Higgs, electroweak and Goldstone bosons production at the Muon Collider

MAR. 26 2021

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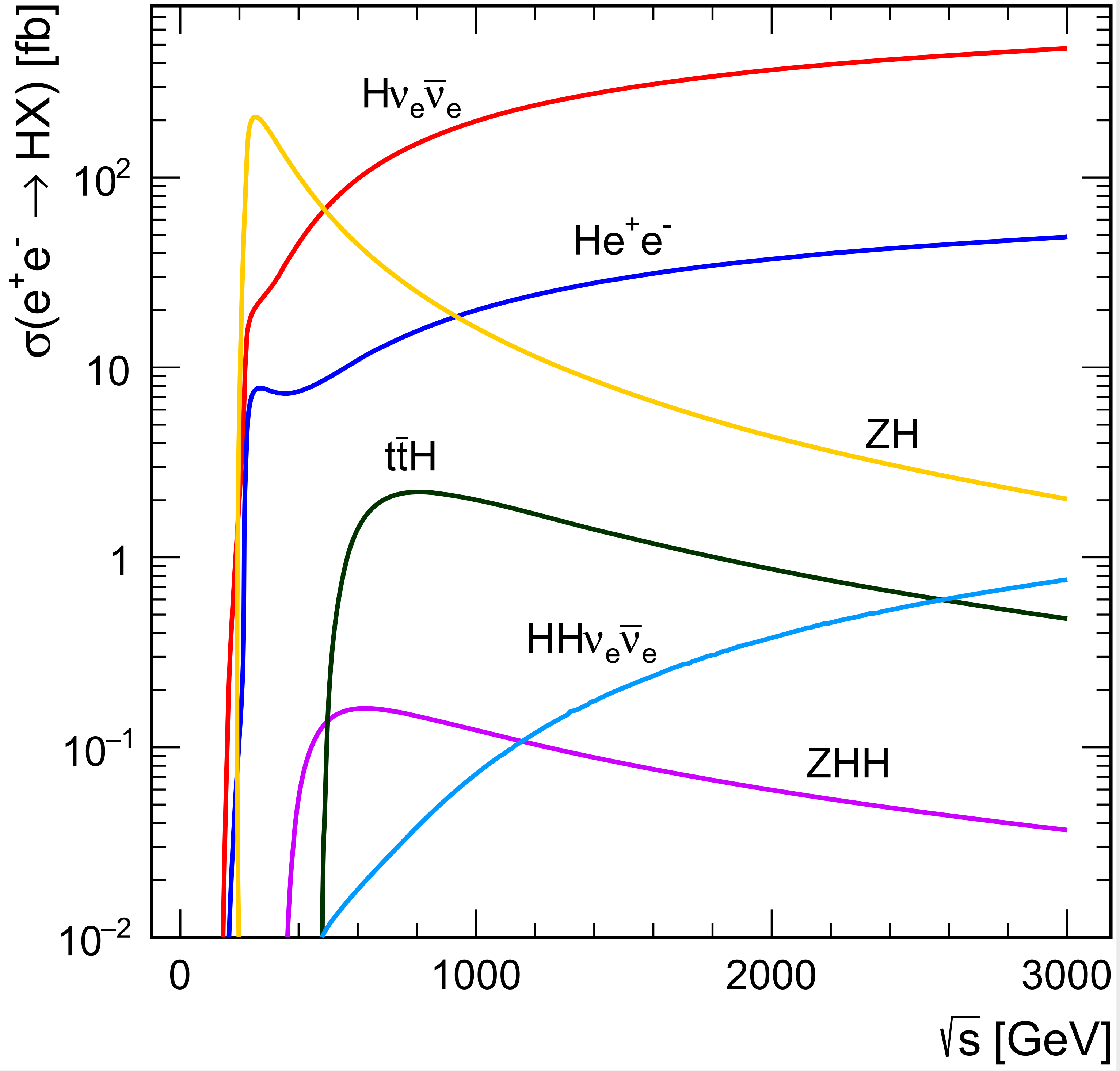
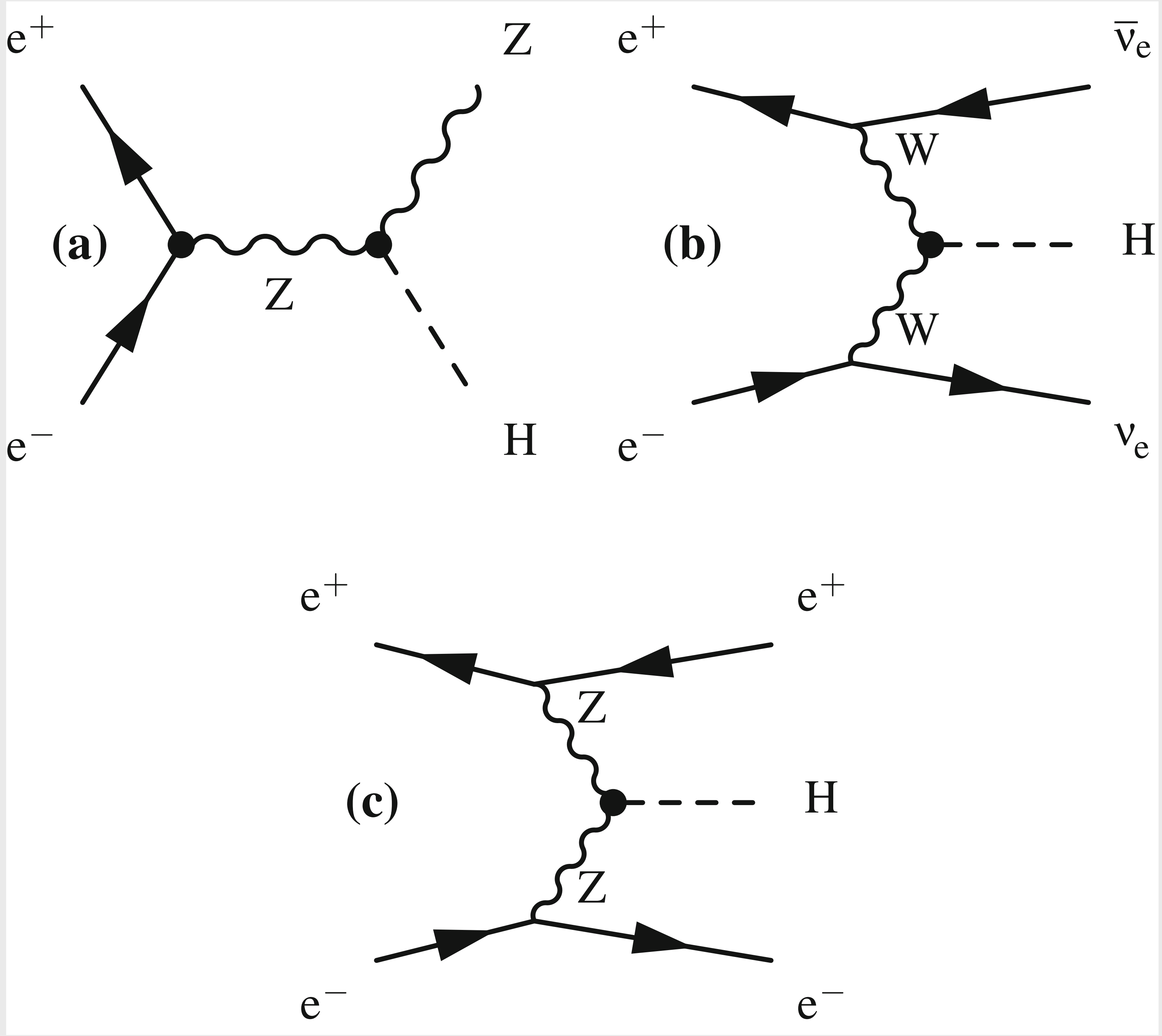
Do you see my second slide? my pointer? and do you hear me well?

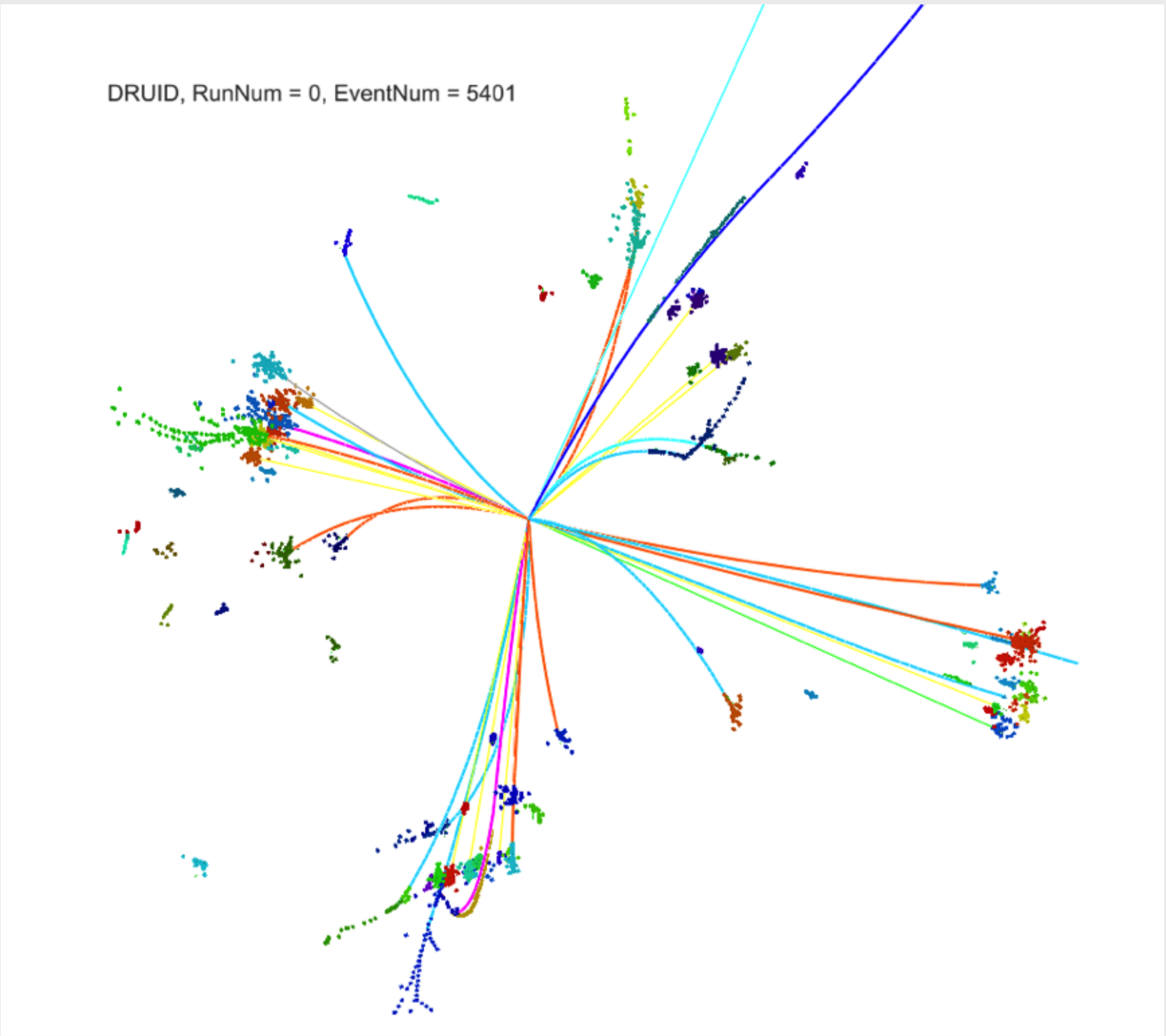
Higgs boson @*h*🏭

Pole, pole, pole

LARGE DATASET AT ZH THRESHOLD ⇒ roughly 1M Higgs bosons ⇒ measurements at 10^{-3} precision are "possible"





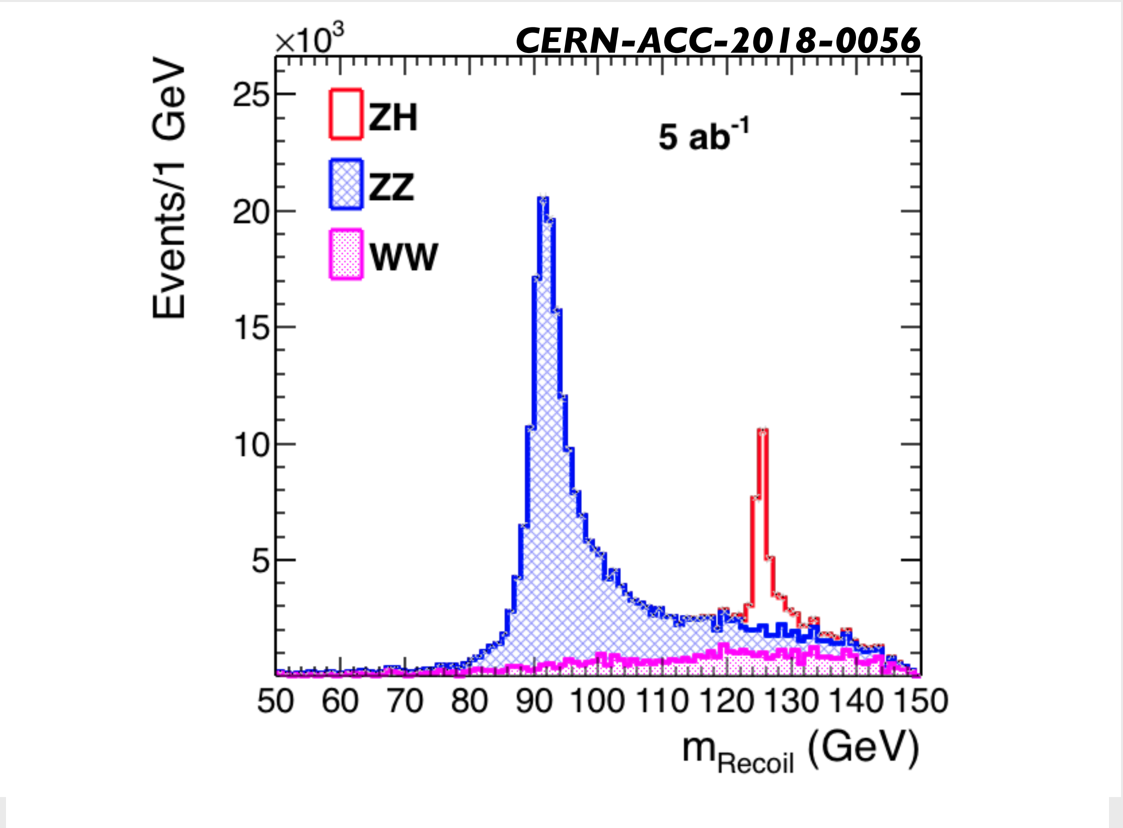


Bottlenecks in sight

$$\sigma(ZH)_{Z\to\ell\ell,H\to\text{untagged}} = BR(Z\to\ell\ell)\cdot\sigma_{ZH} \Rightarrow g^2_{HZZ}@0.4\%\cdot\sqrt{\frac{10^6}{N_{higgs}}}$$

$$\sigma(ZH)_{Z\to\text{anything},H\to XX} = \sigma_{ZH}\cdot BR(h\to XX) \Rightarrow \frac{g^2_{hXX}\cdot g^2_{HZZ}}{\Gamma_{tot}}@0.13\%\cdot\sqrt{\frac{BR(h\to XX)}{0.5}}\cdot\sqrt{\frac{10^6}{N_{higgs}}}$$

ABSOLUTE RATE MEASUREMENT



$$\begin{cases} \dfrac{\sigma(ZH)_{Z\to\text{anything},H\to YY}}{\sigma(ZH)_{Z\to\text{anything},H\to XX}} = \dfrac{g^2_{hYY}}{g^2_{hXX}} = \dfrac{N_{YY}}{N_{XX}} \\ g^2_{hYY} = \dfrac{N_{YY}}{N_{XX}}\cdot\#\dfrac{N_{ZH,recoil}}{\mathscr{L}} \end{cases}$$

$$\Rightarrow \frac{\delta g^2_{hYY}}{g^2_{hYY}} = \frac{\delta N_{YY}}{N_{YY}} \oplus \frac{\delta N_{XX}}{N_{XX}} \oplus \frac{\delta N_{ZH,recoil}}{N_{ZH,recoil}} \oplus \frac{\delta\mathscr{L}}{\mathscr{L}}$$

$$\frac{\delta\Gamma}{\Gamma} = \frac{\delta N_{ZZ}}{N_{ZZ}} \oplus \frac{N_{ZH,recoil}}{\delta N_{ZH,recoil}}$$

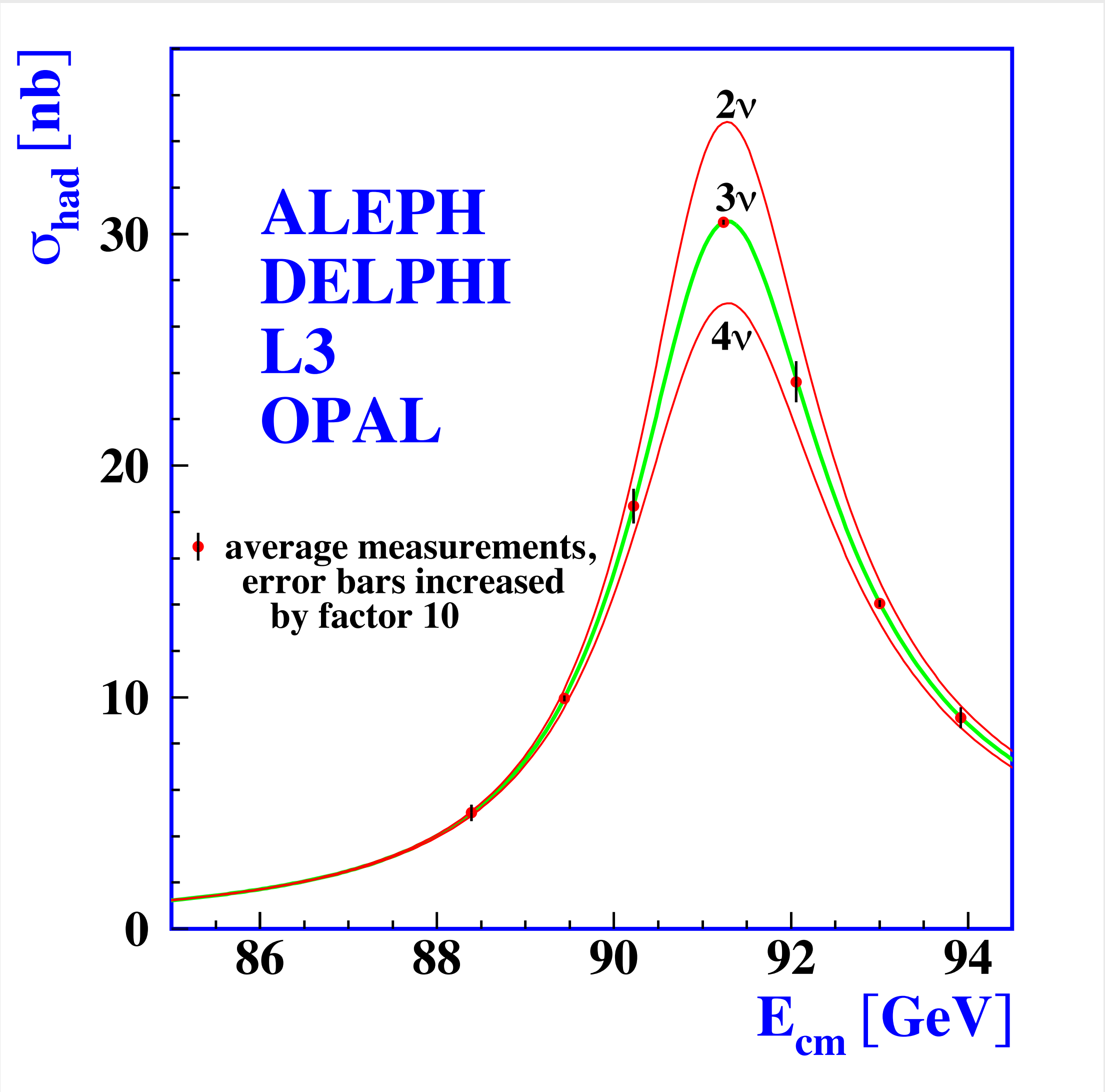
Takes a lot of understanding …

$$N_\nu = 2.9840 \pm 0.0082 = 2.984(8) = 3 - 0.016(8)$$ hep-ex/0509008

$$N_\nu = 2.9975 \pm 0.0074 = 2.997(7) = 3 - 0.003(7)$$ 1912.02067

$$\frac{\delta N_\nu}{N_\nu} = \frac{\delta \mathscr{L}}{\mathscr{L}} \oplus \dots$$

ABSOLUTE WIDTH MEASUREMENT



CERN-ACC-2018-0056

Systematics in sight

STAT-ONLY

Table 4.1: Relative statistical uncertainty on the measurements of event rates, providing $\sigma_{HZ} \times BR(H \to XX)$ and $\sigma_{\nu\bar{\nu}H} \times BR(H \to XX)$, as expected from the FCC-ee data. This is obtained from a fast simulation of the CLD detector and consolidated with extrapolations from full simulations of similar linear-collider detectors (SiD and CLIC). All numbers indicate 68% C.L. intervals, except for the 95% C.L. sensitivity in the last line. The accuracies expected with $5\ ab^{-1}$ at 240 GeV are given in the middle columns, and those expected with $1.5\ ab^{-1}$ at $\sqrt{s} = 365$ GeV are displayed in the last columns.

$\sqrt{s}$ (GeV)	240		365	
Luminosity (ab^{-1})	5		1.5	
$\delta(\sigma BR)/\sigma BR$ (%)	HZ	$\nu\bar{\nu}$ H	HZ	$\nu\bar{\nu}$ H
$H \to$ any	±0.5		±0.9	
$H \to b\bar{b}$	±0.3	±3.1	±0.5	±0.9
$H \to c\bar{c}$	±2.2		±6.5	±10
$H \to gg$	±1.9		±3.5	±4.5
$H \to W^+W^-$	±1.2		±2.6	±3.0
$H \to \mu^+\mu^-$	±19		±40	
$H \to$ invis.	< 0.3		< 0.6	

GLOBAL-FIT

Table 4.2: Precision determined in the κ framework of the Higgs boson couplings and total decay width, as expected from the FCC-ee data, and compared to those from HL-LHC and other e^+e^- colliders exploring the 240-to-380 GeV centre-of-mass energy range. All numbers indicate 68% CL sensitivities, except for the last line which gives the 95% CL sensitivity on the "exotic" branching fraction, accounting for final states that cannot be tagged as SM decays. The FCC-ee accuracies are subdivided in three categories: the first sub-column give the results of the model-independent fit expected with $5\ ab^{-1}$ at 240 GeV, the second sub-column in bold – directly comparable to the other collider fits – includes the additional $1.5\ ab^{-1}$ at $\sqrt{s} = 365$ GeV, and the last sub-column shows the result of the combined fit with HL-LHC. The fit to the HL-LHC projections alone (first column) requires two additional assumptions to be made: here, the branching ratios into $c\bar{c}$ and into exotic particles are set to their SM values. These HL-LHC estimates were obtained by combining the ATLAS and the CMS projected sensitivities for Higgs signal strength measurements, presented in Ref. [17]. We show the results assuming the systematic and theory uncertainties from the S2 scenario described in that reference. Since $H \to Z\gamma$ projections from CMS were not available, we assume the same precision as ATLAS. Finally, the correlations between the ATLAS and CMS sets of projections were not available at the time this fit was performed and were therefore neglected. We note that the absence of that information can result, in some cases, in somewhat optimistic bounds. In particular, this happens for those couplings whose uncertainty is dominated by theoretical errors (e.g. g_{Htt}).

Collider	HL-LHC	FCC-ee$_{240+365}$		
Lumi (ab^{-1})	3	5_{240}	$+1.5_{365}$	+ HL-LHC
Years	25	3	+4	
$\delta\Gamma_H/\Gamma_H$ (%)	SM	2.7	**1.3**	1.1
$\delta g_{HZZ}/g_{HZZ}$ (%)	1.3	0.2	**0.17**	0.16
$\delta g_{HWW}/g_{HWW}$ (%)	1.4	1.3	**0.43**	0.40
$\delta g_{Hbb}/g_{Hbb}$ (%)	2.9	1.3	**0.61**	0.55
$\delta g_{Hcc}/g_{Hcc}$ (%)	SM	1.7	**1.21**	1.18
$\delta g_{Hgg}/g_{Hgg}$ (%)	1.8	1.6	**1.01**	0.83
$\delta g_{Htt}/g_{Htt}$ (%)	2.5	–	–	2.4
BR_{EXO} (%)	SM	< 1.2	$< \mathbf{1.0}$	< 1.0

EFFORTS NEEDED TO USE THE FULL STATISTICAL POWER OF THE 1M HIGGS BOSONS THE FACTORY PRODUCES

Competion from “current” experiments

HL-LHC

TOUCHING THE % PRECISION

kappa-3 scenario	HL-LHC
κ_W (%, ≤ 1)	-1.7
κ_Z (%, ≤ 1)	-1.3
κ_g (%)	± 2.2
κ_γ (%)	± 1.7
$\kappa_{Z\gamma}$ (%)	$\pm 10.$
κ_c (%)	–
κ_t (%)	± 2.8
κ_b (%)	± 2.6
κ_μ (%)	± 4.4
κ_τ (%)	± 1.6
$\mathrm{BR}_{\mathrm{inv}}$ (<%, 95% CL)	1.9
$\mathrm{BR}_{\mathrm{unt}}$ (<%, 95% CL)	i 4.1

kappa-0	HL-LHC	LHeC	HE-LHC	ILC_{250}	ILC_{500}	CLIC_{380}	CLIC_{1500}	CLIC_{3000}	CEPC	$\mathrm{FCC\text{-}ee}_{240}$	$\mathrm{FCC\text{-}ee}_{365}$	FCC-ee/eh/hh
κ_W (%)	1.2	0.75	0.66	1.8	0.29	0.86	0.17	0.11	1.3	1.3	0.43	0.15
κ_Z (%)	1.0	1.2	0.6	0.29	0.23	0.5	0.26	0.23	0.13	0.2	0.17	0.12
κ_g (%)	2.2	3.6	1.4	2.3	0.97	2.5	1.3	0.9	1.5	1.7	1.0	0.52
κ_γ (%)	1.7	7.5	0.98	6.7	3.4	$98\star$	5.0	2.2	3.7	4.7	3.9	0.35
$\kappa_{Z\gamma}$ (%)	10	–	4.0	$99\star$	$86\star$	$120\star$	15	6.9	8.2	$81\star$	$75\star$	0.7
κ_c (%)	–	4.0	–	2.5	1.3	4.3	1.8	1.4	2.2	1.8	1.3	0.95
κ_t (%)	2.8	–	2.0	–	6.9	–	–	2.6	–	–	–	1.0
κ_b (%)	2.7	2.1	1.7	1.8	0.58	1.9	0.48	0.38	1.2	1.3	0.67	0.45
κ_μ (%)	4.4	–	1.8	15	9.4	$320\star$	13	5.8	8.9	10	8.9	0.42
κ_τ (%)	1.6	3.3	1.1	1.9	0.7	3.0	1.3	0.89	1.3	1.4	0.73	0.49

We need (deep) sub-percent on a large set of couplings

Higgs boson @μC

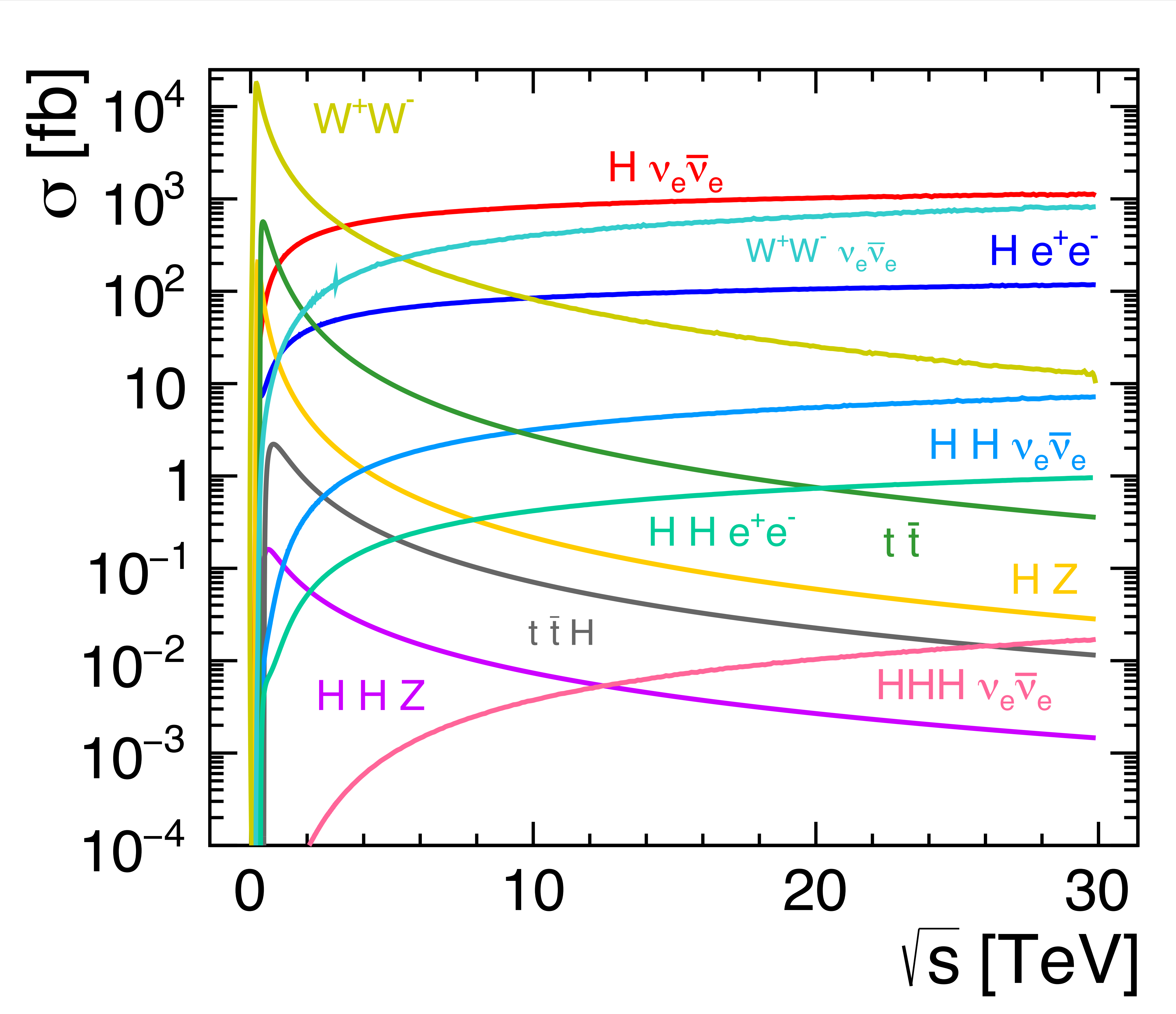
$\ell^+\ell^- \to h\nu\nu$

10⁸ HIGGS BOSONS

100×MEGA-HIGGS FACTORY

$$\sigma \sim log(s) \simeq const$$

$$\mathscr{L} \sim 0.1\ \mathrm{ab}^{-1}\left(\frac{\sqrt{s}}{TeV}\right)^2$$



$$\sqrt{s} = 30\ \mathrm{TeV}$$

$$\sigma \cdot \mathscr{L} \Rightarrow 10^8\ \mathrm{h}$$

- ultra-rare Higgs decays
- differential distribution
- off-shell Higgs bosons
- rare production modes

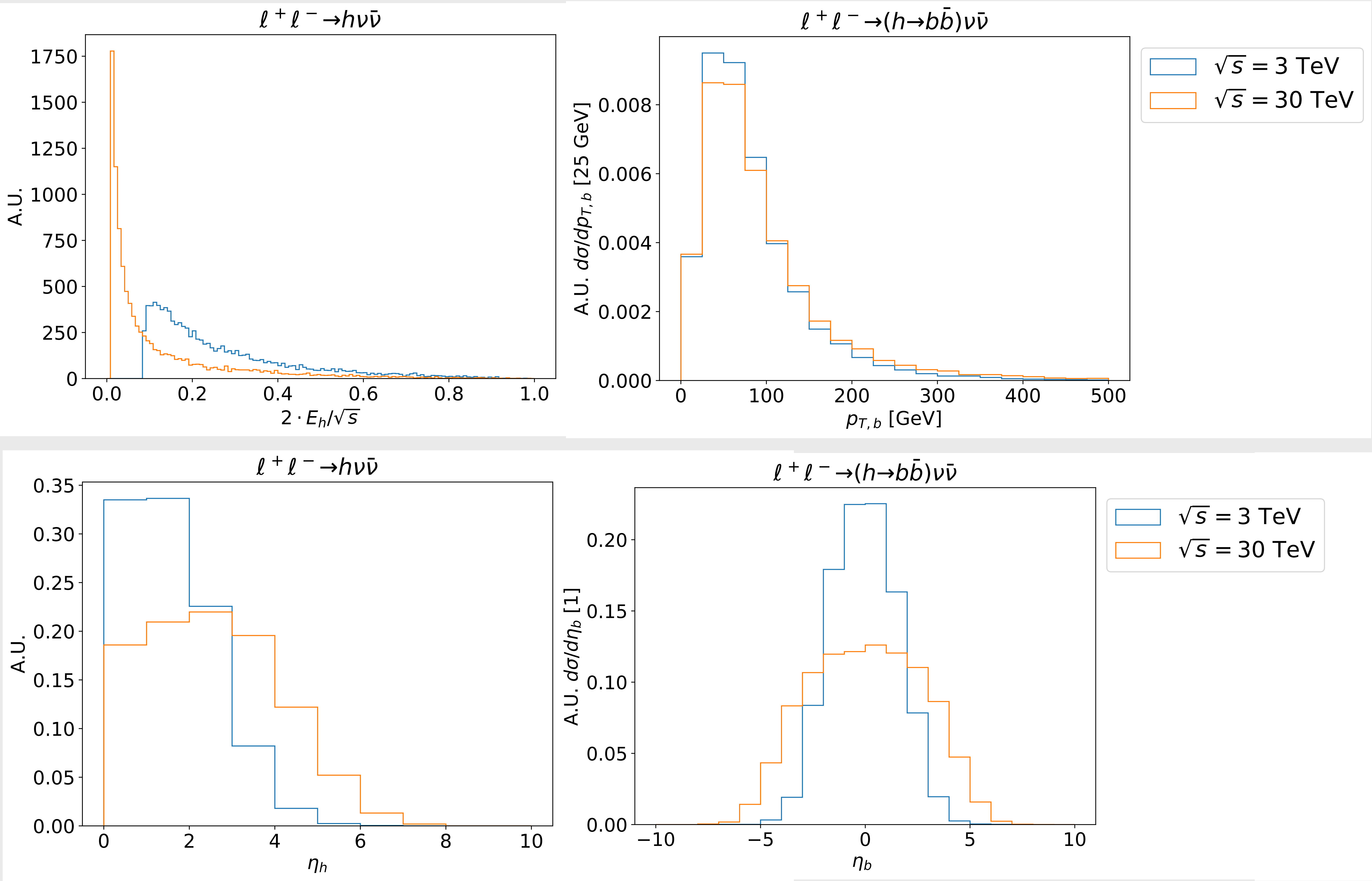
R n/event/1019788/

Buttazzo, RF, Wulzer

$\ell^+\ell^- \rightarrow h\nu\nu$

10⁸ HIGGS BOSONS

100×MEGA-HIGGS FACTORY

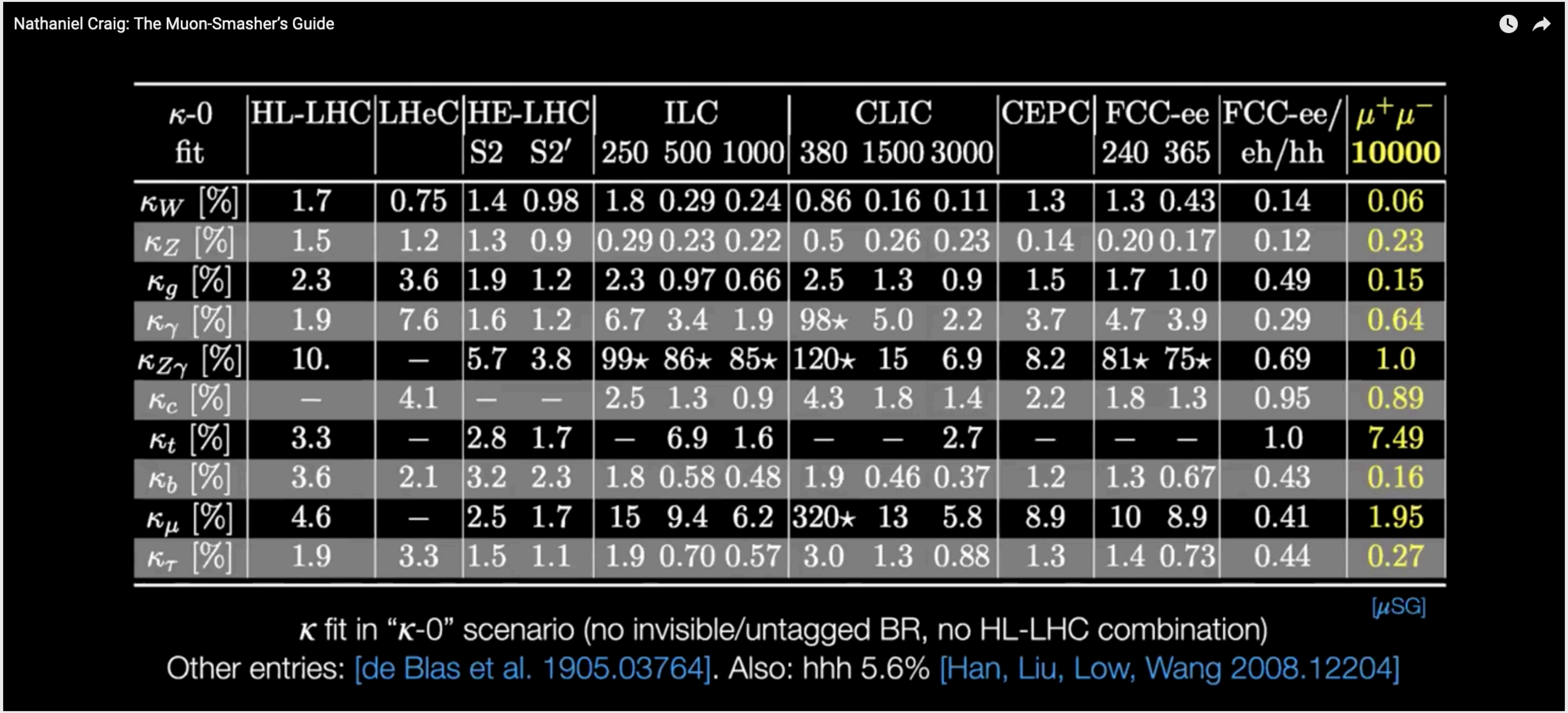


$$\mathscr{L} \simeq 90 \cdot \left(\frac{\sqrt{s}}{30\,\text{TeV}}\right)^2 \text{ab}^{-1}$$

$$\sigma(\ell^+\ell^- \to \nu\nu(h \to bb)) = 1\,\text{pb at 30 TeV}$$

- most Higgs decays in acceptance **2001.04431**
- O(10^4) H→$\mu^+\mu^-$ decays!
- clean decays where systematic may be small will be a key. E.g. 4ℓ, $\ell\ell$ Z, γγ, Zγ

2008.12204, μSG



Nathaniel Craig: The Muon-Smasher's Guide

κ-0	HL-LHC	LHeC	HE-LHC		ILC			CLIC			CEPC	FCC-ee		FCC-ee/	$\mu^+\mu^-$
fit			S2	S2′	250	500	1000	380	1500	3000		240	365	eh/hh	**10000**
κ_W [%]	1.7	0.75	1.4	0.98	1.8	0.29	0.24	0.86	0.16	0.11	1.3	1.3	0.43	0.14	0.06
κ_Z [%]	1.5	1.2	1.3	0.9	0.29	0.23	0.22	0.5	0.26	0.23	0.14	0.20	0.17	0.12	0.23
κ_g [%]	2.3	3.6	1.9	1.2	2.3	0.97	0.66	2.5	1.3	0.9	1.5	1.7	1.0	0.49	0.15
κ_γ [%]	1.9	7.6	1.6	1.2	6.7	3.4	1.9	98⋆	5.0	2.2	3.7	4.7	3.9	0.29	0.64
$\kappa_{Z\gamma}$ [%]	10.	—	5.7	3.8	99⋆	86⋆	85⋆	120⋆	15	6.9	8.2	81⋆	75⋆	0.69	1.0
κ_c [%]	—	4.1	—	—	2.5	1.3	0.9	4.3	1.8	1.4	2.2	1.8	1.3	0.95	0.89
κ_t [%]	3.3	—	2.8	1.7	—	6.9	1.6	—	—	2.7	—	—	—	1.0	7.49
κ_b [%]	3.6	2.1	3.2	2.3	1.8	0.58	0.48	1.9	0.46	0.37	1.2	1.3	0.67	0.43	0.16
κ_μ [%]	4.6	—	2.5	1.7	15	9.4	6.2	320⋆	13	5.8	8.9	10	8.9	0.41	1.95
κ_τ [%]	1.9	3.3	1.5	1.1	1.9	0.70	0.57	3.0	1.3	0.88	1.3	1.4	0.73	0.44	0.27

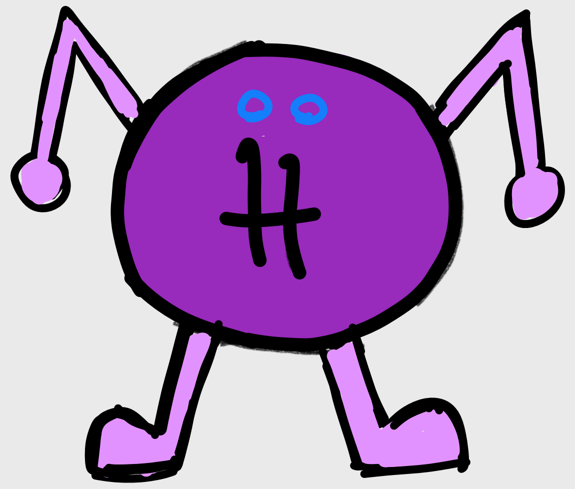
[μSG]

κ fit in "κ-0" scenario (no invisible/untagged BR, no HL-LHC combination)

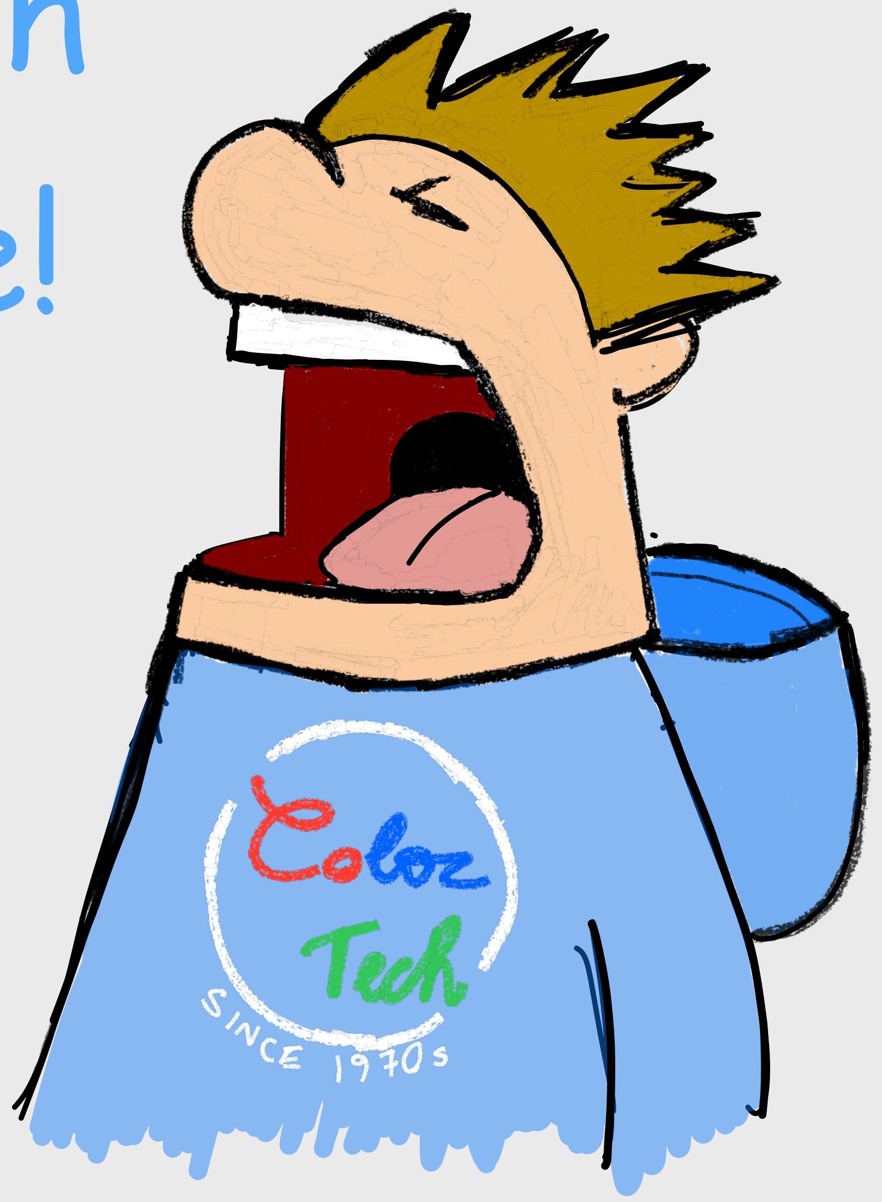
Other entries: [de Blas et al. 1905.03764]. Also: hhh 5.6% [Han, Liu, Low, Wang 2008.12204]

Let’s turn to the real problem …

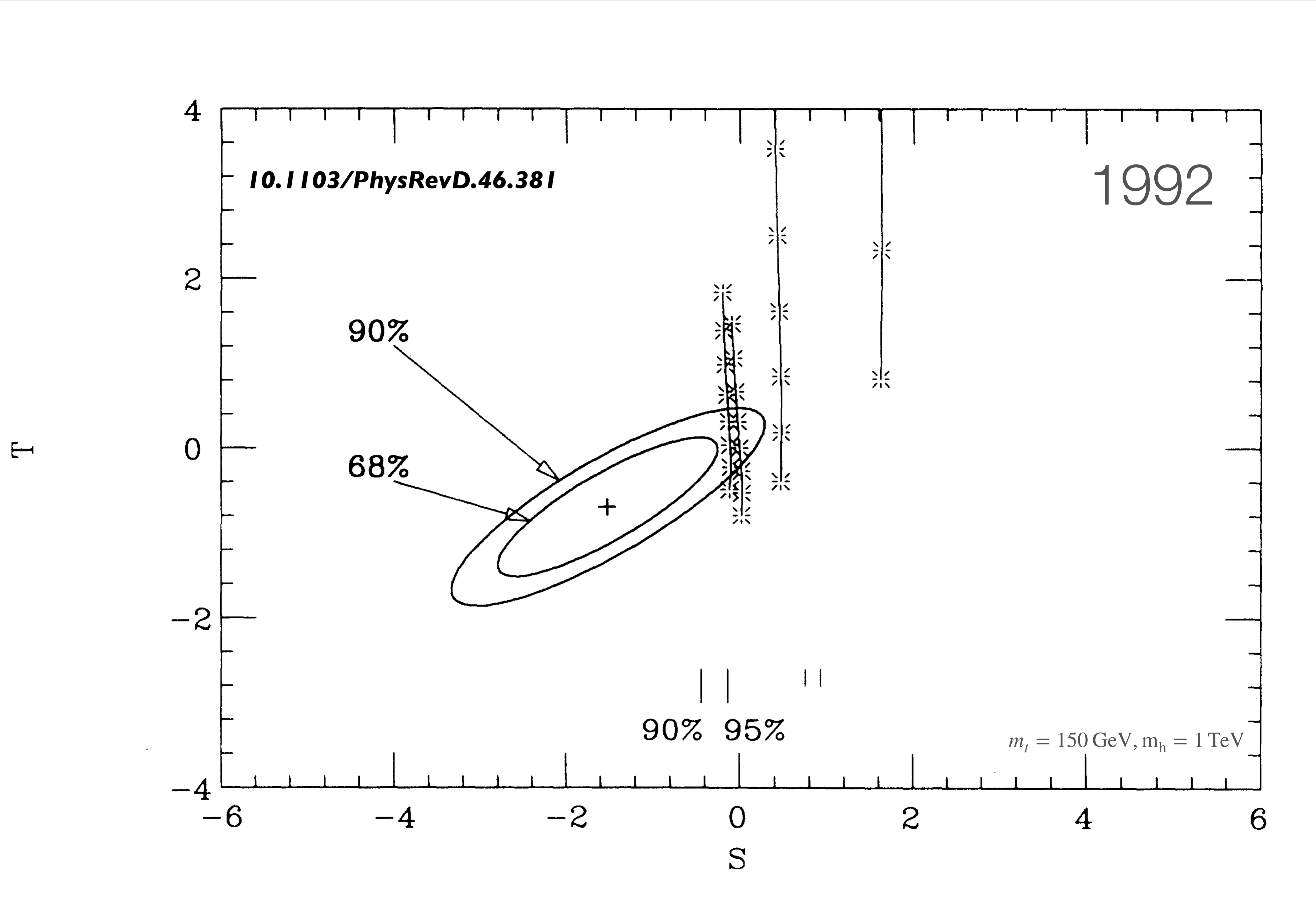
Why am
I so lonely?

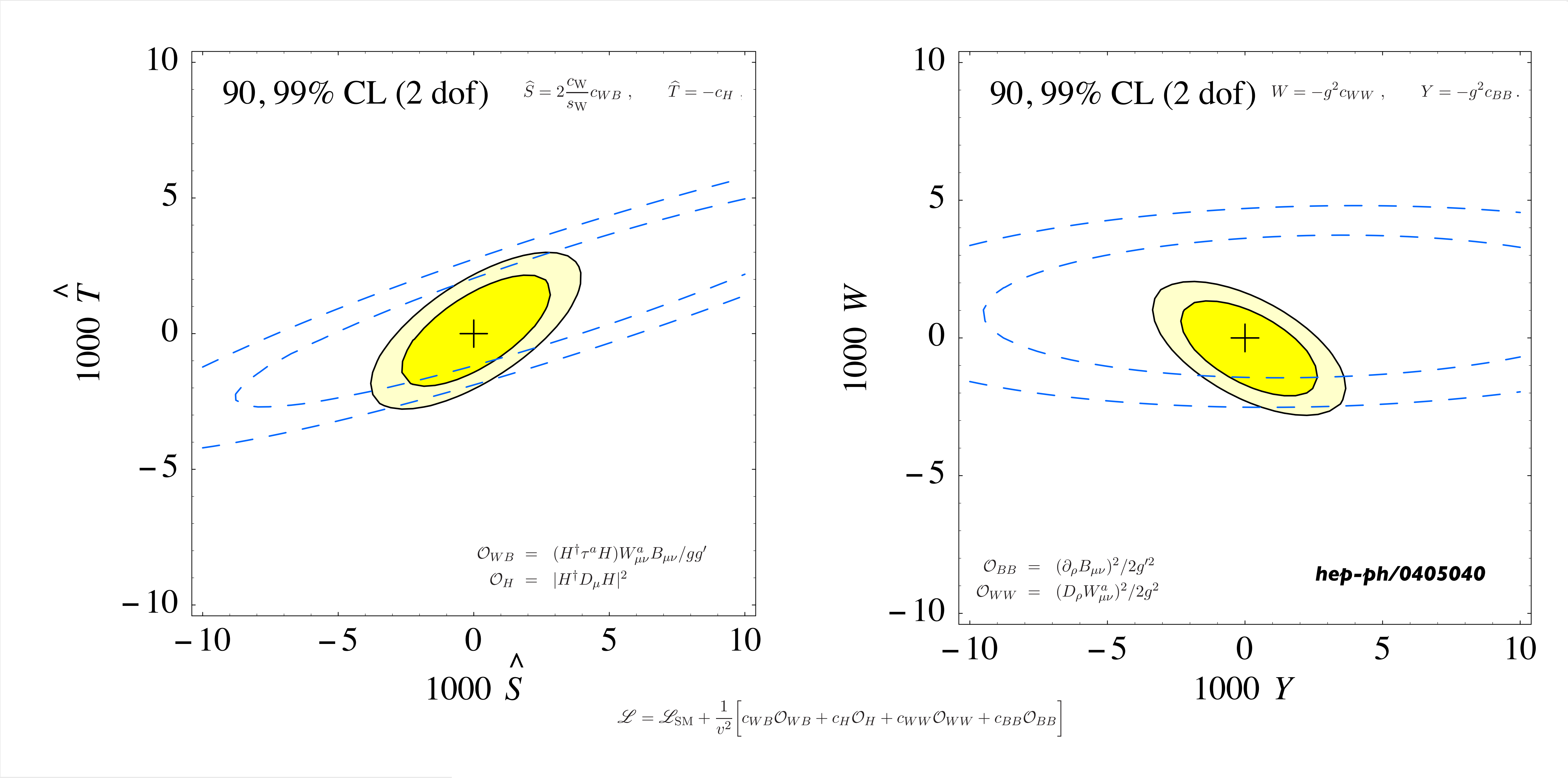


'cause you are
too much
SM-like!



What is the scale we need to reach?





$$S < O(1)$$

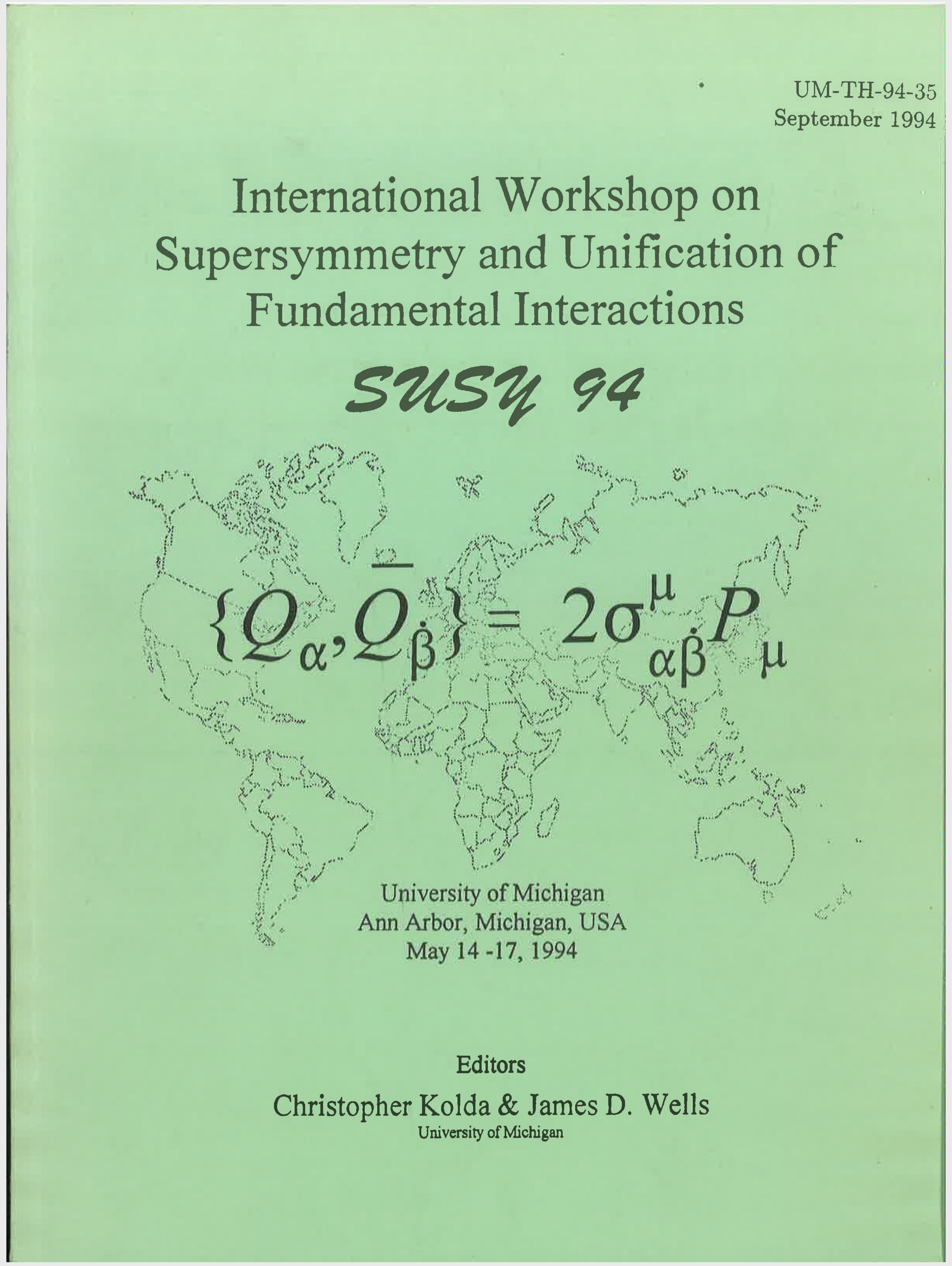
$$M_{NP} > O(10 \cdot m_W)$$

$$S = \frac{4 s_W^2}{\alpha_{em}} \cdot \hat{S} \simeq 119 \cdot \hat{S} < O(0.1)$$

$$M_{NP} > O(30 \cdot m_W)$$

Hints were for new physics above TeV

We had great hopes nevertheless



UM-TH-94-35
September 1994

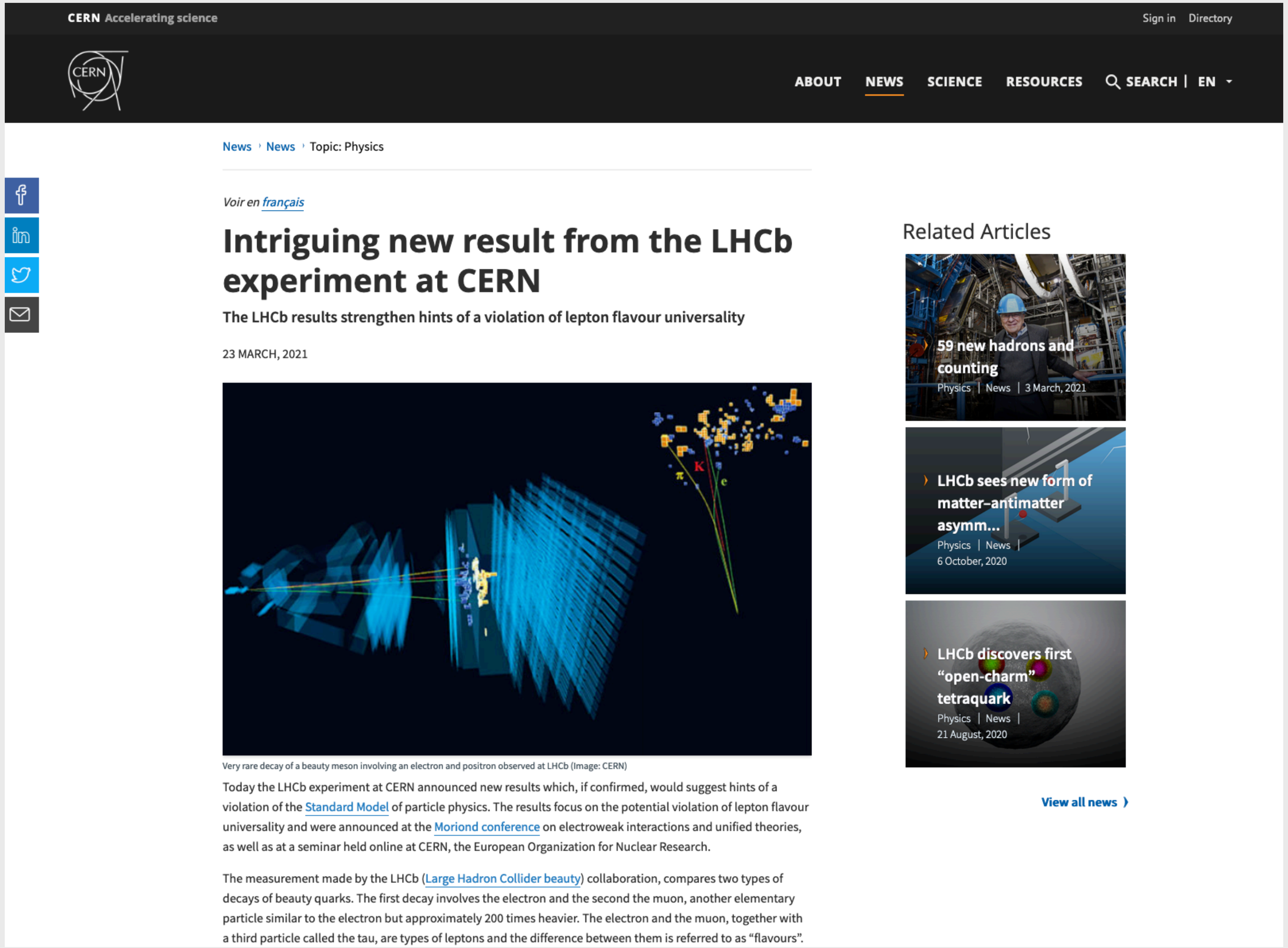
International Workshop on
Supersymmetry and Unification of
Fundamental Interactions

SUSY 94

$$\{Q_\alpha, \bar{Q}_{\dot\beta}\} = 2\sigma^\mu_{\alpha\dot\beta} P_\mu$$

University of Michigan
Ann Arbor, Michigan, USA
May 14 -17, 1994

Editors
Christopher Kolda & James D. Wells
University of Michigan



Voir en français

Intriguing new result from the LHCb experiment at CERN

The LHCb results strengthen hints of a violation of lepton flavour universality

23 MARCH, 2021

Very rare decay of a beauty meson involving an electron and positron observed at LHCb (Image: CERN)

Today the LHCb experiment at CERN announced new results which, if confirmed, would suggest hints of a violation of the Standard Model of particle physics. The results focus on the potential violation of lepton flavour universality and were announced at the Moriond conference on electroweak interactions and unified theories, as well as at a seminar held online at CERN, the European Organization for Nuclear Research.

The measurement made by the LHCb (Large Hadron Collider beauty) collaboration, compares two types of decays of beauty quarks. The first decay involves the electron and the second the muon, another elementary particle similar to the electron but approximately 200 times heavier. The electron and the muon, together with a third particle called the tau, are types of leptons and the difference between them is referred to as “flavours”.

Related Articles

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SM works wonderfully!

‘EFT’ epoch

New Physics may fit well in a EFT (new contact interactions)

- effects grow at larger energies like νe- → νe- in Fermi Theory

HIGH-LUMI PROBES

$m_W, m_Z, \sin\theta_W, A_{FB}^{whatever}, h \to Z\gamma, h \to ZZ, t \to b\tau\nu, \sigma_{tot}(\ell\ell \to hh)$

measurements dominated by a single mass scale

- dominant energy scale is low
- measurement is simple to grasp
- progress is easy to measure (in)significant digits

NP effects may show up in the combination of many precise measurements

fight against systematics

HIGH-ENERGY PROBES

$$\frac{d\sigma}{dp_T}$$

measurements sensitive to a range of mass scales

- sensitive to a range of energy scales
- measurement of a spectrum (not so?!?) simple to grasp
- progress is easy to measure: bounds on new Fermi constants

as NP effects may grow quadratically with energy

$$\Delta O = O_{NP} - O_{SM} \sim \left(\frac{E}{v}\right)^2$$

1% at m_Z is worse than 10% at 1 TeV

“The size of the Higgs boson”

it matters because being “point-like” is the source of all the theoretical questions on the Higgs boson and weak scale

… and if it is not … well, that is physics beyond the Standard Model!

Effects of the size of the Higgs boson

h ~ π STRONGLY INTERACTING LIGHT HIGGS

$$\mathcal{L}^{d=6}_{universal} = c_H \frac{g_*^2}{m_*^2}\mathcal{O}_H + c_T \frac{N_c \epsilon_q^4 g_*^4}{(4\pi)^2 m_*^2}\mathcal{O}_T + c_6 \lambda \frac{g_*^2}{m_*^2}\mathcal{O}_6 + \frac{1}{m_*^2}\left[c_W \mathcal{O}_W + c_B \mathcal{O}_B\right]$$

$$+ \frac{g_*^2}{(4\pi)^2 m_*^2}\left[c_{HW}\mathcal{O}_{HW} + c_{HB}\mathcal{O}_{HB}\right] + \frac{y_t^2}{(4\pi)^2 m_*^2}\left[c_{BB}\mathcal{O}_{BB} + c_{GG}\mathcal{O}_{GG}\right]$$

$$+ \frac{1}{g_*^2 m_*^2}\left[c_{2W} g^2 \mathcal{O}_{2W} + c_{2B} g'^2 \mathcal{O}_{2B}\right] + c_{3W}\frac{3! g^2}{(4\pi)^2 m_*^2}\mathcal{O}_{3W}$$

$$+ c_{y_t}\frac{g_*^2}{m_*^2}\mathcal{O}_{y_t} + c_{y_b}\frac{g_*^2}{m_*^2}\mathcal{O}_{y_b}$$

$1/f \sim g_\star/m_\star$

$1/(g_\star f) \sim 1/m_\star$

$g_{SM}/(g_\star f) \sim g_{SM}/m_\star$

$\ell_{Higgs} \sim 1/m_\star$

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

Ever higher energy colliders can exploit “precise” measurements at the 10% level

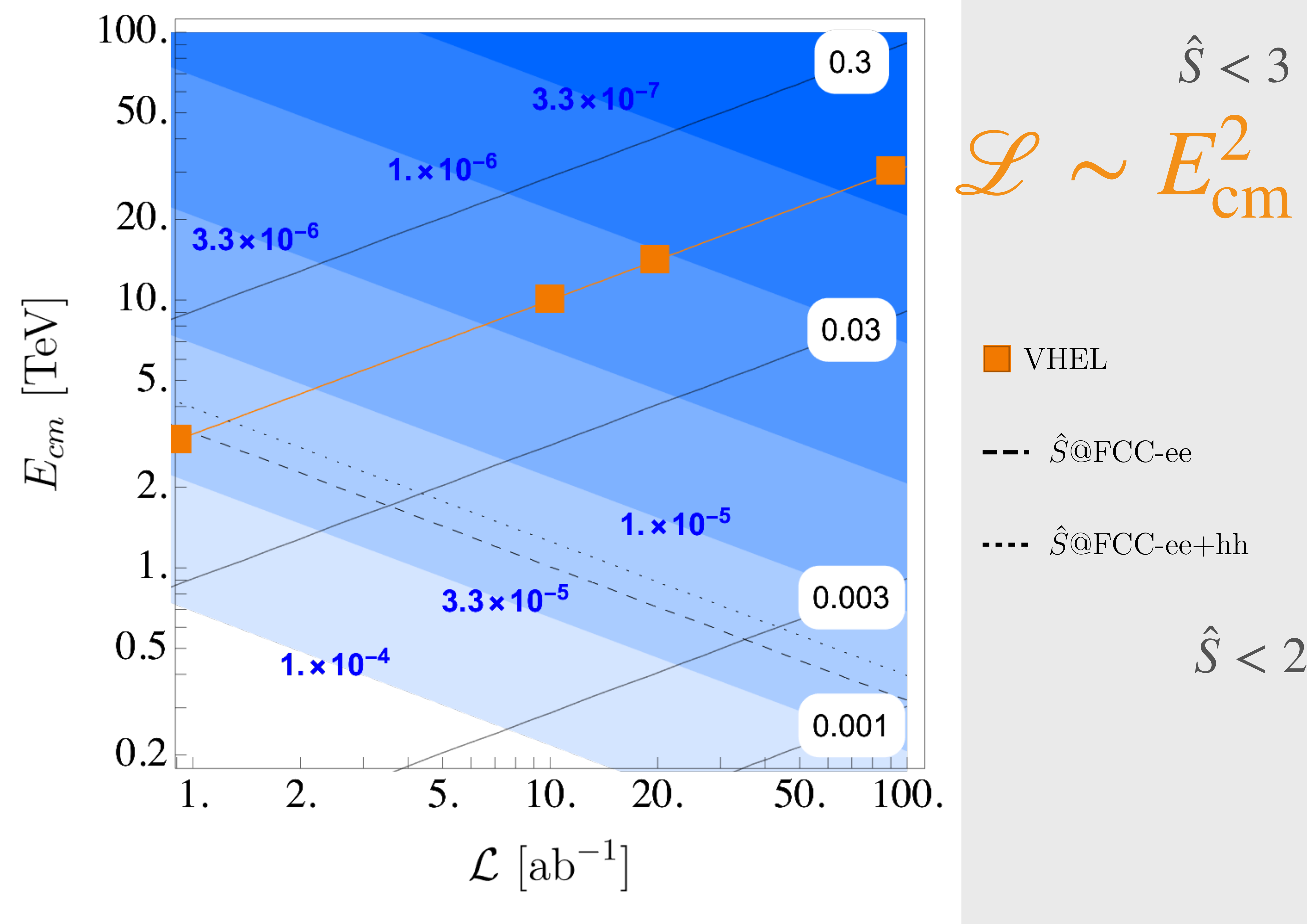
TOTAL **RATE**

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

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

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

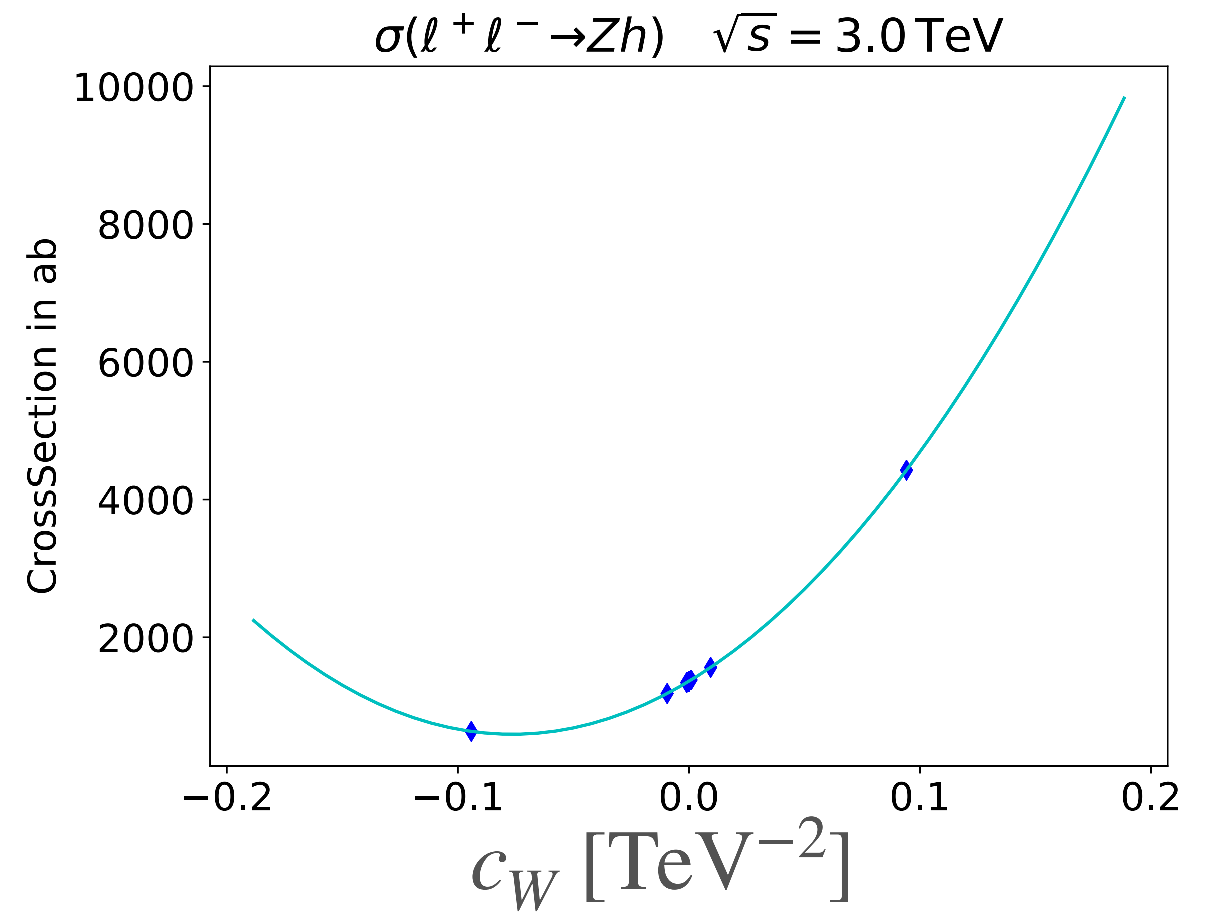
$$\hat{S}_{95\%} \lesssim 1.2\cdot 10^{-4}\frac{1}{E_{beam}/\mathrm{TeV}}\cdot\frac{1}{\sqrt{\mathscr{L}/\mathrm{ab}^{-1}}}$$



$$\mathscr{L} \sim E_{cm}^2$$

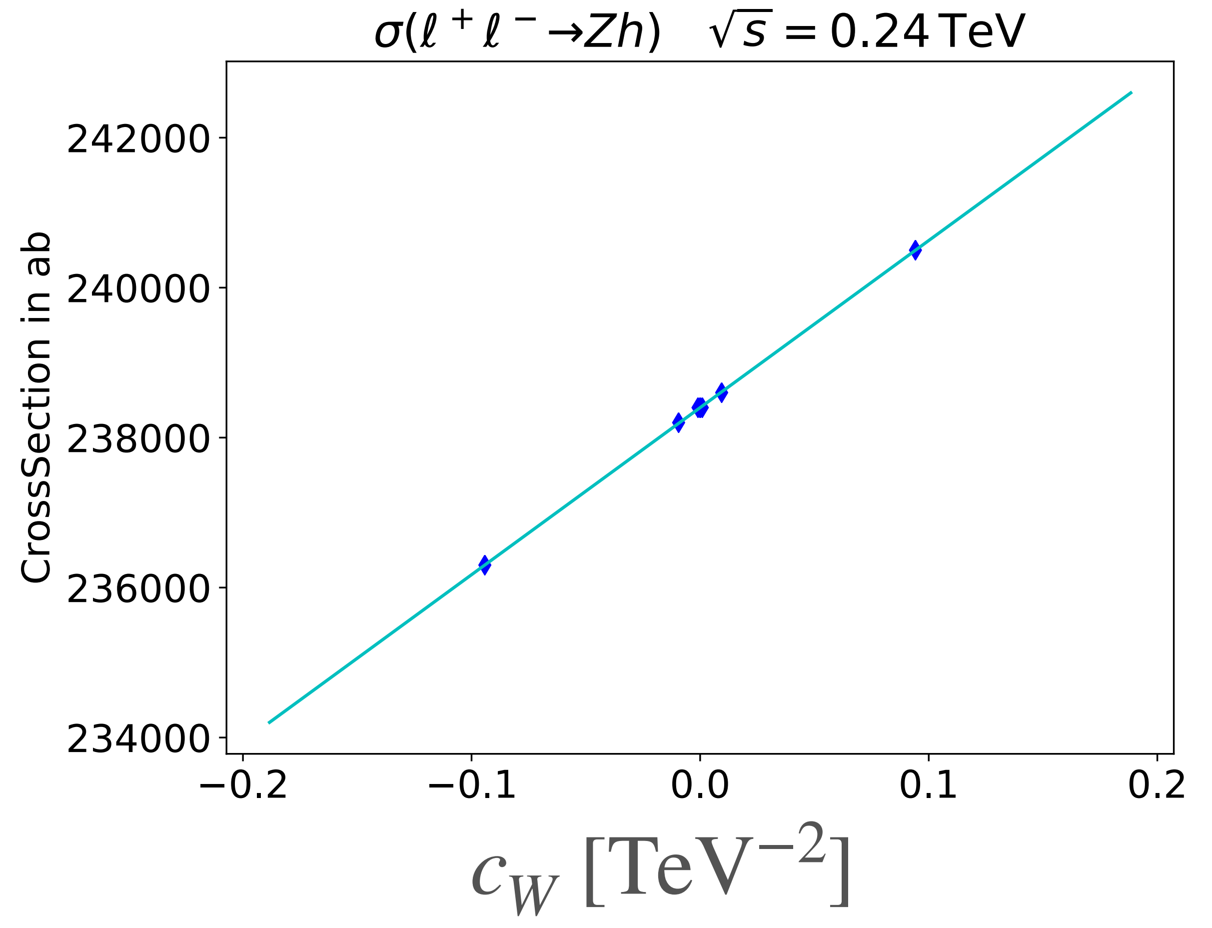
$\hat{S} < 3\cdot 10^{-5}$ (95 % CL)

$\mathscr{L} = 5\ \mathrm{ab}^{-1}$



$\hat{S} < 2\cdot 10^{-4}$ (95 % CL)

$\mathscr{L} = 5\ \mathrm{ab}^{-1}$



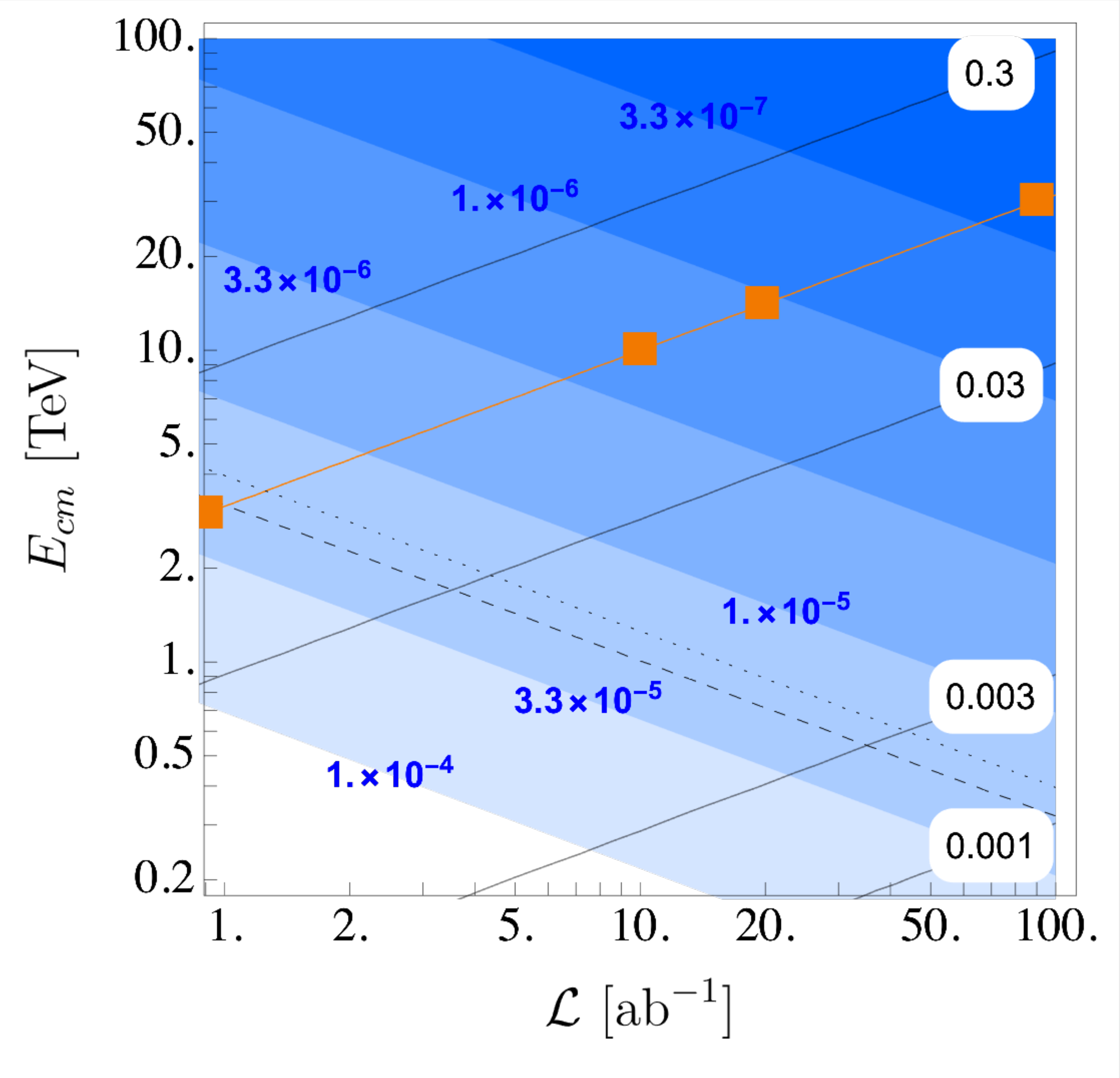
$\ell^+\ell^- \to \mathrm{Zh}$

Ever higher energy colliders can exploit “precise” measurements at the 10% level

TOTAL **RATE**

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

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



$$\hat{S} \equiv c_W/m_W^2 \simeq \frac{\delta O}{O} \text{ at Z pole}$$

GOING TO HIGHER ENERGY WE CAN EXPLOIT “PRECISE” MEASUREMENTS AT THE 10% LEVEL, AVOIDING THE BOTTLENECK OF SYSTEMATIC UNCERTAINTIES

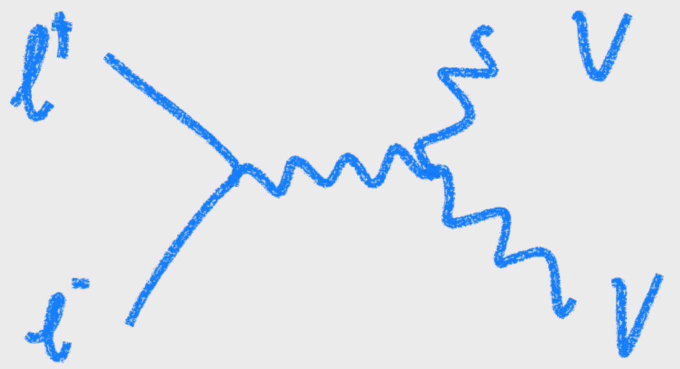
$\ell^+\ell^- \to VV$

EFT EPOCH

LESSON FROM LHC

$$\left.\begin{array}{l}\ell^+\ell^- \to W^+W^- \\ \ell^+\ell^- \to Zh \\ \ell^+\ell^- \to hh\end{array}\right\}$$

two-body charge neutral final states



$$\left.\begin{array}{l}\ell^+\ell^- \to W^+h \;+\; X^- \\ \ell^+\ell^- \to W^+Z \;+\; X^- \\ \ell^+\ell^- \to \dots\end{array}\right\}$$

many-body charge neutral final states

1712.01310

Amplitude	High-energy primaries	Low-energy primaries
$\bar u_L d_L \to W_L Z_L, W_L h$	$\sqrt{2} a_q^{(3)}$	$\sqrt{2}\frac{g^2}{m_W^2}\left[c_{\theta_W}(\delta g^Z_{uL} - \delta g^Z_{dL})/g - c^2_{\theta_W}\delta g^Z_1\right]$
$\bar u_L u_L \to W_L W_L$ $\bar d_L d_L \to Z_L h$	$a_q^{(1)} + a_q^{(3)}$	$-\frac{2g^2}{m_W^2}\left[Y_L t^2_{\theta_W}\delta\kappa_\gamma + T_Z^{u_L}\delta g^Z_1 + c_{\theta_W}\delta g^Z_{dL}/g\right]$
$\bar d_L d_L \to W_L W_L$ $\bar u_L u_L \to Z_L h$	$a_q^{(1)} - a_q^{(3)}$	$-\frac{2g^2}{m_W^2}\left[Y_L t^2_{\theta_W}\delta\kappa_\gamma + T_Z^{d_L}\delta g^Z_1 + c_{\theta_W}\delta g^Z_{uL}/g\right]$
$\bar f_R f_R \to W_L W_L, Z_L h$	a_f	$-\frac{2g^2}{m_W^2}\left[Y_{f_R} t^2_{\theta_W}\delta\kappa_\gamma + T_Z^{f_R}\delta g^Z_1 + c_{\theta_W}\delta g^Z_{fR}/g\right]$

Process	BSM Amplitude
$\ell^+_L\ell^-_L \to Z_0 h$ $\bar\nu_L\nu_L \to W^+_0 W^-_0$	$s\,(G_{3L} + G_{1L})\sin\theta_\star$
$\ell^+_L\ell^-_L \to W^+_0 W^-_0$ $\bar\nu_L\nu_L \to Z_0 h$	$s\,(G_{3L} - G_{1L})\sin\theta_\star$
$\ell^+_R\ell^-_R \to W^+_0 W^-_0\,, Z_0 h$	$s\,G_{lR}\sin\theta_\star$
$\bar\nu_L\ell^-_L \to W^-_0 Z_0\,/\,W^-_0 h$ $\nu_L\ell^+_L \to W^+_0 Z_0\,/\,W^+_0 h$	$\sqrt{2}\,s\,G_{3L}\sin\theta_\star$

$$G_{3L} = \frac{g^2}{4}(C_W + C_{HW})\,, \qquad G_{1L} = \frac{g'^2}{4}(C_B + C_{HB}) = \frac{1}{2}G_{lR}\,,$$

Bottom line: two primary BSM effects describe high energy scattering into "diboson" in universal theories.

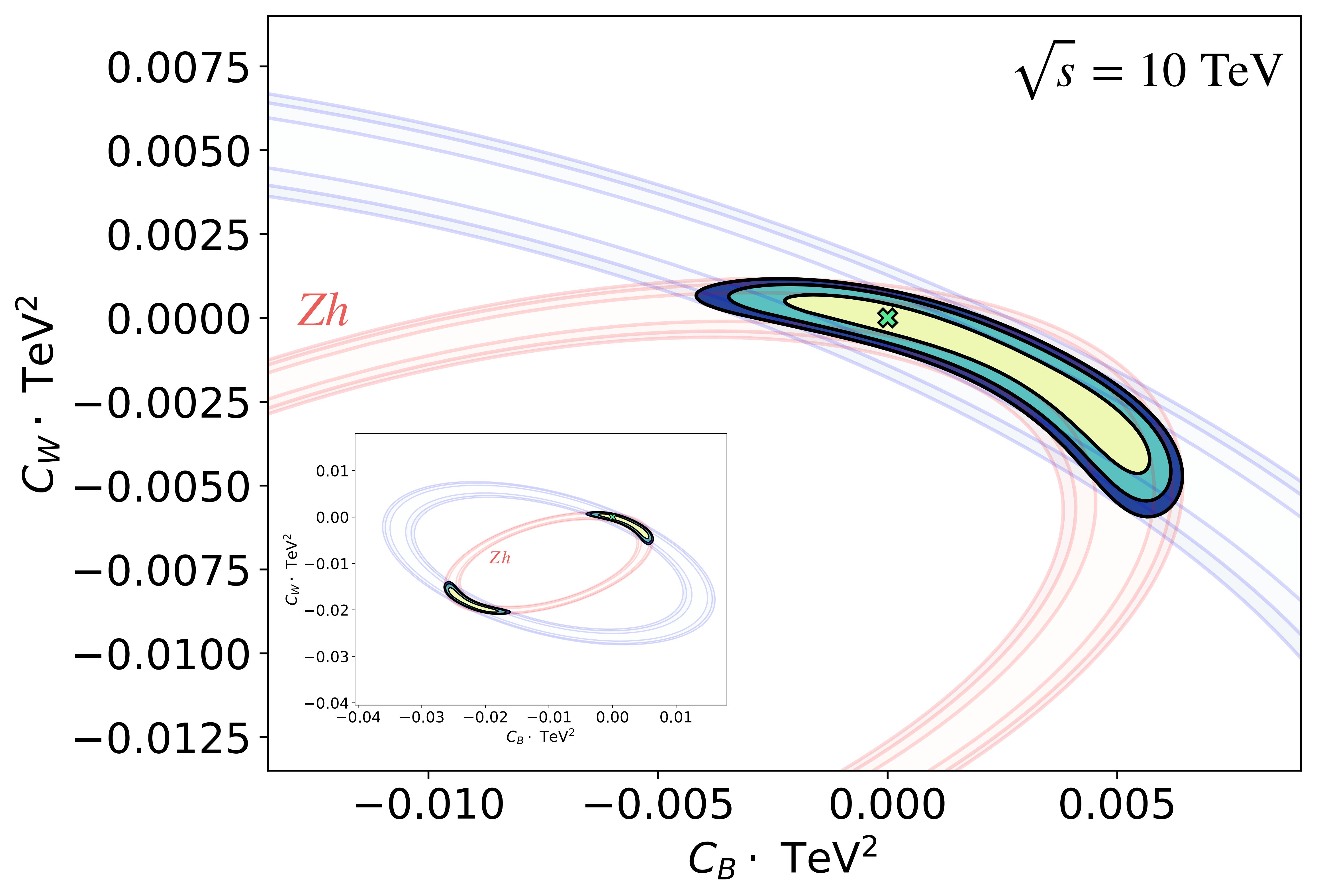
The hard 2→ 2 sub-scattering can be described in the same way, just "dressing" it with low momentum transfer emissions of extra bodies

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

DIBOSON

Z→ HADRONS H→ $b\bar{b}$

BSM and SM amplitudes have the same angular dependences, so the most powerful analysis is a simple cut-and-count.



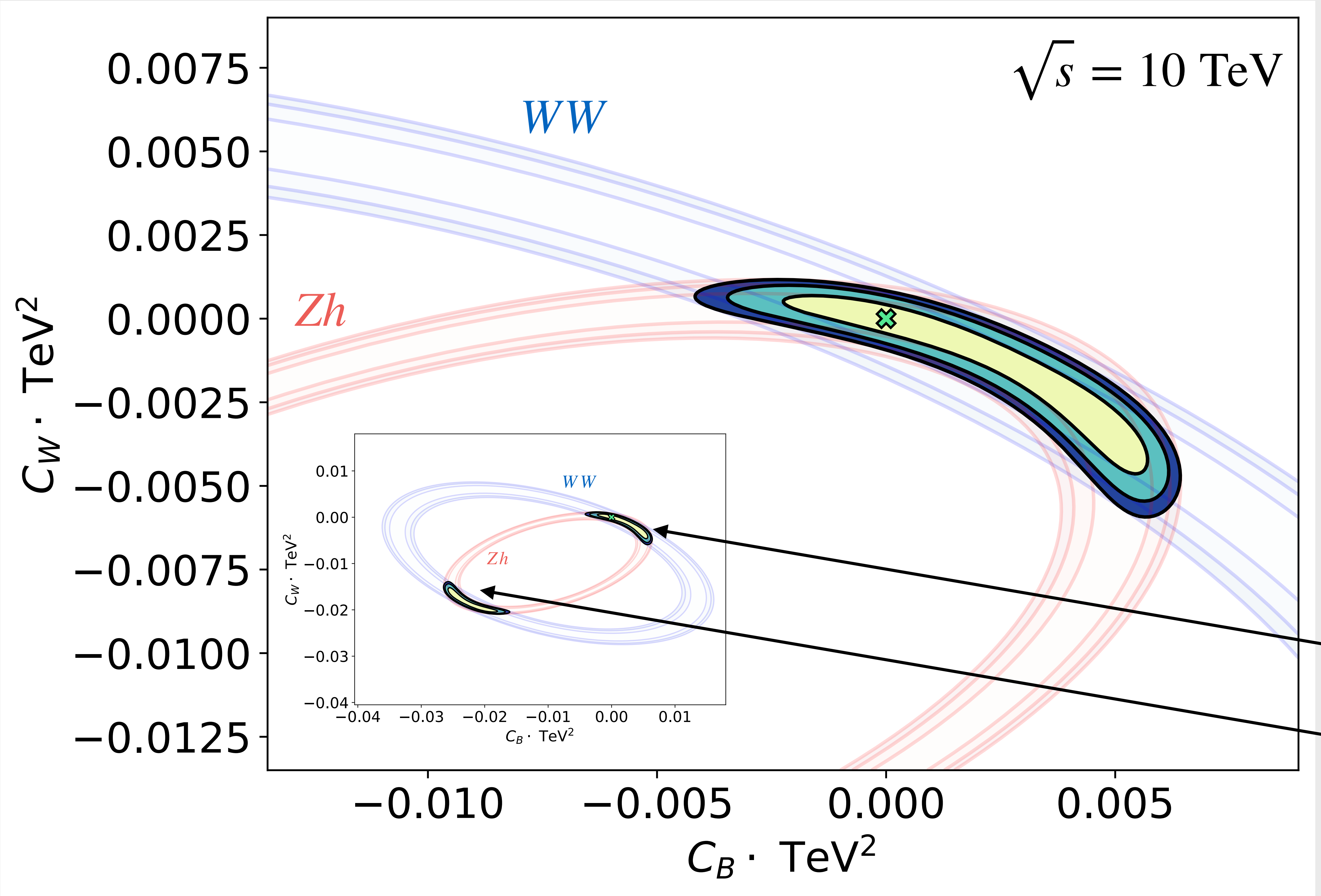
ZH: elliptical belt in 2D BSM coupling space

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

DIBOSON

$W^\pm\to$ HADRONS, $W^\mp\to$ LEPTONS

BSM and SM amplitudes **do not** have the same angular dependences, so the most powerful analysis is differential!



ZH: elliptical belt in 2D BSM coupling space

WW: (simplest) inclusive cut-and-count → elliptical belt in 2D BSM coupling space

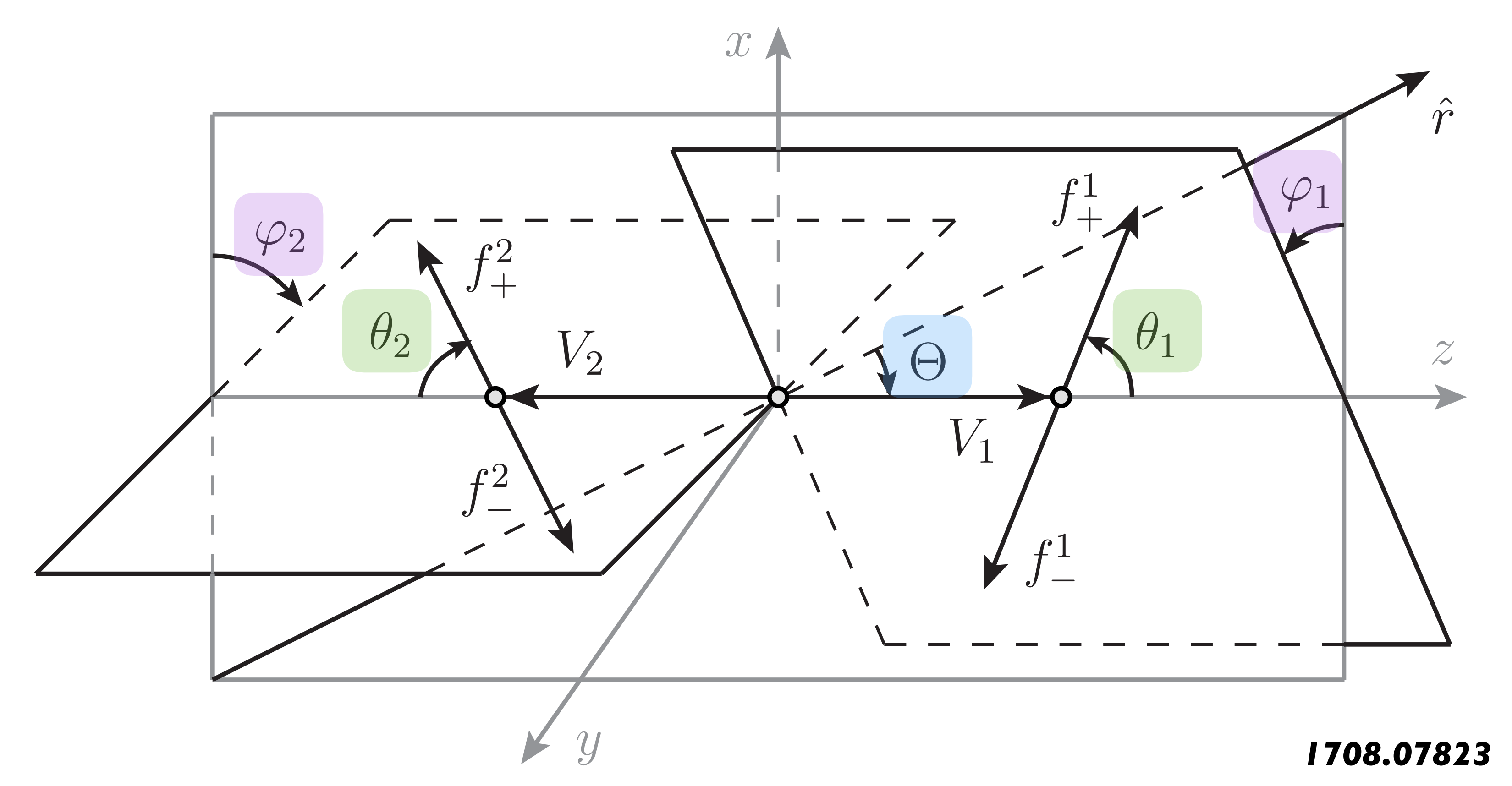
SM

SM-like rate, but large BSM couplings (destructive interference)

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

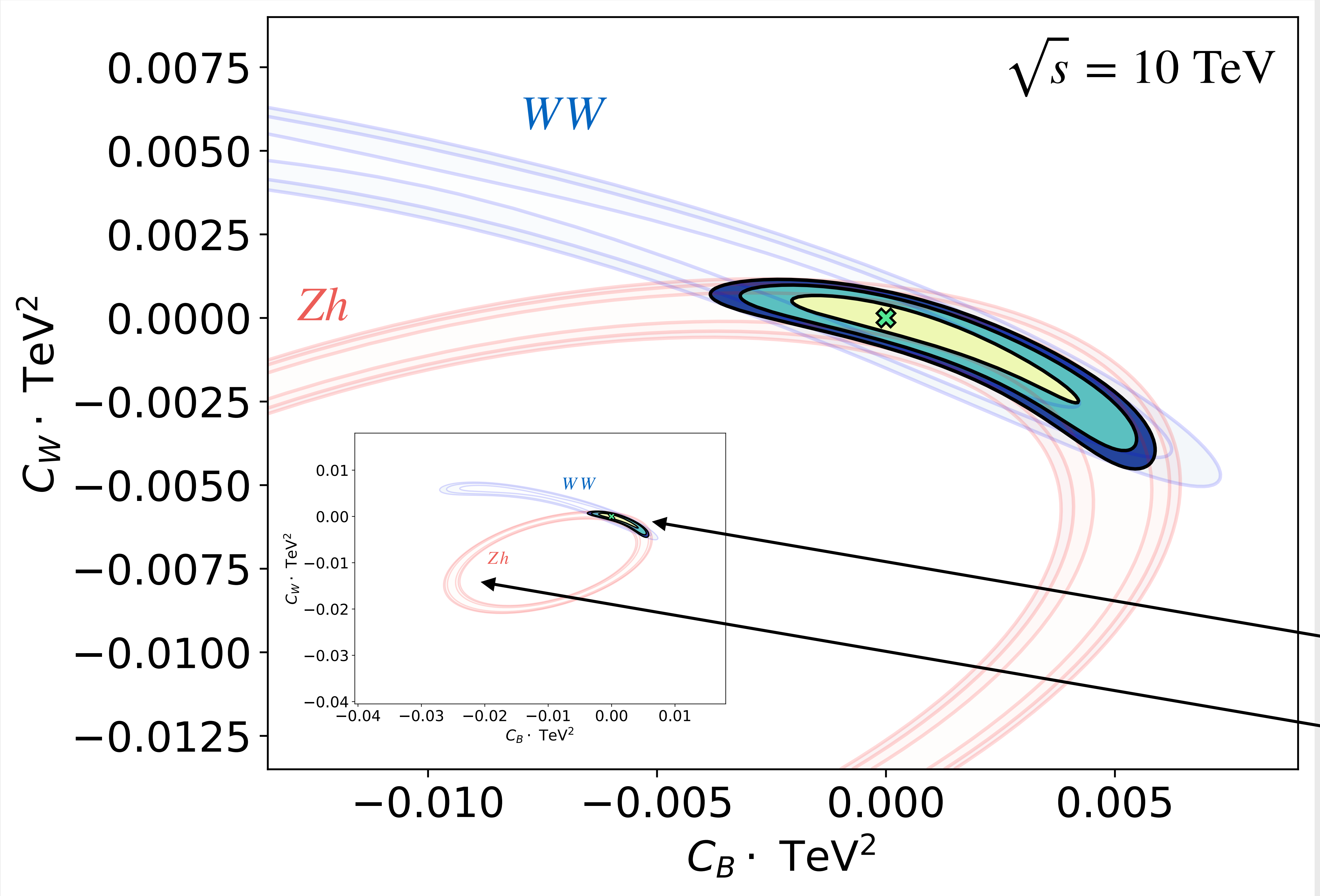
EFT EPOCH

LESSON FROM LHC



1708.07823

BSM and SM amplitudes **do not** have the same angular dependences, so **the most powerful analysis is differential**!



ZH: elliptical belt in 2D BSM coupling space

WW: (most useful) differential analysis tracking

- 🟦 2→ 2 polar scattering angle
- 🟩 W decay polar angles
- 🟪 W decay azimuthal angles 1708.07823

SM

~~SM-like rate, but large BSM couplings (destructive interference)~~

Sharpening the result

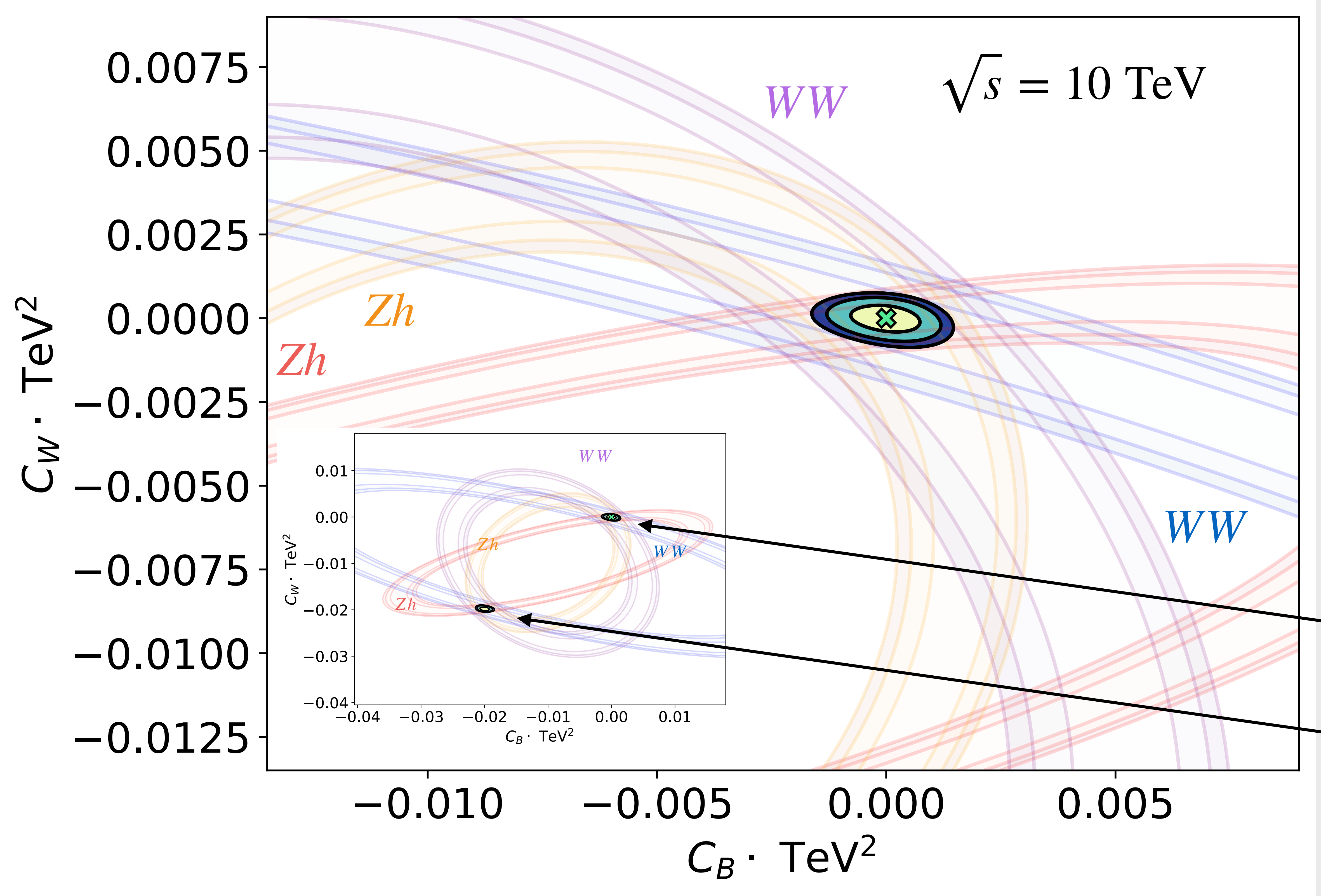
Two less standard way

- Beam polarization
- Multi-body processes

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

POLARIZED BEAMS

polarized BSM and SM amplitudes have each a different dependence on BSM couplings



Beams mostly

RH LH

🟧 🟥 ZH: elliptical belt in 2D BSM coupling space

🟪 🟦 WW: elliptical belt in 2D BSM coupling space

“mostly”: 30% polarization in our analysis (exact value depends on unknown machine parameters)

SM

~~SM-like rate, but very large BSM couplings which correspond to new physics directly accessible at the same collider~~

Sharpening the result

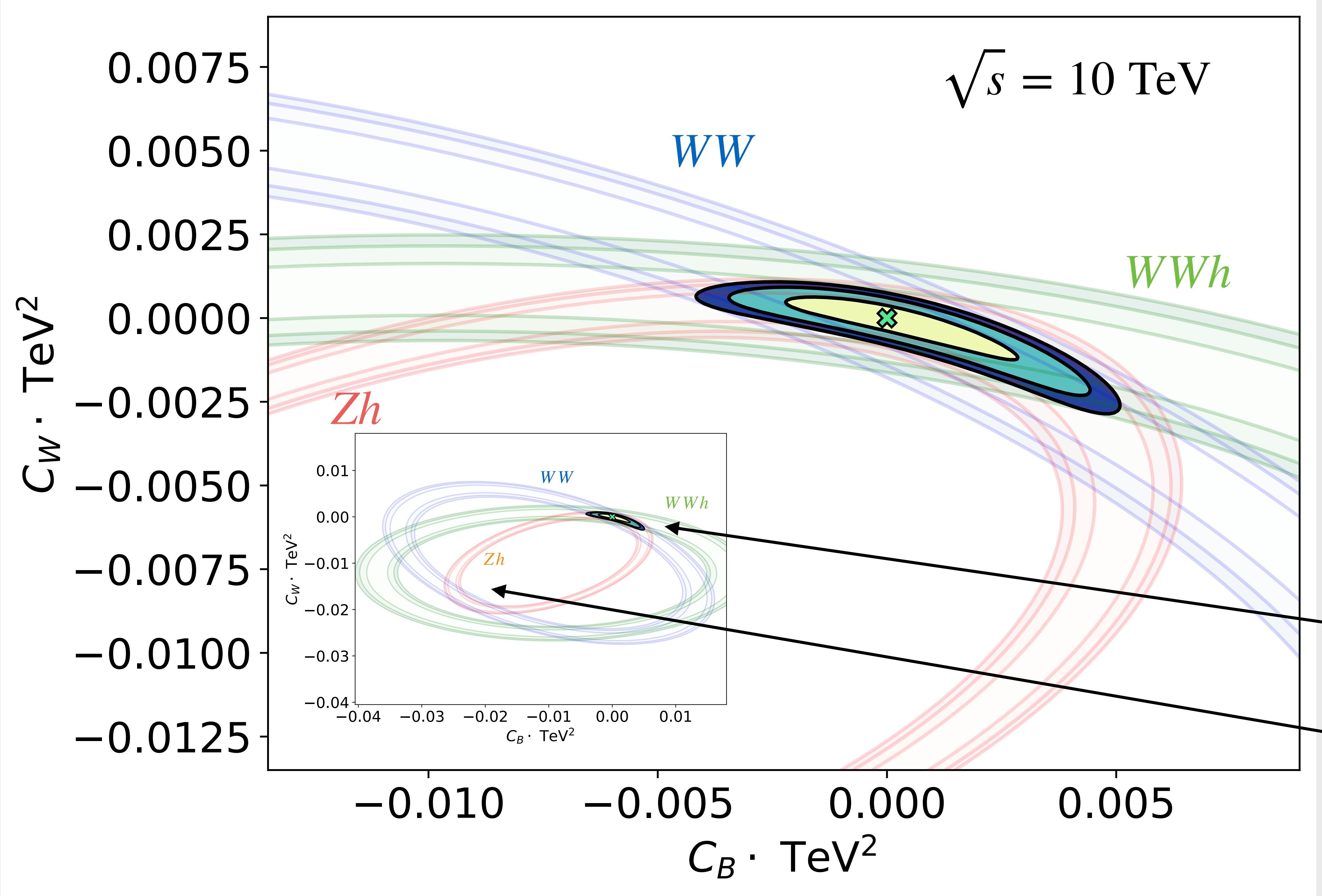
Two less standard way

- Beam polarization
- Multi-body processes

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

MULTI-BODY | **WEAK RADIATION**

multi-body can contain hard sub-scattering with net electric charge, e.g. $e\nu \to Wh, WZ$ with new BSM couplings dependence



🟥 ZH: elliptical belt in 2D BSM coupling space

🟦 WW: elliptical belt in 2D BSM coupling space

🟩 WWh: elliptical belt in 2D BSM coupling space

SM

~~SM-like rate, but very large BSM couplings which correspond to new physics directly accessible at the same collider~~

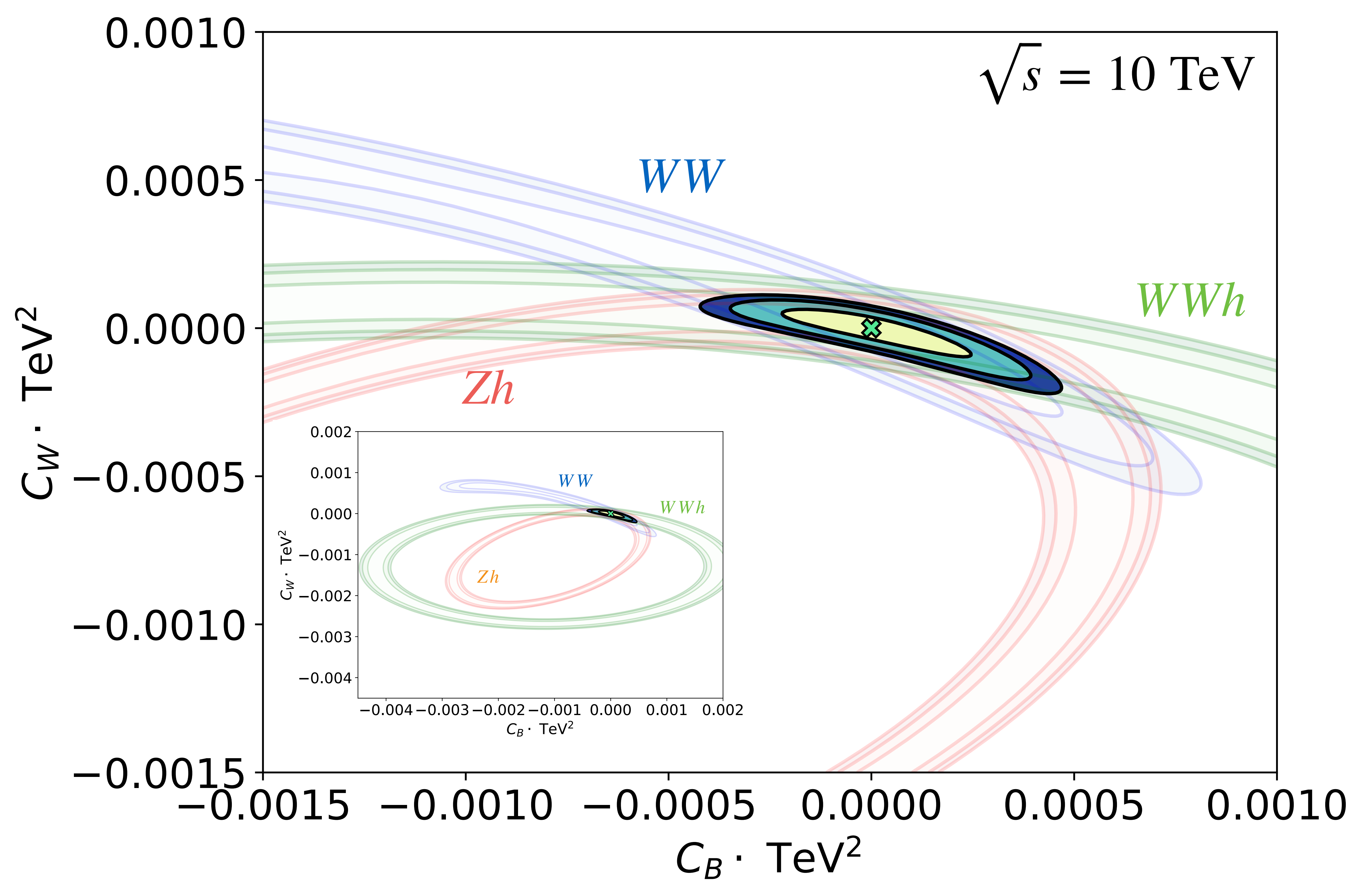
$\ell^+\ell^- \to VV+X$

DI-BOSON ⊕ **MULTI-BOSON**

ZH: BSM and SM amplitudes have the same angular dependences, so the most powerful analysis is a simple cut-and-count.

WW: BSM and SM amplitudes **do not** have the same angular dependences, so the most powerful analysis is differential!

multi-body can contain hard sub-scattering with net electric charge, e.g. $e\nu \to Wh, WZ$ with new BSM couplings dependence



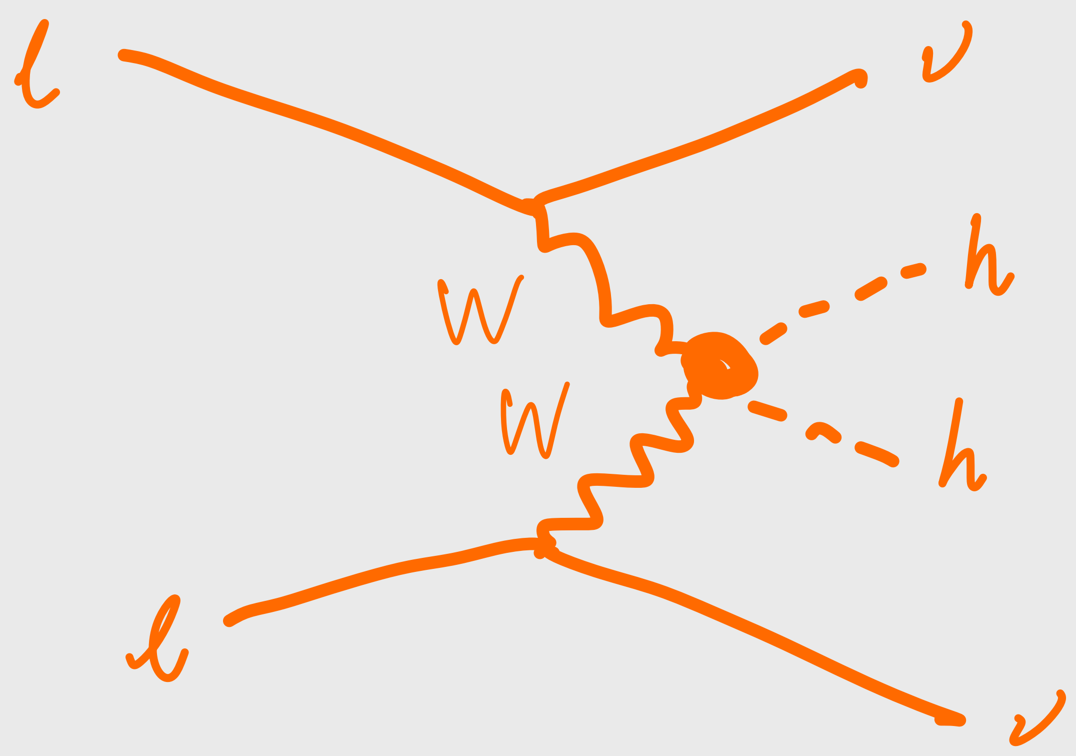
🟥 ZH: elliptical belt in 2D BSM coupling space

🟦 WW: basin in 2D BSM coupling space

🟩 WWh: elliptical belt in 2D BSM coupling space

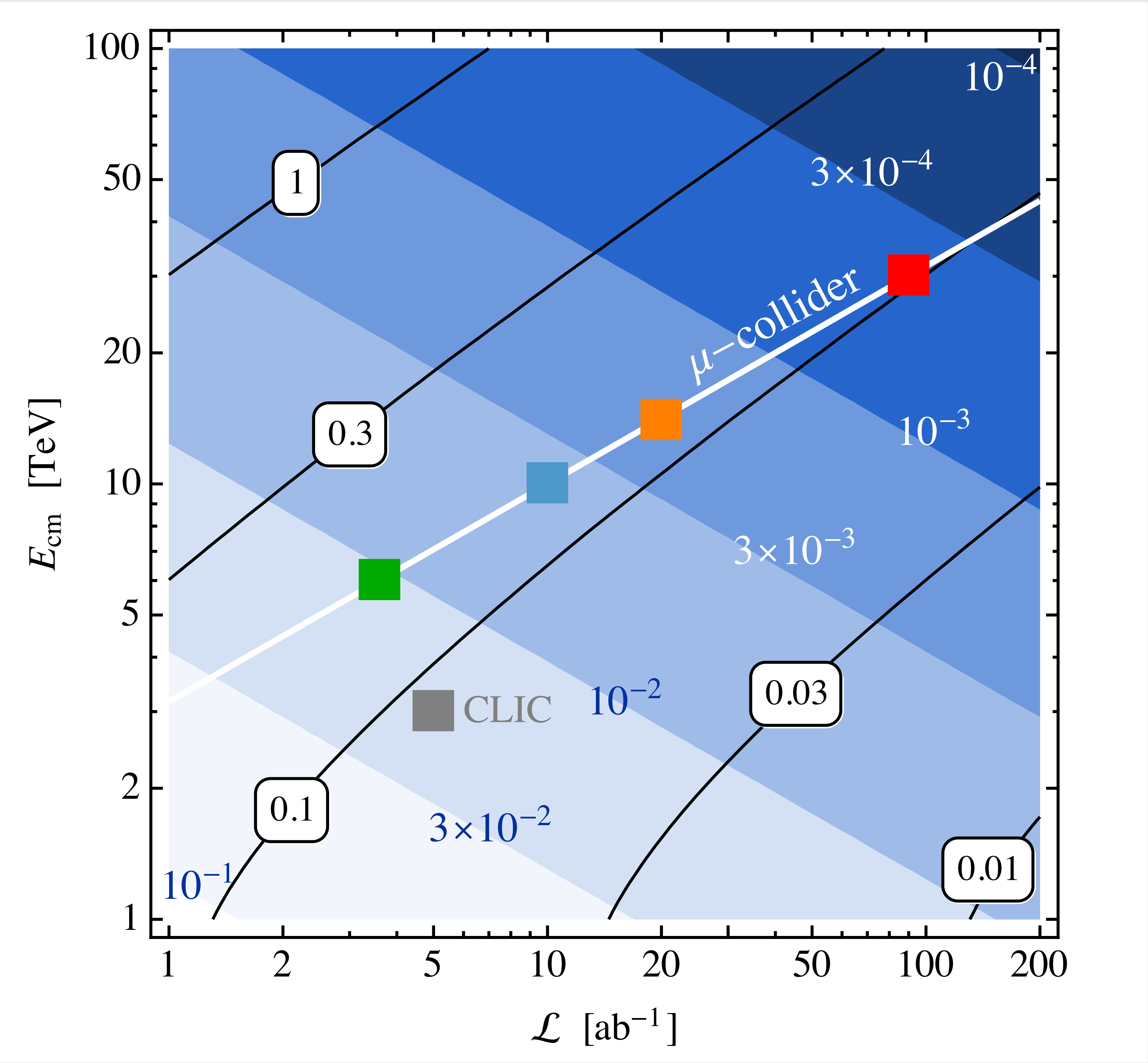
$\ell^+\ell^- \to \mathbf{hh}$

W BOSON **COLLIDER**



High-Energy lepton collider has large flux of "partonic" W bosons

less powerful than $\ell\ell \to VV$ because $WW \to anything$ CoM energy is smaller than $\ell\ell$



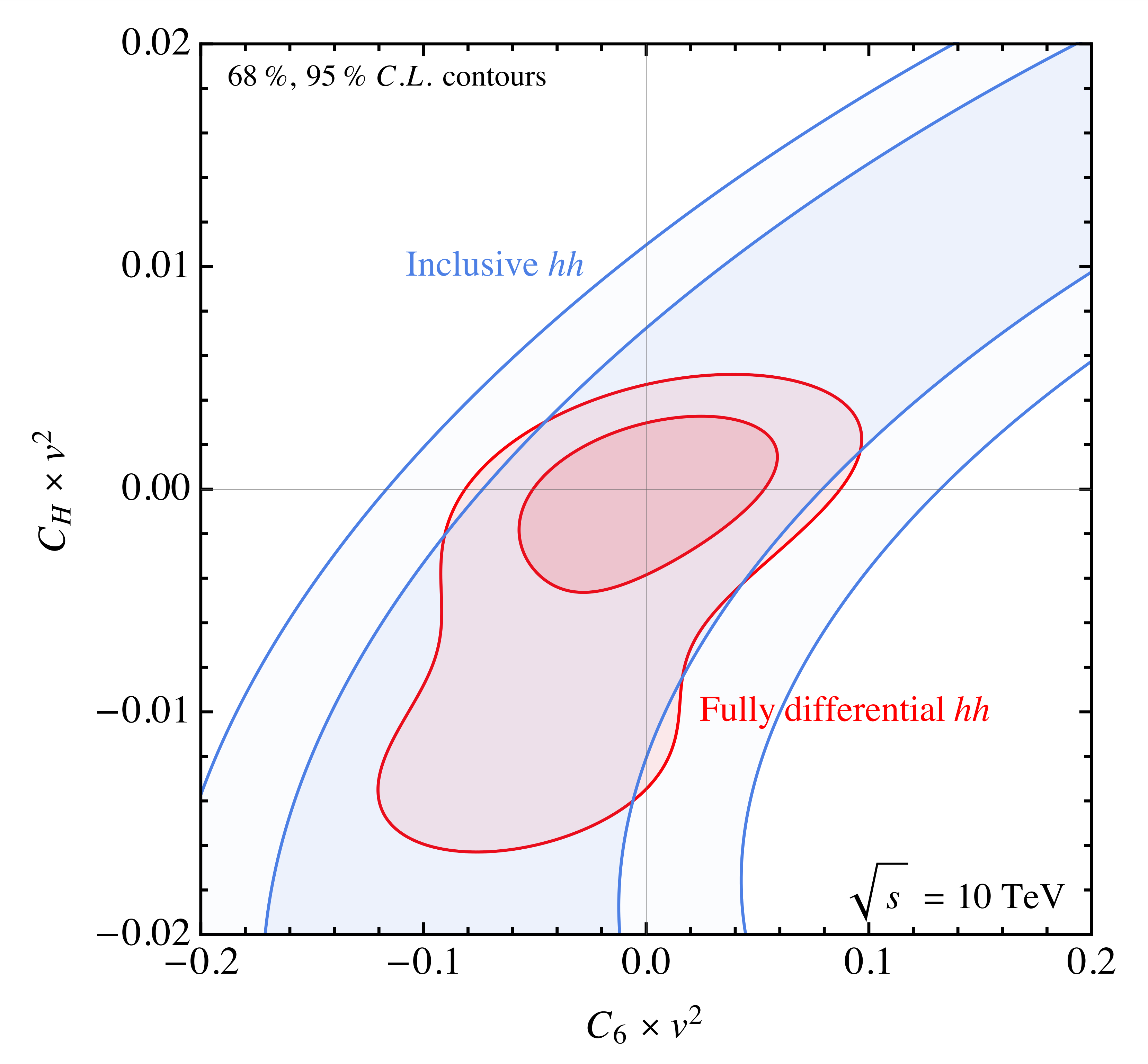
need large p$_T$ Higgs bosons

$$\Rightarrow \text{upper bound on } \xi \sim \frac{1}{E\sqrt{\mathcal{L}}}$$

$$\sqrt{s} = 3 \text{ TeV} \quad \mathcal{L} = 3 \text{ ab}^{-1} \quad \xi = \frac{v^2}{f^2} < 0.01$$

$$\downarrow$$

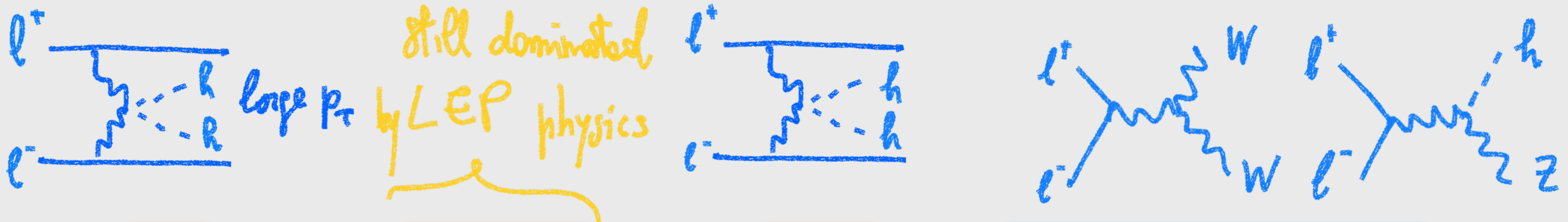
$$\xi < 2 \cdot 10^{-4} \text{ at } \sqrt{s} = 30 \text{ TeV}$$



Effects of the size of the Higgs boson

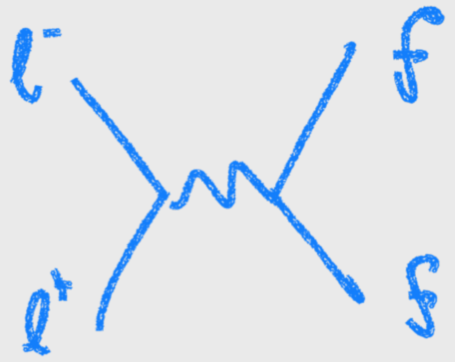
h ~ π

STRONGLY INTERACTING LIGHT HIGGS



$$\mathcal{L}^{d=6}_{universal} = c_H \frac{g_*^2}{m_*^2}\mathcal{O}_H + c_T \frac{N_c \epsilon_q^4 g_*^4}{(4\pi)^2 m_*^2}\mathcal{O}_T + c_6 \lambda \frac{g_*^2}{m_*^2}\mathcal{O}_6 + \frac{1}{m_*^2}\left[c_W\mathcal{O}_W + c_B\mathcal{O}_B\right]$$

$$+ \frac{g_*^2}{(4\pi)^2 m_*^2}\left[c_{HW}\mathcal{O}_{HW} + c_{HB}\mathcal{O}_{HB}\right] + \frac{y_t^2}{(4\pi)^2 m_*^2}\left[c_{BB}\mathcal{O}_{BB} + c_{GG}\mathcal{O}_{GG}\right]$$



$$+ \frac{1}{g_*^2 m_*^2}\left[c_{2W} g^2 \mathcal{O}_{2W} + c_{2B} g'^2 \mathcal{O}_{2B}\right] + c_{3W}\frac{3! g^2}{(4\pi)^2 m_*^2}\mathcal{O}_{3W}$$

$$+ c_{y_t}\frac{g_*^2}{m_*^2}\mathcal{O}_{y_t} + c_{y_b}\frac{g_*^2}{m_*^2}\mathcal{O}_{y_b}$$

$1/f \sim g_\star/m_\star$

$1/(g_\star f) \sim 1/m_\star$

$g_{SM}/(g_\star f) \sim g_{SM}/m_\star$

$\ell_{Higgs} \sim 1/m_\star$

SM works wonderfully!

New Physics may fit well in a EFT (new contact interactions)

- effects grow at larger energies like $\nu e^- \to \nu e^-$ in Fermi Theory

HIGH-LUMI PROBES

$$m_W, m_Z, \sin\theta_W, A_{FB}^{whatever}, h \to Z\gamma, h \to ZZ, t \to b\tau\nu, \sigma_{tot}(\ell\ell \to hh)$$

measurements dominated by a single mass scale

- dominant energy scale is low
- measurement is simple to grasp
- progress is easy to measure (in)significant digits

NP effects may show up in the combination of many precise measurements

fight against systematics

HIGH-ENERGY PROBES

$$\frac{d\sigma}{dp_T}$$

measurements sensitive to a range of mass scales

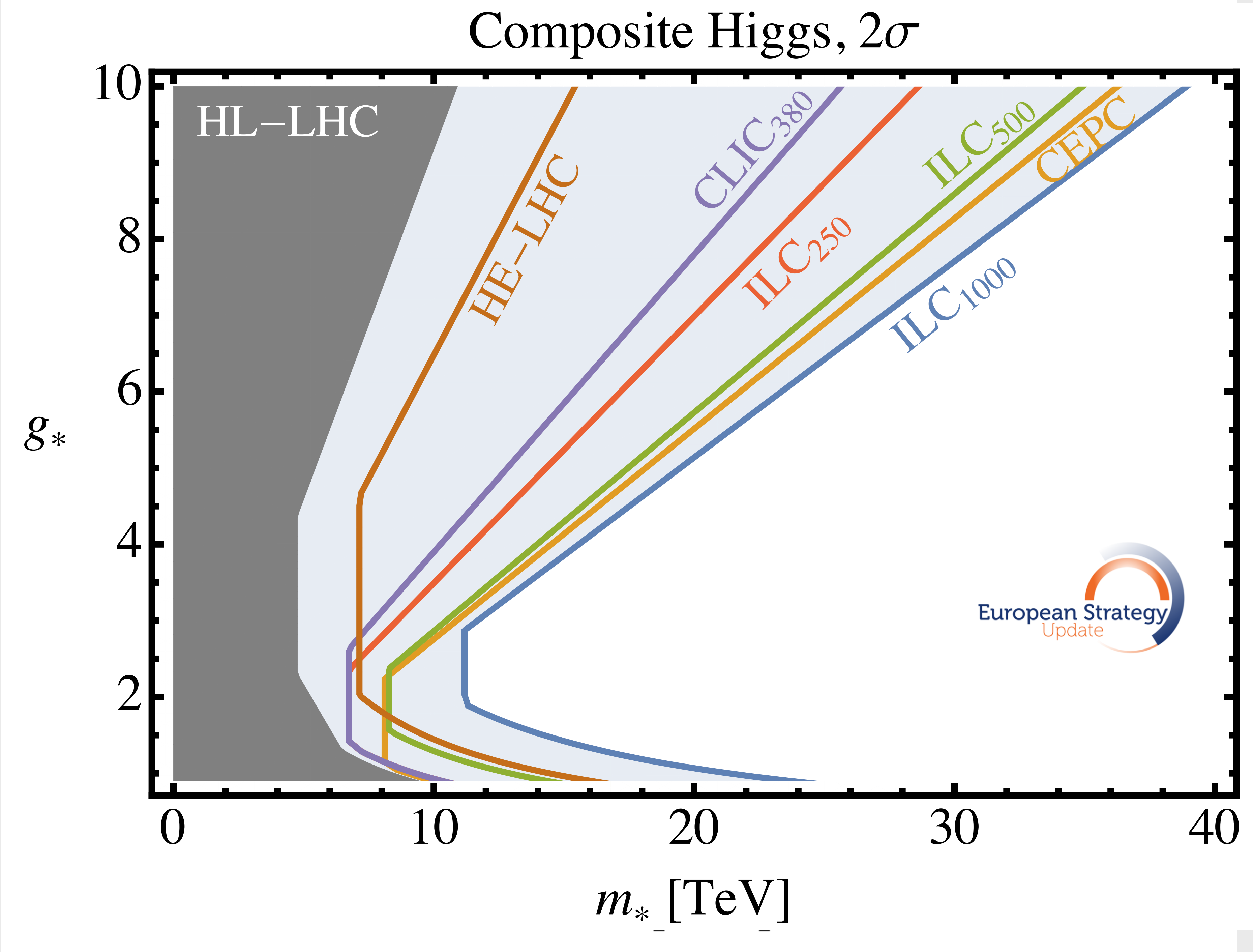
- sensitive to a range of energy scales
- measurement of a spectrum (not so?!?) simple to grasp
- progress is easy to measure: bounds on new Fermi constants

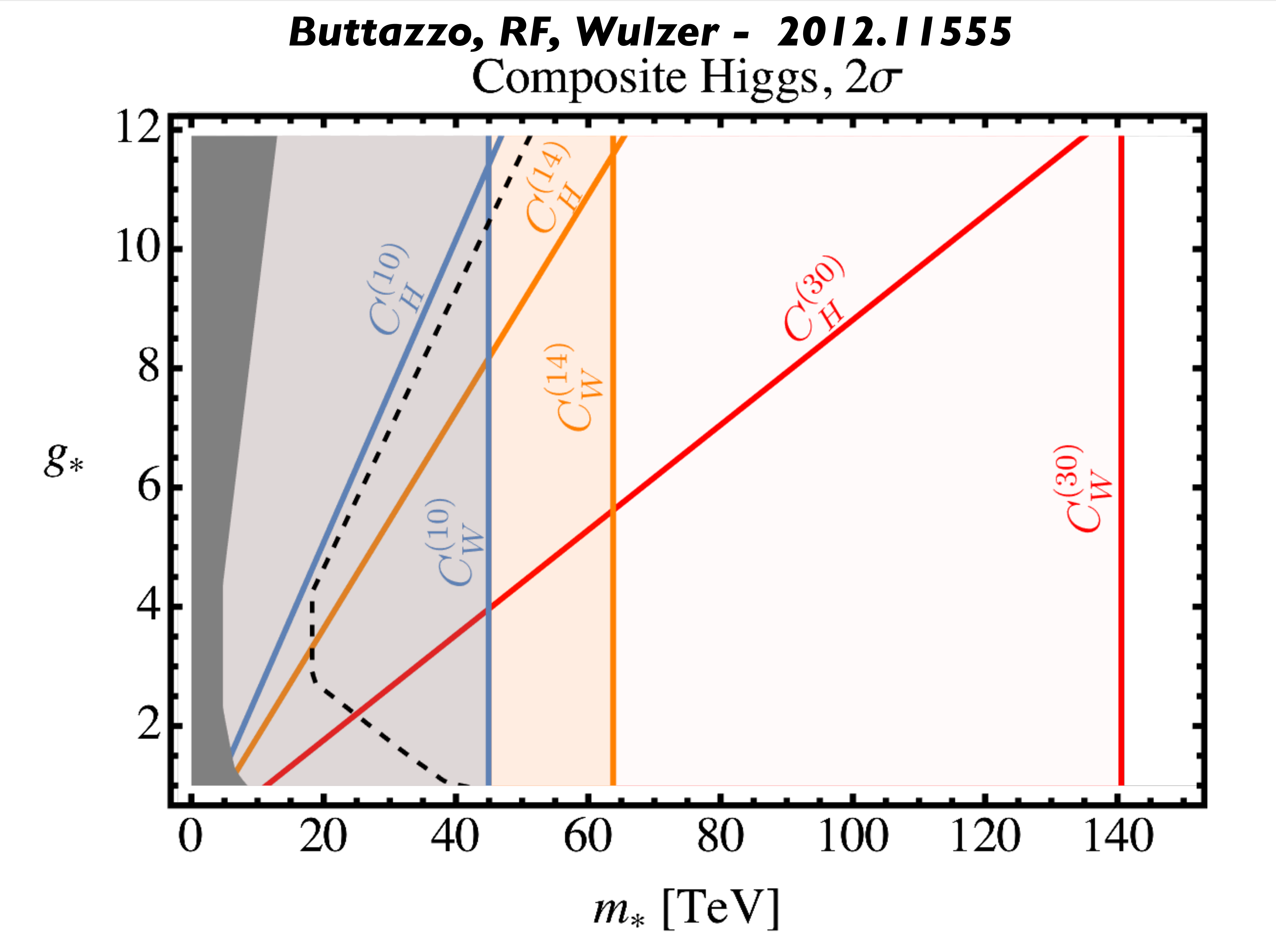
as NP effects may grow quadratically with energy

$$\Delta O = O_{NP} - O_{SM} \sim \left(\frac{E}{v}\right)^2$$

1% at m_Z is worse than 10% at 1 TeV

Looking ahead





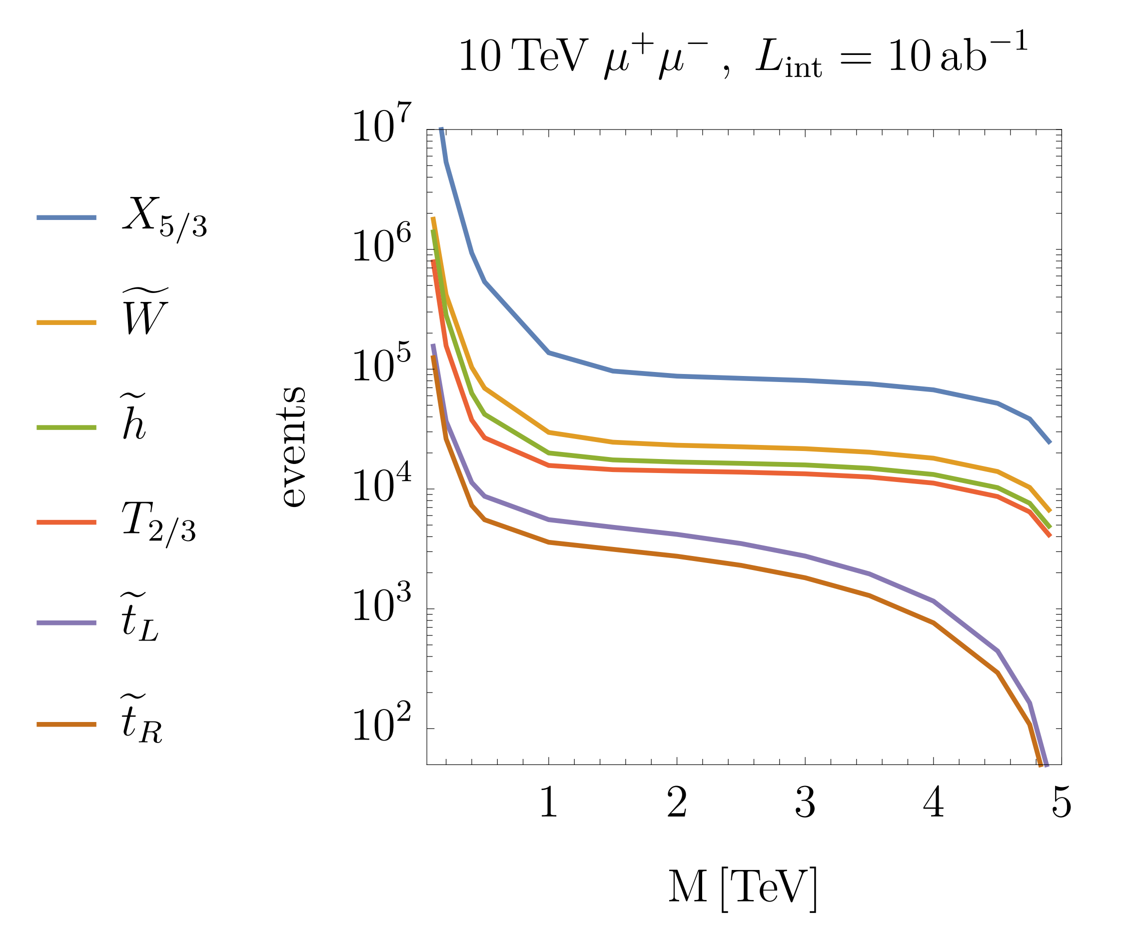
Buttazzo, RF, Wulzer - 2012.11555

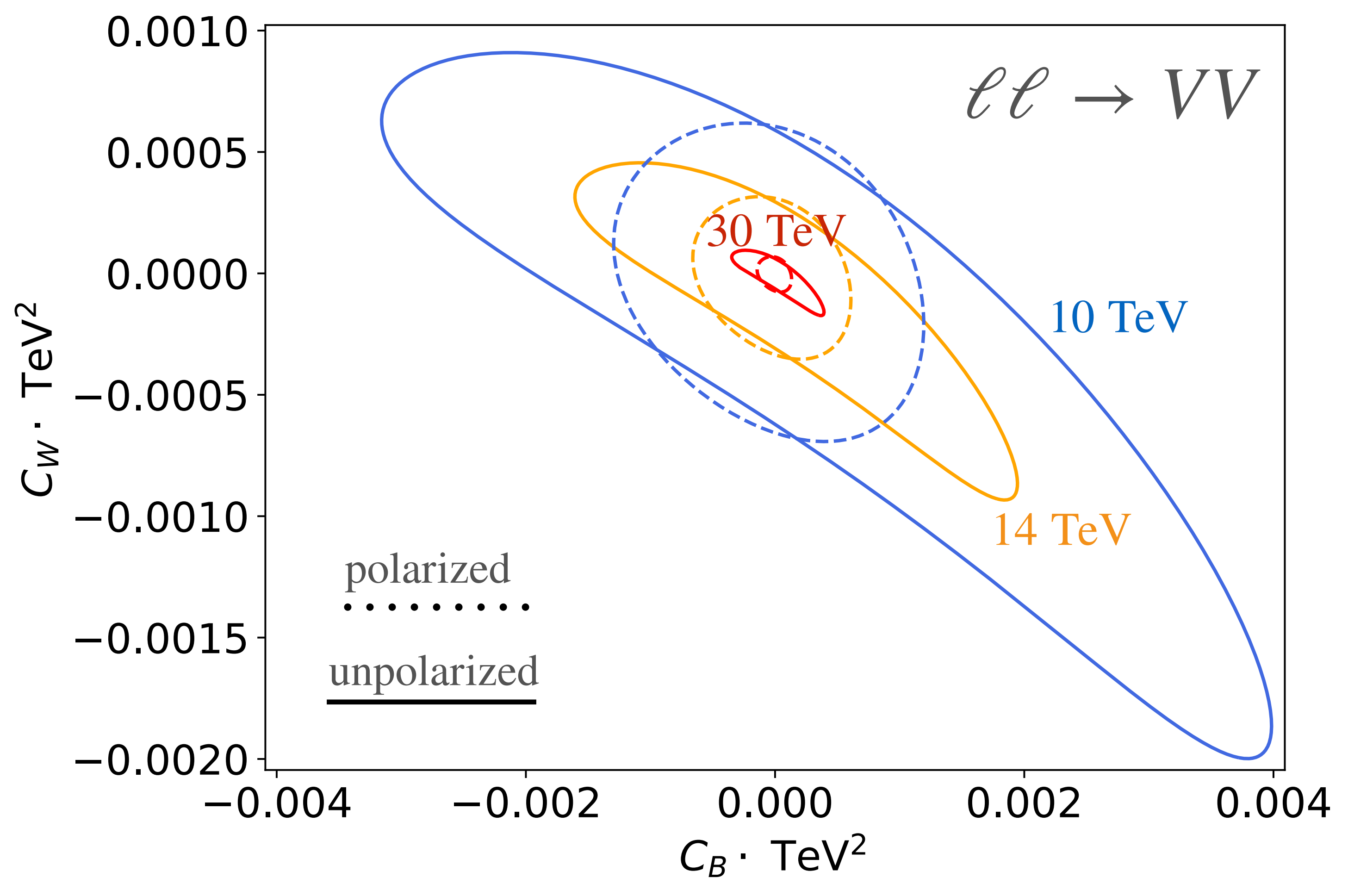
compositeness at 10 TeV-20 TeV

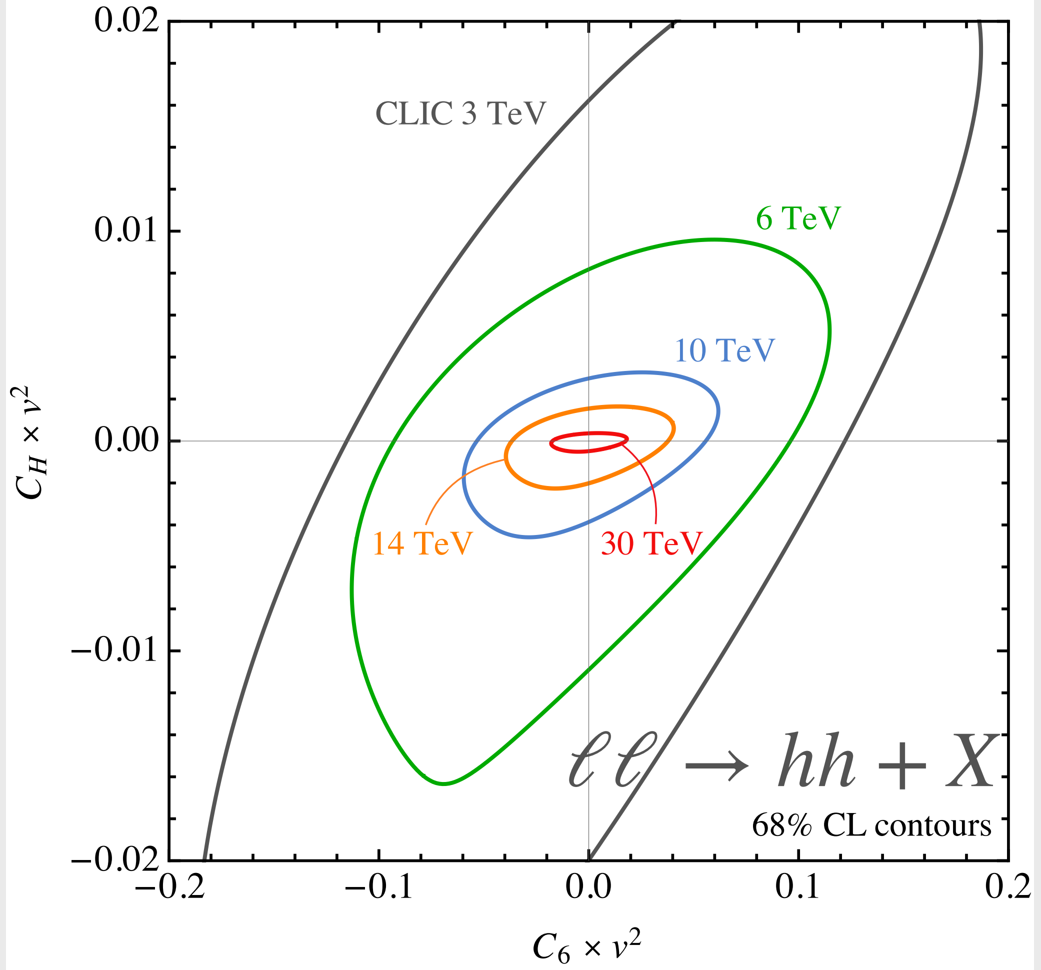
compositeness at 100 TeV-200 TeV

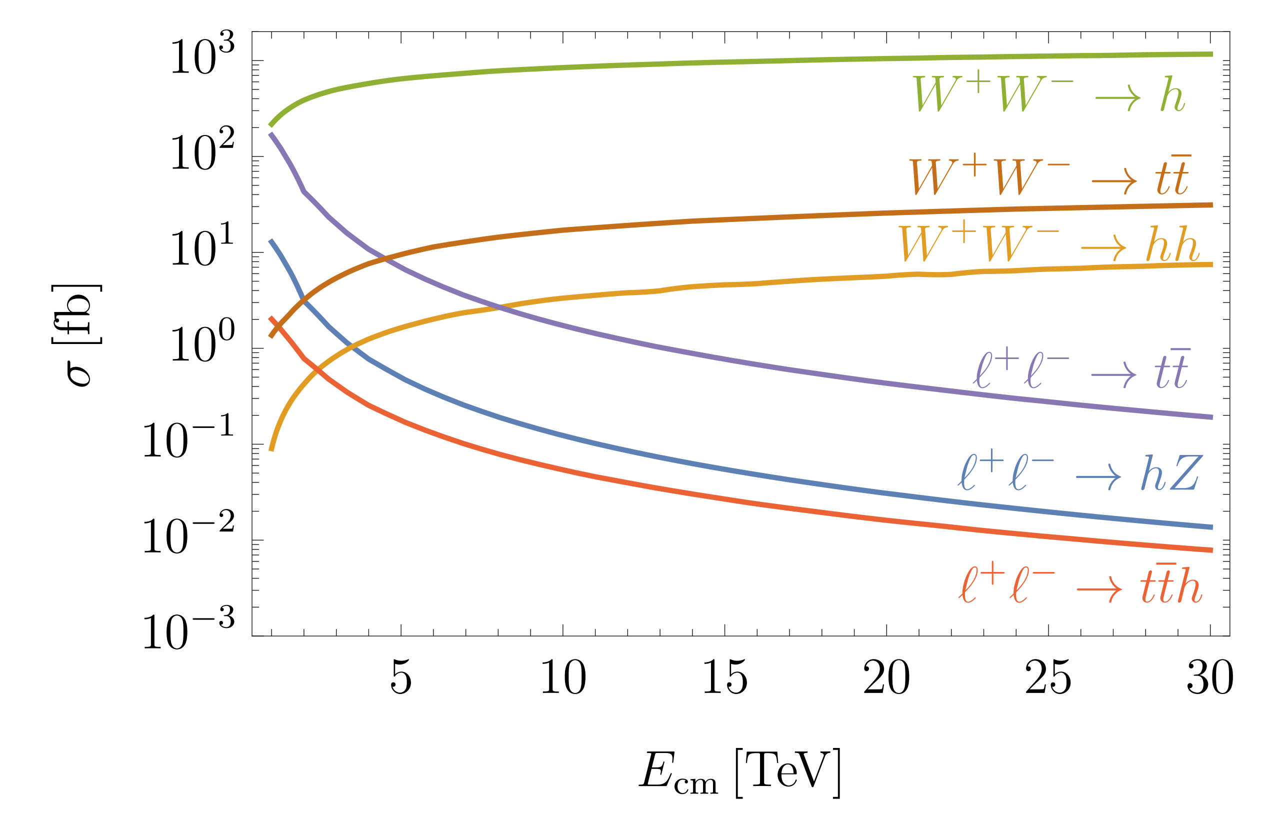
Conclusion

“TWO” COLLIDERS AT ONCE IN A VERY HIGH ENERGY LEPTON COLLIDER





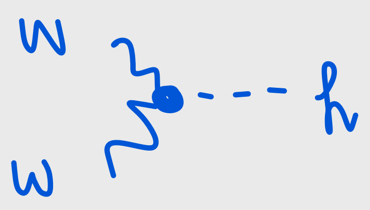




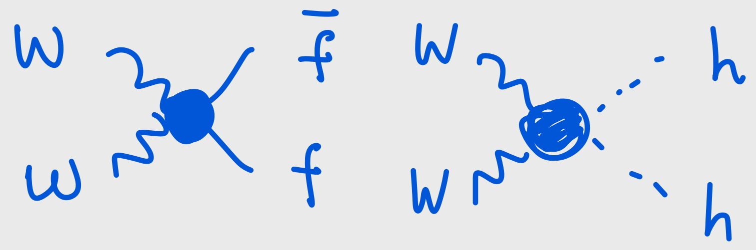
SM “high energy” and “intensity” studies at $\ell^+\ell^-$ colliders

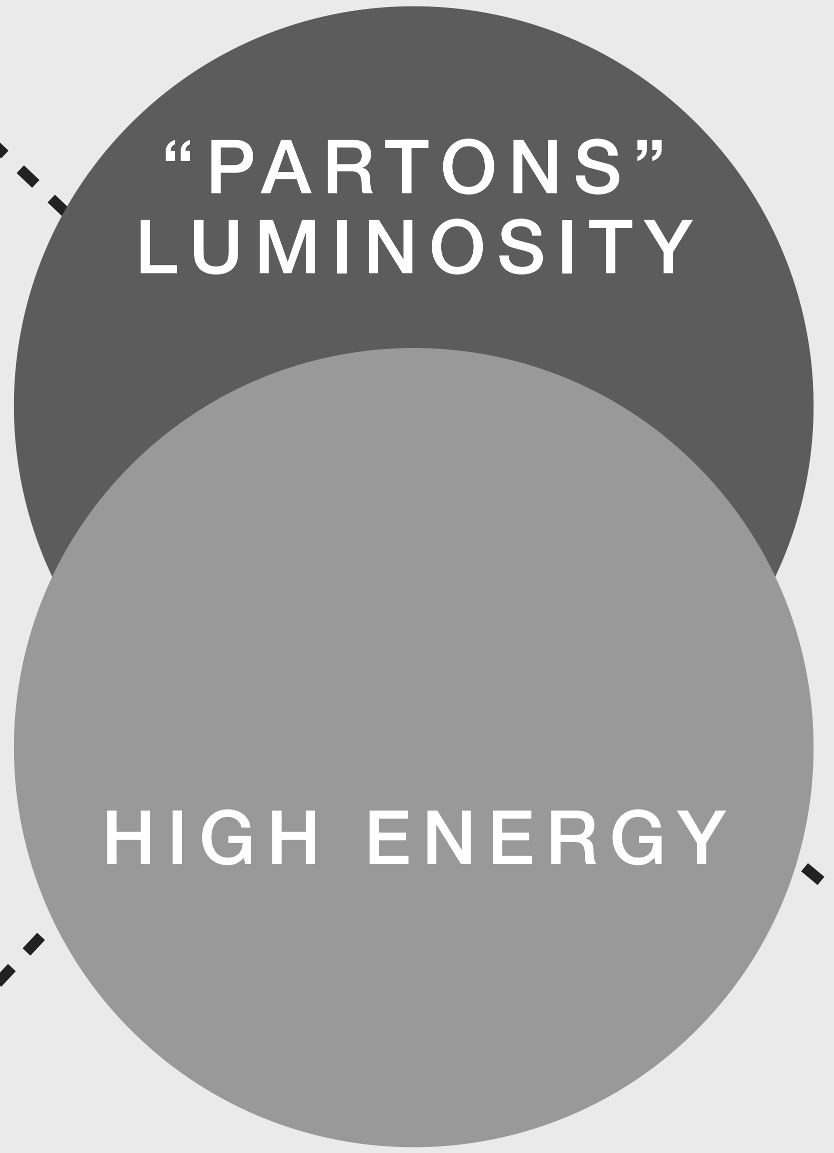
10^8 HIGGS BOSONS

SINGLE HIGGS



WW→XX (PARTONIC W)



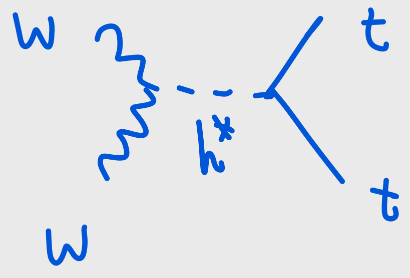


“PARTONS” LUMINOSITY

HIGH ENERGY

10^6 TOP QUARKS

HIGGS FORCE



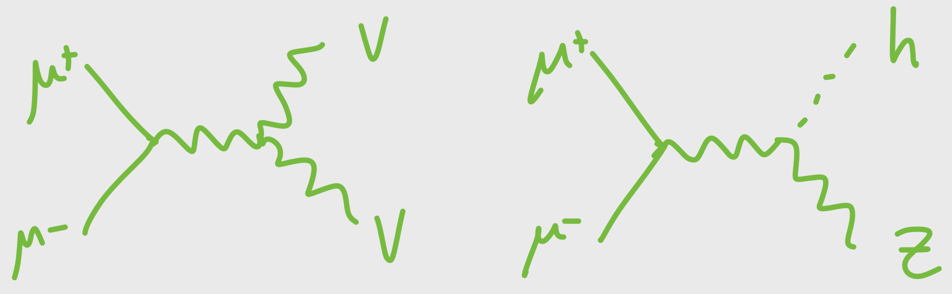
FERMION DRELL-YAN

$>10^4$ TOP QUARKS

HH PRODUCTION

VV PRODUCTION

$>10^4$ WEAK BOSON PAIRS



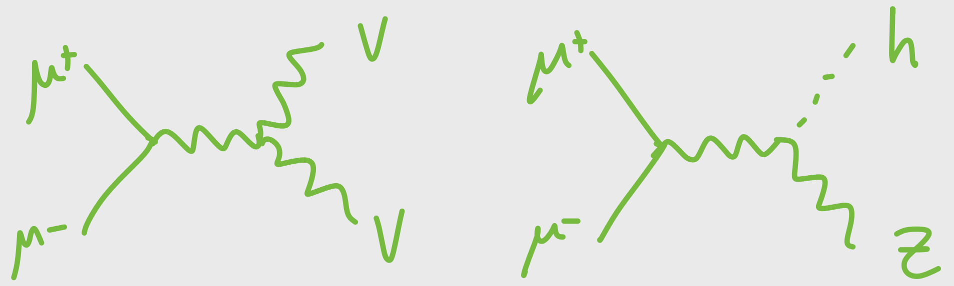
“this is the way”

- systematically improvable way to test the Higgs sector is to search for contact interactions and keep $\mathscr{L} \propto E_{com}^2$

- the current baseline $\mathscr{L} = 10\,\mathrm{ab}^{-1} \dfrac{\sqrt{s}}{10\,\mathrm{TeV}}$ is close to minimum to implement this strategy (factor 2 less is still ok, factor 10 less makes this entire strategy collapse $\Rightarrow \mu$ collider becomes a machine for “just” direct discovery

- Key 5-years ahead in development of future μ colliders and planning

- “diboson” truly becomes* $VV + X, Vh + X, hh + X$



- new physics in Higgs boson up to 100s of TeV can be tested (well off-shore from weak scale waters)

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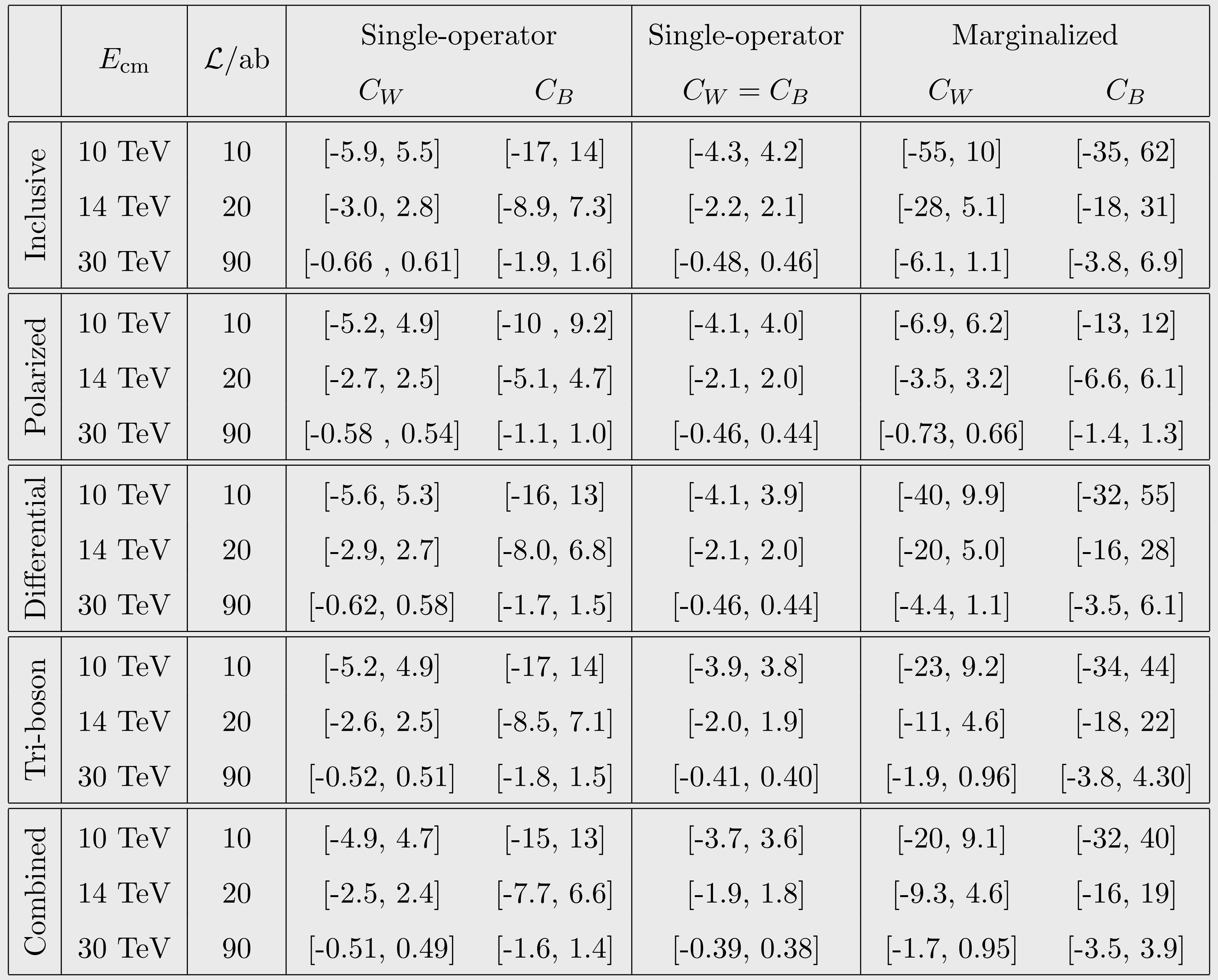
* X can be charged

Thank you!

Full set of results

VERY HIGH ENERGY LEPTON COLLIDER **DIBOSON**



	E_{cm}	$\mathcal{L}$/ab	Single-operator C_W	Single-operator C_B	Single-operator $C_W = C_B$	Marginalized C_W	Marginalized C_B
Inclusive	10 TeV	10	[-5.9, 5.5]	[-17, 14]	[-4.3, 4.2]	[-55, 10]	[-35, 62]
	14 TeV	20	[-3.0, 2.8]	[-8.9, 7.3]	[-2.2, 2.1]	[-28, 5.1]	[-18, 31]
	30 TeV	90	[-0.66 , 0.61]	[-1.9, 1.6]	[-0.48, 0.46]	[-6.1, 1.1]	[-3.8, 6.9]
Polarized	10 TeV	10	[-5.2, 4.9]	[-10 , 9.2]	[-4.1, 4.0]	[-6.9, 6.2]	[-13, 12]
	14 TeV	20	[-2.7, 2.5]	[-5.1, 4.7]	[-2.1, 2.0]	[-3.5, 3.2]	[-6.6, 6.1]
	30 TeV	90	[-0.58 , 0.54]	[-1.1, 1.0]	[-0.46, 0.44]	[-0.73, 0.66]	[-1.4, 1.3]
Differential	10 TeV	10	[-5.6, 5.3]	[-16, 13]	[-4.1, 3.9]	[-40, 9.9]	[-32, 55]
	14 TeV	20	[-2.9, 2.7]	[-8.0, 6.8]	[-2.1, 2.0]	[-20, 5.0]	[-16, 28]
	30 TeV	90	[-0.62, 0.58]	[-1.7, 1.5]	[-0.46, 0.44]	[-4.4, 1.1]	[-3.5, 6.1]
Tri-boson	10 TeV	10	[-5.2, 4.9]	[-17, 14]	[-3.9, 3.8]	[-23, 9.2]	[-34, 44]
	14 TeV	20	[-2.6, 2.5]	[-8.5, 7.1]	[-2.0, 1.9]	[-11, 4.6]	[-18, 22]
	30 TeV	90	[-0.52, 0.51]	[-1.8, 1.5]	[-0.41, 0.40]	[-1.9, 0.96]	[-3.8, 4.30]
Combined	10 TeV	10	[-4.9, 4.7]	[-15, 13]	[-3.7, 3.6]	[-20, 9.1]	[-32, 40]
	14 TeV	20	[-2.5, 2.4]	[-7.7, 6.6]	[-1.9, 1.8]	[-9.3, 4.6]	[-16, 19]
	30 TeV	90	[-0.51, 0.49]	[-1.6, 1.4]	[-0.39, 0.38]	[-1.7, 0.95]	[-3.5, 3.9]

Table 4: 95% C.L. constraints on C_W and C_B, expressed in units of $(100\,\mathrm{TeV})^{-2}$, for the benchmark VHEL energies and luminosities. The first two columns show the constraints on one coefficient setting the other to zero, the third one is the constraint in the direction $C_W = C_B$. The last two columns show the constraints marginalized in the (C_W, C_B) plane.

CUT-AND-COUNT **DIFFERENTIAL WW**