Higgs and Other Resonances in the ‘Golden Channel’ at the LHC

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HEP Seminar: November 28

arXiv:1108.2274: Jamie Gainer, Kunal Kumar, Ian Low, R.V.M

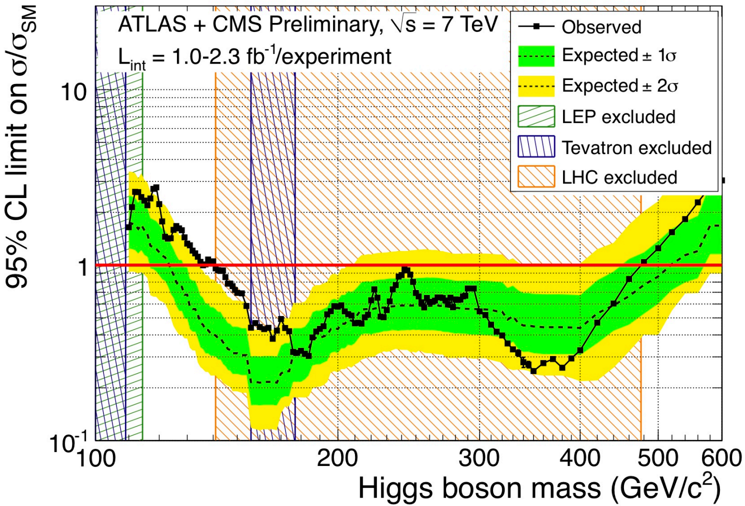
arXiv:????: K. Kumar, Shashank Shalgar, R.V.M

Overview

- Introduction and Objective
- Review of the "Golden Channel"
- Statistical Analysis
- Detector Effects
- Results
- Ongoing/Future Work
- Conclusions

Introduction

- The search for the Higgs boson and the nature of EWSB is among the primary objectives of the LHC
- Strong limits have already been placed by ATLAS and CMS



Introduction

- Standard searches rely on counting methods and looking for excesses over expected background
- In addition the shapes of invariant mass distributions are also used
- In some cases, multiple observables in an event are measured well enough to warrant multi-variate methods
- Have been used at Tevatron and B factories and include neural nets, boosted decision trees, and the Matrix Element Method (MEM)
- These methods optimize the full physics information of an event, but can be computationally intensive
- For some processes analytic expressions for the fully differential cross section can be used in a MEM
- One such process dubbed the 'Golden Channel' is measured very precisely and can be computed analytically in a straightforward way

Objective

- Use analytic expressions for the fully differential cross sections to set up a MEM and examine resonances in the $pp \to ZZ^* \to \ell^+\ell^-\ell^+\ell^-$ channel
- Quantify improvement in discovery/exclusion significance gained by using the full kinematic distribution
- Conduct analysis for a range of masses ($130 - 1000$ GeV) at a 7 TeV LHC
- Apply analysis to the case of hypothesis testing to discriminate between different signals
- Study ability of analysis to extract/constrain parameters as well as spin and CP properties of the resonance

Golden Channel

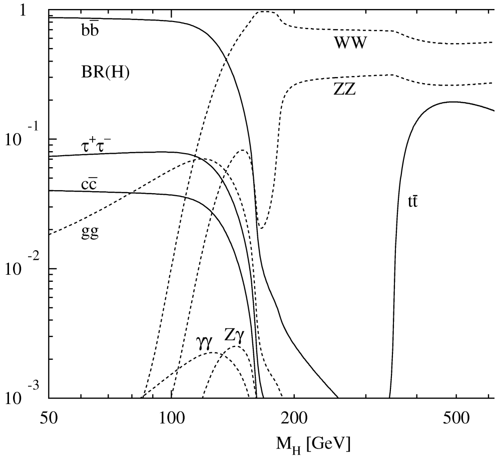
- $R \to ZZ^* \to \ell^+\ell^-\ell^+\ell^-$ referred to as 'golden channel' because of good invariant mass resolution and well controlled background
- Traditional search strategy focuses on measuring invariant mass ($\hat{s}$) of the four leptons
- However, given that four-momenta of leptons can be reconstructed precisely, it is possible to measure more than just $\hat{s}$
- Has been examined using the MEM in earlier studies in the context of signal discrimination for 10 and 14 TeV

  De Rujula, Lykken et al: arXiv:1001.5300, Gao, Gritsan, Melnikov et al: arXiv:1001.3396

- Typically thought to be an "easy" mode of Higgs discovery...however...

Golden Channel

- Suffers from small cross sections due to branching fractions of $H \to ZZ^* \sim .3$ and Zs to leptons $\sim .0335$

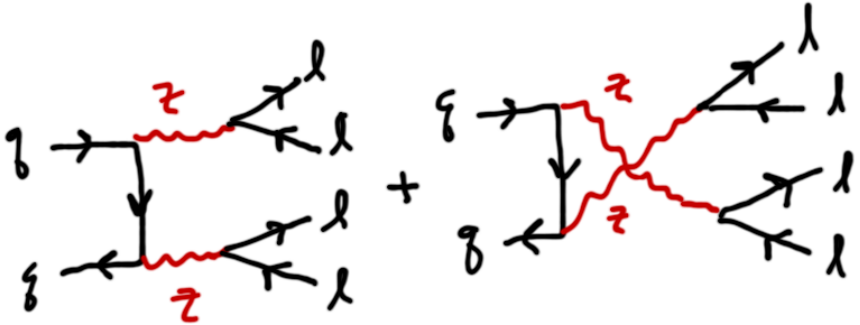


A. Djouadi, J. Kalinowski, M. Spira

hep-ph/9704448v1

Golden Channel: Background

- $q\bar{q} \to ZZ^* \to \ell^+\ell^-\ell^+\ell^-$ is the dominant irreducible background for $170 \lesssim m_h$
- We consider the leading order u and t channel Feynman diagrams



Background: Helicity Amplitudes

- The fully differential cross section is calculated in a helicity basis allowing the Z bosons to be off-shell following,

  Hagiwara,et.al.,Nucl.Phys.B 282, 253 (1987)

- Makes physics of process more transparent and tractable
- The amplitude factorizes into one production and two decay amplitudes

$$q(k_q, \sigma) + \bar{q}(k_{\bar{q}}, \bar{\sigma}) \to Z_1(k_1, \lambda_1) Z_2(k_2, \lambda_2)$$

$$Z_1(k_1, \lambda_1) \to \ell_1(p_1, \sigma_1) + \bar{\ell}_1(p_2, \sigma_2)$$

$$Z_2(k_2, \lambda_2) \to \ell_2(p_3, \sigma_3) + \bar{\ell}_2(p_4, \sigma_4)$$

Background: Production Amplitudes

- The production helicity amplitude for $q\bar{q} \to Z_1 Z_2$ in the CM frame reads

$$\mathcal{M}^{ZZ}_{\sigma\bar{\sigma};\lambda_1\lambda_2} = 4\sqrt{2}\,\left(g^{Zq\bar{q}}_{\Delta\sigma}\right)^2\,\epsilon\,\delta_{|\Delta\sigma|,\pm 1}\,\frac{\mathcal{A}^{\Delta\sigma}_{\lambda_1\lambda_2}(\Theta)\,d^{J_0}_{\Delta\sigma,\Delta\lambda}(\Theta)}{4\beta_1\beta_2\sin^2\Theta + (1-\beta_1\beta_2)^2 - x^2(1+\beta_1\beta_2)^2}$$

  where $\Delta\sigma = \sigma - \bar{\sigma}$, $\epsilon = \Delta\sigma(-1)^{\lambda_2}$, $\Delta\lambda = \lambda_1 - \lambda_2$, $J_0 = \max(|\Delta\sigma|, |\Delta\lambda|)$, and $d^{J_0}_{\Delta\sigma,\Delta\lambda}(\Theta)$ are the d functions defined in PDG
- We can study the high energy behavior by looking at the coefficients $\mathcal{A}^{\Delta\sigma}_{\lambda_1\lambda_2}$

Background: Production Amplitudes

- Looking at the coefficients

$$\mathcal{A}^{\Delta\sigma}_{\pm\mp} = -\sqrt{2}(1 + \beta_1\beta_2)\ ,$$

$$\mathcal{A}^{\Delta\sigma}_{\pm 0} = \frac{1}{\gamma_2(1+x)}\left[(\Delta\sigma\Delta\lambda)\left(1 + \frac{\beta_1^2+\beta_2^2}{2}\right) - 2\cos\Theta\right.$$

$$\left. -(\Delta\sigma\Delta\lambda)(\beta_2^2 - \beta_1^2)x - 2x\cos\Theta - (\Delta\sigma\Delta\lambda)\left(1 - \frac{\beta_1^2+\beta_2^2}{2}\right)x^2\right]$$

$$\mathcal{A}^{\Delta\sigma}_{0\pm} = \mathcal{A}^{\Delta\sigma}_{\pm 0}, \gamma_1 \to \gamma_2, x \to -x$$

$$\mathcal{A}^{\Delta\sigma}_{\pm\pm} = -(1 - \beta_1\beta_2)\cos\Theta - \lambda_1\Delta\sigma(1 + \beta_1\beta_2)x$$

$$\mathcal{A}^{\Delta\sigma}_{00} = 2\gamma_1\gamma_2\cos\Theta\left[((1-x)\beta_1 + (1+x)\beta_2)\sqrt{\frac{\beta_1\beta_2}{1-x^2}} - (1 + \beta_1^2\beta_2^2)\right]$$

Background: Differential Cross Section

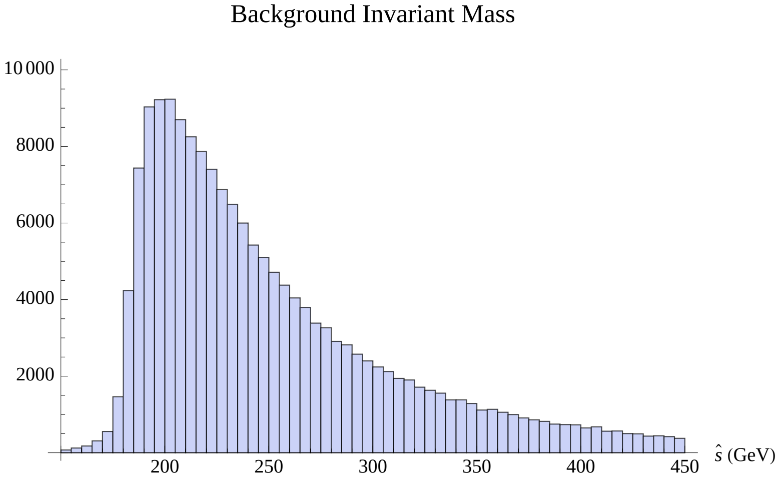
- The final partonic fully differential is found by averaging the squared sum of these amplitudes over spin and color

$$\frac{d\sigma}{d\Omega\, dm_1^2\, dm_2^2} = 2\pi\, \frac{1}{4}\, \frac{1}{3}\, \frac{1}{2\hat{s}}\, \frac{\beta_1(1+x)}{32\pi^2} \left(\frac{1}{32\pi^2}\right)^2 \left(\frac{1}{2\pi}\right)^2 \sum_{\sigma,\bar{\sigma},\sigma_i} |\mathcal{M}(\sigma,\bar{\sigma};\sigma_i)|^2$$

  where $\Omega = \{\Theta, \theta_1, \theta_2, \phi_1, \phi_2\}$ and
  $d\Omega = d\cos\Theta\, d\cos\theta_1\, d\cos\theta_2\, d\phi_1\, d\phi_2$)
- For the initial state we include u, d, s, and c quarks
- For the final state we include the 3 separate channels $ee\mu\mu$, 4μ and $4e$

Background: Invariant Mass

- Energy dependence is dominated by the ZZ^* threshold
- Peaked around threshold and then quickly dies off

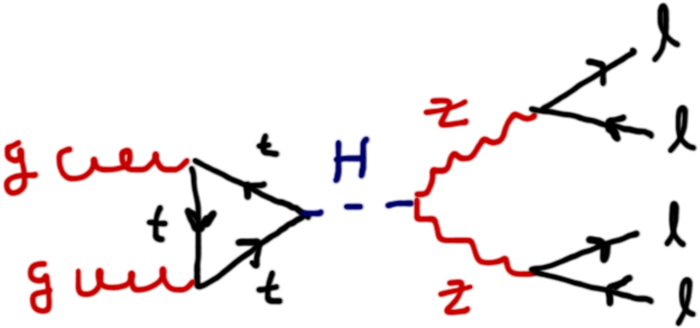


Golden Channel: Higgs

- $gg \to H \to ZZ^* \to \ell^+\ell^-\ell^+\ell^-$ through a top quark loop generated by effective the operator

$$\mathcal{L} = \frac{\alpha_s}{12\pi v} H G_{\mu\nu} G^{\mu\nu}$$

- We consider the LO contribution only which is given by



Higgs: Production Amplitudes

- For a Higgs, being a scalar, the two Z bosons can only have the the helicity combinations $(0,0)$ and $(\pm1,\pm1)$
- The amplitudes are

$$\mathcal{M}^{ZZ}_{h;\pm1\pm1} = \frac{\alpha_s m_Z^2 \hat{s}}{3\pi v^2((\hat{s}-m_h^2)^2 + m_h^2\Gamma_h^2)^{1/2}}$$

$$\mathcal{M}^{ZZ}_{h;00} = \gamma_1\gamma_2(1+\beta_1\beta_2)\frac{\alpha_s m_Z^2 \hat{s}}{3\pi v^2((\hat{s}-m_h^2)^2 + m_h^2\Gamma_h^2)^{1/2}}$$

- As expected from the Higgs mechanism the $\mathcal{M}^{ZZ}_{h;00}$ amplitudes dominate in the high energy limit
- The fully differential cross section is formed similarly as for the background

Golden Channel: Other Resonances

- We also consider general spin 0, 1, and 2 cases which couple to ZZ^* through the following operators:
- Spin-0 Scalar

$$\mathcal{L}_{0^+} = \frac{1}{\Lambda} H(A_1 \vec{W}_{\mu\alpha} \vec{W}^{\mu\alpha} + A_2 B_{\mu\alpha} B^{\mu\alpha})$$

- Spin-0 Pseudo-Scalar

$$\mathcal{L}_{0^-} = \frac{i}{\Lambda} \epsilon^{\mu\alpha\sigma\tau} H(A_3 \vec{W}_{\mu\alpha} \vec{W}_{\sigma\tau} + A_4 B_{\mu\alpha} B_{\sigma\tau})$$

Golden Channel: Other Resonances

- Spin-1 Vector

$$\mathcal{L}_{1^+} = \frac{1}{\Lambda^2}(\partial^\mu H^\alpha + \partial^\alpha H^\mu)(A_1 \vec{W}^\lambda_\mu \vec{W}_{\alpha\lambda} + A_2 B^\lambda_\mu B_{\alpha\lambda})$$

- Spin-1 Pseudo-Vector

$$\mathcal{L}_{1^-} = \frac{i}{\Lambda^2}\epsilon^{\mu\nu\alpha\rho}[A_3(\vec{W}^\lambda_\mu(D_\alpha \vec{W}_{\nu\rho}) - (D_\alpha \vec{W}^\lambda_\mu)\vec{W}_{\nu\rho}$$

$$+A_4 B^\lambda_\mu(D_\alpha B_{\nu\rho}) - (D_\alpha B^\lambda_\mu)B_{\nu\rho}]H_\rho$$

- Spin-2 Vector

$$\mathcal{L}_{2^+} = \frac{1}{\Lambda}H_{\mu\nu}(A_1 \vec{W}^\mu_\alpha \vec{W}^{\nu\alpha} + A_2 B^\mu_\alpha B^{\nu\alpha})$$

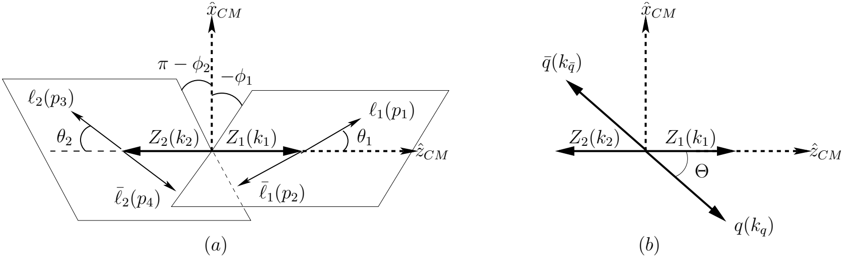
- Spin-2 Pseudo-Vector

$$\mathcal{L}_{2^-} = \frac{i}{\Lambda}\epsilon_{\mu\nu\alpha\rho}H^{\nu\rho}(A_3 \vec{W}^{\mu\alpha} \vec{W}^{\rho\beta} + A_4 B^{\mu\alpha} B^{\rho\beta})$$

Golden Channel: Observables

- We consider only the exclusive $ZZ^* \to 4\ell$ process
- In the $ee\mu\mu$ channel there is no ambiguity in defining the lepton angles since the final states are distinguishable
- For the 4μ and 4e channels we use the reconstructed Z masses to distinguish the pairs
- In the massless lepton approximation there are 12 observables per event (pT, η, Φ for each lepton)
- Using momentum conservation and the azimuthal symmetry of the detector we can reduce these to the set $x_i \equiv (x_1, x_2, M_1, M_2, \hat{s}, \Theta, \theta_1, \phi_1, \theta_2, \phi_2)$

Golden Channel: Observables



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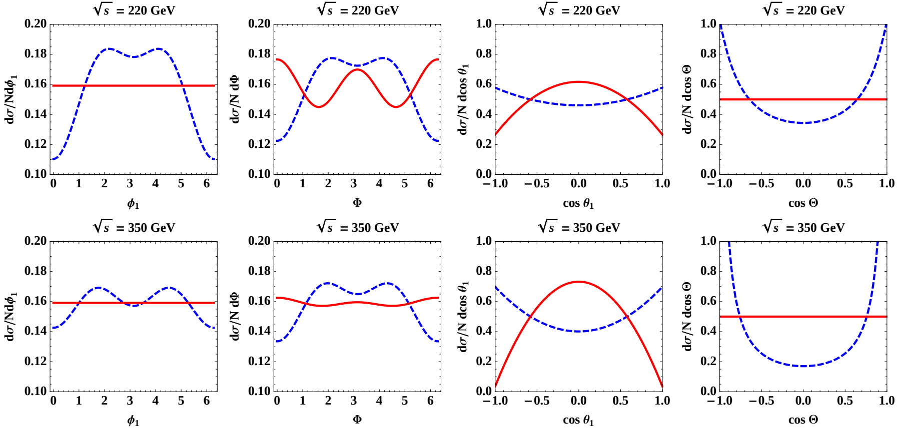
- Θ: polar angle of the incoming quark in the CM frame
- $\theta_{1,2}$: polar angle of $\ell_{1,2}$ in the $\mathcal{Z}_{1,2}$ frame
- $\phi_{1,2}$: azimuthal angle of $\ell_{1,2}$ in the $\mathcal{Z}_{1,2}$ frame

Golden Channel: Distributions

- The angular distributions can add to our discriminating power



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Statistical Analysis: Matrix Element Method

- Likelihood methods are frequently employed to establish the presence, or lack of a signal using kinematic distributions which discriminate signal from background
- A likelihood function is defined for each hypothesis to quantify the probability of obtaining the actual data under that particular hypothesis
- To reject or accept a hypothesis a test statistic must also be defined
- In QFT there is a natural object for quantifying the probability of obtaining a particular event for a given data set; the differential cross section
- The Matrix Element Method: use of likelihood methods where normalized differential cross sections are used as pdf in the likelihood

Statistical Analysis: Likelihood Function

- When the overall number of events is not fixed one needs to employ an Extended Maximum Likelihood (EML) method
- The unbinned likelihood for some collider signature with unknown expected number of events μ is given by,

$$\mathcal{L}(\mu; \boldsymbol{\theta}) = \frac{e^{-\mu}\mu^N}{N!}\prod_{i=1}^{N} P(\boldsymbol{\theta}; x_i)$$

- The EML function for a signal plus background hypothesis is then

$$\mathcal{L}_{s+b}(\mu, f, m_h) = \frac{e^{-\mu}\mu^N}{N!}\prod_{i=1}^{N}[fP_s(m_h; x_i) + (1-f)P_b(x_i)]$$

Statistical Analysis: PDFs

- P_s and P_b are the signal and background pdfs (normalized differential cross sections)
- For the Higgs signal we have

$$P_s(m_h; \boldsymbol{x}) = \frac{1}{\epsilon_s \sigma_s(m_h)} \left(\frac{f_g(x_1) f_g(x_2)}{s} \right) \frac{d\widehat{\sigma}_h(m_h, \hat{s}, m_1, m_2, \Omega)}{dm_1^2 \, dm_2^2 \, d\Omega}$$

- For the $q\bar{q}$ background

$$P_b(\boldsymbol{x}) = \frac{1}{\epsilon_b \sigma_{q\bar{q}}} \left(\left(\frac{f_q(x_1) f_{\bar{q}}(x_2)}{s} \right) \frac{d\widehat{\sigma}_{q\bar{q}}(\hat{s}, m_1, m_2, \Omega)}{dm_1^2 \, dm_2^2 \, d\Omega} + \left(\frac{f_{\bar{q}}(x_1) f_q(x_2)}{s} \right) \frac{d\widehat{\sigma}_{q\bar{q}}(\hat{s}, m_1, m_2, \Omega')}{dm_1^2 \, dm_2^2 \, d\Omega'} \right)$$

where $\Omega' \equiv (\pi - \Theta, \theta_1, \theta_2, \phi_1 + \pi, \phi_2 + \pi)$ for initial quark in the $-z$ direction and we have switched x_1 and x_2

Statistical Analysis: Test Statistic

- As a test statistic we would like one who's distribution tends to a gaussian even in the low statistics regime
- For this we can define our significance in terms of the log likelihood ratio

$$\mathcal{S} = \sqrt{2ln\mathcal{Q}}$$

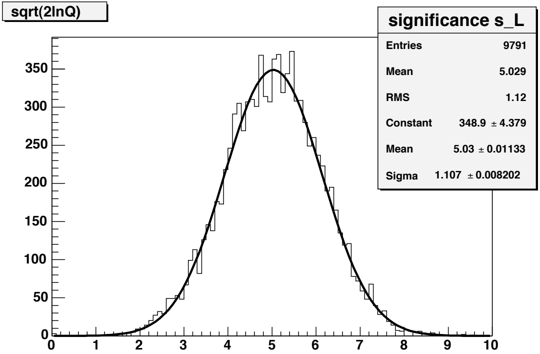
where $\mathcal{Q}$ is the likelihood ratio given by

$$\mathcal{Q} = \frac{\mathcal{L}_{s+b}}{\mathcal{L}_b}$$

- To obtain the expected significance we construct the PDF for $\mathcal{S}$ by conducting a large number of pseudo experiments and obtaining $\mathcal{S}$ for each one
- From these pseudo experiments, a distribution for the expected significance along with the spread is obtained

Analysis: Expected Significance

- The log likelihood ratio was shown to be a robust test statistic even in the low statistics regime
- For a large enough set of pseudo experiments, the distribution $\mathcal{S}$ defined in terms of $\mathcal{Q}$ converges to a gaussian



LEP Working Group: arXiv:9903282, V. Bartsch, G. Quast:CMS NOTE 2005/004

Expected Significance

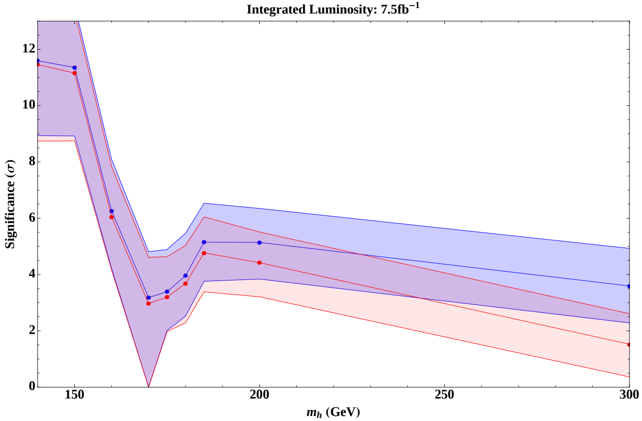
- When there exist free parameters in the underlying hypothesis, the likelihood will in general depend on parameters which are not directly observable (i.e. mass, couplings, etc.)
- Thus we remove the dependance of $\mathcal{S}$ on the undetermined parameters by maximizing the EML function prior to the construction of the likelihood ratio
- So we have for the likelihood ratio

$$\mathcal{Q} = \frac{\mathcal{L}_{s+b}(\hat{N}t, \hat{f}s, \hat{m}h; x_i)}{\mathcal{L}_b(\hat{N}_t; x_i)}$$

where $\hat{N}t, \hat{f}s, \hat{m}h$ are the values which maximize the EML function for a given pseudo experiment (i.e. the statistically preferred values)

Expected Significance: All Obervables vs. $\hat{s}$

- We can compare the performance of the fully differential cross section vs the invariant mass distribution before detector effects



- We see that for $m_h \lesssim 170 GeV$ no sensitivity is gained by including the angles
- Still useful for signal discrimination in the range $m_h \lesssim 170 GeV$

Statistical Analysis: Exclusion Limit

- We determine the exclusion limit by setting an upper limit on the signal fractional yield, $0 < f = \frac{\mu_s}{\mu_s+\mu_b} < 1$
- We define a pdf by considering $\mathcal{L}_{s+b}$ as a function of f

$$p(f) = \frac{\mathcal{L}_{s+b}(N, f, \hat{m}_h)}{\int_0^1 \mathcal{L}_{s+b}(N, \bar{f}, \hat{m}_h)\, d\bar{f}}$$

The 95% C.L. limit on f for a given set of data is given by α as follows:

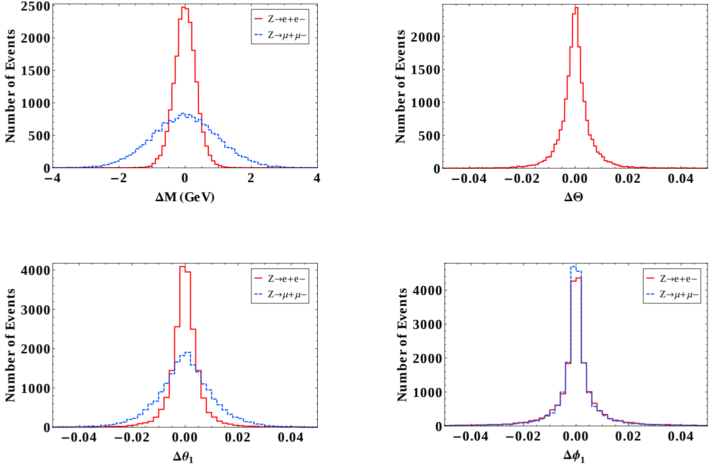
$$\int_0^\alpha p(f)\, df = 0.95$$

- Can translate α into a 95% C.L upper limit on σ_s through

$$\sigma_s = \left(\frac{\epsilon_b}{\epsilon_s}\right)\left(\frac{f}{1-f}\right)\sigma_b$$

Detector Effects: Smearing

- We apply separate smearing to energy of the electrons and p_T of the muons according to CMS TDR



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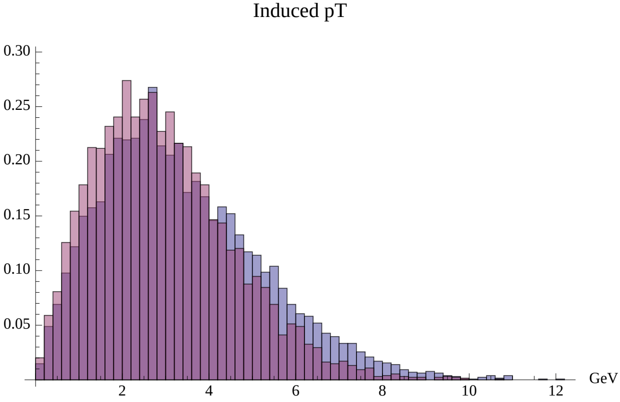
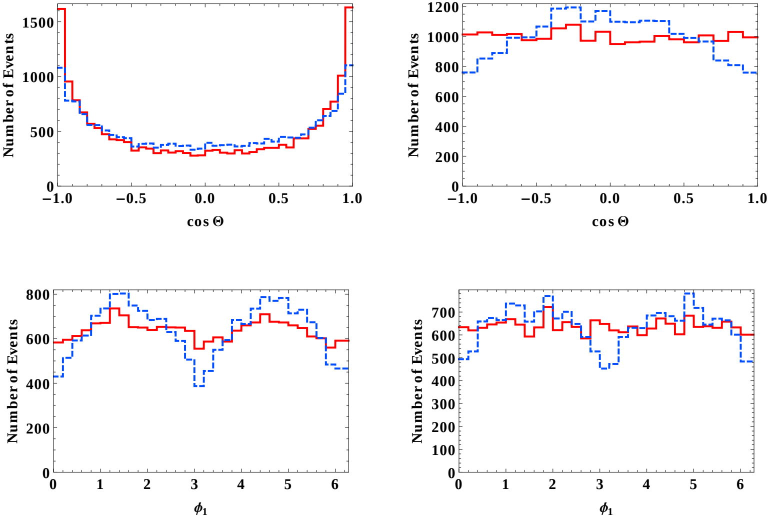
Detector Effects: pT dependence

- For simplicity we consider only the 0-jet bin and since we are considering only LO assume events have no intrinsic *pT*
- Cuts and detector smearing can shape distributions and introduce a *pT* dependence even when only considering the LO process
- To find the ZZ CM frame, must ensure *pT* is be properly boosted away on an event by event basis



Detector Effects: Cuts

- We require: pT > 10 GeV, η < 2.5, and $150 < \hat{s} < 450$



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Efficiencies and Yields

- After detector effects and cuts we obtain the following efficiencies and yields for the $2e2\mu$ channel at $2.5fb^{-1}$

	m_h(GeV)	σ(fb)	ϵ	$\langle N \rangle$
Signal	175	0.218	0.512	0.279
	200	1.26	0.594	1.87
	220	1.16	0.625	1.81
	250	0.958	0.654	1.57
	300	0.714	0.701	1.25
	350	0.600	0.708	1.06
Background	-	8.78	0.519	11.4

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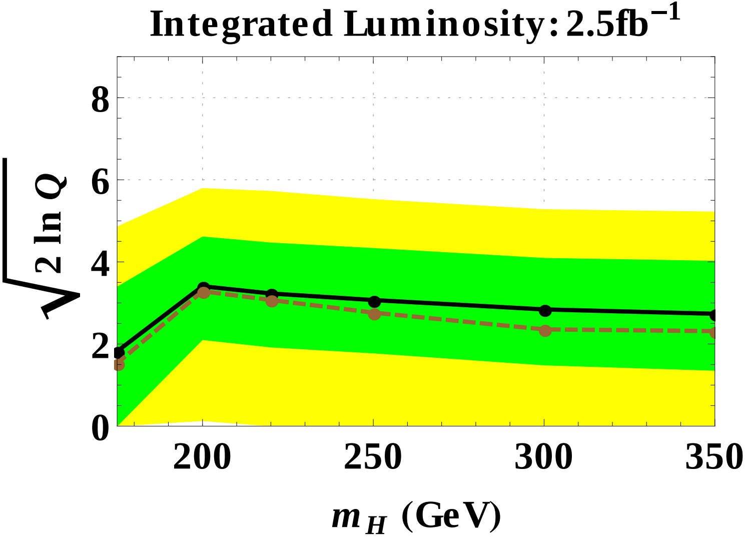
- The efficiencies for $4e$ and 4μ are the same as for $2e2\mu$ while the yields (cross sections) are half as large
- It is these cross sections $\times$ efficiencies which we use to normalize our pdfs in the likelihood function

Results: Expected Significance



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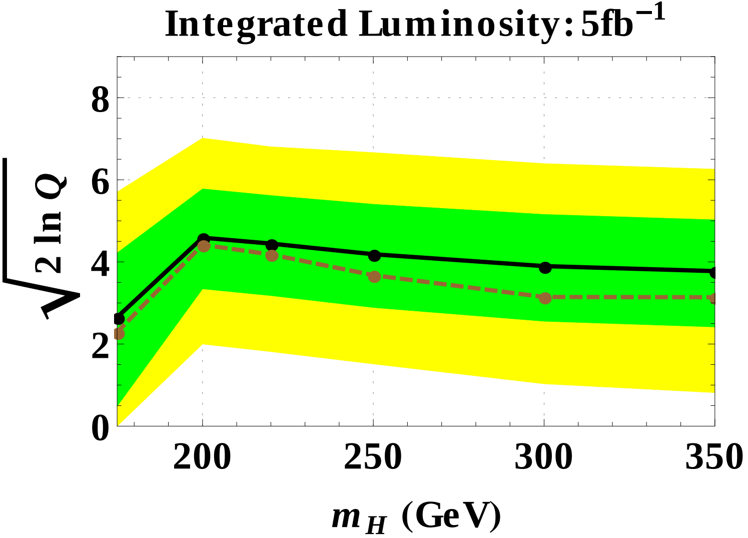

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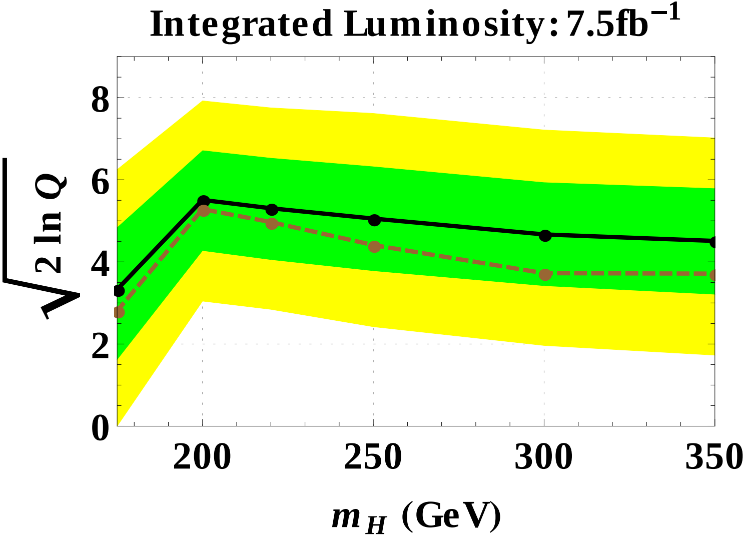
Results: Expected Significance



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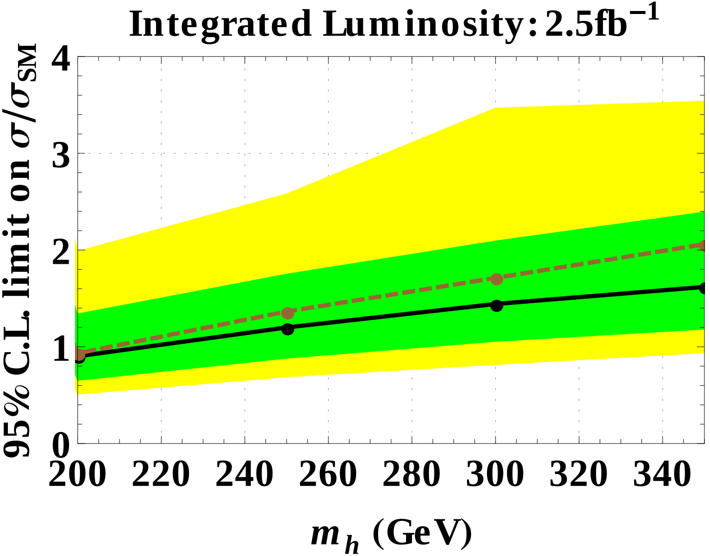
Results: Exclusion Limits



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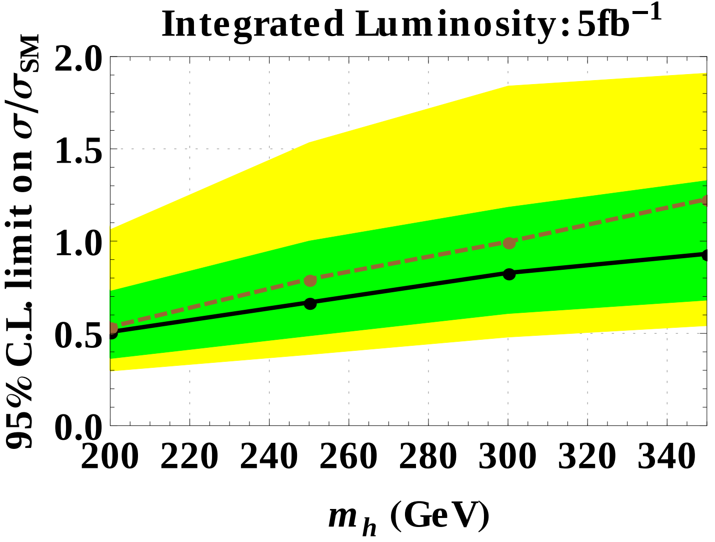

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Ongoing and Future Work

- Currently working to implement analysis for other resonances including CP odd/even spin 1 and 2 which decay to ZZ^*
- Working to also conduct signal discrimination studies in regions with low background where clean signal samples can be obtained
- Would like to include other production mechanism such as weak vector boson fusion
- Would like to include other final states such as those where one Z is allowed to decay to jets or missing E_T as well as allow for ISR
- Include higher order corrections to increase the precision of these analysis

Conclusions

- We have analyzed the Higgs “Golden Channel” at a 7TeV LHC using a Matrix Element Method analysis
- We have compared how the MEM performs when one uses the full kinematic information of the event in addition to the total invariant mass and find improvements on the order of $10 - 20\%$ depending on the Higgs mass
- Multi-variate methods can be powerful analysis tools for processes where multiple observables are measured sufficiently well