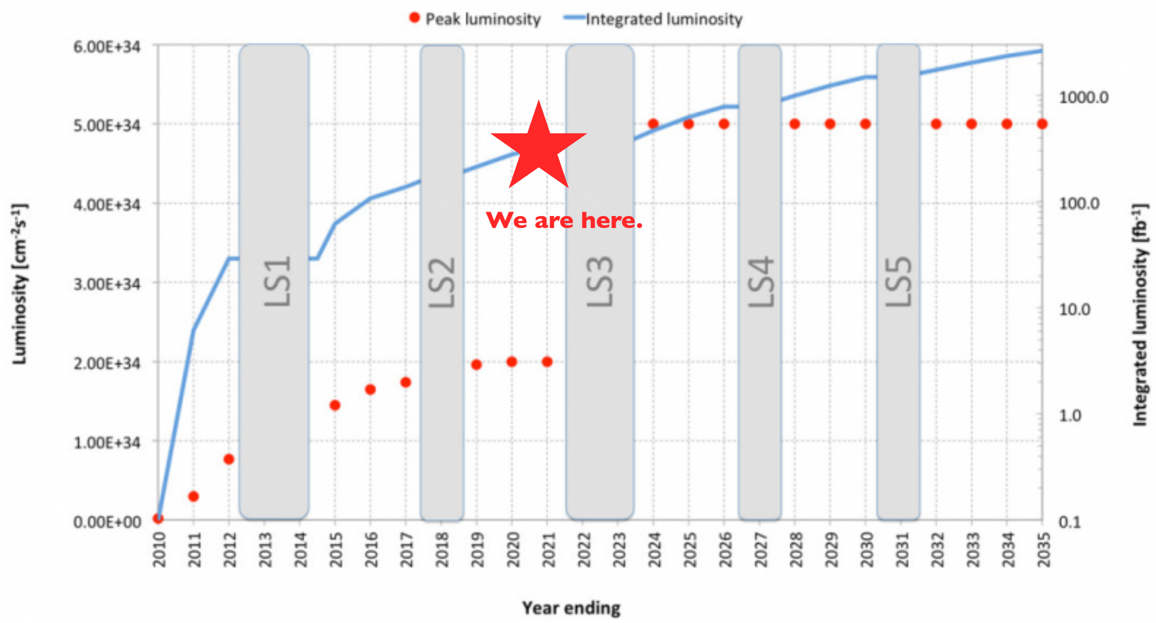
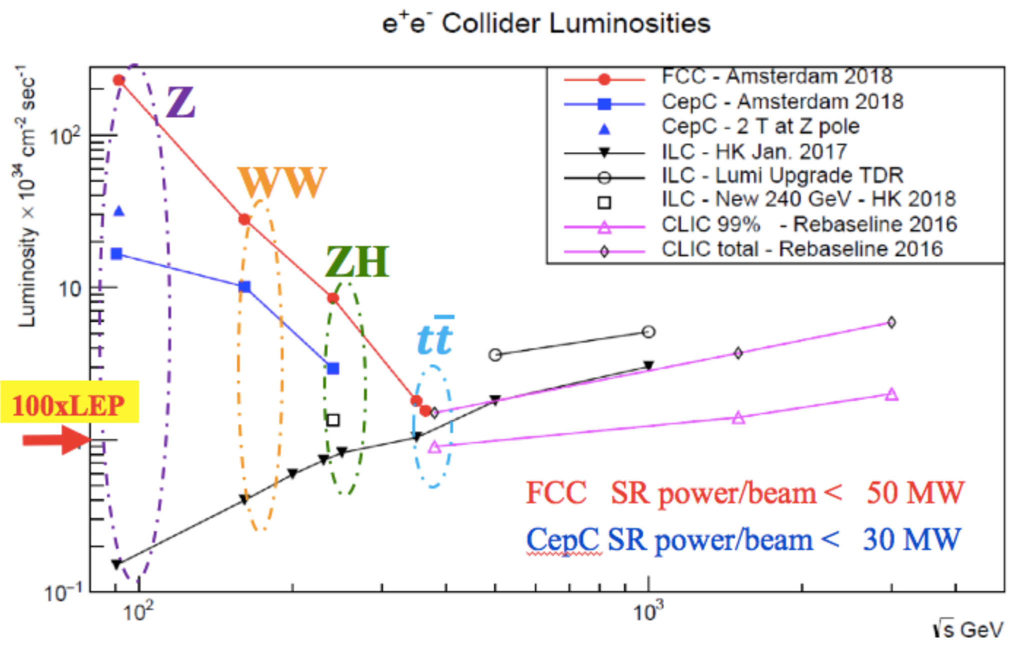
Recent progresses on Physics Opportunities at e+e- colliders

LianTao Wang
Univ. of Chicago

IAS program on High Energy Physics. HKUST. Jan 18, 2022

The coming decades

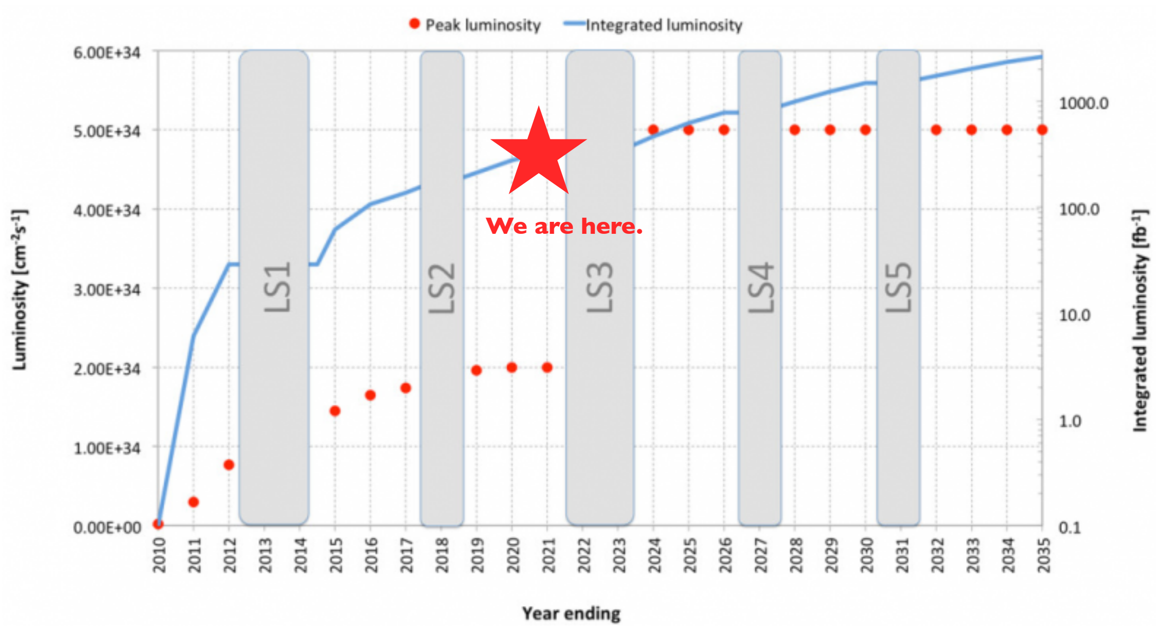


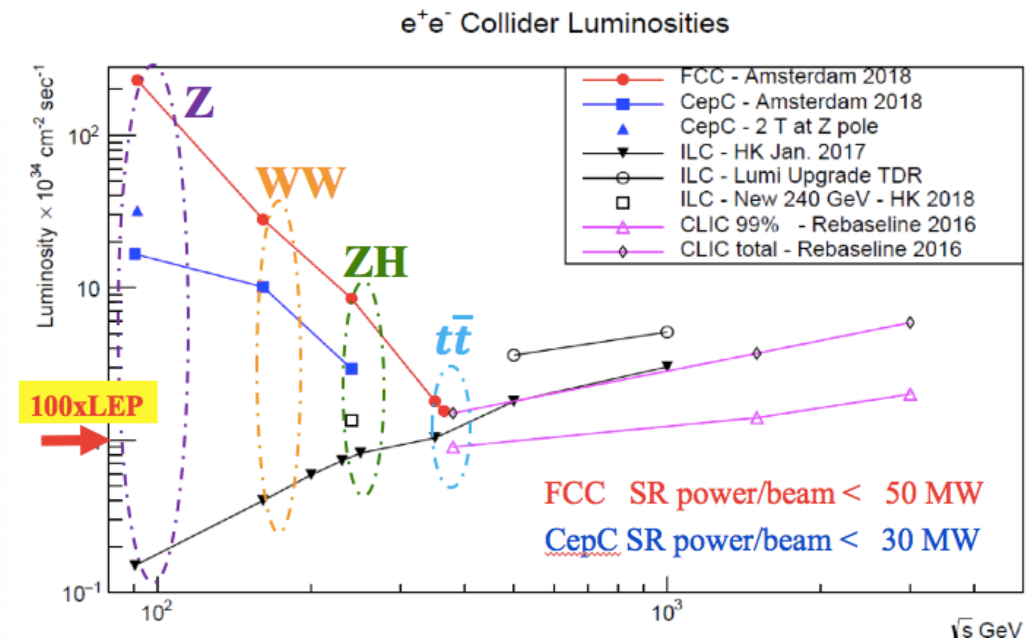


Higher energies?

- 10s -100 TeV: pp collider, muon collider, new technology?
- Great! We should keep advocate and pursue them.
- However, these are longer term prospects due to technological and resource constraints.

The coming decades

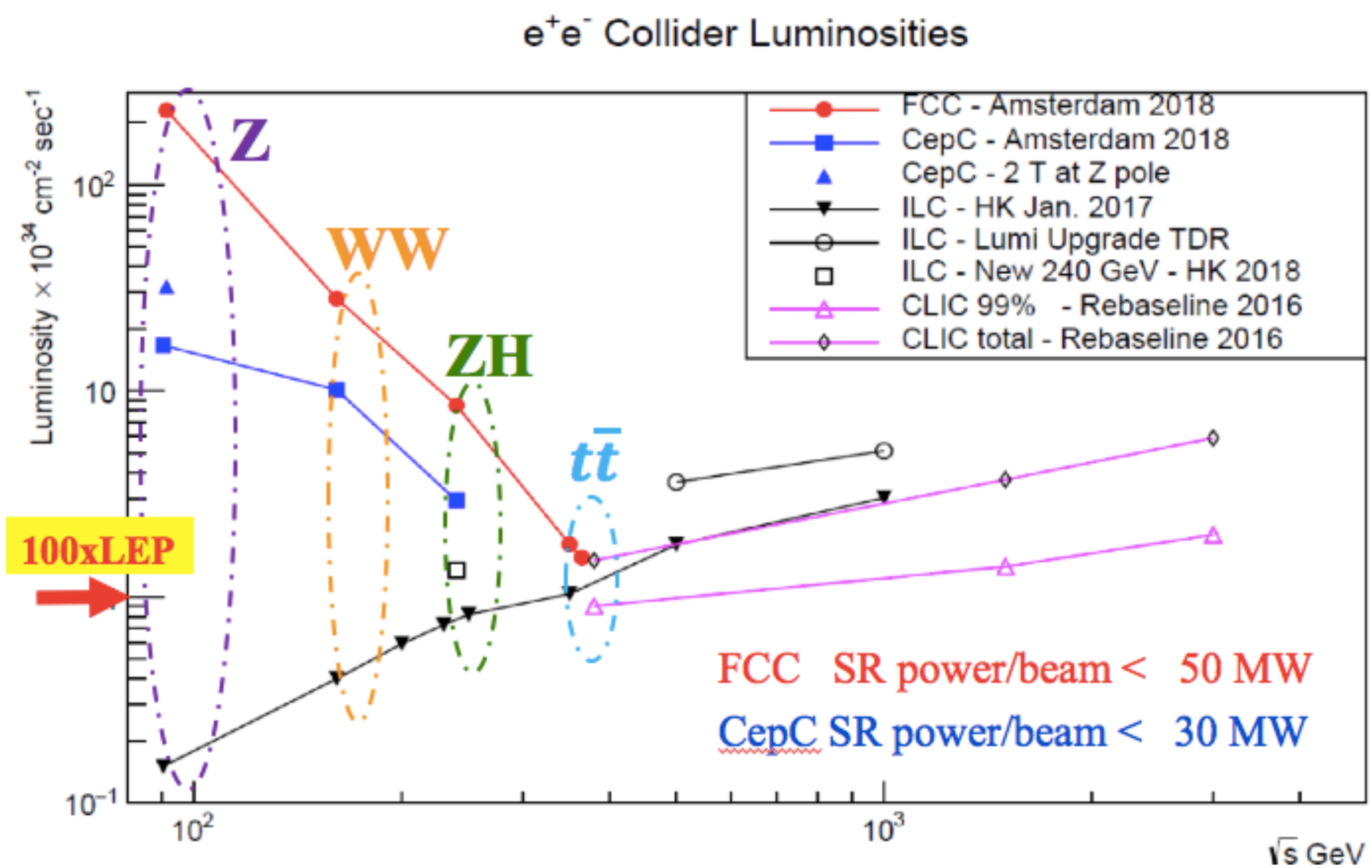




- More data, cleaner collisions.
- Main target: precision, rare processes.

History on our side

- First signal of something new are often "indirect".
  - Beta decay: W (1933)
  - Kaon rare decay: charm (1970)
  - Neutrino scattering: Z (1973)
  - Electroweak precision: top and Higgs (1980s-1990s)
  - ....
- We expect an equally fruitful journey in the coming decades.



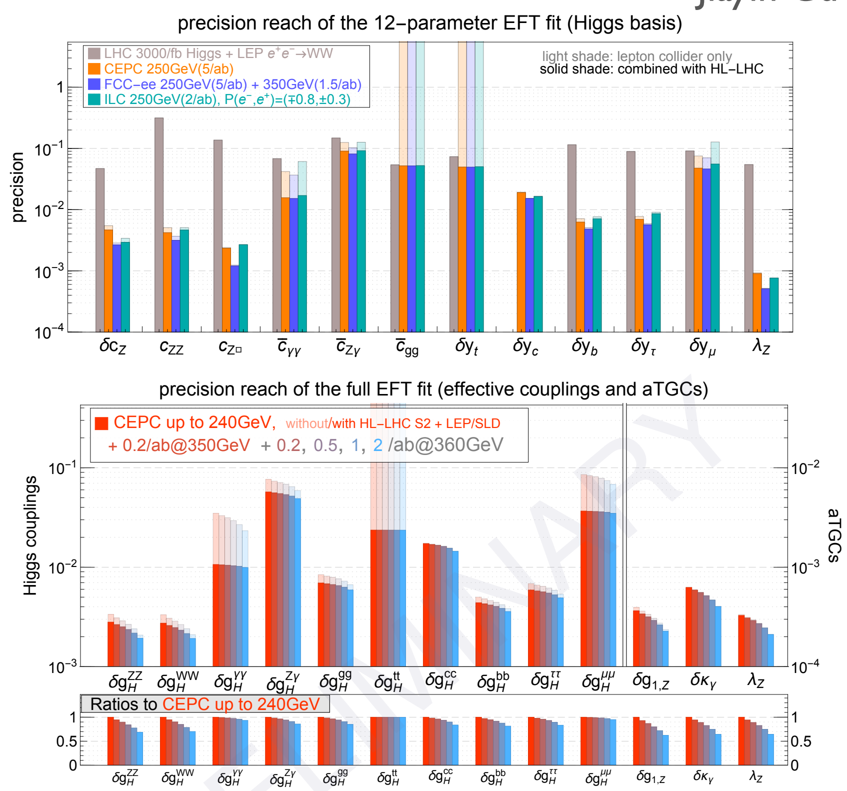
e+ e- colliders will play an essential role!

Offer rich program, covering 90 eV - TeV(s).

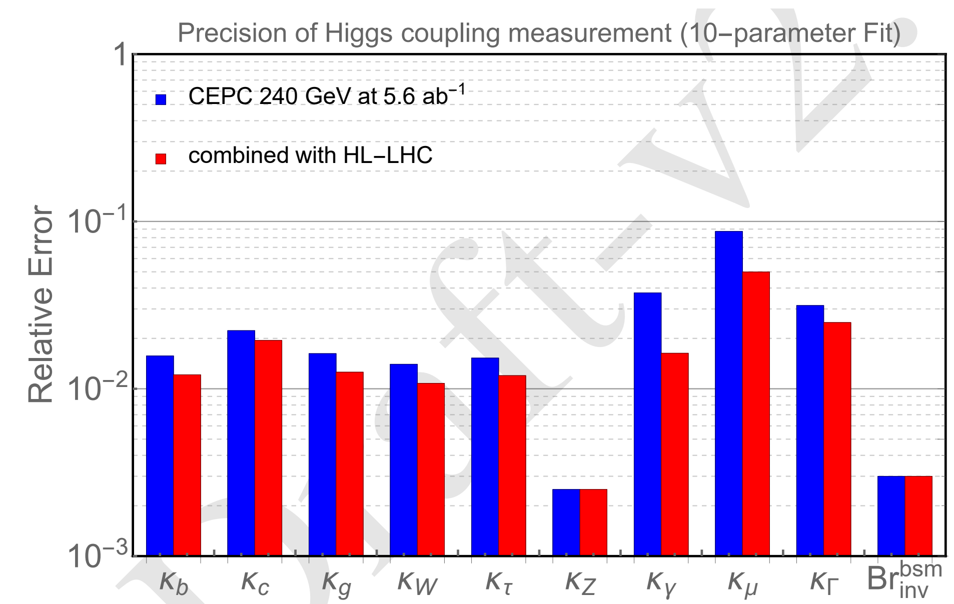
Main physics drivers

- Higgs, Electroweak precision measurements.

Jiayin Gu



Zhen Liu



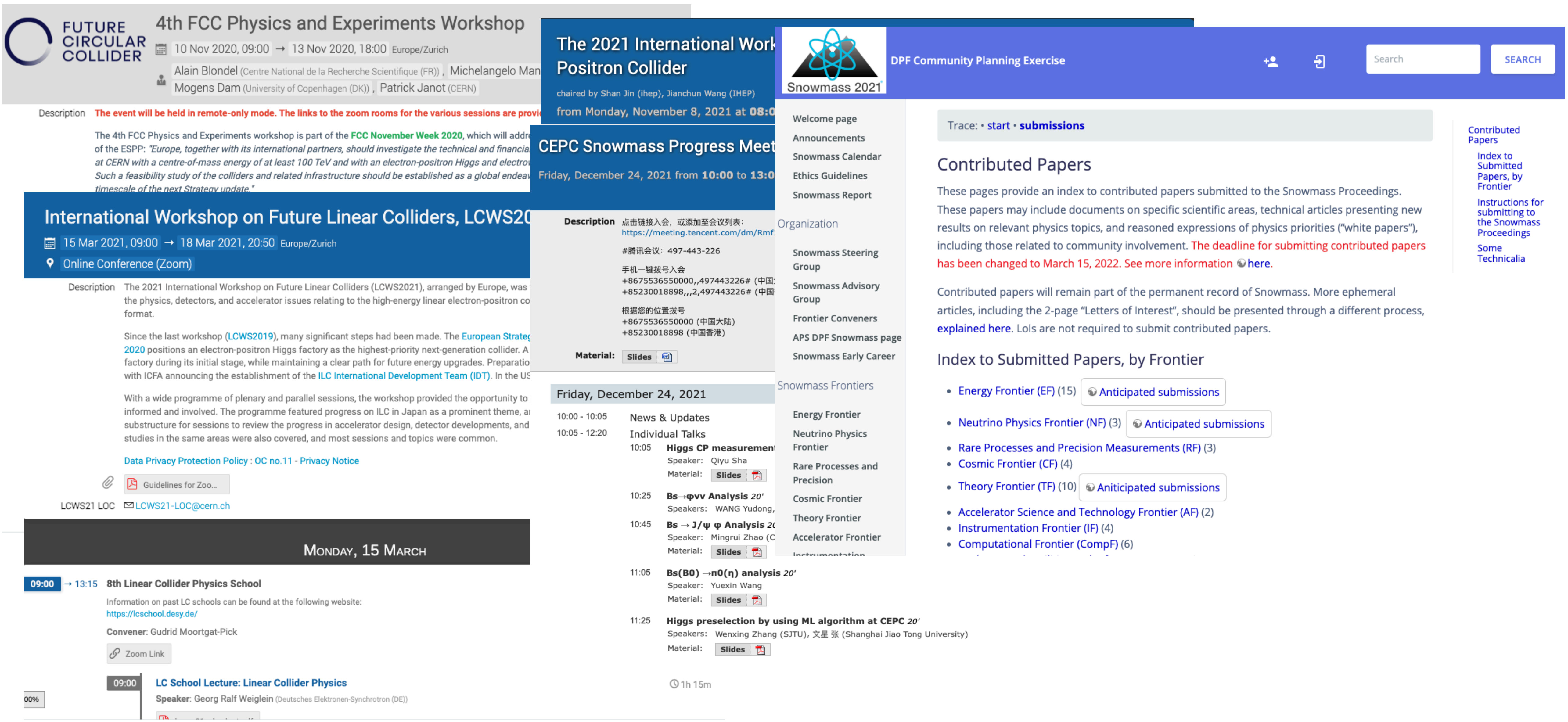
Well documented: European strategy update, CEPC/FCC/ILC/CLIC study documents

I will be very brief on these familiar points.

My talk

- Focus on new developments, promising new directions.
    - Enriching the physics program of future e+e- colliders.
    - Informing design and planning.

A lot of on-going work



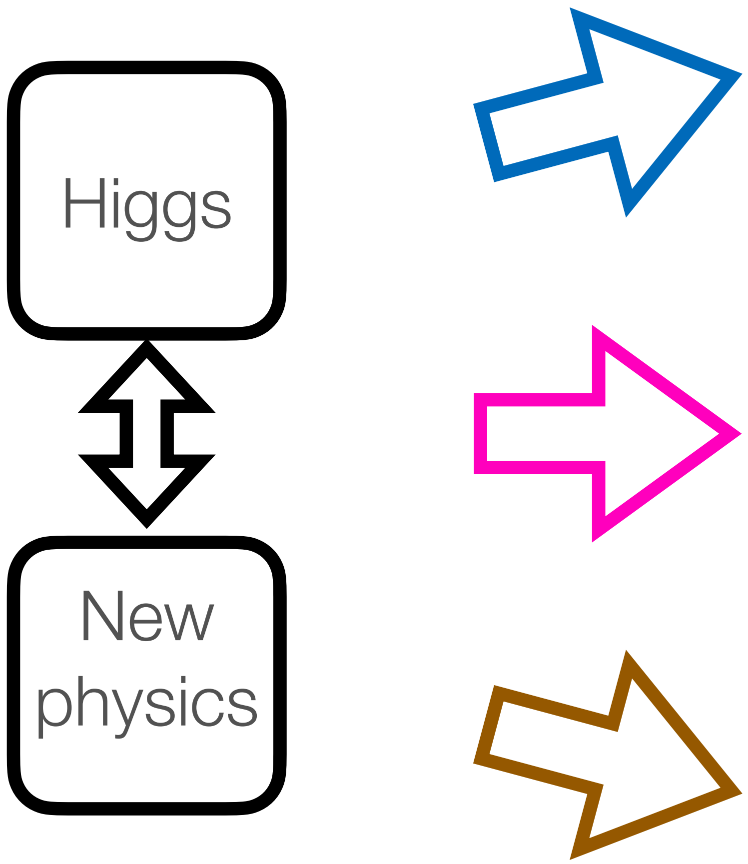
Snowmass white papers: https://snowmass21.org/submissions/start

2021 CEPC workshop: https://indico.ihep.ac.cn/event/14938/other-view?view=standard

4th FCC physics symposium: https://indico.cern.ch/event/932973/timetable/#20201110.detailed

LCWS 2021: https://indico.cern.ch/event/995633/timetable/?view=standard

Possible new signals



Traces in Higgs couplings,
EW precision

Rare decays

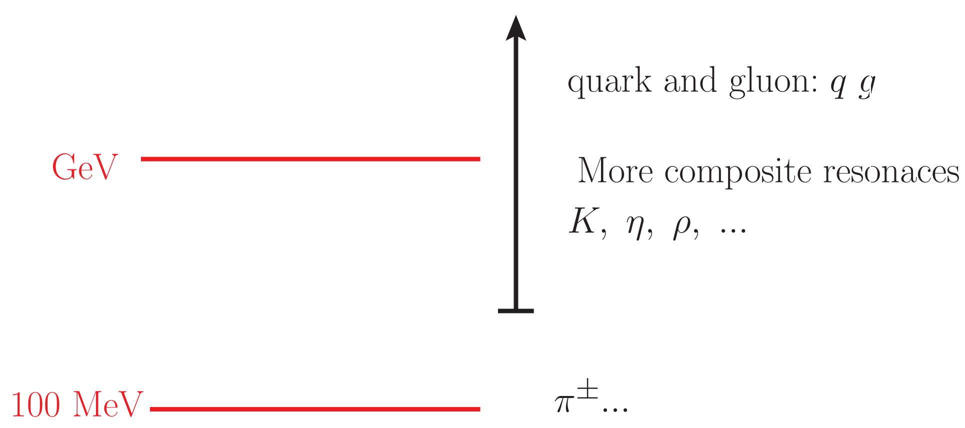
Production at high energy colliders

My talk

- Precision measurements: Higgs and beyond
- New physics searches
- Higher energies (brief comment)

Why Higgs?

- Spin 0 elementary particle, unique one of its kind.
- We have seen spin-0 particles.
  - They are composite, with other states around.



Higgs looks very different.

Why Higgs?

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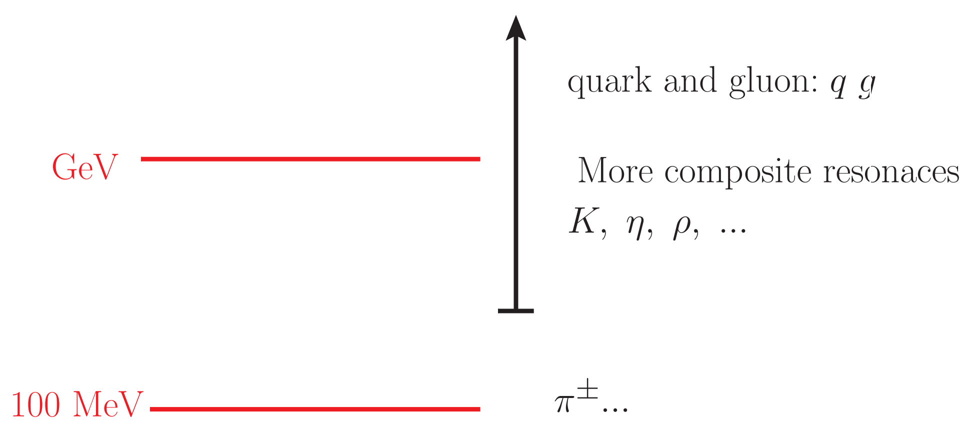
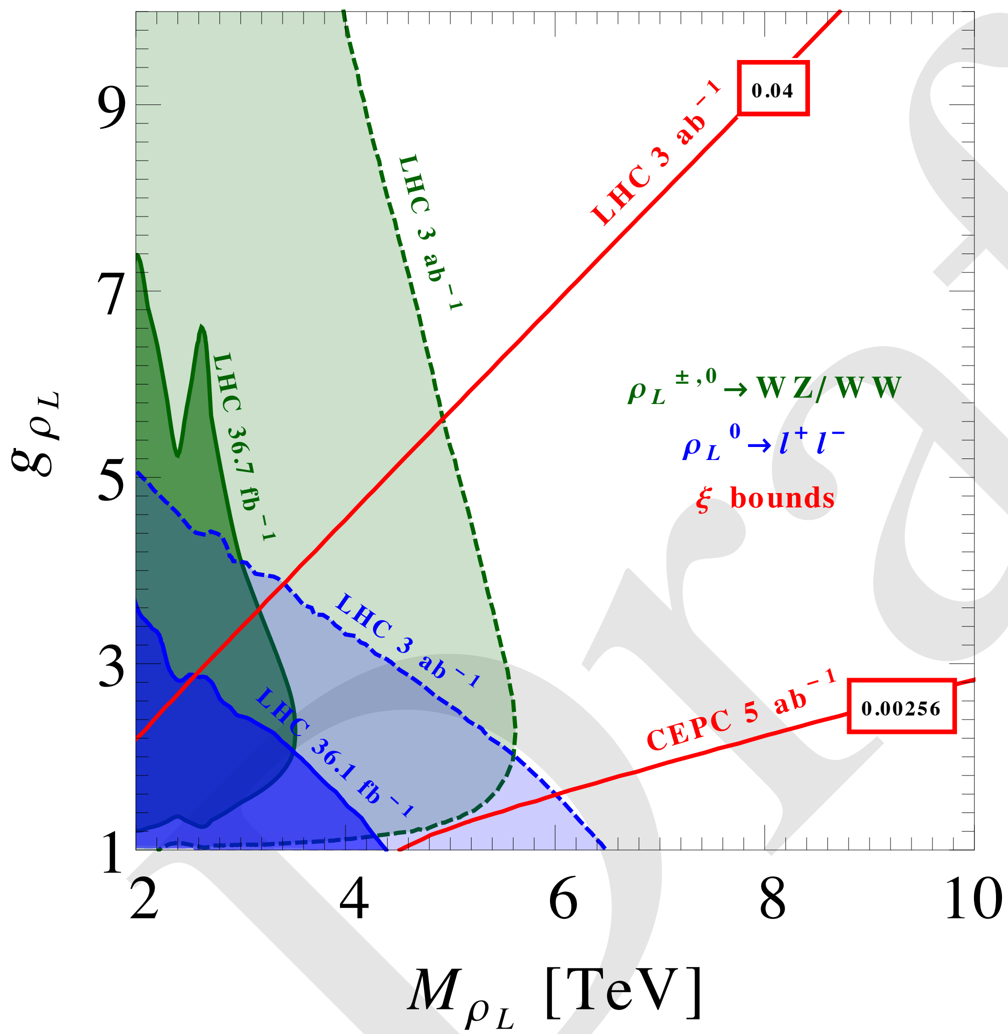


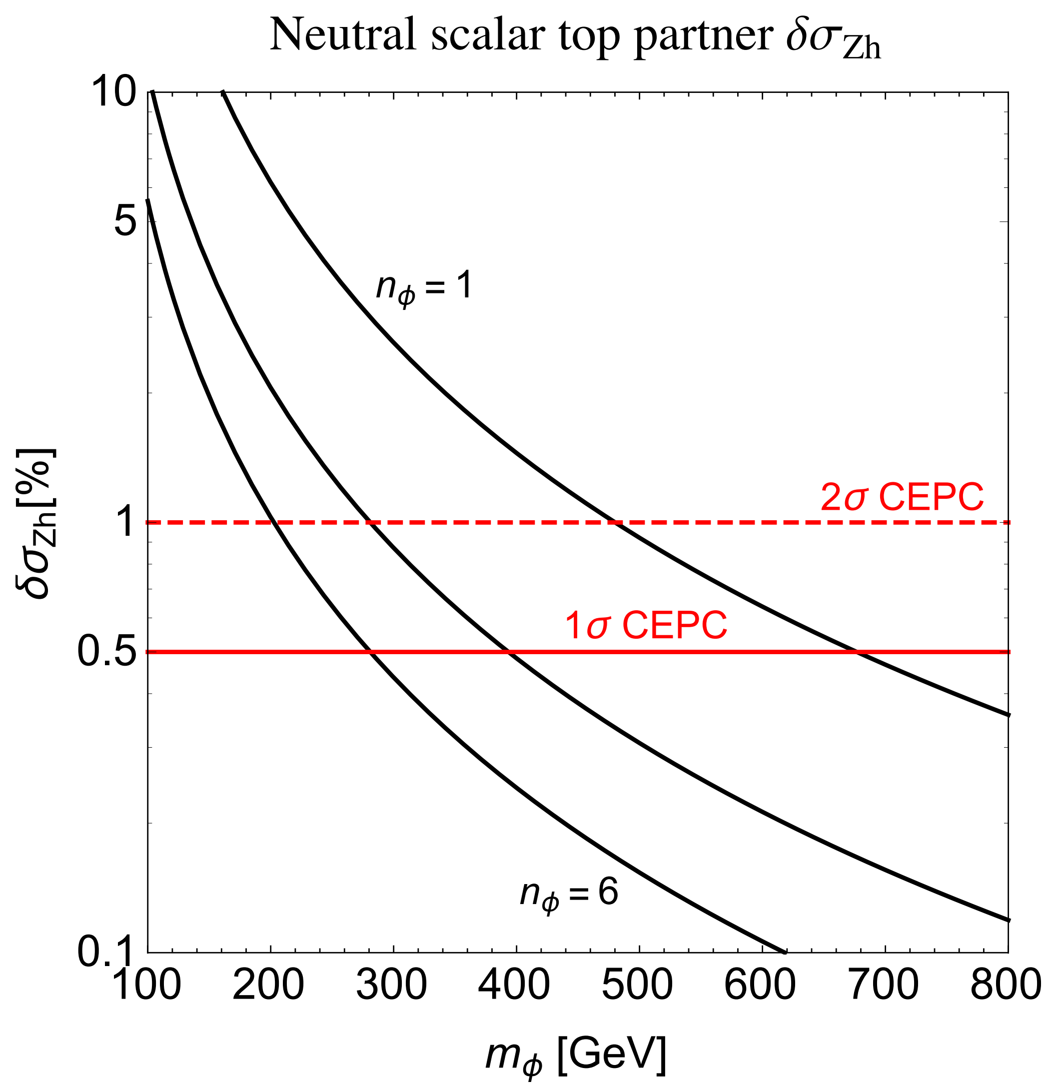
Higgs looks very different.

- So, where does the Higgs come from?

Example: naturalness



Composite Higgs



Neutral naturalness

Better measurements
More information

Machine learning techniques:

Precision (%)	J1 (Jet)	J2 (Jet+FW)	J3 (Jet+FW+track)	E1 (Image)	E2 (Image+track)
$\sigma(Z_\nu h_{W_{lq}})$	1.7 (1.6)	1.4 (1.6)	1.5 (1.6)	1.5 (1.4)	1.5 (1.4)
$\sigma(Z_\nu h_{W_{qq}})$	1.6 (1.6)	1.2 (1.2)	1.1 (1.1)	1.1 (1.1)	1.1 (1.1)
$\sigma(\nu\nu h_h)$	2.8 (2.7)	1.8 (1.7)	1.9 (1.8)	1.4 (1.4)	1.3 (1.3)
Γ_h	$3.2^{+0.9}_{-0.3}$ (3.1)	$2.3^{+0.7}_{-0.2}$ (2.2)	$2.3^{+0.7}_{-0.2}$ (2.3)	$1.9^{+0.5}_{-0.1}$ (1.9)	$1.9^{+0.4}_{-0.1}$ (1.9)

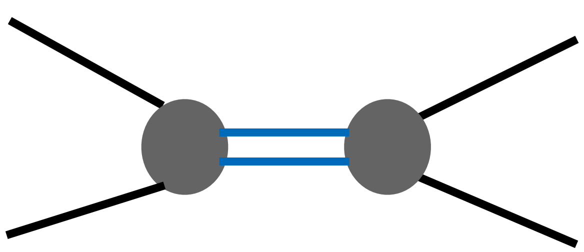
DNN based analysis L.F. Li, Y. Y. Li, T. Liu, S. Xu, 2004.15013

Many more studies on refining measurement techniques:
Energy dependence, differential distribution, smart variables…

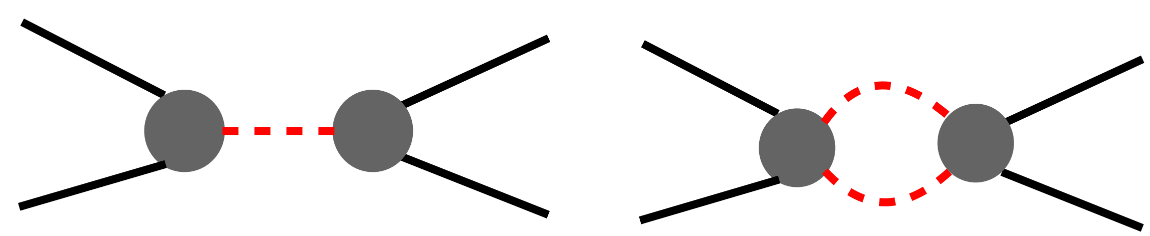
EFT and beyond

- Effective field theory has been widely used to characterize new physics effects.
- There could be important exceptions.

New physics effects beyond the simple EFT parameterization



Strongly coupled, continuum



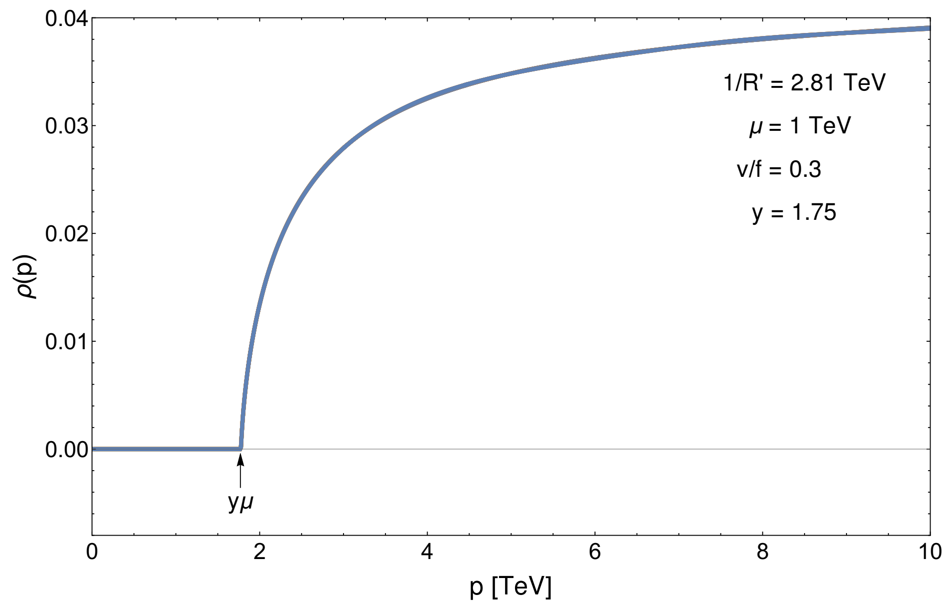
Light new physics

EFT and beyond

- Effective field theory has been widely used to characterize new physics effects.

- There could be important exceptions.

Csaki, G. Lee, S. Lee, Lombardo, Telem, 1811.06019



e.g.: top partner as a continuum

EFT and beyond

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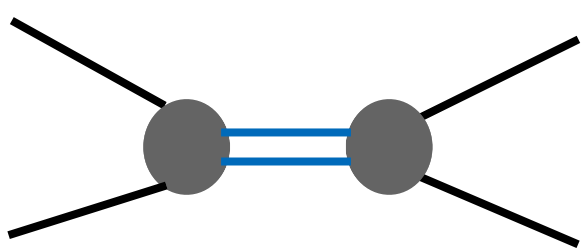
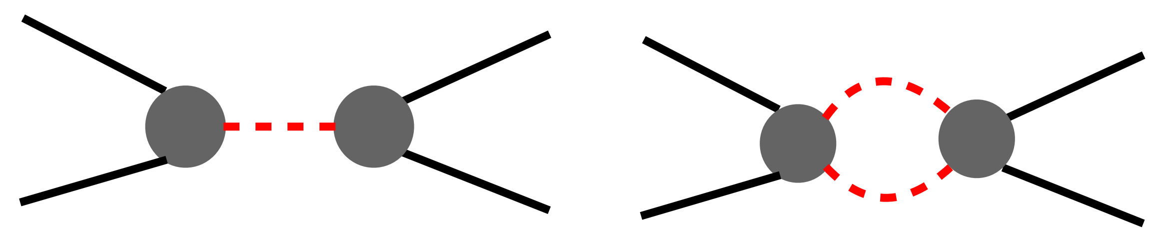
New physics effects beyond the simple EFT parameterization



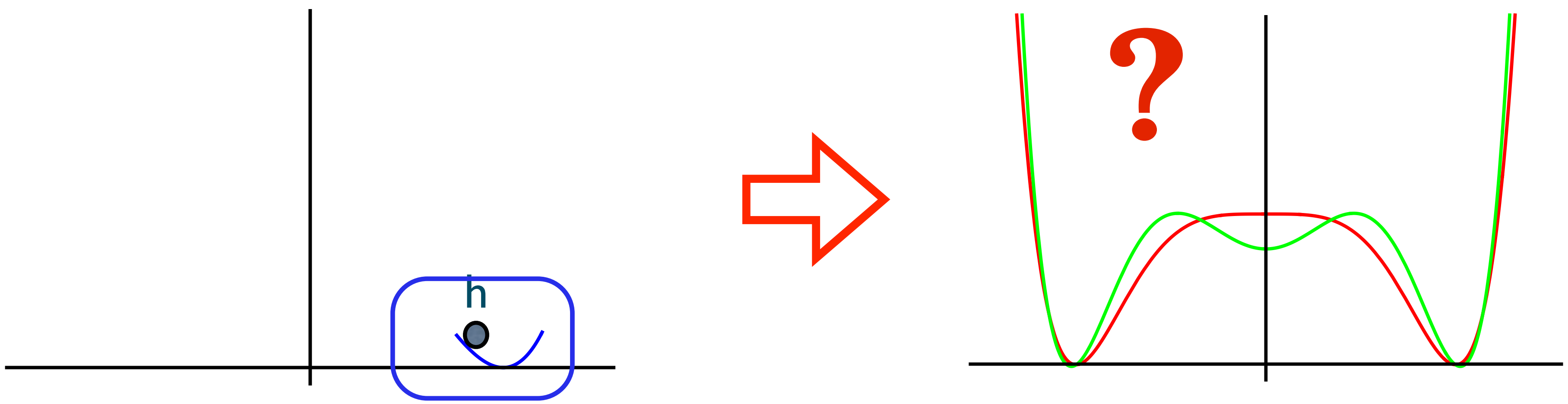
Strongly coupled, continuum



Light new physics

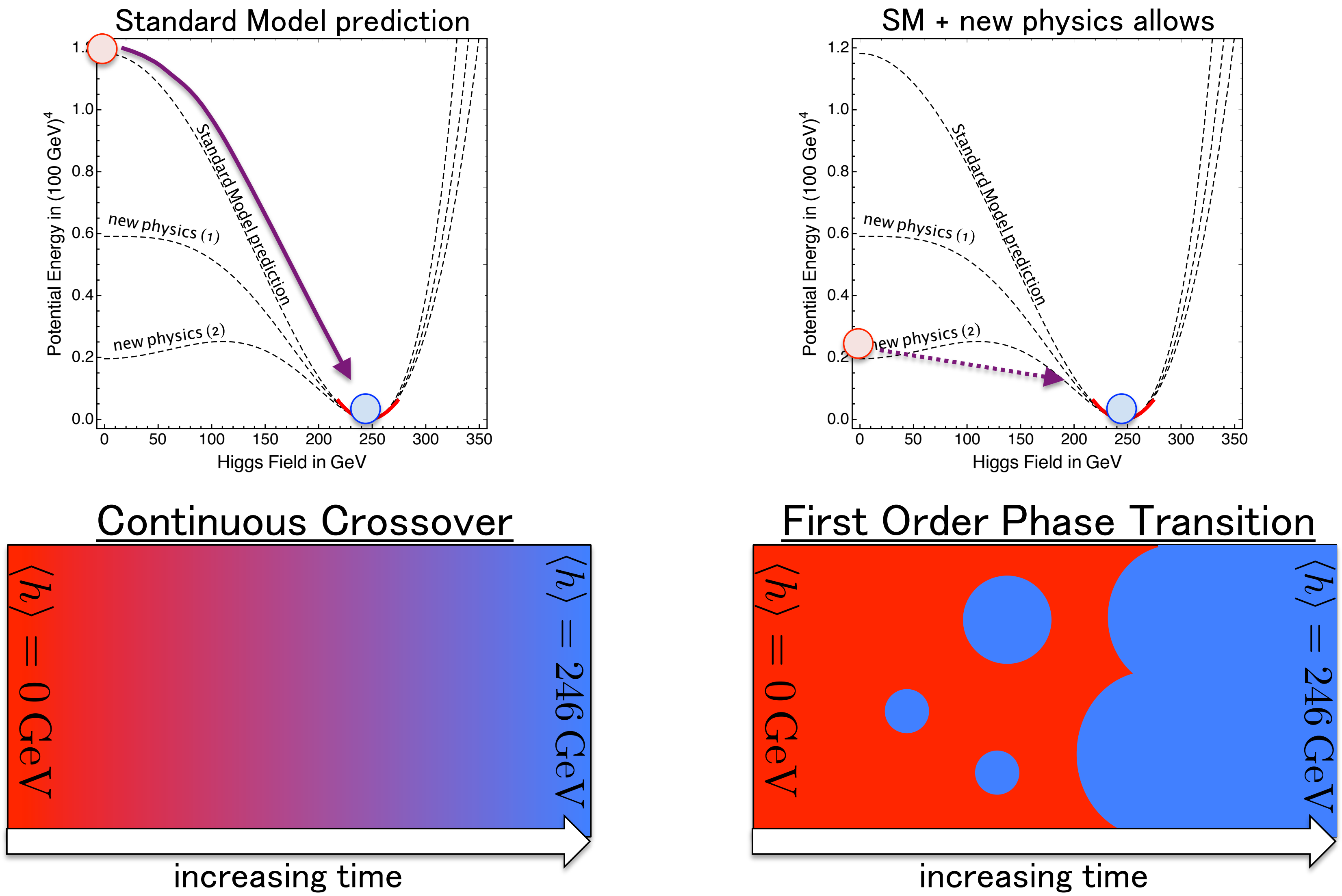
It would be interesting to study a few examples to understand better their signal and impact for precision measurements.

EW phase transition



What we know from LHC
LHC upgrades won’t go much further

Early universe



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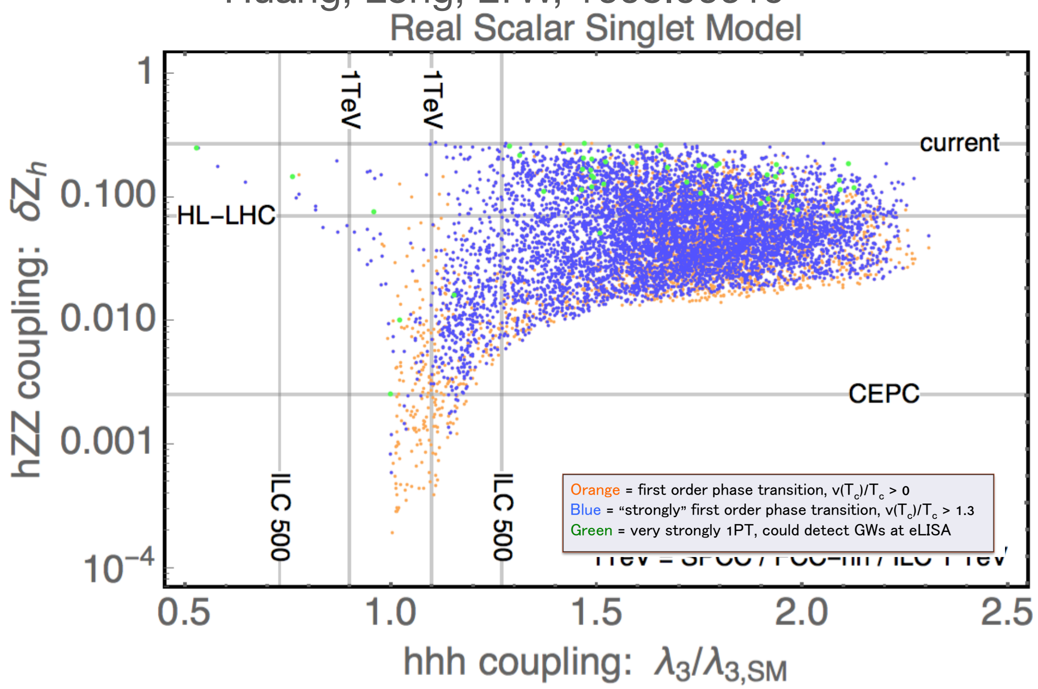
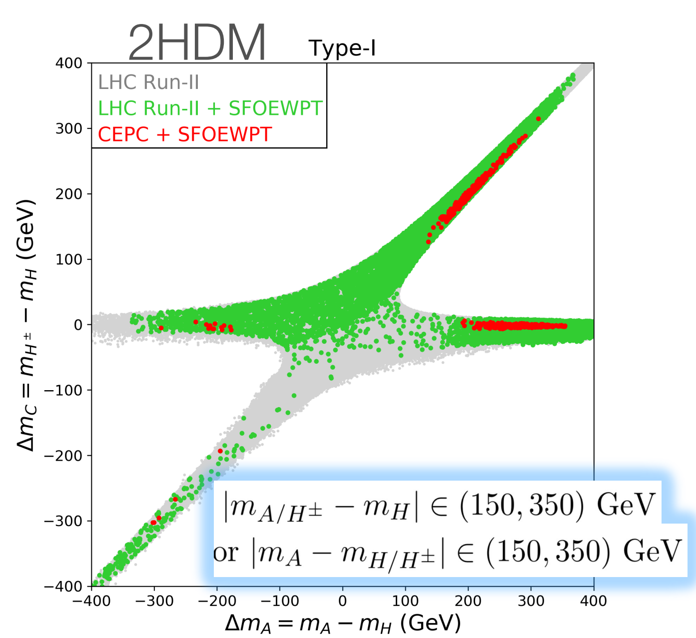
- How does Higgs evolve in the early universe?

EW phase transition

Huang, Long, LTW, 1608.06619



Su, Williams, Zhang, 2011.04540



Salient points:

Significant deformation of the SM Higgs potential
→Need new physics close to weak scale

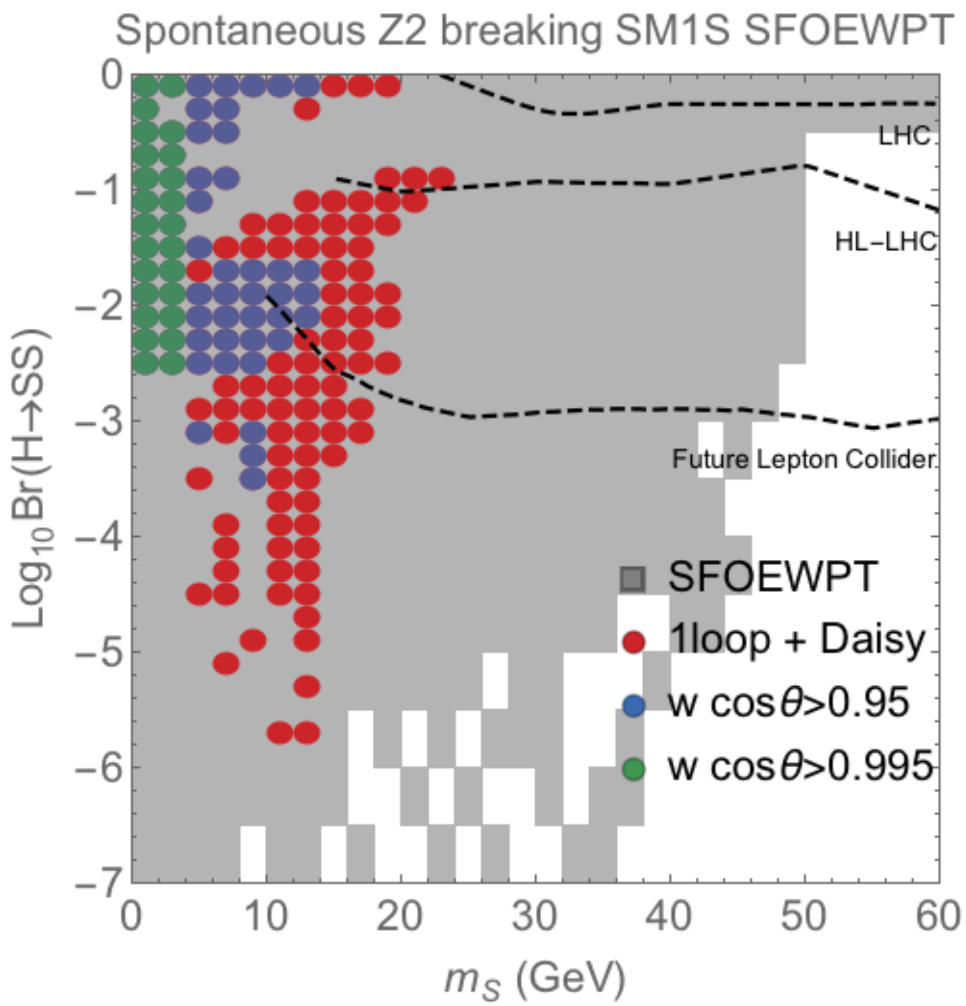
Leads to large modification to the Higgs couplings:

Self-coupling (most emphasized)

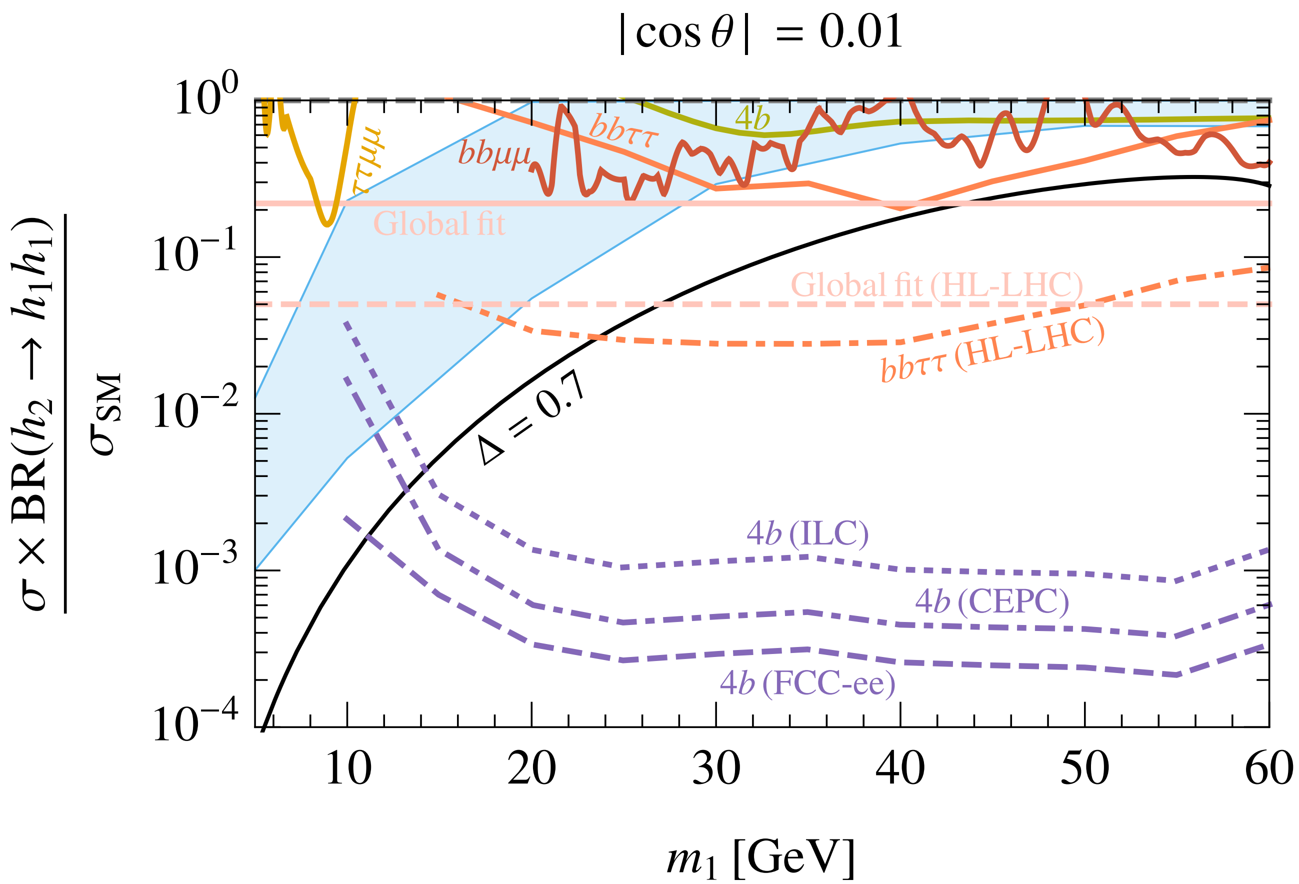
At the same time, similar deviation expected on other H(easier to measure) Higgs couplings

Could have very light new physics

Singlet extension, h→ss



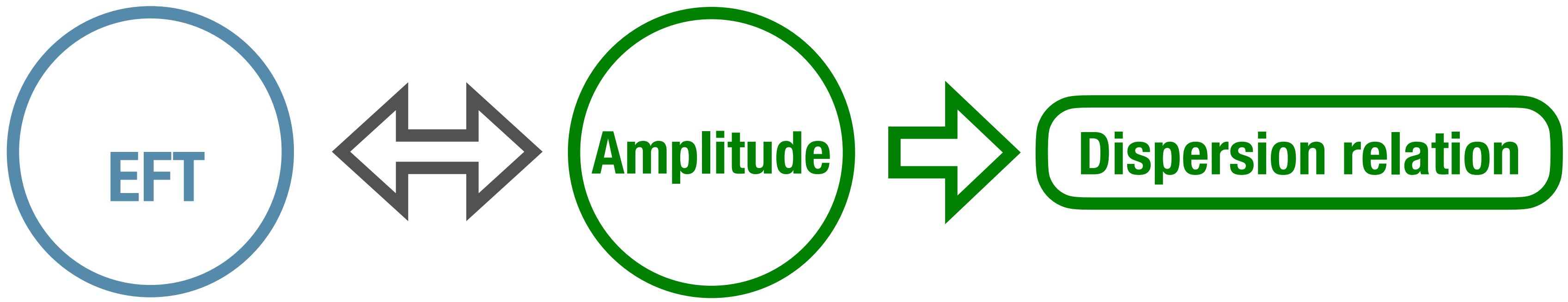
Carena, Liu, Wang, 1911.10206



Kozaczuk, Ramsey-Musolf, Shelton, 1911.10210

Interesting to look at more benchmarks for EWPT, more signals.

Back to fundamentals



- Recent years have seen fast theoretical developments on scattering amplitudes, dispersion relations, and their connection with EFTs.
- This leads to non-trivial constraints, “positivity bounds”, “EFT-hedron”.
- Useful to test these new relations.
- Lepton collider, with clean environment, provides a unique opportunity

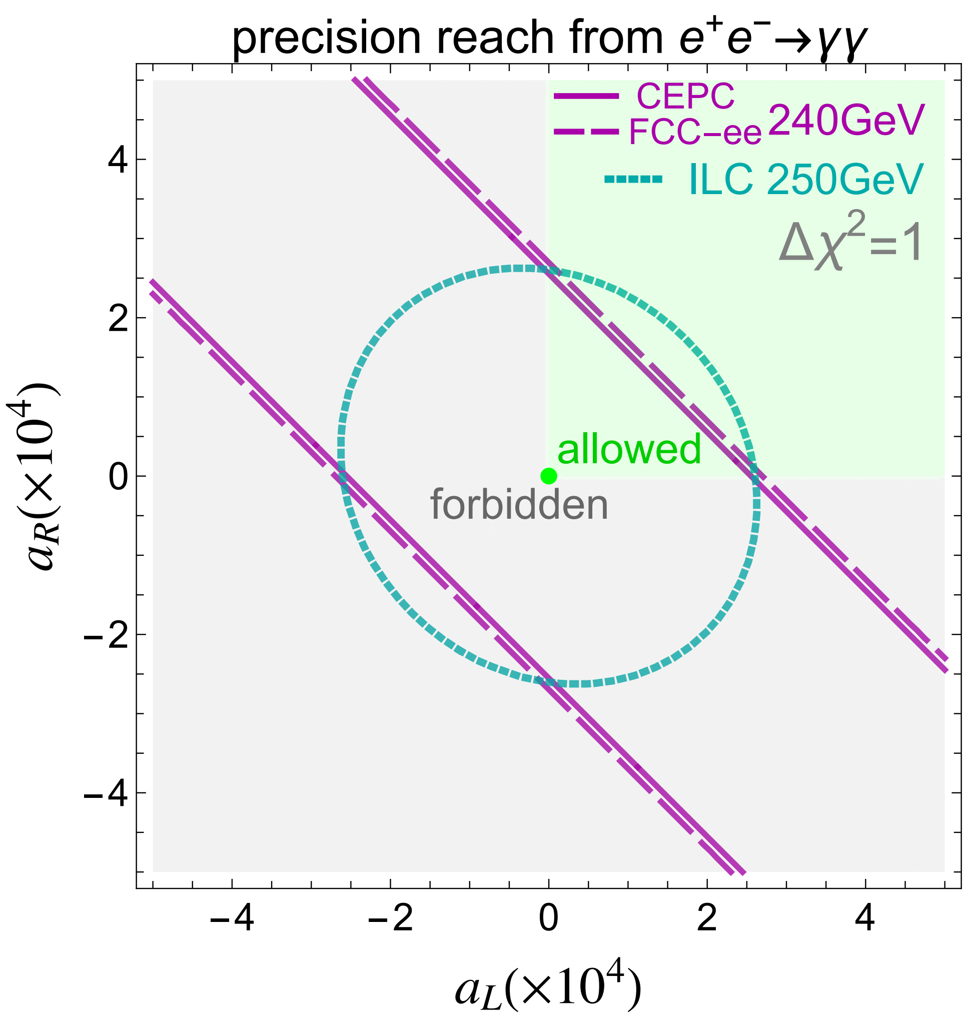
Adams, Arkani-Hamed, Dubovsky, Nicolis, Rattazzi, 2006
+ a lot of recent activities

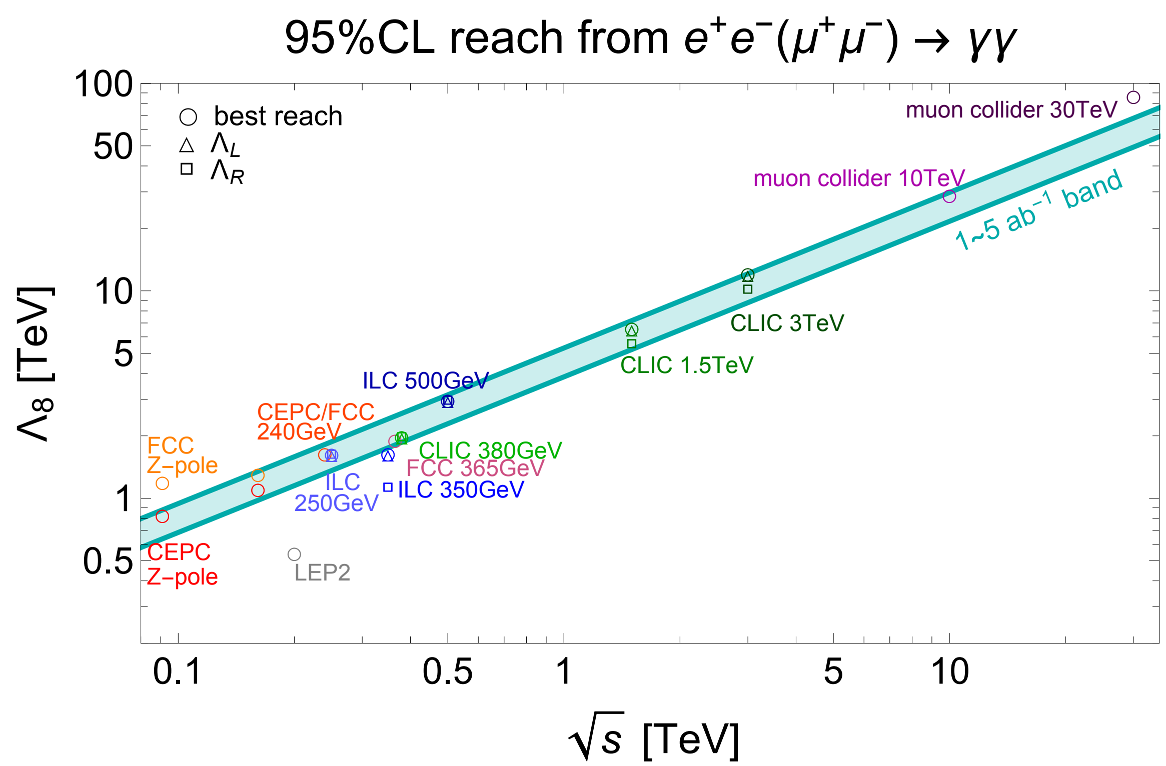
The $e^+ e^- \to \gamma\gamma$ channel

J. Gu, C. Zhang, LTW, 2011.03055

- Effect from dim-6 operator either vanishing or suppressed.
  - Due to the nature of the amplitude and the experimental constraints.
- SM × dim-8 interference is the leading channel.
- Positivity bound on dim-8 leads to prediction

$$\sigma(e^+e^- \to \gamma\gamma) > \sigma_{\text{SM}}(e^+e^- \to \gamma\gamma)$$





Can be used break degeneracies in the EFT fit.
Could also be an interesting test of the fundamental principles of QFT.

Other sensitive channels, interesting scenarios to test?

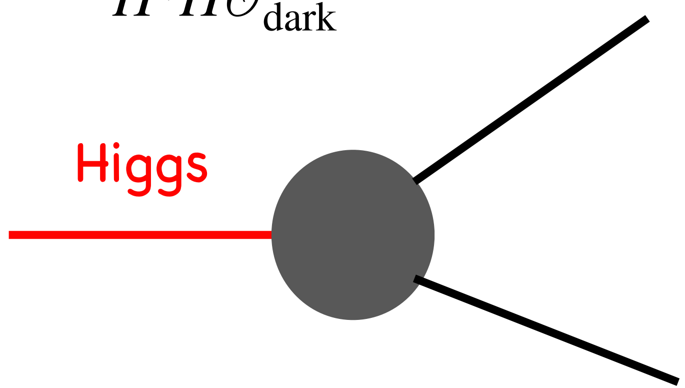
My talk

- Precision measurements: Higgs and beyond
- New physics searches

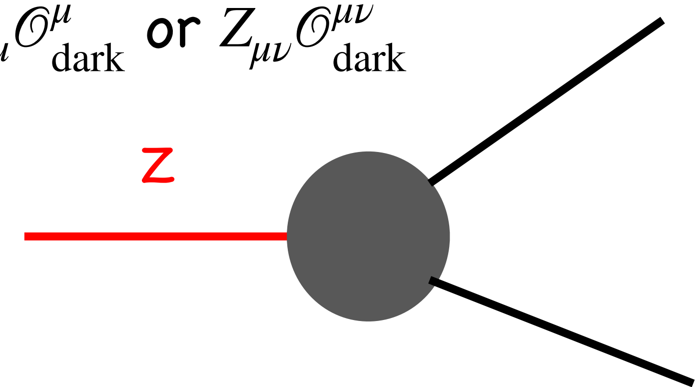
Windows into dark sector: portals

- Any known (SM) particle can in principle have small couplings to dark matter/dark sector.

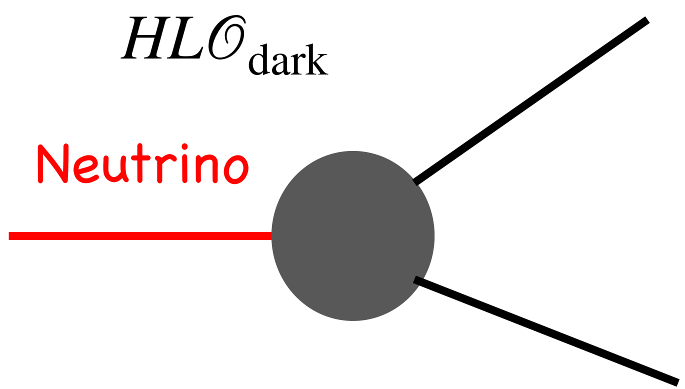
$H^\dagger H \mathcal{O}_{\text{dark}}$



$Z_\mu \mathcal{O}^\mu_{\text{dark}}$ or $Z_{\mu\nu} \mathcal{O}^{\mu\nu}_{\text{dark}}$



$HL\mathcal{O}_{\text{dark}}$

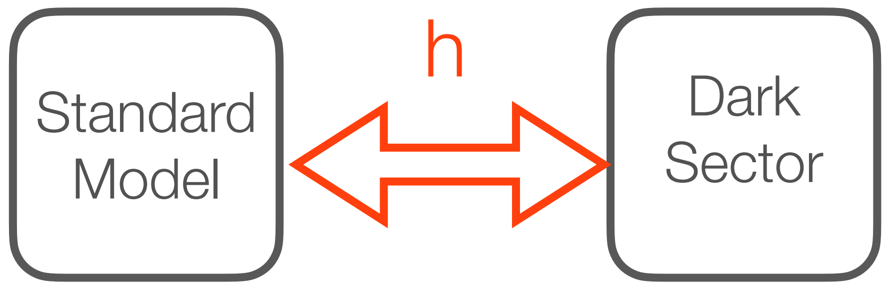


$\mathcal{O}_{\text{dark}} =$ SM singlet

Higgs/Z factories, such as CEPC

Neutrino facilities, fixed target experiments...

Higgs portal



- Dark sector coupling to the SM

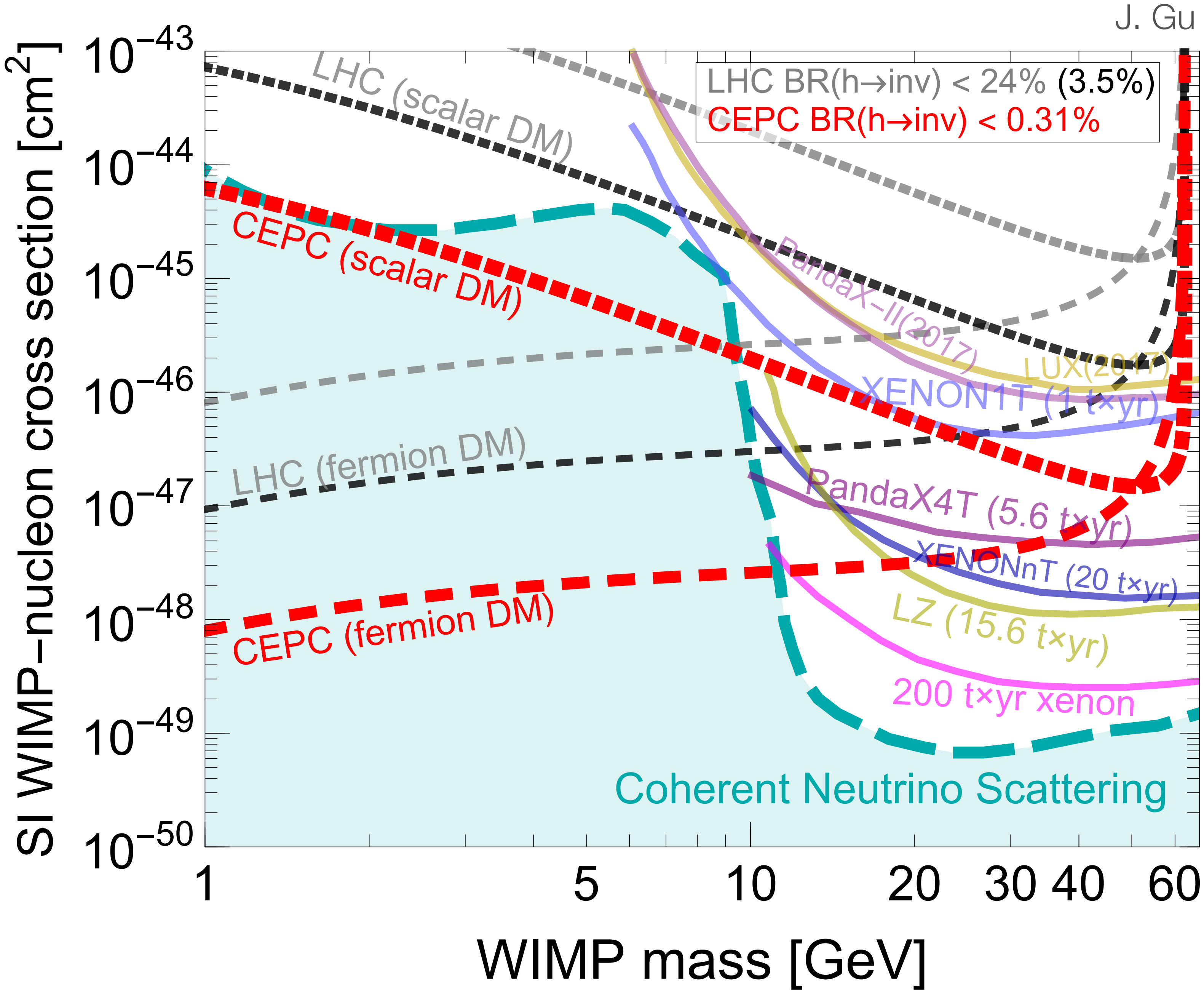
$$O_{\rm SM} \cdot O_{\rm dark}$$

$O_{\rm SM}$: gauge inv. SM operator $O_{\rm dark}$: dark sector operator

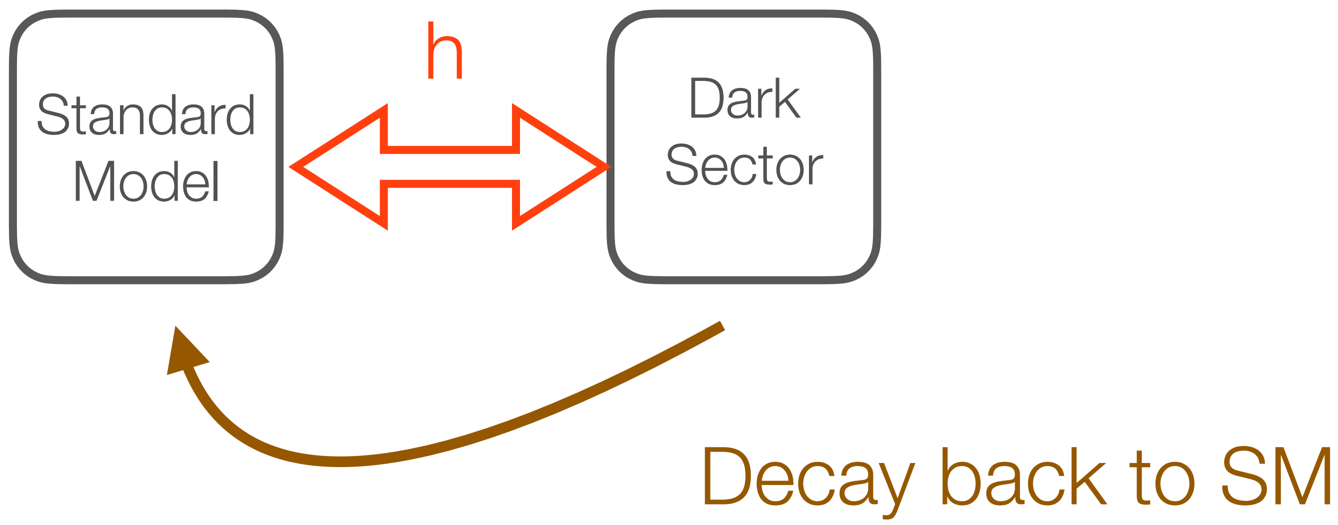
- More relevant coupling ⇔ lowest dim operator
  - Unique choice: $O_{SM} = HH^\dagger$. Higgs portal.

Higgs portal dark matter

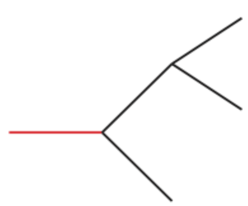
$$\mathcal{O} = H^\dagger H X_{\rm dm} X_{\rm dm} \quad \Rightarrow \quad h \to X_{\rm dm} X_{\rm dm}$$



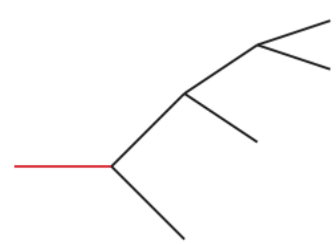
Higgs rare decay



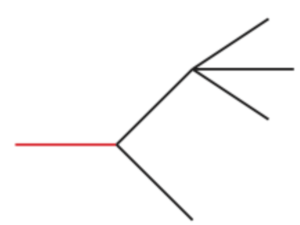
$h \to 2 \to 3$



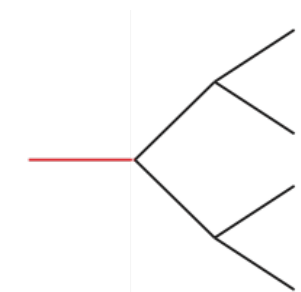
$h \to 2 \to 3 \to 4$



$h \to 2 \to (1+3)$

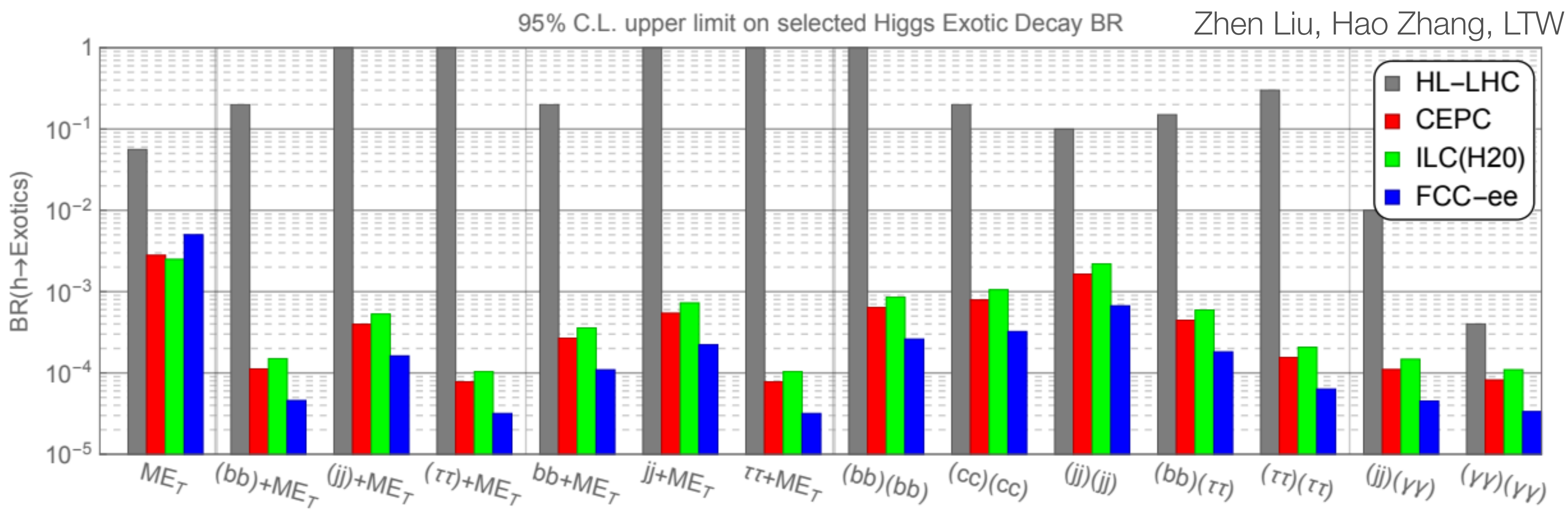


$h \to 2 \to 4$



....

Higgs exotic decay

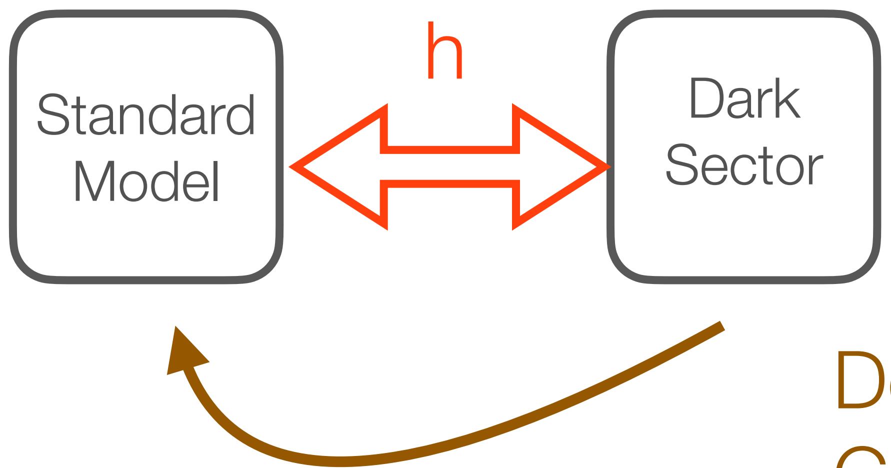


Complementary to hadron collider searches

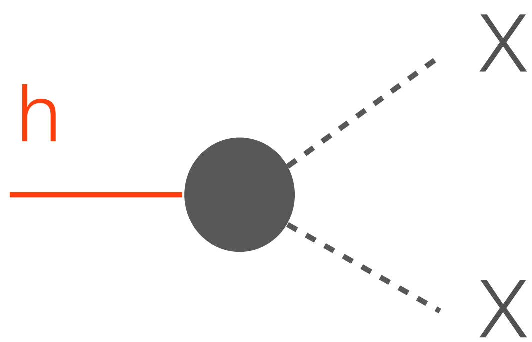
Can probe interesting physics cases, such as the models of electroweak phase transition mentioned above.

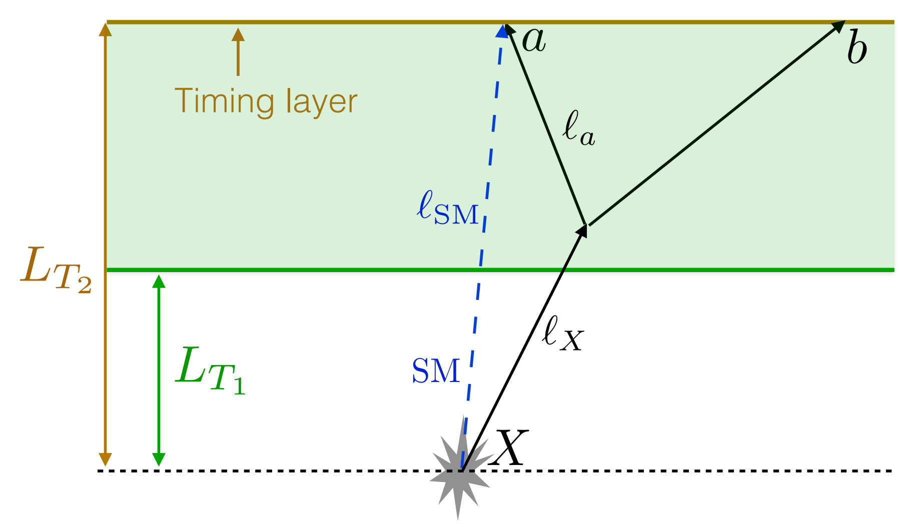
Only a partial list here. More channels and models need to be studied.

Long lived particle?



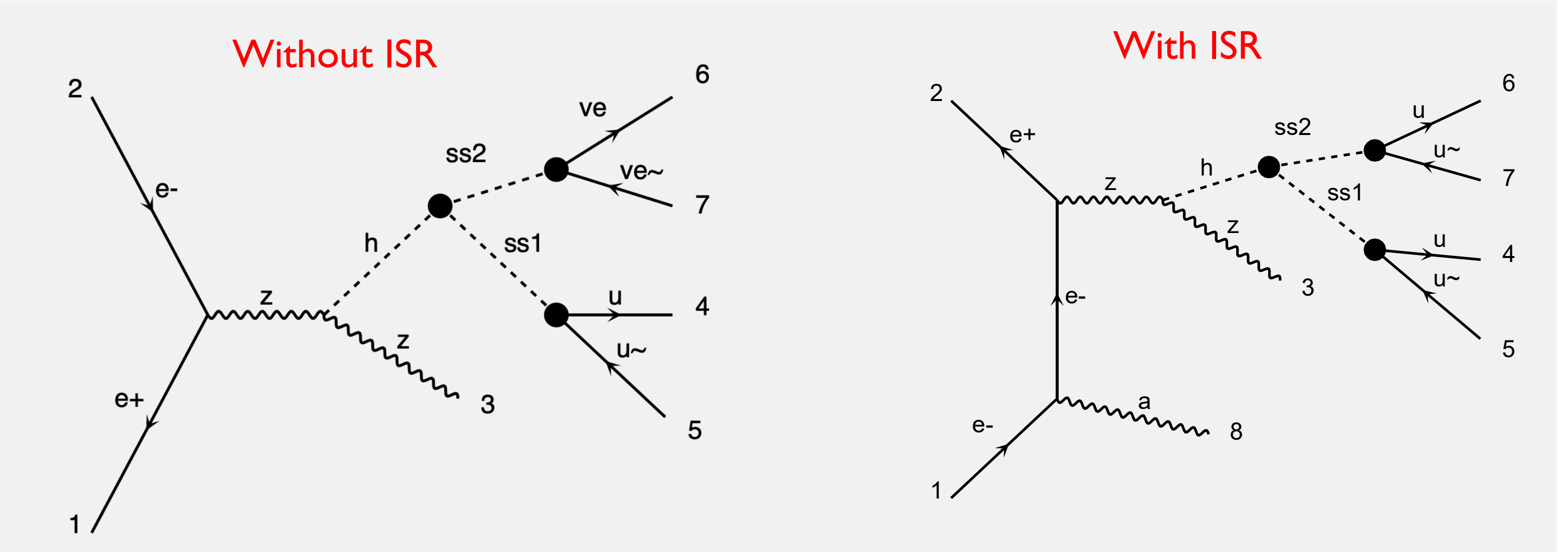
Decay back to SM
Can be long lived.
cτ can be 1 km or more

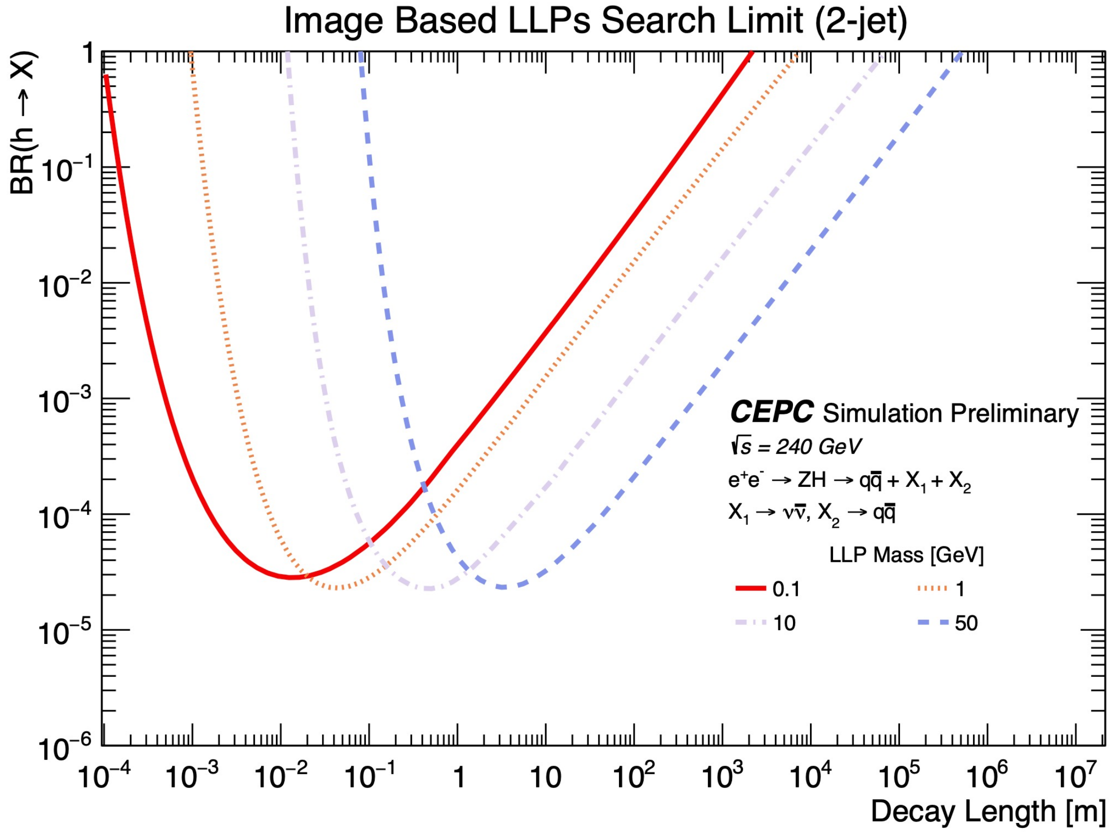




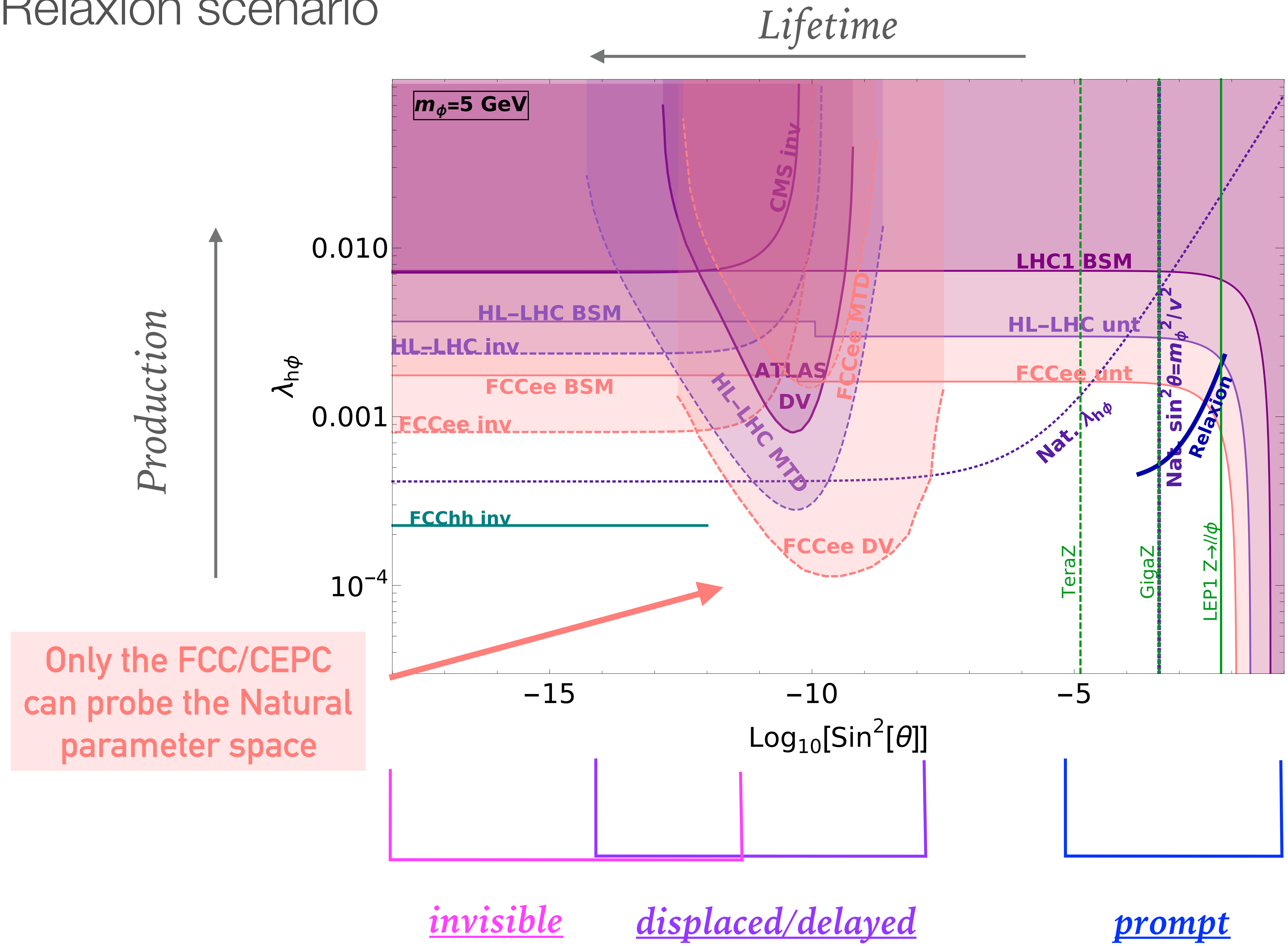
A recent study for CEPC

Yuelei Zhang, Xiang Chen, Jifeng Hu, Liang Li





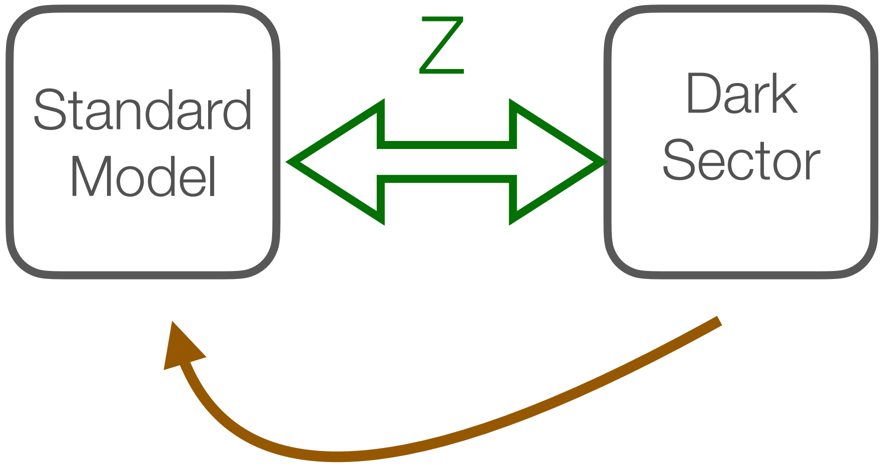
Relaxion scenario



Alipour-Fard, Craig, Jiang, Koren, 1812.05588
Banerjee, Matsedonskyi, Kim, Perez, Safronova, 2004.02899
Fuchs, Matsedonskyi, Savoray and Schlaffer, 2008.12773

Talk by Savoray at CEPC 2021 workshop

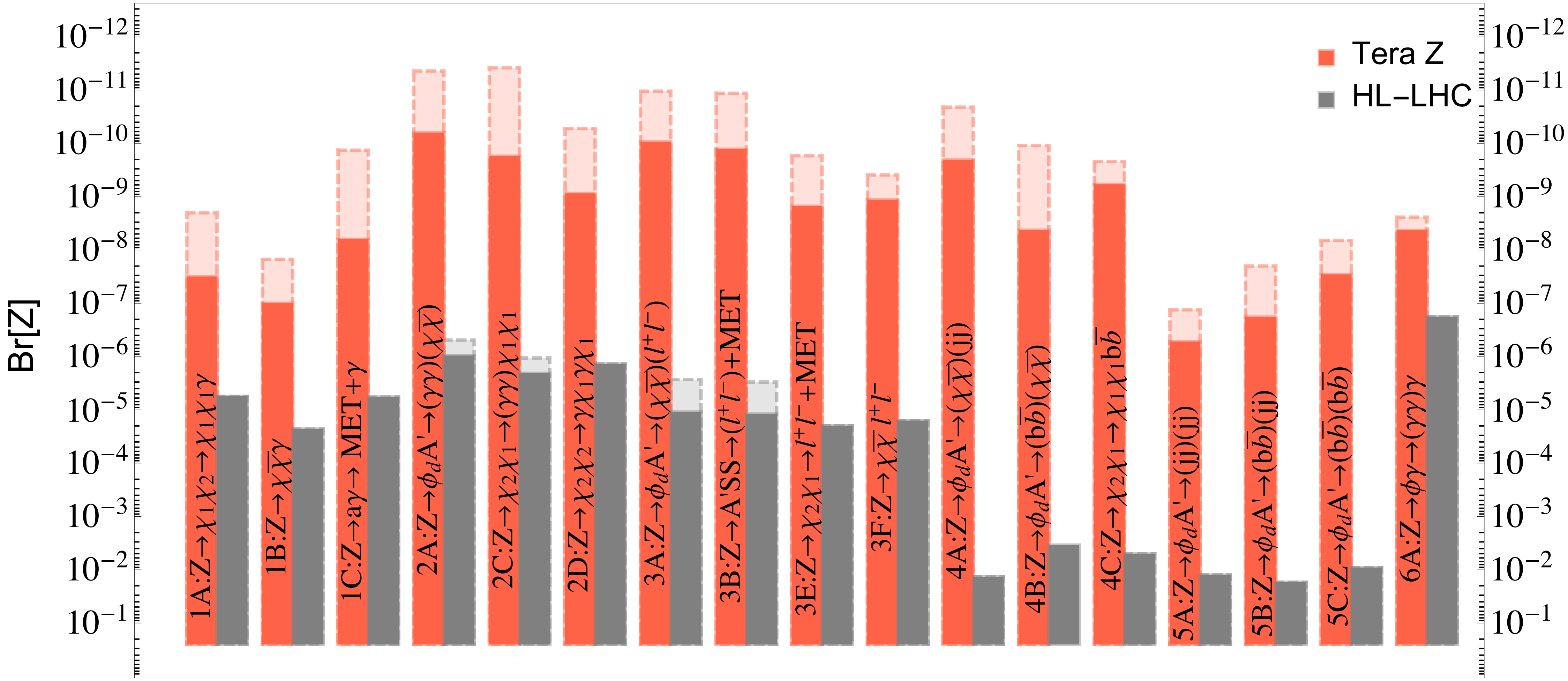
Z decay



- 10^{12} Zs at the CEPC goes a long way in probing the dark sector.

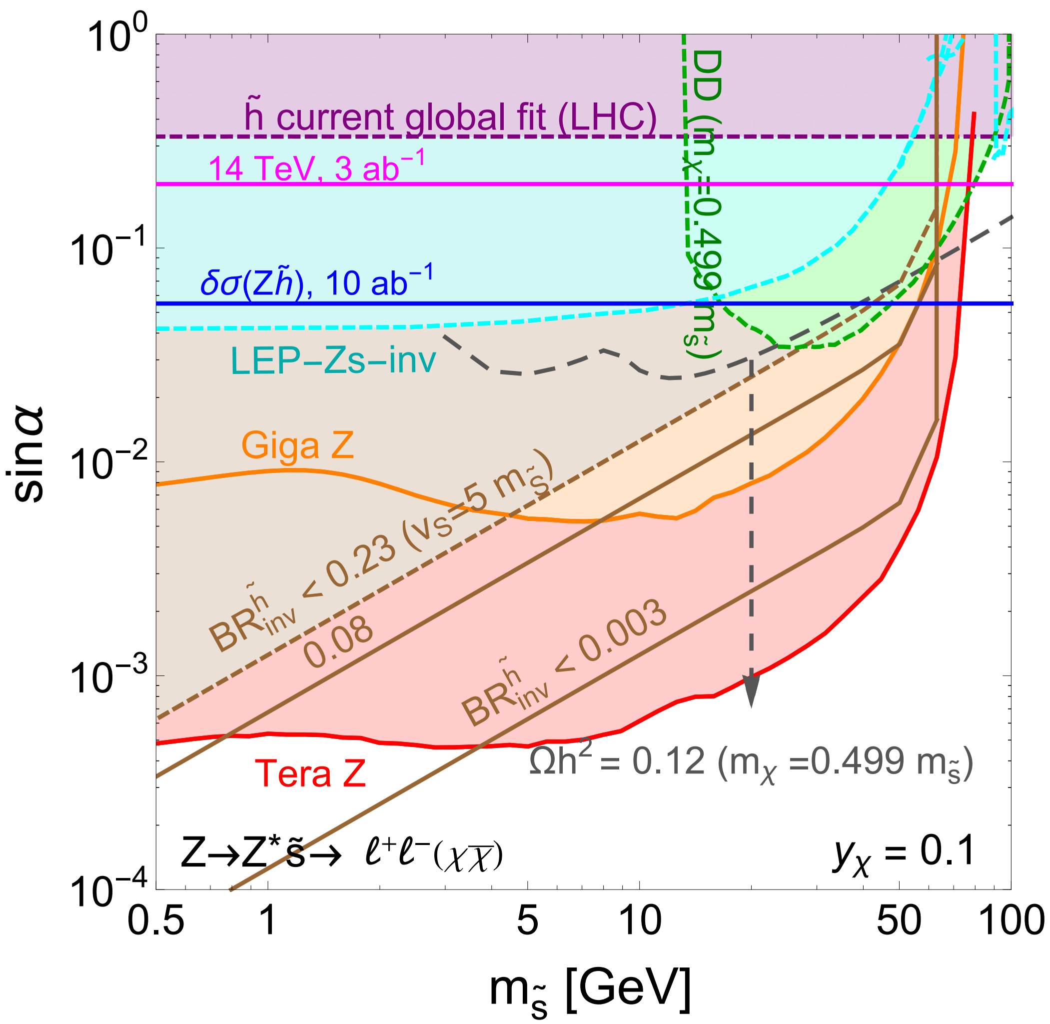
Rare Z decay

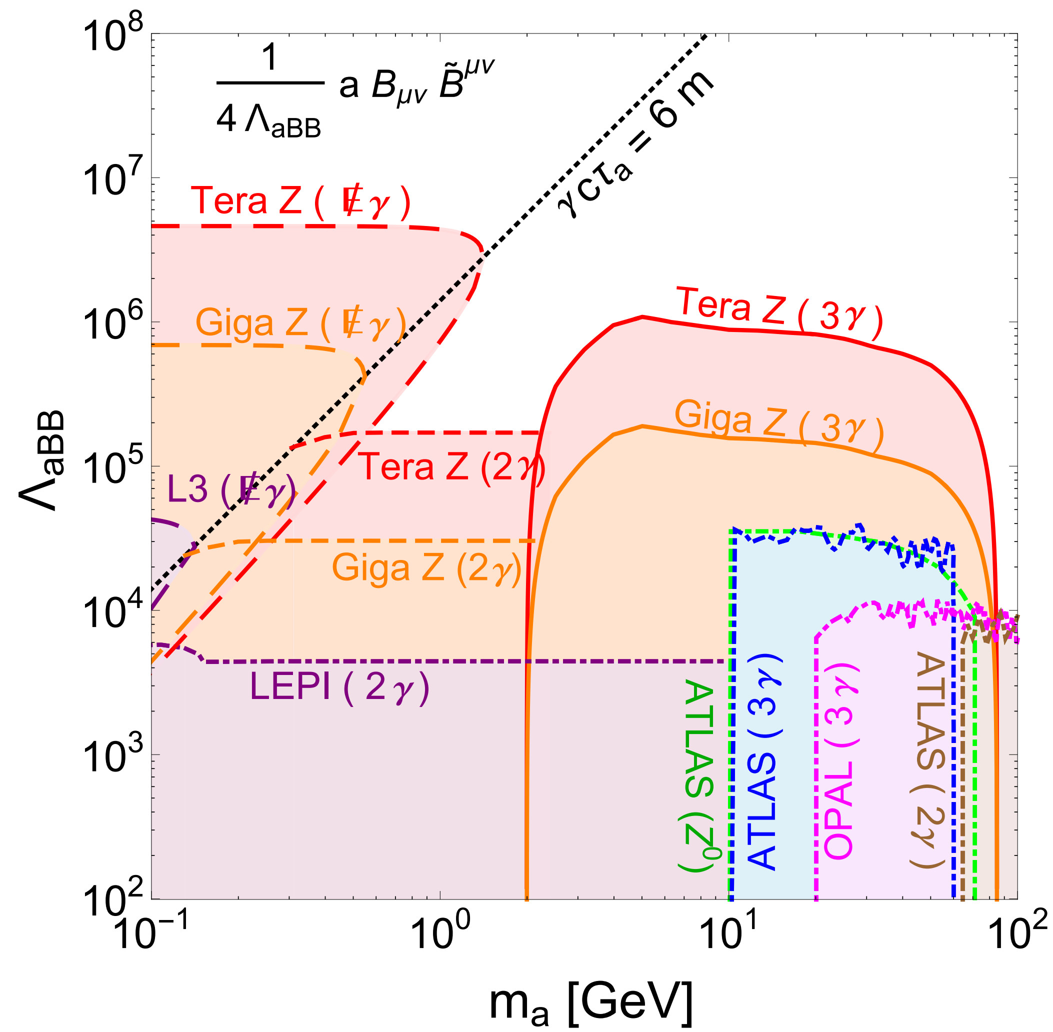
J. Liu, X.P. Wang, W. Xue, LTW



Window into dark sector

J. Liu, X.P. Wang, W. Xue, LTW

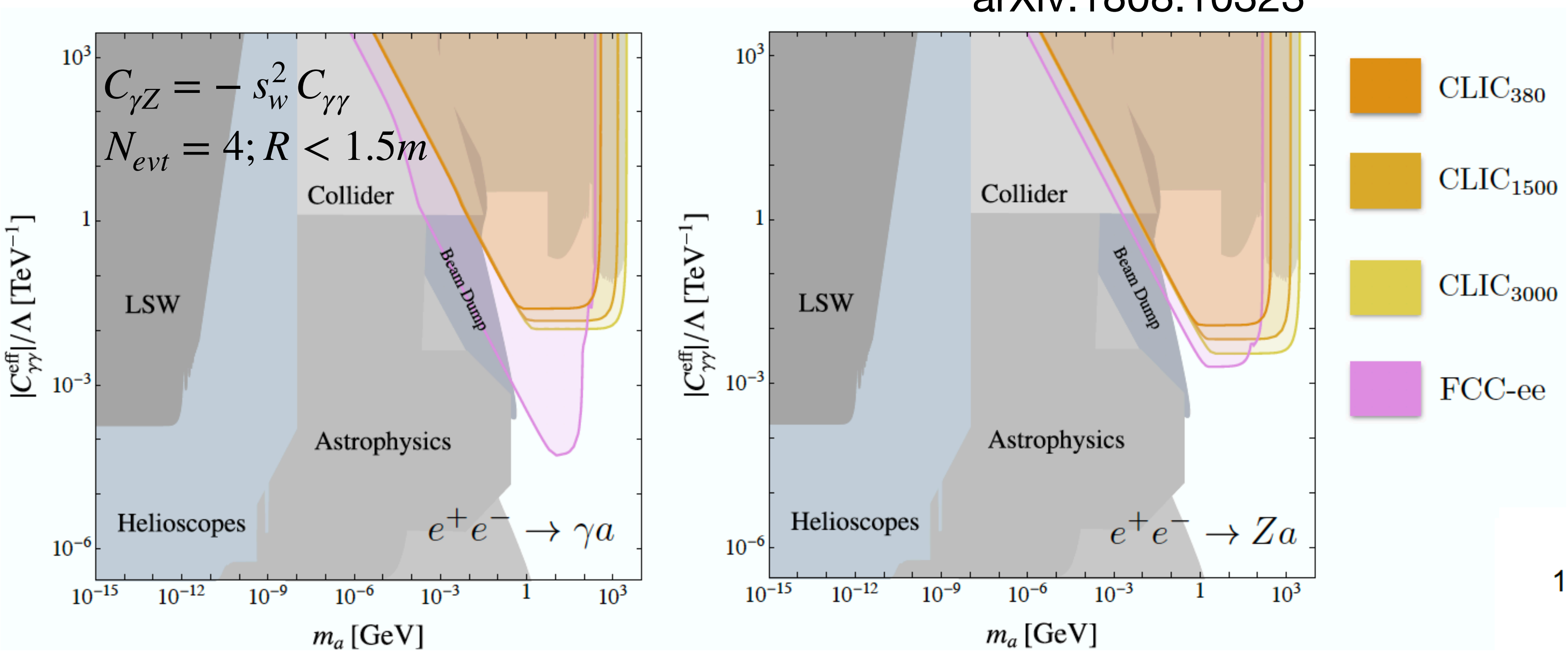


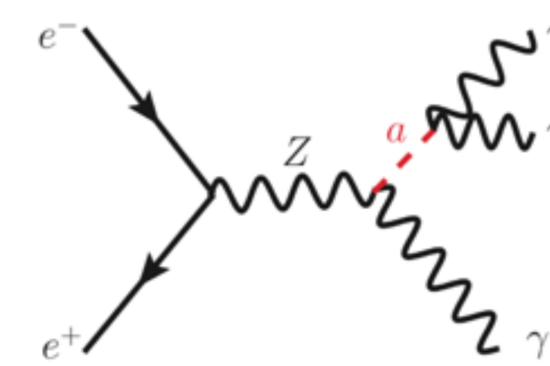


There are certainly many more scenarios to explore here.

ALPs

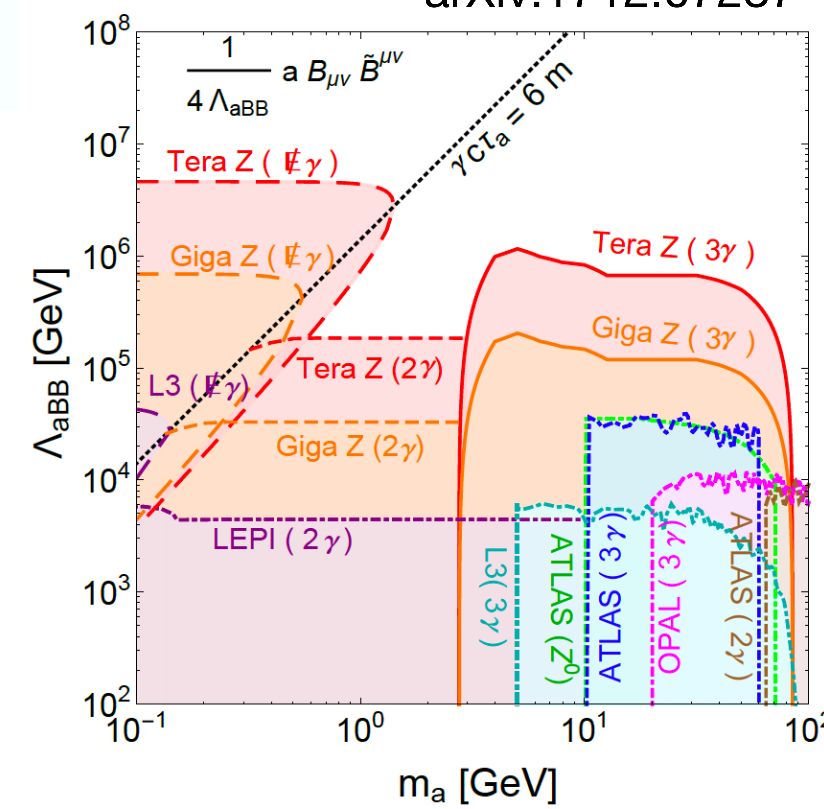
arXiv:1808.10323



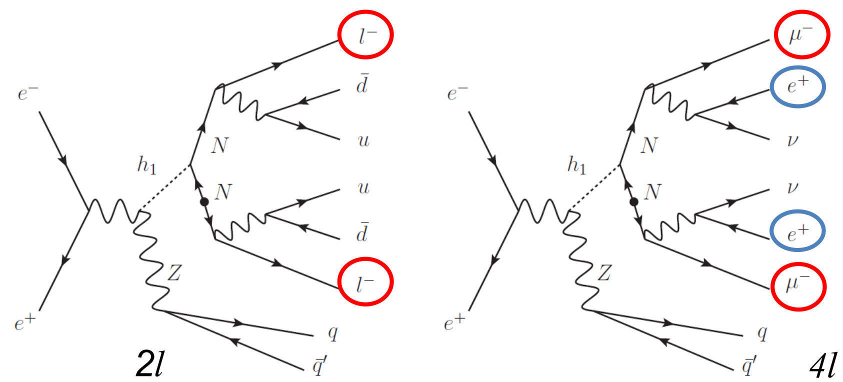


Lepton collider can be complementary to other probes.

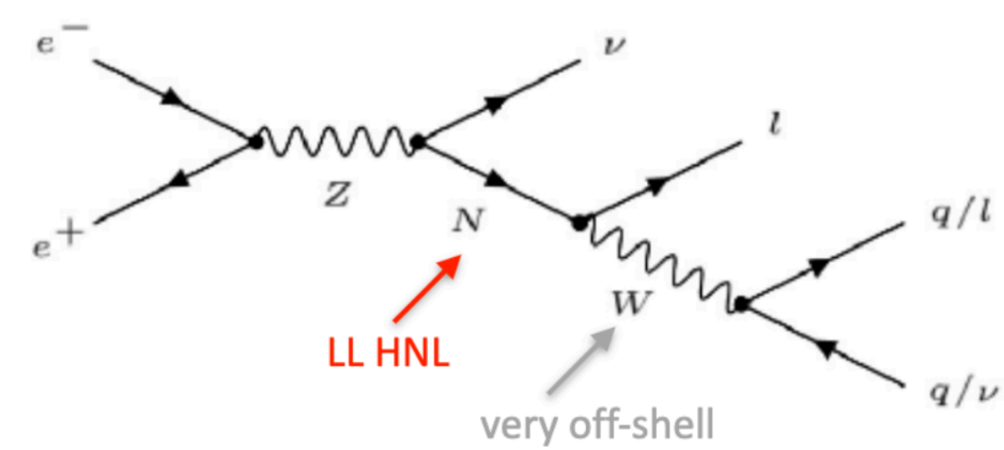
arXiv:1712.07237

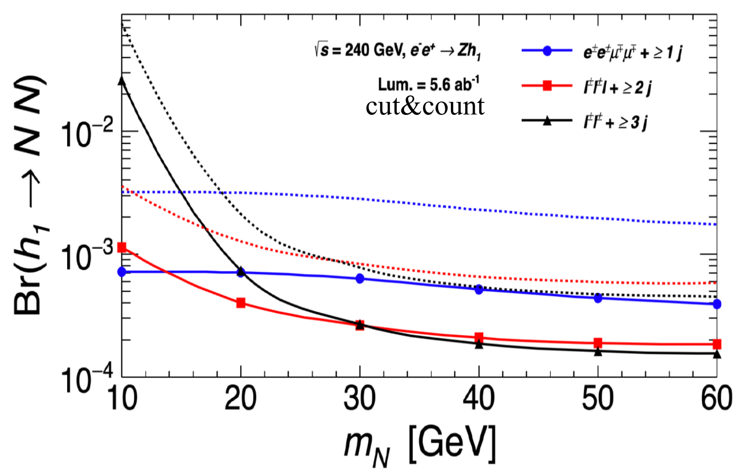


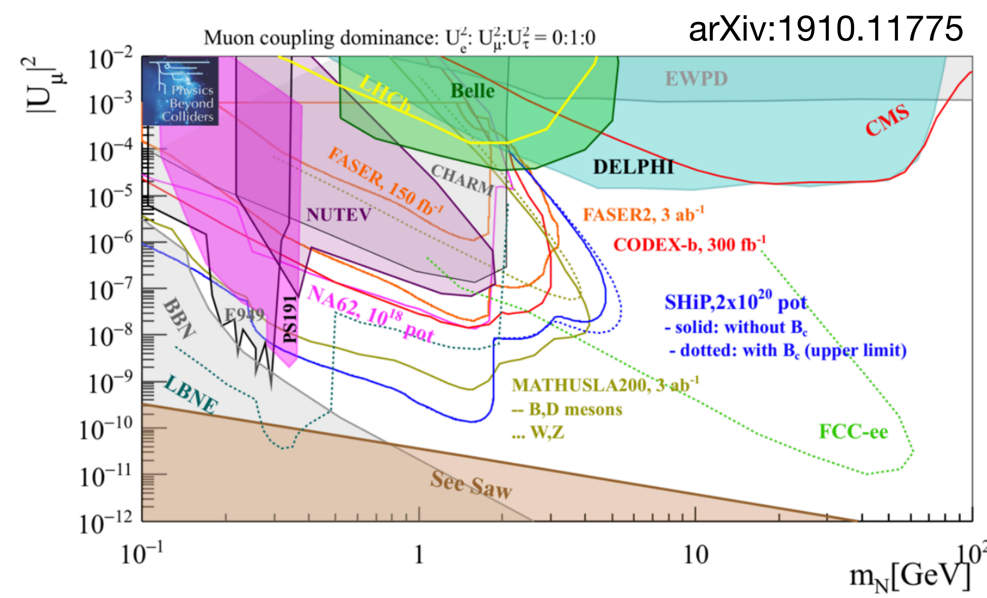
Heavy neutrino

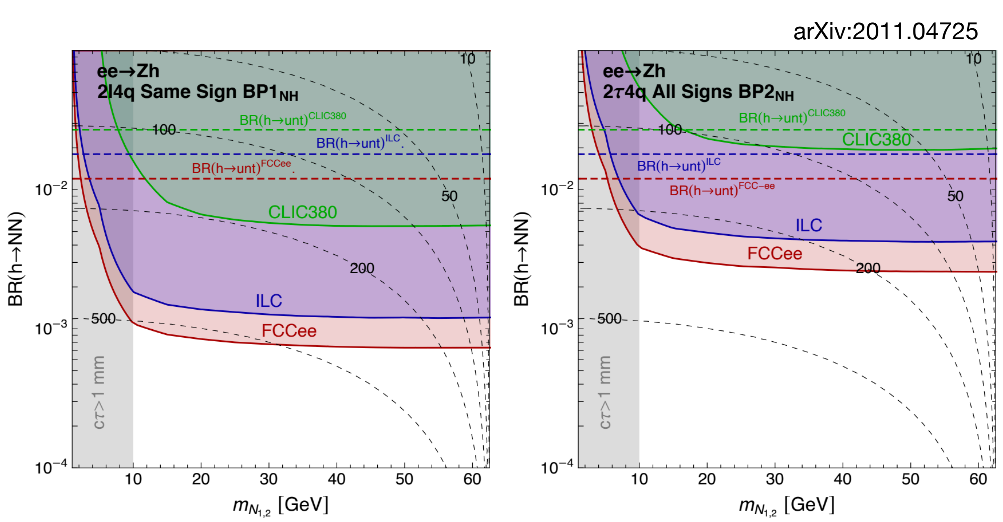


Y. Gao and K. Wang, 2102.12826









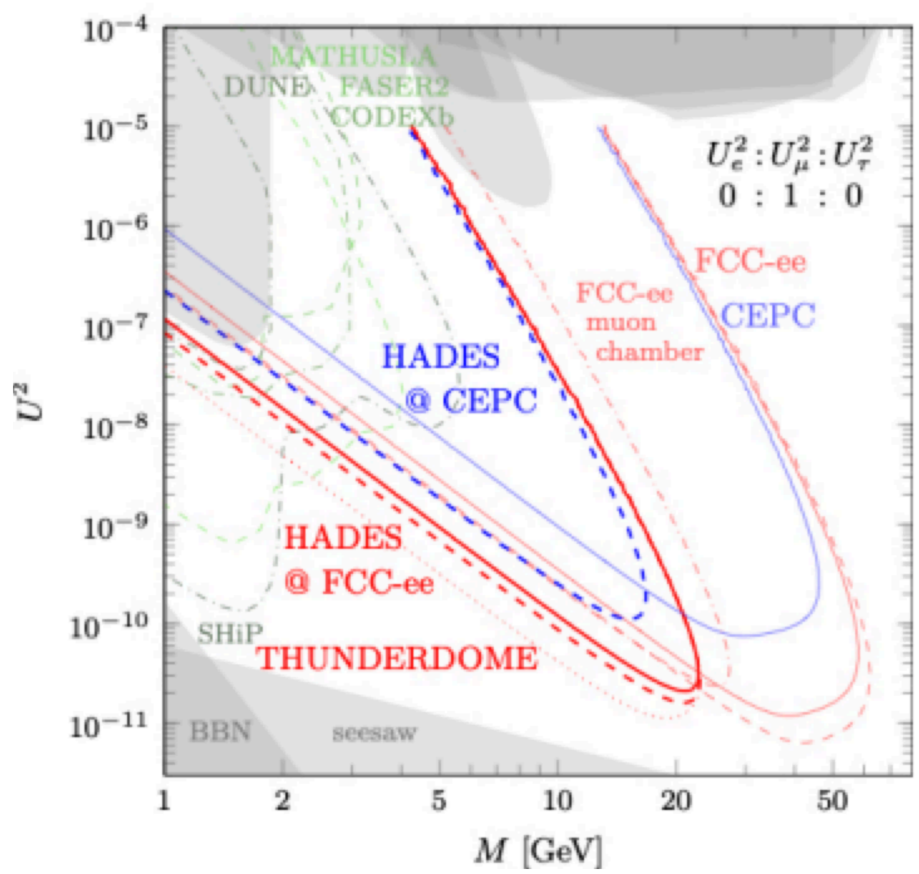
New detectors

- LHC has proposals for dedicated detectors of LLP searches.
  - CODEX, FASER, MATHUSLA.
- Similar for lepton colliders?

An example proposal: HADES

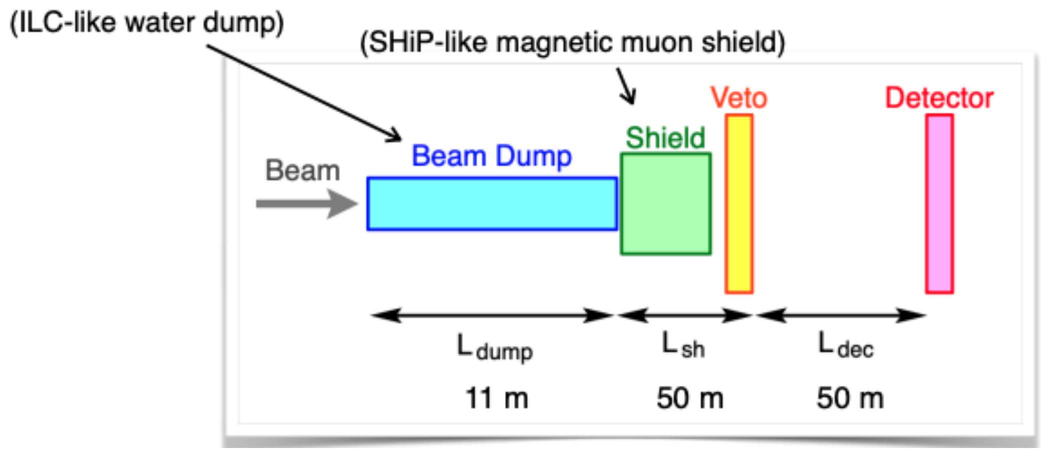
With extra instrumentation of detector cavern walls

2011.01005

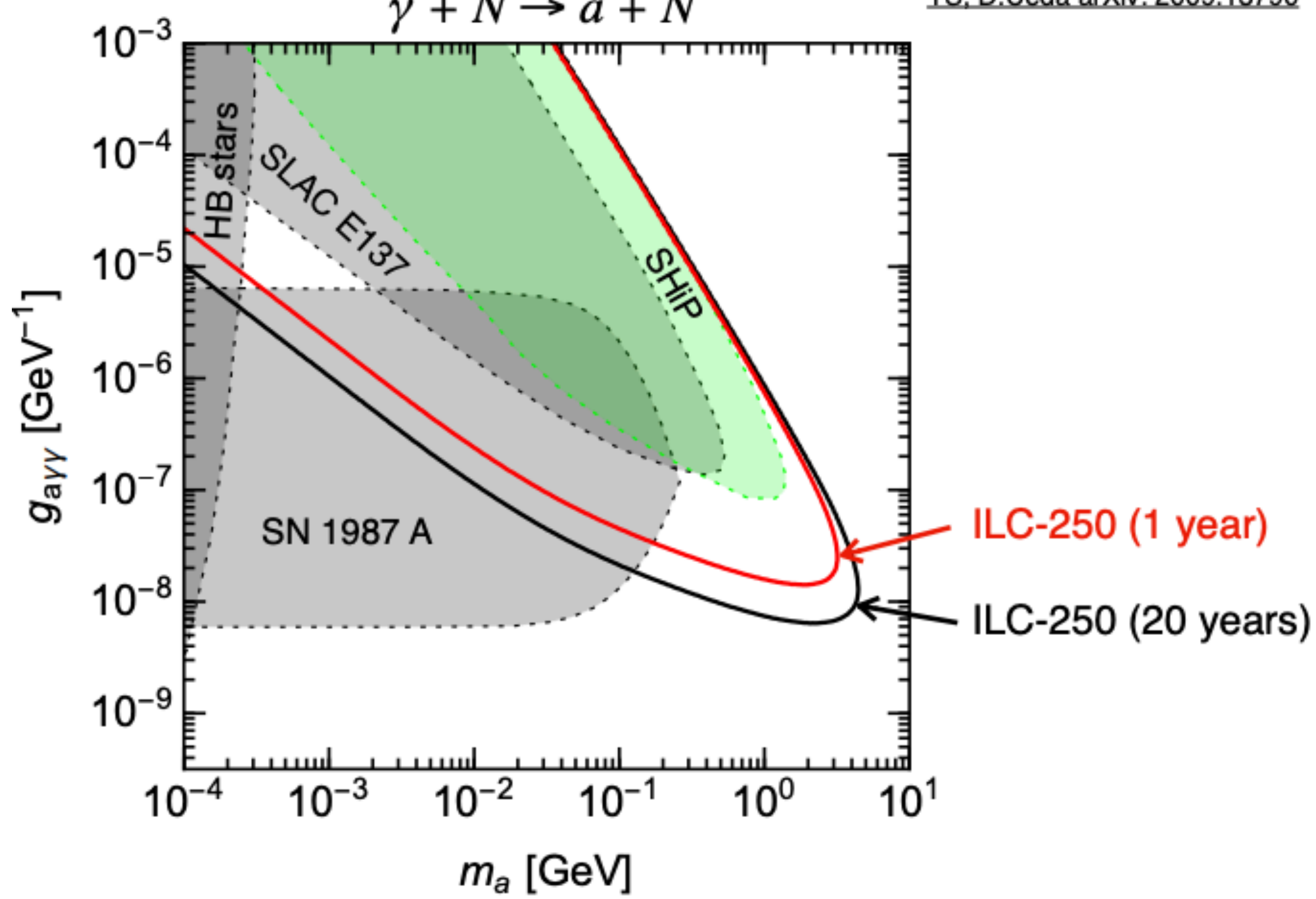


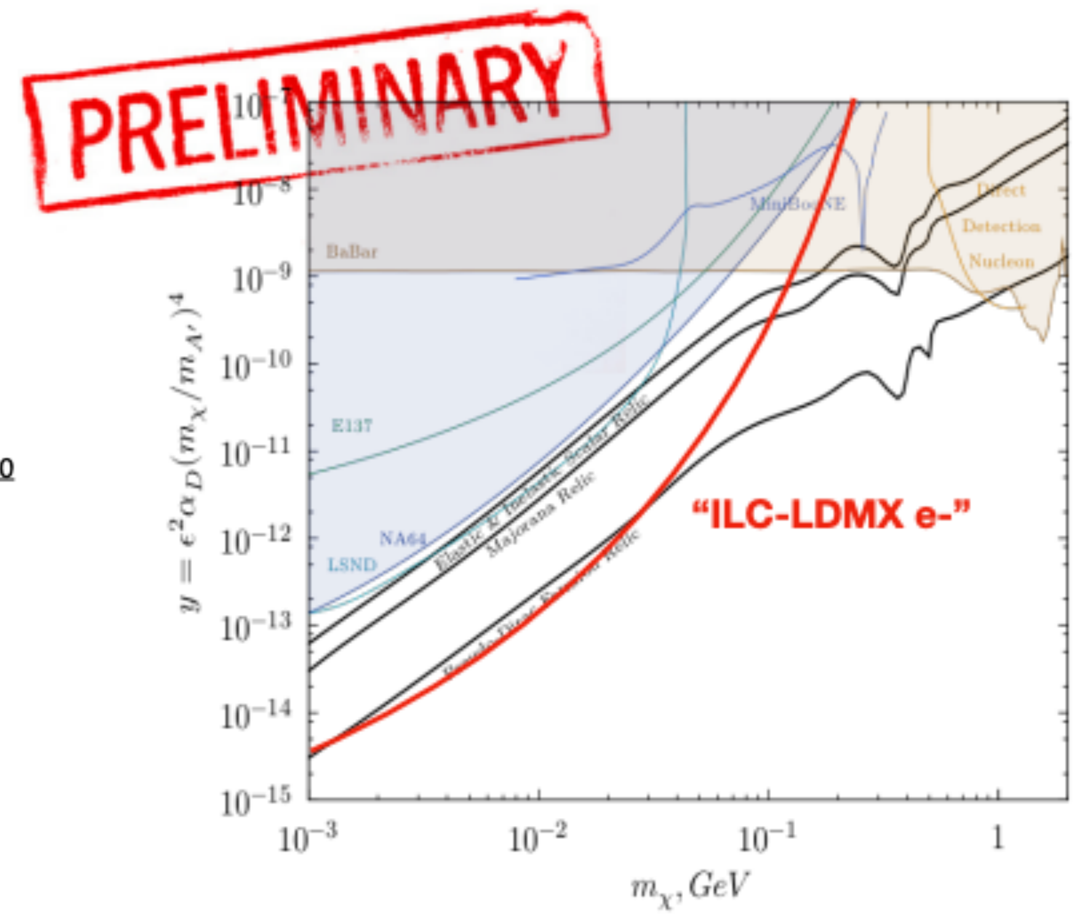
Beam dump?

Kanemura, Moroi, Tanabe, 1507.02809



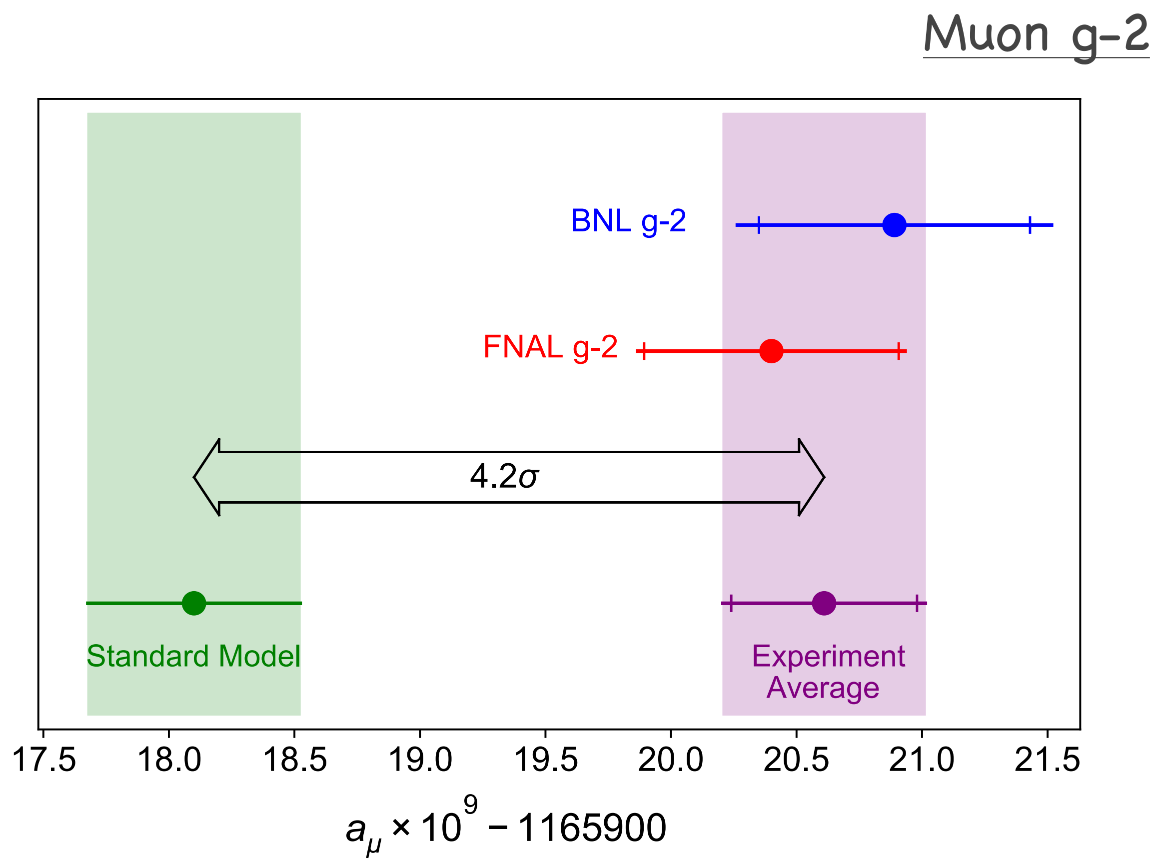
YS, D.Ueda arXiv: 2009.13790





Talk by M. Perelstein at LCWS 2021

IF:



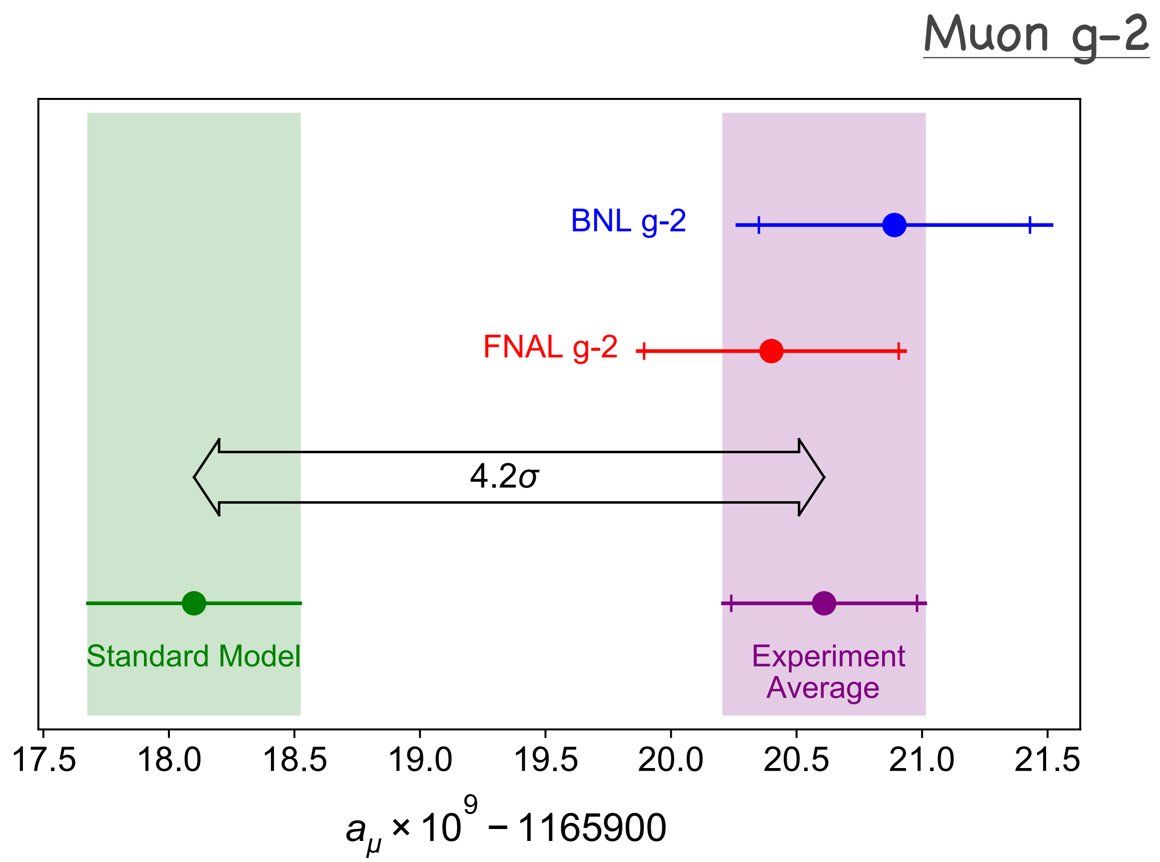
$$\mathscr{L} \supset \frac{e}{16\pi^2}\frac{m_\mu}{M_{\rm NP}^2} H\bar{L}\sigma_{\mu\nu}\mu_R F^{\mu\nu} \;\rightarrow\; \delta a_\mu \simeq \frac{e}{16\pi^2}\frac{m_\mu^2}{M_{\rm NP}^2}$$

Disagreement with SM

$\Rightarrow$ 1-loop contribution $M_{NP} \sim 300$ GeV.

Or, 2-loop contribution, $M_{NP} \sim 30$ GeV.

IF:



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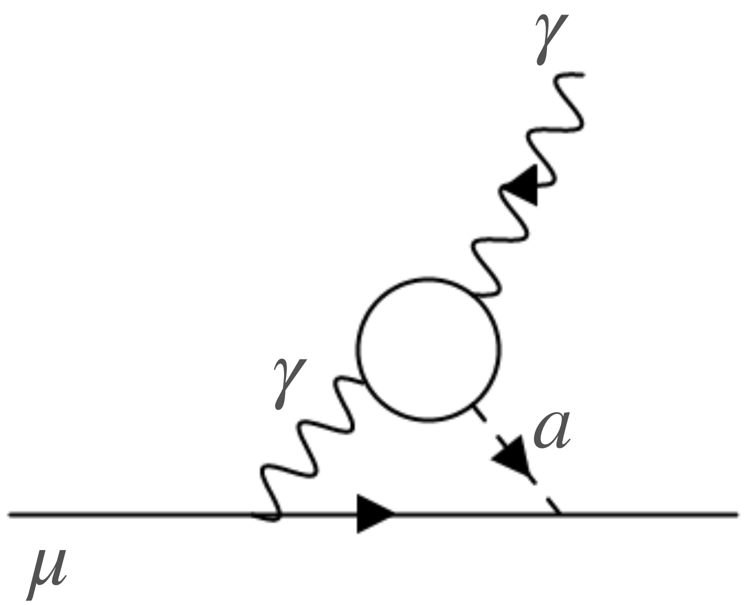
Disagreement with SM

$\Rightarrow$ 1-loop contribution $\boxed{M_{NP} \sim 300 \text{ GeV.}}$

Or, 2-loop contribution, $M_{NP} \sim 30$ GeV.

A suite of sensitive searches and measurement at lepton colliders.

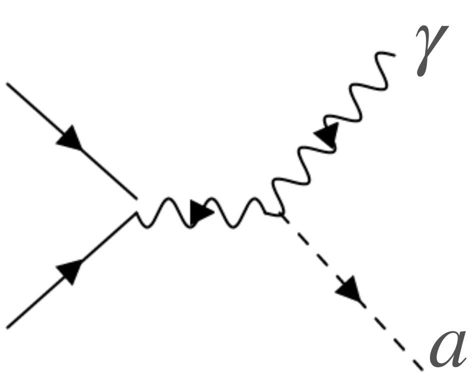
Example: 2-loop

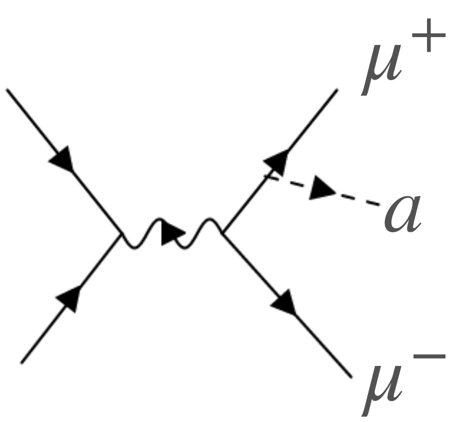


a : axion-like particle, pseudo-scalar Higgs, …

$m_a < 100$ GeV

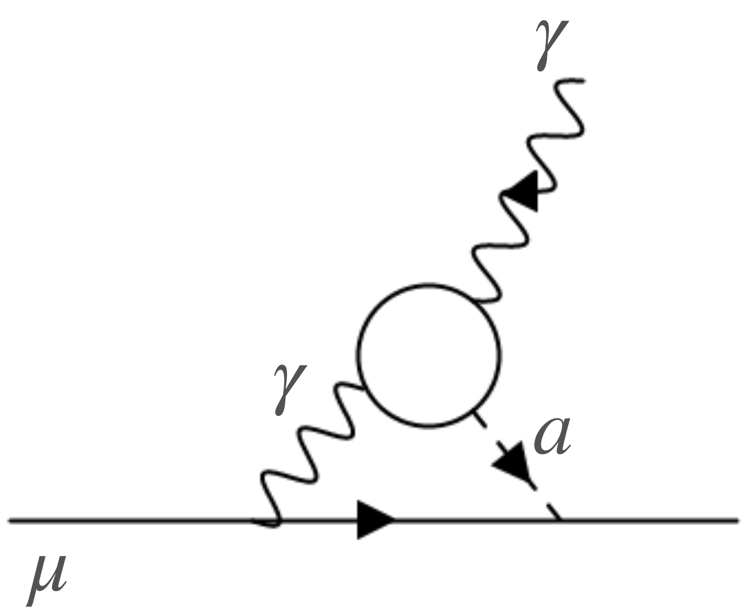
LHC discovery difficult.





Tiny rate (∼ab), large background

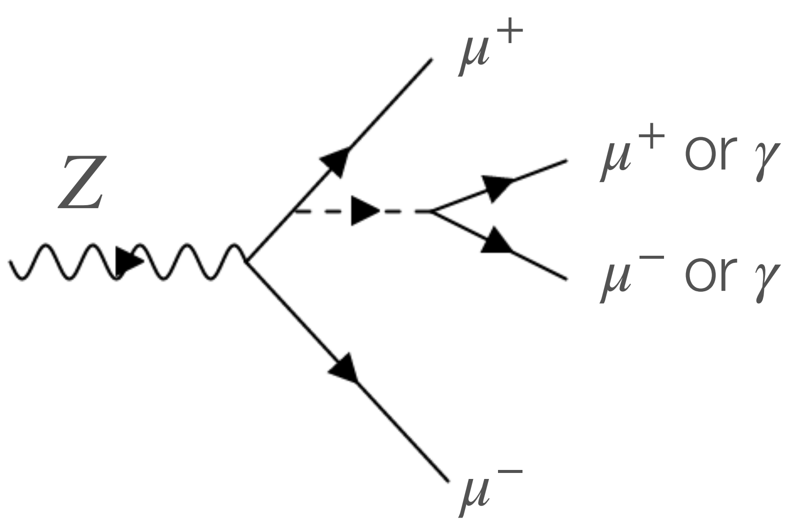
2-loop



$\boldsymbol{a}$: axion-like particle, pseudo-scalar Higgs, …

$m_a < 100$ GeV

CEPC:



BR($Z \to 4\mu$ or $2\mu 2\gamma$) $\sim 10^{-7}$

Within the reach of Tera Z.

Somewhat more model dependent: $Z \to 3\gamma$ can also be sensitive.

B, charm, hadron, τ

Particle production

Particle	@ Tera-Z	@ Belle II		@ LHCb
***b* hadrons**				
B^+	6×10^{10}	3×10^{10}	$(50\,\mathrm{ab}^{-1}$ on $\Upsilon(4S))$	3×10^{13}
B^0	6×10^{10}	3×10^{10}	$(50\,\mathrm{ab}^{-1}$ on $\Upsilon(4S))$	3×10^{13}
B_s	2×10^{10}	3×10^{8}	$(5\,\mathrm{ab}^{-1}$ on $\Upsilon(5S))$	8×10^{12}
b baryons	1×10^{10}			1×10^{13}
Λ_b	1×10^{10}			1×10^{13}
***c* hadrons**				
D^0	2×10^{11}			
D^+	6×10^{10}			
D_s^+	3×10^{10}			
Λ_c^+	2×10^{10}			
τ^+	3×10^{10}	5×10^{10}	$(50\,\mathrm{ab}^{-1}$ on $\Upsilon(4S))$	

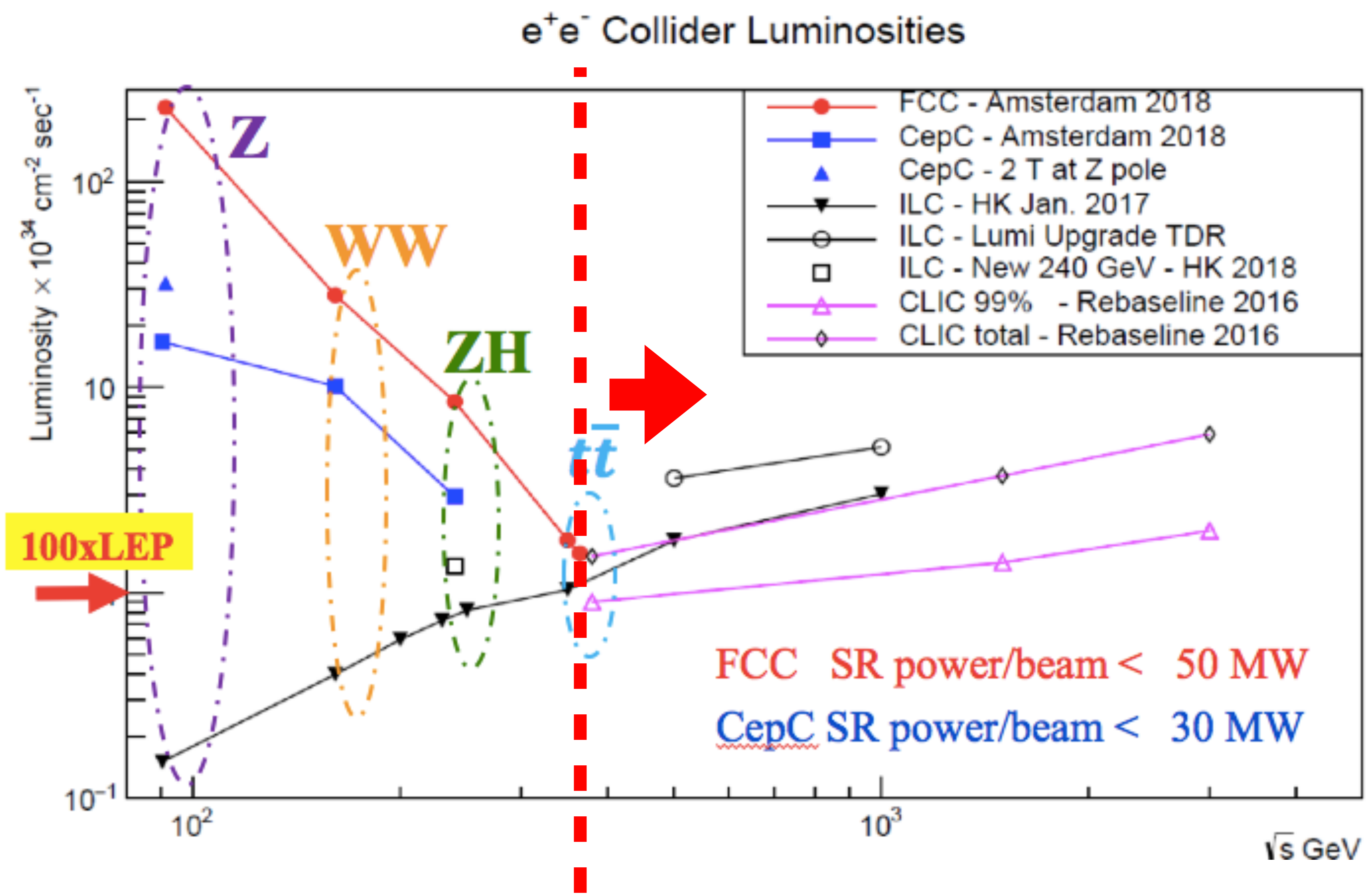
From CEPC's CDR using fragmentation ratios from Amhis et al, 17

- Similar statistical sample of $B^{0,\pm}$, τ's at Belle 2 and CEPC
- Two order of magnitude more B_s at CEPC wrt to Belle 2
- b-baryon physics possible at the CEPC
- Limited possibilities for charm physics at Belle 2

Great place to probe rare flavor processes!

See talk by L. Li in this session

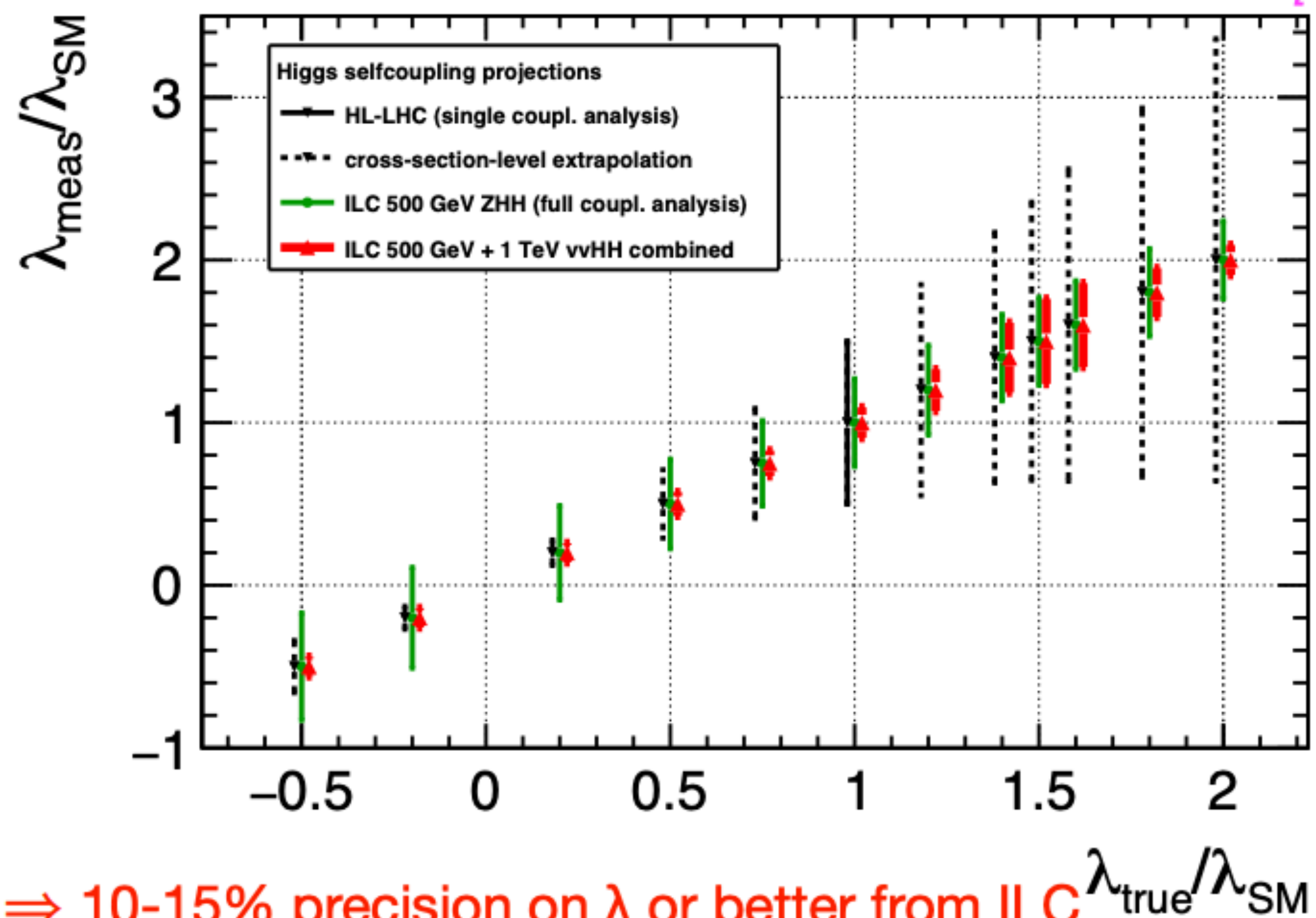
Higher energies beyond top threshold



What are the physics targets?

500 GeV (maybe up to 1 TeV) Self couplings

[J. List et al. '21]

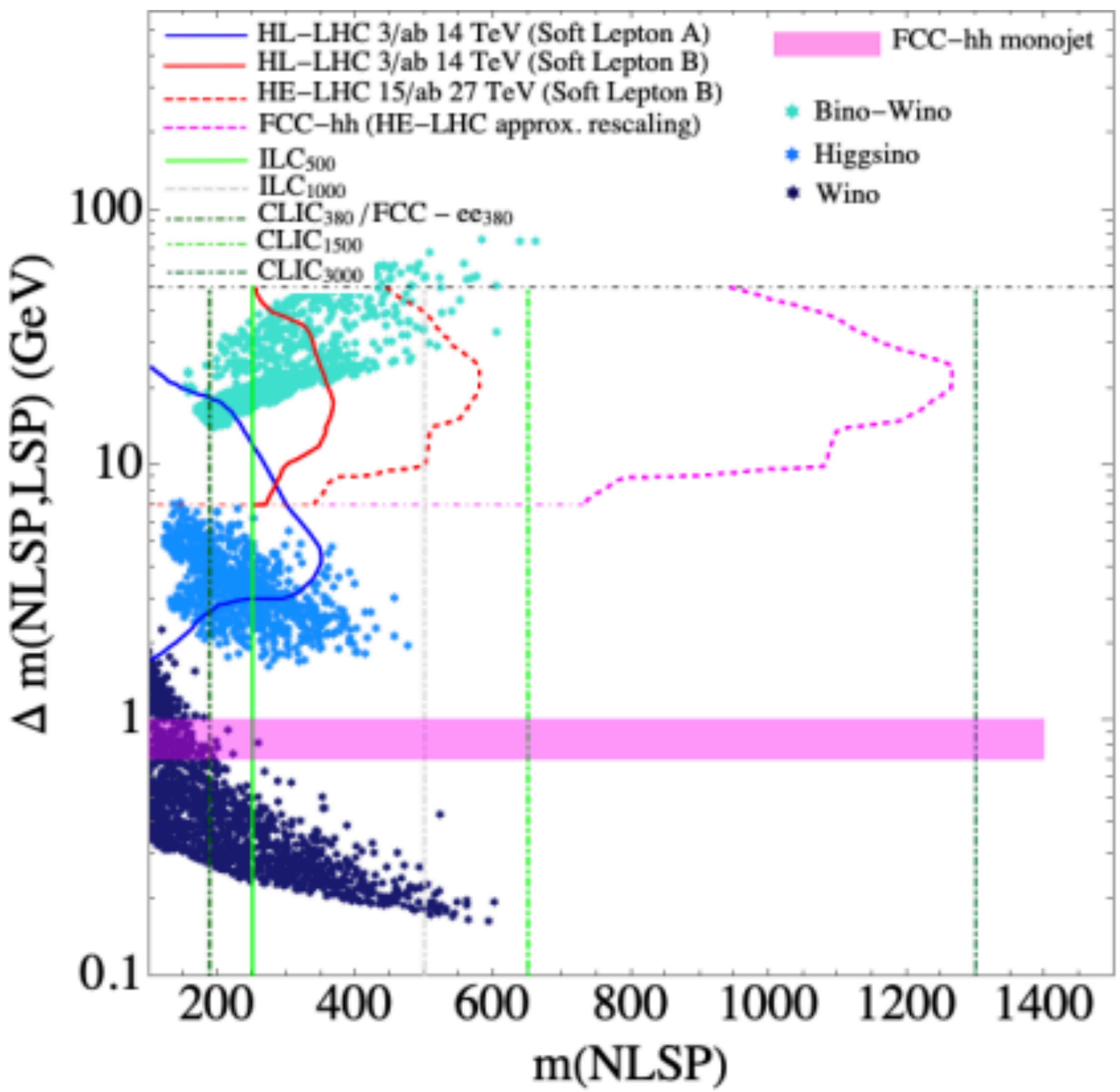


⇒ 10-15% precision on λ or better from ILC with ZHH (500 GeV) + ννHH (1 TeV)

To a few TeV

* Direct SUSY, composite, extra Higgs boson, …up to kinematic threshold.

g-2 motivated?



Breggren ' 20

To a few TeV

- Direct SUSY, composite, extra Higgs boson, …up to kinematic threshold.
- WIMP dark matter (only the Higgsino case, others need higher energy).
- EFT type of measurements. Probing a scale about 10(s) TeV.

Certainly great to have this.
Need more thinking to have a stronger physics case.

Conclusions

- The main physics goal: precision measurement of Higgs.
  - Well documented. Refinement underway.
- Still have many topics open to explore.
- New searches, new detectors. All enriching the physics program, opening up new opportunities.
  - Great opportunities to make progresses.