Theory Summary

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University of Chicago

CEPC workshop. IHEP Nov. 15, 2018

Where we are and the road ahead.

- Many contribution from international theory community, solidified the physics case of CEPC.
  - Most summarized in the CDR.
- Some new developments (reported in this workshop).
- Strong interests among theorists to stay engaged for the road ahead.
  - Many future directions.

This talk:
Will give a brief overview, highlight new results reported here.
Apologies for not being able to include everything and more details

Many thanks to the conveners and participants!

Writing of the physics case (chapter 2)

- Started 2+ years ago.
- Built on pre-CDR.
- Closer connection with CEPC, reflecting newest results of physics simulation.
- Including new theoretical developments.

Team of "facilitators"

XiaoJun Bi (IHEP)
Qing Hong Cao (Peking U.)
Nathanial Craig (U. C. Santa Barbara)
JiJi Fan (Brown U.)
Tao Liu (Hong Kong U. of Sci. Tech.)
Yan Qing Ma (Peking U.)
Matthew Reece (Harvard U.)
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Contributors (text + editing)

- W. Altermanshofer
- Xiao Jun Bi
- Nate Craig
- Marco Drewes
- JiJi Fan
- Jiayin Gu
- Zhen Liu
- Jia Liu
- Andrew Long
- Matthew Low
- Matthew Reece
- Shufang Su
- Emmanuel Stamou
- Xiaoping Wang
- Felix Yu
- Hua Xing Zhu

Plus inputs from many others.
Many valuable comments from the international review committee.

Main strength of a lepton collider (running at relatively low energies)

- It offers a clean experimental environment.
- Good for precision measurements.
- Top target is the Higgs boson.
  - Discovered in 2012. Many key properties still not well known.
- Physics program also includes W/Z, and more.

Physics goals of CEPC

- CEPC can significantly go beyond the HL-LHC: higher precision, and complementarity.
- With this, CEPC can make significant progress in addressing important questions in particle physics.

No lose theorem?

- Refers to a guarantee of discovering new particles.
  - Often viewed as a necessary part of the physics for future experimental facilities.
- Standard Model can be consistent up to the Planck scale. Such a no lose theorem does not exist.
- Standard Model is not a complete model. Many unanswered questions.
  - CEPC can make progress on some of the most important ones.

Strong physics case made for the precision physics program

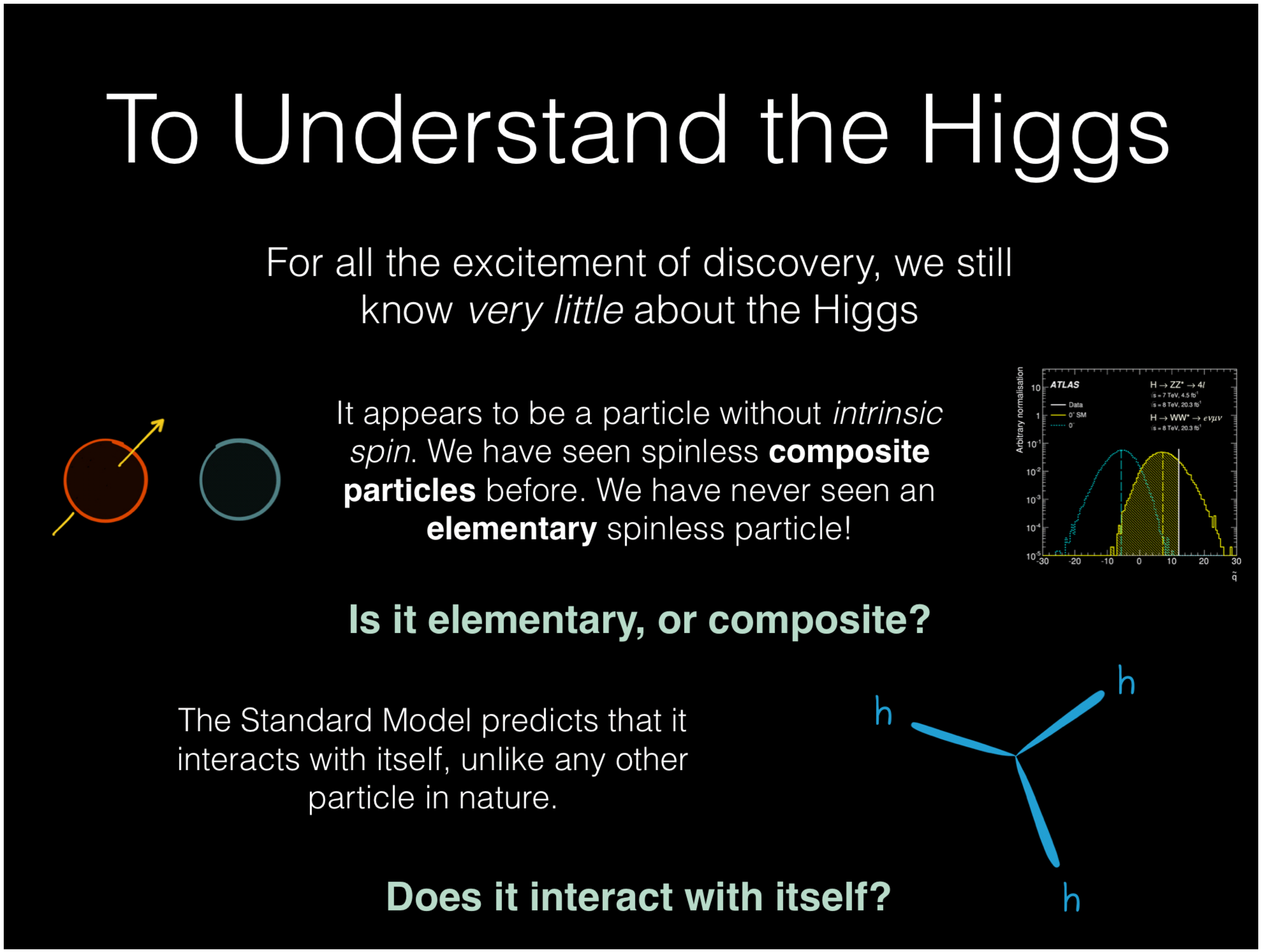
International review:

“These landmark precision measurements in the Higgs and electroweak sectors, with exquisite indirect sensitivity to physics beyond the Standard Model, yield a compelling physics case. The scientific potential of the CEPC project is supported by solid studies and is widely recognized by the international particle physics community.”

M. Vos’s talk

Higgs physics.

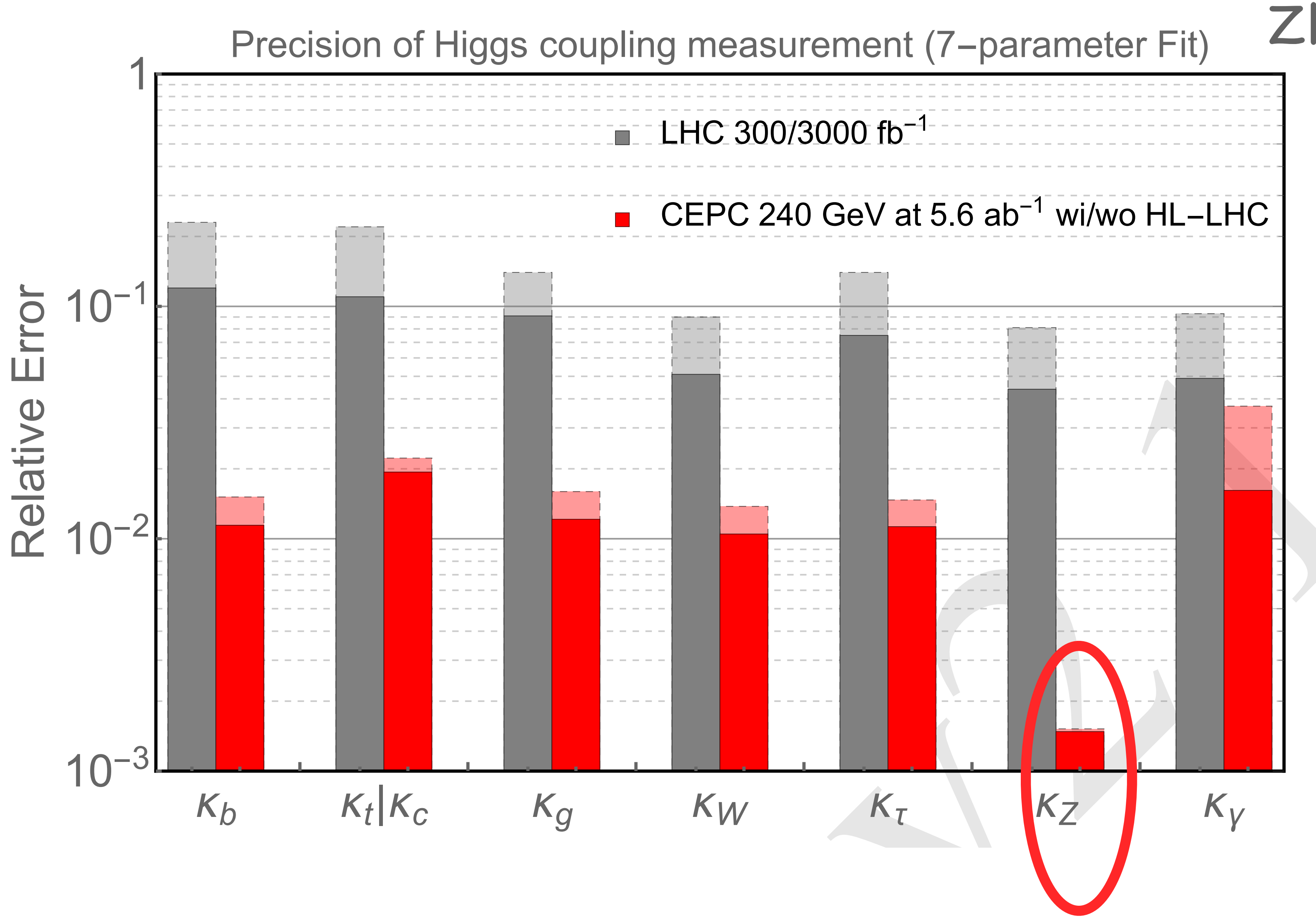
- Many mysteries, much to learn



N. Craig

CEPC can do very well

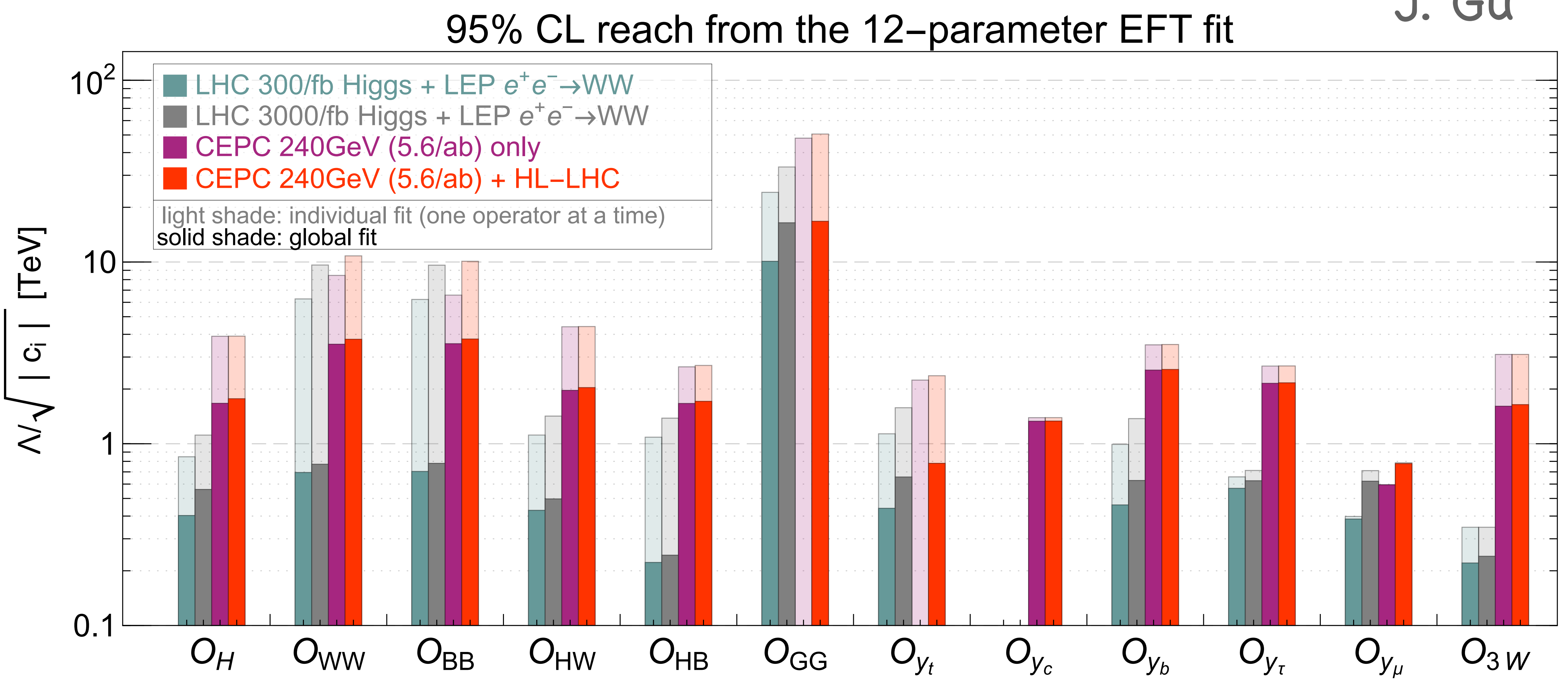
Zhen Liu



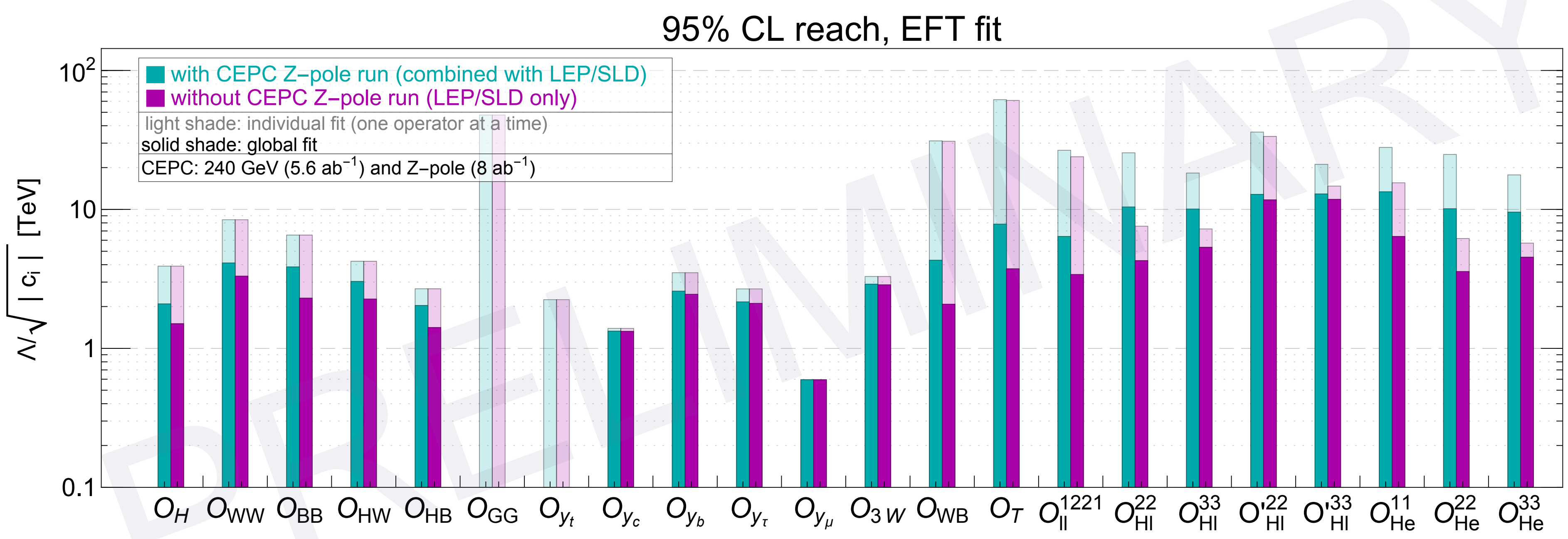
Up to sub percent precision, reach to new physics at multi-TeV scale.
Far beyond the reach of LHC.

EFT fits v1.0

J. Gu



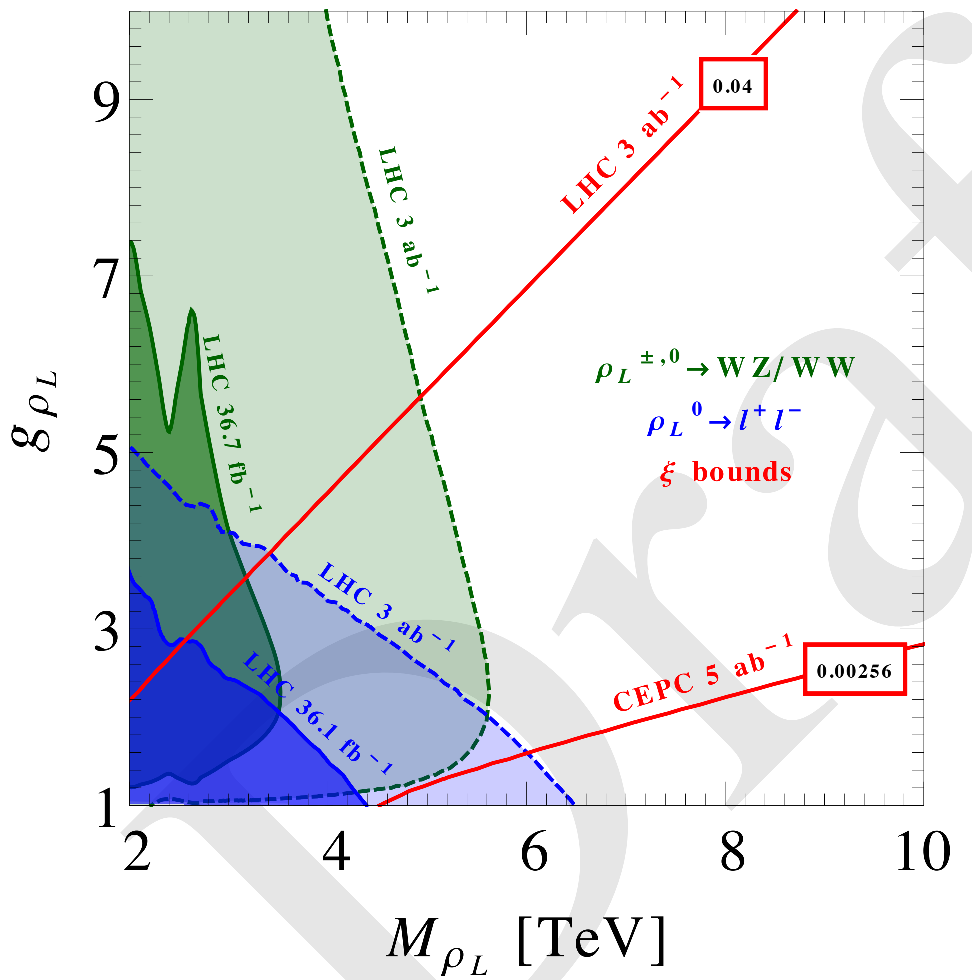
State of art, EFT v2.0



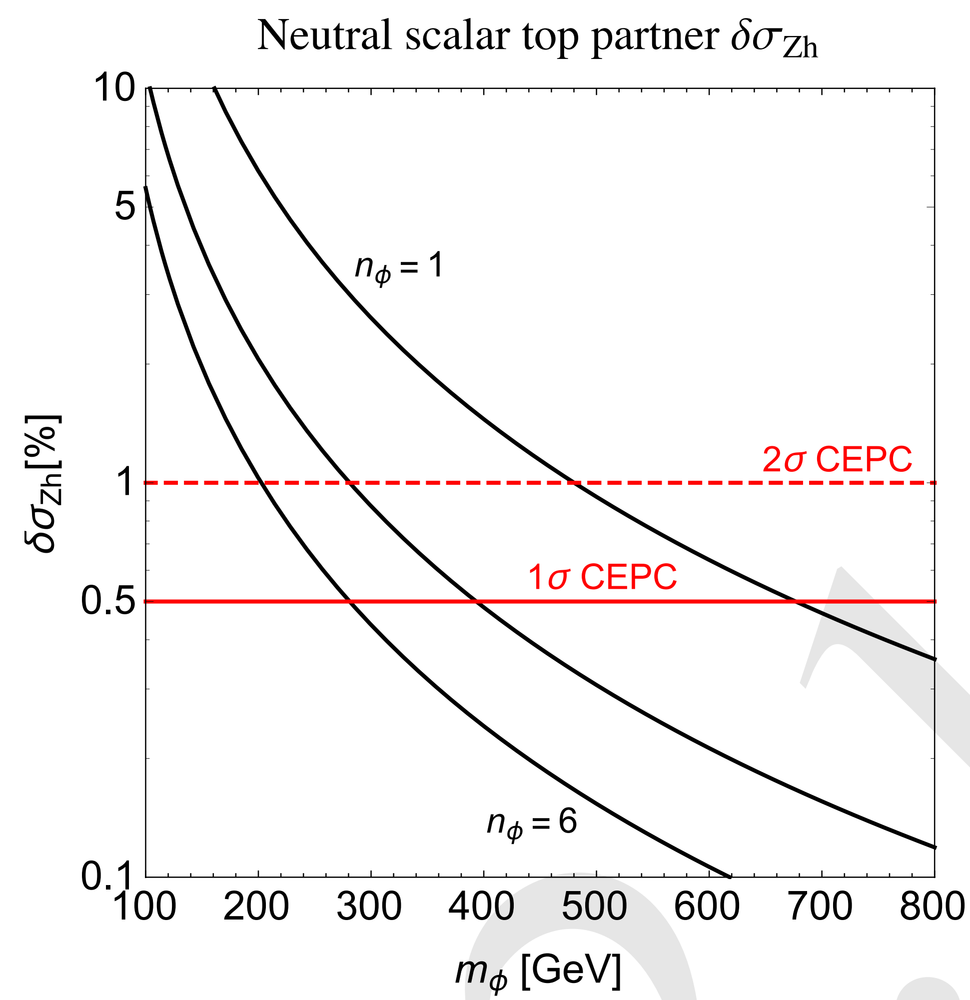
- The first 12 parameters can not be probed by Z-pole measurements at leading order (no effect on individual fit), but the Z-pole measurements can constrain the other operator that also contribute to Higgs/WW processes.
- Some operators can be well-constrained by WW measurements (e.g. $O'^{22}_{H\ell}$ and $O'^{33}_{H\ell}$).

– Powerful tools to extract physics out of precision measurements.

Testing Naturalness



Composite Higgs



Twin Higgs

Naturalness ⟷ Higgs mass

Model independently, new physics will show up in Higgs couplings

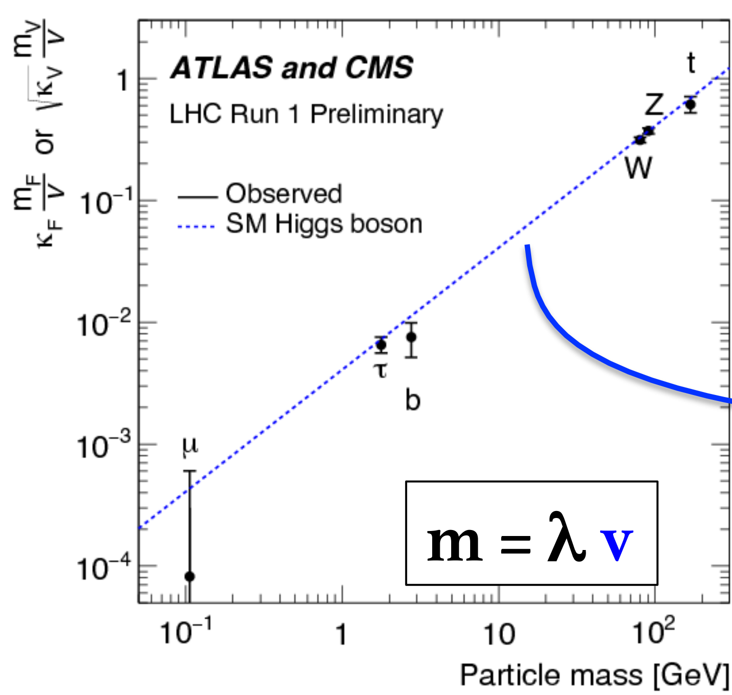
Nature of EW phase transition

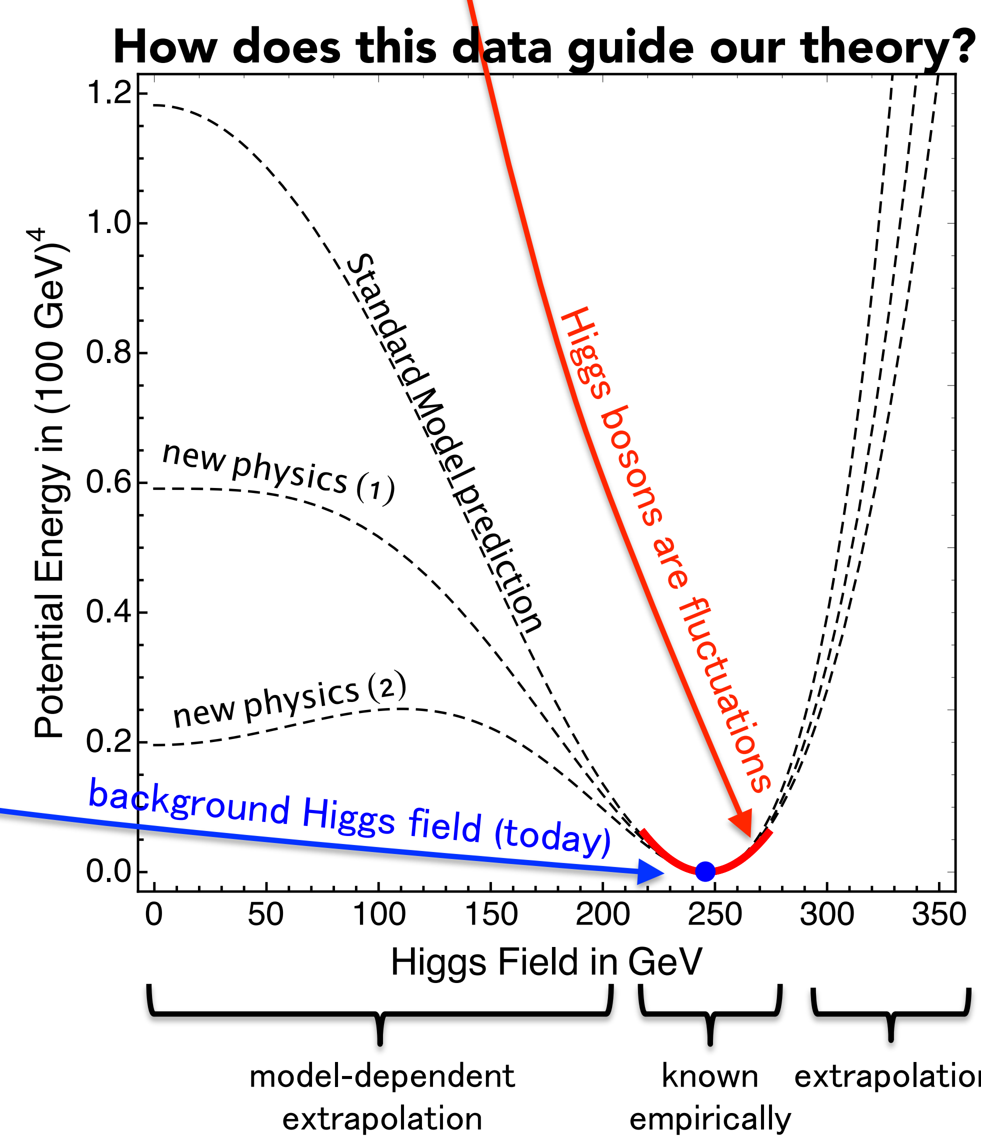
$$\mathrm{SM)}\quad V = \frac{1}{2}m^2h^2 + \frac{1}{4}\lambda h^4$$

$$\mathrm{NP\ 1)}\quad V = \frac{1}{4}\lambda h^4 \log\frac{h^2}{\Lambda^2}$$

$$\mathrm{NP\ 2)}\quad V = \frac{1}{2}m^2h^2 + \frac{1}{4}\lambda h^4 + \frac{1}{8\Lambda^2}h^6$$

$$\mathbf{m_h \simeq 125.09 \pm 0.24\,GeV/c^2}$$



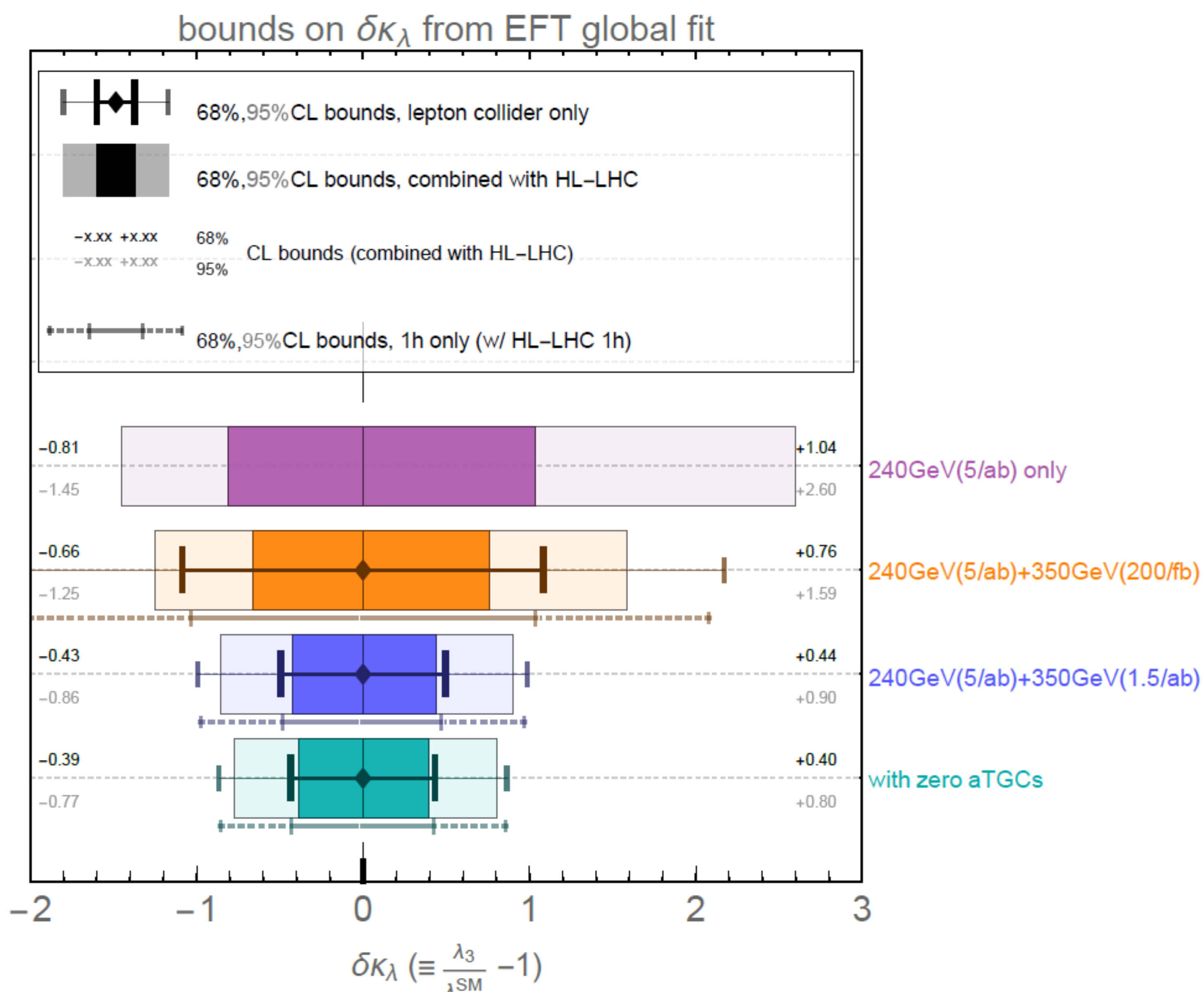


A. Long

Possible connection with baryogengesis. Z. Qian

trilinear Higgs coupling

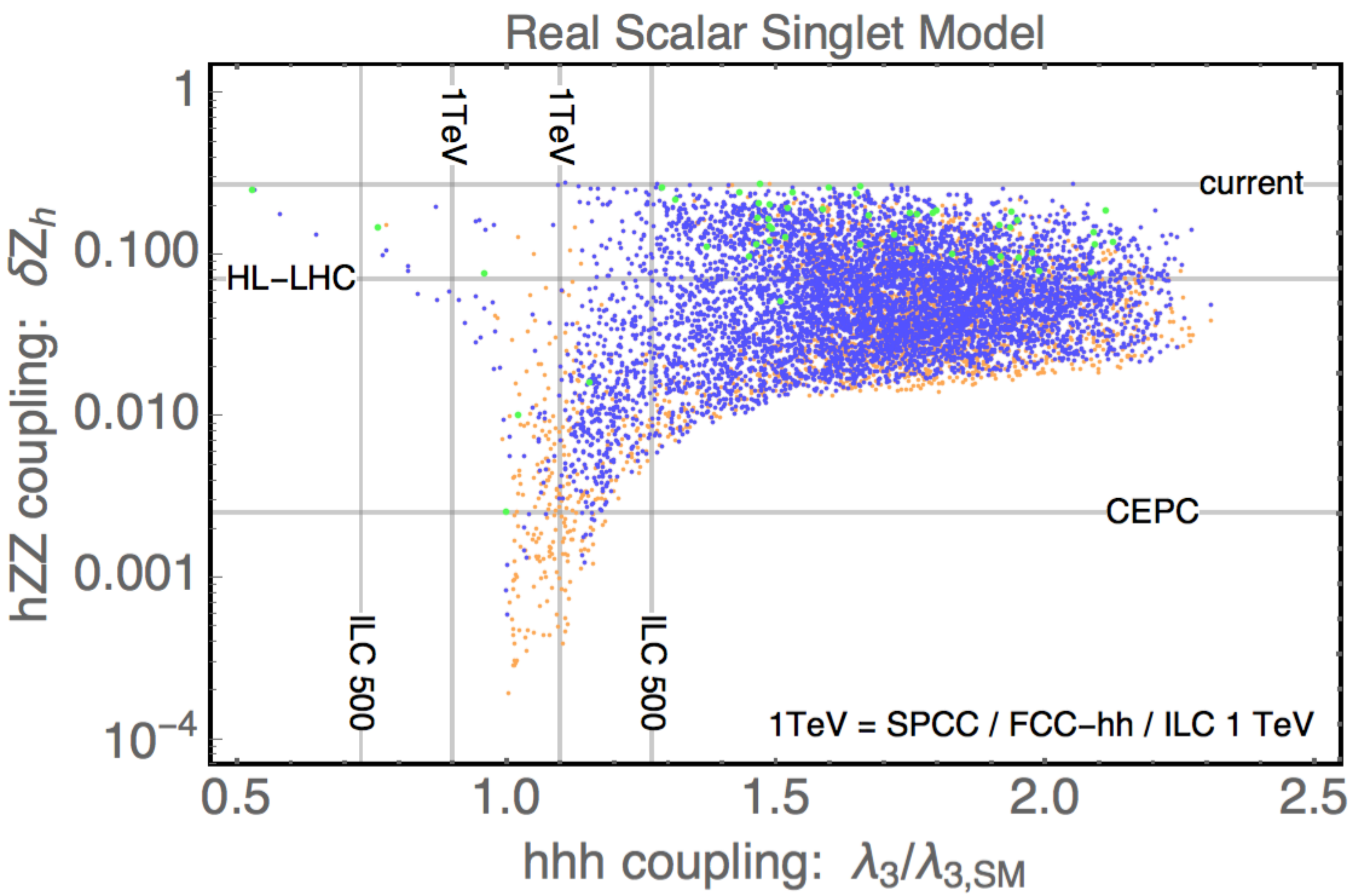
Results: complementarities



*After profiling over other parameters and use $\Delta\chi^2 = 1$ anc 4. we define the 68% and 95% C.L. level:

Argument for 350 GeV, 100 TeV pp

Probing EWSB at CEPC

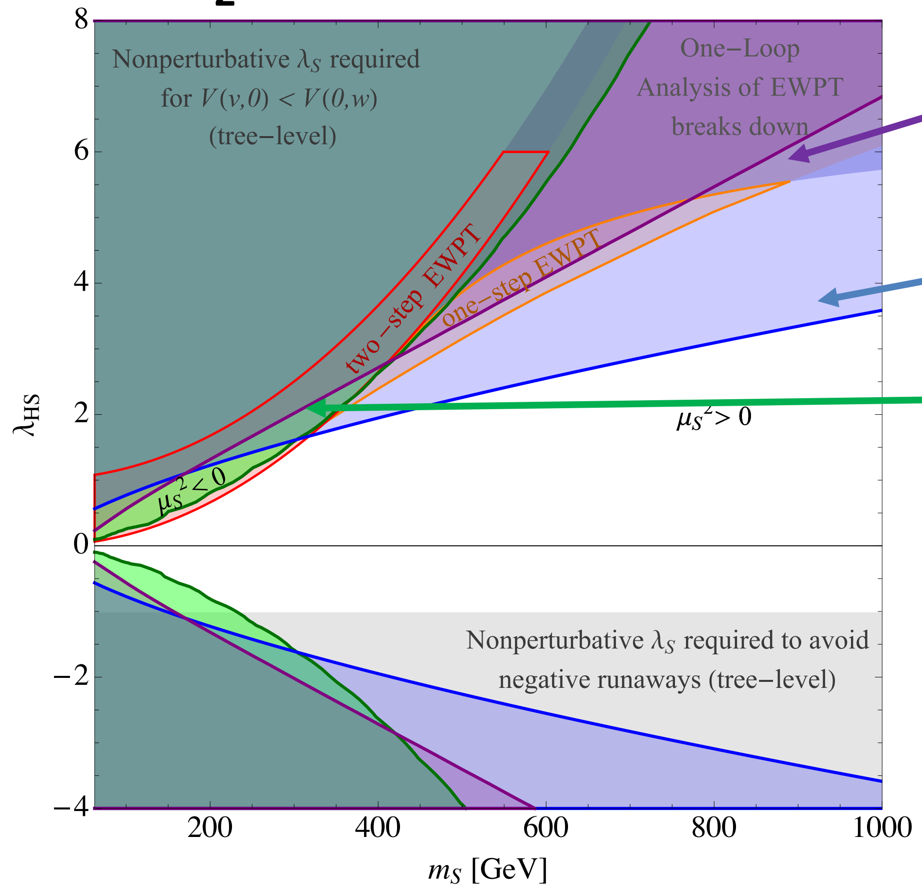


Orange = first order phase transition, $v(T_c)/T_c > 0$
Blue = "strongly" first order phase transition, $v(T_c)/T_c > 1.3$
Green = very strongly 1PT, could detect GWs at eLISA

Can probe most of the models.

More difficult case

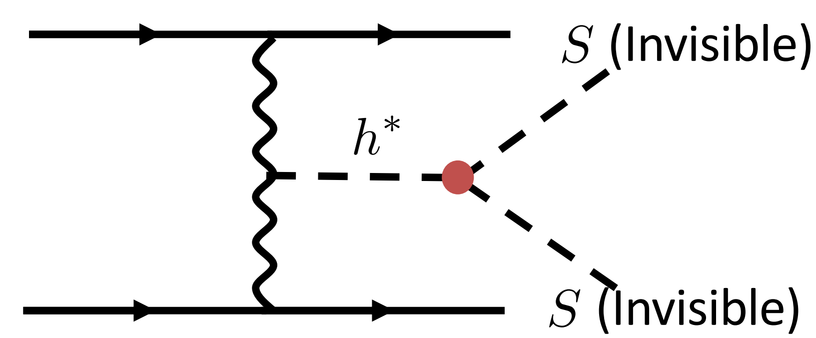
Z_2 limit: Curtin, Meade, Yu, 2014



$e^+e^- \rightarrow Zh$ cross-section deviation > 0.6%

Higgs self-coupling deviation > 10%

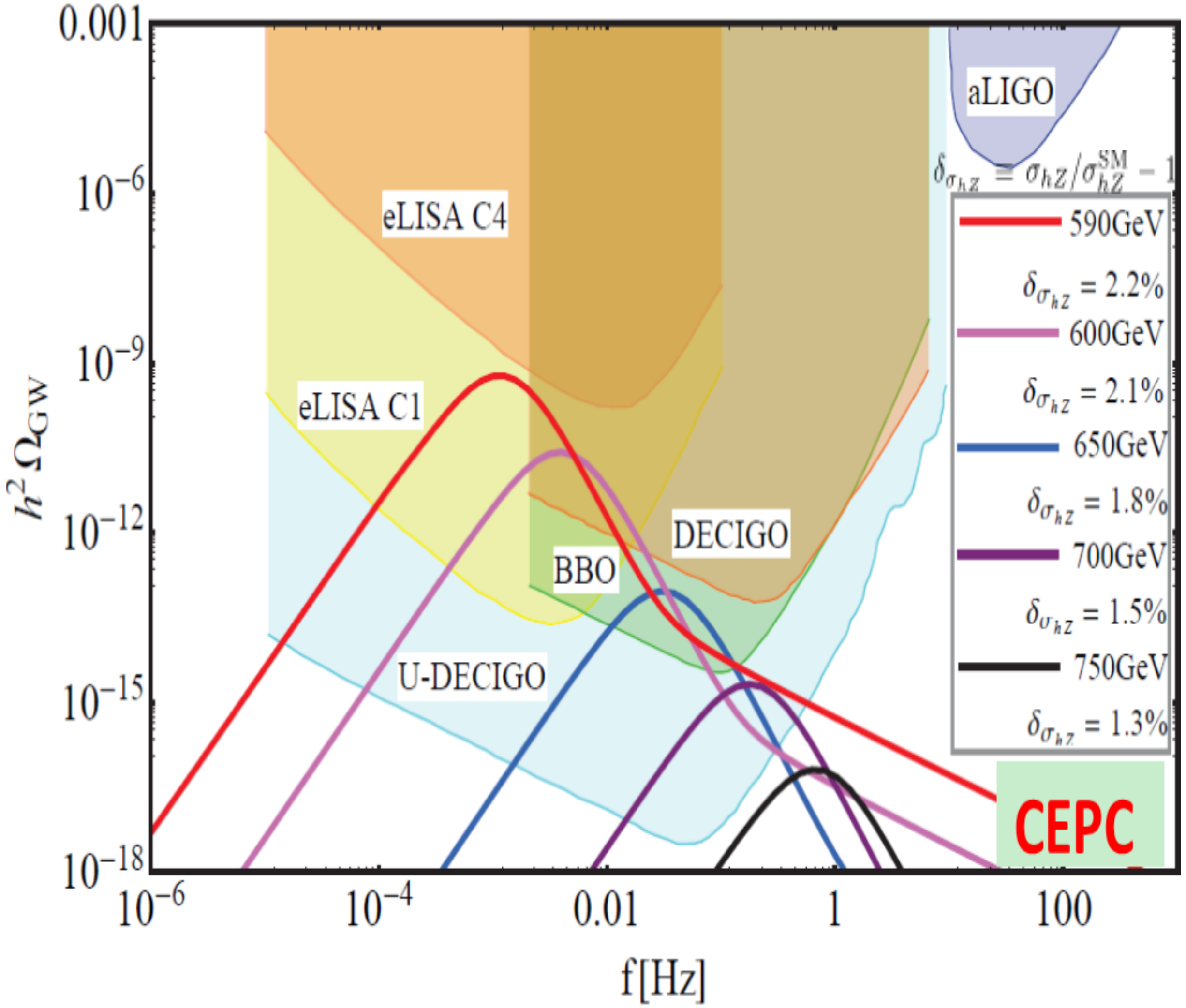
Non-res ss production (30 ab^{-1})



Kozaczuk 6

Connection with gravitational wave

Correlate particle collider and GW signals: Double test on Higgs nature and baryogenesis from particle to wave



FPH, et.al, Phys.Rev.D94(2016)no.4,041702
Phys.Rev.D93 (2016) no.10,103515

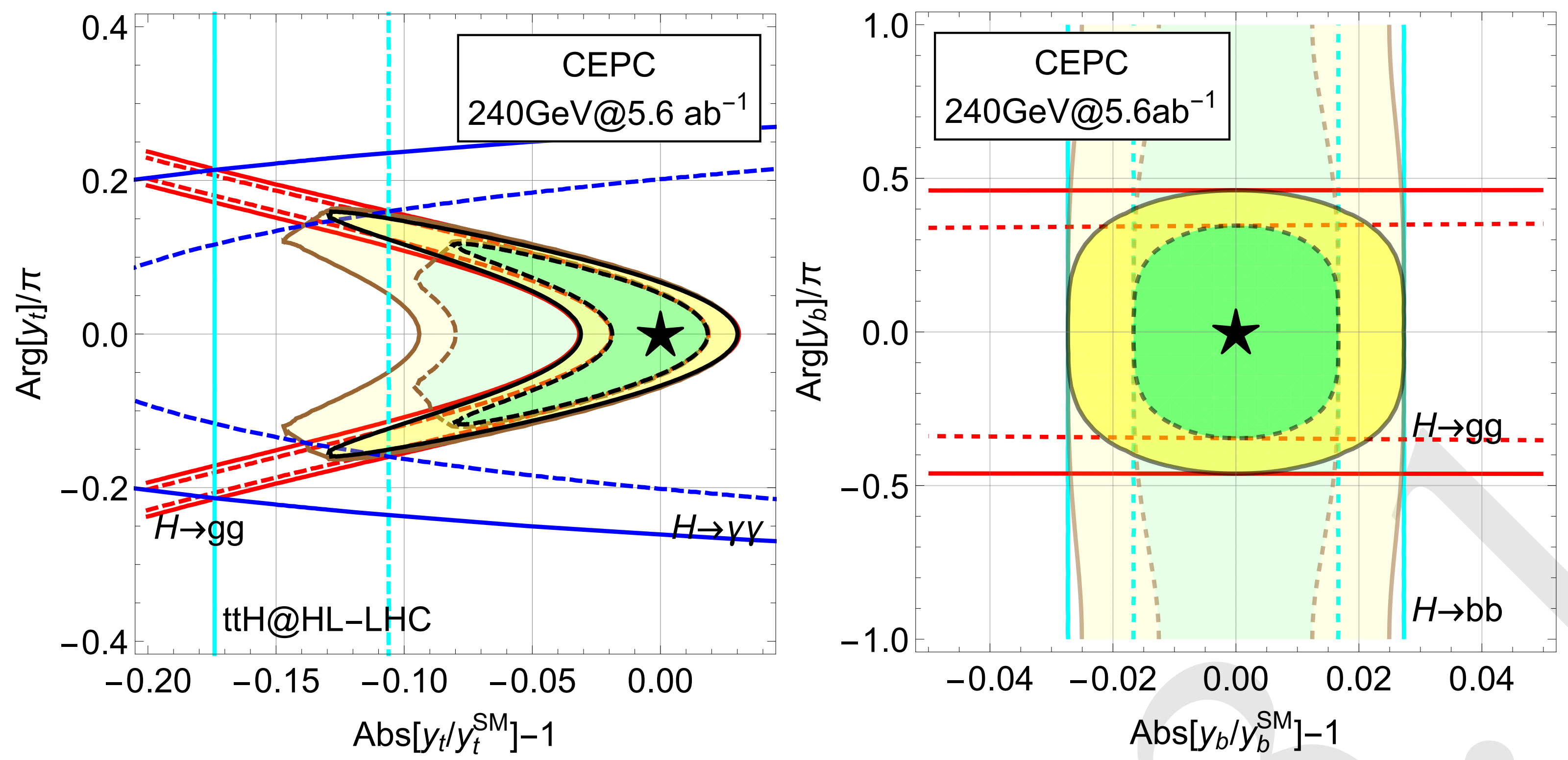
- **For CEPC with 10 ab^{-1} at $\sqrt{s} = 240$ GeV , precision of σ_{zh} may be about 0.4% and can test the scenario.**
- **LISA, BBO,U-DECIGO are capable of detection**
- **The study on EW phase transition naturally bridges the particle physics at collider with GW survey and baryogenesis**

Top

Top physics is absent in the CDR, but the top quark casts a long shadow
- precision EW is strongly affected by uncertainty on the top mass
- Higgs BR to gg, $\gamma\gamma$ and $Z\gamma$ are affected by top EW couplings in loops

Do not forget about the top.

M. Vos's talk

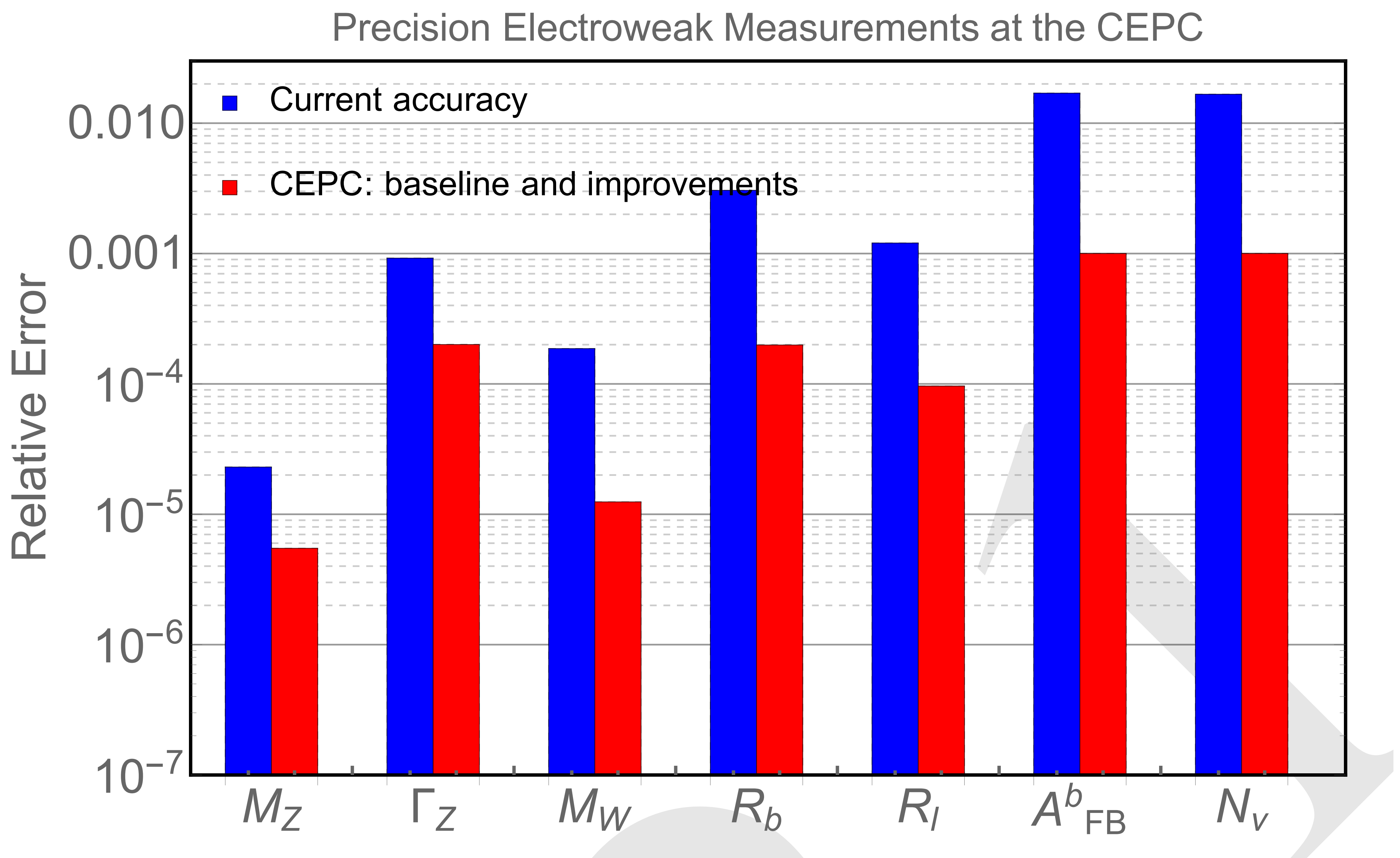


(a) (b)

Zhen Liu

Covered in CDR, needs to strengthen

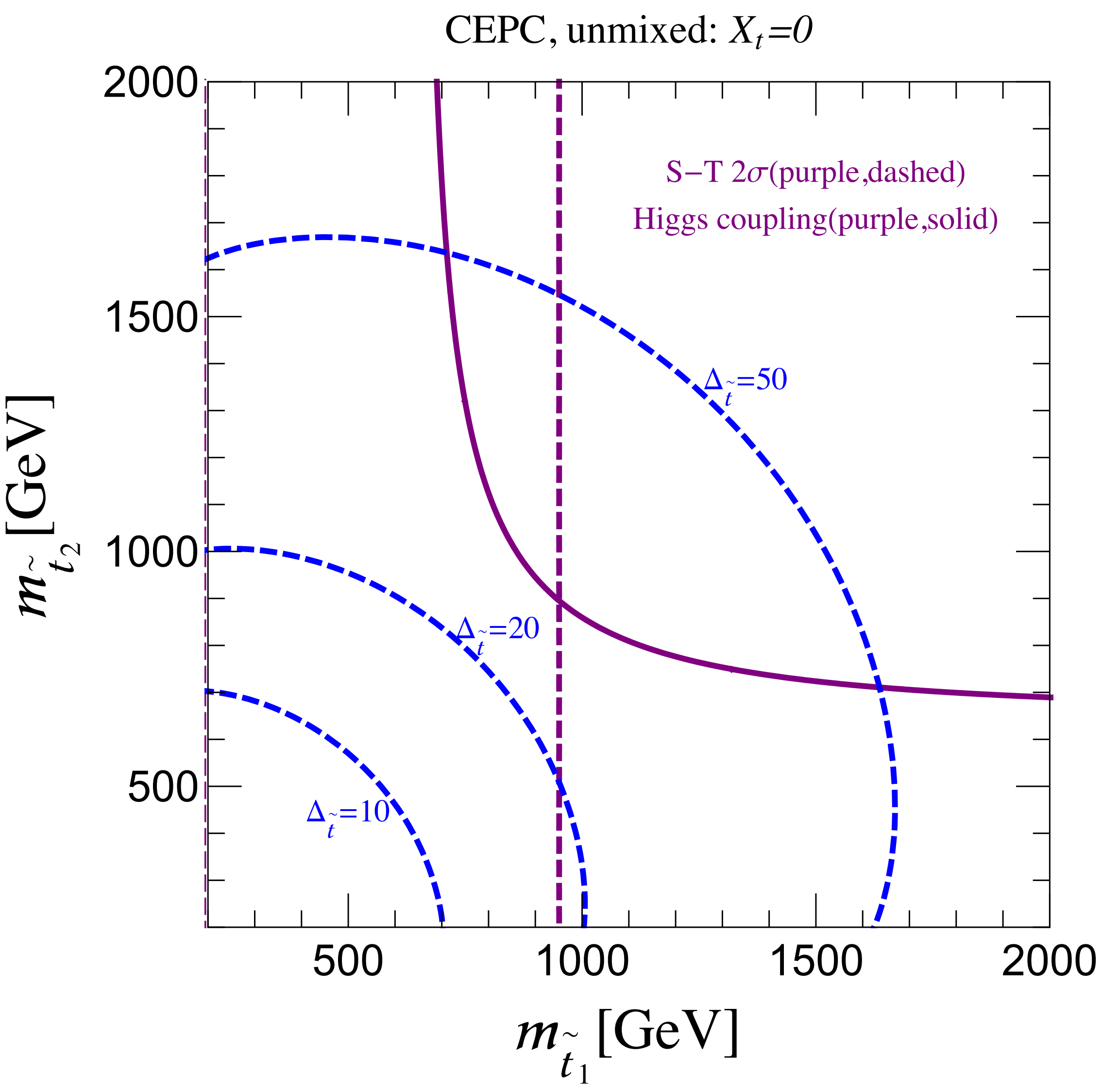
Z-pole and precision



Projections by Z. Liang

Complementary to Higgs coupling measurement

Testing SUSY



Recent theoretical advances

- most recent achievement is the complete bosonic two-loop calculation to Z decay

Dubovik et al. 2018

$Z \to b\bar{b}$			
Number of topologies	1 loop	2 loops	3 loops
	1	$14 \stackrel{(A)}{\to} 7 \stackrel{(B)}{\to} 5$	$211 \stackrel{(A)}{\to} 84 \stackrel{(B)}{\to} 51$
Number of diagrams	15	$2383 \stackrel{(A,B)}{\to} 1074$	$490387 \stackrel{(A,B)}{\to} 120472$
Fermionic loops	0	150	17580
Bosonic loops	15	924	102892
Planar / Non-planar	15 / 0	981/133	84059/36413
QCD / EW	1 / 14	98 / 1016	10386/110086

$Z \to e^+e^-, \ldots$			
Number of topologies	1 loop	2 loops	3 loops
	1	$14 \stackrel{(A)}{\to} 7 \stackrel{(B)}{\to} 5$	$211 \stackrel{(A)}{\to} 84 \stackrel{(B)}{\to} 51$
Number of diagrams	14	$2012 \stackrel{(A,B)}{\to} 880$	$397690 \stackrel{(A,B)}{\to} 91472$
Fermionic loops	0	114	13104
Bosonic loops	14	766	78368
Planar / Non-planar	14 / 0	782/98	65487/25985
QCD / EW	0 / 14	0 / 880	144/91328

F. Piccinini

More needed to deliver the desired accuracy for both Higgs and Z programs.

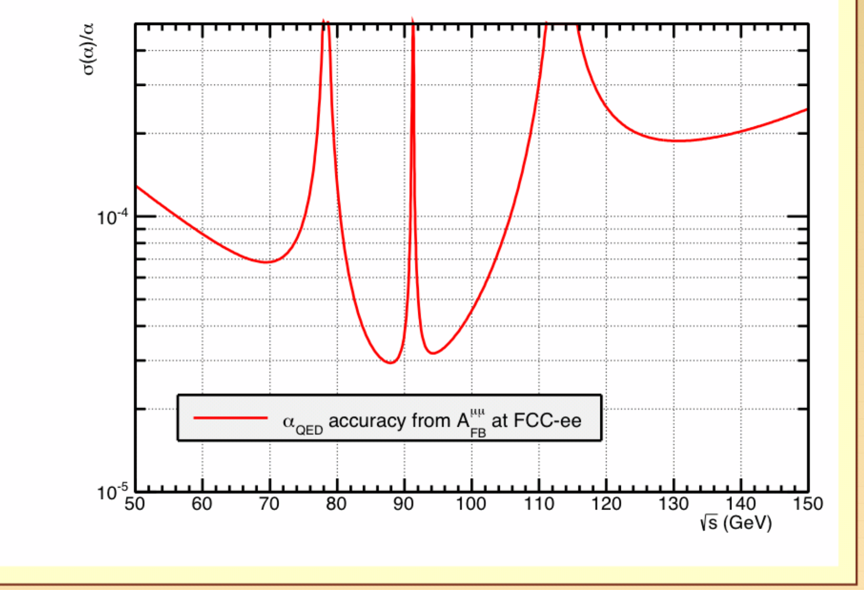
New approaches in EW precision

Shift of finestructure constant

- $\Delta\alpha_{\text{had}}$: Could be limiting factor
  - a) From $e^+e^- \to$ had. using dispersion relation
    Current: $\delta(\Delta\alpha_{\text{had}}) \sim 10^{-4}$
    Improvement to $\delta(\Delta\alpha_{\text{had}}) \sim 5 \times 10^{-5}$ likely
  - b) Direct determination at FCC-ee from $e^+e^- \to \mu^+\mu^-$ off the Z peak
    (i.e. $A_{\text{FB}}^{\mu\mu}$ at $\sqrt{s} \sim 88$ GeV and $\sqrt{s} \sim 95$ GeV)
    $\longrightarrow \delta_{\text{th}}(\Delta\alpha_{\text{had}}) \sim 3 \times 10^{-5}$

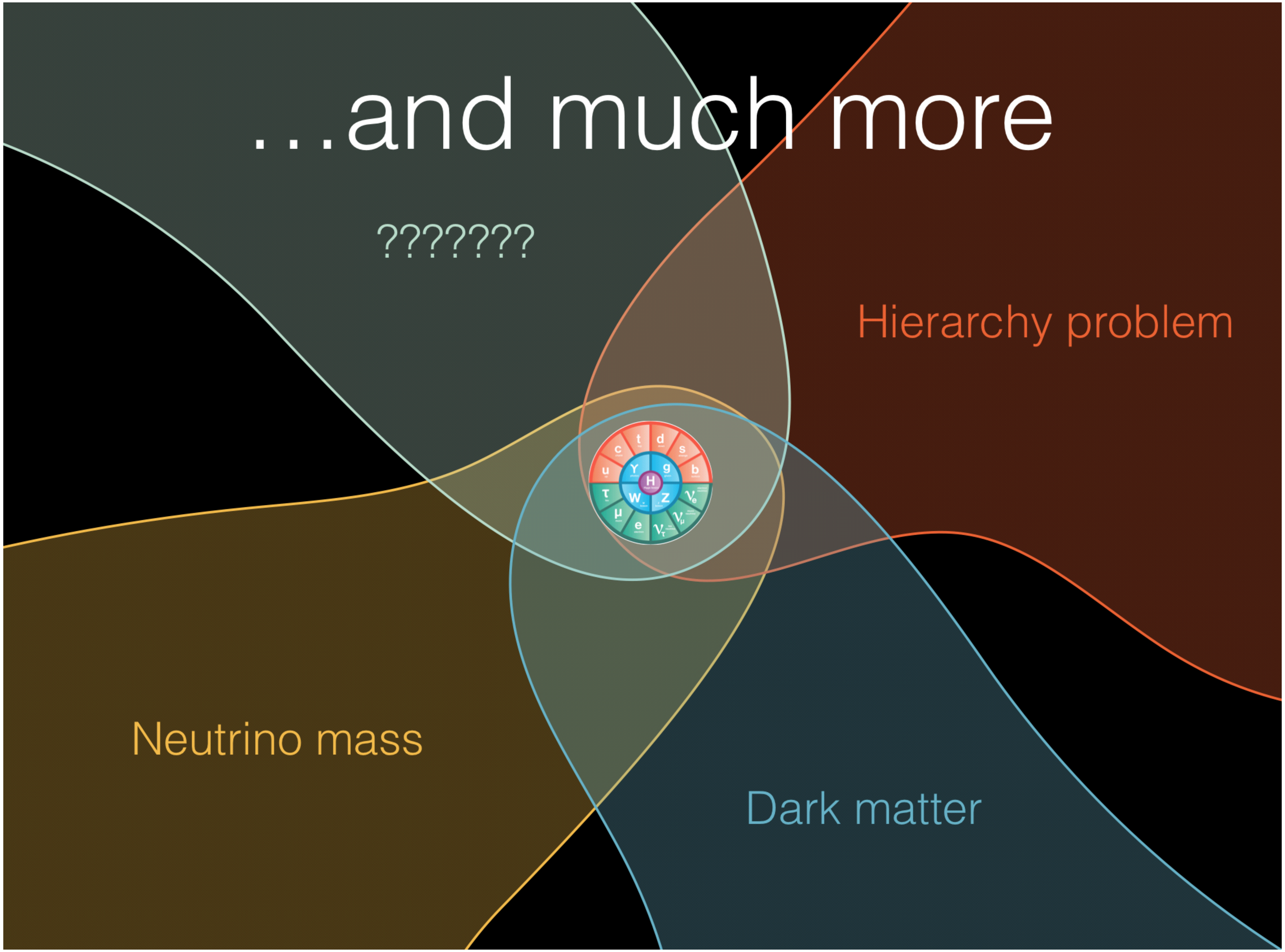
Janot '15

Requires high-precision theory prediction for $e^+e^- \to \mu^+\mu^-$ including 2/3-loop corrections for γ-exchange and box contributions



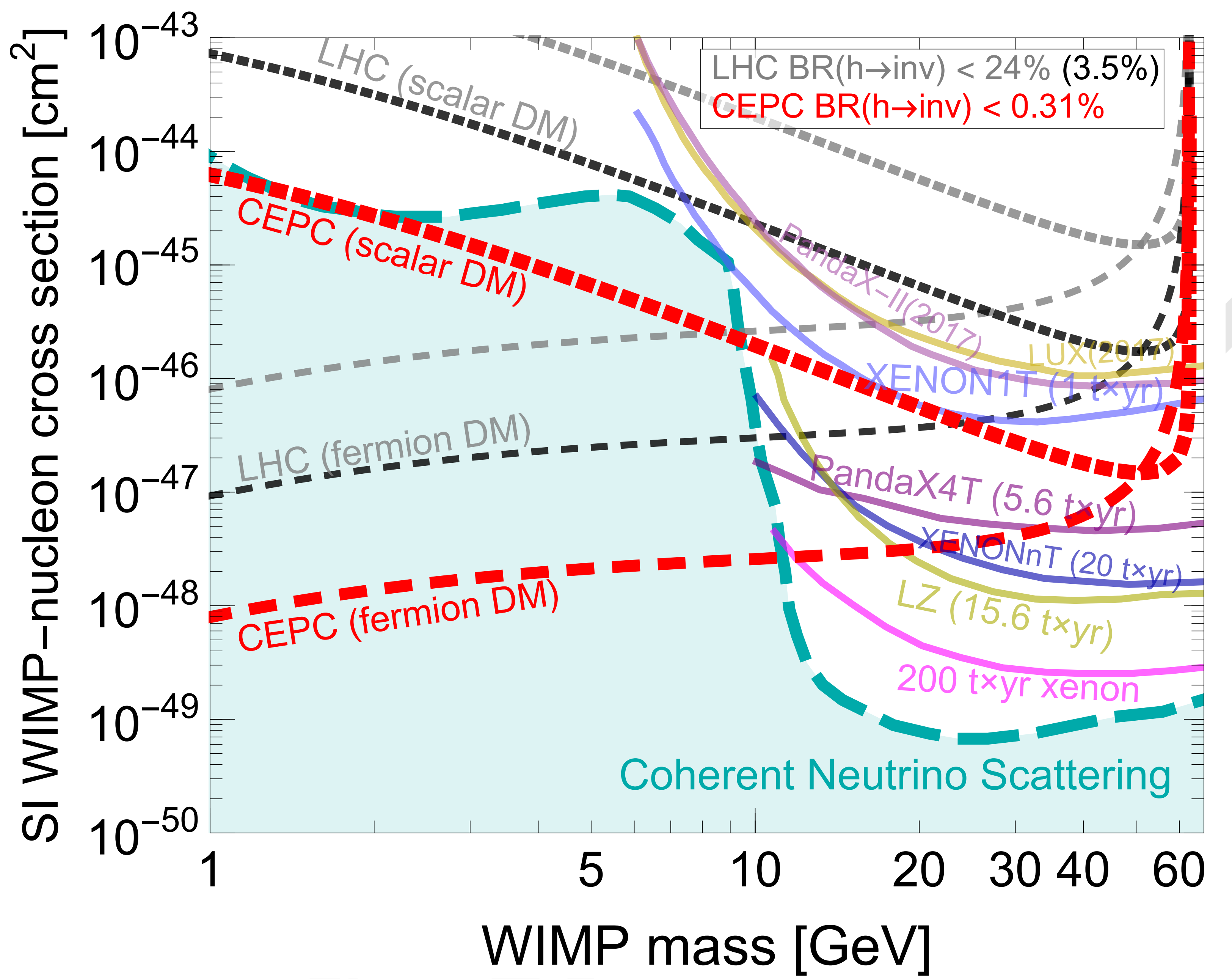
A. Freitas

Exotics, enriching the physics program



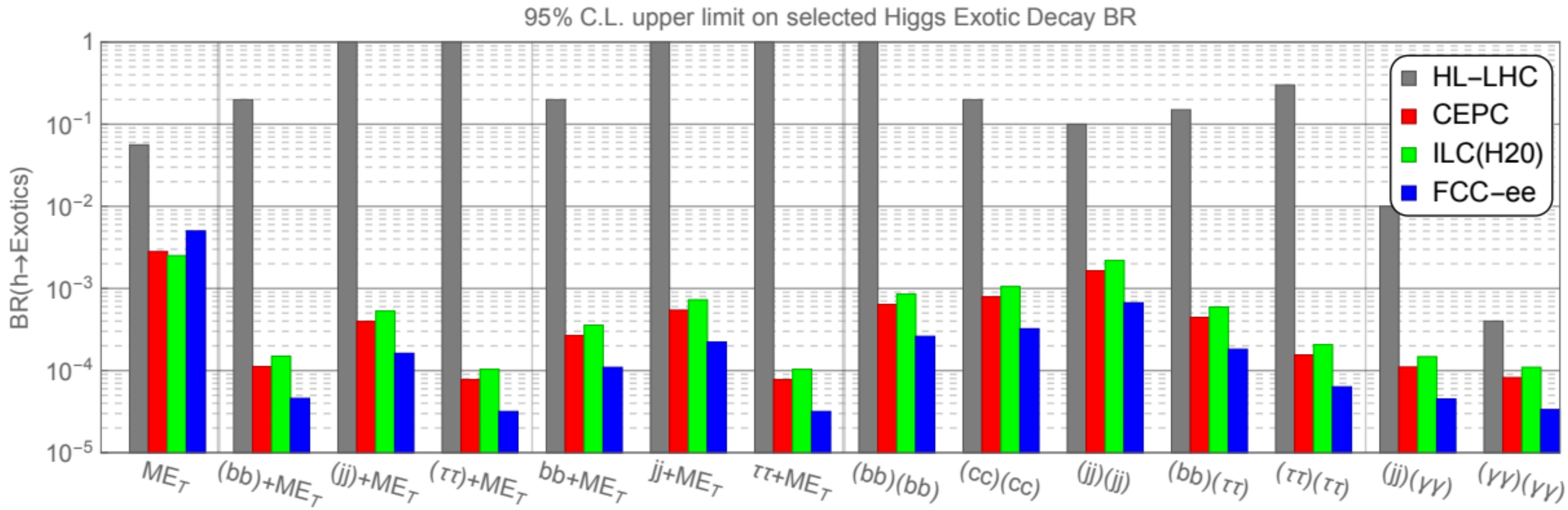
Higgs portal dark matter

$H^{\dagger}HXX$



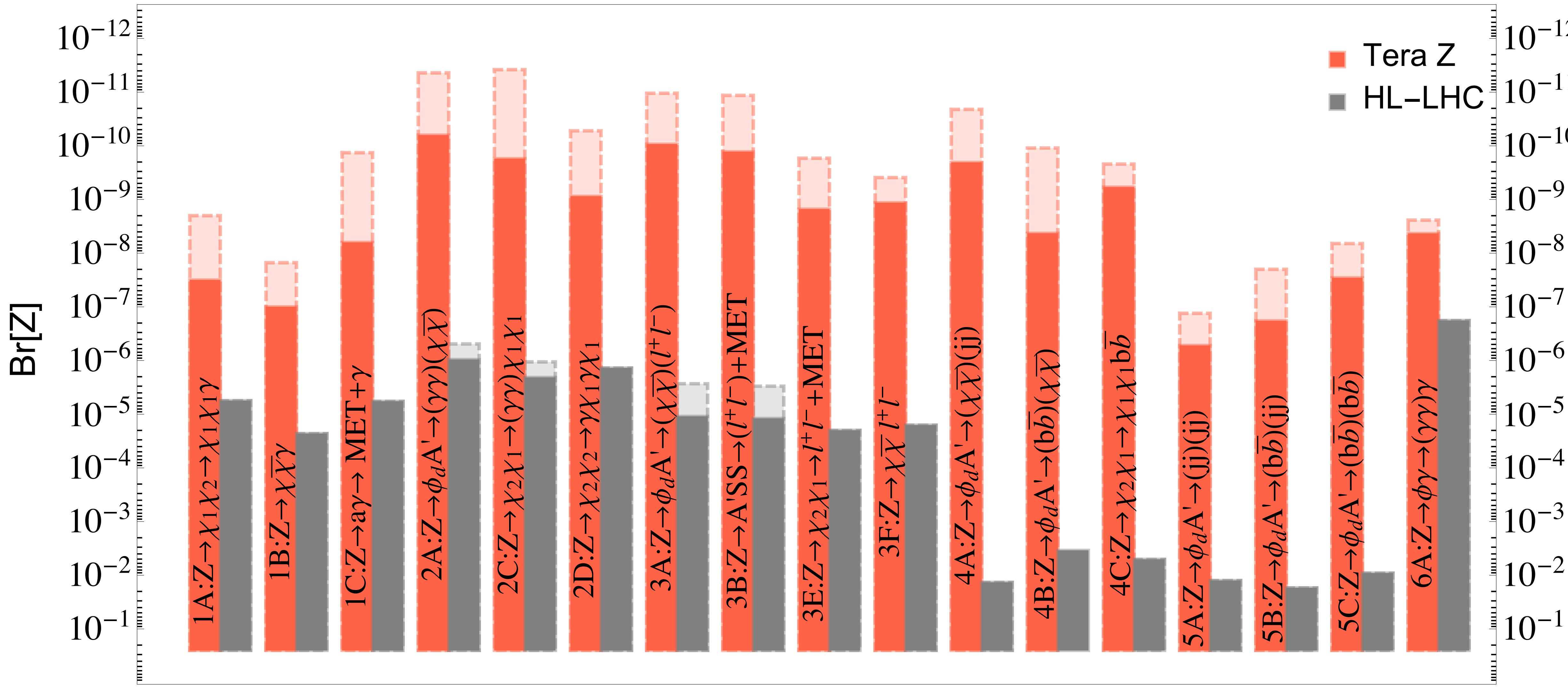
From Higgs invisible decay

Higgs exotic decay



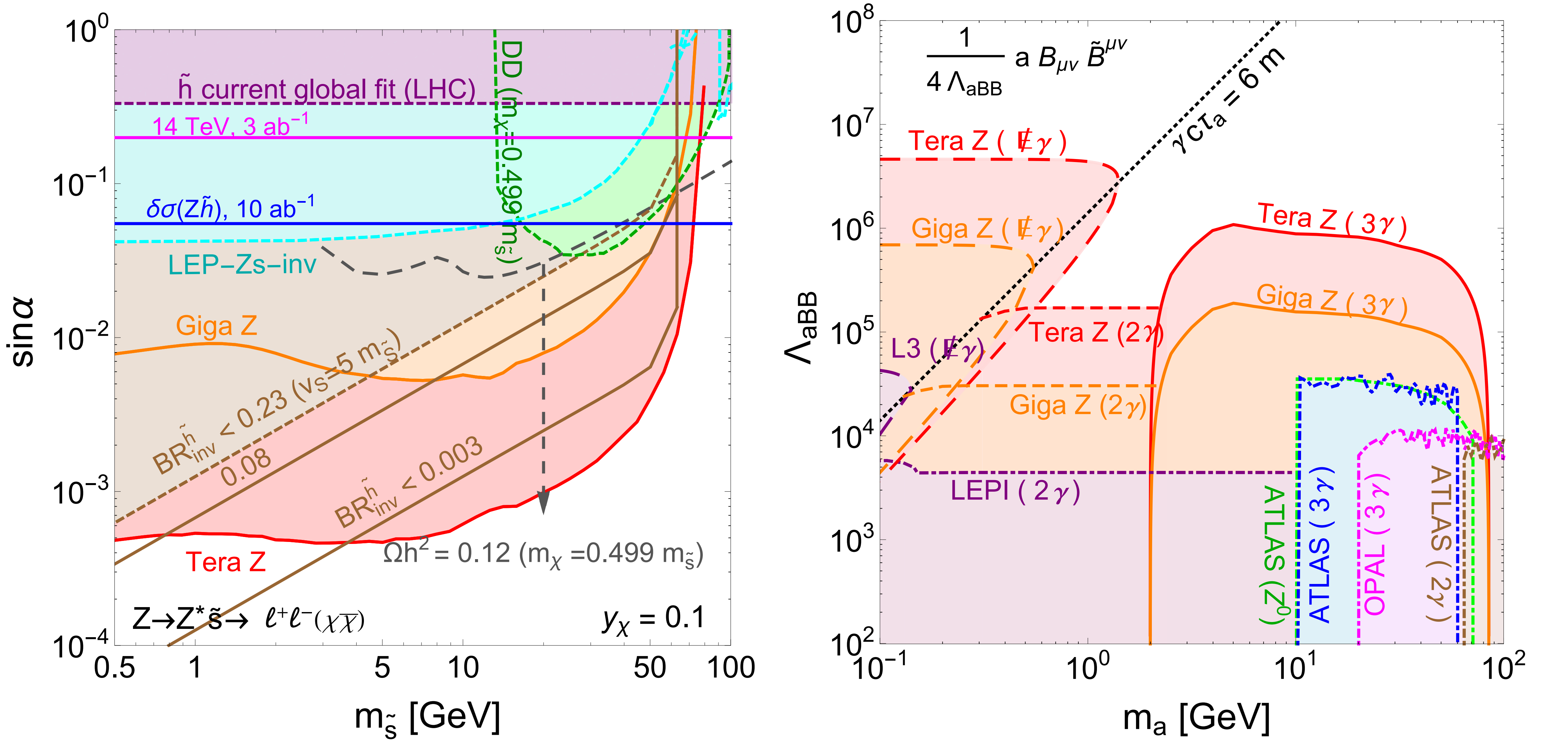
Complementary to hadron collider searches.
Strong in hadronic modes, MET, …

Rare Z decay

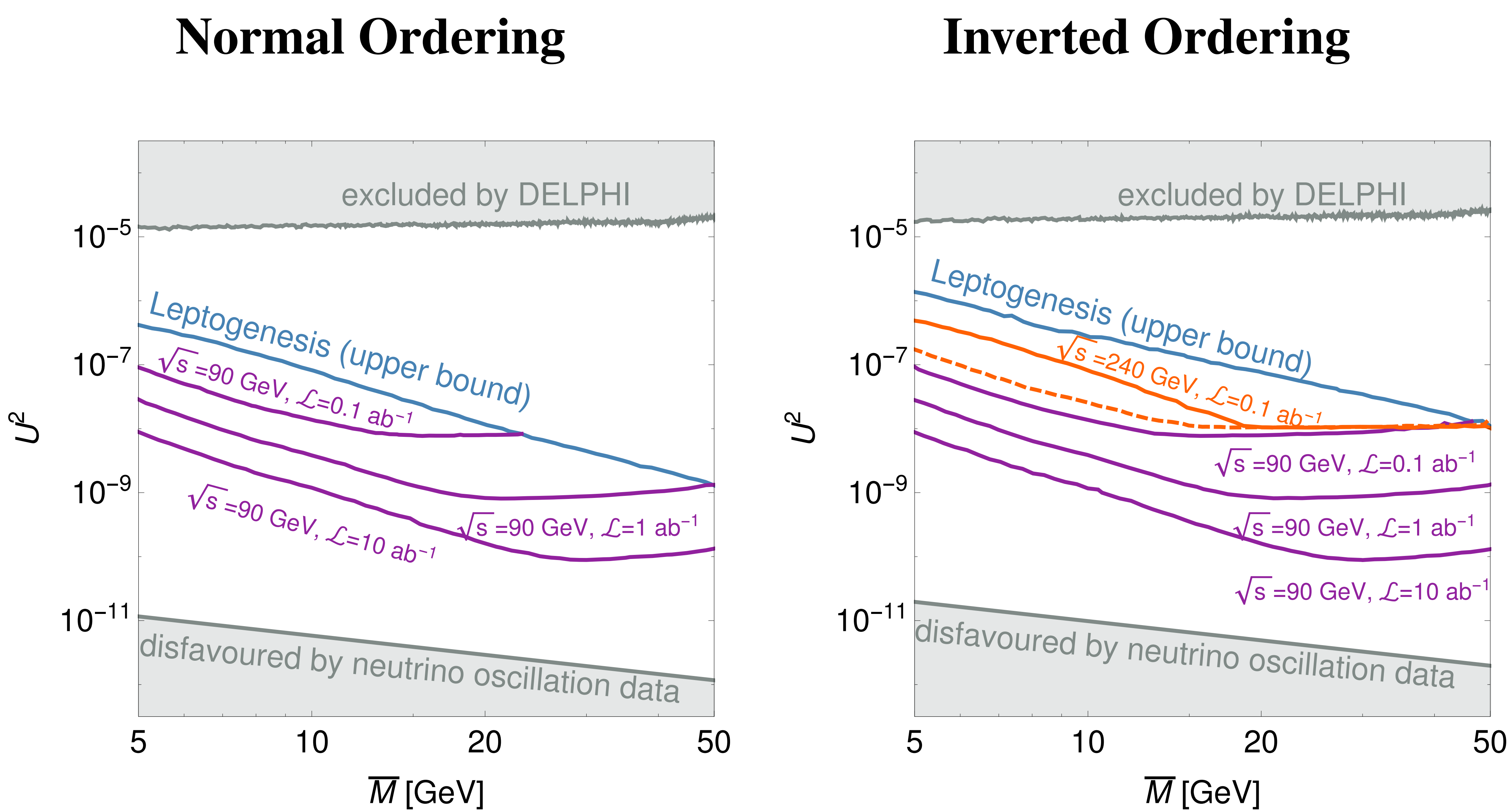


Tera Z
HL−LHC
Br[Z]
10^{-12}
10^{-11}
10^{-10}
10^{-9}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1A:$Z\to\chi_1\chi_2\to\chi_1\chi_1\gamma$
1B:$Z\to\chi\overline{\chi}\gamma$
1C:$Z\to a\gamma\to$ MET+γ
2A:$Z\to\phi_d A'\to(\gamma\gamma)(\chi\overline{\chi})$
2C:$Z\to\chi_2\chi_1\to(\gamma\gamma)\chi_1\chi_1$
2D:$Z\to\chi_2\chi_2\to\gamma\chi_1\gamma\chi_1$
3A:$Z\to\phi_d A'\to(\chi\overline{\chi})(l^+l^-)$
3B:$Z\to A'SS\to(l^+l^-)$+MET
3E:$Z\to\chi_2\chi_1\to l^+l^-$+MET
3F:$Z\to\chi\overline{\chi}\, l^+l^-$
4A:$Z\to\phi_d A'\to(\chi\overline{\chi})(jj)$
4B:$Z\to\phi_d A'\to(b\overline{b})(\chi\overline{\chi})$
4C:$Z\to\chi_2\chi_1\to\chi_1\chi_1 b\overline{b}$
5A:$Z\to\phi_d A'\to(jj)(jj)$
5B:$Z\to\phi_d A'\to(b\overline{b})(jj)$
5C:$Z\to\phi_d A'\to(b\overline{b})(b\overline{b})$
6A:$Z\to\phi\gamma\to(\gamma\gamma)\gamma$

Dark sector at Z factory

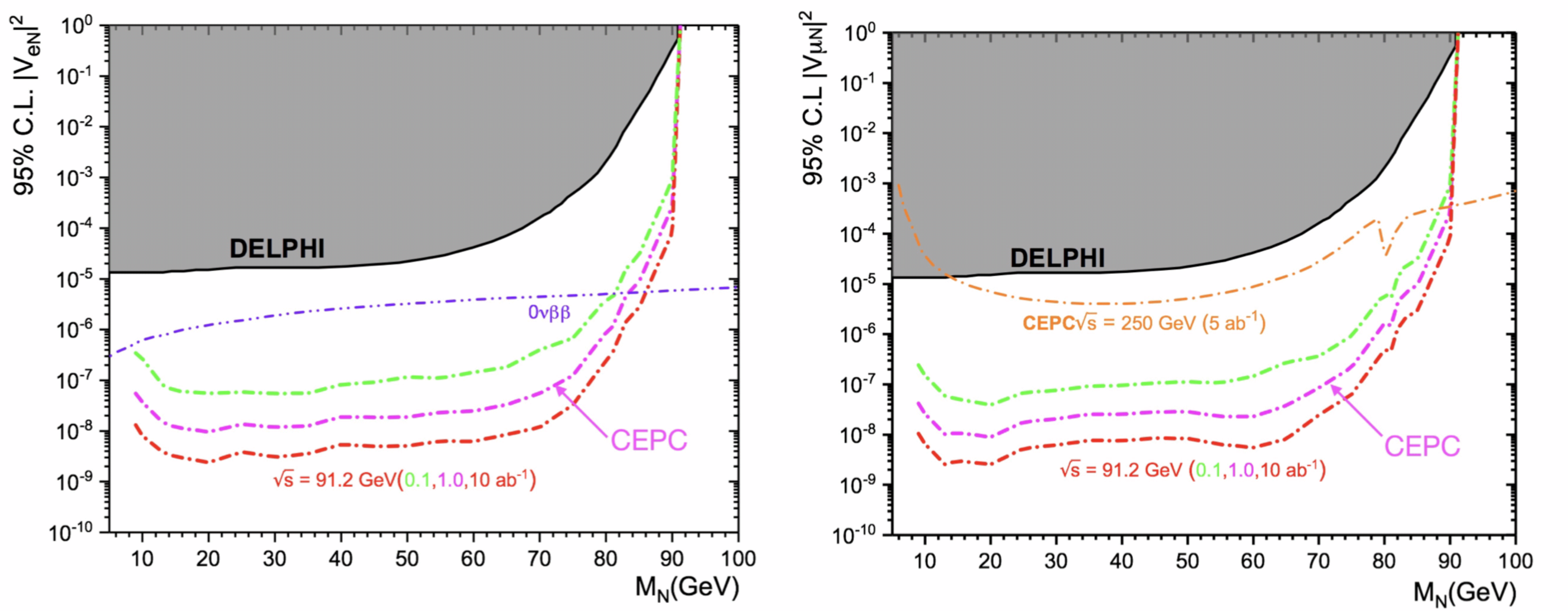


Sterile neutrino

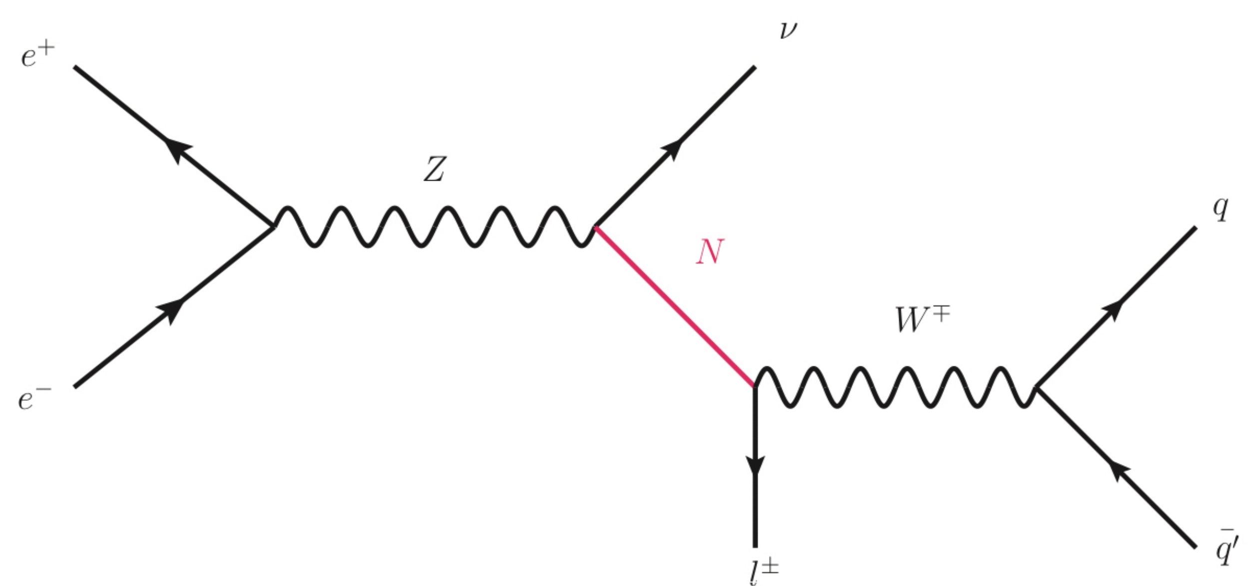


low scale see-saw models

Constraints of mixing parameters at Z pole of CEPC



☼ Z



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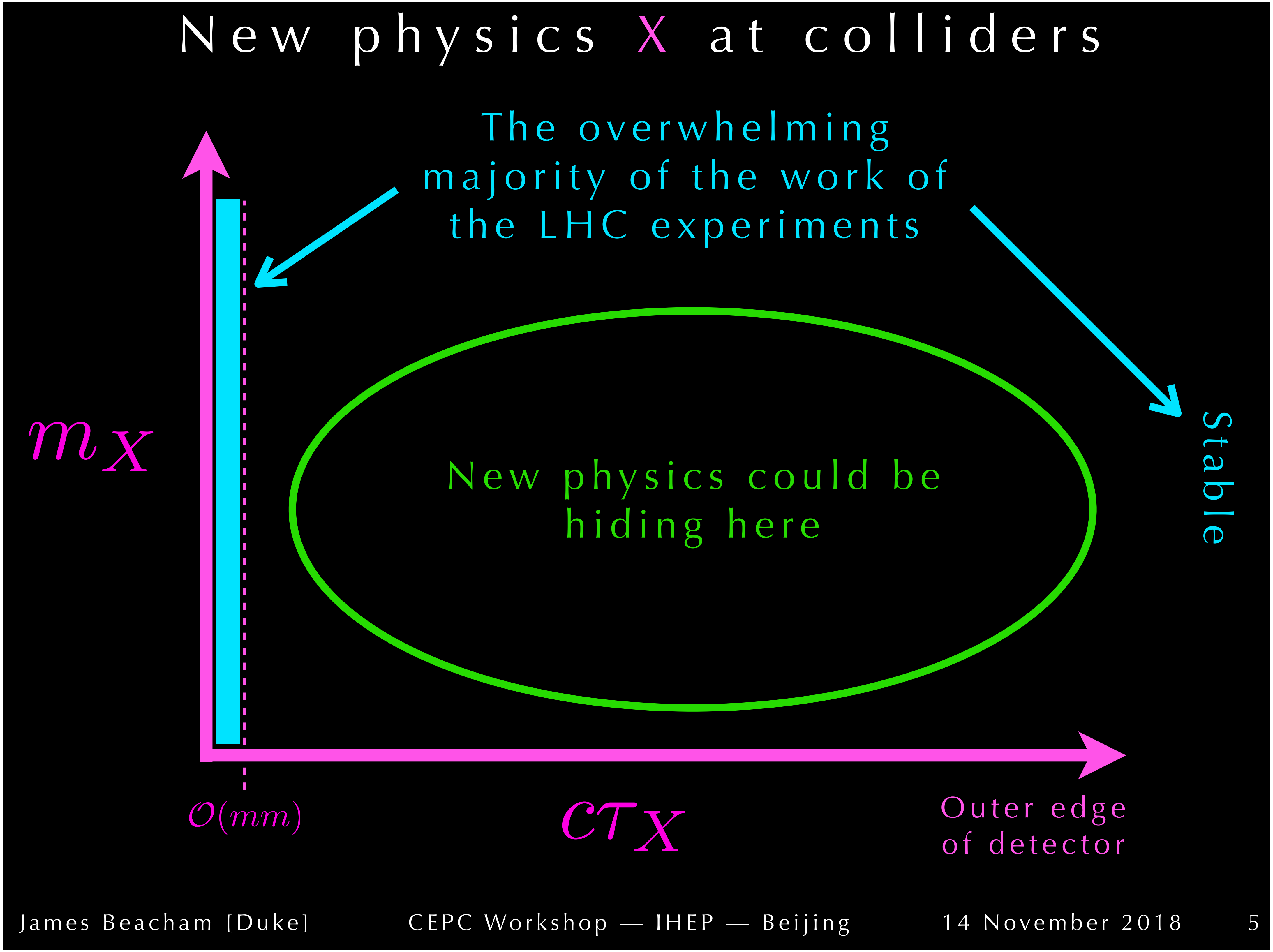
gy

Sterile neutrino

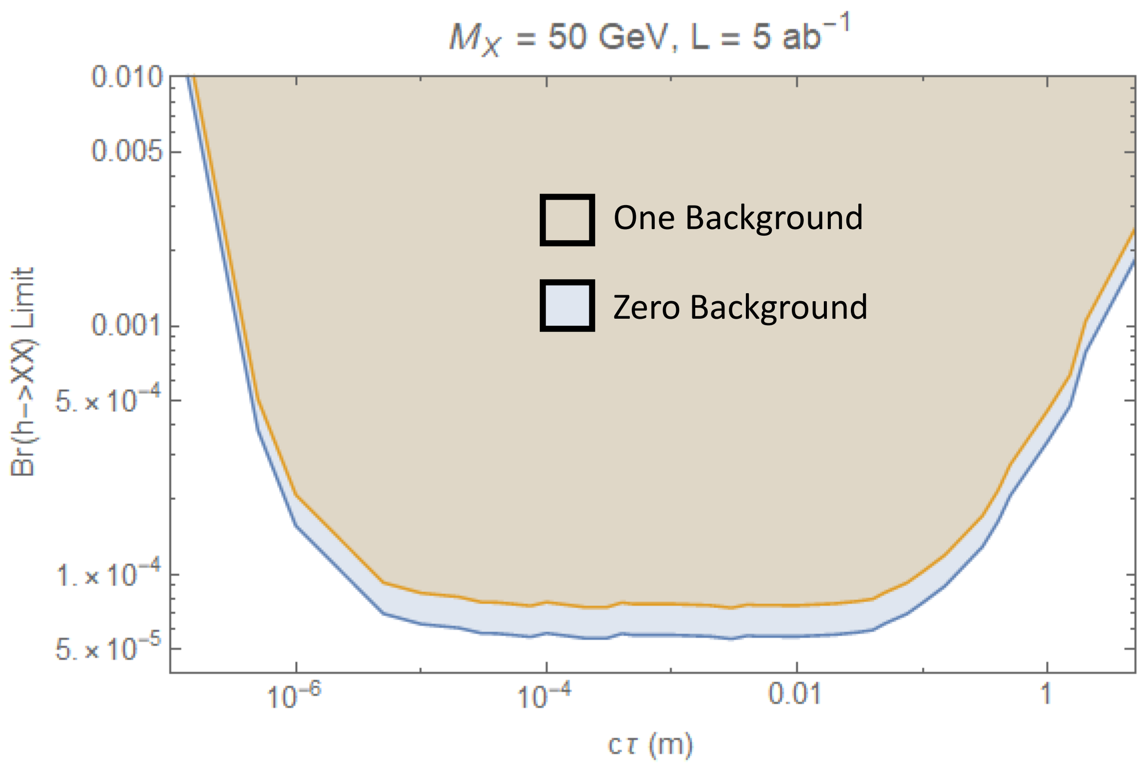
Long lived particles



LLP searches at the CEPC

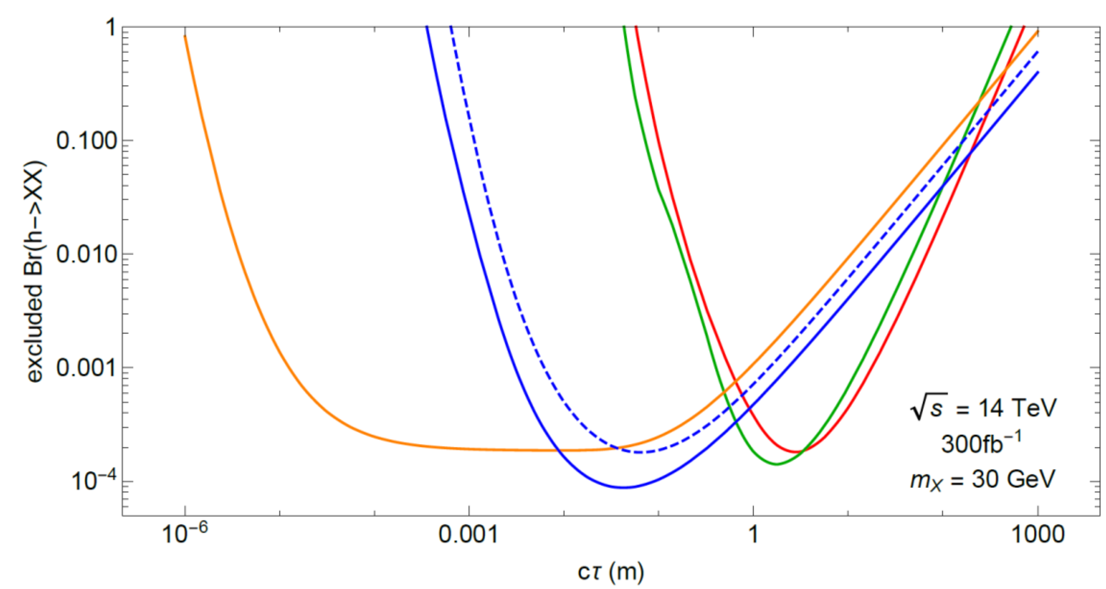
Comparison with LHC

This work



No official projections (yet) for LHC14, just theory estimates

(Curtin & Verhaaren, `15)



(See also Csaki, Kuflik, Lombardo, Slone `15)

LHC produces more total Higgses, but CEPC has better impact parameter resolution, better vertex reconstruction, and cleaner environment.

S. Koren

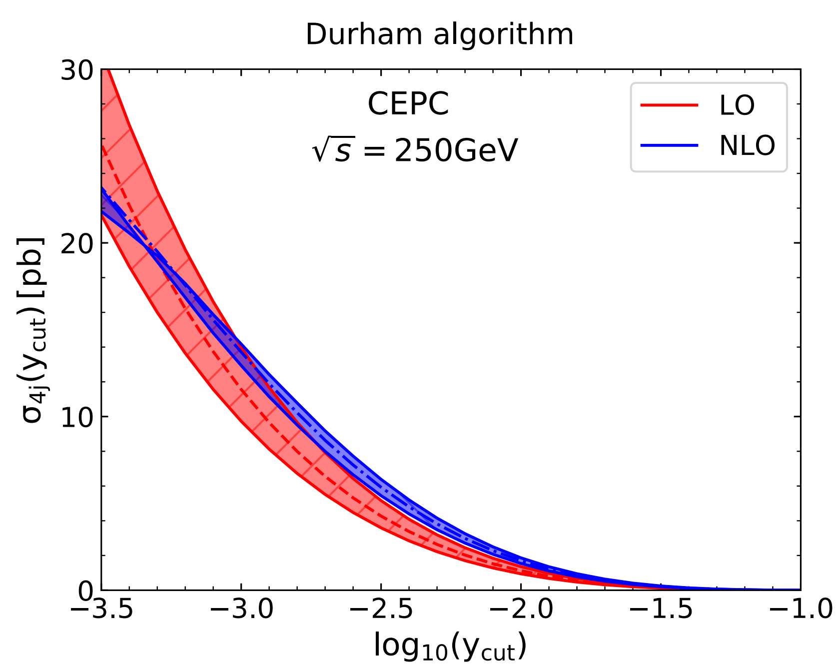
Further inform detector design, vertexing, timing, etc.

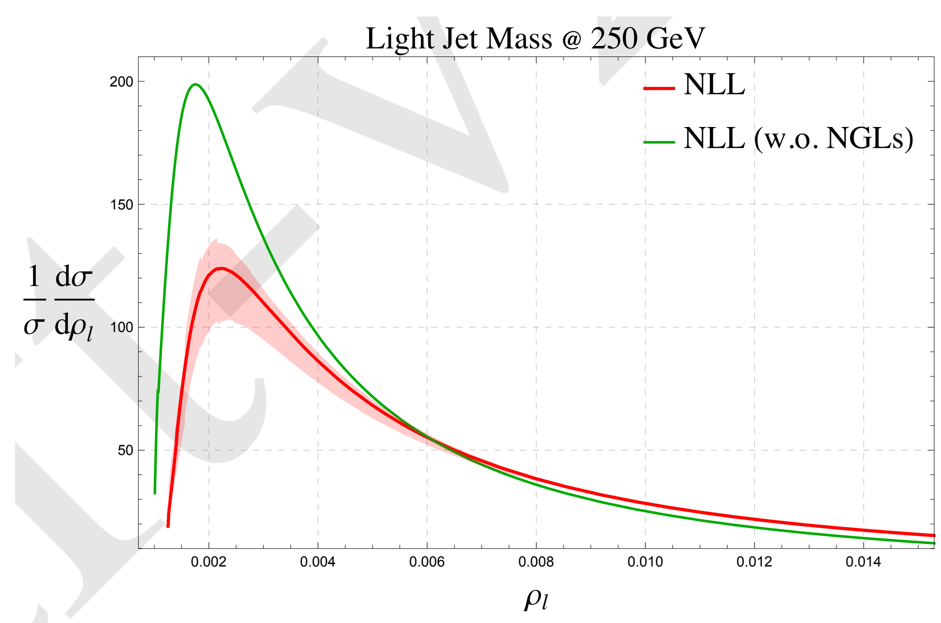
QCD

- Similar to LEP, but at much higher statistics, higher energy, better detector.

- Measurement of α_S .

- Subtle effects in QCD.



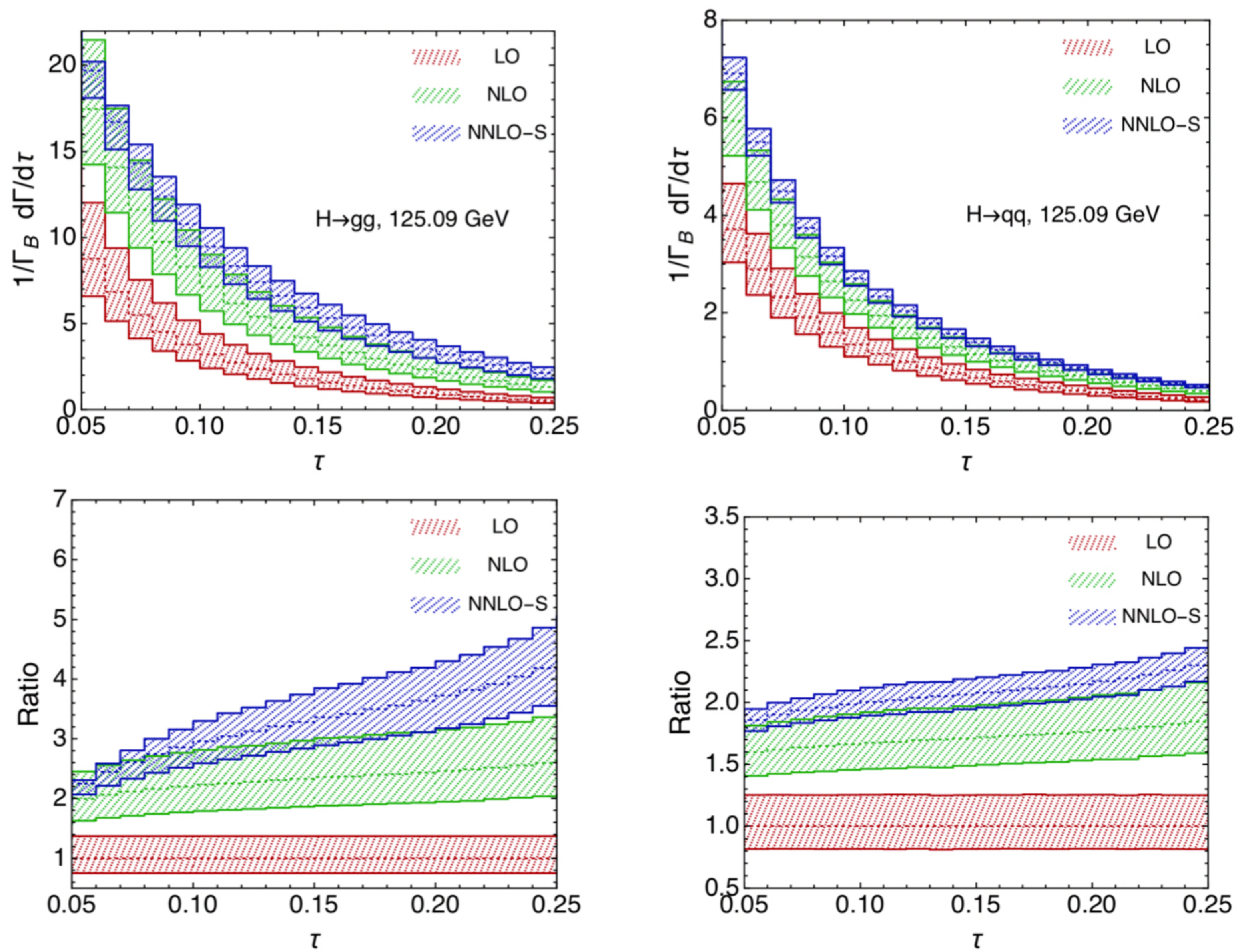


International review

Further work is highly encouraged to derive solid QCD prospects for the TDR

New studies

Numeric Result at NNLO-S



Event shape from h-> gg decay

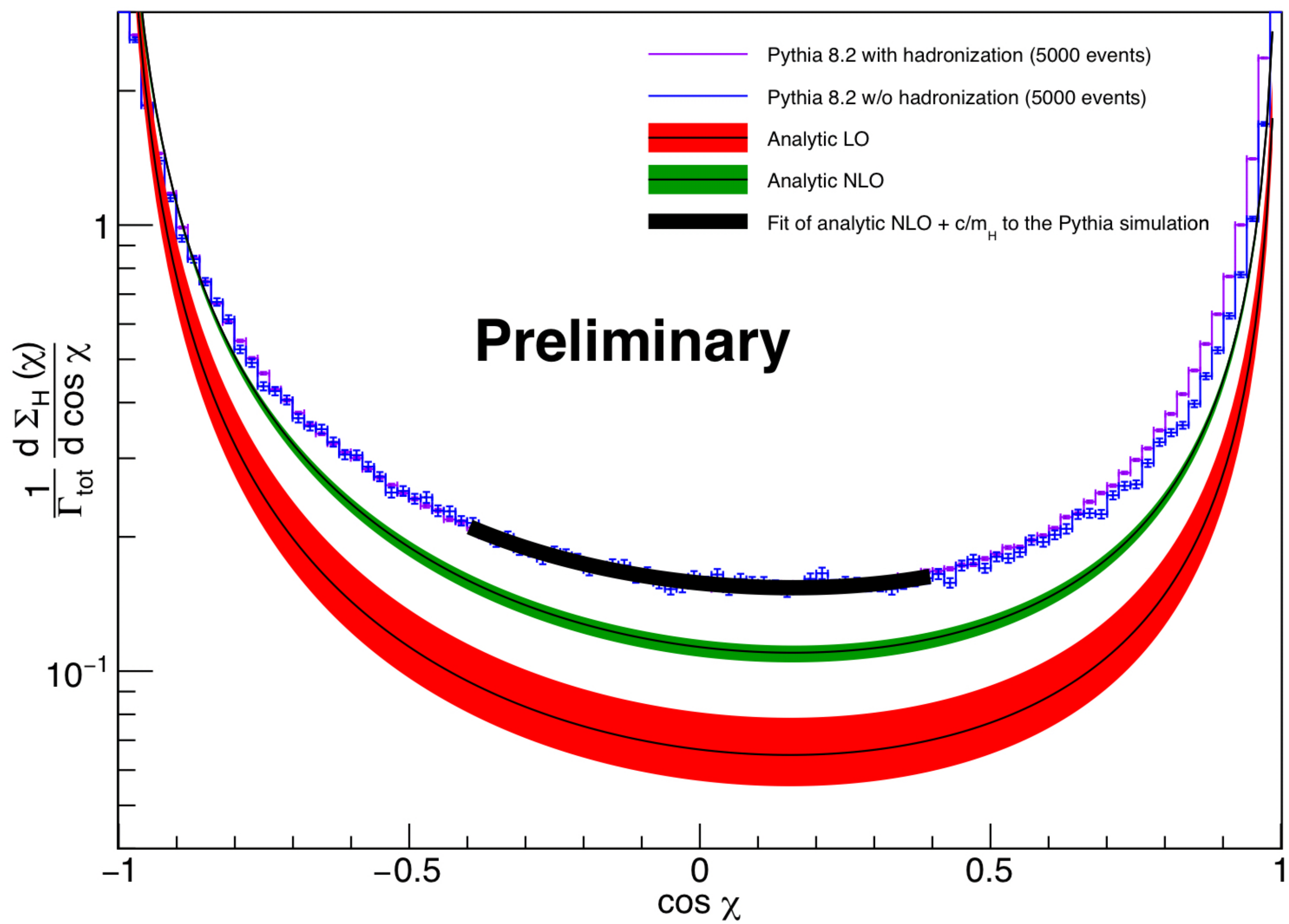
Yin-Qiang Gong

New results

- Our binned maximum likelihood fit yields

$$c = (3.34 \pm 1.98)\ \text{GeV}, \quad \alpha_s(m_H) = 0.130 \pm 0.015, \quad \chi^2/\text{NDF} = 51/38$$

- This is just a fit to the Pythia simulation, not to the real data!
- It is not even clear how well Pythia can model this process.



Energy correlation from h-> gg decay

Flavor

Particle production

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

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

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

Highlights

[From CEPC's CDR]

Observable	Current sensitivity	Future sensitivity	Tera-Z sensitivity
$\mathrm{BR}(B_s \to ee)$	2.8×10^{-7} (CDF) [10]	$\sim 7 \times 10^{-10}$ (LHCb) [18]	$\sim$ few $\times 10^{-10}$
$\mathrm{BR}(B_s \to \mu\mu)$	0.7×10^{-9} (LHCb) [8]	$\sim 1.6 \times 10^{-10}$ (LHCb) [18]	$\sim$ few $\times 10^{-10}$
$\mathrm{BR}(B_s \to \tau\tau)$	5.2×10^{-3} (LHCb) [9]	$\sim 5 \times 10^{-4}$ (LHCb) [18]	$\sim 10^{-5}$
R_K, R_{K^*}	$\sim 10\%$ (LHCb) [5, 4]	$\sim$few% (LHCb/Belle II) [18, 40]	$\sim$few %
$\mathrm{BR}(B \to K^*\tau\tau)$	–	$\sim 10^{-5}$ (Belle II) [40]	$\sim 10^{-8}$
$\mathrm{BR}(B \to K^*\nu\nu)$	4.0×10^{-5} (Belle) [44]	$\sim 10^{-6}$ (Belle II) [40]	$\sim 10^{-6}$
$\mathrm{BR}(B_s \to \phi\nu\bar{\nu})$	1.0×10^{-3} (LEP) [15]	–	$\sim 10^{-6}$
$\mathrm{BR}(\Lambda_b \to \Lambda\nu\bar{\nu})$	–	–	$\sim 10^{-6}$
$\mathrm{BR}(\tau \to \mu\gamma)$	4.4×10^{-8} (BaBar) [24]	$\sim 10^{-9}$ (Belle II) [40]	$\sim 10^{-9}$
$\mathrm{BR}(\tau \to 3\mu)$	2.1×10^{-8} (Belle) [37]	$\sim$ few $\times 10^{-10}$ (Belle II) [40]	$\sim$ few $\times 10^{-10}$
$\frac{\mathrm{BR}(\tau \to \mu\nu\bar{\nu})}{\mathrm{BR}(\tau \to e\nu\bar{\nu})}$	3.9×10^{-3} (BaBar) [23]	$\sim 10^{-3}$ (Belle II) [40]	$\sim 10^{-4}$
$\mathrm{BR}(Z \to \mu e)$	7.5×10^{-7} (ATLAS) [3]	$\sim 10^{-8}$ (ATLAS/CMS)	$\sim 10^{-9} - 10^{-11}$
$\mathrm{BR}(Z \to \tau e)$	9.8×10^{-6} (LEP) [17]	$\sim 10^{-6}$ (ATLAS/CMS)	$\sim 10^{-8} - 10^{-11}$
$\mathrm{BR}(Z \to \tau\mu)$	1.2×10^{-5} (LEP) [13]	$\sim 10^{-6}$ (ATLAS/CMS)	$\sim 10^{-8} - 10^{-10}$

International review:

This exploration (scaling LEP and Belle II results) is appreciated; turn into solid prospects for TDR

Further work is encouraged to explore the flavour physics potential for the TDR

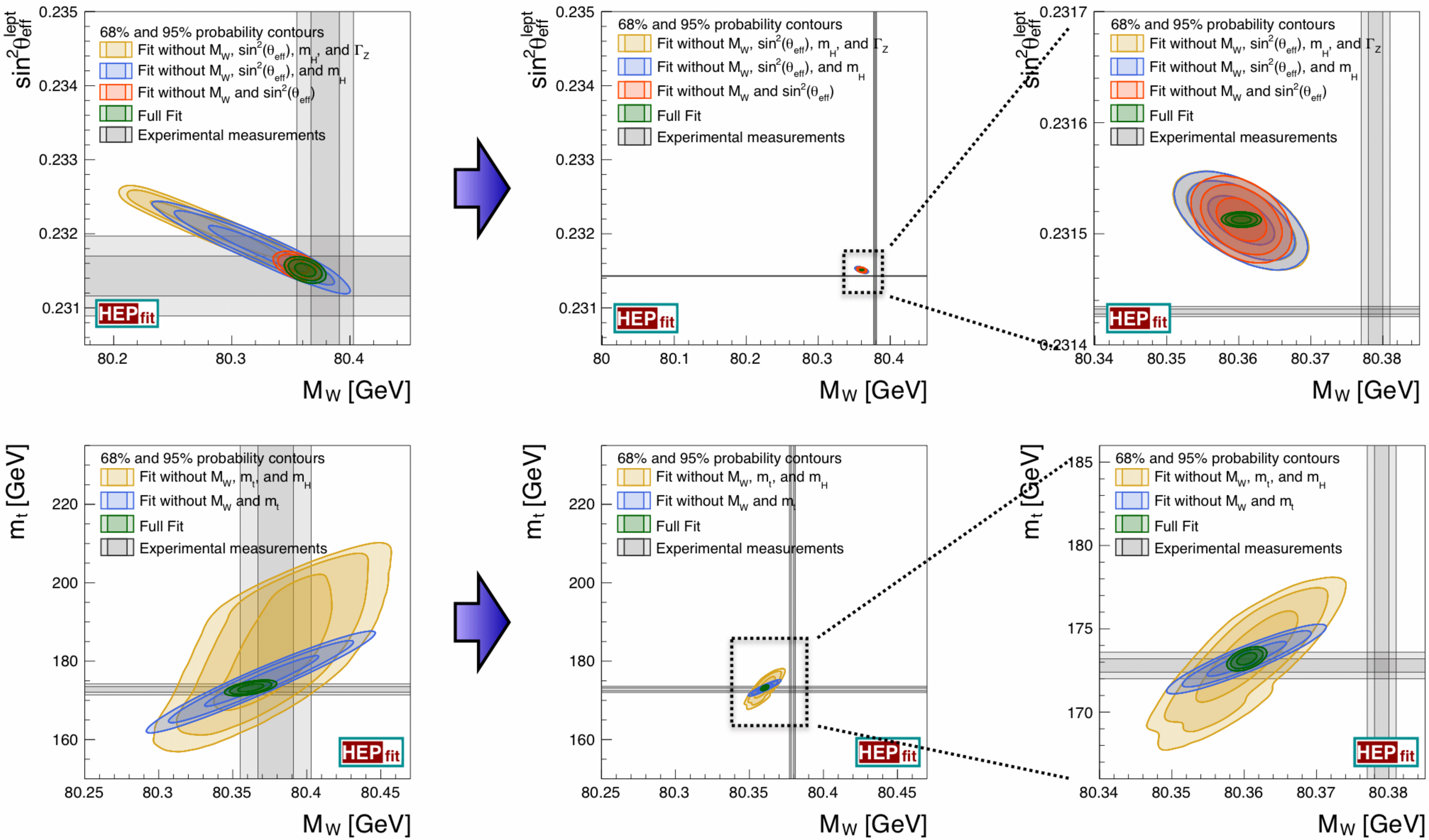
Tools

- Crucial for delivering physics results.
- Not fully covered in the CDR study.
- Many new developments of tools tailored to lepton collider physics
  - Madgraph, Whizard, HEPfit, ...
- Need to be further integrated into simulations.

CEPC sensitivity

preliminary

Today CEPC



Satoshi Mishima (KEK)

A FEW PROCESSES AT CEPC

LPTHE
LABORATOIRE DE PHYSIQUE THEORIQUE ET HAUTES ENERGIES

- A (developing and not public) MG5_aMC branch is under construction to solve all the mentioned beam issues at lepton-lepton colliders. Frixione, Zaro, Zhao, et al.
- I take the branch with rush runs at CEPC (240 GeV) WITH initial-state radiation (beamstrahlung is expected to be small within CEPC configuration).

PRELIMINARY

$\sqrt{S} = 240$ GeV	$\sigma(e^+e^- \to ZH)$ [pb]	$\sigma(e^+e^- \to ZZ)$ [pb]	$\sigma(e^+e^- \to W^+W^-)$ [pb]
LO_1	$2.05 \cdot 10^{-1}$	$1.11 \cdot 10^{0}$	$1.67 \cdot 10^{1}$
LO_2			
LO_3			
NLO_1			
NLO_2	$-4.1 \cdot 10^{-3}$	$-5.0 \cdot 10^{-2}$	$-4.0 \cdot 10^{-2}$
NLO_3			
NLO_4			
Sum	$2.01 \cdot 10^{-1} \pm 0.1\%_{\text{scale}}$	$1.06 \cdot 10^{0} \pm 0.05\%_{\text{scale}}$	$1.67 \cdot 10^{1} \pm 0.03\%_{\text{scale}}$

* Gmu scheme and same parameter setup as done in Frederix, Frixione, Hirschi, Pagani, HSS, Zaro, JHEP (2018)

Road ahead.

Suggestions from the international review

"The review committee encourages the CEPC study group to extend the studies presented in the conceptual design report in several directions, keeping a close eye on new developments. A deeper understanding is needed of the synergy with the LHC and possible new hadron collider facilities, as well as the inter-relations between precision measurements in e^+e^- collisions at different center-of-mass energies. We encourage the CEPC study group to investigate the potential of the CEPC project for QCD, flavour and neutrino physics in greater depth."

M. Vos's talk

Road ahead.

- More studies needed to further strengthen the physics potential.
- Provide input to detector/machine design.
- The international collaboration of theorists and experimentalist forged during the making of (pre)CDR will continue.
- A discussion/planning session on Thursday afternoon.
- Meeting in early July 2019.

CEPC Operation Plan

Particle type	Energy (c.m.) (GeV)	Luminosity per IP (10^{34} $cm^{-2}s^{-1}$)	Luminosity per year (ab^{-1}, 2 IPs)	Years	Total luminosity (ab^{-1}, 2 IPs)	Total number of particles
H	240	3	0.8	**7**	5.6	1×10^6
Z	91	32	8	**2**	16	7×10^{11}
W	160	10	2.6	**1**	2.6	8×10^6

CEPC yearly run time assumption:

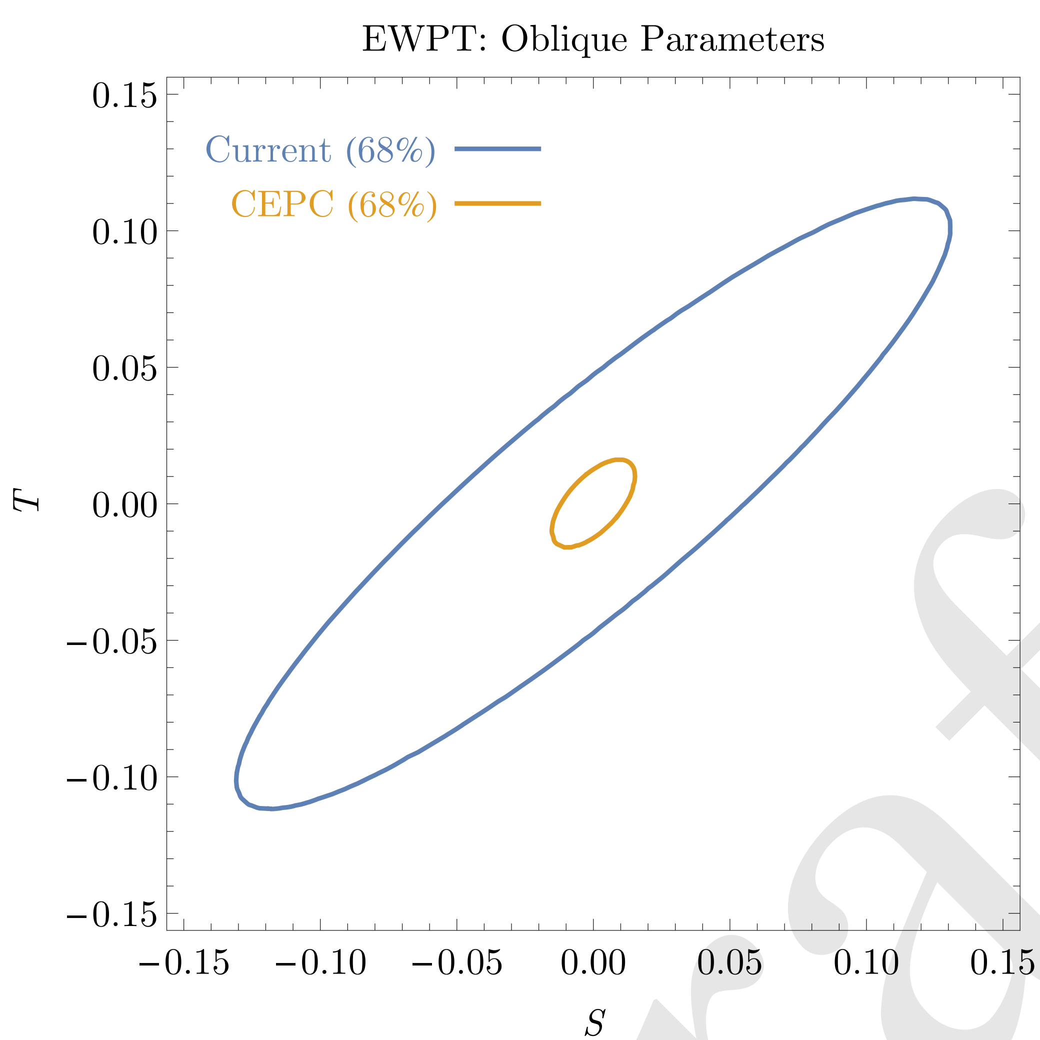
- Operation – 8 months, or 250 days, or 6,000 hrs
- Physics (60%) – 5 months, or 150 days, or **3,600 hrs**, or 1.3 Snowmass Unit.

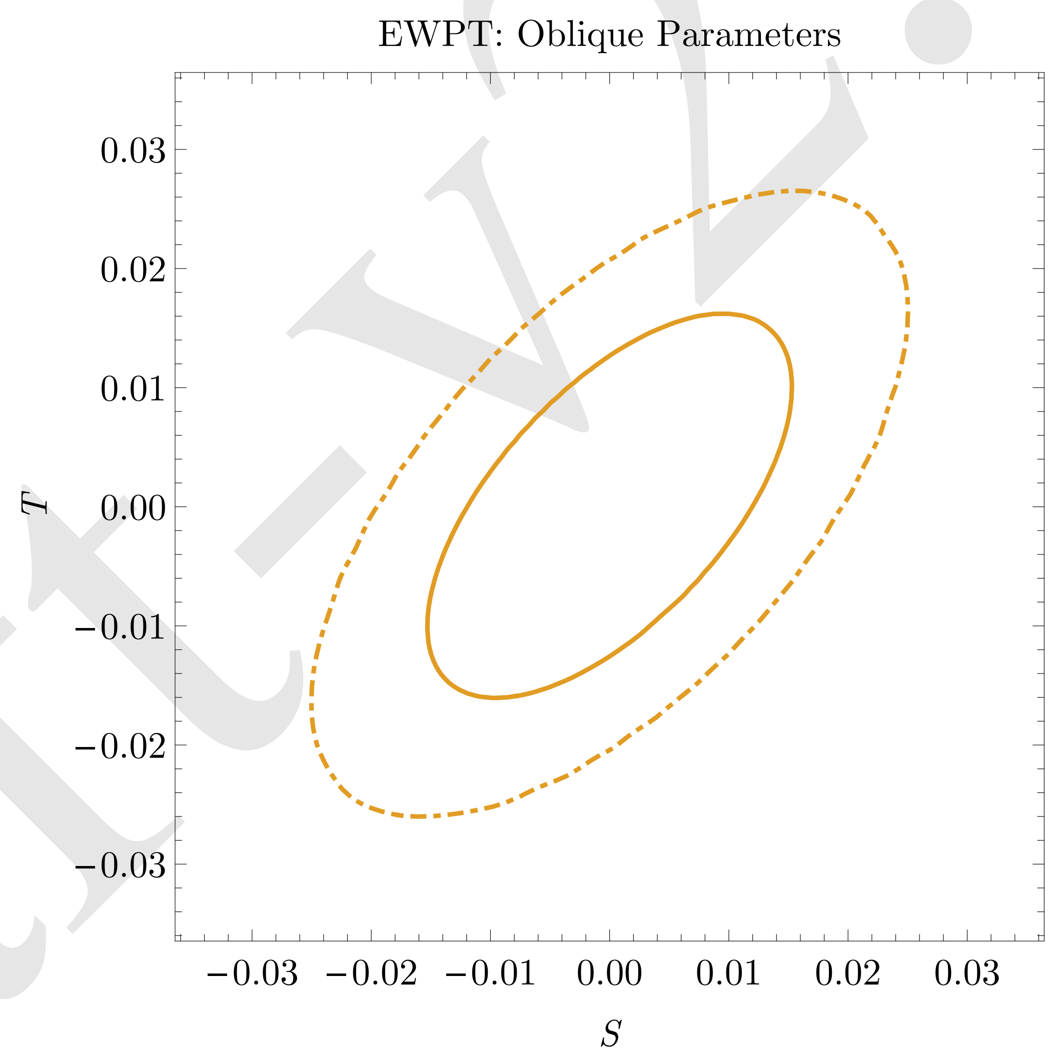
Currently, no plan to scan the ttbar threshold.

CEPC

staging scheme	physics focus
7 year at Higgs **~1M events** 240 GeV (initial stage)	H indir. BSM
2 years at Z **upto 10^{12} events** 1 year at WW **~20M events**	Z, W EW Physics

Constraining oblique parameters



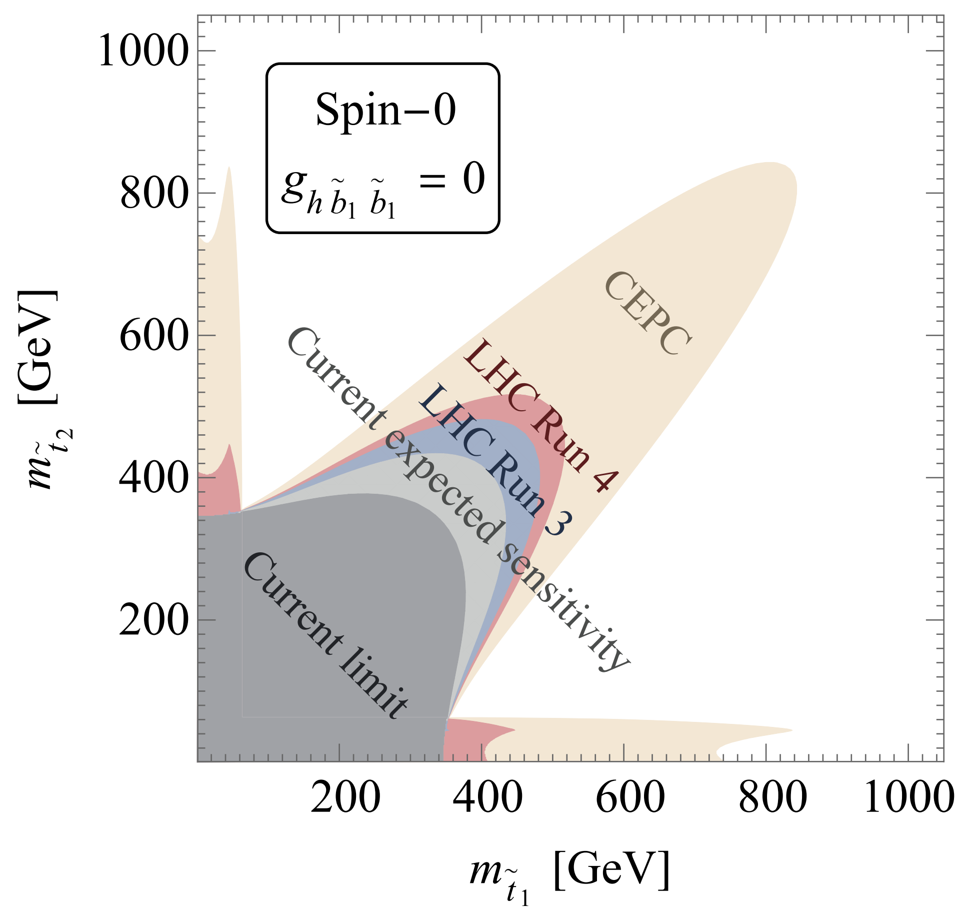


M. Reece and J. Fan

About a factor of 10 improvement

Supersymmetry

$$h \to gg,\ \gamma\gamma$$



Probing stop mass up to TeV, percentage fine-tuning

Reach does not depend on stop production and decay, complimentary to LHC direct searches.

Observable	Value	Exp. Uncertainty	Th. Uncertainty
$\alpha_s(m_Z^2)$	0.1185	1.0×10^{-4} [36]	1.5×10^{-4}
$\Delta\alpha_{\rm had}^{(5)}(m_Z^2)$	276.5×10^{-4}	4.7×10^{-5} [144]	–
m_Z [GeV]	91.1875	**0.0005**	–
m_t [GeV] (pole)	173.34	0.6 [145]	0.25 [146]
m_H [GeV]	125.14	0.1 [144]	–
m_W [GeV]	80.358617 [147]	**0.001**	1.4×10^{-3}
$A_{\rm FB}^{0,b}$	0.102971 [124, 148]	$\mathbf{1.0 \times 10^{-4}}$	8.3×10^{-5}
$A_{\rm FB}^{0,\mu}$	0.016181 [148]	$\mathbf{4.9 \times 10^{-5}}$	2.6×10^{-5}
$A_{\rm FB}^{0,e}$	0.016181 [148]	$\mathbf{8.1 \times 10^{-5}}$	2.6×10^{-5}
Γ_Z [GeV]	2.494682 [101]	**0.0005**	2×10^{-4}
$R_b \equiv \Gamma_b/\Gamma_{\rm had}$	0.2158459 [101]	$\mathbf{4.3 \times 10^{-5}}$	7×10^{-5}
$R_\ell \equiv \Gamma_{\rm had}/\Gamma_\ell$	20.751285 [101]	$\mathbf{2.1 \times 10^{-3}}$	1.5×10^{-3}
$\Gamma_{Z\to{\rm inv}}$ [GeV]	0.167177 [101]	$\mathbf{8.4 \times 10^{-5}}$	–