# Searching for lepton portal dark matter with colliders and gravitational waves

Ke-Pan Xie (谢柯盼)
University of Nebraska-Lincoln

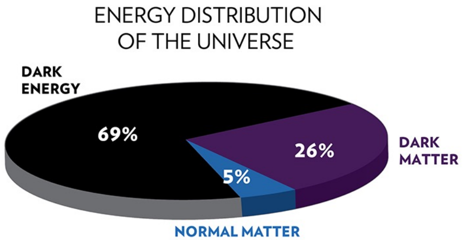
2021.11.9 @The 2021 CEPC Workshop (online)

In collaboration with Jia Liu and Xiao-Ping Wang

JHEP06(2021)149, arXiv: 2104.06421 [hep-ph]

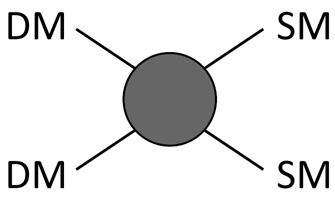
## • WIMPs as the particle explanation of dark matter

Dark matter contributes 26% of the total energy of the Universe;

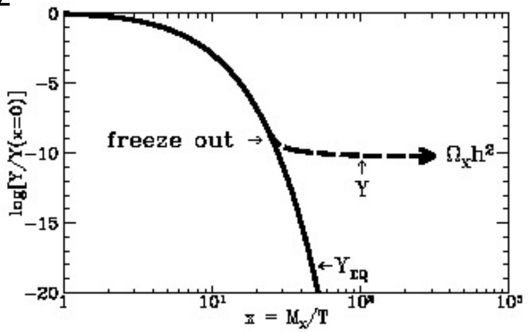



<u>Weakly interacting massive particles (WIMPs)</u>

[Lee & Weinberg, PRL1977]

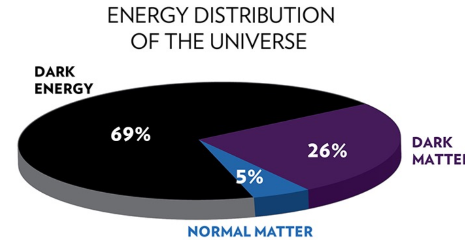



$$\Omega_{\rm DM}h^2 \sim 0.1\left(\frac{0.01}{\alpha_{\rm DM}}\right)^2\left(\frac{M_{\rm DM}}{100~{\rm GeV}}\right)^2$$

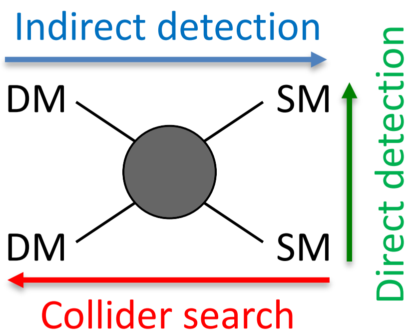


# • WIMPs as the particle explanation of dark matter

Dark matter contributes 26% of the total energy of the Universe;

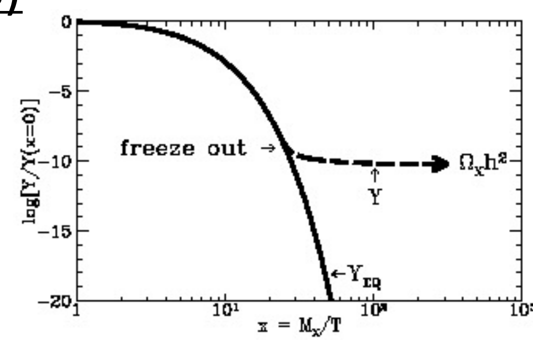


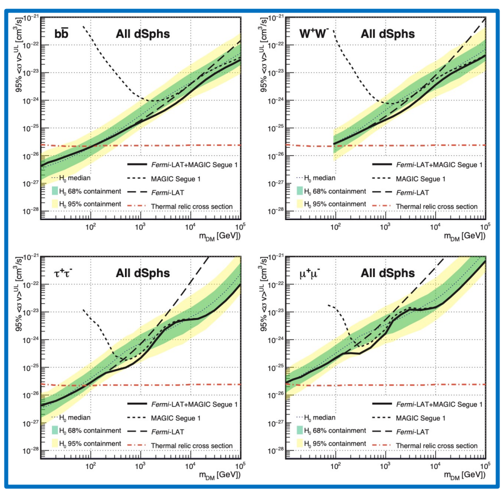

<u>Weakly interacting massive particles (WIMPs)</u>

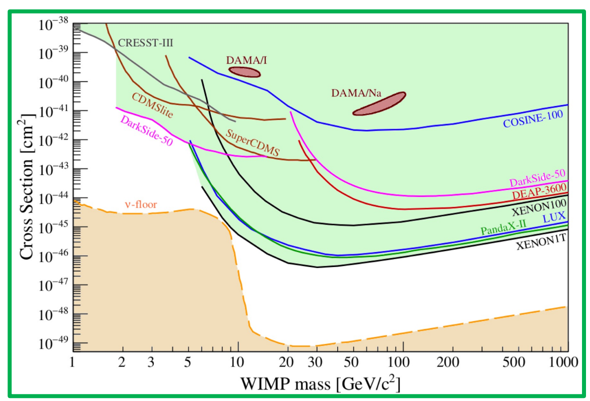


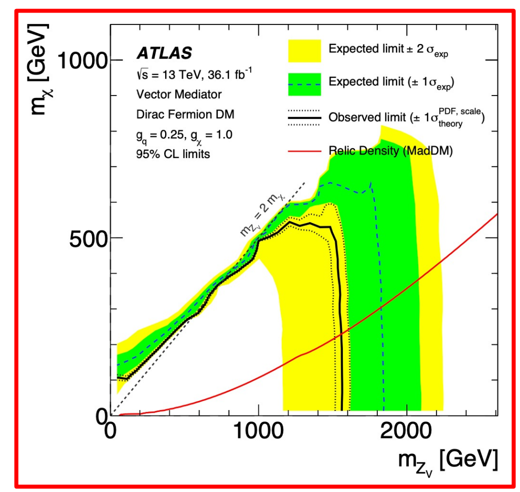

[Lee & Weinberg, PRL1977]

$$\Omega_{\rm DM}h^2 \sim 0.1\left(\frac{0.01}{\alpha_{\rm DM}}\right)^2\left(\frac{M_{\rm DM}}{100~{\rm GeV}}\right)^2$$



# • The lepton portal dark matter

## The Lagrangian [Y. Bai and J. Berger, 1402.6696]

**Mediator**, singlet scalar with hypercharge −1

SM leptons ($e$ $\mu$ $\tau$)

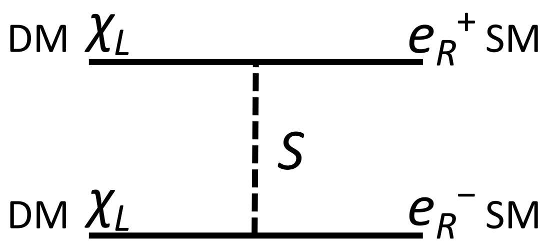
$$\mathcal{L}_\chi = \frac{1}{2}\bar{\chi} i\gamma^\mu \partial_\mu \chi - \frac{1}{2} m_\chi \bar{\chi}\chi + y_\ell \left( \bar{\chi}_L S^\dagger \ell_R + \text{h.c.} \right),$$

**DM candidate**, Majorana fermion

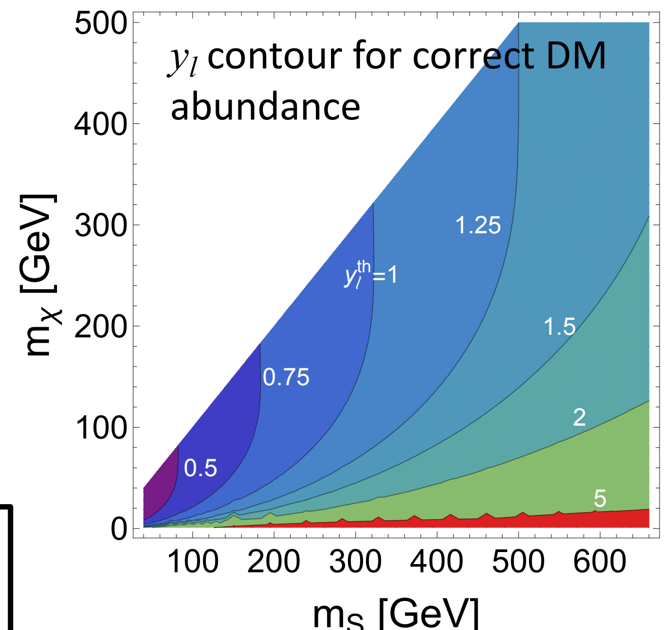
lepton portal coupling

## The freeze-out process:

- *t*-channel mediator exchange;
- *p*-wave dominant

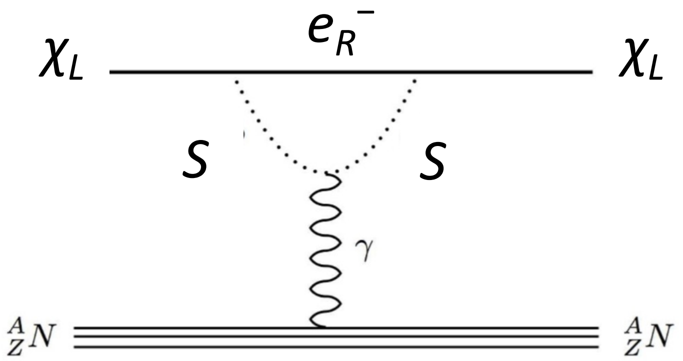



$$\sigma v_{\text{rel}} \approx v_{\text{rel}}^2 \frac{y_\ell^4}{48\pi m_S^2} \frac{x(1+x^2)}{(1+x)^4}, \quad x \equiv \frac{m_\chi^2}{m_S^2}.$$



- # Direct & indirect & collider searches

## Direct detection:

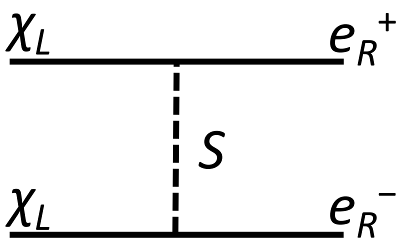



One-loop induced operator [Y. Bai and J. Berger, 1402.6696]

$$\mathcal{O} = \left(\bar{\chi}\gamma^\mu\gamma^5\partial^\nu\chi + \mathrm{h.c.}\right) F_{\mu\nu},$$

- Due to the Majorana feature;
- $p$-wave suppressed, $\sigma_{\rm SI} \approx 10^{-49}$ cm$^2$, hopeless to detect.

## Indirect detection:




Also $p$-wave suppressed and hence negligible.

## We therefore focus on the collider searches.

- In addition to the lepton portal coupling, a more complete scalar sector is considered;
- Gravitational waves signals could be complementary to the collider searches.

# The collider searches

## The Lagrangian: lepton portal + scalar sector

$$\mathcal{L}_\chi = \frac{1}{2}\bar{\chi}i\gamma^\mu\partial_\mu\chi - \frac{1}{2}m_\chi\bar{\chi}\chi + y_\ell\left(\bar{\chi}_L S^\dagger \ell_R + \text{h.c.}\right),$$

$$\mathcal{L}_S = \left(D^\mu S\right)^\dagger D_\mu S - V(H,S),$$

$$V(H,S) = \mu_H^2|H|^2 + \mu_S^2|S|^2 + \lambda_H|H|^4 + \lambda_S|S|^4 + 2\lambda_{HS}|H|^2|S|^2,$$

- Target: probe the lepton portal coupling and scalar portal coupling

## Main collider signals:

- Pair production of the charged mediators *$S^+S^-$*, and the corresponding di-lepton signals;

LHC
$$q\bar{q} \to Z^*/\gamma^* \to S^+S^- \to \ell^+\chi\ell^-\chi$$
$$gg \to h^* \to S^+S^- \to \ell^+\chi\ell^-\chi$$

$$e^+e^- \to Z^*/\gamma^* \to S^\pm S^{\mp(*)} \to \ell^+\chi\ell^-\chi$$
CEPC

- Higgs/*Z* coupling deviation/exotic decay.

$$h/Z \to S^{\pm(*)}S^{\mp(*)} \to \ell^+\chi\ell'^-\chi$$ LHC

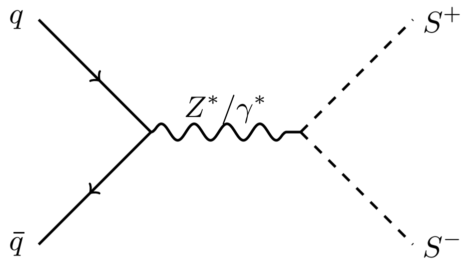
$$h \to \chi\chi,\ h \to \ell^+\ell^-$$ CEPC

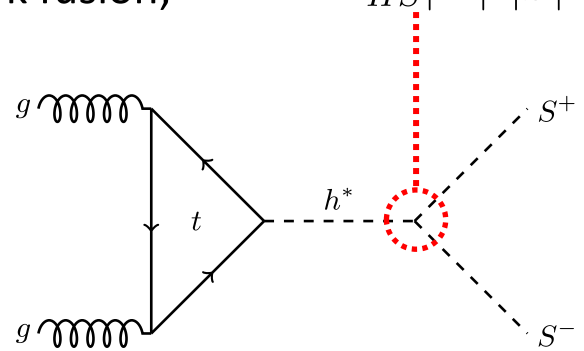
# • LHC signals: $S^+S^-$

## Production channels

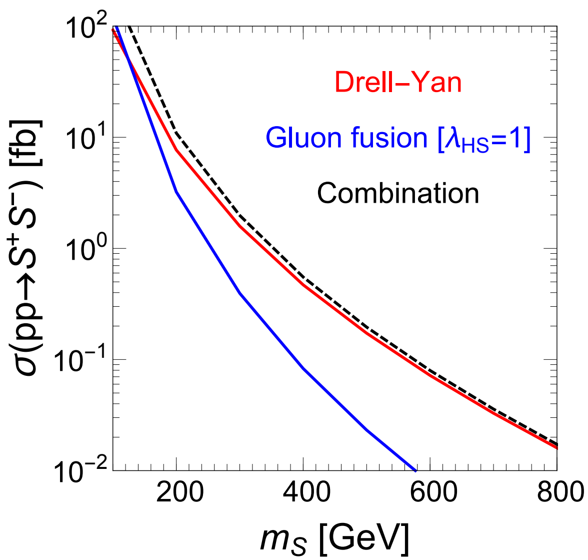
- Drell-Yan production by quark-antiquark fusion;
- Gluon fusion to off-shell Higgs to $S^+S^-$.

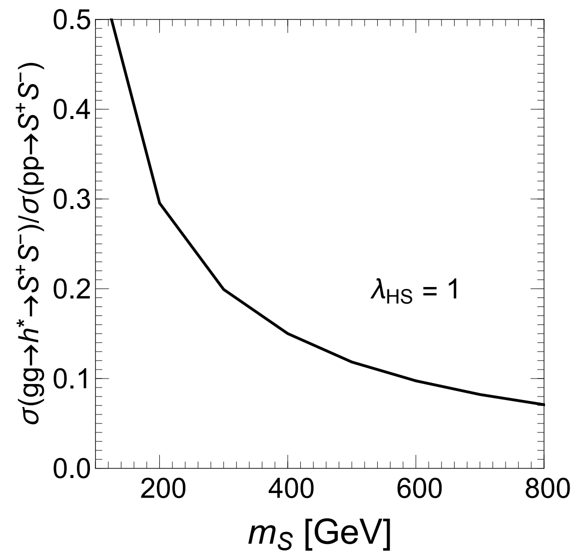
$2\lambda_{HS}|H|^2|S|^2,$




- The gluon fusion can be important for the low $m_S$ region.



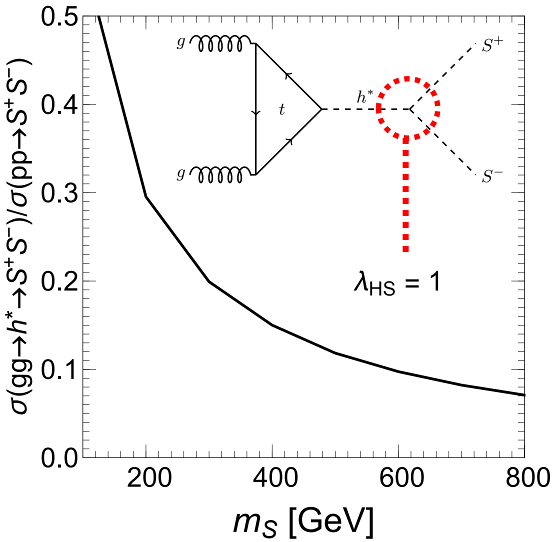
# • LHC signals: $S^+S^-$

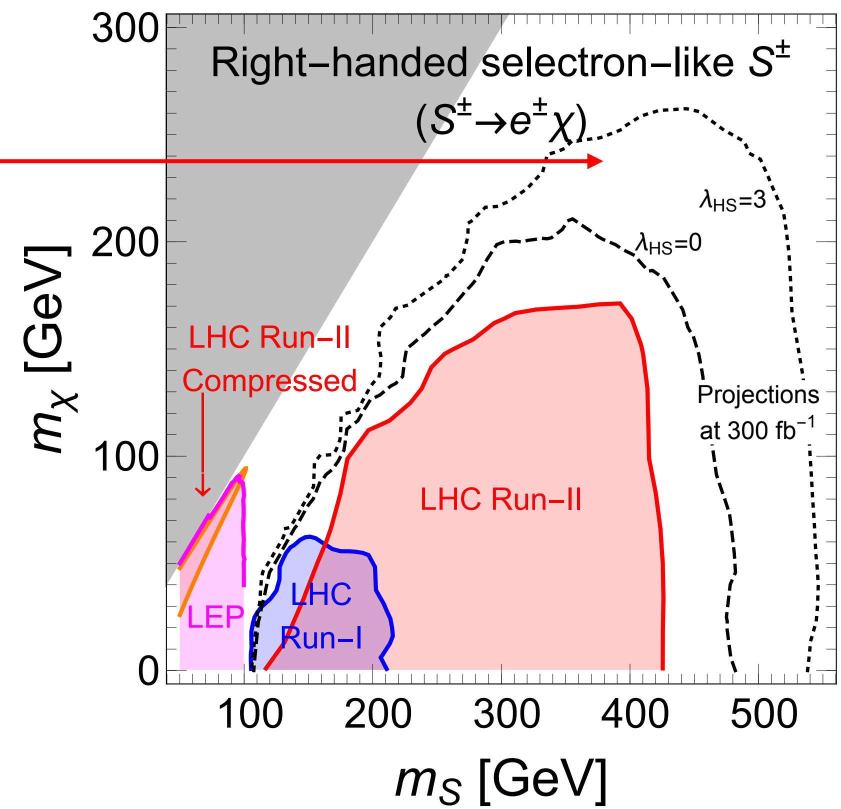
## Phenomenology

*S* decays exclusively to lepton + DM: di-lepton + MET signal; Cuts:

1. Two opposite charged leptons with $p_T > 25$ GeV and $|\eta| < 2.47$;
2. At most one light-flavor jet with $p_T > 20$ GeV and $|\eta| < 2.4$;
3. M(di-lepton) > 100 GeV, MET > 110 GeV;
4. $M_{T2} > 100$ or 160 GeV.

**Enhanced reach** due to $gg \to h^* \to S^+S^-$



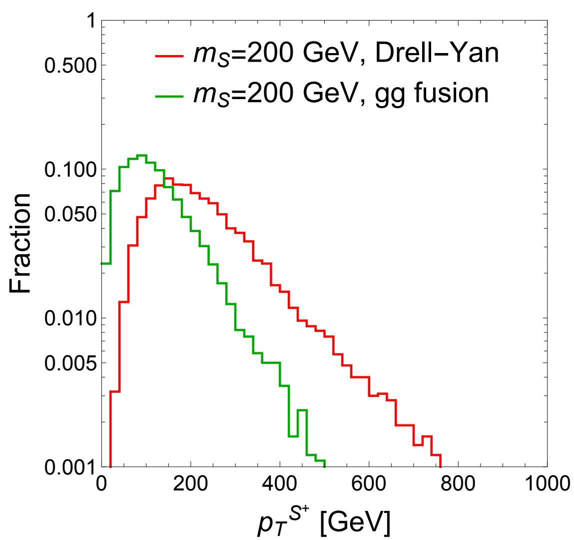
# • LHC signals: $S^+S^-$

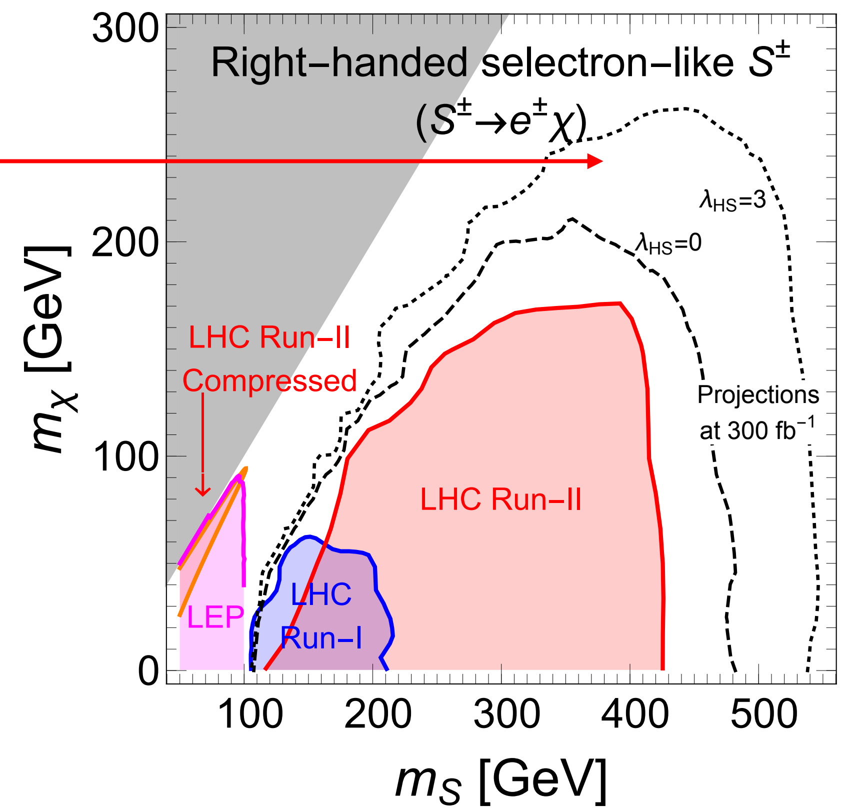
## Phenomenology

*S* decays exclusively to lepton + DM: di-lepton + MET signal; Cuts:

1. Two opposite charged leptons with $p_T > 25$ GeV and $|\eta| < 2.47$;
2. At most one light-flavor jet with $p_T > 20$ GeV and $|\eta| < 2.4$;
3. M(di-lepton) > 100 GeV, MET > 110 GeV;
4. $M_{T2} > 100$ or 160 GeV.

**Enhanced reach** due to $gg \to h^* \to S^+S^-$



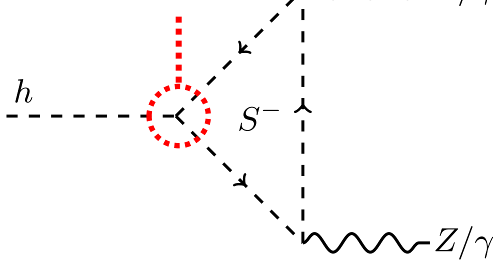



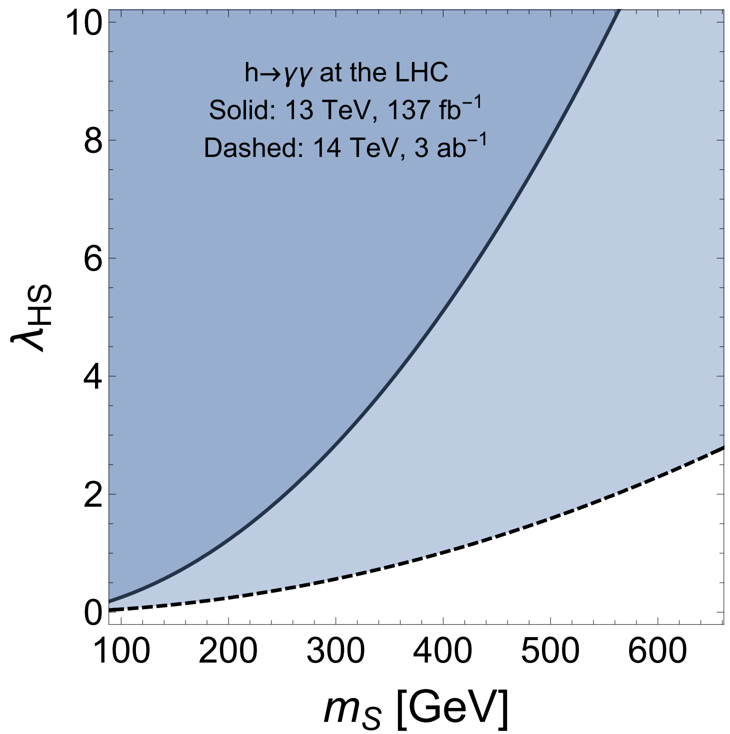
# • LHC signals: Higgs coupling deviation

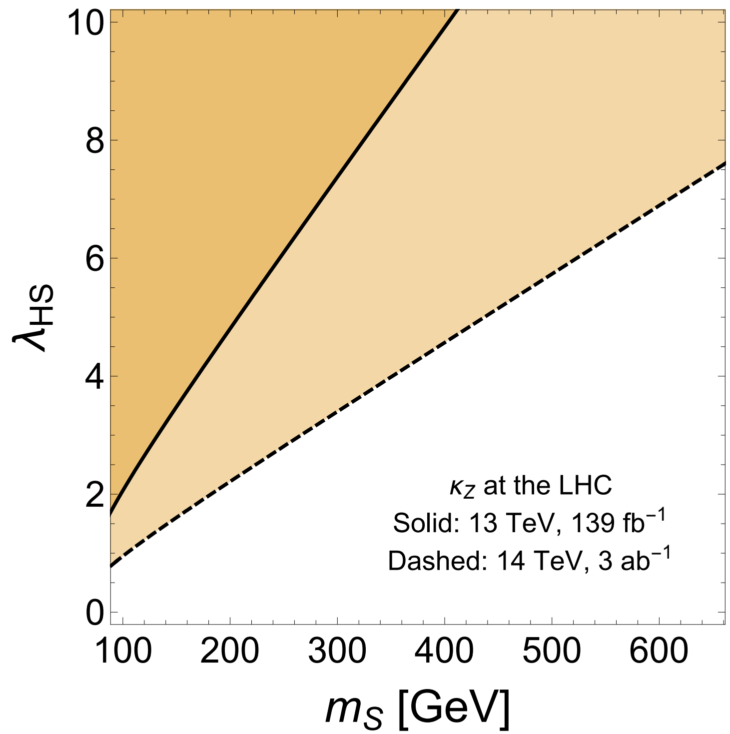
## Phenomenology

- The constraints on scalar portal coupling $\lambda_{HS}$ at the LHC;
- Derived based on the ATLAS results [2103.06956, 2004.03447]

$$2\lambda_{HS}|H|^2|S|^2,$$



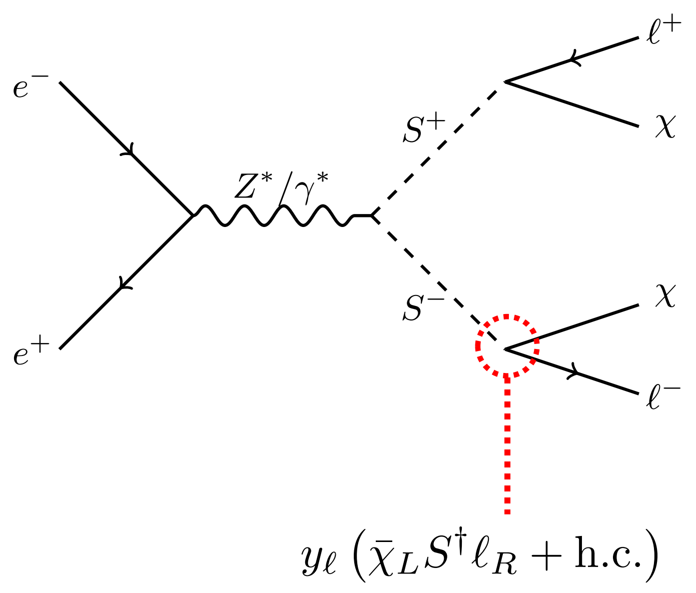



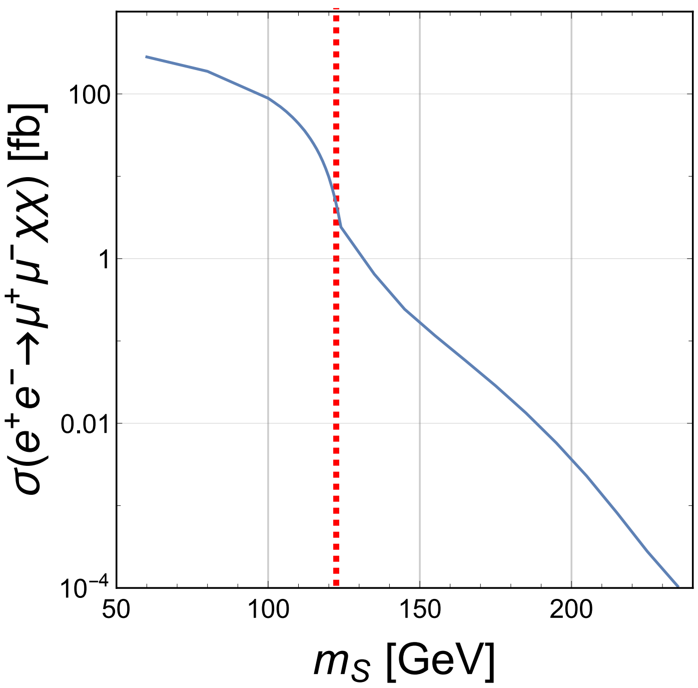



# • CEPC signals: $S^+S^-$

## Production channels

- Drell-Yan production by $e^+e^-$ fusion;
- For $m_S < 125$ GeV, $S^+S^-$ are produced on-shell, and decay exclusively into lepton + DM;
- For 125 GeV < $m_S$ < 250 GeV, one $S$ can be off-shell, leading to the direct probe for lepton-portal coupling $y_l$.



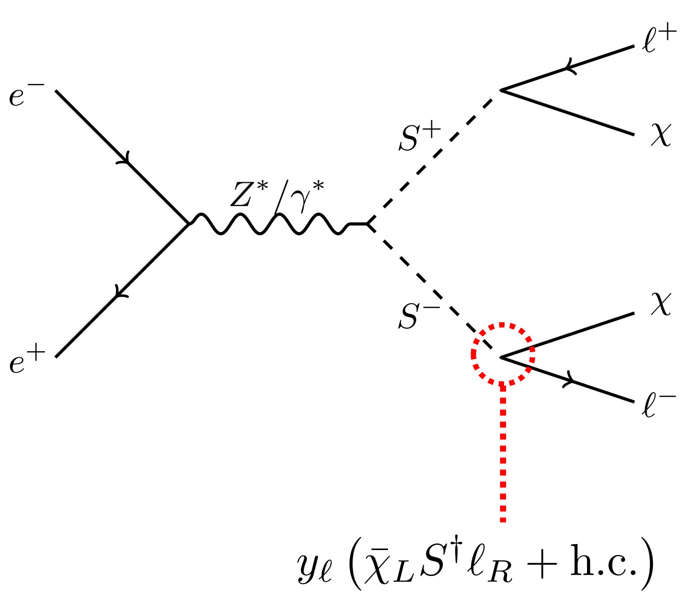



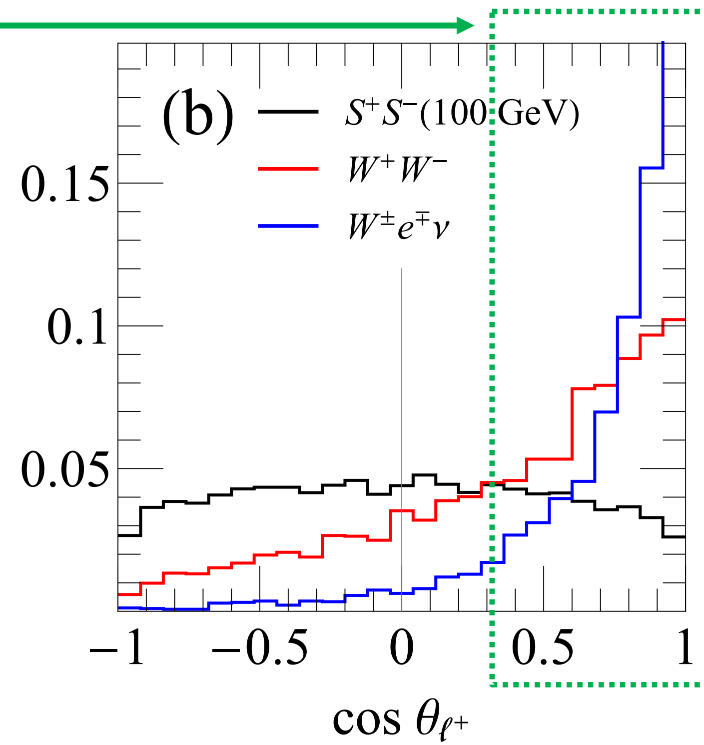
- # CEPC signals: $S^+S^-$

## Phenomenology

Signals: di-lepton + MET; Selection cuts: [Cao, Li, **KPX**, Zhang, 1810.07659 (PRD)]

1. Two charged leptons $p_T > 5$ GeV and $|\eta| < 3$;
2. Veto jets within the above region;
3. MET > 5 GeV;
4. $M_{T2} > 20$ GeV;
5. $\cos\vartheta(l^+) < 0.3$ and $\cos\vartheta(l^-) > -0.3$.



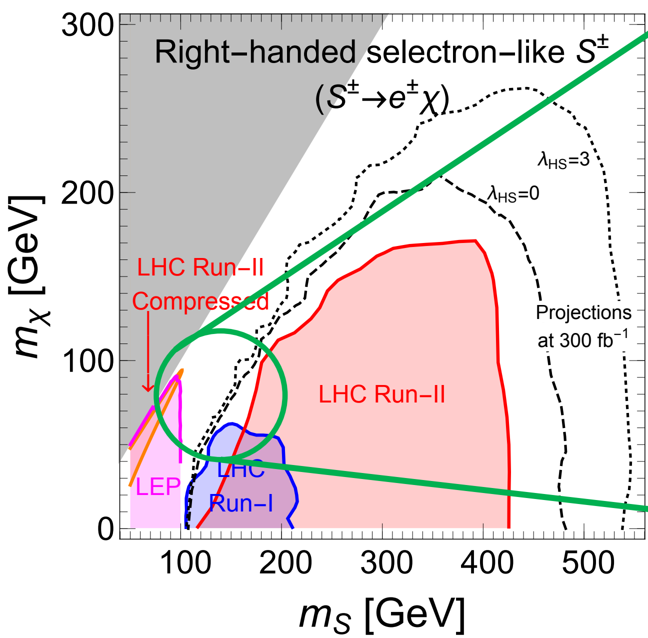



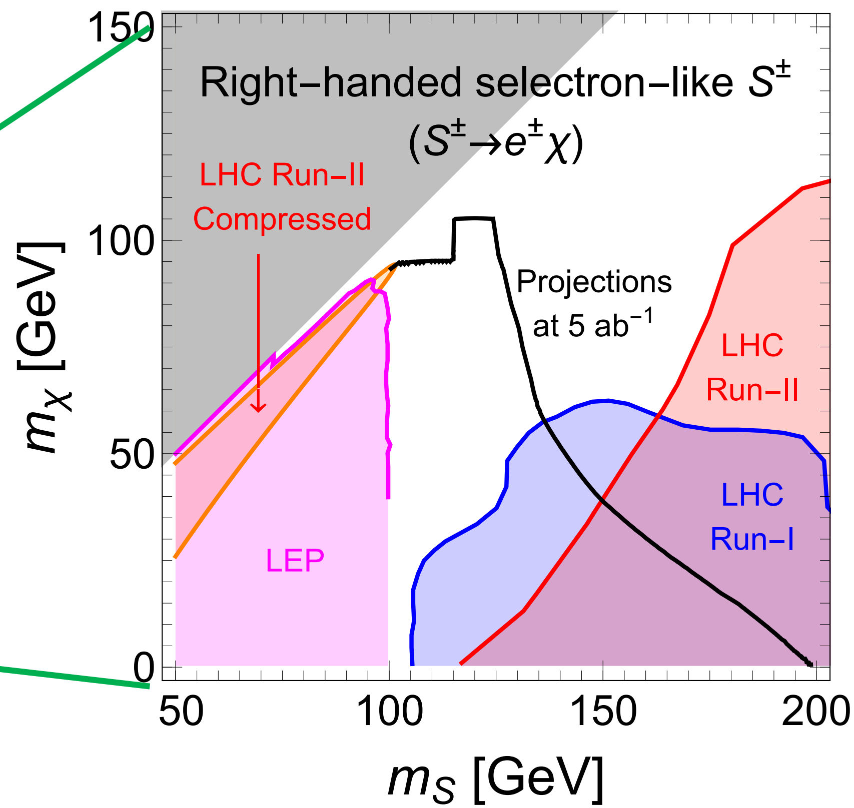
# • CEPC signals: $S^+S^-$

## Phenomenology

Signals: di-lepton + MET; Selection cuts: [Cao, Li, **KPX**, Zhang, 1810.07659 (PRD)]

1. Two charged leptons $p_T$ > 5 GeV and $|\eta|$ < 3;
2. Veto jets within the above region;
3. MET > 5 GeV;
4. $M_{T2}$ > 20 GeV;
5. $\cos\vartheta(l^+) < 0.3$ and $\cos\vartheta(l^-) > -0.3$.



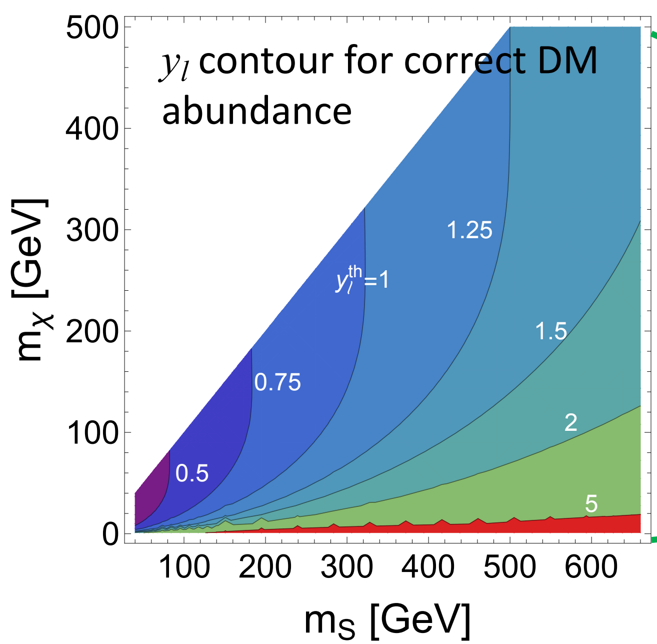



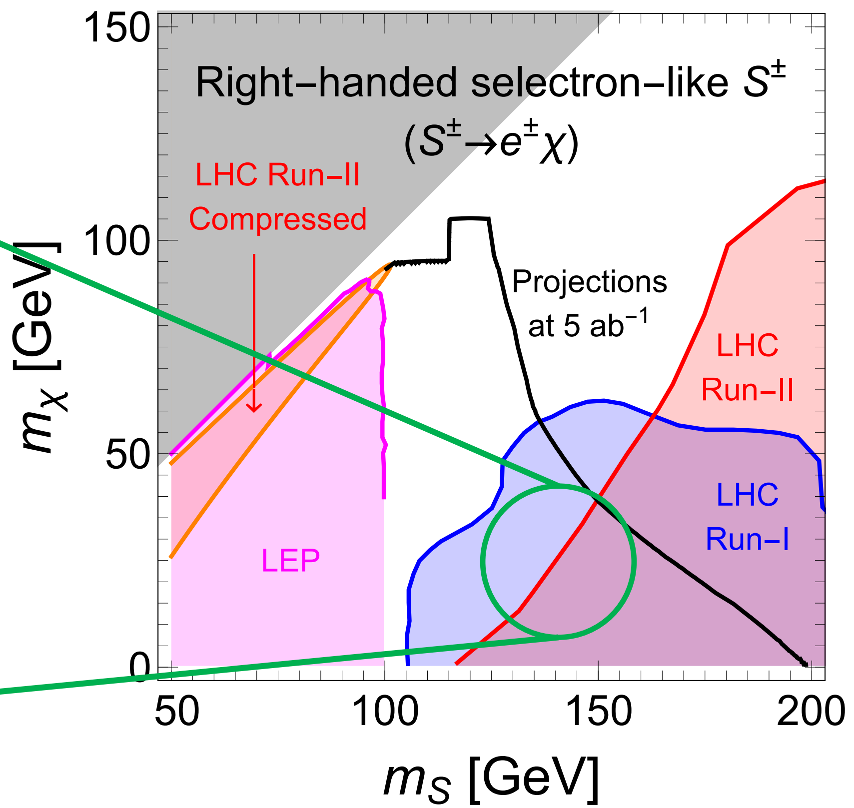
- # CEPC signals: $S^+S^-$

## Phenomenology

Signals: di-lepton + MET; Selection cuts: [Cao, Li, **KPX**, Zhang, 1810.07659 (PRD)]

1. Two charged leptons $p_T > 5$ GeV and $|\eta| < 3$;
2. Veto jets within the above region;
3. MET > 5 GeV;
4. $M_{T2} > 20$ GeV;
5. $\cos\vartheta(l^+) < 0.3$ and $\cos\vartheta(l^-) > -0.3$.

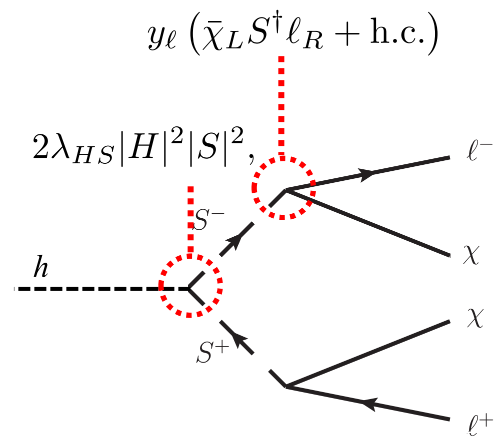


# CEPC signals: exotic decays (I)

## Higgs exotic decays to di-lepton + MET

- For Higgs: $m_S < 62.5$ GeV is already excluded; thus we consider 3-body ($S l \chi$) or 4-body ($l^+ \chi l^- \chi$);
- Probe the combination $y_l \lambda_{HS}$ or $y_l^2 \lambda_{HS}$.

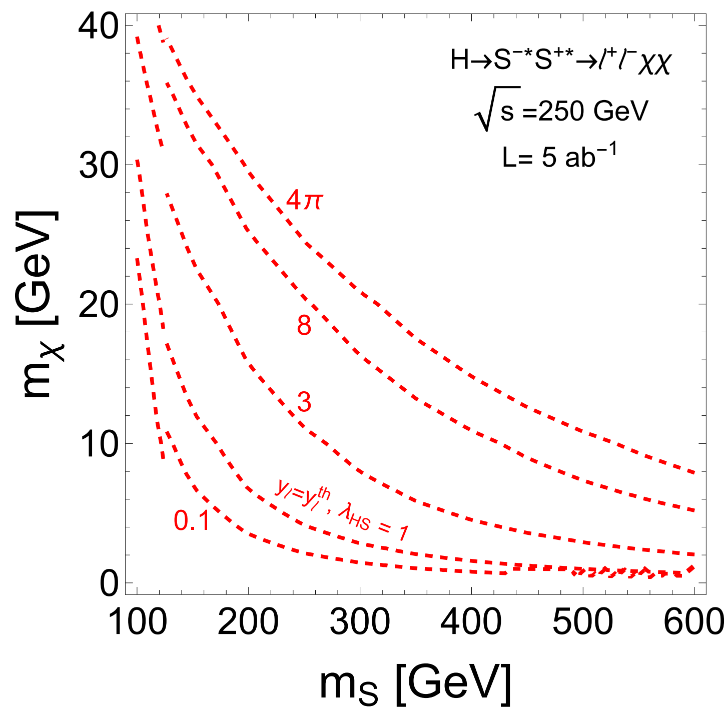



## Phenomenology

Use the $Zh$ associated production with $Z$ decaying leptonically:

1. Four charged leptons $p_T > 10$ GeV and $|\eta| < 2.47$;
2. Two opposite charged leptons within the $Z$ pole $\pm$ 5 GeV;
3. MET > 20 GeV;
4. The reconstructed Higgs mass within the [120, 130] GeV;

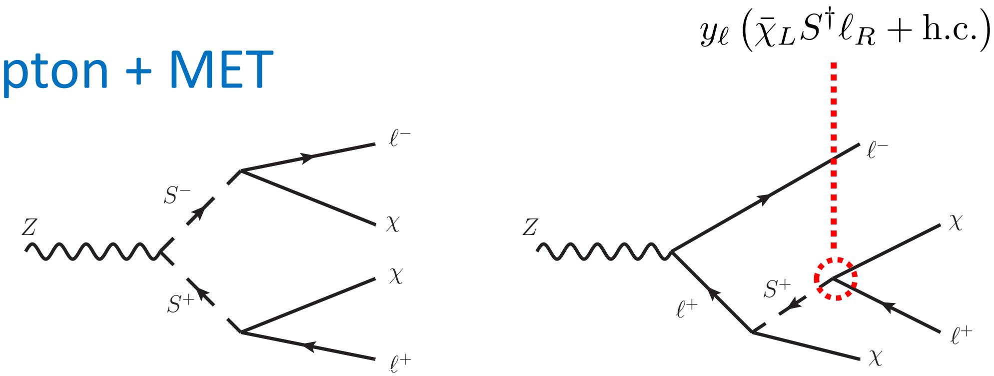
Main backgrounds: SM $W^+W^-Z$, $Z\tau^+\tau^-$.



# • CEPC signals: exotic decays (II)

## *Z* exotic decays to di-lepton + MET

- 4-body decay ($l^+\chi l^-\chi$)
- Probe the lepton portal coupling $y_l$.

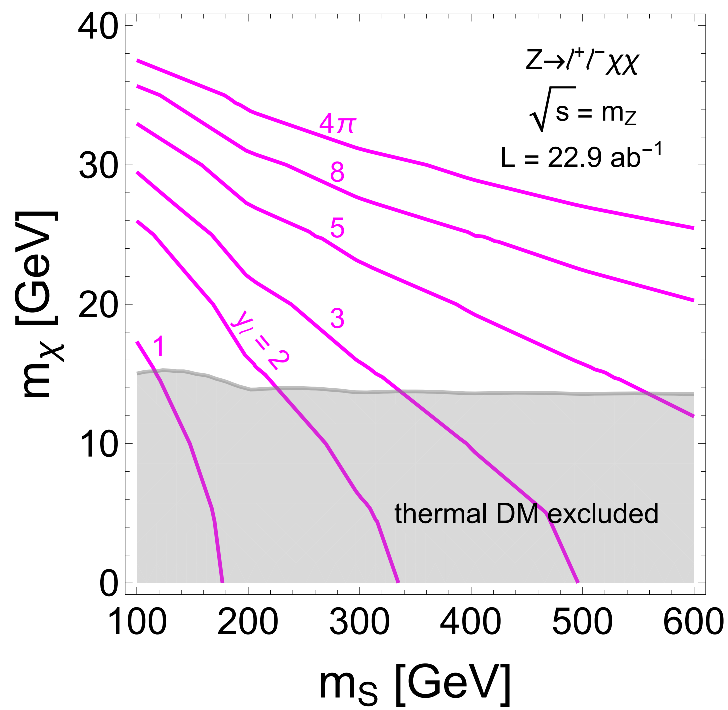



## CEPC projections

For the *Z*-pole run

1. Two opposite-sign leptons $p_T$ > 10 GeV and $|\eta|$ < 2.5;
2. MET > 10 GeV;

Main backgrounds: SM di-boson.

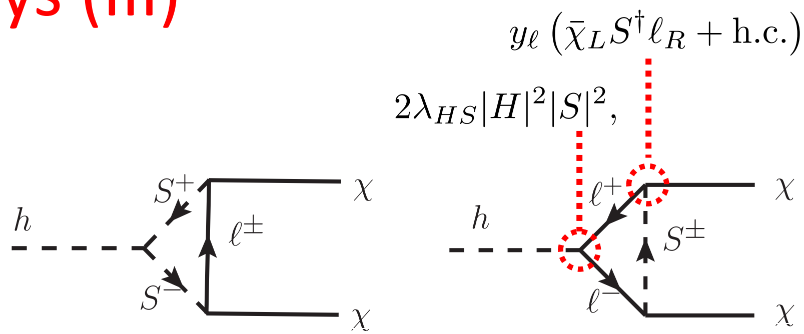



* "thermal DM excluded": the DM overproduced region.

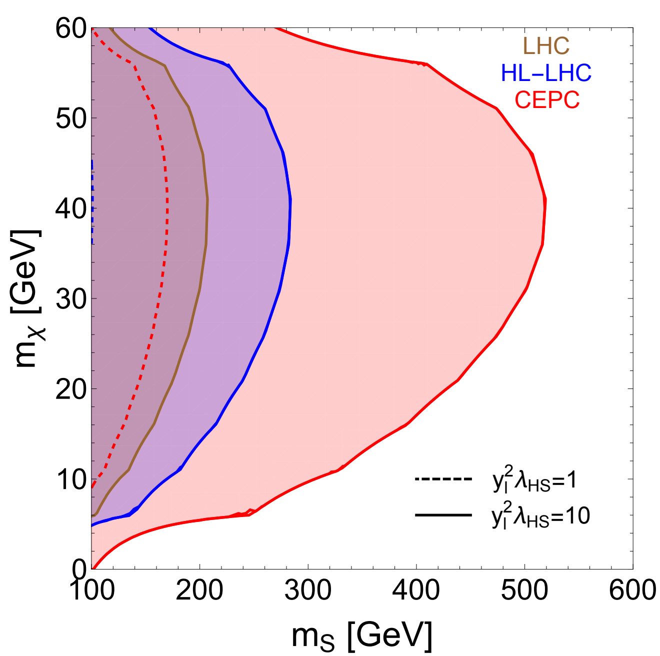
# • CEPC signals: exotic decays (III)

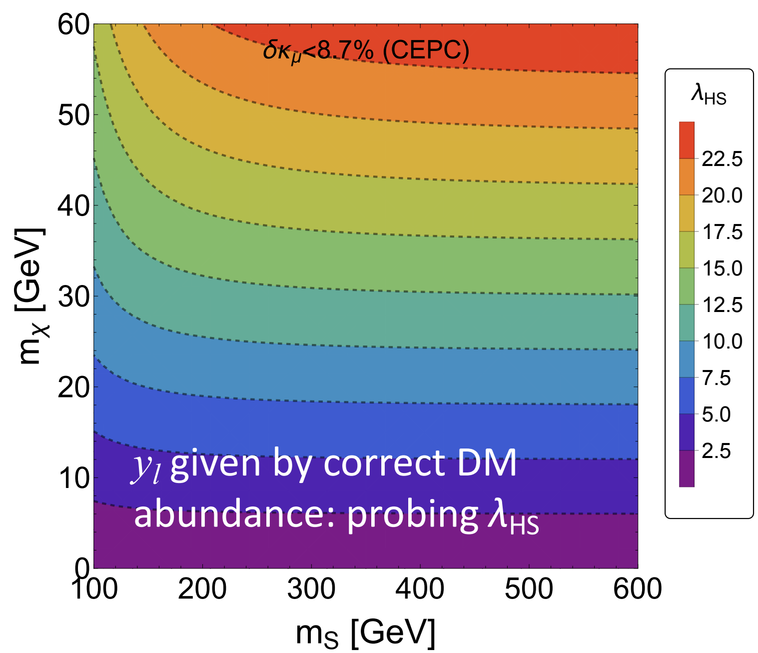
## Higgs invisible decays

- Current ATLAS bound: Br < 13%;
- HL-LHC projection: Br < 3.5%;
- CEPC projection: Br < 0.3%.
- Probe the combination $y_l^2\lambda_{HS}$ (lepton portal and scalar portal)

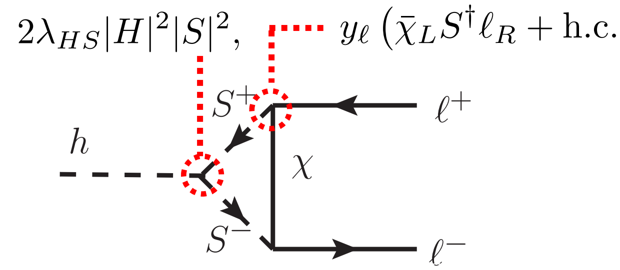



## Projections



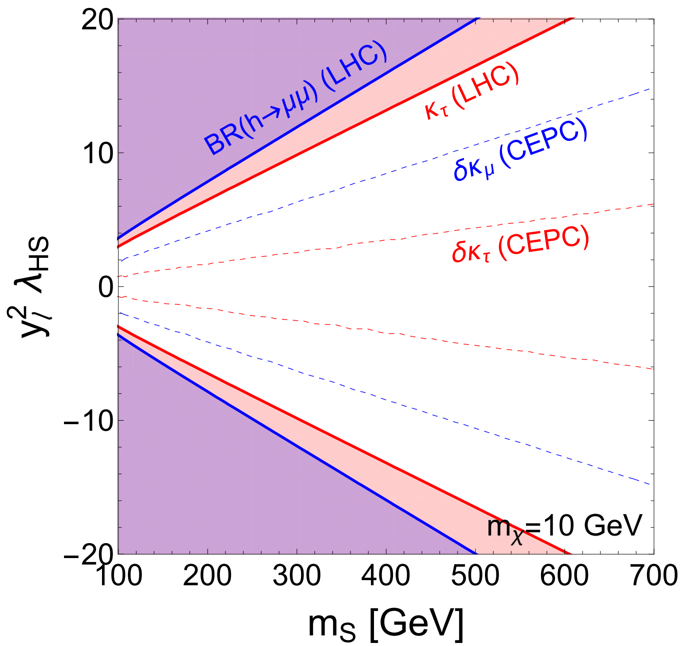
- # CEPC signals: Higgs coupling deviation

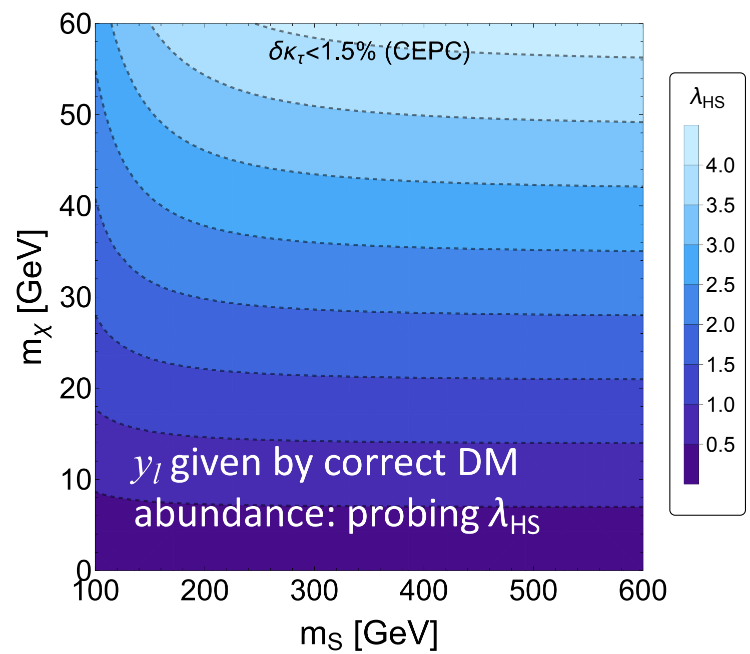



## Higgs to di-lepton

- CEPC projections: $\delta\kappa_\mu$< 8.7%, and $\delta\kappa_\tau$ < 1.5%
- Probe the combination $y_l^2\lambda_{HS}$ (lepton portal and scalar portal)

## Projections



# A summary for the collider phenomenology

## The model

$$\mathcal{L}_\chi = \frac{1}{2}\bar{\chi}i\gamma^\mu\partial_\mu\chi - \frac{1}{2}m_\chi\bar{\chi}\chi + y_\ell\left(\bar{\chi}_L S^\dagger \ell_R + \text{h.c.}\right),$$

$$\mathcal{L}_S = \left(D^\mu S\right)^\dagger D_\mu S - V(H,S),$$

$$V(H,S) = \mu_H^2|H|^2 + \mu_S^2|S|^2 + \lambda_H|H|^4 + \lambda_S|S|^4 + 2\lambda_{HS}|H|^2|S|^2,$$

- The relevant parameters: mass $m_S$ and $m_\chi$, the lepton portal coupling $y_l$ and the scalar portal coupling $\lambda_{HS}$.

## Phenomenology at the LHC

- $S^+S^-$ : $\lambda_{HS}$ (for the gluon fusion);
- Higgs coupling to di-boson: $\lambda_{HS}$;

## Phenomenology at the CEPC

- $S^+S^-$ : $y_l$ (for the off-shell $S$);
- Higgs exotic decay to ($l^+\chi l^-\chi$): $y_l^2\lambda_{HS}$ (3-body) or $y_l^4\lambda_{HS}$ (4-body);
- $Z$ exotic decay to ($l^+\chi l^-\chi$): $y_l$;
- Higgs invisible decay to $\chi\chi$: $y_l^2\lambda_{HS}$;
- Higgs coupling to leptons: $y_l^2\lambda_{HS}$;

# • Gravitational waves probe

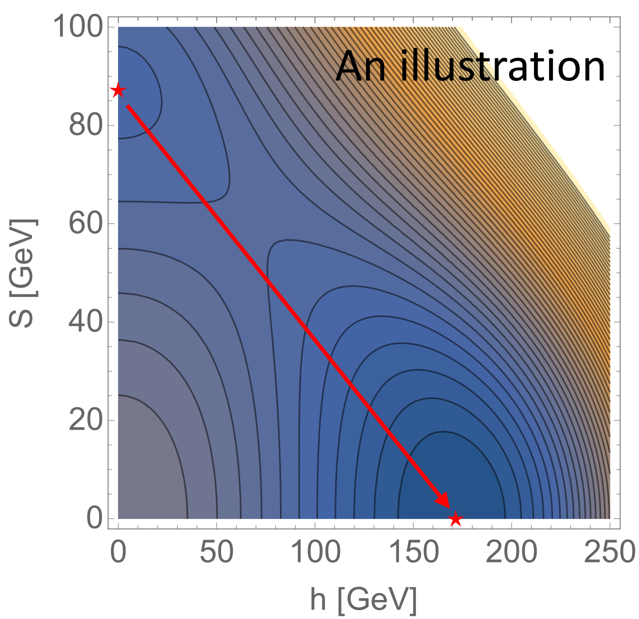
## A first-order electroweak phase transition

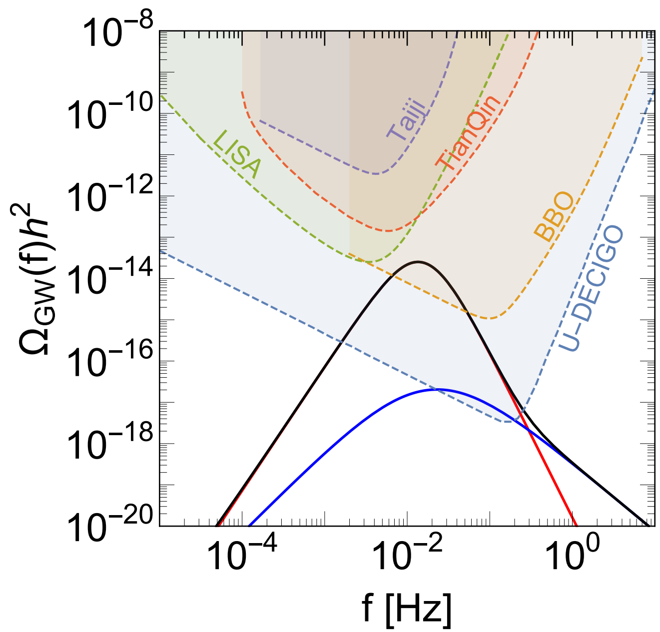
- The potential receives thermal correction in the early Universe;

$$V(H,S,T) \approx (\mu_H^2 + c_h T^2)|H|^2 + (\mu_S^2 + c_s T^2)|S|^2 + \lambda_H|H|^4 + \lambda_S|S|^4 + 2\lambda_{HS}|H|^2|S|^2;$$

$$c_h = \frac{3g^2 + g'^2}{16} + \frac{y_t^2}{4} + \frac{\lambda_H}{2} + \frac{\lambda_{HS}}{6}, \quad c_s = \frac{g'^2}{4} + \frac{\lambda_S}{3} + \frac{\lambda_{HS}}{3}$$

- If $\mu_S^2 < 0$ and $\lambda_{HS}$ is sizable, the potential $V(H,S)$ might triger a 1st-order EW phase transition and provide detectable GWs;



# • Gravitational waves probe

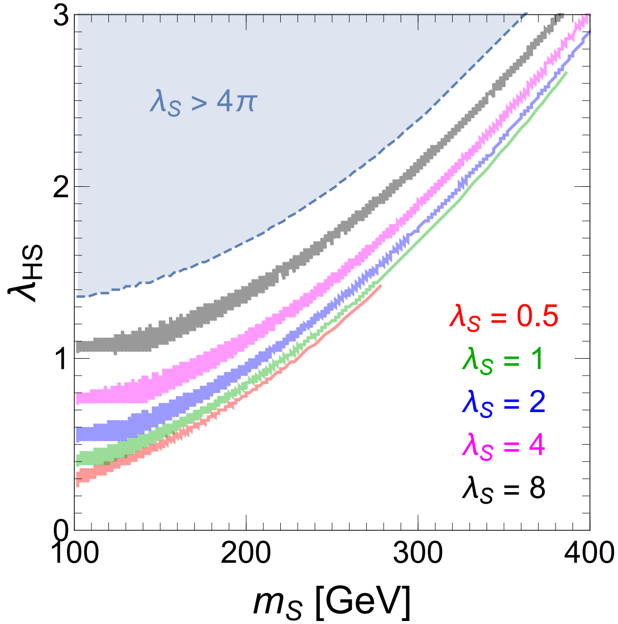
## A first-order electroweak phase transition

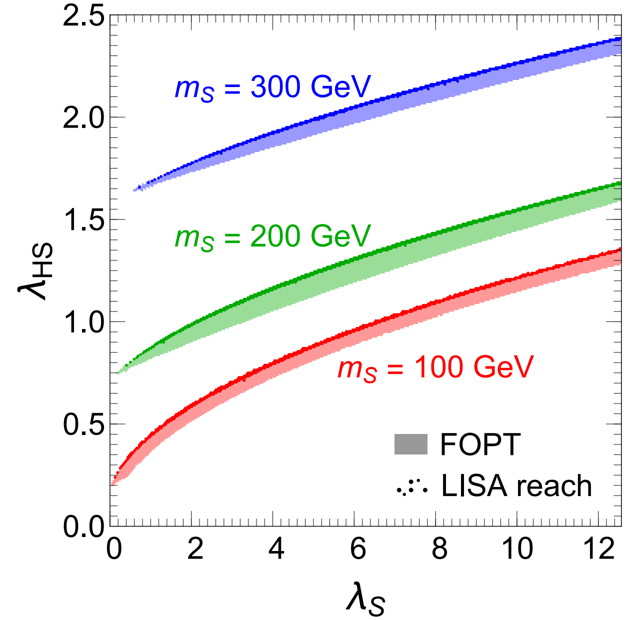
- The potential receives thermal correction in the early Universe;

$$V(H,S,T) \approx (\mu_H^2 + c_h T^2)|H|^2 + (\mu_S^2 + c_s T^2)|S|^2 + \lambda_H |H|^4 + \lambda_S |S|^4 + 2\lambda_{HS}|H|^2|S|^2;$$

$$c_h = \frac{3g^2 + g'^2}{16} + \frac{y_t^2}{4} + \frac{\lambda_H}{2} + \frac{\lambda_{HS}}{6}, \quad c_s = \frac{g'^2}{4} + \frac{\lambda_S}{3} + \frac{\lambda_{HS}}{3}$$

- If $\mu_S^2 < 0$ and $\lambda_{HS}$ is sizable, the potential $V(H,S)$ might triger a 1st-order EW phase transition and provide detectable GWs;

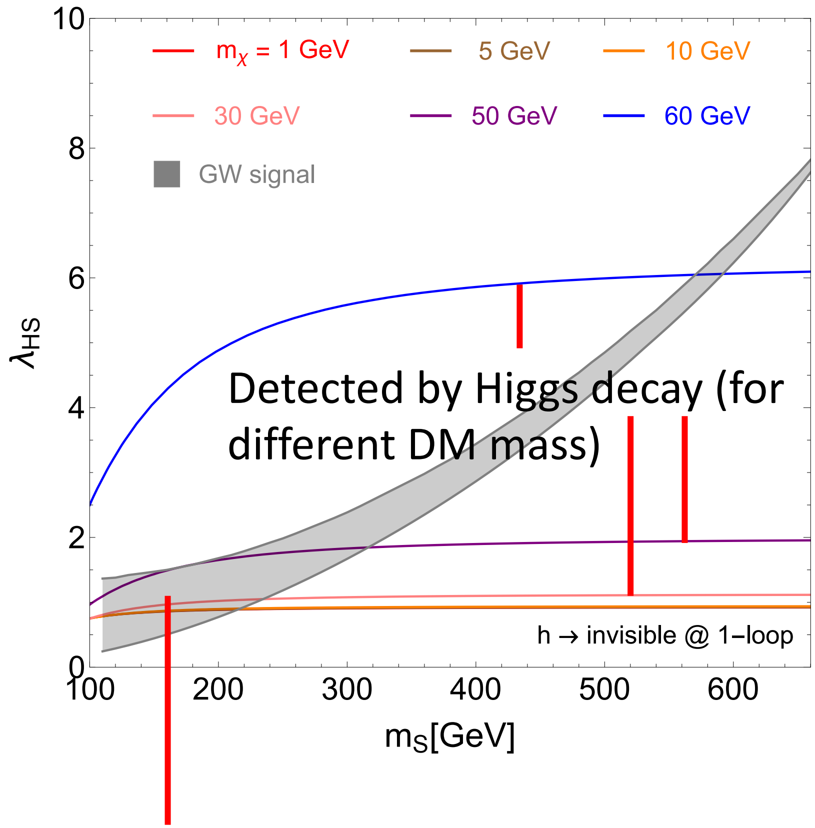


# • Gravitational waves complementarity

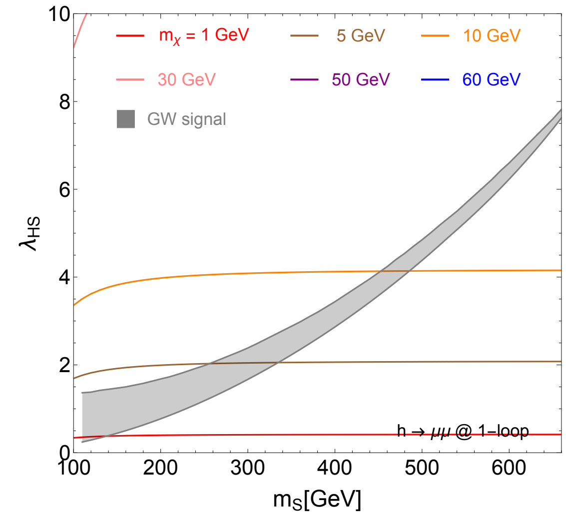
## Interplay with the CEPC experiments

$$h \to \chi\chi$$

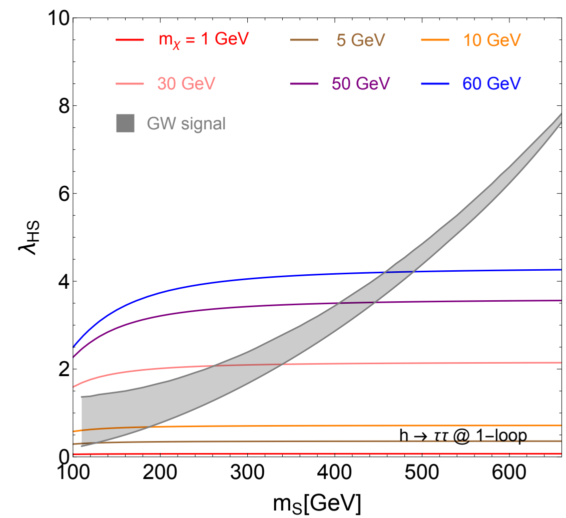



Shaded region: Detected by phase transition GWs

$$h \to \mu^+\mu^-$$




$$h \to \tau^+\tau^-$$



# Thank you!