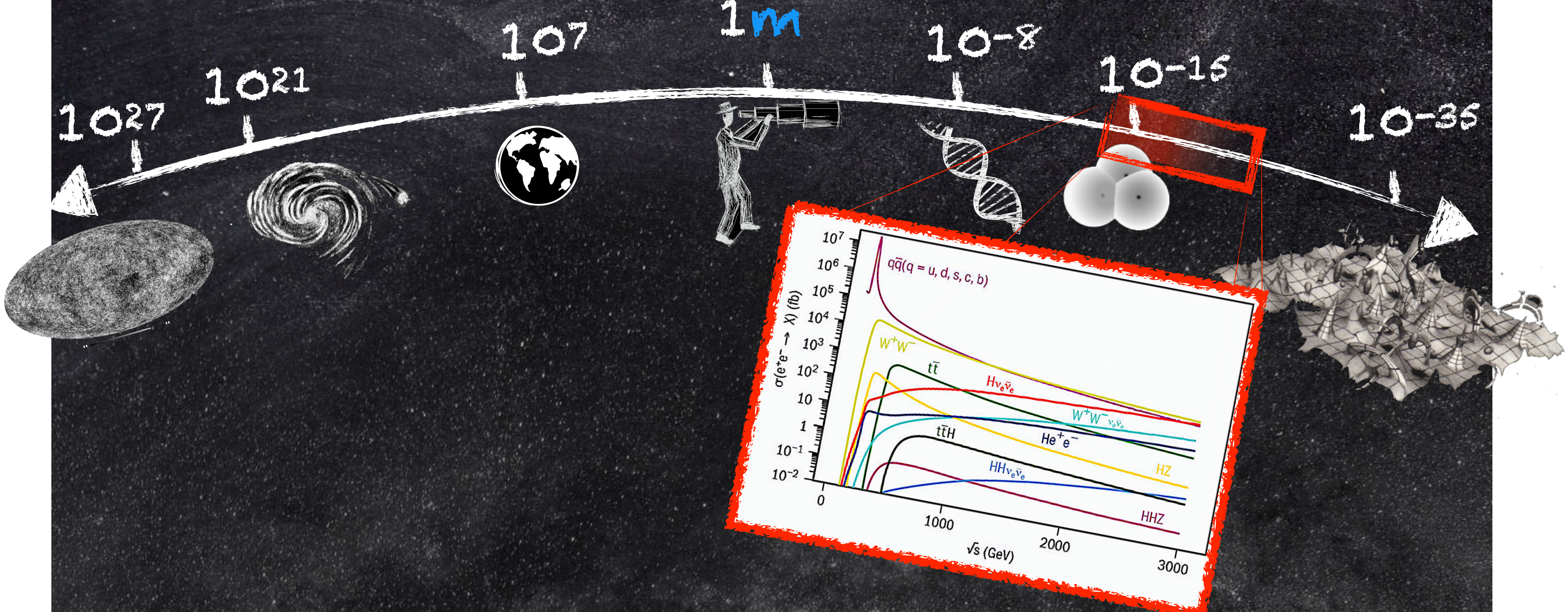
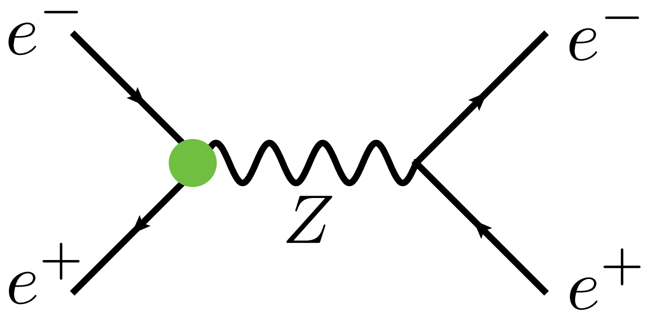
Precision at Linear Colliders



Francesco Riva
(Université de Genève)

Precision (B)SM Tests

At Low Energy: $\sqrt{s} = m_Z$



m_Z [GeV]
Γ_Z [GeV]
$\sigma^0_{\rm had}$ [nb]
R^0_ℓ
$A^{0,\ell}_{\rm FB}$

← Simple Observables

Simple Information →

$\delta g_{Z\nu}$
δg_{Ze_L}
δg_{Ze_R}

modified Z-couplings
=
constant rescaling of SM

Precision (B)SM Tests

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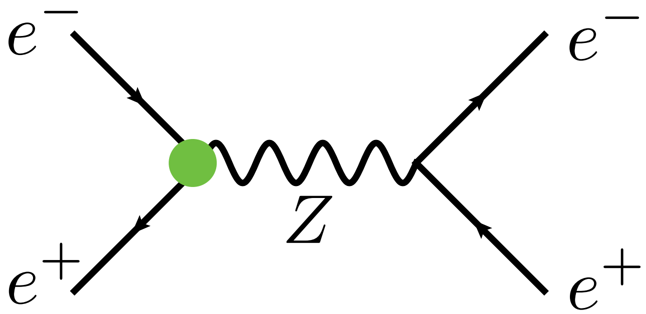

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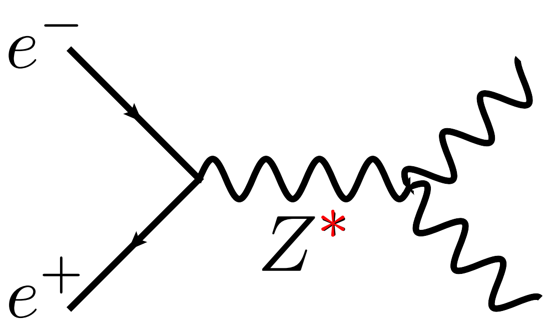
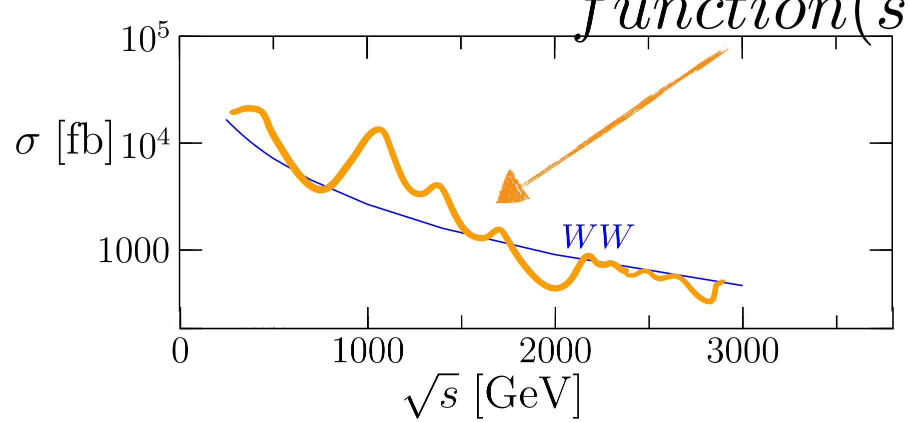
At High Energy: Infinite Observables → Infinite Information



$$function(s) \overset{\text{Taylor expansion}}{=} f(0) + f'(0)s + f''(0)s^2 + \cdots$$



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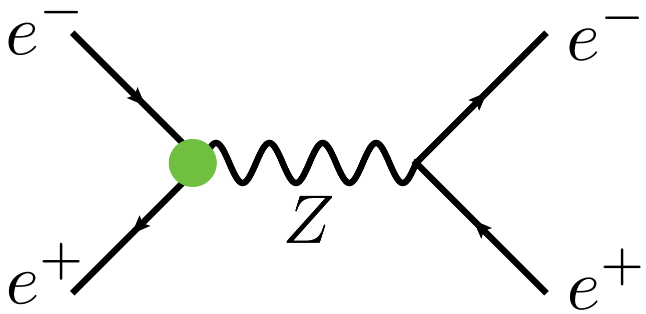

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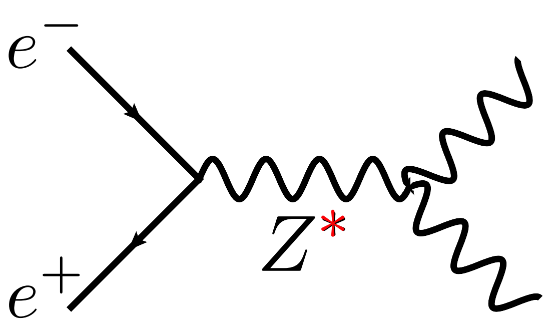

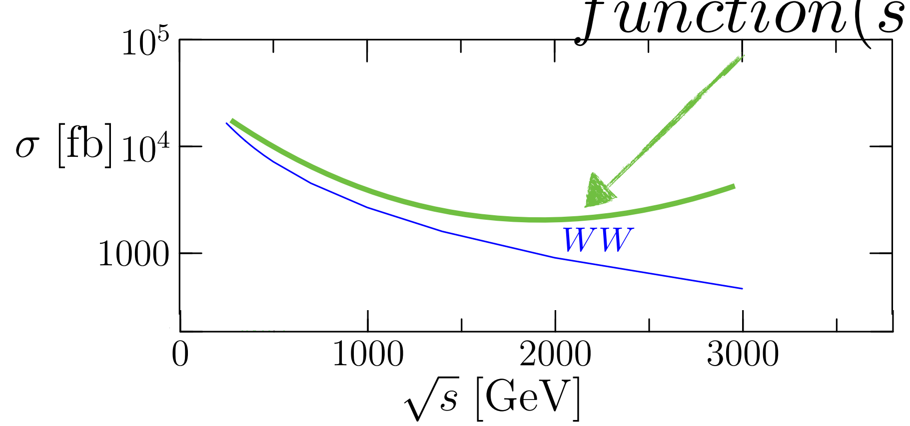

Taylor expansion

$$function(s) = f(0) + f'(0)s + f''(0)s^2 + \cdots$$

↓

Effective Field Theory (EFT)

= systematic Taylor expansion for all observables

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

Precision (B)SM Tests

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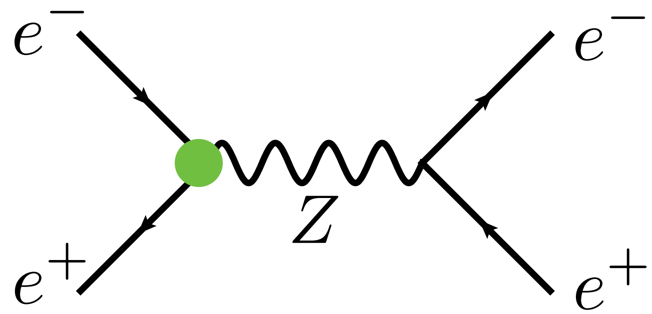

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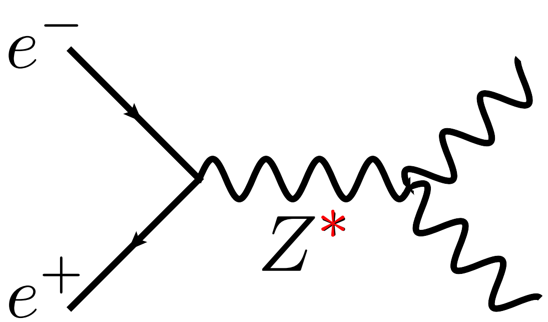

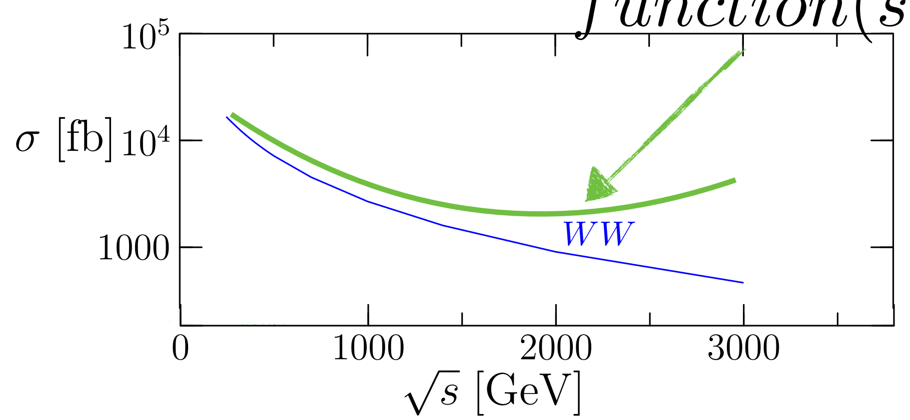

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$f(0)$ and $f'(0)$ at same order

(dimension-6 EFT)

Precision (B)SM Tests

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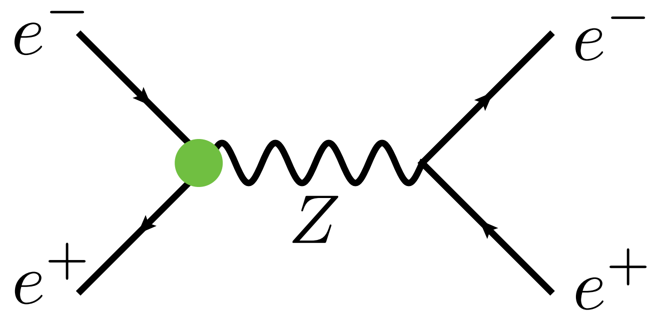

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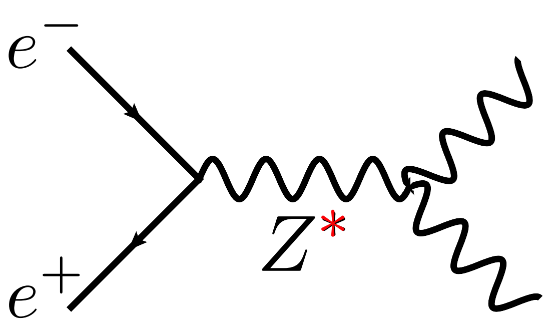

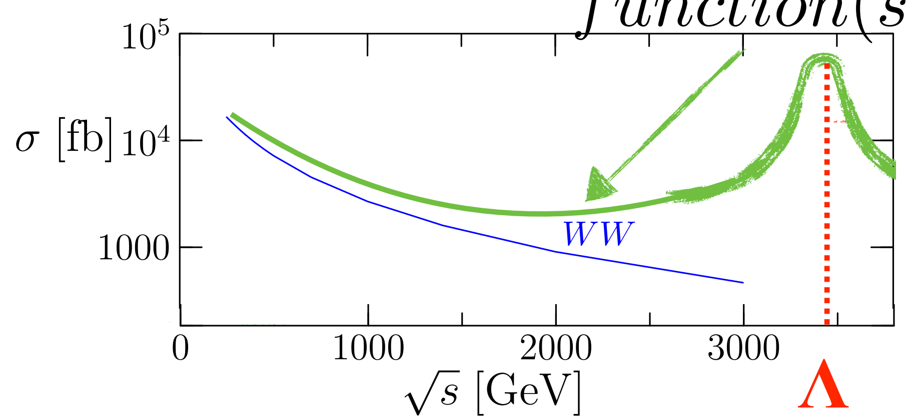

Taylor expansion

$$function(s) = f(0) + f'(0)s + f''(0)s^2 + \cdots$$

Effective Field Theory (EFT)

= systematic Taylor expansion for all observables

It captures **all** heavy new physics ▸ $$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda^2}\sum_i c_i \mathcal{O}_i + \cdots$$

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Precision (B)SM Tests

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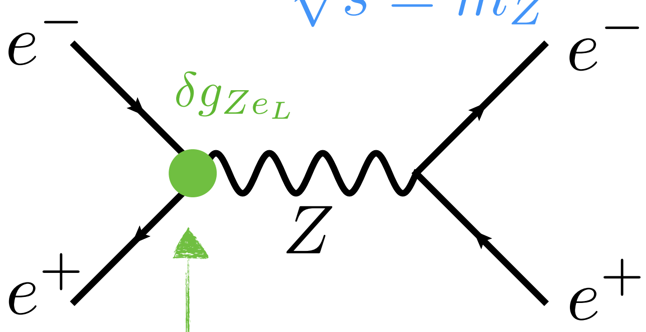
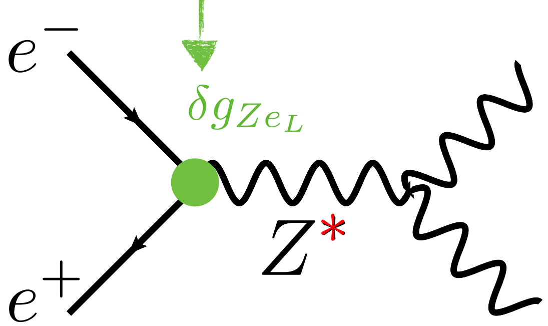


Imagine measuring $\left.\frac{\delta\sigma}{\sigma_{\rm SM}}\right|_{\sqrt{s}=m_Z} \sim 10^{-4}$ ▸ $\delta g_{Ze_L} \sim 10^{-4}$

(surely a precise measurement)

Effect grows ≈ s

$$\left(\frac{3000}{91.2}\right)^2 \approx 1000$$



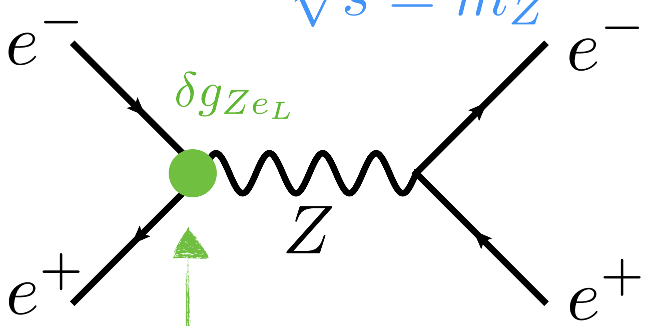
At High Energy

$\sqrt{s} = 3\,\text{TeV}$

Precision (B)SM Tests

At Low Energy

$\sqrt{s} = m_Z$



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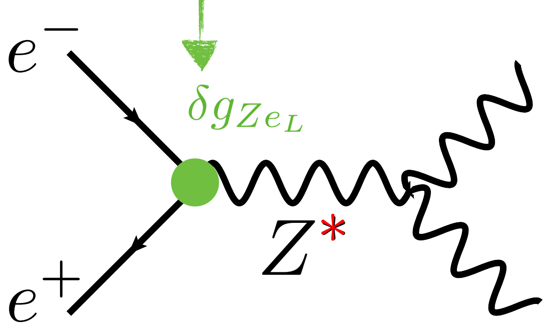


... equivalent to $\left.\dfrac{\delta\sigma}{\sigma_{\rm SM}}\right|_{\sqrt{s}=3\,{\rm TeV}} \sim 10\%$ ◂ $\delta g_{Ze_L} \sim 10^{-4}$

(naively not so precise)

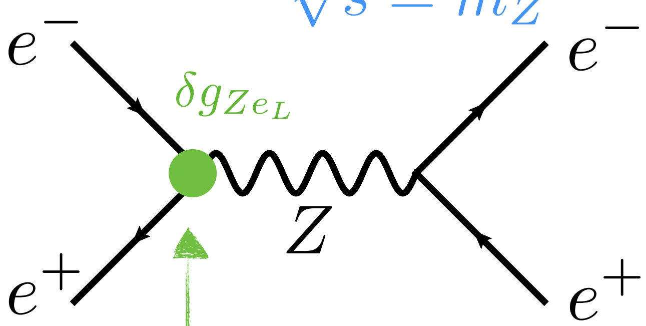
At High Energy

$\sqrt{s} = 3\,{\rm TeV}$

Precision (B)SM Tests

At Low Energy

$\sqrt{s} = m_Z$



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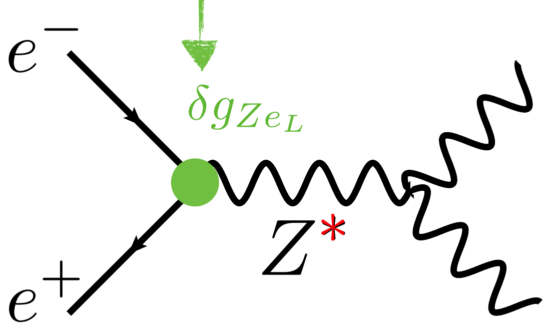
Same Precision!



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At High Energy

$\sqrt{s} = 3\,{\rm TeV}$

Precision (B)SM Tests

At Low Energy

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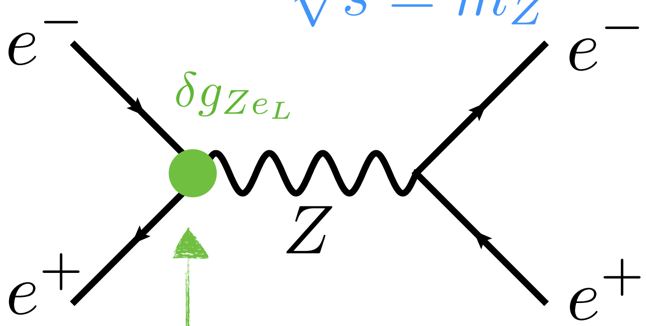


Imagine measuring $\left.\frac{\delta\sigma}{\sigma_{SM}}\right|_{\sqrt{s}=m_Z} \sim 10^{-4}$ ▸ $\delta g_{Ze_L} \sim 10^{-4}$

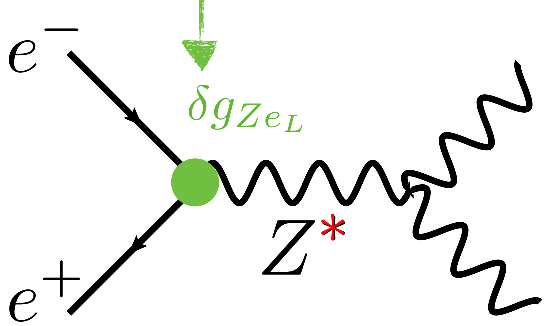
$\frac{\delta\sigma}{\sigma_{SM}} \sim 10^{-5}$

(surely a precise measurement)

Effect grows ≈ s

$\left(\frac{3000}{91.2}\right)^2 \approx 1000$

Same Precision!



... equivalent to $\left.\frac{\delta\sigma}{\sigma_{SM}}\right|_{\sqrt{s}=3\,\text{TeV}} \sim 10\%$ ◂ $\delta g_{Ze_L} \sim 10^{-4}$

$\frac{\delta\sigma}{\sigma_{SM}} \sim 1\%$

(naively not so precise)

At High Energy

$\sqrt{s} = 3\,\text{TeV}$

Precision (B)SM Tests

This talk:

Precision Program @ High Energy Linear Lepton Colliders

CLIC - ILC

High Intensity
1)

High Energy
2)

Direct Searches
3)

(ignoring systematics: a factor of 100 in Lumi ≈ a factor 3 in energy)

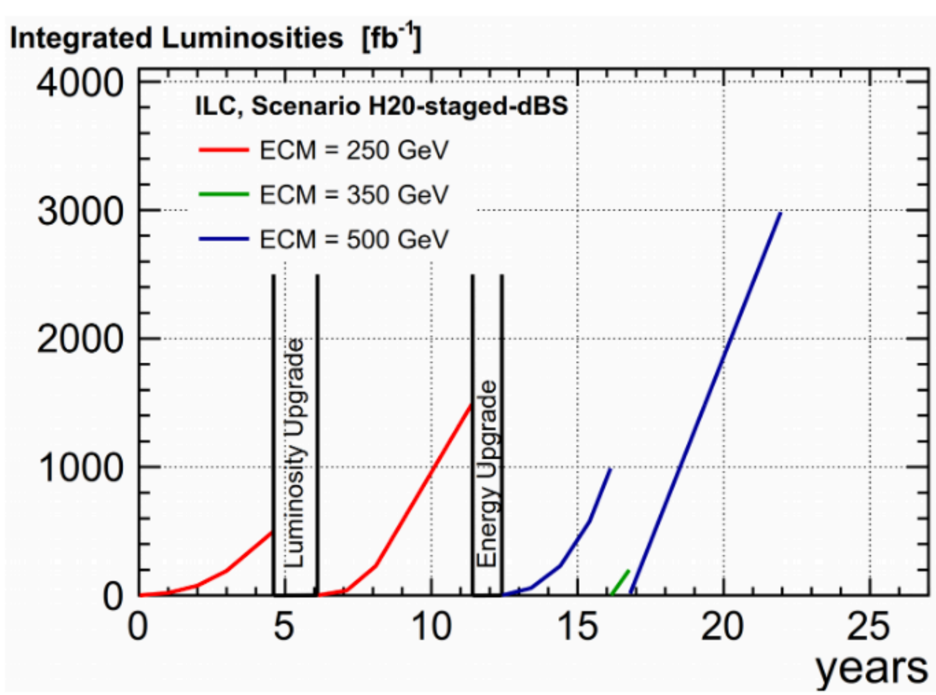
Linear Collider Stages

ILC

Energy	Tot. Lumi
250 GeV	2 ab^{-1}
350 GeV	0.2 ab^{-1}
500 GeV	4 ab^{-1}

e^-/e^+ beams polarised: ±80%/±30%
(≈40% of lumi with +/− polarization)

- σ increases: $\sigma_{\rm VBF} \to 2.34\,\sigma_{\rm VBF}$
  $\sigma_{\rm ZH} \to 1.4\,\sigma_{\rm ZH}$

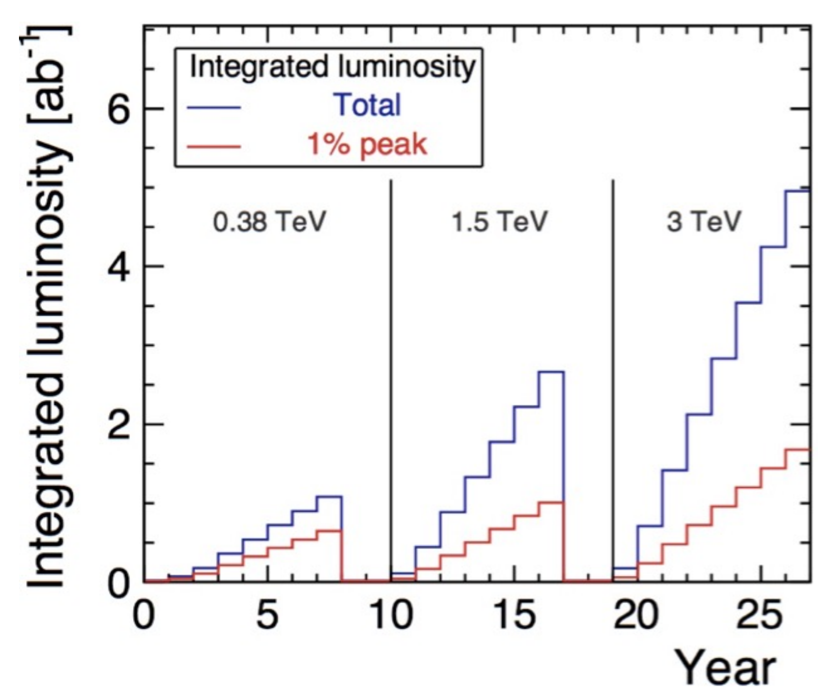


CLIC

Energy	Tot. Lumi
350-380 GeV	0.5 + 0.5 ab^{-1}
1.5 TeV	2 + 0.5 ab^{-1}
3 TeV	4 + 1 ab^{-1}

e^- beam polarised: -80% / +80%

- σ increases: $\sigma_{\rm VBF} \to 1.8\,\sigma_{\rm VBF}$
  $\sigma_{\rm ZH} \to 1.12\,\sigma_{\rm ZH}$



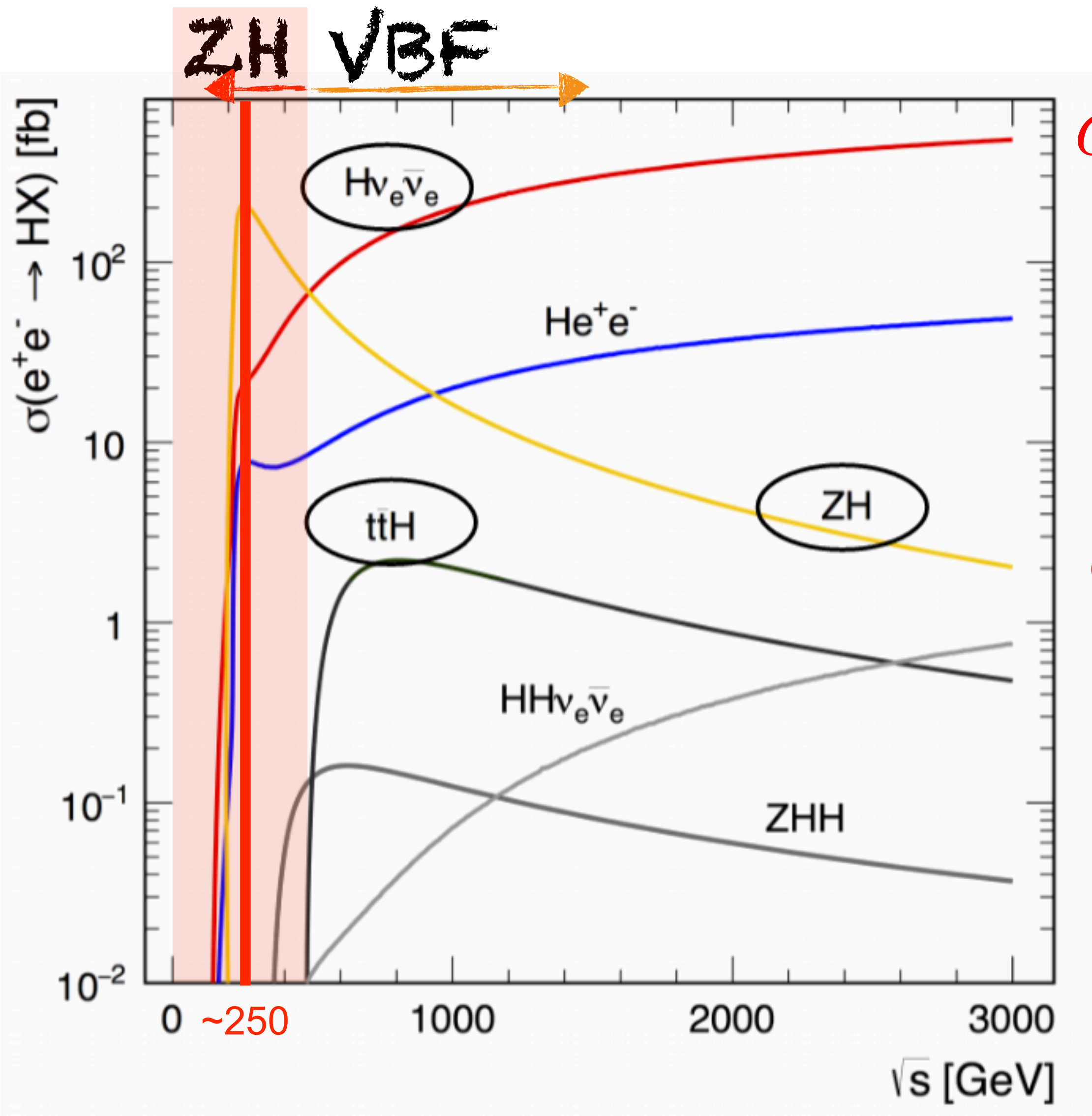
1) High-Intensity Probes

Processes and Effects (EFT)
without Energy-growth

e.g. many Higgs Couplings dont depend on energy in single-Higgs processes (k-framework, equivalent to EFT)

$$\kappa_i^2 = \Gamma_i / \Gamma_i^{\rm SM}$$

Higgs at Linear Lepton Colliders



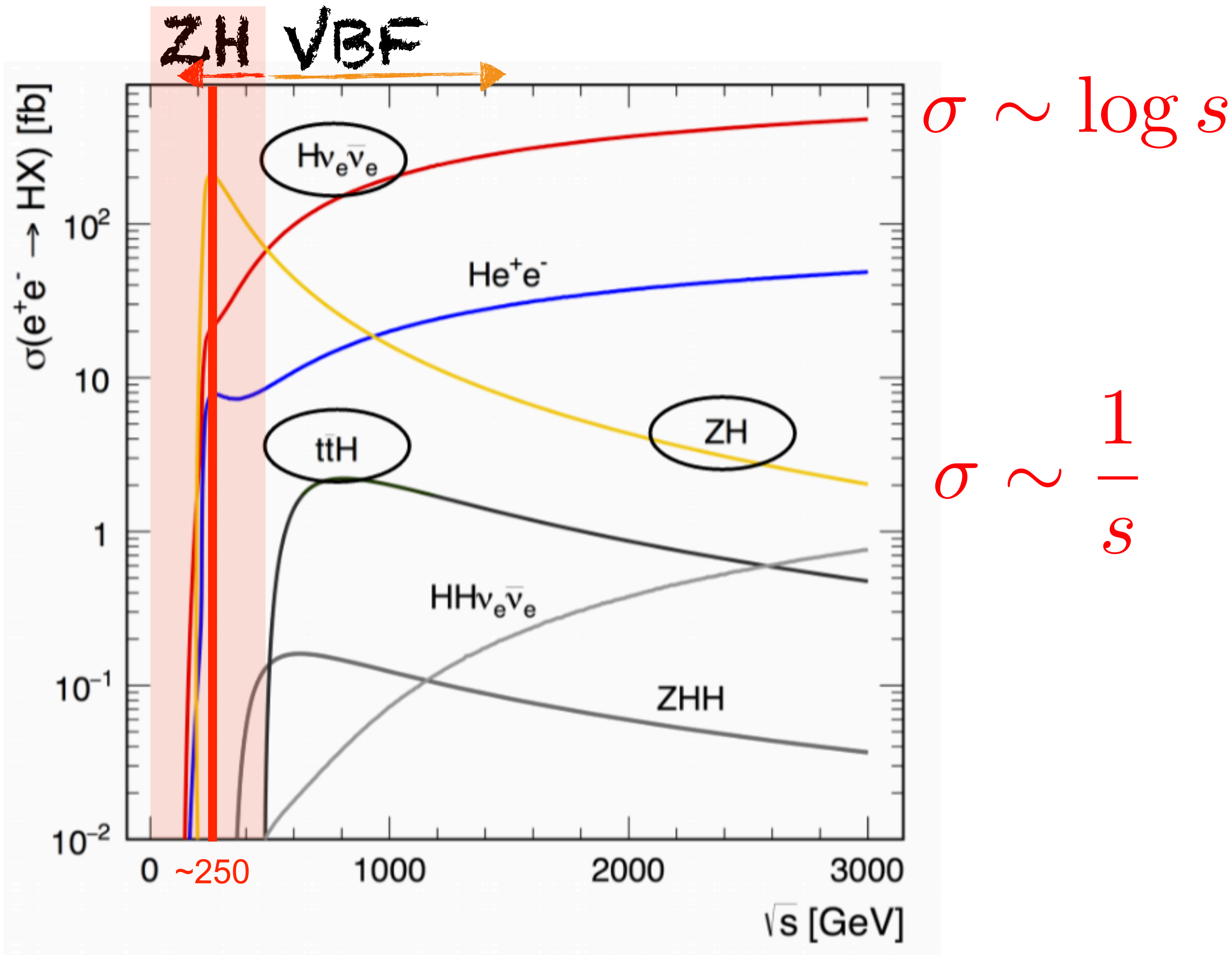
$\sigma \sim \log s$

$\sigma \sim \frac{1}{s}$

High Energy
also
largest x-sections

High Intensity

Higgs at Linear Lepton Colliders



High Energy also largest x-sections

High Intensity

Number of H produced:

ILC_{250}	5×10^5
$CLIC_{380}$	1.6×10^5
ILC_{500}	5×10^5
$CLIC_{1500}$	1×10^6
$CLIC_{3000}$	3.3×10^6

(No Triggers -> All events usable)

Higgs Couplings

ILC*			CLIC				HL-LHC
	Stage 1	Stage 1+2		Stage 1	Stage 1+2	Stage 1+2+3	HL-LHC S1 (S2)
$g(hbb)$	1.8	0.60	κ_{Hbb}	1.3 %	0.3 %	0.2 %	4.8(3.4) %
$g(hcc)$	2.4	1.2	κ_{Hcc}	4.1 %	1.8 %	1.3 %	–
$g(hgg)$	2.2	0.97	κ_{Hgg}	2.1 %	1.2 %	0.9 %	3.6(2.3) %
$g(hWW)$	1.8	0.40	κ_{HWW}	0.8 %	0.2 %	0.1 %	2.3(1.7) %
$g(h\tau\tau)$	1.9	0.80	$\kappa_{H\tau\tau}$	2.7 %	1.2 %	0.9 %	2.6(1.9) %
$g(hZZ)$	0.38	0.30	κ_{HZZ}	0.4 %	0.3 %	0.2 %	2.2(1.6) %
$g(h\gamma\gamma)$	1.1	1.0	$\kappa_{H\gamma\gamma}$	–	4.8 %	2.3 %	2.7(2.0) %
$g(h\mu\mu)$	5.6	5.1	$\kappa_{H\mu\mu}$	–	12.1 %	5.6 %	6.6(5.0) %
$g(h\gamma Z)$	16	16	$\kappa_{HZ\gamma}$	–	13.3 %	6.6 %	
			κ_{Htt}	–	2.9 %	2.9 %	4.7(2.8) %

κ_{tot}

*= ILC fit uses from HL-LHC: $BR_{\gamma\gamma}/BR_{ZZ}$, $BR_{\gamma Z}/BR_{\gamma\gamma}$ and $BR_{\mu\mu}/BR_{\gamma\gamma}$

ILC 1708.08912 and CLIC YR

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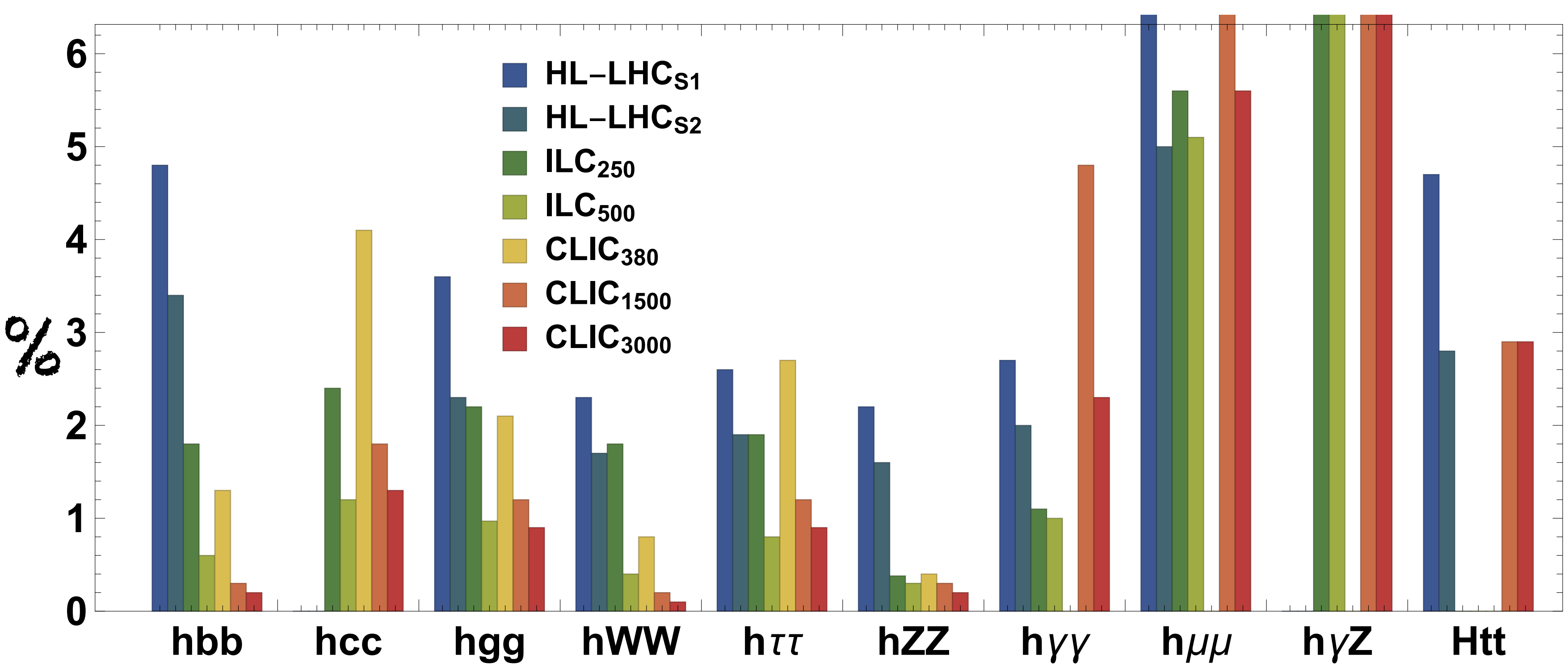

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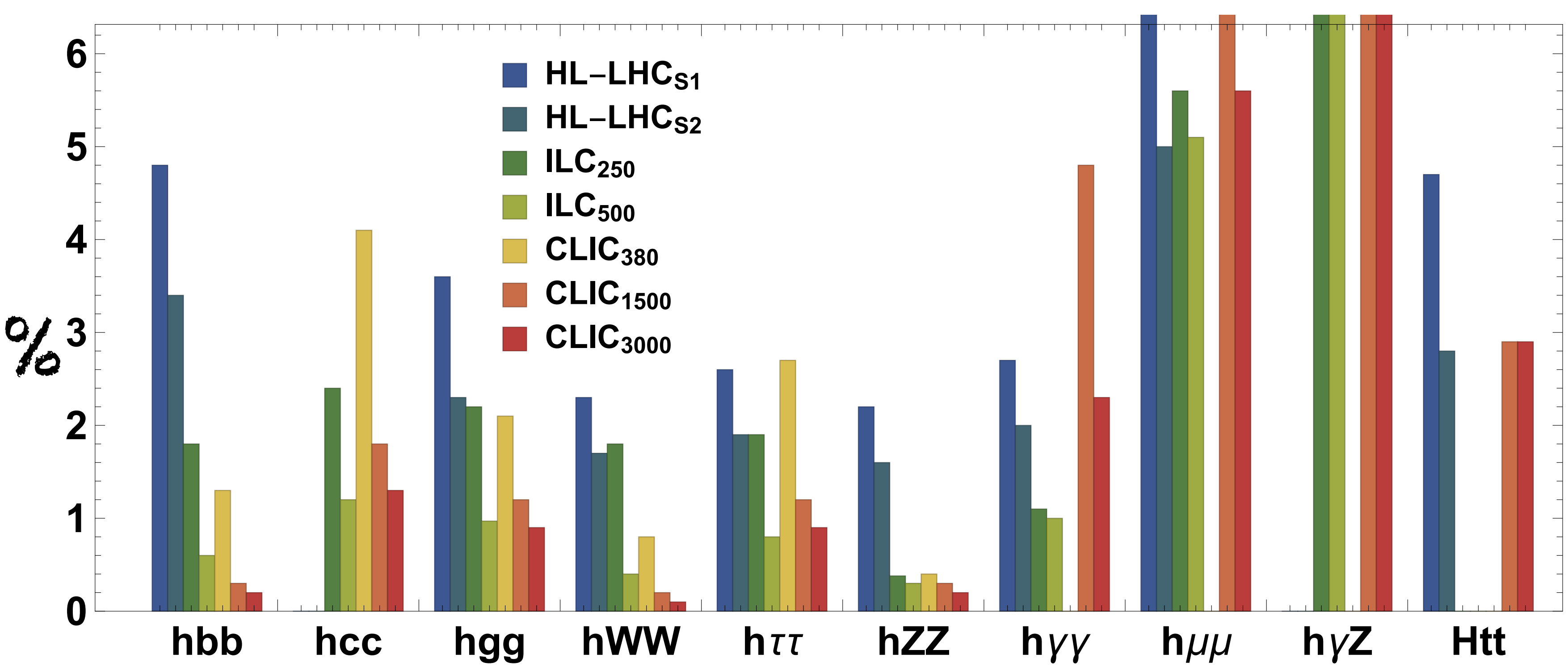
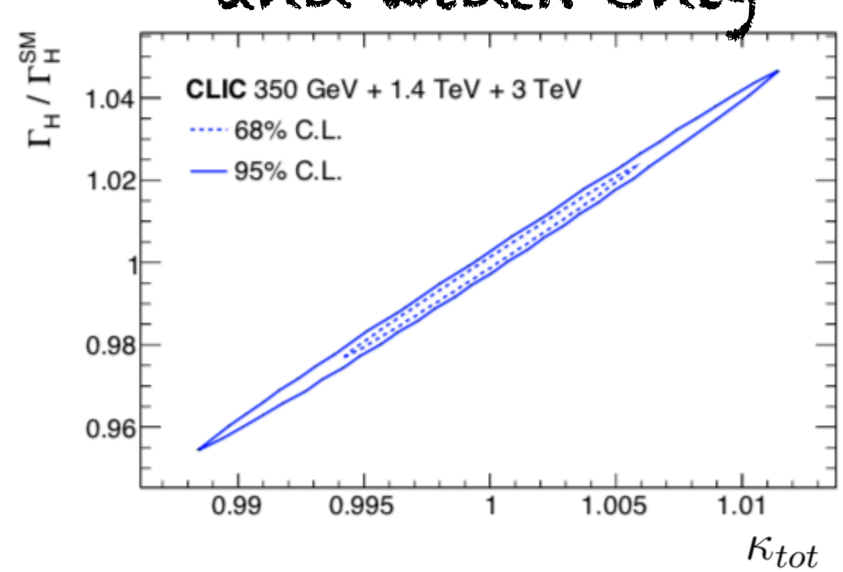
			κ_{tot}	0.22 %	0.10 %	0.06 %	
Γ_h	3.9	1.7	Γ_h	6.7 %	4 %	3.5 %	Impossible



One parameter and width only



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ILC 1708.08912 and CLIC YR

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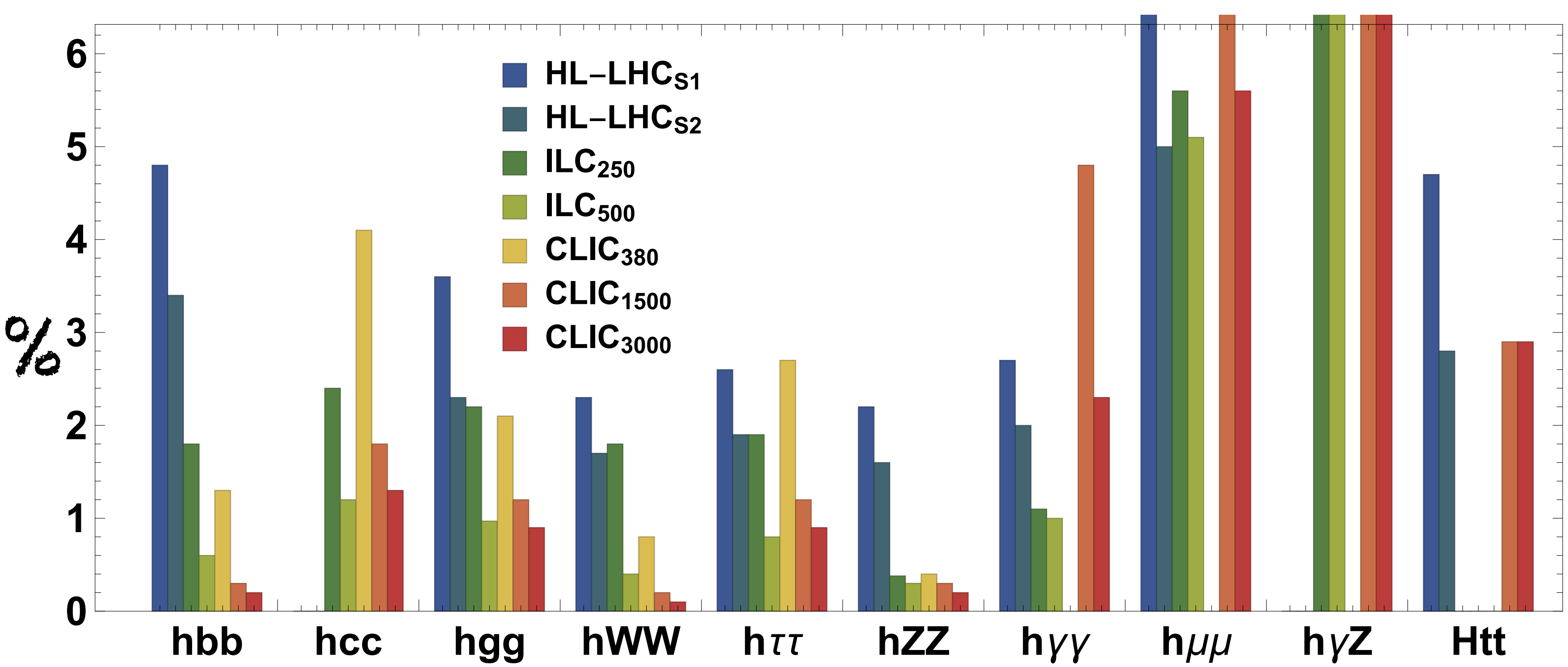

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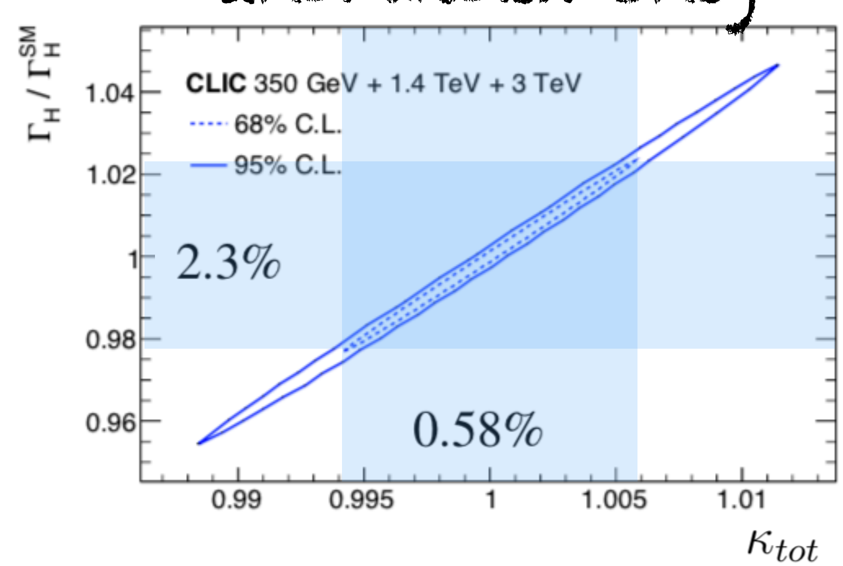

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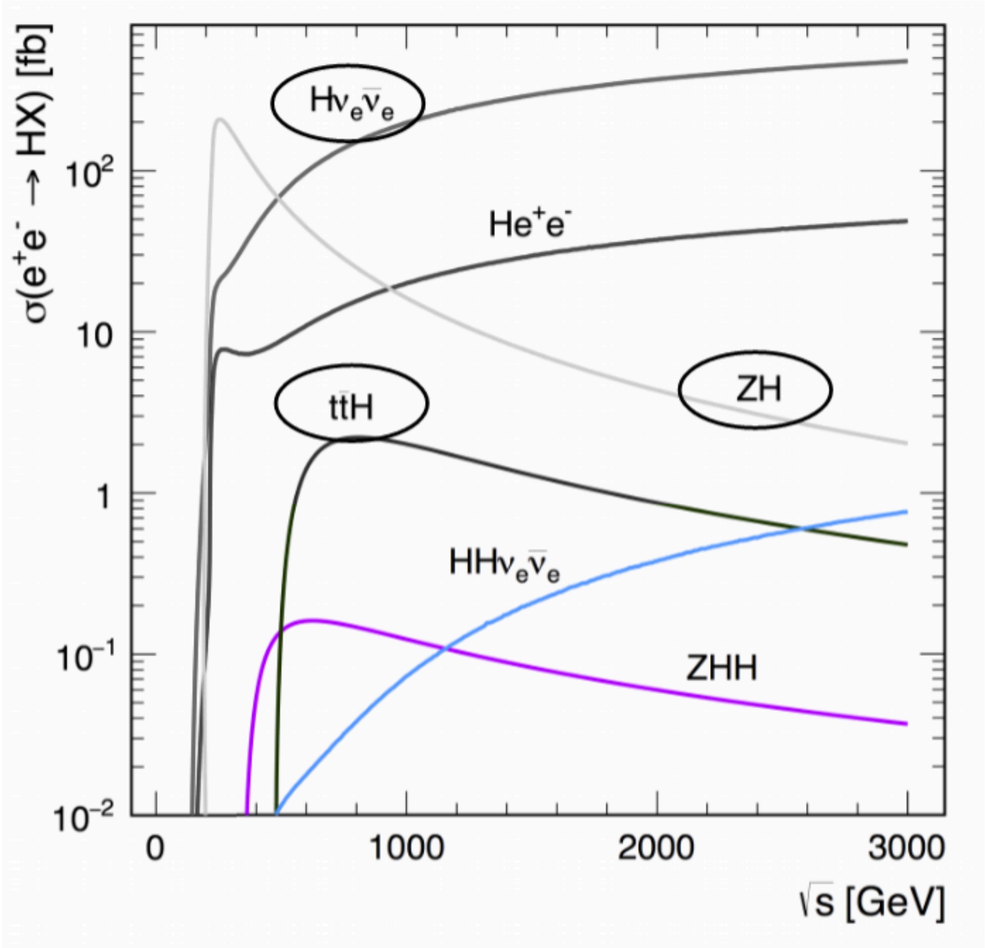
ILC 1708.08912 and CLIC YR

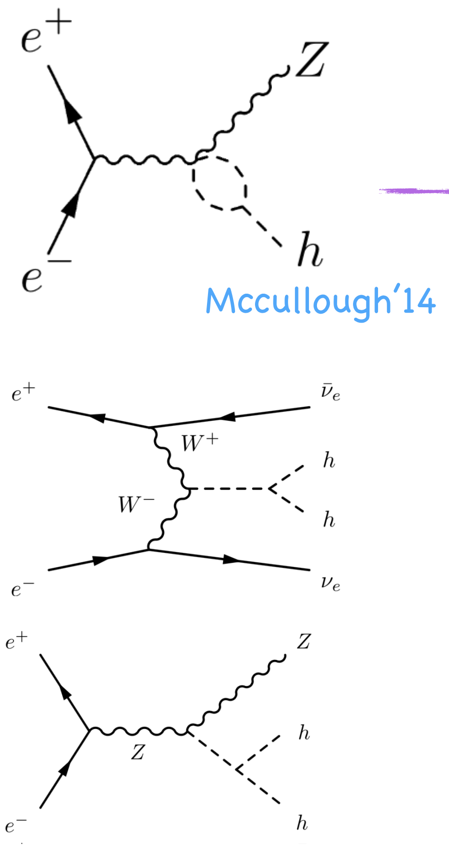
Higgs Self-Coupling

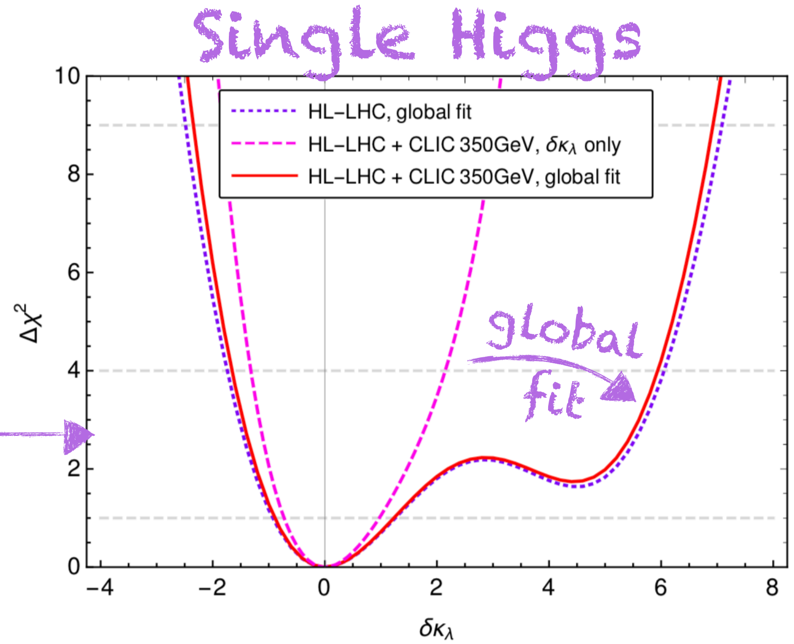
See Ulrike's talk

Modifications of h³ dont grow with energy in $ZHH, HH\nu\nu$

Measurable also below threshold





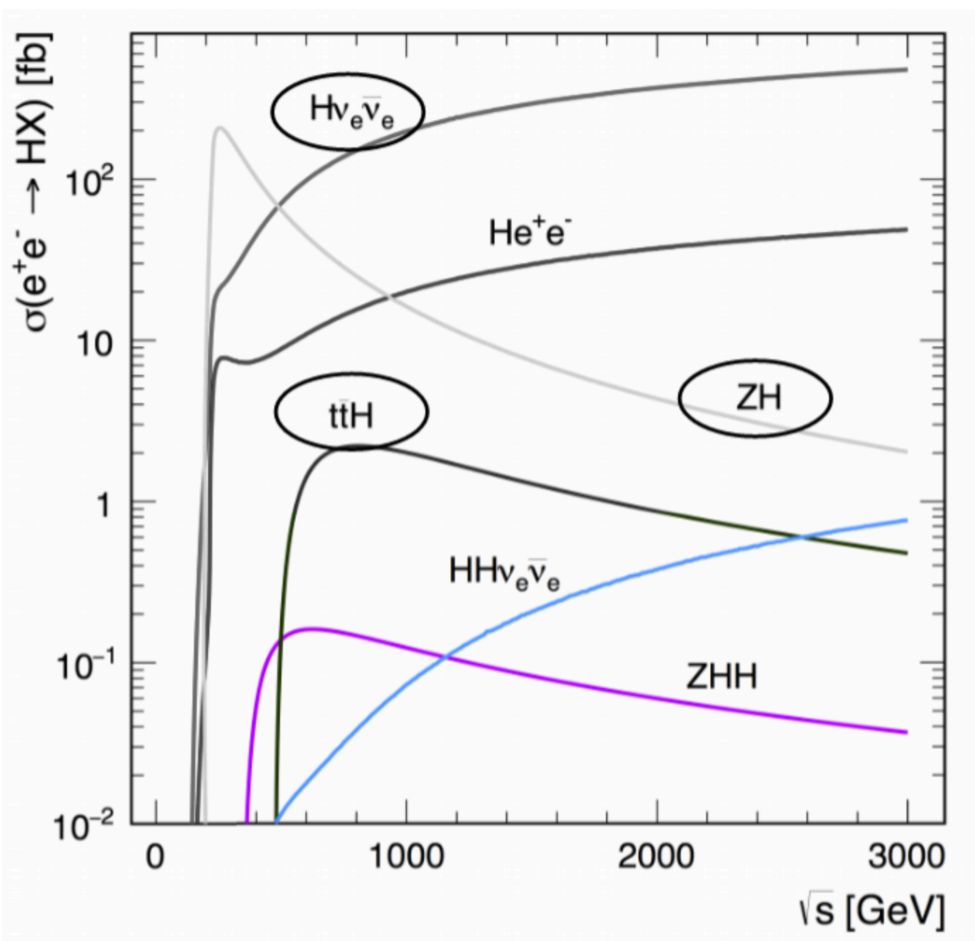


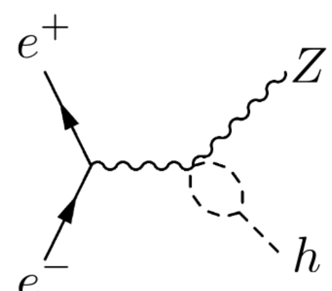
Higgs Self-Coupling

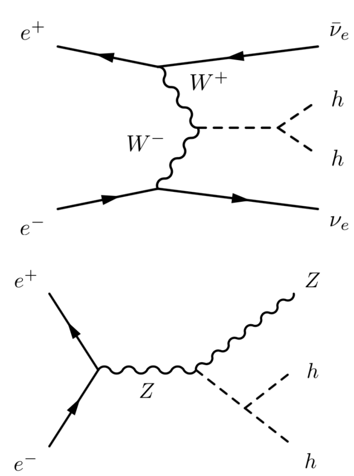
See Ulrike's talk

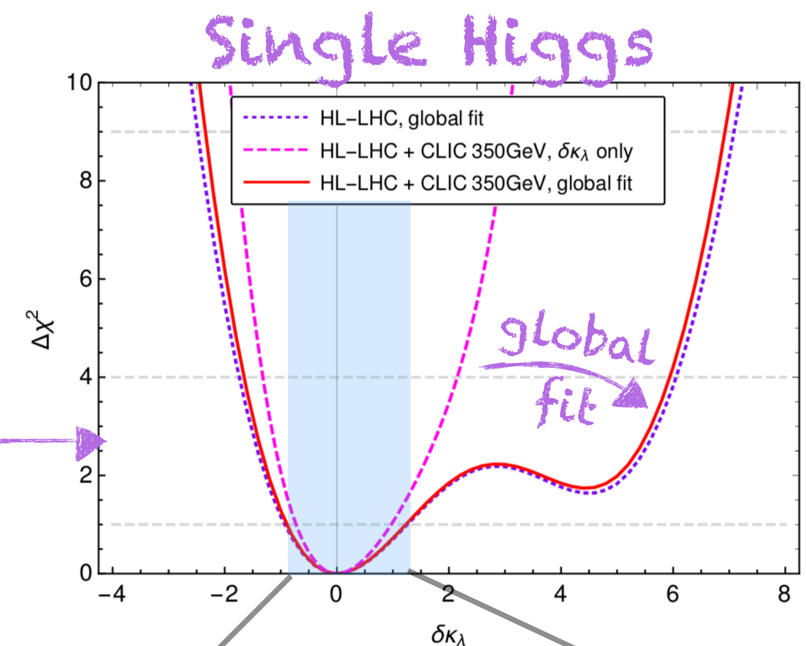
Modifications of h³ dont grow with energy in $ZHH, HH\nu\nu$

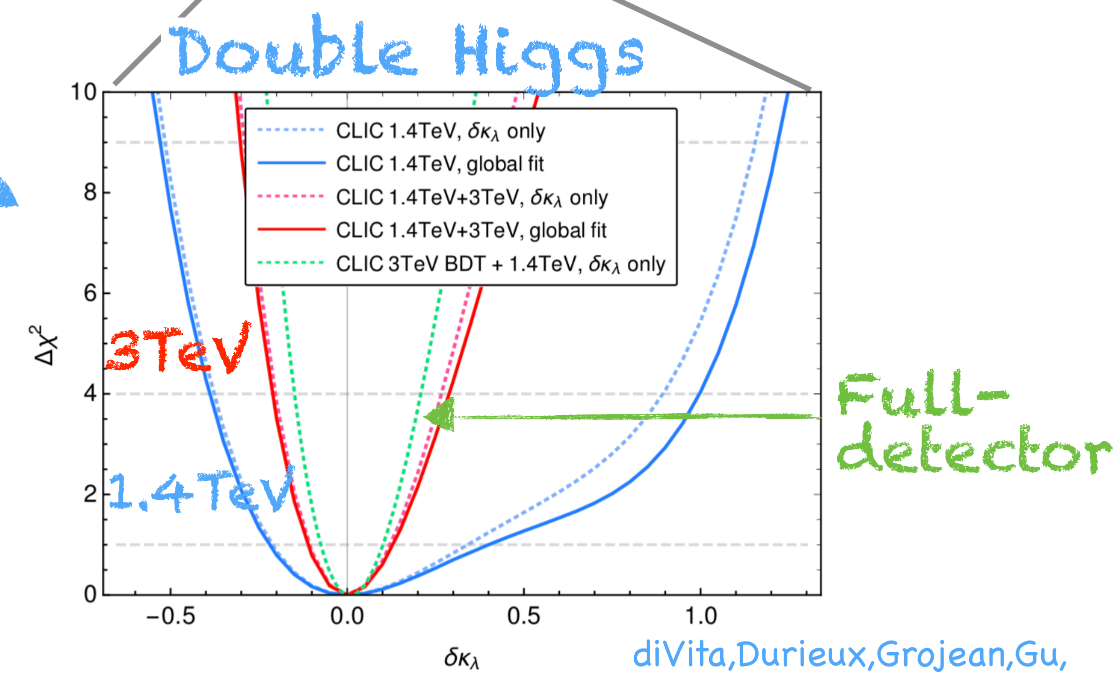
Measurable also below threshold











diVita,Durieux,Grojean,Gu,
Liu,Panico,Riembau,Vantalon'17

Higgs Self-Coupling

See Ulrike's talk

Modifications of h³ dont grow with energy in $ZHH, HH\nu\nu$

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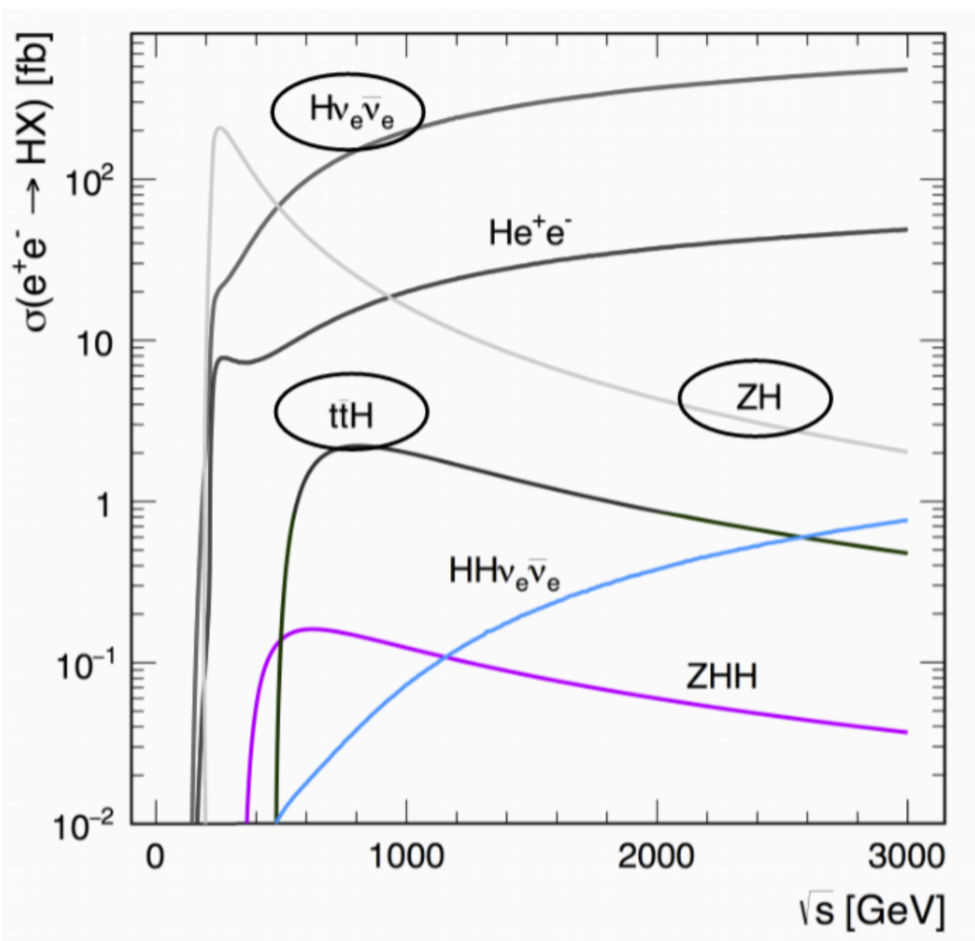
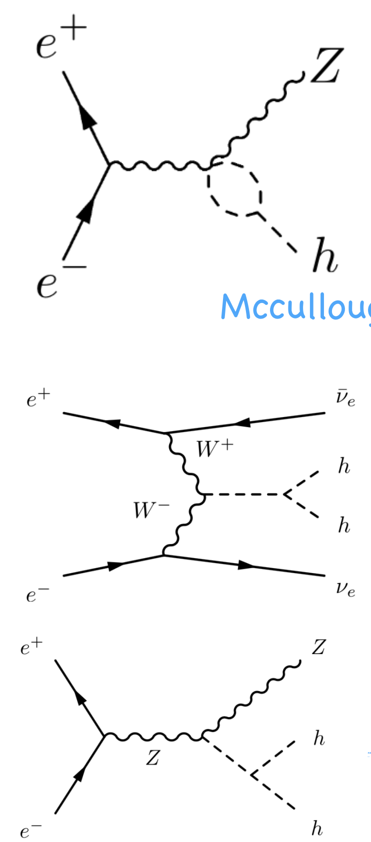
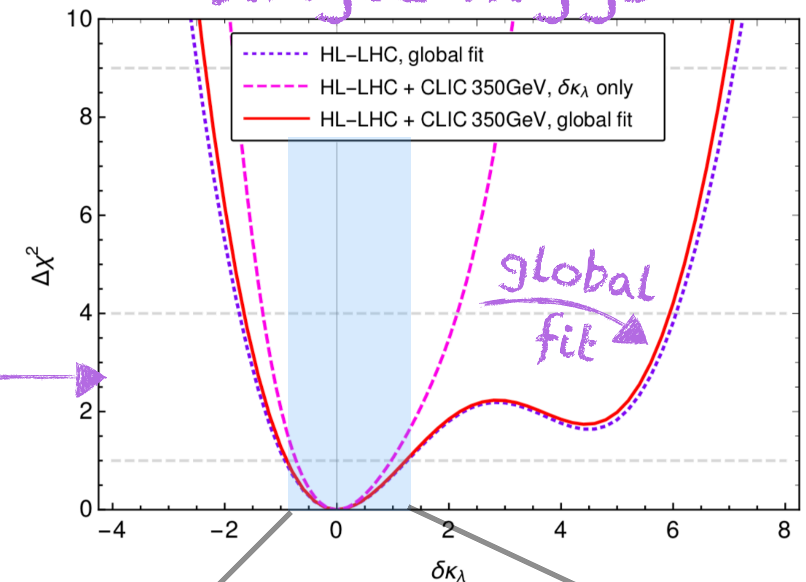


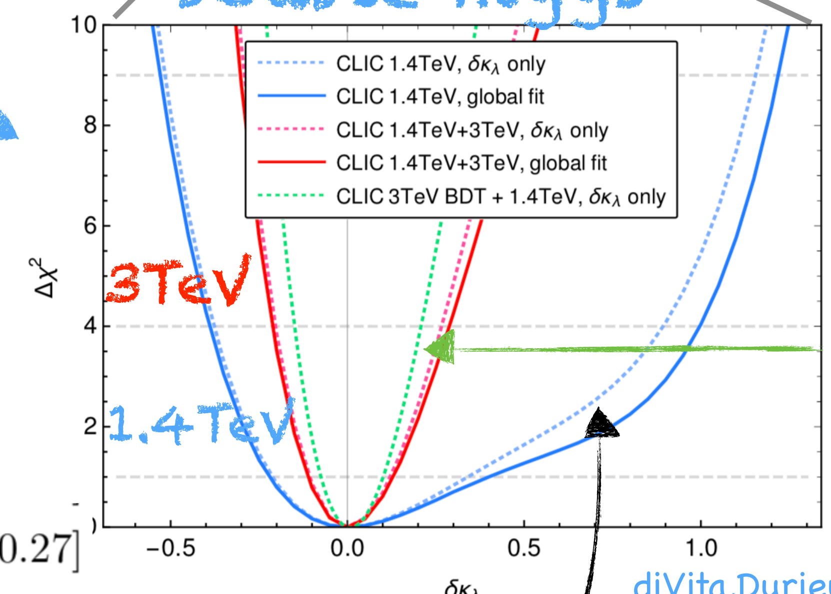


Mccullough'14

Single Higgs



Double Higgs



Full-detector

CLIC Stage 2+3, exclusive	[−0.11, 0.12]	[−0.20, 0.27]
CLIC Stage 2+3, global	[−0.11, 0.13]	[−0.21, 0.29]

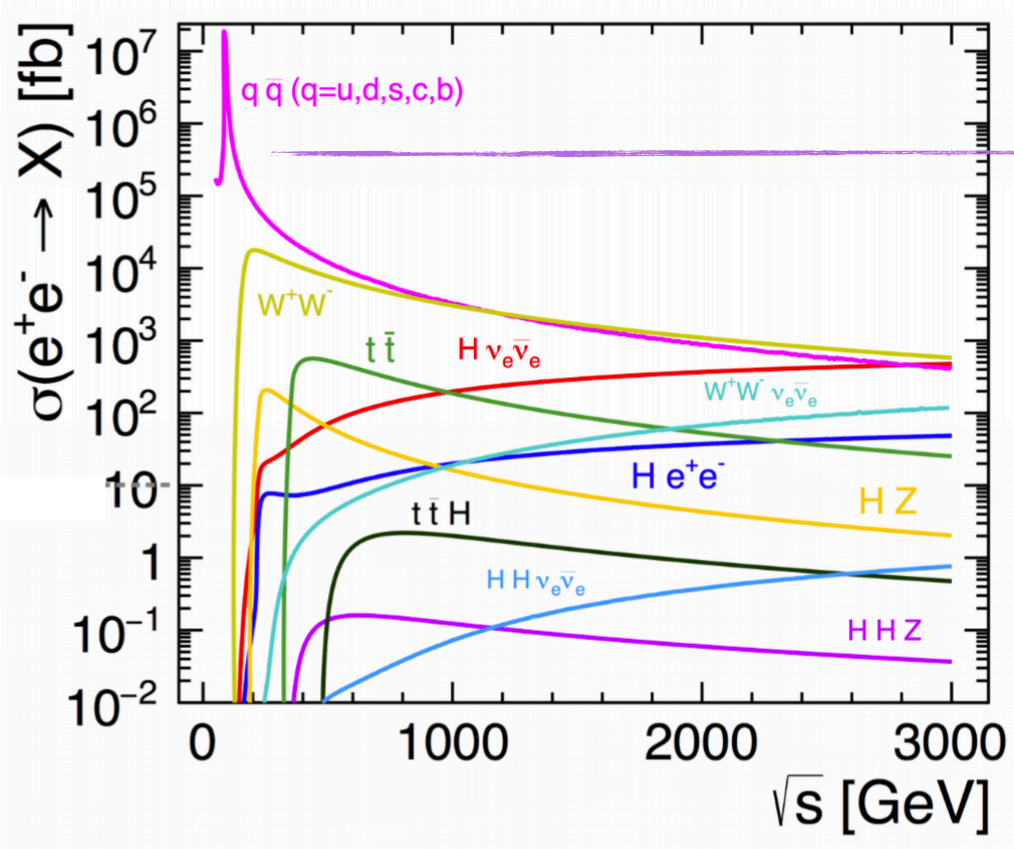
diVita, Durieux, Grojean, Gu, Liu, Panico, Riembau, Vantalon'17

Stable under additional effects

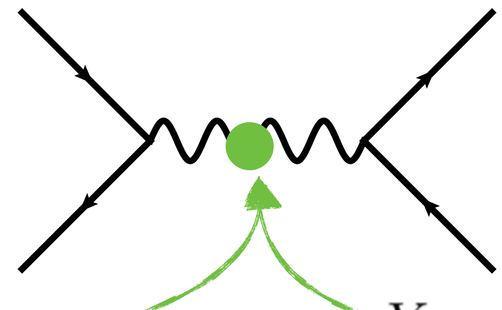
2) High-Energy Probes

Best reach from identifying processes and Effects (EFT)
with Energy-growth

Drell Yann



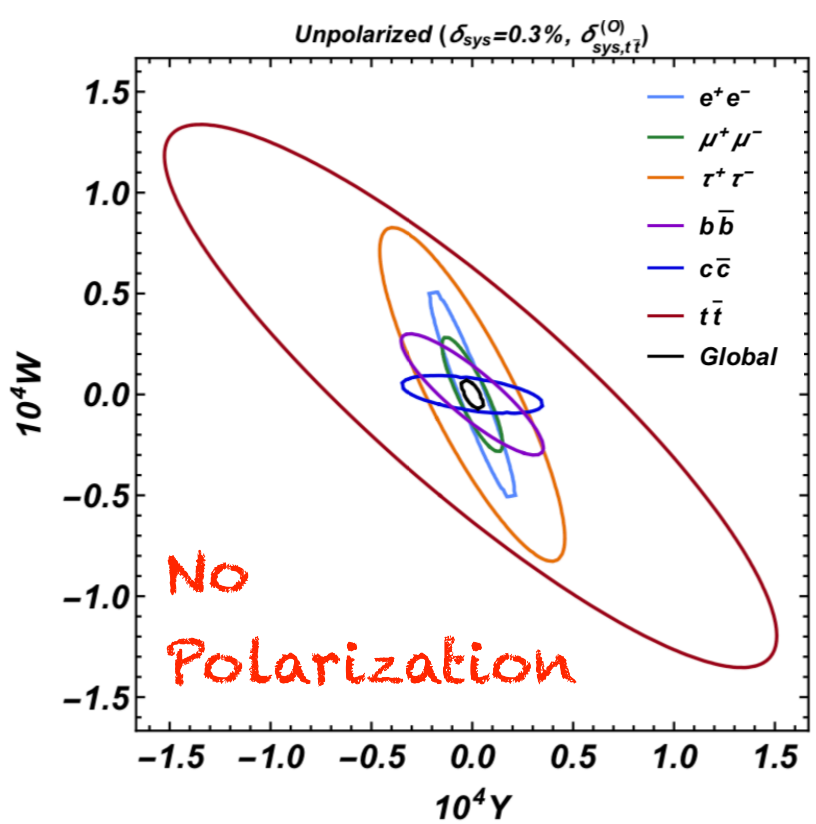
Largest x-section



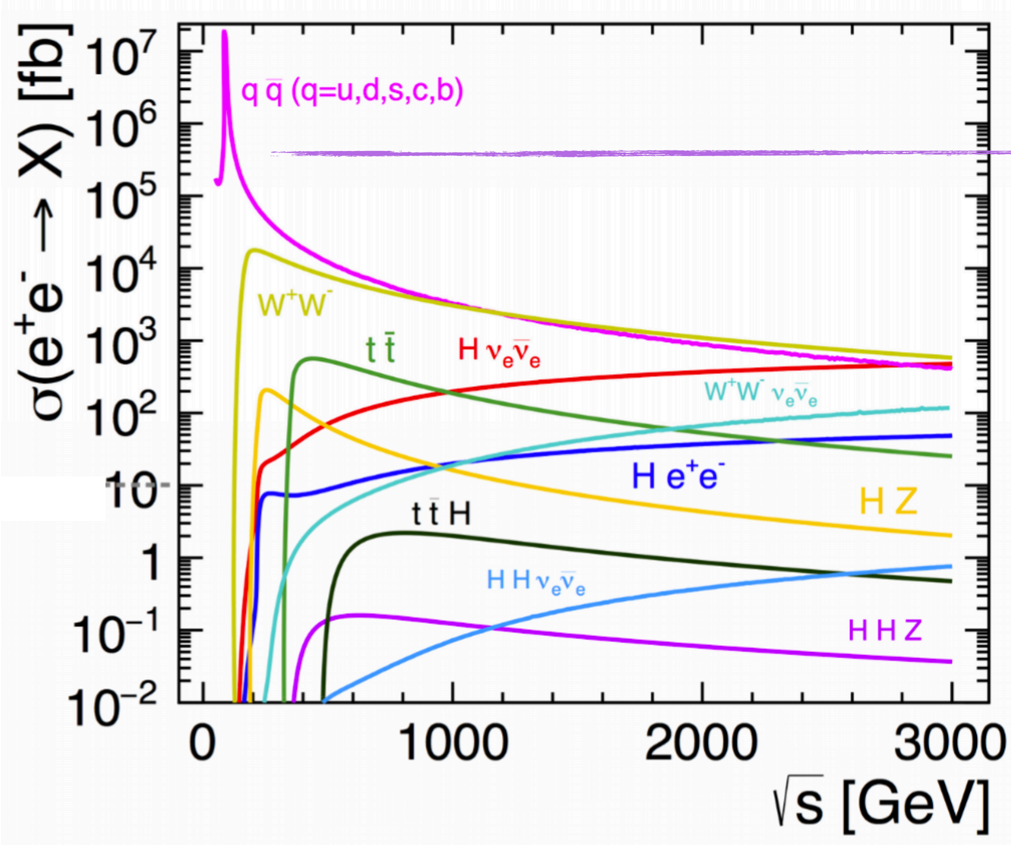
$$-\frac{W}{4m_W^2}(D_\rho W^a_{\mu\nu})^2\,, \qquad -\frac{Y}{4m_W^2}(D_\rho B_{\mu\nu})^2$$

Effects in Z propagator grow $\propto s$

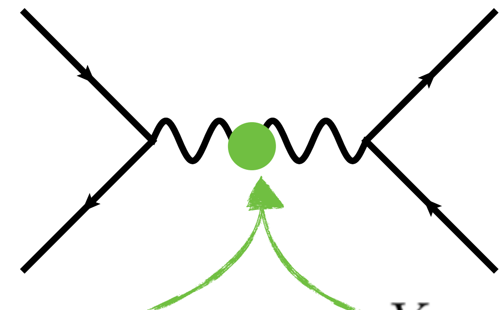
Barbieri,Pomarol,Rattazzi,Strumia'04
Farina,Panico,Pappadopulo,Ruderman,Torre,Wulzer'16



Drell Yann



Largest x-section



$$-\frac{W}{4m_W^2}(D_\rho W^a_{\mu\nu})^2\,, \qquad -\frac{Y}{4m_W^2}(D_\rho B_{\mu\nu})^2$$

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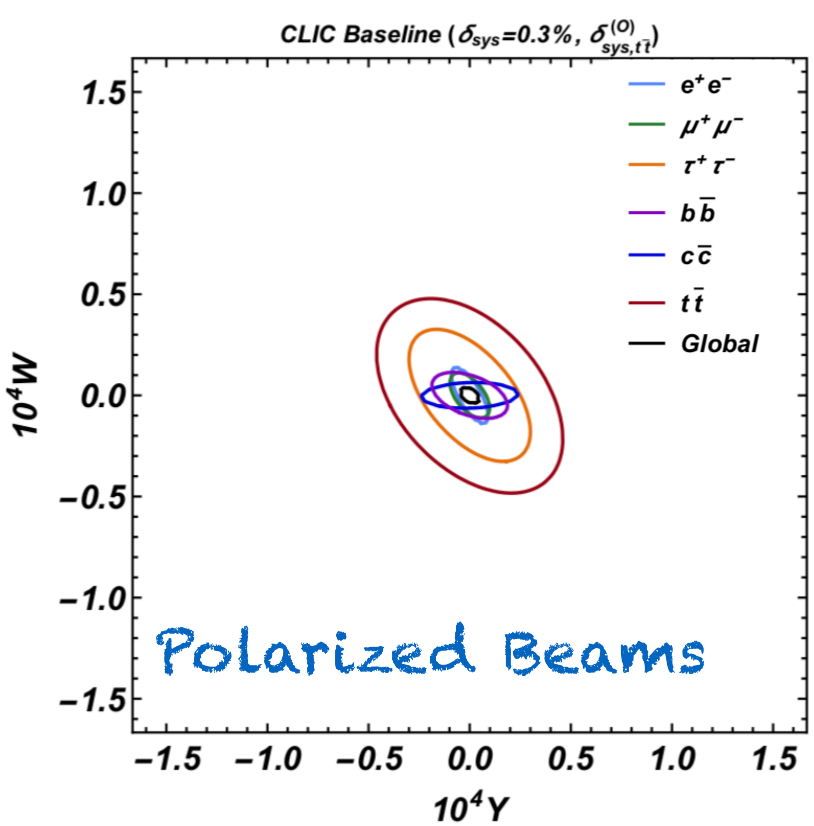
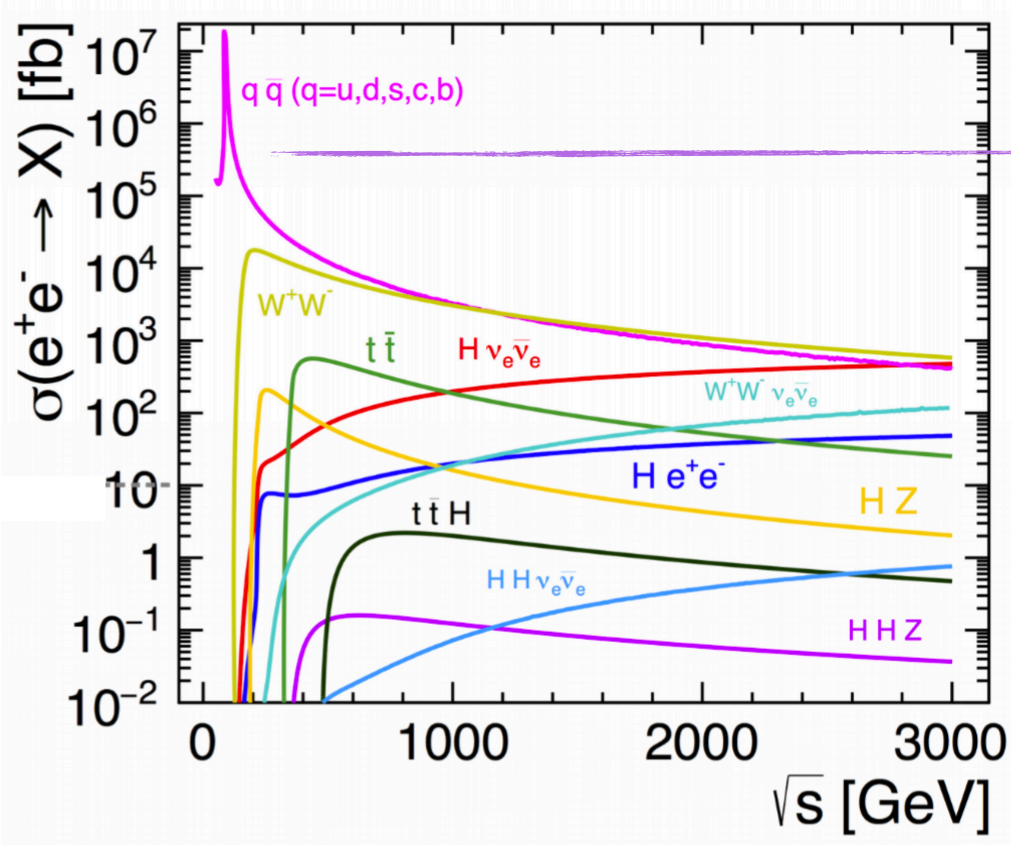
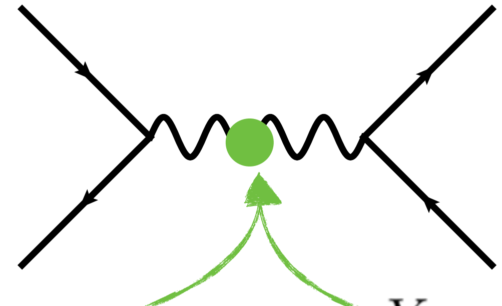


Drell Yann



Largest x-section



$$-\frac{W}{4m_W^2}(D_\rho W^a_{\mu\nu})^2\,, \qquad -\frac{Y}{4m_W^2}(D_\rho B_{\mu\nu})^2$$

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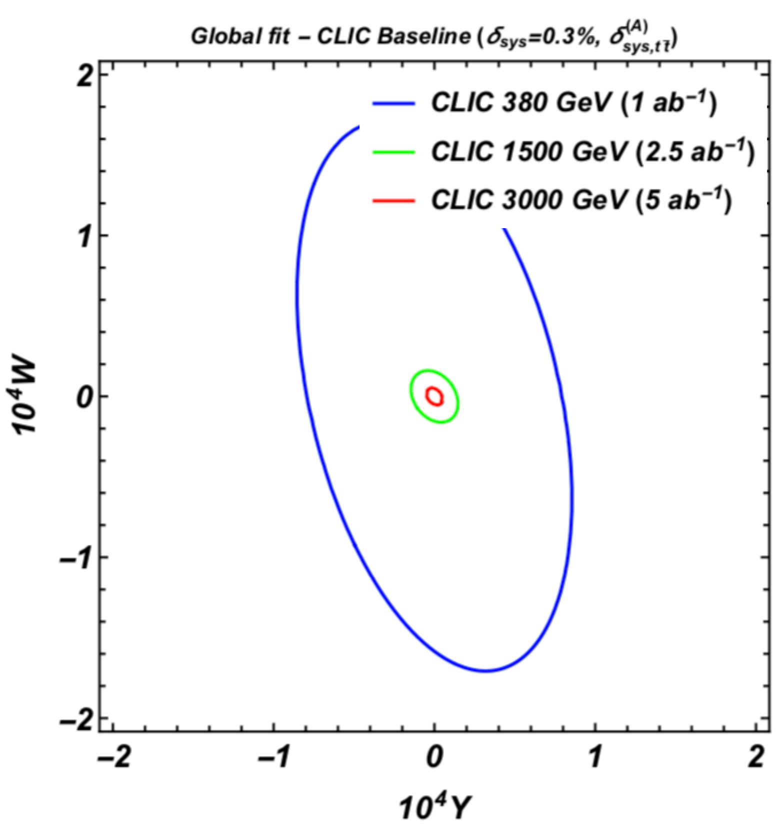
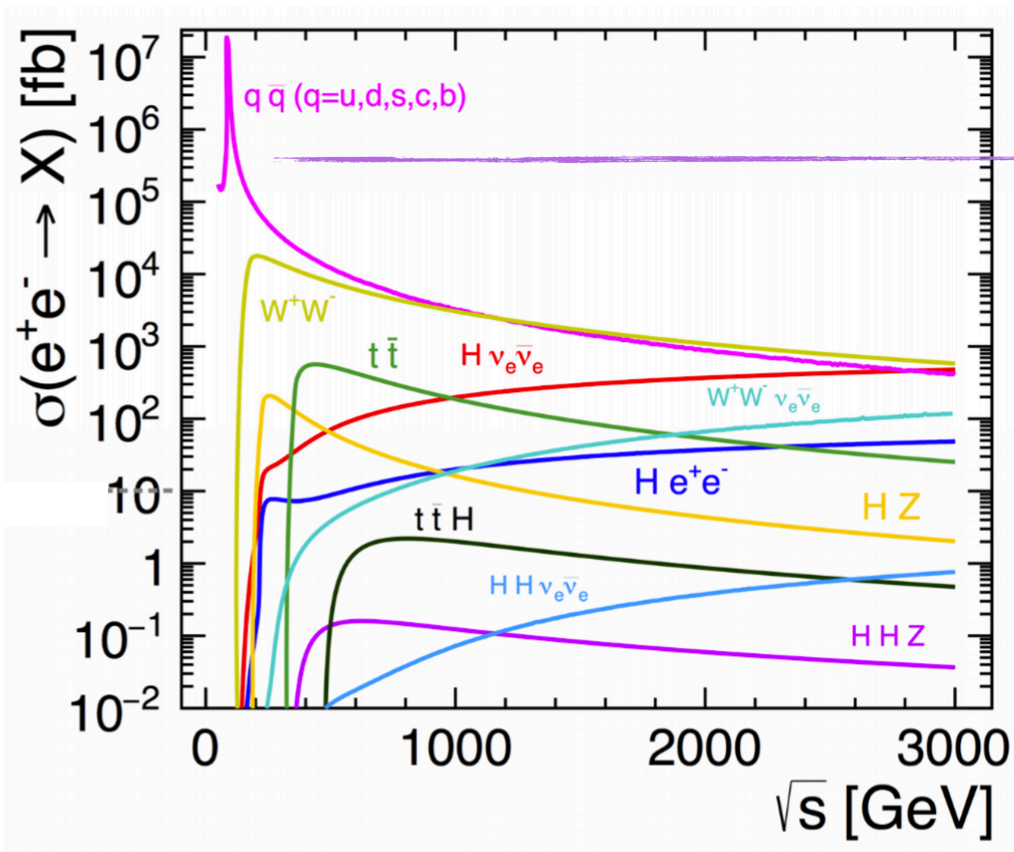
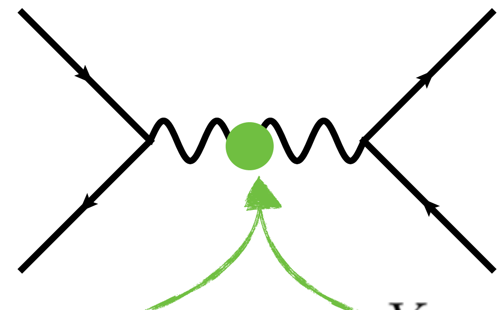


Drell Yann



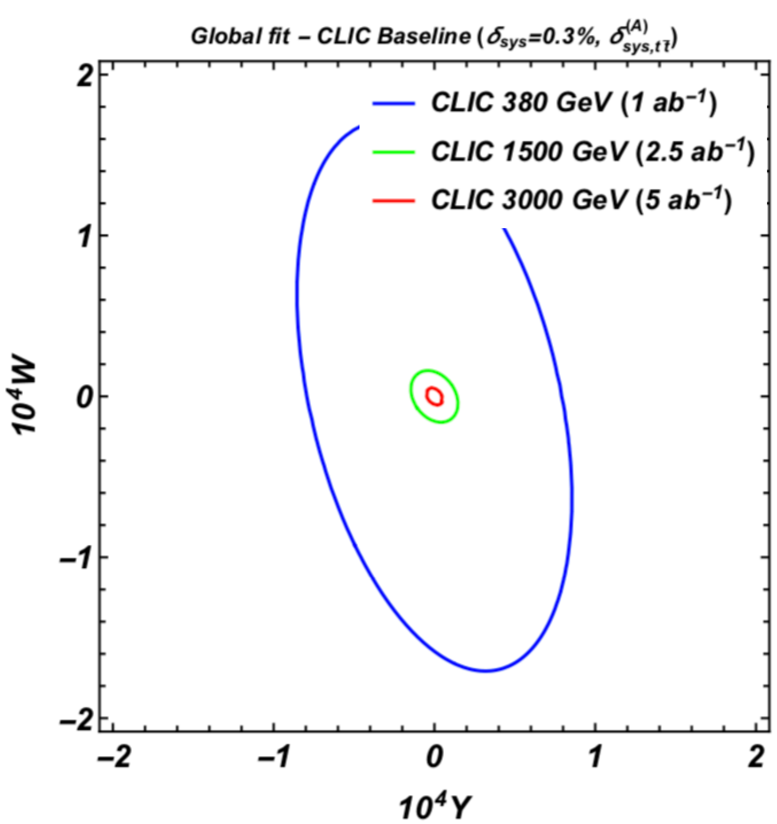
Largest x-section

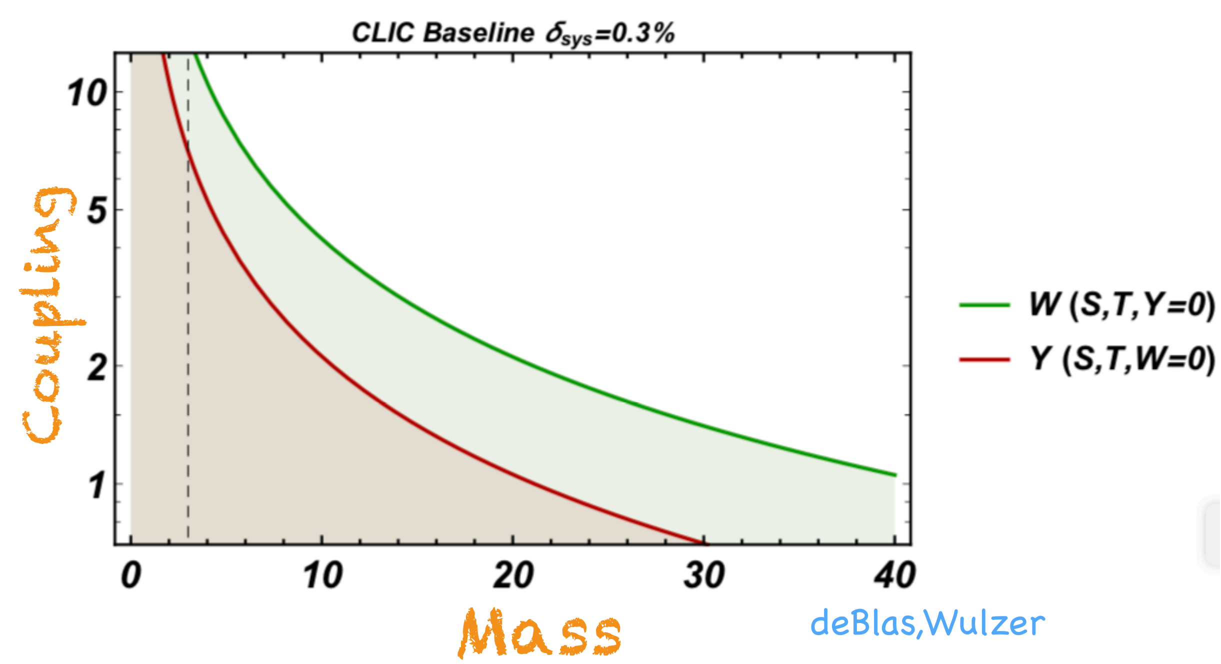


$$-\frac{W}{4m_W^2}(D_\rho W^a_{\mu\nu})^2\,, \qquad -\frac{Y}{4m_W^2}(D_\rho B_{\mu\nu})^2$$

Effects in Z propagator grow $\propto s$

Barbieri,Pomarol,Rattazzi,Strumia'04
Farina,Panico,Pappadopulo,Ruderman,Torre,Wulzer'16

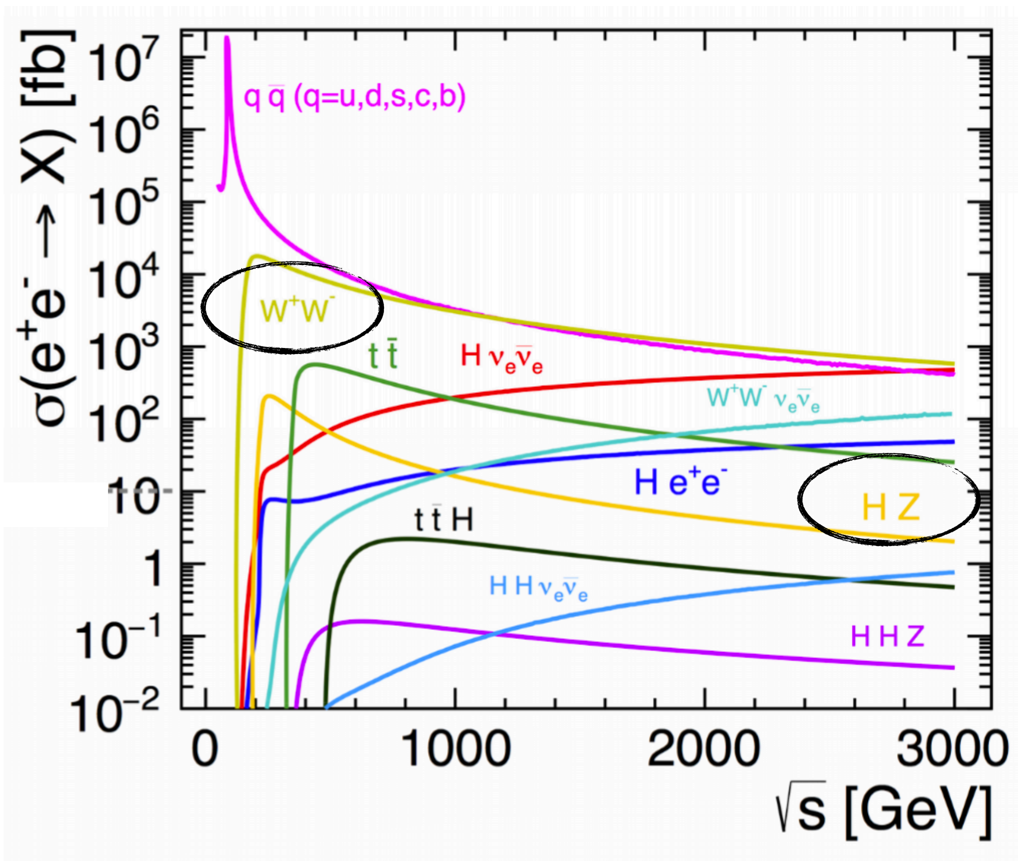




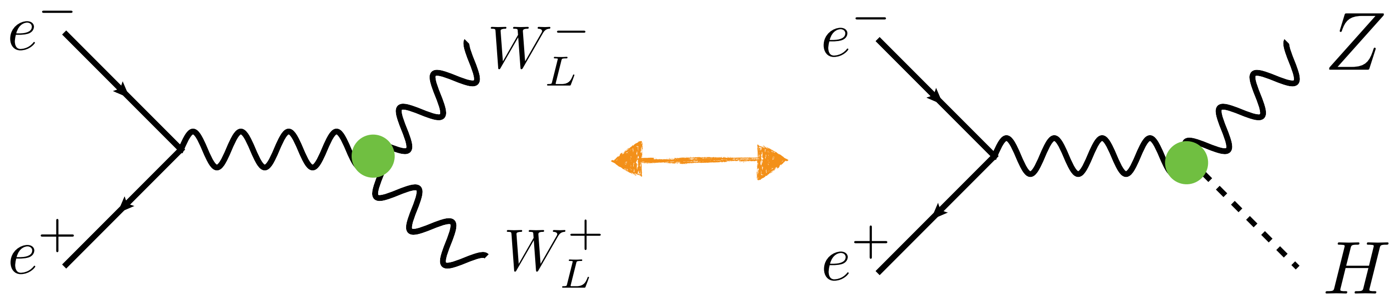
deBlas,Wulzer

Heavy SU(2) triplets generate W,Y
(e.g composite Higgs)

Dibosons - WW/HZ



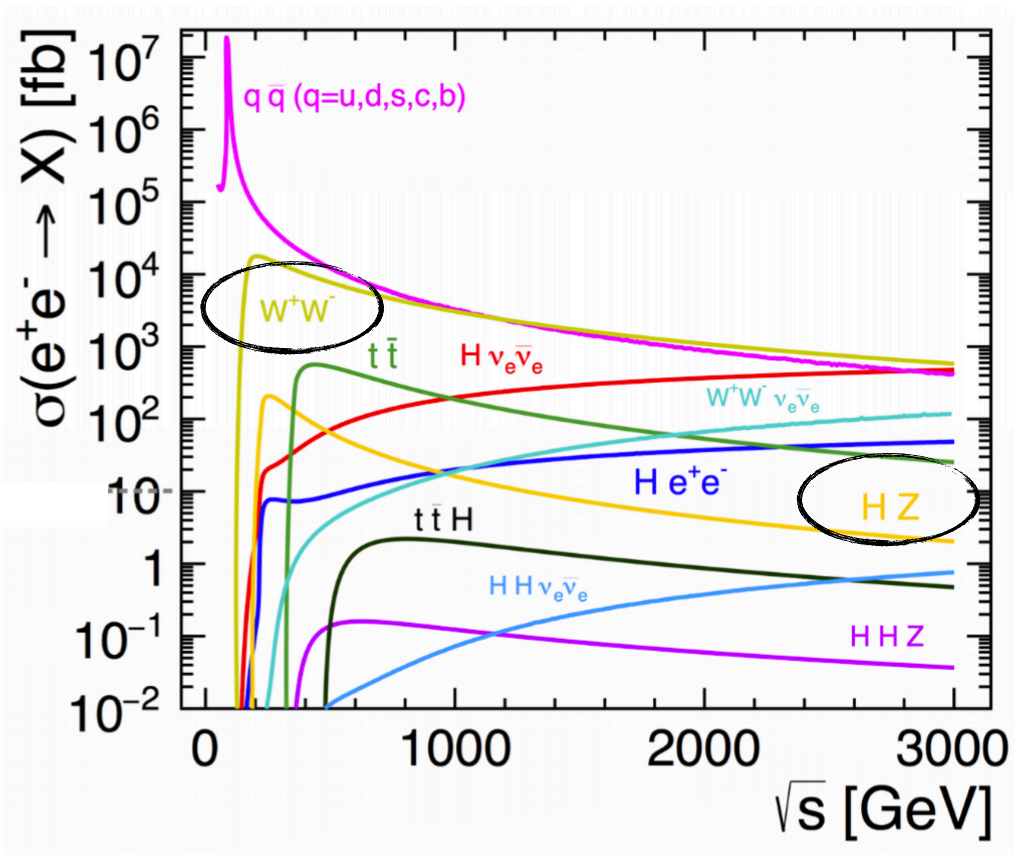
Equivalence theorem:



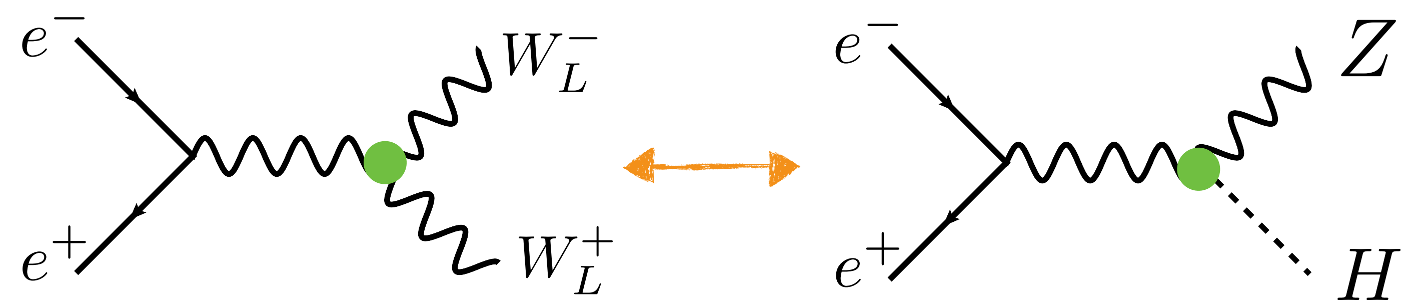
Effects in $W_L W_L$ ≈ Effects in ZH

(WW tests Higgs physics)

Dibosons - WW/HZ



Equivalence theorem:



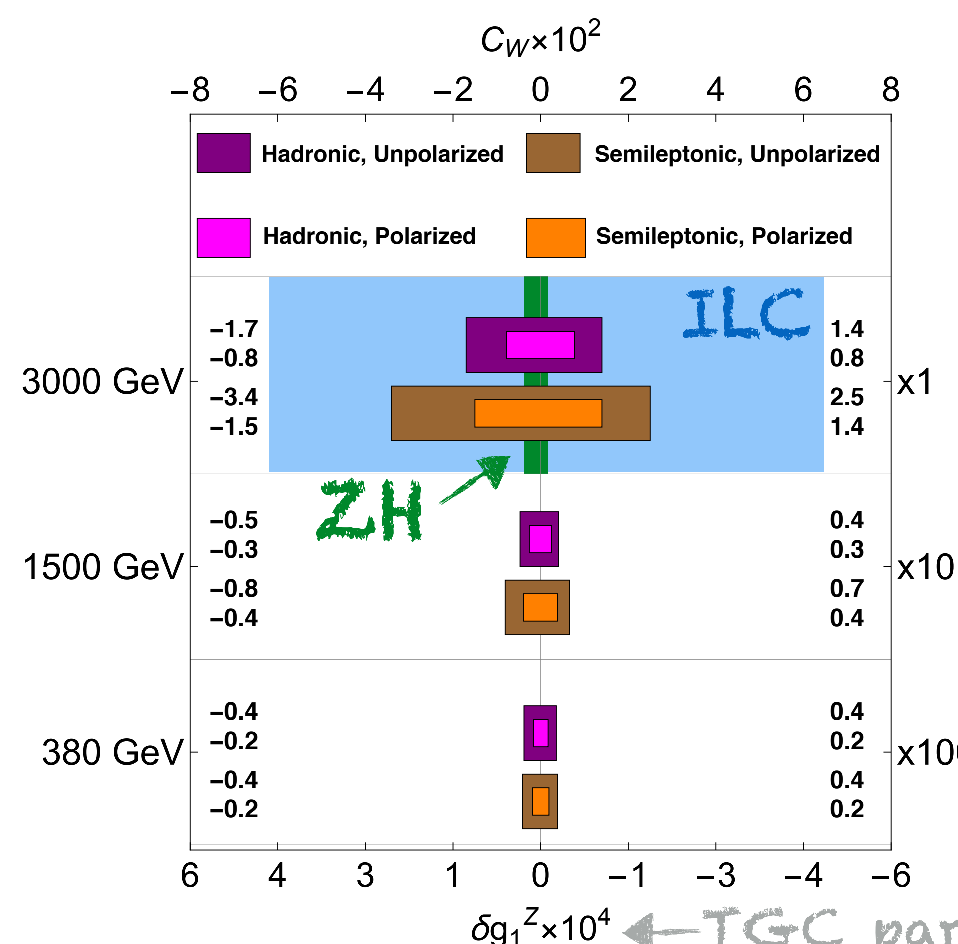
Effects in $W_L W_L$ ≈ Effects in ZH

(WW tests Higgs physics)

WW:

focus on longitudinals difficult ($W_T W_T$ large)

- +80% Polarization helps



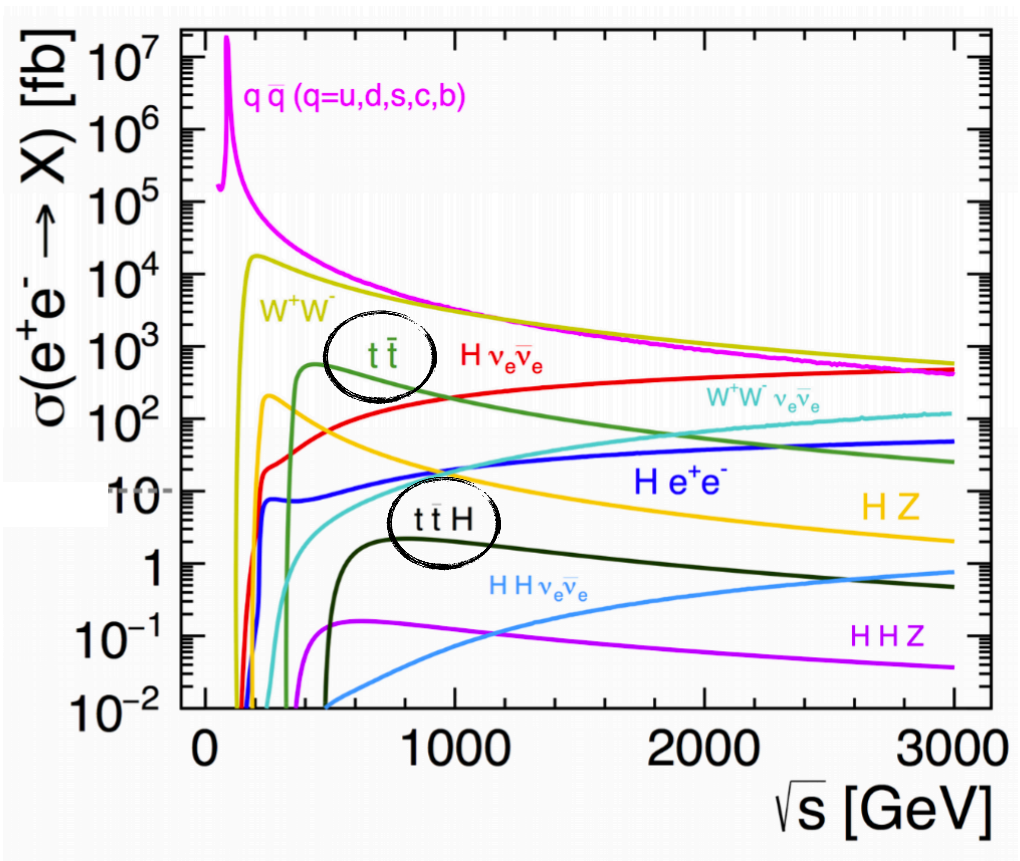
← TGC parameter

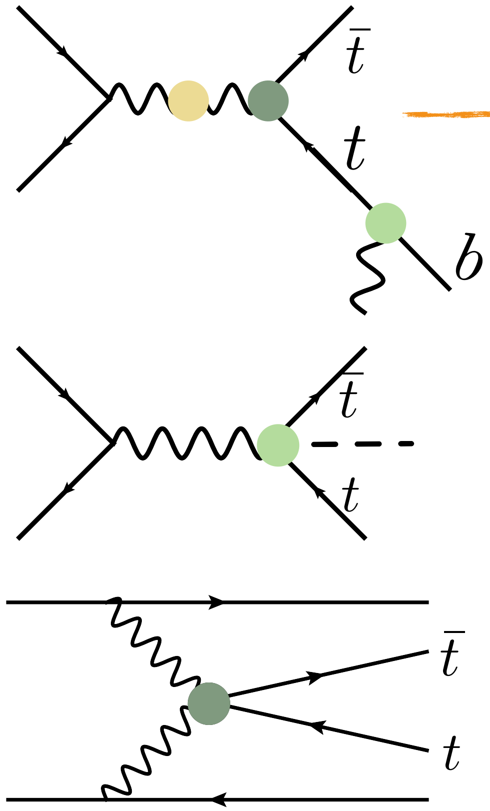
More Energy

More Precision

Lombardo

Top Physics - CLIC

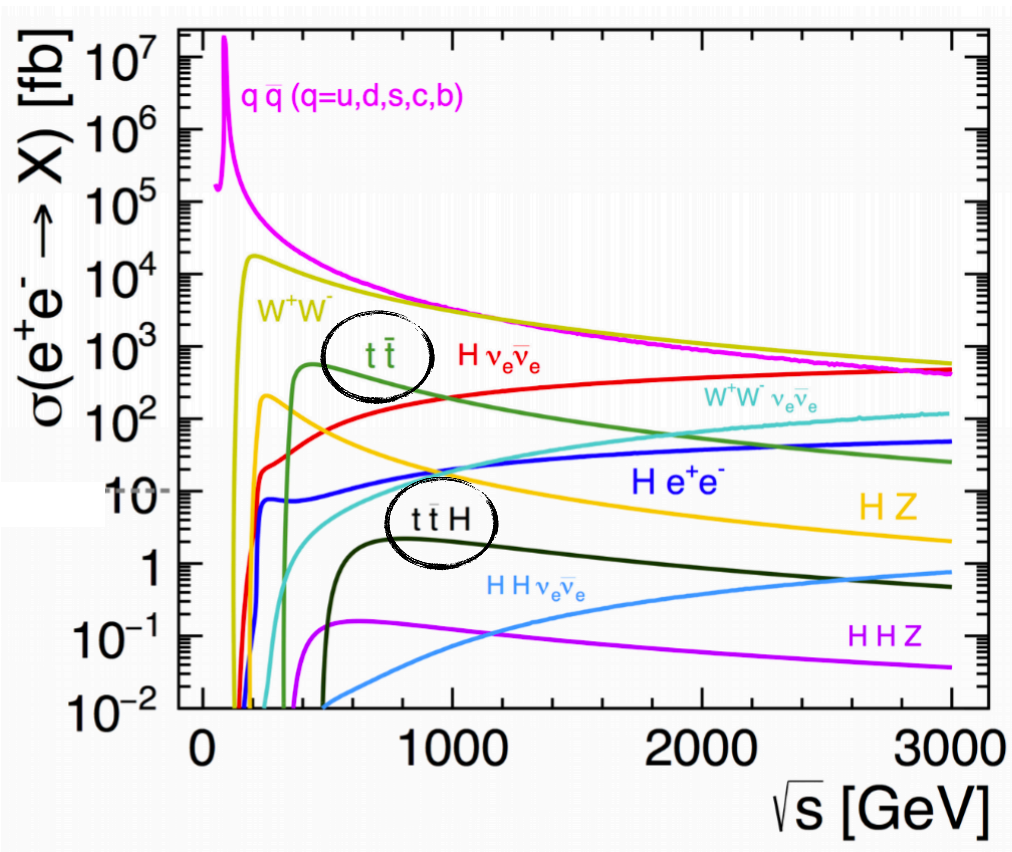


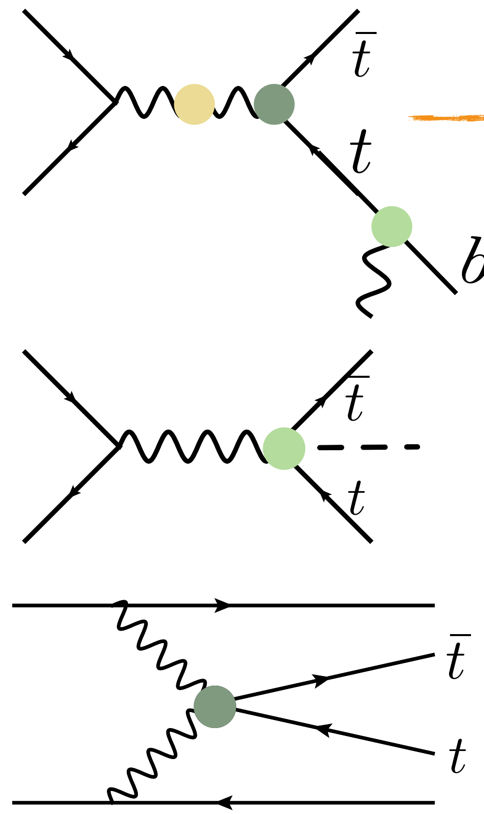


Substantial info
(combining different stages)

Exploit high-energy best

Top Physics - CLIC





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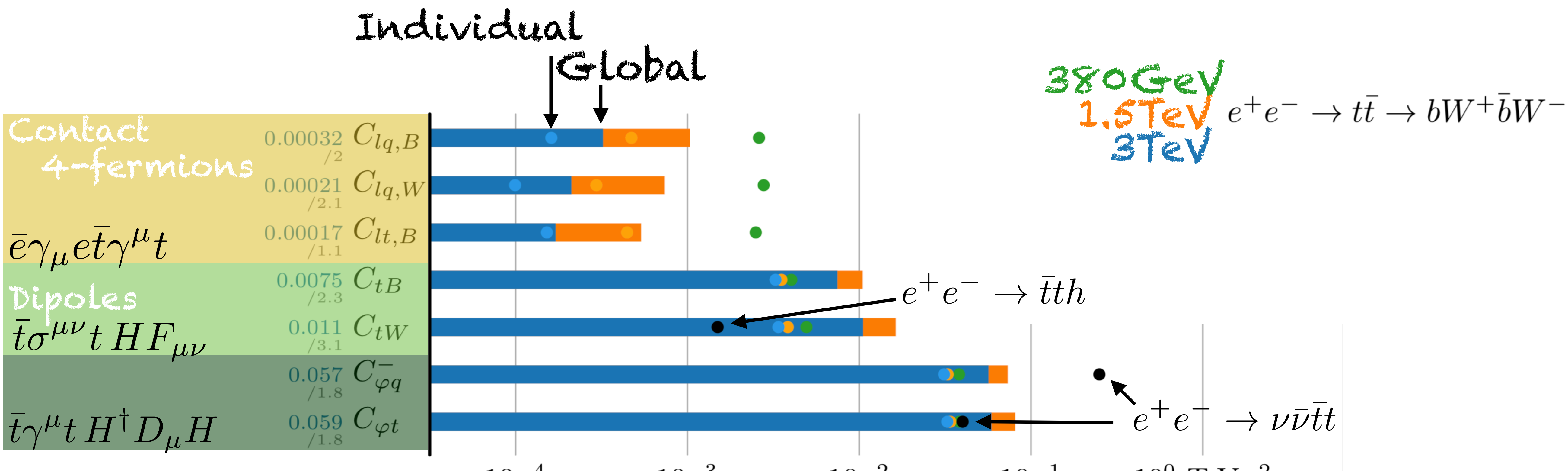
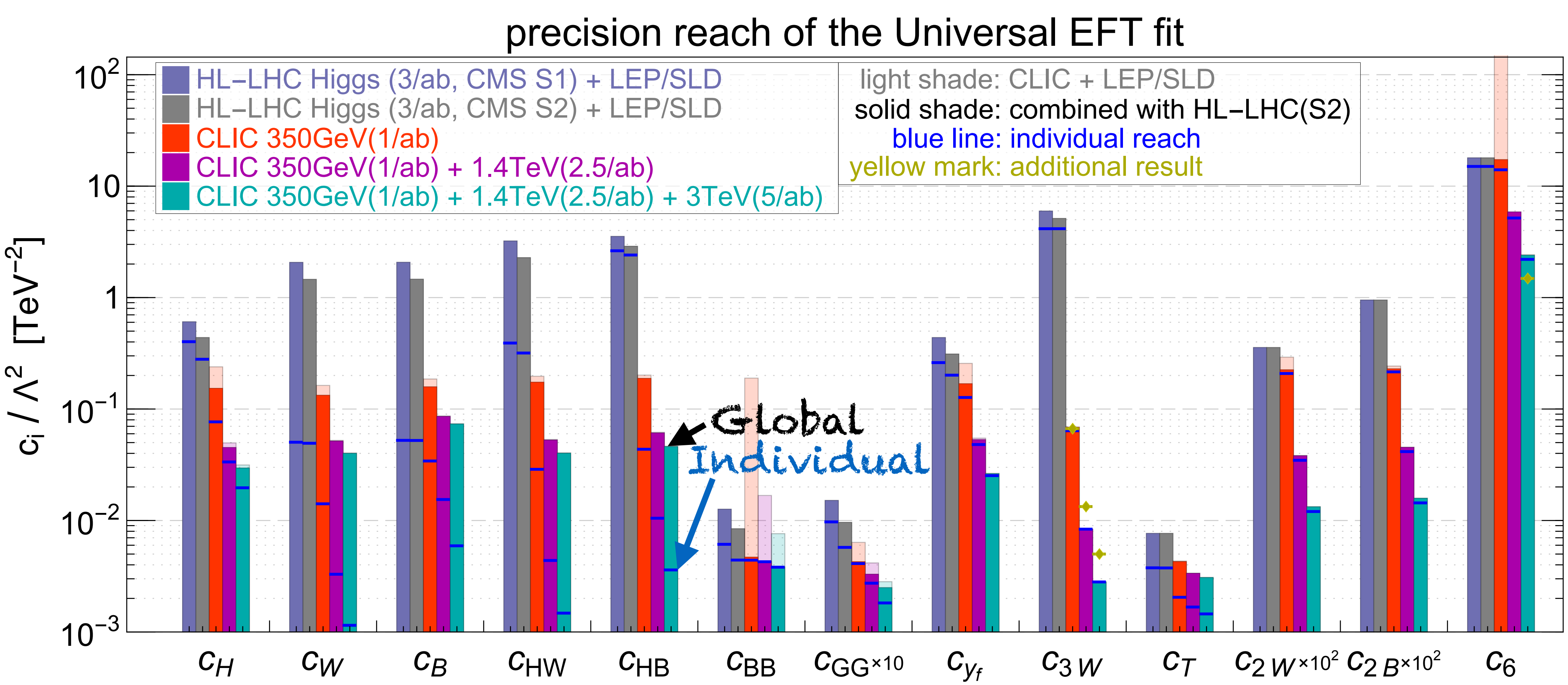


Durieux,Perello,Vos,Zhang'18

Global Fit

Processes discussed so far are sensitive to all universal effects

new physics couples only to bosons



Single Higgs

WW/ZH

Single Higgs

Drell Yann

Double Higgs

BSM Reach

≈ 1 TeV

≈ 3 TeV

≈ 10 TeV

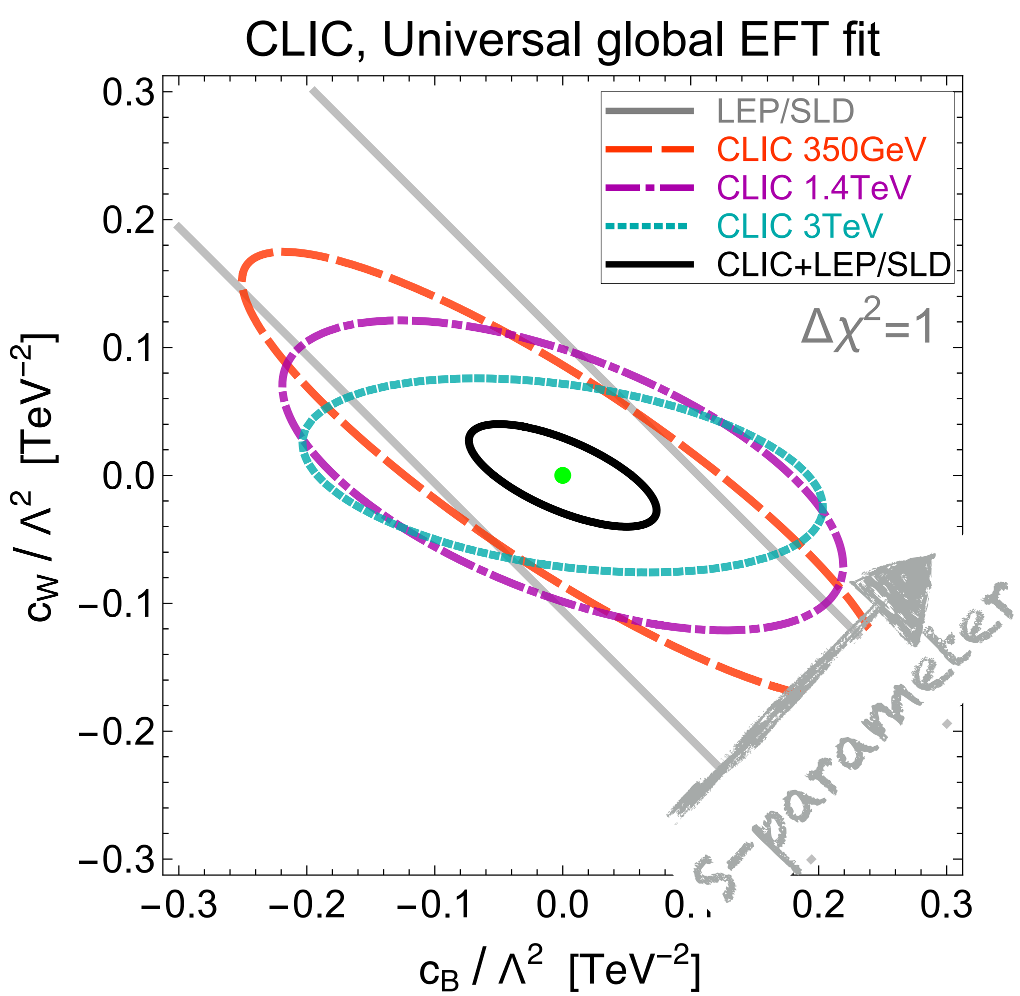
Correlation, CLIC 350GeV+1.4TeV+3TeV

	c_H	c_W	c_B	c_{HW}	c_{HB}	c_{BB}	c_{GG}	c_{y_f}	c_{3W}	c_T	c_{2W}	c_{2B}
c_H	100	9	−17	−4	13	2	−62	−12	0	9	4	−2
c_W	9	100	−68	−95	94	8	−3	16	0	−8	2	−1
c_B	−17	−68	100	42	−88	−6	0	−9	−1	62	−6	6
c_{HW}	−4	−95	42	100	−79	−7	4	−16	0	−15	0	−1
c_{HB}	13	94	−88	−79	100	8	−2	14	1	−34	4	−4
c_{BB}	2	8	−6	−7	8	100	2	7	0	0	0	0
c_{GG}	−62	−3	0	4	−2	2	100	4	0	0	0	0
c_{y_f}	−12	16	−9	−16	14	7	4	100	0	6	1	0
c_{3W}	0	0	−1	0	1	0	0	0	100	−1	0	0
c_T	9	−8	62	−15	−34	0	0	6	−1	100	0	4
c_{2W}	4	2	−6	0	4	0	0	1	0	0	100	−42
c_{2B}	−2	−1	6	−1	−4	0	0	0	0	4	−42	100

Gu’18

Z-Pole Comparison

Z-pole measurements / high-energy measurements are complementary in a global fit



Z-Pole Comparison

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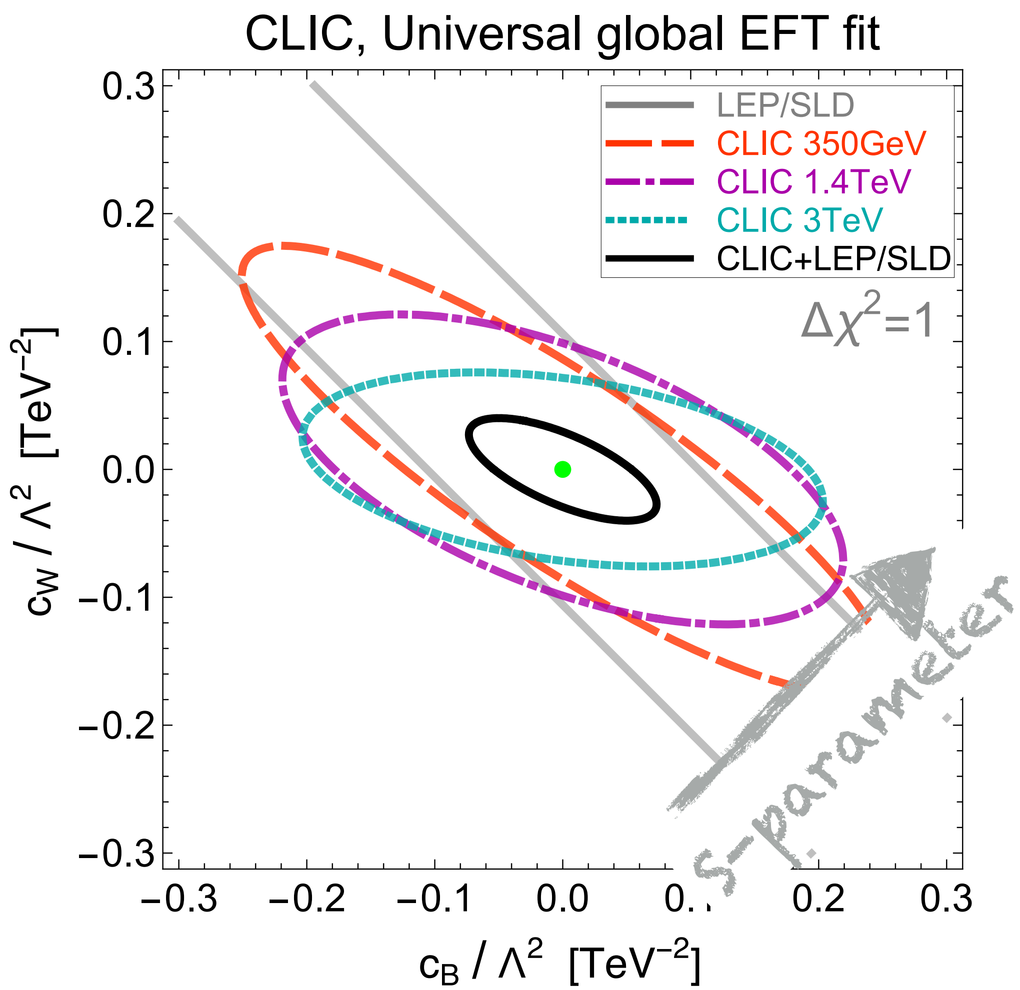
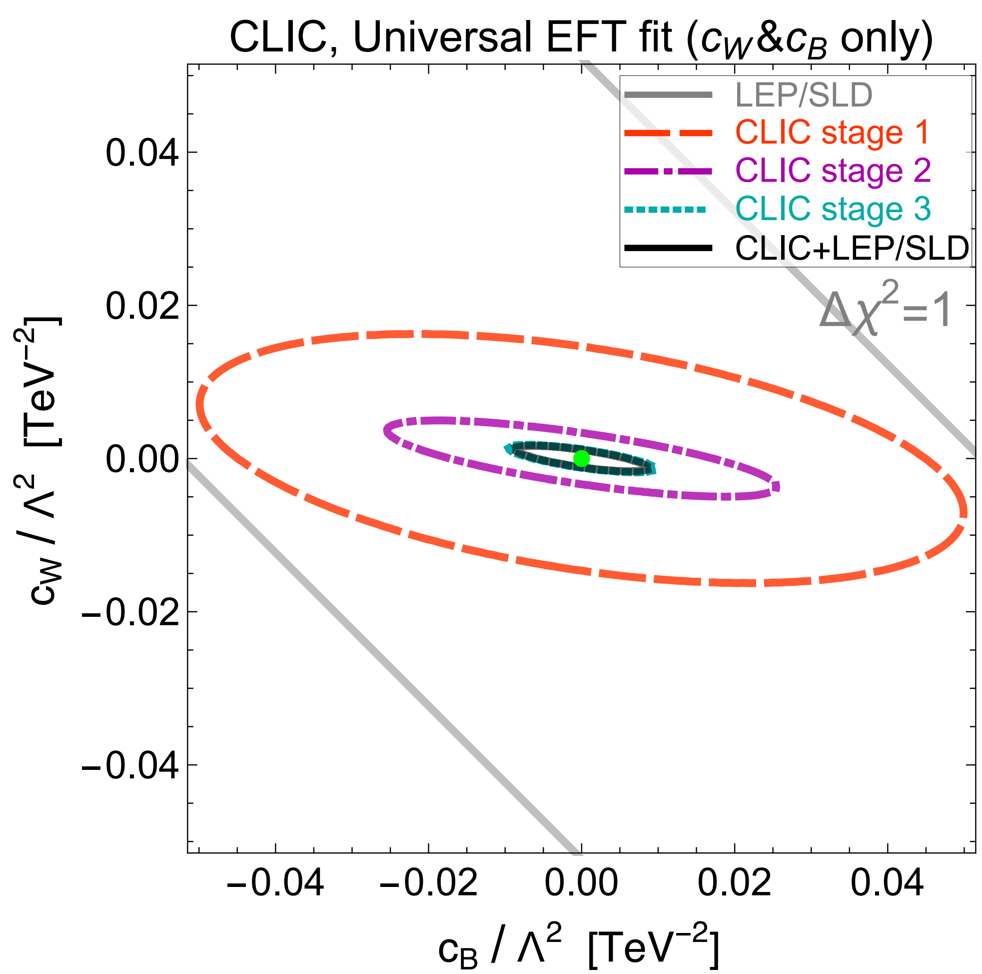
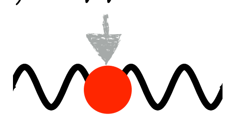




$c_B, c_W \propto S$

However: focus on  → CLIC equivalent to O(few10-5) precision on the Z-pole

(cB,cW can be generated at tree-level, so it makes sense to focus on these)

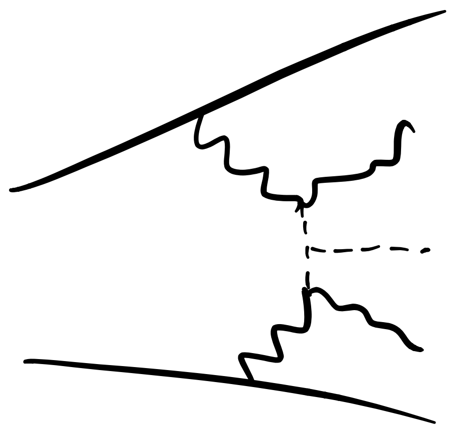
Higgs Couplings... without a Higgs

Henning,Lombardo,Riembau,FR'18

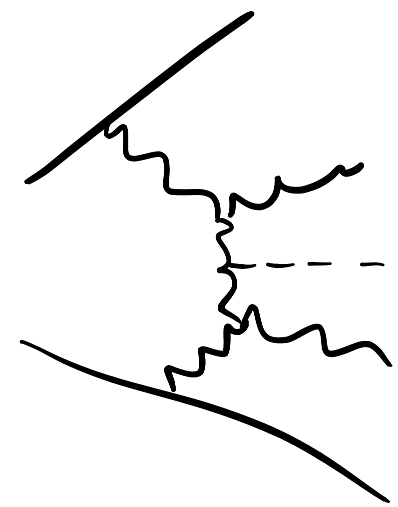
Any modifications of Higgs couplings induces
E^2 growth in some process with longitudinal W,Z bosons!

One way of seeing this:

SM =



+



= finite

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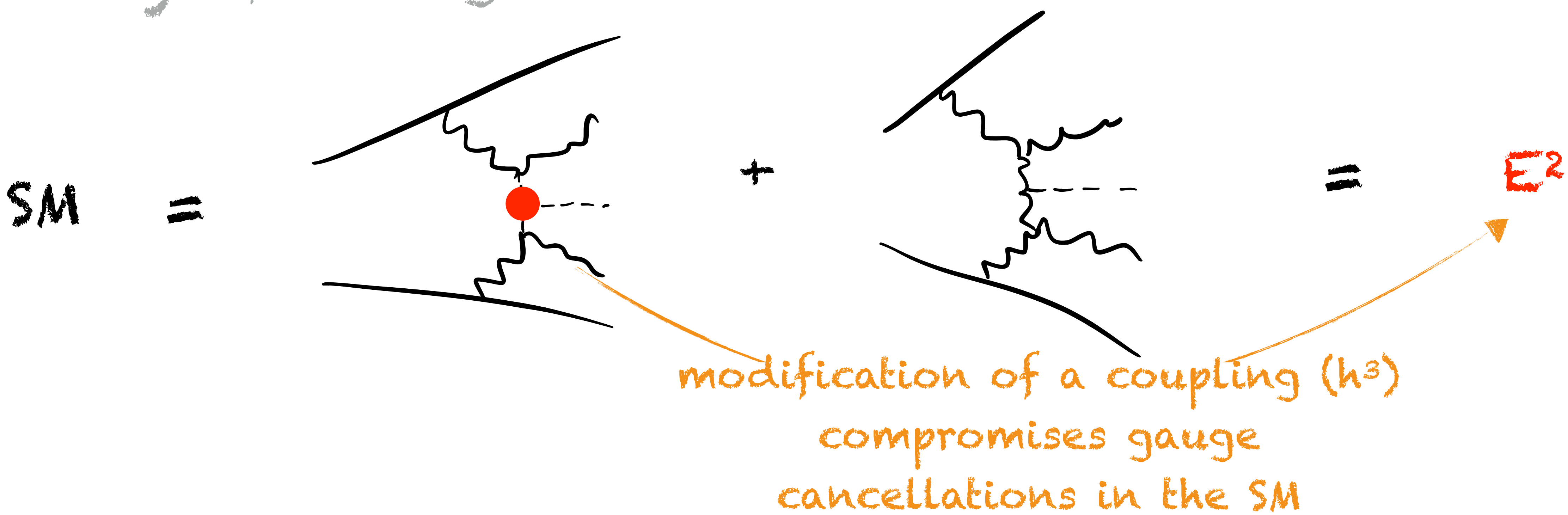
One way of seeing this:



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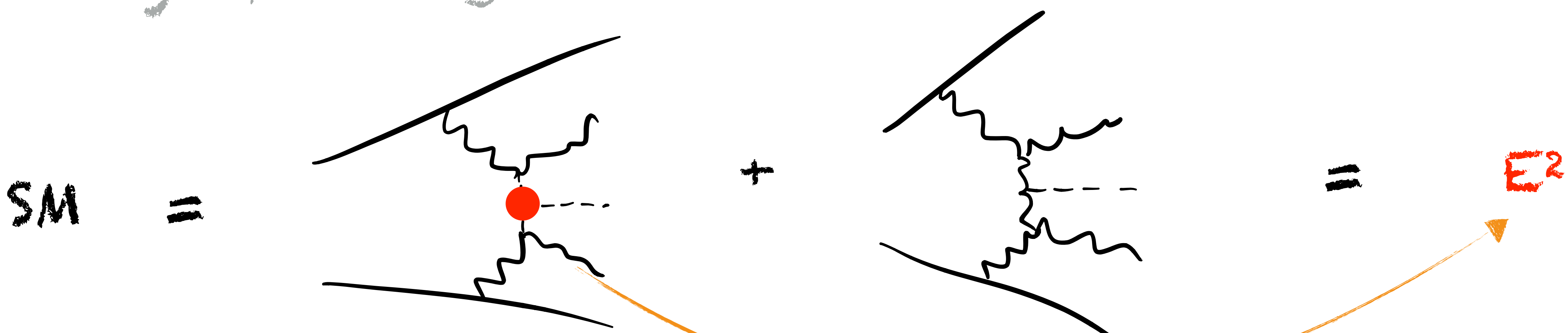


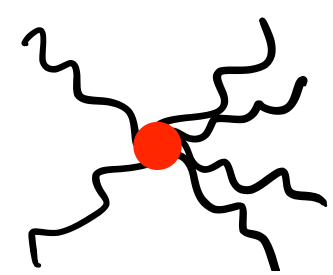
modification of a coupling (h^3)
compromises gauge
cancellations in the SM

Another way:

$$h^3 \in \frac{|H|^6}{\Lambda^2}$$

Golstones = W_L, Z_L

$$|H|^2 = \frac{1}{2}\left(v^2 + 2hv + h^2 + 2\phi^+\phi^- + (\phi^0)^2\right)$$

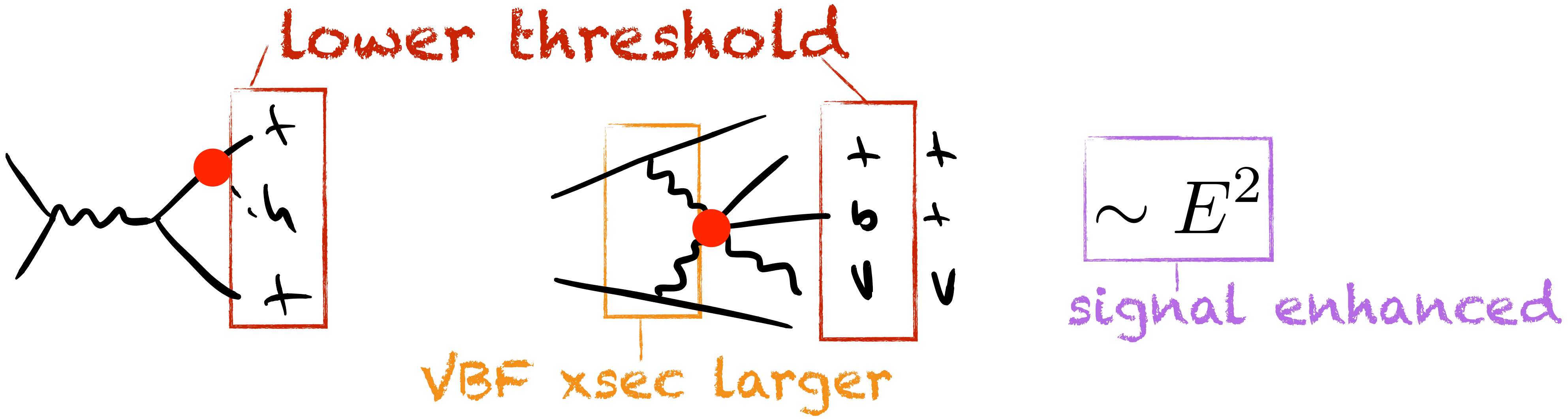


$$\sim \frac{E^2}{\Lambda^2}$$

Higgs Couplings... without a Higgs

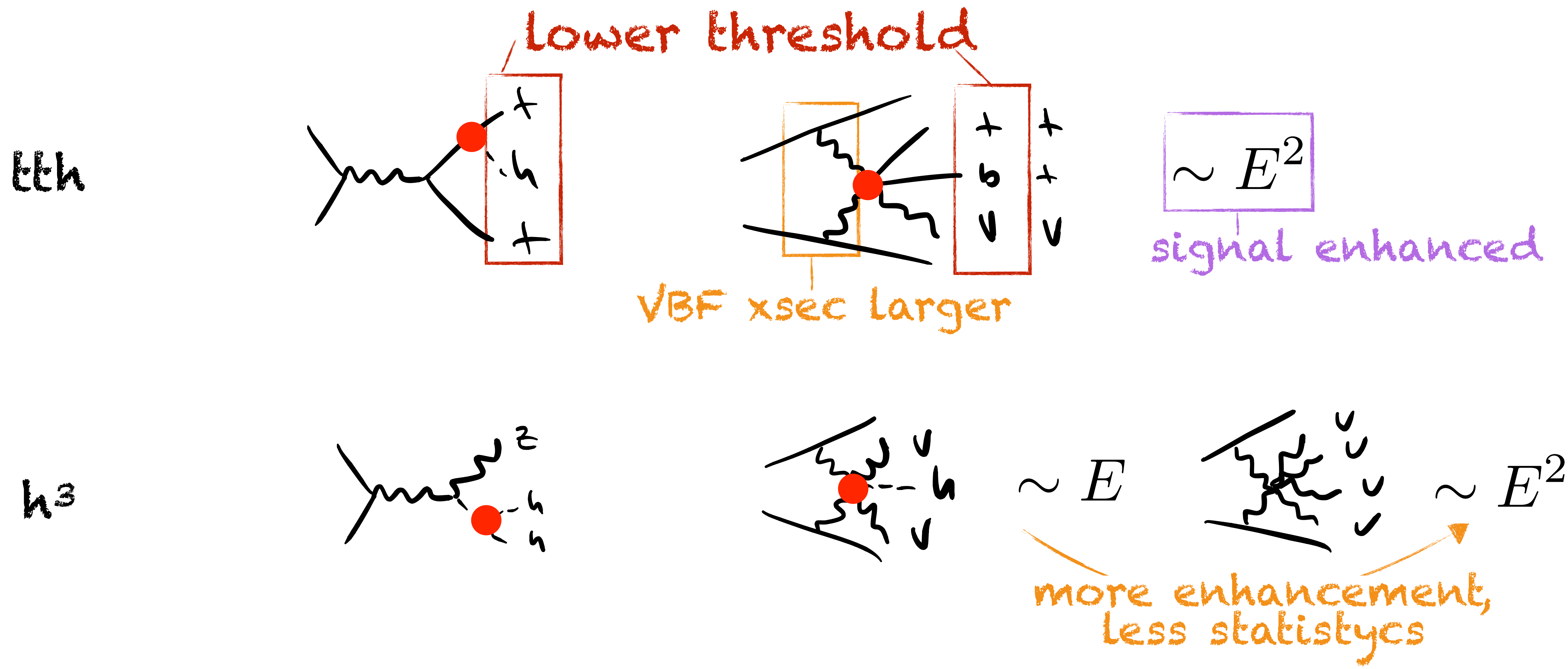
Henning,Lombardo,Riembau,FR'18

tth



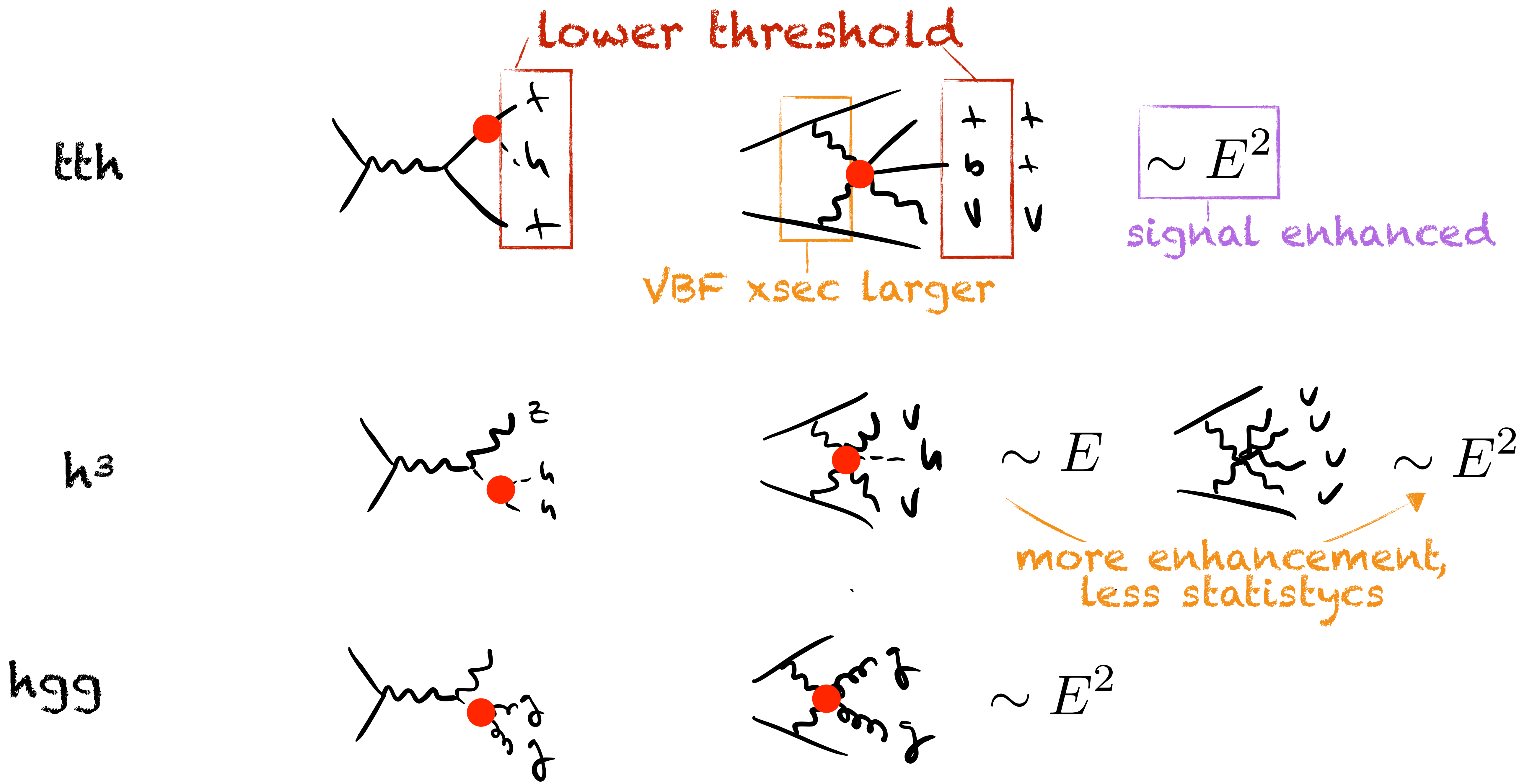
Higgs Couplings... without a Higgs

Henning,Lombardo,Riembau,FR'18



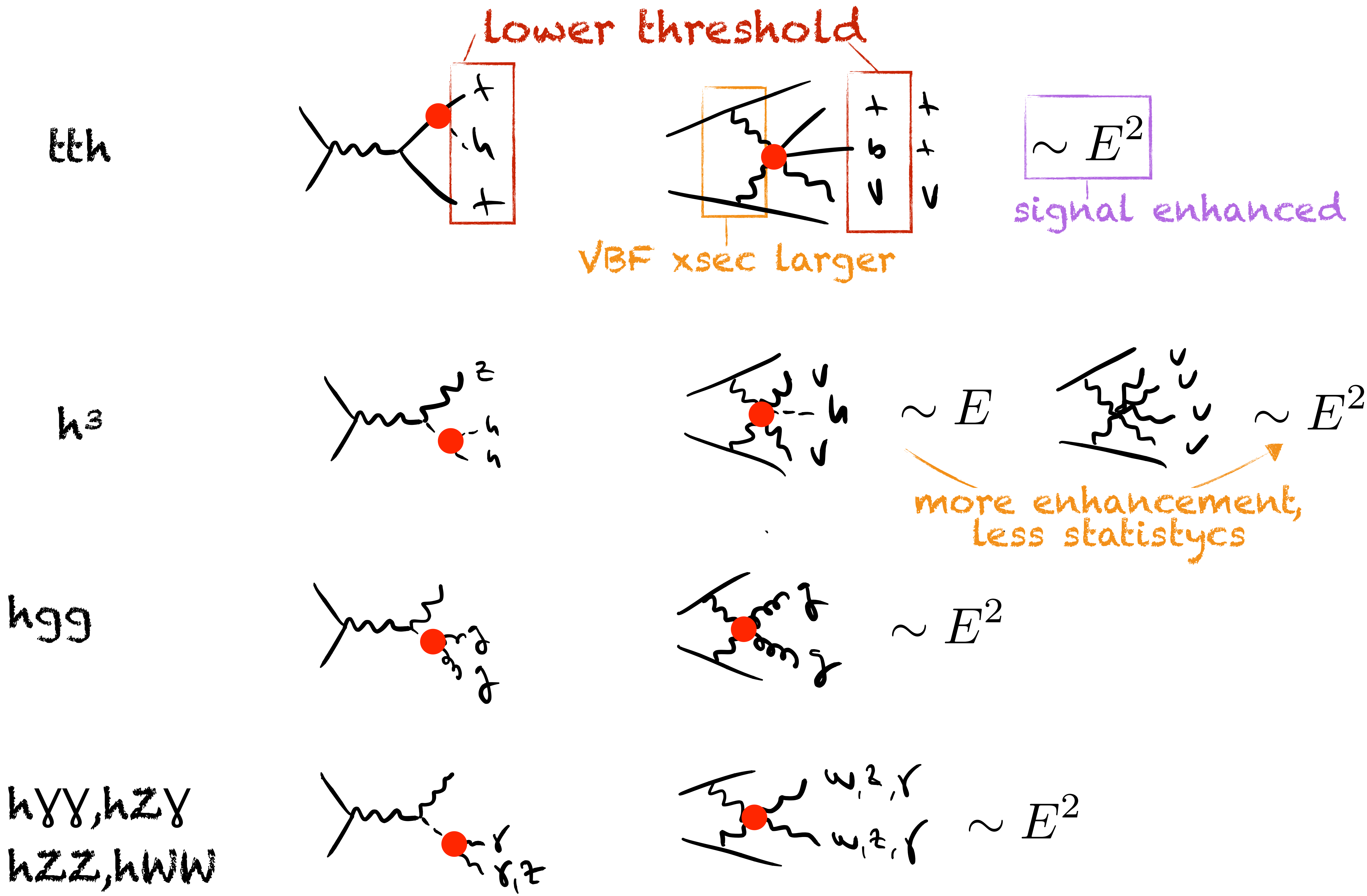
Higgs Couplings... without a Higgs

Henning,Lombardo,Riembau,FR'18



Higgs Couplings... without a Higgs

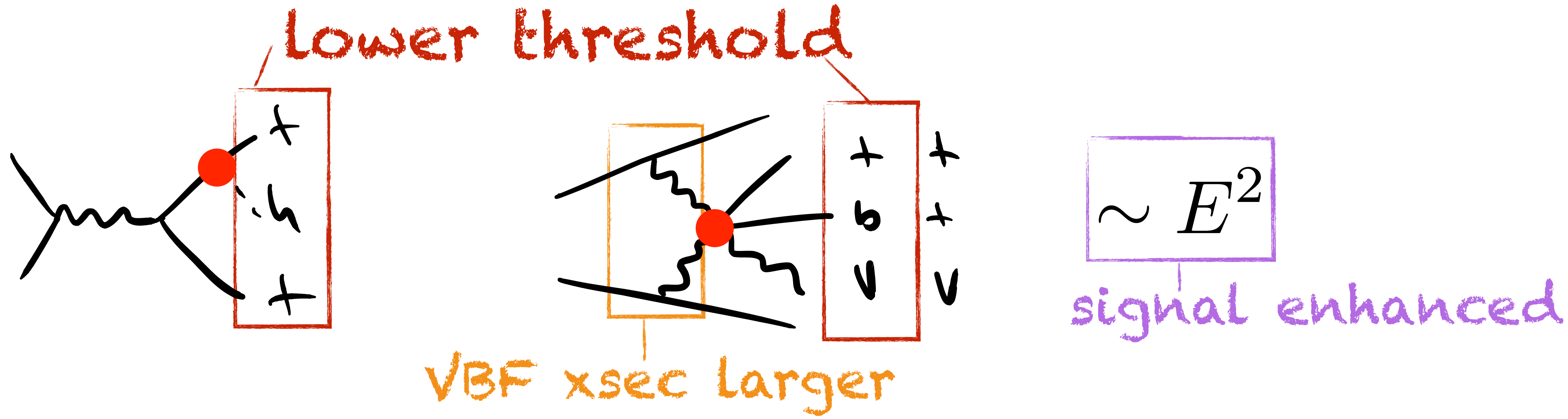
Henning,Lombardo,Riembau,FR'18



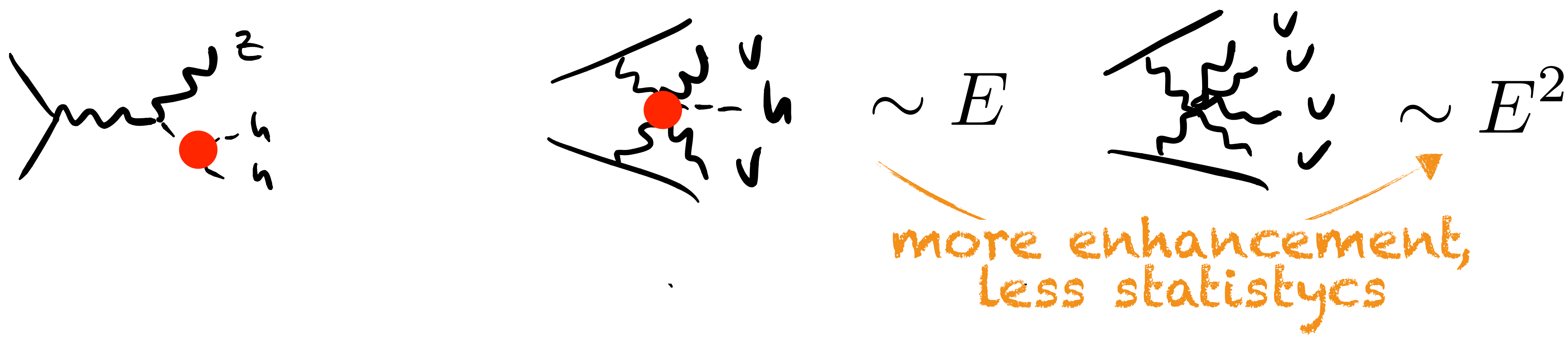
Higgs Couplings... without a Higgs

Henning,Lombardo,Riembau,FR'18

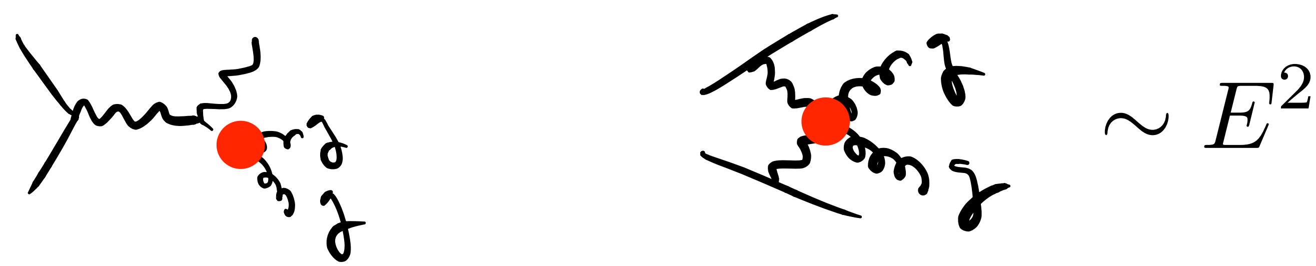
tth



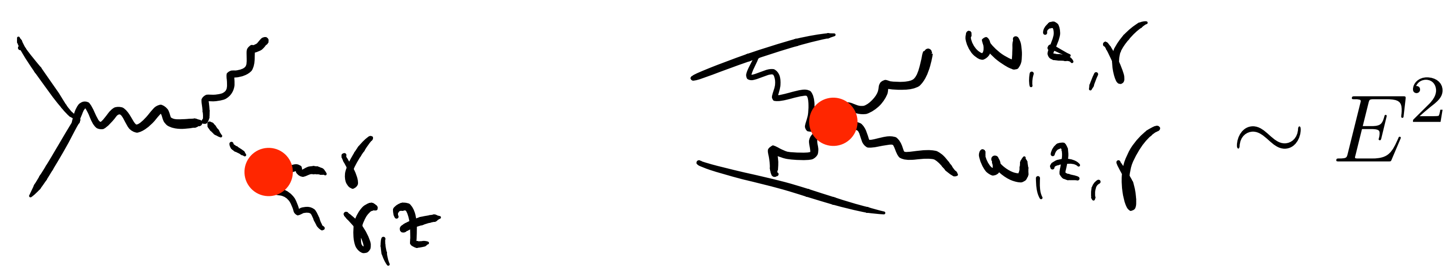
h^3



hgg



hγγ,hZγ
hZZ,hWW



for CLIC: work in progress...

3) Direct Searches

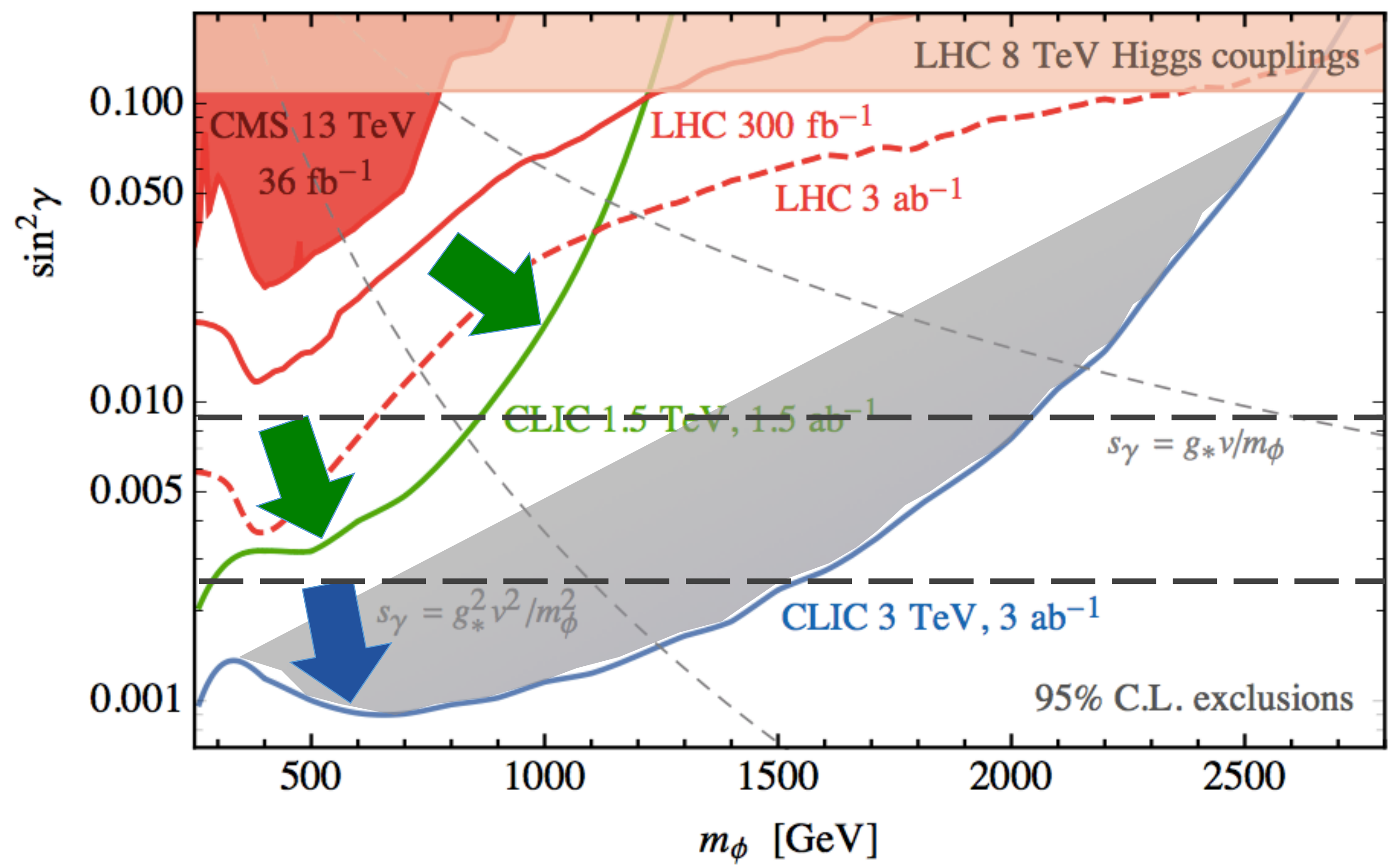
Advantage of high-energy CLIC:
direct access to heavy resonances

Heavy Scalar Singlets

Heavy neutral spin-0 appear in many BSM scenario

ϕ-h mix: $\phi = S\cos\gamma - h_0 \sin\gamma,$ → inherit Higgs couplings → Direct Searches

$h = h_0 \cos\gamma + S\sin\gamma,$ → reduce Higgs couplings → Indirect Searches



Buttazzo,Redigolo,Sala,Tesi'18

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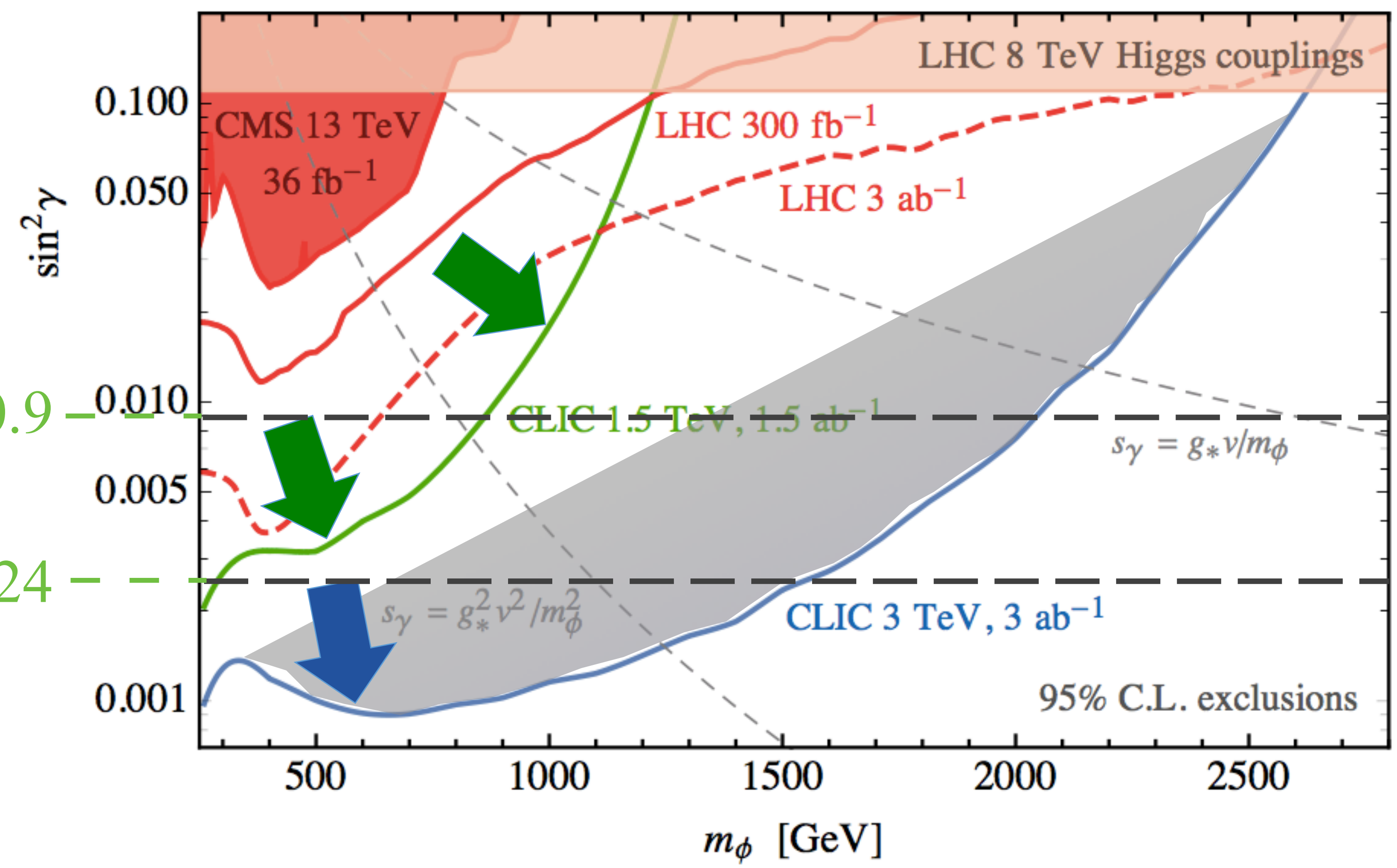
Indirect Searches

CLIC (380) 0.9

CLIC (3000) 0.024



Buttazzo,Redigolo,Sala,Tesi'18

Heavy Scalar Singlets

Heavy neutral spin-0 appear in many BSM scenario

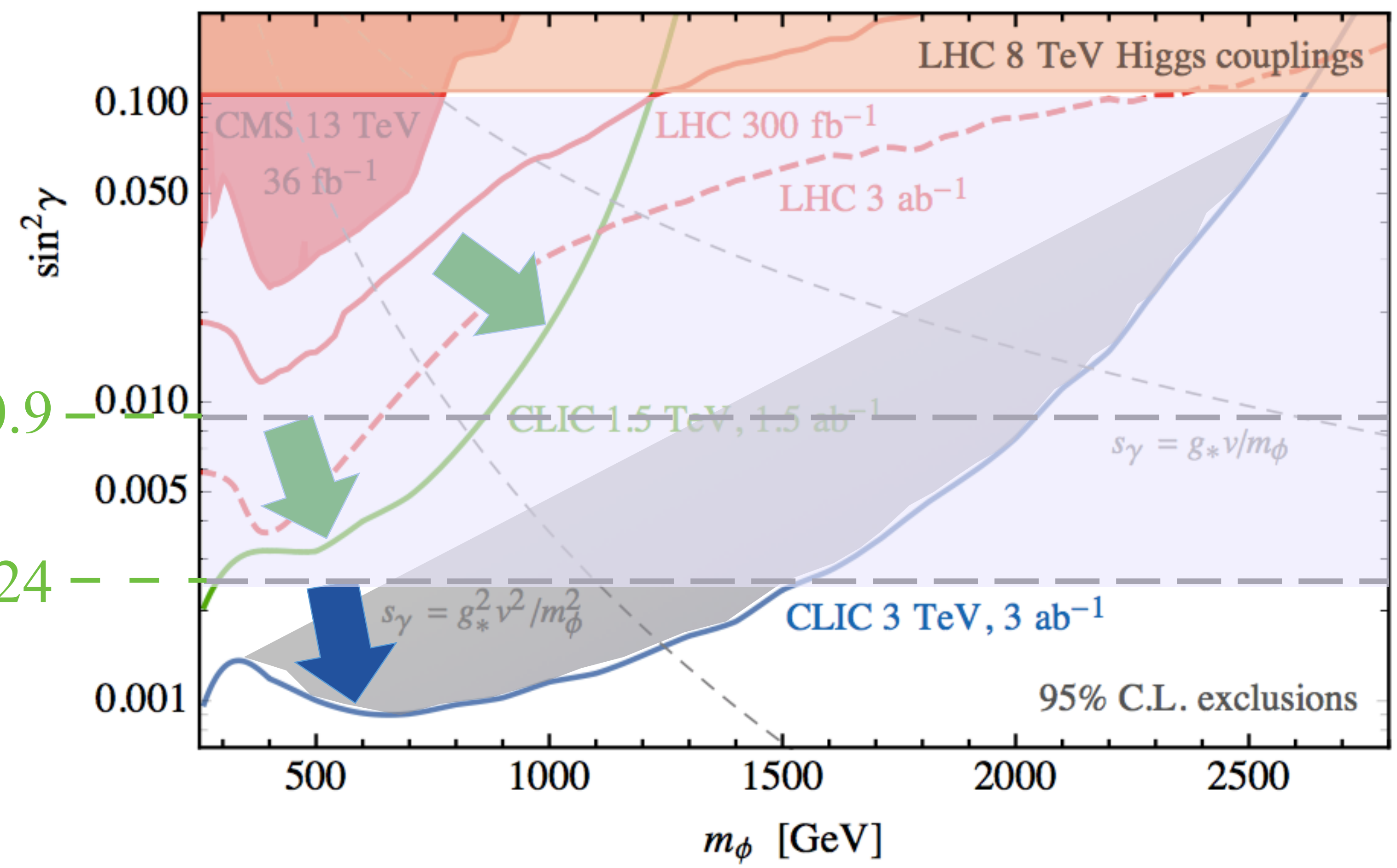
ϕ-h mix: $\phi = S\cos\gamma - h_0 \sin\gamma$, → inherit Higgs couplings → Direct Searches

$h = h_0 \cos\gamma + S\sin\gamma$, → reduce Higgs couplings → Indirect Searches

Indirect Searches

CLIC (380) 0.9

CLIC (3000) 0.024



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Conclusion

- High-Energy linear colliders ≈ Ultimate precision machines

- Precision tests: Indirect reach to even higher scales (->EFT, dim-6)

$$1\%@3\,\text{TeV} \longrightarrow \begin{array}{l} M \gtrsim 30\ \text{TeV} \\ M \gtrsim 300\ \text{TeV} \end{array}$$

(for weakly coupled BSM)
(for strongly coupled BSM)

↓

Equivalent to O(10⁻⁵) on Z-pole

Higgs-Only Operators		
$\mathcal{O}_H = \frac{1}{2}(\partial^\mu \lvert H \rvert^2)^2$	$\mathcal{O}_6 = \lambda \lvert H \rvert^6$	
$\mathcal{O}_{y_u} = y_u \lvert H \rvert^2 \bar{Q}\widetilde{H}u$	$\mathcal{O}_{y_d} = y_d \lvert H \rvert^2 \bar{Q}Hd$	$\mathcal{O}_{y_e} = y_e \lvert H \rvert^2 \bar{L}He$
$\mathcal{O}_{BB} = g'^2 \lvert H \rvert^2 B_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{GG} = g_s^2 \lvert H \rvert^2 G^A_{\mu\nu}G^{A\mu\nu}$	$\mathcal{O}_{WW} = g^2 \lvert H \rvert^2 W^I_{\mu\nu}W^{I\mu\nu}$
Universal Operators		
$\mathcal{O}_T = \frac{1}{2}(H^\dagger \overleftrightarrow{D}_\mu H)^2$	$\mathcal{O}_{HD} = (H^\dagger D^\mu H)^*(H^\dagger D_\mu H)$	
$\mathcal{O}_W = \frac{ig}{2}(H^\dagger \sigma^a \overleftrightarrow{D^\mu} H) D^\nu W^a_{\mu\nu}$	$\mathcal{O}_B = \frac{ig'}{2}(H^\dagger \overleftrightarrow{D^\mu} H)\partial^\nu B_{\mu\nu}$	$\mathcal{O}_{WB} = gg'(H^\dagger \sigma^I H)W^I_{\mu\nu}B^{\mu\nu}$
$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$	$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$	
$\mathcal{O}_{3W} = \frac{1}{3!} g \epsilon_{abc} W^{a\,\nu}_\mu W^b_{\nu\rho} W^{c\,\rho\mu}$	$\mathcal{O}_{2B} = \frac{1}{2}\left(\partial_\rho B_{\mu\nu}\right)^2$	$\mathcal{O}_{2W} = \frac{1}{2}\left(D_\rho W^a_{\mu\nu}\right)^2$
and $\mathcal{O}_H, \mathcal{O}_6, \mathcal{O}_{BB}, \mathcal{O}_{WW}, \mathcal{O}_{GG}, \mathcal{O}_y = \sum_\psi \mathcal{O}_{y_\psi}$		
Non-Universal Operators that modify Z/W couplings to fermions		
$\mathcal{O}_{HL} = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{L}\gamma^\mu L)$	$\mathcal{O}^{(3)}_{HL} = (iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)(\bar{L}\sigma^a \gamma^\mu L)$	$\mathcal{O}_{He} = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}\gamma^\mu e)$
$\mathcal{O}_{HQ} = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{Q}\gamma^\mu Q)$	$\mathcal{O}^{(3)}_{HQ} = (iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)(\bar{Q}\sigma^a \gamma^\mu Q)$	
$\mathcal{O}_{Hu} = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}\gamma^\mu u)$	$\mathcal{O}_{Hd} = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{d}\gamma^\mu d)$	
CP-odd operators		
$\mathcal{O}_{H\widetilde{W}} = (H^\dagger H)\widetilde{W}^I_{\mu\nu}W^{I\mu\nu}$	$\mathcal{O}_{H\widetilde{B}} = (H^\dagger H)\widetilde{B}_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{\widetilde{W}B} = (H^\dagger \sigma^I H)\widetilde{W}^I_{\mu\nu}B^{\mu\nu}$
	$\mathcal{O}_{3\widetilde{W}} = \frac{1}{3!} g \epsilon_{abc} W^{a\,\nu}_\mu W^b_{\nu\rho} \widetilde{W}^{c\,\rho\mu}$	