Physics goals of CEPC
Progress towards CDR

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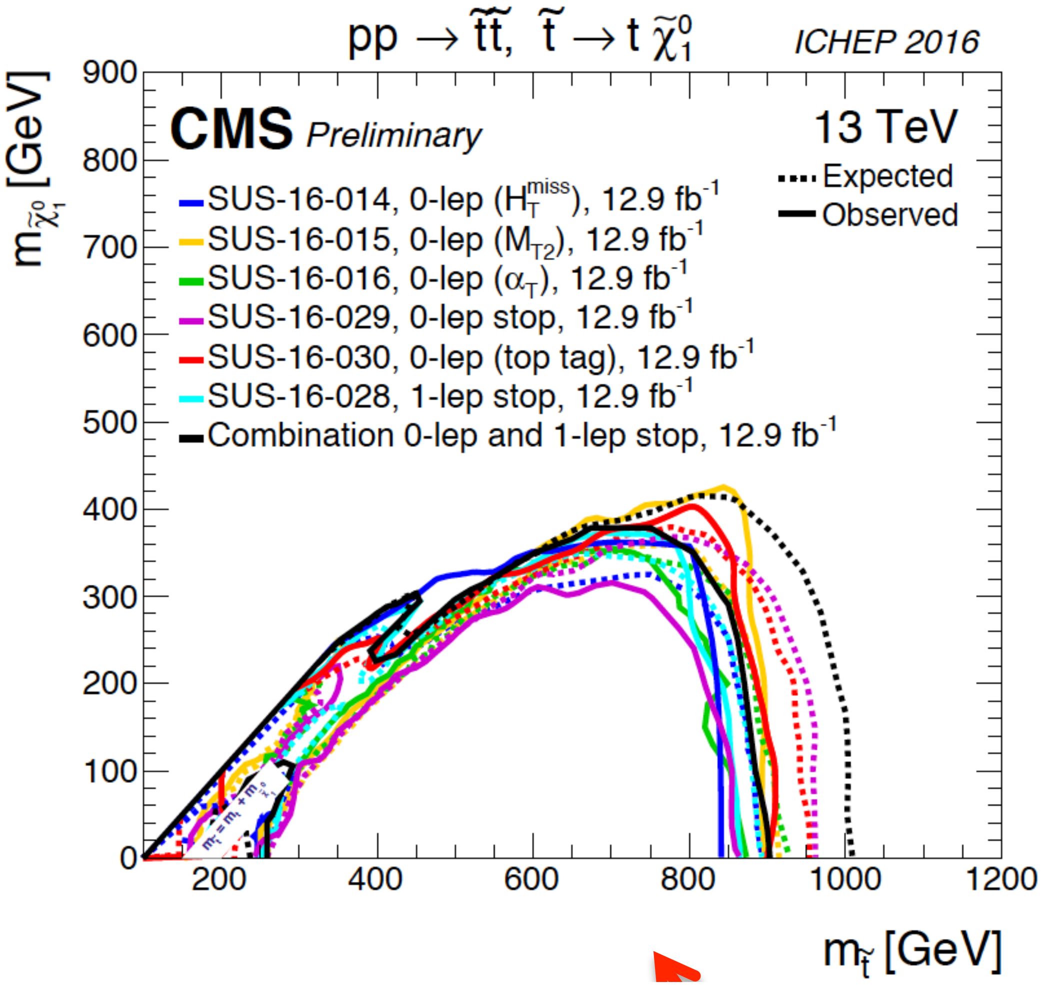
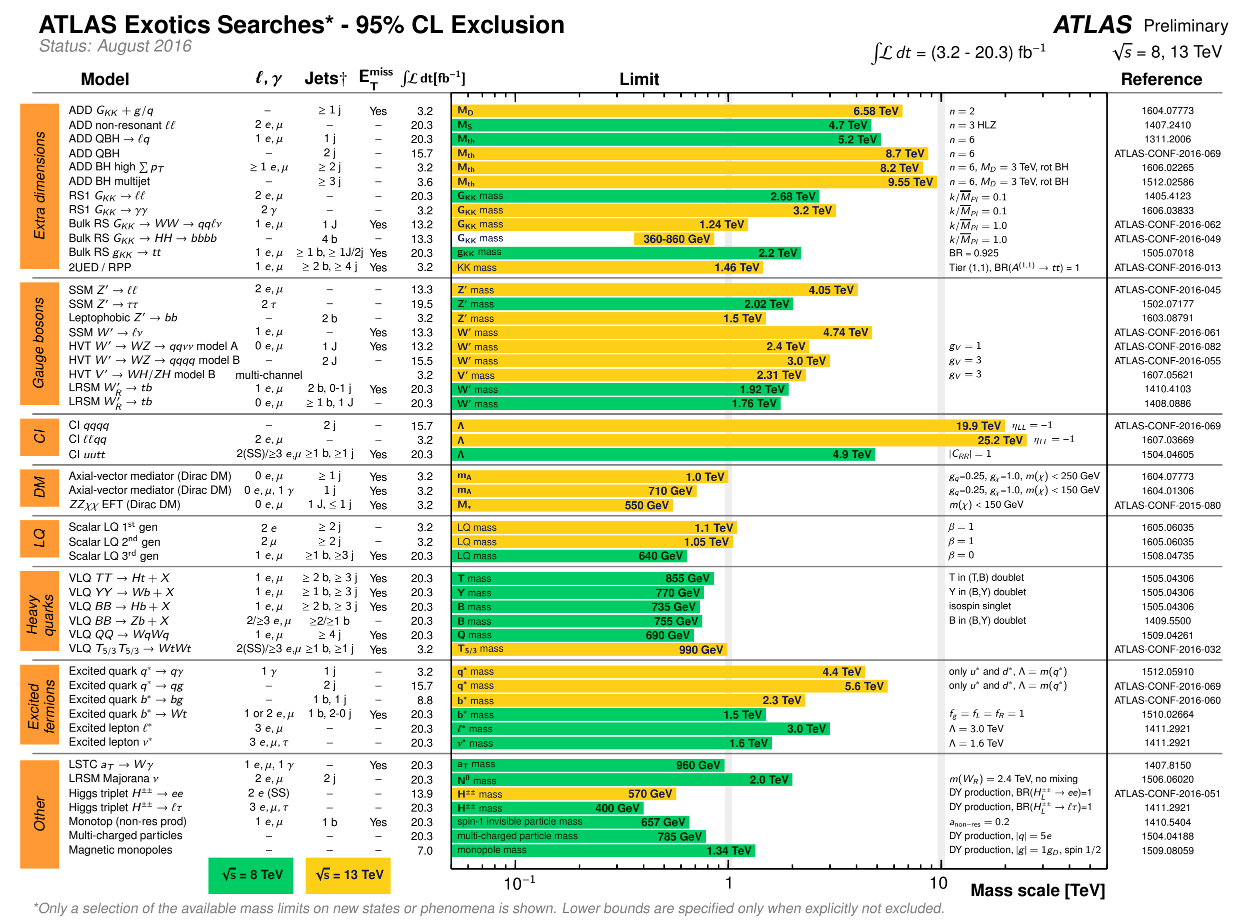
University of Chicago

CEPC-SPPC Symposium. IHEP/BUAA, Sept 3, 2016

Update from the LHC





– No “early” discovery.

– Disappointed? Yes. Surprised? Not much.

Physics case for CEPC

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- Focus on longer term future.

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- Focus on longer term future.
- Assuming no discovery of new particle at the LHC.
- Physics case for CEPC.
  - Cover significant ground beyond the LHC.
  - Answering important questions beyond the reach of the LHC

Even longer term

- Without LHC discovery.
  - Physics case for a 100 TeV pp collider stronger than HE-LHC at 28 TeV.
  - Cost+technological challenge. Perhaps easier to "sell" only as a second step of a circular Higgs factory in longer term.
- Circular Higgs factory is an essential step.

This talk

- Outline of the theory part of CDR
- Results. Including new results in the past year and presented here in this workshop.
- Work to be done. (highlighted with this color)

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- Brief introduction. (a few pages)
  - Overview of project, machine/lumi parameters.

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CEPC at the precision frontier

Probing NP with precision measurements

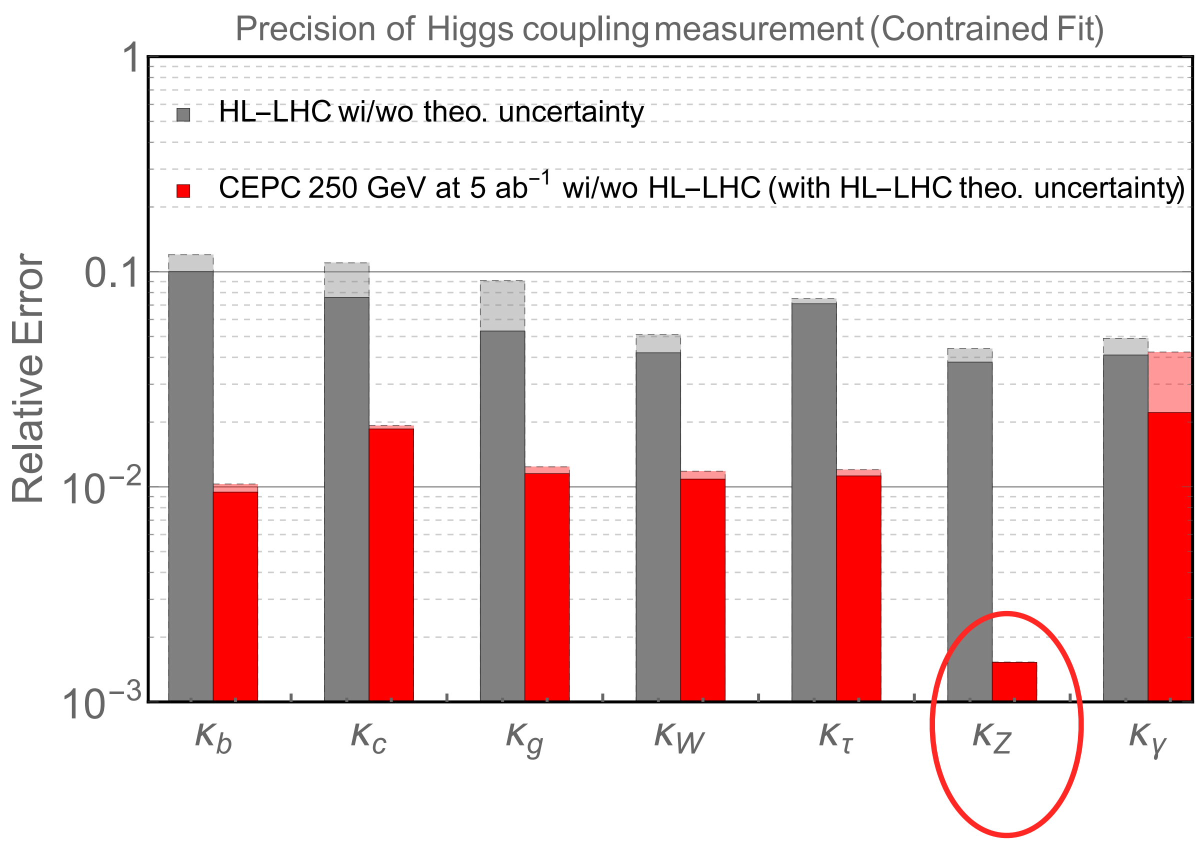
- CEPC: clean environment, good for precision.
- We are going after deviations of the form

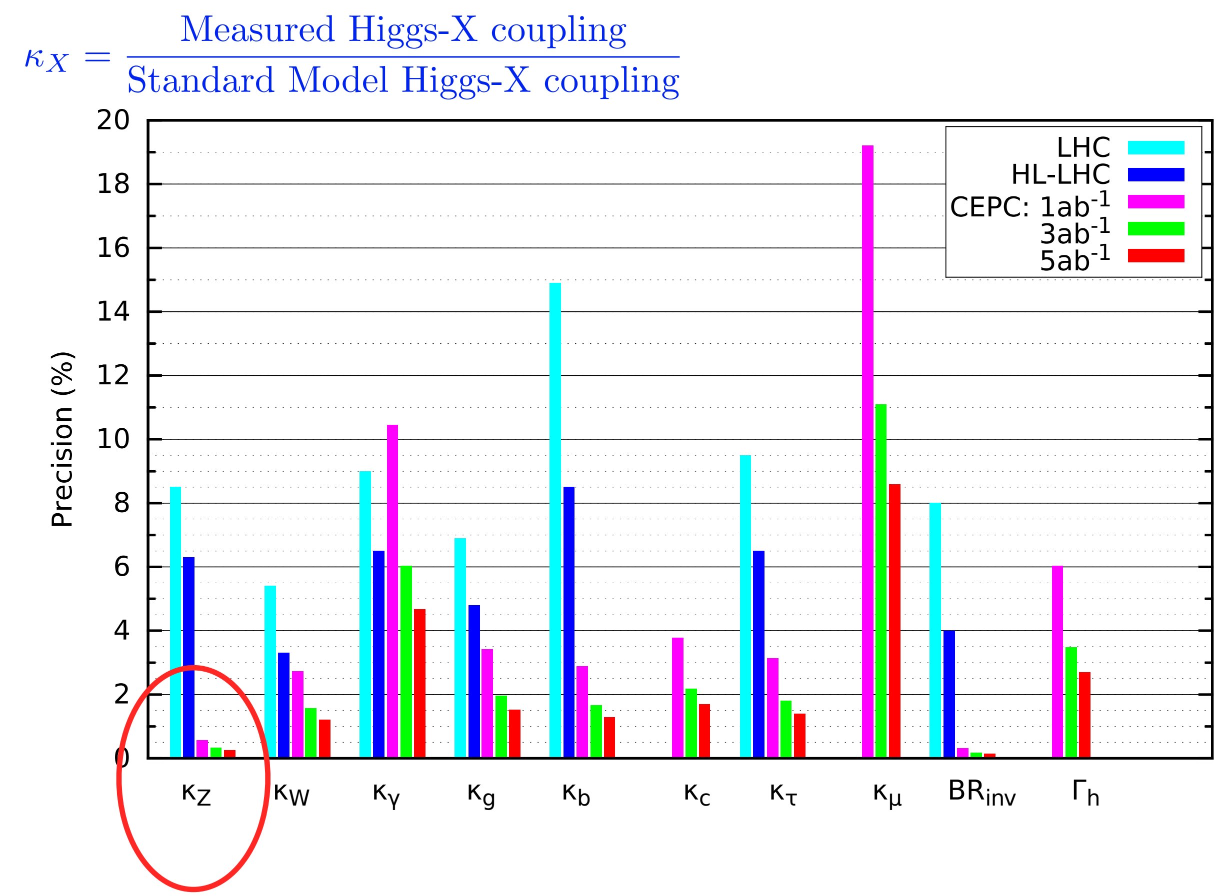
$$\delta \simeq c \frac{v^2}{M_{\mathrm{NP}}^2}$$

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

- Take for example the Higgs coupling.
  - LHC precision: 5-10% ⇒ 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.

CEPC can do it.

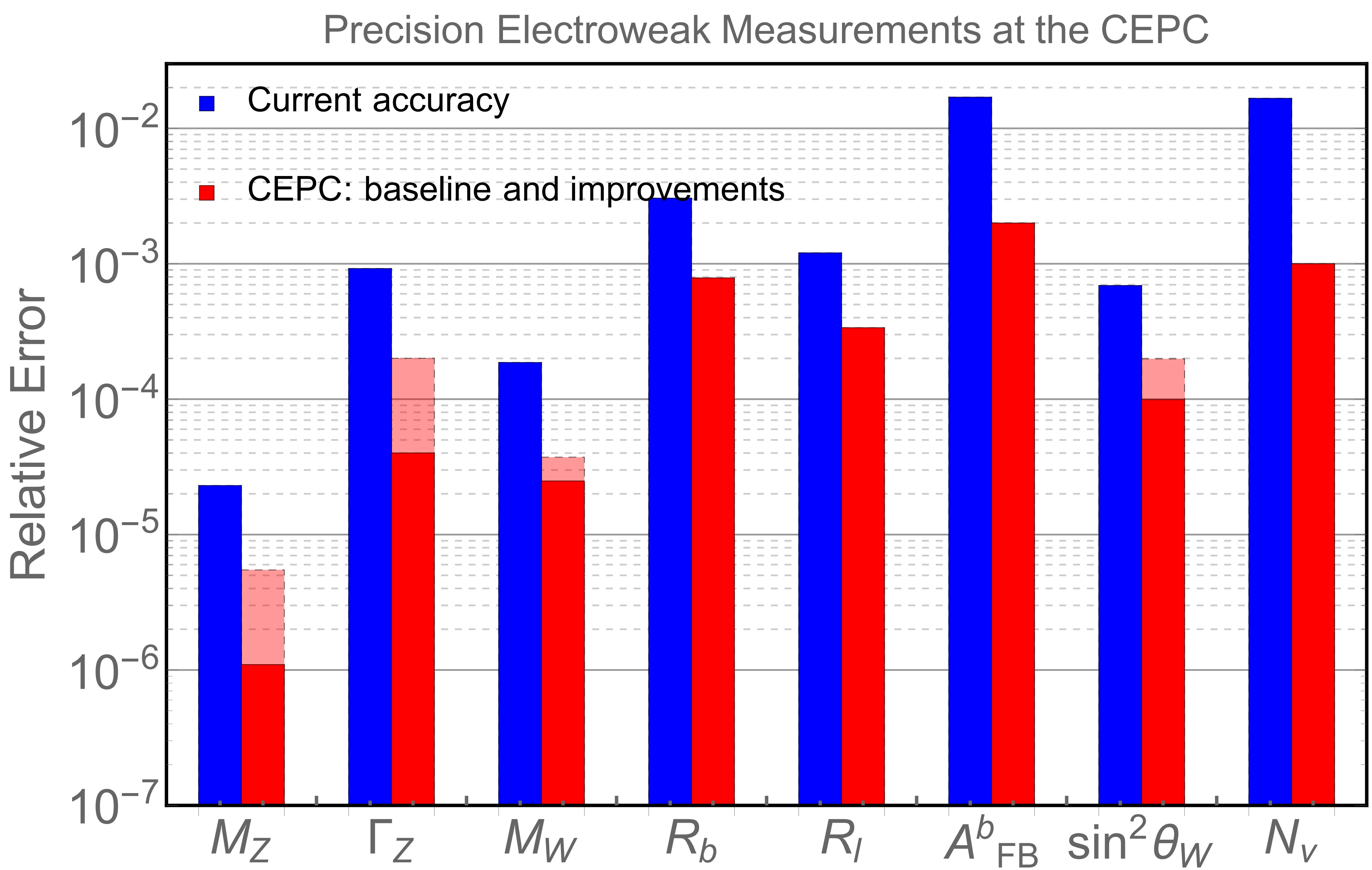




Highlights:

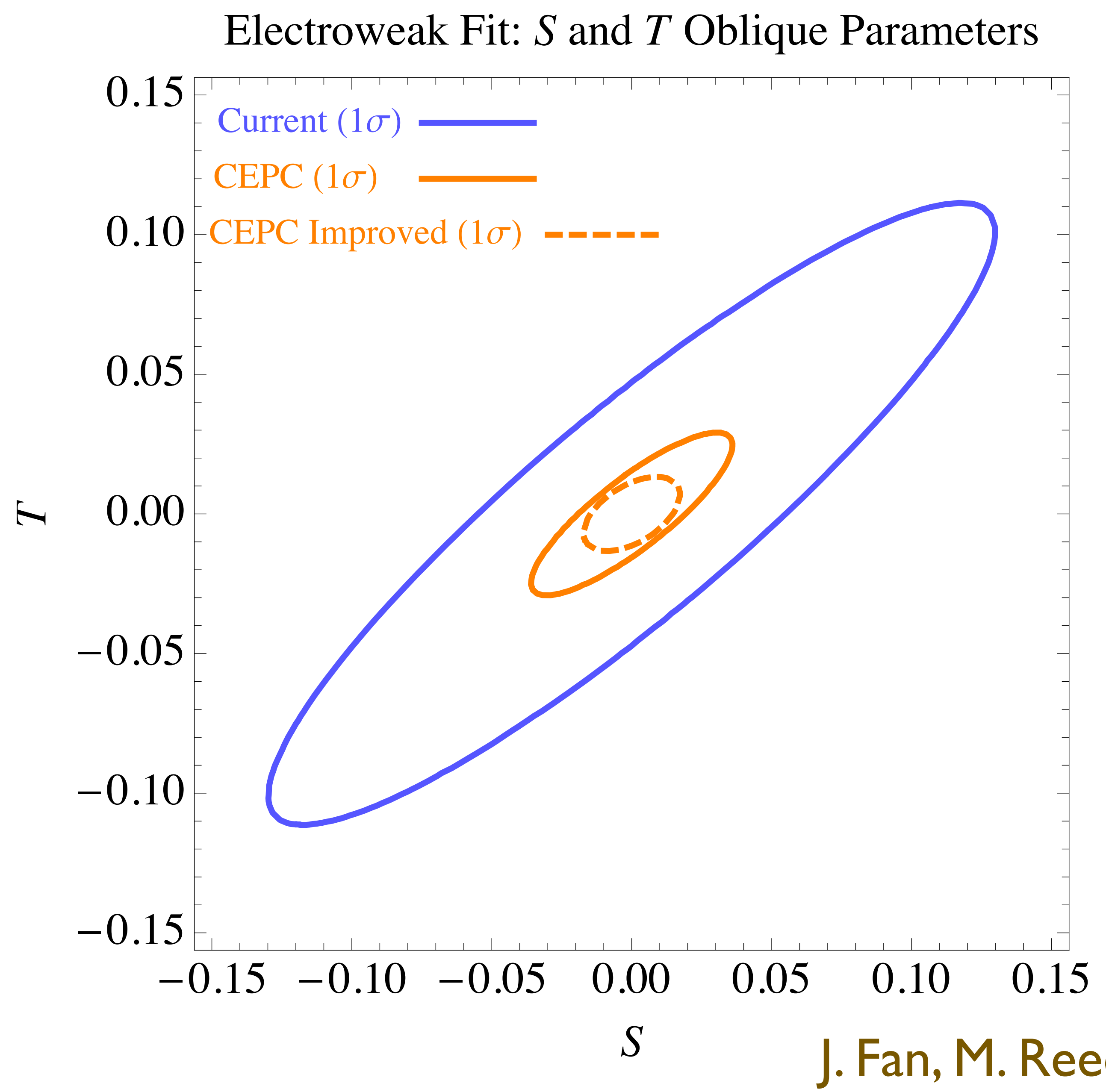
HZ coupling to sub-percent level.
Many couplings to percent level.
Model independent measurement of total width.
Sensitive to the triple Higgs coupling: 20-30%

Big advance in electroweak precision



Large improvements across the board

Electroweak precision at CEPC

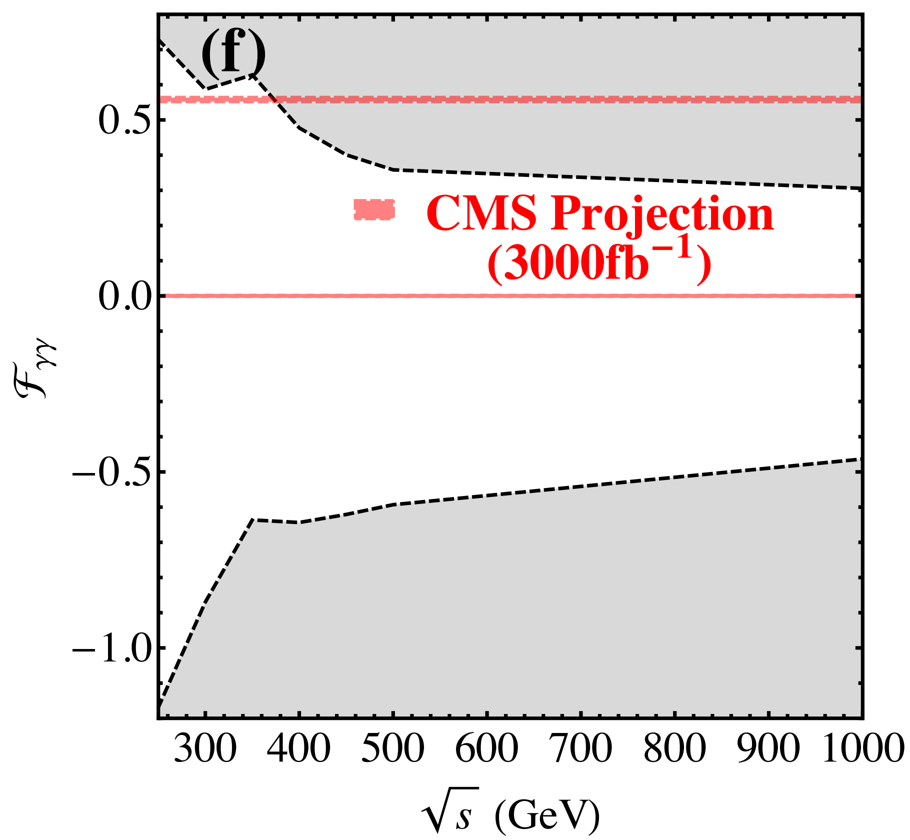


J. Fan, M. Reece, LT Wang, 1411.1054

- A big step beyond the current precision.

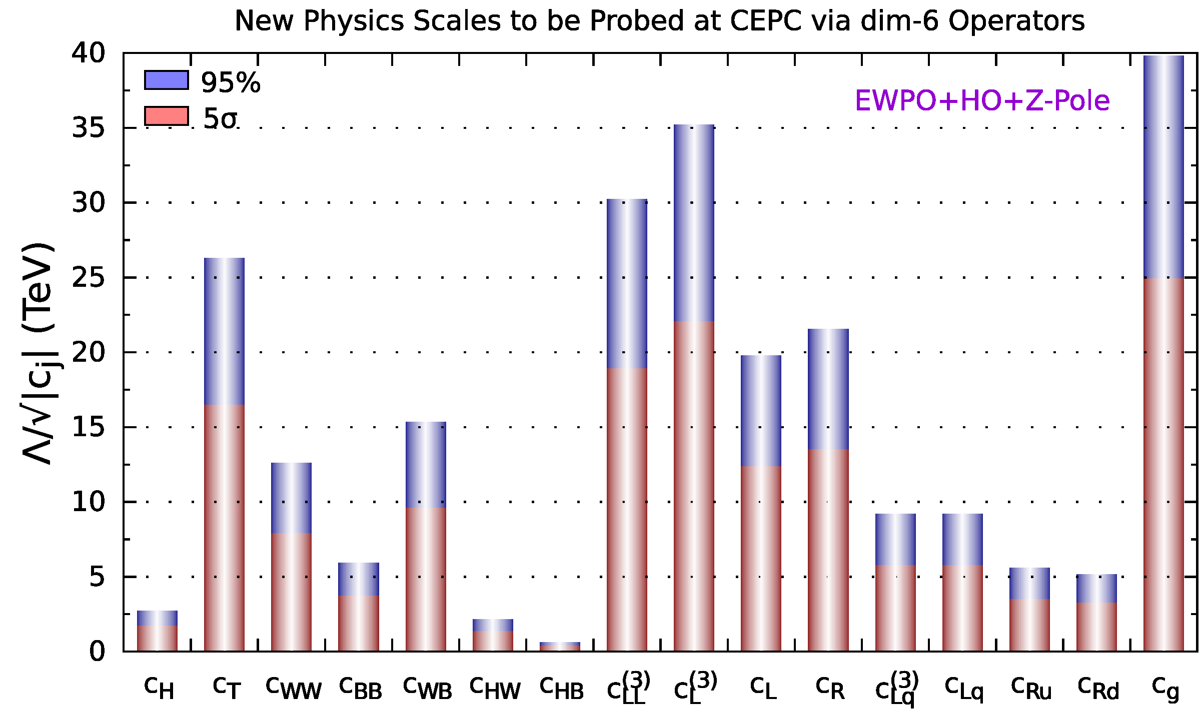
Scale of new physics.

anomalous Higgs
to gamma and Z coupling

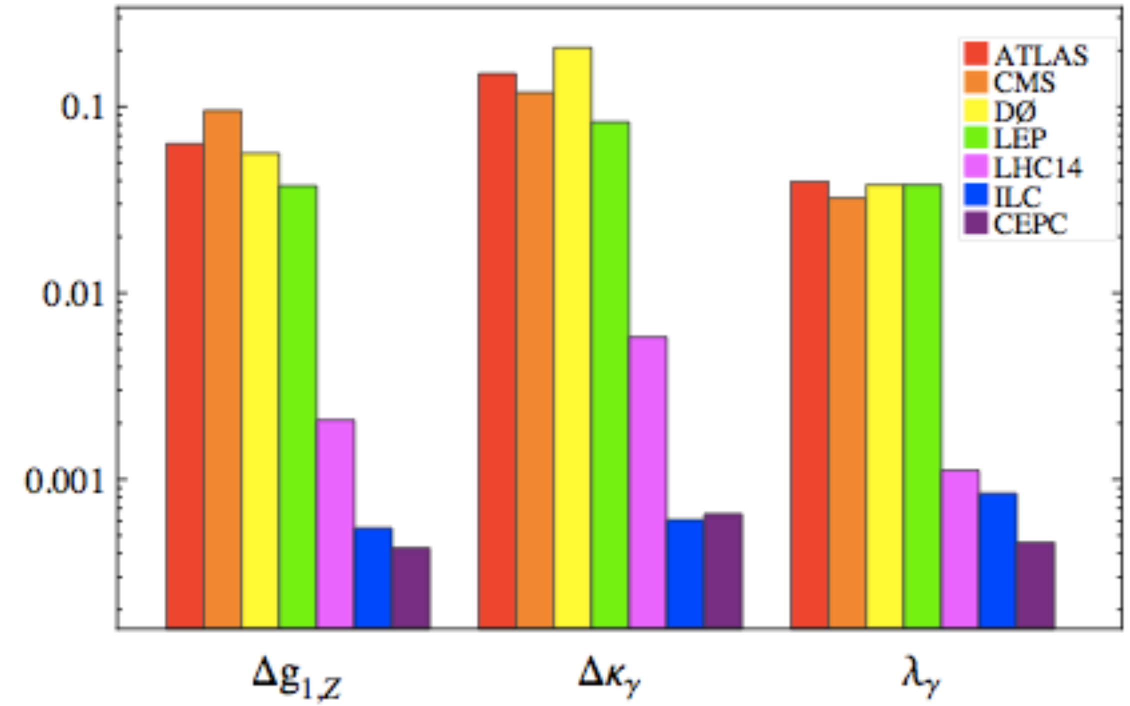


Q. Cao, B.Yan, 1507.06204

In the regime of multiple TeVs!



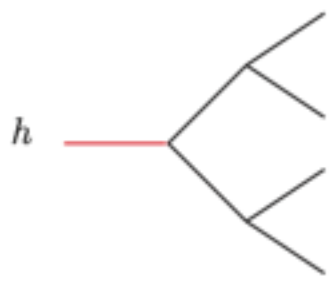
S. Ge, H. He, R. Xiao, 1603.03385



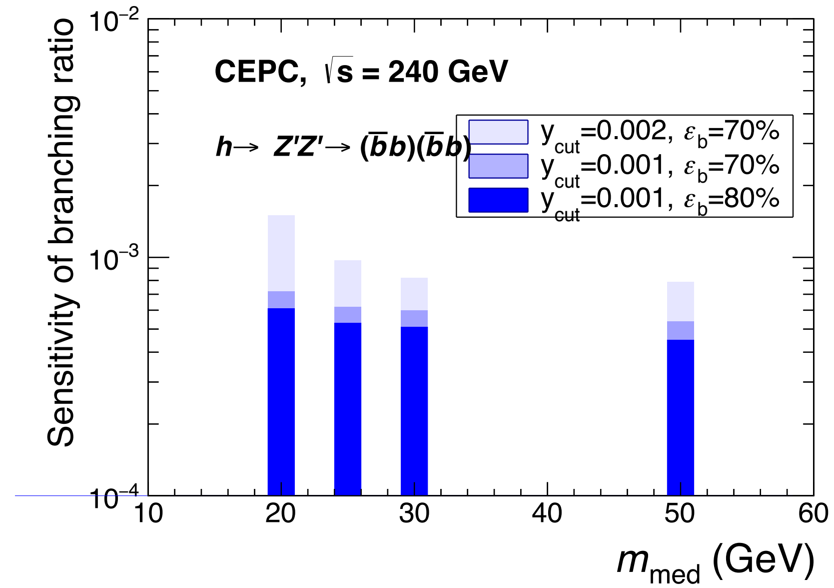
L. Bian, J. Shu, Y. Zhang, 1507.02238

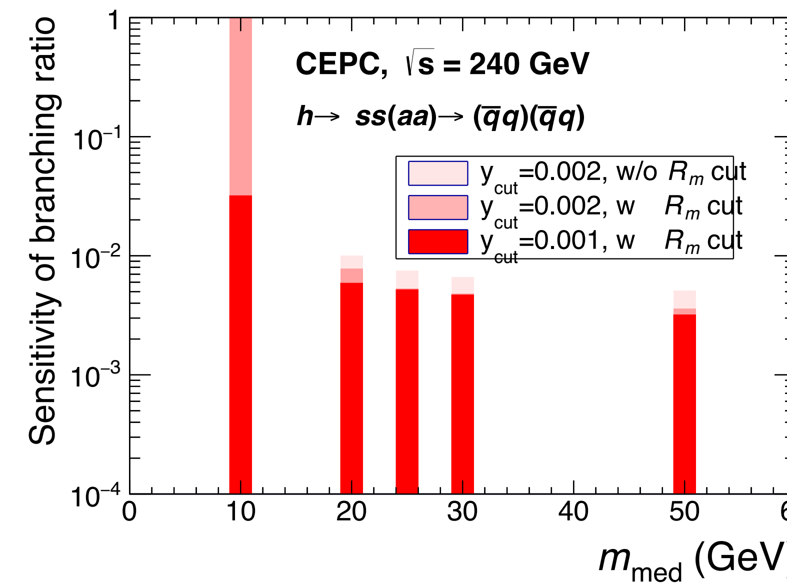
Jing Shu talk at this workshop

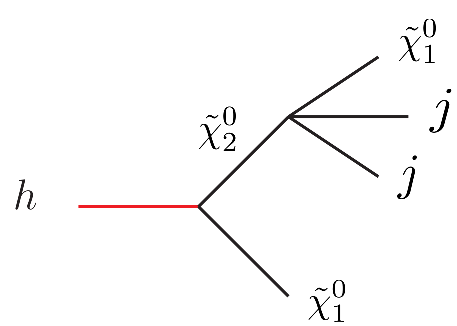
Higgs as portal to unknown



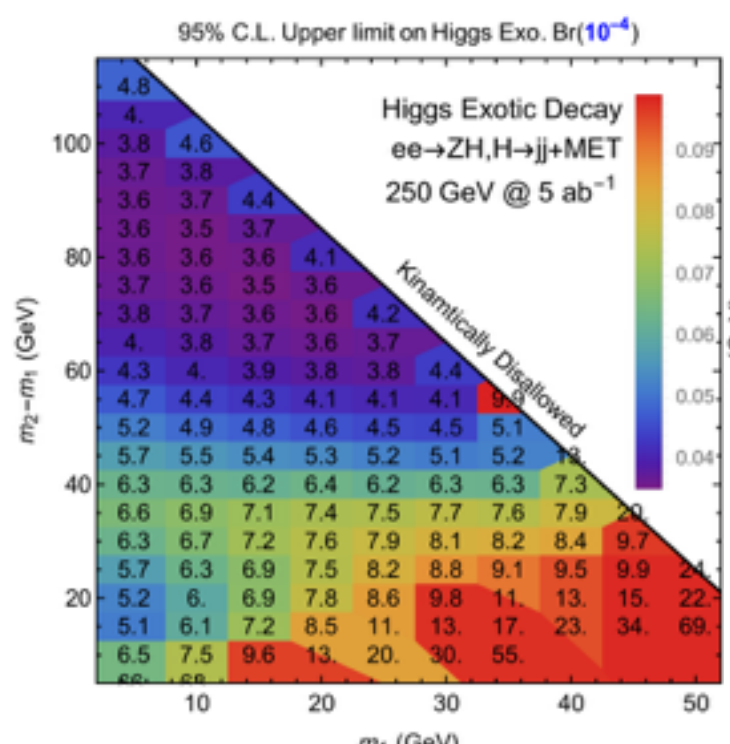
$h \to 2 \to 4$

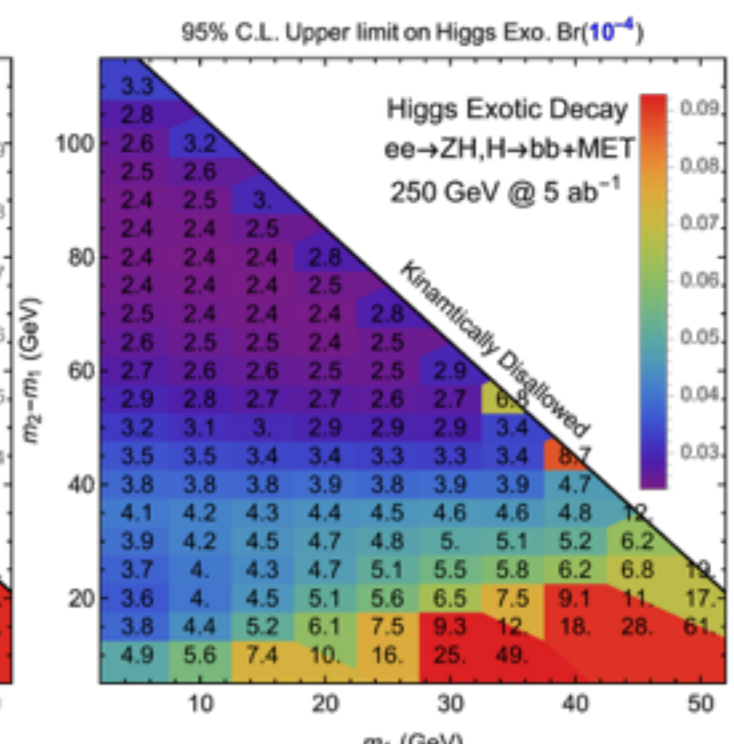






$h \to 2 \to (1+3)$





bb case is around 50%

Zhang Hao's talk at this workshop

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What can we do with this knowledge?

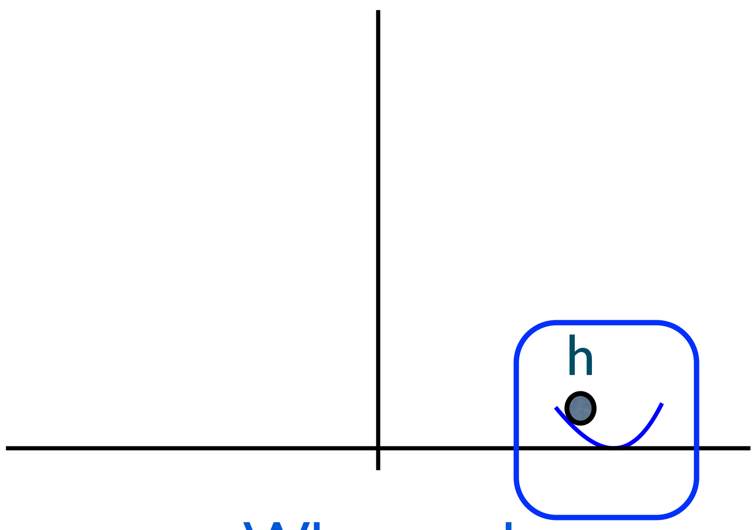
Our physics goals.

Addressing big questions

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

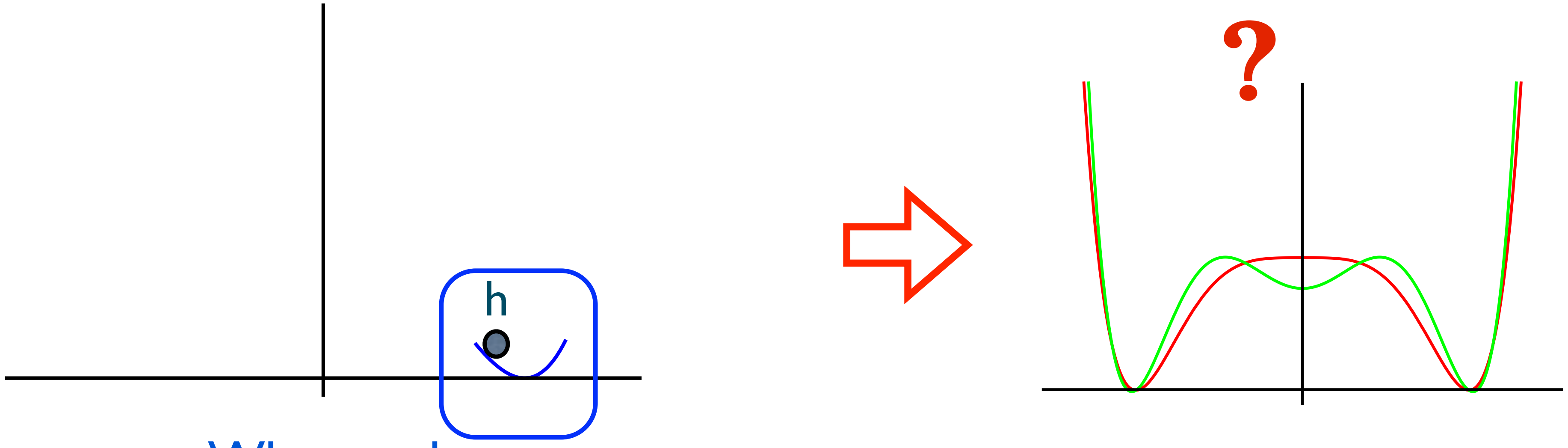
Electroweak phase transition

Electroweak phase transition



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

Electroweak phase transition



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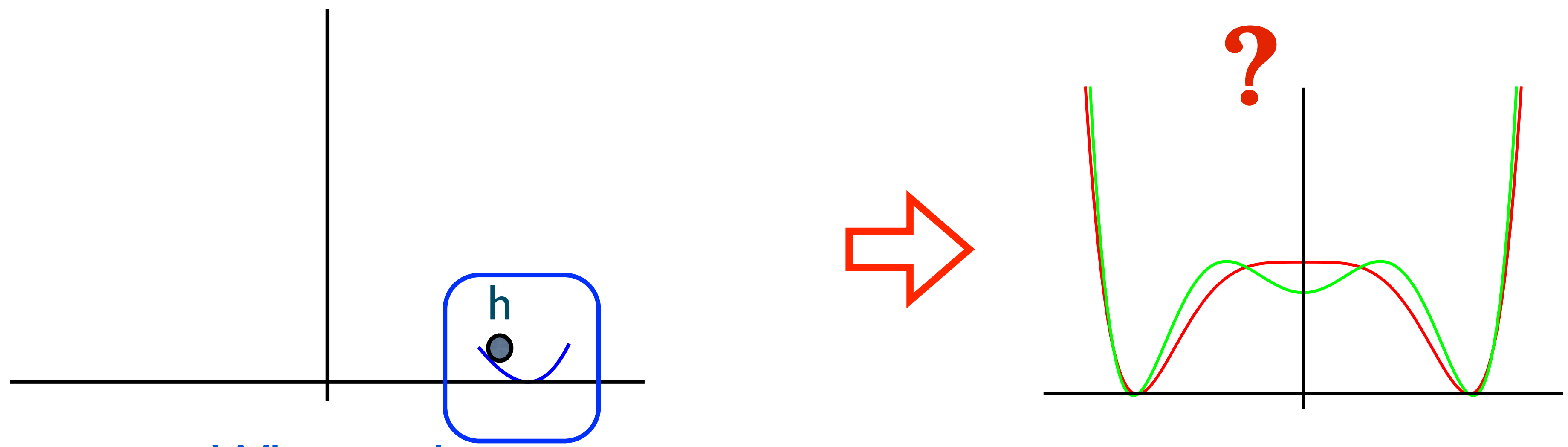


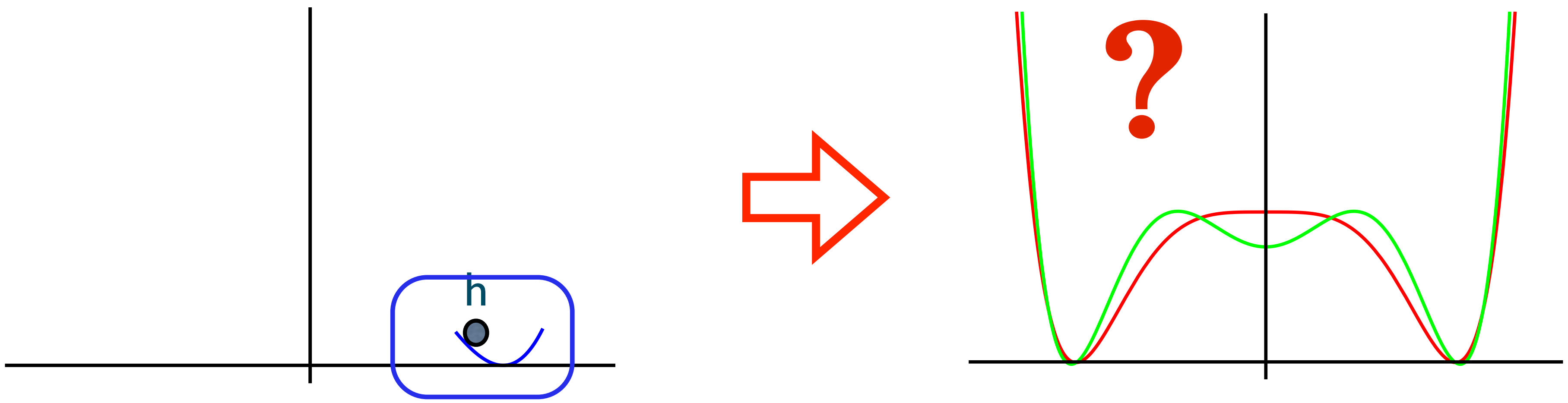
What we know now
LHC upgrades won't go much further

A monumental event in the early universe.

A milestone in particle physics and cosmology.

Is the EW phase transition first order?

Nature of EW phase transition

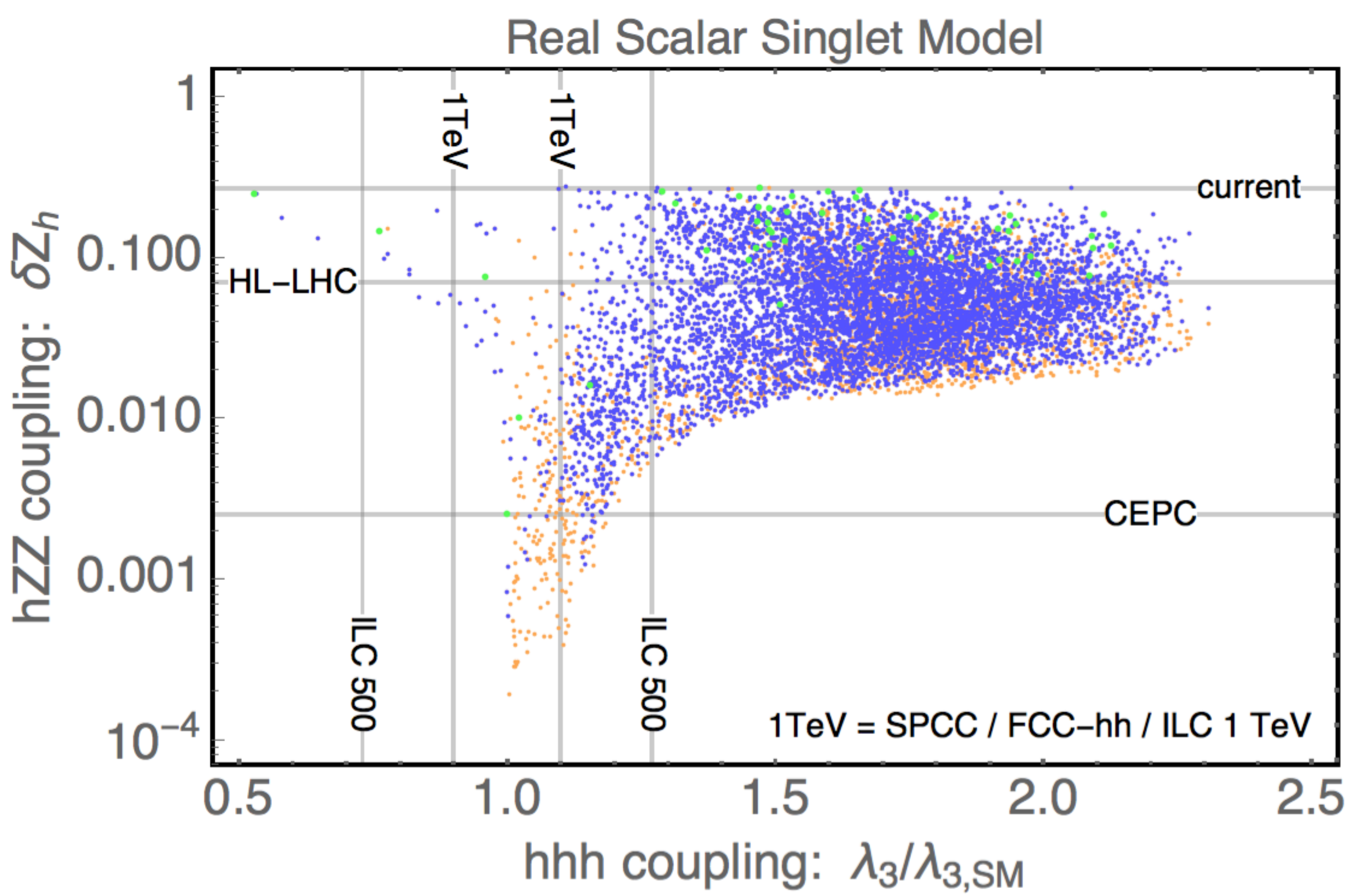


What we know from LHC
LHC upgrades won't go much further

Shift in h-Z coupling > 0.5%

Order 1 deviation in triple Higgs

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 of electroweak symmetry breaking

M: The energy scale of new physics responsible for EWSB

What is M? Can it be very high, such as $M_{Planck} = 10^{19}$ GeV, …?

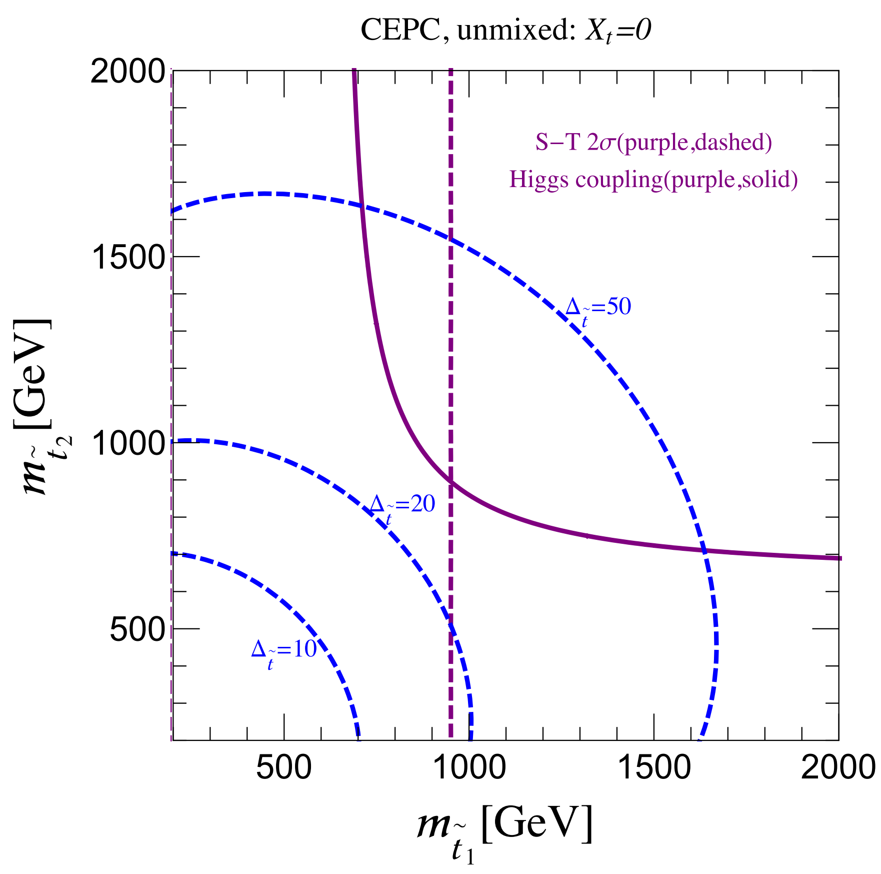
If so, why is so different from 100 GeV?

TeV new physics.
Naturalness motivated

Electroweak scale, 100 GeV.
m_h , m_W …

Naturalness, fine-tuning

- LHC searches model dependent, many blind spots.
- Precision measurement at CEPC provides a powerful and complementary probe.

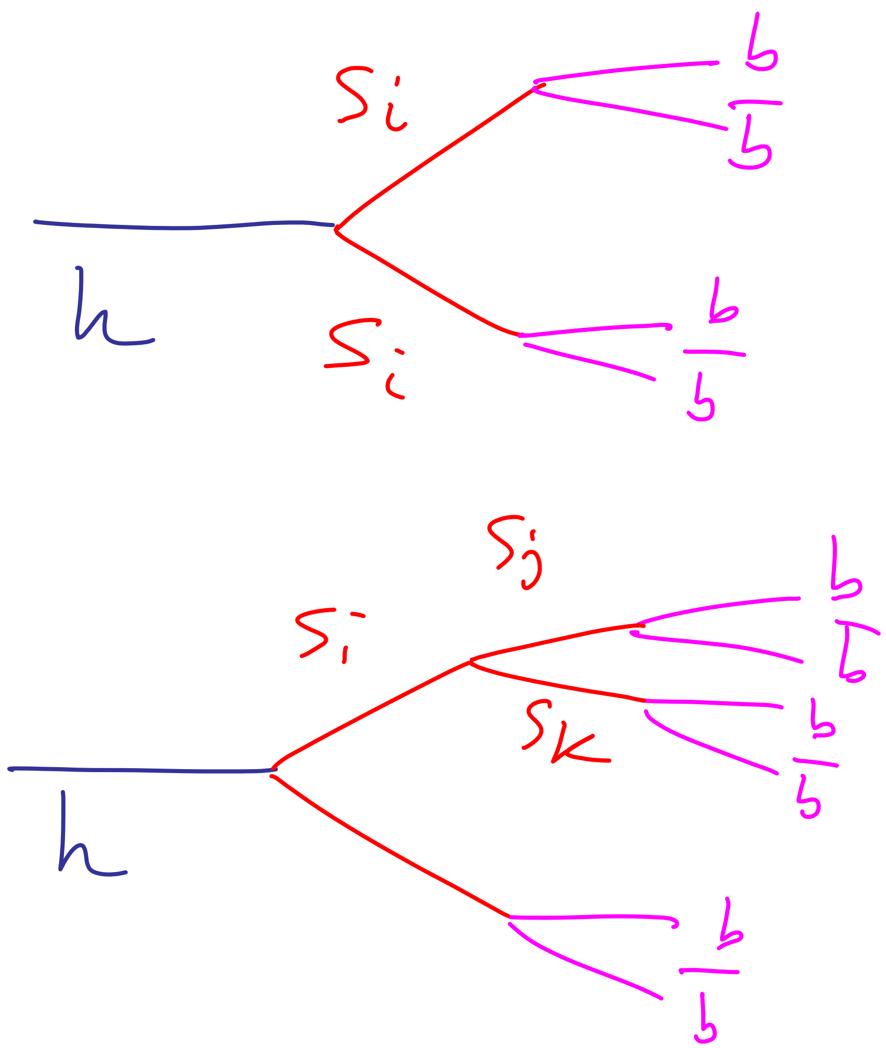


J. Fan, M. Reece, LT Wang, 1412.3107

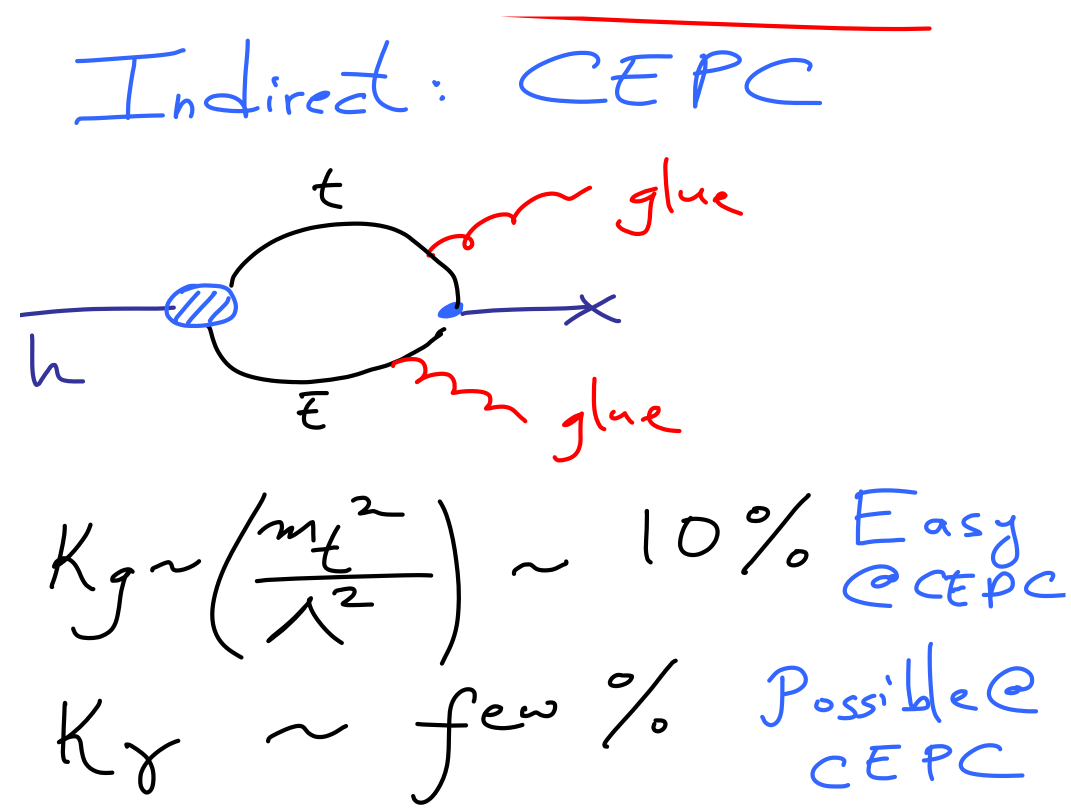
- Model independent testing fine-tuning down to percent level.

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.
- Plays the most important role in EWSB.
- Higgs top coupling a likely window to new physics.

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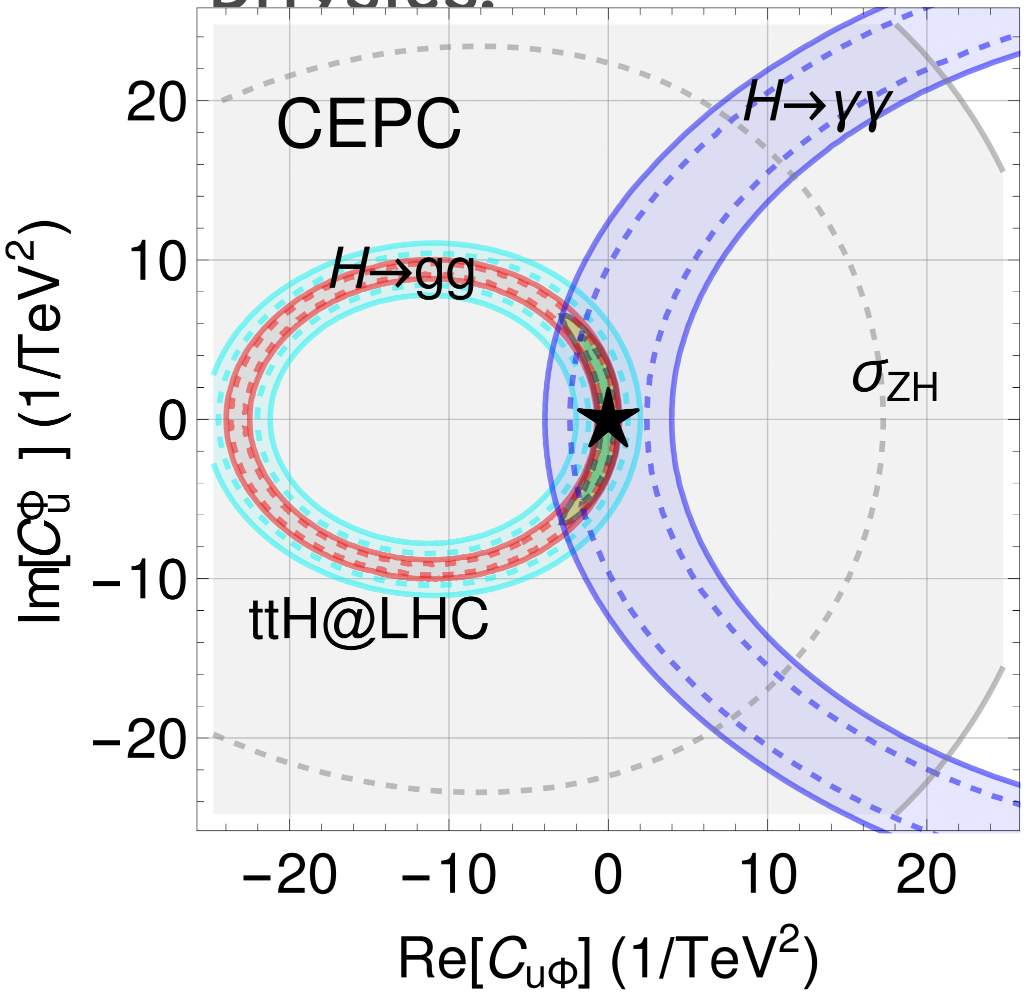


C. Shen, S. Zhu 1504.05626
Z. Liu, I. Low, LTW, in progress

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.
  - ...

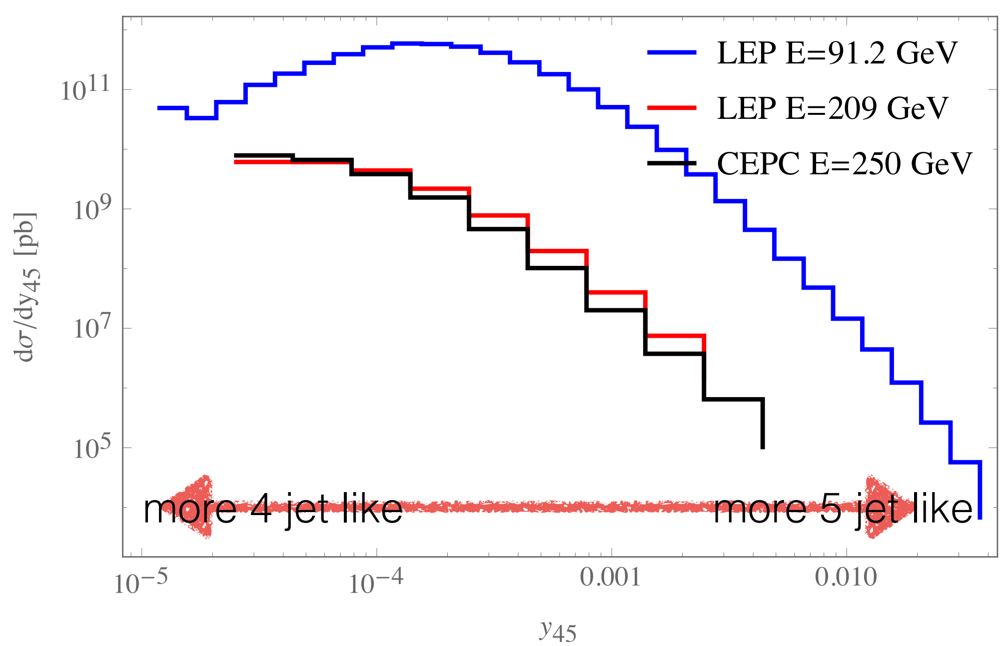
Preliminary discussion in the preCDR.
Efforts of studying this underway.
More studies needed.

Learning about QCD.

CEPC as a "clean" jet factory

- Jet cross section scale as $1/Q^2$. Going to higher energy reduce the jet cross section
- Compensated by huge increase in luminosity at CEPC (5 ab^{-1} expected)

y_{45}: four jets to five jets transition parameter

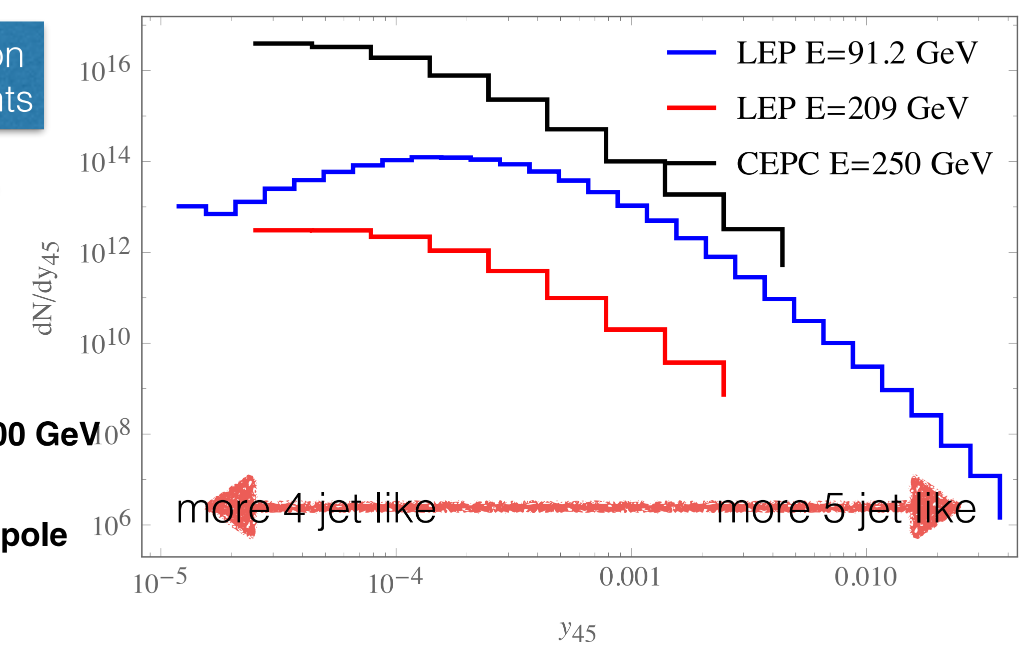


From cross section to number of events

5 ab^{-1} at CEPC

~ 500 pb^{-1} at LEP 200 GeV

~ 210 pb^{-1} at LEP Z pole



- **More five jets event at CEPC than at LEP Z pole !**
- **Hadronization and experimental uncertainty will be negligible at CEPC. If the theory uncertainty can be reduced to the same level might enable α_s extraction at the precision comparable to Lattice!**

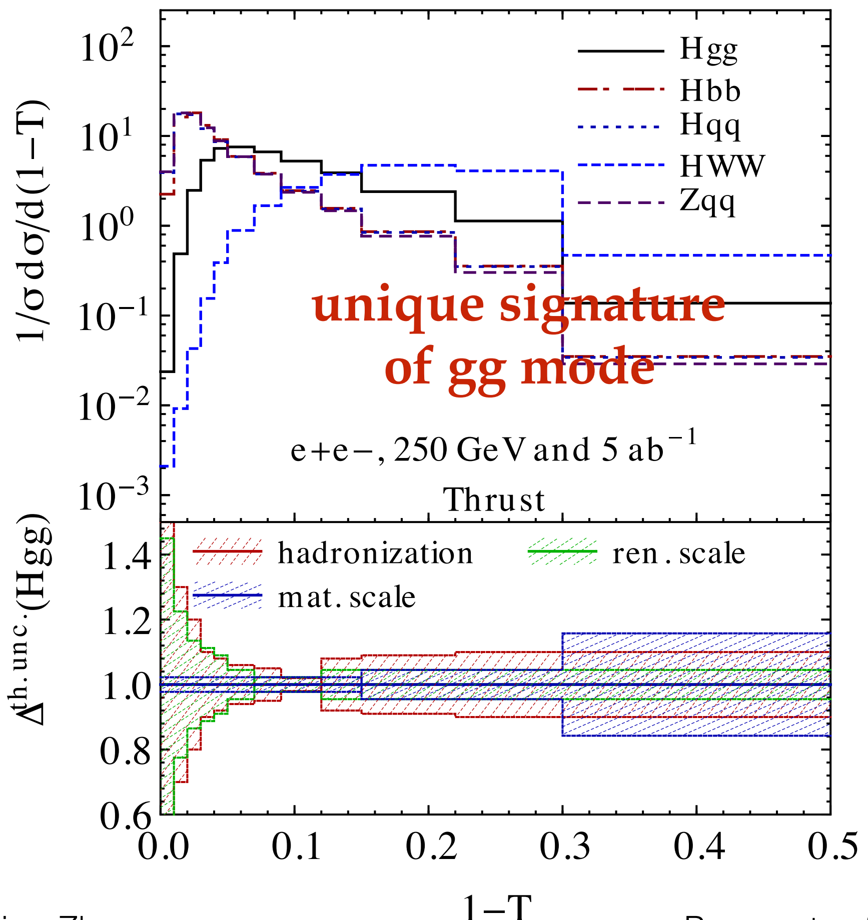
QCD and Higgs physics at CEPC

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

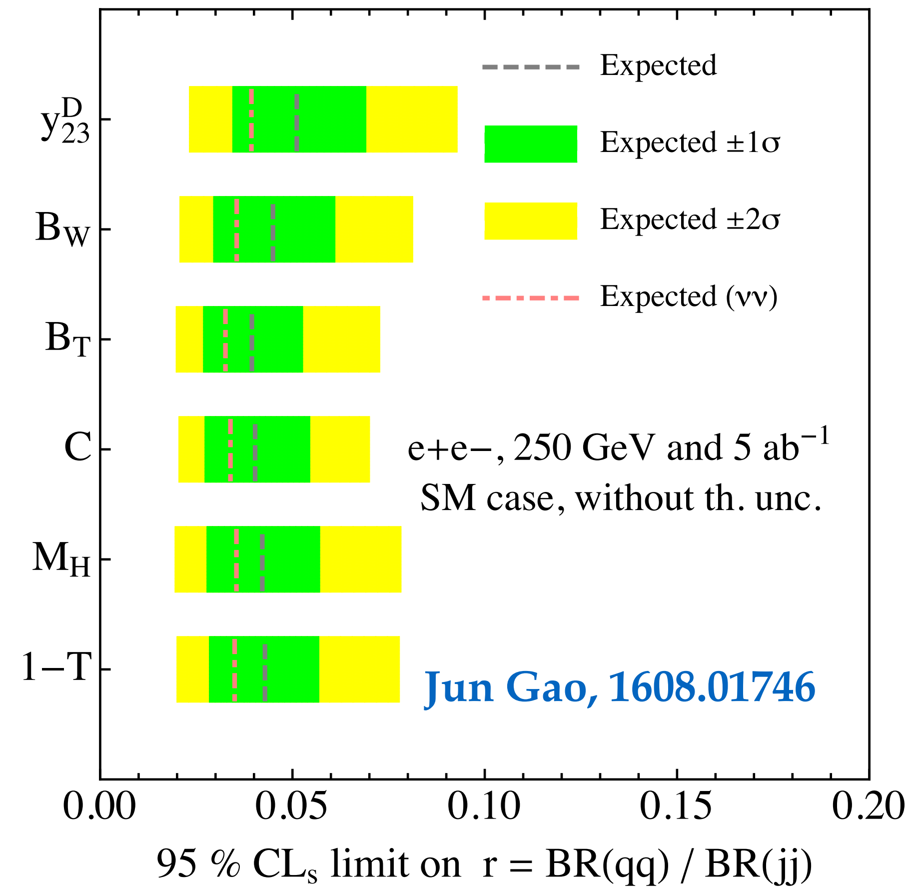
Expected event numbers for different hadronic decay modes of the SM Higgs boson at 250 GeV and with 5 ab^{-1}

$Z(l^+l^-)H(X)$	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

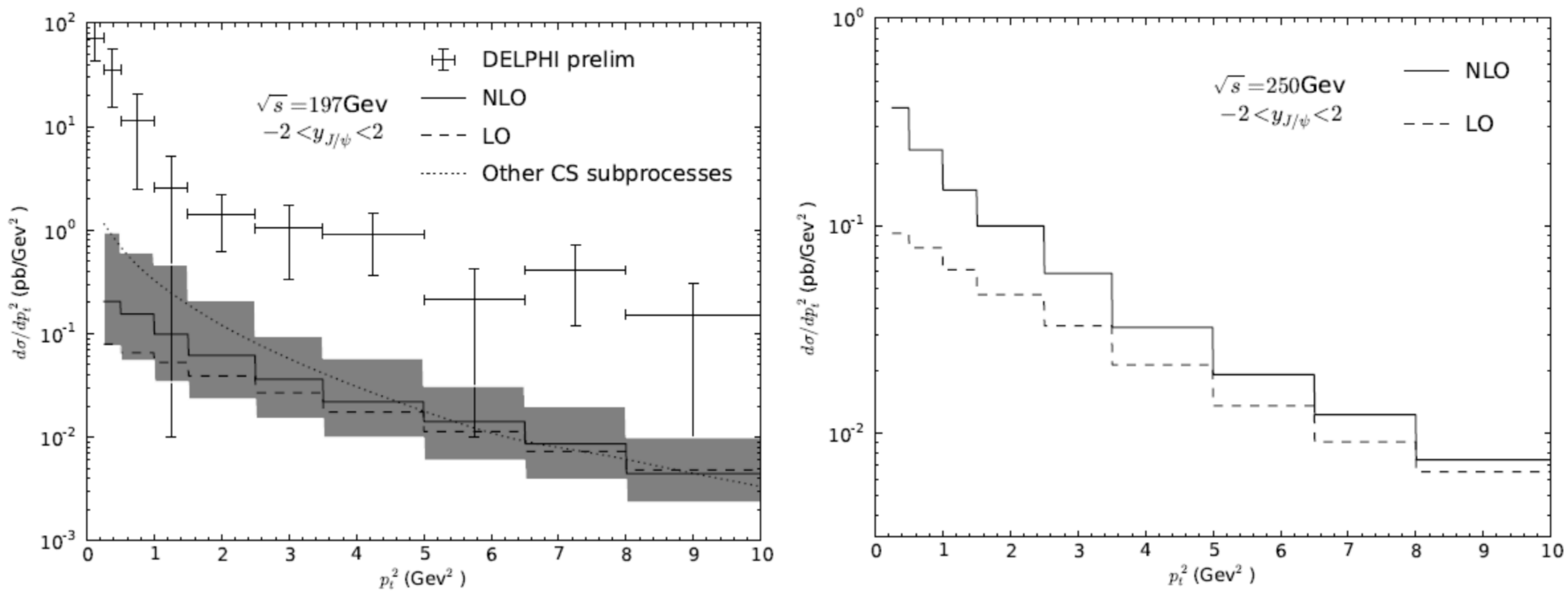


Quarkonium physics

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

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

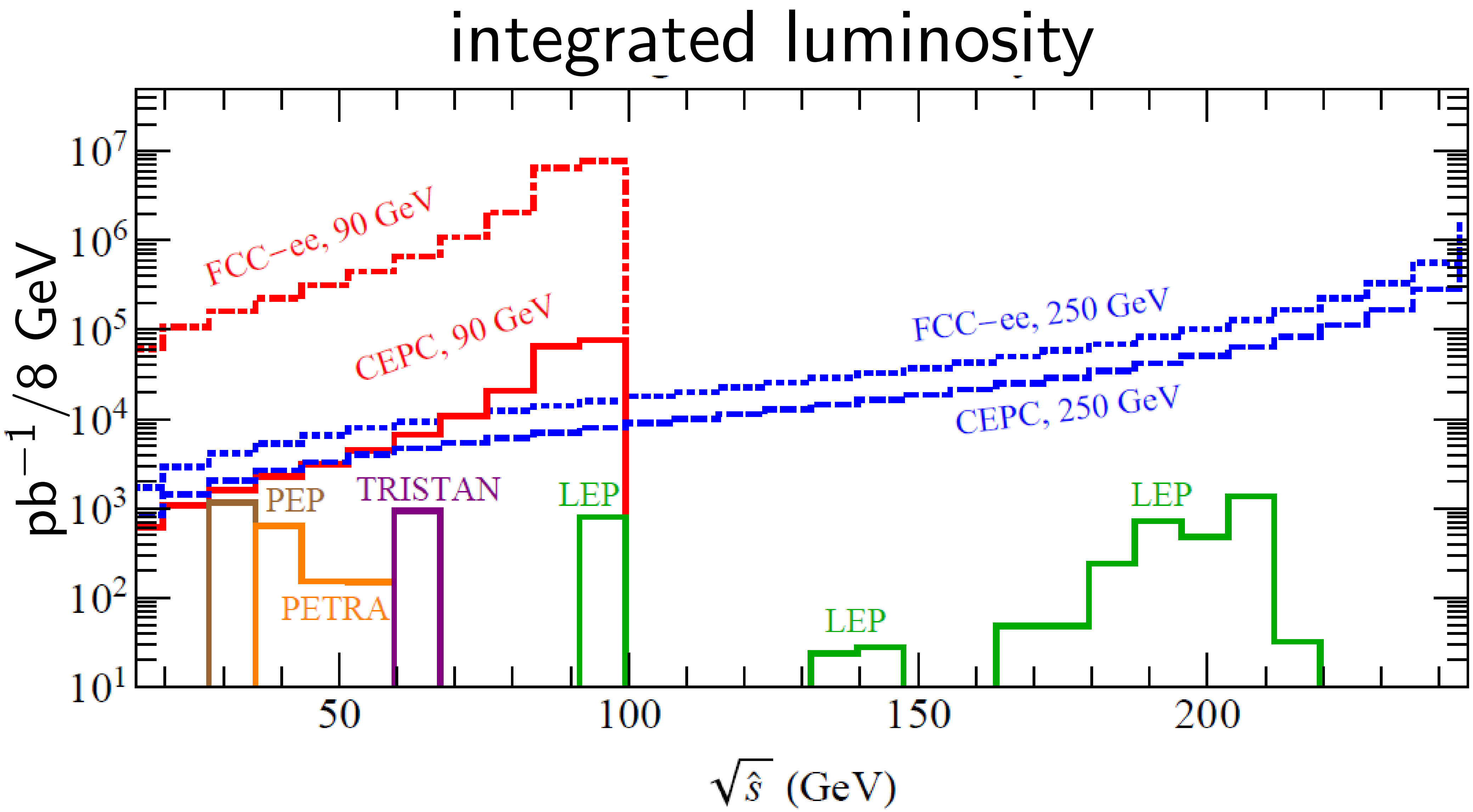
Chen, Chen, Qiao, 1608.06231



- **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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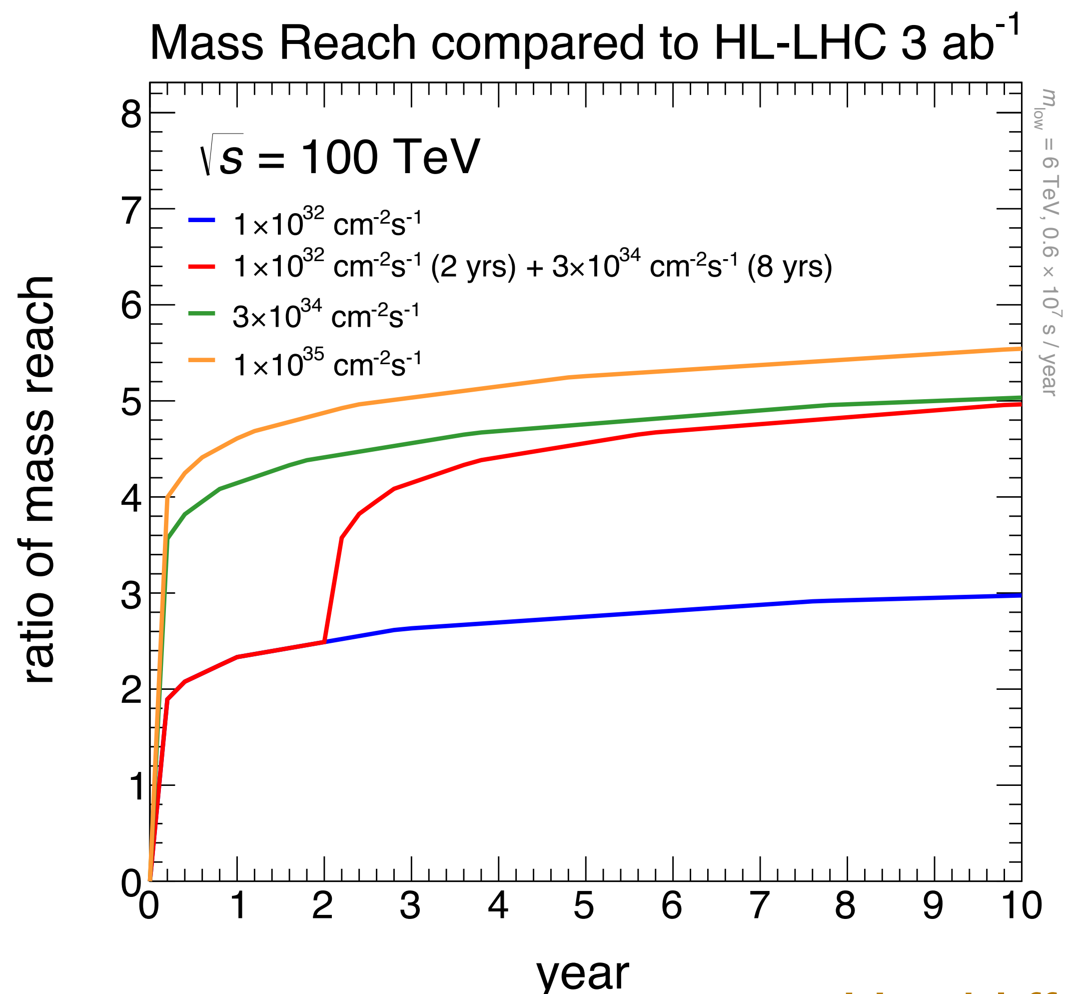
100-ish TeV SPPC

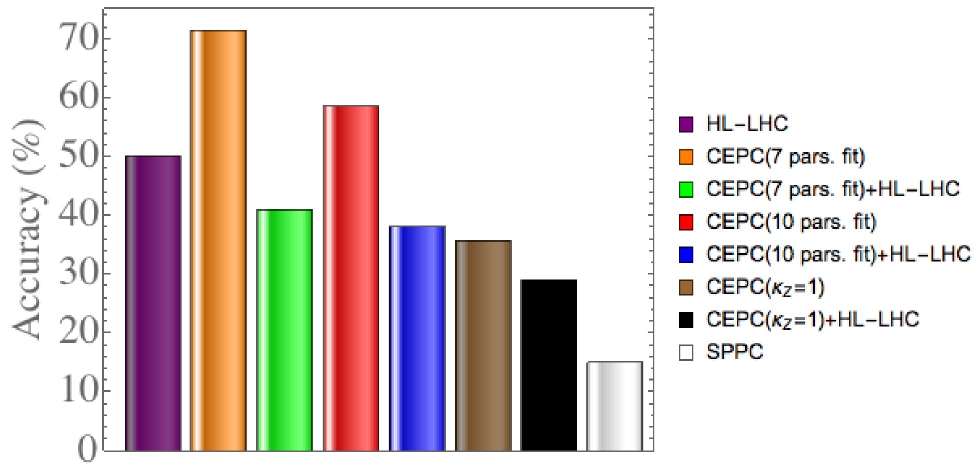


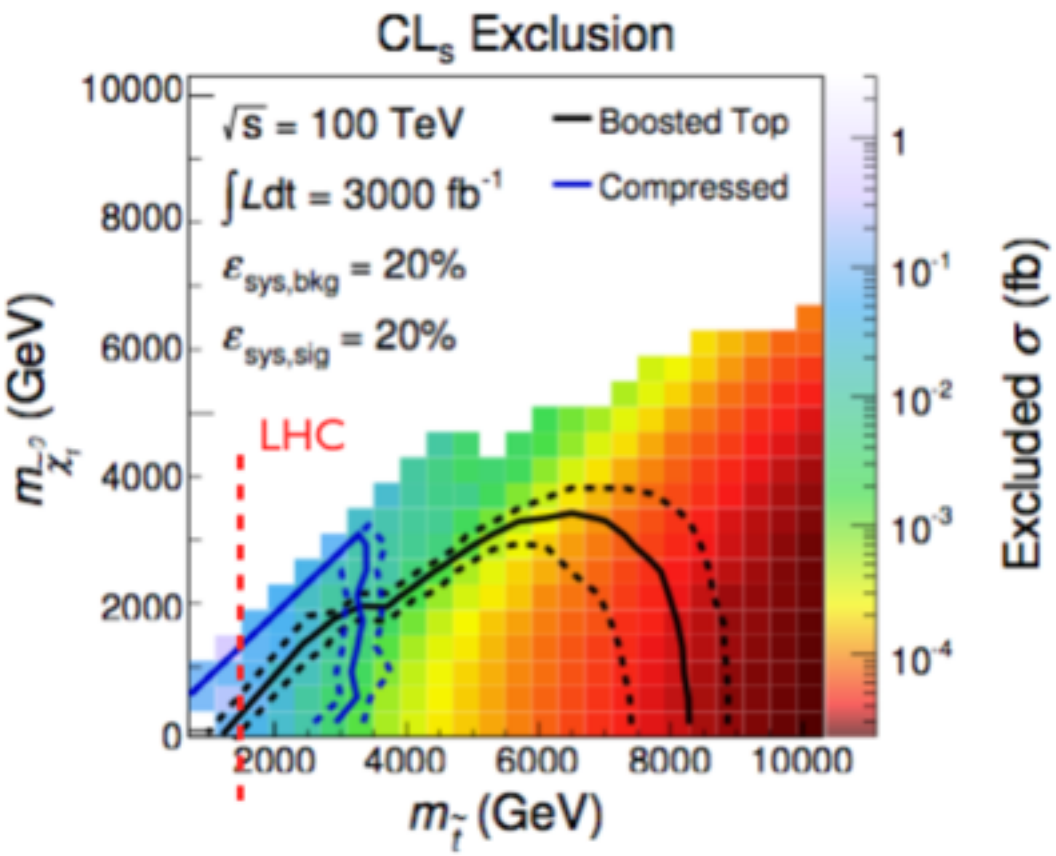
Hinchliffe, Kotwal, Mangano, Quigg, LTW

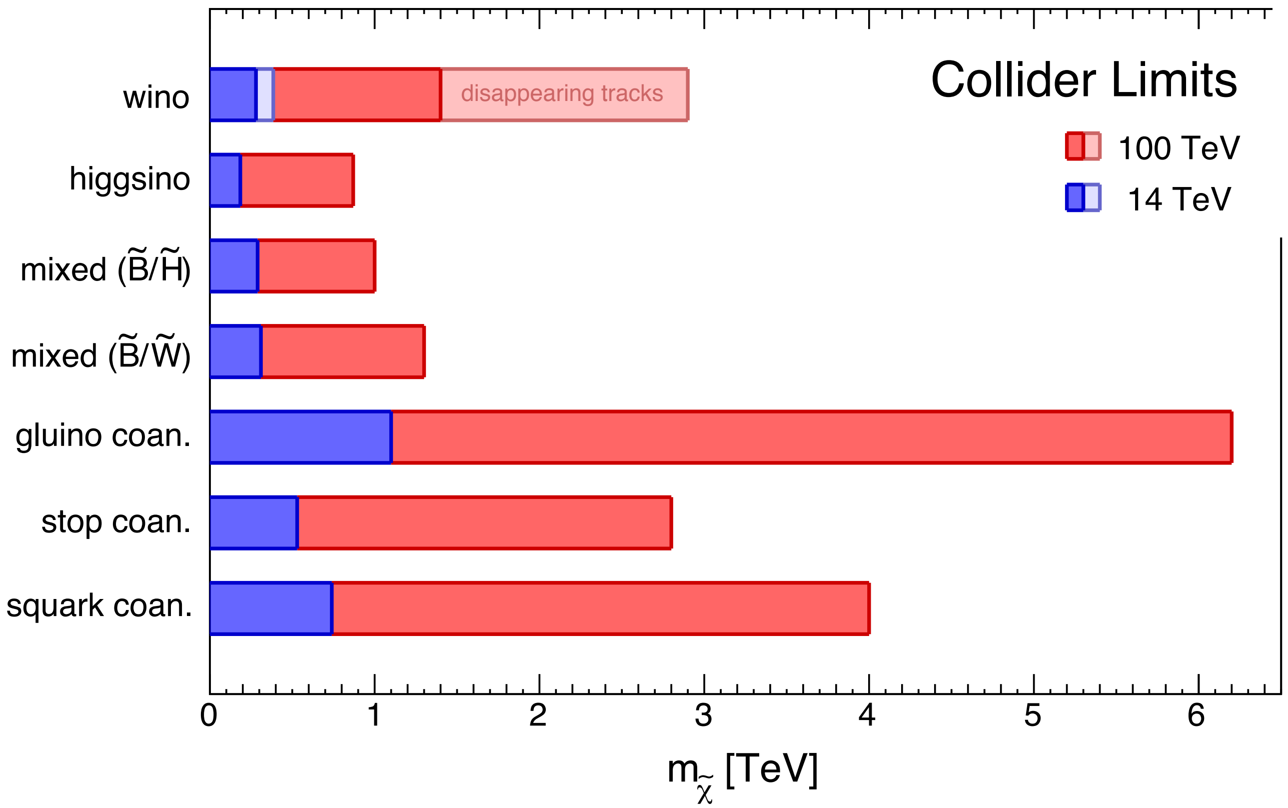
A factor of about 5 increase in reach
with modest luminosity

SPPC

Cohen et. al., 2014

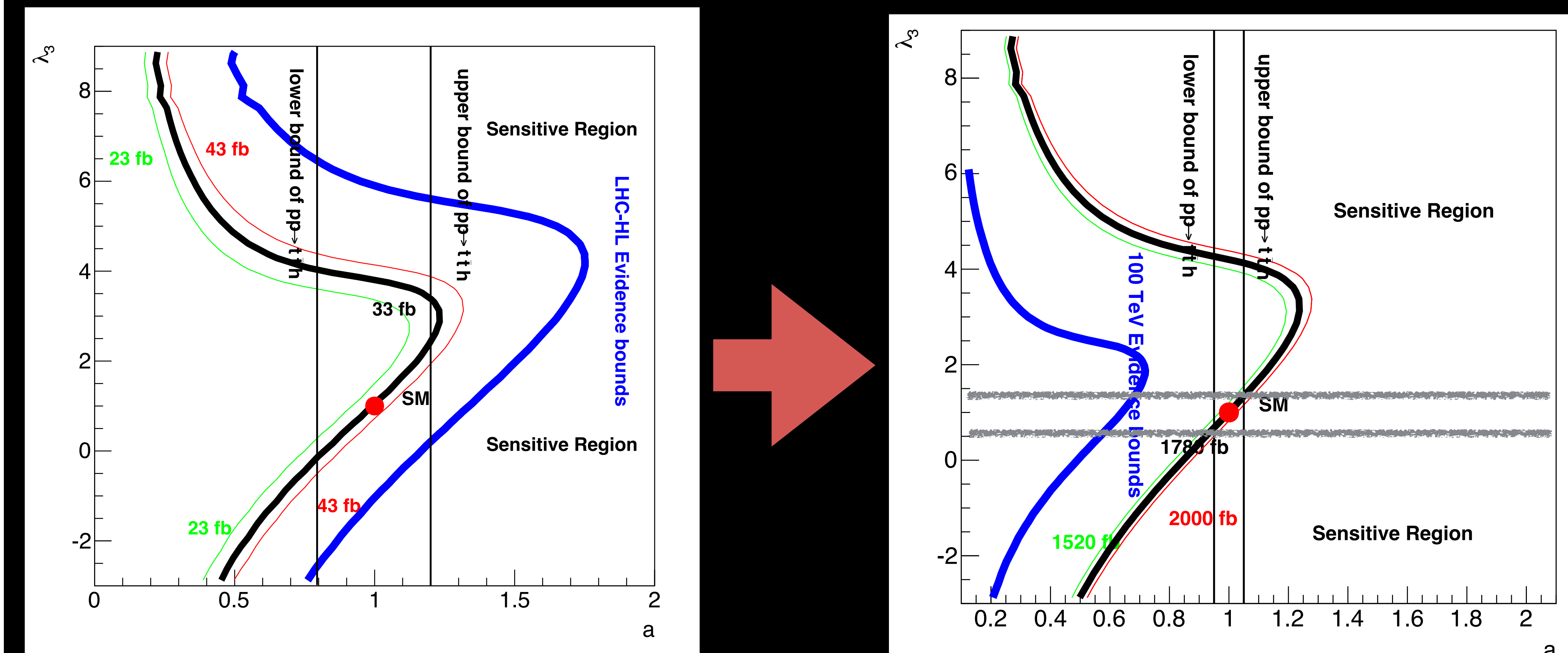






Higgs couplings at SPPC

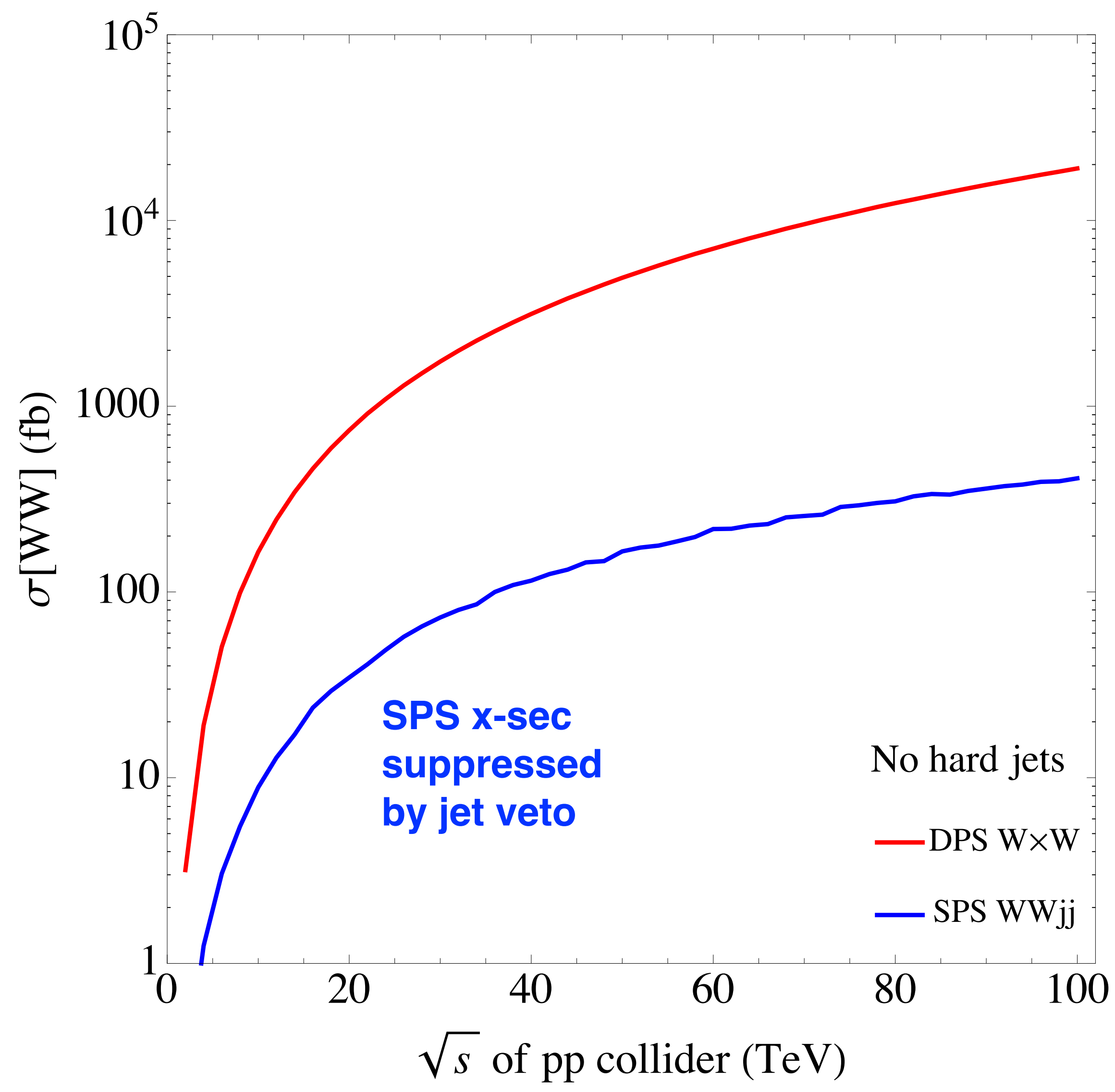
Correlation between Higgs pair production and tth measurement

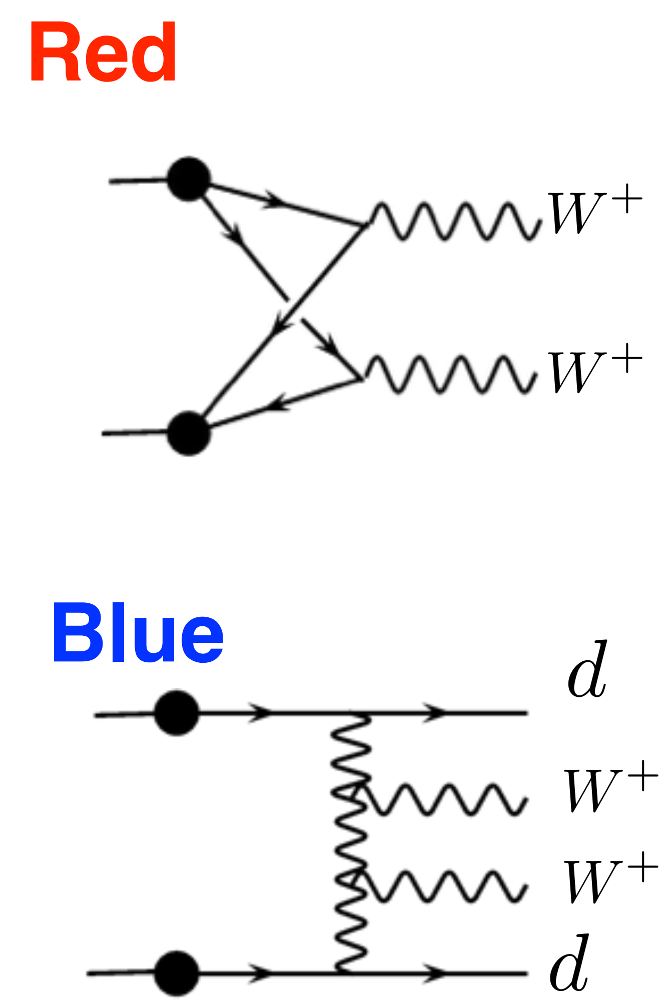


Yan Qishu's talk at this workshop

2) Same-sign WW pair production

(golden channel of DPS)





Cao QingHong's talk at this workshop

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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

- 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

- 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.

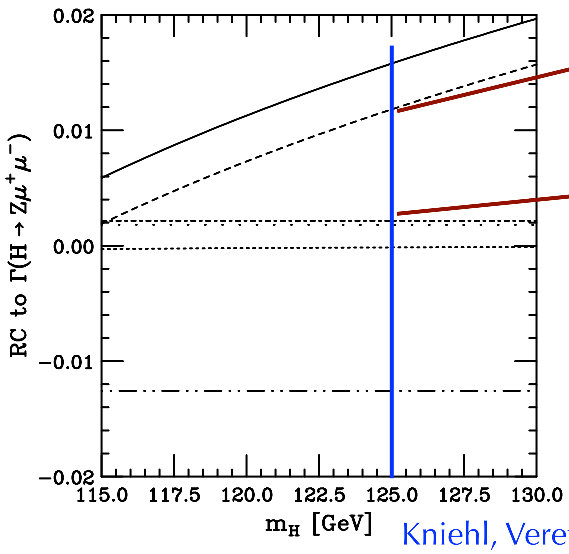
Theoretical uncertainty

11

Precision theory for precision measurements

How well do we know σ(ZH) in the SM?

Update for a closely related process: $H \to ZZ^{*} \to Zl^{+}l^{-}$



One-loop weak corrections

Top-mass enhanced higher-order contributions

For σ(ZH) need to go beyond large m_t!

Kniehl, Veretin: 1206.7110

Result

Gong, Li, Xu, **LLY: 1609.xxxxx**

1% for CEPC (240 GeV); important effect!

xpansion in $1/m_t$

reliminary

$_t^2$	m_t^0	m_t^{-2}	m_t^{-4}
~ 82%	~ 16%	~ 1%	< 1%

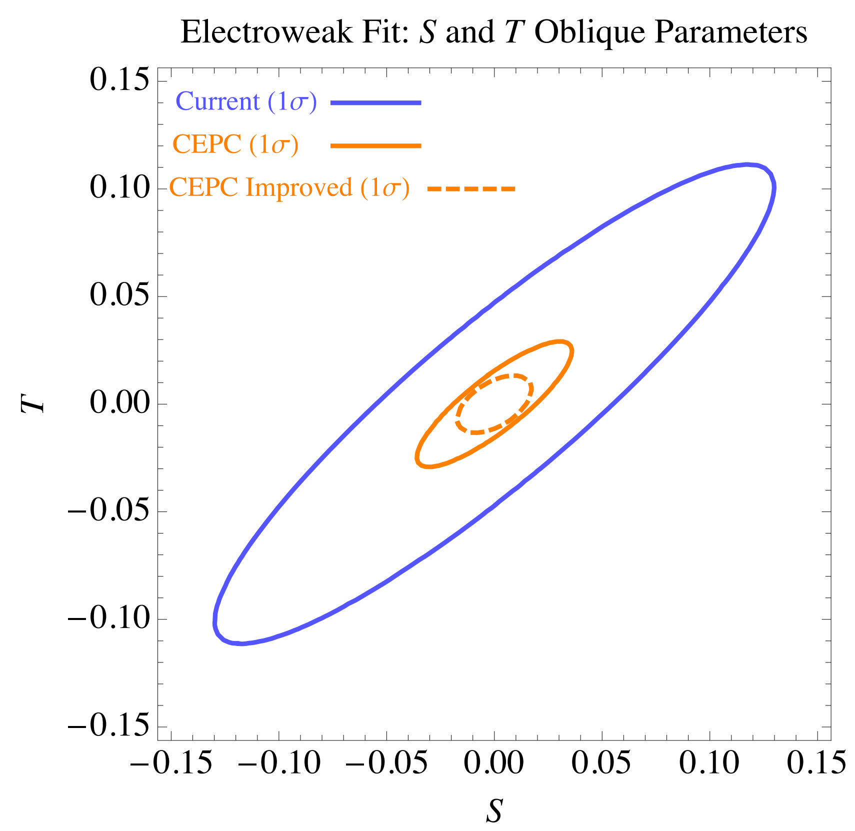
Fast convergence

Expansion in $1/m_t$ will not work for higher energies (e.g. ILC and FCC-ee)!

Future: the more difficult (but also important) $O(\alpha^2)$ correction

Li-lin Yang's talk at this workshop
Also Sun Hao's talk at this workshop

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

- $\delta m_W < 5$ MeV
- $\delta \sin^2\theta_{eff} < 2\text{x}10^{-5}$ (and/or Γ_Z about 100 keV)
- $\delta m_Z < 500$ keV
- $\delta m_t < 100$ MeV
- Theoretical breakthrough in calculating $\Delta\alpha_{had}$?

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

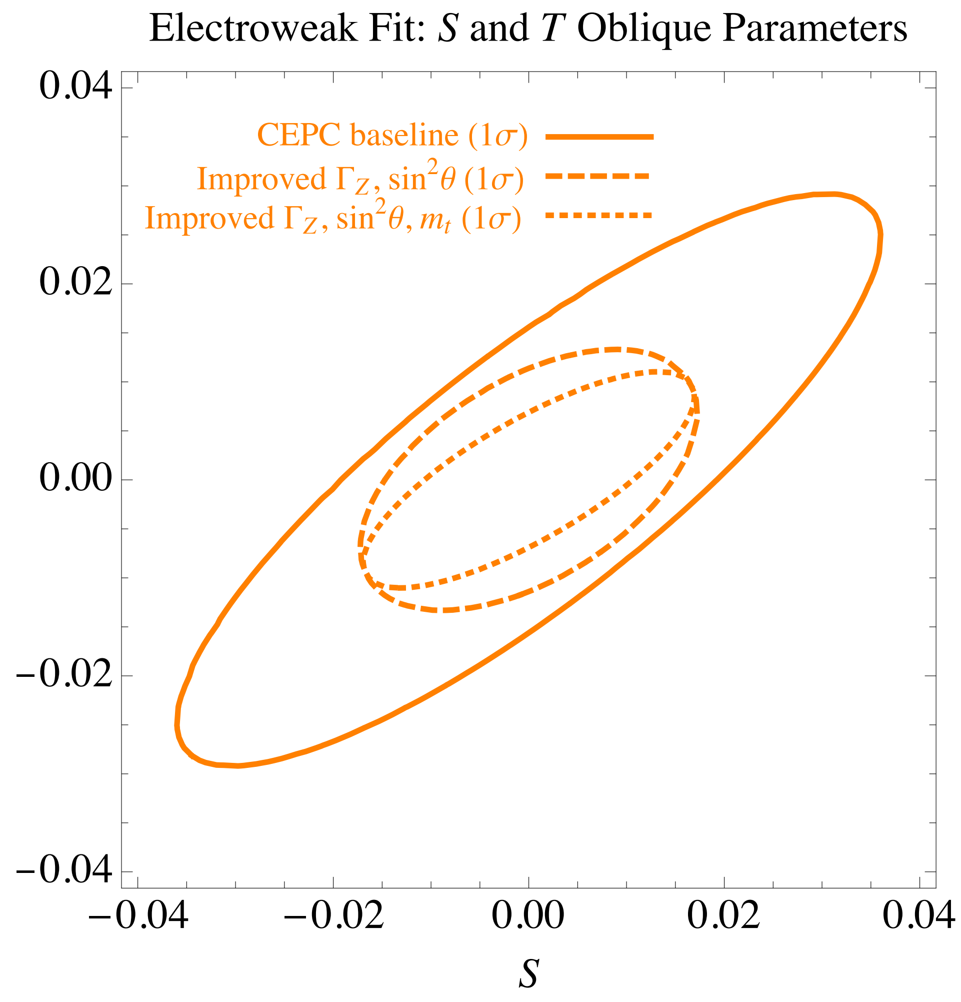
CEPC Z-factory

- 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?

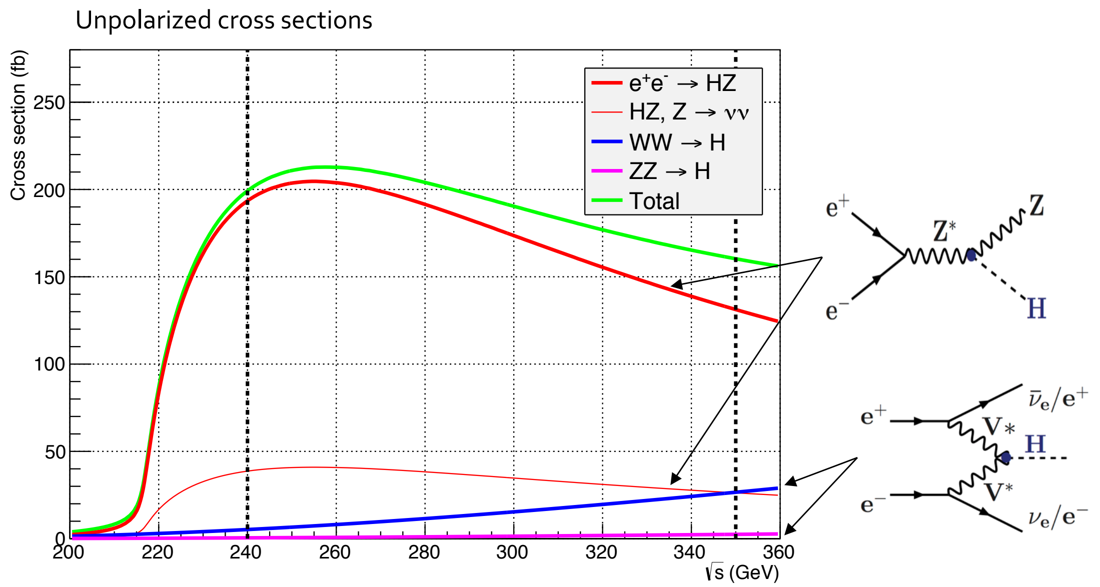
- Seems not as crucial for precision electroweak.
- A small improvement for the fit to S and T.
- Is this optimistic or pessimistic on the systematics?



CEPC: higher energy, ttbar threshold?

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

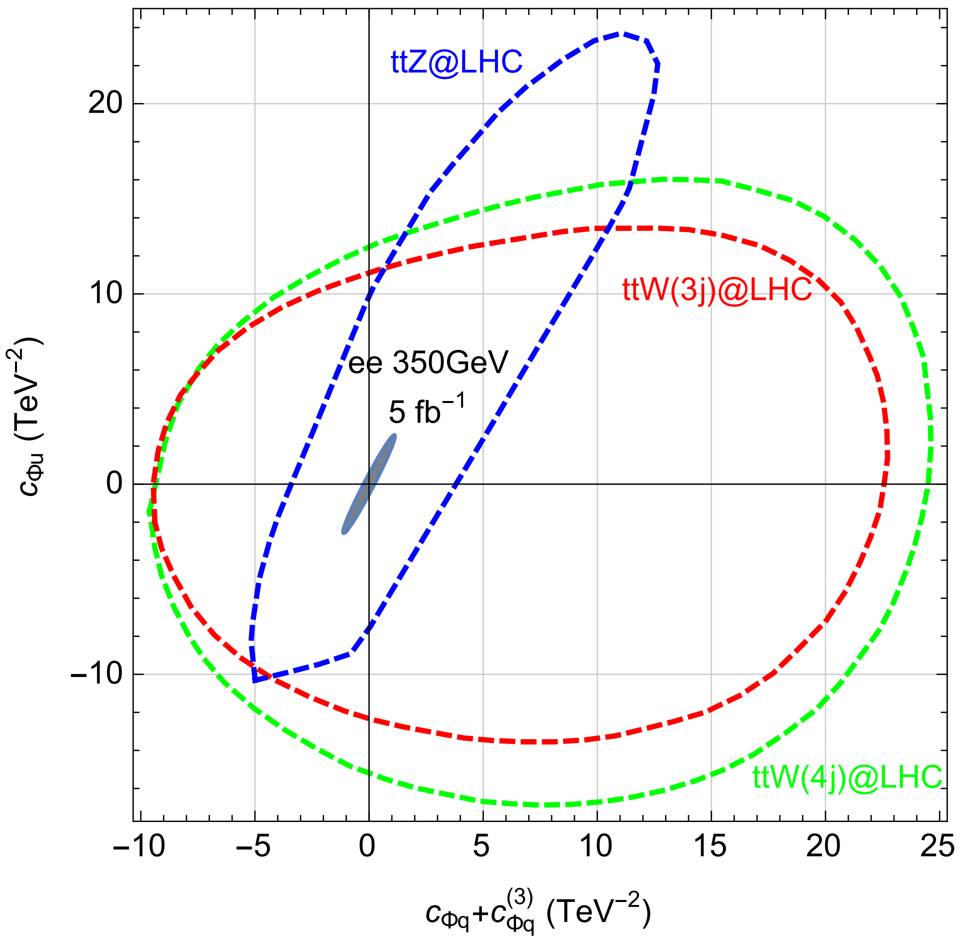
For example:



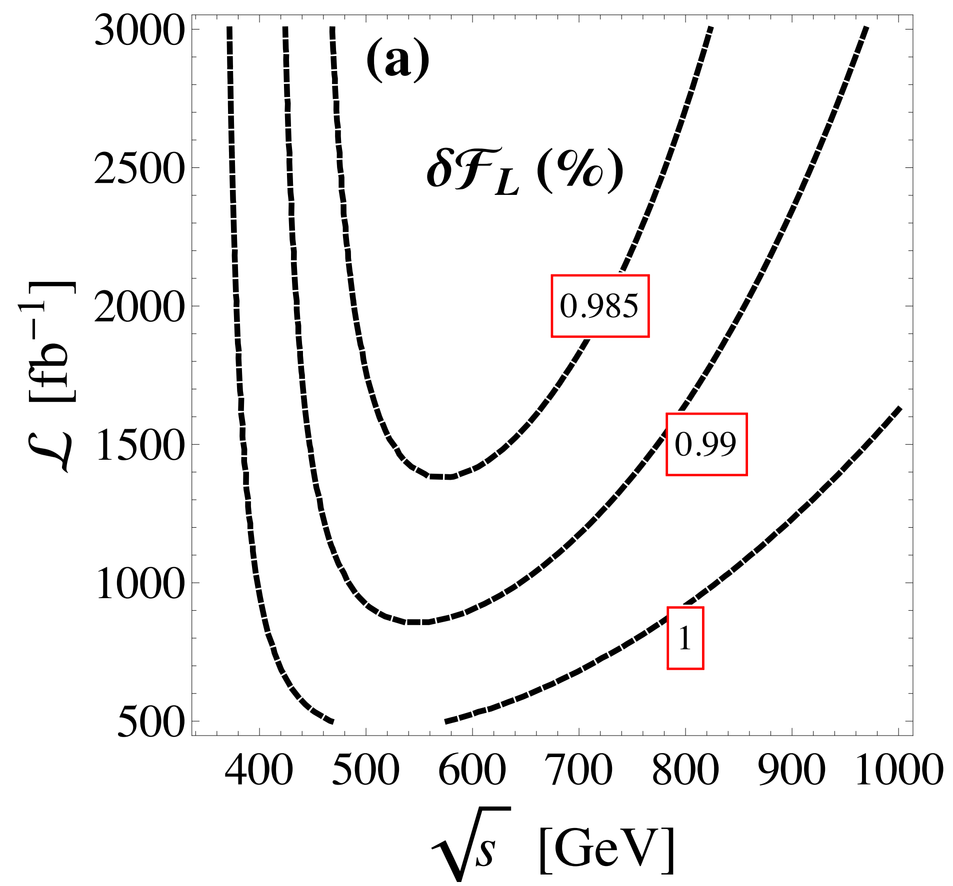
- Scan, energy dependence brings in more discovery and distinguishing power.

- Many more studies needed.

Learning more about top couplings



Z. Liu, I. Low, LTW in progress



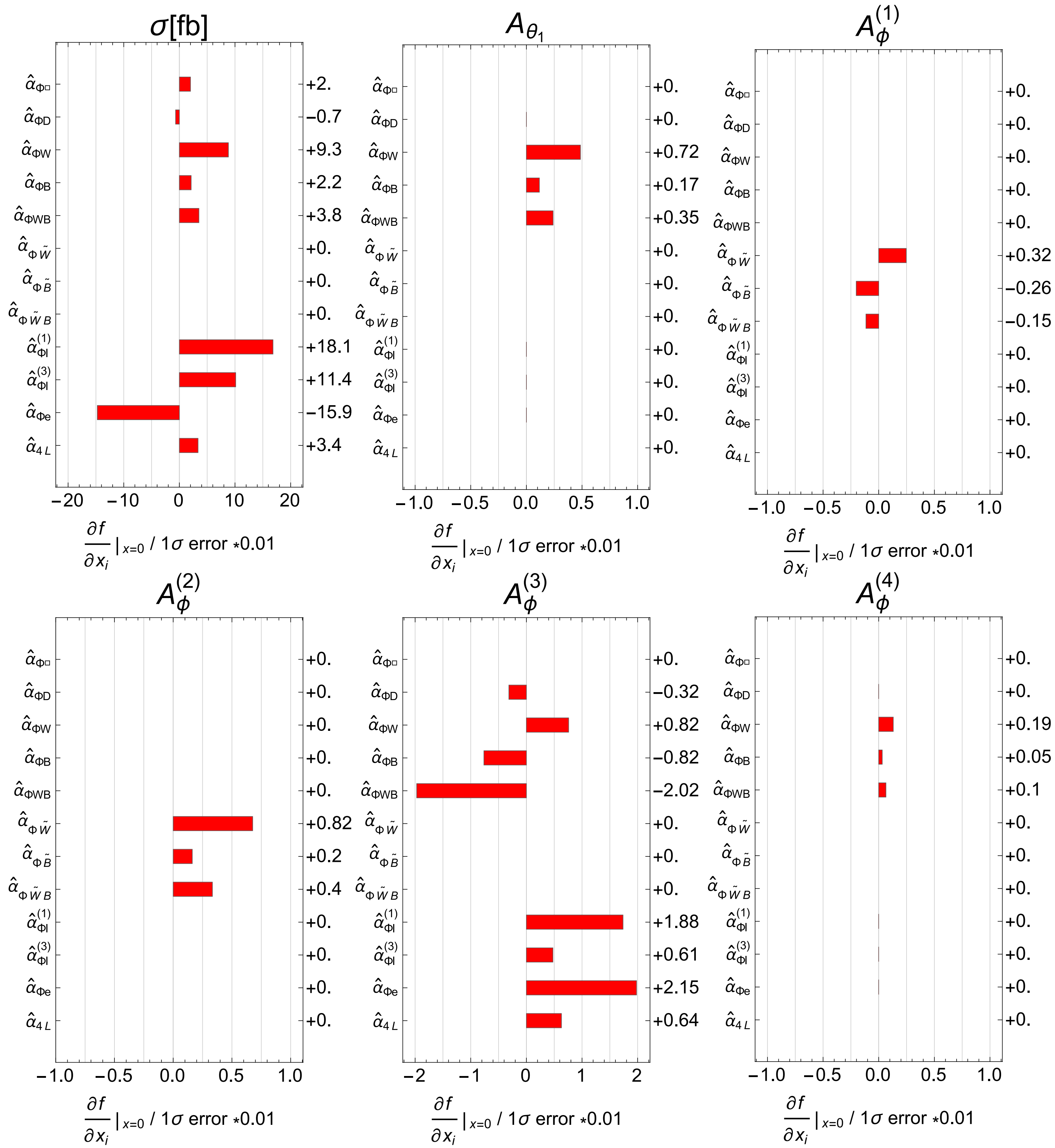
Q. Cao, B. Yan 1507.06204

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.

More details, more understanding.

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

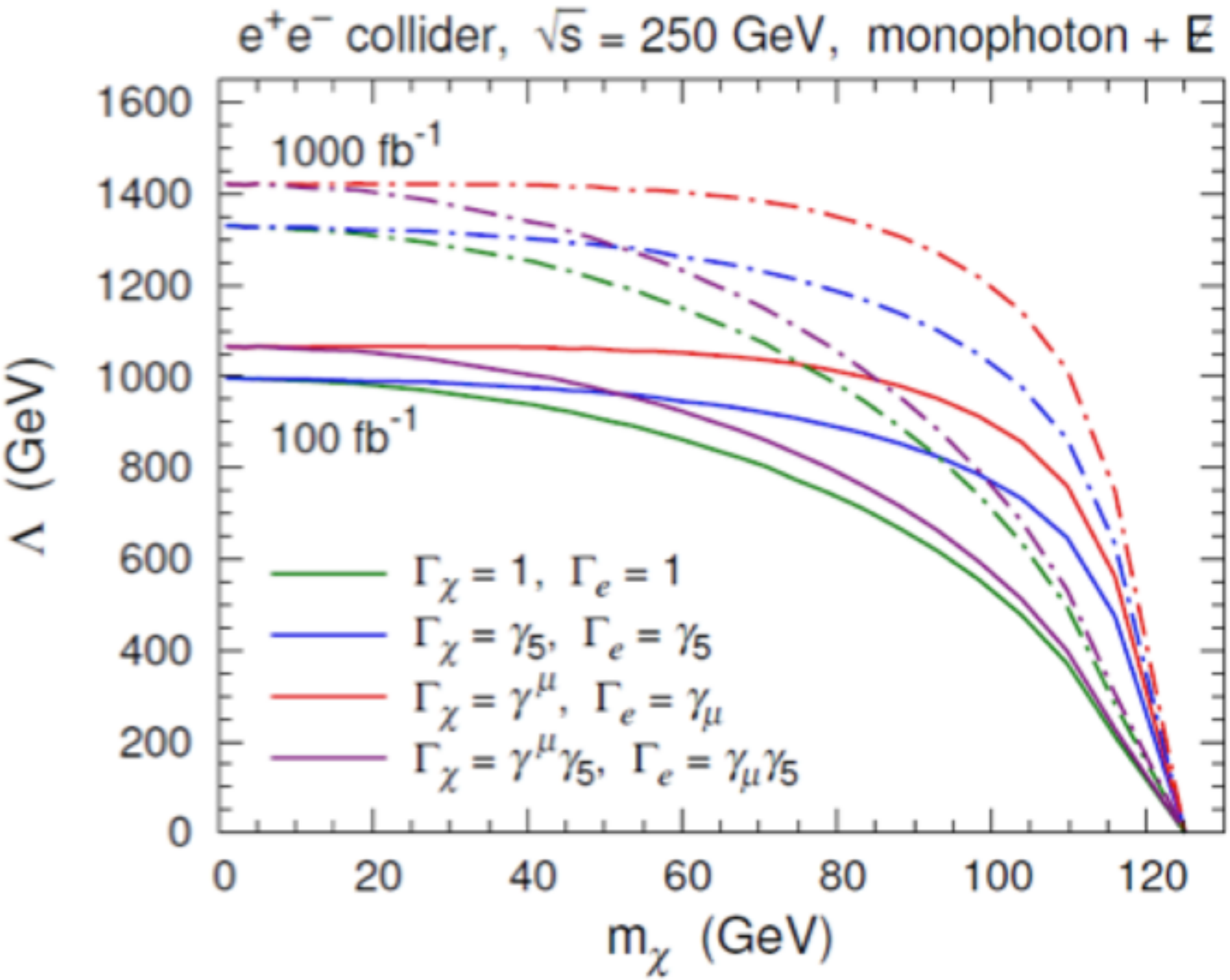


CEPC sensitive not only to coupling shifts, but different tensor structures.

- 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

Constraints on the 4-fermion operators @CEPC



X. Bi

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

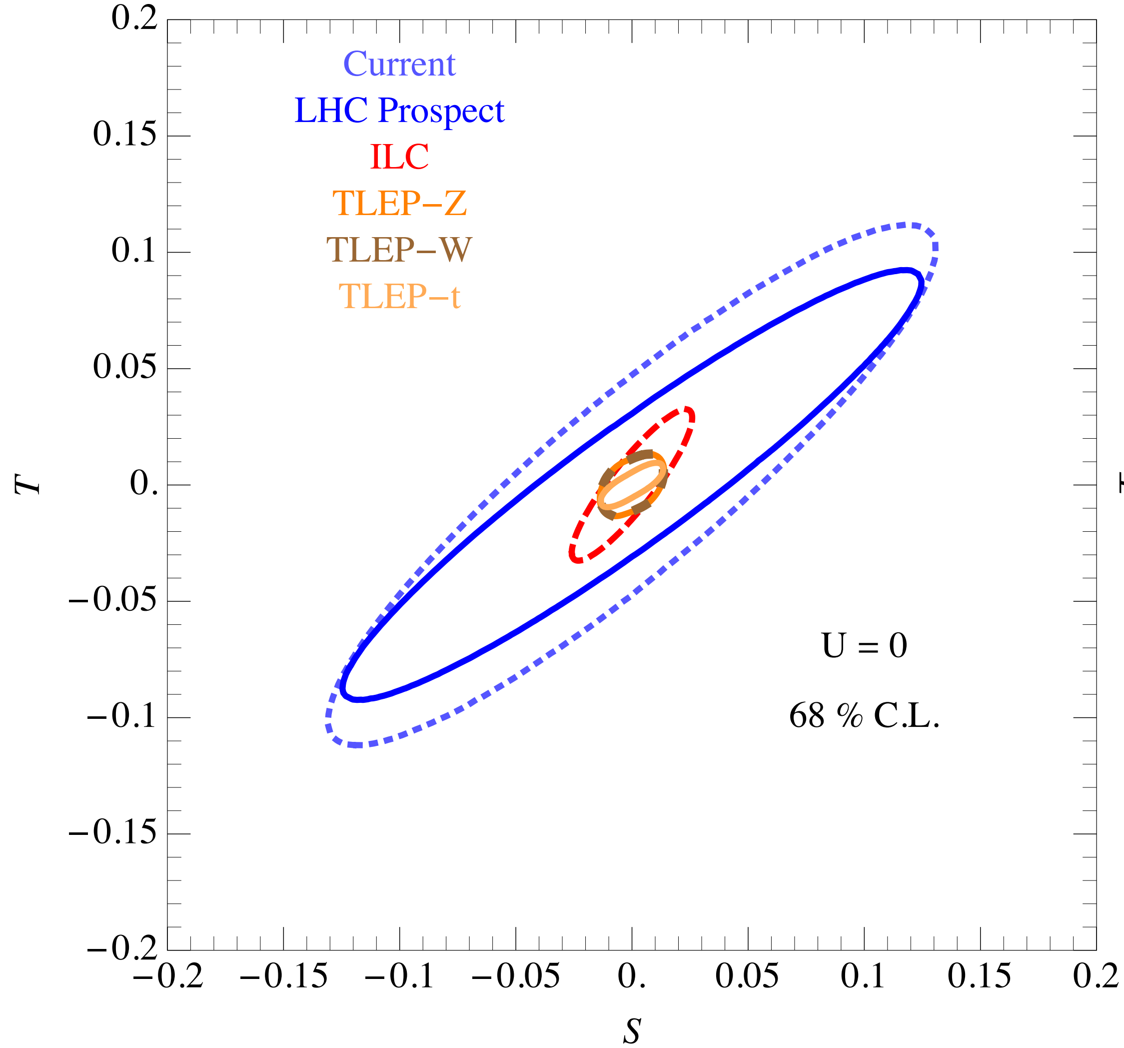
x4 statistics off Z-pole

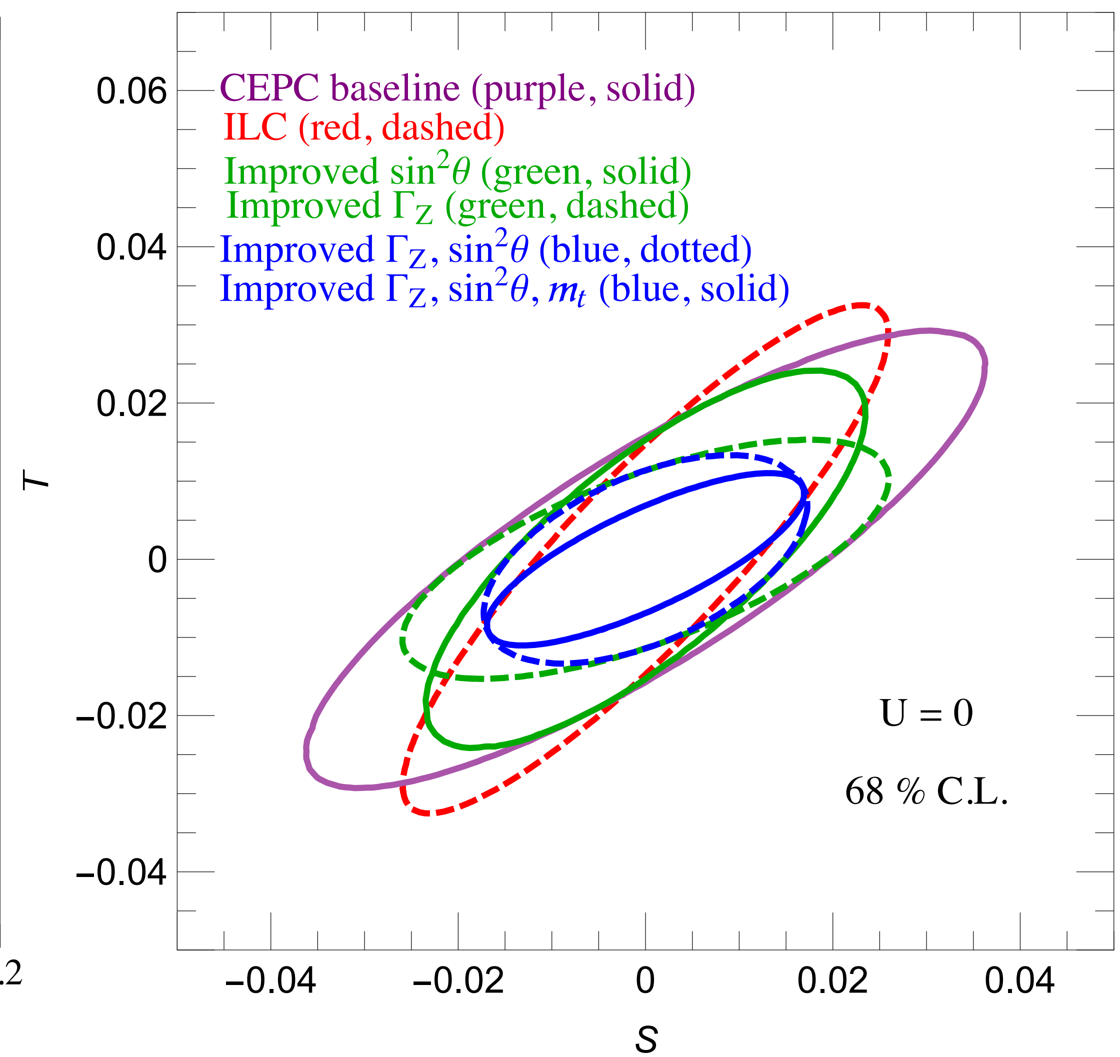
energy calibration

ILC?

Electroweak Precision tests

J. Fan, M. Reece, LTW, 1411.1054

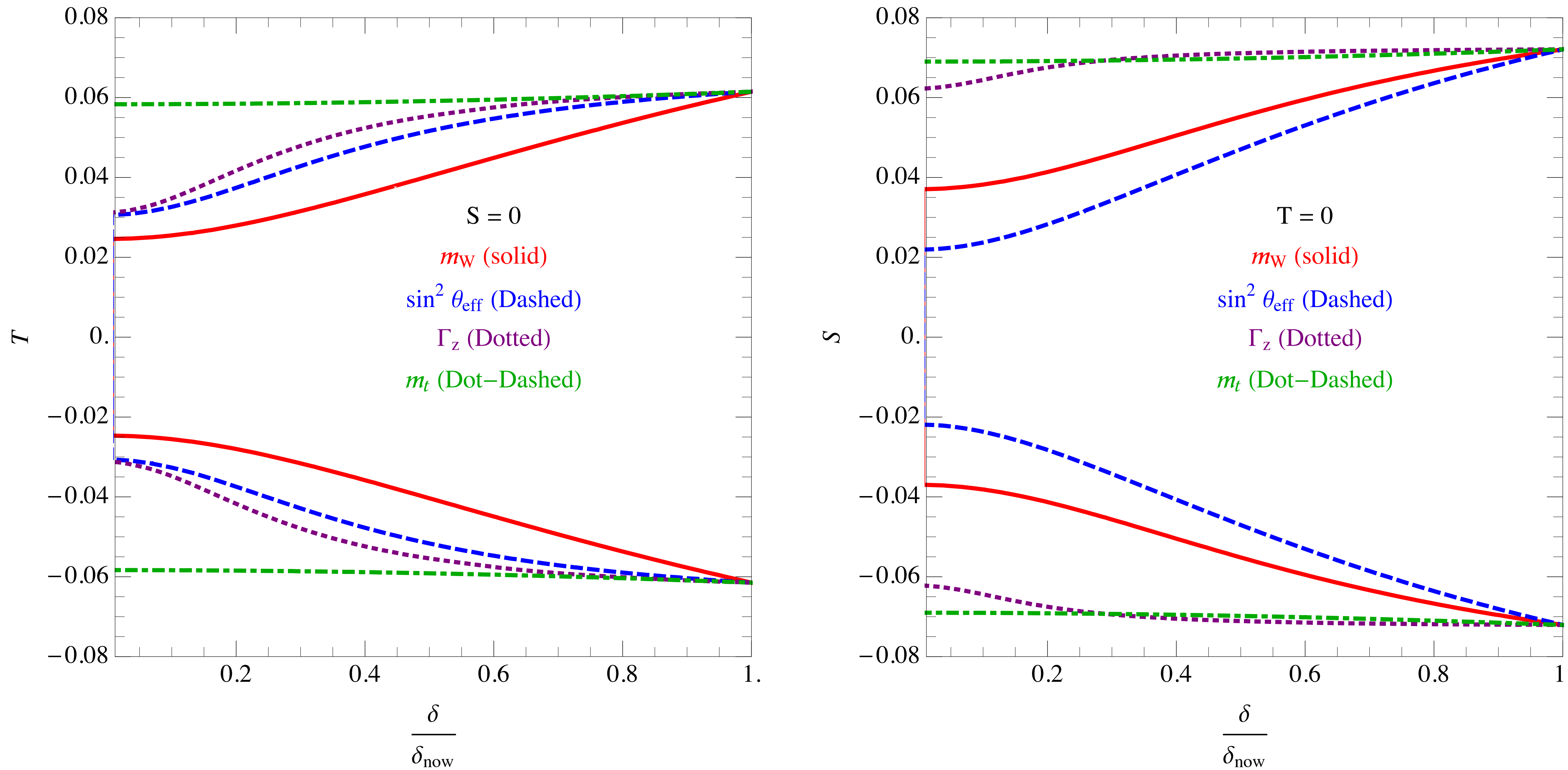




- Large step above the current precision.
- A factor of 10 improvement in S and T.

Electroweak Precision tests: lessons

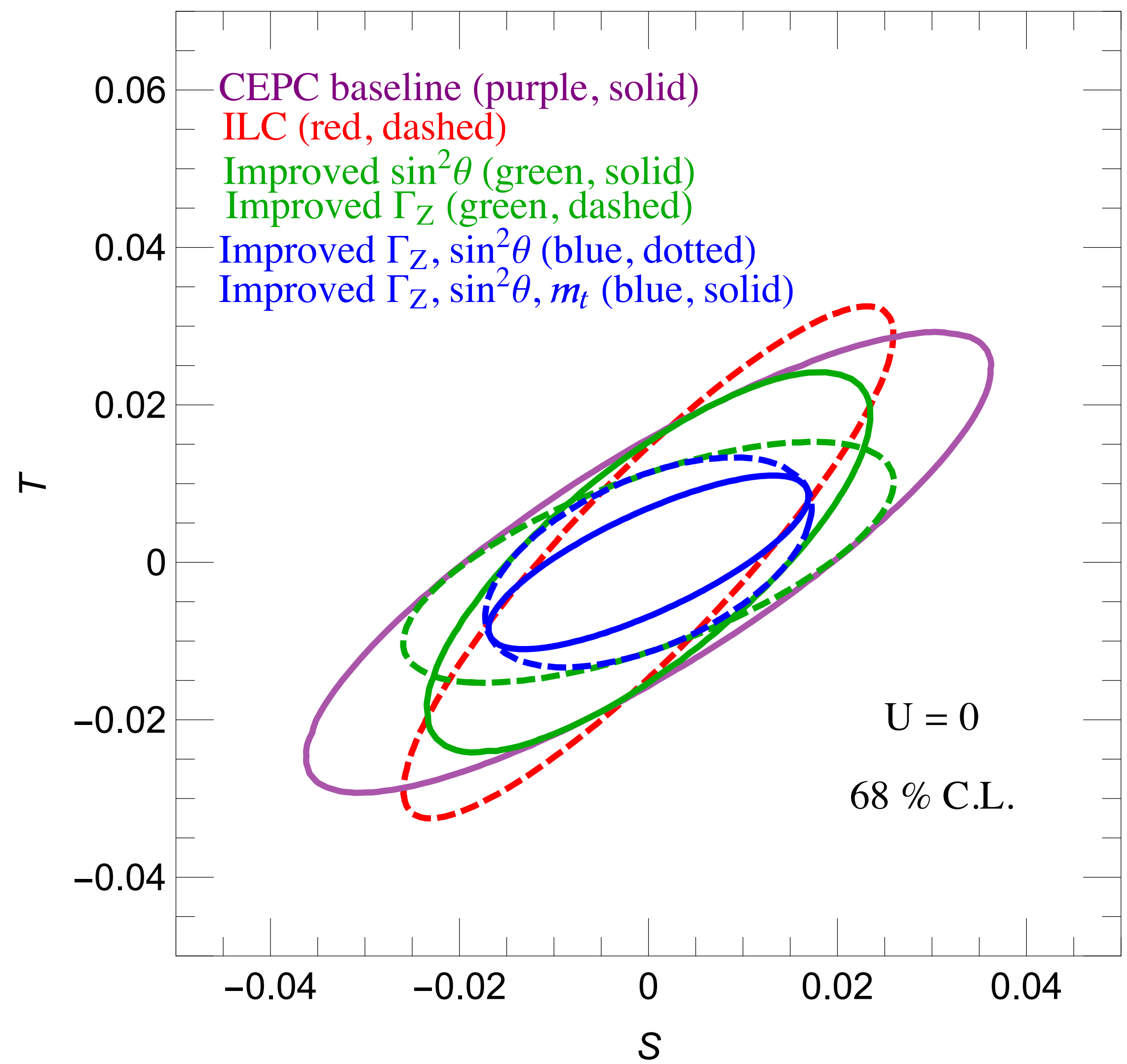
J. Fan, M. Reece, LTW, 1411.1054



- 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

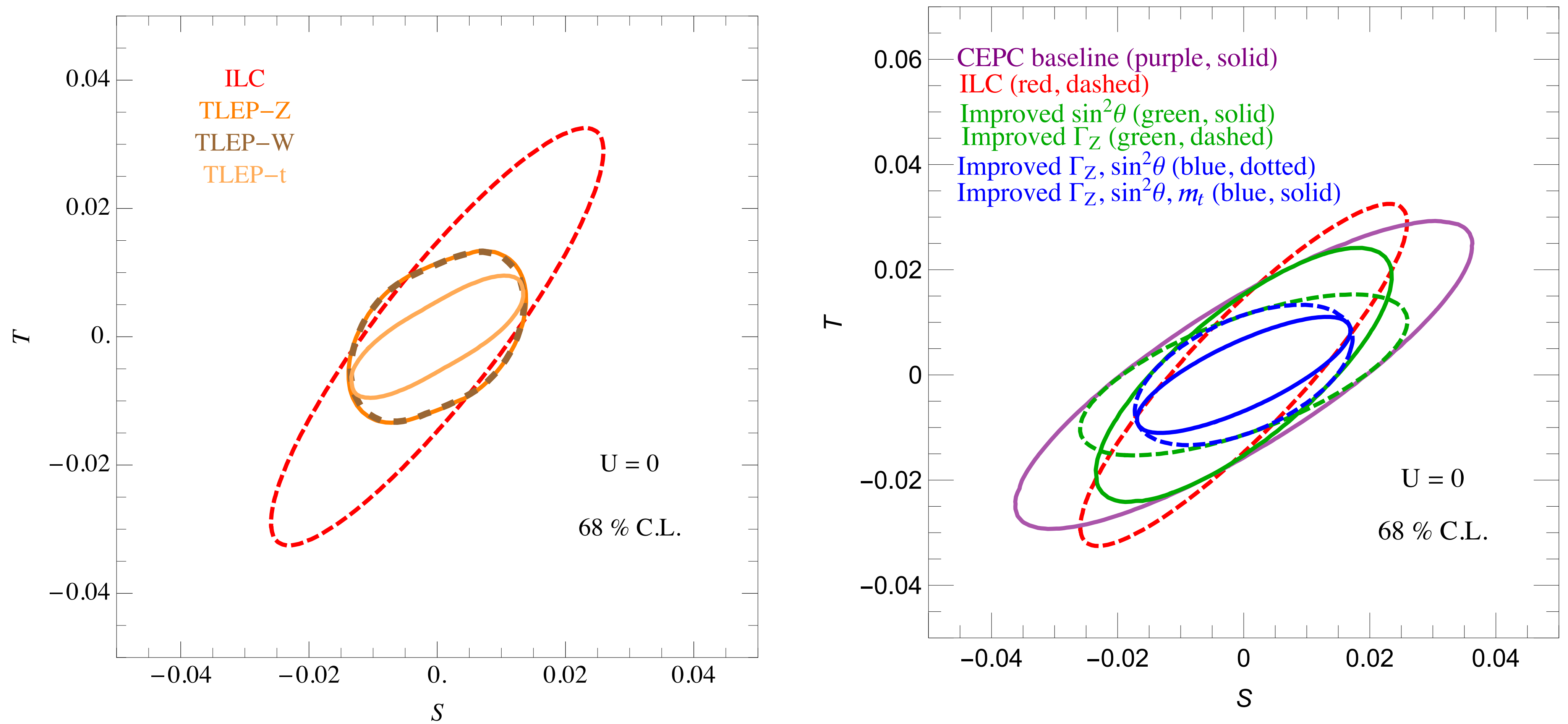
Electroweak Precision tests: lessons

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 .

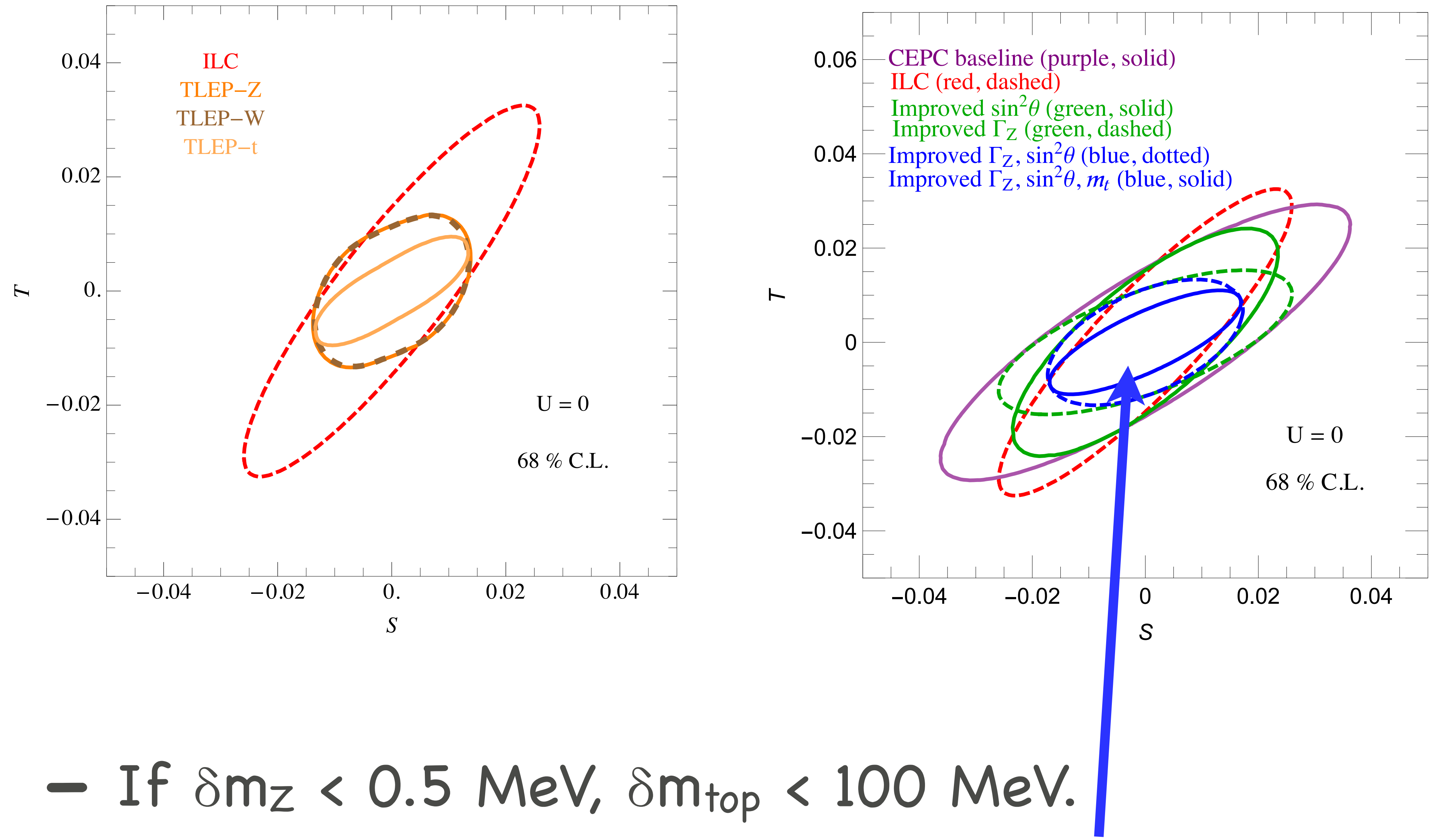
Electroweak precision tests: lessons



- 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

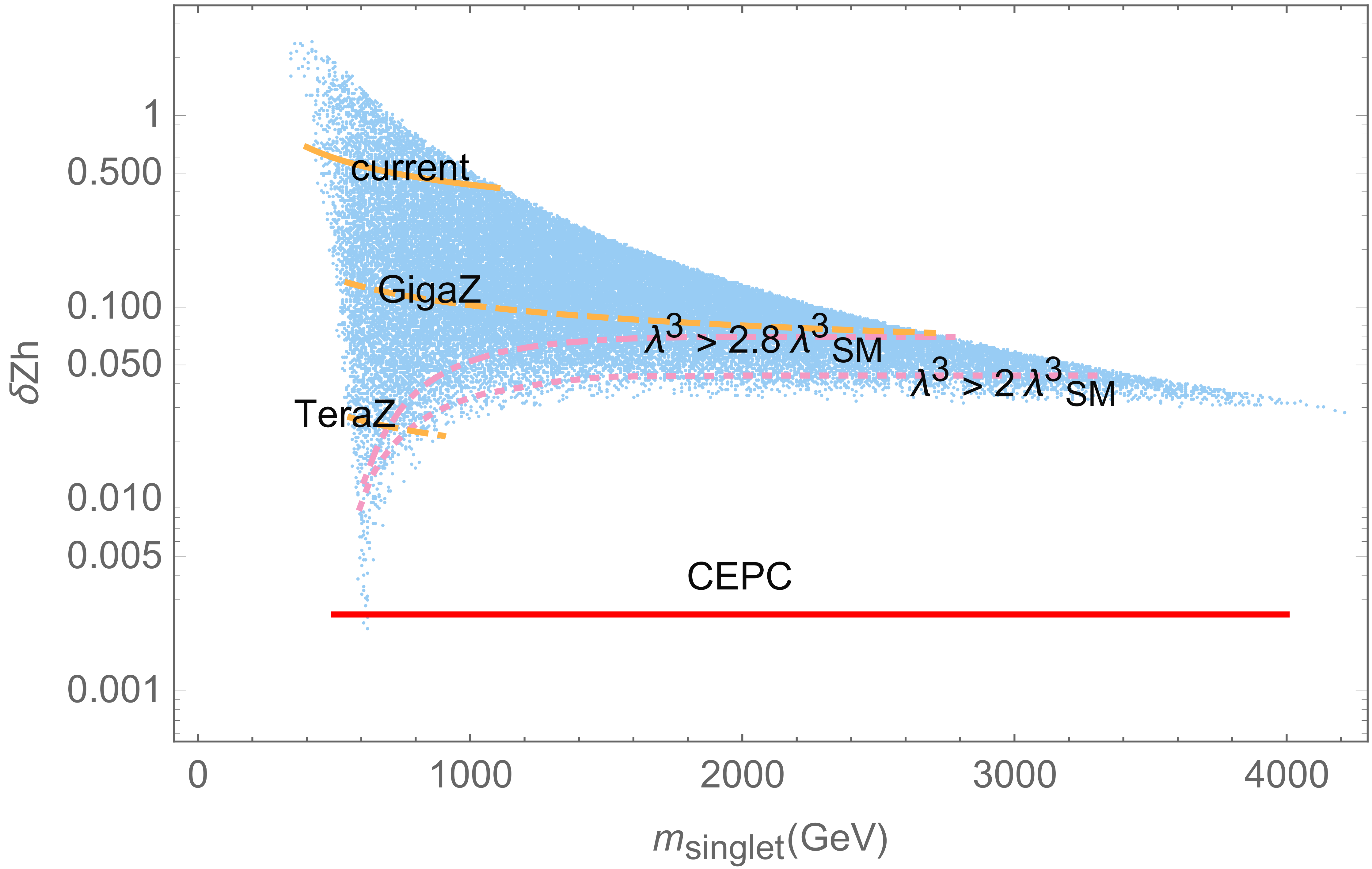
Electroweak precision tests: lessons



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

CEPC can test it.

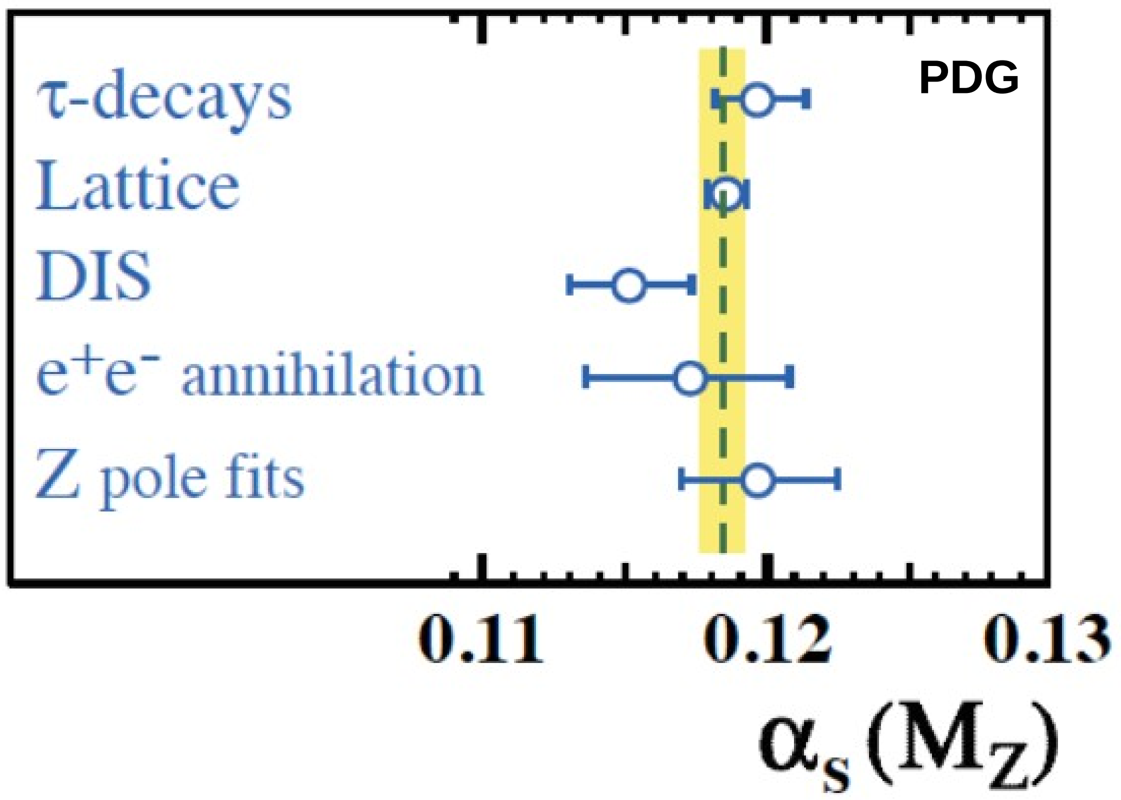
P. Huang , A. Long, LTW, in progress



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

QCD at CEPC

World average on alphas



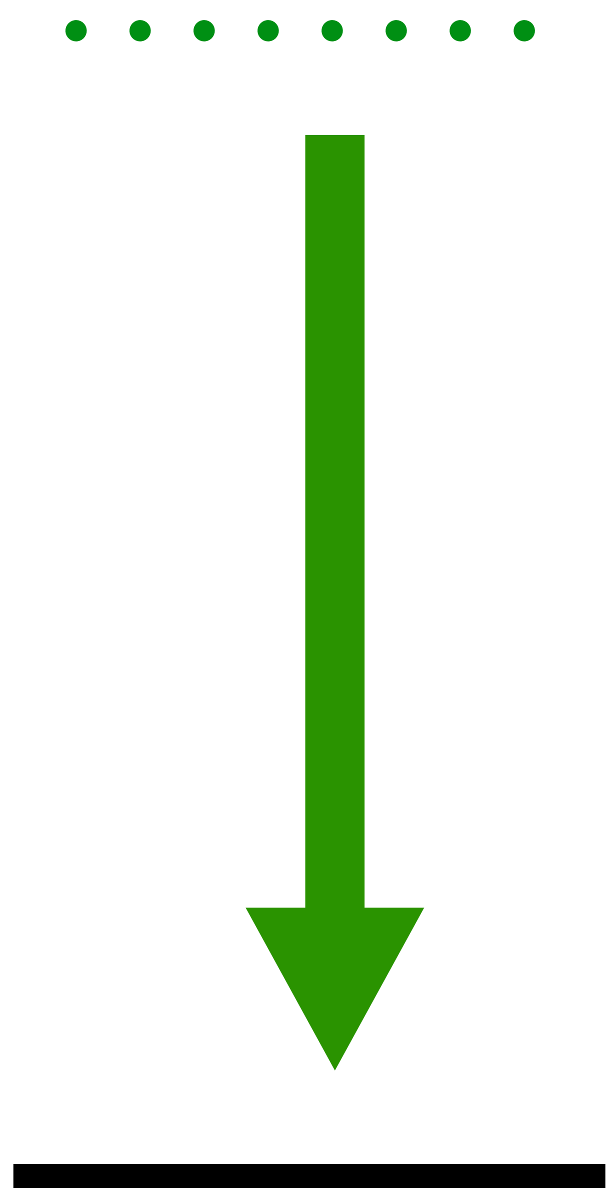
- Dominated my Lattice results
- O(100^{-1}fb) at CEPC v.s. O(100^{-1}pb) at LEP, plus higher energy, smaller power corrections, good news for event shape analysis.
- New challenges to theorists. NNLO corrections to four jet rates? Completing the NNNLL resummation by computing the four loop cusp anomalous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

Only tip of the iceberg.

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

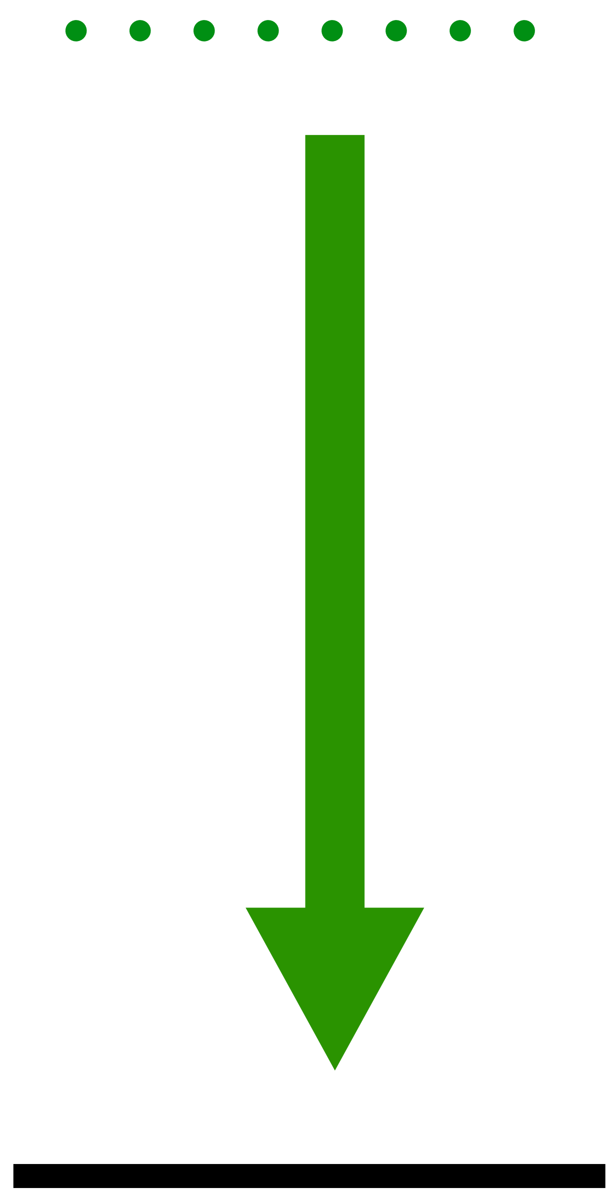
Explaining EWSB: naturalness

M: The energy scale of new physics
responsible for EWSB



Electroweak scale, 100 GeV.
m_h , m_W …

Explaining EWSB: naturalness



M: The energy scale of new physics responsible for EWSB

What is M? Can it be very high, such as $M_{Planck} = 10^{19}$ GeV, …?

If so, why is so different from 100 GeV?

Electroweak scale, 100 GeV.
m_h , m_W …

Dark matter at CEPC