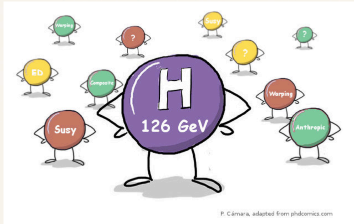
Making the most of the Higgs



Joseph Lykken
Fermilab

Outline

- The challenge of Higgs precision measurements
- Why m_H = 126 GeV? Why not 125.9?
- The Higgs Golden Channel mass extraction
- The importance of using all the information in the final state
- Optimizing parameter extraction in the Golden Channel

Collaborators:
Yi Chen, Emanuele DiMarco, Maria Spiropulu, Roberto Vega-Morales

The Challenge of Higgs Precision Measurements

- Most (!) of us are hoping that the 126 GeV Higgs boson is not “just” the Higgs boson of the Standard Model
- The most direct way to demonstrate this is an LHC discovery of some other new particles
- These particles may be produced directly, in which case their quantum numbers and masses may already allow to compute their effects on Higgs properties, e.g. light staus or stops affect (at one loop) Higgs couplings to diphotons or digluons
- This is probably the best-case scenario in terms of matching relatively straightforward capabilities of the LHC to an extended sector of new Higgs-related physics

The Challenge of Higgs Precision Measurements

- Likely to be more challenging are extended Higgs sectors with extra heavy electroweak doublet, triplet, and singlet scalars that couple directly to, and may mix with, the 126 GeV Higgs.
- These other Higgses may be difficult to observe directly because
  - they are heavy
  - they have suppressed couplings
  - their main decay modes have large SM backgrounds
  - they are almost mass-degenerate with the 126 GeV Higgs (!)
- Some of these particles might also occur in Higgs decay, e.g. Higgs decay to pairs of dark matter particles, but this will be hard to pin down

The Challenge of Higgs Precision Measurements

- A lot of work is going into defining a comprehensive program to observe the 126 GeV Higgs in as many different decay and production modes as possible, and compare this data to, e.g. a general d=6 Higgs Lagrangian
- Part of the hope here is that future LHC running will produce some reasonably large (and therefore believable) discrepancy with SM Higgs expectations
- This is a good hope and an important program
- Another good hope is that somebody will build a new e+e- collider, greatly improving both the precision and robustness of our ability to characterize Higgs properties

See talks at this workshop by Chiara Mariotti, Adam Falkowski, José-Ramón Espinosa, and Christophe Grojean

Higgs Factories?

- However Nature has already decreed that we will never have a “Higgs Factory” in the same sense that LEP was a Z Factory

- Roughly speaking we can get our hands on about 10 to 100K Higgs events in the cleaner channels that have the smallest systematics

collider	energy	$\int \mathcal{L}dt$ (fb^{-1})	production	σ (fb)	decay	$\sigma \times \mathcal{B}$ (fb)	N_{prod}	N_{reco}	f_{jet}
pp	14 TeV	3000	$gg \to H$	49850	$H \to ZZ^* \to 4\ell$	6.23	18694	5608	0.1
pp	14 TeV	3000	$V^*V^* \to H$	4180	$H \to ZZ^* \to 4\ell$	0.52	1568	470	0.6
pp	14 TeV	3000	$W^* \to WH$	1504	$H \to ZZ^* \to 4\ell$	0.19	564	169	0.5
pp	14 TeV	3000	$Z^* \to ZH$	883	$H \to ZZ^* \to 4\ell$	0.11	331	99	0.5
pp	14 TeV	3000	$t\bar{t} \to t\bar{t}H$	611	$H \to ZZ^* \to 4\ell$	0.08	229	69	1.0
pp	14 TeV	3000	$V^*V^* \to H$	4180	$H \to \gamma\gamma$	9.53	28591	8577	0.6
pp	14 TeV	3000	$Z^* \to ZH$	883	$H \to b\bar{b}$, $Z \to \ell\ell$	34.3	102891	690	–
e^+e^-	250 GeV	250	$Z^* \to ZH$	240	$H \to b\bar{b}$, $Z \to \ell\ell$	9.35	2337	1870	–
e^+e^-	350 GeV	350	$Z^* \to ZH$	129	$H \to b\bar{b}$, $Z \to \ell\ell$	5.03	1760	1408	–
e^+e^-	500 GeV	500	$Z^* \to ZH$	57	$H \to b\bar{b}$, $Z \to \ell\ell$	2.22	1110	888	–
e^+e^-	1 TeV	1000	$Z^* \to ZH$	13	$H \to b\bar{b}$, $Z \to \ell\ell$	0.51	505	404	–
e^+e^-	250 GeV	250	$Z^*Z^* \to H$	0.7	$H \to b\bar{b}$	0.4	108	86	–
e^+e^-	350 GeV	350	$Z^*Z^* \to H$	3	$H \to b\bar{b}$	1.7	587	470	–
e^+e^-	500 GeV	500	$Z^*Z^* \to H$	7	$H \to b\bar{b}$	4.1	2059	1647	–
e^+e^-	1 TeV	1000	$Z^*Z^* \to H$	21	$H \to b\bar{b}$	12.2	12244	9795	–

I. Anderson, S. Bolognesi, F. Caola, Y. Gao, A. Gritsan, C. Martin,
K. Melnikov, M. Schulze, N. Tran, A. Whitbeck, Y. Zhou, arXiv:1309.4819

Why m_H = 126 GeV? Why not 125.9?

- At this workshop we have seen that achieving the maximum precision on the extracted Higgs mass may be one of the most important things that we do with future data
- Looking at how this is done in current data, and how we might improve it in the future, is also a good way of seeing how we might get the most out of the future data for other important Higgs properties
- As you might imagine, the basic idea is to exploit all of the information that you have in channels with the smallest systematics

Why m_H = 126 GeV? Why not 125.9?

The mass

Collaboration	channel	mass (GeV)
ATLAS	$\gamma\gamma$	$126.8 \pm 0.2 \pm 0.7$
CMS	$\gamma\gamma$	$125.4 \pm 0.5 \pm 0.6$
ATLAS	4ℓ	$124.3^{+0.6+0.5}_{-0.5-0.3}$
CMS	4ℓ	$125.8 \pm 0.5 \pm 0.2$
ATLAS	combination	$125.5 \pm 0.2^{+0.5}_{-0.6}$
CMS	combination	$125.7 \pm 0.3 \pm 0.3$

$H \rightarrow ZZ \rightarrow 4l$:

Very small systematics due the very good control of the leptons scale and resolution.
In CMS: Mass estimation with m_{4l}, KD and $\sigma(m_{4l})$.

$H \rightarrow \gamma\gamma$:

Systematics on the extrapolation from the $Z \rightarrow ee$ to $H \rightarrow \gamma\gamma$
(0.25% from e to γ, 0.4% from Z to H)

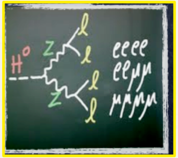
Chiara Mariotti 32

The CMS 4-lepton “Golden Channel” mass extraction is the best: why?

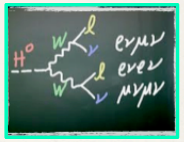
leptonic final states at the LHC

- Higgs decays into purely leptonic (e or mu) final states are **much** better measured at LHC than decays involving jets or hadronic taus

$\mathbf{h \to ZZ^* \to 4\ell}$



$\mathbf{h \to WW^* \to 2\ell + 2\nu}$



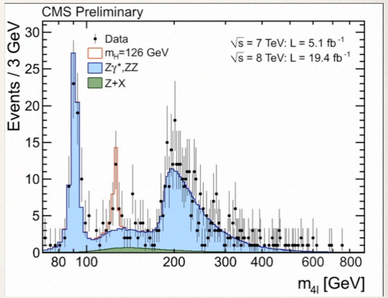
- Higgs decays to diphotons and leptons + photons are also special, but still cannot compete with the purely leptonic modes on systematics

$\mathbf{h \to \gamma\gamma}$ $\mathbf{h \to Z\gamma \to 2\ell + \gamma}$

the Higgs Golden Channel

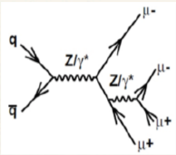
- It has been known since the dawn of the Standard Model that the rare decay mode $\mathbf{h} \to \mathbf{4}\ell$ is both the cleanest decay and the one containing the most information in the final state

- It was an unimpeachable discovery channel, especially at 126 GeV where the SM background is both small and flat:



the Higgs Golden Channel

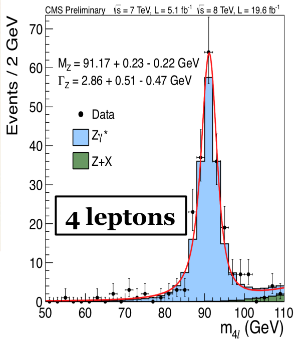
- At CMS electrons and muons are measured with exquisite precision, leading to a small systematic on observables such as the reconstructed 4-lepton invariant mass
- Don't believe it? Look at the extracted mass of the Z boson from its rare 4-lepton decays!
- Compare to PDG value MZ = 91.188 +- 0.002



momentum scale:

0.1% for muons

0.2% for electrons of 35<pT<50 up to 1.5% at low pT

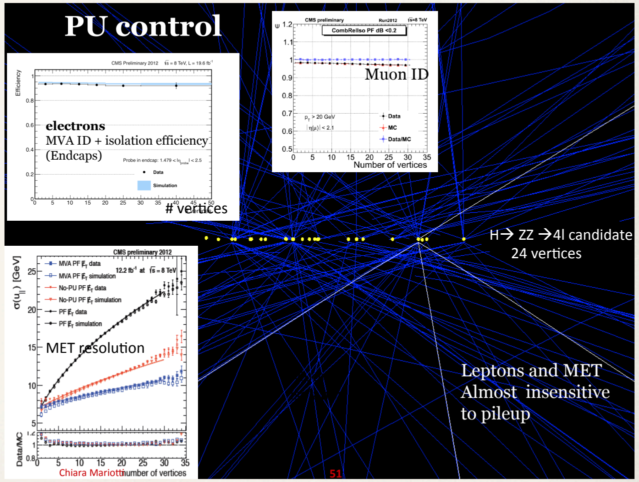


Lepton resolution= 1 - 2%
uncertainty: 20%

Talk by Chiara Mariotti

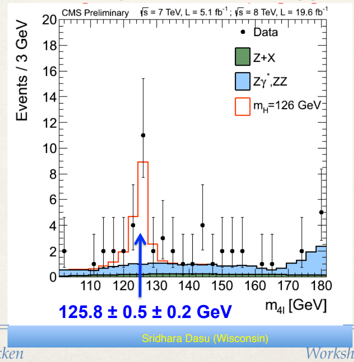
Validated in situ with Z(4l)

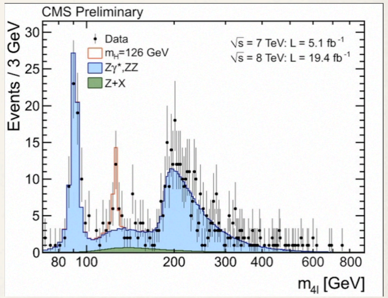
- If you show the soft tracks and zoom in, even the Golden Channel looks like a mess
- But (so far!) this doesn't matter
- If we spend enough money on HL-LHC upgrades, it also won't matter in the future



"Its the Systematics, Stupid"

- The CMS Higgs mass from diphotons is already systematics limited
- The CMS Higgs peak in 4 leptons currently has an estimated systematic of only 200 MeV, and is statistics limited
- In fact the CMS 4-lepton Higgs peak is only 20-30 events, depending on how tight you make the selections
- So how can you extract the Higgs mass to 0.5% accuracy?





Using more information

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H →ZZ→4l:
Very small systematics due the very good control of the leptons scale and resolution.
In CMS: Mass estimation with m_{4l}, KD and $\sigma(m_{4l})$.

H →γγ:
Systematics on the extrapolation from the Z→ee to H→γγ
(0.25% from e to γ, 0.4% from Z to H)

Chiara Mariotti 32

- **This** is an event-by-event estimate of the mass error from the lepton track fits and (for electrons) the ECAL measurements

Using more information

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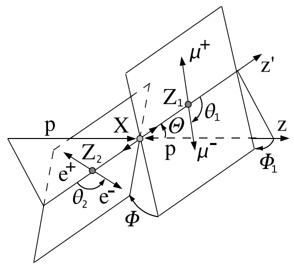
Chiara Mariotti 32

- **This** is a 1D kinematic discriminant based on how signal-like is each event

Higgs Golden Channel kinematics

- Ignoring production there are 8 observables in CM frame per event

$\mathbf{M_{4\ell}, M_{Z_1}, M_{Z_2}}$, $\Theta, \theta_1, \theta_2, \Phi_1, \Phi)$ (N. Cabibbo, A. Maksymowicz, Phys. Rev. 137 (1968))



(Y. Chen, N. Tran, RVM: 1211.1959)

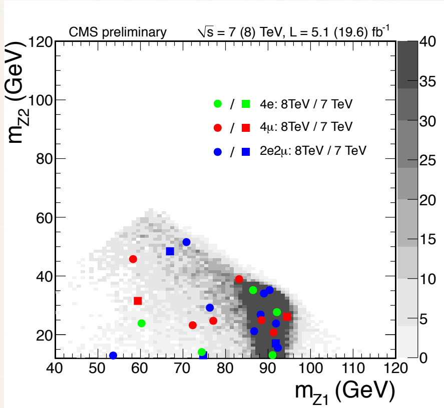
- All angles defined in 4ℓ CM frame (or X in case of signal)
- Correlations between lepton angles studied for some time

J.F. Gunion, Z. Kunszt (1986); Matsurra, J.J. Van Der Bij (1991), + many others

Slide from Roberto Vega-Morales

Higgs Golden Channel kinematics

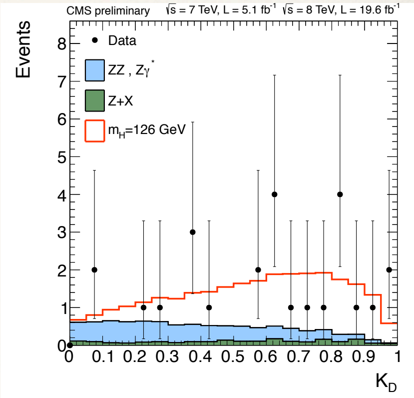
- For a 126 GeV Higgs, one of the Z's in the decay is always badly off shell, and the other one can be pretty off shell too
- Also about 1% of the time the signal event is actually from Higgs decays to 4 leptons through $\mathbf{Z}\gamma$ or $\gamma\gamma$, not $\mathbf{Z}\mathbf{Z}$
- The two "Z" masses reconstructed event by event are important discriminators
- This was not noticed until recently!



See A. De Rujula, JL, M. Pierini, C. Rogan, M. Spiropulu, arXiv:1001.5300

What can we do with ALL of the decay information?

- The 0.5% CMS mass measurement uses a 3D fit, where all 8D of the kinematics is processed into a 1D discriminator K_D
- But in principle you could do a 9D fit, using ALL of the (decay) kinematic information
- Of course this presupposes that what you have is in fact a SM Higgs...



What can we do with ALL of the decay information?

Objectives

- Build an analysis framework to fully utilize the power of the golden channel in a model independent manner which takes into account detector effects and systematic uncertainties
- Set up a likelihood analysis based on the analytic fully differential cross sections in order to perform (multi-) parameter extraction of the various scalar-tensor couplings including any correlations
- Construct a continuous detector level likelihood as a function of underlying lagrangian parameters
- Utilizing all 8 possible decay observables in minimal computing time
- Directly extract the Higgs couplings (ratios of couplings) to neutral electroweak gauge bosons in the golden channel final state

Scalar Signal Parametrization

- Parametrize scalar couplings to vector boson pairs as the following,

$$\Gamma^{\mu\nu}_{ij}(k,k') = \frac{1}{v}\left(A_{1ij} m_Z^2 g^{\mu\nu} + A_{2ij}\left(k^\nu k'^\mu - k\cdot k' g^{\mu\nu}\right) + + A_{3ij}\epsilon^{\mu\nu\alpha\beta}k_\alpha k'_{2\beta}\right)$$

- The A_{nij} in principal complex and $ij = ZZ, Z\gamma, \gamma\gamma$ ($A_{1Z\gamma} = A_{1\gamma\gamma} = 0$)
- k, k' momentum of vector bosons (or lepton pair system)

- Use the general spin 0 tensor structure, parameterized by form factors
- With derivative expansion, need to extract at least 3 or 4 coupling constants each for $\mathbf{ZZ}$, $\mathbf{Z}\gamma$, $\gamma\gamma$, more if you allow phases
- Of course all of the couplings besides $\mathbf{A_{1ZZ}}$ are probably small or tiny
- The whole game is looking for small deviations and trying to establish that they are from new physics

Higgs CP violation?

The relevant (and difficult) CP question about the Higgs

A 0⁺ Higgs can have CP violating couplings

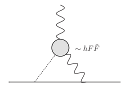
fermionic sector — marginal operators (dim-4) ➤ phase of V_{CKM} matrix
already bounded by flavor physics

bosonic sector — irrelevant operators (dim-6) only
➤ edm's
➤ Higgs signal strengths
➤ Higgs kinematical distribution

Among the 59 irrelevant directions, 3 of them induce ~~CP~~ Higgs couplings in the EW bosonic sector

$$H^\dagger H B_{\mu\nu}\tilde{B}^{\mu\nu} \qquad (D^\mu H)^\dagger \sigma^i (D^\nu H)\tilde{W}^i_{\mu\nu} \qquad (D^\mu H)^\dagger (D^\nu H)\tilde{B}_{\mu\nu}$$

γ operator:
already severely constrained by e and q EDMs
McKeen, Pospelov, Ritz '12



Z operator(s):
studied in the kinematical distributions for h → ZZ → 4l

see the f_{a3} CMS study

Higgs rates?
poor constraints since no interference with SM
effects ≈ dim-8 CP-even operators

need to look for CP-odd observables that are linear in the ~~CP~~ Wilson coeffs

Even here you need to close the circle, since EDM constraints assume 1st gen Higgs couplings that you can't measure

Christophe Grojean — Higgs coupling puzzles — 11 — Madrid, 25th Sept. 2013

Parameter extraction in the Golden Channel

- The signal *pdf* is formed out of fully differential cross section for $h \to V_1 V_2 \to 4\ell$ where $4\ell = 2e2\mu, 4e, 4\mu$ and $V_{1,2} = Z, \gamma$

$$\mathcal{P}_S(m_h^2, M_1, M_2, \vec{\Omega}|\vec{\lambda}) = \frac{d\sigma_{h\to 4\ell}}{dM_1^2 dM_2^2 d\vec{\Omega}}$$

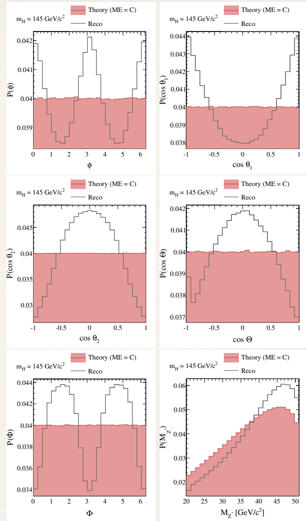
- Can also contain production spectrum for $\vec{p}_T$ and Y **(see next slide)**
- Many possible couplings between Higgs and neutral gauge boson pairs
- We assume only Lorentz invariance between a spin-0 scalar and vector boson pairs and allow for general CP mixtures and phases
- Would like to directly extract as many of the parameters as possible (even if they are zero)

Slide from Roberto Vega-Morales

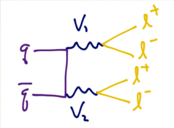
production information?

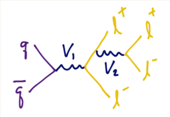
- In principle spin 0 decay information is decoupled from production information
- This is good since the theoretical and experimental uncertainties on production are pretty large
- But the finite phase space acceptance of the detector means you care about the boost to the CM frame, and thus decays know about production
- Fortunately this is a small effect and even smaller if you normalize all the extracted parameters to $\mathbf{A_{1ZZ}}$

See A. De Rujula, JL, M. Pierini, C. Rogan, M. Spiropulu, arXiv:1001.5300



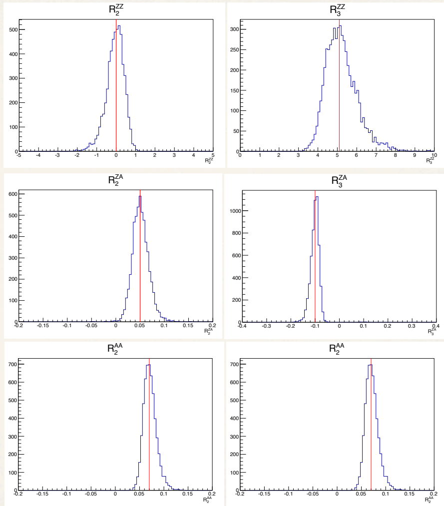
The Hard Parts: backgrounds, systematics





- Want also to include the fully differential decay amplitudes for the non-Higgs SM backgrounds, and the signal-background interferences
- Want to include the detector effects, since the crucial point is to show that you can discriminate a small BSM effect from systematics
- Then make the full 8D (well, 7D for now) likelihood distributions by running pseudoexperiments
- Do not try this at home (unless you have a big cluster...)

Results: 7D likelihoods



Yi Chen, Emanuele DiMarco, JL, Maria Spiropulu, Roberto Vega-Morales, to appear

Results: 7D likelihoods

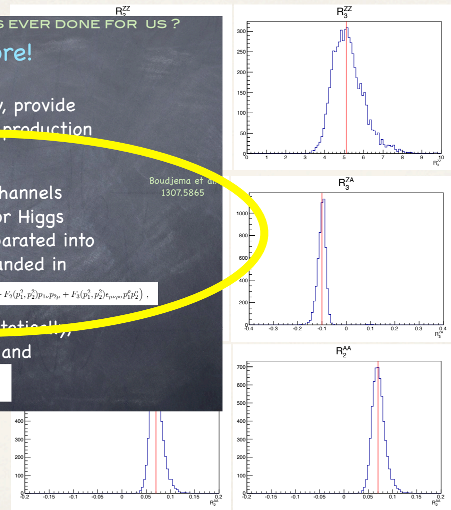
WHAT HAVE THE EXPERIMENTALISTS EVER DONE FOR US ?

!We Want More!

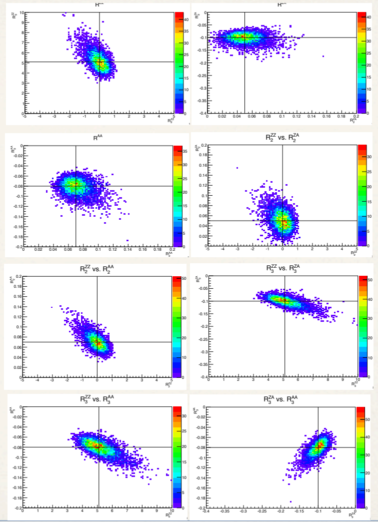
- [6D likelihoods]: For each decay, provide likelihoods separated into all 5 production modes (ggF, VBF, WH, ZH, ttH).
- [Tensor structure]: For decay channels sensitive to tensor structure for Higgs couplings provide likelihood separated into each allowed form factor (expanded in momentum). $\mathcal{A}(H \to V_\mu^1 V_\nu^2) = \frac{1}{v}\left(F_1(p_1^2,p_2^2) 2m_V^2 \eta_{\mu\nu} + F_2(p_1^2,p_2^2) p_{1\nu} p_{2\mu} + F_3(p_1^2,p_2^2) \epsilon_{\mu\nu\rho\sigma} p_1^\rho p_2^\sigma\right)$.
- [Fiducial cross sections]: Asymptotically, publish a set of cross sections and acceptances. $\sigma_i^{\rm fid} = \sum_j A_{ij}^{\rm th} \times \sigma_j^{\rm tot}$,

Boudjema et al 1307.5865

Talk by Adam Falkowski



Results: correlations between extracted values



- Now you can start to investigate issues such as to what extent systematics can fake or hide a particular kind of BSM effect

Yi Chen, Emanuele DiMarco, JL, Maria Spiropulu, Roberto Vega-Morales, to appear

Conclusions

- We have the Higgs. Let's make the most of it
- The Golden Channel is golden. Let's make the most of it
- Even with non-infinite statistics hadron colliders produce precision measurements (e.g. Tevatron surpassed LEP in some cases)
- But you need to work hard to optimize your sensitivity...
- Theorists are useful for this part!