Physics at CEPC & SPPC

- Current Status & Future Plan

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Outline

★ Success of Standard Model

★ Questions in Fundamental Physics
★ Motivation by BSM Physics
→ SM not end, need new collider

★ Physics at High Energy Colliders
- CEPC (Z & H Factories), SPPC

★ Current Status

★ Future Work

★ Conclusion

Important Statement

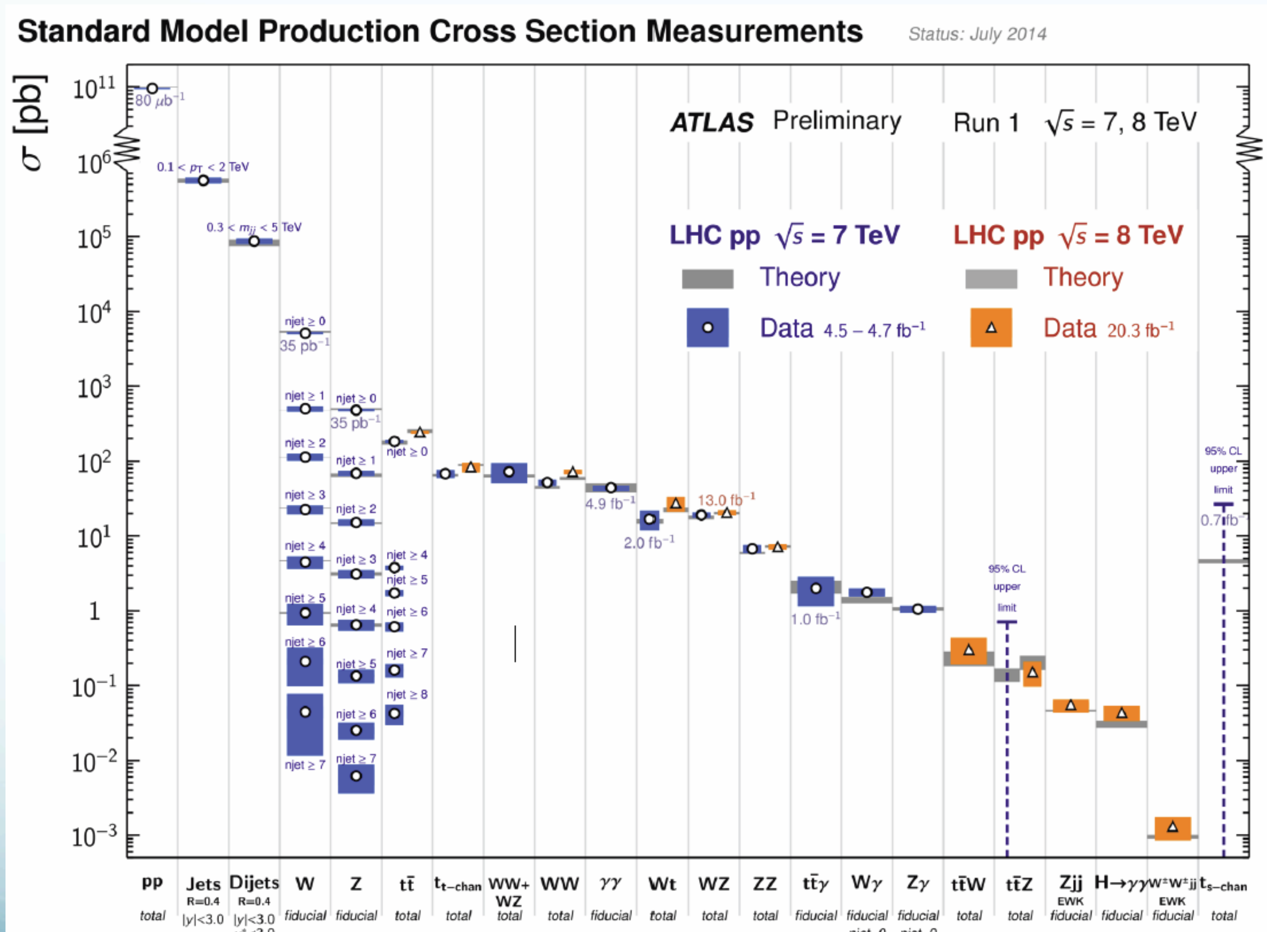
✧ Framework, not details

✧ Questions, not answers

✧ Incomplete, not perfect

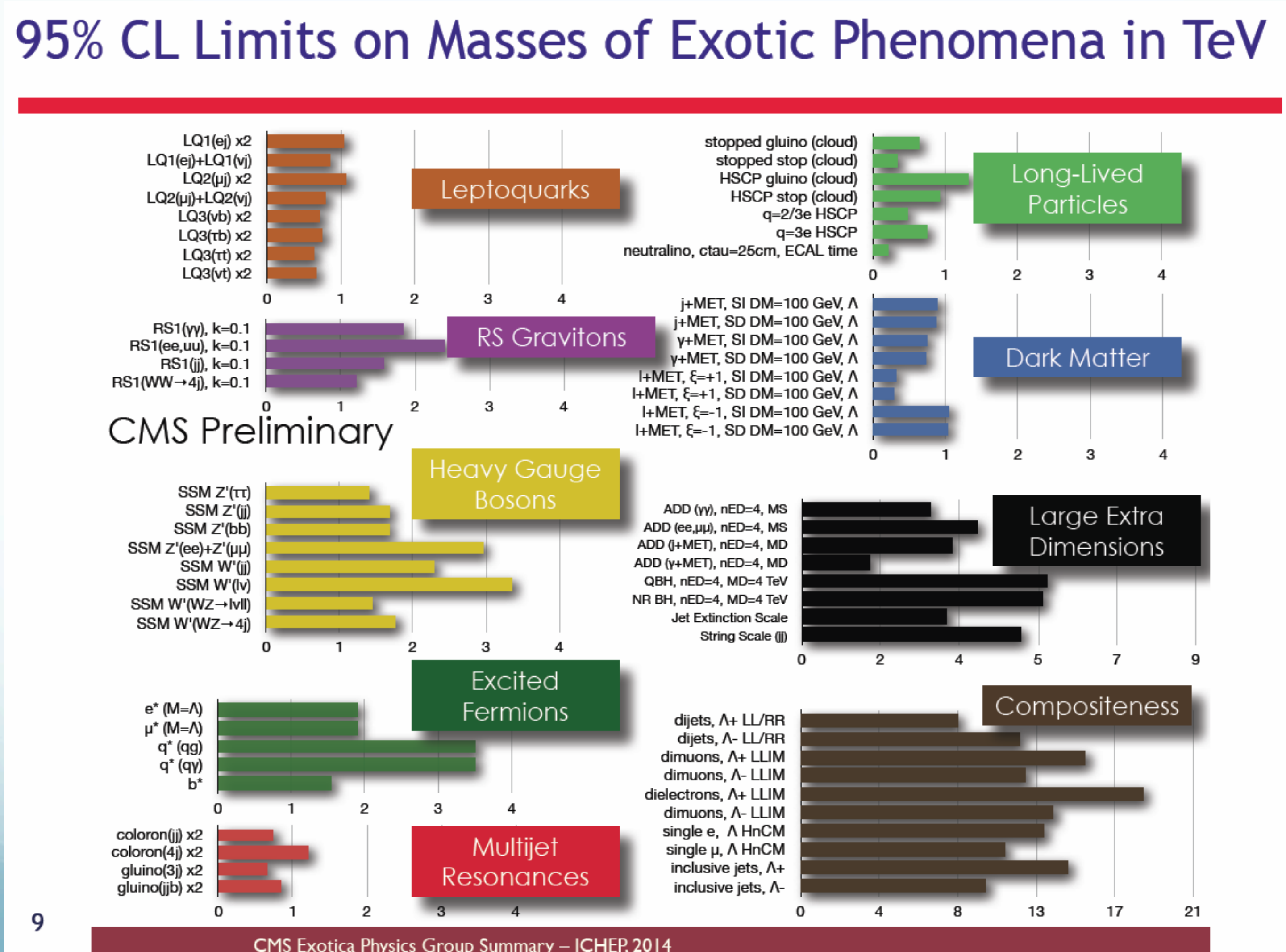
Success of Standard Model

SM Deepest Tests by LHC



Success of Standard Model

No Hints of New Physics after Run 1

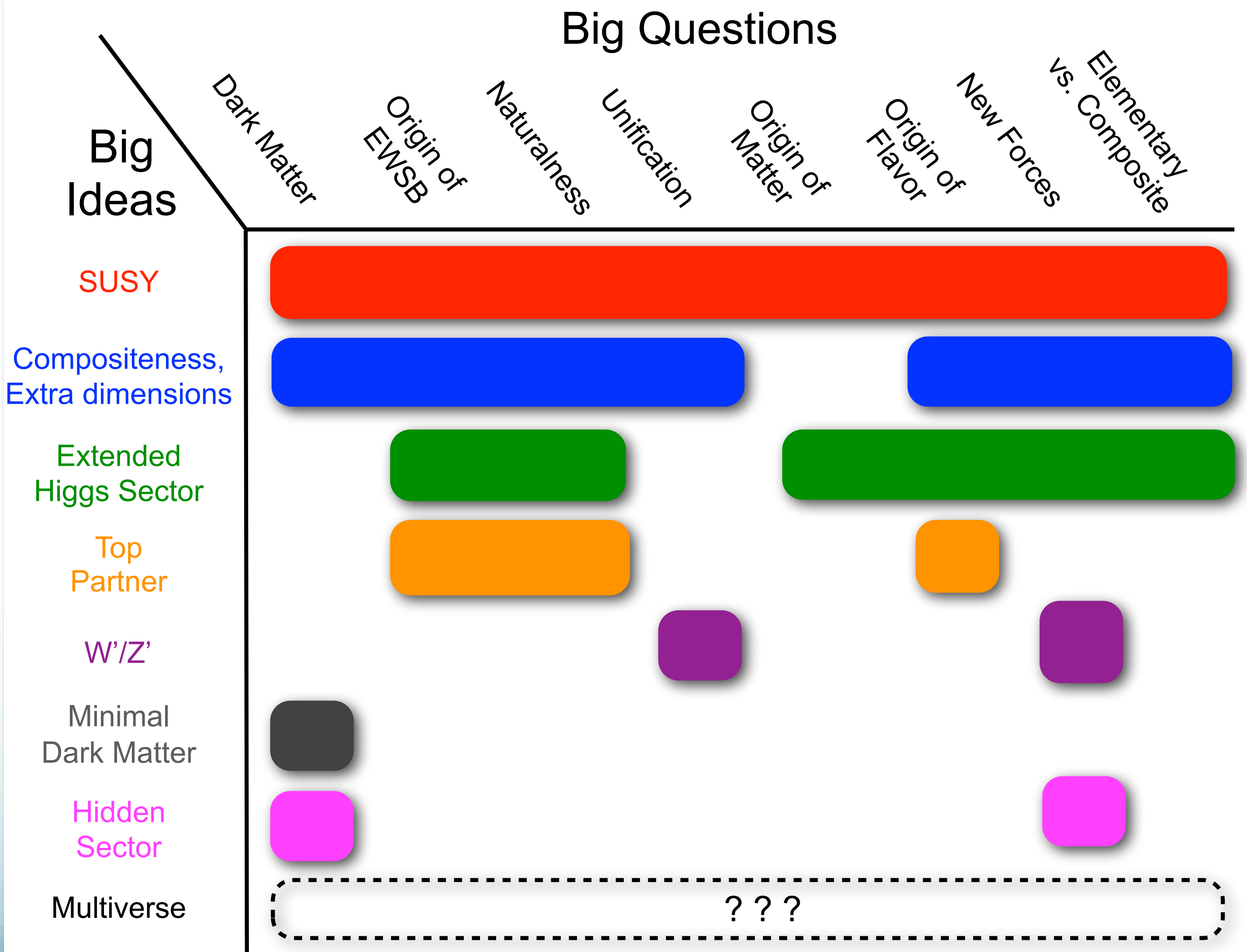


Questions in Fundamental Physics

Experiment:
Dark Matter,
Dark Energy,
Muon g-2, neutron EDM,
Baryongenesis

Theory:
Naturalness,
Neutrino Mass & Oscillation,
Flavor,
EWPT,
Quantum Gravity, Unification,

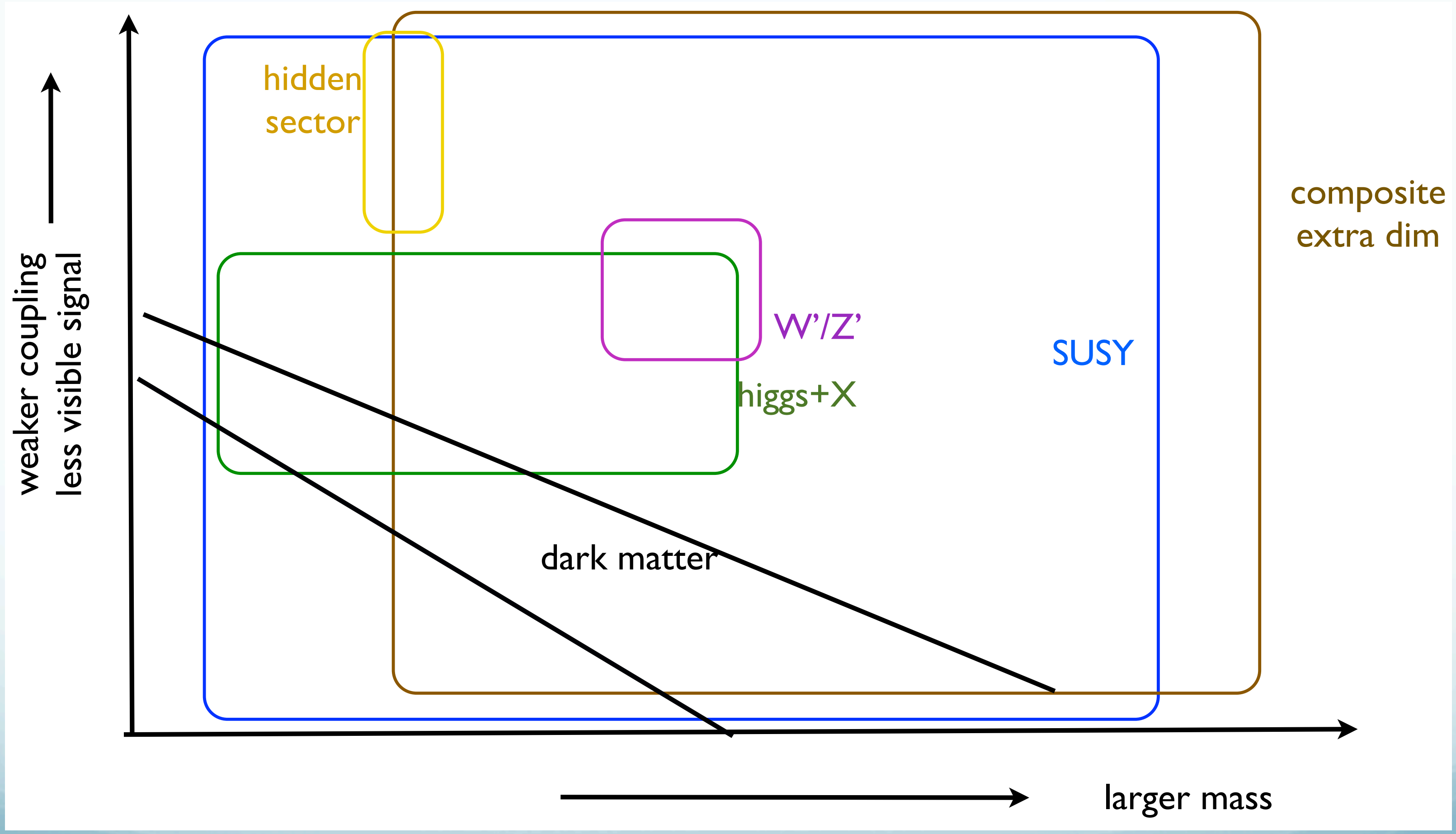
New Theory Market



Snowmass new physics working group report

New Theory Market

[from Liantao Wang]



Experiments Sensitive to New Theories

→ High Energy Collider experiments

→ Neutrino experiments
(oscillation, telescope, ...).

→ Dark matter searches
(Direct like LUX & Indirect like AMS, ...).

→ Muon magnetic moment measurement

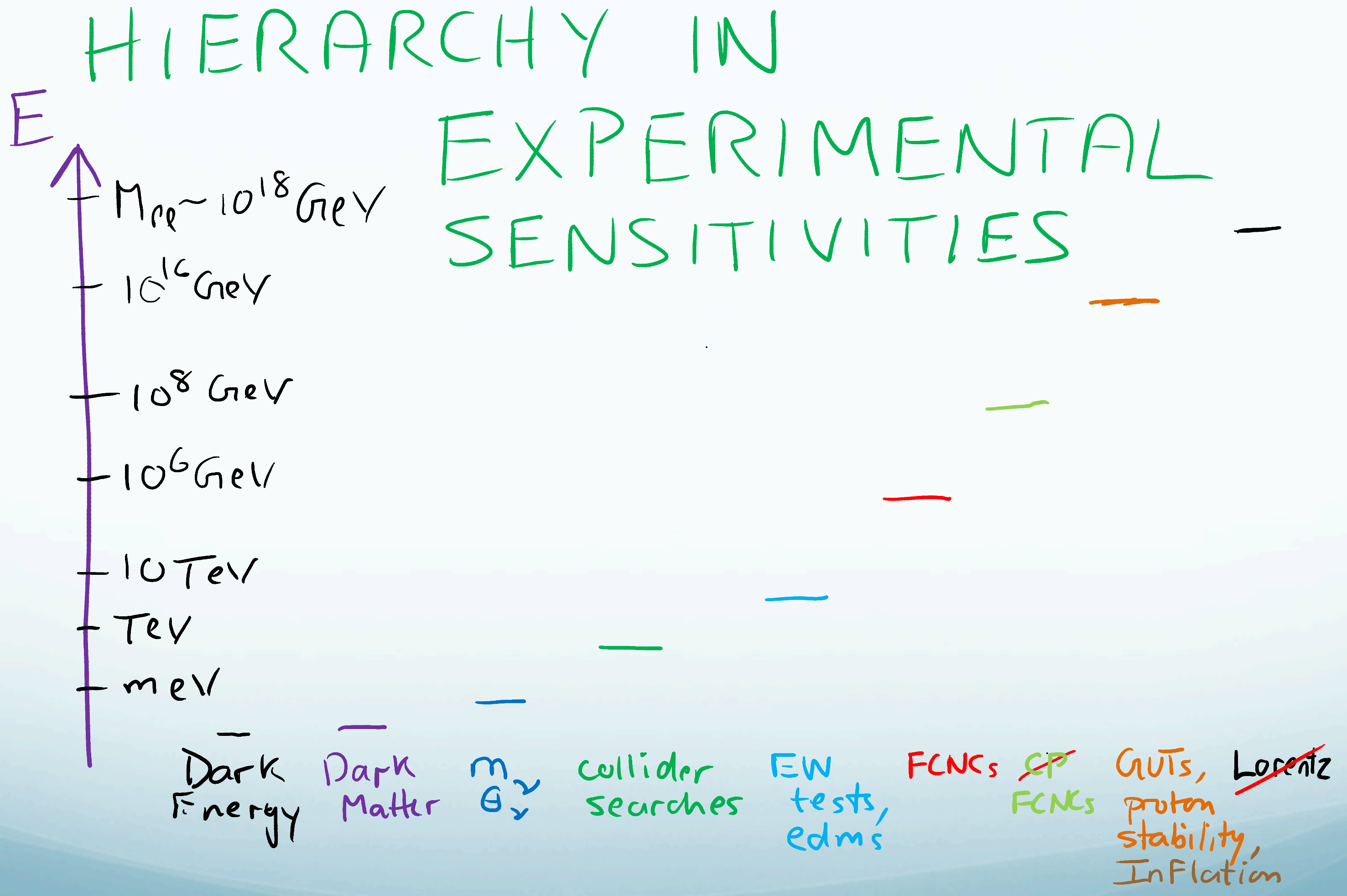
→ Flavor physics experiment (B physics, ...)

→ Astrophysics experiment
(CMB, BICEP, Dark Energy Survey, ...).

→ Gravitational wave searches

Experiment Sensitivity to New Theories

[plot from Raman Sundrum]



Possible BSM Status after LHC

We are potentially on the edge of an important discovery / breakthrough.
Next Higher energy Collider is a powerful & straightforward Tool for BSM Physics.

Future Lepton Collider (FLC) & Future Hadron Collider (FHC) complement each other.

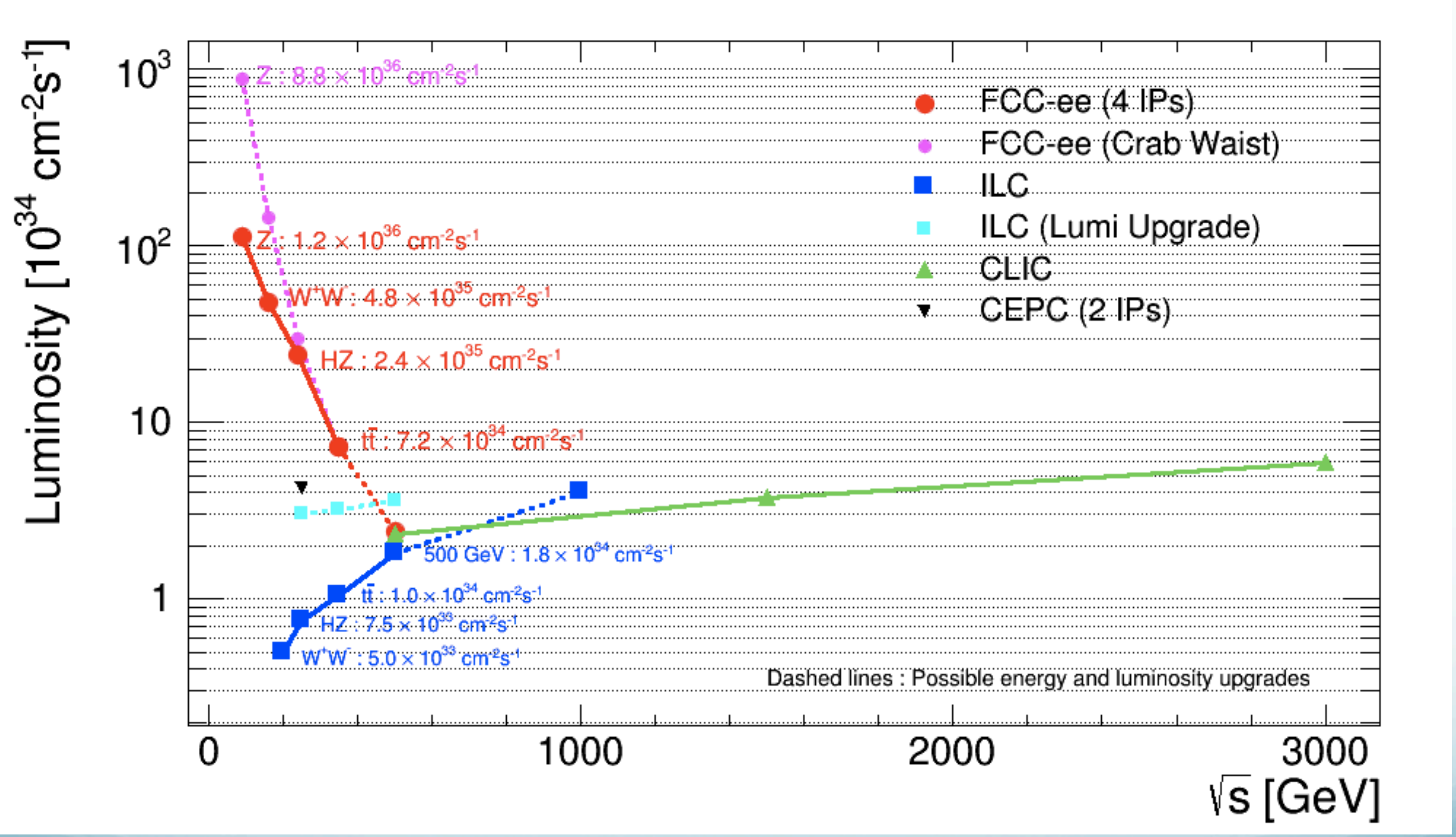
If no new particle discovered after LHC

☑ FLC, like Circular Electron-Positron Collier (CEPC):
Clean, but low energy → **indirect probe** by precision measurement.

If a new particle discovered after LHC,

☑ FHC, like Super Proton-Proton Collider (SPPC):
High energy, but dirty → **direct discovery** by production search.

Some Proposed Future Colliders



Some Proposed Future Colliders

[Table from 1310.8631]

Table 1-1. *Proposed running periods and integrated luminosities at each of the center-of-mass energies for each facility.*

Facility	HL-LHC	ILC	ILC(LumiUp)	CLIC	TLEP (4 IPs)	HE-LHC	VLHC
$\sqrt{s}$ (GeV)	14,000	250/500/1000	250/500/1000	350/1400/3000	240/350	33,000	100,000
$\int \mathcal{L}dt$ (fb^{-1})	3000/expt	250+500+1000	1150+1600+2500	500+1500+2000	10,000+2600	3000	3000
$\int dt$ (10^7s)	6	3+3+3	(ILC 3+3+3) + 3+3+3	3.1+4+3.3	5+5	6	6

Productions of e^+e^- collider at different center-of-mass energy

Process	Z	WW	HZ	TTbar			
sqrt(s) (GeV)	90	160	240	350	500	1000	1400

Design goals of CEPC & SPPC (c = 50 km) [from pre-CDR]

Table 1.2: Top Level Parameters for CEPC.

Parameter	Design Goal
Particles	*e+, e-*
Center of mass energy	240 GeV
Integrated luminosity (per IP per year)	250 fb^{-1}
No. of IPs	2

Table 1.3: Top Level Parameters for SPPC.

Parameter	Design Goal
Particles	*p, p*
Center of mass energy	70 TeV
Integrated luminosity (per IP per year)	(TBD)
No. of IPs	2

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- ★ Future Work

- ★ Conclusion

Physics at CEPC
Z Factory

Electroweak Precision Measurements

Flavor (B) physics

....

Physics at CEPC
H Factory

Precision Measurements
- Electroweak Precision Observables (EWPO)
- Triple Gauge Couplings (TGC)
- Higgs coupling
- Higgs production cross section

Flavor Physics
Rare processes
Exotics

Electroweak Phase Transition
Naturalness, Fine-tuning
Dark Matter

SUSY, Composite Higgs, L-R, ...

Physics at SPPC

New Particle Discovery & Study
→extra Higgs, new resonance

Naturalness

EWPT (1st or 2nd order ?), EW Brayogenesis
← Higgs Self Coupling

Dark Matter Search

SUSY, Composite, L-R, ...

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Pre-CDR Work at CEPC
EW Precision Physics

→ Estimating the precisions of EW measurements

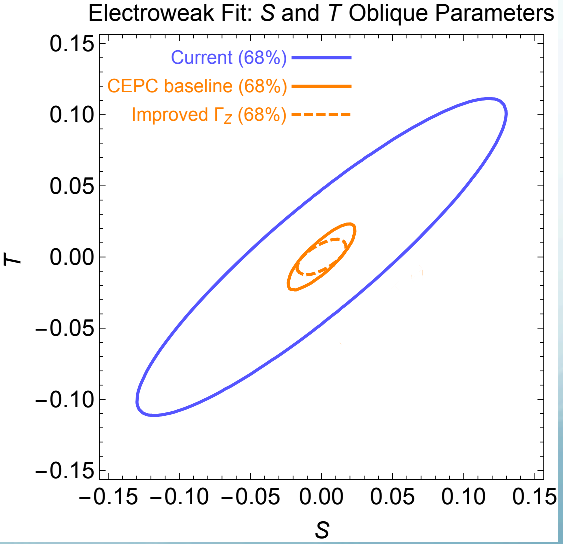
→ Fitting the EW parameters S & T

→ Constraining the NP

Table 4.1 The expected precision in a selected set of EW precision measurements and the comparison with the precision from LEP experiments. The current precisions for $\sin^2\theta_W^{\rm eff}$ and R_b include the measurements at the SLC.

Observable	LEP precision	CEPC precision	CEPC runs	$\int\mathcal{L}$ needed in CEPC
m_Z	2 MeV	0.5 MeV	Z lineshape	> 150 fb^{-1}
m_W	33 MeV	3 MeV	ZH (WW) thresholds	> 100 fb^{-1}
A_{FB}^b	1.7%	0.15%	Z pole	> 150 fb^{-1}
$\sin^2\theta_W^{\rm eff}$	0.07%	0.01%	Z pole	> 150 fb^{-1}
R_b	0.3%	0.08%	Z pole	> 100 fb^{-1}
N_ν (direct)	1.7%	0.2%	ZH threshold	> 100 fb^{-1}
N_ν (indirect)	0.27%	0.1%	Z lineshape	> 150 fb^{-1}
R_μ	0.2%	0.05%	Z pole	> 100 fb^{-1}
R_τ	0.2%	0.05%	Z pole	> 100 fb^{-1}

$2*10^9$ Z's.



Pre-CDR Work at CEPC
Higgs Physics

- → Detector simulation
- → Estimating the precisions of Higgs measurements
- → Fitting the Higgs couplings
- → Constraining the NP: extra singlet scalar model

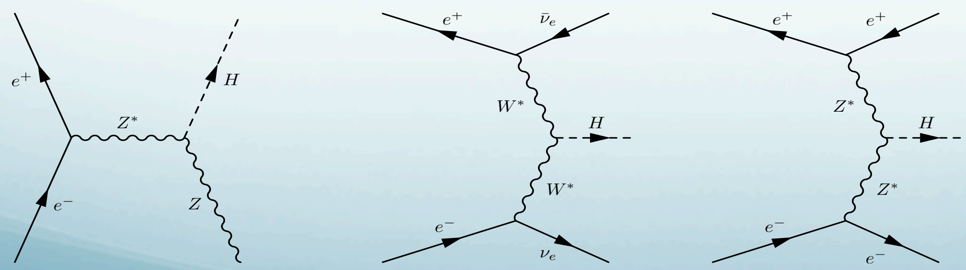
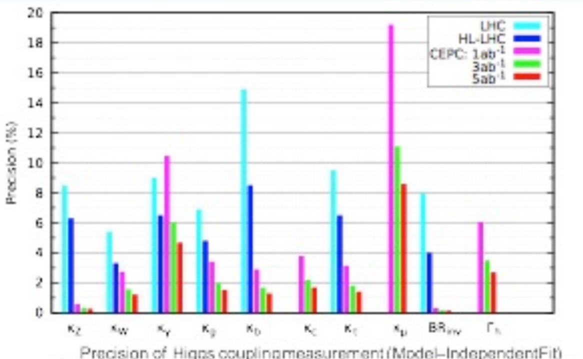


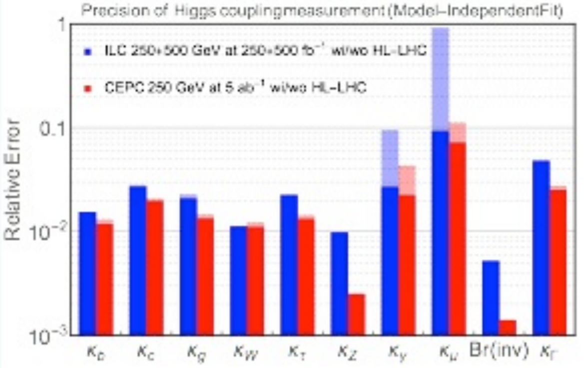
Figure 3.6 Feynman diagrams of the $e^+e^- \to ZH$, $e^+e^- \to \nu\bar{\nu}H$ and $e^+e^- \to e^+e^-H$ processes.

Pre-CDR Work at CEPC
Higgs Physics

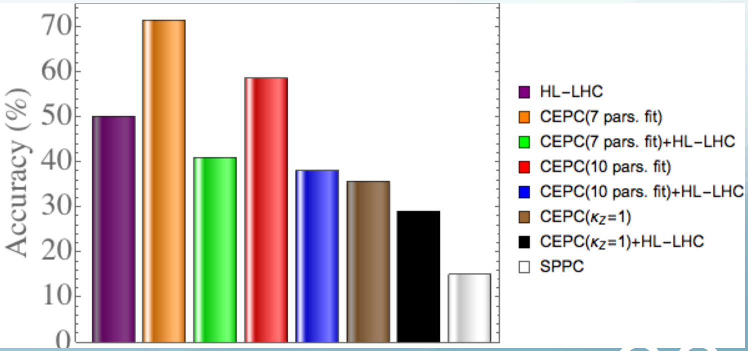
Table 3.13 Comparison of the projections between CEPC and various luminosity upgrades of the ILC. The ILC luminosity upgrade assumes an extended running period on top of the low luminosity program and cannot be directly compared to CEPC numbers without accounting for the additional running period. ILC numbers include a 0.5% theory uncertainty. For invisible decays of the Higgs, the number quoted is the 95% confidence upper limit on the branching ratio.

Facility		ILC		ILC(LumiUp)	CEPC (2 IP)	
$\sqrt{s}$ (GeV)	250	500	1000	250/500/1000	240–250	
$\int \mathcal{L}dt$ (ab^{-1})	0.25	+0.5	+1	+1.15+1.6+2.5	0.5	5
$P(e^-, e^+)$	$(-.8, +.3)$	$(-.8, +.3)$	$(-.8, +.2)$	(same)	$(0, 0)$	$(0, 0)$
Γ_H	12%	5.0%	4.6%	2.5%	8.7%	2.8%
κ_γ	18%	8.4%	4.0%	2.4%	15%	4.7%
κ_g	6.4%	2.3%	1.6%	0.9%	4.8%	1.5%
κ_W	4.9%	1.2%	1.2%	0.6%	3.9%	1.2%
κ_Z	1.3%	1.0%	1.0%	0.5%	0.80%	0.25%
κ_μ	91%	91%	16%	10%	28%	8.6%
κ_τ	5.8%	2.4%	1.8%	1.0%	4.5%	1.4%
κ_c	6.8%	2.8%	1.8%	1.1%	5.4%	1.7%
κ_b	5.3%	1.7%	1.3%	0.8%	4.1%	1.3%
κ_t	–	14%	3.2%	2.0%	–	–
BR_{inv}	0.9%	$< 0.9\%$	$< 0.9\%$	0.28%	0.89%	0.28%





Higgs self-coupling



Pre-CDR Work at CEPC
Flavor Physics

	$\tau \to 3\mu$	$\tau \to \mu\gamma$	$\tau \to \mu\pi^+\pi^-$	$\tau \to \mu K \bar{K}$	$\tau \to \mu\pi$	$\tau \to \mu\eta^{(\prime)}$
$O^{4\ell}_{S,V}$	✓	–	–	–	–	–
O_D	✓	✓	✓	✓	–	–
O^q_V	–	–	✓ (I=1)	✓(I=0,1)	–	–
O^q_S	–	–	✓ (I=0)	✓(I=0,1)	–	–
O_{GG}	–	–	✓	✓	–	–
O^q_A	–	–	–	–	✓ (I=1)	✓ (I=0)
O^q_P	–	–	–	–	✓ (I=1)	✓ (I=0)
$O_{G\tilde{G}}$	–	–	–	–	–	✓

Table 5.2 *Sensitivity of LFV τ decays to the different effective operators at tree-level. The symbol ✓ (–) denotes that the operator does (not) contribute at tree-level to a given process. For operators involving quark bilinears, the relevant isospin structure ($I = 0, 1$) probed by a given decay is also specified. Table taken from Ref. [84]*

→ Possible flavor physics

Pre-CDR Work at SPPC

→ SUSY at 100 TeV with 3000 fb^{-1} luminosity

→ Z', Kaluza–Klein gluon

→ Jets, W, Z radiation, top-quark PDF

→ 2HDM, Higgs portal, Higgs-charm Yukawa coupling k_c, dark photon

Pre-CDR Work at Heavy-ion and Electron-ion Colliders

→ Possible Heavy-ion and Electron-ion collisions

→ QCD study

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Future Work at Z Factory

EW precision measurement
→ Simulation more precisely (detector effect)
→ systematical uncertainty estimation
→ theoretical uncertainty requirement
→ triple gauge coupling (TGC)

Non-oblique observables (A_{FB}, ...)
→ Precision
→ constrain NP

Future Work at Z Factory

Flavor physics
→ Exotic decay (B_c, Λ_b, τ, ...)
→ B_s, D meson mixing
→ CP breaking
→ QCD precision (SCET method, ...)

g-2, EDM, lepton number violation

M_W, Γ_W @ WW threshold without polarization
4-fermion contact-interactions from fermion pair production

Complementary with Higgs factory
Luminosity requirement from important physics
Requirement for detector design

Future Work at H Factory
Higgs Property

Higgs coupling measurement
→ Simulation more precisely (detector effect)
→ More final state (semi-leptonic, fully hadronic, ...)
→ More decay channel
→ Higgs exotic decay (dark photon, SUSY, hidden valley, h->mu tau), ...

Higgs CP violation
→pin down the CP phase

EW phase transition
→ htt, hhh couplings (indirect, direct at sqrt(s)>350, 305 GeV, ...)

Exotic, rare decay
→ these with trigger problems @ LHC
→ h-> Z gamma

Future Work at H Factory
Higgs Property, Additional

Constrained fit
→Improve sensitivity assuming only SM production / decay modes, ...

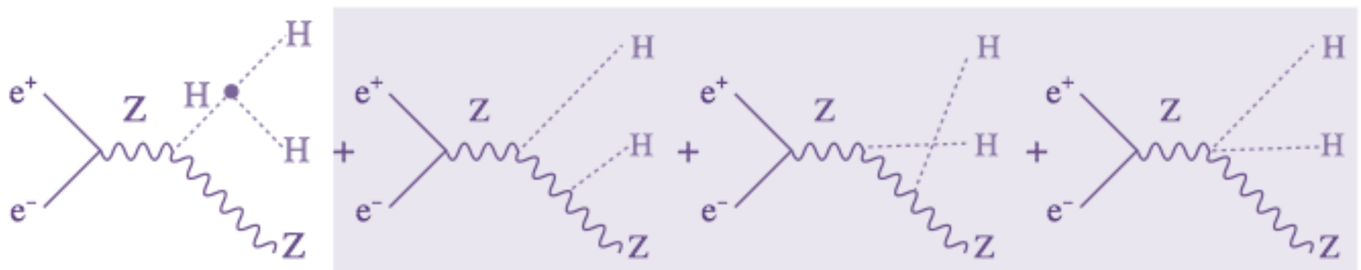
Angular distributions in the decay products of Higgs
→ Higgs coupling
→ CP, ...

SM loop corrections
→ Higgs couplings
→ htt coupling from loop

Future Work at H Factory
Example: Higgs Self Coupling

sqrt(s) > 305 GeV

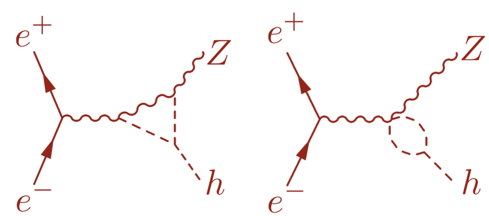
- At ILC (Requires $E_{CM} > 2\,m_h + m_Z$):

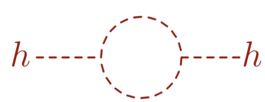


sqrt(s) < 305 GeV

Self-Coupling Indirectly at NLO

- At NLO modified coupling enters in the following loops:



- And also: 

Future Work at H Factory
Example: Complementary with ILC

- ILC helps CEPC:
  - A_{LR} measurement and top mass
  - Precise g_{HWW} measurement reduces errors on all Higgs couplings
  - Top Yukawa coupling
  - ILC σ(ZHH) measurement (and others I assume) help interpret precision CEPC σ(ZH) meas.
  - New particle searches at 500 GeV

- CEPC helps ILC:
  - Many EW precision measurements: M_Z, Γ_Z, α_S, Nν, MW, …
  - Precise g_{HZZ} measurement reduces errors on all Higgs couplings
  - Much better meas. of Higgs invisible width, BSM decays, rare decays such as $\gamma\gamma$ and $\mu\mu$
  - In general, CEPC gives ILC more flexibility to concentrate on higher E_{cm} running.

- CEPC+ILC combination helps the particle physics community:
  - Higgs Z coupling error $\Delta g_{HZ} = 0.2\%$
  - Higgs W coupling error $\Delta g_{WW} = 0.3\%$
  - Higgs b coupling error $\Delta g_{bb} = 0.5\%$
  - Higgs self coupling error $\Delta g_{HHH} = 22\%$

Future Work at H Factory
QCD & Jet-substructure

Reconstruction
→ QCD precision, Heavy quarkonia production,
s & p wave, ...
→ Jet clustering, substructure
→ c-tagging, b-tagging, ...
→ gluon-jet vs. quark-jet

Tau physics
→tau-tagging, polarization
→asymmetries @ Z-pole and ZH

Future Work at H Factory
Detector & Accelerator

Running time for Z factory and H factory
→ a complete analysis of higher dimensional operators

Correlated analysis of Higgs precision
→ systematical uncertainty
→ interference in signal processes, ...

Complementary with LHC, SPPC, Z factory

Future Work at H Factory
Constraints & Predictions on NP

Two Approaches:
(i) Model Independent.: EFT operators
(ii) Model Dependent: complete UV models

Constraining NP:
→ Using precision measurements @ Z-pole & Higgs coupling
→ Cross section to constrain NP
→ Kinematical distribution (differential cross section) to enhance sensitivity
→ Extra Higgs search (refer to LEP)
→ 2HDM, L-R, DM, dark photon, sterile neutrino ....

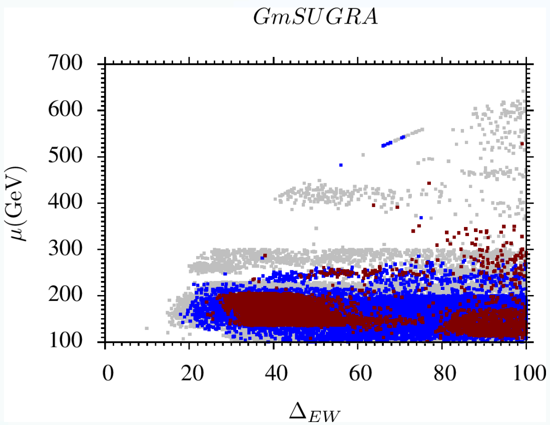
Naturalness, Fine-tuning
→ complete theory based on SUSY with neutral scalar top partner,
like theory based on global symmetries (Twin Higgs, ...)
→ SUSY, composite, twin Higgs, Higgs portal

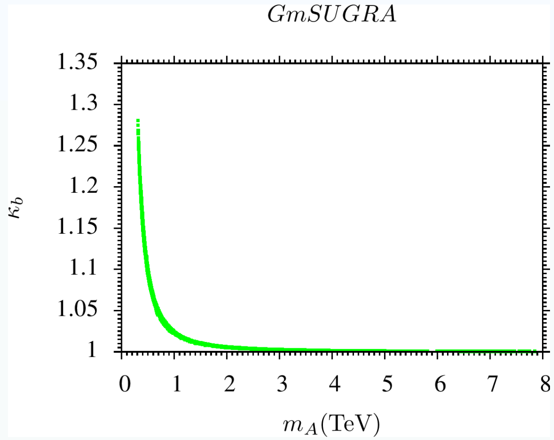
Flavor Physics
→ Rare processes, exotics

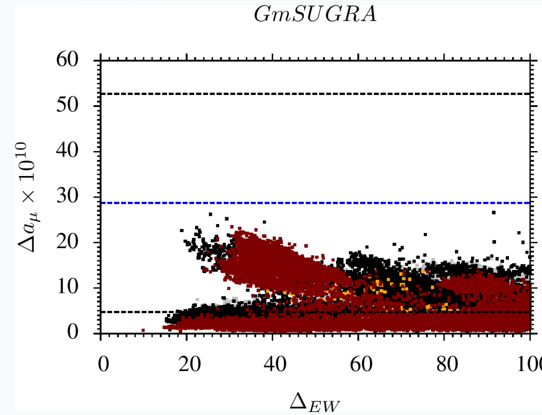
Complementary with LHC, SPPC, Z factory

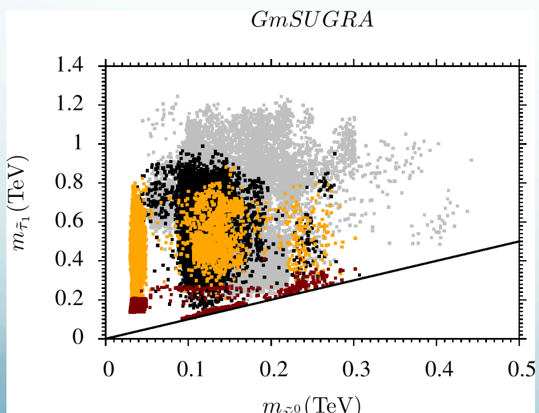
Constraint & Prediction on NP
Example: Natural SUSY

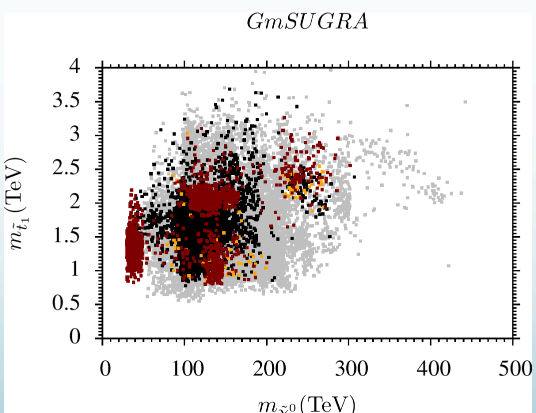
- Constraining natural SUSY using muon g-2 & Higgs coupling @ HL-LHC, ILC & CEPC Collaboration with Tianjun Li, Shabbar (ITP, CAS)











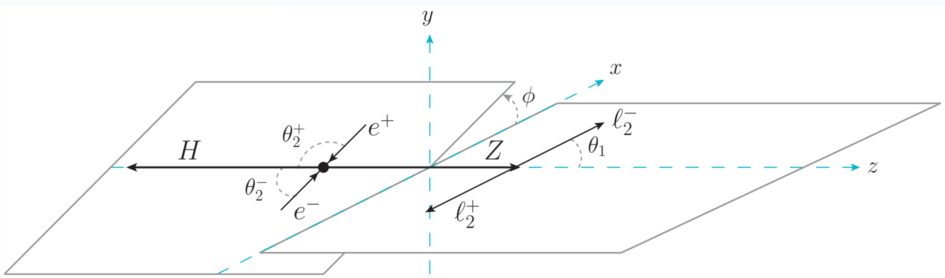
← Basic constraints: REWSB, neutralino LSP, sparticle mass, Higgs mass, B-physics, fine-tuning.

← Muon magnetic moment

← Higgs coupling

Constraint & Prediction on NP
Example: Angular Asymmetry

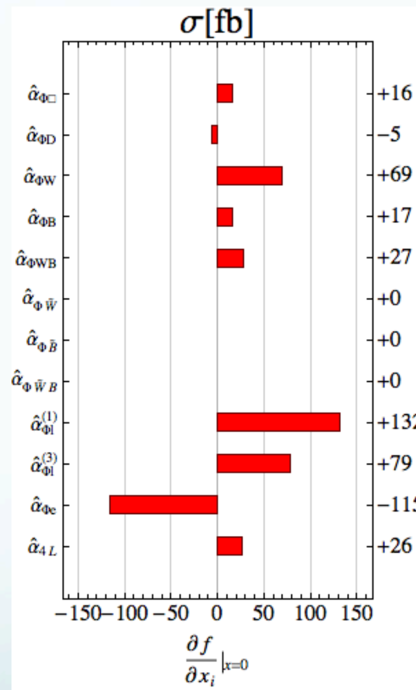
- **Angular Asymmetry @ CEPC**
  Collaboration with Jiayin Gu, Nathaniel Craig (UCSB, US), Zhen Liu (Fermi Lab, US)

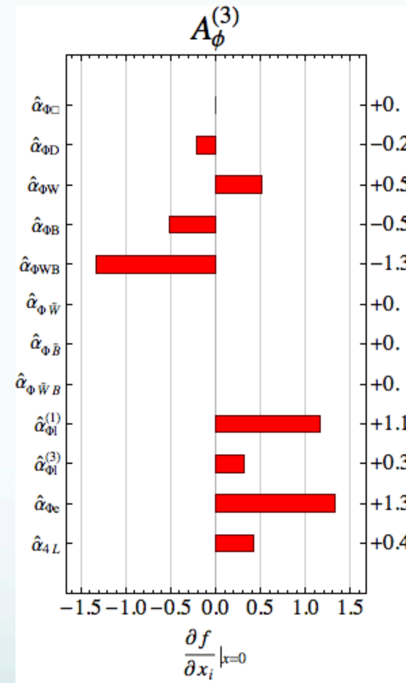


Plot and table from [M. Beneke, D. boito, Y.M. Wang, hep-ph/1406.1361]

Table 1: The subset of $d = 6$ operators that contribute to $H \to Z\ell^+\ell^-$ and $e^+e^- \to HZ$ in the basis defined in Ref. [14]. The four-lepton operator given in Eq. (8) gives an indirect contribution solely through the redefinition of δ_{G_F} and is not listed in this table.

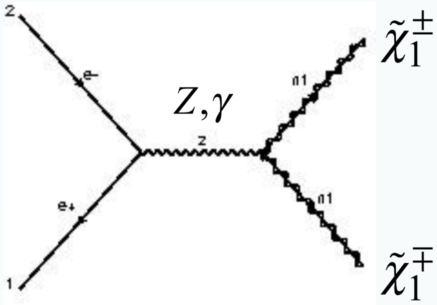
$\Phi^4 D^2$	$X^2 \Phi^2$	$\psi^2 \Phi^2 D$
$\mathcal{O}_{\Phi\Box} = (\Phi^\dagger\Phi)\Box(\Phi^\dagger\Phi)$	$\mathcal{O}_{\Phi W} = (\Phi^\dagger\Phi)W^I_{\mu\nu}W^{I\mu\nu}$	$\mathcal{O}^{(1)}_{\Phi\ell} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar\ell\gamma^\mu\ell)$
$\mathcal{O}_{\Phi D} = (\Phi^\dagger D^\mu\Phi)^*(\Phi^\dagger D_\mu\Phi)$	$\mathcal{O}_{\Phi B} = (\Phi^\dagger\Phi)B_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}^{(3)}_{\Phi\ell} = (\Phi^\dagger i\overleftrightarrow{D}^I_\mu\Phi)(\bar\ell\gamma^\mu\tau^I\ell)$
	$\mathcal{O}_{\Phi WB} = (\Phi^\dagger\tau^I\Phi)W^I_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{\Phi e} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar e\gamma^\mu e)$
	$\mathcal{O}_{\Phi\widetilde{W}} = (\Phi^\dagger\Phi)\widetilde{W}^I_{\mu\nu}W^{I\mu\nu}$	
	$\mathcal{O}_{\Phi\widetilde{B}} = (\Phi^\dagger\Phi)\widetilde{B}_{\mu\nu}B^{\mu\nu}$	
	$\mathcal{O}_{\Phi\widetilde{W}B} = (\Phi^\dagger\tau^I\Phi)\widetilde{W}^I_{\mu\nu}B^{\mu\nu}$	





Constraint & Prediction on NP
Example: Dark Matter

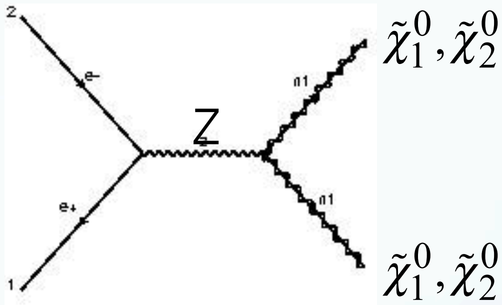
- Dark Matter @ CEPC
  Collaboration with Jiang-Hao Yu (UT, Austin, US),



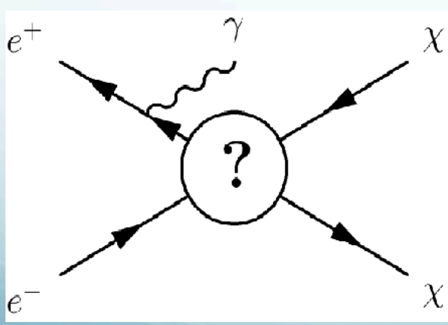
➔SUSY dark matter (Higgsino, etc.)

$$\sqrt{s} = 250\ \text{GeV},\quad m_{\tilde{\chi}_1^0} \sim m_{\tilde{\chi}_2^0} \sim m_{\tilde{\chi}_1^{\pm}},\quad \chi = \tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_1^{\pm}$$

$$\sigma(e^+ e^- \to \chi\, \chi\, \gamma) = 6\ \text{fb}^{-1},\quad m_{\tilde{\chi}} = 120\,\text{GeV}$$



➔Effective Field Theory $m_{\text{mediator}} \gg \sqrt{s}$



Interaction: by parameters

- Λ: energy scale of new physics ($\sigma \propto 1/\Lambda^4$)
- types of mediator: vector, axial-vector,…

$\Lambda, m_{\tilde{\chi}}$: constrained by CEPC.

Future Work at SPPC
Higgs & NP

Higgs coupling measurement
→SM BG simulation, ...

Approach:
Model Dep.: complete UV models

New Particle Discovery & Study
→extra Higgs, new resonance

EW phase transition
→1st or 2nd order, EW brayogenesis
→hhh coupling, ...

Constraining NP
→Naturalness, SUSY, DM,....

Requirement for detector design
→parameters, sqrt(s), luminosity, polarization, ...

Future Work at Other Options
Higgs & NP

Heavy ion collider

electron-ion collider

Conclusion

- ☐ Standard Model is surprisingly successful.

- ☐ Still Unsolved Questions in Fundamental Physics
  → need BSM physics.

- ☐ Higher energy collider experiment → BSM Physics
  FLC (Future Lepton Collider):
  clean, but low energy, **indirect probe** by precision measurement.
  FHC (Future Hadron Collider):
  high energy, but dirty, **direct discovery** by production search.

- ☐ BSM Physics at High Energy Collider
  - Z factory, H factory, SPPC

Conclusion

- Current Status
  → Z & H factories, SPPC

- Future Work
  ← Precision @ CEPC, Discovery @ SPPC
  → EWPT, Naturalness, DM
  → Exotics, Rare, Flavor-Violation, LV, ...
  → BSM: SUSY, Composite, L-R, Extended scalar, ...

- ....