MELA: Spin, parity, and couplings of a Higgs-like resonance

Markus Schulze
Argonne National Laboratory
Yanyan Gao, Nhan Tran
Fermi National Accelerator Laboratory
Sara Bolognesi, Andrei Gritsan, Kirill Melnikov, Andrew Whitbeck
Johns Hopkins University

Implications of LHC results on TeV-scale physics
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introduction

- discovery is just the beginning – need to understand properties of any new resonance
  - model-independent approach to extraction of resonance spin, parity, and couplings
- explore Higgs properties using decay kinematics
  - angular analysis of decay products
  - complimentary approach to measurement of Higgs branching ratios
- MELA approach
  - Matrix Element Likelihood Analysis – a flexible likelihood approach

Mela (Sanskrit: मेला) is a Sanskrit word meaning 'gathering' or 'to meet' ...

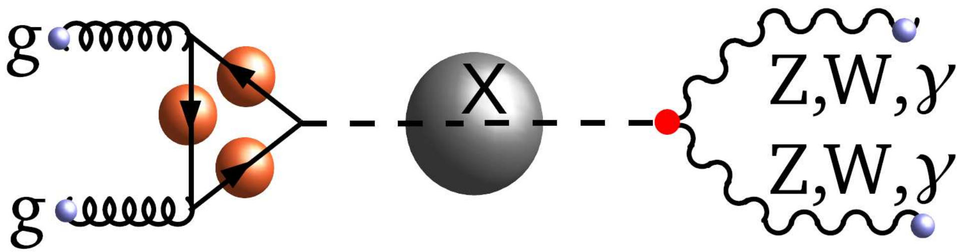
References:

Gao et al., PRD81,075022(2010); CMS PAS HIG-2011/027 (2l2q)

outline

- brief review of phenomenology and helicity amplitude formalism
- practical applications and tools
  - MC generator details
  - MELA analysis – a technical implementation of likelihood approach
- preliminary results: discovery significance and hypothesis separation
- outlook

spin-0 resonance kinematics



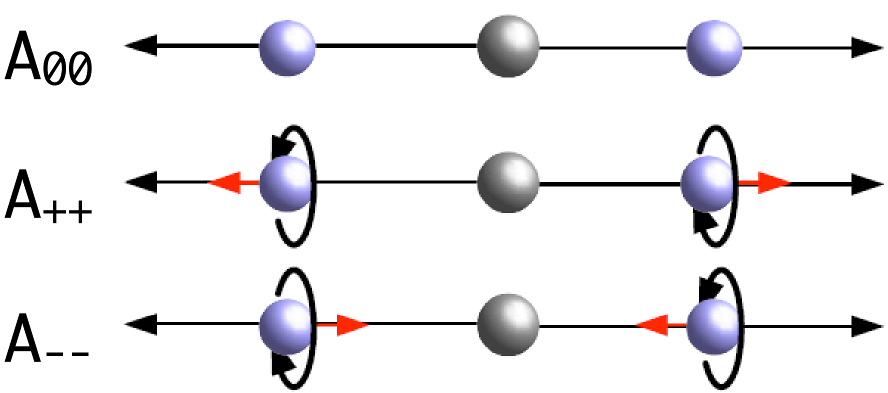
- amplitude X→VV is characterized by a_1,a_2,a_3 couplings

$$A(H_{J=0} \to V_1 V_2) = v^{-1} \epsilon_1^{*\mu} \epsilon_2^{*\nu} \left(a_1 g_{\mu\nu} M_X^2 + a_2\, q_\mu q_\nu + a_3 \epsilon_{\mu\nu\alpha\beta}\, q_1^\alpha q_2^\beta \right)$$

- For X→ZZ,WW:
  - SM Higgs ($J^P = 0^+$): $a_1 \neq 0$, $a_2 = a_3 = 0$
  - pseudoscalar Higgs ($J^P = 0^-$): $a_3 \neq 0$, $a_1 = a_2 = 0$
- general amplitude can be separated into various helicity amplitudes
  - helicity amplitudes are used to characterize event kinematics

helicity amplitude formalism

- from a general amplitude, we can compute the helicity amplitude via polarization vectors, $\epsilon(\pm,0)$
- for generic X→VV decay, 9 possible amplitudes, A_{jk} where j,k = ±1, 0
  - no longitudinal polarization for massless γ and g
  - for spin−0, allowed amplitudes A_{++}, A_{--}, A_{00}
- helicity amplitudes used as parameters for angular distributions



$$A_{00} = -\frac{m_X^2}{v}\left(a_1\chi + a_2\eta(\chi^2 - 1)\right)$$

$$A_{\pm\pm} = \frac{m_X^2}{v}\left(a_1 \pm i a_3 \eta \sqrt{\chi^2 - 1}\right)$$

$$\chi = (m_X^2 - m_1^2 - m_2^2)/(2m_1m_2)$$

$$\eta = m_1 m_2/m_X^2$$

a model-independent approach

- generic resonances other than spin-0 possible as well
  - examples include Z', KK gluons, RS graviton, etc.
- e.g. can consider spin-1 and spin-2 as well
- play same game as spin-0 case
  - write down general amplitude, extract helicity amplitude parameterized by dimensionless couplings

e.g. X(J=1) → ZZ

$$A(X \to ZZ) = g_1^{(1)} \left[(\epsilon_1^* q)(\epsilon_2^* \epsilon_X) + (\epsilon_2^* q)(\epsilon_1^* \epsilon_X)\right] + g_2^{(1)} \epsilon_{\alpha\mu\nu\beta} \epsilon_X^\alpha \epsilon_1^{*,\mu} \epsilon_2^{*,\nu} \tilde{q}^\beta$$

e.g. X(J=2) → ZZ

$$A(X \to ZZ) = \Lambda^{-1} e_1^{*\mu} e_2^{*\nu} \Big[c_1 (q_1 q_2) t_{\mu\nu} + c_2 g_{\mu\nu} t_{\alpha\beta} \tilde{q}^\alpha \tilde{q}^\beta + c_3 \frac{q_{2\mu} q_{1\nu}}{m_X^2} t_{\alpha\beta} \tilde{q}^\alpha \tilde{q}^\beta + 2c_4 (q_{1\nu} q_2^\alpha t_{\mu\alpha} + q_{2\mu} q_1^\alpha t_{\nu\alpha}) + c_5 t_{\alpha\beta} \frac{\tilde{q}^\alpha \tilde{q}^\beta}{m_X^2} \epsilon_{\mu\nu\rho\sigma} q_1^\rho q_2^\sigma + c_6 t^{\alpha\beta} \tilde{q}_\beta \epsilon_{\mu\nu\alpha\rho} q^\rho + \frac{c_7 t^{\alpha\beta} \tilde{q}_\beta}{m_X^2} (\epsilon_{\alpha\mu\rho\sigma} q^\rho \tilde{q}^\sigma q_\nu + \epsilon_{\alpha\nu\rho\sigma} q^\rho \tilde{q}^\sigma q_\mu) \Big]$$

event kinematics

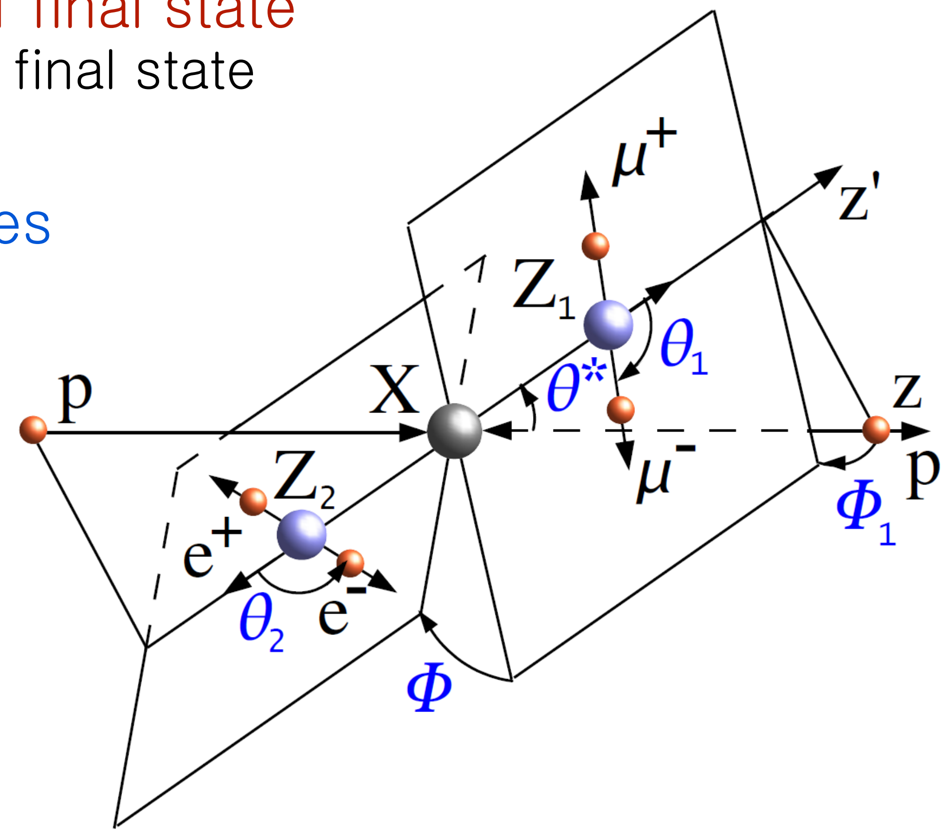
Let us consider the X→VV→4f final state

– more information in four-body final state

Θ_1, Θ_2, Φ: helicity (decay) angles

Θ^*, Φ_1: production angles

Θ^*, Φ_1 uncorrelated with spin 0 kinematics (flat), used in separation from background



full event kinematics described by:

$\{m_{4l}, m_1, m_2, \Theta_1, \Theta_2, \Phi, \Theta^*, \Phi_1, Y_H, pT_H\}$

** pT_H from NLO effects, Y_H from parton distribution functions

angular distributions

angular distribution parameterized by helicity amplitudes

$$F^J_{00}(\theta^*) \times \Big\{4\, f_{00}\, \sin^2\theta_1 \sin^2\theta_2 + (f_{++} + f_{--})\big((1+\cos^2\theta_1)(1+\cos^2\theta_2) + 4R_1R_2\cos\theta_1\cos\theta_2\big)$$
$$- 2\,(f_{++} - f_{--})\,\big(R_1\cos\theta_1(1+\cos^2\theta_2) + R_2(1+\cos^2\theta_1)\cos\theta_2\big)$$
$$+ 4\sqrt{f_{++}f_{00}}\,(R_1 - \cos\theta_1)\sin\theta_1(R_2 - \cos\theta_2)\sin\theta_2\cos(\Phi + \phi_{++})$$
$$+ 4\sqrt{f_{--}f_{00}}\,(R_1 + \cos\theta_1)\sin\theta_1(R_2 + \cos\theta_2)\sin\theta_2\cos(\Phi - \phi_{--})$$
$$+ 2\sqrt{f_{++}f_{--}}\,\sin^2\theta_1\sin^2\theta_2\cos(2\Phi + \phi_{++} - \phi_{--})\Big\}$$

Jz = 0

$$+4F^J_{11}(\theta^*) \times \Big\{(f_{+0} + f_{0-})(1 - \cos^2\theta_1\cos^2\theta_2) - (f_{+0} - f_{0-})(R_1\cos\theta_1\sin^2\theta_2 + R_2\sin^2\theta_1\cos\theta_2)$$
$$+ 2\sqrt{f_{+0}f_{0-}}\,\sin\theta_1\sin\theta_2(R_1R_2 - \cos\theta_1\cos\theta_2)\cos(\Phi + \phi_{+0} - \phi_{0-})\Big\}$$
$$+(-1)^J \times 4F^J_{-11}(\theta^*) \times \Big\{(f_{+0} + f_{0-})(R_1R_2 + \cos\theta_1\cos\theta_2) - (f_{+0} - f_{0-})(R_1\cos\theta_2 + R_2\cos\theta_1)$$
$$+ 2\sqrt{f_{+0}f_{0-}}\,\sin\theta_1\sin\theta_2\cos(\Phi + \phi_{+0} - \phi_{0-})\Big\}\sin\theta_1\sin\theta_2\cos(2\Psi)$$

Jz = ±1

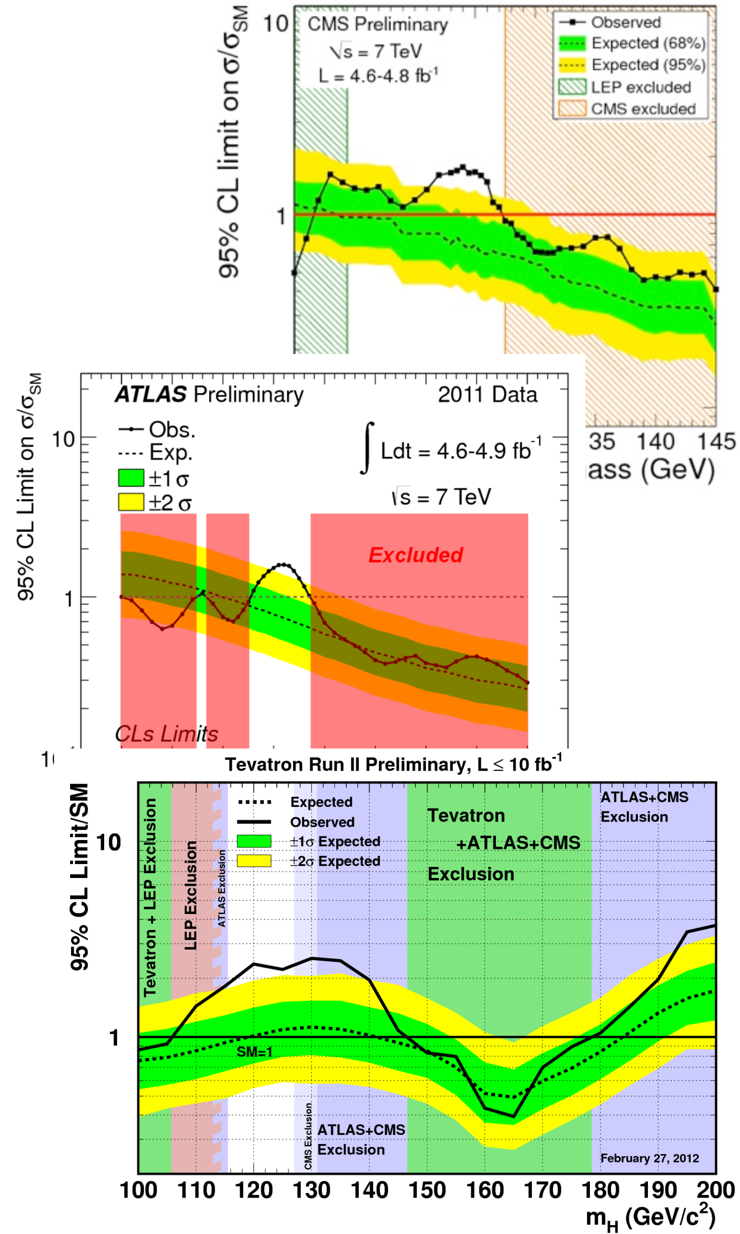
$$+2F^J_{22}(\theta^*) \times f_{+-}\Big\{(1+\cos^2\theta_1)(1+\cos^2\theta_2) - 4R_1R_2\cos\theta_1\cos\theta_2\Big\}$$
$$+(-1)^J \times 2F^J_{-22}(\theta^*) \times f_{+-}\sin^2\theta_1\sin^2\theta_2\cos(4\Psi)$$

Jz = ±2

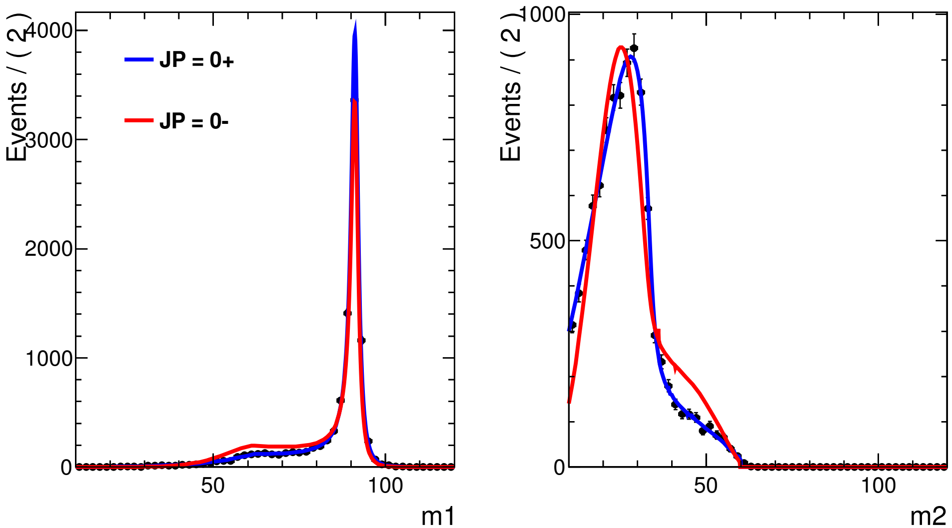
+ interference terms

the region of interest

- Recent results put great focus on the low mass Higgs region, ~120–130 GeV
- Consider off-shell vector boson masses, can also be used for signal or background discrimination



Z1 and Z2 masses for 125 GeV resonance

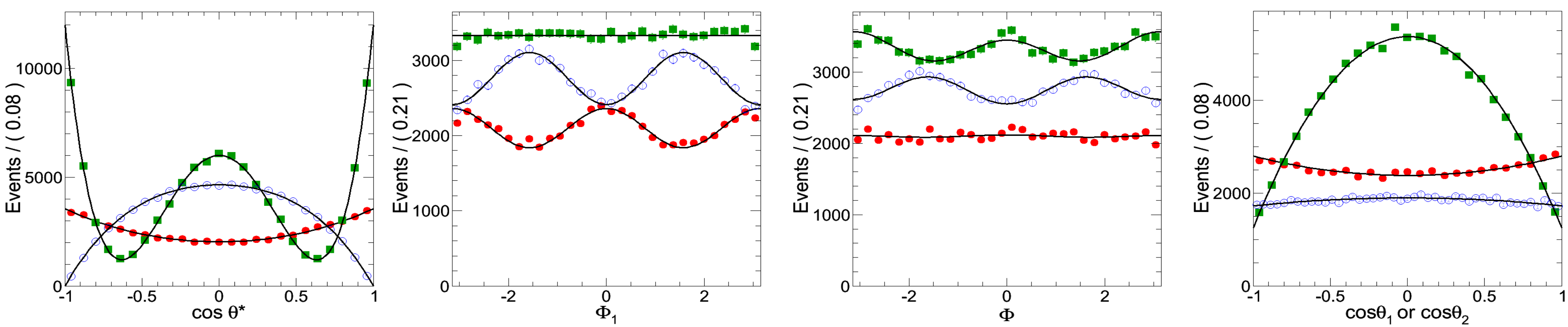


tools and multivariate analysis

jhu generator

- A MC program developed to simulate production and decay of X with spin-zero, -one, or -two
  - Includes all spin correlations and all possible couplings
  - Inputs are general dimensionless couplings – calculates matrix elements
  - Both gg and $q\bar{q}$ production
  - Output in LHE format; e.g. can interface to Pythia for hadronization
  - All code publicly available: www.pha.jhu.edu/spin

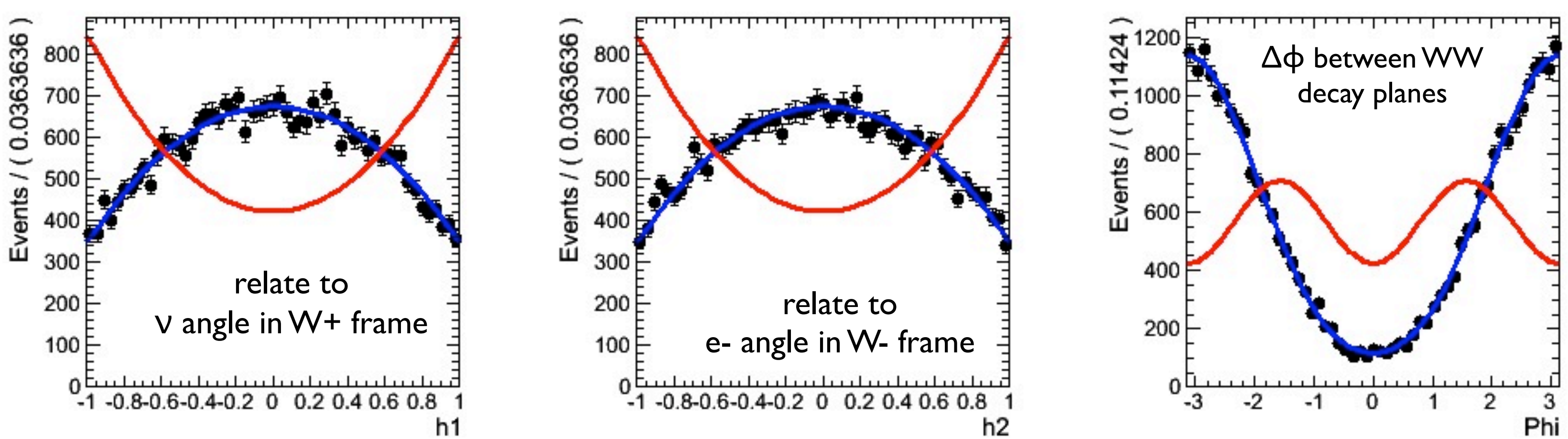
validation: comparison of analytic p.d.f with MC for various spin-2 models



jhu generator – updates

- expansion of final states for spin-0,1,2
  - ZZ→ 4l, 2l2τ, 2l2ν, 2l2q
  - WW → 2l2ν, lντν, lνqq
- on-going work...
  - consider other final states such as γγ
  - new features to be included into an updated version of generator

validation of X → WW decay implementation

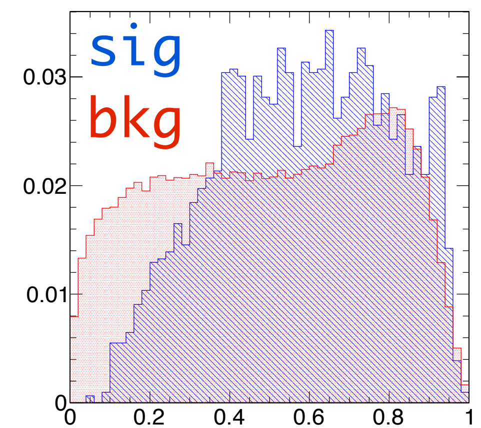


analysis implementation

- angular variables can be used to improve signal sensitivity over background and to distinguish between various signal hypotheses
  - consider ZZ → 4l for the following tests though there are interesting possibilities for other final states such as WW, $\gamma\gamma$, etc
  - use the JHU generator as signal MC for tests; background with Powheg ZZ – include detector smearing and analysis cuts
- consider 2 epochs based on available statistics and channel resolution: hypothesis testing and parameter fitting
  - hypothesis testing with lower statistics – nearer term – to distinguish between different models
  - parameter fitting with more statistics – longer term – to extract couplings directly
- in both cases, a multivariate model for both signal and background are necessary

hypothesis testing

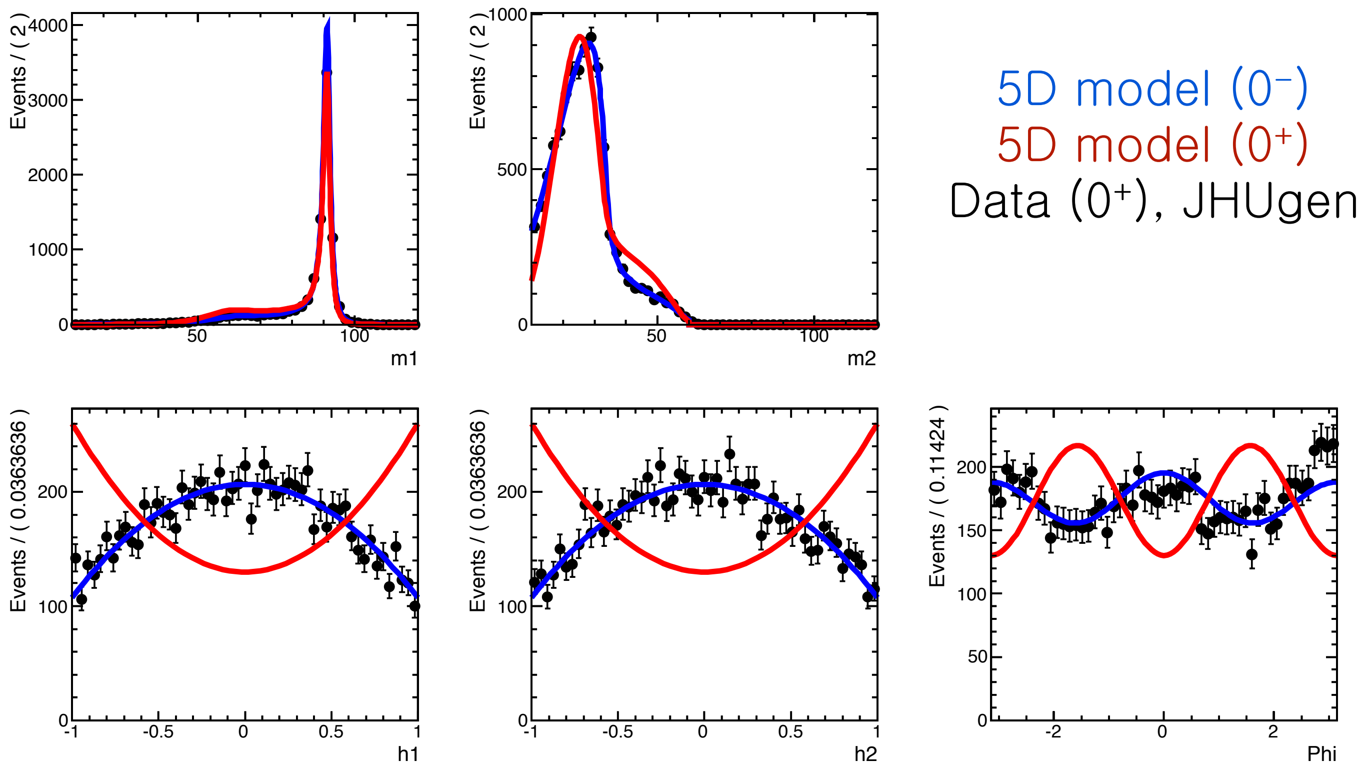
- direct approach: use 8-dimensional model and use likelihood ratios
- discriminant approach: condense N-d into discriminant
  - given technical considerations, propose a 2-d model $\{m_{4l}, D\}$
    - conceptually an 8-d PDF $\{m_{ZZ}, m_{Z1}, m_{Z2}, \Theta_1, \Theta_2, \Phi, \Theta^*, \Phi_1\}$ reduced to a 2-d PDF to handle issue computing N-d statistical tests requiring many toy experiments
  - MELA discriminant, develop correlated 2-d $\{m_{4l}, D\}$ PDFs to discriminate between various hypotheses
  - advantage – computational improvement given limit setting chains in experimental collaborations, cancellation in acceptance effects
  - disadvantage – for signal separation, background not optimally modeled
- other discriminants for comparison such as BDT, ME, BNN, etc



signal model

- Signal model is fully correlated analytic 8-d model $\{m_{ZZ}, m_1, m_2, \Theta_1, \Theta_2, \Phi, \Theta^*, \Phi_1\}$
  - Model takes as inputs directly spin-0 couplings a_1, a_2, a_3
  - N.B. production angles Θ^*, Φ_1 are uncorrelated and flat

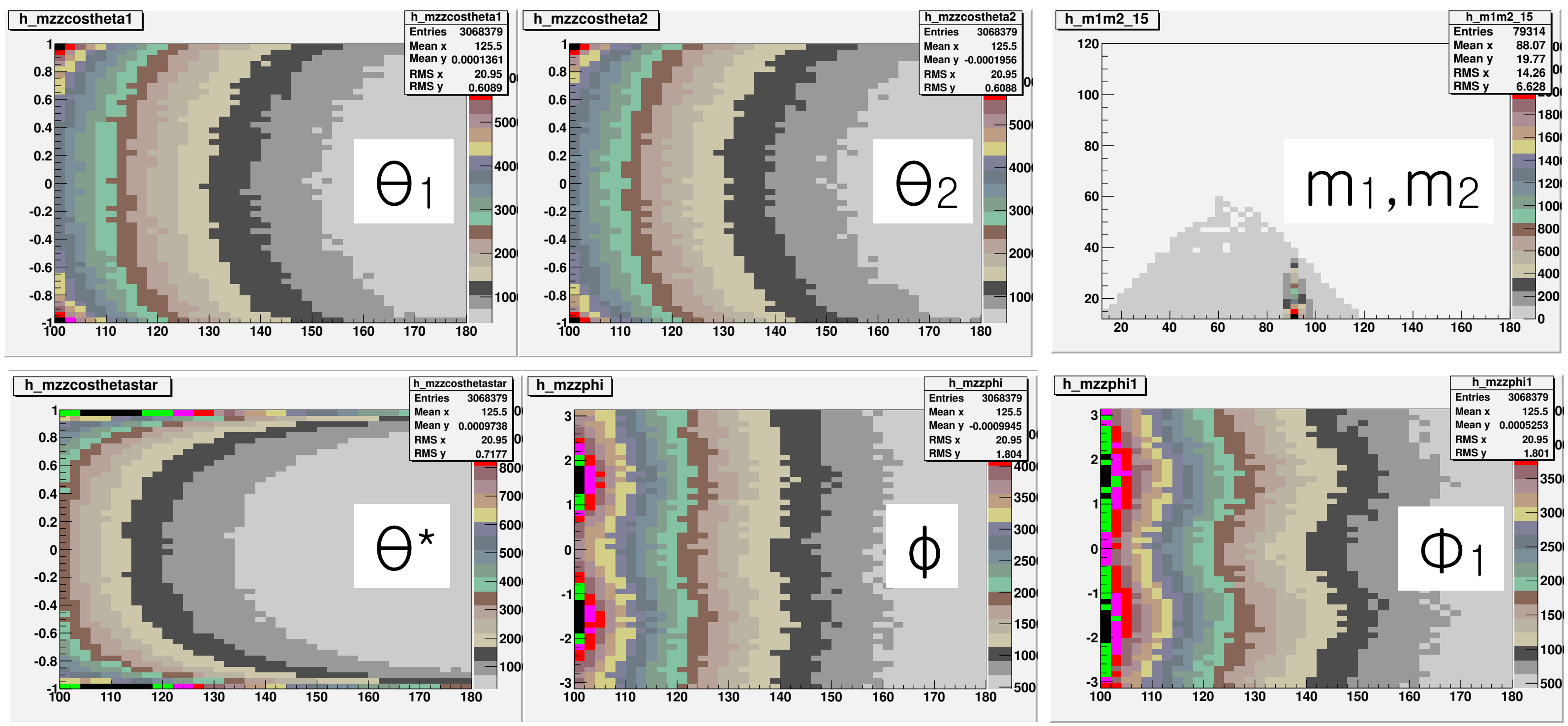
m_X = 125 GeV



models (continued)

background model templated in bins of m_{4l}

$$P(D, m_{4l}) = P(m_{Z1}, m_{Z2}; m_{4l}) \times P(\Theta_1; m_{4l}) \times P(\Theta_2; m_{4l}) \times P(\Phi; m_{4l}) \times P(\Theta^*; m_{4l}) \times P(\Phi_1; m_{4l})$$



background template model shown; effort for analytic PDFs of background in literature, to be adapted for experimental techniques:

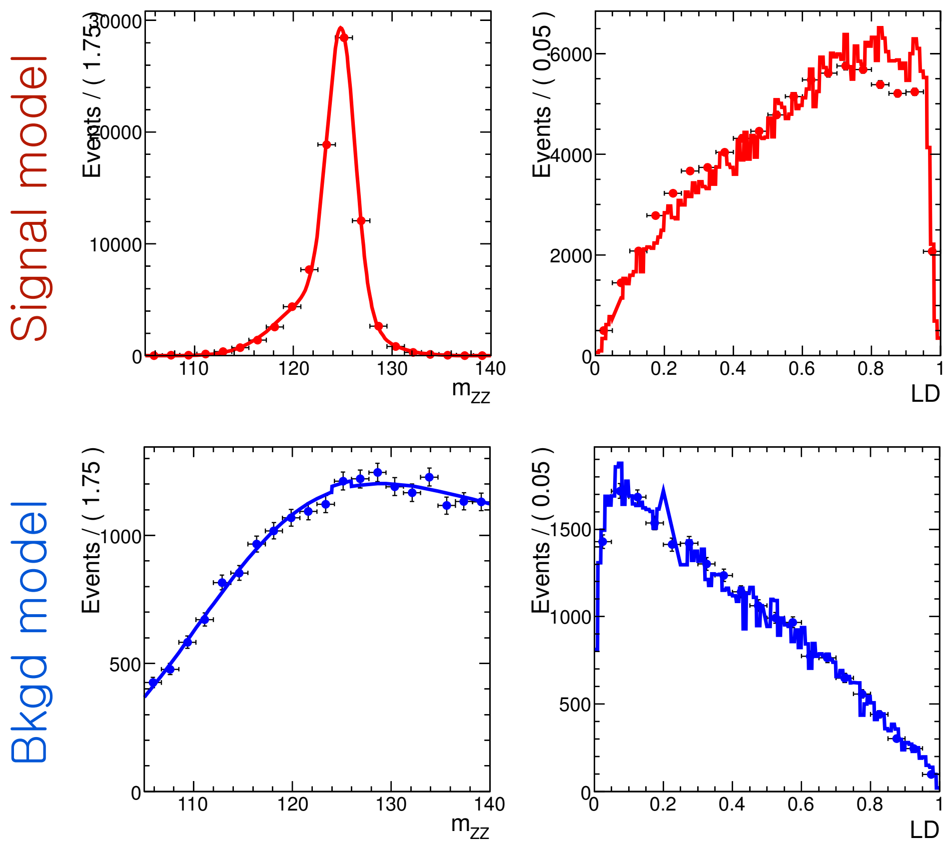
Low, Gainer, Kumar, Vega-Morales, arXiv:1108.2274

discriminant MELA, S vs. B

Build a discriminant using signal and background models

condense 8-d model into 2-d model {mZZ, LD} for discriminant approach

$$\mathcal{LD}(m_1, m_2, \vec{\Omega} \mid m_{4\ell}) = \left[1 + \frac{\mathcal{P}_{\rm bkg}(m_1, m_2, \vec{\Omega} \mid m_{4\ell})}{\mathcal{P}_{\rm sig}(m_1, m_2, \vec{\Omega} \mid m_{4\ell})}\right]^{-1}$$



signal = SM Higgs

mH = 125 GeV

Statistically independent samples to build D (lines) and validate (points)

Realistic smeared samples with "CMS-like"analysis cuts

pT > 20,10,7,7

$|\eta| < 2.4$

cuts on $m_{Z1/Z2}$ = [12/50, 120]

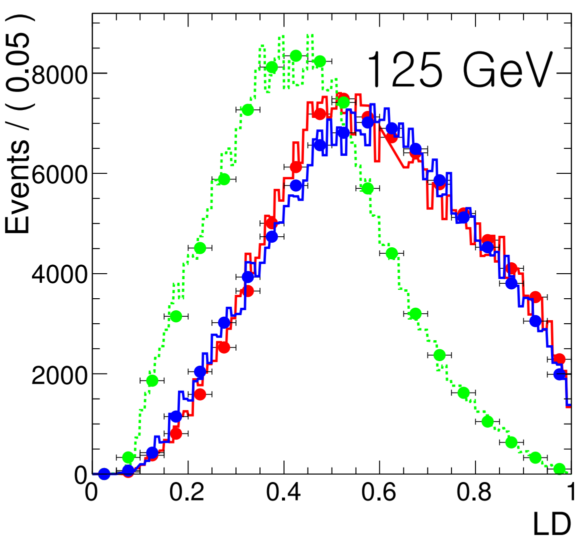
discriminant MELA, S_{0+} vs S_{0-}

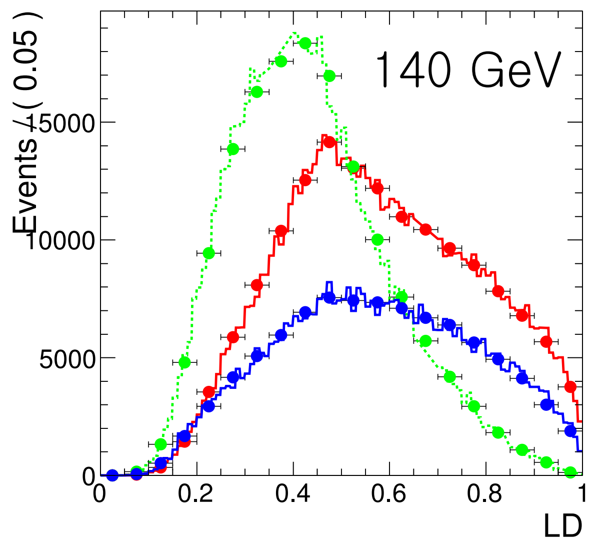
To separate two hypotheses, we build a discriminant using two different signal models

$$\mathcal{LD}(m_1, m_2, \vec{\Omega} \mid m_{4\ell}) = \left[1 + \frac{\mathcal{P}_{\text{bkg}}(m_1, m_2, \vec{\Omega} \mid m_{4\ell})}{\mathcal{P}_{\text{sig}}(m_1, m_2, \vec{\Omega} \mid m_{4\ell})} \right]^{-1}$$

PS Higgs
SM Higgs

Background, Signal 0^+, Signal 0^-





Compute background PDF in order to do hypothesis separation tests.

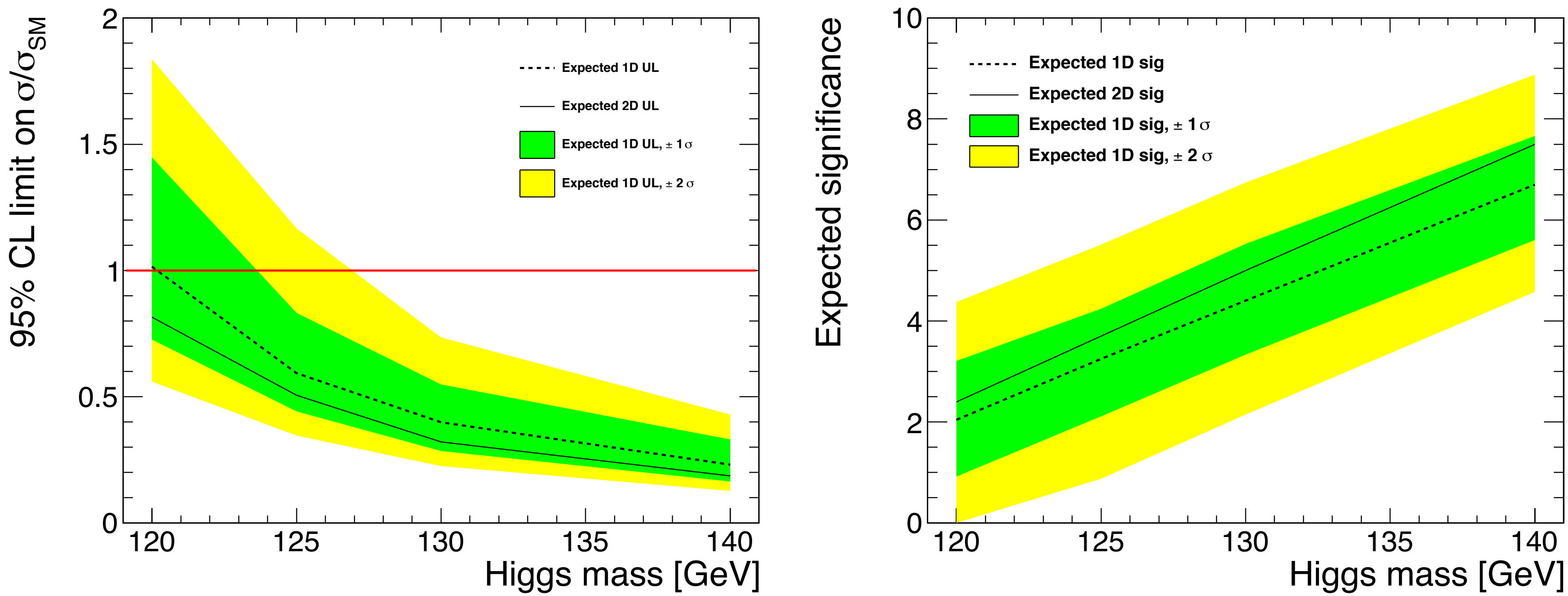
S_{0+} + B vs S_{0-} + B

Loss of information from discriminant approach

statistical tests

using the MELA 2-d PDFs, look at expected improvement over simple 1-d {m_{ZZ} only} approach

Yields for expected number of events at 20 fb^{-1} @ 8 TeV



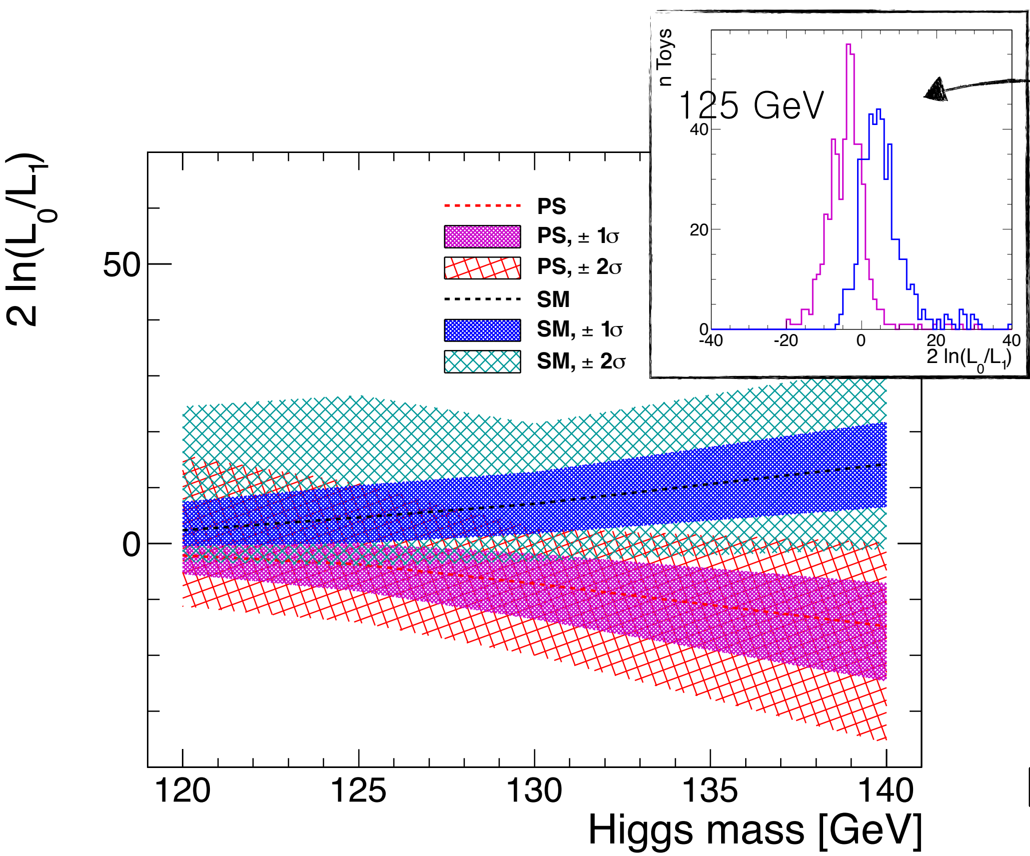
Expect 15% improvement on UL and significance

N.B. systematics not included, evaluation of MELA shape systematics on-going

signal separation

For 20 fb^{-1} of data, also use MELA discriminant to separate SM (0^+) from pseudoscalar (0^-) signal hypothesis

compute estimator $S = 2\ln(L_0/L_1)$ as test statistic



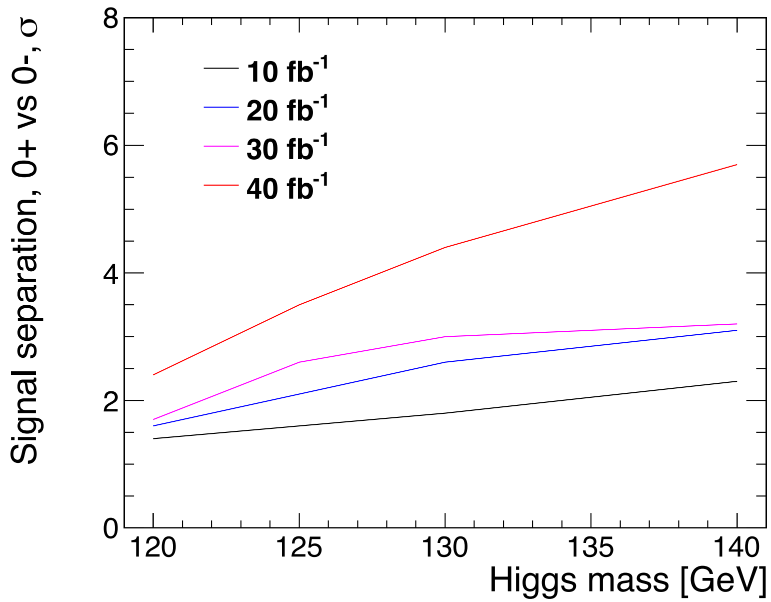
Neyman−Pearson hypothesis testing, effective separation of Gaussian peaks

mass	expected separation
120	1.6 σ
125	2.1 σ
130	2.7 σ
140	3.8 σ

Better separation at higher Higgs mass due to larger σ*BR

projections

projection of signal separation for 0^+ and 0^- for different luminosities @ 8 TeV



expand more than just 0^+ and 0^-:

define many scenarios and create a "matrix" of how well we can separate different signal hypotheses

example for 250 GeV, 30 signal events

	0^-	1^+	1^-	2^+_m	2^+_L	2^-
0^+	4.1	2.3	2.6	2.8	2.6	3.3
0^-	–	3.1	3.0	2.4	4.8	2.9
1^+	–	–	2.2	2.6	3.6	2.9
1^-	–	–	–	1.8	3.8	3.4
2^+_m	–	–	–	–	3.8	3.2
2^+_L	–	–	–	–	–	4.3

Previous studies include following motivated models:

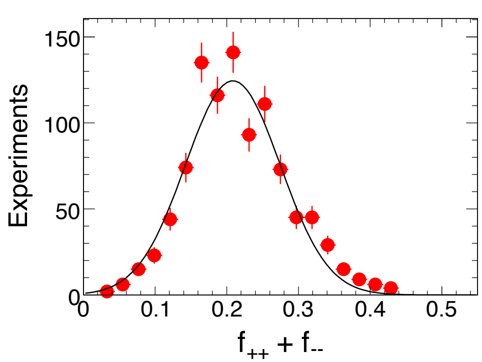
$J^P = 1^+$ (pseudovector), 1^- (vector)

$J^P = 2^+_m$ (RS graviton), 2^+_L (RSG, SM in bulk), 2^- (pseudotensor)

parameter fitting

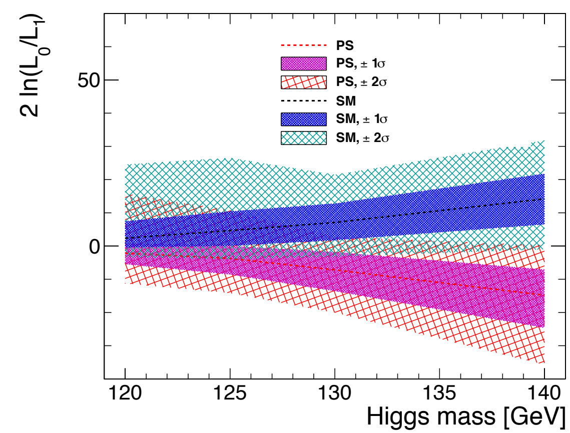
- most general approach to maximize likelihood w.r.t. angular parameters
- with more accumulated statistics, can directly fit for helicity amplitudes or couplings
  - no discriminant, fit directly from 8-d distribution
  - computationally advantageous, numerically would have to scan in a multi-dimensional parameter space
- example, for 150 signal events, m_X = 250 GeV
  - equivalent to ~200 fb^{-1} at 125 GeV
  - fit for SM higgs helicity amplitudes and phases

	$m_X = 250$ GeV generated	$m_X = 250$ GeV fitted without detector	$m_X = 250$ GeV fitted with detector	$m_X = 1$ TeV generated	$m_X = 1$ TeV fitted without detector	$m_X = 1$ TeV fitted with detector
$n_{\rm sig}$	150	150 ± 13	153 ± 15	150	150 ± 12	152 ± 12
$(f_{++} + f_{--})$	0.208	0.21 ± 0.07	0.23 ± 0.08	0.000	0.00 ± 0.03	0.00 ± 0.03
$(f_{++} - f_{--})$	0.000	0.01 ± 0.13	0.01 ± 0.14	0.000	0.00 ± 0.02	0.00 ± 0.02
$(\phi_{++} + \phi_{--})$	2π	6.30 ± 1.46	6.39 ± 1.54	2π	free	free
$(\phi_{++} - \phi_{--})$	0	0.00 ± 1.06	0.01 ± 1.09	0	free	free



outlook & summary

- a program is presented for extracting spin, CP, and couplings of a new resonance using event kinematics
- MELA approach – a flexible likelihood approach including fully differential distributions for improved sensitivity over background, signal separation and fitting directly for couplings
- implementation for $ZZ \to 4l$ in m_H = 120–140 region
  - MELA 2-d PDF gives boost of ~15% in UL and significance
  - for a ~3σ significance, can distinguish between 0^+ and 0^- signal at ~2σ
- Preparations on-going including extensions in other modes such as WW and γγ
  - improved spin-0 vs spin-2 signal separation



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