Precision at Future Colliders

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Fundamental physics at colliders

The main goal of the collider program is to deepen our knowledge of fundamental physics

In practical terms, this means **testing the SM**

looking for its possible **failures** ⟶ evidence of **New Physics** (BSM)

Testing the SM

Complementarity

using different strategies to test the SM predictions
and to cover different types of new physics

- direct vs indirect searches
- different collider types (eg. e^+e^- vs hh, low-energy vs high-energy, …)
- …

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improve and optimize the new-physics probes to achieve better sensitivity

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HL-LHC and future colliders will provide a huge amount of data

↓

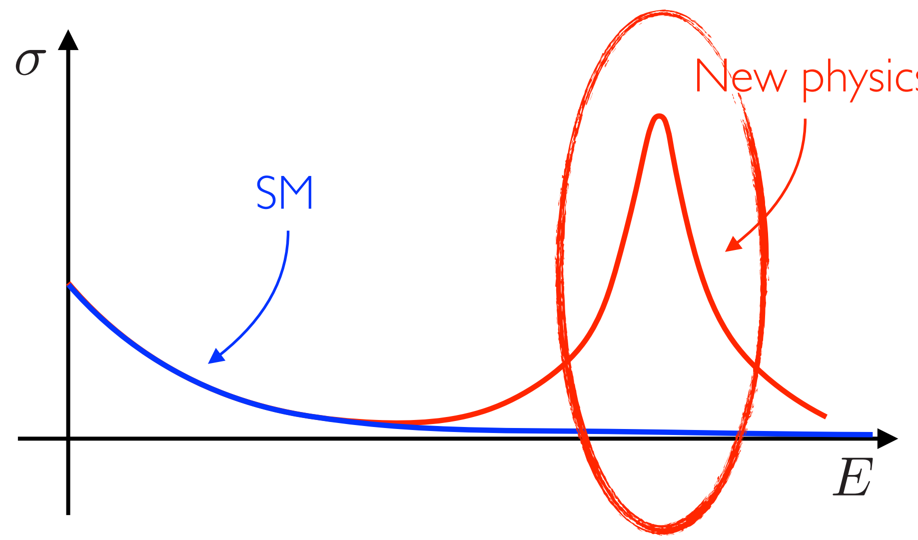
Fine details of the SM can be tested with high precision

How to look for new physics

Direct searches:

look for signals of production
of new particles

- resonant effects in kinematic distributions
- “bump” on top of a smooth SM background
(that can be often extracted from the data)



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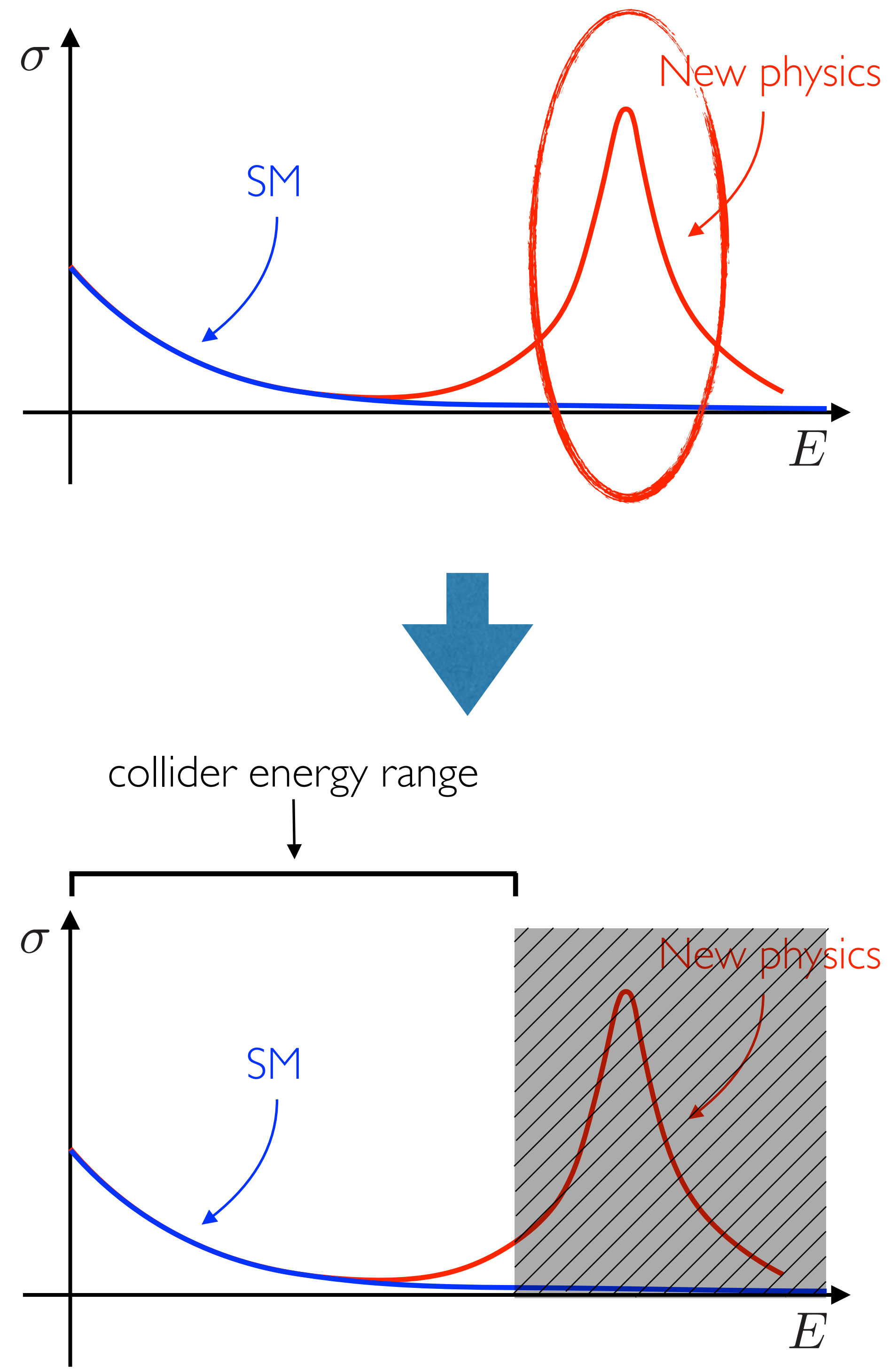

Limitations:

- new particle must be resonantly produced and must decay to reconstructable final state
- limited by collider energy range

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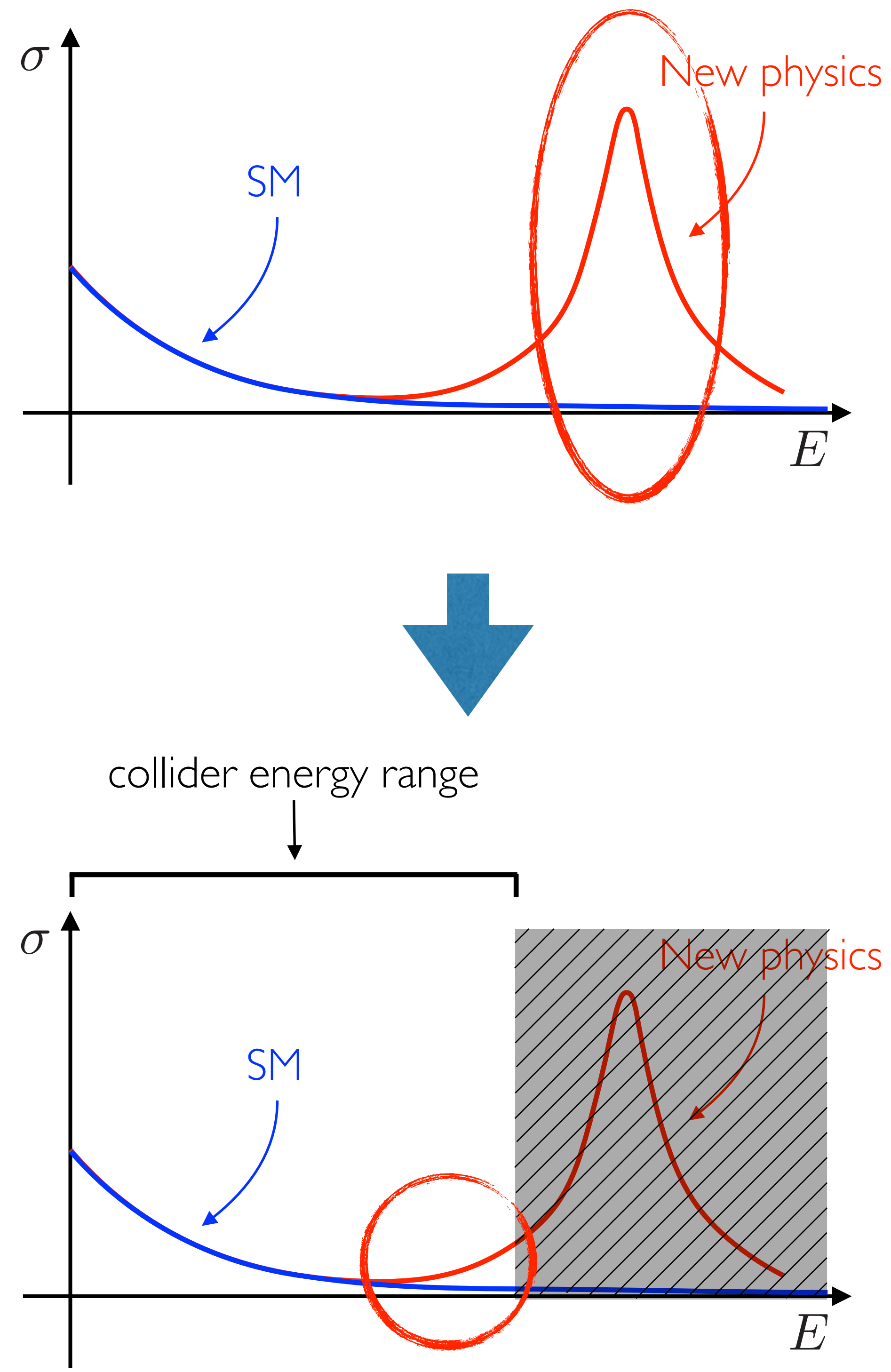


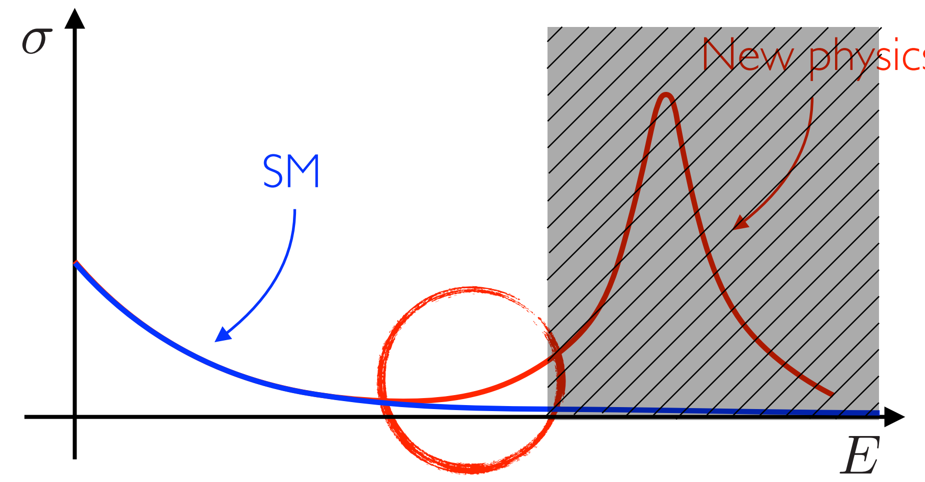
Looking for the tail: Indirect searches

even if we can not directly produce the new particles, we can test their **indirect effects**

- LEP data at 200 GeV tested new particles with masses up to 3 TeV !

Tails are "universal"

Indirect searches have important advantages



"universality"

- deviations from SM exhibit small number of behaviors dictated by symmetries
- simple parametrization in terms of EFT operators

"model independence"

- captures a huge class of new-physics models

"ubiquity"

- deviations are present also in channels with non-resonant new physics production
- can often be seen also in channels where the final state can not be fully reconstructed

The challenges of indirect searches

Performing indirect searches is a challenging task
that requires several key ingredients

- Accurate theoretical knowledge of the SM and BSM predictions
  (i.e. small theoretical systematic uncertainty)

  → needed to compare theoretical expectation with the experimental data

- Accurate experimental measurements
  (i.e. small experimental systematic and statistical uncertainty)

  → in many cases we expect small deviations with respect to the SM

- Use of effective search strategies and optimized statistical analysis

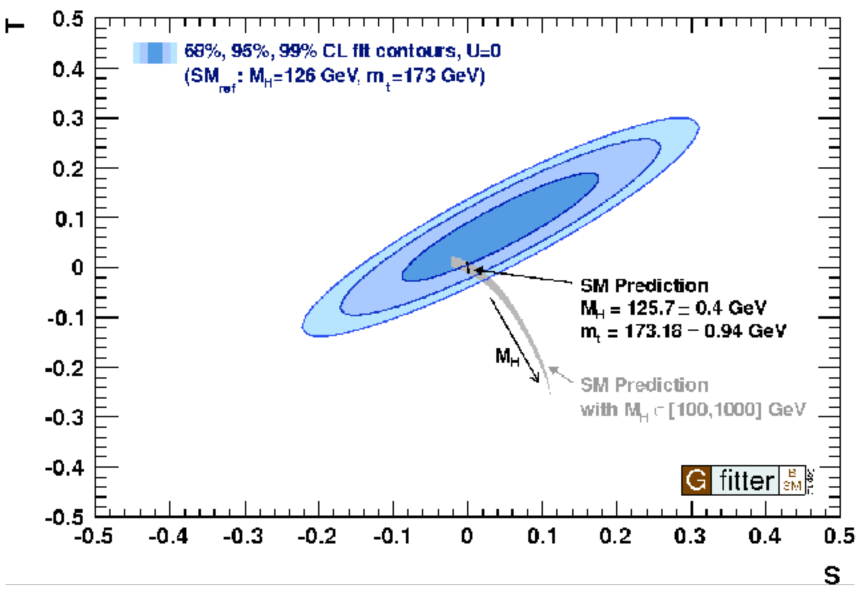
Precision EW measurements

at Lepton Colliders

Precision at lepton colliders

Precision measurements at lepton colliders have a long and successful history

<u>example</u>: oblique parameters at LEP



✦ 0.1% precision possible thanks to very low systematic errors

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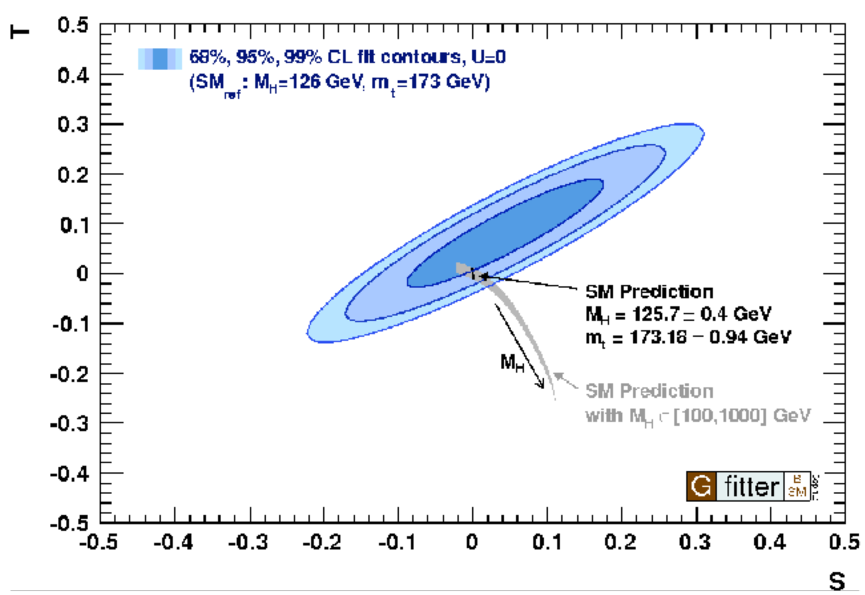
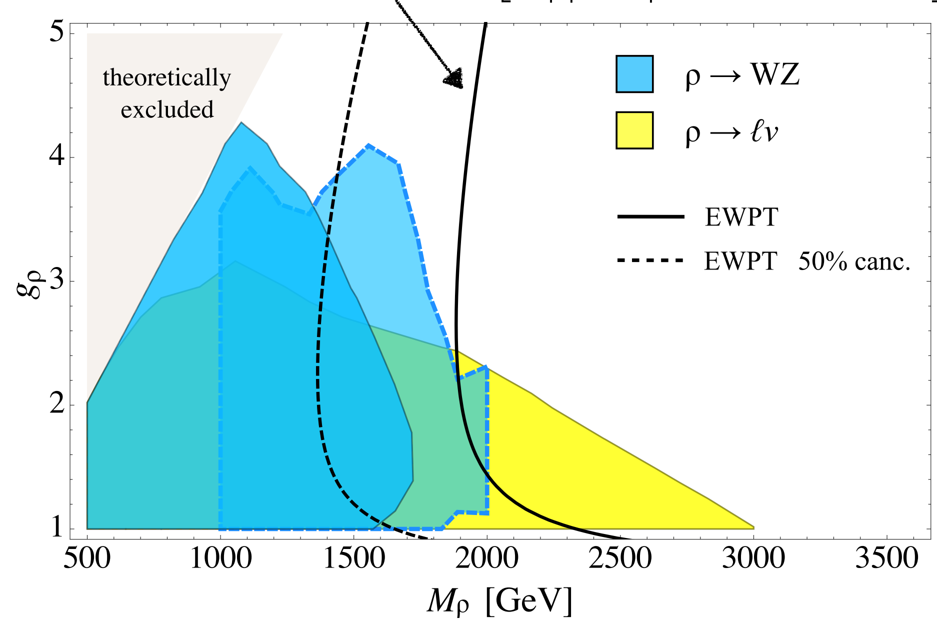


bounds from S parameter

[Pappadopulo, Thamm et al.]

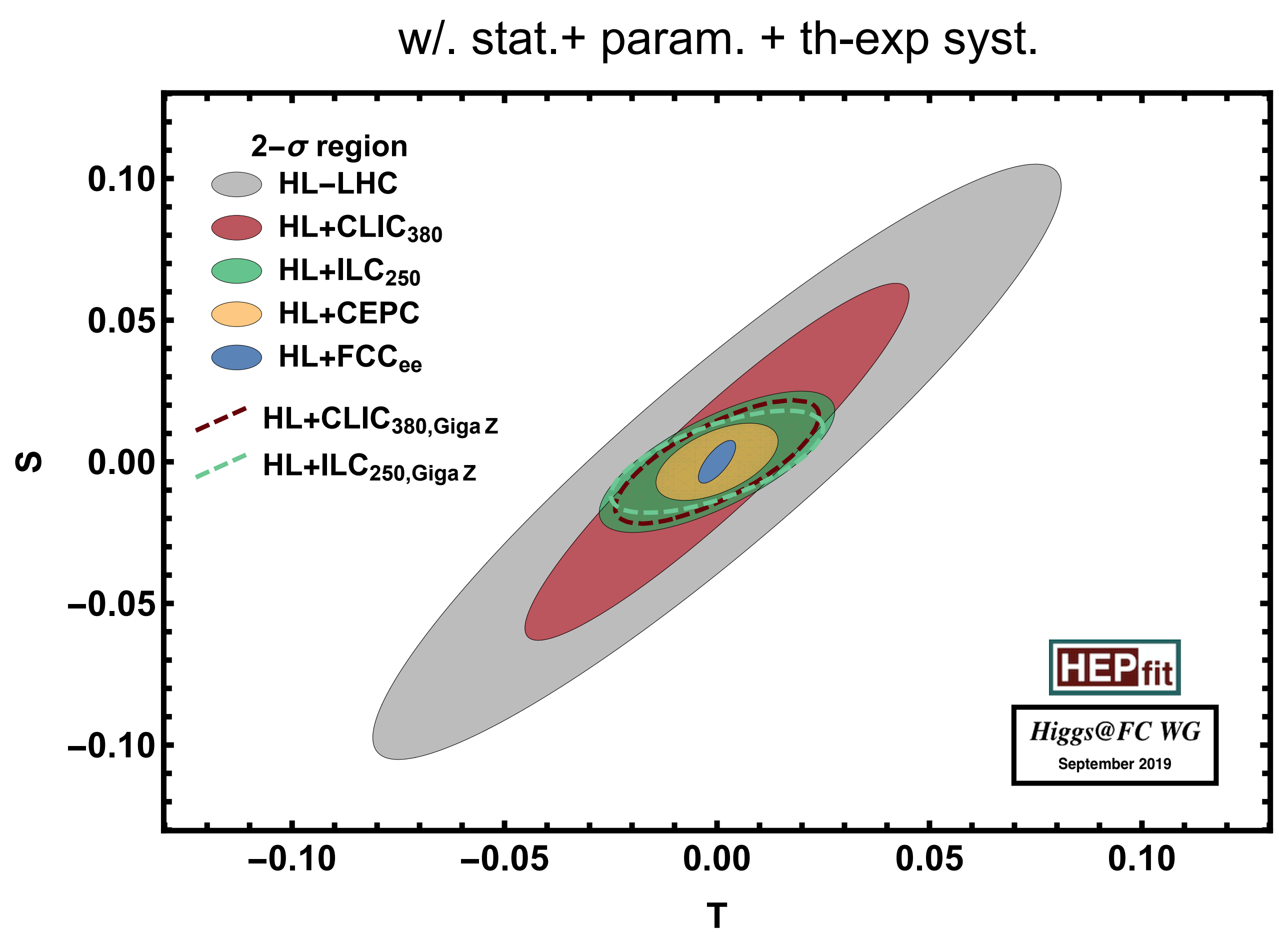


- ✦ 0.1% precision possible thanks to very low systematic errors
- ✦ can probe new physics at the TeV scale

Precision at lepton colliders

Future e^+e^- lepton colliders can significantly improve the reach

✦ Bounds on oblique parameters will become one order of magnitude stronger



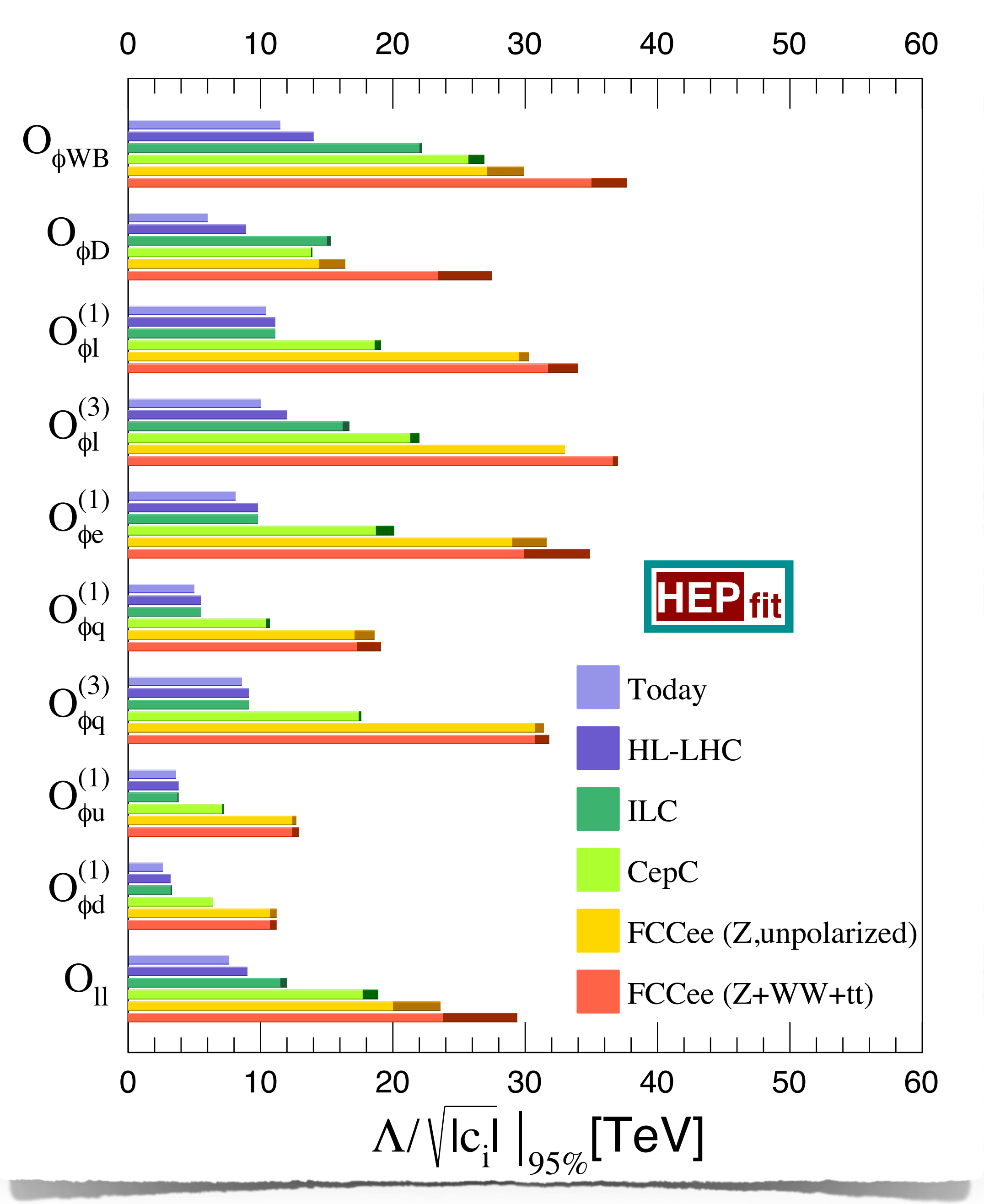
Precision at lepton colliders

Indirect probes of new physics
can test high energy scales

HL-LHC : $\Lambda \sim 10$ TeV

ILC - CepC : $\Lambda \sim 20$ TeV

FCCee : $\Lambda \sim 30$ TeV



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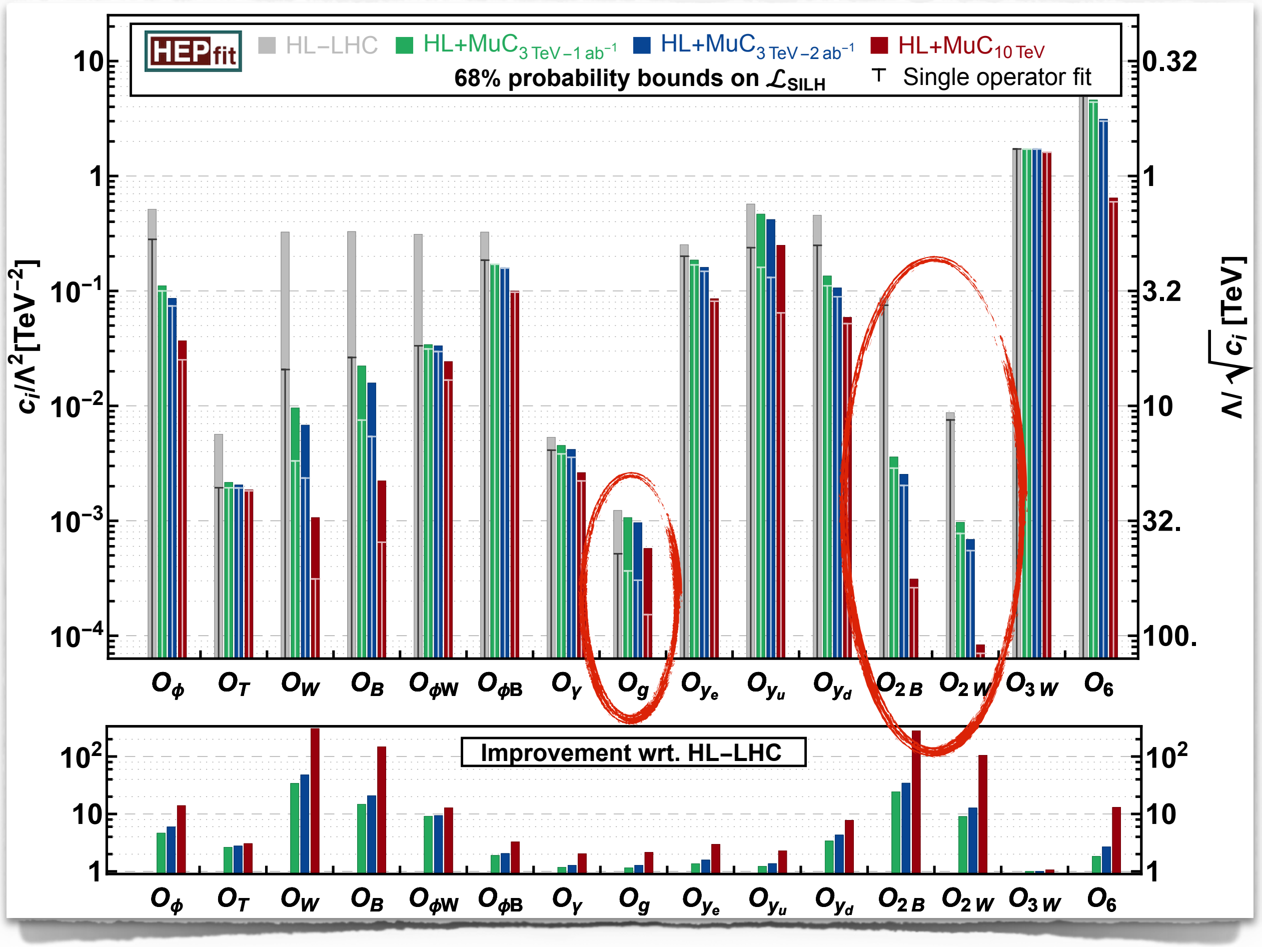
MuC_{10TeV} : $\Lambda \sim 50 - 100$ TeV



Precision vs direct searches

Precision measurements are competitive with direct detection reach

Example: **Minimal/Accidental dark matter**

[Cirelli, Fornengo, Strumia '05; …
Del Nobile, Nardecchia, Panci '15;
Di Luzio, Gröber et al. '15;
Mitridate, Redi et al. '17]

New EW multiplets at the TeV scale

- accidentally stable
  (no renormalizable $\chi\,\mathrm{SM}\,\mathrm{SM}$ interactions)
- viable DM candidates

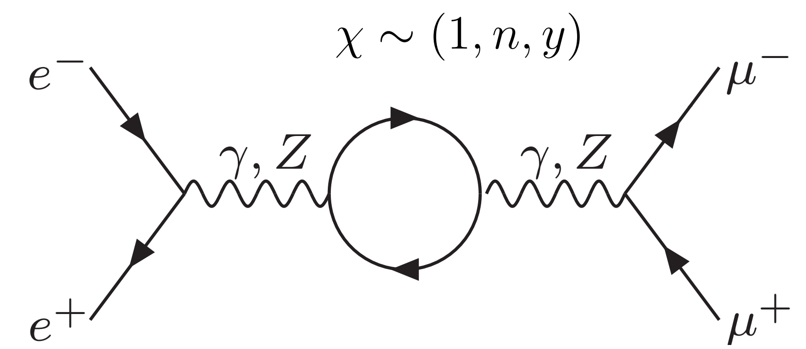
χ / m_χ [TeV]	DM
$(1,2,1/2)^{*}_{\mathrm{DF}}$	1.1
$(1,3,\epsilon)_{\mathrm{CS}}$	1.6
$(1,3,\epsilon)_{\mathrm{DF}}$	2.0
$(1,3,0)^{**}_{\mathrm{MF}}$	2.8
$(1,5,\epsilon)_{\mathrm{CS}}$	6.6
$(1,5,\epsilon)_{\mathrm{DF}}$	6.6
$(1,5,0)^{***}_{\mathrm{MF}}$	14
$(1,7,\epsilon)_{\mathrm{CS}}$	16
$(1,7,\epsilon)_{\mathrm{DF}}$	16

RS = Real Scalar
CS = Complex Scalar
MF = Majorana Fermion
DF = Dirac Fermion

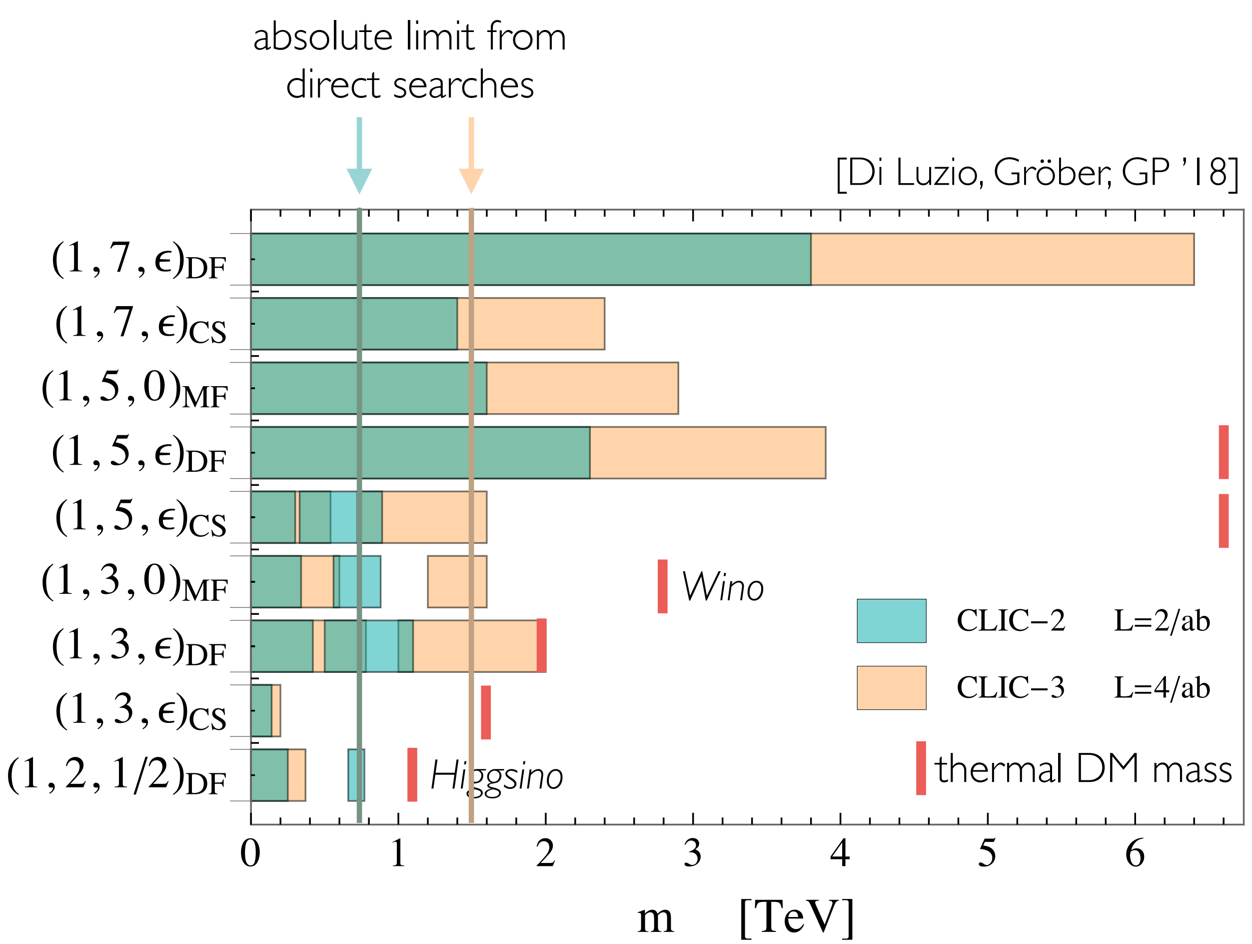
* Higgsino DM
** Wino DM
*** Minimal DM

Minimal dark matter

- ✦ Universal corrections to 2 → 2 fermion scattering
- ✦ Testable deviations in angular distributions



[Harigaya et al. '15;
Matsumoto et al. '17;
Di Luzio, Gröber, GP '18]



Indirect probes can extend direct detection reach for large multiplets at CLIC

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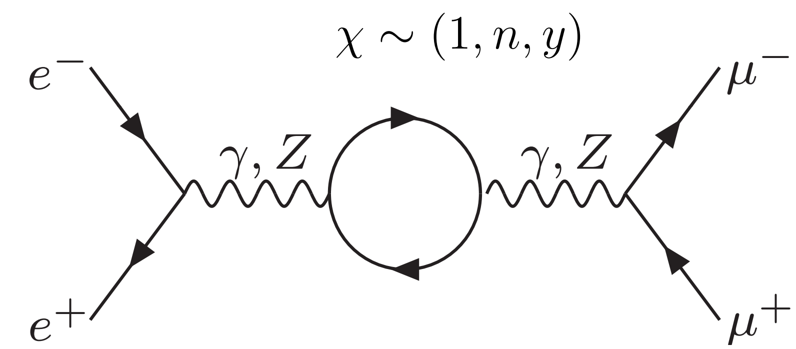

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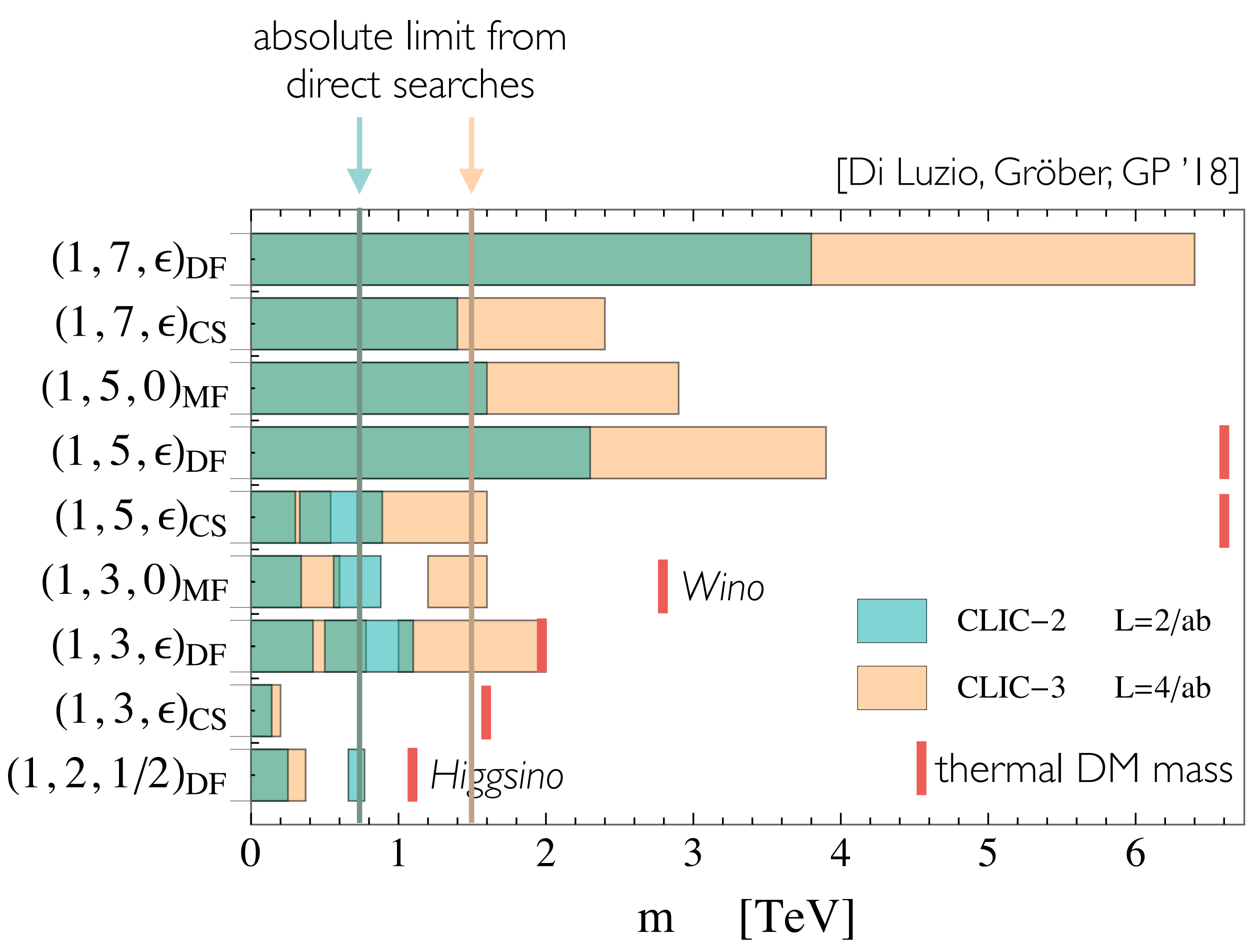

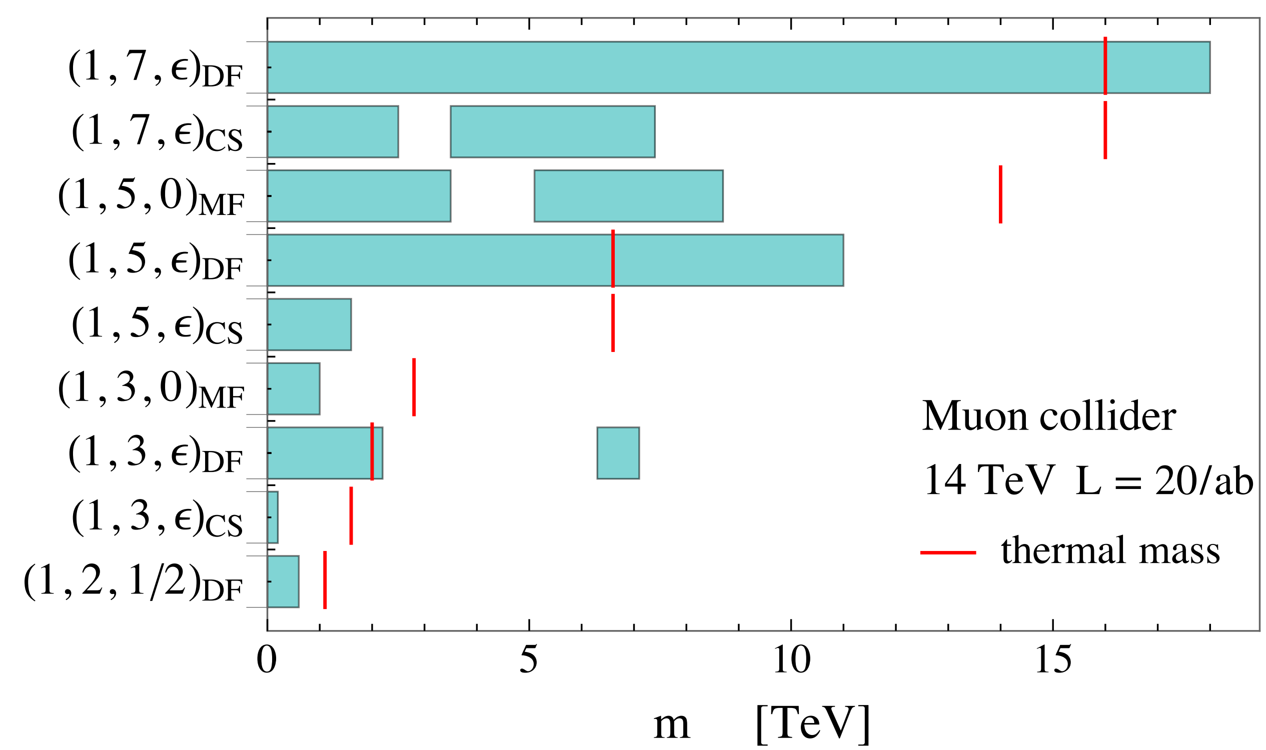

Indirect probes can extend direct detection reach for large multiplets at CLIC

Precision EW measurements

at Hadron Colliders

Precision at hadron colliders

New ideas allow us to exploit also **hadron colliders!**

- ✦ sizeable systematic errors in many cases do not allow for pole precision measurements

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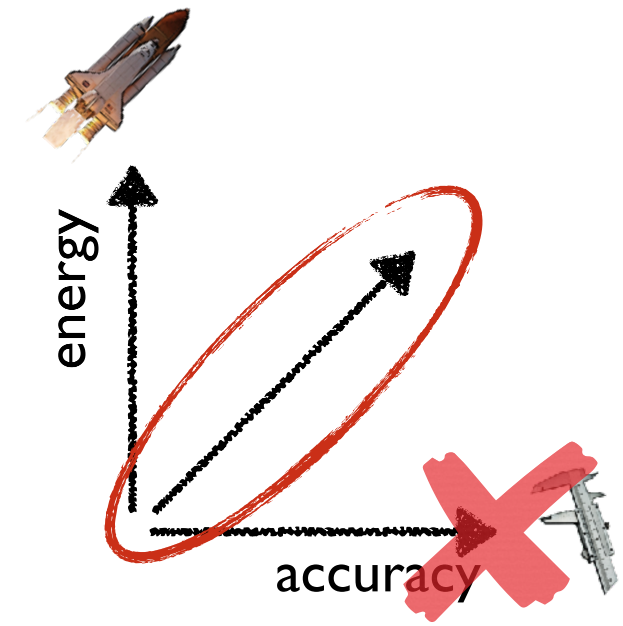

- sizeable systematic errors in many cases do not allow for pole precision measurements
- however we can exploit the high energy reach

→ **energy helps accuracy!**

[Farina, GP, Pappadopulo, Ruderman, Torre, Wulzer '16]

Precision at hadron colliders

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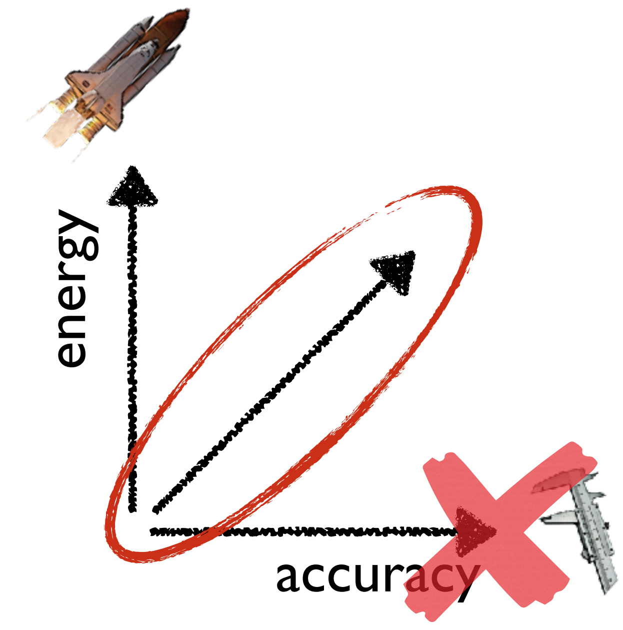

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- ✦ however we can exploit the high energy reach

  → **energy helps accuracy!**

[Farina, GP, Pappadopulo, Ruderman, Torre, Wulzer '16]

- ✦ key point: deviations from SM typically **grow with energy**

$$\frac{\mathcal{A}_{\text{SM+BSM}}}{\mathcal{A}_{\text{SM}}} \sim 1 + \# \frac{E^2}{\Lambda^2}$$

→ LHC can match LEP sensitivity exploiting the **high energy** reach

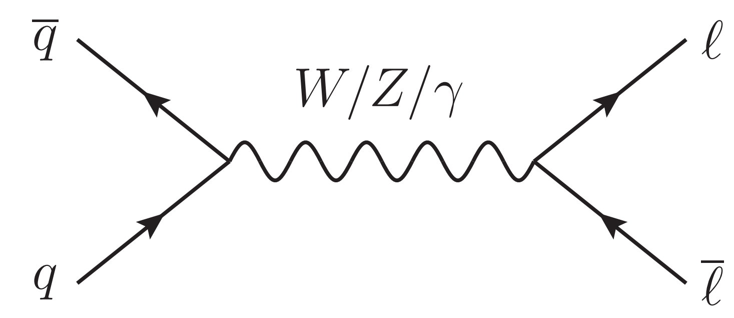
$$0.1\ \% \quad \text{at} \quad 100\ \text{GeV} \quad \longrightarrow \quad 10\ \% \quad \text{at} \quad 1\ \text{TeV}$$

LEP energy *LHC energy*

Proof of Principle: Di-lepton DY

Drell-Yan production ($\ell^+\ell^-$ or $\ell\nu$)

- large cross section → good statistics
- small theory and exp. systematic uncertainty



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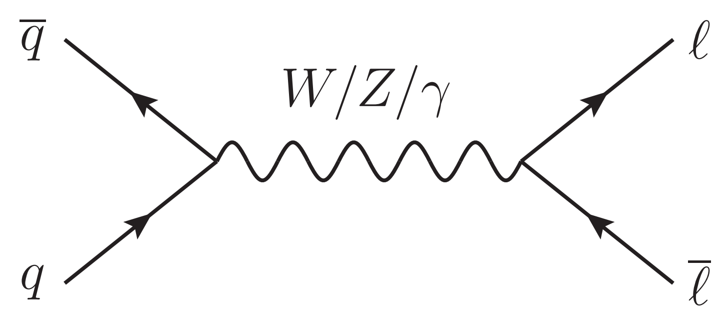

Simple BSM effects: **oblique parameters**

✦ Deformation of the gauge propagators from dimension-6 operators

$$\frac{gg'\hat{S}}{16m_W^2}(H^\dagger\sigma^a H)W^a_{\mu\nu}B^{\mu\nu} \qquad -\frac{g^2\hat{T}}{2m_W^2}|H^\dagger D_\mu H|^2$$

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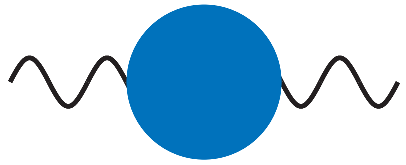

→ **LEP** bounds at the **0.1% level**

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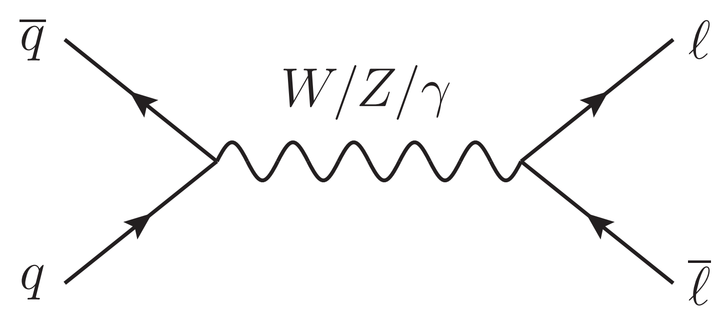

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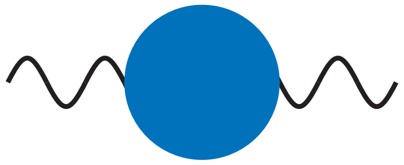


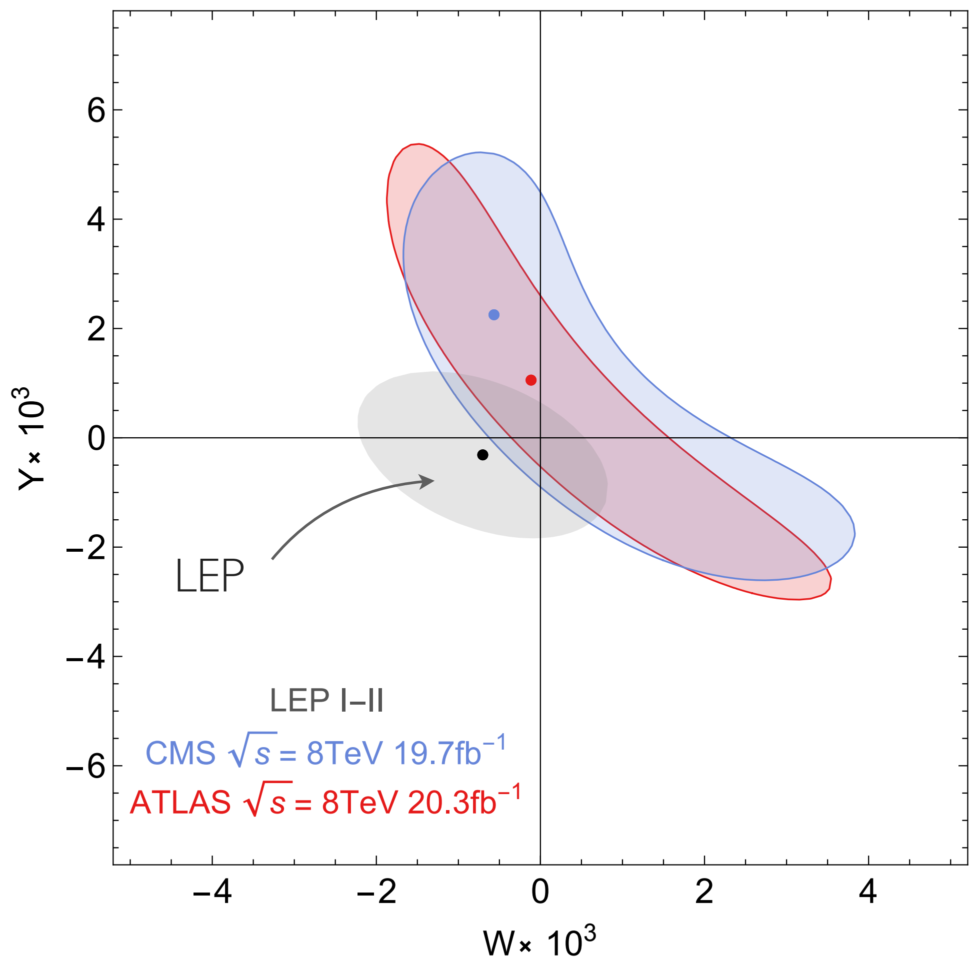
induce quadratic growth with energy

→ **LEP** bounds at the **0.1% level**

Oblique parameters

- ✦ **LHC** can significantly **surpass LEP** sensitivity on W and Y!
  - 8 TeV runs competitive with LEP

[Farina, GP, Pappadopulo, Ruderman, Torre, Wulzer '16]



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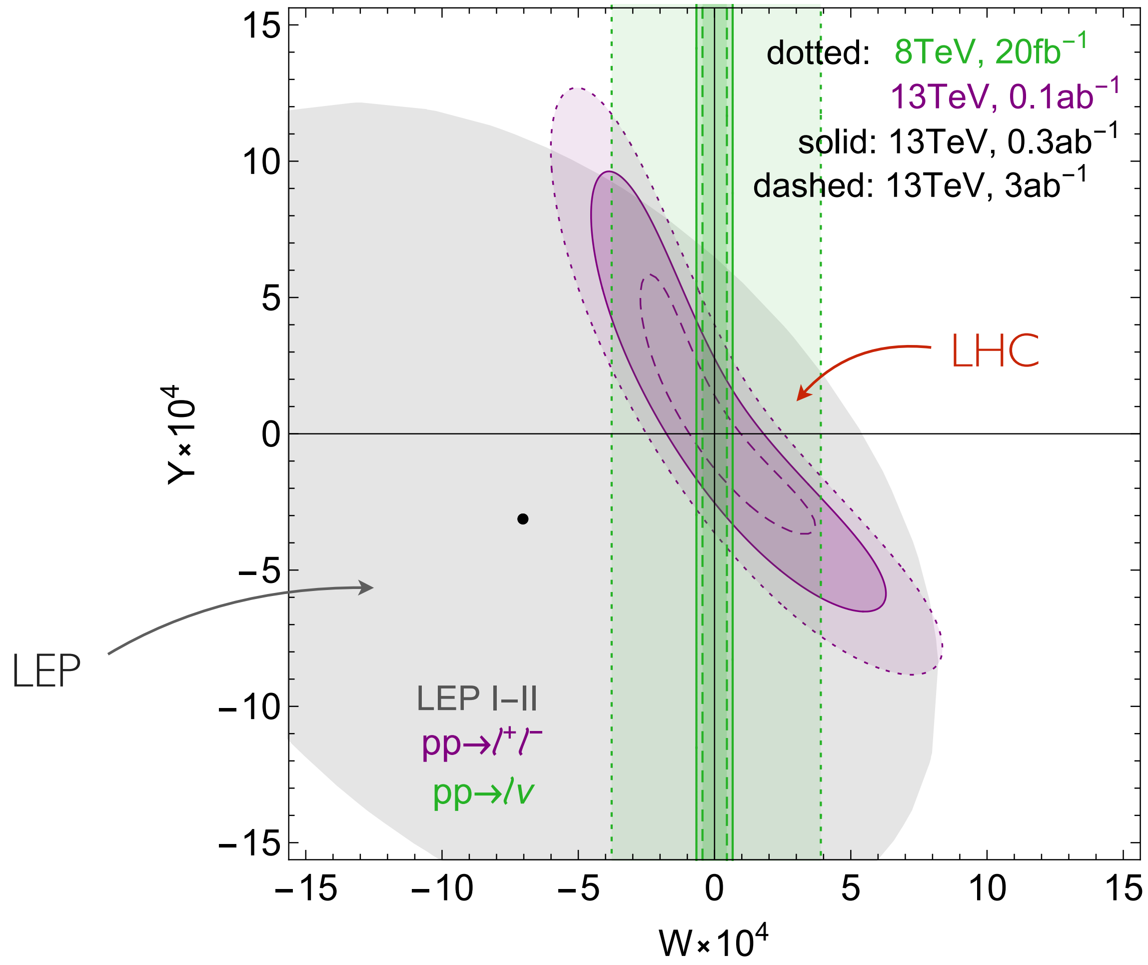

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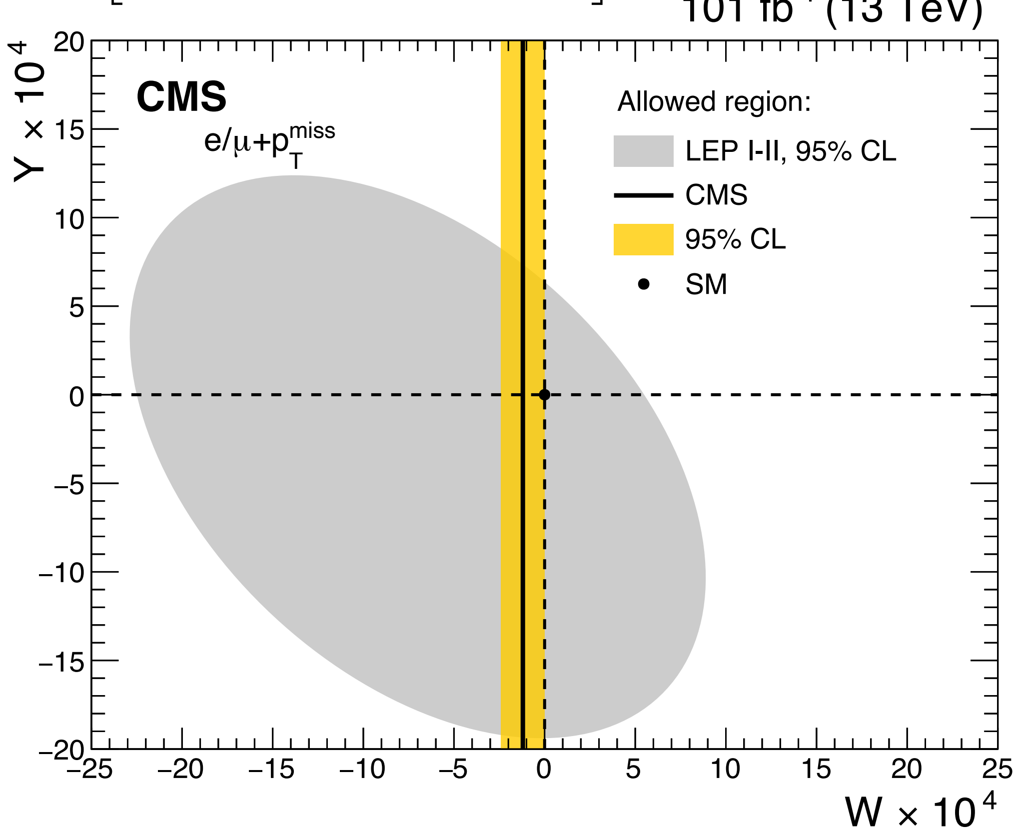
[CMS Collab. 2202.06075]



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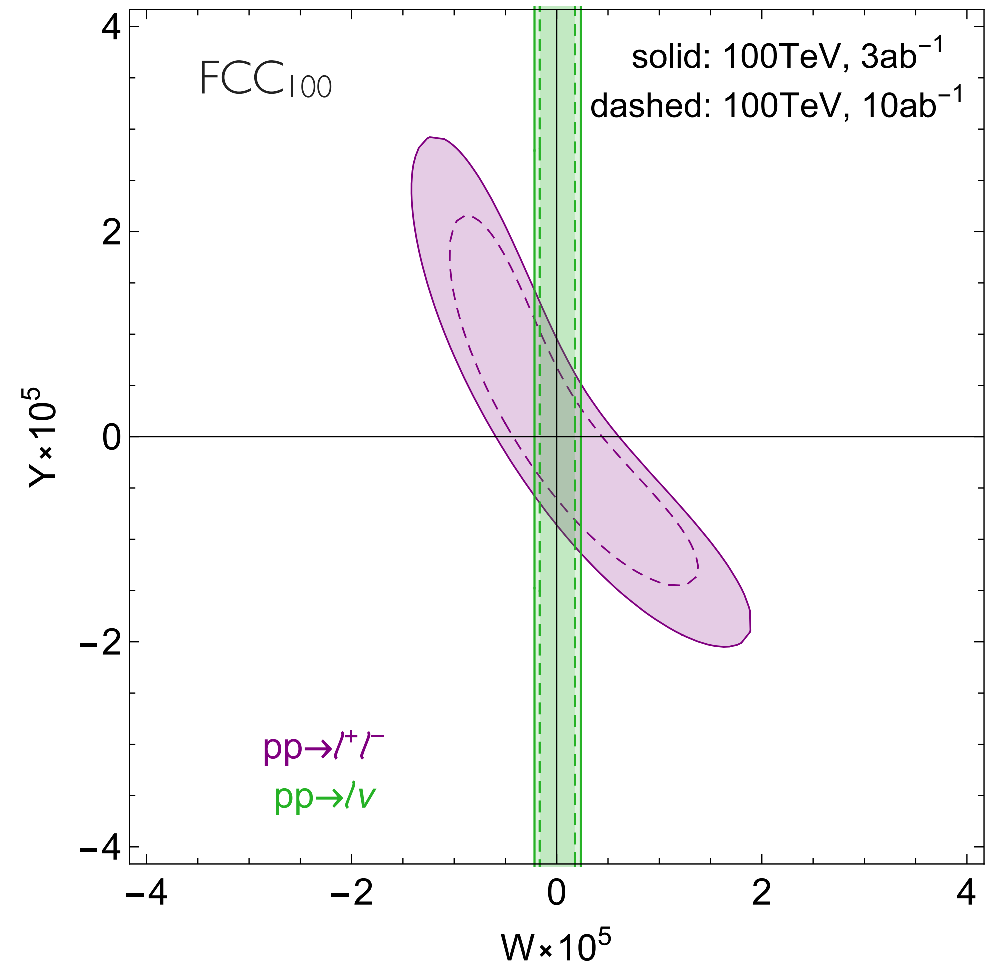
- Future high-energy hadron colliders can tighten further the bounds
  - FCC_{100} can reach 10^{-5} precision

[Farina, GP, Pappadopulo, Ruderman, Torre, Wulzer '16]



Comparison with future colliders

Bounds on W and Y at different colliders

	LEP	LHC 13		FCC 100	ILC	TLEP	CEPC	ILC 500	CLIC 1	CLIC 3
luminosity	$2 \times 10^7\ Z$	0.3/ab	3/ab	10/ab	$10^9\ Z$	$10^{12}\ Z$	$10^{10}\ Z$	3/ab	1/ab	1/ab
W $\times 10^4$	$[-19, 3]$	± 0.7	± 0.45	± 0.02	± 4.2	± 1.2	± 3.6	± 0.3	± 0.5	± 0.15
Y $\times 10^4$	$[-17, 4]$	± 2.3	± 1.2	± 0.06	± 1.8	± 1.5	± 3.1	± 0.2	$\sim \pm 0.5$	$\sim \pm 0.15$

- ✦ HL-LHC comparable with TLEP
- ✦ FCC_{100} much better than ILC 500 GeV and CLIC 3 TeV

Testing the Higgs dynamics

To **test the Higgs dynamics** we need to probe additional channels

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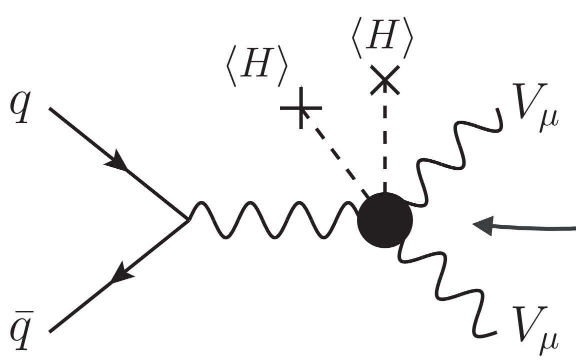
✦ **di-boson** production can probe deviations in the Higgs couplings



$$\mathcal{O}_W = (H^\dagger \sigma^i \overleftrightarrow{D}_\mu H)(D^\nu W_{\mu\nu})^i$$

$$\mathcal{O}_{HW} = (D_\mu H)^\dagger \sigma^i (D^\nu H) W^i_{\mu\nu}$$

More challenging than di-lepton

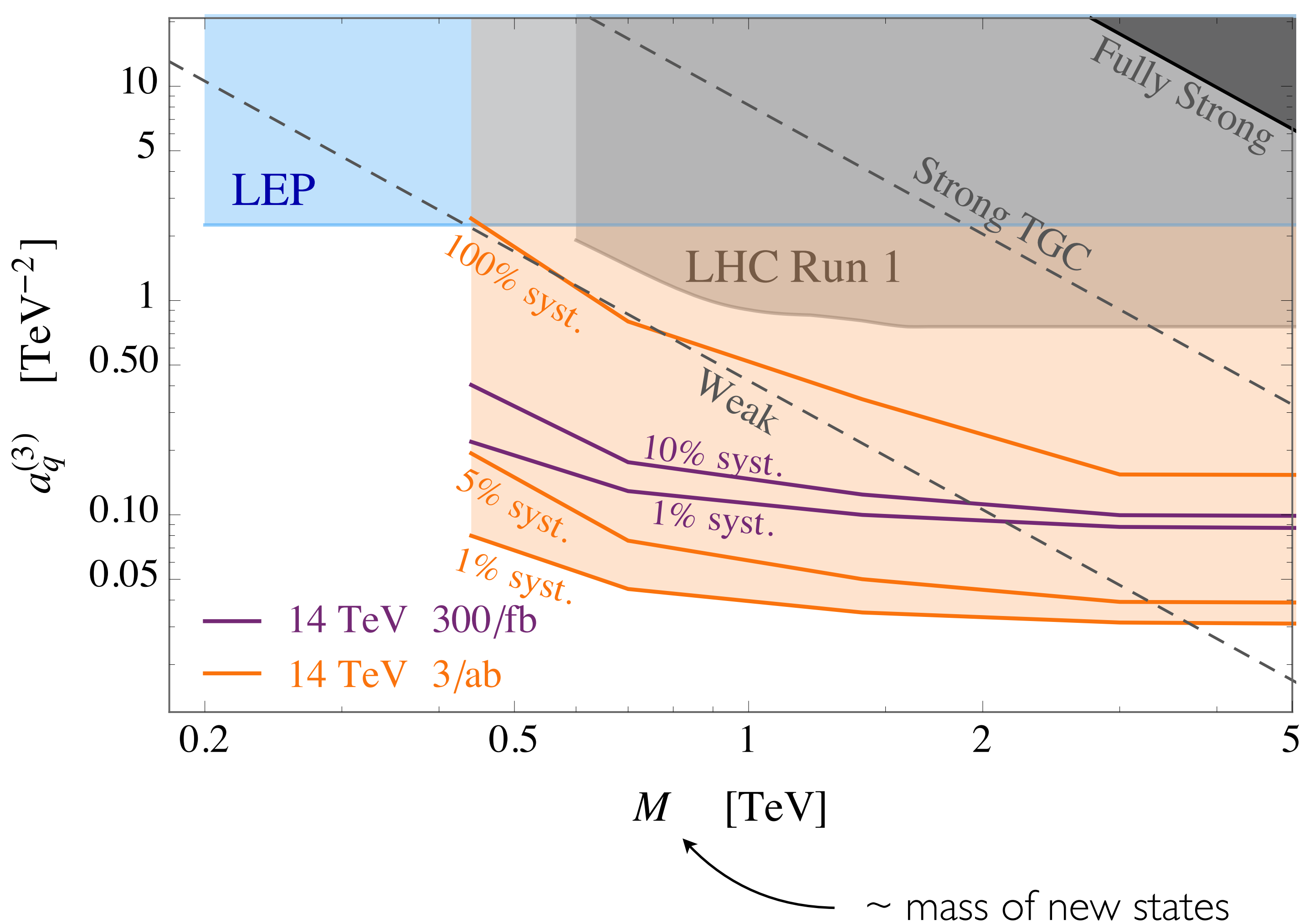
- energy-growing new physics effects confined to subleading helicity channels (longitudinal) (→ **interference resurrection** via differential measurements)
- more complex final states

… but **more interesting** → can be used to test a larger set of BSM theories

WZ production: LHC

Estimate of the bounds on $a_q^{(3)}(\bar{q}_L\sigma^a\gamma^\mu q_L)(iH^\dagger\sigma^a\overleftrightarrow{D}_\mu H)$

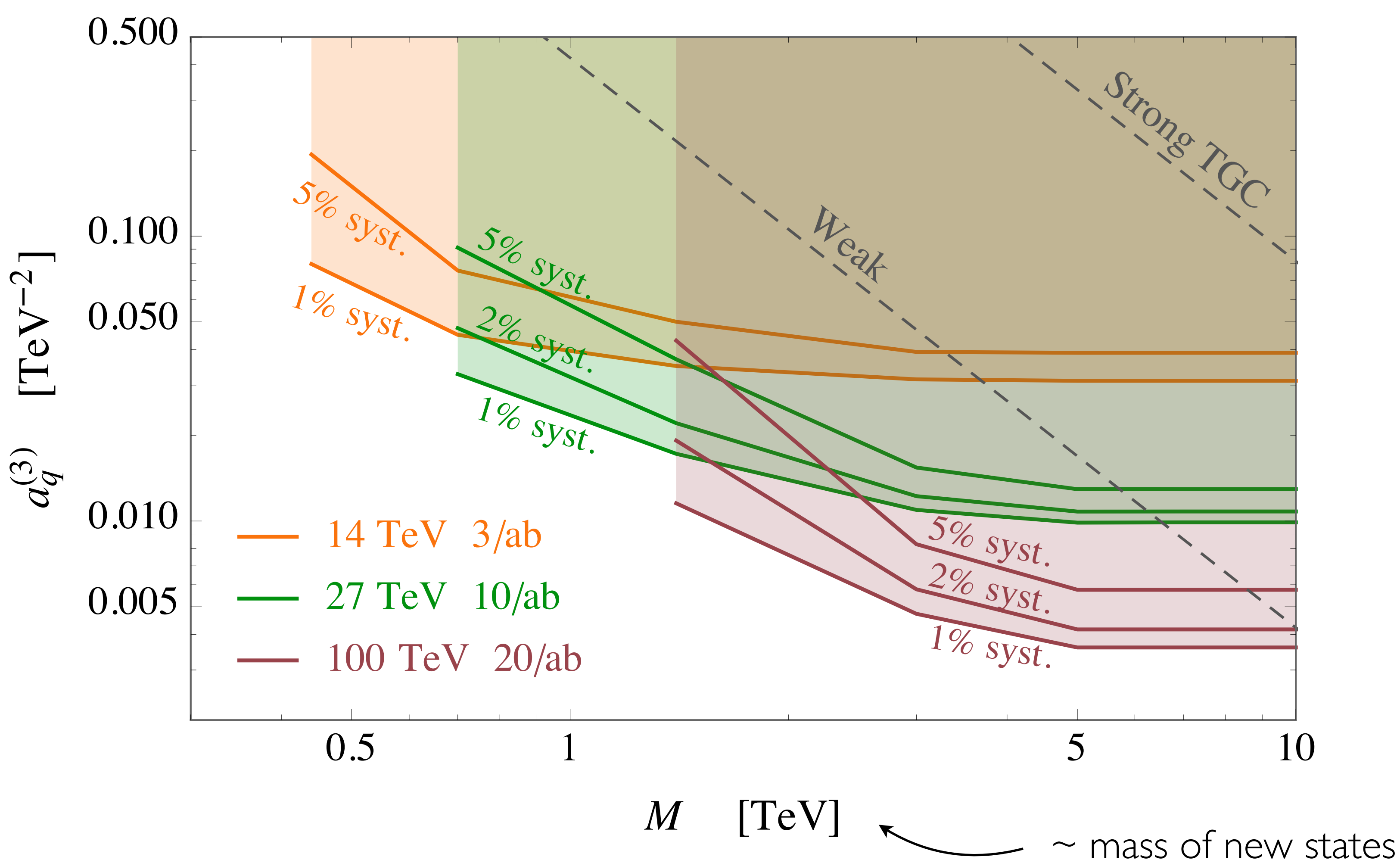
[Franceschini, GP, Pomarol, Riva, Wulzer '17]



- Non-trivial analysis: longitudinal channels small → exploit transverse zeroes
- Big improvement with respect to LEP

WZ production: Future colliders

Estimate of the bounds on $a_q^{(3)}(\bar{q}_L\sigma^a\gamma^\mu q_L)(iH^\dagger\sigma^a\overleftrightarrow{D}_\mu H)$



- additional improvement possible at future colliders
- reach at FCC-hh comparable with CLIC see [Ellis, Roloff, Sanz, You '17]

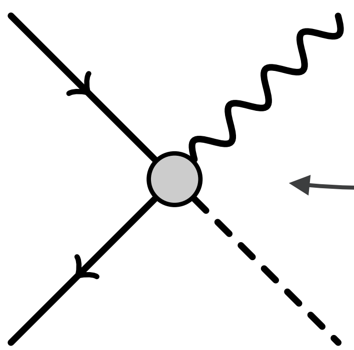
High luminosity and rare channels

High integrated luminosity → **very rare** but **very clean** channels

High luminosity and rare channels

High integrated luminosity ⟶ **very rare** but **very clean** channels

Example: **VH production**



$$a_q^{(3)}(\overline{q}_L \sigma^a \gamma^\mu q_L)(iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)$$

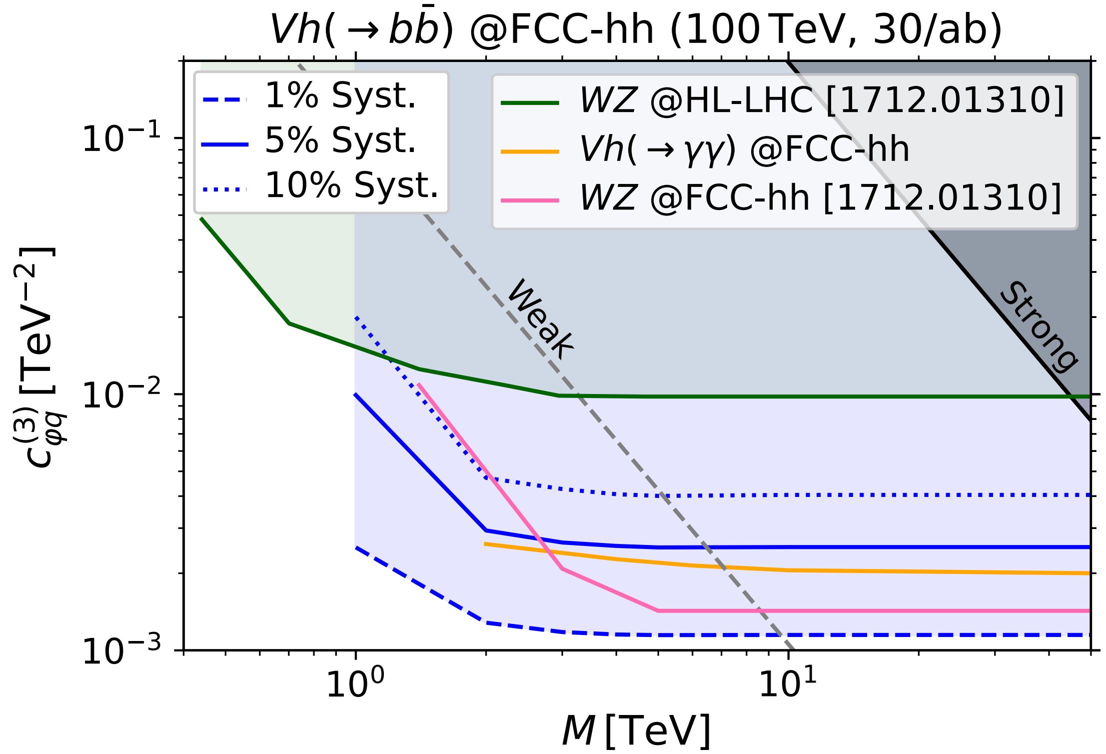
Different decay channels:

- $H \to bb$ ⟶ large cross section, but sizeable background
- $H \to \gamma\gamma$ ⟶ tiny cross section (only accessible at FCC-hh), but very clean

VH at FCC-hh

[Bishara, Englert et al. '22]

- $VH(\to bb)$ and $VH(\to \gamma\gamma)$ provide similar sensitivity
- Bounds competitive with WZ



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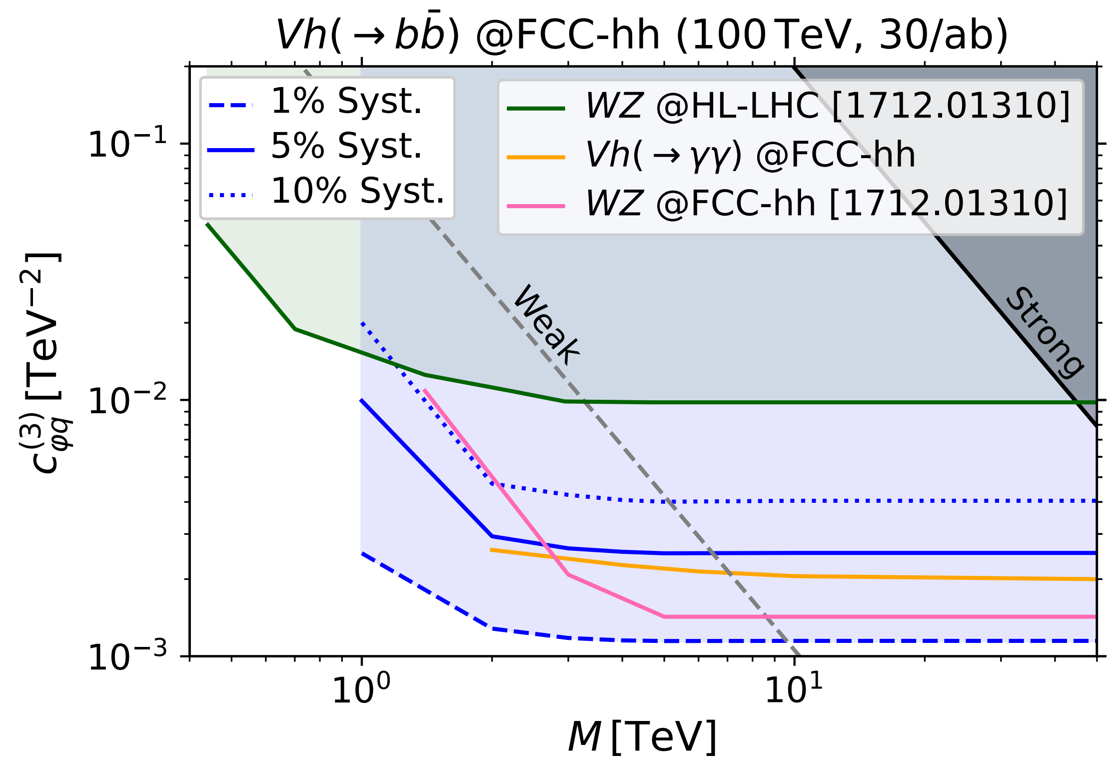
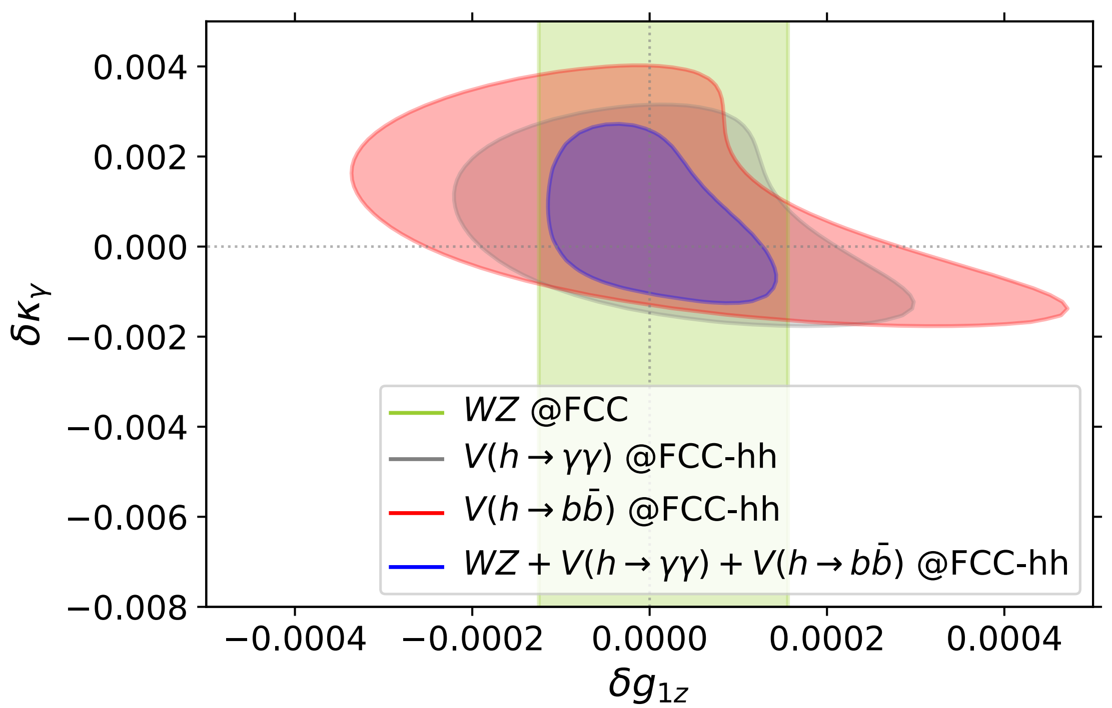
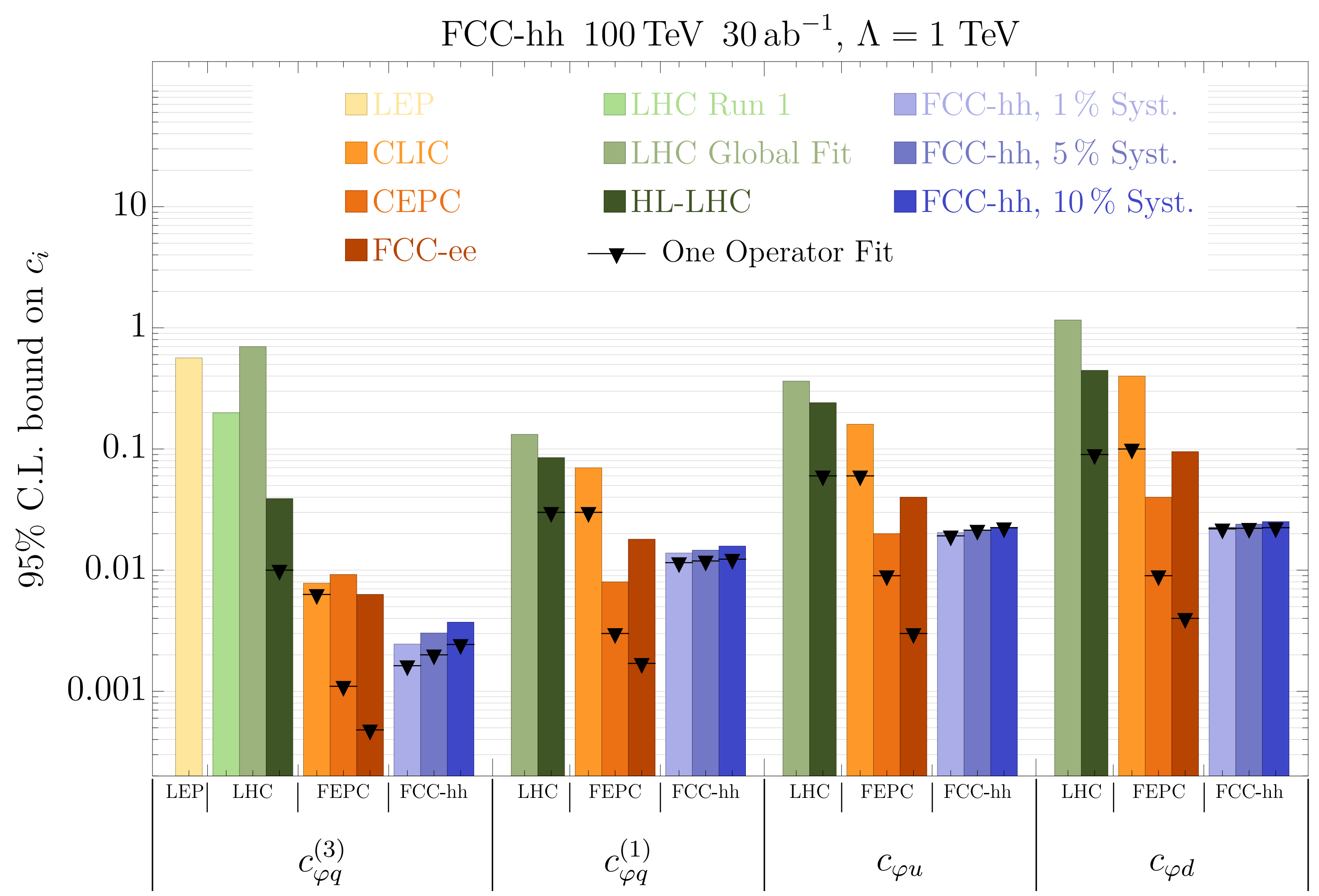


- Combination of the two channels can significantly improve the bounds



VH at FCC-hh

[Bishara, De Curtis et al. '20]



FCC-hh can match (or surpass) sensitivity at e^+e^- colliders

Higgs “pole” measurements

Low-energy e⁺e⁻ colliders

Low-energy e⁺e⁻ colliders can test several Higgs "pole" properties

- determination of **absolute normalization of couplings** (via recoil method $HZ(\to \ell^+\ell^-)$)

- sensitivity to **invisible decays**

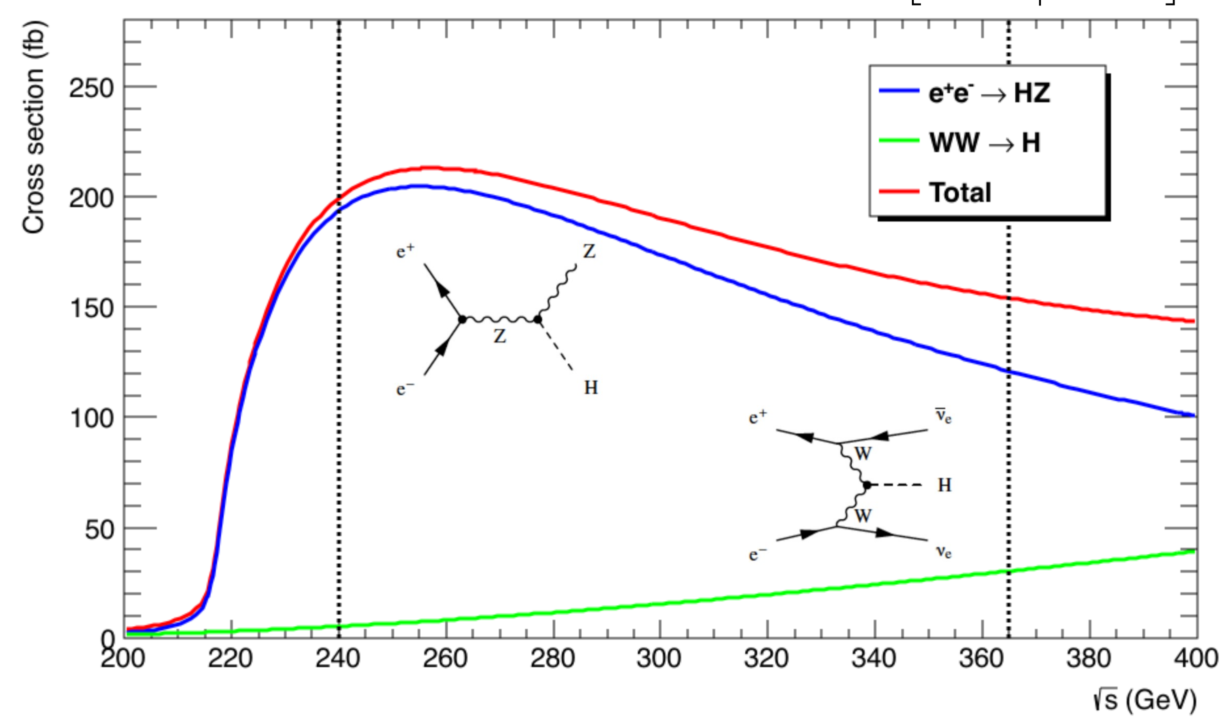
- measurement of Higgs **width**

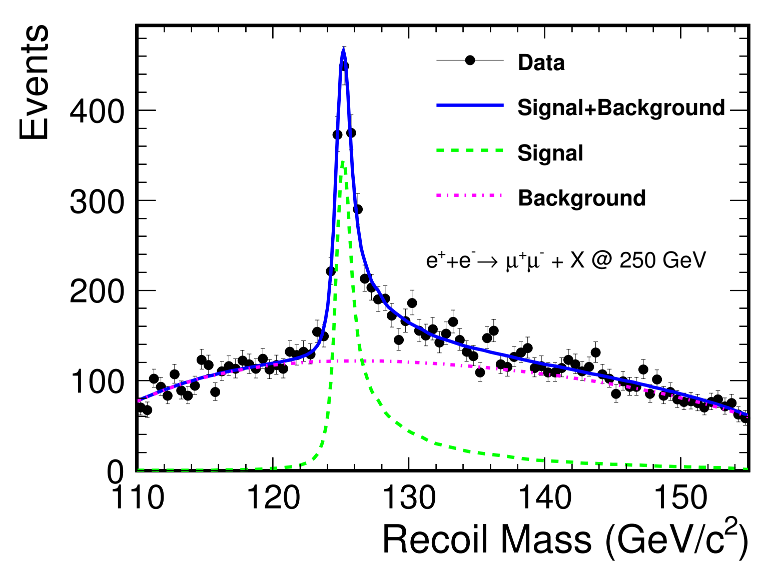
$$\delta\Gamma_H \sim 1\%$$

- measurement of Higgs **mass**

$$\delta m_H \sim 3\,\mathrm{MeV}$$

[FCC report '18]





Low-energy e^+e^- colliders

Higgs coupling sensitivity

Coupling	HL-LHC	FCC-ee (240–365 GeV) 2 IPs / 4 IPs
κ_W [%]	1.5*	0.43 / 0.33
κ_Z [%]	1.3*	0.17 / 0.14
κ_g [%]	2*	0.90 / 0.77
κ_γ [%]	1.6*	1.3 / 1.2
$\kappa_{Z\gamma}$ [%]	10*	10 / 10
κ_c [%]	–	1.3 / 1.1
κ_t [%]	3.2*	3.1 / 3.1
κ_b [%]	2.5*	0.64 / 0.56
κ_μ [%]	4.4*	3.9 / 3.7
κ_τ [%]	1.6*	0.66 / 0.55
$\mathrm{BR_{inv}}$ (<%, 95% CL)	1.9*	0.20 / 0.15
$\mathrm{BR_{unt}}$ (<%, 95% CL)	4*	1.0 / 0.88

[Table from mid-term report, from C. Grojean, Corfu '24]

- Model-independent measurement of linear Higgs couplings
- Significant improvement with respect to HL-LHC in

$$g^{eff}_{HZZ},\quad g^{eff}_{HWW},\quad g^{eff}_{Hgg},\quad g^{eff}_{Hbb},\quad g^{eff}_{Hcc},\quad g^{eff}_{H\tau\tau}$$

Low-energy e^+e^- colliders

Higgs coupling sensitivity

Coupling	HL-LHC	FCC-ee (240–365 GeV) 2 IPs / 4 IPs
κ_W [%]	1.5*	0.43 / 0.33
κ_Z [%]	1.3*	0.17 / 0.14
κ_g [%]	2*	0.90 / 0.77
κ_γ [%]	1.6*	1.3 / 1.2 ←
$\kappa_{Z\gamma}$ [%]	10*	10 / 10 ←
κ_c [%]	–	1.3 / 1.1
κ_t [%]	3.2*	3.1 / 3.1 ←
κ_b [%]	2.5*	0.64 / 0.56
κ_μ [%]	4.4*	3.9 / 3.7
κ_τ [%]	1.6*	0.66 / 0.55
$\mathrm{BR_{inv}}$ (<%, 95% CL)	1.9*	0.20 / 0.15
$\mathrm{BR_{unt}}$ (<%, 95% CL)	4*	1.0 / 0.88

[Table from mid-term report, from C. Grojean, Corfu '24]

- Model-independent measurement of linear Higgs couplings

- Significant improvement with respect to HL-LHC in

$$g^{eff}_{HZZ},\quad g^{eff}_{HWW},\quad g^{eff}_{Hgg},\quad g^{eff}_{Hbb},\quad g^{eff}_{Hcc},\quad g^{eff}_{H\tau\tau}$$

- **Exception**: decay channels with low BR

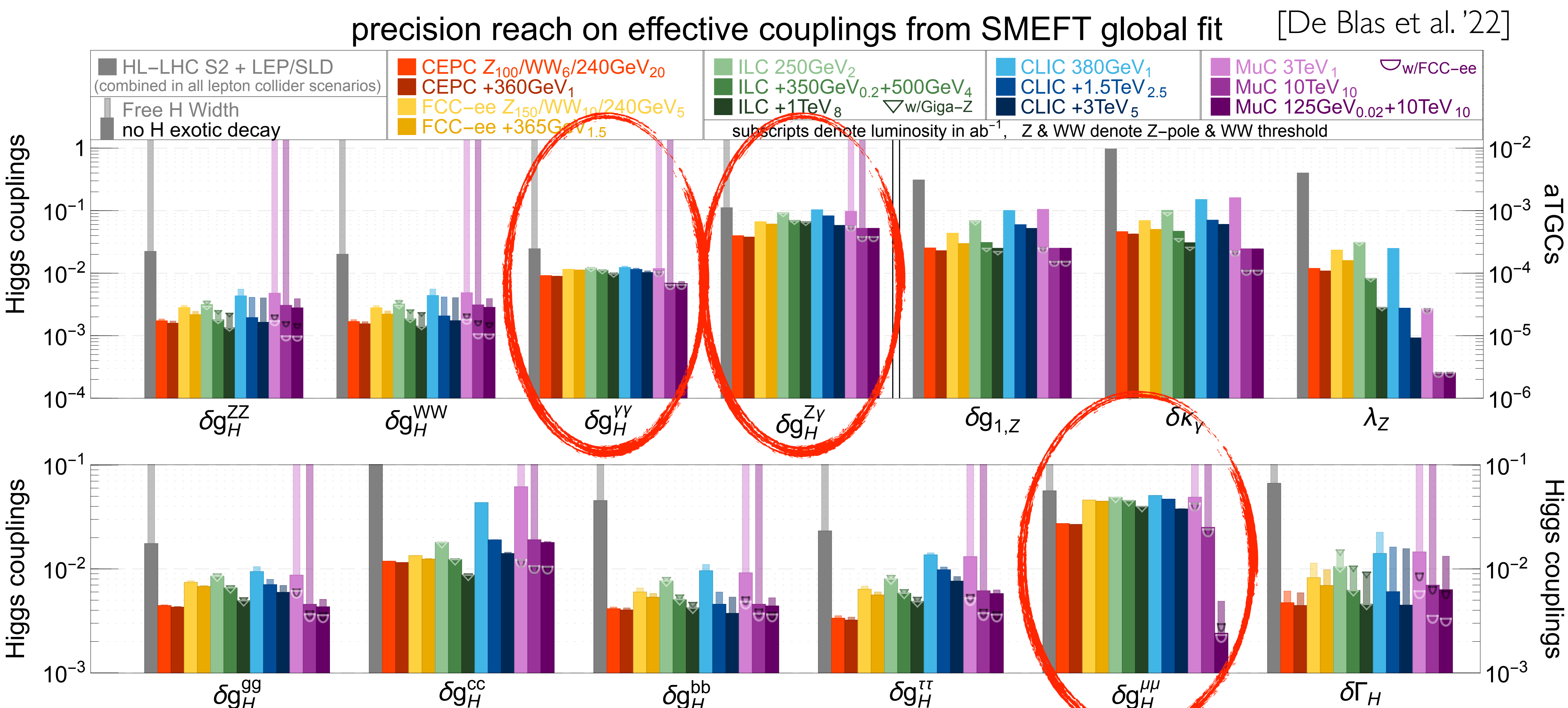
$$g^{eff}_{H\gamma\gamma},\quad g^{eff}_{H\mu\mu},\quad g^{eff}_{HZ\gamma}$$

Muon collider

A muon collider can improve the determination of some couplings

- improvement in $g^{eff}_{H\gamma\gamma}$ (and $g^{eff}_{HZ\gamma}$) with 10 TeV (and 125GeV) run
- improvement in $g^{eff}_{H\mu\mu}$ with 10 TeV run; excellent determination with 125GeV run

[De Blas et al. '22]



High-energy hadron collider

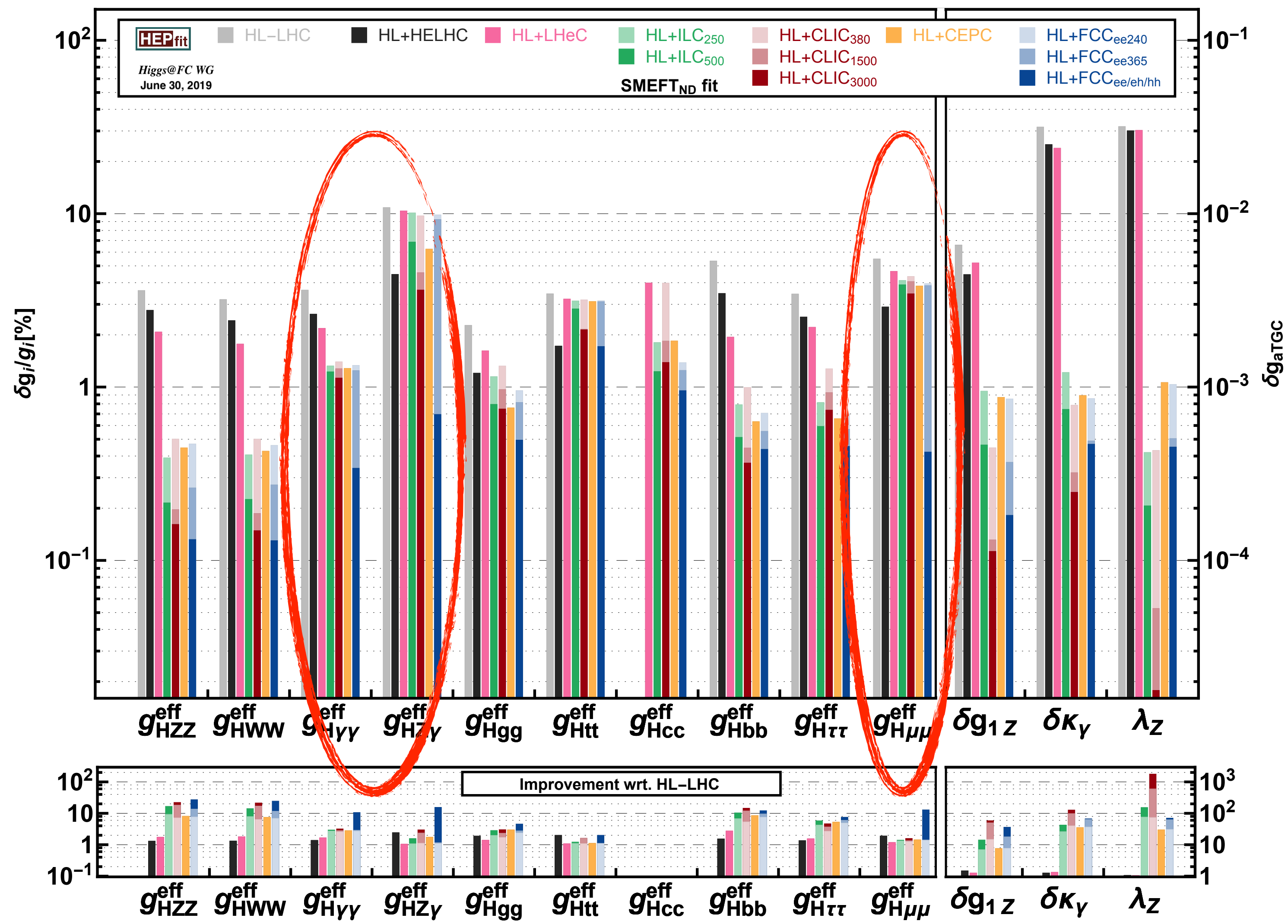
FCC-hh can test $g^{eff}_{H\gamma\gamma}, g^{eff}_{H\mu\mu}, g^{eff}_{HZ\gamma}$ with high precision

$g^{eff}_{H\gamma\gamma} \longrightarrow 0.4\%$

$g^{eff}_{H\mu\mu} \longrightarrow 0.7\%$

$g^{eff}_{HZ\gamma} \longrightarrow 0.9\%$

[De Blas et al. '22]



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$g^{eff}_{H\mu\mu} \longrightarrow 0.7\%$

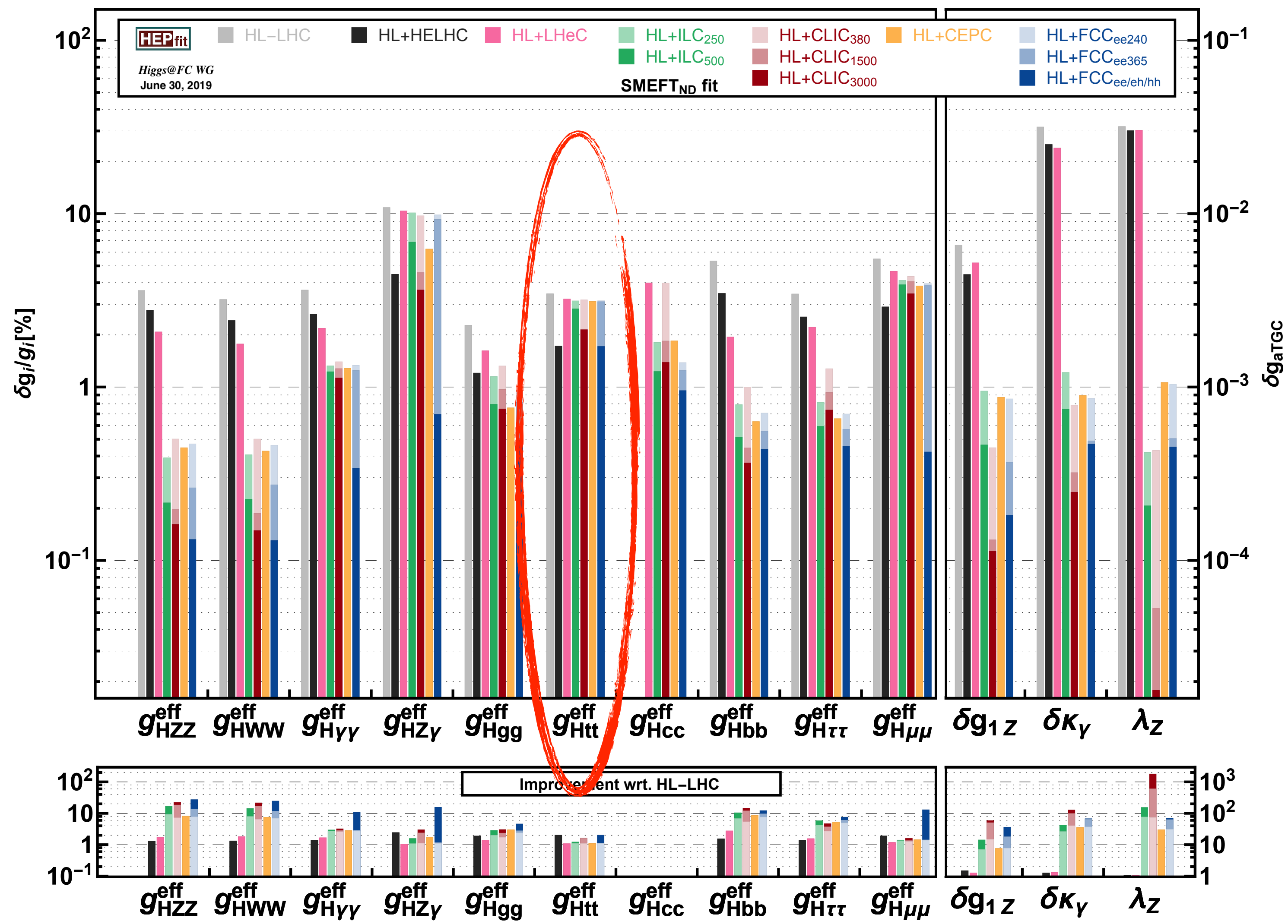
$g^{eff}_{HZ\gamma} \longrightarrow 0.9\%$

FCC-hh can improve the measurement of the top Yukawa

$g^{eff}_{Htt} \longrightarrow 1\%$

(improvement also possible at HE-LHC and CLIC 3TeV)

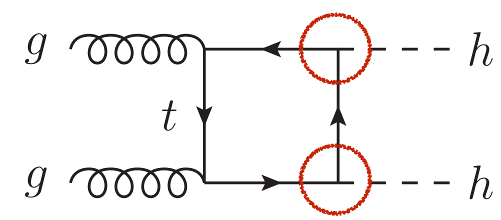
[De Blas et al. '22]

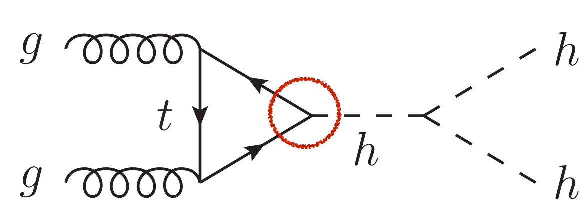


Higgs trilinear coupling

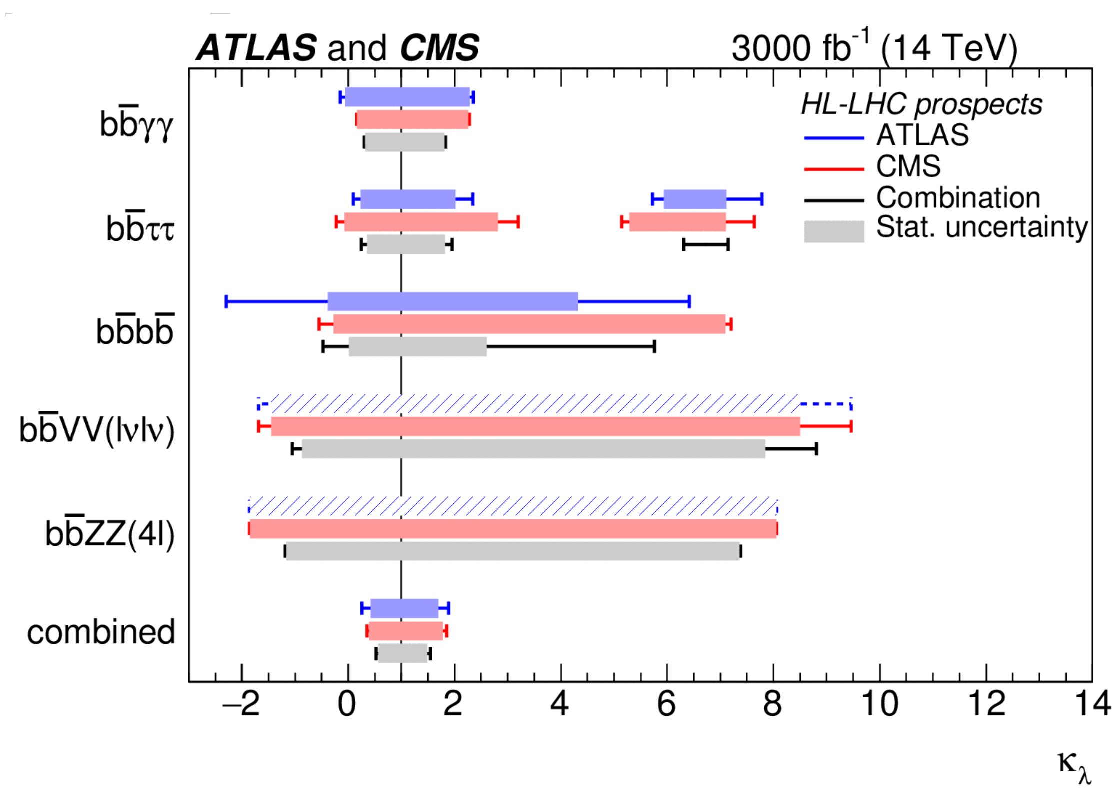
High-luminosity LHC

Main sensitivity from gg → HH





combination of several decay channels



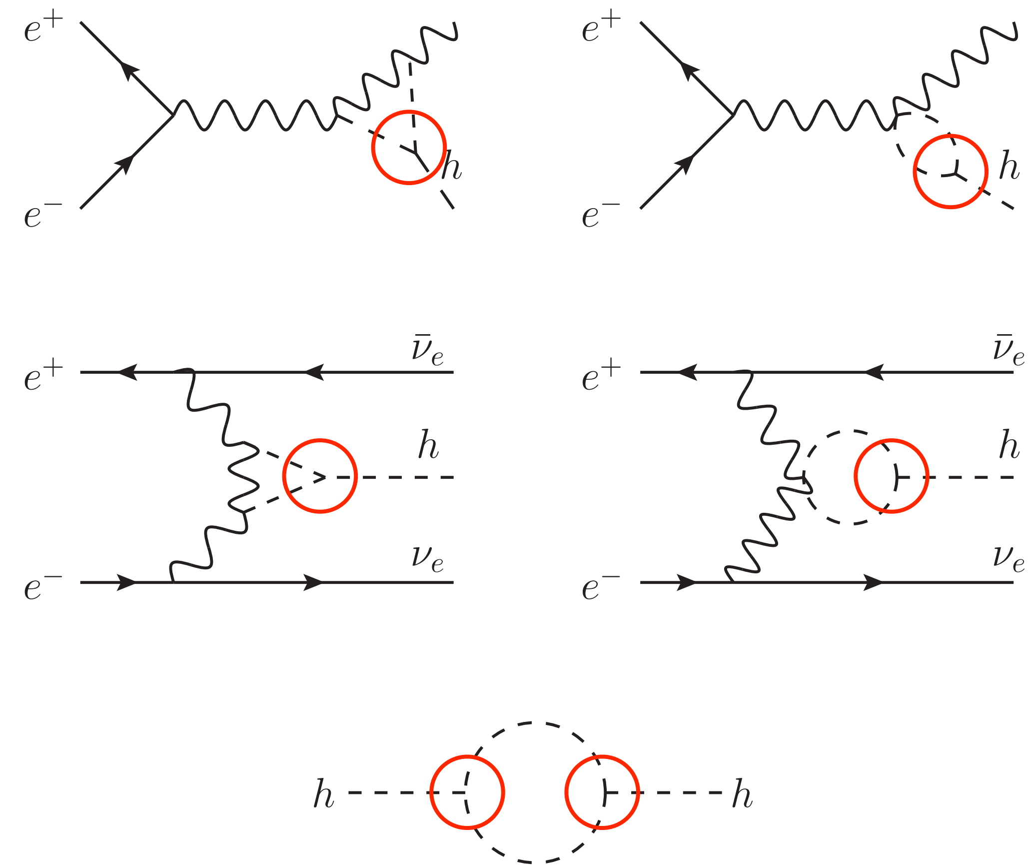
✦ HL-LHC can test the Higgs trilinear with O(50%) precision [See Di Micco et al. '19]

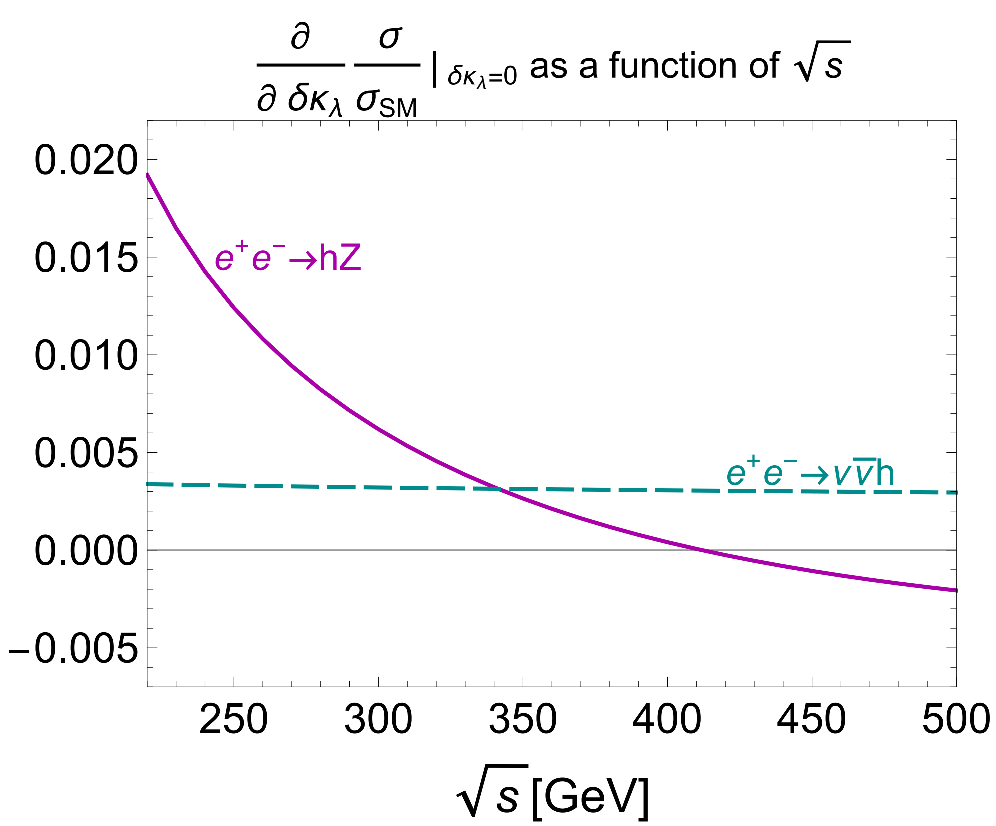
$$-0.43 \leq \delta\kappa_\lambda \leq 0.5 \qquad \text{at} \qquad 68\% \text{ C.L.}$$

Low-energy e⁺e⁻ colliders

Higgs self-interaction can be probed indirectly through one-loop corrections to **single-Higgs processes**

[McCullough '13]





Good sensitivity at low energy in HZ (and $\nu\bar{\nu}H$) channels

Low-energy e^+e^- colliders

Expected precision from 1-parameter fit (1σ bounds)

collider	1-parameter
CEPC 240	18%
FCC-ee 240	21%
FCC-ee 240/365	21%
FCC-ee (4IP)	15%
ILC 250	36%
ILC 250/500	32%
ILC 250/500/1000	29%
CLIC 380	117%
CLIC 380/1500	72%
CLIC 380/1500/3000	49%

[Di Micco et al. '19]

CECP and FCC-ee provide fair sensitivity

collider	Full $\mathcal{L}$ [ab^{-1}]
CECP 240	5.6
FCC-ee 240	5.0
FCC-ee 365	1.5
FCC-ee (4IP)	12.0 + 5.5
ILC 250	2.0
ILC 500	4.0
ILC 1000	8.0
CLIC 380	1.0
CLIC 1500	2.5
CLIC 3000	5.0

Low-energy e^+e^- colliders

Expected precision from global fit (1σ bounds)

collider	1-parameter	full SMEFT
CEPC 240	18%	-
FCC-ee 240	21%	-
FCC-ee 240/365	21%	44%
FCC-ee (4IP)	15%	27%
ILC 250	36%	-
ILC 250/500	32%	58%
ILC 250/500/1000	29%	52%
CLIC 380	117%	-
CLIC 380/1500	72%	-
CLIC 380/1500/3000	49%	-

runs at single energy do not provide significant bounds

[Di Micco et al. '19]

collider	Full $\mathcal{L}$ [ab^{-1}]
CECP 240	5.6
FCC-ee 240	5.0
FCC-ee 365	1.5
FCC-ee (4IP)	12.0 + 5.5
ILC 250	2.0
ILC 500	4.0
ILC 1000	8.0
CLIC 380	1.0
CLIC 1500	2.5
CLIC 3000	5.0

Low-energy e⁺e⁻ colliders

Expected precision from global fit (1σ bounds)

collider	1-parameter	full SMEFT
CEPC 240	18%	-
FCC-ee 240	21%	-
FCC-ee 240/365	21%	44%
FCC-ee (4IP)	15%	27%
ILC 250	36%	-
ILC 250/500	32%	58%
ILC 250/500/1000	29%	52%
CLIC 380	117%	-
CLIC 380/1500	72%	-
CLIC 380/1500/3000	49%	-

[Di Micco et al.'19]

runs at single energy do not provide significant bounds

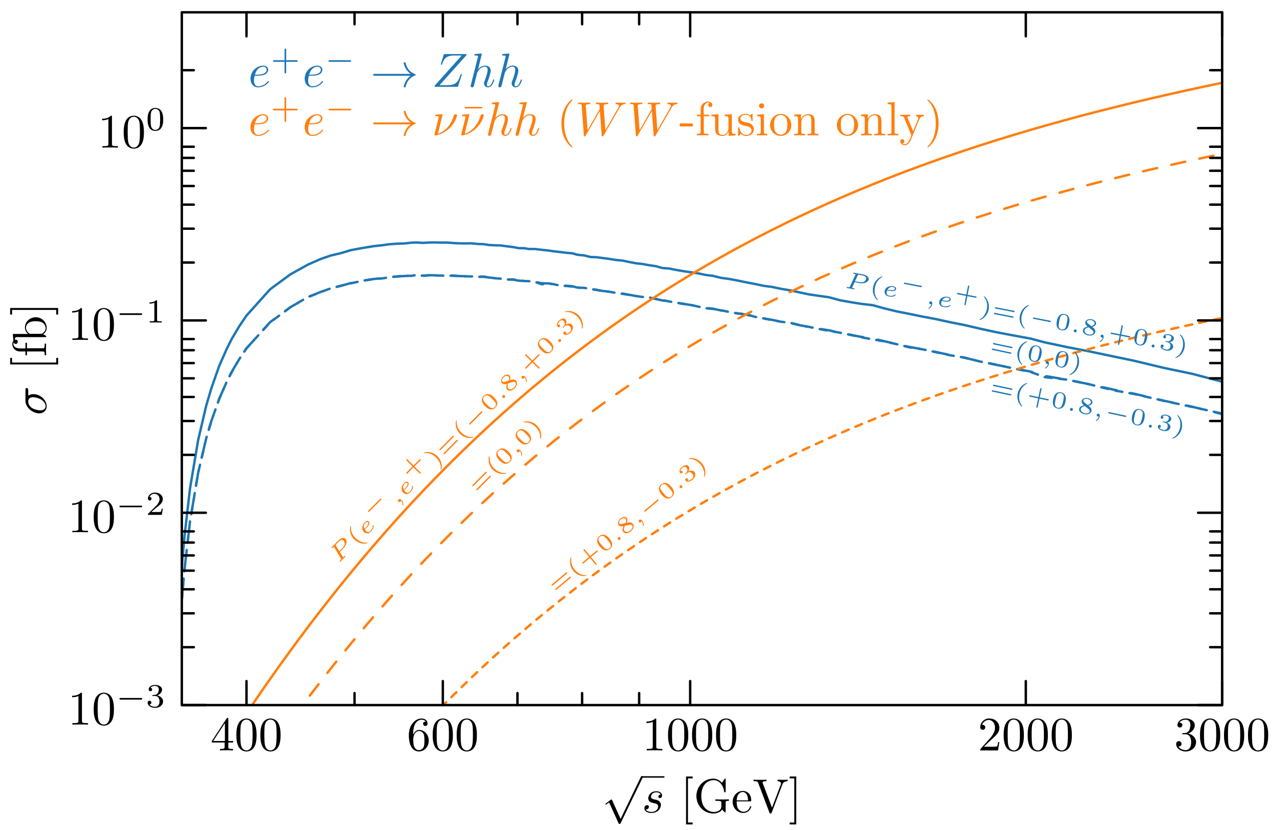
determination can reach 27% at FCC-ee with 4 interaction points

collider	Full $\mathcal{L}$ [ab^{-1}]
CECP 240	5.6
FCC-ee 240	5.0
FCC-ee 365	1.5
FCC-ee (4IP)	12.0 + 5.5
ILC 250	2.0
ILC 500	4.0
ILC 1000	8.0
CLIC 380	1.0
CLIC 1500	2.5
CLIC 3000	5.0

High-energy e⁺e⁻ colliders

Two main channels

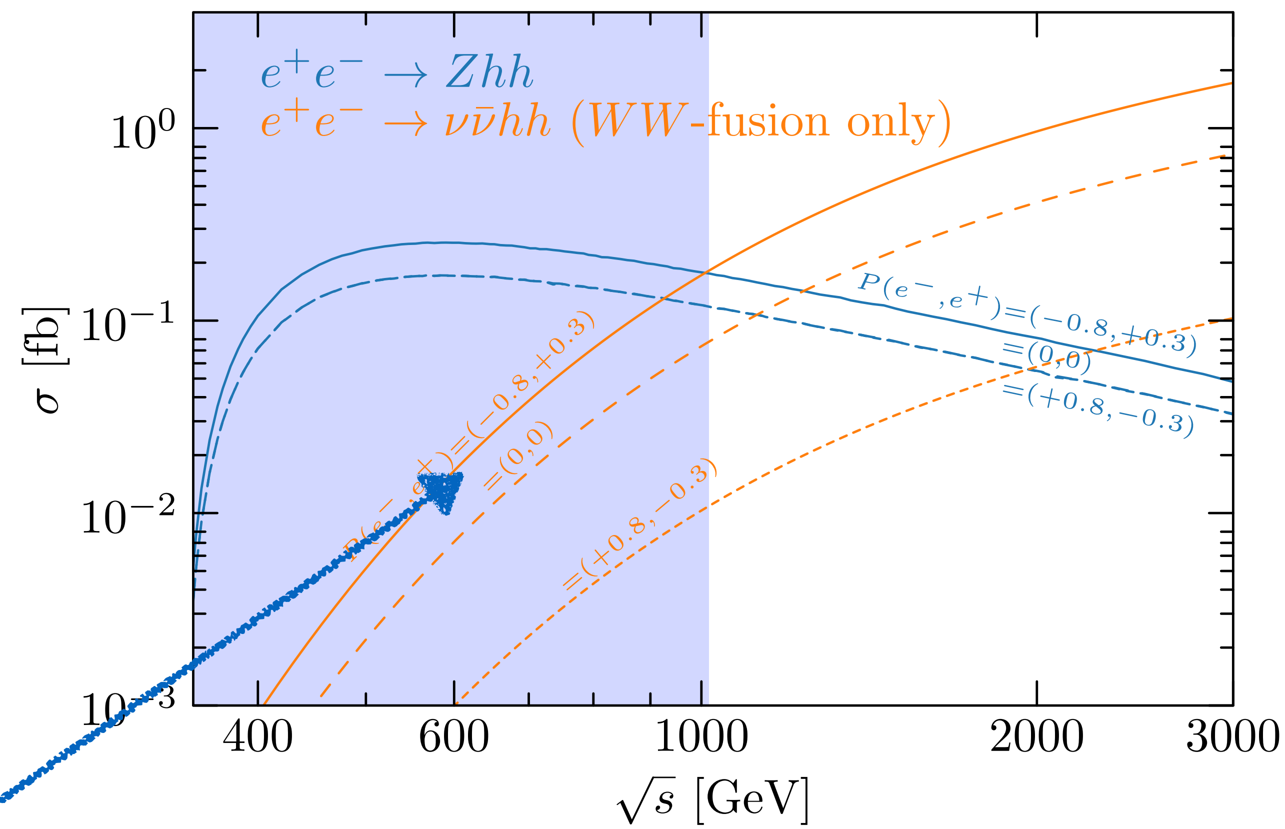
ZHH and $\nu\bar{\nu}HH$

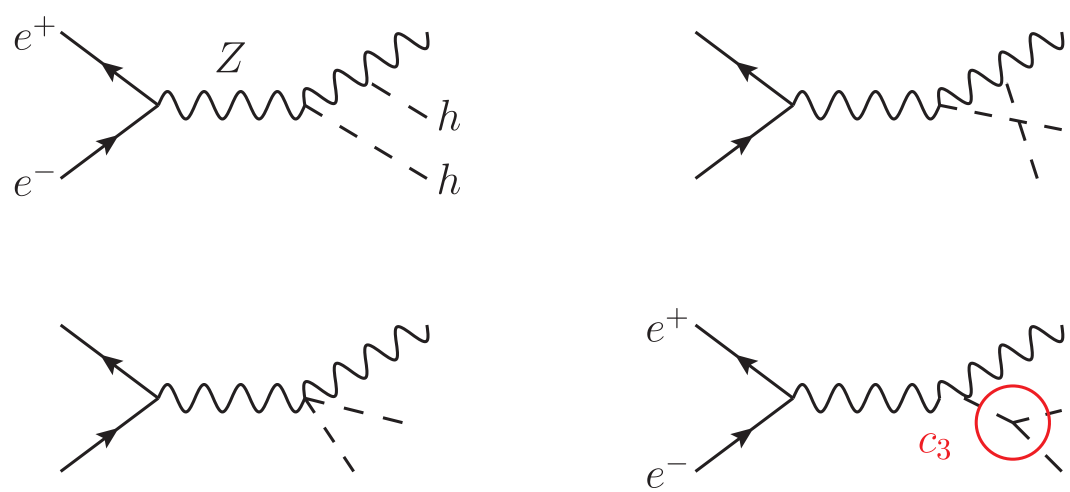


High-energy e⁺e⁻ colliders

Two main channels

ZHH and $\nu\bar{\nu}HH$

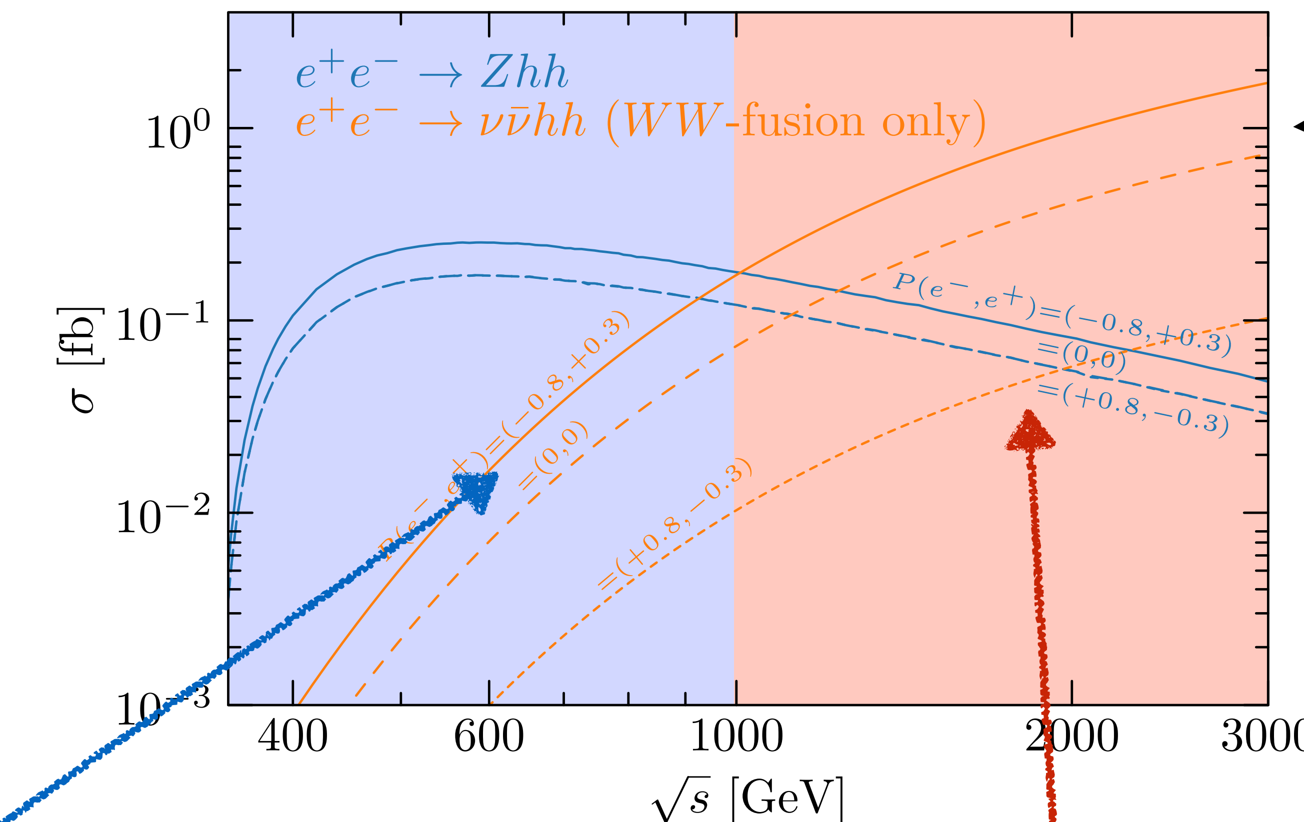




High-energy e⁺e⁻ colliders

Two main channels

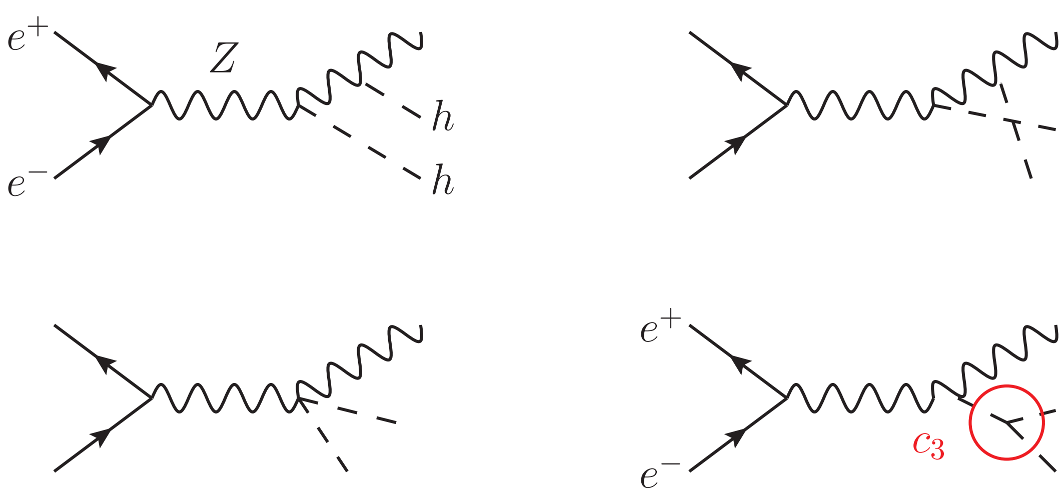
ZHH and $\nu\bar{\nu}HH$



beam polarization can enhance cross-section

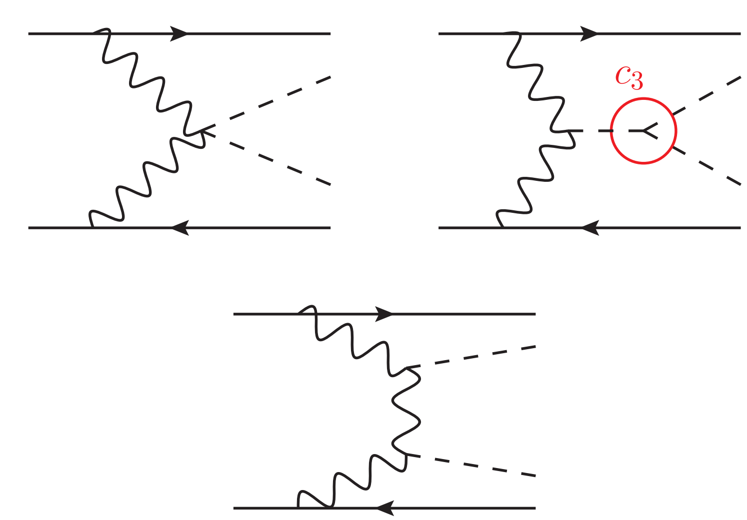
Double Higgs-strahlung (DHS)

dominant below 1 TeV



Vector Boson Fusion (VBF)

dominant above 1 TeV



Precision reach at ILC and CLIC

Expected precision from HH production channels
(1σ bounds)

collider	excl. from HH
HL-LHC	50%
ILC 500	27%
ILC 1000	10%
CLIC 1500	36%
CLIC 3000	[-7%, 11%]

Can reach the 10% threshold

FCC-hh

Exclusive fit on $\delta\kappa_\lambda$

$\sqrt{s} = 100$ TeV $\mathcal{L} = 30$ ab^{-1}

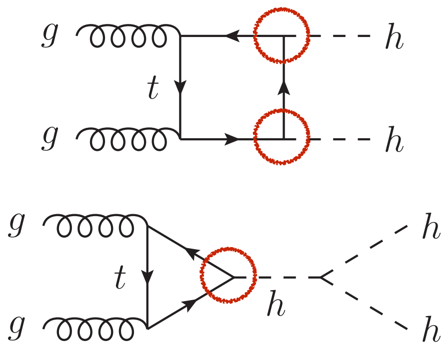
	$b\bar{b}\gamma\gamma$	$b\bar{b}\tau^+\tau^-$	$b\bar{b}ZZ^*$ (4ℓ)	$b\bar{b}WW^*$ (2j$\ell\nu$)	$b\bar{b}b\bar{b}$ +jet
$\delta\kappa_\lambda$	6%	8%	14%	40%	30%

[Di Micco et al. '19]

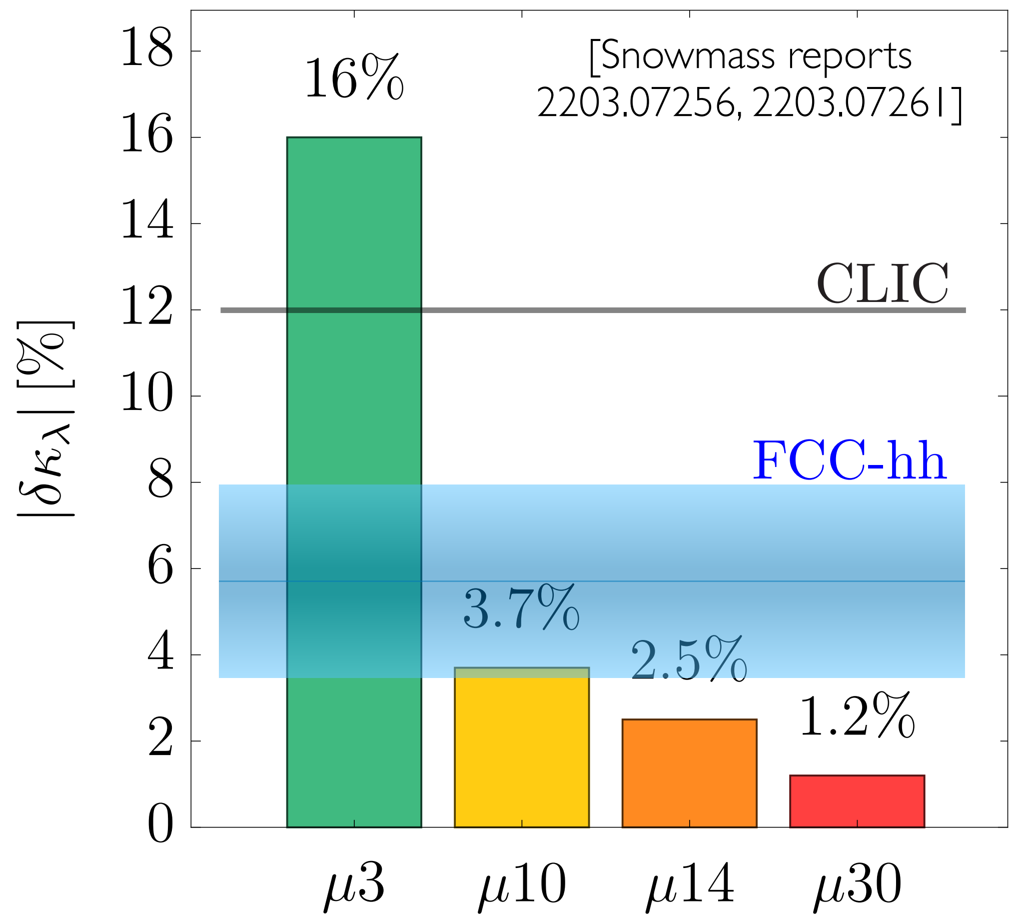
- precision likely to be limited by systematics
  (theory systematics dominant for $\Delta_S \gtrsim 2.5\%$, leading to $\delta\kappa_\lambda \simeq 2\Delta_S$)

- ultimate FCC-hh reach in the 3.4 - 7.8% range [Mangano et al. 2004.03505]

- global fit could affect the prediction
  (strong dependence on top Yukawa coupling)



Muon collider



energy	Full $\mathcal{L}$ [ab^{-1}]
3 TeV	$\approx$2
10 TeV	10
14 TeV	$\approx$20
30 TeV	90

- High-energy muon collider can be competitive with FCC-hh

Conclusions and Outlook

Conclusions and outlook

Precision measurements can provide promising information at HL-LHC and future colliders

- complements direct searches
- can extend reach beyond collider energy threshold (eg. e^+e^- machines)

Can be performed both at **lepton** and at **hadron colliders**

Challenging aspects:

- good statistics (especially in the high-energy tails)
- good control on theoretical and experimental systematics

Conclusions and outlook

Crucial aspect: approaching **optimality**

- important to fully exploit data and reach maximal sensitivity

Challenging aspects:

- huge amount of data
- information ‘hidden’ in high-dimensional kinematic distributions
- need for simultaneous fit of several quantities
  (eg. PDF determination together with fit of SMEFT operators)

Promising approaches through **machine learning**