ELECTROWEAK OBSERVABLES FOR COMBINED *HL-LHC* AND e^+e^- INTERPRETATIONS

ROBERTO FRANCESCHINI, APRIL 22nd 2022
ECFA WHF WG1 WORKSHOP (CERN)

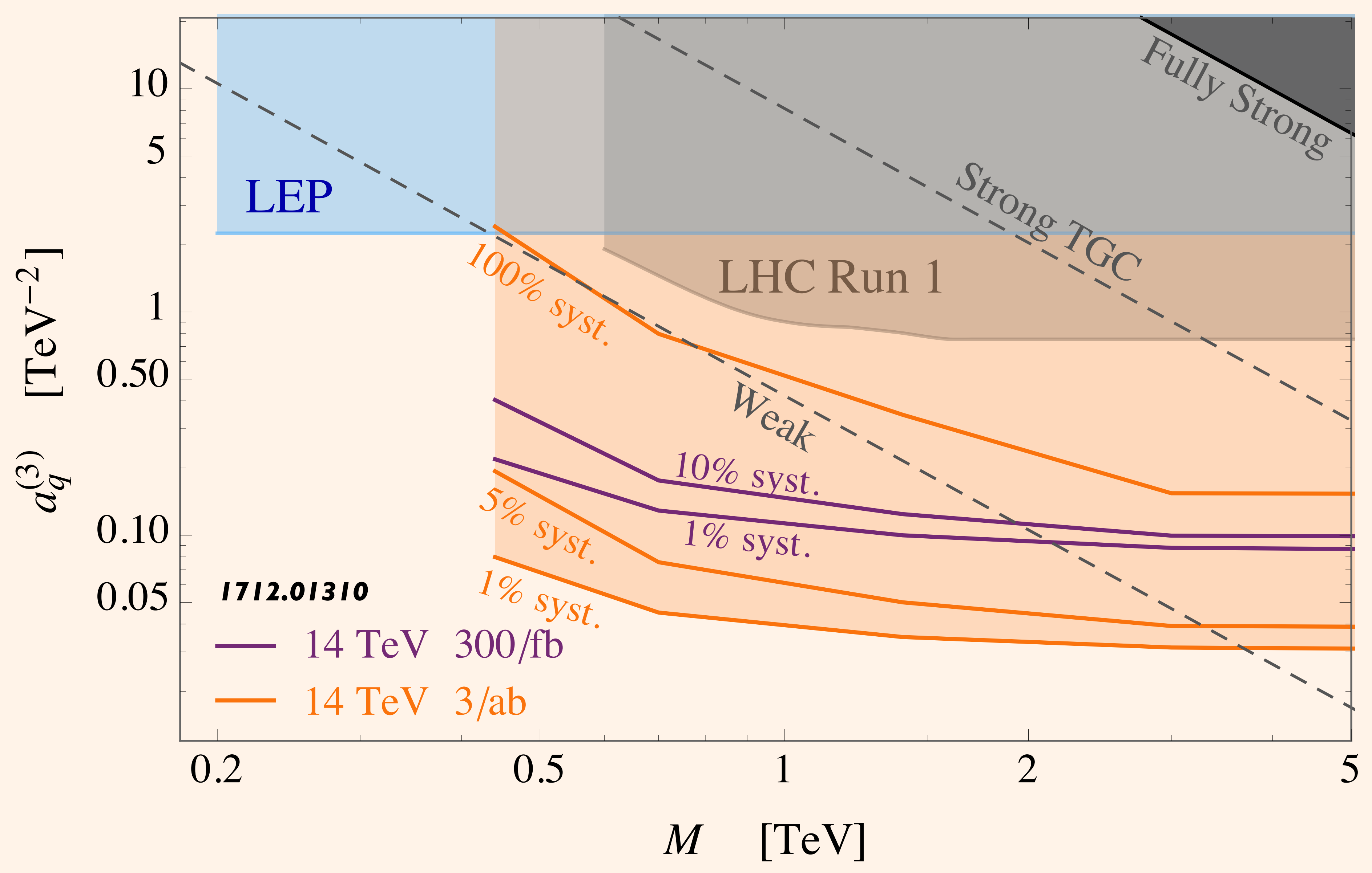
ROMA TRE UNIVERSITÀ DEGLI STUDI
INFN Roma3

https://indico.cern.ch/event/1132480/

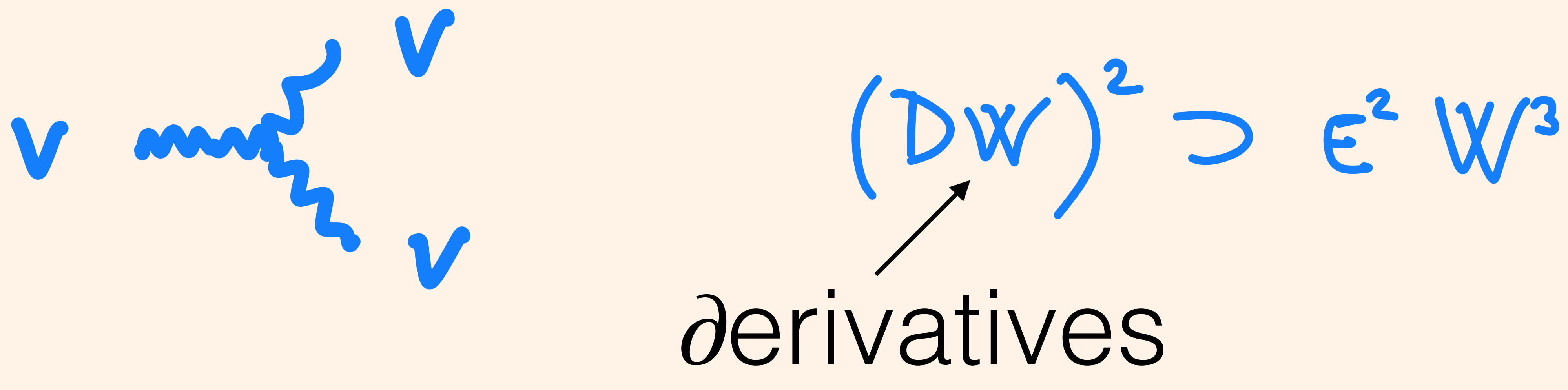
Outline

- What probes are available at HL-LHC
- What probes are available at e^+e^-
- Simplest off-pole observables
- Going beyond …

HL-LHC capabilities



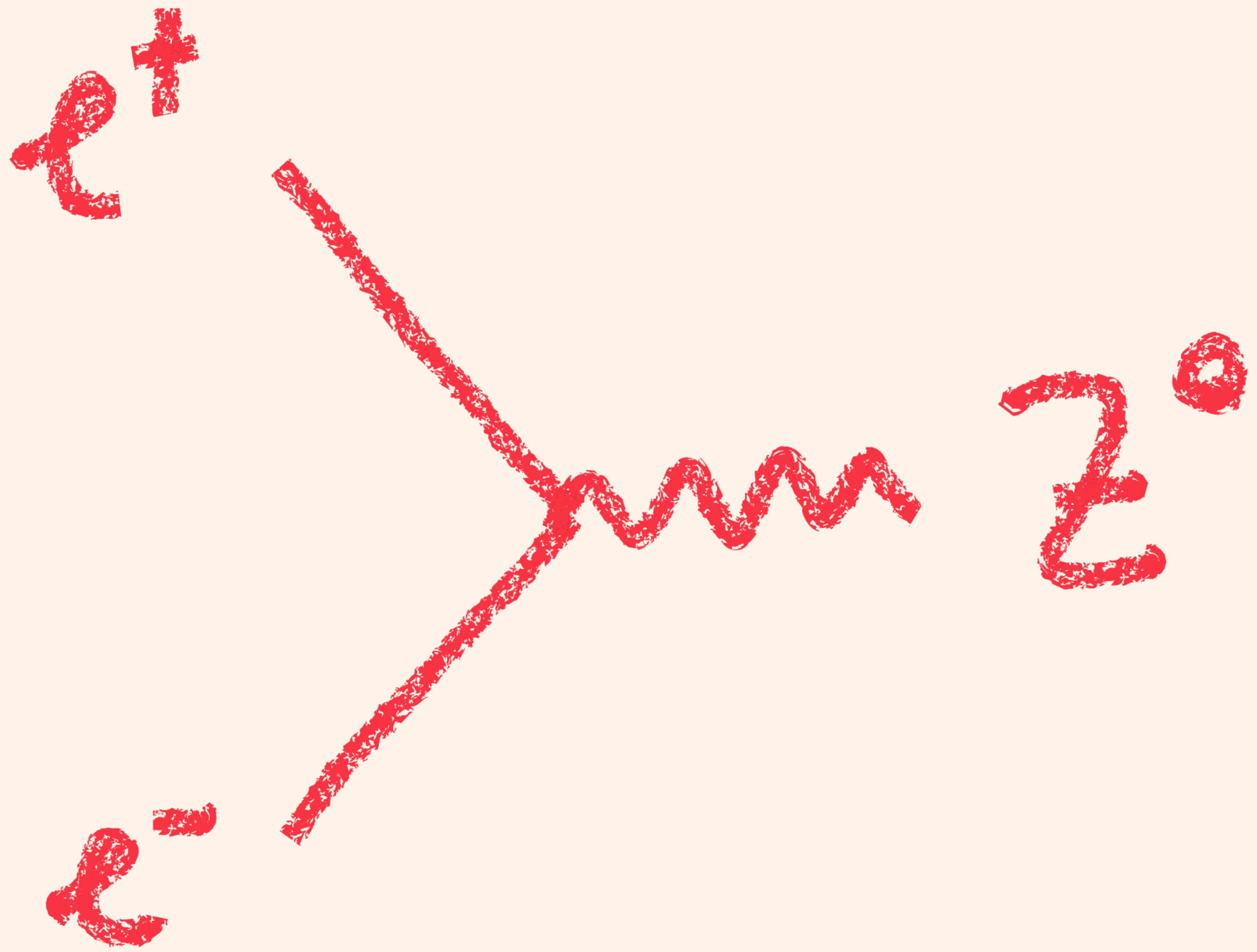
Ascribing the possible BSM effects onto EW quantities (low energy couplings, e.g. ZWW) to new contact interactions from heavy new physics the LHC can probe these contact interactions instead of the low energy couplings directly.

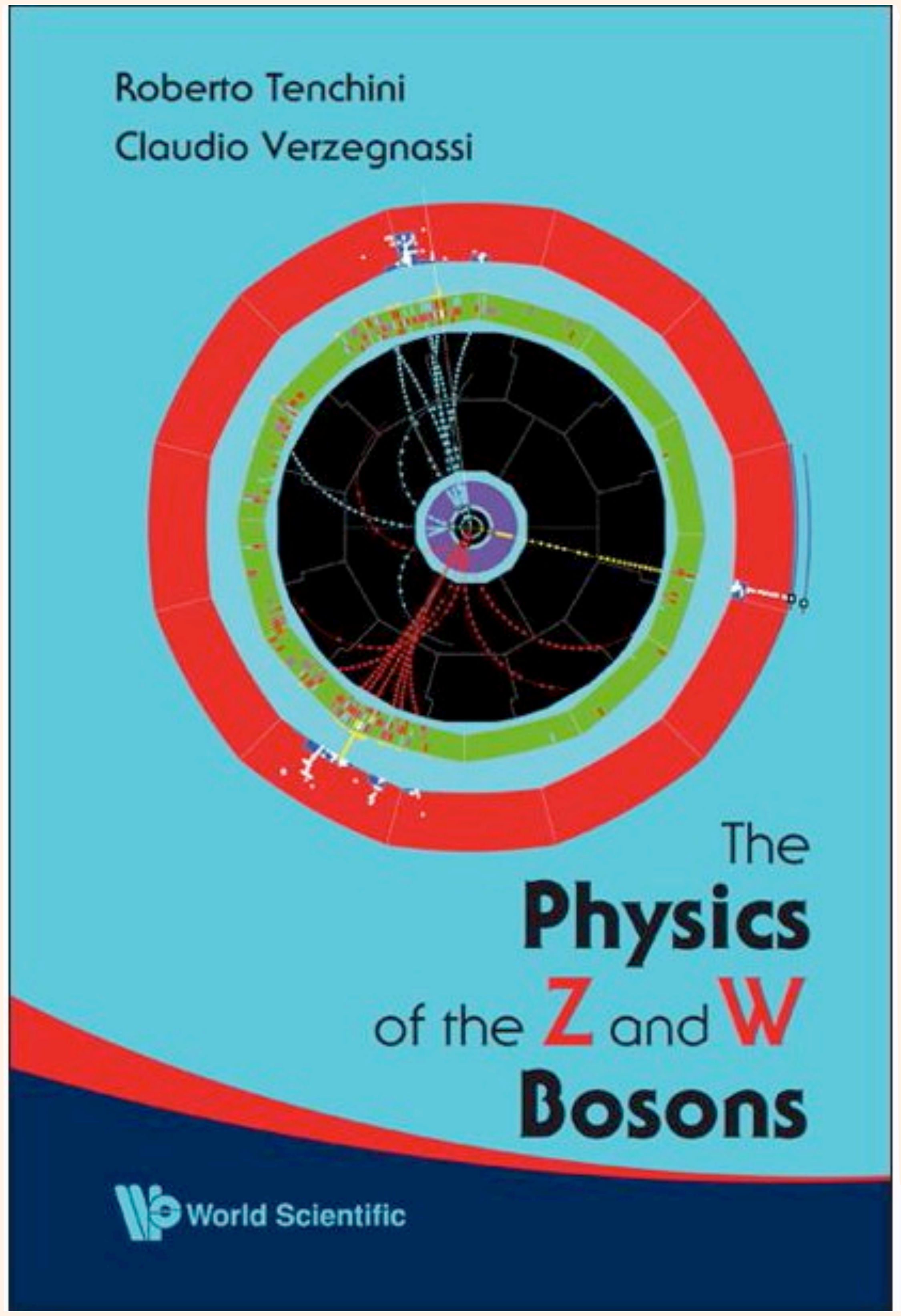


In the age of EFTs this is as good as doing LEP-like INTENSITY studies of EW properties.

The great advantage of the LHC is that it can reach VERY HIGH PARTONIC ENERGIES, especially if one has the time to “fish” the rare events in which constituent quarks collide with large fraction of the proton energy. This is where High-Lumi is crucial(!)

e^+e^- capabilities

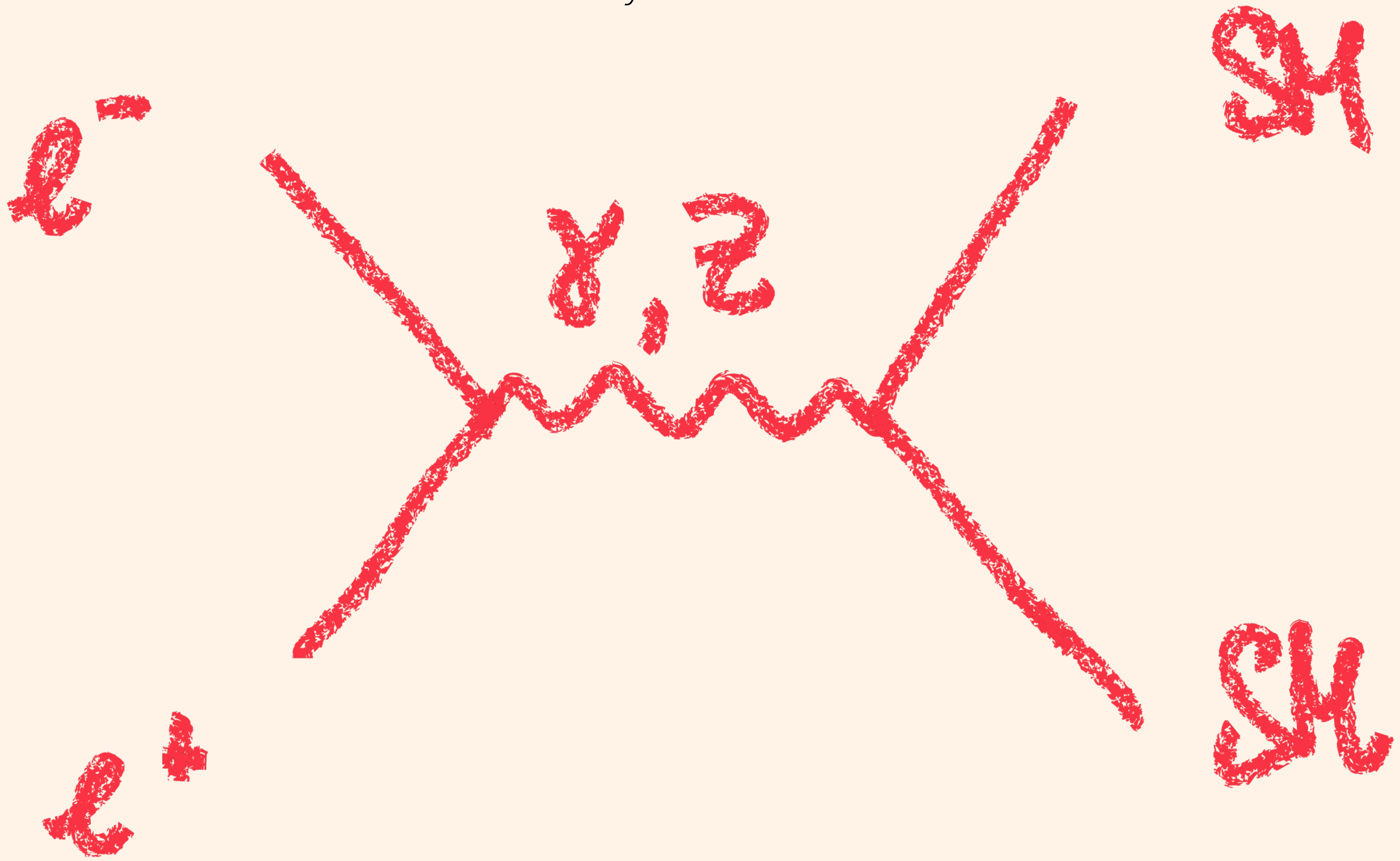




However, I have been asked to discuss “Off Pole observables” … → LATER TALKS

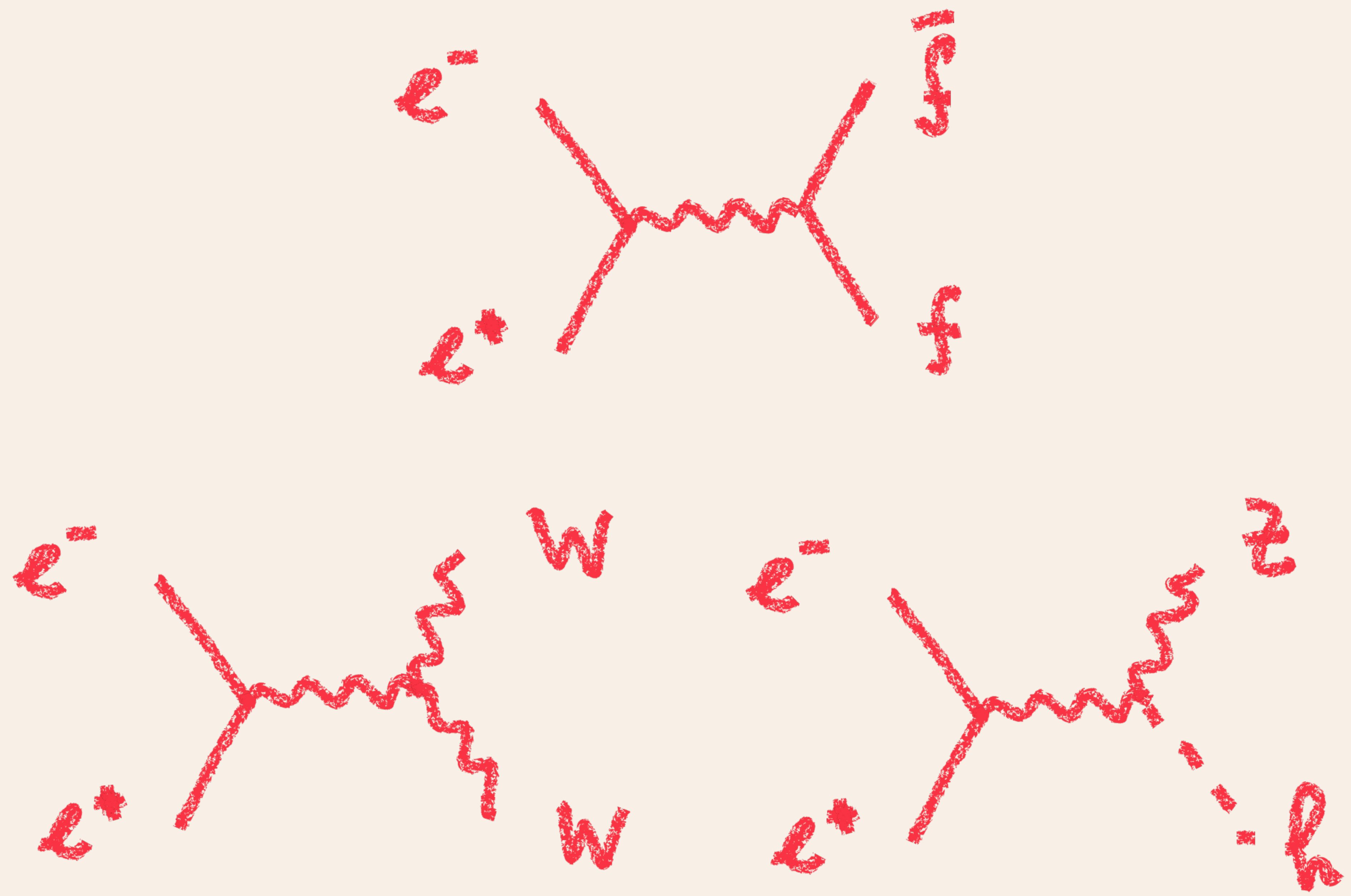
e^+e^- capabilities at $\sqrt{s} > m_Z$

n-body final states



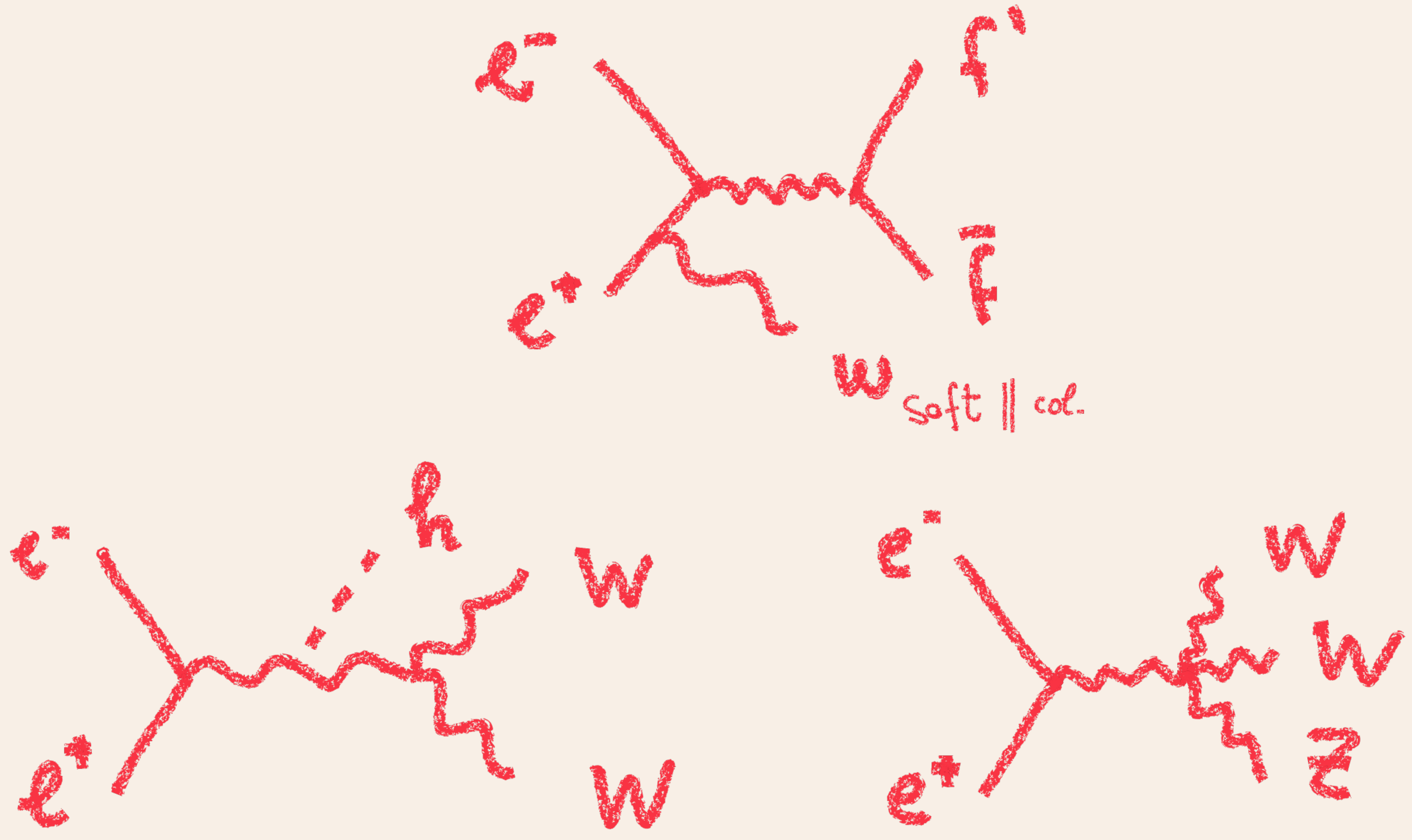
e^+e^- capabilities at $\sqrt{s} > m_Z$

2-body final states



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

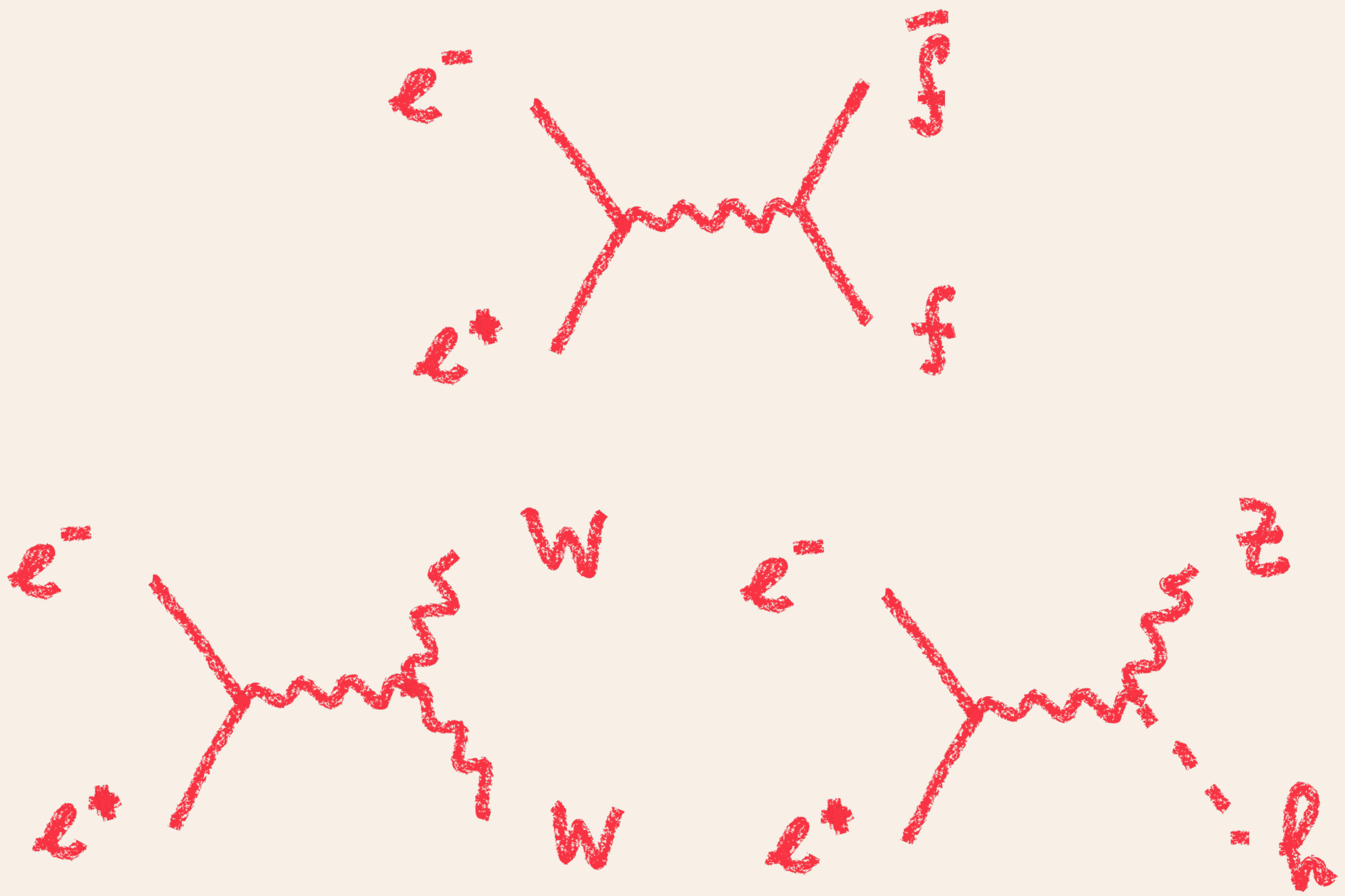
3-body final states*



$$\sigma \simeq \sigma_{2-body} \cdot \frac{\alpha}{2^{\#}\pi}(\dots)$$

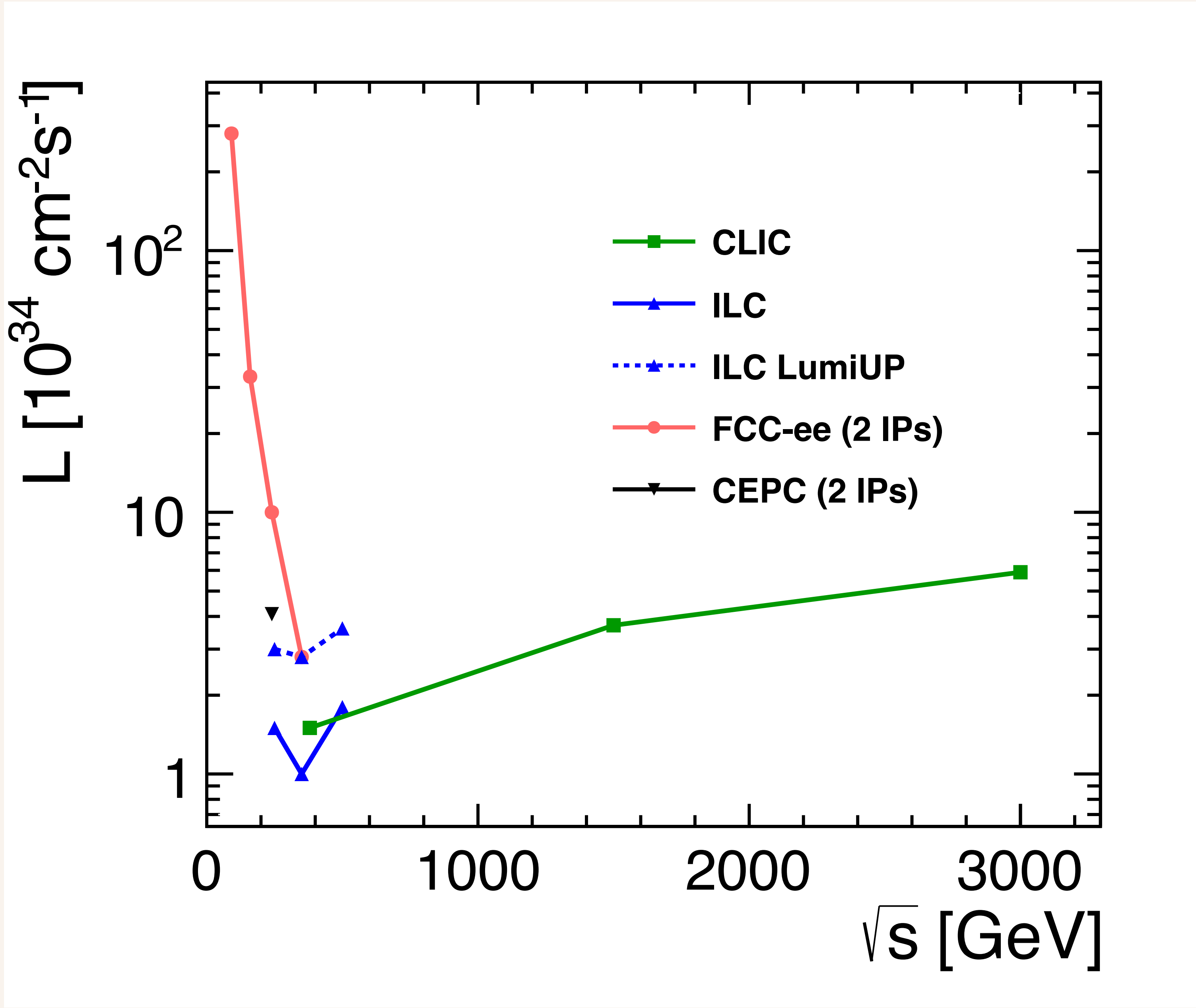
e^+e^- capabilities at $\sqrt{s} > m_Z$

2-body final states



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

Luminosity available at any HTE option falls very fast as $\sqrt{s}$ grows.

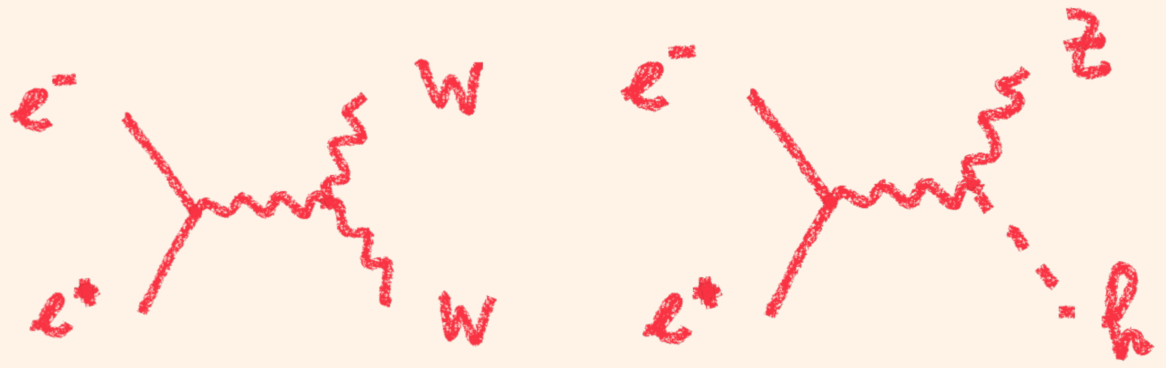


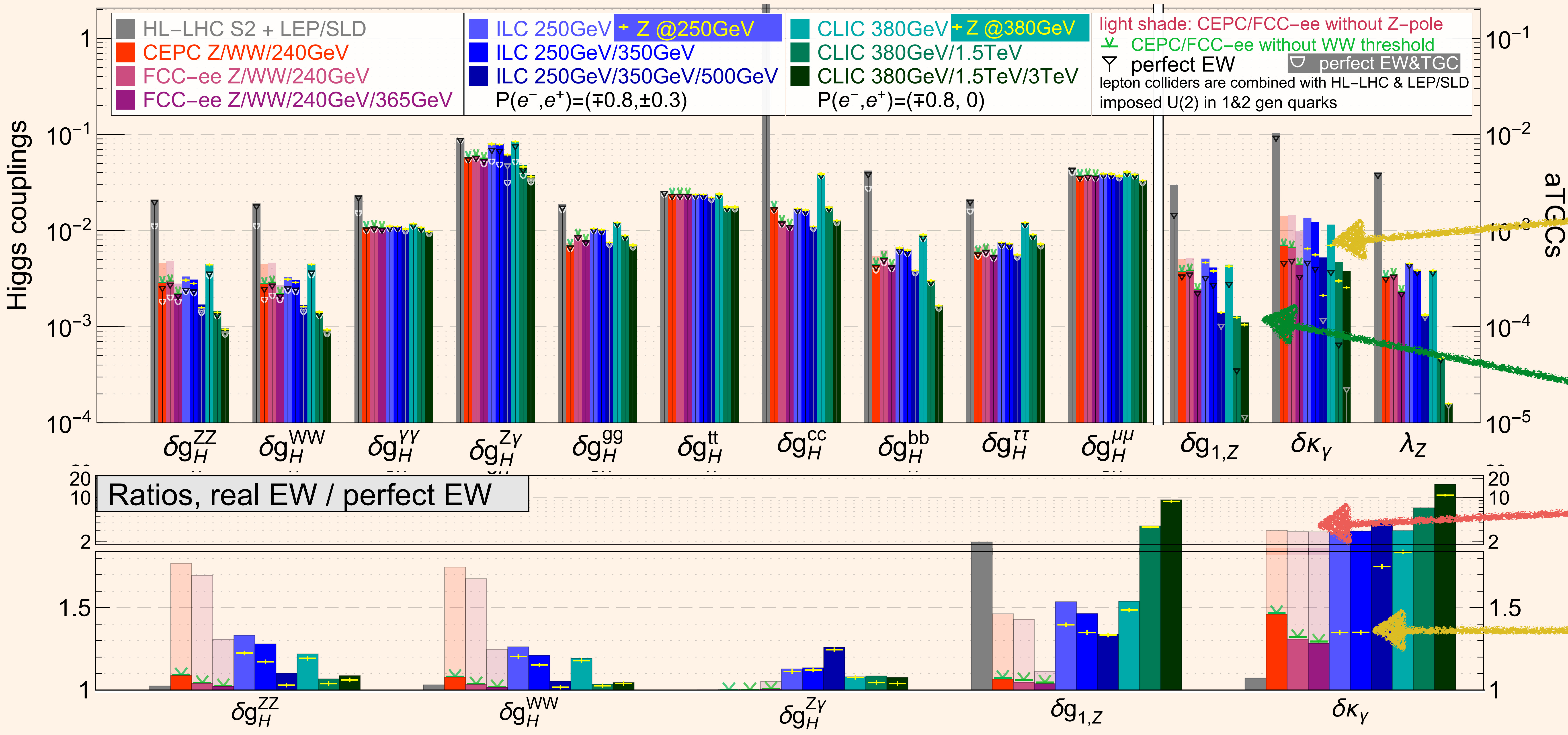
These processes are sensitive to EW quantities (couplings, masses, …) but the measurements are limited by the available statistics

e^+e^- capabilities at $\sqrt{s} > m_Z$

1907.04311

	HL-LHC	CEPC		FCC-ee				ILC [P1 ⇒ (∓80%,±30%)] [UP ⇒ unpolarized]						CLIC		
		240 GeV		240 GeV		+365 GeV		250 GeV		+350 GeV		+500 GeV		380 GeV	+1.5 TeV	+3 TeV
	S2	~~Z-pole~~	Z-pole	~~Z-pole~~	Z-pole	~~Z-pole~~	Z-pole	P1	UP	P1	UP	P1	UP	(∓80%,0%)		
$\delta g_{1,Z}$ (‰)	2.96*	0.52*	0.38	0.53*	0.39	0.26*	0.24	0.50*	0.63*	0.41*	0.52*	0.14	0.20*	0.42*	0.14*	0.13*
	1.46	0.34		0.36		0.22		0.33	0.50	0.28	0.44	0.11	0.17	0.27	0.03	0.01
$\delta\kappa_\gamma$ (‰)	9.93	1.57*	0.72*	1.58*	0.64*	1.09*	0.43*	1.53*	1.73*	1.39*	1.58*	0.58*	0.75*	1.29*	0.47*	0.32*
	9.49	0.50		0.53		0.36		0.51	0.77	0.44	0.68	0.13	0.23	0.39	0.07	0.02
λ_Z (‰)	3.99	0.34	0.33	0.35	0.34	0.24	0.24	0.46	0.51	0.39	0.45	0.13	0.14	0.39	0.05	0.02
	3.86	0.33		0.34		0.23		0.45	0.50	0.38	0.43	0.13	0.14	0.38	0.05	0.02



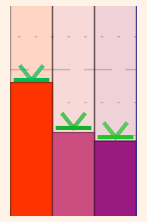


Z-pole necessary to exploit fully the measurements for the extraction of aTGCs

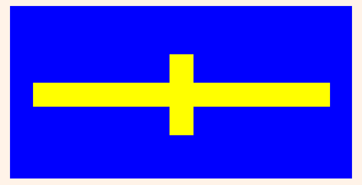
"Free" Z-bosons from radiative return can help

Higher energies can help

Shaded bars indicate no Z-pole



Yellow marks indicate radiative return Z boson studies



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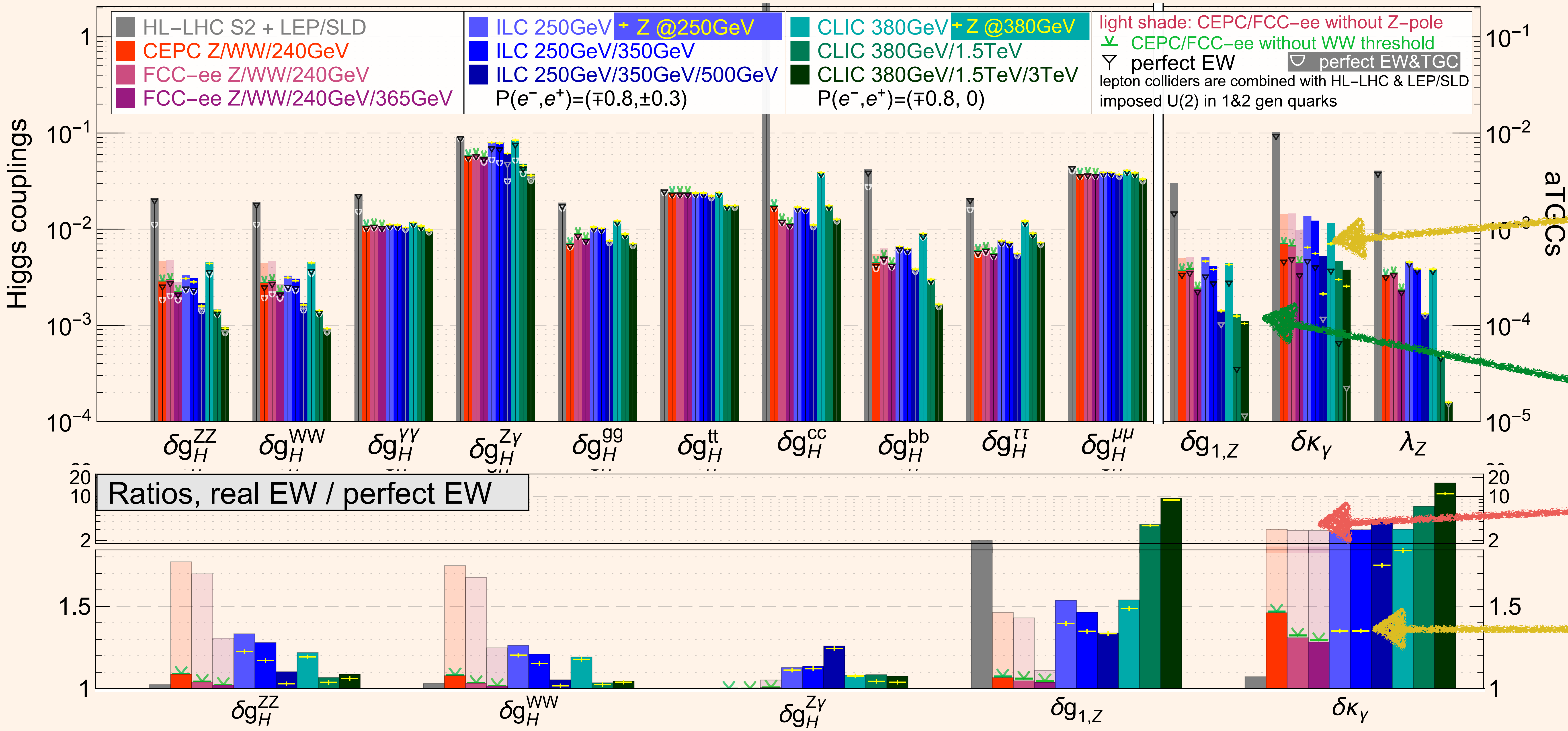
Future Circular Colliders: CEPC, FCC-ee. Future Linear Colliders: ILC [P1 ⇒ (∓80%,±30%)] [UP ⇒ unpolarized], CLIC.



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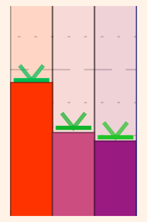

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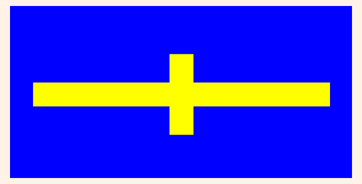
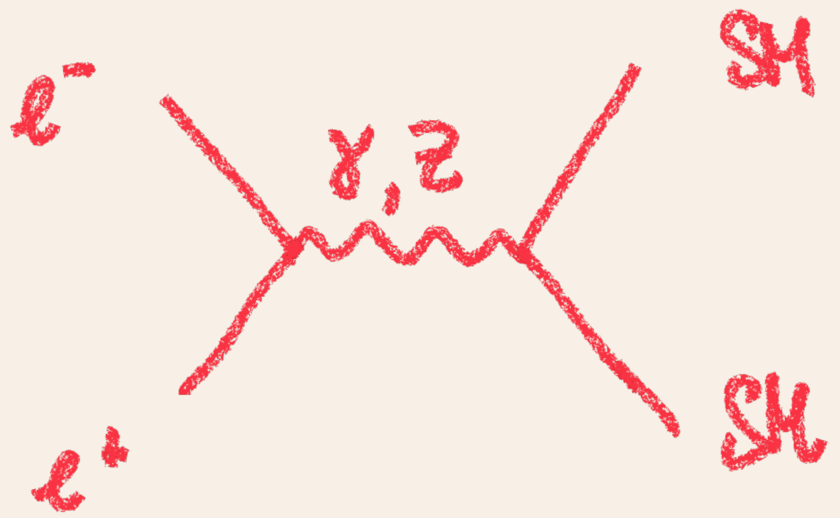


Focus on 2-body processes

Observables and Interpretation



- fiducial (total) rates
- differential distributions:
  - * p_T **1909.01937, 1708.07823, 1704.02333, 1512.06877, 1406.1361**
  - * angles
  - * fancy kinematical variables (not much room for "fancy", as phase-space dimensionality is limited)

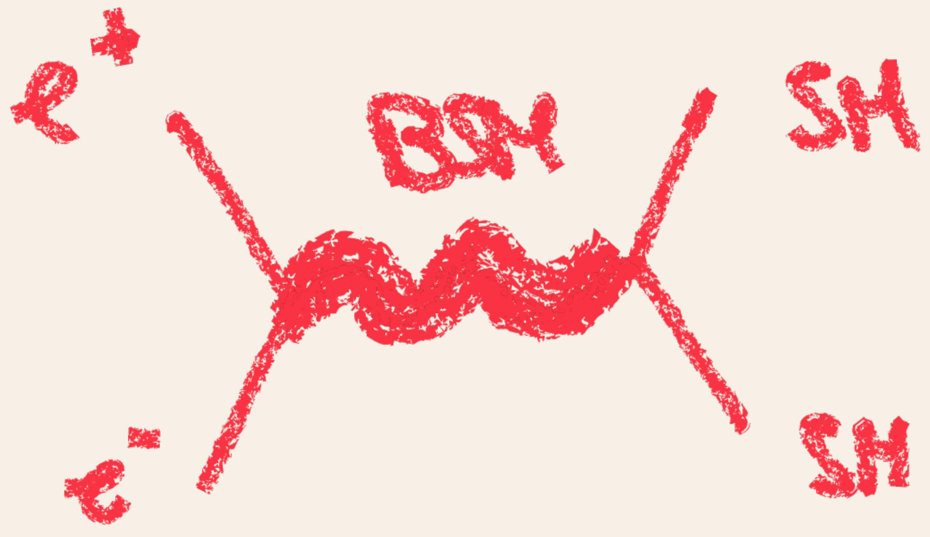
$$\mathcal{O}'_{Hq} = iH^\dagger \sigma^a \overleftrightarrow{D_\mu} H \bar{q}_L \sigma^a \gamma^\mu q_L$$
$$\mathcal{O}'_{H\ell} = iH^\dagger \sigma^a \overleftrightarrow{D_\mu} H \bar{\ell}_L \sigma^a \gamma^\mu \ell_L$$
$$\mathcal{O}_W = \frac{ig}{2} (H^\dagger \sigma^a \overleftrightarrow{D_\mu} H) D^\nu W^a_{\mu\nu}$$
$$\mathcal{O}^{(3)}_{\varphi q} = (\overline{Q}_L \sigma^a \gamma^\mu Q_L) \left(iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H \right)$$

hep-ph/0602154

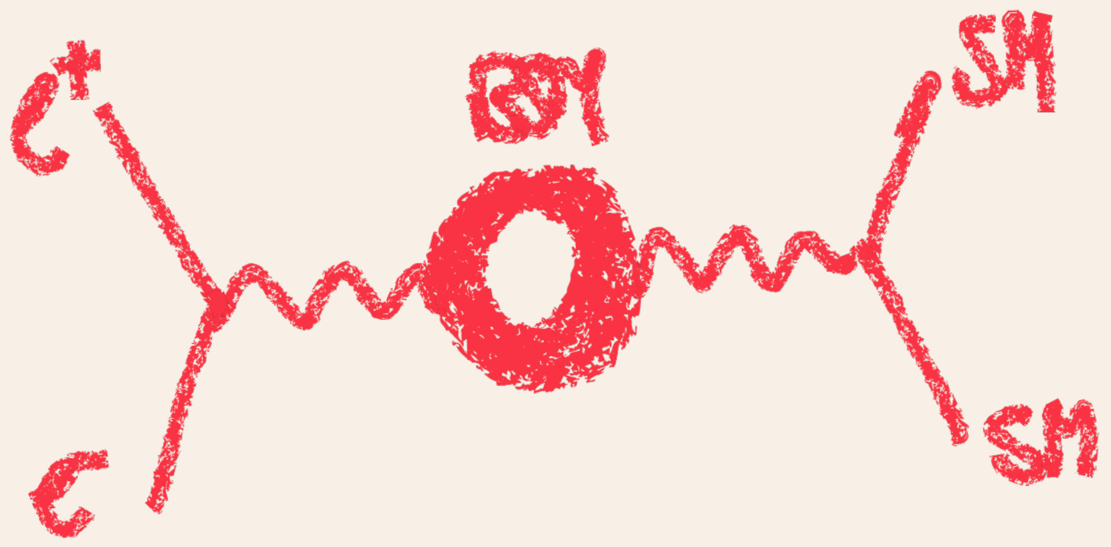
$$\partial^\mu B_{\mu\nu} + i\frac{g'}{2}(h^\dagger D_\nu h - D_\nu h^\dagger h) + g' \sum_f Y_f \overline{f} \gamma_\nu f = 0,$$
$$D^\mu W^a_{\mu\nu} + i\frac{g}{2}(h^\dagger \sigma^a D_\nu h - D_\nu h^\dagger \sigma^a h) + \frac{g}{2} \sum_f \overline{f}_L \gamma_\nu \sigma^a f_L = 0,$$

$$2g' O_h - \frac{g}{2} O_{WB} + g' O^Y_{hf} = 2iB_{\mu\nu} D^\mu h^\dagger D^\nu h - g' h^\dagger h\, D^\mu h^\dagger D_\mu h + \frac{g'}{2} h^\dagger h (B_{\mu\nu})^2 - \frac{g'}{2} h^\dagger h \left(h^\dagger D^2 h + (D^2 h^\dagger) h \right),$$
$$-g' O_{WB} + g(O^t_{hl} + O^t_{hq}) = 4iW^a_{\mu\nu} D^\mu h^\dagger \sigma^a D^\nu h - 6g h^\dagger h\, D^\mu h^\dagger D_\mu h + g h^\dagger h (W^a_{\mu\nu})^2 - g h^\dagger h \left(h^\dagger D^2 h + (D^2 h^\dagger) h \right),$$

$$O_{WB} = (h^\dagger \sigma^a h) W^a_{\mu\nu} B^{\mu\nu}, \quad O_h = |h^\dagger D_\mu h|^2,$$
$$O^s_{hl} = i(h^\dagger D^\mu h)(\bar{l} \gamma_\mu l) + \text{h.c.}, \quad O^t_{hl} = i(h^\dagger \sigma^a D^\mu h)(\bar{l} \gamma_\mu \sigma^a l) + \text{h.c.},$$
$$O^s_{hq} = i(h^\dagger D^\mu h)(\overline{q} \gamma_\mu q) + \text{h.c.}, \quad O^t_{hq} = i(h^\dagger \sigma^a D^\mu h)(\overline{q} \gamma_\mu \sigma^a q) + \text{h.c.},$$
$$O_{hu} = i(h^\dagger D^\mu h)(\overline{u} \gamma_\mu u) + \text{h.c.}, \quad O_{hd} = i(h^\dagger D^\mu h)(\overline{d} \gamma_\mu d) + \text{h.c.},$$
$$O_{he} = i(h^\dagger D^\mu h)(\overline{e} \gamma_\mu e) + \text{h.c.}.$$



HEAVY BSM EFFECTS GROW WITH ENERGY



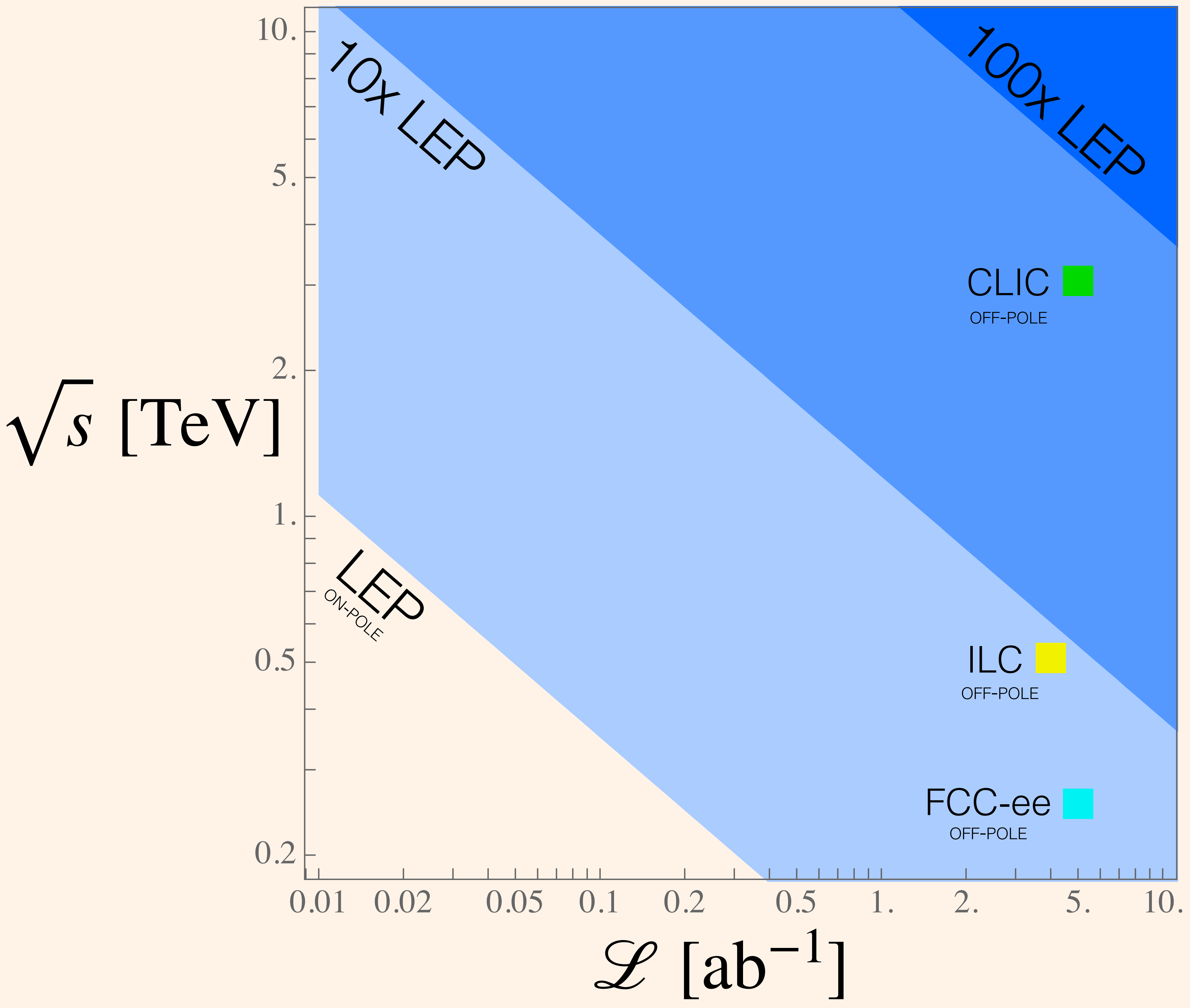
HEAVY BSM EFFECTS GROW WITH ENERGY

$e^+e^- \to Zh$

TOTAL RATE

$$\left|A_{SM}^{(00)}\right|^2 + A_{SM}^{00} \cdot A_{BSM}^{00} + \ldots$$

$$\hat{S}_{95\%} \lesssim 1.2 \cdot 10^{-4} \frac{1}{E_{beam}/\mathrm{TeV}} \cdot \frac{1}{\sqrt{\mathscr{L}/\mathrm{ab}^{-1}}}$$



$e^+e^- \to Zh$

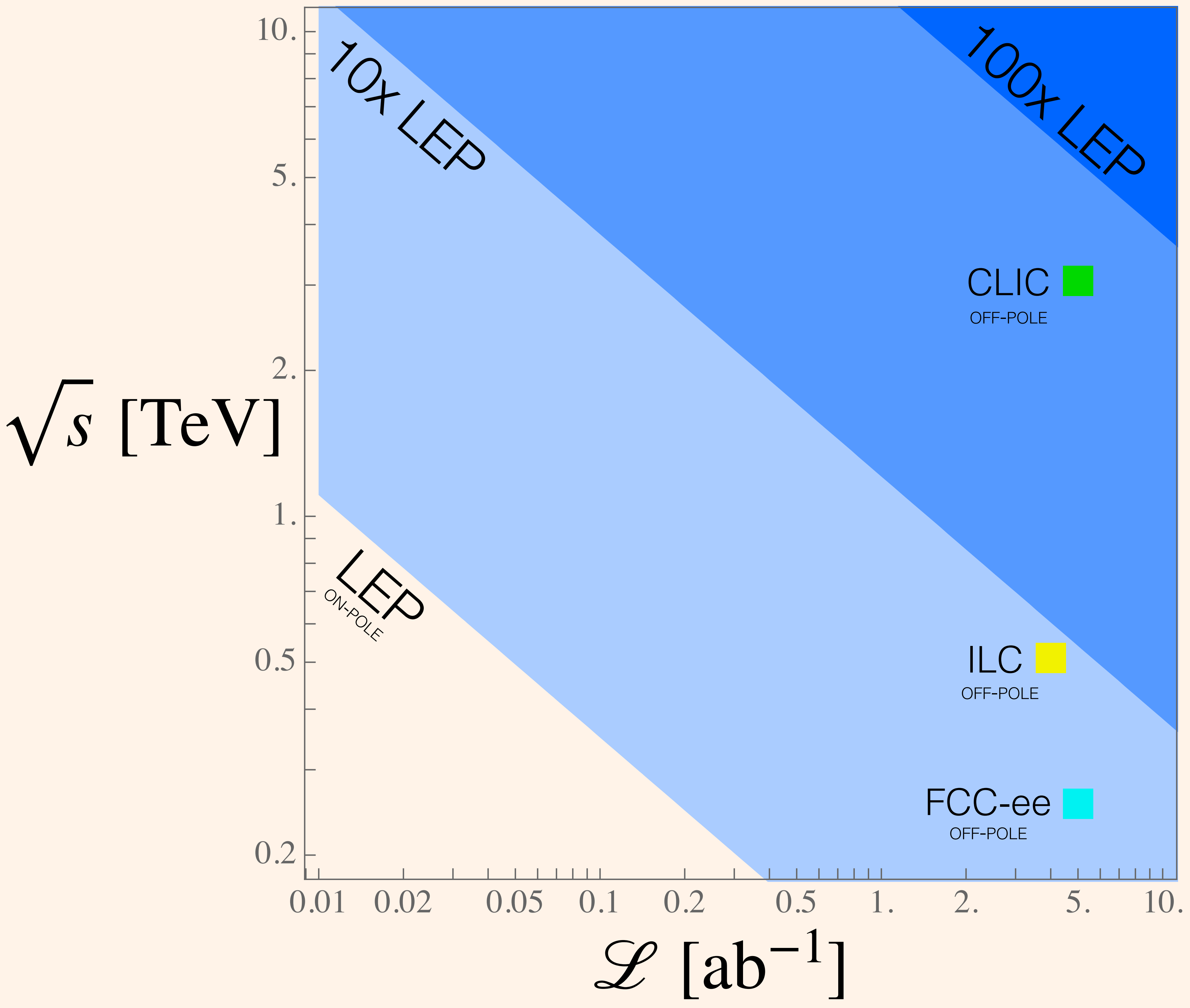
TOTAL RATE

$$\left|A^{(00)}_{SM}\right|^2 + A^{00}_{SM}\cdot A^{00}_{BSM} + \dots$$

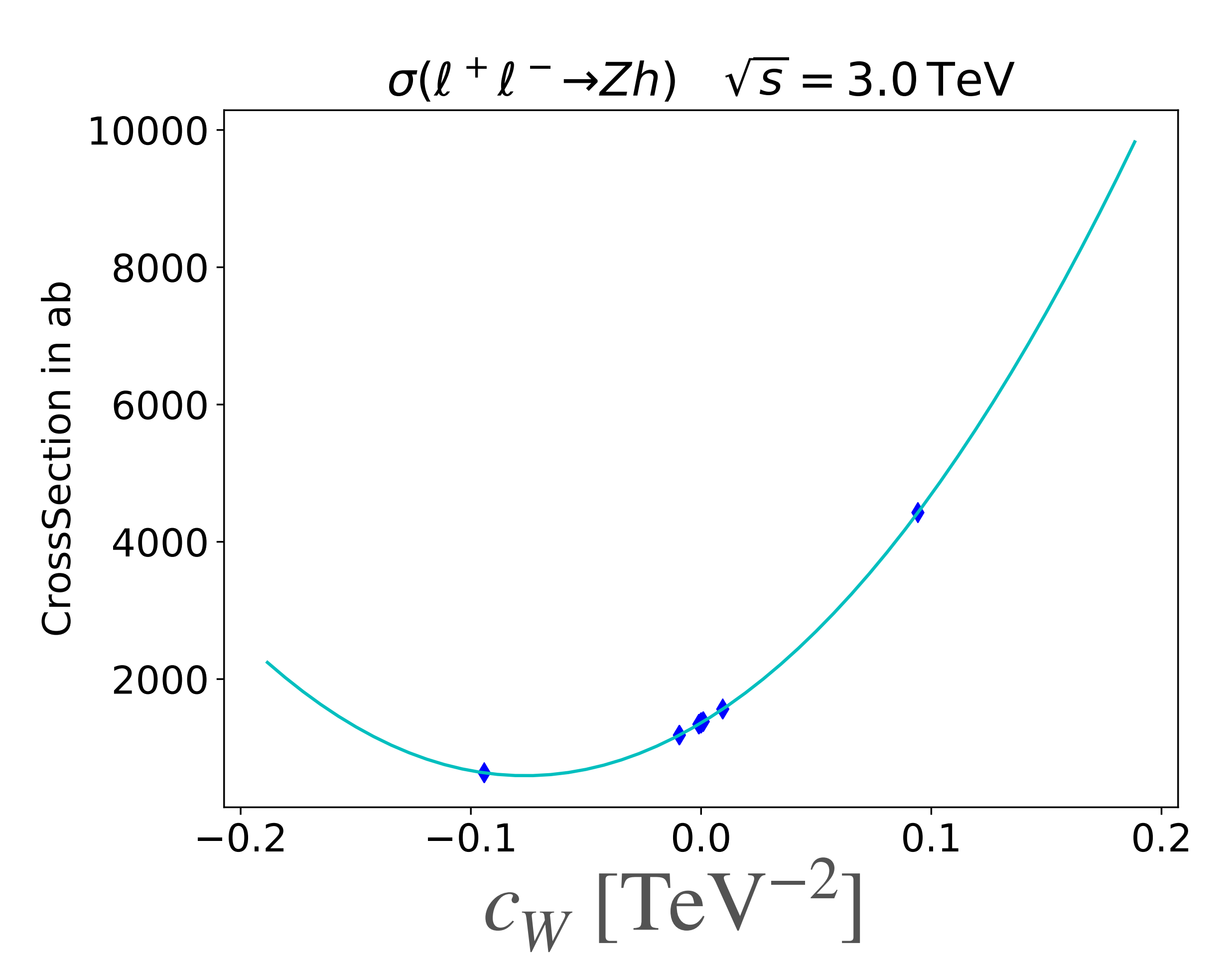
$$c_W = \hat{S}/m_W^2$$

$$c_W \lesssim 0.02\,\mathrm{TeV}^{-2}\frac{1}{E_{beam}/\mathrm{TeV}}\cdot\frac{1}{\sqrt{\mathscr{L}/\mathrm{ab}^{-1}}}$$

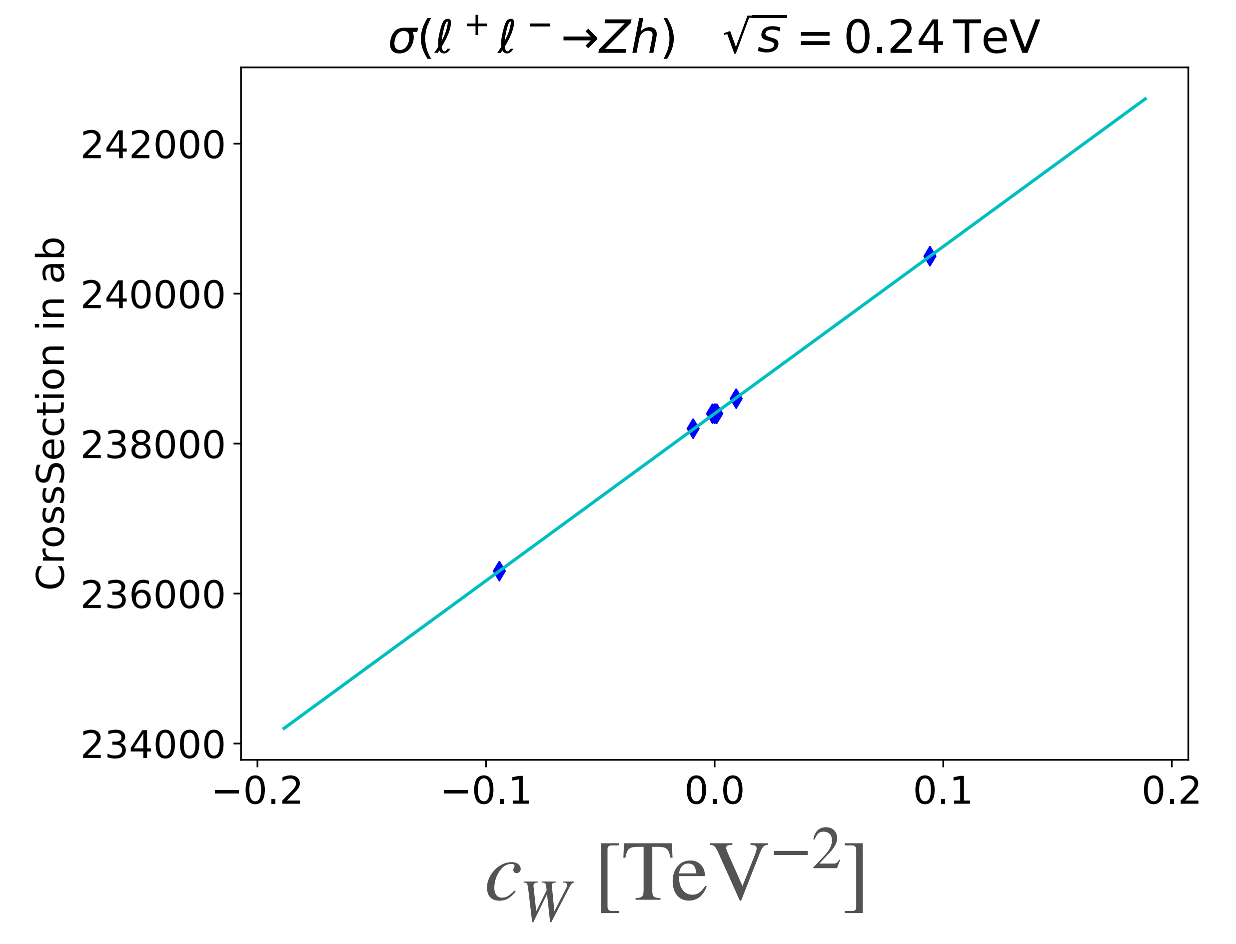
$$\hat{S}_{95\%} \lesssim 1.2\cdot 10^{-4}\frac{1}{E_{beam}/\mathrm{TeV}}\cdot\frac{1}{\sqrt{\mathscr{L}/\mathrm{ab}^{-1}}}$$



$\hat{S} < 3\cdot 10^{-5}$ (95 % CL) ⟵ $\mathscr{L} = 5\,\mathrm{ab}^{-1}$



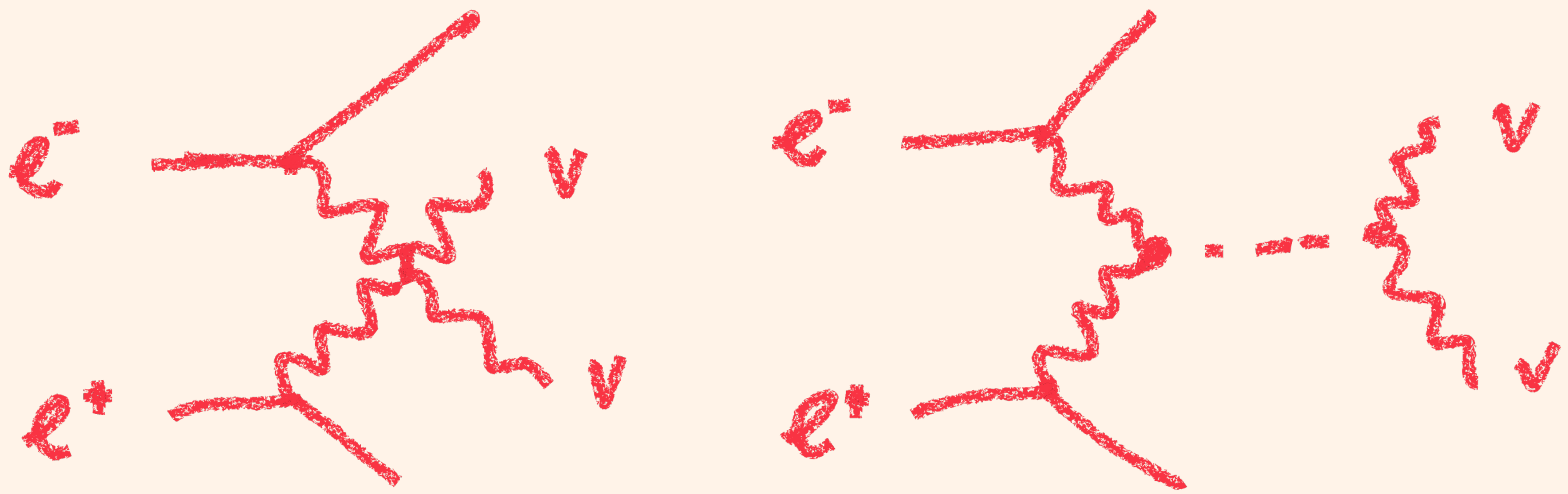
$\hat{S} < 2\cdot 10^{-4}$ (95 % CL) ⟵ $\mathscr{L} = 5\,\mathrm{ab}^{-1}$



Going beyond?

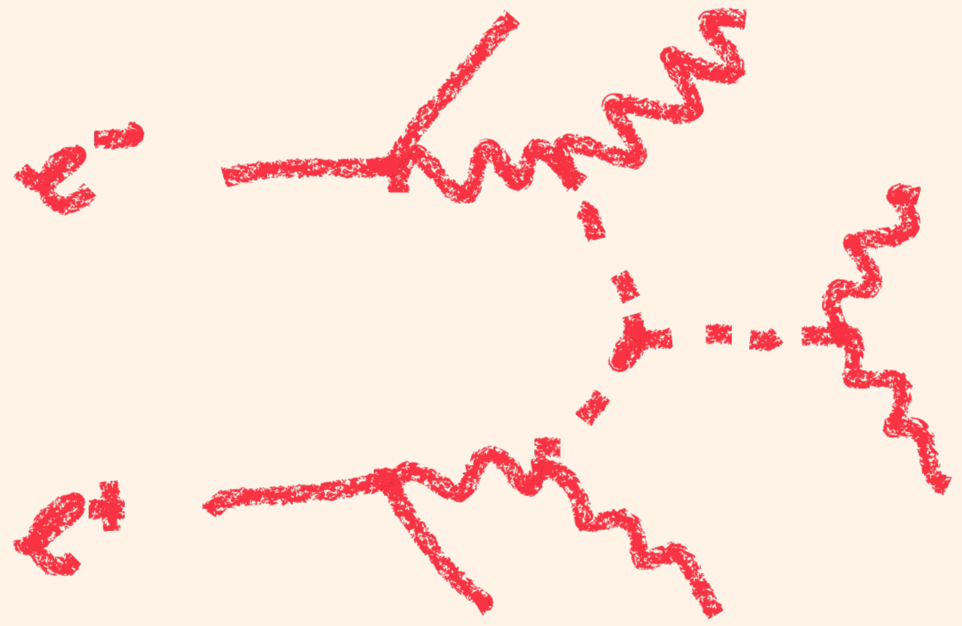
e^+e^- capabilities at $\sqrt{s} \gg m_Z$

4-body final states, sometimes described as "effective" 2→2 processes*



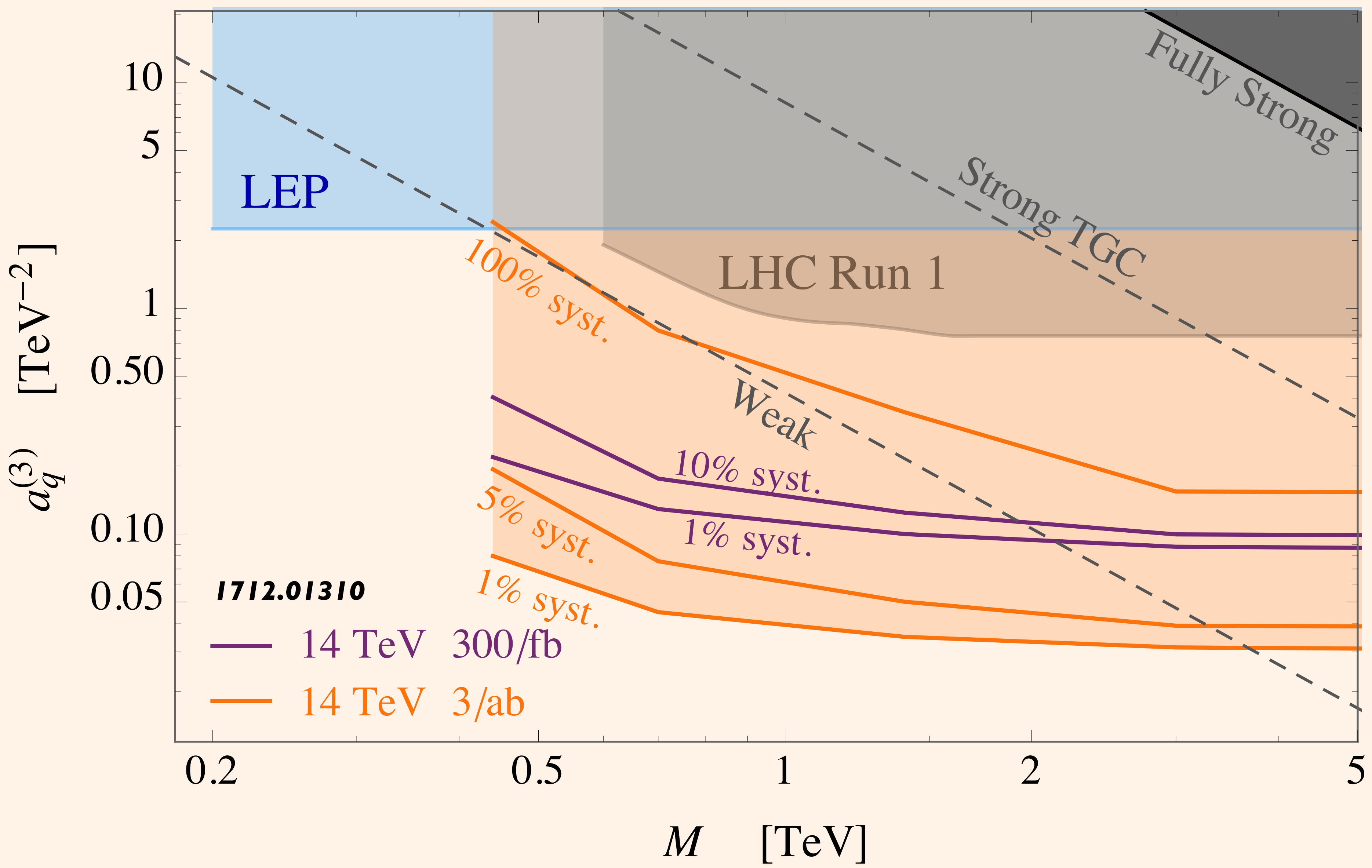
n-body final states with energy-enhanced effects

1812.09299
1902.05556, 2009.11293, 2203.09512



Simply put: energy is not enough at the HTE factory to be in this regime.

HL-LHC capabilities



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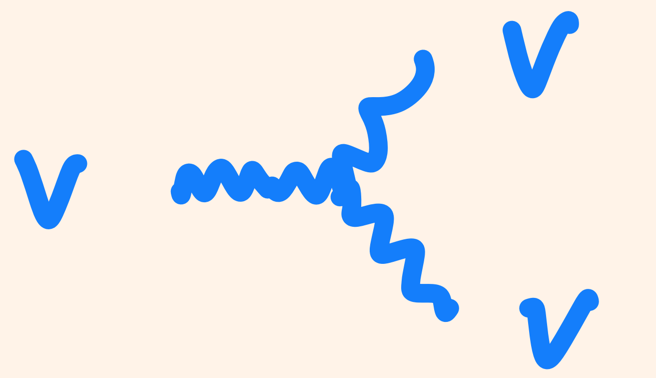

$(DW)^2 \supset E^2 W^3$

∂erivatives

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Beyond HL-LHC capabilities at *pp*

NEUTRAL

$pp \to WW$ 1708.07823

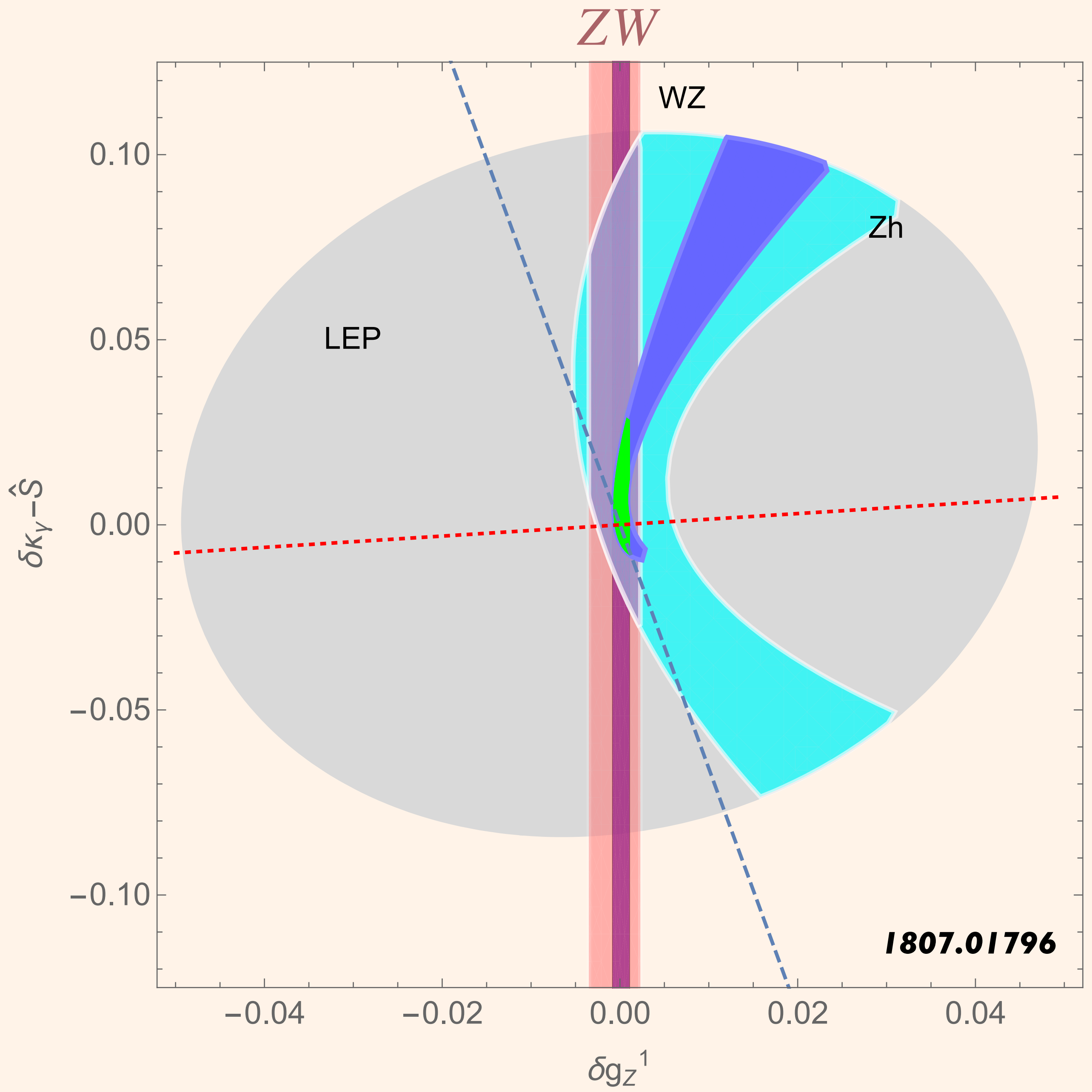
$pp \to Zh$ 1807.01796 2011.13941

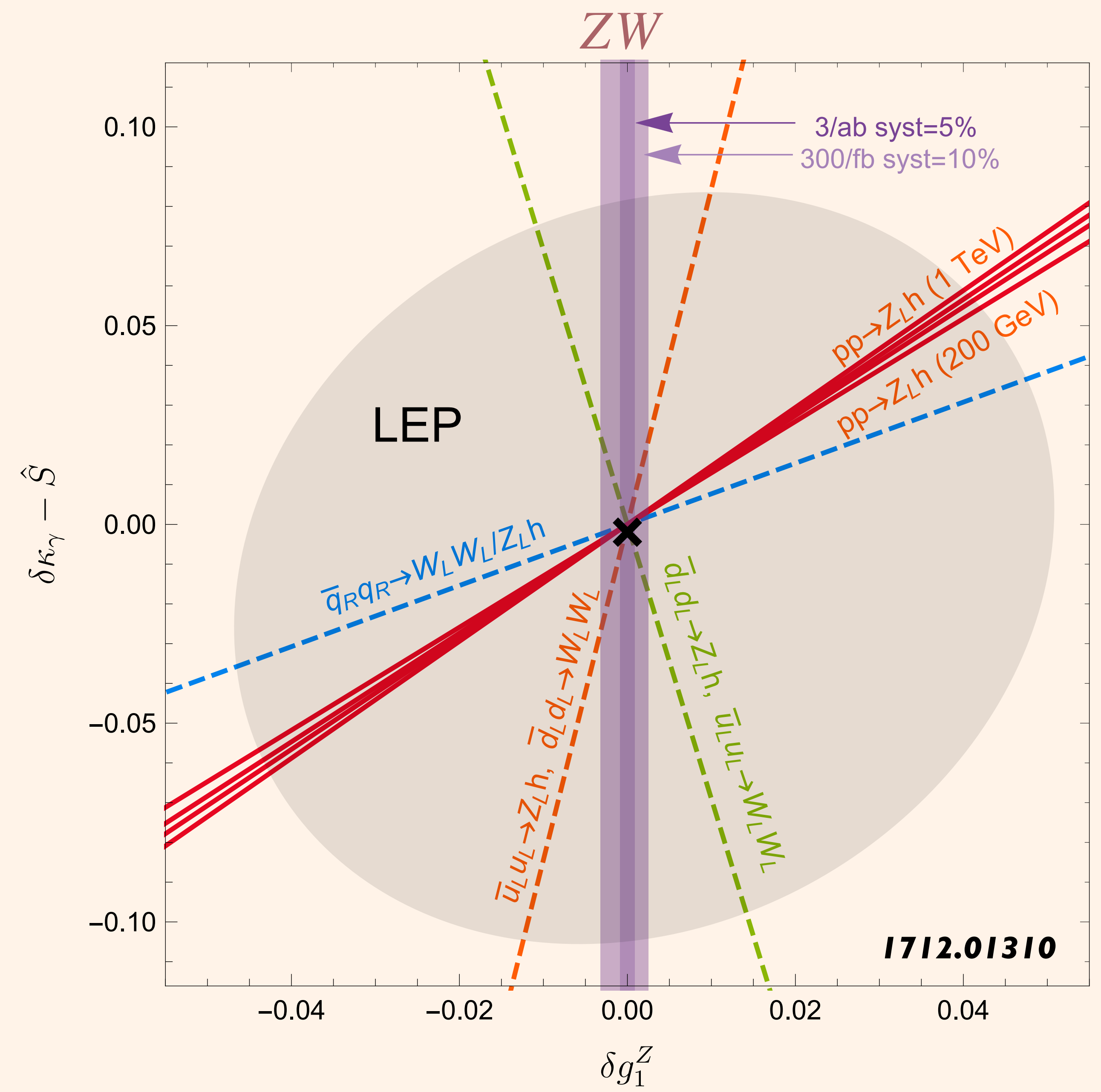
CHARGED

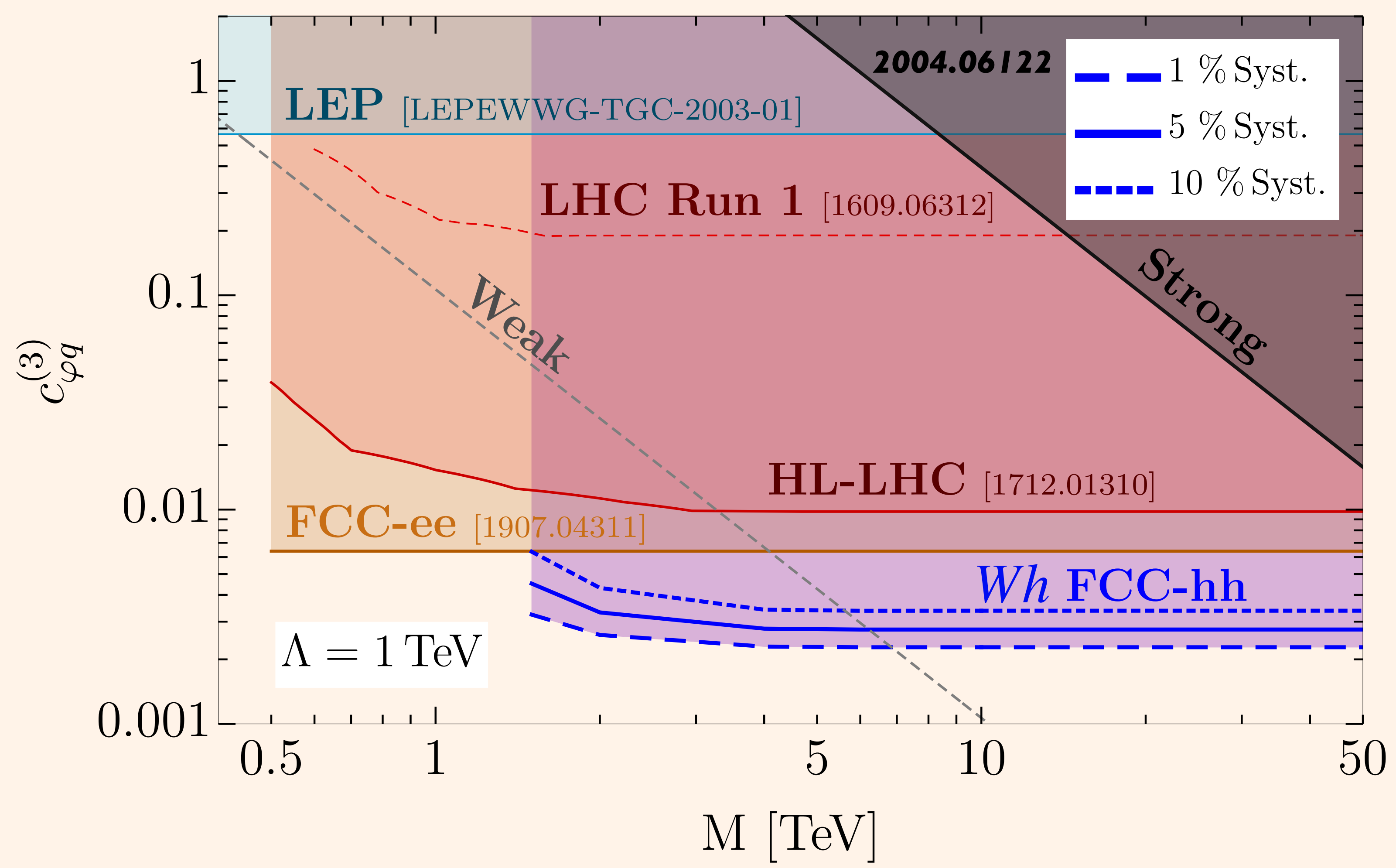
$pp \to ZW$ 1707.08060 1712.01310

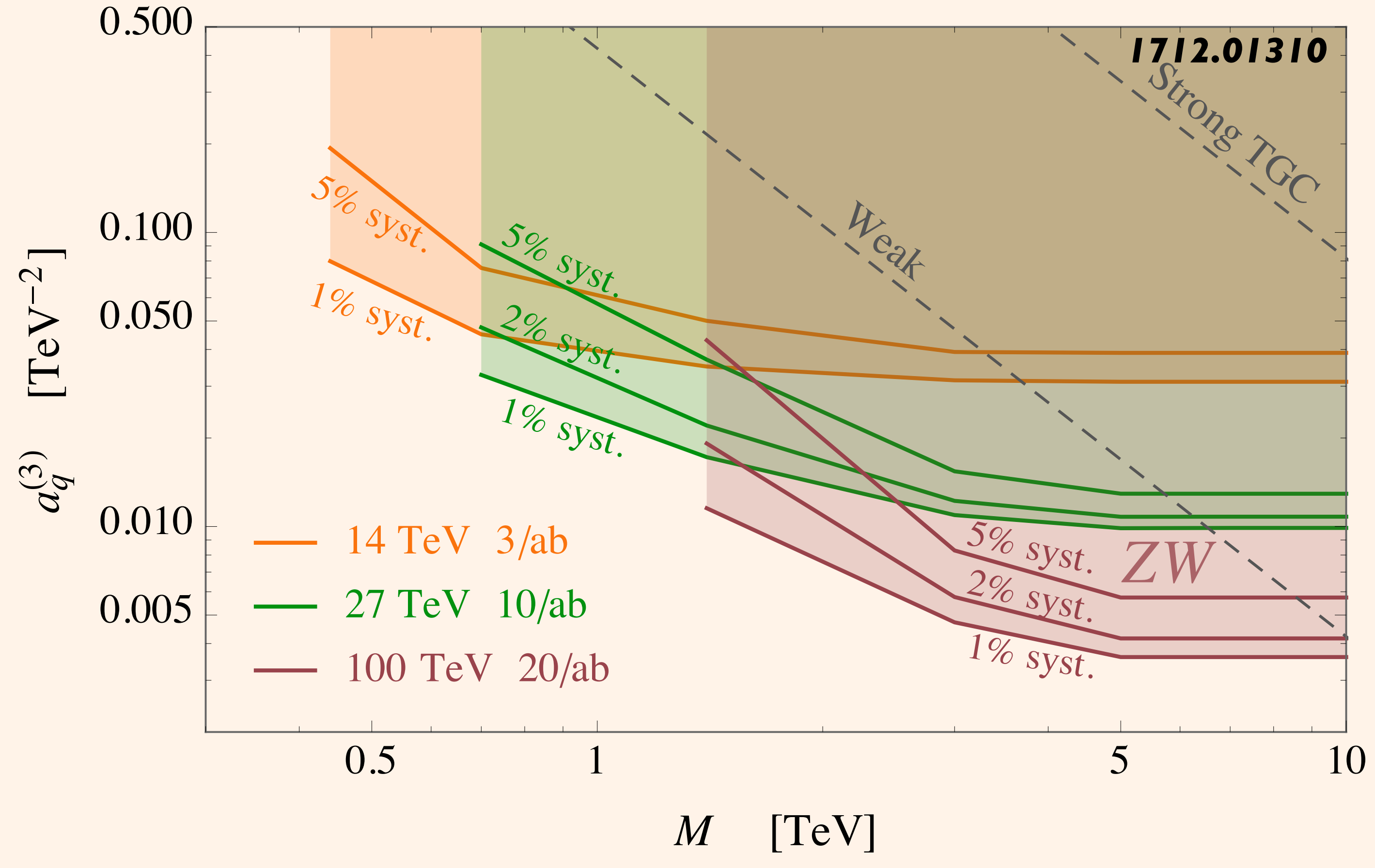
$pp \to Wh$ 2004.06122

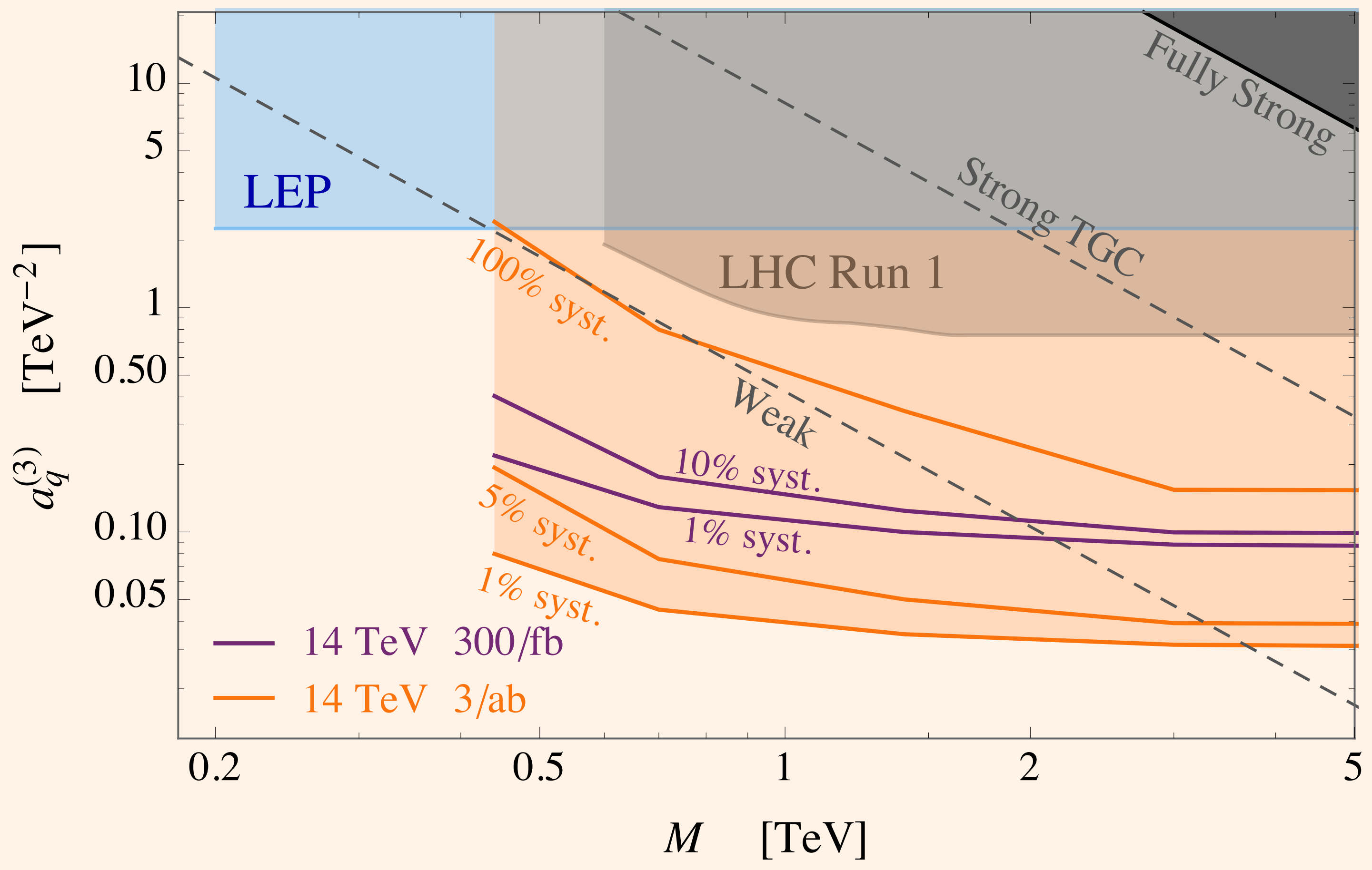
Systematics are crucial











Conclusions

- Full program HTE factory can bring very good progress on the EW properties
- Z-pole has still a key role if $\sqrt{s} \leq 500$ GeV
- Processes are simple $2 \to 2$ $(Zh, WW$ final states)
- Higher energies in principle can do without much improvement from Z-pole
- High partonic energy makes pp colliders are competitive (challenge of low systematics, high-luminosity needed)
- Very similar arguments can be used for $2 \to 2$ $(f\bar{f}$ final states)
    - Same types of observables:
        - fiducial rates, simple distributions usually capture the BSM effects

Thank you!

Beyond 500 GeV capabilities at $\ell^+\ell^-$

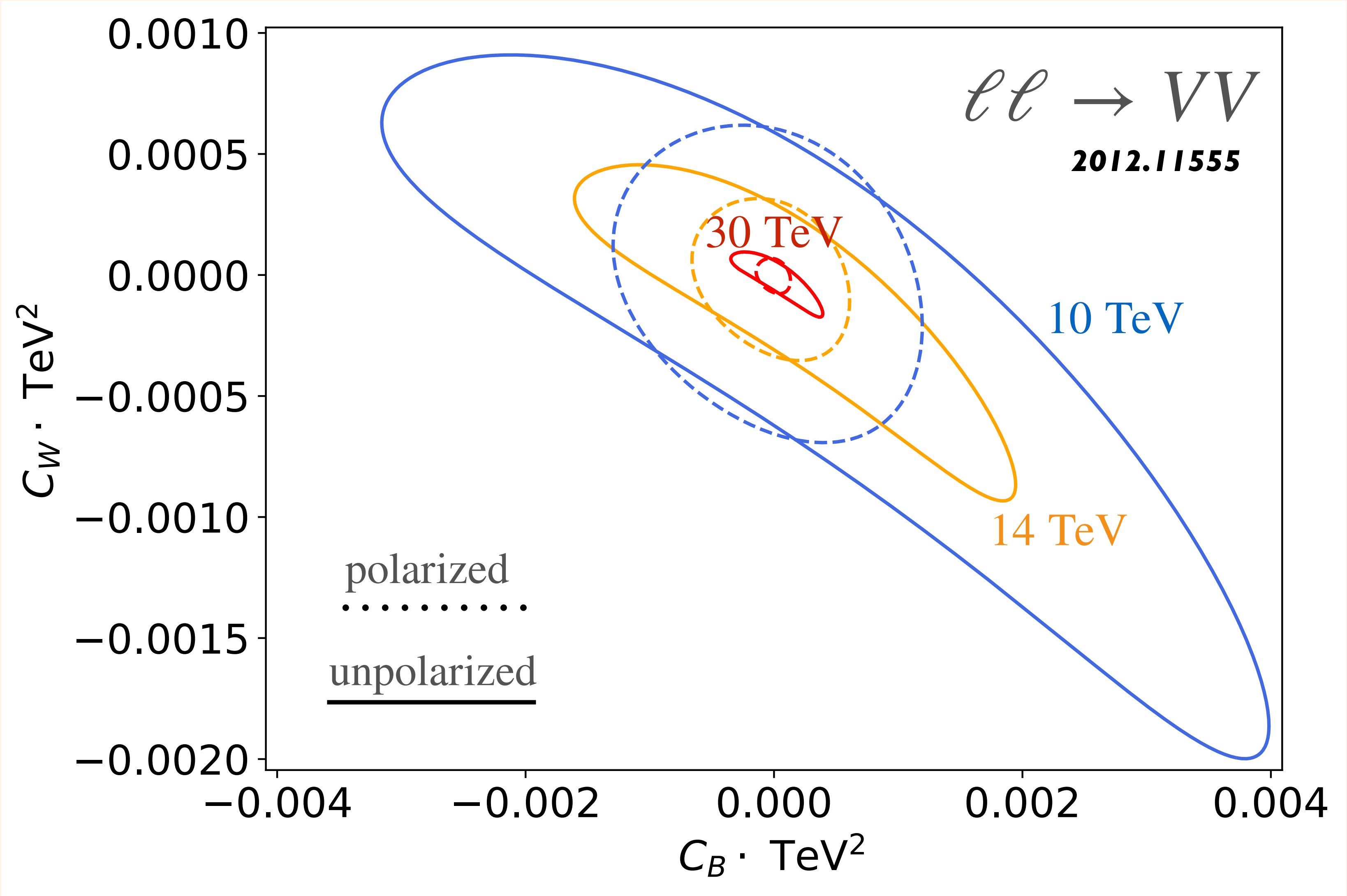
NEUTRAL

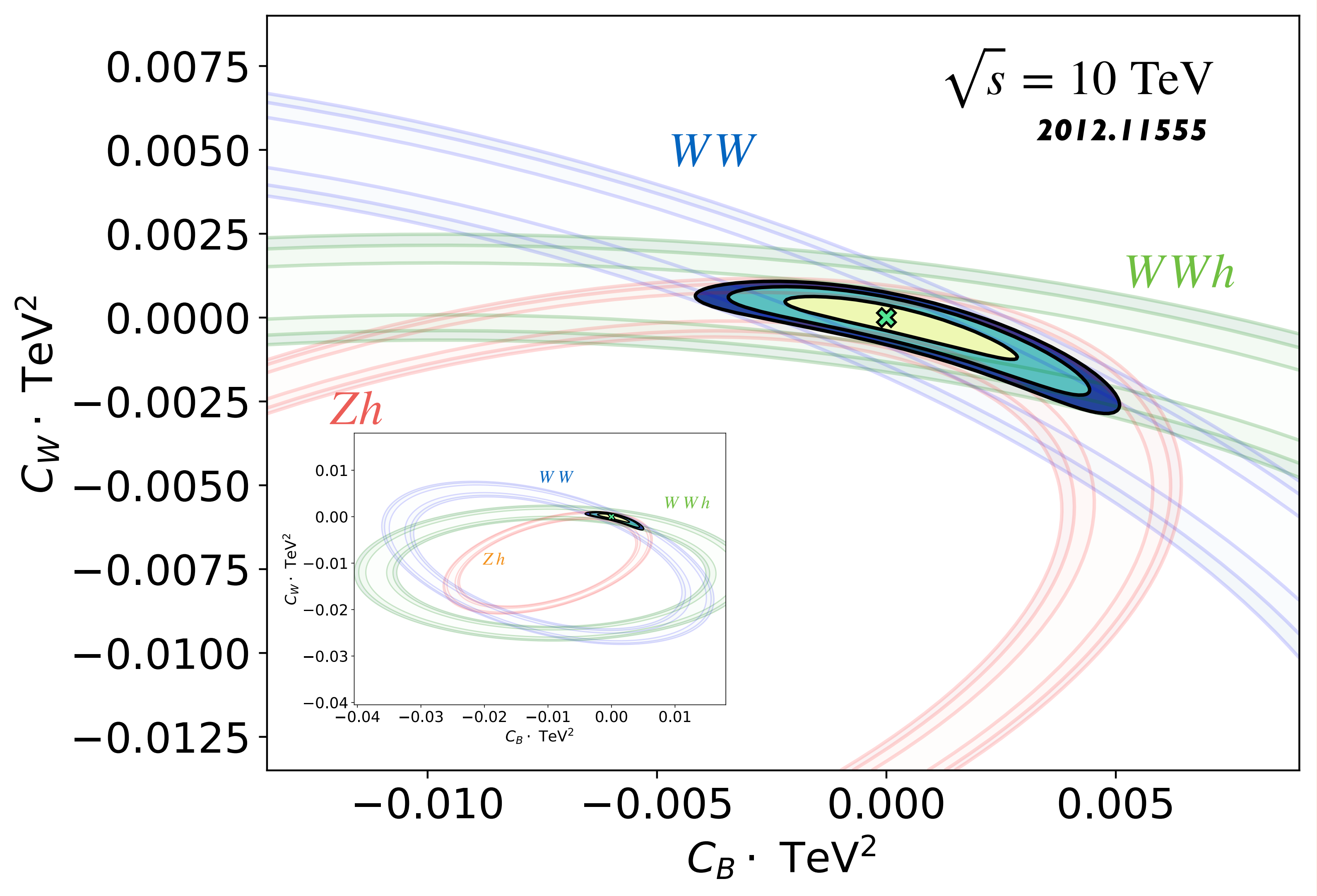
$\ell^+\ell^- \to WW$

$\ell^+\ell^- \to Zh$

CHARGED

$\ell^+\ell^- \to WWh$





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