HIGGS MEASUREMENTS AT FUTURE HADRON COLLIDERS

Carleton University
Department of Physics

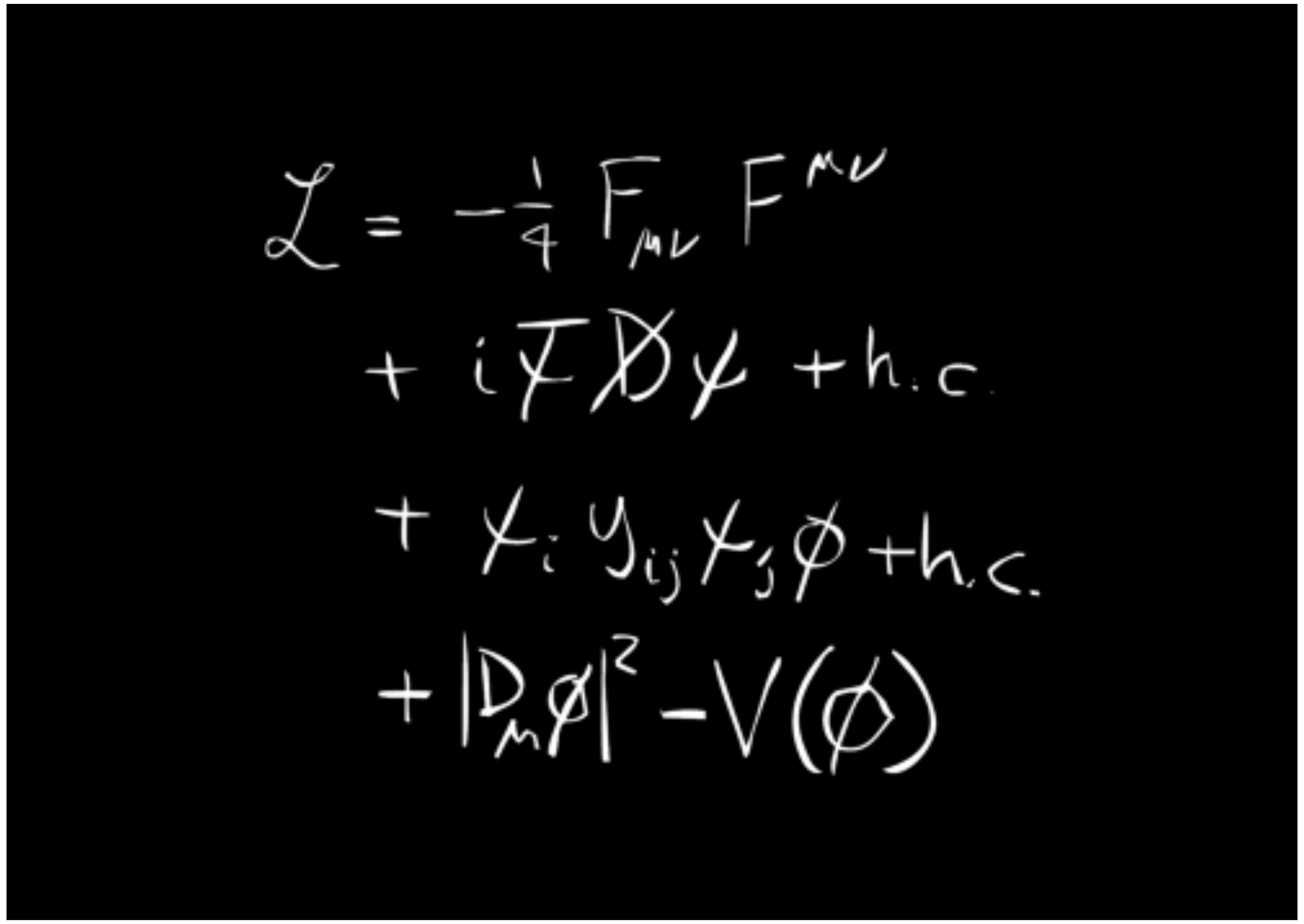
DANIEL STOLARSKI

Physics Potential at Future Colliders Sept 18, 2024

IS IT THE HIGGS?

Properties of the H(125) agree with SM prediction at ~10% precision.

Once mass is measured, everything about Higgs is predicted from SM.



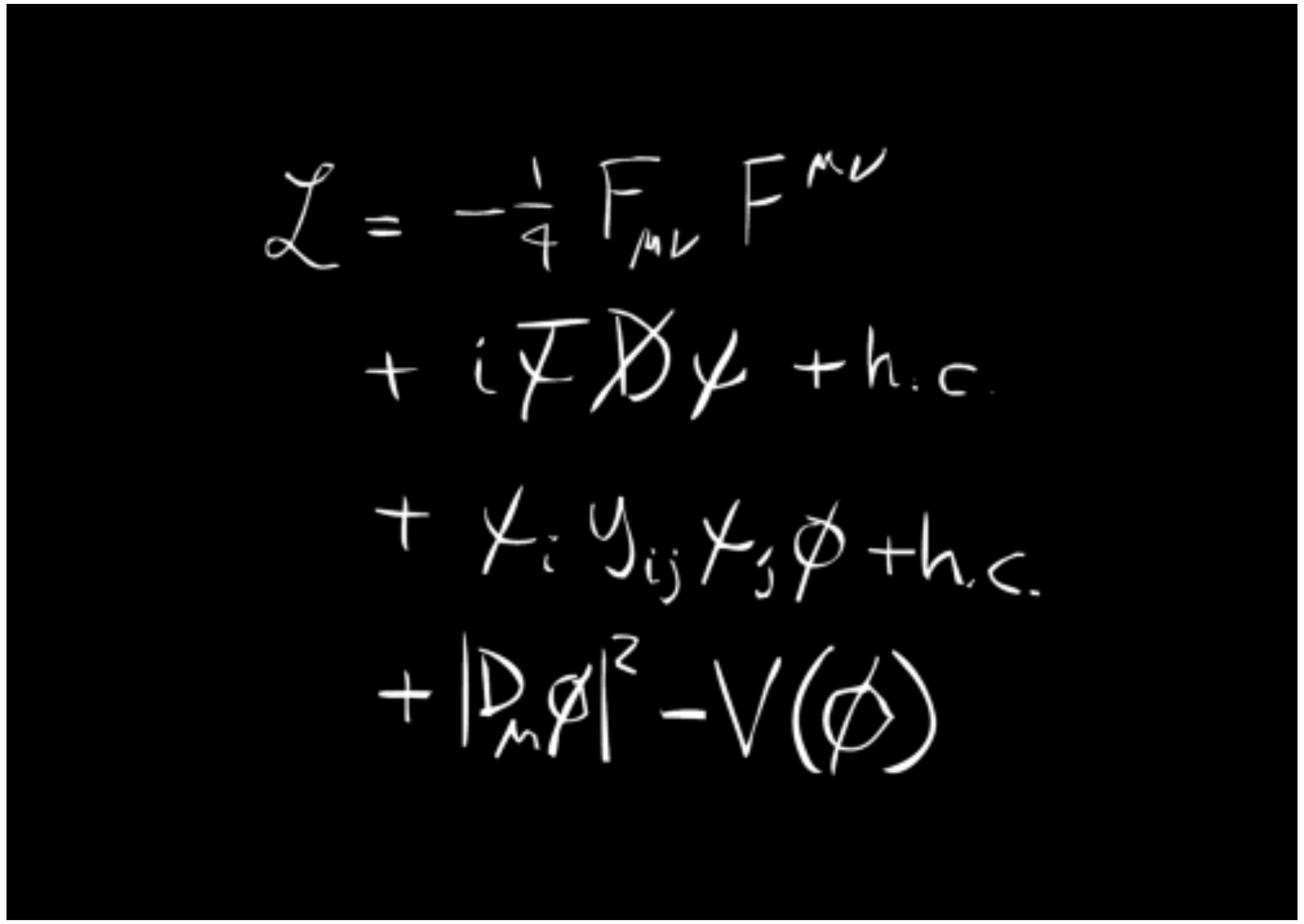
$$
\begin{aligned}
\mathcal{L} = & -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \\
& + i\bar{\psi} \not{D} \psi + h.c. \\
& + \psi_i y_{ij} \psi_j \phi + h.c. \\
& + |D_\mu \phi|^2 - V(\phi)
\end{aligned}
$$

IS IT THE HIGGS?

Properties of the H(125) agree with SM prediction at ~10% precision.

Once mass is measured, everything about Higgs is predicted from SM.

Even small deviations in Higgs properties imply new laws of nature.



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$$\mathcal{L} = ?$$

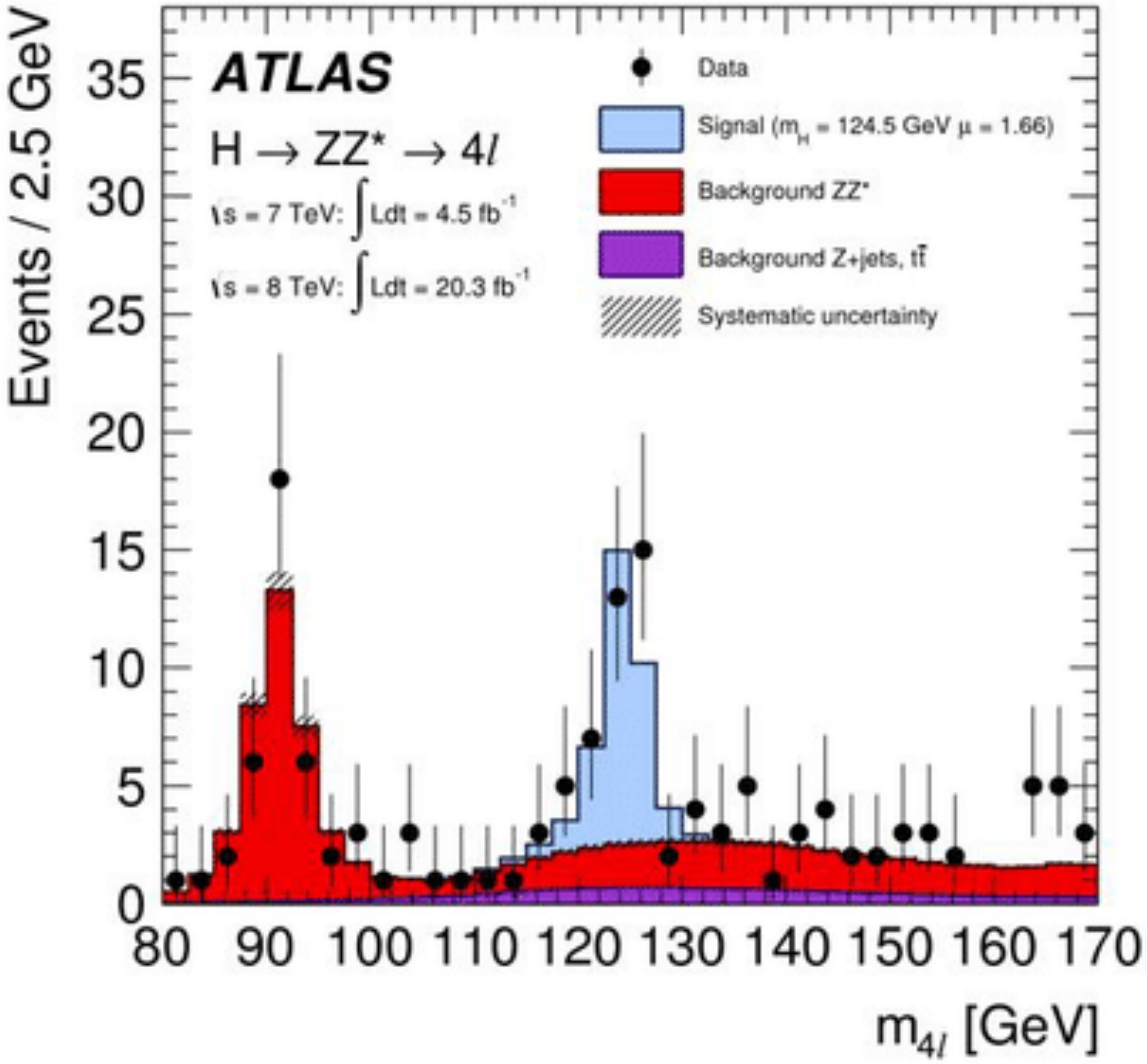
GOLDEN CHANNEL

Consider the Higgs decay:

$$h \to ZZ^{\star} \to \ell^{+}\ell^{-}\ell^{+}\ell^{-}$$

$(\ell = e, \mu)$

Rare decay, BR $\approx 10^{-4}$.



GOLDEN CHANNEL

Consider the Higgs decay:

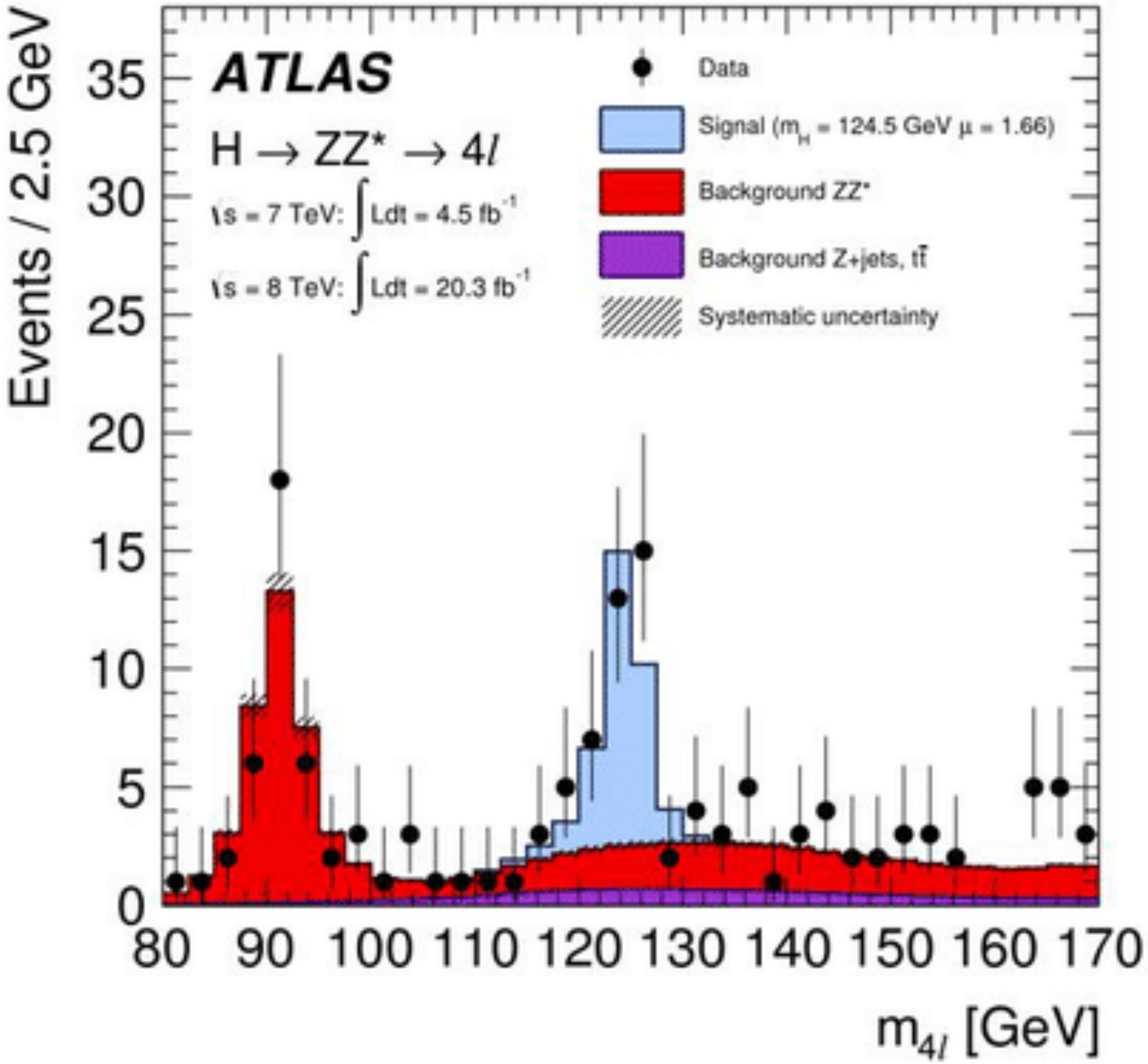
$h \to ZZ^\star \to \ell^+\ell^-\ell^+\ell^-$

$(\ell = e, \mu)$

Rare decay, BR $\approx 10^{-4}$.

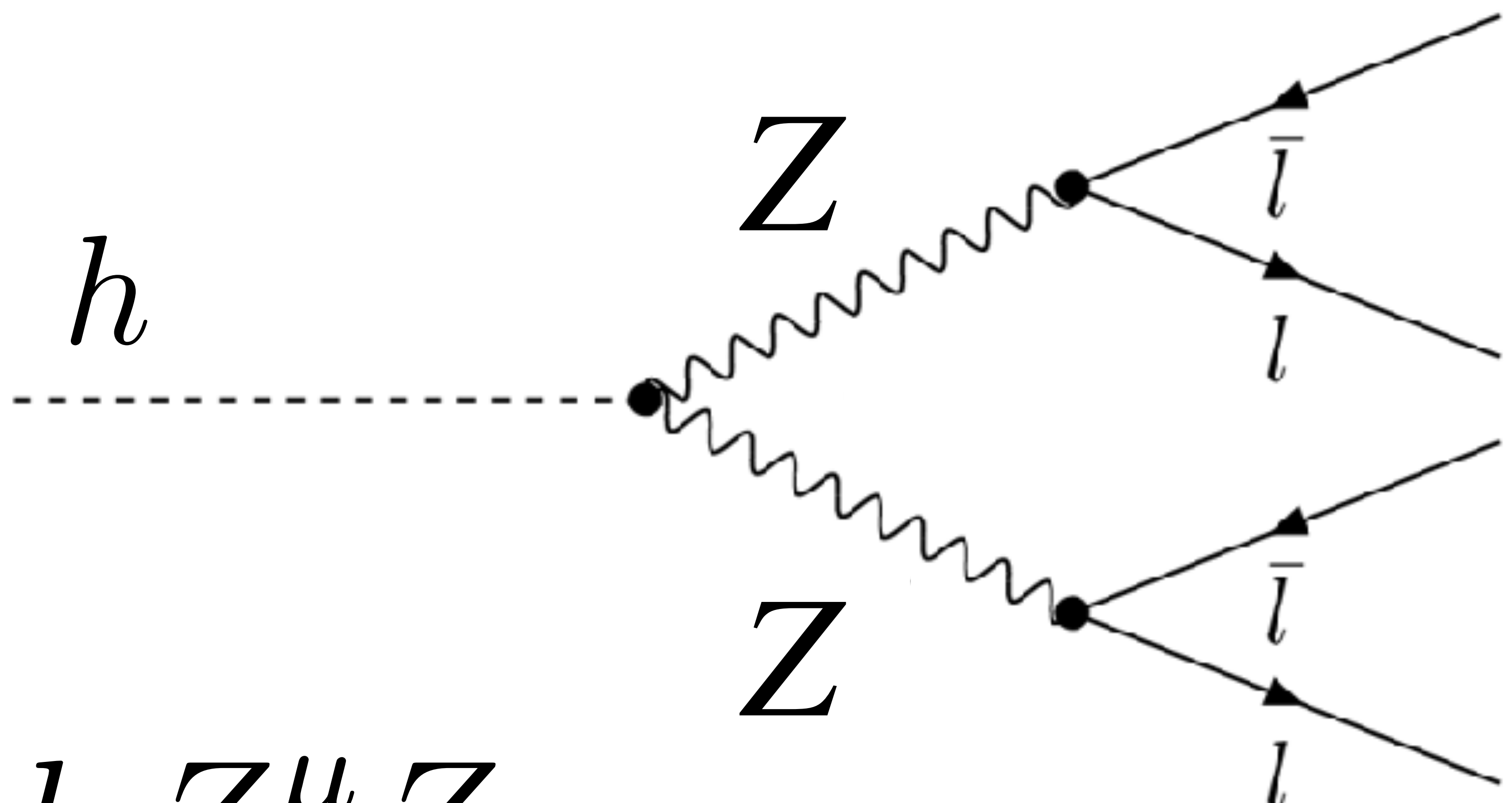
Easy to reconstruct precisely.

Low background.



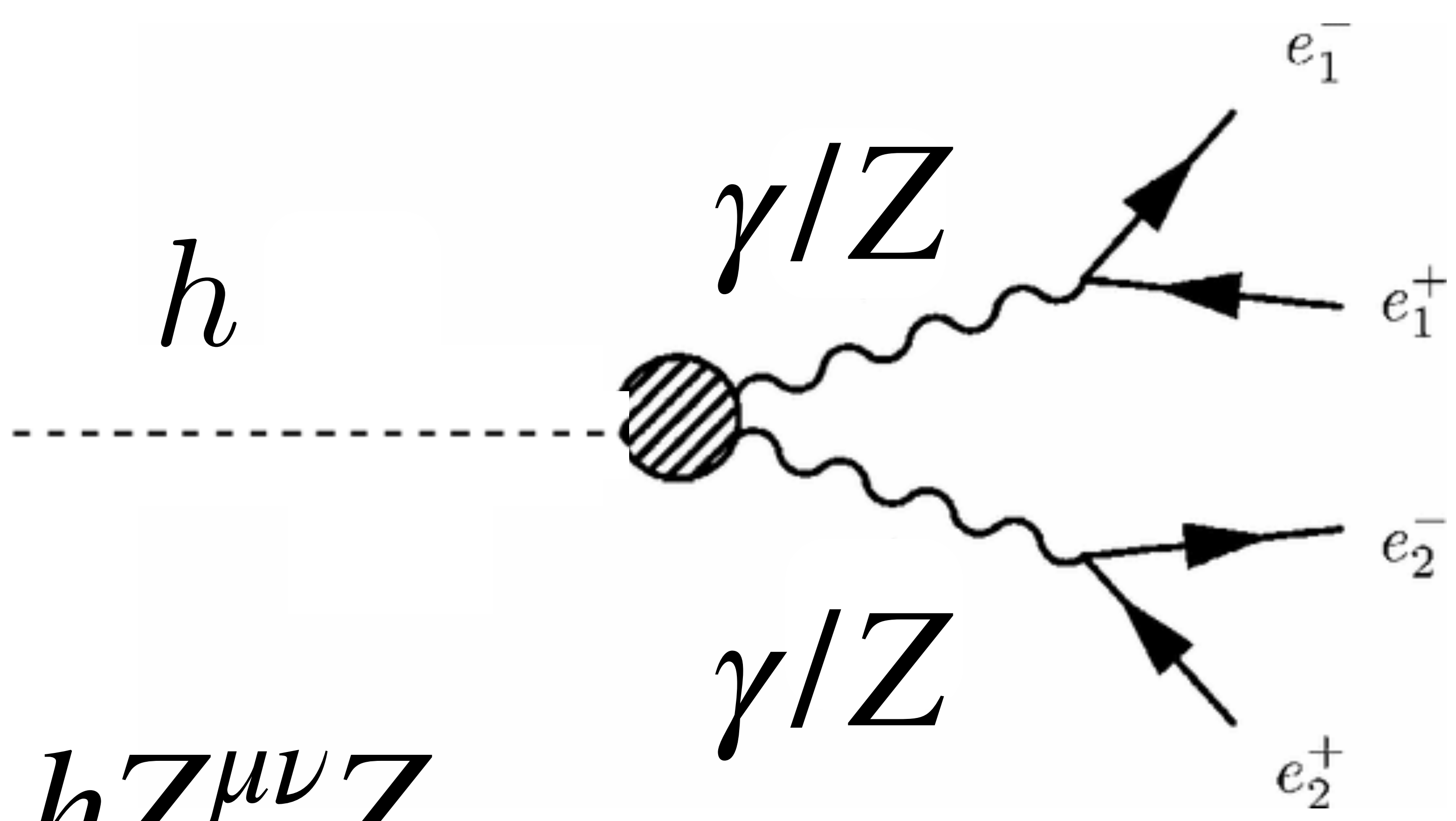
INTERMEDIATE STATES

Leading order:



$$h\, Z^{\mu}\, Z_{\mu}$$

NLO:



$$hZ^{\mu\nu}Z_{\mu\nu}$$
$$hF^{\mu\nu}Z_{\mu\nu}$$
$$hF^{\mu\nu}F_{\mu\nu}$$

DS, R. Vega-Morales, Phys.Rev.D.86, 117504 (2012) [arXiv:1208.4840].

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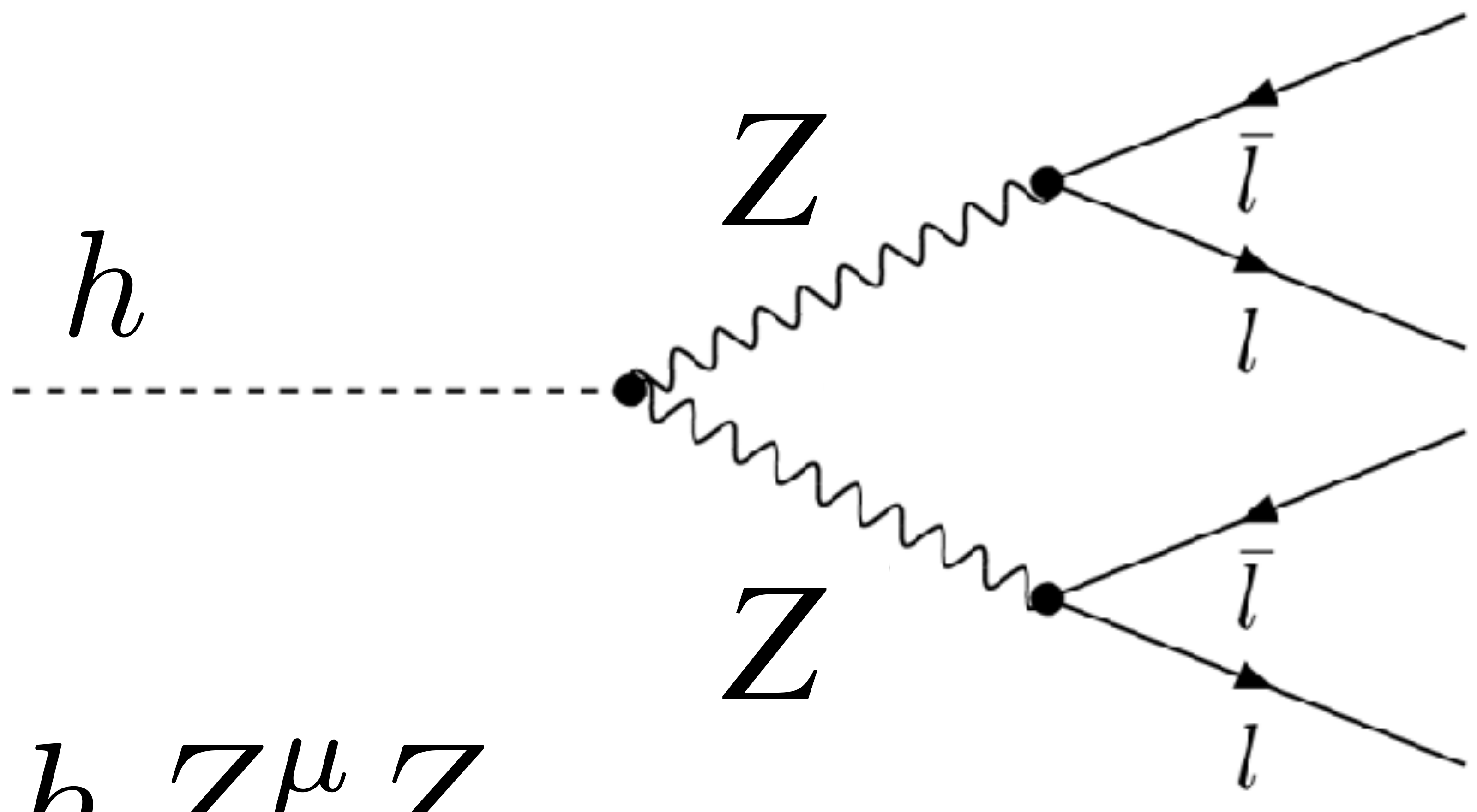
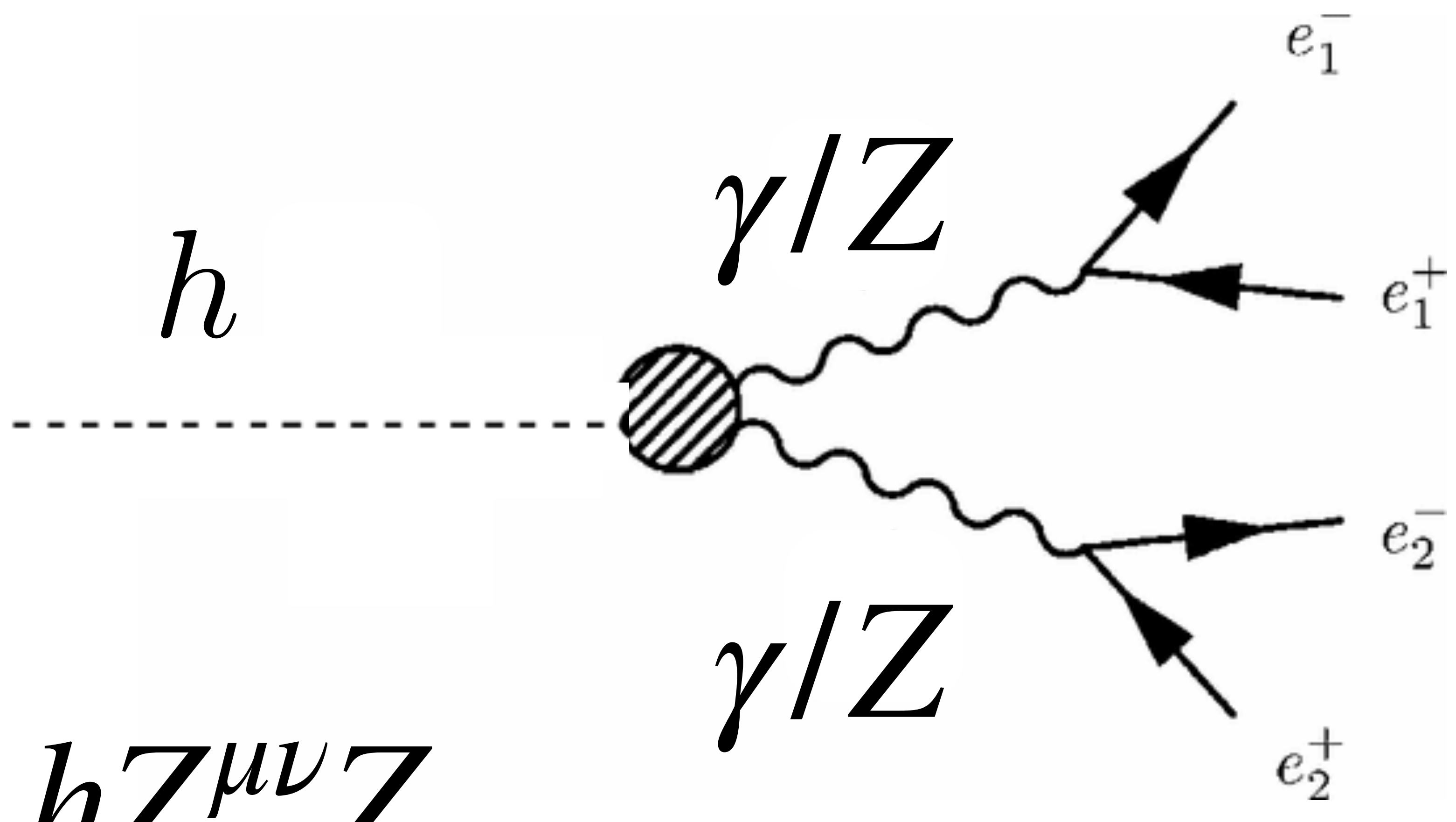


$h\, Z^{\mu}\, Z_{\mu}$

Not exclusively $h \to ZZ^{\star}$!

NLO:



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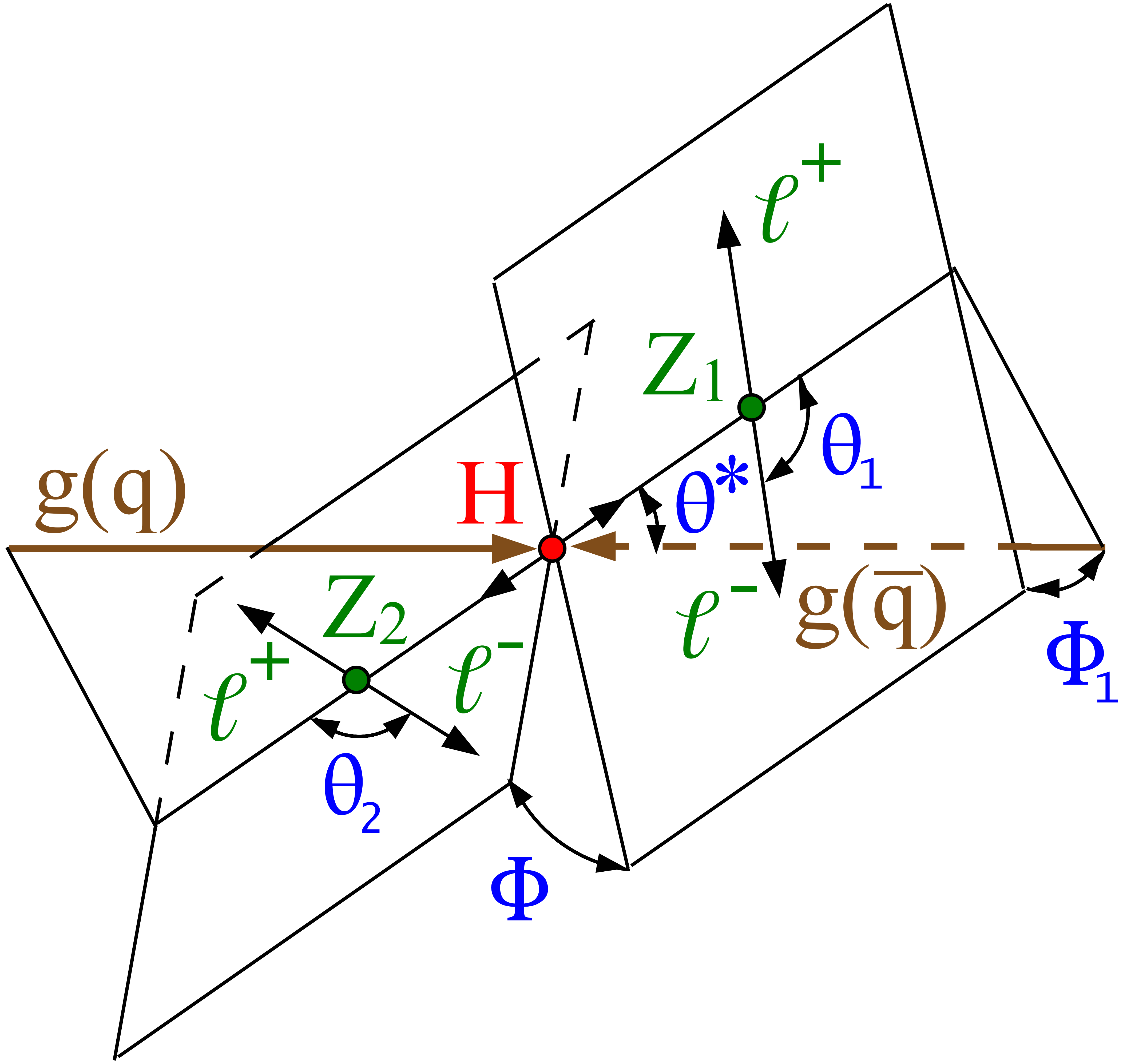
KINEMATICS

Four body final state kinematics are **8** dimensional.

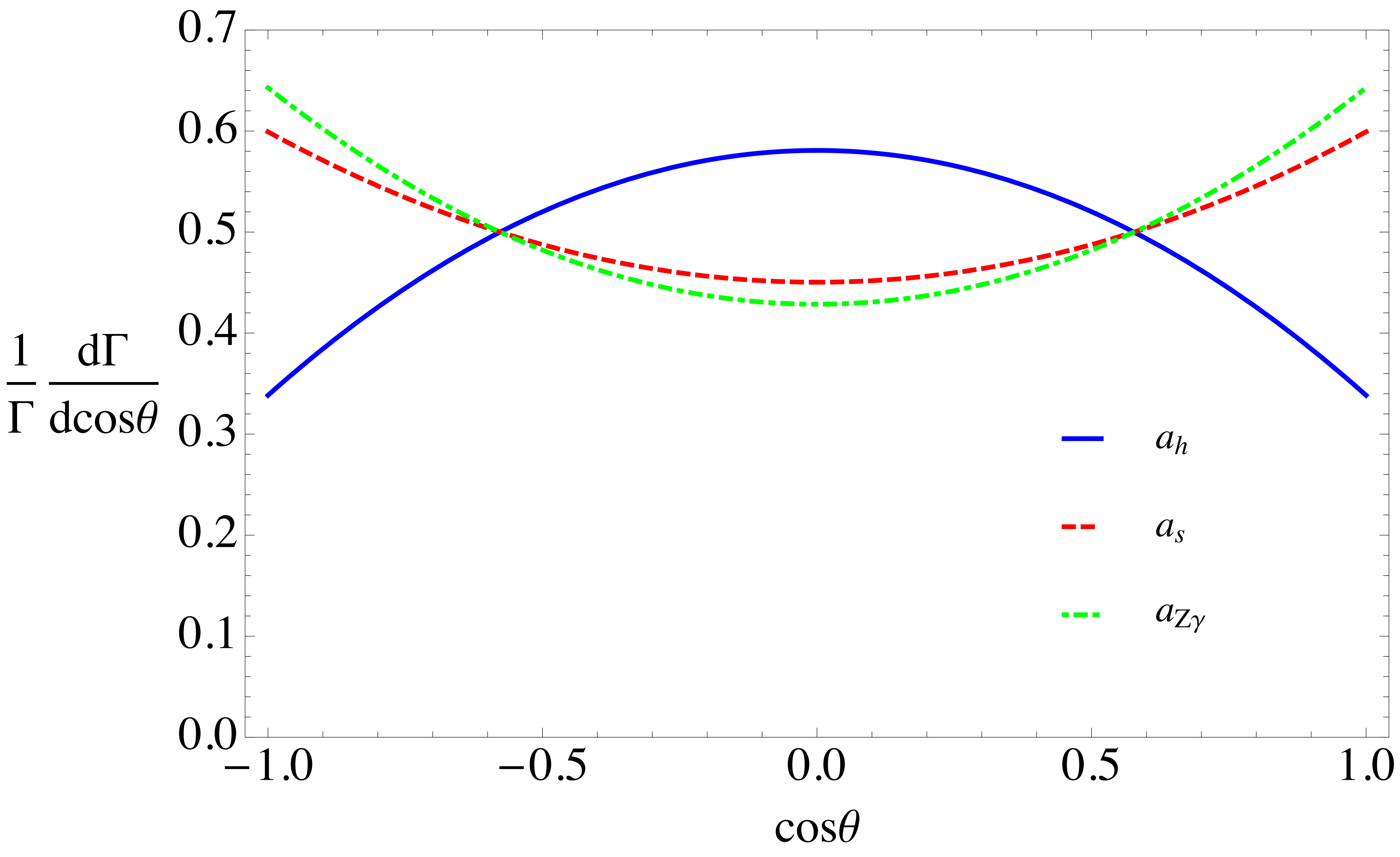
Assuming Higgs is a scalar, still **5** variables that characterize decay.

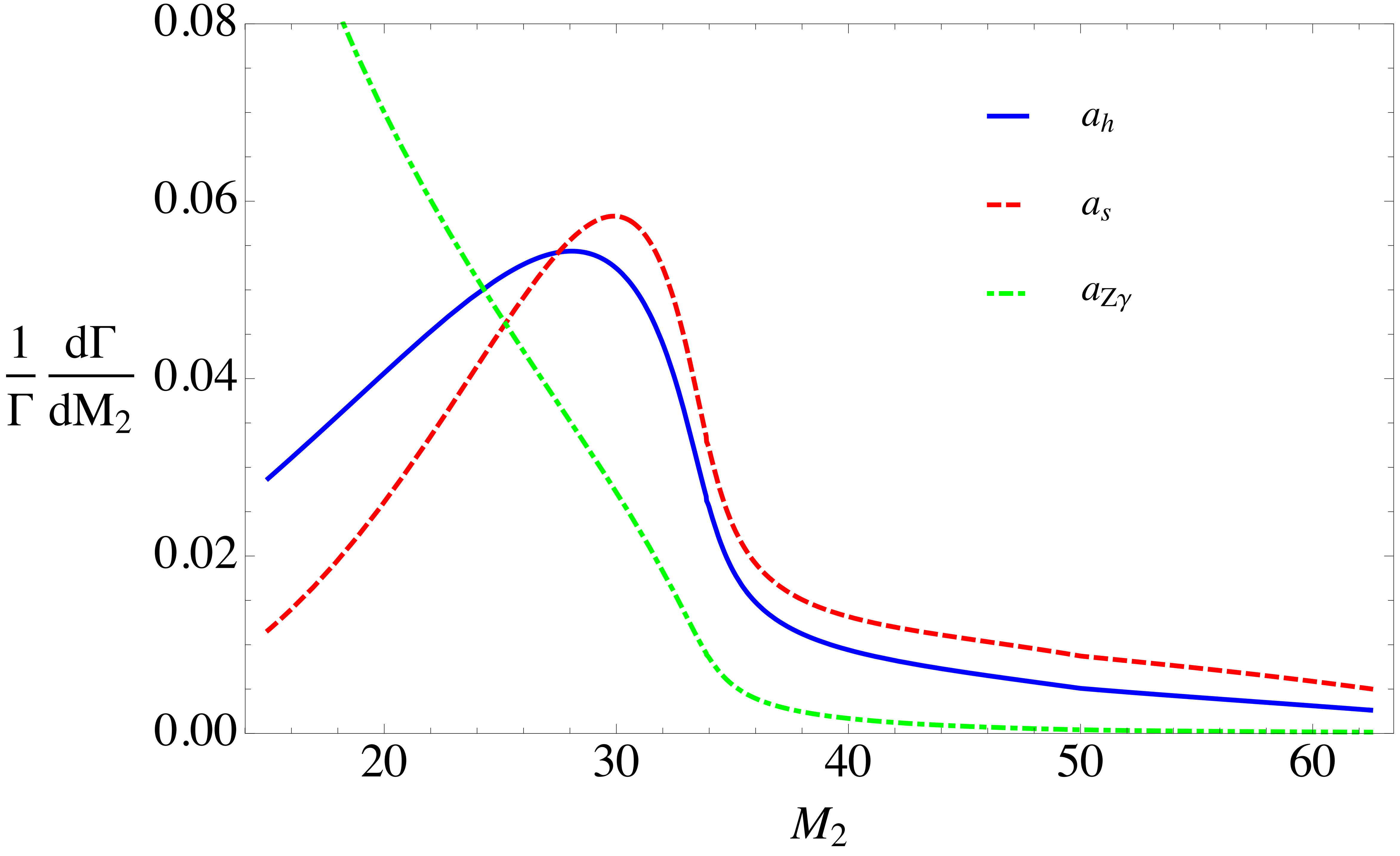
Compare to $h \to \gamma\gamma$.

Final state contains lots of information!



SIMPLE EXAMPLE



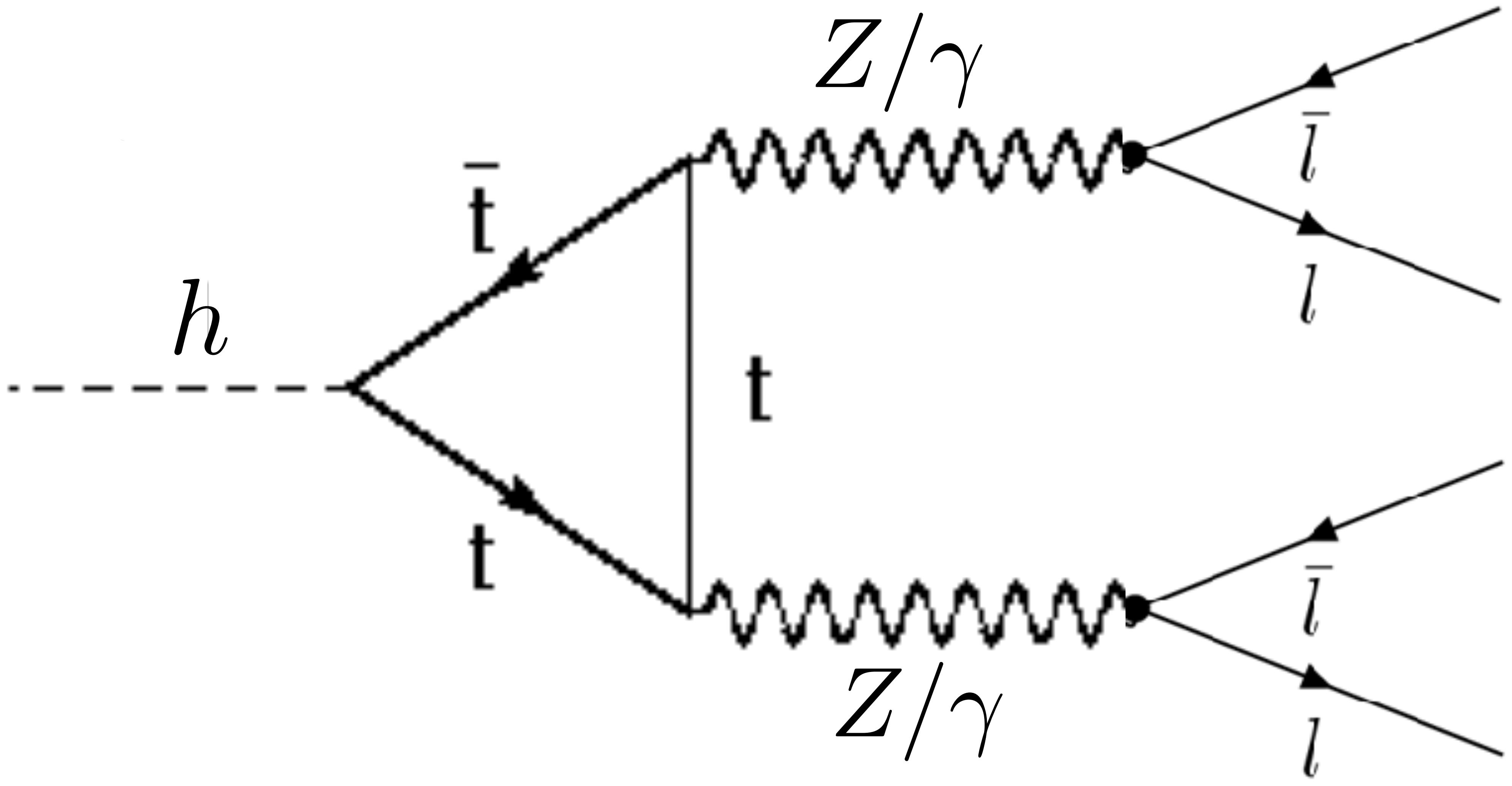


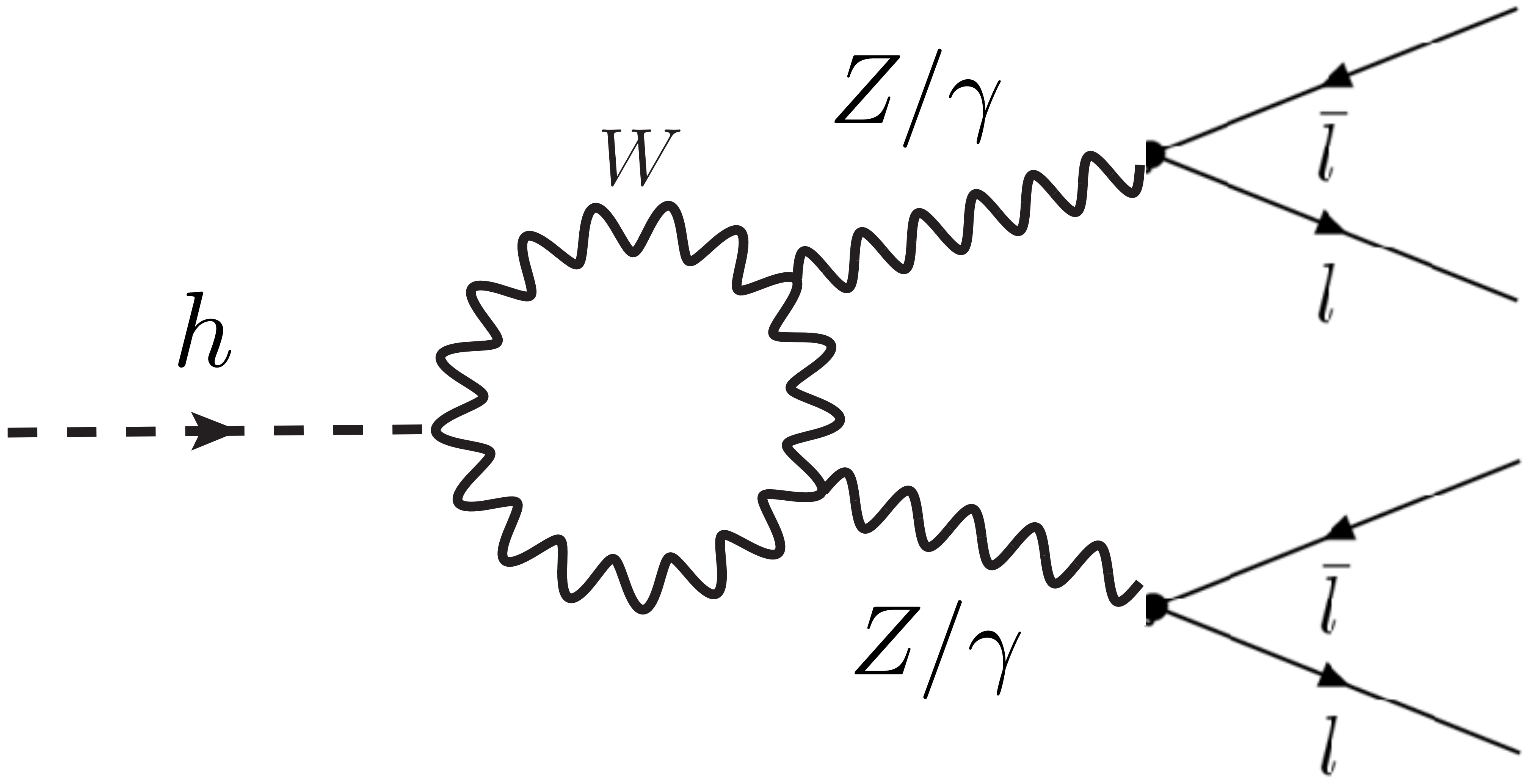
Simple example distinguishing different tensor structures.

DS, R. Vega-Morales, Phys.Rev.D.86, 117504 (2012) [arXiv:1208.4840].

LOOP PROCESS

NLO contributions to $h \to 4\ell$ in SM:





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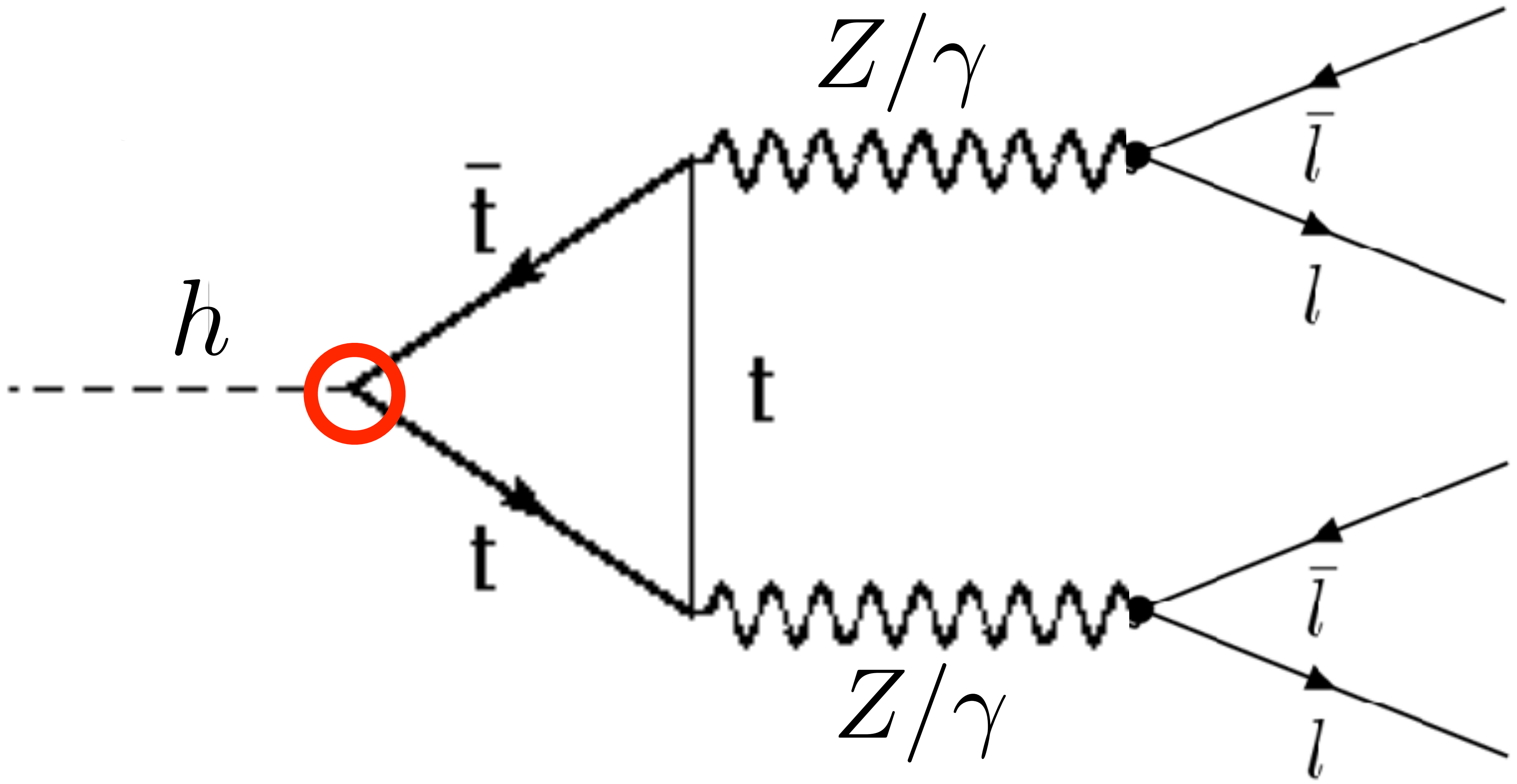
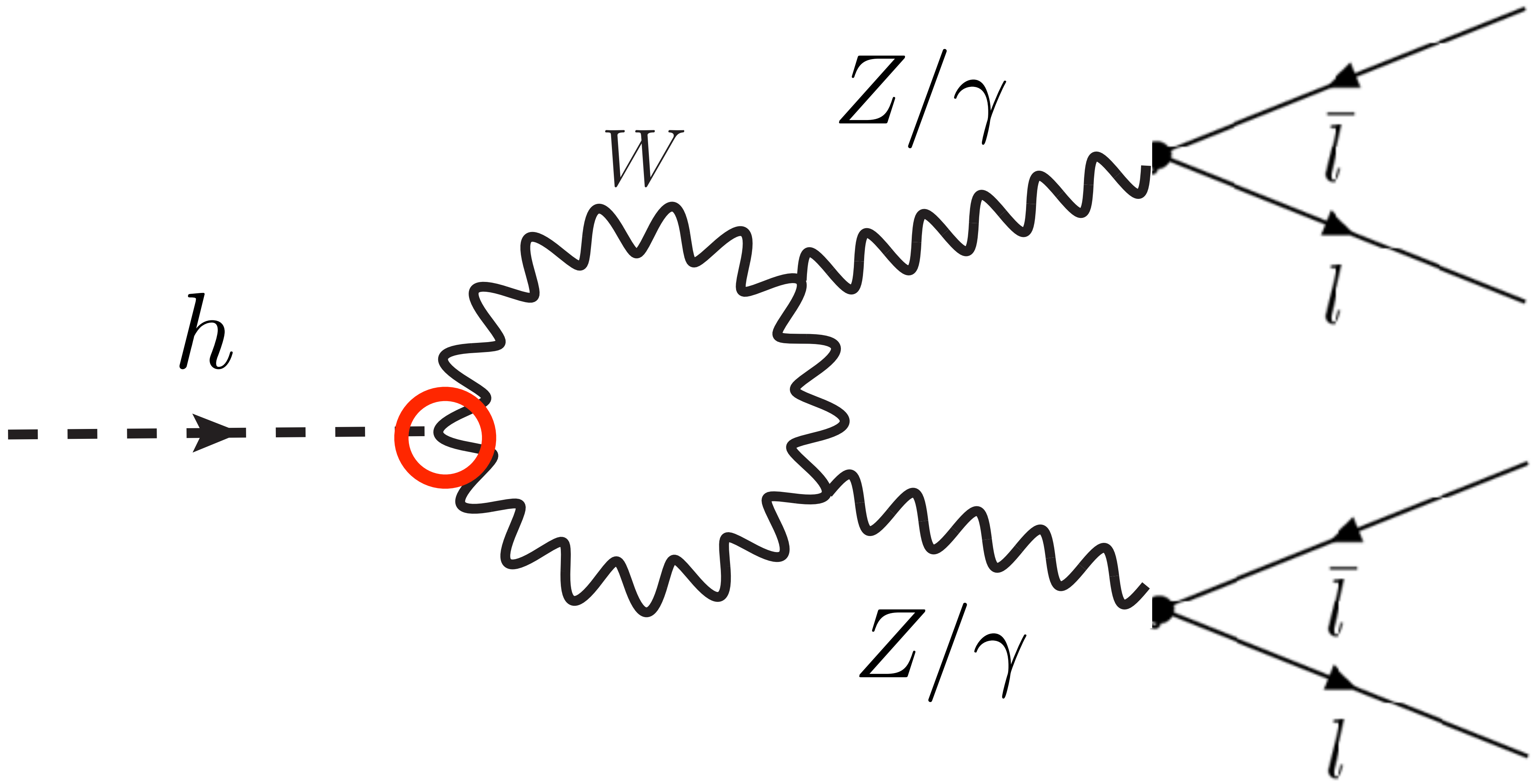
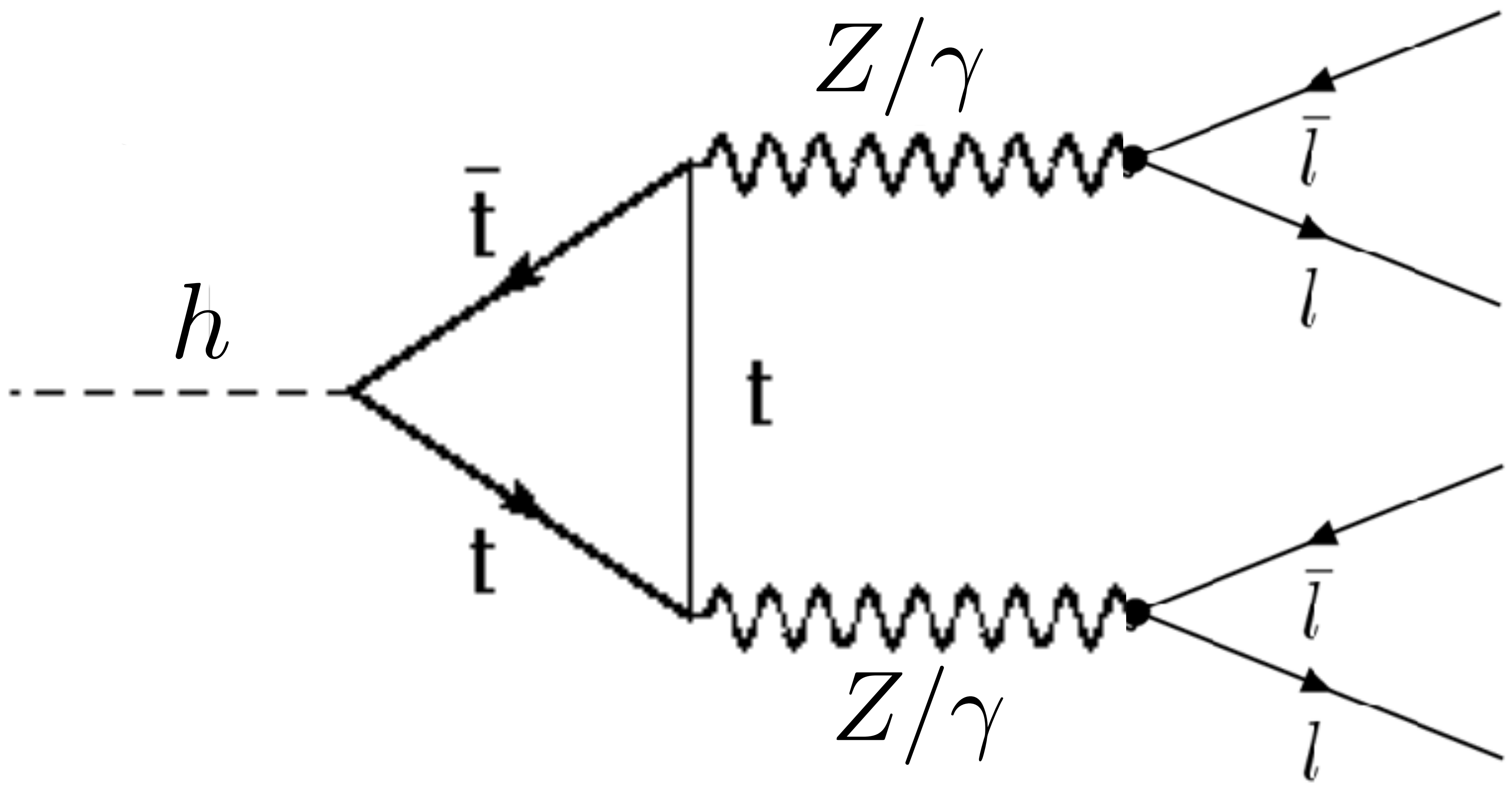


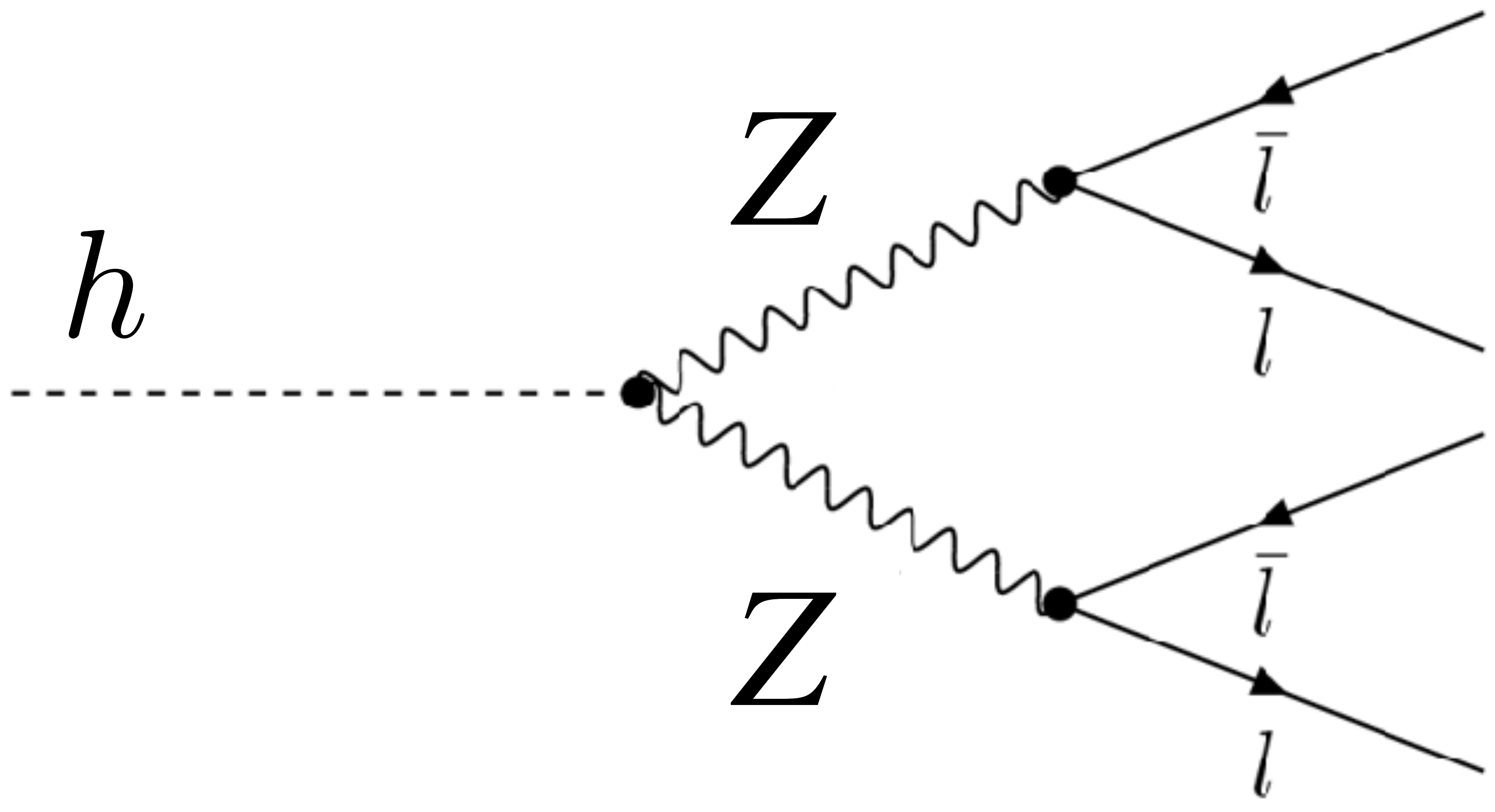


Kinematic distributions are sensitive to Higgs couplings to top and W.

BIGGER THAN YOU THINK

Effect is of course suppressed by a loop factor.





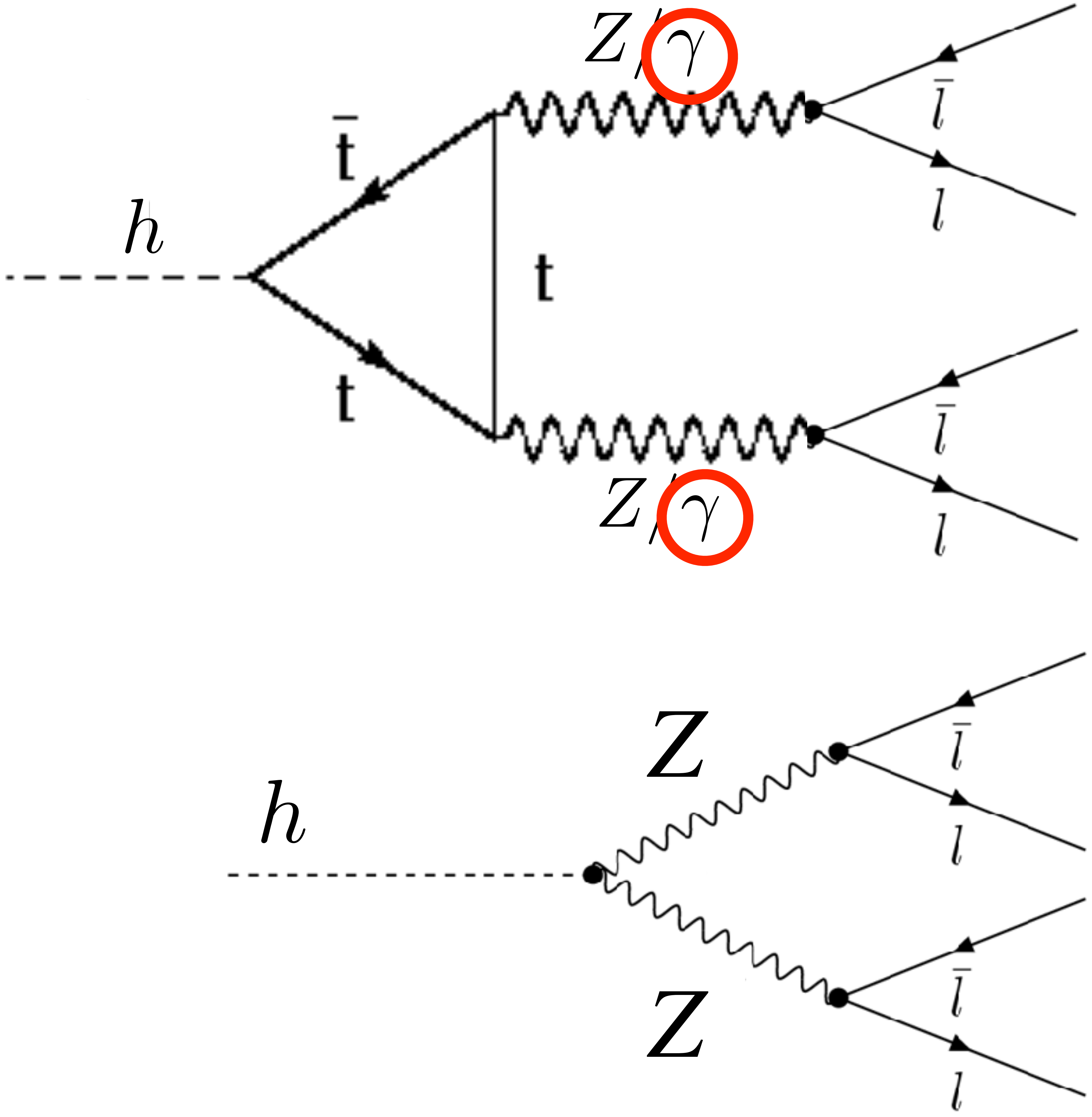
BIGGER THAN YOU THINK

Effect is of course suppressed by a loop factor.

Photon intermediate state gives enhancements.

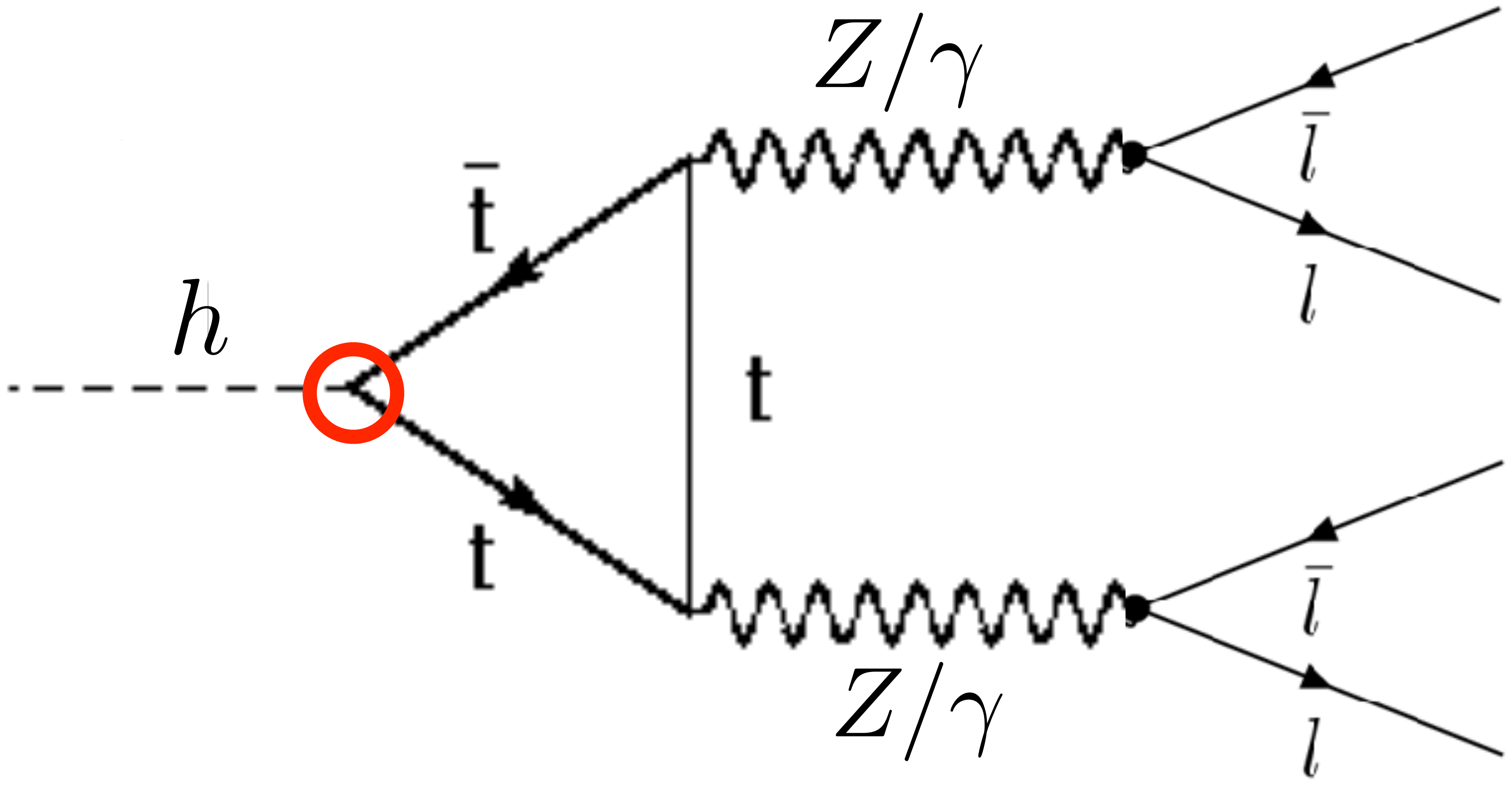
Can look in regions of phase space away from Z peak.

Coupling of leptons to photons larger than to Z.



LOOP PROCESS

Start with top Yukawa coupling, keep all others fixed.



$$h\,\bar{t}\,(y_t + i\,\tilde{y}\,\gamma^5)\,t$$

SM: $y \approx 1, \tilde{y} \approx 0$

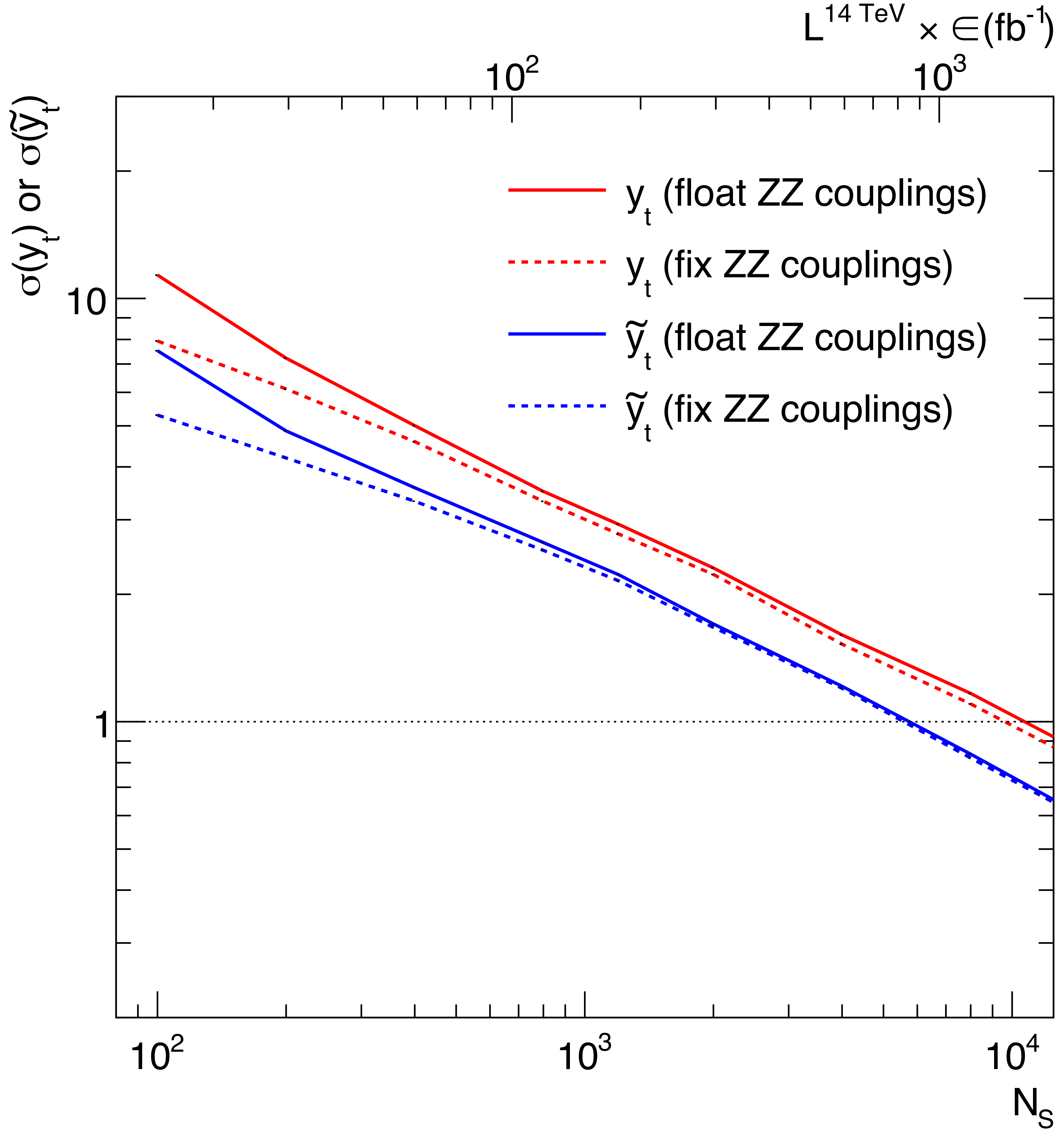
Sensitivity to CP phase of coupling.

SENSITIVITY

Can measure both top Yukawa couplings.

More sensitivity to CP odd coupling.

Need LARGE number of events.



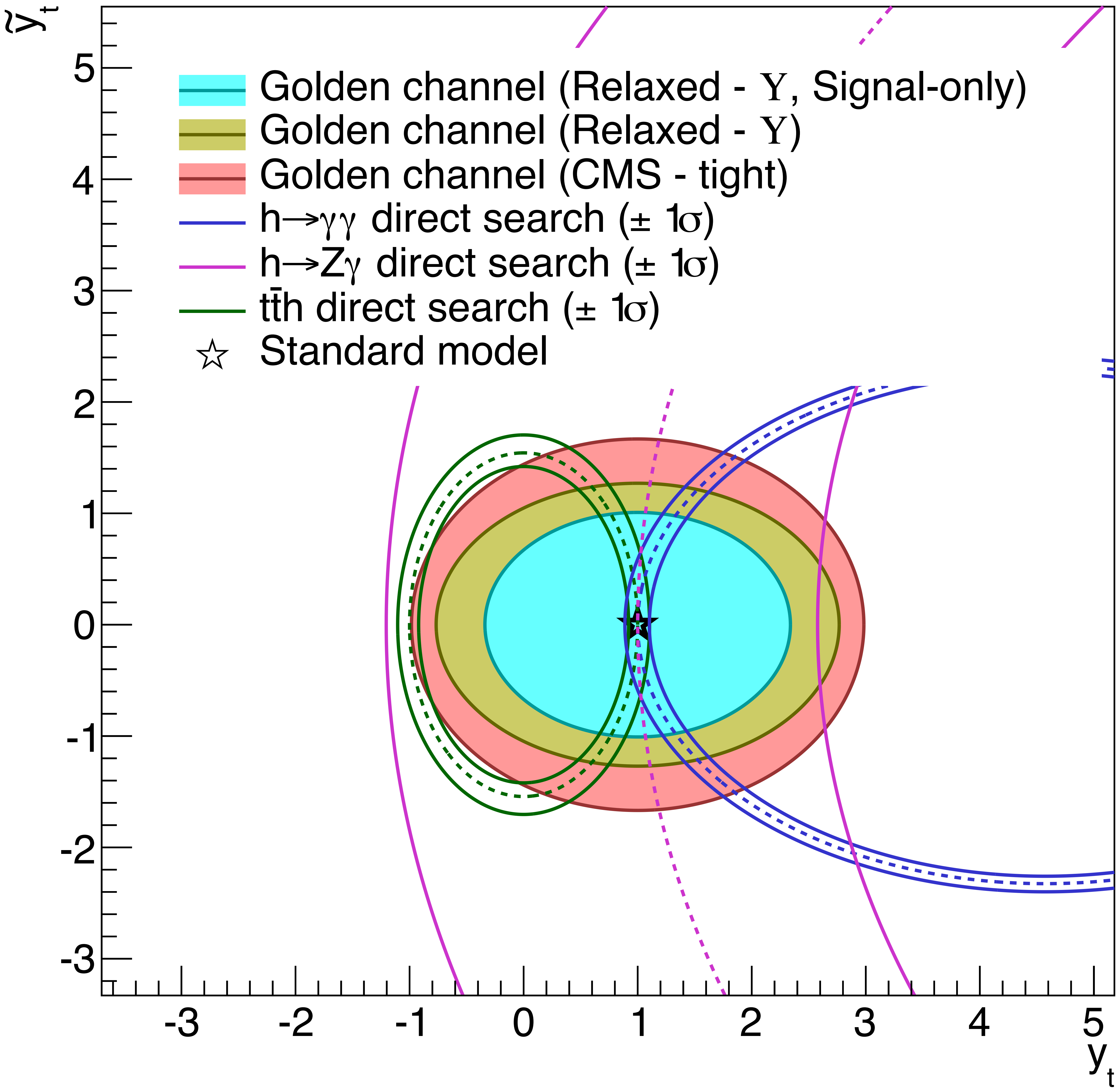
Chen, DS, Vega-Morales, Phys.Rev.D.92, 053003 (2015) [arXiv:1505.01168].

HL-LHC

8,000 events ~ 3,000 fb^{-1}.

If there is an anomaly in $h \to \gamma\gamma$ or tth production will help characterize.

Chen, DS, Vega-Morales, Phys.Rev.D.92, 053003 (2015) [arXiv:1505.01168].



100 TEV HADRON COLLIDER

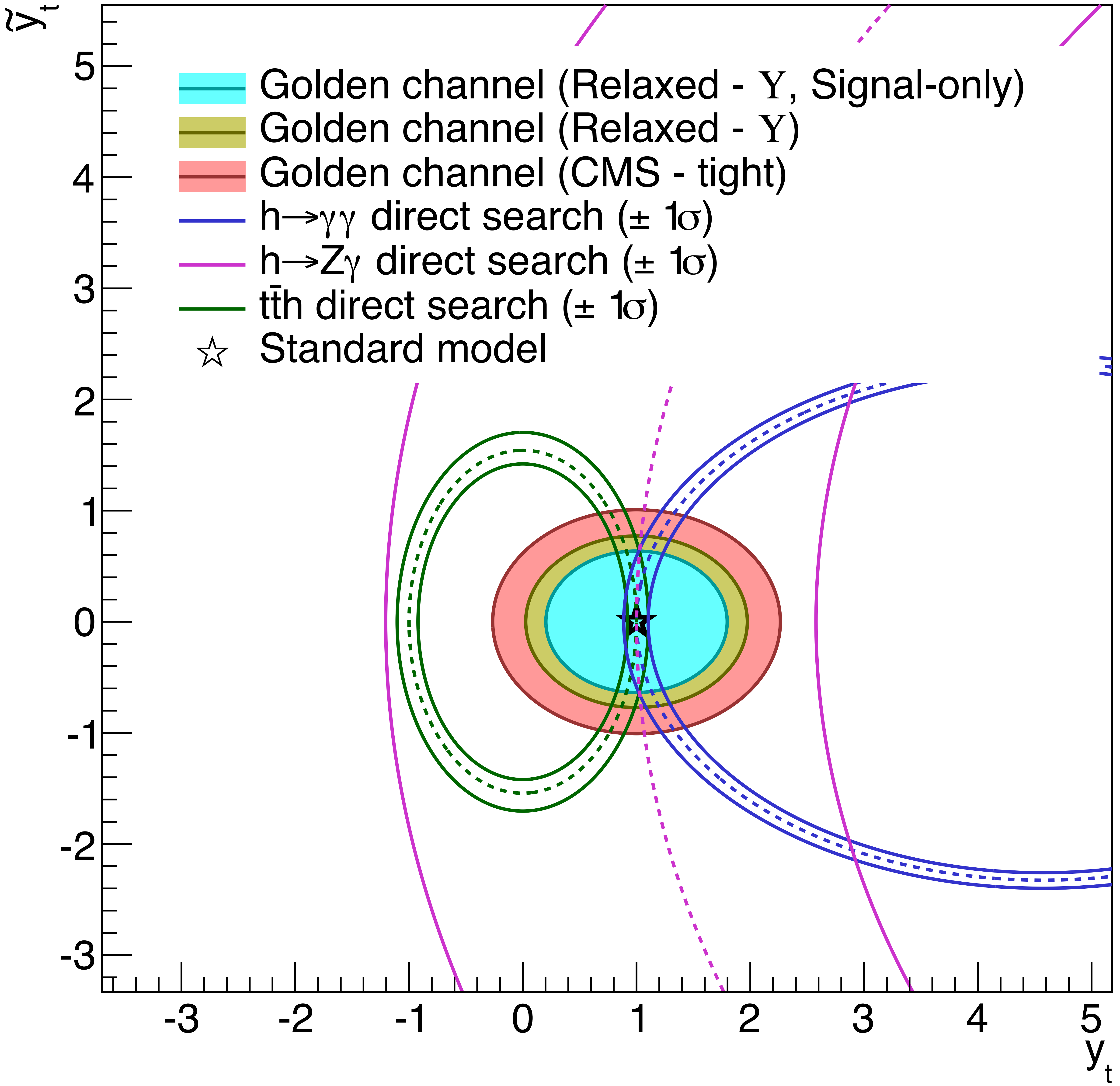
3,000 fb^{-1} @ 100 TeV ~ 20,000 events.

High energy →

More rate →

Better measurements.

Chen, DS, Vega-Morales, Phys.Rev.D.92, 053003 (2015) [arXiv:1505.01168].



LEPTON COLLIDER?

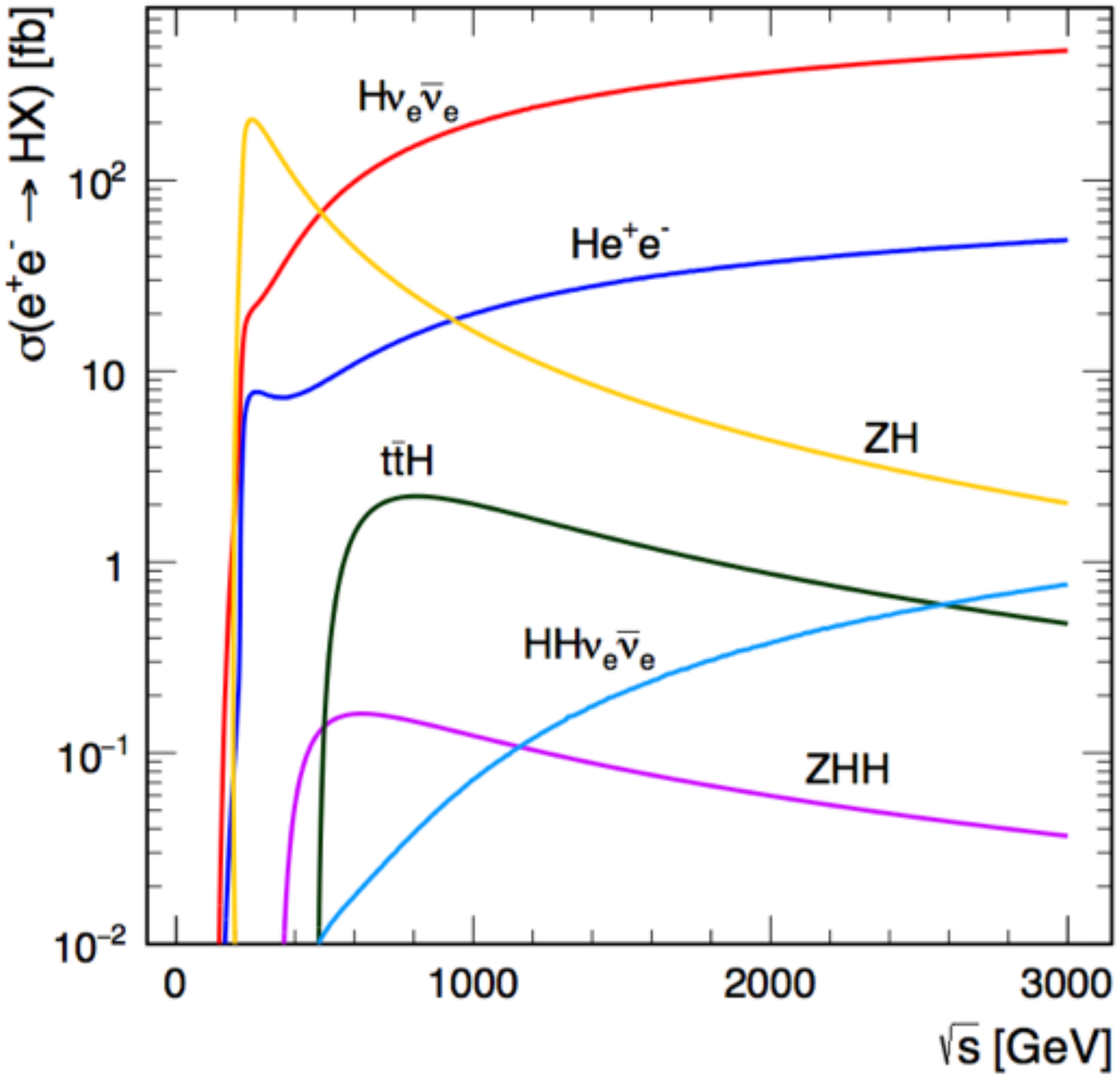
Can we do this at a lepton collider?

There will be less background, but…

$$\sigma(e^+e^- \to Zh, \sqrt{s} = 240\,\text{GeV}) \approx 300\,\text{fb}$$

$\mathscr{L}$(FCC-ee) $\approx 10^4$ / fb has most luminosity.

Get less than 1/20 of HL-LHC number of events.

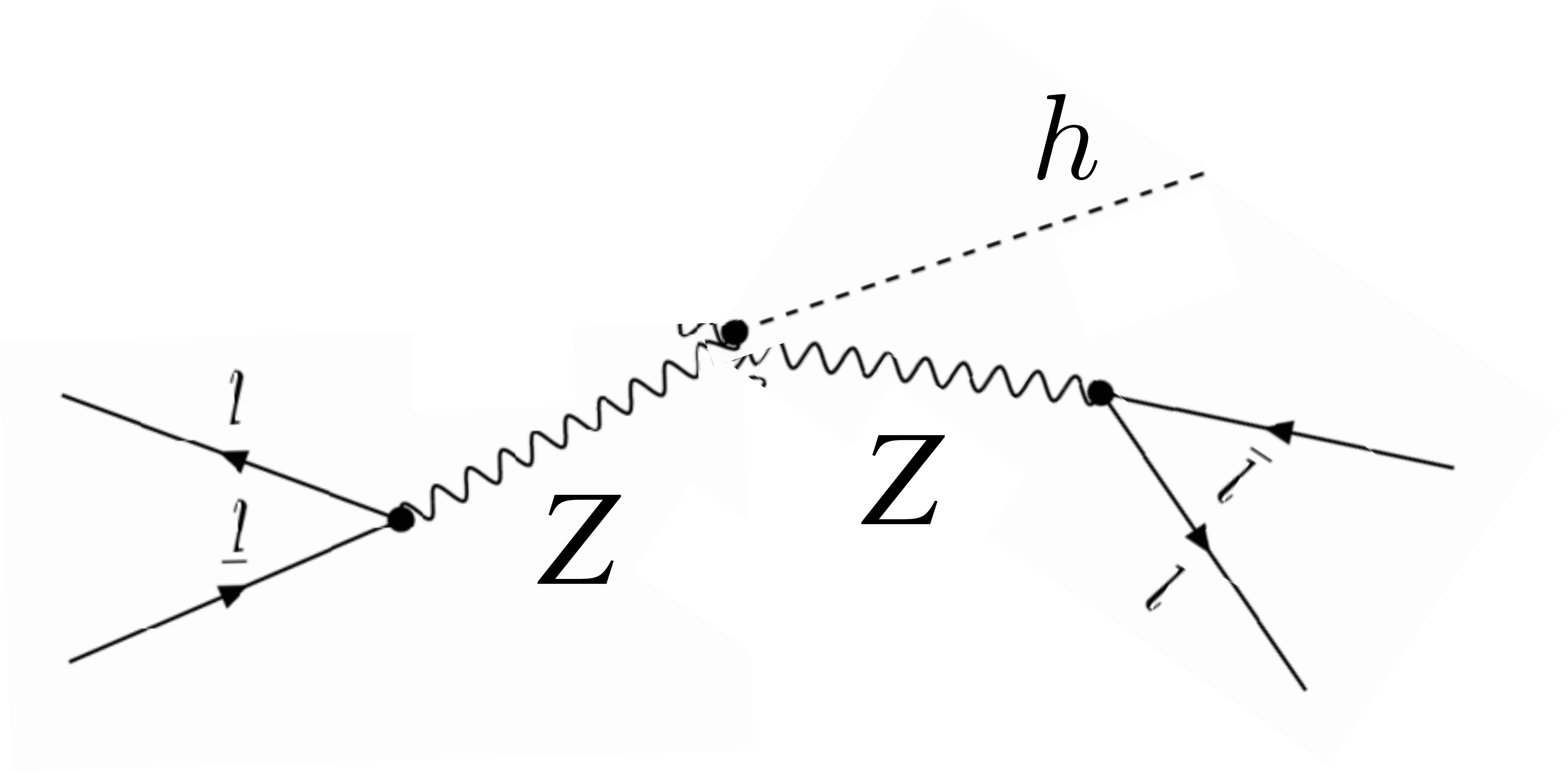


Junping Tian, Reconnotres de Vietnam '22.

CROSSING SYMMETRY

Rearrange diagram for lepton colliders.

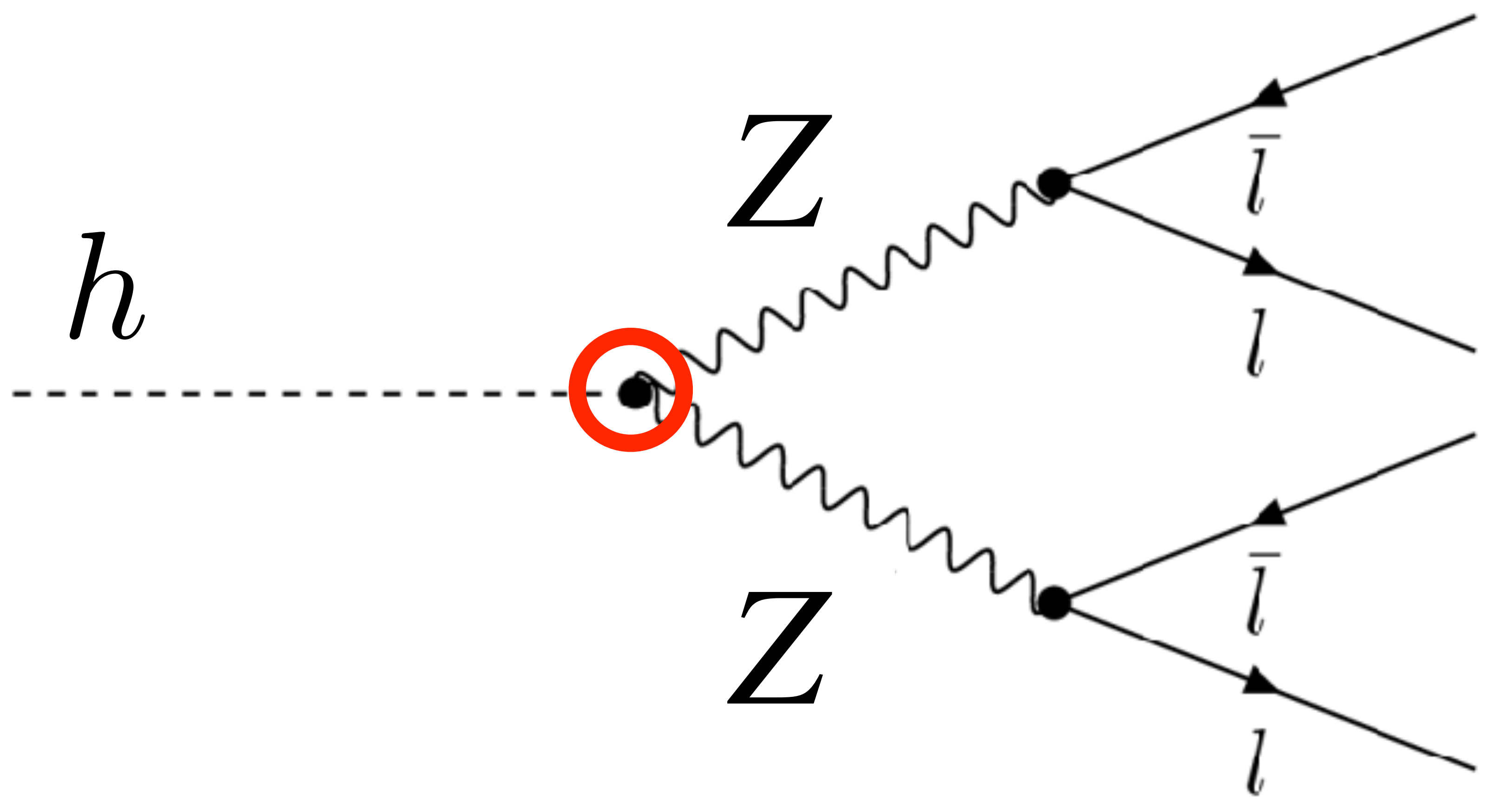
Just need to measure Higgs momentum, can use any decay.

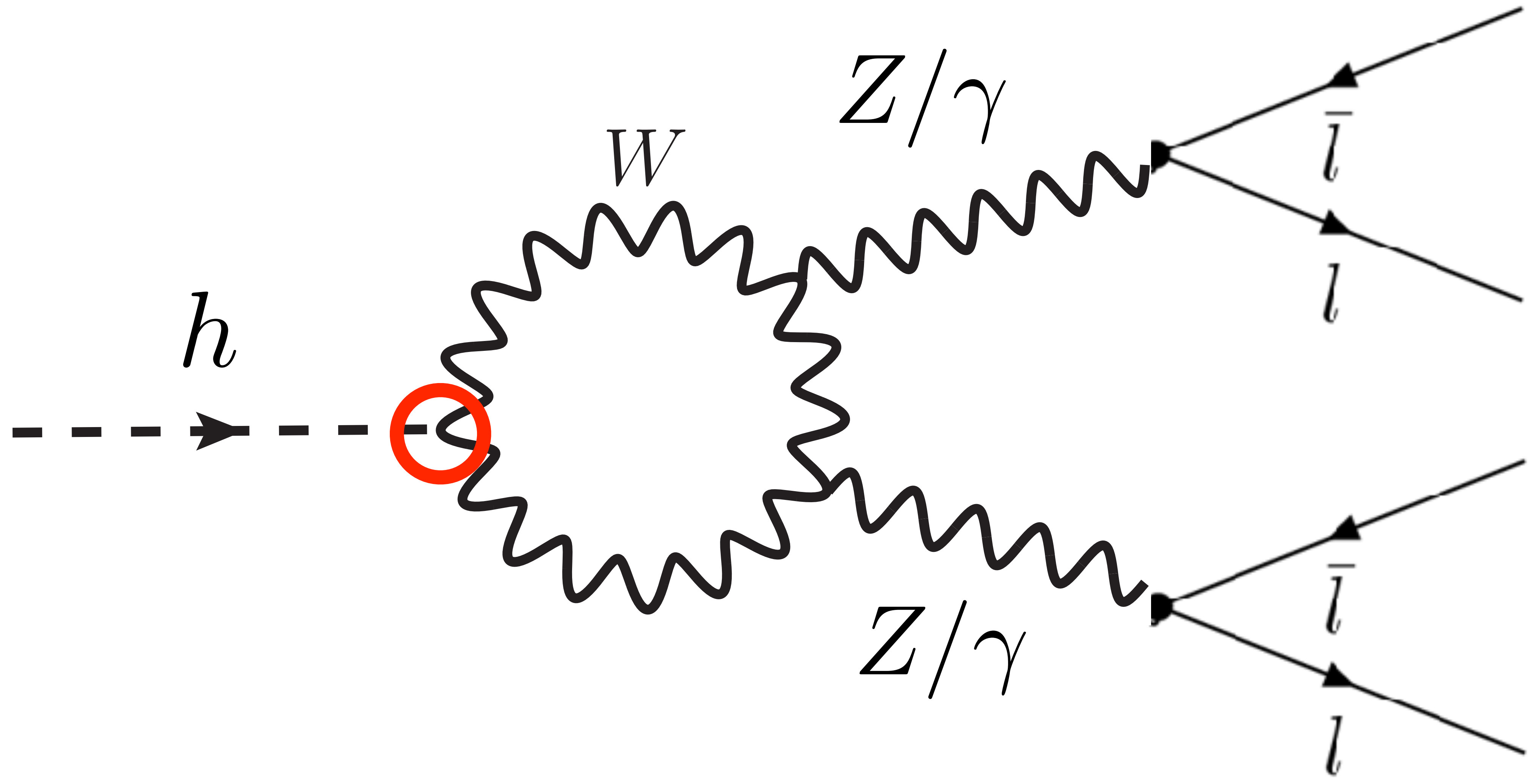


Shen, Zhu, 1504.05625.
Rindani, Singh, 1805.03417.
Nakamura, Shivaji, 1812.01576

COUPLING TO GAUGE BOSONS

Can measure ratio of W to Z coupling.



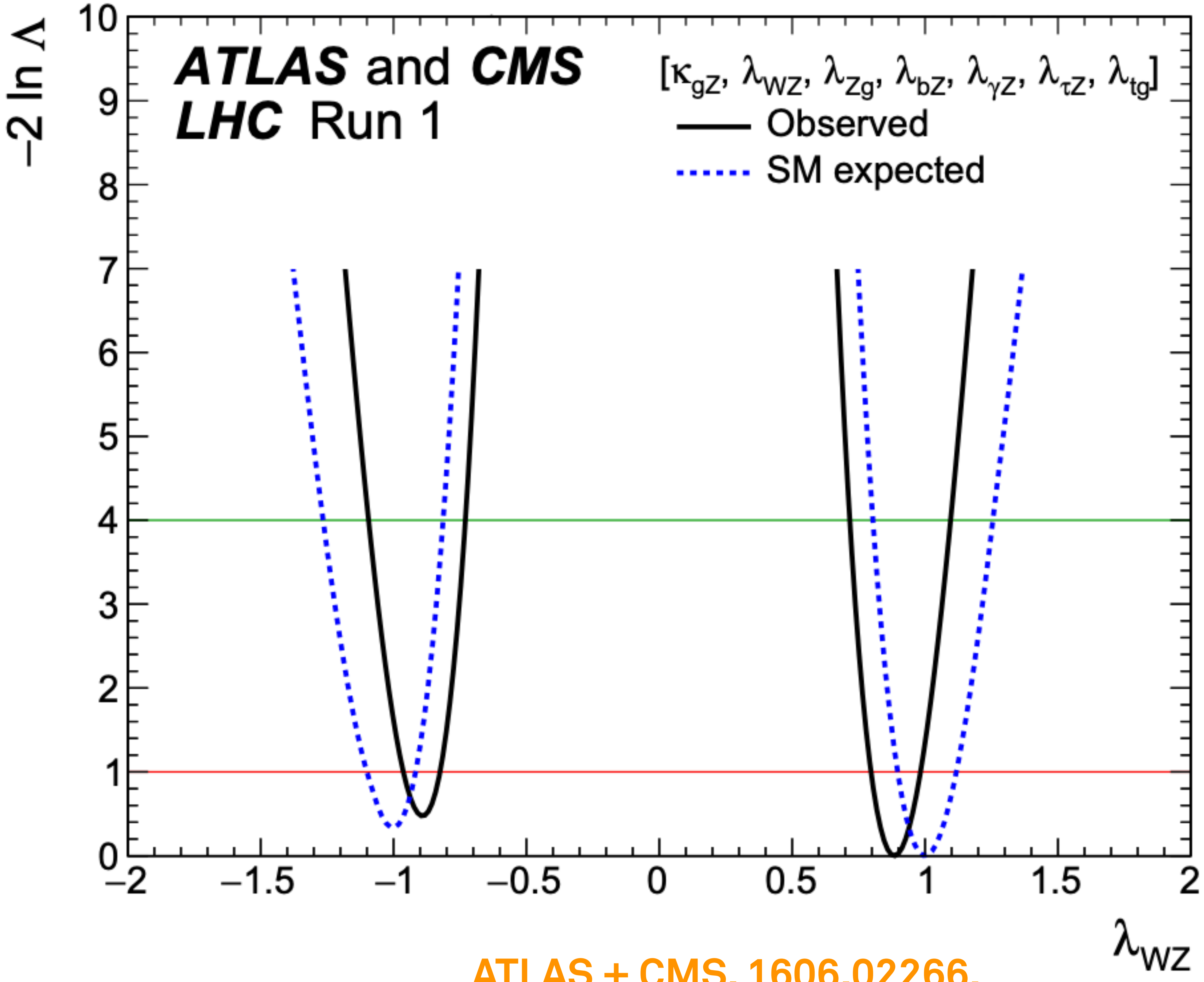


$$\mathcal{L} = h\left(\kappa_W\, g\, m_W W^+_\mu W^-_\mu + \kappa_Z\, g\, \frac{m_Z^2}{2m_W} Z_\mu Z_\mu\right) \qquad \lambda_{WZ} = \frac{\kappa_W}{\kappa_Z}$$

SIGN INSTENTIVITY

Rage measurements of tree level-processes are insensitive to sign of λ_{WZ}.

Very difficult to distinguish between $\lambda_{WZ} = \pm 1$.



ATLAS + CMS, 1606.02266.

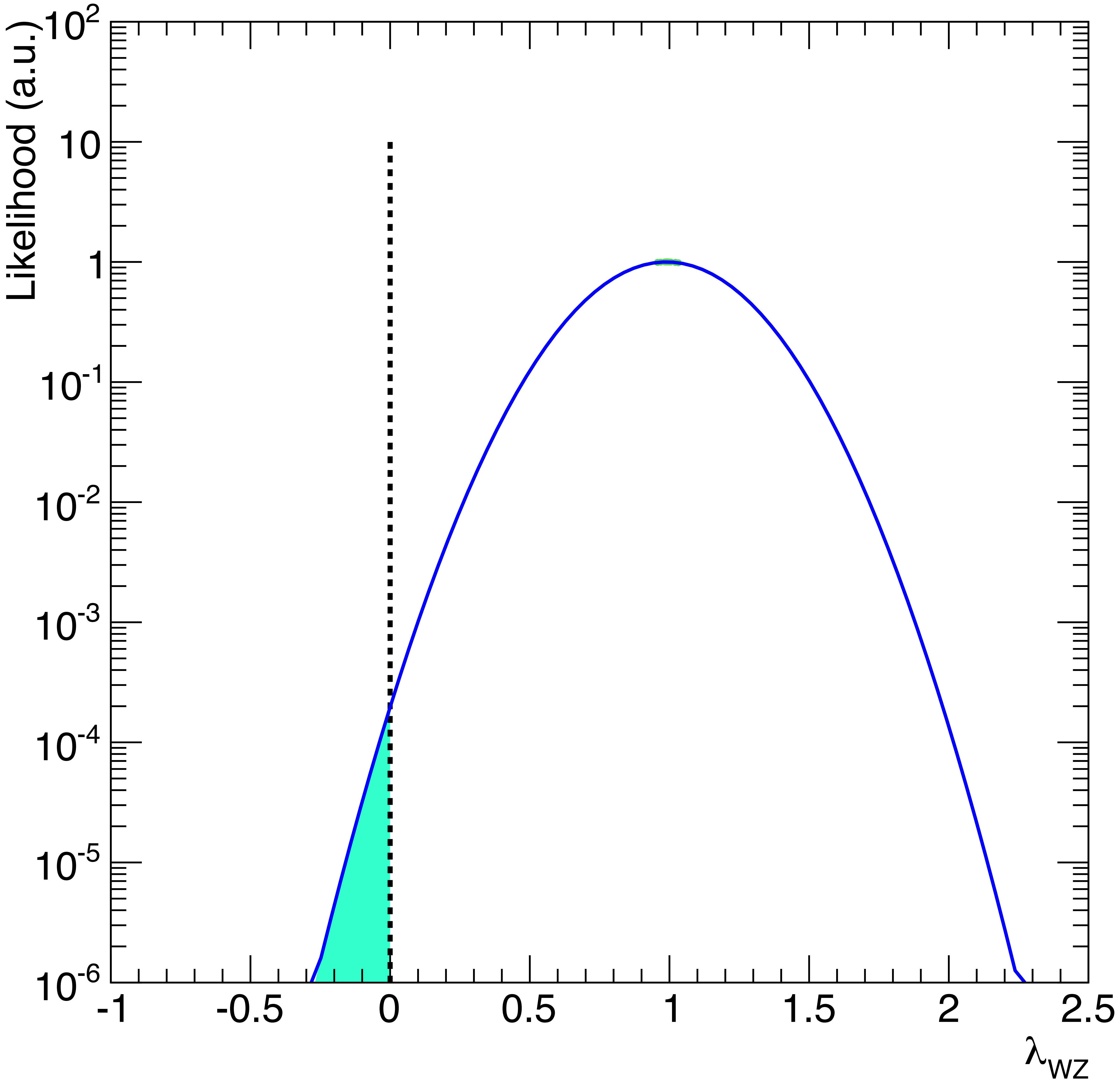
GOLDEN CHANNEL MEASUREMENT

Example likelihood extracted with 2,000 events at LHC ~ 800/fb.

Can exclude negative coupling at ~3σ.

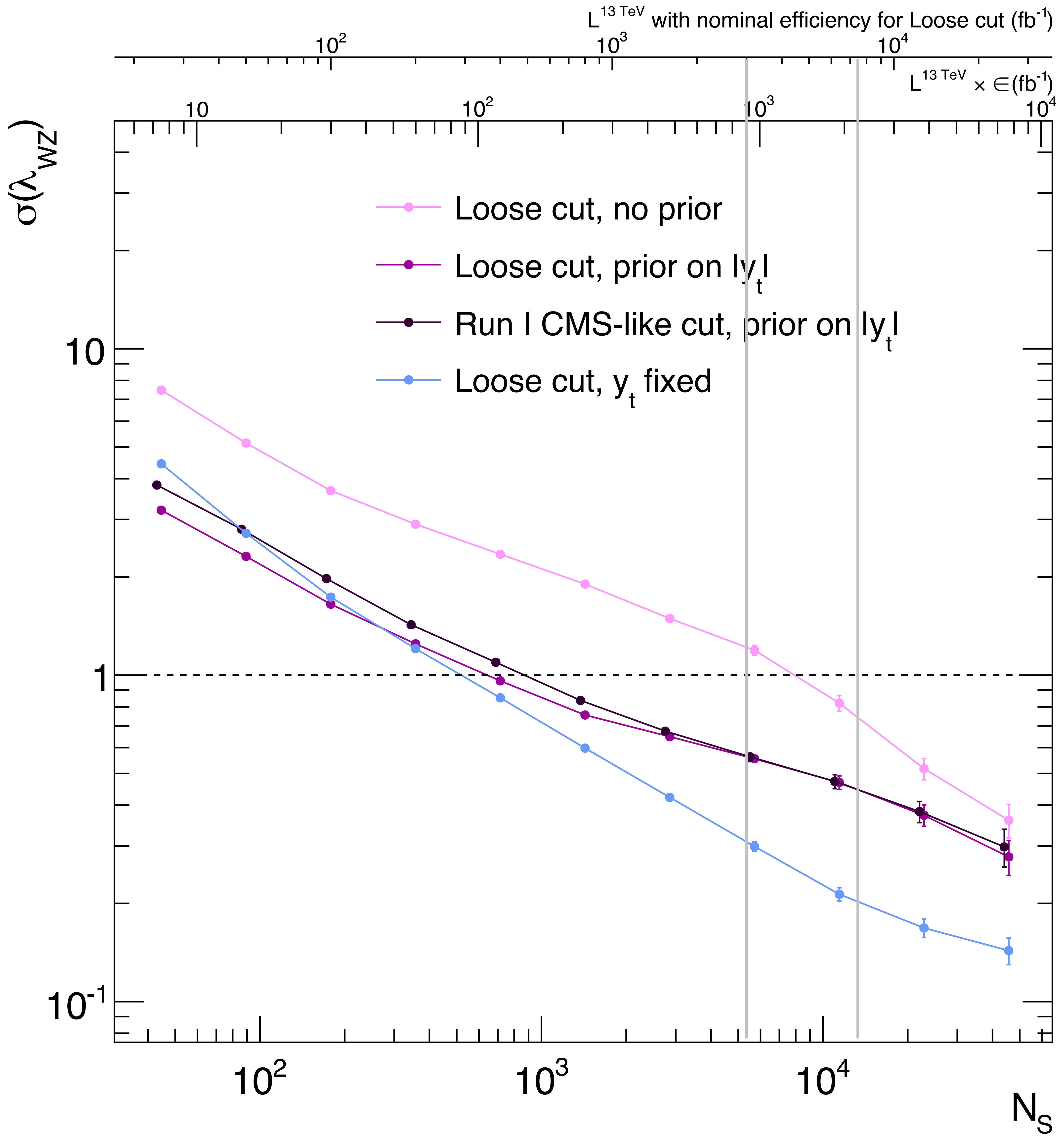
Have assumed top Yukawa is fixed to SM value.

Y. Chen, J. Lykken, M. Spiropulu, DS, R. Vega-Morales, PRL, 2016 [arXiv:1608.02159].



GOLDEN CHANNEL MEASUREMENT

Can get good precision on λ_{WZ} with large number of signal events.

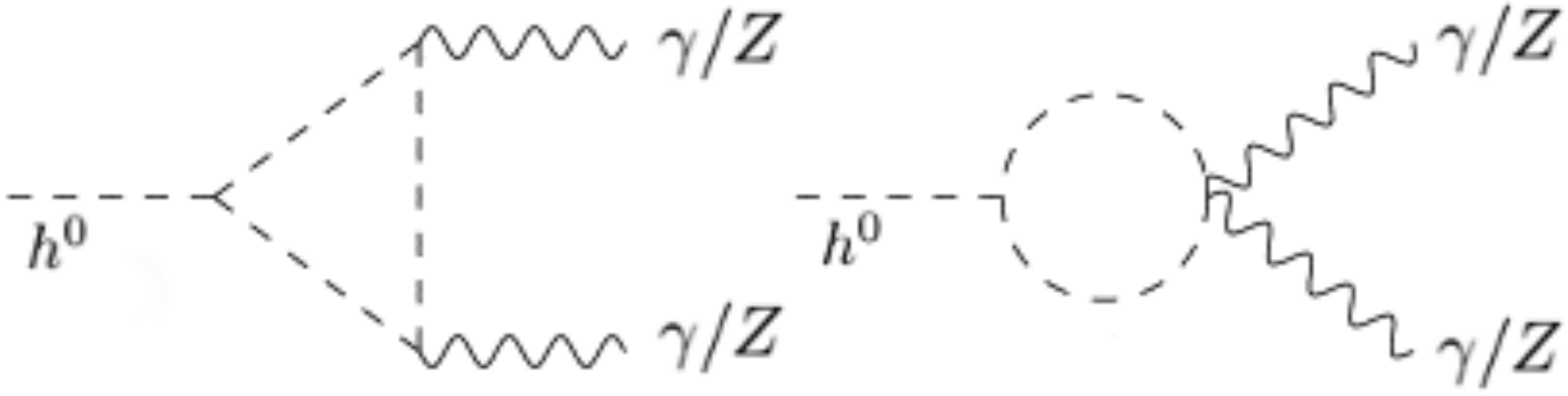


Y. Chen, J. Lykken, M. Spiropulu, DS, R. Vega-Morales, PRL, 2016 [arXiv:1608.02159].

BSM PHYSICS

If there are new EM or weak charged states that couple to the Higgs, they will also contribute to $h \to 4\ell$ at NLO.

Models that solve the hierarchy problem must have new states coupling tot he Higgs!



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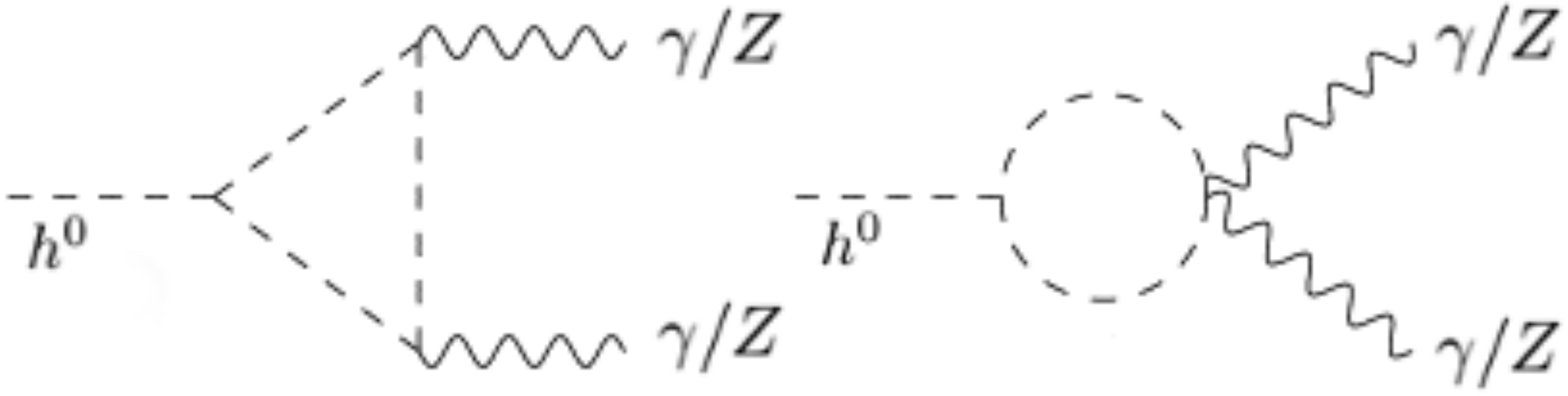


Models that solve the hierarchy problem must have new states coupling tot he Higgs!

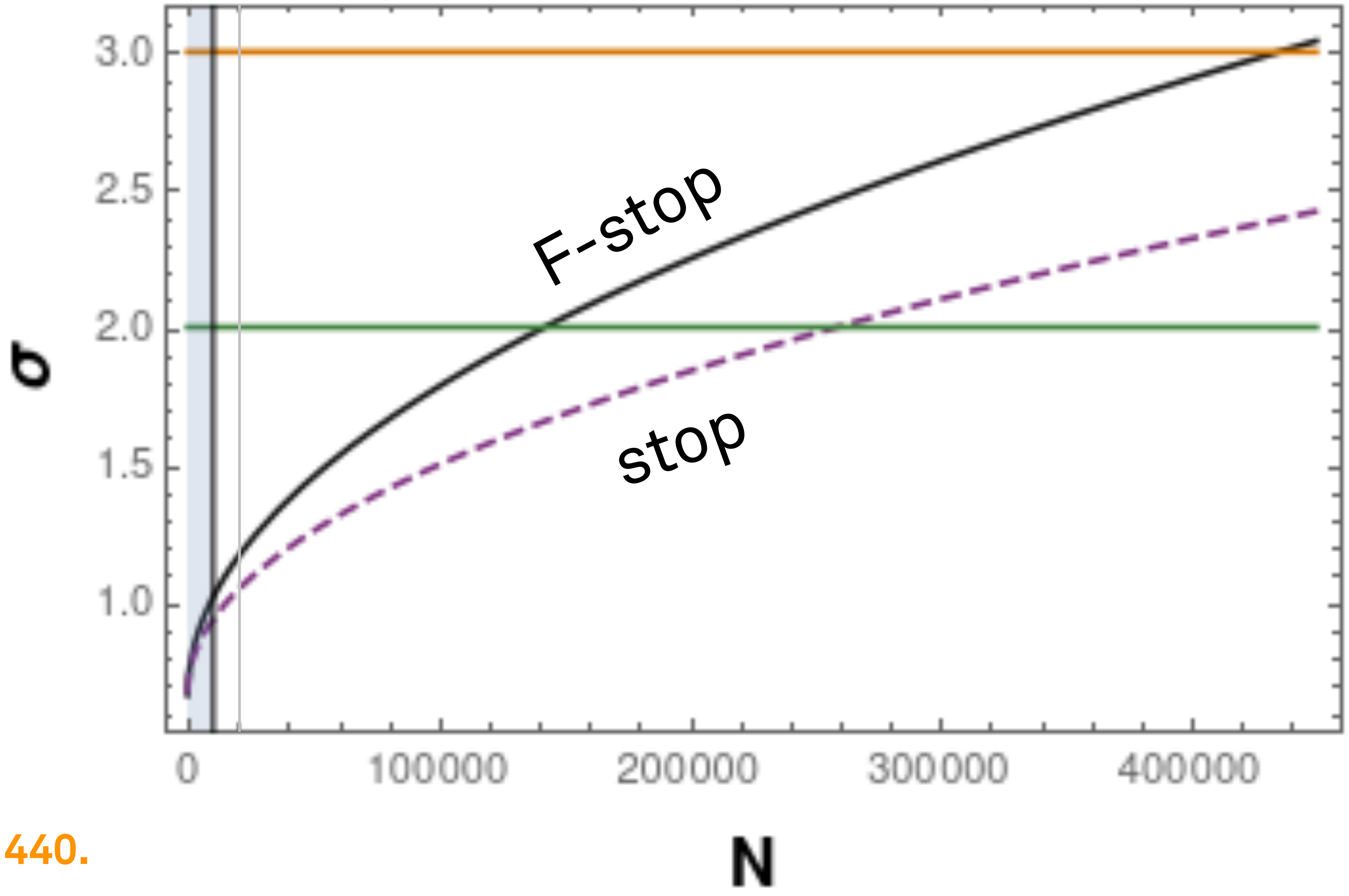
SUSY: scalar top partner (stop)

Folded SUSY: F-stops (no QCD charge, much weaker limits)

VERY FUTURISTIC

Impose constraints from $h \to \gamma\gamma$ and $h \to Z\gamma$.

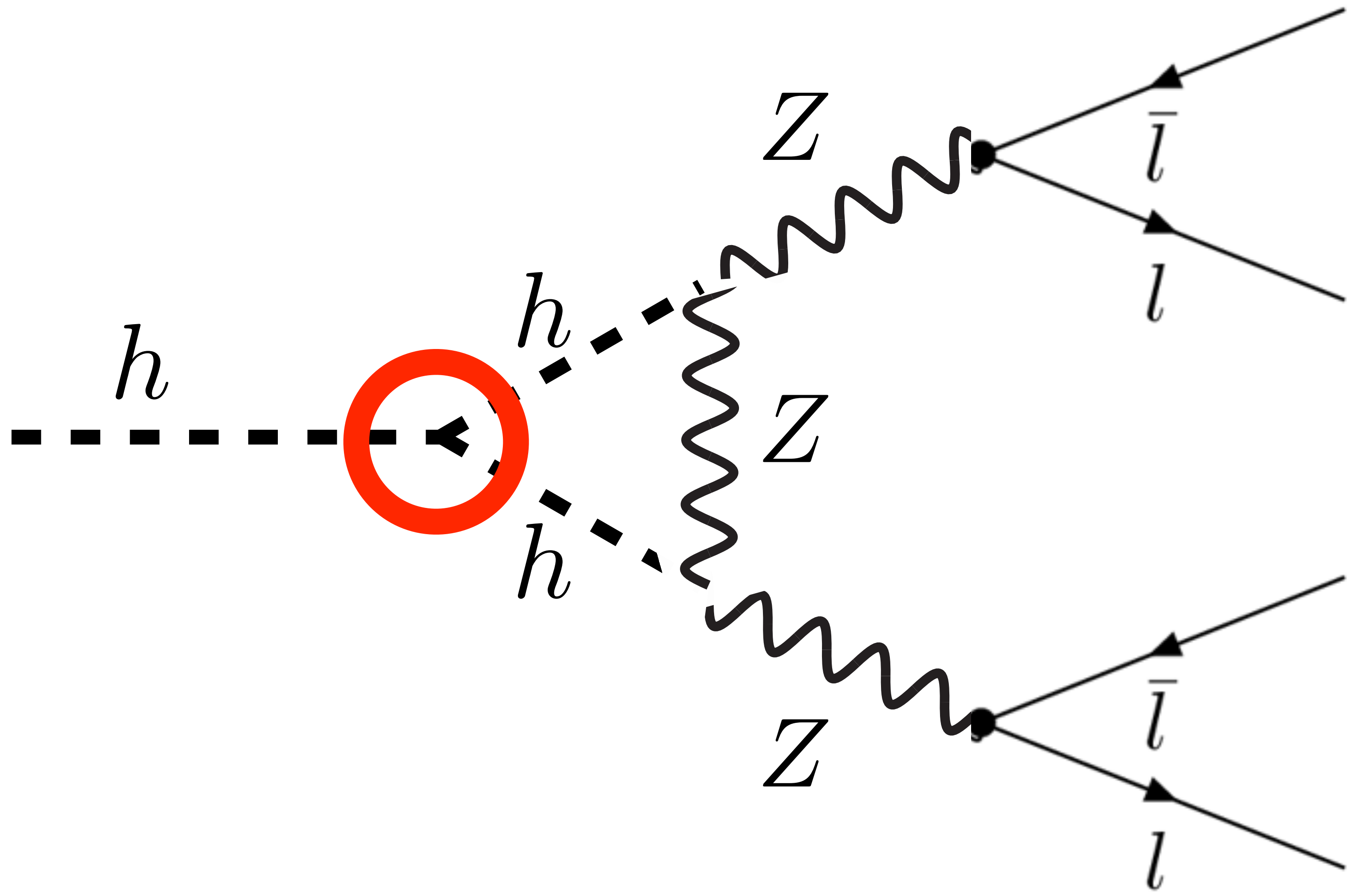
Ultra super duper futuristic collider.

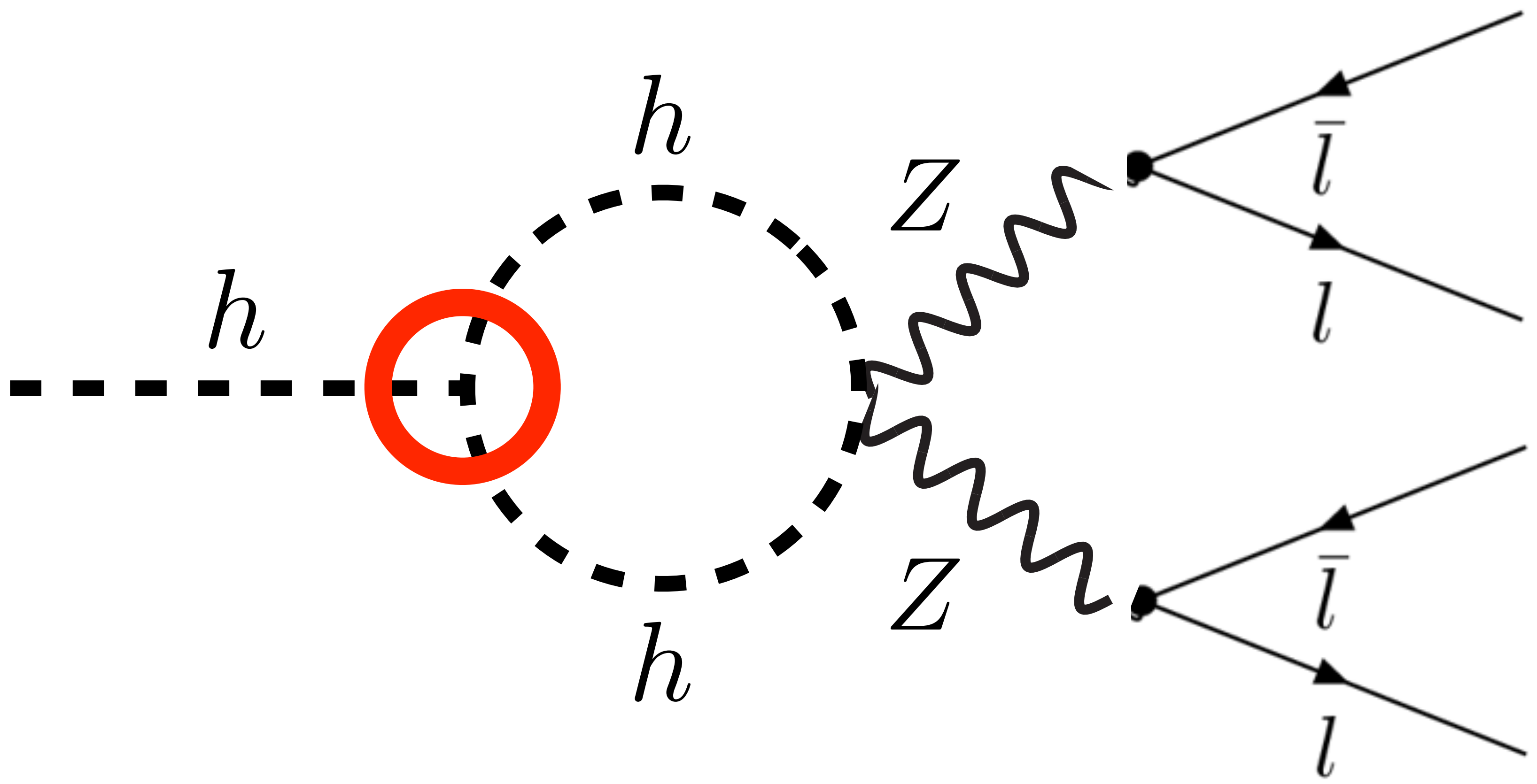


P. Archer-Smith, DS, R. Vega-Morales, arXiv:2012.01440.

HIGGS SELF COUPLING

Can use NLO effects in $h \to 4\ell$ to measure Higgs self coupling.





Probably hard because only contributes with intermediate Z’s.

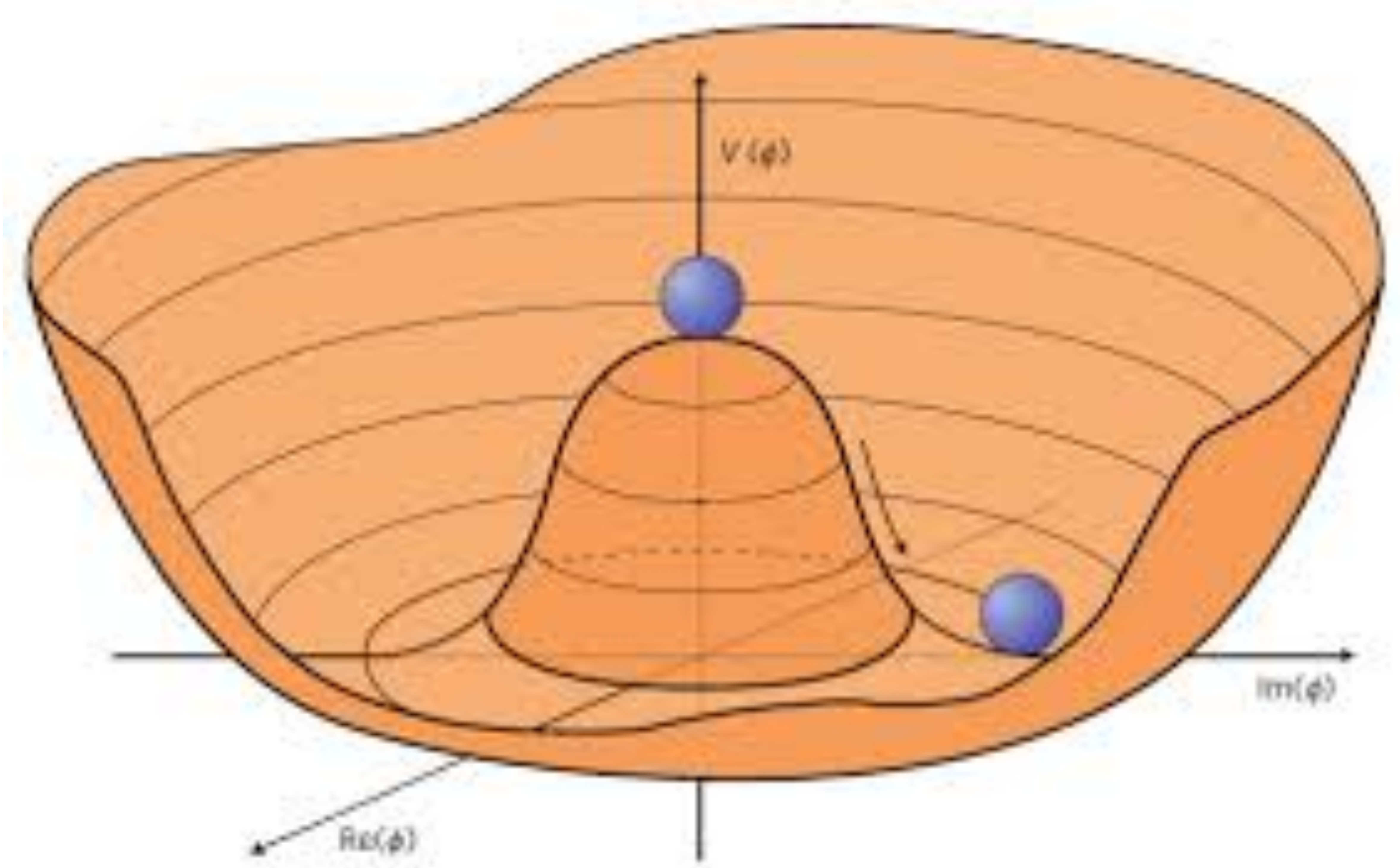
Work in progress (kinda).

HIGGS SELF COUPLING

Current constraints are quite weak

$$-1.1 < \kappa_{hhh} < 6.0.$$

Give insight into how electroweak symmetry is actually broken in nature?



Work in progress (kinda).

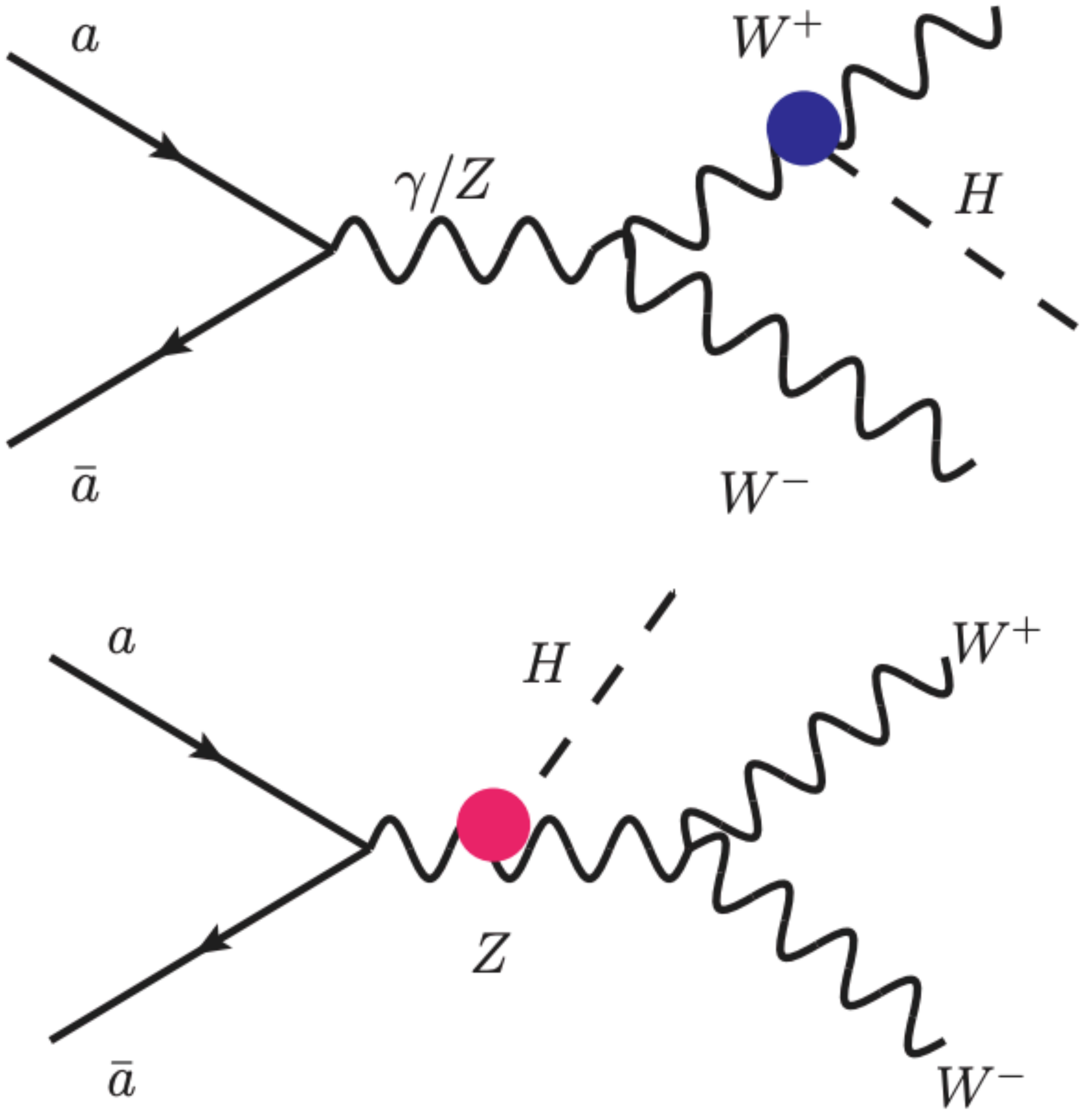
HOW ELSE TO MEASURE SIGN?

Another process:

W^+W^-h production

Rate is tiny at LHC.

Could possibly do at lepton collider.



Chiang, He, Li, 1805.01689.

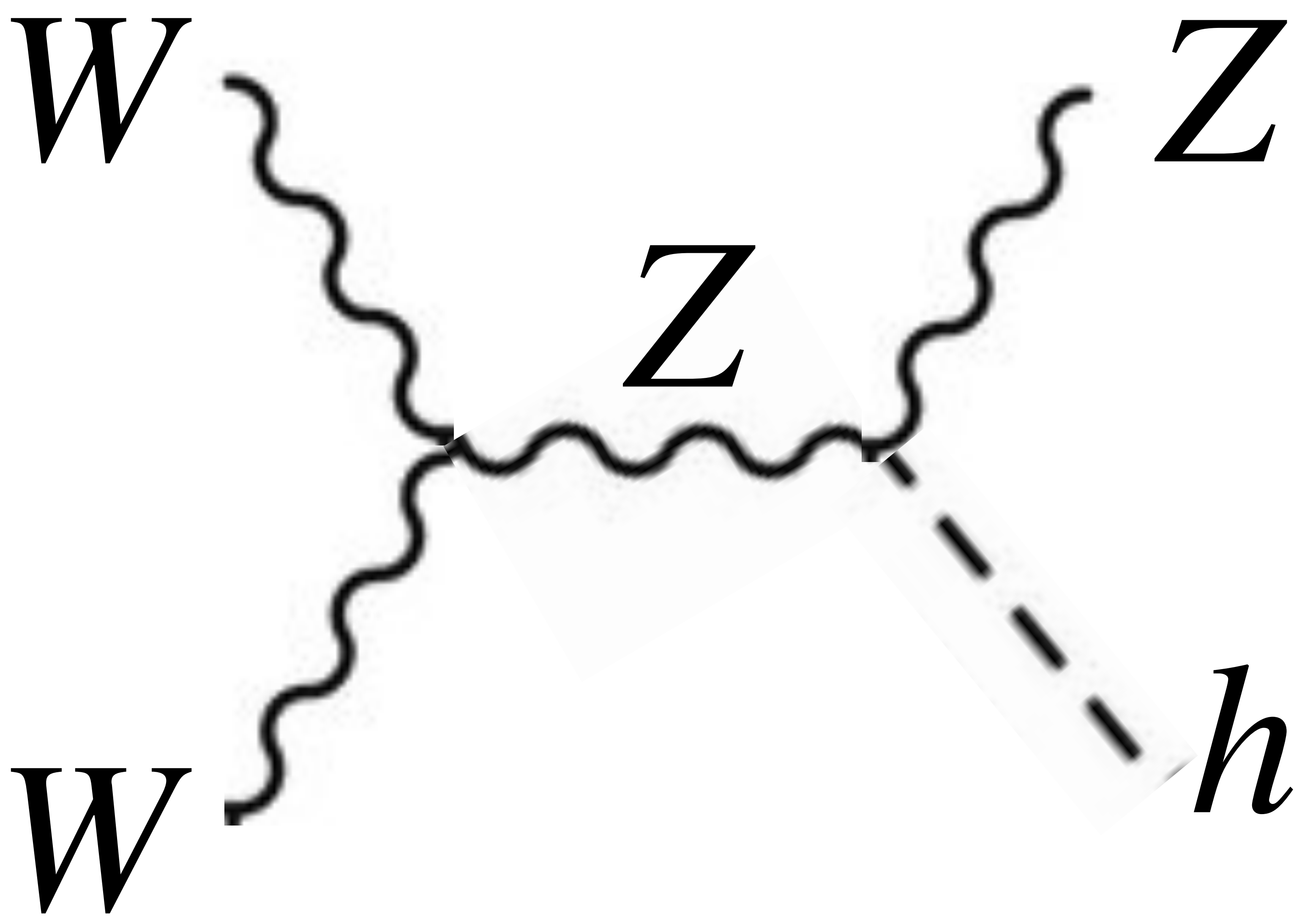
GAUGE BOSON SCATTERING

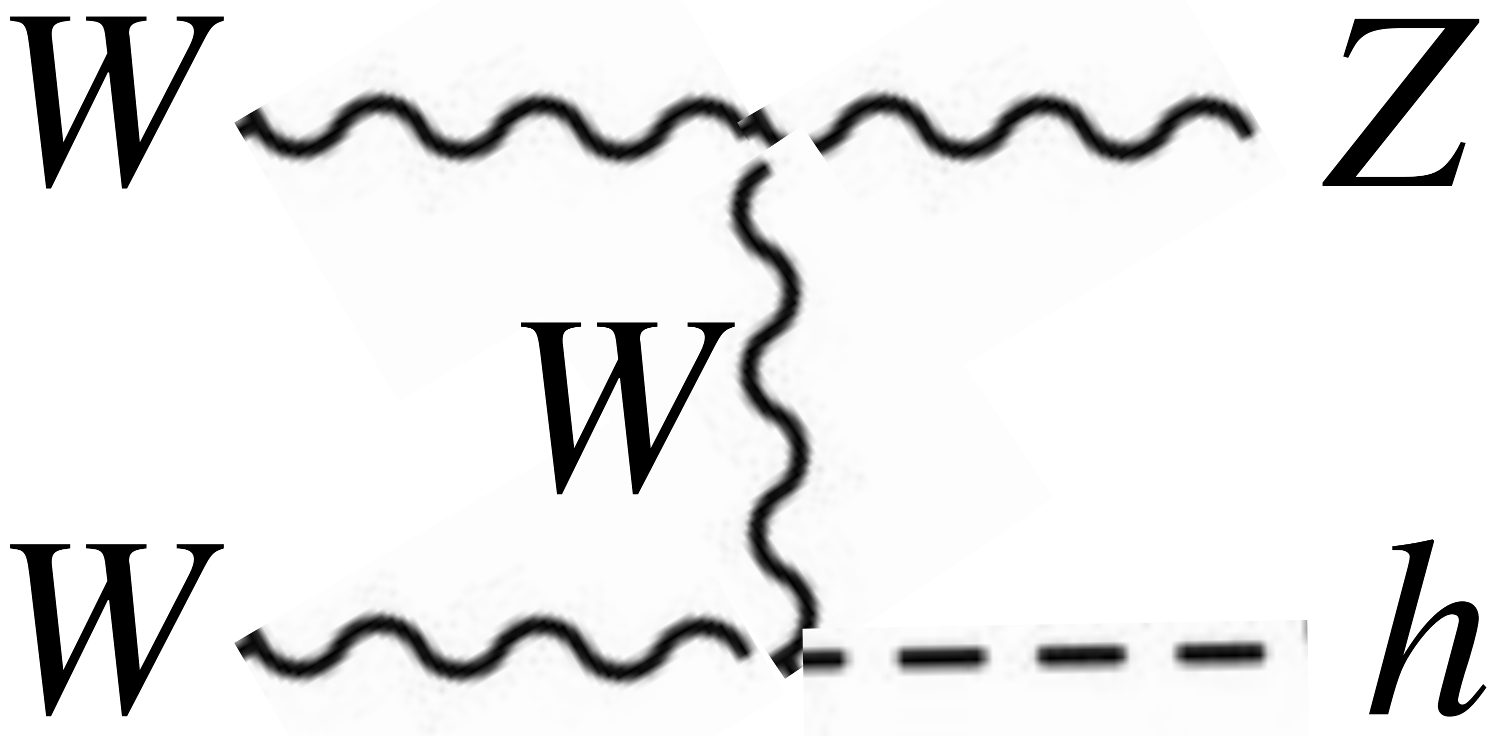
Learn a lot about the Higgs by studying WW scattering.

What about the processes:

$$WW \to Zh$$

$$WZ \to Wh$$





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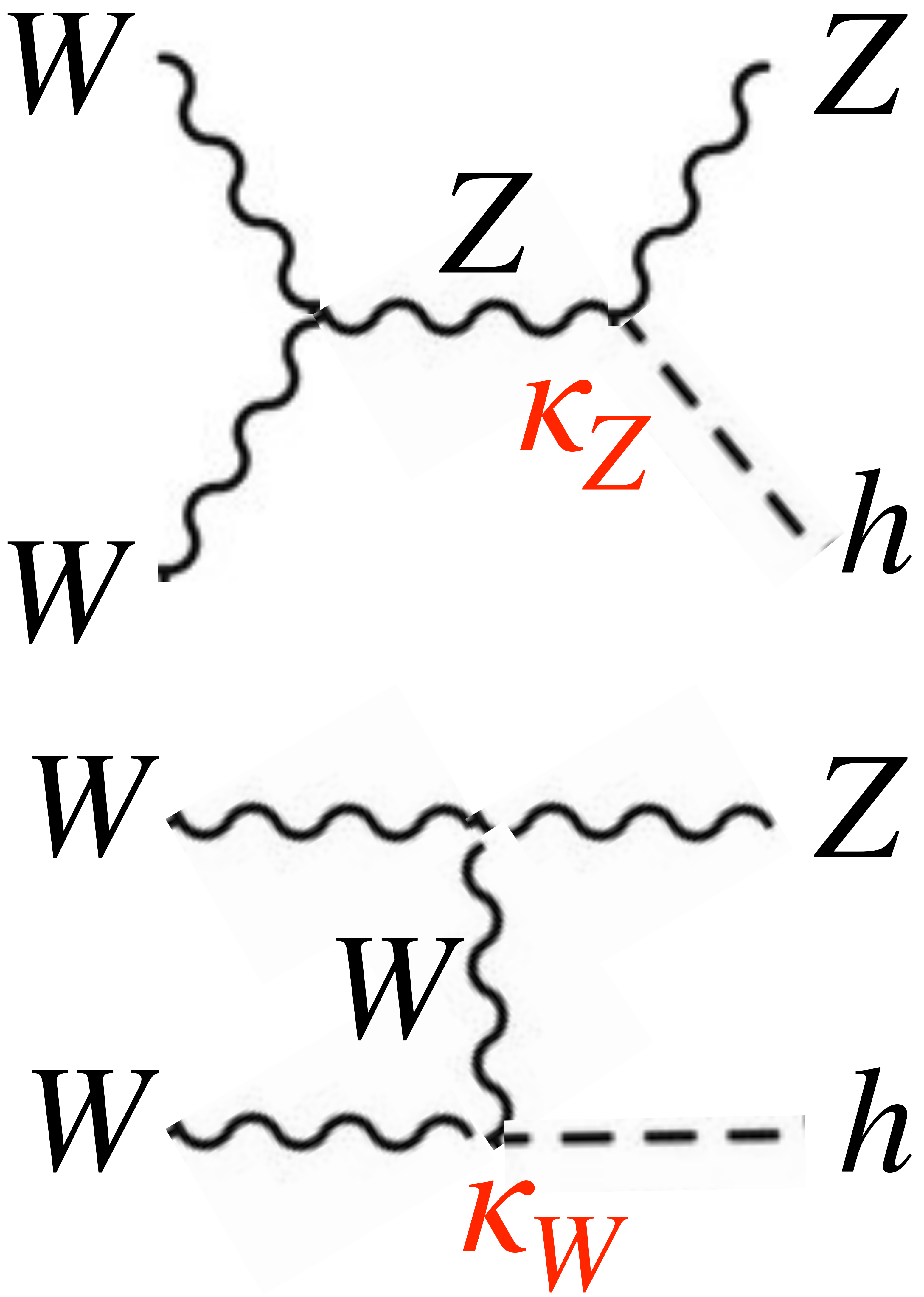
Tree-level interference.

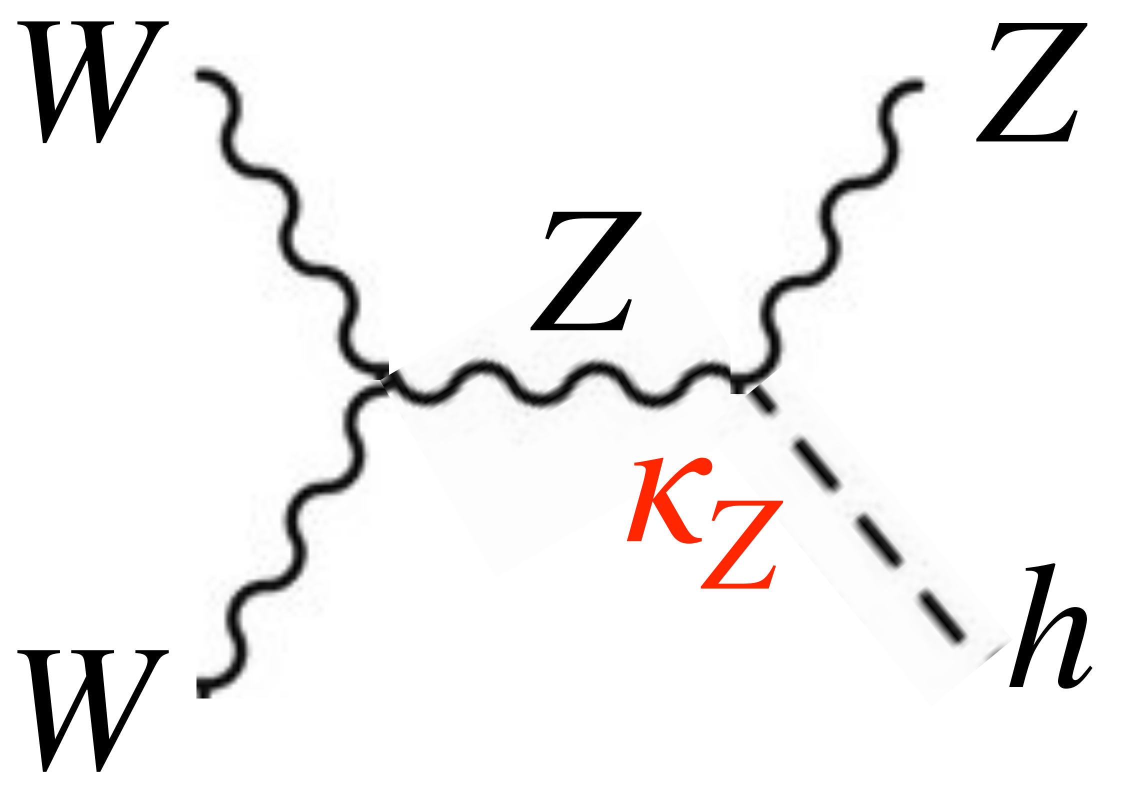


HIGH ENERGY BEHAVIOUR

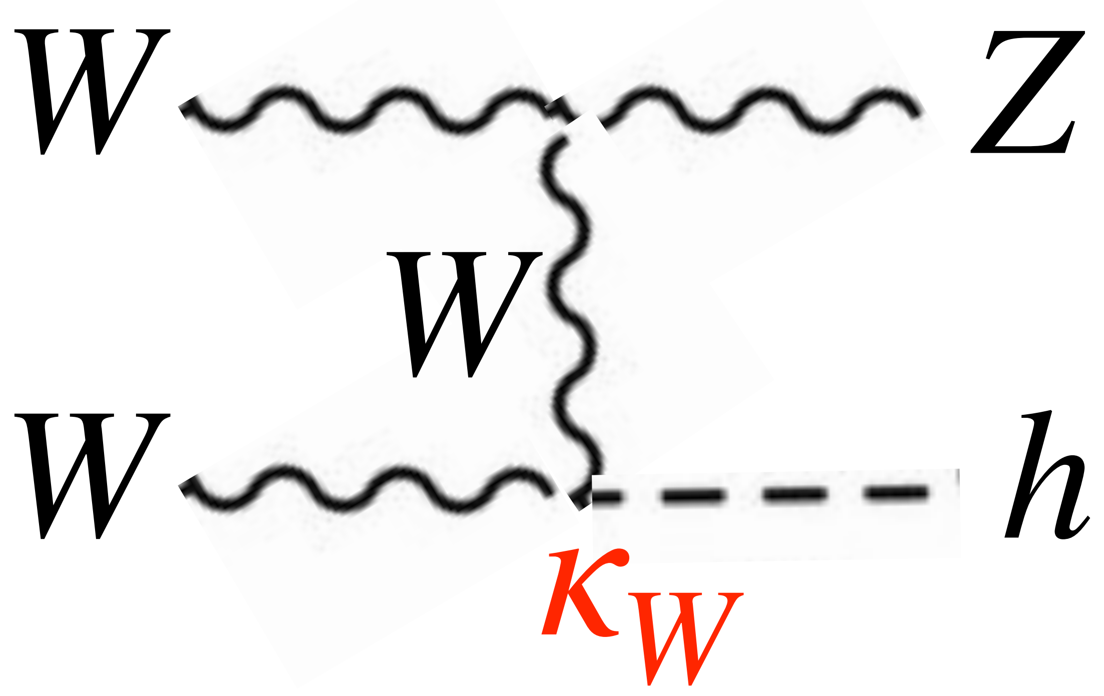
Compute matrix elements in the high energy limit.

Both diagrams grow with s.

$$\mathscr{M}_s(LLL) \approx \kappa_Z \frac{g^2 \cos\theta}{4m_W^2} s$$



$$\mathscr{M}_t(LLL) \approx -\kappa_W \frac{g^2 \cos\theta}{4m_W^2} s$$



DS, Y. Wu, 2006.09347.

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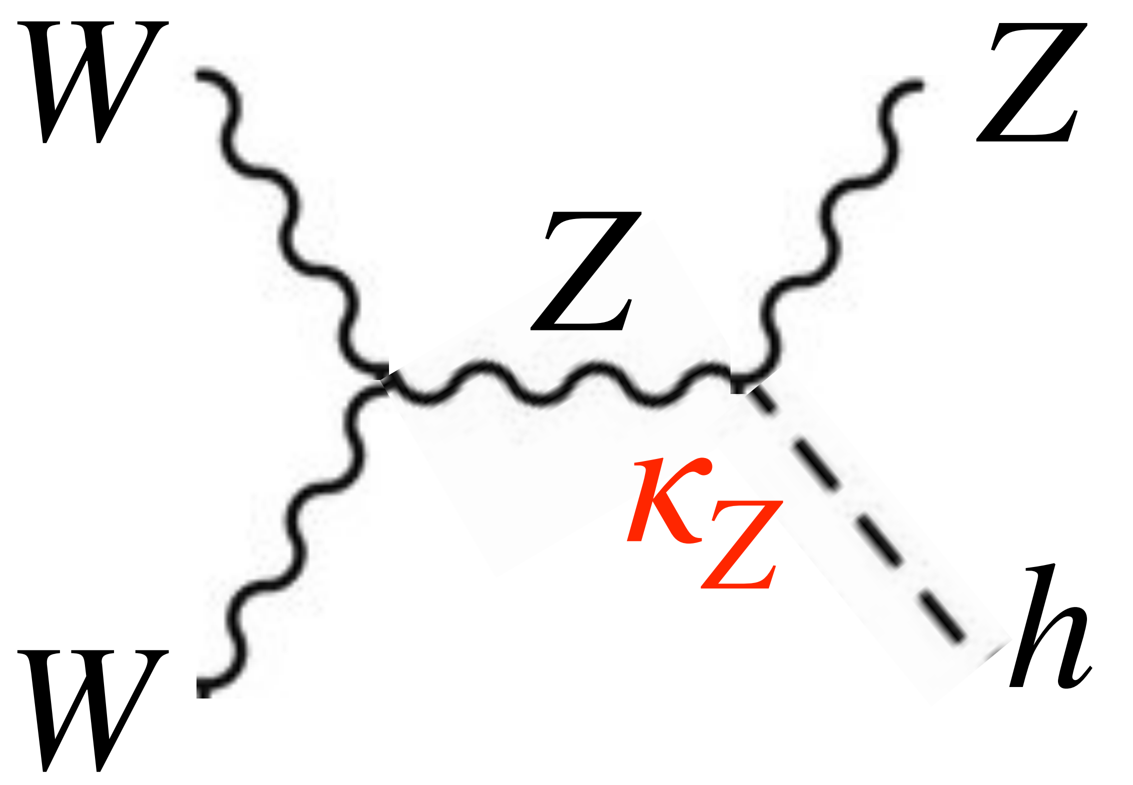
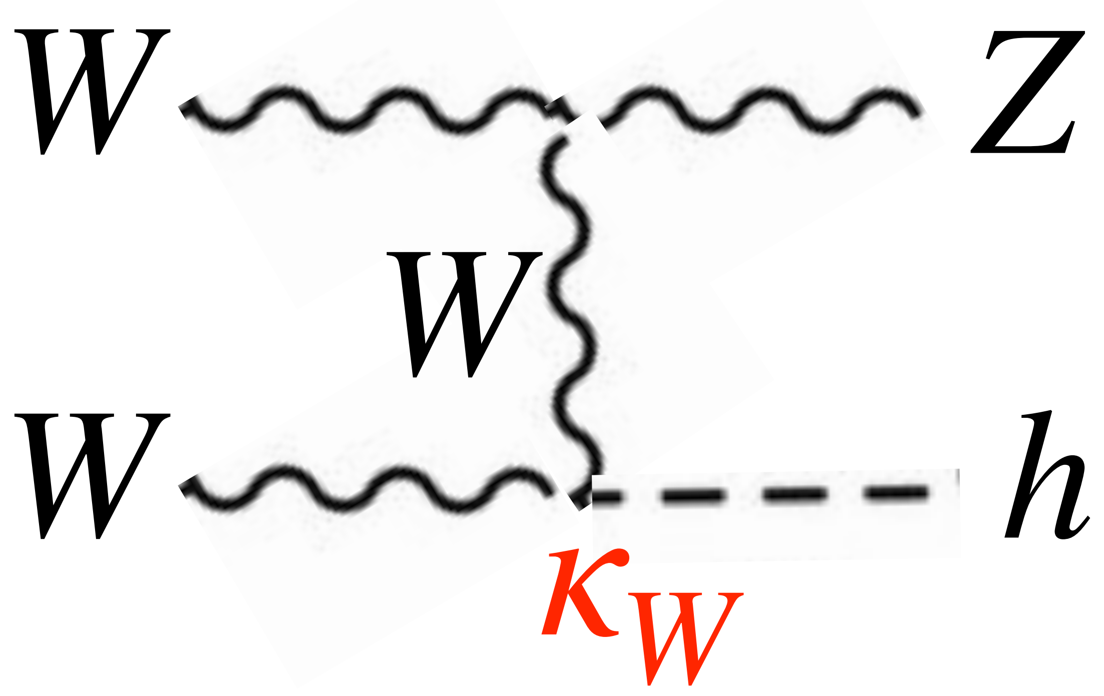


Both diagrams grow with s.

Sum is well behaved only in the Standard Model.

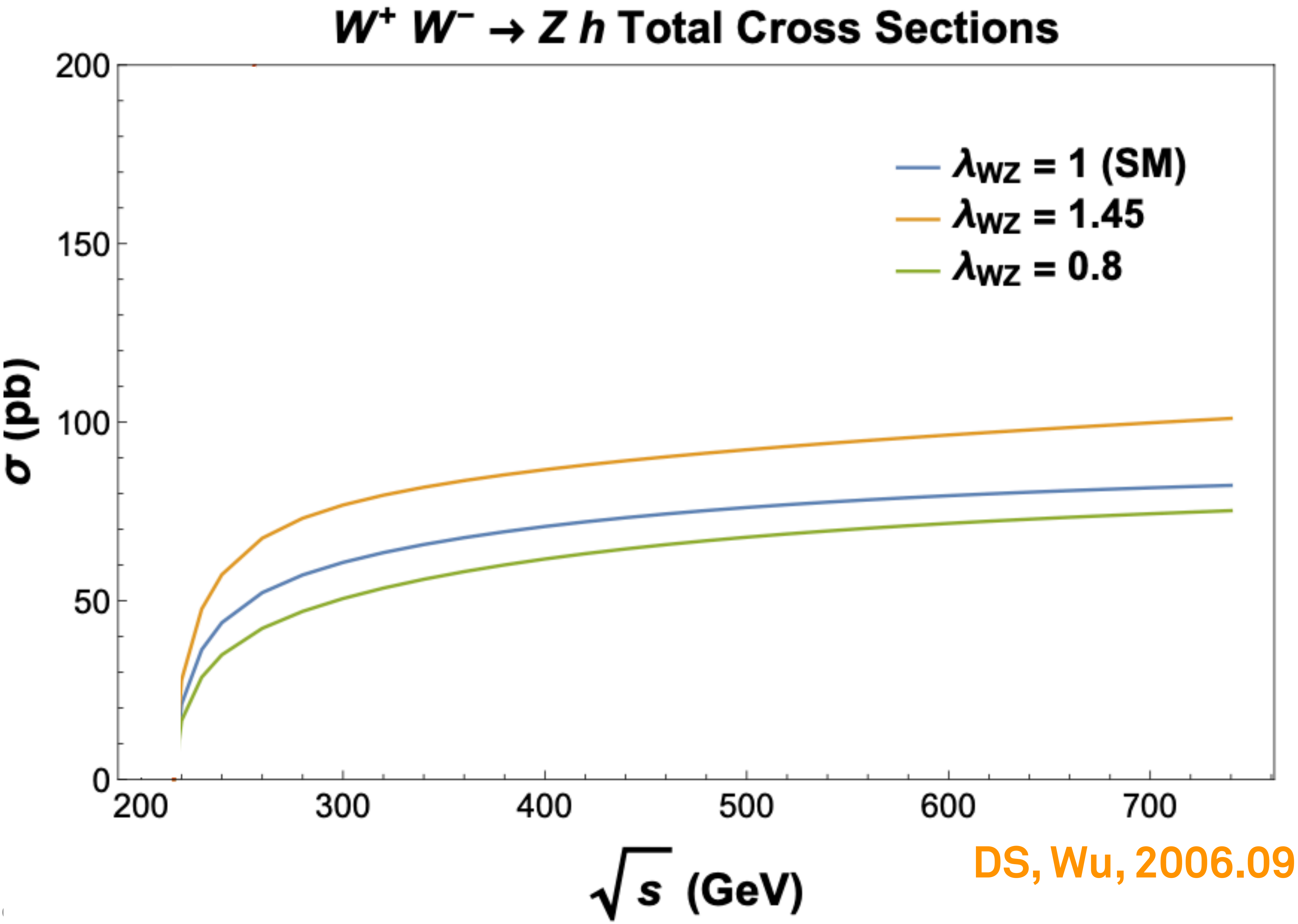
$$\mathcal{M}_t(LLL) \approx -\kappa_W \frac{g^2 \cos\theta}{4m_W^2} s$$



$$\mathcal{M}_{s+t}(LLL) \approx \frac{\kappa_Z g^2 \cos\theta}{4m_W^2} \left(1 - \lambda_{WZ}\right) s + \mathcal{O}(s^0)$$

DS, Y. Wu, 2006.09347.

CROSS SECTION



DS, Wu, 2006.09347.

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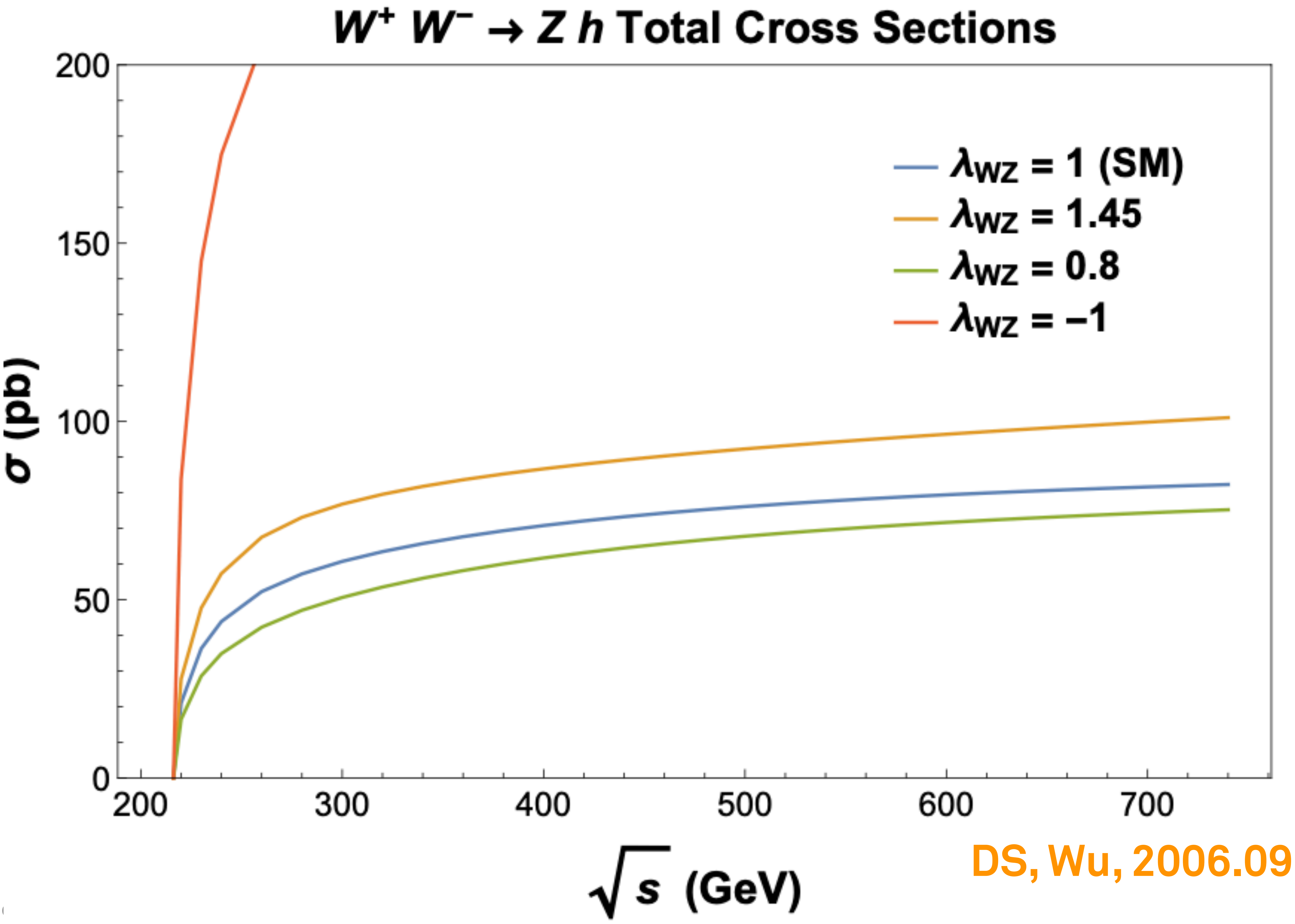


DS, Wu, 2006.09347.

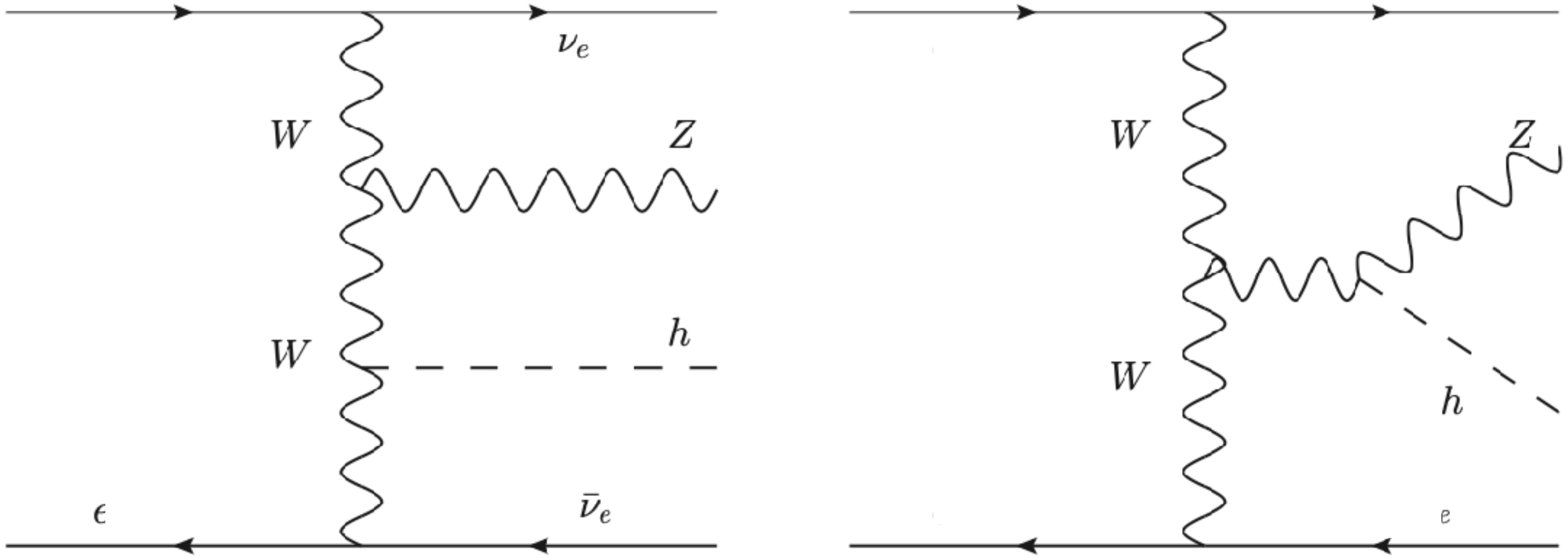
MORE REALISTIC MEASUREMENT

Don’t have a WW collider unfortunately. What do we do?

MORE REALISTIC MEASUREMENT

Don't have a WW collider unfortunately. What do we do?

Radiate vectors from the initial state: Vector Boson Fusion (VBF).



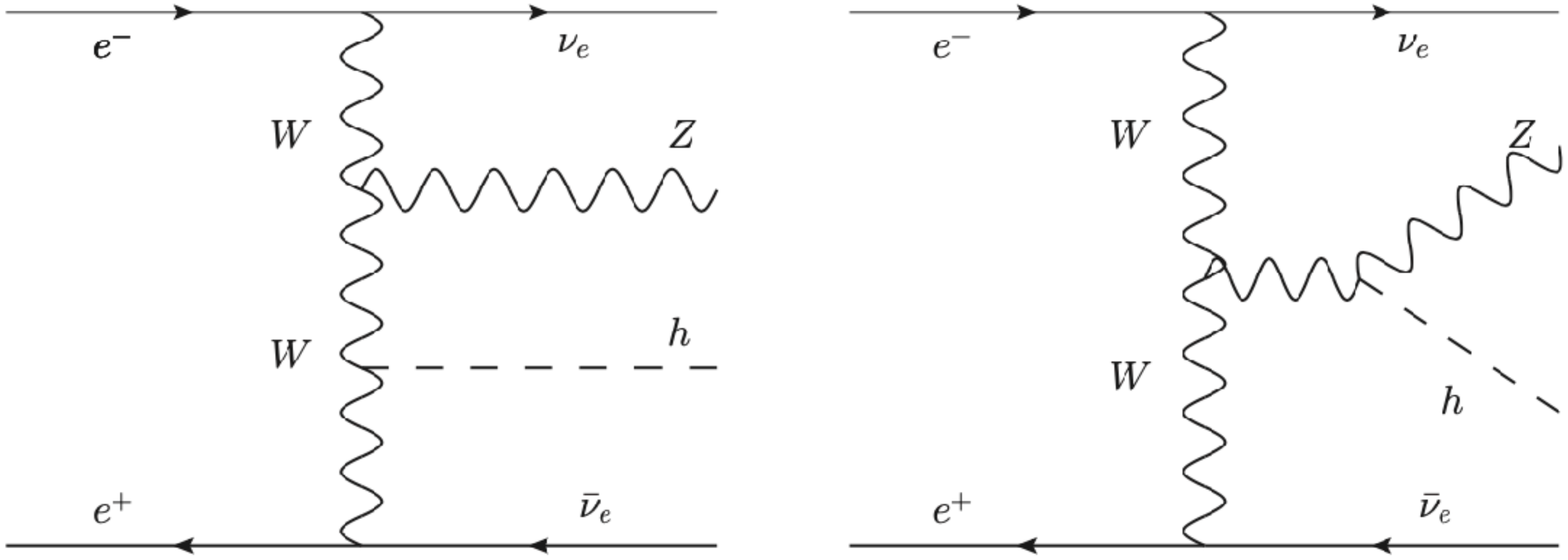
Sub-diagrams are same as had before.

DS, Wu, 2006.09347.

LEPTON COLLIDER

Start with easier case of lepton collider.

The higher the energy the better.

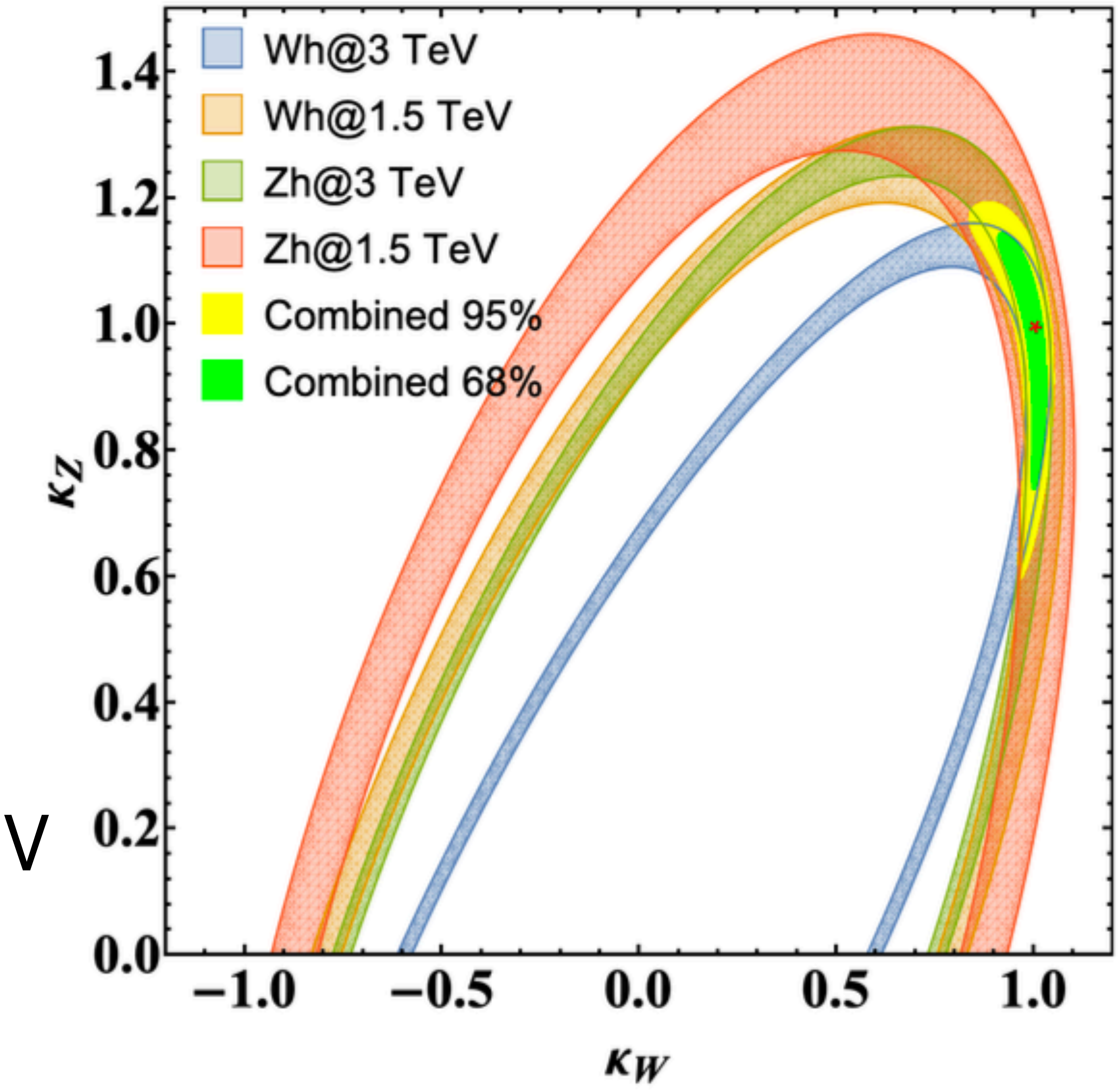


DS, Wu, 2006.09347.

LEPTON COLLIDER RESULTS

Benchmark	$\sqrt{s} = 3.0$ TeV	$\sqrt{s} = 1.5$ TeV
$\kappa_W = \pm 1,\ \kappa_Z = \mp 1$	$3.4\ \text{fb}^{-1}$	$14.1\ \text{fb}^{-1}$
$\kappa_W = 1,\ \kappa_Z = 0$	$29.3\ \text{fb}^{-1}$	$243.3\ \text{fb}^{-1}$
$\kappa_W = 0,\ \kappa_Z = 1$	$62.1\ \text{fb}^{-1}$	$1772.4\ \text{fb}^{-1}$

$$\mathscr{L} = 2000\ \text{fb}^{-1} @ \sqrt{s} = 1.5\ \text{TeV}$$
$$\mathscr{L} = 4000\ \text{fb}^{-1} @ \sqrt{s} = 3\ \text{TeV}$$



DS, Wu, 2006.09347.

HL-LHC ATTEMPT

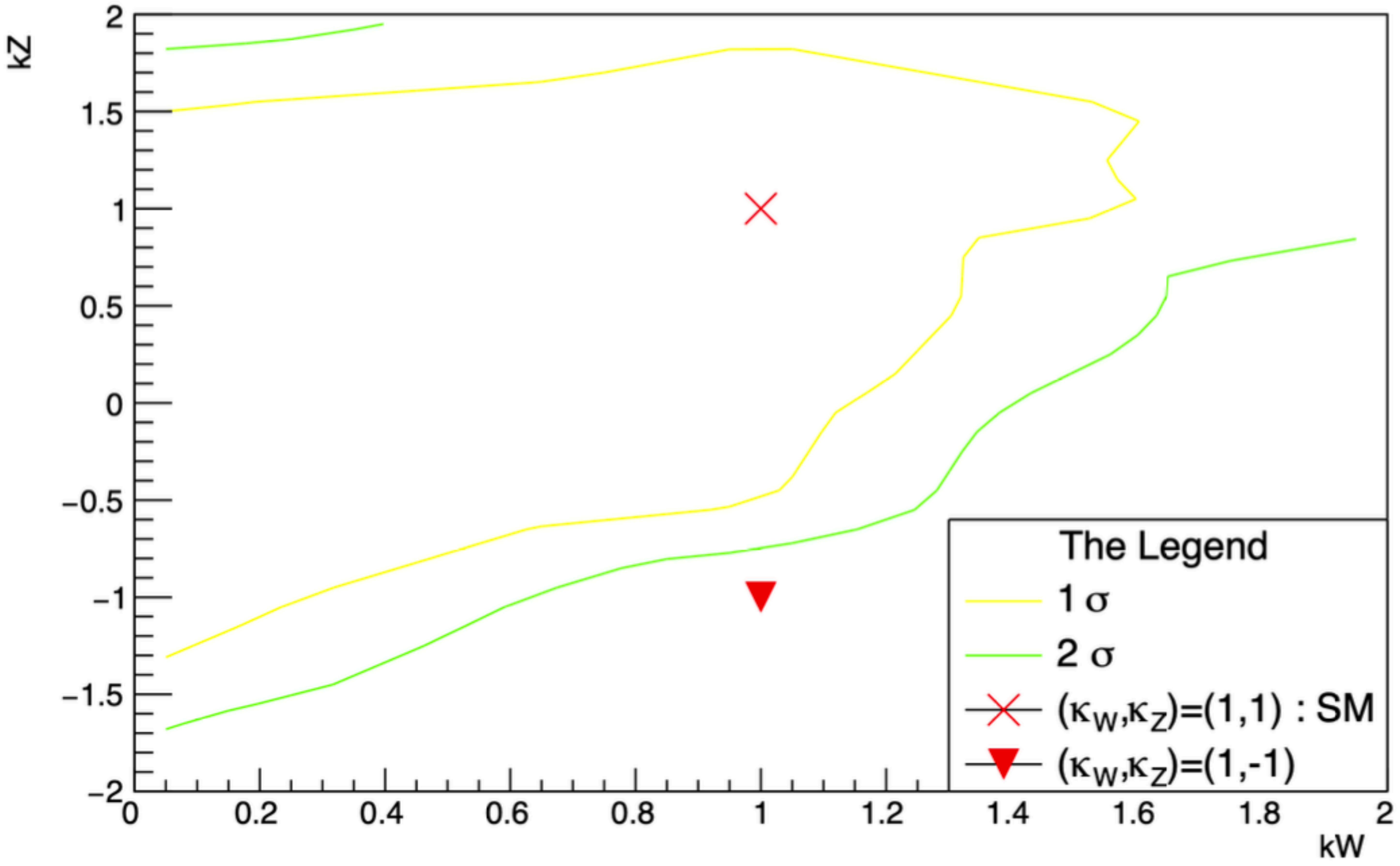
$$pp \to Zhjj$$

$$Z \to \ell^+\ell^-$$

$$h \to b\bar{b}$$

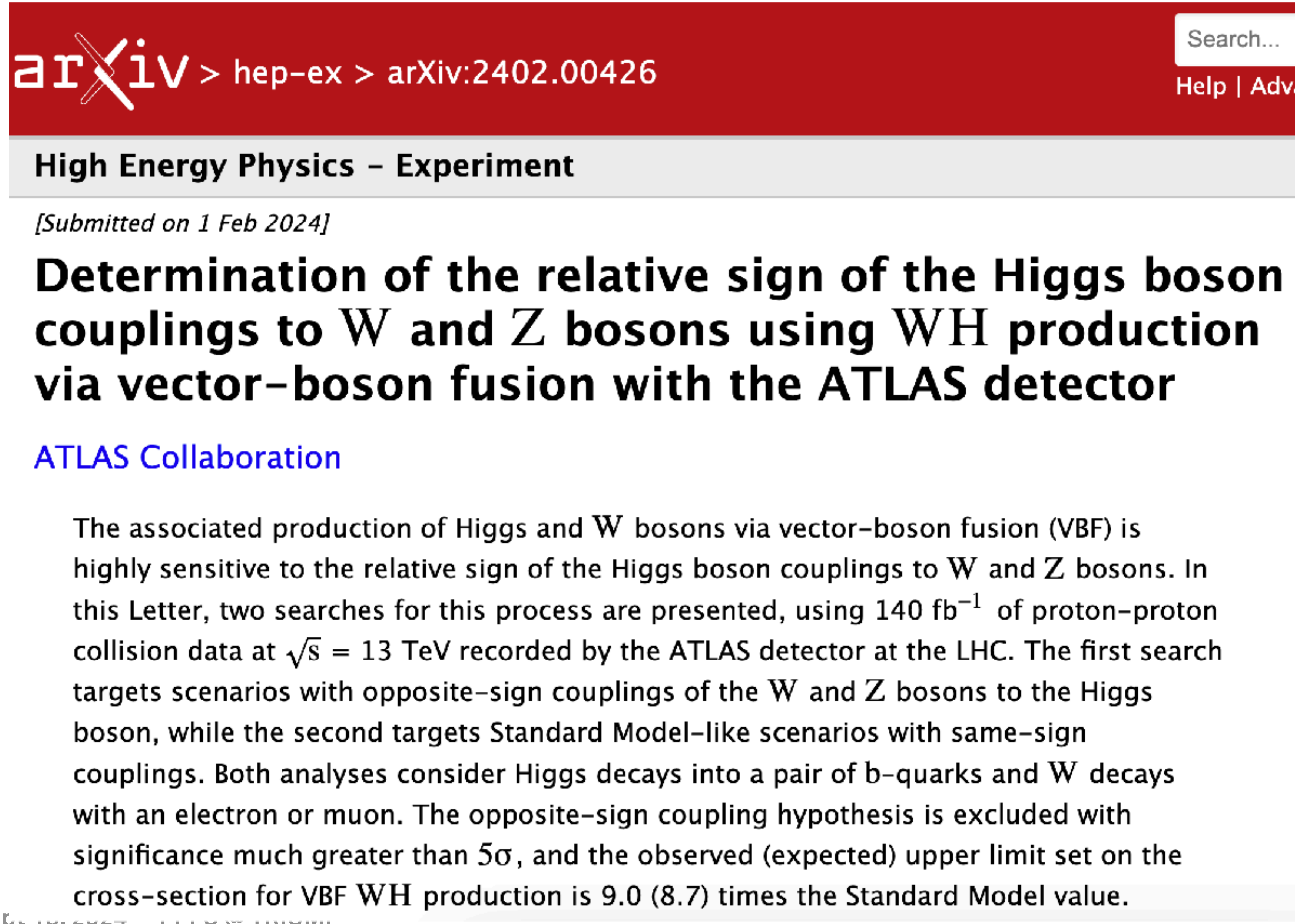
$$\mathscr{L} = 3000\ \text{fb}^{-1}$$

Can exclude wrong-sign scenario!



Paranjape, DS, Wu, 2203.05729.

ATLAS RESULT



High Energy Physics – Experiment

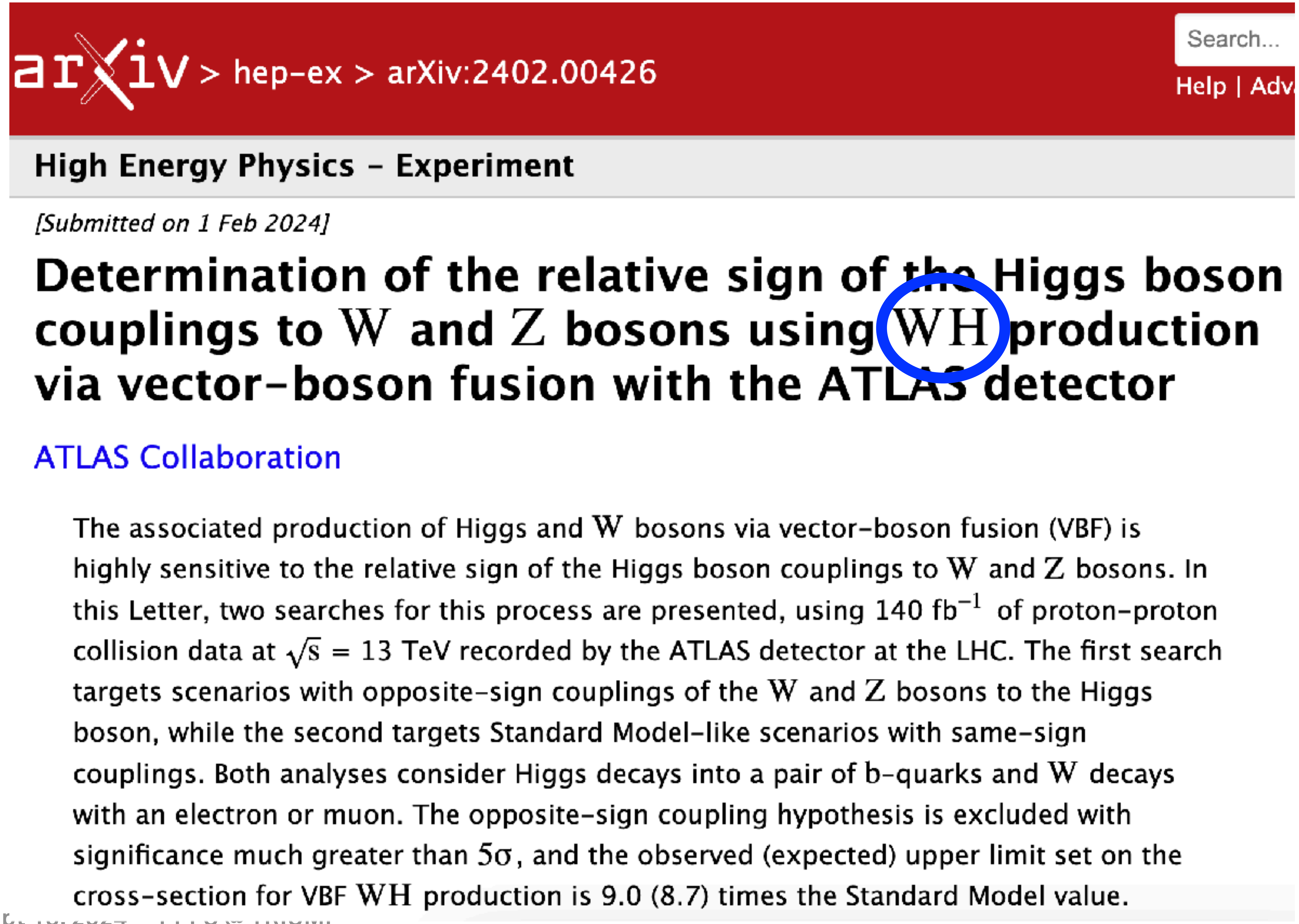
[Submitted on 1 Feb 2024]

Determination of the relative sign of the Higgs boson couplings to W and Z bosons using WH production via vector-boson fusion with the ATLAS detector

ATLAS Collaboration

The associated production of Higgs and W bosons via vector-boson fusion (VBF) is highly sensitive to the relative sign of the Higgs boson couplings to W and Z bosons. In this Letter, two searches for this process are presented, using 140 fb^{-1} of proton-proton collision data at $\sqrt{s} = 13$ TeV recorded by the ATLAS detector at the LHC. The first search targets scenarios with opposite-sign couplings of the W and Z bosons to the Higgs boson, while the second targets Standard Model-like scenarios with same-sign couplings. Both analyses consider Higgs decays into a pair of b-quarks and W decays with an electron or muon. The opposite-sign coupling hypothesis is excluded with significance much greater than 5σ, and the observed (expected) upper limit set on the cross-section for VBF WH production is 9.0 (8.7) times the Standard Model value.

ATLAS RESULT



arXiv > hep-ex > arXiv:2402.00426

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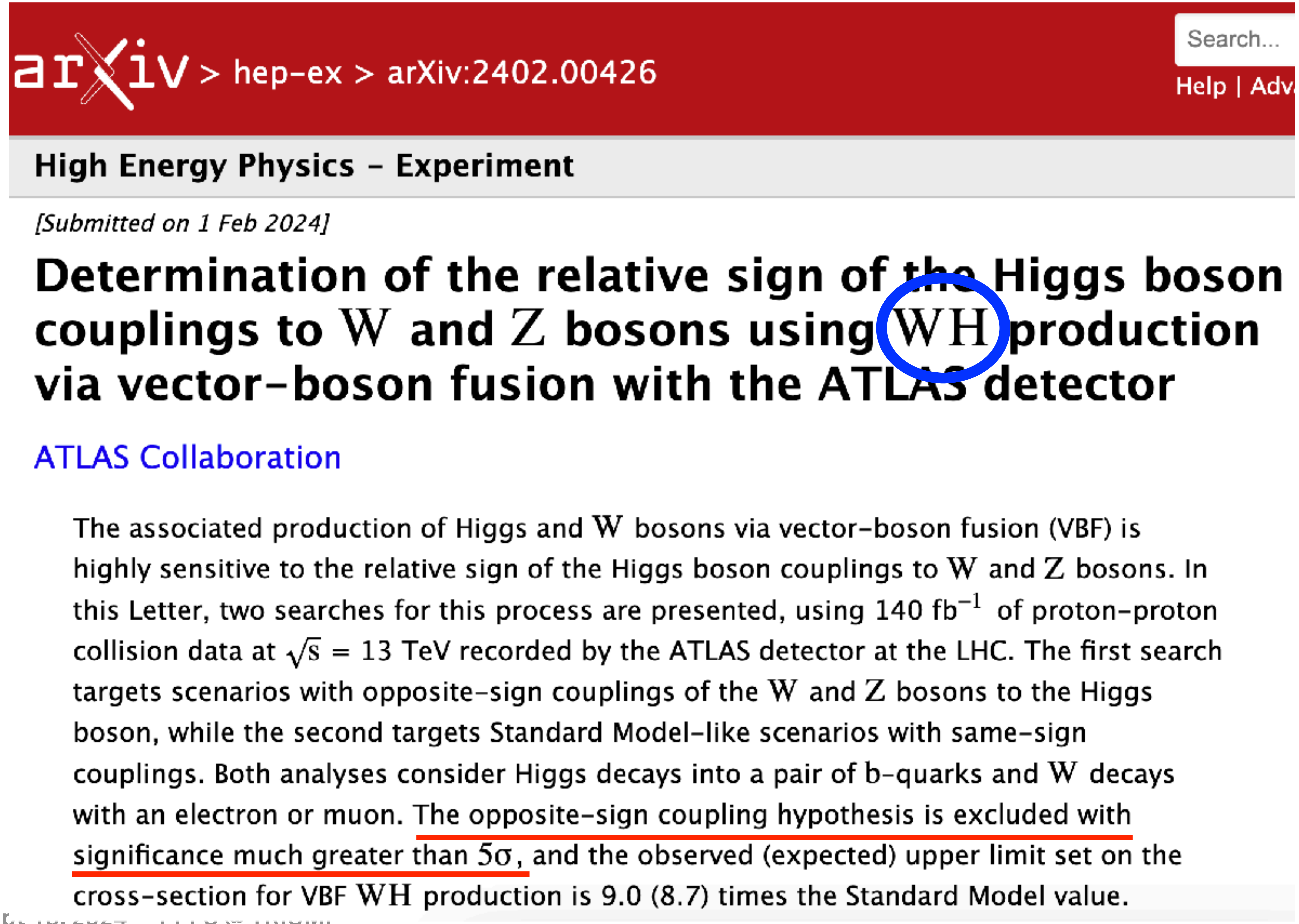

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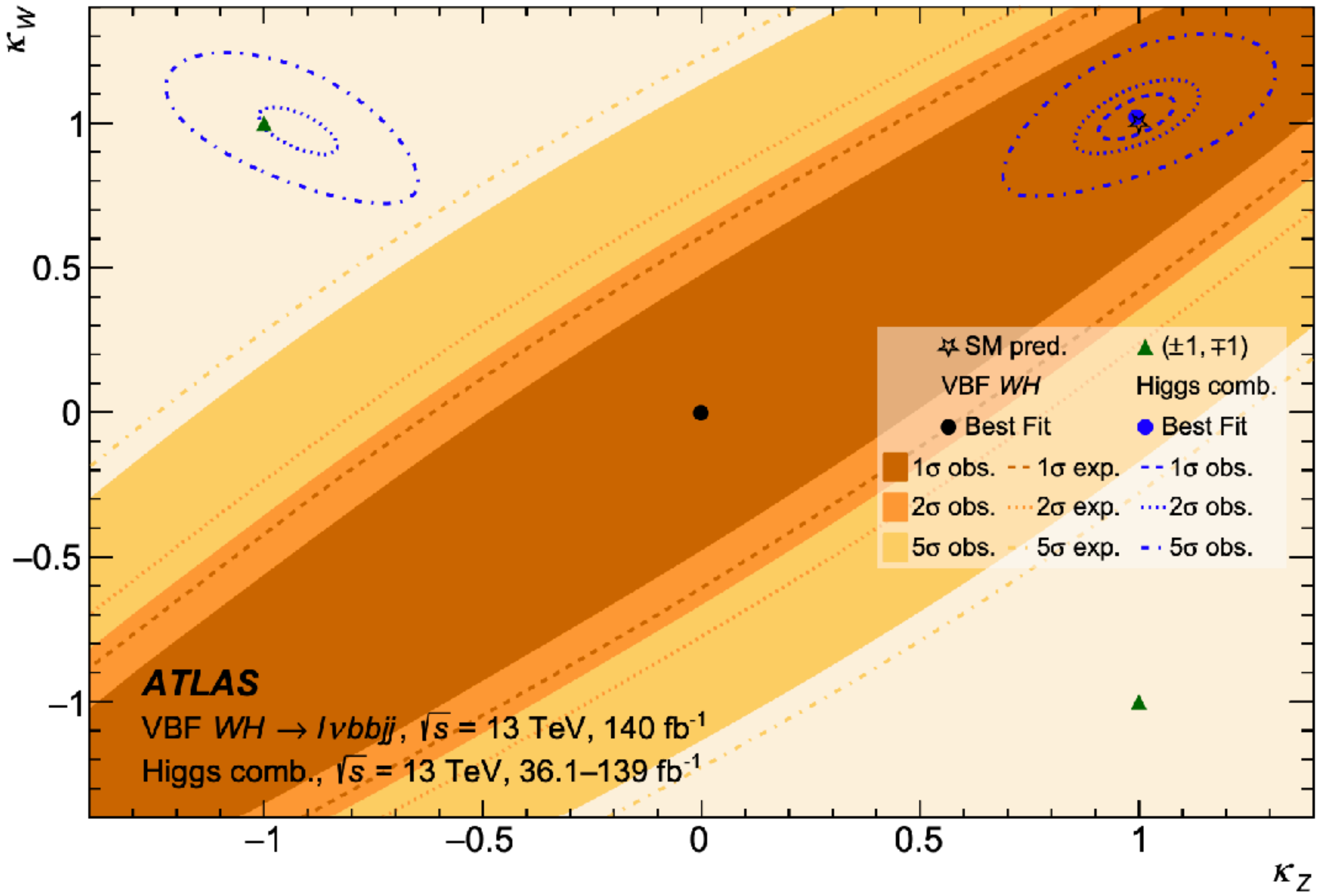
ATLAS RESULT

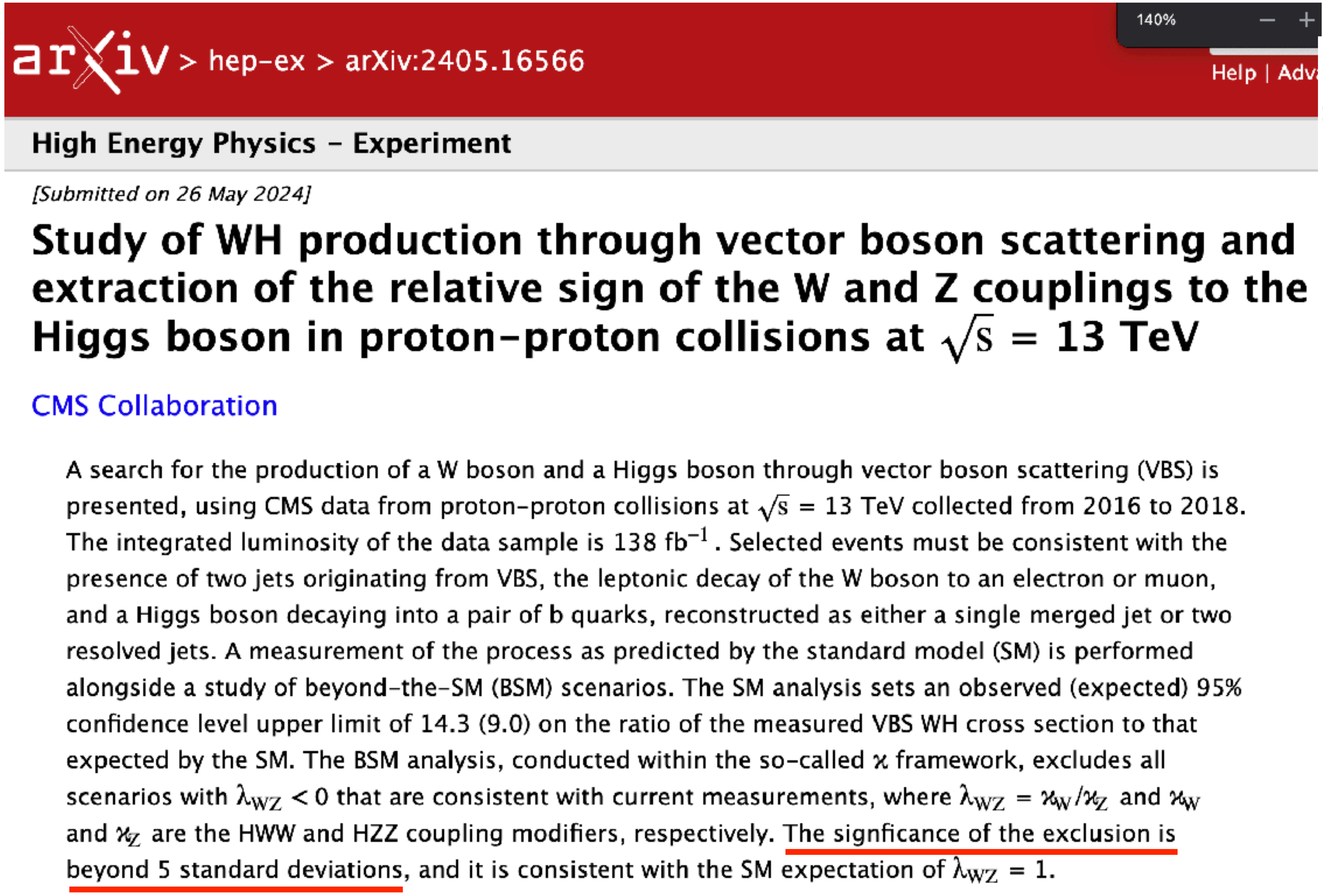
Breaks degeneracy of $\lambda_{WZ} = \pm 1$.

Use $W \to \ell\nu$ and $h \to b\bar{b}$.

Did measurement with $140\ \mathrm{fb}^{-1}$.



CMS RESULT



arXiv > hep-ex > arXiv:2405.16566

140% – +

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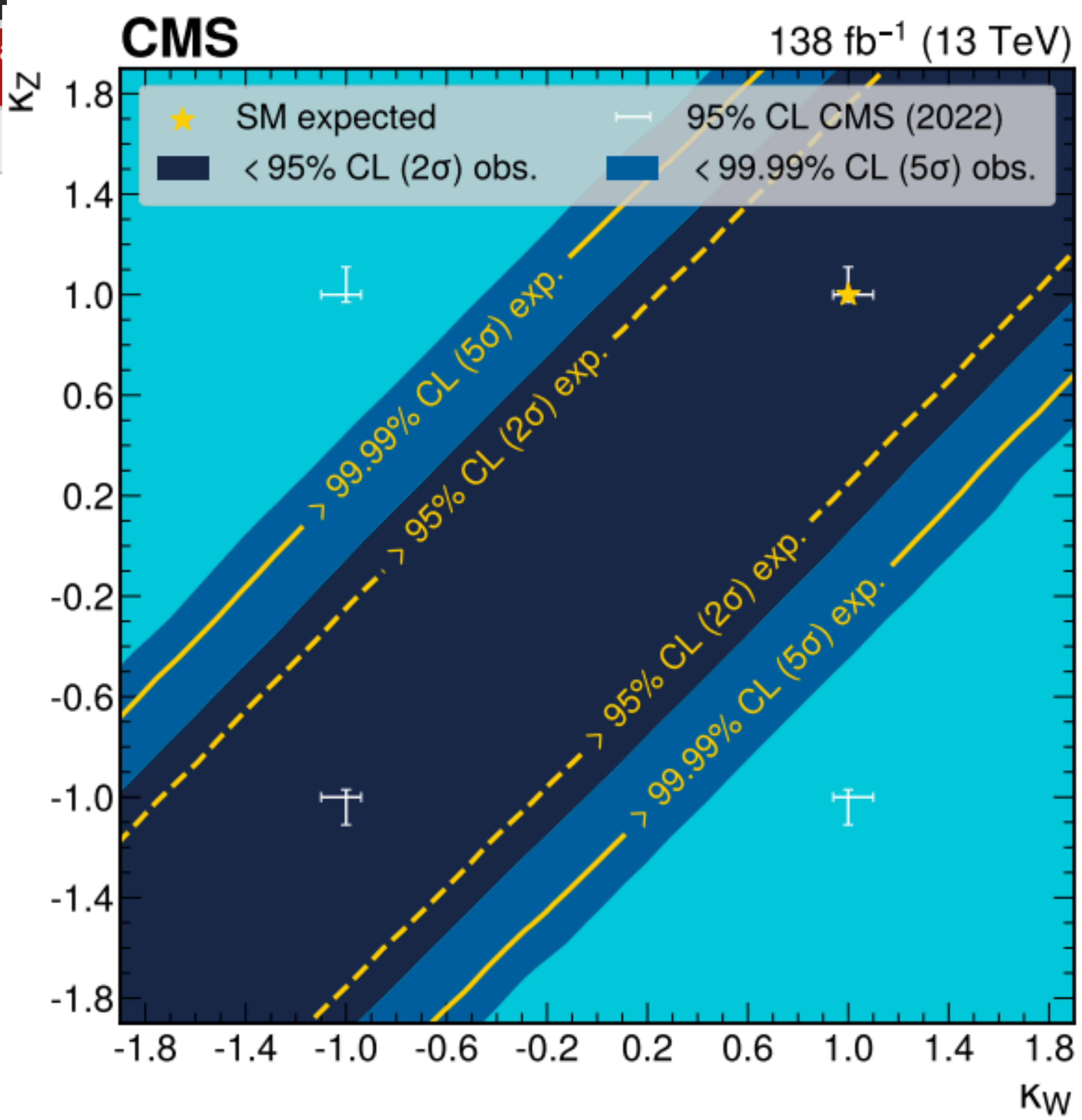
High Energy Physics – Experiment

[Submitted on 26 May 2024]

Study of WH production through vector boson scattering and extraction of the relative sign of the W and Z couplings to the Higgs boson in proton-proton collisions at $\sqrt{s}$ = 13 TeV

CMS Collaboration

A search for the production of a W boson and a Higgs boson through vector boson scattering (VBS) is presented, using CMS data from proton-proton collisions at $\sqrt{s}$ = 13 TeV collected from 2016 to 2018. The integrated luminosity of the data sample is 138 fb^{-1} . Selected events must be consistent with the presence of two jets originating from VBS, the leptonic decay of the W boson to an electron or muon, and a Higgs boson decaying into a pair of b quarks, reconstructed as either a single merged jet or two resolved jets. A measurement of the process as predicted by the standard model (SM) is performed alongside a study of beyond-the-SM (BSM) scenarios. The SM analysis sets an observed (expected) 95% confidence level upper limit of 14.3 (9.0) on the ratio of the measured VBS WH cross section to that expected by the SM. The BSM analysis, conducted within the so-called $\varkappa$ framework, excludes all scenarios with $\lambda_{WZ} < 0$ that are consistent with current measurements, where $\lambda_{WZ} = \varkappa_W/\varkappa_Z$ and $\varkappa_W$ and $\varkappa_Z$ are the HWW and HZZ coupling modifiers, respectively. The signficance of the exclusion is beyond 5 standard deviations, and it is consistent with the SM expectation of λ_{WZ} = 1.



SUMMARY

Higgs to 4 lepton is a rare process, but has rich kinematic distributions.

Can measure phase of Higgs coupling to top, and relative sign of W/Z couplings at HL-HLC (and better with 100 TeV!).

VBF-Wh production is very sensitive to the wrong sign scenario because of tree-level interference. There are now 2 measurements.

More in Carlos' talk this afternoon.

THANK YOU

MATRIX ELEMENT METHOD

For a given $h \to 4\ell$ event, we can compute probability of that event given underlying theory.

$$P(\vec{\phi}\,|a_i) = \frac{|\mathcal{M}(\vec{\phi})|^2}{\int d\vec{\phi}\,|\mathcal{M}(\vec{\phi})|^2}$$

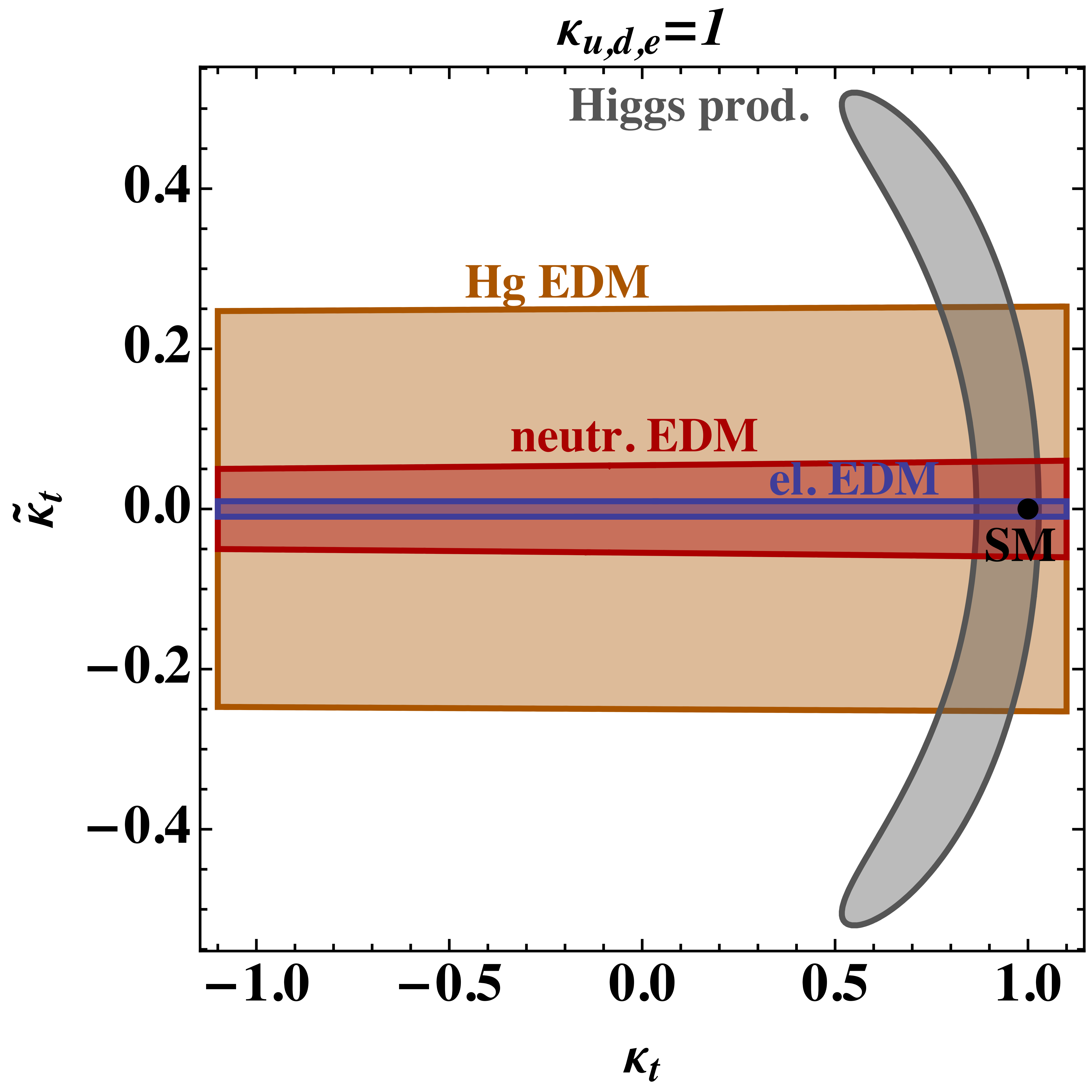
Phase space point

Underlying model

For N events, can compute likelihood for different theories.

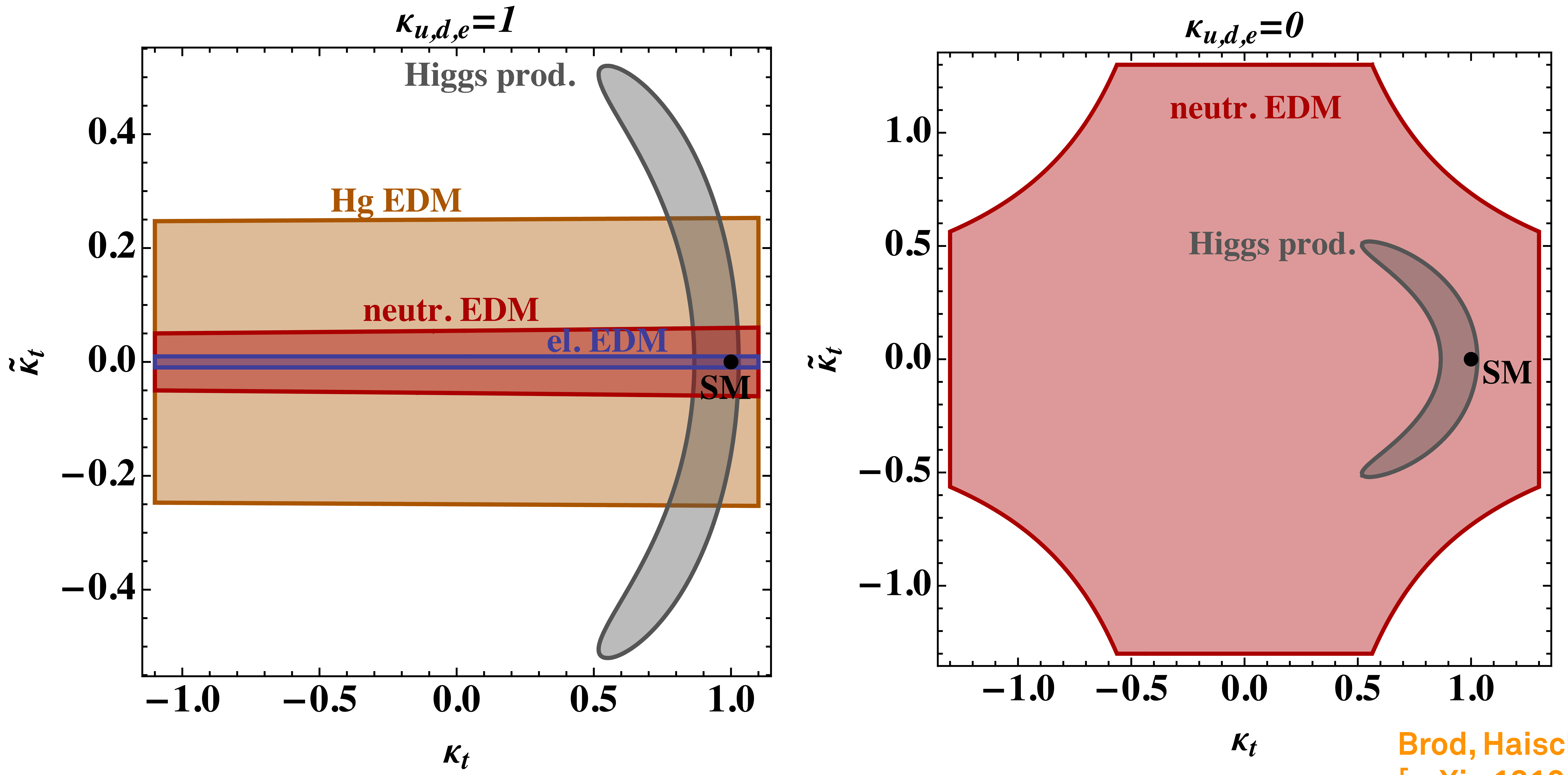
$$\mathcal{L}(a_i) = \prod_{j=1}^{N} P(\vec{\phi}_j\,|a_i)$$

EDM BOUNDS



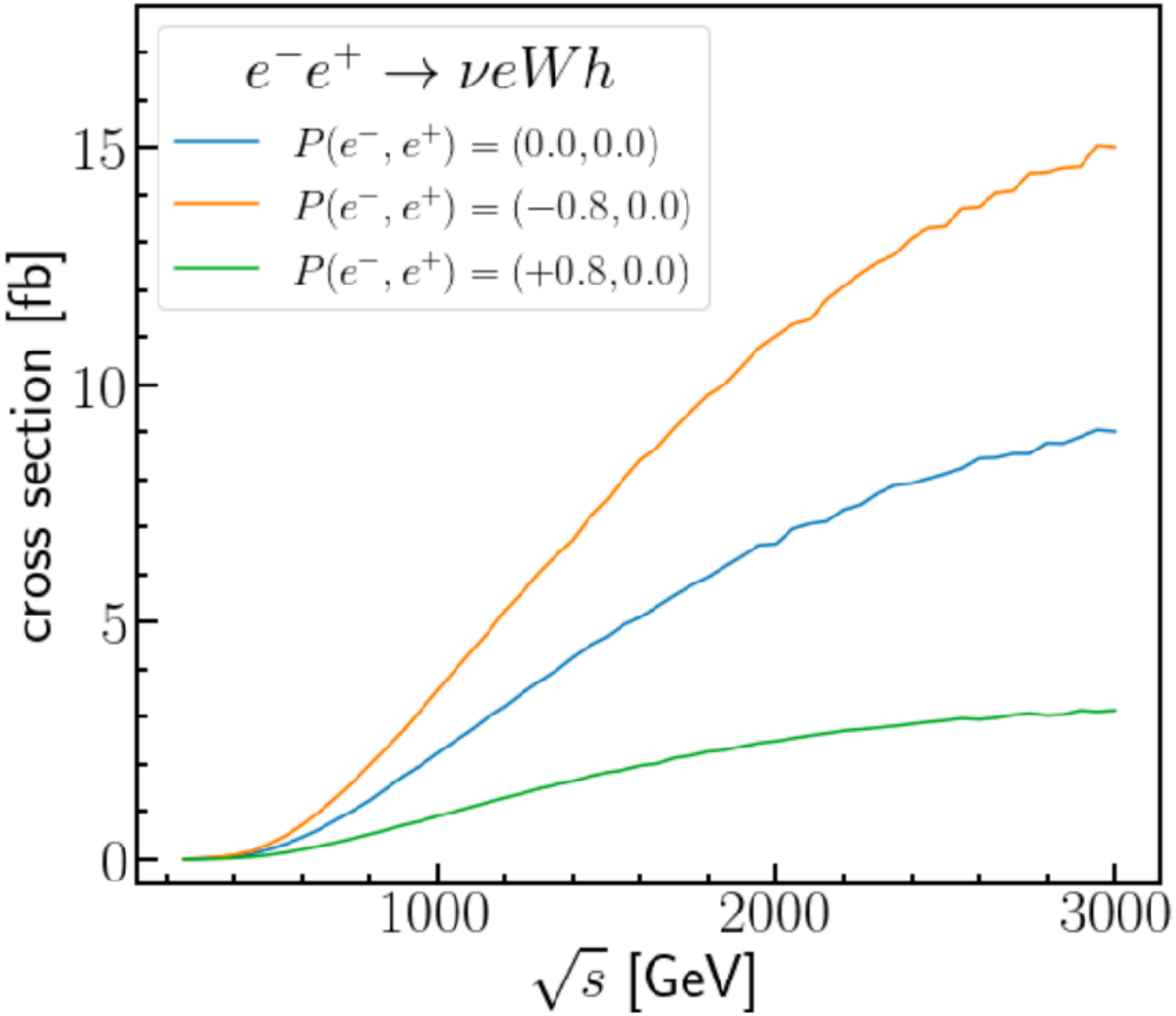
Brod, Haisch, Zupan, [arXiv:1310.1385].

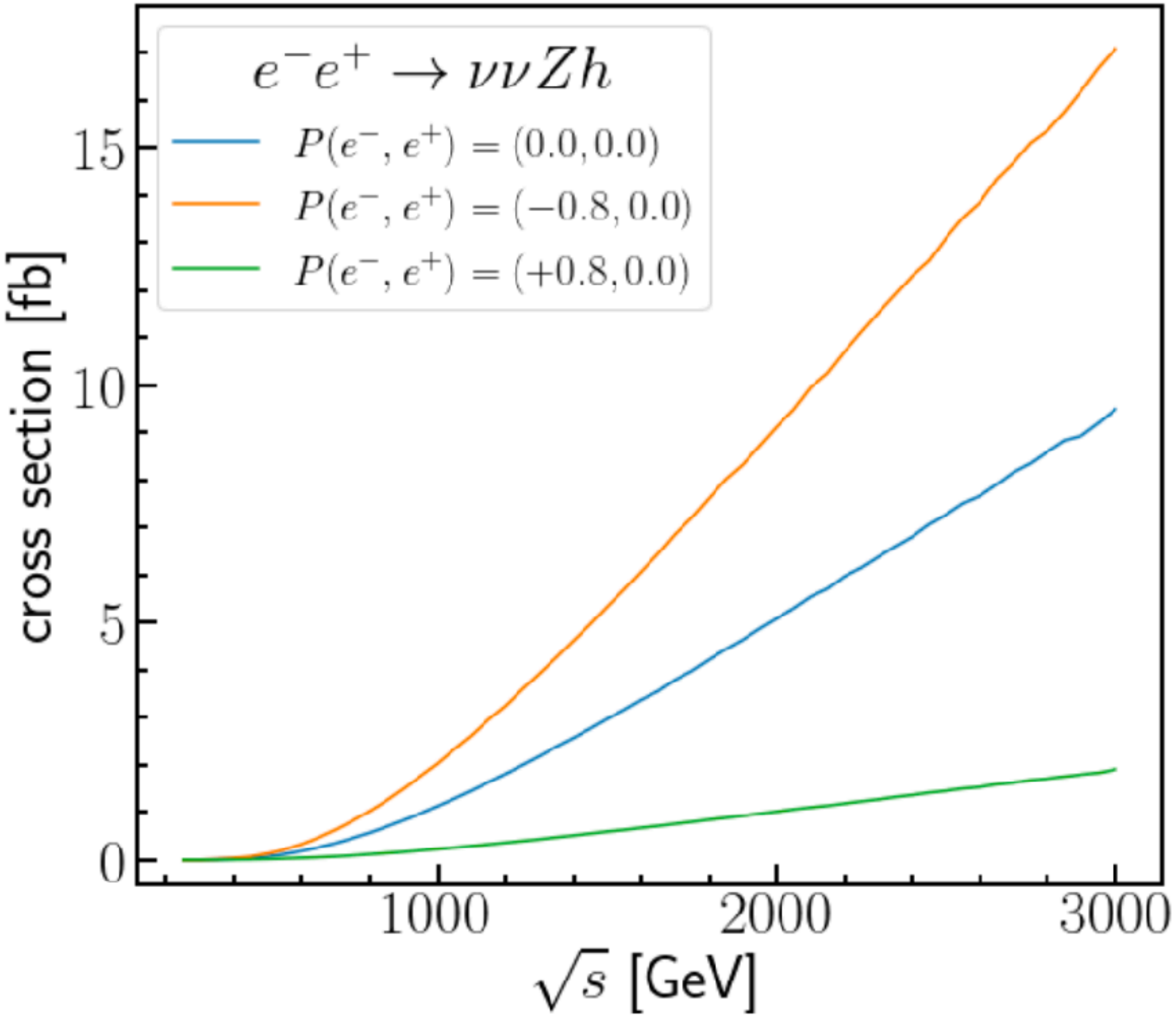
EDM BOUNDS



Brod, Haisch, Zupan, [arXiv:1310.1385].

STANDARD MODEL RATE





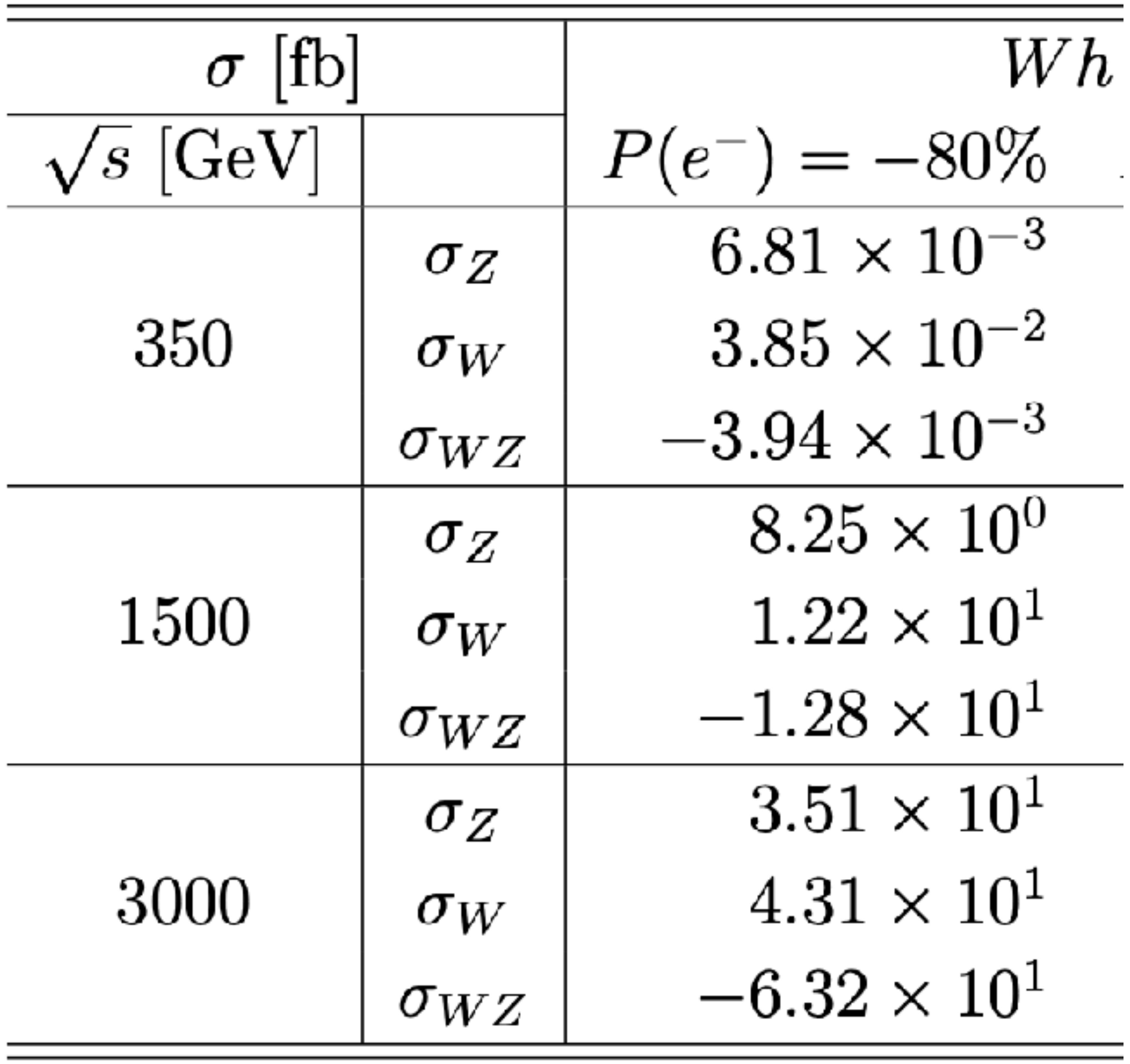
DS, Wu, 2006.09347.

INTERFERENCE

There is large destructive interference in the SM.

Get enormous cross section if $\lambda_{WZ} \approx -1$.

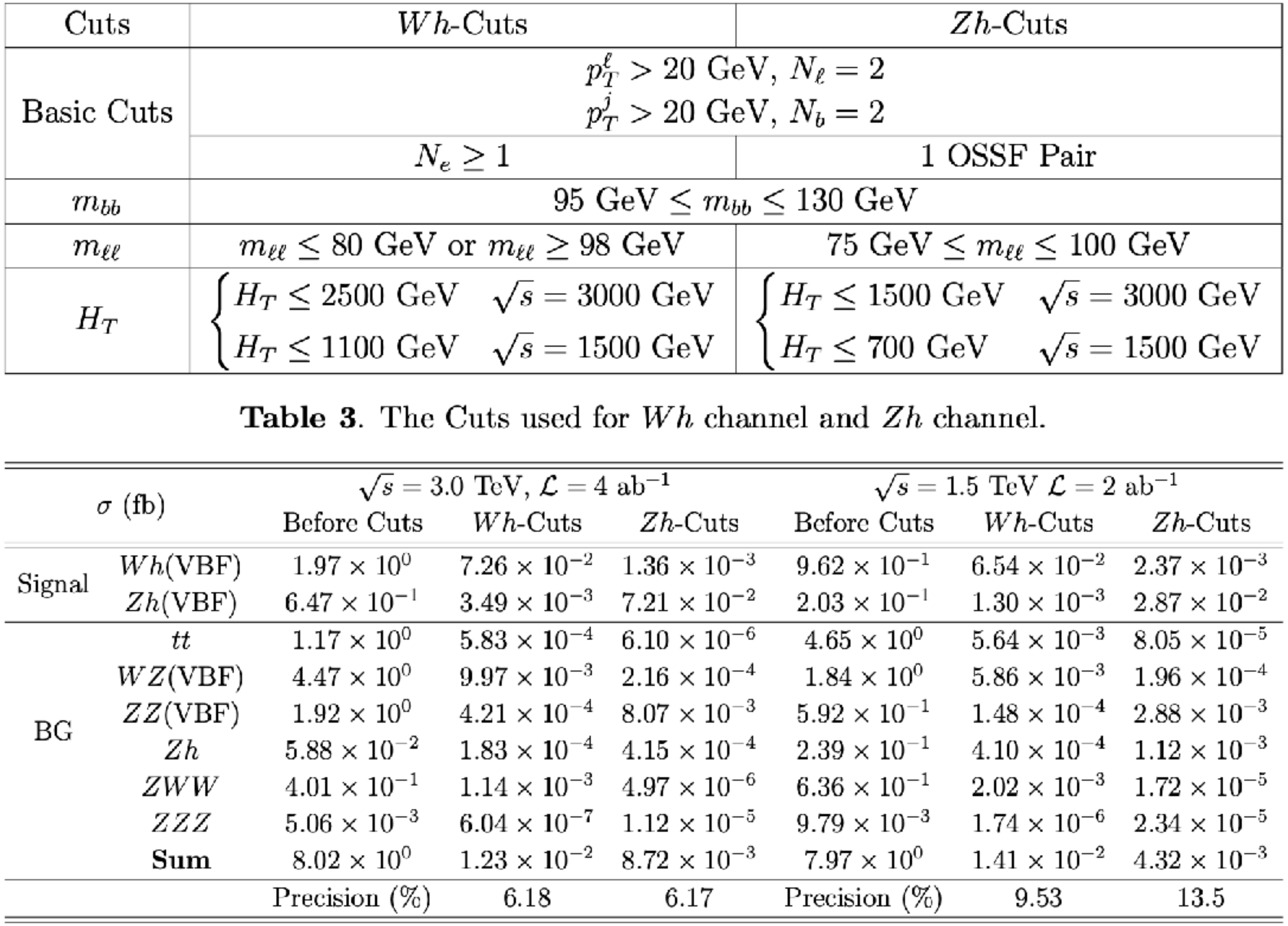
$$\sigma = \kappa_W^2 \sigma_W + \kappa_Z^2 \sigma_Z + \kappa_W \kappa_Z \sigma_{WZ}$$



σ [fb]		Wh
$\sqrt{s}$ [GeV]		$P(e^-) = -80\%$
350	σ_Z	6.81×10^{-3}
	σ_W	3.85×10^{-2}
	σ_{WZ}	-3.94×10^{-3}
1500	σ_Z	8.25×10^{0}
	σ_W	1.22×10^{1}
	σ_{WZ}	-1.28×10^{1}
3000	σ_Z	3.51×10^{1}
	σ_W	4.31×10^{1}
	σ_{WZ}	-6.32×10^{1}

DS, Wu, 2006.09347.

LEPTON COLLIDER RESULTS



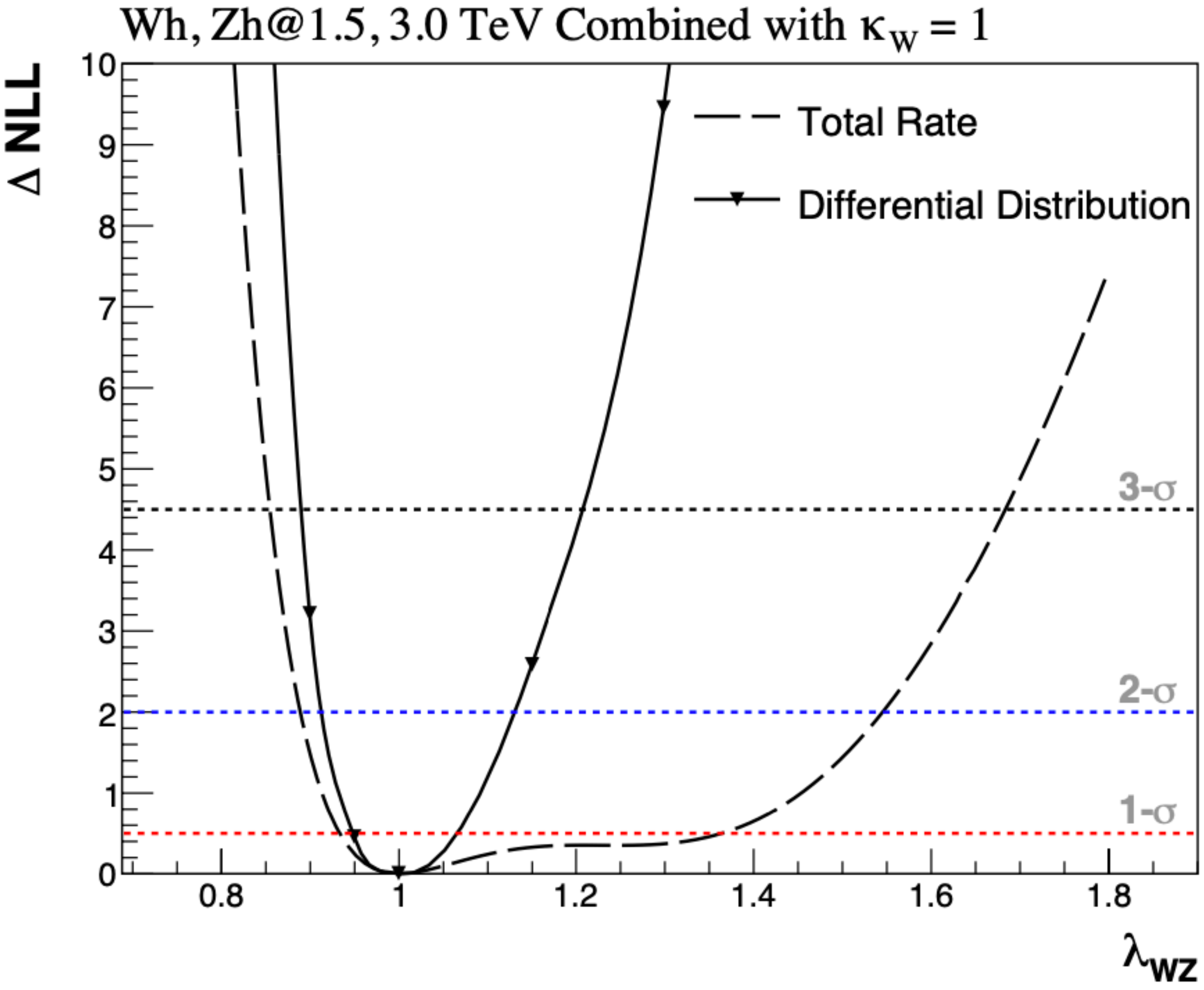
Cuts	Wh-Cuts	Zh-Cuts
Basic Cuts	$p_T^\ell > 20$ GeV, $N_\ell = 2$ $p_T^j > 20$ GeV, $N_b = 2$	
	$N_e \geq 1$	1 OSSF Pair
m_{bb}	$95 \text{ GeV} \leq m_{bb} \leq 130 \text{ GeV}$	
$m_{\ell\ell}$	$m_{\ell\ell} \leq 80$ GeV or $m_{\ell\ell} \geq 98$ GeV	$75 \text{ GeV} \leq m_{\ell\ell} \leq 100 \text{ GeV}$
H_T	$\begin{cases} H_T \leq 2500 \text{ GeV} & \sqrt{s} = 3000 \text{ GeV} \\ H_T \leq 1100 \text{ GeV} & \sqrt{s} = 1500 \text{ GeV} \end{cases}$	$\begin{cases} H_T \leq 1500 \text{ GeV} & \sqrt{s} = 3000 \text{ GeV} \\ H_T \leq 700 \text{ GeV} & \sqrt{s} = 1500 \text{ GeV} \end{cases}$

Table 3. The Cuts used for Wh channel and Zh channel.

σ (fb)		$\sqrt{s} = 3.0$ TeV, $\mathcal{L} = 4$ ab^{-1}			$\sqrt{s} = 1.5$ TeV $\mathcal{L} = 2$ ab^{-1}		
		Before Cuts	Wh-Cuts	Zh-Cuts	Before Cuts	Wh-Cuts	Zh-Cuts
Signal	Wh(VBF)	1.97×10^0	7.26×10^{-2}	1.36×10^{-3}	9.62×10^{-1}	6.54×10^{-2}	2.37×10^{-3}
	Zh(VBF)	6.47×10^{-1}	3.49×10^{-3}	7.21×10^{-2}	2.03×10^{-1}	1.30×10^{-3}	2.87×10^{-2}
BG	tt	1.17×10^0	5.83×10^{-4}	6.10×10^{-6}	4.65×10^0	5.64×10^{-3}	8.05×10^{-5}
	WZ(VBF)	4.47×10^0	9.97×10^{-3}	2.16×10^{-4}	1.84×10^0	5.86×10^{-3}	1.96×10^{-4}
	ZZ(VBF)	1.92×10^0	4.21×10^{-4}	8.07×10^{-3}	5.92×10^{-1}	1.48×10^{-4}	2.88×10^{-3}
	Zh	5.88×10^{-2}	1.83×10^{-4}	4.15×10^{-4}	2.39×10^{-1}	4.10×10^{-4}	1.12×10^{-3}
	ZWW	4.01×10^{-1}	1.14×10^{-3}	4.97×10^{-6}	6.36×10^{-1}	2.02×10^{-3}	1.72×10^{-5}
	ZZZ	5.06×10^{-3}	6.04×10^{-7}	1.12×10^{-5}	9.79×10^{-3}	1.74×10^{-6}	2.34×10^{-5}
	Sum	8.02×10^0	1.23×10^{-2}	8.72×10^{-3}	7.97×10^0	1.41×10^{-2}	4.32×10^{-3}
		Precision (%)	6.18	6.17	Precision (%)	9.53	13.5

DS, Wu, 2006.09347.

LEPTON COLLIDER RESULTS



DS, Wu, 2006.09347.