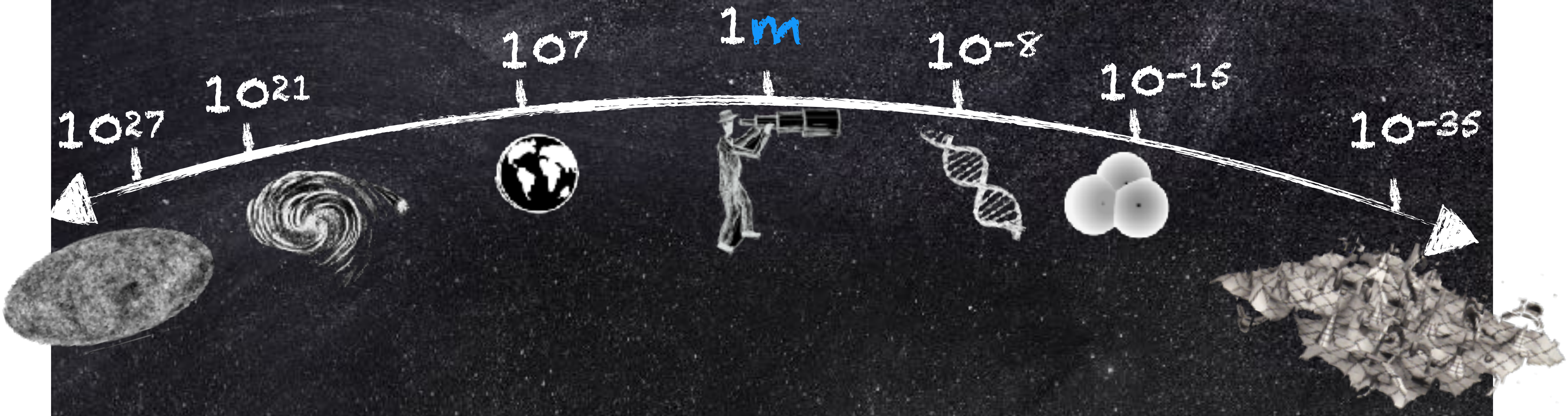
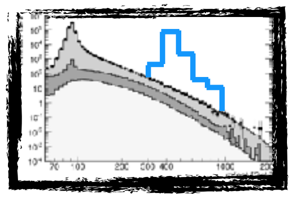
With FCCee beyond the FCCee



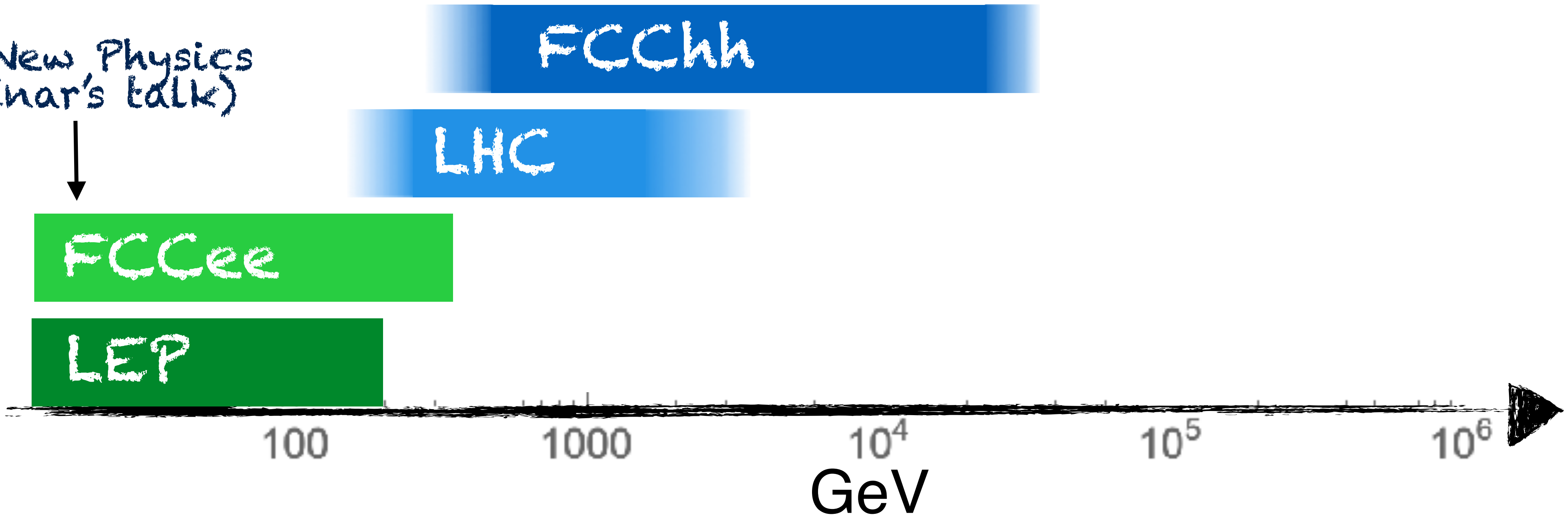
Francesco Riva
(UNIGE)

Circular Colliders

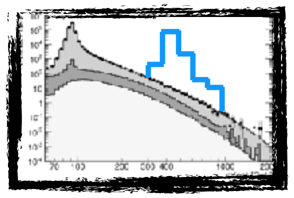


Reach of Direct Searches

Light New Physics
(See Inar's talk)

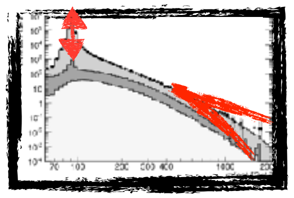


Circular Colliders



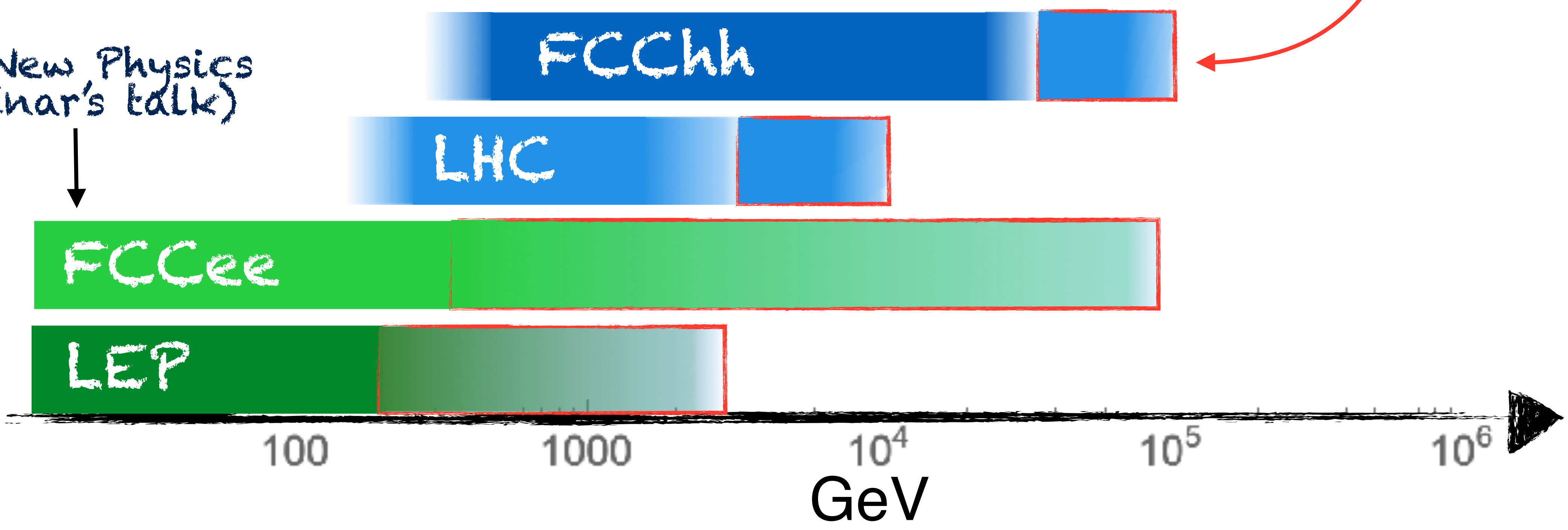
Reach of Direct Searches

Reach of Indirect Searches

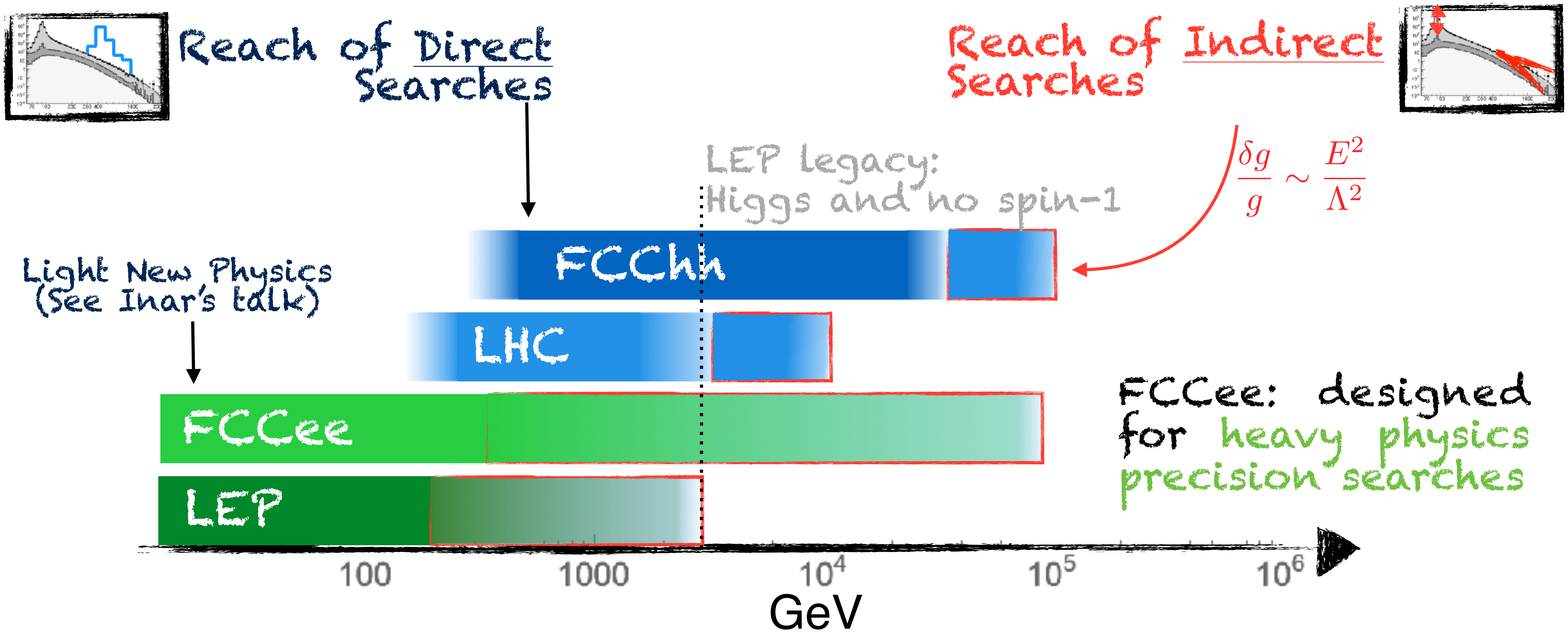


$$\frac{\delta g}{g} \sim \frac{E^2}{\Lambda^2}$$

Light New Physics (See Inar's talk)



Circular Colliders



Reach of Direct Searches

Reach of Indirect Searches

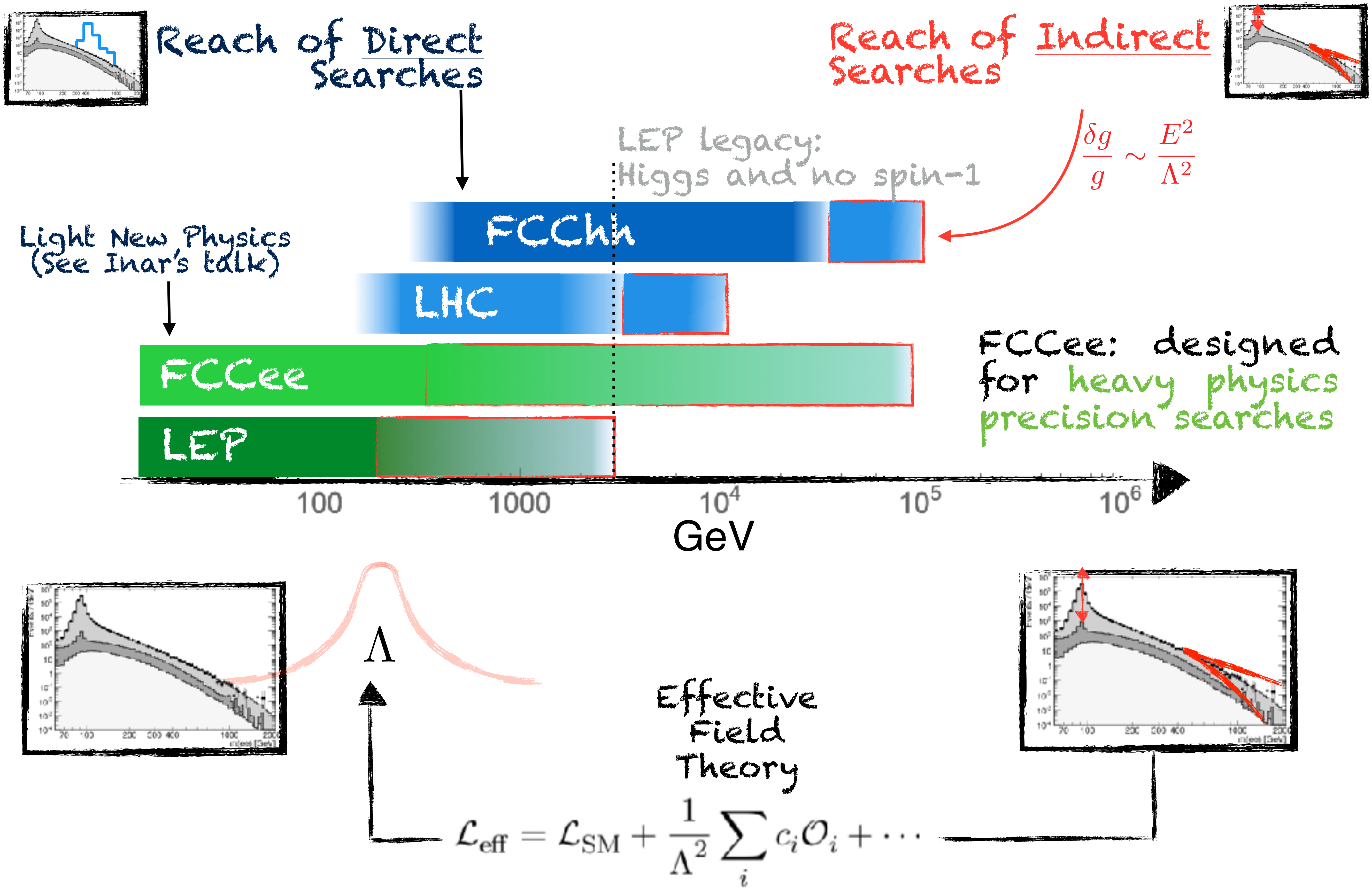
$$\frac{\delta g}{g} \sim \frac{E^2}{\Lambda^2}$$

LEP legacy:
Higgs and no spin-1

Light New Physics
(See Inar's talk)

FCCee: designed for heavy physics precision searches

Circular Colliders



Reach of Direct Searches

Reach of Indirect Searches

$$\frac{\delta g}{g} \sim \frac{E^2}{\Lambda^2}$$

LEP legacy:
Higgs and no spin-1

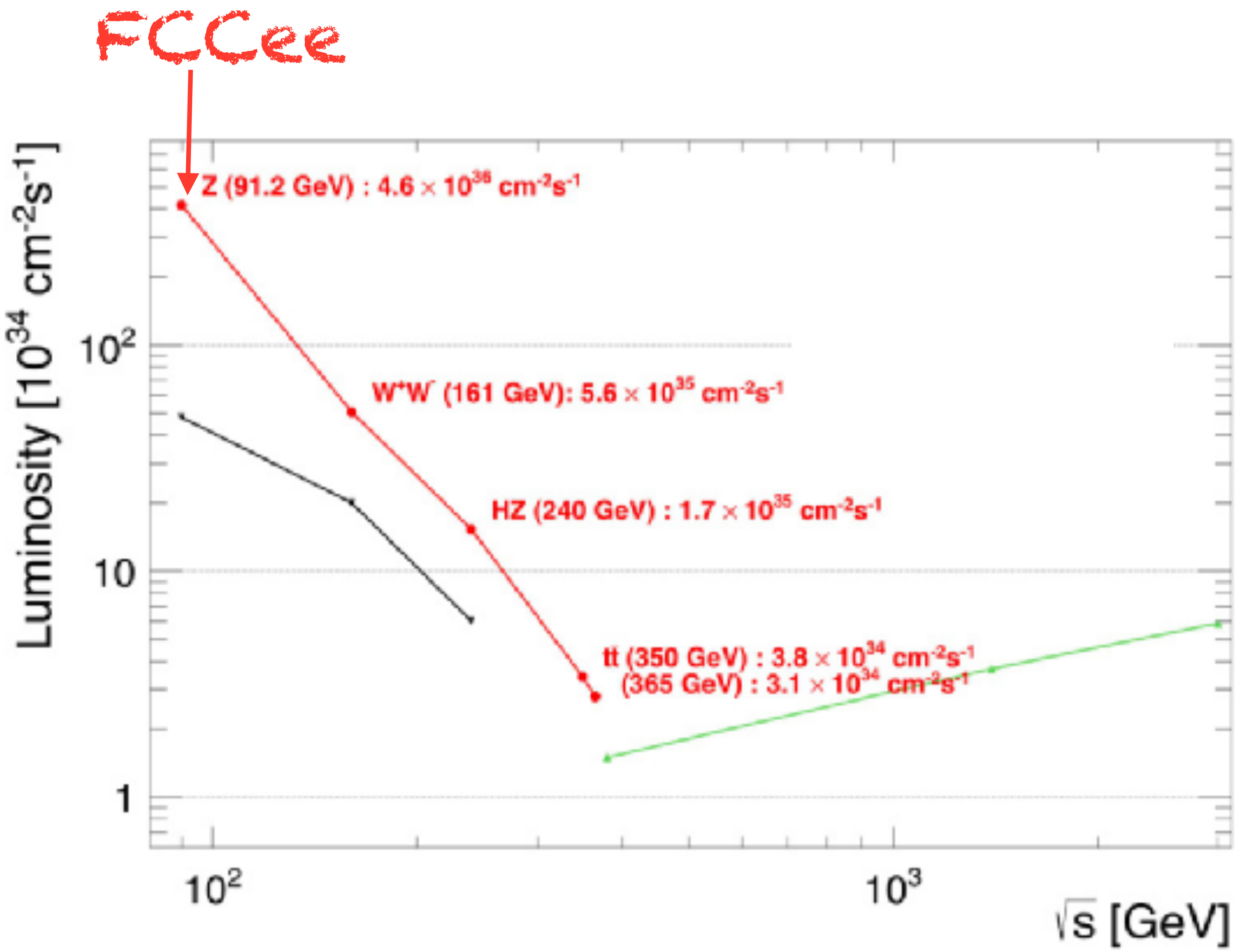
Light New Physics
(See Inar's talk)

FCCee: designed for heavy physics precision searches

Effective Field Theory

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda^2}\sum_i c_i \mathcal{O}_i + \cdots$$

Precision at FCCee

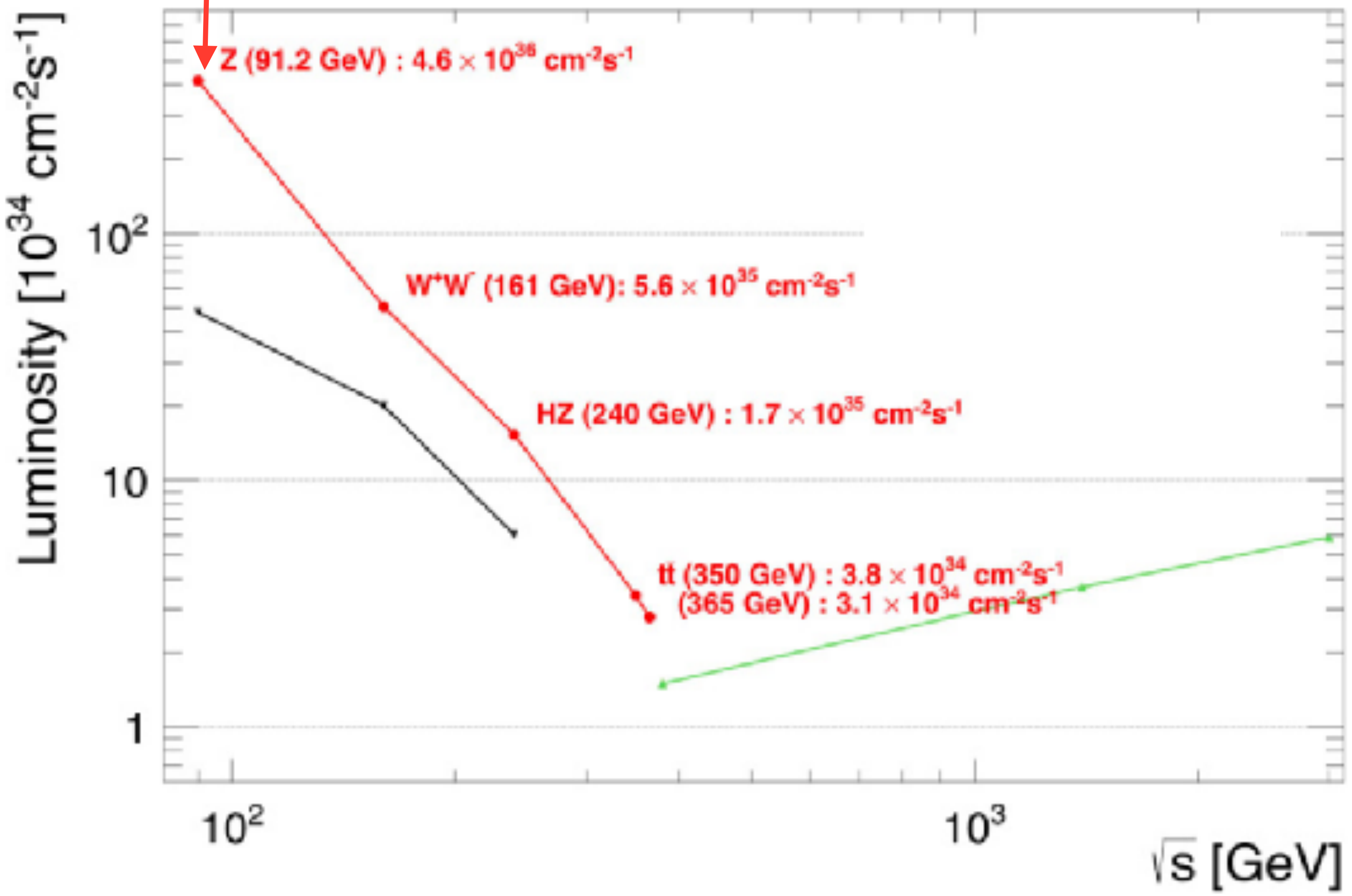


FCCee

	Precision $\sim \sqrt{N}/N$
10^{12} Z bosons	10^{-6}
10^{8} WW pairs	10^{-4}
10^{6} Higgs bosons	10^{-3}
10^{6} Top-quark pairs	10^{-3}

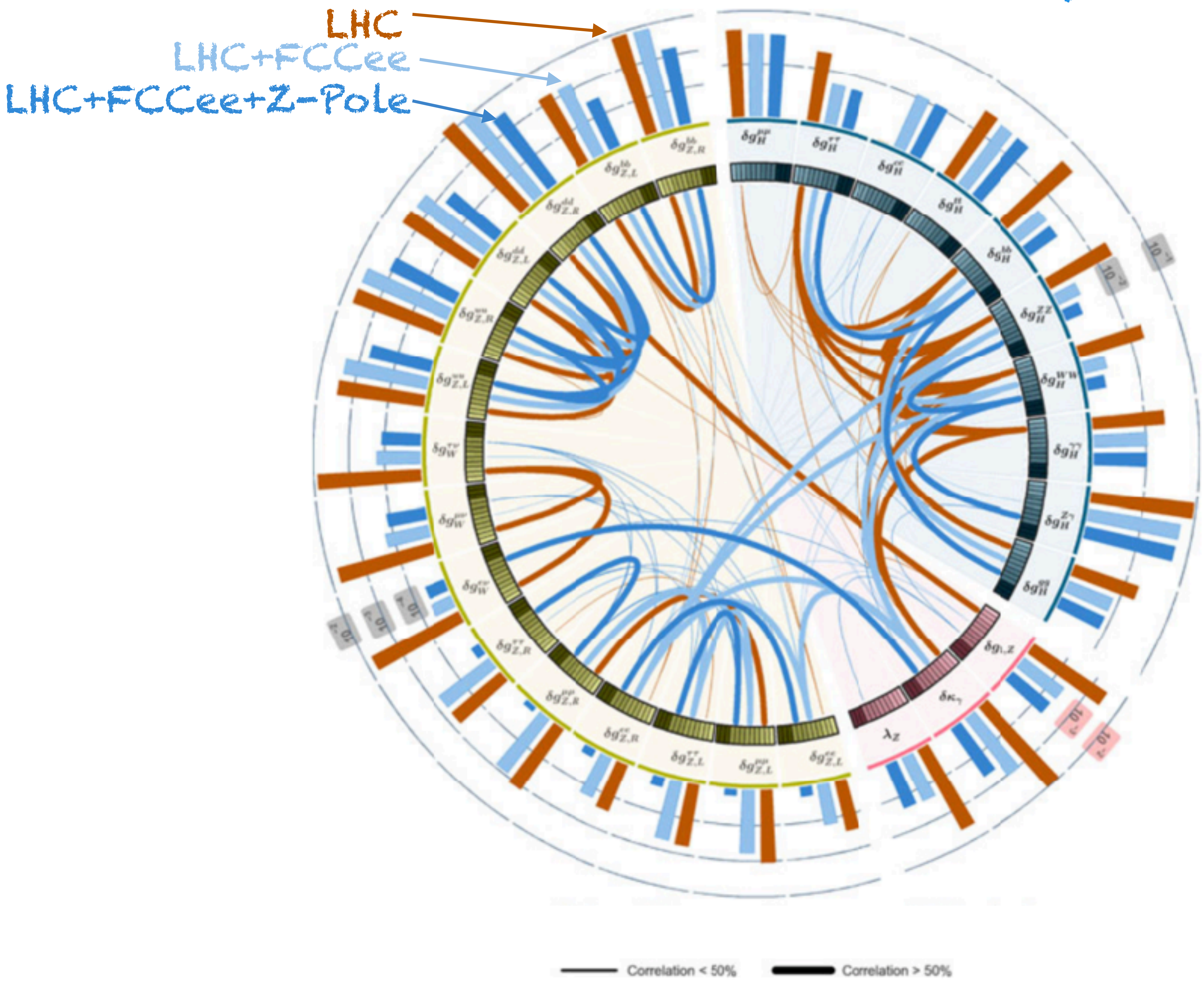
Precision at FCCee

FCCee



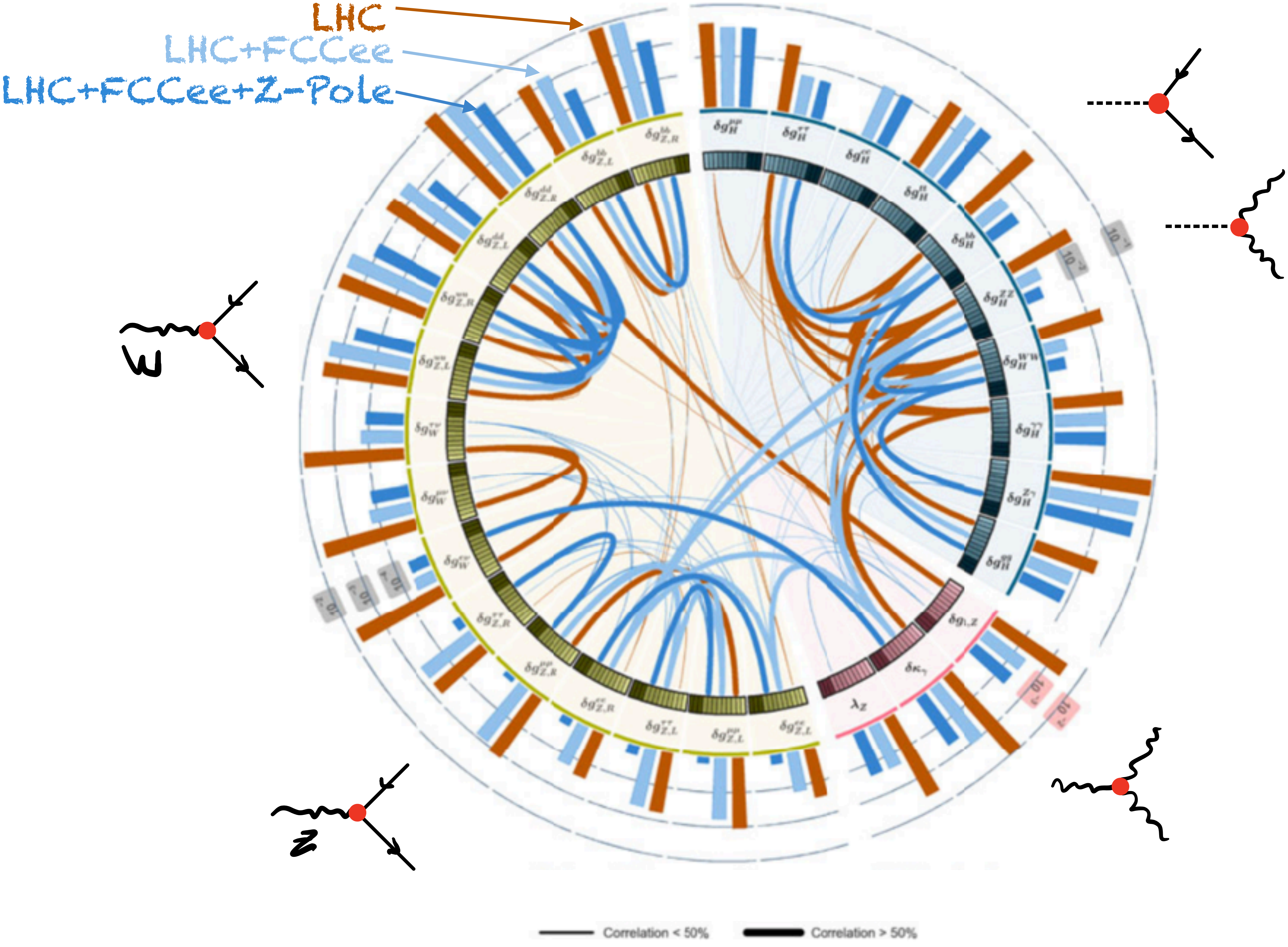
Assume TH-error comparable (3/4 loop) See Spira's talk and Blondel et al'18	Precision $\sim \sqrt{N}/N$
10^{12} Z bosons	10^{-6}
10^{8} WW pairs	10^{-4}
10^{6} Higgs bosons	10^{-3}
10^{6} Top-quark pairs	10^{-3}

Reach on modified Couplings



From deBlas'21 and deBlas,Durieux,Grojean,Gu,Paul'19

Reach on modified Couplings



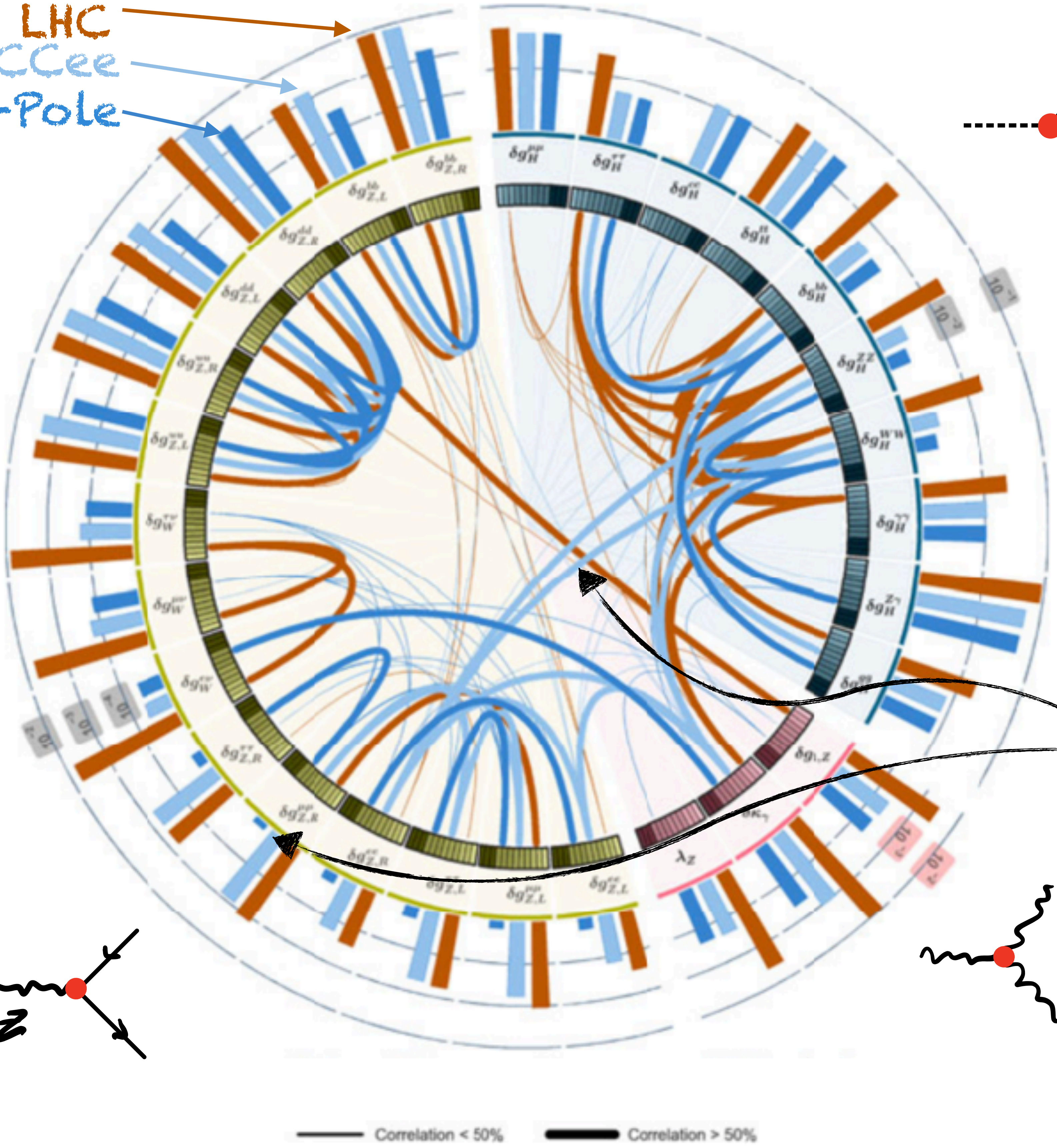
From deBlas'21 and deBlas,Durieux,Grojean,Gu,Paul'19

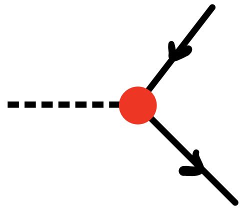
Reach on modified Couplings

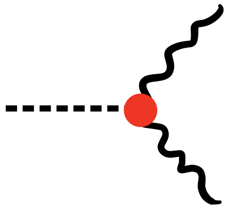
LHC

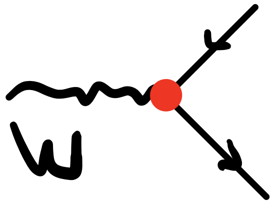
LHC+FCCee

LHC+FCCee+Z-Pole





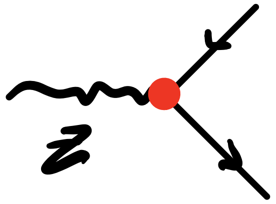


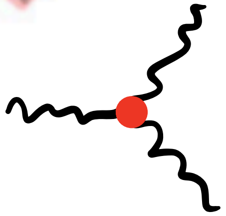


Z-Pole

→ less correlation

→ Up to 100x better than LHC

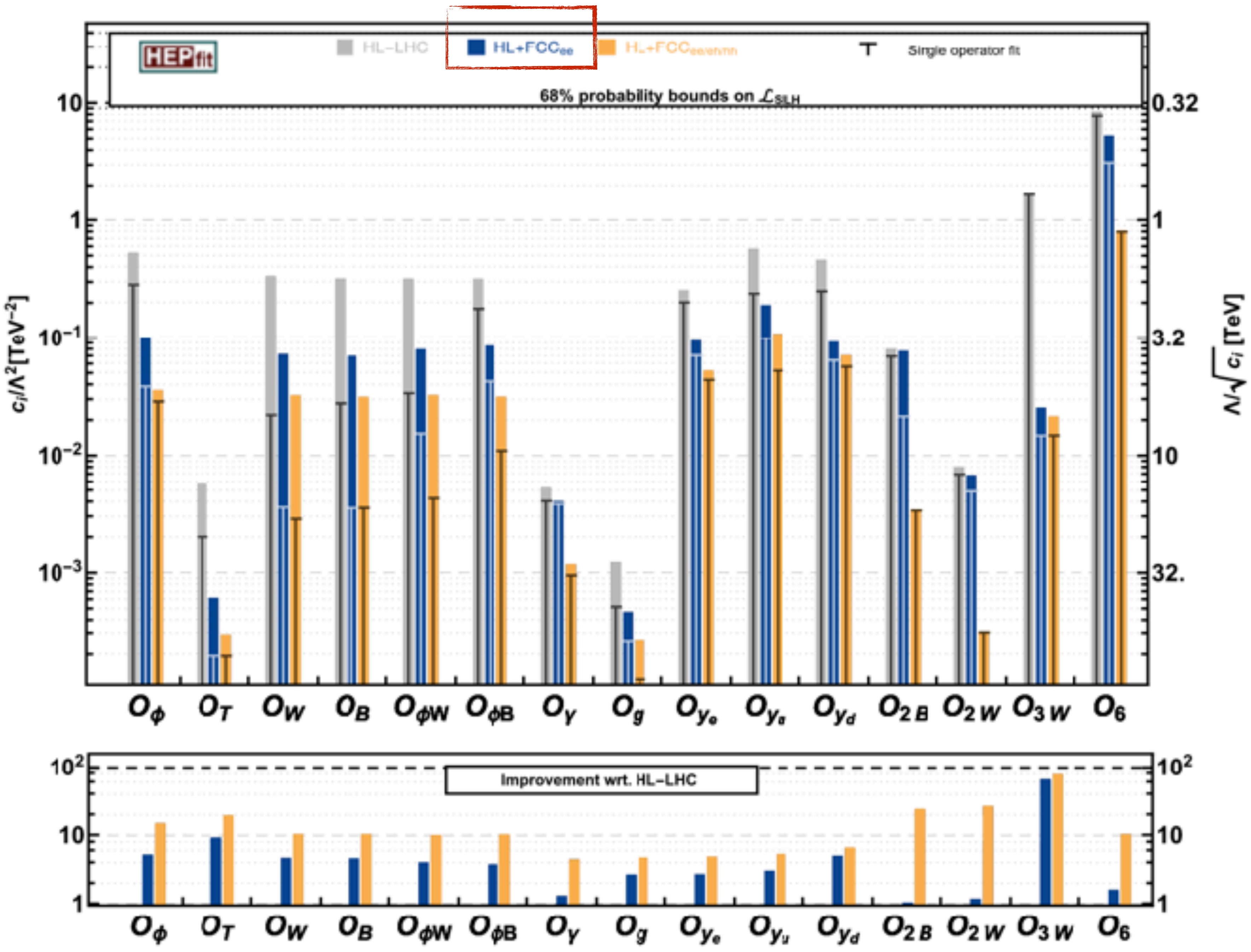




From deBlas'21 and deBlas,Durieux,Grojean,Gu,Paul'19

Reach on modified Propagators

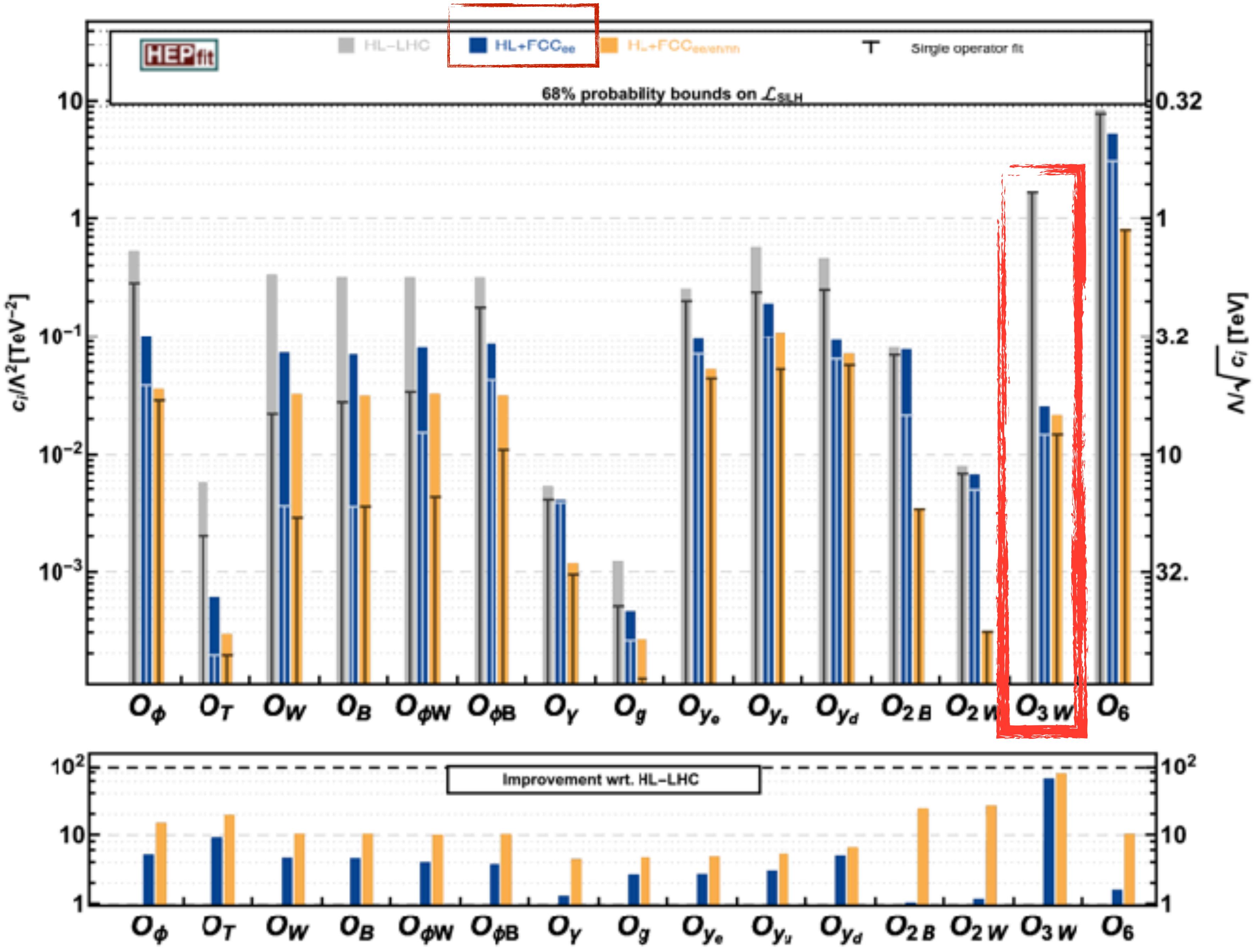
Certain EFT effects can be thought as modifying particles propagation



deBlas et al'19

Reach on modified Propagators

Certain EFT effects can be thought as modifying particles propagation



deBlas et al'19

New level of precision = New experiments

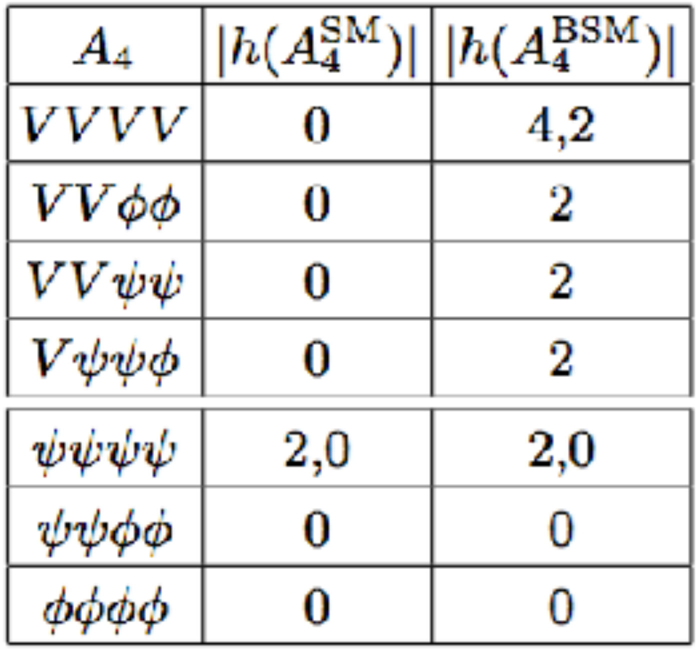
Problem:

(2->2,high-E,tree-level)

SM

Any BSM
dim-6 operator

helicity



A_4	$\lvert h(A_4^{\text{SM}})\rvert$	$\lvert h(A_4^{\text{BSM}})\rvert$
$VVVV$	0	4,2
$VV\phi\phi$	0	2
$VV\psi\psi$	0	2
$V\psi\psi\phi$	0	2
$\psi\psi\psi\psi$	2,0	2,0
$\psi\psi\phi\phi$	0	0
$\phi\phi\phi\phi$	0	0

Azatov,Contino,Machado,FR ‘16

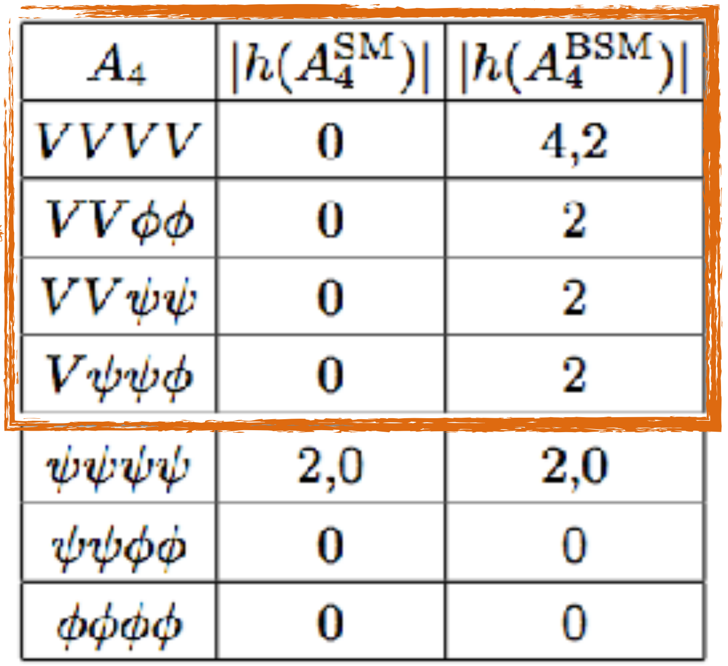
New level of precision = New experiments

Problem:

(2->2,high-E,tree-level)

SM

Any BSM
dim-6 operator



A_4	$\lvert h(A_4^{\rm SM})\rvert$	$\lvert h(A_4^{\rm BSM})\rvert$
$VVVV$	0	4,2
$VV\phi\phi$	0	2
$VV\psi\psi$	0	2
$V\psi\psi\phi$	0	2
$\psi\psi\psi\psi$	2,0	2,0
$\psi\psi\phi\phi$	0	0
$\phi\phi\phi\phi$	0	0

helicity

Azatov,Contino,Machado,FR ‘16

Different helicity

New level of precision = New experiments

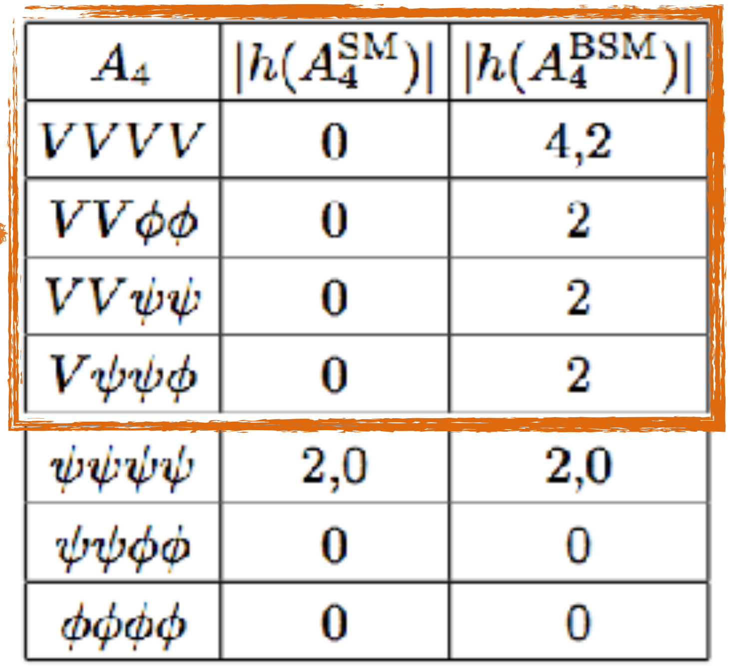
Problem:

(2->2,high-E,tree-level)

SM

Any BSM dim-6 operator

helicity



A_4	$\lvert h(A_4^{\rm SM})\rvert$	$\lvert h(A_4^{\rm BSM})\rvert$
$VVVV$	0	4,2
$VV\phi\phi$	0	2
$VV\psi\psi$	0	2
$V\psi\psi\phi$	0	2
$\psi\psi\psi\psi$	2,0	2,0
$\psi\psi\phi\phi$	0	0
$\phi\phi\phi\phi$	0	0

Azatov,Contino,Machado,FR '16

Different helicity

⇓

No-Interference

$$SM^2(1+\cancel{\delta_{BSM}}+\delta_{BSM}^2)$$

New level of precision = New experiments

Problem:

(2->2,high-E,tree-level)

SM

Any BSM
dim-6 operator

helicity

A_4	$\|h(A_4^{\rm SM})\|$	$\|h(A_4^{\rm BSM})\|$
$VVVV$	0	4,2
$VV\phi\phi$	0	2
$VV\psi\psi$	0	2
$V\psi\psi\phi$	0	2
$\psi\psi\psi\psi$	2,0	2,0
$\psi\psi\phi\phi$	0	0
$\phi\phi\phi\phi$	0	0

Azatov,Contino,Machado,FR ‘16

Different helicity

⇩

No-Interference

$$SM^2(1+\cancel{\delta_{BSM}}+\delta^2_{BSM})$$

⇩

Poor Measurement

New level of precision = New experiments

Problem:

(2->2,high-E,tree-level)

SM

Any BSM dim-6 operator

helicity

A_4	$\lvert h(A_4^{\rm SM})\rvert$	$\lvert h(A_4^{\rm BSM})\rvert$
$VVVV$	0	4,2
$VV\phi\phi$	0	2
$VV\psi\psi$	0	2
$V\psi\psi\phi$	0	2
$\psi\psi\psi\psi$	2,0	2,0
$\psi\psi\phi\phi$	0	0
$\phi\phi\phi\phi$	0	0

Azatov,Contino,Machado,FR '16

Different helicity

⇩

No-Interference

$$SM^2(1+\cancel{\delta_{BSM}}+\delta^2_{BSM})$$

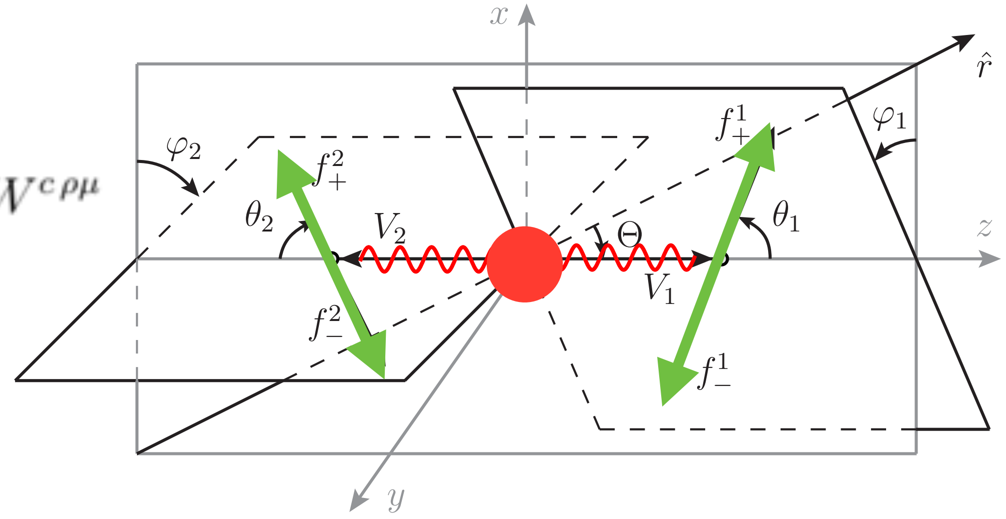
⇩

Poor Measurement

⇨ **Interference Resurrection**

Panico, FR, Wulzer '17
Henning, Lombardo, FR '19

$$\epsilon_{abc}W_\mu^{a\,\nu}W^b_{\nu\rho}W^{c\,\rho\mu}$$



New level of precision = New experiments

Problem:

(2->2,high-E,tree-level)

SM

Any BSM dim-6 operator

helicity

A_4	$\lvert h(A_4^{SM})\rvert$	$\lvert h(A_4^{BSM})\rvert$
$VVVV$	0	4,2
$VV\phi\phi$	0	2
$VV\psi\psi$	0	2
$V\psi\psi\phi$	0	2
$\psi\psi\psi\psi$	2,0	2,0
$\psi\psi\phi\phi$	0	0
$\phi\phi\phi\phi$	0	0

Azatov,Contino,Machado,FR '16

Different helicity

No-Interference

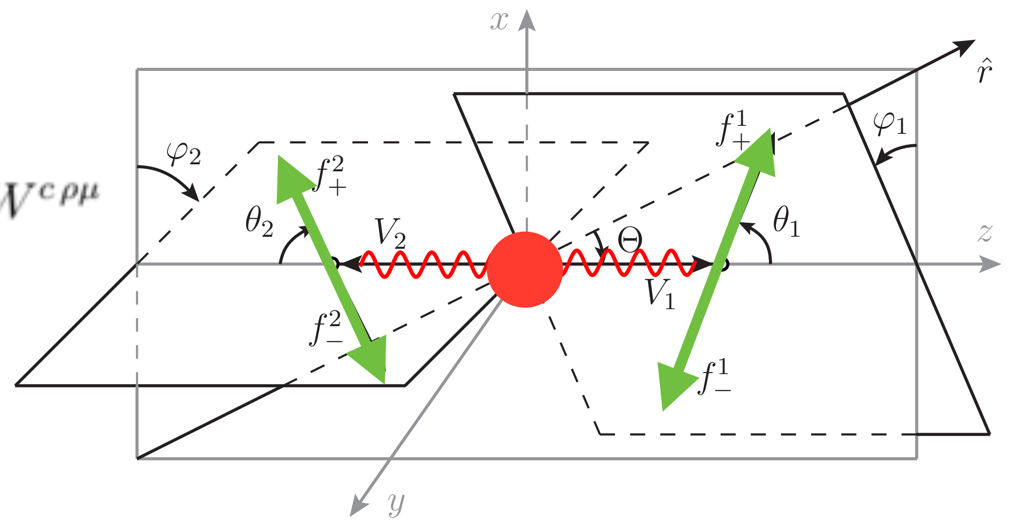
$$SM^2(1+\cancel{\delta_{BSM}}+\delta_{BSM}^2)$$

Poor Measurement

Interference Resurrection

Panico, FR, Wulzer '17
Henning, Lombardo, FR '19

$\epsilon_{abc}W_\mu^{a\,\nu}W_{\nu\rho}^{b}W^{c\,\rho\mu}$

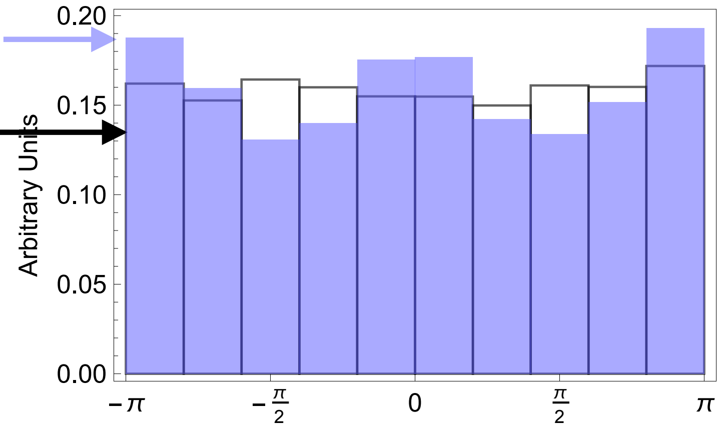


Interference $\propto$ azimuthal angle of decay products

Well measurable at FCCee

BSM $\sim \cos 2\varphi$

SM $\sim const.$



Reach of ee>WW: 4x better!

Adapted from: Henning, Lombardo, FR '19

Reach on modified Propagators

Certain EFT effects can be thought as modifying particles propagation

What will we learn?

deBlas et al'19

What will we learn?

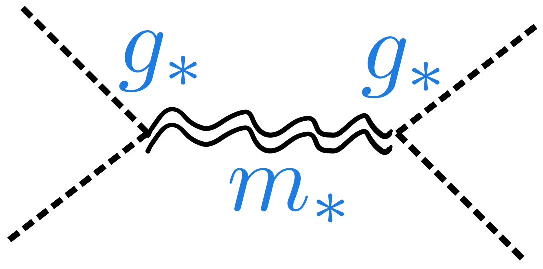
Simple way of visualising physics potential reach:

New Physics

=

1 Scale + 1 Coupling

m_* g_*



What will we learn?

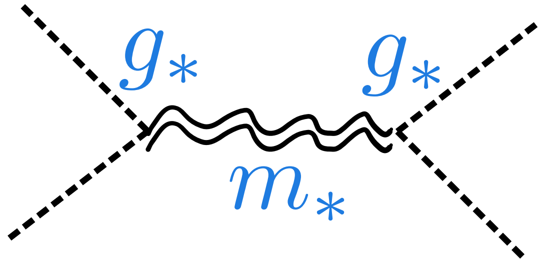
Simple way of visualising physics potential reach:

New Physics

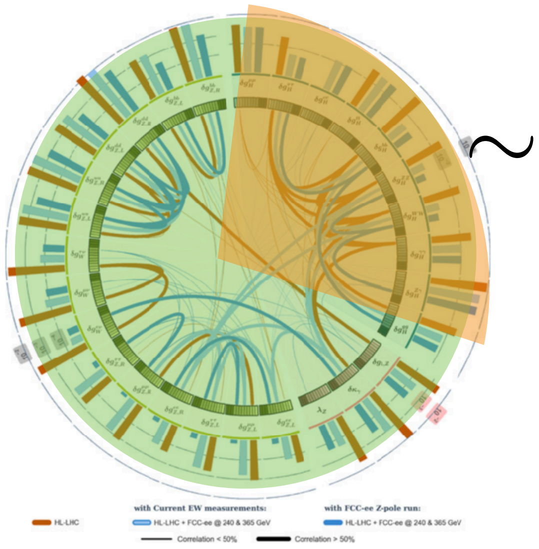
=

1 Scale + 1 Coupling

m_* g_*



e.g Composite Higgs Giudice,Grojean,Pomarol,Rattazzi'07



$$\sim \frac{E^2}{m_*^2}$$

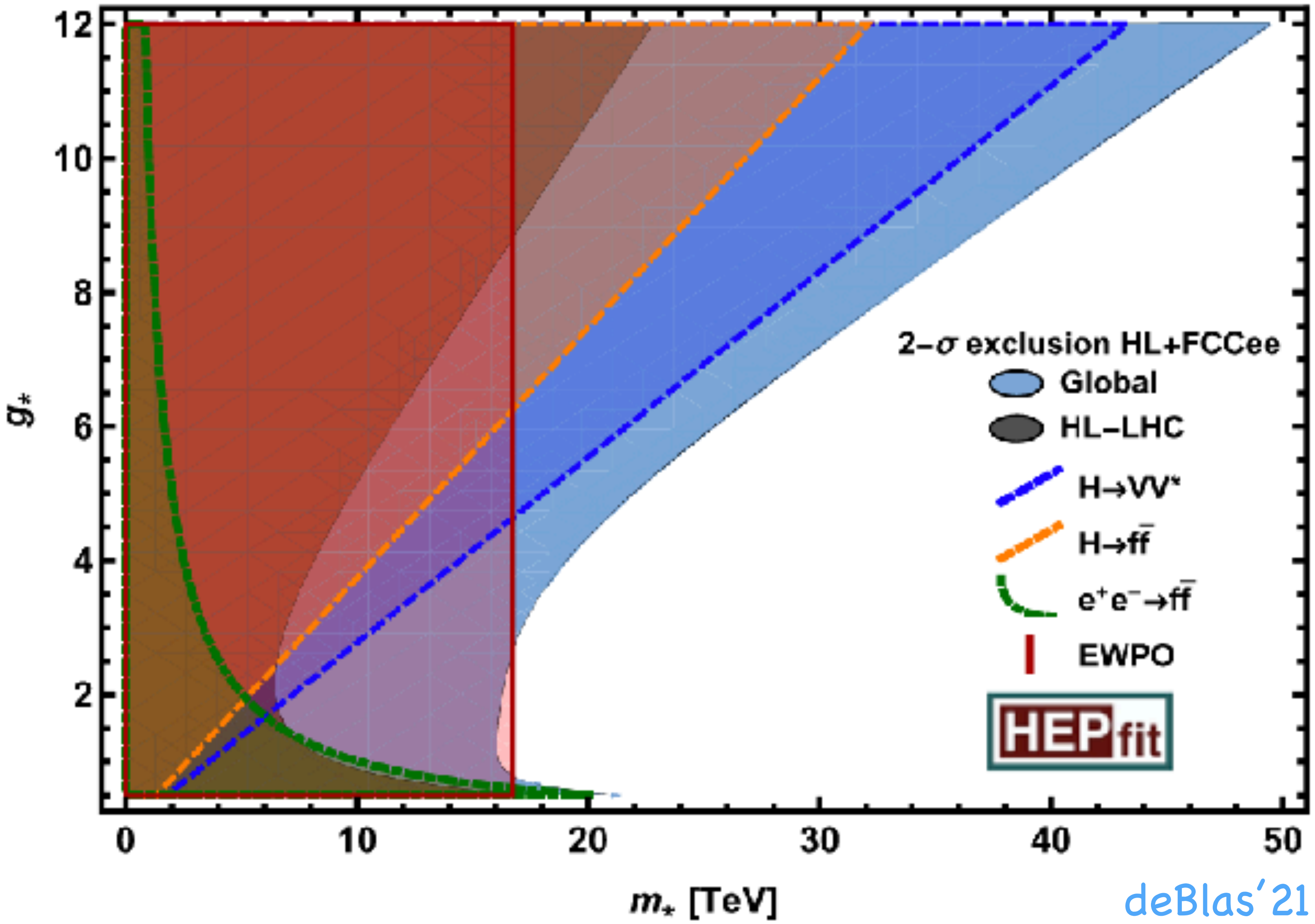
$$\sim \frac{g_*^2}{g_{SM}^2}\frac{E^2}{m_*^2} \rightarrow$$

Higgs couplings enhanced by g_*

What will we learn?

Universal New Physics with g_* coupling and m_* mass

(complementary to Gino's talk)

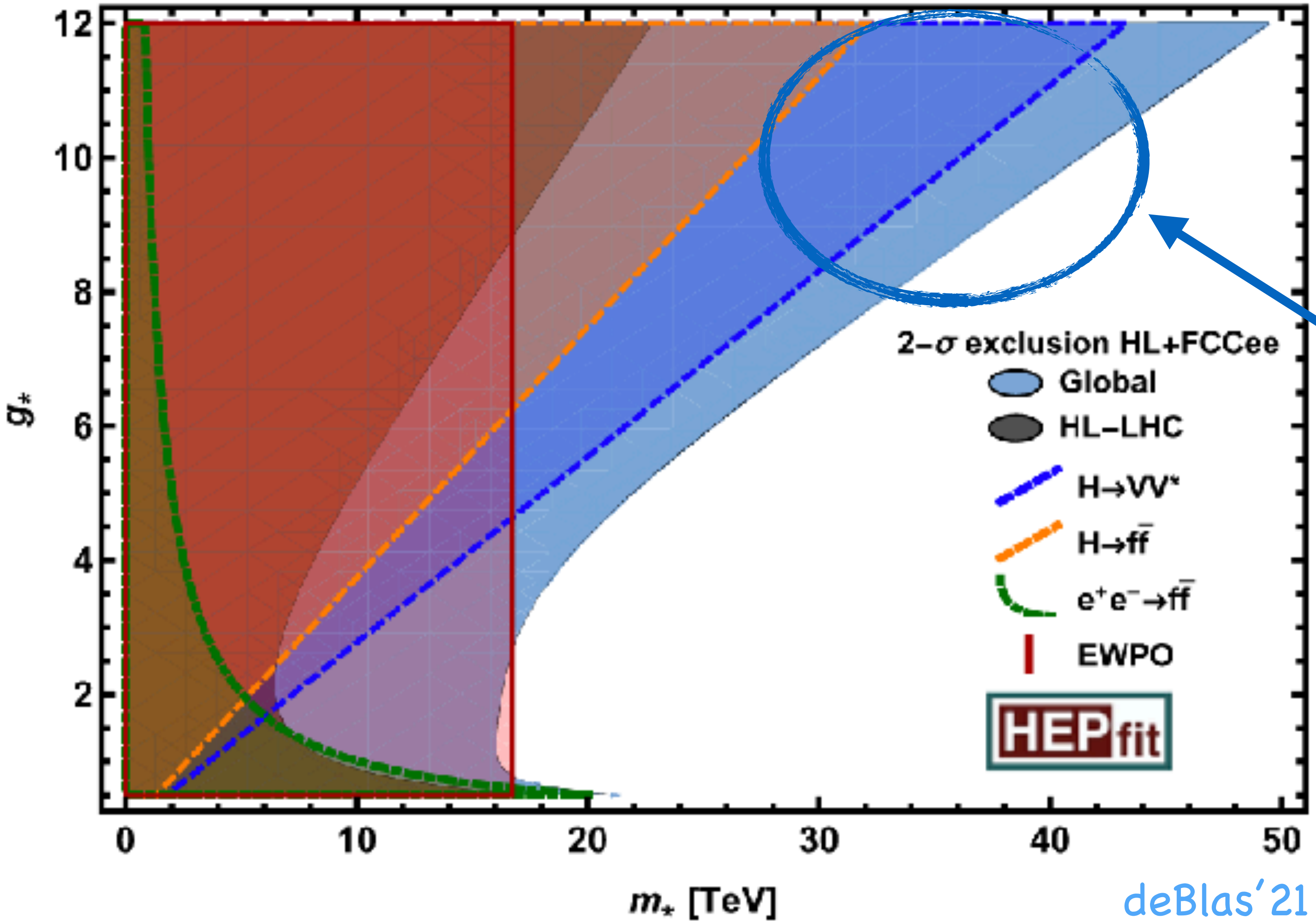


deBlas'21

What will we learn?

Universal New Physics with g_* coupling and m_* mass

(complementary to Gino's talk)



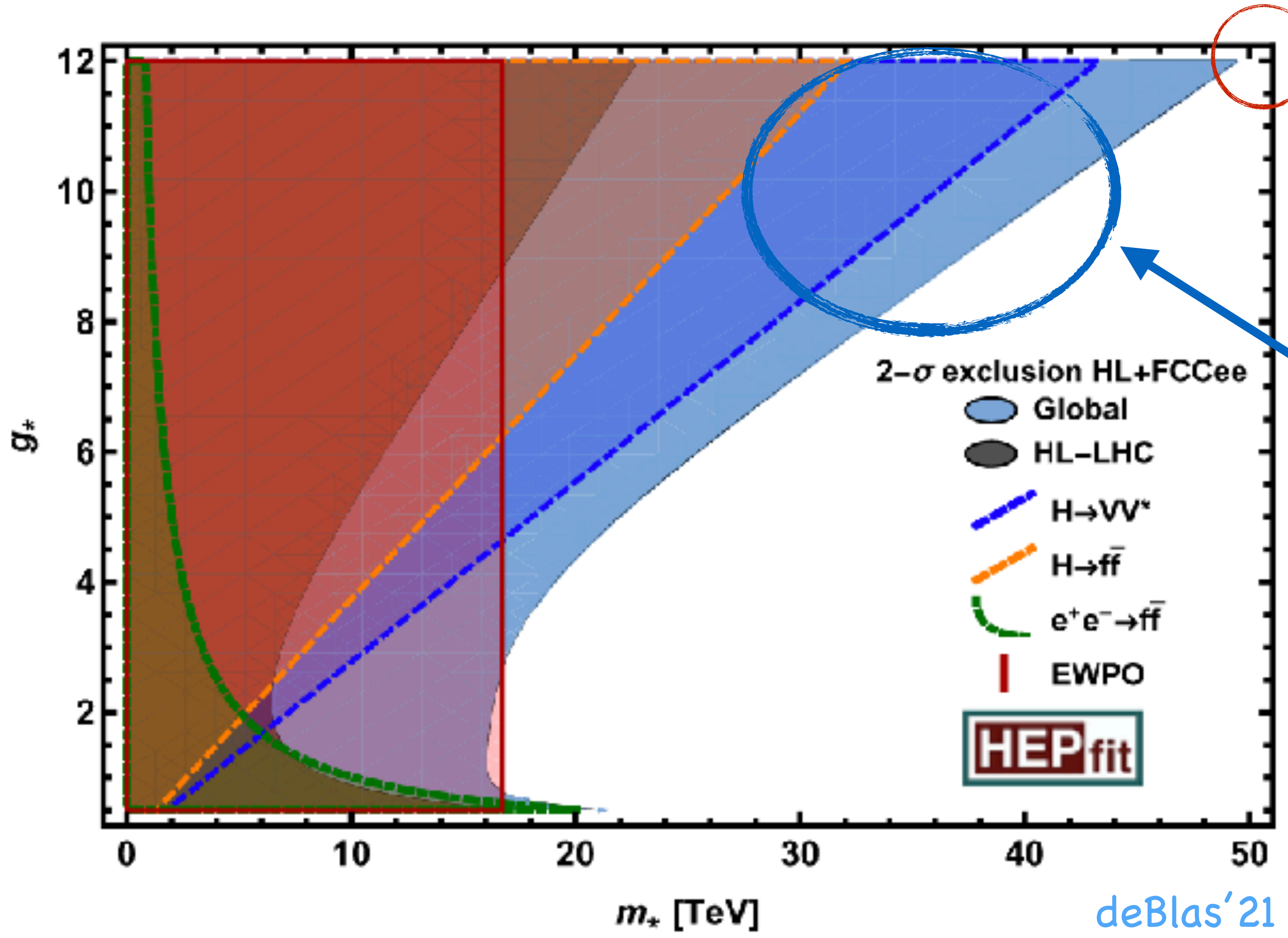
deBlas'21

Higgs physics: important at strong coupling

What will we learn?

Universal New Physics with g_* coupling and m_* mass

(complementary to Gino's talk)



deBlas'21

If Higgs is composite of QCD-like dynamics

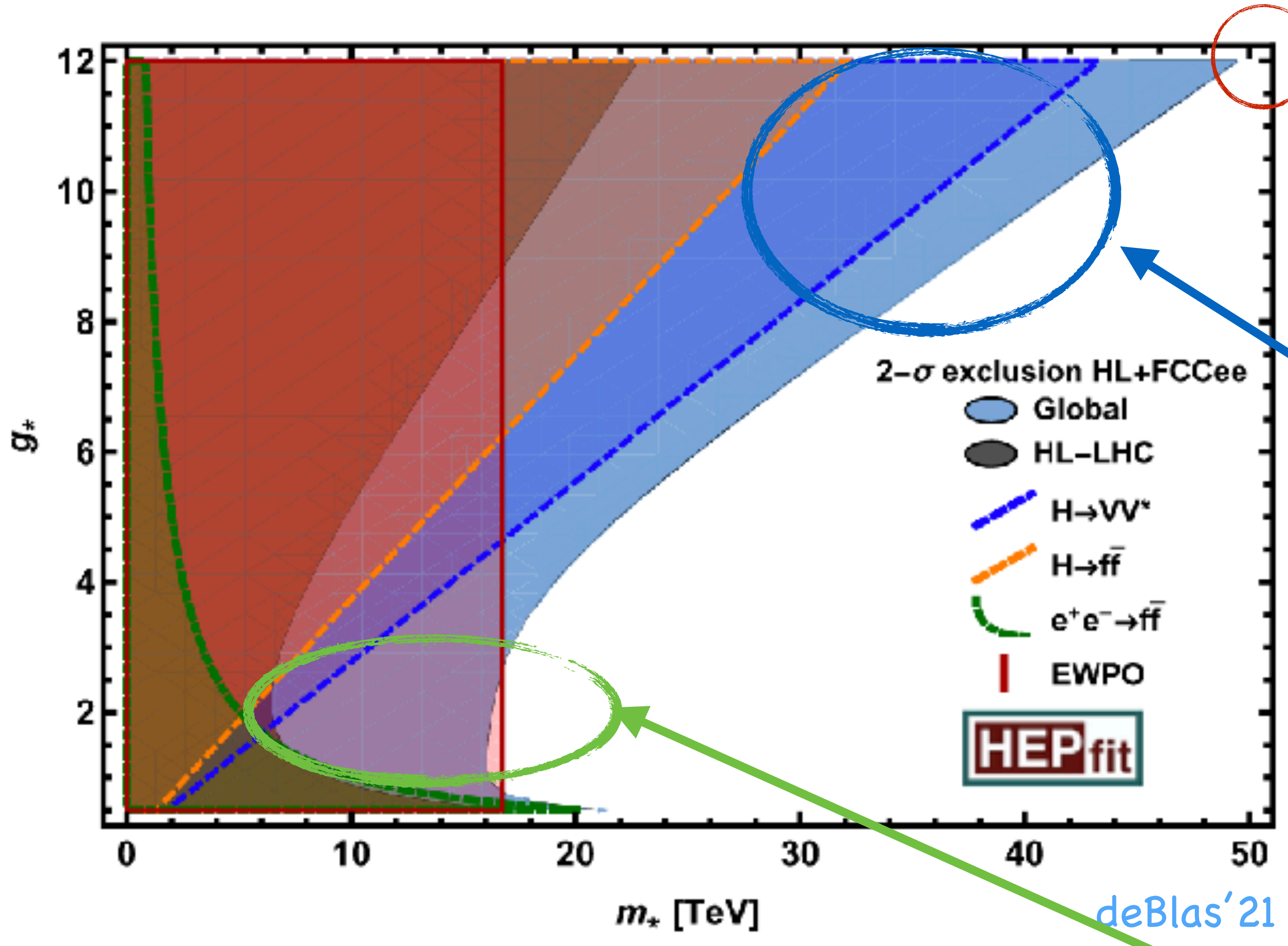
$$m_* > 50 \text{ TeV}$$

Higgs physics: important at strong coupling

What will we learn?

Universal New Physics with g_* coupling and m_* mass

(complementary to Gino's talk)



deBlas'21

If Higgs is composite of QCD-like dynamics

$$m_* > 50\ \text{TeV}$$

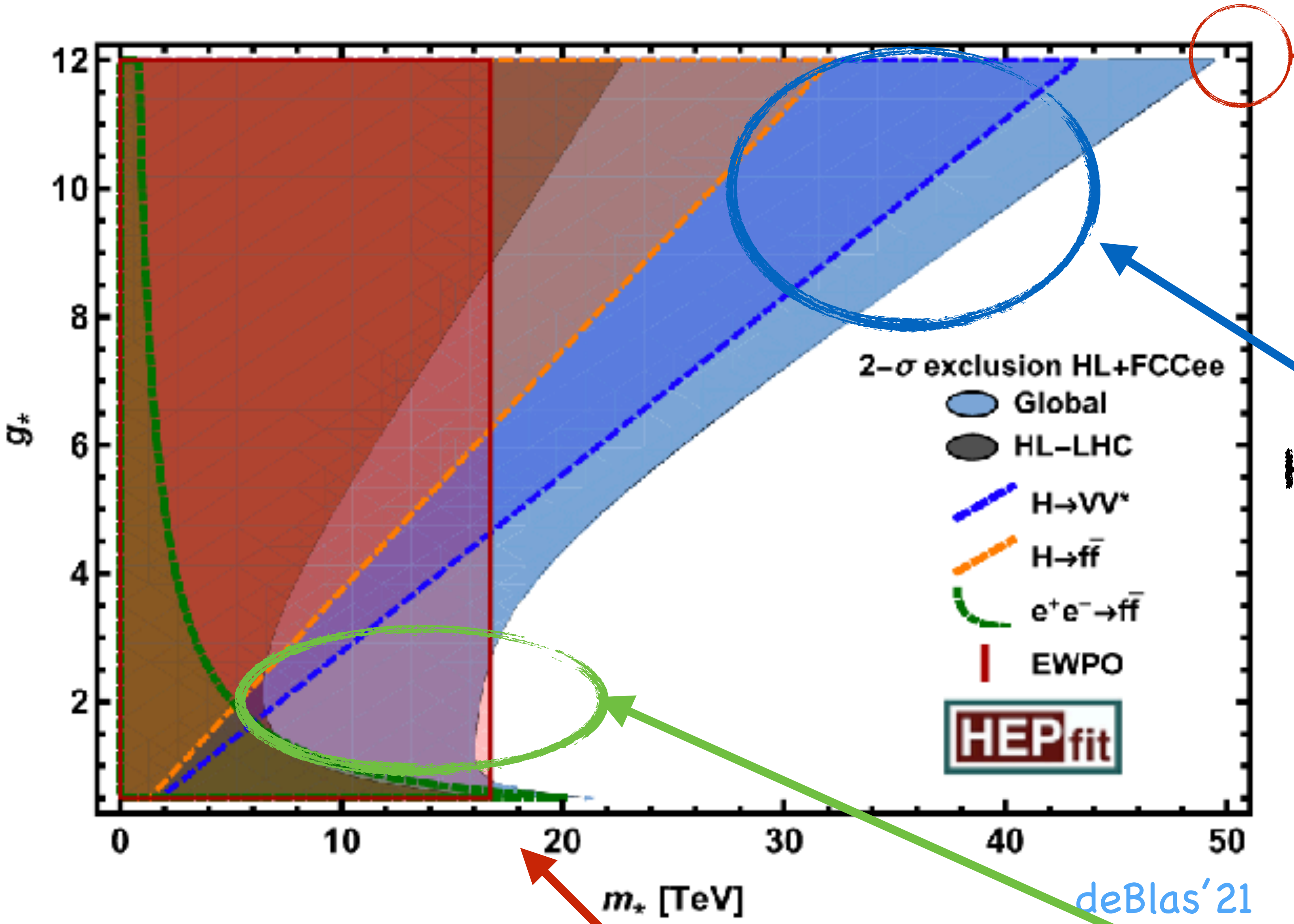
Higgs physics: important at strong coupling

Z-Pole: most important at weak coupling

What will we learn?

Universal New Physics with g_* coupling and m_* mass

(complementary to Gino's talk)



deBlas'21

If Higgs is composite of QCD-like dynamics

$$m_* > 50\text{ TeV}$$

Higgs physics: important at strong coupling

Z-Pole: most important at weak coupling

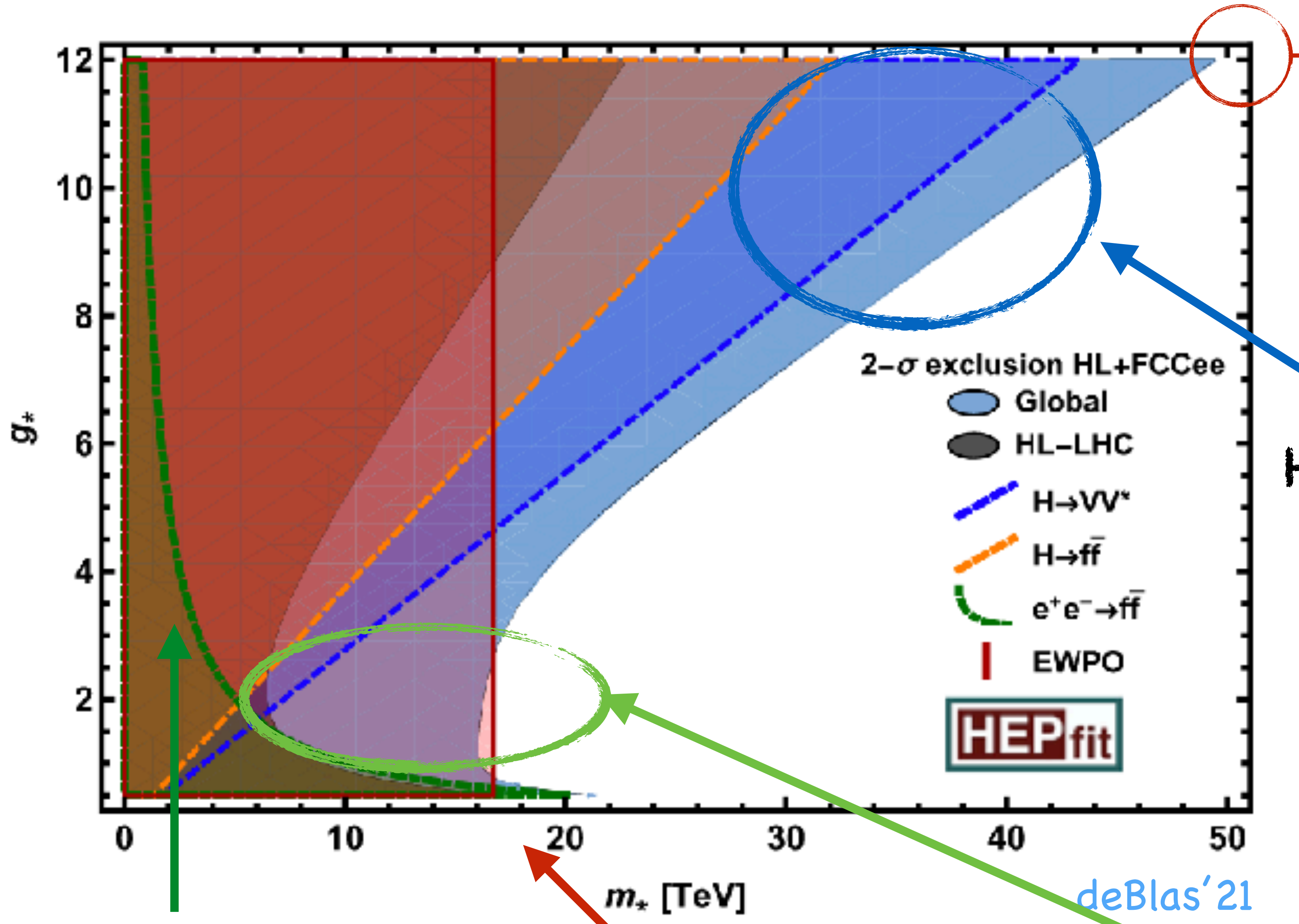
Spin-1 resonances

$$m_* > 17\text{ TeV}$$

What will we learn?

Universal New Physics with g_* coupling and m_* mass

(complementary to Gino's talk)



deBlas'21

If Higgs is composite of QCD-like dynamics

$$m_* > 50 \text{ TeV}$$

Higgs physics: important at strong coupling

Drell-Yann

$$\sim \frac{g^2}{g_*^2}$$

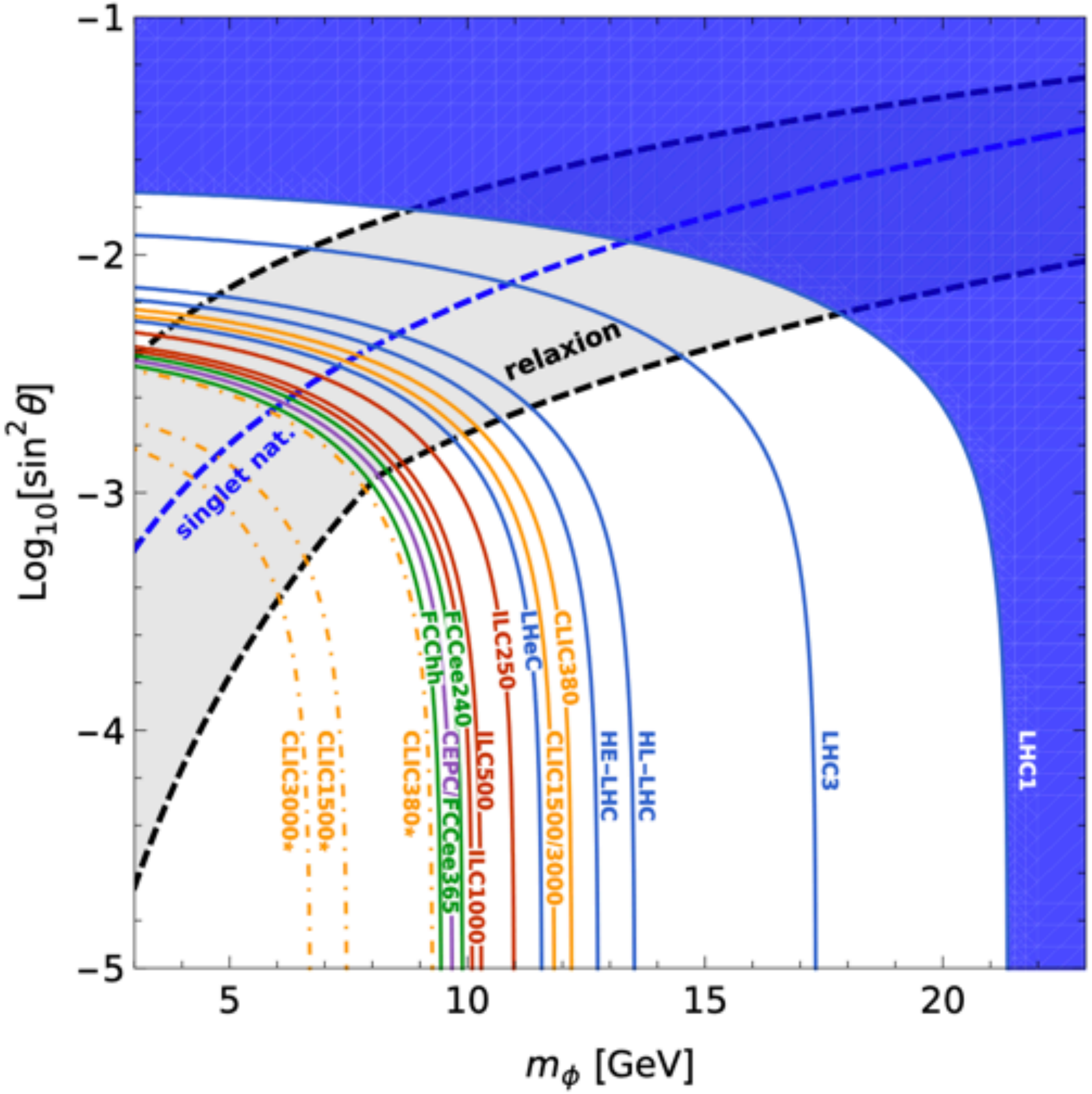
Spin-1 resonances

$$m_* > 17 \text{ TeV}$$

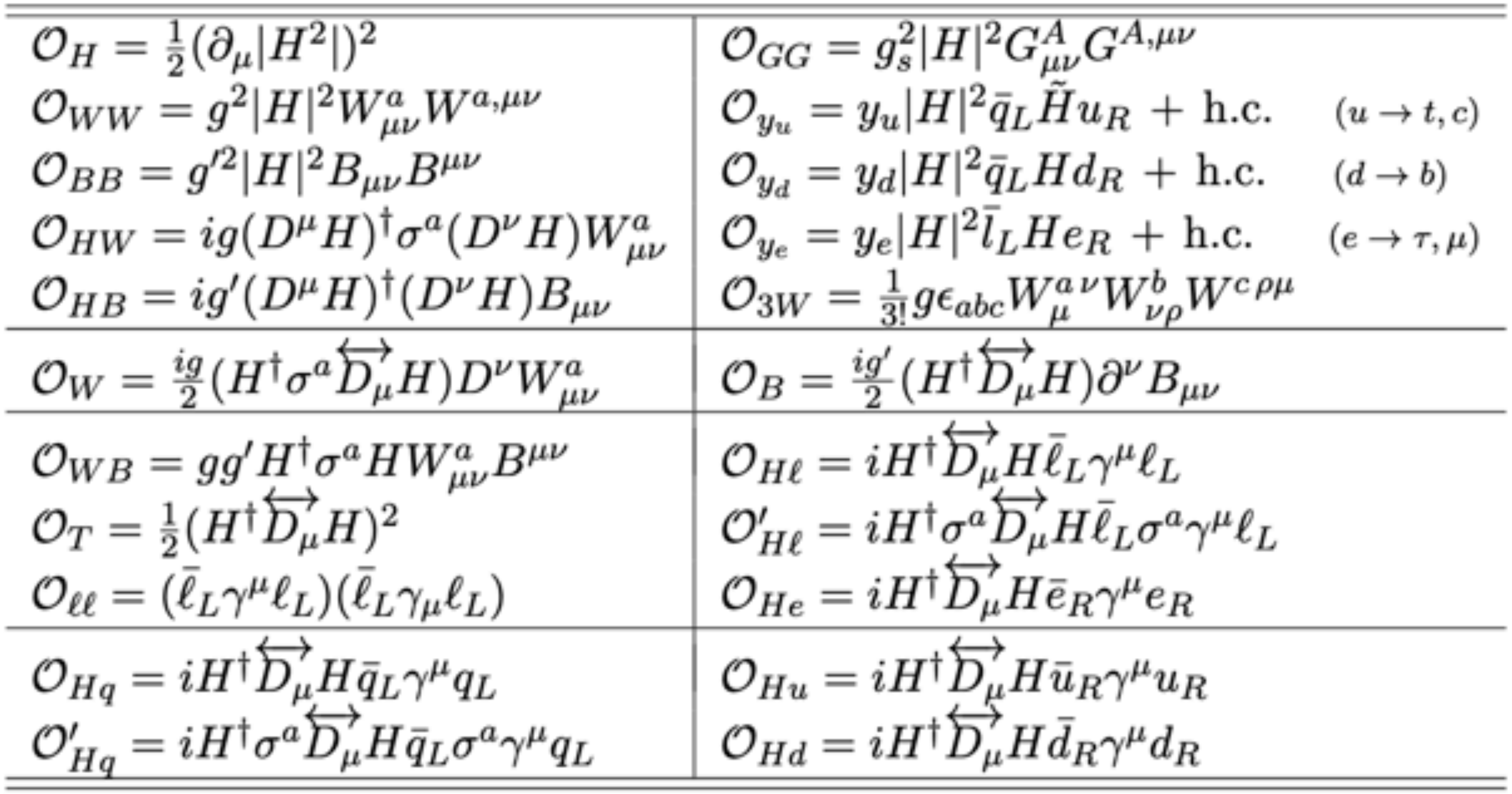
Z-Pole: most important at weak coupling

Conclusions

- FCCee design priority on non-resonant heavy physics searches
- Search mode particularly suitable for strongly coupled BSM
- Precision opens door to genuinely new measurements (e.g. azimuthal distributions → 4x better reach on aTGCs)



−1
−2
−3
−4
−5
$\mathrm{Log}_{10}[\sin^2\theta]$
5
10
15
20
m_ϕ [GeV]
relaxion
singlet nat.
FCChh
FCCee240
ILC250
LHeC
CLIC380
CLIC3000*
CLIC1500*
CLIC380*
CEPC/FCCee365
ILC500
ILC1000
CLIC1500/3000
HE−LHC
HL−LHC
LHC3
LHC1



$\mathcal{O}_H = \frac{1}{2}(\partial_\mu \lvert H^2 \rvert)^2$	$\mathcal{O}_{GG} = g_s^2 \lvert H \rvert^2 G_{\mu\nu}^A G^{A,\mu\nu}$
$\mathcal{O}_{WW} = g^2 \lvert H \rvert^2 W_{\mu\nu}^a W^{a,\mu\nu}$	$\mathcal{O}_{y_u} = y_u \lvert H \rvert^2 \bar{q}_L \tilde{H} u_R + \text{h.c.} \quad (u \to t, c)$
$\mathcal{O}_{BB} = g'^2 \lvert H \rvert^2 B_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_{y_d} = y_d \lvert H \rvert^2 \bar{q}_L H d_R + \text{h.c.} \quad (d \to b)$
$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W_{\mu\nu}^a$	$\mathcal{O}_{y_e} = y_e \lvert H \rvert^2 \bar{l}_L H e_R + \text{h.c.} \quad (e \to \tau, \mu)$
$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$	$\mathcal{O}_{3W} = \frac{1}{3!} g \epsilon_{abc} W_\mu^{a\,\nu} W_{\nu\rho}^b W^{c\,\rho\mu}$
$\mathcal{O}_W = \frac{ig}{2}(H^\dagger \sigma^a \overleftrightarrow{D}_\mu H) D^\nu W_{\mu\nu}^a$	$\mathcal{O}_B = \frac{ig'}{2}(H^\dagger \overleftrightarrow{D}_\mu H) \partial^\nu B_{\mu\nu}$
$\mathcal{O}_{WB} = g g' H^\dagger \sigma^a H W_{\mu\nu}^a B^{\mu\nu}$	$\mathcal{O}_{H\ell} = i H^\dagger \overleftrightarrow{D}_\mu H \bar{\ell}_L \gamma^\mu \ell_L$
$\mathcal{O}_T = \frac{1}{2}(H^\dagger \overleftrightarrow{D}_\mu H)^2$	$\mathcal{O}'_{H\ell} = i H^\dagger \sigma^a \overleftrightarrow{D}_\mu H \bar{\ell}_L \sigma^a \gamma^\mu \ell_L$
$\mathcal{O}_{\ell\ell} = (\bar{\ell}_L \gamma^\mu \ell_L)(\bar{\ell}_L \gamma_\mu \ell_L)$	$\mathcal{O}_{He} = i H^\dagger \overleftrightarrow{D}_\mu H \bar{e}_R \gamma^\mu e_R$
$\mathcal{O}_{Hq} = i H^\dagger \overleftrightarrow{D}_\mu H \bar{q}_L \gamma^\mu q_L$	$\mathcal{O}_{Hu} = i H^\dagger \overleftrightarrow{D}_\mu H \bar{u}_R \gamma^\mu u_R$
$\mathcal{O}'_{Hq} = i H^\dagger \sigma^a \overleftrightarrow{D}_\mu H \bar{q}_L \sigma^a \gamma^\mu q_L$	$\mathcal{O}_{Hd} = i H^\dagger \overleftrightarrow{D}_\mu H \bar{d}_R \gamma^\mu d_R$