23rd International Conference from the Planck Scale to the Electroweak scale

Higgs boson physics at Future^2 Colliders

JUN. 29 2021

ROBERTO FRANCESCHINI (ROMA 3 UNIVERSITY)

ROMA TRE UNIVERSITÀ DEGLI STUDI

INFN Roma3

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

We got it!

- The Higgs boson is part of the SM since long before it was discovered

- Tons of BSM was based on $SU(2)_W \times U(1)_Y \rightarrow U(1)_e$ via a simple scalar VEV well before the Higgs boson was discovered

- We could have got the interesting puzzle to figure out a "***higgsless***" world. We got instead the puzzle of figuring out the a "***BSMless***" Higgs.

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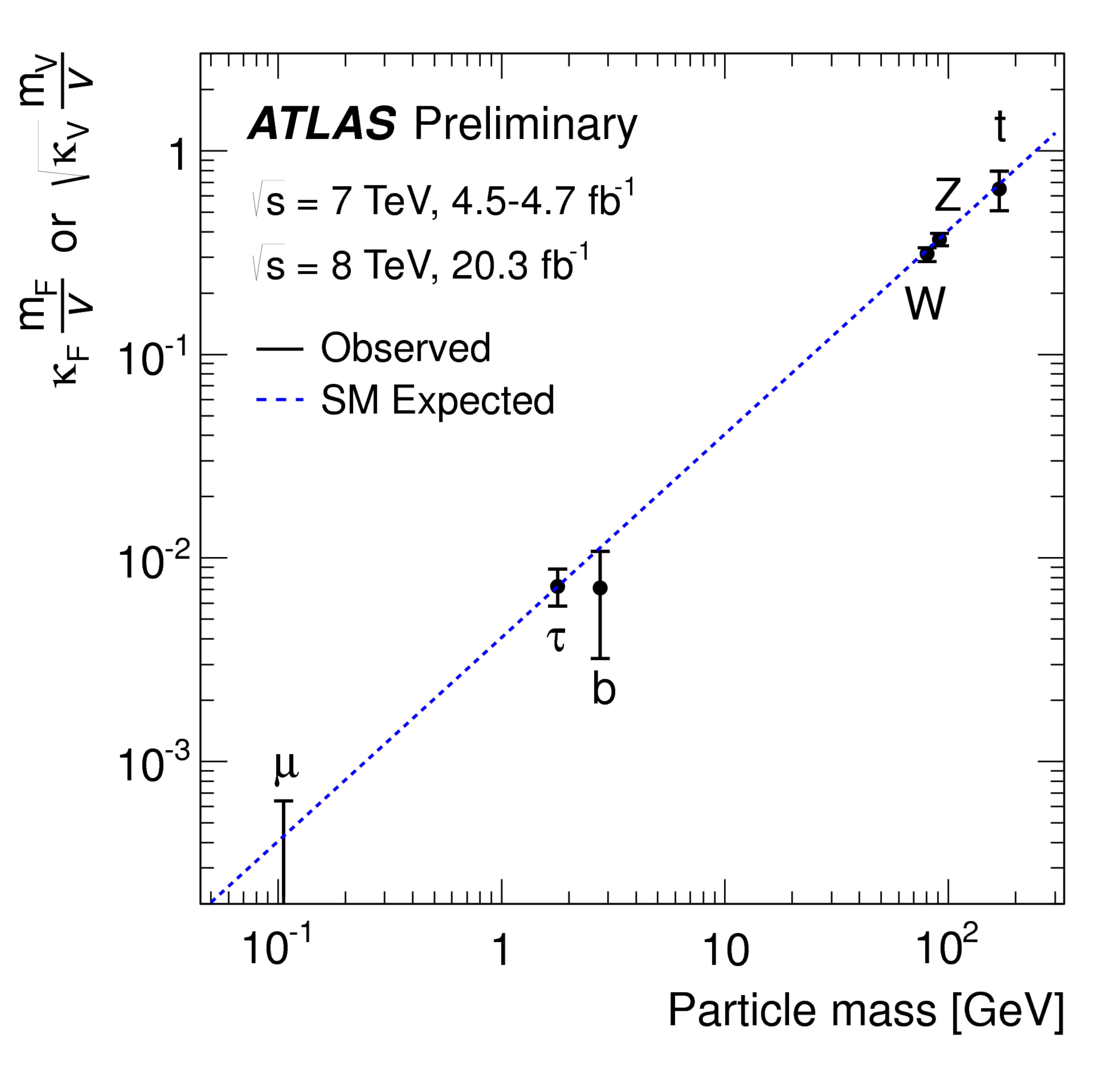


SSB and Higgs/Amplitude modes

- Goldstone bosons from SSB are well visible in many physical phenomena (pions, lots of condensed matter systems, …)
- Higgs/Amplitudes modes are far less obvious to arise ⇒ “*We don’t live in a crappy metal!*”
- “How special is our metal?”

SSB and Higgs/Amplitude modes

★ New heavy degrees of freedom can in principle affect m_h, still they do not:

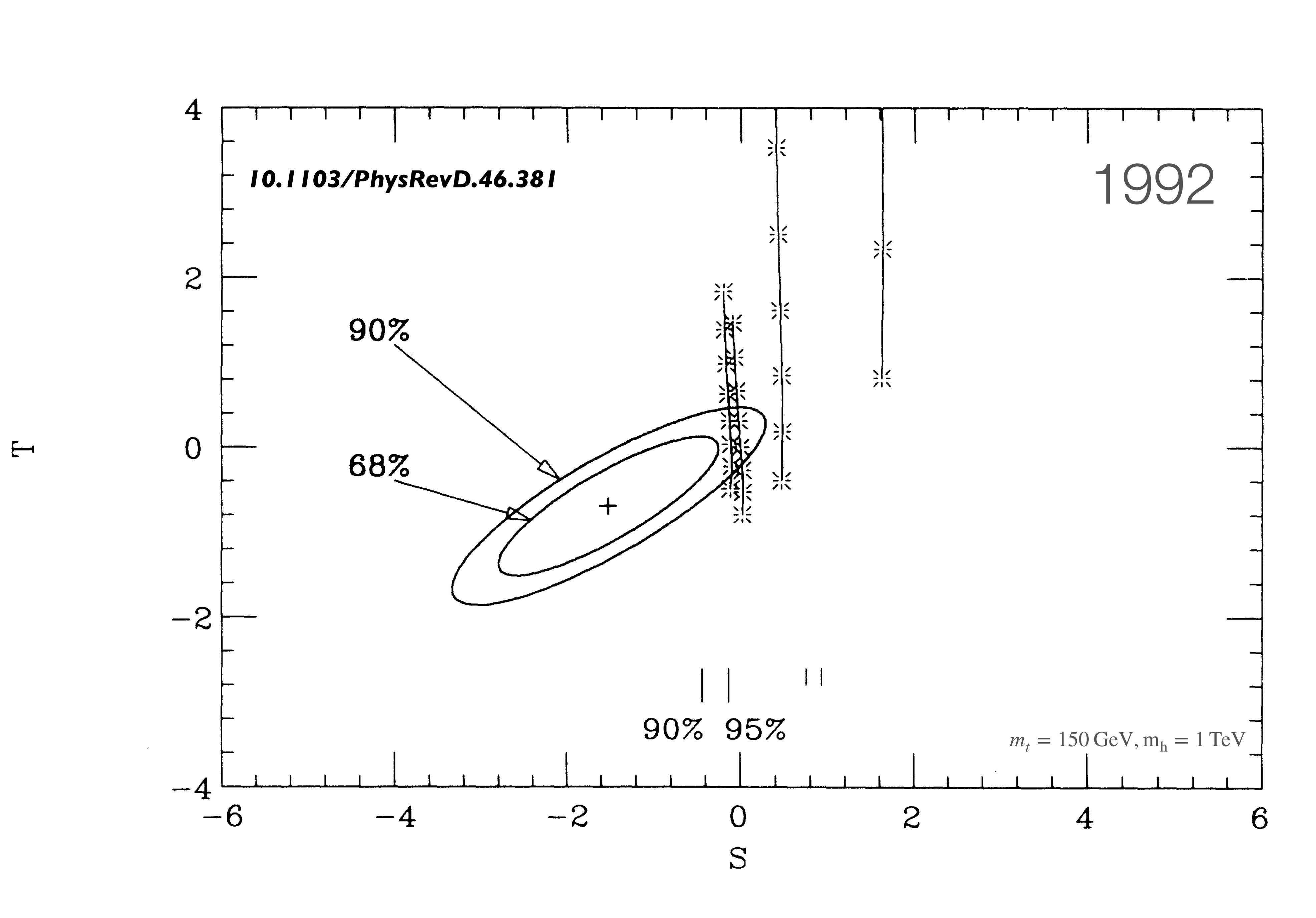
- either because they do not exist at all (SM up to the highest energy)
- or they are "magical"

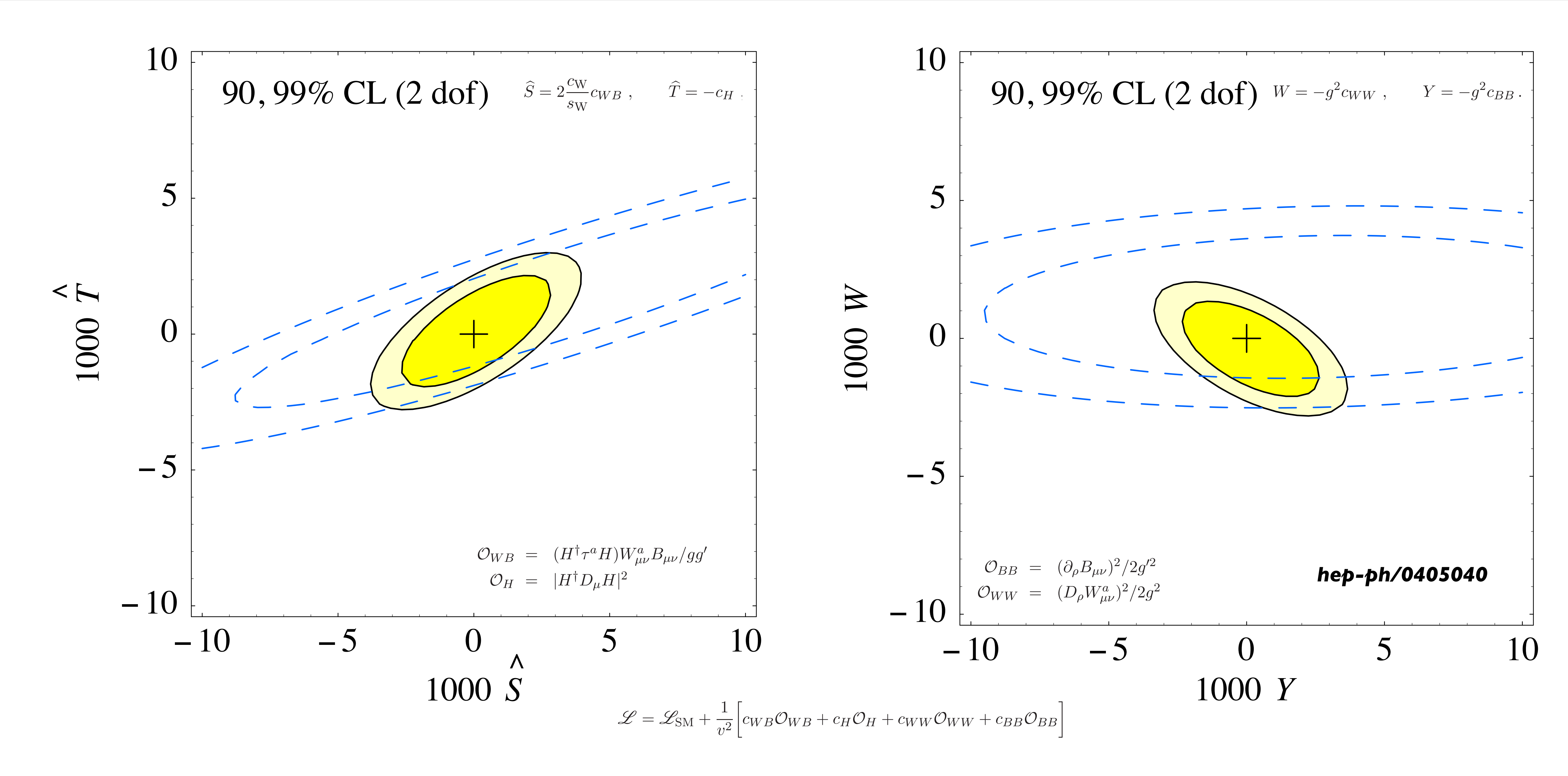
★ The task we have with the Higgs boson has to do with

- either finding out the magic trick (new physics and its screening dynamics)
- or convincing ourselves that the Higgs boson of the EW theory is truly special as a narrow and isolated resonance "in the desert"

★ Both these efforts require to probe the Higgs boson harder

What is the scale we need to reach?





$$S < O(1)$$

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

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

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

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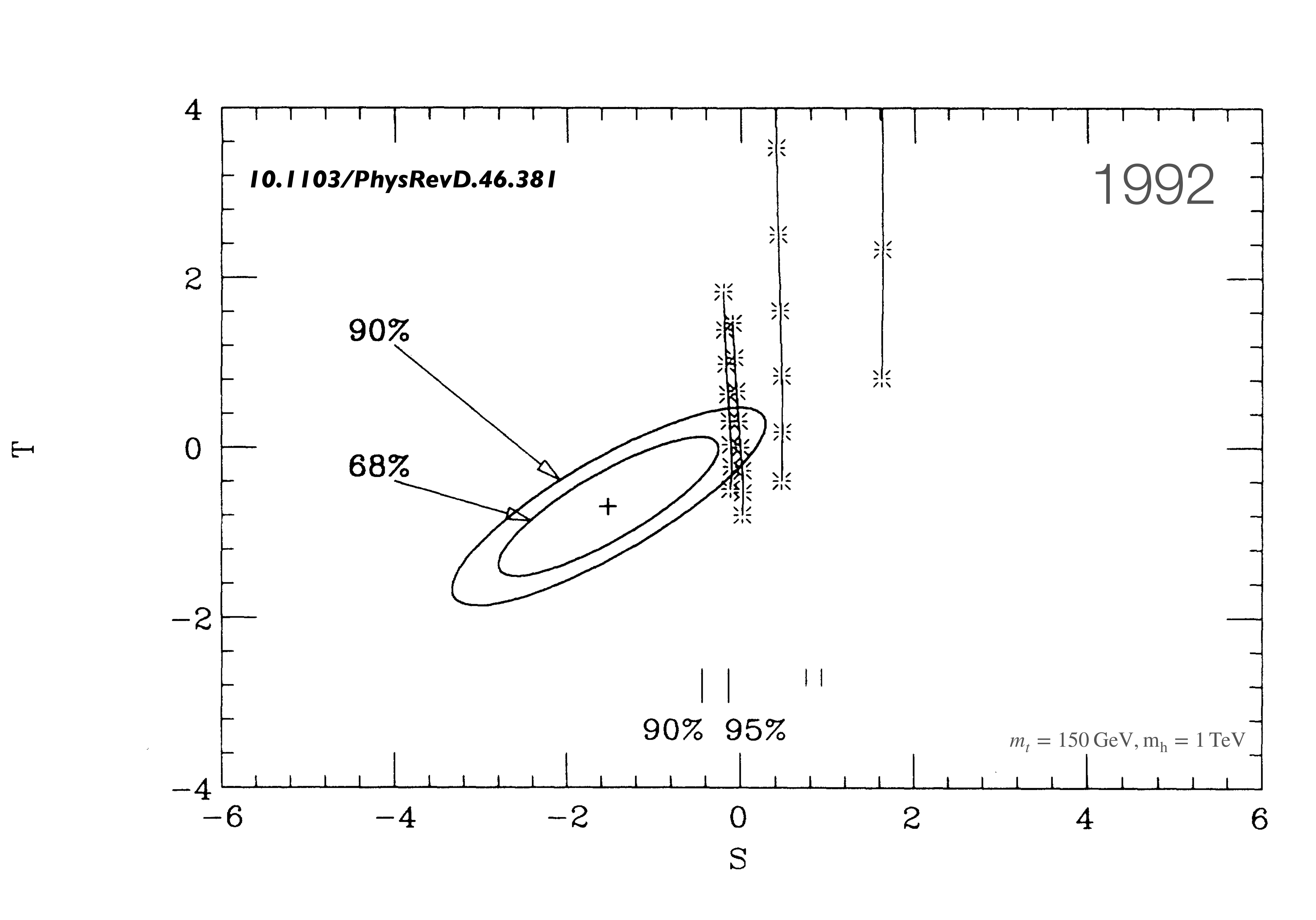

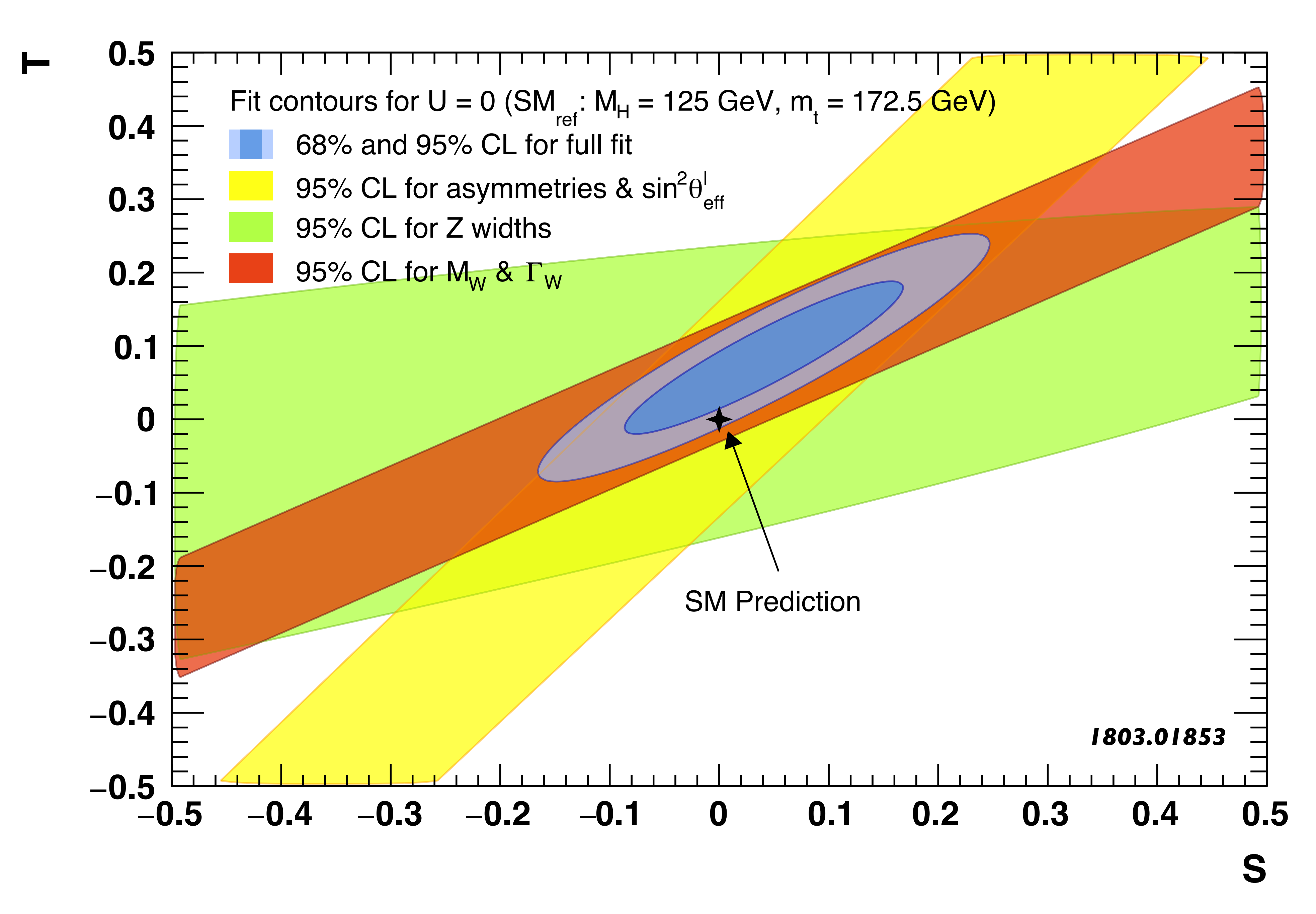

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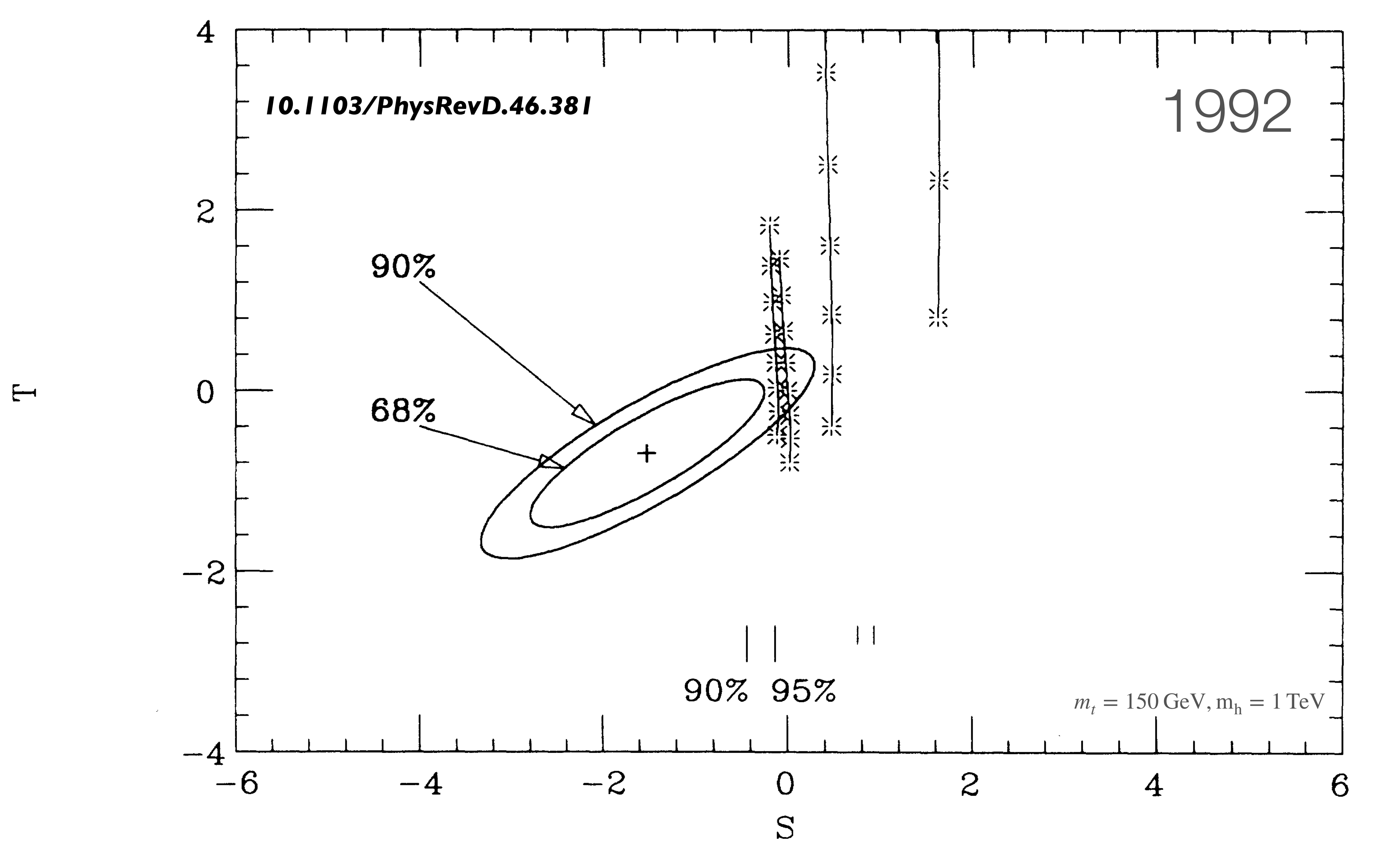


$$S < O(1)$$

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

IT USED TO BE EASY:

For “finding the Higgs boson” we knew there was a maximum scale to find it or find its substitute

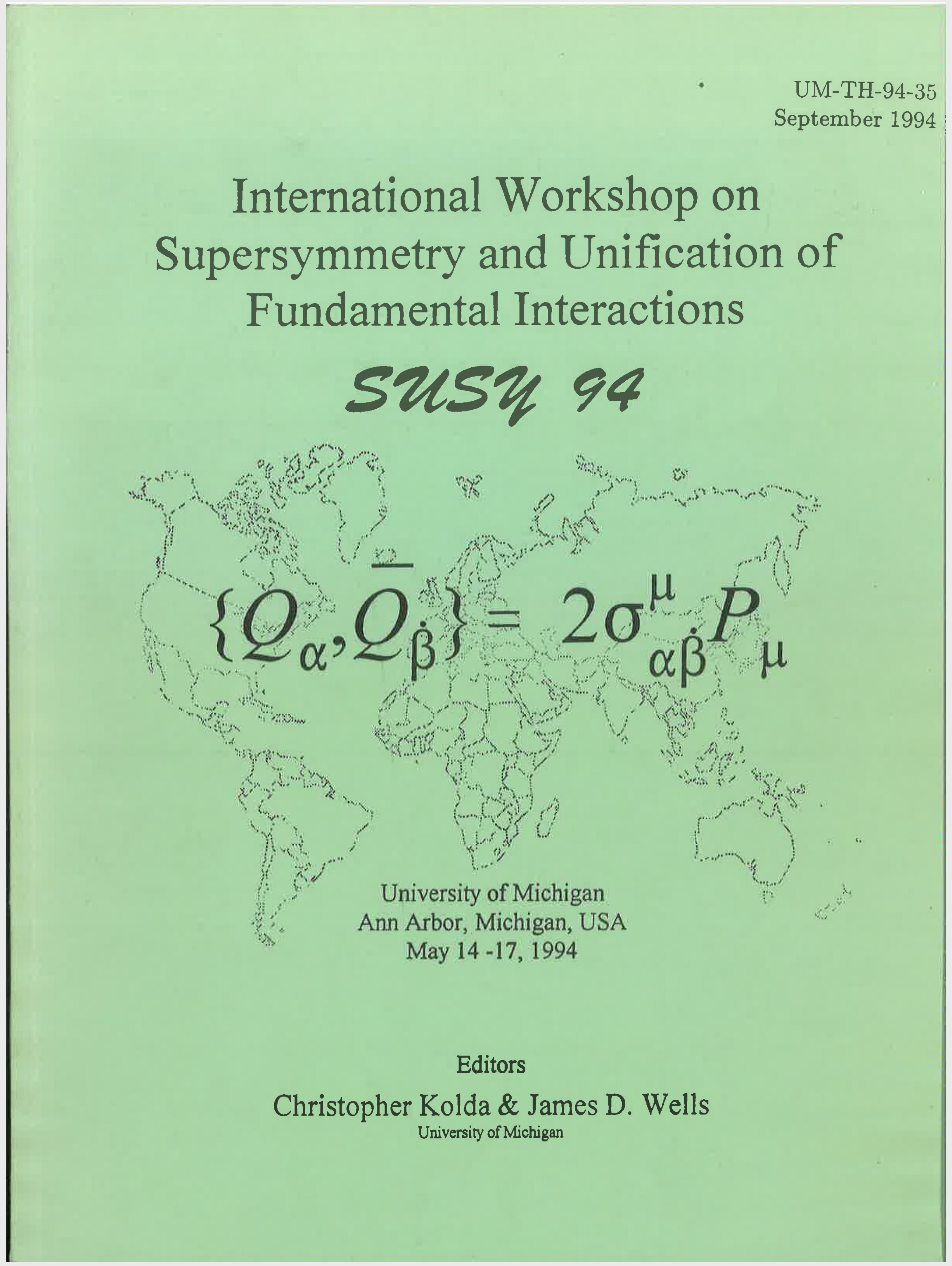
ELECTROWEAK SYMMETRY BREAKING WELL TESTED BEFORE THE HIGGS WAS DISCOVERED

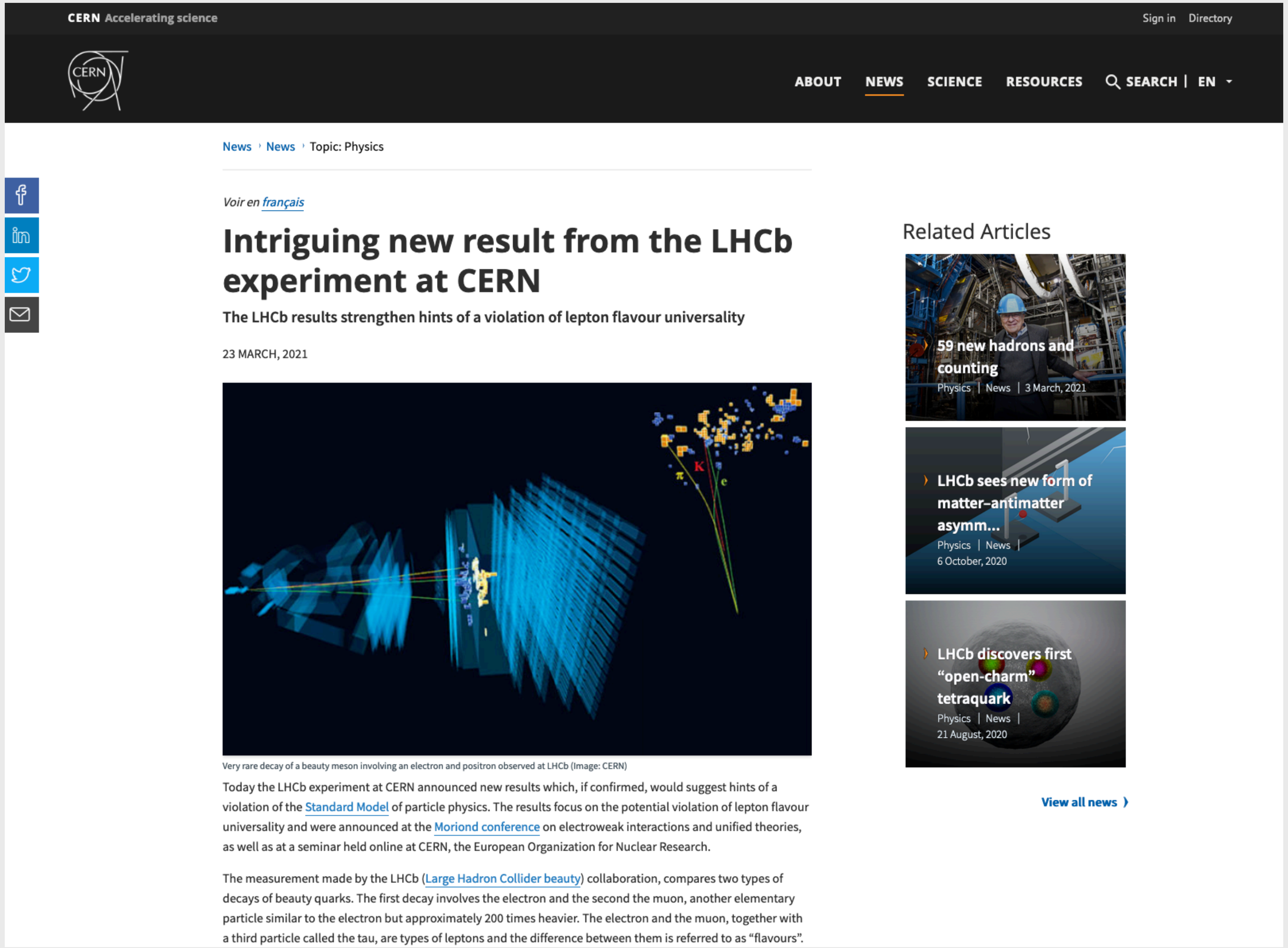
At the same time we had hints there was little new physics in the EWSB until few TeV

Once the Higgs was discovered we had to (hopefully) look at its properties, as some largish deviation was still possible

Hints were for new physics above TeV

We had great hopes nevertheless



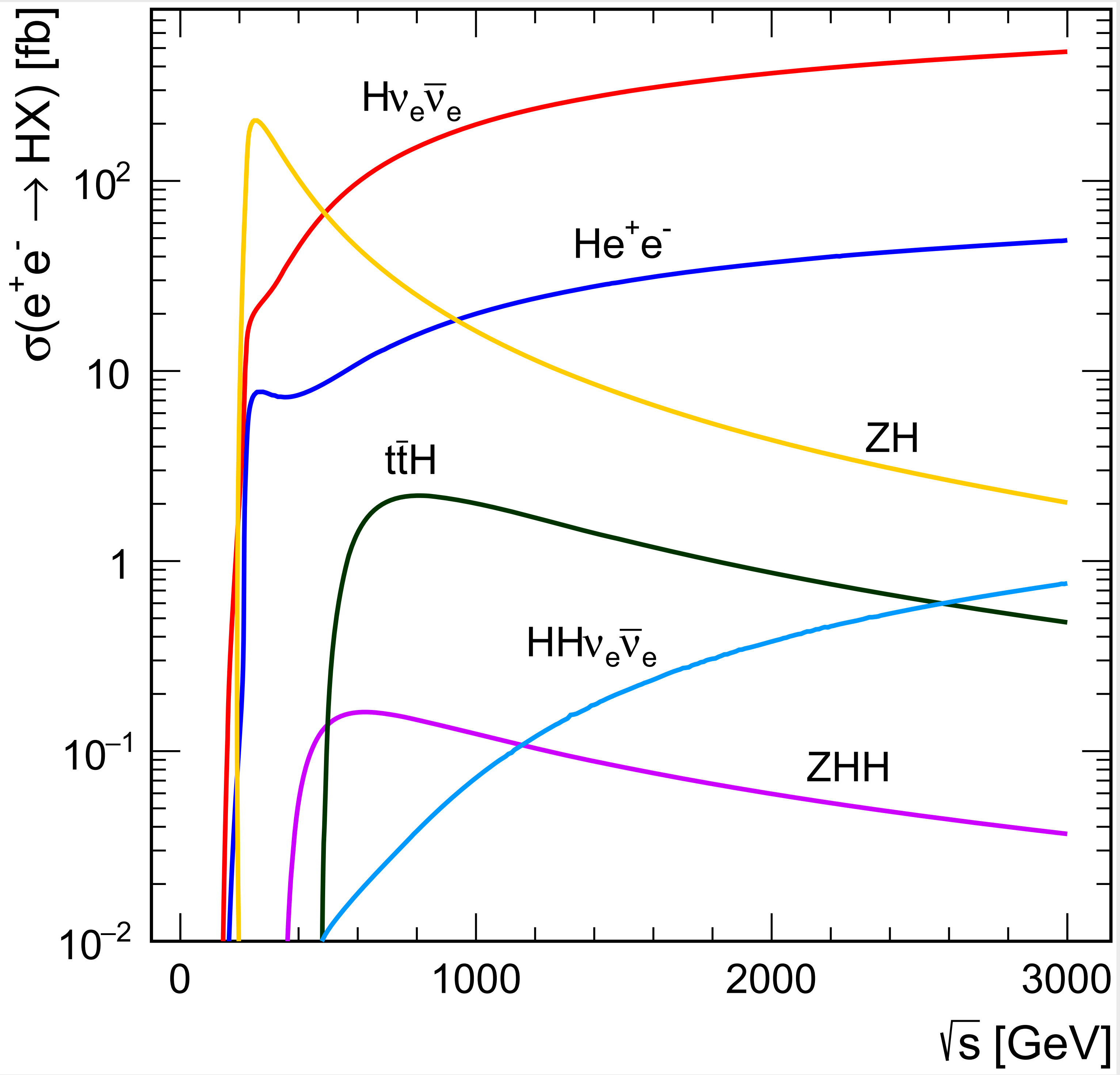


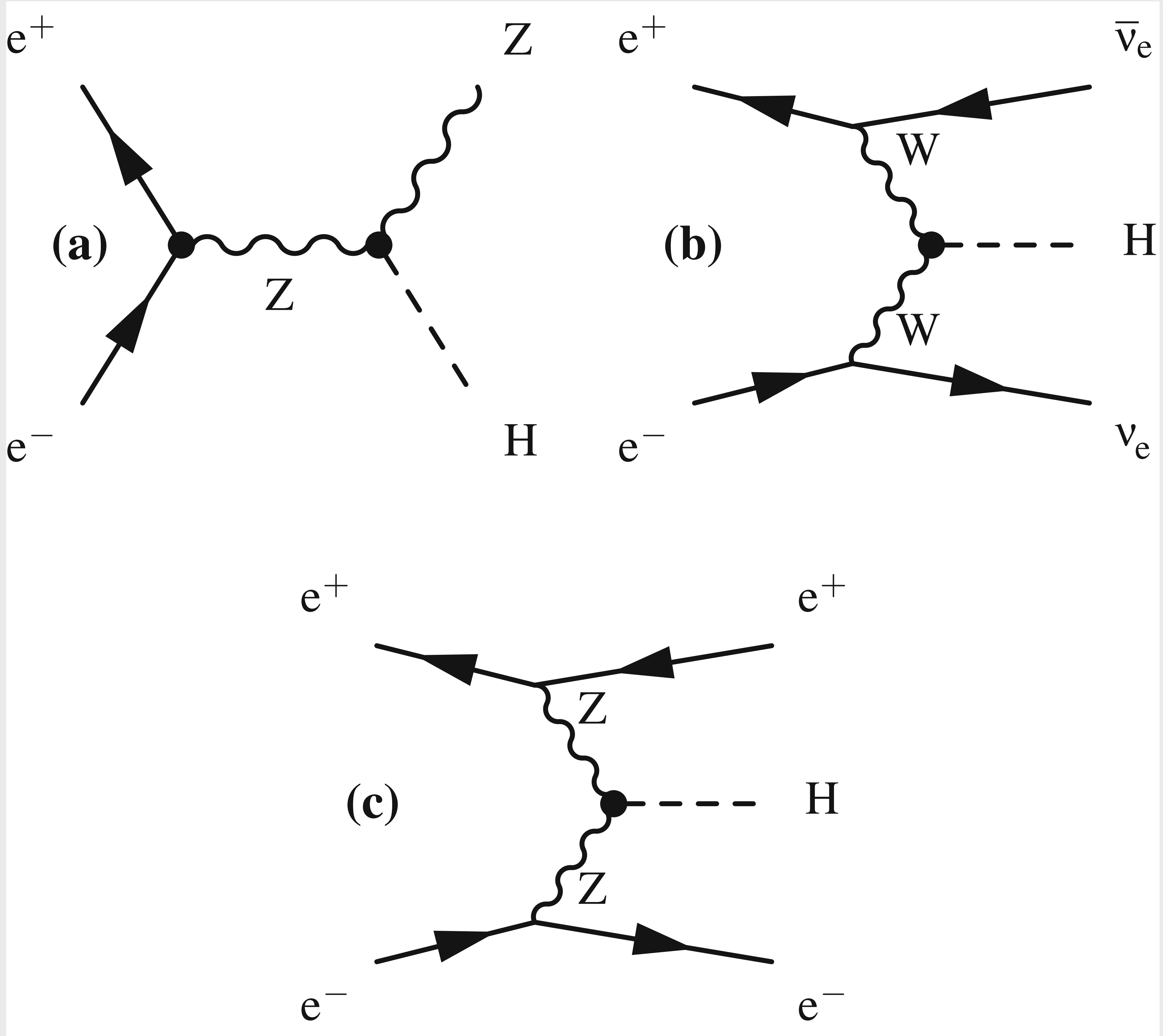
Higgs boson @*h*

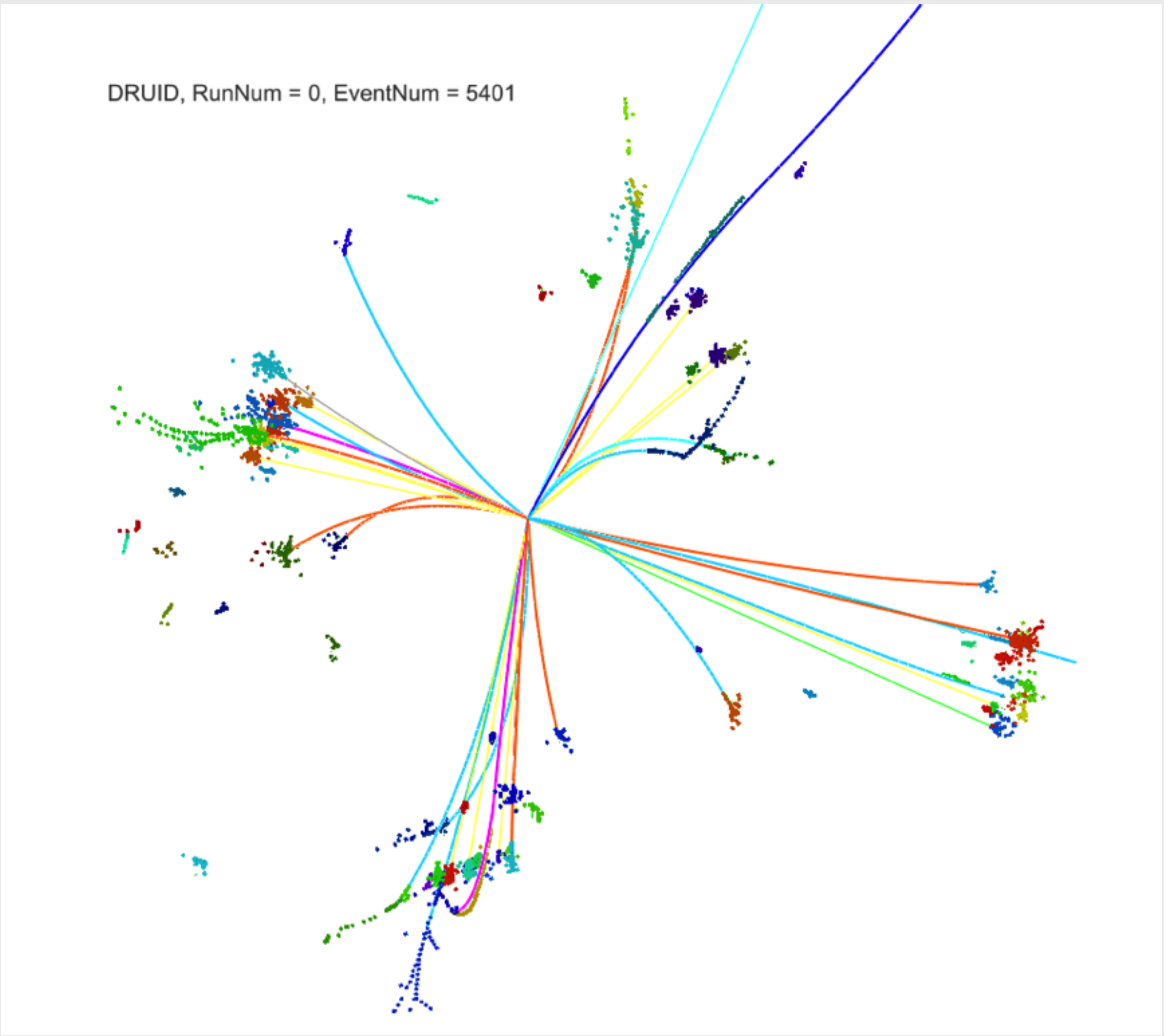
Pole, pole, pole

LARGE | DATASET AT ZH THRESHOLD

$\Rightarrow$ roughly 1M Higgs bosons $\Rightarrow$ measurements at 10^{-3} precision are "possible"





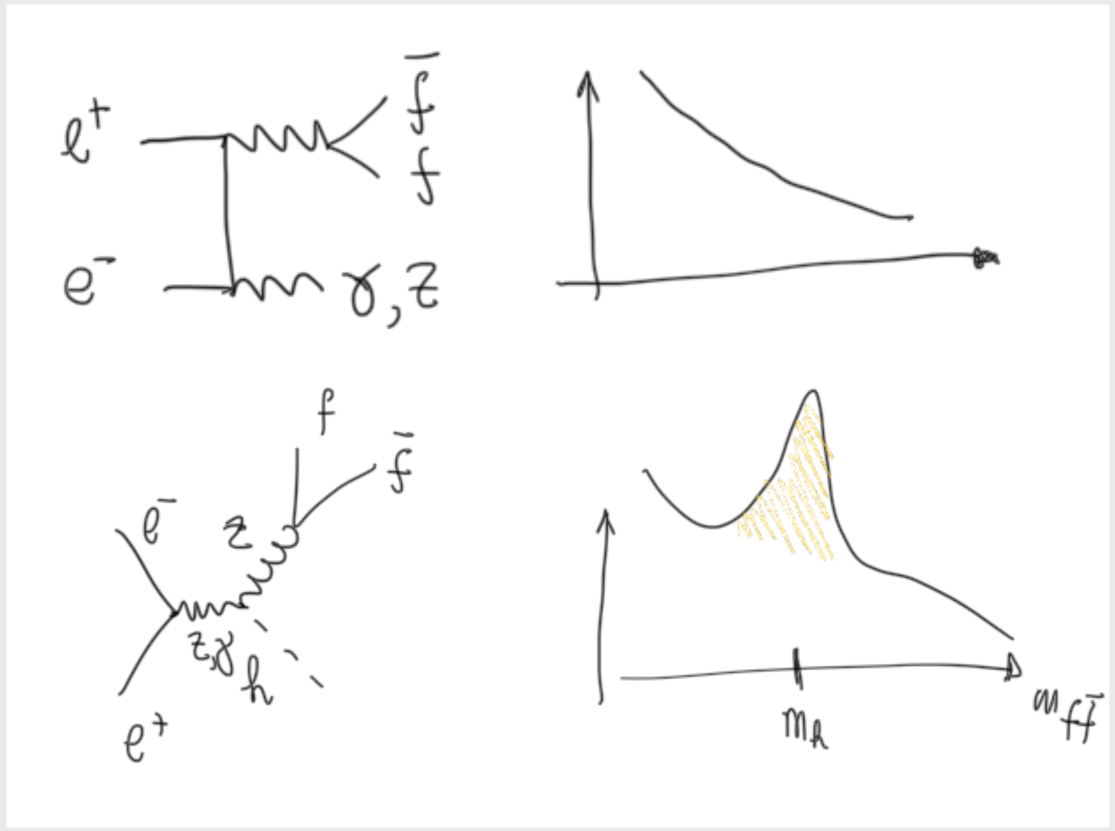


Bottlenecks in sight

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

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

ABSOLUTE RATE MEASUREMENT



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

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

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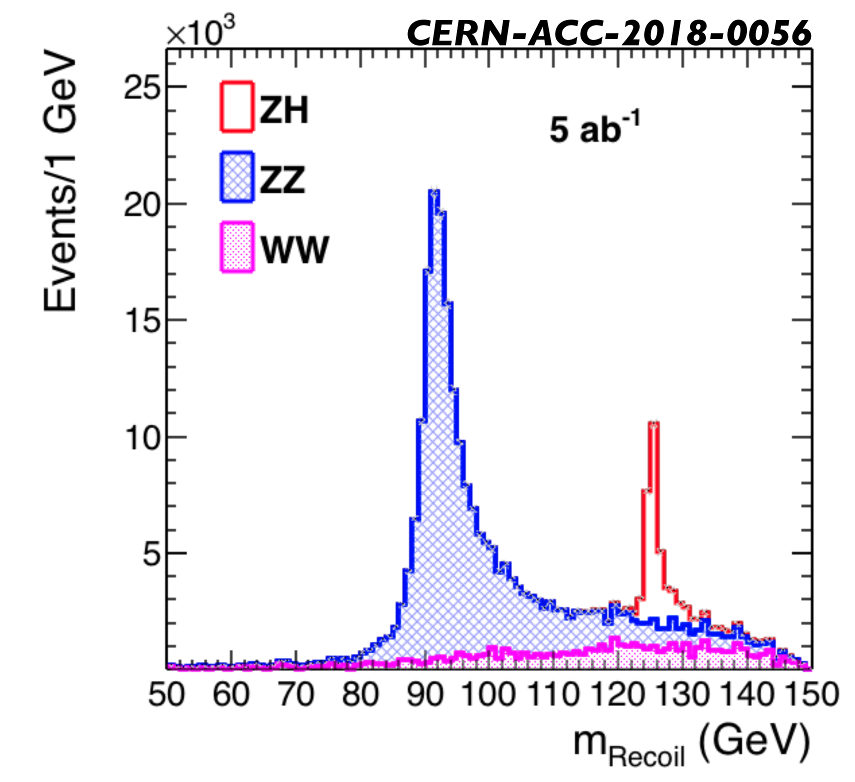

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$$\Rightarrow \quad \frac{\delta g^2_{hYY}}{g^2_{hYY}} = \frac{\delta N_{YY}}{N_{YY}} \oplus \frac{\delta N_{XX}}{N_{XX}} \oplus \frac{\delta N_{ZH,recoil}}{N_{ZH,recoil}} \oplus \frac{\delta\mathscr{L}}{\mathscr{L}}$$

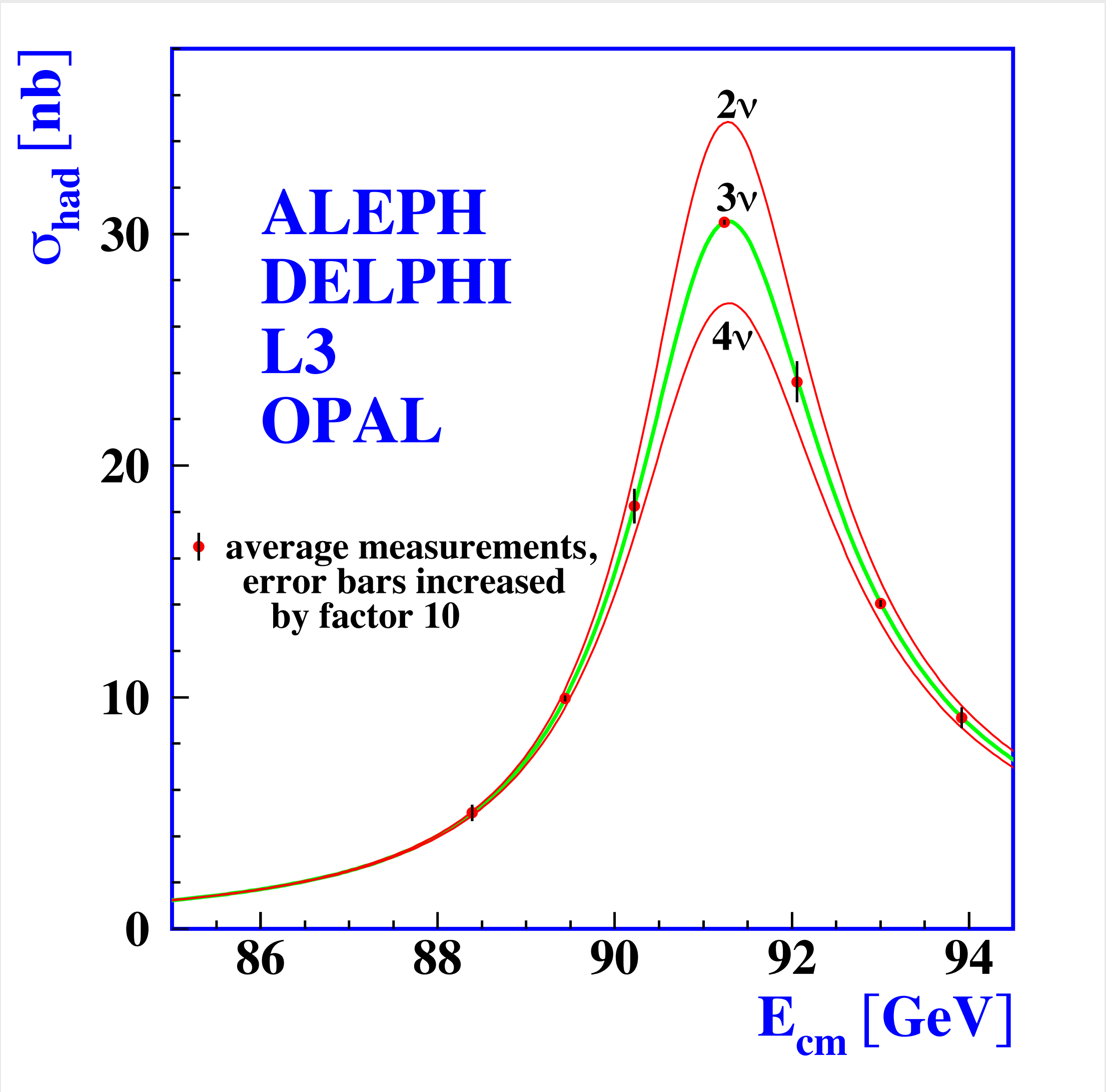
Takes a lot of understanding …

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

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

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

ABSOLUTE WIDTH MEASUREMENT



Systematics in sight

STAT-ONLY

$\sqrt{s}$ (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
$H \to ZZ$	± 4.4		± 12	± 10
$H \to \tau\tau$	± 0.9		± 1.8	± 8
$H \to \gamma\gamma$	± 9.0		± 18	± 22
$H \to \mu^+\mu^-$	± 19		± 40	
$H \to$ invis.	< 0.3		< 0.6	

GLOBAL-FIT

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
$\delta g_{H\tau\tau}/g_{H\tau\tau}$ (%)	1.8	1.4	**0.74**	0.64
$\delta g_{H\mu\mu}/g_{H\mu\mu}$ (%)	4.4	10.1	**9.0**	3.9
$\delta g_{H\gamma\gamma}/g_{H\gamma\gamma}$ (%)	1.6	4.8	**3.9**	1.1
$\delta g_{Htt}/g_{Htt}$ (%)	2.5	–	–	2.4
BR_{EXO} (%)	SM	< 1.2	$< \mathbf{1.0}$	< 1.0

CERN-ACC-2018-0056

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

Competition 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
BR_{inv} (<%, 95% CL)	1.9
BR_{unt} (<%, 95% CL)	4.1

kappa-0	HL-LHC	LHeC	HE-LHC	ILC_{250}	ILC_{500}	$CLIC_{380}$	$CLIC_{1500}$	$CLIC_{3000}$	CEPC	FCC-ee_{240}	FCC-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⋆	5.0	2.2	3.7	4.7	3.9	0.35
$\kappa_{Z\gamma}$ (%)	10	–	4.0	99⋆	86⋆	120⋆	15	6.9	8.2	81⋆	75⋆	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⋆	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

Journal of Instrumentation Special Issue https://iopscience.iop.org/journal/1748-0221/page/extraproc46

Muon sources

BALANCE | NUMBER AND SPREAD

MAP

$$p\mathcal{N} \to \pi^{\pm} + X \to \mu^{\pm} + \dots$$

- large cross-section
- large spread of muon velocity

MAP Conclusion

- Multi-TeV MC ➩ potentially only cost-effective route to lepton collider capabilities with E_{CM} > 5 TeV
- Capability strongly overlaps with next generation neutrino source options, i.e., the neutrino factory
- Key technical hurdles have been addressed:
  - High power target demo (MERIT)
  - Realizable cooling channel designs with acceptable performance
  - Breakthroughs in cooling channel technology
  - Significant progress in collider & detector design concepts

Accelerator	Energy Scale	Performance
Cooling Channel	**~200 MeV**	**Emittance Reduction**
MICE	*160-240 MeV*	*5%*
Muon Storage Ring	**3-4 GeV**	**Useable μ decays/yr***
νSTORM	*3.8 GeV*	*$3x10^{17}$*
Intensity Frontier ν Factory	**4-10 GeV**	**Useable μ decays/yr***
NuMAX (Initial)	*4-6 GeV*	*$8x10^{19}$*
NuMAX+	*4-6 GeV*	*$5x10^{20}$*
IDS-NF Design	*10 GeV*	*$5x10^{20}$*
Higgs Factory	**~126 GeV CoM**	**Higgs/10^7s**
s-Channel μ Collider	~126 GeV CoM	3,500-13,500
Energy Frontier μ Collider	**> 1 TeV CoM**	**Avg. Luminosity**
Opt. 1	*1.5 TeV CoM*	*$1.2x10^{34}cm^{-2}s^{-1}$*
Opt. 2	*3 TeV CoM*	*$4.4x10^{34}cm^{-2}s^{-1}$*
Opt. 3	*6 TeV CoM*	*$12x10^{34}cm^{-2}s^{-1}$*

* Decays of an individual species (ie, μ^+ or μ^-)

Muon collider capabilities offer unique potential for the future of high energy physics research

47 ARIES MC Workshop July 2-3, 2018

BROOKHAVEN NATIONAL LABORATORY

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muoncollider.web.cern.ch

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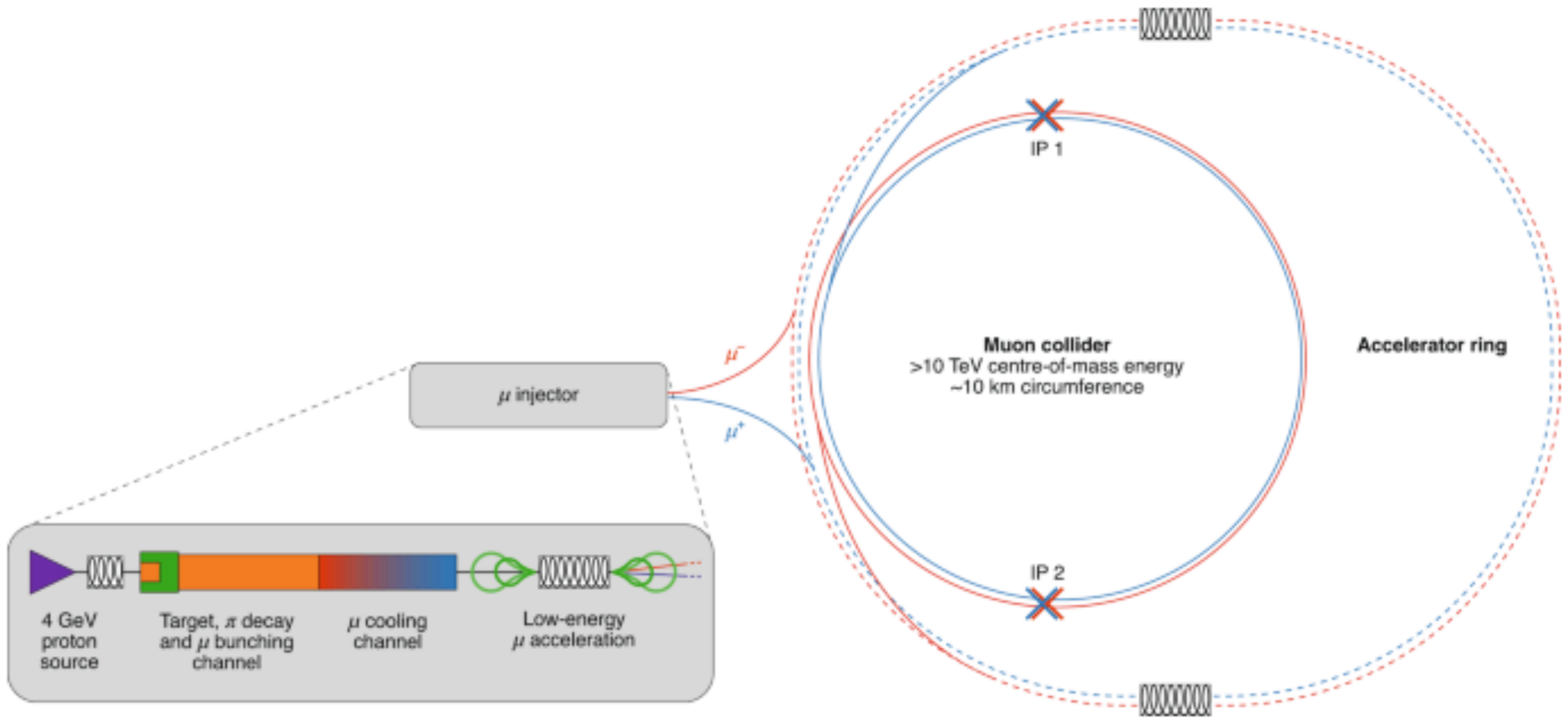
International MUON Collider Collaboration

HOME OVERVIEW ORGANISATION DESIGN COLLABORATION MATERIALS CALENDAR

Overview

Introduction

Muon colliders have a great potential for high-energy physics. They can offer collisions of point-like particles at very high energies, since muons can be accelerated in a ring without limitation from synchrotron radiation. However, the need for high luminosity faces technical challenges which arise from the short muon lifetime at rest and the difficulty of producing large numbers of muons in bunches with small emittance. Addressing these challenges requires the development of innovative concepts and demanding technologies.



The Update of the European Strategy for Particle Physics recommended to integrate an international design study for a muon collider in the European Roadmap muoncollider.web.cern.ch

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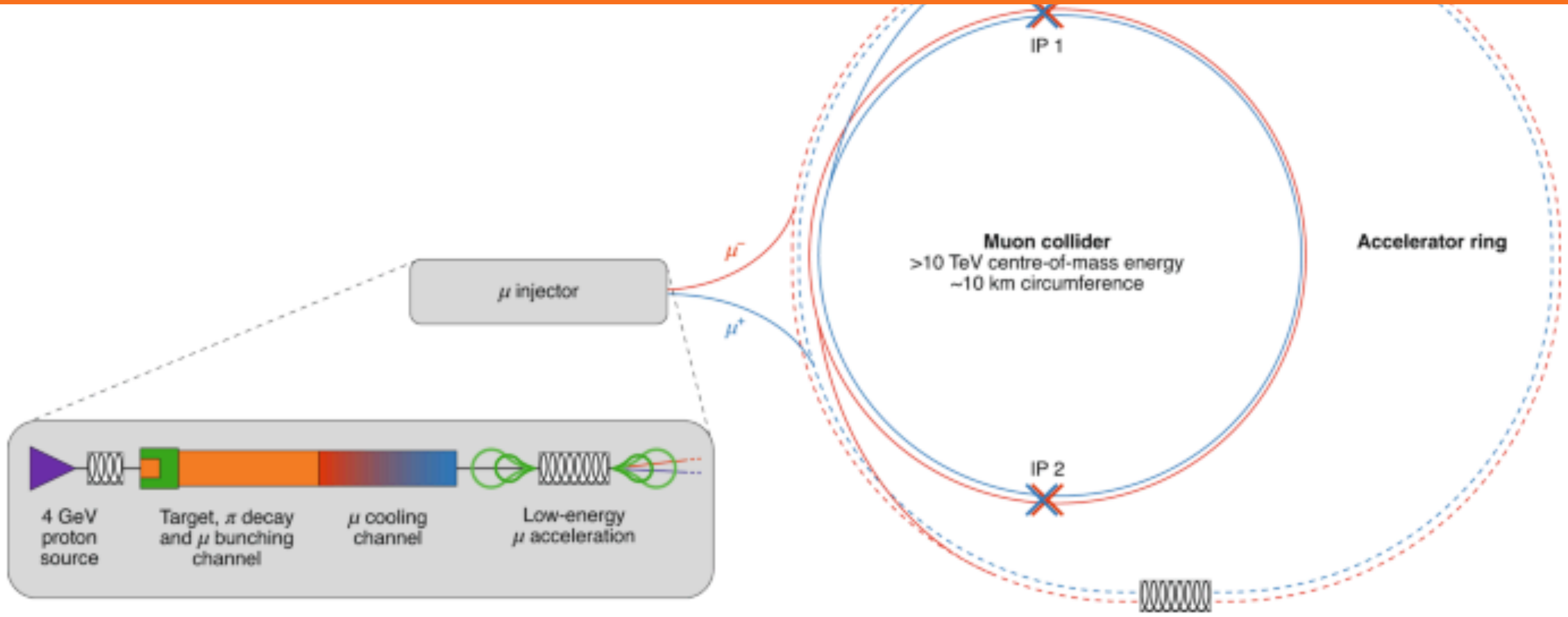
INNOVATIVE AND DEMANDING: FIRST OF A NEW KIND OF MACHINES



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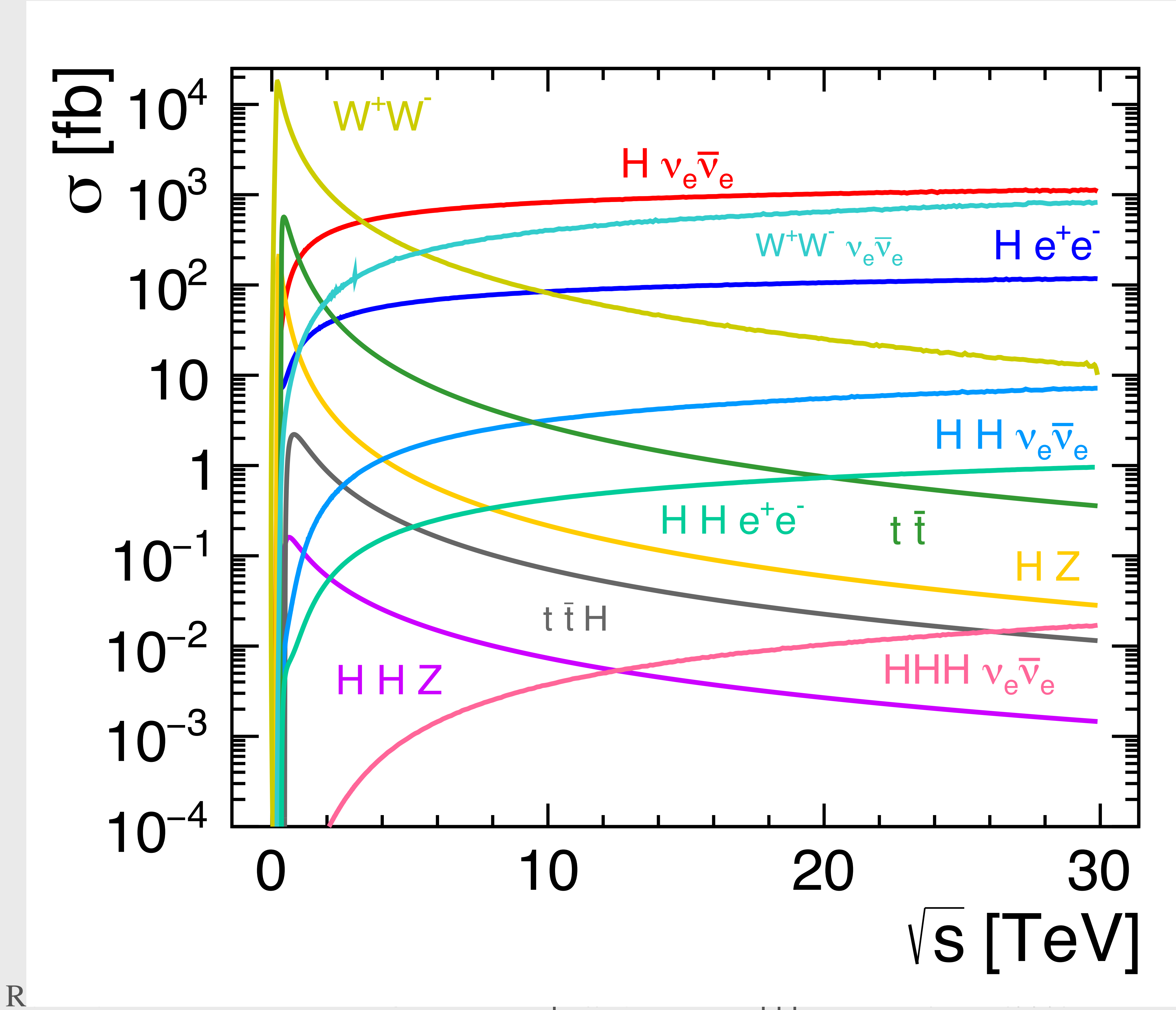
$\ell^+\ell^- \to h\nu\nu$

10⁸ HIGGS BOSONS

100×MEGA-HIGGS FACTORY

$$\sigma \sim log(s) \simeq const \qquad \mathscr{L} \sim E^2$$



$$\sqrt{s} = 30\,\text{TeV}$$

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

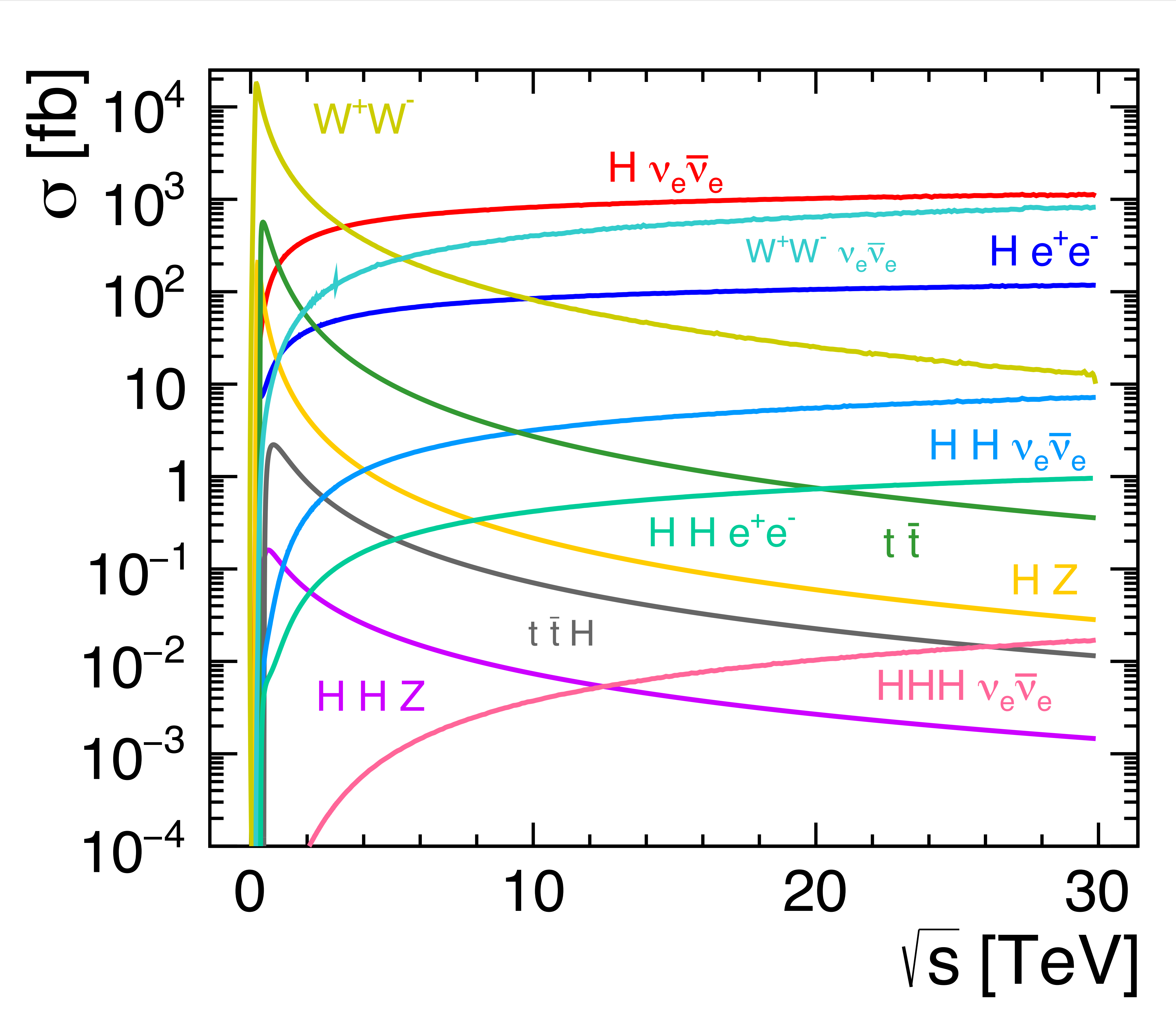
- ultra-rare Higgs decays
- differential distribution
- off-shell Higgs bosons
- rare production modes

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

10^8 HIGGS BOSONS | **100×MEGA-HIGGS FACTORY**

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

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



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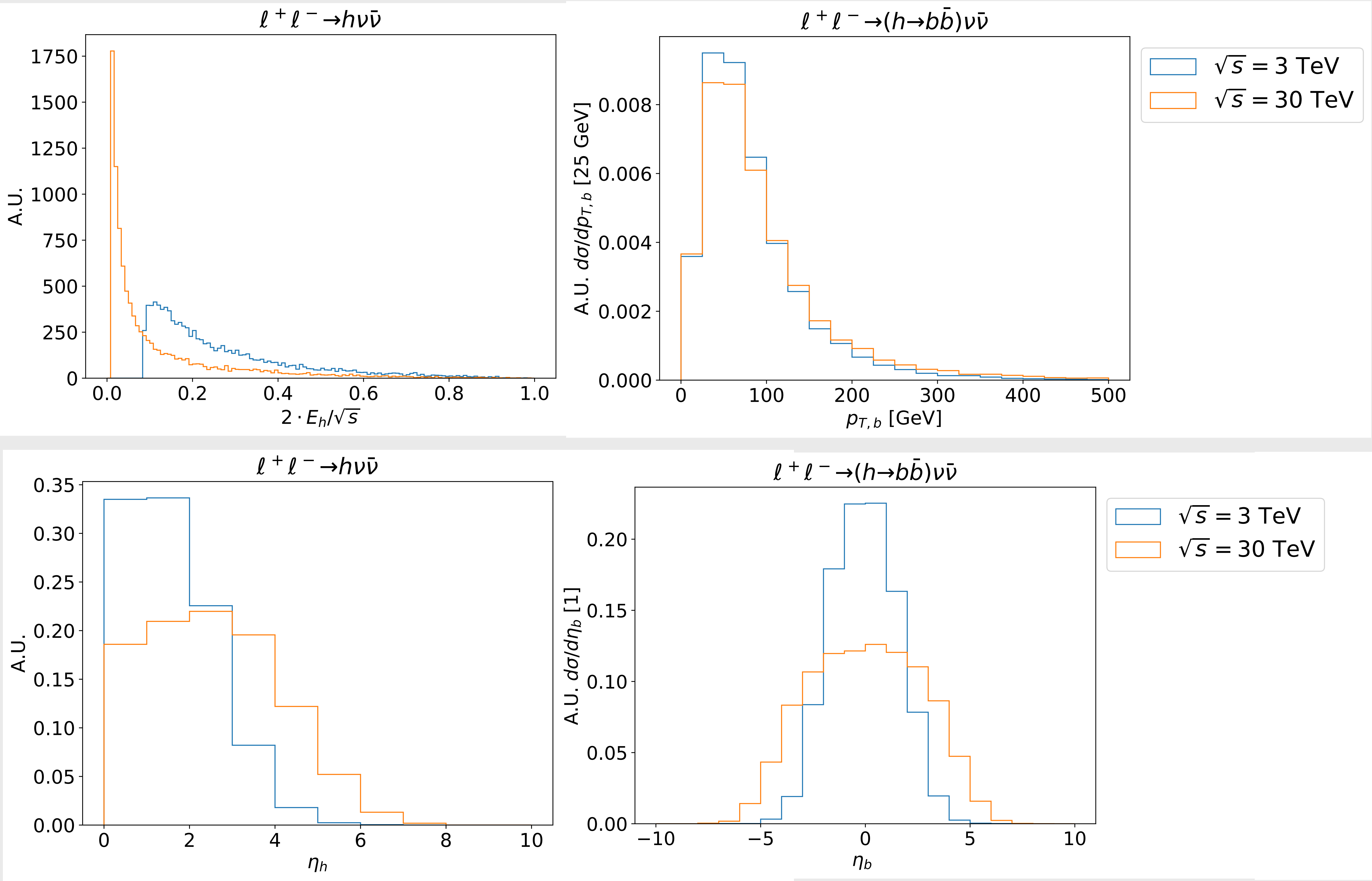

$$\mathscr{L} \simeq 90 \cdot \left(\frac{\sqrt{s}}{30\,\mathrm{TeV}}\right)^2 \mathrm{ab}^{-1}$$

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

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

Nathaniel Craig: The Muon-Smasher's Guide

κ-0 fit	HL-LHC	LHeC	HE-LHC S2	HE-LHC S2′	ILC 250	ILC 500	ILC 1000	CLIC 380	CLIC 1500	CLIC 3000	CEPC	FCC-ee 240	FCC-ee 365	FCC-ee/eh/hh	$\mu^+\mu^-$ 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]

High energy Higgs boson @μC

SM works wonderfully!

“EFT epoch”

"EFT epoch"

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

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

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HIGH-LUMI PROBES

HIGH-ENERGY PROBES

“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

HIGH-ENERGY 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

“EFT epoch”

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

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HIGH-LUMI PROBES

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

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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

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

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

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

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

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

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

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

Effects of the size of the Higgs boson

h ~ π STRONGLY INTERACTING LIGHT HIGGS

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

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

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

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

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

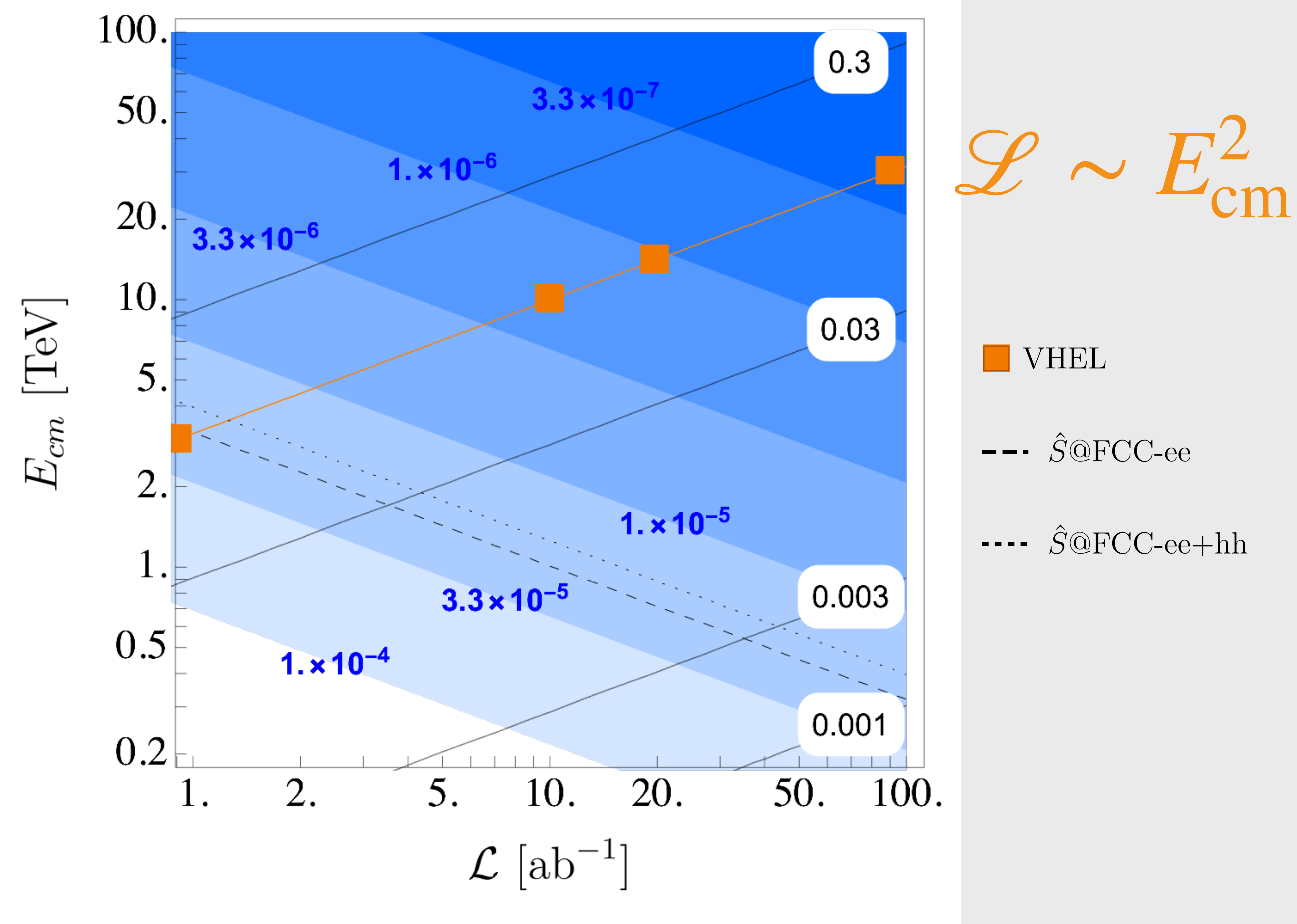
$\ell^+\ell^- \to Zh$

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

TOTAL RATE

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

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



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TOTAL RATE

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

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

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

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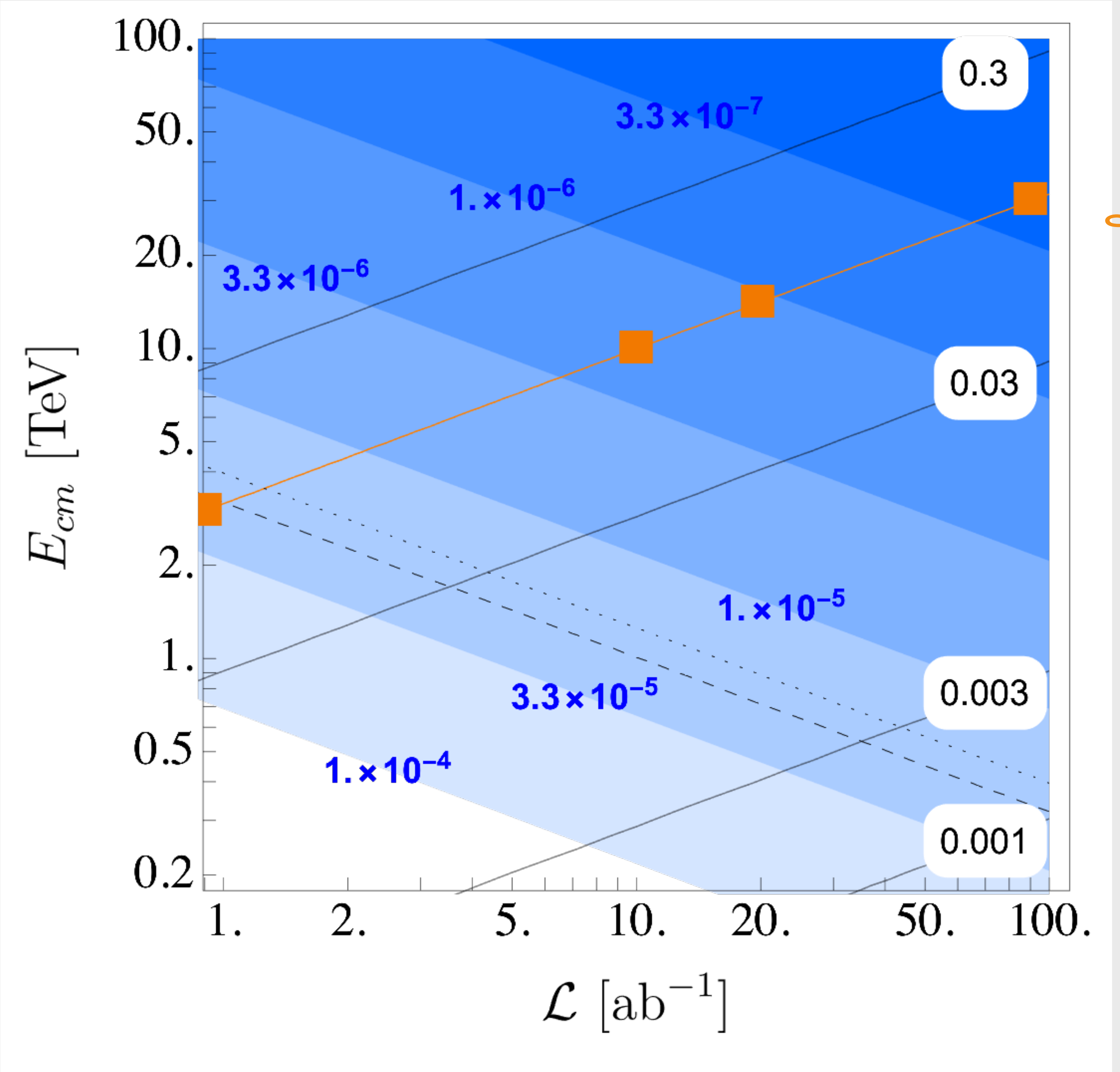


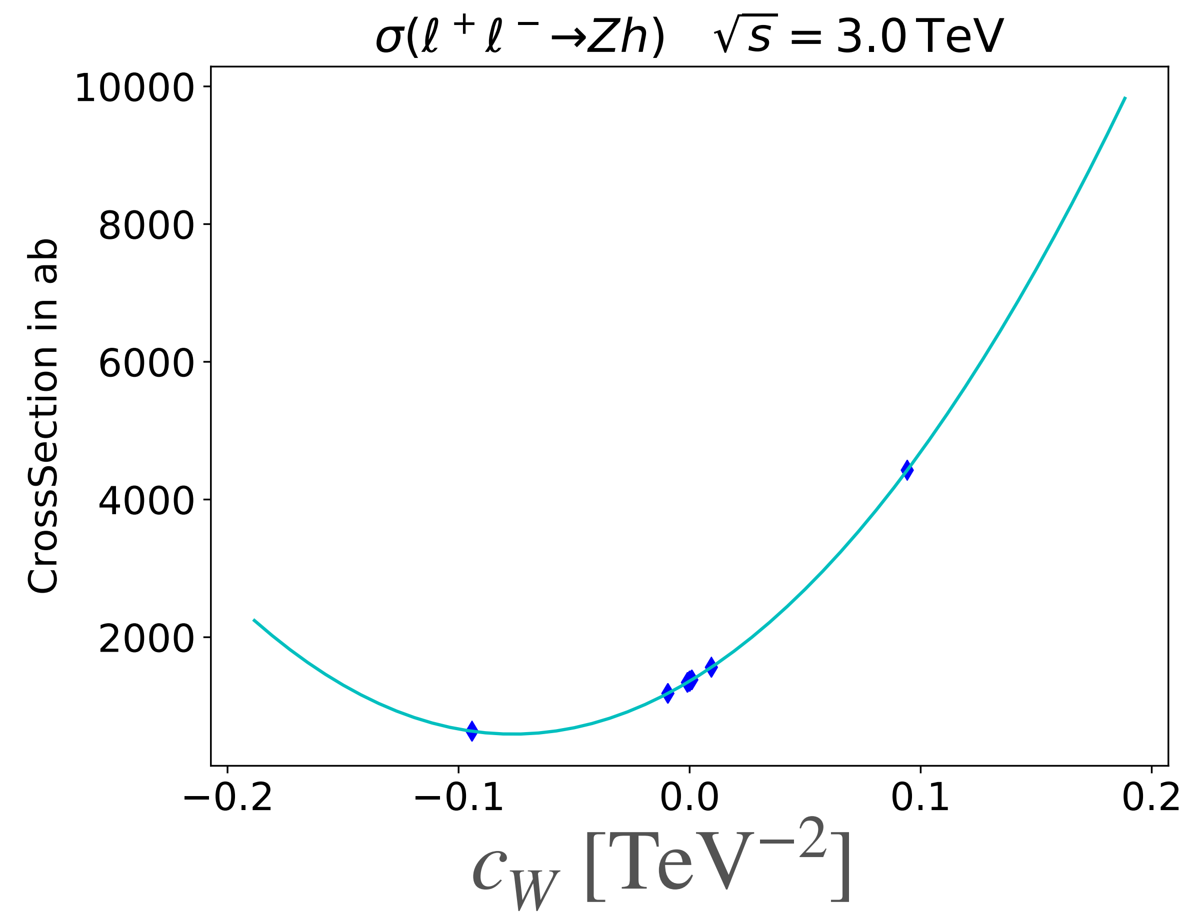
$\mathscr{L} \sim E_{cm}^2$

VHEL

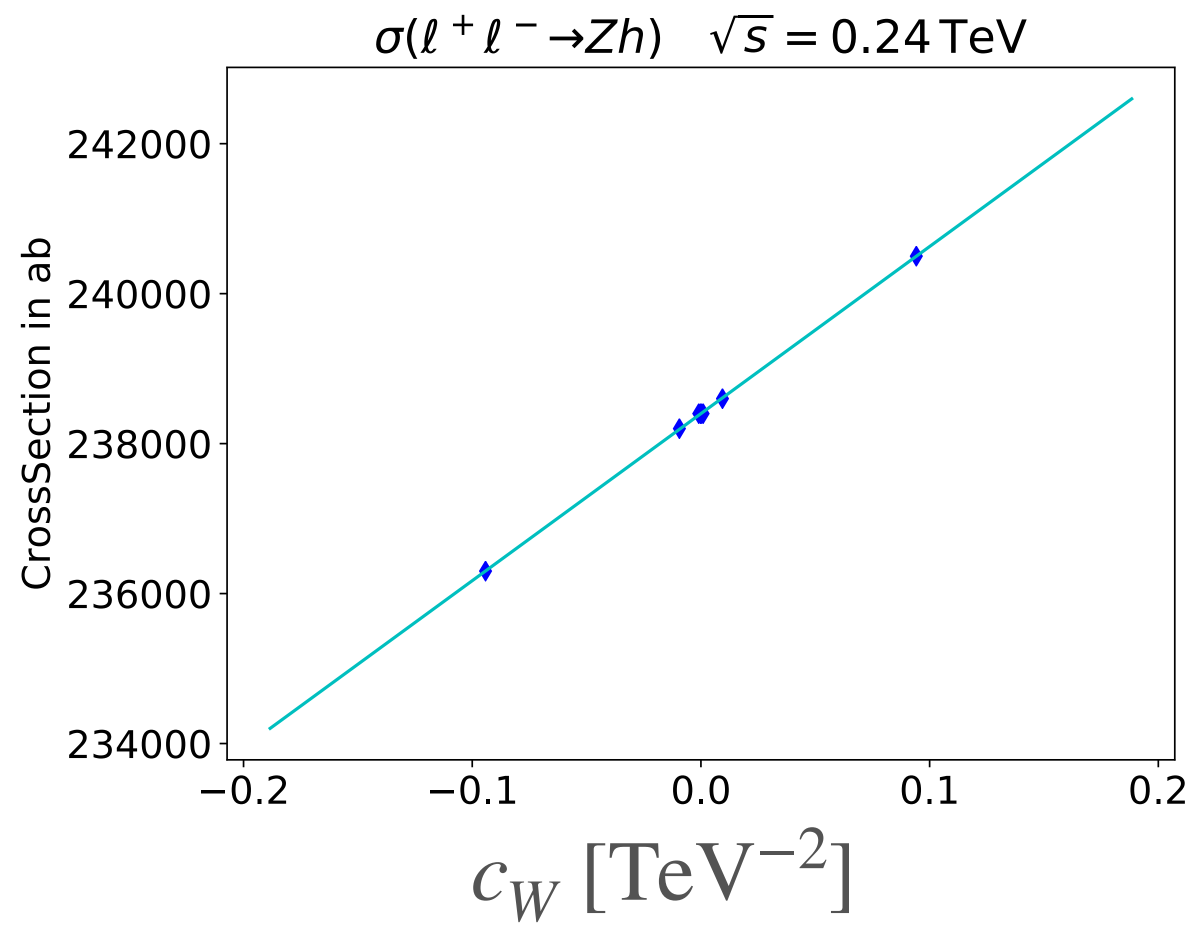
$\hat{S}$@FCC-ee

$\hat{S}$@FCC-ee+hh

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



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



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

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

TOTAL RATE

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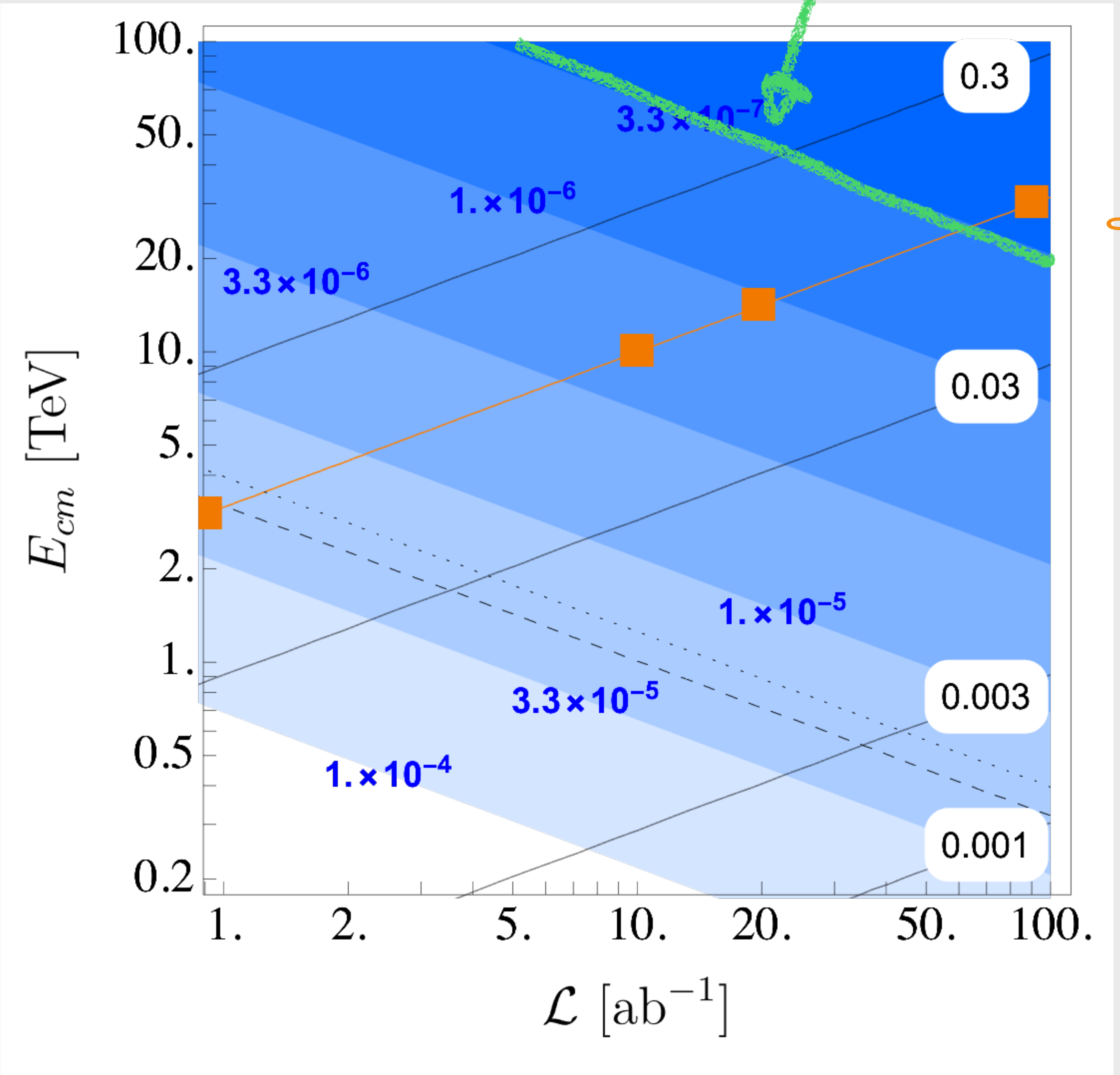
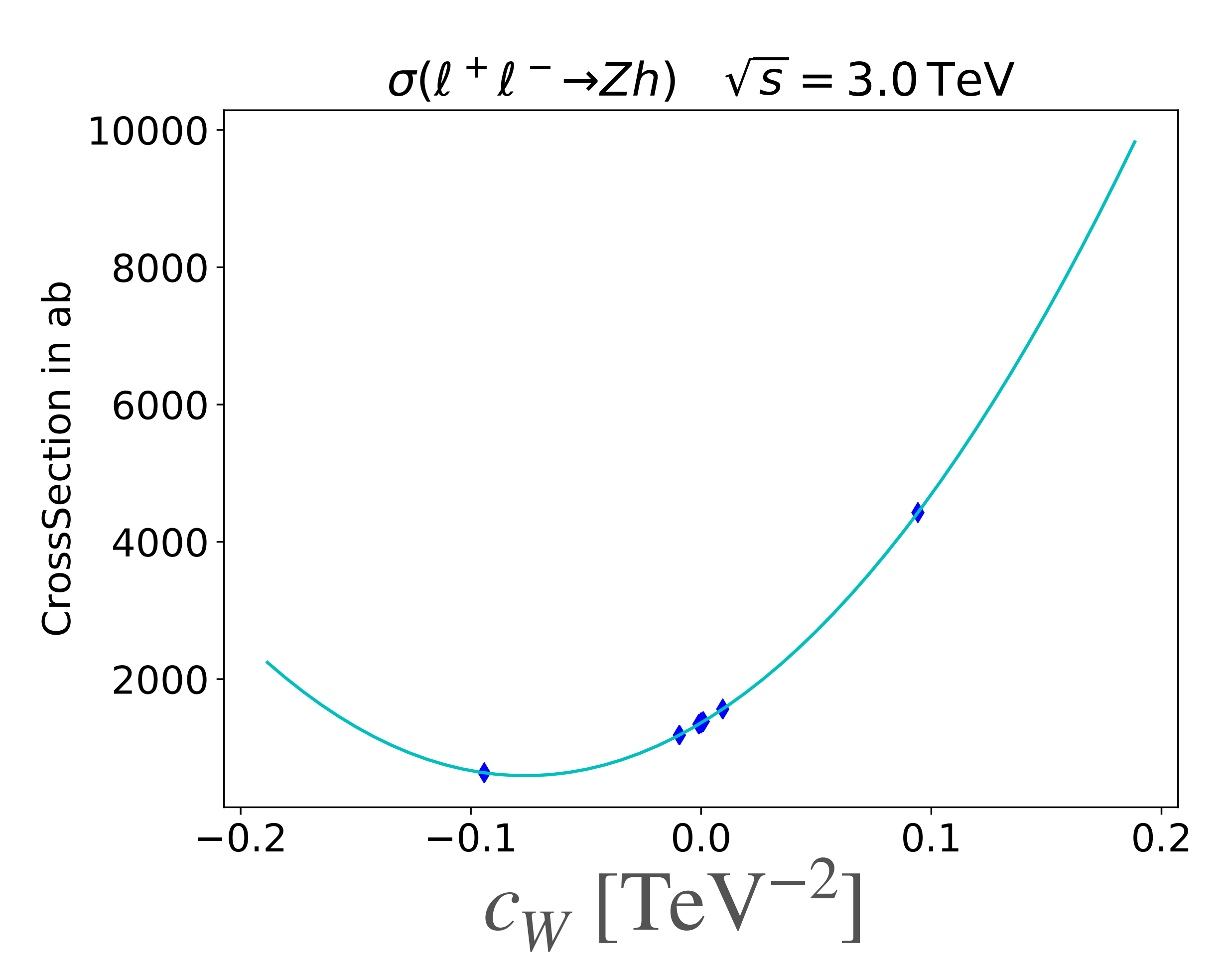
$$\hat{S}_{95\%} \lesssim 1.2\cdot 10^{-4}\frac{1}{E_{beam}/\text{TeV}}\cdot\frac{1}{\sqrt{\mathscr{L}/\text{ab}^{-1}}}$$

$\hat{S}\sim 10^{-7}$



$\mathscr{L}\sim E^2_{cm}$

$\hat{S} < 3\cdot10^{-5}$ (95 % CL) ← $\mathscr{L} = 5\,\text{ab}^{-1}$



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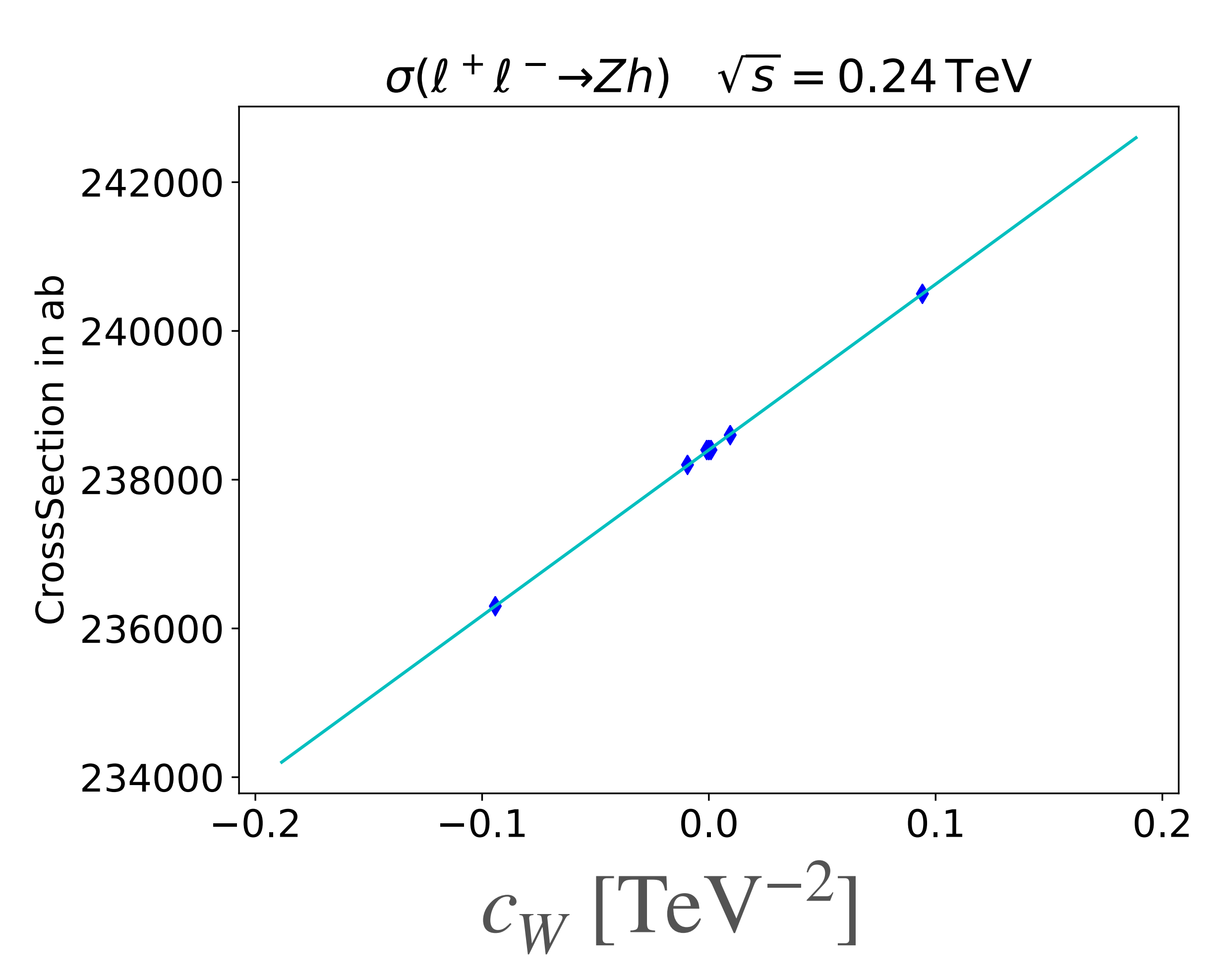

$\ell^+\ell^- \to Zh$

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

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

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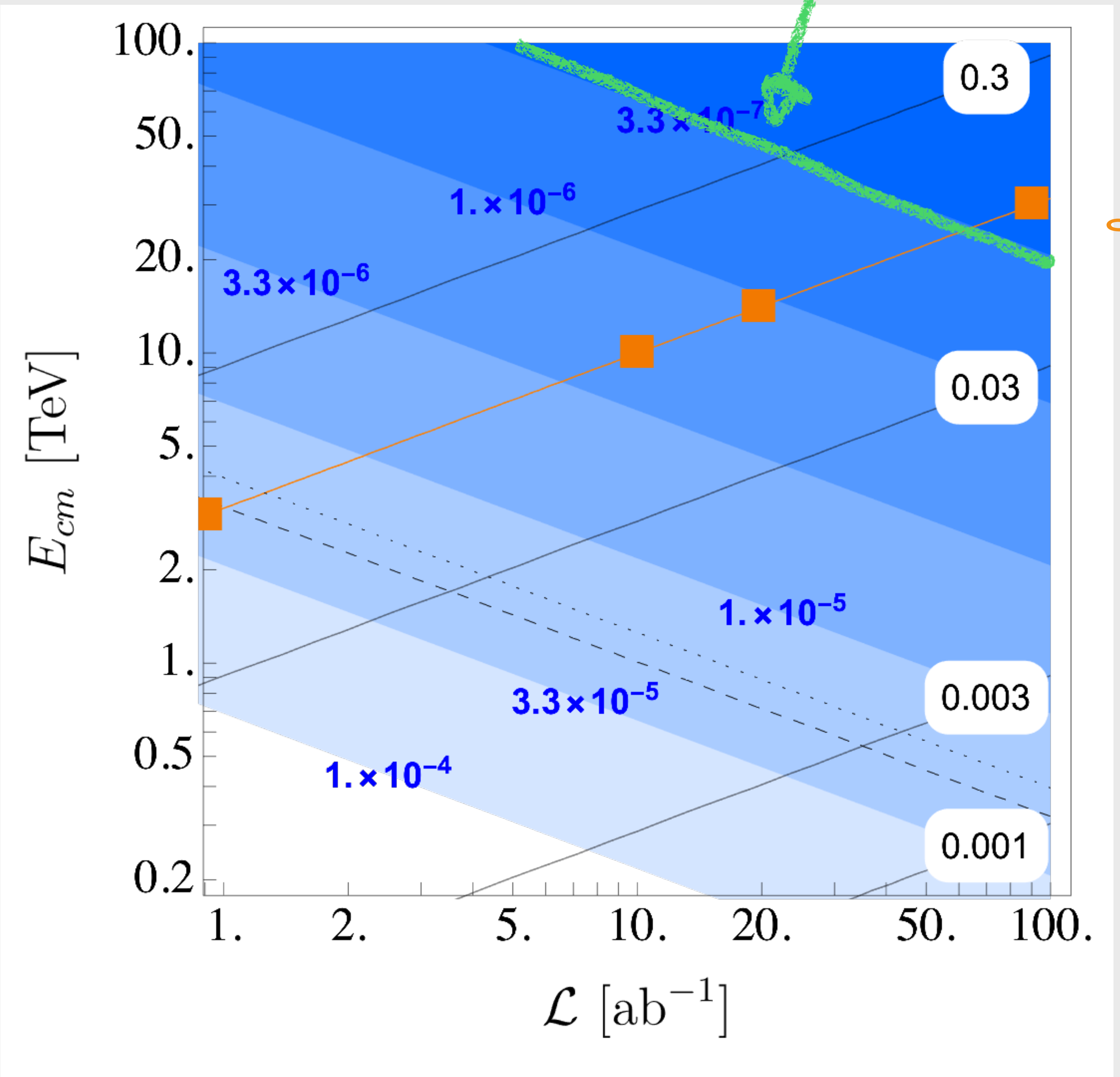
$$\hat{S}_{95\%} \lesssim 1.2 \cdot 10^{-4} \frac{1}{E_{beam}/\mathrm{TeV}} \cdot \frac{1}{\sqrt{\mathscr{L}/\mathrm{ab}^{-1}}}$$

$\hat{S} \sim 10^{-7}$ minus 7



VHEL

$\hat{S}$@FCC-ee

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

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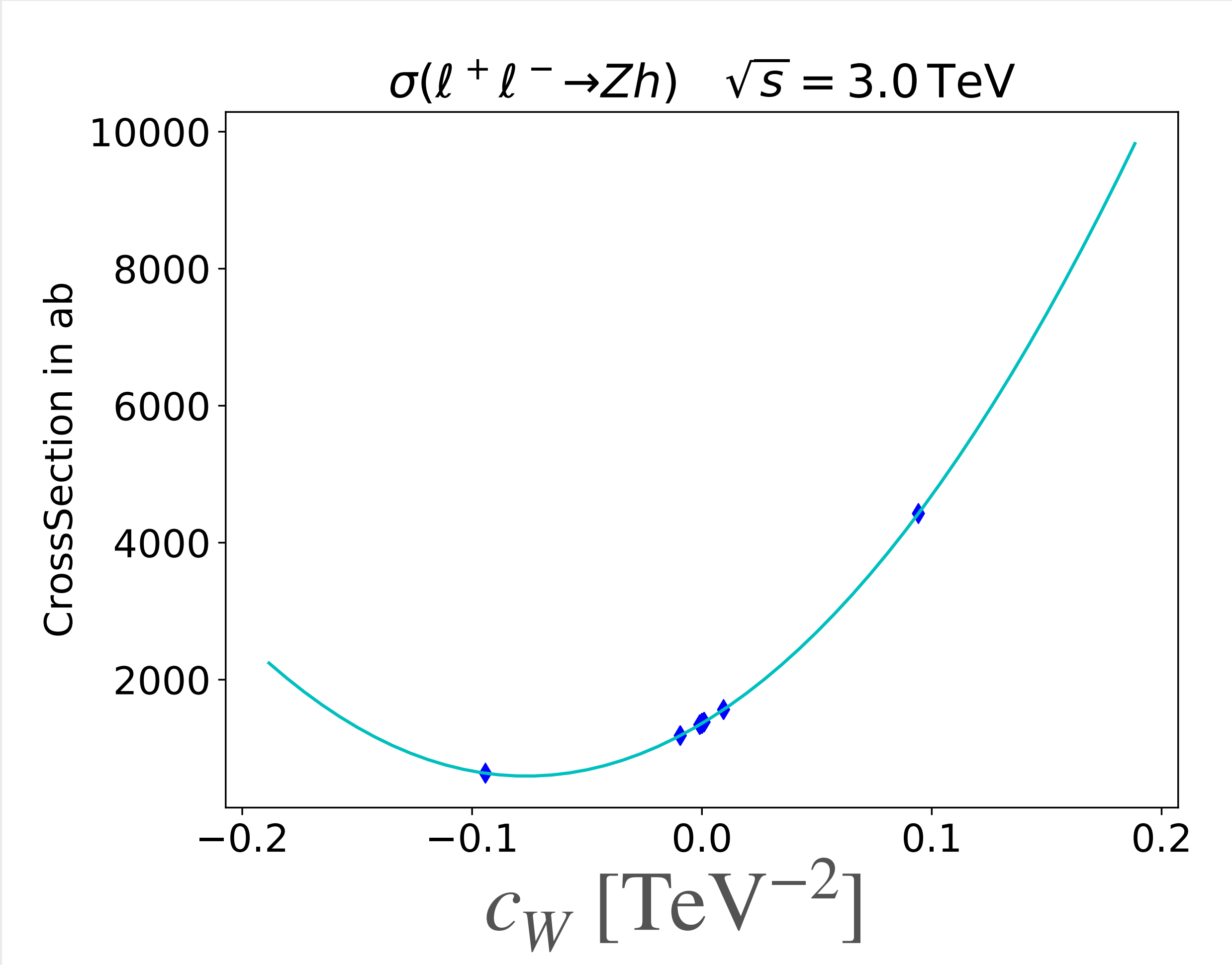

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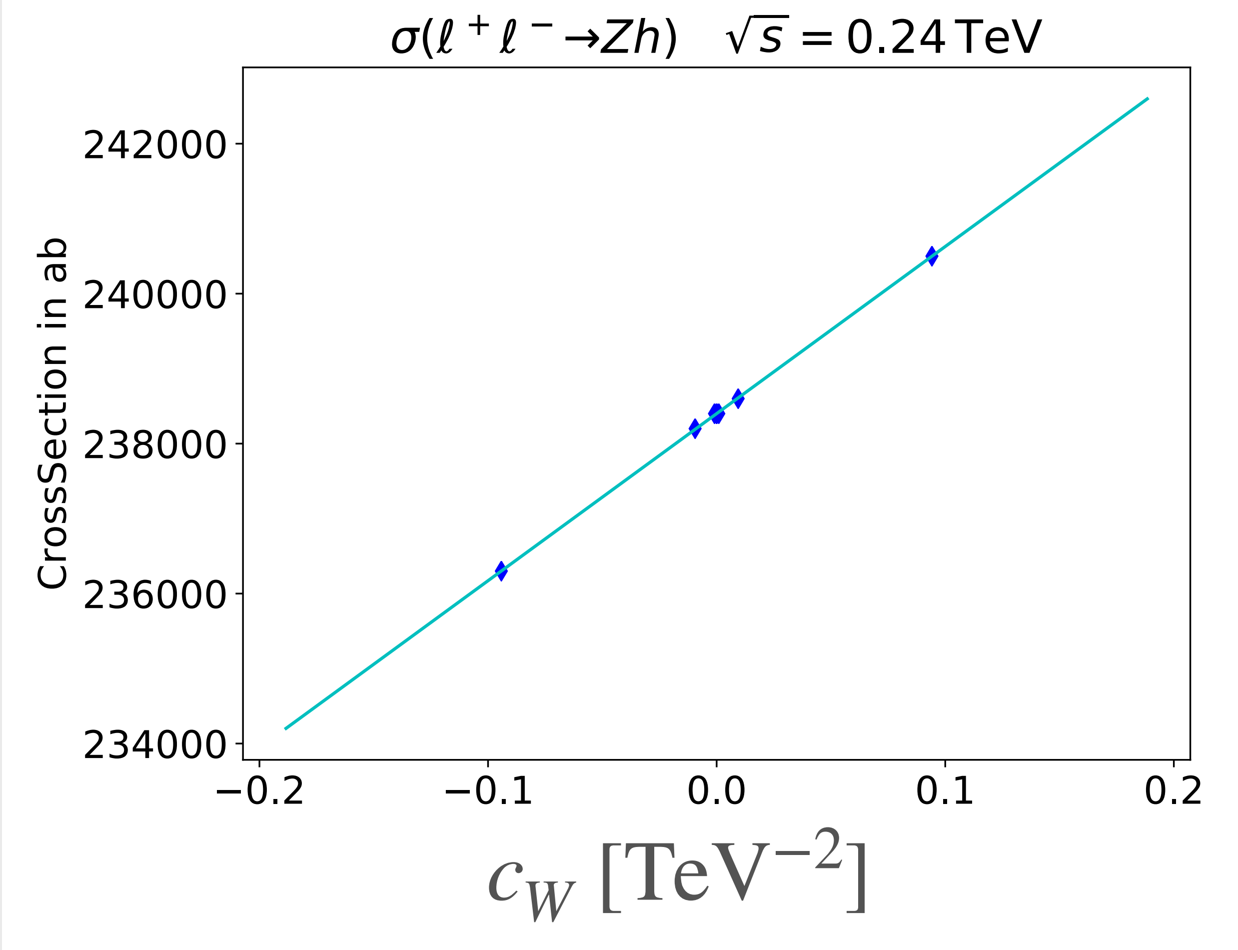

$\ell^+\ell^- \to Zh$

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

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

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

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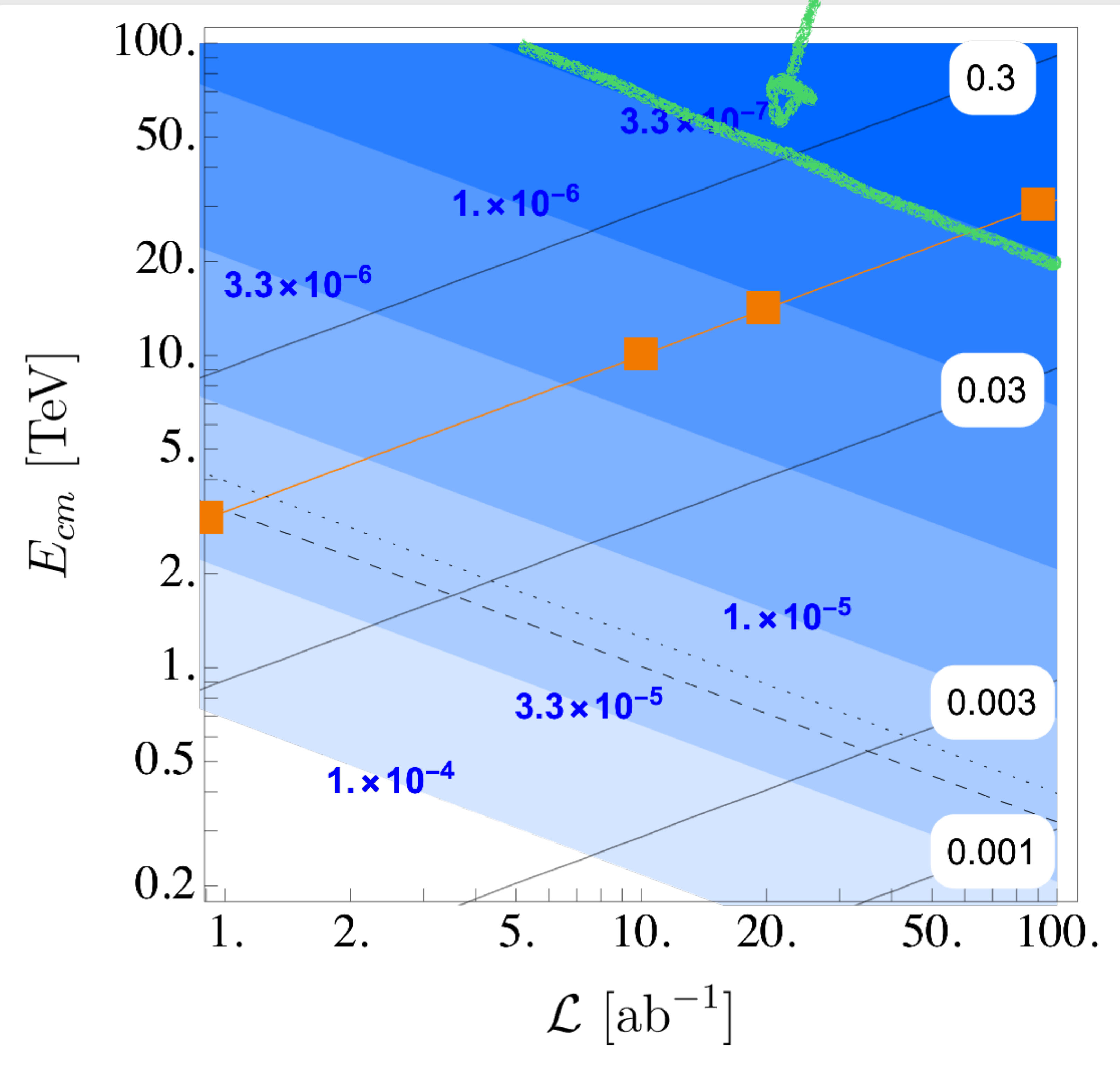

$$\hat{S} \equiv c_W/m_W^2 \simeq \frac{\delta O}{O} \text{ at Z pole}$$

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

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

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

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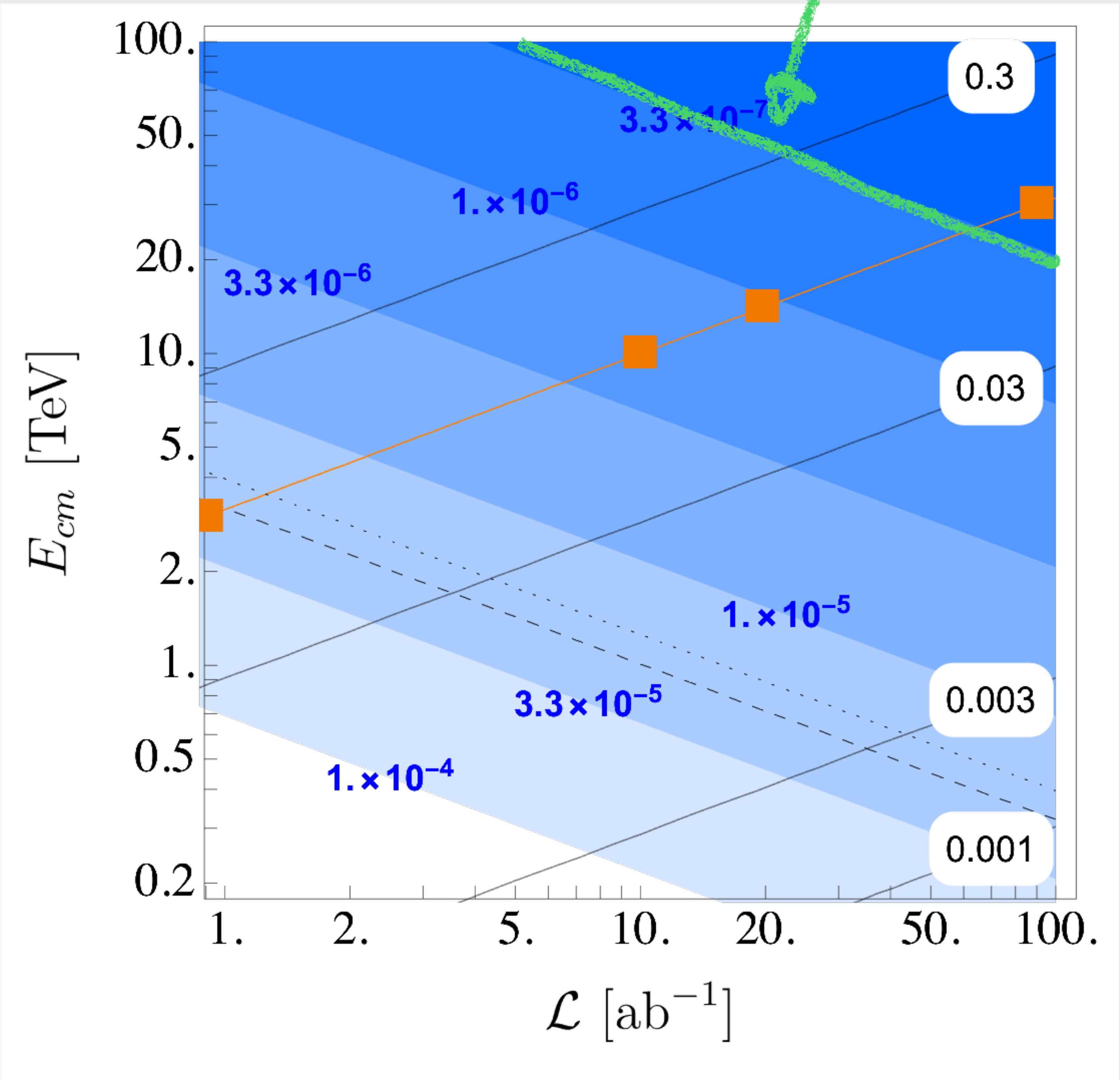


$$\hat{S} \equiv c_W/m_W^2 \simeq \frac{\delta O}{O} \text{ at Z pole}$$

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

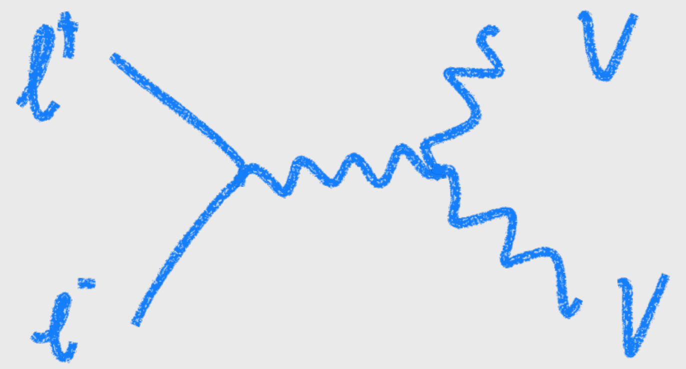
$\ell^+\ell^- \to VV$

EFT EPOCH

LESSON FROM LHC

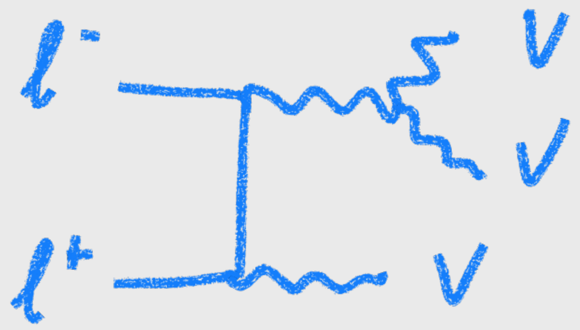
$$\left.\begin{array}{l} \ell^+\ell^- \to W^+W^- \\ \ell^+\ell^- \to Zh \\ \ell^+\ell^- \to hh \end{array}\right\}$$

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
$\bar{u}_L d_L \to W_L Z_L, W_L h$	$\sqrt{2} a_q^{(3)}$	$\sqrt{2}\frac{g^2}{m_W^2}\left[c_{\theta_W}(\delta g_{uL}^Z - \delta g_{dL}^Z)/g - c_{\theta_W}^2 \delta g_1^Z\right]$
$\bar{u}_L u_L \to W_L W_L$ $\bar{d}_L d_L \to Z_L h$	$a_q^{(1)} + a_q^{(3)}$	$-\frac{2g^2}{m_W^2}\left[Y_L t_{\theta_W}^2 \delta\kappa_\gamma + T_Z^{u_L}\delta g_1^Z + c_{\theta_W}\delta g_{dL}^Z/g\right]$
$\bar{d}_L d_L \to W_L W_L$ $\bar{u}_L u_L \to Z_L h$	$a_q^{(1)} - a_q^{(3)}$	$-\frac{2g^2}{m_W^2}\left[Y_L t_{\theta_W}^2 \delta\kappa_\gamma + T_Z^{d_L}\delta g_1^Z + c_{\theta_W}\delta g_{uL}^Z/g\right]$
$\bar{f}_R f_R \to W_L W_L, Z_L h$	a_f	$-\frac{2g^2}{m_W^2}\left[Y_{f_R} t_{\theta_W}^2 \delta\kappa_\gamma + T_Z^{f_R}\delta g_1^Z + c_{\theta_W}\delta g_{fR}^Z/g\right]$

Process	BSM Amplitude
$\ell_L^+\ell_L^- \to Z_0 h$ $\bar{\nu}_L \nu_L \to W_0^+ W_0^-$	$s\,(G_{3L} + G_{1L})\sin\theta_\star$
$\ell_L^+\ell_L^- \to W_0^+ W_0^-$ $\bar{\nu}_L \nu_L \to Z_0 h$	$s\,(G_{3L} - G_{1L})\sin\theta_\star$
$\ell_R^+\ell_R^- \to W_0^+ W_0^-, Z_0 h$	$s\, G_{lR}\sin\theta_\star$
$\bar{\nu}_L \ell_L^- \to W_0^- Z_0 \,/\, W_0^- h$ $\nu_L \ell_L^+ \to W_0^+ Z_0 \,/\, W_0^+ h$	$\sqrt{2}\, s\, G_{3L}\sin\theta_\star$

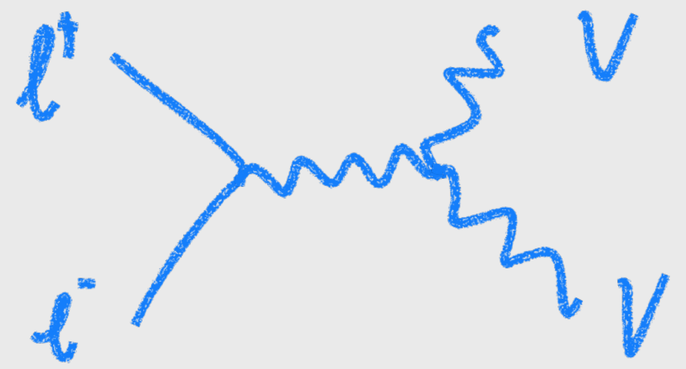
$$G_{3L} = \frac{g^2}{4}(C_W + C_{HW})\,, \qquad G_{1L} = \frac{g'^2}{4}(C_B + C_{HB}) = \frac{1}{2}G_{lR}\,,$$

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

EFT EPOCH | LESSON FROM LHC

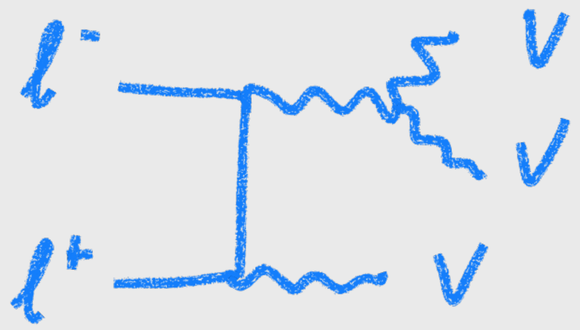
$\ell^+\ell^- \to W^+W^-$
$\ell^+\ell^- \to Zh$
$\ell^+\ell^- \to hh$

} two-body charge neutral final states



$\ell^+\ell^- \to W^+h + X^-$
$\ell^+\ell^- \to W^+Z + X^-$
$\ell^+\ell^- \to \ldots$

} many-body charge neutral final states



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$\bar{u}_L d_L \to W_L Z_L, W_L h$	$\sqrt{2} a_q^{(3)}$	$\sqrt{2}\frac{g^2}{m_W^2}\left[c_{\theta_W}(\delta g^Z_{uL} - \delta g^Z_{dL})/g - c^2_{\theta_W}\delta g_1^Z\right]$
$\bar{u}_L u_L \to W_L W_L$ $\bar{d}_L d_L \to Z_L h$	$a_q^{(1)} + a_q^{(3)}$	$-\frac{2g^2}{m_W^2}\left[Y_L t^2_{\theta_W}\delta\kappa_\gamma + T_Z^{u_L}\delta g_1^Z + c_{\theta_W}\delta g^Z_{dL}/g\right]$
$\bar{d}_L d_L \to W_L W_L$ $\bar{u}_L u_L \to Z_L h$	$a_q^{(1)} - a_q^{(3)}$	$-\frac{2g^2}{m_W^2}\left[Y_L t^2_{\theta_W}\delta\kappa_\gamma + T_Z^{d_L}\delta g_1^Z + c_{\theta_W}\delta g^Z_{uL}/g\right]$
$\bar{f}_R f_R \to W_L W_L, Z_L h$	a_f	$-\frac{2g^2}{m_W^2}\left[Y_{f_R} t^2_{\theta_W}\delta\kappa_\gamma + T_Z^{f_R}\delta g_1^Z + c_{\theta_W}\delta g^Z_{fR}/g\right]$

Process	BSM Amplitude
$\ell^+_L\ell^-_L \to Z_0 h$ $\bar{\nu}_L\nu_L \to W_0^+W_0^-$	$s\,(G_{3L} + G_{1L})\sin\theta_\star$
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$\ell^+_R\ell^-_R \to W_0^+W_0^-, Z_0 h$	$s\,G_{lR}\sin\theta_\star$
$\bar{\nu}_L\ell^-_L \to W_0^- Z_0\,/\,W_0^- h$ $\nu_L\ell^+_L \to W_0^+ Z_0\,/\,W_0^+ h$	$\sqrt{2}\,s\,G_{3L}\sin\theta_\star$

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

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

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

EFT EPOCH

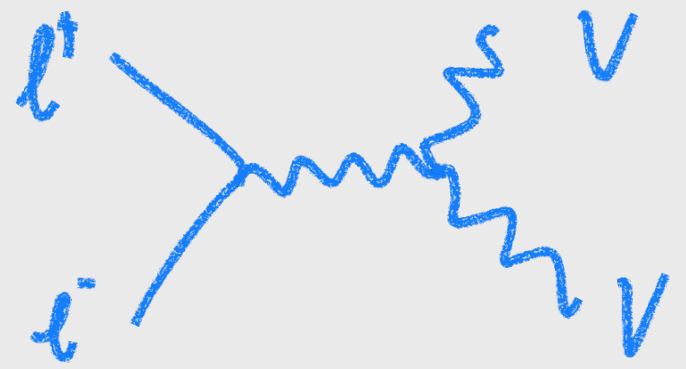
LESSON FROM LHC

$\ell^+\ell^- \to W^+W^-$

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

$\ell^+\ell^- \to hh$

two-body charge neutral final states

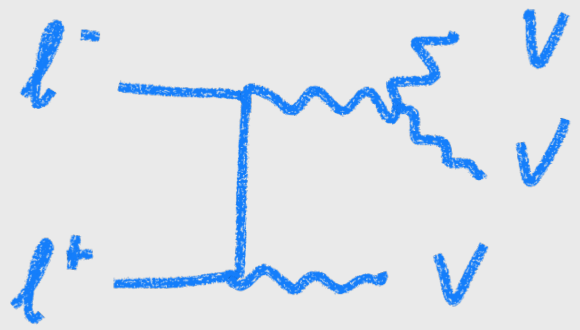


$\ell^+\ell^- \to W^+h \, + \, X^-$

$\ell^+\ell^- \to W^+Z \, + \, X^-$

$\ell^+\ell^- \to \ldots$

many-body charge neutral final states



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Amplitude	High-energy primaries	Low-energy primaries
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$\bar{u}_L u_L \to W_L W_L$ $\bar{d}_L d_L \to Z_L h$	$a_q^{(1)} + a_q^{(3)}$	$-\frac{2g^2}{m_W^2}\left[Y_L t_{\theta_W}^2 \delta\kappa_\gamma + T_Z^{u_L}\delta g_1^Z + c_{\theta_W}\delta g_{dL}^Z/g\right]$
$\bar{d}_L d_L \to W_L W_L$ $\bar{u}_L u_L \to Z_L h$	$a_q^{(1)} - a_q^{(3)}$	$-\frac{2g^2}{m_W^2}\left[Y_L t_{\theta_W}^2 \delta\kappa_\gamma + T_Z^{d_L}\delta g_1^Z + c_{\theta_W}\delta g_{uL}^Z/g\right]$
$\bar{f}_R f_R \to W_L W_L, Z_L h$	a_f	$-\frac{2g^2}{m_W^2}\left[Y_{f_R} t_{\theta_W}^2 \delta\kappa_\gamma + T_Z^{f_R}\delta g_1^Z + c_{\theta_W}\delta g_{fR}^Z/g\right]$

Process	BSM Amplitude
$\ell_L^+\ell_L^- \to Z_0 h$ $\bar{\nu}_L \nu_L \to W_0^+ W_0^-$	$s\,(G_{3L} + G_{1L})\sin\theta_\star$
$\ell_L^+\ell_L^- \to W_0^+ W_0^-$ $\bar{\nu}_L \nu_L \to Z_0 h$	$s\,(G_{3L} - G_{1L})\sin\theta_\star$
$\ell_R^+\ell_R^- \to W_0^+ W_0^-, Z_0 h$	$s\, G_{lR}\sin\theta_\star$
$\bar{\nu}_L \ell_L^- \to W_0^- Z_0 \,/\, W_0^- h$ $\nu_L \ell_L^+ \to W_0^+ Z_0 \,/\, W_0^+ h$	$\sqrt{2}\, s\, G_{3L}\sin\theta_\star$

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

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

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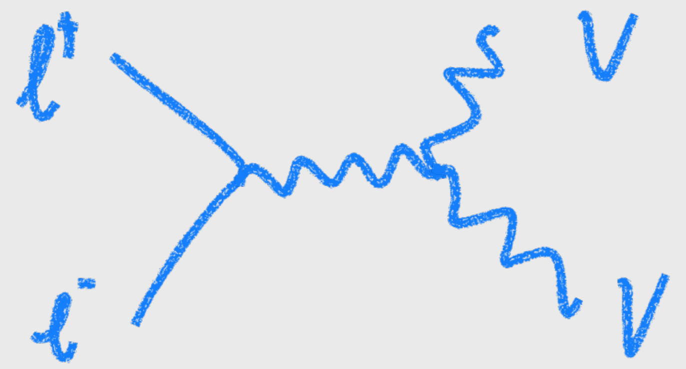
$\ell^+\ell^- \to W^+W^-$
$\ell^+\ell^- \to Zh$
$\ell^+\ell^- \to hh$

} two-body charge neutral final states



$\ell^+\ell^- \to W^+h\ +\ X^-$
$\ell^+\ell^- \to W^+Z\ +\ X^-$
$\ell^+\ell^- \to \dots$

} many-body charge neutral final states

1712.01310

Amplitude	High-energy primaries	Low-energy primaries
$\bar{u}_L d_L \to W_L Z_L, W_L h$	$\sqrt{2} a_q^{(3)}$	$\sqrt{2}\frac{g^2}{m_W^2}\left[c_{\theta_W}(\delta g^Z_{uL} - \delta g^Z_{dL})/g - c^2_{\theta_W}\delta g_1^Z\right]$
$\bar{u}_L u_L \to W_L W_L$ $\bar{d}_L d_L \to Z_L h$	$a_q^{(1)} + a_q^{(3)}$	$-\frac{2g^2}{m_W^2}\left[Y_L t^2_{\theta_W}\delta\kappa_\gamma + T_Z^{u_L}\delta g_1^Z + c_{\theta_W}\delta g^Z_{dL}/g\right]$
$\bar{d}_L d_L \to W_L W_L$ $\bar{u}_L u_L \to Z_L h$	$a_q^{(1)} - a_q^{(3)}$	$-\frac{2g^2}{m_W^2}\left[Y_L t^2_{\theta_W}\delta\kappa_\gamma + T_Z^{d_L}\delta g_1^Z + c_{\theta_W}\delta g^Z_{uL}/g\right]$
$\bar{f}_R f_R \to W_L W_L, Z_L h$	a_f	$-\frac{2g^2}{m_W^2}\left[Y_{f_R} t^2_{\theta_W}\delta\kappa_\gamma + T_Z^{f_R}\delta g_1^Z + c_{\theta_W}\delta g^Z_{fR}/g\right]$

Process	BSM Amplitude
$\ell^+_L\ell^-_L \to Z_0 h$ $\bar{\nu}_L\nu_L \to W_0^+W_0^-$	$s\,(G_{3L}+G_{1L})\sin\theta_\star$
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$\ell^+_R\ell^-_R \to W_0^+W_0^-, Z_0 h$	$s\,G_{lR}\sin\theta_\star$
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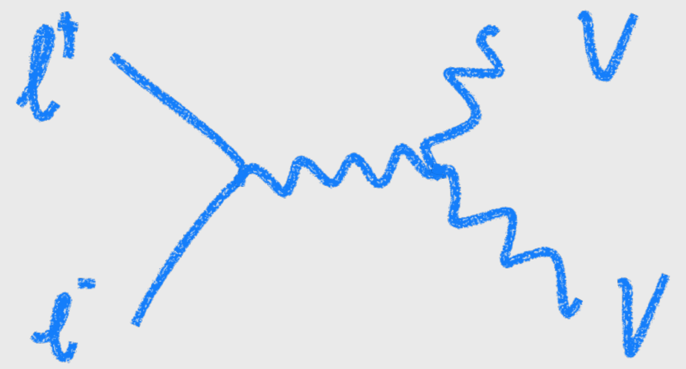
two-body charge neutral final states



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

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1712.01310

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$\bar{\nu}_L\ell^-_L \to W^-_0 Z_0\,/\,W^-_0 h$ $\nu_L\ell^+_L \to W^+_0 Z_0\,/\,W^+_0 h$	$\sqrt{2}\,s\,G_{3L}\sin\theta_\star$

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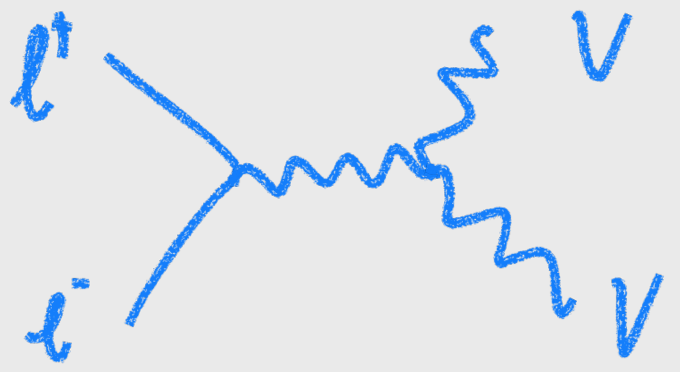

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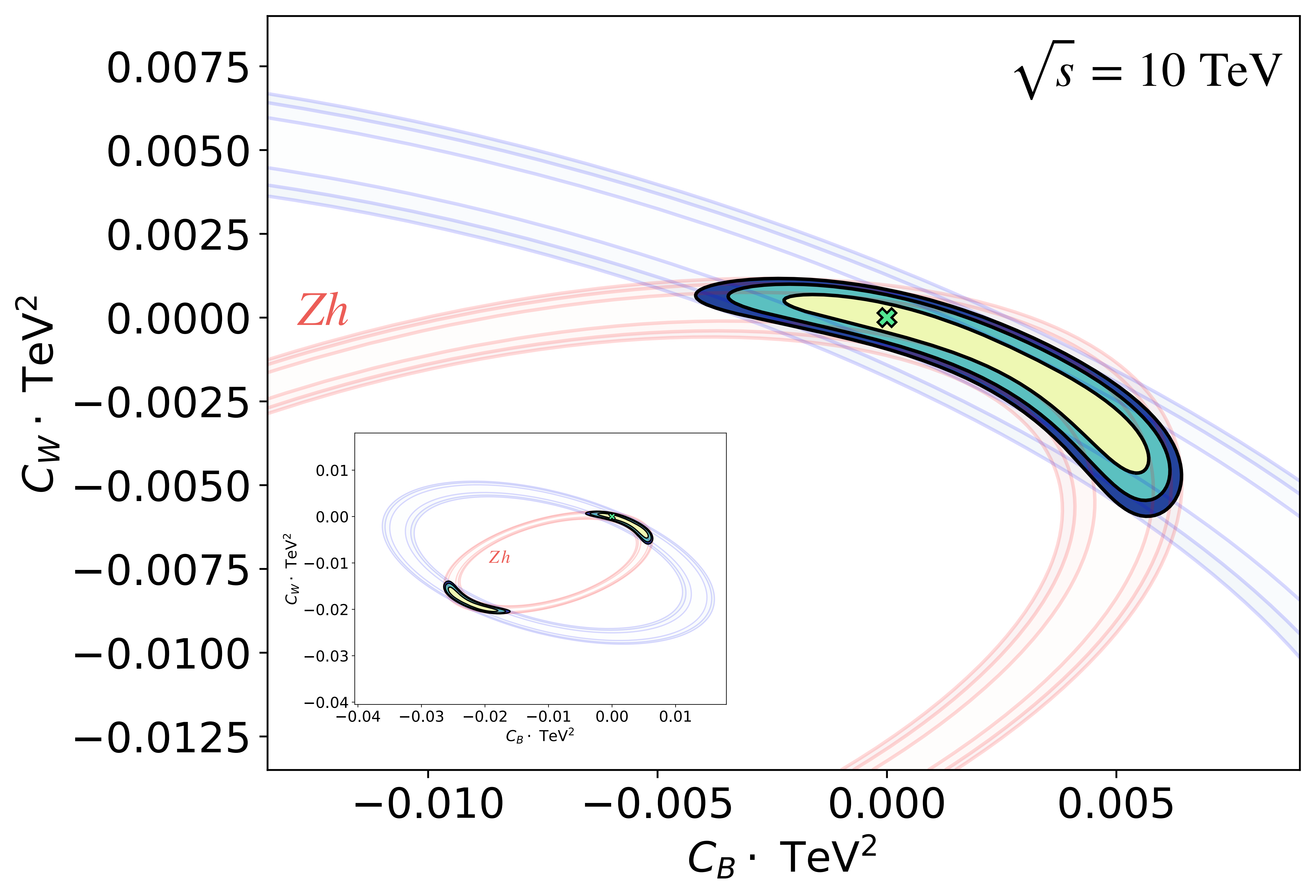
DIBOSON

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

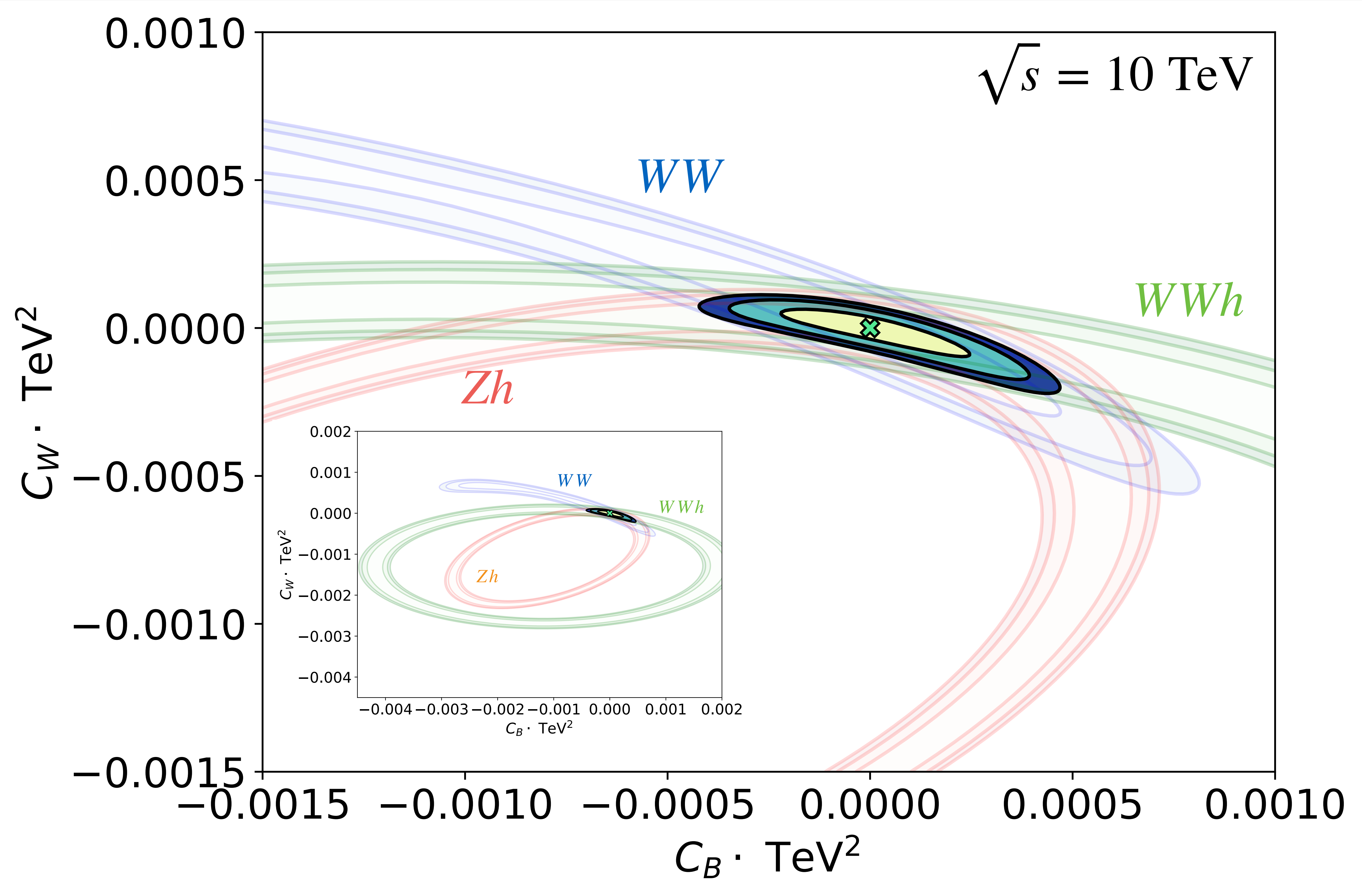
$\ell^+\ell^- \to \mathrm{VV}+\mathrm{X}$

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



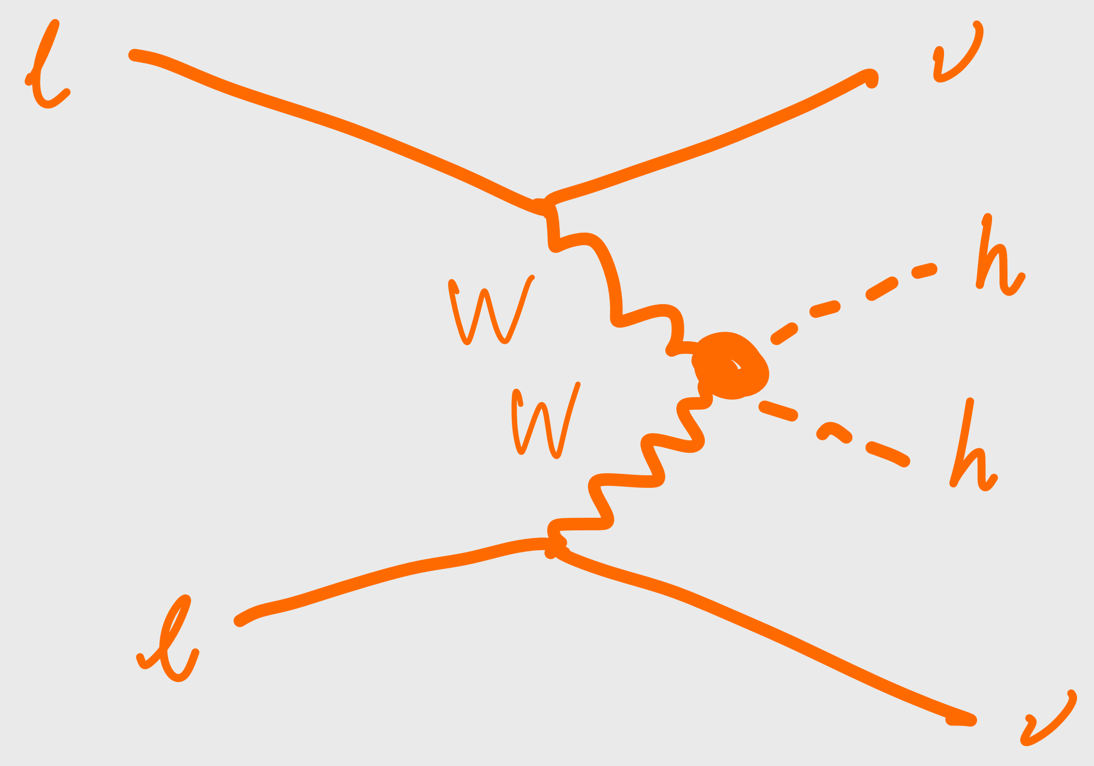
ZH: elliptical belt in 2D BSM coupling space

WW: basin in 2D BSM coupling space

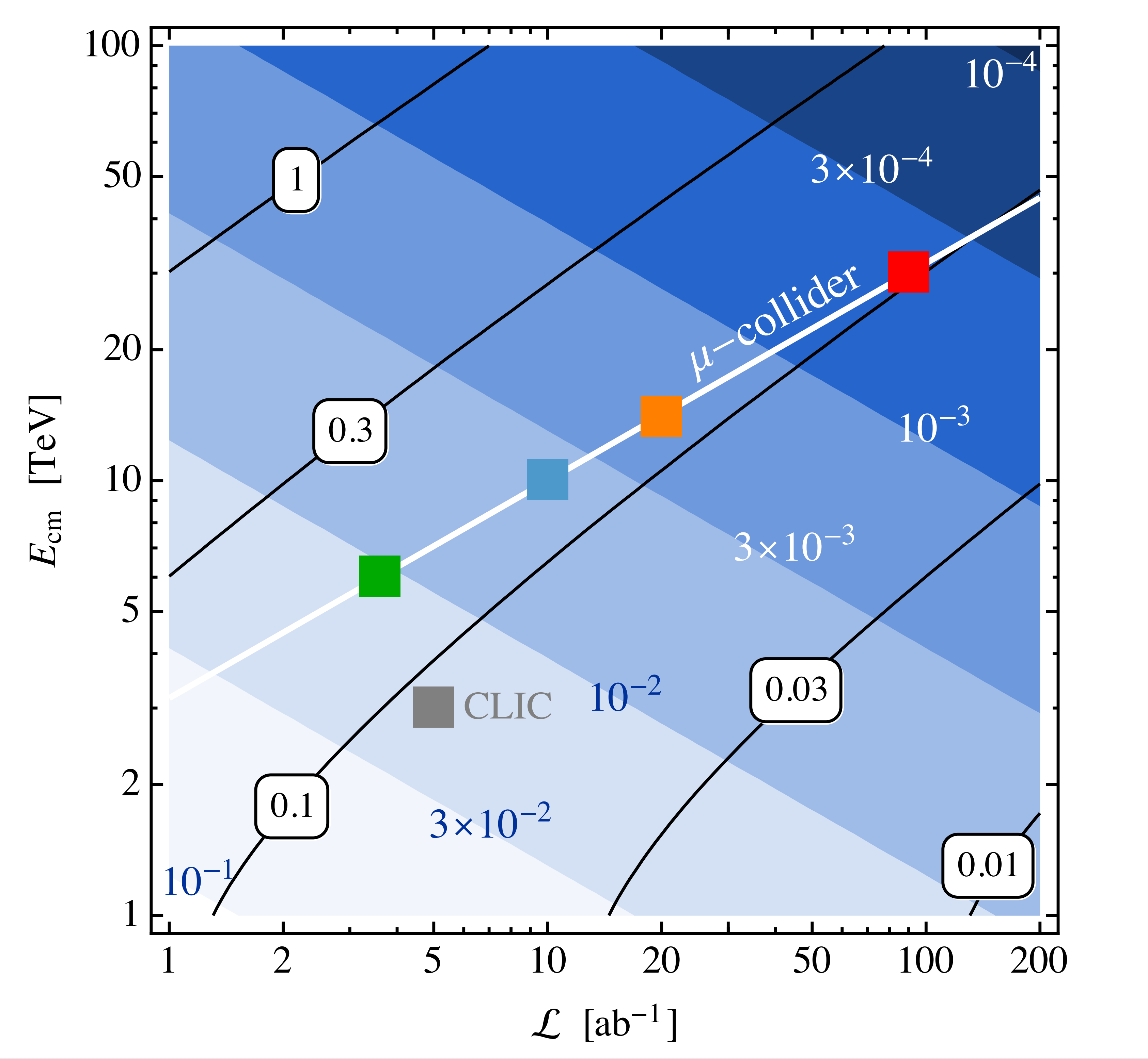
WWh: elliptical belt in 2D BSM coupling space

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

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 $\ell\ell$



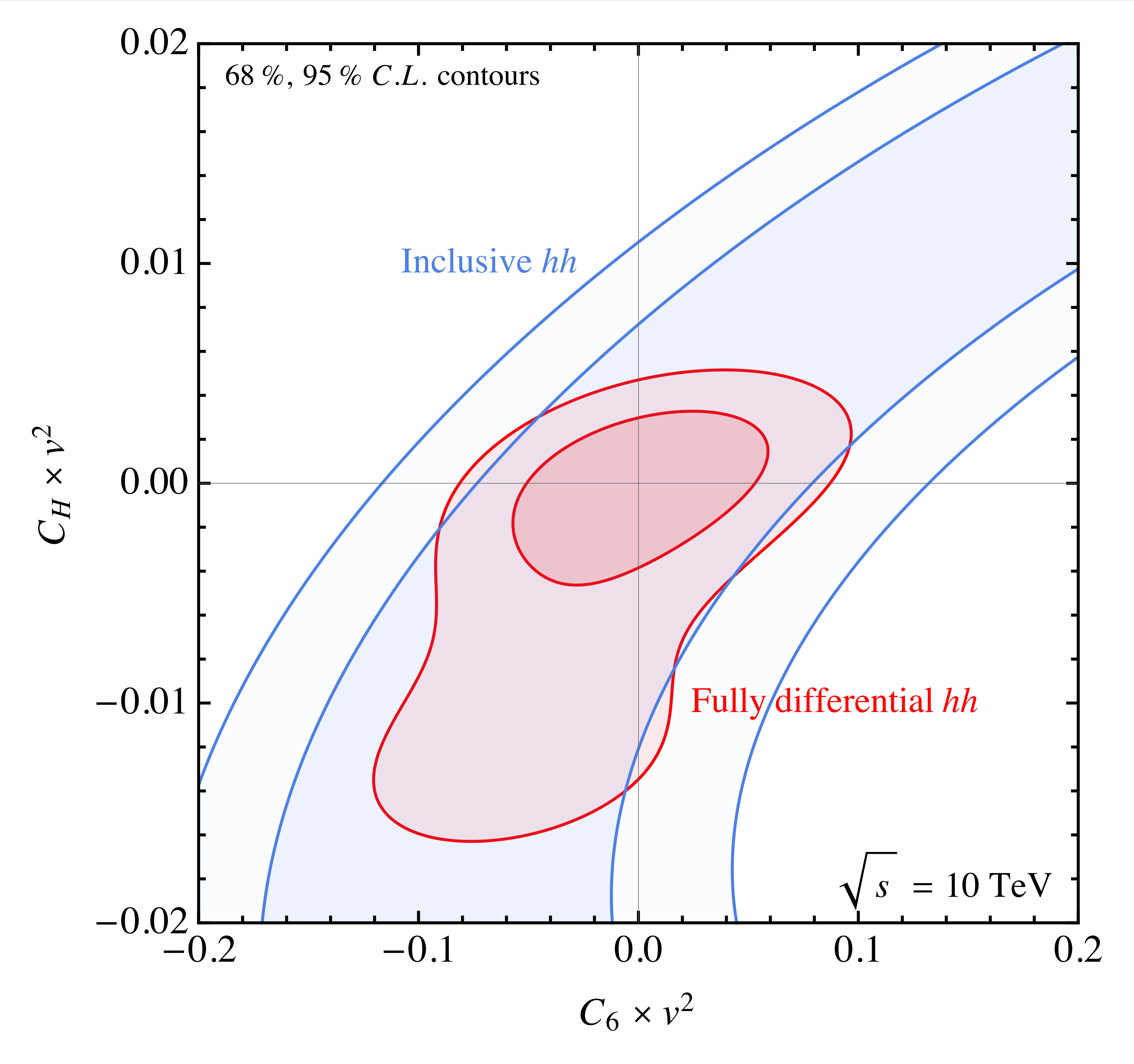
need large p_T Higgs bosons

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

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

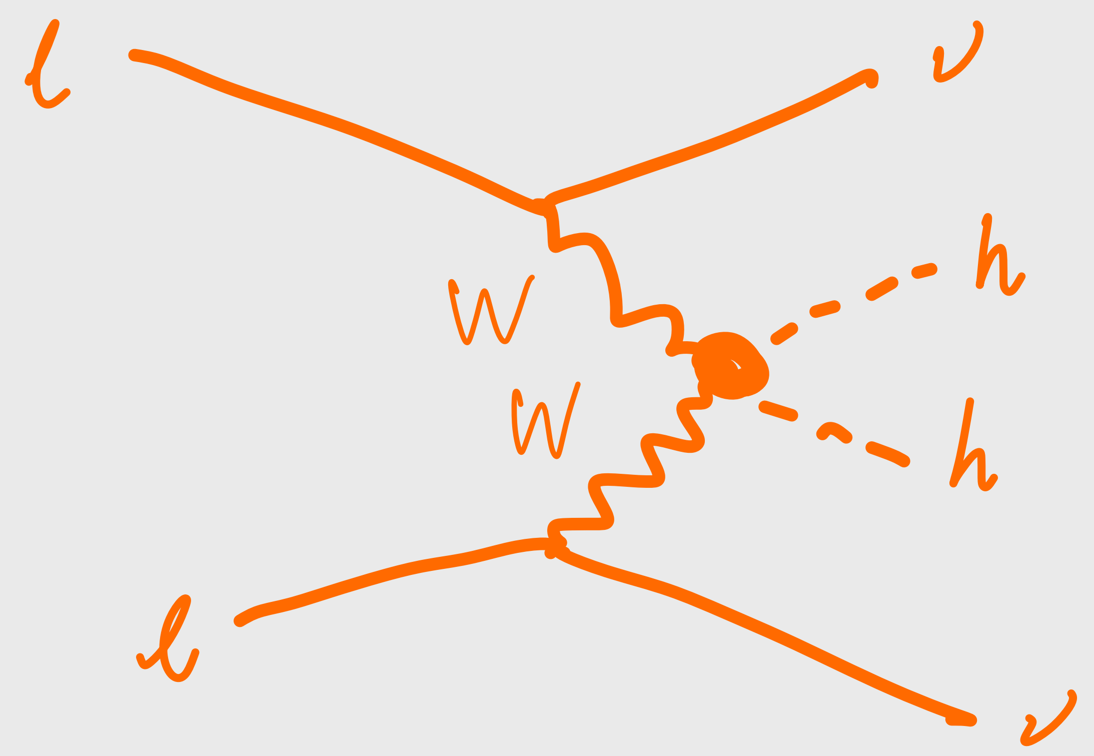
↓

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



$\ell^+\ell^- \to hh$

W BOSON **COLLIDER**



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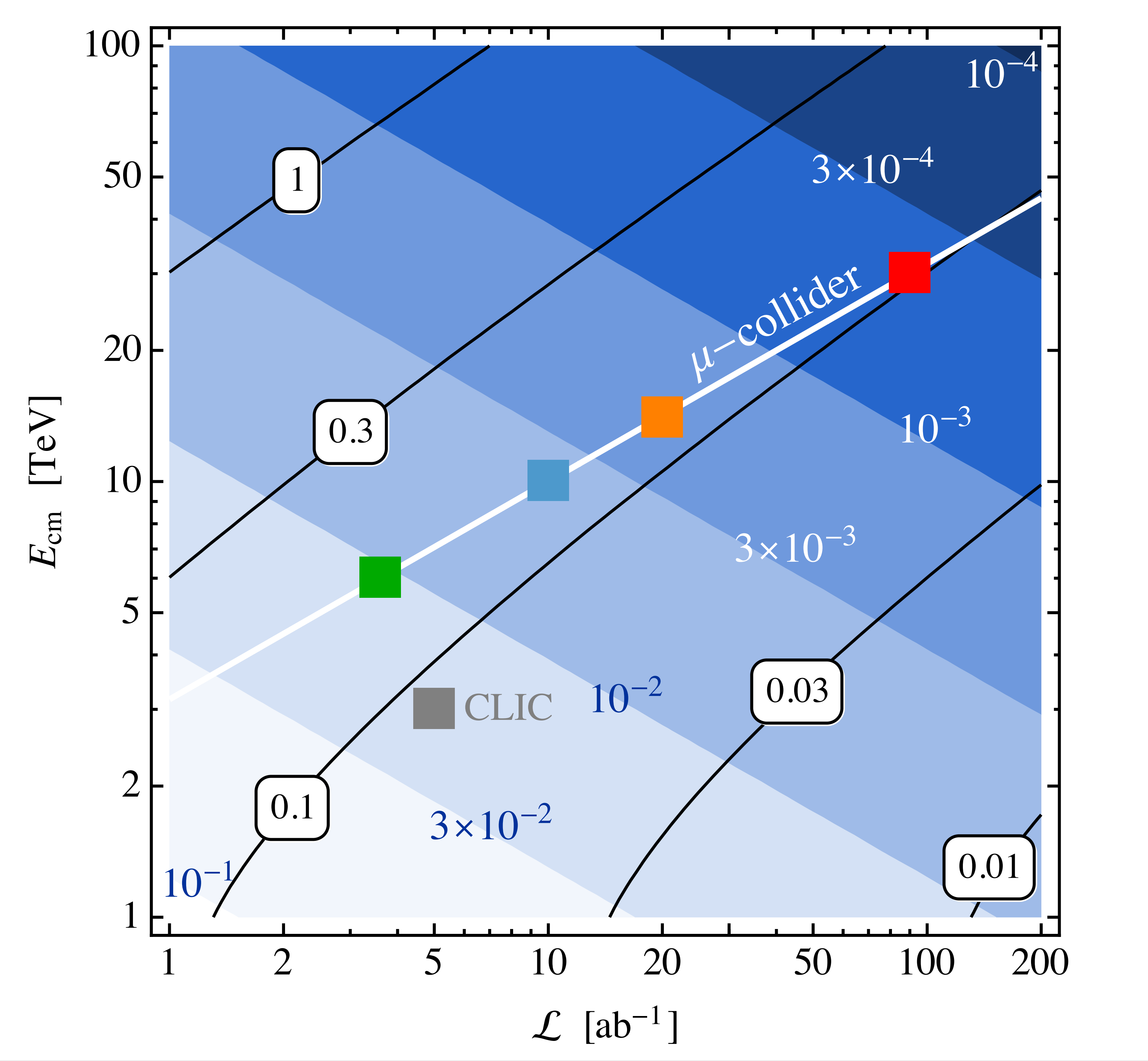

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$$\downarrow$$

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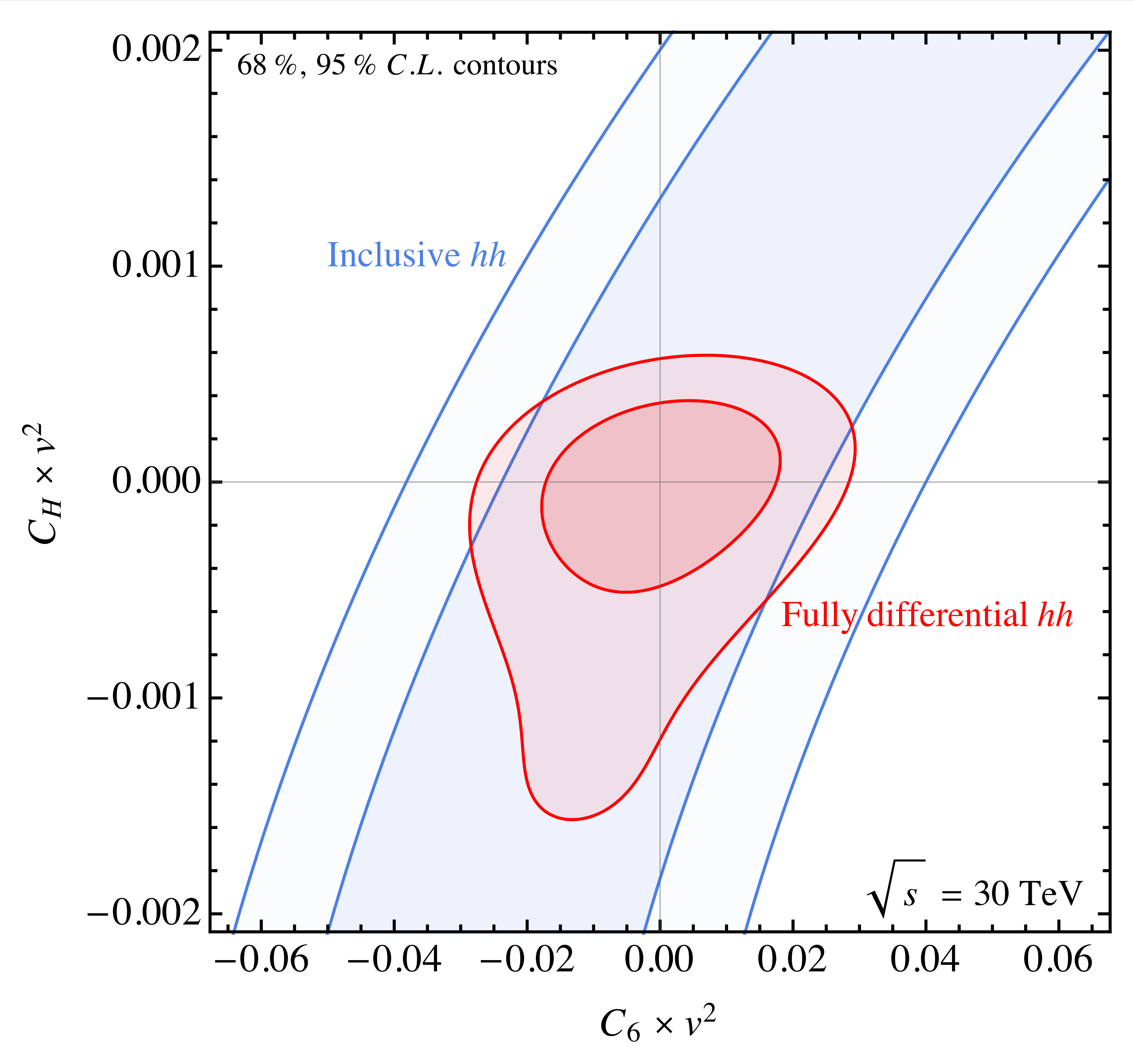


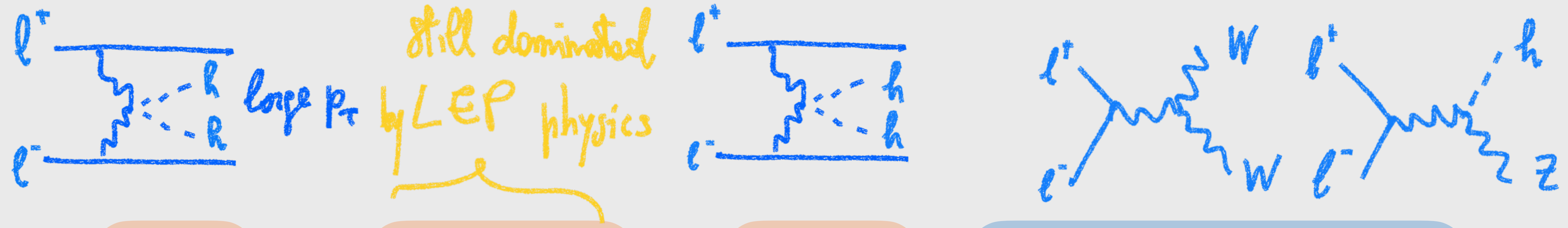
Effects of the size of the Higgs boson

h ~ π STRONGLY INTERACTING LIGHT HIGGS

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

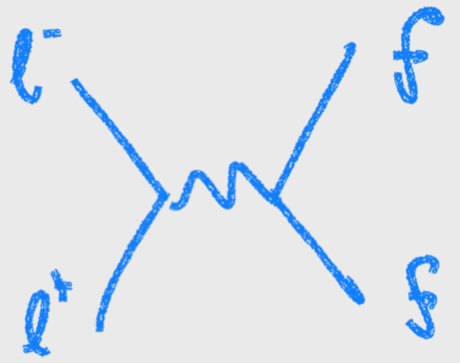
$1/(g_\star f) \sim 1/m_\star$

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



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

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



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

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

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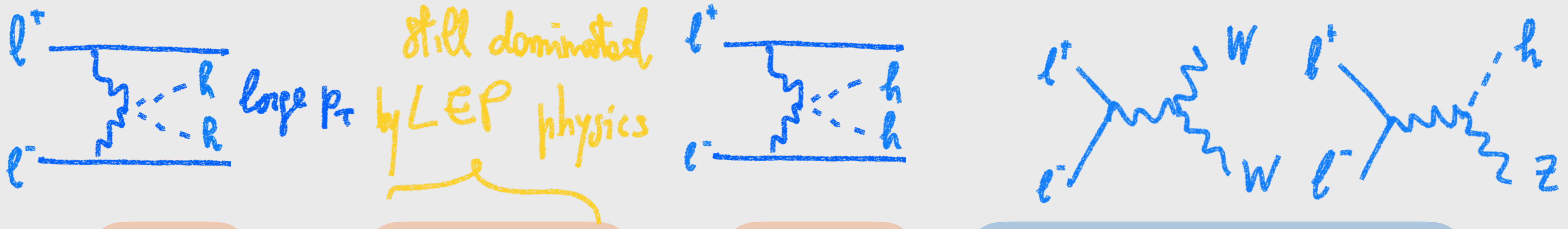

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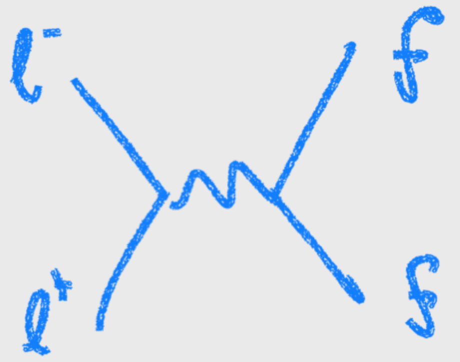

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$1/f \sim g_\star/m_\star$

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

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

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

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

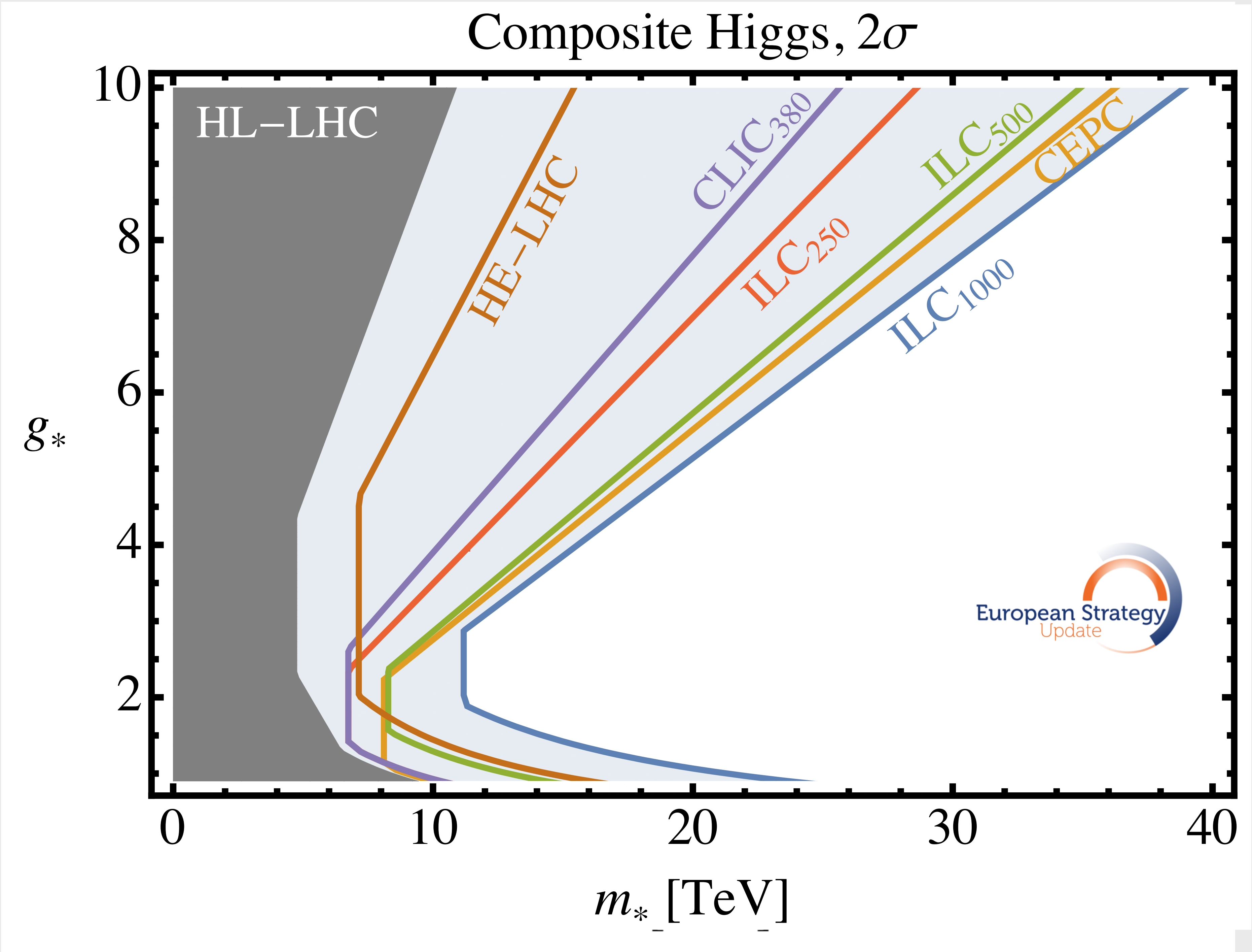
- sensitive to a range of energy scales
- measurement of a spectrum (not so?!?) simple to grasp
- progress is easy to measure: bounds on new Fermi constants

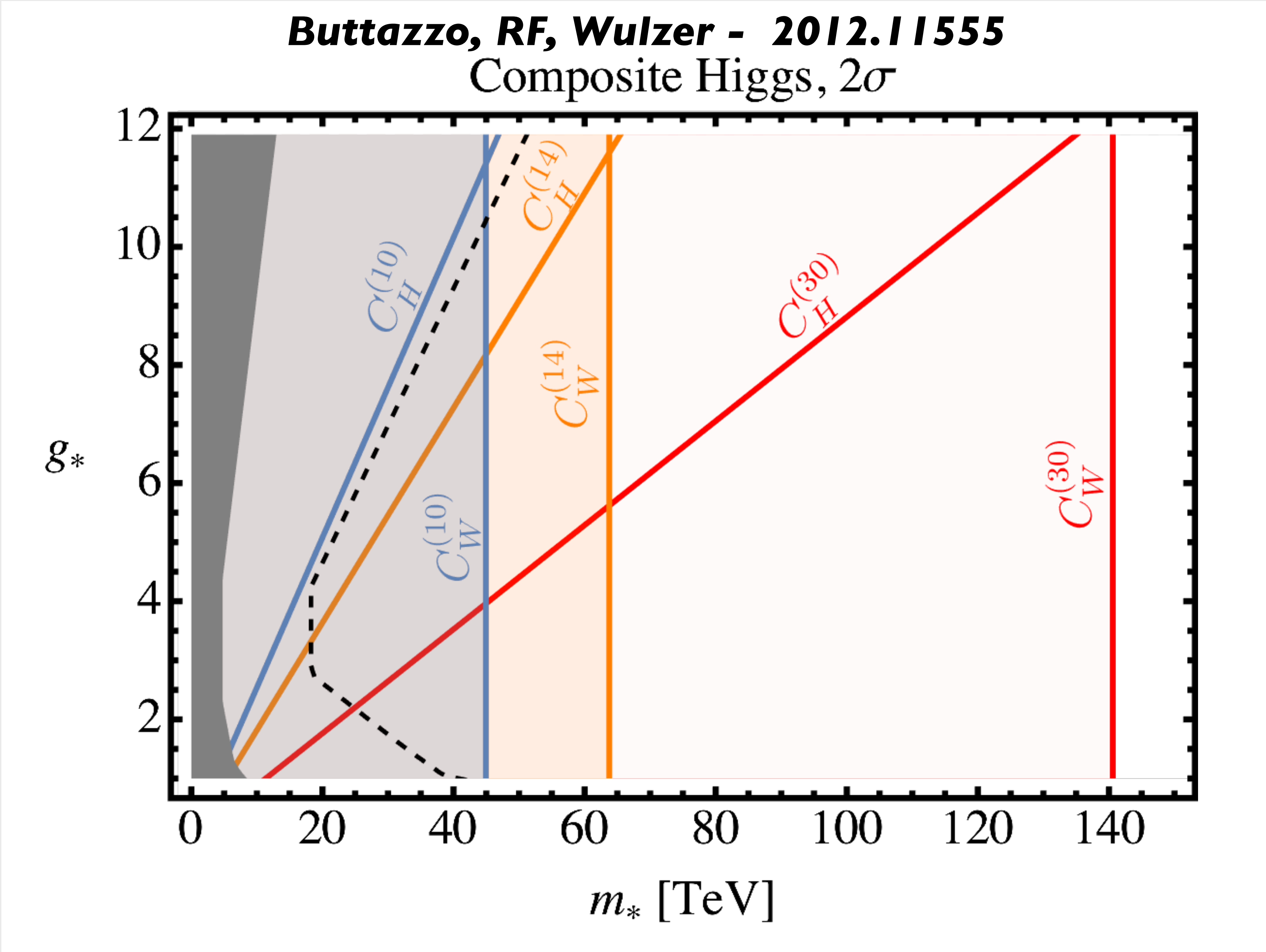
as NP effects may grow quadratically with energy

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

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

Looking ahead





compositeness at 10 TeV-20 TeV

compositeness at 100 TeV-200 TeV

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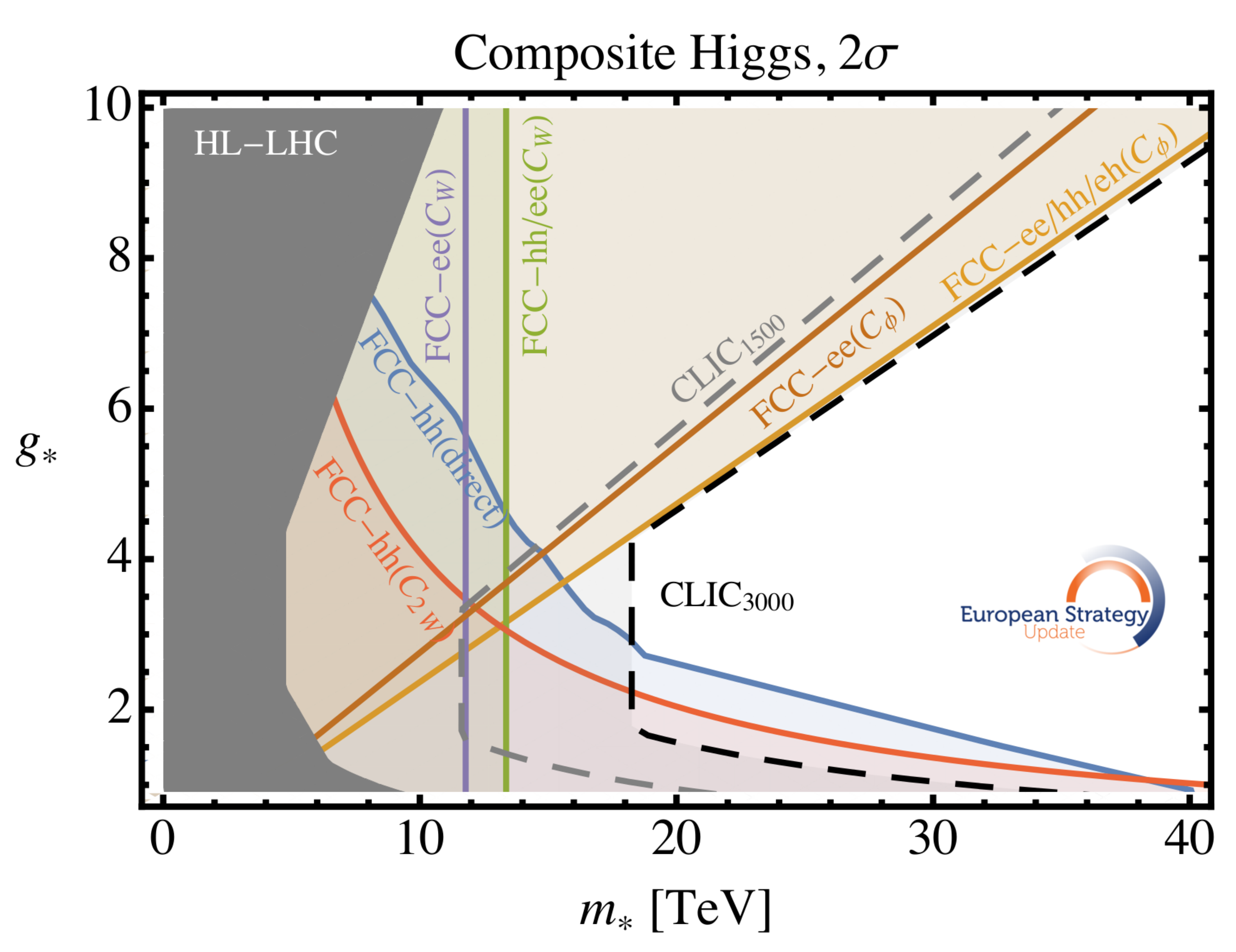
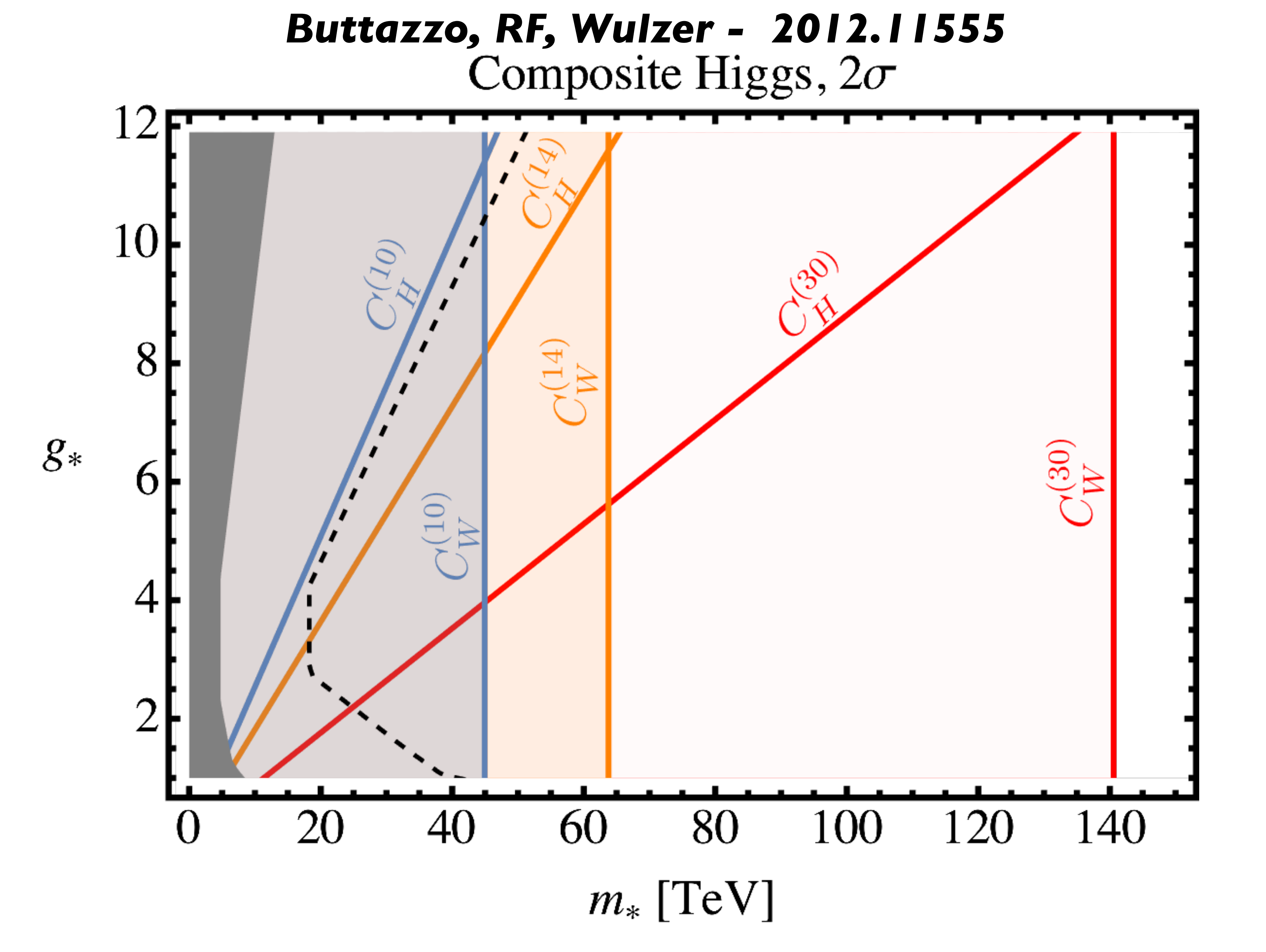




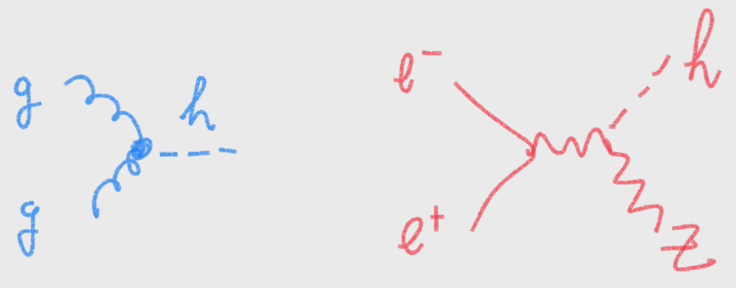
compositeness at 10 TeV-20 TeV

compositeness at 100 TeV-200 TeV

Conclusion

- We need ambitious plans to thoroughly probe the Higgs boson

- A tentative measure of progress:
$$\Lambda^2 \sim \left(16\pi^2\right)^{\alpha} \cdot m_h^2$$
  - $\alpha = 1$ is feasible with "established" Higgs factories



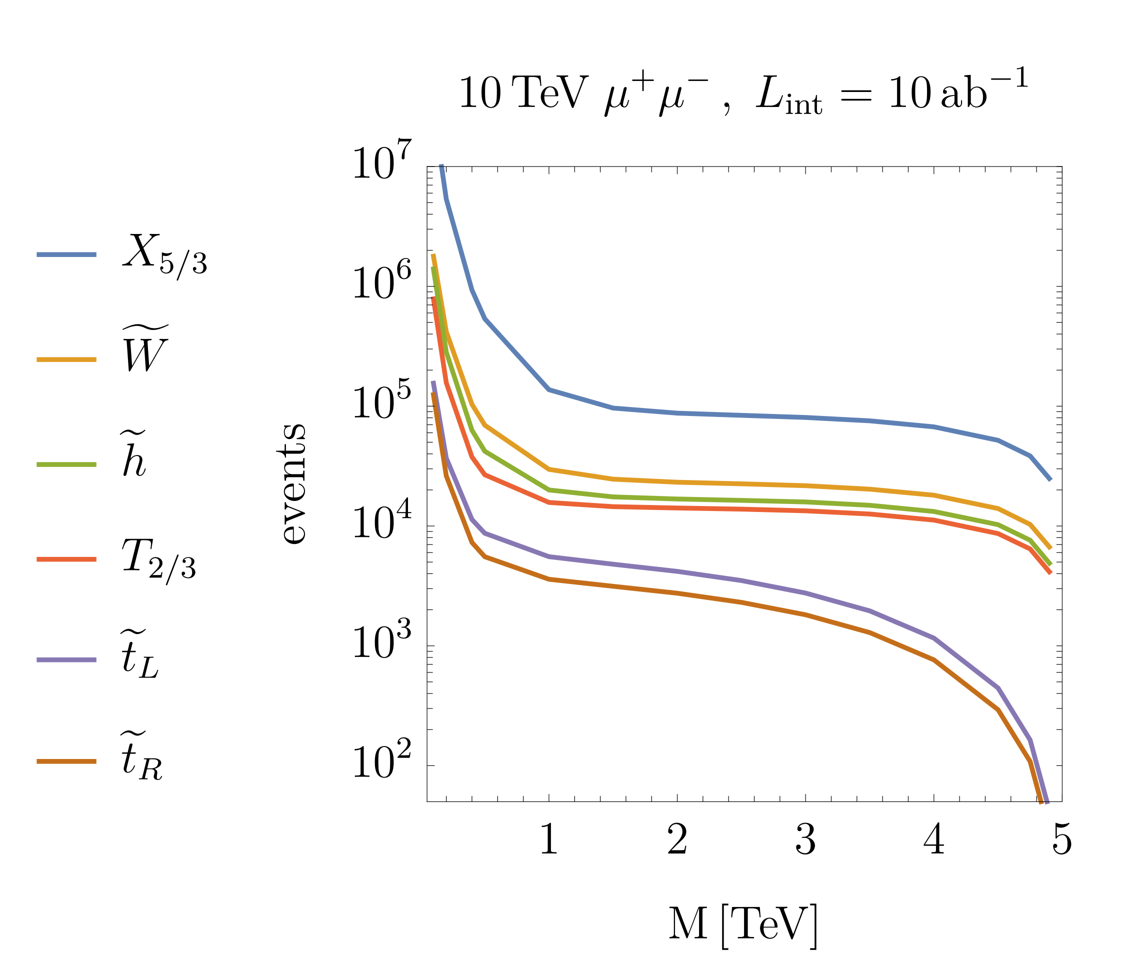
  - $\alpha > 1$ requires a new approach

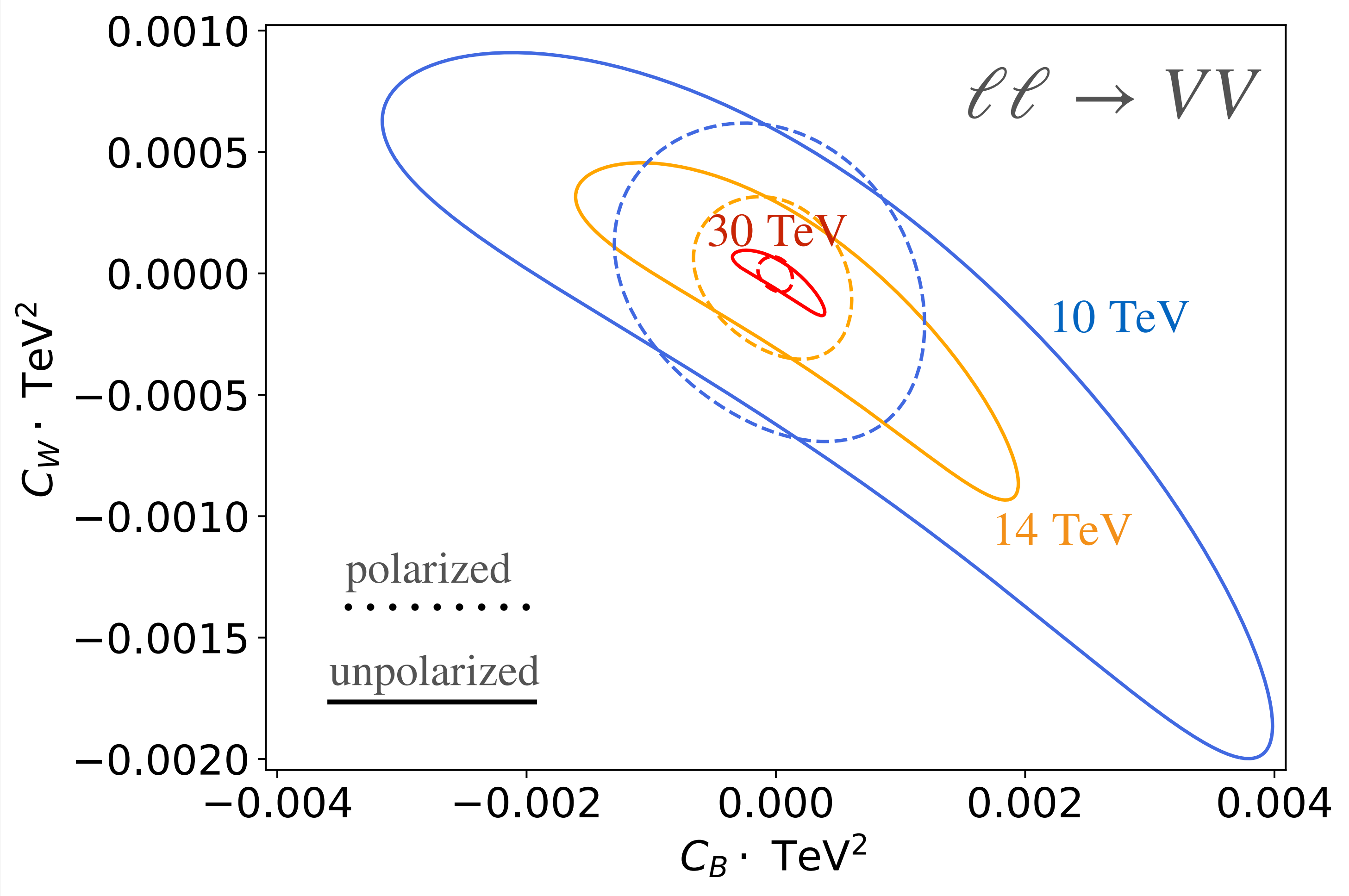
- When is it enough to be satisfied and call the Higgs an elementary scalar?

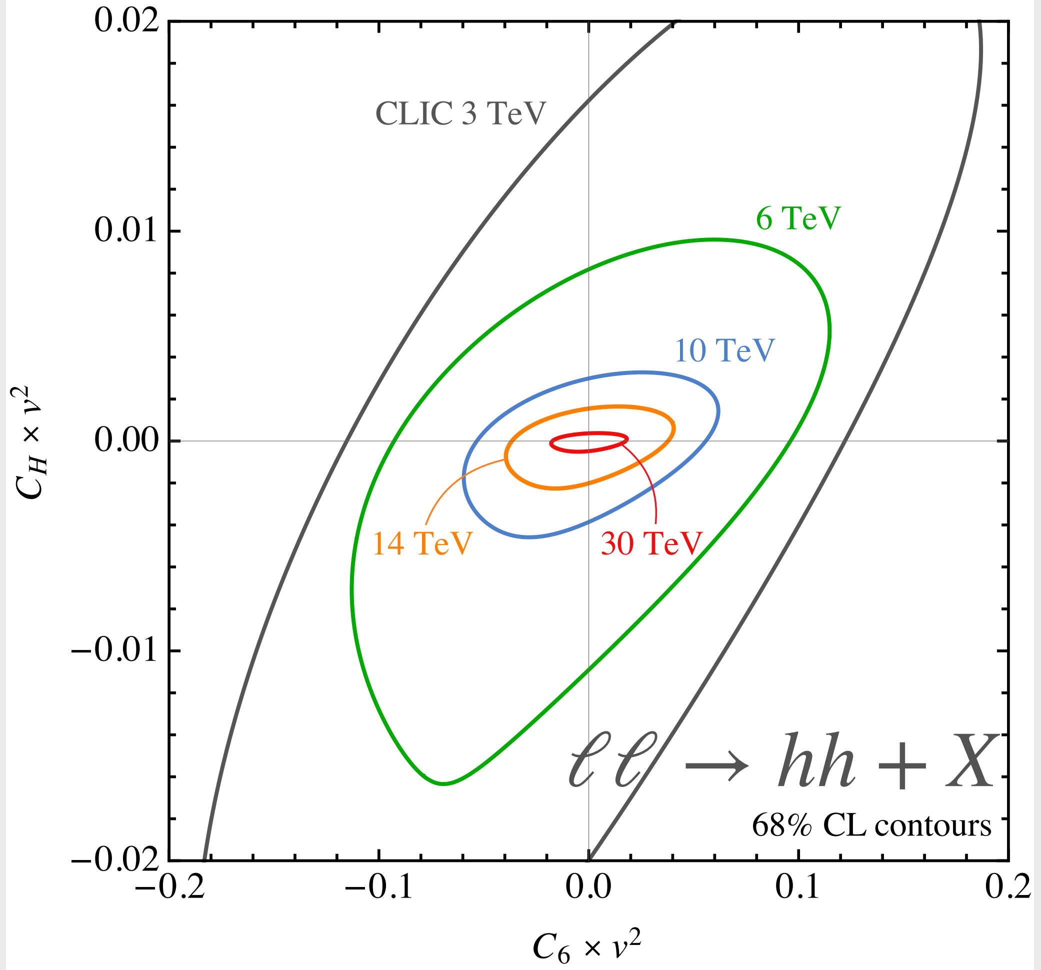
Conclusion

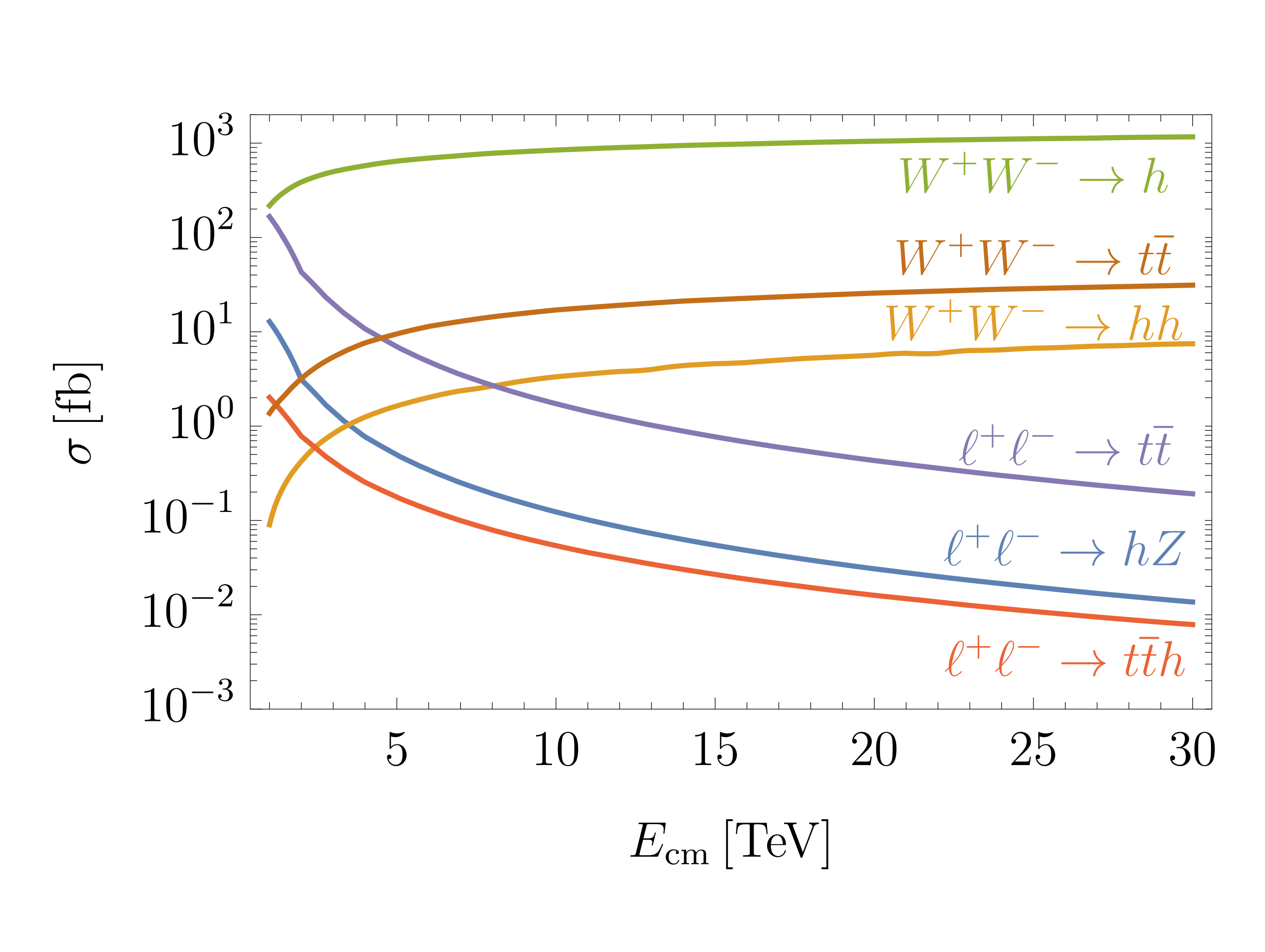
"TWO" COLLIDERS AT ONCE IN A VERY HIGH ENERGY LEPTON COLLIDER

Energy ⟷ Intensity

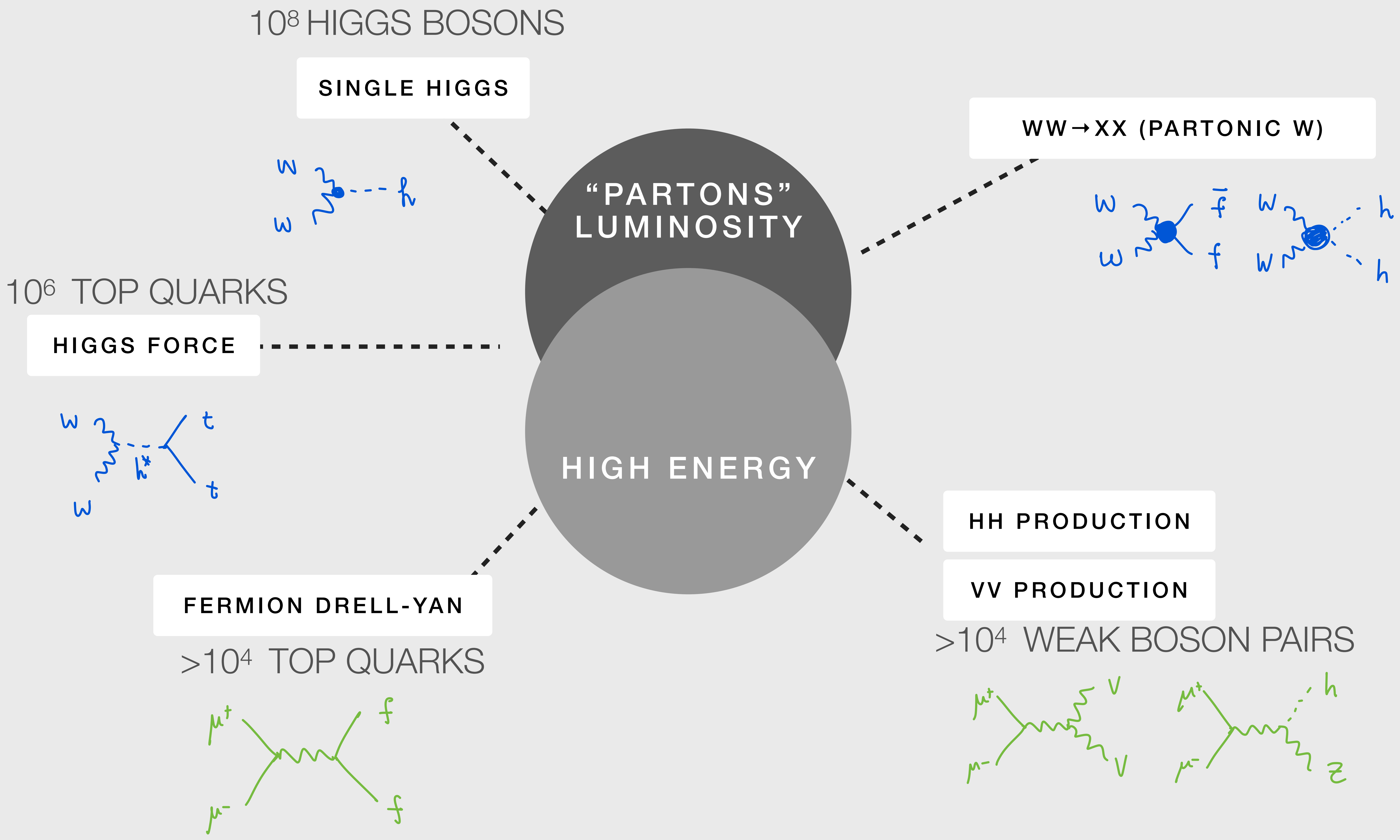








SM "high energy" and "intensity" studies at $\ell^+\ell^-$ colliders



Thank you!

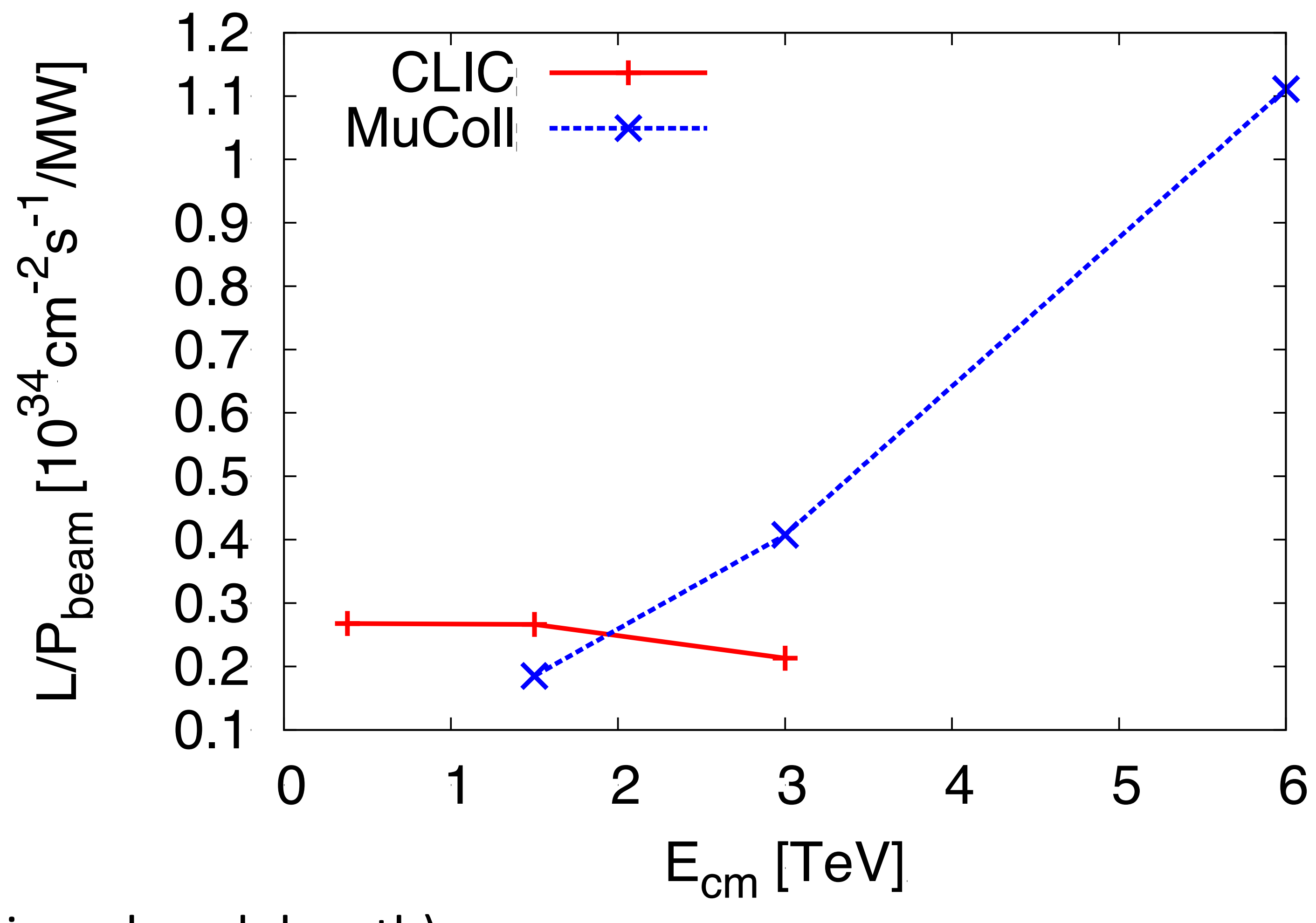
Muon colliders

MASS AND LIFETIME | BLESSING AND CURSE

Luminosity Comparison

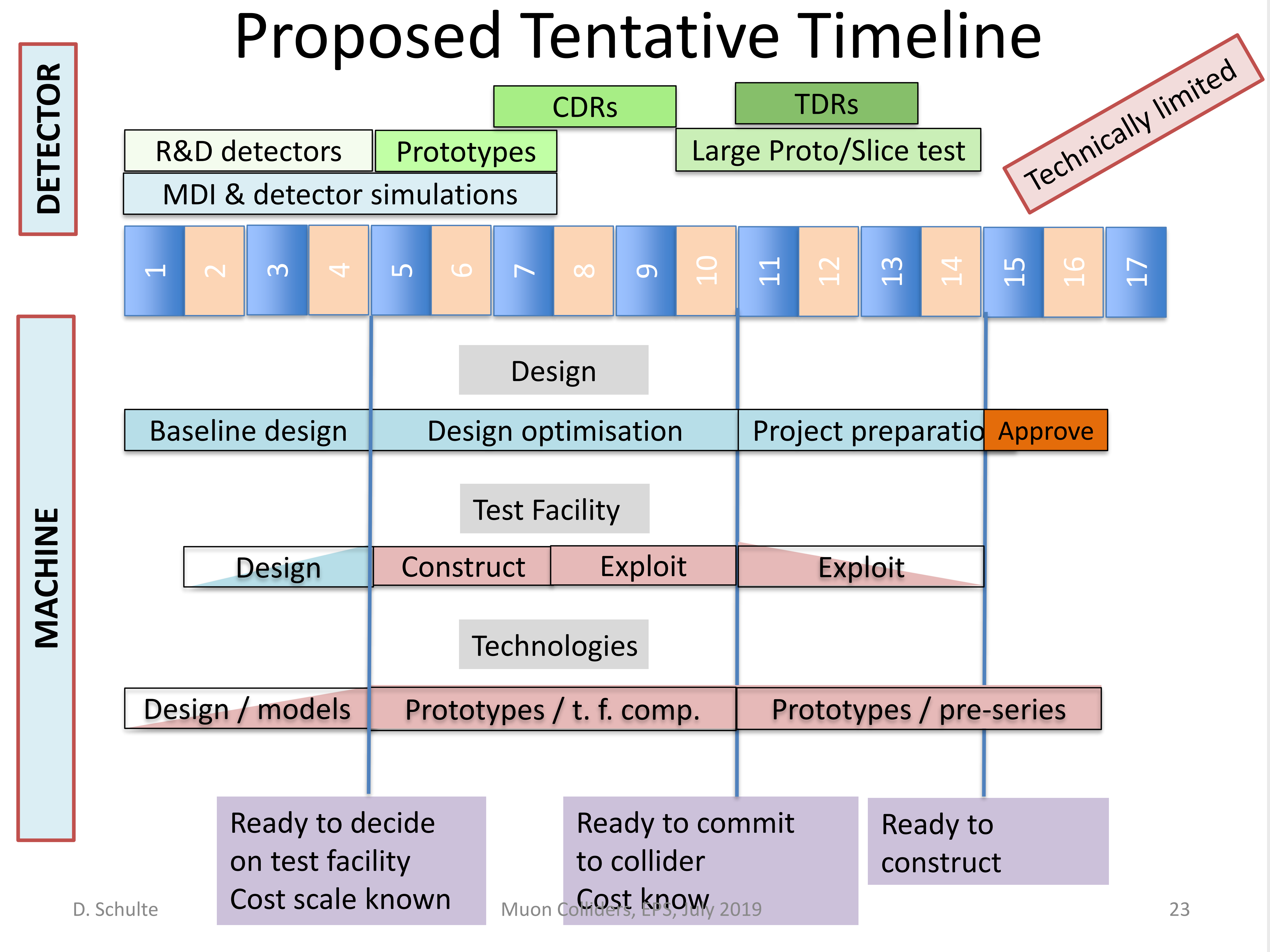
The luminosity per beam power is about constant in linear colliders

It can increase in proton-based muon colliders



Strategy CLIC:
Keep all parameters at IP constant
(charge, norm. emittances, betafunctions, bunch length)
⇒ Linear increase of luminosity with energy (beam size reduction)

Strategy muon collider:
Keep all parameters at IP constant
With exception of bunch length and betafunction
⇒ Quadratic increase of luminosity with energy (beam size reduction)



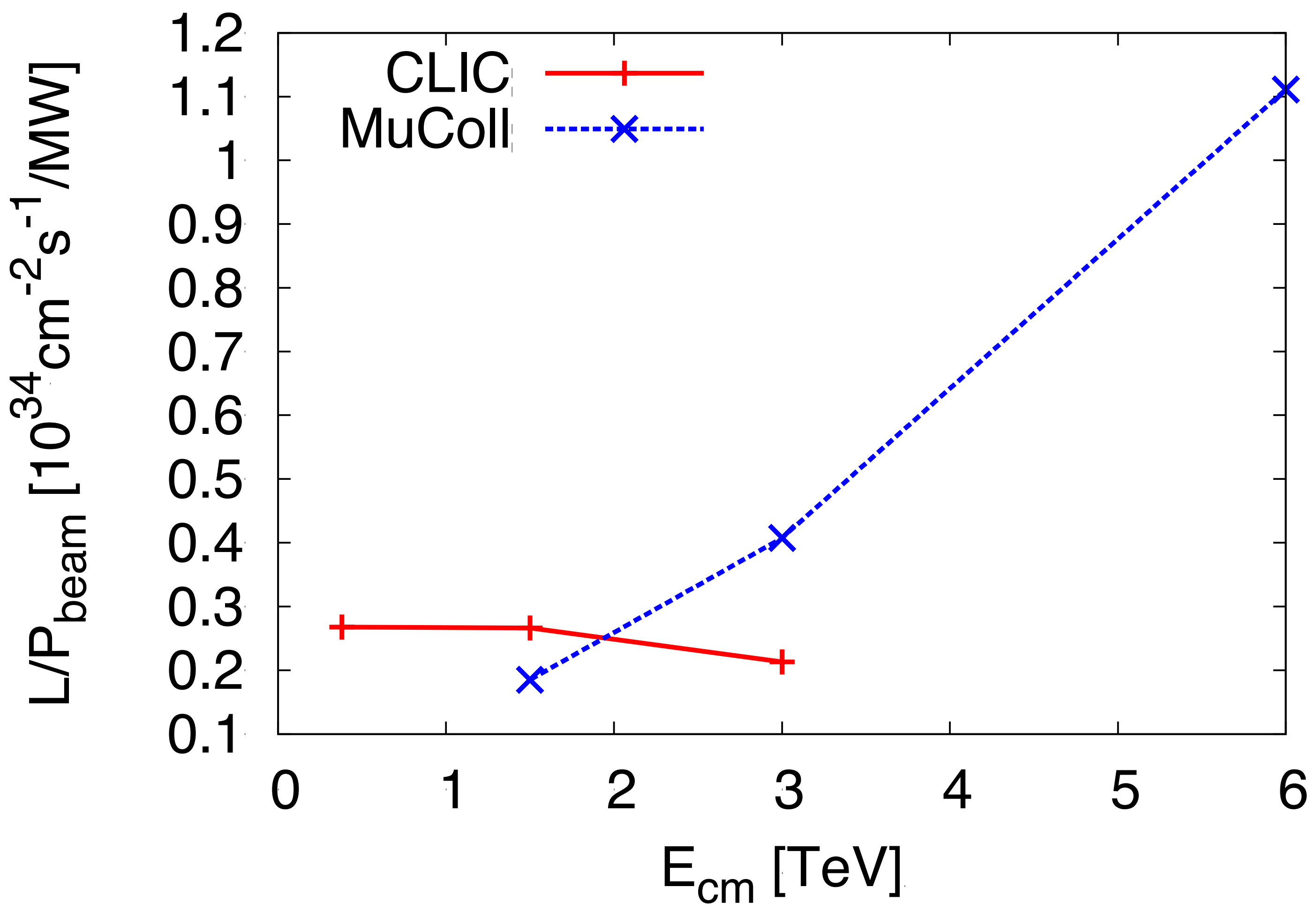
Muon colliders

MASS AND LIFETIME | BLESSING AND CURSE

Luminosity Comparison

The luminosity per beam power is about constant in linear colliders

It can increase in proton-based muon colliders



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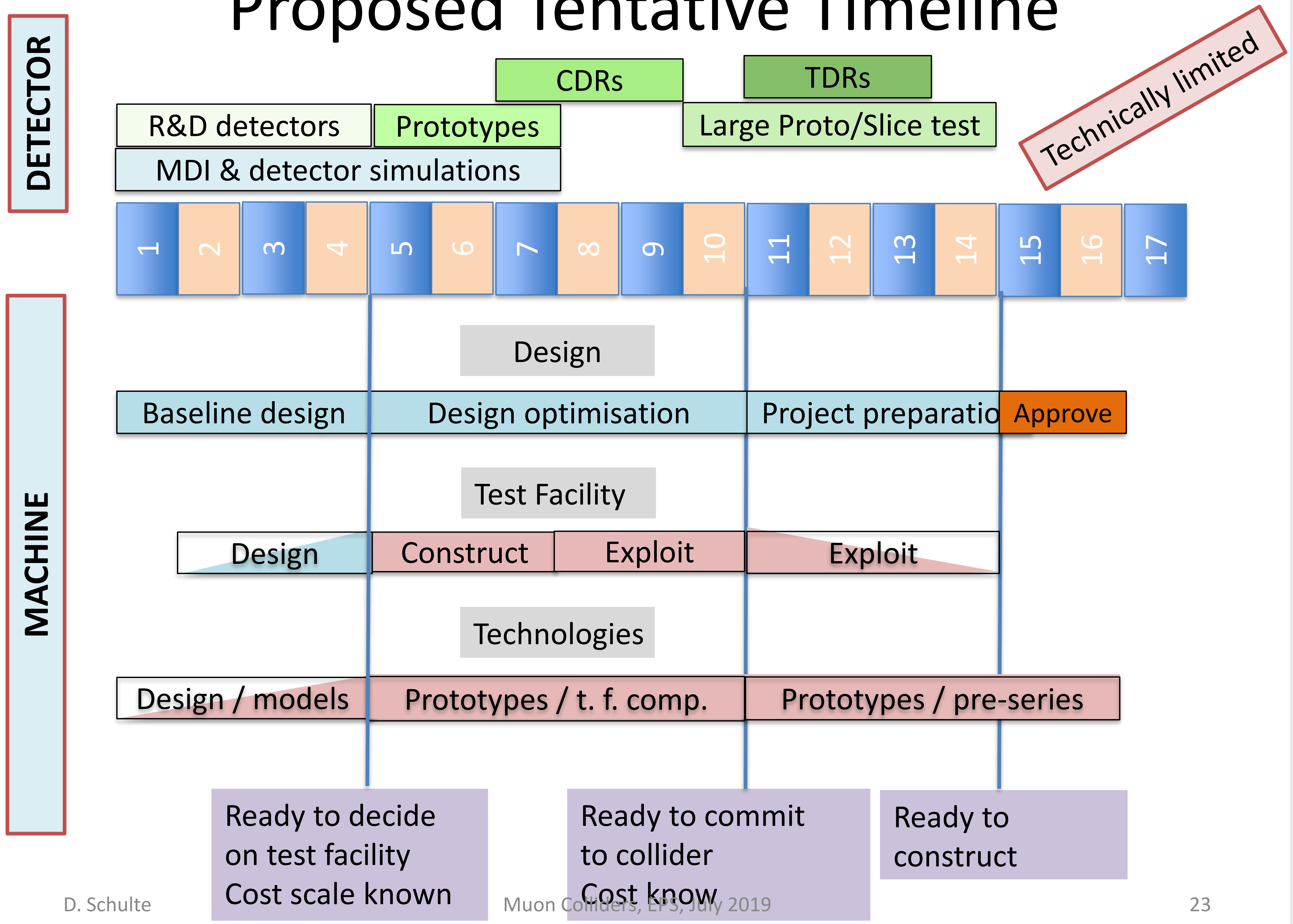
D. Schulte Muon Colliders, EPS, July 2019 7

Proposed Tentative Timeline

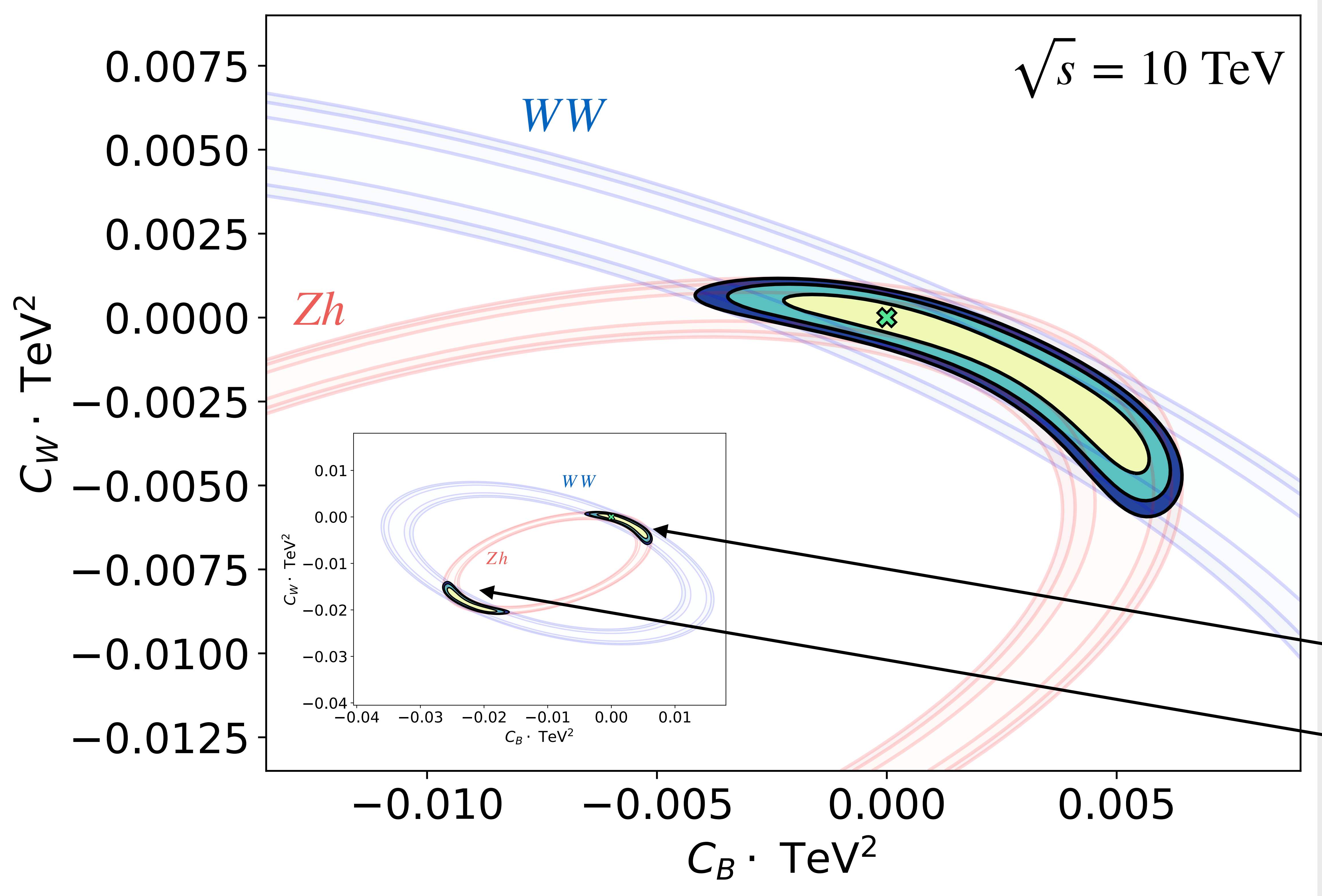


D. Schulte Muon Colliders, EPS, July 2019 23

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

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

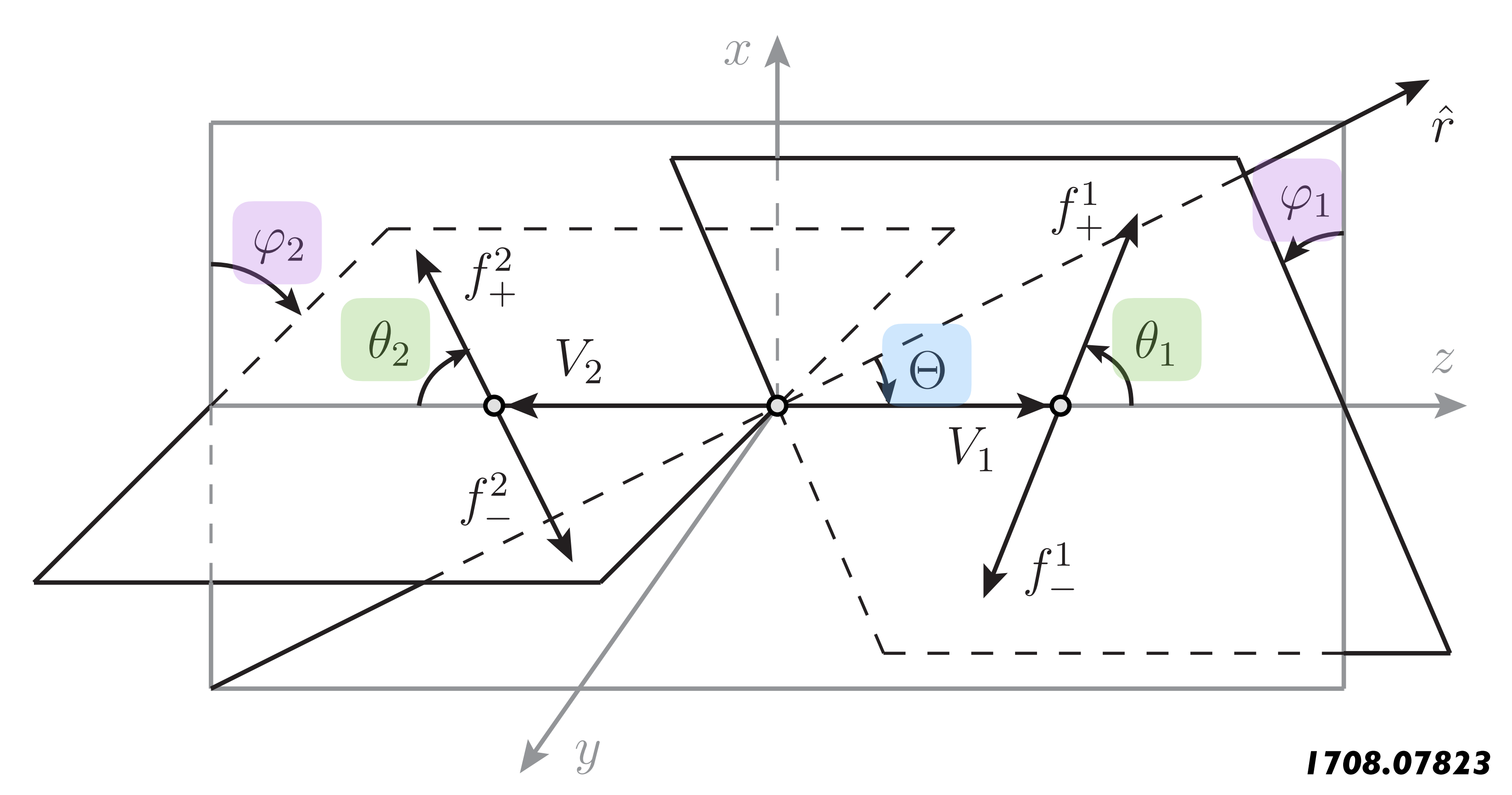
SM

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

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

EFT EPOCH

LESSON FROM LHC



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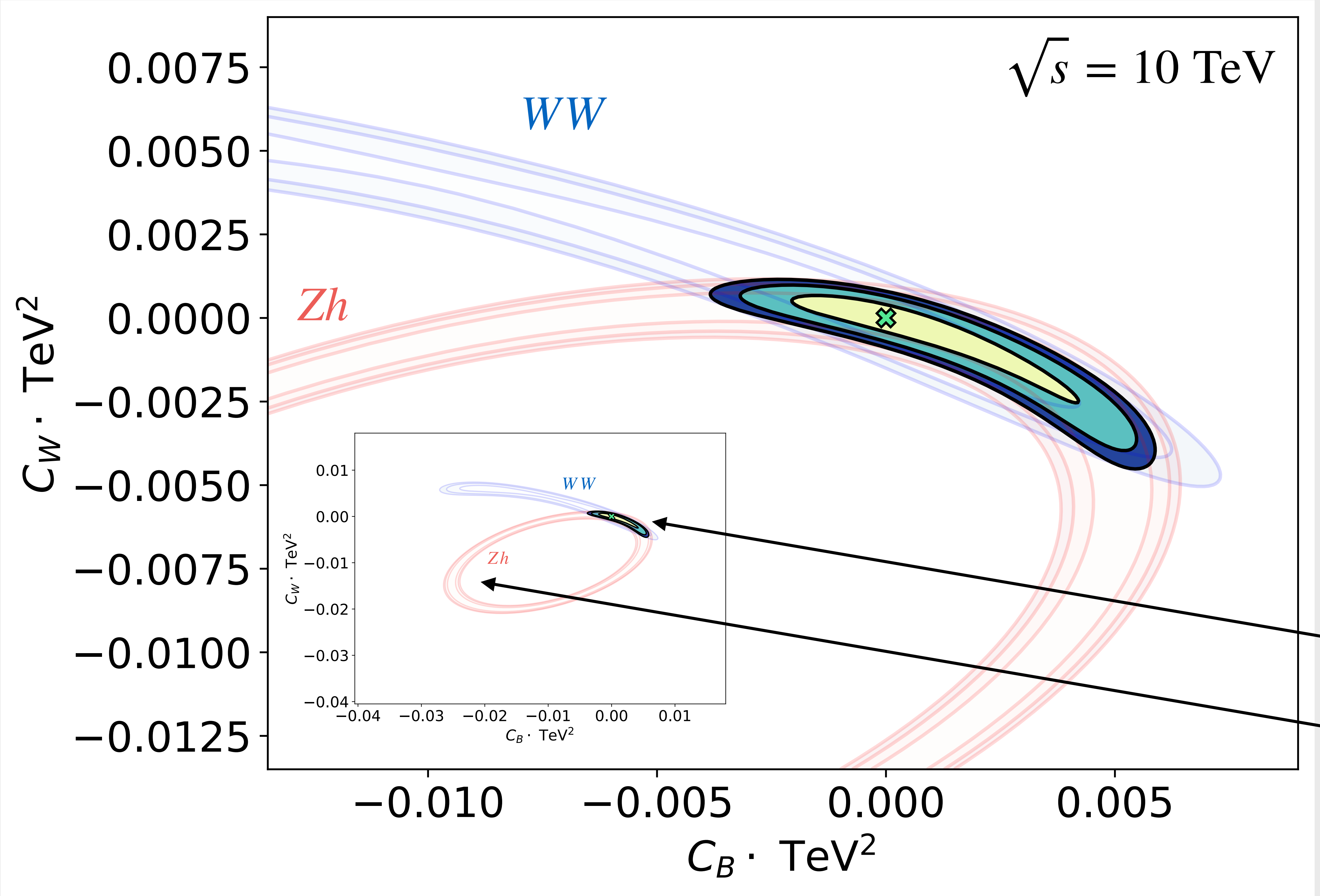


ZH: elliptical belt in 2D BSM coupling space

WW: (most useful) differential analysis tracking

- $2 \to 2$ polar scattering angle
- W decay polar angles
- W decay azimuthal angles 1708.07823

SM

SM[illegible]e r[illegible] but[illegible]ge B[illegible] co[illegible]ngs (d[illegible]s[illegible]ct[illegible]nte[illegible]e[illegible]nc[illegible]

Sharpening the result

Two less standard way

- Beam polarization
- Multi-body processes

Sharpening the result

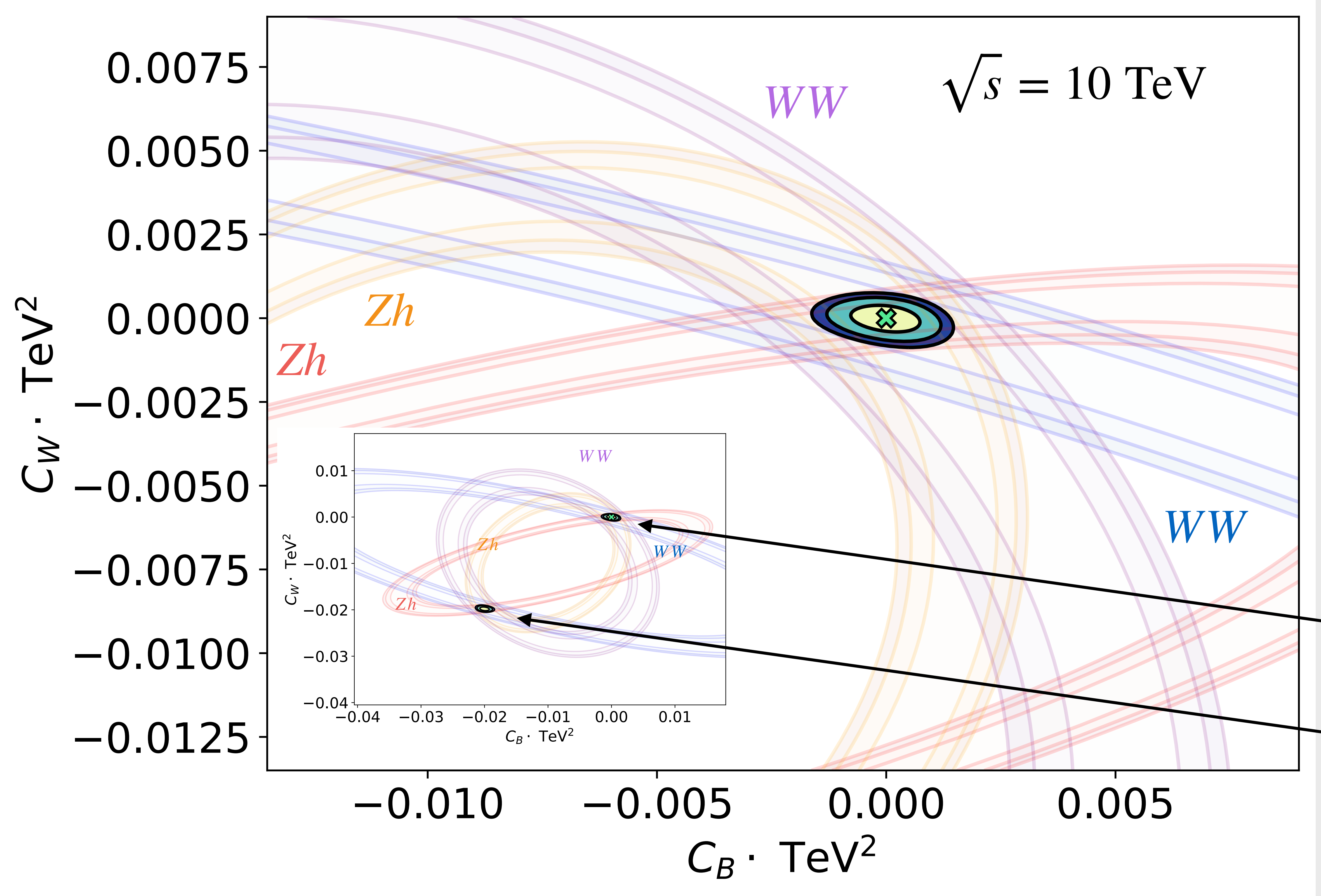
Two less standard way

- 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

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“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

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

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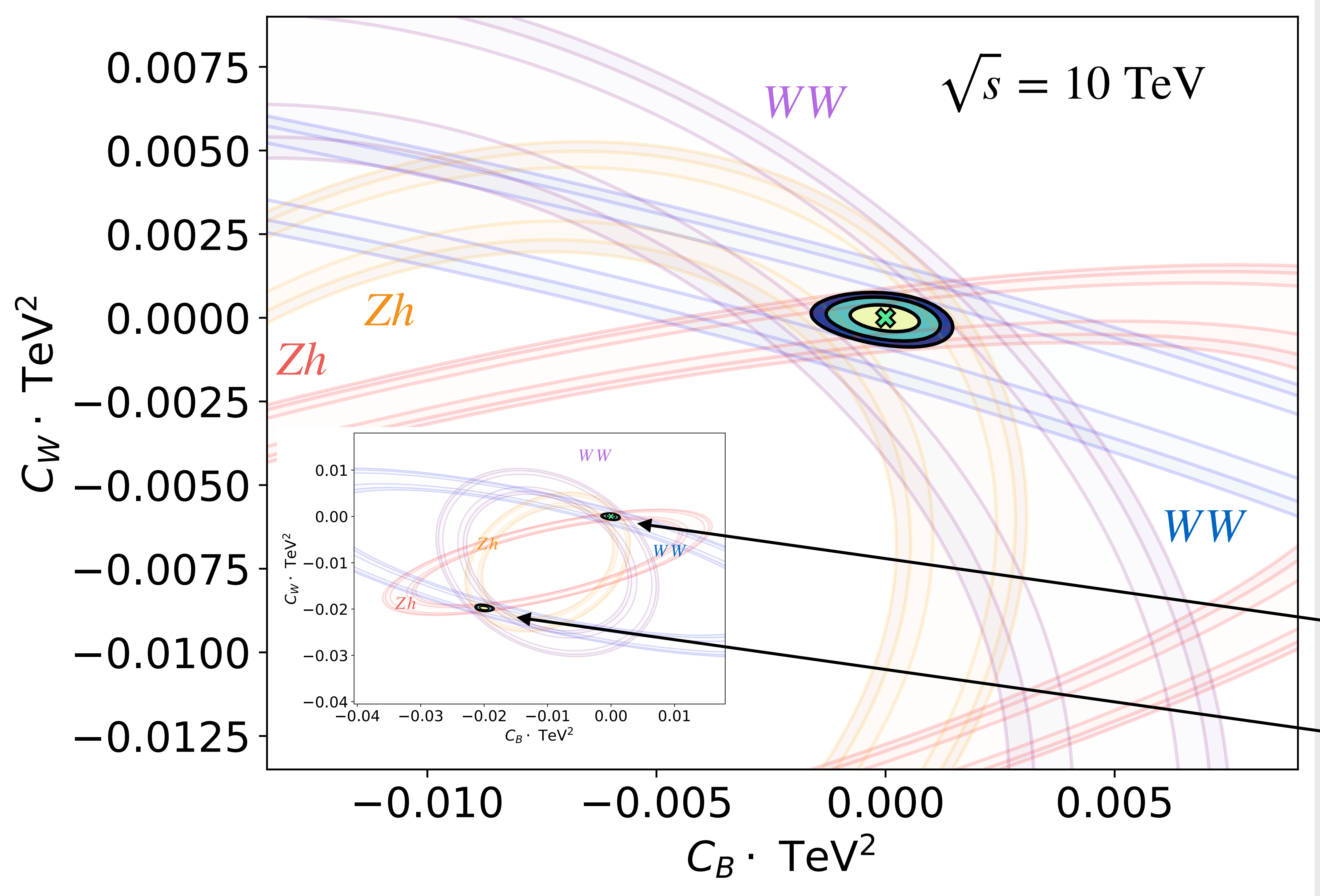

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Sharpening the result

Two less standard way

- Beam polarization
- Multi-body processes

Sharpening the result

Two less standard way

- Beam polarization
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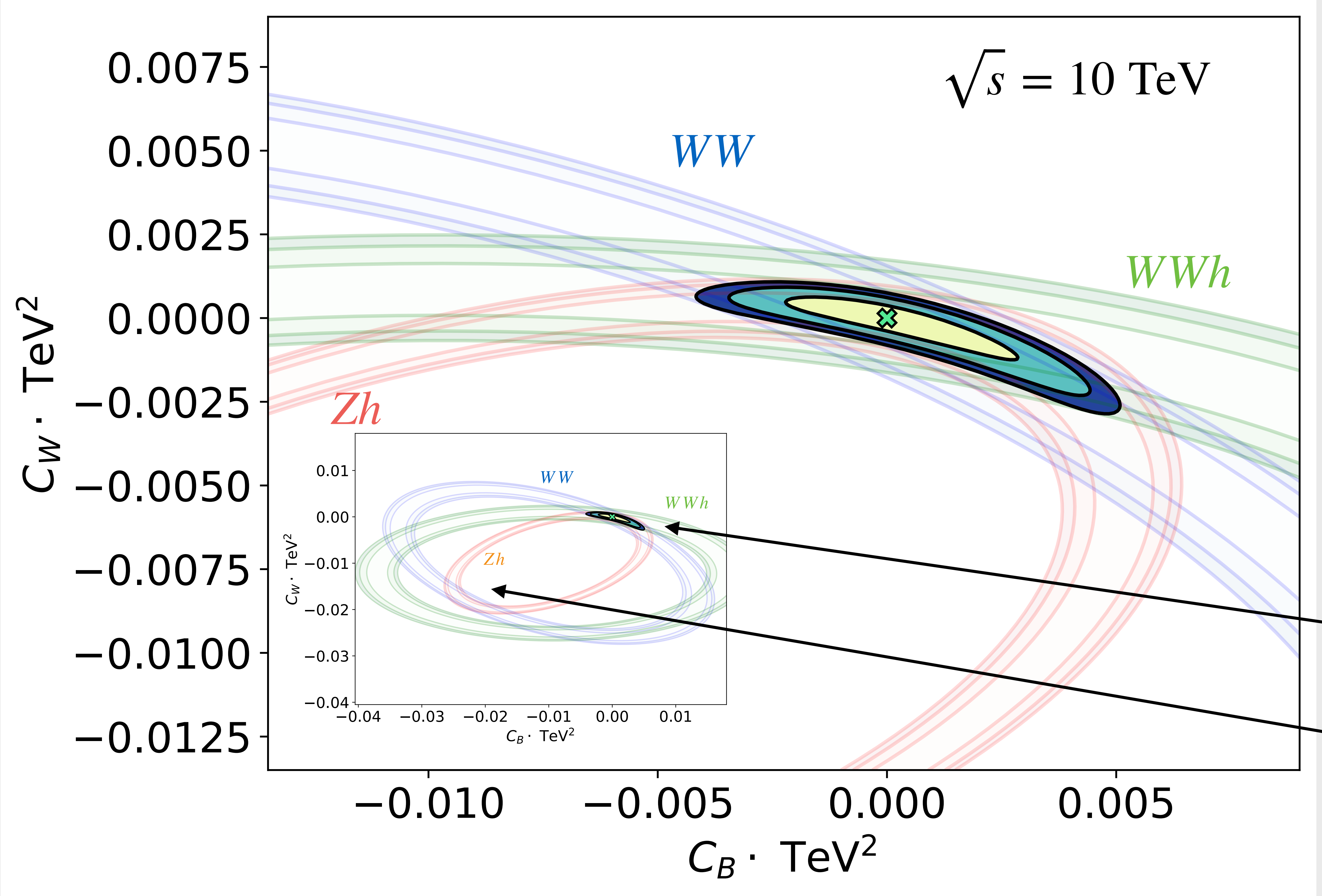
$\ell^+\ell^- \to \mathbf{WWh}$

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



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SM

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

Full set of results

VERY HIGH ENERGY LEPTON COLLIDER

DIBOSON

	$E_{\rm cm}$	$\mathcal{L}$/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 $(100\,\text{TeV})^{-2}$, 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