"Tell me that you have found no sign of New Physics again, I dare you. I double dare you. Tell me one more goddamn time!"

Highlights and future perspective of the CEPC Physics

Sven Heinemeyer, IFT/IFCA (CSIC, Madrid/Santander)

Shanghai/virtual, 10/2020

- Status of the field
- Highlights at this workshop
- Outlook / what is needed for the future

Status of the field

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Where are we in this respect? (Status? What is needed? Achievement?)

- SM/EW $\to$ 13 talks
- QCD $\to$ 7 talks
- Higgs $\to$ 14 talks
- BSM $\to$ 9 talks
- Flavor $\to$ 8 talks

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- BSM $\to$ 9 talks
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$\Rightarrow$ Impossible (and useless) to cover every single talk

$\Rightarrow$ Flavor of what has been discussed

Further complications for an overview:

Everything is connected:

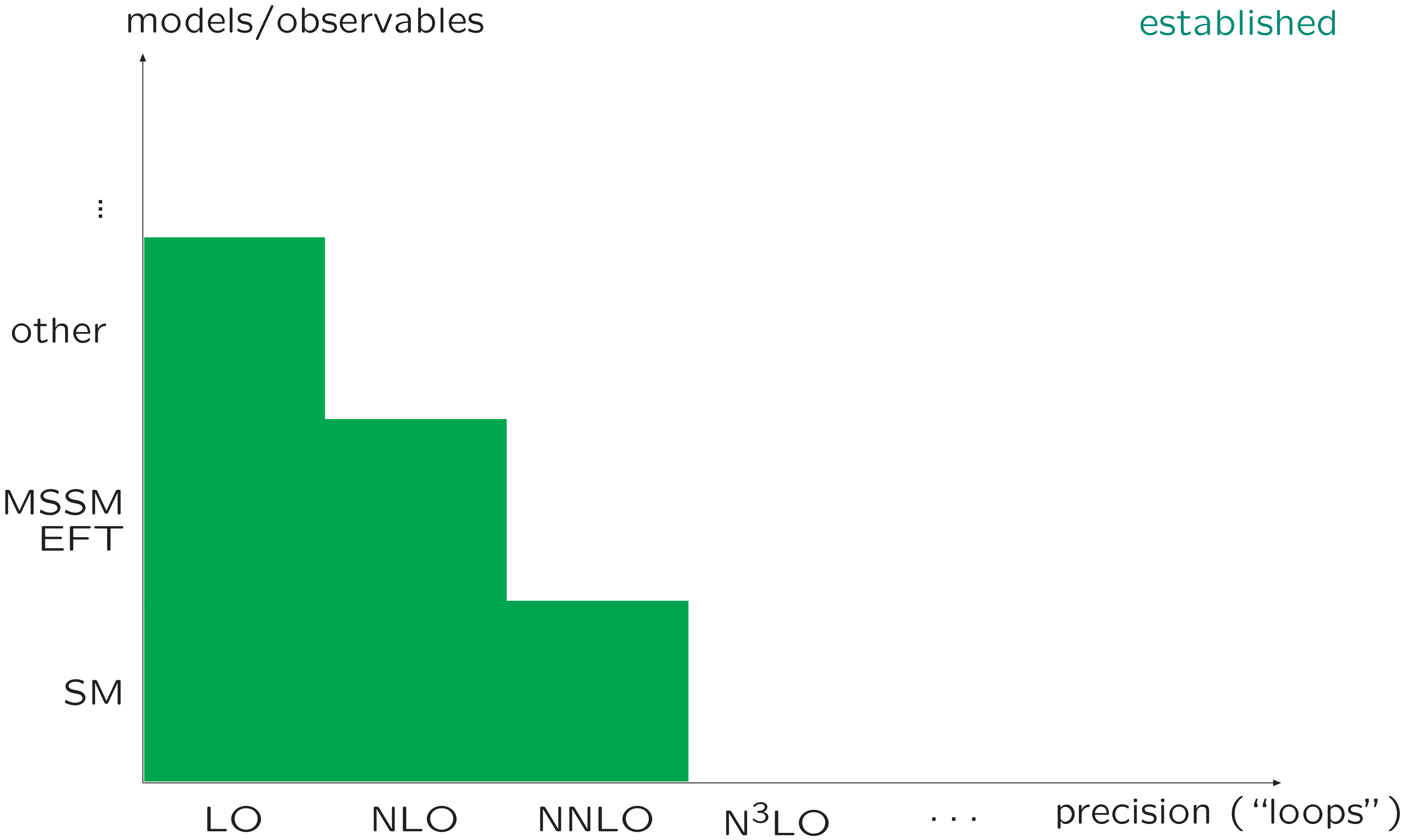
– SM must be fully understood to find BSM physics
– SM predictions require SM parameter determination, BSM impact?
– Higgs talks in Higgs, BSM, Flavor
– BSM talks in Higgs, BSM, Flavor
– ...

Even some of the parallel talks were already overview talks ...

Each "subfield" itself is multi-dimensional

$\Rightarrow$ example: Higgs

Example for complicated situation: Higgs



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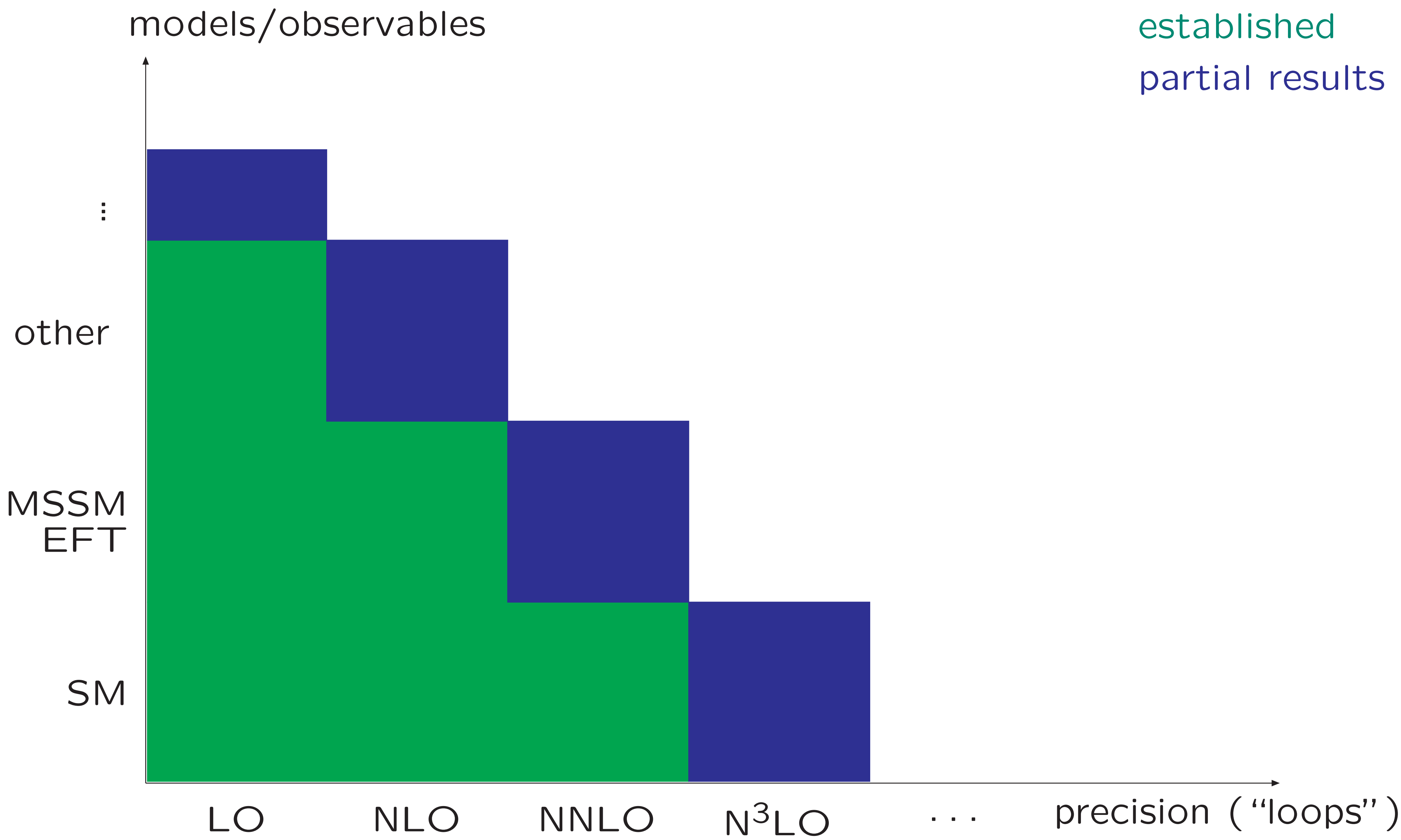

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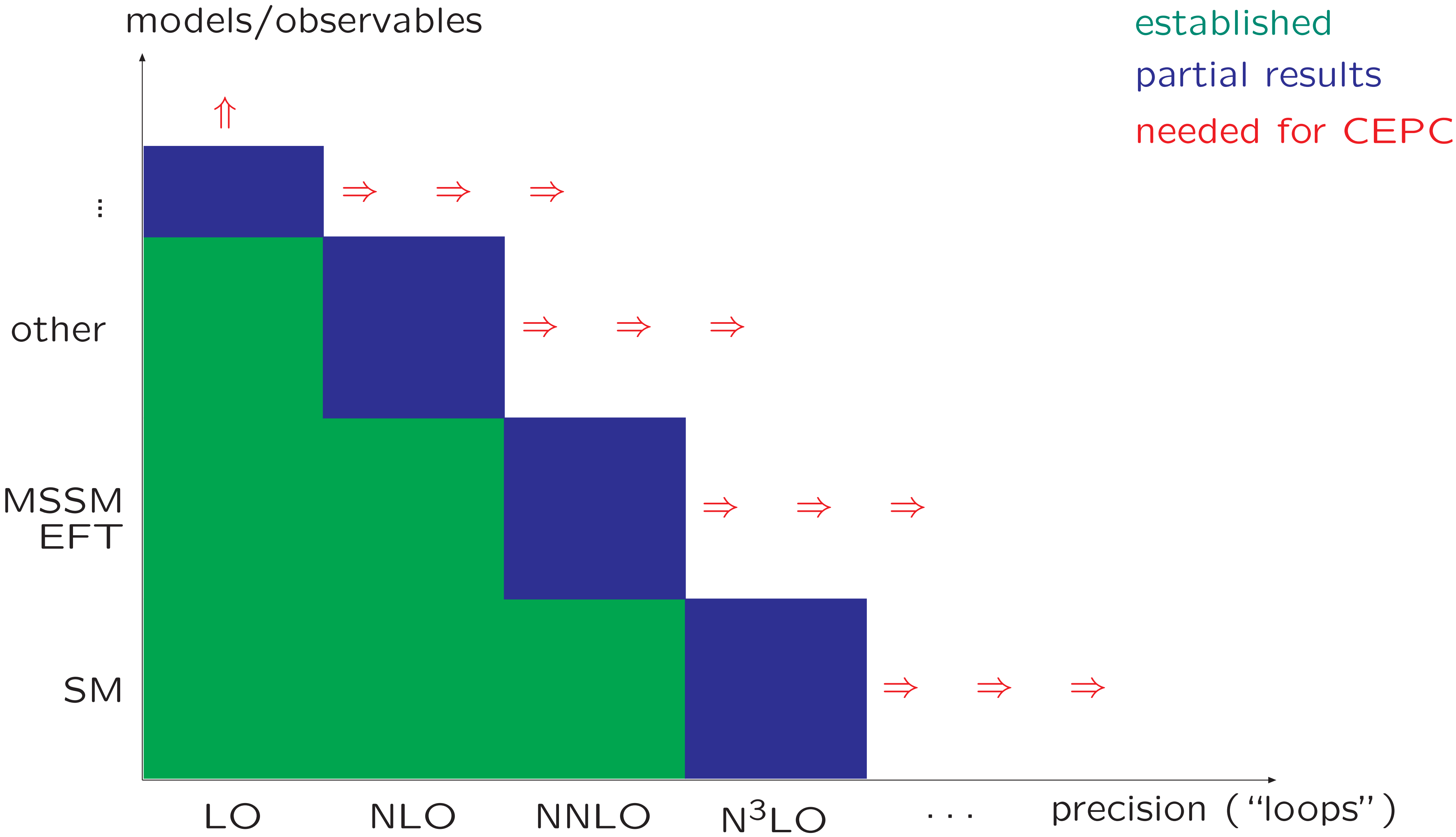

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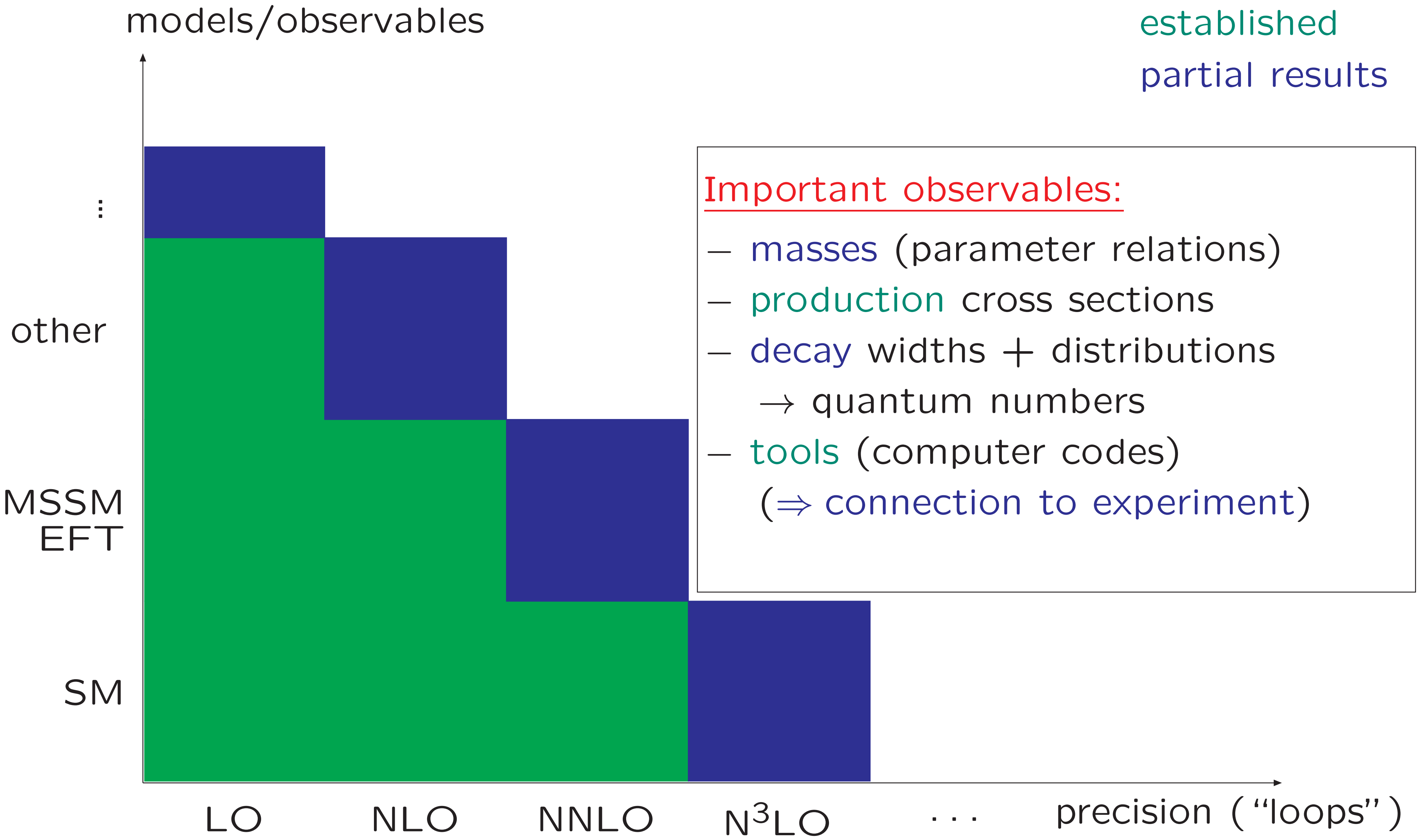
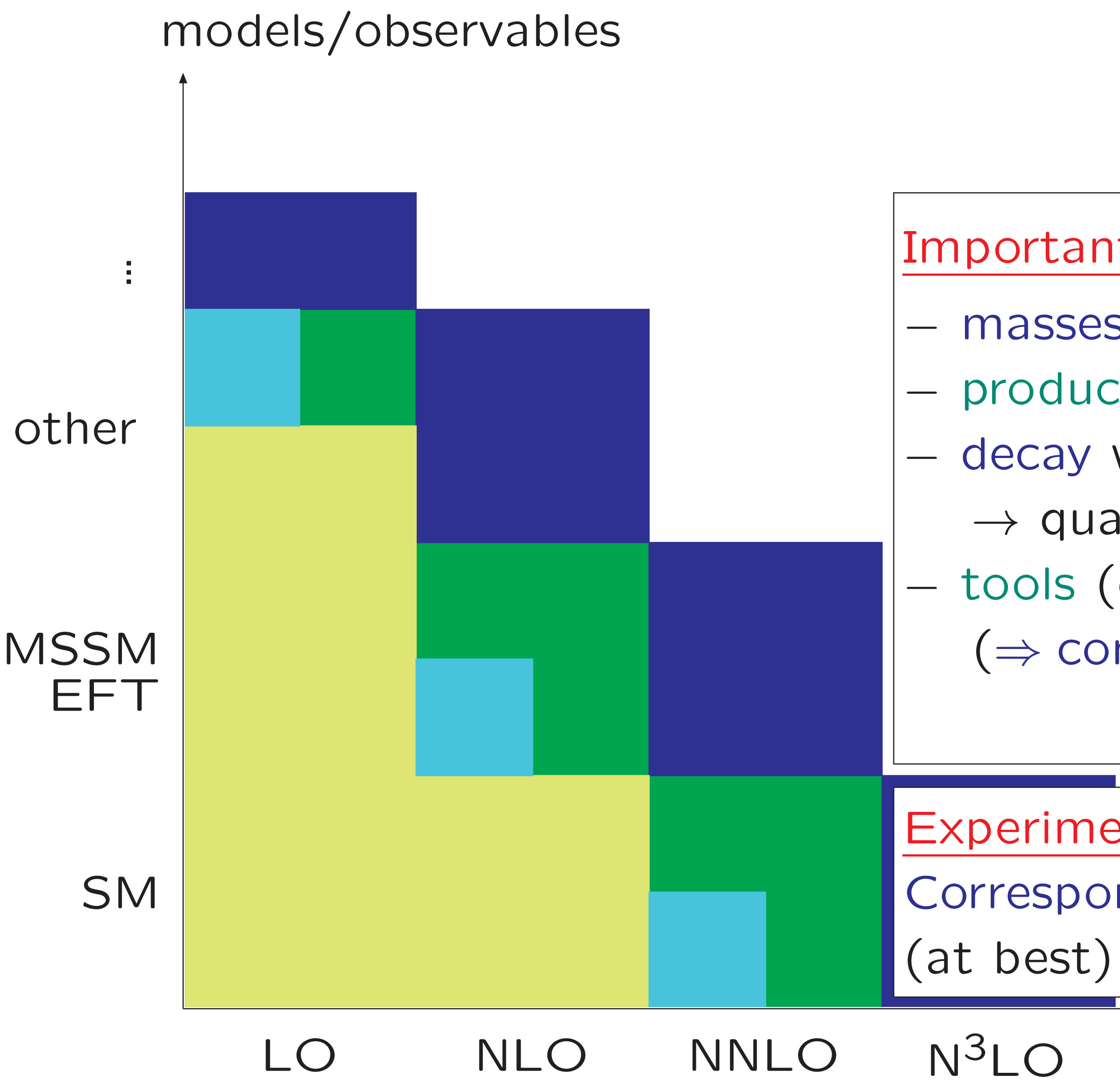


Important observables:

– masses (parameter relations)
– production cross sections
– decay widths + distributions
  $\to$ quantum numbers
– tools (computer codes)
  ($\Rightarrow$ connection to experiment)

Example for complicated situation: Higgs

experiment	theory
established	established
partial	partial results



Important observables:

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– production cross sections
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  $\to$ quantum numbers
– tools (computer codes)
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Experimental situation:

Corresponding analyses
(at best) full simulations

Some important questions:

$\Rightarrow$ that partially have been addressed at this workshop . . .

Q: Is SM Higgs physics a done deal?

Q: Are we prepared for rare/BSM Higgs decays?

Q: Does SMEFT cover all relevant BSM Higgs physics?

Q: Are we prepared for light BSM Higgs bosons?

Q: Are we happy with the λ_{hhh} situation?

Q: Are EWPO a done deal?

Q: Is CEPC350 just a nice extension of the main programe?

Q: How relevant is polarization?
Can we always compensate with high lumi?

Q: Are we ready for LLPs?

Q: Often we see FCC-ee results. Can they always be taken over?

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Q: Often we see FCC-ee results. Can they always be taken over?

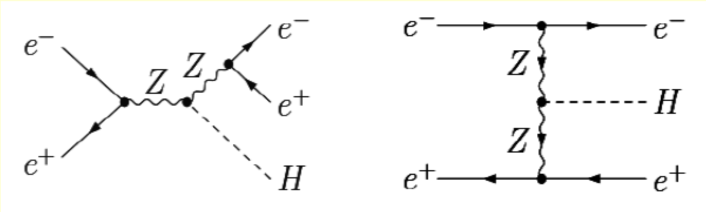
Most of the time: **A: NO** (or at least: not yet)

SM Higgs physics

[*Freitas*]

hZ production:

- $\mathcal{O}(\alpha)$ corr. to hZ production and Z decay — Kniehl '92; Denner, Küblbeck, Mertig, Böhm '92; Consoli, Lo Presti, Maiani '83; Jegerlehner '86; Akhundov, Bardin, Riemann '86
- Technology for $\mathcal{O}(\alpha)$ with off-shell Z-boson available — Boudjema et al. '04; Denner, Dittmaier, Roth, Weber '03



- Can be combined with h.o. ISR QED radiation — Greco et al. '17
- $\mathcal{O}(\alpha\alpha_s)$ corrections — Gong et al. '16; Chen, Feng, Jia, Sang '18

Theory error: $\Delta_{\rm th} \sim O(1\%)$

With full 2-loop corrections for $ee \to HZ$: $\Delta_{\rm th} \lesssim O(0.3\%)$

Parametric error: negligible if $\delta M_{\rm H} < 100$ MeV

$\Rightarrow$ more work is needed to get to the required precision

SM Higgs physics: progress in calculations

[*Buccioni*]

Higgs at e+e- colliders: couplings and ZH

Lepton colliders as Higgs factories

For the foreseen accuracy, computation of higher orders for H decays will be needed

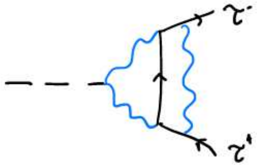
N4LO QCD: massless 4/5 loop integrals for $H \to bb/gg$

inclusive $O(\alpha_s^4)$ corrections to $H \to bb$ [Baikov, Chetyrkin, Kuhn hep-ph/0511063]

considering the inclusion of **top mass effects at N3LO QCD**

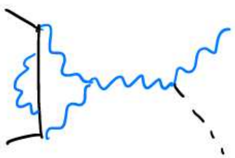
NNLO EW: massive 2-loop vertex correction

not available, but within reach

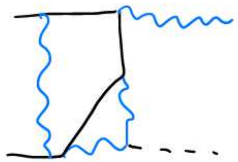


This program will depend also on advances on NNLO EW corrections to $e^+e^- \to ZH$

2 loop corrections to $e^+e^- \to ZH$



Form-factor type corrections



Could be approached with known techniques

Property	Estimated Precision
m_H	5.9 MeV
Γ_H	3.1%
$\sigma(ZH)$	0.5%
$\sigma(\nu\bar{\nu}H)$	3.2%

Decay mode	$\sigma(ZH) \times \mathrm{BR}$	BR
$H \to b\bar{b}$	0.27%	0.56%
$H \to c\bar{c}$	3.3%	3.3%
$H \to gg$	1.3%	1.4%
$H \to WW^*$	1.0%	1.1%
$H \to ZZ^*$	5.1%	5.1%
$H \to \gamma\gamma$	6.8%	6.9%
$H \to Z\gamma$	15%	15%
$H \to \tau^+\tau^-$	0.8%	1.0%
$H \to \mu^+\mu^-$	17%	17%
$H \to \mathrm{inv}$	–	$< 0.30\%$

CEPC CDR Oct 18

2 loop corrections to $e^+e^- \to Z(l^+l^-)H$

Extremely challenging.
Beyond current technologies and methods.
It will require a huge conceptual and computing effort

$\Rightarrow$ progress possible, but difficult

Why Loop Integrals ?

Precision computation of the cross-section in perturbation theory requires the computation of multi-leg / multi loop Feynman Integrals.

Reduction of scalar integrals to Master integrals using IBP

Computation of the MIs

The main bottleneck

Evaluation of MIs

Analytical approach

- 🙂 Stable and fast numerical evaluation
- ☹ Not Flexible

☑ Direct Integration (Feynman Parameter, Mellin Barnes Method)
Smirnov (1999); Tausk (1999); Czakon (2005); Czakon, Gluza, Reimann (2005); Brown (2009); Panzer (2015);

☑ Differential Equation
Kotikov (1991); Remiddi (1997); Gehrmann, Remiddi (2000); Argeri, Mastrolia (2007) Henn(2013)

Numerical approach

- 🙂 Flexible
- ☹ Numerical instabilities, not fast

☑ Sector Decomposition
Hepp (1966); Roth, Denner (1996); Binoth, Heinrich (2000); Carter, Heinrich (2010); Borowka, Carter, Heinrich (2012); Smirnov, Smirnov, Tentyukov (2011), Bogner, Weinzierl (2008); Borowka, Heinrich, Jahn, Jones, Kerner, Schlenk, Zirke (2017)

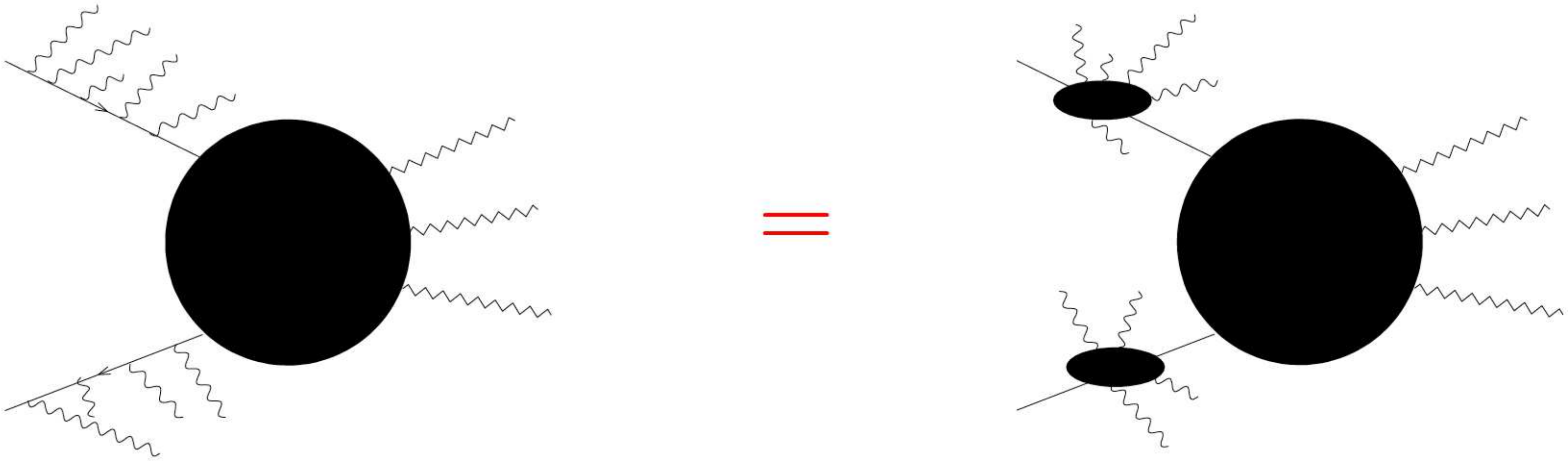
☑ Loop-Tree Duality
Catani, Gleisberg, Krauss, Rodrigo, Winter (2008); Bierenbaum, Catani, Draggiotis, Rodrigo (2010); Runkel, Szr, Vesga, Weinzierl (2019); Capatti, Hirschi, Kermanschah, Ruijl (2019); Aguilera-Verdugo, Hernandez-Pinto, Rodrigo, Sborlini, Bobadilla (2020); Ramrez-Uribe, Hernndez-Pinto, Rodrigo, Sborlini, Bobadilla (2020)

☑ Differential Equation
Boughezal, Czakon, Schutzmeier (2007); Czakon (2008); Liu, Ma, Wang (2017); MKM, Zhao (2018)

Goal: increase the accuracy in the computations of e^+e^- cross sections

Framework: a factorisation formula

- aka structure-function approach: best to *not* use this terminology



$$\sigma = \mathrm{PDF}\star\mathrm{PDF}\star\hat{\sigma}$$

PDFs collect (universal) small-angle dynamics

SM physics: progress in calculations - lepton PDFs

[*Frixione*]

Goal: increase the accuracy in the computations of e^+e^- cross sections

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These results are not yet public, since they must be double-checked.
Some *preliminary* findings are the following:

- The inclusion of NLL contributions into the electron PDF has an impact between 0.1% and 0.5%. We expect this to be somewhat observable dependent

PDFs collect (universal) small-angle dynamics

We do not only need calculations - we need them in MCs [*Pellen*]

Use in public Monte Carlo

→ WHIZARD [Kilian, Ohl, Reuter; 0708.4233]

→ SHERPA [Bothmann et al.; 1905.09127)

→ MADGRAPH5_AMC@NLO [Alwall et al.; 1405.0301]

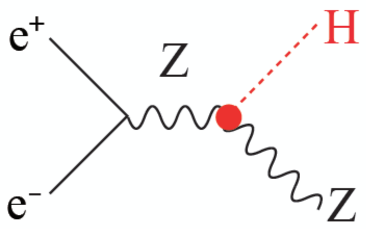
Automatised NLO EW for e^+e^- already achieved!

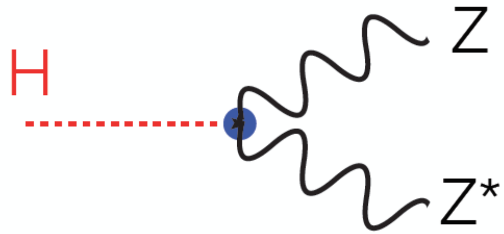
- Not working and public for all generators yet
- Electron PDF, non-perturbative effects etc. to be implemented

→ All this will be there before any e^+e^- machine is built!

- if BSM induces new Lorentz structures in hZZ interaction

$$\delta\mathcal{L} = (1+\eta_Z)\frac{m_Z^2}{v} h Z_\mu Z^\mu + \zeta_Z \frac{h}{2v} Z_{\mu\nu} Z^{\mu\nu}$$





$$\sigma(e^+e^- \to Zh) = (SM)\cdot (1 + 2\eta_Z + (5.5)\zeta_Z) \neq \Gamma(h \to ZZ^*) = (SM)\cdot (1 + 2\eta_Z - (0.50)\zeta_Z)$$

$\Rightarrow$ more complicated coupling structure $\Rightarrow$ more complicated analysis

- CEPC / FCC-ee: important role by ***Z-pole run***, ~x2 better δg_{HVV}

- ILC/ CLIC: important role by ***beam polarizations***, made up ∫L

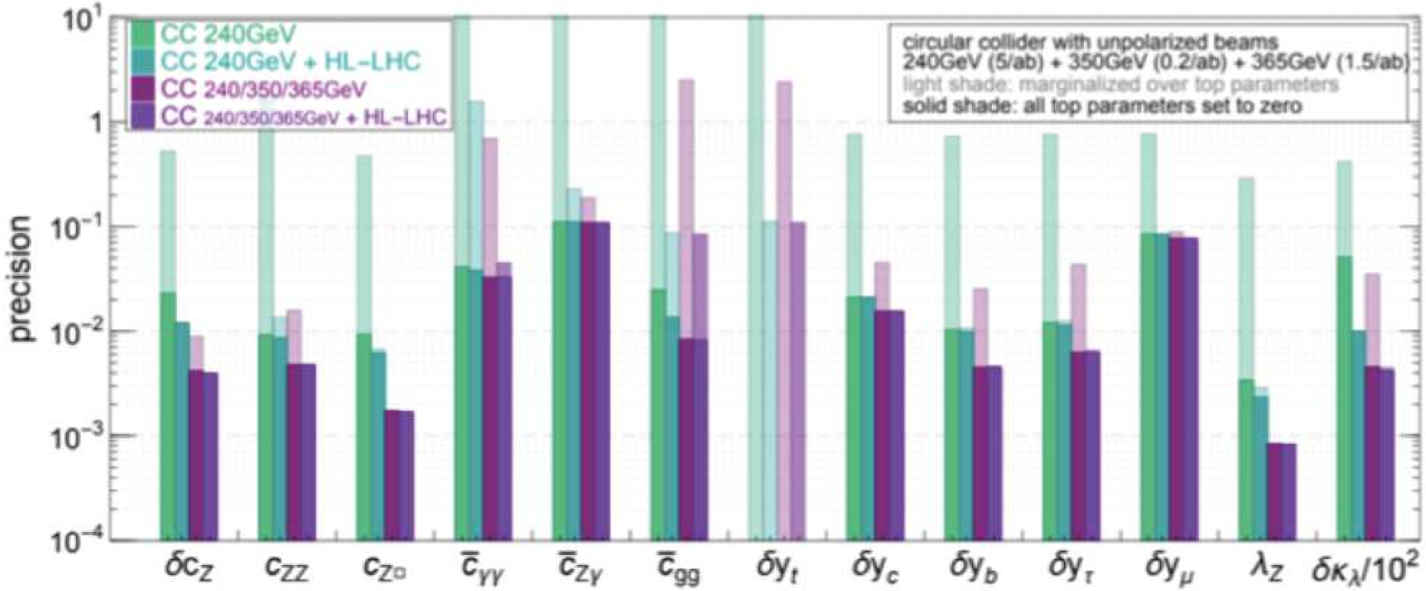
$\Rightarrow$ Luminosity can compensate for missing polarization! Always?

Higgs EFT analysis

[*Fang*]

light shades: 12 Higgs op. floated + 6 top op. floated

dark shades: 12 Higgs op. floated + 6 top op. $\to$ 0

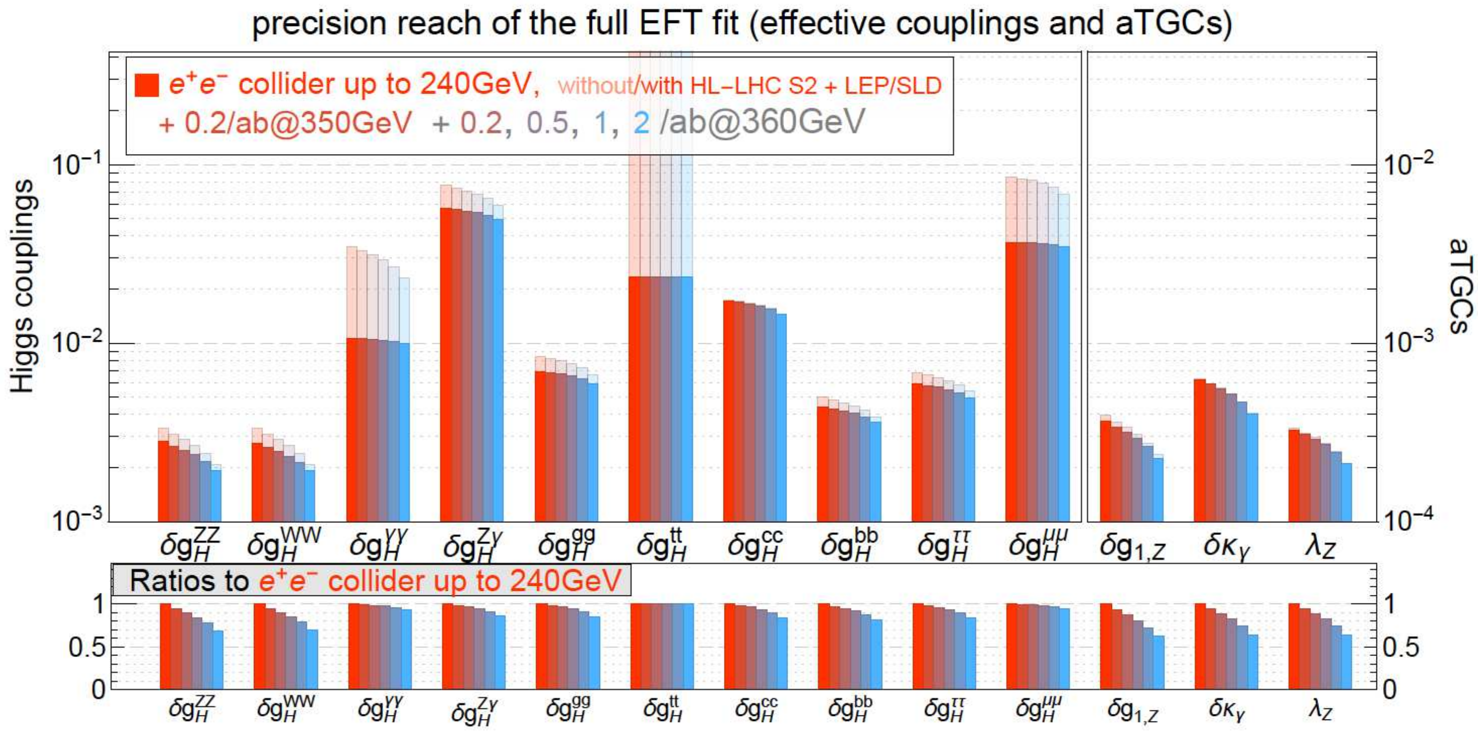


Uncertainties on the top have a big effect on the Higgs

- Higgsstr. run: insufficient
- Higgsstr. run $\oplus$ $e^+e^- \to t\bar{t}$: large y_t contaminations in various coefficients
- Higgsstr. run $\oplus$ top@HL-LHC: large top contaminations in $\bar{c}_{\gamma\gamma,gg,Z\gamma,ZZ}$
- Higgsstr. run $\oplus$ $e^+e^- \to t\bar{t}$ $\oplus$ top@HL-LHC: top contam. in $\bar{c}_{gg}$ only

$\Rightarrow$ $e^+e^- \to t\bar{t}$ becomes important

Impact of a hypothetical 350/360 GeV run

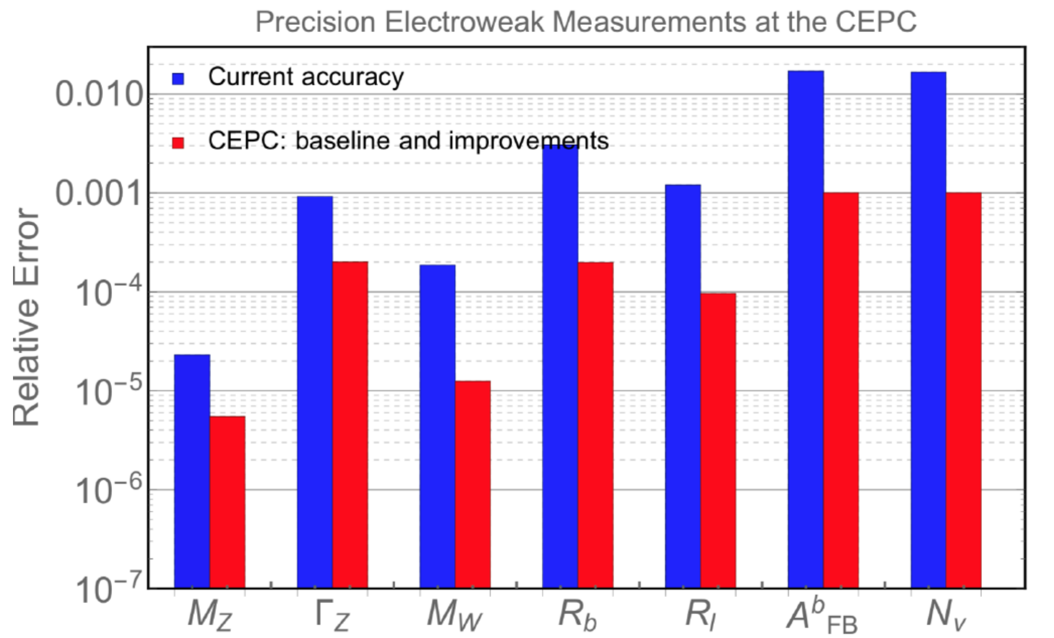


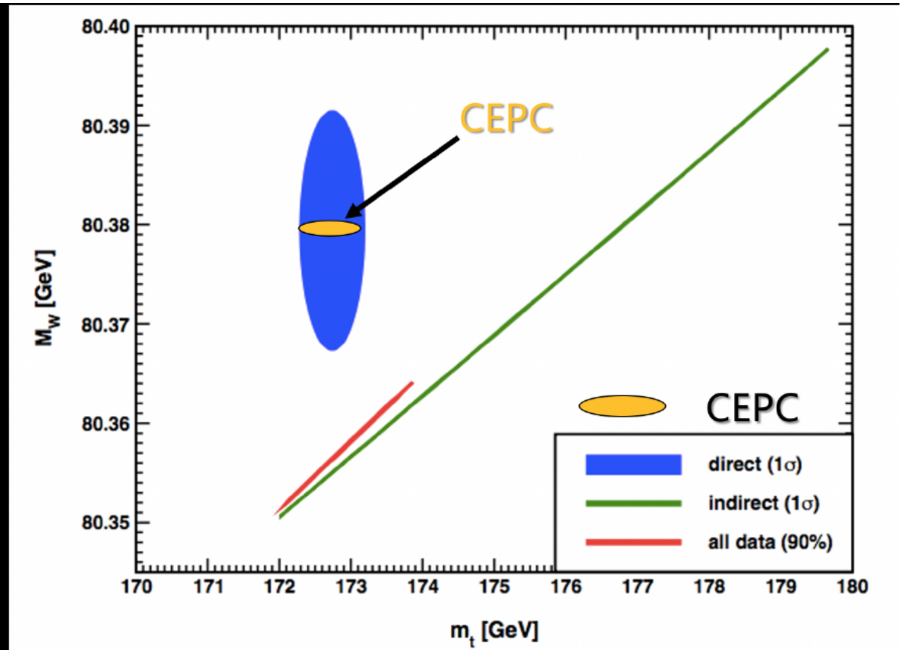
- Measurements at 350/360 GeV provides additional handles on the anomalous couplings (*e.g.* $hZ^{\mu}Z_{\mu}$ *vs.* $hZ^{\mu\nu}Z_{\mu\nu}$).
- Also improves the measurements of aTGCs.

$\Rightarrow e^+e^- \to t\bar{t}$ becomes important

EWPO at CEPC

[*Liang*]





⇒ large statistical improvement

⇒ various theory uncertainties?

M_W at CEPC (threshold scan) [*Schwinn*]

WW threshold

- Sensitivity to M_W

$$\Delta\sigma \sim 1\% \Leftrightarrow \Delta M_W \sim 15\,\text{MeV}$$

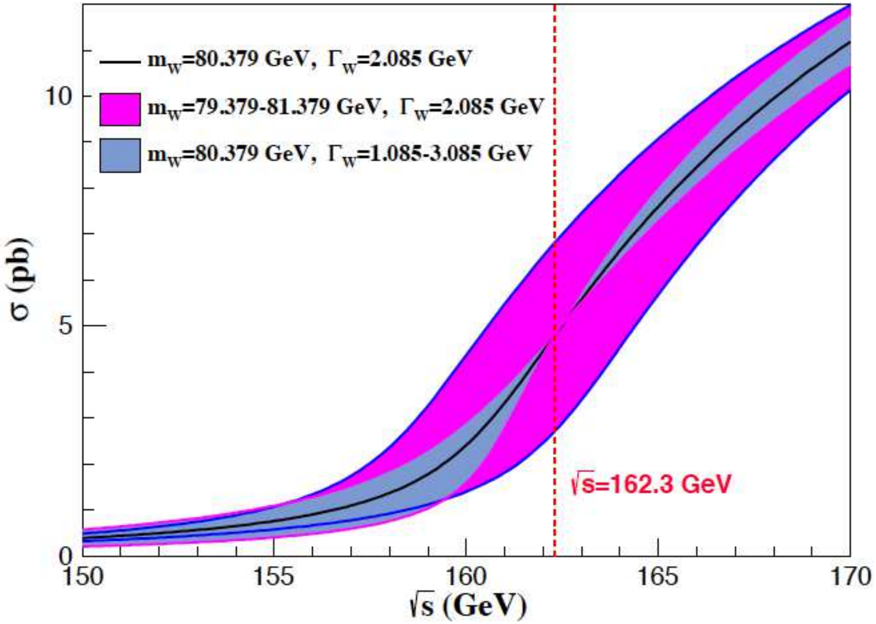
- CEPC sensitivity: (arXiv:1812.09855)

$\Delta M_W \simeq 1\,\text{MeV},\ \Delta\Gamma_W \simeq 3.2\,\text{MeV}$

(FCC-ee: $\Delta M_W \simeq 0.4\,\text{MeV},\ \Delta\Gamma_W \simeq 1.1\,\text{MeV}$)

- required theory precision

$\delta\sigma^{\text{th.}}_{WW} < 0.01 - 0.05\%$



⇒ very high requirements for theoretical precision

Prospects for CEPC/FCC-ee accuracy (CS in arXiv:1905.05078 [hep-ph])

How to achieve 0.01% accuracy for $e^-e^+ \to WW \to 4f$ near threshold?

Estimate size of NNLO-EFT corrections:

$$\mathcal{O}(\delta^2): \quad \underbrace{v^4}_{\text{Born}} \quad \underbrace{\alpha v^2}_{\text{included in NLO}_{4f}} \quad \underbrace{\alpha^2}_{\text{two-loop soft/hard}} \quad \underbrace{\alpha^3/v^2}_{\text{Coulomb-enhanced N}^3\text{LO}} \quad \underbrace{\alpha^4/v^4}_{\text{4th Coulomb}}$$

- $\mathcal{O}(\alpha^2)$ EFT corrections: estimate $C^{(2)} \approx (C^{(1)})^2$
  $\Delta\sigma_{\alpha^2} \approx 0.06\%$ $\Rightarrow$ mandatory for CEPC/FCC-ee

- subset of $\mathcal{O}(\alpha^3/v^2)$ corrections computable
  using known ingredients: (extension of Actis et al. 08)
  $\Delta\sigma_{\alpha^3} \sim 0.01\%$ $\Rightarrow$ relevant for CEPC/FCC-ee

Is a full NNLO $e^-e^+ \to 4f$ calculation required? Naive estimate:

$$\sigma^{4\mathrm{f}}_{\mathrm{NNLO}}(s) - \sigma^{(2)}_{\mathrm{EFT}}(s) \approx \frac{\alpha}{s_w^2}\left(\sigma^{4\mathrm{f}}_{\mathrm{NLO}}(s) - \sigma^{(1)}_{\mathrm{EFT}}(s)\right) = \sigma^{4\mathrm{f}}_{\mathrm{Born}}(s) \times 0.02\%$$

$\Rightarrow$ effects need to be controlled!

$\Rightarrow$ very high requirements for theoretical precision

	CEPC	perturb. error with 3-loop†	Param. error CEPC*	main source
M_W [MeV]	1	1	2.1	m_t, $\Delta\alpha$
Γ_Z [MeV]	0.5	0.15	0.15	m_t, α_s
R_b $[10^{-5}]$	4.3	5	< 1	
$\sin^2\theta^\ell_{\rm eff}$ $[10^{-5}]$	<1	1.5	2	m_t, $\Delta\alpha$

† **Theory scenario:** $\mathcal{O}(\alpha\alpha_s^2)$, $\mathcal{O}(N_f\alpha^2\alpha_s)$, $\mathcal{O}(N_f^2\alpha^2\alpha_s)$,
leading 4-loop $\mathcal{O}(\alpha_t^{4-n}\alpha_s^n)$,
$[N_f^n$ = at least n closed fermion loops, $\alpha_t = y_t^2/(4\pi)]$

Parametric inputs:

***CEPC:** $\delta m_t = 600$ MeV, $\delta\alpha_s = 0.0002$, $\delta M_Z = 0.5$ MeV,
$\delta(\Delta\alpha) = 5 \times 10^{-5}$

$\Rightarrow$ needed: theory improvement, $e^+e^- \to t\bar{t}$, $\Delta\alpha_{\rm had}$ and α_s

$\Delta\alpha_{\rm had}$ improvements? [*Passera*]

How can we improve the precision of $\Delta\alpha_{had}^{(5)}(M_Z^2)$?

- **New low-energy data for $\sigma_{had}(s)$ (CMD-3, SND, KEDR, BESIII, Belle-2, ...). Radiative Corrections to $\sigma_{had}(s)$ are crucial.**
- **Direct determination of $\Delta\alpha_{had}^{(5)}(M_Z^2)$ measuring the muon asymmetry $A^{\mu\mu}_{FB}(s)$ in the vicinity of the Z pole** Patrick Janot, JHEP 2016
- **Euclidean split method (Adler function). Needs spacelike offset $\Delta\alpha_{had}^{(5)}(-M_0^2)$ with M_0~ 2 GeV and pQCD.** Fred Jegerlehner, hep-ph/9901386
- **Future muon-electron scattering data at the MUonE experiment may help determine the spacelike offset $\Delta\alpha_{had}^{(5)}(-M_0^2)$** (see later)
- **Lattice QCD? Lots of work in progress for the hadronic vacuum polarization contribution to the muon g-2.**

$\Rightarrow$ improvements possible, but far beyond trivial

α_s relevance and improvements

[d'Entierra]

- Impacts all QCD x-sections & decays (H), precision top & parametric EWPO:

Process	σ (pb)	$\delta\alpha_s(\%)$	PDF $+\alpha_s(\%)$	Scale(%)
ggH	49.87	± 3.7	-6.2 +7.4	-2.61 +0.32
ttH	0.611	± 3.0	$\pm$ 8.9	-9.3 +5.9

Channel	M_H[GeV]	$\delta\alpha_s(\%)$	Δm_b	Δm_c
$H \to c\bar{c}$	126	± 7.1	$\pm 0.1\%$	± 2.3 %
$H \to gg$	126	± 4.1	$\pm 0.1\%$	± 0 %

Msbar mass error budget (from threshold scan)

$(\delta M_t^{\text{SD-low}})^{\text{exp}}$	$(\delta M_t^{\text{SD-low}})^{\text{theo}}$	$(\delta\overline{m}_t(\overline{m}_t))^{\text{conversion}}$	$(\delta\overline{m}_t(\overline{m}_t))^{\alpha_s}$
40 MeV	50 MeV	7 – 23 MeV	70 MeV

$\Rightarrow$ improvement in α_s crucial $\qquad \delta\alpha_s(M_z) = 0.001$

Quantity	FCC-ee	future param.unc.	Main source
Γ_Z [MeV]	0.1	0.1	$\delta\alpha_s$
R_b $[10^{-5}]$	6	< 1	$\delta\alpha_s$
R_ℓ $[10^{-3}]$	1	1.3	$\delta\alpha_s$

- FCC-ee:

– Huge Z pole stats. ($\times 10^5$ LEP)

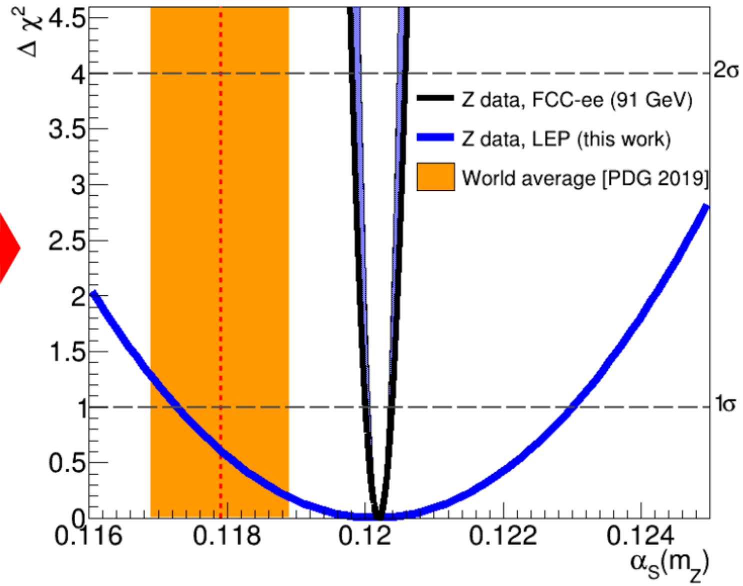
– Exquisite systematic/parametric precision (stat. uncert. much smaller):

$$\Delta R_Z = 10^{-3}, \qquad R_Z = 20.7500 \pm 0.0010$$
$$\Delta\Gamma_Z^{\text{tot}} = 0.1 \text{ MeV}, \quad \Gamma_Z^{\text{tot}} = 2495.2 \pm 0.1 \text{ MeV}$$
$$\Delta\sigma_Z^{\text{had}} = 4.0 \text{ pb}, \quad \sigma_Z^{\text{had}} = 41\,494 \pm 4 \text{ pb}$$
$$\Delta m_Z = 0.1 \text{ MeV}, \quad m_Z = 91.18760 \pm 0.00001 \text{ GeV}$$
$$\Delta\alpha = 3 \cdot 10^{-5}, \quad \Delta\alpha_{\text{had}}^{(5)}(m_Z) = 0.0275300 \pm 0.0000009$$

– TH uncertainty reduced by $\times 4$ computing missing α_s^5, α^3, $\alpha\alpha_s^2$,$\alpha\alpha_s^2$,$\alpha^2\alpha_s$ terms

- 10 times better precision than today: $\delta\alpha_s/\alpha_s \sim \pm 0.2\%$ (tot), $\pm 0.1\%$ (exp)

DdE, Jacobsen: arXiv:2005.04545 [hep-ph]



$\alpha_s(m_Z) = 0.12030 \pm 0.00028$ ($\pm 0.2\%$)

$\Rightarrow$ evaluated for FCC-ee! Applicable for CEPC?

What can be learned at CEPC350?

[*Maier*]

- Mass in well-defined scheme:
  - $\sigma(e^+e^- \to t\bar{t})$ at $\sqrt{s} \approx 350\,\text{GeV}$: $\Delta m_t \approx 50\,\text{MeV}$
  - $\sigma(e^+e^- \to t\bar{t}\gamma)$ at $\sqrt{s} \approx 380\,\text{GeV}$: $\Delta m_t \approx 150\,\text{MeV}$

  [Boronat, Fullana, Fuster, Gomis, Vos, Hoang, Widl, Mateu 2020]
- Width:
  - $\sigma(e^+e^- \to t\bar{t})$ at $\sqrt{s} \approx 350\,\text{GeV}$: $\Delta\Gamma_t \approx 60\,\text{MeV}$
- Yukawa coupling:
  - $\Gamma_{h\to gg}, \Gamma_{h\to\gamma\gamma}$: $\Delta\kappa_t < 0.01$

    [Boselli, Hunter, Mitov 2018]
  - $\sigma(e^+e^- \to t\bar{t}h)$ at $\sqrt{s} \geq 550\,\text{GeV}$: $\Delta\kappa_t \approx 0.04$
  - $\sigma(e^+e^- \to t\bar{t}h)$ at $\sqrt{s} \approx 500\,\text{GeV}$: $\Delta\kappa_t \approx 0.06$

    [arXiv:1409.7157, arXiv:1506.05992, arXiv:1807.02441]

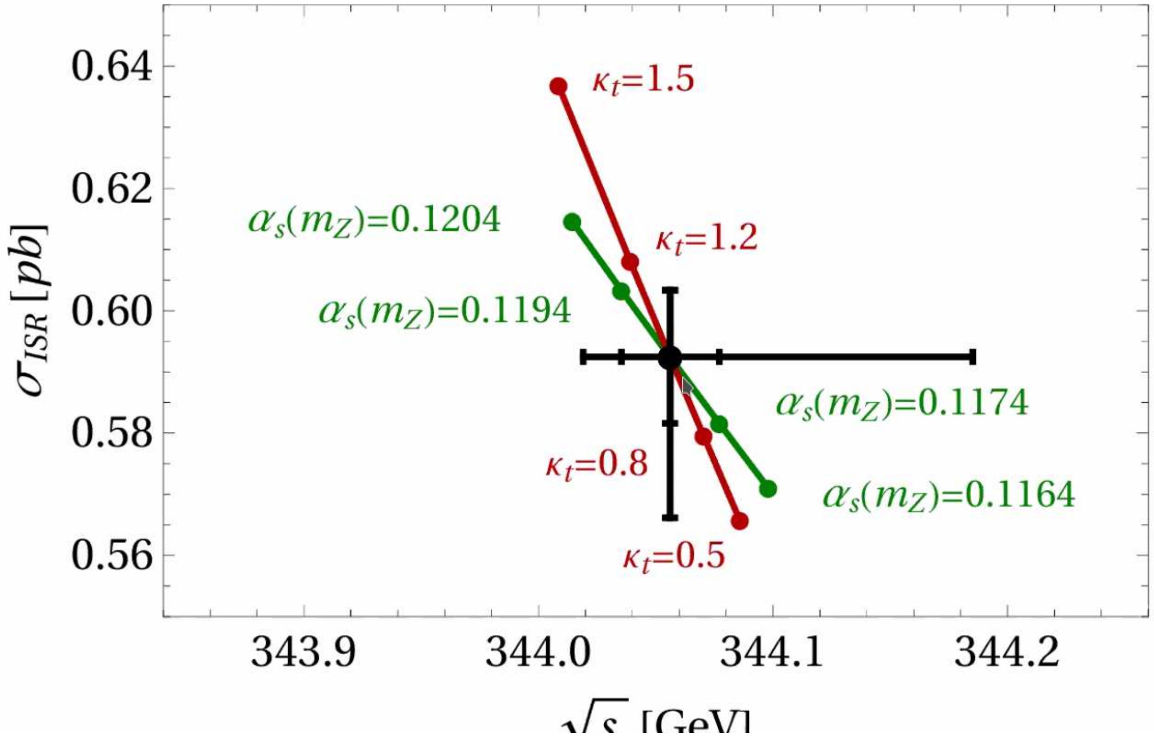
    [Farell, Hoang 2005; Dawson, Reina 2017]
  - $\sigma(e^+e^- \to t\bar{t})$ at $\sqrt{s} \approx 350\,\text{GeV}$: $\Delta\kappa_t \approx 0.25$

$\Rightarrow$ CEPC350 is crucial and interesting

Top parameter "extraction"

[*Maier, Hoang*]

Peak position



There are still many interesting unresolved problems to work on to sharpen the theoretical tools for future lepton colliders.

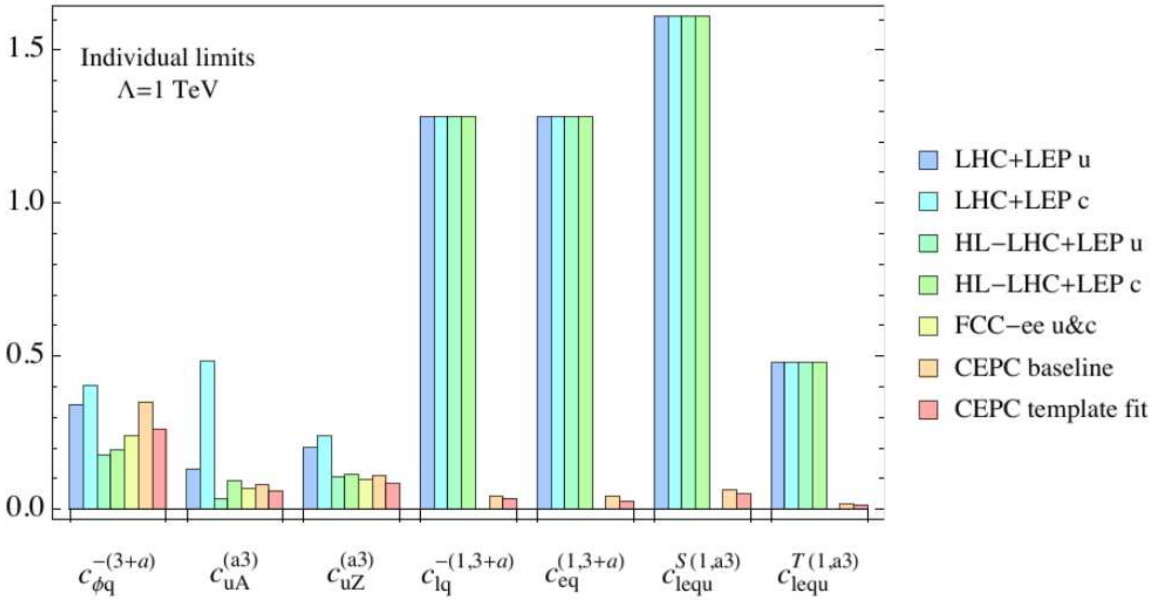
Development of a new generation of more precise Monte-Carlo generators must receive high priority in the community as being theory work that is valuable by itself (such as loop calculations).

$\Rightarrow$ Much more theory effort needed!

Top physics at CEPC240

[Altmanshofer]

- Running in Higgs factory mode (240 GeV) is not sufficient for $t\bar{t}$ production. But, single top production possible in the presence of non-standard flavor violating interactions $(\bar{t}q)(\bar{e}e)$ (negligible in the SM)



- Four fermion operators $(\bar{t}q)(\bar{e}e)$ can be probed up to several TeV

(Shi, Zhang 1906.04573)

⇒ possibly interesting top physics at CEPC240 already?!

EFT evolution for the CEPC

[*Gu*]

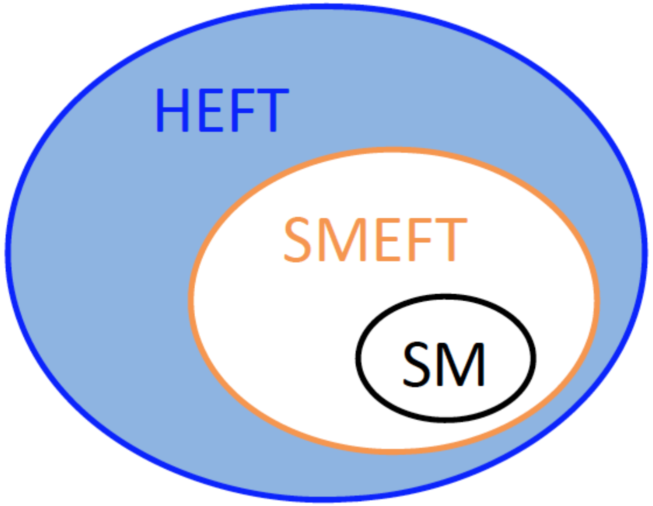
- EFT fit **v1.0** (CEPC CDR) based on [arXiv:1704.02333] Durieux, Grojean, JG, and Wang, [arXiv:1711.03978] Di Vita, Durieux, Grojean, JG, Liu, Panico, Riembau, and Vantalon
  - **Higgs + aTGCs** (anomalous triple gauge couplings)
  - Z-pole, W mass, width and BRs all assumed to be **perfectly SM-like**.
  - Simple binned analysis to extract aTGCs from $e^+e^- \to WW$.
  - Indirect probes on the triple Higgs coupling.
- EFT fit **v1.5** (progress made after CDR)

  based on [arXiv:1907.04311] De Blas, Durieux, Grojean, JG, Paul
  - **Higgs + EW (+ aTGCs)**
  - Realistic Z-pole, W mass, width and BRs measurements.
  - Optimal observable analysis for $e^+e^- \to WW$, full EFT parameterization.
- EFT fit **v1.6?**
  - Towards a realistic $e^+e^- \to WW$ analysis.
  - A hypothetical 350/360/365 GeV run? (Top operators, triple Higgs coupling, ...)
- EFT fit **v2.0?** (CEPC TDR)
  - **Higgs + EW + Top?** (see also Junping's talk)
  - 1-loop contributions: triple Higgs coupling, top couplings, others?
  - Dimension 8 operators?

$\Rightarrow$ substantial evolution! But which EFT is needed?

Various EFTs:

[Lu]

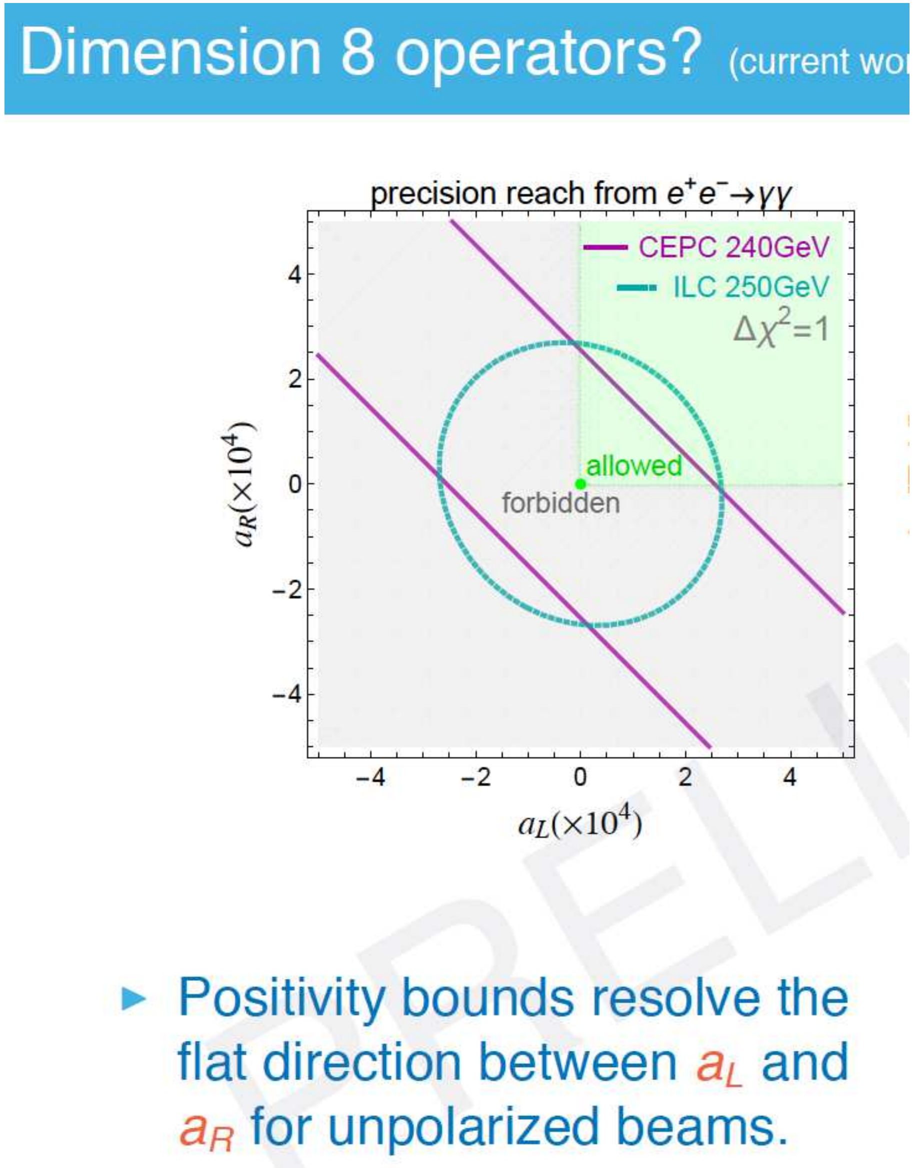


$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \frac{C_H}{\Lambda^2}|H|^6 + \frac{C_{H\Box}}{\Lambda^2}|H|^2 \partial^2 |H|^2 + \frac{C_R}{\Lambda^2}|H|^2 |DH|^2 + \cdots$$

UV theories that will generate HEFT?

$\Rightarrow$ Not apriori clear which EFT is adequate

$\Rightarrow$ Which (part of an) EFT is phenomenologically relevant?



Example: $e^+e^- \to \gamma\gamma$

dim-8 operators for triple boson couplings can be resolved with polarization

Luminosity?
CEPC answer?

Future measurement of the hhh coupling

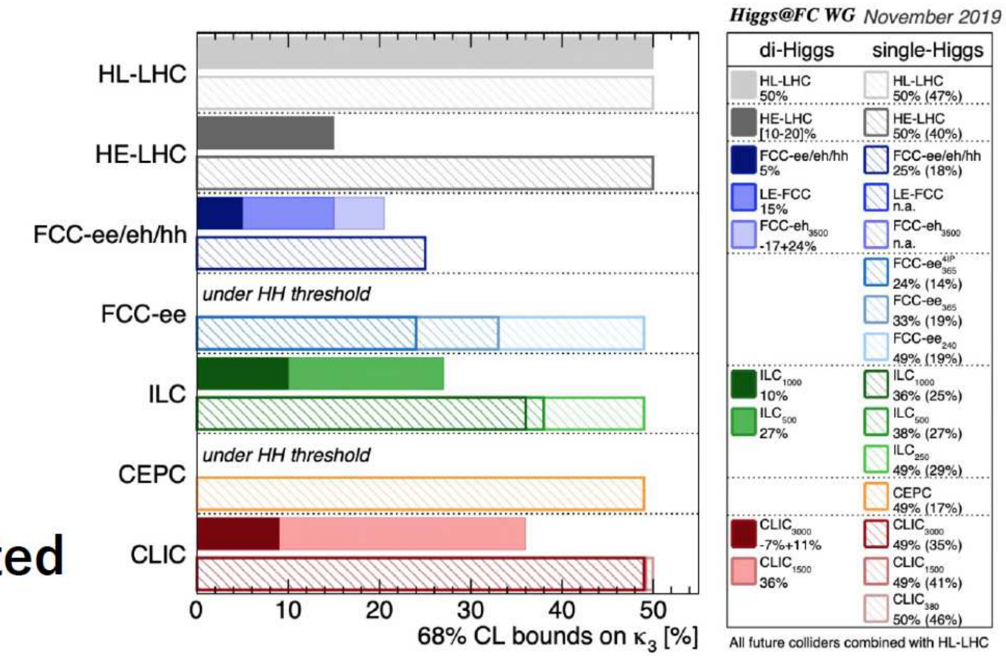
HE-LHC, FCC$_{hh}$, ⋯

$$pp \to hhX$$

ILC500, ILC1000, CLIC, ⋯

$$e^+e^- \to Zhh$$
$$e^+e^- \to \nu\bar{\nu}hh$$

The triple Higgs coupling is expected to be measured with 10% at ILC1000, CLIC3000, FCC$_{hh}$, ⋯



arXiv: 1905.03764

We do not miss to test the 1st order phase transition for EW baryogenesis

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⇒ deviations in BSM models, relevant for FOEWPT!

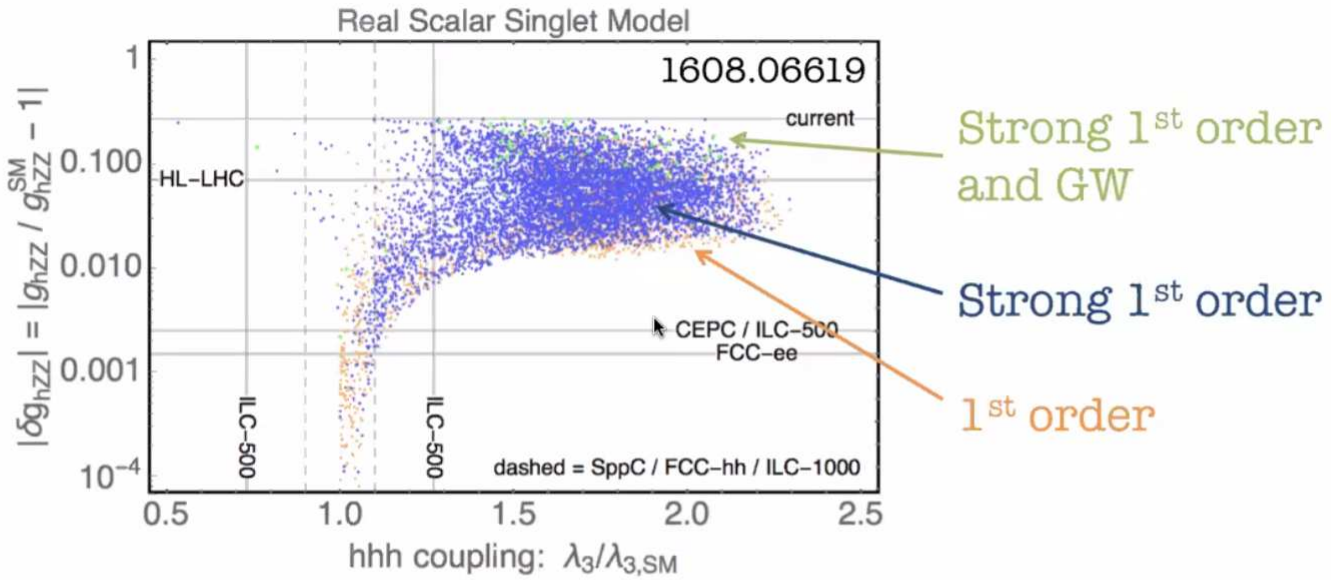
⇒ Can the measurement of λ_{hhh} be improved for the CEPC?

What if $\lambda_{hhh} \neq \lambda_{hhh}^{\text{SM}}$?

[*McCullough*]

The Electroweak Phase Transition

Difficult to make model-independent statements, however scenarios with modified EWPT produce correlated deviations in precision Higgs. Example:



Very simple: Add a singlet scalar.

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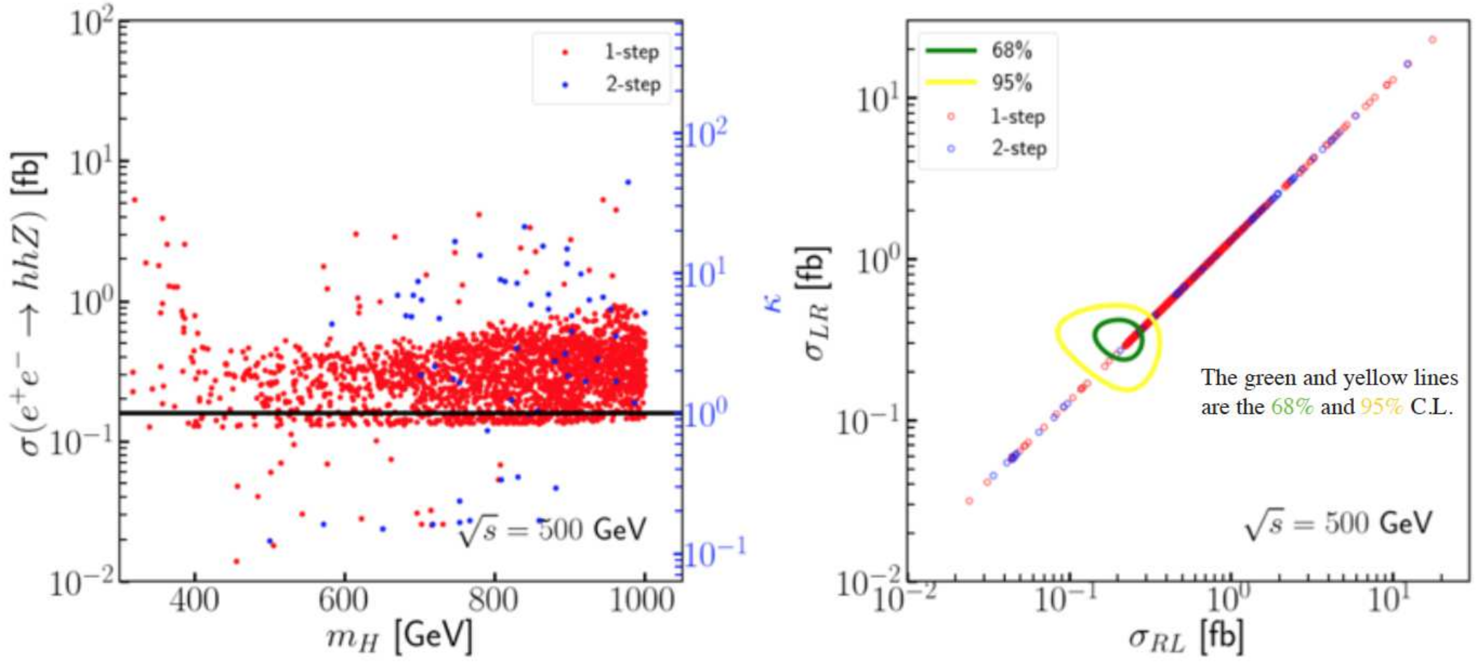
$\Rightarrow$ How well does the single Higgs EFT work for $\lambda_{hhh} \neq \lambda_{hhh}^{\text{SM}}$?

Note: also $\lambda_{hhh}^{\text{HxSM}} < \lambda_{hhh}^{\text{SM}}$ is possible [*Ramsey-Musolf*]

Lepton collider Search xSM

$\sigma_{LR}(\sigma_{RL})$ denotes the cross section at beam polarization configurations of $(P_{e^+}, P_{e^-}) = (+1,-1)((-1,+1))$.



ILC/CEPC will exclude most one-step as well as two-step points in the xSM.

⇒ interesting complementarity, but difficult at CEPC . . .

Example for BSM physics at CEPC:

[*Englert*]

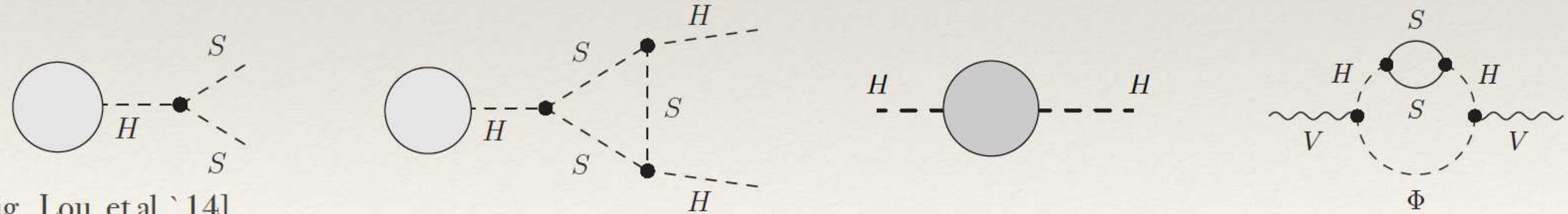
- $\mathbb{Z}_2$-symmetric Higgs portal

[Craig , Lou. et al. ` 14]
[Curtin, Meade, Yu ` 14]
...

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{1}{2}(\partial_\mu S)^2 - \frac{m_S^2}{2} S^2 - \lambda S^2 (\Phi^\dagger \Phi - v^2/2)$$

- for $m_S > m_H/2$ no direct SM Higgs decays
- BSM Higgs physics via momentum- or loop-suppressed effects

off-shell production | di-Higgs physics | Higgs couplings | Oblique corrections



[Craig , Lou. et al. ` 14]
[Ruhdorfer, Salvioni, Weiler ` 19]

[Curtin, Meade, Yu ` 14]
[He, Zhu ` 16]
[Voigt, Westhoff ` 17]

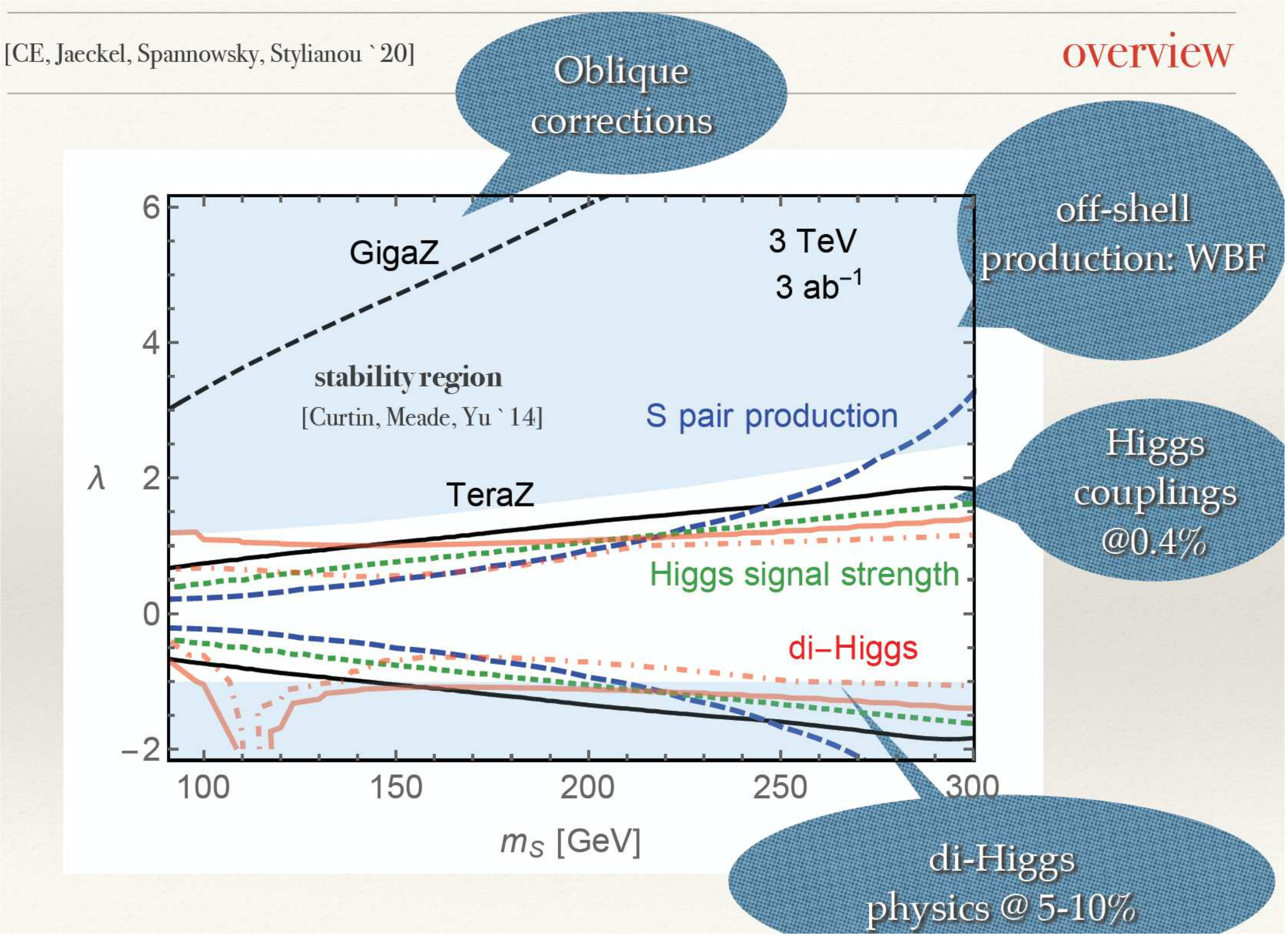
[CE, McCullough ` 13]
[Craig, CE, McCullough ` 13]
[Goncalves, Han, Mukhopadhyay ` 18]

[CE, Jaeckel, Spannowsky, Stylianou ` 20]

$\Rightarrow$ many ways to test a singlet, partially(!) at CEPC

Example for BSM physics at CEPC:

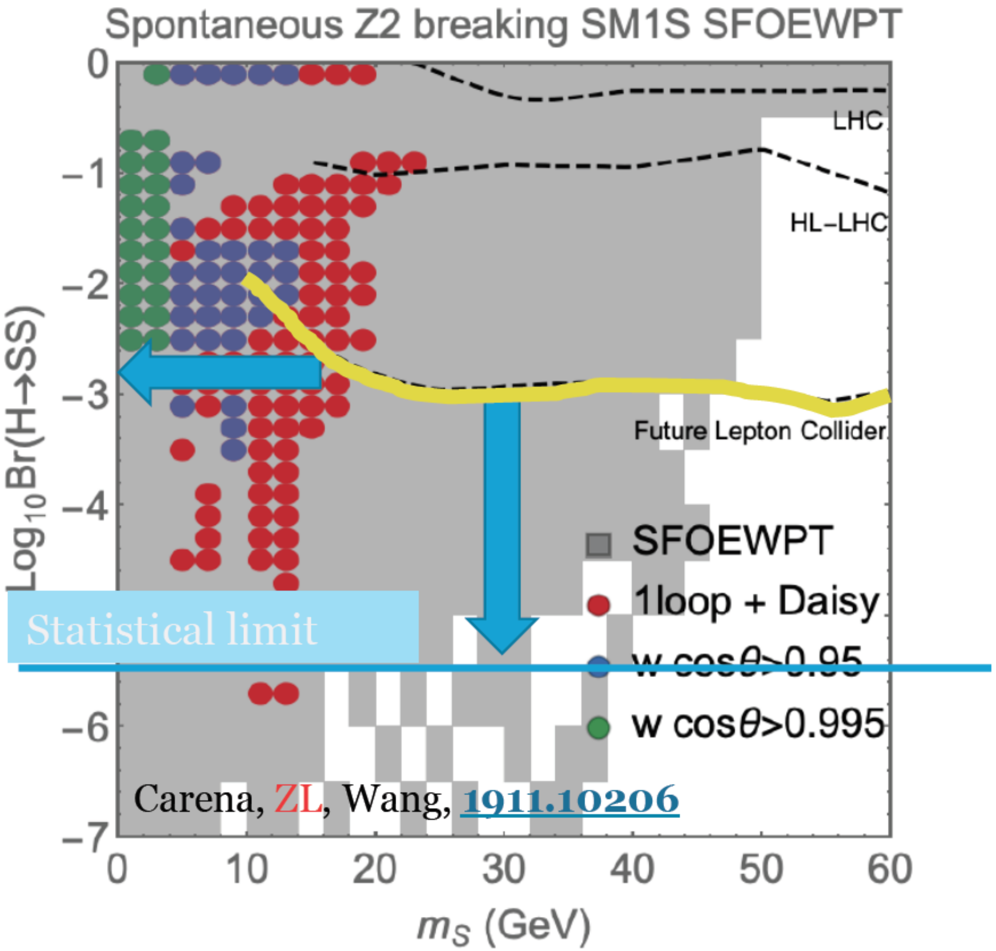
[*Englert*]



⇒ many ways to test a singlet, partially(!) at CEPC

Example for BSM physics at CEPC: [*Liu*]

Exotic Decays (example 3): Higgs & EWPT

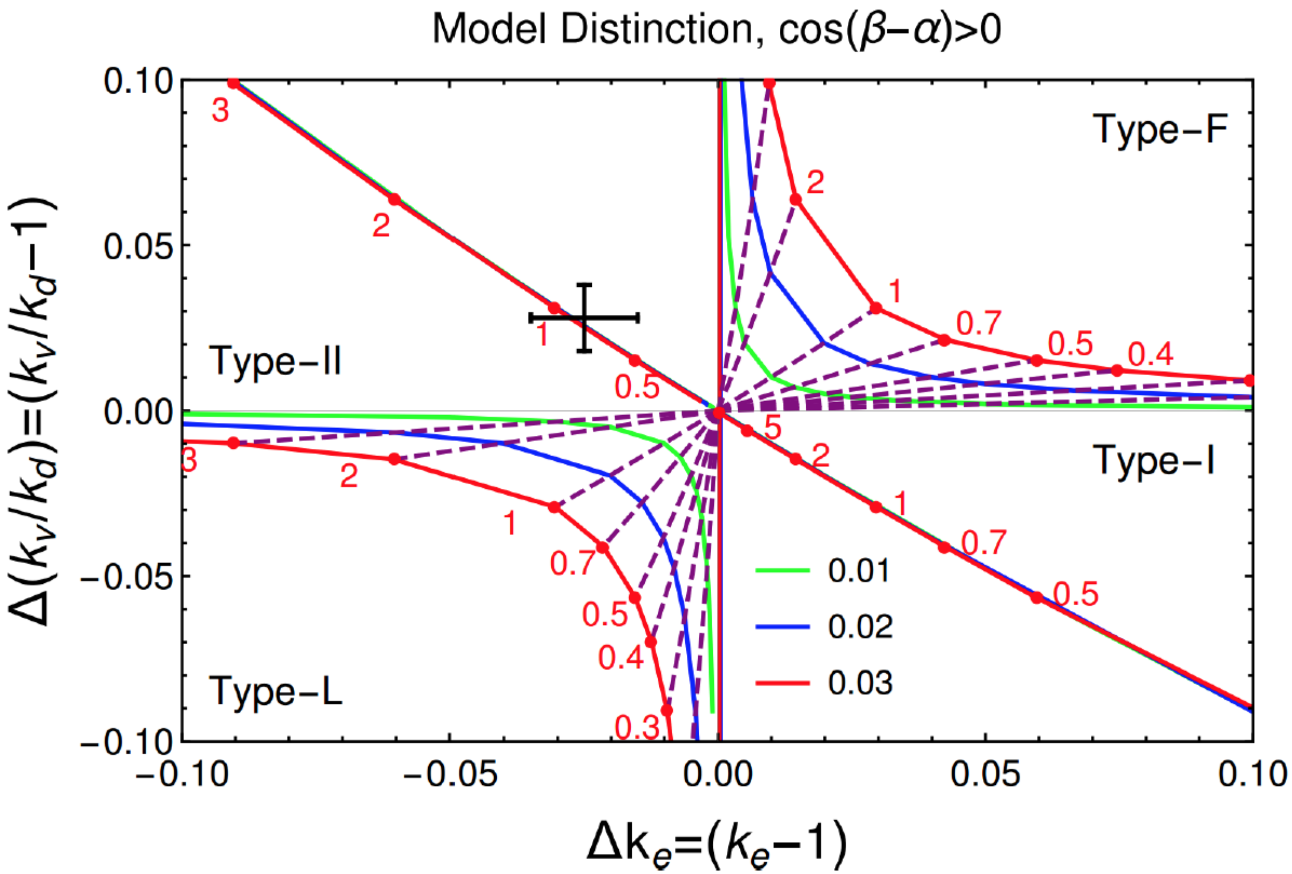


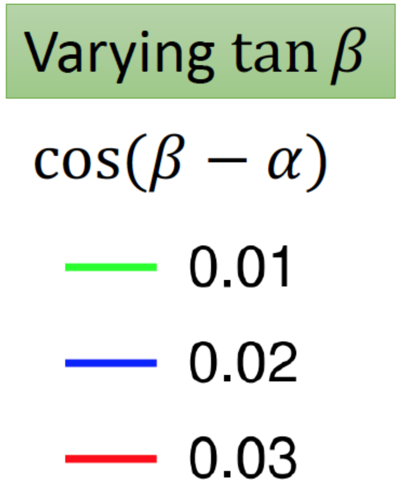
- A firm prediction of a light scalar in this model;
- Higgs exotic decay into a pair of light scalars is a crucial probe;
- Higgs exotic decays complements the Higgs precision program;
- Higgs exotic decays requires further studies of **merged jets** for lighter singlet masses;
- Also possible to have long-lived Higgs exotic decays in certain parameter space

$\Rightarrow$ thrilling physics can be tested at CEPC?

$\Rightarrow$ Extend reach?!!

2HDM: Tree Level Model Distinction



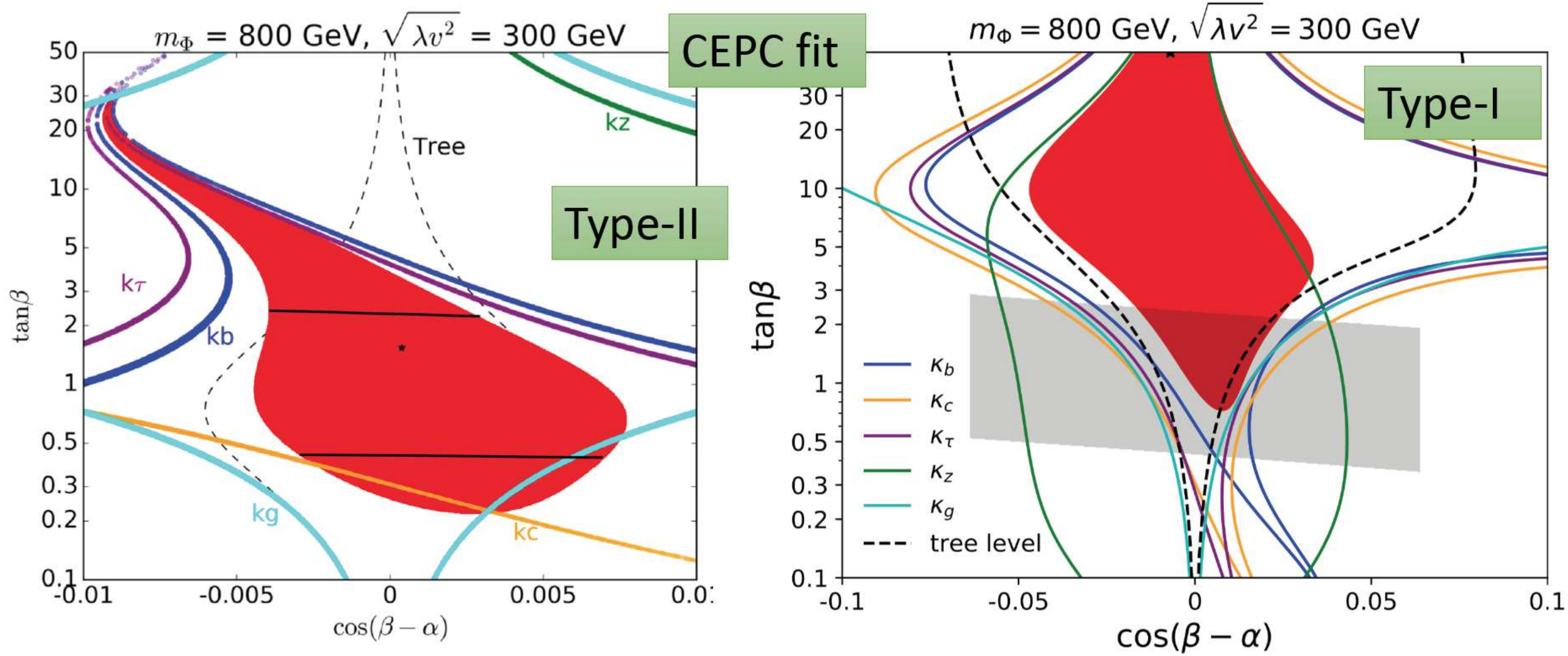


⇒ Higgs precision measurements can be decisive

⇒ beyond tree-level?

2HDM at 1-loop at CEPC:

[*W. Su*]

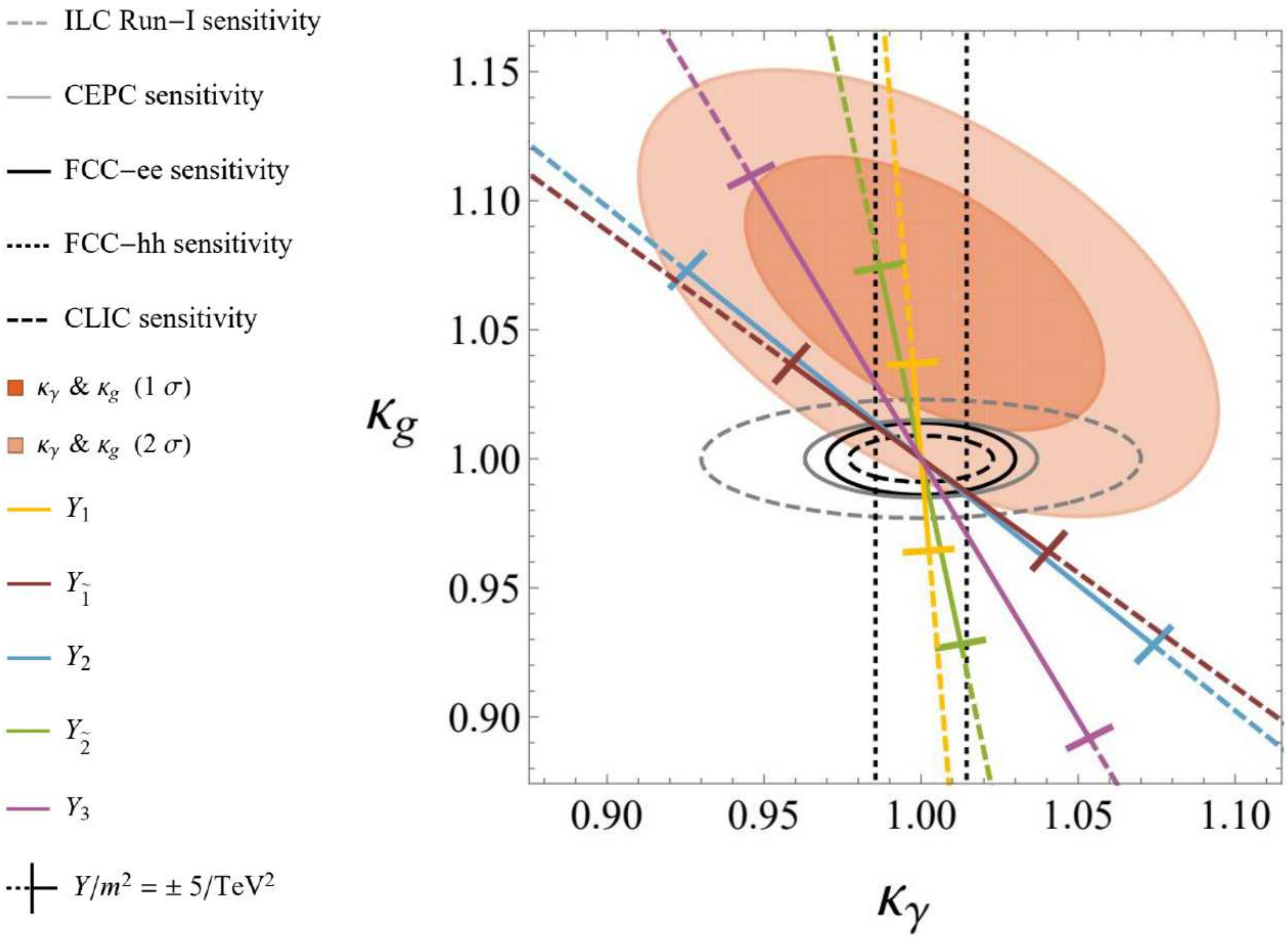


⇒ phenomenology depends strongly on loop corrections!

⇒ for which model are we ready??

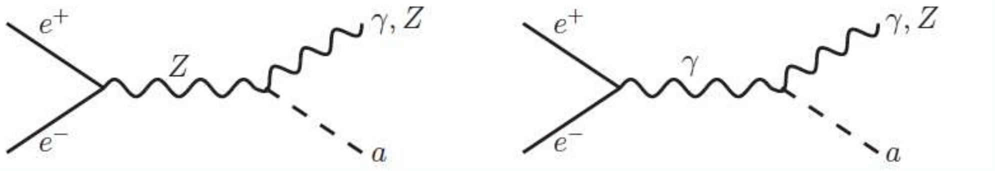
Leptoquark model distinction at CEPC

[*Crivellin*]

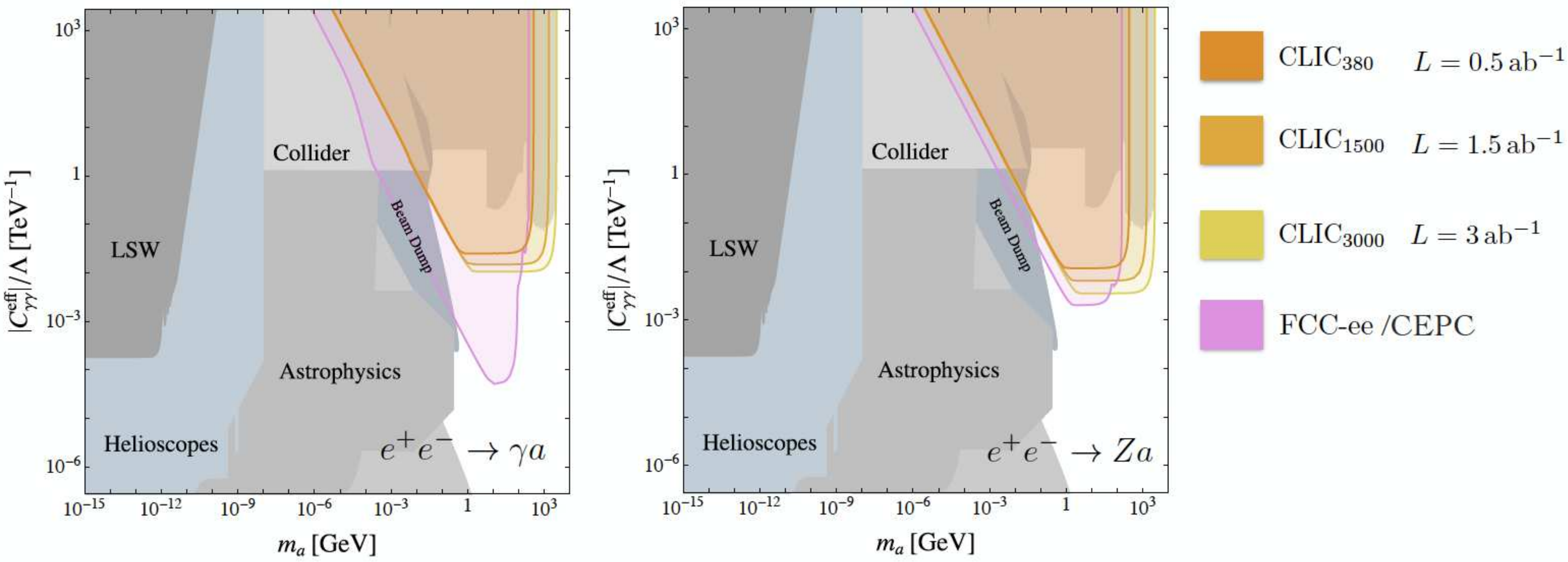


⇒ Higgs precision measurements can be crucial

- ALP associated production with a photon or Z



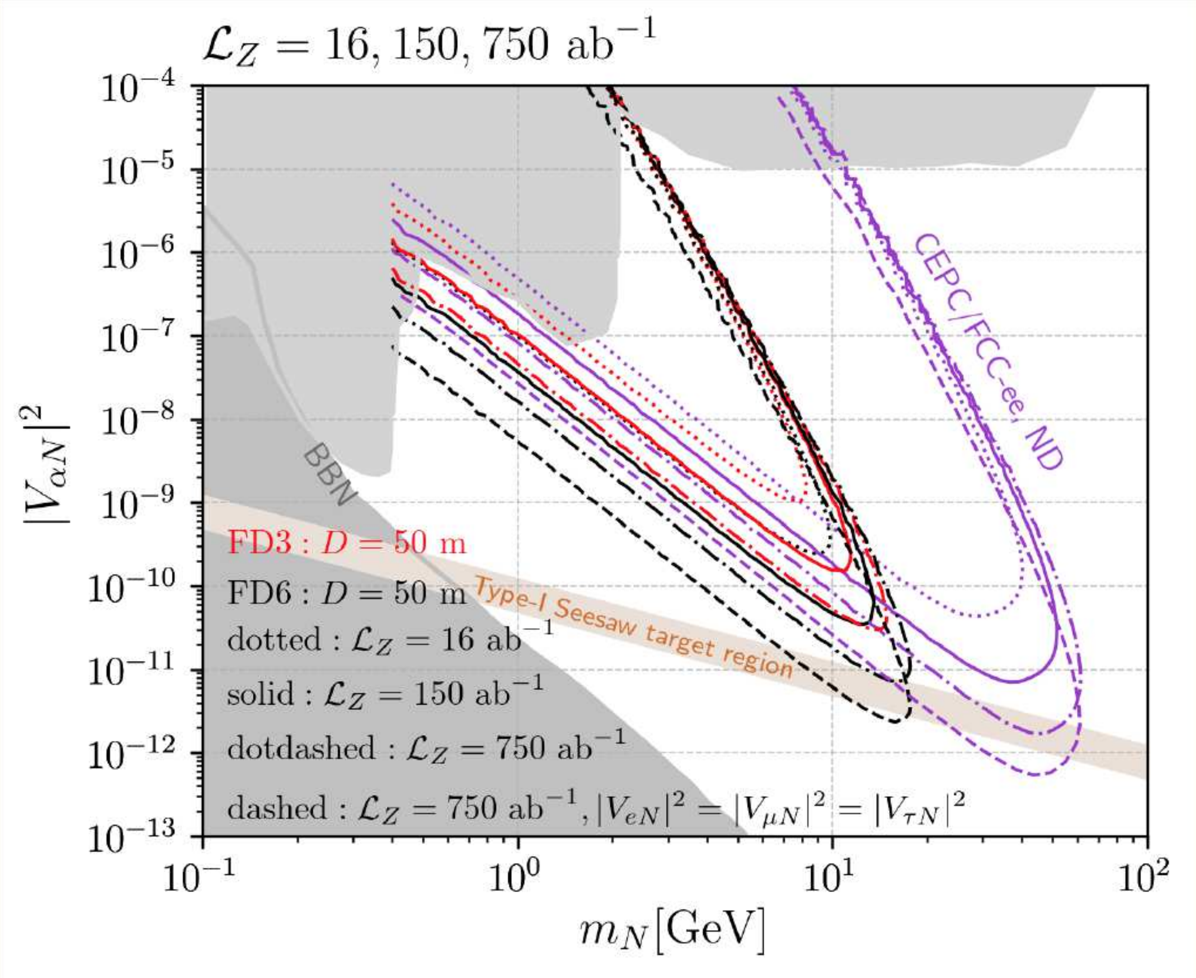
- ALP decay into photons



⇒ Interesting reach? Extensions?

Heavy Neutral Leptons

$Z \to N\nu$ @ $\sqrt{s} = 91.2$ GeV



750 ab^{-1}, 10 years, 4 IPs;
or to increase the instantaneous luminosity;
or to relax the theoretical assumptions

Can test the Type-I seesaw directly!

$\Rightarrow$ New(?) idea of "far detectors": new BSM physics opportunities!

Circular e^+e^- Colliders are Flavor Factories

Running on the Z pole allows one to probe the flavor structure of Z couplings with extreme precision.

In addition one gets very large samples of all b hadrons, c hadrons, τ's with large boost in a clean environment.

Running in Higgs factory mode can probe FCNC single top production

$\Rightarrow$ unique sensitivity to a large number of flavor processes that are not accessible at LHC(b) or Belle II

CEPC vs. Belle II, LHCb, . . .

[*Altmanshofer, Li*]

- CEPC vs. Belle II:
  - similar numbers of B^+ and B^0, but not much B_s and no Λ_b at Belle II.
  - $b\bar{b}$ from Z decays are boosted; efficient b tag from vertexing.

- CEPC vs. LHCb:
  - lower yields at CEPC, but cleaner environment (e^+e^- vs. pp).
  - much better access to final states with neutrals (π^0, γ, ...).

Giga-Z, Tera-Z and 10×Tera-Z: a phase of future linear/circular lepton colliders. [Fujii et al.(2019), Dong et al.(2018), Abada et al.(2019)]

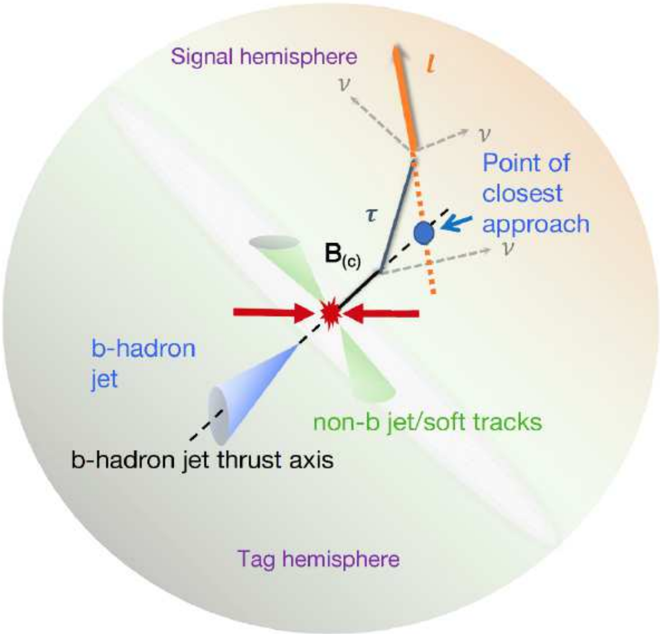
Z factories are also $b(c/\tau)$ factories:

Channel	Belle II	LHCb	Giga-Z	Tera-Z	10×Tera-Z
B^0, $\bar{B}^0$	5.3×10^{10}	$\sim 6 \times 10^{13}$	1.2×10^8	1.2×10^{11}	1.2×10^{12}
$B^\pm$	5.6×10^{10}	$\sim 6 \times 10^{13}$	1.2×10^8	1.2×10^{11}	1.2×10^{12}
B_s, $\bar{B}_s$	5.7×10^8	$\sim 2 \times 10^{13}$	3.2×10^7	3.2×10^{10}	3.2×10^{11}
$B_c^\pm$	-	$\sim 4 \times 10^{11}$	2.2×10^5	2.2×10^8	2.2×10^9
Λ_b, $\bar{\Lambda}_b$	-	$\sim 2 \times 10^{13}$	1.0×10^7	1.0×10^{10}	1.0×10^{11}

⇒ TeraZ is a flavor factory!

Studying $B_c \to \tau\nu$ at CEPC

Lepton colliders such as CEPC, FCC-ee etc. will provide a good opportunity for the study of $B_c \to \tau\nu$. The CEPC will produce up to 1 trillion Z bosons (Tera-Z).



$B_{(c)} \to \tau\nu, \tau \to l\nu\bar{\nu}$ in $Z \to b\bar{b}$. The most critical background for $B_c \to \tau\nu$ is $B \to \tau\nu$, which share similar event topology.

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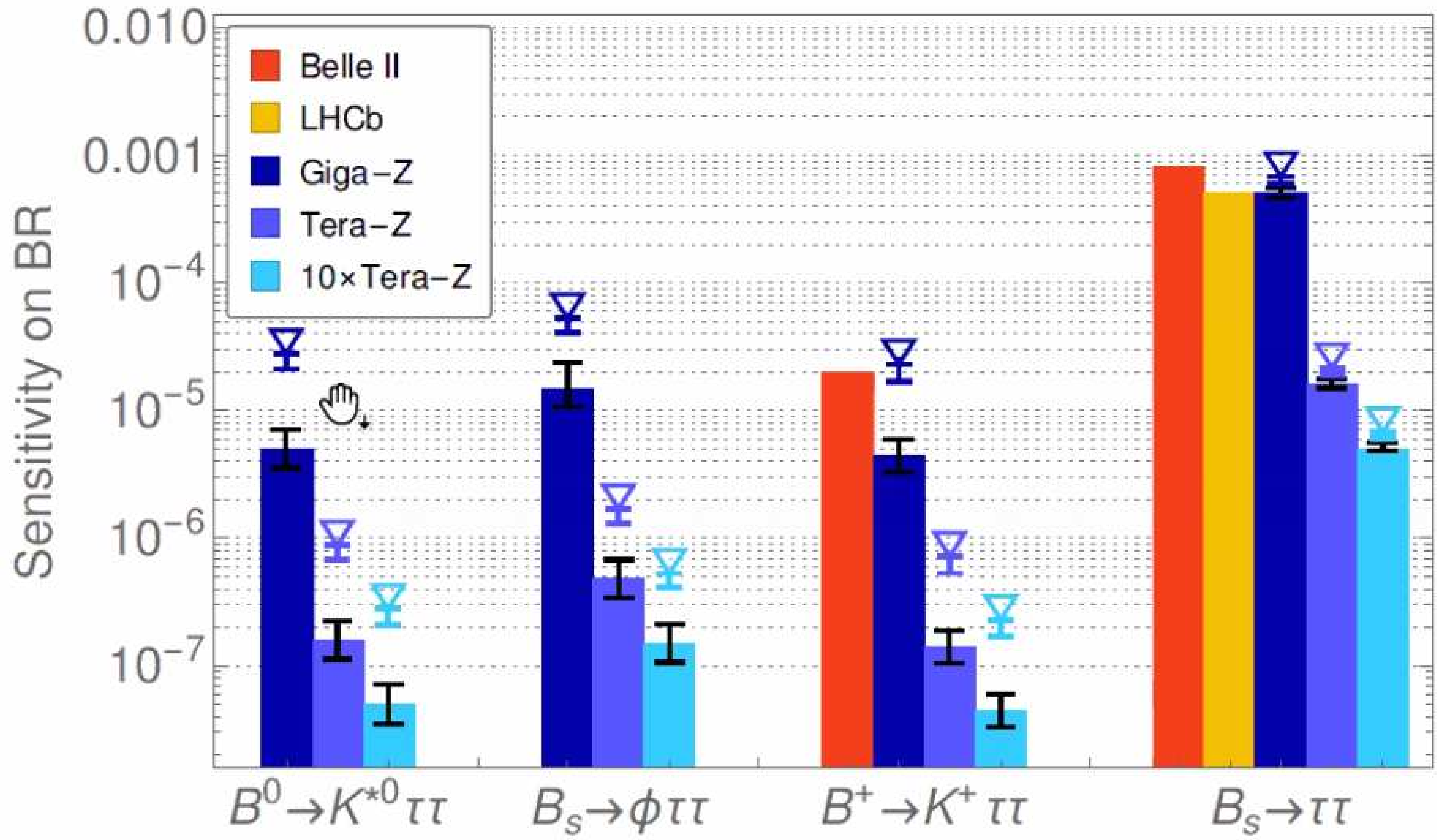
Example: senstivity on rare decays

[Li]



⇒ TeraZ can test (some) rare B decays better than Belle II, LHCb

Some important questions:

⇒ that partially have been addressed at this workshop . . .

Q: Is SM Higgs physics a done deal?

Q: Are we prepared for rare/BSM Higgs decays?

Q: Does SMEFT cover all relevant BSM Higgs physics?

Q: Are we prepared for light BSM Higgs bosons?

Q: Are we happy with the λ_{hhh} situation?

Q: Are EWPO a done deal?

Q: Is CEPC350 just a nice extension of the main programe?

Q: How relevant is polarization?
Can we always compensate with high lumi?

Q: Are we ready for LLPs?

Q: Often we see FCC-ee results. Can they always be taken over?

Some important questions:

⇒ that partially have been addressed at this workshop . . .

Q: Is SM Higgs physics a done deal? ⇒ huge calc. effort

Q: Are we prepared for rare/BSM Higgs decays?

Q: Does SMEFT cover all relevant BSM Higgs physics? ⇒ too simple

Q: Are we prepared for light BSM Higgs bosons? ⇒ not addressed

Q: Are we happy with the λ_{hhh} situation? ⇒ certainly not

Q: Are EWPO a done deal? ⇒ huge calc. effort

Q: Is CEPC350 just a nice extension of the main programe? ⇒ crucial

Q: How relevant is polarization?
Can we always compensate with high lumi?

Q: Are we ready for LLPs?

Q: Often we see FCC-ee results. Can they always be taken over?
⇒ must be studied in detail!

Outlook - what is needed for the future?

$\Rightarrow$ We need a motivation boost (for TH)
this is particularly important for precise (Higgs/EW) calculations
take a long time. How to motivate (young) physicists?
$\Rightarrow$ a clear positive signal from China would certainly help!

$\Rightarrow$ We need more TH $\leftrightarrow$ EXP interaction
– “guidance” for EXP
– “understanding” for TH
$\Rightarrow$ could be better . . .

We need precision top measurements for all other “subfields”
$\Rightarrow$ CEPC350 important!

“How many person-years are needed?
– FCC-ee estimate for Higgs/EW: 500
– Similar for CEPC (or other e^+e^- colliders)
– Still to cover: QCD, Flavor, BSM, . . .

The Physics case is there!

$\Rightarrow$ for Higgs and SM/EW

$\Rightarrow$ equally for top/QCD, BSM, Flavor!!

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But I am convinced:

The Physics case is there!

$\Rightarrow$ for Higgs and SM/EW

$\Rightarrow$ equally for top/QCD, BSM, Flavor!!

$\Rightarrow$ We need a motivation boost (for TH) for higher precision

But I am convinced:

If we continue with the hard work,
we will be ready for the CEPC start


Further Questions?