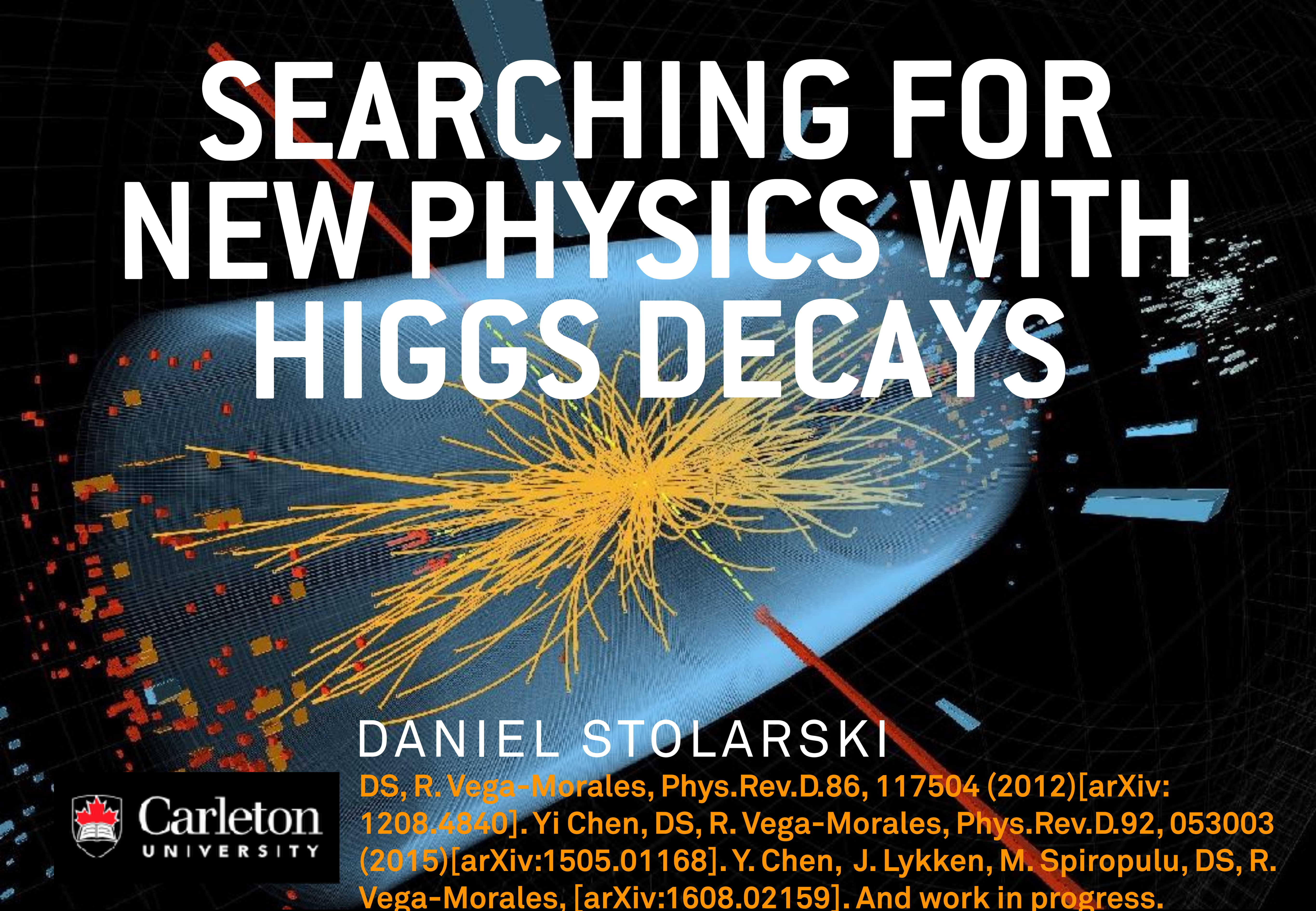


SEARCHING FOR NEW PHYSICS WITH HIGGS DECAYS

DANIEL STOLARSKI

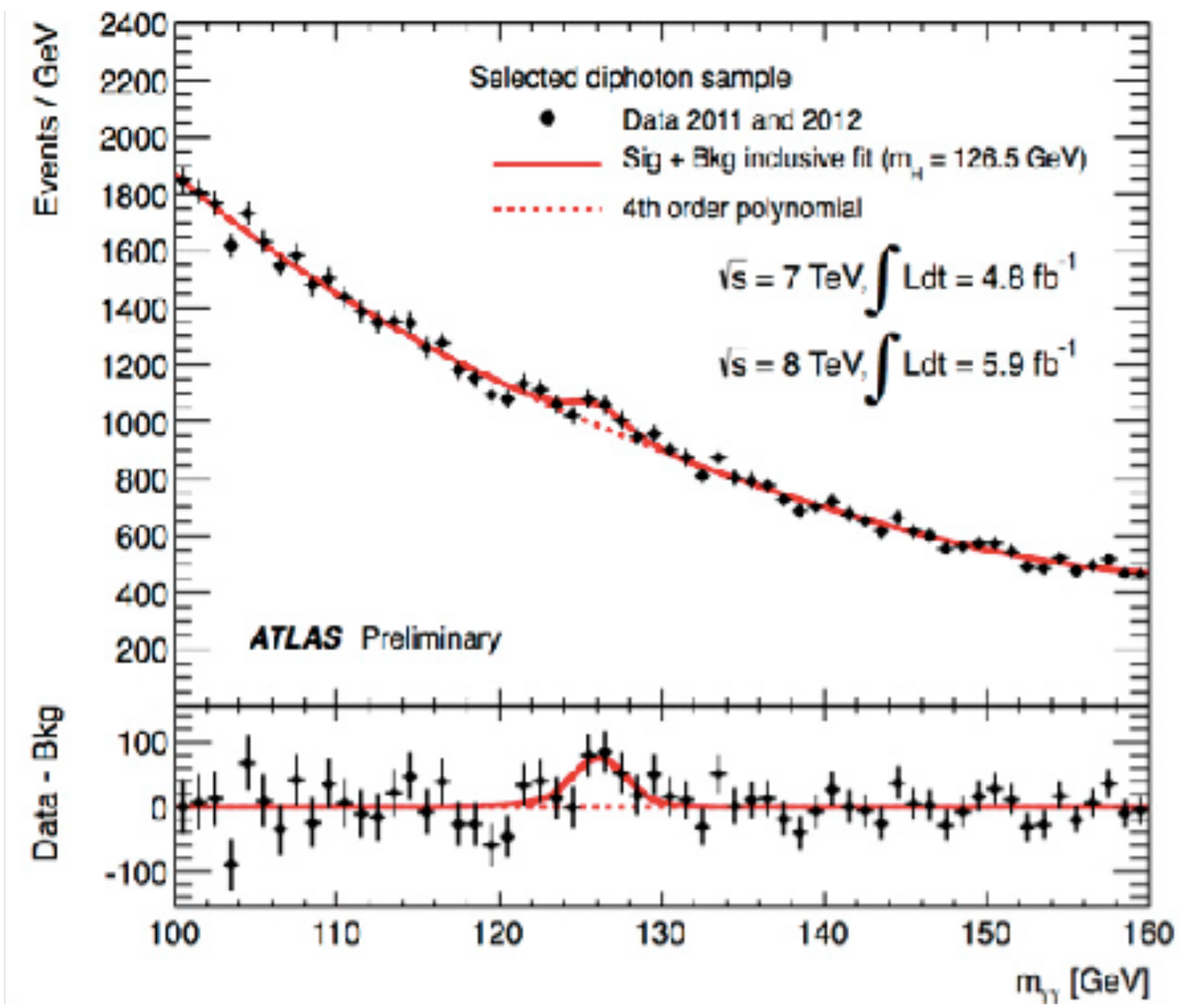
Carleton UNIVERSITY

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.

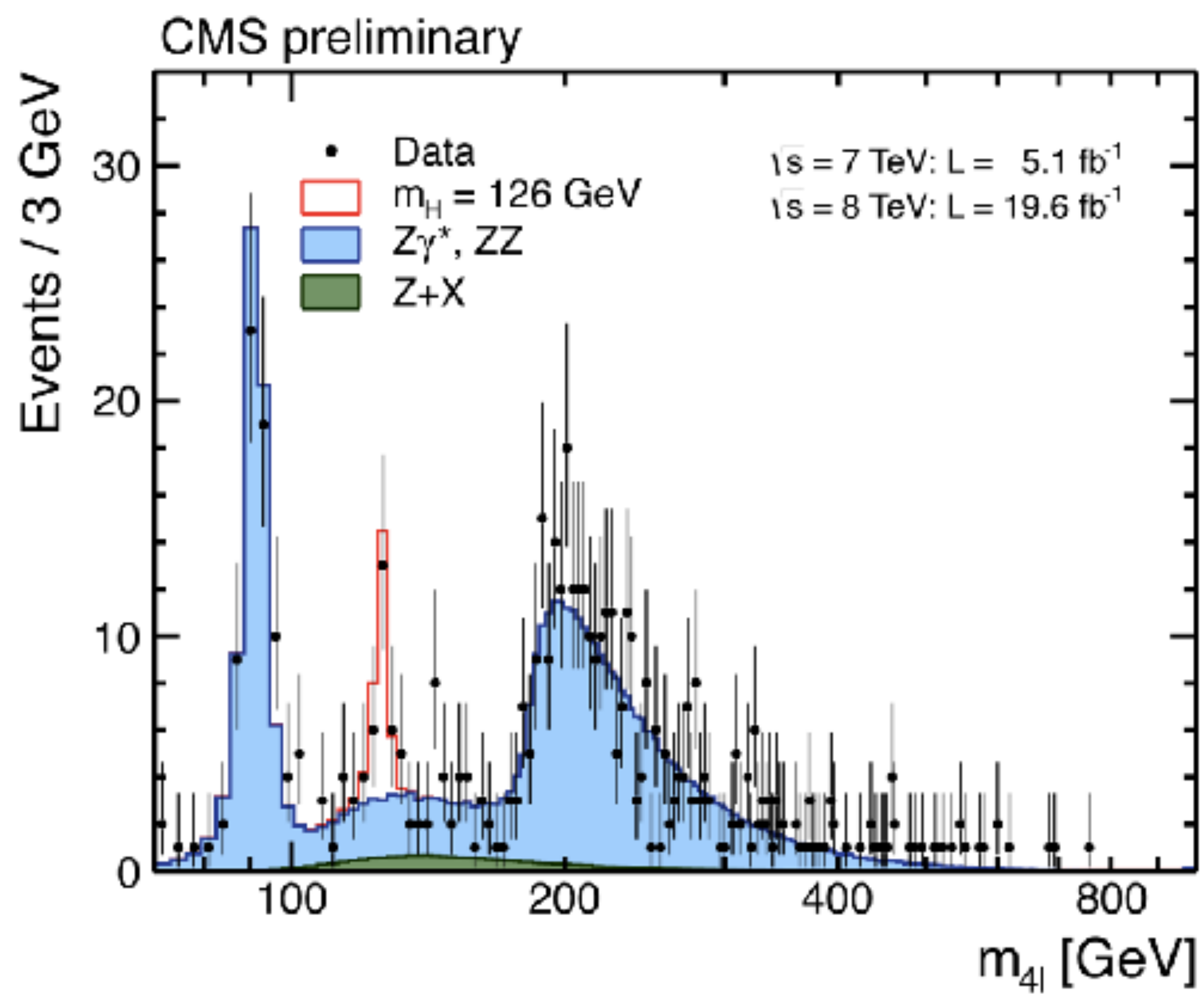
University of Toronto Seminar November 22, 2016

A NEW PARTICLE

July 2012:



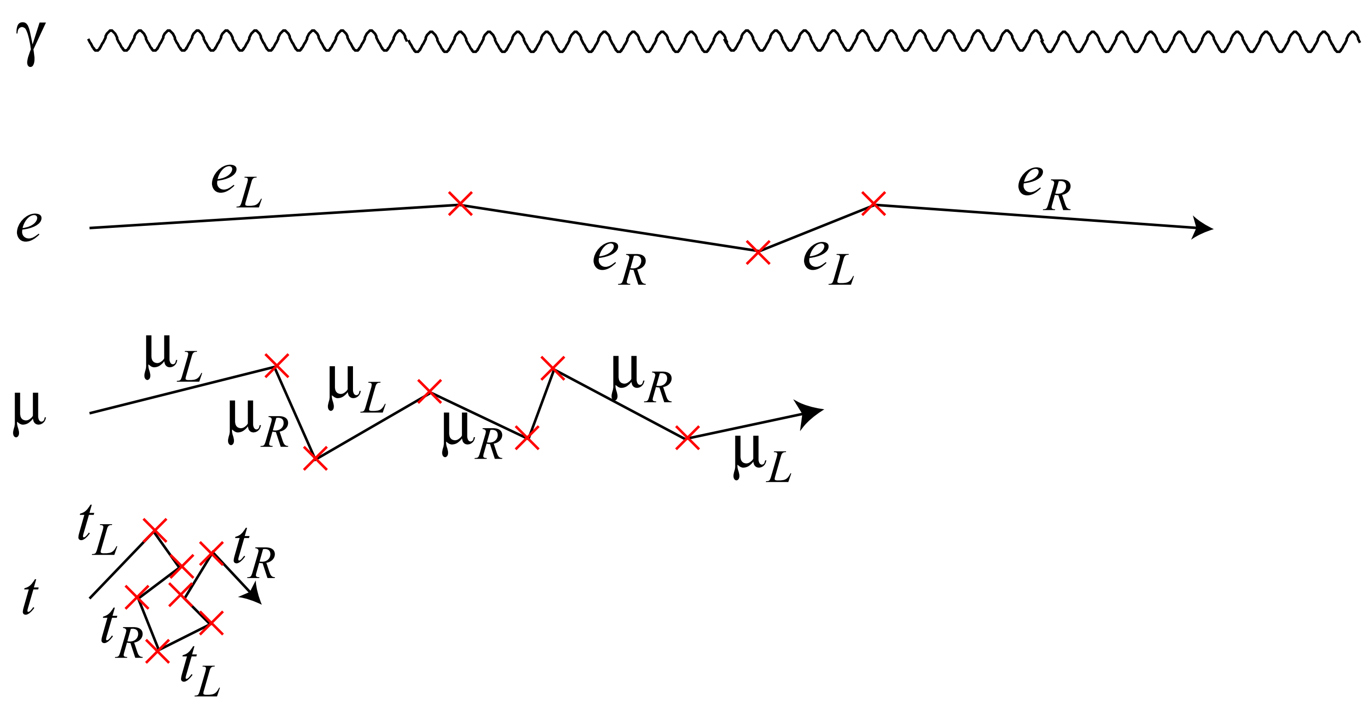
$$h \to \gamma\gamma$$



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

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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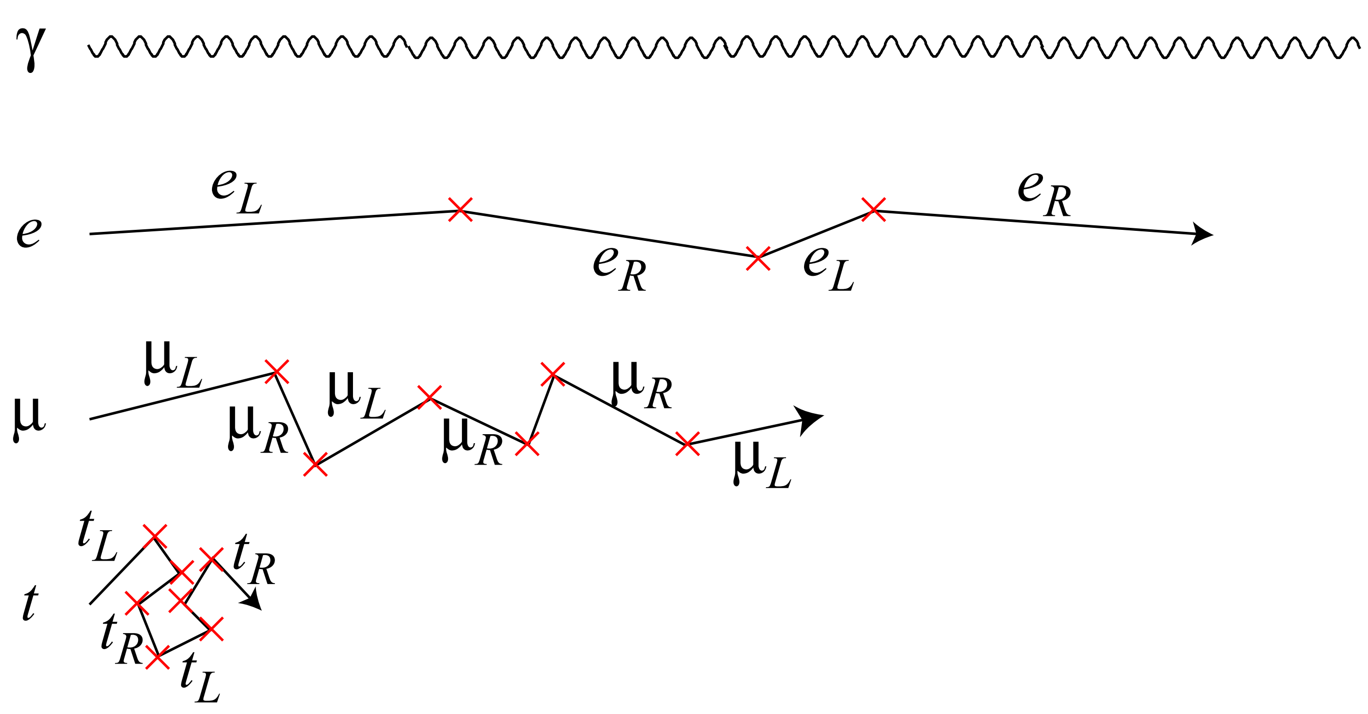

Anderson, 1963

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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Quantum 2nd order perturbation theory:

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

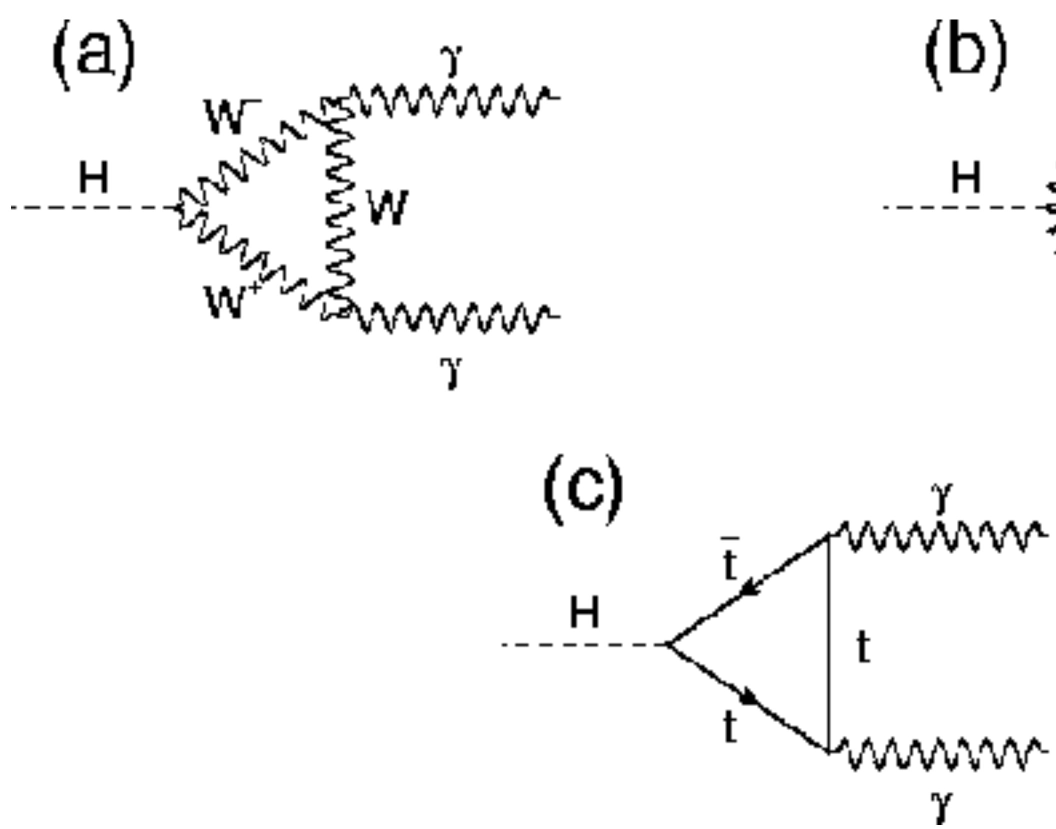
Griffiths, Quantum Mechanics, Eq. 6.15

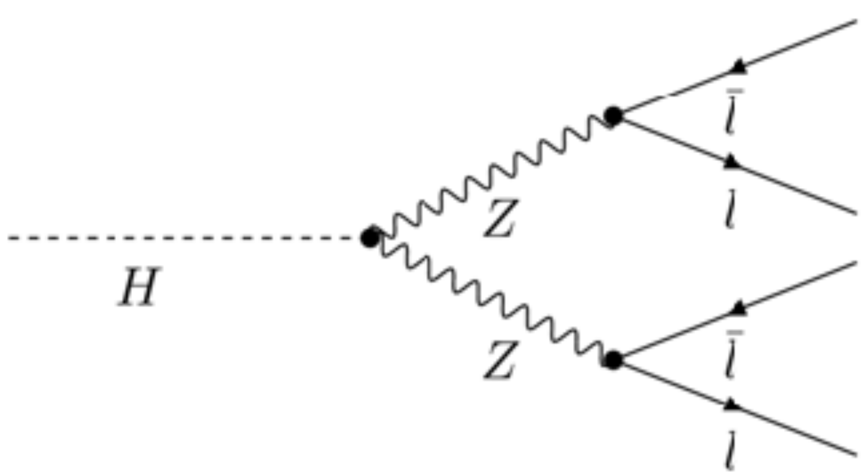
Sensitive to all other states in the theory.

DISCOVERY MODES

$h \to \gamma\gamma$

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

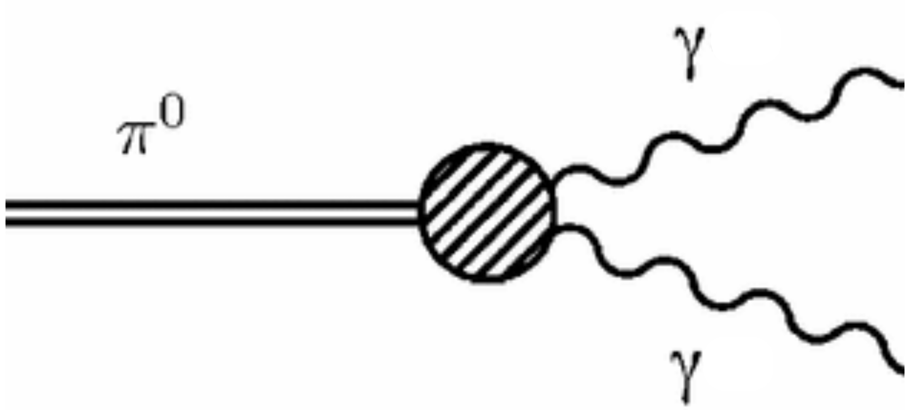


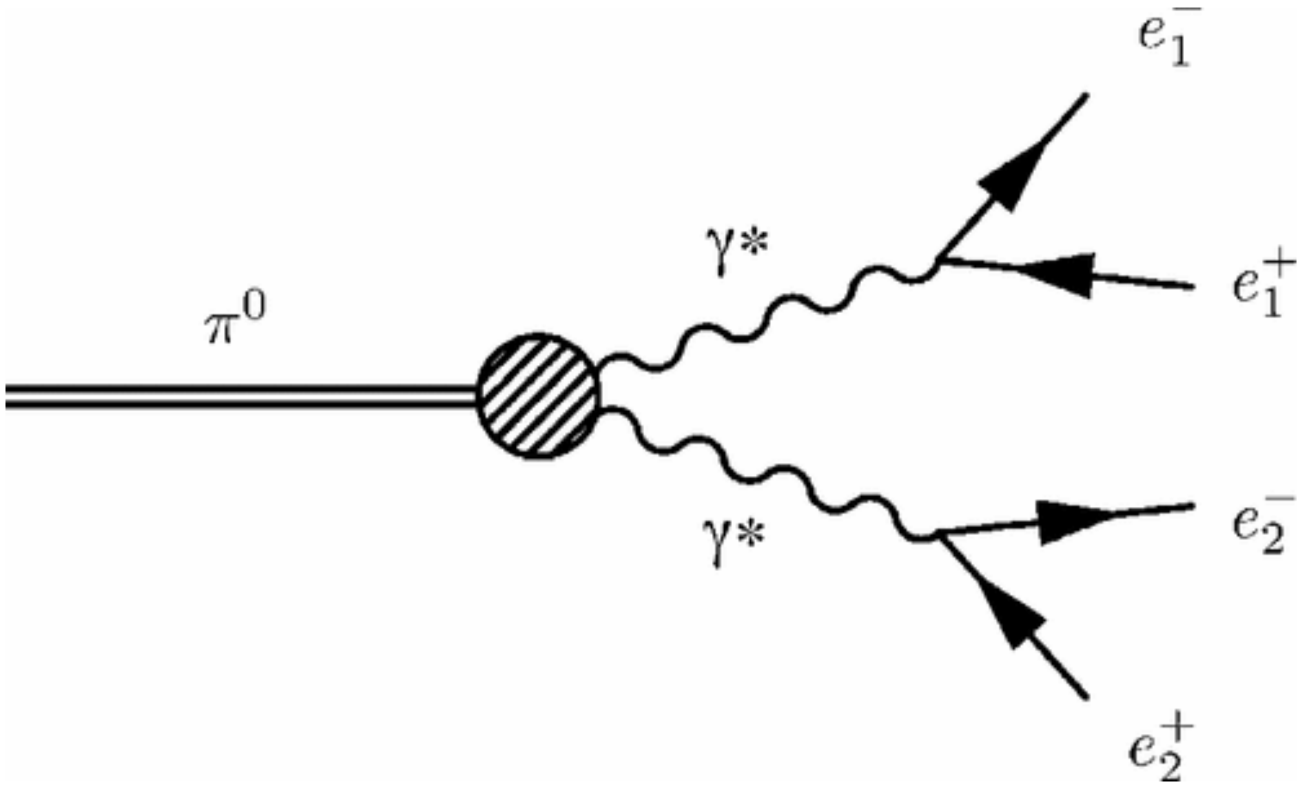


IS IT THE HIGGS?

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

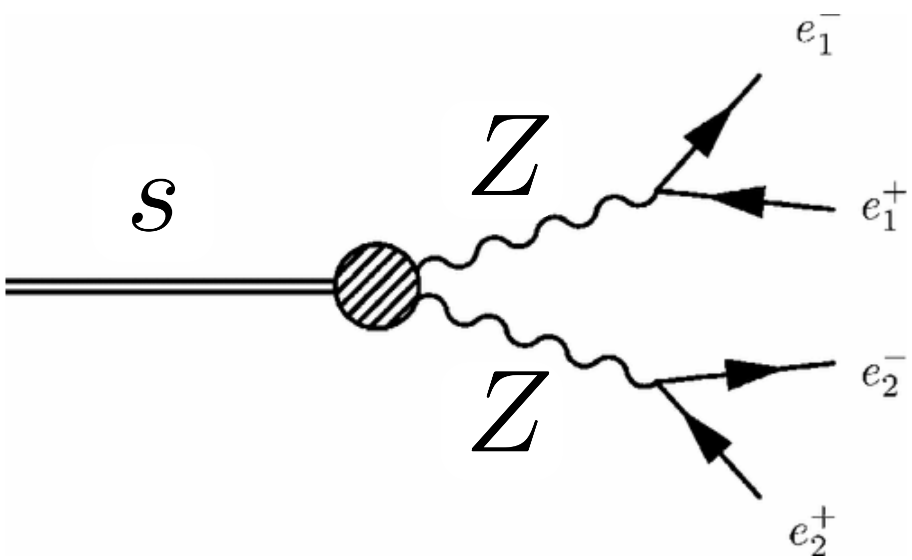
Neutral pion decays to two photons *and* four electrons, but its much more boring.



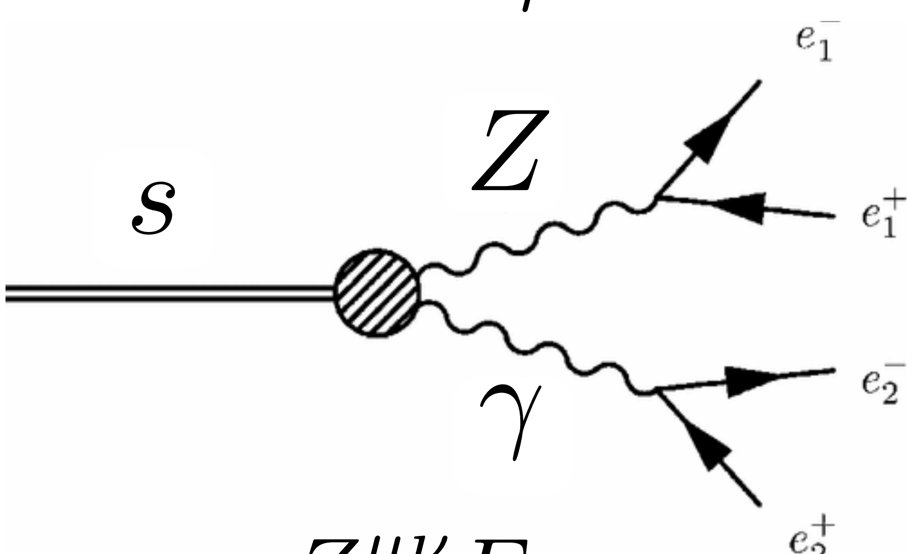


WARM UP EXERCISE

Assume parity even scalar:

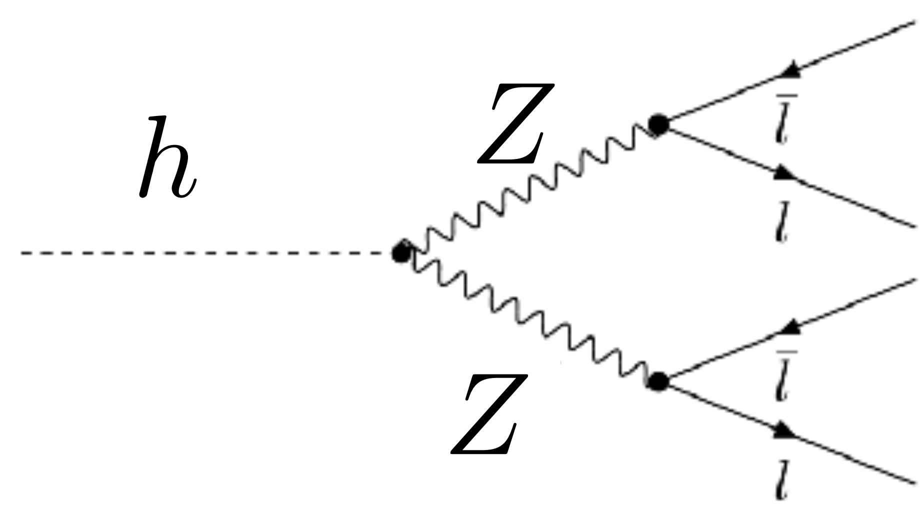


$$s\, Z^{\mu\nu} Z_{\mu\nu}$$



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

OR

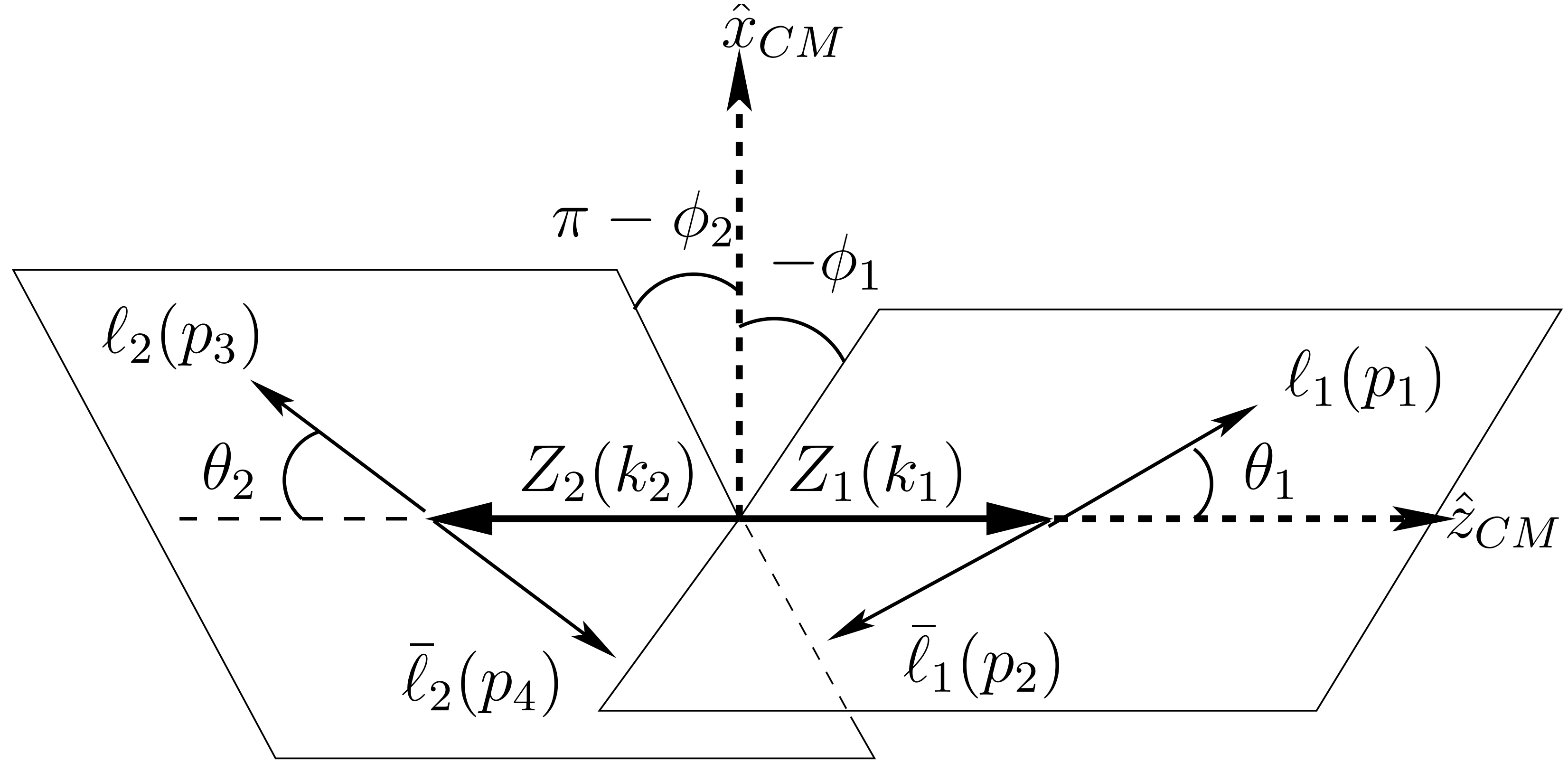


$$h\, Z^{\mu} Z_{\mu}$$

KINEMATIC DISTRIBUTIONS

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

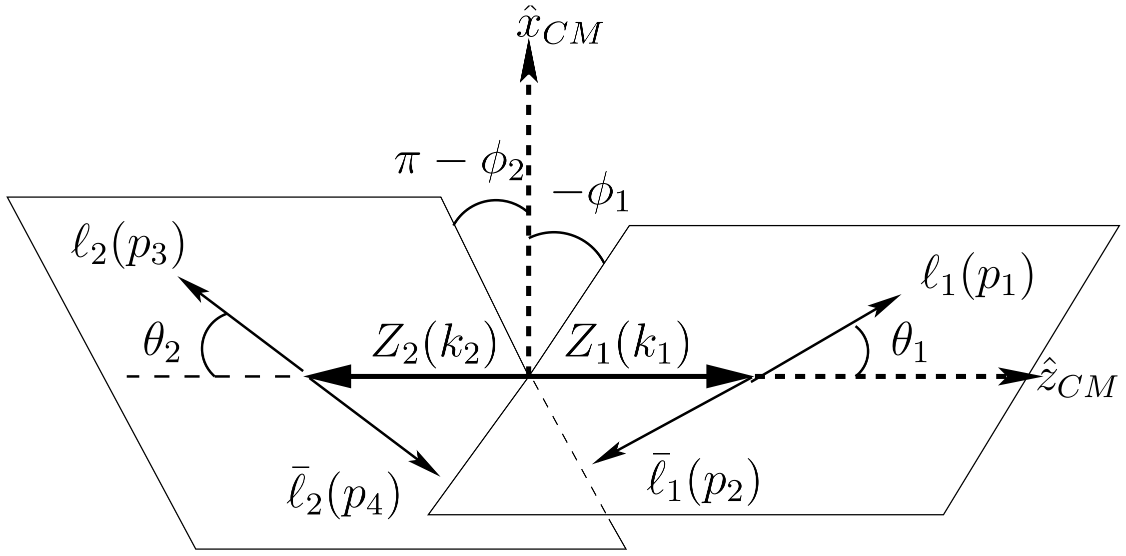
Each event is characterized by five different variables.

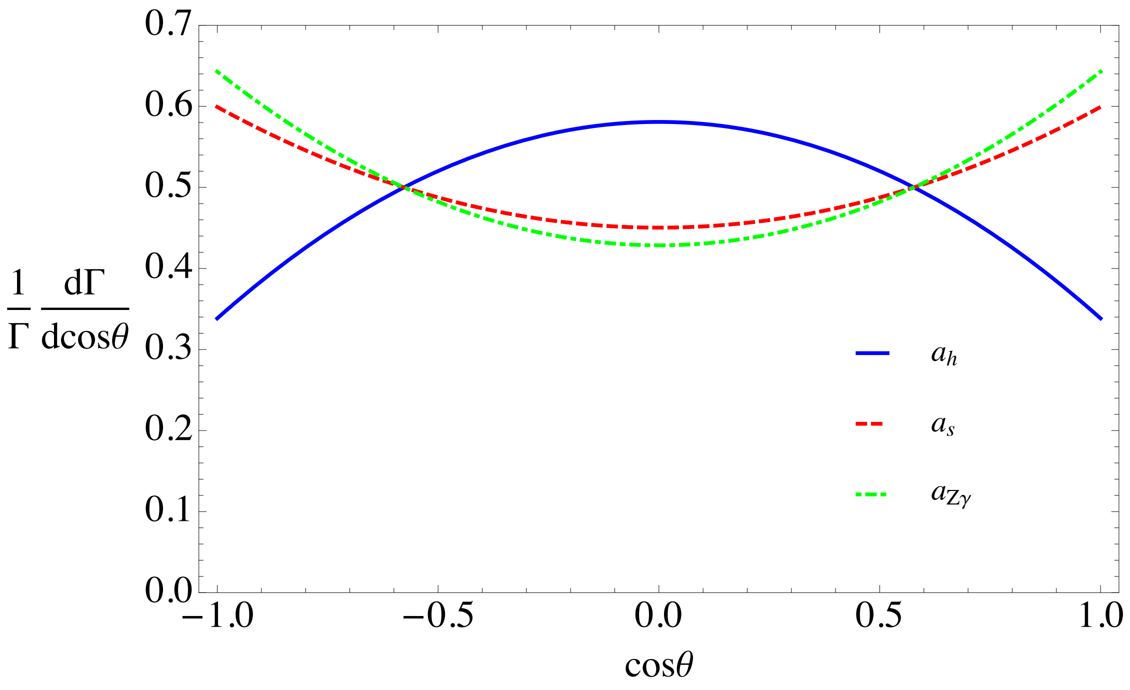


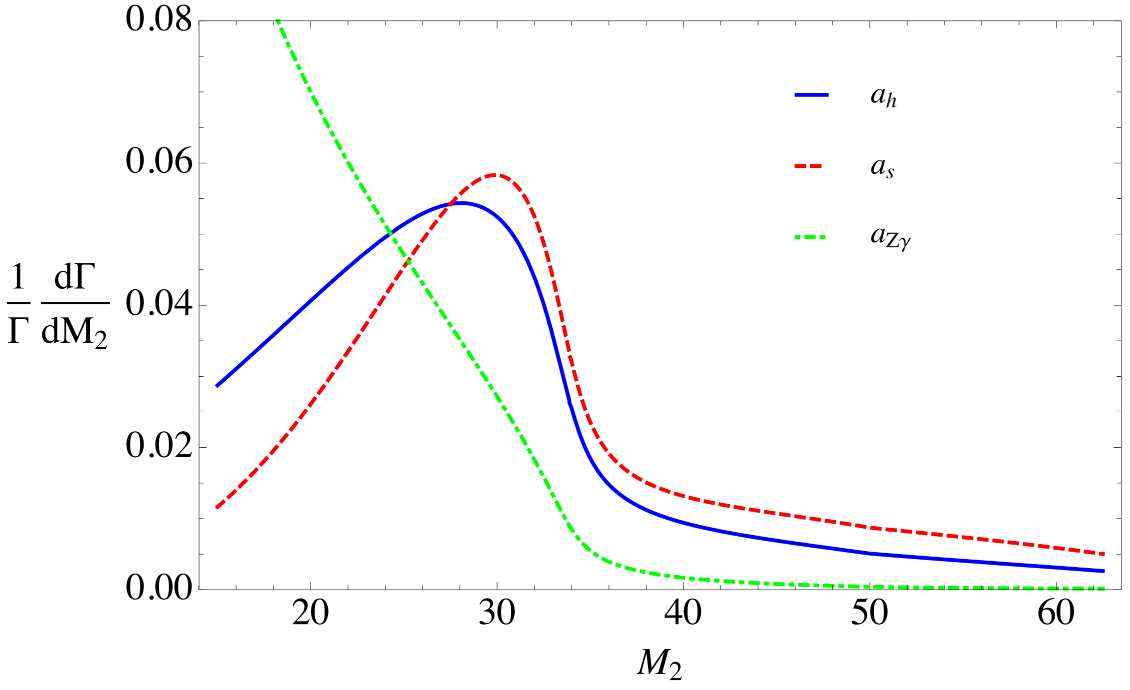
Compare to $h \to \gamma\gamma$.

KINEMATIC DISTRIBUTIONS

Distributions encode information about tensor structure.







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

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

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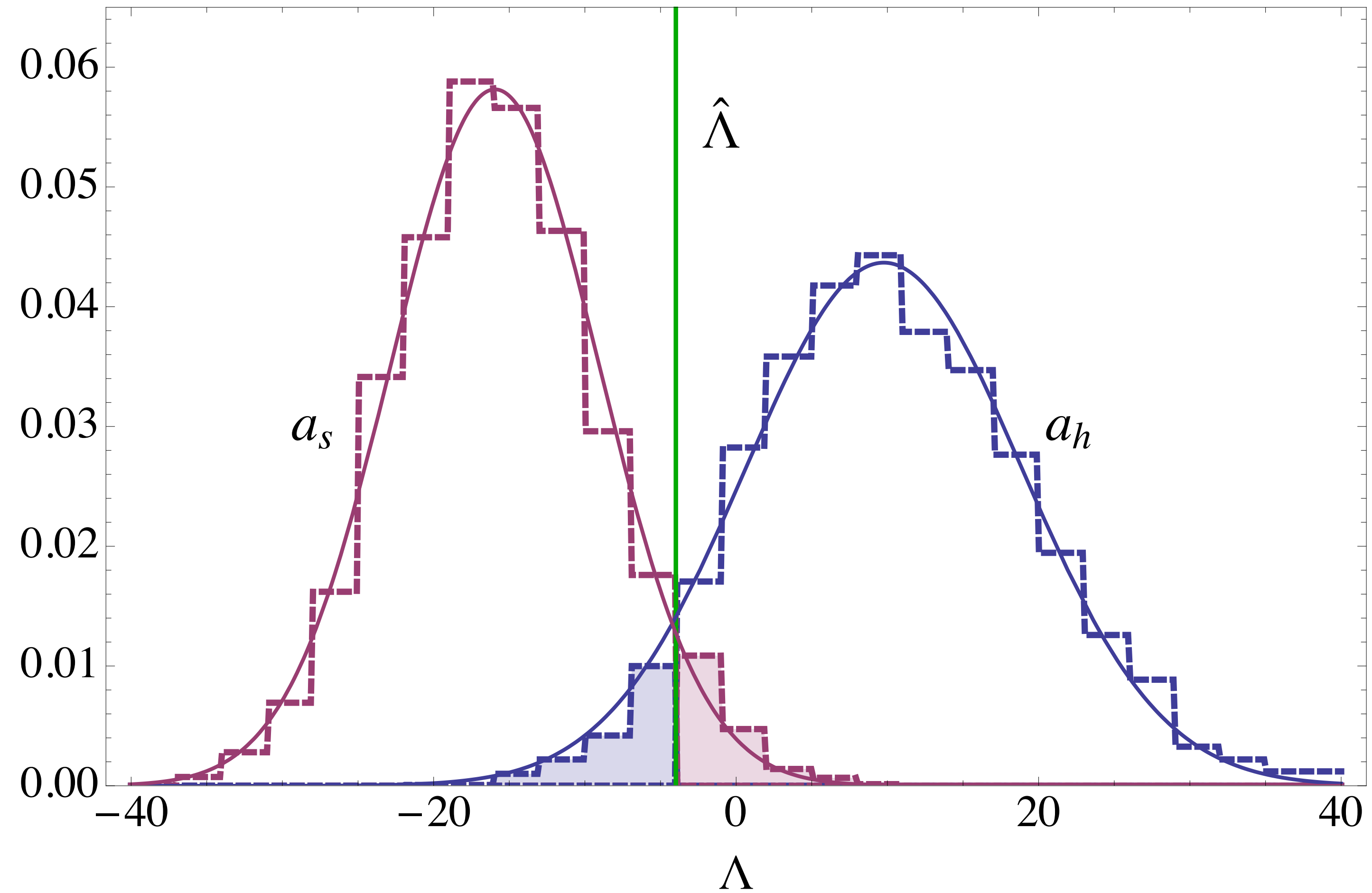
For *N* events, can compute likelihood for different underlying theories.

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

LIKELIHOOD DISTRIBUTION

Can do pseudo-experiments to see separation power of *N* events.

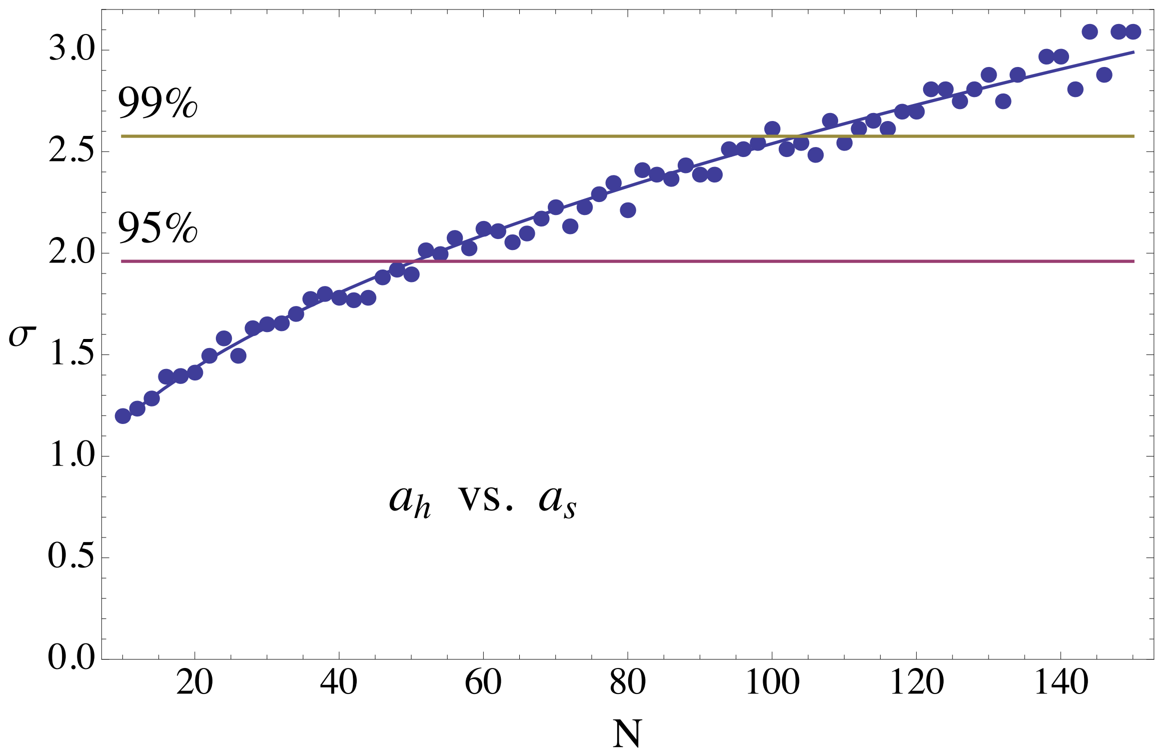
Example for 50 events:

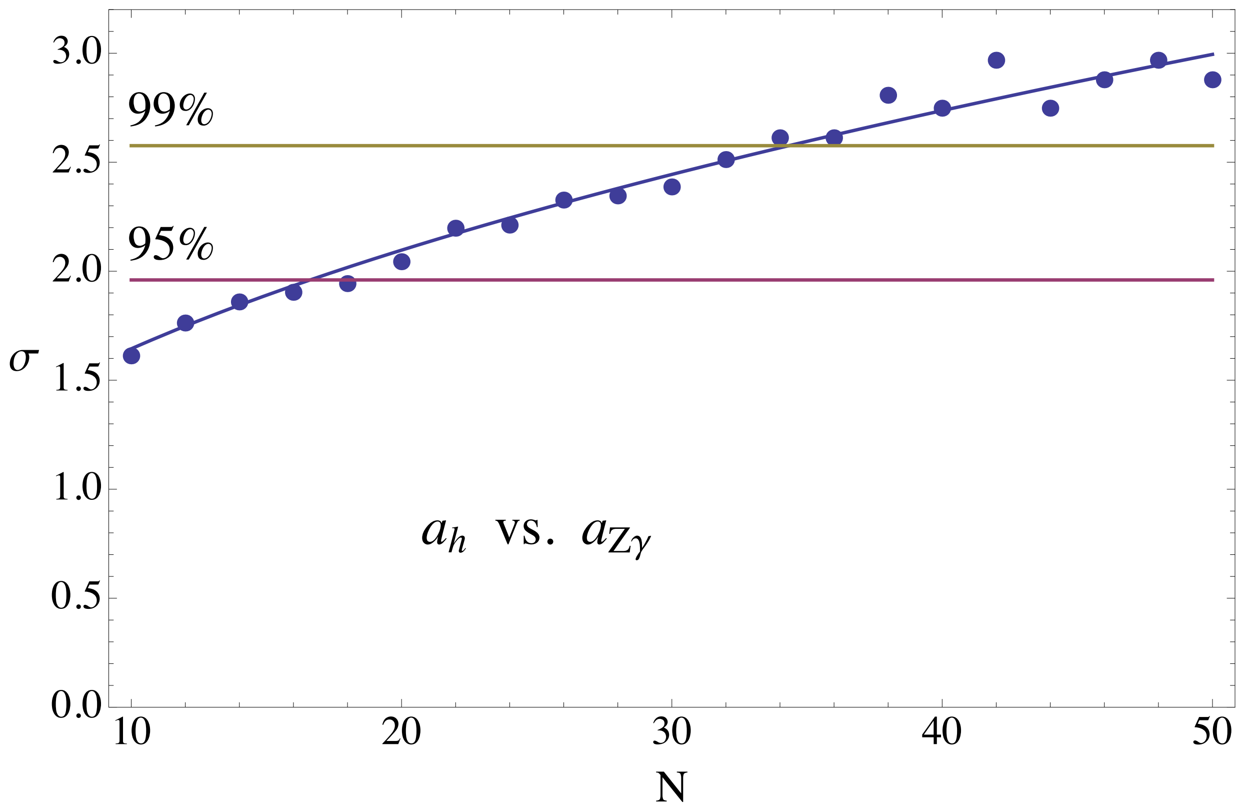


$$\Lambda = 2\log[\mathcal{L}(a_1)/\mathcal{L}(a_2)]$$

KINEMATIC DISTRIBUTIONS

Get better discrimination with more events.





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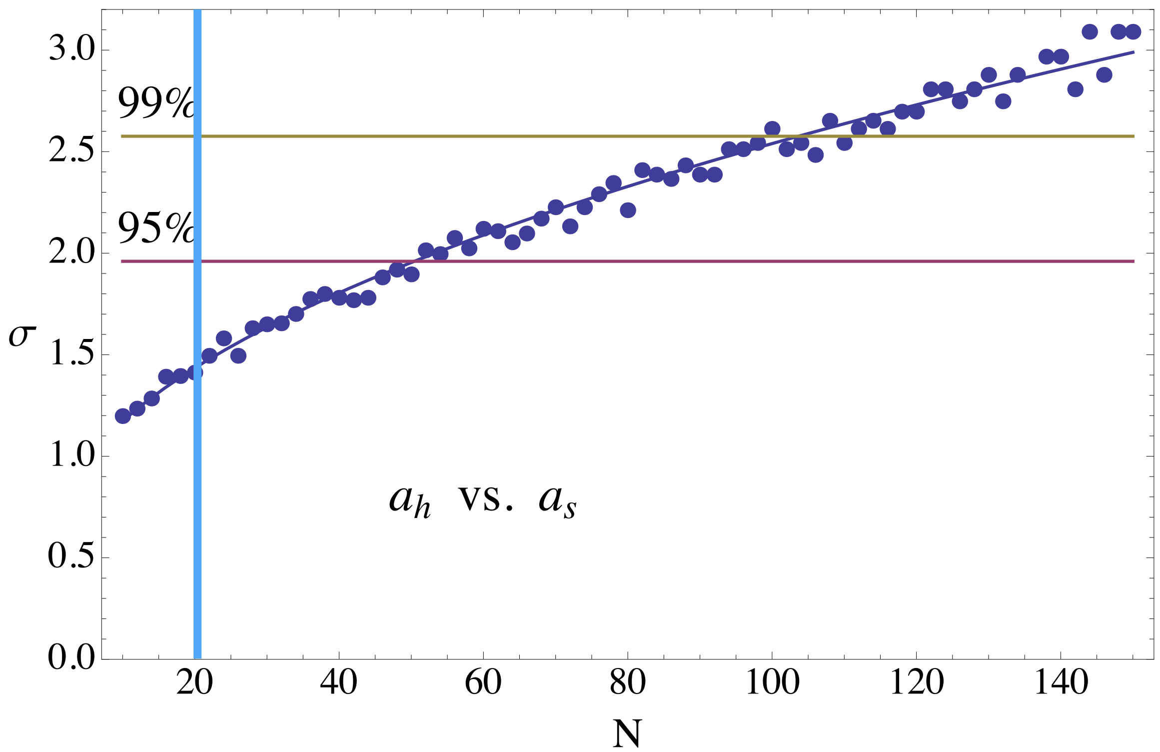
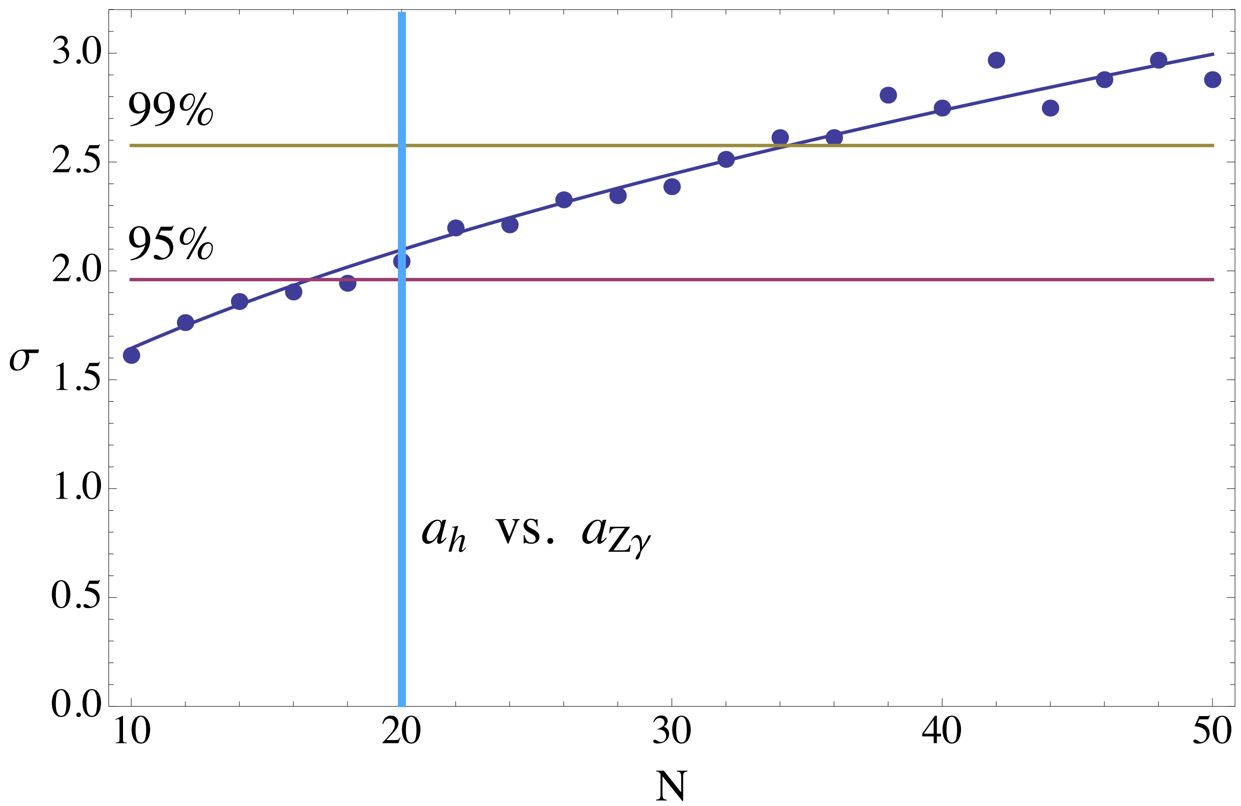
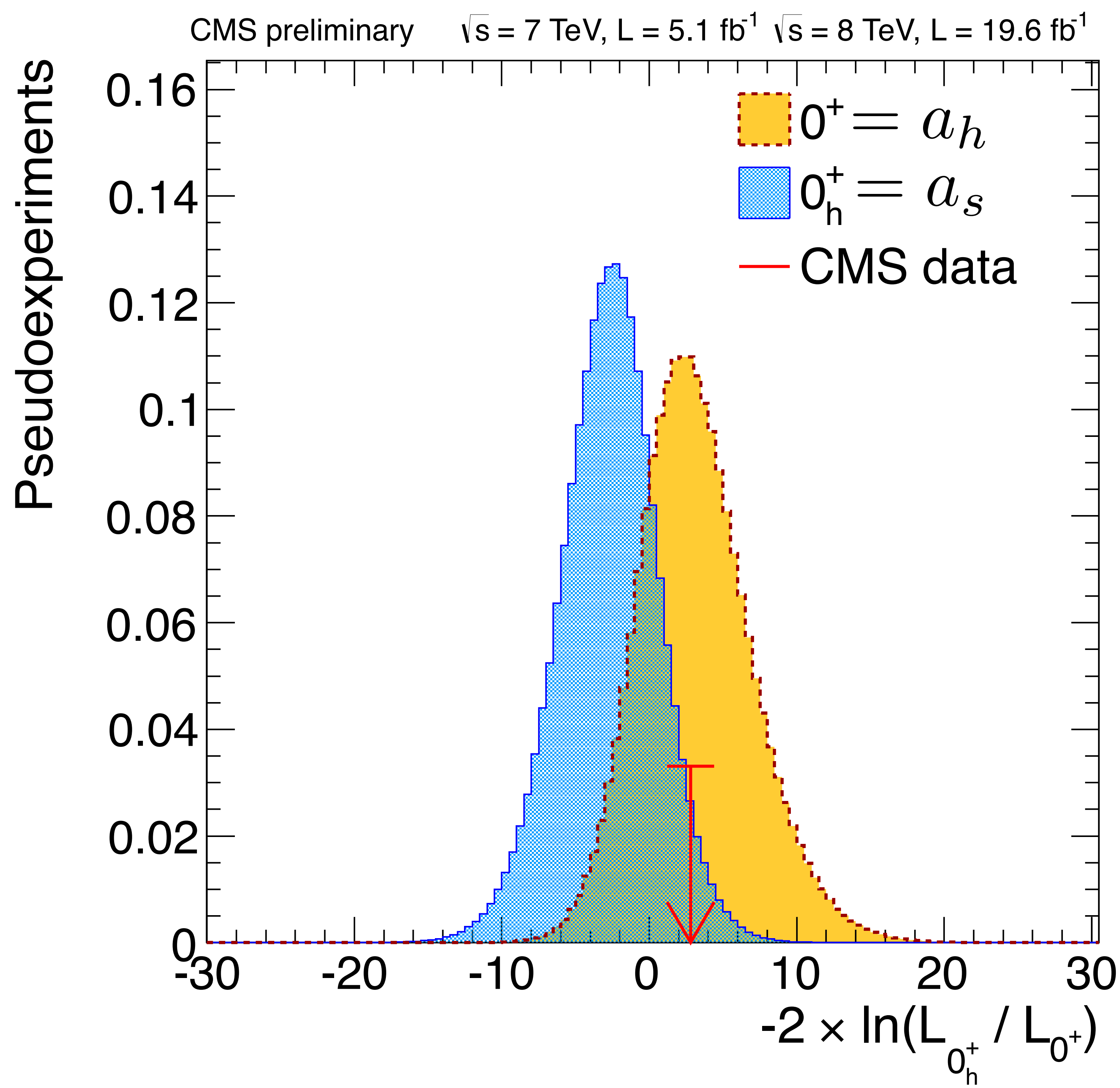




Run I data

DATA

Evidence for the Higgs:



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:

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

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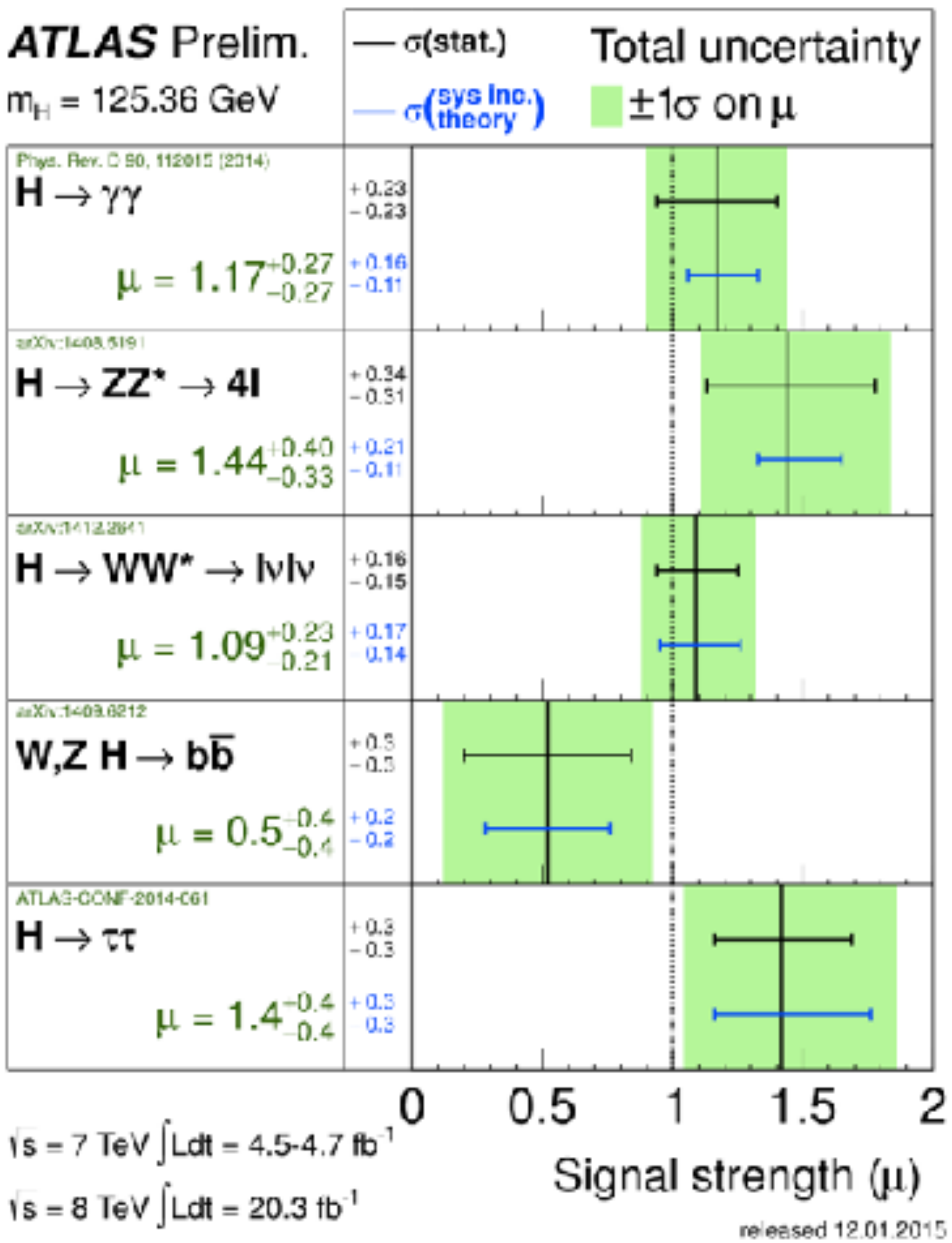
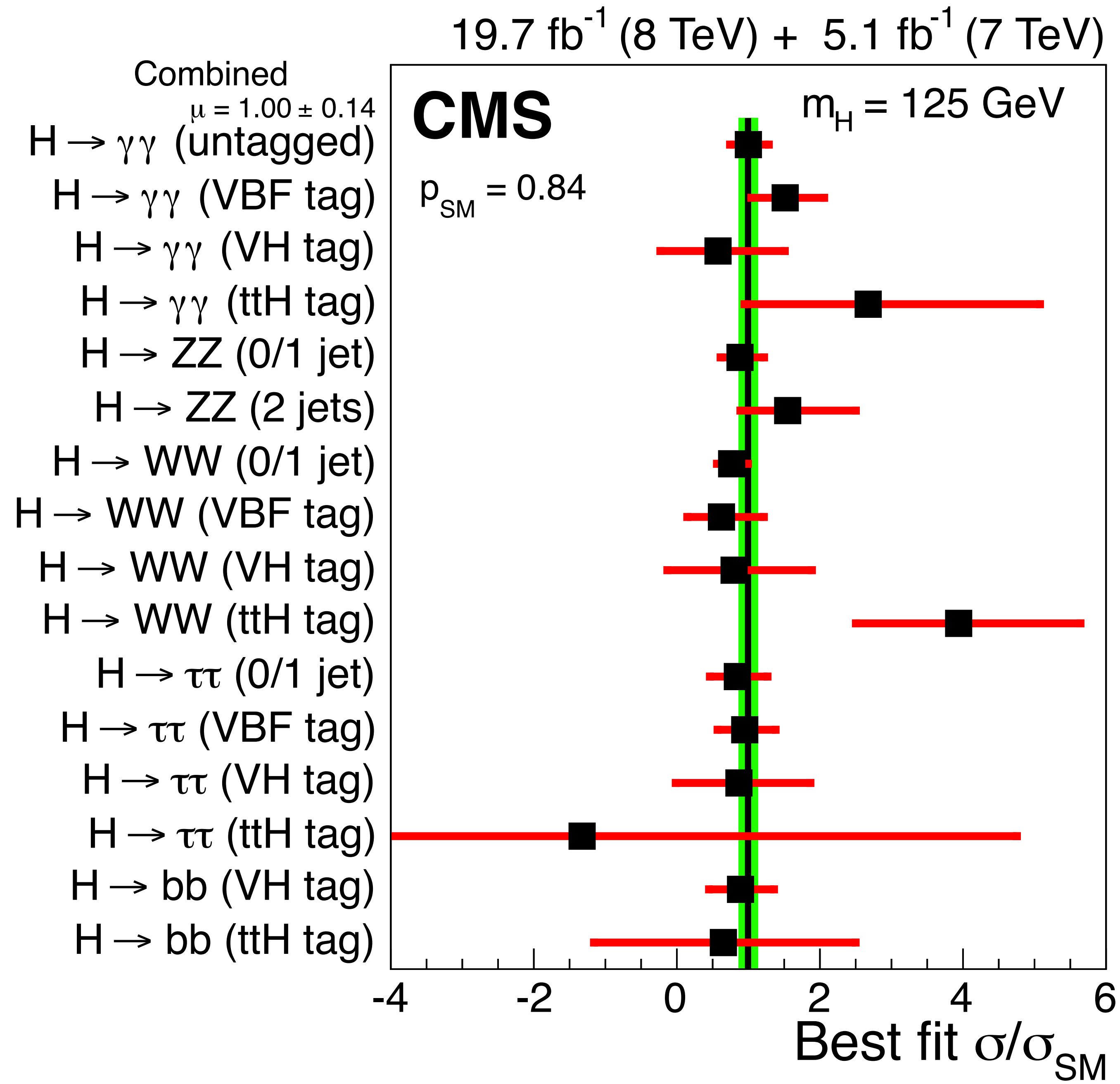
Worthwhile to test SM and rule out all other logical possibilities.

Techniques become extremely important if there is an anomaly.

RATE MEASUREMENTS

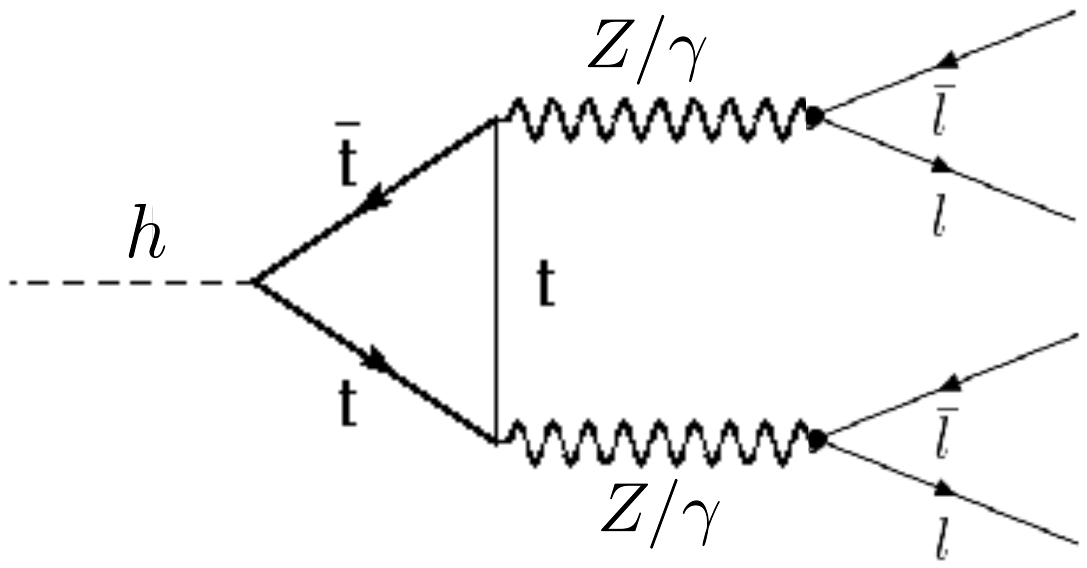


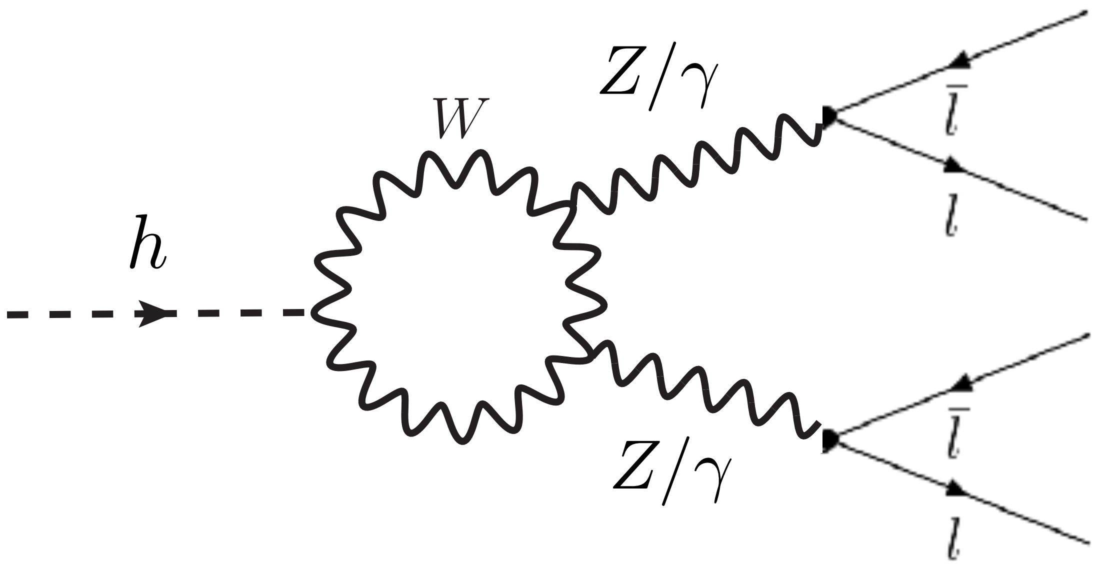


LOOP PROCESSES

Kinematic distributions can reveal more than just rate measurements can.

Put this to use with loop processes.





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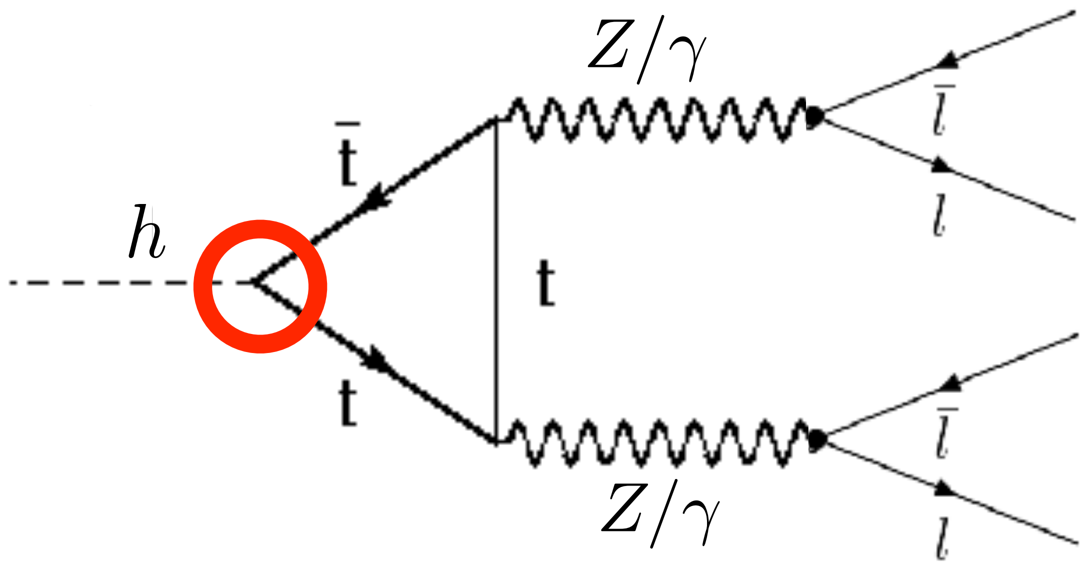
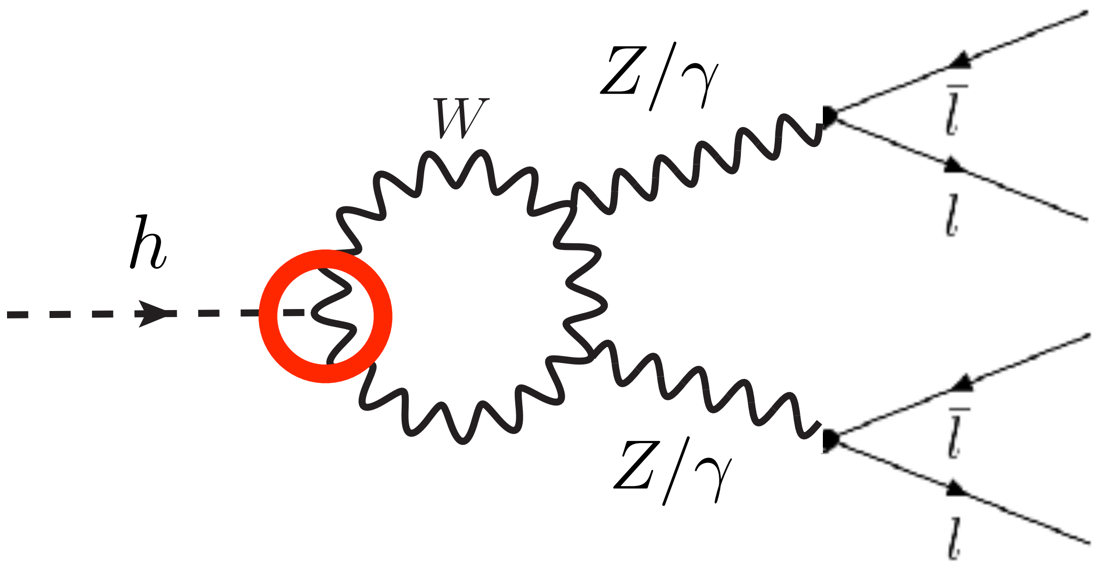


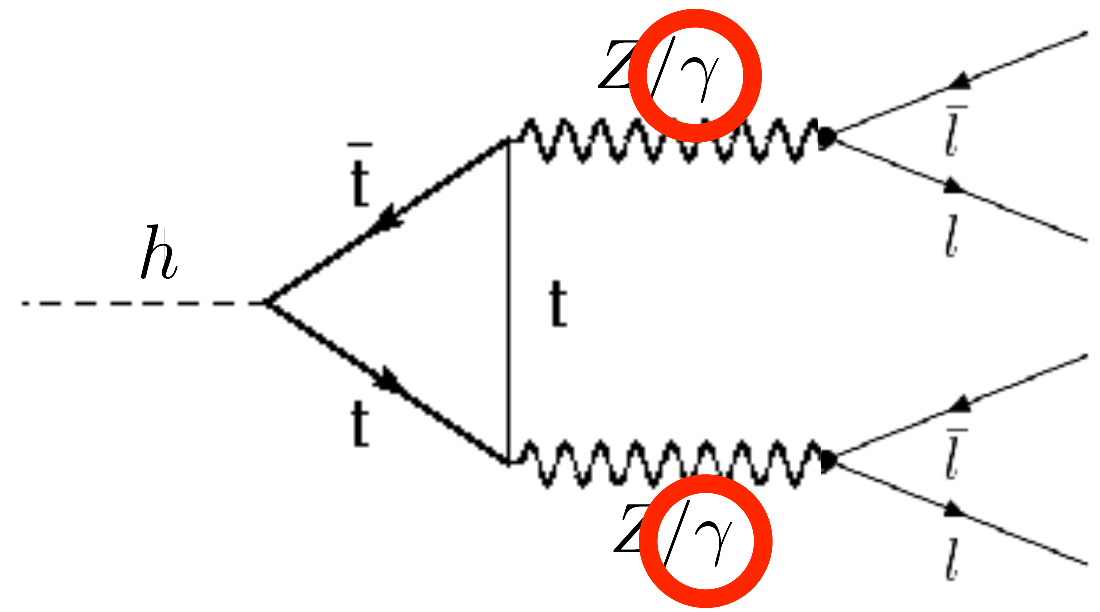


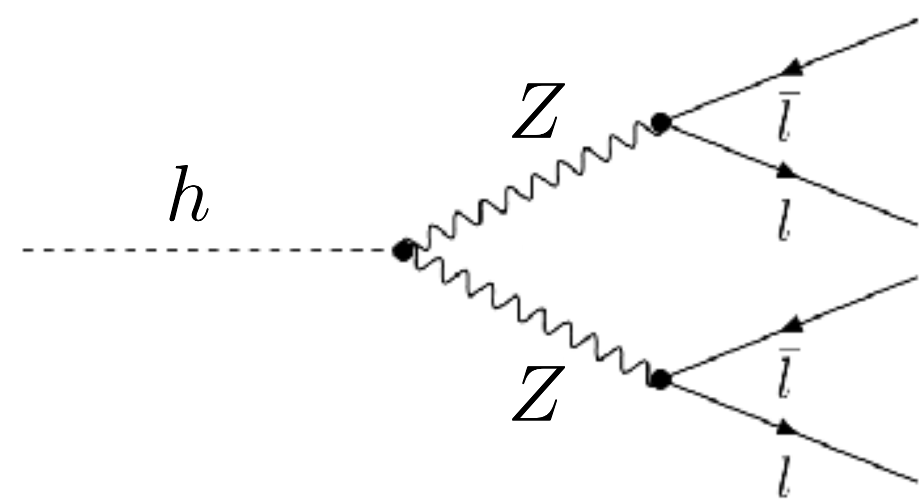
BIGGER THAN YOU THINK

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.

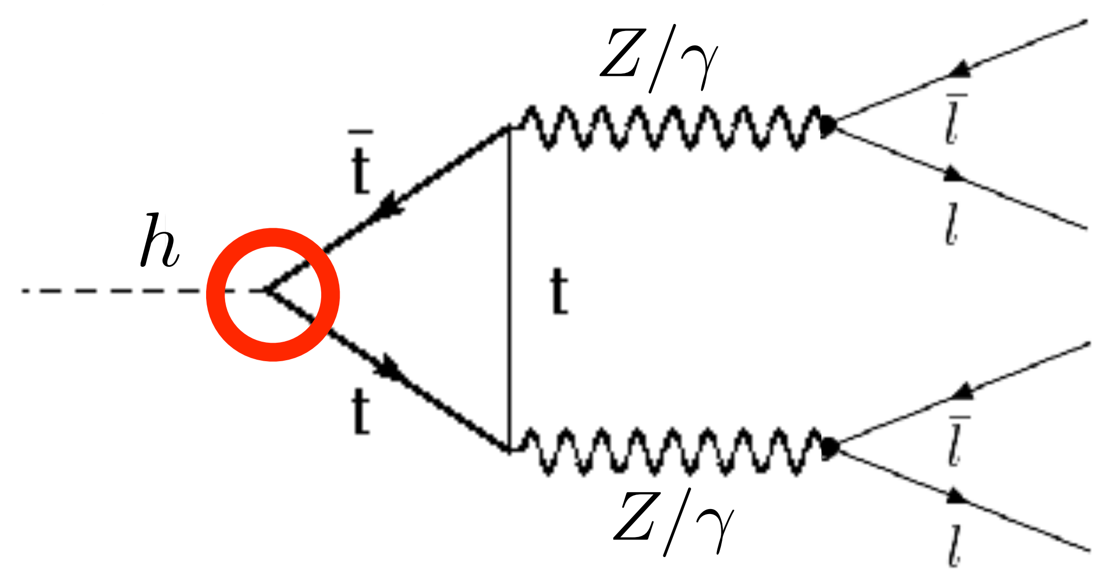




TOP YUKAWA

Start with just top, keep all other couplings fixed.

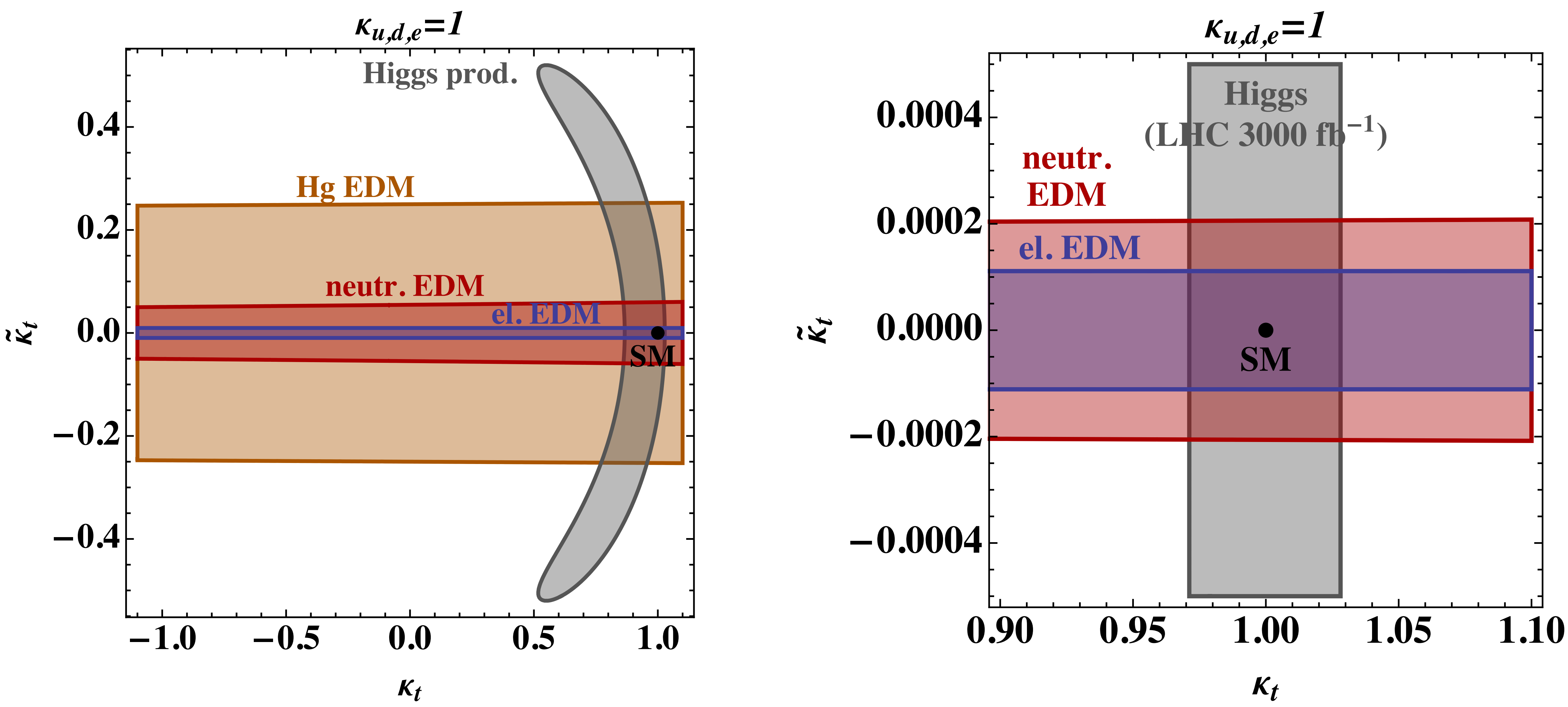
$$h\,\bar{t}\,(y_t + i\,\tilde{y}\,\gamma^5)\,t$$



Can probe CP nature of top Yukawa coupling.

EDM BOUNDS

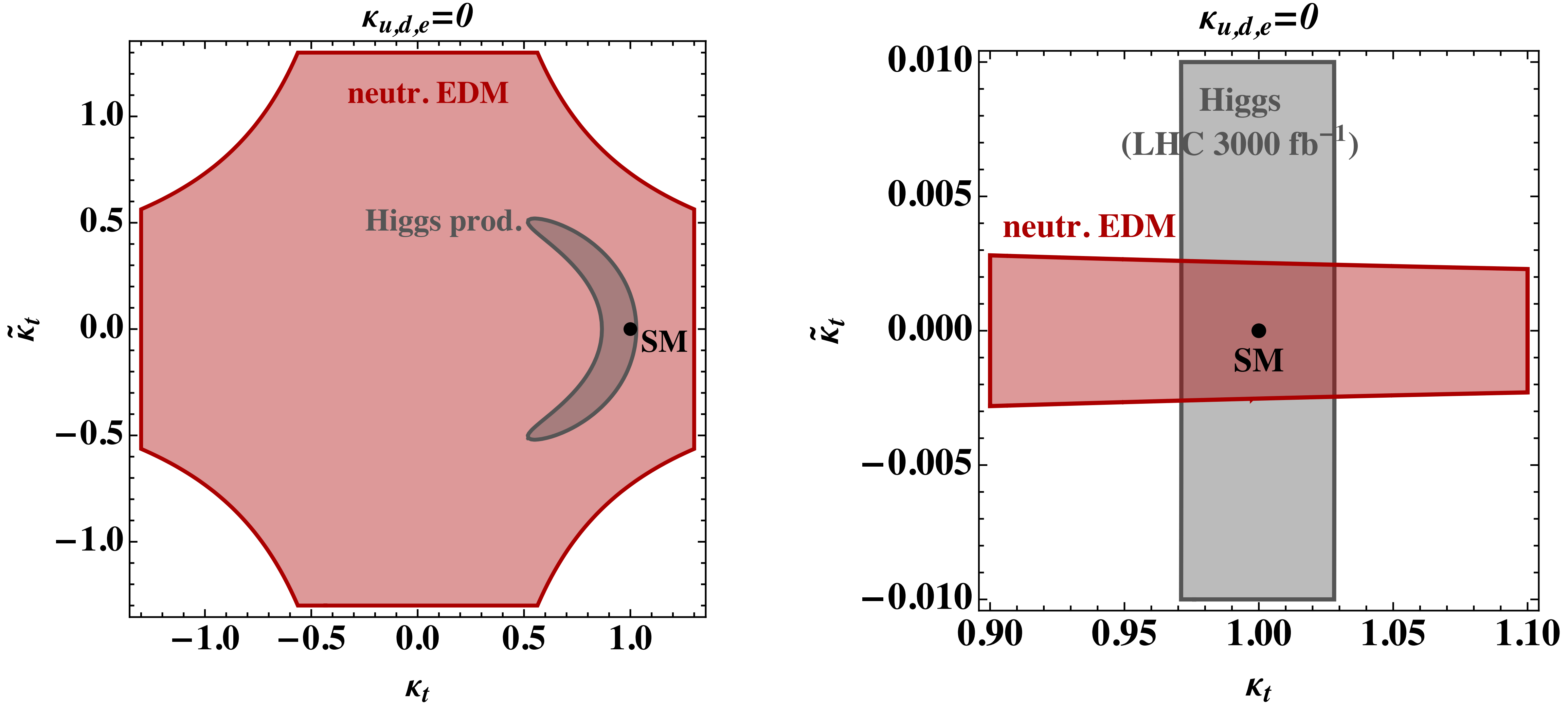
Can place strong bounds on CP violation from EDMs.



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

EDM BOUNDS

Depend on knowing Higgs coupling to first generation.



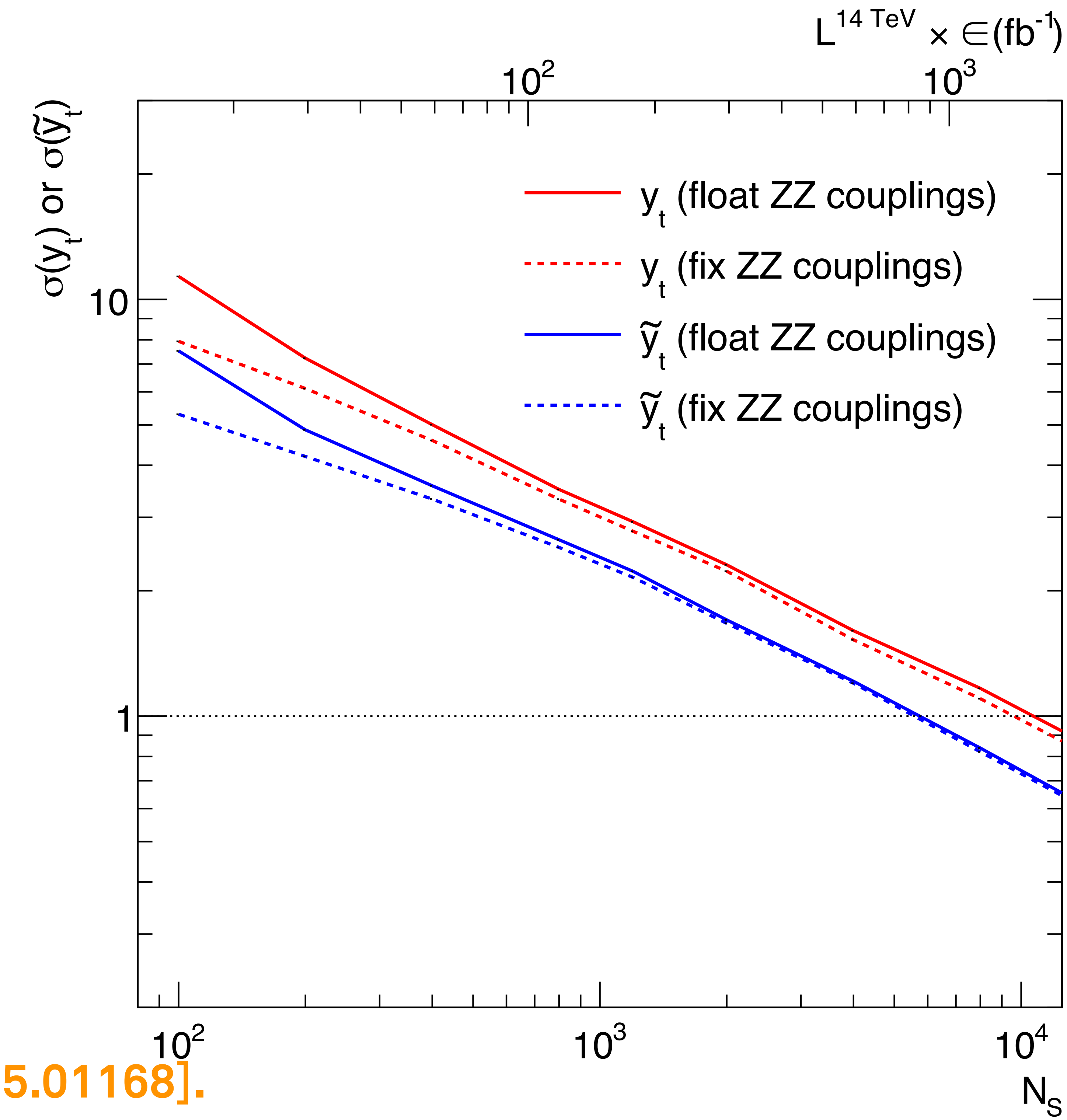
Brod, Haisch, Zupan, [arXiv:1310.1385].

SENSITIVITY

Measurement gets better with more events.

Better sensitivity to pseudo-scalar coupling.

Need large number of events.



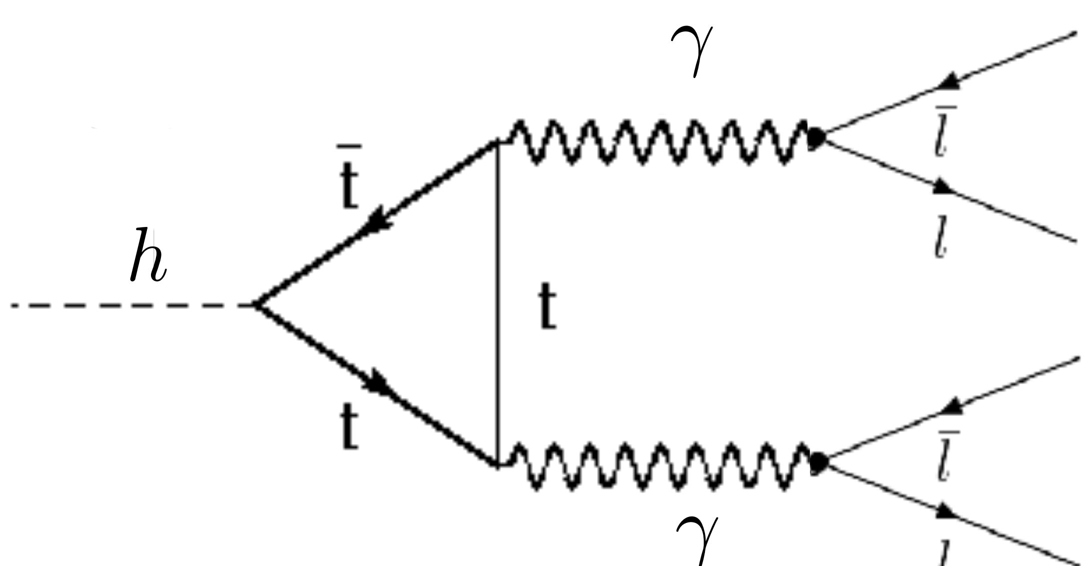
Chen, DS, Vega-Morales, [arXiv:1505.01168].

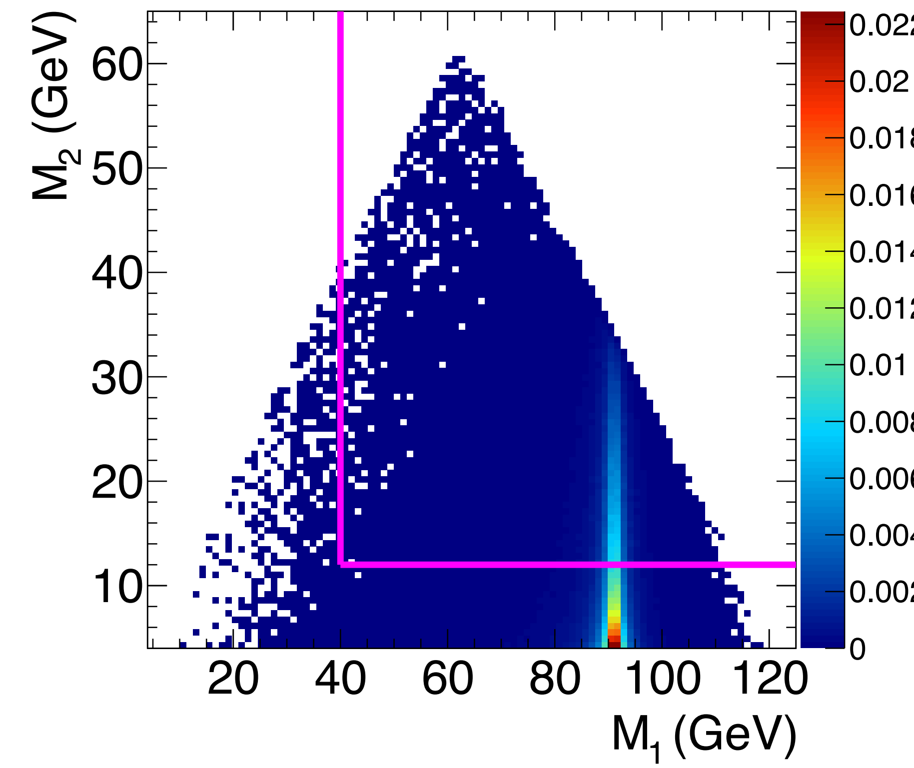
EXPERIMENTAL CUTS

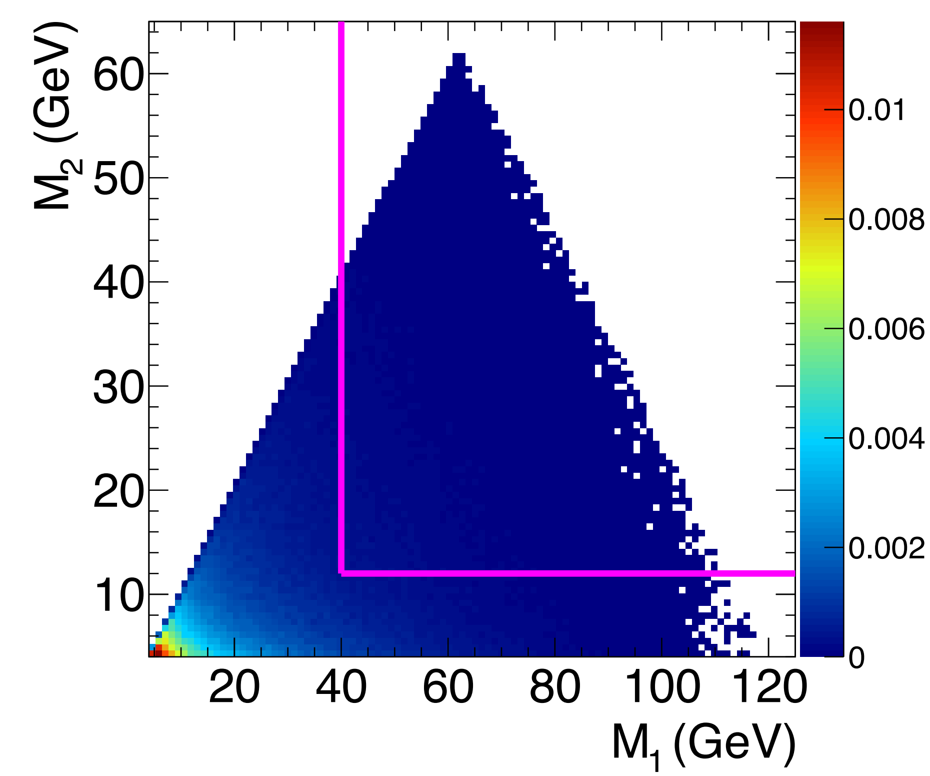
CMS cuts optimized for discovery:

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

Want to gain sensitivity to NLO effects.







EXPERIMENTAL CUTS

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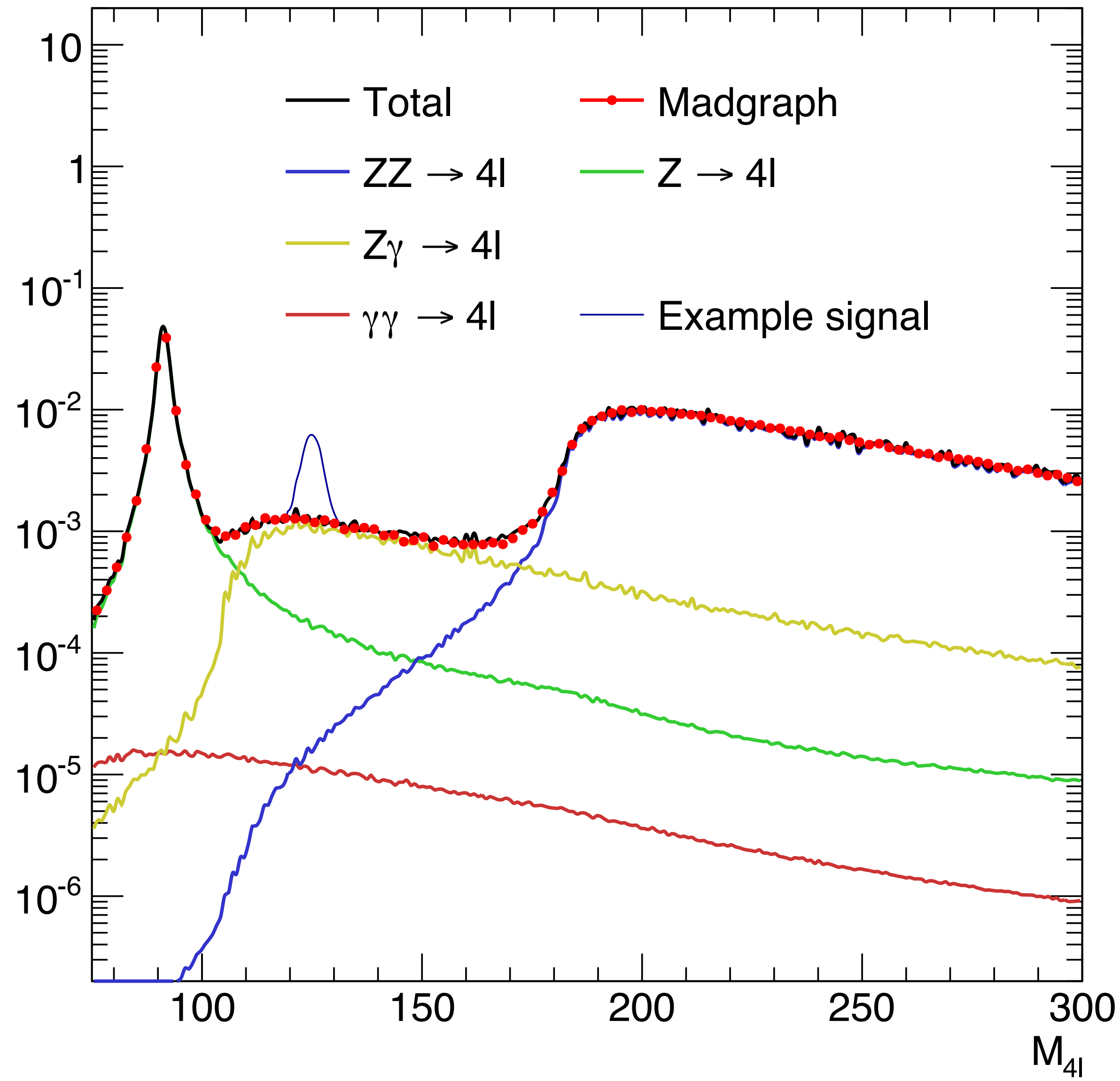
Modified "Relaxed - ϒ"

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

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

S/B gets worse, but sensitivity improves.

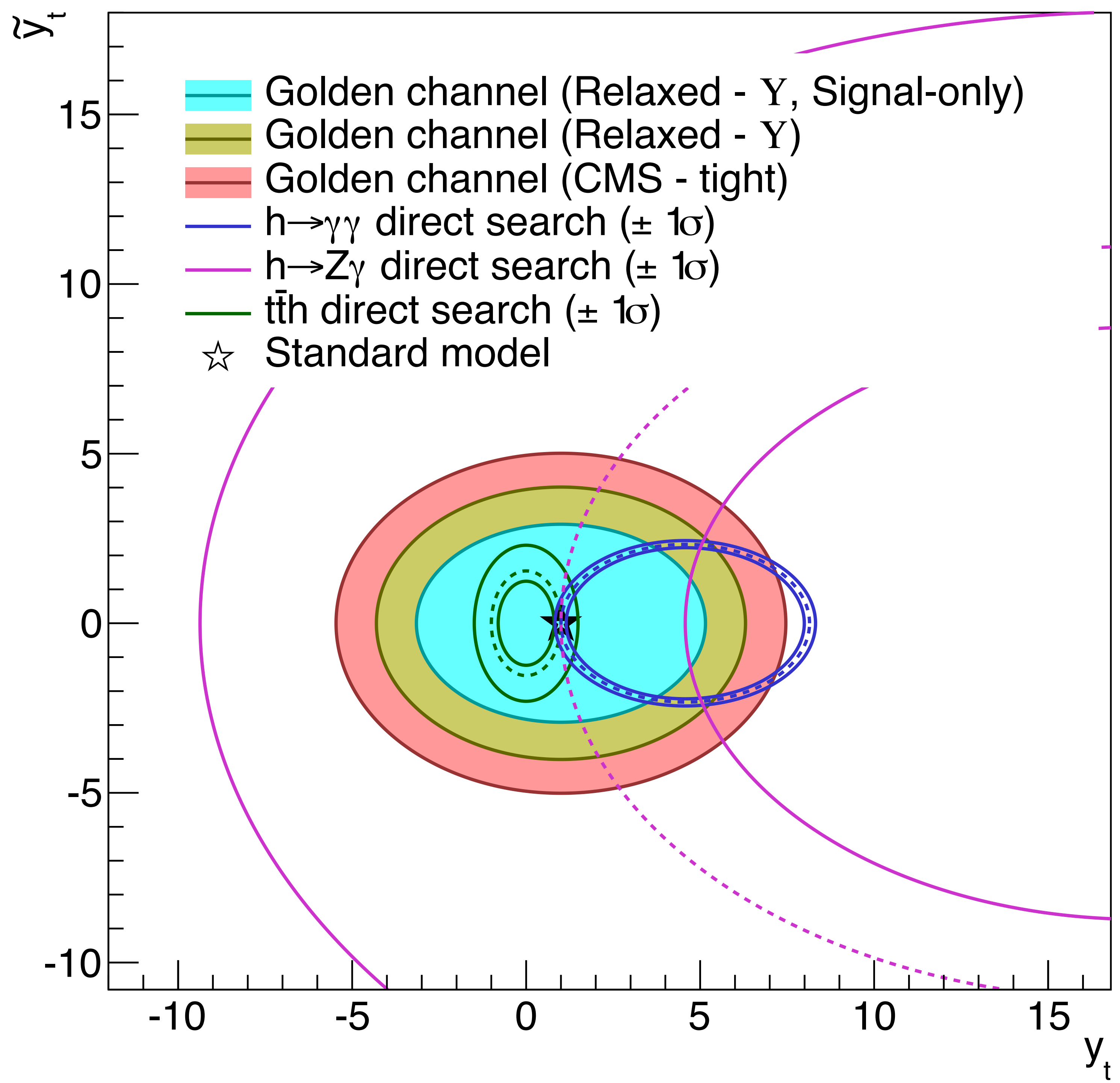


Chen, Harnik, Vega-Morales, [arXiv:1503.05855].

SENSITIVITY

800 events ~ 300 fb^{-1}

Non-trivial constraint.

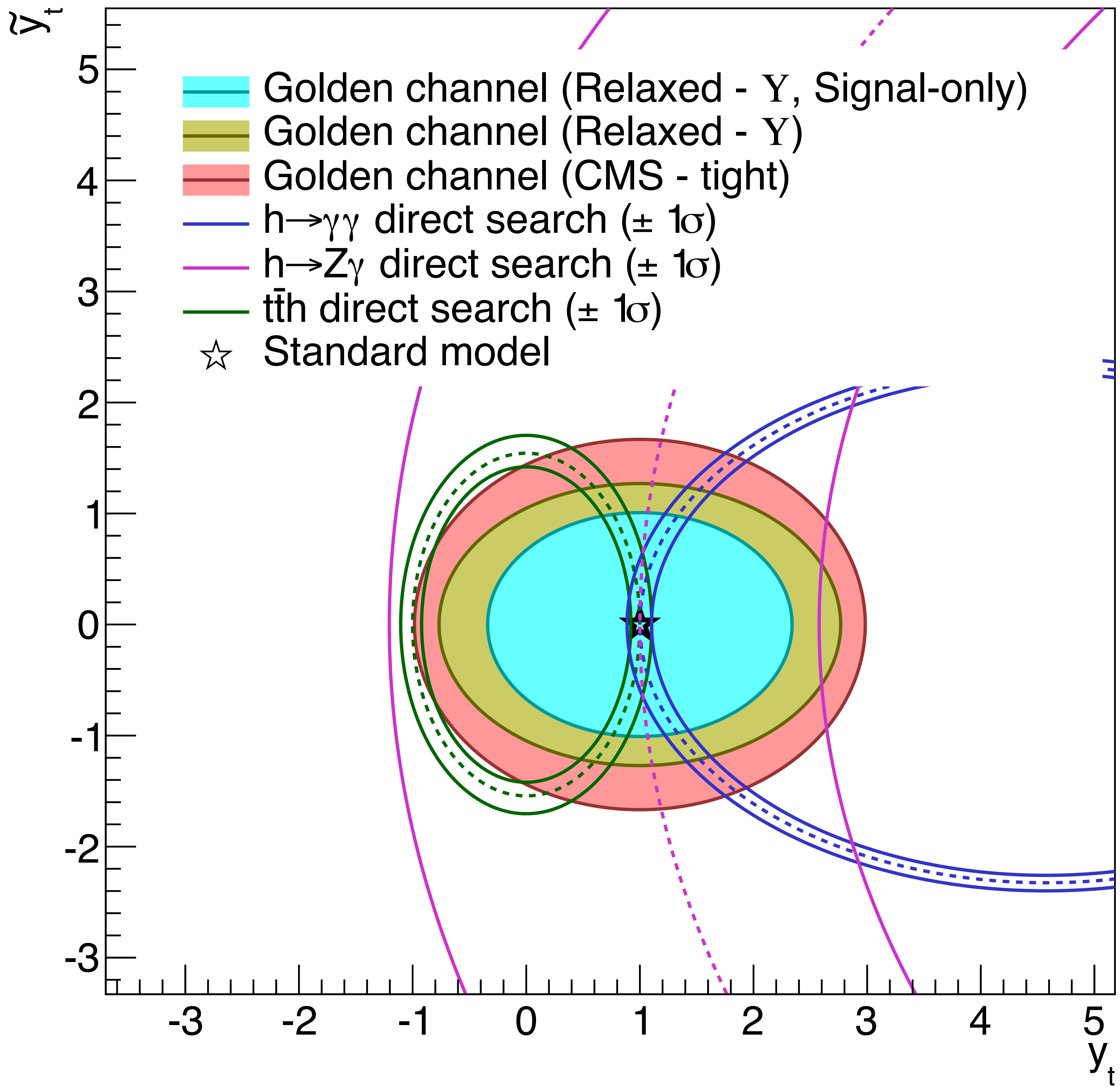


HIGH LUMINOSITY

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

Better constraint.

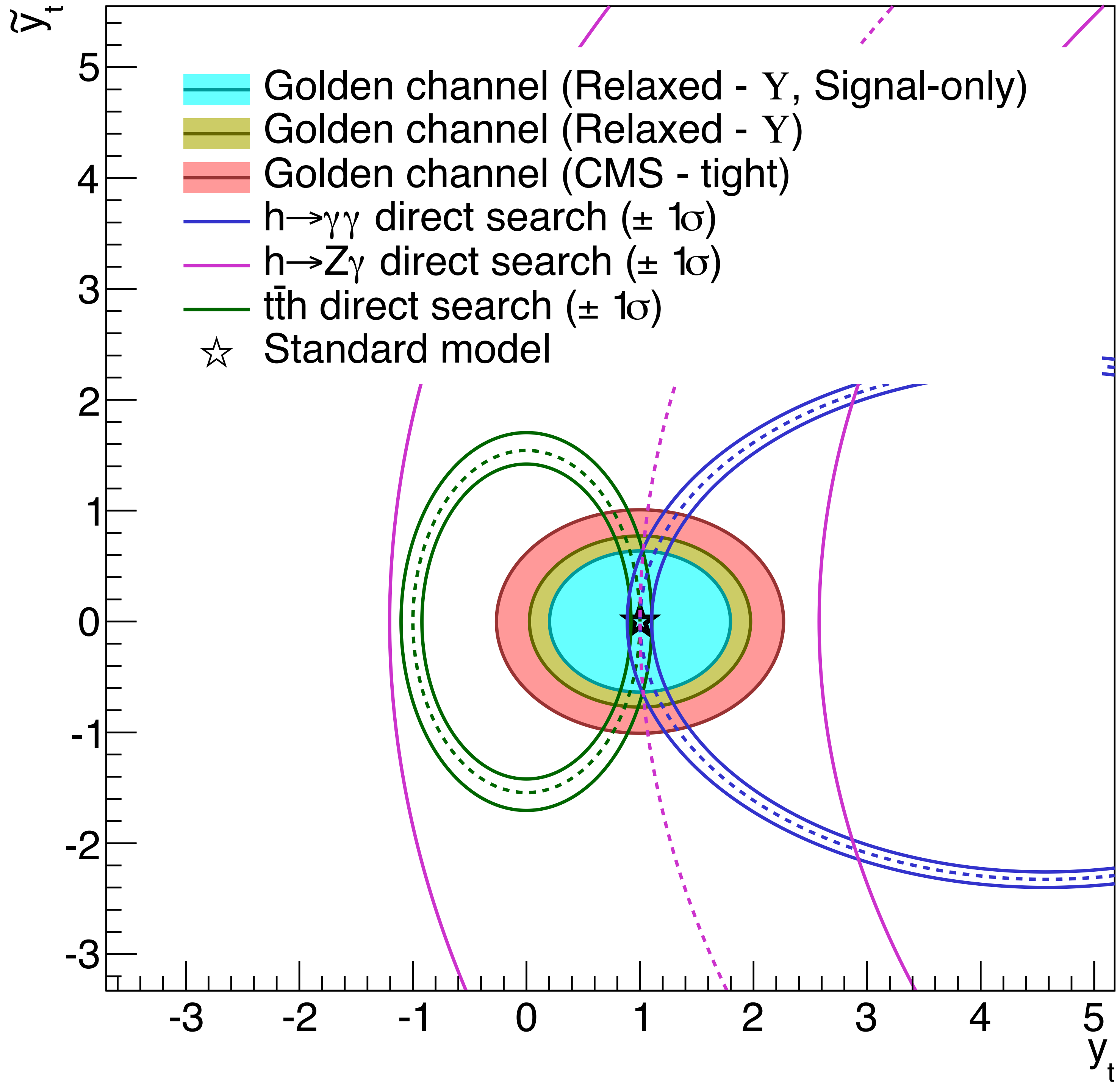
If there is anomaly, will help characterize.



100 TEV?

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

Further improved.



LEPTON COLLIDER

Can we do this at a lepton collider?

Cleaner environment…

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

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

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

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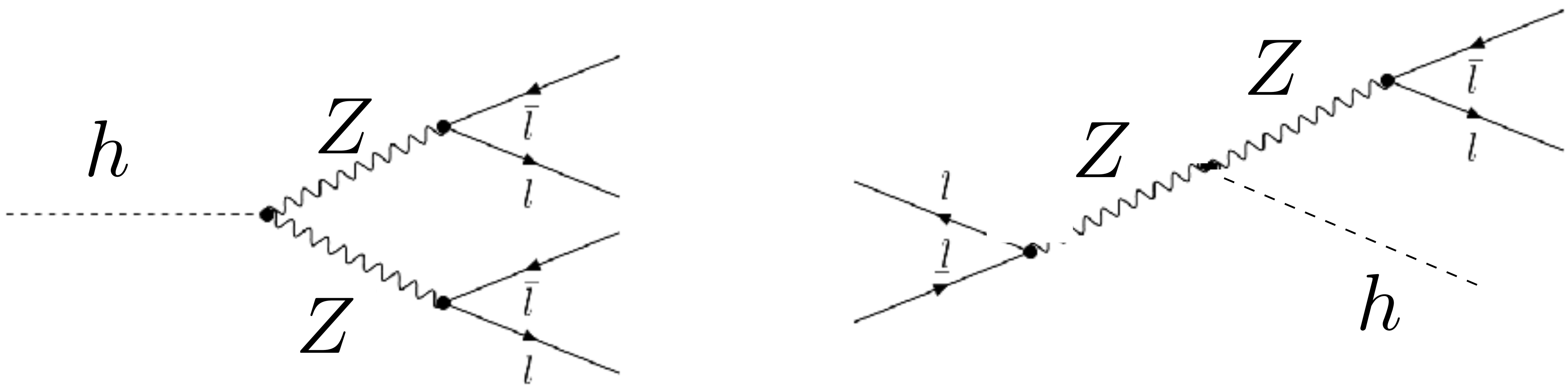
15 events per year.

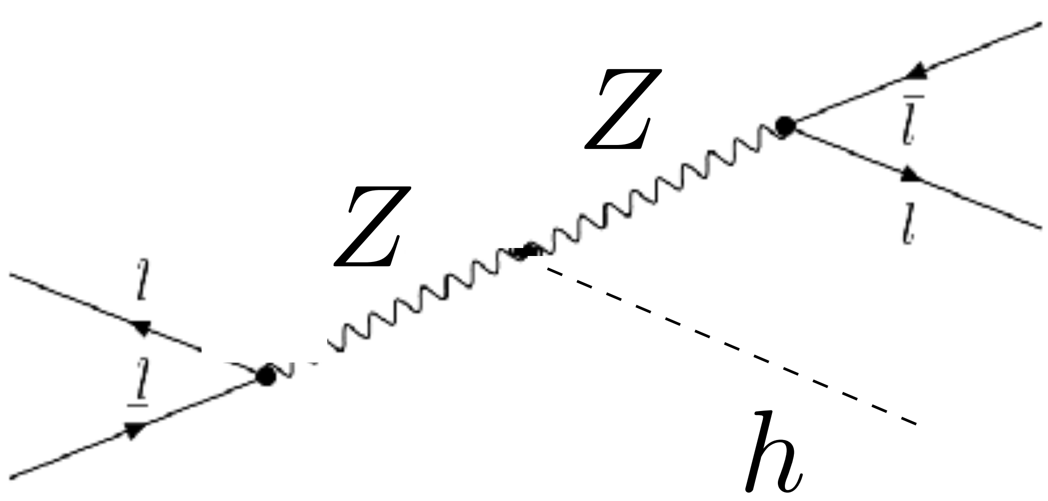
CROSSING SYMMETRY

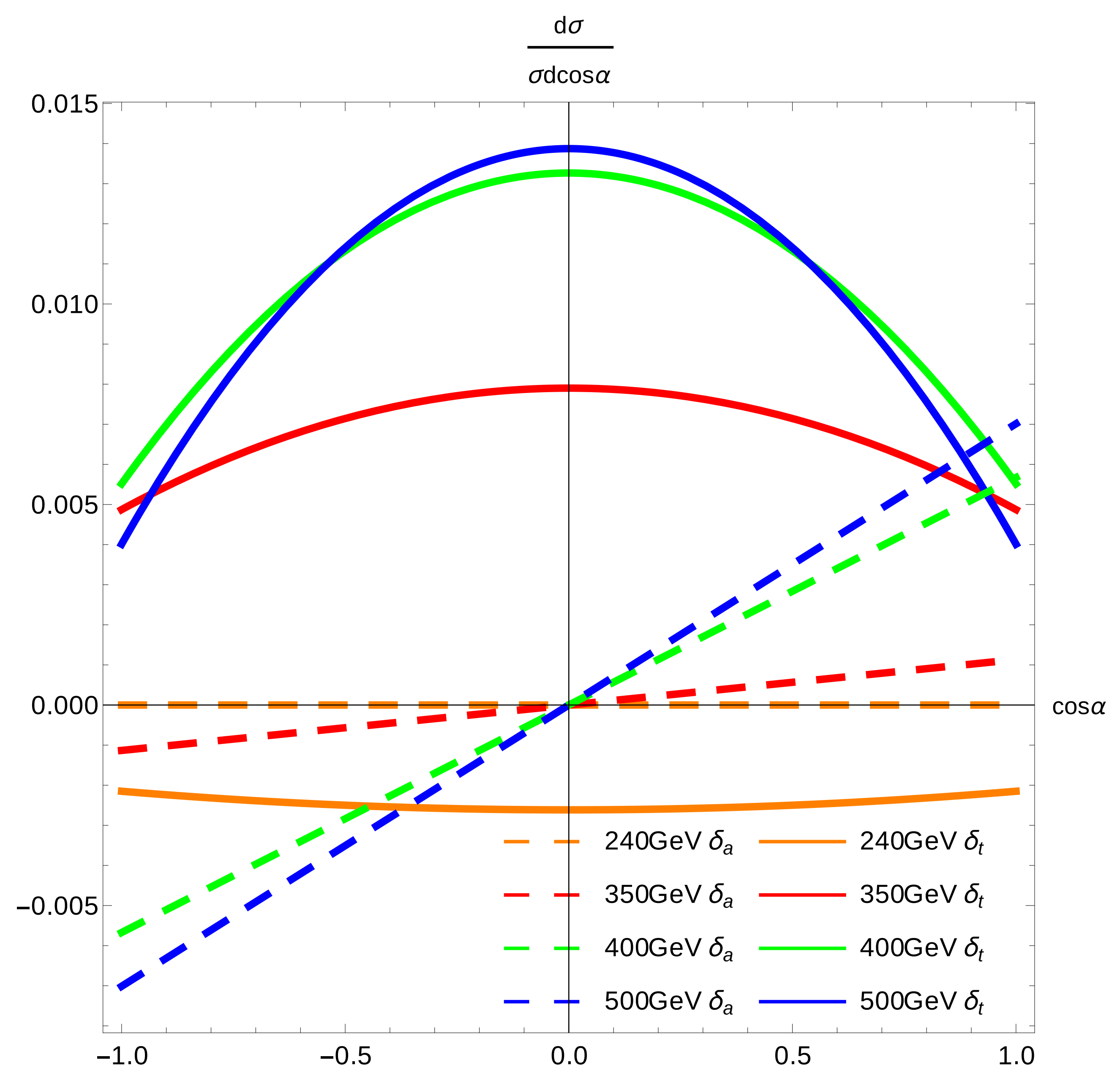


Can probe same coupling with crossed diagram.

No longer have to pay branching ratio penalty.

CROSSING SYMMETRY



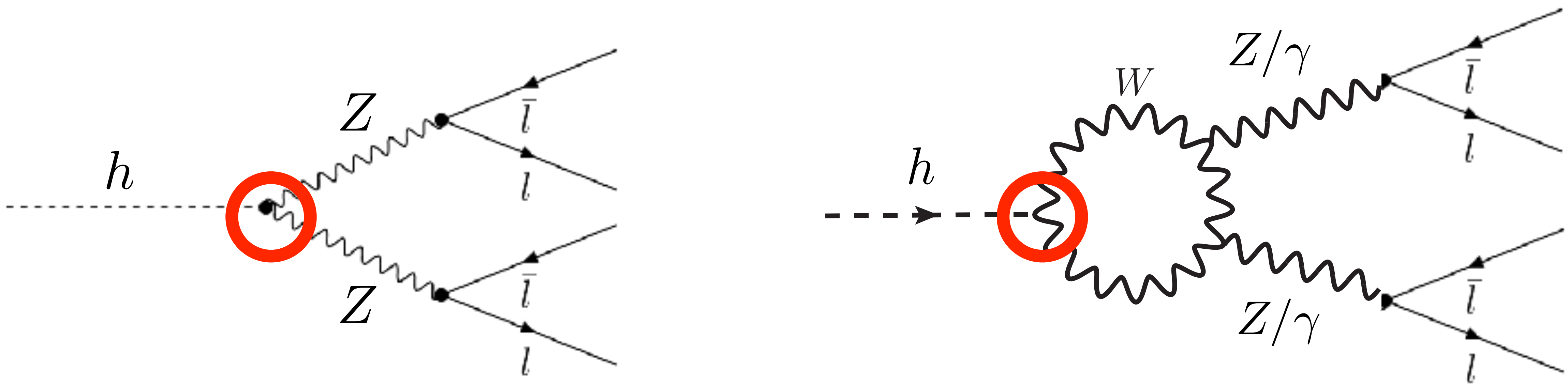


See for example:
Shen and Zhu, arXiv:1504.05626.

COUPLING TO GAUGE BOSONS

Now consider the other large loop process.

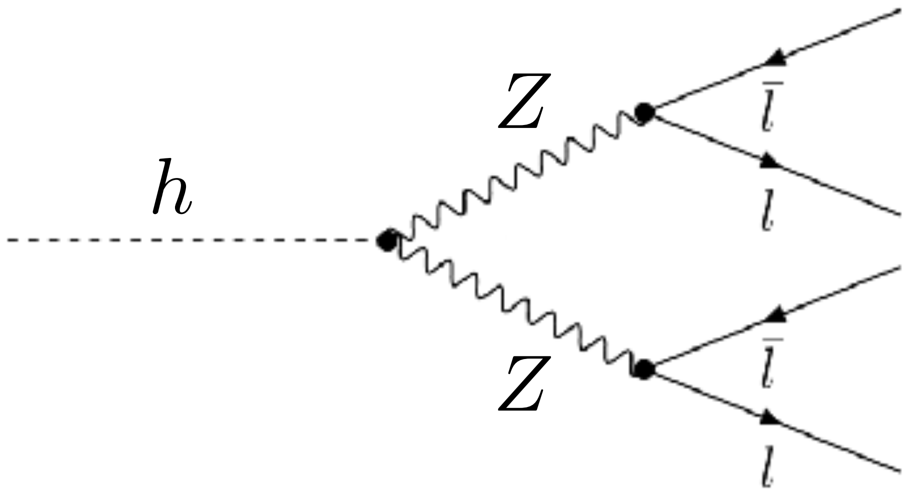
Recall that this interferes with tree-level process.

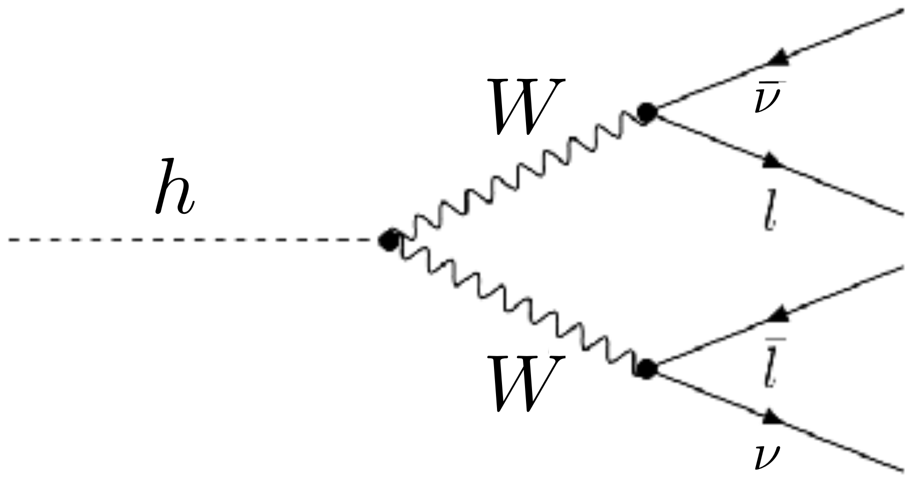


Kinematic distributions are sensitive to ratio of these two couplings.

TREE-LEVEL MEASUREMENTS

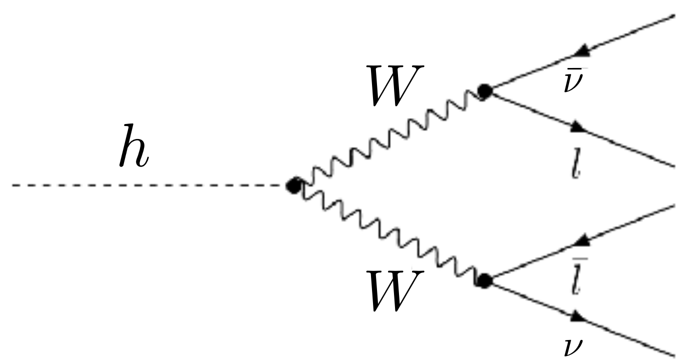
Can also measure these couplings at tree level.

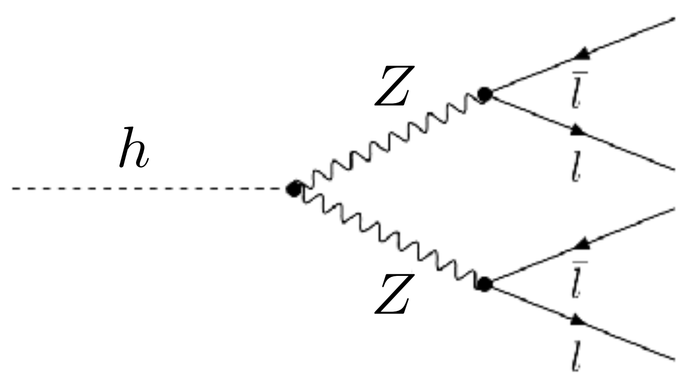




TREE-LEVEL MEASUREMENTS

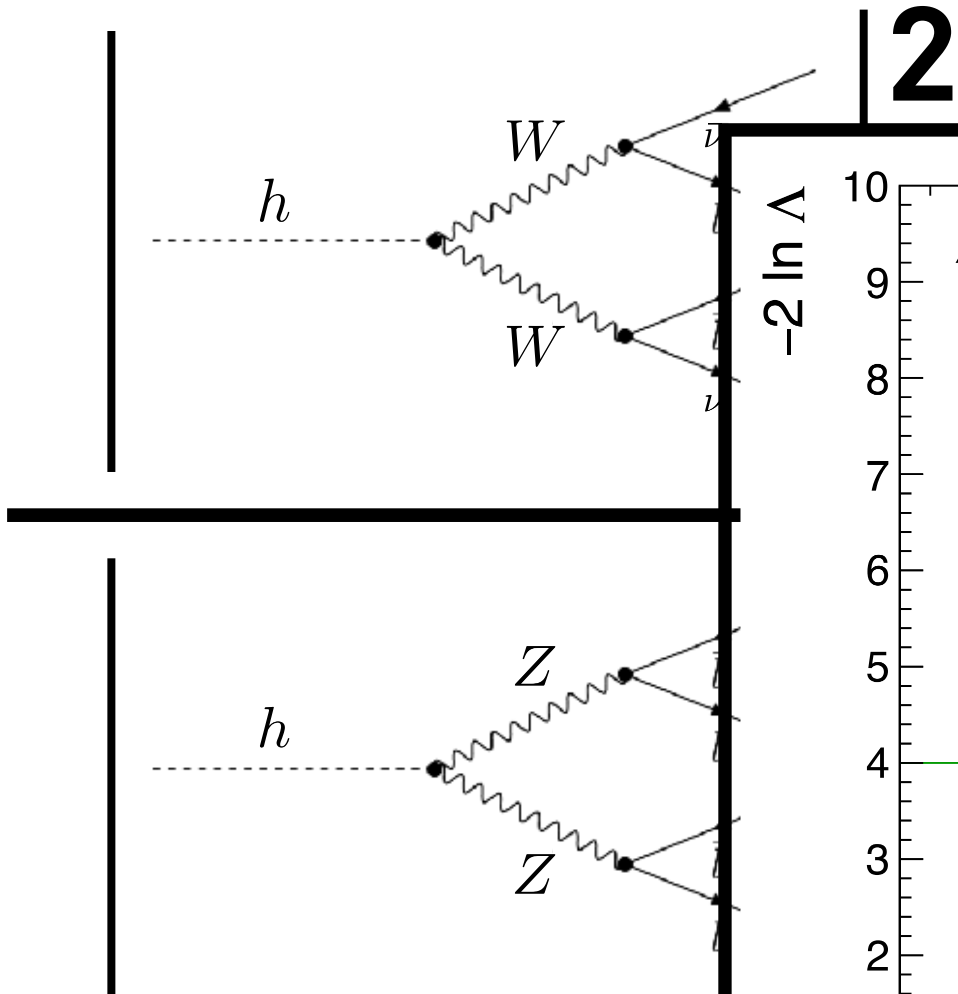
$$\lambda_{WZ}^2 \simeq \frac{\left| \text{(diagram 1)} \right|^2}{\left| \text{(diagram 2)} \right|^2}$$

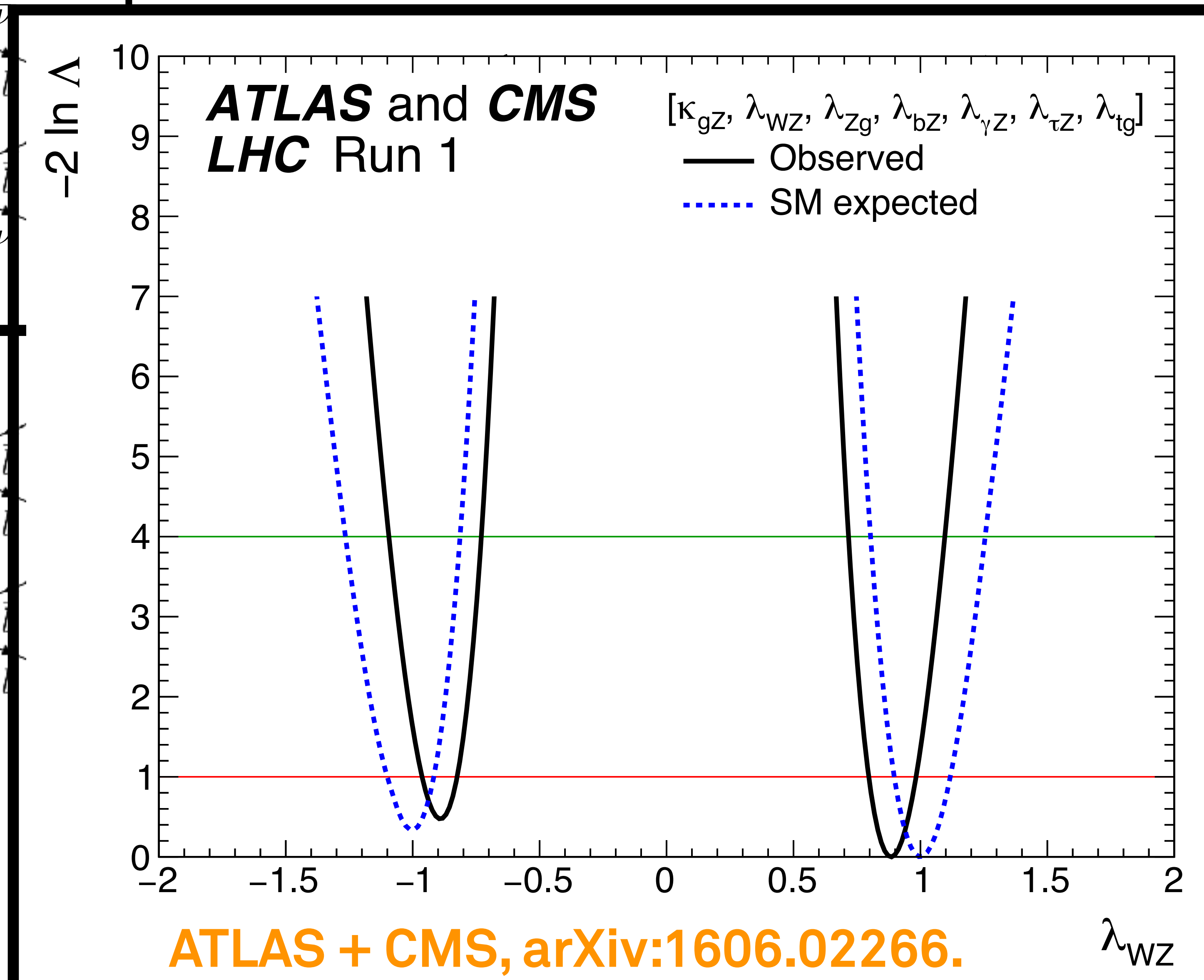




TREE-LEVEL MEASUREMENTS

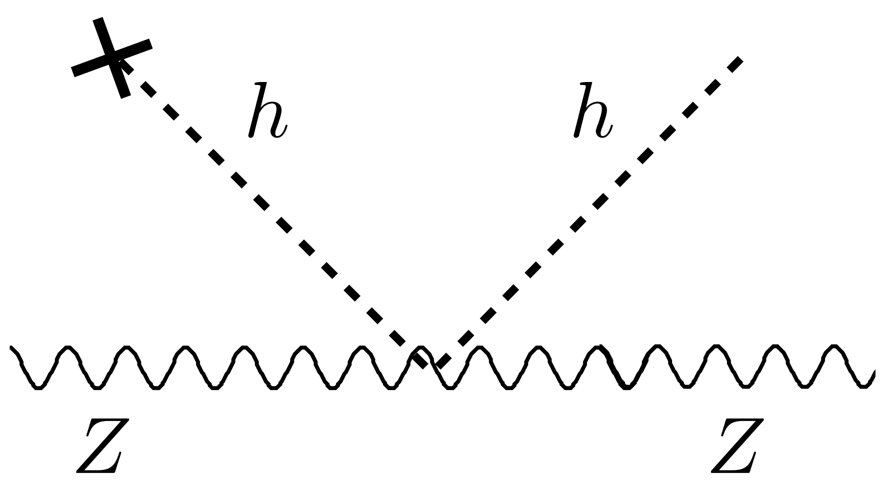
$\lambda_{WZ}^2 \simeq$

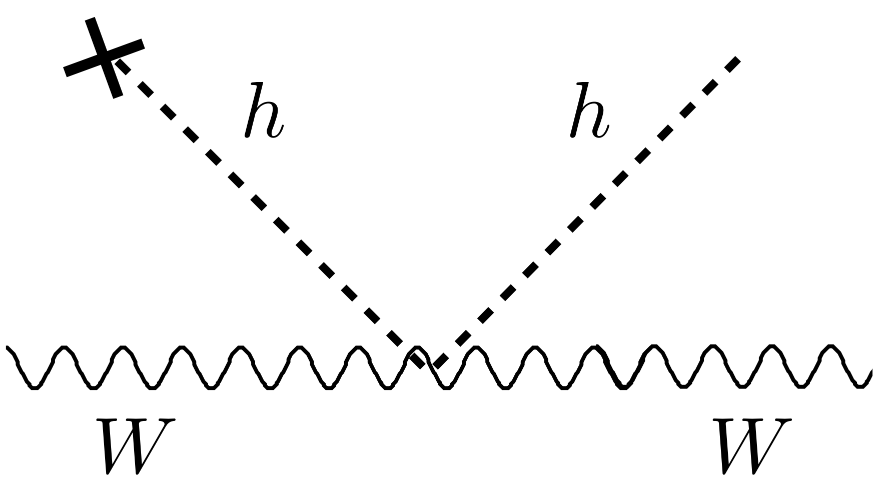




ATLAS + CMS, arXiv:1606.02266.

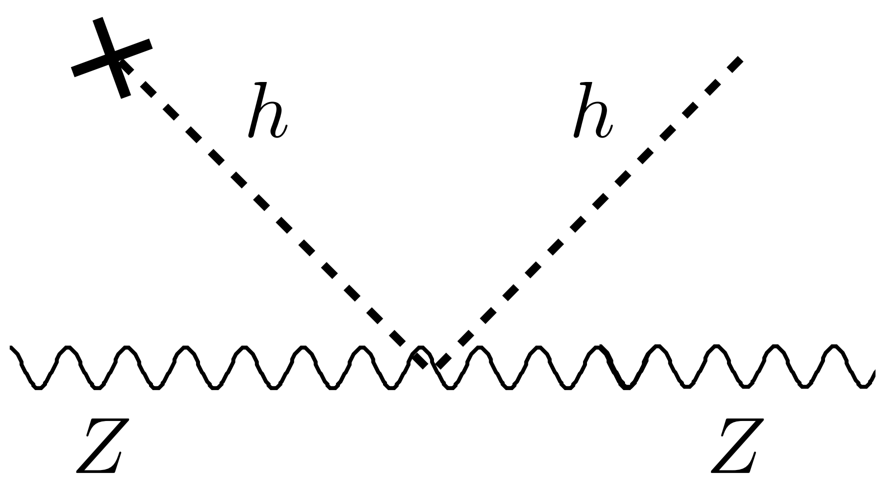
CUSTODIAL SYMMETRY

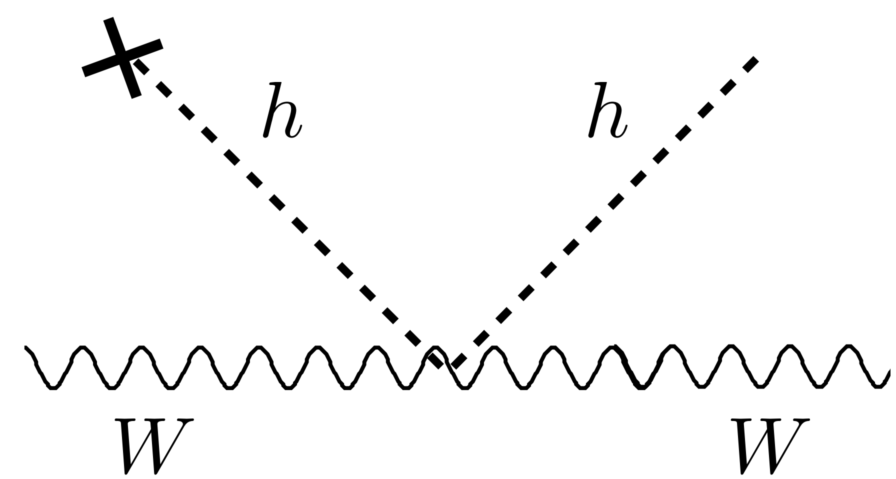




CUSTODIAL SYMMETRY

Ratio of couplings to gauge bosons dictated by custodial symmetry.

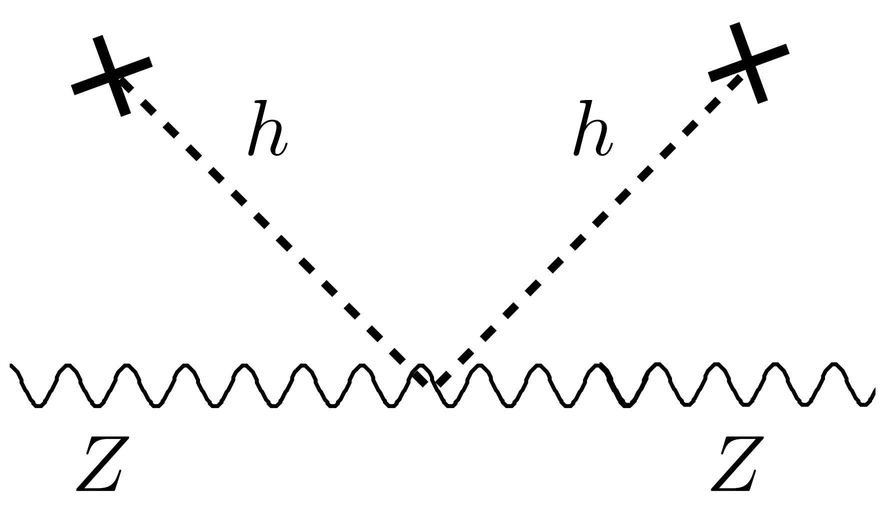


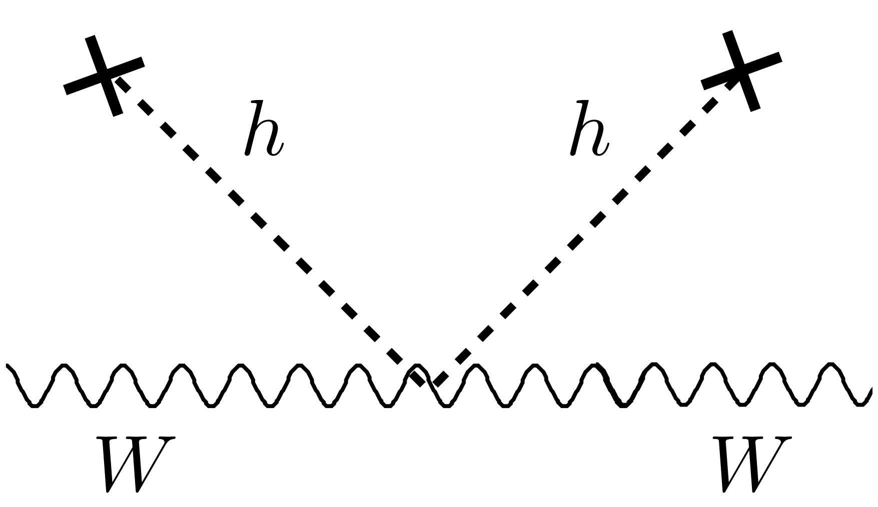


CUSTODIAL SYMMETRY

Ratio of couplings to gauge bosons dictated by custodial symmetry.

Also dictates ratio of masses of gauge bosons.





CUSTODIAL SYMMETRY

Ratio of couplings to gauge bosons dictated by custodial symmetry.

Also dictates ratio of masses of gauge bosons.

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

REVIEW

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

Explicit breakings: hypercharge and Yukawas.

W and *Z* are **3** under $SU(2)_C$.

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

Goldstones (→ **3**)   h (→ **1**)

GENERAL EWSB

Low and Lykken, [arXiv:1005.0872].

GENERAL EWSB

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

Low and Lykken, [arXiv:1005.0872].

GENERAL EWSB

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

⇓ 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*.

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

Which ones can decay to gauge bosons
(via CP even operator)?

Low and Lykken, [arXiv:1005.0872].

GENERAL EWSB

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

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W x W = **1 + 3 + 5**

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GENERAL EWSB

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

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

Which ones can decay to gauge bosons
(via CP even operator)?

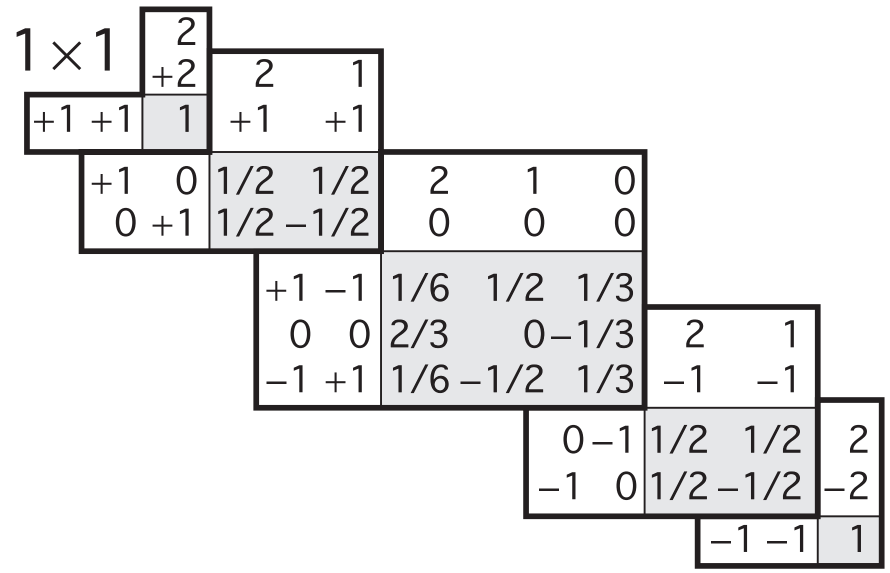
W x W = **1 + ~~3~~ + 5**

CP odd

Low and Lykken, [arXiv:1005.0872].

COUPLINGS

Can compute ratios using Clebsch-Gordan tables:



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

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

$H_5\ (W^+\ W^- — Z\ Z)$

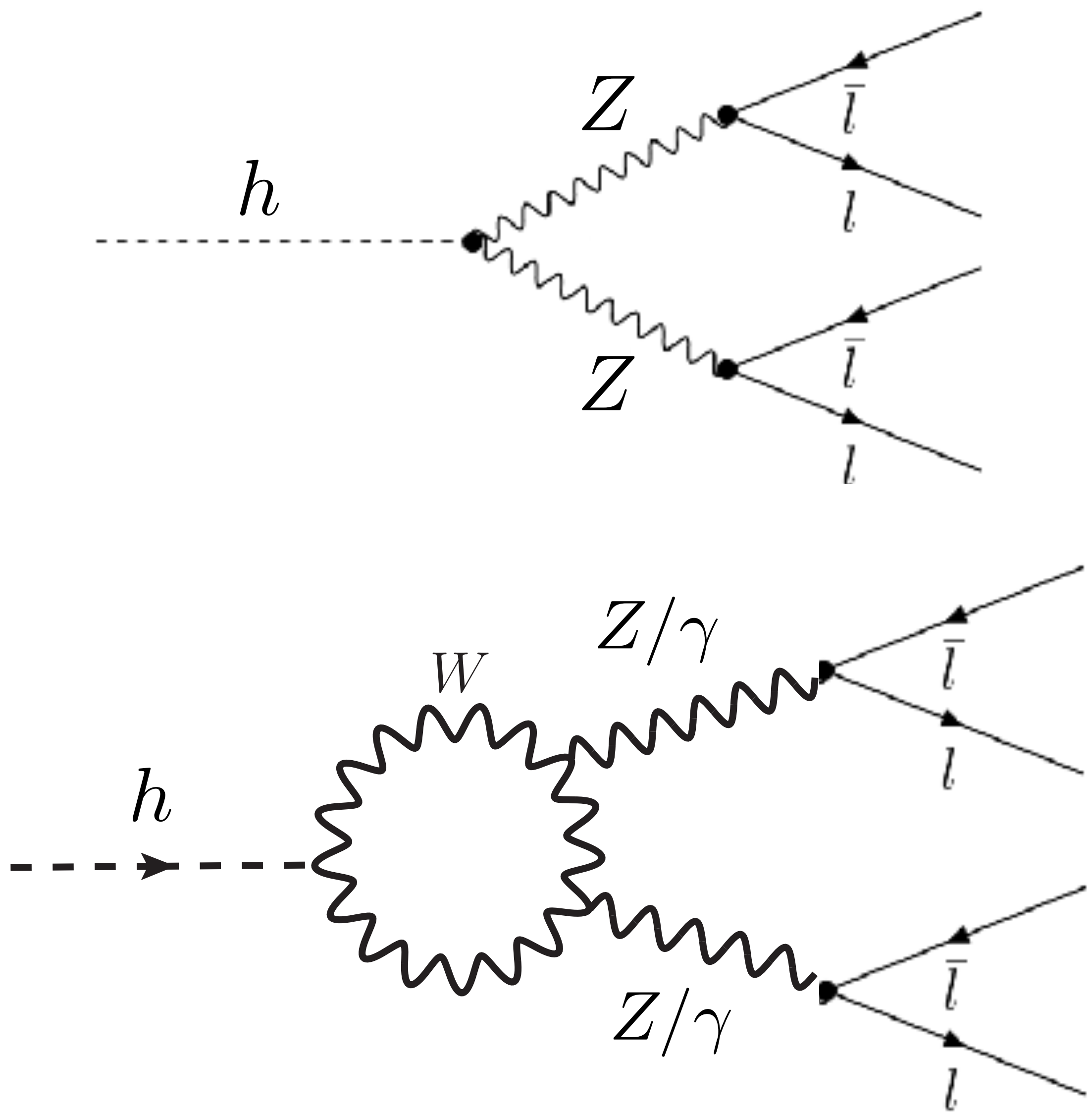
$$\lambda_{WZ} = -1/2$$

Two cases predict opposite signs!

Low and Lykken, [arXiv:1005.0872].

$H(125)$

Only two custodial preserving cases.
Predict opposite sign for λ_{WZ}.

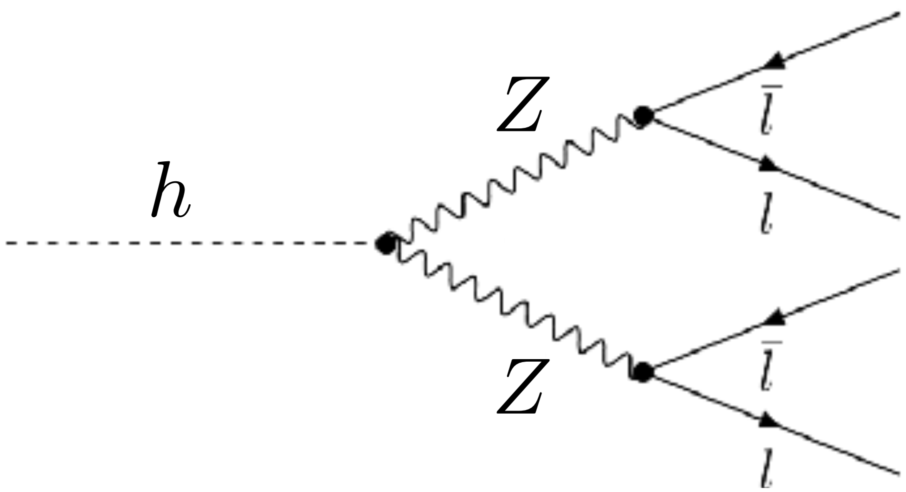


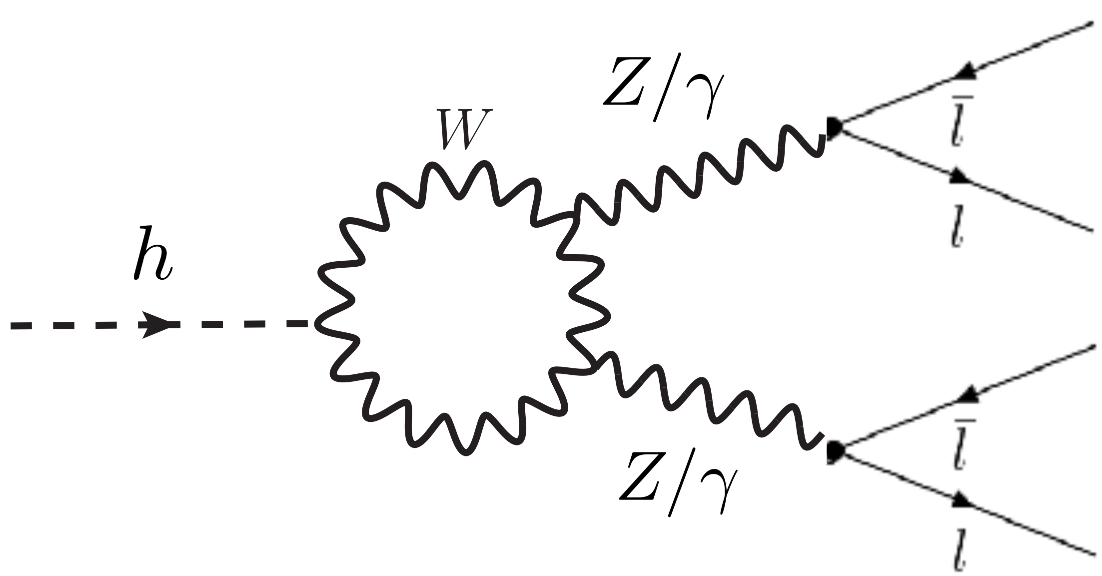
$H(125)$

Only two custodial preserving cases.
Predict opposite sign for λ_{WZ}.

Can $H(125)$ be a **5**?

Rate measurements insensitive to sign.





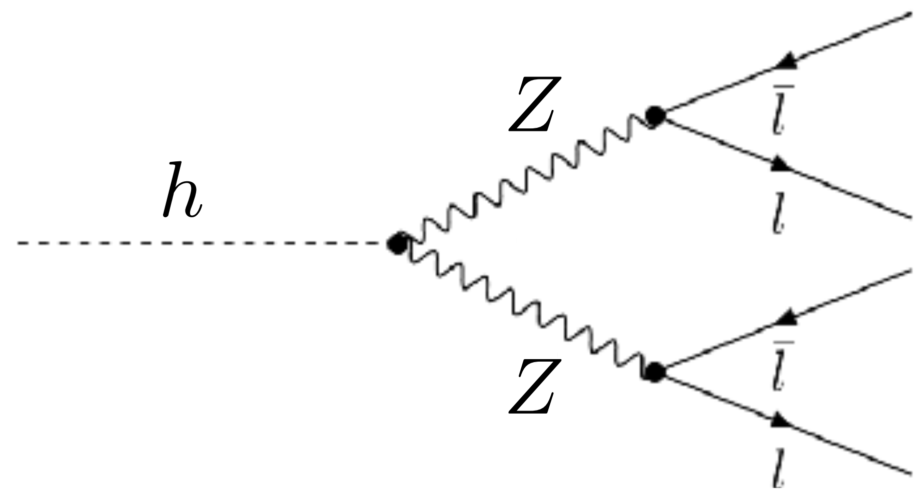
$H(125)$

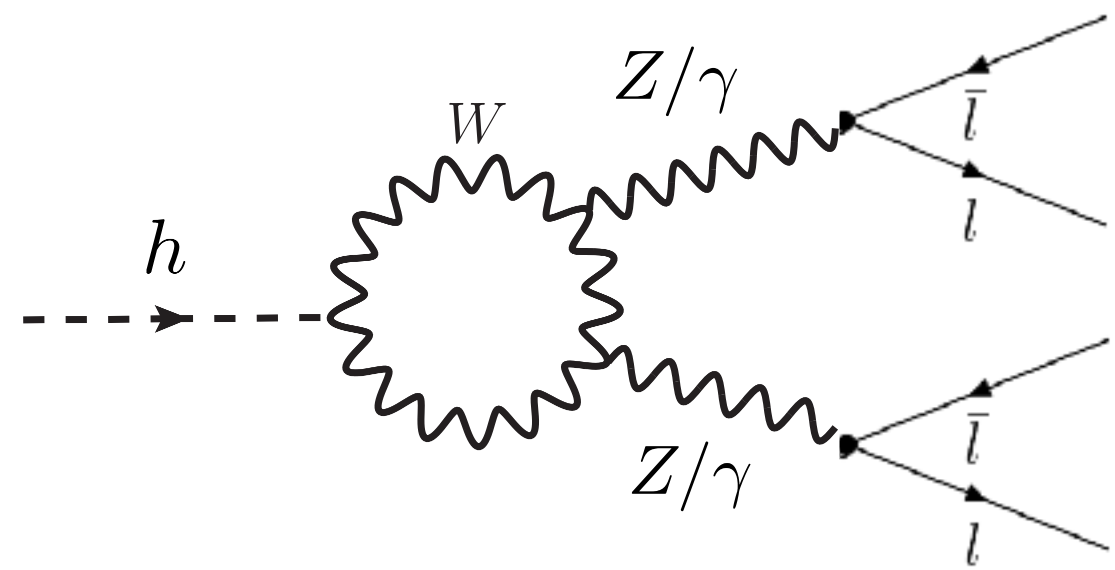
Only two custodial preserving cases.
Predict opposite sign for λ_{WZ}.

Can $H(125)$ be a **5**?

Rate measurements insensitive to sign.

Can use interference effects.



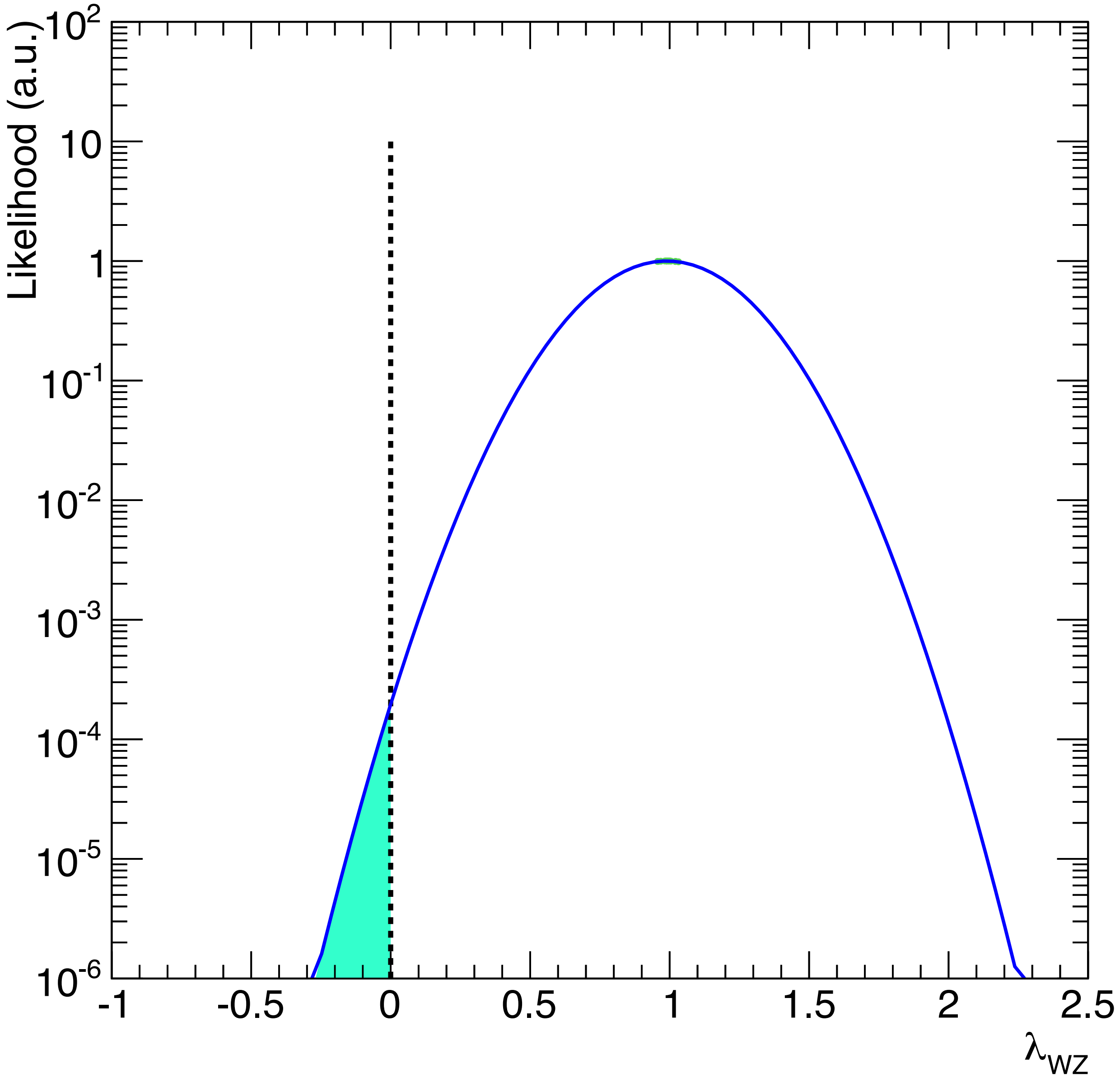


MEASURING THE SIGN

Build up likelihood with data.

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

What is probability that it is negative?



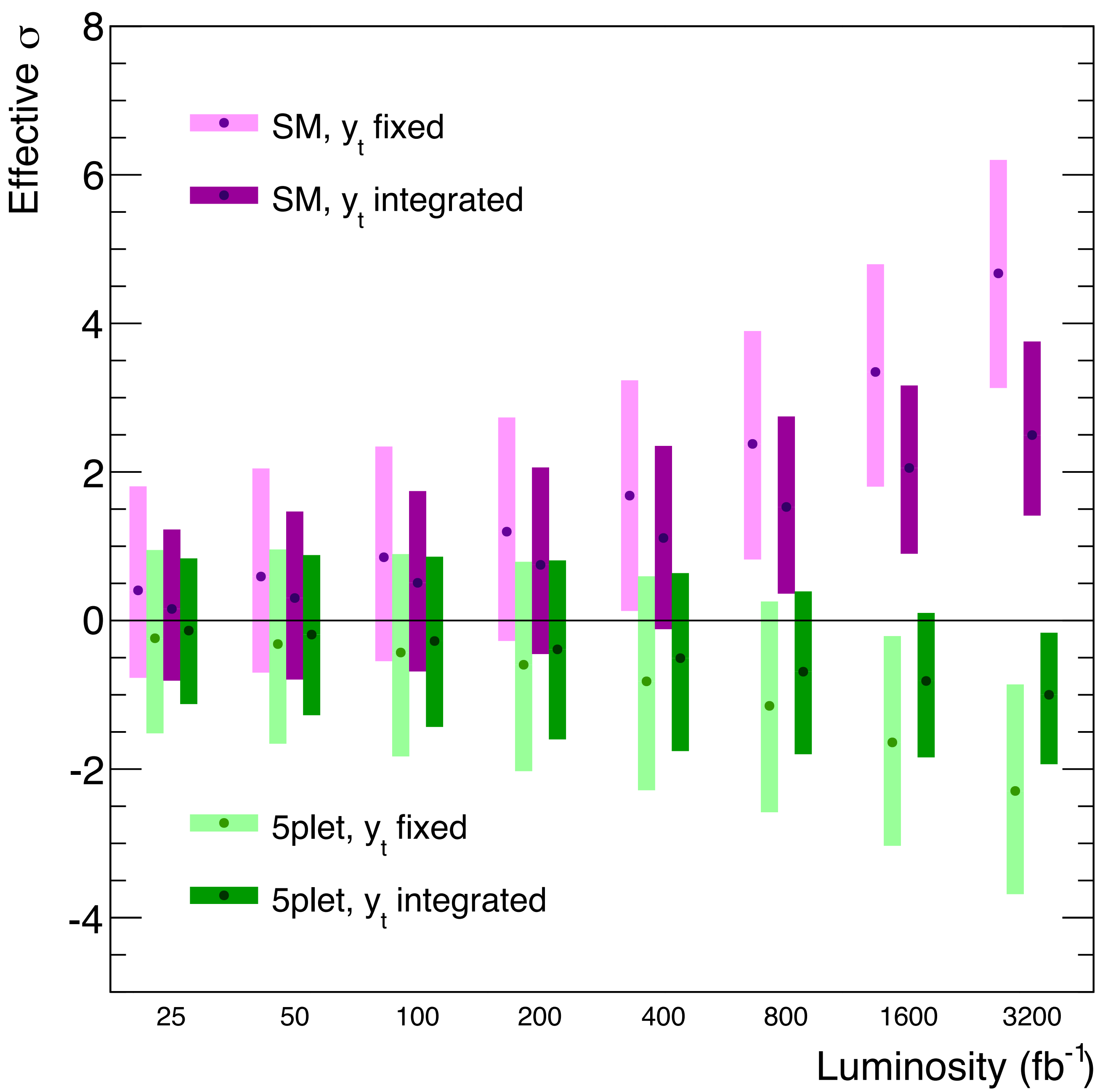
2,000 events

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

MEASURING THE SIGN

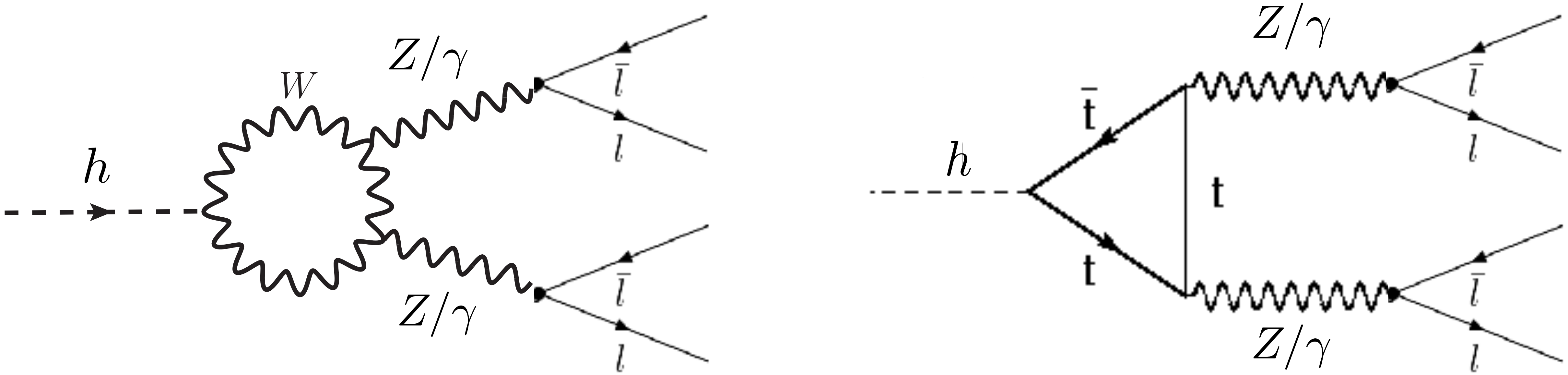
Can distinguish two different cases with (high-luminosity) LHC data.

Nearly independent of top Yukawa coupling.



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

TOP AND W LOOPS



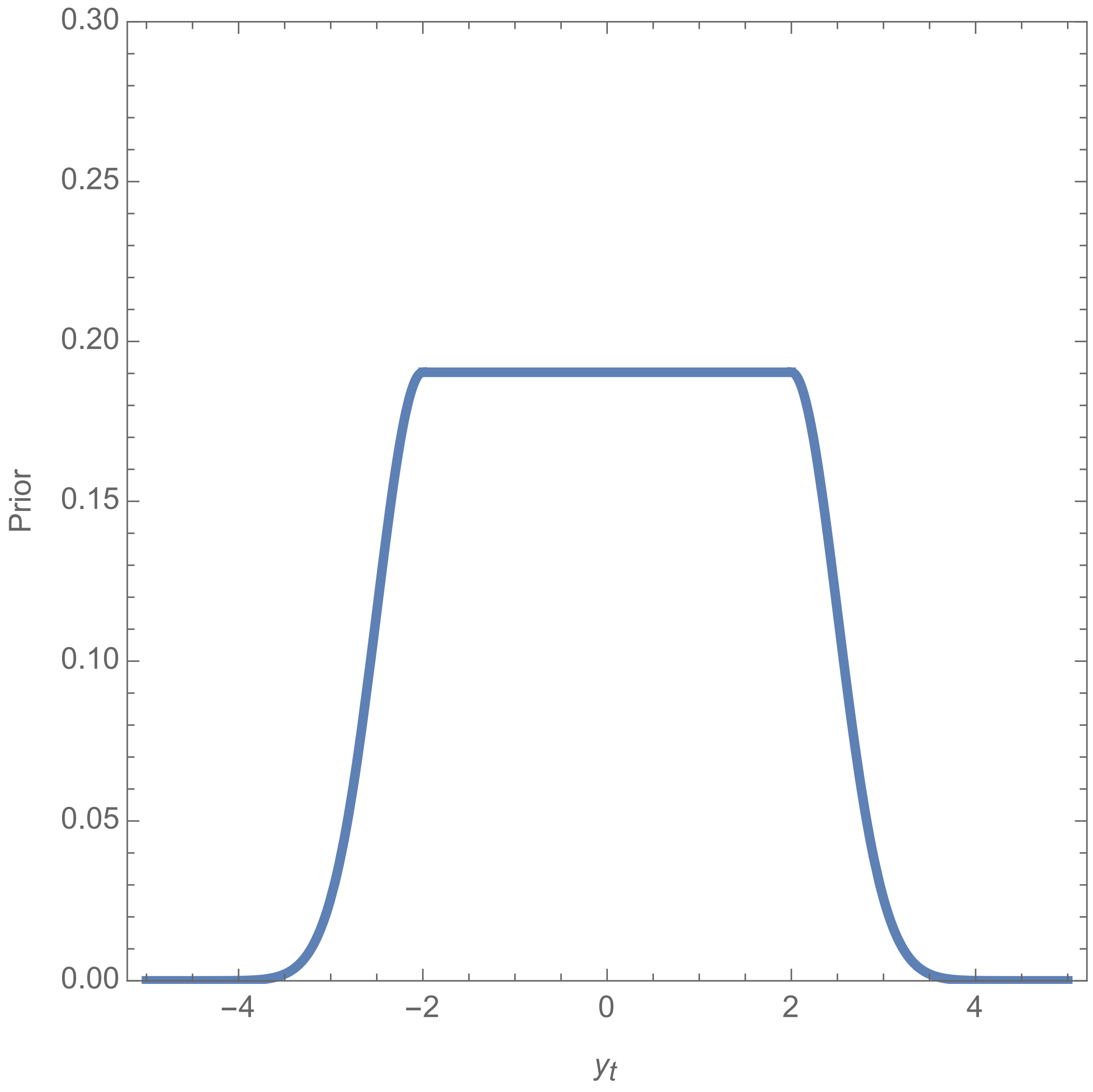
Top and W contribute to same operators, can substitute one for the other.

What happens if you float both couplings?

BAYESIAN PRIOR

Use prior for top Yukawa coupling in numerical fit.

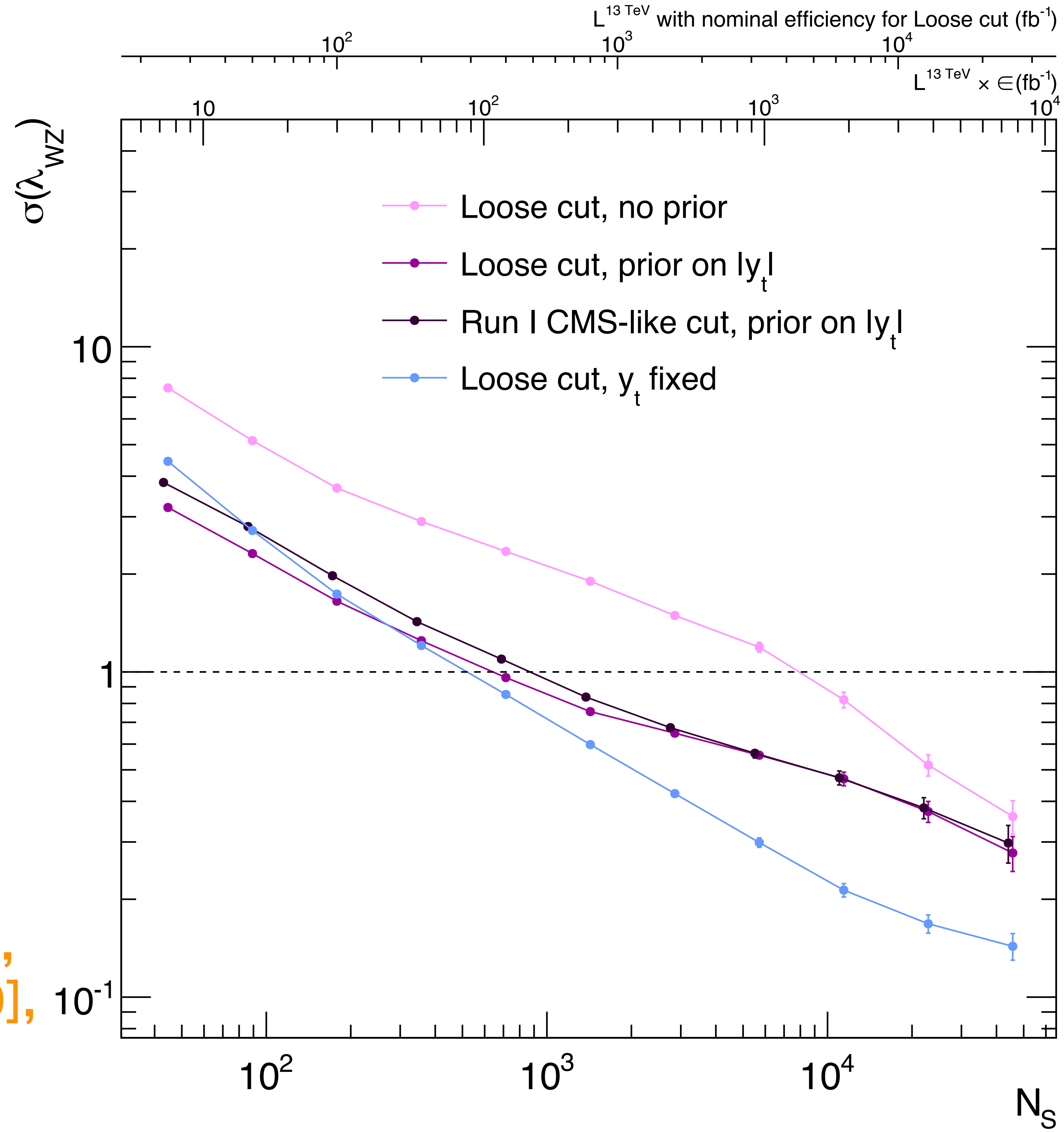
Keep it approximately perturbative as it is in all realistic models.



FIT BOTH COUPLINGS

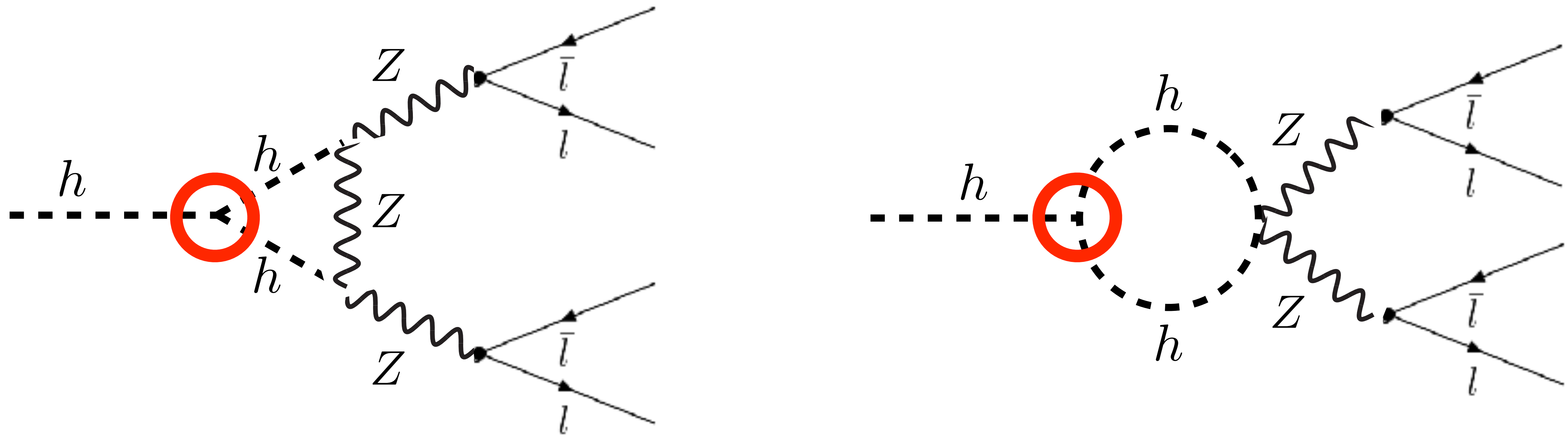
Can float multiple couplings simultaneously.

Full LHC run will give lots of information.



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

TRIPLE HIGGS COUPLING



Triple Higgs coupling also comes into NLO corrections.

Only contributes when *Z*'s are in final state.

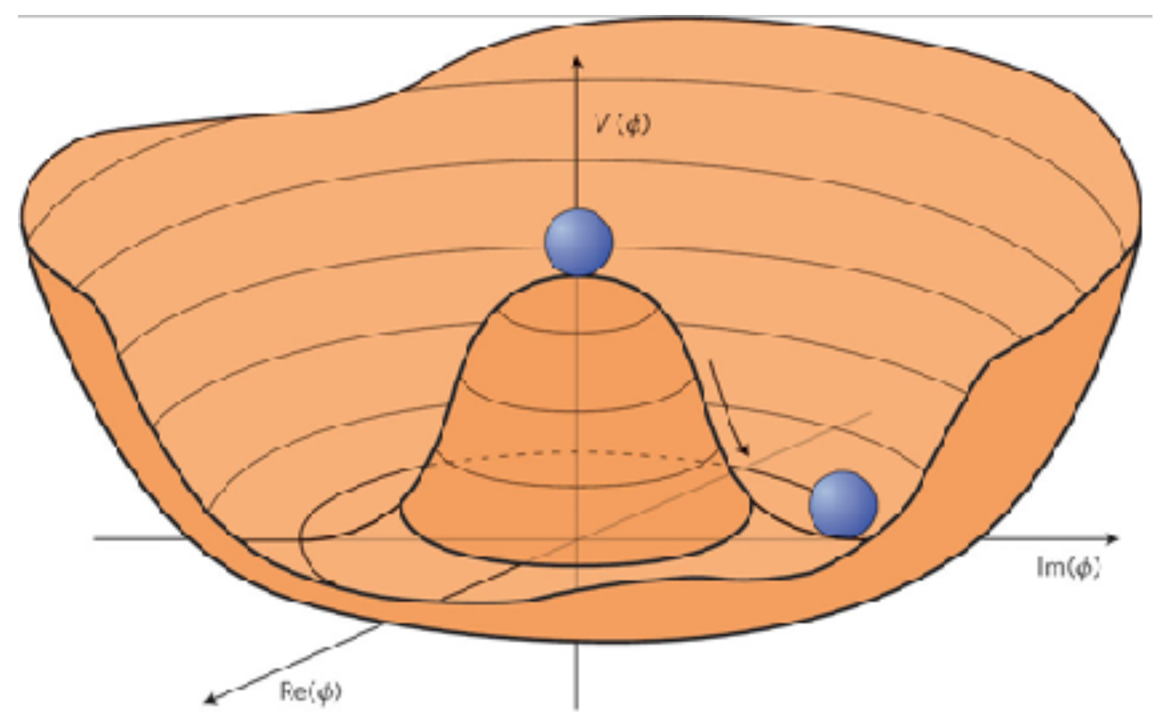
Work in progress.

ACCESS HIGGS POTENTIAL

Currently we have no information about Higgs potential.

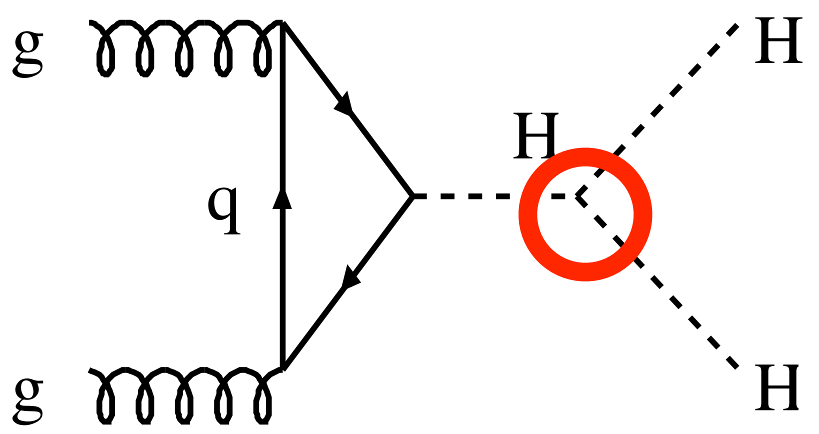
SM uses Mexican hat, but no direct evidence for that.

Triple Higgs coupling is first place to access potential.

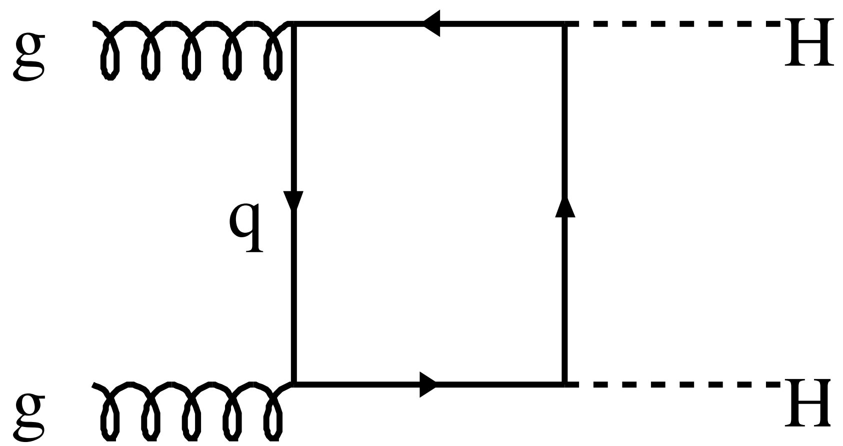


DI-HIGGS

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



Cross section is quite small.

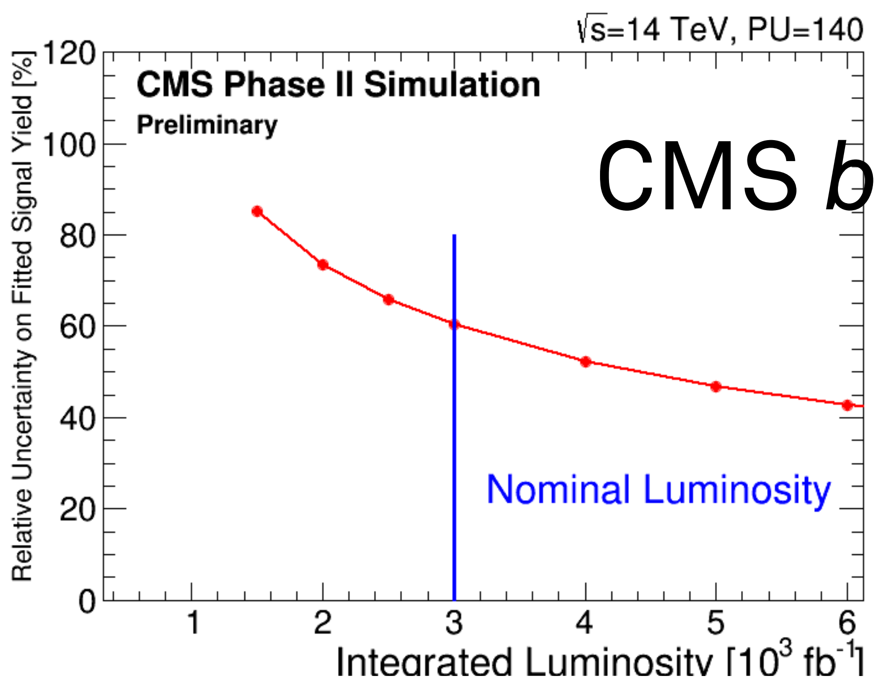


Baglio, et. al. [arXiv:1212.5581].

$\sqrt{s}$ [TeV]	$\sigma^{\rm NLO}_{gg\to HH}$ [fb]	$\sigma^{\rm NLO}_{qq'\to HHqq'}$ [fb]	$\sigma^{\rm NNLO}_{q\bar{q}'\to WHH}$ [fb]	$\sigma^{\rm NNLO}_{q\bar{q}\to ZHH}$ [fb]	$\sigma^{\rm LO}_{q\bar{q}/gg\to t\bar{t}HH}$ [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

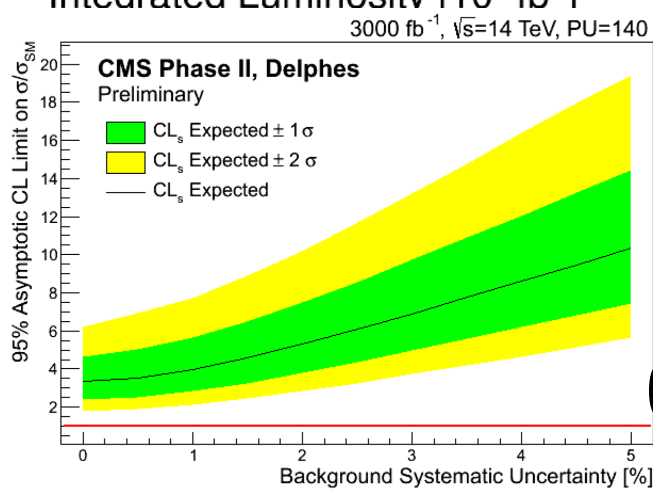
Preliminary studies by experiments show that measurement is very difficult even at high-lumi.



CMS *bbγγ*

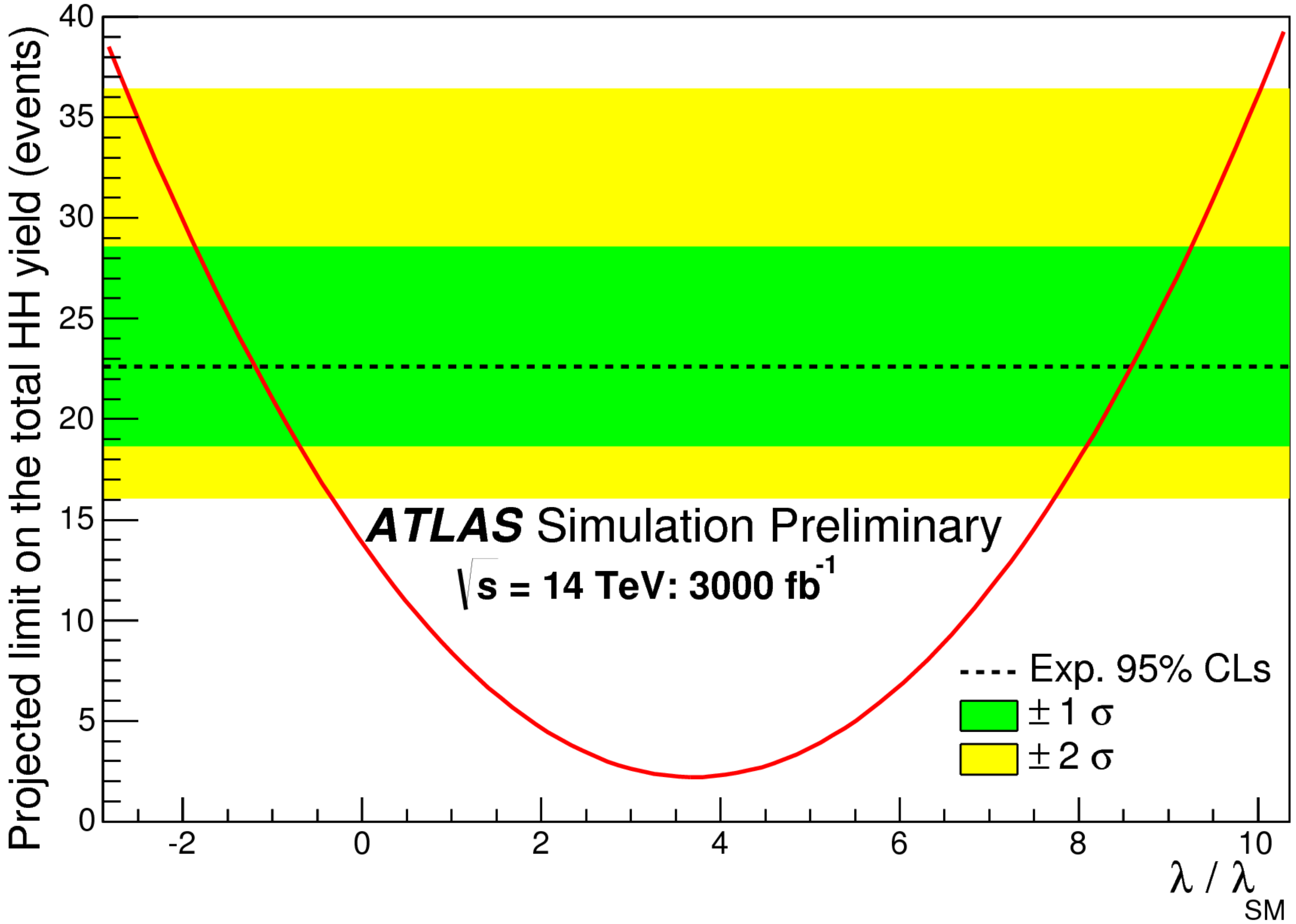
Expected yields (3000 fb^{-1}) Samples	Total	Barrel	End-cap
$H(b\bar{b})H(\gamma\gamma)(\lambda/\lambda_{SM}=1)$	8.4±0.1	6.7±0.1	1.8±0.1
$H(b\bar{b})H(\gamma\gamma)(\lambda/\lambda_{SM}=0)$	13.7±0.2	10.7±0.2	3.1±0.1
$H(b\bar{b})H(\gamma\gamma)(\lambda/\lambda_{SM}=2)$	4.6±0.1	3.7±0.1	0.9±0.1
$H(b\bar{b})H(\gamma\gamma)(\lambda/\lambda_{SM}=10)$	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.

LHC PROSPECTS

Theorist studies are more optimistic (still need HL).

Studies in *bbγγ, bbττ, bbWW,* 4*b,*

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.

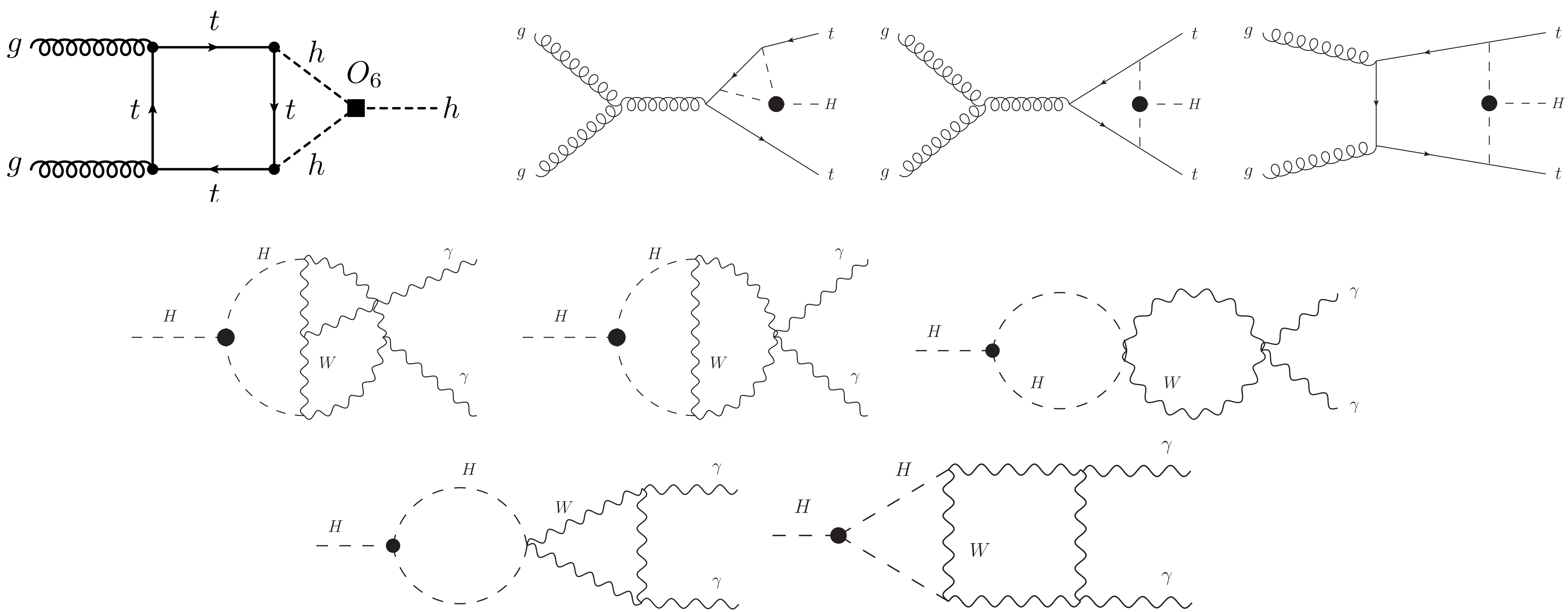
[81] A. J. Barr, M. J. Dolan, C. Englert, and M. Spannowsky, Phys.Lett. **B728**, 308 (2014), 1309.6318.

[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.

OTHER LOOP PROCESSES

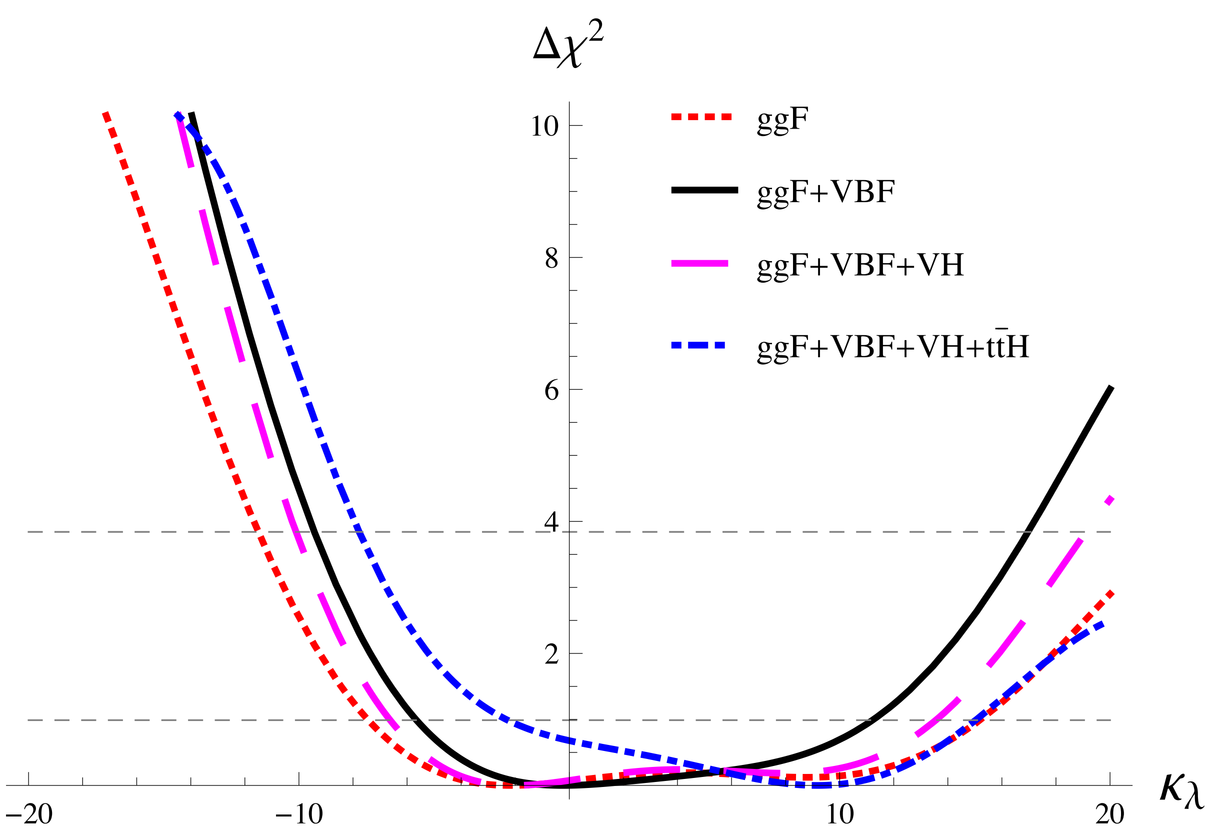
Triple Higgs coupling appears in many loop processes including Higgs production and Higgs decay to photons.



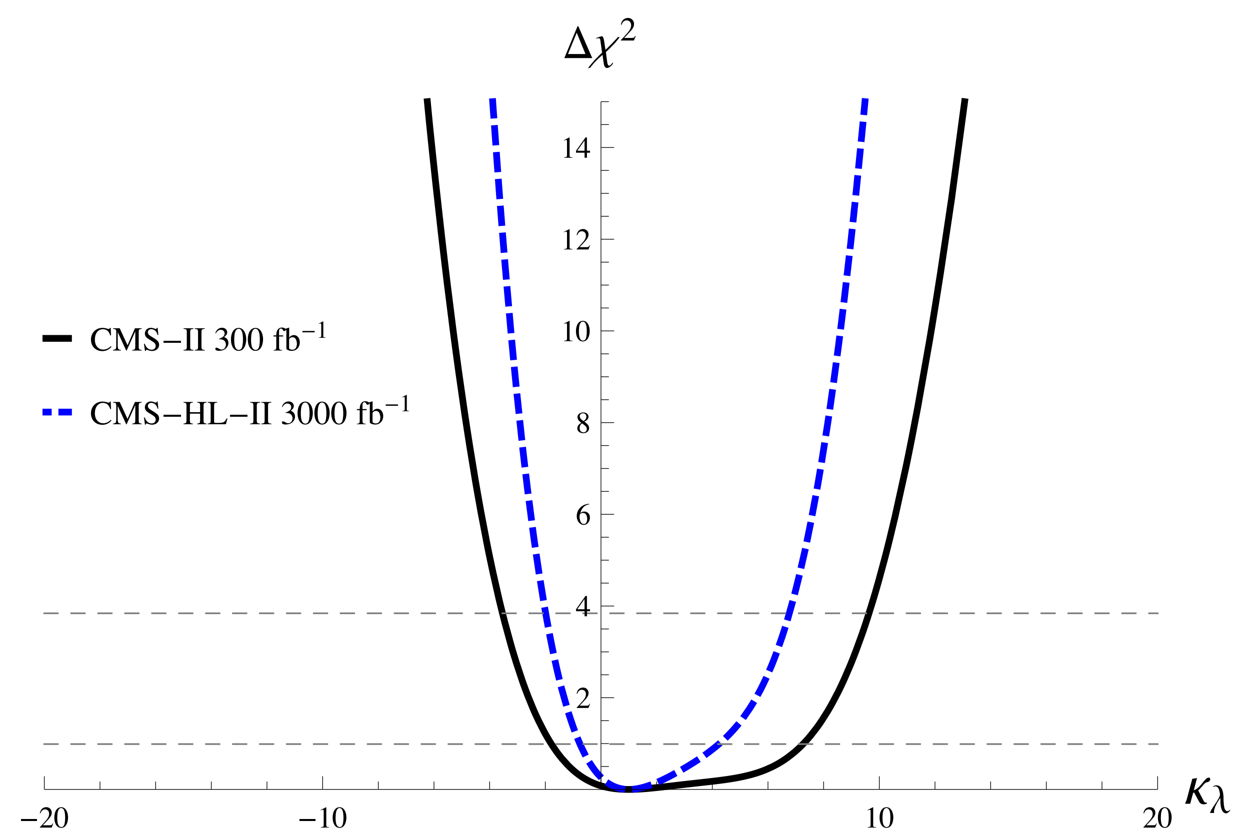
Gorbahn and Haisch [arXiv:1607.03773]. Degrassi et.al. [arXiv:1607.04521].

OTHER LOOP PROCESSES

Constraints are similar(ly bad).



Current data



Future projections

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

WHY CLIMB EVEREST?

"Because it's there...The answer is instinctive, a part, I suppose, of man's desire to conquer the universe."
— George Mallory, 1923

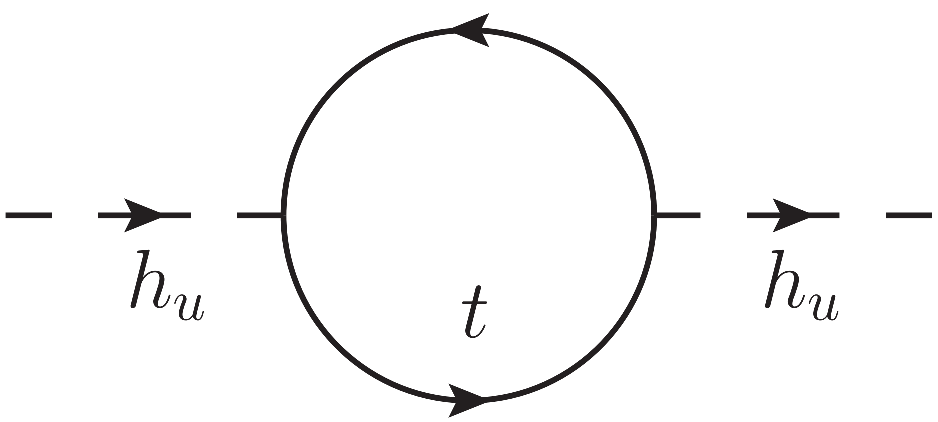
WHY STUDY THE HIGGS?

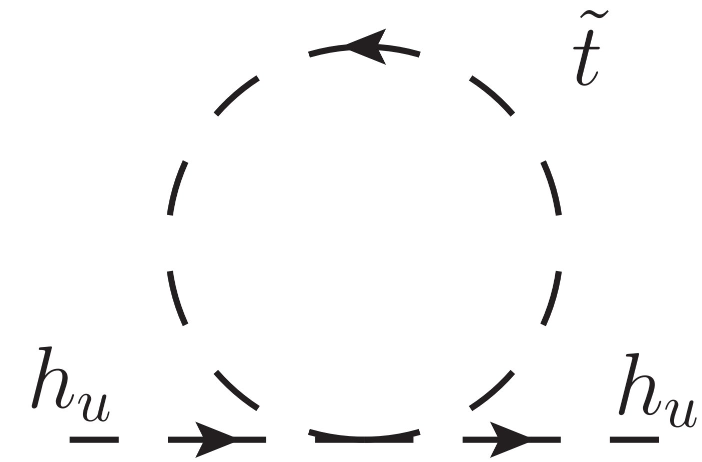
“Because it’s there…The answer is instinctive, a part, I suppose, of man’s desire to conquer the universe.”
— George Mallory, 1923

HIERARCHY PROBLEM

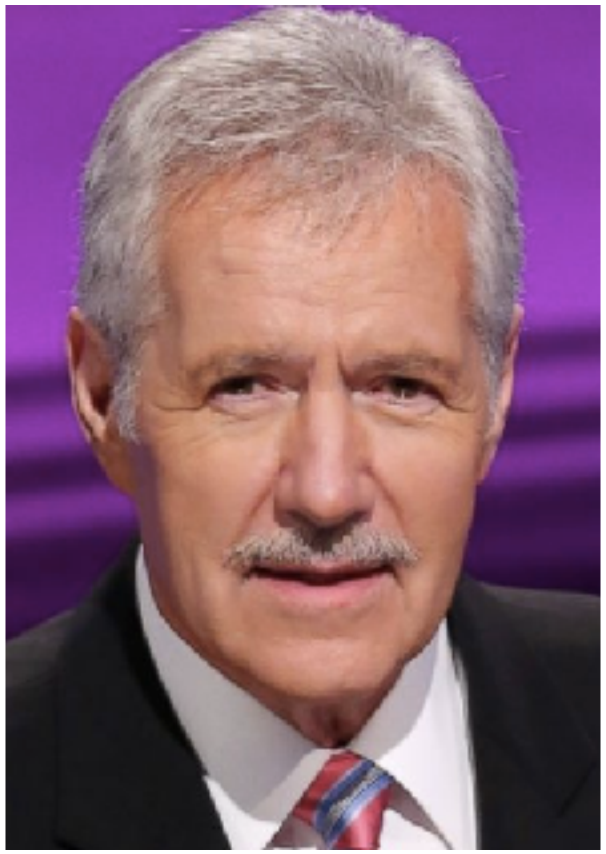
SM Higgs has a hierarchy problem.

Quantum correction make Higgs mass sensitive to high scale physics.



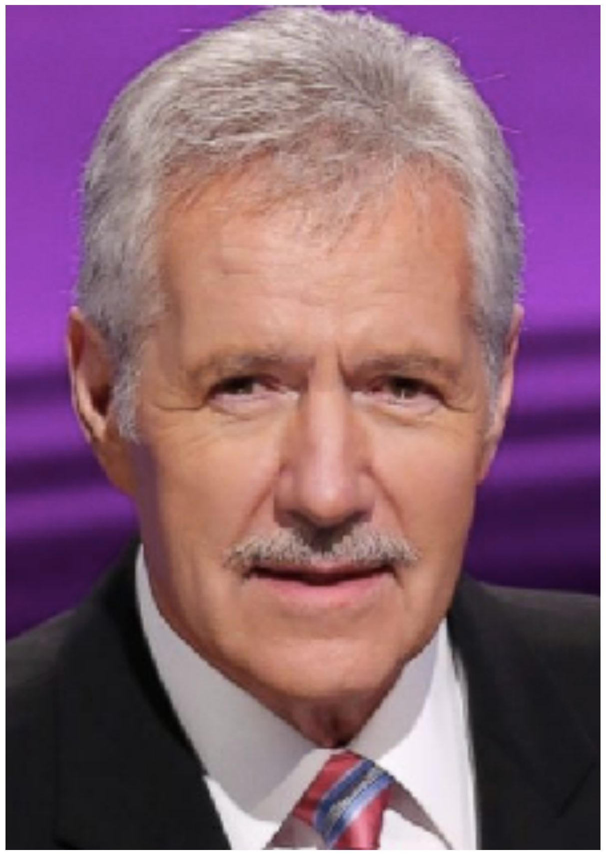


PUZZLE



Balance: $74

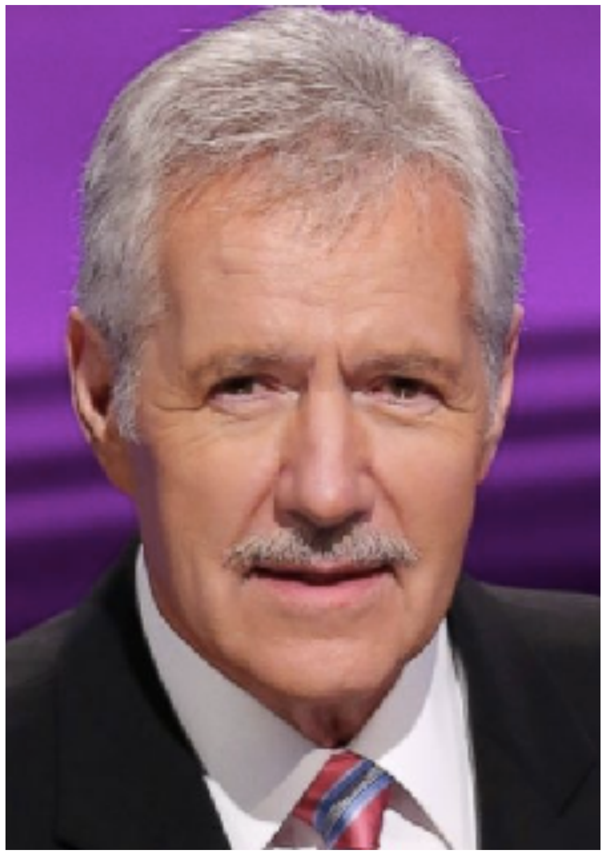
PUZZLE



Balance: $74

$52 + $22

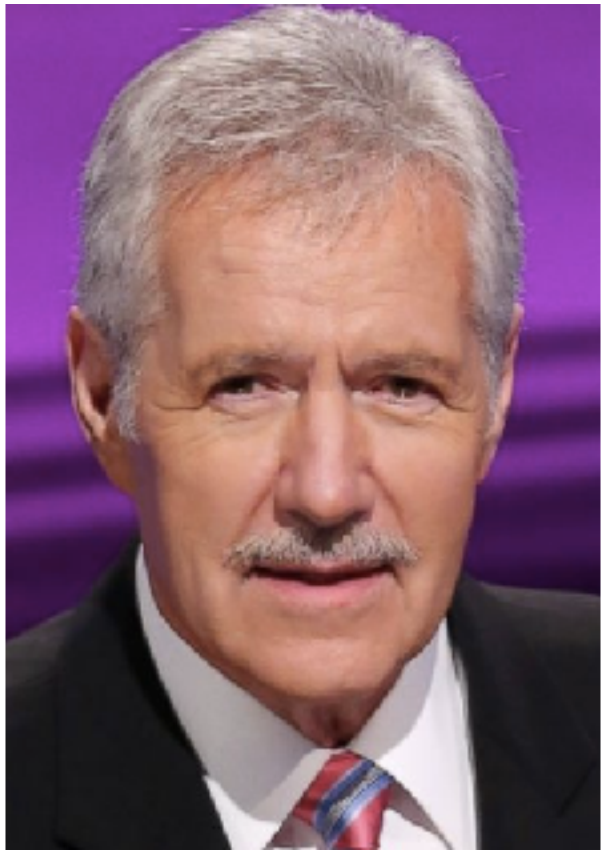
PUZZLE



Balance: $74

$107 - $33

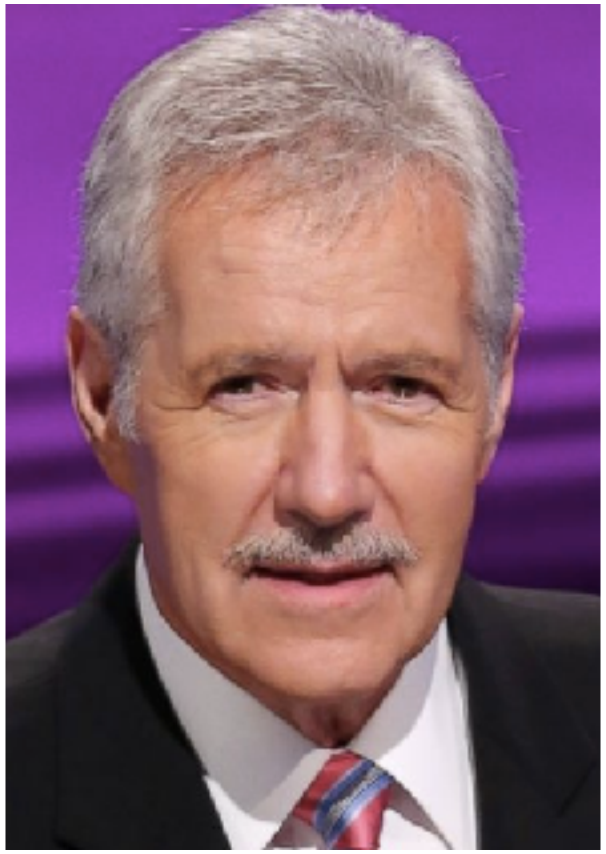
PUZZLE



Balance: $74

$913 - $839

PUZZLE



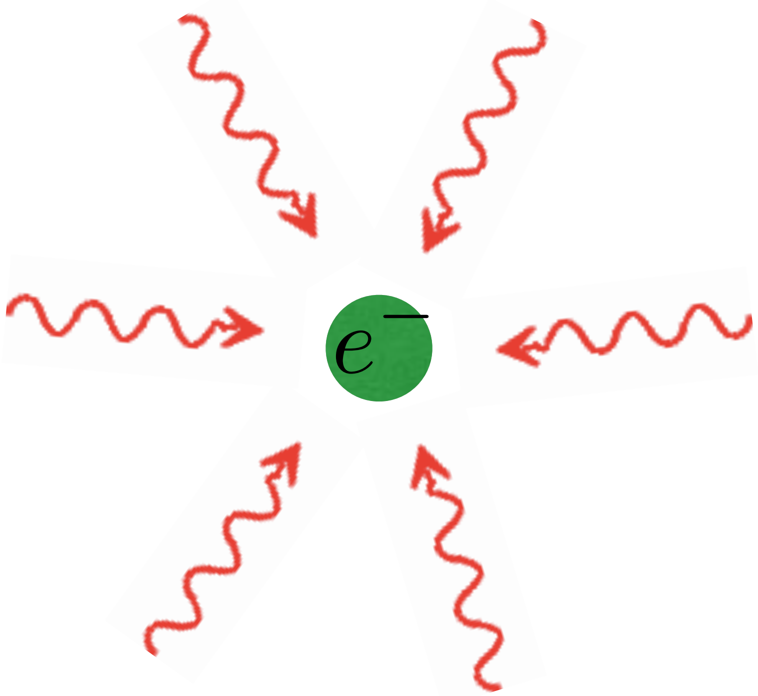
Balance: $74

$829,375,293 - $829,375,219

HISTORICAL ANALOGY

Electron has classical self energy.

$$E_{\text{self}} \sim \frac{1}{4\pi\epsilon_0}\frac{e^2}{r_e}$$



HISTORICAL ANALOGY

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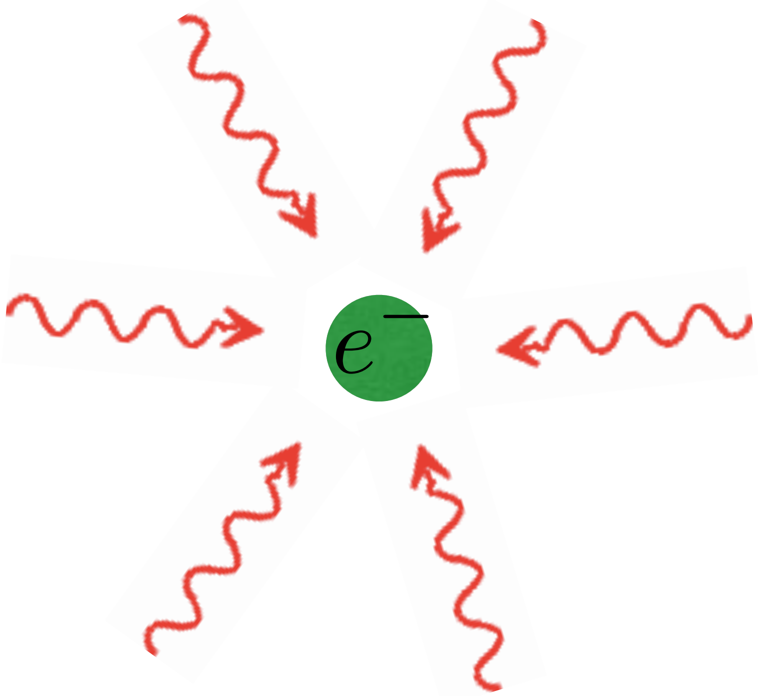

$$E_{\text{self}} \sim \frac{1}{4\pi\epsilon_0}\frac{e^2}{r_e}$$

$$m_e\, c^2 \sim m_0\, c^2 + E_{\text{self}}$$

HISTORICAL ANALOGY

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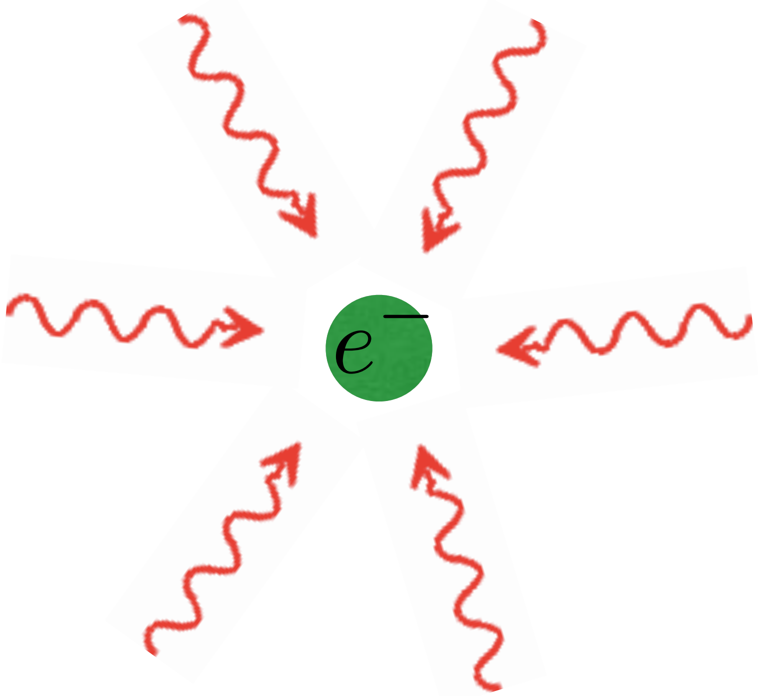
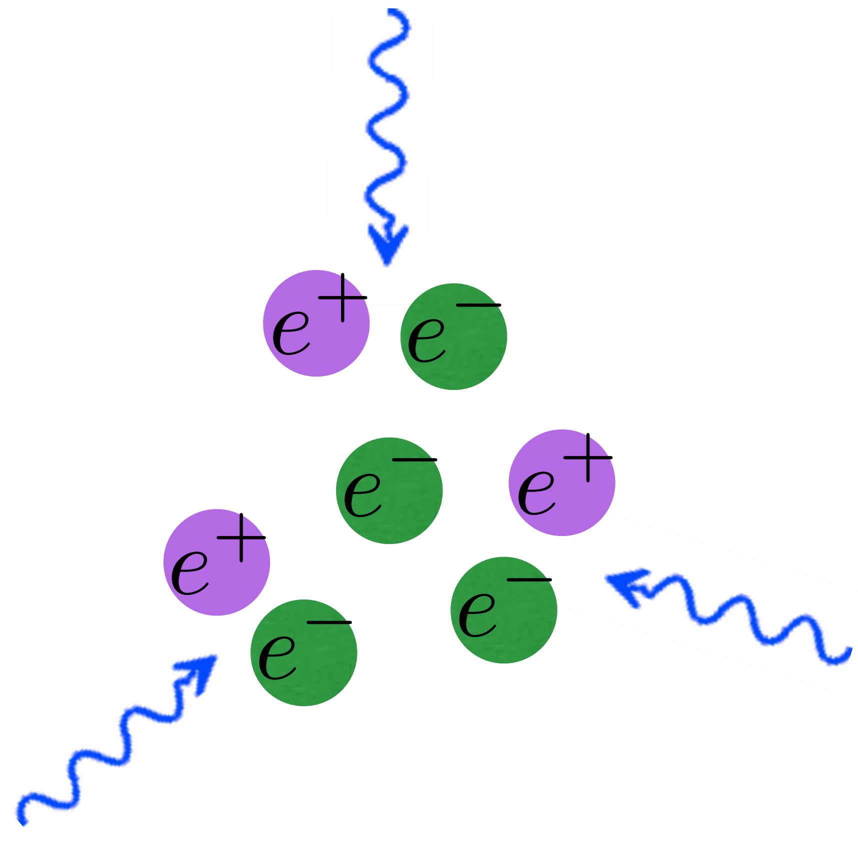


Problem if electron is pointlike, begins to be an issue for r ~ 4 fm, well above current maximum size.

Energy (mass) is sensitive to short distance (high energy).

HISTORICAL ANALOGY

At high energy, start to see electron-positron pairs.



$$E_{\text{self}} \sim \frac{e^2}{4\pi\epsilon_0}\frac{m_e c}{\hbar}\log\left(\frac{m_e c\, r_e}{\hbar}\right)$$

Only log-sensitive to actual radius.

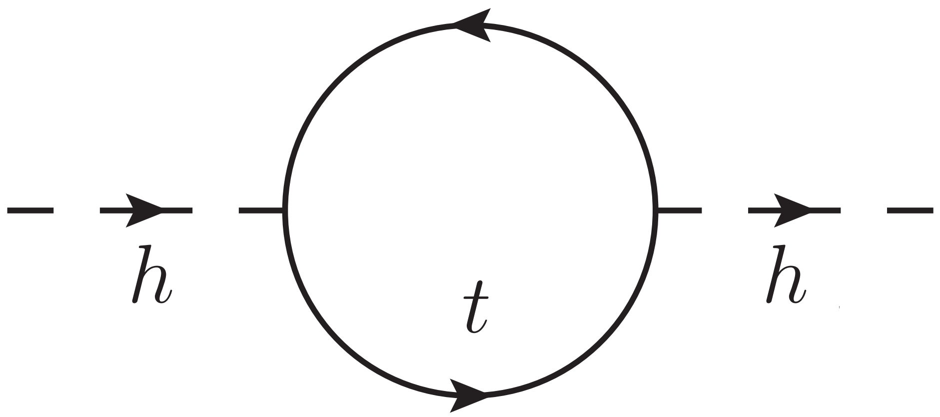
New particle (positron) comes in and saves separation of scales.

HIGGS SELF ENERGY

Higgs self-energy sensitive to high energy scale.

$$E_{\text{self}} \sim \frac{y}{2\pi}\Lambda$$

High energy scale



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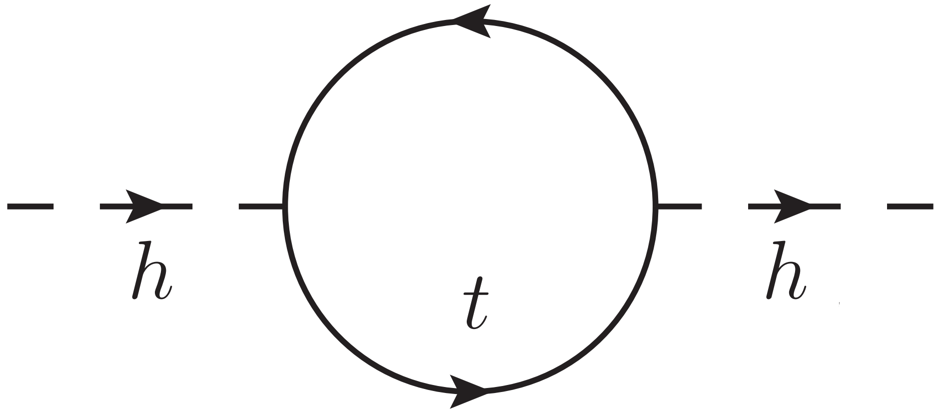

15,270,932,974,520,497,610,934,762,105,716
- 15,270,932,974,520,497,610,934,762,105,714

2

HIGGS SELF ENERGY

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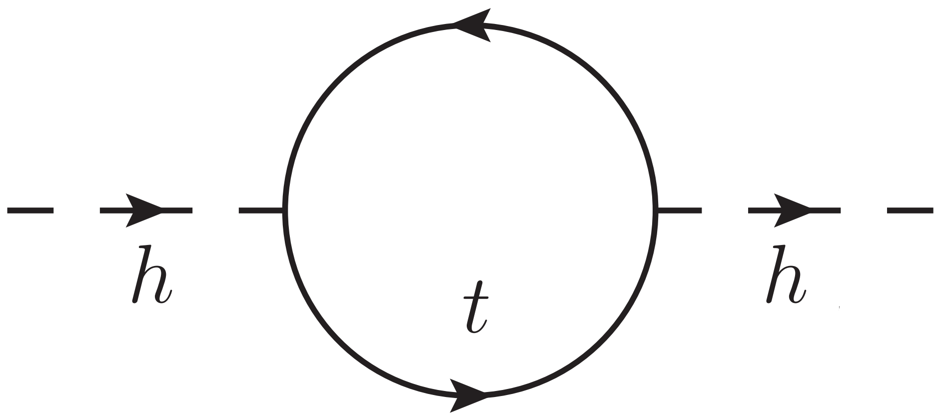
High energy scale




```
  15,270,932,974,520,497,610,934,762,105,716
- 15,270,932,974,520,497,610,934,762,105,714
                                           2
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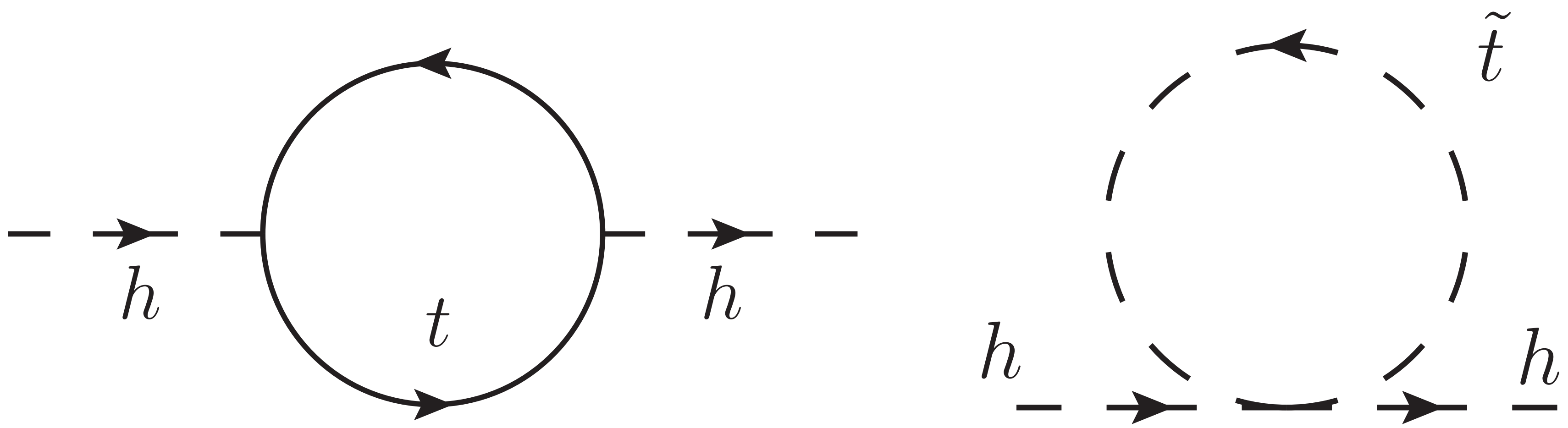
Standard Model violates decoupling principle: hierarchy problem.

CANCELLATION

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

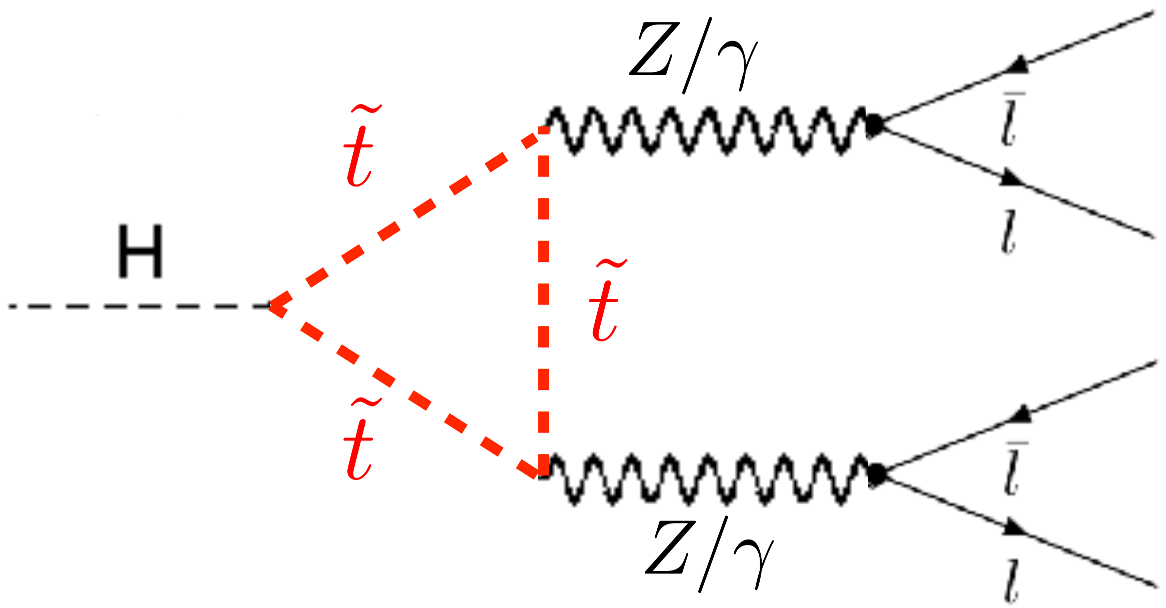


$$E_{\rm self} \sim \frac{y}{2\pi} m_t \log(\Lambda/m_t)$$

Particle has to have same coupling to the Higgs.

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.

CONCLUSIONS

- Kinematic distributions in $h \to 4\ell$ can provide information that is independent from and complimentary to rate measurements.
- NLO contributions make this channel sensitive to large Higgs couplings.
- Can measure CP violation in top Yukawa or violations of custodial symmetry.
- This can be used to place model-independent bounds (or discover) new physics which couples to the Higgs.

THANK YOU

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]

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