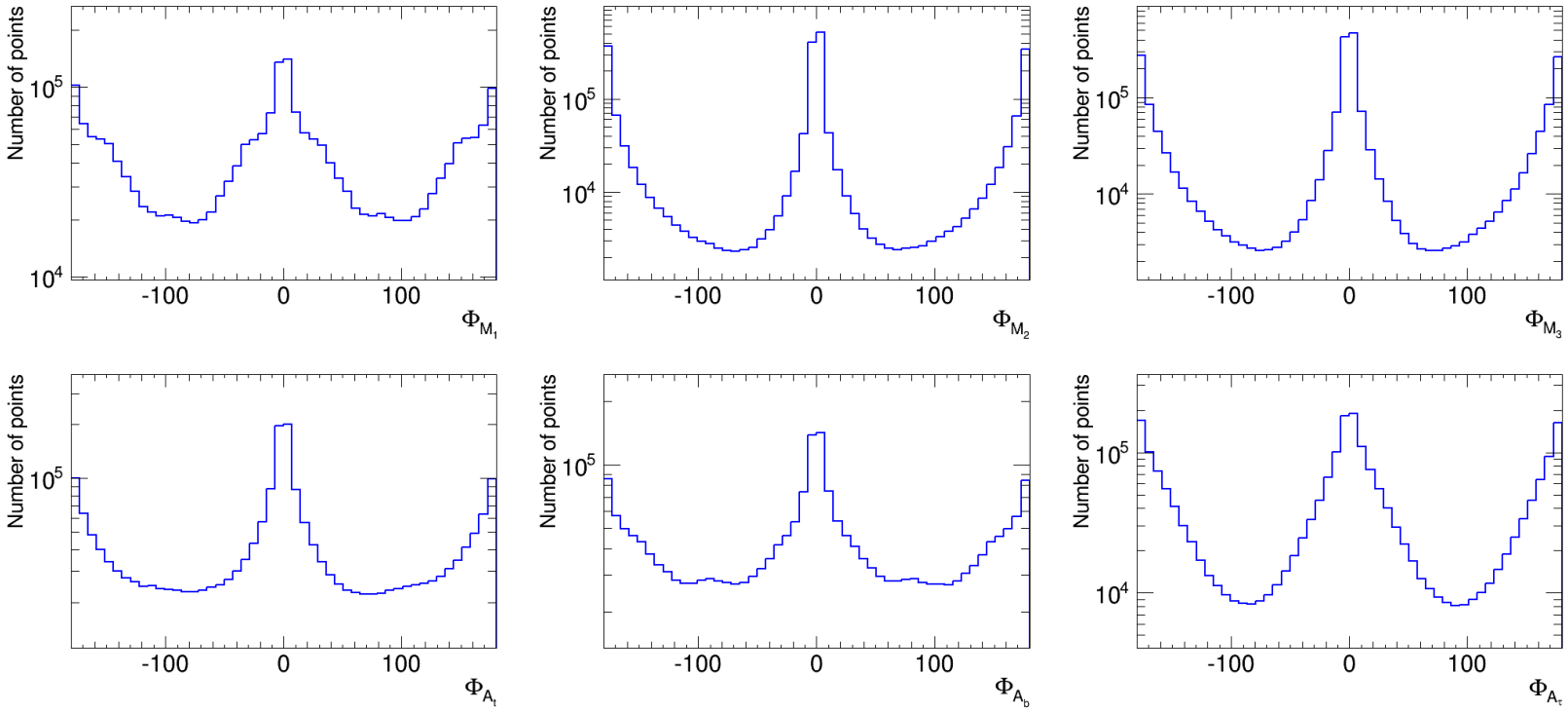
Higgs signal strengths ($M_{h_1} \in [122, 128]$ GeV)





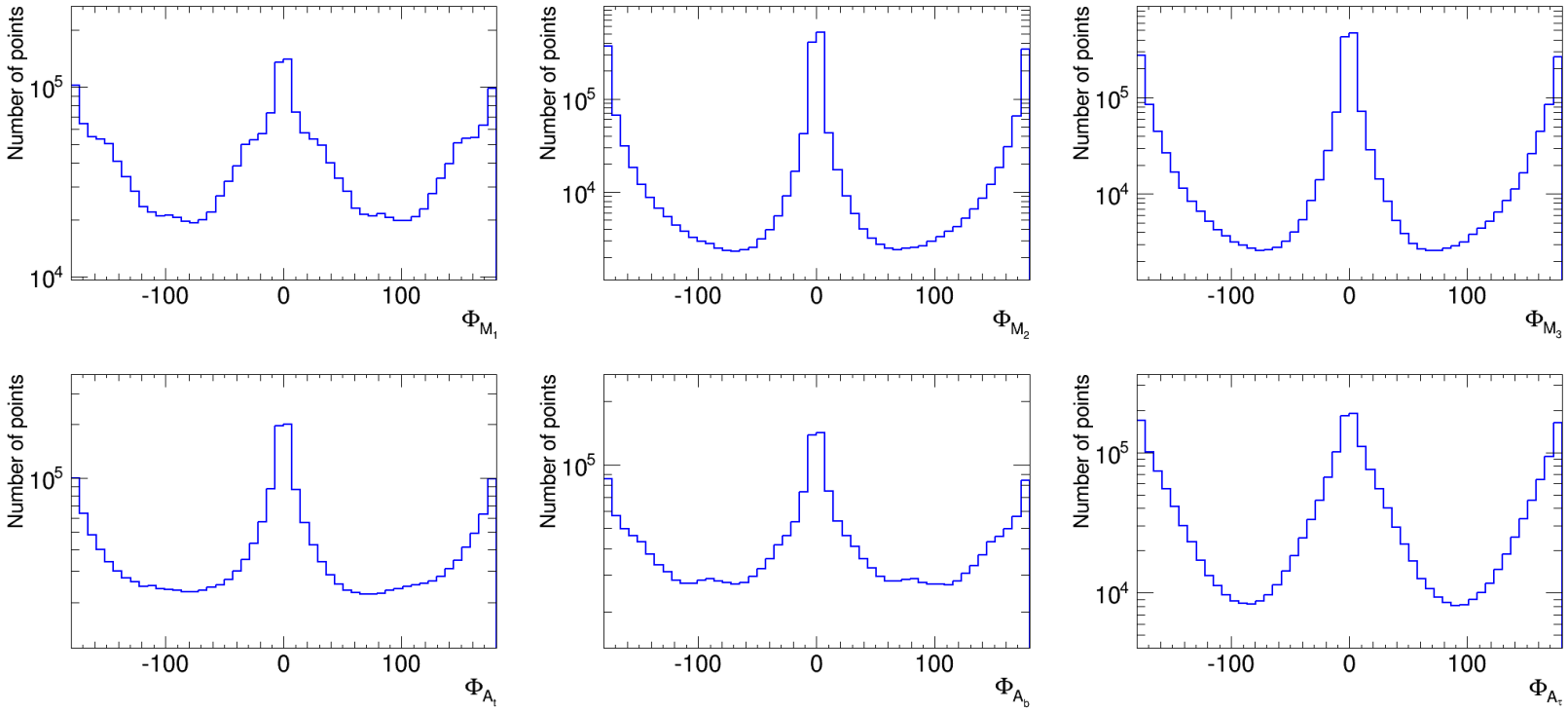
Effects of the EDMs on the CP-violating phases

Original sample with no EDM constraints



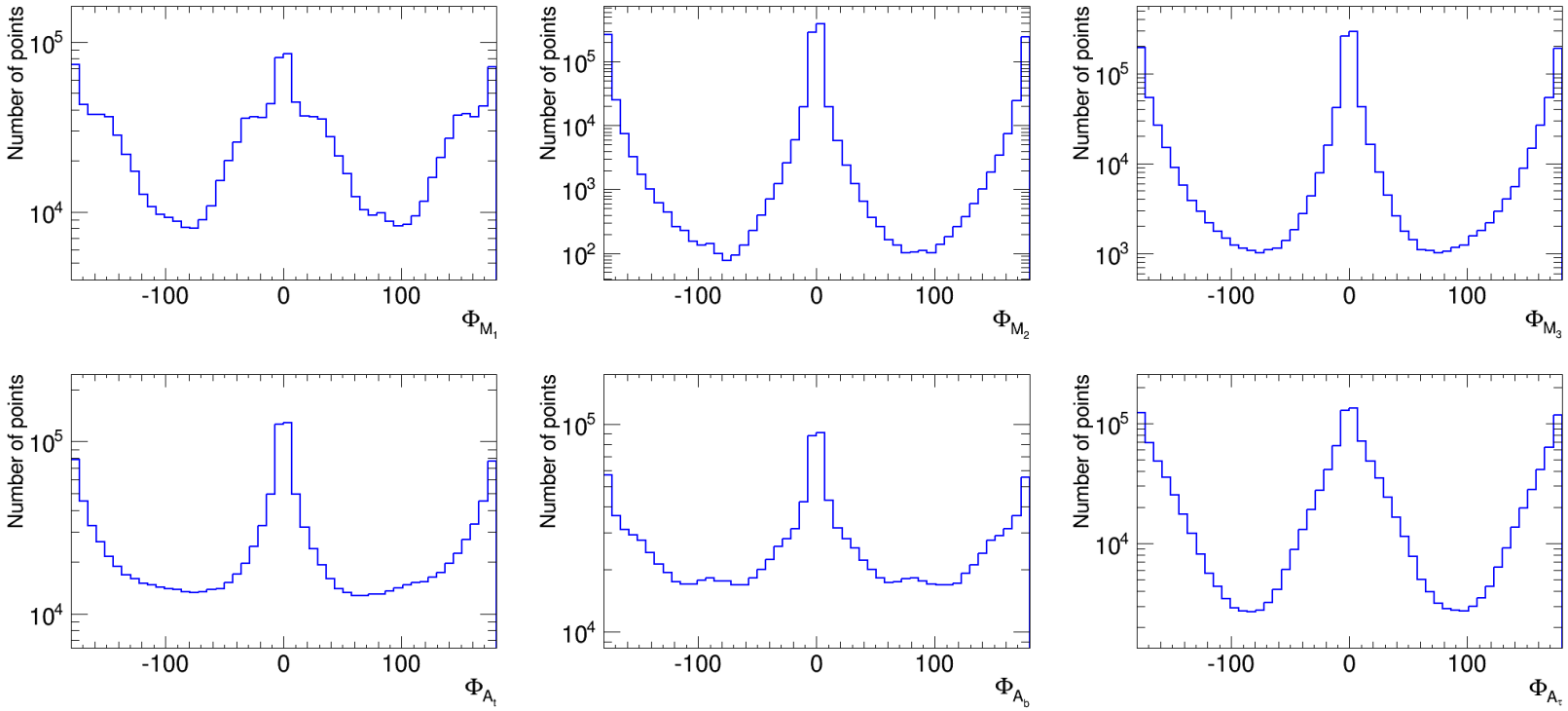
Effects of the EDMs on the CP-violating phases

Adding EDM constraints: Muon



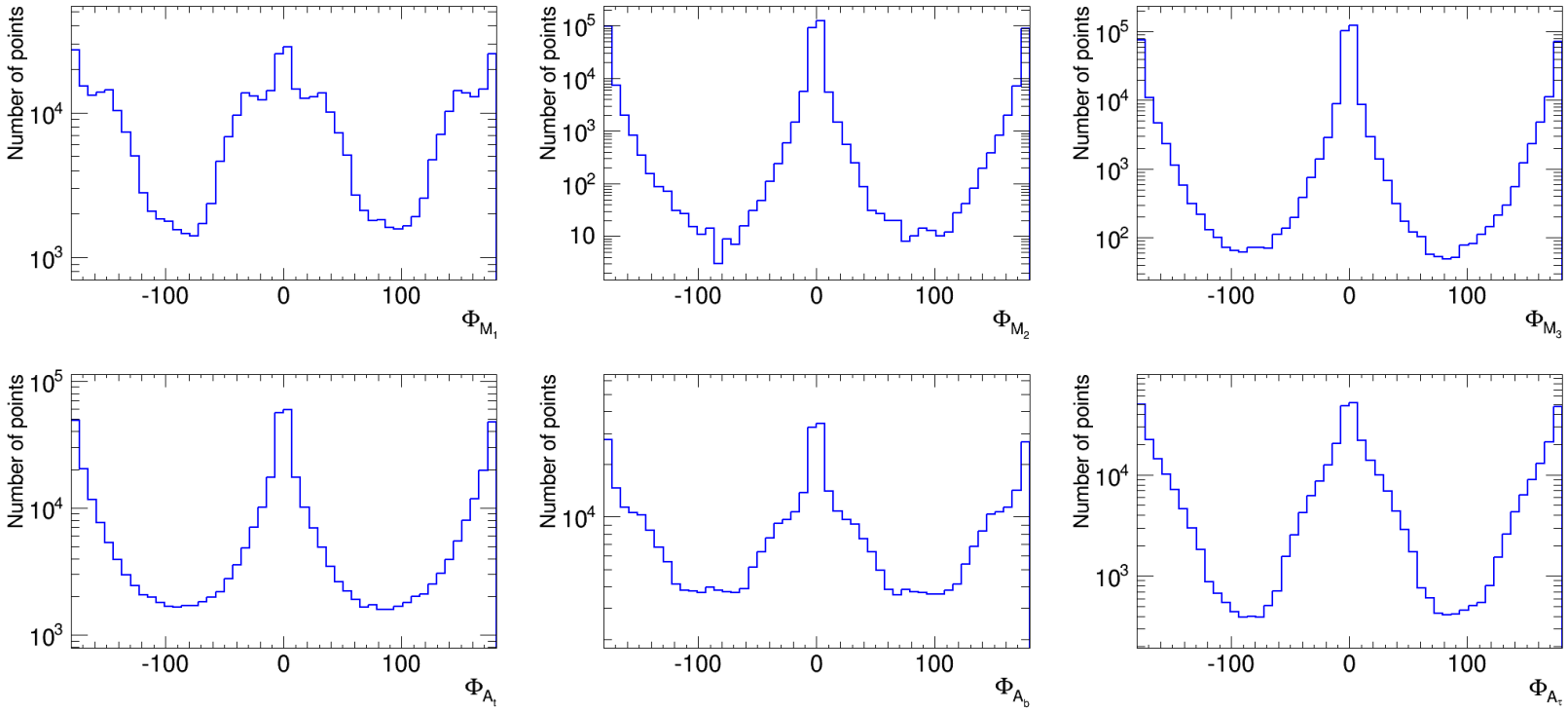
Effects of the EDMs on the CP-violating phases

Adding EDM constraints: Muon, Thallium



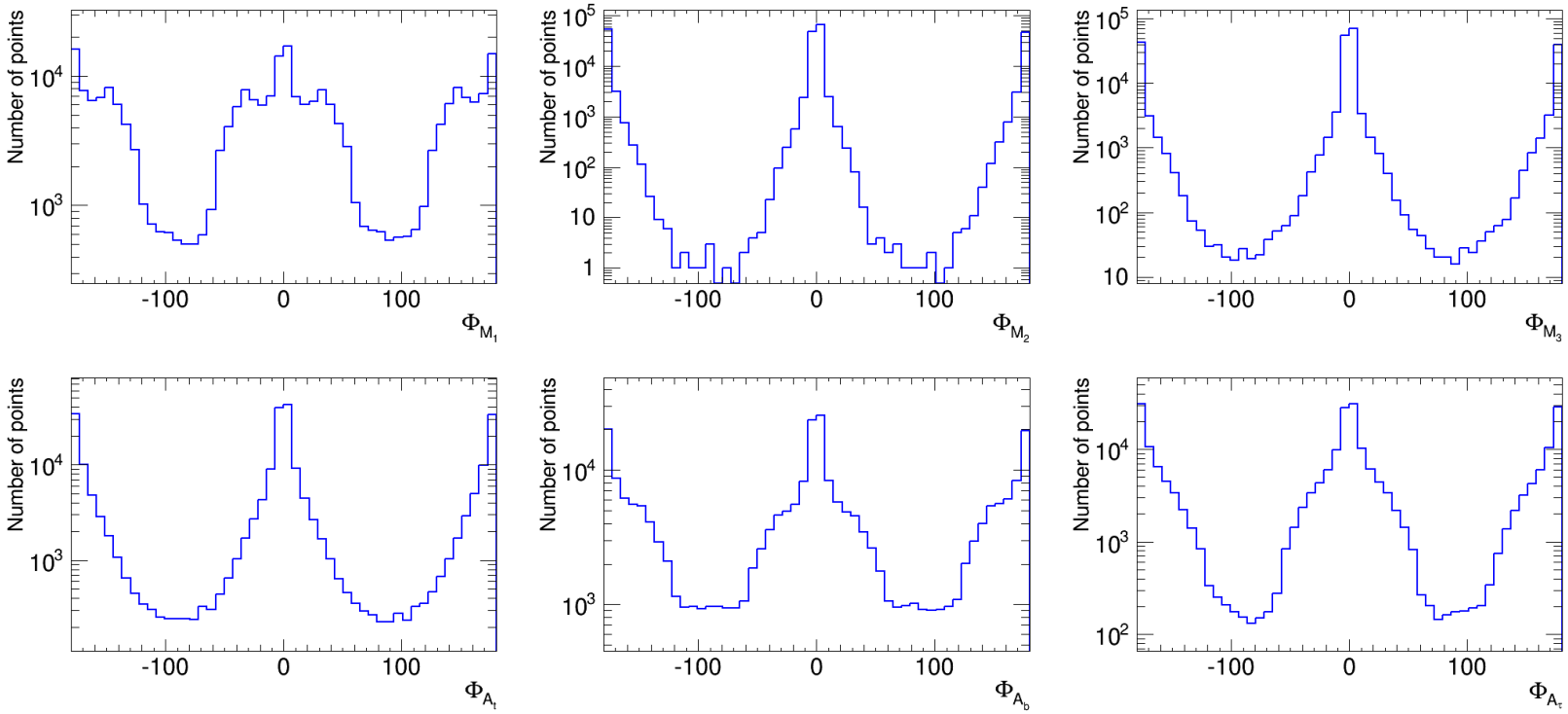
Effects of the EDMs on the CP-violating phases

Adding EDM constraints: Muon, Thallium, Mercury



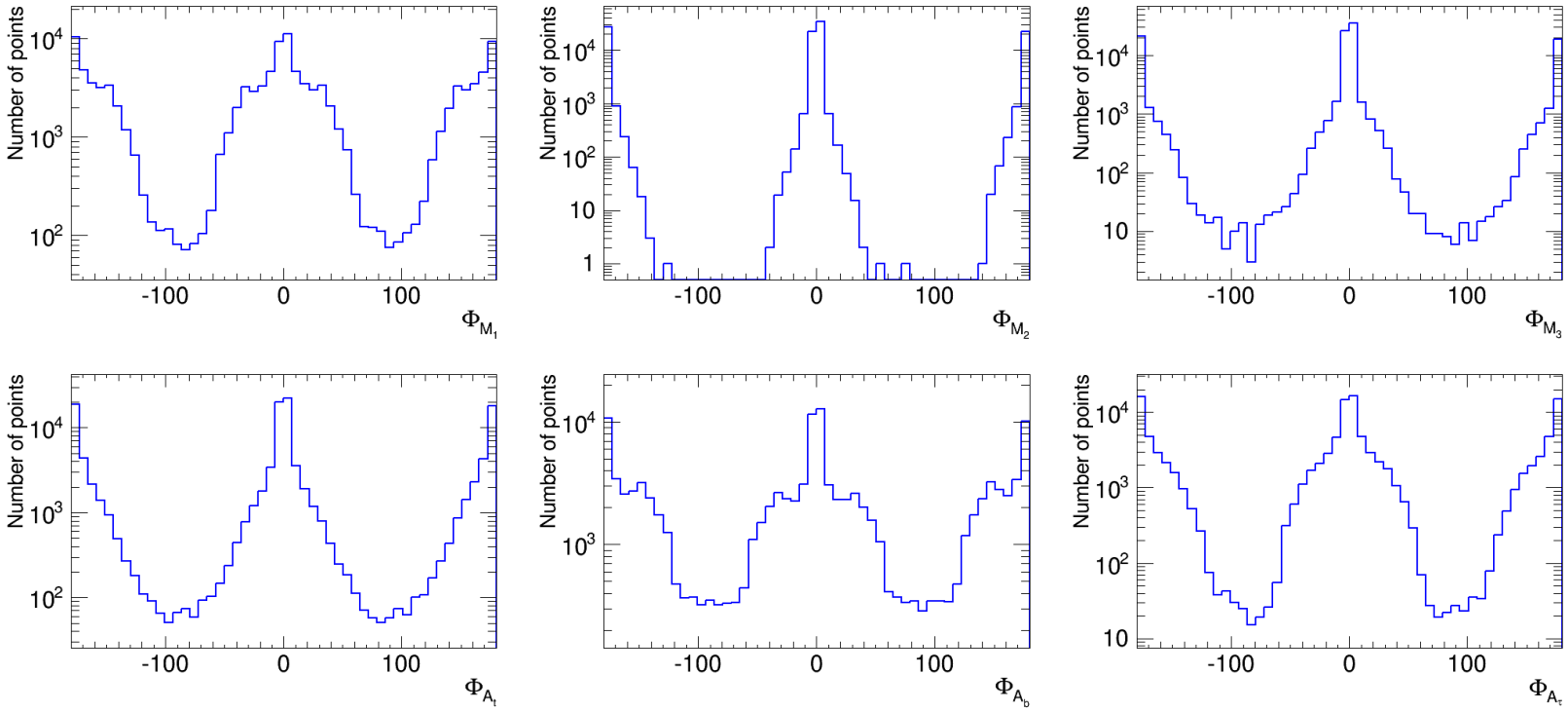
Effects of the EDMs on the CP-violating phases

Adding EDM constraints: Muon, Thallium, Mercury, Neutron



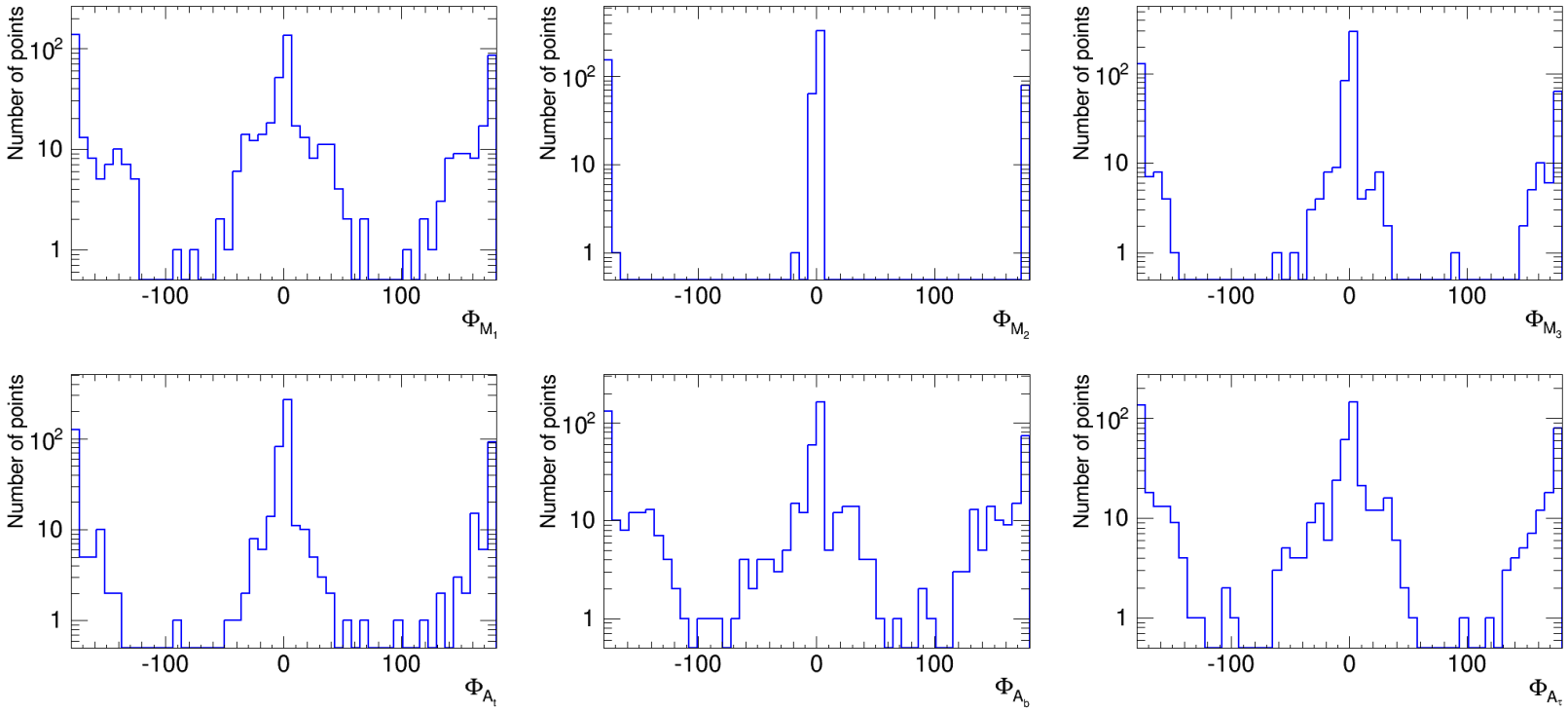
Effects of the EDMs on the CP-violating phases

Adding EDM constraints: Muon, Thallium, Mercury, Neutron, Thorium Monoxyde



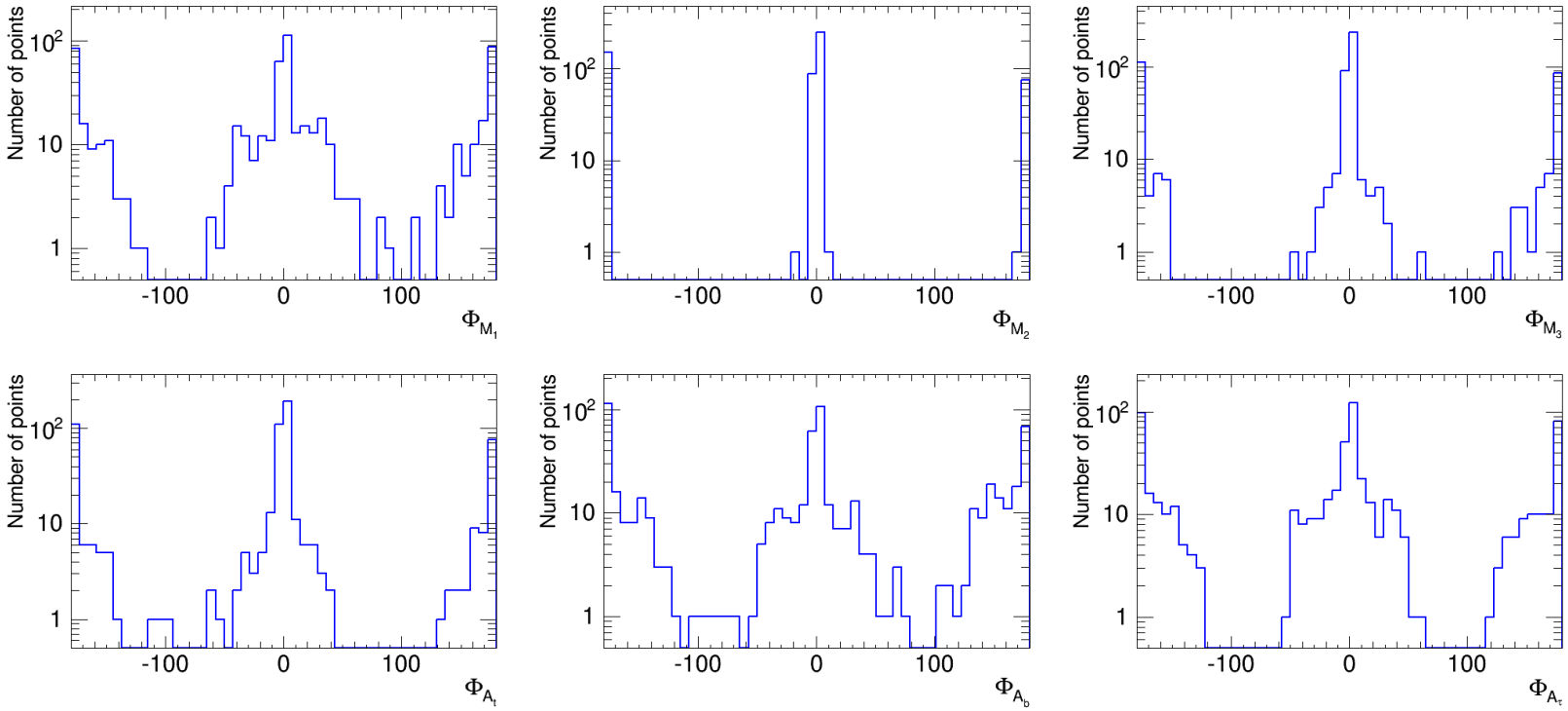
Effects of the EDMs on the CP-violating phases

Adding EDM constraints: Muon, Thallium, Mercury, Neutron, Thorium Monoxyde + Proton



Effects of the EDMs on the CP-violating phases

Adding EDM constraints: Muon, Thallium, Mercury, Neutron, Thorium Monoxyde + Proton 2



Effects of the EDMs on the CP-violating phases

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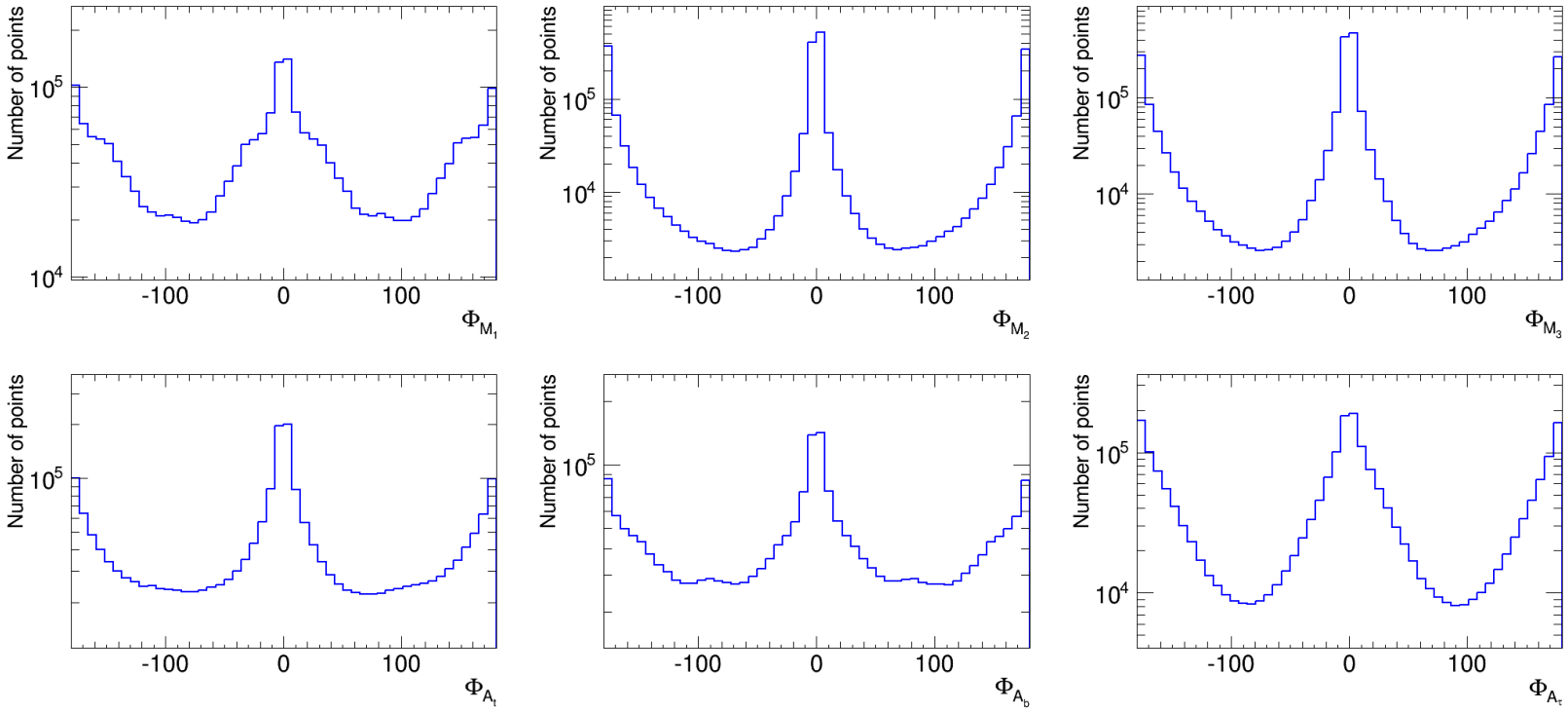
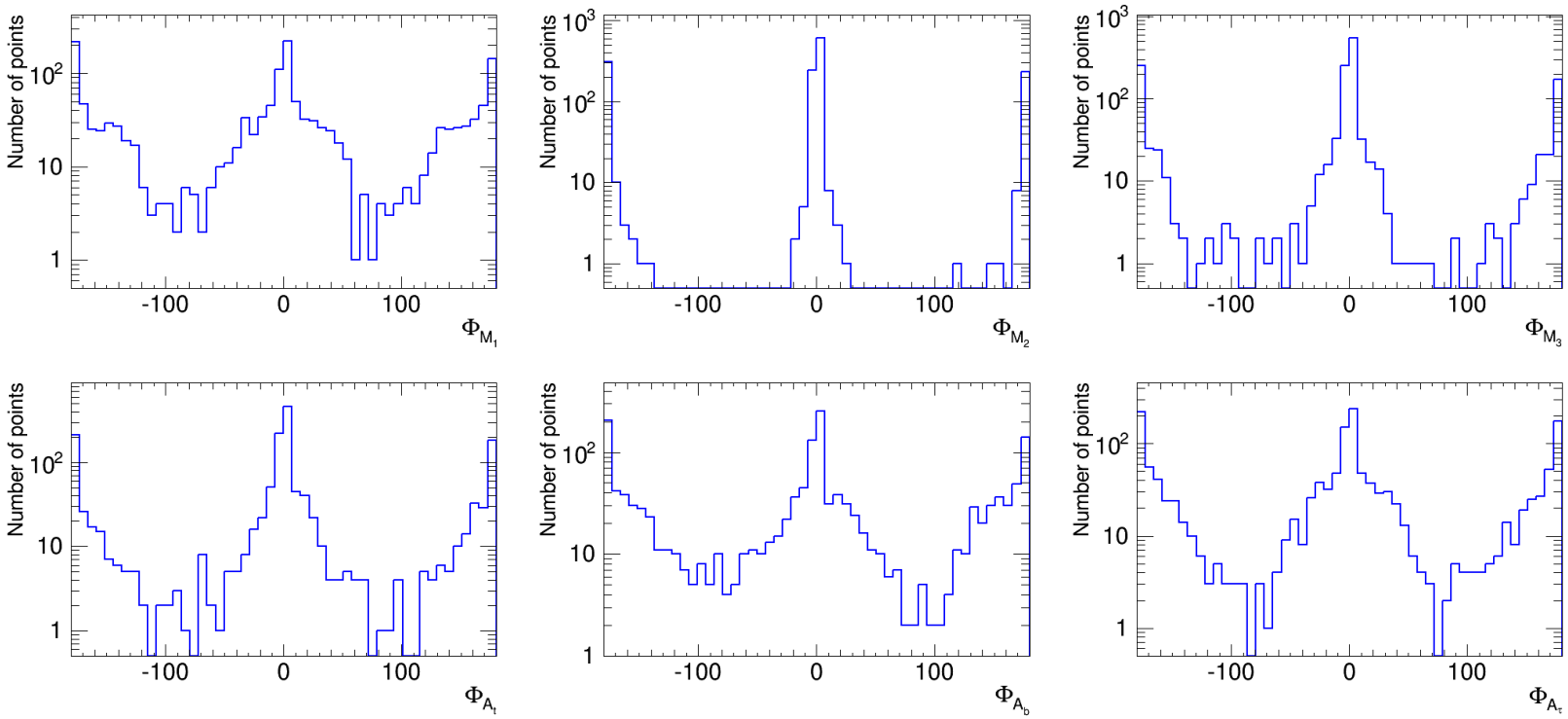


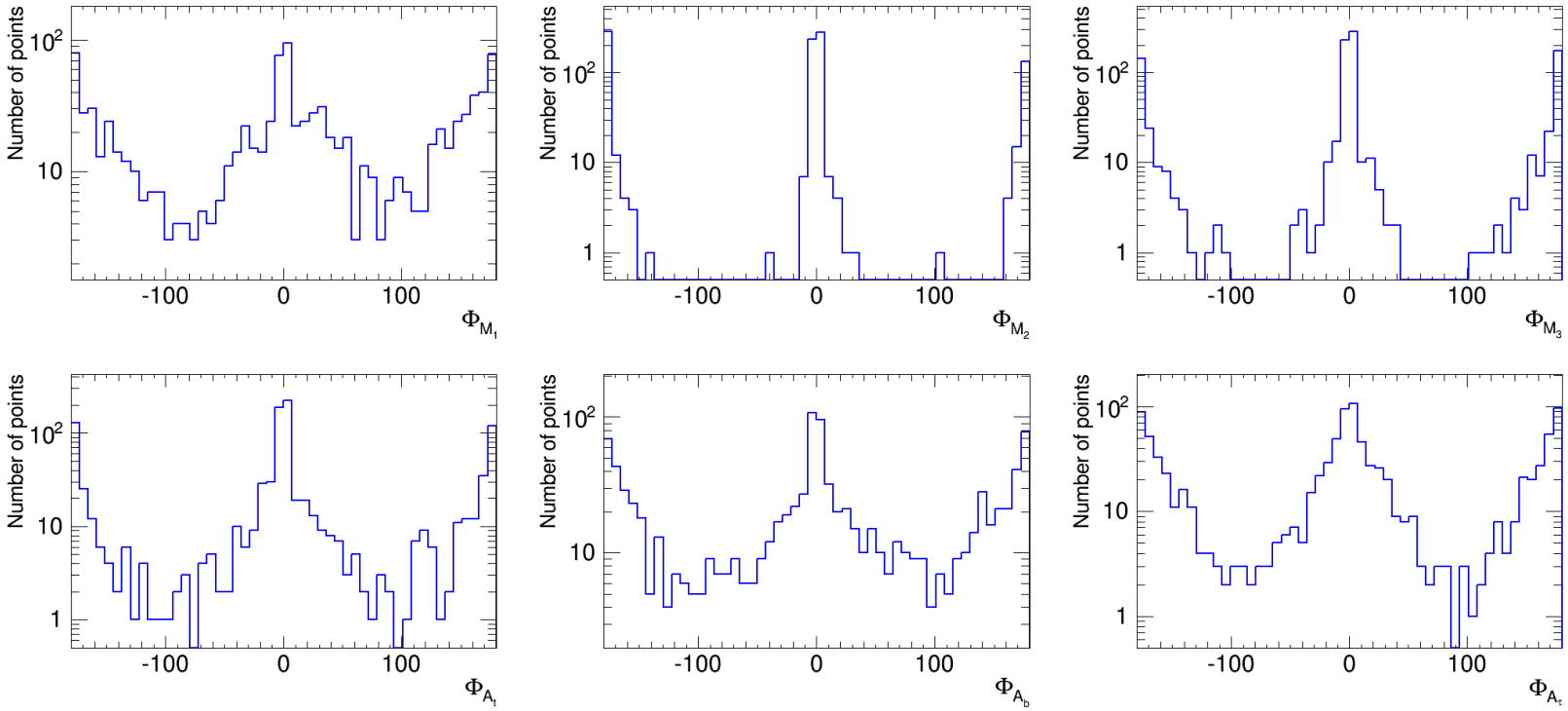
Effects of the EDMs on the CP-violating phases

Adding EDM constraints: Proton only



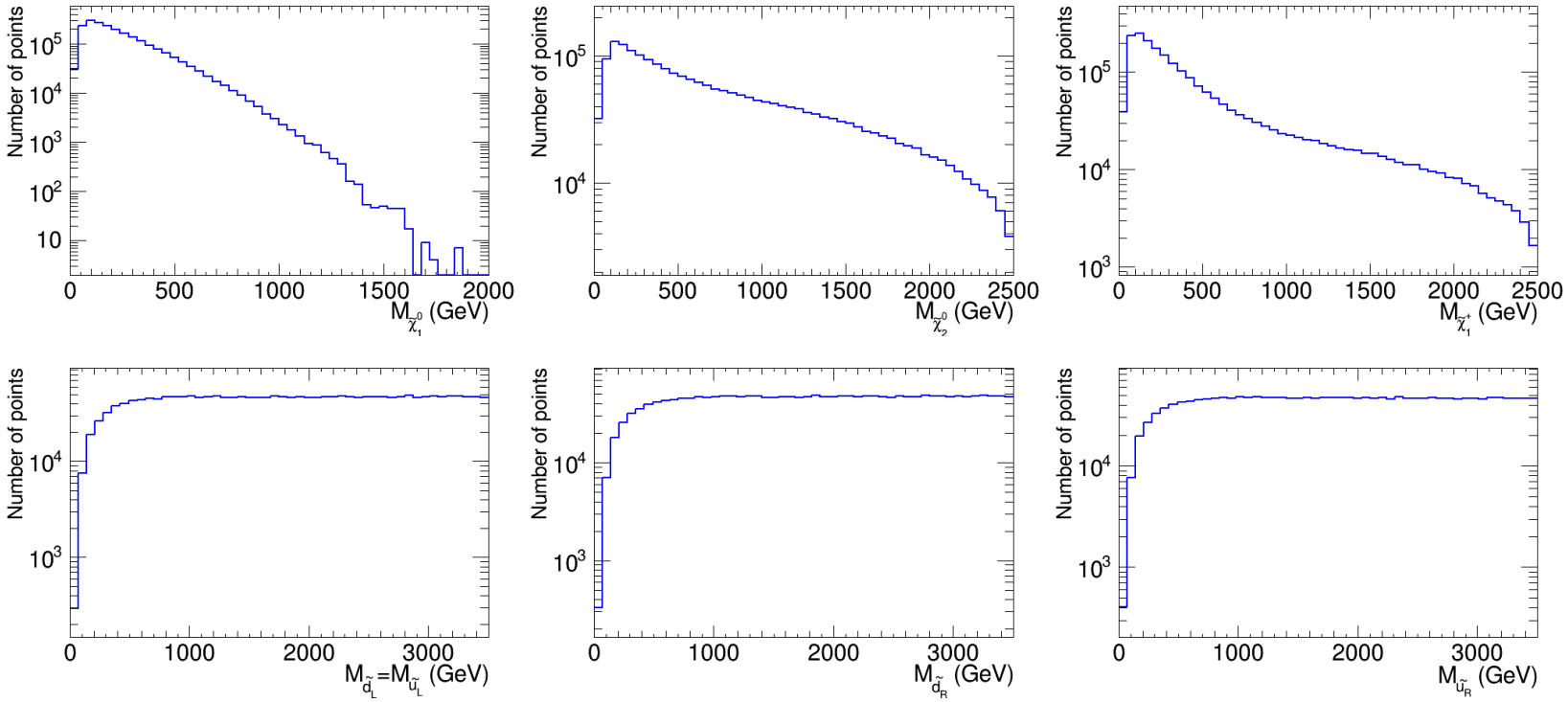
Effects of the EDMs on the CP-violating phases

Adding EDM constraints: Proton 2 only



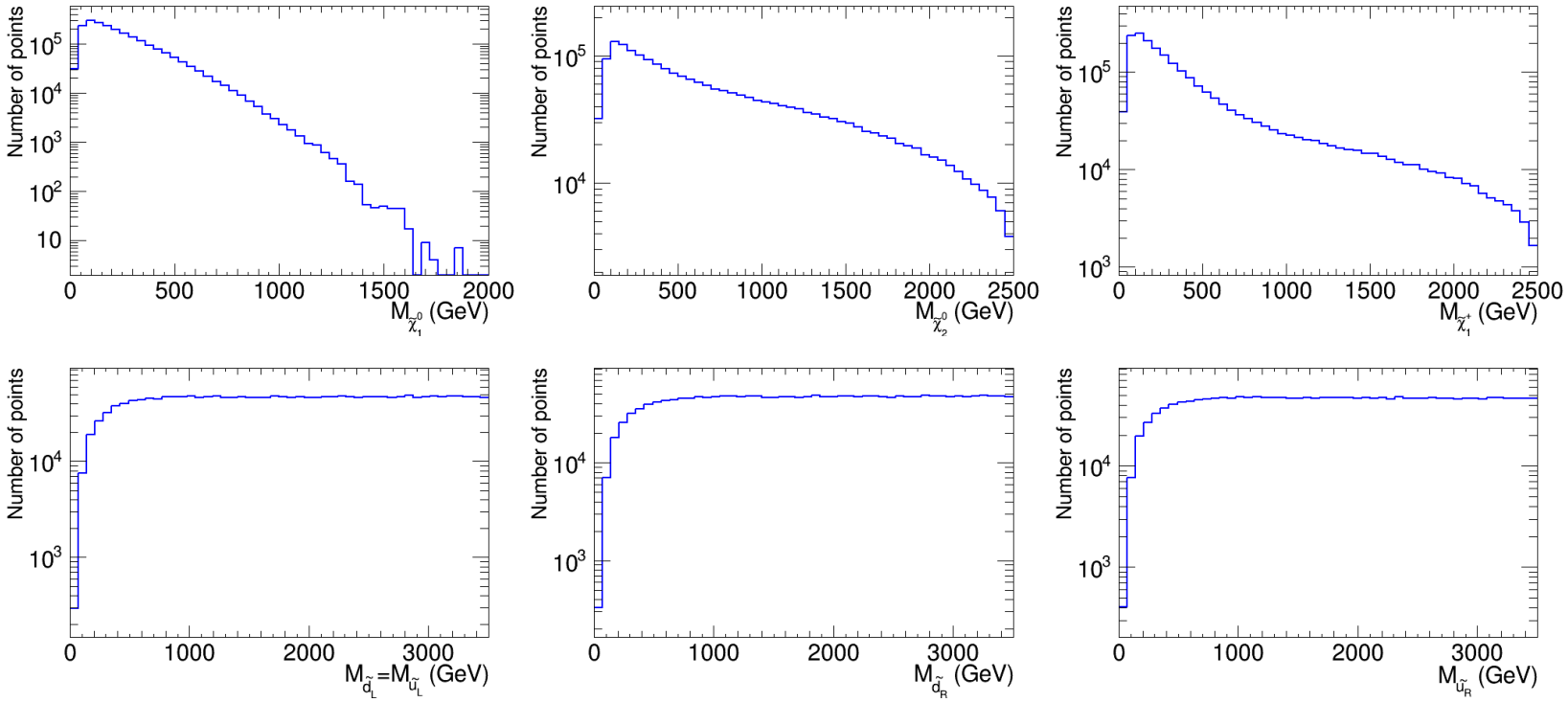
Effects of the EDMs on the SUSY masses

Original sample with no EDM constraints



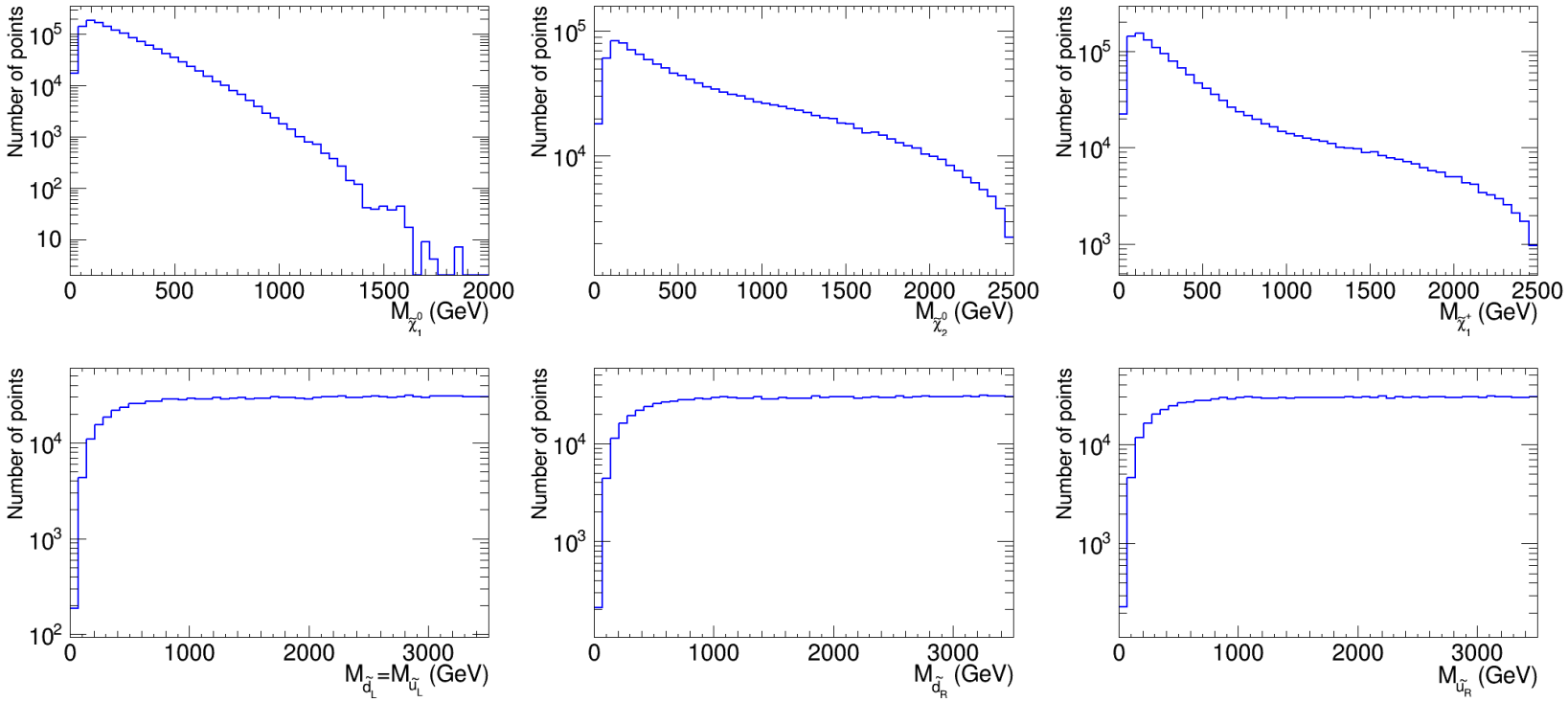
Effects of the EDMs on the SUSY masses

Adding EDM constraints: Muon



Effects of the EDMs on the SUSY masses

Adding EDM constraints: Muon, Thallium



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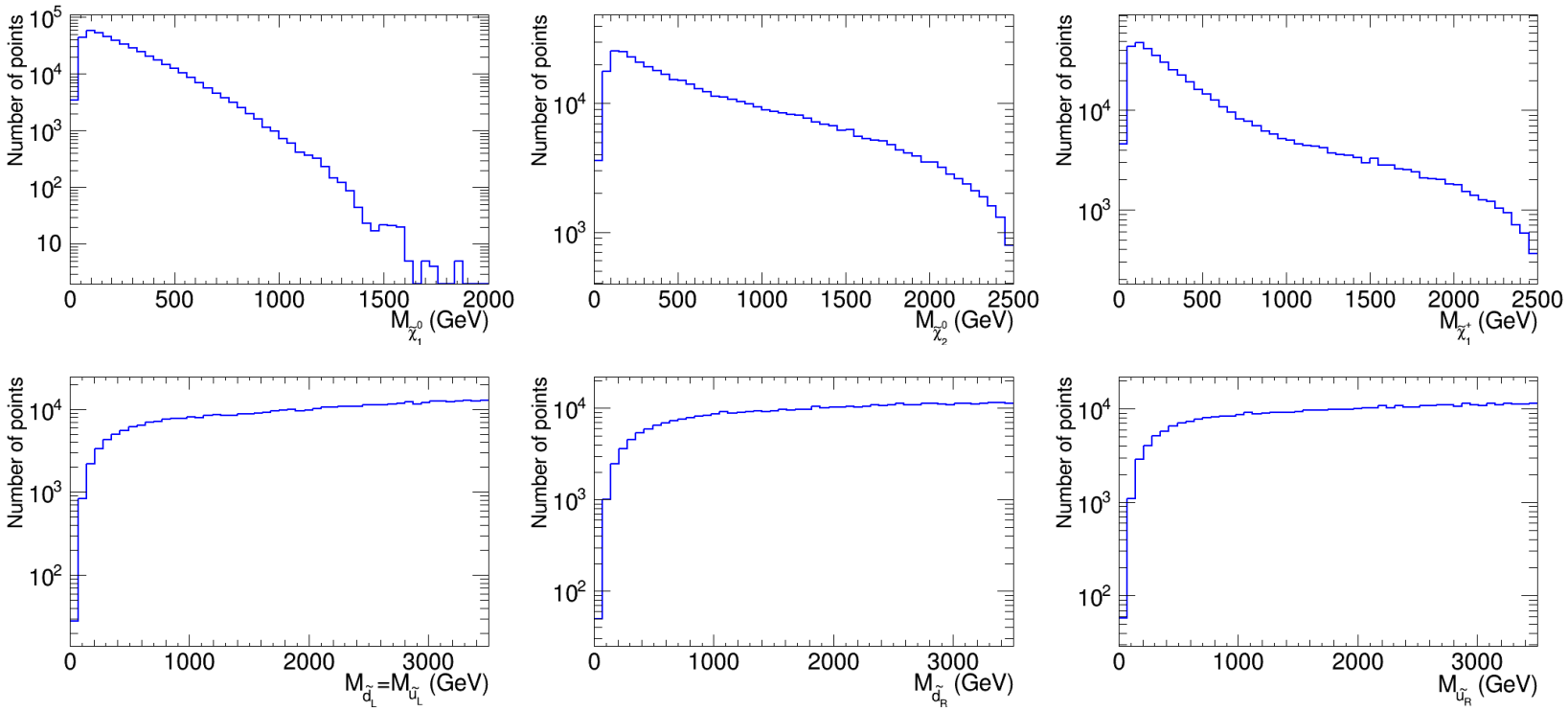
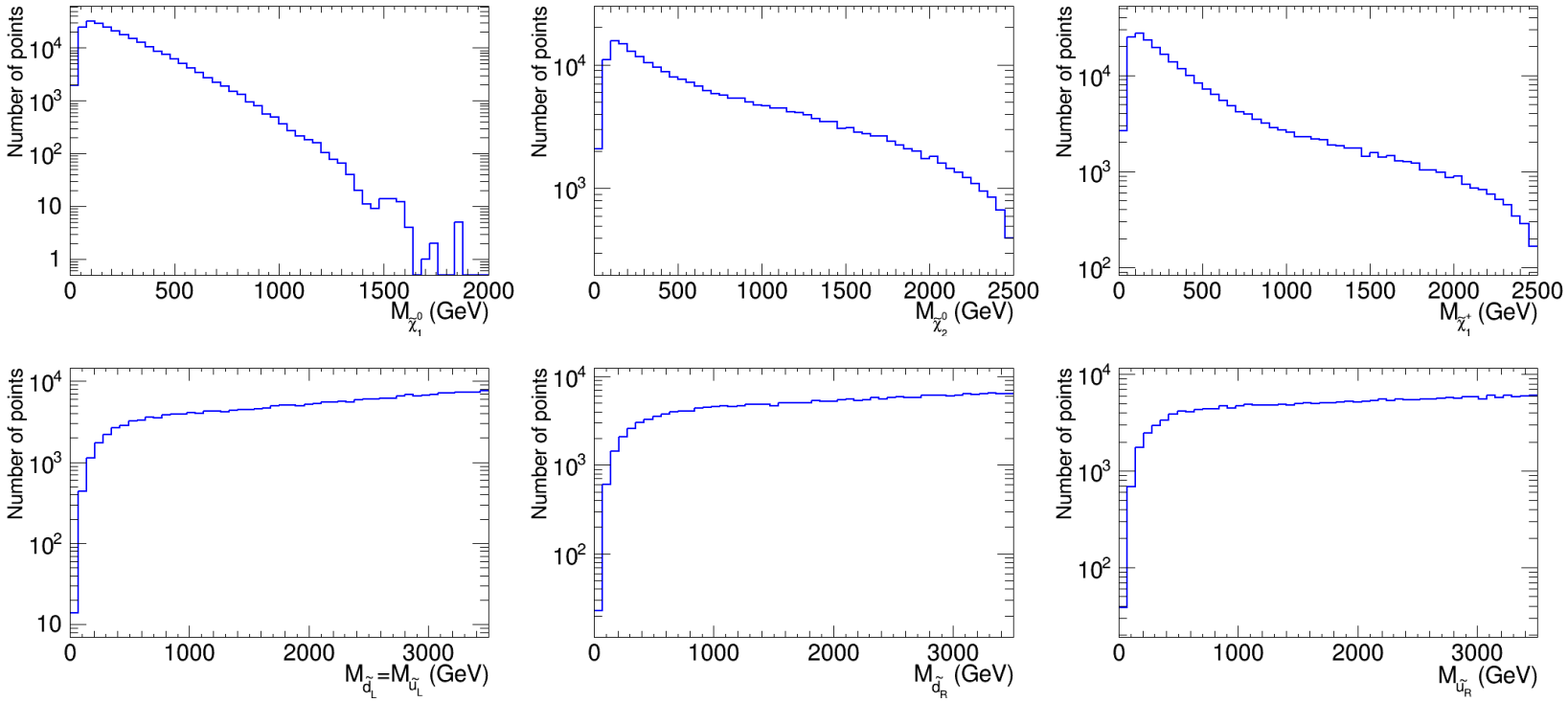
Adding EDM constraints: Muon, Thallium, Mercury



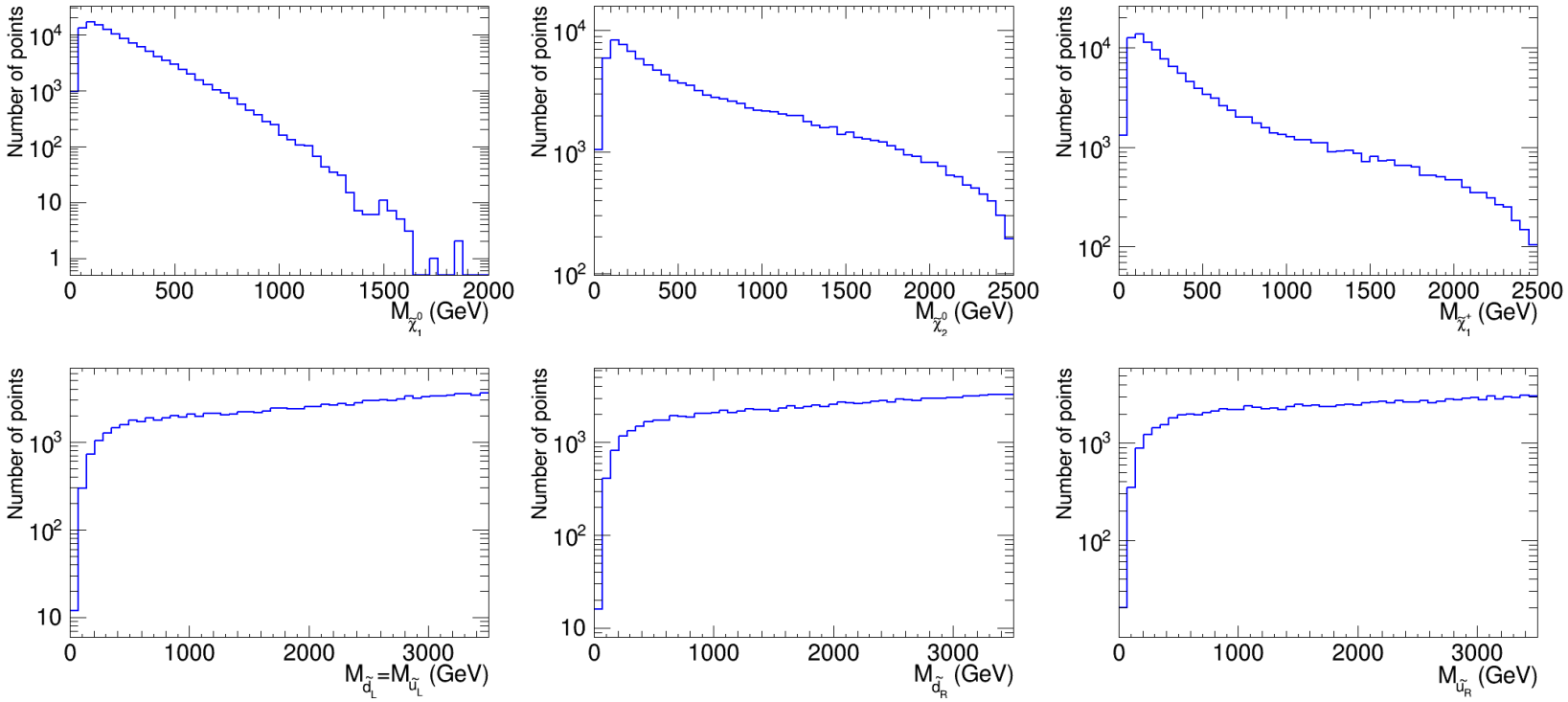
Effects of the EDMs on the SUSY masses

Adding EDM constraints: Muon, Thallium, Mercury, Neutron



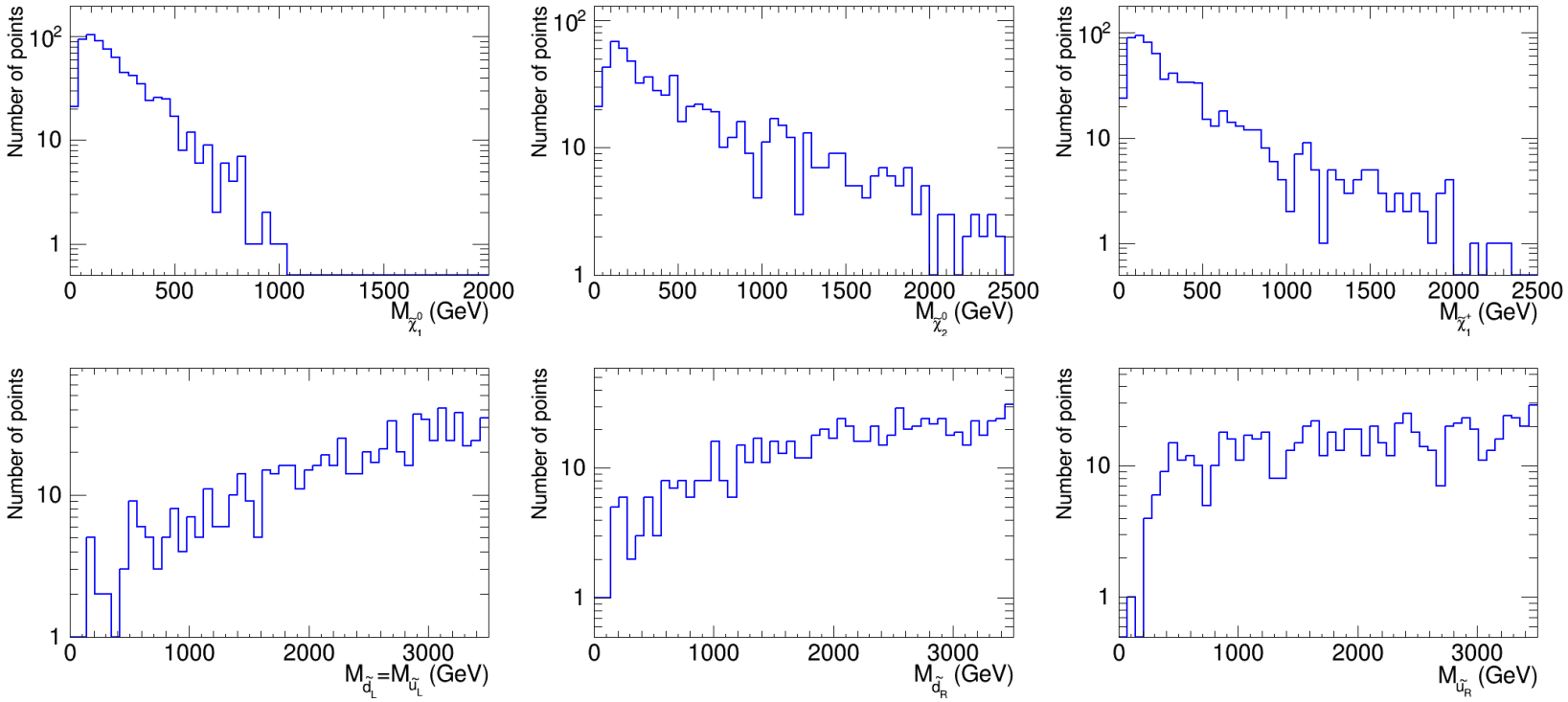
Effects of the EDMs on the SUSY masses

Adding EDM constraints: Muon, Thallium, Mercury, Neutron, Thorium Monoxyde



Effects of the EDMs on the SUSY masses

Adding EDM constraints: Muon, Thallium, Mercury, Neutron, Thorium Monoxyde + Proton



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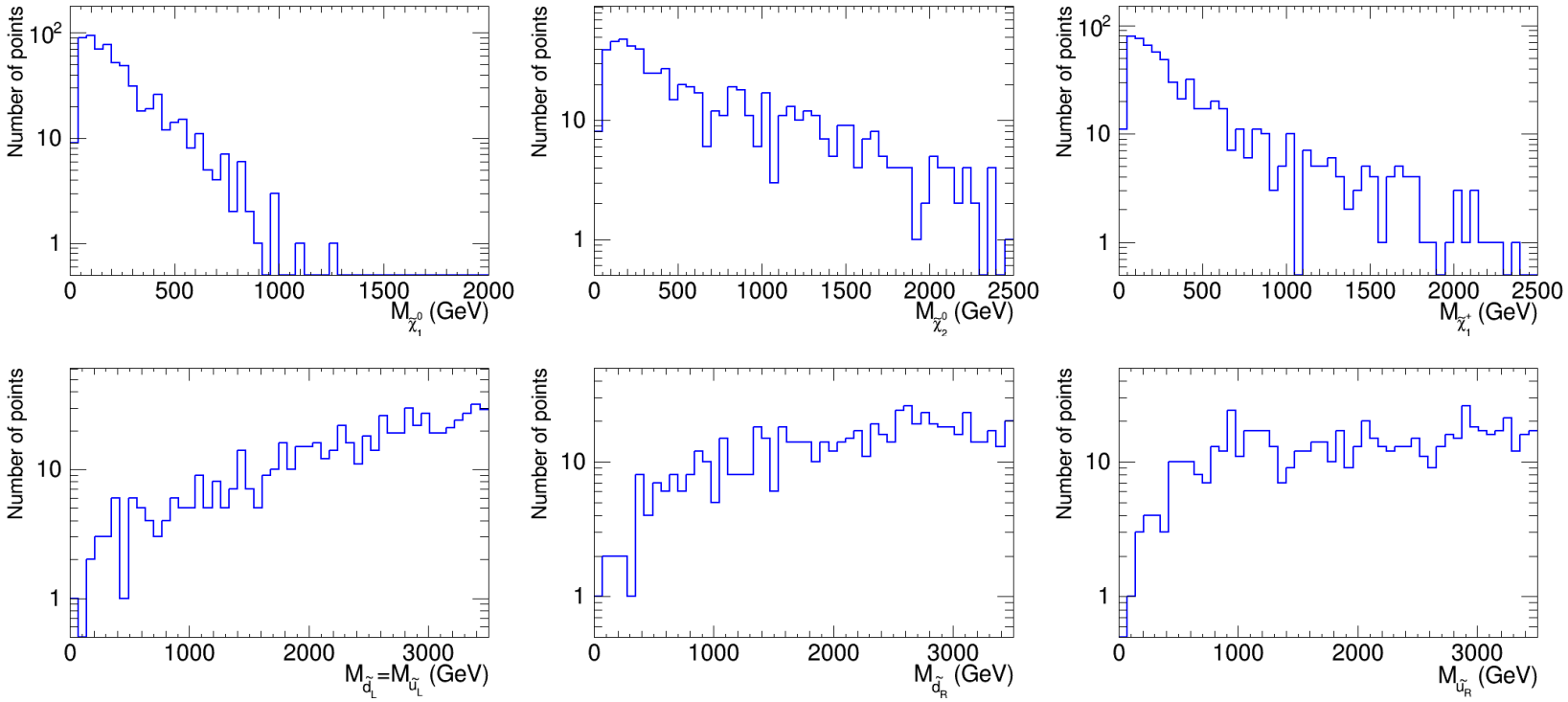

Effects of the EDMs on the SUSY masses

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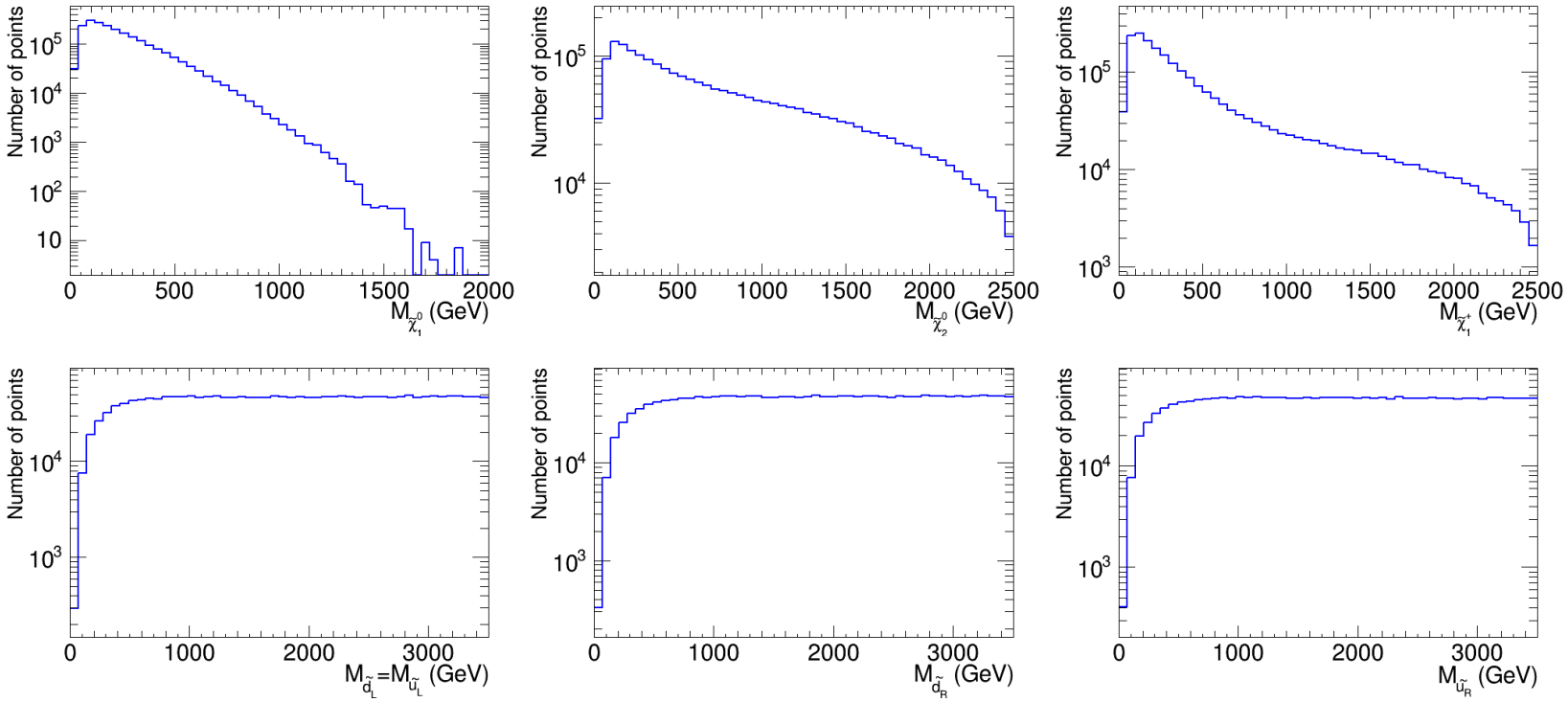

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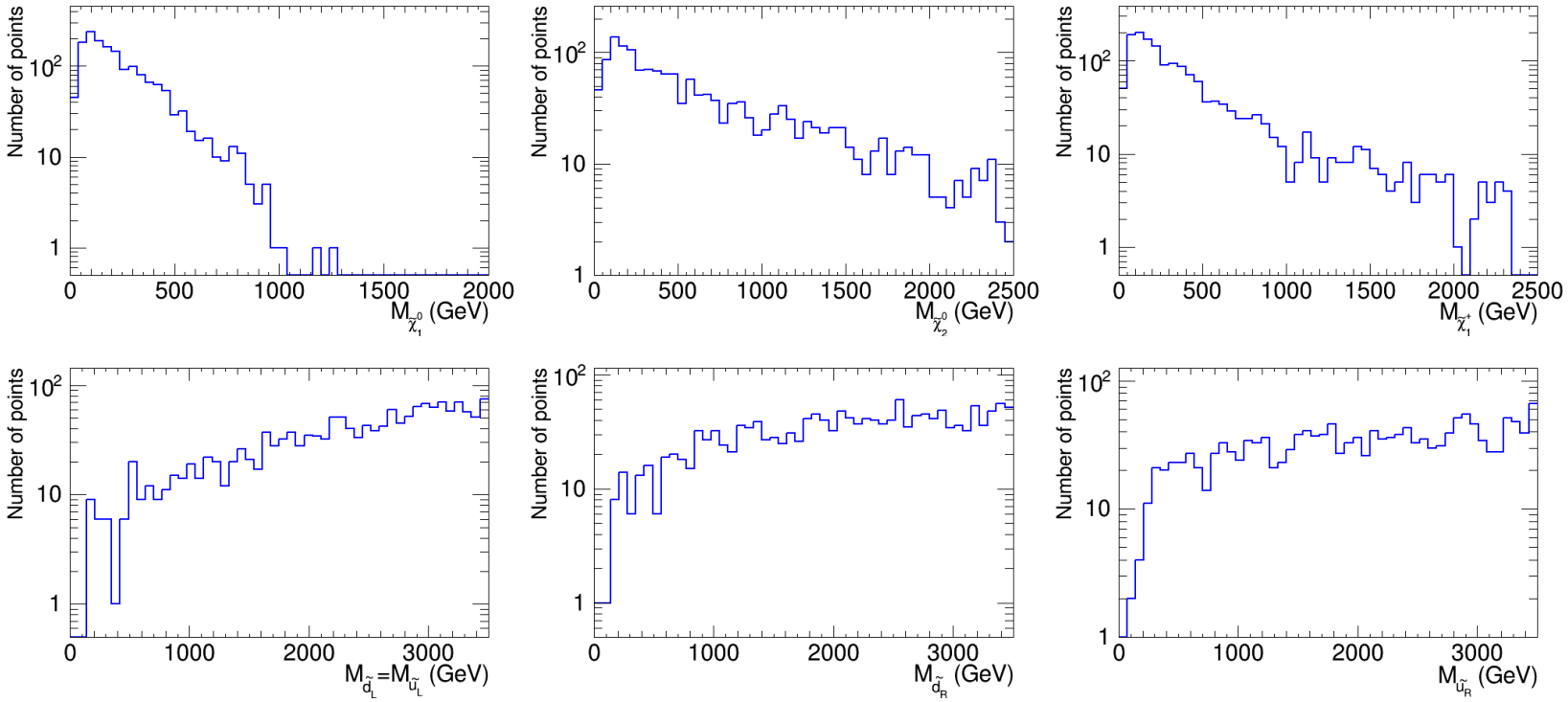
Adding EDM constraints: Proton only



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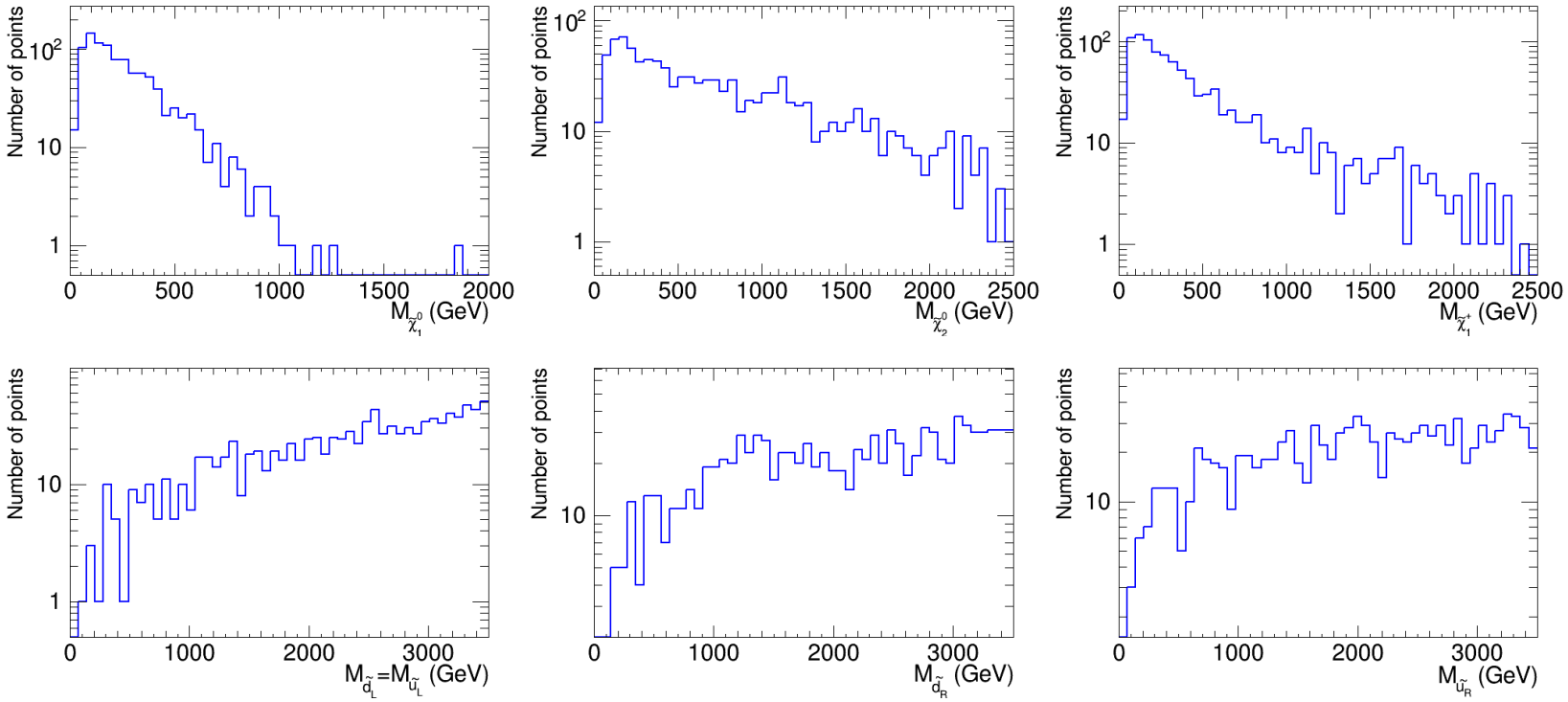


CP violation in the Higgs sector

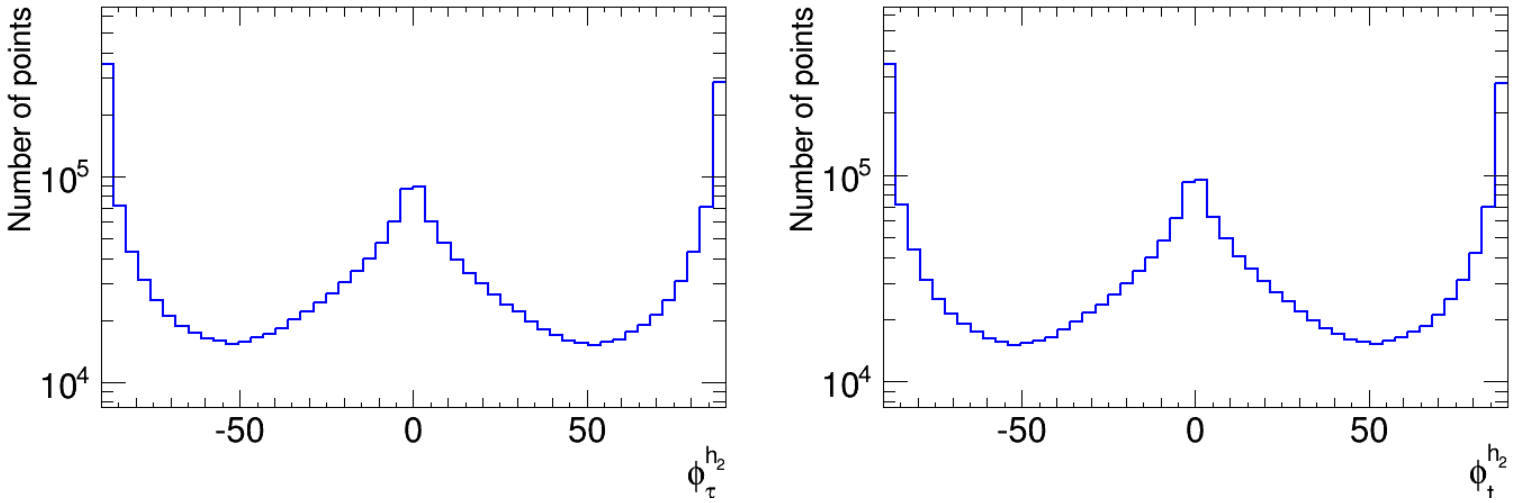
The Higgs bosons can be mixtures of scalar and pseudoscalar components

The LHC constraints impose the h_1 to be a scalar with negligible pseudoscalar component

We define ($g_{S,P}^{h_i \bar{f} f}$: scalar,pseudoscalar coupling of h_i to $\bar{f} f$):

$$\tan \phi_\tau^{h_i} \equiv \frac{g_P^{h_i \tau\tau}}{g_S^{h_i \tau\tau}}, \quad \tan \phi_t^{h_i} \equiv \frac{g_P^{h_i \bar{t} t}}{g_S^{h_i \bar{t} t}}$$

Original sample with no EDM constraints



Similar plots for h_3

CP violation in the Higgs sector

The Higgs bosons can be mixtures of scalar and pseudoscalar components

The LHC constraints impose the h_1 to be a scalar with negligible pseudoscalar component

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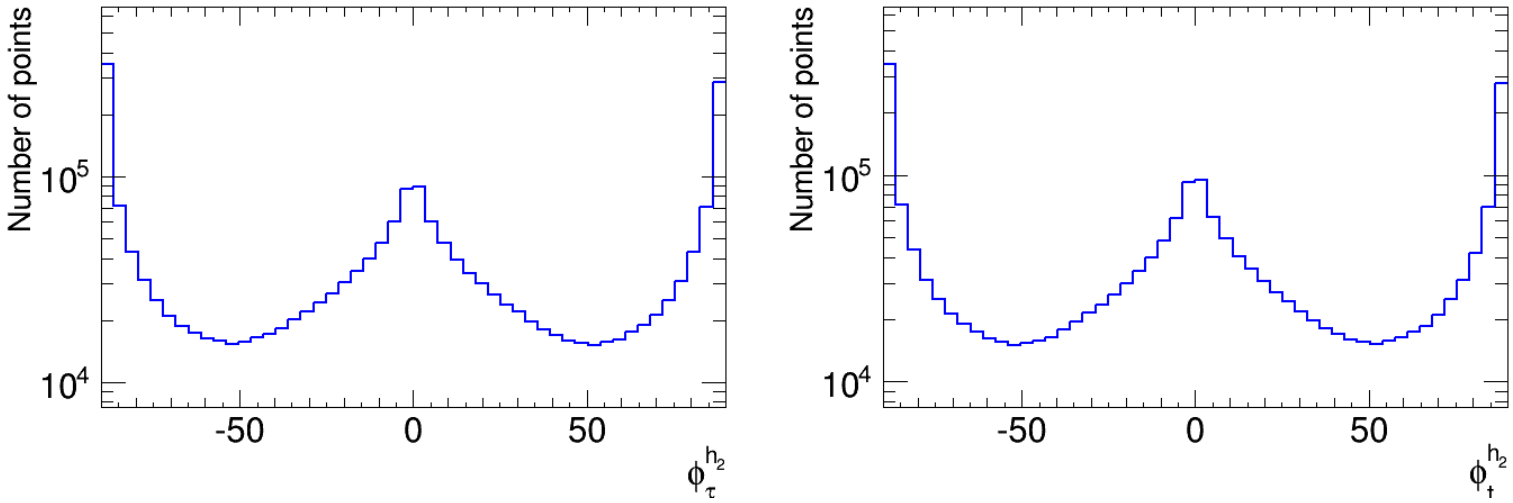
Adding EDM constraints: Muon



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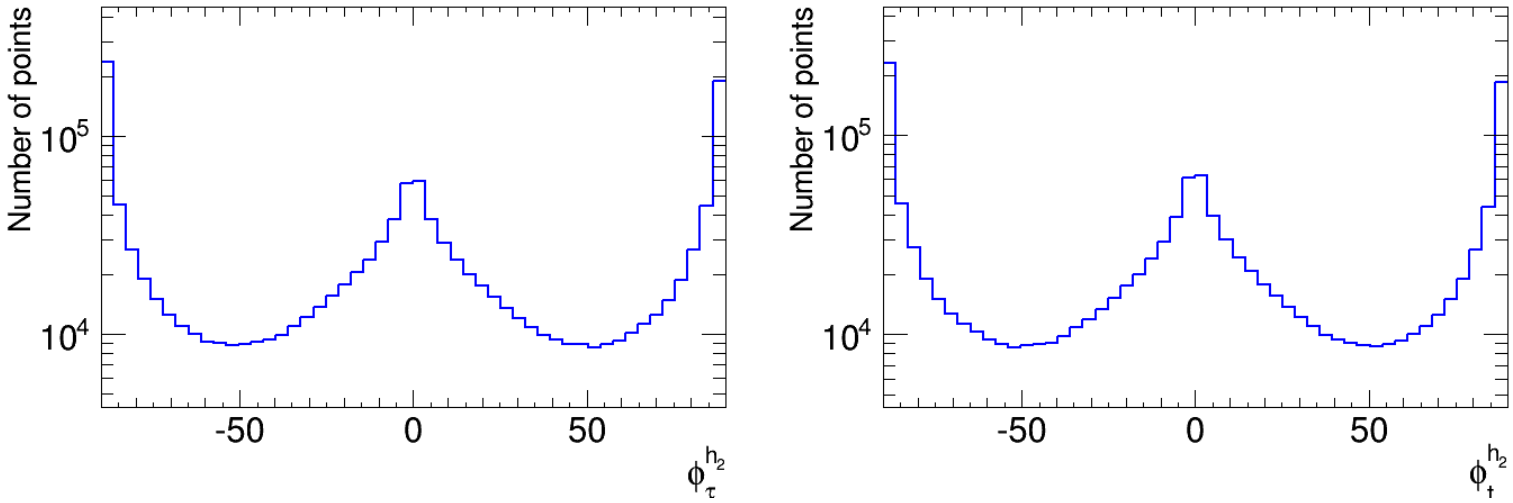
Adding EDM constraints: Muon, Thallium



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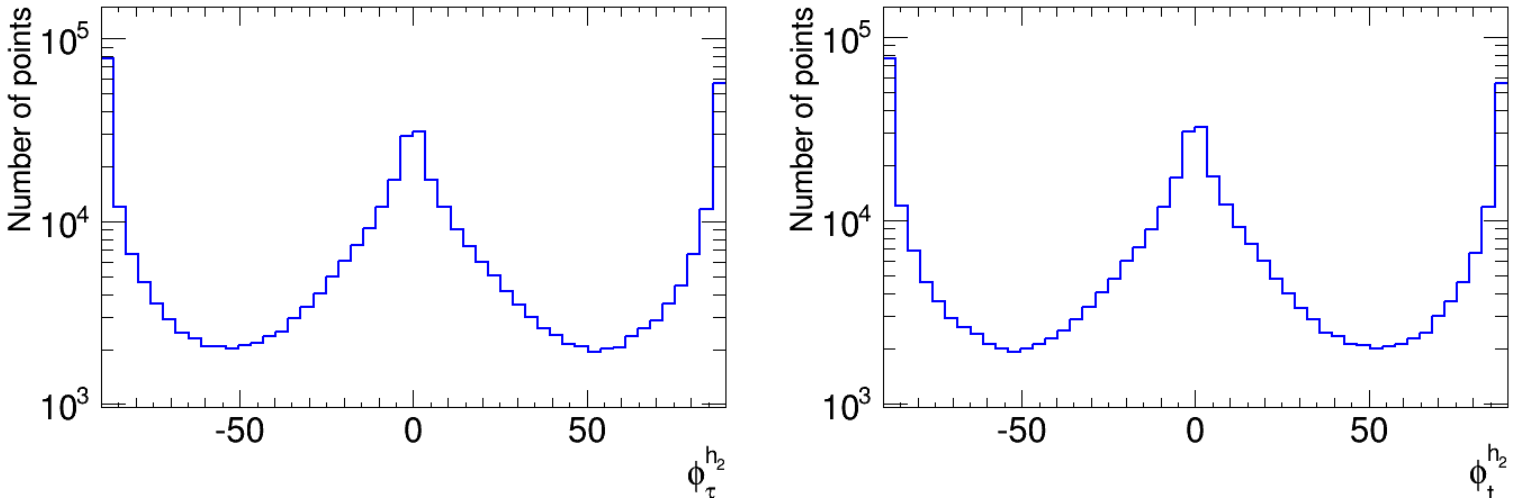
Adding EDM constraints: Muon, Thallium, Mercury



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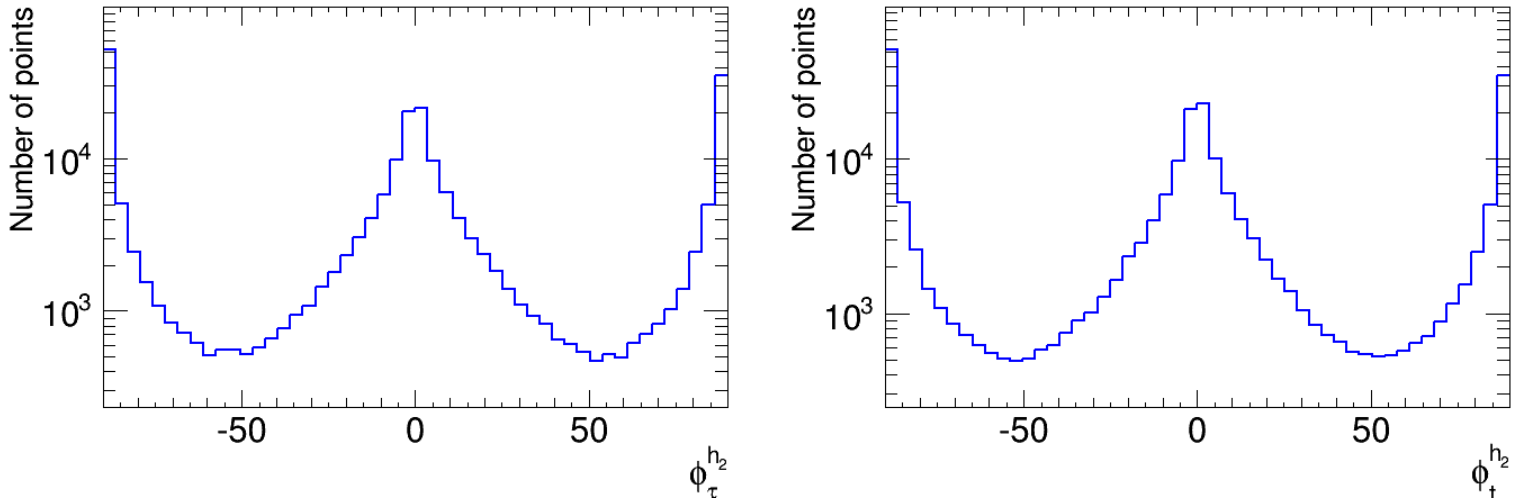
Adding EDM constraints: Muon, Thallium, Mercury, Neutron



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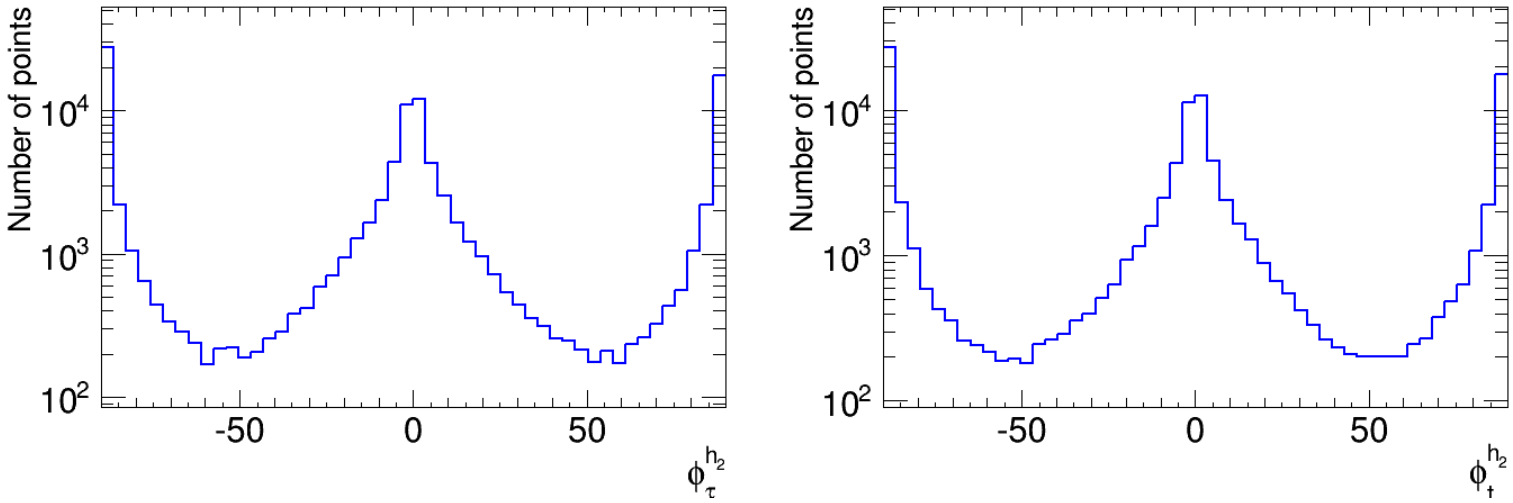

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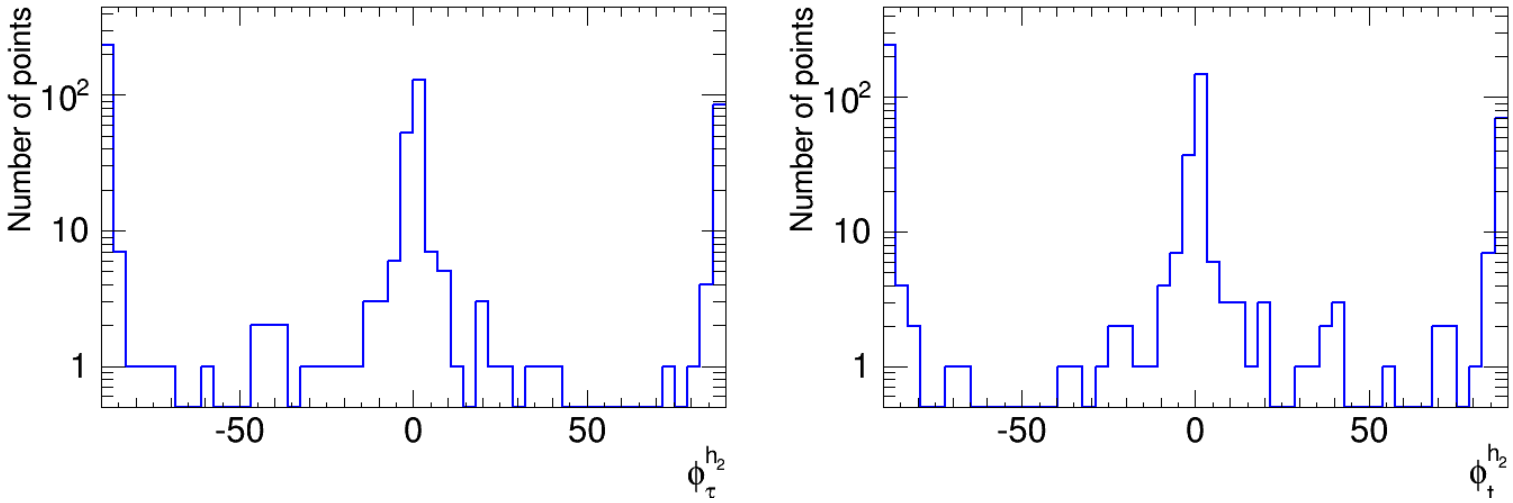
Adding EDM constraints: Muon, Thallium, Mercury, Neutron, Thorium Monoxyde + Proton



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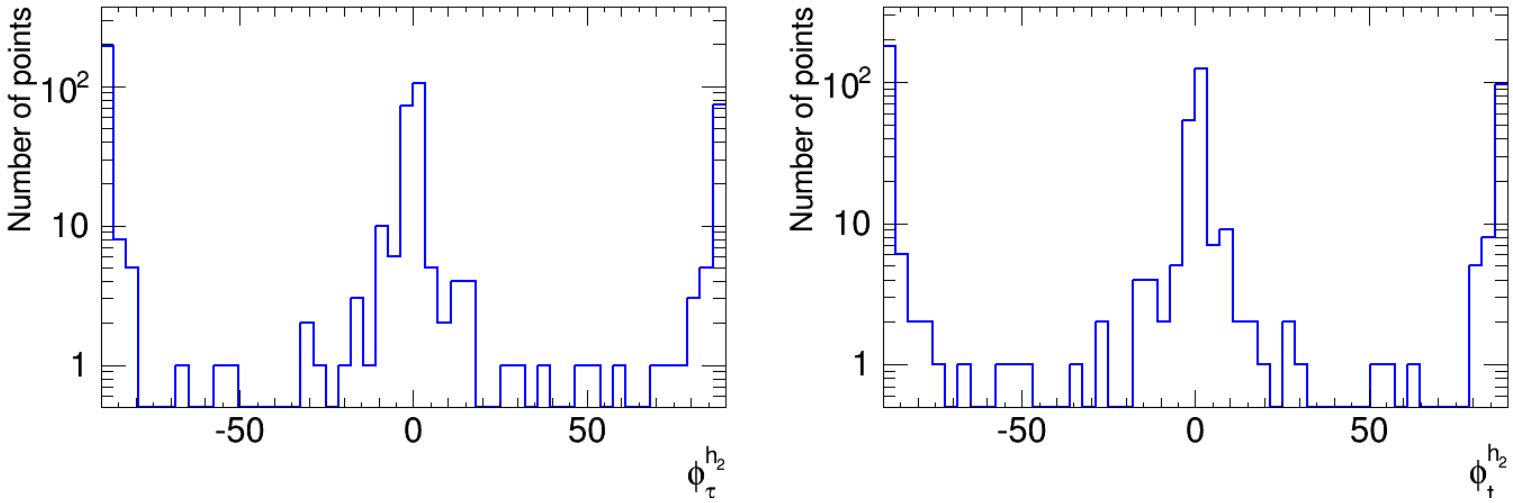
Adding EDM constraints: Muon, Thallium, Mercury, Neutron, Thorium Monoxyde + Proton 2



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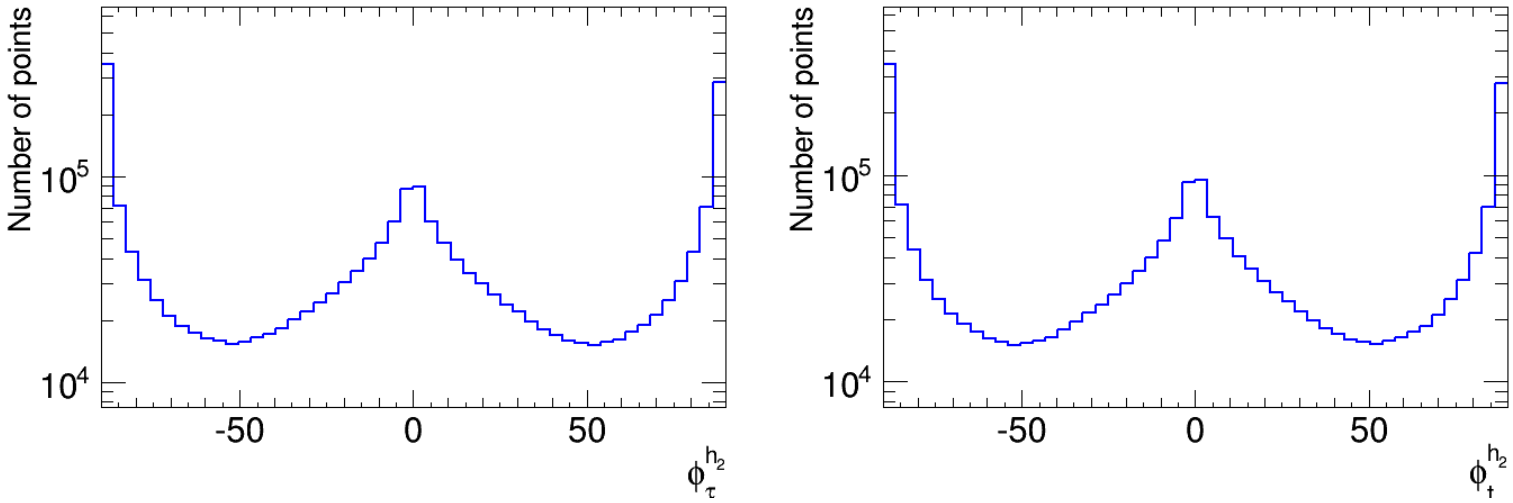

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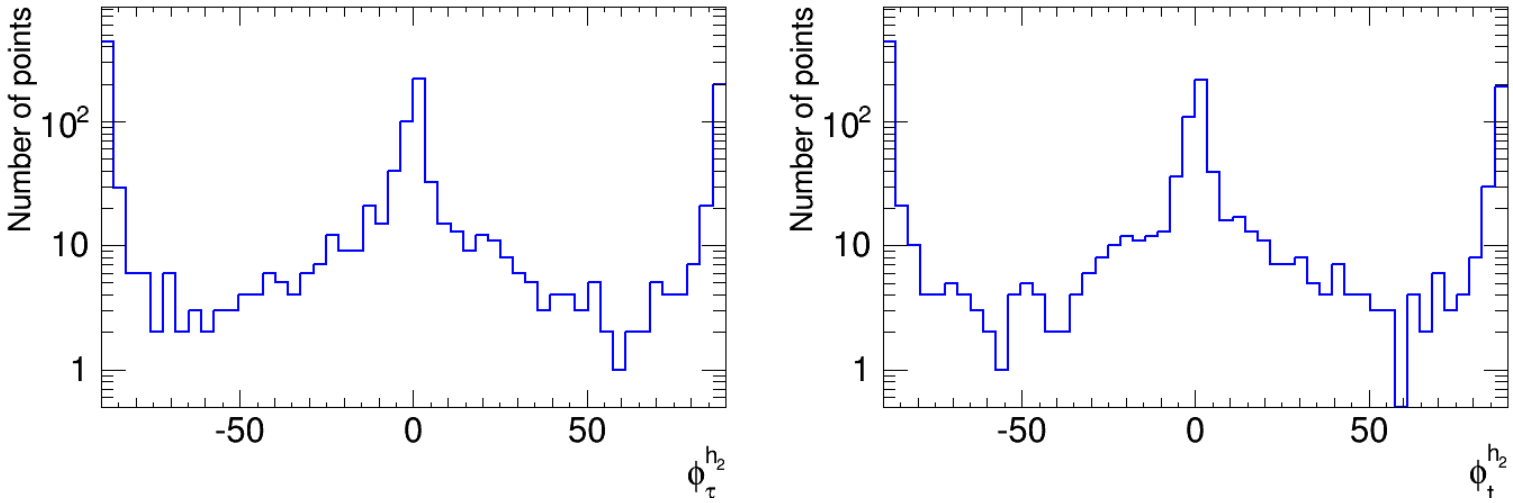
Adding EDM constraints: Proton only



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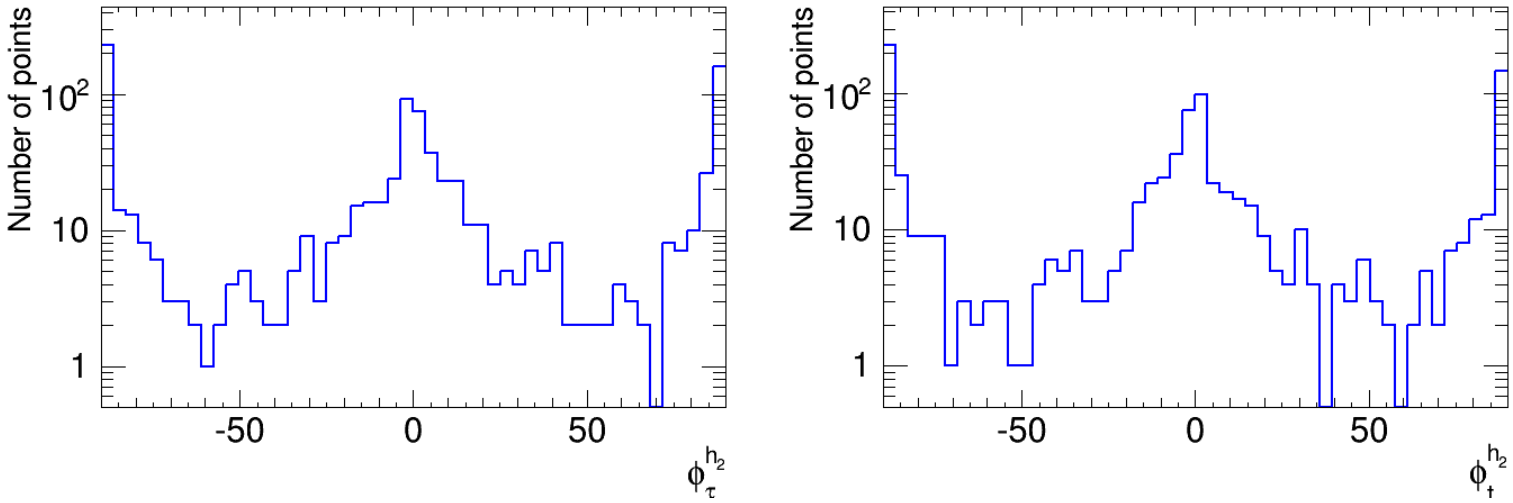
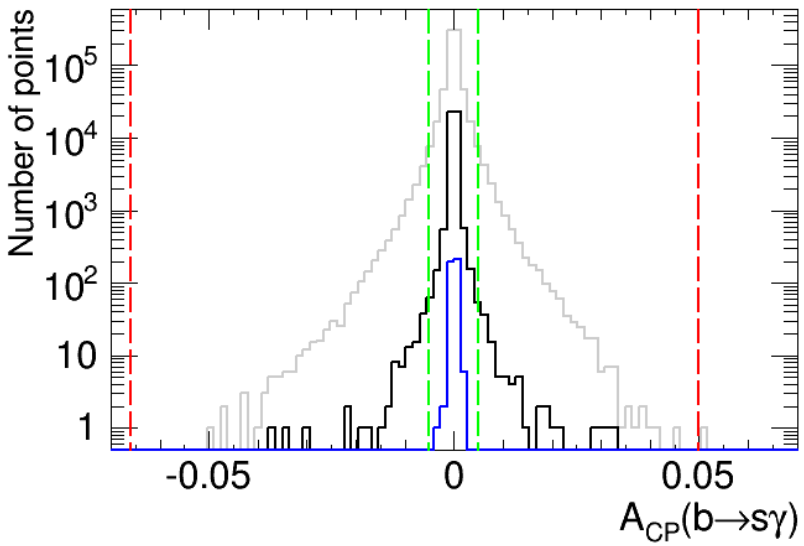
Adding EDM constraints: Proton 2 only



Similar plots for h_3

Flavour sector

CP asymmetry in $b \to s\gamma$

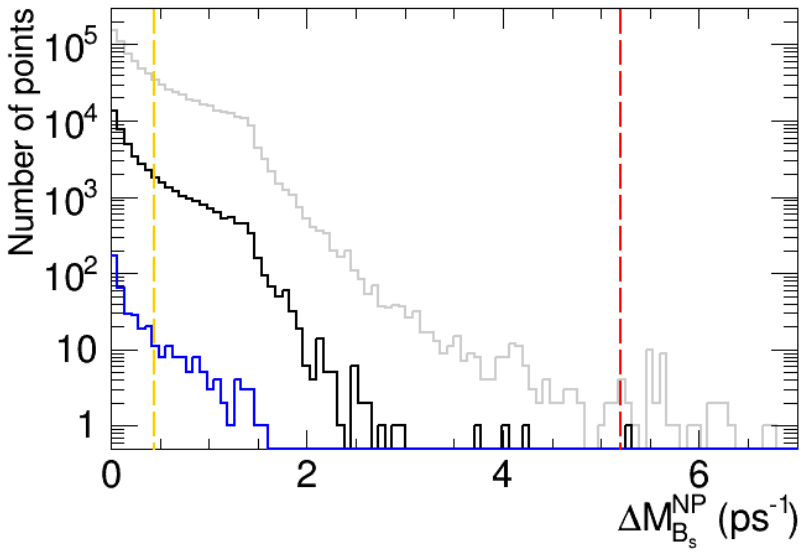


gray: without EDMs – black: with EDMs
blue: + prospective proton EDM
red: current limits – green: prospective Belle-II

Current experiment limits superseded by EDM constraints

Good perspectives for the future

B_s meson mixing $\Delta M_{B_s}^{NP}$



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Constraints limited by the theoretical uncertainties

Good perpectives if order of magnitude improvement on theoretical uncertainties

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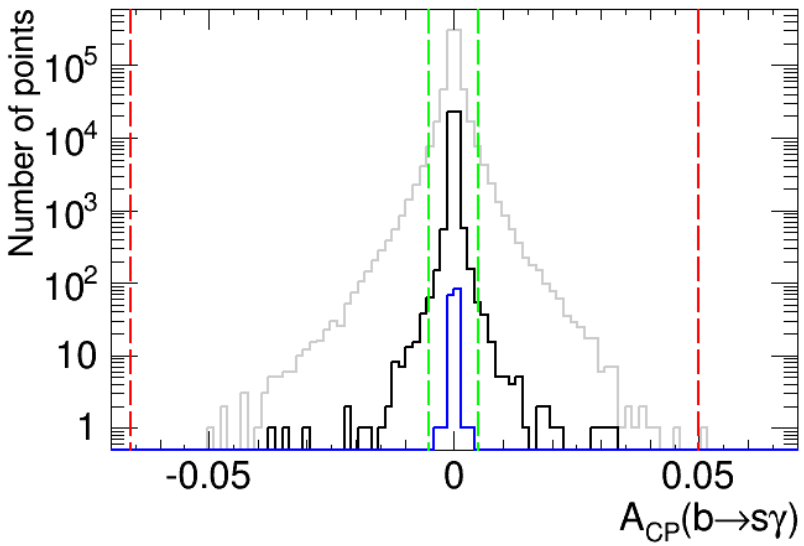

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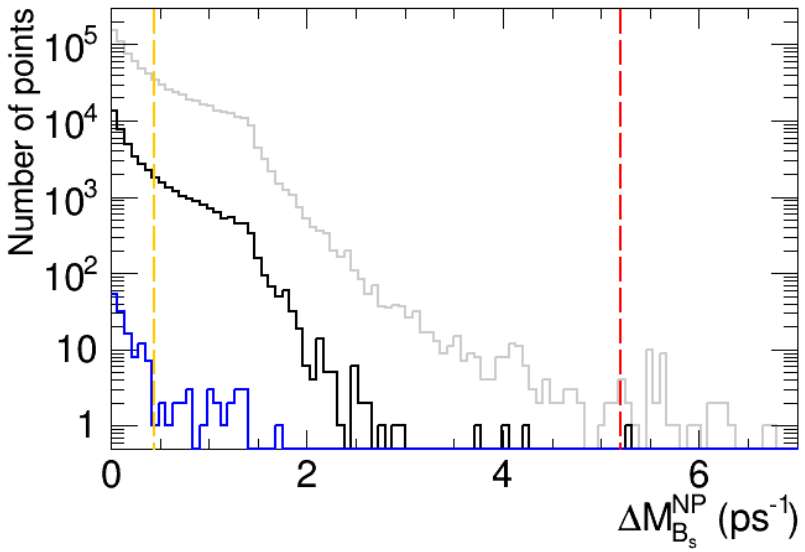

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Conclusions

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- ... but still a viable model
- Electric dipole moments very constraining...
- ... but large CP violating phases still possible
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