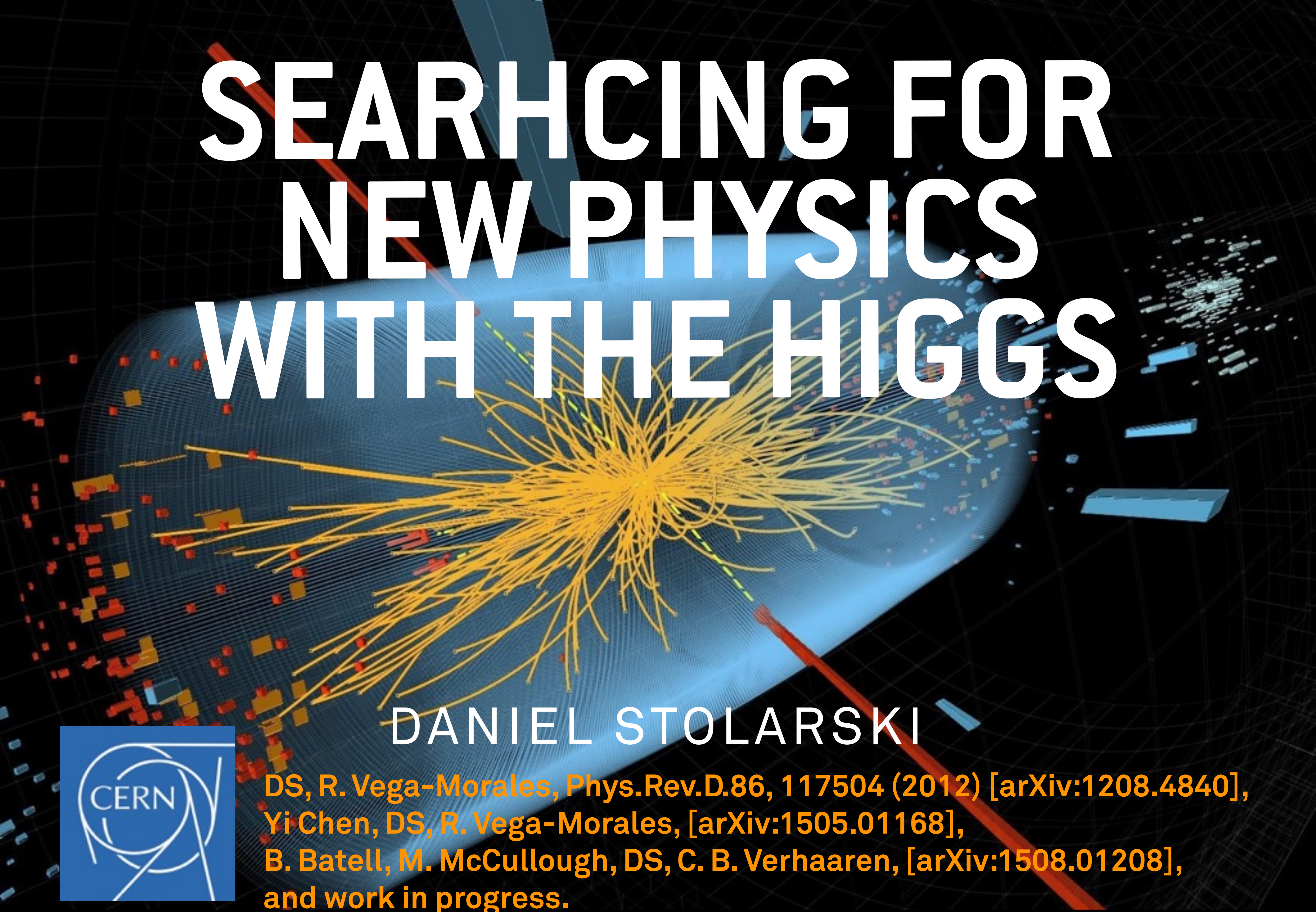


SEARHCING FOR NEW PHYSICS WITH THE HIGGS

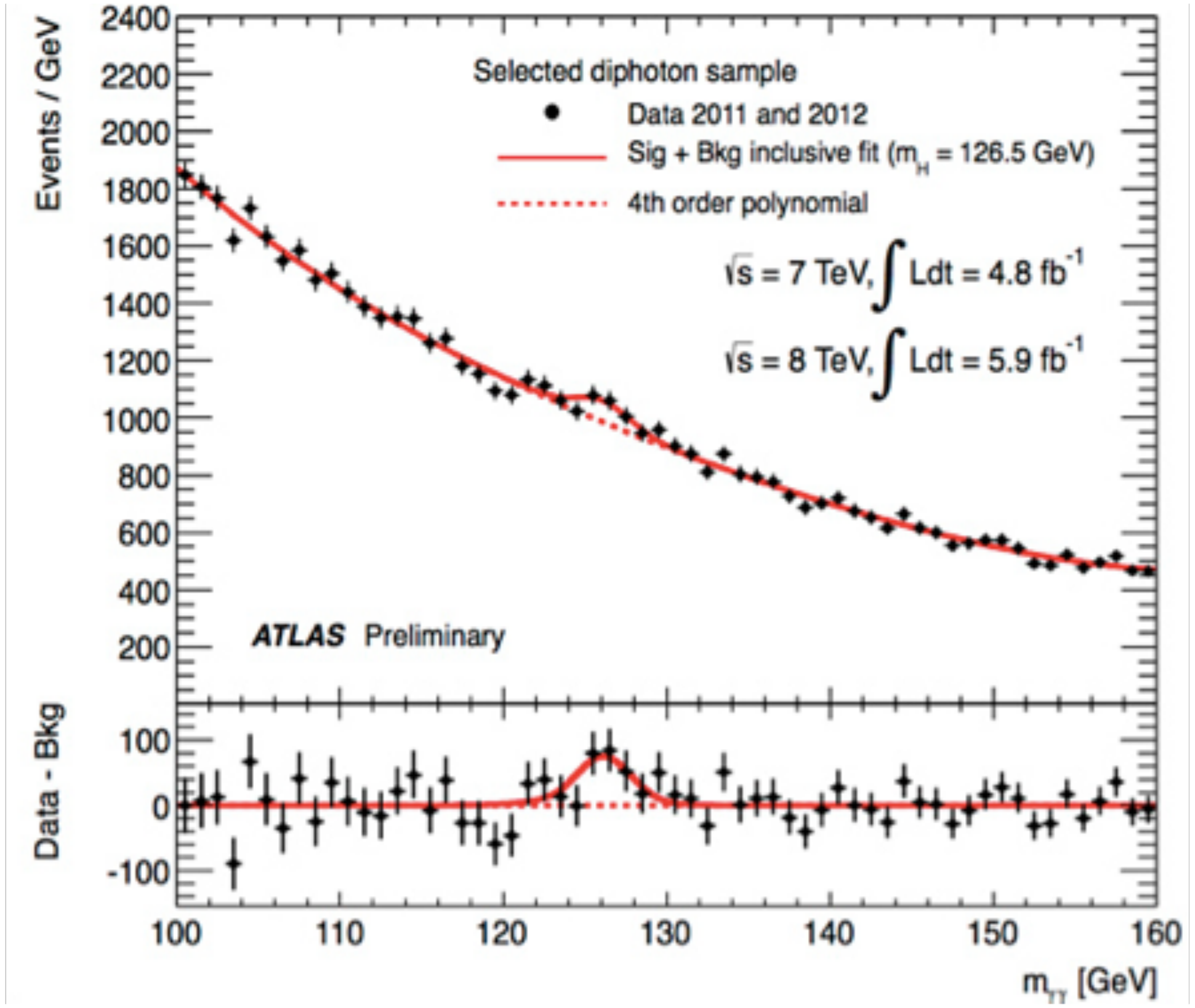
DANIEL STOLARSKI

DS, R. Vega-Morales, Phys.Rev.D.86, 117504 (2012) [arXiv:1208.4840],
Yi Chen, DS, R. Vega-Morales, [arXiv:1505.01168],
B. Batell, M. McCullough, DS, C. B. Verhaaren, [arXiv:1508.01208],
and work in progress.

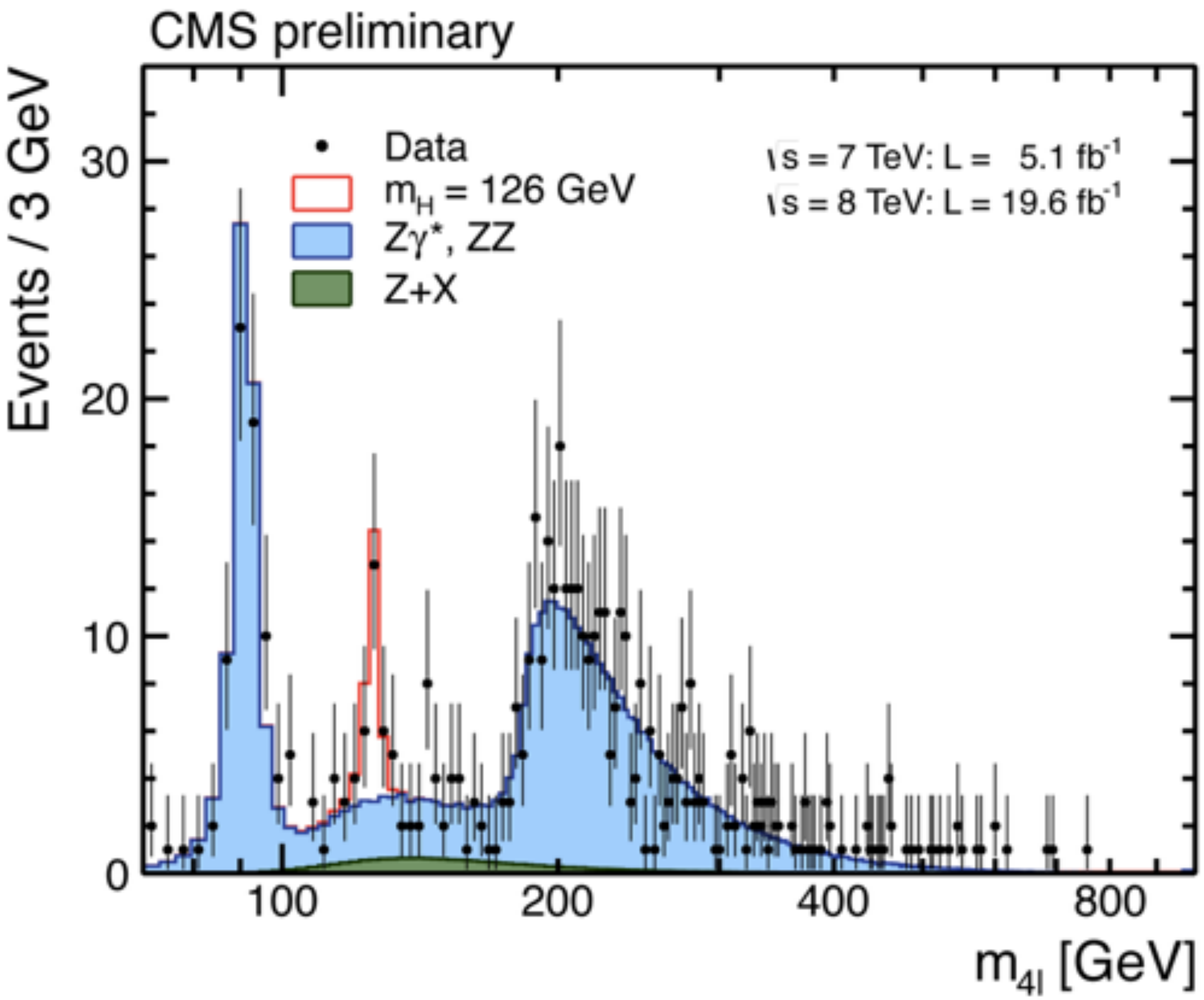
GGI SEPTEMBER 11, 2015

A NEW PARTICLE

July 2012:



$$h \to \gamma\gamma$$

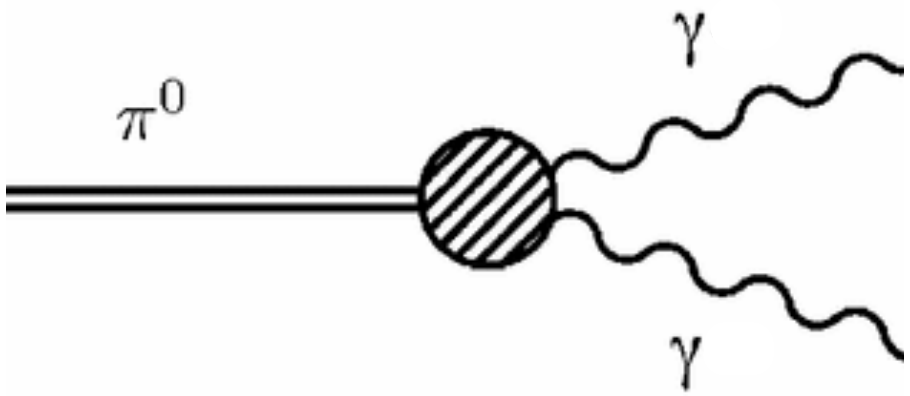


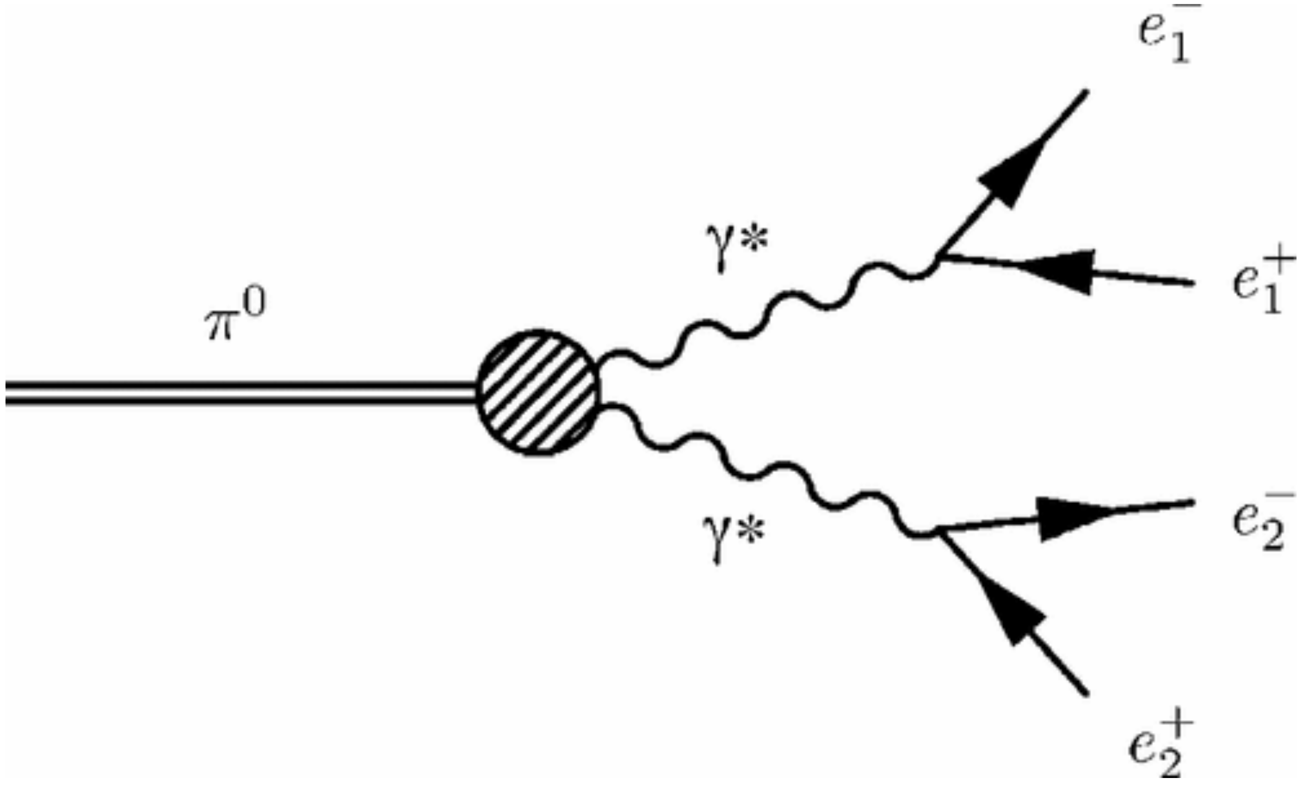
$$h \to 4e/4\mu/2e2\mu$$

IS IT THE HIGGS?

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

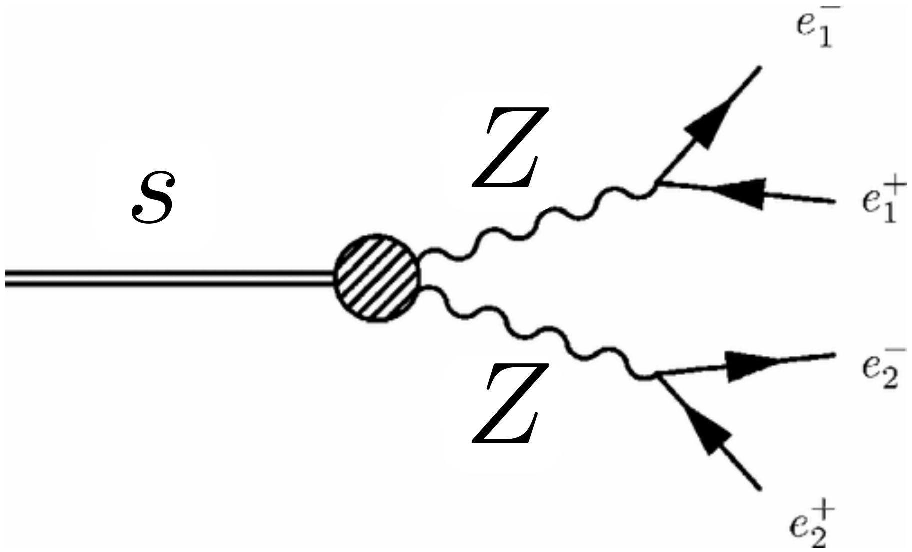
Neutral pion decays to two photons *and* four electrons, but its much more boring.



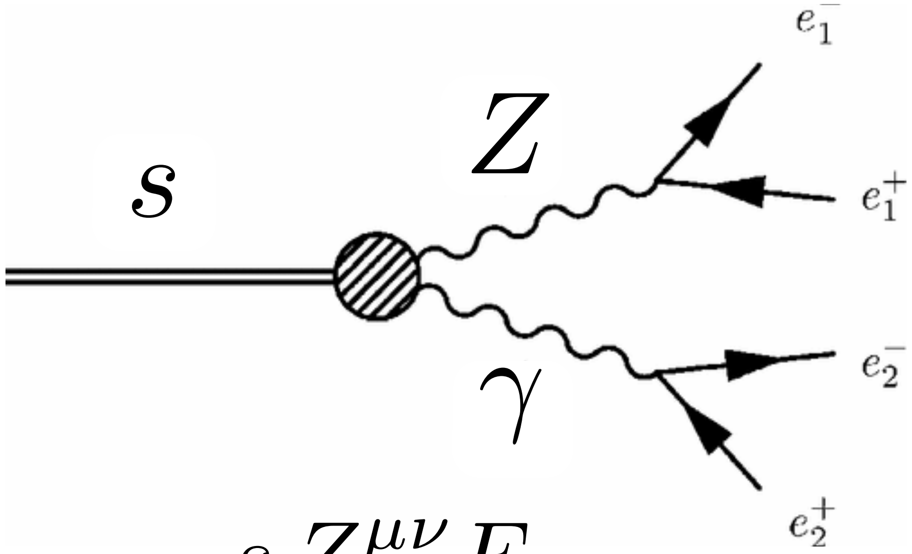


WARM UP EXERCISE

Assume parity even scalar:

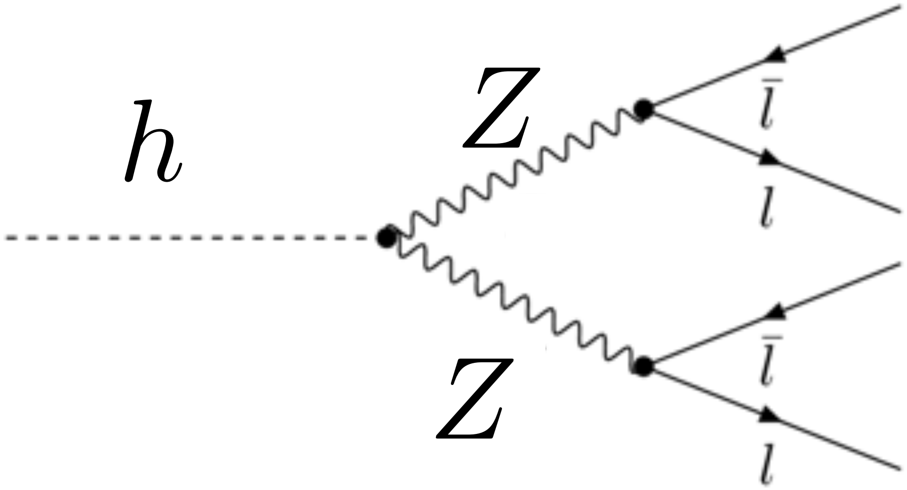


$s\, Z^{\mu\nu} Z_{\mu\nu}$



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

OR

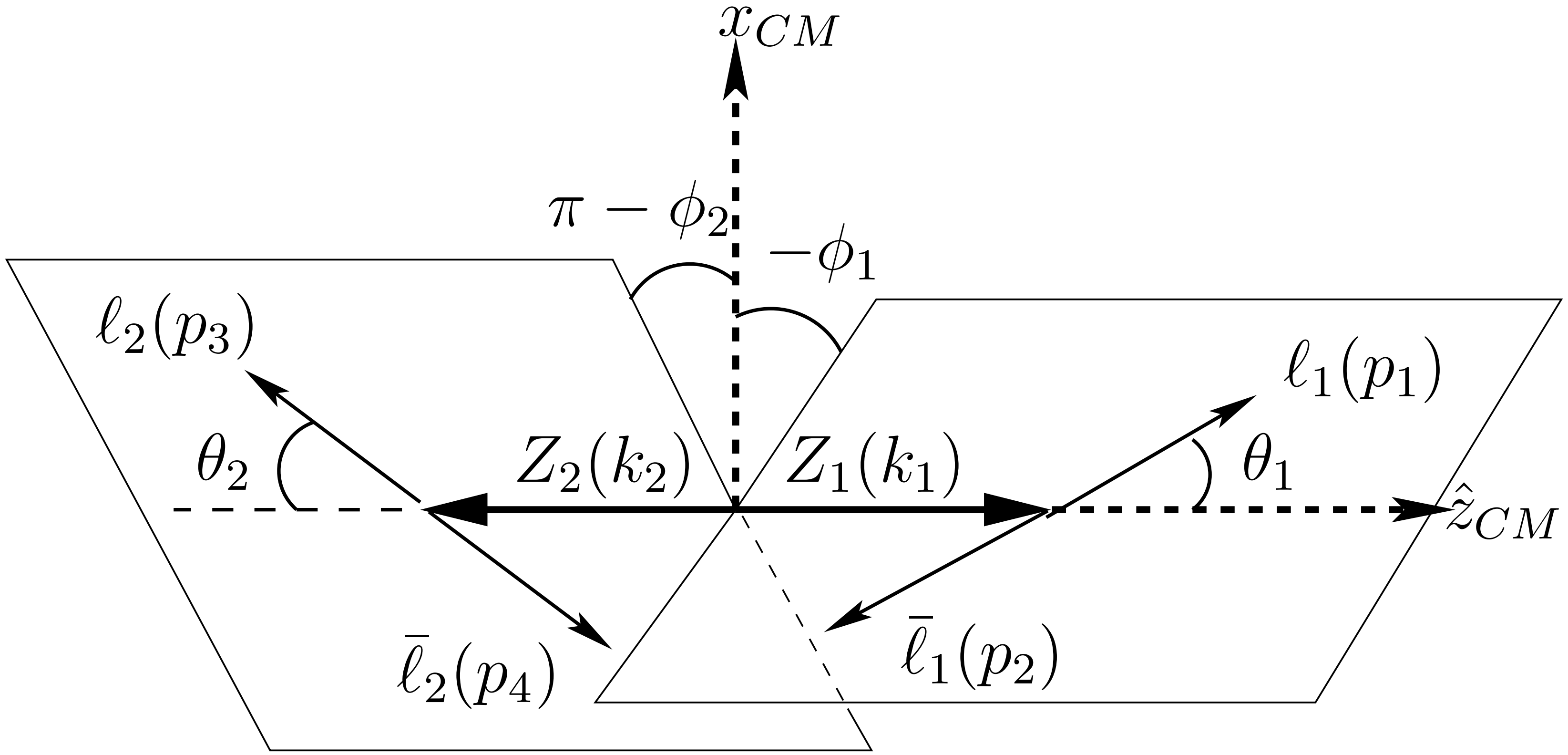


$h\, Z^{\mu} Z_{\mu}$

KINEMATIC DISTRIBUTIONS

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

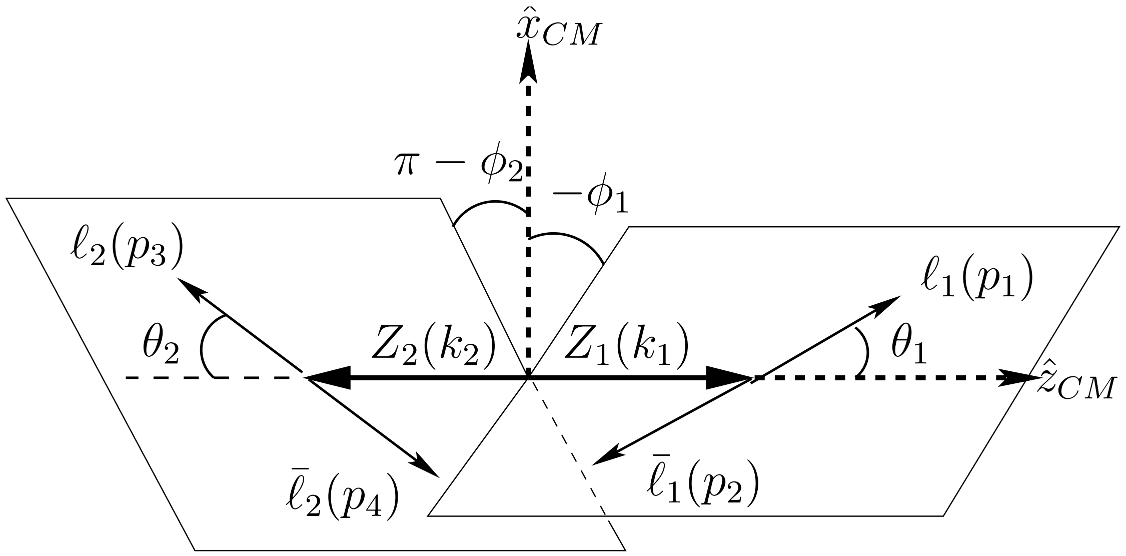
Each event is characterized by five different variables.

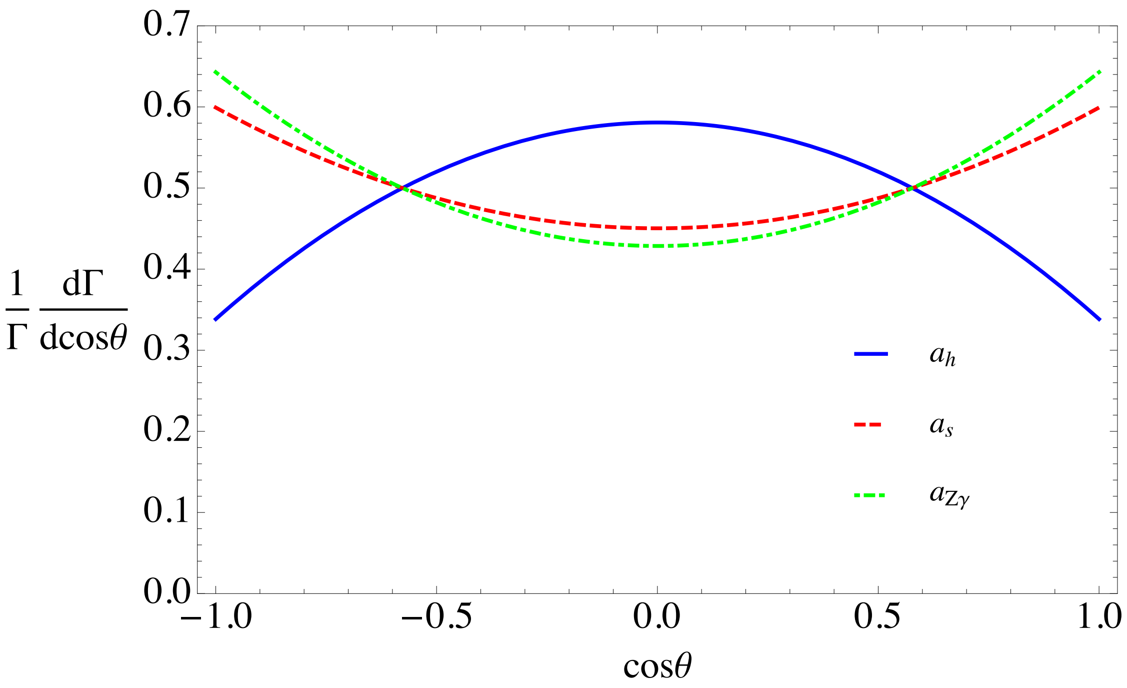


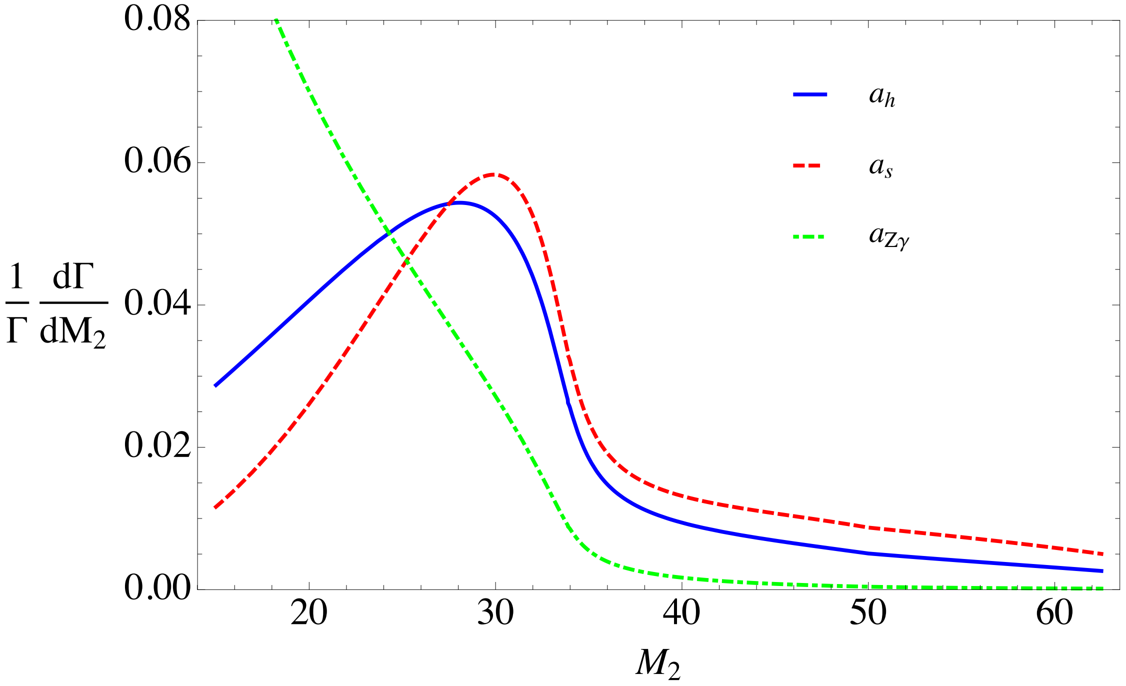
Compare to $h \to \gamma\gamma$.

KINEMATIC DISTRIBUTIONS

Distributions encode information about tensor structure.





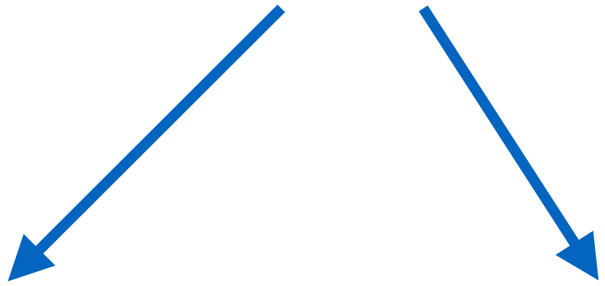


DS, R. Vega-Morales, Phys.Rev.D.86, 117504 (2012) [arXiv:1208.4840].

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

MATRIX ELEMENT METHOD

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

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

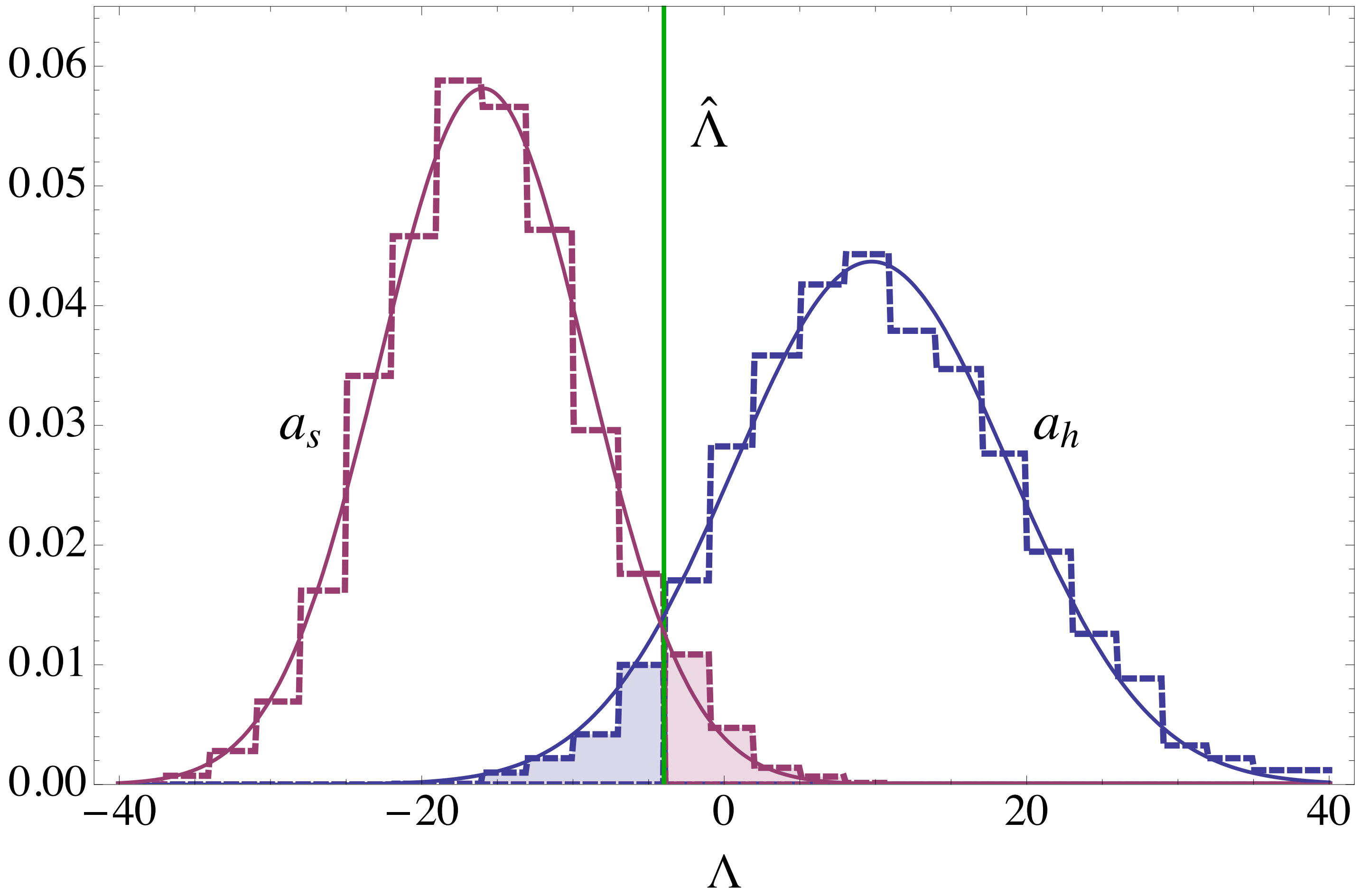
For *N* events, can compute likelihood for different underlying theories.

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

LIKELIHOOD DISTRIBUTION

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

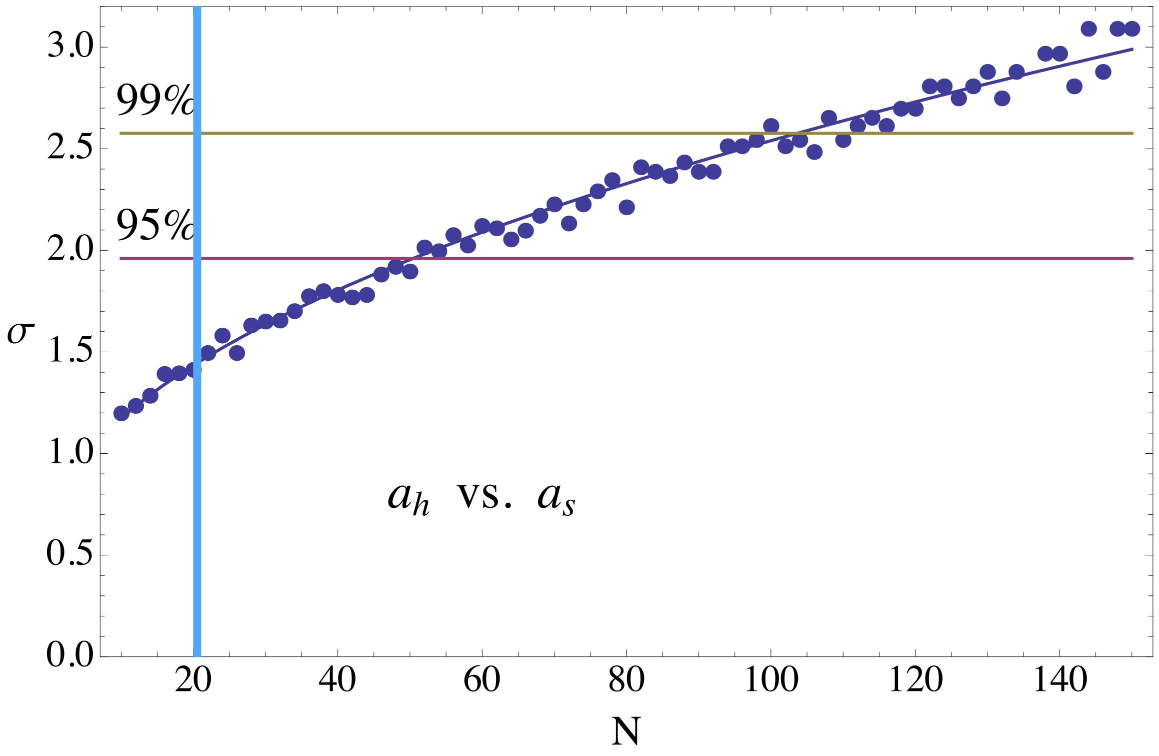
Example for 50 events:

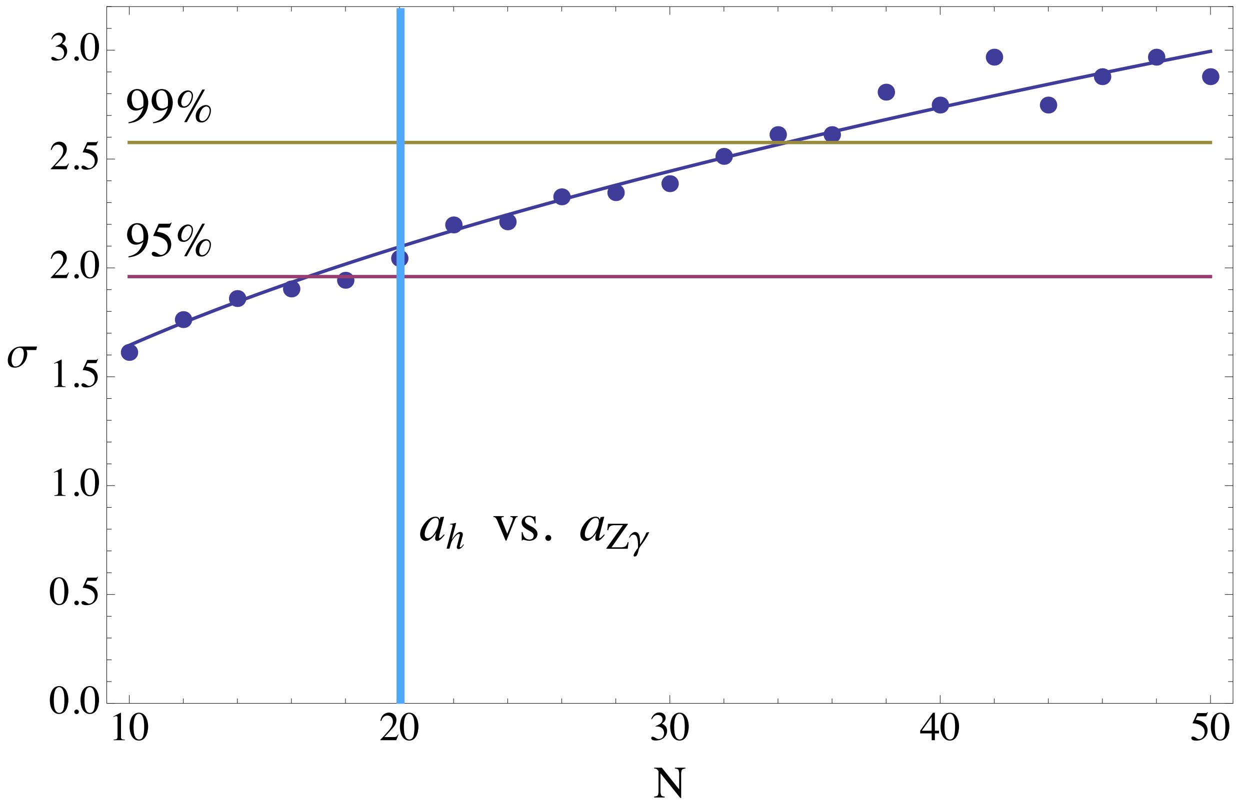


$$\Lambda = 2\log[\mathcal{L}(a_1)/\mathcal{L}(a_2)]$$

KINEMATIC DISTRIBUTIONS

Get better discrimination with more events.

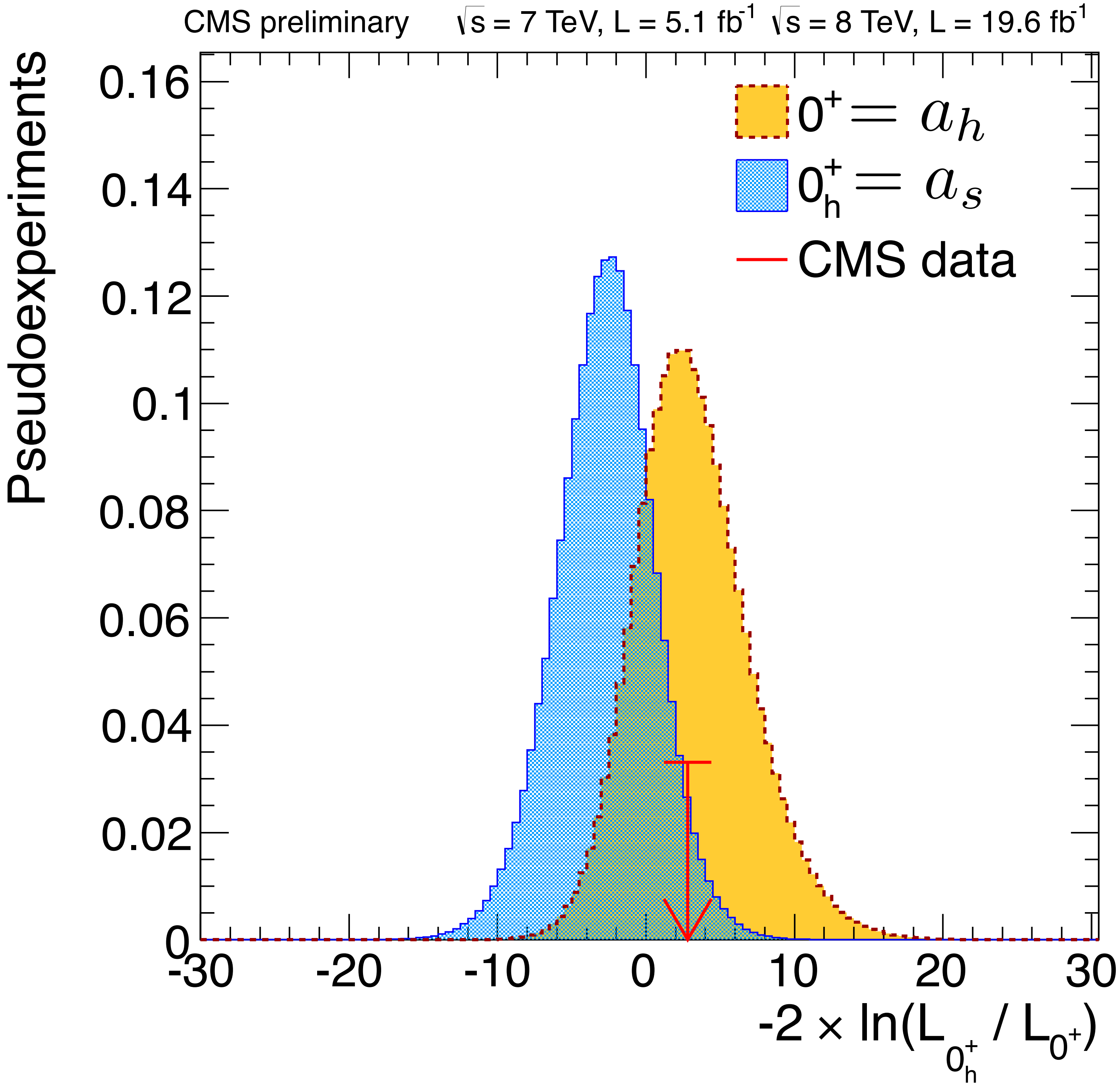




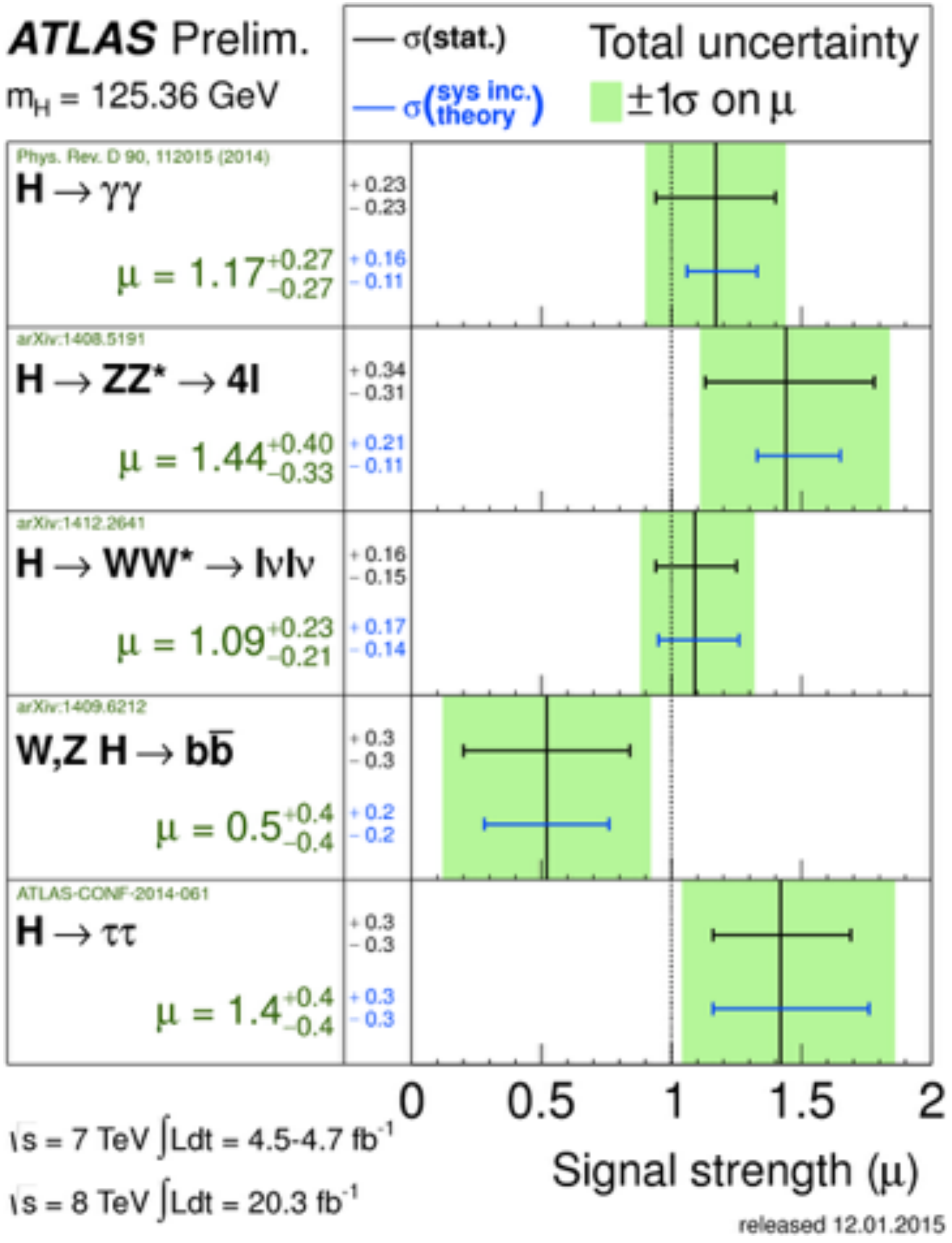
Today's data

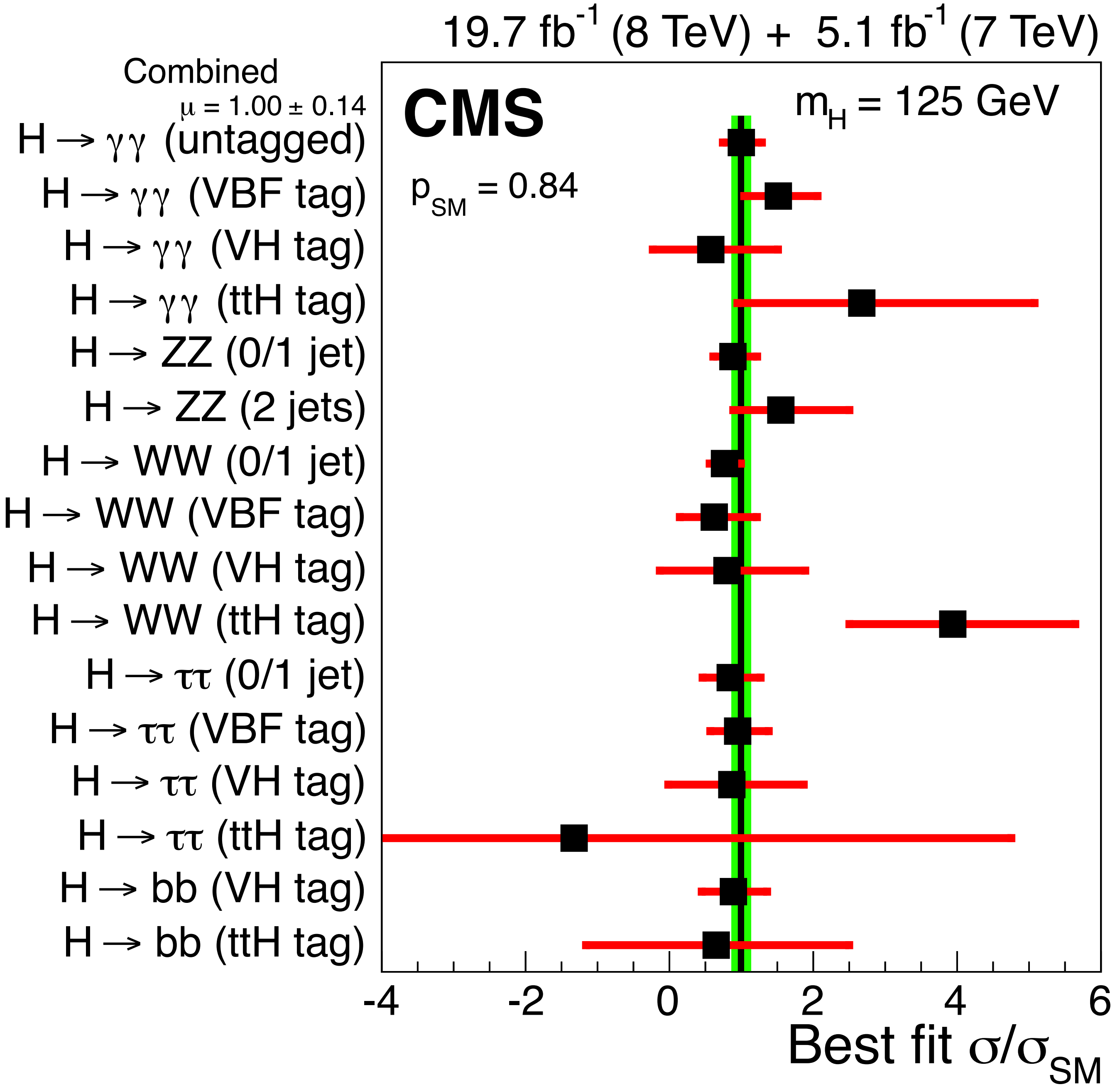
DATA

Evidence for the Higgs:



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:

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

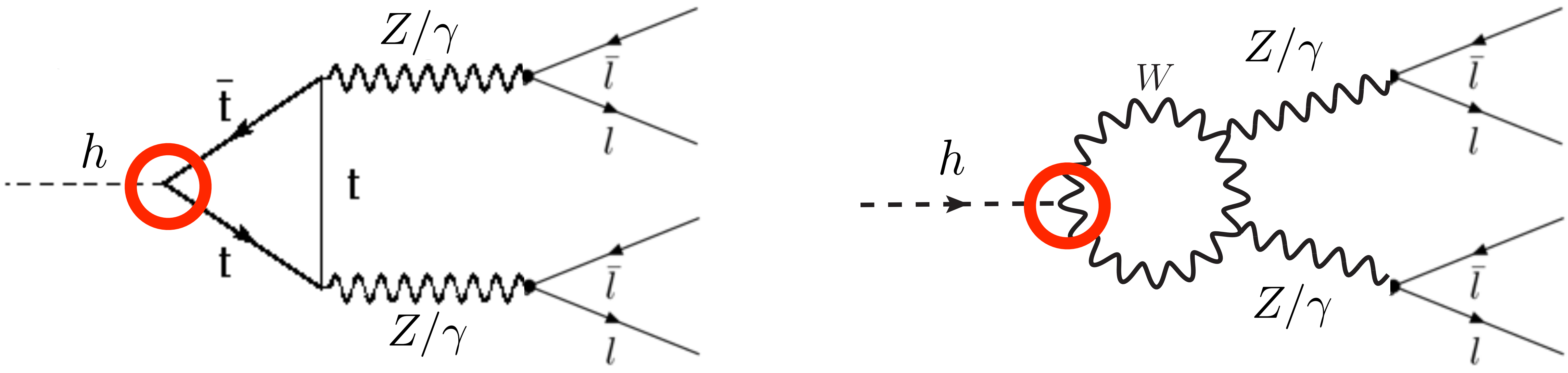
Worthwhile to test SM and rule out all other logical possibilities.

Techniques become extremely important if there is an anomaly.

LOOP PROCESSES

Kinematic distributions can reveal more than just rates measurements can.

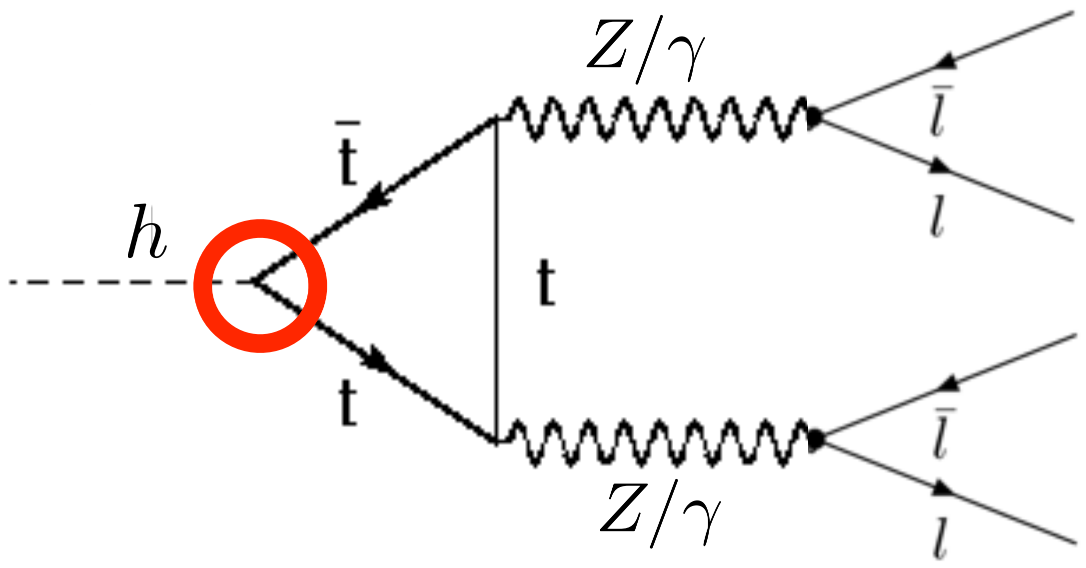
Put this to use with loop processes.



TOP YUKAWA

Start with just top, keep all other couplings fixed.

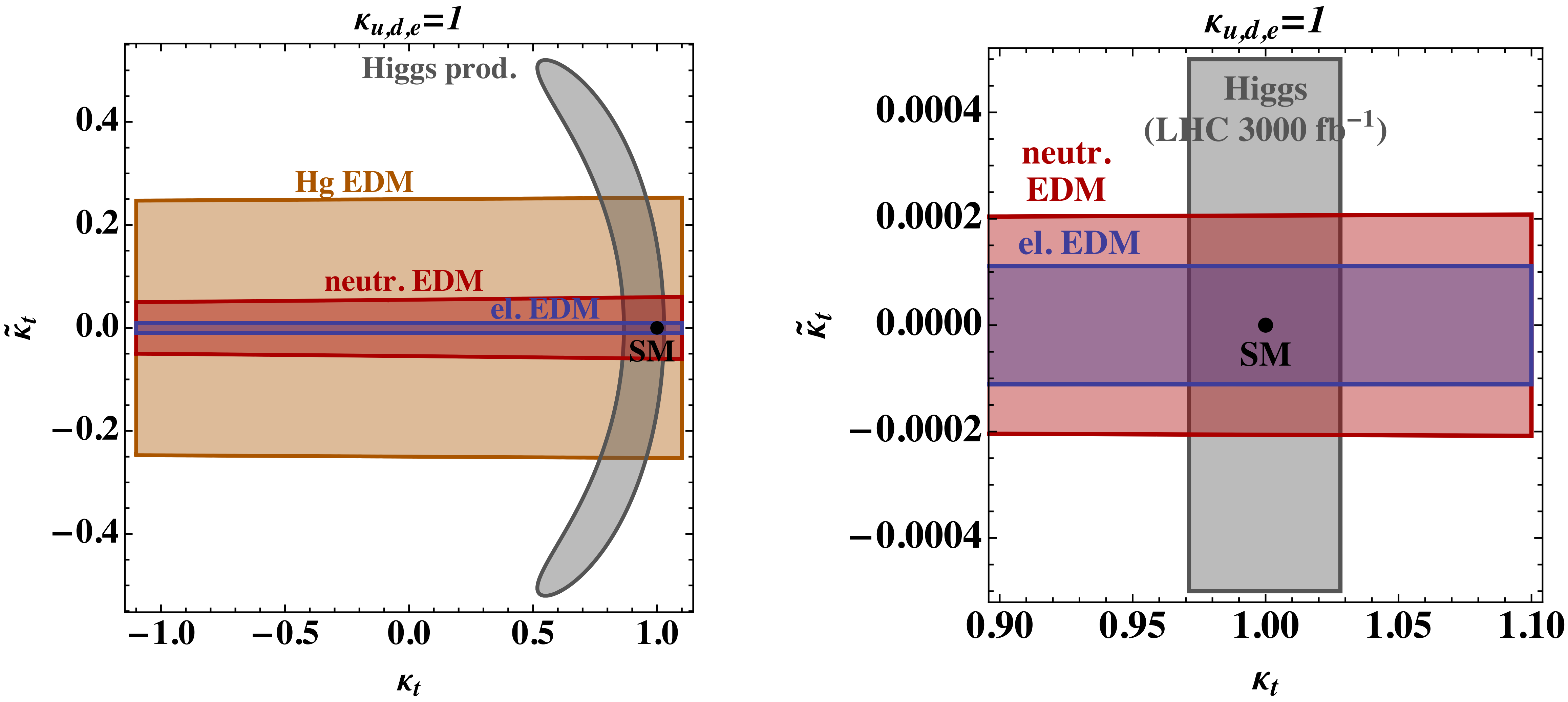
$$h\,\bar{t}\,\left(y_t + i\,\tilde{y}\,\gamma^5\right)\,t$$



Can probe CP nature of top Yukawa coupling.

EDM BOUNDS

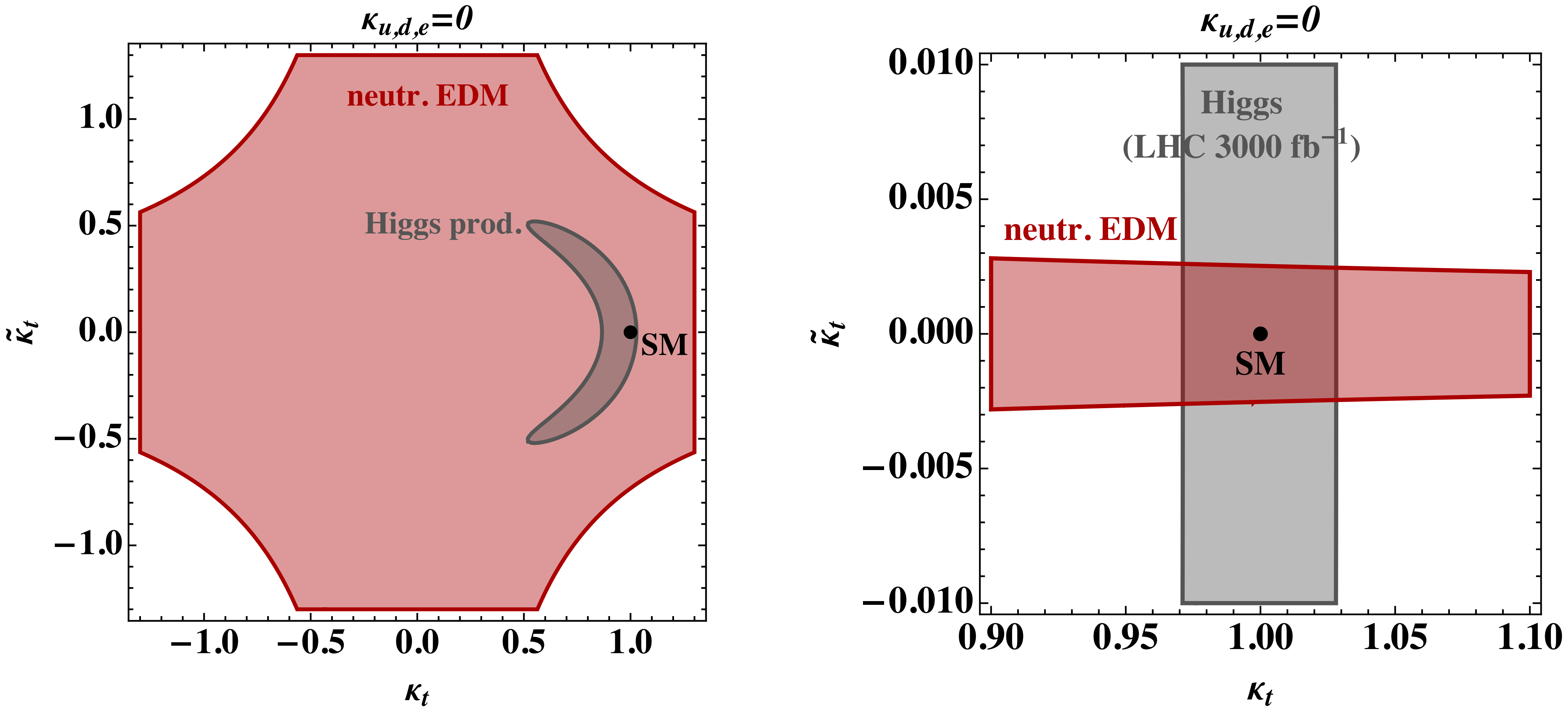
Can place strong bounds on CP violation from EDMs.



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

EDM BOUNDS

Depend on knowing Higgs coupling to first generation.



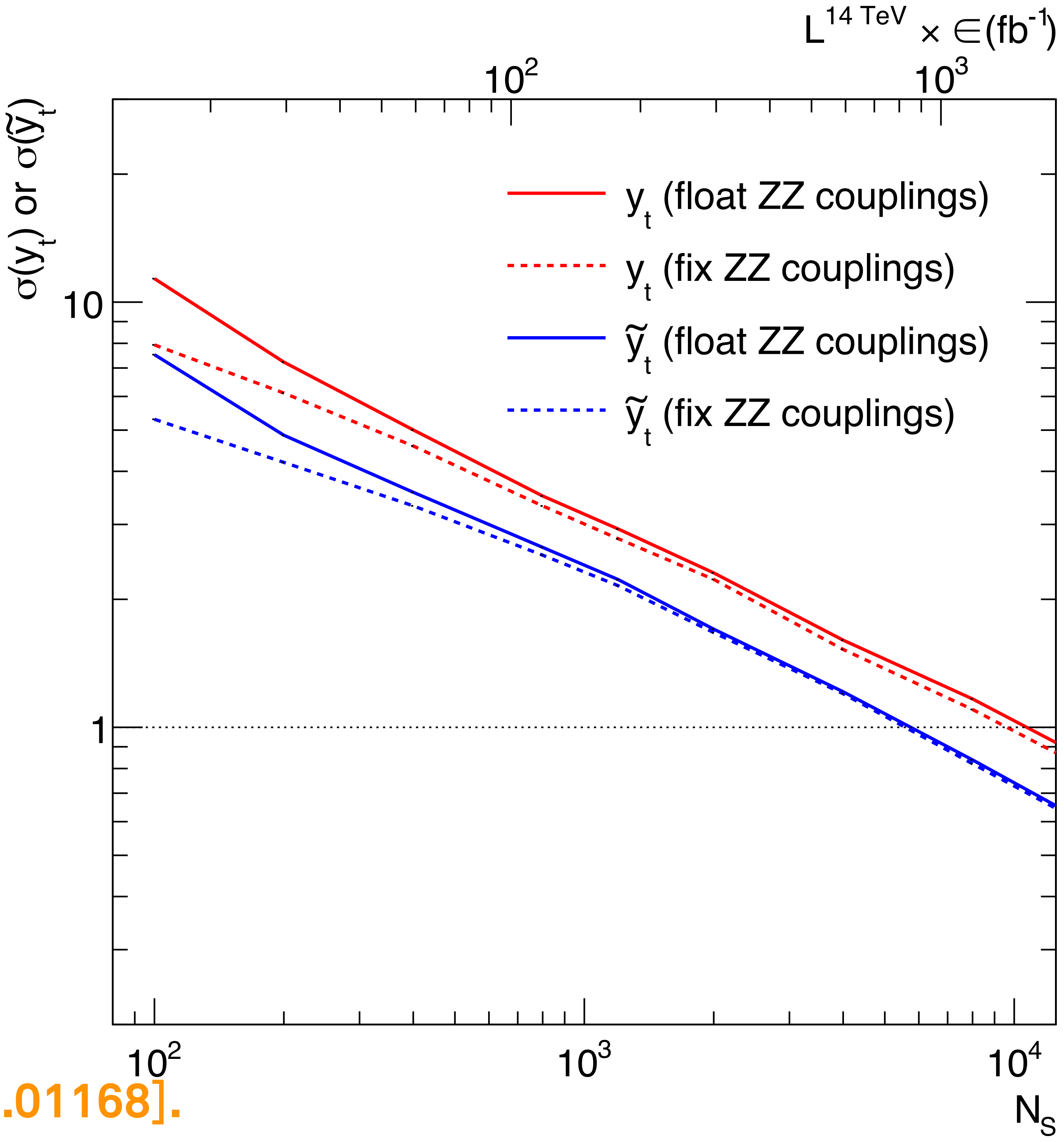
Brod, Haisch, Zupan, [arXiv:1310.1385].

SENSITIVITY

Measurement gets better with more events.

Better sensitivity to pseudo-scalar coupling.

Need large number of events.



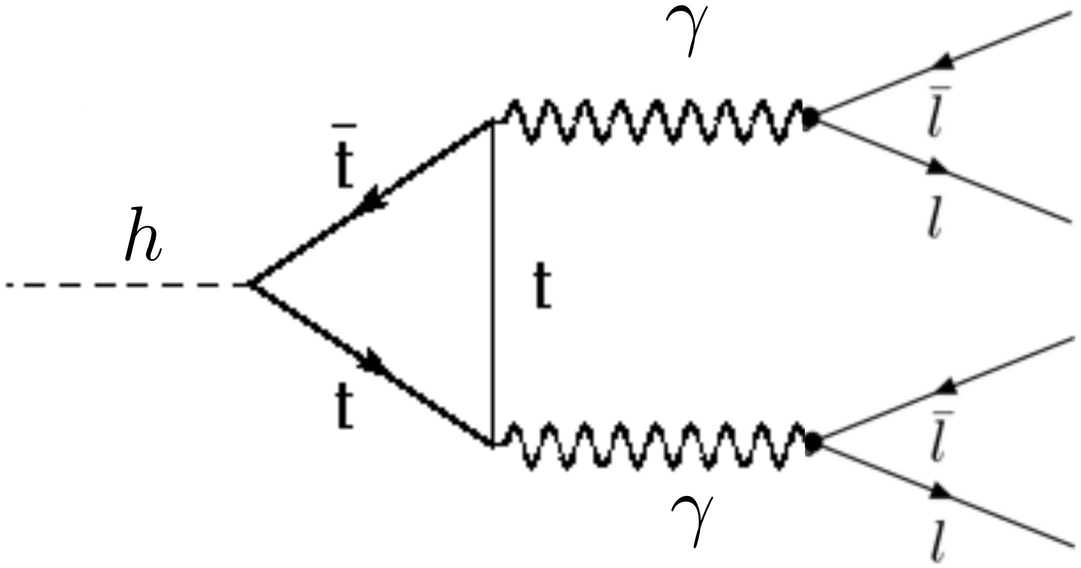
Chen, DS, Vega-Morales, [arXiv:1505.01168].

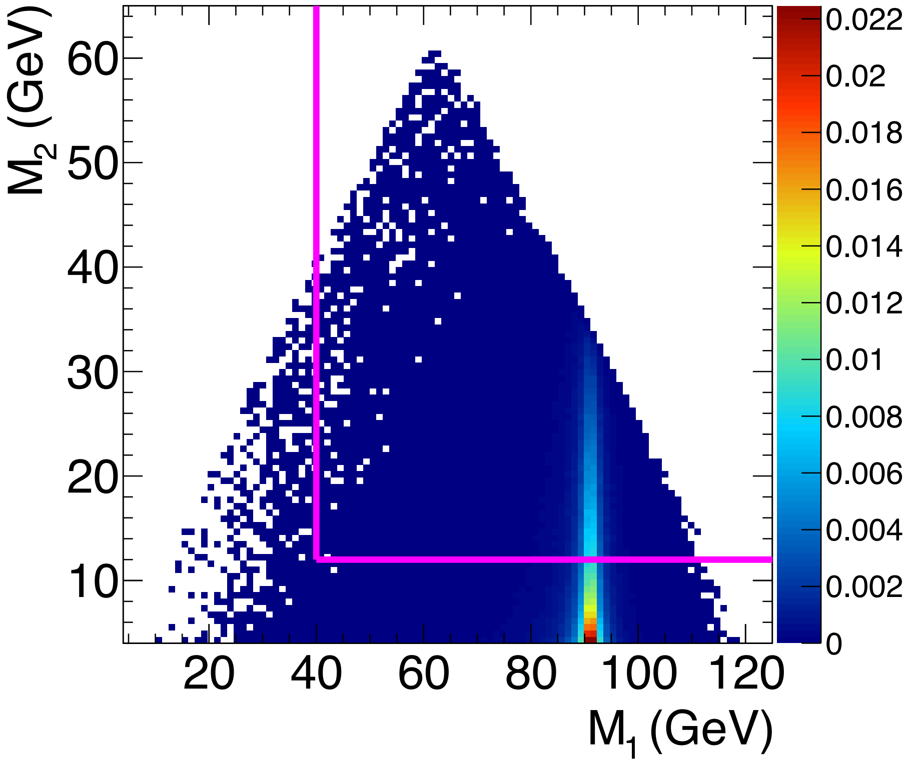
EXPERIMENTAL CUTS

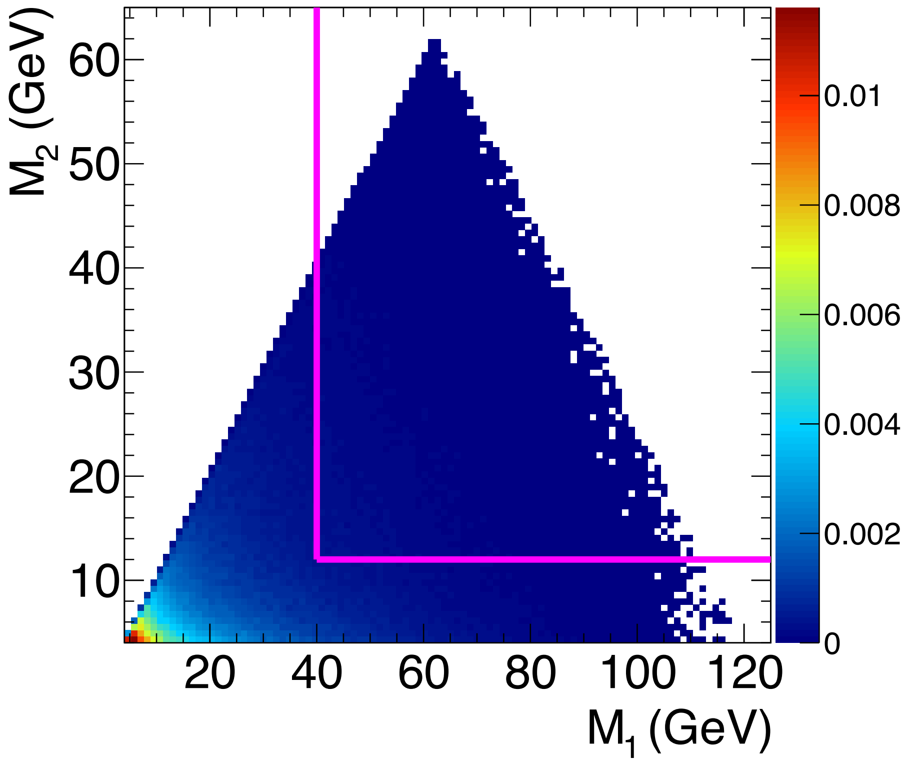
CMS cuts optimized for discovery:

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

Want to gain sensitivity to NLO effects.







EXPERIMENTAL CUTS

CMS cuts optimized for discovery:

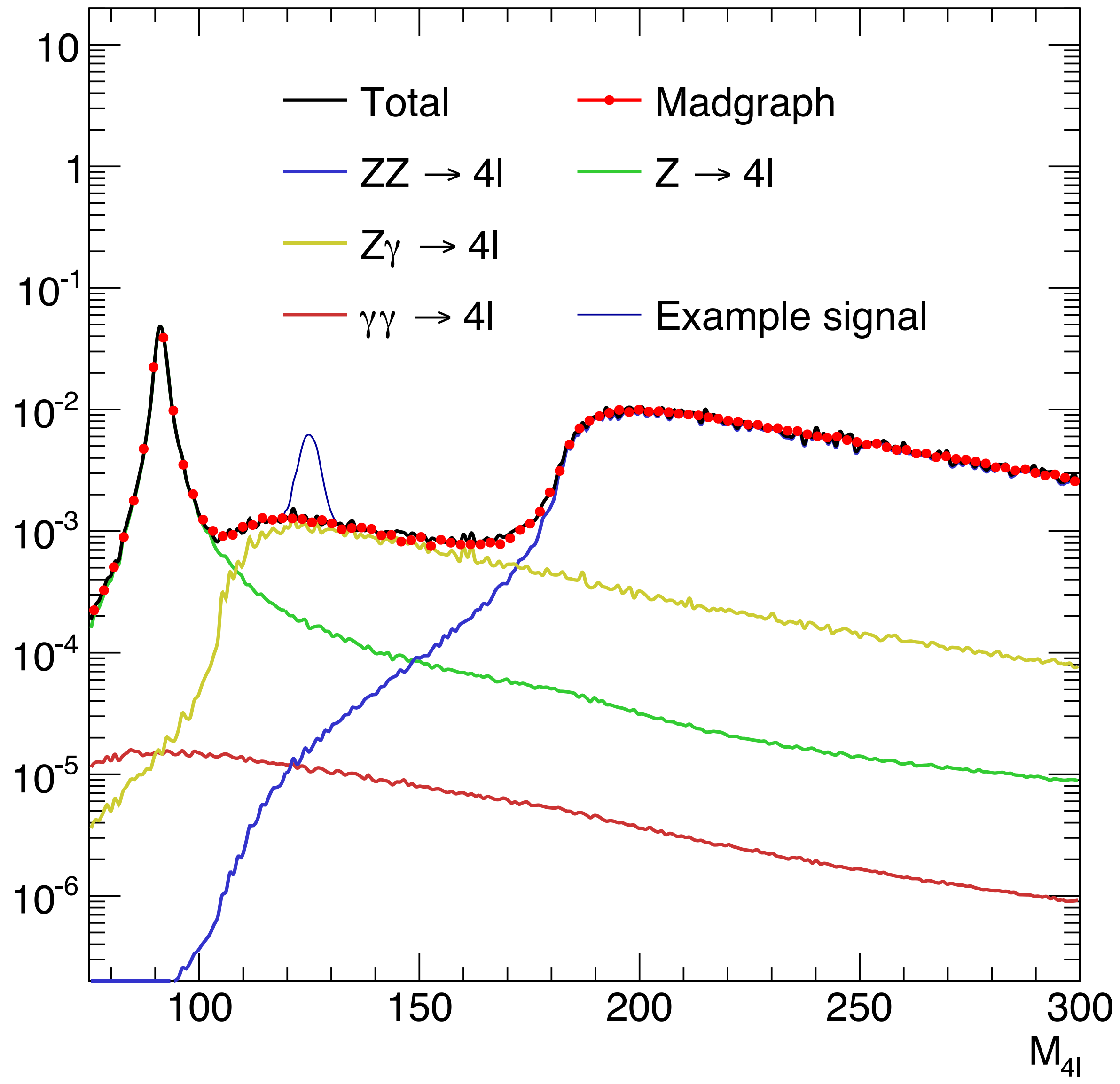
$$M_1 > 40, \;\; M_2 > 12, \;\; M_{\ell\ell} > 4$$

Modified "Relaxed - Υ"

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

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

S/B gets worse, but sensitivity improves.

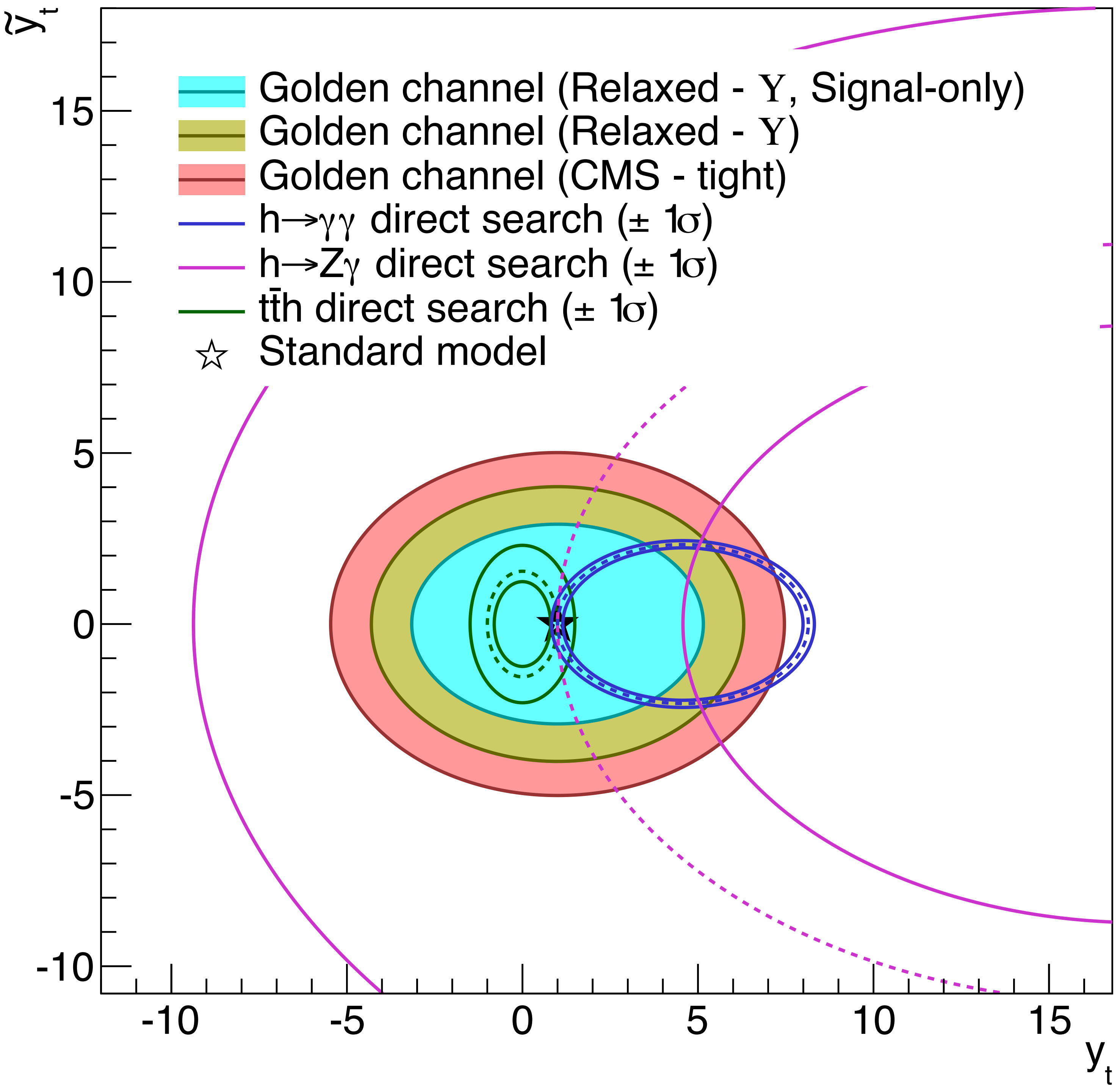


Chen, Harnik, Vega-Morales, [arXiv:1503.05855].

SENSITIVITY

800 events ~ 300 fb^{-1}

Non-trivial constraint.

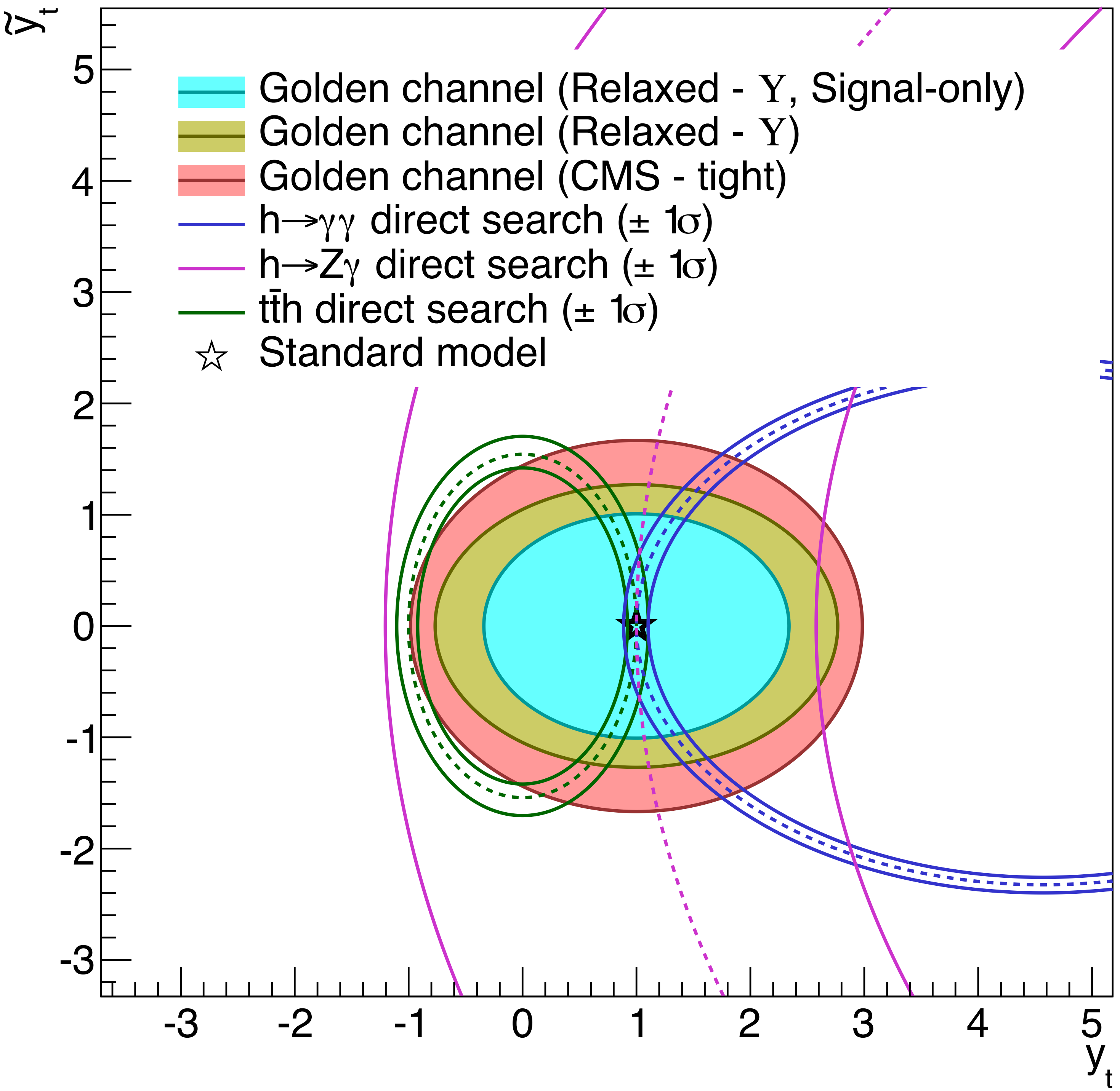


HIGH LUMINOSITY

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

Better constraint.

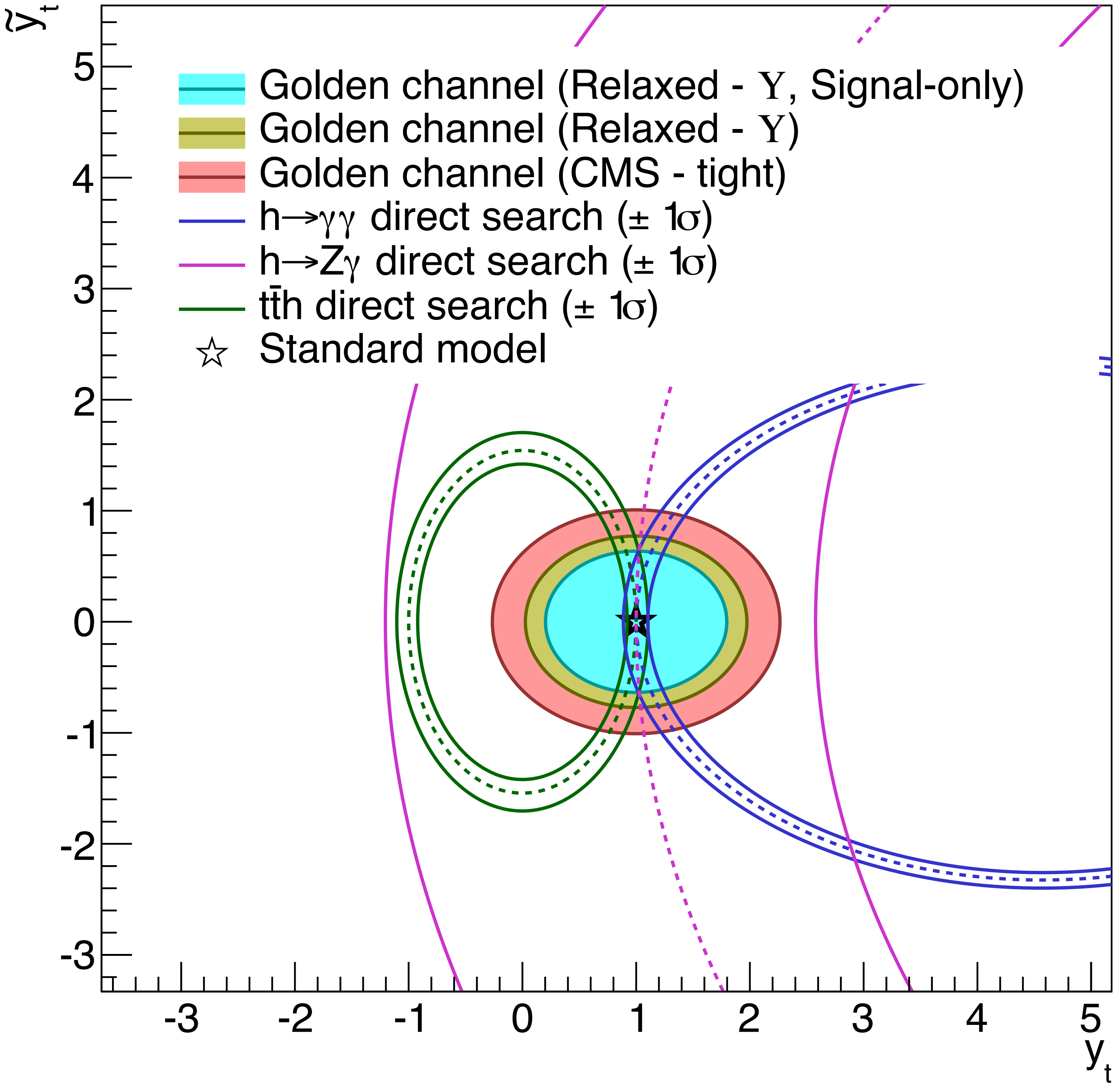
If there is anomaly, will help characterize.



100 TEV?

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

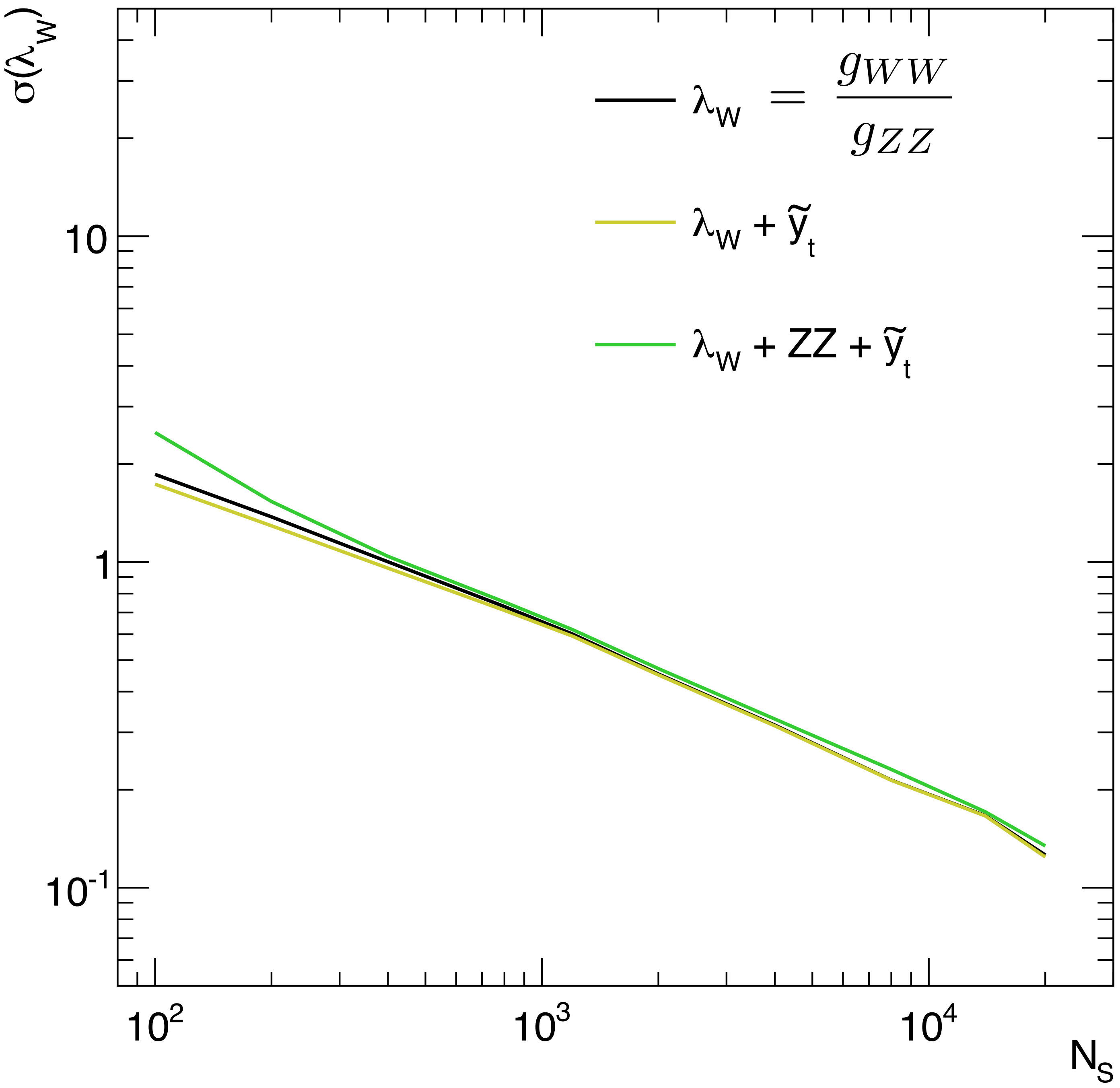
Further improved.



CUSTODIAL SYMMETRY

Can measure deviations from custodial symmetry.

Can rule out $\lambda_W = -1$ at LHC.



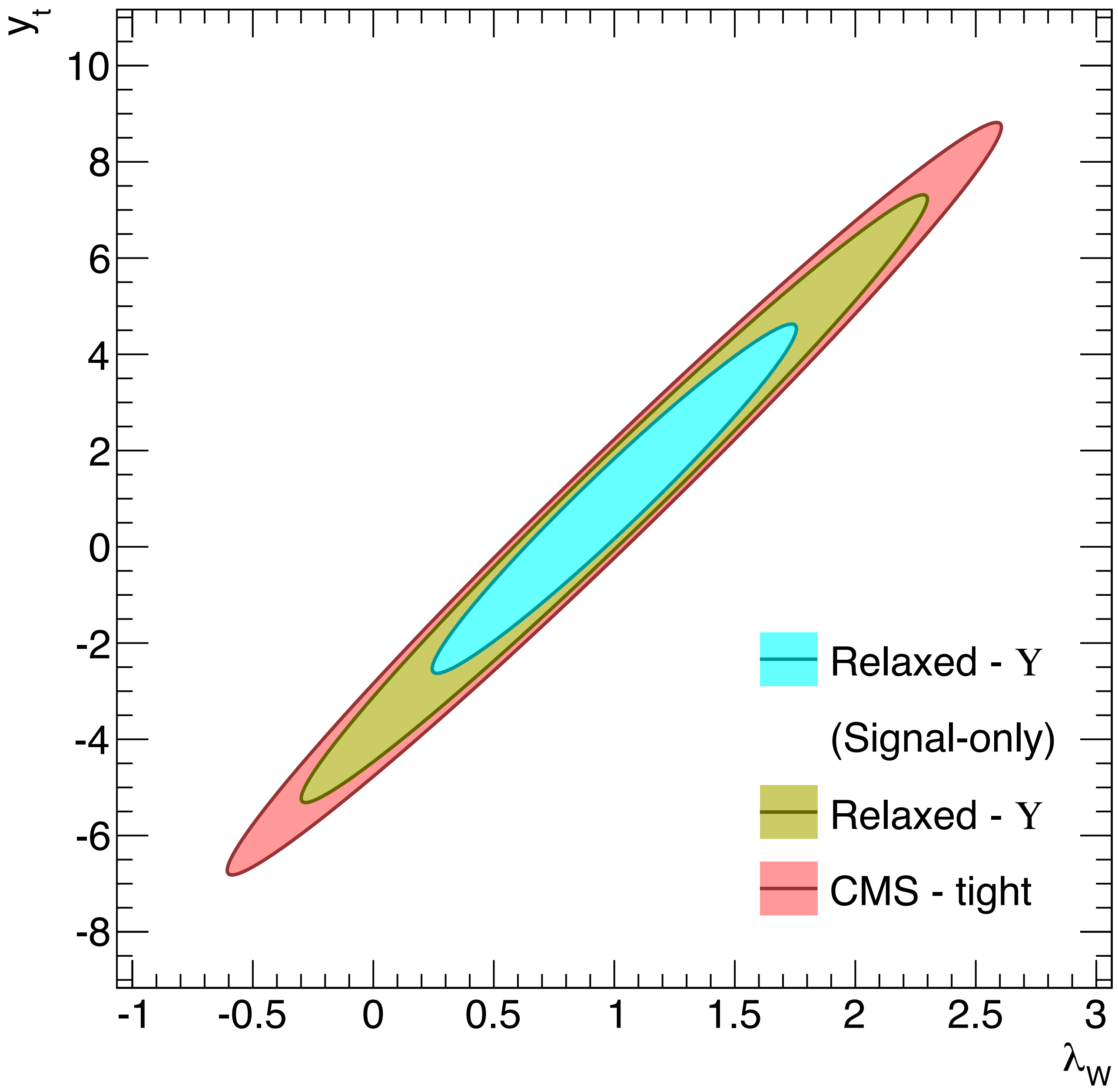
Work in progress with R. Vega-Morales and Y. Chen.

BREAK FLAT DIRECTIONS?

Can simultaneously measure *t* and *W* couplings.

Absolute flat direction in $h \to \gamma\gamma$.

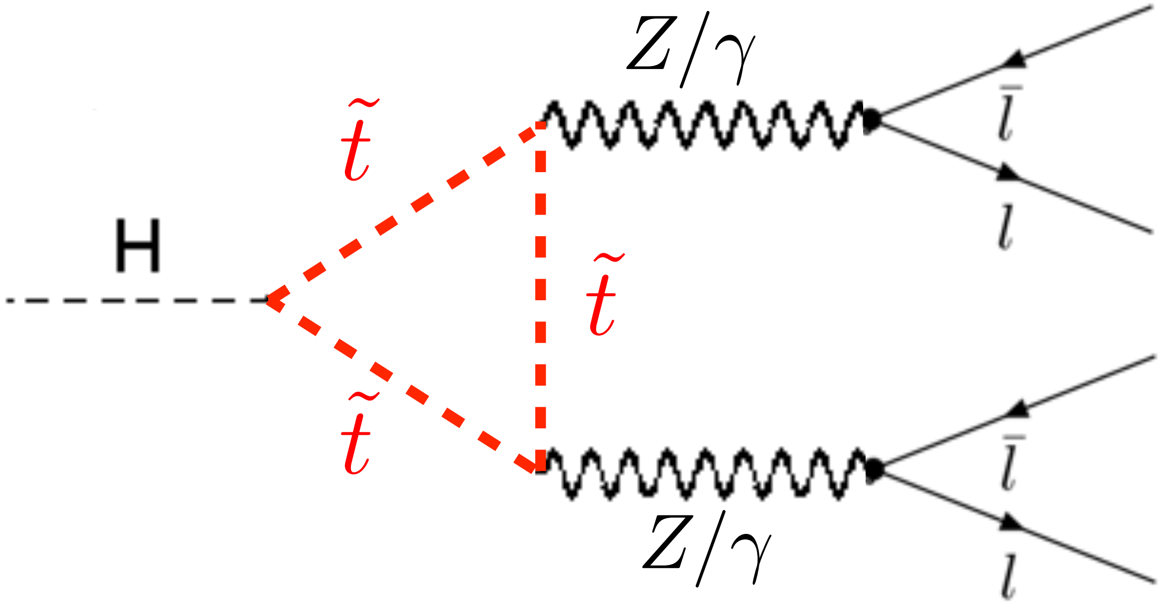
Can disfavor $\lambda_W = -1$



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

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 color.

Work in progress with
R. Vega-Morales and Y. Chen.

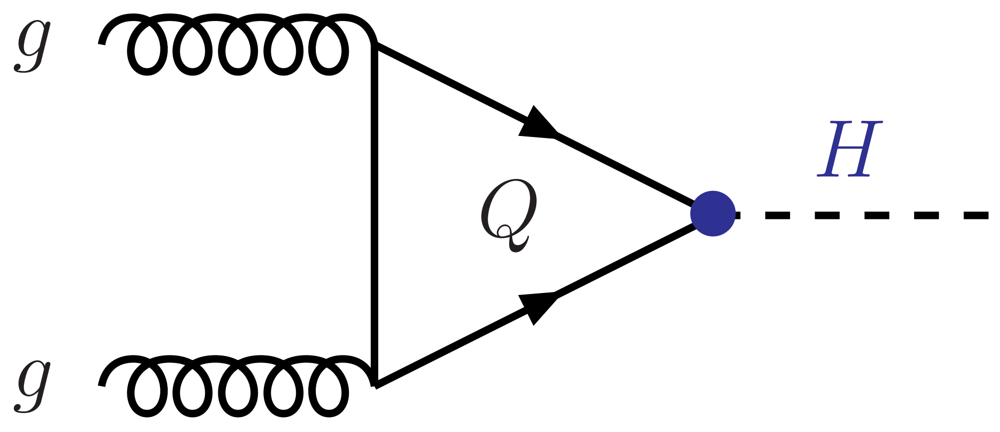
HIGGS PRODUCTION

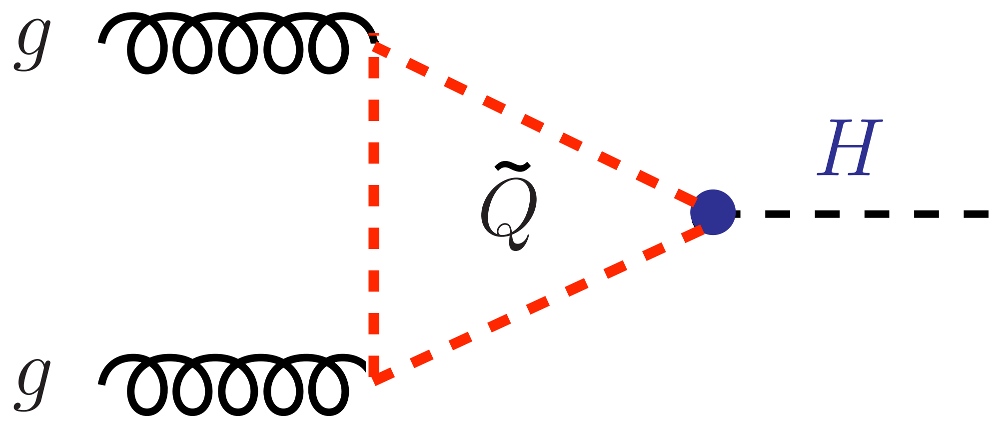
HIGGS PRODUCTION

Dominant Higgs production mechanism via loop process.

What if other colored particles couple to the Higgs?

Naturalness is a guiding hint…





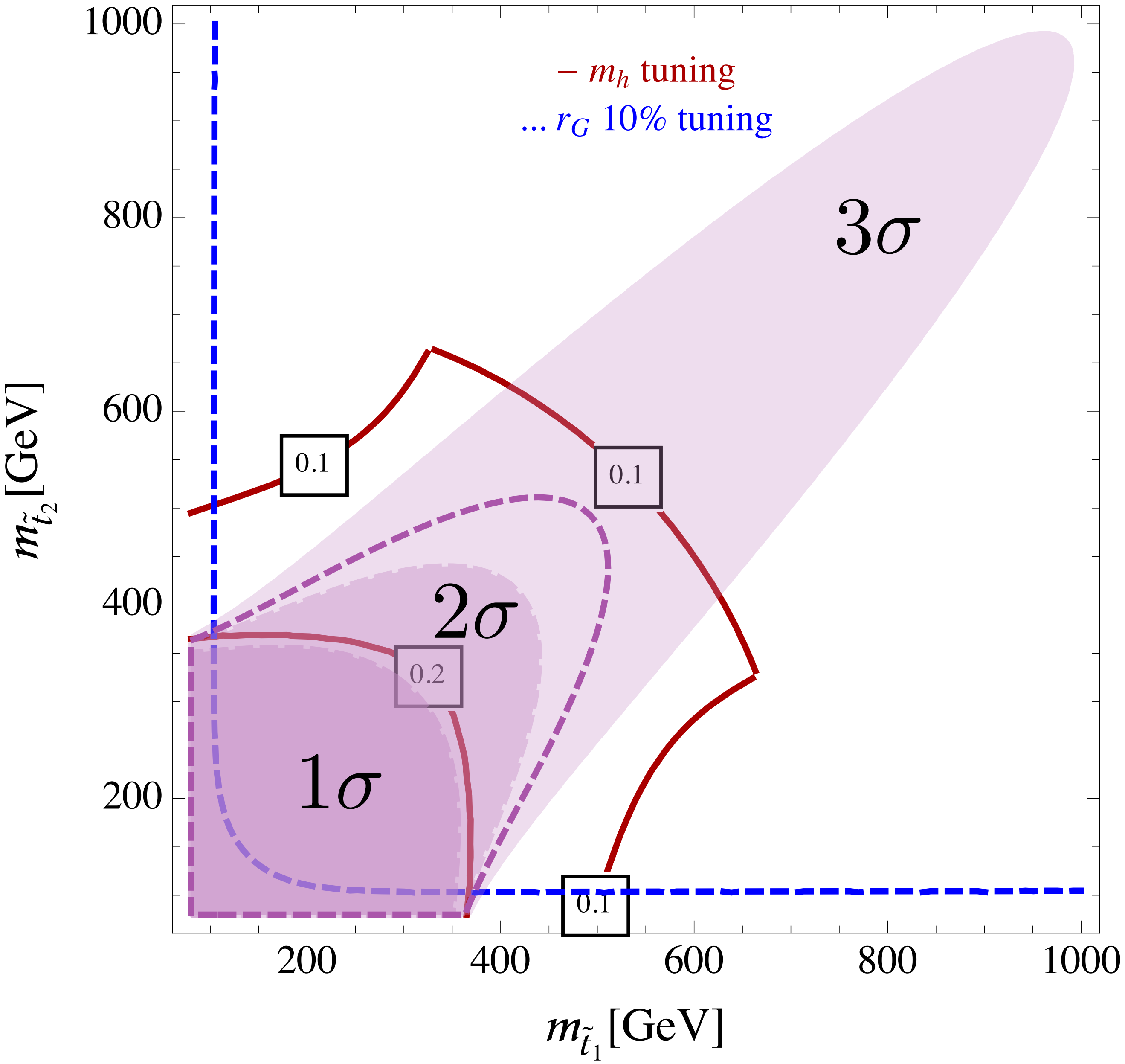
EXCLUSIONS

$$|\mu(gg \to h) - 1| \lesssim 20\%$$

Can use this diagram to exclude light stops.

Have to make assumption about mixing angle.

$$\lambda_{\tilde{t}_1 \tilde{t}_1 h} \simeq \frac{\sqrt{2}}{v}\left[m_t^2 + \frac{1}{2}\sin 2\theta_t m_t X_t\right]$$



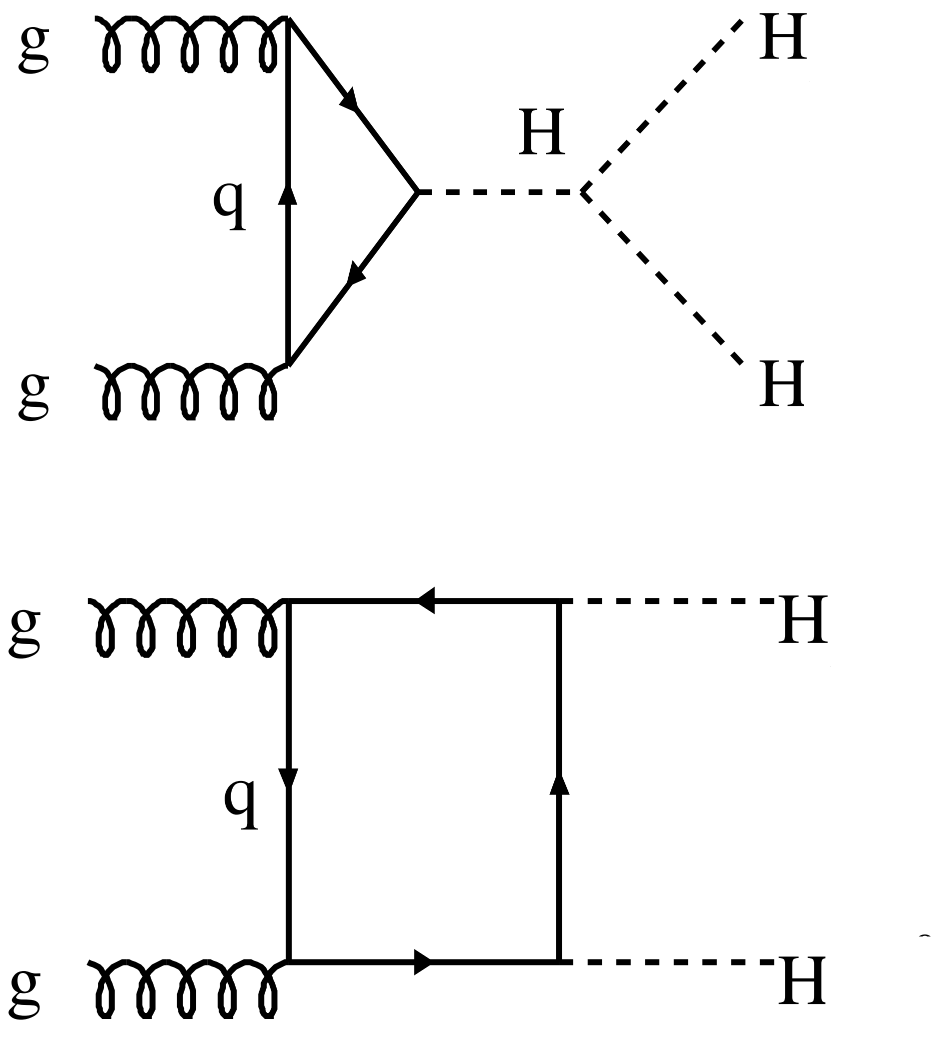
Fan and Reece [arXiv:1401.7671].

DI-HIGGS PRODUCTION

Di-Higgs production also loop process at LHC.

Two diagrams, strong destructive interference —amplitude vanishes at threshold.

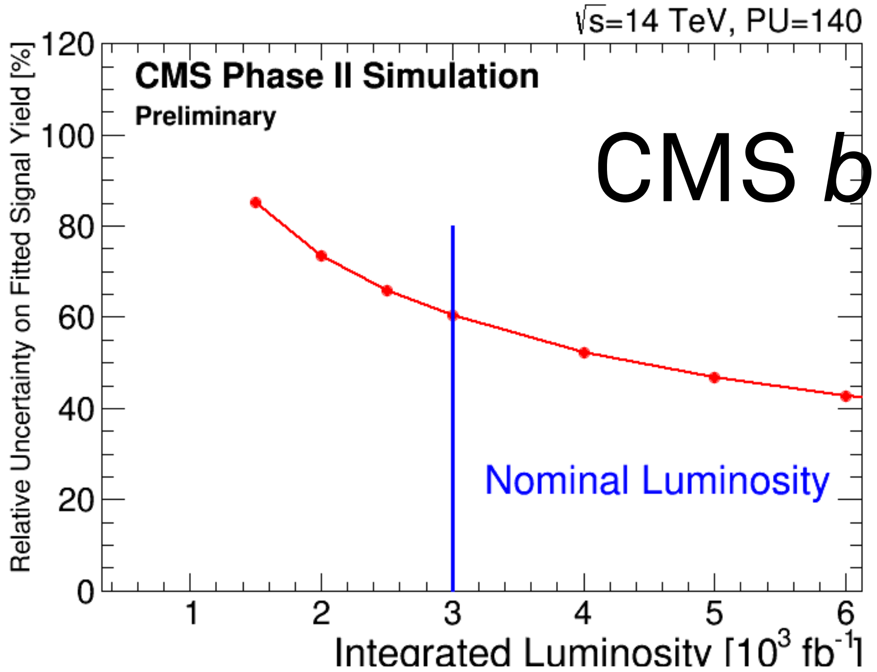
Perhaps can be sensitive to new physics?



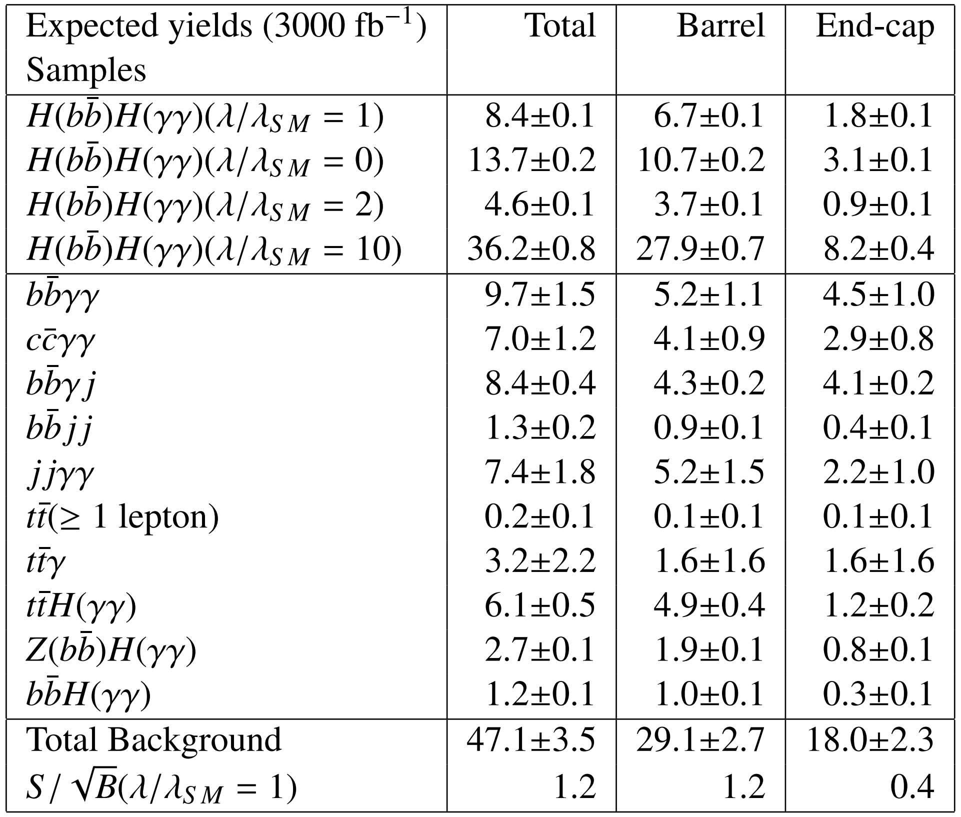
Li and Voloshin [arXiv:1311.5156].

LHC PROSPECTS

Preliminary studies by experiments show that measurement is possible but difficult at high-lumi.

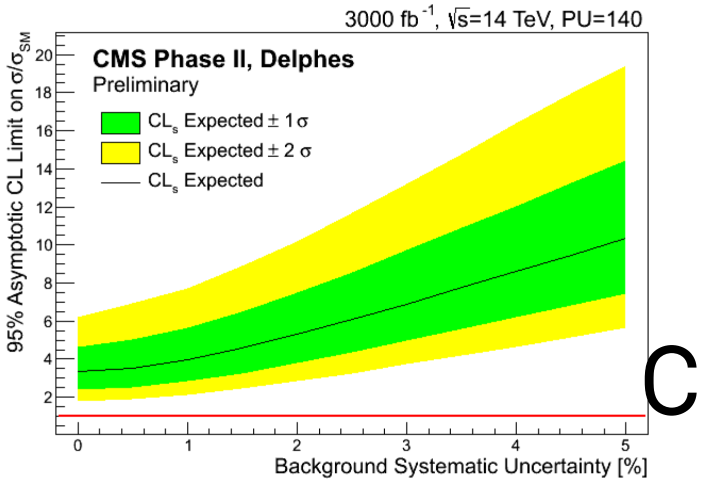


CMS *bbγγ*



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*

LHC PROSPECTS

Theorist studies are more optimistic (still need HL).

Studies in $bb\gamma\gamma$, $bb\tau\tau$, $bbWW$, $4b$,

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.

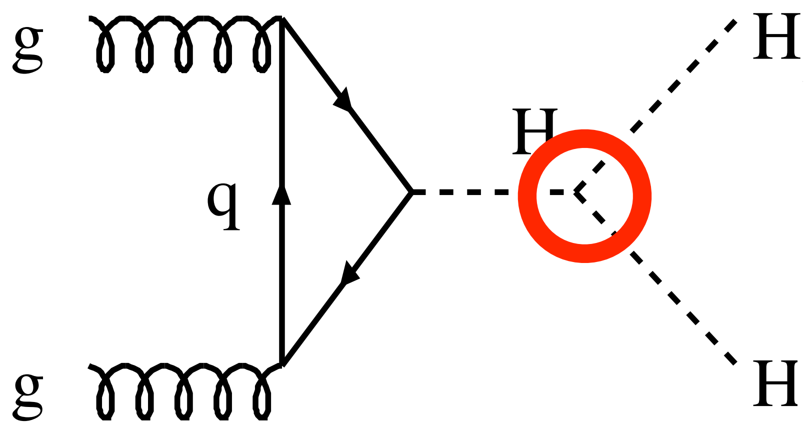
[82] A. Papaefstathiou, L. L. Yang, and J. Zurita, Phys.Rev. **D87**, 011301 (2013), 1209.1489.

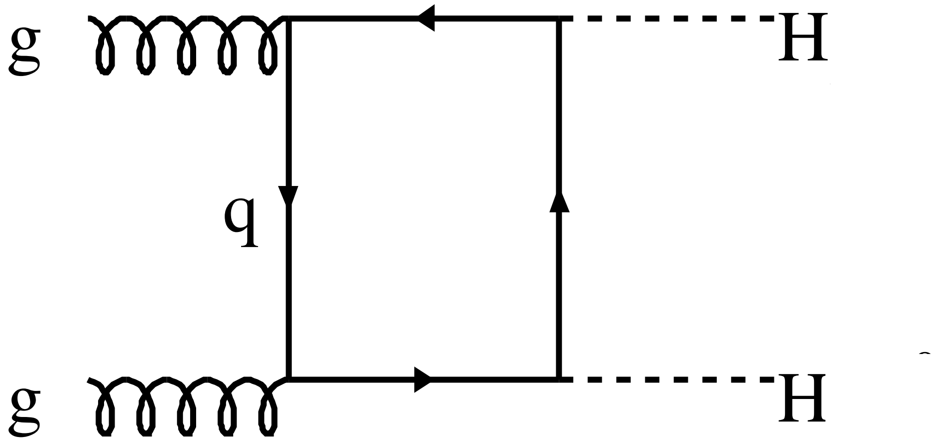
[83] D. E. Ferreira de Lima, A. Papaefstathiou, and M. Spannowsky, JHEP **1408**, 030 (2014), 1404.7139.

NON-RESONANT DI-HIGGS

Most studies focus on measuring Higgs self coupling.

Here I will assume its SM like and focus on new physics in loops.





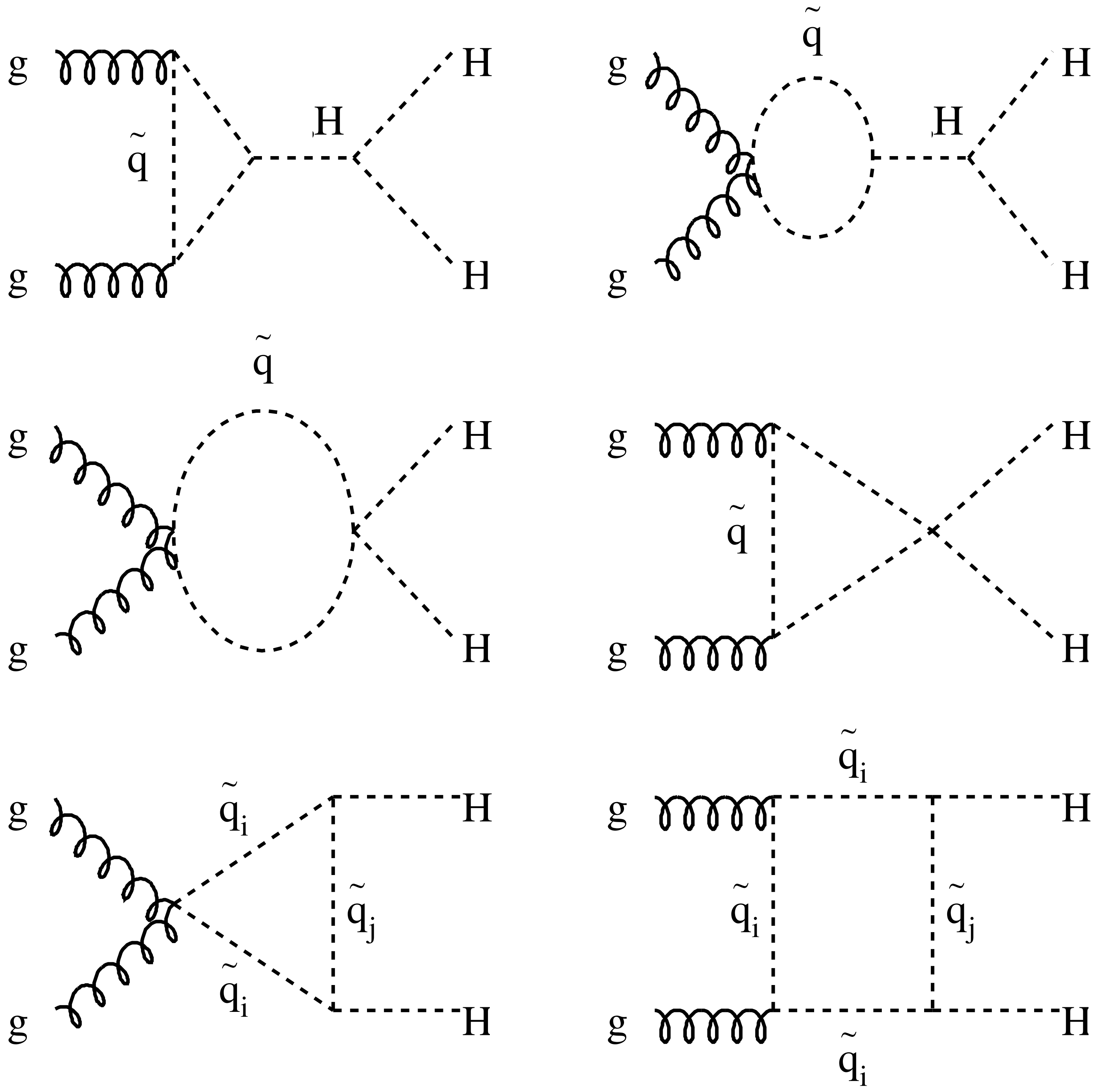
STOPS

No cancellation in the presence of new physics.

Effects could be large.

Balyaev et. al., hep-ph/9905266.

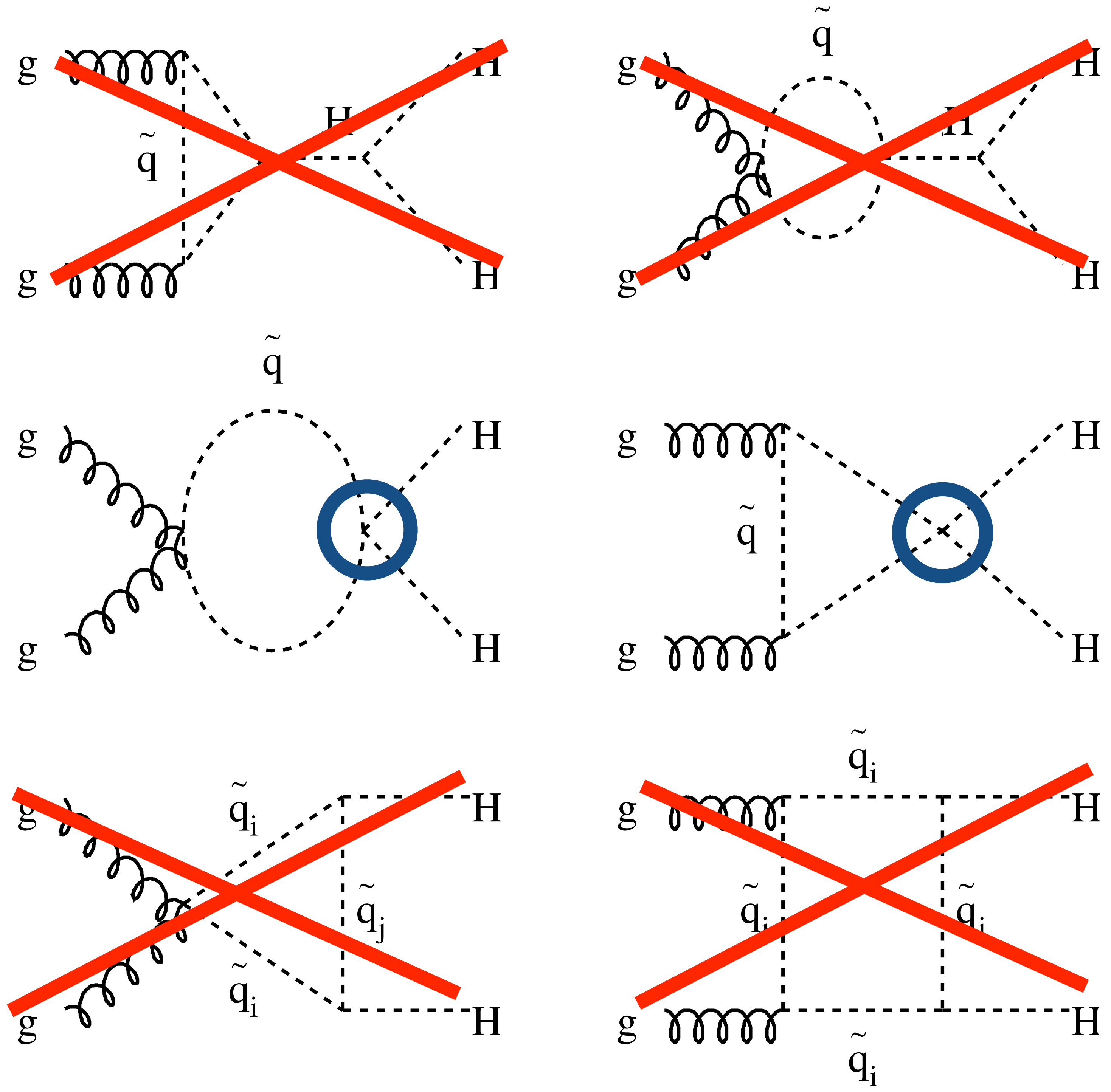
Barrientos Bendezu and Kniehl, hep-ph/0103182.



CAN PROBE BLIND SPOTS?

Di-Higgs sensitive to different couplings than single Higgs.

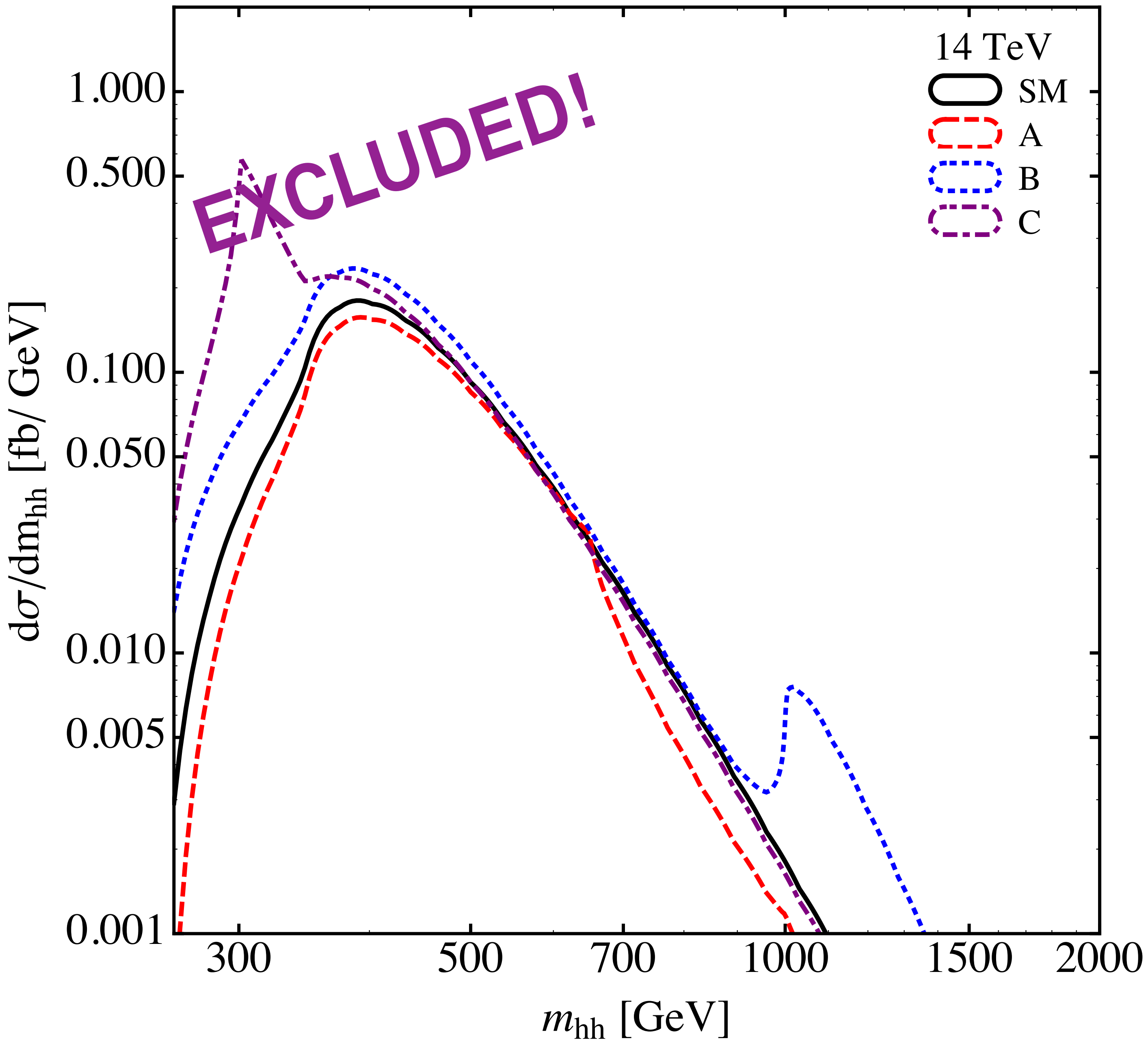
$$\lambda_{\tilde{t}_1\tilde{t}_1 hh} \simeq \frac{m_t^2}{v^2}$$



SPECTRA

Often get spectra with huge enhancements at low invariant mass.

They are almost always excluded.



EFFECTIVE FIELD THEORY

If usual rules of EFT apply:

$$\left(\frac{c_1}{\Lambda^2}|H|^2 + \frac{c_2}{\Lambda^4}|H|^4 + \ldots\right) G_{\mu\nu}G^{\mu\nu}$$

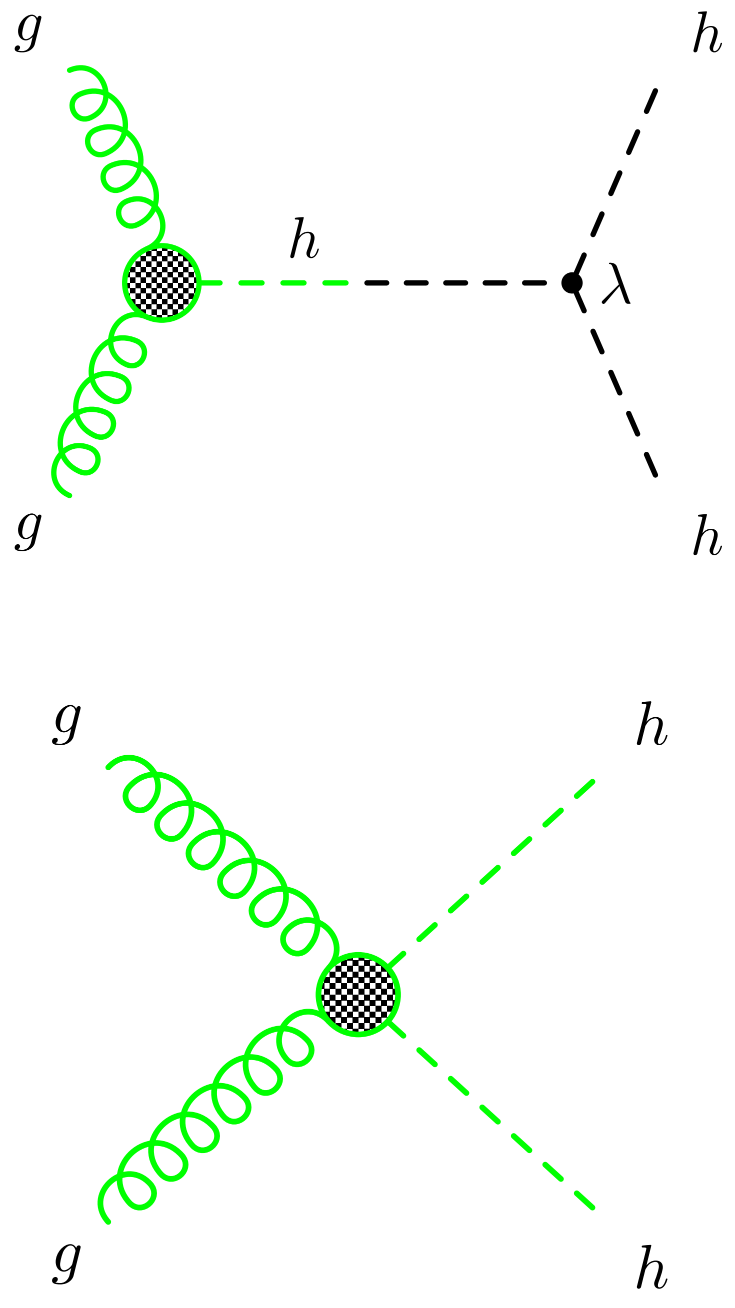
descends down to:

$$\frac{h}{\sqrt{2}v}\left(c_{\rm SM} + \boxed{\frac{2c_1v^2}{\Lambda^2}} + \frac{4c_2v^4}{\Lambda^4} + \ldots\right) G_{\mu\nu}G^{\mu\nu} +$$

$$\frac{h^2}{4v^2}\left(-c_{\rm SM} + \frac{2c_1v^2}{\Lambda^2} + \frac{12c_2v^4}{\Lambda^4} + \ldots\right) G_{\mu\nu}G^{\mu\nu}$$

Run I implies this must be small.

Won't see big effects in di-Higgs.



LOW ENERGY THEOREM

Stops can be non-decoupling:

$$\mathcal{L} \supset \frac{\alpha_s b_0^c}{16\pi} \left[\log \det \mathcal{M}_{\tilde{t}}^2\right] G_{\mu\nu}G^{\mu\nu}$$

gives

$$\mathcal{L} = \frac{\alpha_s}{12\sqrt{2}\pi v}(\kappa_t^h + \kappa_{\tilde{t}}^h)h\, G_{\mu\nu}G^{\mu\nu} - \frac{\alpha_s}{48\pi v^2}(\kappa_t^{hh} + \kappa_{\tilde{t}}^{hh})h^2\, G_{\mu\nu}G^{\mu\nu}$$

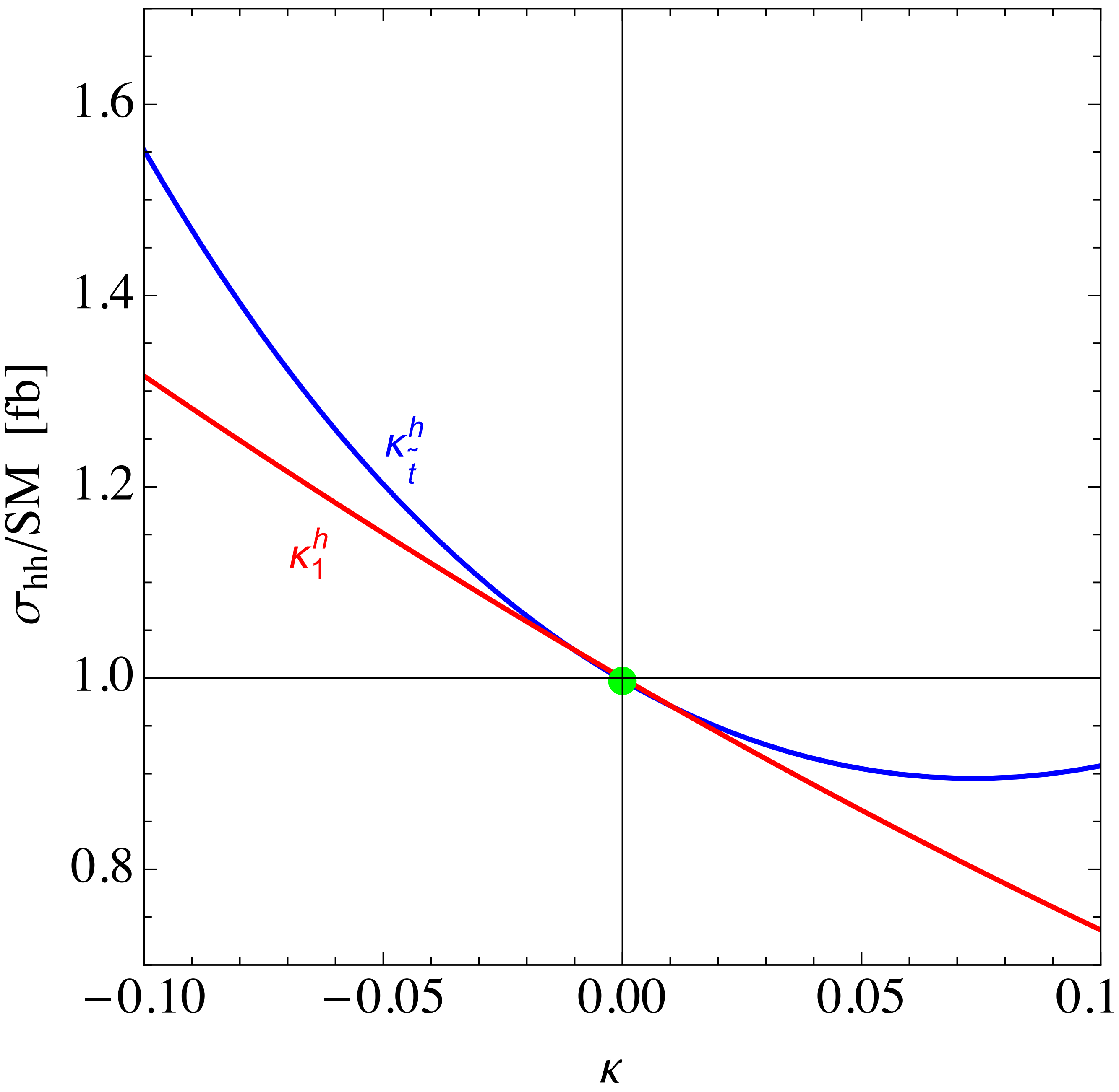
$$\kappa_{\tilde{t}}^h = \frac{1}{4}\frac{m_t^2\left(m_1^2 + m_2^2 - X_t^2\right)}{m_1^2 m_2^2} \qquad \kappa_{\tilde{t}}^{hh} = \kappa_{\tilde{t}}^h(8\,\kappa_{\tilde{t}}^h - 1) - \frac{m_t^4}{m_1^2 m_2^2},$$

Small effects if at least one stop is heavy.

LET AND EFT

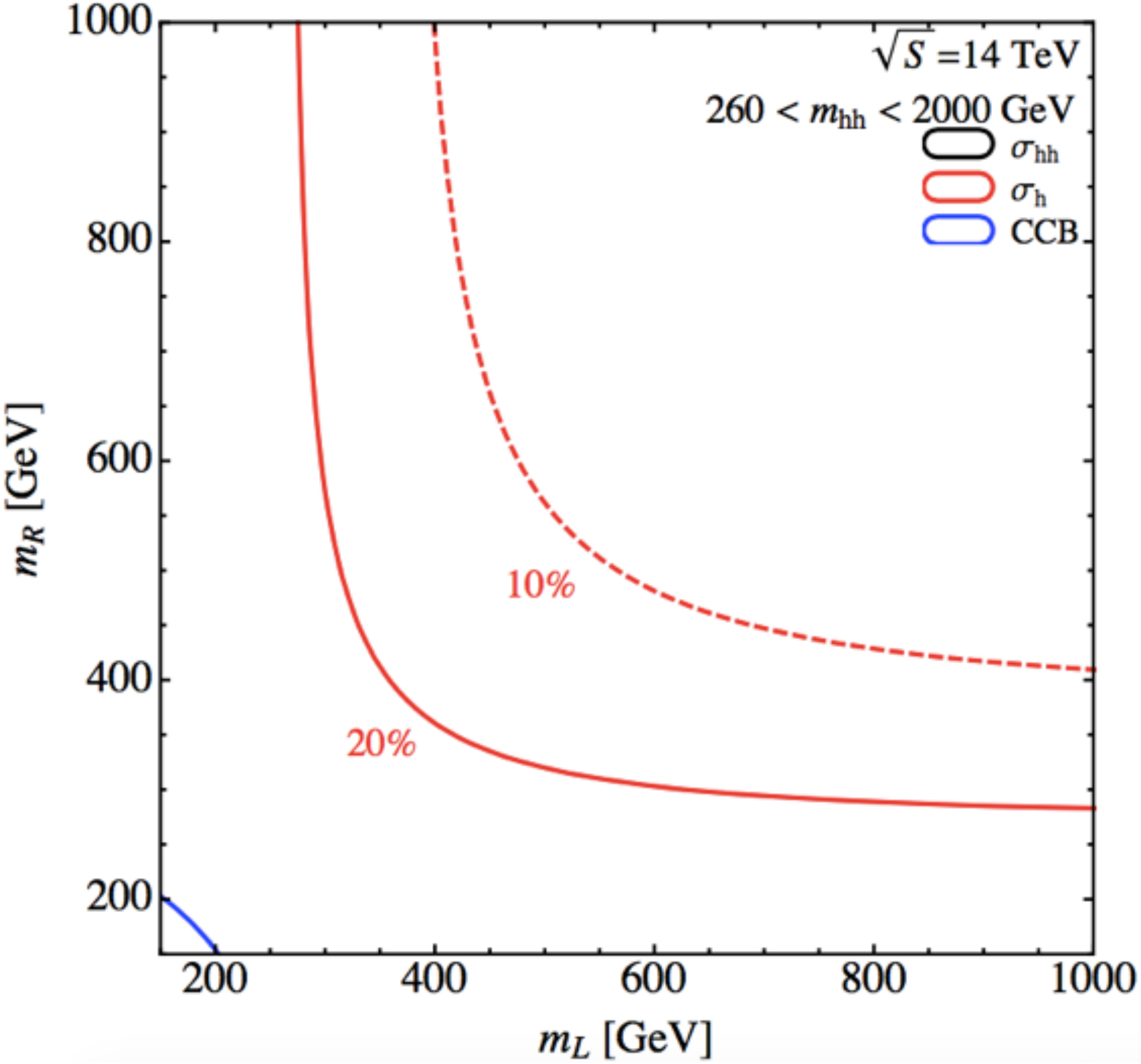
Deviations in single and di-Higgs are anti-correlated.

Non decoupling theories can give larger effects.



RESULTS

No stop mixing = no effects in di-Higgs.

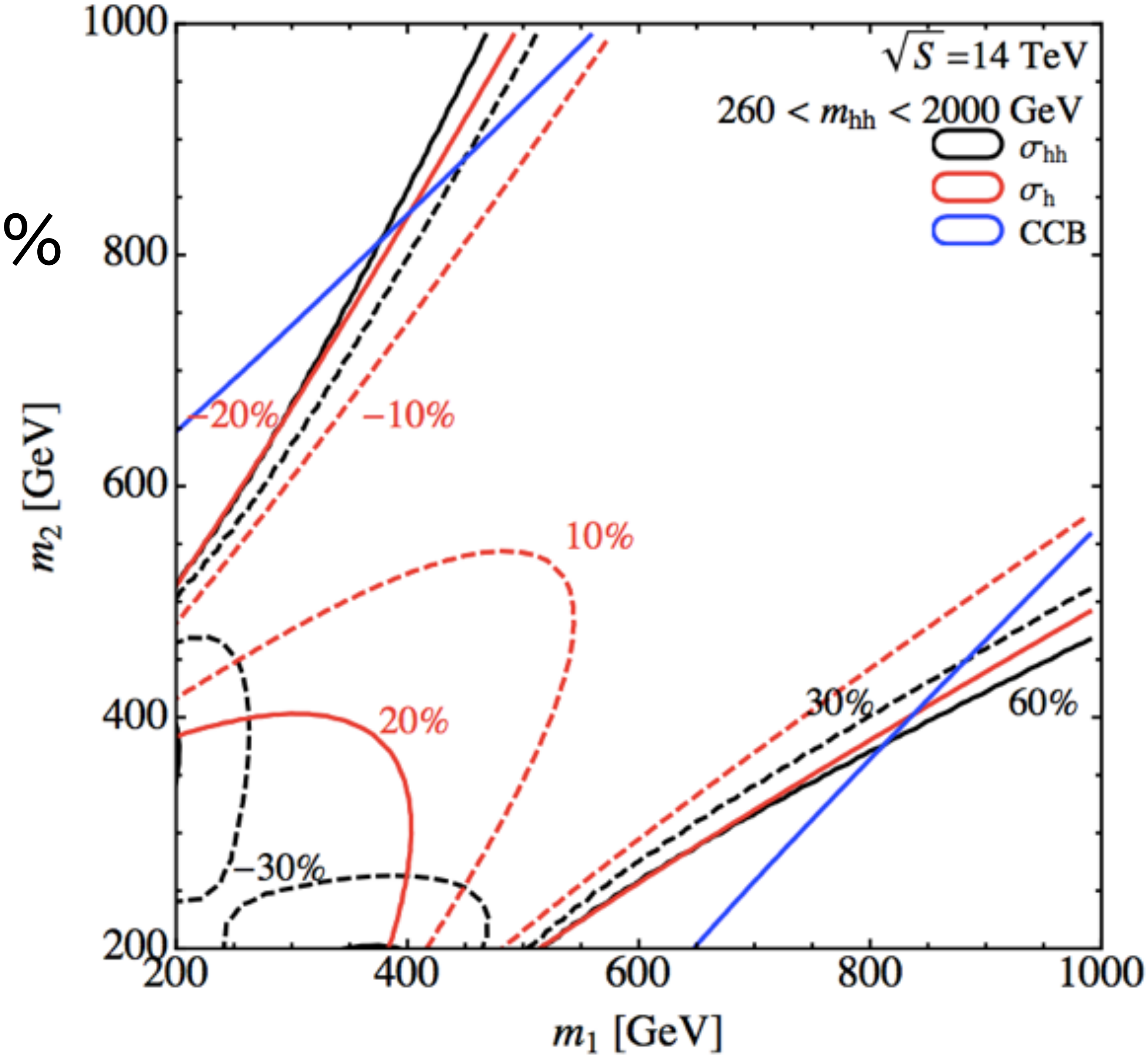


RESULTS

Equal soft masses.

Tuned region with ~30% modification.

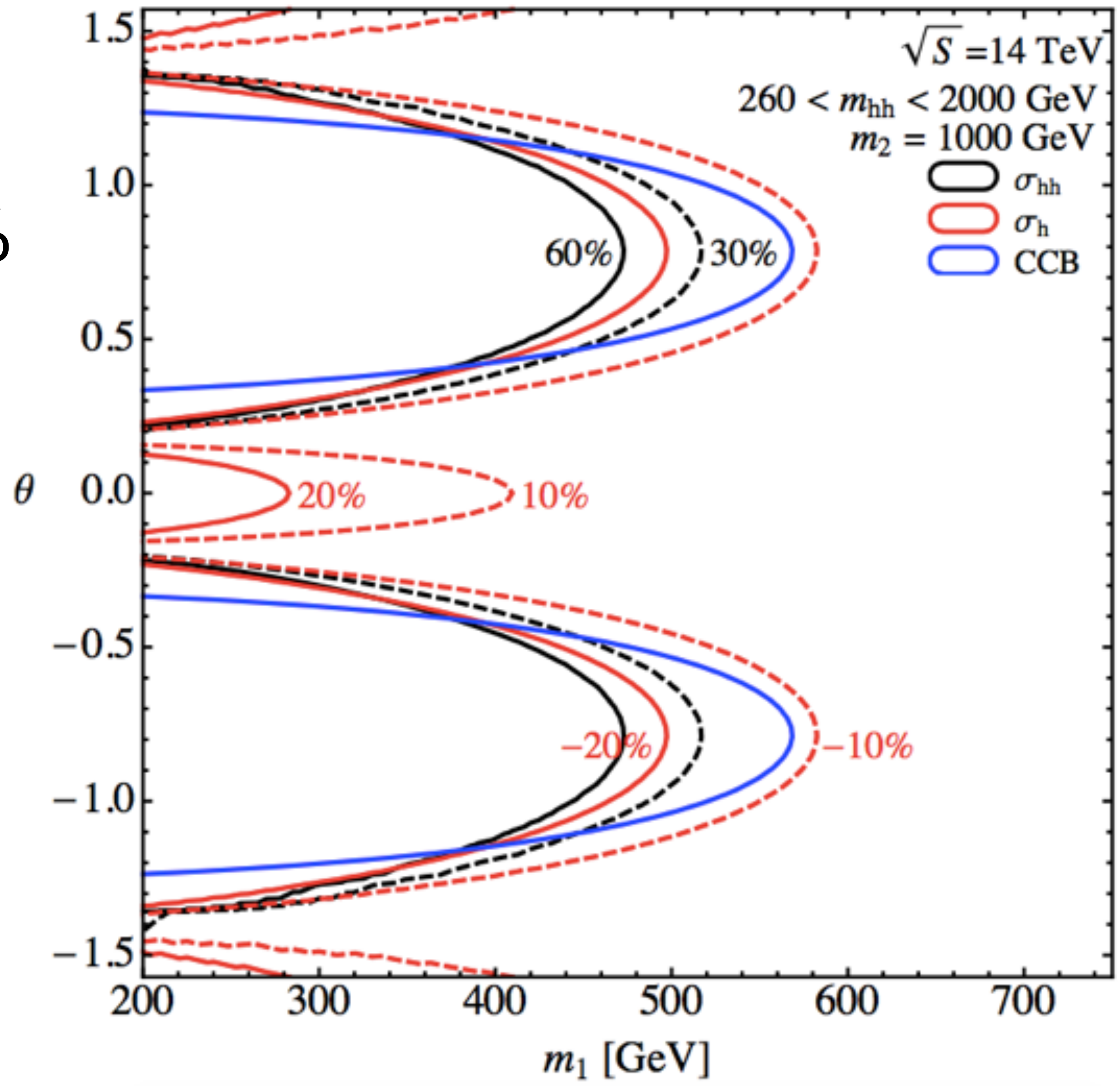
Larger modifications excluded.



RESULTS

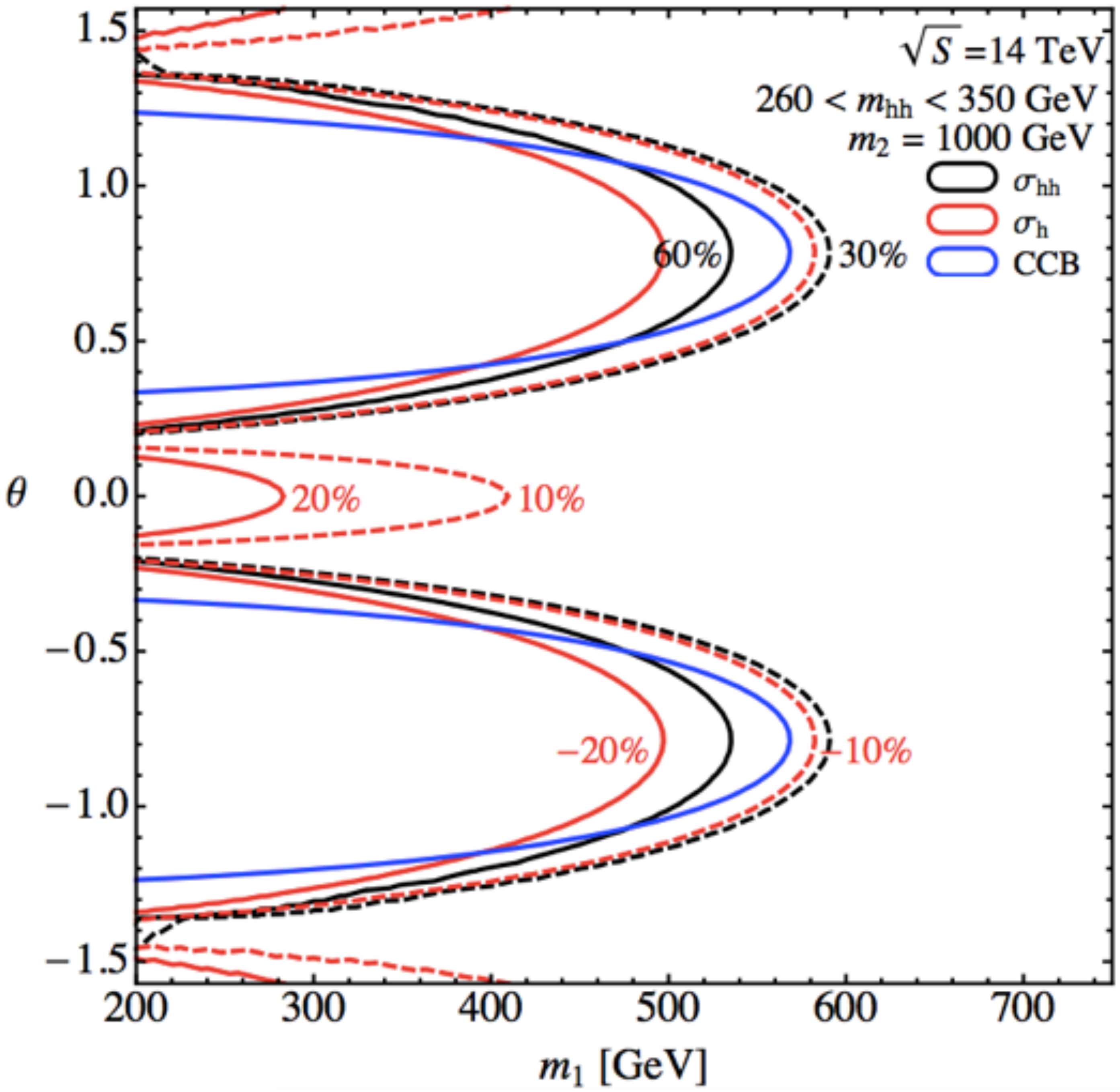
Fix heavy stop mass.

Tuned region with ~50% modification.



CHANGE INVARIANT MASSS

Can do better with different invariant mass cuts.



SPECTRA

A: m = 325, 500 GeV

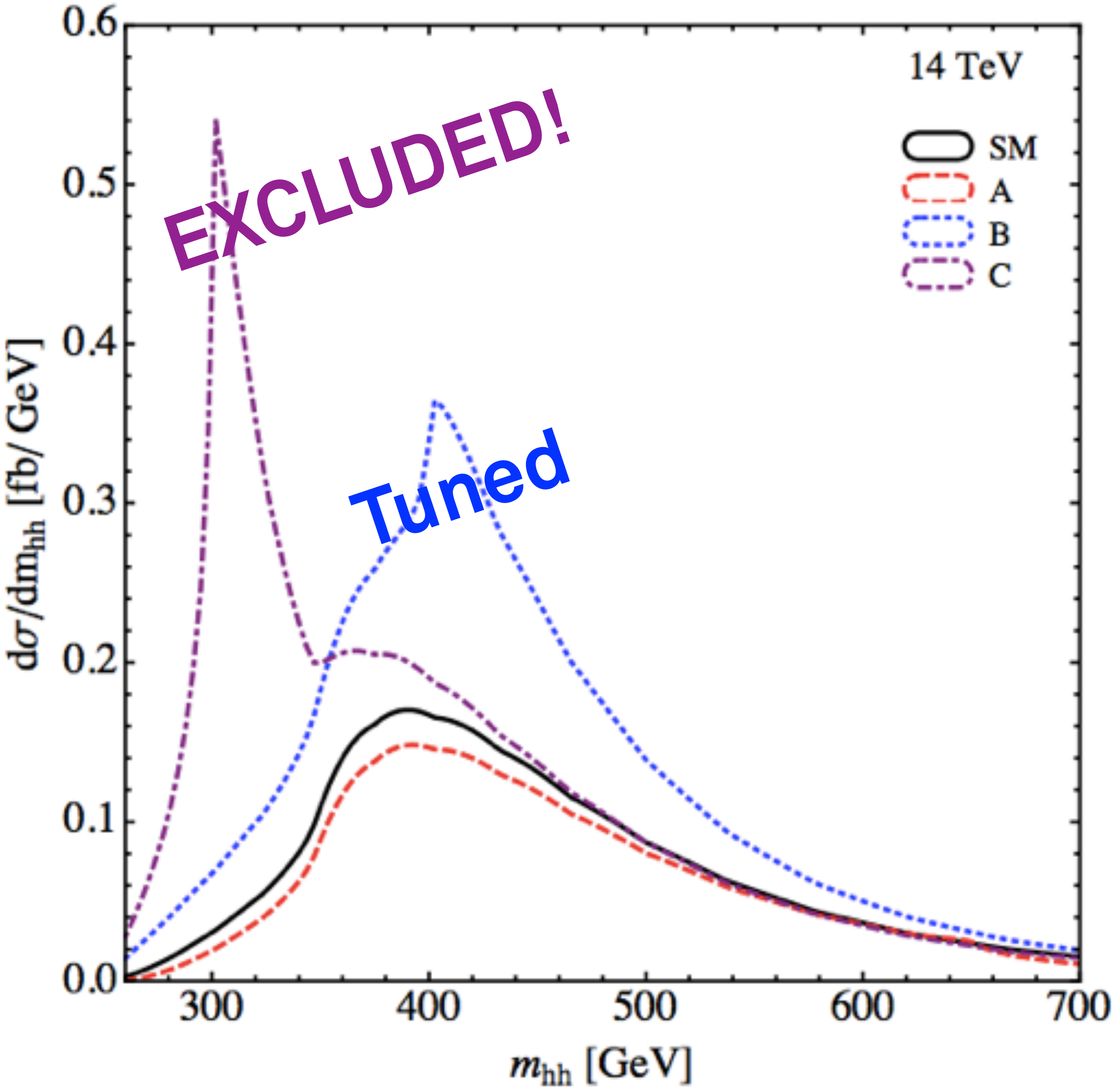
sinθ = 0.4

B: m=200, 1000 GeV

sinθ=0.223

C: m=150, 1000 GeV

sinθ=0



CONCLUSIONS 1

- 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.

- Use to place model-independent bounds (or discover) new fields which couple to Higgs.

CONCLUSIONS 2

- Higgs produced in loop process at LHC. Production rate can be sensitive to colored new physics.
- Measurement of rate in Run I already puts strong constraints on new physics.
- EFT arguments say it will be difficult to see large effects in *non-resonant* double Higgs production.
- Future measurements can place constraints on difficult regions of parameters space.

THANK
YOU

4 LEPTON DETAILS

- $115 \text{ GeV} < M_{4\ell} < 135 \text{ GeV}$
- $p_T > (20, 10, 5, 5)$ 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]

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

100 TEV DI-HIGGS