Title: Now what?: Higgs physics after discovery

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Abstract: With the discovery of a new Higgs-like particle at the LHC, there is an unprecedented opportunity to use the Higgs as a probe for physics beyond the Standard Model. I will discuss a variety of recent ideas to look for new physics via the Higgs, including measurements of Higgs couplings and associated indirect observables; searches for Higgs production in association with new physics; and strategies for probing extended electroweak symmetry breaking sectors.

Now what?: Higgs physics after discovery

Nathaniel Craig (IAS & Rutgers)

Based on recent work with Scott Thomas; Jared Evans, Can Kilic, Michael Park; Alex Azatov, Spencer Chang, Jamison Galloway; David Shih, Simon Knapen, Yue Zhao; Emmanuel Contreras-Campana, Richard Gray, Sunil Somalwar, Matt Walker

PI 10.16.12

What to do after the Higgs?

"Tja, 2 months without writing a post is my personal best since I started this blog. It cannot be just laziness. I blame it on the frantic atmosphere surrounding the Higgs discovery, which resulted in post-coital tristesse. Indeed, a face-to-face with a genuine discovery only makes you realize the day-to-day misery of high-energy physics today. Now it's much harder to get excited about setting limits on new physics or even about seeing hints of new physics that will surely go away before you blink."

--Resonaances

Overcoming post-Higgs tristesse

- Higgs mass and implications for new physics
- Higgs couplings and implications for new physics
- Studying Higgs physics in multi-lepton final states
- Looking for Higgs production in association with new physics
- Looking for extended Higgs sectors
- New precision physics measurements via the Higgs

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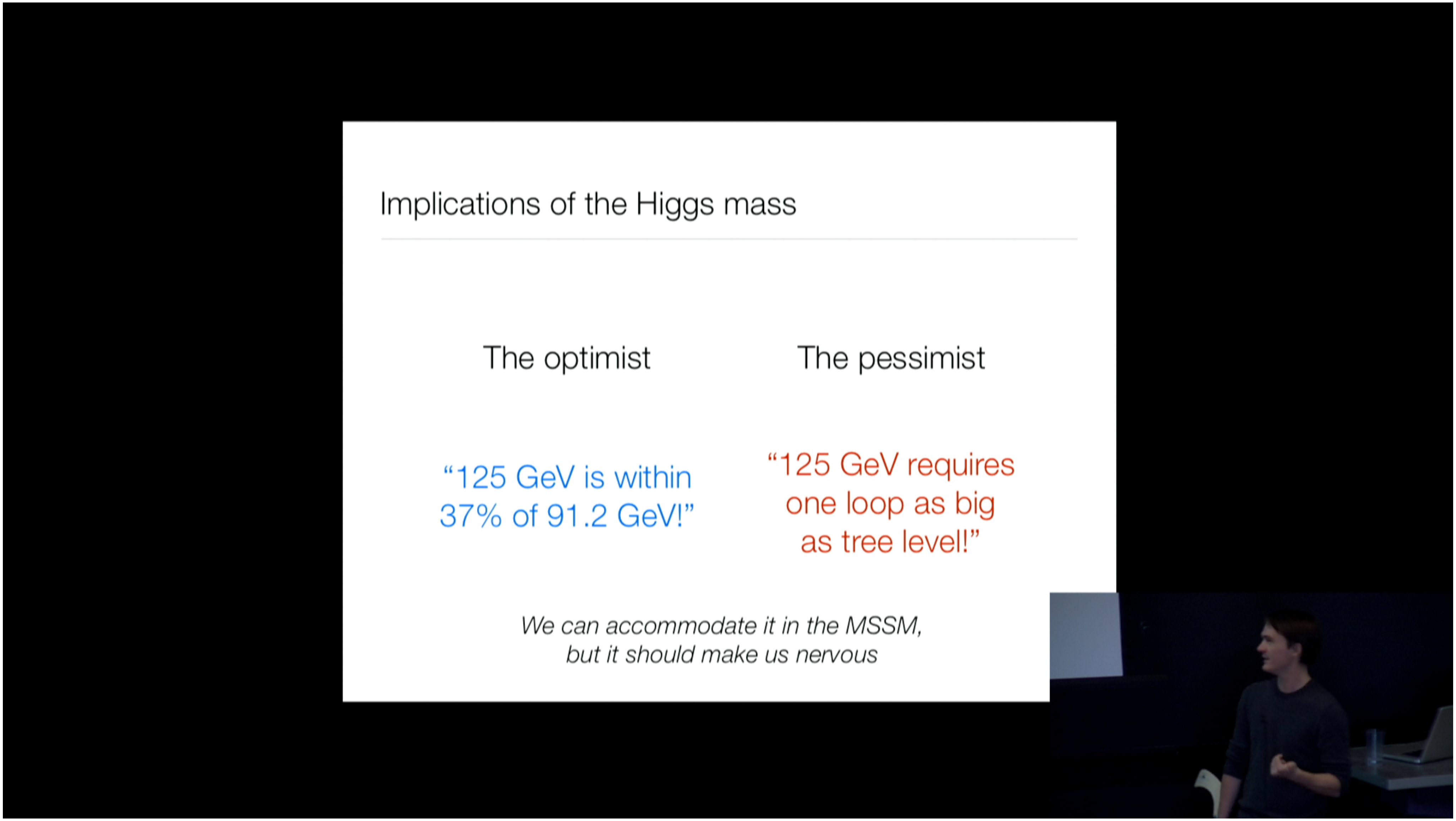
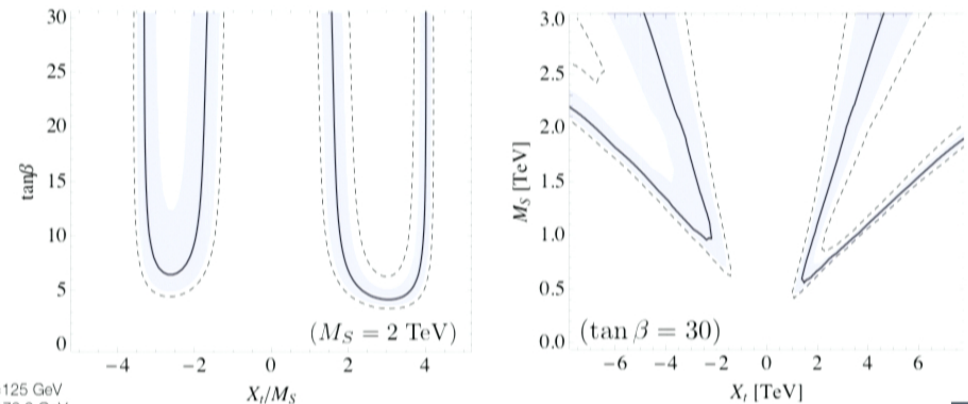

Implications of the Higgs mass
The optimist
The pessimist
“125 GeV is within 37% of 91.2 GeV!”
“125 GeV requires one loop as big as tree level!”
We can accommodate it in the MSSM, but it should make us nervous

(plots from Draper, Meade, Reece, & Shih, arXiv:1112.3068)

The Higgs mass in the MSSM

$$m_h^2 = m_Z^2 c_{2\beta}^2 + \frac{3m_t^4}{4\pi^2 v^2}\left(\log\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12M_S^2}\right)\right) \qquad (X_t \equiv A_t - \mu\cot\beta)$$



m_h=125 GeV
m_t=173.2 GeV
(FeynHiggs fixed-order result)

$\tan\beta \gtrsim 3.5 \qquad M_S \gtrsim 1\ \mathrm{TeV} \qquad |X_t| \gtrsim 2\ \mathrm{TeV}$

A-terms must be large in the MSSM!

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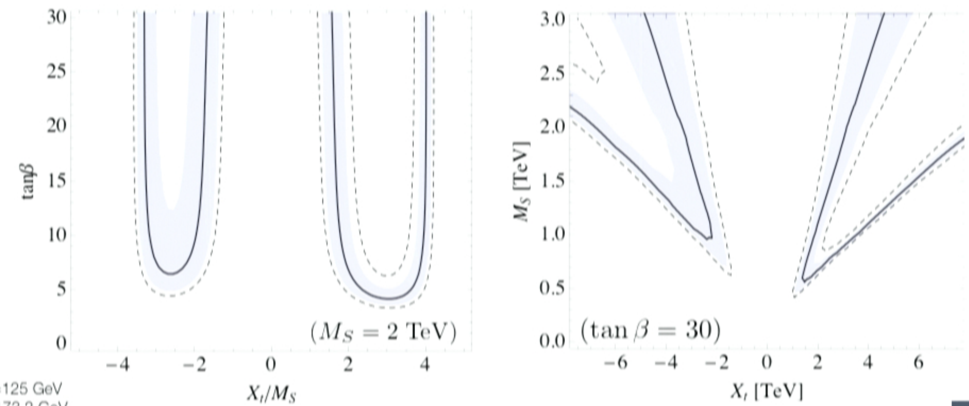

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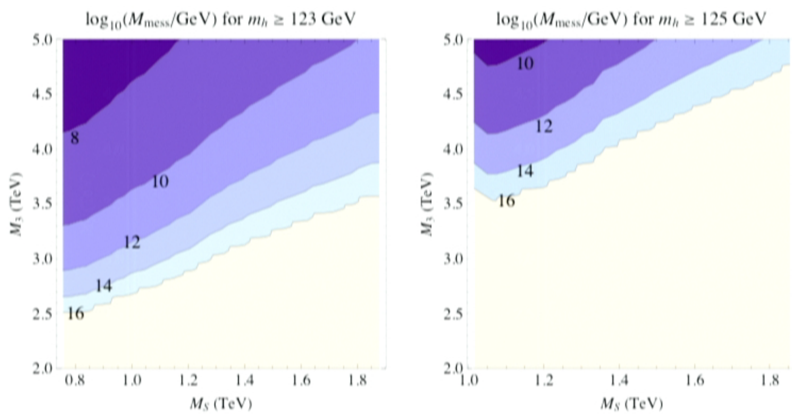
Bad news for gauge mediation

- A-terms are zero at the messenger scale
- Large A_t possible due to RG, but requires large M_3 and M_{mess}.



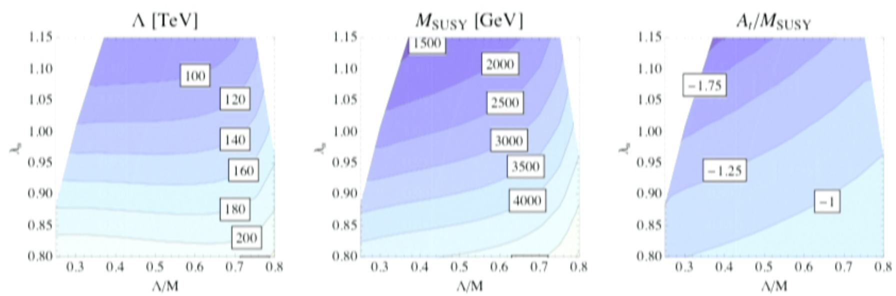
NC, Simon Knapen, David Shih,
Yue Zhao (arXiv:1206.4086)

New interactions to the rescue

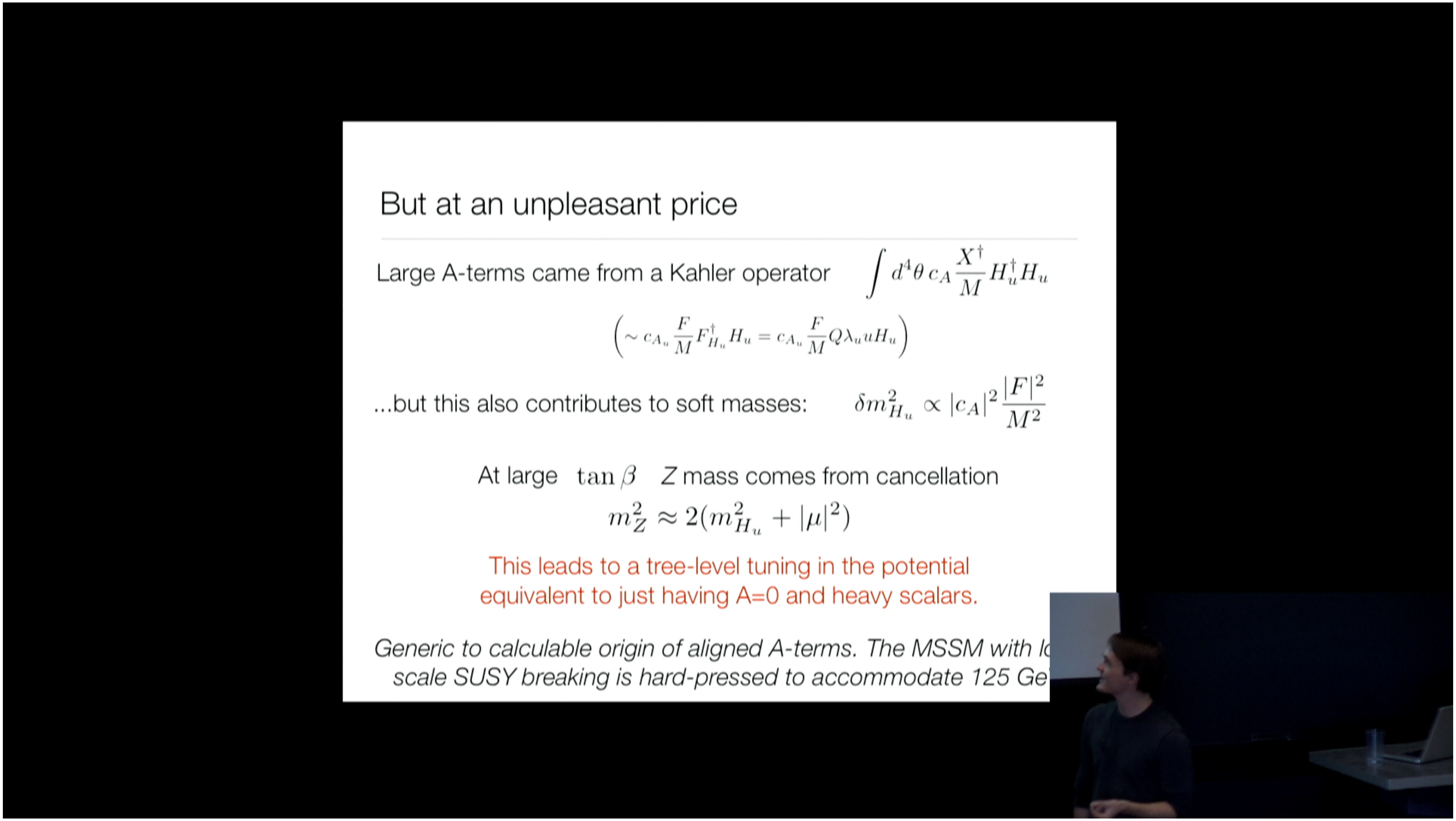
Can induce A-terms by introducing Higgs-messenger interactions, e.g.

$$W = \lambda X \Phi_i \cdot \tilde{\Phi}_i + \lambda_{uij} H_u \cdot \Phi_i \cdot \tilde{\Phi}_j + y_t H_u \cdot Q \cdot U + \mu H_u \cdot H_d$$

This gives A-terms at one loop (as well as one-loop, F/M^2-suppressed and two-loop unsuppressed Higgs soft masses)



Suffices to raise the Higgs mass with stops around 1.5 TeV


But at an unpleasant price
Large A-terms came from a Kahler operator $\int d^4\theta \, c_A \frac{X^\dagger}{M} H_u^\dagger H_u$
$\left(\sim c_{A_u} \frac{F}{M} F_{H_u}^\dagger H_u = c_{A_u} \frac{F}{M} Q \lambda_u u H_u \right)$
...but this also contributes to soft masses: $\delta m_{H_u}^2 \propto |c_A|^2 \frac{|F|^2}{M^2}$
At large $\tan\beta$ Z mass comes from cancellation
$m_Z^2 \approx 2(m_{H_u}^2 + |\mu|^2)$
This leads to a tree-level tuning in the potential
equivalent to just having A=0 and heavy scalars.
Generic to calculable origin of aligned A-terms. The MSSM with
scale SUSY breaking is hard-pressed to accommodate 125

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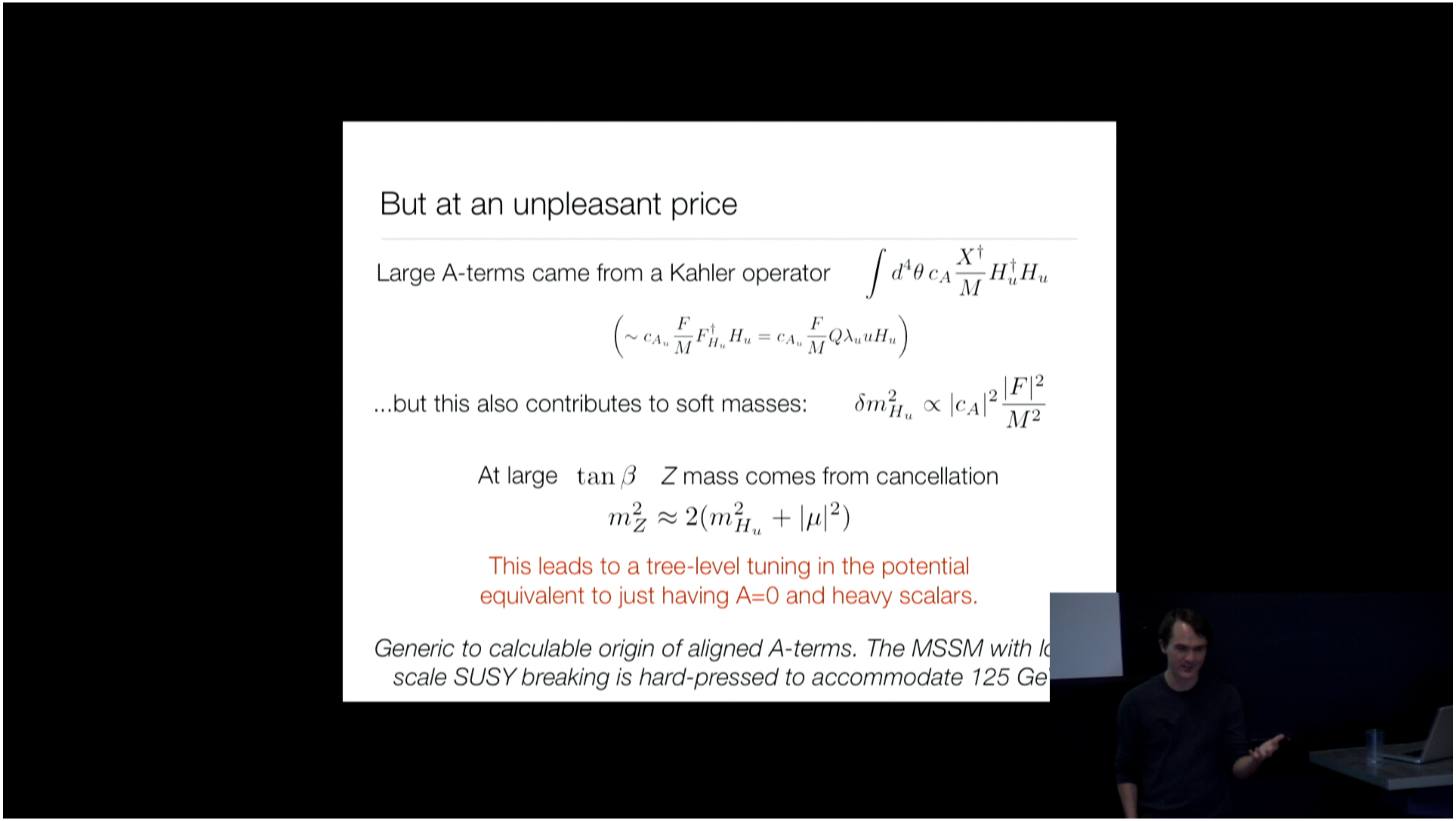
Generic to calculable origin of aligned A-terms. The MSSM with lo scale SUSY breaking is hard-pressed to accommodate 125 Ge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Alex Azatov, Spencer Chang, NC, Jamison Galloway (arXiv:1206.1058)

New physics in Higgs couplings

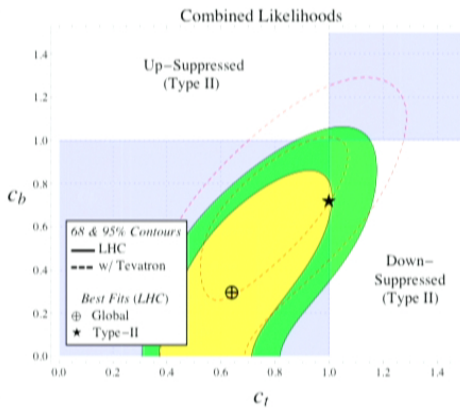
What about couplings? Are they SM-like?

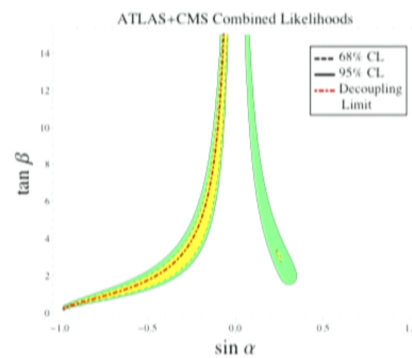
Many ways to approach this question (collaborations increasingly doing it for us)

One interesting avenue: focus on fermion couplings

$$a \equiv \frac{g_{hVV}}{g_{hVV}^{\rm SM}} = \sin(\beta - \alpha),$$

$$c_t \equiv \frac{g_{htt}}{g_{htt}^{\rm SM}} = \frac{\cos\alpha}{\sin\beta}, \quad c_b \equiv \frac{g_{hbb}}{g_{hbb}^{\rm SM}} = -\frac{\sin\alpha}{\cos\beta},$$





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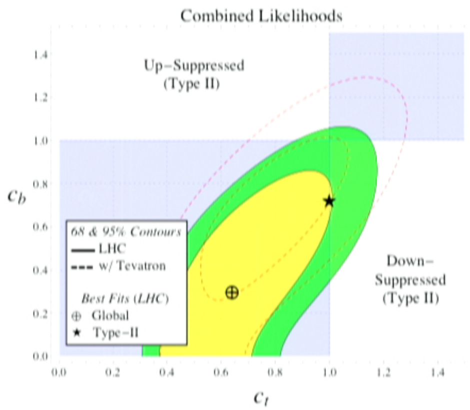

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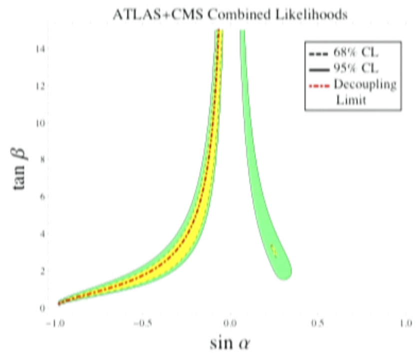
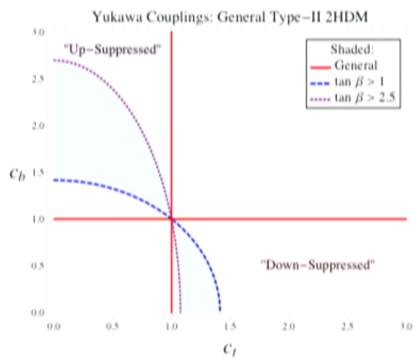


Coupling implications for the MSSM

The preference for down-suppression has interesting implications for the MSSM



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Focus on tree-level potential:

$$\begin{aligned}\Delta V \;=\; & \lambda_1 \left|H_u^0\right|^4 + \lambda_2 \left|H_d^0\right|^4 - 2\lambda_3 \left|H_u^0\right|^2 \left|H_d^0\right|^2 \\ & + \Big[\lambda_4 \left|H_u^0\right|^2 H_u^0 H_d^0 + \lambda_5 \left|H_d^0\right|^2 H_u^0 H_d^0 \\ & + \lambda_6 (H_u^0 H_d^0)^2 + \text{c.c.}\Big]\end{aligned}$$

For $\tan\beta \gtrsim 3$ need

$$\lambda_1 + \lambda_3 - \frac{\lambda_4}{2}\tan\beta \lesssim 0$$

$$\lambda_1 = \lambda_2 = \lambda_3 = \frac{1}{8}(g^2 + g'^2)$$
$$\lambda_4 = \lambda_5 = \lambda_6 = 0.$$

MSSM tree-level

The tree-level potential is unpromising

Loops typically don't help

Dominant correction to quartics from the top/stop

$$\delta\lambda_1 = \frac{3y_t^4}{16\pi^2}(\bar{A}_t{}^2 - \bar{A}_t{}^4/12) \quad \leftrightarrow \quad \text{typically} > 0$$

$$\delta\lambda_3 = \frac{3y_t^4\bar{\mu}^2}{64\pi^2}(\bar{A}_t{}^2 - 2) \quad \leftrightarrow \quad > 0 \text{ at max mixing}$$

$$\delta\lambda_4 = \frac{y_t^4\bar{\mu}}{32\pi^2}(\bar{A}_t{}^3 - 6\bar{A}_t) \quad \leftrightarrow \quad \sim 0 \text{ at max mixing}$$

($\bar{\mu} = \mu/m_{\tilde{t}}$ and $\bar{A}_t = A_t/m_{\tilde{t}}$)

Loop corrections go the wrong way at maximal mixing.
Better prospects if we are shy of maximal mixing.

If these coupling preferences hold up, favors either a non-MSSM potential or light new physics in loops.

Looking for new physics with multi-leptons

- We can learn much by studying the Higgs directly, but we can also pursue the complementary strategy of producing new physics associated with the Higgs.
- This includes looking for the Higgs in association with additional tagging information (leptons, MET, HT, etc.) and looking for direct production/decays of new states in the EWSB sector.
- Quite likely that these new states have (at least) electroweak quantum numbers. So a good place to look is in leptonic final states. There may or may not be significant MET or hadronic energy, so it's useful to cast as wide a net as possible.
- It helps that the CMS multi-lepton search is produced down the hall at Rutger

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CMS-SUS-11-013
CMS-SUS-12-006

CMS Multi-leptons: a theorist's dream study

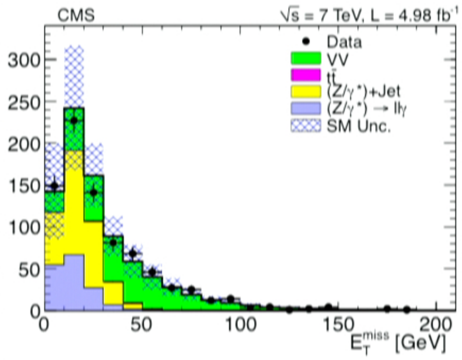
Every channel is a signal channel (data-driven backgrounds inferred from dilepton sample)

Selection	$N(\tau)=0$ obs	$N(\tau)=0$ expect	$N(\tau)=1$ obs	$N(\tau)=1$ expect	$N(\tau)=2$ obs	$N(\tau)=2$ expect
4ℓ Lepton Results						
4ℓ >50,>200, no Z	0	0.018 ± 0.005	0	0.09 ± 0.06	0	0.7 ± 0.7
4ℓ >50,> 200, Z	0	0.22 ± 0.05	0	0.27 ± 0.11	0	0.8 ± 1.2
4ℓ >50,<200, no Z	1	0.20 ± 0.07	3	0.59 ± 0.17	1	1.5 ± 0.6
4ℓ >50,<200, Z	1	0.79 ± 0.21	4	2.3 ± 0.7	0	1.1 ± 0.7
4ℓ <50,>200, no Z	0	0.006 ± 0.001	0	0.14 ± 0.08	0	0.25 ± 0.07
4ℓ <50,>200, Z	1	0.83 ± 0.33	0	0.55 ± 0.21	0	1.14 ± 0.42
4ℓ <50,<200, no Z	1	2.6 ± 1.1	5	3.9 ± 1.2	17	10.6 ± 3.2
4ℓ <50,<200, Z	33	37 ± 15	20	17.0 ± 5.2	62	43 ± 16
3ℓ Lepton Results						
3ℓ >50,>200,no-OSSF	2	1.5 ± 0.5	33	30.4 ± 9.7	15	13.5 ± 2.6
3ℓ >50,<200,no-OSSF	7	6.6 ± 2.3	159	143 ± 37	82	106 ± 16
3ℓ <50,>200,no-OSSF	1	1.2 ± 0.7	16	16.9 ± 4.5	18	31.9 ± 4.8
3ℓ <50,<200,no-OSSF	14	11.7 ± 3.6	446	356 ± 55	1006	1026 ± 171
3ℓ >50,>200, no Z	8	5.0 ± 1.3	16	31.7 ± 9.6	–	–
3ℓ >50,>200, Z	20	18.9 ± 6.4	13	24.4 ± 5.1	–	–
3ℓ >50,<200, no Z	30	27.0 ± 7.6	114	107 ± 27	–	–
3ℓ <50,>200, no Z	11	4.5 ± 1.5	45	51.9 ± 6.2	–	–
3ℓ >50,<200, Z	141	134 ± 50	107	114 ± 16	–	–
3ℓ <50,>200, Z	15	19.2 ± 4.8	166	244 ± 24	–	–
3ℓ <50,<200, no Z	123	144 ± 36	3721	2907 ± 412	–	–
3ℓ <50,<200, Z	657	764 ± 183	17857	15519 ± 2421	–	–
Total 4ℓ	37	42 ± 15	32.0	24.9 ± 5.4	80	59 ± 16
Total 3ℓ	1029	1138 ± 193	22693	19545 ± 2457	1121	1177 ± 172
Total	1066	1180 ± 194	22725	19570 ± 2457	1201	1236 ± 173

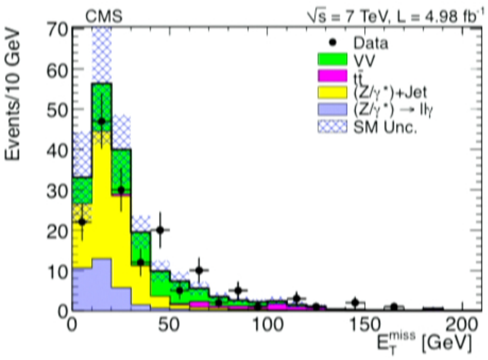
Power of the search arises from the exclusive combination of all channels; sensitive to correlated signals arising in multiple channels

Particularly useful for nonresonant electroweak production/decay of new physics.

Multi-leptons and MET



3L HT LOW; 0 tau; Z+no Z

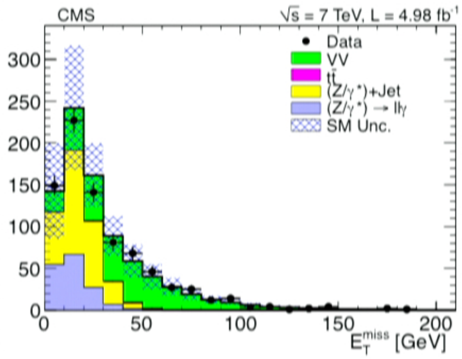


3L HT LOW; 0 tau; no Z

Added sensitivity from looking off Z; both high and low MET regions have sensitivity

Can factorize off-Z events further by whether or not there are OSSF pairs

Multi-leptons and MET



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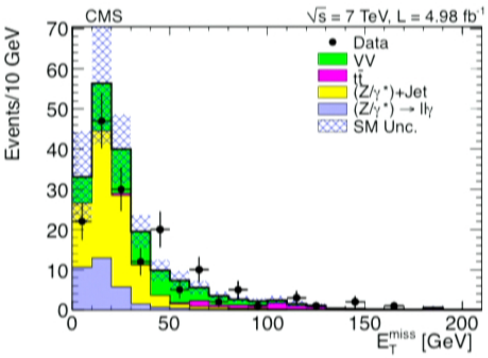

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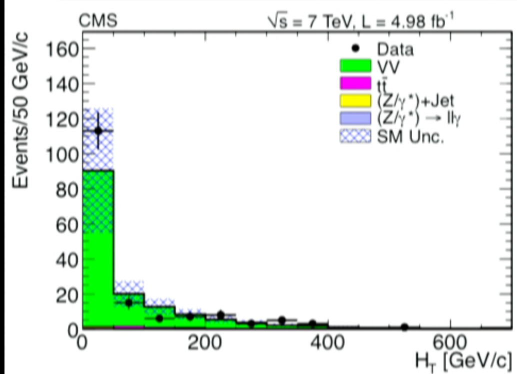
Multi-leptons and HT



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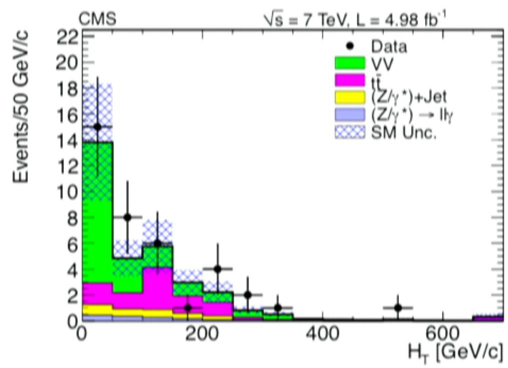
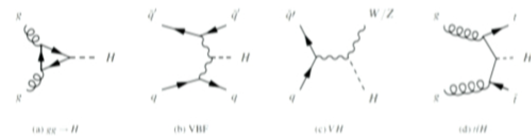


3L MET LOW; 0 tau; no Z

Added sensitivity from looking off Z; both high and low HT regions have sensitivity

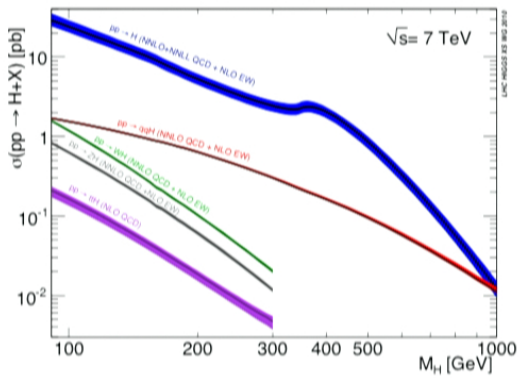
*Future data should have b-tags as well

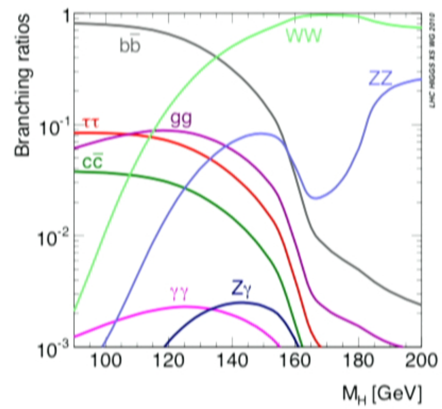
Multi-lepton signals of the Higgs



Why not look for the Higgs?

Leptonic decays of associated products plus leptonic decays of the Higgs lead to various multilepton final states





Looking for the Higgs in rare decays

			Observed	Expected	Signal
4 Leptons					
MET HIGH	HT HIGH	No Z	0	0.018 ± 0.005	0.02
MET HIGH	HT HIGH	Z	0	0.22 ± 0.05	0.0
MET HIGH	HT LOW	No Z	1	0.2 ± 0.07	0.11
MET HIGH	HT LOW	Z	1	0.79 ± 0.21	0.04
MET LOW	HT HIGH	No Z	0	0.006 ± 0001	0.0
MET LOW	HT HIGH	Z	1	0.83 ± 0.33	0.04
MET LOW	HT LOW	No Z	1	2.6 ± 1.1	0.08
MET LOW	HT LOW	Z	33	37 ± 15	0.15
3 Leptons					
MET HIGH	HT HIGH	DY0	2	1.5 ± 0.5	0.48
MET HIGH	HT LOW	DY0	7	6.6 ± 2.3	2.1
MET LOW	HT HIGH	DY0	1	1.2 ± 0.7	0.26
MET LOW	HT LOW	DY0	14	11.7 ± 3.6	1.68
MET HIGH	HT HIGH	DY1 No Z	8	5 ± 1.3	1.54
MET HIGH	HT HIGH	DY1 Z	20	18.9 ± 6.4	0.41
MET HIGH	HT LOW	DY1 No Z	30	27 ± 7.6	5.8
MET HIGH	HT LOW	DY1 Z	141	134 ± 50	2.0
MET LOW	HT HIGH	DY1 No Z	11	4.5 ± 1.5	0.80
MET LOW	HT HIGH	DY1 Z	15	19.2 ± 4.8	0.72
MET LOW	HT LOW	DY1 No Z	123	144 ± 36	3.1
MET LOW	HT LOW	DY1 Z	657	764 ± 183	2.4

Signal for 1% Br

Expect

$$\mathrm{Br}(t \to ch) < 1.7\%$$

Observe

$$\mathrm{Br}(t \to ch) < 2.7\%$$

Corresponds to

$$\sqrt{|\lambda^h_{tc}|^2 + |\lambda^h_{ct}|^2} < 0.31$$

Best limit on these couplings.

Can improve significantly with b-tags, top tagging

NC, Jared Evans, Richard Gray, Can Kilic, Michael Park, Sunil Somalwar, Scott Thomas (arXiv:1210.0559)

Looking for extended EWSB in multi-leptons

- What about additional particles in the EWSB sector? For example, additional states in a 2HDM (supersymmetric or otherwise)?

- Can look for these states in the same standard channels as the Higgs, but this may not be fruitful -- rates to those final states may be suppressed or nonexistent. Direct decays to SM states may be in high-background channels.

- One possibility is to instead look for collective, non-resonant signals -- exploit the totality of production and decay modes.

- Multi-lepton search is an ideal approach: sensitive to totality of SM-like Higgs decays to leptonic final states; new scalar decays to leptonic final states; and scalar cascades.

- Straightforward to apply the existing multi-lepton search to 2HDM...

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Looking for extended EWSB in multi-leptons

	2HDM I	2HDM II	2HDM III	2HDM IV
u	H_u	H_u	H_u	H_u
d	H_u	H_d	H_u	H_d
e	H_u	H_d	H_d	H_u

Consider four discrete types w/out tree-level FCNC

Fixes couplings to fermions and vectors in terms of two angles

y_{2HDM}/y_{SM}	2HDM I	2HDM II	2HDM III	2HDM IV
hVV	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
hQu	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
hQd	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
hLe	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$
HVV	$\cos(\beta-\alpha)$	$\cos(\beta-\alpha)$	$\cos(\beta-\alpha)$	$\cos(\beta-\alpha)$
HQu	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$
HQd	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$
HLe	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$
AVV	0	0	0	0
AQu	$\cot\beta$	$\cot\beta$	$\cot\beta$	$\cot\beta$
AQd	$-\cot\beta$	$\tan\beta$	$-\cot\beta$	$\tan\beta$
ALe	$-\cot\beta$	$\tan\beta$	$\tan\beta$	$-\cot\beta$

	SM (GeV)	Spectrum 1 (GeV)	Spectrum 2 (GeV)	Spectrum 3 (GeV)	Spectrum 4 (GeV)
h	125	125	125	125	125
H	–	300	140	500	200
A	–	500	250	230	80
$H^\pm$	–	500	250	230	250

Consider a few benchmark spectra to exemplify certain topologies

For simplicity, impose PQ symmetry; fixes scalar widths in terms of masses and angles.

$$V_{\rm scalar} = m_u^2 H_u^\dagger H_u + m_d^2 H_d^\dagger H_d + \frac{1}{2}\lambda_1 (H_u^\dagger H_u)^2 + \frac{1}{2}\lambda_2 (H_d^\dagger H_d)^2 + \lambda_3 (H_u^\dagger H_u)(H_d^\dagger H_d) + \lambda_4 (H_u^\dagger H_d)(H_d^\dagger H_u) + \left[\frac{1}{2}\lambda_5 (H_u^\dagger H_d)^2 + {\rm h.c.}\right]$$

Looking for extended EWSB in multi-leptons

Production	Decay
$gg \to h$	$h \to 4\ell$
$\mathrm{VBF} \to h$	$h \to 4\ell$
$gg \to H$	$H \to 4\ell$
	$H \to hh \to 4W, WW\tau\tau, 4\tau, ZZbb, ZZWW, 4Z, ZZ\tau\tau$
	$H \to AA \to 4\tau$
	$H \to AA \to \tau\tau Zh \to \tau\tau ZWW, \tau\tau Z\tau\tau, \tau\tau Zbb, \tau\tau ZZZ$
	$H \to AA \to ZhZh \to ZZWWWW, ZZWW\tau\tau, ZZWWbb, ZZ\tau\tau bb, ZZ\tau\tau\tau\tau$
	$H \to AA \to ZhZh \to ZZbbbb, ZZZZbb, ZZZZ\tau\tau, ZZZZWW, 6Z$
	$H \to H^+H^- \to WhWh \to WWWWWW, WWWW\tau\tau, WWWWbb, WW\tau\tau\tau\tau$
	$H \to H^+H^- \to WhWh \to WW\tau\tau bb, WWZZbb, WWWWZZ, WWZZZZ, WWZZ\tau\tau$
	$H \to H^+H^- \to \tau\nu Wh \to \tau\nu WWW, \tau\nu W\tau\tau, \tau\nu WZZ$
	$H \to H^+H^- \to tbWh \to tbWWW, tbW\tau\tau, tbWZZ$
	$H \to ZA \to Z\tau\tau$
	$H \to ZA \to ZZh \to ZZ\tau\tau, ZZWW, ZZbb, ZZZZ$
	$H \to WH^\pm \to WWh \to WW\tau\tau, WWWW, WWZZ$
$\mathrm{VBF} \to H$	$H \to 4\ell$
	$H \to hh \to 4W, WW\tau\tau, 4\tau, ZZbb, ZZWW, 4Z, ZZ\tau\tau$
	$H \to AA \to 4\tau$
	$H \to AA \to \tau\tau Zh \to \tau\tau ZWW, \tau\tau Z\tau\tau, \tau\tau Zbb, \tau\tau ZZZ$
	$H \to AA \to ZhZh \to ZZWWWW, ZZWW\tau\tau, ZZWWbb, ZZ\tau\tau bb, ZZ\tau\tau\tau\tau$
	$H \to AA \to ZhZh \to ZZbbbb, ZZZZbb, ZZZZ\tau\tau, ZZZZWW, 6Z$
	$H \to H^+H^- \to WhWh \to WWWWWW, WWWW\tau\tau, WWWWbb, WW\tau\tau\tau\tau$
	$H \to H^+H^- \to WhWh \to WW\tau\tau bb, WWZZbb, WWWWZZ, WWZZZZ, WWZZ\tau\tau$
	$H \to H^+H^- \to \tau\nu Wh \to \tau\nu WWW, \tau\nu W\tau\tau, \tau\nu WZZ$
	$H \to H^+H^- \to tbWh \to tbWWW, tbW\tau\tau, tbWZZ$
	$H \to ZA \to Z\tau\tau$
	$H \to ZA \to ZZh \to ZZ\tau\tau, ZZWW, ZZbb, ZZZZ$
	$H \to WH^\pm \to WWh \to WW\tau\tau, WWWW, WWZZ$
$gg \to A$	$A \to Zh \to ZWW, Z\tau\tau, ZZZ$
$qq \to Wh$	$Wh \to WWWW, W\tau\tau$
$qq \to Zh$	$Zh \to ZWW, Z\tau\tau$
tth	$tth \to ttWW, tt\tau\tau$
ttA	$ttA \to tt\tau\tau$
	$ttA \to ttZh \to ttZWW, ttZ\tau\tau, ttZbb, ttZZZ$
$tbH^\pm$	$tbH \to tbWh \to tbWWW, tbW\tau\tau, tbWZZ$

105 channels!

Many possible multi-lepton channels for each benchmark. Would be prohibitive to simulate inclusively as a function of the mixing angles. Instead factorize into topologies, compute acceptance for each topology, then re-weight analytically using functional dependence of cross section and branching ratios.

$$h/A/H^\pm/H : 125/230/230/500 \text{ GeV}$$

$$\sigma \cdot \mathrm{Br} \cdot \mathcal{A}(pp \to f) = \sum_t \sigma(pp \to t)\mathcal{A}(pp \to t \to f) \prod_a \mathrm{Br}_a(t \to f)$$

Looking for extended EWSB in multi-leptons

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	$H \to AA \to \tau\tau Zh \to \tau\tau ZWW, \tau\tau Z\tau\tau, \tau\tau Zbb, \tau\tau ZZZ$
	$H \to AA \to ZhZh \to ZZWWWW, ZZWW\tau\tau, ZZWWbb, ZZ\tau\tau bb, ZZ\tau\tau\tau\tau$
	$H \to AA \to ZhZh \to ZZbbbb, ZZZZbb, ZZZZ\tau\tau, ZZZZWW, 6Z$
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	$H \to ZA \to Z\tau\tau$
	$H \to ZA \to ZZh \to ZZ\tau\tau, ZZWW, ZZbb, ZZZZ$
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$gg \to A$	$A \to Zh \to ZWW, Z\tau\tau, ZZZ$
$qq \to Wh$	$Wh \to WWW, W\tau\tau$
$qq \to Zh$	$Zh \to ZWW, Z\tau\tau$
tth	$tth \to ttWW, tt\tau\tau$
ttA	$ttA \to tt\tau\tau$
	$ttA \to ttZh \to ttZWW, ttZ\tau\tau, ttZbb, ttZZZ$
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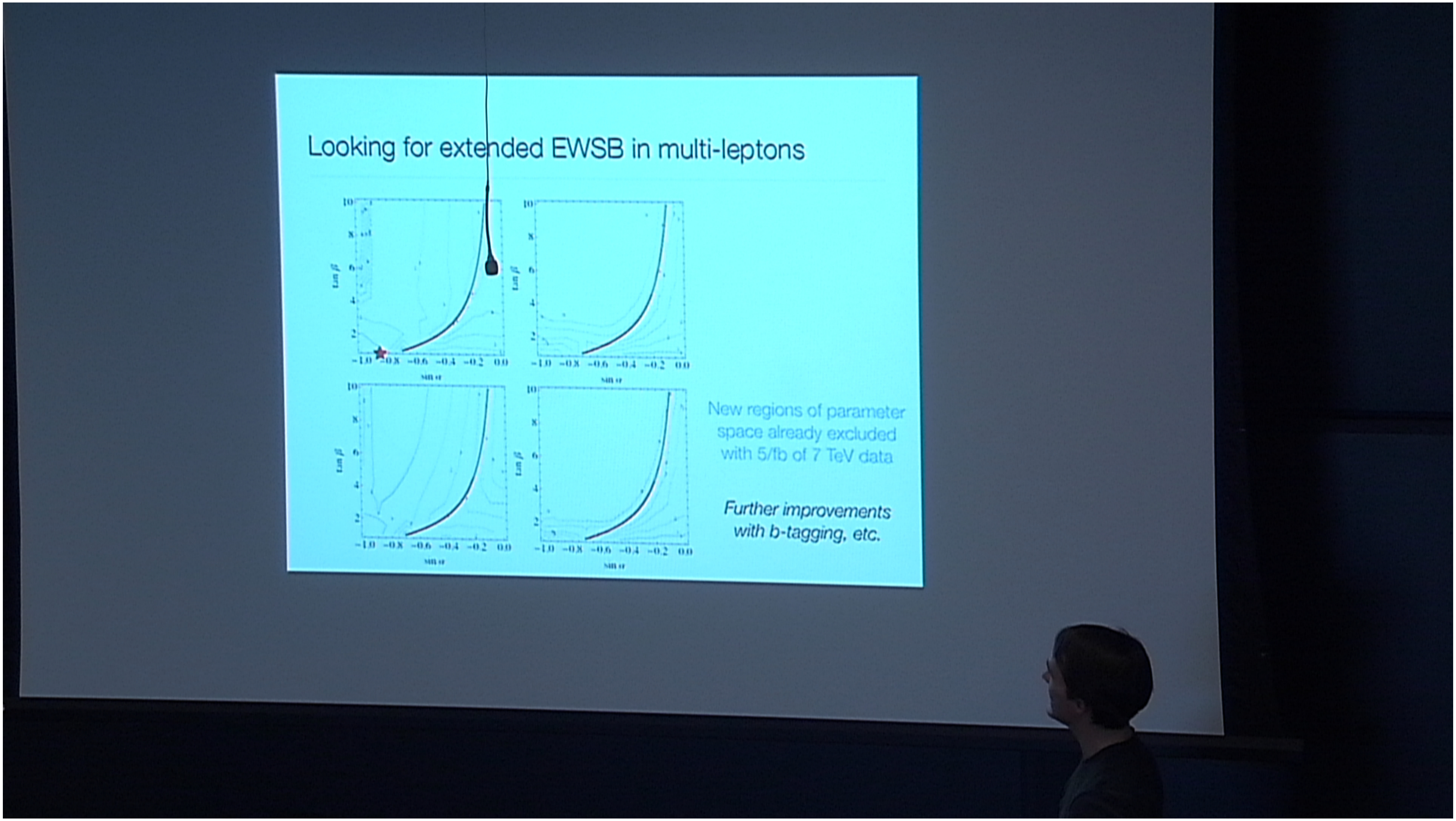
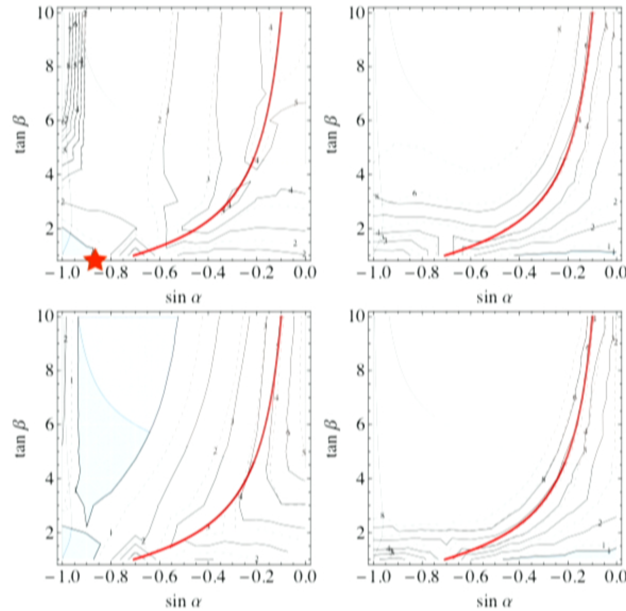

Looking for extended EWSB in multi-leptons
tan β
sin α
New regions of parameter space already excluded with 5/fb of 7 TeV data
Further improvements with b-tagging, etc.

Looking for extended EWSB in multi-leptons



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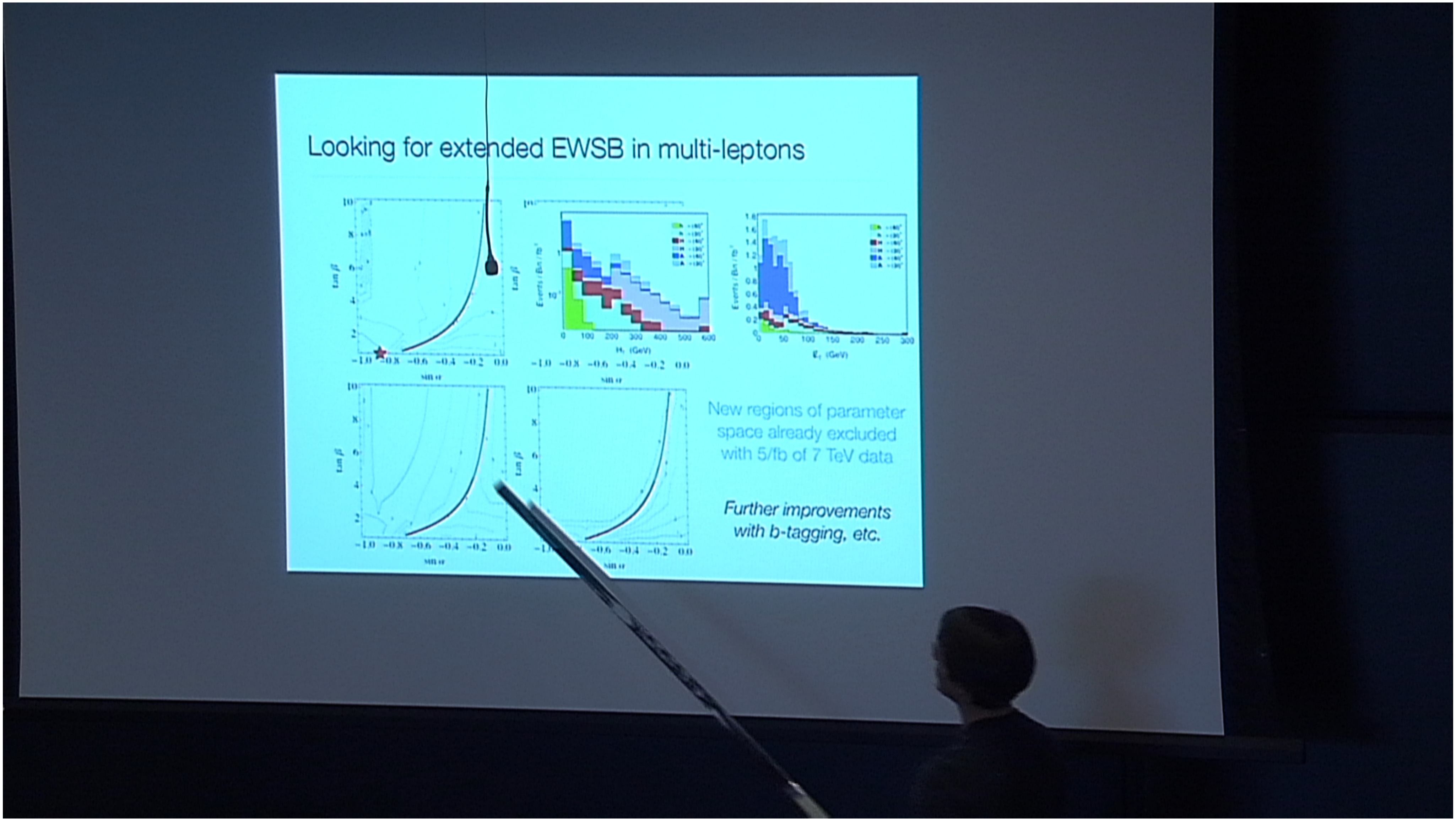
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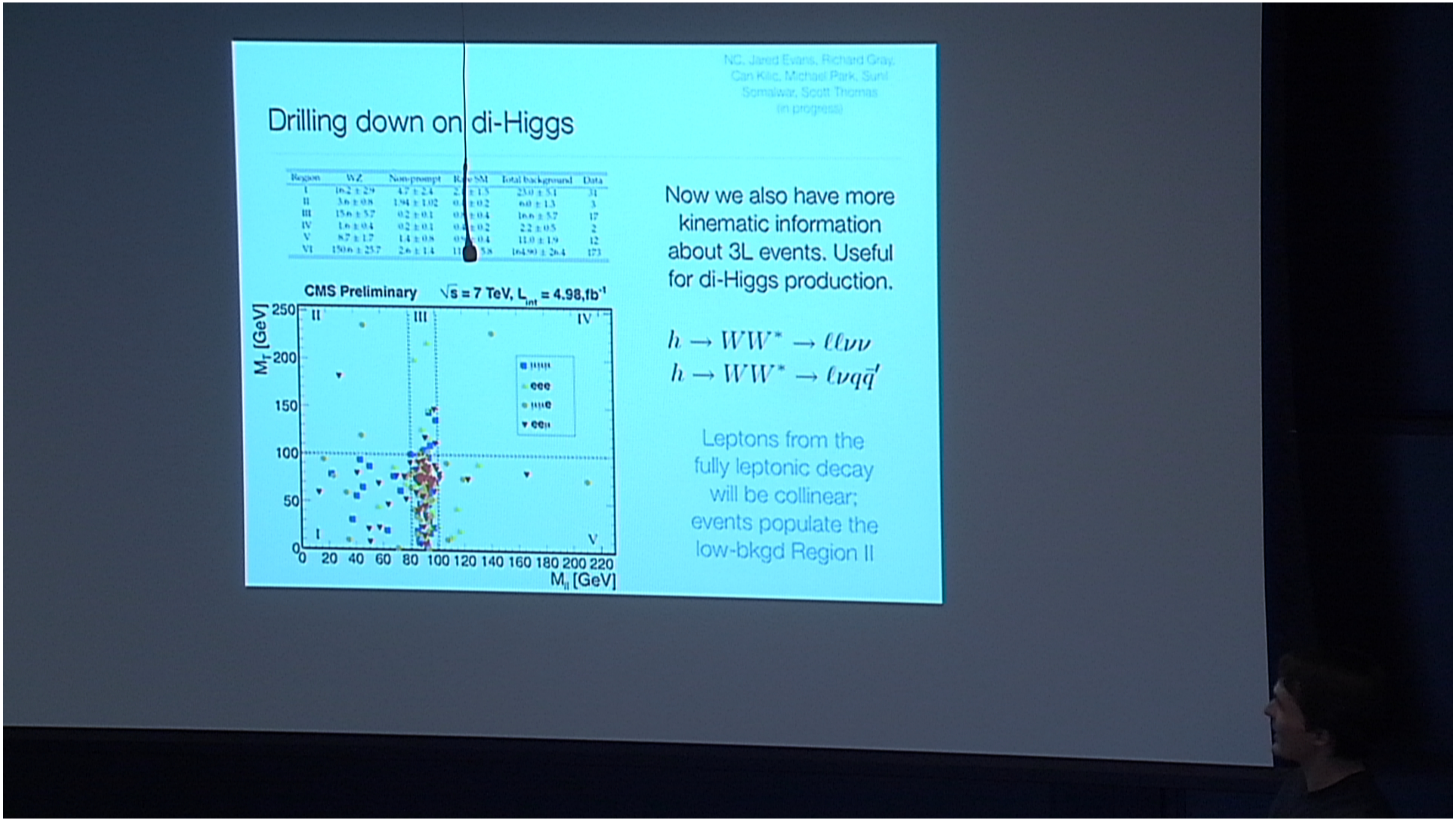
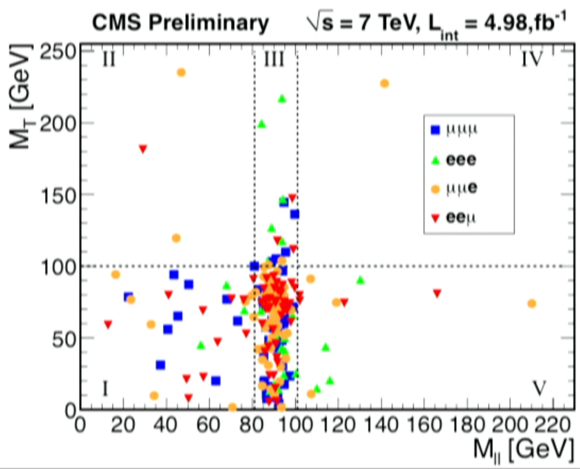

NC, Jared Evans, Richard Gray, Can Kilic, Michael Park, Sunil Somalwar, Scott Thomas (in progress)
Drilling down on di-Higgs
CMS Preliminary √s = 7 TeV, L_int = 4.98,fb⁻¹
M_T [GeV]
M_ll [GeV]
I
II
III
IV
V
eee
Now we also have more kinematic information about 3L events. Useful for di-Higgs production.
h → WW* → ℓℓνν
h → WW* → ℓνqq̄′
Leptons from the fully leptonic decay will be collinear; events populate the low-bkgd Region II

NC, Jared Evans, Richard Gray,
Can Kilic, Michael Park, Sunil
Somalwar, Scott Thomas
(in progress)

Drilling down on di-Higgs

Region	WZ	Non-prompt	Rare SM	Total background	Data
I	16.2 ± 2.9	4.7 ± 2.4	2.1 ± 1.5	23.0 ± 5.1	31
II	3.6 ± 0.8	1.94 ± 1.02	0.4 ± 0.2	6.0 ± 1.3	3
III	15.6 ± 5.7	0.2 ± 0.1	0.8 ± 0.4	16.6 ± 5.7	17
IV	1.6 ± 0.4	0.2 ± 0.1	0.4 ± 0.2	2.2 ± 0.5	2
V	8.7 ± 1.7	1.4 ± 0.8	0.9 ± 0.4	11.0 ± 1.9	12
VI	150.6 ± 25.7	2.6 ± 1.4	11.7 ± 5.8	164.90 ± 26.4	173



Now we also have more kinematic information about 3L events. Useful for di-Higgs production.

$$h \to WW^* \to \ell\ell\nu\nu$$
$$h \to WW^* \to \ell\nu q\bar{q}'$$

Leptons from the fully leptonic decay will be collinear; events populate the low-bkgd Region II

NC, Scott Thomas (in progress)

Precision physics through the Higgs

Can write NP in terms of effective operators involving the Higgs...

$\frac{\xi_T}{M^2}(H^\dagger D_\mu H)(H^\dagger D^\mu H)$ $\leftrightarrow$ one-to-one with T parameter

$\frac{g_1 g_2 \xi_{S_{12}}}{M^2} H^\dagger W_{\mu\nu} H\, B^{\mu\nu}$ $\leftrightarrow$ one-to-one with S parameter

$\frac{g_1^2 \xi_{S_{11}}}{2M^2} H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$

$\frac{g_2^2 \xi_{S_{22}}}{2M^2} H^\dagger H\, W_{\mu\nu} W^{\mu\nu}$

New information from Higgs!

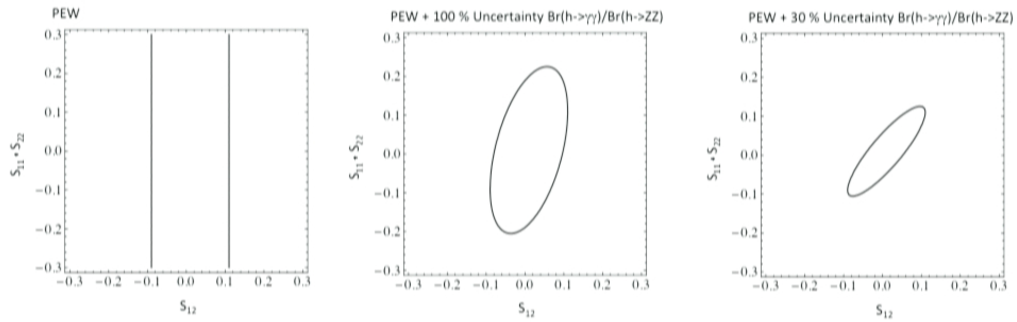
$$\mathrm{Br}(h \to \gamma\gamma) \propto S_{11} + S_{22} - S_{12}$$

Isolate this by measuring inclusive ratios to find

$$\frac{\mathrm{Br}(h \to \gamma\gamma)}{\mathrm{Br}(h \to ZZ)} \simeq \left.\frac{\mathrm{Br}(h \to \gamma\gamma)}{\mathrm{Br}(h \to ZZ)}\right|_{\mathrm{SM}} \left[1 + \mathcal{O}\left(\frac{4\pi v^2}{\alpha}\frac{\xi}{M^2}\right)\right]$$

Sensitive because the leading SM contribution starts at one loop

A new precision ellipse



Systematics: m_t, $\log(m_h)$, α_s

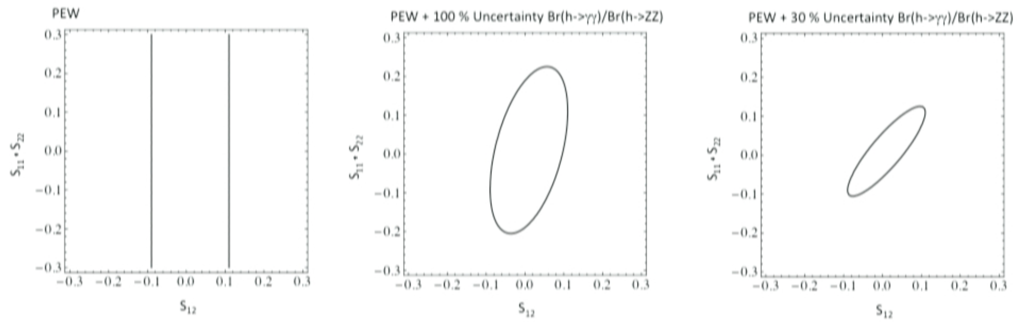
Systematics: statistics, resonance-continuum interference

S = 0.01 +- 0.10

T = 0.03 +- 0.11

Also can get orthogonal information from $Z\gamma$

A new precision ellipse



Systematics: m_t, $\log(m_h)$, α_s

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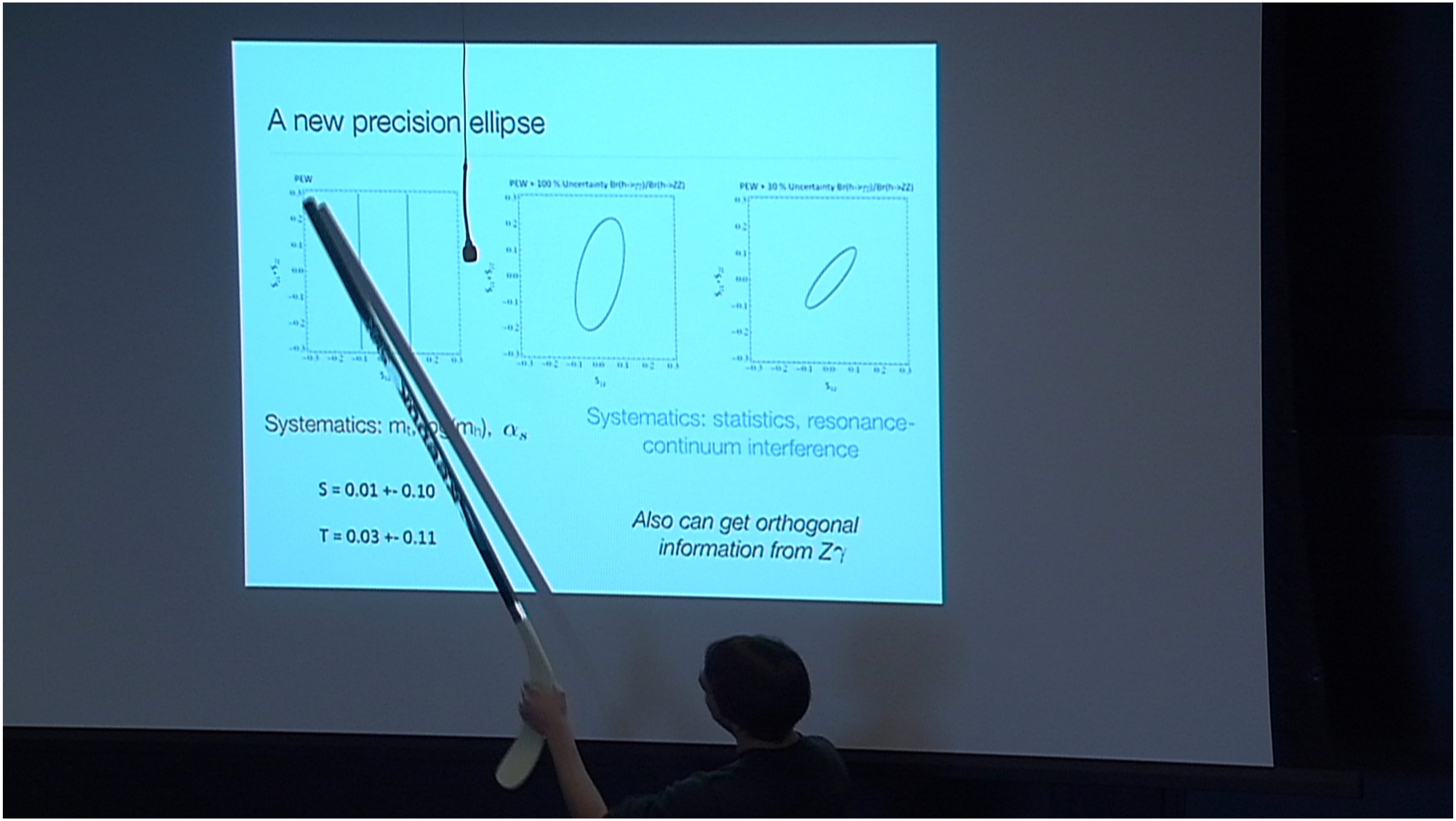
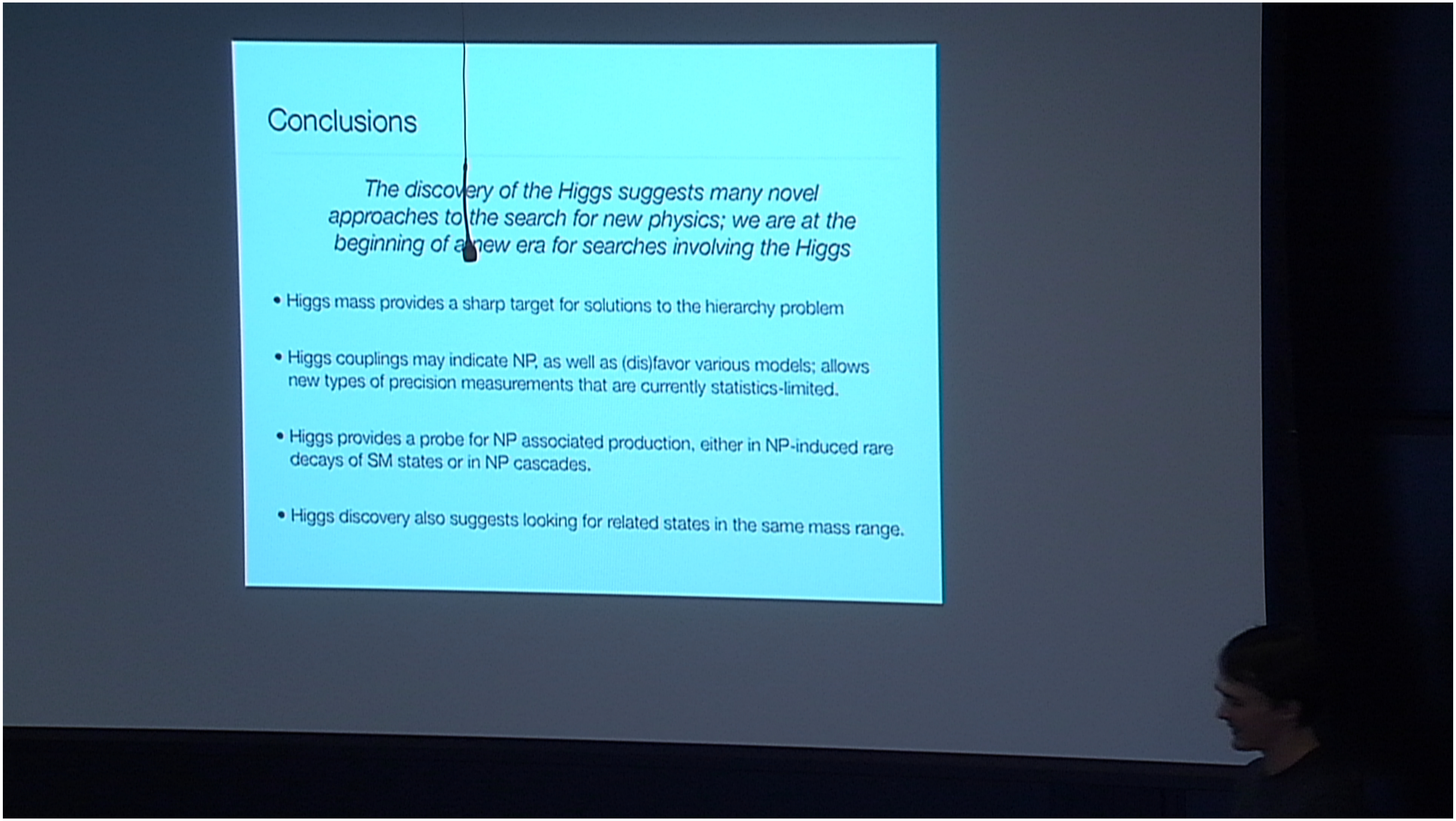

A new precision ellipse
PEW
PEW + 100 % Uncertainty Br(h->γγ)/Br(h->ZZ)
PEW + 30 % Uncertainty Br(h->γγ)/Br(h->ZZ)
Systematics: statistics, resonance-continuum interference
S = 0.01 +- 0.10
T = 0.03 +- 0.11
Also can get orthogonal information from Zγ

Conclusions

The discovery of the Higgs suggests many novel approaches to the search for new physics; we are at the beginning of a new era for searches involving the Higgs

- Higgs mass provides a sharp target for solutions to the hierarchy problem
- Higgs couplings may indicate NP, as well as (dis)favor various models; allows new types of precision measurements that are currently statistics-limited.
- Higgs provides a probe for NP associated production, either in NP-induced rare decays of SM states or in NP cascades.
- Higgs discovery also suggests looking for related states in the same mass range.


Conclusions
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