기초과학연구원
Institute for Basic Science

Exploring dynamical CP violation induced baryogenesis by gravitational waves and colliders

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(IBS-CTPU)

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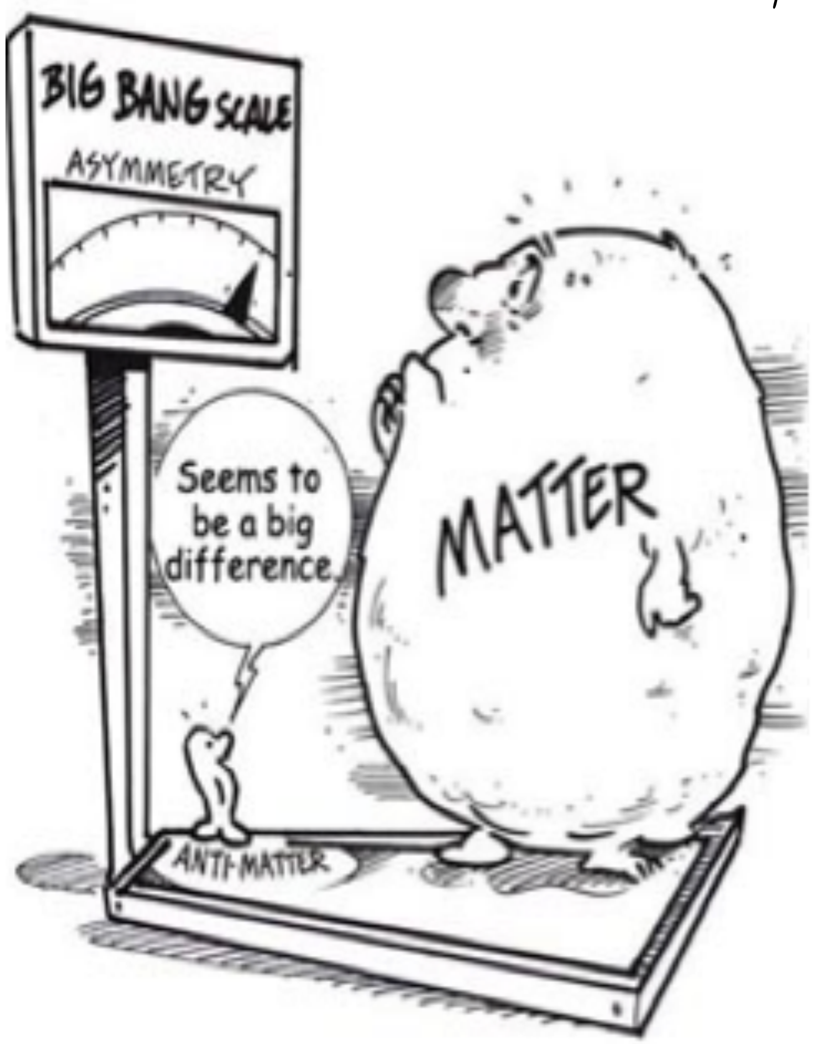
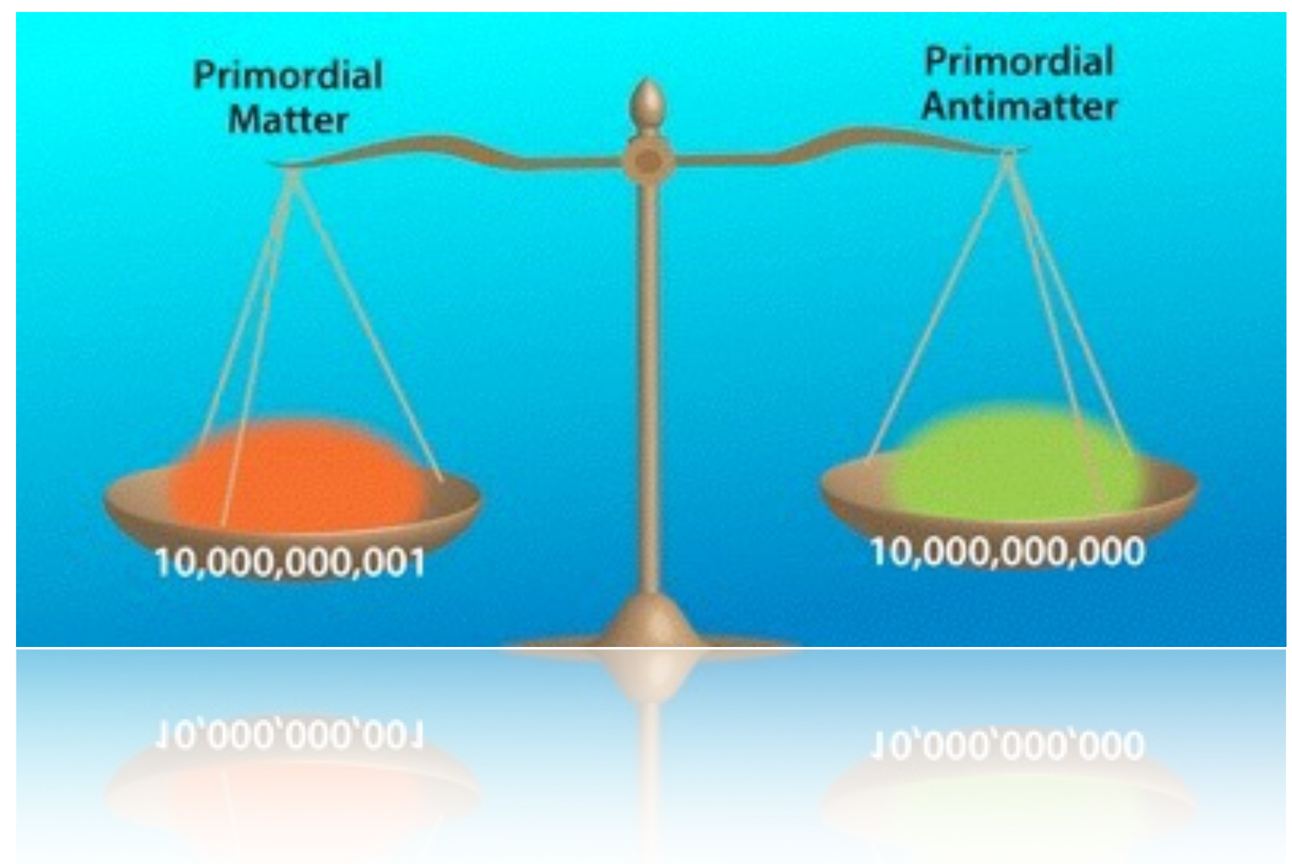
(Based on work in Collaboration with Fa Peng Huang, Mengchao Zhang)

The observed universe seems to be dominated by matter over anti-matter. Or, baryon asymmetry of the universe (BAU):

$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 6 \times 10^{-10} \quad (\mathrm{CMB},\ \mathrm{BBN})$$





picture from web: https://www.michaelgstrauss.com/2017/11/should-we-be-here.html

Sakharov conditions necessary for BAU:

Does the SM work?

- baryon number violation ✓
  possible through non-perturbative sphaleron process
- C and CP symmetry violation ⊗
  CKM in weak interaction, but insufficient
- Departure from thermal equilibrium ⊗
  Crossover (smooth) EW phase transition

✳ Stringent constraints from electric dipole moment (EDM) measurement limits new physics source of CP violation

Dynamical CPV: Large CPV in the early universe, suppressed at current time

A simple example realized with:
Additional scalar S with a CPV dim-5 operator:

$$\boxed{\mathcal{L} = \mathcal{L}_{\rm SM} - y_t \frac{\eta}{\Lambda} S \bar{Q}_L \tilde{\Phi} t_R + \text{H.c} + \frac{1}{2}\partial_\mu \text{S} \partial^\mu \text{S} + \frac{1}{2}\mu^2 \text{S}^2 - \frac{1}{4}\lambda \text{S}^4 - \frac{1}{2}\kappa \text{S}^2 (\Phi^\dagger \Phi)}$$

(arXiv: 1110.2876)

with $y_t = \sqrt{2} m_t / v$ and $\eta = a + ib$

The singlet and the dim-5 operator can come from many types composite Higgs models
arXiv:0902.1483 , arXiv:1703.10624 ,arXiv:1704.08911,

Parameters: $\{\Lambda, \mu, \lambda, \kappa\}$

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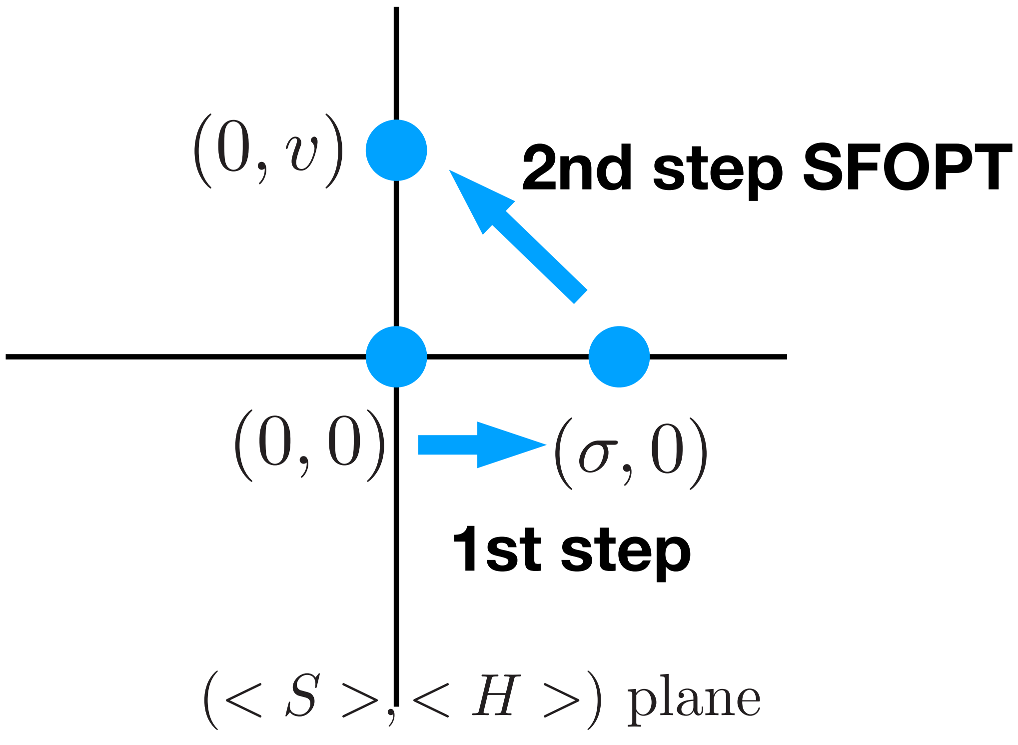

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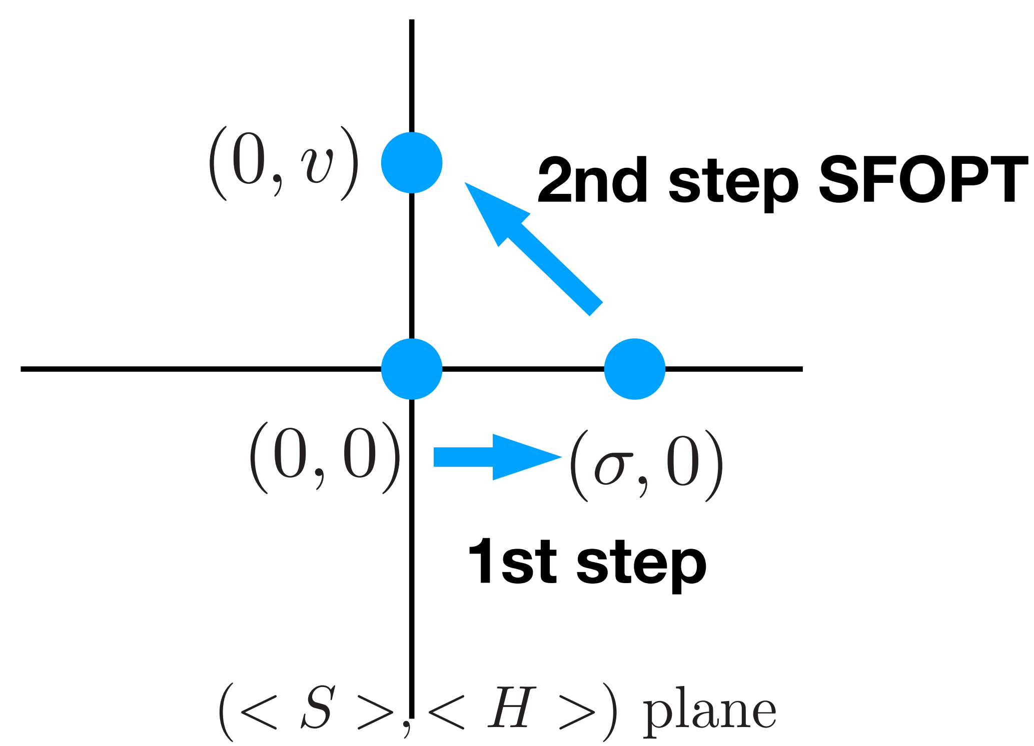
The Lagrangian provides:

- **sizable CPV when S has a vev** ✓
- **strong first-order phase transition (SFOPT)**



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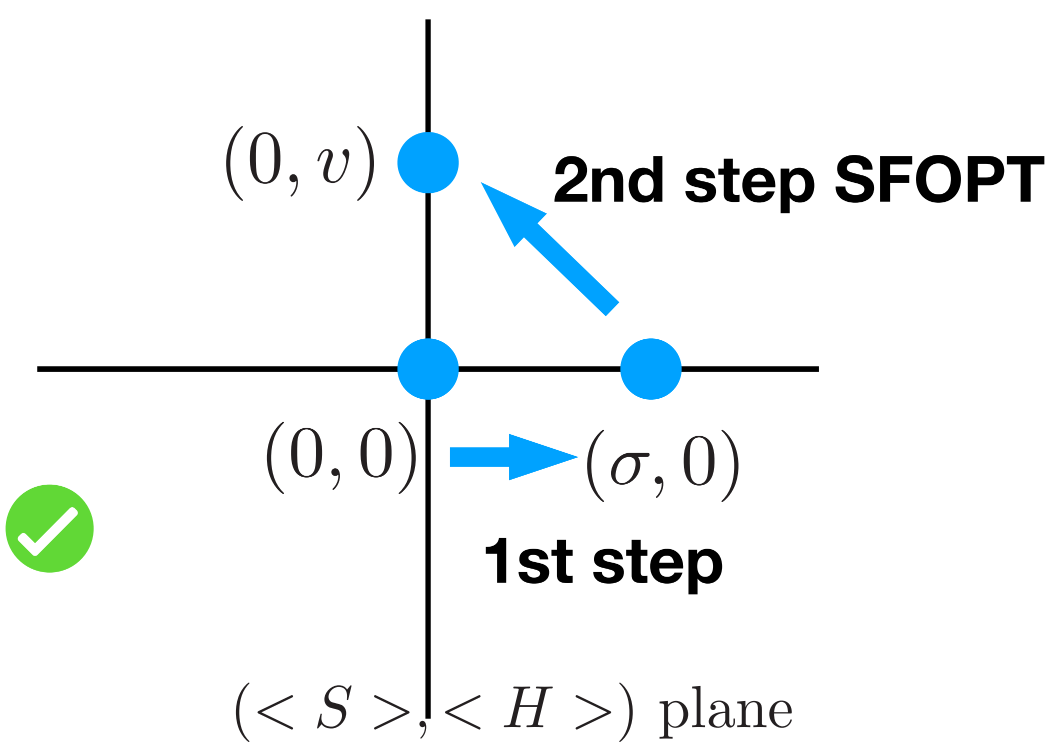

Approximate analytics with Finite temperature potential:

$$V_{\rm tree}(H,\sigma) = -\frac{1}{2}\mu_{SM}^2 H^2 - \frac{1}{2}\mu^2\sigma^2 + \frac{1}{4}\lambda_{SM}H^4 + \frac{1}{4}\lambda\sigma^4 + \frac{1}{4}\kappa H^2\sigma^2$$

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$$D_H = \frac{1}{32}(8\lambda_{SM} + g'^2 + 3g^2 + 4y_t^2 + 2\kappa/3), \quad D_\sigma = \frac{1}{24}(2\kappa + 3\lambda)\ ,$$

$$\Rightarrow \quad \frac{v(T_c)}{T_c} \sim \frac{2v}{m_H}\sqrt{\frac{D_H - D_\sigma}{\delta_\lambda - 2\delta_{\mu^2}}}$$

“wash-out parameter”

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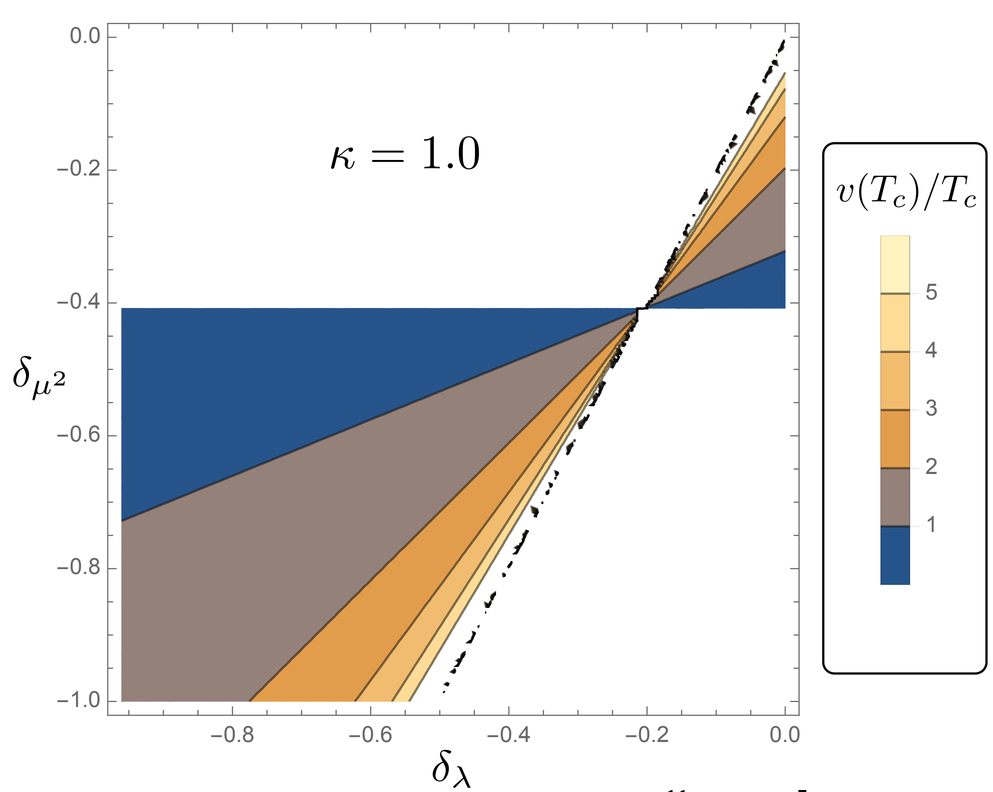

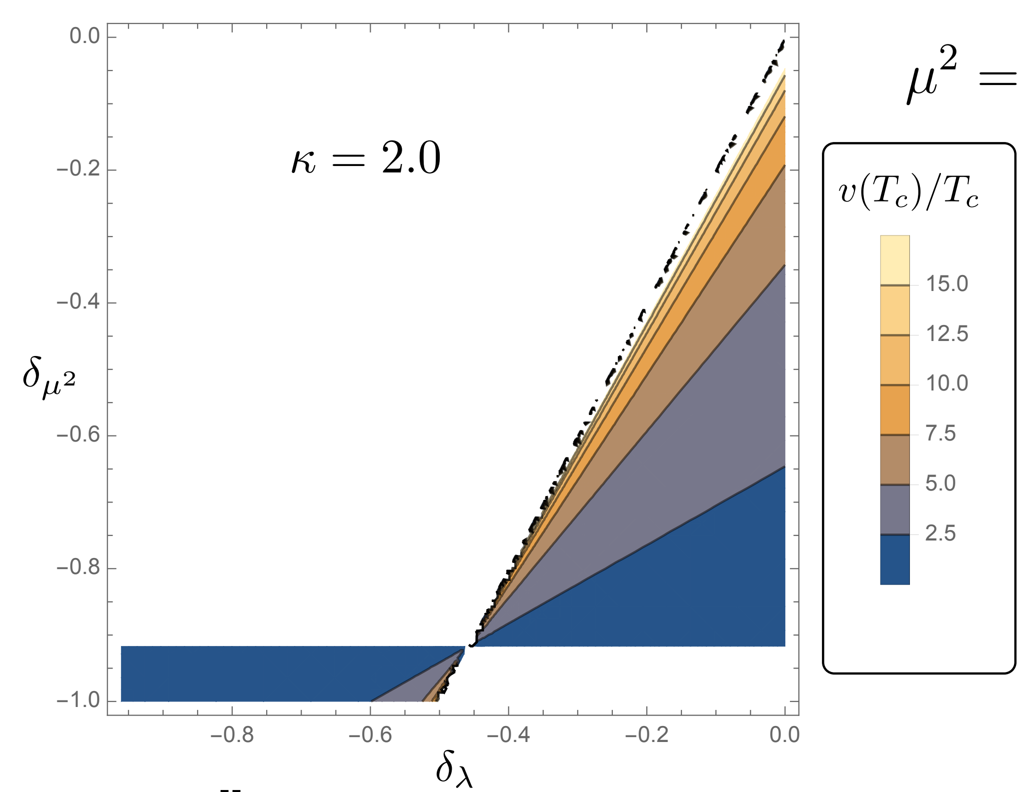

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Numerical results with Finite temperature effective 1-loop potential:

$$V_{\mathrm{eff}}(H,\sigma,T) = V_{\mathrm{tree}}(H,\sigma) + \Delta V_1^{T\neq 0}(H,\sigma,T) + V_1^{T=0}(H,\sigma)$$

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BAU estimation:

$$\eta_B = \frac{405\Gamma_{\rm sph}}{4\pi^2 \tilde{v}_b g_* T} \int dz\, \mu_{B_L} f_{\rm sph}\, e^{-45\,\Gamma_{\rm sph}|z|/(4\tilde{v}_b)}$$

Observed BAU: → $\Delta\sigma/\Lambda \sim 0.1 - 0.3$ → $\Lambda \sim 1~\text{TeV}$

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Benchmark points, which can give a SFOPT and produce phase transition GWs.

Benchmark set	κ	m_S [GeV]	T_N [GeV]	α	$\tilde{\beta}$
I	2.00	115	106.6	0.035	107
II	2.00	135	113.6	0.04	120

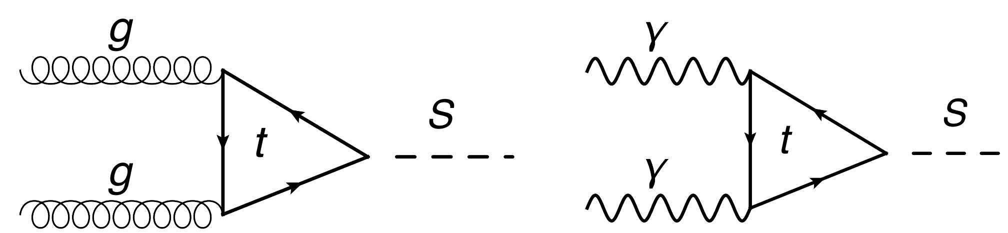
EDM and Collider Analysis

$$\mathcal{L}_{Stt} = -\left(\frac{m_t}{\Lambda} + \frac{m_t H}{\Lambda v}\right) S \left(a\bar{t}t + ib\bar{t}\gamma_5 t\right)$$

>> Rich Collider signature

- **Effective operators: SGG, SFF induced (CDE: covariant derivative expansion mothod)**

$$\begin{aligned}\mathcal{L}'_{SVV} &= \frac{a\alpha_S}{12\pi\Lambda} S G^a_{\mu\nu} G^{a\mu\nu} - \frac{b\alpha_S}{8\pi\Lambda} S G^a_{\mu\nu} \tilde{G}^{a\mu\nu} \\ &+ \frac{2a\alpha_{EW}}{9\pi\Lambda} S F_{\mu\nu} F^{\mu\nu} - \frac{b\alpha_{EW}}{3\pi\Lambda} S F_{\mu\nu} \tilde{F}^{\mu\nu}\end{aligned}$$



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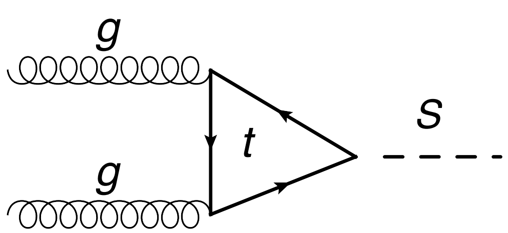

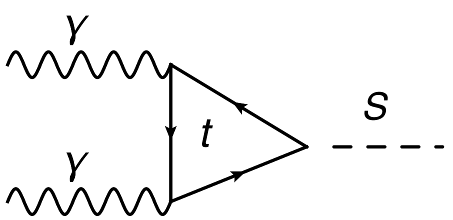

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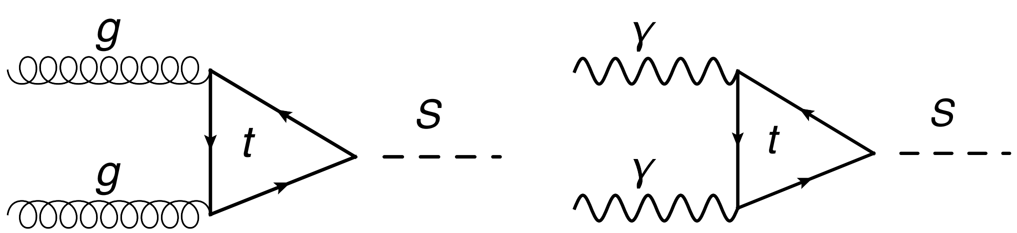

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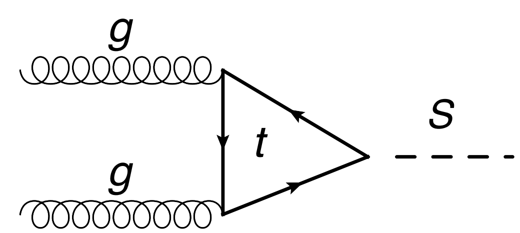

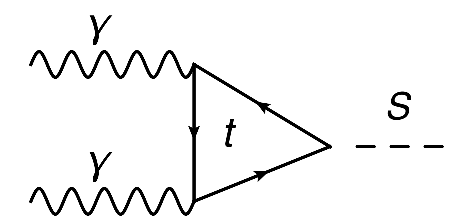

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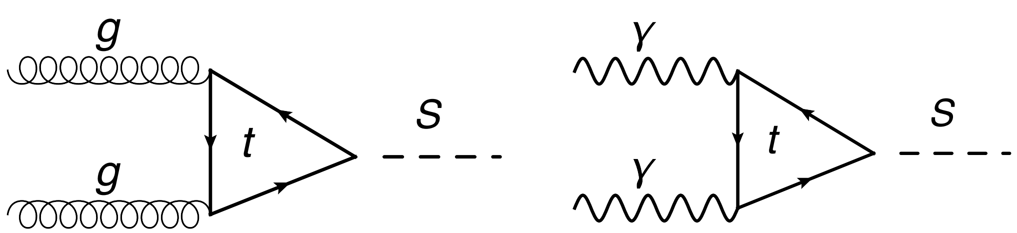

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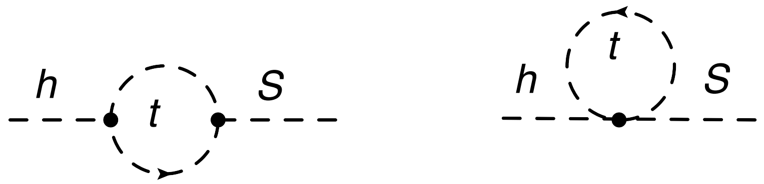

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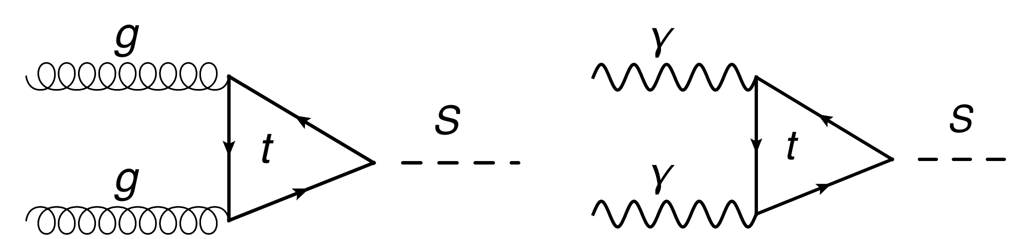

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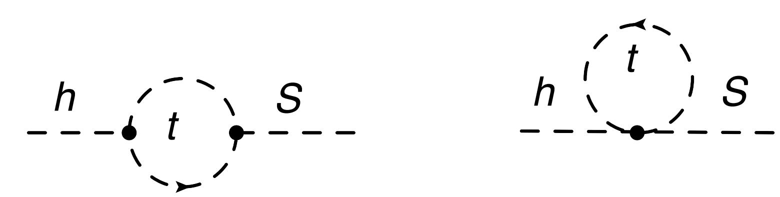

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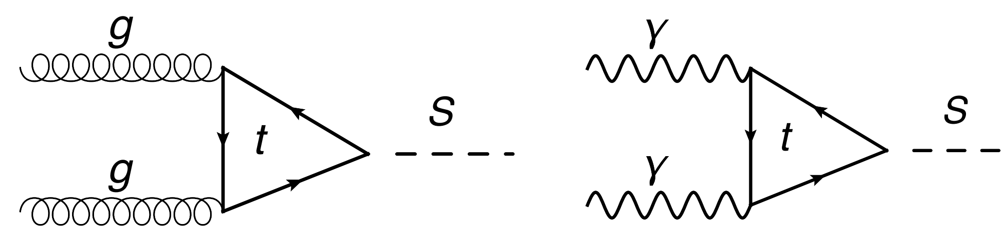

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$$\mathcal{O} \begin{pmatrix} m^2_{S,\mathrm{tree}} + \Delta m^2_S & \Delta m^2_{HS} \\ \Delta m^2_{HS} & m^2_{H,\mathrm{tree}} + \Delta m^2_H \end{pmatrix} \mathcal{O}^T = \begin{pmatrix} m^2_{S,\mathrm{phy}} & 0 \\ 0 & m^2_{H,\mathrm{phy}} \end{pmatrix}$$

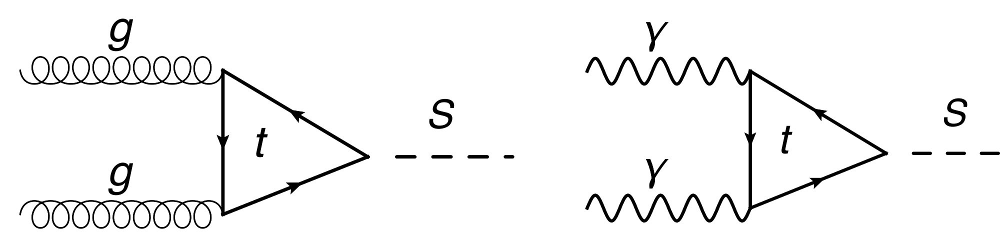
EDM and Collider Analysis

$$\mathcal{L}_{Stt} = -\left(\frac{m_t}{\Lambda} + \frac{m_t H}{\Lambda v}\right) S\,(a\bar{t}t + ib\bar{t}\gamma_5 t)$$

>> Rich Collider signature

- **Effective operators: SGG, SFF induced (CDE: covariant derivative expansion mothod)**

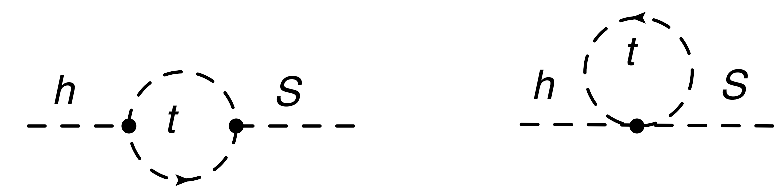
$$\mathcal{L}'_{SVV} = \frac{a\alpha_S}{12\pi\Lambda} S G^a_{\mu\nu} G^{a\mu\nu} - \frac{b\alpha_S}{8\pi\Lambda} S G^a_{\mu\nu} \tilde{G}^{a\mu\nu} + \frac{2a\alpha_{EW}}{9\pi\Lambda} S F_{\mu\nu} F^{\mu\nu} - \frac{b\alpha_{EW}}{3\pi\Lambda} S F_{\mu\nu} \tilde{F}^{\mu\nu}$$



loop induced effective couplings

&

mixing between S and H



$$\mathcal{L}_{mass} = -\frac{1}{2} \begin{pmatrix} S & H \end{pmatrix} \begin{pmatrix} m^2_{S,\mathrm{tree}} + \Delta m^2_S & \Delta m^2_{HS} \\ \Delta m^2_{HS} & m^2_{H,\mathrm{tree}} + \Delta m^2_H \end{pmatrix} \begin{pmatrix} S \\ H \end{pmatrix}$$

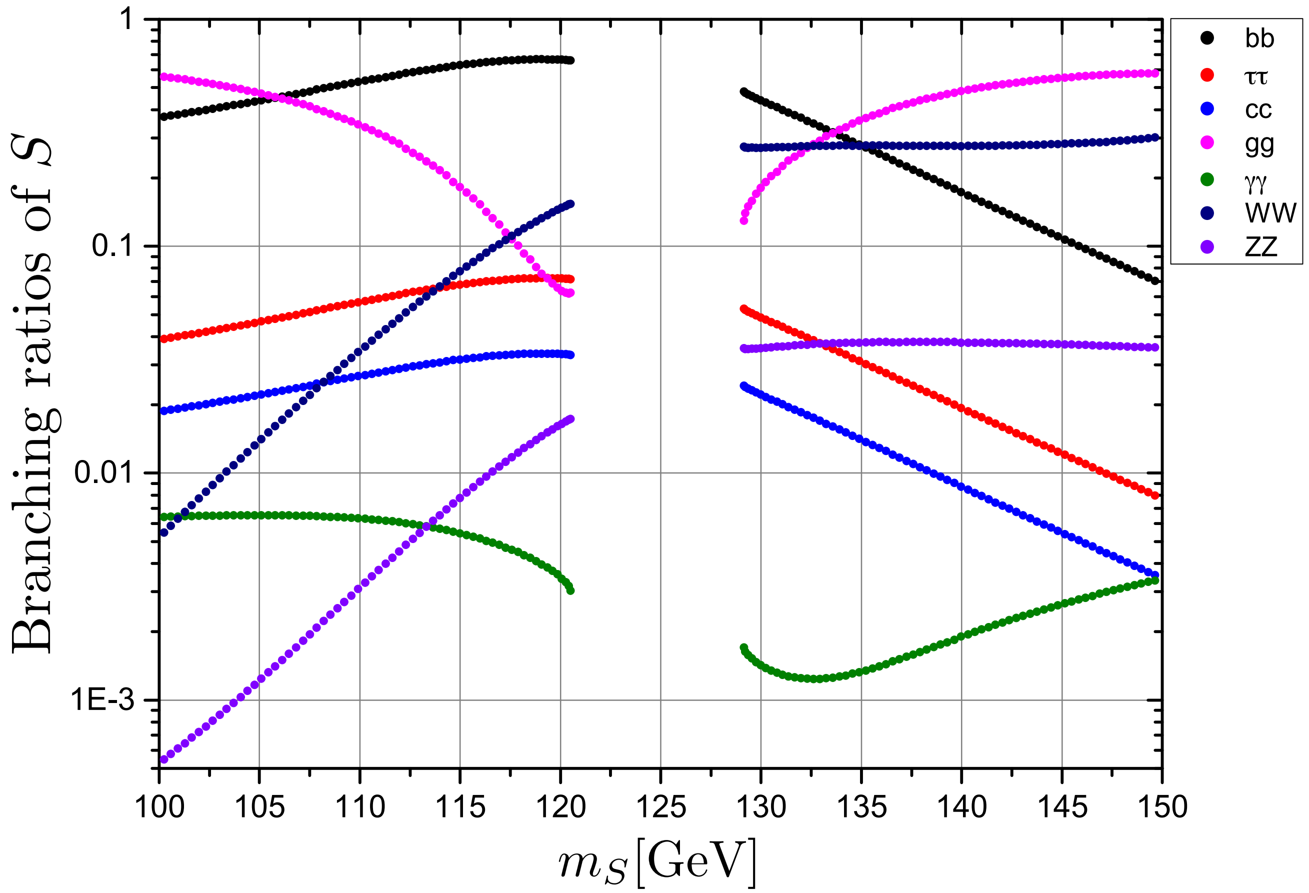
$$\Delta m^2_H = \frac{3m_t^4}{4\pi^2 v^2}\,, \quad \Delta m^2_{HS} = a\frac{3m_t^4}{2\pi^2 \Lambda v}\,, \quad \Delta m^2_S = (a^2 - b^2)\frac{3m_t^4}{4\pi^2\Lambda^2}$$

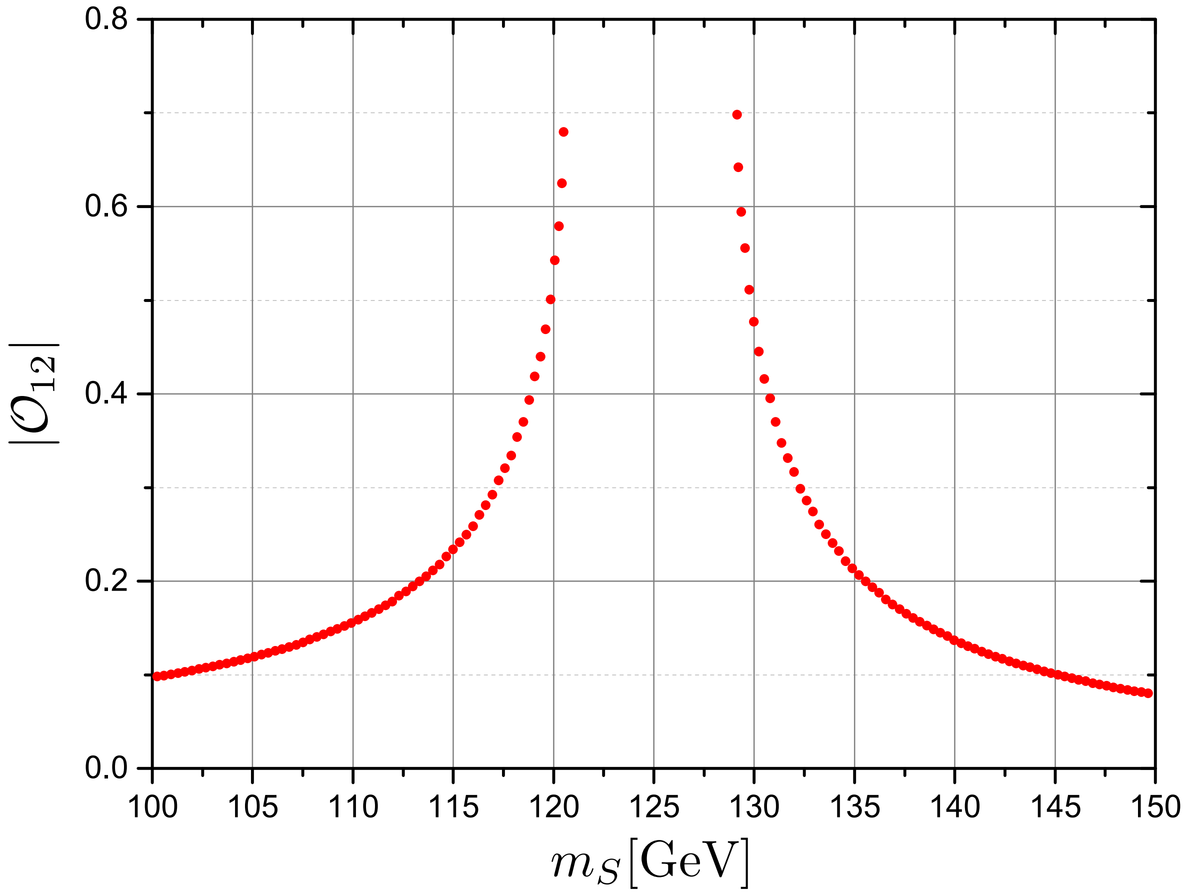
$$\mathcal{O} \begin{pmatrix} m^2_{S,\mathrm{tree}} + \Delta m^2_S & \Delta m^2_{HS} \\ \Delta m^2_{HS} & m^2_{H,\mathrm{tree}} + \Delta m^2_H \end{pmatrix} \mathcal{O}^T = \begin{pmatrix} m^2_{S,\mathrm{phy}} & 0 \\ 0 & m^2_{H,\mathrm{phy}} \end{pmatrix}$$

$$\begin{cases} S_{\mathrm{phy}} = \mathcal{O}_{11} S + \mathcal{O}_{12} H, \\ H_{\mathrm{phy}} = \mathcal{O}_{21} S + \mathcal{O}_{22} H. \end{cases}$$

EDM and Collider Analysis

- **Property of S from loop-induced mixing with H**



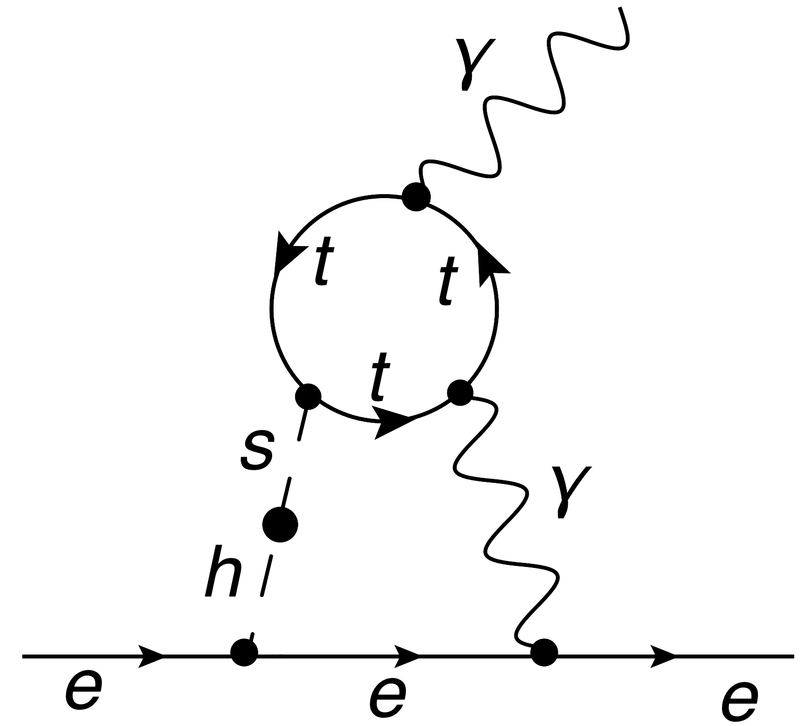


EDM and Collider Analysis

- **contribution to electron EDM**

$$|d_e| < 8.7 \times 10^{-29}\ \mathrm{cm} \cdot \mathrm{e}$$ **(ACME 2014)**

$$|d_e| \sim< 1 \times 10^{-29}$$ **(ACME 2018)**



J. Brod, U. Haisch and J. Zupan, JHEP **1311**, 180 (2013) doi:10.1
[arXiv:1310.1385 [hep-ph]].

R. Harnik, J. Kopp and J. Zupan, JHEP **1303**, 026 (2013) doi:10.1
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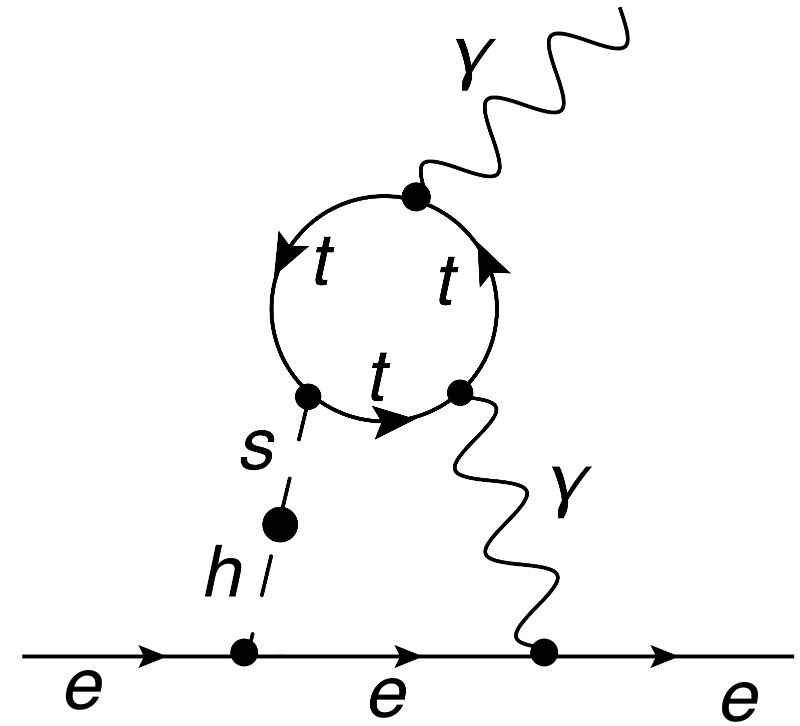

2-loop Barr-Zee contribution to EDM

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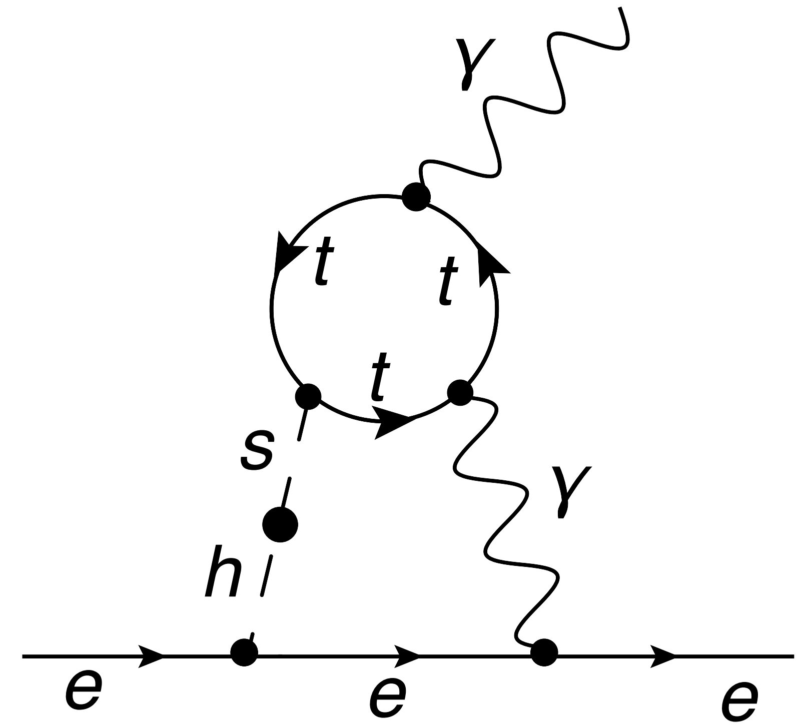

2-loop Barr-Zee contribution to EDM

$$d_e^{\text{2-loop}} = \frac{e}{3\pi^2}\left(\frac{\alpha_{EW} G_F v}{\sqrt{2}\pi m_t}\right) m_e \left(\frac{vb}{2\Lambda}\right) \mathcal{O}_{11}\mathcal{O}_{12}\Big[-g(z_{ts}) + g(z_{th})\Big]$$

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EDM and Collider Analysis

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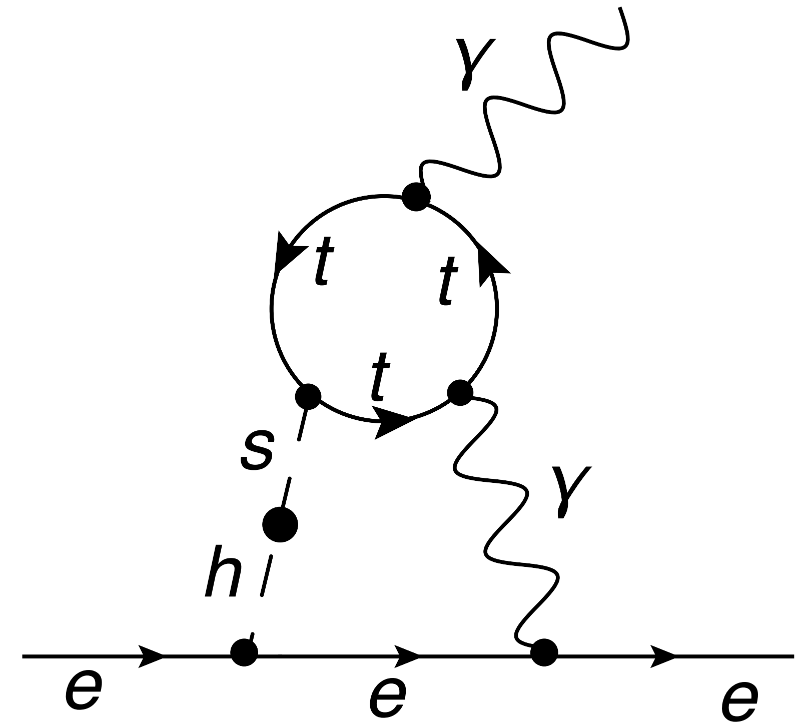

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$$z_{ts} = \frac{m_t^2}{m_S^2}\ ,\ z_{th} = \frac{m_t^2}{m_H^2}\ ,\ g(z) = \frac{1}{2} z \int_0^1 dx \frac{1}{x(1-x)-z} \log\left(\frac{x(1-x)}{z}\right)$$

J. Brod, U. Haisch and J. Zupan, JHEP **1311**, 180 (2013) doi:10.1
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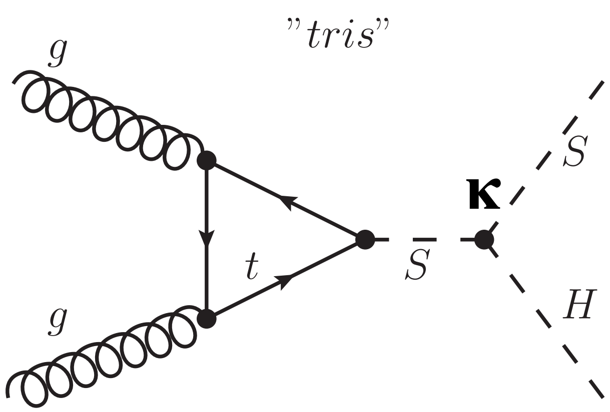
- **LHC Direct Search through: di-photon, 4-leptons**

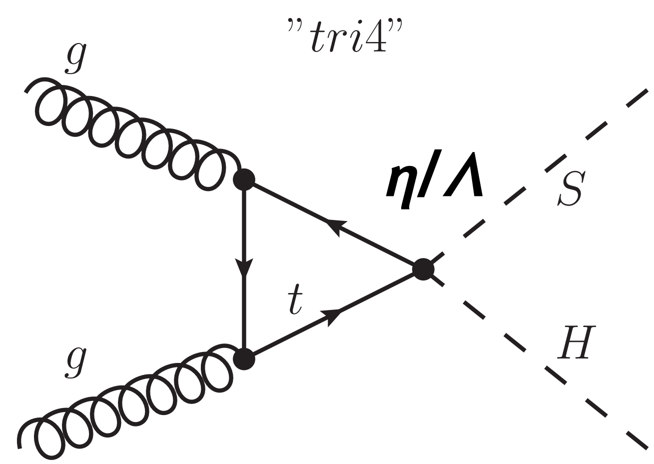
Production cross sections of S times branching ratios at 14 TeV LHC

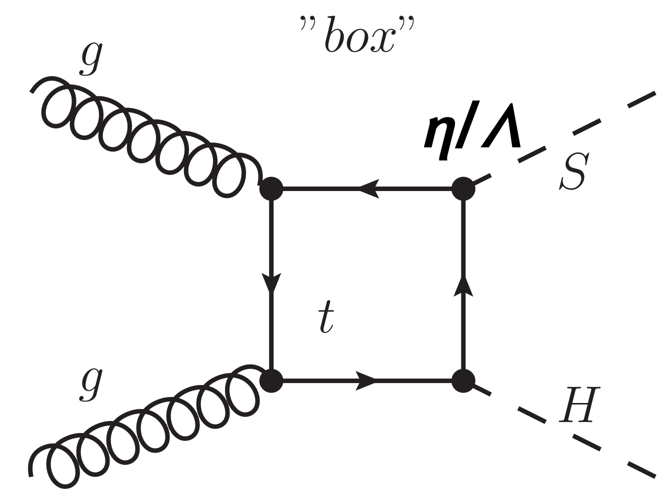
m_S[GeV]	$\sigma(pp \to S) \times BR(S \to \gamma\gamma)$	$\sigma(pp \to S) \times BR(S \to ZZ^*)$
115	37.73 fb	54.69 fb
135	18.38 fb	520.60 fb

EDM and Collider Analysis

- **LHC Direct Search: pp-> SH**







EDM and Collider Analysis

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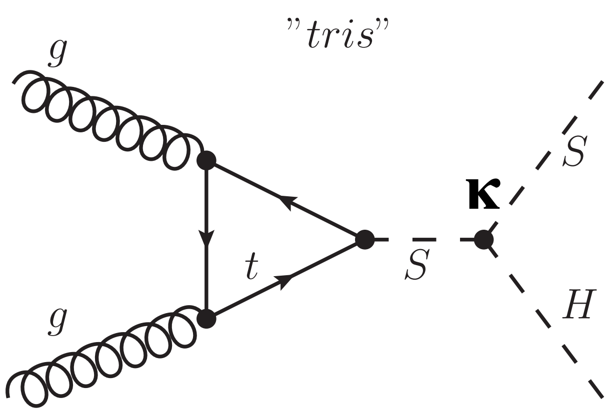

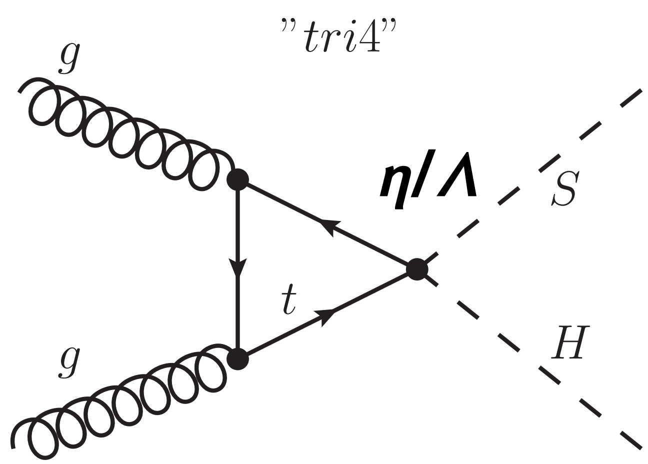

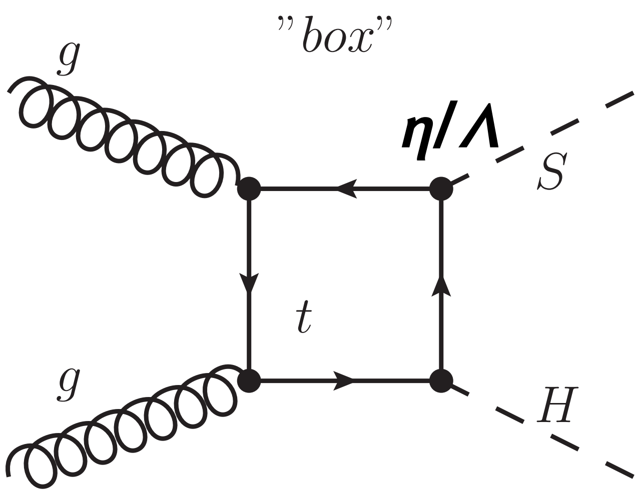

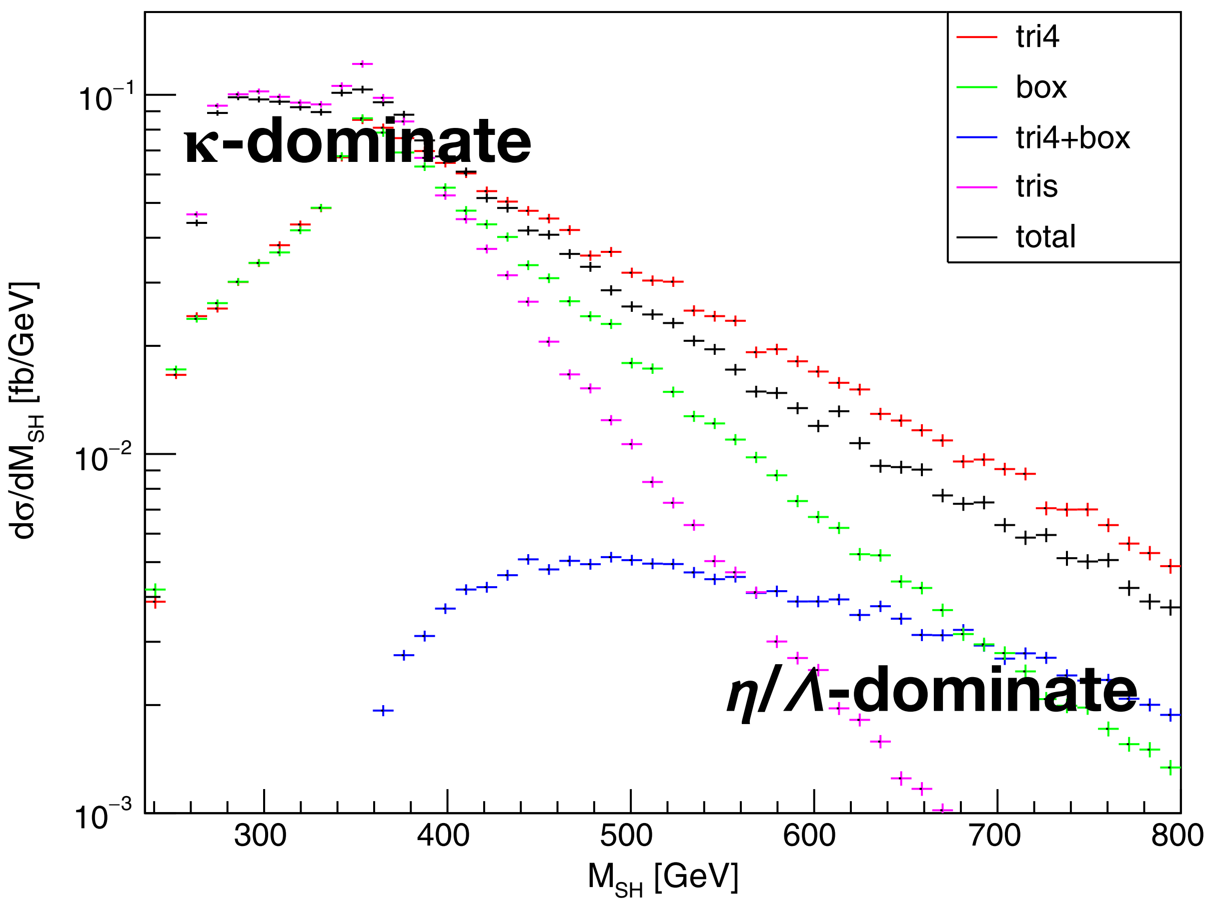

EDM and Collider Analysis

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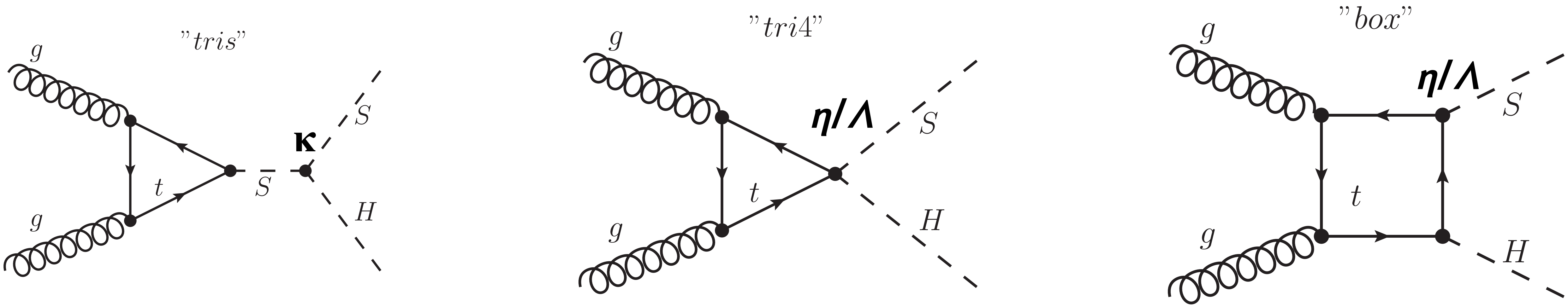

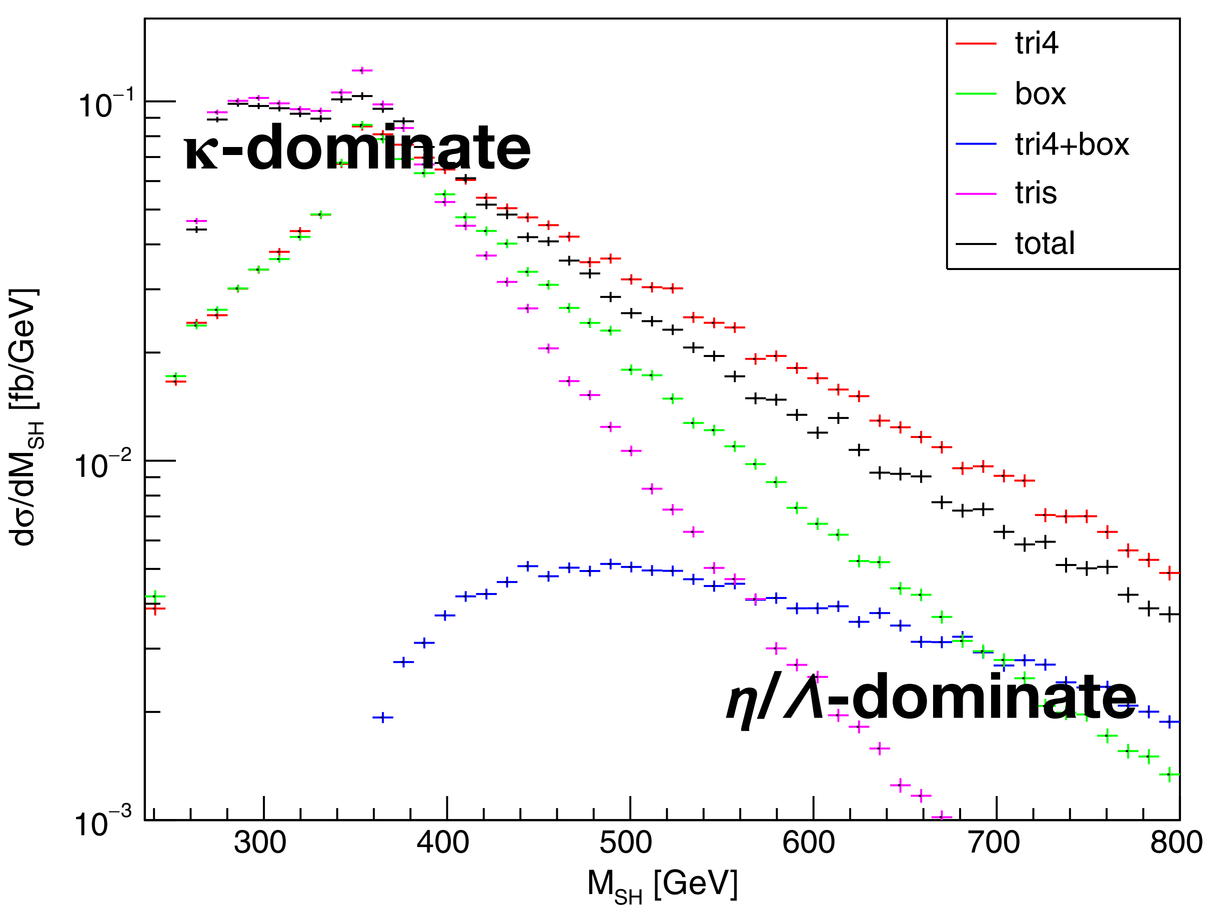

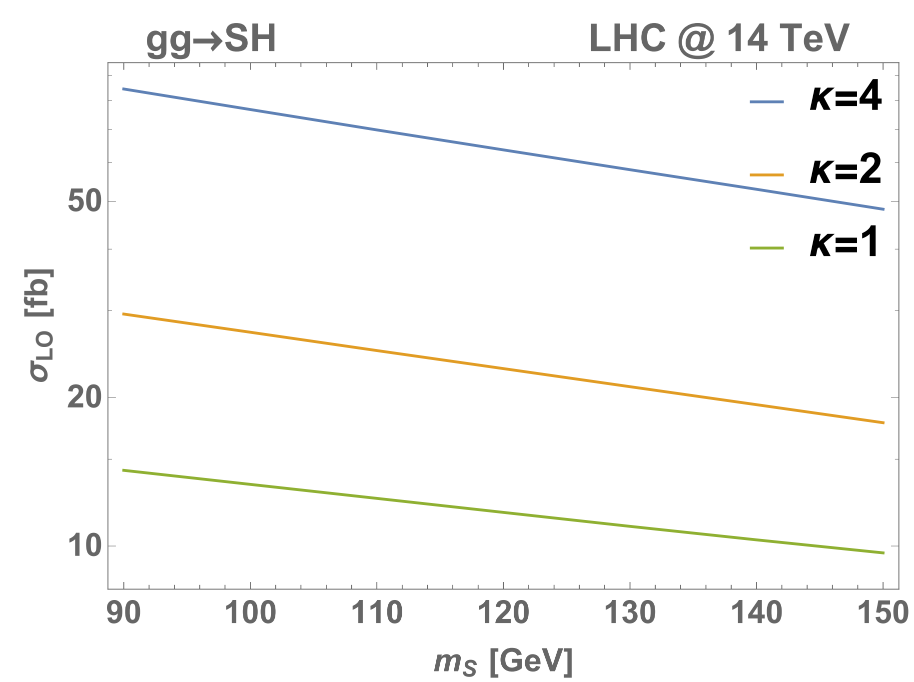

EDM and Collider Analysis

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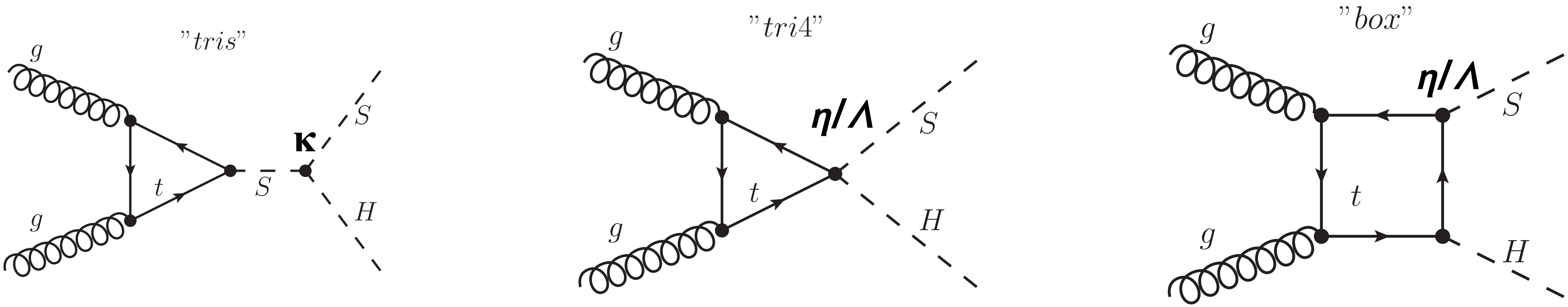
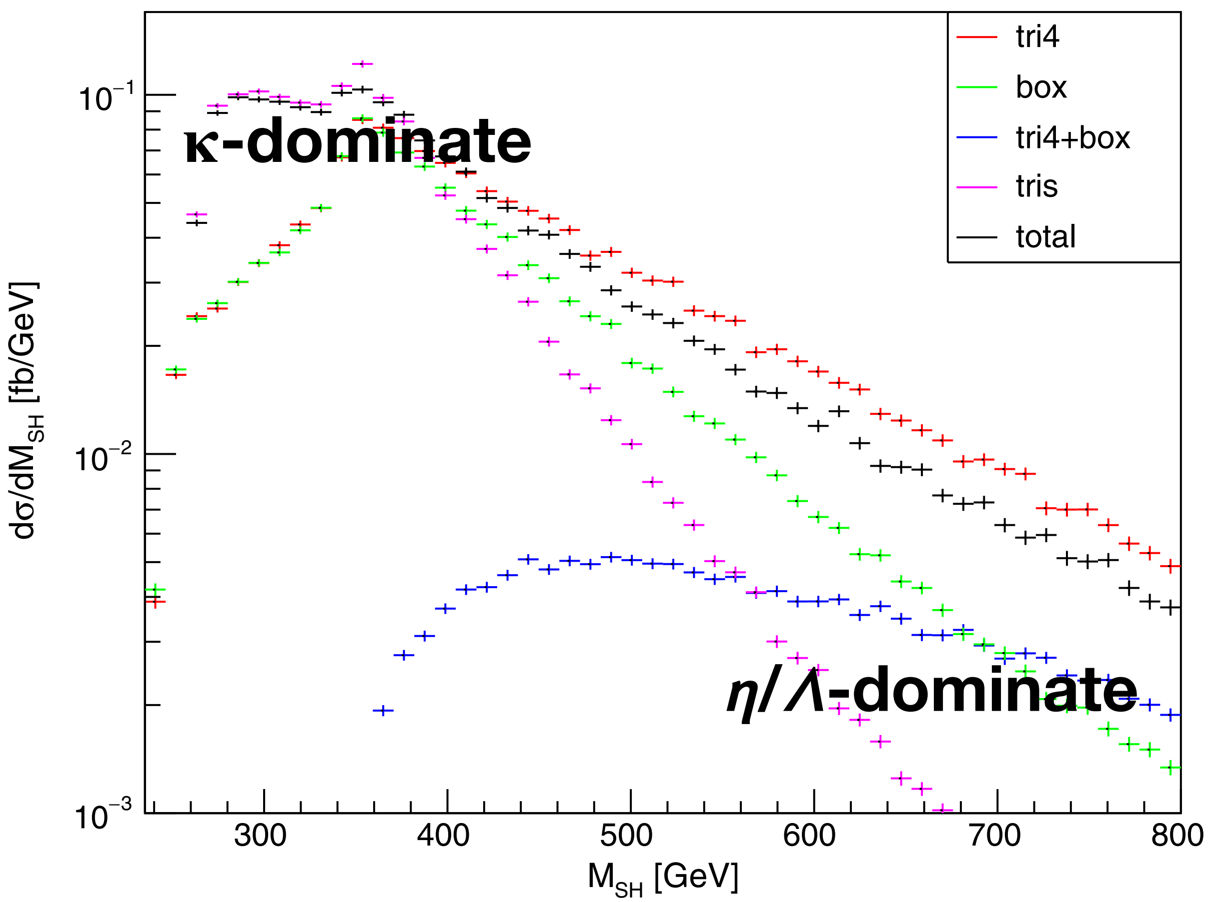
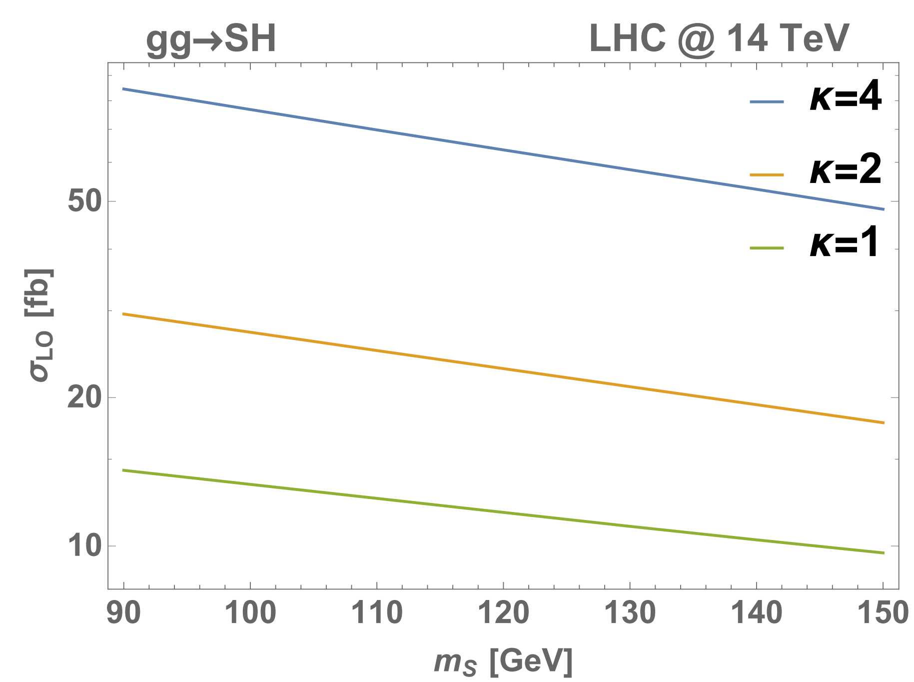


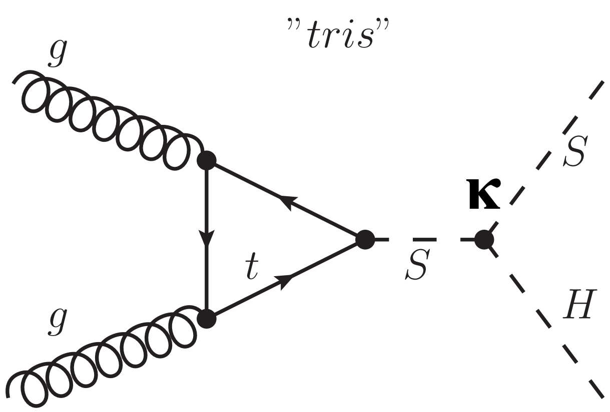


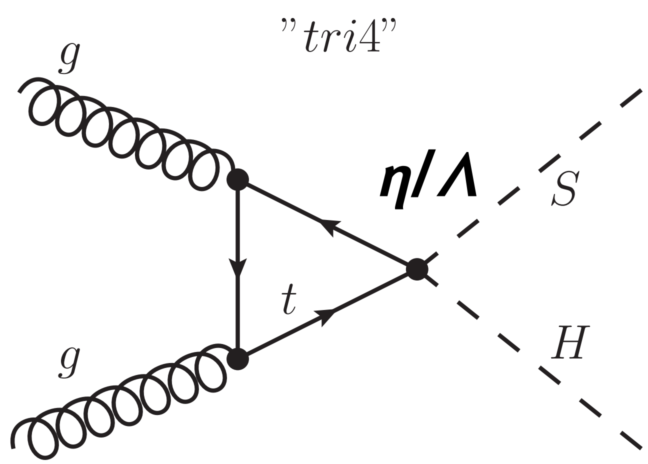


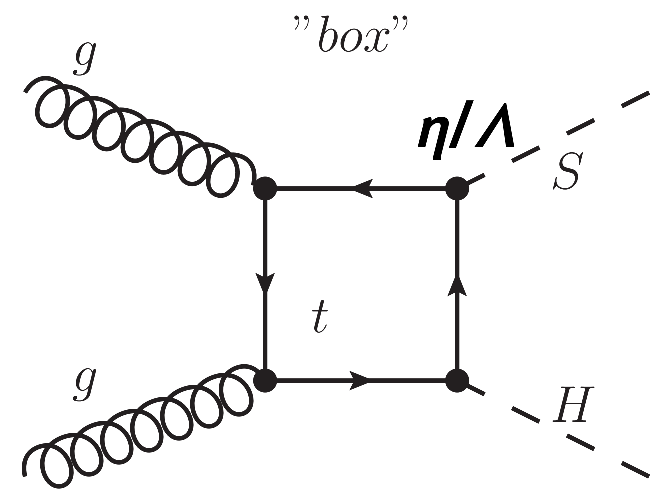
$$\kappa = 2, \;\; m_S = 115 \text{ GeV}$$

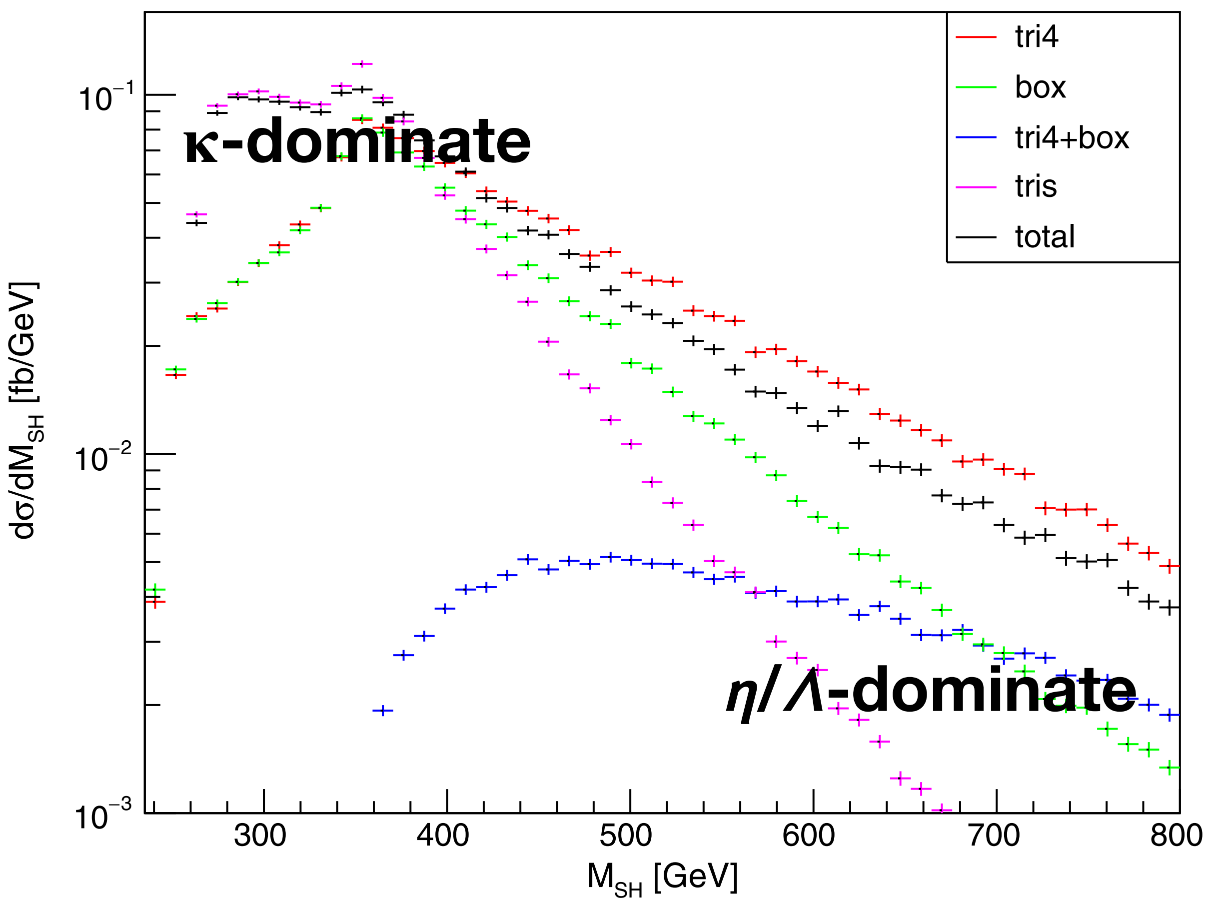
EDM and Collider Analysis

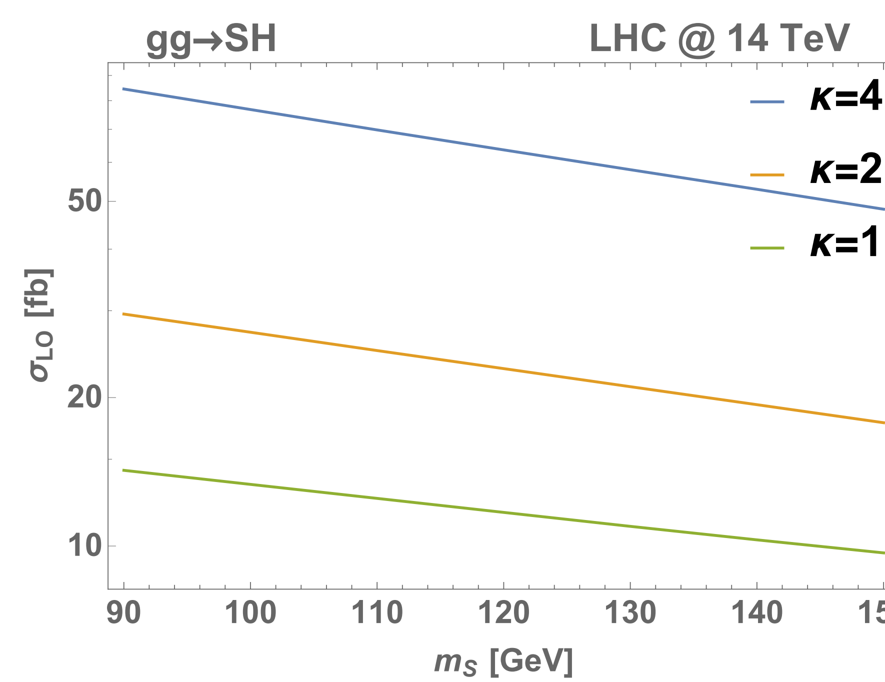
- **LHC Direct Search: pp-> SH**











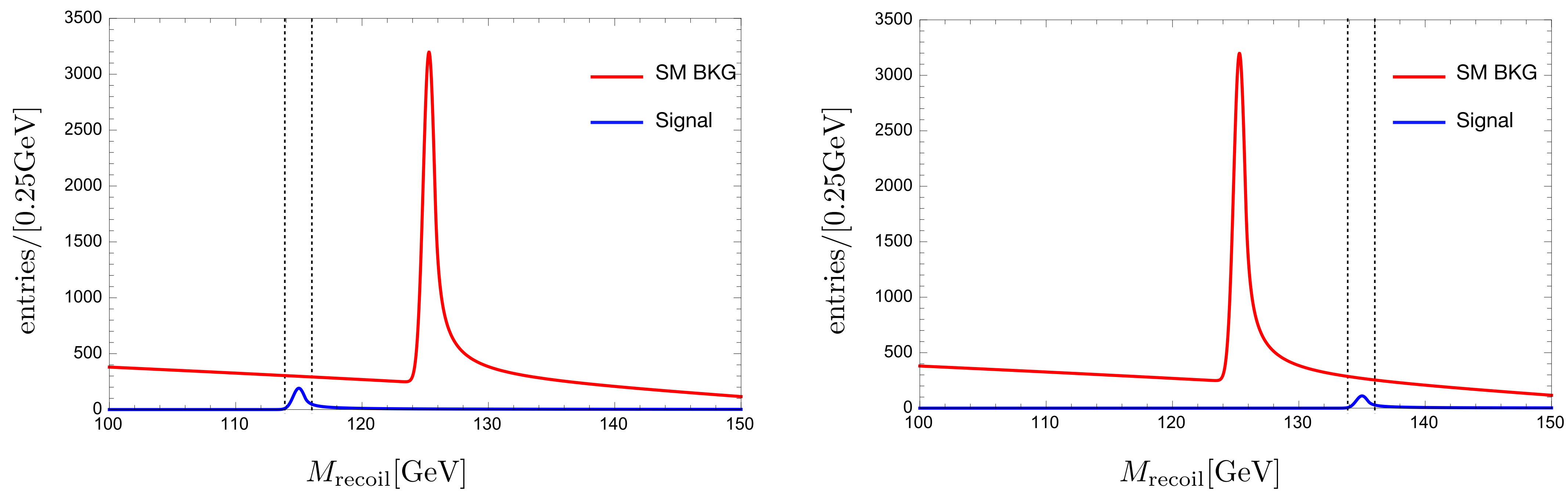
$$\kappa = 2,\ m_S = 115\ \mathrm{GeV}$$

$$\sigma_{\mathrm{LO}} \sim 25\mathrm{fb}$$

EDM and Collider Analysis

- **Lepton Collider: CEPC@240, 5 ab^{-1}: Direct Resonance Search**

★ Recoiled mass distribution:



- **Recoil mass distribution of channel:** $ZH,\ Z \to \mu^- \mu^+$
- **Fit with crystal ball function and polynomial function as CEPC report**
- **S-peak is fitted by re-scaling and shifting from the Higgs signal**

(stats: 2 GeV mass window; syst: $\epsilon_{\rm sys} = 1\%$ **)**

✳ arXiv: 1601.05352
✳ CEPC-SPPC Study Group IHEP-CEPC-DR-2015-01, IHEP-TH-2015-01, IHEP-EP-2015-01

EDM and Collider Analysis

- **Lepton Collider: CEPC@240, 5 ab^{-1}: Indirect Higgs Data**

★ ZH Inclusive total Cross section deviation:

$$\sigma(e^+e^- \to HZ) \text{ rescaled by a factor } |\mathcal{O}_{22}|^2\mathcal{Z}$$

✳ CEPC-SPPC Study Group IHEP-CEPC-DR-2015-01, IHEP-TH-2015-01, IHEP-EP-2015-01

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wave-function renormalization from $\boldsymbol{\kappa}$S^{2}H^2

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Loop induced SH-mixing

wave-function renormalization from $\kappa S^2 H^2$

✳ CEPC-SPPC Study Group IHEP-CEPC-DR-2015-01, IHEP-TH-2015-01, IHEP-EP-2015-01

EDM and Collider Analysis

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$\sigma(e^+e^- \to HZ)$ rescaled by a factor $|\mathcal{O}_{22}|^2 \mathcal{Z}$

Loop induced SH-mixing

wave-function renormalization from κS^2H^2

$$\mathcal{Z} = 1 + \frac{\kappa^2 v^2}{32\pi^2 m_H^2}\left(1 - \frac{4m_S^2}{m_H^2}\frac{1}{\sqrt{\frac{4m_S^2}{m_H^2} - 1}} \arctan\frac{1}{\sqrt{\frac{4m_S^2}{m_H^2} - 1}}\right)$$

✳ CEPC-SPPC Study Group IHEP-CEPC-DR-2015-01, IHEP-TH-2015-01, IHEP-EP-2015-01

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"Sensitive to $m_{S} \approx m_{H}$"

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EDM and Collider Analysis

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wave-function renormalization from κS²H²

"Sensitive to $m_S \approx m_H$"

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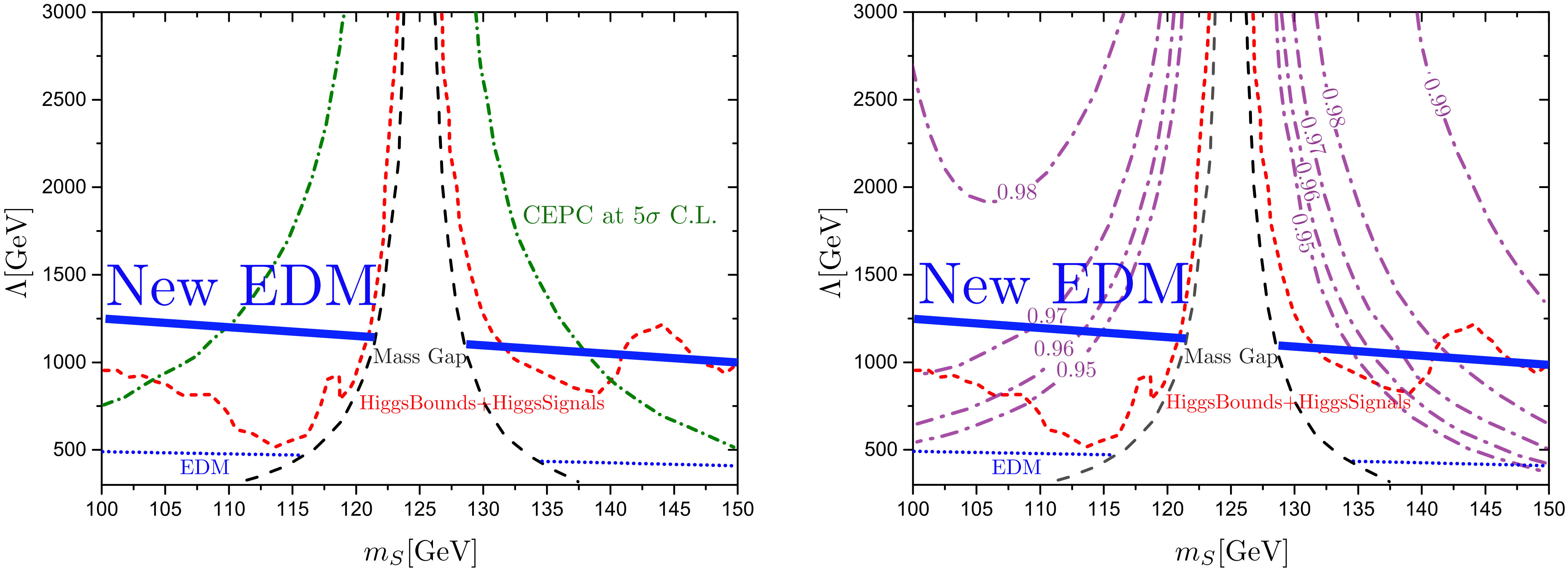
"Sensitive to light m_S"

✳ CEPC-SPPC Study Group IHEP-CEPC-DR-2015-01, IHEP-TH-2015-01, IHEP-EP-2015-01

Current bound and Future Reach



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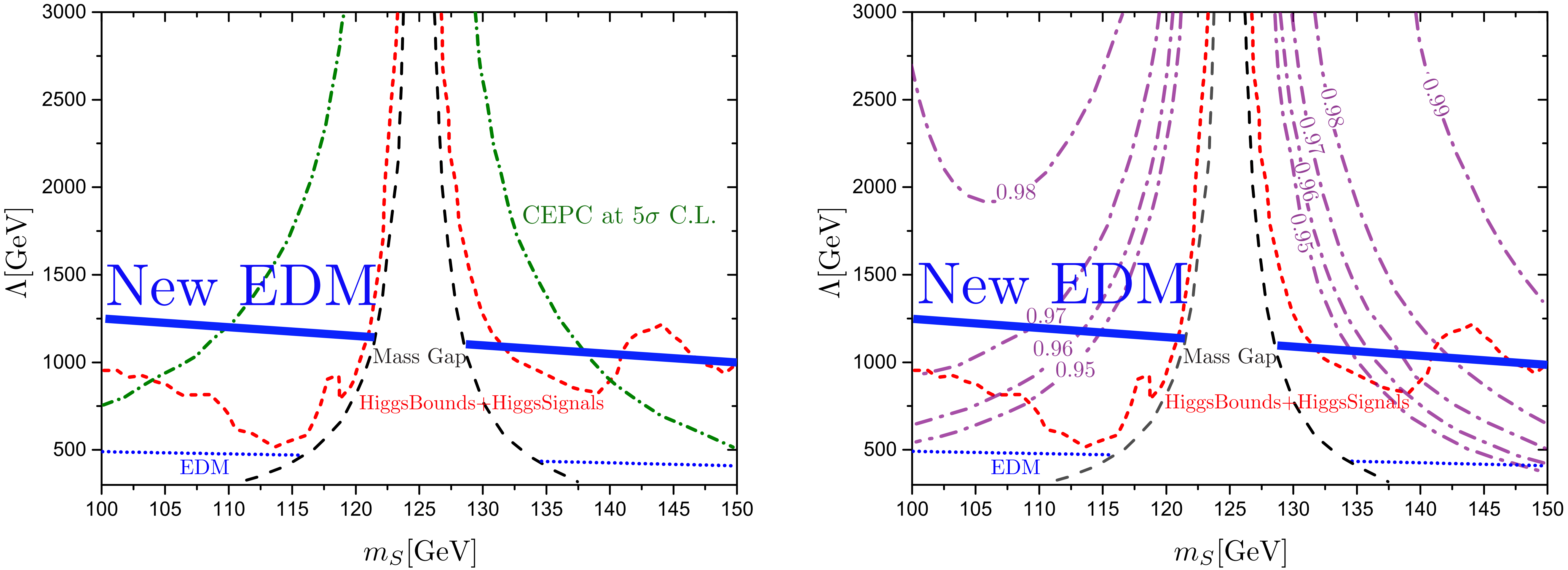
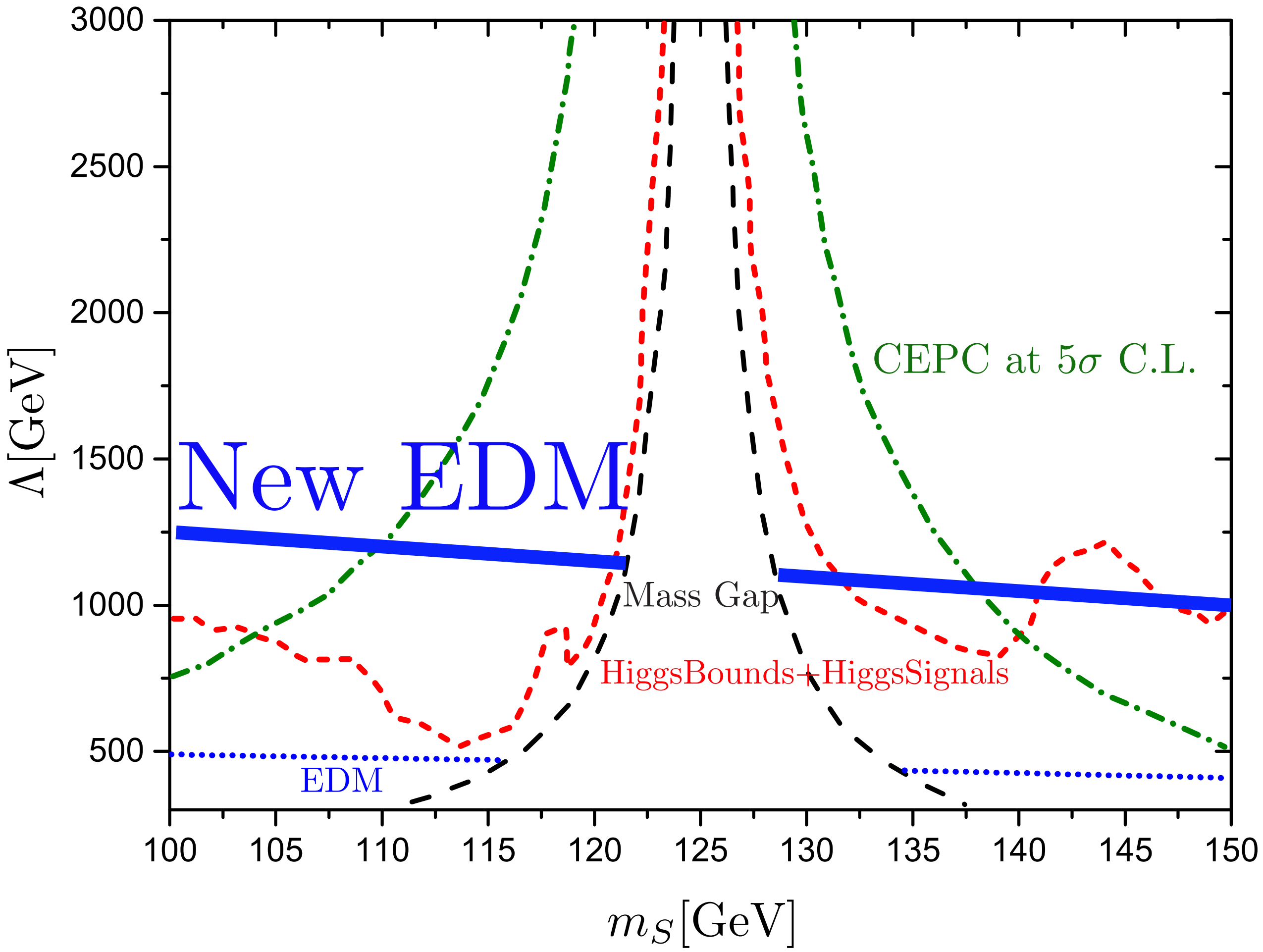
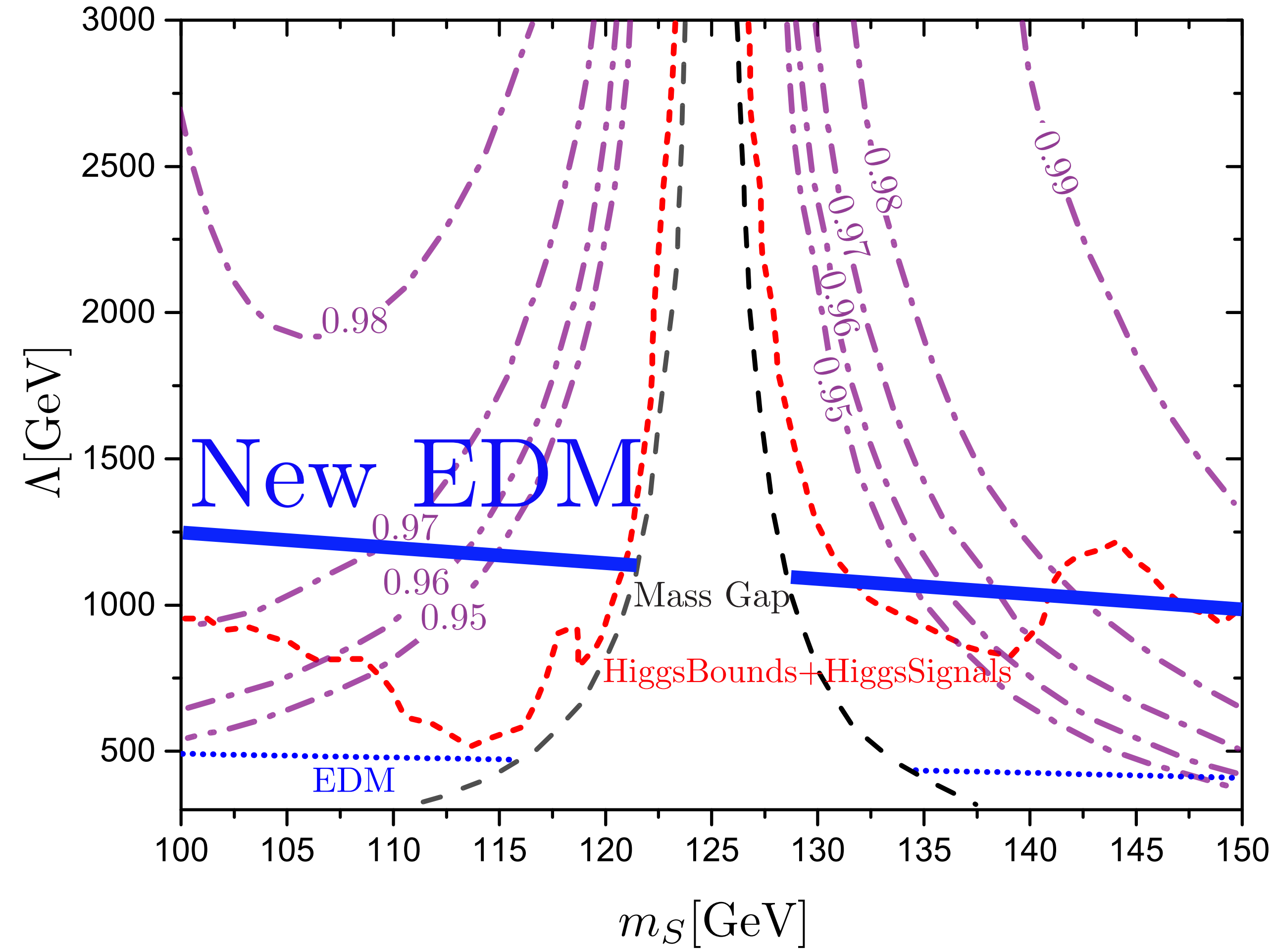


Constraints from Resonance search, Higgs signal data

Current bound and Future Reach

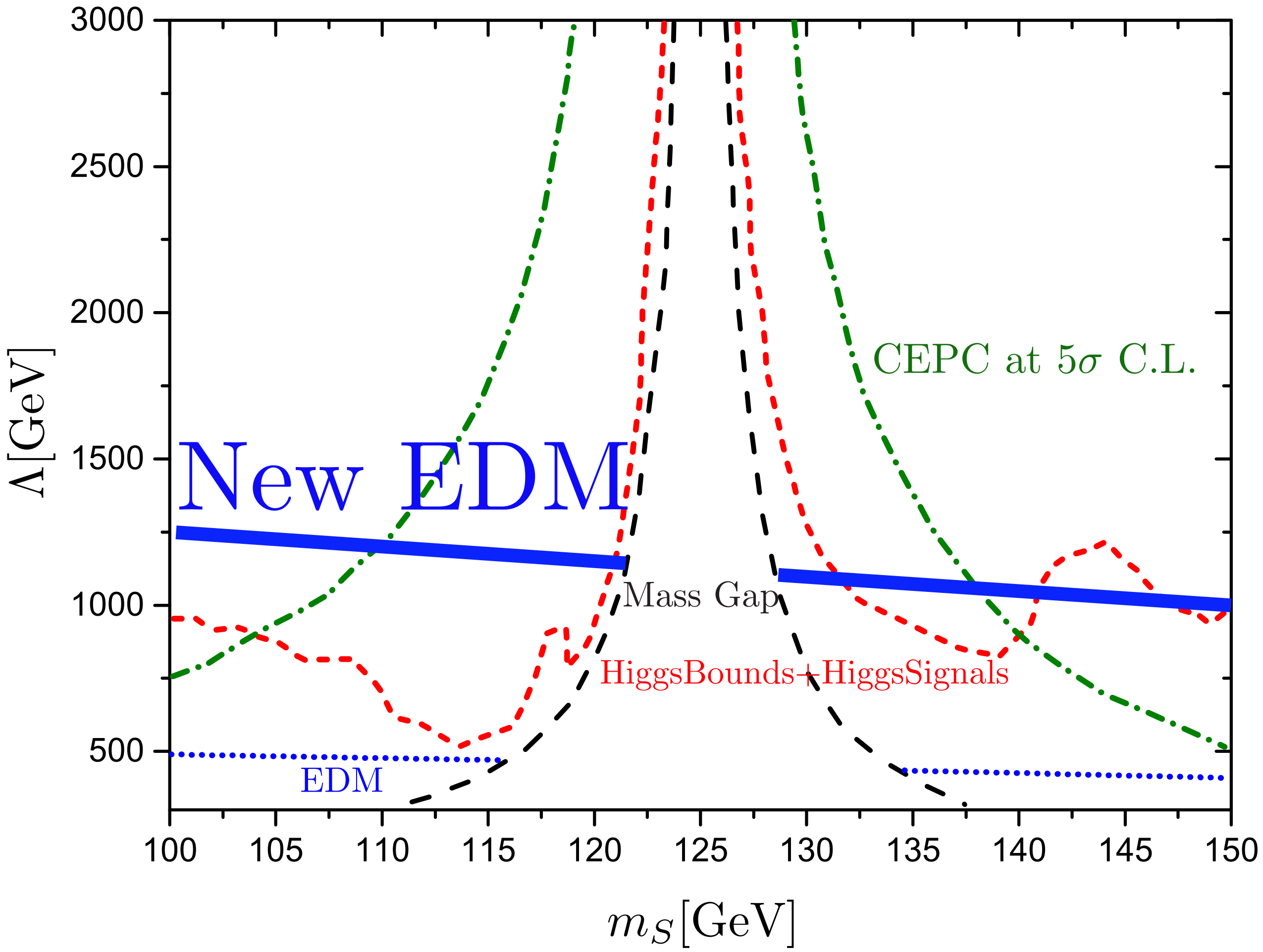


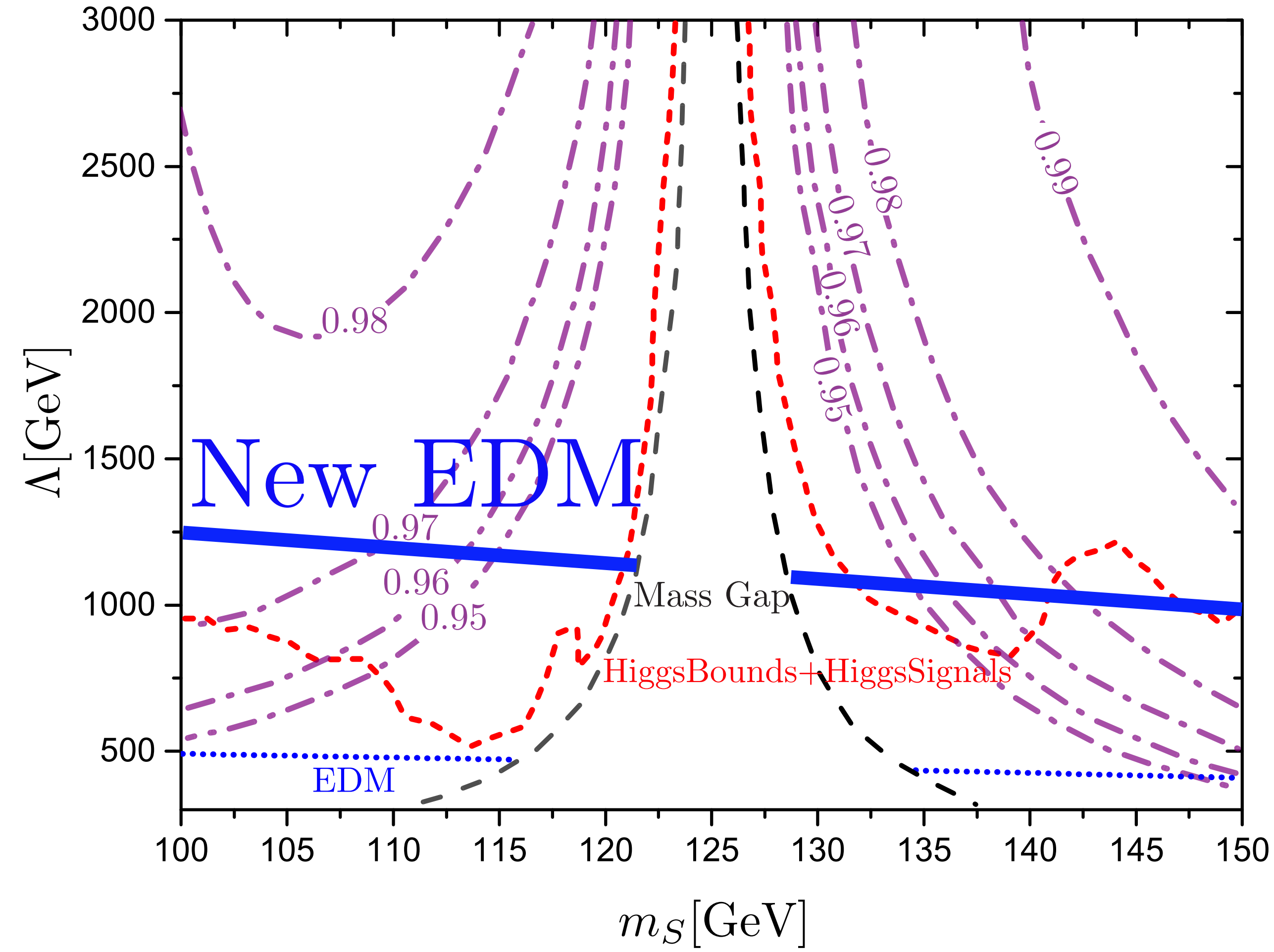


Constraints from Resonance search, Higgs signal data

- **Reach from CEPC indirect Zh inclusive measure**

Current bound and Future Reach

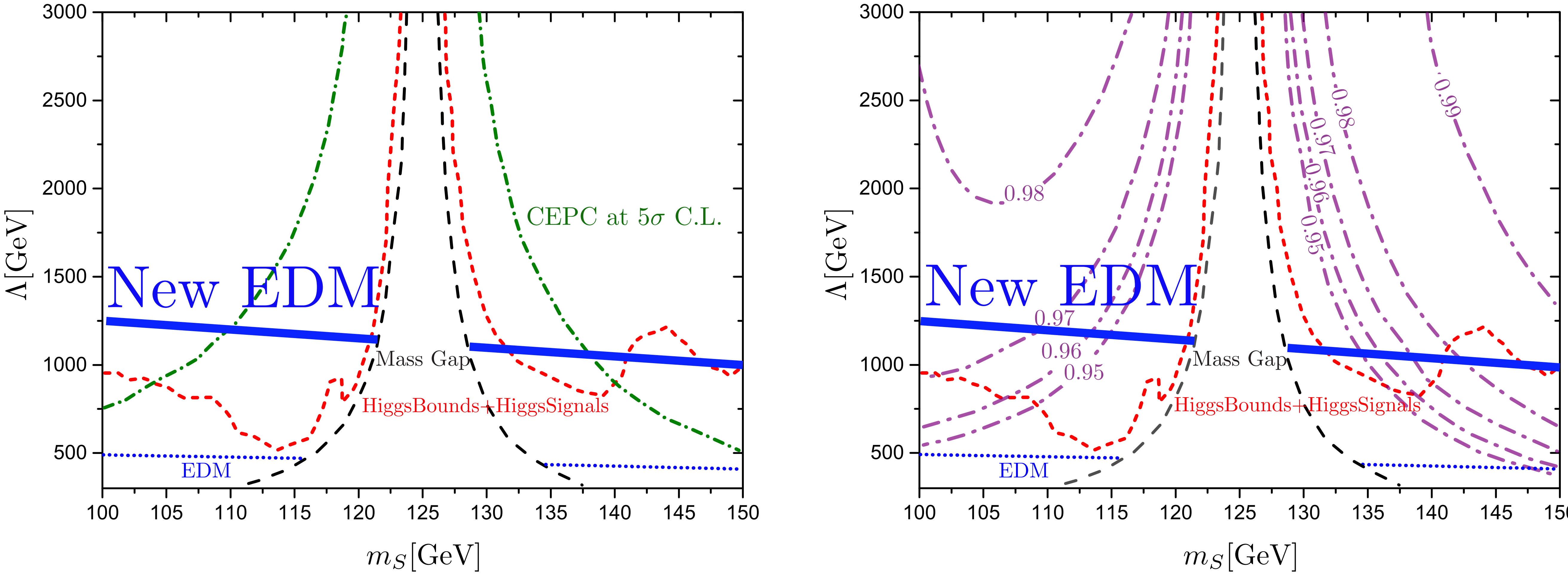




Constraints from Resonance search, Higgs signal data

- **Reach from CEPC direct search**
- **Reach from CEPC indirect Zh inclusive measure**

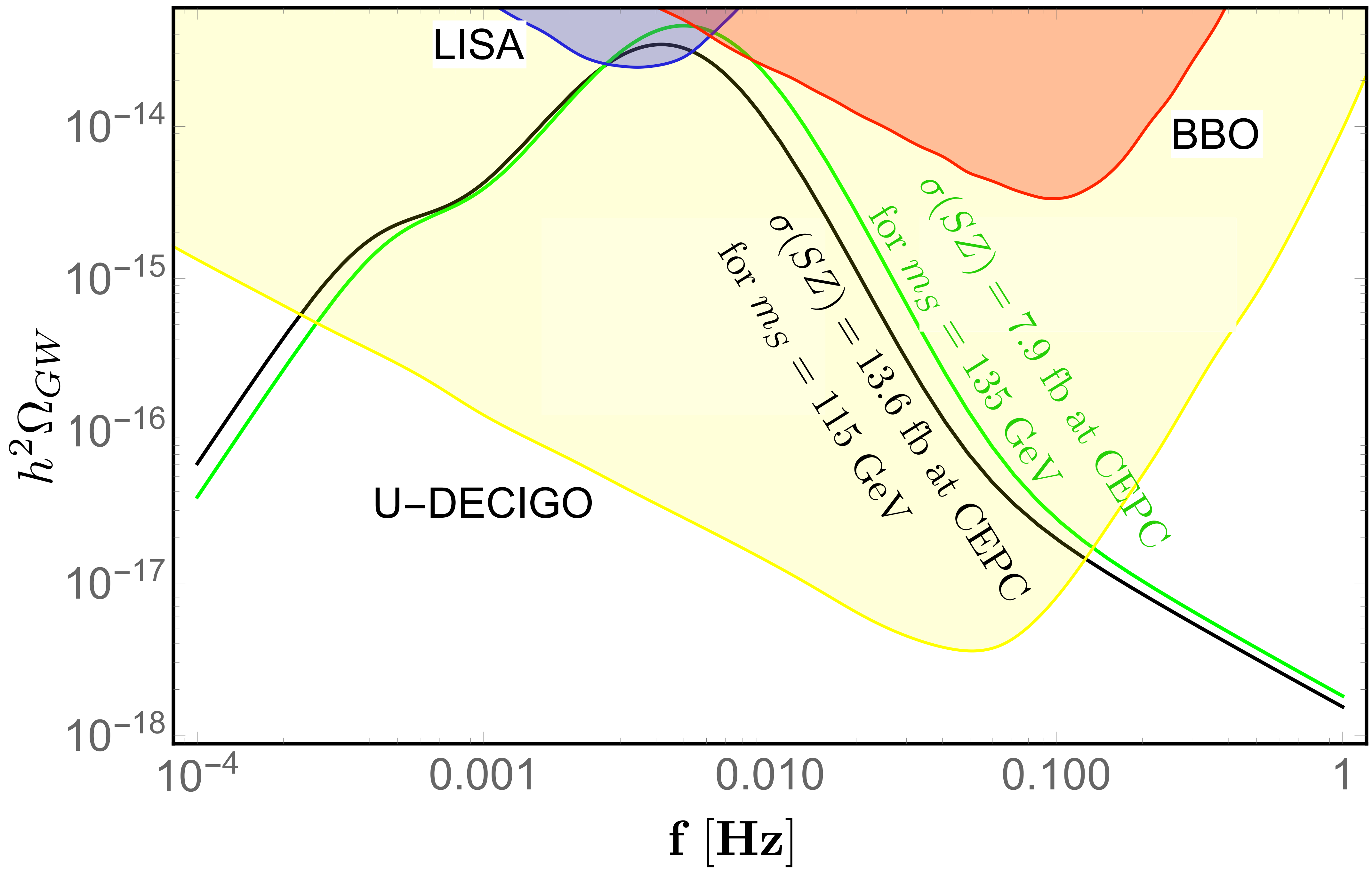
Current bound and Future Reach



Constraints from Resonance search, Higgs signal data

- Reach from CEPC direct search
- Reach from CEPC indirect Zh inclusive measure
- Constraints from updated EDM
(Comparable and Complementary to collider search)

Current bound and Future Reach



Conclusion

We evaluate the experimental observables including,

Current and future collider search, EDM and

gravitational wave signals

for a simple and viable EW-baryogenesis scenario, that is soon to be probed/ruled out by EDM result and future lepton collider.