Future circular colliders update

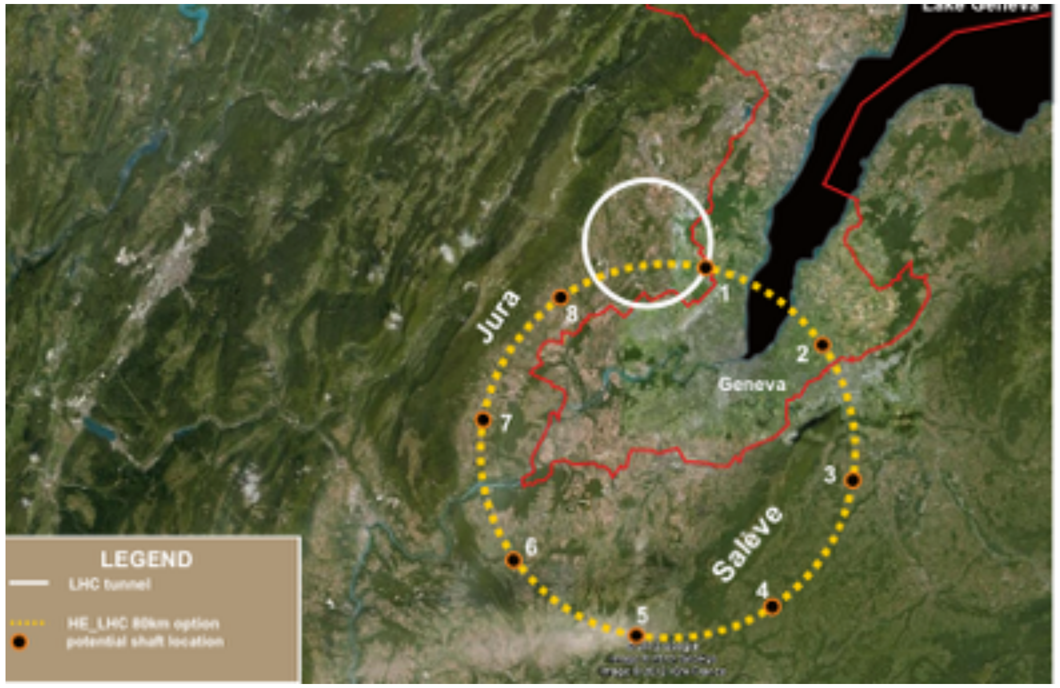
LianTao Wang
University of Chicago

Hidden workshop. Maryland, April 29 2016

This talk

- Physics of circular colliders. (brief)
- Updates (Mostly developments in China)
- Physics questions.

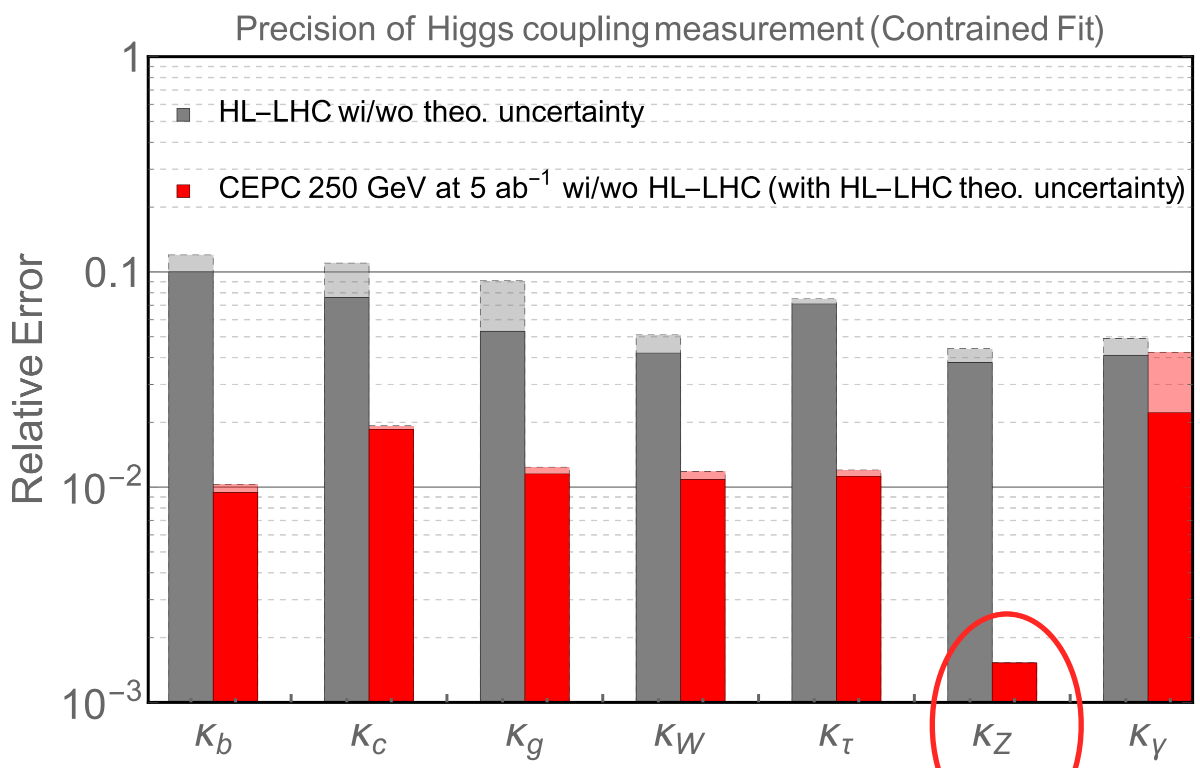
Future circular colliders

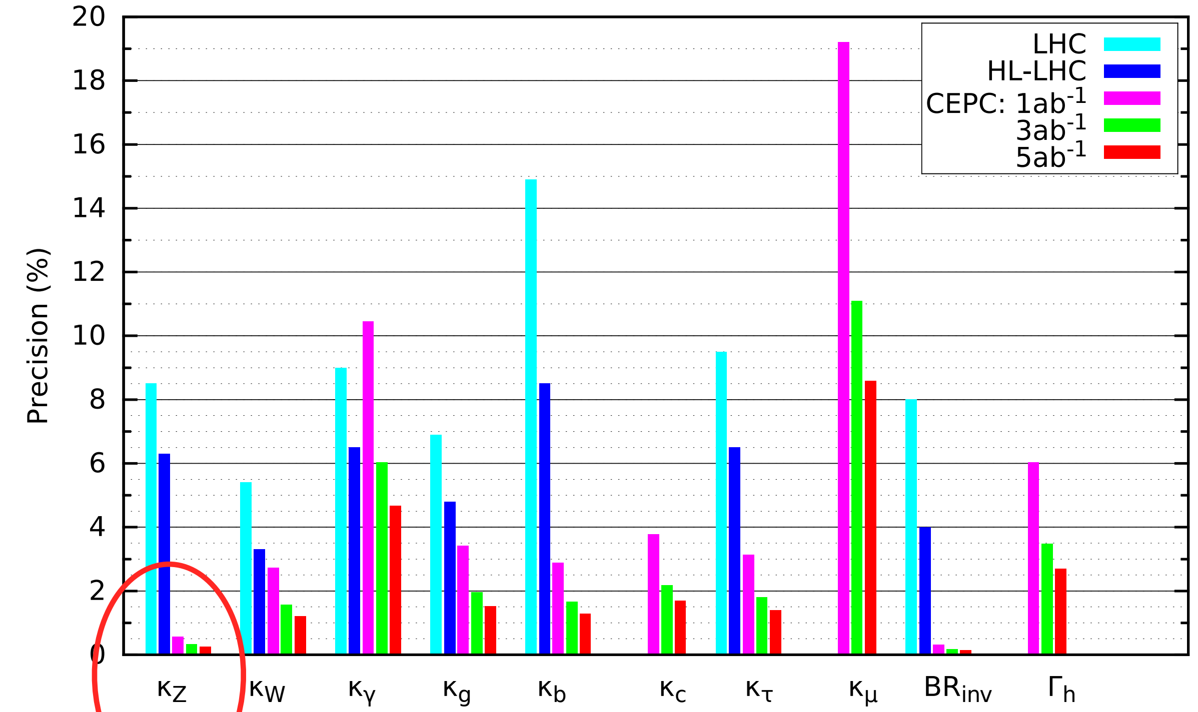


CERN
Higgs/Z factory: FCC-ee
pp Collider: FCC-hh

China.
Higgs/Z factory: CEPC
pp Collider: SppC

Higgs factory: precision frontier





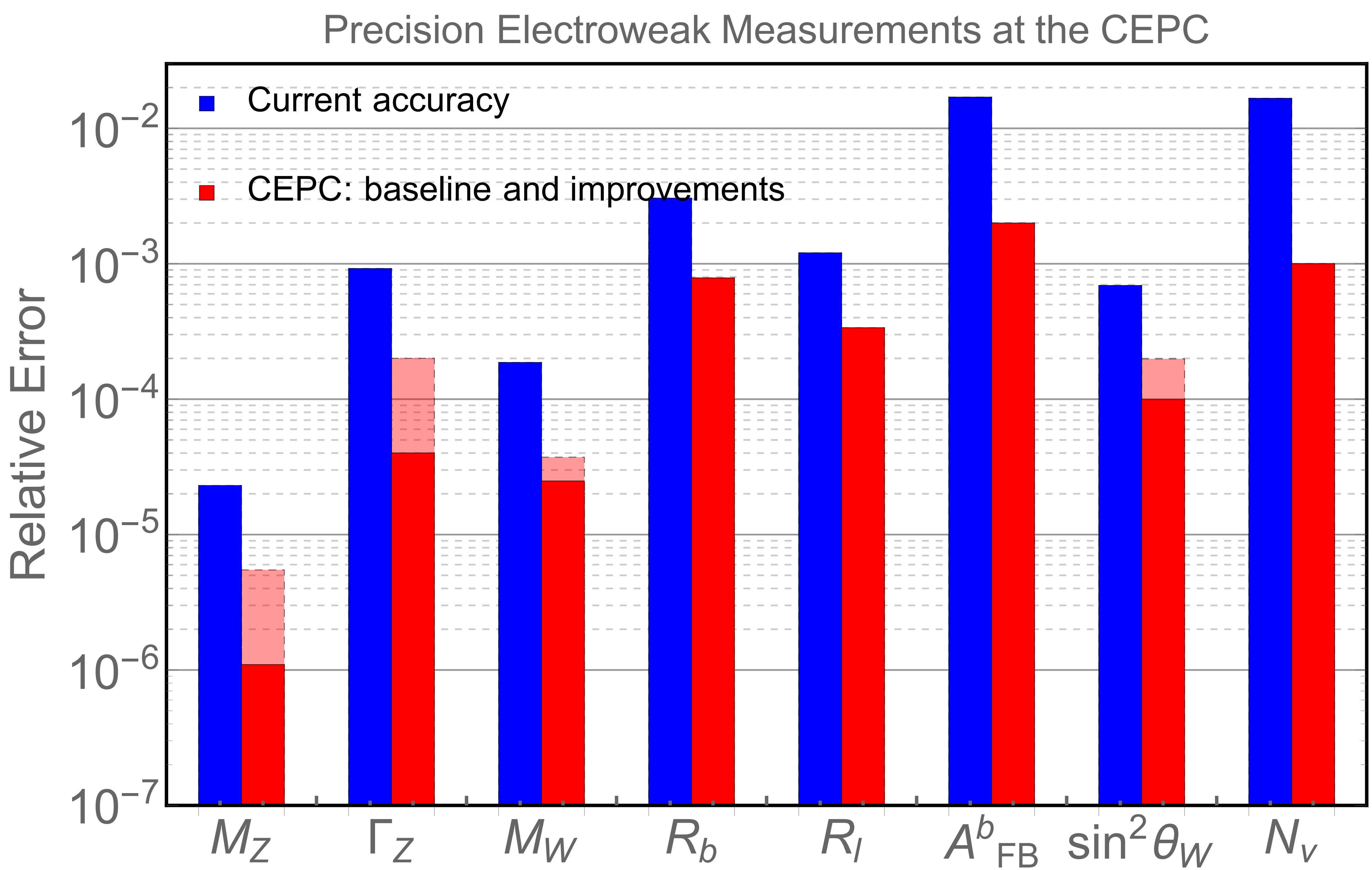
$$\kappa_X = \frac{\text{Measured Higgs-X coupling}}{\text{Standard Model Higgs-X coupling}}$$

Highlights:

HZ coupling to sub-percent level.
Many couplings to percent level.
Model independent measurement of total width.

Statistics limited

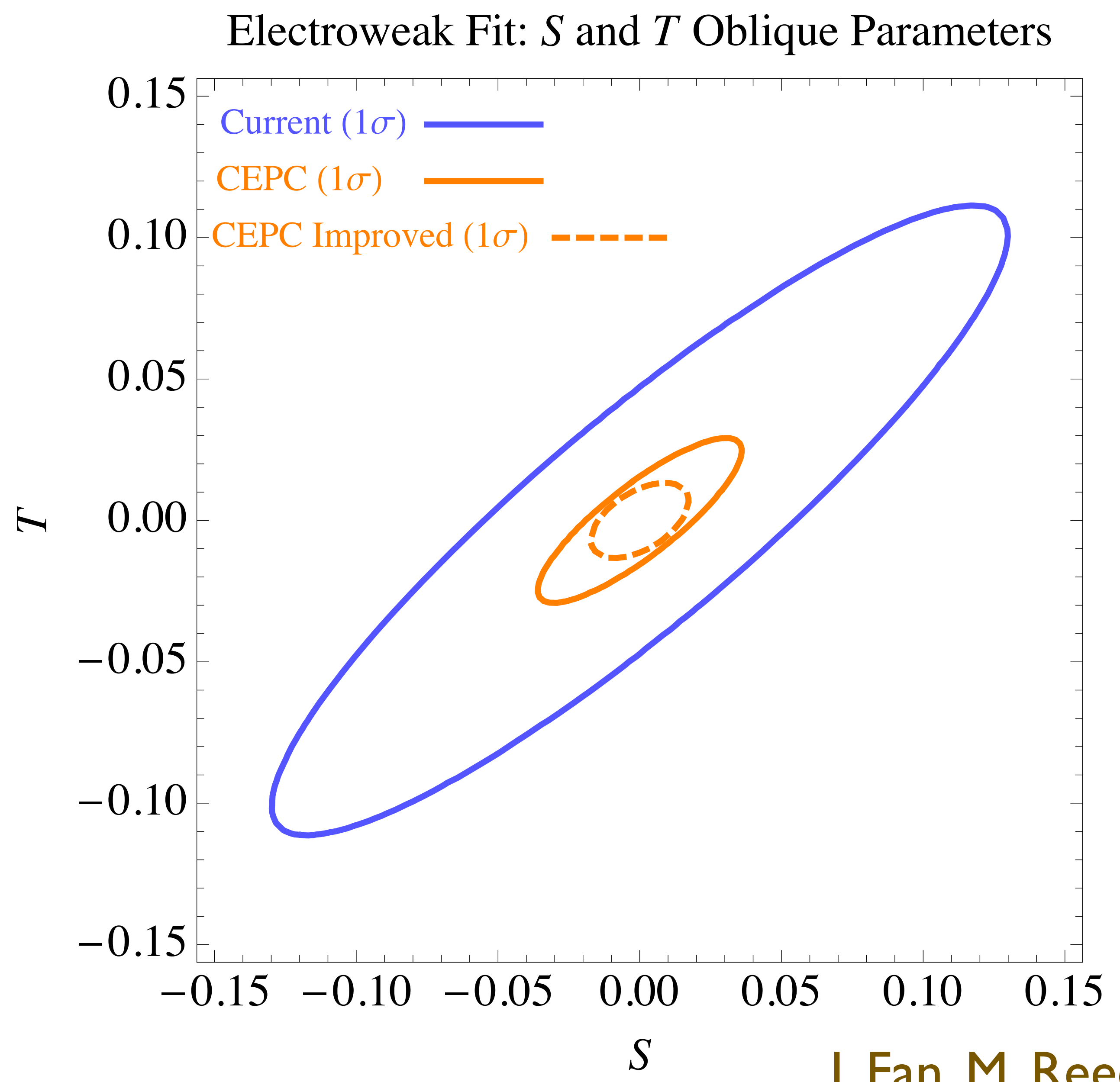
Big advance in electroweak precision



Large improvements across the board

Systematics limited

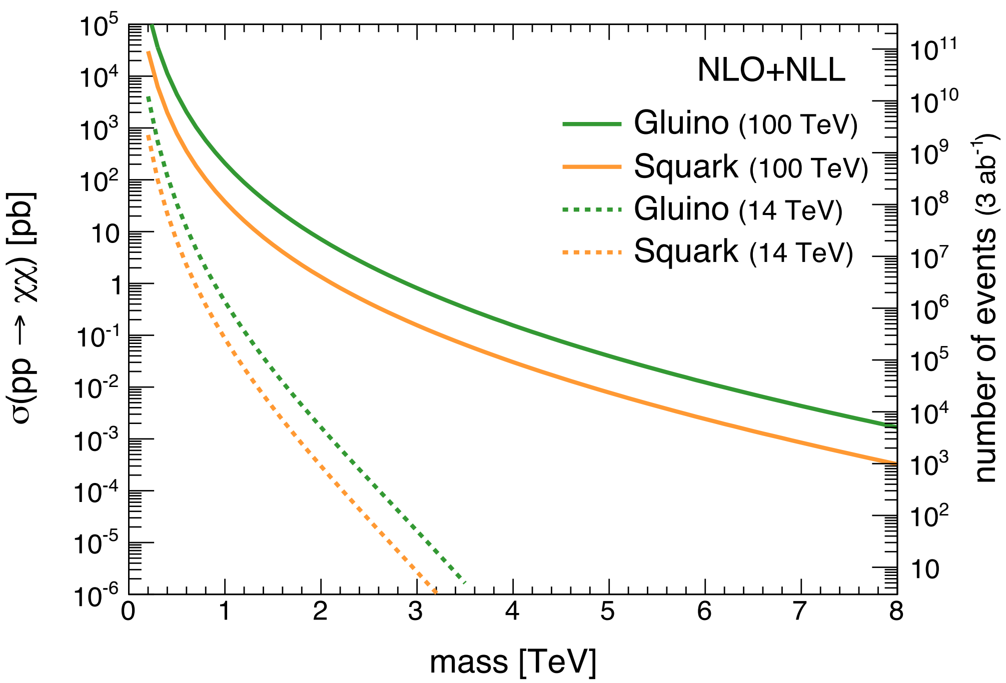
Electroweak precision at CEPC

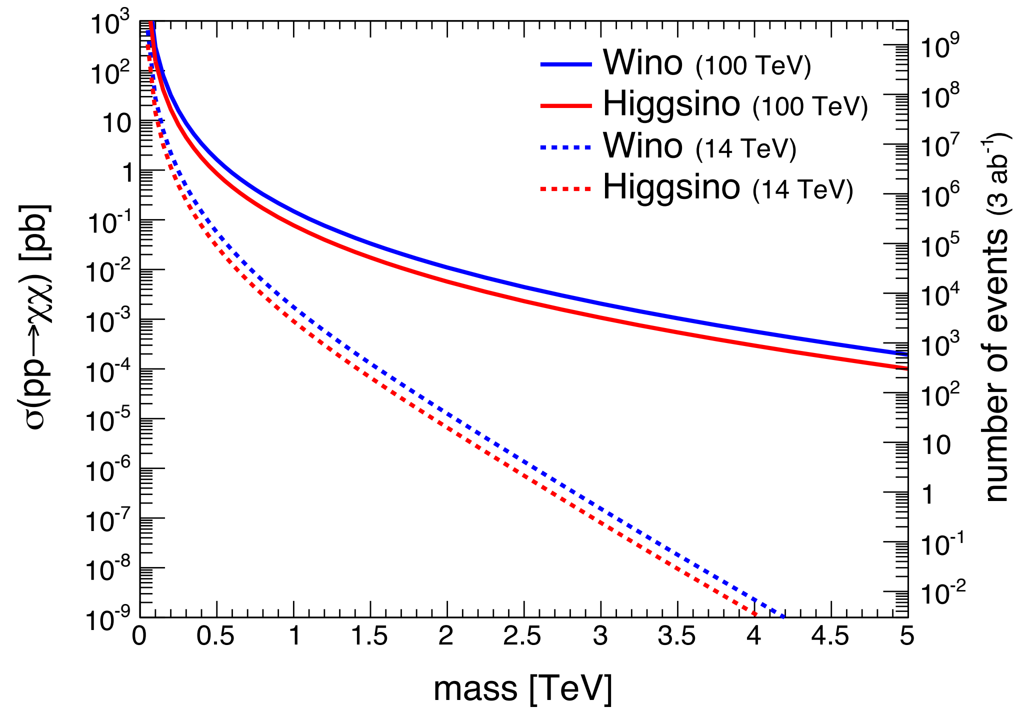


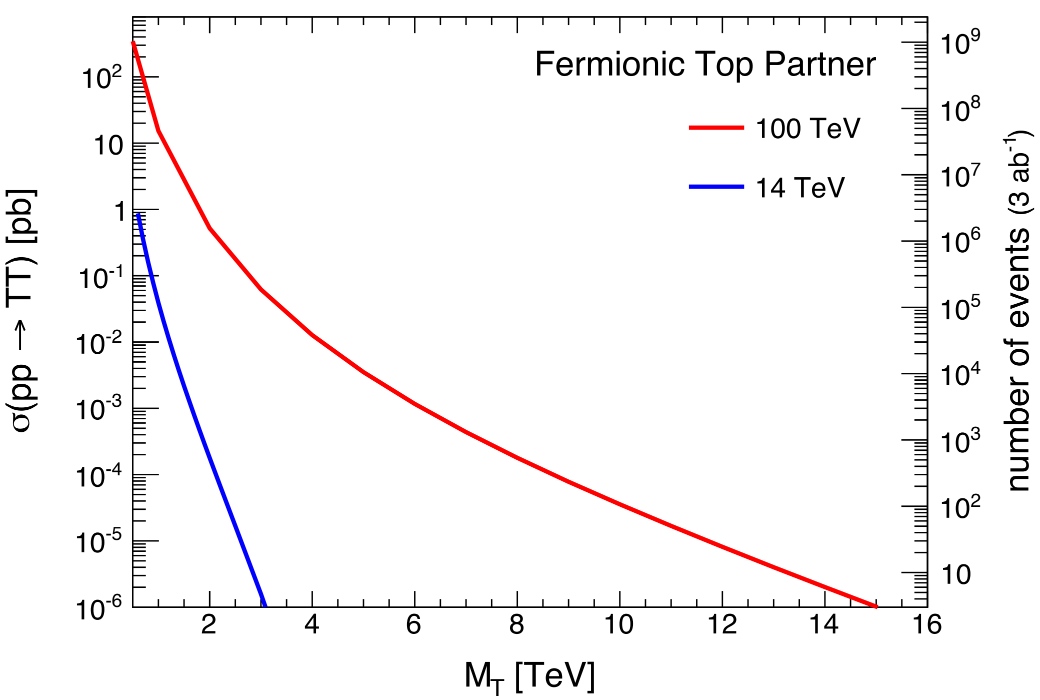
J. Fan, M. Reece, LT Wang, 1411.1054

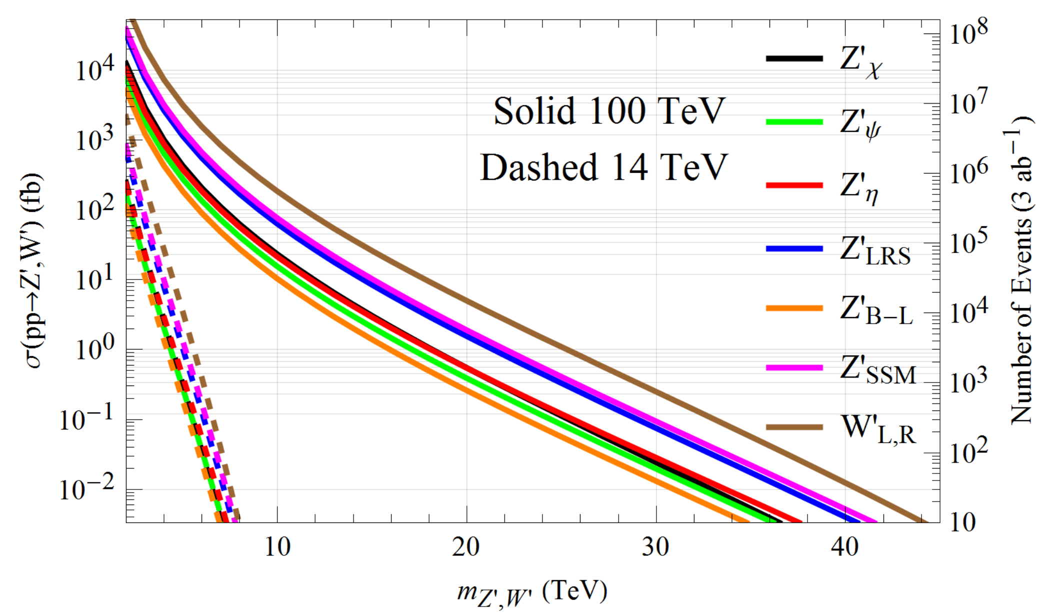
- A big step beyond the current precision.

100 TeV pp collider, a big step in energy





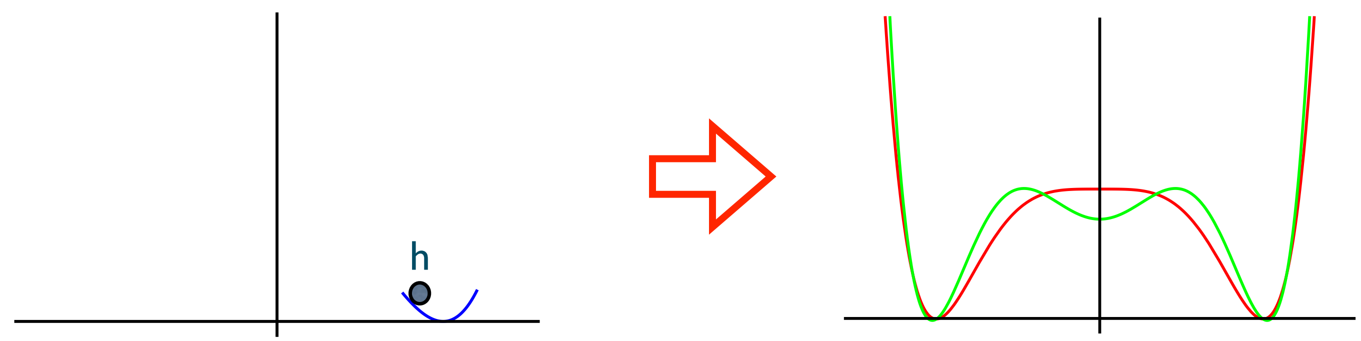


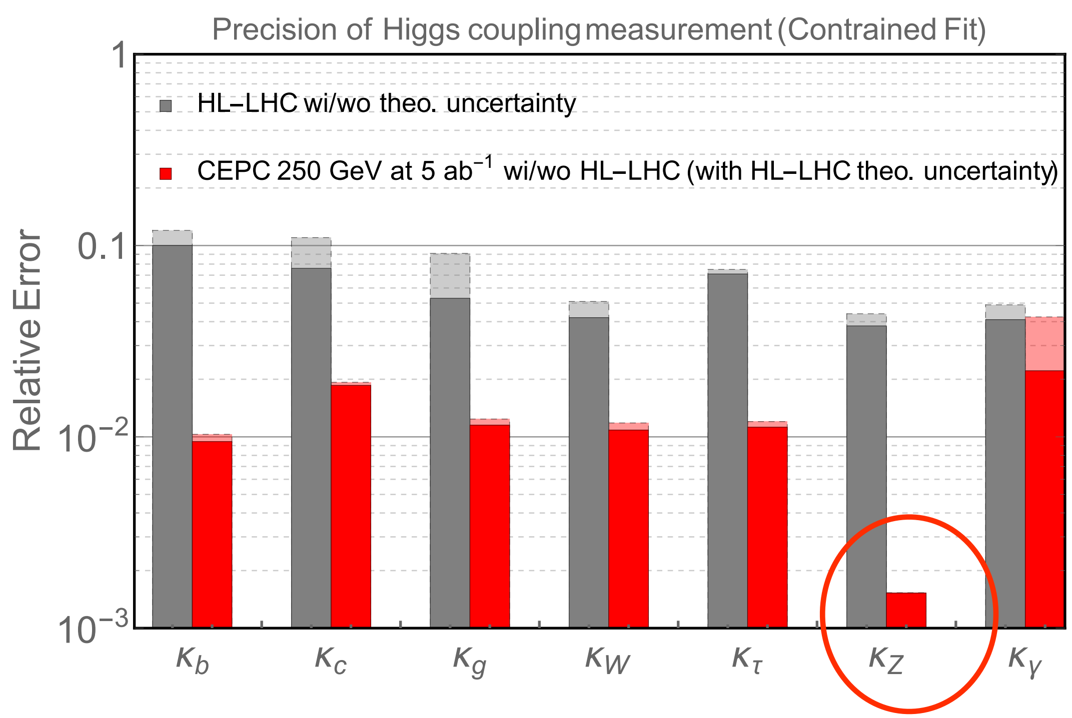


Physics goals

- Measuring Higgs potential.
- Naturalness.
- Dark matter.
- ...

Nature of EW phase transition





Triple Higgs coupling at 100 TeV pp collider
30 ab^{-1}

$$\frac{\lambda}{\lambda_{\rm SM}} \in \begin{cases} [0.891, 1.115] & \text{no background syst.} \\ [0.882, 1.126] & 25\%\ hh, 25\%\ hh+\text{jet} \\ [0.881, 1.128] & 25\%\ hh, 50\%\ hh+\text{jet} \end{cases}$$

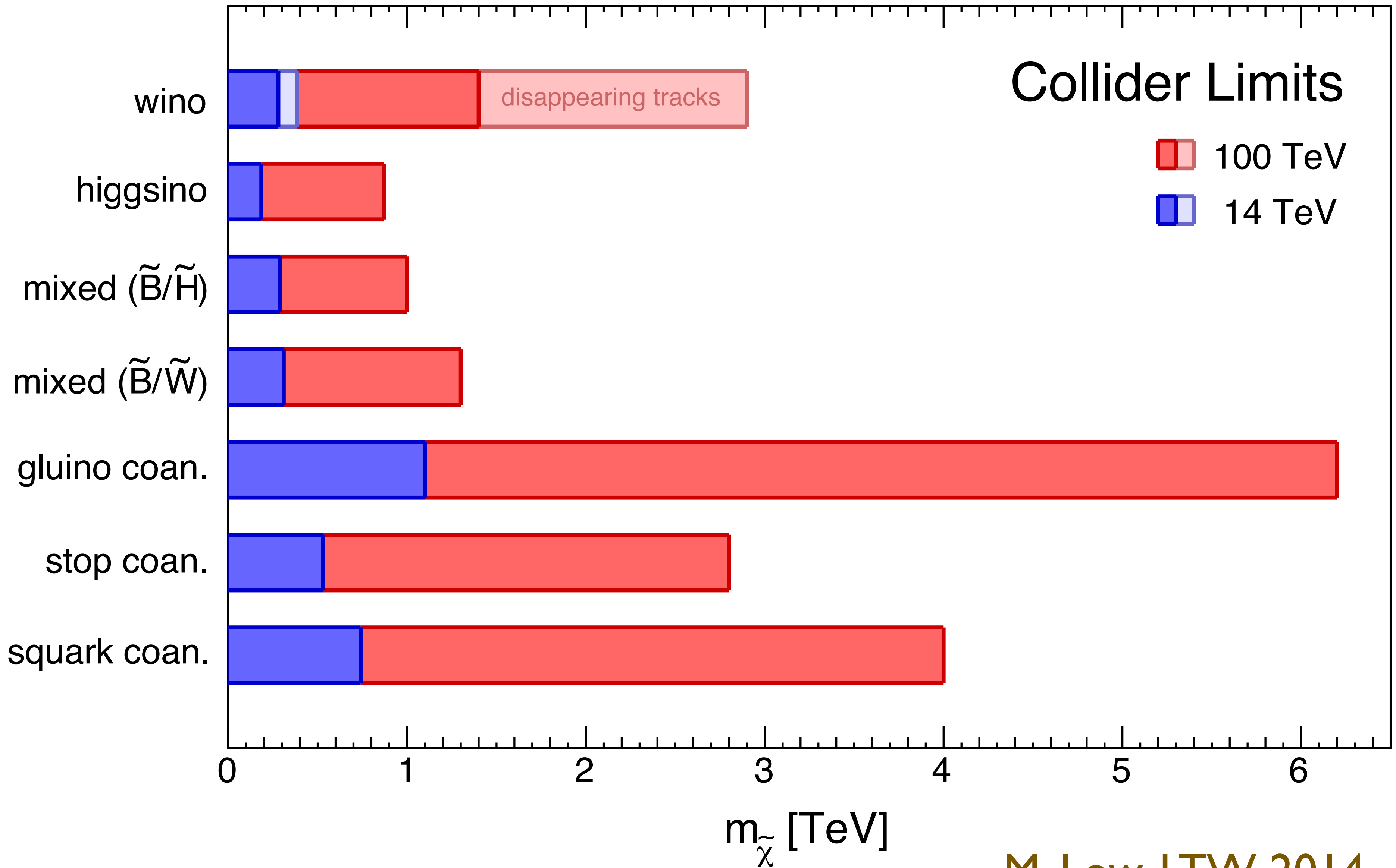
Barr, Dolan, Englert, de Lima, Spannowsky

Shift in h-Z coupling

Order 1 deviation in triple Higgs

} Both within the reach

Dark matter at 100 TeV



M. Low, LTW 2014

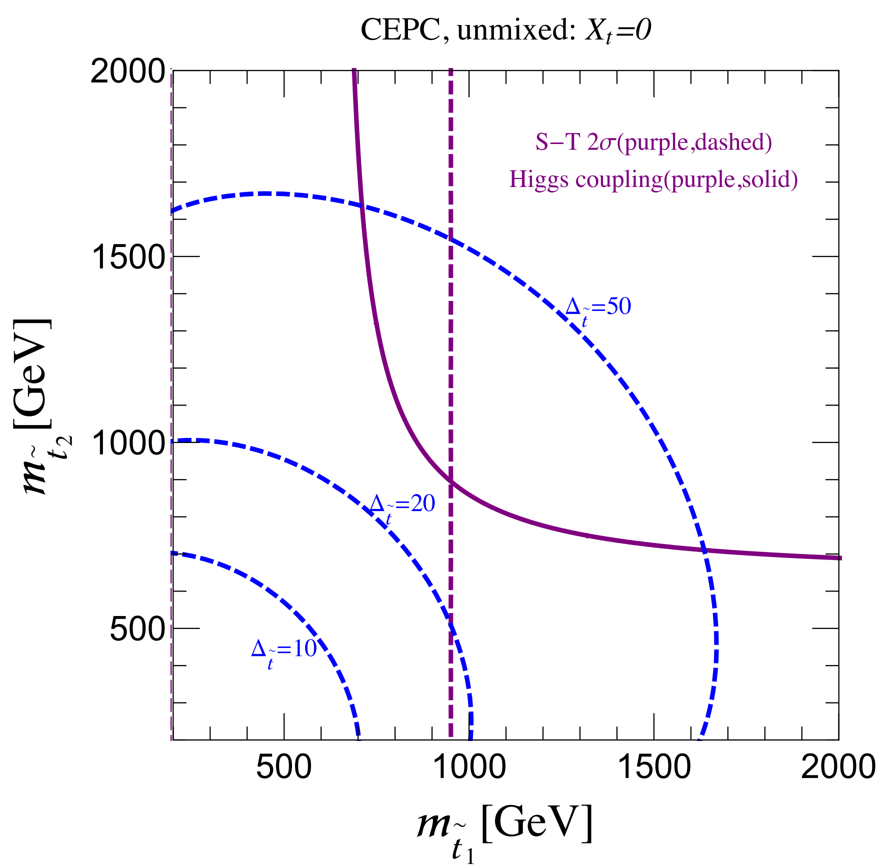
$$M_{\rm WIMP} \leq 1.8 \text{ TeV} \left(\frac{g^2}{0.3}\right)$$

Naturalness

Testing naturalness at Higgs factory

- LHC searches model dependent, many blind spots.

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

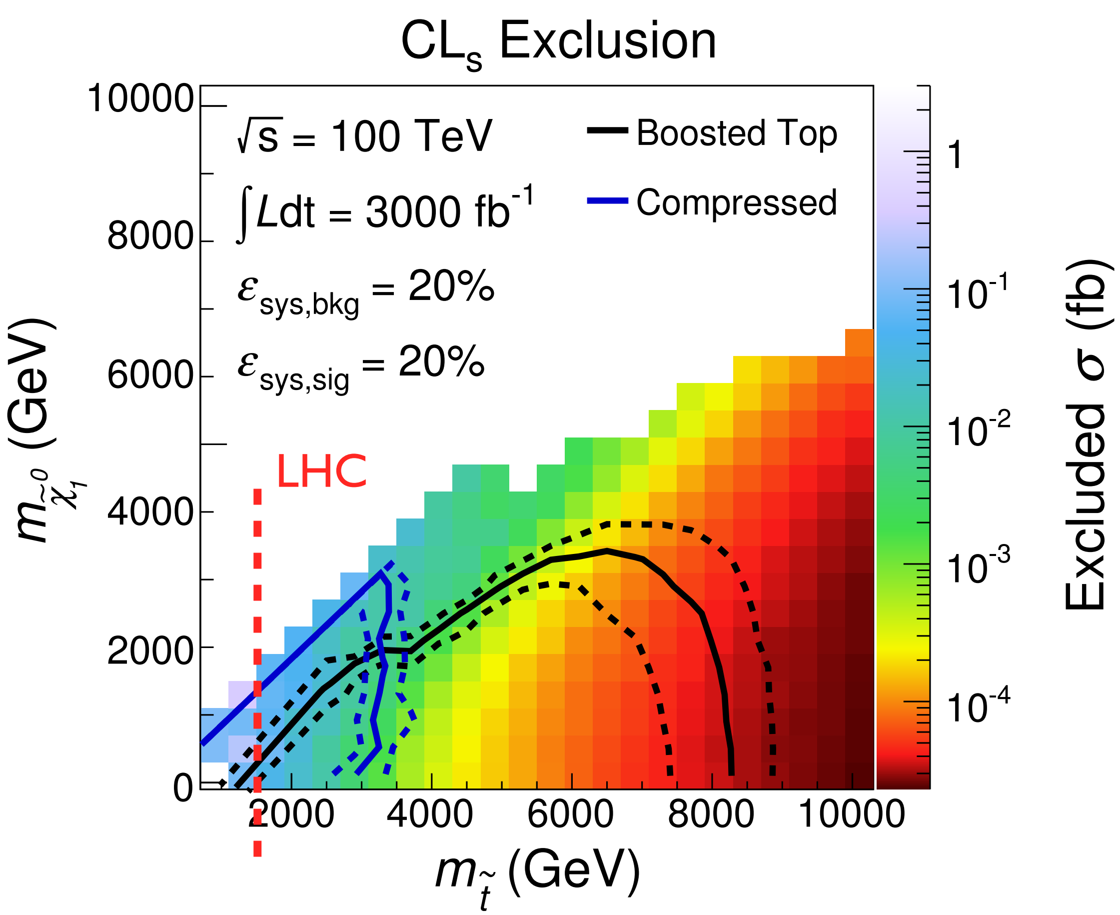


Fan, Reece and LT W, 1412.3107

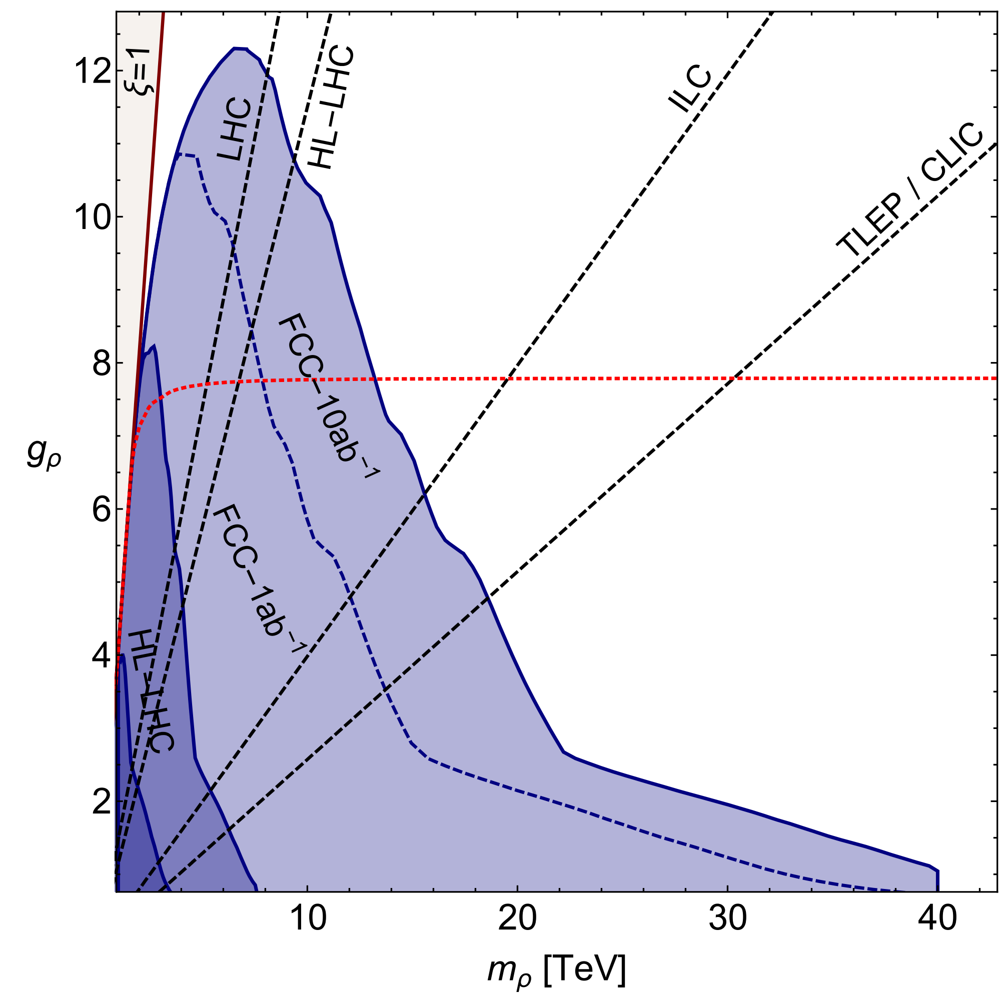
- Model independent testing fine-tuning down to percent level.

Test naturalness at 100 TeV collider

Cohen et. al., 2014



Pappadopulo, Thamm, Torre, Wulzer, 2014

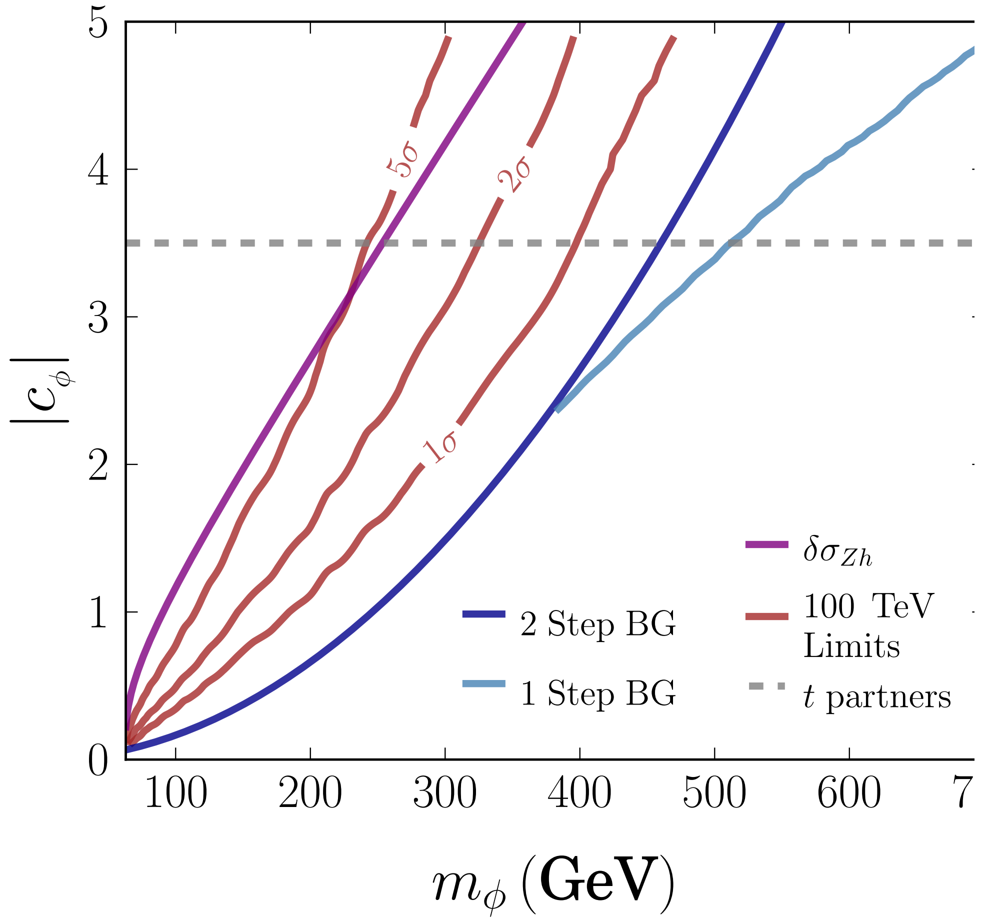


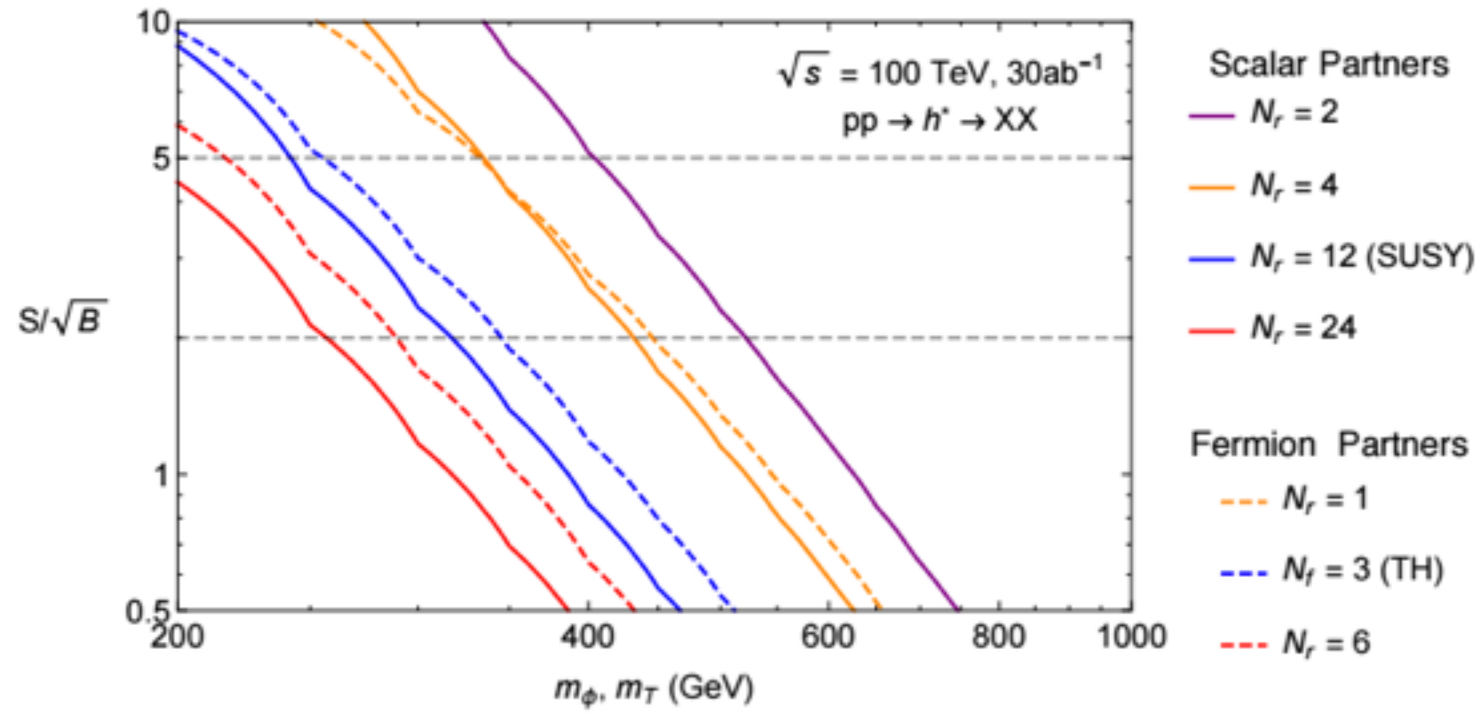
- tune proportional to $(m_{NP})^2$.
  - Much better test than LHC, by orders of magnitude!
  - Potential for discovery (would be a victory for naturalness).

Neutral naturalness?

- Twin Higgs.
- Folded SUSY.
- Searching for a beautiful model.
    - Is neutralness natural?
- Someone knows we can only build proton colliders?

Try harder at higher energy

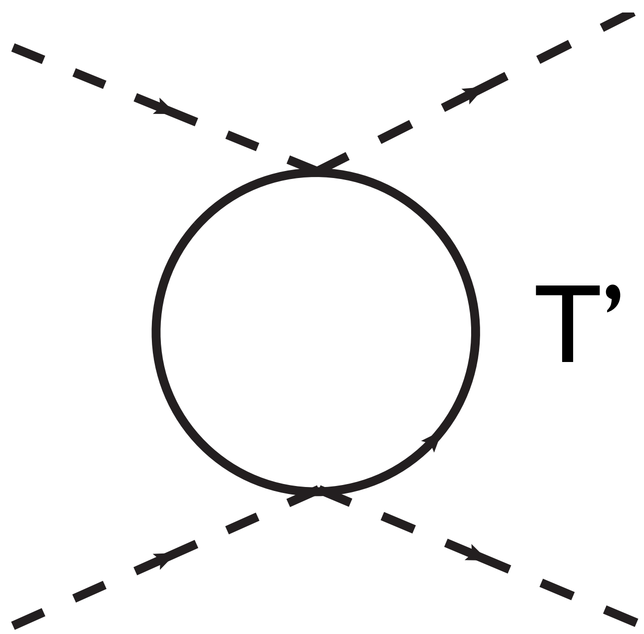




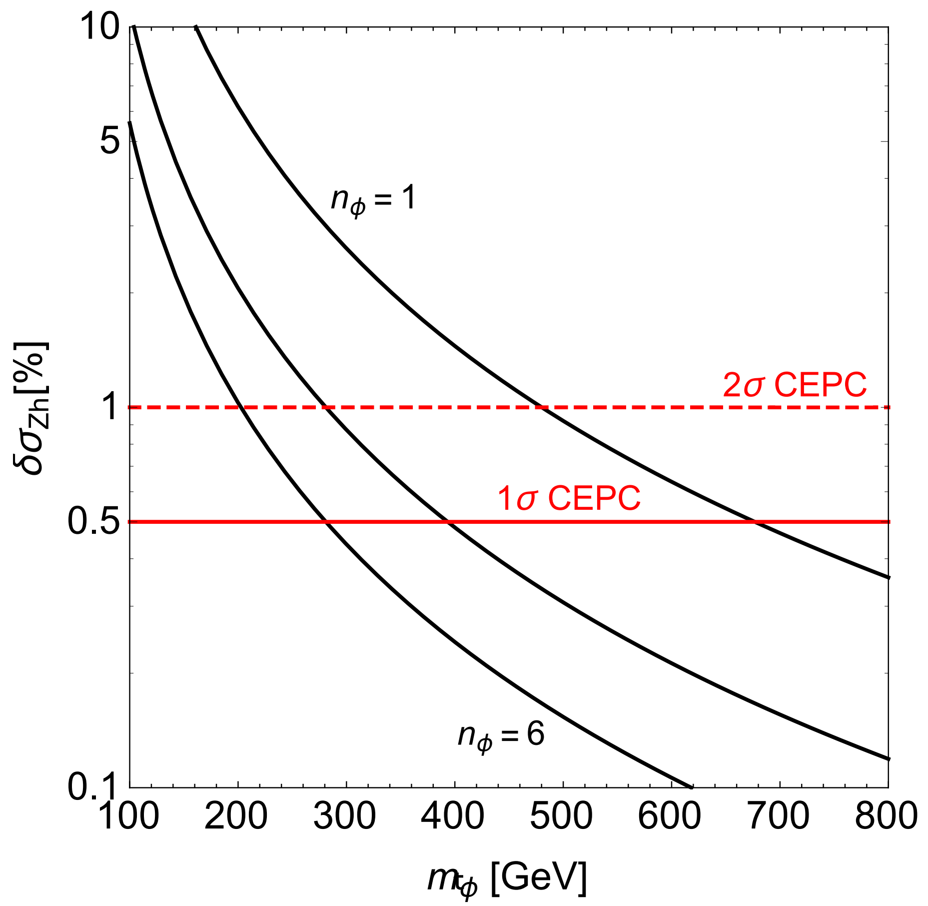
Craig, Lou, McCullough, Thalapillil, 2014

Curtin and Saraswat, 2015

We can do lepton collider as well.



Top partner only couple to Higgs.
Wavefunction renormalization
Induce shift in Higgs coupling.



Craig, Englert, McCullough, 2013

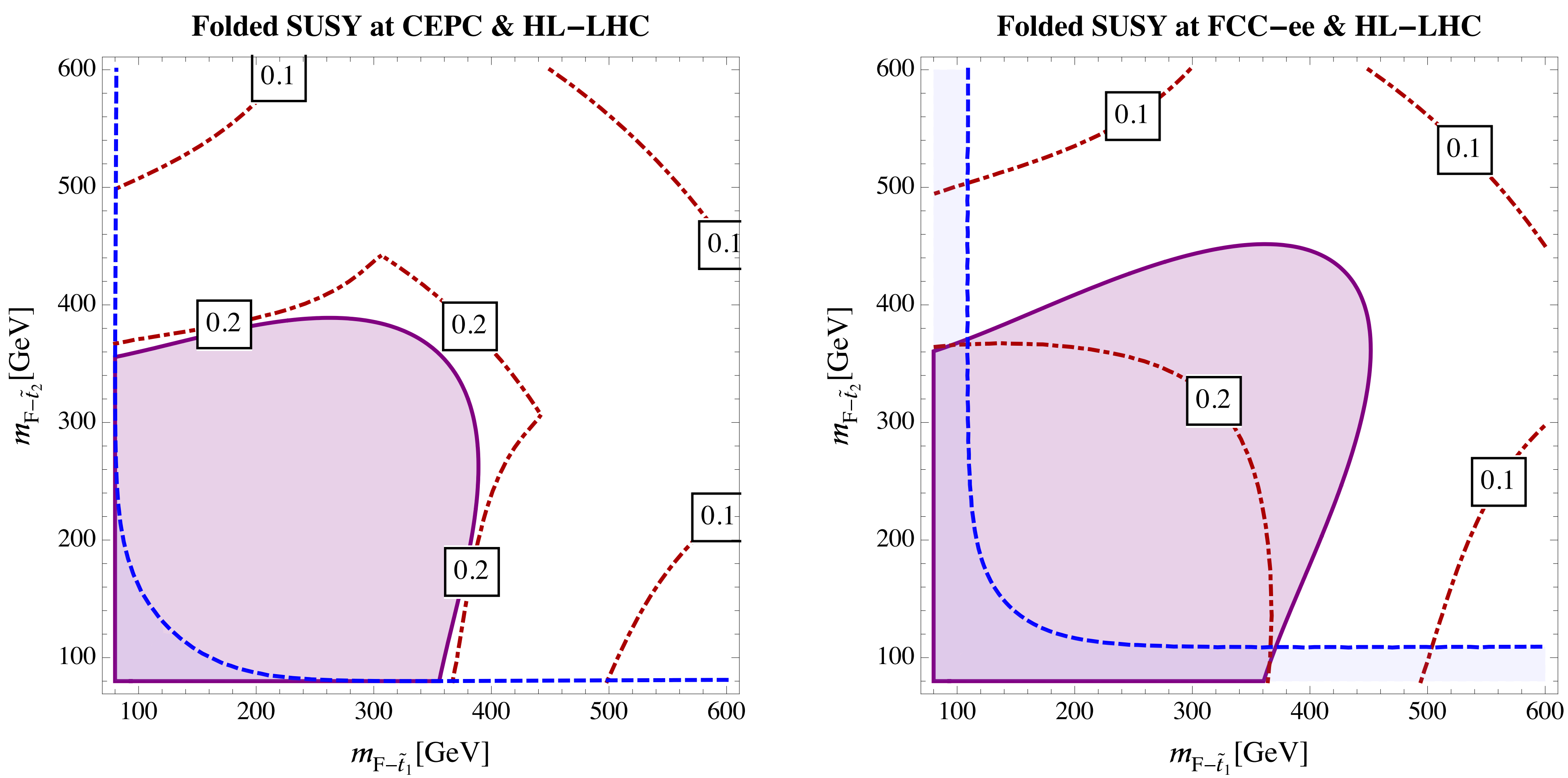
- LHC reach poor. Theory can be completely natural.
- Higgs factory can test this.

Hidden SUSY?

- Folded SUSY.

- Top partner has SM electroweak couplings only.

- No hgg. Only $h\gamma\gamma$. Weak limit from Higgs

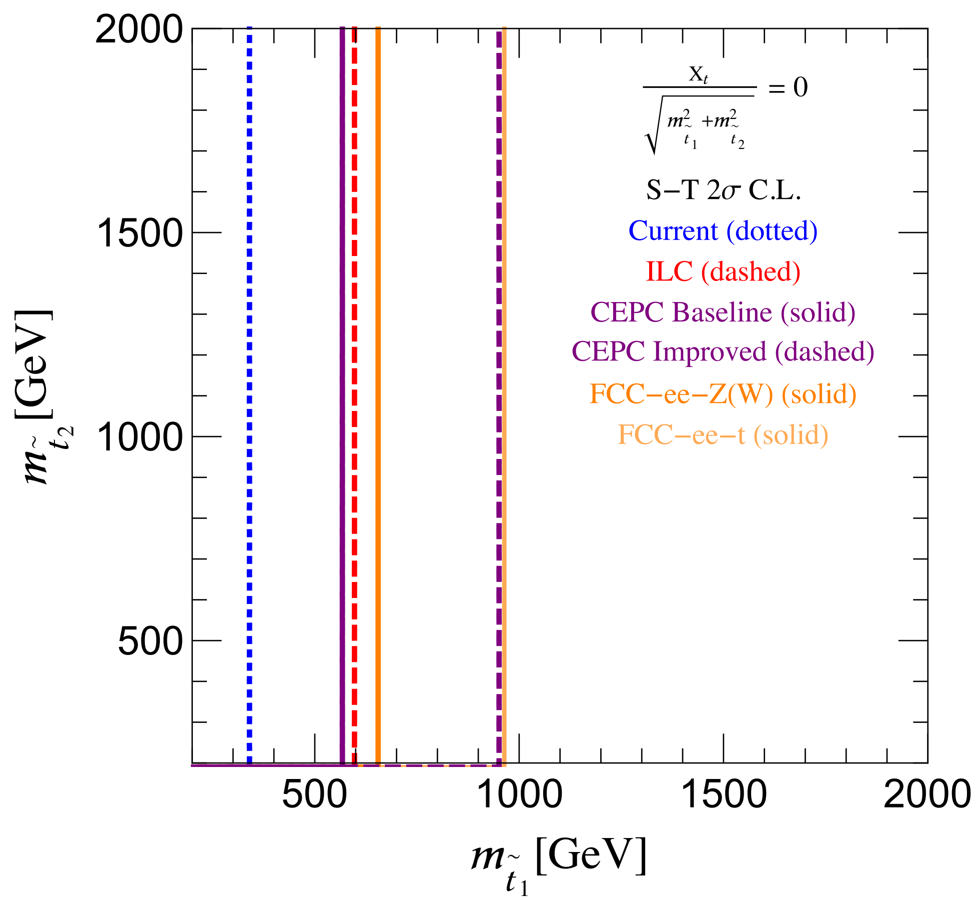


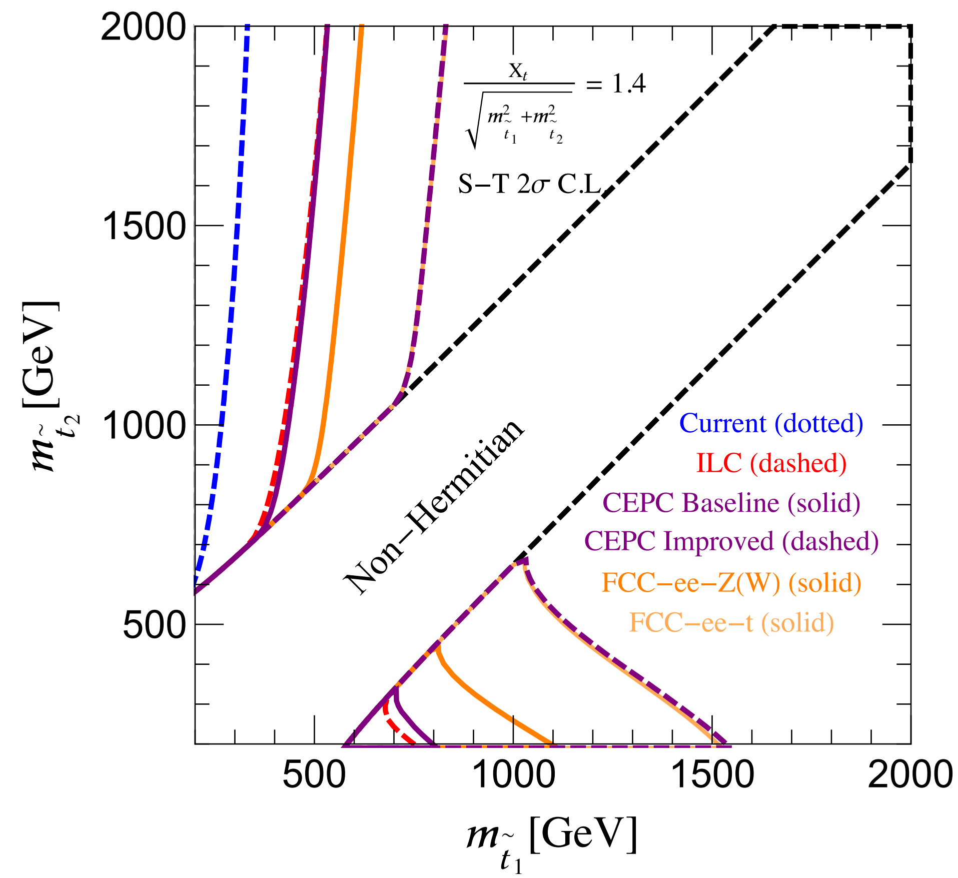
J. Fan, M. Reece, LTW, 1412.3107

Folded SUSY

- They also introduce correction in EW precision observables.

- Leads to stronger limit.





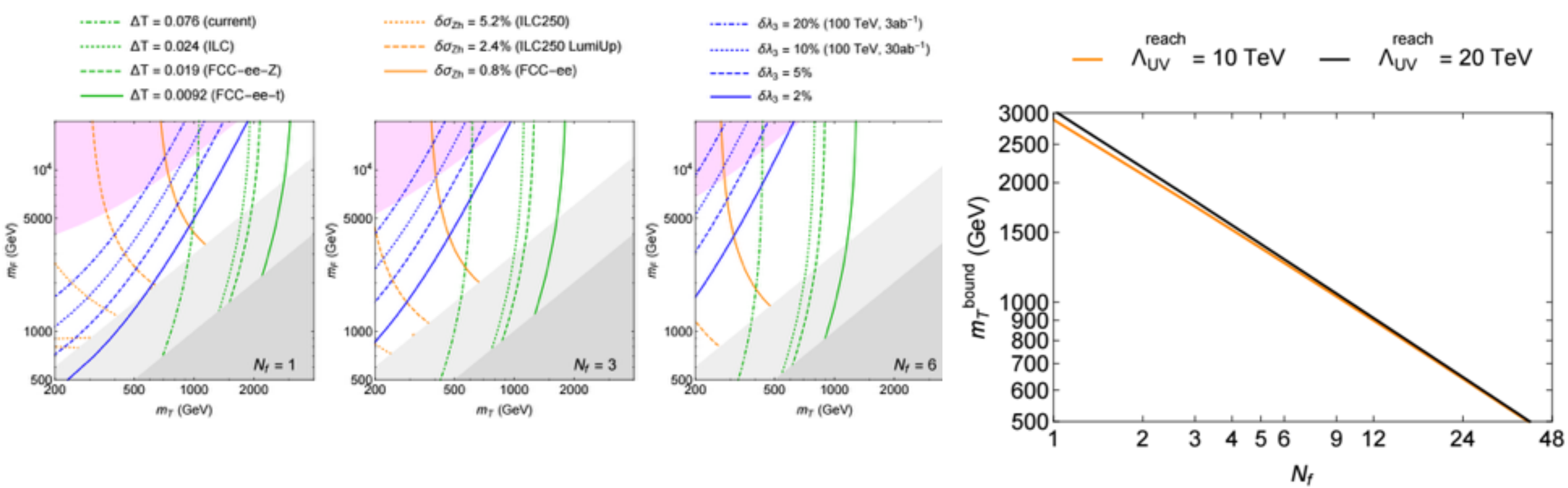
J. Fan, M. Reece, LTW, 1412.3107

Need to consider UV completions. A no-lose theorem?

Curtin and Saraswat, 1509.04284

- Induce measurable shifts in Higgs couplings, precision observables.

- UV completions can be directly probed at 100 TeV.



Status update

Progress in China

Timeline (dream)

- **CPEC**
  - Pre-study, R&D and preparation work
    - Pre-study: 2013-15
      - **Pre-CDR for R&D funding request**
    - R&D: 2016-2020
    - Engineering Design: 2015-2020
  - Construction: 2022-2028
  - Data taking: 2029-2035
- **SppC**
  - Pre-study, R&D and preparation work
    - Pre-study: 2013-2020
    - R&D: 2020-2030
    - Engineering Design: 2030-2035
  - Construction: 2035-2042
  - Data taking: 2042 -

Timeline (dream)

- **CPEC**
  - Pre-study, R&D and preparation work
    - Pre-study: 2013-15
      - **Pre-CDR for R&D funding request** ← done!
    - R&D: 2016-2020
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  - Construction: 2035-2042
  - Data taking: 2042 -

Can be downloaded from

http://cepc.ihep.ac.cn/preCDR/volume.html

IHEP-CEPC-DR-2015-01

IHEP-EP-2015-01

IHEP-TH-2015-01

CEPC-SPPC

Preliminary Conceptual Design Report

Volume I - Physics & Detector

403 pages, 480 authors

The CEPC-SPPC Study Group

March 2015

IHEP-CEPC-DR-2015-01

IHEP-AC-2015-01

CEPC-SPPC

Preliminary Conceptual Design Report

Volume II - Accelerator

328 pages, 300 authors

The CEPC-SPPC Study Group

March 2015

0, 2015

CEPC Accelerator

J Gao *et. al.*

Funding： IHEP IF

same layout and hardware at the Z(91) and ZH(240)

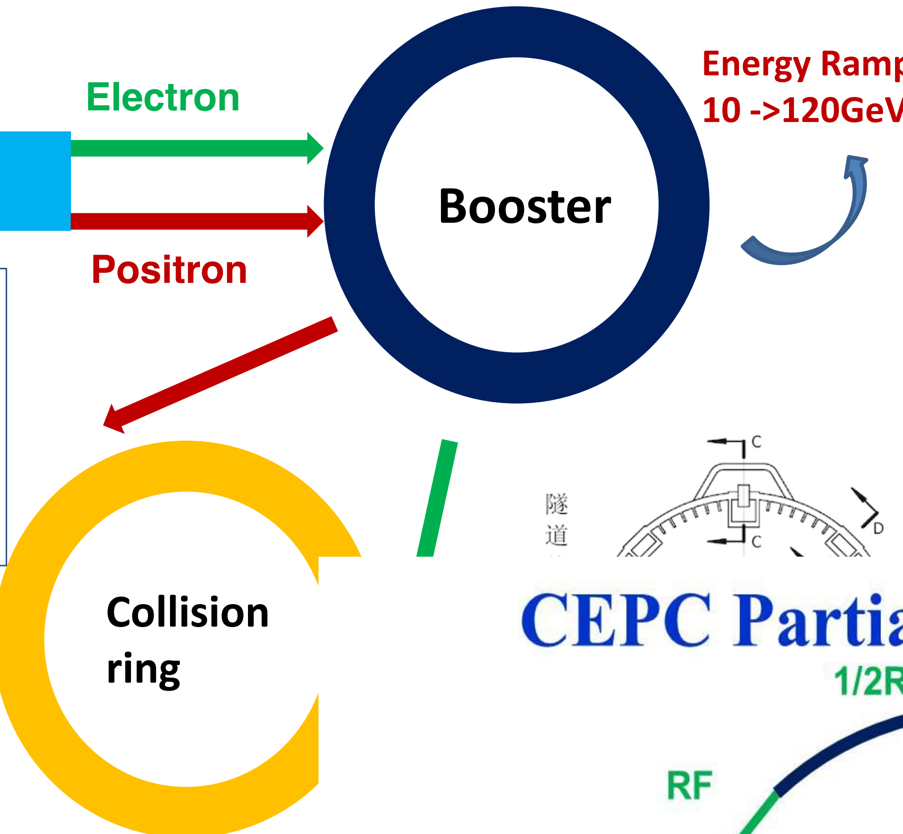
CEPC Design Goal –Higgs Parameters

Parameter	Design Goal
Particles	e+, e-
Center of mass energy	240 GeV
Luminosity (peak)	2*10^34/cm^2s
No. of IPs	2

CEPC Design Goal – Z-pole Parameters

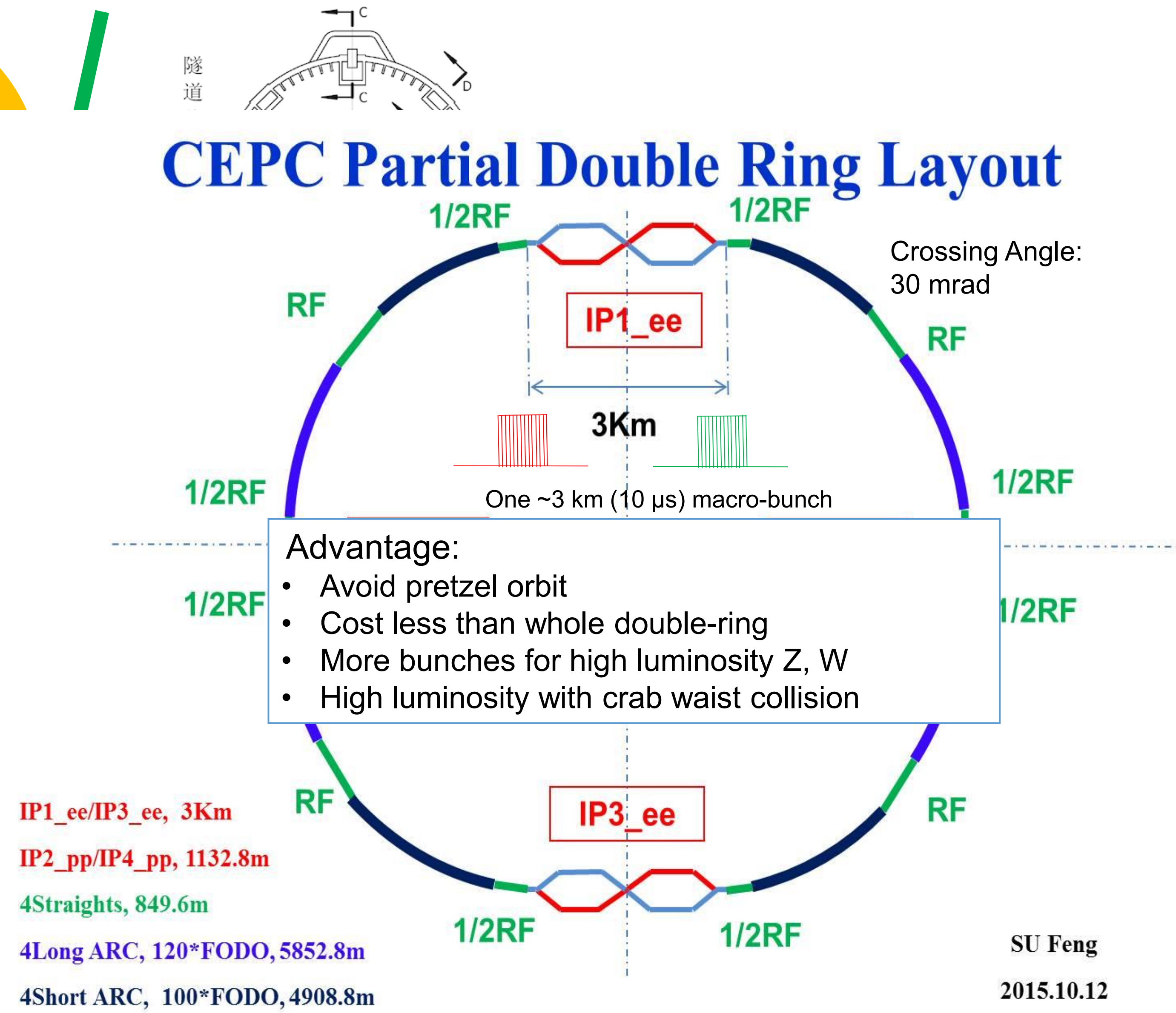
Parameter	Design Goal
Particles	e+, e-
Center of mass energy	45.5 GeV
Integrated luminosity (peak)	>1*10^34/cm^2s
No. of IPs	2
Polarization	Consider in the second round

CEPC Accelerator



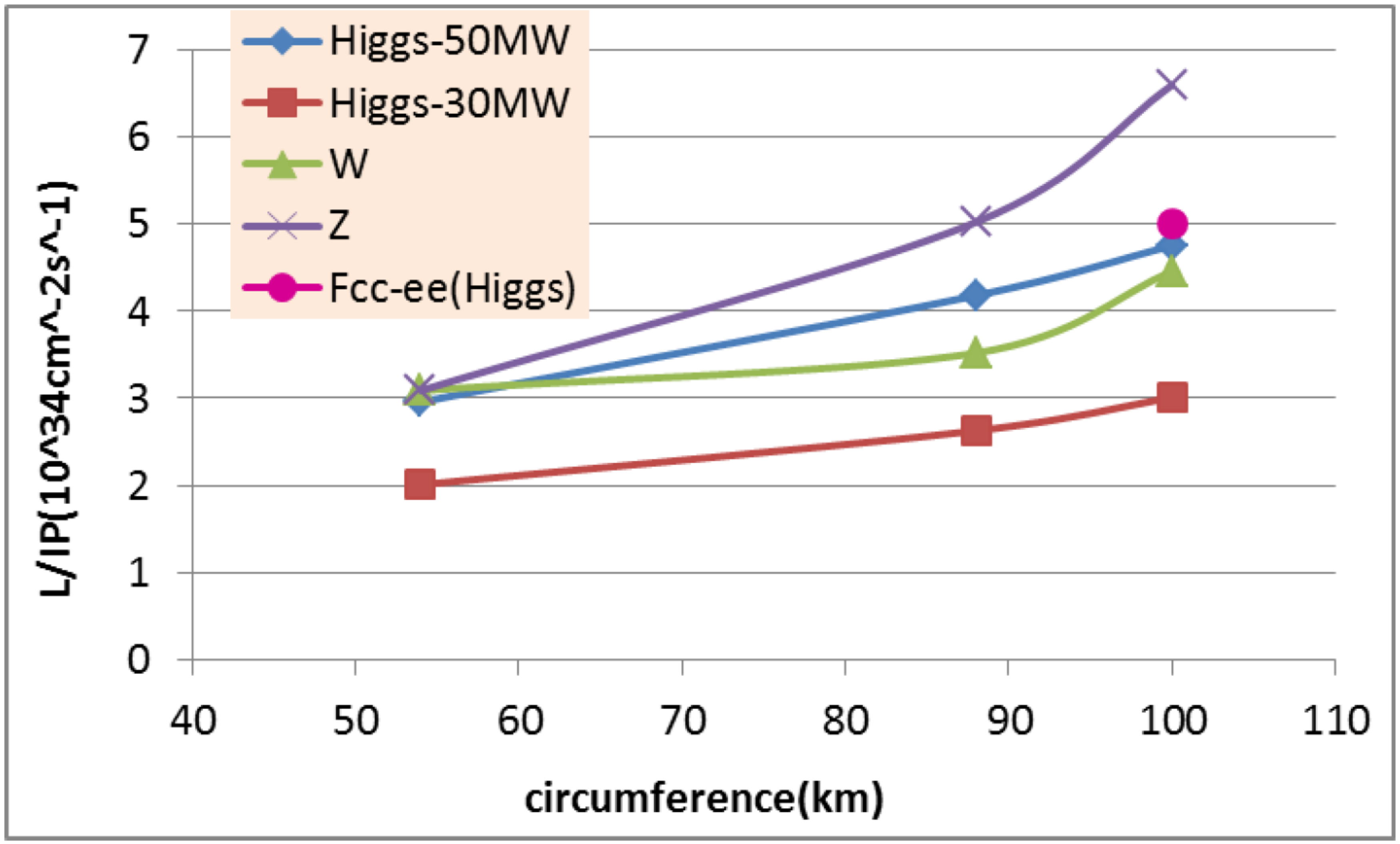
- 3 machines in one tunnel
  - CEPC & booster
  - SppC
- Main choice of CEPC:
  - One ring machine
  - Head-on collision

Compatibility is the main Issue



J Gao *et. al.*

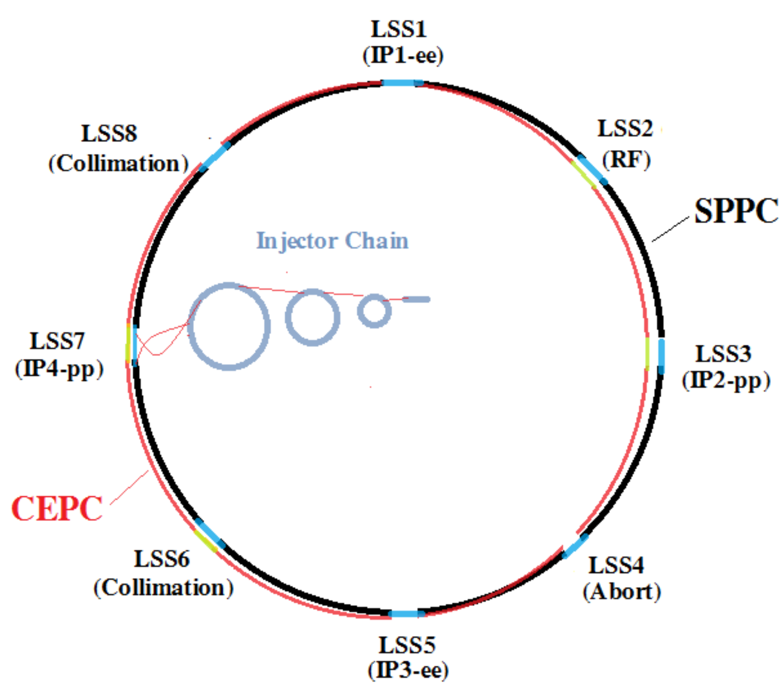
CEPC PDR Luminosity vs circumference

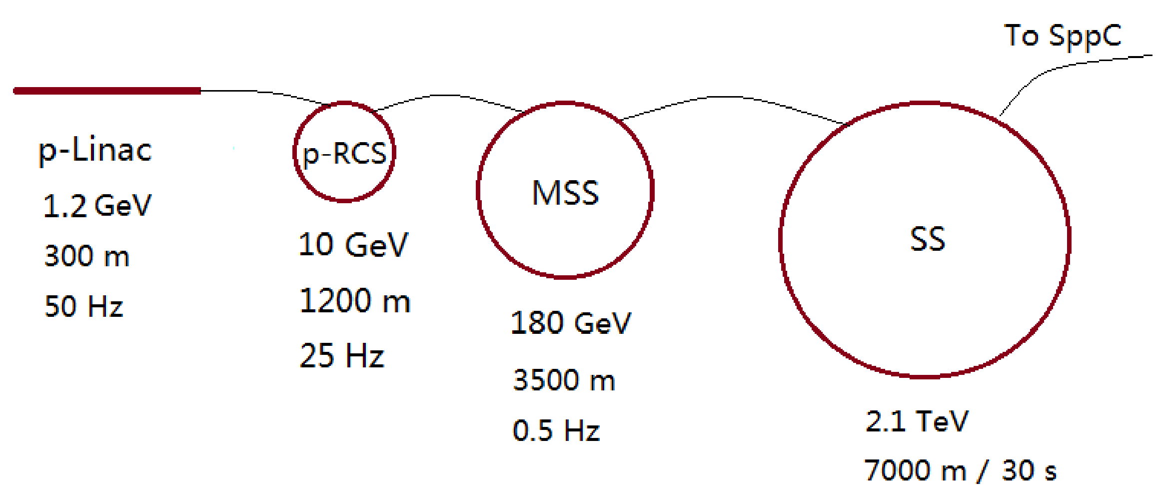


SppC Accelerator

JY Tang *et. al.*

- Study team is still growing, regular meetings
- We are making progress on SPPC study steadily, on both the collider and injector accelerators.
  - Pre-conceptual designs (main parameters, accelerator frame, stage schemes, lattice and layout, etc)
  - Key accelerator problems (collimation, beam screen, etc.)
  - Key technology R&D (high-field superconducting magnets, cryogenic vacuum, etc.)





Parameter choice for SPPC (Potential)

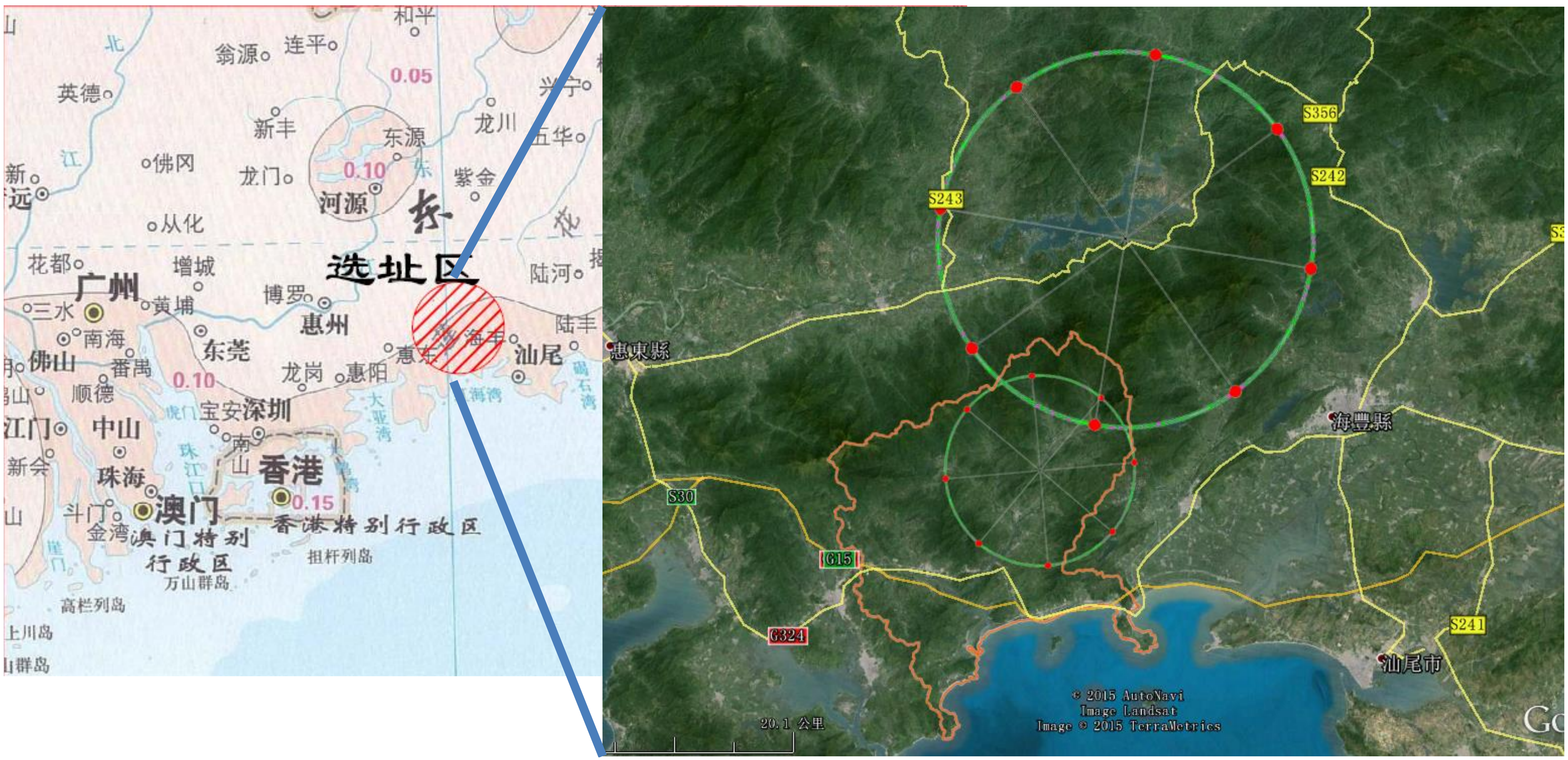
(F. Su et al)

Table 4. Parameter lists for LHC HL-LHC HE-LHC FCC-hh and SPPC.

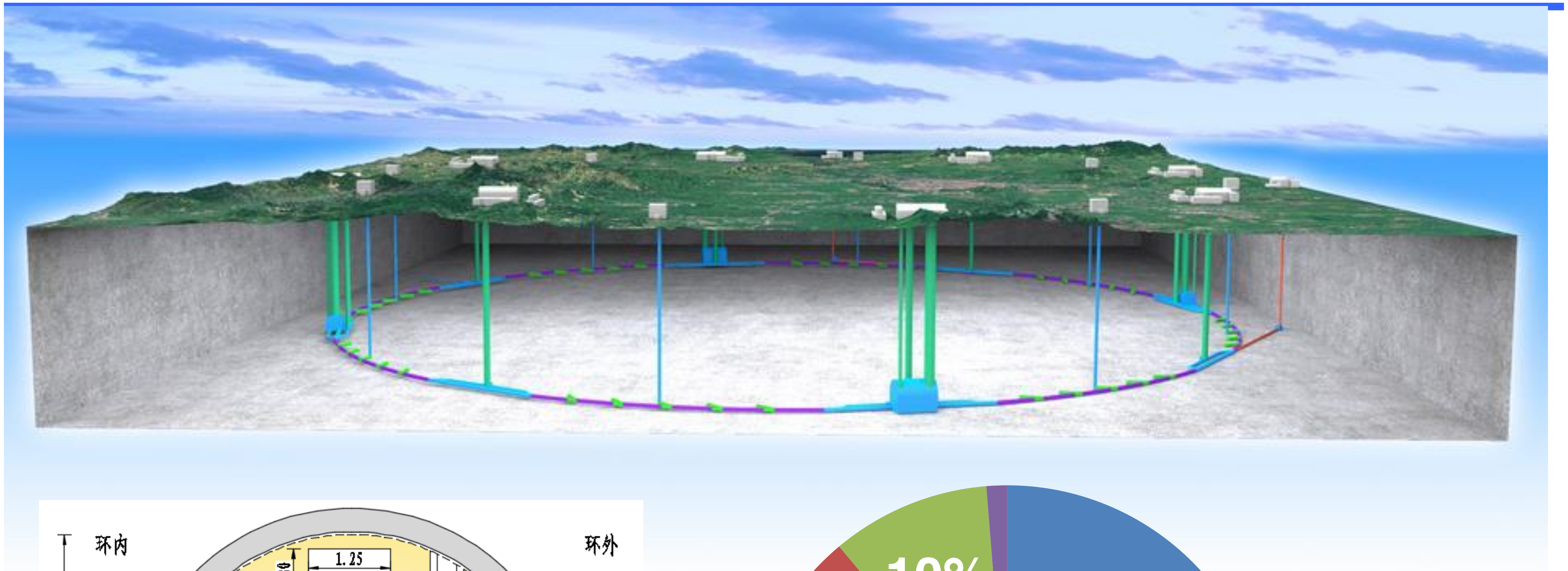
	LHC	HL-LHC	HE-LHC	FCC-hh	SPPC-Pre-CDR	SPPC-54.7Km	SPPC-100Km	SPPC-100Km	SPPC-78Km	
	Value									Unit
Main parameters and geometrical aspects										
Beam energy[E_0]	7	7	16.5	50	35.6	35.0	50.0	68.0	50.0	TeV
Circumference[C_0]	26.7	26.7	26.7	100(83)	54.7	54.7	100	100	78	km
Lorentz gamma[γ]	7463	7463	14392	53305	37942	37313	53305	72495	53305	
Dipole field[B]	8.33	8.33	20	16(20)	20	19.69	14.73	20.03	19.49	T
Dipole curvature radius[ρ]	2801	2801	2250	10416 (8333.3)	5928	5922.6	11315.9	11315.9	8549.8	m
Bunch filling factor[f_2]	0.78	0.78	0.63	0.79	0.8	0.8	0.8	0.8	0.8	
Arc filling factor[f_1]	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	
Total dipole magnet length [L_{Dipole}]	17599	17599	14062	65412 (52333)	37246	37213	71100	71100	53720	m
Arc length[L_{ARC}]	22476	22476	22476	83200 (66200)	47146	47105	90000	90000	68000	m
Total straight section length[L_{ss}]	4224	4224	4224	16800	7554	7595	10000	10000	10000	m
Energy gain factor in collider rings	15.6	15.6	13.5	15.2	17.0	16.67	17.5	17.5	17.5	
Injection energy [E_{inj}]	0.45	0.45	>1.0	3.3	2.1	2.1	2.9	3.9	2.9	TeV
Number of IPs[N_{IP}]	4	2	2	2	2	2	2	2	2	

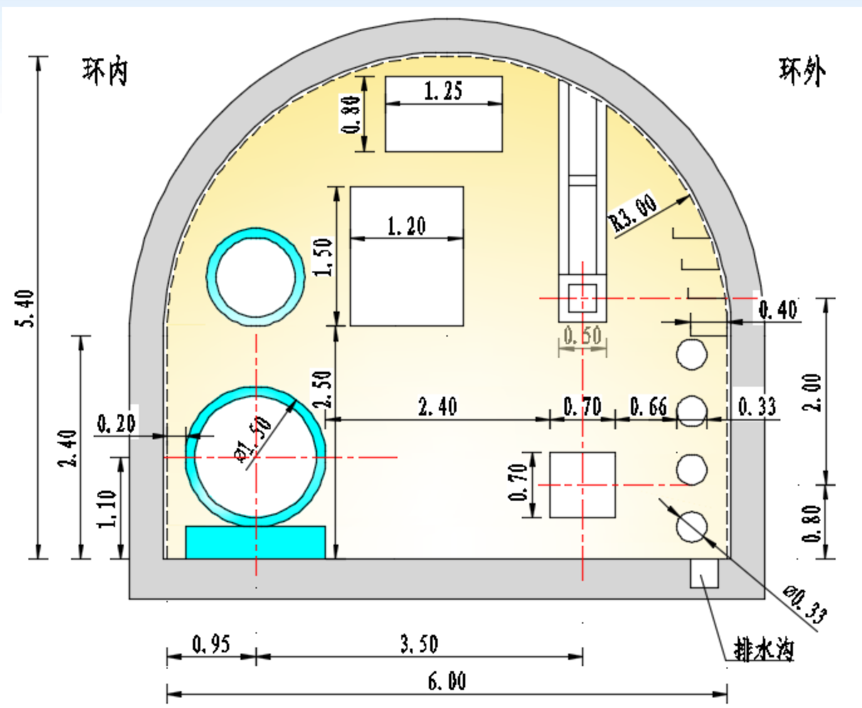
Site Selection

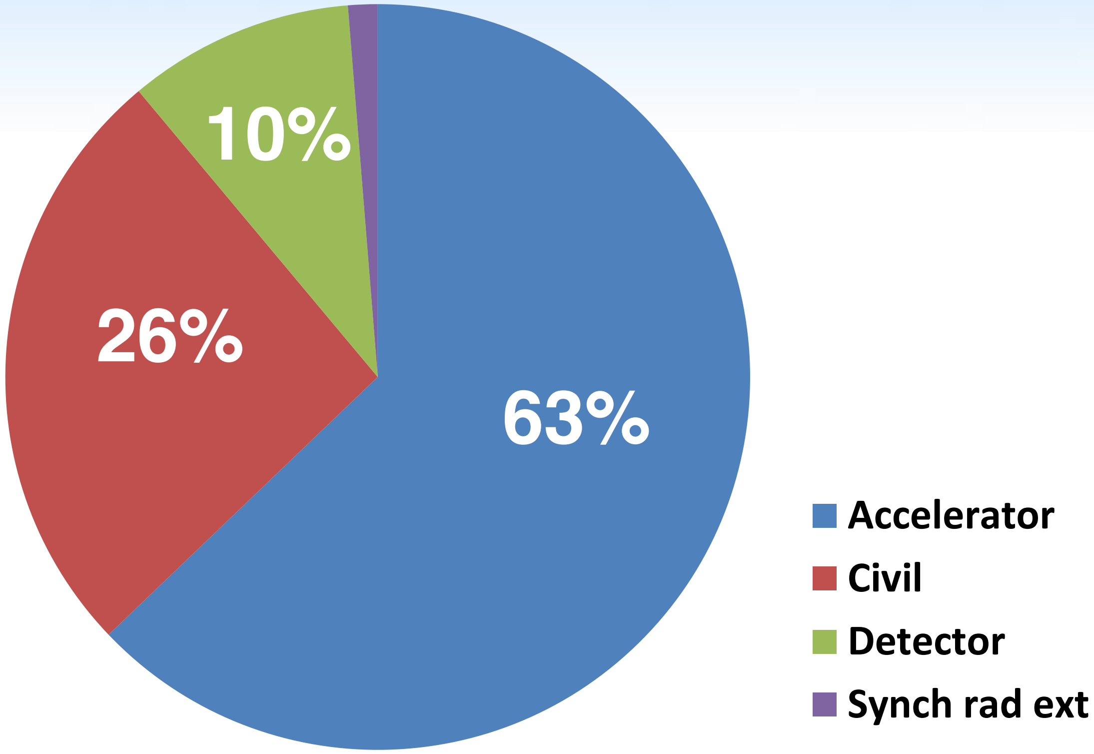
- Continue to work on site selection
- A new possibility, invited by the local government



Civil Construction







Yifang Wang. FCC week Rome. April 11

International Collaboration

- Limited international participation for the pre-CDR
  - An excise for us
  - Build confidence for the Chinese HEP community
- Chinese government welcomes international collaboration
  - to integrate China better into the international community
  - to modernize China's research system("open door" policy)
  - to obtain needed help on funding, technology, etc.
- This machine will be built and owned by the international community, but a new scheme of collaboration and management need to be explored
- An international advisory board is formed last Sep. to consult on this issue, in addition to scientific and technological discussions

Global Effort

CEPC Accelerator International Collaboration Status

- **CEPC accelerator design group members sent out to the collaborating labs**

- KEK: Yiwei Wang, Yun Zhang (on Lattice collaboration) (done)
- SLAC: Tianjian Bian (On booster design) (now)
- BNL: Feng Su (On dynamic aperture optimizations) (now)
- LAL: Sha Bai (On MDI) (now)
- CERN: Na Wang (done) and Xiaohao Cui (now) (On collective effects and lattice)

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China plans world's most powerful particle collider

By Cheng Yingqi (China Daily)

Updated: 2015-10-29 07:49

Comments Print Mail Large Medium Small

The first phase of the project's construction is scheduled to begin between 2020 and 2025

Chinese scientists have completed an initial conceptual design of a super giant particle

Media is media
Chinese media is also media
Don't get too excited, nor panic
CEPC will not be easy and quick
R&D will come gradually

Five-year plan boosts basic research funding

Blueprint gives few details, but scientists foresee more generous grants and new facilities

By **Hao Xin**, *in Beijing*

Science, vol. 351, no. 6280, pp. 1382, 2016

C a windfall for basic science. Cosmic evolution, the structure of matter, the origins of life, and understanding how the brain works all deserve strengthened support, according to China's latest 5-year development plan, which could triple funding for basic research by 2020.

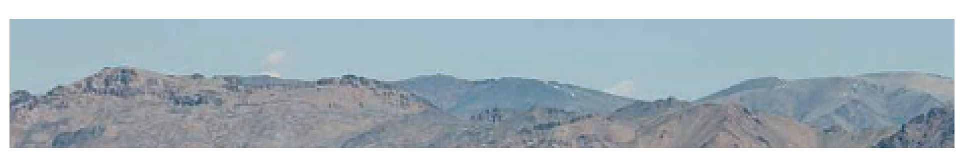
An outline of the plan, which covers 2016 through 2020, received pro forma approval by the National People's Congress (NPC) on 16 March at its closing session. The plan signals that top leaders are looking to researchers, even those doing fundamental work, for innovations that will drive the economy as it

of Science and Technology (MOST), which ...ed research, can ...s under the new 5-year plan. CAS is holding expert meetings to help it decide which programs to support, according to its website. MOST has already called for proposals in nine areas, including precision medicine, reproductive health, biomedical materials, global change, and cloud computing and big data mining.

New big science projects, too, are vying for a share of the increased funding. After the U.S.-based Advanced Laser Interferometer Gravitational-Wave Observatory an-

at the South Pole and made a premature detection claim 2 years ago. Some in the Chinese scientific community have suggested that the Ngari project should enlist international collaborators.

For one high-profile project the news is not as good. China plans to hold off on construction of the Circular Electron Positron Collider (CEPC), intended to generate large numbers of Higgs bosons to precisely measure the particle's mass. The project would cost somewhere between \$3.8 billion and \$5.4 billion, depending on its circumference. Wang Yifang, director of CAS's Institute of High Energy Physics in Beijing, the chief sponsor of the CEPC, says the project continues to get R&D funding.



科技部国家重点研发计划 ~90M RMB

"大科学装置前沿研究"重点专项2016年度项目申报指南

新一代粒子加速器和探测器关键技术和方法的预先研究

- 高能环形正负电子对撞机预先研究 ~45M RMB

国家重点研发计划
项目预申报书

已于3月递交

项目名称：	高能环形正负电子对撞机相关的物理和关键技术预研究
所属专项：	大科学装置前沿研究
指南方向：	新一代粒子加速器和探测器关键技术和方法的预先研究
推荐单位：	教育部
申报单位：（公章）	清华大学
项目负责人：	高原宁

期待2017年

- 高能环形正负电子对撞机关键技术验 ~45M RMB

Current Status and the Plan

- **Pre-CDR completed**
  - No show-stoppers
  - Technical challenges identified → R&D issues
  - Preliminary cost estimate
- **Working towards CDR**
  - A working machine on paper
  - Ready to be reviewed by government
- **R&D issues identified and funding request underway**
  - Seed money from IHEP available: 12 M RMB/3 years
  - MOST: ~ 45 M + 45 M / 5 yr, proposal submitted, approval this year ?
  - NCDR: ~1 B RMB / 5 yr, process may start this year
- **Start international collaboration once funding is available**

Physics goals
and
machine options

We need concrete answers to these questions.
Need your input!

Machine design, big options

- Questions
  - How big is the ring?
  - Is the current design of Higgs factory adequate?
  - Case for Z factory and requirement
  - Going to higher energy, ttbar threshold?
  - ....

80+ km vs 50 km

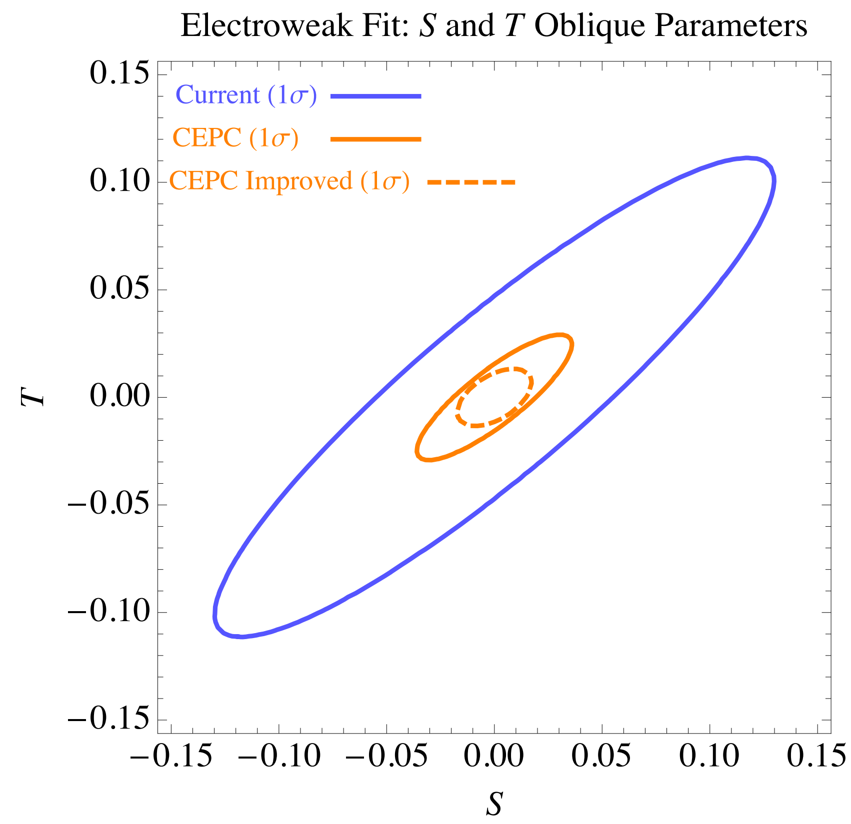
- Prefer longer.
- Main physics motivation, beyond CEPC. SppC.
  - The bigger, the better. 100 TeV seems to be the highest that is doable.
  - Can measure Higgs self coupling, probe dark matter, test naturalness.
  - Completely discover and study the new physics showing up in precision measurements of CEPC.
  - Other benefits, easier to go to higher energy, tt threshold.

The main physics goal: understanding the Higgs

- High precision measurement of Higgs coupling.
- Phase transition in early universe, naturalness, etc.
- Based on simple estimate and simulation, the CEPC will be able to deliver on these goals.

Need to make sure it is indeed the case.

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

Systematics dominated.

CEPC Z-factory

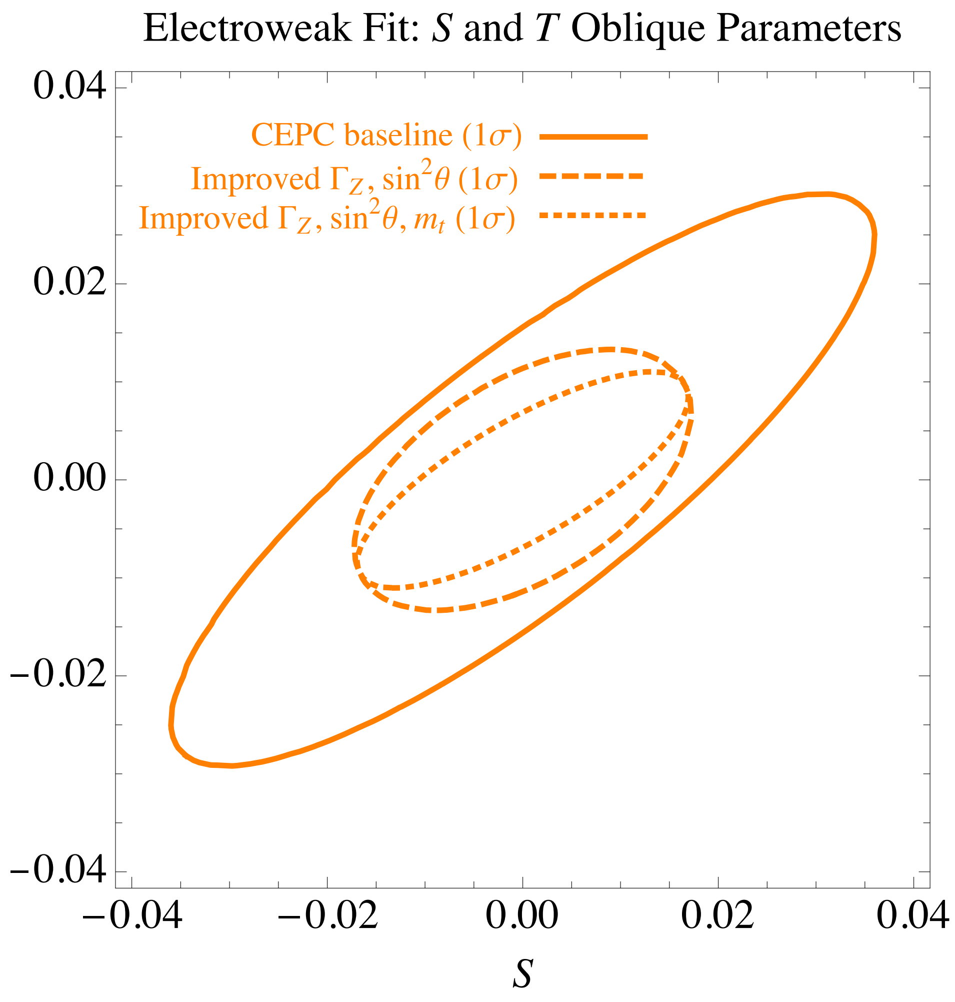
How many Zs do we need?

- Tera-Z or more.
- Can do a lot more with precision measurements.
  - Exotic Z-decay, tau, B, QCD...

Is there a very good case can be made based on these?

CEPC: ttbar threshold?

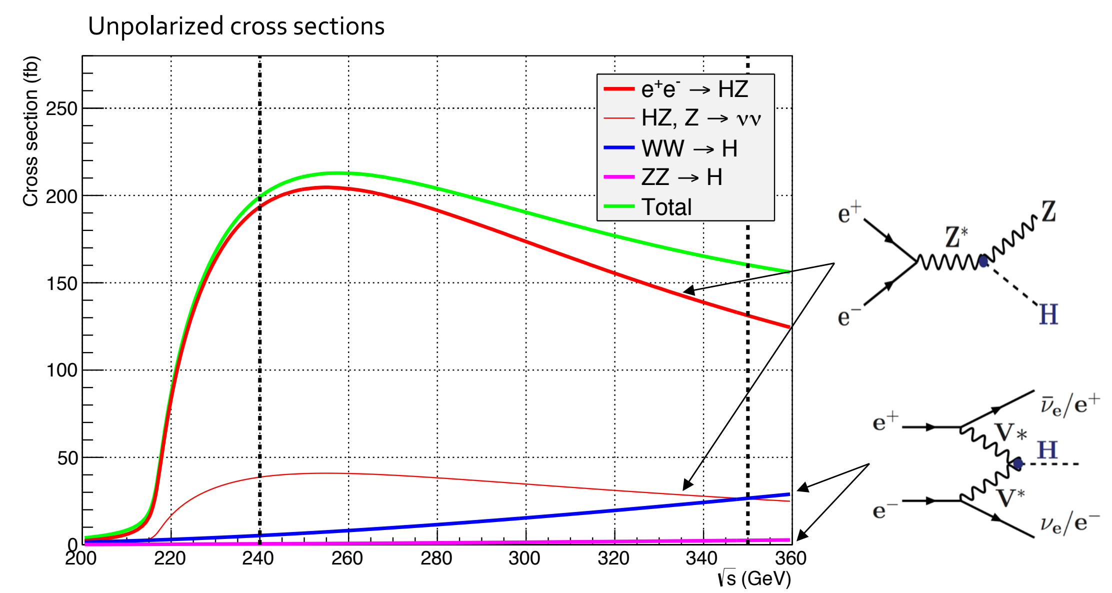
- Seems not as crucial for precision electroweak.
- A small improvement for the fit to S and T.
- Is this gain worth the effort?



CEPC: higher energy, ttbar threshold?

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

For example:



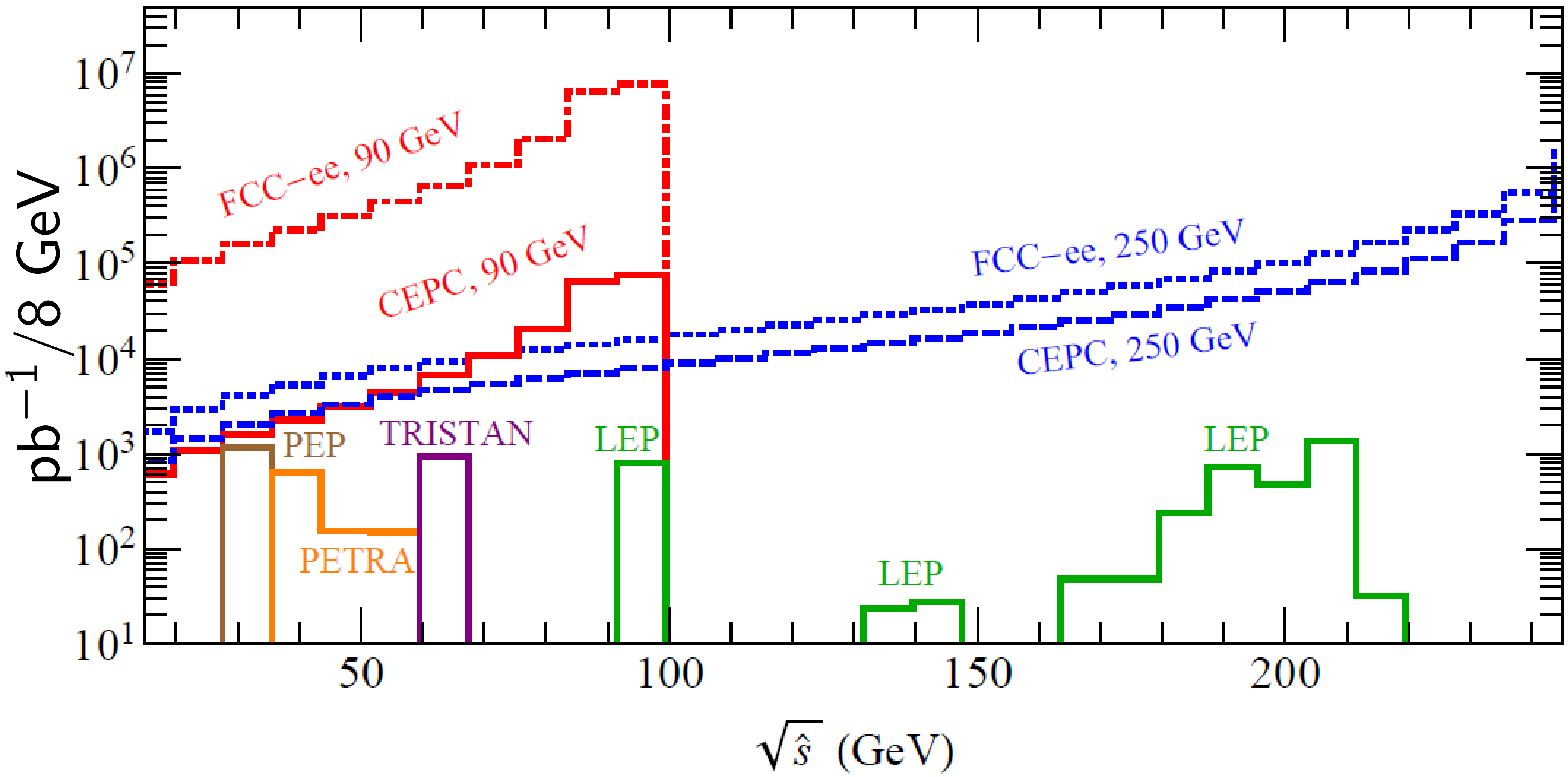
- Scan, energy dependence brings in more discovery and distinguishing power.

- Is there a good physics case here?

Filling gaps with radiative return

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

integrated luminosity

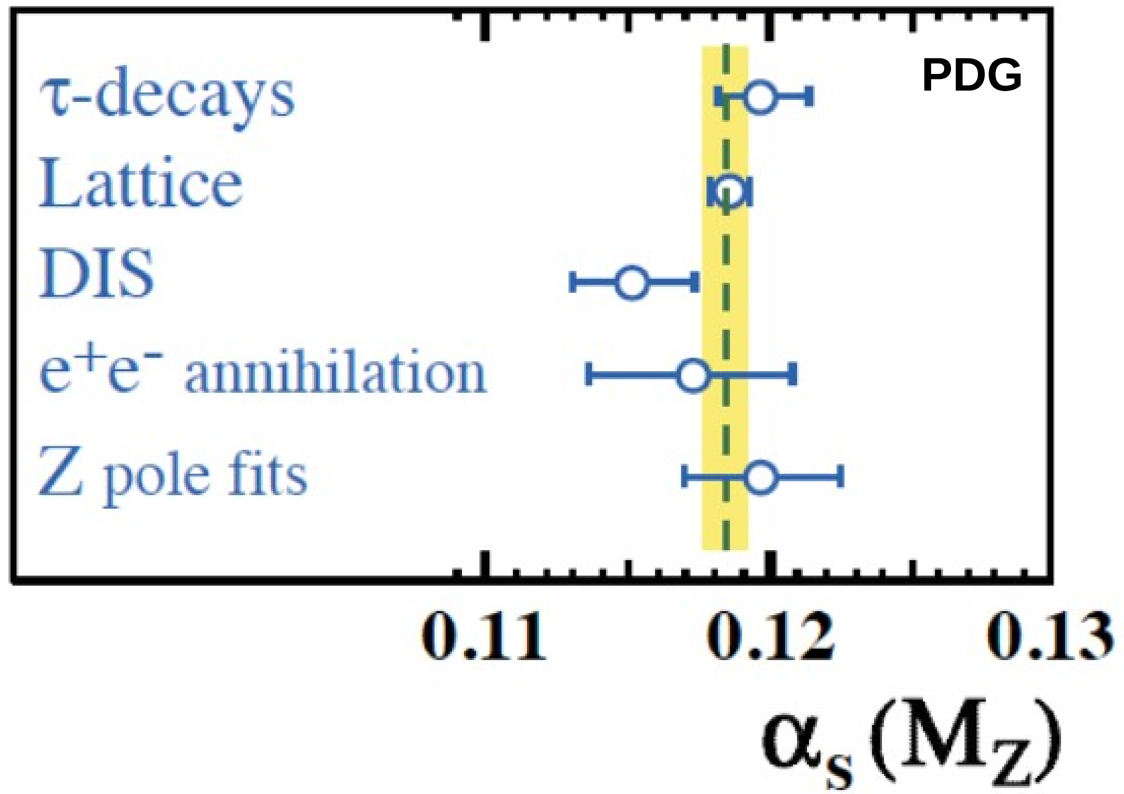


Integrated luminosity from past low energy e^+e^- colliders at their nominal center-of-mass energies compared to the effective luminosity through radiative return from future e^+e^- colliders at $\sqrt{s} = 90$ or 250 GeV

How can we best use this?

QCD at CEPC

World average on alphas



- Dominated my Lattice results
- O(100^{-1}fb) at CEPC v.s. O(100^{-1}pb) 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? …

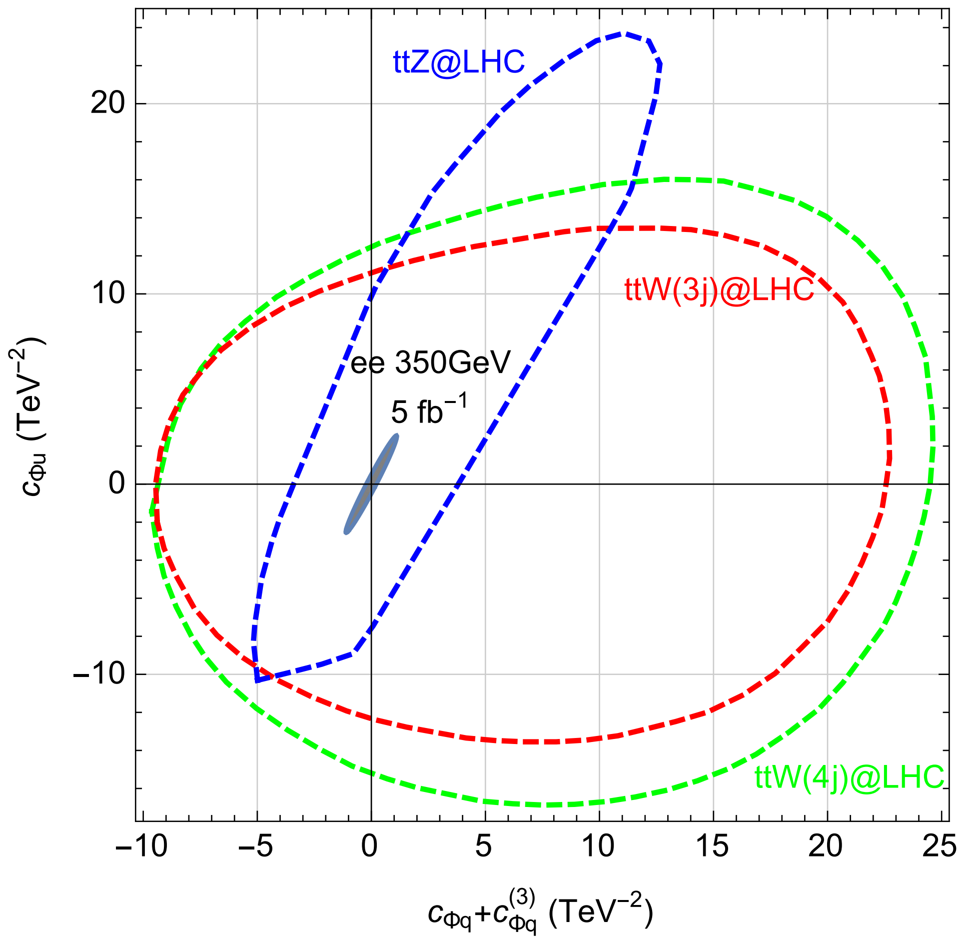
Only tip of the iceberg.

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

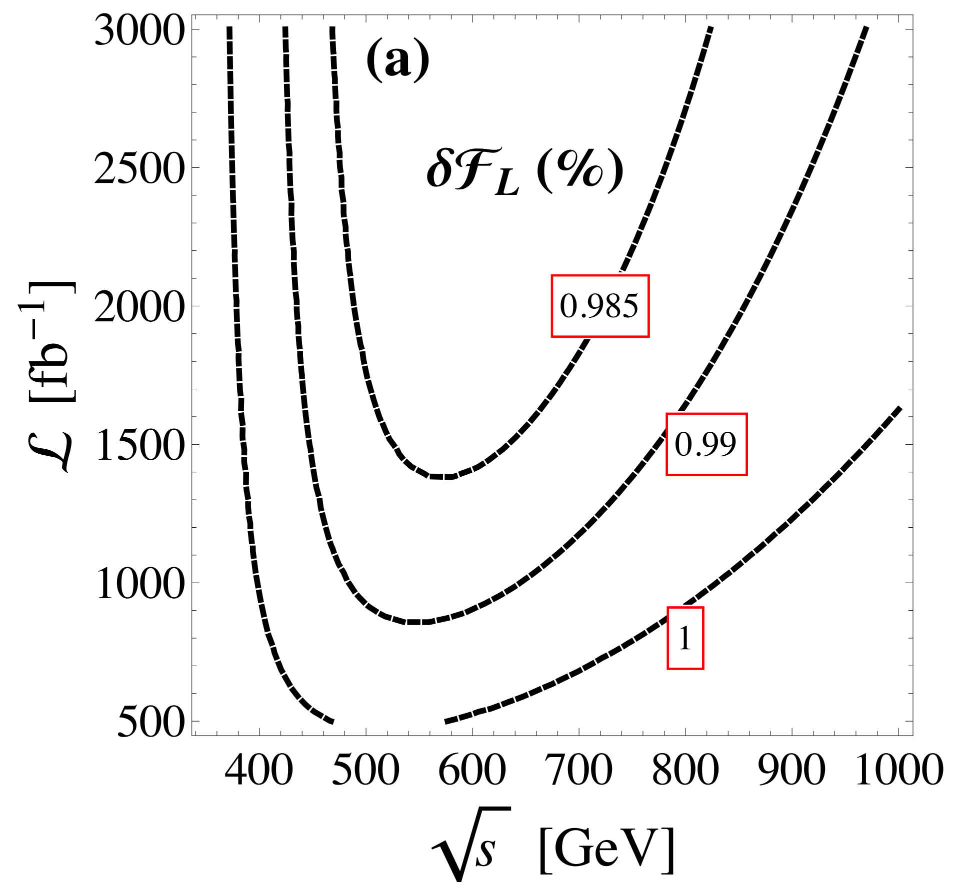
Looking ahead

- We have a broad understanding of the basic physics capabilities of next generation circular colliders.
- CDR will be a place to set clear physics goals.
  - Several important questions need answers.
  - Supporting and backed up by the design choices.
- In China, they are progressing assuming R&D funding will be there.

Learning more about top couplings



Z. Liu, I. Low, LTW in progress



Q. Cao, B. Yan 1507.06204

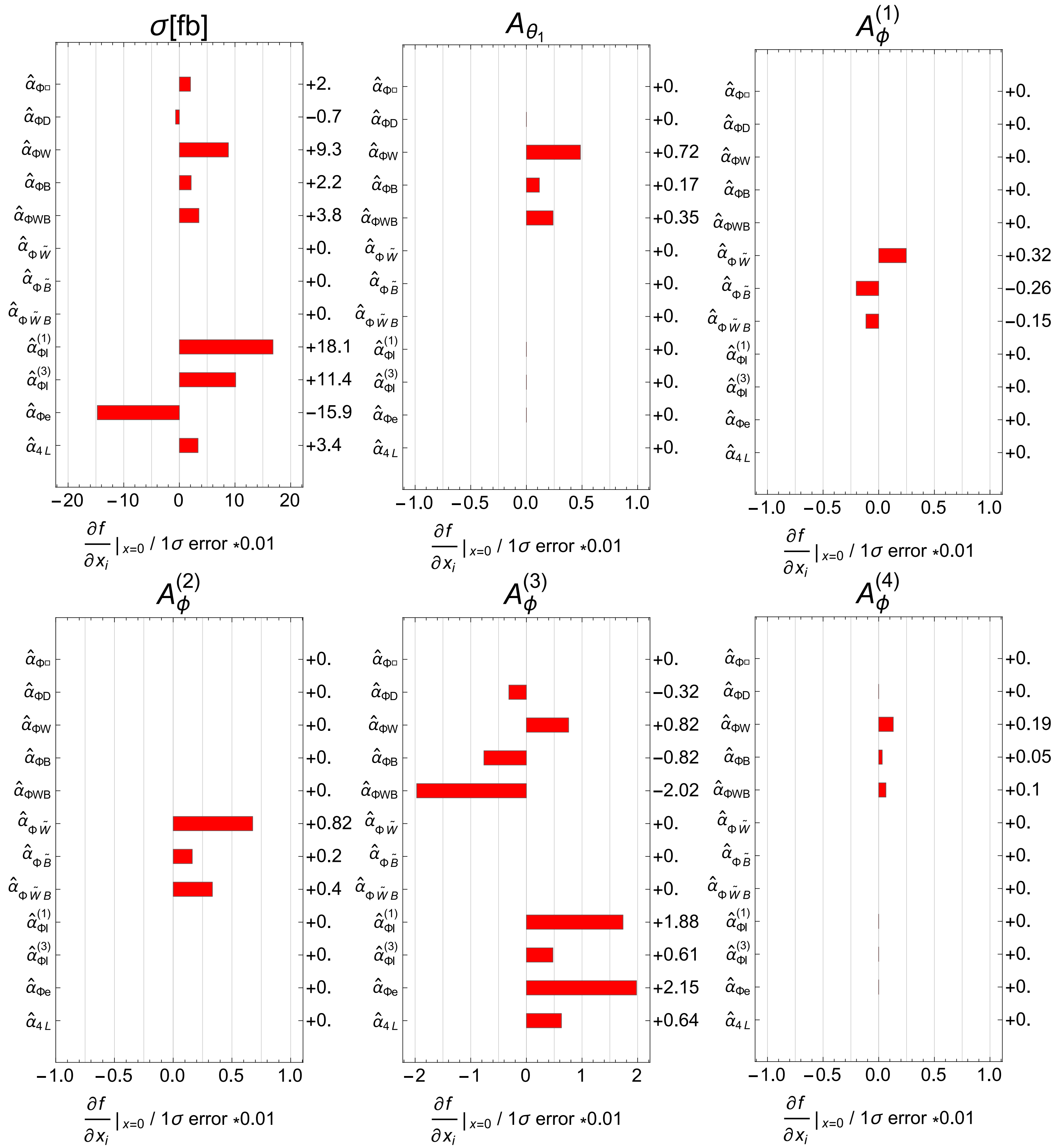
Electroweak precision tests: roughly estimated targets

- $\delta m_W < 5$ MeV
- $\delta \sin^2\theta_{eff} < 2\times10^{-5}$ (and/or Γ_Z about 100 keV)
- $\delta m_Z < 500$ keV
- $\delta m_t < 100$ MeV
- Theoretical breakthrough in calculating $\Delta\alpha_{had}$?

Systematics important. Need to make sure assumptions realistic.

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

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	$(\pm 2.3_{\rm exp} \pm 1.5_{\rm th}) \times 10^{-5}$	$(\pm 1_{\rm exp} \pm 0.8_{\rm th}) \times 10^{-4}$	$\pm 0.03_{\rm exp} \pm 0.1_{\rm th}$

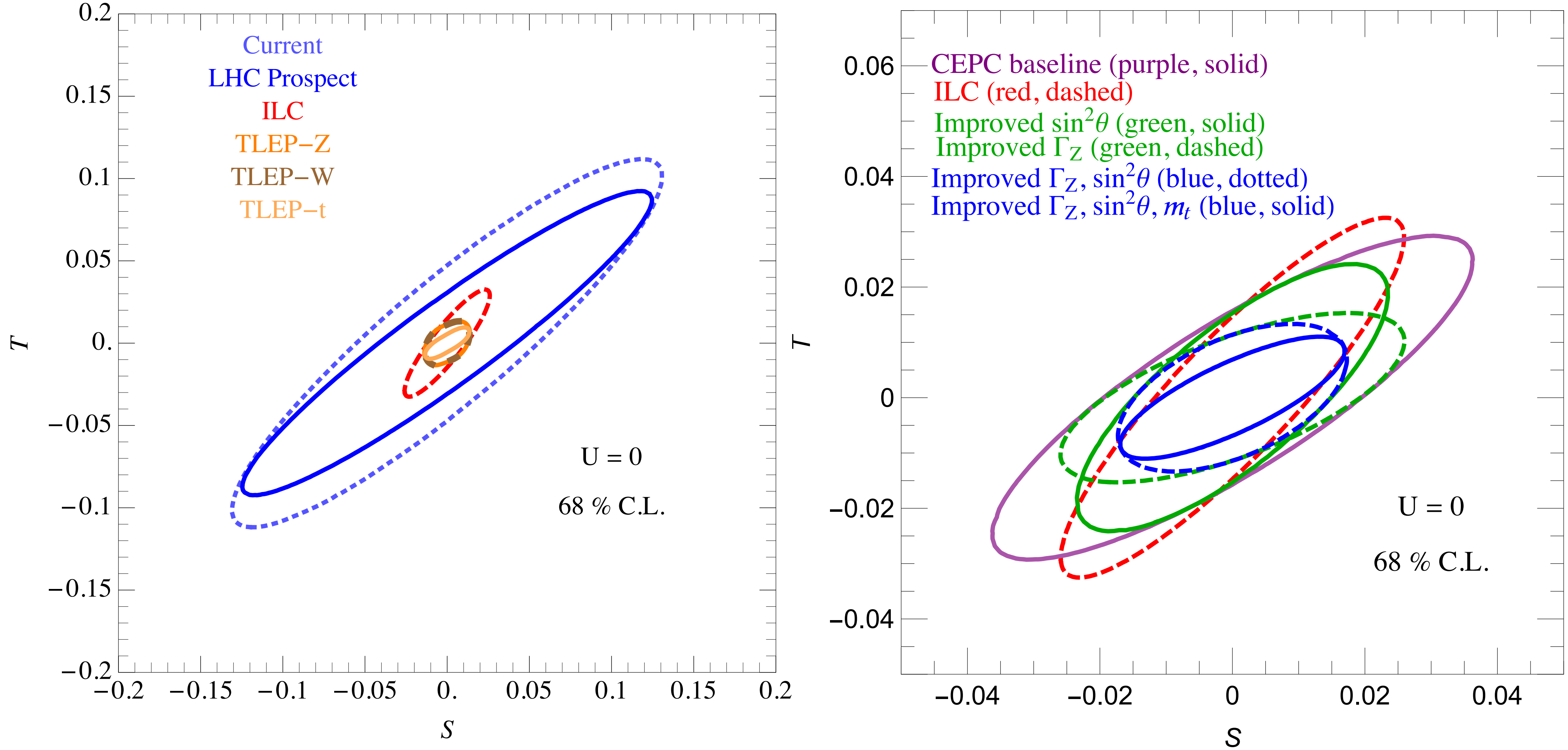
x4 statistics off Z-pole

energy calibration

ILC?

Electroweak Precision tests

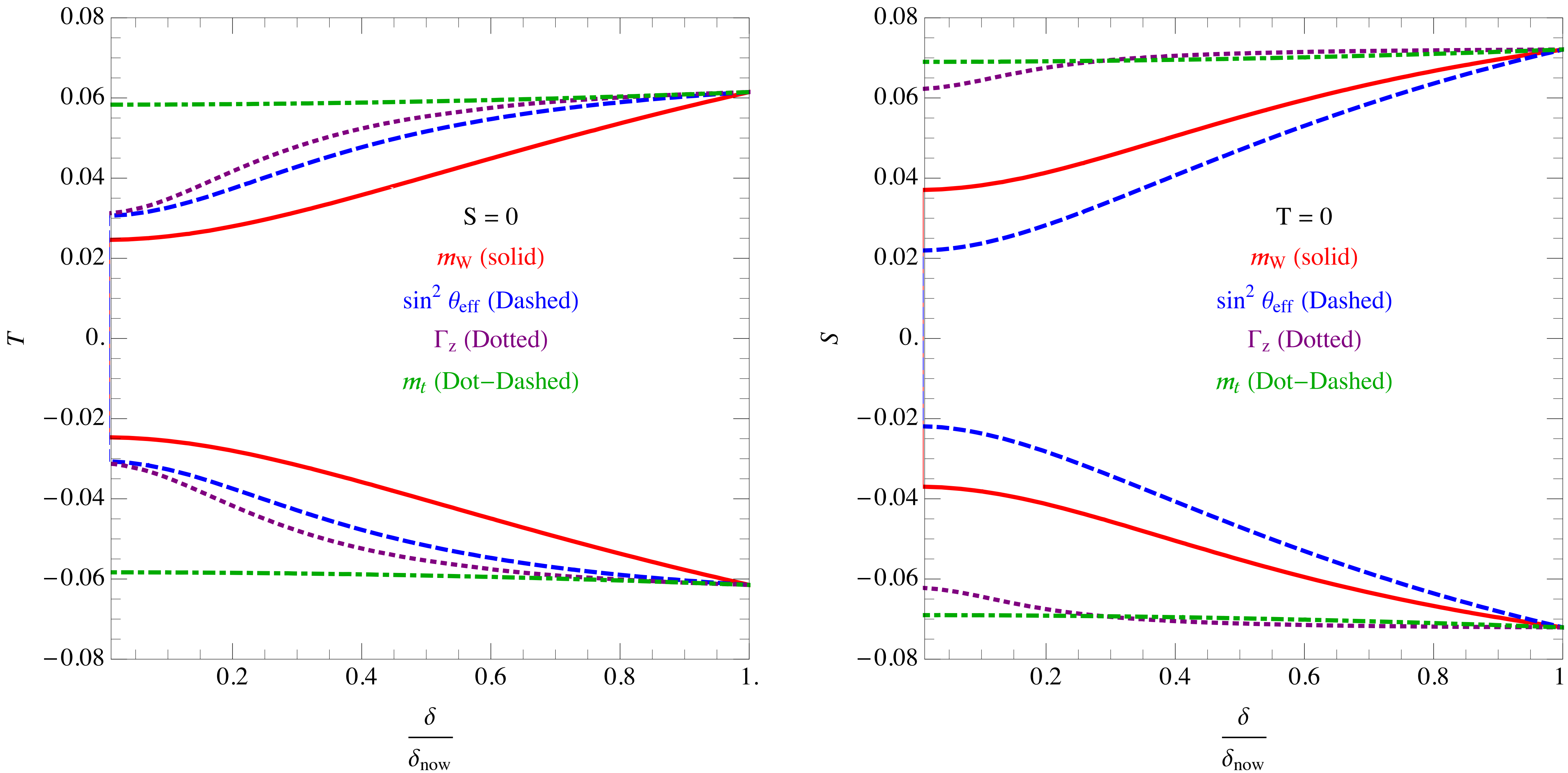
J. Fan, M. Reece, LTW, 1411.1054



- Large step above the current precision.
- A factor of 10 improvement in S and T.

Electroweak Precision tests: lessons

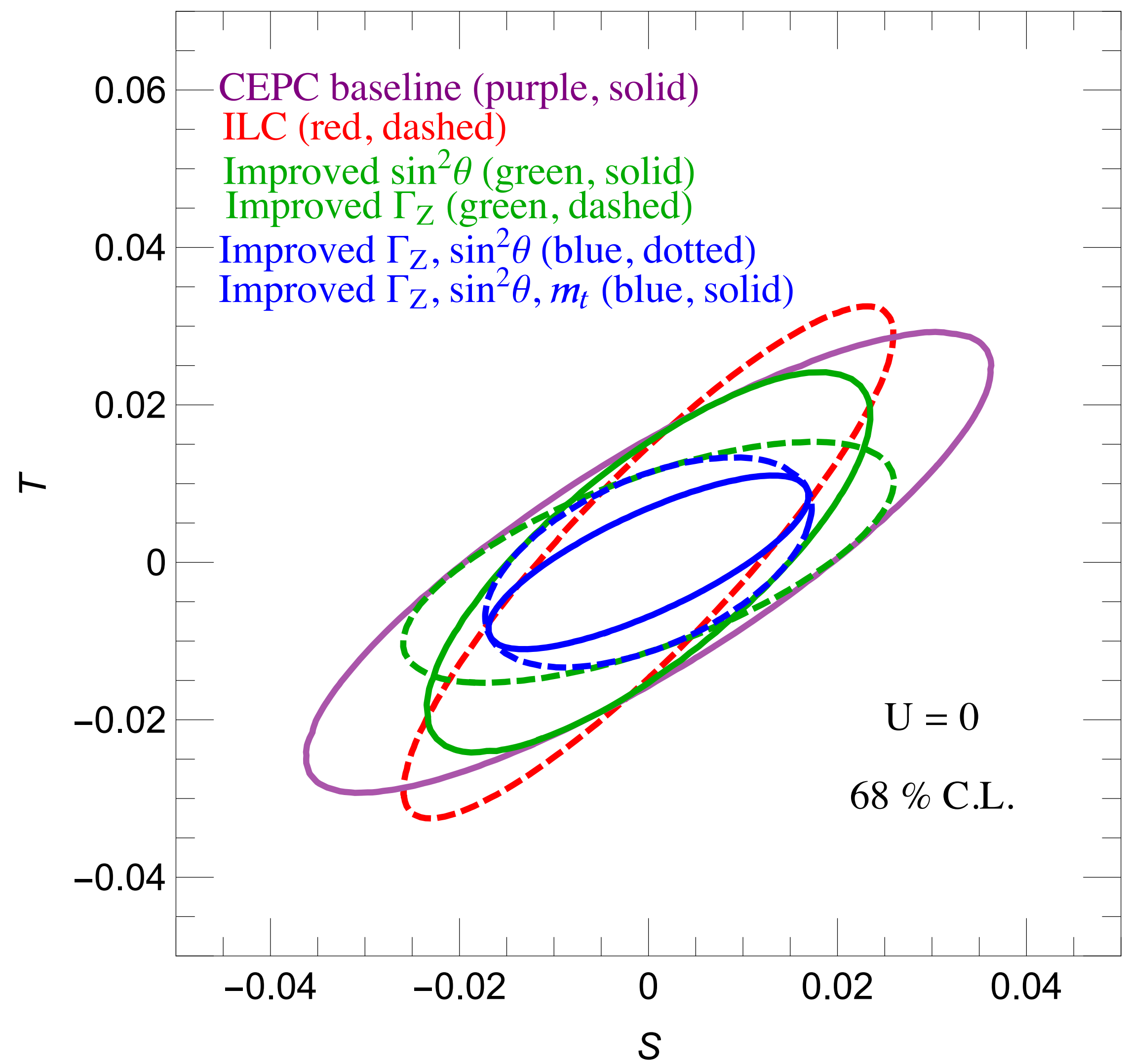
J. Fan, M. Reece, LTW, 1411.1054



- Better measurement of m_W and $\sin^2\theta_{eff}$ ⇒ Large improvement from current precision.
- Good to have: δm_W < 5 MeV, $\delta \sin^2\theta_{eff} < 2\times10^{-5}$, factor of 10 better on Γ_Z

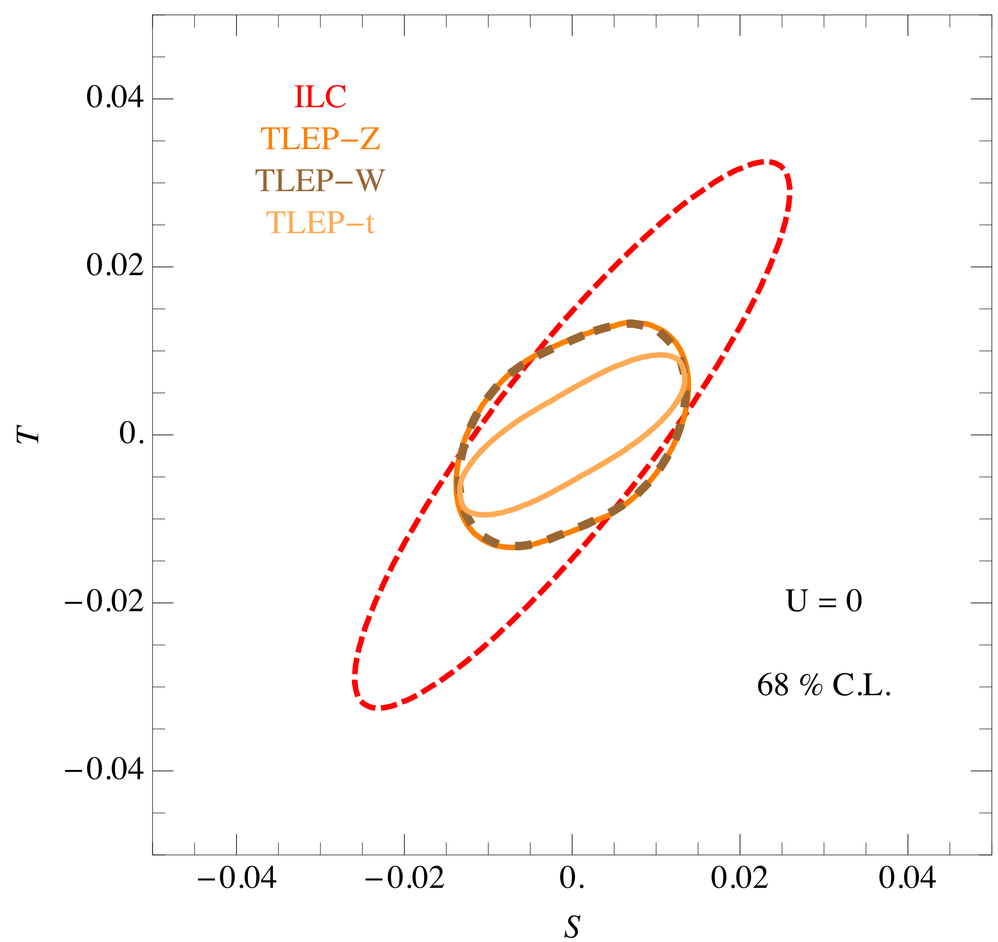
Electroweak Precision tests: lessons

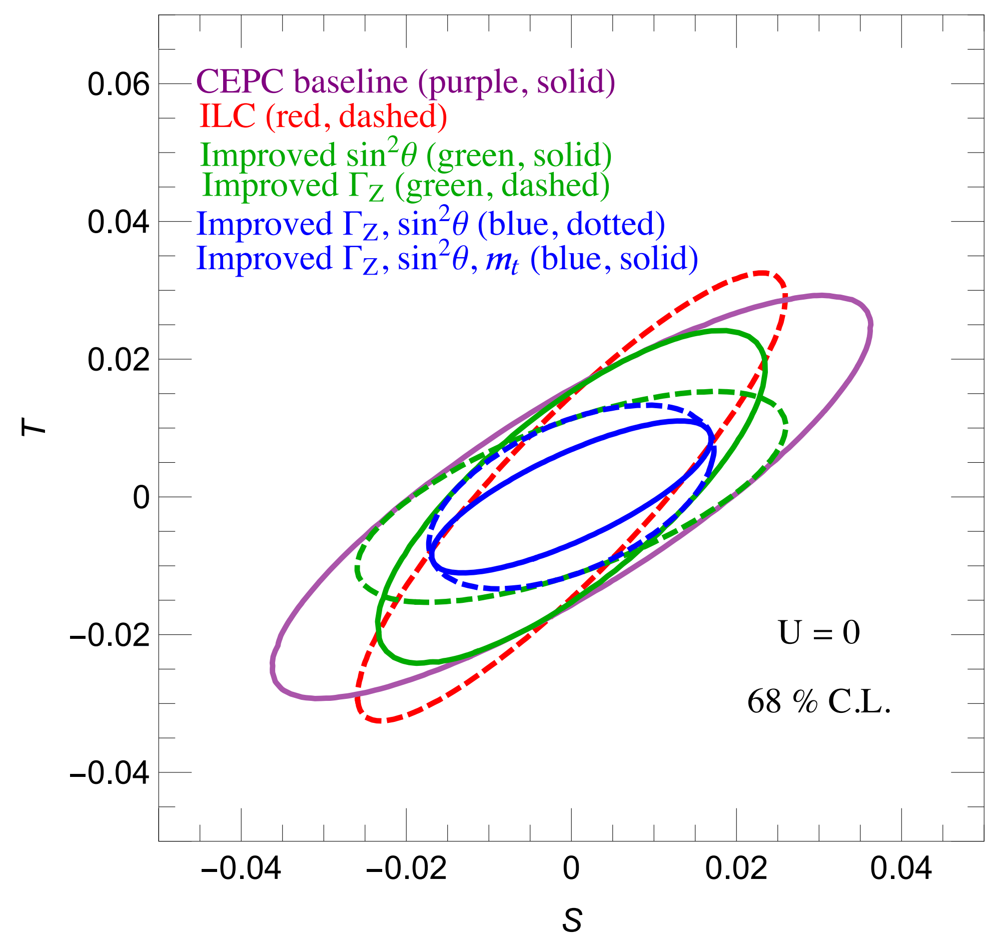
J. Fan, M. Reece, LTW, 1411.1054



- Good to have: $\delta m_W < 5$ MeV, $\delta \sin^2\theta_{eff} < 2\times10^{-5}$, factor of 10 better on Γ_Z .

Electroweak precision tests: lessons

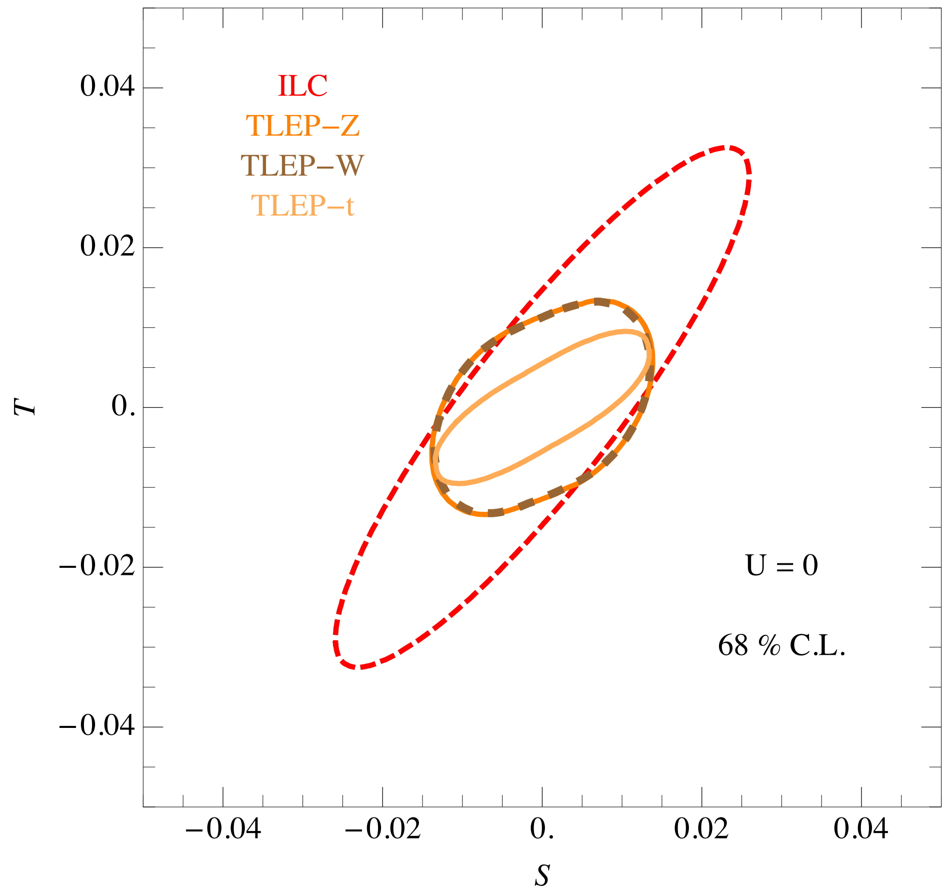


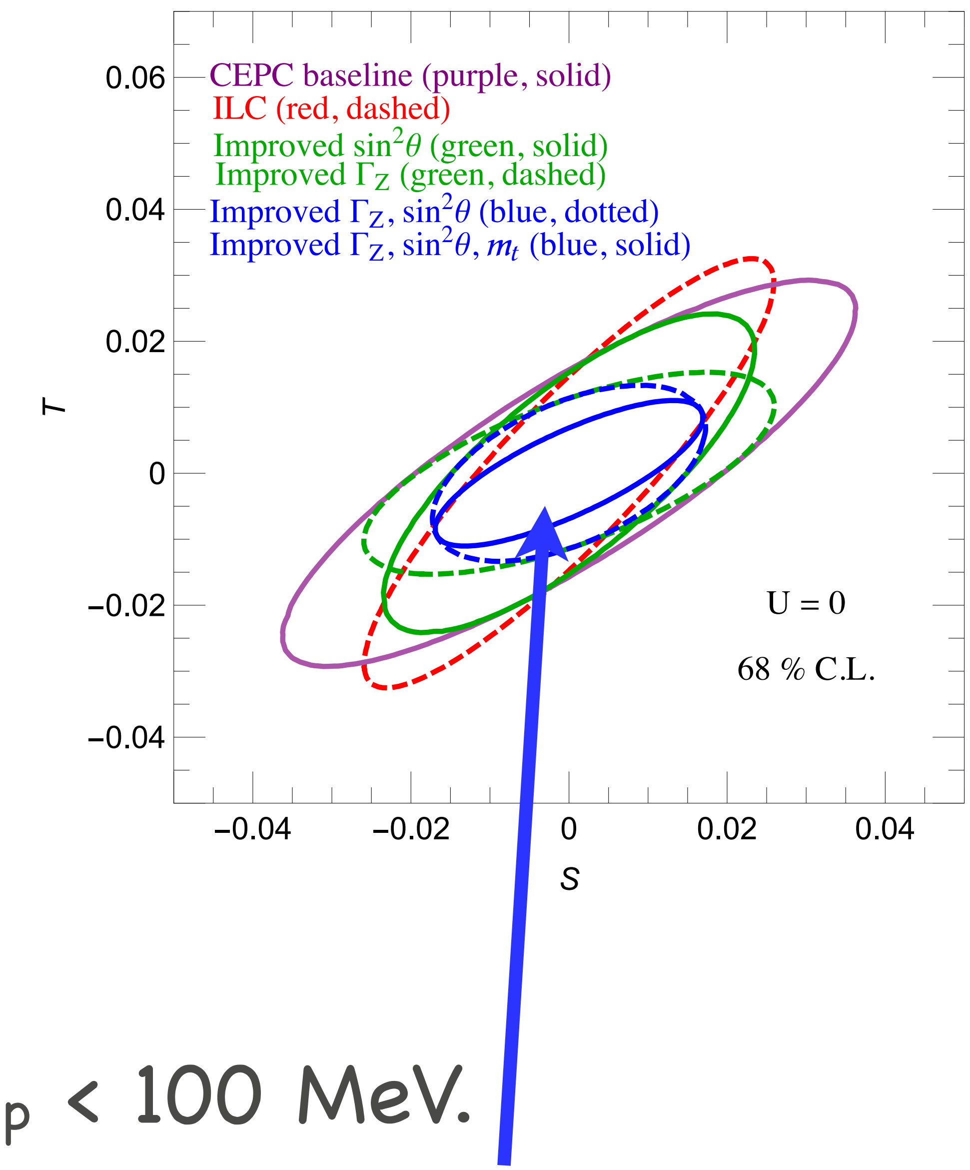


- Similar reaches from FCC-ee and CEPC.

- The ultimate precision will be limited not by statistics, but by the accuracies of m_Z, m_{top} and

Electroweak precision tests: lessons

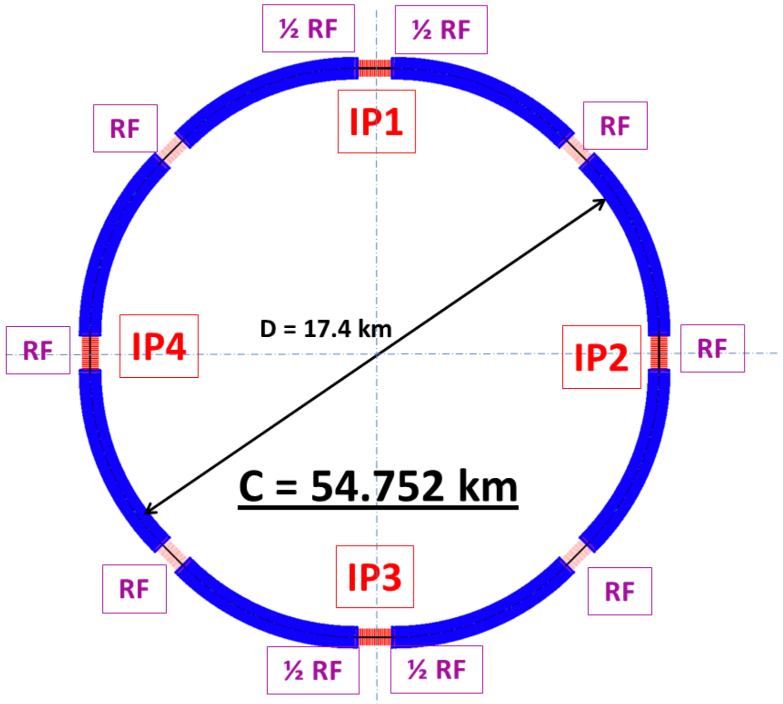




- If $\delta m_Z < 0.5$ MeV, $\delta m_{top} < 100$ MeV.
  - $\Delta\alpha_{had}$ (assuming 4.7×10^{-5}) dominates.

CEPC Design

- Beam physics: dynamic aperture, momentum acceptance, electron cloud, pretzel scheme, …
- SRF system: High-Q cavity, power loading, HOM dumping, …
- Total power consumption

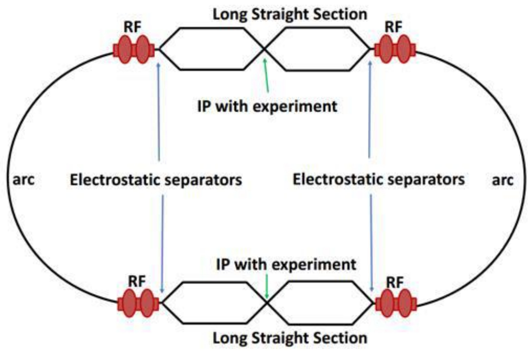


Parameter	Unit	Value	Parameter	Unit	Value
Beam energy [E]	GeV	120	**Circumference [C]**	m	54752
Number of IP[N_{IP}]		2	**SR loss/turn [U_0]**	GeV	3.11
Bunch number/beam[n_B]		50	**Energy acceptance RF [h]**	%	5.99
SR power/beam [P]	MW	51.7	**Beam current [I]**	mA	16.6
emittance (x/y)	nm	6.12/0.018	**β_{IP}(x/y)**	mm	800/1.2
Transverse size (x/y)	μm	69.97/0.15	**Luminosity /IP[L]**	$cm^{-2}s^{-1}$	2.04E+34

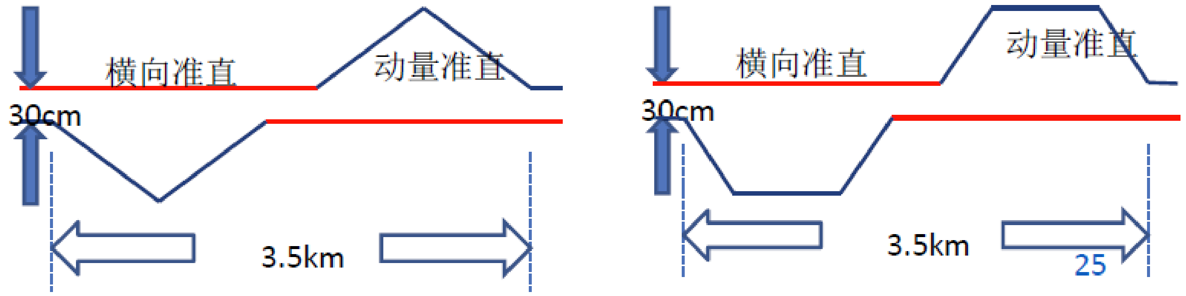
JY Tang *et. al.*

SppC Accelerator

- Lattice design: three persons (1 postdoc, 2 students) working on the SPPC lattice
  - Race-track lattice to be compatible with CEPC
  - We do not need to by-pass the CEPC detectors
  - Different schemes (@70, 100 TeV)



- Collimation Study: two persons (1 postdoc, 1 student) working on collimation method and schemes
  - Transverse and longitudinal collimation in the same long straight section (overcoming beam loss at arc encountered by LHC)



- High-field SC magnets: seeking collaboration with industry, HT conductor research units, international partners

Probing NP with precision measurements

- CEPC: clean environment, good for precision.
- We are going after deviations of the form

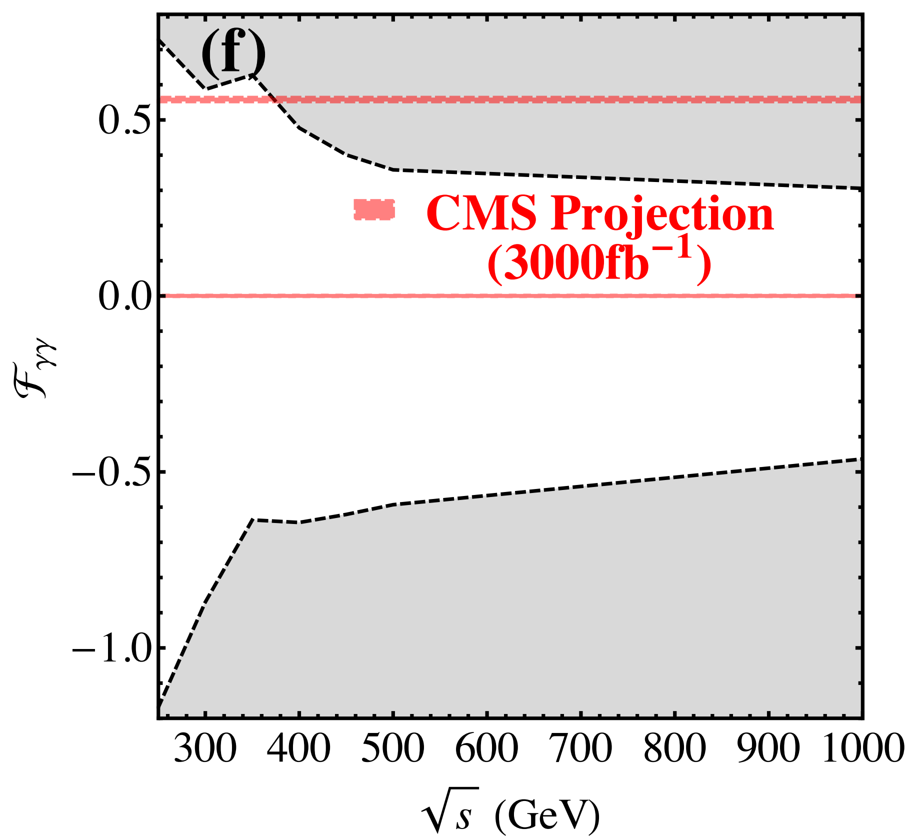
$$\delta \simeq c\frac{v^2}{M_{\rm NP}^2}$$

M_{NP} : mass of new physics
c: $O(1)$ coefficient

- Take for example the Higgs coupling.
  - LHC precision: 5-10% $\Rightarrow$ sensitive to M_{NP} < TeV
  - However, M_{NP} < TeV largely excluded by direct NP searches at the LHC.
  - To go beyond the LHC, need 1% or less precision.

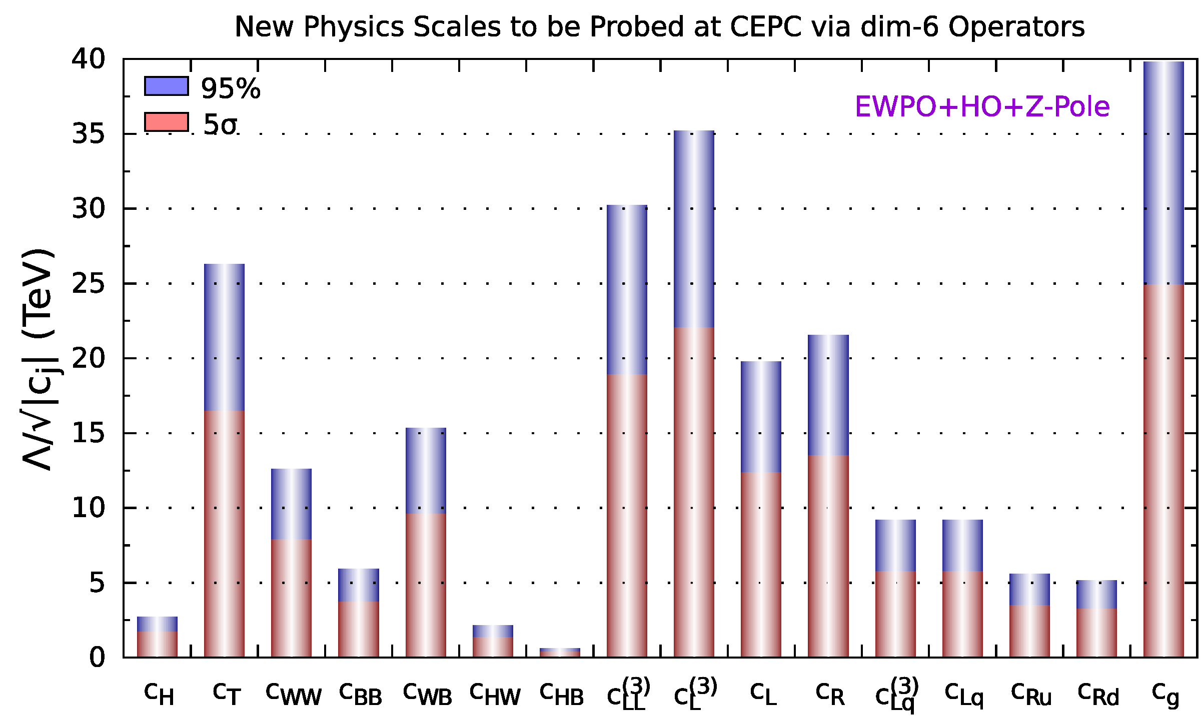
Scale of new physics.

anomalous Higgs
to gamma and Z coupling



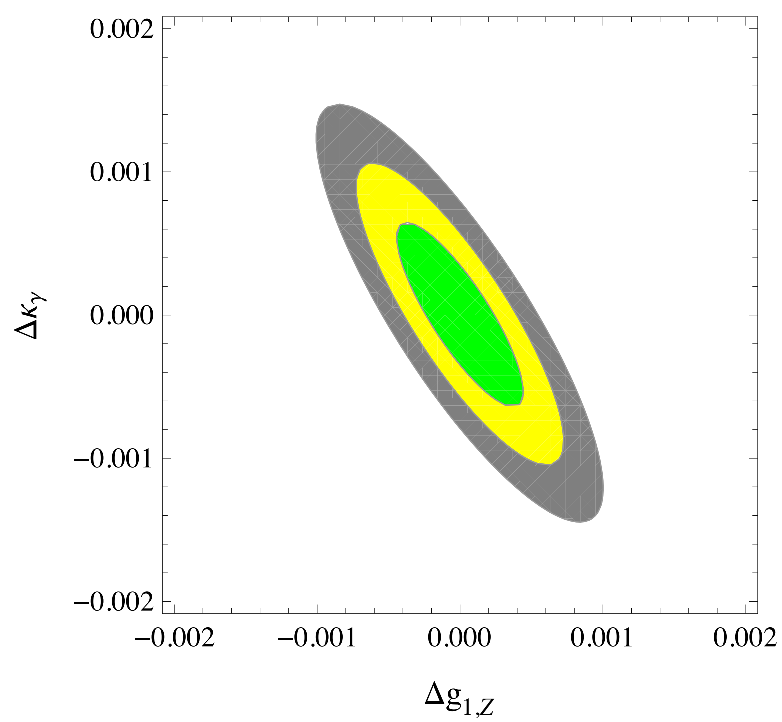
Q. Cao, B. Yan, 1507.06204

Qing-Hong Cao talk at this workshop



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

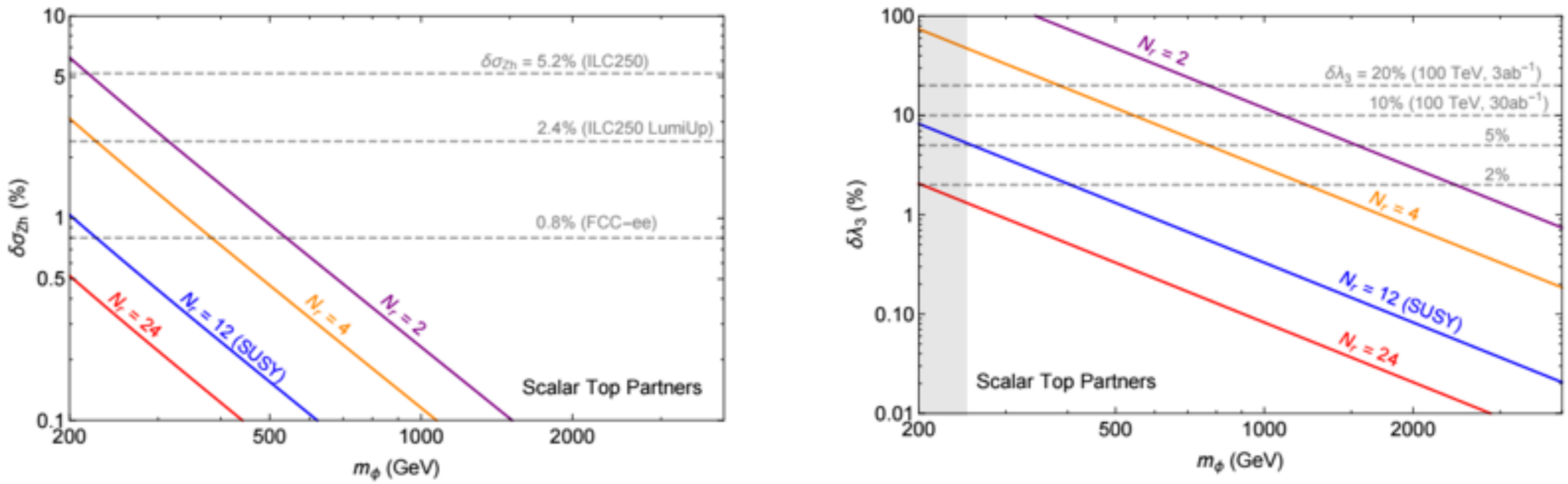
ShaoFeng Ge talk at this workshop



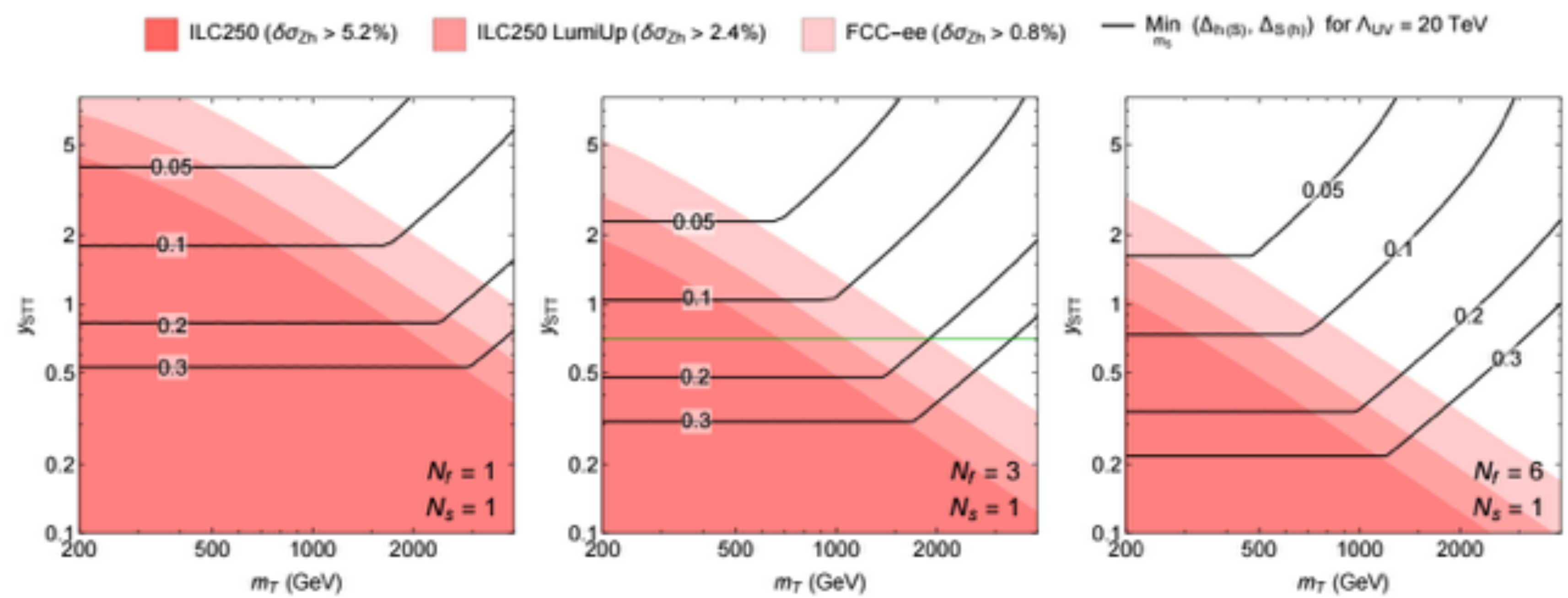
L. Bian, J. Shu, Y. Zhang, 1507.02238

Jing Shu talk at this workshop

In the regime of multiple TeVs!



δσ_Zh (%)
δσ_Zh = 5.2% (ILC250)
2.4% (ILC250 LumiUp)
0.8% (FCC-ee)
N_r = 24
N_r = 12 (SUSY)
N_r = 4
N_r = 2
Scalar Top Partners
m_ϕ (GeV)
δλ_3 (%)
δλ_3 = 20% (100 TeV, 3ab^-1)
10% (100 TeV, 30ab^-1)
5%
2%
N_r = 2
N_r = 4
N_r = 12 (SUSY)
N_r = 24
Scalar Top Partners
m_ϕ (GeV)



ILC250 (δσ_Zh > 5.2%)
ILC250 LumiUp (δσ_Zh > 2.4%)
FCC-ee (δσ_Zh > 0.8%)
Min_{m_S} (Δ_h(S), Δ_S(h)) for Λ_UV = 20 TeV
y_STT
m_T (GeV)
0.05
0.1
0.2
0.3
N_f = 1
N_s = 1
N_f = 3
N_s = 1
N_f = 6
N_s = 1