CDR discussion

CEPC physics workshop, CFHEP IHEP, Dec 15, 2016

Draft of an outline

- Brief introduction. (a few pages)
  - Overview of project, machine/lumi parameters.
- Big step in the precision frontier.
  - Reaches in precision, new physics scale
- Addressing important physics questions
  - Electroweak symmetry breaking, naturalness, ...
- Brief discussion of SPPC
- Executive summary.
  - Supporting the options favored by CDR.

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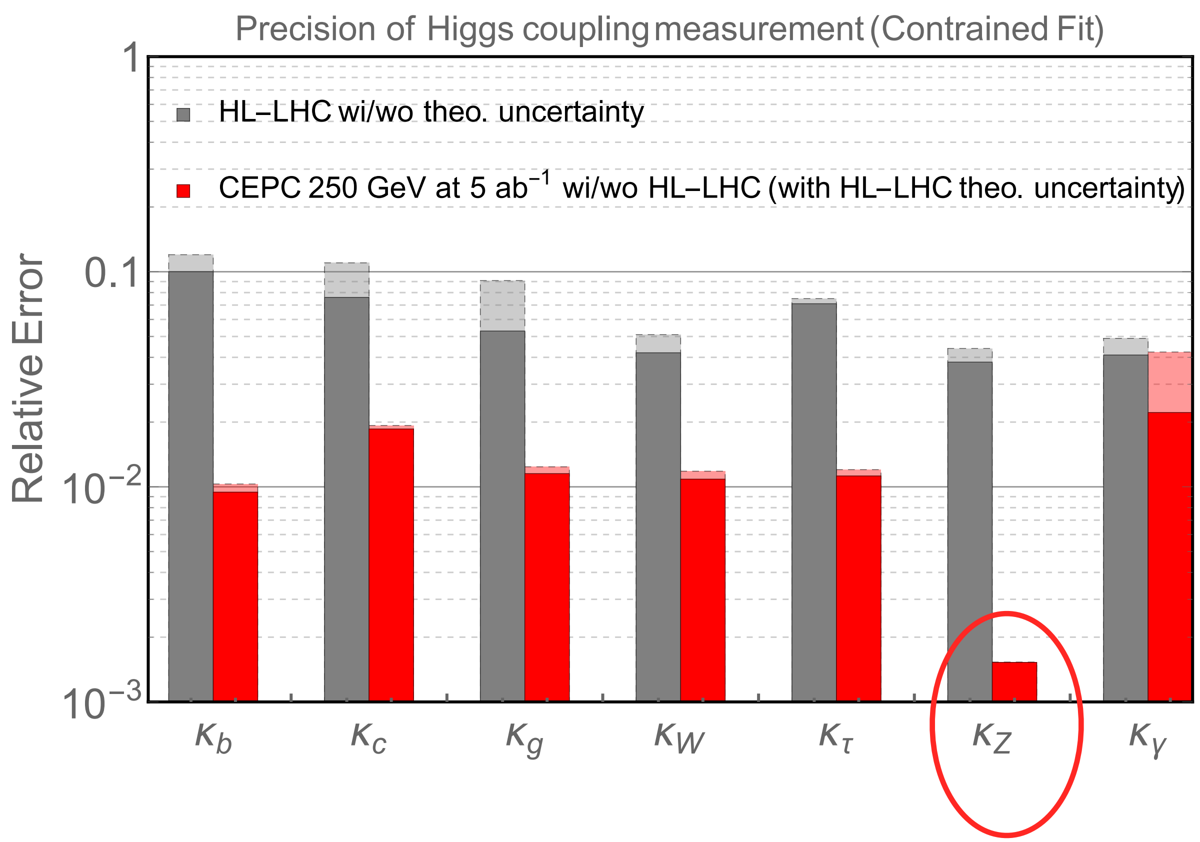
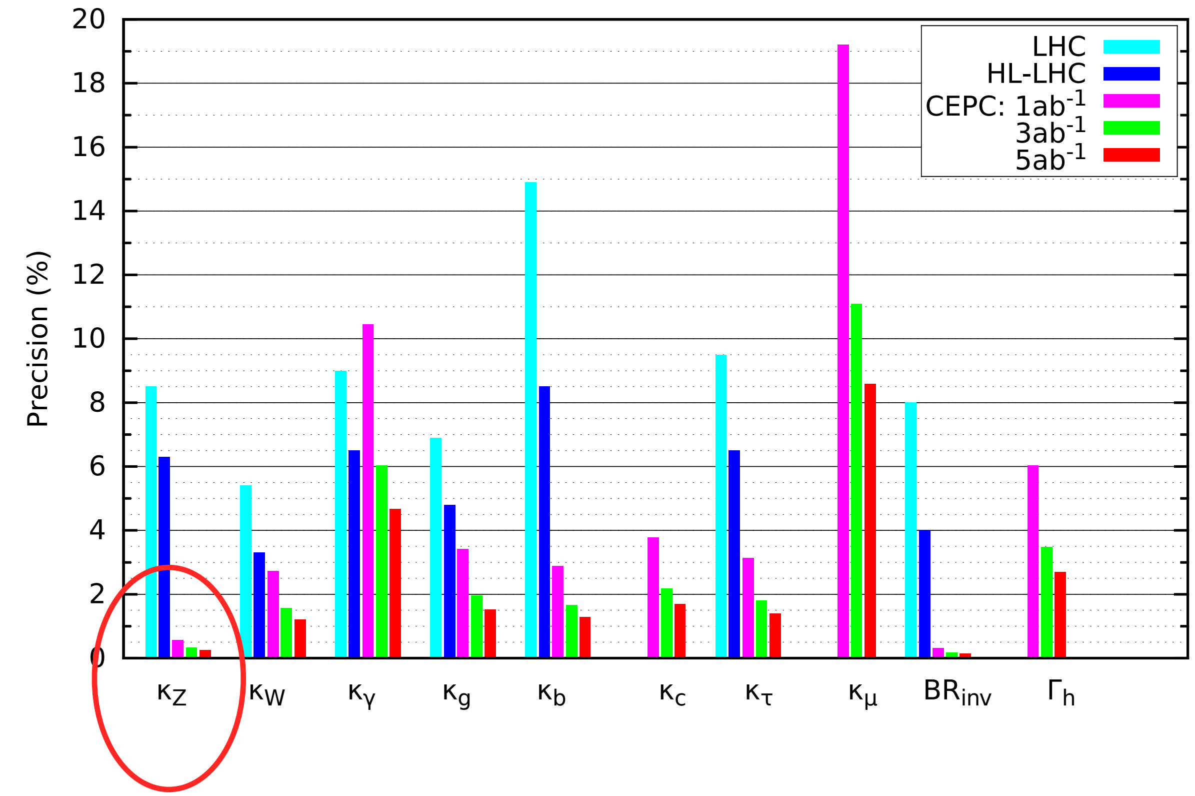
CEPC at the precision frontier

CEPC can do it.



$$\kappa_X = \frac{\text{Measured Higgs-X coupling}}{\text{Standard Model Higgs-X coupling}}$$



Highlights:

HZ coupling to sub-percent level.
Many couplings to percent level.
Model independent measurement of total width.
Sensitive to the triple Higgs coupling: 20-30%

Theoretical uncertainty

$\sqrt{s}$ (GeV)	σ_{LO} (fb)	σ_{NLO} (fb)	σ_{NNLO} (fb)	$\sigma_{\mathrm{NNLO}}^{\mathrm{exp.}}$ (fb)
240	256.3(9)	228.0(1)	230.9(4)	230.9(4)
250	256.3(9)	227.3(1)	230.2(4)	230.2(4)
300	193.4(7)	170.2(1)	172.4(3)	172.4(3)
350	138.2(5)	122.1(1)	123.9(2)	123.6(2)
500	61.38(22)	53.86(2)	54.24(7)	54.64(10)

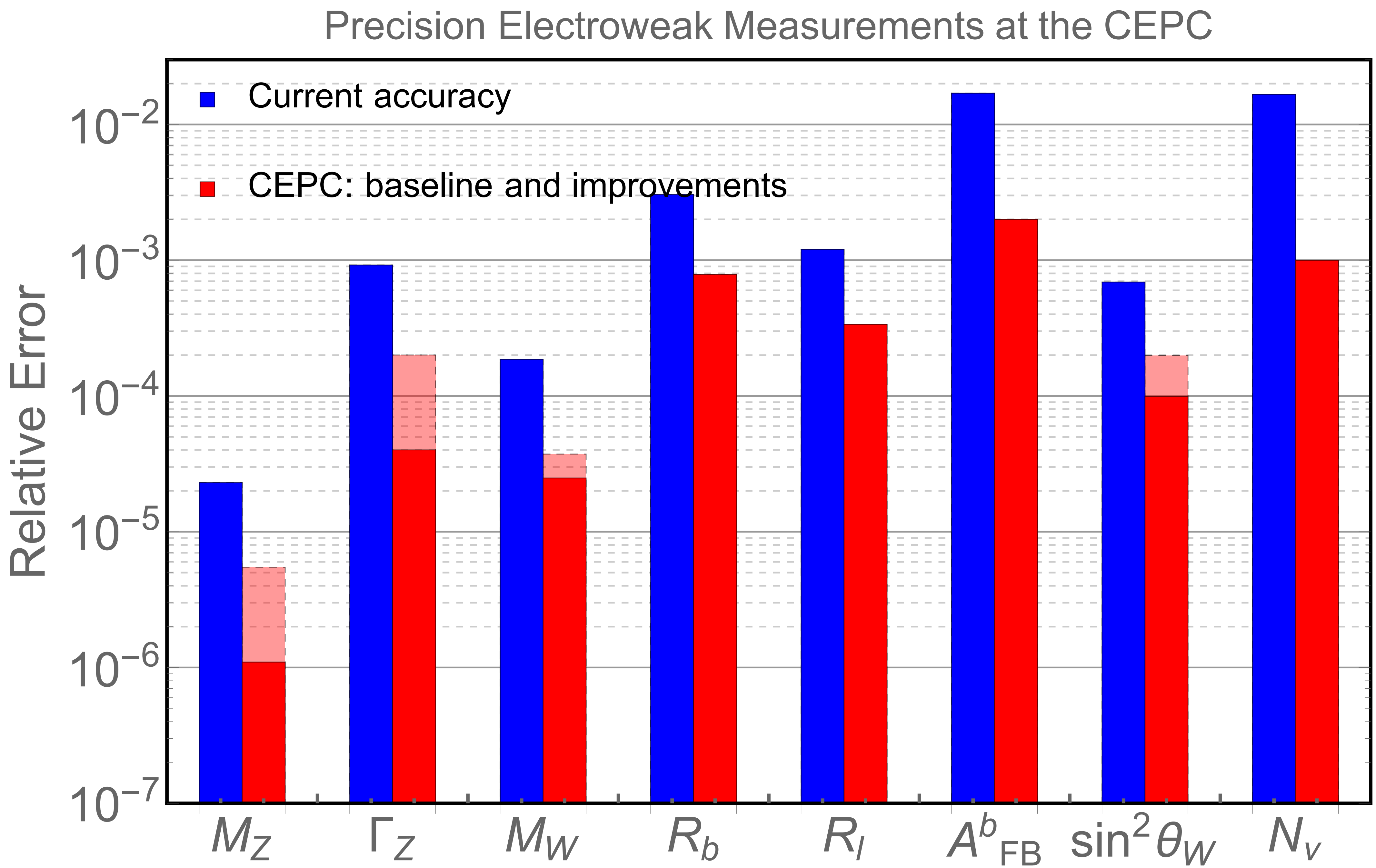
TABLE I. The NNLO predictions for the total cross sections at various collider energies.

$\sqrt{s}$ (GeV)		LO (fb)	NLO Weak (fb)		NNLO mixed EW-QCD (fb)				
		$\sigma^{(0)}$	$\sigma^{(\alpha)}$	$\sigma^{(0)}+\sigma^{(\alpha)}$	$\sigma_{eeZ}^{(\alpha\alpha_s)}$	$\sigma_{Z}^{(\alpha\alpha_s)}$	$\sigma_{\gamma}^{(\alpha\alpha_s)}$	$\sigma^{(\alpha\alpha_s)}$	$\sigma^{(0)}+\sigma^{(\alpha)}+\sigma^{(\alpha\alpha_s)}$
240	Total	**223.14**	6.90	230.03	0.83(7)	1.58(14)	0.008(1)	2.42(21)	232.45(21)
	L	88.67	3.29	91.96	0.33(3)	0.63(5)	0.003(1)	0.96(8)	92.92(8)
	T	134.46	3.61	138.07	0.50(4)	0.95(8)	0.005(1)	1.46(13)	139.53(13)
250	Total	**223.12**	6.34	229.46	0.83(7)	1.57(14)	0.009(1)	2.41(21)	231.87(21)
	L	94.30	3.42	97.72	0.35(3)	0.66(6)	0.004(1)	1.02(9)	98.74(9)
	T	128.82	2.92	131.74	0.48(4)	0.91(8)	0.005(1)	1.39(12)	133.13(12)

TABLE I: The (un)polarized Higgsstrahlung cross sections at $\sqrt{s}=240$ GeV and 250 GeV. We enumerate the NLO weak corrections, together with the NNLO EW-QCD $\mathcal{O}(\alpha\alpha_s)$ corrections. For the latter, we also list contribution from each individual component in Eq. (20).

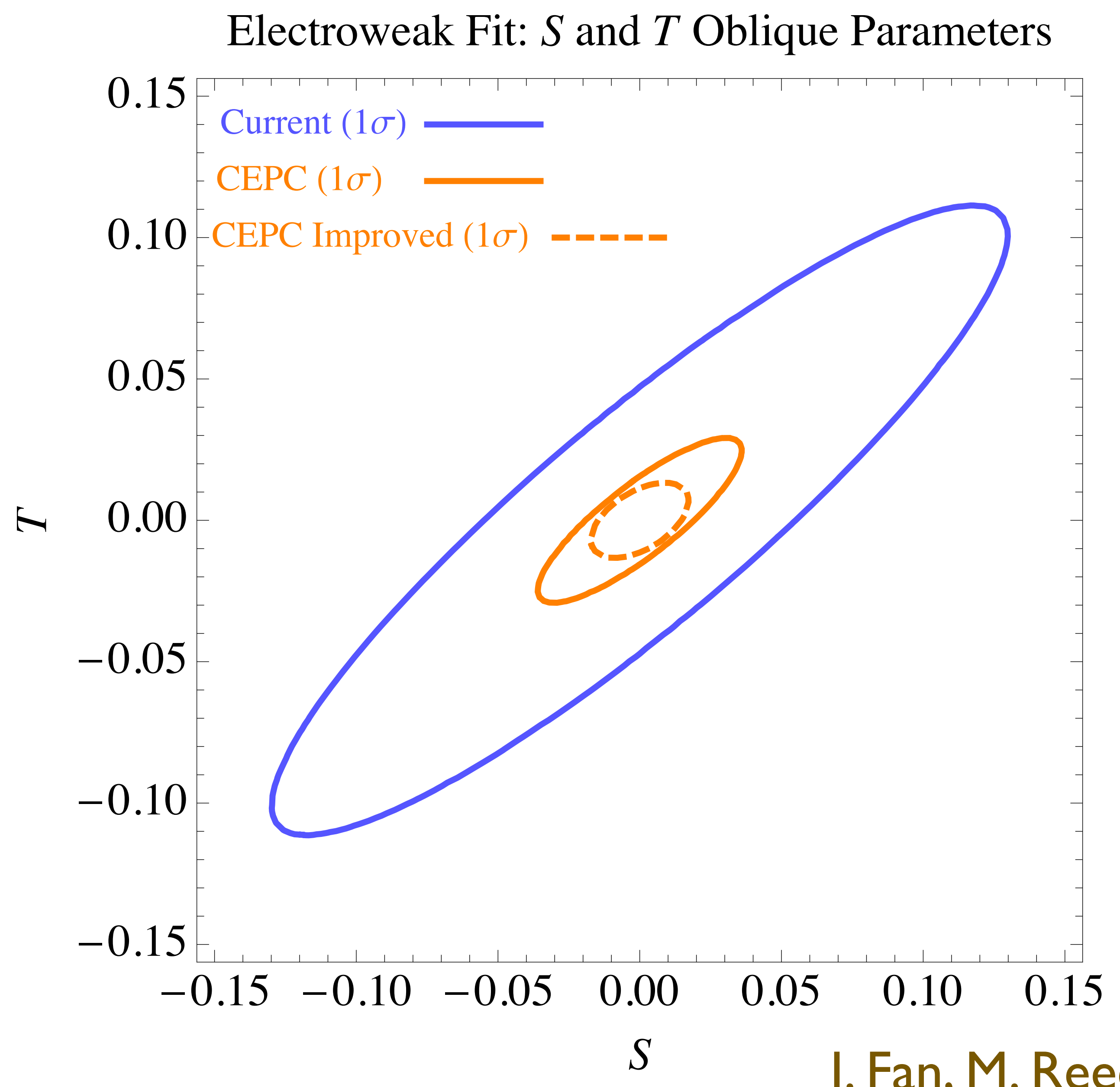
Talks by Jia Yu, Gexing Li

Big advance in electroweak precision



Large improvements across the board

Electroweak precision at CEPC

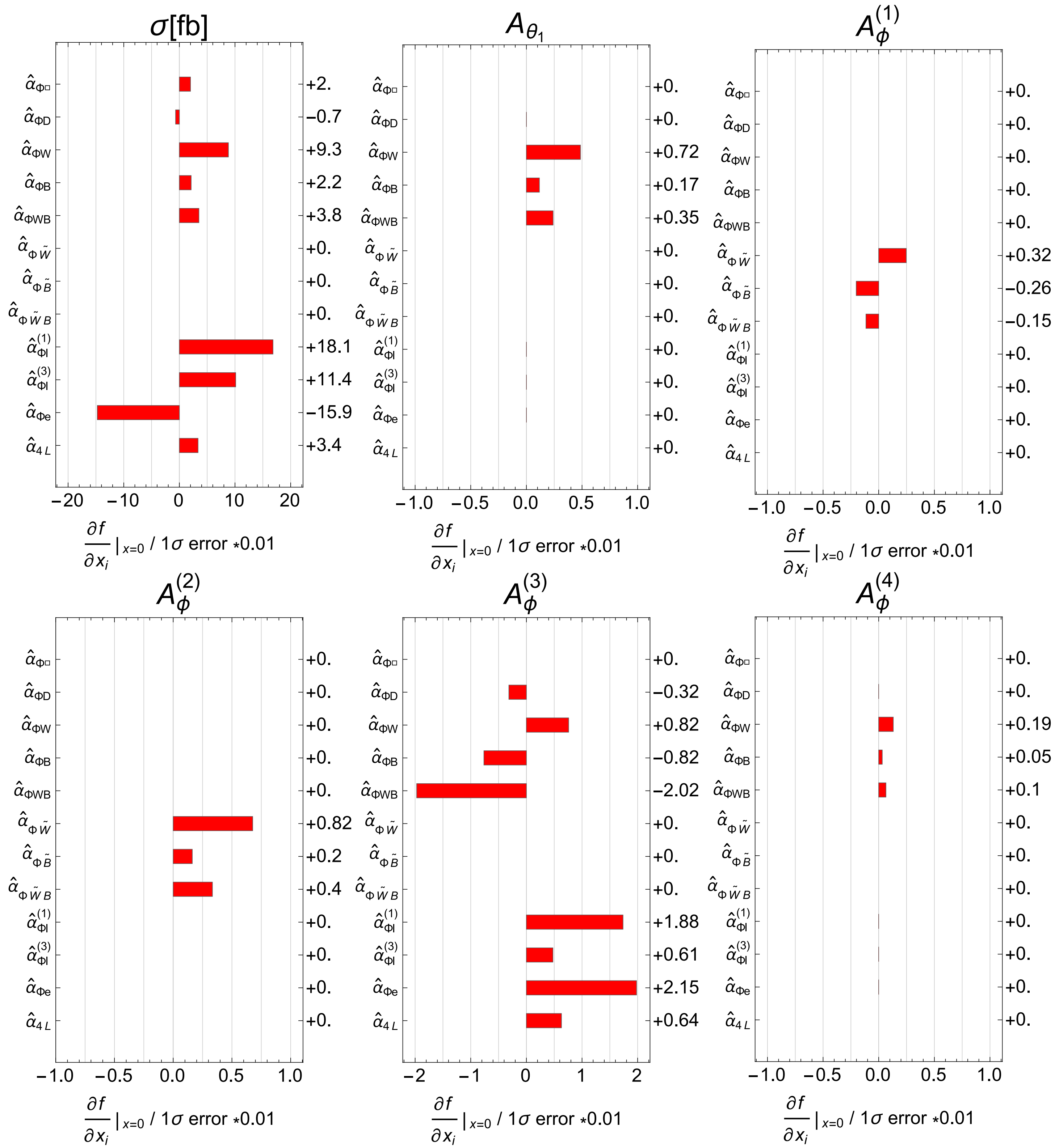


J. Fan, M. Reece, LT Wang, 1411.1054

– A big step beyond the current precision.

More details, more understanding.

NC, Jiayin Gu, Zhen Liu, Kechen Wang, *In Progress*



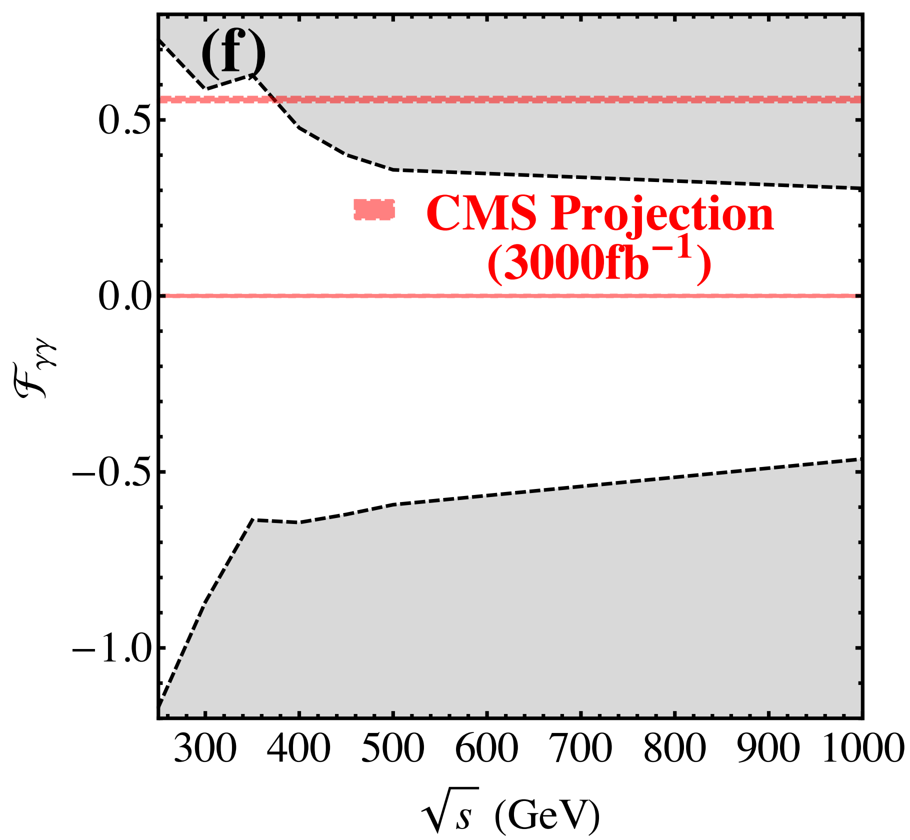
CEPC sensitive not only to coupling shifts, but different tensor structures.

- Truncate flat directions in the HEFT.
- Improve BSM reach by using added information.
- Distinguish between different BSM models with similar total cross section shifts.

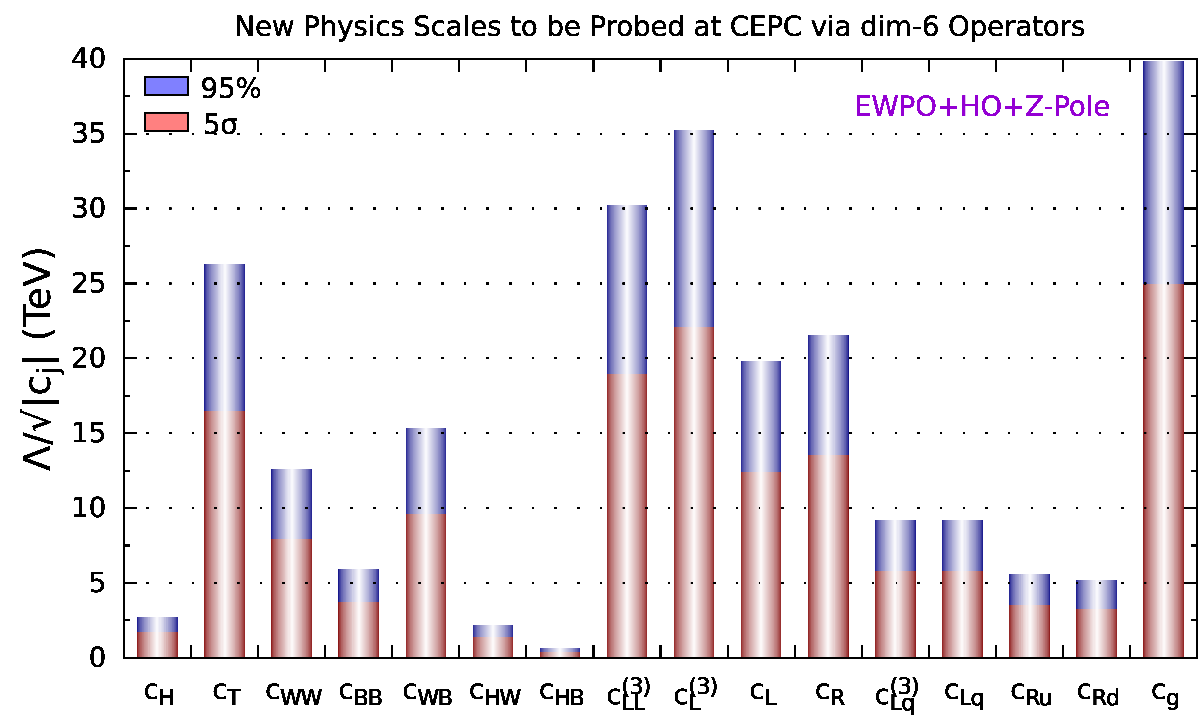
N. Craig, J. Gu, Z. Liu, K. Wang

Scale of new physics.

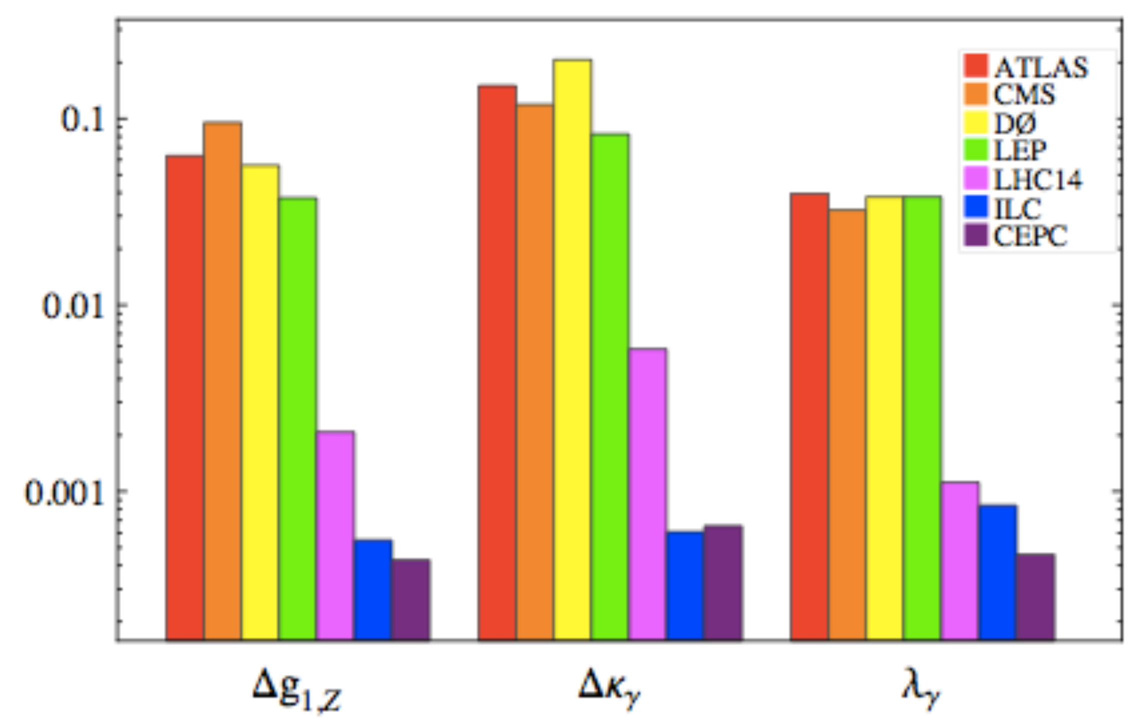
anomalous Higgs
to gamma and Z coupling



Q. Cao, B. Yan, 1507.06204



S. Ge, H. He, R. Xiao, 1603.03385



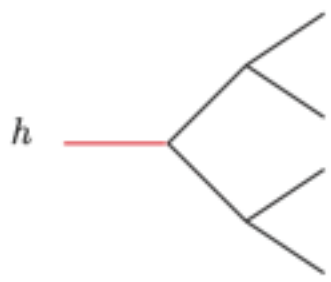
L. Bian, J. Shu, Y. Zhang, 1507.02238

In the regime of multiple TeVs!

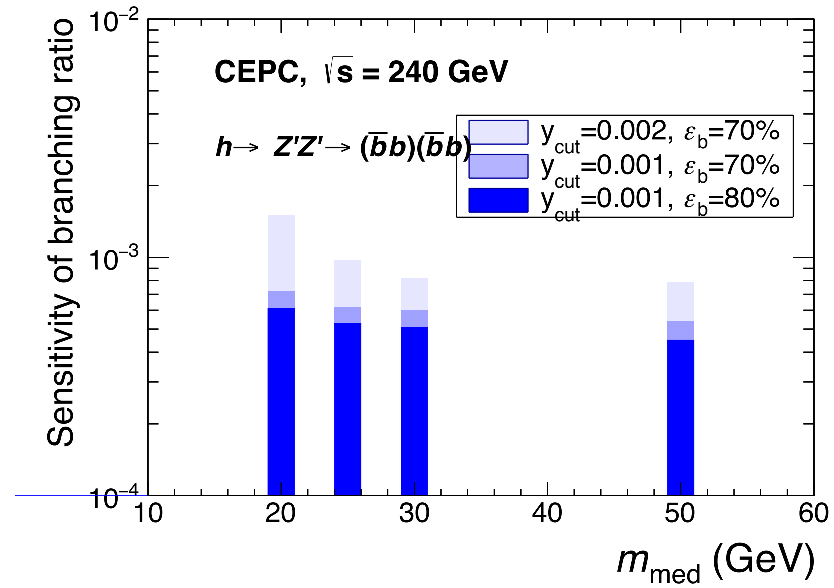
At this workshop

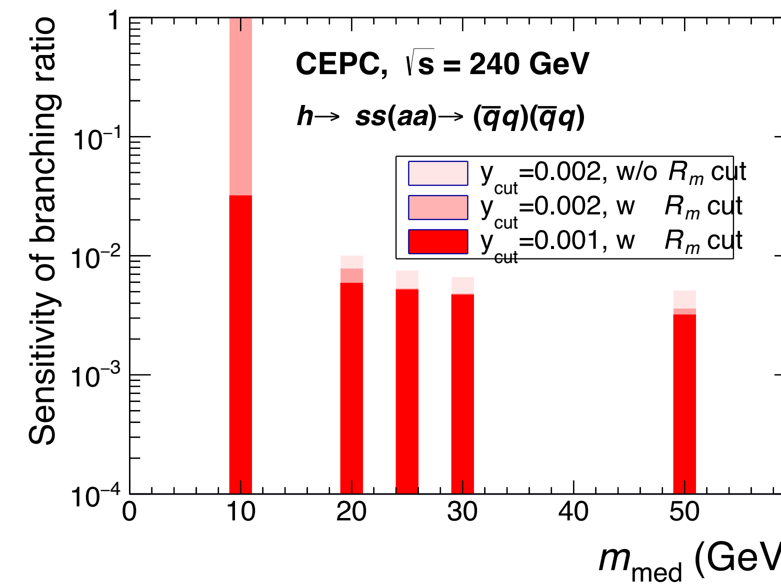
- Results presented for more comprehensive fitting to constrain new physics.
  - Taking into account of electroweak precision, higgs observables.
  - Tao Liu, Tim Barklow, Jiayin Gu

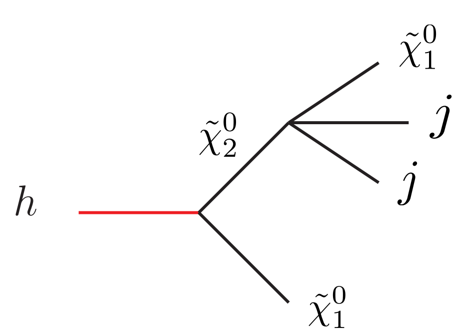
Higgs as portal to unknown



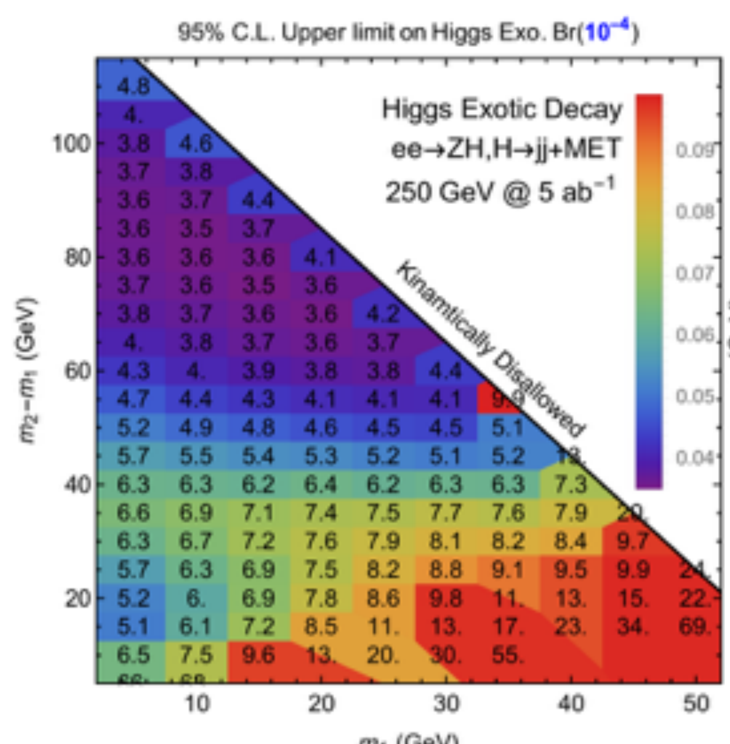
$h \to 2 \to 4$

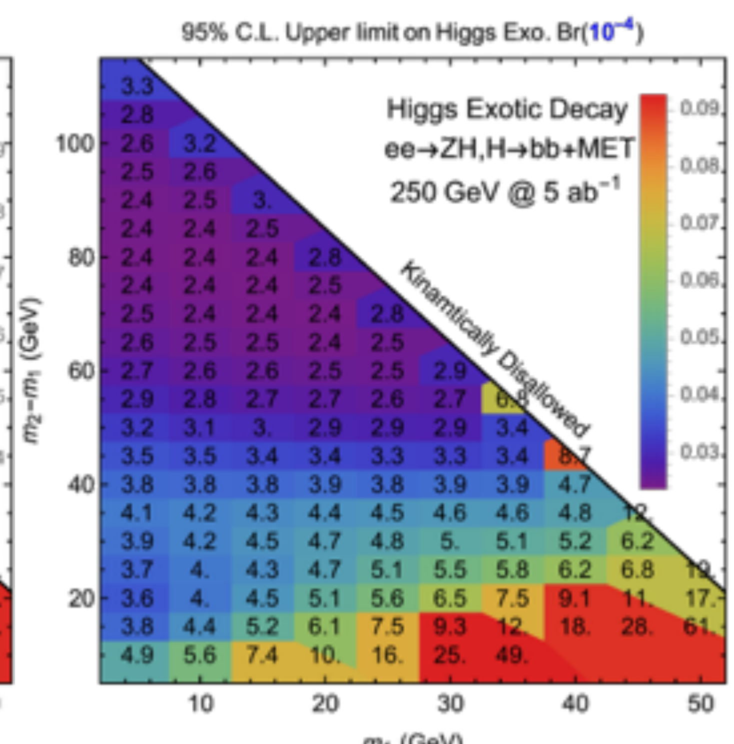






$h \to 2 \to (1+3)$





bb case is around 50%

Zhang Hao's talk at this workshop

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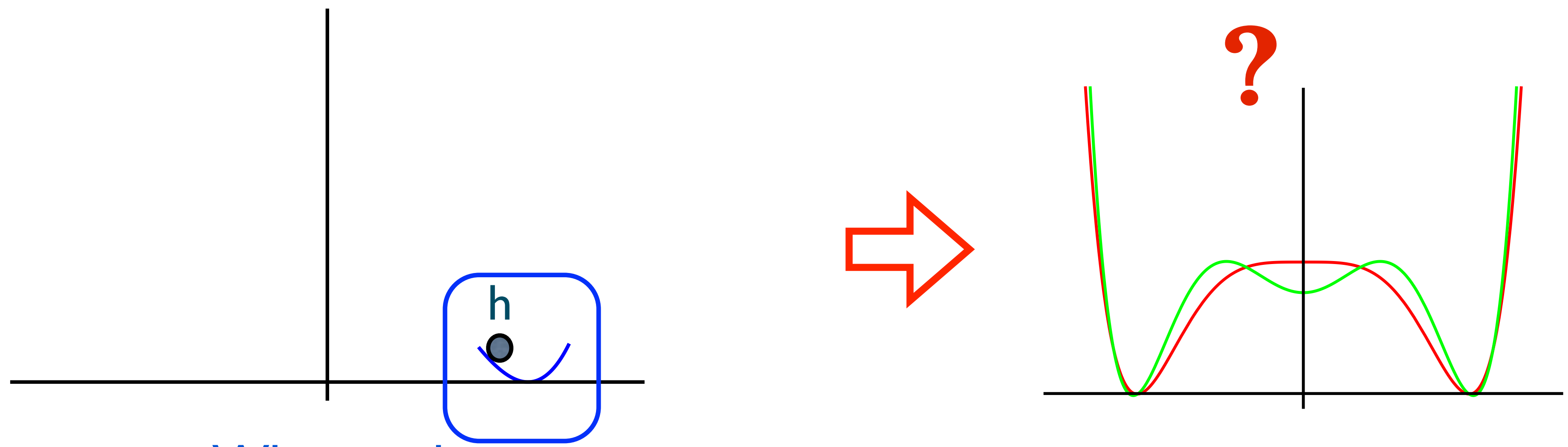
What can we do with this knowledge?

Our physics goals.

Addressing big questions

- EWSB phase transition in early universe.
- Naturalness
- Mystery of the heavy top quark
- Flavor, understanding QCD...

Electroweak phase transition



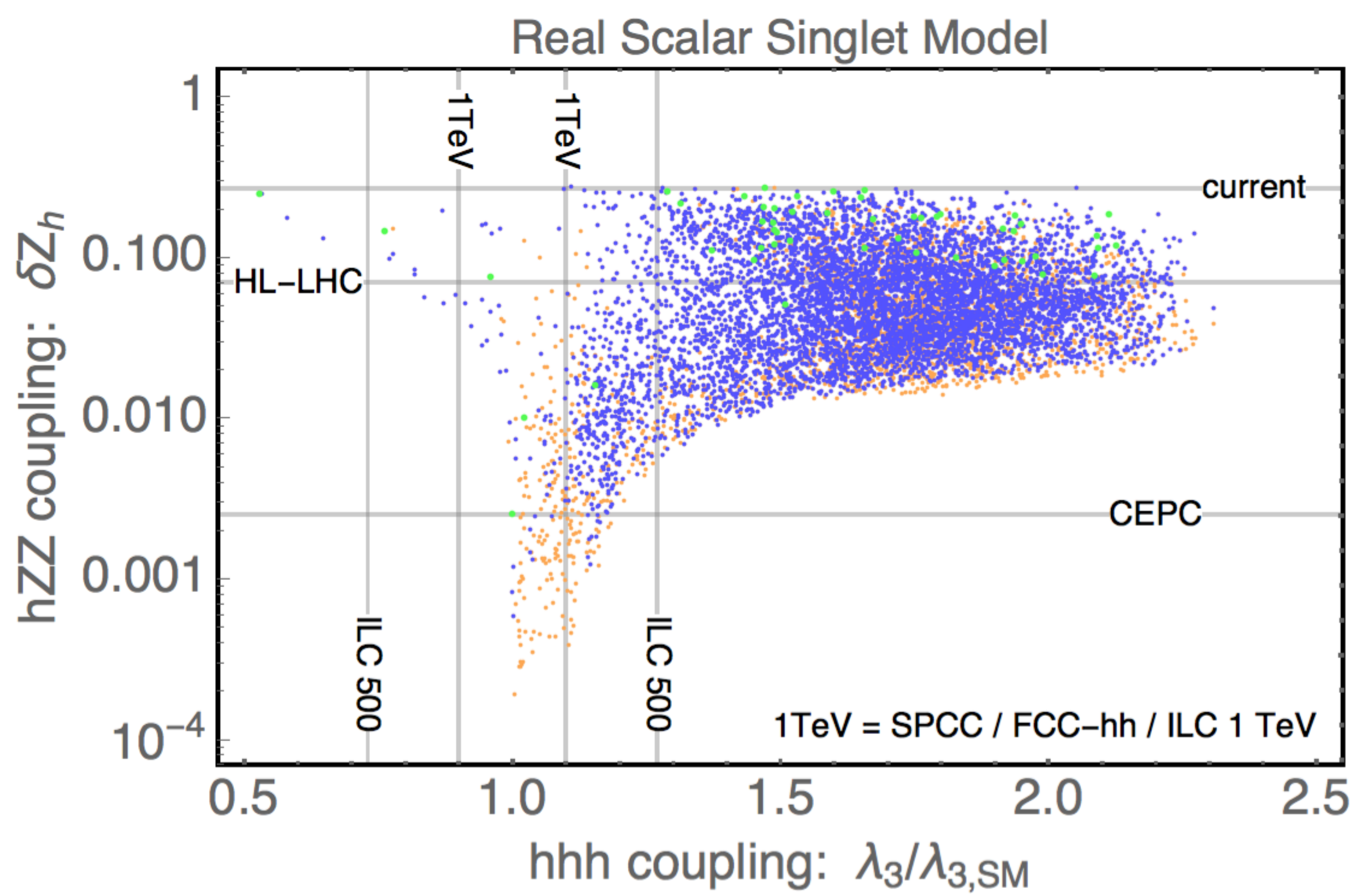
What we know now
LHC upgrades won't go much further

A monumental event in the early universe.

A milestone in particle physics and cosmology.

Is the EW phase transition first order?

Probing EWSB at higgs factories



Huang, Long, LTW

Orange = first order phase transition, $v(T_c)/T_c > 0$
Blue = "strongly" first order phase transition, $v(T_c)/T_c > 1.3$
Green = very strongly 1PT, could detect GWs at eLISA

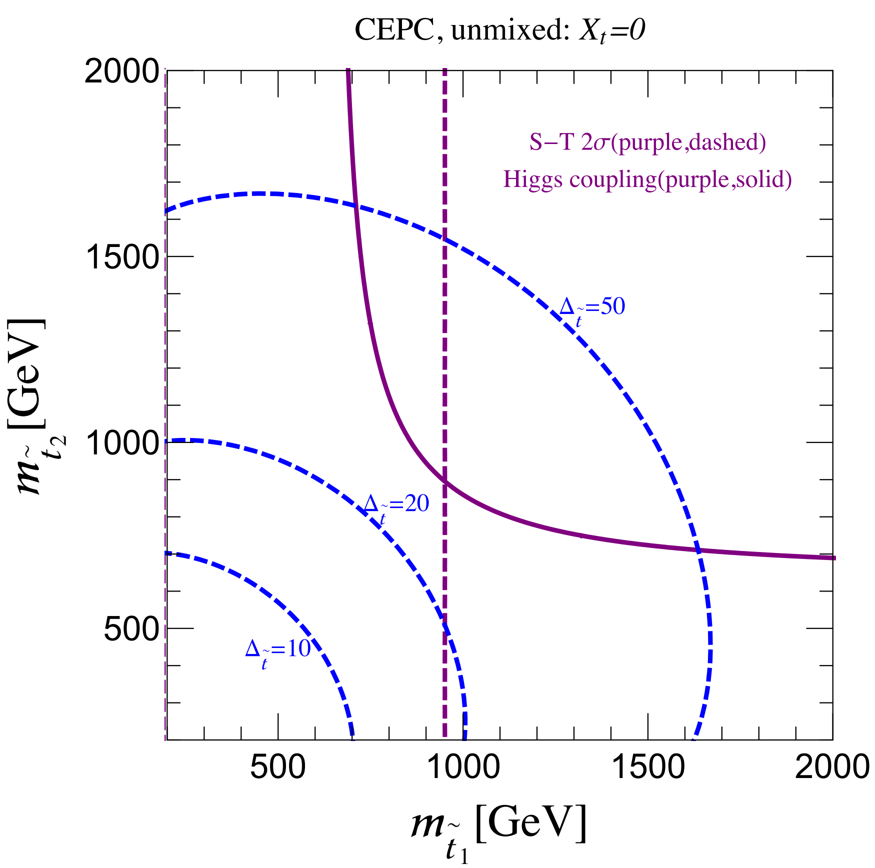
Good coverage in model space

See also: F. Huang, Y. Wan, D. Wang, Y. Cai, X. Zhang

Naturalness, fine-tuning

- LHC searches model dependent, many blind spots.

- Precision measurement at CEPC provides a powerful and complementary probe.

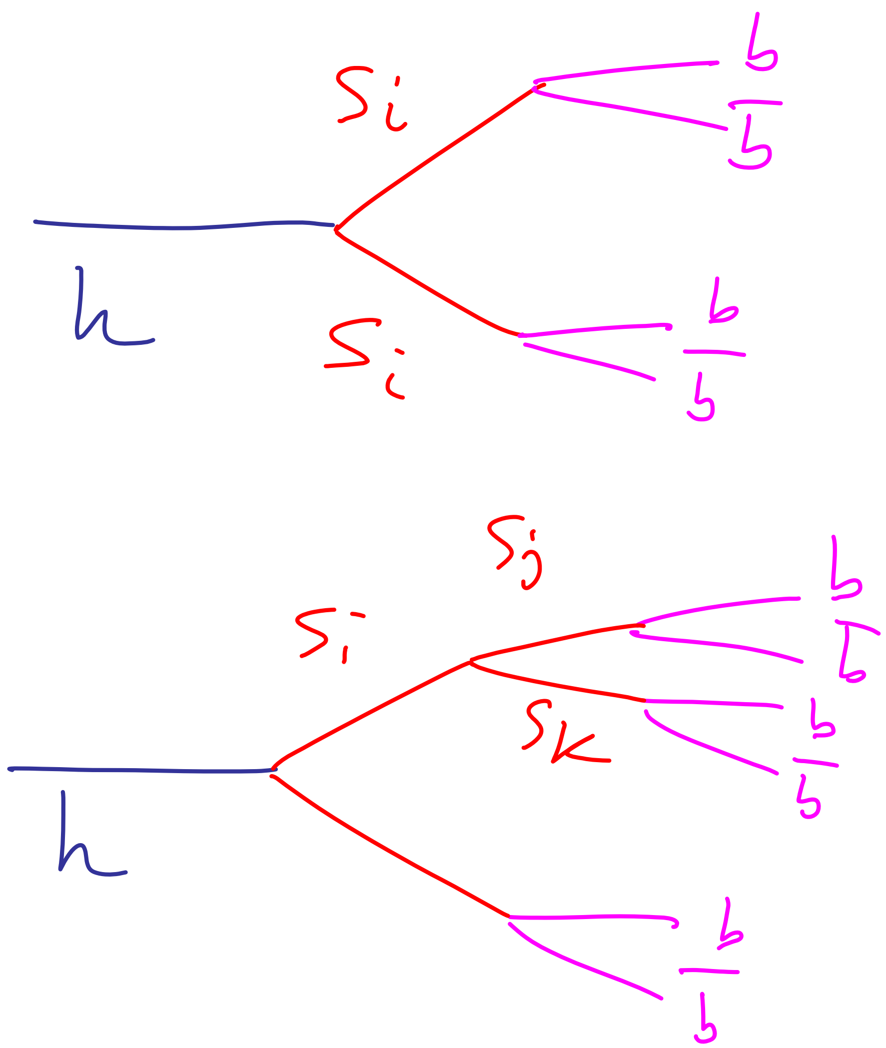


J. Fan, M. Reece, LT Wang, 1412.3107

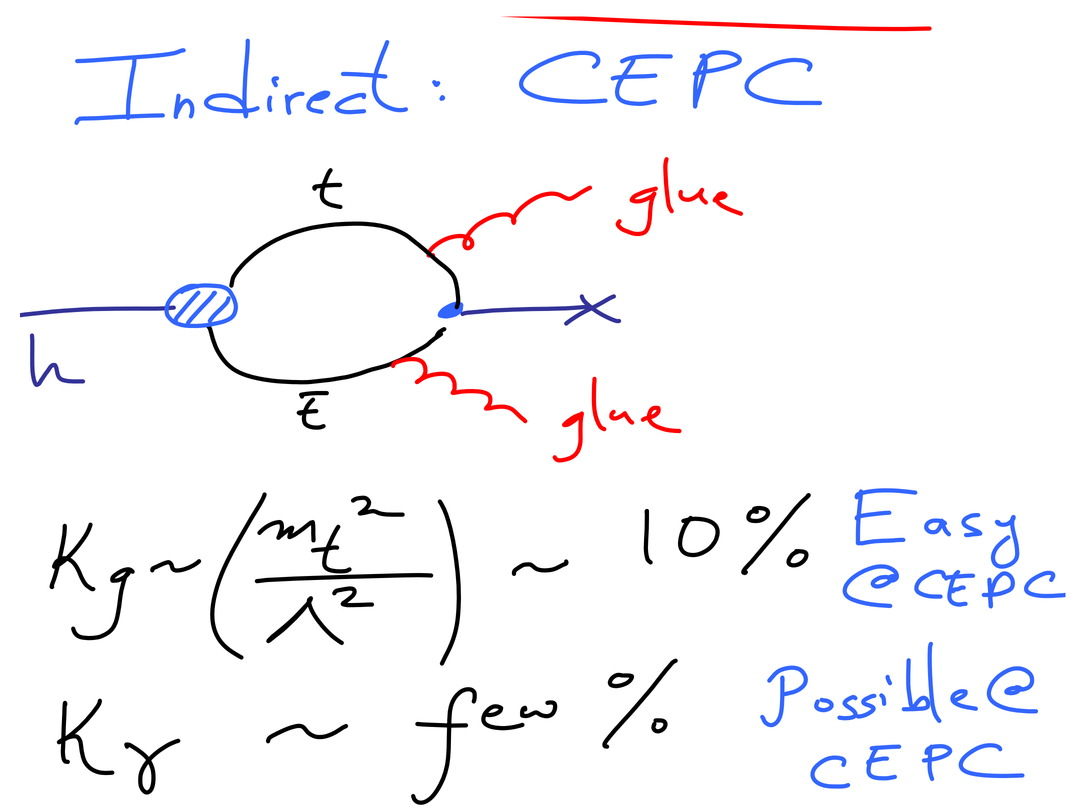
- Model independent testing fine-tuning down to percent level.

More alternatives

More relevant without discovery at the LHC



Low scale landscape

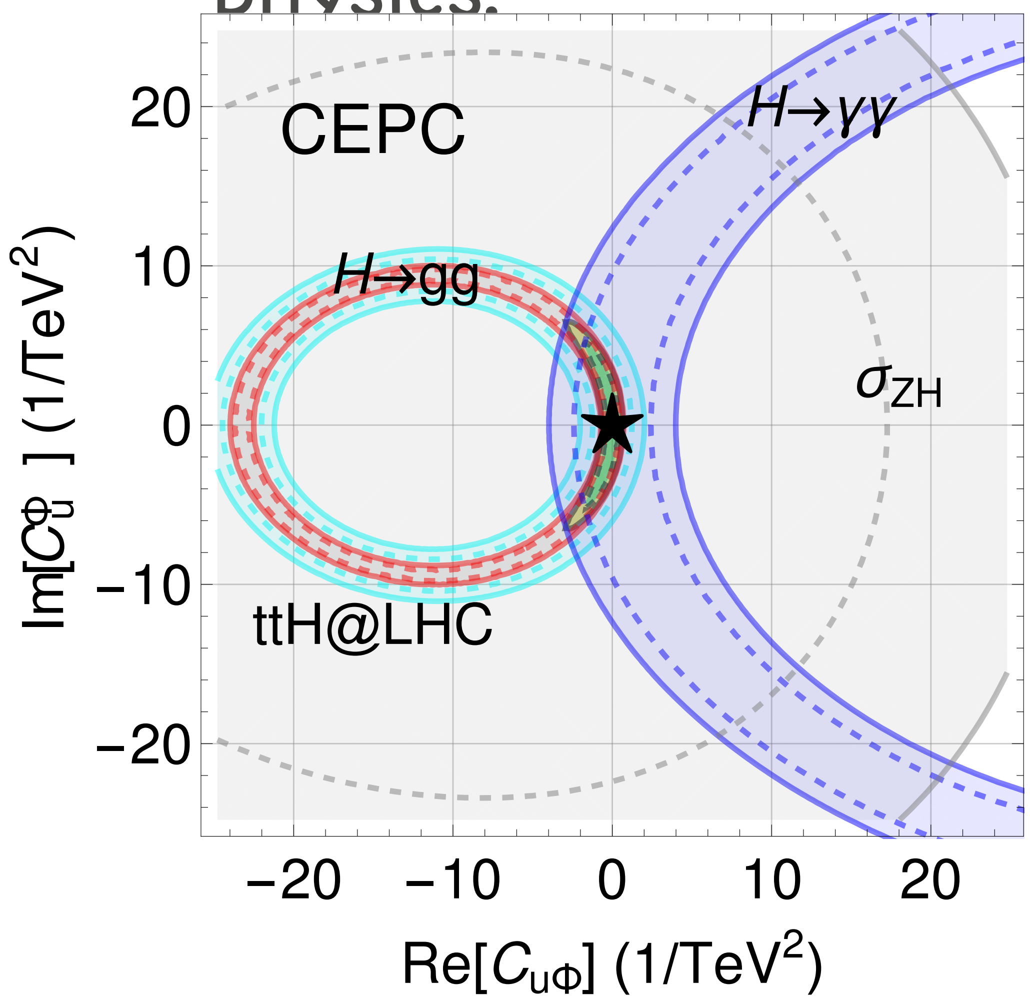


fat Higgs

Nima's talk at this workshop

Mystery of the heavy top quark

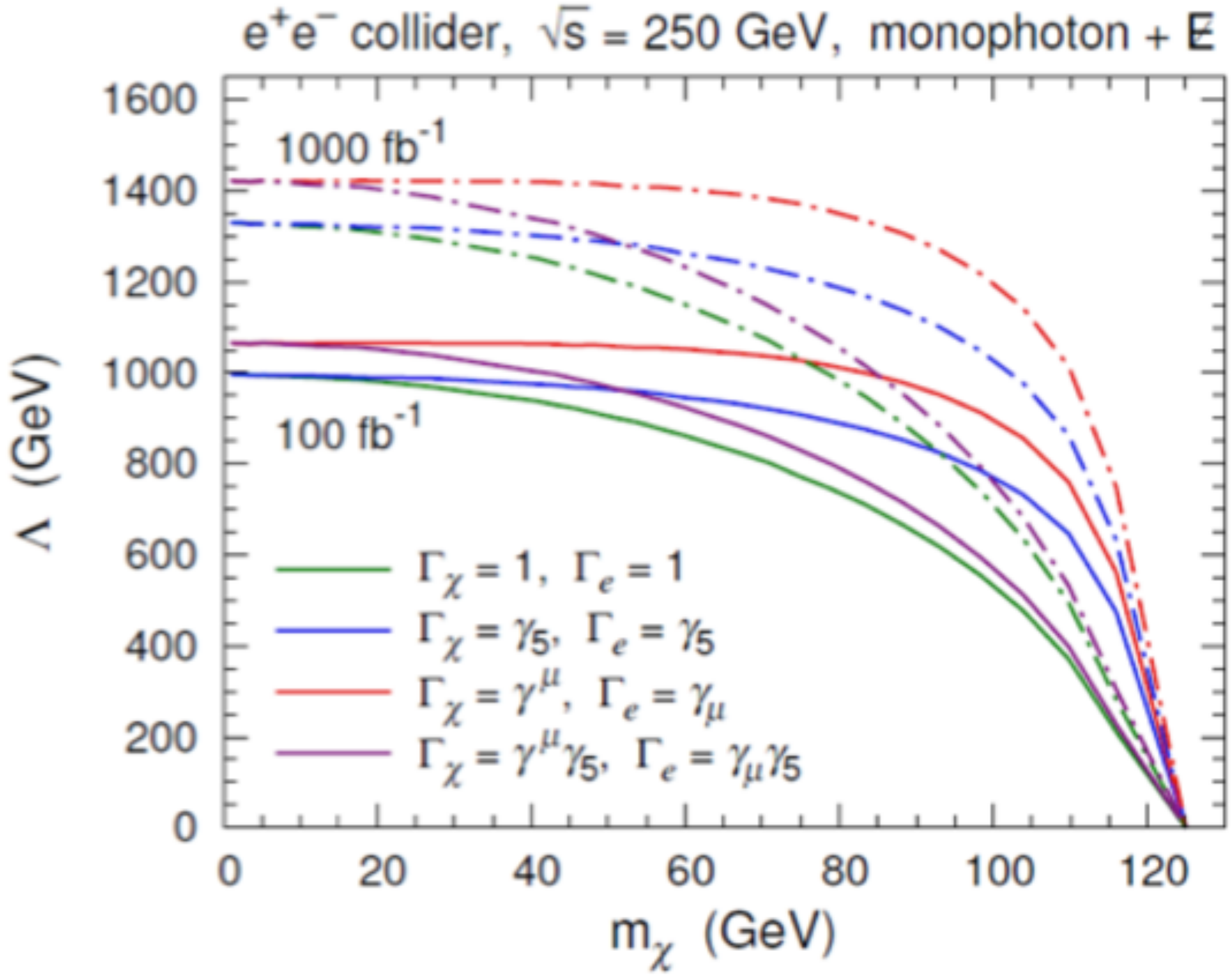
- Heaviest. Zhen Liu's talk.
- Plays the most important role in EWSB.
- Higgs top coupling a likely window to new physics.



C. Shen, S. Zhu 1504.05626
Z. Liu, I. Low, LTW, in progress

Dark matter

Constraints on the 4-fermion operators @CEPC



Yi PengFei's talk.

Also, Chengfeng Cai's talk, using precision measurements

Flavor physics at Z-pole

- Flavorful new physics can show up.
  - Rare Z decays.
  - Z-factory as a τ-factory,
  - Z factory as B-factory.
  - ...
  - SiHou Zhou's presentation.

Preliminary discussion in the preCDR.
Efforts of studying this underway.
More studies needed.

Learning about QCD.

Jun Gao's talk

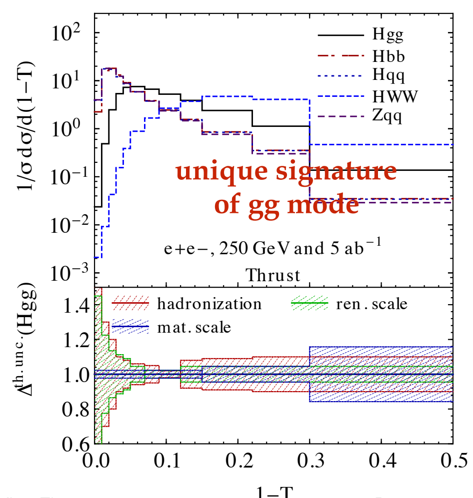
QCD and Higgs physics at CEPC

- CEPC provides an unique opportunity of testing QCD via decay of the Higgs boson

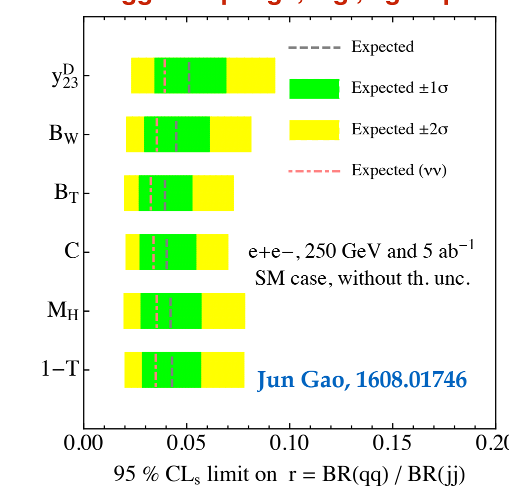
Expected event numbers for different hadronic decay modes of the SM Higgs boson at 250 GeV and with 5 ab^{-1}

$Z(l^+l^-)H(X)$	gg	$b\bar{b}$	$c\bar{c}$	$WW^*(4h)$	$ZZ^*(4h)$	$q\bar{q}$
BR [%]	8.6	57.7	2.9	9.5	1.3	~ 0.02
N_{event}	6140	41170	2070	6780	930	14

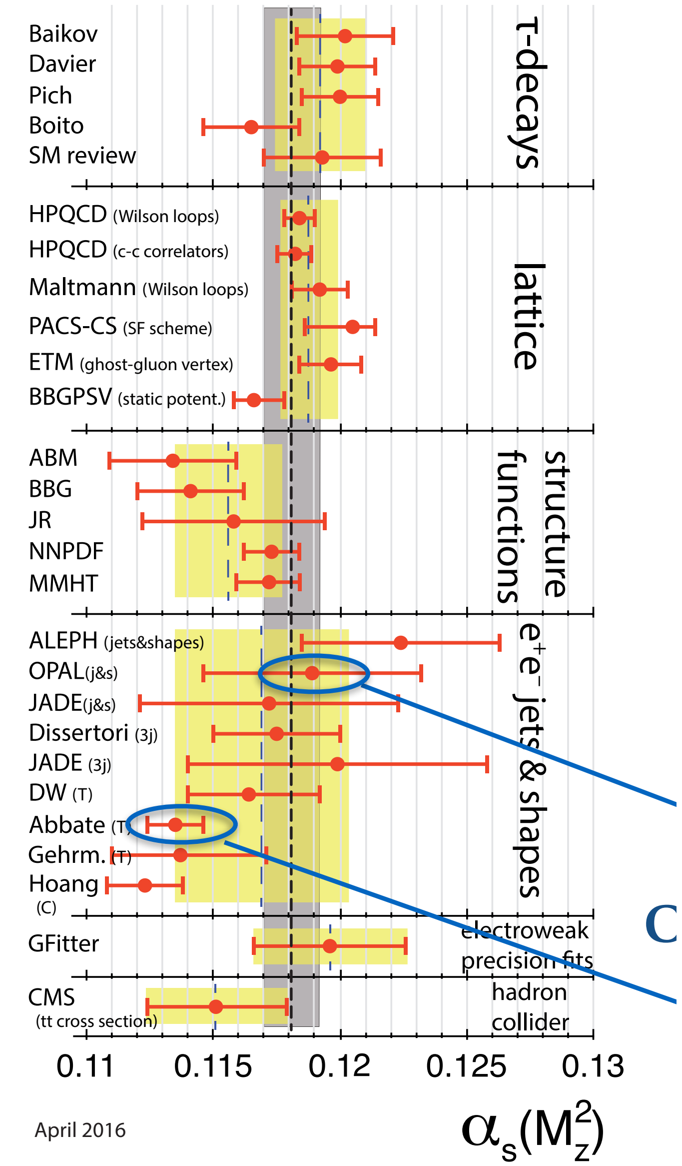
QCD event shape distributions



in another way, using QCD observables to test Higgs couplings, e.g., light-quark



Hua Xing Zhu   7   Prospects of Precision QCD Physics at CEPC   September CEPC meeting



Need more studies on QCD precision measurements

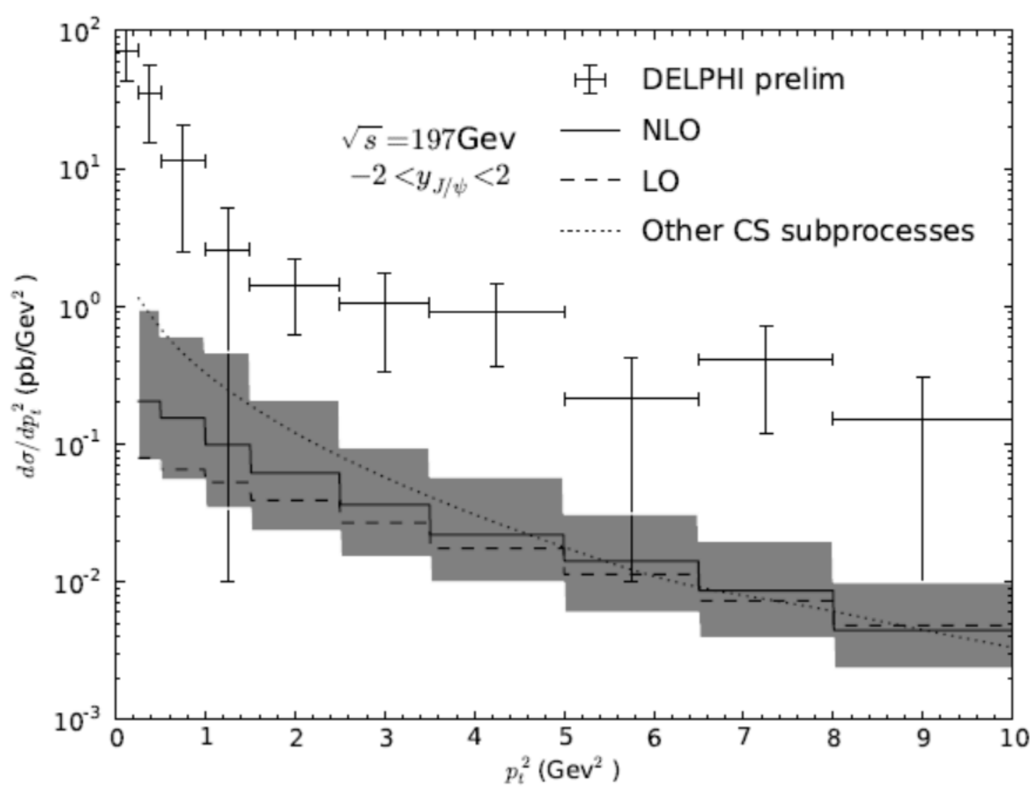
Quarkonium physics

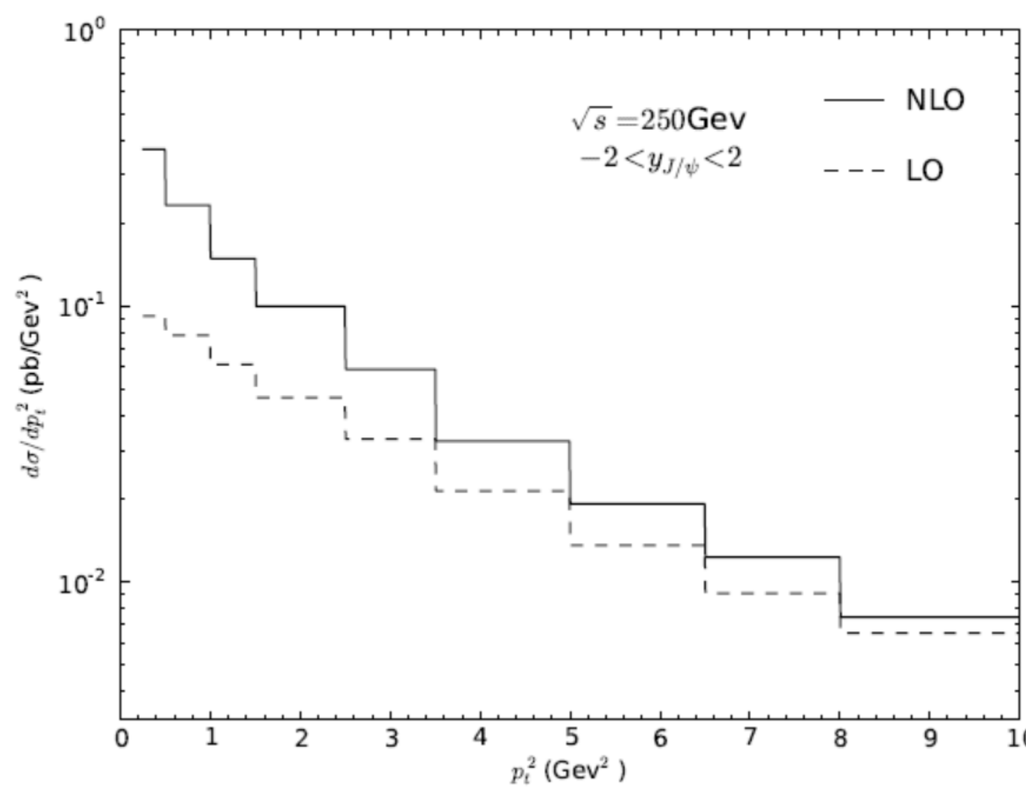
YanQing Ma's talk

$\gamma\gamma \rightarrow J/\psi + X$ at e^+e^- collision

- **CS contribution can not explain $\gamma\gamma$ data**

Chen, Chen, Qiao, 1608.06231

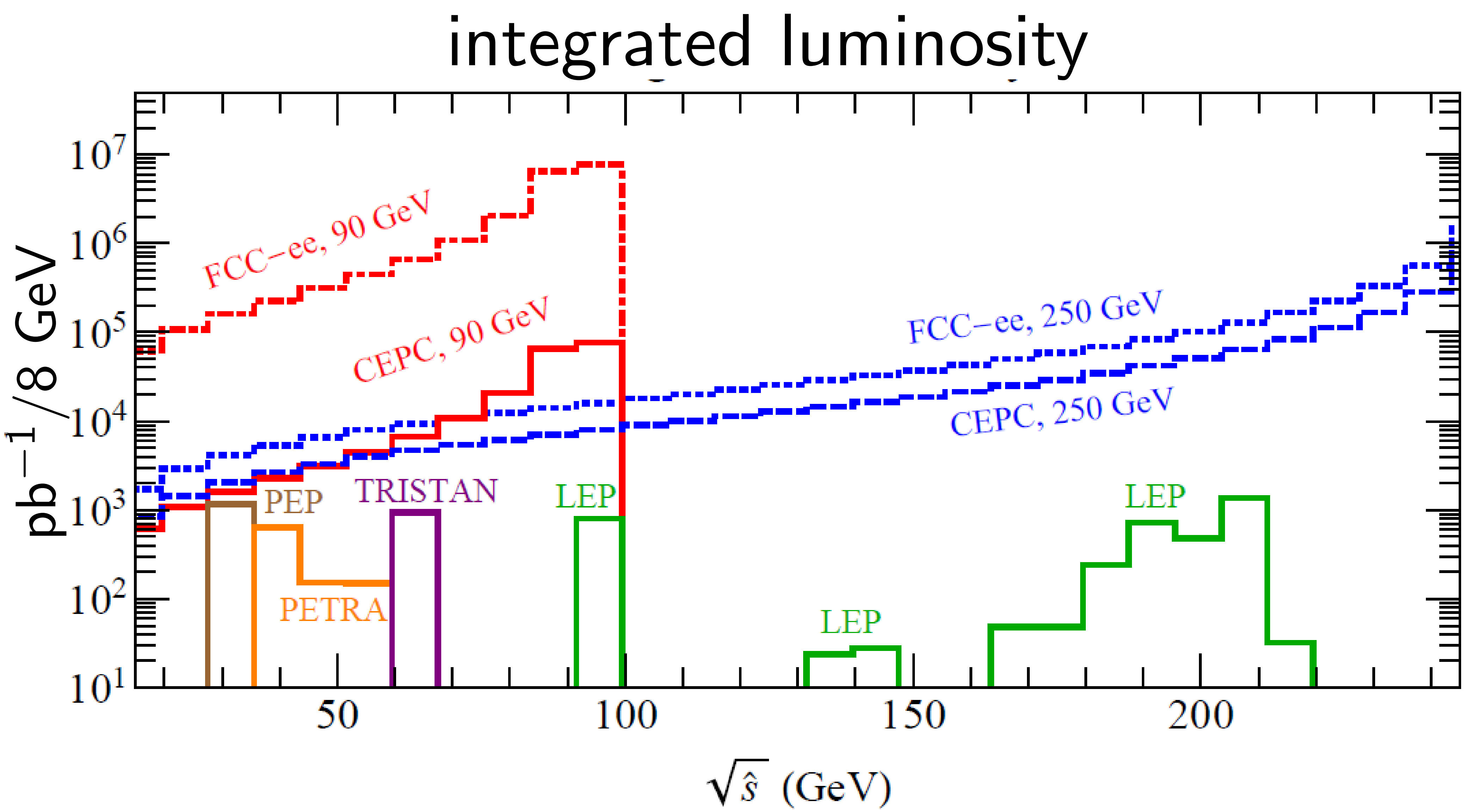




- **Large experimental error**

Filling gaps with radiative return

M. Karliner, M. Low, J. Rosner, LTW



Integrated luminosity from past low energy e^+e^- colliders at their nominal center-of-mass energies compared to the effective luminosity through radiative return from future e^+e^- colliders at $\sqrt{s} = 90$ or 250 GeV

How can we best use this?

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Physics goals
and
machine options

Machine design, big options

- Questions
  - How big is the ring?
  - Case for Z factory and requirement
  - Going to higher energy, ttbar threshold?
  - ....
- Using physics case to support the choice made in the CDR.

80+ km vs 50 km

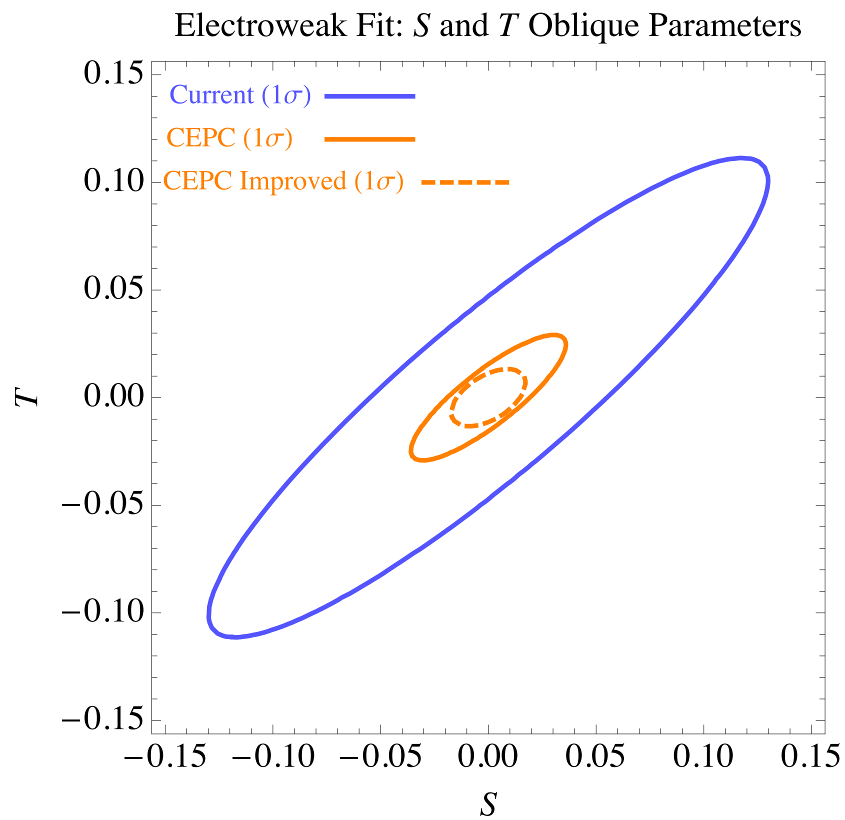
- Settled on 100km.

The main physics goal, understanding the Higgs

- Phase transition in early universe, naturalness, etc.
- Based on simple estimate and simulation, the CEPC will be able to deliver on these goals.
- We need to work closely together (physics studies and detector and accelerator designs) to make sure this can be realized.

Progresses in Manqi Ruan, Gang Li, and Jin Wang's talk

CEPC on the Z-pole



- "Bread and butter" precision measurement
  - Gain a factor of 10 with about Giga Z.
  - Very valuable information, complimentary to Higgs measurements

Electroweak precision tests: roughly estimated targets

- δm_W < 5 MeV
- $\delta \sin^2\theta_{eff}$ < 2×10^{-5} (and/or Γ_Z about 100 keV)
- δm_Z < 500 keV
- δm_t < 100 MeV
- Theoretical breakthrough in calculating $\Delta\alpha_{had}$?

Much more work needed to produce more accurate and realistic numbers.

Status report from Zhijun Liang's talk

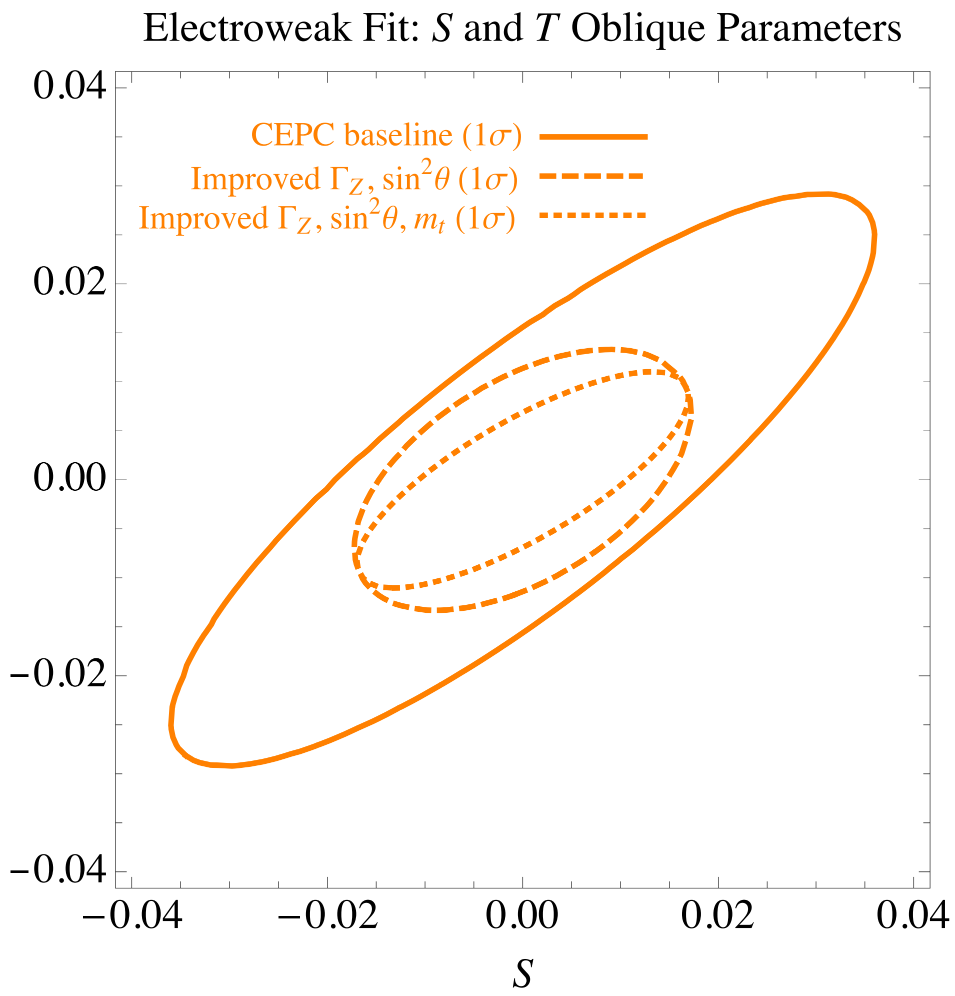
CEPC Z-factory

- Tera-Z or more?
  - Can do a lot more with precision measurements.
  - Many interesting topics.
  - Exotic Z-decay, tau, B, flavor...

More work needed to make concrete cases and compare.

CEPC: higher E, ttbar threshold?

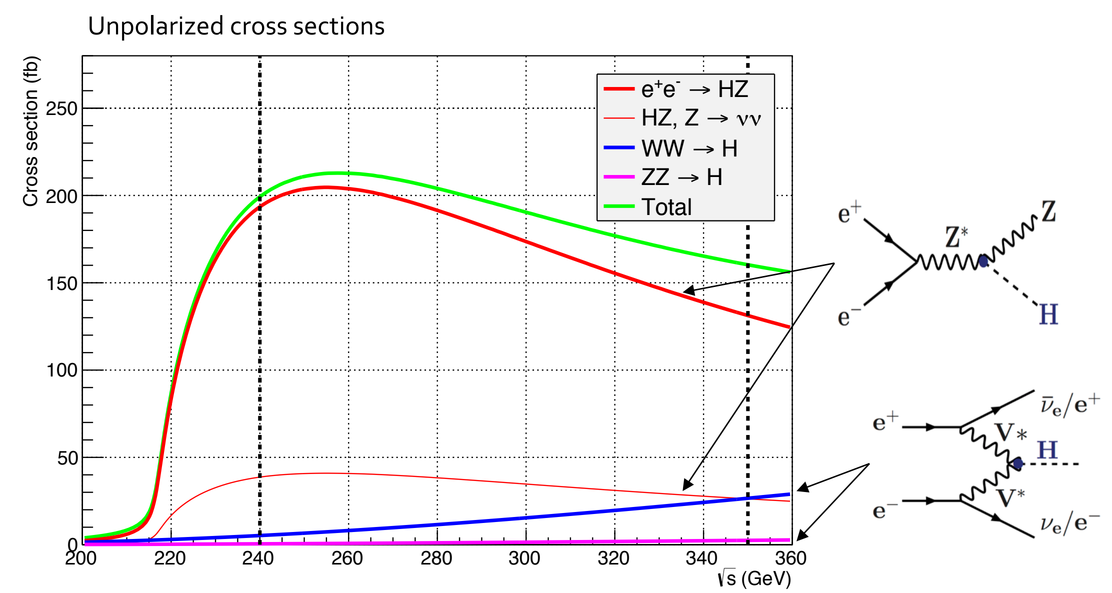
- Seems not as crucial for precision electroweak.
- A small improvement for the fit to S and T.
- Is this optimistic or pessimistic on the systematics?



CEPC: higher energy, ttbar threshold?

- However, going up from 250 to 350 can improve other measurements.

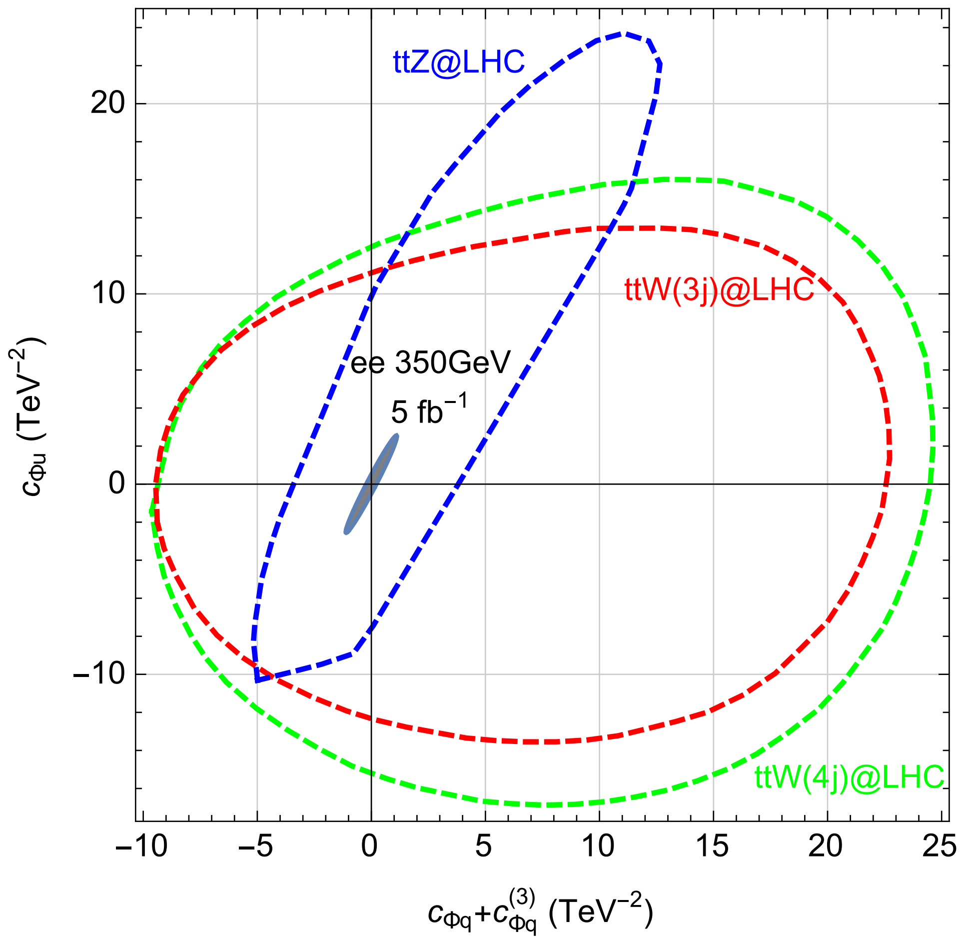
For example:



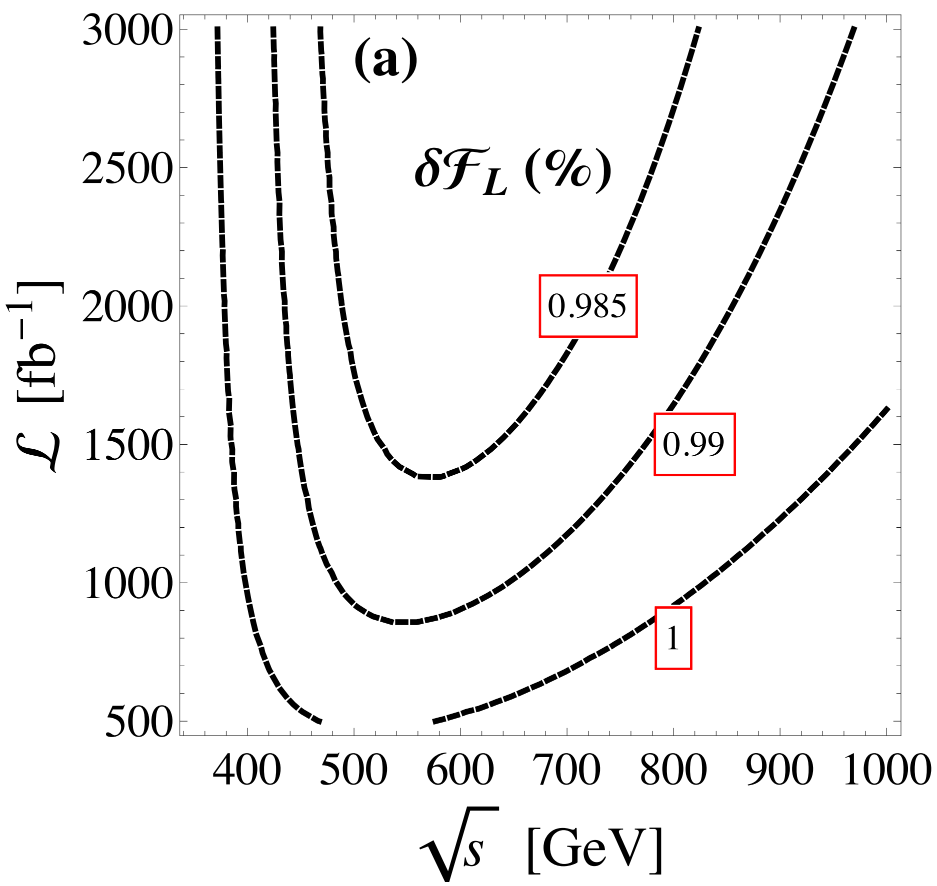
- Scan, energy dependence brings in more discovery and distinguishing power.

- Many more studies needed.

Learning more about top couplings



Z. Liu, I. Low, LTW in progress



Q. Cao, B. Yan 1507.06204

Looking ahead

- We have a broad understanding of the basic physics capabilities of CEPC.
- CDR will be a place to set clear physics goals.
  - The big questions we will address.
  - Supporting and backed up by the design choices.
- Need to work together.
  - Theory + experiment joint working groups in key areas crucial for progress.
- Intense (and very exciting) work ahead.

Inputs for the further study

Baseline option

	Present data	CEPC fit
$\alpha_s(M_Z^2)$	0.1185 ± 0.0006 [17]	$\pm 1.0 \times 10^{-4}$ [18]
$\Delta\alpha_{\rm had}^{(5)}(M_Z^2)$	$(276.5 \pm 0.8) \times 10^{-4}$ [19]	$\pm 4.7 \times 10^{-5}$ [20]
m_Z [GeV]	91.1875 ± 0.0021 [21]	$\pm \mathbf{0.0005}$
m_t [GeV] (pole)	$173.34 \pm 0.76_{\rm exp}$ [22] $\pm 0.5_{\rm th}$ [20]	$\pm 0.6_{\rm exp} \pm 0.25_{\rm th}$ [20]
m_h [GeV]	125.14 ± 0.24 [20]	$< \pm 0.1$ [20]
m_W [GeV]	$80.385 \pm 0.015_{\rm exp}$ [17] $\pm 0.004_{\rm th}$ [23]	$(\pm \mathbf{3}_{\rm exp} \pm 1_{\rm th}) \times 10^{-3}$ [23]
$\sin^2\theta_{\rm eff}^{\ell}$	$(23153 \pm 16) \times 10^{-5}$ [21]	$(\pm \mathbf{4.6}_{\rm exp} \pm 1.5_{\rm th}) \times 10^{-5}$ [24]
Γ_Z [GeV]	2.4952 ± 0.0023 [21]	$(\pm \mathbf{5}_{\rm exp} \pm 0.8_{\rm th}) \times 10^{-4}$ [25]
$R_b \equiv \Gamma_b/\Gamma_{\rm had}$	0.21629 ± 0.00066 [21]	$\pm \mathbf{1.7} \times 10^{-4}$
$R_\ell \equiv \Gamma_{\rm had}/\Gamma_\ell$	20.767 ± 0.025 [21]	$\pm \mathbf{0.007}$

With possible improvements.

CEPC	$\sin^2\theta_{\rm eff}^{\ell}$	Γ_Z [GeV]	m_t [GeV]
Improved Error	$(\pm 2.3_{\rm exp} \pm 1.5_{\rm th}) \times 10^{-5}$	$(\pm 1_{\rm exp} \pm 0.8_{\rm th}) \times 10^{-4}$	$\pm 0.03_{\rm exp} \pm 0.1_{\rm th}$

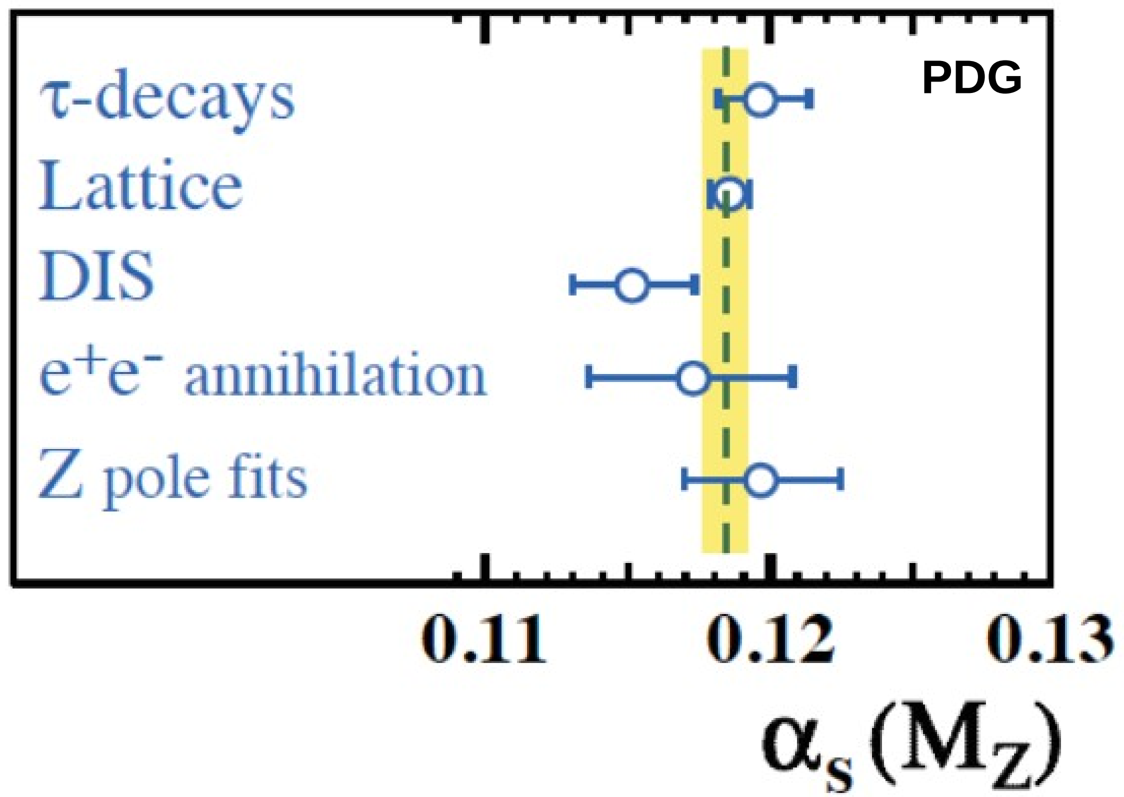
x4 statistics off Z-pole

energy calibration

ILC?

QCD at CEPC

World average on alphas

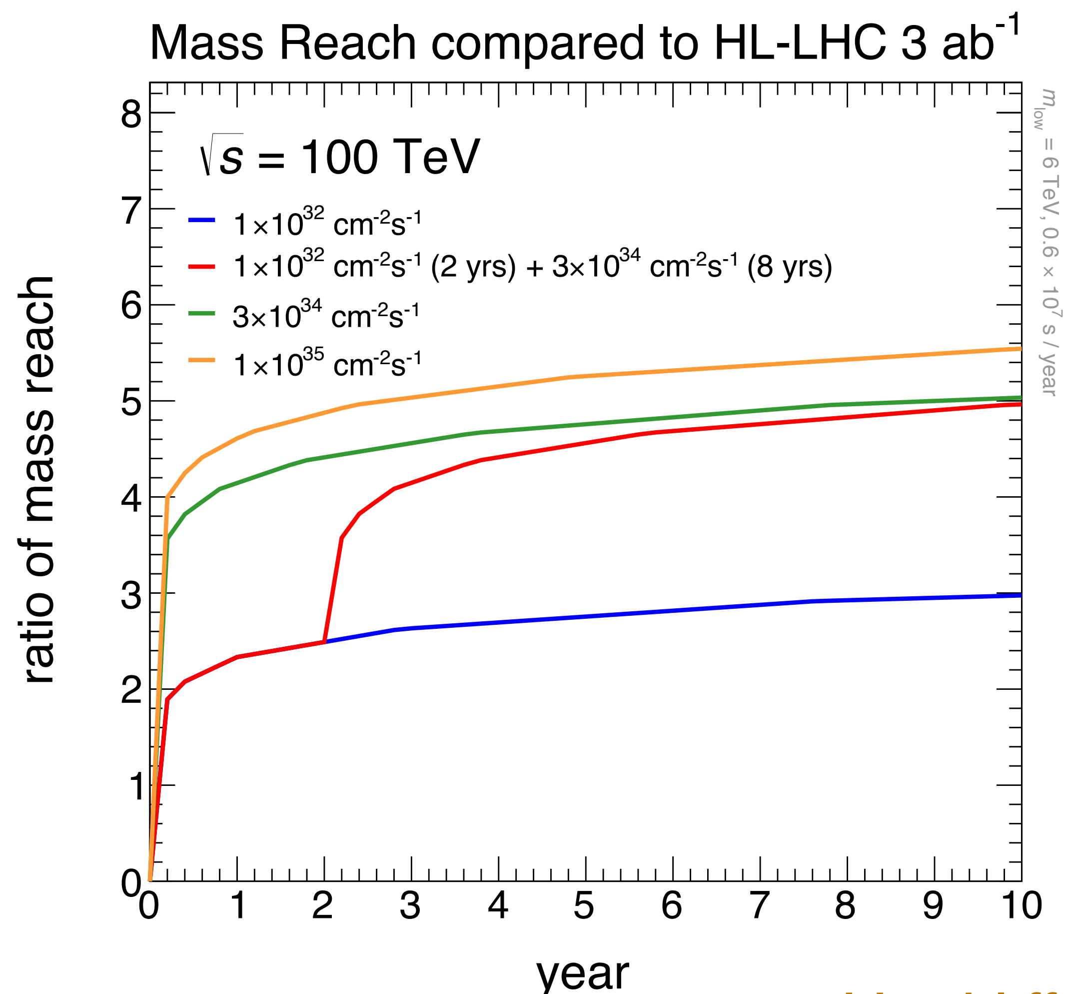


- Dominated my Lattice results
- O(100-1fb) at CEPC v.s. O(100-1pb) at LEP, plus higher energy, smaller power corrections, good news for event shape analysis.
- New challenges to theorists. NNLO corrections to four jet rates? Completing the NNNLL resummation by computing the four loop cusp anomalous dimension? …

Only tip of the iceberg.

H. X. Zhu at CEPC workshop. Aug. 2015

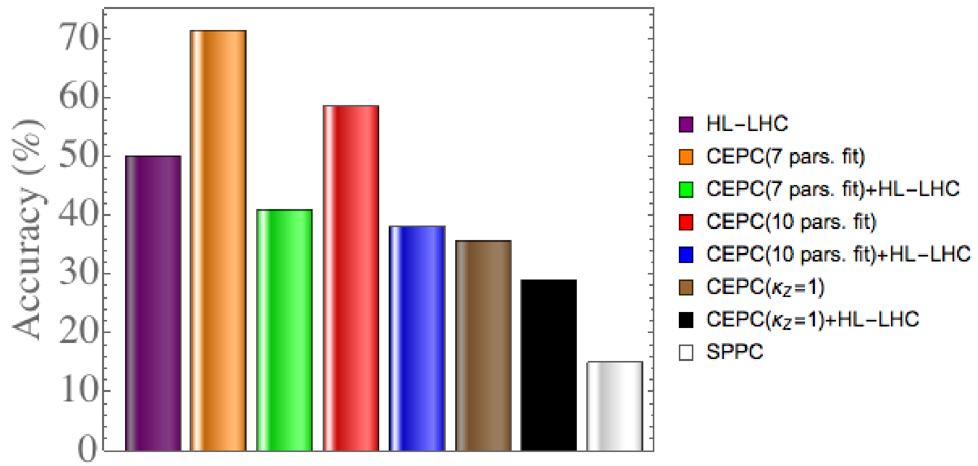
100-ish TeV SPPC



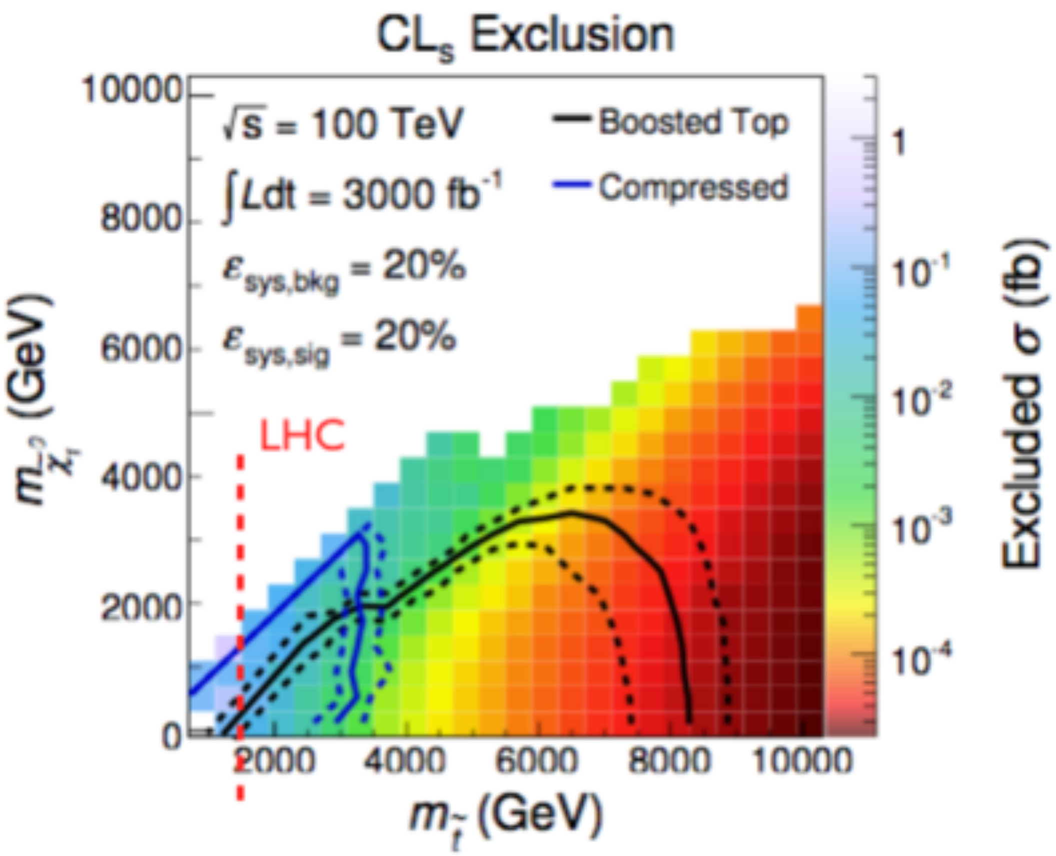
Hinchliffe, Kotwal, Mangano, Quigg, LTW

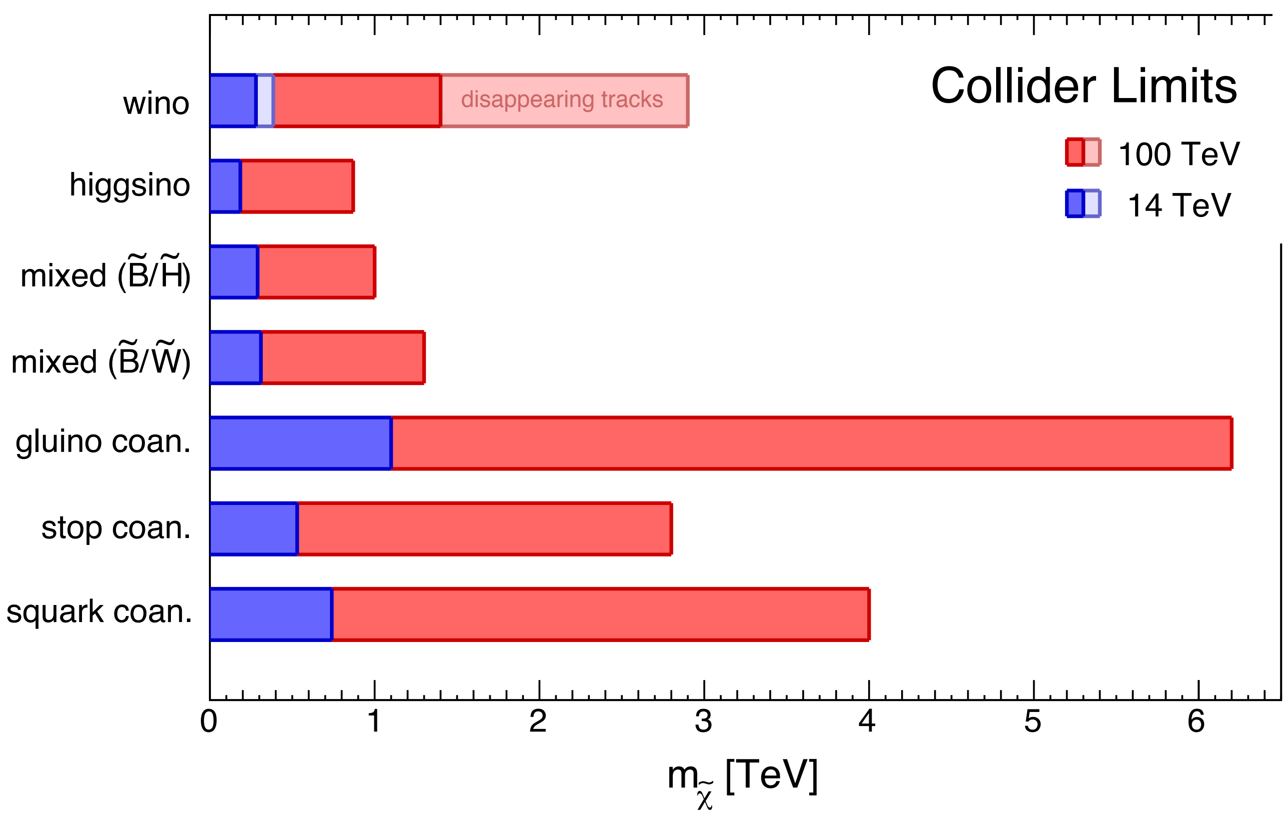
A factor of about 5 increase in reach with modest luminosity

SPPC



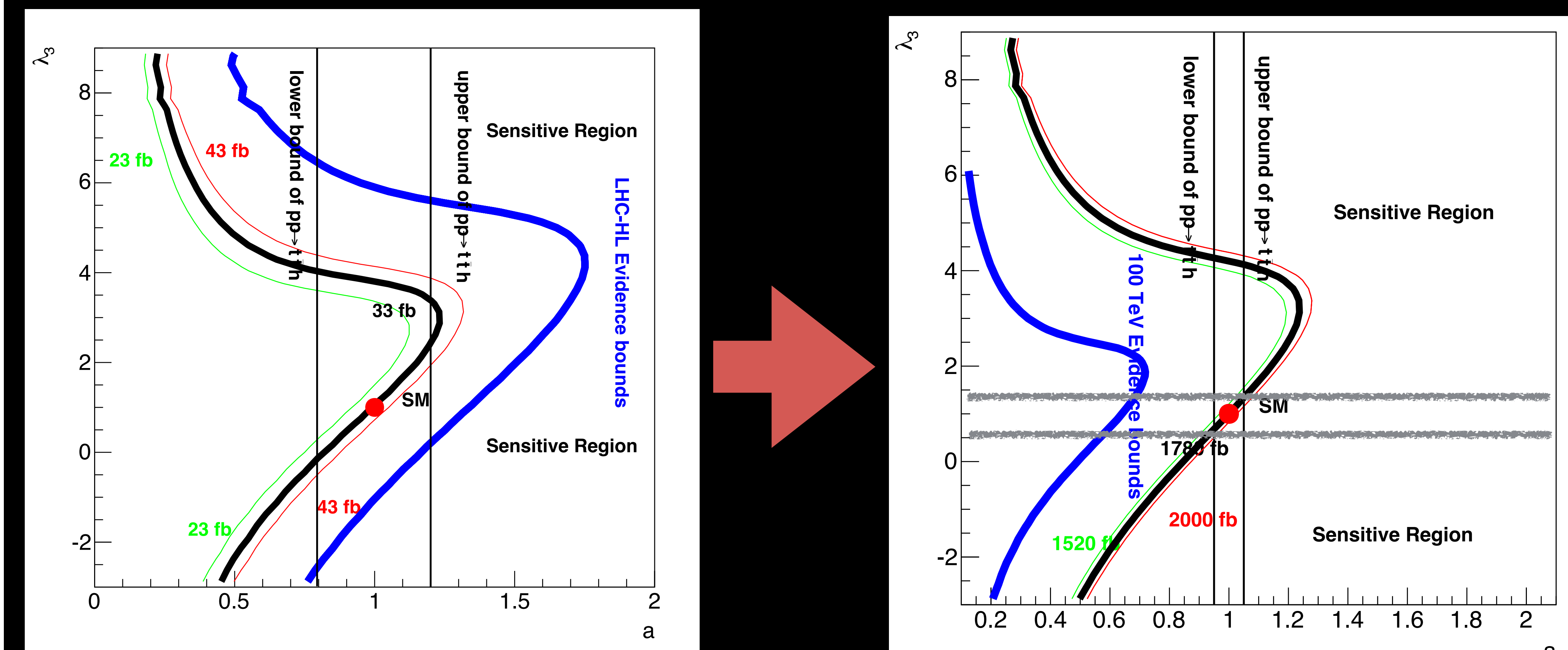
Cohen et. al., 2014





Higgs couplings at SPPC

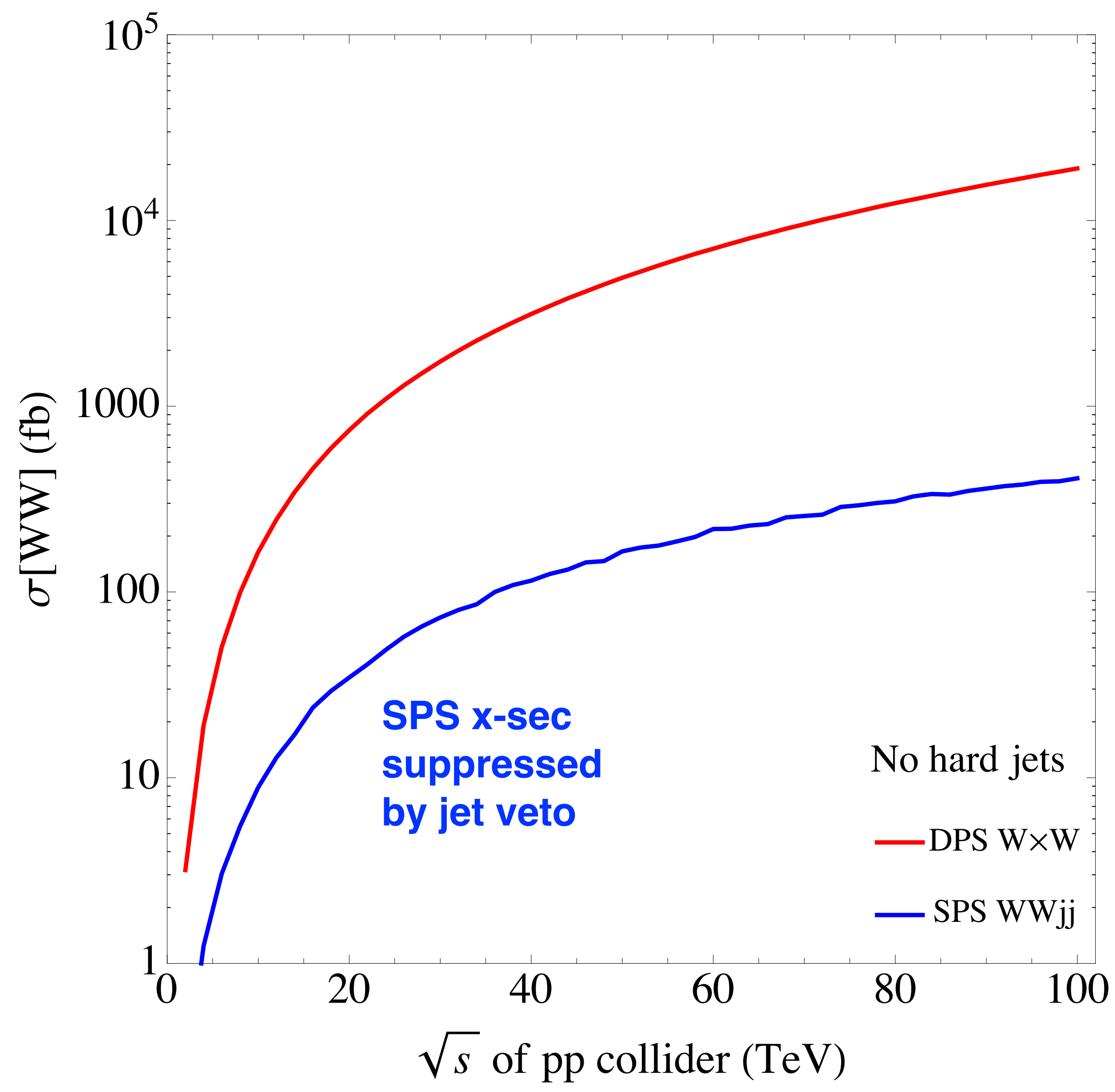
Correlation between Higgs pair production and tth measurement

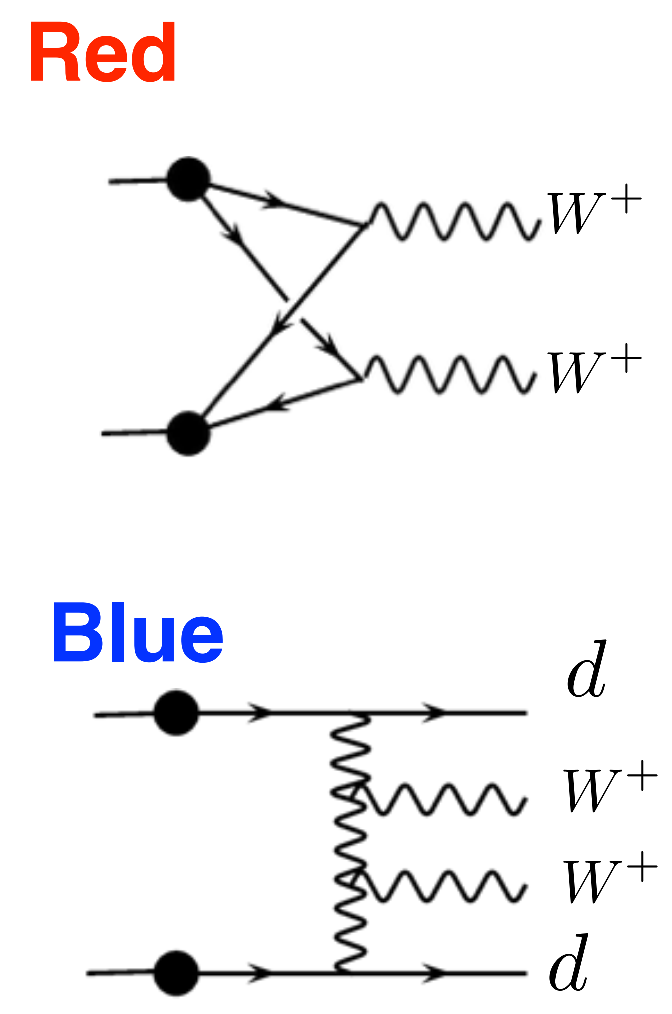


Yan Qishu's talk at this workshop

2) Same-sign WW pair production

(golden channel of DPS)





Cao QingHong's talk at this workshop