Golden Obsessions: Identifying the Higgs Through the Golden Channel

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Currently with Kunal Kumar, Ian Low, Joe Lykken and Yi Chen, Emanuele DiMarco, Maria Spiropulu, Nhan Tran, Si Xie

Previous work also done with James Gainer, Andre Gritsan, Daniel Stolarski

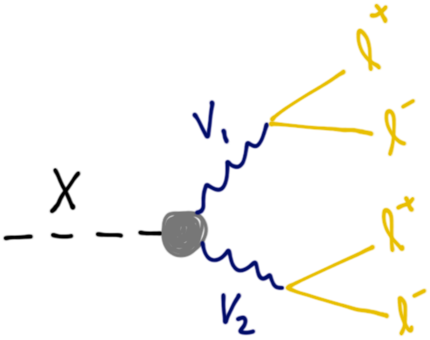
Supported by Fermilab Graduate Student Fellowship

Overview

- What is the Golden Channel?
- Why the Golden Channel?
- Experimental Searches
- Scrutinizing the Golden Channel
- Matrix Element Method
- Ongoing Studies
- Conclusions

What is the Golden Channel?: Signal

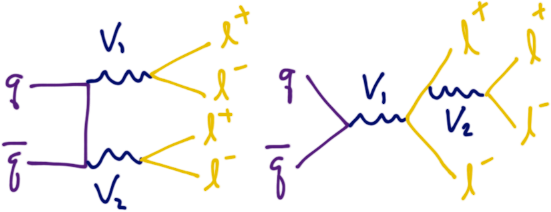
- Signal consists of $\varphi \to V_1 V_2 \to 4\ell$



- X can in principal be spin 0, 1, or 2
- V_1 and V_2 can be any combination of Z and γ
- In principal $\gamma\gamma$, $Z\gamma$, and ZZ all contribute
- Can lead to a myriad of interference effects

What is the Golden Channel?: Background

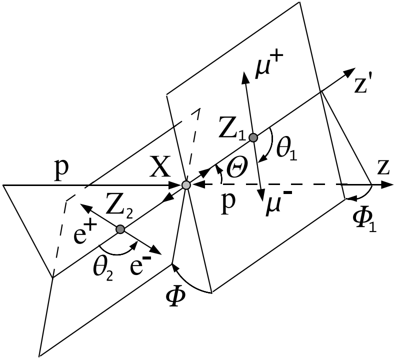
- Background is primarily $q\bar{q} \to 4\ell$
- This includes both the t-channel and s-channel process



- Can also have contribution from fakes
- These are subdominant to the $q\bar{q} \to 4\ell$ process
- We have included both the Z and γ (including interference) contributions in our analytic calculation
- A rich interference structure between various intermediate states as well as between s and t-channel

What is the Golden Channel?: Kinematics

- Ignoring production there are 8 observables per event $(\hat{s}, M_1, M_2, \Theta, \theta_1, \theta_2, \Phi_1, \Phi)$
  (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: Phys. Rev. (1986); Matsurra, J.J. Van Der Bij: Z. Phys. (1991), + many others

Why the Golden Channel?: ‘Practical’ Reasons

- It is very well measured with 1-2% mass resolution at $\sim$ 130 GeV
- Good signal to background ratio and well understood theoretically
- NLO corrections are small and mainly affect production
- Make it conducive to ‘analytic’ methods based on LO calculation
- Can be used to construct likelihoods functions and perform MEM
- Analyzed using an analytic framework in numerous recent studies

Y. Gao, A. V. Gritsan, Z. Guo, K. Melnikov, M. Schulze, et. al: **1001.3396**
A. De Rujula, J. Lykken, M. Pierini, C. Rogan, M. Spiropulu: **1001.5300**
J. Gainer, K. Kumar, I. Low, RVM: **1108.2274**
R. Boughezal, T. J. LeCompte, F. Petriello: **1208.4311**
S. Bolognesi, Y. Gao, A. V. Gritsan, K. Melnikov, M. Schulze, et. al: **1208.4018**
D. Stolarski, RVM: **1208.4840**

- Focused primarily on *ZZ* contribution to golden channel
- Golden Channel also analyzed using Madgraph based framework

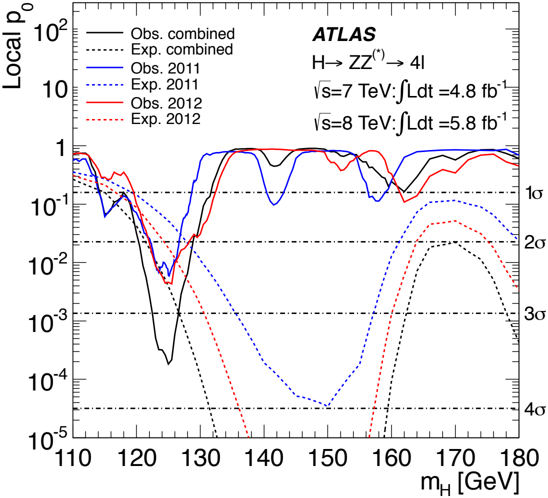
Avery, Bourilkov, Chen, Cheng, Drozdetskiy, et. al: **1210.0896**

Why the Golden Channel?: Physics Reasons

- Can directly test the EWSB mechanism
- Can measure spin of resonance directly
- Rate suppression perhaps make *WW* or $\gamma\gamma$ currently more useful for spin determination, but these channels can not probe CP directly (perhaps VBF$\rightarrow$ $jj\gamma\gamma$ or $WW \rightarrow jj\ell\nu$)
- Golden Channel direct probe of CP properties and can be used to extract phases
- $Z\gamma$ and $\gamma\gamma$ occur through higher dim operators $\Rightarrow$ sensitive to NP
- Eventually high precision studies can be performed

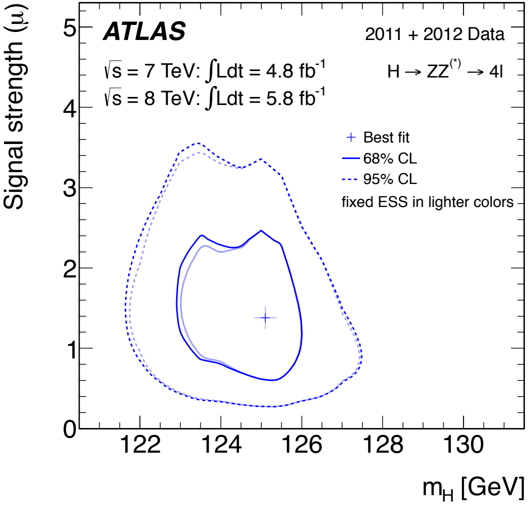
Experimental Searches: ATLAS (A. Morley: HCP)

- ATLAS sees an excess with a local significance of 3.6σ (may change very soon!)



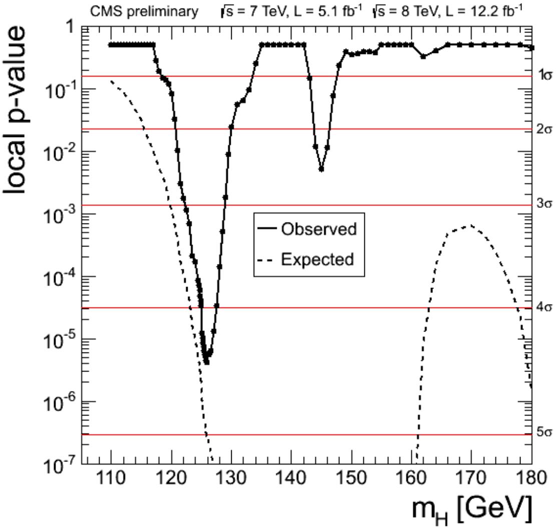
Experimental Searches: ATLAS (A. Morley: HCP)

- At a mass of $\sim$ 125 GeV and signal strength $\sim$ 1.4

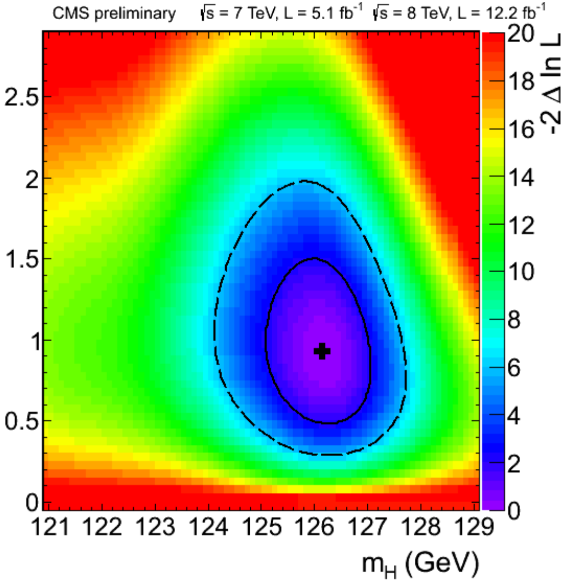


Experimental Searches: CMS (S. Xie: FNAL Seminar)

- CMS observes an excess with 4.5σ significance

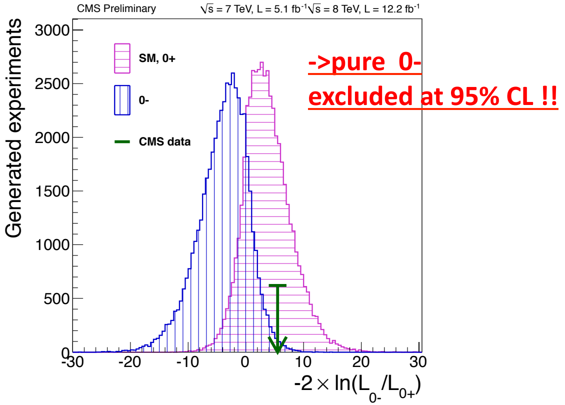


- At a mass of $\sim$ 126 GeV and signal strength $\sim$ .9



Exp. Searches: CMS (S. Bolognesi: FNAL Seminar)

- CMS has also performed a study excluding a pure CP odd scalar



- Does not imply that resonance is pure CP even
- CP odd/even mixtures are more challenging

Model Dependent Parity Studies

- Assuming EW gauge invariance

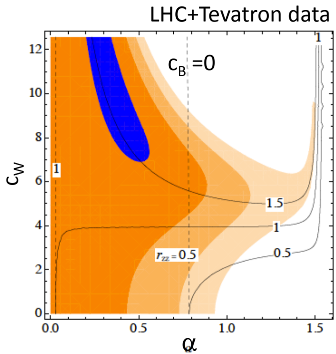
$$\mathcal{L}_{\text{dim5}} = \frac{1}{4}\frac{c_G}{(4\pi)^2 v} A G_{\mu\nu}\widetilde{G}^{\mu\nu} + \frac{1}{4}\frac{c_B}{(4\pi)^2 v} A B_{\mu\nu}\widetilde{B}^{\mu\nu} + \frac{1}{4}\frac{c_W}{(4\pi)^2 v} A W_{\mu\nu}\widetilde{W}^{\mu\nu}$$

- Using ratios of rates show pure CP odd case disfavored

Coleppa, Kumar, Logan: 1208.2692; I. Low, J. Lykken, G. Shaughnessy: 1207.1093

- Ratios can also be used to constrain CP odd/even mixed case

Freitas, Schwaller: 1211.1980

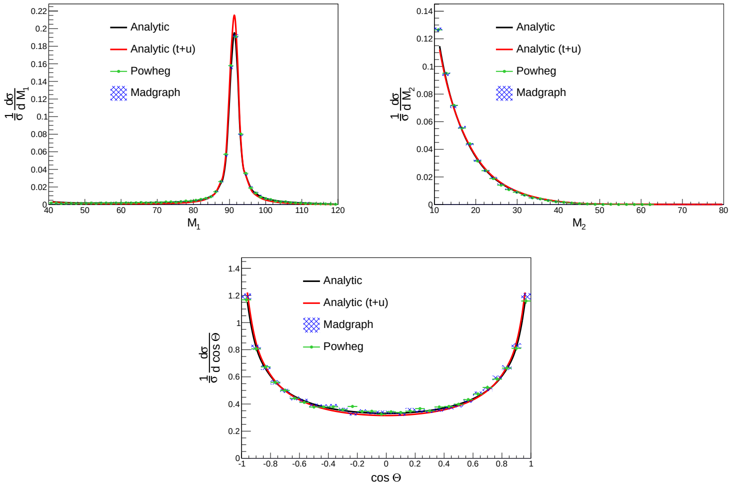


Scrutinizing the Golden Channel: Y. Chen, N. Tran, RVM: 1211.1959

- Would like a model independent approach free of theory bias
- Would also like to perform parameter extraction
- This will require a more detailed understanding of signal and BG
- Need to understand how all the different effects may manifest themselves in the various kinematic distributions
- Must ensure we don't mistake one effect for another
- We have extended previous analytic calculations of signal (scalar) and background to include $Z\gamma$ and $\gamma\gamma$ contributions to the $2e2\mu$ final state including all interference between intermediate states
- These expressions can be used in a variety of ways in MEM analyses of the golden channel

Scrutinizing the Golden Channel: Validation

- We compare our analytic result to POWHEG and Madgraph
- Phase space: 110 GeV $\sqrt{s} < 140$ GeV with 40 GeV$< M_1 <$120 GeV and 10 GeV$< M_2 <$120 GeV



Scrutinizing the Golden Channel: (M_1, M_2) Diff Cxn

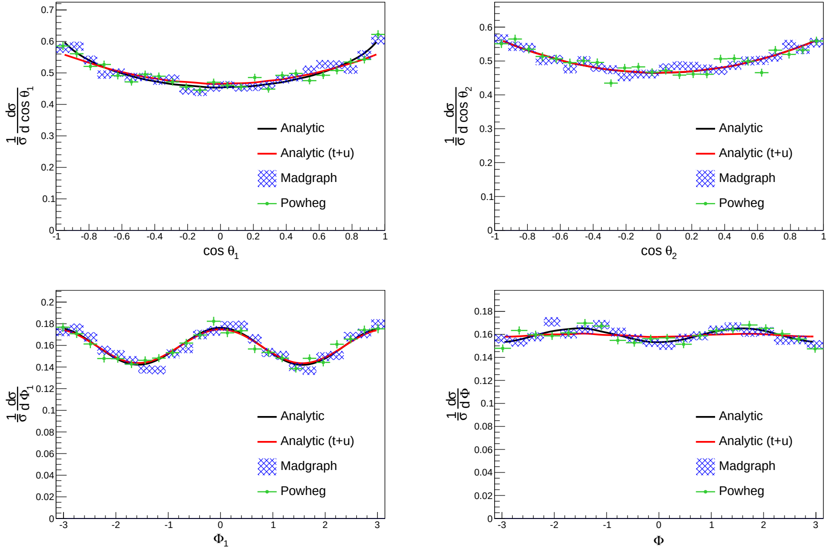
- BG t+u contribution only good approximation for $\hat{s} \gtrsim 110$ GeV

$$
\begin{aligned}
&\frac{d\sigma^{BG}_{t+u}}{dM_1^2 dM_2^2} = \\
&-\Big(((g_{qL}^4 + g_{qR}^4)(g_L^2 + g_R^2)^2 M_1^4 M_2^4 + 2e_l e_q (g_{qL}^3 + g_{qR}^3)(g_L + g_R)(g_L^2 + g_R^2) M_1^2 M_2^2 (2M_1^2 M_2^2 - (M_1^2 + M_2^2) m_z^2) \\
&\quad + 8e_l^4 e_q^4 ((M_1^2 - m_z^2)^2 + m_z^2 \Gamma_z^2)((M_2^2 - m_z^2)^2 + m_z^2 \Gamma_z^2) + 4e_l^3 e_q^3 (g_{qL} + g_{qR})(g_L + g_R)((M_2 - m_z)(M_2 + m_z)(-M_1^2 + m_z^2) \\
&(-2M_1^2 M_2^2 + (M_1^2 + M_2^2) m_z^2) + m_z^2 (M_1^4 + M_2^4 - (M_1^2 + M_2^2) m_z^2) \Gamma_z^2) + 2e_l^2 e_q^2 (g_{qL}^2 + g_{qR}^2)(4 g_L g_R M_1^2 M_2^2 (M_1 - m_z)(M_2 - m_z) \\
&(M_1 + m_z)(M_2 + m_z) + g_L^2 ((-2M_1^2 M_2^2 + (M_1^2 + M_2^2) m_z^2)^2 + (M_1^4 + M_2^4) m_z^2 \Gamma_z^2) + g_R^2 ((-2M_1^2 M_2^2 + (M_1^2 + M_2^2) \\
&m_z^2)^2 + (M_1^4 + M_2^4) m_z^2 \Gamma_z^2))) \Big(4(M_1^2 + M_2^2 - s)\sqrt{M_1^4 + (M_2^2 - s)^2 - 2M_1^2 (M_2^2 + s)} - ((M_1^2 + M_2^2)^2 + s^2) \\
&\Big(\log\Big[\Big(M_1^2 + M_2^2 - s + \sqrt{M_1^4 + (M_2^2 - s)^2 - 2M_1^2 (M_2^2 + s)}\Big)^2\Big] - 2\log\Big[- M_1^2 - M_2^2 + s + \sqrt{M_1^4 + (M_2^2 - s)^2 - 2M_1^2 (M_2^2 + s)}\Big]\Big)\Big)\Big) \\
&/\Big(27648\ M_1^2 M_2^2 \pi^5 (M_1^2 + M_2^2 - s) s^2 ((M_1^2 - m_z^2)^2 + m_z^2 \Gamma_z^2)((M_2^2 - m_z^2)^2 + m_z^2 \Gamma_z^2)\Big)
\end{aligned}
$$

- Can perform simplified, yet powerful studies with only (M_1, M_2) Diff Cxn

Scrutinizing the Golden Channel: Validation

- The lepton decay angles

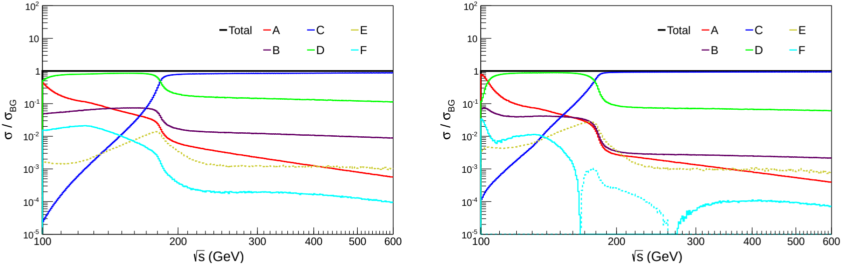


Scrutinizing the Golden Channel: BG Components

- Studies of CP/spin and parameter extraction require detailed understanding of all effects
- The analytic expressions allow us to easily isolate the various components of BG and Signal
- First separate the background into its various components:
  - **A**: s-channel $2e2\mu$ process
  - **B**: $t + u$-channel $\gamma\gamma$
  - **C**: $t + u$-channel ZZ (only contribution calculated previously)
  - **D**: $t + u$-channel $Z\gamma$
  - **E**: $t + u$-channel $ZZ/Z\gamma/\gamma\gamma$ interference only
  - **F**: $ZZ + Z\gamma + \gamma\gamma$ s/t-channel interference only
- The relative fraction of these components depends on $\hat{s}$

Scrutinizing the Golden Channel: Relative Fractions

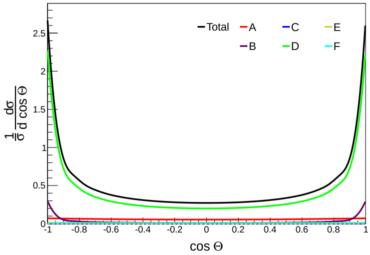
- Left: 4 GeV$< M_{1,2} <$ 120 GeV
- Right: 40 GeV$< M_1 <$ 120 GeV and 10 GeV$< M_2 <$ 120 GeV



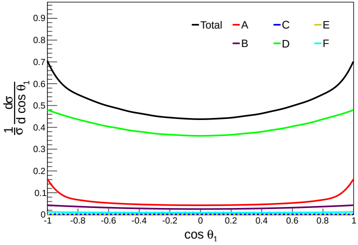
- Note that the relative $\gamma\gamma$ fraction is still small for 'relaxed' cuts
- Of course fakes may begin to cause trouble

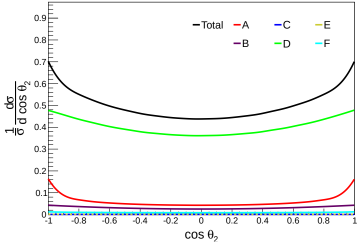
Scrutinizing the Golden Channel: BG Distributions

- The 'production angle' Θ of the vector bosons



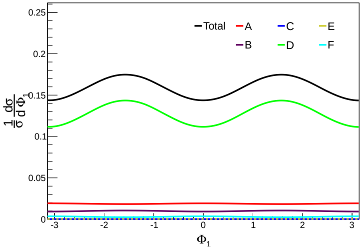
- The polar angles θ_1 and θ_2 of the final state leptons



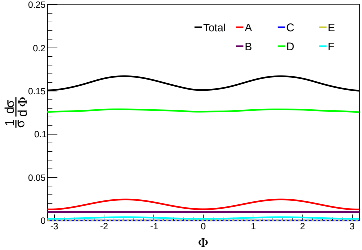


Scrutinizing the Golden Channel: BG Distributions

- Angle Φ_1 between production plane and lepton decay plane



- Angle Φ between decay planes of the final state leptons



Scrutinizing the Golden Channel: Scalar Resonance

- We can parametrize the most general scalar couplings to vector boson pairs as,

$$i\Gamma_{ij}^{\mu\nu} = v^{-1}\Big(A_{1ij}m_Z^2 g^{\mu\nu} + A_{2ij}(k_1 \cdot k_2 g^{\mu\nu} - k_1^\nu k_2^\mu) + A_{3ij}\epsilon_{\mu\nu\alpha\beta}k_1^\alpha k_2^\beta\Big)$$

- These can be derived from the Lagrangian generating the scalar interactions with Z and γ given by,

$$\mathcal{L} \sim \frac{1}{v}\varphi\Big(g_h m_Z^2 Z^\mu Z_\mu + g_Z Z^{\mu\nu} Z_{\mu\nu} + \tilde{g}_Z Z^{\mu\nu}\widetilde{Z}_{\mu\nu} + g_{Z\gamma}F^{\mu\nu}Z_{\mu\nu} + \tilde{g}_{Z\gamma}F^{\mu\nu}\widetilde{Z}_{\mu\nu} + g_\gamma F^{\mu\nu}F_{\mu\nu} + \tilde{g}_\gamma F^{\mu\nu}\widetilde{F}_{\mu\nu} + ...\Big)$$

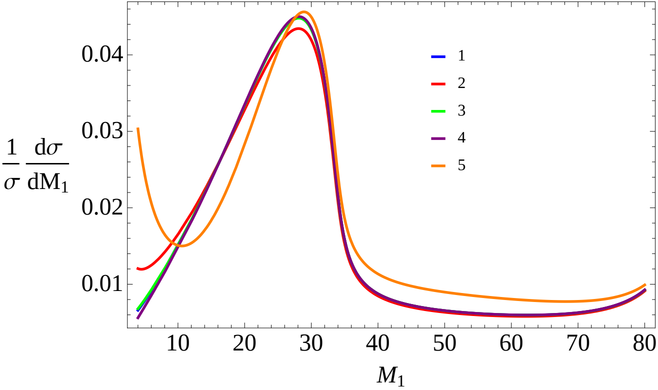
- We include all of these operators in our analytic calculation

Scrutinizing the Golden Channel: Signal Hypotheses

- WIth this parametrization we can examine various hypotheses:
  - **1**: SM including $Z\gamma$ and $\gamma\gamma$
  - **2**: SM coupling to *ZZ* plus enhanced $Z\gamma$ and $\gamma\gamma$
  - **3**: SM coupling to *ZZ* plus CP odd couplings to $\gamma\gamma$ and $Z\gamma$
  - **4**: CP odd/even mixed coupling to *ZZ* only
  - **5**: General CPV Scalar
- By examining the distributions we can get a feel for how much one can discriminate between these cases

Scrutinizing the Golden Channel: Sig Distributions

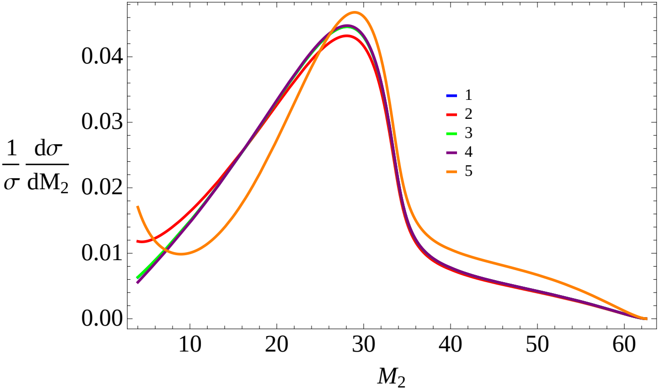
- We can examine the M_1 distribution for the various hypothesis



- We have taken 4 GeV $< M_{1,2} <$ 120 GeV
- We note the rise below $\sim$ 10 GeV for those with large $\gamma\gamma$

Scrutinizing the Golden Channel: Sig Distributions

- We can also examine M_2 after requiring an M_1 window around M_Z



- Slope of M_2 as upper cutoff is approached contains information about CP properties [R. Boughezal, T. LeCompte, Petriello: 1208.4311]
- Should aim to push M_2 reach down to 4 GeV, as done by CMS for $Z \to 4\ell$ process [CMS Collaboration: 1210.3844]

Scrutinizing the Golden Channel: (M_1, M_2) Distribution

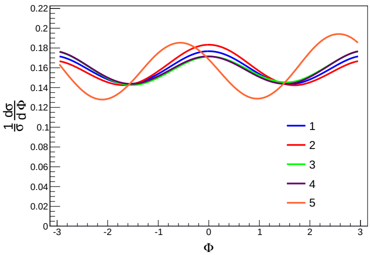
- Can integrate over angles to obtain (M_1, M_2) Diff Cxn

$$
\begin{aligned}
&\frac{d\Gamma_{SM+Z\gamma}}{dM_1^2 dM_2^2} = \\
&v_h^{-2}(\frac{1}{230400\pi^4})(\frac{M_1 M_2}{s})\sqrt{(M_1^4+(M_2^2-s)^2-2M_1^2(M_2^2+s))/s^2}\Big((25A_{1ZZ}^2(g_L^2+g_R^2)^2 M_1 M_2 m_z^4(1+(5+4\beta_1\beta_2-3\beta_2^2 \\
&+\beta_1^2(-3+5\beta_2^2))\gamma_1^2\gamma_2^2))/(((M_1^2-m_z^2)^2+m_z^2\Gamma_z^2)((M_2^2-m_z^2)^2+m_z^2\Gamma_z^2))-(25A_{1ZZ}A_{2Z\gamma}e_l(g_L+g_R)(g_L^2+g_R^2)m_z^2 \\
&(-2M_1^2M_2^2+(M_1^2+M_2^2)m_z^2)(1+\beta_1\beta_2)\gamma_1\gamma_2(3-2(-1+\beta_2^2)\gamma_2^2+(-1+\beta_1^2)\gamma_1^2(-2+5(-1+\beta_2^2)\gamma_2^2))) \\
&/(((M_1^2-m_z^2)^2+m_z^2\Gamma_z^2)((M_2^2-m_z^2)^2+m_z^2\Gamma_z^2))+e_l^2 M_1 M_2\Big(2A_{2Z\gamma}^2+2A_{3Z\gamma}^2-6A_{2Z\gamma}^2(-1+\beta_1^2)\gamma_1^2+7 \\
&(A_{2Z\gamma}-A_{3Z\gamma})(A_{2Z\gamma}+A_{3Z\gamma})(-1+\beta_1^2)^2\gamma_1^4+(-6A_{2Z\gamma}^2(-1+\beta_2^2)+(-3A_{3Z\gamma}^2(7+8\beta_1\beta_2-3\beta_2^2+\beta_1^2 \\
&(-3+7\beta_2^2))+A_{2Z\gamma}^2(43+60\beta_1\beta_2-13\beta_2^2+\beta_1^2(-13+43\beta_2^2)))\gamma_1^2-3(-1+\beta_1^2)(A_{3Z\gamma}^2(2+18\beta_1\beta_2+7\beta_2^2+\beta_1^2 \\
&(7+2\beta_2^2))+A_{2Z\gamma}^2(7+10\beta_1\beta_2-2\beta_2^2+\beta_1^2(-2+7\beta_2^2)))\gamma_1^4)\gamma_2^2+(-1+\beta_2^2)(7(A_{2Z\gamma}-A_{3Z\gamma})(A_{2Z\gamma}+A_{3Z\gamma}) \\
&(-1+\beta_2^2)-3(A_{3Z\gamma}^2(2+18\beta_1\beta_2+7\beta_2^2+\beta_1^2(7+2\beta_2^2))+A_{2Z\gamma}^2(7+10\beta_1\beta_2-2\beta_2^2+\beta_1^2(-2+7\beta_2^2)))\gamma_1^2+(-1+\beta_1^2) \\
&(A_{3Z\gamma}^2(21+116\beta_1\beta_2+37\beta_2^2+\beta_1^2(37+21\beta_2^2))+A_{2Z\gamma}^2(37+80\beta_1\beta_2+3\beta_2^2+\beta_1^2(3+37\beta_2^2)))\gamma_1^4)\gamma_2^4\Big) \\
&\Big(2(g_L+g_R)^2((M_1-m_z)(M_2-m_z)(M_1+m_z)(M_2+m_z)+m_z^2\Gamma_z^2)/(((M_1^2-m_z^2)^2+m_z^2\Gamma_z^2)((M_2^2-m_z^2)^2+m_z^2\Gamma_z^2)) \\
&+(2(g_L^2+g_R^2)M_1^2)/(M_2^2((M_1^2-m_z^2)^2+m_z^2\Gamma_z^2))+(2(g_L^2+g_R^2)M_2^2)/(M_1^2((M_2^2-m_z^2)^2+m_z^2\Gamma_z^2))\Big)\Big)
\end{aligned}
$$

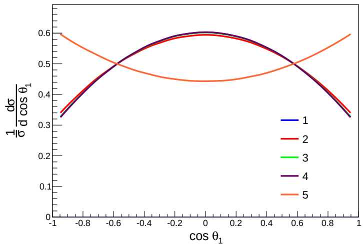
- Along with BG (M_1, M_2) can be used for simplified, but powerful studies

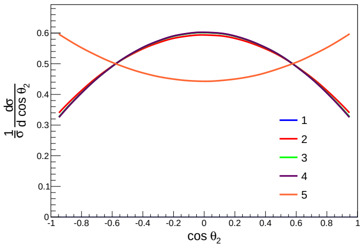
Scrutinizing the Golden Channel: Sig Distributions

- Angle Φ between decay planes of the final state leptons



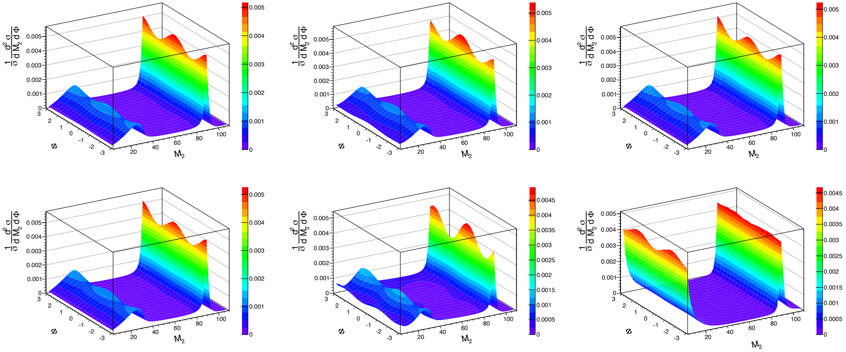
- The polar angles θ_1 and θ_2 of the final state leptons





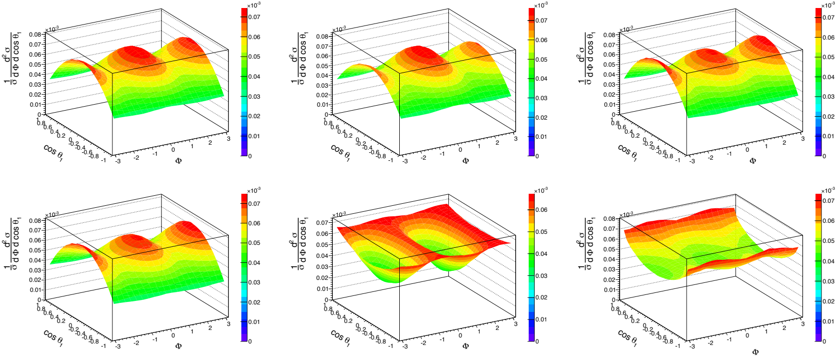
Scrutinizing the Golden Channel: 2D Distributions

- $(M_{1,2}, \Phi)$ doubly differential spectrum



Scrutinizing the Golden Channel: 2D Distributions

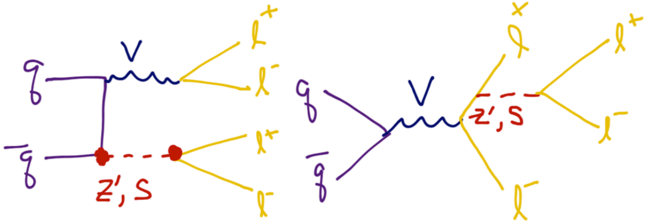
- $(\theta_{1,2}, \Phi)$ doubly differential spectrum



- Working on animations for webpage (soon to be public)

Other New Physics Possibilities

- Of course other resonances may be discovered (hopefully!)
- Can also potentially ‘contaminate’ background

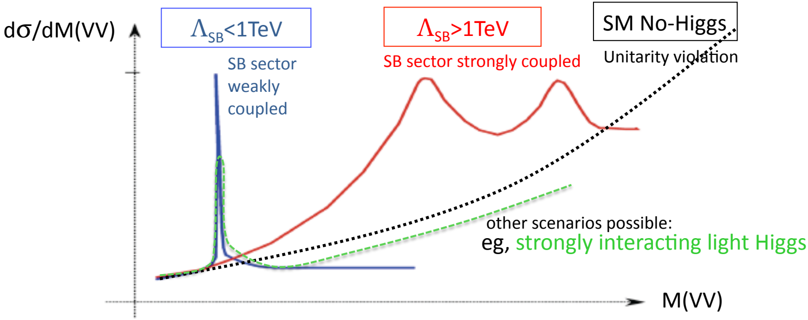


- May show up as subtle effects in distributions
- Currently implementing these into analytic expressions
- Note still possible new particle is spin-1, but its ugly

J. Ralston: 1211.2288

Other New Physics Possibilities

- Still important to measure Golden Channel at high mass



S. Bolognesi: FNAL Seminar

- Only then can we be sure of a weakly coupled EWSB mechanism i.e. 'Higgs mechanism' as generator of W, Z masses and unitarity

Matrix Element Method: Analytic Approach

- Uses differential cross sections to construct likelihoods

$$\mathcal{L}(a_i) = \prod_{j=1}^{N} P_j(a_i)$$

- One can then build a test statistic out of the ratio of likelihoods

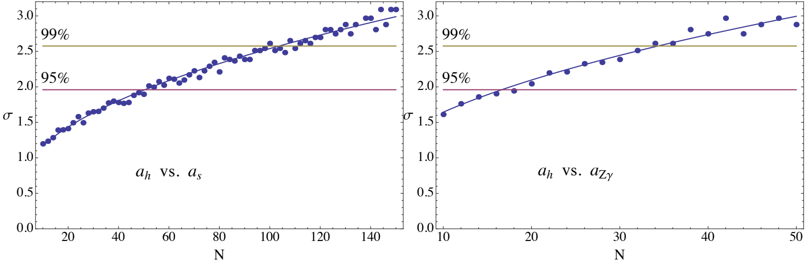
$$\Lambda = 2\log[\mathcal{L}(a_1)/\mathcal{L}(a_2)]$$

- Advantages of the analytic approach:
  - No training and connection to physics is transparent
  - Computing benefits
  - Ability to perform multi-parameter fits
  - Can focus on interesting subsets of variables
  - Flexibility in implementation and inclusion of NP
- Can perform a variety analyses with this framework

Matrix Element Method: Simple Hypothesis Test

- Performed a simple study to assess ability to distinguish operators corresponding to g_h, g_Z, and $g_{Z\gamma}$ assuming pure signal sample
- Even if 0^+ establish, important to distinguish between g_h and g_Z

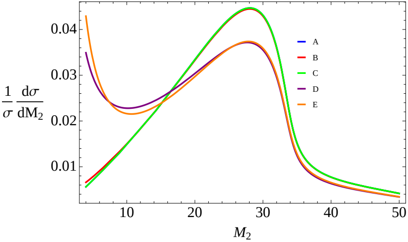
D. Stolarski, RVM: 1208.4840

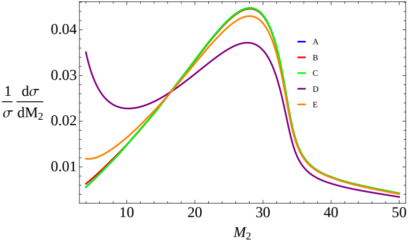


- Golden channel can distinguish g_h and g_Z with $\mathcal{O}(40)$ events
- Can distinguish g_h and g_{Z_γ} with $\mathcal{O}(20)$ events
- A more complete study will include background and more realistic detector effects

Ongoing Work: Probing $Z\gamma$ and $\gamma\gamma$ Couplings

- Is golden channel sensitive to $Z\gamma$ or $\gamma\gamma$ couplings?
- Can it extract the CP nature of the $Z\gamma$ and/or $\gamma\gamma$ couplings?





In collaboration with Y. Chen, K. Kumar, I. Low, N. Trahn, S. Xie: **PRELIMINARY**

- Again we see $M_{1,2}$ cuts affect sensitivity to particular hypothesis
- Working to include background and detector effects

Ongoing Work: LHC Reach to Observe and Extract CP Odd Component of $\varphi \to ZZ$

In collaboration with Y. Chen, E. DiMarco, J. Lykken, M. Spiropulu, S. Xie: **PRELIMINARY**

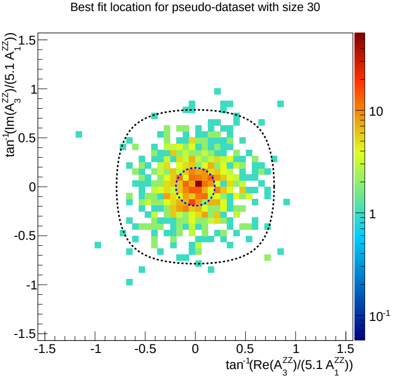
- We consider a CP odd/even scalar mixture for *ZZ* couplings
- Small deficit in ZZ signal strength would be a hint
- Discovery of other mostly CP odd scalar would be BIG hint
- Would like to extract $|\frac{A_{3ZZ}}{A_{1ZZ}}|$ as well as phase of A_{3ZZ}
- Ratio is expected to be small!
- Requires careful consideration of all systematics

Ongoing Work: LHC Reach to Observe and Extract CP Odd Component of $\varphi \to ZZ$

- Use full 8D likelihoods of $(\hat{s}, M_1, M_2, \Theta, \theta_1, \theta_2, \Phi_1, \Phi)$
- Include detector acceptance as well as resolution effects directly in likelihoods
- Treat systematics as nuisance parameters, including:
    - BG fraction and BG modeling uncertainties
    - Production uncertainies
    - Lepton energy scale
    - etc.
- Can then perform a MEM to extract ratio and phase

Ongoing Work: LHC Reach to Observe and Extract CP Odd Component of $\varphi \to ZZ$

In collaboration with Y. Chen, E. DiMarco, J. Lykken, M. Spiropulu, S. Xie: **PRELIMINARY**



- Example of fit results for 1K pseudo exp. for 30 SM Higgs events
- Black dashed indicates $A_{3ZZ} = 5.1 A_{1ZZ}$ (equal yields)
- Blue dashed indicates $A_{1ZZ} = A_{3ZZ}$

Ongoing Work: MEM and 4e and 4μ and Production

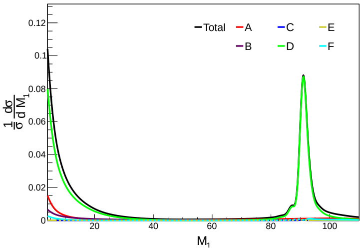
- Currently working to add 4e and 4μ channels to sig and bg
- Can be sizable interference effects between identical final states
- Crucial to understand this effect especially when performing parameter extraction
- Will also allow for greater statistics for the same amount of luminosity
- Eventually would like to include production in our analysis as well
- Also working to develop MEM analysis framework (to eventually be made publicly available)

Conclusion

- Important to not only maximize significance, but also our understanding
- Golden Channel indispensable window to underlying physics
- Only channel which can directly measure CP properties w/out theory assumptions
- NP could show up in small deviations of the kinematic distributions
- Crucial to push M_2 reach below 10 GeV (and lower M_1 if possible)
- Sensitivity to specific hypothesis depends on $M_{1,2}$ cuts
- An amazing channel and we should squeeze every drop out of it
- Should be carefully studied from all angles (no pun intended)

$M_{1,2}$ Background Distributions (Extra)

- M_1



- M_2