Natural SUSY, Muon g-2, and Higgs Measurements at Future e^-e^+ Colliders

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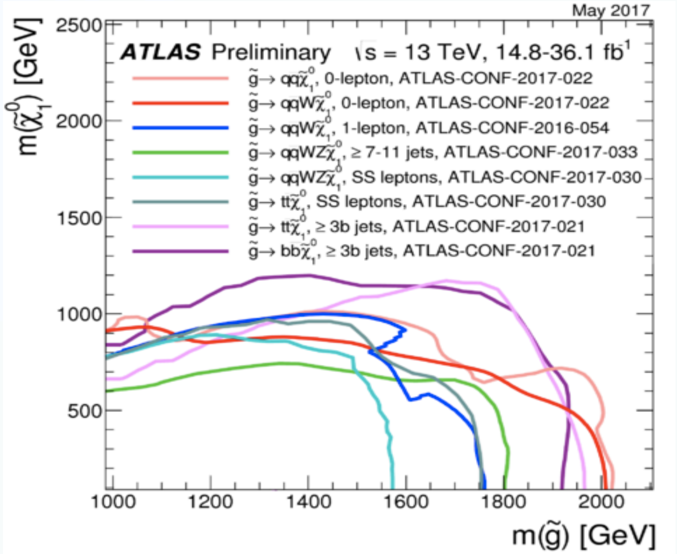
Based on [Phys. Rev. D **93** (2016) 055040], with T. Li, S. Raza

Outline

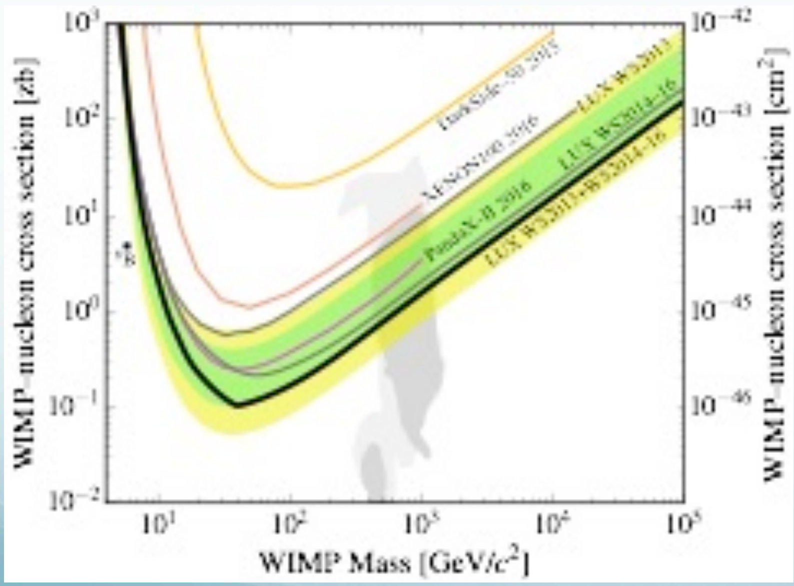
- ★ Parameter Space Scan
  - Motivation
  - Theoretical Dependences
  - Input Constraints
- ★ Numerical Results
  - Electroweak Fine-tuning
  - Higgs Coupling Measurements
  - Muon Magnetic Moment Measurement
  - Collider Phenomenology
- ★ Summary

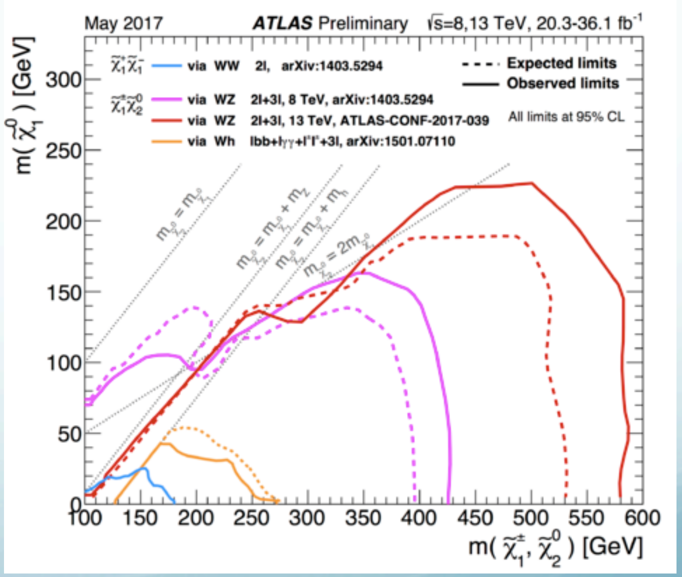
Current Status of BSM Searches

SUSY from LHC:
→ m_gluino > 1.9 TeV
→ m_stop > 950 GeV
→ m_chargino > 600 GeV



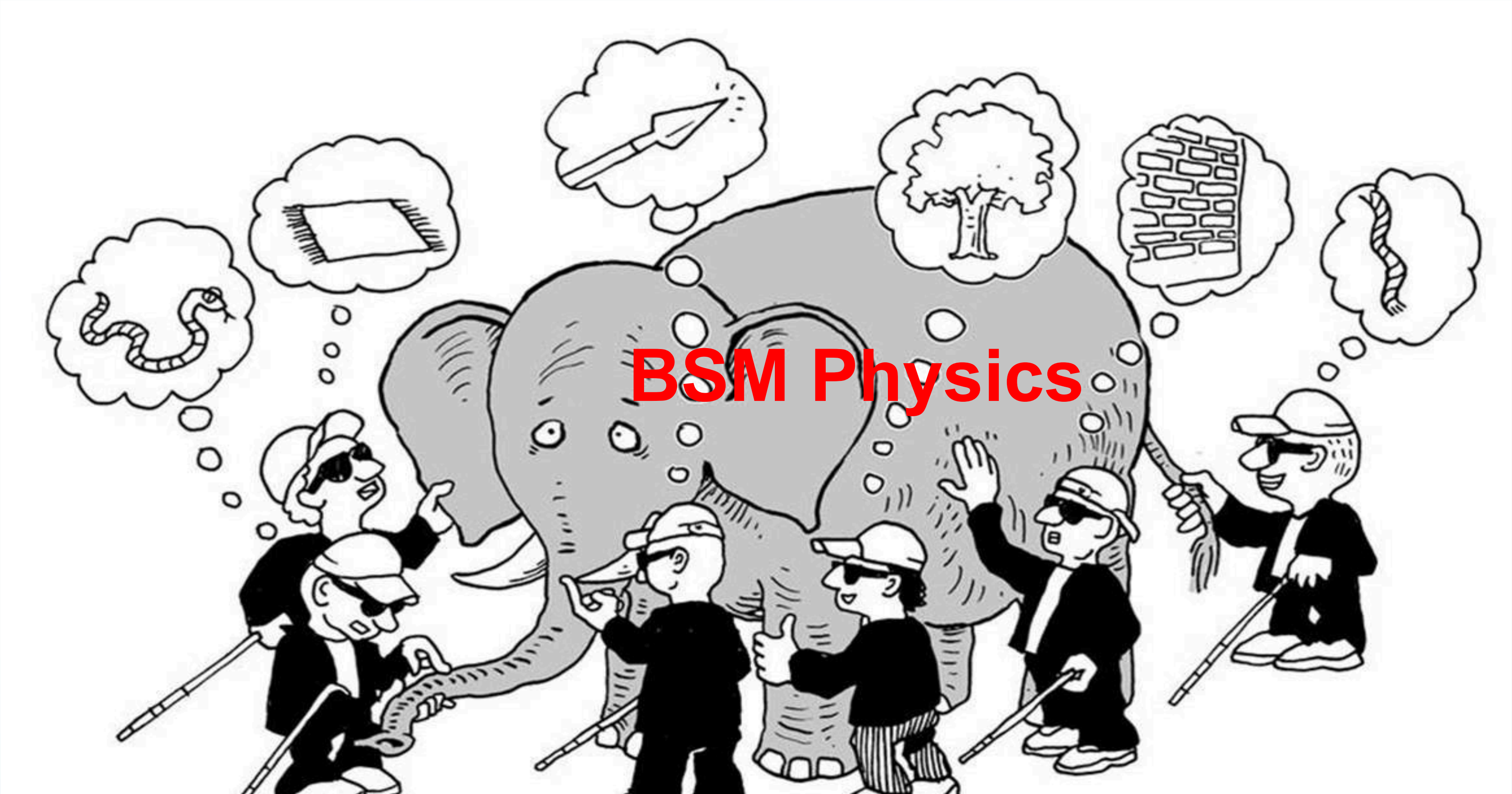
DM from direct detection [1608.07648]
→ lots of parameter space excluded





→ No clear Hints of New Physics so far.

Current Status of BSM Searches



Plot from google

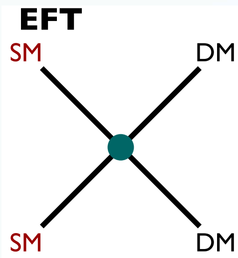
Perhaps we will have to face the “nightmare scenario” after LHC
→ no clear hints of BSM physics.
→ no definite guidance to BSM physics.
=> have to search for all possible directions.

Two Approaches to Constrain BSM

Feasible step after LHC:
Higgs property (couplings, decay width, spin & CP) measurements @ e^-e^+ colliders
=> new physics indirectly

EFT

(see talks of C. Grojean, T. Vantalon, J. Gu, ...)



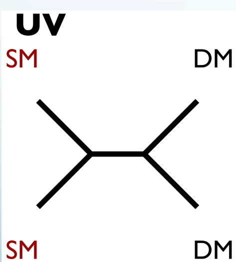
D>4 EFT Operators

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum_i \frac{1}{\Lambda^{d_i-4}} c_i \mathcal{O}_i$$

✔ Simple, Generic, model-independent
✖ Validation, may not be valid

UV-complete Models

(see talks of M. Drees, A. Choudhury, ...)



SUSY, Composite, Extra-D, ...

✔ Concrete, more details & predicable
✖ Specified, model-dependent

This talk: scanning the parameter space of a natural SUSY model
← Higgs coupling & Muon anomalous magnetic moment measurements

Theoretical Dependences

Higgs Couplings in MSSM model

In the decoupling limit of $m_A \gg m_Z$

$$k_V \equiv \frac{g_{hVV}^{\rm SUSY}}{g_{hVV}^{\rm SM}} = \sin(\alpha+\beta) \sim 1 - \mathcal{O}\left(\frac{m_Z^4}{m_A^4}\frac{2}{\tan^2\beta}\right), \text{ for V} = \text{W, Z}$$

$$k_{b,\tau} \sim 1 - \mathcal{O}\left(\frac{m_Z^4}{m_A^4}\frac{2}{\tan^2\beta}\right) + \mathcal{O}\left(\frac{m_Z^2}{m_A^2}\frac{2}{\tan\beta}\tan\beta\right) \sim 1 + \mathcal{O}\left(2\frac{m_Z^2}{m_A^2}\right)$$

$$k_t \sim 1 - \mathcal{O}\left(\frac{m_Z^4}{m_A^4}\frac{2}{\tan^2\beta}\right) - \mathcal{O}\left(\frac{m_Z^2}{m_A^2}\frac{2}{\tan\beta}\cot\beta\right) \sim 1 - \mathcal{O}\left(\frac{m_Z^2}{m_A^2}\frac{2}{\tan^2\beta}\right)$$

$$k_g \approx 1 + \frac{m_t^2}{4}\left[\frac{1}{m_{\tilde{t}_1}^2} + \frac{1}{m_{\tilde{t}_2}^2} - \frac{X_t^2}{m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2}\right] \qquad X_t = |A_t - \mu/\tan\beta|$$

Muon anomalous magnetic moment from $\tilde{e}_{R,L} - \tilde{\chi}_1^0$ and $\tilde{\nu} - \tilde{\chi}_1^\pm$ loops

$$\Delta a_\mu^{\rm SUSY} \sim \frac{M_i \mu \tan\beta}{m_{\rm SUSY}^4}$$

$M_{1,2}$ → weak-scale gaugino masses;
μ → Higgsino mass parameter;
$m_{\rm SUSY}$ → sparticle mass circulating in the loop

Input Constraints

Scan the parameter space of GmSUGRA model with small fine-tuning $\Delta_{\rm EW} \leq 100$

Using the ISAJET 7.85 package

(*I*) Basic constraints:

neutralino LSP;

fine-tuning;

sparticle mass

Higgs mass;

B-physics.

from LEP2
$$\begin{aligned} m_{\tilde{t}_1}, m_{\tilde{b}_1} &\geq 100\,\text{GeV}, \\ m_{\tilde{\tau}_1} &\geq 105\,\text{GeV}, \\ m_{\tilde{\chi}_1^\pm} &\geq 103\,\text{GeV}. \end{aligned}$$

from LHC
$$\begin{aligned} 1.7\,\text{TeV} \leq m_{\tilde{g}}\ (\text{for } m_{\tilde{g}} \sim m_{\tilde{q}}) \\ 1.3\,\text{TeV} \leq m_{\tilde{g}}\ (\text{for } m_{\tilde{g}} \ll m_{\tilde{q}}) \\ 300\,\text{GeV} \leq m_A \end{aligned}$$

$$123\,\text{GeV} \leq m_h \leq 127\,\text{GeV}$$

$$\begin{aligned} 1.6 \times 10^{-9} \leq \text{BR}(B_s \to \mu^+\mu^-) \leq 4.2 \times 10^{-9}\ (2\sigma) \\ 2.99 \times 10^{-4} \leq \text{BR}(b \to s\gamma) \leq 3.87 \times 10^{-4}\ (2\sigma) \\ 0.70 \times 10^{-4} \leq \text{BR}(B_u \to \tau\nu_\tau) \leq 1.5 \times 10^{-4}\ (2\sigma) \end{aligned}$$

Input Constraints

(*II*) Muon magnetic moment constraint

$$4.7 \times 10^{-10} \leq \Delta a_\mu \leq 52.7 \times 10^{-10} \ (3\sigma)$$

(*III*) Higgs couplings constraint

Collider	HL-LHC	ILC	CEPC (2 IP)	FCC-ee (4 IP)
$\sqrt{s}$ (GeV)	14000	500	$\boxed{240}$	$\boxed{240}$
$\mathcal{L}$ (fb^{-1})	3000	500	$\boxed{5000}$	$\boxed{10000}$
polarization (e^-, e^+)	-	(-0.8, +0.3)	(0, 0)	(0, 0)
k_g	9.1	2.3	1.5	1.1
k_W	5.1	1.2	1.2	0.85
k_Z	4.4	1.0	0.26	0.16
k_γ	4.9	8.4	4.7	1.7
k_b	12	1.7	1.3	0.88
k_τ	9.7	2.4	1.4	0.94
k_t	11	14	-	-

Table 1: Summary for the precisions of Higgs boson coupling measurements in percentage at different colliders.

5 ~10 %

~1 %

For ILC, 250 GeV running & luminosity upgrade → better precisions.

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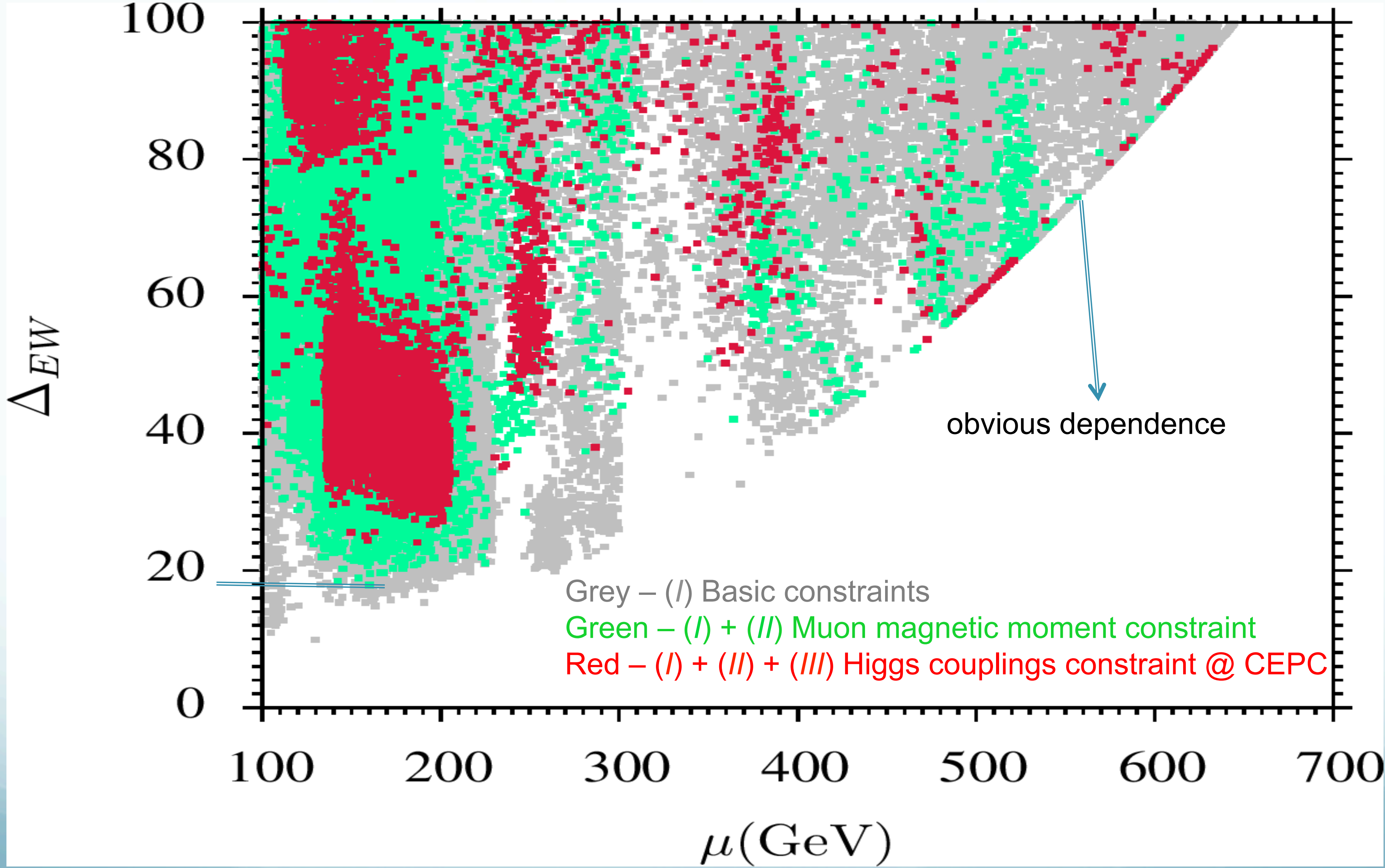
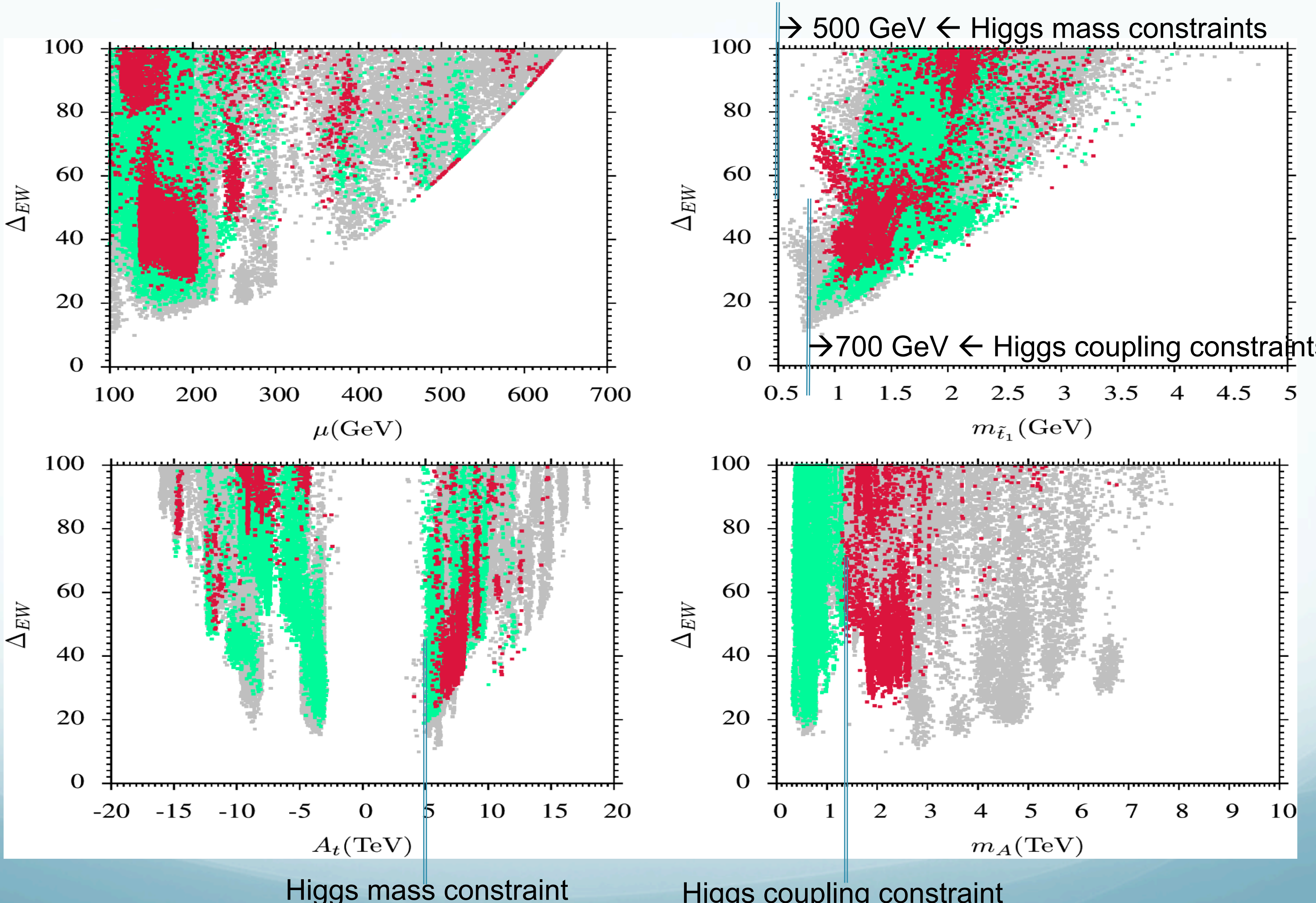
★ Summary

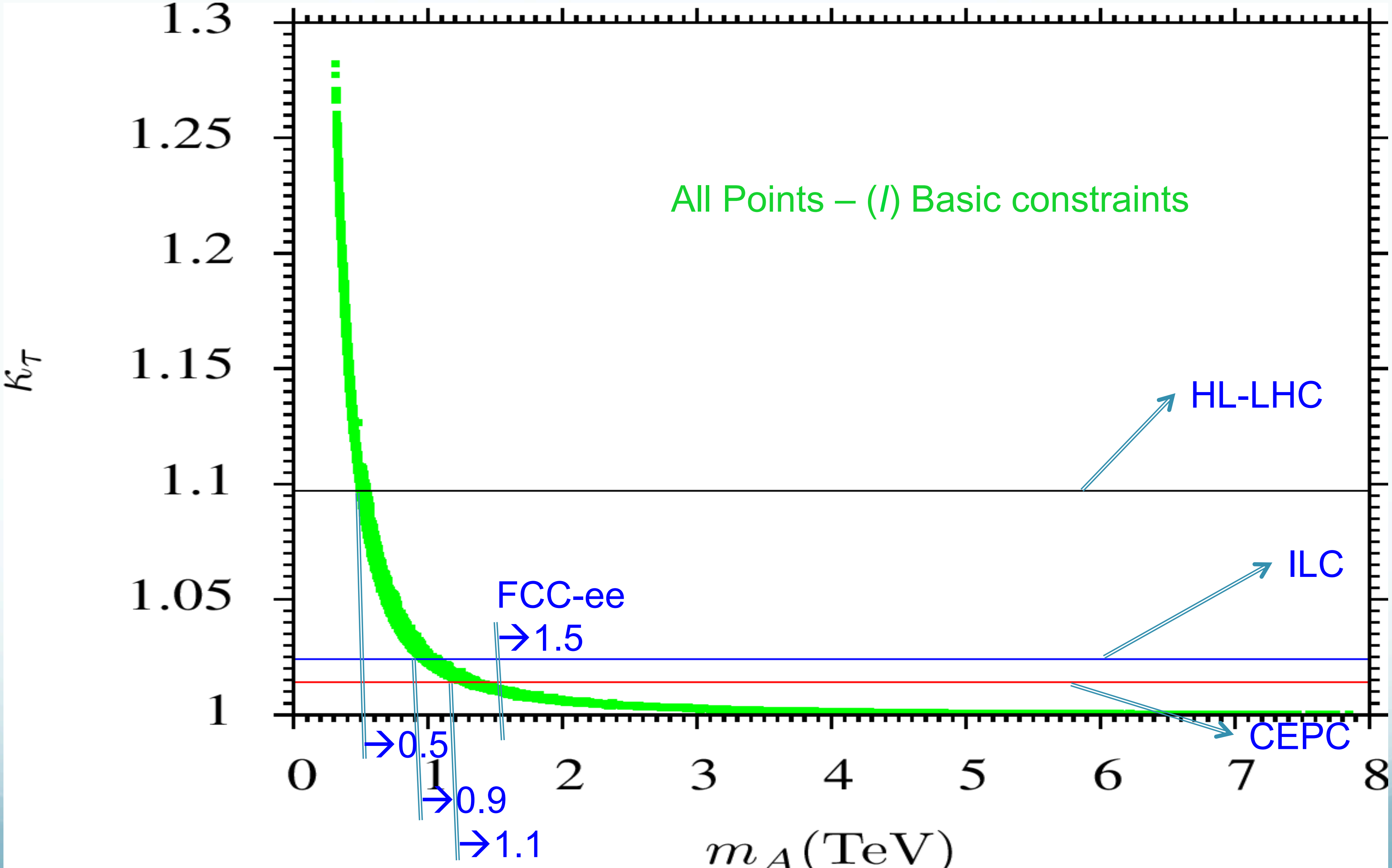
Electroweak Fine-tuning Δ_{EW}



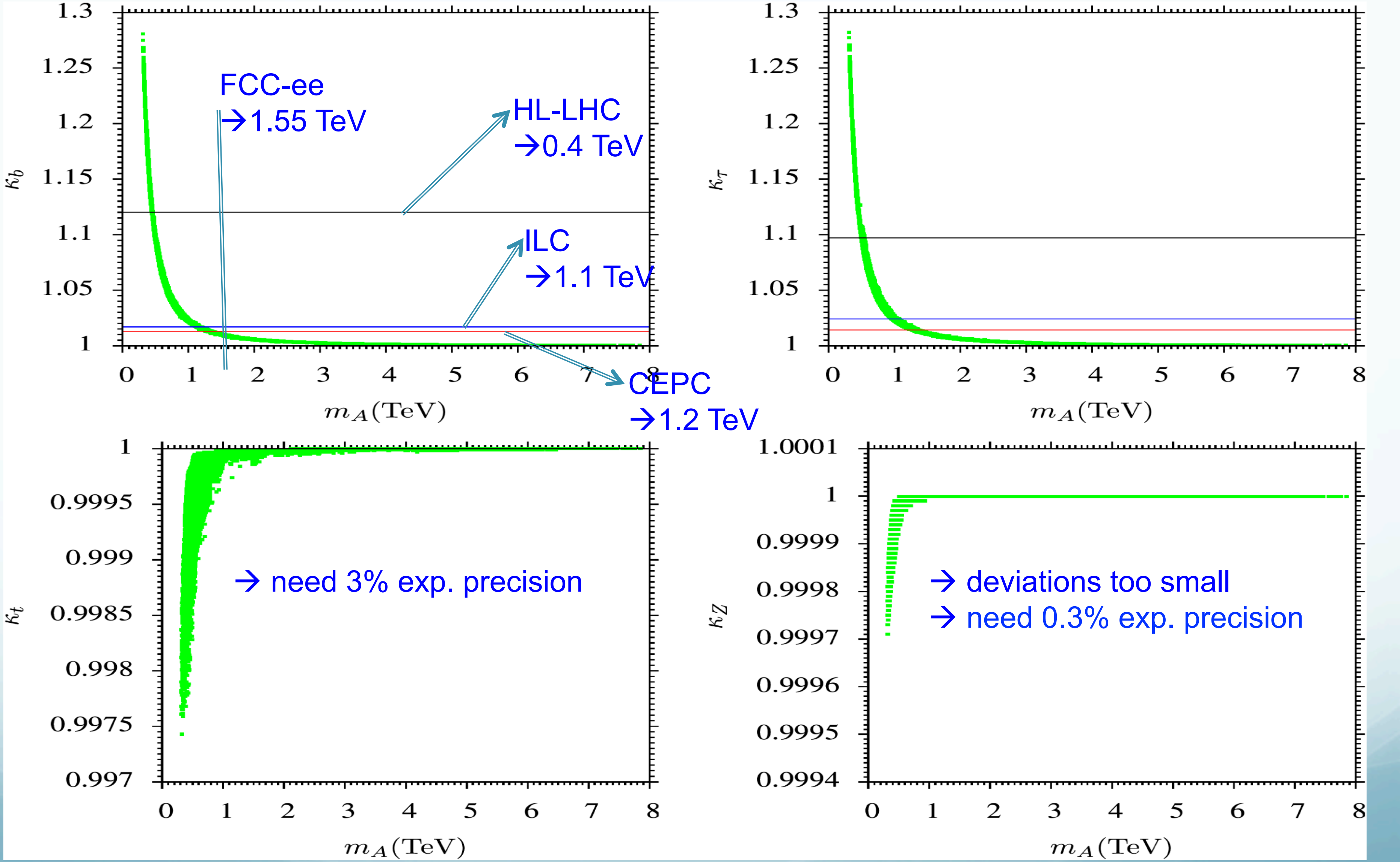
Electroweak Fine-tuning Δ_{EW}



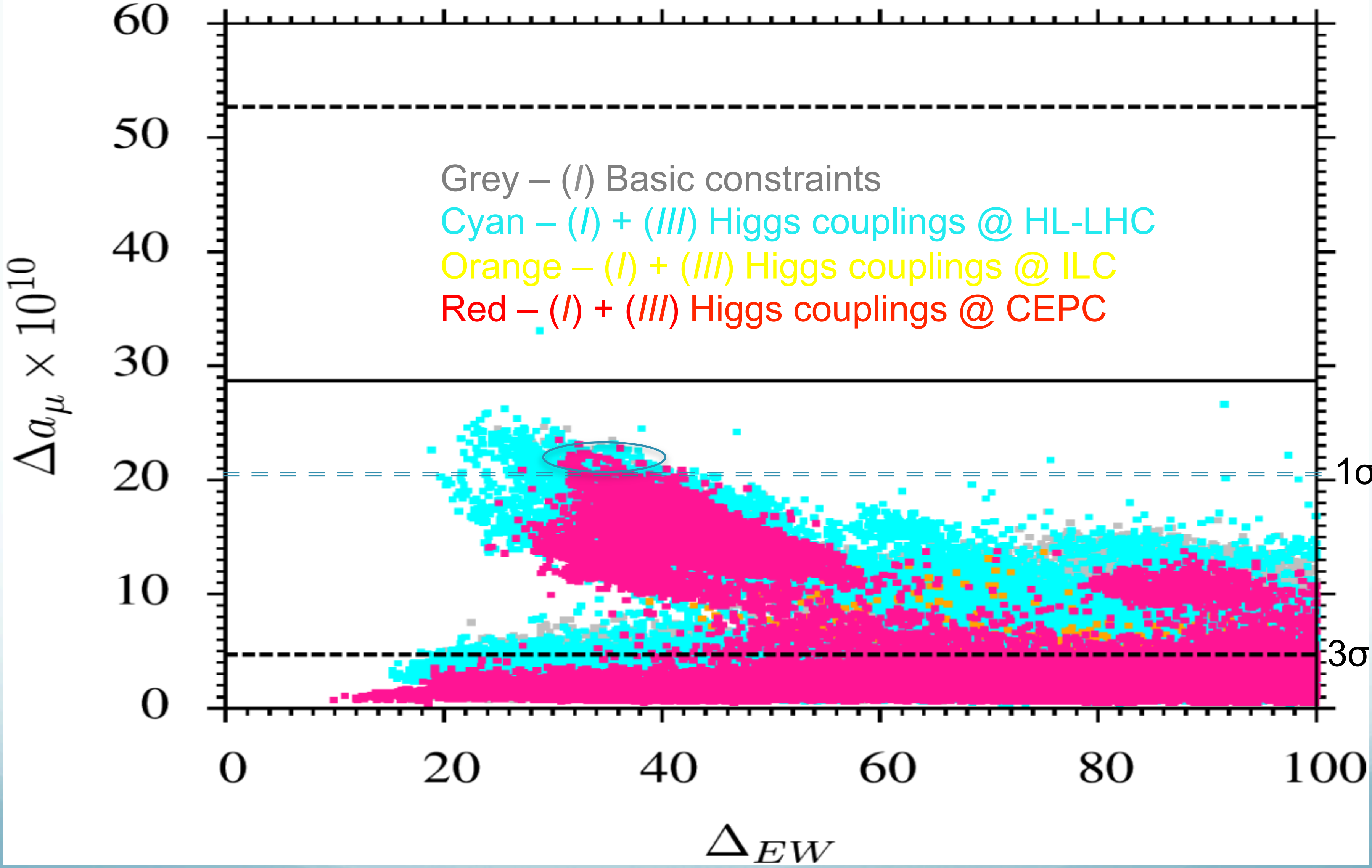
Higgs Coupling Measurements



Higgs Coupling Measurements

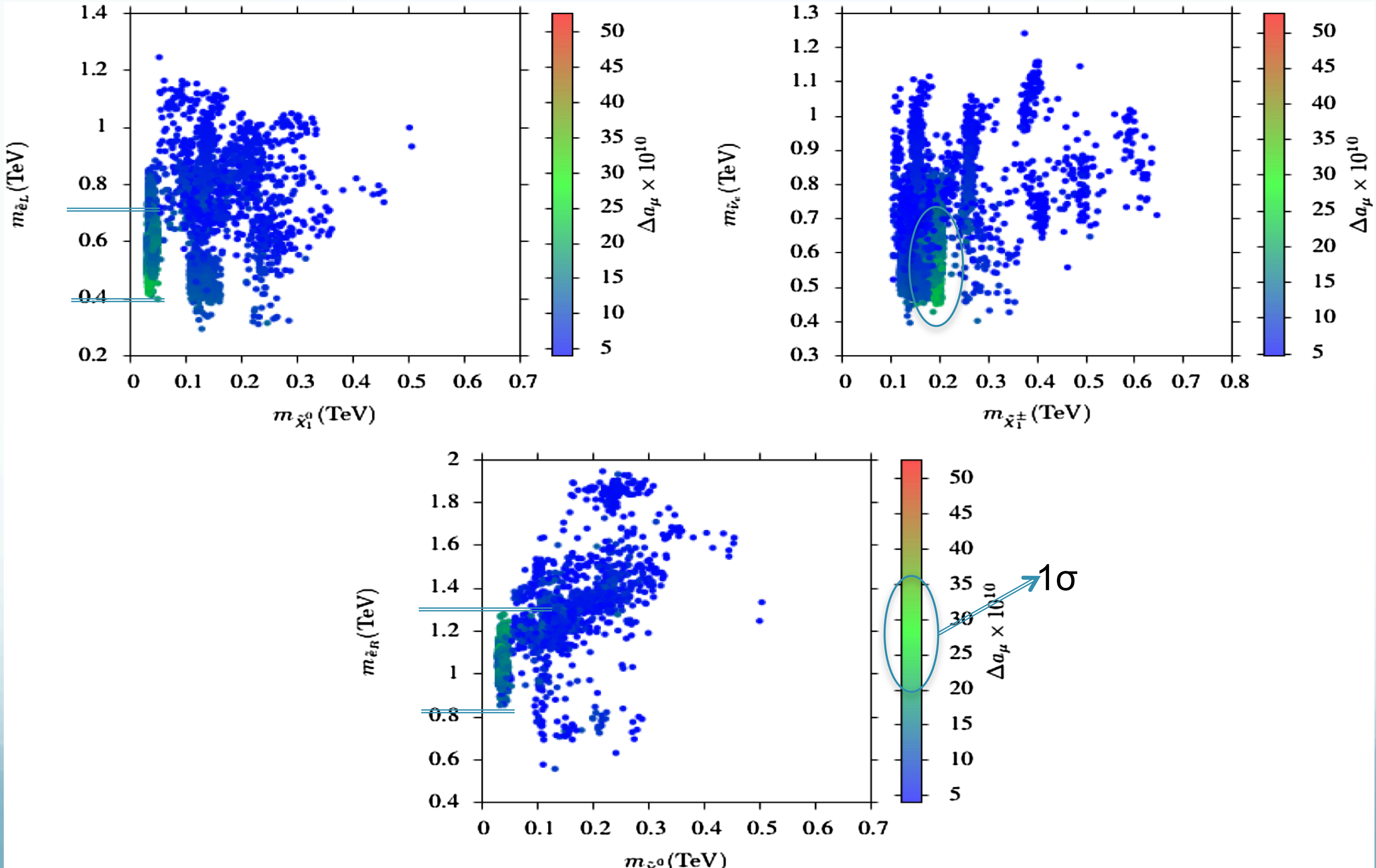


Muon Magnetic Moment Measurement

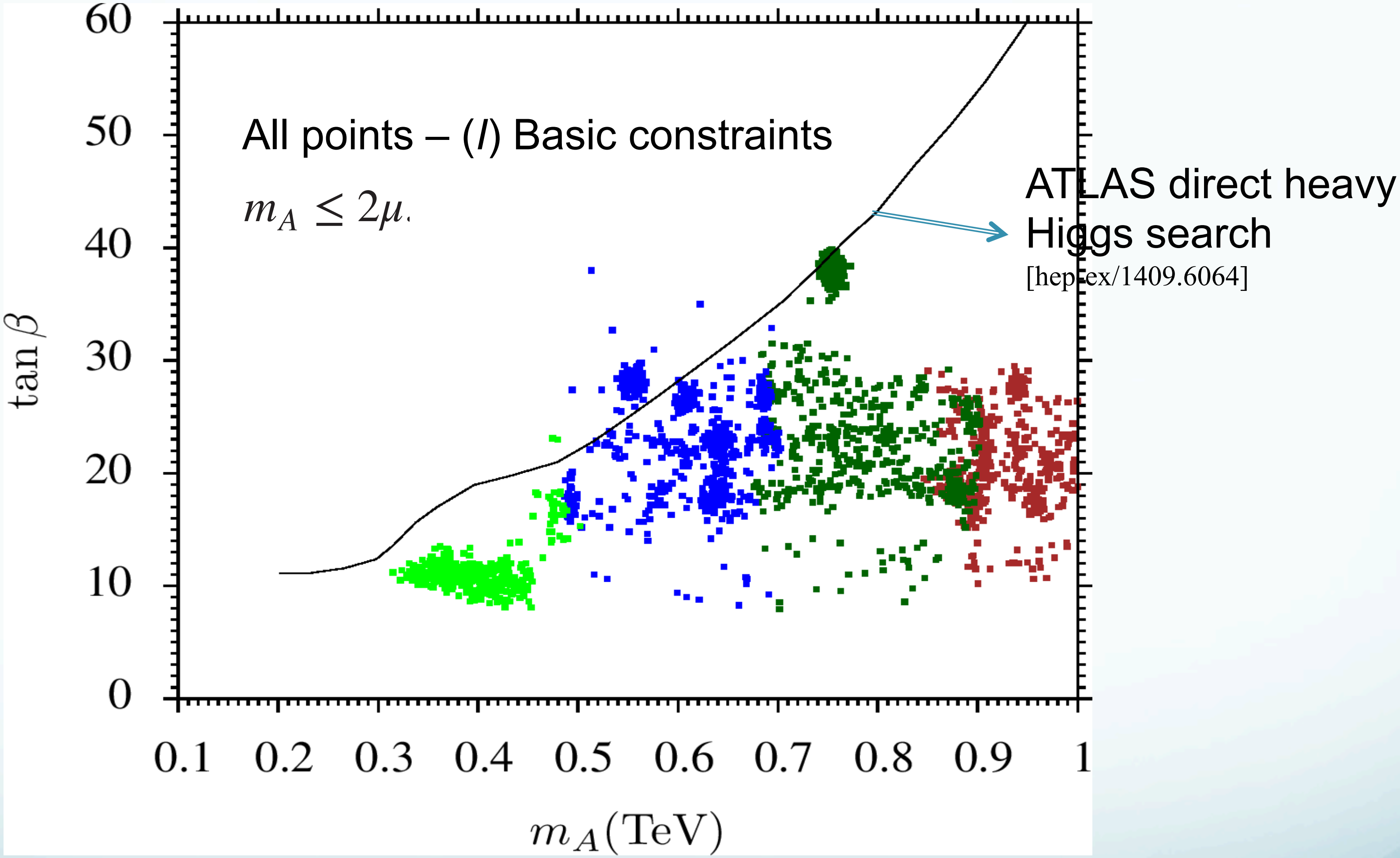


Muon Magnetic Moment Measurement

All points – (*I*) + (*II*) + (*III*) Higgs couplings @ CEPC



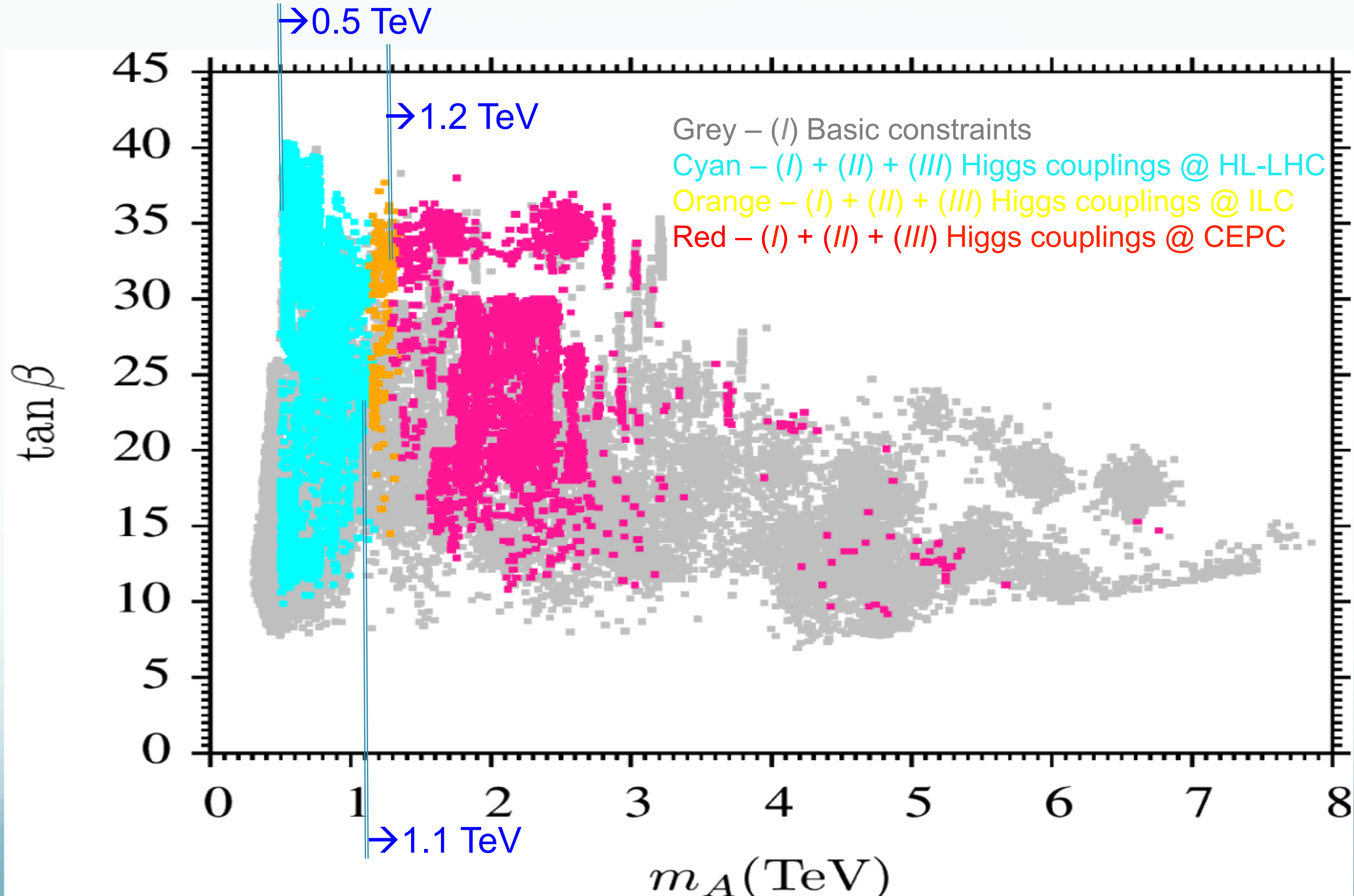
Collider Phenomenology



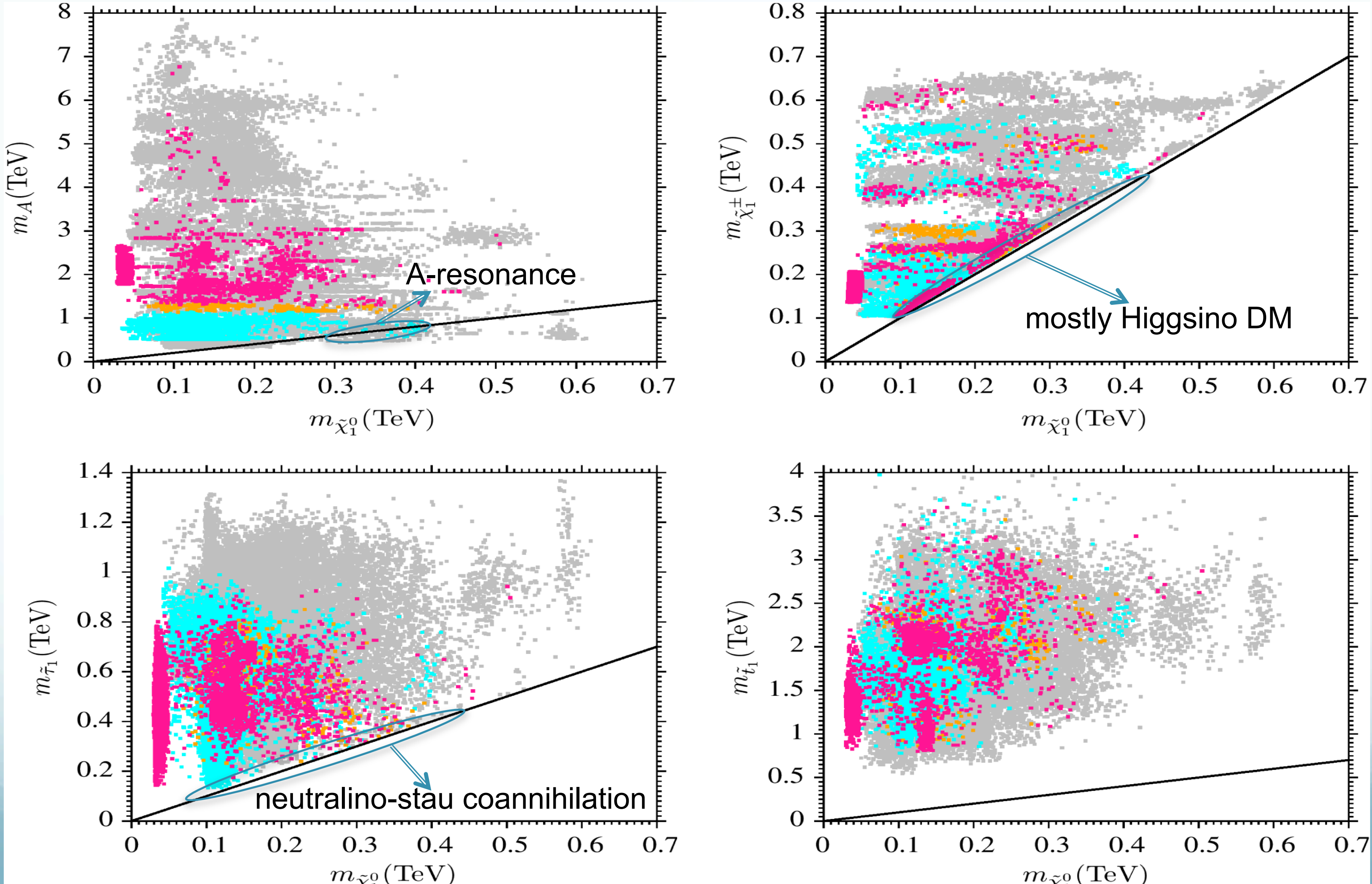
Precisions of Hbb coupling: > 10%, 5%~10%, 3%~5%, < 3%

→ Complementary to the direct collider searches

Collider Phenomenology



Collider Phenomenology



Benchmark Points

	large Higgs deviations	large Δa_μ	A resonance	stau-neutralino coannihilation
	Point 1	Point 2	Point 3	Point 4
m_{0^U}	1037	2582	5057	5327
$m_{\tilde{Q}}$	1003.3	2366.4	4631	4879.2
$m_{\tilde{U}^c}$	1162.1	3306.7	6487	6830.6
$m_{\tilde{D}^c}$	1311.7	3326.3	6474.9	6841.3
$m_{\tilde{L}}$	328.1	264.8	1023	858.2
$m_{\tilde{E}^c}$	814.1	514.8	900.9	978.6
M_1	857.1	350.9	602.7	686.5
M_2	656	993	634.3	828.8
M_3	1158.8	−612.25	555.3	473.05
$A_t = A_b$	−3292	5390	−9095	−9684
$A_{\tilde{\tau}}$	−691.6	1192	−1570	−2937
$\tan\beta$	11.6	33.8	19.7	21.4
μ	183	172.5	377.5	168.2
m_A	338.9	754.9	$\boxed{603}$	846
$\Delta_{\rm HS}$	1883	3151	10873	11993.67
$\Delta_{\rm EW}$	27	23	87	87
Δa_μ	4.731×10^{-10}	$\boxed{16.63 \times 10^{-10}}$	7.683×10^{-10}	12.161×10^{-10}
m_h	123	123	125	125
m_H	342	751	607	856
$m_{H^\pm}$	348	750	608	850
$\kappa_b,\ \kappa_t$	$\boxed{1.22541,}$ 0.99817	1.04295, 0.99996	1.06459, 0.99983	1.03296, 0.99992
$\kappa_\tau,\ \kappa_W = \kappa_Z$	$\boxed{1.22756,}$ 0.99981	1.04787, 0.99999	1.06644, 0.99999	1.03454, 0.99999
$\kappa_g,\ \kappa_\gamma$	0.99083, 1.00369	1.00473, 0.99763	0.99954, 1.00008	1.00038, 0.99714
$m_{\tilde{\chi}^0_{1,2}}$	171, 191	131, 183	$\boxed{260,}$ 376	$\boxed{161,}$ 178
$m_{\tilde{\chi}^0_{3,4}}$	368, 541	195, 834	390, 567	312, 717
$m_{\tilde{\chi}^\pm_{1,2}}$	185, 534	179, 823	378, 555	175, 702
$m_{\tilde{g}}$	2548	1539	1498	1317
$m_{\tilde{u}_{L,R}}$	2419, 2558	2705, 3476	4721, 6513	4942, 6832
$m_{\tilde{t}_{1,2}}$	1036, 1798	1151, 1762	2311, 3401	2326, 3543
$m_{\tilde{d}_{L,R}}$	2421, 2532	2706, 3547	4722, 6595	4943, 6938
$m_{\tilde{b}_{1,2}}$	1771, 2468	1212, 3089	2380, 6340	2401, 6630
$m_{\tilde{\nu}_{1,2}}$	726	521	698	507
$m_{\tilde{\nu}_3}$	718	343	645	308
$m_{\tilde{e}_{L,R}}$	737, 525	514, 787	651, 1409	398, 1487
$m_{\tilde{\tau}_{1,2}}$	518, 728	353, 568	627, 1338	$\boxed{185,}$ 1333
$\Omega_{\rm CDM}h^2$	0.0014	0.0846	0.1017	0.0099

Summary

★ Higgs & Other Low Energy Measurements => BSM physics

→ If no clear hints of BSM after LHC

→ EFT or a UV-complete model

★ Scanning Parameter Space of a Natural SUSY Model

→ Using Higgs coupling @ HL-LHC, ILC, CEPC & muon g-2

→ $\Delta_{EW} \sim 30$

→ m_A > 1.2 (1.1) TeV from k_b (k_τ) at CEPC

→ $\tilde{l}_R$: [0.6 – 2] TeV, $\tilde{l}_L, \tilde{\nu}$: [0.4 – 1.2] TeV with $\tilde{\chi}_1^0$: < 400 GeV from Δa_μ

→ tanβ vs. m_A: complementary to the direct collider searches

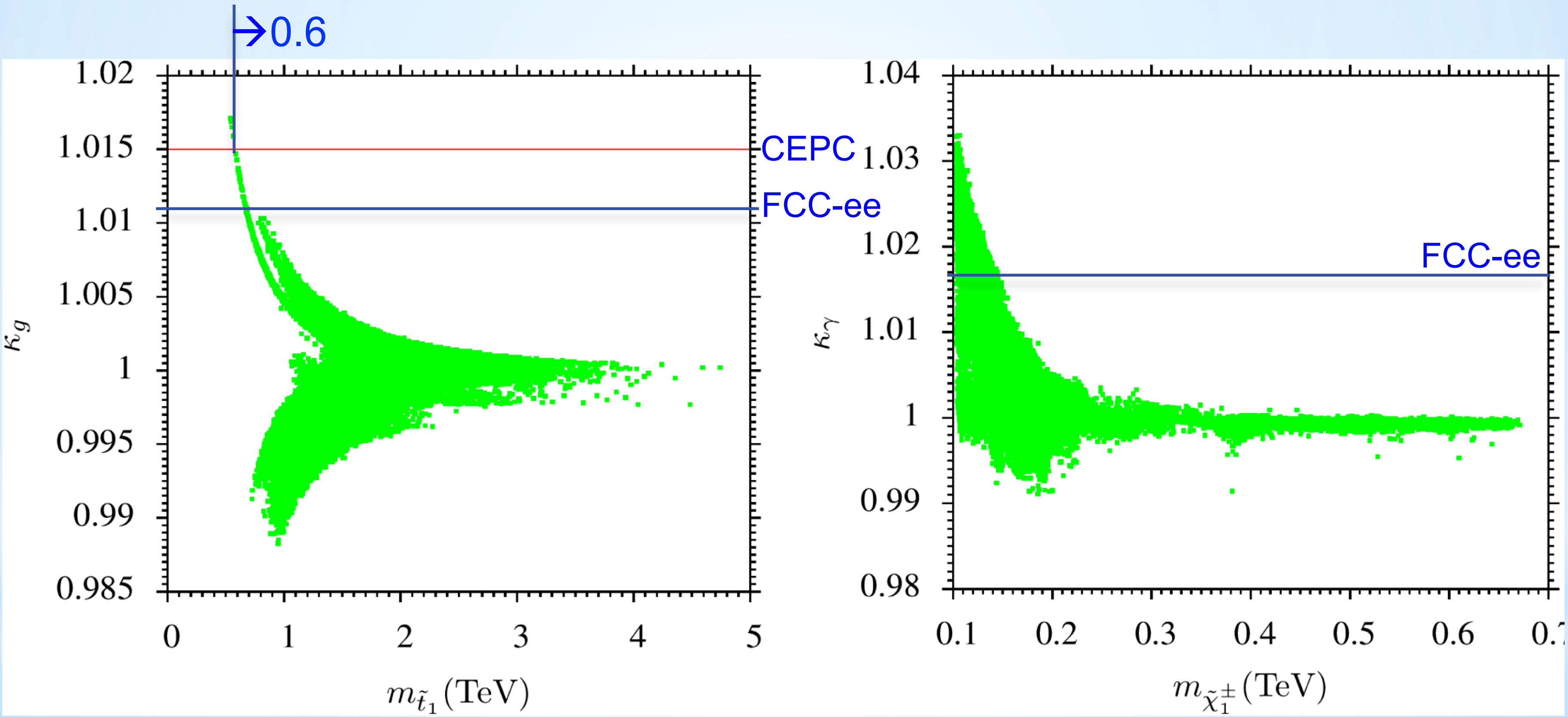
→ 4 Benchmark points

Thank you for your attention !

Any Questions ?

Backup Slide

Higgs Coupling Measurements



$k_\gamma < 1$
← negative contributions from sbottom & stau

Backup Slide

General Minimal Supergravity (GmSUGRA) Model

Scanning the parameter space

$$
\begin{aligned}
0\,\mathrm{GeV} &\leq m_0^U \leq 9000\,\mathrm{GeV}, \\
100\,\mathrm{GeV} &\leq M_1 \leq 2000\,\mathrm{GeV}, \\
100\,\mathrm{GeV} &\leq M_2 \leq 2100\,\mathrm{GeV}, \\
100\,\mathrm{GeV} &\leq m_{\tilde{L}} \leq 1200\,\mathrm{GeV}, \\
100\,\mathrm{GeV} &\leq m_{\tilde{E}^c} \leq 1200\,\mathrm{GeV}, \\
100\,\mathrm{GeV} &\leq \mu \leq 1500\,\mathrm{GeV}, \\
0\,\mathrm{GeV} &\leq m_A \leq 9500\,\mathrm{GeV}, \\
-16000\,\mathrm{GeV} &\leq A_U = A_D \leq 18000\,\mathrm{GeV} \\
-6000\,\mathrm{GeV} &\leq A_E \leq 6000\,\mathrm{GeV}, \\
2 &\leq \tan\beta \leq 60.
\end{aligned}
$$

→ sleptons, charginos, bino, wino, Higgsinos within one TeV;

→ squarks, gluinos can be in several TeV mass

Backup Slide

Electroweak Fine-turning

Use ISAJET 7.85 to calculate the fine- tuning measure at the EW scale M_{EW}
→ lower values of ΔEW corresponds to less fine-tuning

Z boson mass M_Z, after including the one-loop effective potential contributions to the tree-level MSSM Higgs potential

$$\frac{m_Z^2}{2} = \frac{m_{H_d}^2 + \Sigma_d^d - (m_{H_u}^2 + \Sigma_u^u)\tan^2\beta}{\tan^2\beta - 1} - \mu^2$$

$$\Delta_{\mathrm{EW}} \equiv \max(C_k)/(M_Z^2/2)$$