INTERFERENCE EFFECTS IN HIGGS DECAYS

DANIEL STOLARSKI

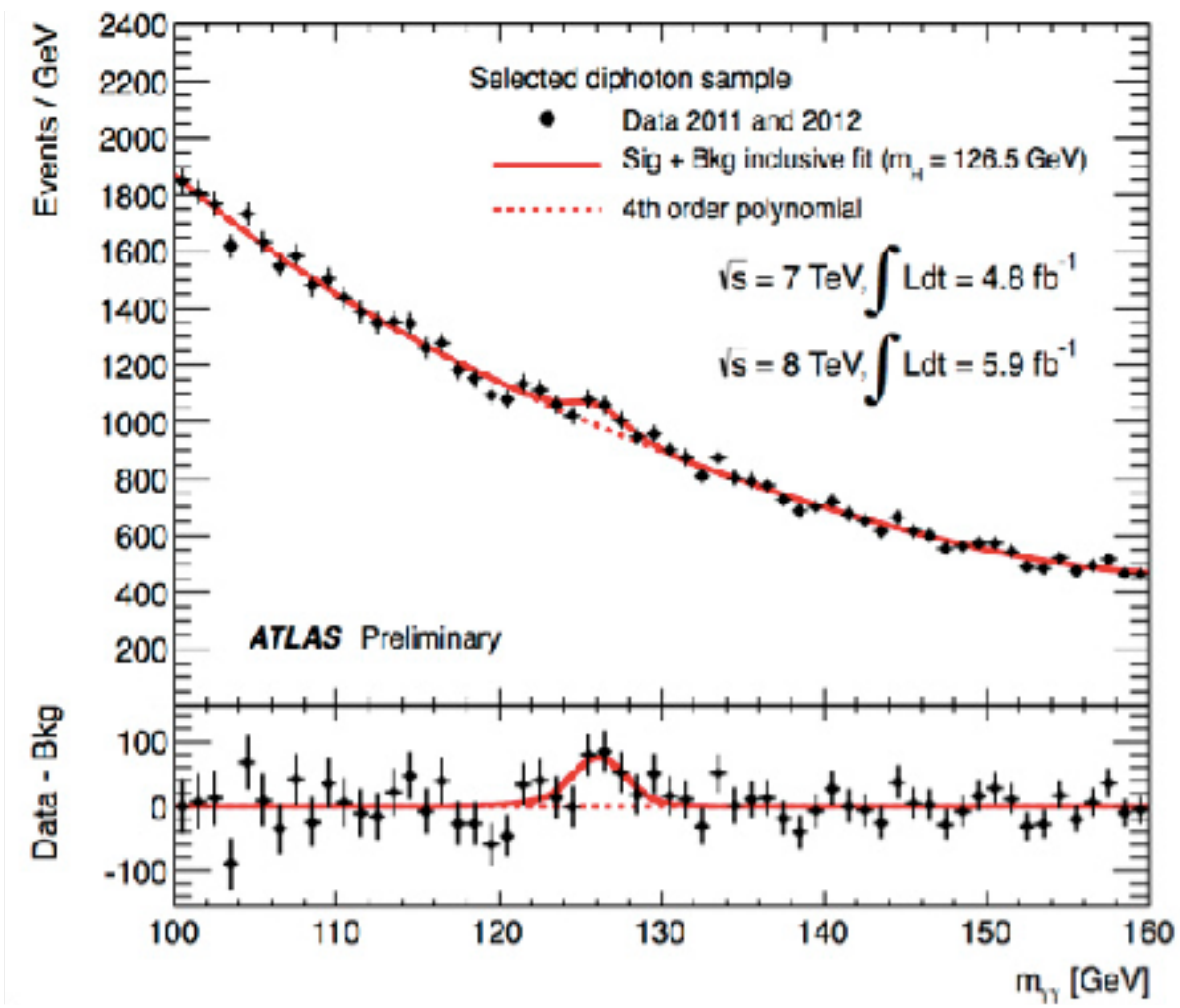
Carleton University

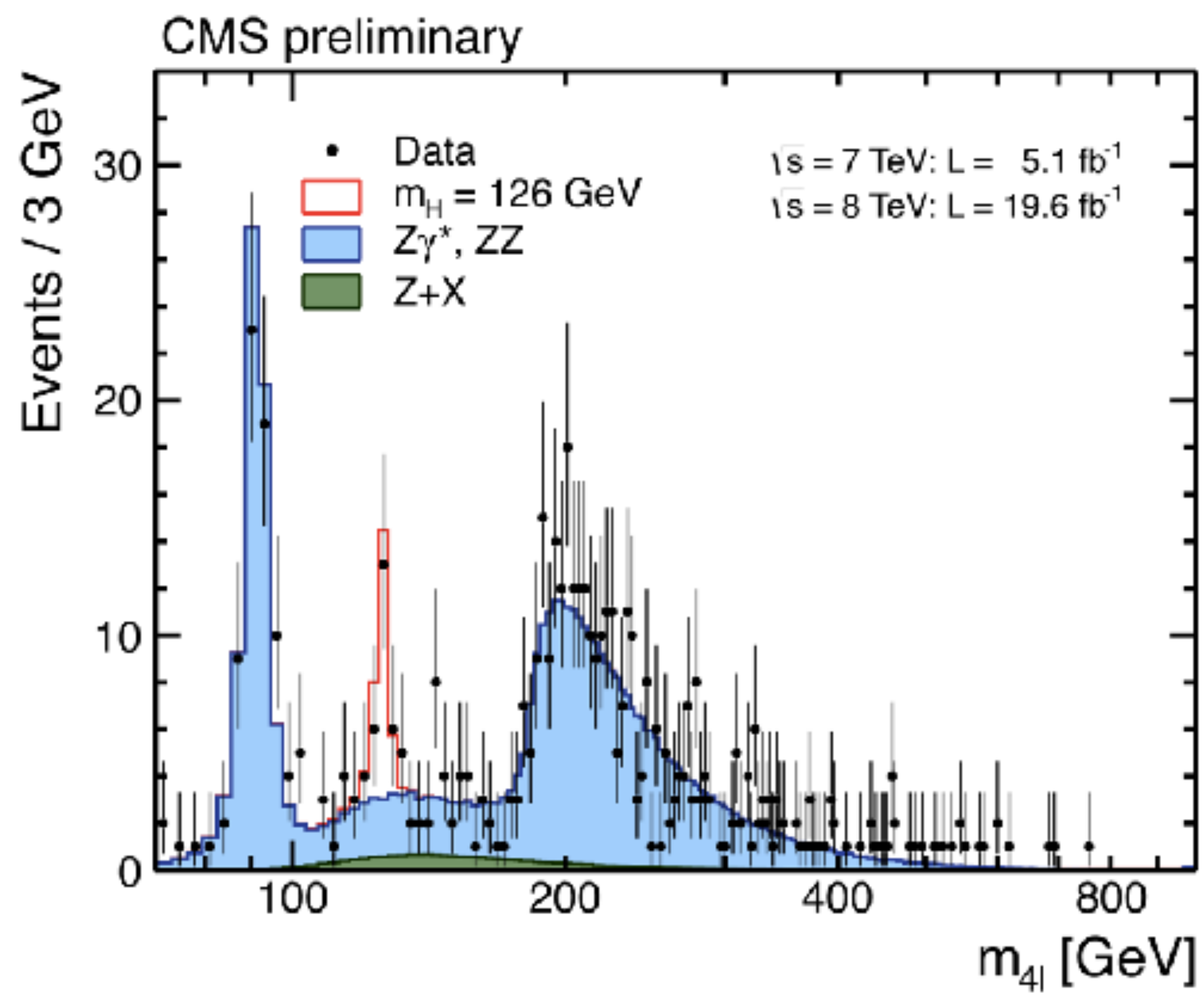
DS, R. Vega-Morales, Phys.Rev.D.86, 117504 (2012)[arXiv:1208.4840]. Yi Chen, DS, R. Vega-Morales, Phys.Rev.D.92, 053003 (2015)[arXiv:1505.01168]. Y. Chen, J. Lykken, M. Spiropulu, DS, R. Vega-Morales, [arXiv:1608.02159]. And work in progress.

Theory Canada 14 June 1, 2019

A NEW PARTICLE

July 2012:



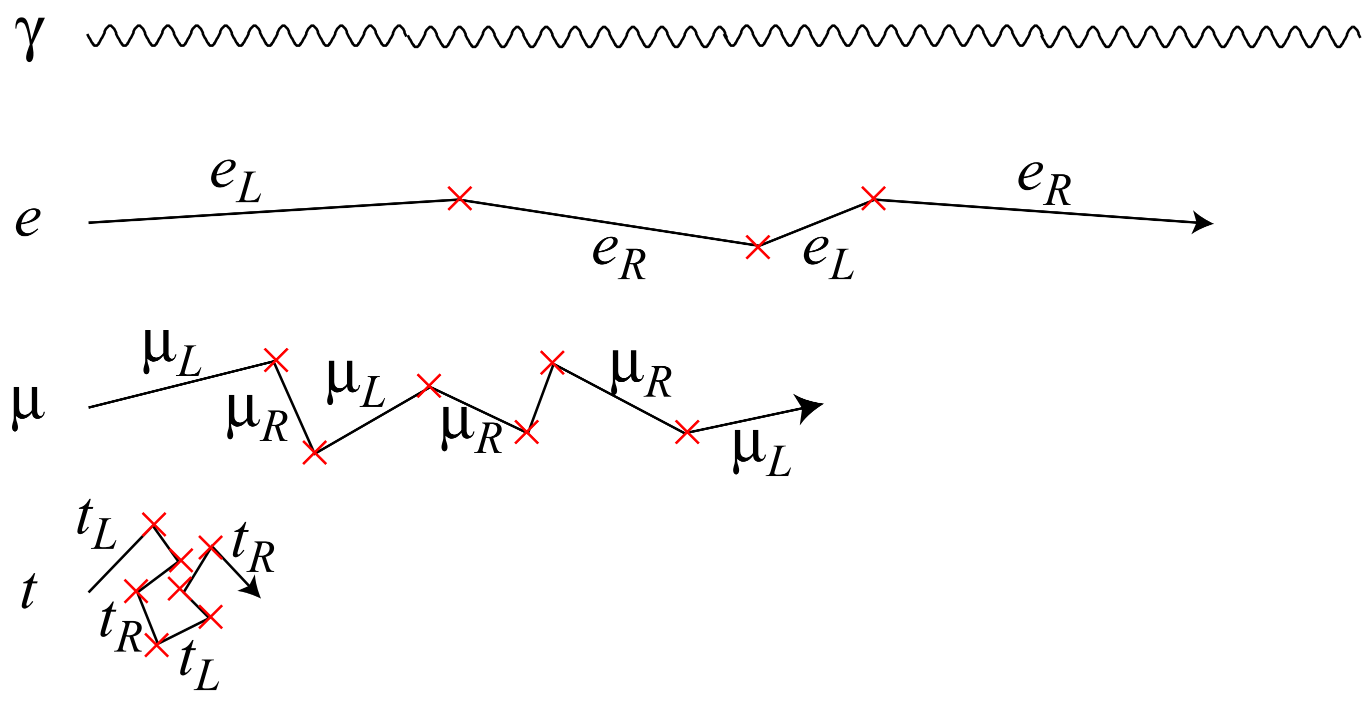


$h \to \gamma\gamma$

$h \to 4e/4\mu/2e2\mu$

HIGGS MECHANISM

Entire universe is a superconductor, condensate of something that talks to fermions, W, Z but not photon.



Anderson, 1963

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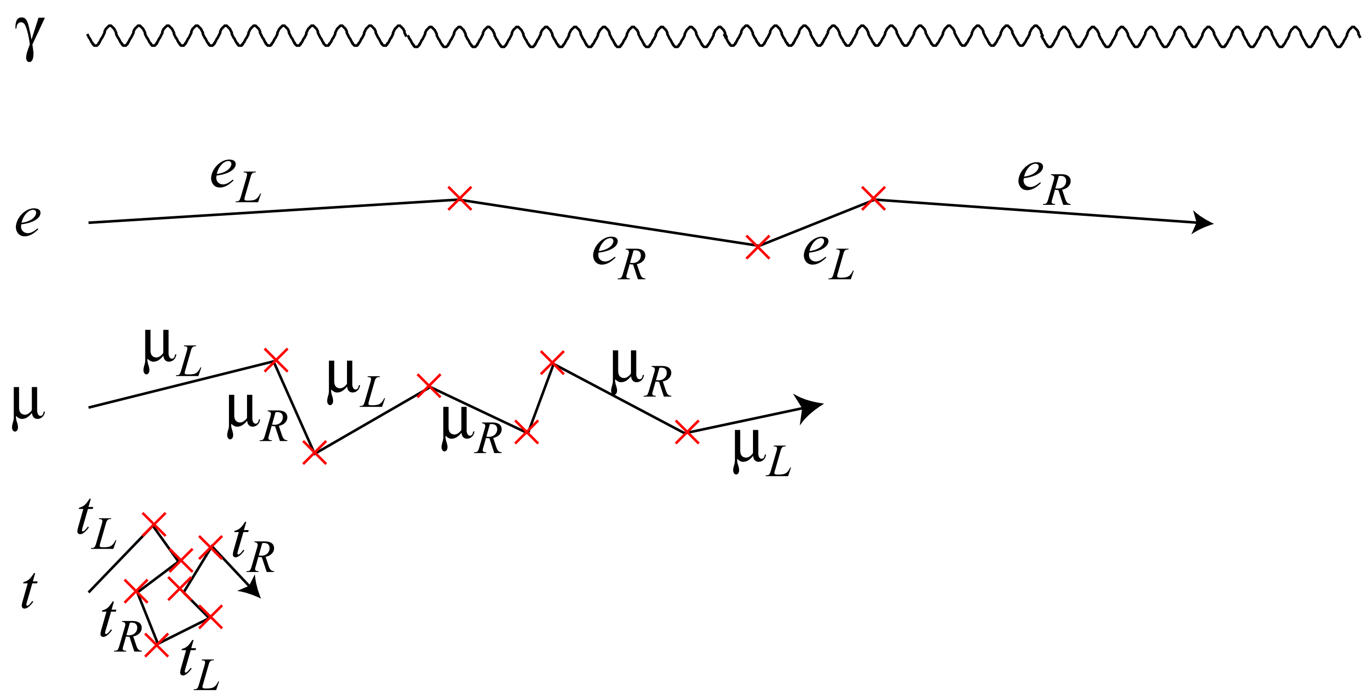

Anderson, 1963

One model is an elementary scalar field proposed by Brout, Englert, Higgs and others.

DISCOVERY MODES

$$h \to \gamma\gamma \qquad\qquad h \to 4e/4\mu/2e2\mu$$

All final states are light!

Higgs is supposed to be responsible for mass…

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Second order quantum effect:

$$E_n^2 = \sum_{m\neq n} \frac{\left|\langle\psi_m^0|H'|\psi_n^0\rangle\right|^2}{E_n^0 - E_m^0}$$

Griffiths, *Quantum Mechanics, Eq. 6.15*

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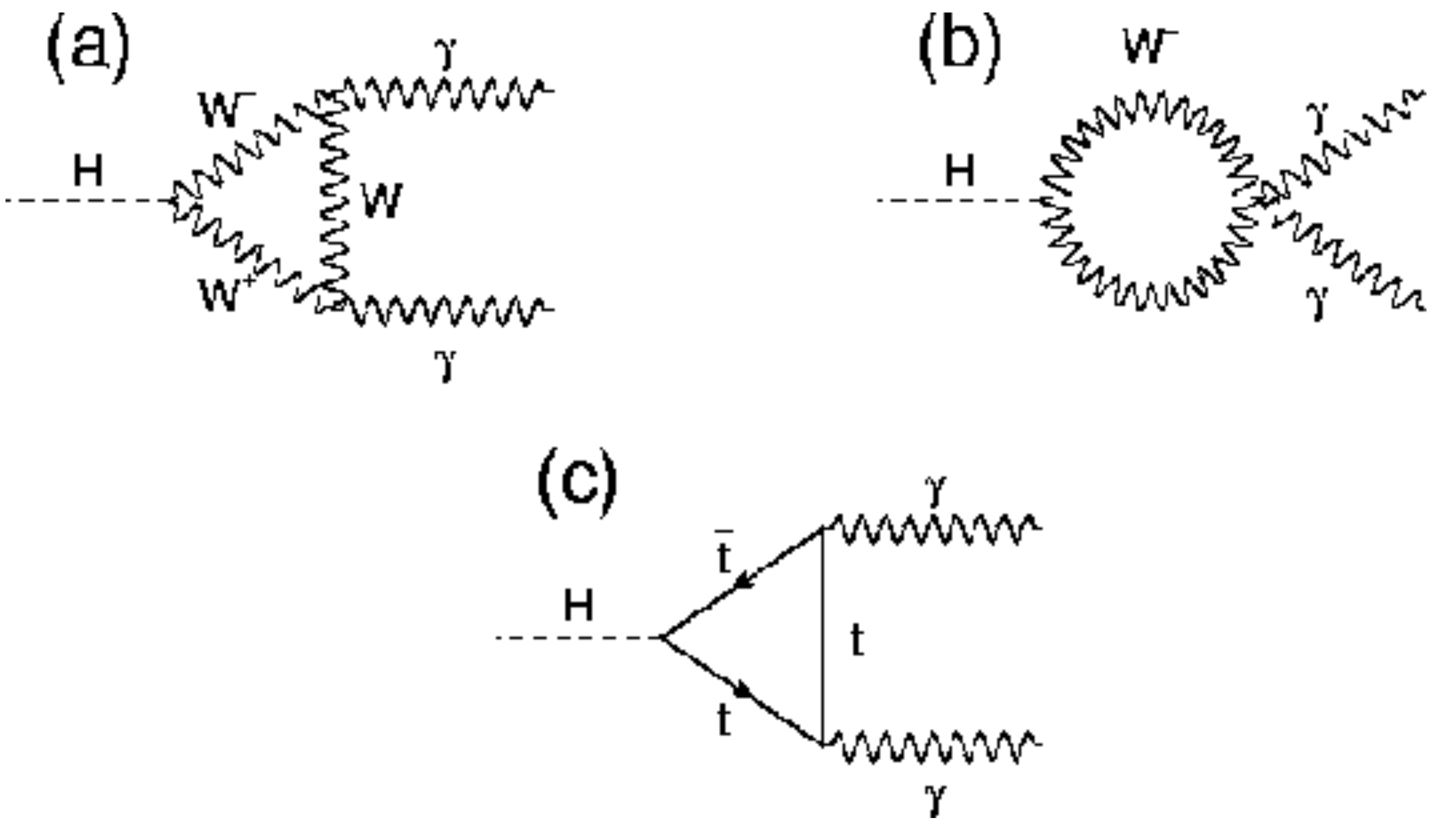
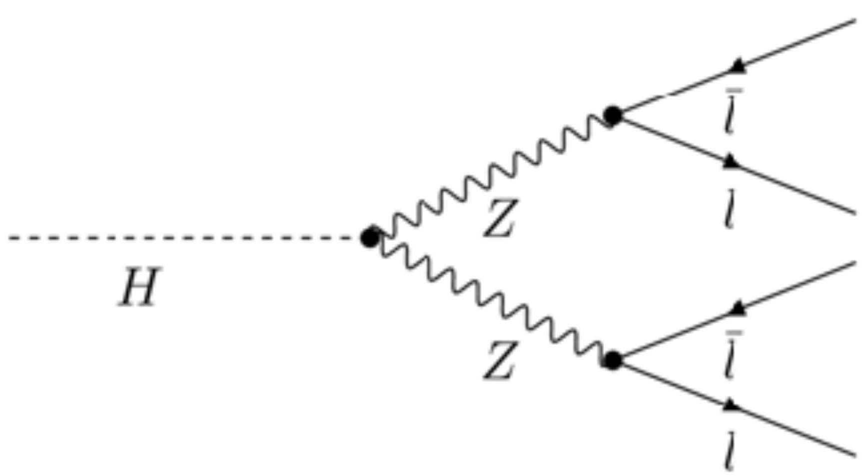
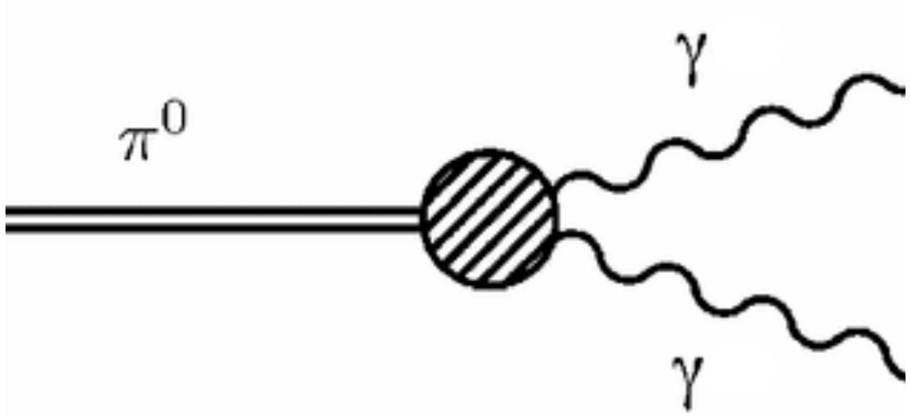


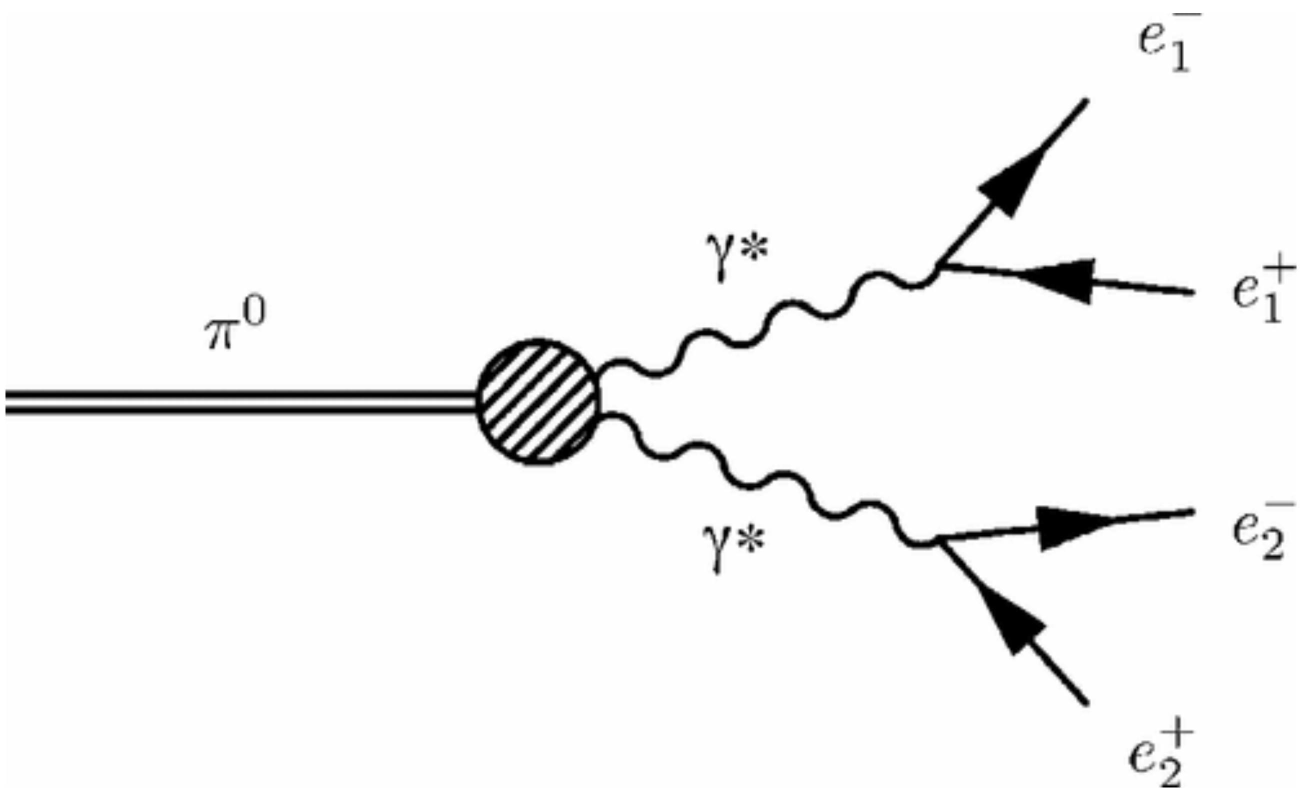


IS IT THE HIGGS?

Consistent with the Higgs, but could also be something else.

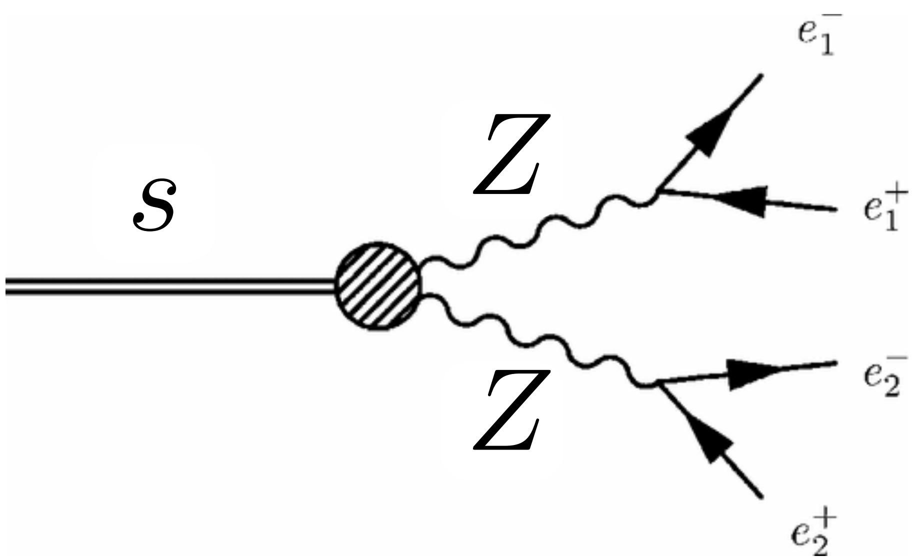
Neutral pion decays to two photons and four electrons, but its just a bound state of quarks.



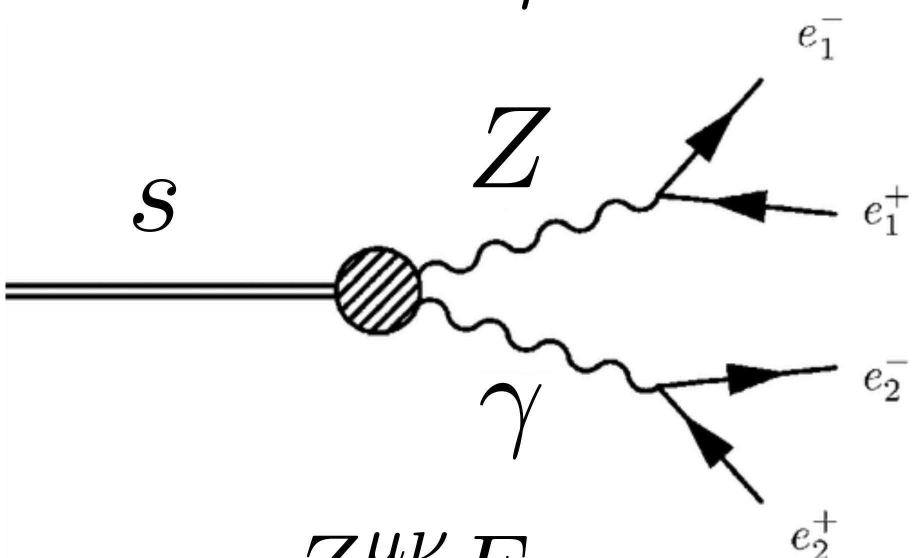


WARM UP EXERCISE

Assume parity even scalar:

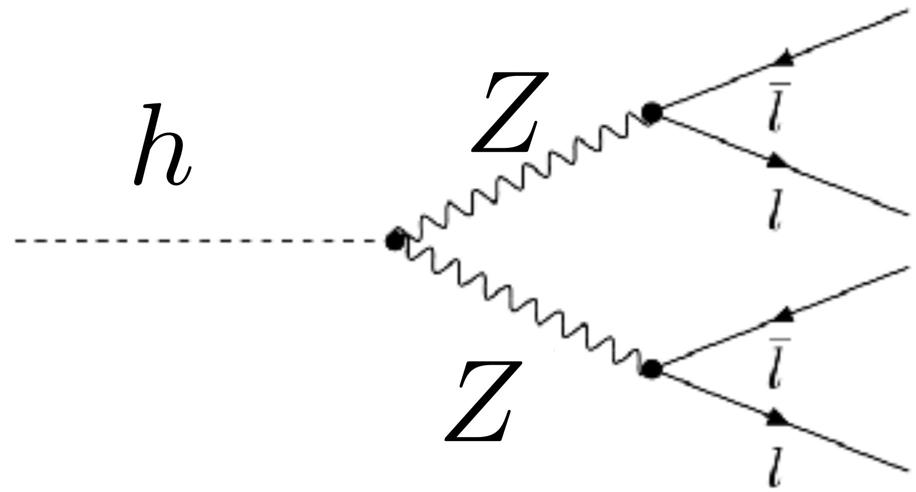


$$s\, Z^{\mu\nu} Z_{\mu\nu}$$



$$s\, Z^{\mu\nu} F_{\mu\nu}$$

OR

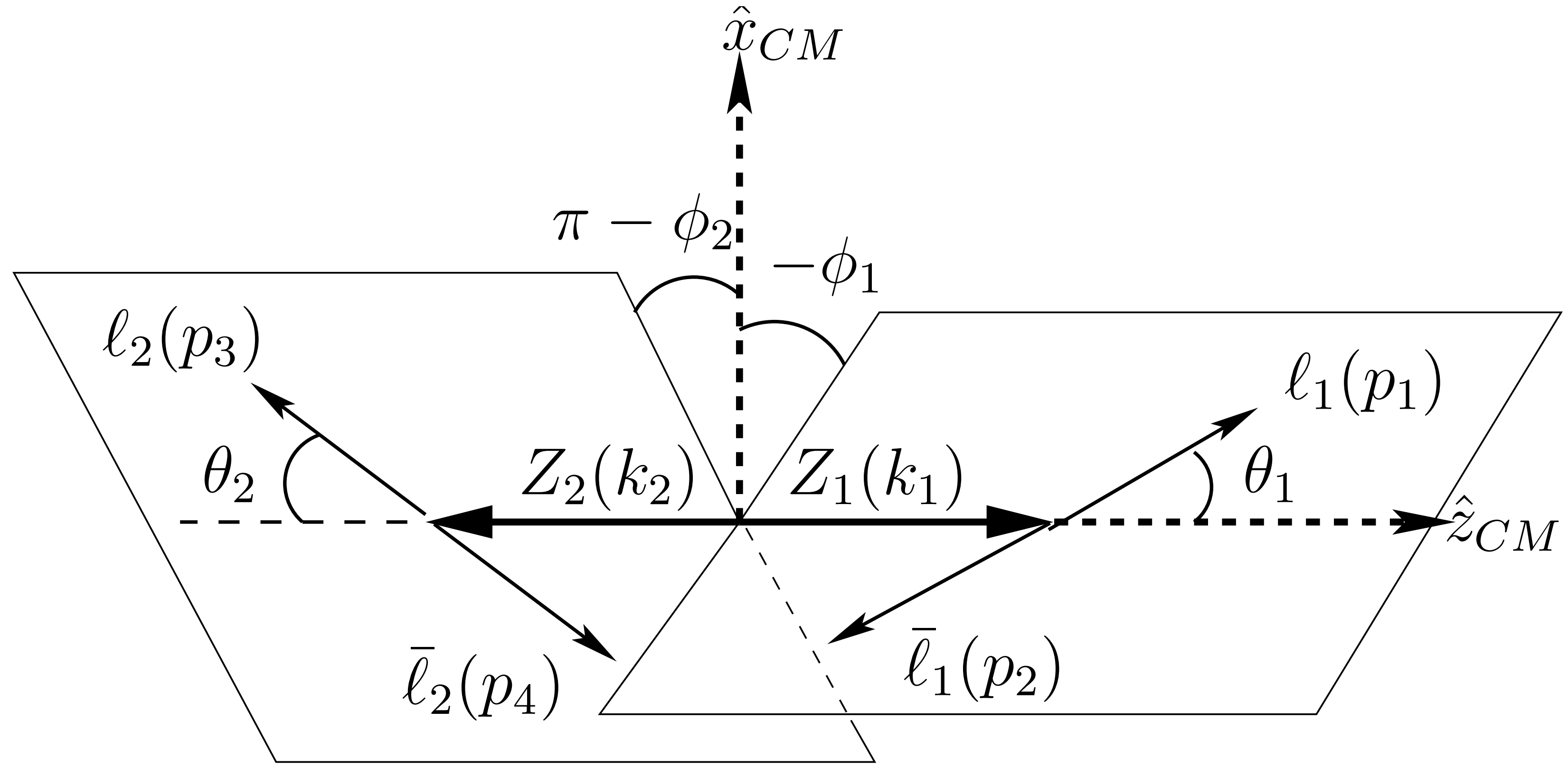


$$h\, Z^{\mu} Z_{\mu}$$

KINEMATIC DISTRIBUTIONS

Study $h \to 4e/4\mu/2e2\mu$:

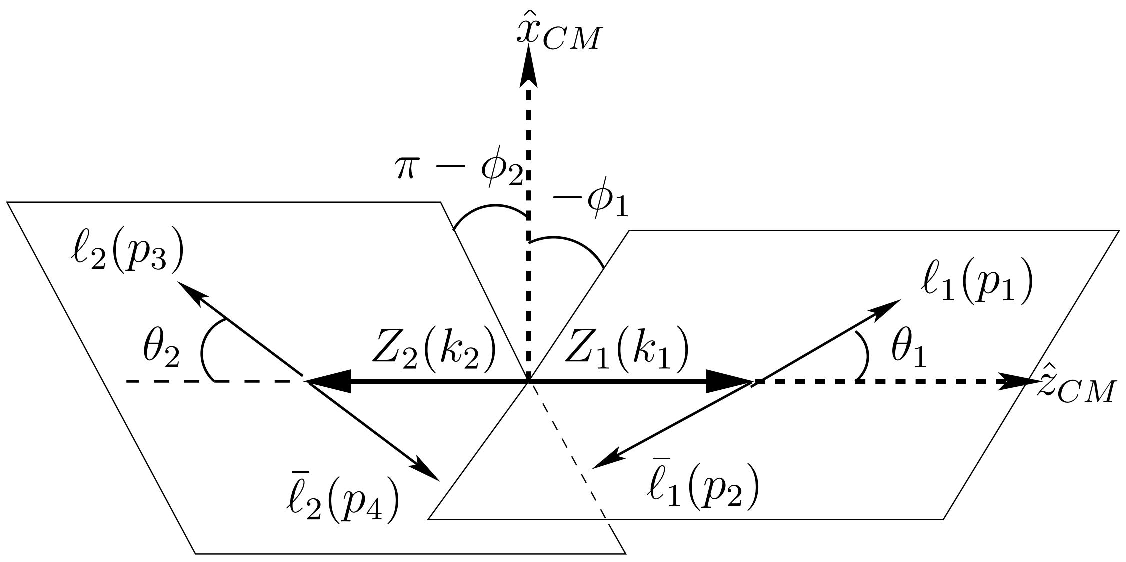
Each event is characterized by five different variables.



In $h \to \gamma\gamma$, conservation of 4-momentum means there is no additional information.

KINEMATIC DISTRIBUTIONS

Distributions encode information about tensor structure.



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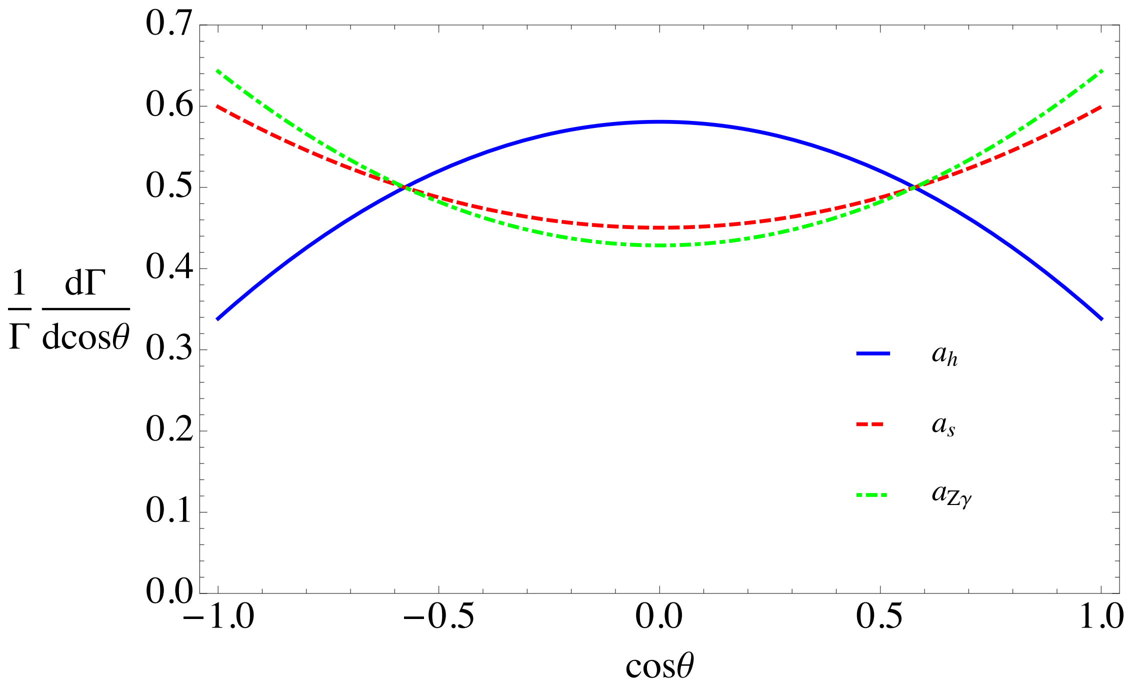
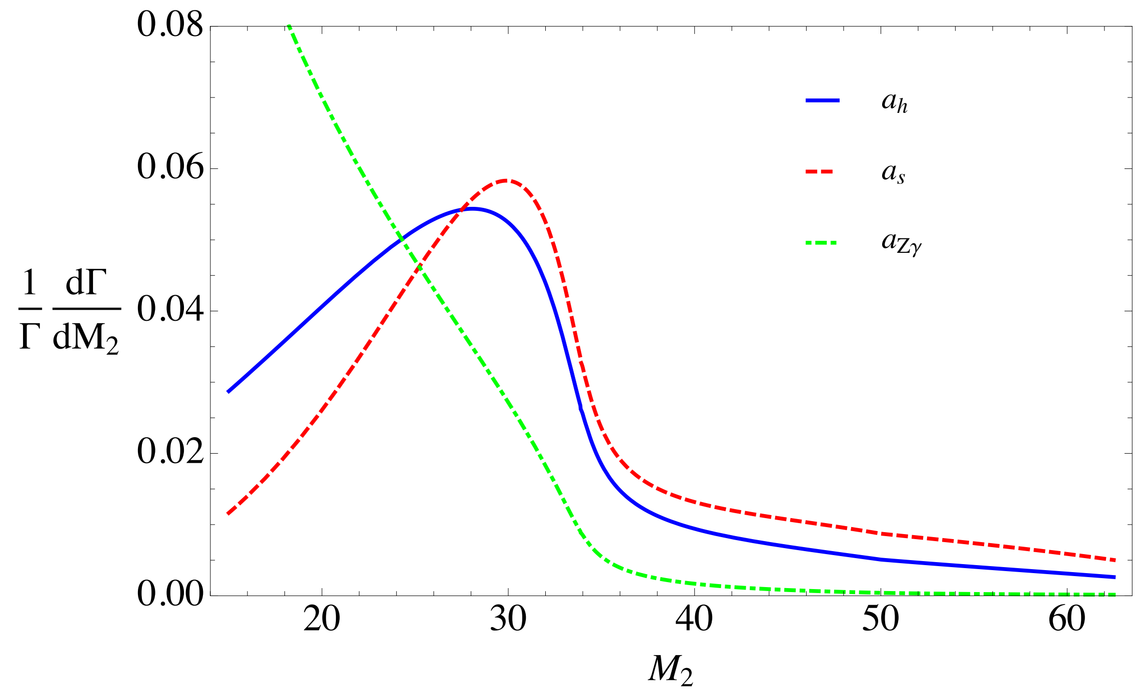
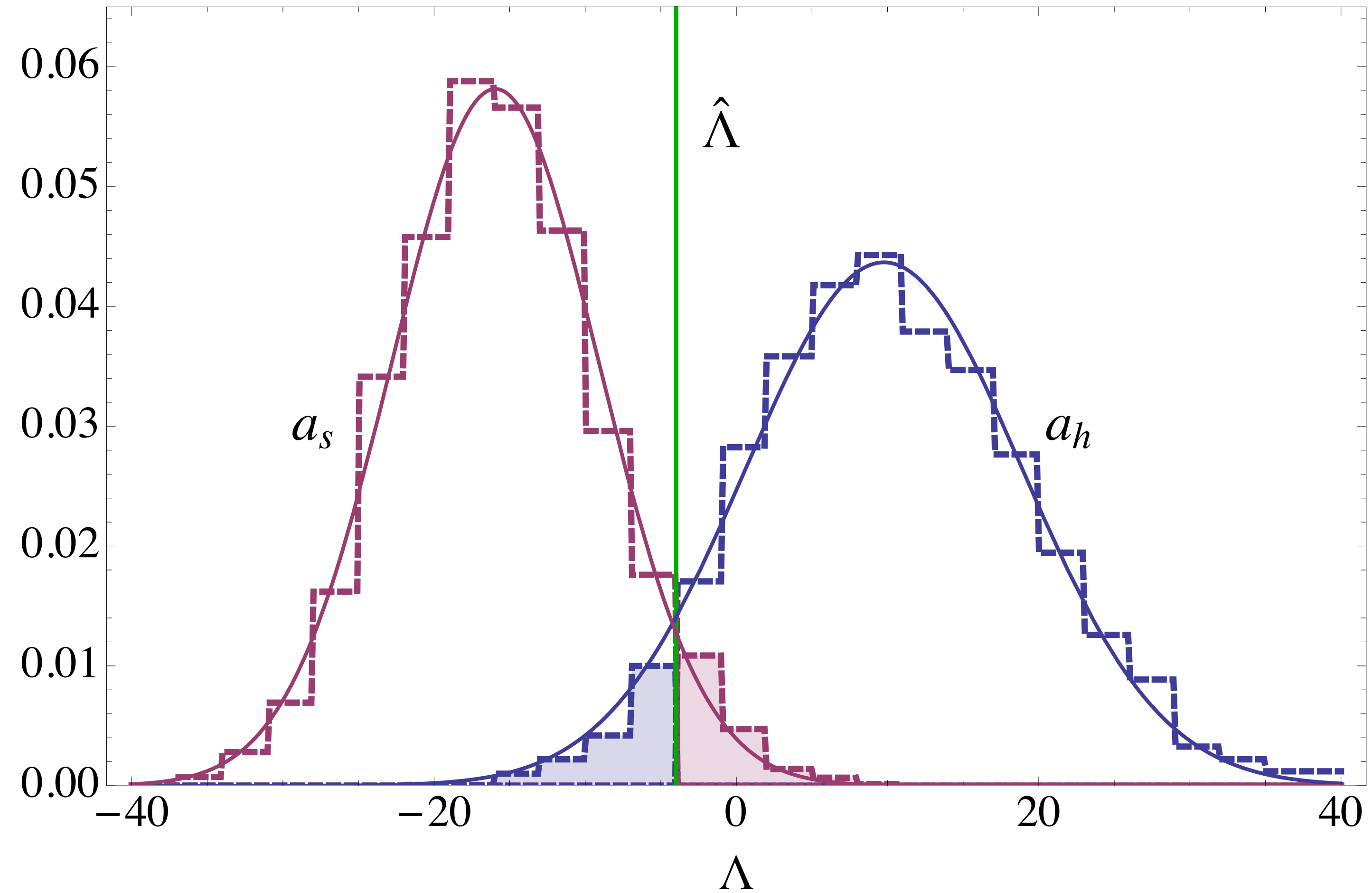




LIKELIHOOD DISTRIBUTION

Can do statistical testing among different discrete hypotheses using Monte Carlo data.

Example for 50 events:

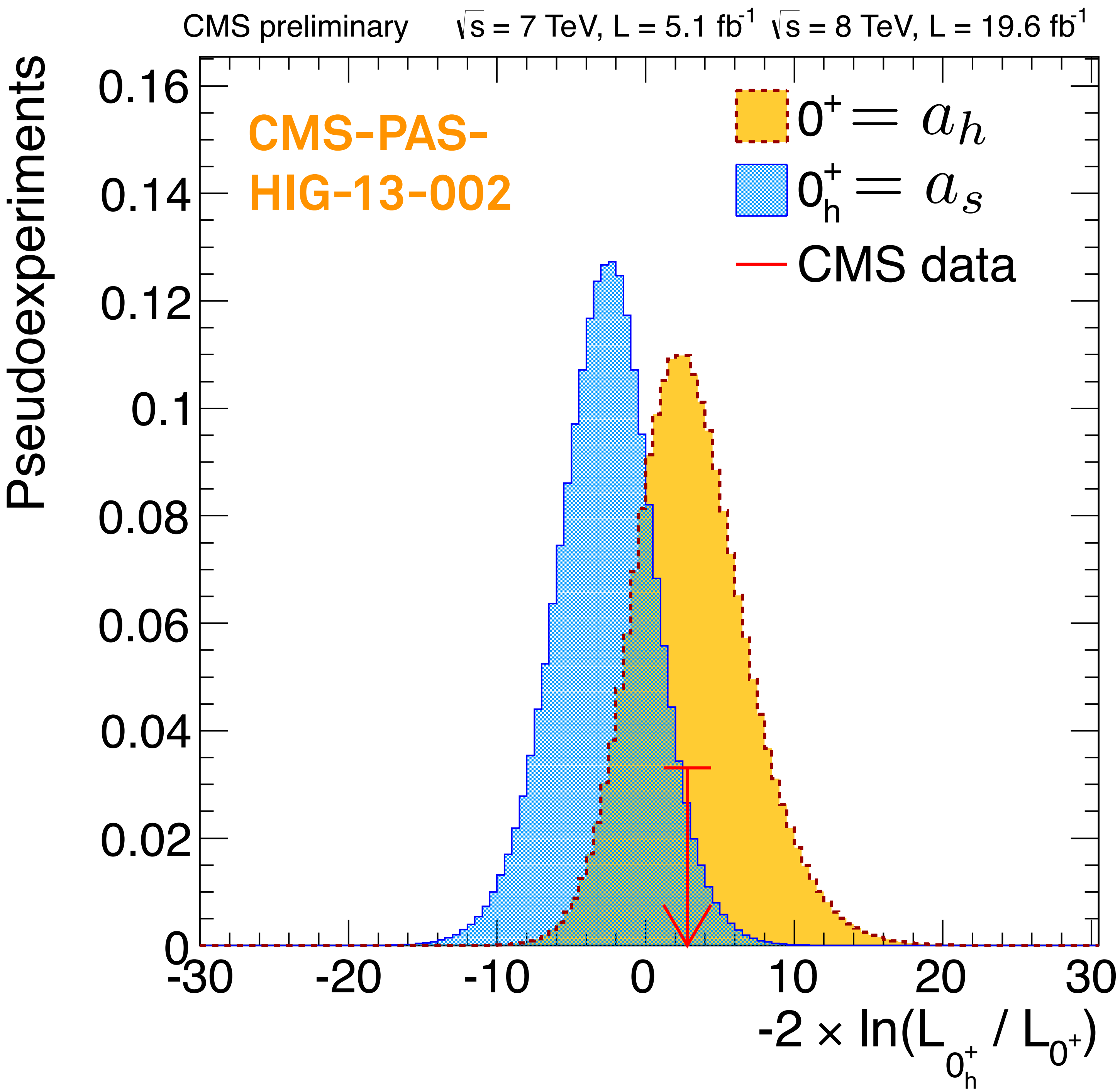


$$\Lambda = 2\log[\mathcal{L}(a_1)/\mathcal{L}(a_2)]$$

DATA

Evidence for the Higgs:

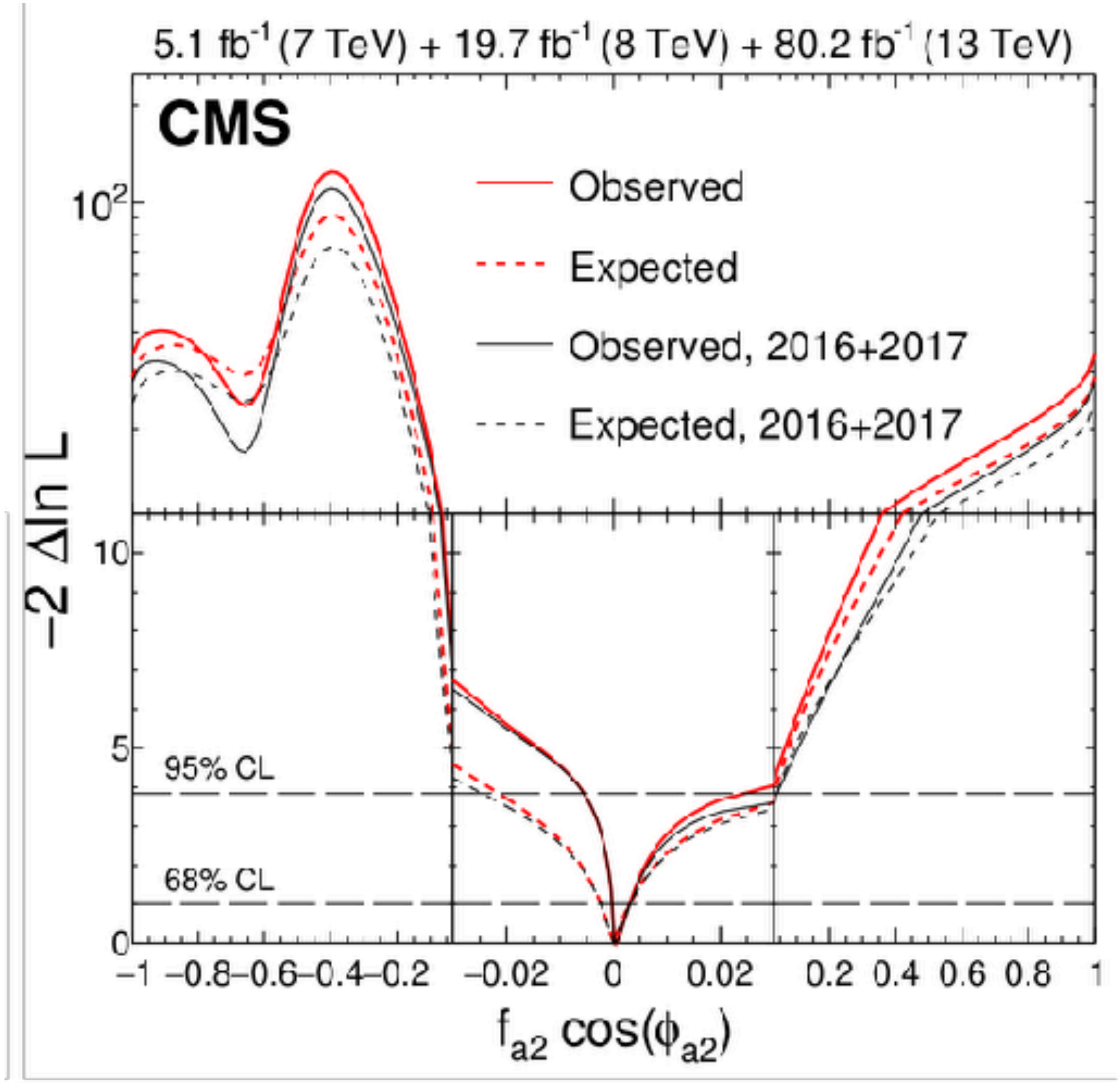
This data is a bit old…



DATA

Recent measurements assume:

SM Higgs + deviations.



CMS, arXiv:1901.00174.

IS IT THE HIGGS?

Properties of new boson agree with SM Higgs at ~20% level.

SM predicts all properties of the Higgs.

Even small deviations in Higgs properties imply new terms in the Lagrangian of nature.

$$\mathcal{L} = ?$$

NEW PHYSICS?

Problems with the Standard Model:

- Dark Matter

NEW PHYSICS?

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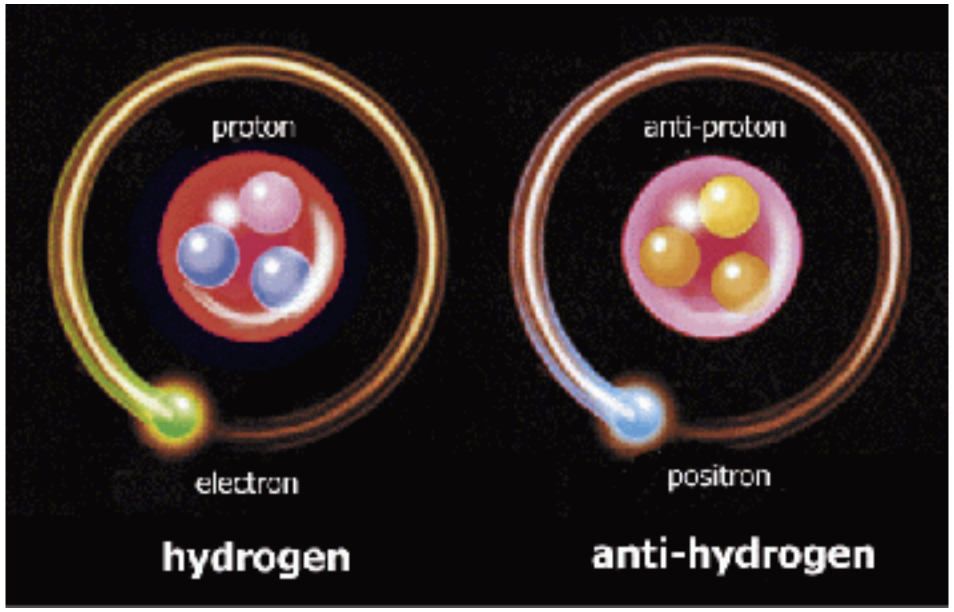
- Baryon asymmetry of the universe



NEW PHYSICS?

Problems with the Standard Model:

- Dark Matter
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- Neutrino mass
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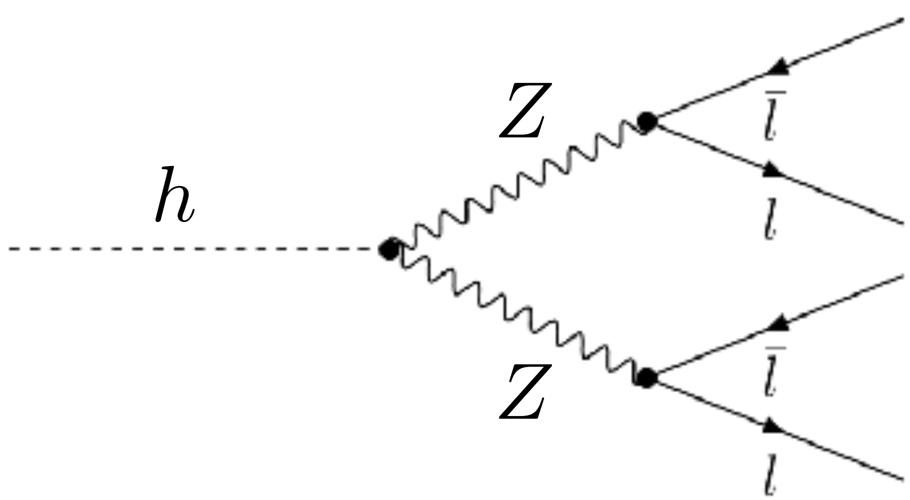
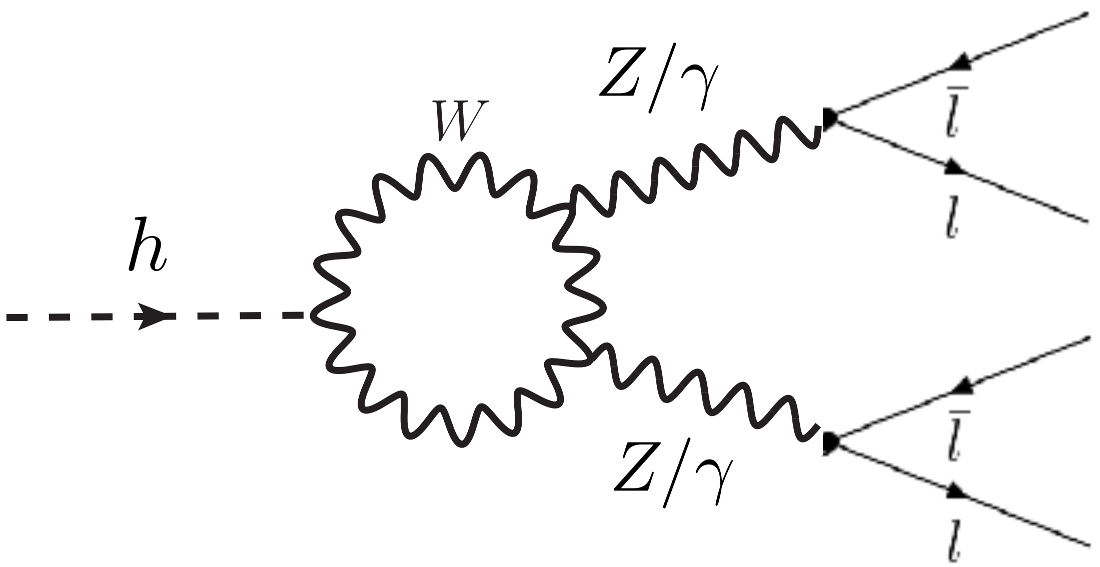
Experimental studies of the Higgs could give insights into these problems.

COUPLING TO GAUGE BOSONS

Kinematic distributions can reveal more than just rate measurements can.

Put this to use in interference effects.



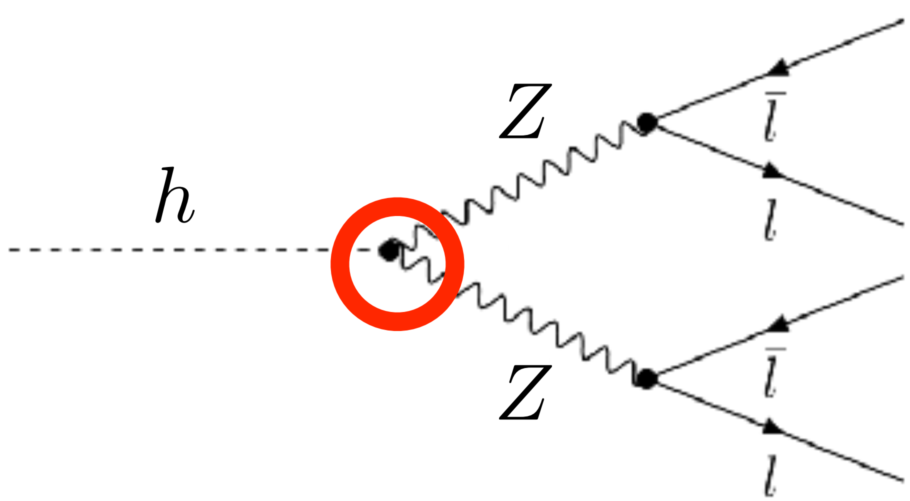


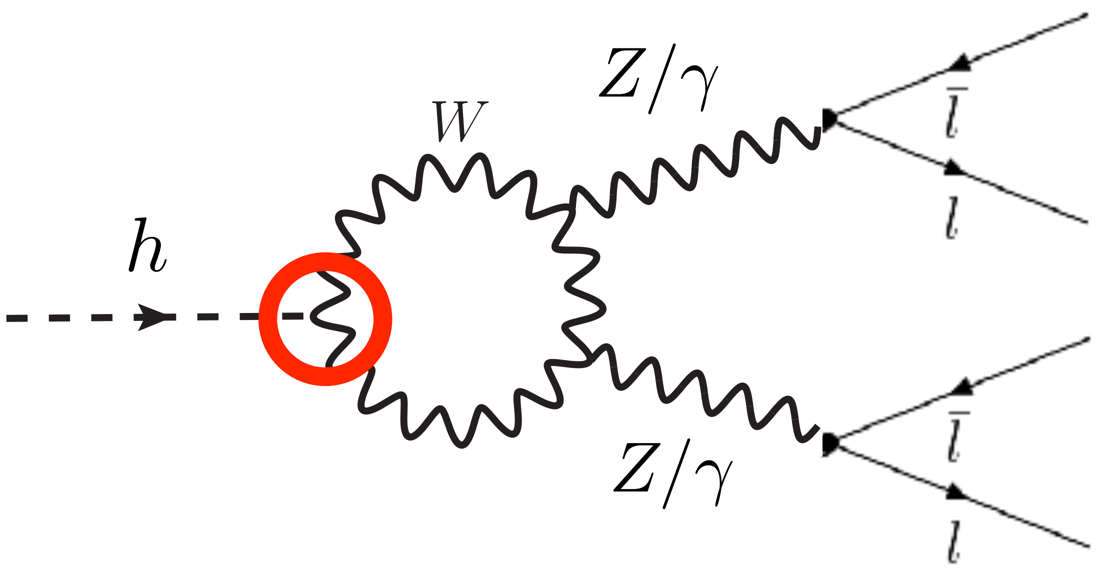
Leading quantum effect (one-loop) interferes with tree level effect.

COUPLING TO GAUGE BOSONS

Two diagrams contain different Higgs couplings.

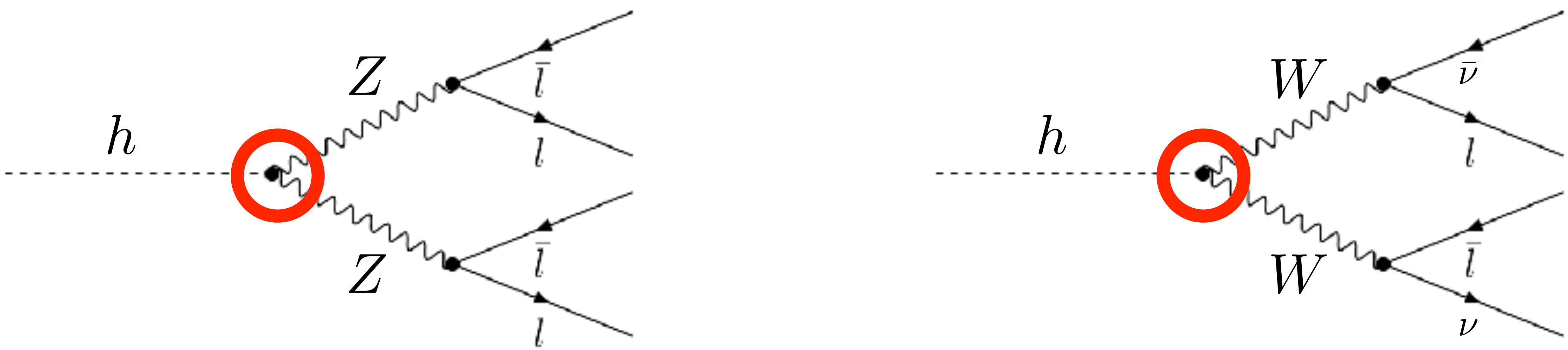
Can use this to measure gauge-Higgs structure.





TREE-LEVEL MEASUREMENTS

Can also measure these couplings at tree level.

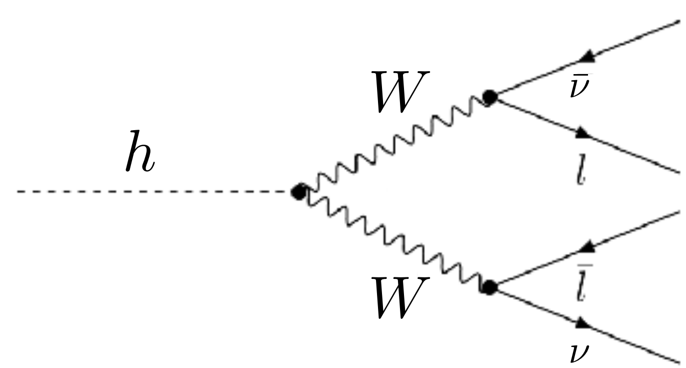


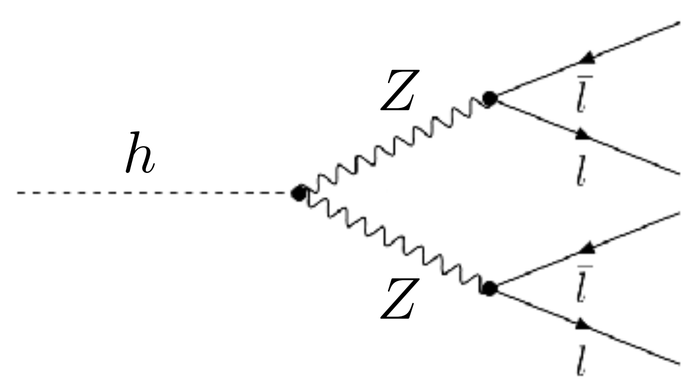
Tree-level effects are much bigger than quantum effects, what's the point?

TREE-LEVEL MEASUREMENTS

Define the ratio of those two couplings: $\lambda_{WZ} \equiv \frac{g_{hWW}}{g_{hZZ}}$

Tree level measurement:

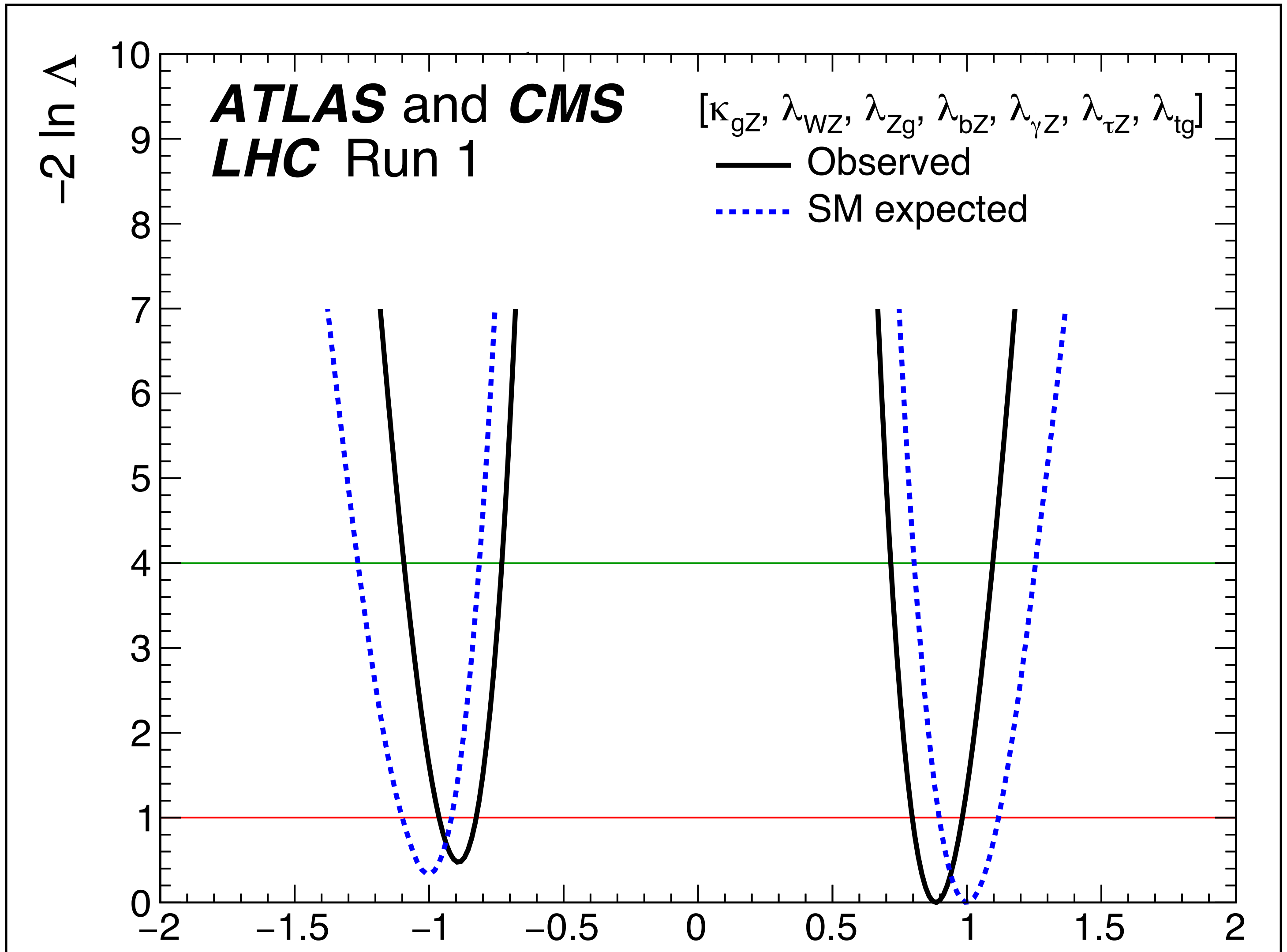




$$\frac{\left|\ \text{(}h \to WW\text{ diagram)}\ \right|^2}{\left|\ \text{(}h \to ZZ\text{ diagram)}\ \right|^2} \propto \frac{g_{hWW}^2}{g_{hZZ}^2} = \lambda_{WZ}^2$$

TREE-LEVEL MEASUREMENTS

Tree level processes have no information about sign of λ_{WZ}.



ATLAS + CMS, arXiv:1606.02266.

CUSTODIAL SYMMETRY

Ratio of couplings to gauge bosons dictated by SM custodial isospin symmetry.

$$\vec{W} = \begin{pmatrix} W^+ \\ Z^0 \\ W^- \end{pmatrix}$$

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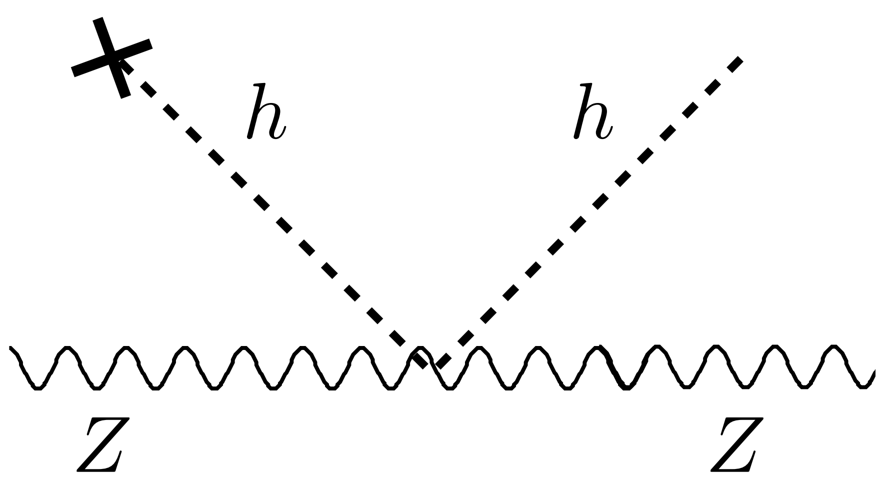

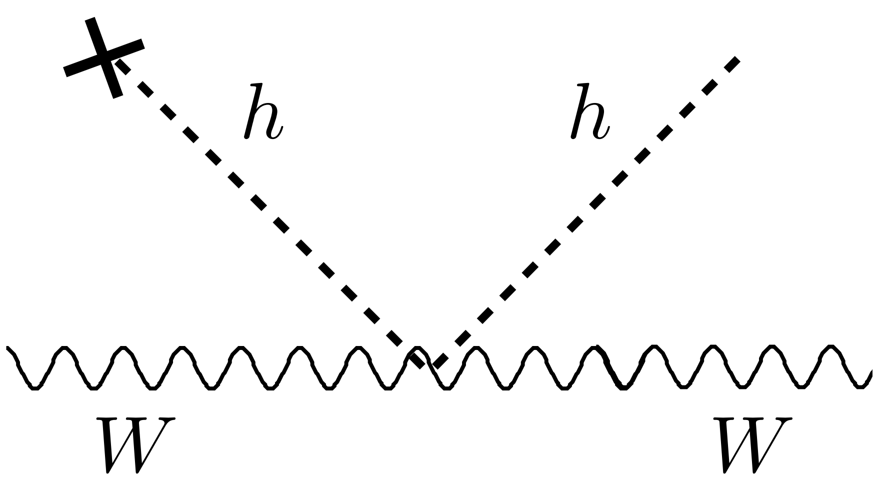

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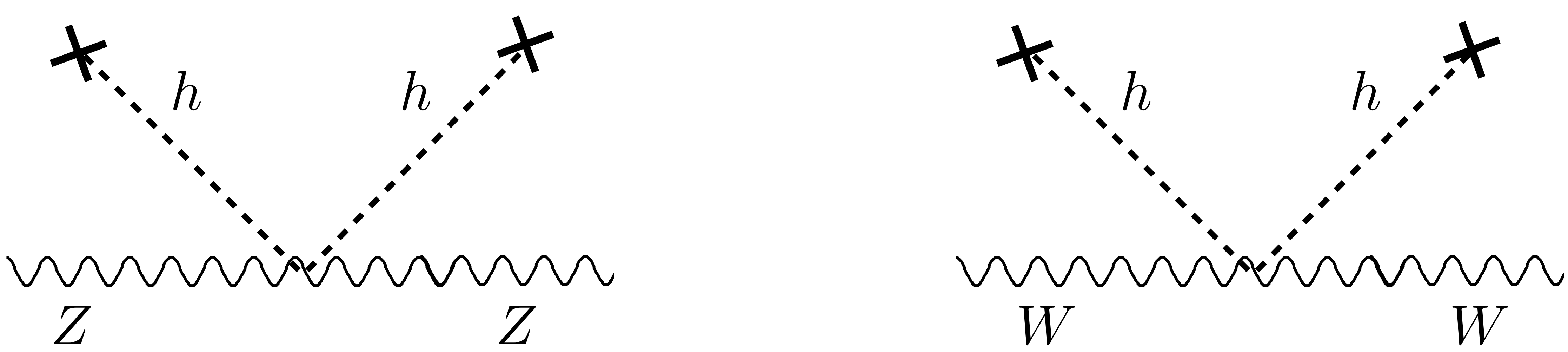
Ratio of couplings to gauge bosons dictated by SM custodial isospin symmetry.

Also dictates ratio of masses of gauge bosons.



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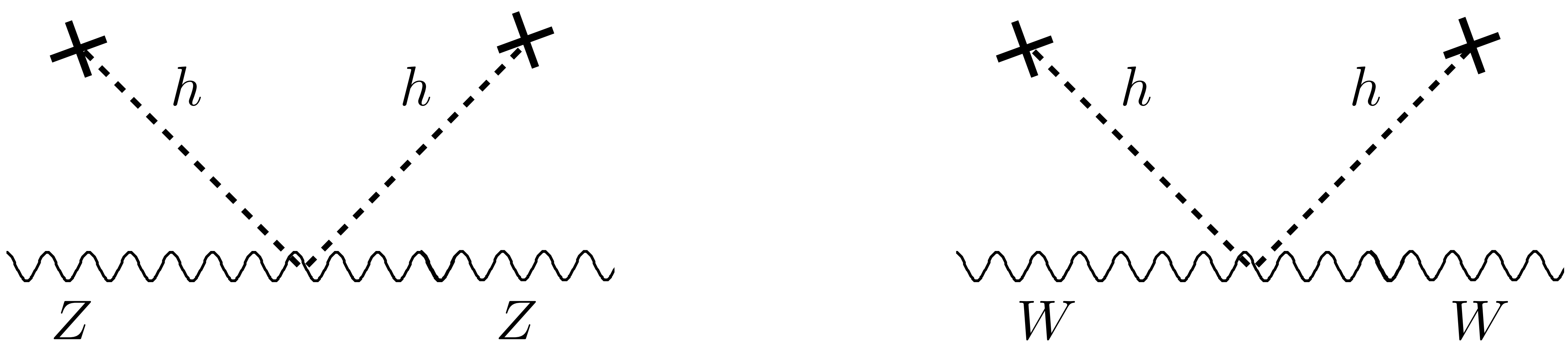

$$\rho \equiv \frac{M_W^2}{M_Z^2 \cos\theta_W^2} = 1.00040 \pm 0.00024$$

REVIEW

SM: $SU(2)_L \times SU(2)_R \rightarrow SU(2)_C$

Explicit breakings: hypercharge and Yukawas.

W and Z are **3** under SU(2)C. $\vec{W} = \begin{pmatrix} W^+ \\ Z^0 \\ W^- \end{pmatrix}$

SM Higgs: **(2,2) = 3 + 1**

Longitudinal modes. (→ 3)

h (→ 1)

GENERAL EWSB

H = **(n, m)** under L x R

responsible for breaking $SU(2)_L \times SU(2)_R \rightarrow SU(2)_C$.

Low and Lykken, [arXiv:1005.0872].

GENERAL EWSB

H = **(n, m)** under L x R

responsible for breaking $SU(2)_L \times SU(2)_R \to SU(2)_C$.

$\Downarrow$ There is a neutral state under C.

n = m.

Low and Lykken, [arXiv:1005.0872].

GENERAL EWSB

H = **(n, n)** under L x R.

H = **1 + 3 + 5 + … + (2n+1)** under C.

n = 3 simplest non-SM model. **Georgi and Machacek, PLB 1985.**

Triplet of $SU(2)_L$ triplets with Y=+1, 0, -1.

Avoids usual problems of electroweak triplets.

GENERAL EWSB

H = **(n, n)** under L x R.

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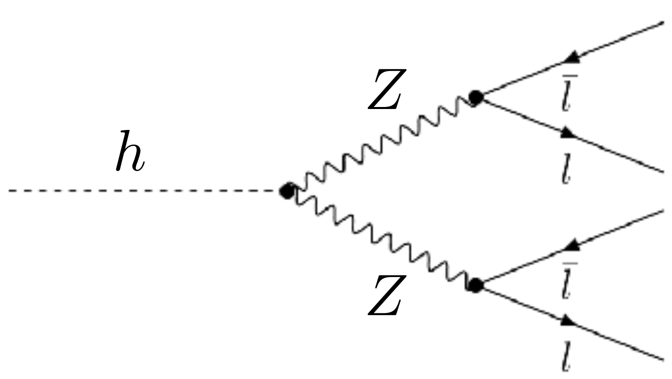
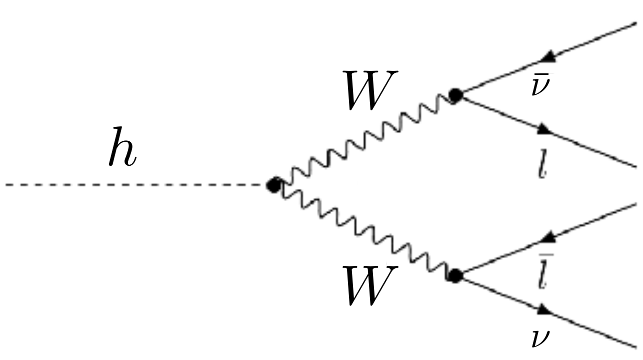
The H(125) decays to a pair of gauge bosons.





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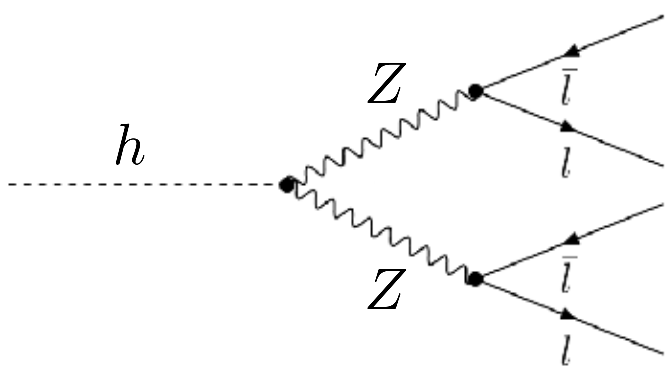

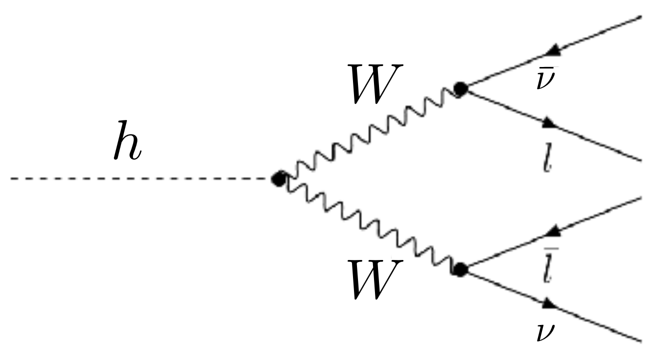

Which of the above representations can do that?

GENERAL EWSB

H = **(n, n)** under L x R.

H = **1 + 3 + 5 + … + (2n+1)** under C.

Need: $H \otimes \overrightarrow{W} \otimes \overrightarrow{W} = \mathbf{1}$ under C.

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$$\vec{W} \otimes \vec{W} = \mathbf{3} \otimes \mathbf{3} = \mathbf{1} \oplus \mathbf{3} \oplus \mathbf{5}$$

Isospin 1

Low and Lykken, [arXiv:1005.0872].

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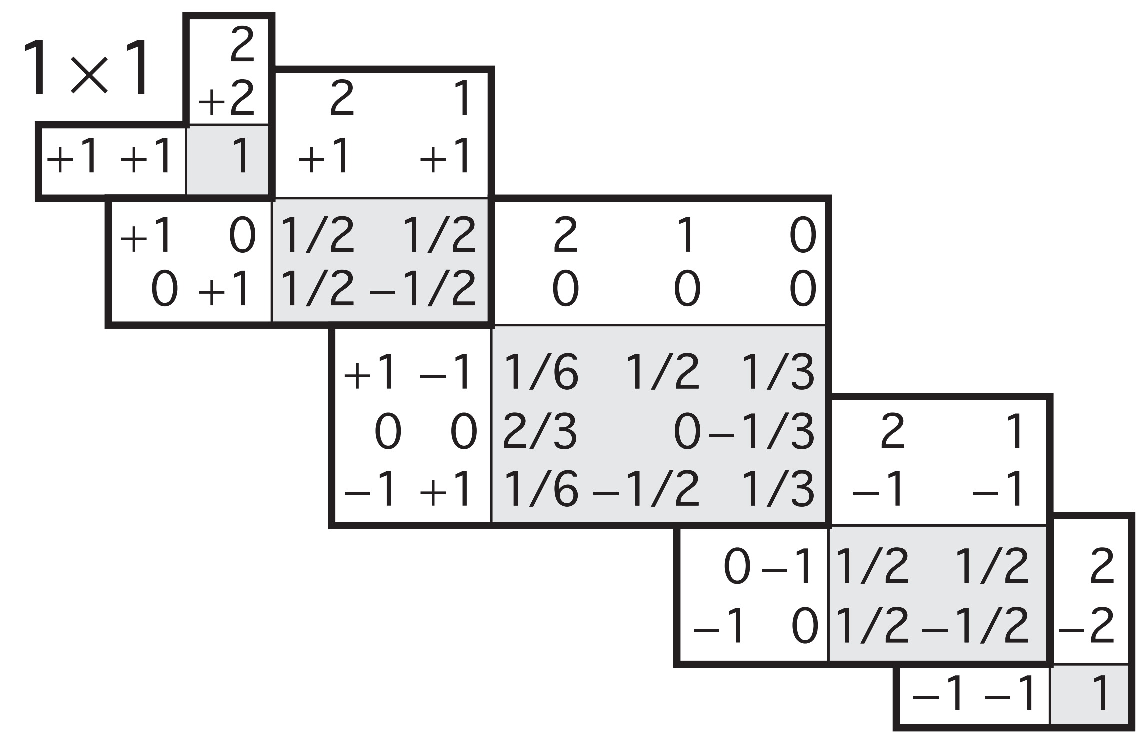
Reduced possibilities for H to finite set.

Low and Lykken, [arXiv:1005.0872].

COUPLINGS

Let's look at the couplings for the different possibilities.

Look up Clebsch-Gordan coefficients.



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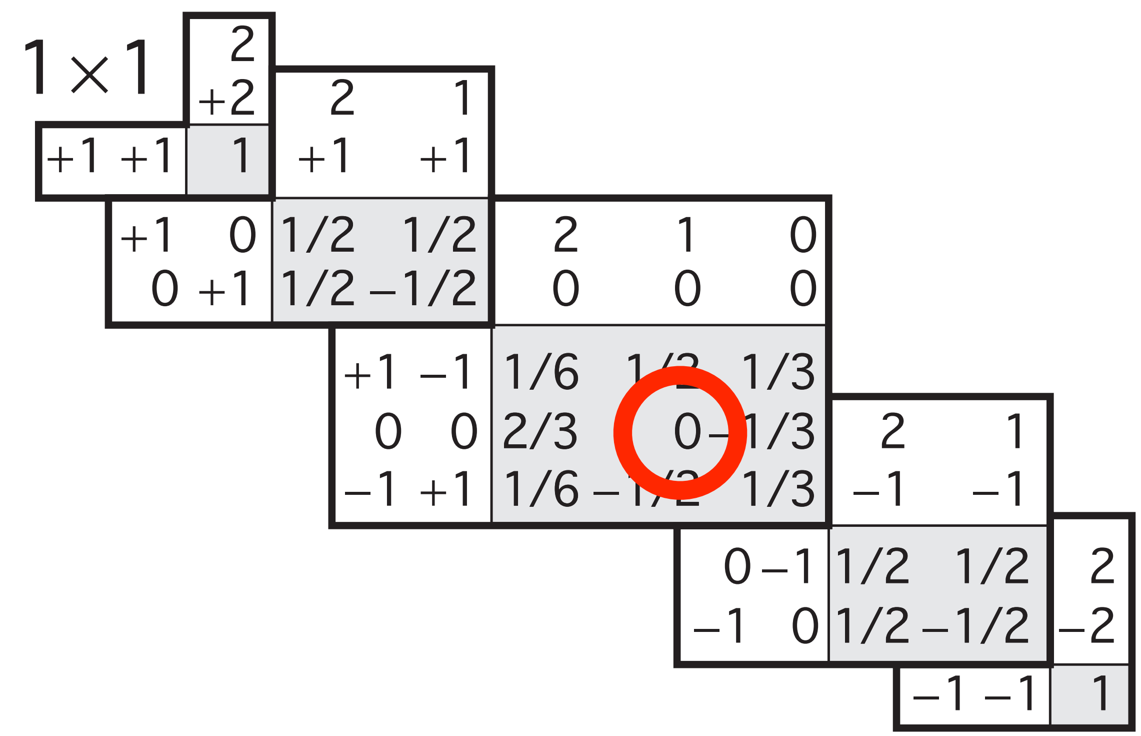
Isospin 1 "Higgs" cannot couple to pair of m=0 vectors, namely ZZ.



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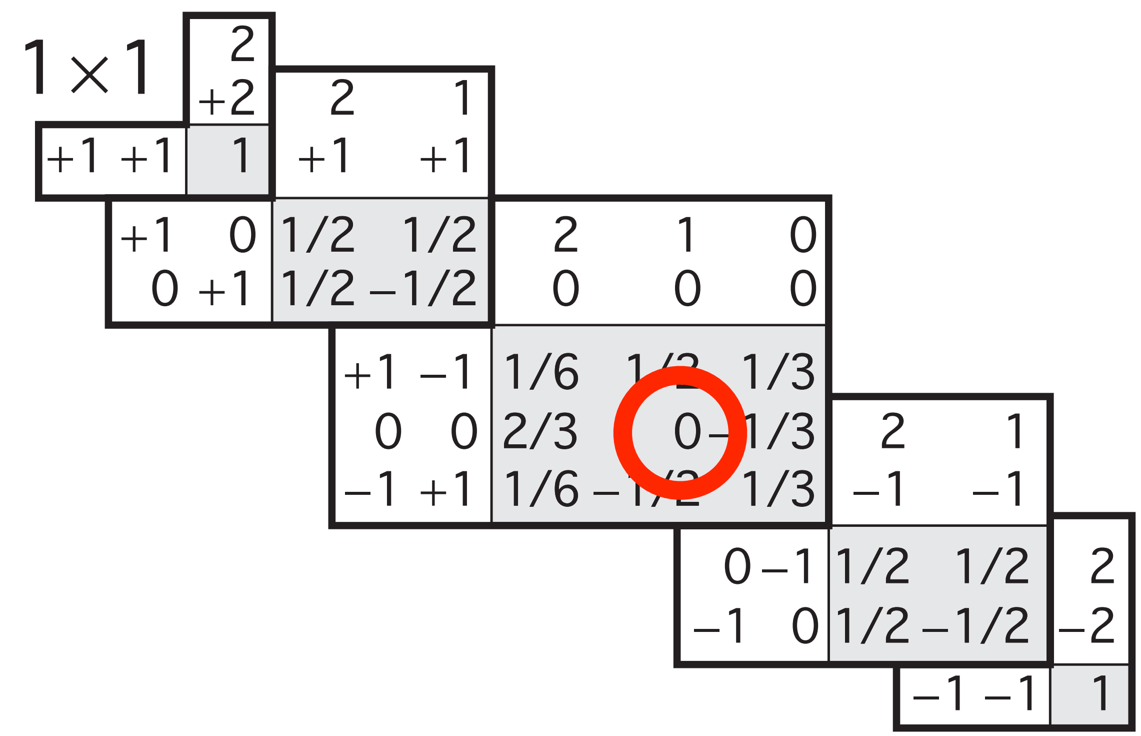

H = **1** or **5** are only possibilities.

Low and Lykken, [arXiv:1005.0872].

COUPLINGS

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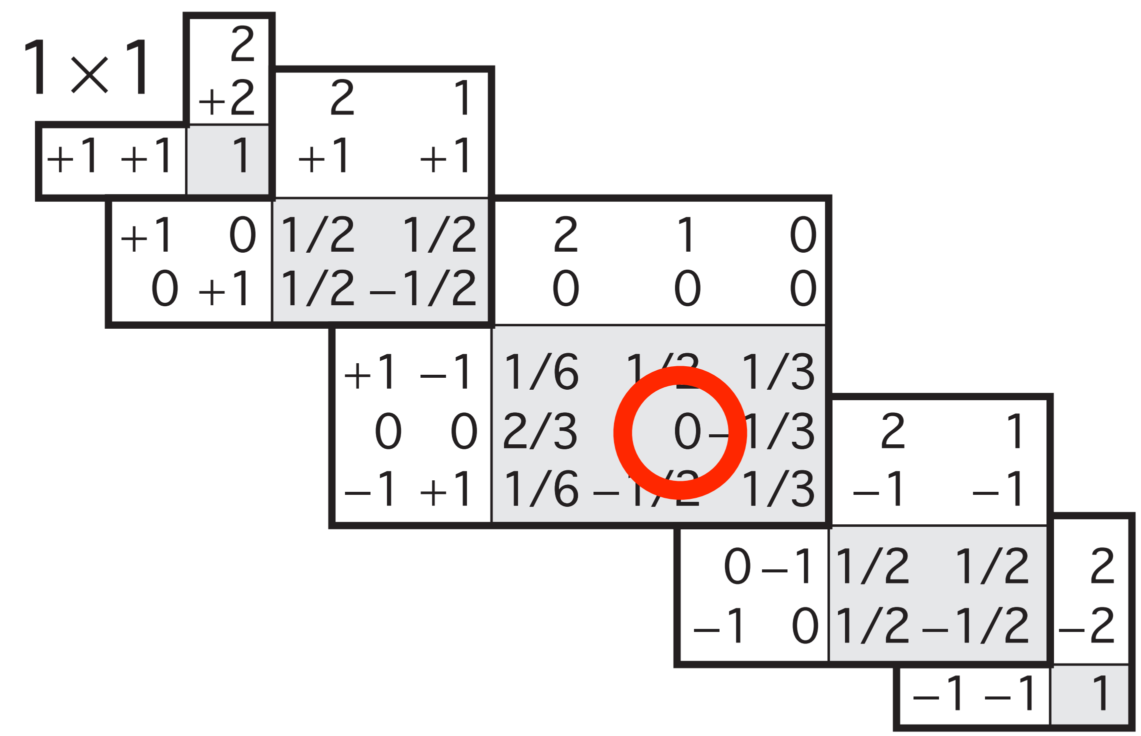


Look up Clebsch-Gordan coefficients.

Isospin 1 "Higgs" cannot couple to pair of m=0 vectors, namely ZZ.

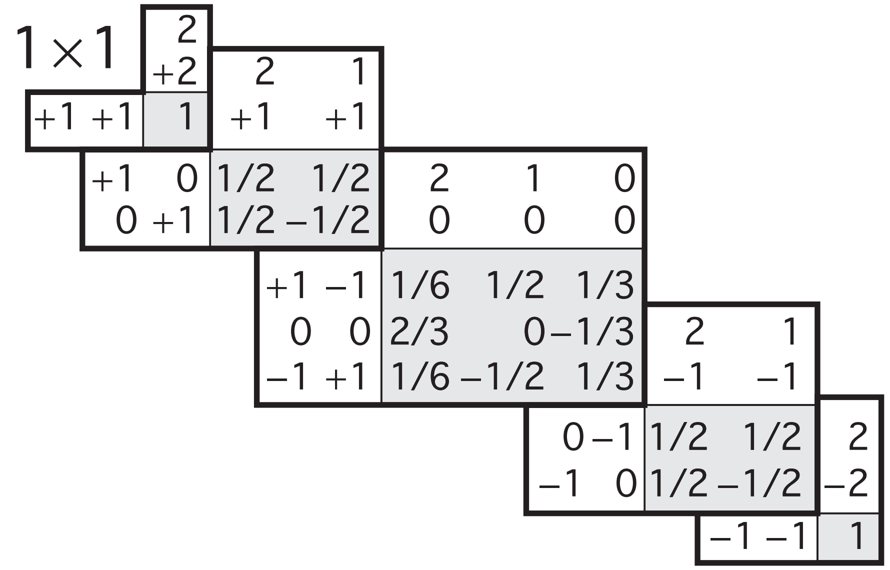
Isospin 2

H = **1** or **5** are only possibilities.

Low and Lykken, [arXiv:1005.0872].

COUPLINGS

Can compute ratios of couplings for **1** and **5**.



H_1 (2 W^+ W^- + Z Z)

$$\lambda_{WZ} = +1$$

H_5 (W^+ W^- — Z Z)

$$\lambda_{WZ} = -1/2$$

Two cases predict opposite signs!

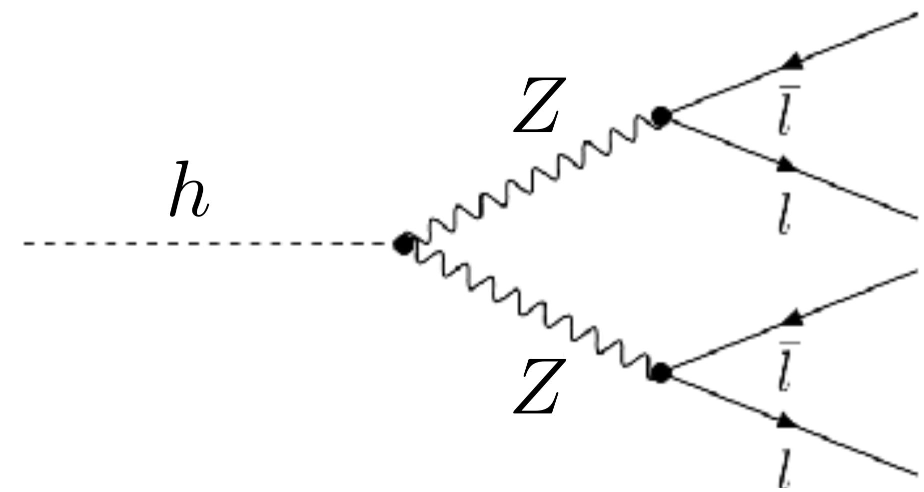
Low and Lykken, [arXiv:1005.0872].

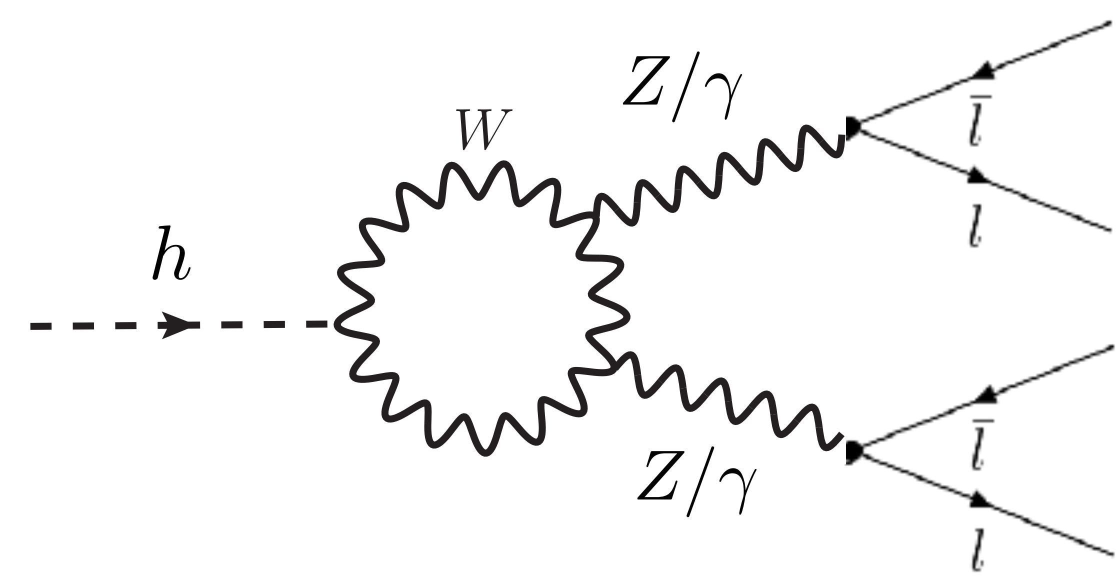
H(125)

Let's measure the sign:

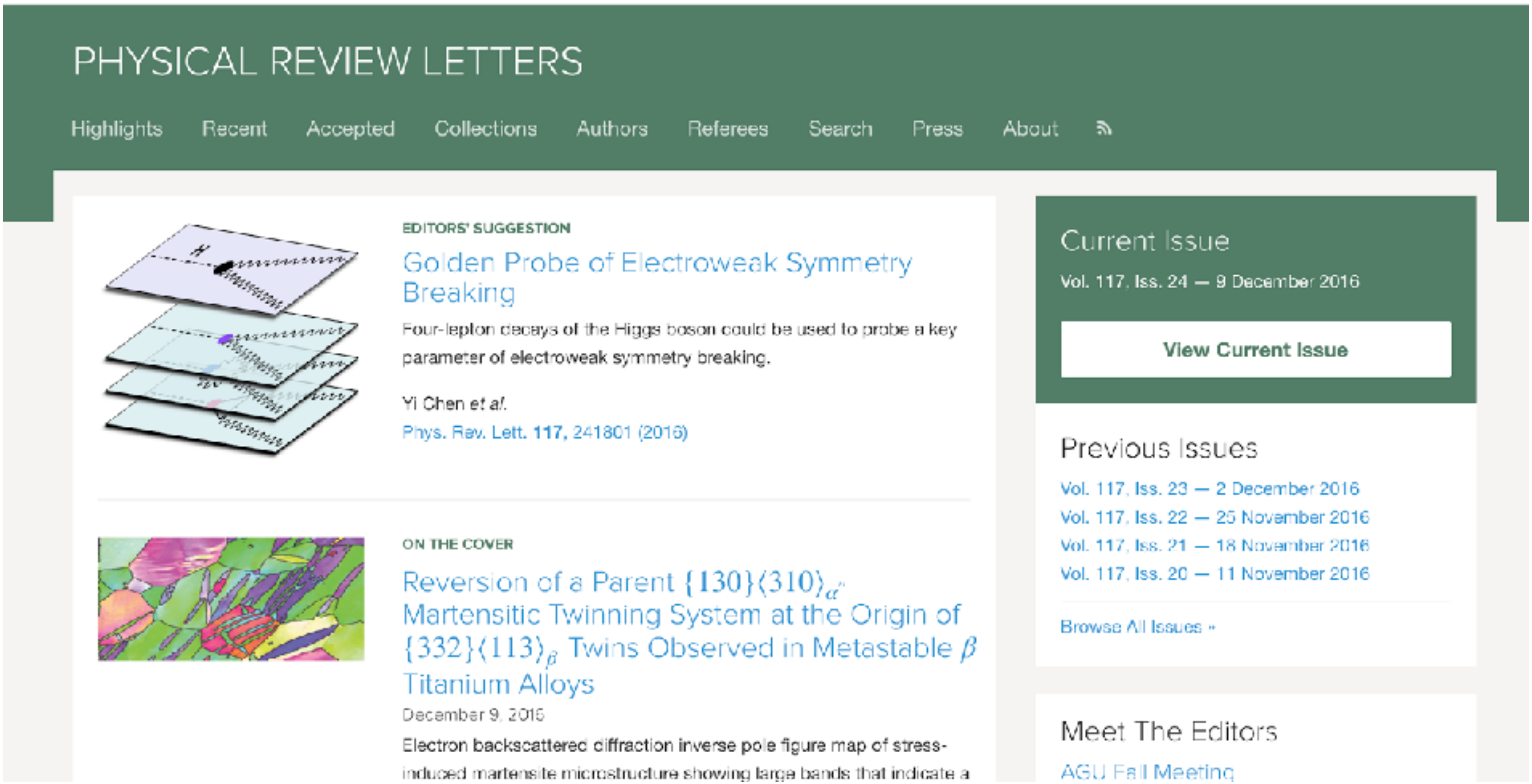
Rate measurements insensitive to sign.

Can use interference effects.





HUMBLEBRAG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Yi Chen *et al.*
Phys. Rev. Lett. **117**, 241801 (2016)
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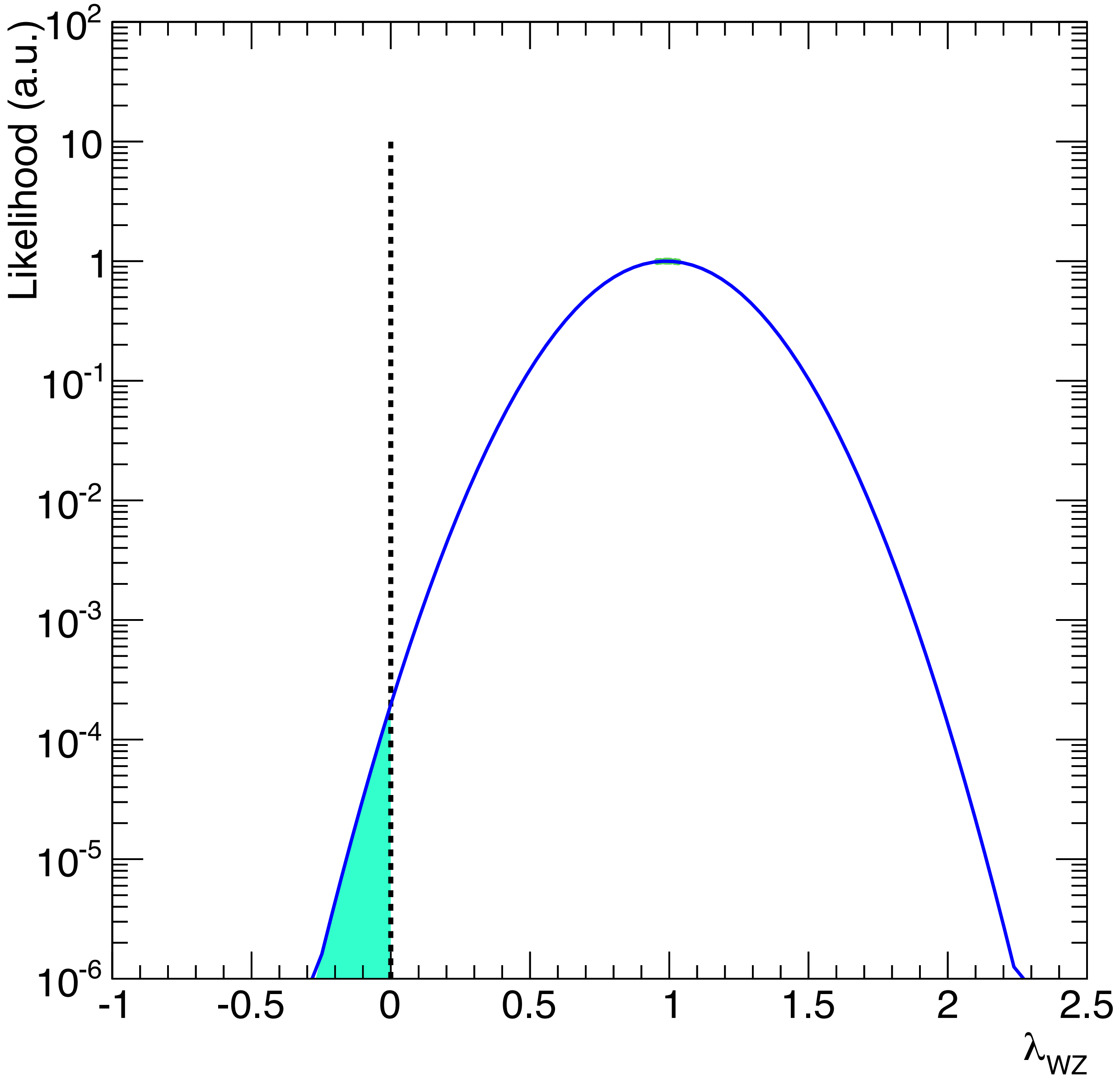
MEASURING THE SIGN

Build up likelihood with data.

Will now be function of continuous parameter λ_{WZ}.

What is probability that it is negative?



2,000 events

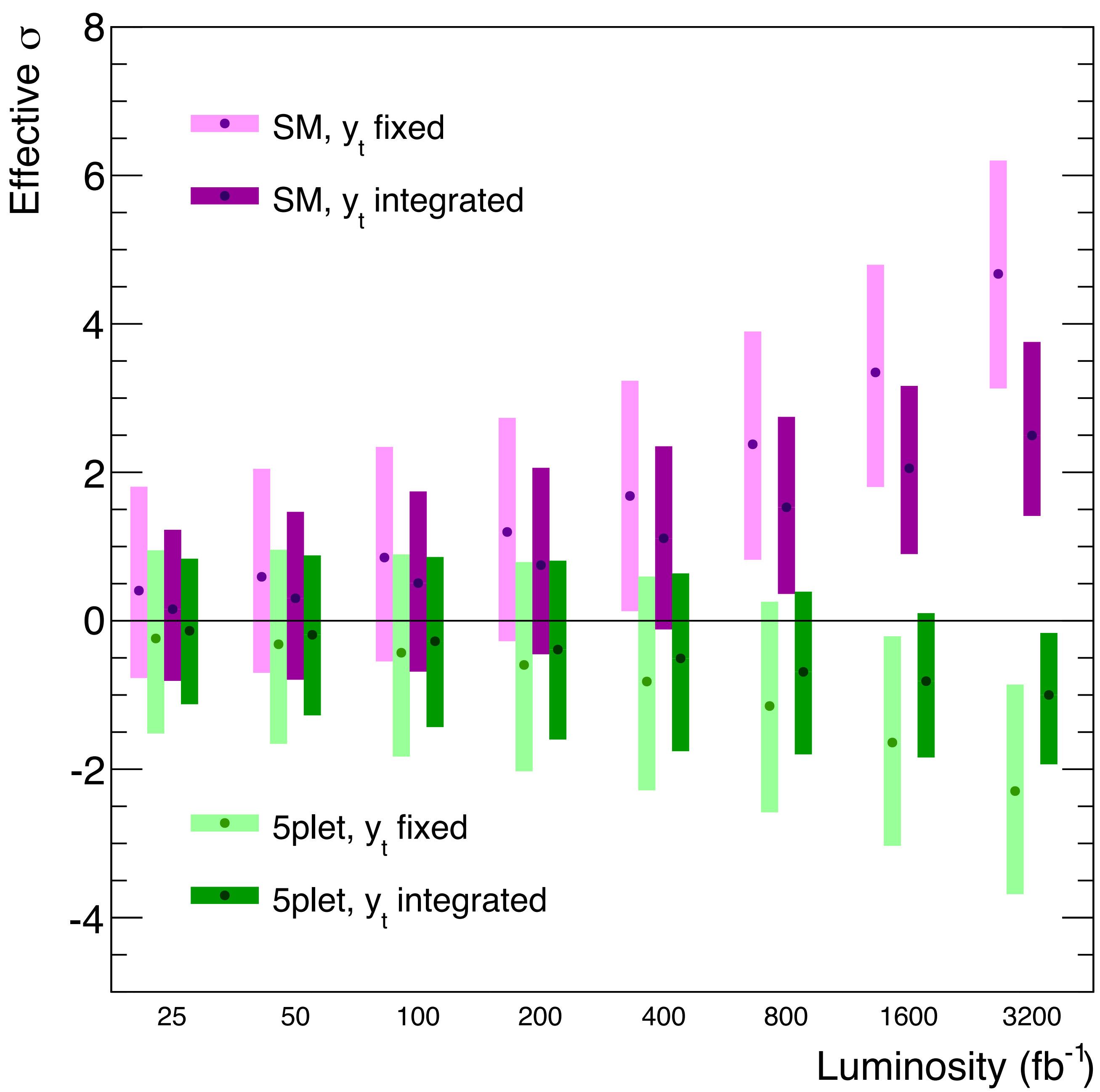
Y. Chen, J. Lykken, M. Spiropulu, DS, R. Vega-Morales, Phys.Rev.Lett.117, no. 24, 241801, 2016 [arXiv:1608.02159].

MEASURING THE SIGN

Can distinguish two different cases with (high-luminosity) LHC data.

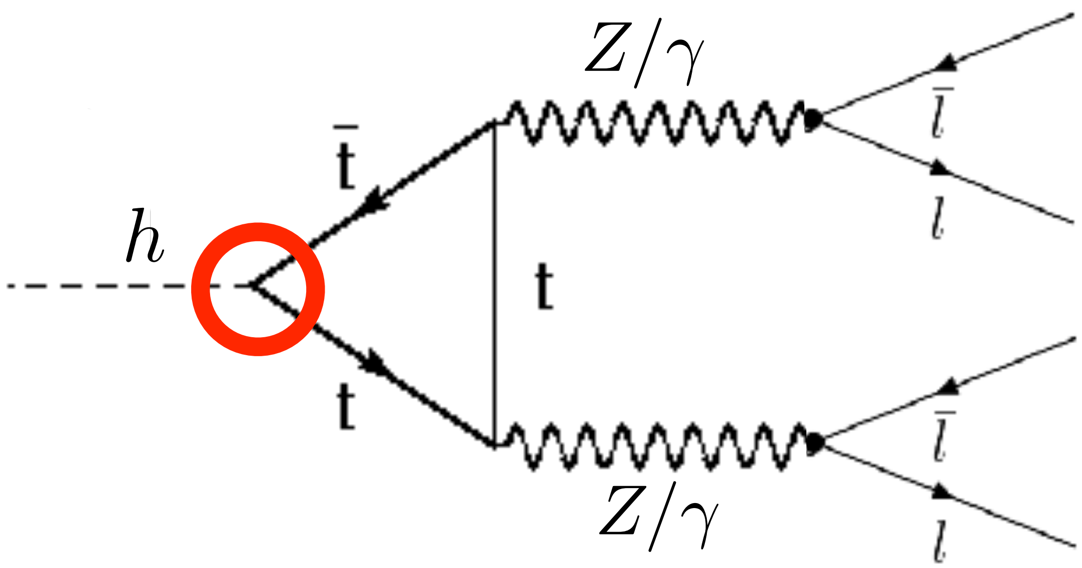
Nearly independent of other parameters (mainly top Yukawa coupling).

Y. Chen, J. Lykken, M. Spiropulu, DS, R. Vega-Morales, Phys.Rev.Lett.117, no. 24, 241801, 2016 [arXiv:1608.02159].



TOP YUKAWA

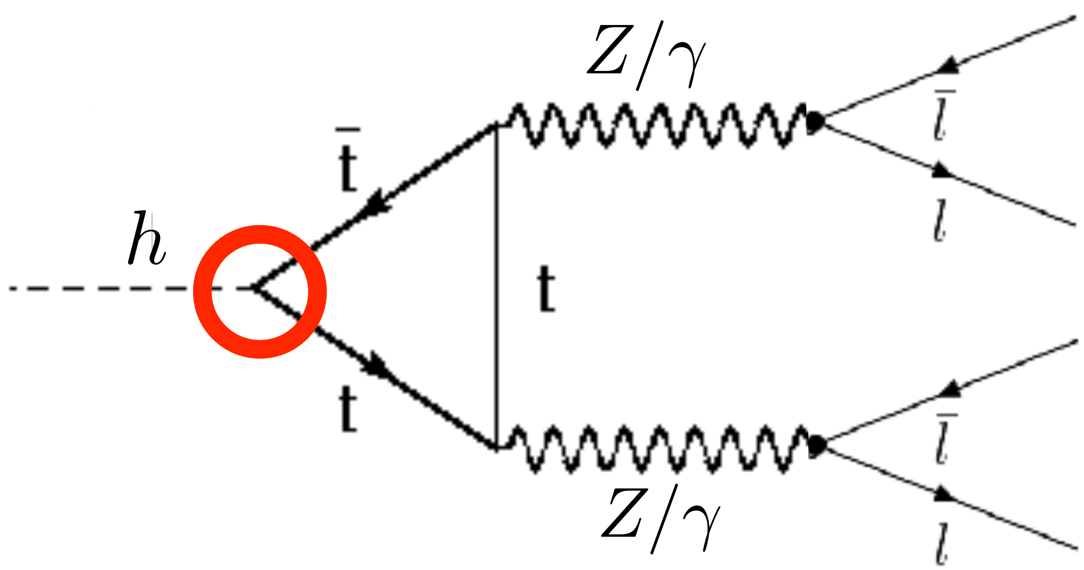
Next largest interference effect: the top quark.



SM predicts this coupling is P and CP even.

Can we test that with data?

TOP YUKAWA



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

$$\text{SM } y \approx 1 \;\&\; \tilde{y} \approx 0$$

Equivalent to measurement of phase of Yukawa.

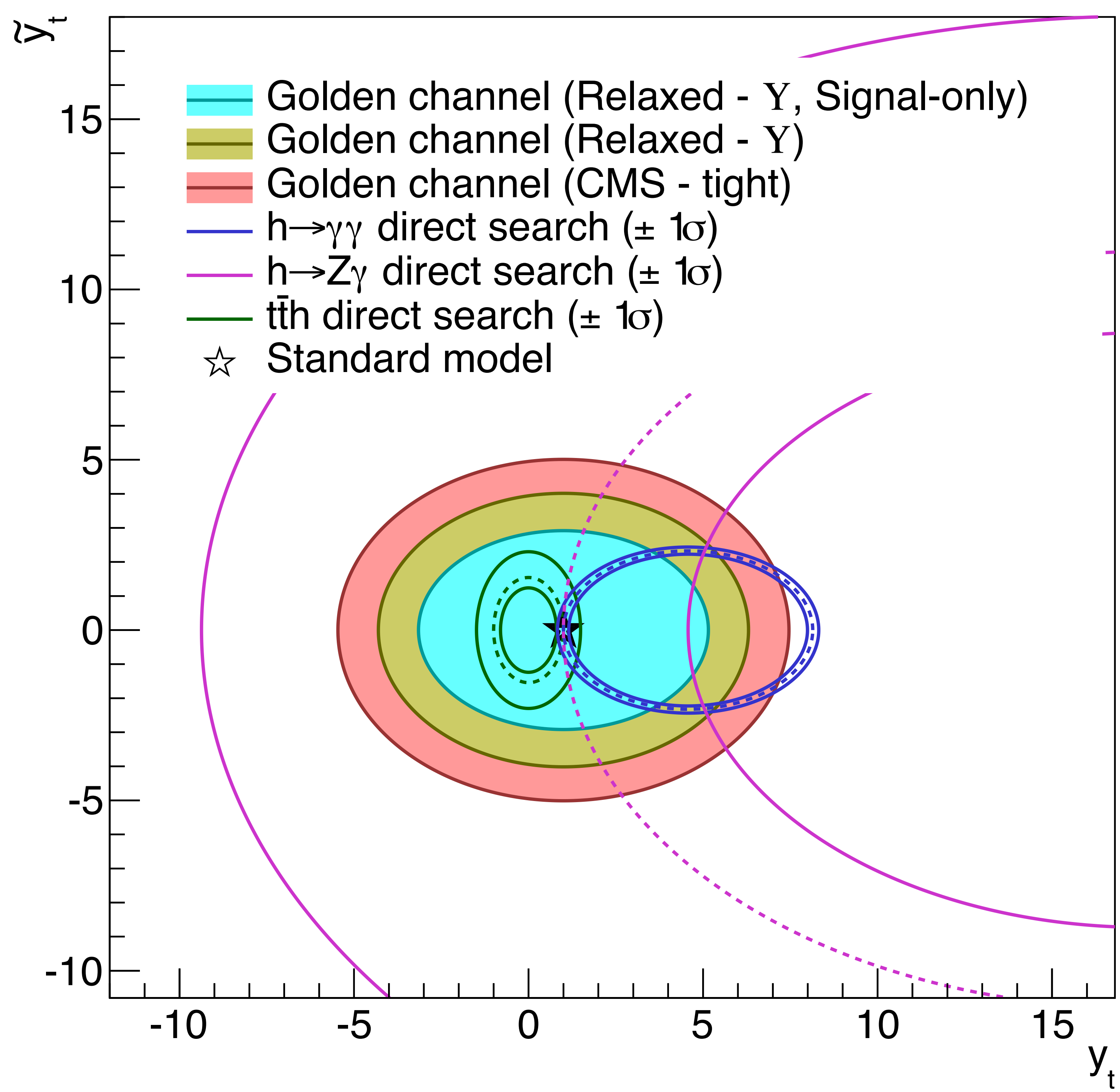
Rate measurements only sensitive to $y^2 + \tilde{y}^2$.

Make non-trivial measurements using interference.

SENSITIVITY

800 events ~ 300 fb^{-1}

Non-trivial constraint.

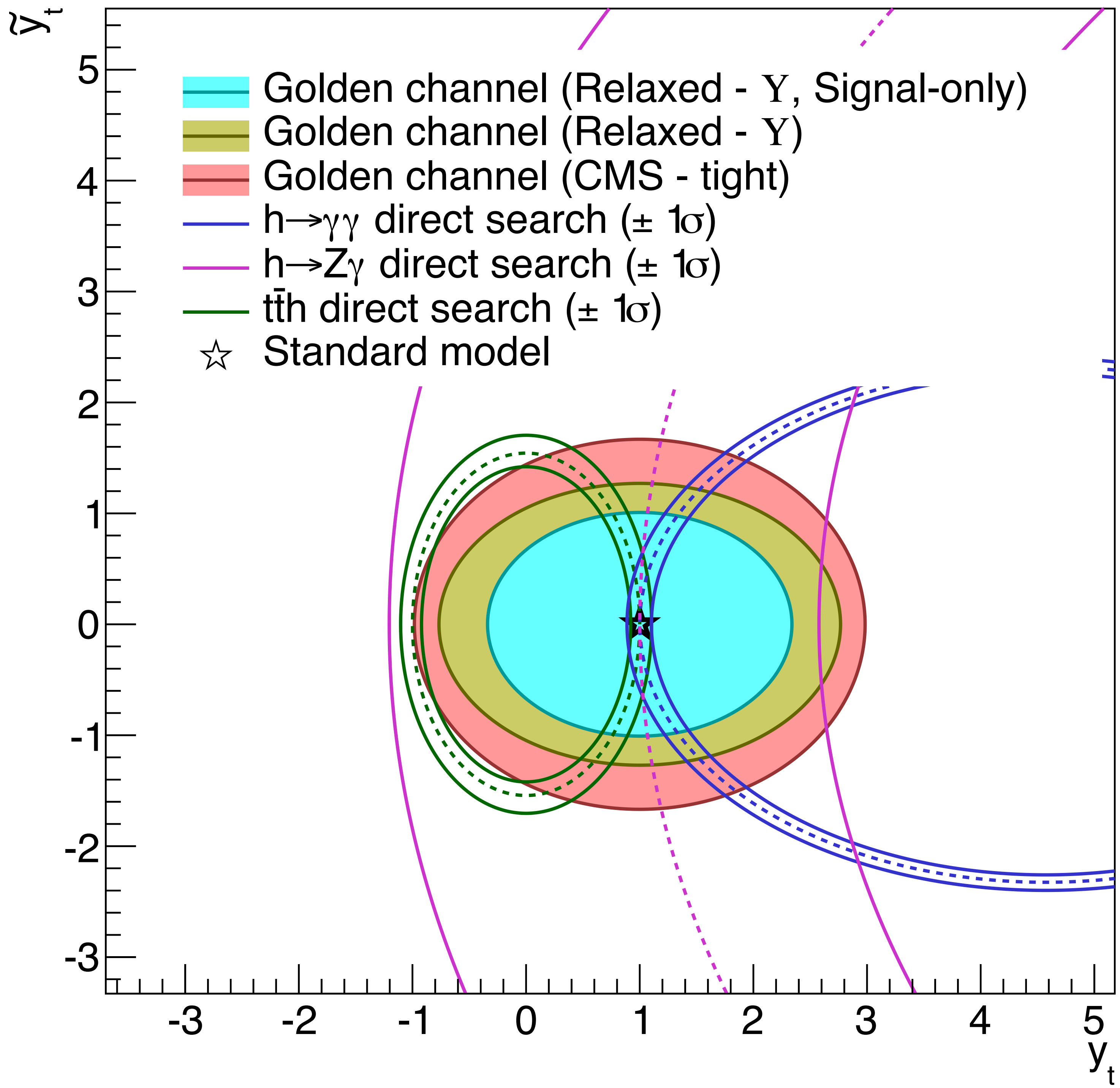


HIGH LUMINOSITY

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

Better constraint.

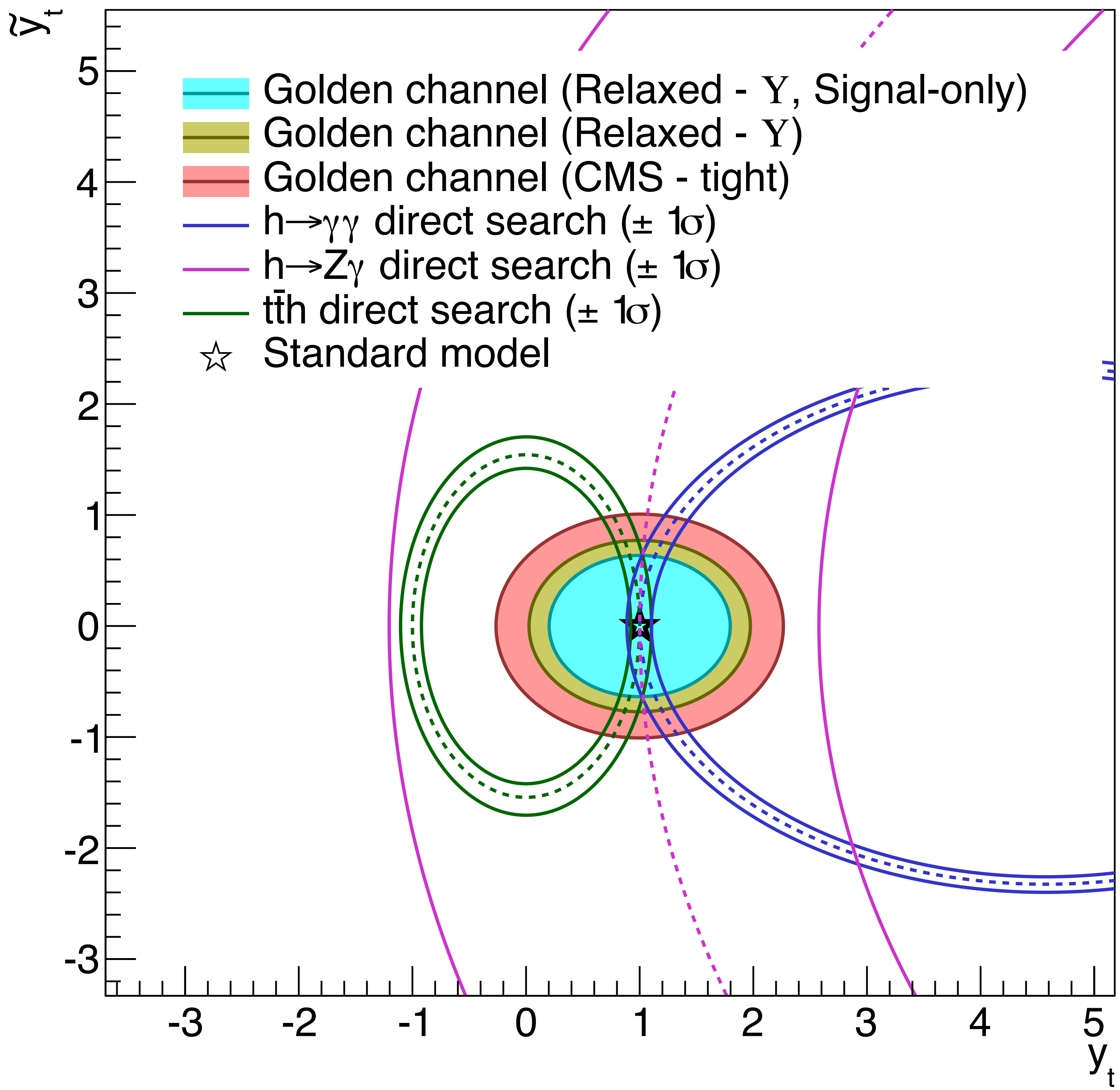
If there is anomaly, will help characterize.



100 TEV?

Can see significant improvement with future high energy collider.

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



LEPTON COLLIDER

Can we do this at a lepton collider?

Cleaner environment…

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Cleaner environment...

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

$$\mathcal{L}(\mathrm{TLEP}) \simeq 500\,/\mathrm{fb}/\mathrm{year}$$

$$\mathrm{BR}(h \to 4\ell) \simeq 10^{-4}$$

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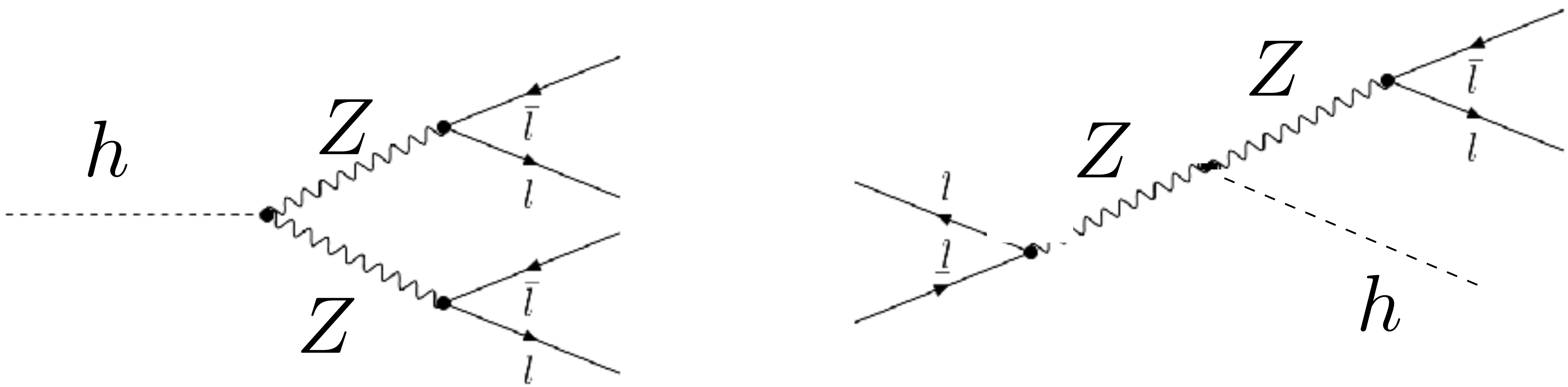
15 events per year.

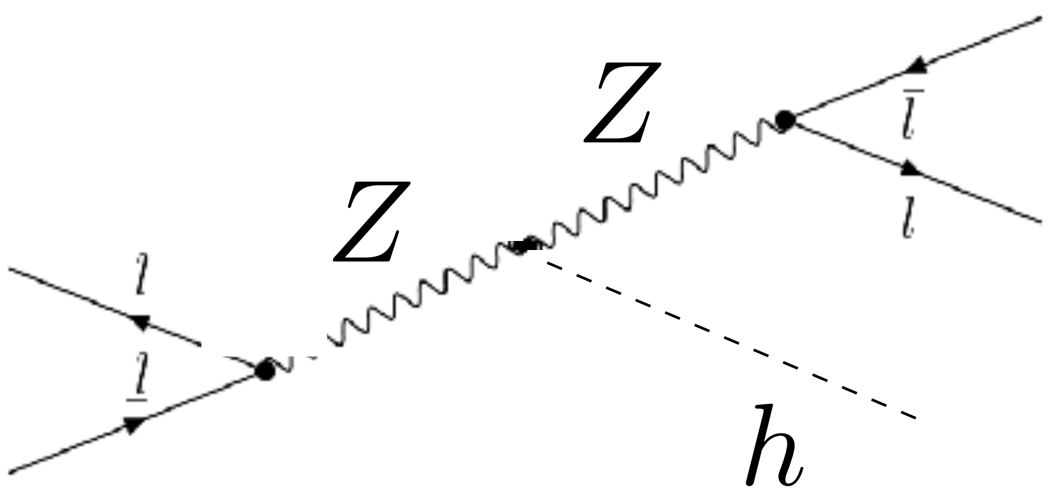
CROSSING SYMMETRY

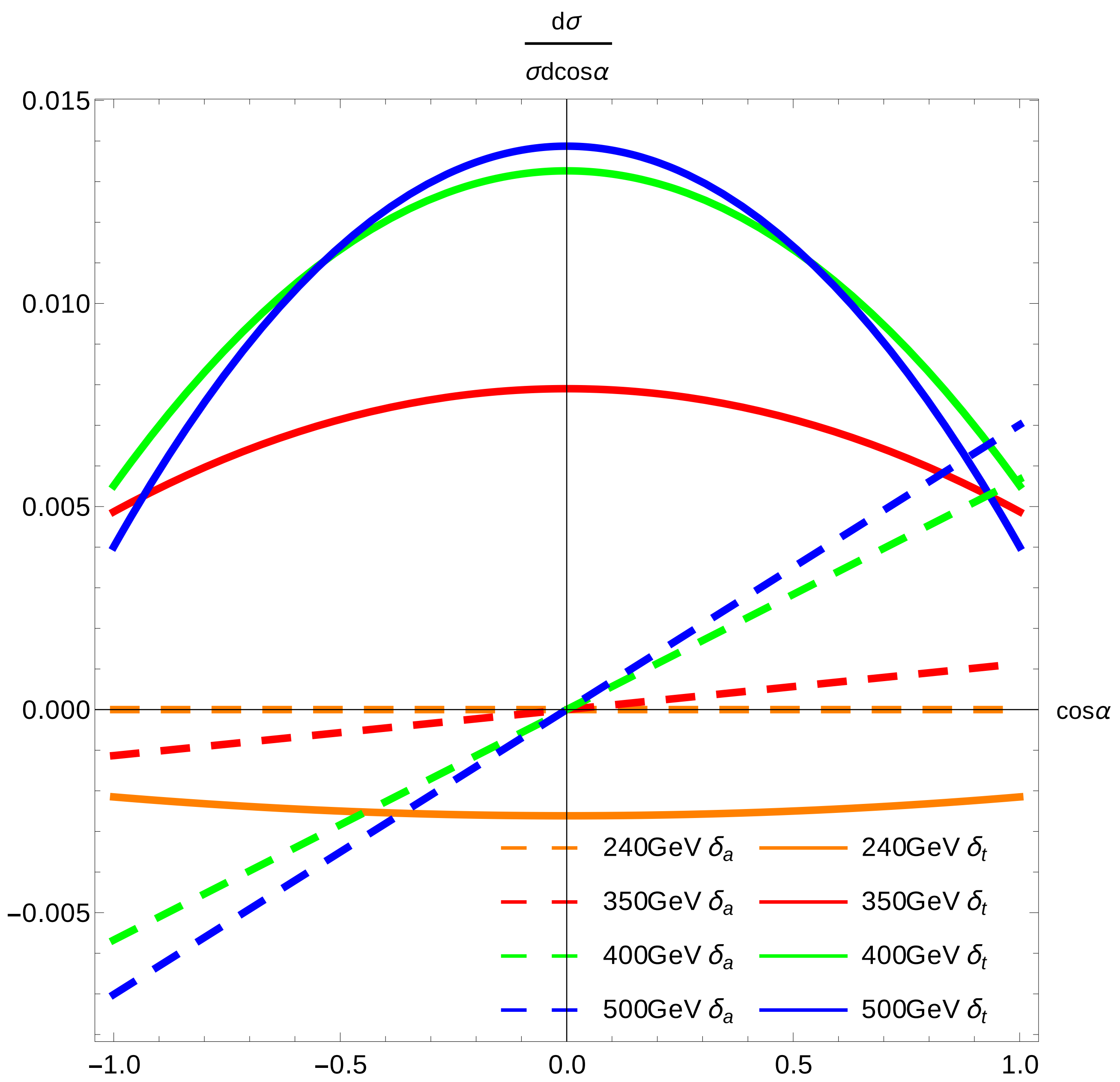


Can probe same coupling with crossed diagram.

No longer have to pay branching ratio penalty.

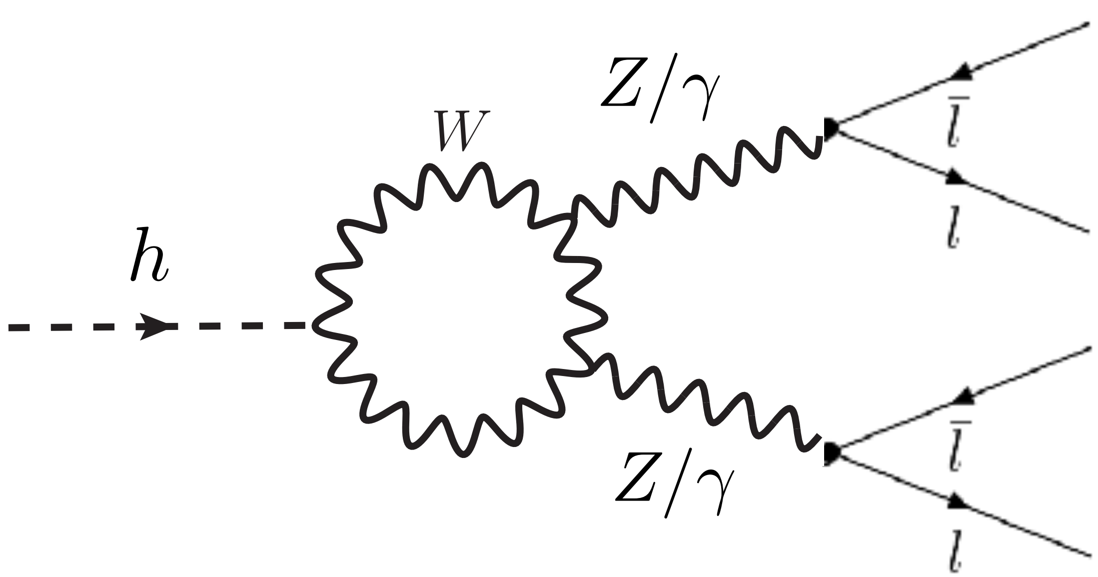
CROSSING SYMMETRY

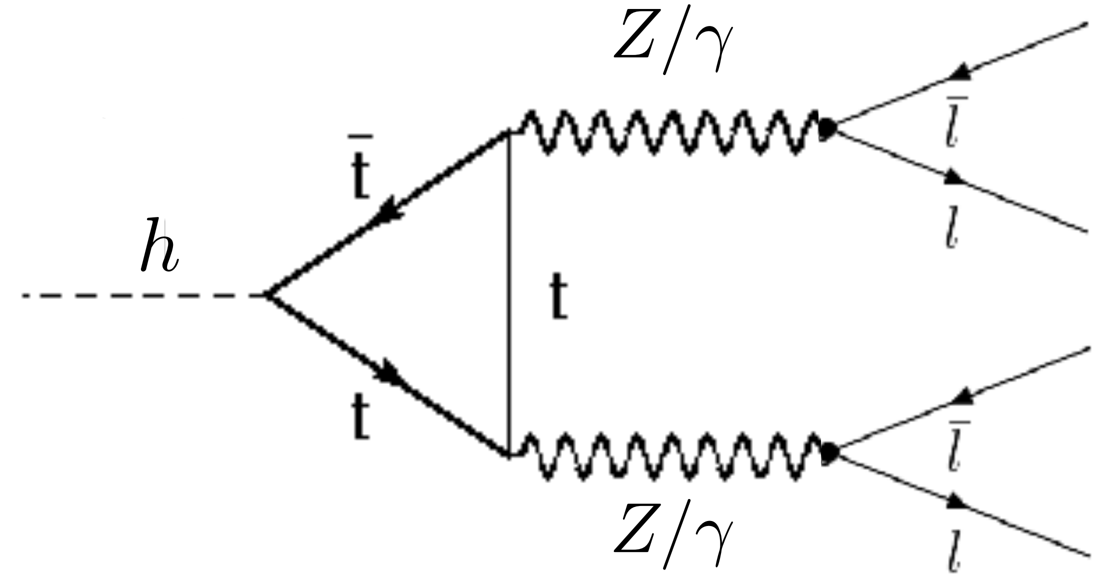




See for example:
Shen and Zhu, arXiv:1504.05626.

TOP AND W LOOPS





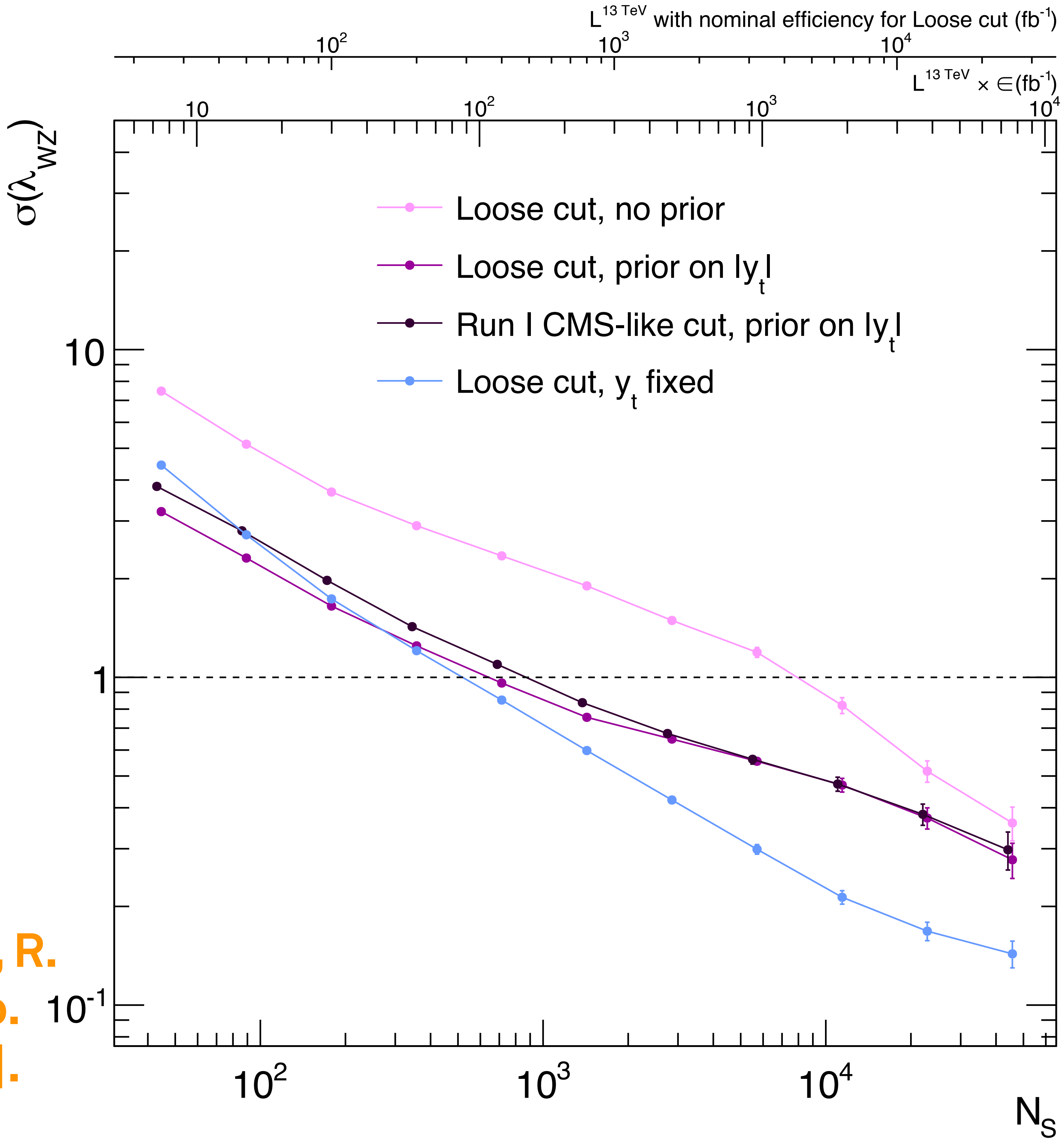
Top and W contribute to same operators, can substitute one for the other.

What happens if you float both couplings?

FIT BOTH COUPLINGS

Can float multiple couplings simultaneously.

Full LHC run will give lots of information.

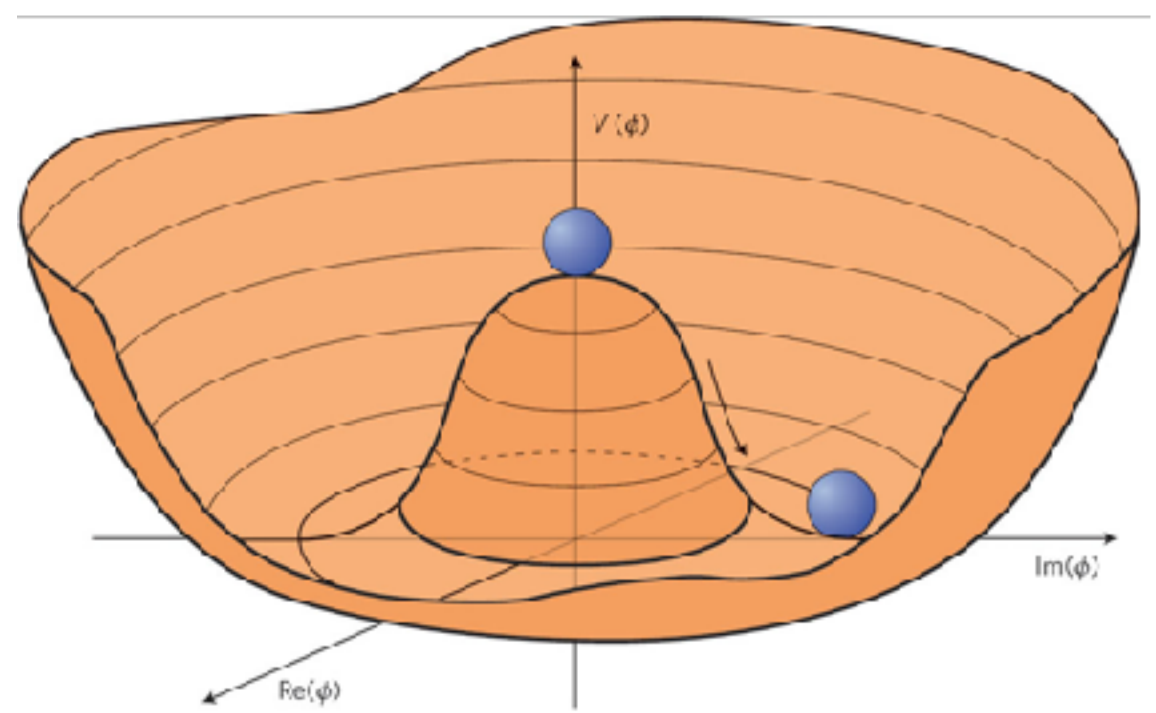


Y. Chen, J. Lykken, M. Spiropulu, DS, R. Vega-Morales, Phys.Rev.Lett.117, no. 24, 241801, 2016 [arXiv:1608.02159].

ACCESS HIGGS POTENTIAL

Currently we have no information about Higgs potential.

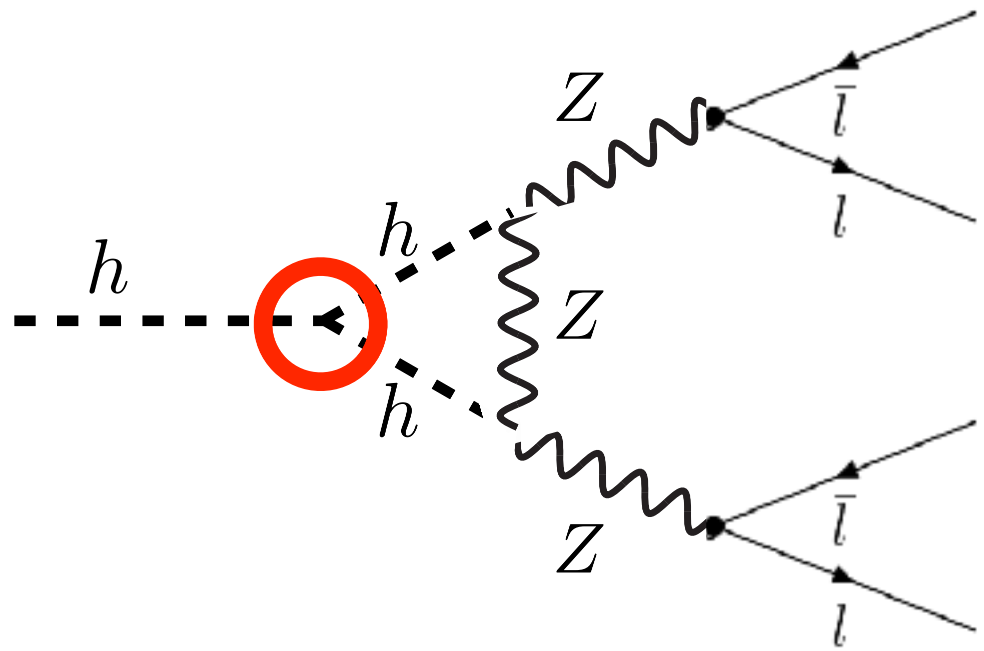
SM uses Mexican hat, but no direct evidence for that.

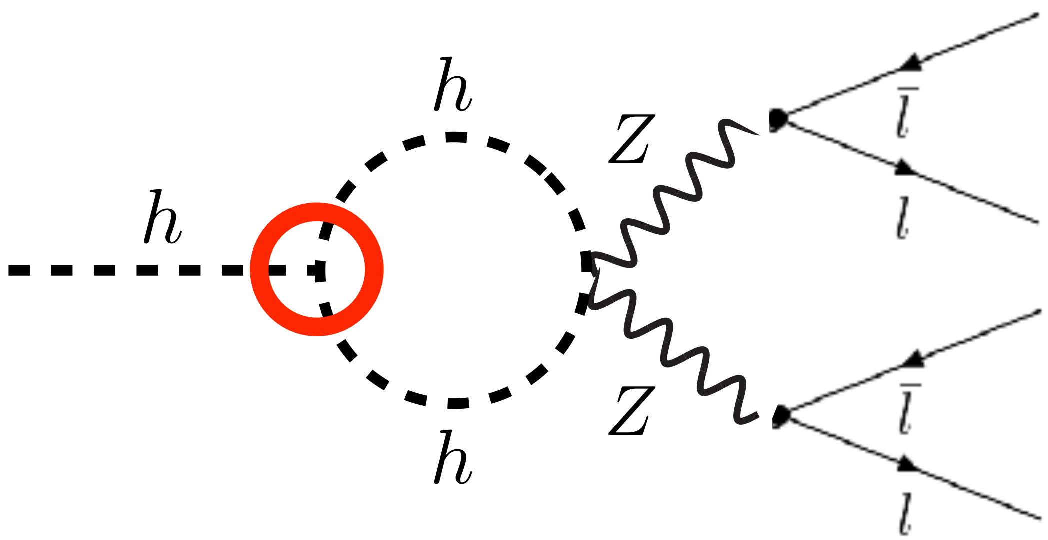


Triple Higgs coupling (HHH) is a measure of third derivative of potential at the minimum.

First direct measurement of structure of potential.

TRIPLE HIGGS COUPLING





Triple Higgs coupling also comes into NLO corrections.

Only contributes when Z's are in final state.

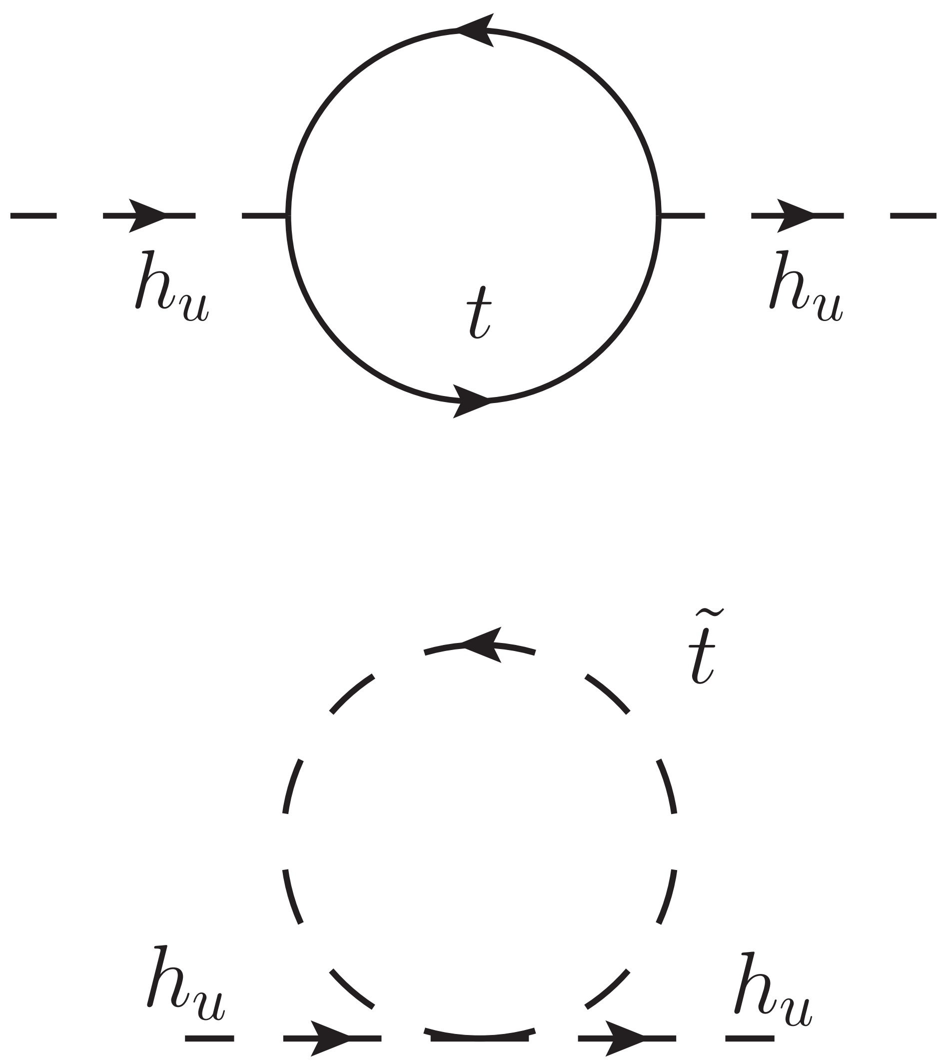
Work in progress.

HIERARCHY PROBLEM

SM Higgs has a hierarchy problem.

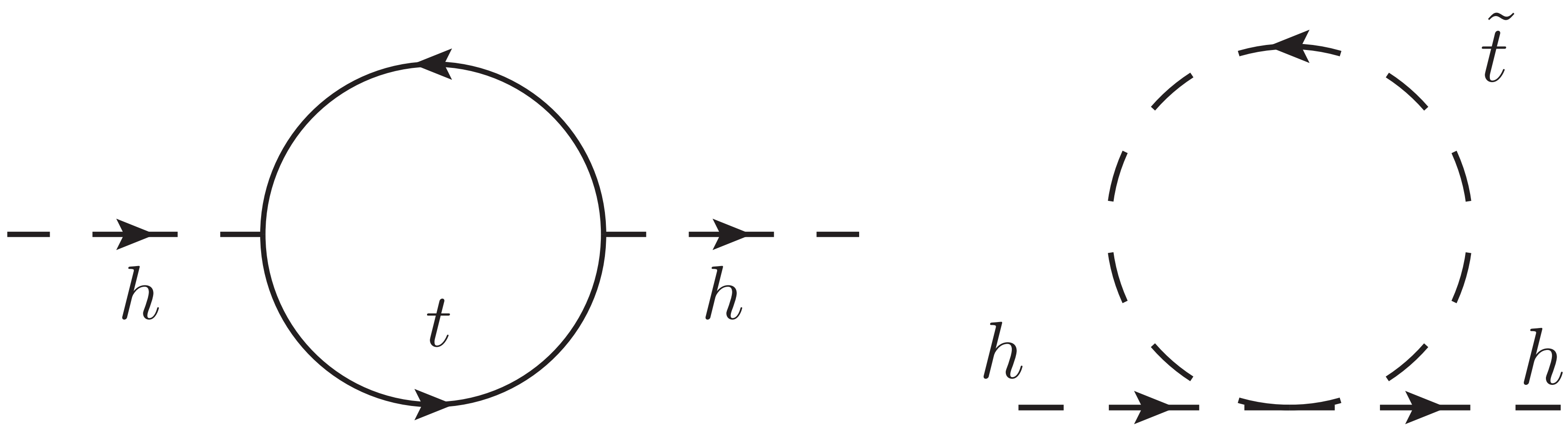
Quantum correction make Higgs mass sensitive to high scale physics.

SM is fine-tuned to 1 part in 10^{32}.



CANCELLATION

Adding new particles can cancel sensitivity (to a log).

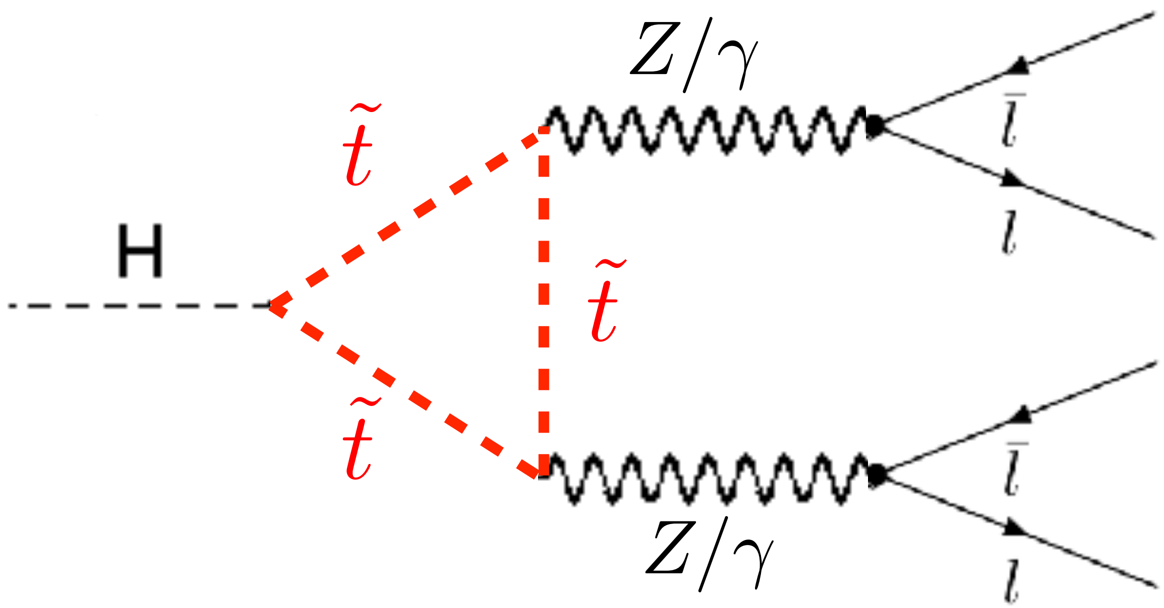


$$E_{\text{self}} \sim \frac{y}{2\pi} m_t \log(\Lambda/m_t)$$

Particle has to have same coupling to the Higgs.
(Supersymmetry is most famous example).

BSM PHYSICS

Can use Higgs coupling to stop to directly probe other fields that couple to Higgs.



Independent of decay, do not have to carry colour.

Work in progress with Paul Smith.

CONCLUSIONS

- Kinematic distributions in $h \to 4\ell$ can provide unique and complementary tests of the SM.
- NLO contributions make this channel sensitive to large Higgs couplings.
- Can probe non-standard custodial representations of custodial symmetry.
- Sensitivity to CP violation in the top-Higgs sector.

THANK
YOU

MATRIX ELEMENT METHOD

For a given $h \to 4\ell$ event, can compute probability of that even 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

MATRIX ELEMENT METHOD

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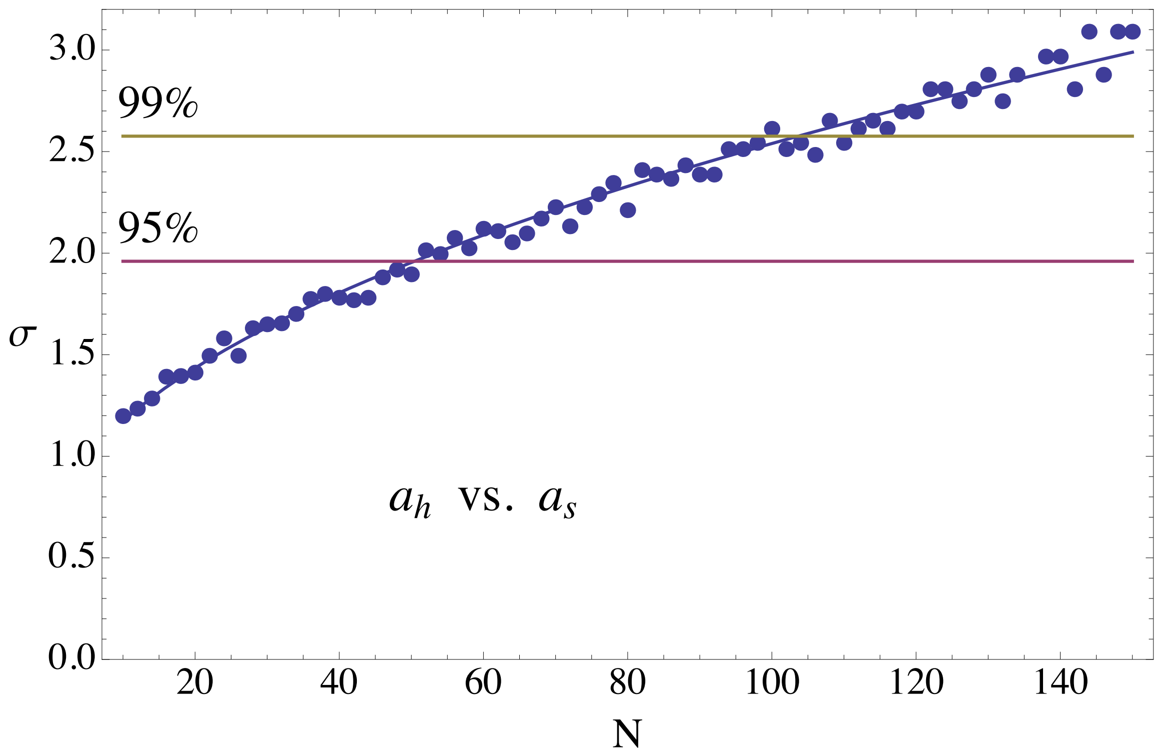
$$P(\vec{\phi}\,|a_i) = \frac{|\mathcal{M}(\vec{\phi})|^2}{\int d\vec{\phi}\,|\mathcal{M}(\vec{\phi})|^2}$$

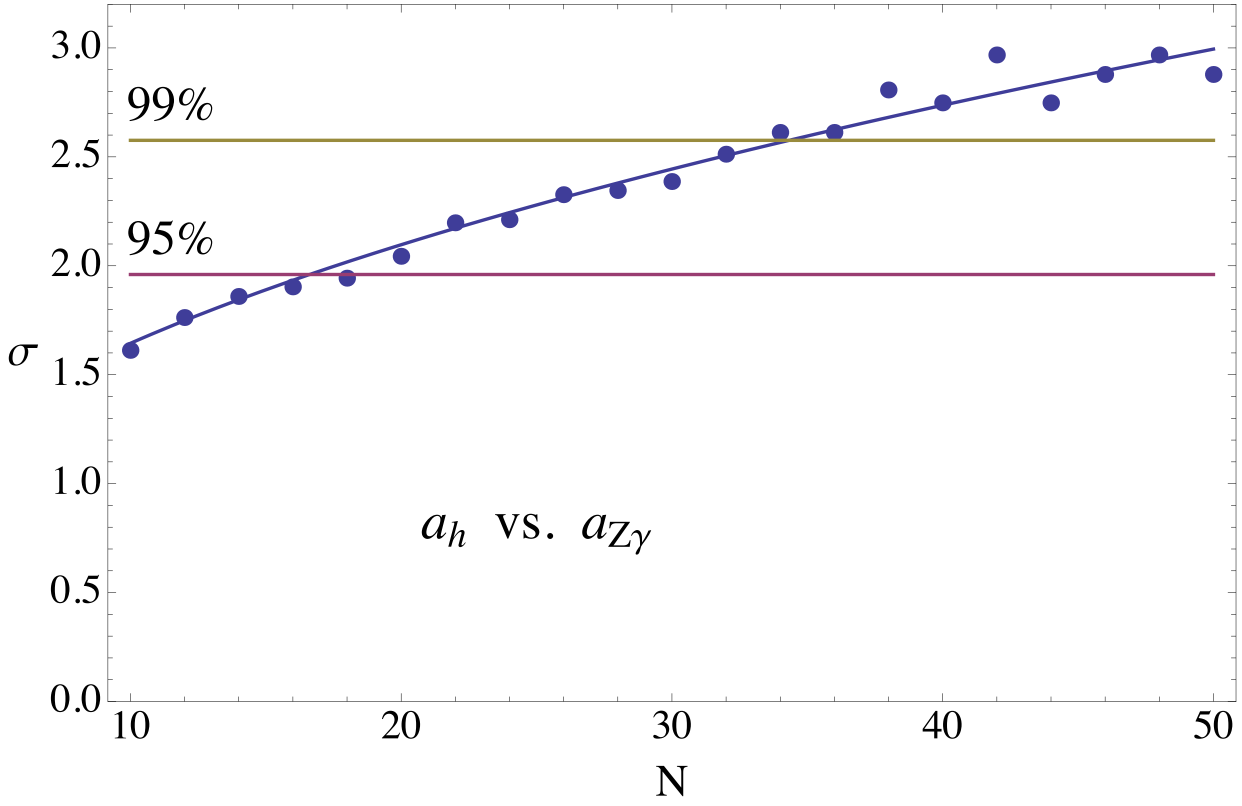
For N events, can compute likelihood for different underlying theories.

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

KINEMATIC DISTRIBUTIONS

Get better discrimination with more events.





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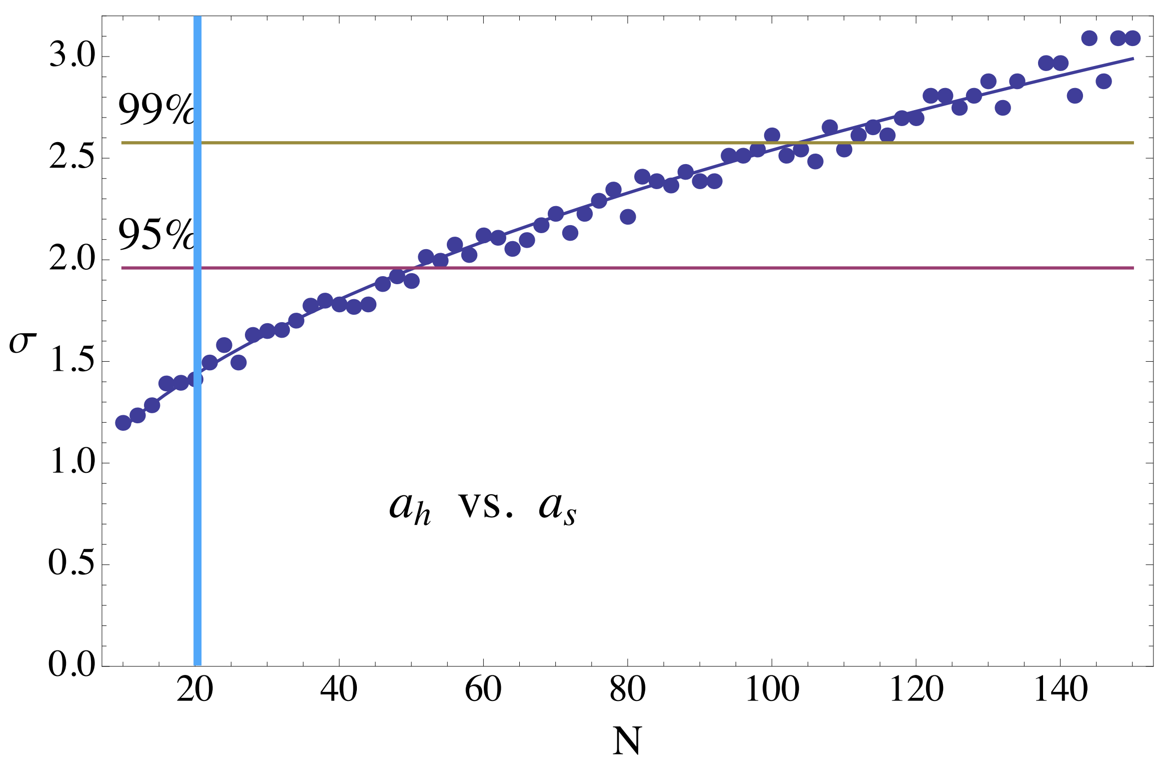
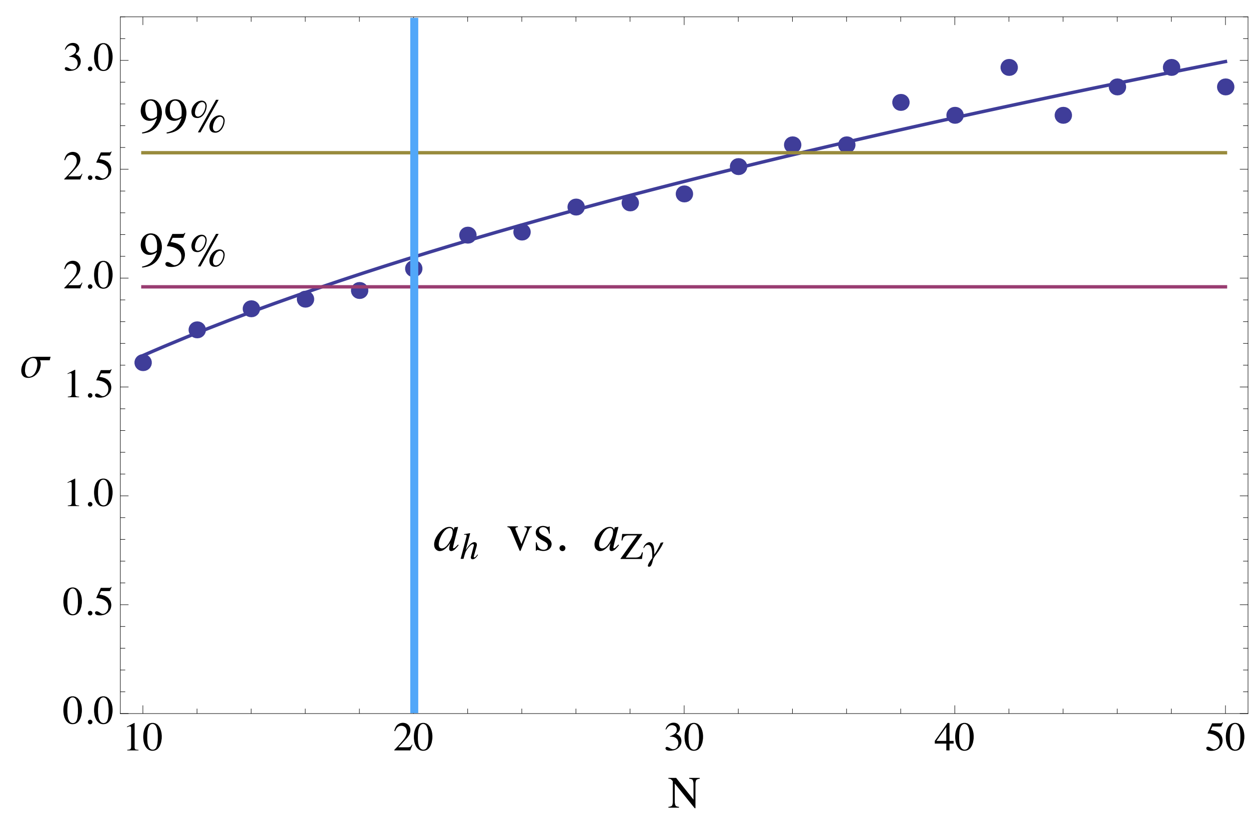
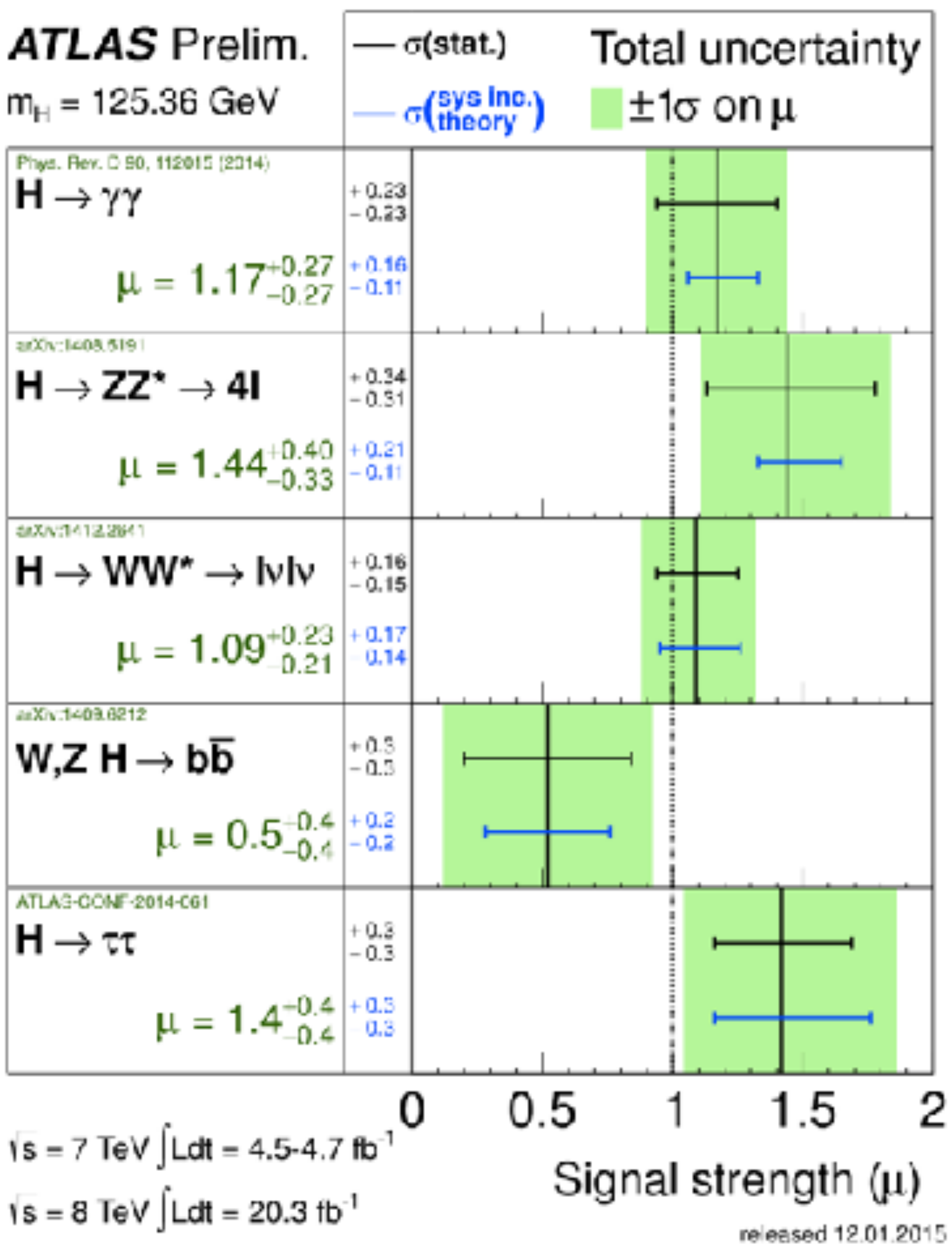
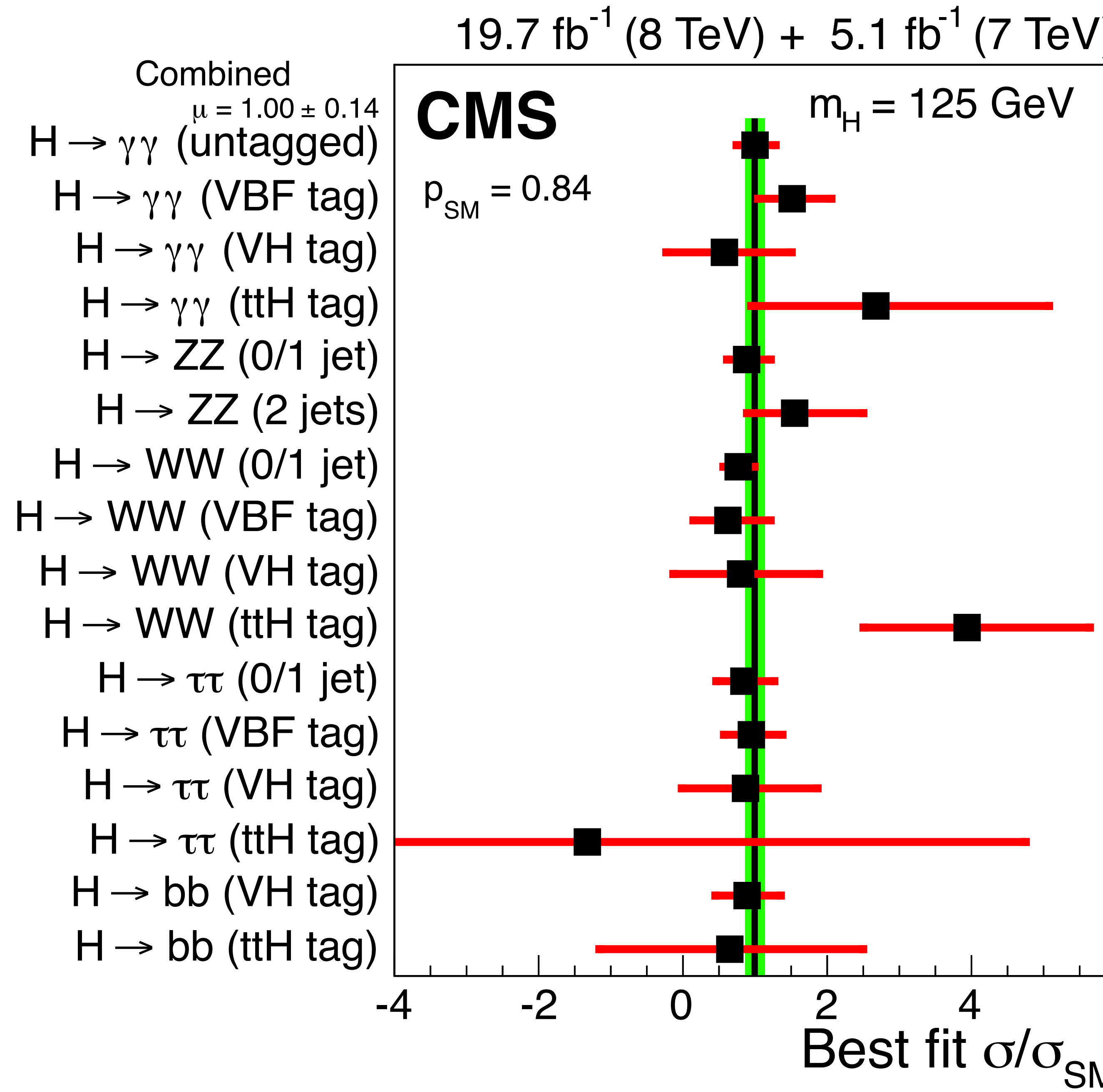




Run I data

RATE MEASUREMENTS





BIG PICTURE

At discovery, rate measurements pointed to 4 lepton coming from tree level and 2 photon at one loop.

Could imagine a tuned model:

$$c_B \, s \, B^{\mu\nu} B_{\mu\nu} \qquad\qquad c_W \, s \, W^{a\mu\nu} W^a_{\mu\nu}$$

BIG PICTURE

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Could imagine a tuned model:

$$c_B \, s \, B^{\mu\nu} B_{\mu\nu} \qquad\qquad c_W \, s \, W^{a\mu\nu} W^a_{\mu\nu}$$

Worthwhile to test SM and rule out all other logical possibilities.

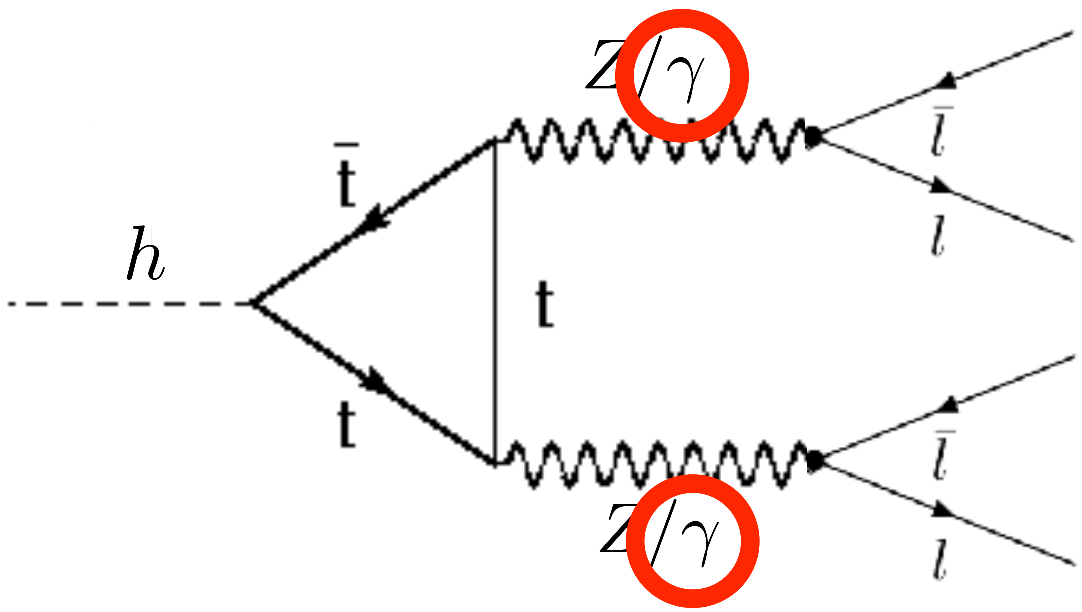
Techniques become extremely important if there is an anomaly.

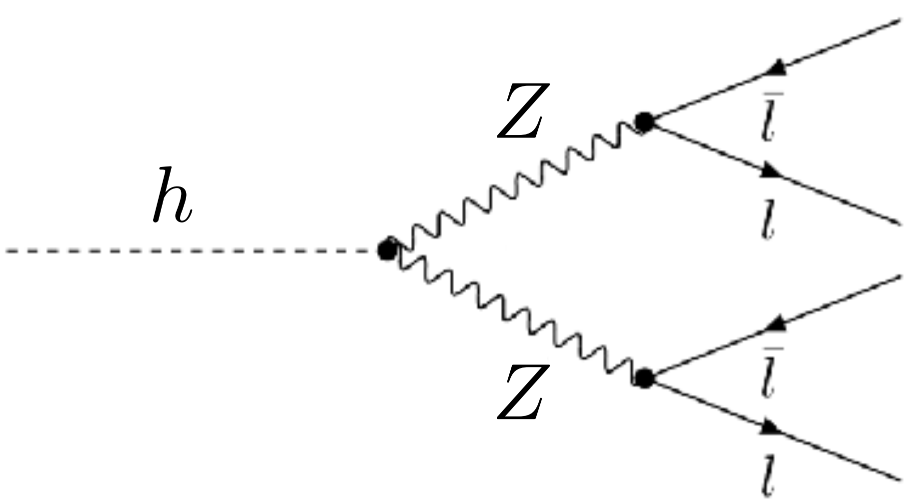
BIGGER THAN YOU THINK

Photon in final state makes NLO effect larger than naive one-loop size.

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

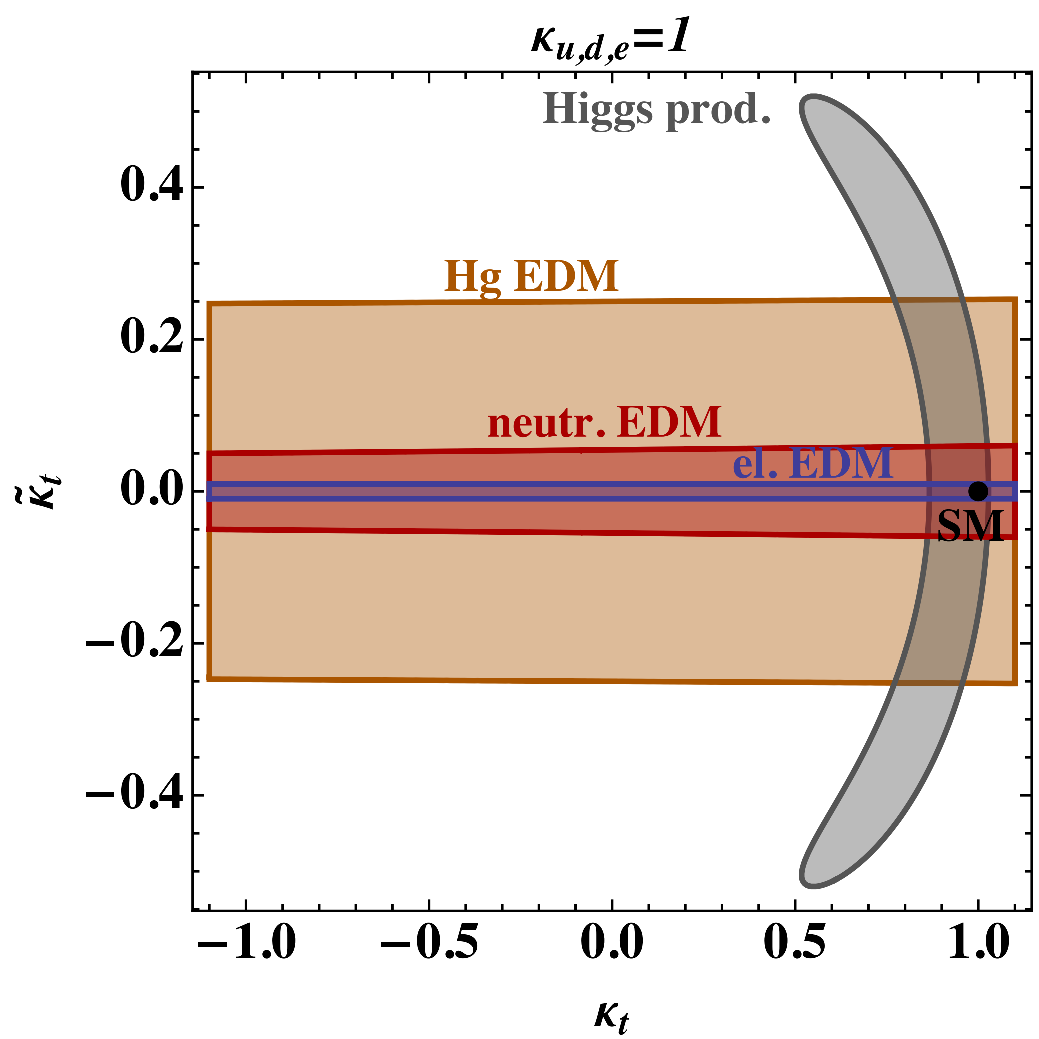
Photon coupling to leptons bigger than for Z.

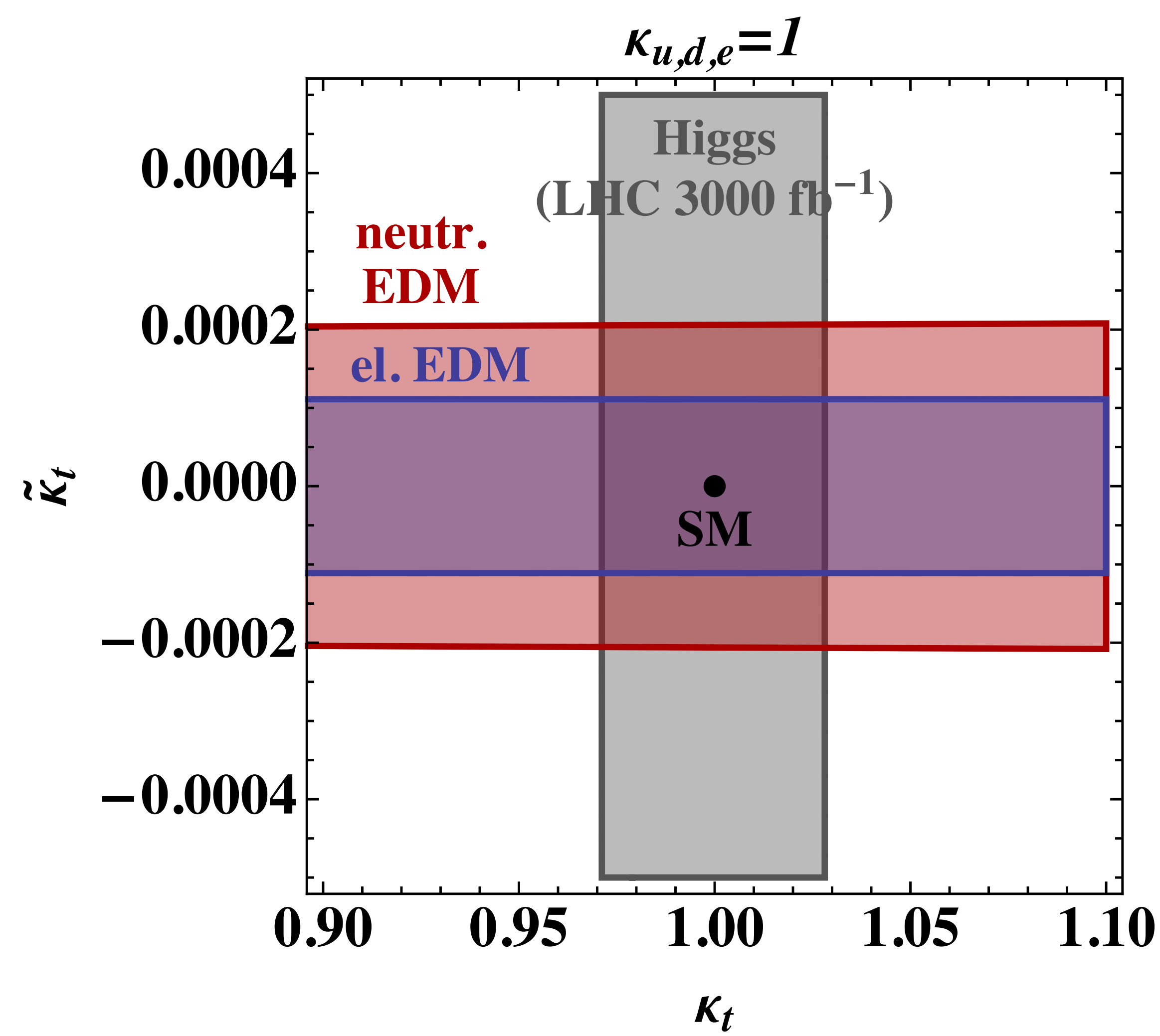




EDM BOUNDS

Can place strong bounds on CP violation from EDMs.

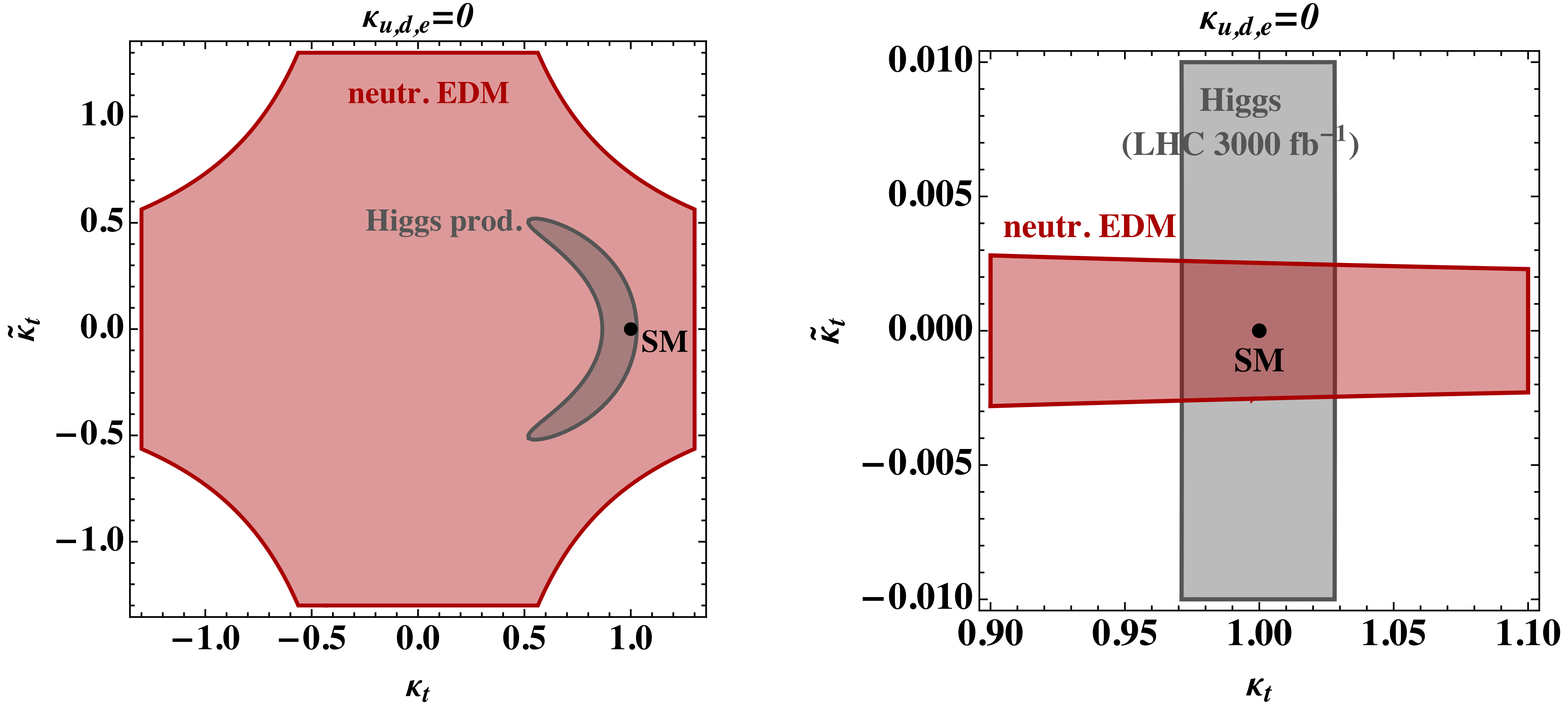




Brod, Haisch, Zupan, [arXiv:1310.1385].

EDM BOUNDS

Depend on knowing Higgs coupling to first generation.



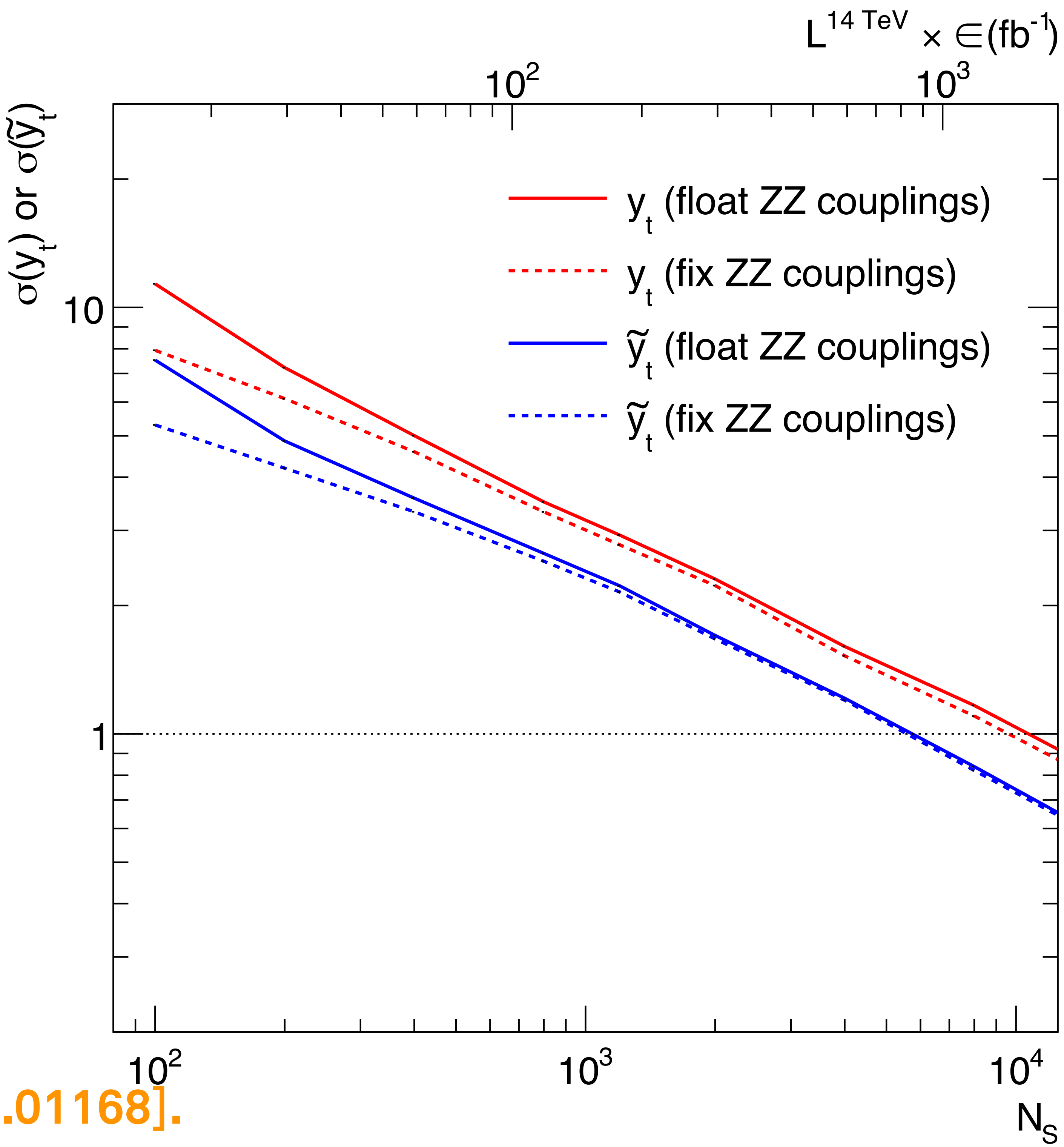
Brod, Haisch, Zupan, [arXiv:1310.1385].

SENSITIVITY

Measurement gets better with more events.

Better sensitivity to pseudo-scalar coupling.

Need large number of events.



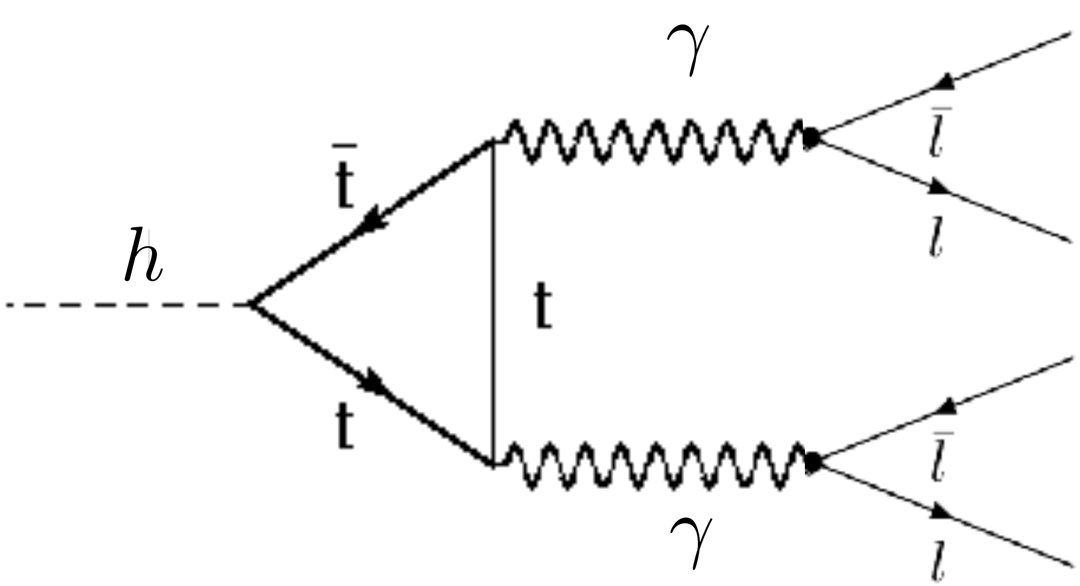
Chen, DS, Vega-Morales, [arXiv:1505.01168].

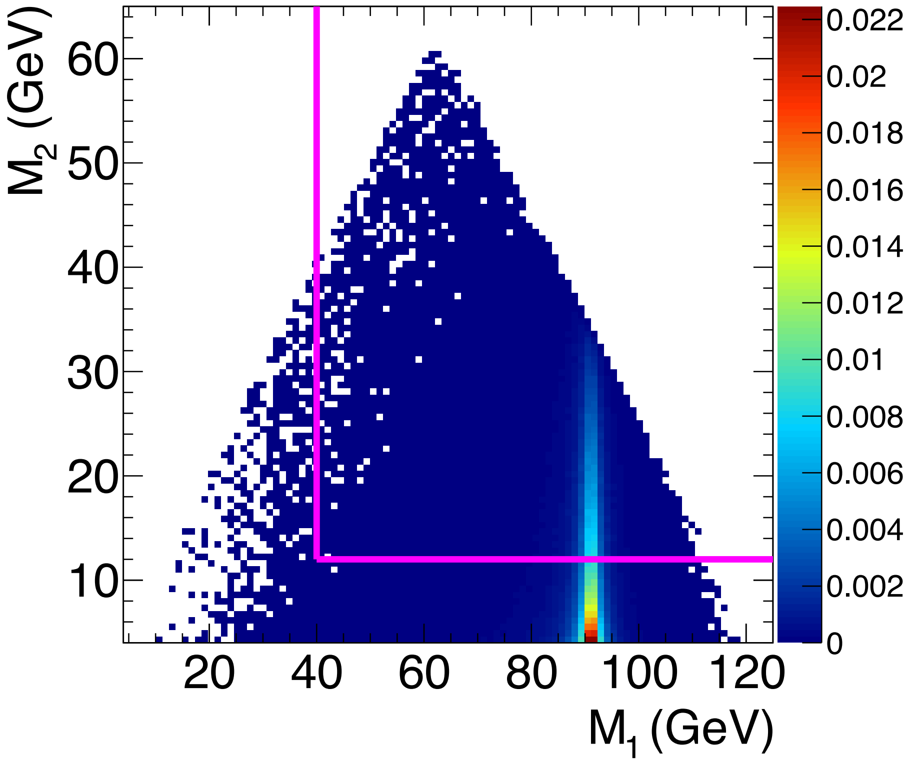
EXPERIMENTAL CUTS

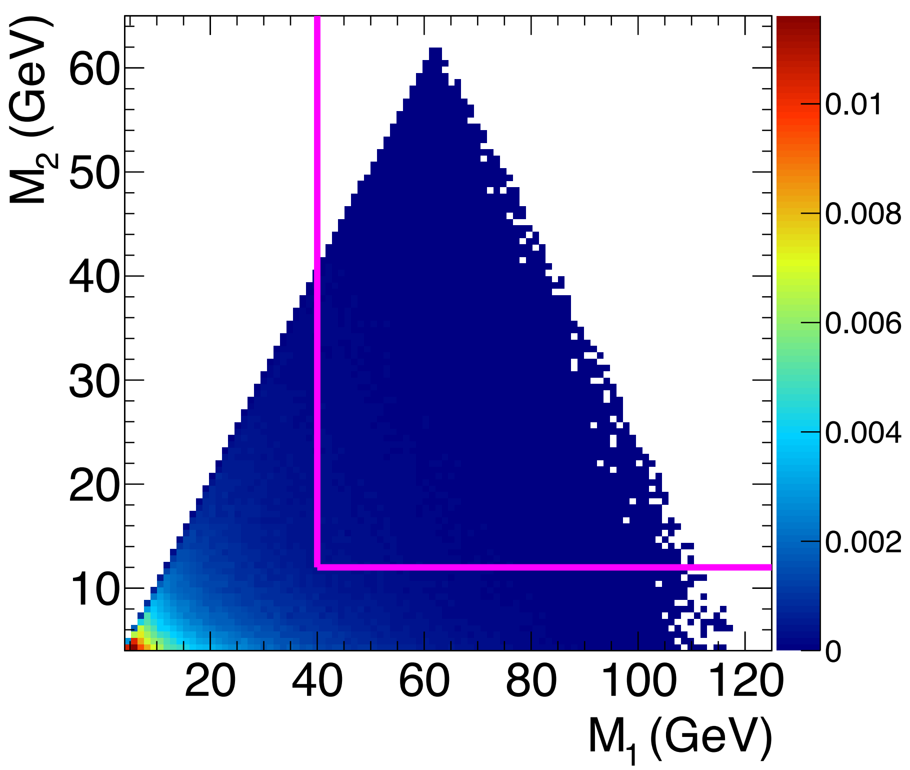
CMS cuts optimized for discovery:

$$M_1 > 40,\ M_2 > 12,\ M_{\ell\ell} > 4$$

Want to gain sensitivity to NLO effects.







EXPERIMENTAL CUTS

CMS cuts optimized for discovery:

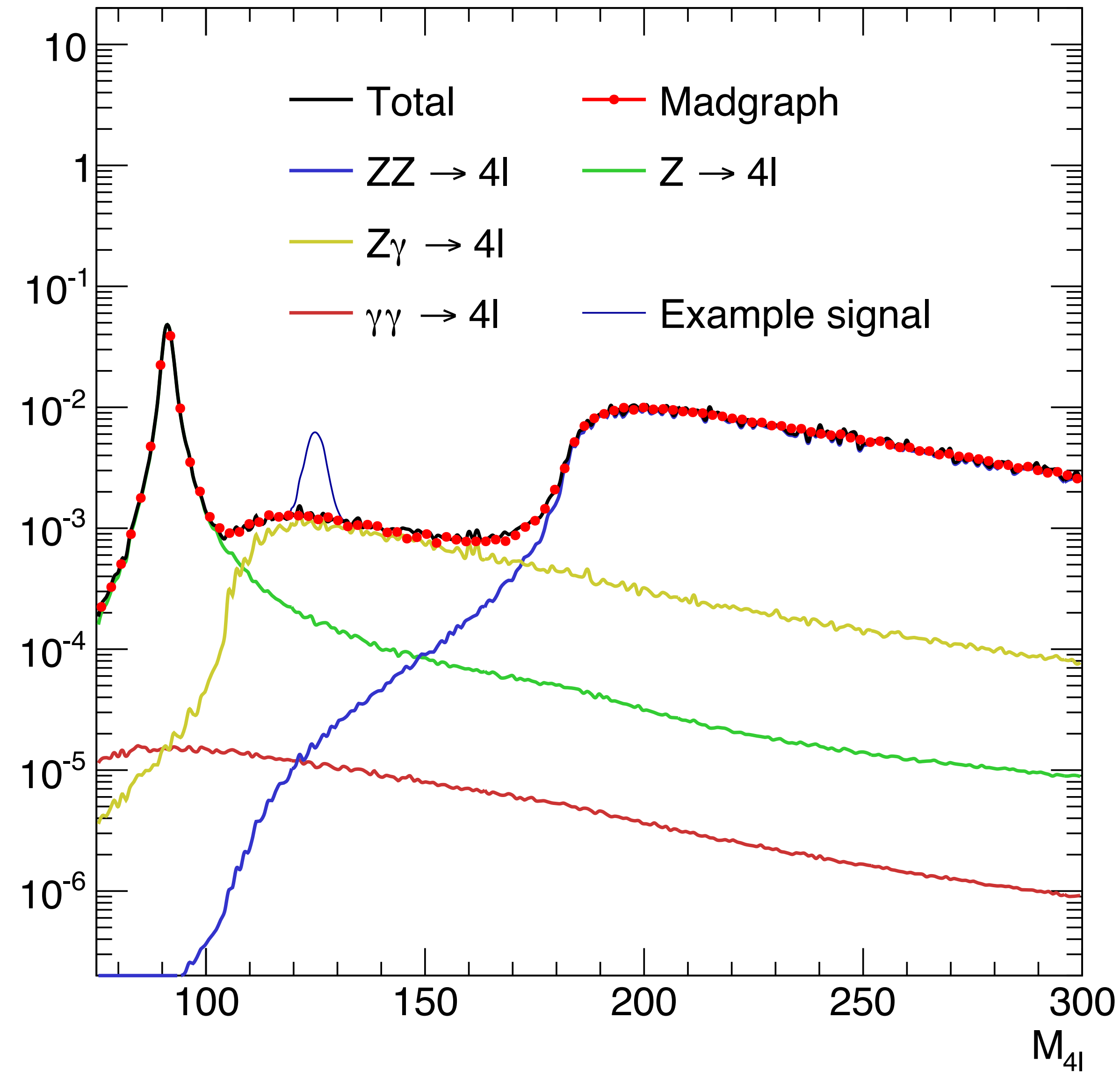
$$M_1 > 40,\ M_2 > 12,\ M_{\ell\ell} > 4$$

Modified "Relaxed - Υ"

$M_{\ell\ell} > 4,$

$M_{\ell\ell}(\mathrm{OSSF}) \notin (8.8, 10.8)$

S/B gets worse, but sensitivity improves.

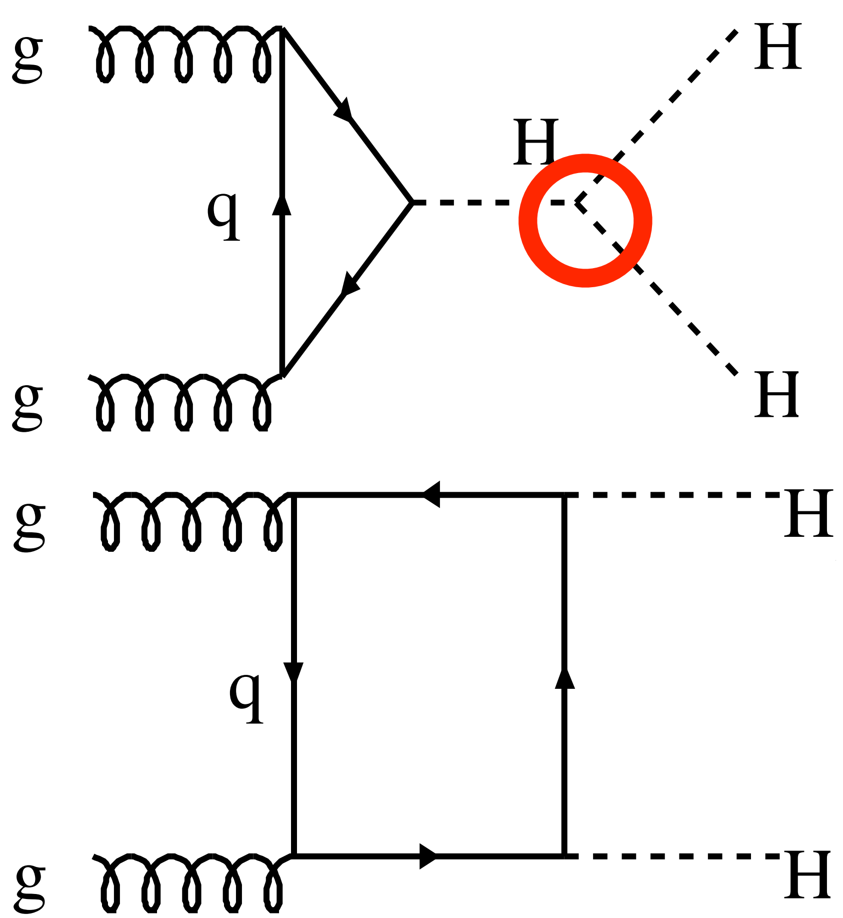


Chen, Harnik, Vega-Morales, [arXiv:1503.05855].

DI-HIGGS

Traditional way to measure triple Higgs coupling is via di-Higgs production.

Cross section is quite small.



Baglio, et. al. [arXiv:1212.5581].

$\sqrt{s}$ [TeV]	$\sigma^{NLO}_{gg\to HH}$ [fb]	$\sigma^{NLO}_{qq'\to HHqq'}$ [fb]	$\sigma^{NNLO}_{q\bar{q}'\to WHH}$ [fb]	$\sigma^{NNLO}_{q\bar{q}\to ZHH}$ [fb]	$\sigma^{LO}_{q\bar{q}/gg\to t\bar{t}HH}$ [fb]
8	8.16	0.49	0.21	0.14	0.21
14	33.89	2.01	0.57	0.42	1.02
33	207.29	12.05	1.99	1.68	7.91
100	1417.83	79.55	8.00	8.27	77.82

LHC PROSPECTS

Theorist studies are more optimistic (still need HL).

Studies in bbγγ, bbττ, bbWW, 4b,

ranging from 2-6σ significance.

[76] U. Baur, T. Plehn, and D. L. Rainwater, Phys.Rev. **D69**, 053004 (2004), hep-ph/0310056.

[77] J. Baglio, A. Djouadi, R. Grber, M. Mhlleitner, J. Quevillon, et al., JHEP **1304**, 151 (2013), 1212.5581.

[78] W. Yao (2013), 1308.6302.

[79] V. Barger, L. L. Everett, C. Jackson, and G. Shaughnessy, Phys.Lett. **B728**, 433 (2014), 1311.2931.

[80] A. Azatov, R. Contino, G. Panico, and M. Son (2015), 1502.00539.

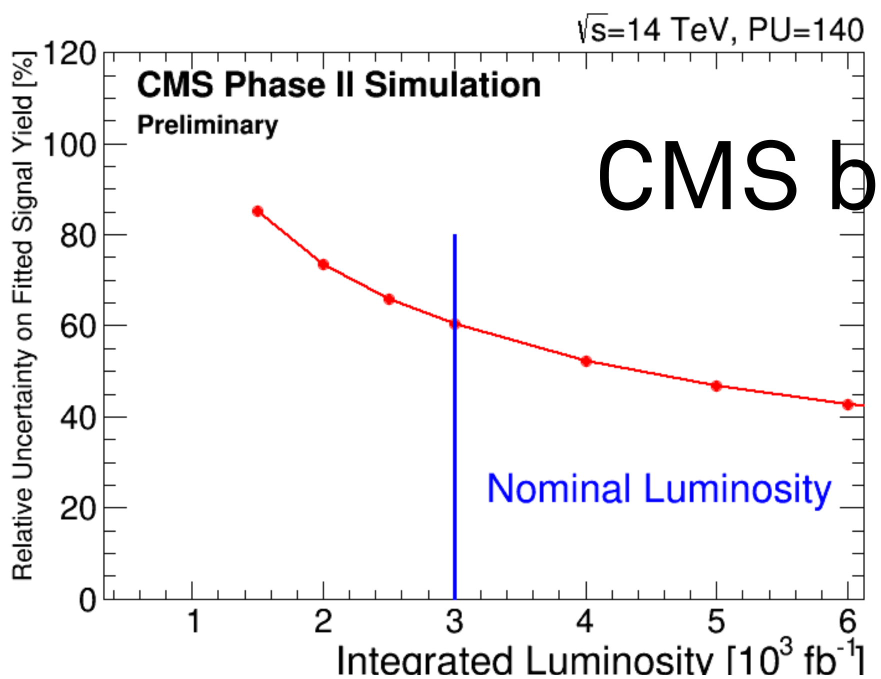
[81] A. J. Barr, M. J. Dolan, C. Englert, and M. Spannowsky, Phys.Lett. **B728**, 308 (2014), 1309.6318.

[82] A. Papaefstathiou, L. L. Yang, and J. Zurita, Phys.Rev. **D87**, 011301 (2013), 1209.1489.

[83] D. E. Ferreira de Lima, A. Papaefstathiou, and M. Spannowsky, JHEP **1408**, 030 (2014), 1404.7139.

LHC PROSPECTS

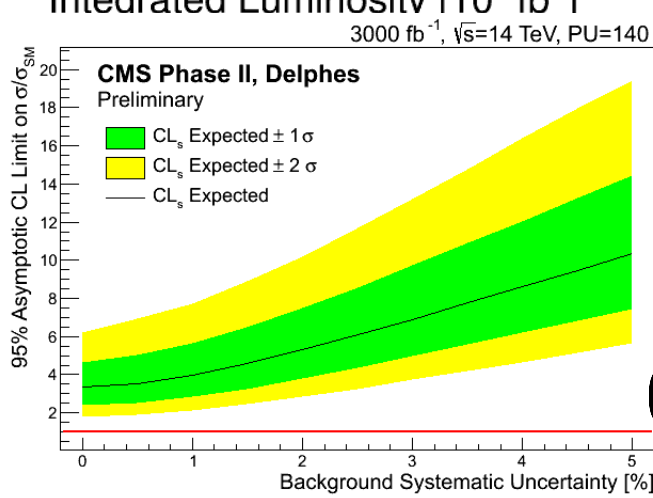
Preliminary studies by experiments show that measurement is very difficult even at high-lumi.



CMS bbγγ

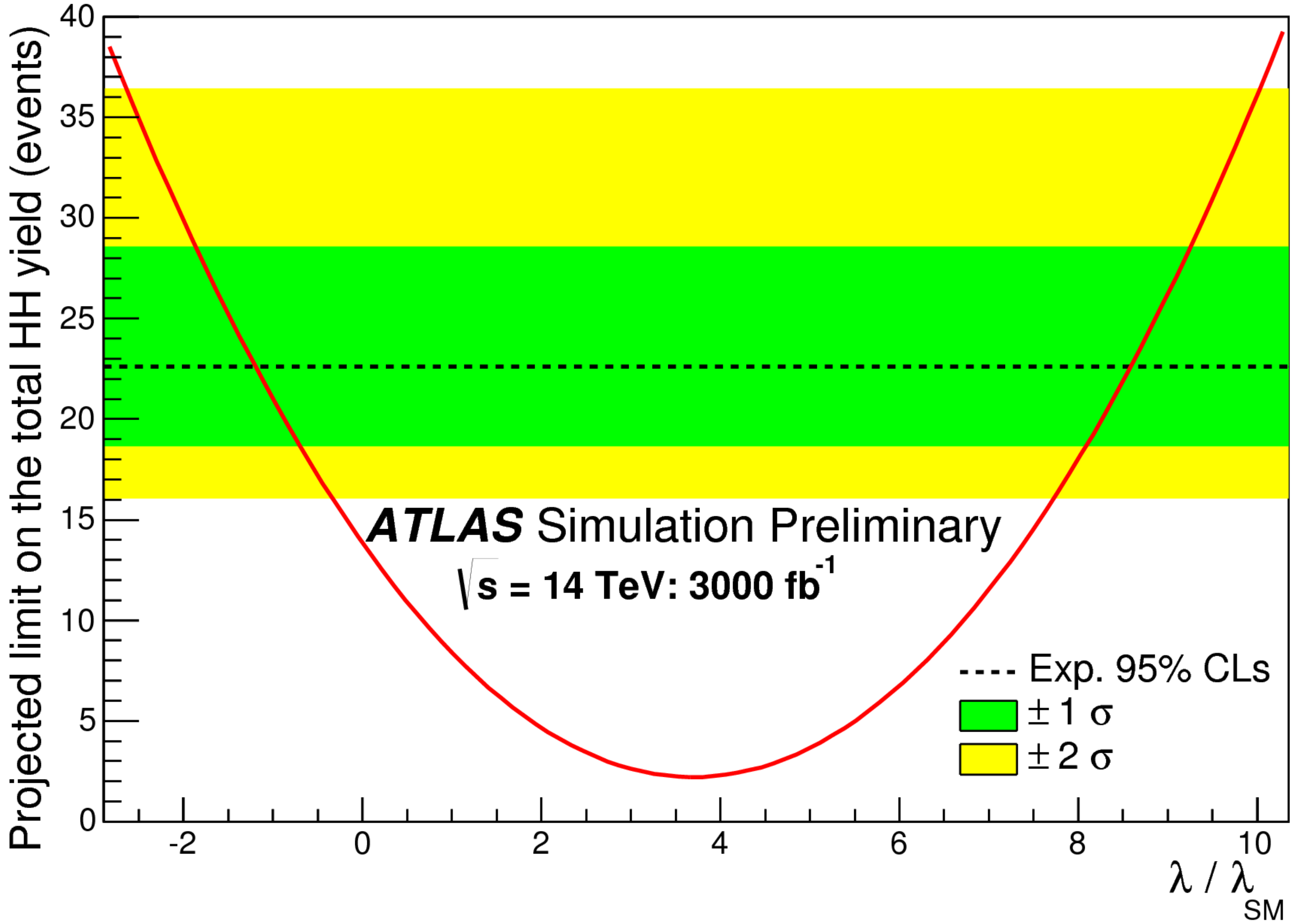
Expected yields (3000 fb^{-1}) Samples	Total	Barrel	End-cap
$H(b\bar{b})H(\gamma\gamma)(\lambda/\lambda_{SM}=1)$	8.4±0.1	6.7±0.1	1.8±0.1
$H(b\bar{b})H(\gamma\gamma)(\lambda/\lambda_{SM}=0)$	13.7±0.2	10.7±0.2	3.1±0.1
$H(b\bar{b})H(\gamma\gamma)(\lambda/\lambda_{SM}=2)$	4.6±0.1	3.7±0.1	0.9±0.1
$H(b\bar{b})H(\gamma\gamma)(\lambda/\lambda_{SM}=10)$	36.2±0.8	27.9±0.7	8.2±0.4
$b\bar{b}\gamma\gamma$	9.7±1.5	5.2±1.1	4.5±1.0
$c\bar{c}\gamma\gamma$	7.0±1.2	4.1±0.9	2.9±0.8
$b\bar{b}\gamma j$	8.4±0.4	4.3±0.2	4.1±0.2
$b\bar{b}jj$	1.3±0.2	0.9±0.1	0.4±0.1
$jj\gamma\gamma$	7.4±1.8	5.2±1.5	2.2±1.0
$t\bar{t}(\geq 1$ lepton$)$	0.2±0.1	0.1±0.1	0.1±0.1
$t\bar{t}\gamma$	3.2±2.2	1.6±1.6	1.6±1.6
$t\bar{t}H(\gamma\gamma)$	6.1±0.5	4.9±0.4	1.2±0.2
$Z(b\bar{b})H(\gamma\gamma)$	2.7±0.1	1.9±0.1	0.8±0.1
$b\bar{b}H(\gamma\gamma)$	1.2±0.1	1.0±0.1	0.3±0.1
Total Background	47.1±3.5	29.1±2.7	18.0±2.3
$S/\sqrt{B}(\lambda/\lambda_{SM}=1)$	1.2	1.2	0.4

ATLAS bbγγ



CMS bbWW

COUPLING SENSITIVITY

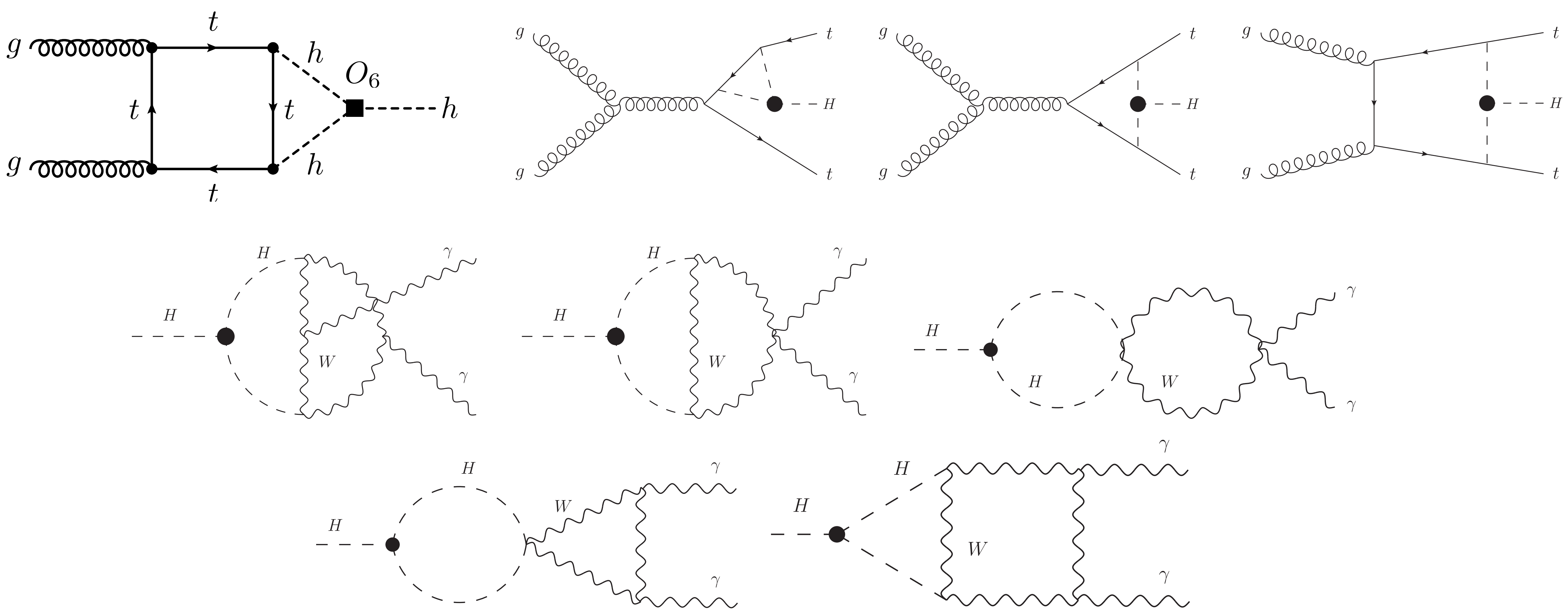


> Based on these results, we should be able to exclude values of the self-coupling strength larger than 8.7xSM, and smaller than -1.3xSM

Talk by N. Styles at MITP.

OTHER LOOP PROCESSES

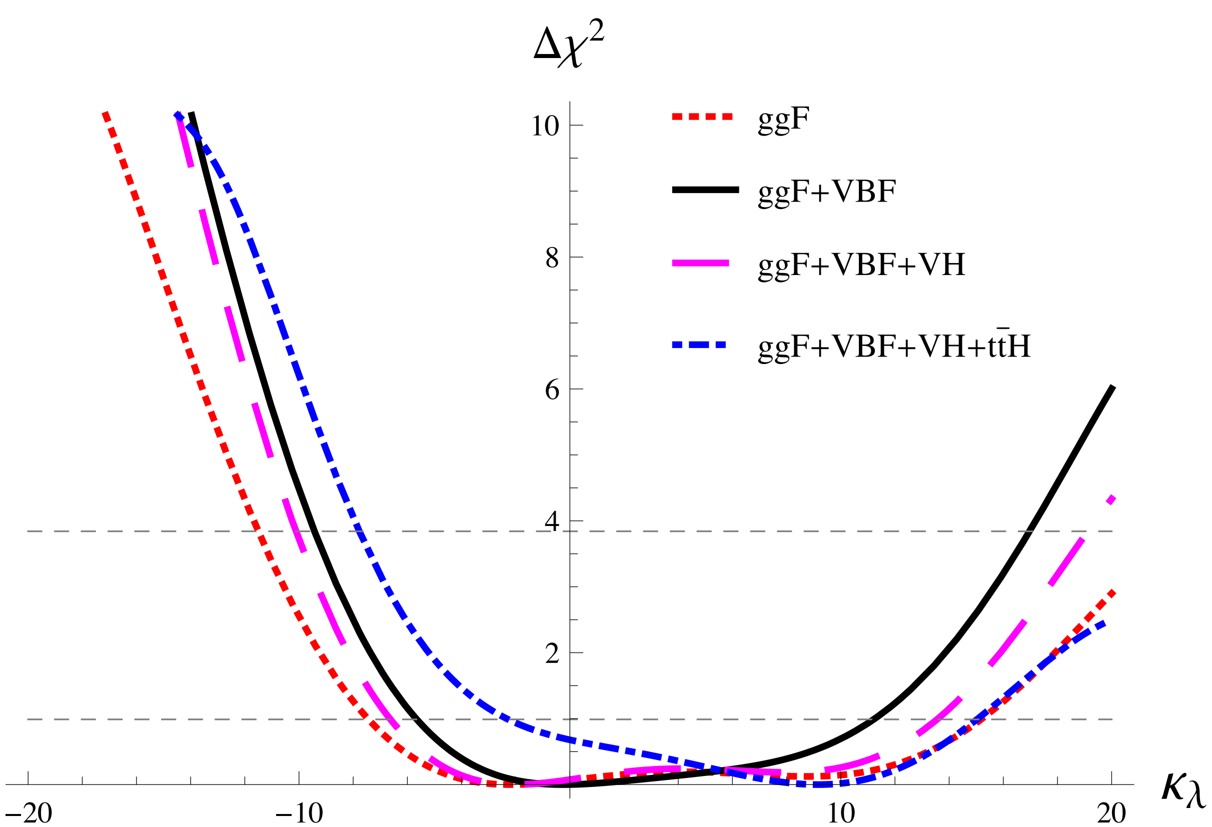
Triple Higgs coupling appears in many loop processes including Higgs production and Higgs decay to photons.



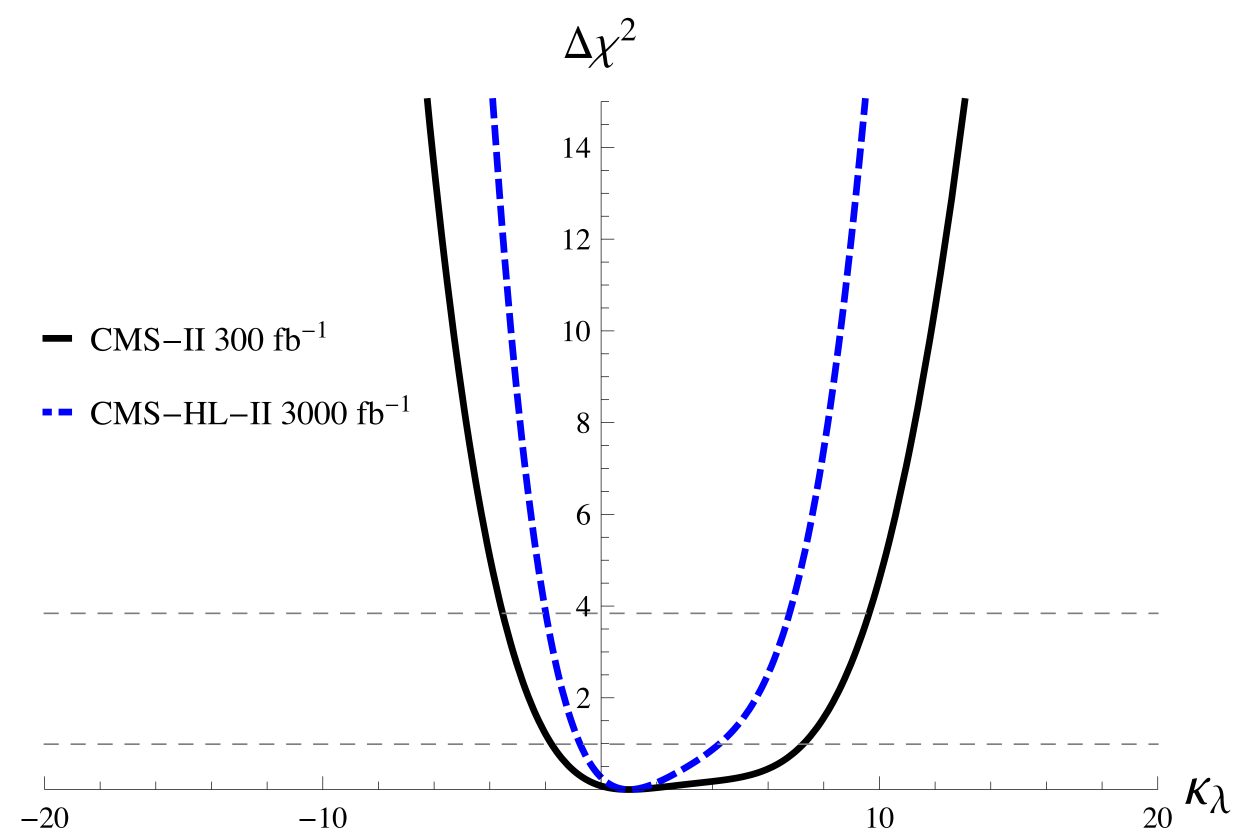
Gorbahn and Haisch [arXiv:1607.03773]. Degrassi et.al. [arXiv:1607.04521].

OTHER LOOP PROCESSES

Constraints are similar(ly bad).



Current data



Future projections

Gorbahn and Haisch [arXiv:1607.03773]. Degrassi et.al. [arXiv:1607.04521].

DETAILS

- 115 GeV $< M_{4\ell} <$ 135 GeV
- $p_T > (20, 10, 5, 5)$ GeV for lepton p_T ordering,
- $|\eta_\ell| < 2.4$ for the lepton rapidity,
- $M_{\ell\ell} > 4$ GeV, $M_{\ell\ell}(\text{OSSF}) \notin (8.8, 10.8)$ GeV,

$\mathcal{L}$	$\mu(tth)$	$\mu(h \to \gamma\gamma)$	$\mu(h \to Z\gamma)$
Current	2.8 ± 1.0 [5]	1.14 ± 0.25 [103]	NA
300 fb^{-1}	1.0 ± 0.55 [105]	1.0 ± 0.1 [104]	1.0 ± 0.6 [106]
3000 fb^{-1}	1.0 ± 0.18 [105]	1.0 ± 0.05 [104]	1.0 ± 0.2 [106]

$$\mu(tth) \simeq y_t^2 + 0.42\,\tilde{y}_t^2$$
$$\mu(h \to \gamma\gamma) \simeq (1.28 - 0.28\,y_t)^2 + (0.43\,\tilde{y}_t)^2$$
$$\mu(h \to Z\gamma) \simeq (1.06 - 0.06\,y_t)^2 + (0.09\,\tilde{y}_t)^2,$$