The Higgs Boson in the Golden Channel

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Particle Physics Seminar
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Based on

- **1108.2274**/ JHEP 1111 (2011) 027

  JSG, Kumar, Low, Vega-Morales

- **1210.0896**/ PRD 87 (2013) 055006

  Avery, Bourilkov, Chen, Cheng, Drozdetskiy, JSG, Korytov, Matchev, Milenovic, Mitselmakher, Park, Rinkevicius, and Snowball

- **1304.4936** / PRL 111 (2013) 041801

  JSG, Lykken, Matchev, Mrenna, Park

- **1310.1397**

  Chen, Cheng, JSG, Korytov, Matchev, Milenovic, Mitselmakher, Park, Rinkevicius, Snowball

Outline

- Discovering the Higgs in $H \rightarrow ZZ^* \rightarrow 4\,\ell$
  - General information
  - The Matrix Element Method
- Measuring Higgs Properties
  - Geolocation
  - Interference

Why look at $H \rightarrow ZZ^* \rightarrow 4\ \ell$?

The Standard Model Higgs

- A major motivation for the Higgs is to give mass to the W and Z bosons.

$$\Phi(x) = \begin{pmatrix} \theta_2 + i\theta_1 \\ \frac{1}{\sqrt{2}}(v+H) - i\theta_3 \end{pmatrix} = e^{i\theta_a(x)\tau^a(x)/v} \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}}(v+H(x)) \end{pmatrix}$$

- The $|D_\mu\Phi|^2$ term in the Lagrangian gives both

cf. Djouadi, (2005); Dawson, Gunion, Haber, Kane (1989)

$$-\frac{\sqrt{g_1^2+g_2^2}}{8}v^2 g_{\mu\nu}Z^\mu Z^\nu = -\frac{1}{2}M_Z^2 g_{\mu\nu}Z^\mu Z^\nu$$

and

$$-\frac{\sqrt{g_1^2+g_2^2}}{8}(2vH)g_{\mu\nu}Z^\mu Z^\nu = -\frac{M_Z^2}{v}g_{\mu\nu}HZ^\mu Z^\nu$$

similar story for WW

- unsuppressed tree level HZZ coupling-- strength determined by M_Z

The Standard Model Higgs

- In the Standard Model, the Higgs is also the source of fermion masses

$$\mathcal{L}_F = -\frac{1}{\sqrt{2}}\lambda_e\,(\bar{\nu}_e, \bar{e}_L)\begin{pmatrix} 0 \\ v+H \end{pmatrix} e_R + \cdots$$
$$= -\frac{1}{\sqrt{2}}\lambda_e\,(v+H)\,\bar{e}_L e_R + \cdots$$

- Since the fermion mass comes from v, the coupling of a massive fermion to the Higgs is given by

$$\lambda_f = y_f = \frac{\sqrt{2} m_f}{v}$$

- v = 246 GeV, so other than the top quark, all SM fermions couple relatively weakly to the Higgs

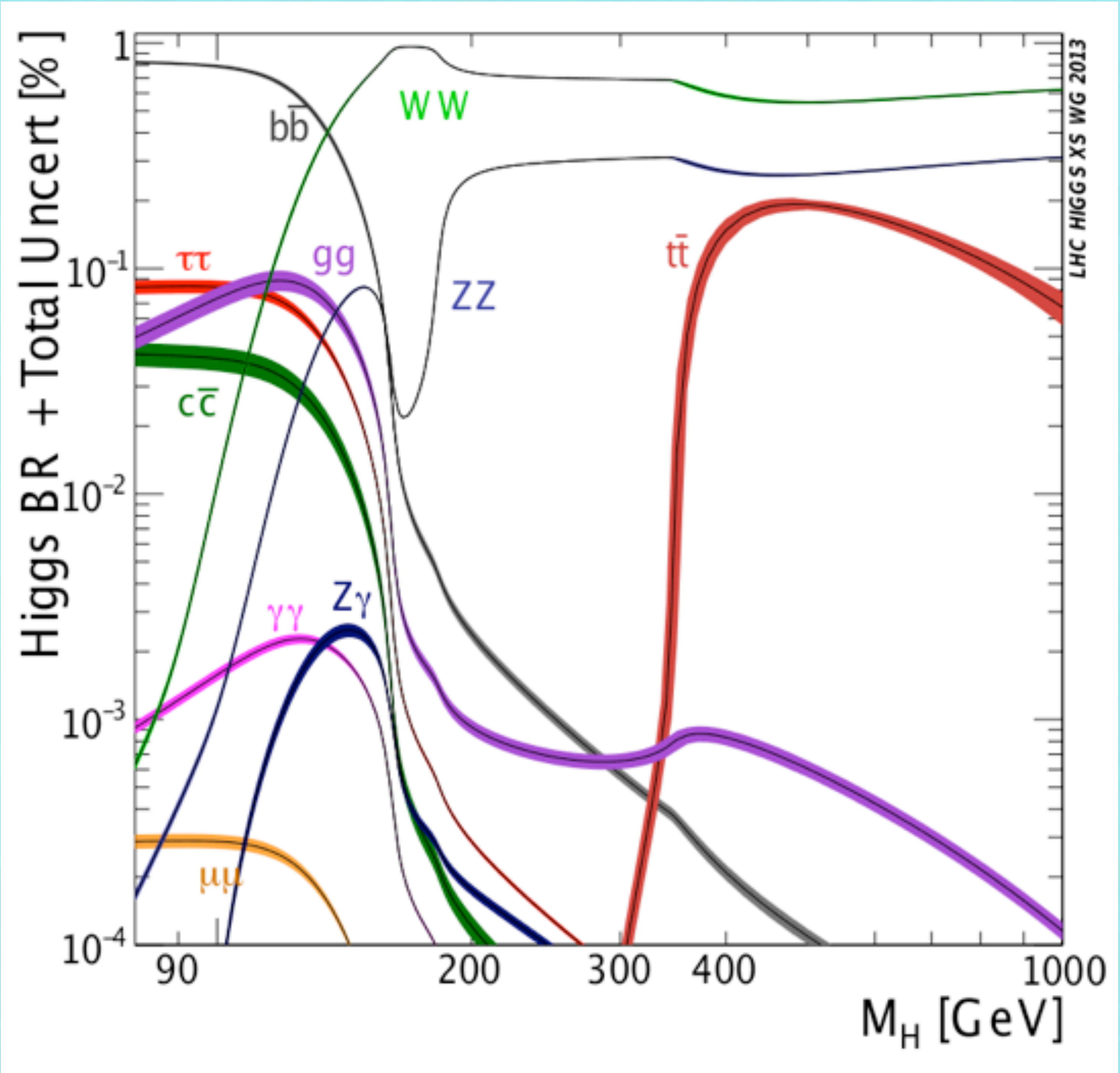
- So "if" $2\,M_Z < M_H < 2\,m_t$, (i.e. the Higgs has an on-shell two body decays into Zs but not tops) **$H \to ZZ$ sizable** (actually even if $M_H > 2\,m_t$).

Time Machine to 2011

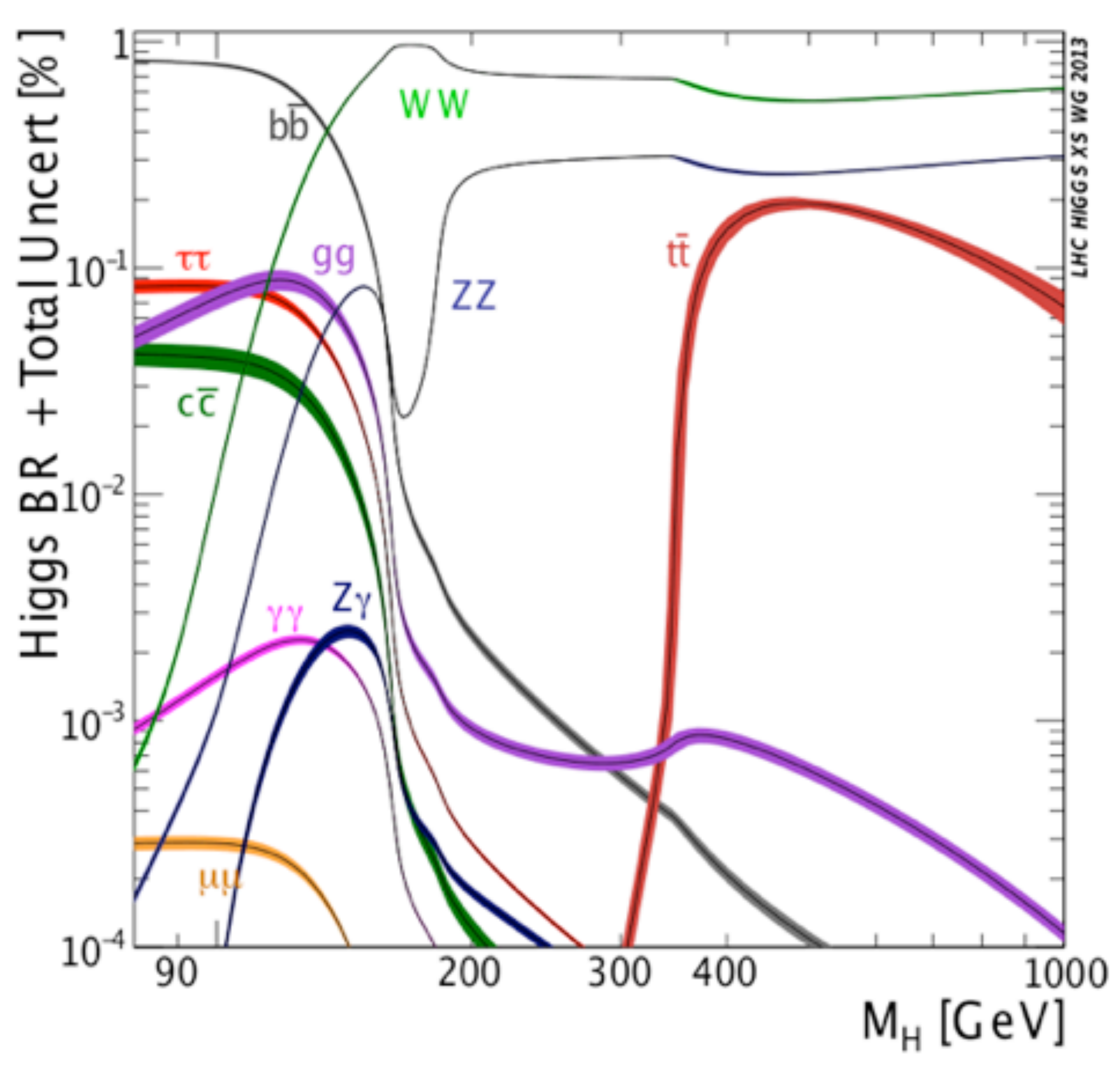
- We're going to pretend that we haven't discovered the Higgs
- Don't worry, we'll re-discover it in about 15 minutes.
  - Really I want to introduce the study of the Higgs with the $4\ \ell$ final state without assuming $m_H \approx 125$ GeV

SM Higgs Branchings

- If $M_H \gtrsim 200$ GeV, decays to WW and ZZ dominate, even above $2\ m_t$
- For $M_H \lesssim 2\ M_W$, decays to WW^* and ZZ^* still important because with $H \to b\bar{b}$ one has to contend with huge QCD backgrounds



Time Machine to 2011



- Clearly, if $M_H \gtrsim 200$ GeV, we should focus on ZZ, WW final states
- Of these, $H \to ZZ \to 4\ \ell$ is the unique fully leptonic, fully reconstructable final state

The Golden Channel

- Leptons are comparatively easy to reconstruct and measure in detectors (QCD makes life hard)
- Downside is $Z \rightarrow \ell^+ \ell^-$ (ℓ = e, μ) is only ≈ 1/16, so leptonic branching fractions cost us a factor of ≈ 260
- So what do S and S/B look like, taking into account the irreducible (LO) $q\bar{q} \rightarrow Z\,(Z/Z^*/g^*) \rightarrow 4\,\ell$ background?

	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

$\langle N \rangle$ for 2.5 fb^{-1} at 7 TeV

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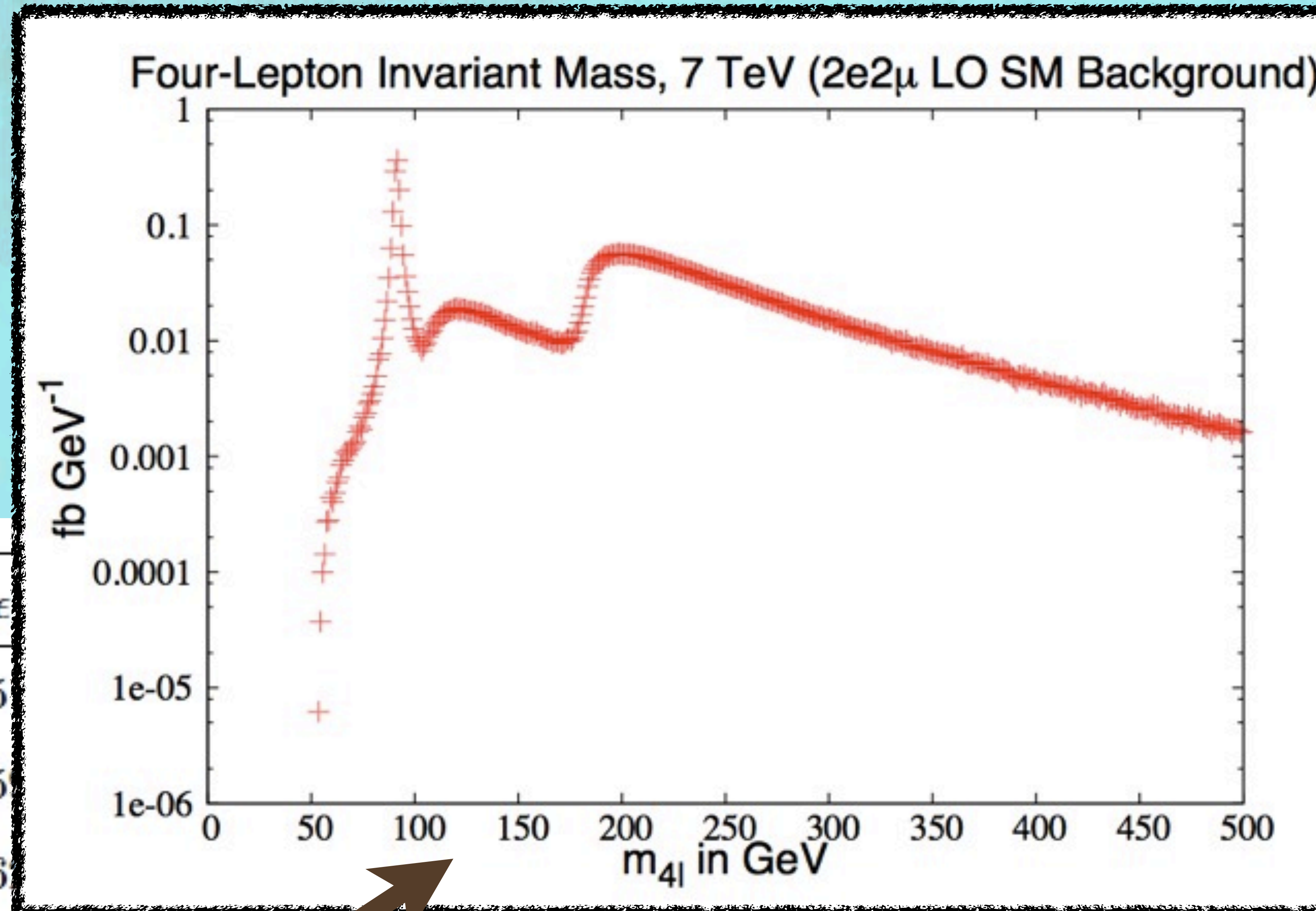

	m_h(GeV)	σ(fb)	ϵ[illegible]	[illegible]
Signal	175	0.218	0.5[illegible]	[illegible]
	200	1.26	0.5[illegible]	[illegible]
	220	1.16	0.6[illegible]	[illegible]
	250	0.958	0.654	1.57
	300	0.714	0.701	1.2[illegible]
	350	0.600	0.7[illegible]8	1.06
Background	-	8.78	0.519	11.4

<N> for 2.5 fb^{-1} at 7 TeV

1108.2274

8.78 fb is spread over wide range of m_{4l}.

Relevant background cross section for a given Higgs mass is substantially smaller.

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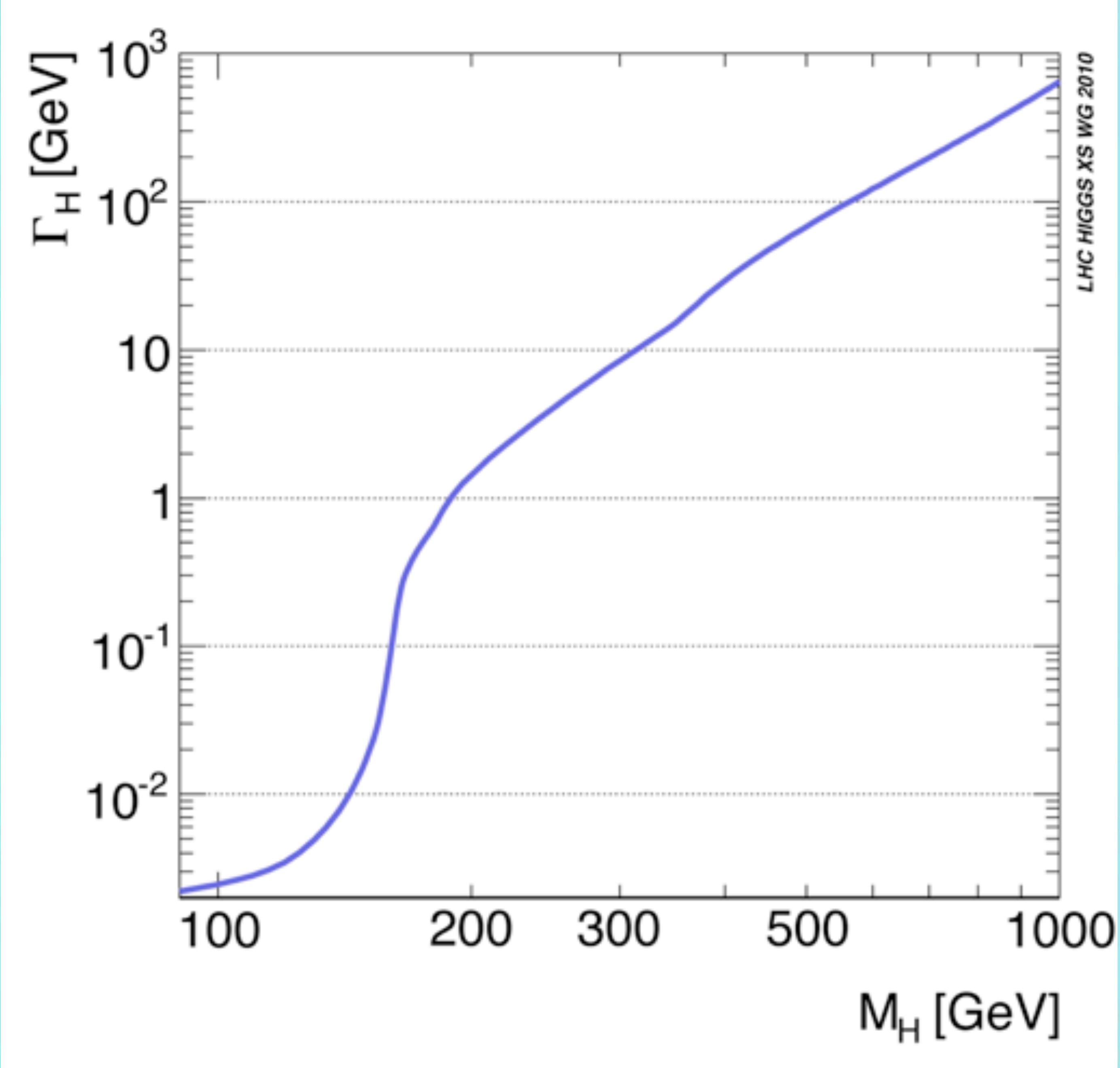

Background is relatively small, but remember Higgs is wide when $M_H > 2\ M_Z$

Taking background with m_{4l} within $2\Gamma_H$ of M_H

	m_h(GeV)	σ(fb)	ϵ	$\langle N \rangle$
Signal	175	0.218	0.512	0.279
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<N> for 2.5 fb^{-1} at 7 TeV

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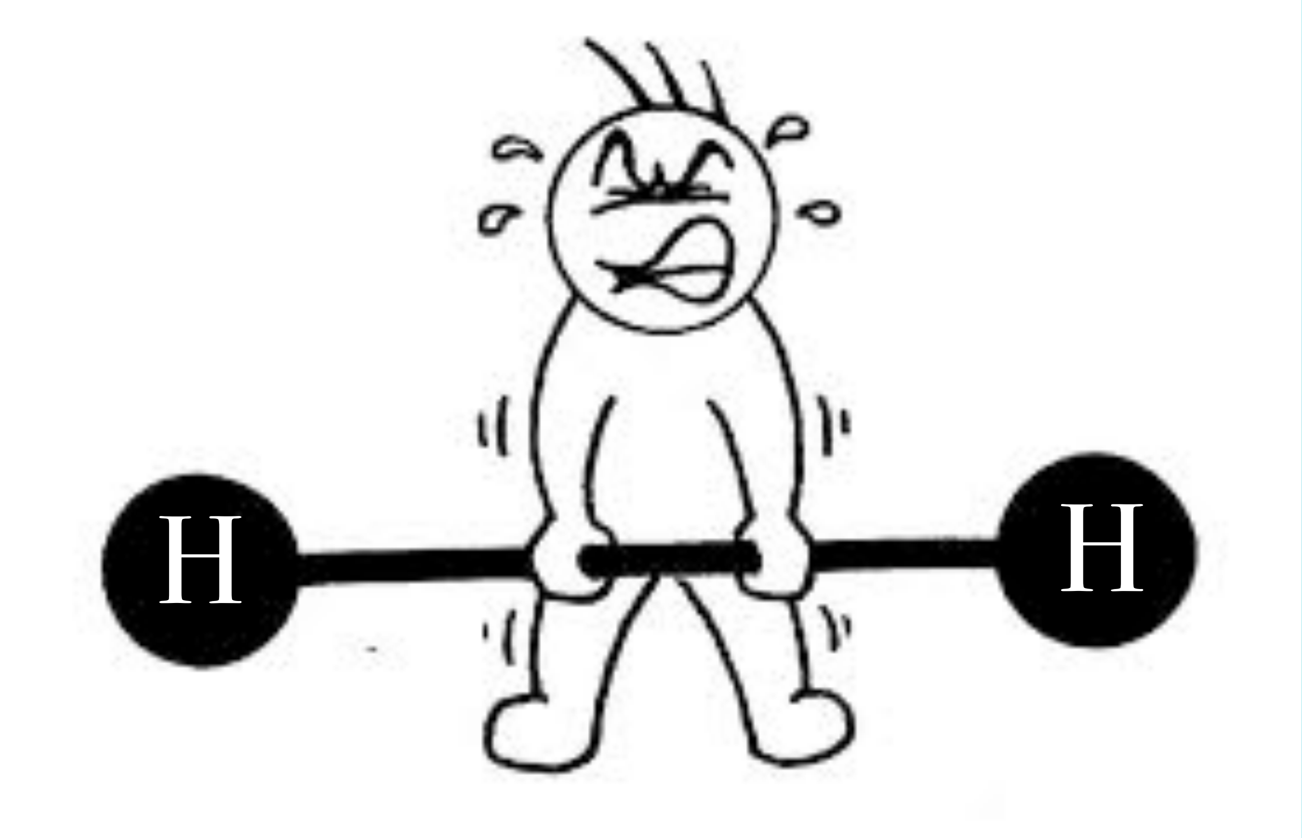
	m_h(GeV)	B	S/B	$S/B^{1/2}$
Background	220	0.94	1.9	1.9
	250	1.1	1.4	1.5
	300	1.1	1.1	1.2
	350	1.1	0.98	1.0

<N> for 2.5 fb^{-1} at 7 TeV

High Higgs Masses

- For a heavy SM Higgs S/ B is fine (~1)
- But S is small



- How can we get the most significance from a small number of events, if M_H is large?

- Use the "**Matrix Element Method**"

- Multivariate Analysis (MVA) which uses the likelihood for all kinematic variables calculated from theory

- Uses all available information in an optimal way

Likelihood Methods

- In general, assume we have N events $\{\mathbf{x}_1, \mathbf{x}_2, \ldots, \mathbf{x}_N\}$
- and we have a model for the process that generates the events $P(\boldsymbol{\alpha}, \mathbf{x})$, where $\boldsymbol{\alpha}$ are parameters of the model
- Then we can find best fit values for the parameters by maximizing the likelihood function (also P) with respect to the parameters, $\boldsymbol{\alpha}$
- i.e. we maximize
  $P(\boldsymbol{\alpha}, \mathbf{x}_1) \times P(\boldsymbol{\alpha}, \mathbf{x}_2) \times P(\boldsymbol{\alpha}, \mathbf{x}_3) \ldots \times P(\boldsymbol{\alpha}, \mathbf{x}_N)$
  with respect to the parameters $\boldsymbol{\alpha}$
- (Really people use $2 \times$ log likelihood since it translates more directly to p-values, σ, etc.)

Matrix Element Method

- In particle physics, the likelihood/ probability function P(**α**, **x**) is the differential cross section

$$\mathcal{P}(\mathbf{p}_i^{\text{vis}}|\alpha) = \frac{1}{\sigma_\alpha}\int dx_1 dx_2 \frac{f_1(x_1)f_2(x_2)}{2sx_1x_2} \times \left[\prod_{i\in\text{final}}\int \frac{d^3p_i}{(2\pi)^3 2E_i}\right] |M_\alpha(p_i)|^2 \prod_{i\in\text{vis}} \delta(\mathbf{p}_i - \mathbf{p}_i^{\text{vis}})$$

Matrix Element Method

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$$\mathcal{P}(\mathbf{p}_i^{\text{vis}}|\alpha) = \boxed{\frac{1}{\sigma_\alpha}} \int dx_1 dx_2 \frac{f_1(x_1) f_2(x_2)}{2 s x_1 x_2} \times \left[\prod_{i \in \text{final}} \int \frac{d^3 p_i}{(2\pi)^3 2 E_i} \right] |M_\alpha(p_i)|^2 \prod_{i \in \text{vis}} \delta(\mathbf{p}_i - \mathbf{p}_i^{\text{vis}})$$

- Normalized by the total cross section after acceptances and efficiencies

- So that the integral over kinematic variables gives 1.

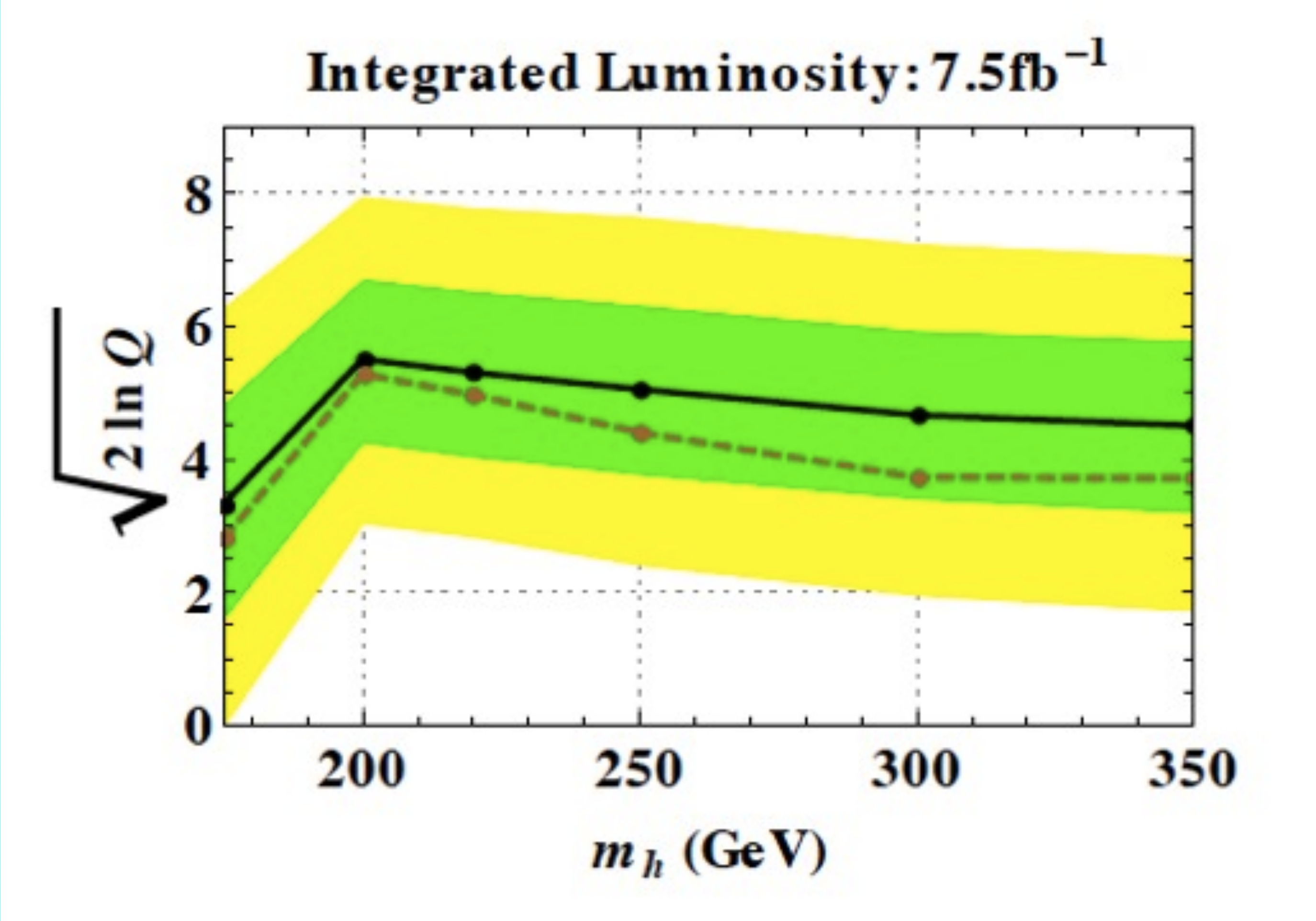
Matrix Element Method

- In general need to integrate over momentum of invisible particles (neutrinos, neutralinos)
- and take into account finite detector resolution by integrating over "transfer functions" that describe how likely the observed momenta is given the true momenta
- For $H \rightarrow ZZ \rightarrow 4\ell$, we can ignore these complications

  (except possibly for m_{4l})

Improving the Sensitivity of Higgs Boson Searches in the Golden Channel

- Quantified the extent to which sensitivity in Golden Channel could be increased using the Matrix Element Method



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

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

$$: \quad \mathcal{A}^{\Delta\sigma}_{0\pm} = \frac{1}{\gamma_1(1-x)}\Bigg[(\Delta\sigma\Delta\lambda)\left(1+\frac{\beta_1^2+\beta_2^2}{2}\right) - 2\cos\Theta$$
$$-(\Delta\sigma\Delta\lambda)(\beta_2^2-\beta_1^2)x + 2x\cos\Theta - (\Delta\sigma\Delta\lambda)\left(1-\frac{\beta_1^2+\beta_2^2}{2}\right)x^2\Bigg]$$

$$\Delta\lambda = 0 \ : \quad \mathcal{A}^{\Delta\sigma}_{\pm\pm} = -(1-\beta_1\beta_2)\cos\Theta - \lambda_1\Delta\sigma(1+\beta_1\beta_2)x \ ,$$

$$\Delta\lambda = 0 \ : \quad \mathcal{A}^{\Delta\sigma}_{00} = 2\gamma_1\gamma_2\cos\Theta\left[((1-x)\beta_1+(1+x)\beta_2)\sqrt{\frac{\beta_1\beta_2}{1-x^2}} - (1+\beta_1^2\beta_2^2)\right]$$

- To calculate differential cross section in a way that also gives a qualitative understanding, we used helicity amplitudes

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

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- i.e. we broke the calculation up into the amplitude for qq (or gg -> H) -> ZZ for each choice of Z helicity
- and the amplitude for Zs of a given helicity to decay to a fermion of specified helicity and angles in the Z rest frame

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- Values shown are for general M_1, M_2

  (Zs not necessarily on-shell)

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(Hagiwara, Hikasa, Peccei, Zeppenfeld, 1986)

TABLE 8
Coefficients for the helicity amplitudes for the processes
$e^+e^- \to ZZ$ and $e^+e^- \to Z\gamma$

$\Delta\lambda$	$(\lambda_1\lambda_2)$	$\mathscr{A}_{\lambda_1\lambda_2}$	$\mathscr{B}_{\lambda_1\lambda_2}$
± 2	$(\pm\mp)$	$-\sqrt{2}(1+\beta^2)$	$\sqrt{2}$
± 1	(± 0)	$\gamma^{-1}[\Delta\sigma\cdot\Delta\lambda(1+\beta^2)-2\cos\Theta]$	
± 1	$(0\pm)$	$\gamma^{-1}[\Delta\sigma\cdot\Delta\lambda(1+\beta^2)-2\cos\Theta]$	$2r(\cos\Theta+\Delta\sigma\cdot\lambda_2)$
0	$(\pm\pm)$	$-\gamma^{-2}\cos\Theta$	$r^2(\cos\Theta+\Delta\sigma\cdot\lambda_2)$
0	(00)	$-2\gamma^{-2}\cos\Theta$	

- The on-shell limit of our expressions reproduces the above results
- In high energy limit +- and -+ dominate
- All amplitudes are, in general, non-vanishing

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(Hagiwara, Hikasa, Peccei, Zeppenfeld, 1986)

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0	$(\pm\pm)$	$-\gamma^{-2}\cos\Theta$	$r^2(\cos\Theta+\Delta\sigma\cdot\lambda_2)$
0	(00)	$-2\gamma^{-2}\cos\Theta$	

- For signal, only ++, --, and 00 are non-zero (due to spin-zero nature of Higgs)
- 00 dominates in high energy limit

1108.2274

(Hagiwara, Hikasa, Peccei, Zeppenfeld, 1986)

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0	$(\pm\pm)$	$-\gamma^{\;2}\cos\Theta$	$r^2(\cos\Theta+\Delta\sigma\cdot\lambda_2)$
0	(00)	$-2\gamma^{\;2}\cos\Theta$	

- So additional ability to distinguish signal from background (beyond m_{4l}) comes from differences in helicity amplitudes

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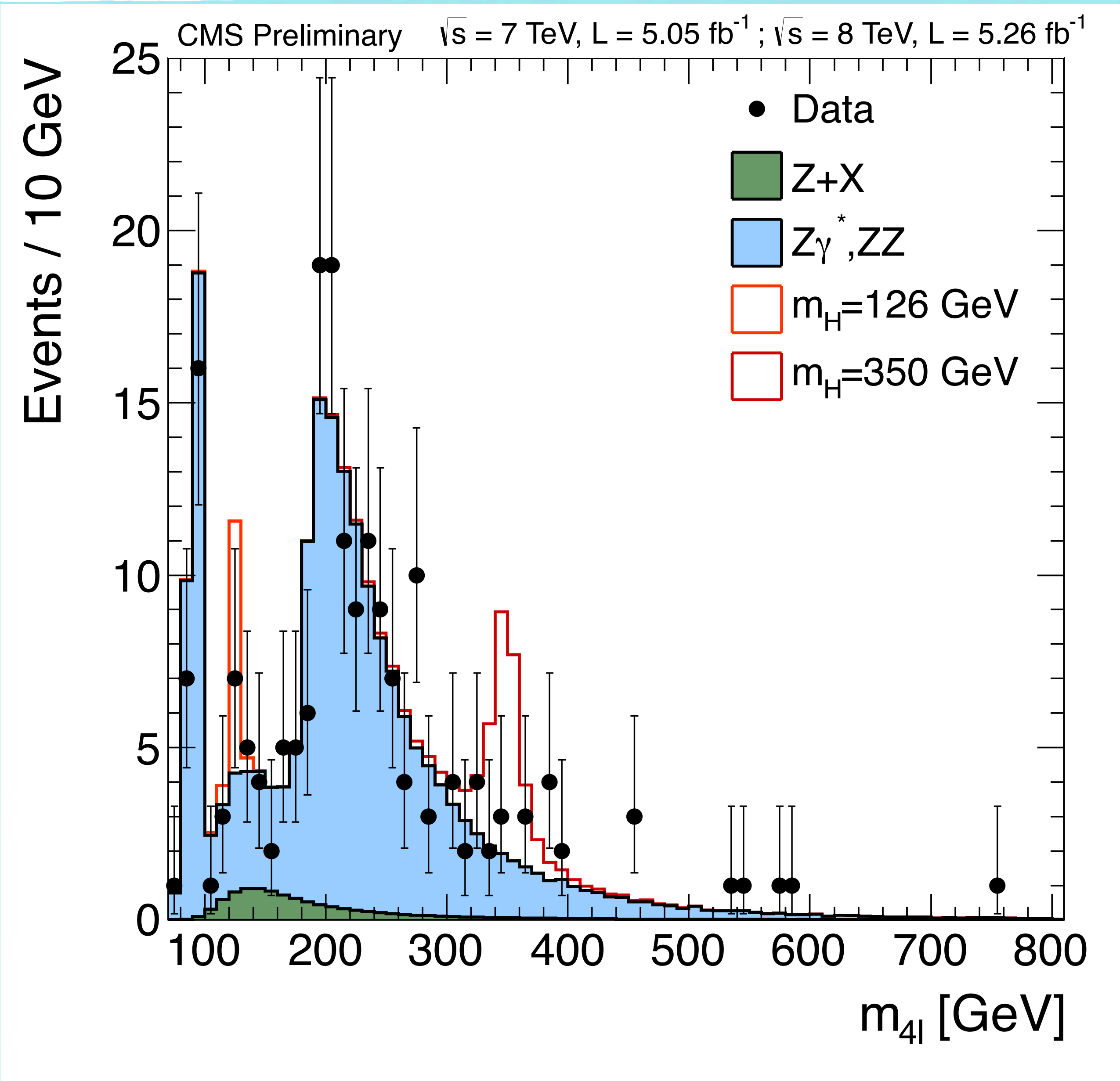
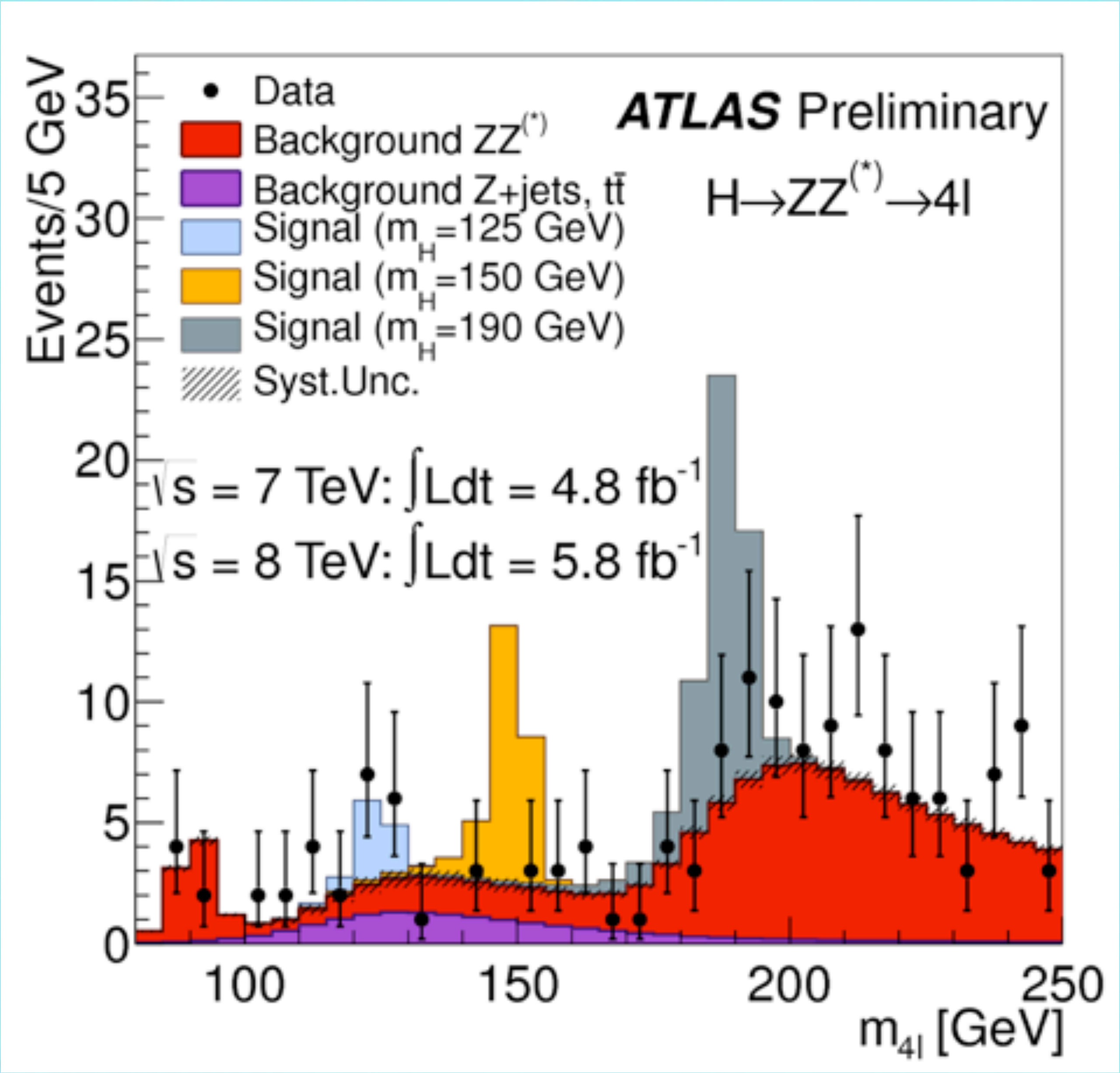
Moving forward to July 2012…

Discovery Plots in 4 ℓ

CMS-PAS-HIG-12-016

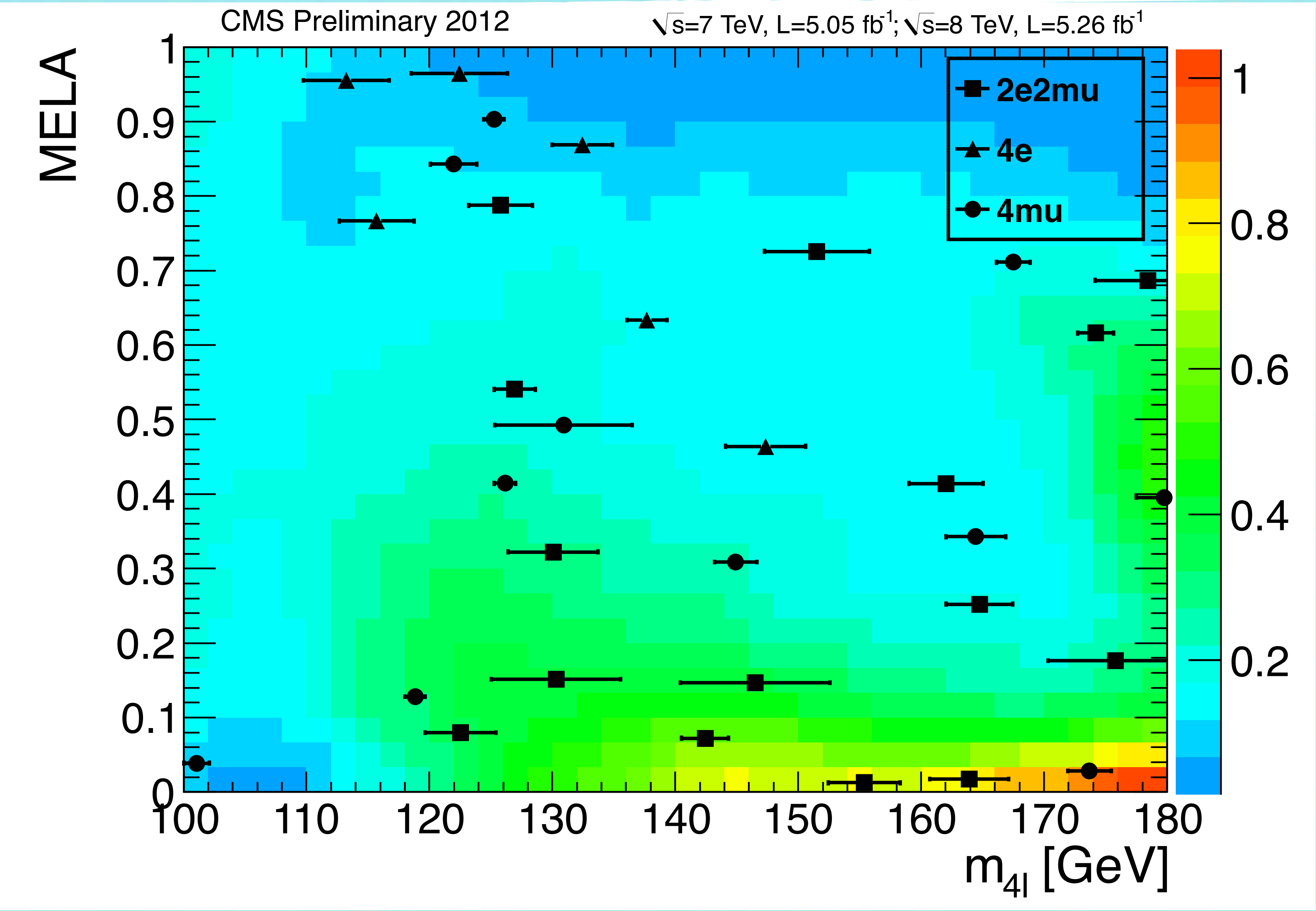


ATLAS-CONF-2012-092



- **Discovery!!!**
- **S/B is in the 1-2 range.**

Matrix Element Method/ MELA



$$KD = P_s/(P_s + P_b)$$

CMS-PAS-HIG-12-016

- CMS used MELA KD
- MELA = Matrix Element Likelihood Analysis
- KD = Kinematic Discriminant: ratio involving signal and background likelihoods
- Quantifies how "signal-like" events are.
- Contours give expected distribution for background events

MELA

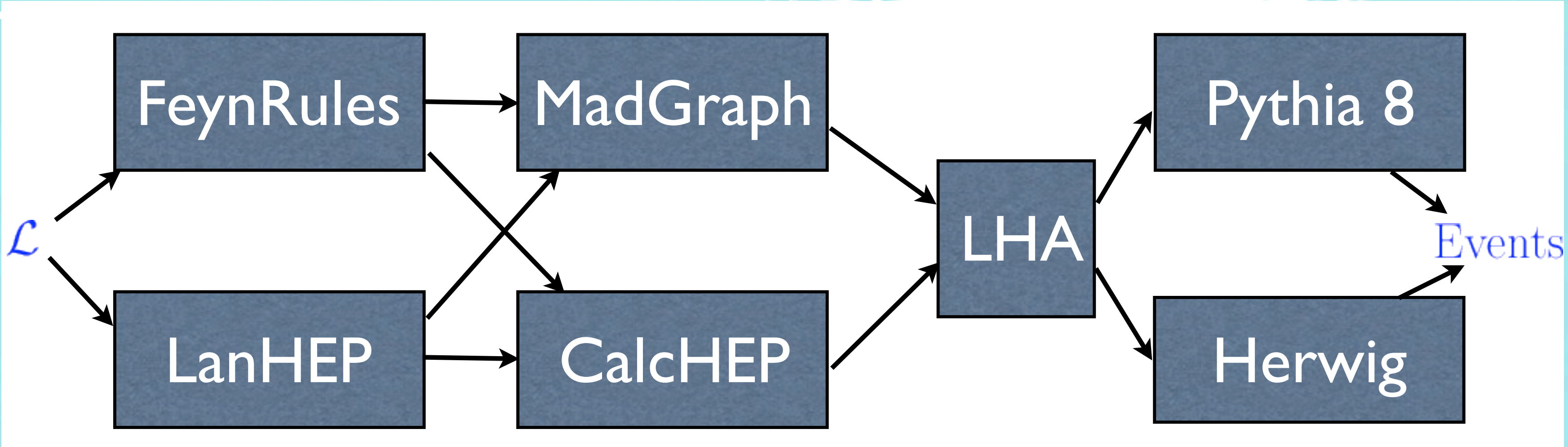
- Used analytic expressions for signal
- POWHEG templates for background < 2 M_Z
(at discovery time-- now use analytic expressions from Chen, Tran, and Vega-Morales (2012))
- Our analytic expressions (from **1108.2274**) for background > 2 M_Z!

- Success of MELA motivates the use of the MEM in experimental analyses

- Not always best to use totally analytic expressions for likelihoods

- Is there a safe (from bugs!), efficient way to develop codes for performing the Matrix Element Method in any given channel?

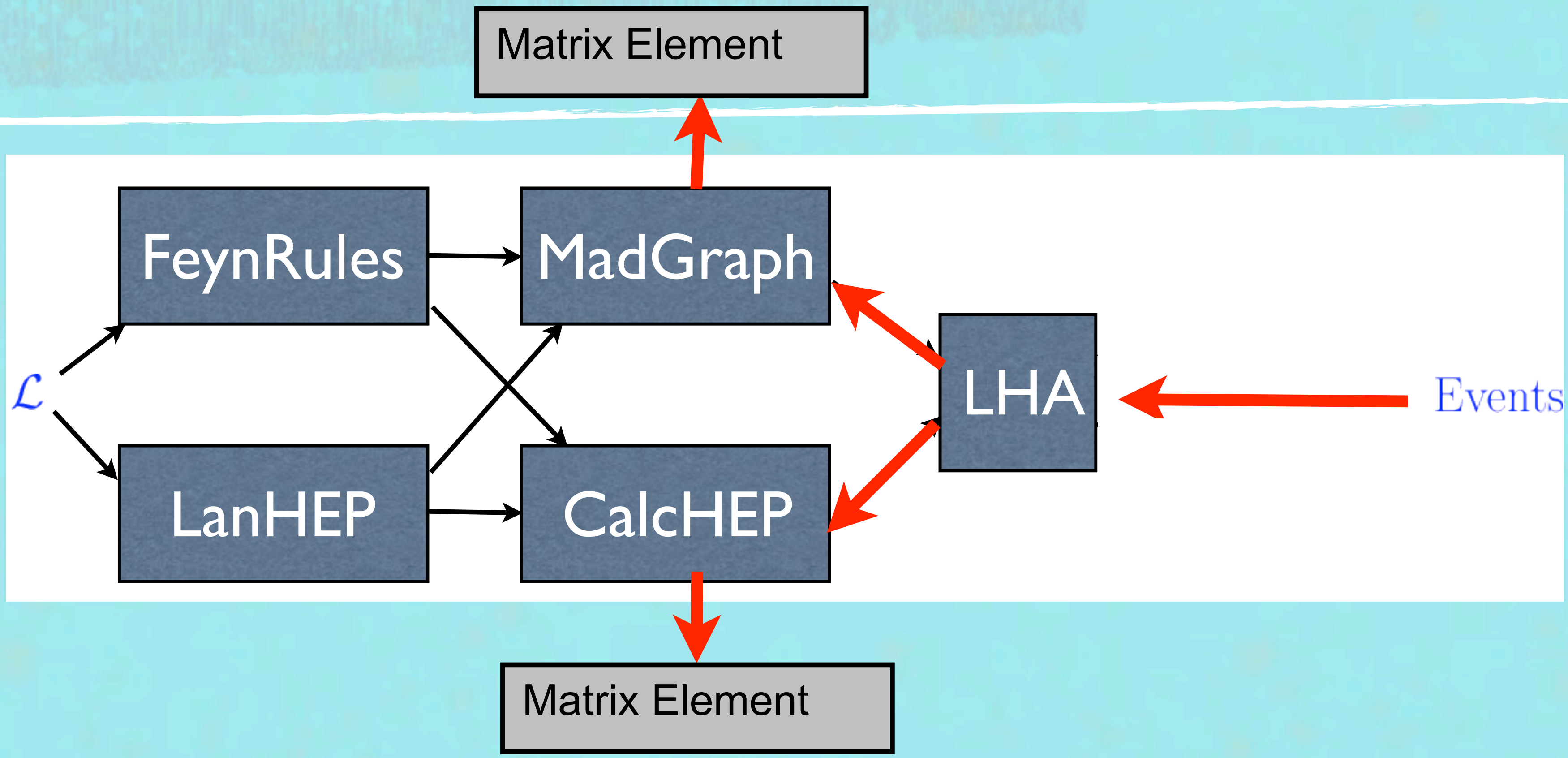
Progress in MC Simulation Tools



From Lagrangian to Events

- There has been a major effort in the theory community toward the automatization and generalization of the MC tools
- Increasingly one can go automatically from Lagrangian to events (calculating matrix elements along the way) for an arbitrary model

From events to ... matrix elements

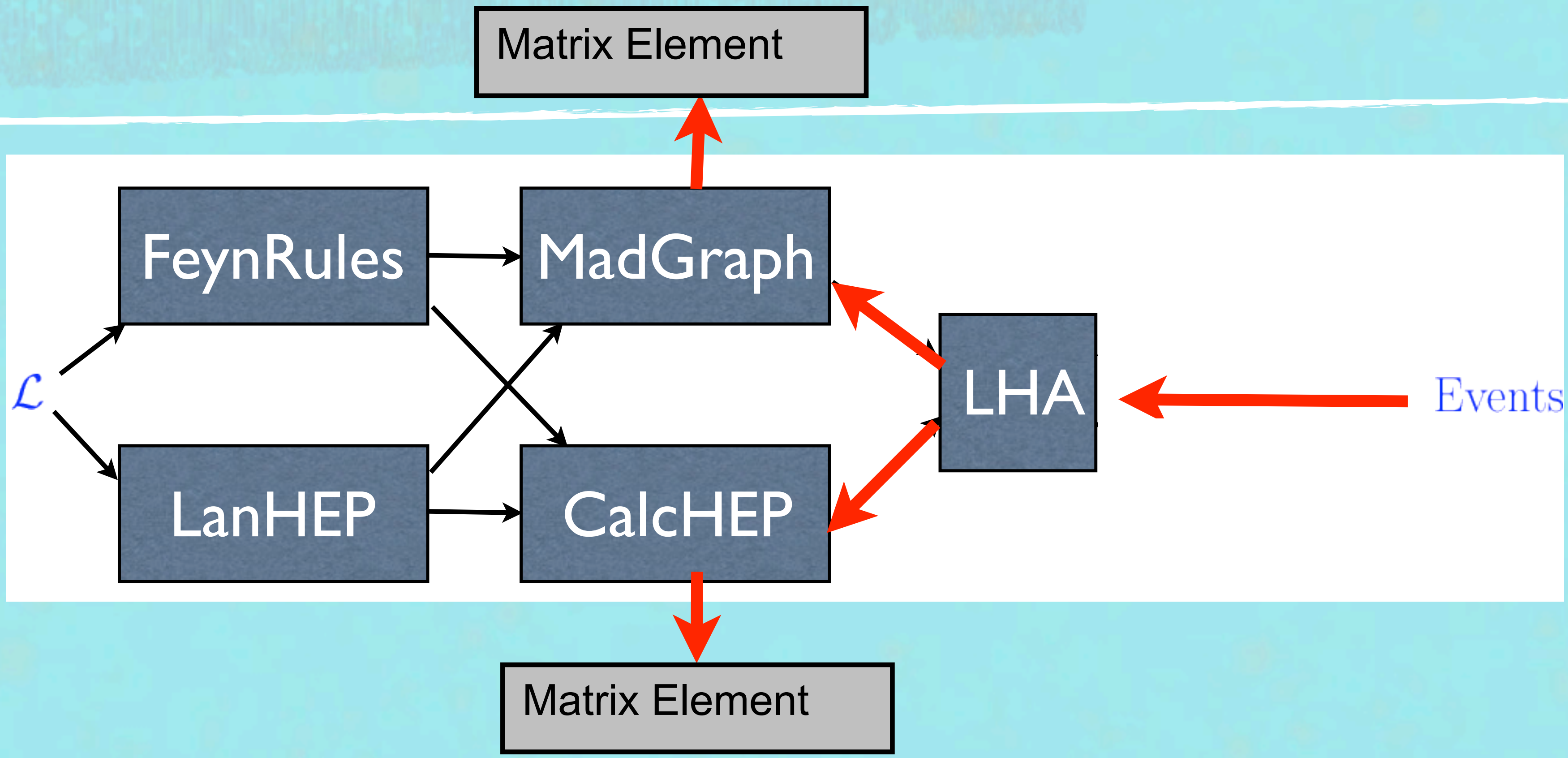


- The same chain of tools can be run in a different direction:

  We can use standard tools to automatically generate code which finds the signal and background squared matrix elements.

- Can be done for an arbitrary signal hypothesis and virtually any background

From events to … matrix elements



- MadWeight is an existing tool along these lines
- Artoisenet, Mattelaer (2008)

  Artoisenet, Lemaitre, Maltoni, Mattelaer (2010)
- Good for many processes, but currently cannot do H -> ZZ -> 4 ℓ

MEKD

- With members of the UF CMS group and Myeonghun Park, created a **publicly available** tool (MEKD) to calculate differential cross sections, etc. for performing the Matrix Element Method in the Golden Channel

- Using well-verified, publicly available packages to automatically generate the matrix-element calculating code

- With as many options/ features relevant to analyses involving the golden channel as possible.

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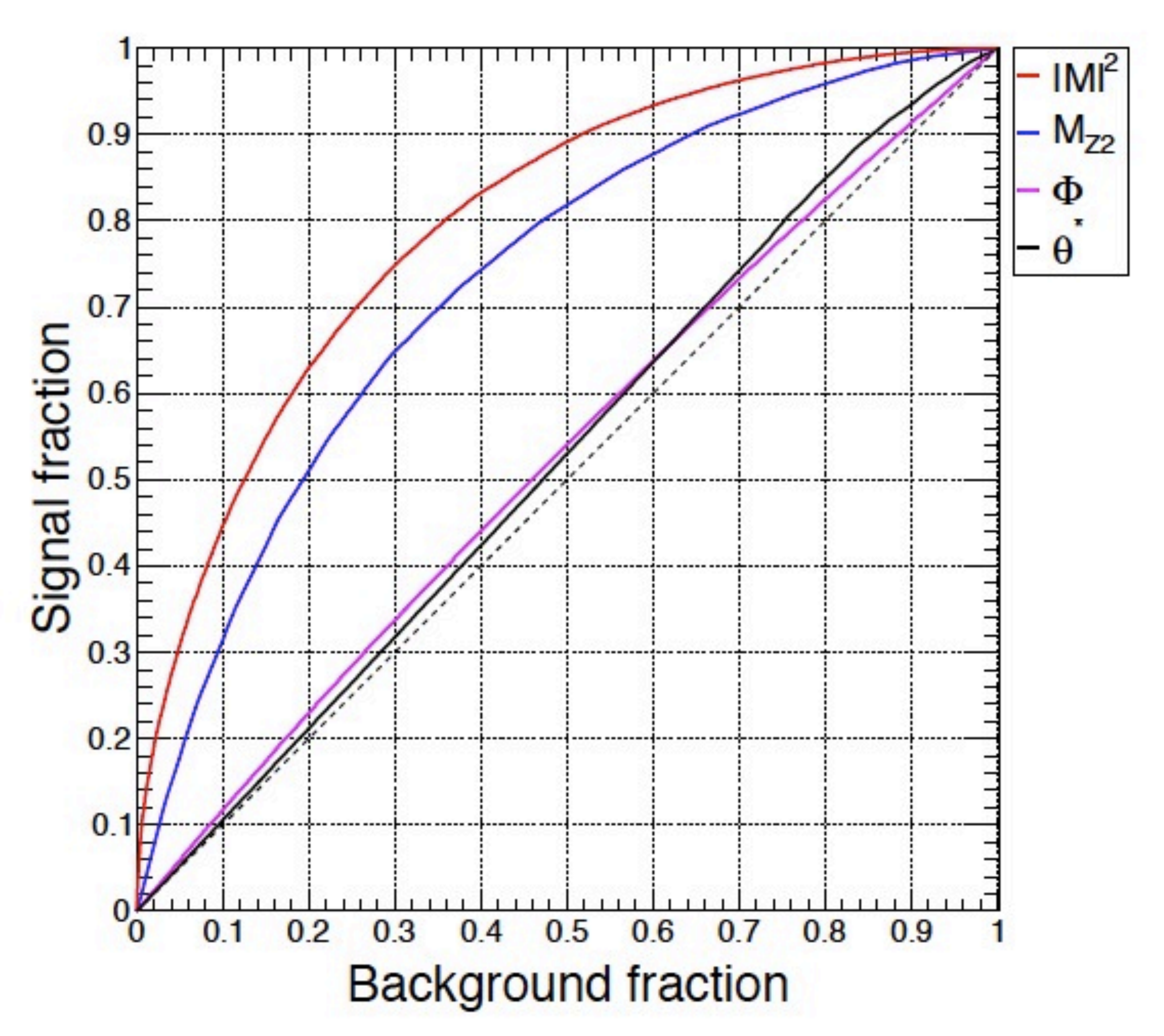

M_2 is a very good variable, though the Matrix Element Method outperforms all single variable analyses

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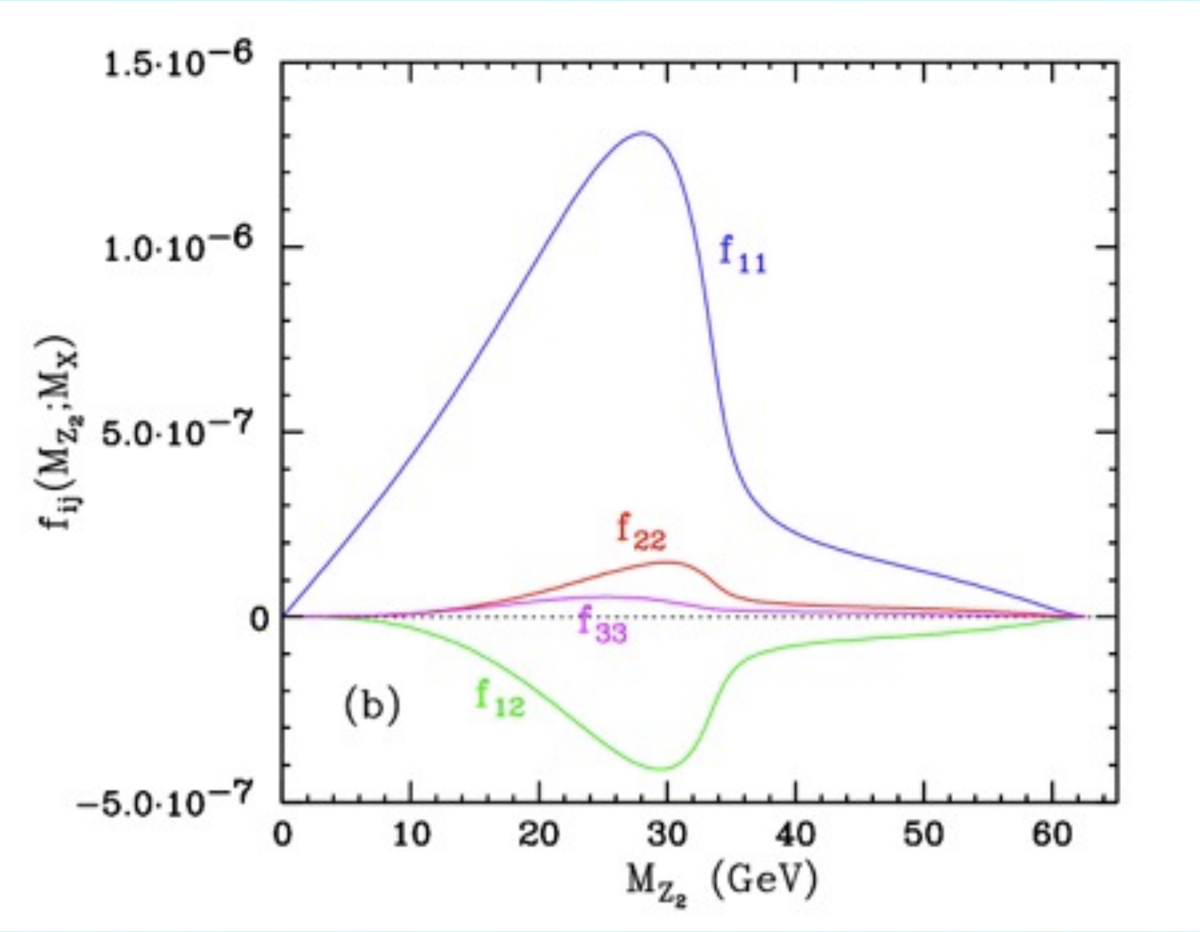
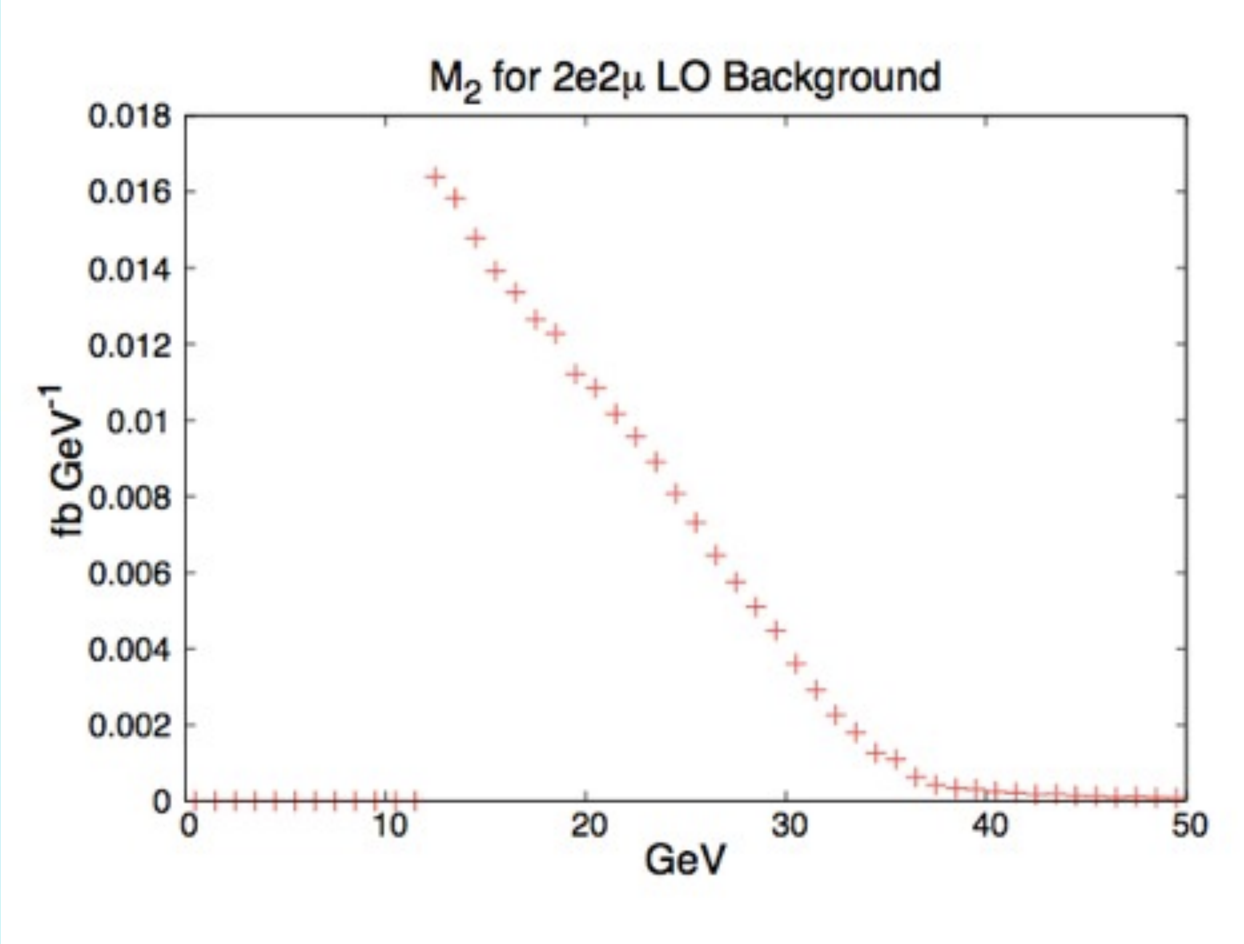
Why M_2 is a Good Variable





f_{11} is SM Higgs

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$M_2 > 12$ GeV from cuts, without cuts, would be singular in limit of massless leptons

Same Method: Different Physics

- MEM increased sensitivity for high mass Higgs because of different ZZ helicity amplitudes
- MEM increased sensitivity for lower (actual) Higgs mass because signal is ZZ^* while background is $Z\gamma^*$
- In both cases, the driver of MVA sensitivity can be clearly related to physics
- Interestingly, in each case different physics drives the sensitivity

Back to the Future…

Moving Forward: Motivation

- Having discovered "a Higgs", we want to measure its properties, in particular its couplings to Z bosons
- **Goal 1**: Be as general as possible (reduce model dependence)
- **Goal 2**: Use as few parameters as possible (keep things manageable)
- To provide a useful framework for presenting experimental results, projections, etc.

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Preliminaries

- We consider a scalar, X, which is a linear combination of CP eigenstates H (0^+) and A (0^-)

$$X \equiv H\cos\alpha + A\sin\alpha$$

- In general, X is not a CP eigenstate
  - $\alpha = 0$ corresponds to pure 0+
  - $\alpha = \pi/2$ corresponds to pure 0-
- We assume that the other mass eigenstate is heavy and can be ignored

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Effective Theory

- We write down general CP-conserving couplings of the H and the A to two Z's
(CP violation will come from mixing)

$$\mathcal{L} \ni \boxed{-\frac{M_Z^2}{v} H Z^\mu \hat{f}^{(H)}_{\mu\nu} Z^\nu} \boxed{-\frac{1}{2} H F^{\mu\nu} \hat{f}^{(H)}_{\mu\nu\rho\sigma} F^{\rho\sigma}}$$
$$\boxed{-\frac{1}{2} A F^{\mu\nu} \hat{f}^{(A)}_{\mu\nu\rho\sigma} F^{\rho\sigma}}$$

The *f* are form factors which generate operators with different symmetry properties.

1304.4936

Form Factors

- CP even couplings which must violate gauge invariance

$$\hat{f}^{(H)}_{\mu\nu} \equiv g_1 g_{\mu\nu} + \frac{g_5}{\Lambda^2}\left(\vec{\partial}_\mu \overleftarrow{\partial}_\nu + g_{\mu\nu}\vec{\partial}^\rho \overleftarrow{\partial}_\rho\right) + \frac{g_6}{\Lambda^2} g_{\mu\nu}\left(\overleftarrow{\Box} + \vec{\Box}\right) + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)$$

Note: g_5, g_6 operators are dimension-5*

- CP even couplings which may preserve gauge invariance

$$\hat{f}^{(H)}_{\mu\nu\rho\sigma} \equiv \frac{g_2}{\Lambda} g_{\mu\rho} g_{\nu\sigma} + \frac{g_3}{\Lambda^3} g_{\mu\rho}\partial_\nu \partial_\sigma + \mathcal{O}\left(\frac{1}{\Lambda^5}\right)$$

- CP Odd Couplings (which preserve gauge invariance)

$$\hat{f}^{(A)}_{\mu\nu\rho\sigma} = \frac{g_4}{\Lambda}\varepsilon_{\mu\nu\rho\sigma} + \mathcal{O}\left(\frac{1}{\Lambda^5}\right)$$

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Couplings

- Keeping only the lowest dimensional terms from each of the three form factors we obtain the following Lagrangian for the coupling of the mass eigenstate X to two Z bosons.

$$\mathcal{L} = X \left[\boxed{\kappa_1 \frac{m_Z^2}{v} Z_\mu Z^\mu} + \boxed{\frac{\kappa_2}{2v} F_{\mu\nu} F^{\mu\nu}} + \boxed{\frac{\kappa_3}{2v} F_{\mu\nu} \tilde{F}^{\mu\nu}} \right]$$

- These operators cover all possible Lorentz structures in the amplitude

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

Gao, Gritsan, Guo, Melnikov, Schulze, Tran (2010)

De Rújula, Lykken, Pierini, Rogan, Spiropulu (2010)

Bolognesi, Gao, Gritsan, Melnikov, Schulze, Tran, Whitbeck (2012)

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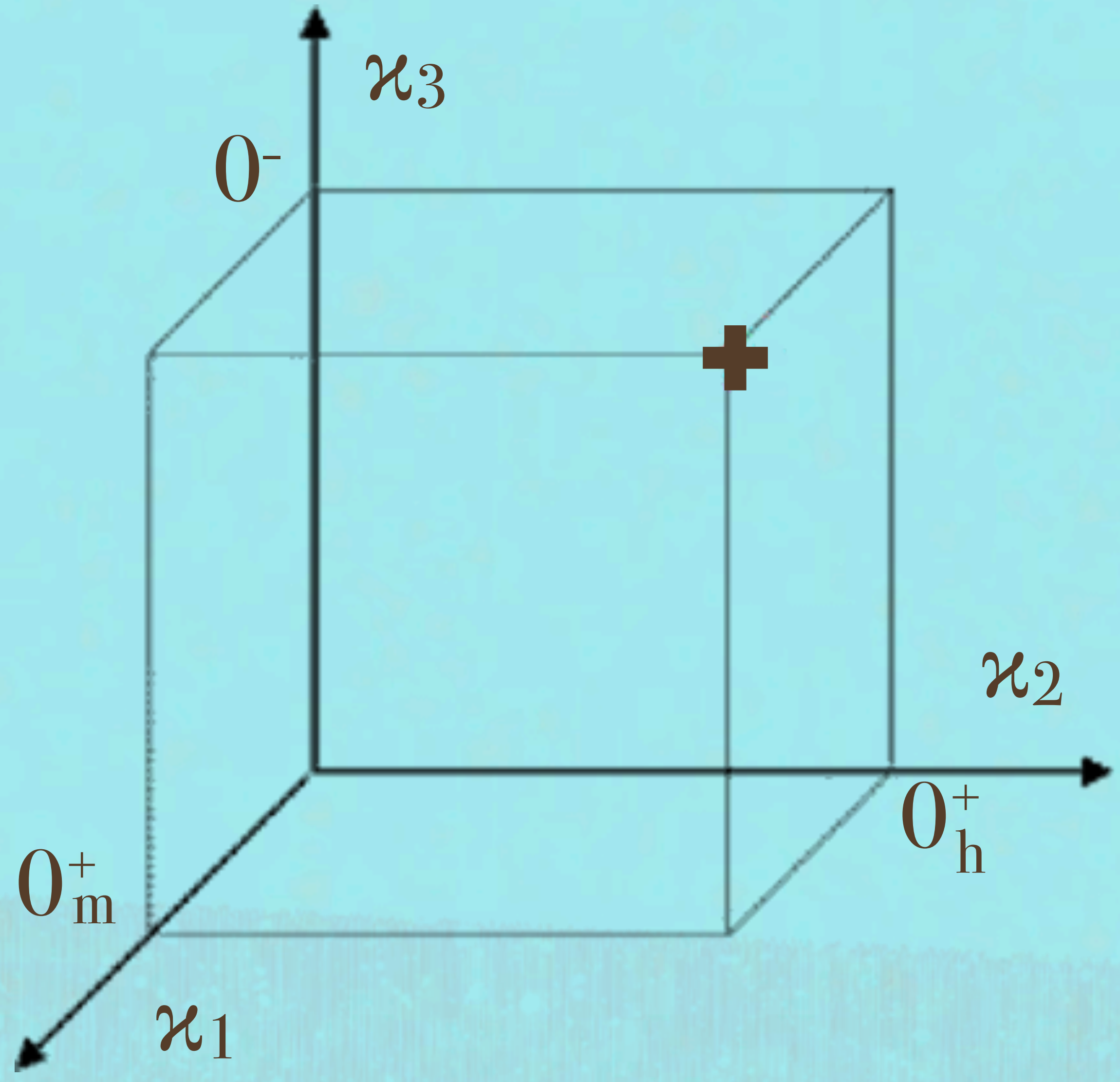
Keeping it Real

- Lagrangians must be real, so the $\varkappa$'s must be real
- The amplitude receives corrections from loops
  - ★ Contributions from heavy particle loops are real
  - ★ Contributions from light particle loops are complex
    - These complex contributions can be mimicked with complex $\varkappa$'s



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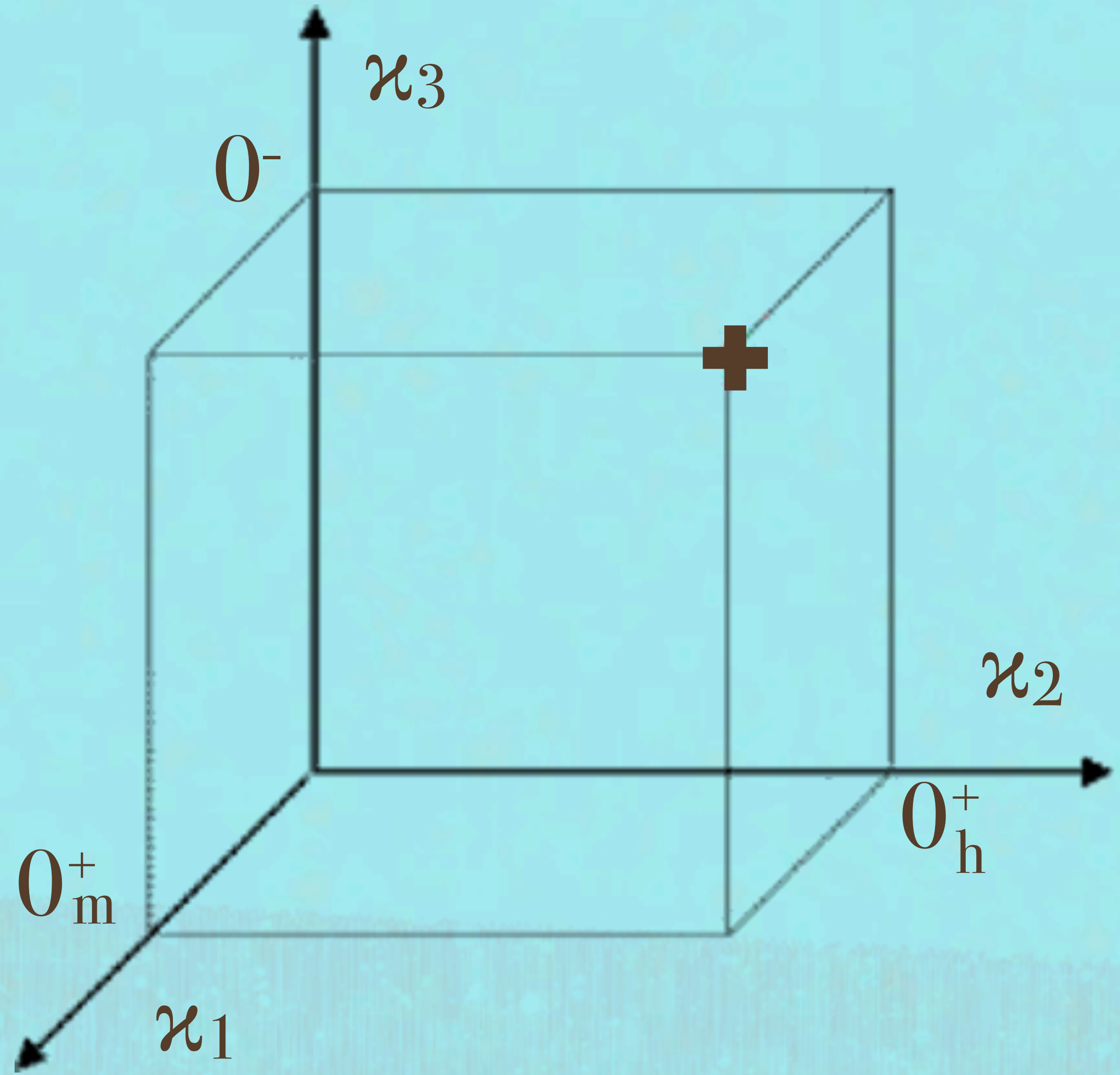
Real or Complex? That is the Question

- Lagrangians must be real, so the $\varkappa$'s must be real
- The amplitude receives corrections from loops
  - ★ Contributions from heavy particle loops are real
  - ★ Contributions from light particle loops are complex
    - These complex contributions can be mimicked with complex $\varkappa$'s



Generally these contributions are subdominant! (see 1310.1397)

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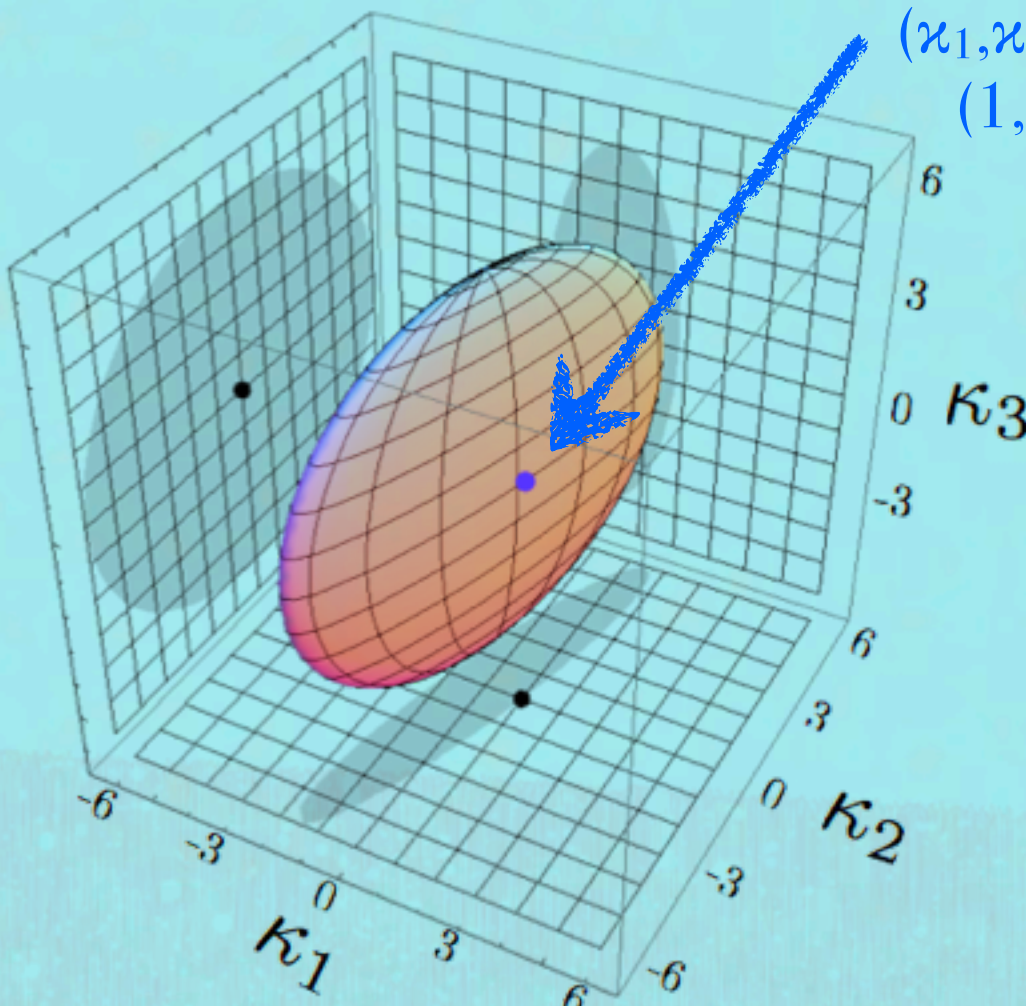
Rate Constraint

- Consider $\varkappa_1$, $\varkappa_2$, $\varkappa_3$ real
- Measured rate implies correlations among couplings
- Defines an ellipsoidal "pancake" in $\varkappa$ space
- Larger (smaller) total rate: pancake inflated (deflated), but shape stays the same
- Removes one degree of freedom

$$\Gamma(X \to ZZ) = \Gamma_{SM} \sum_{i,j} \gamma_{ij} \kappa_i \kappa_j$$

(Tree level) SM:
$(\varkappa_1, \varkappa_2, \varkappa_3)$ =
(1,0,0)



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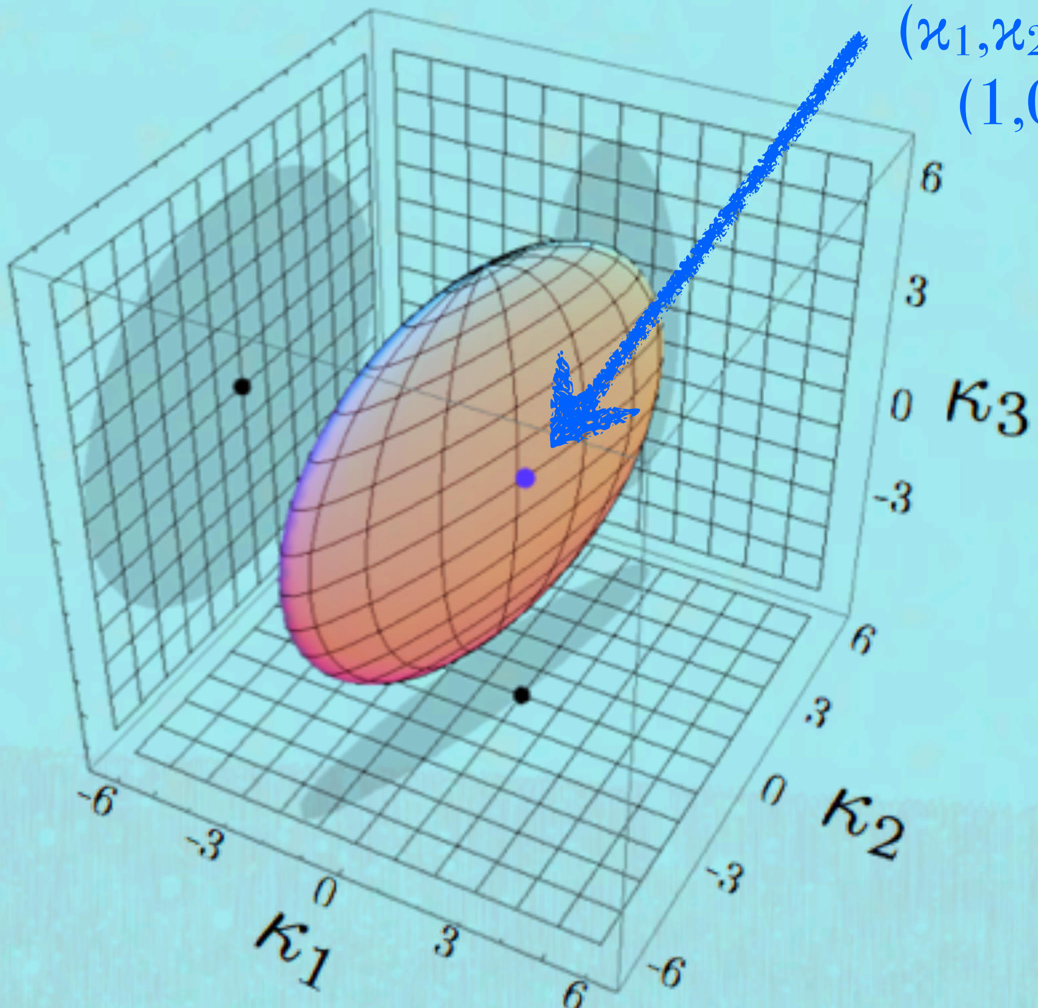
Rate Constraint

- Consider $\varkappa_1$, $\varkappa_2$, $\varkappa_3$ real
- Measured rate implies correlations among couplings
- Defines an ellipsoidal "pancake" in $\varkappa$ space
- Larger (smaller) total rate: pancake inflated (deflated), but shape stays the same
- Helpful when maximizing likelihoods

$$\Gamma(X \to ZZ) = \Gamma_{SM} \sum_{i,j} \gamma_{ij} \kappa_i \kappa_j$$

(Tree level) SM:
$(\varkappa_1,\varkappa_2,\varkappa_3)$ =
(1,0,0)



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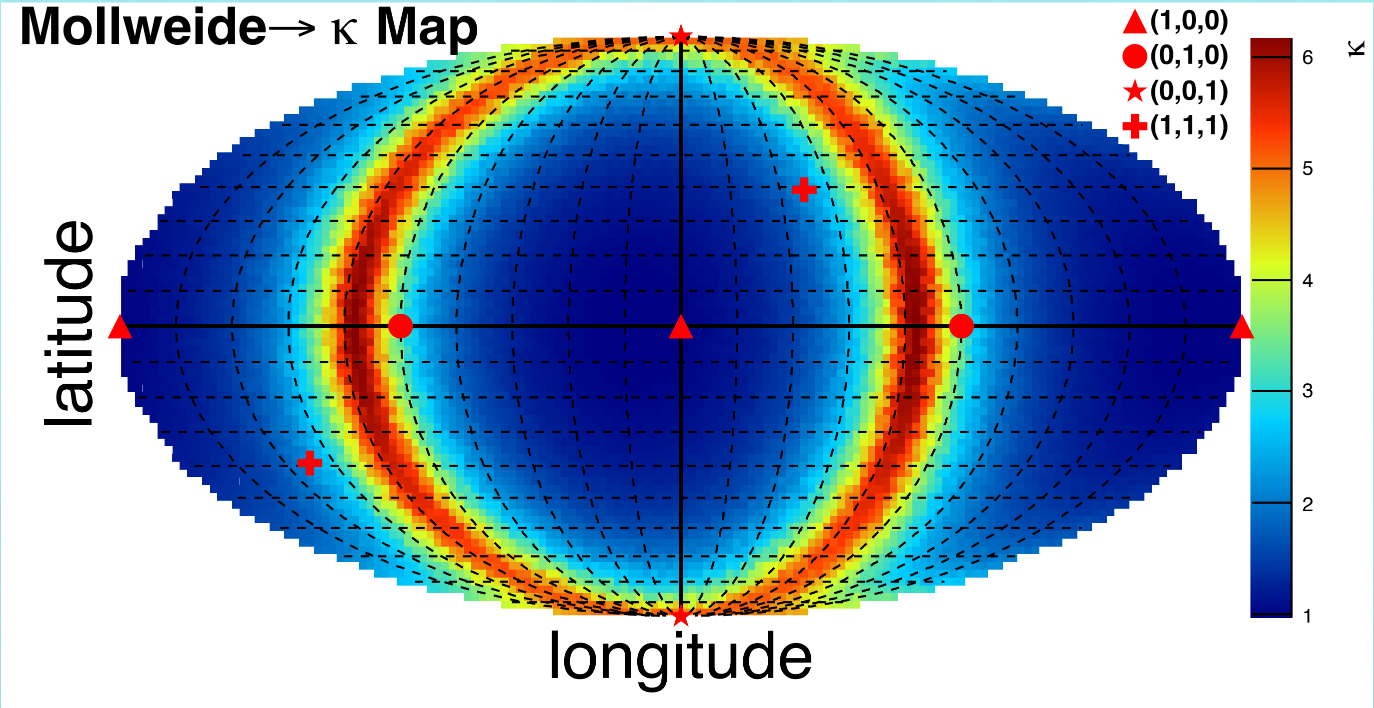
Parametrizing the Pancake 1

- Different points on the pancake correspond to different admixtures of Higgs couplings, but constant rate
- How should we parametrize the surface of the pancake?
- One choice: spherical coordinates in κ space

$$\boxed{\begin{aligned} \kappa_1 &= \kappa \sin\theta \cos\phi \\ \kappa_2 &= \kappa \sin\theta \sin\phi \\ \kappa_3 &= \kappa \cos\theta \end{aligned}}$$

Map of κ as function of θ and ϕ



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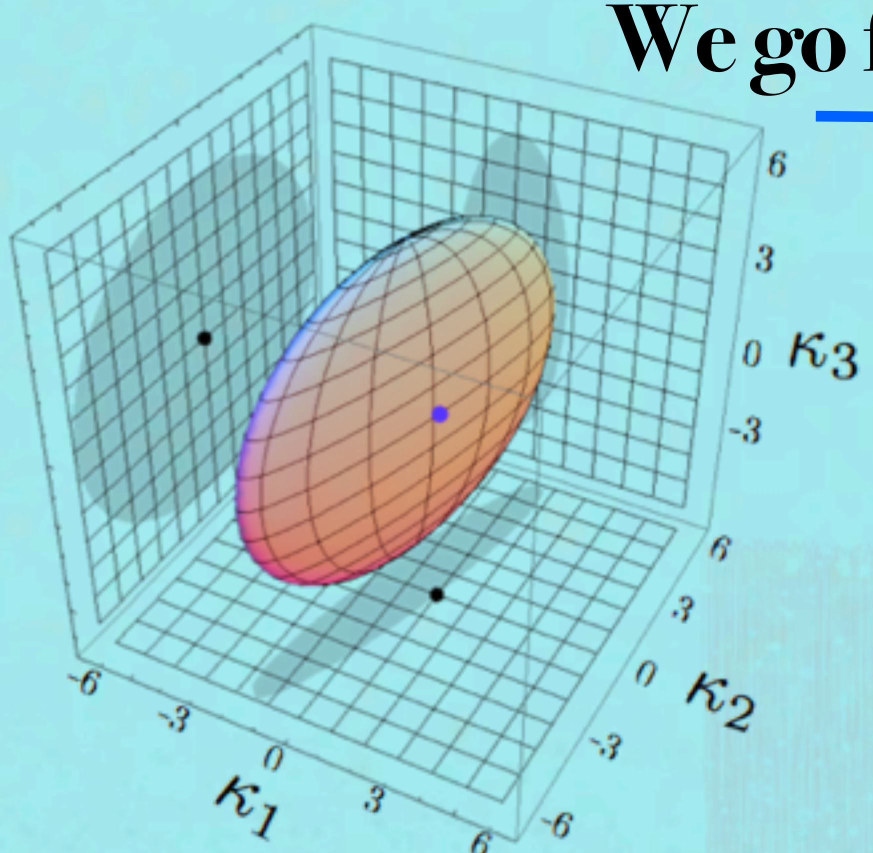
Parametrizing the Pancake 2

- Alternatively one can change variables to deform the pancake into an "equal rate sphere"
- This involves a linear transformation:

We go from

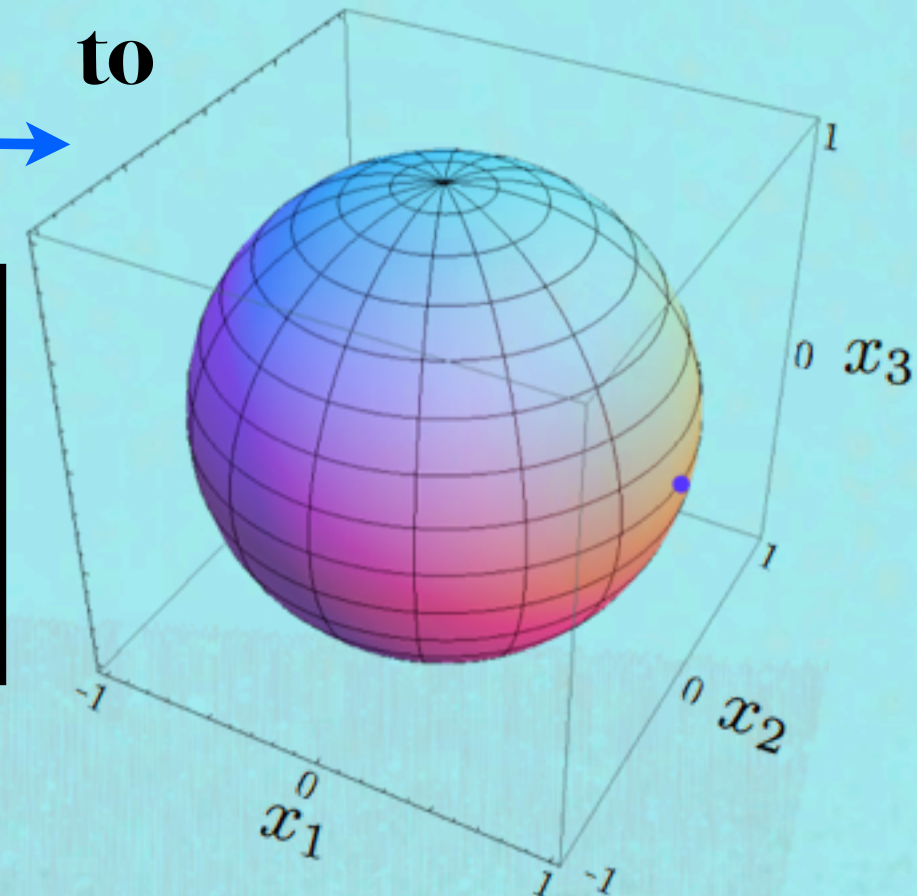


using

$$\boxed{\begin{aligned} x_1 &= \kappa_1 - 0.25\ \kappa_2 \\ x_2 &= 0.17\ \kappa_2 \\ x_3 &= 0.19\ \kappa_3 \end{aligned}}$$

DF, before cuts

to



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Geolocating the Higgs

- Any given value of $(\varkappa_1, \varkappa_2, \varkappa_3)$, corresponding to a given rate, maps to a point on the sphere

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Cuts and Efficiencies

- If we use the values of γ_{ij} before cuts to construct our sphere, then we find significant variation in the acceptance x efficiency at different points on the sphere.

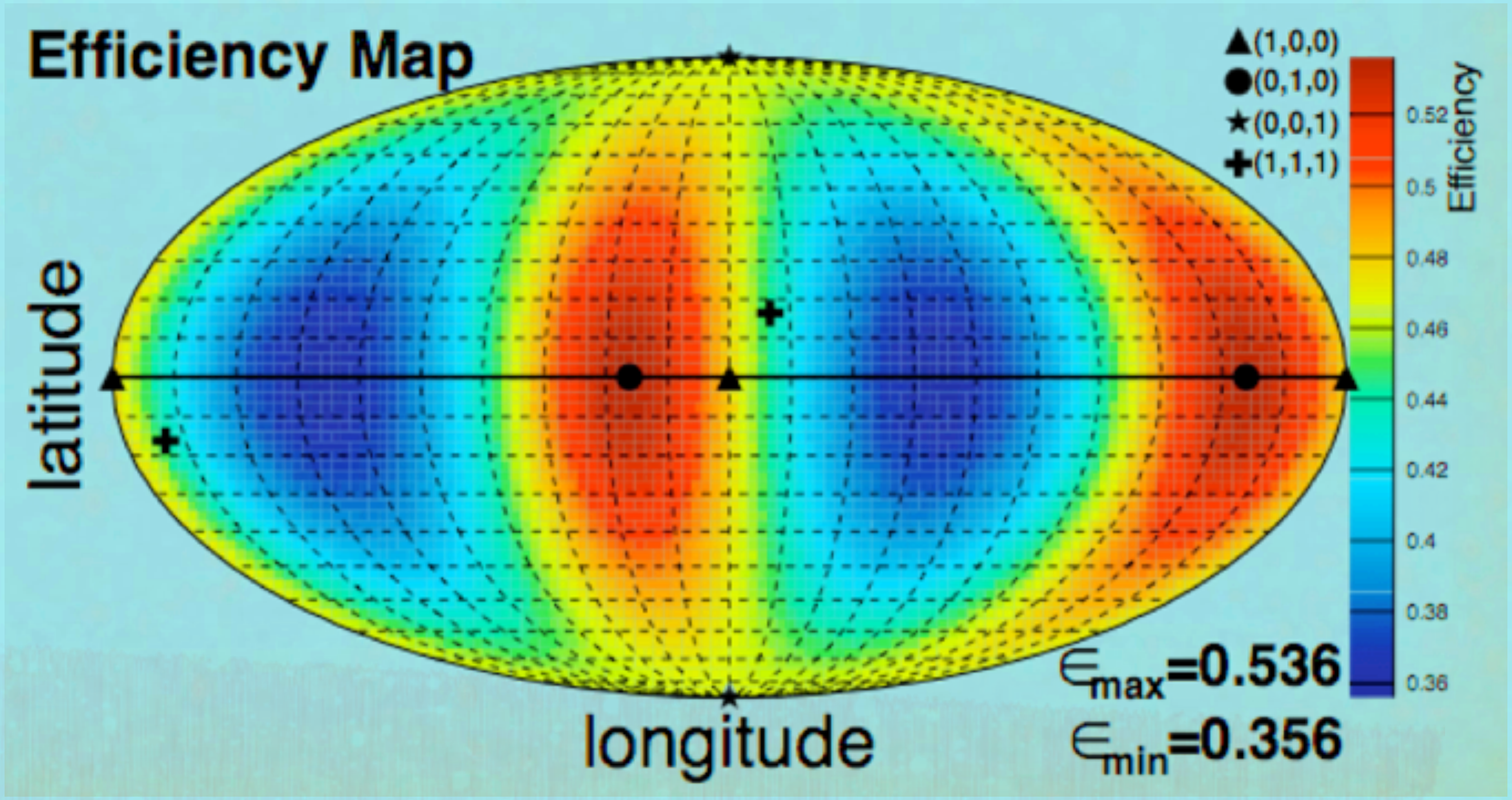
- Efficiency varies from ∼35% to ∼55%

- pT > 7 GeV
  $|\eta| < 2.5$ for electrons

- pT > 5 GeV
  $|\eta| < 2.4$ for muons

- $M_1 > 40$ GeV

- $M_2 > 12$ GeV



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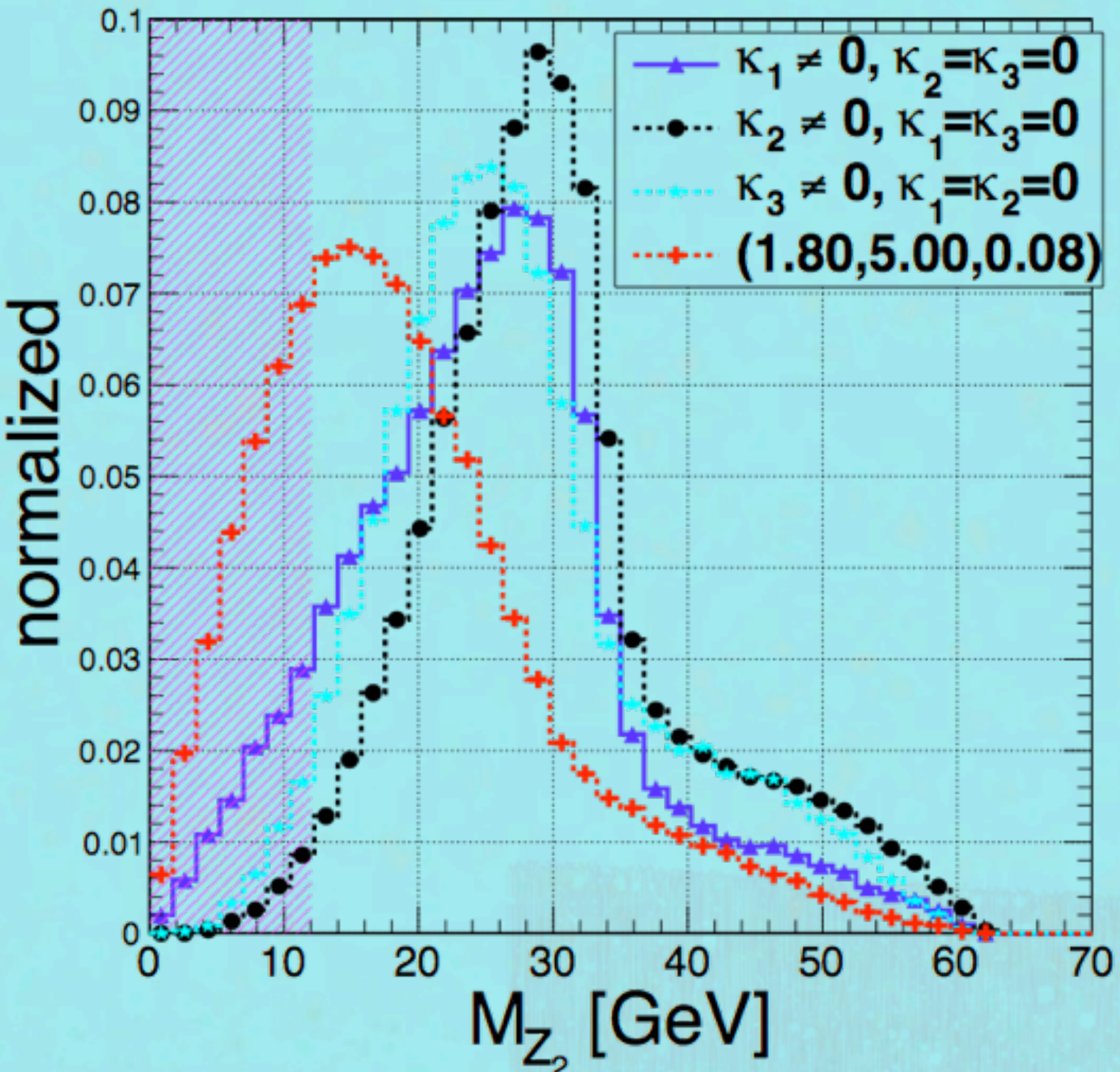
Cuts and Efficiencies



- The main driver of the changes in efficiency on the sphere seems to be the invariant mass of the less massive
  intermediate Z^* (M_2)
- (Choi, Miller, Muhlleitner, and Zerwas, 2003),
  (Godbole, Miller, and Muhlleitner, 2007),
  (Boughezal, LeCompte, and Petriello, 2012), etc.
- I'll say more about M_2 distributions later!

1304.4936

Example Analysis

- We illustrate the use of the sphere for displaying results with a toy analysis
- We generate 1000 pseudoexperiments
  - 300 DF signal events for each of 4 benchmark points (~300 fb^{-1} at 14 TeV): three pure states and one completely mixed state
  - Impose cuts (p_T, $|\eta|$, M_{Z1}, M_{Z2})
  - Find the point on the sphere that maximizes the likelihood for each pseudoexperiment and plot

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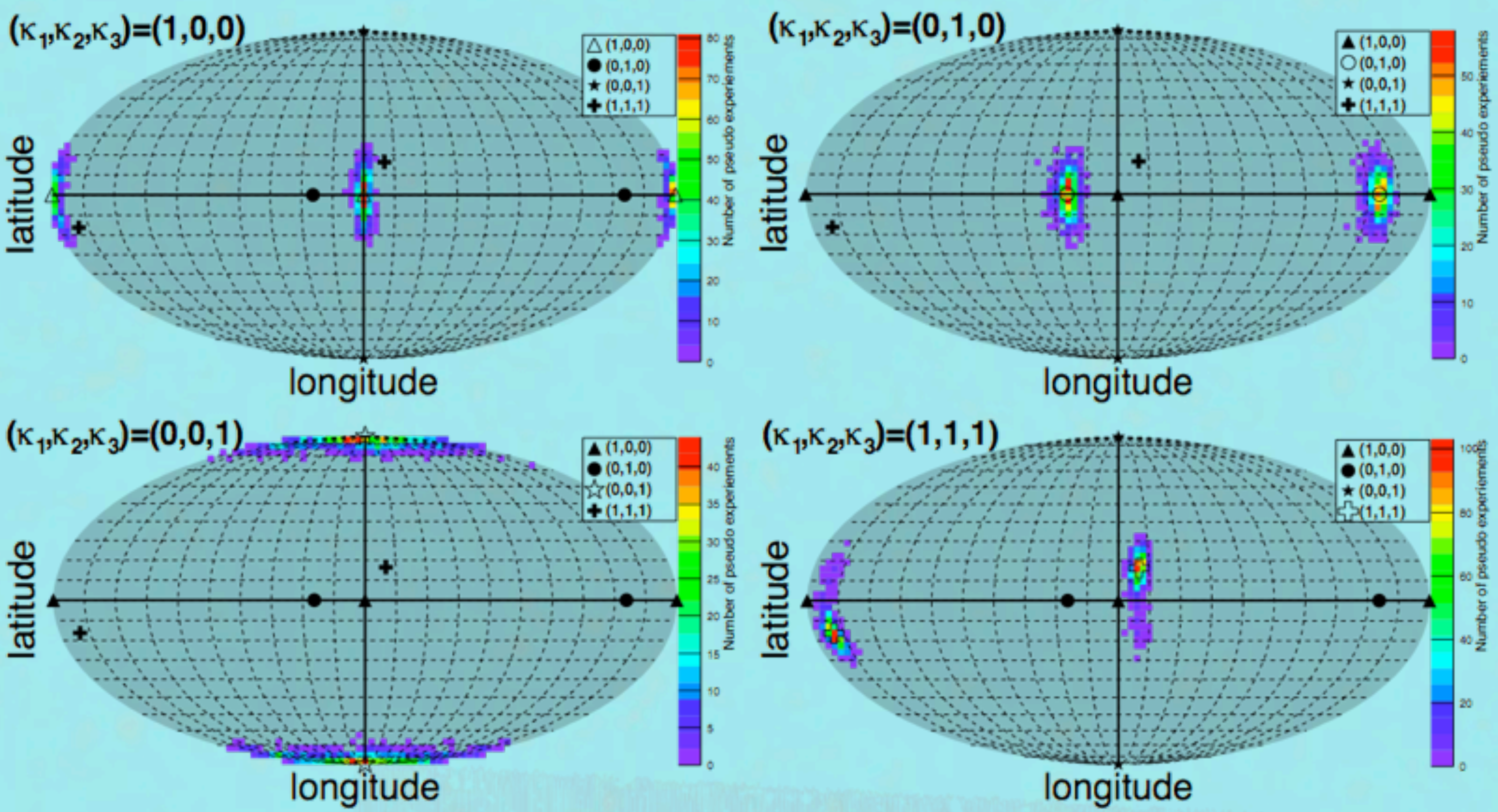
Example Analysis



- Note: a point and its antipode are effectively equivalent

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Other Spheres

$$\mathcal{L} = X\left[\boxed{\kappa_1 \frac{m_Z^2}{v} Z_\mu Z^\mu} + \boxed{\frac{\kappa_2}{2v} F_{\mu\nu} F^{\mu\nu}} + \boxed{\frac{\kappa_3}{2v} F_{\mu\nu} \tilde{F}^{\mu\nu}}\right]$$

- **Scenario 1**: $\varkappa_1 = 0$. $\varkappa_2$ and $\varkappa_3$ arbitrary and complex. Coupling can be gauge invariant. Example: X is SM singlet.

- **Scenario 2**: $\varkappa_2 = 0$. Mixing of SM scalar and pseudoscalar.

- **Scenario 3**: $\varkappa_3 = 0$. Arbitrary CP-even scalar.

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Example: Scenario 2

- Now we allow $\kappa 1$, $\kappa 3$ to be complex

$$\mathcal{L} = X\left[\boxed{\kappa_1 \frac{m_Z^2}{v} Z_\mu Z^\mu} + \boxed{\cancel{\frac{\kappa_2}{2v} F_{\mu\nu} F^{\mu\nu}}} + \boxed{\frac{\kappa_3}{2v} F_{\mu\nu} \tilde{F}^{\mu\nu}}\right]$$

- Degrees of freedom: 2 magnitudes and 2 phases
- One overall phase is irrelevant
- We can call relative phase ϕ_{13}
- Rate restricts overall magnitude of couplings
- Remaining degree of freedom is ratio of couplings

$$x_{13} = \frac{|\kappa_3|^2}{|\kappa_1|^2 + |\kappa_3|^2} = \sin^2\theta_{13}$$

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Geolocating Conclusions

- While many operators may affect the coupling of a scalar to bosons, it is reasonable to focus on three lowest dimensional operators from each class of couplings
- Overall rate eliminates one degree of freedom
- We propose the following scenarios all of which involve two degrees of freedom:
  - Three real couplings (general mixture of 0^+_m, 0^+_h, 0^-)
  - $\varkappa_1 = 0$, $\varkappa_2$, $\varkappa_3$ complex: θ_{23}, ϕ_{23}
  - $\varkappa_2 = 0$, $\varkappa_1$, $\varkappa_3$ complex: θ_{13}, ϕ_{13}
  - $\varkappa_3 = 0$, $\varkappa_1$, $\varkappa_2$ complex: θ_{12}, ϕ_{12}

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Importance of Interference

- We saw from the above that it is important to look for the Higgs on the entire Earth, not just along the Prime Meridian or the Equator

- Interference effects between operators can increase sensitivity to non-SM couplings, give sensitivity to sign of couplings (relative to SM)

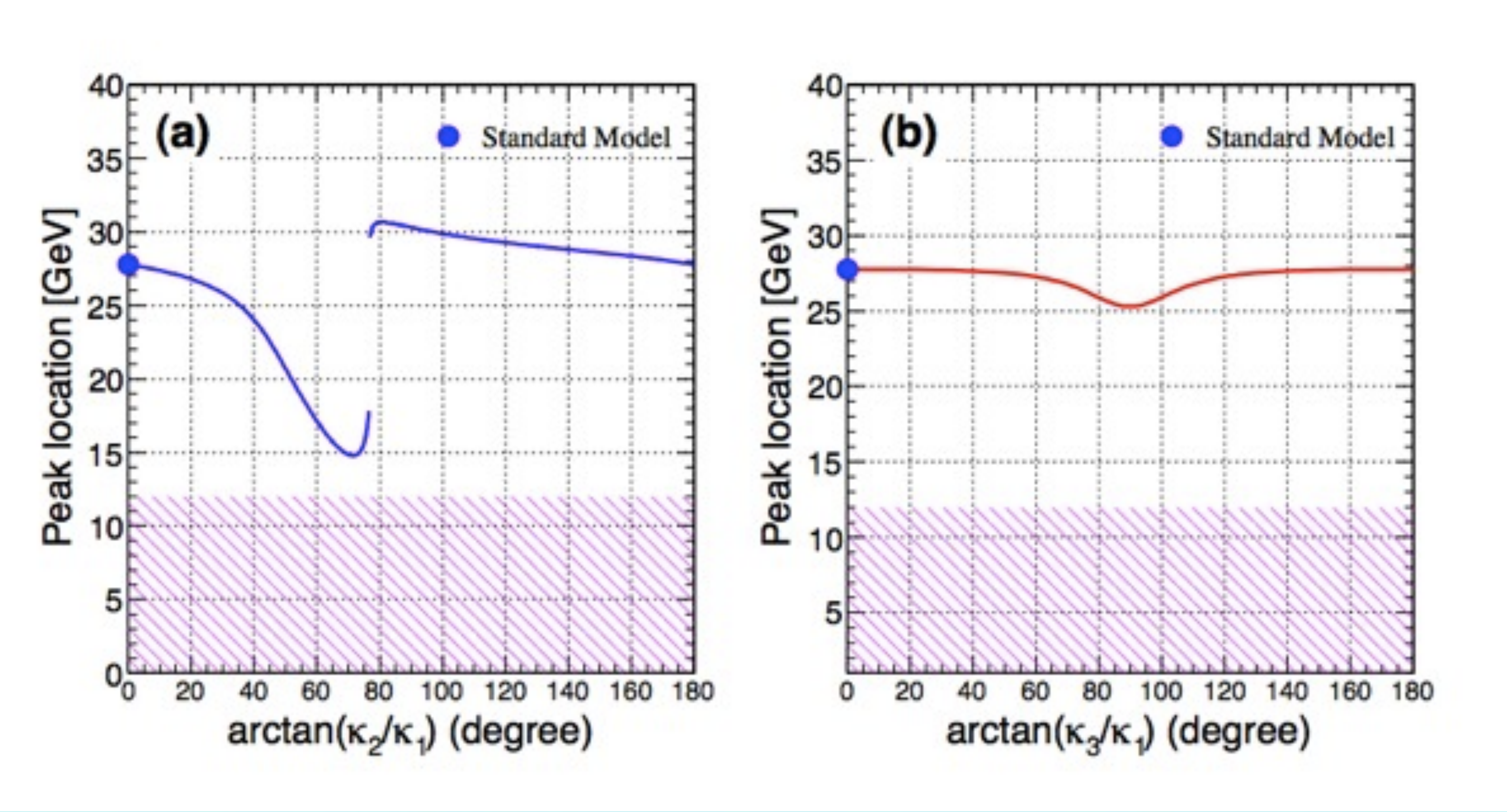
- If non-SM coupling are discovered, can study if there is one particle with e.g. scalar and pseudoscalar couplings, or
two not-quite-degenerate CP-eigenstates.

Greenwich, UK

1310.1397

Importance of Interference

- One thing we've found is that the M_2 distribution changes dramatically as we vary $\varkappa_1$ and $\varkappa_2$ due to the effect of interference:



Peak of M_2 distribution displays "first order phase transition" from $\varkappa_1$-$\varkappa_2$ interference , no such feature when considering $\varkappa_1$ and $\varkappa_3$

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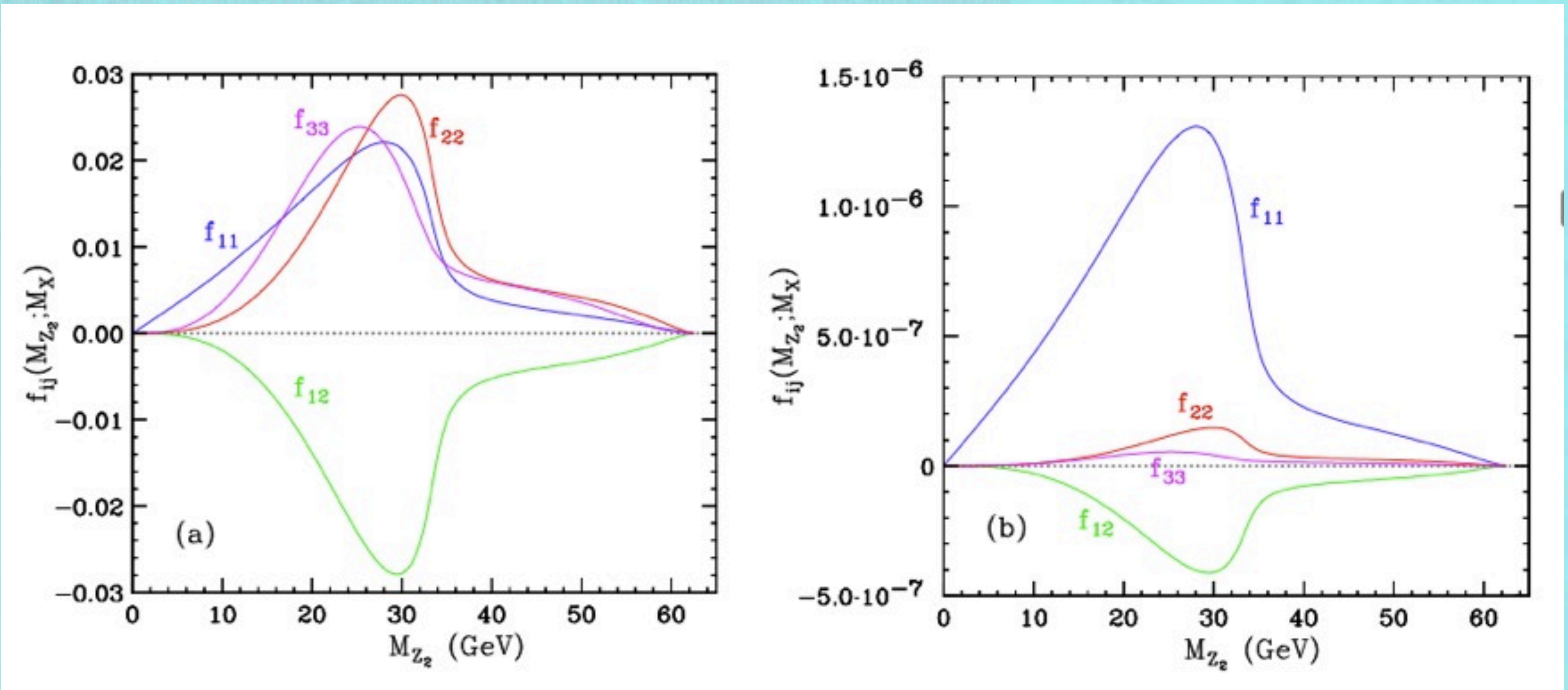
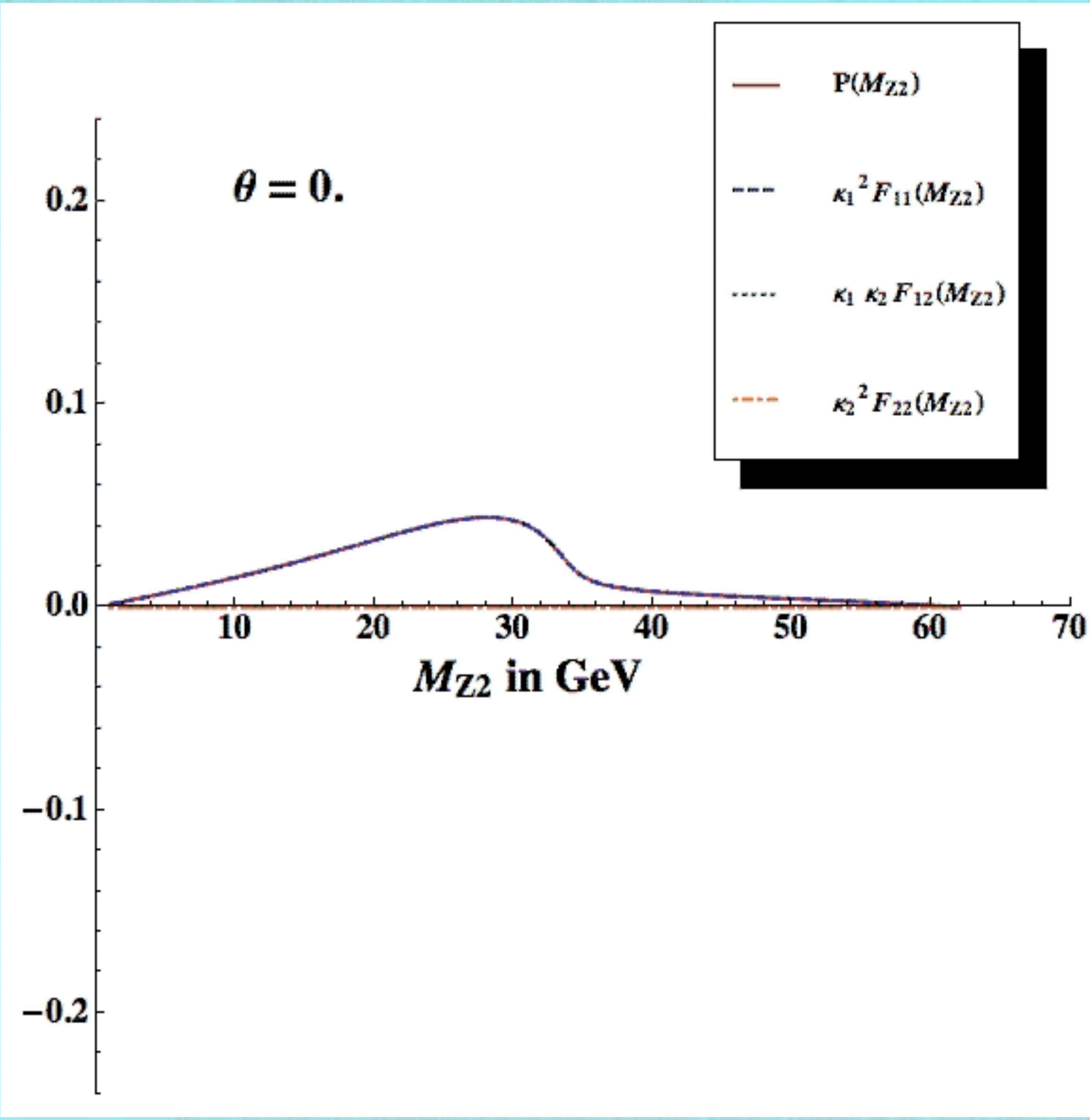


- Distribution (unit normalized on left) of M_2 due to pure $\varkappa_i$ (f_{ii}) and from $\varkappa_1$-$\varkappa_2$ interference (f_{12})

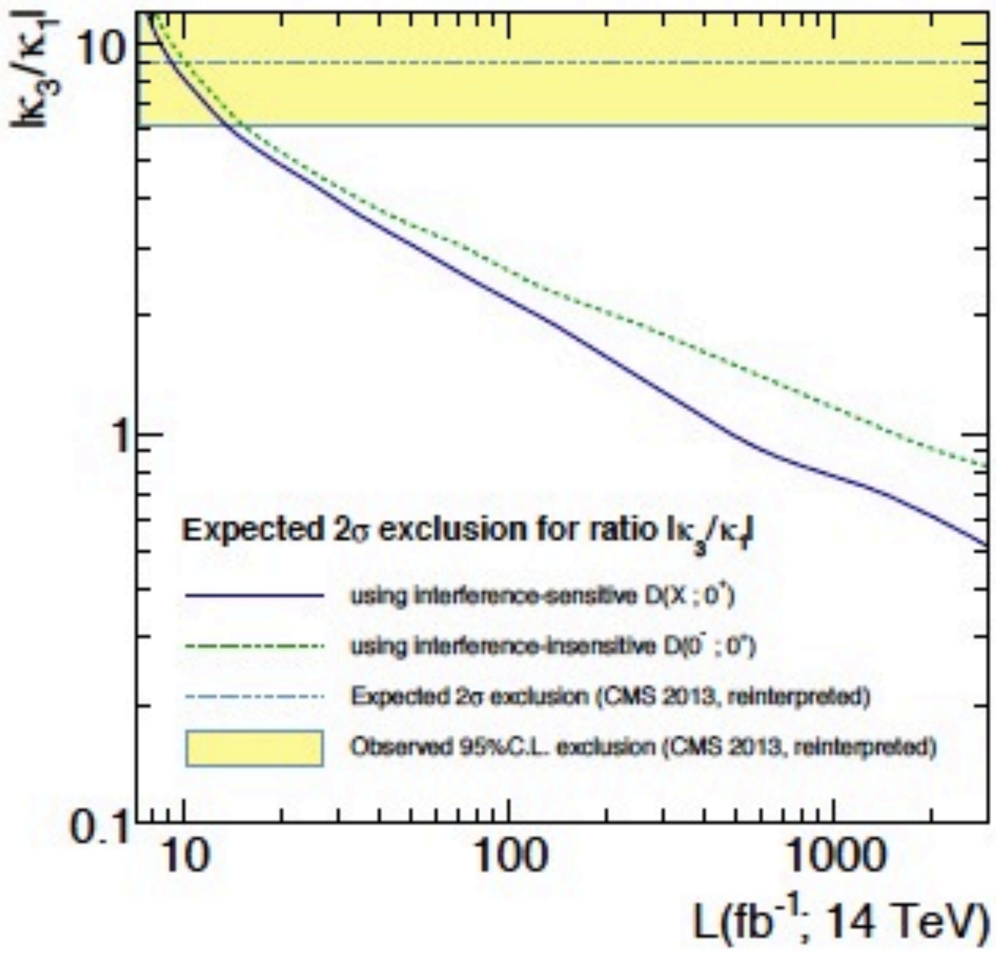
- Note: f12 relatively large, negative.

$$\frac{d^2\,\Gamma}{dM_{Z_1}dM_{Z_2}} = \frac{1}{v}\sum_{i,j}\kappa_i\kappa_j F_{ij}(M_{Z_1},M_{Z_2};M_X)$$

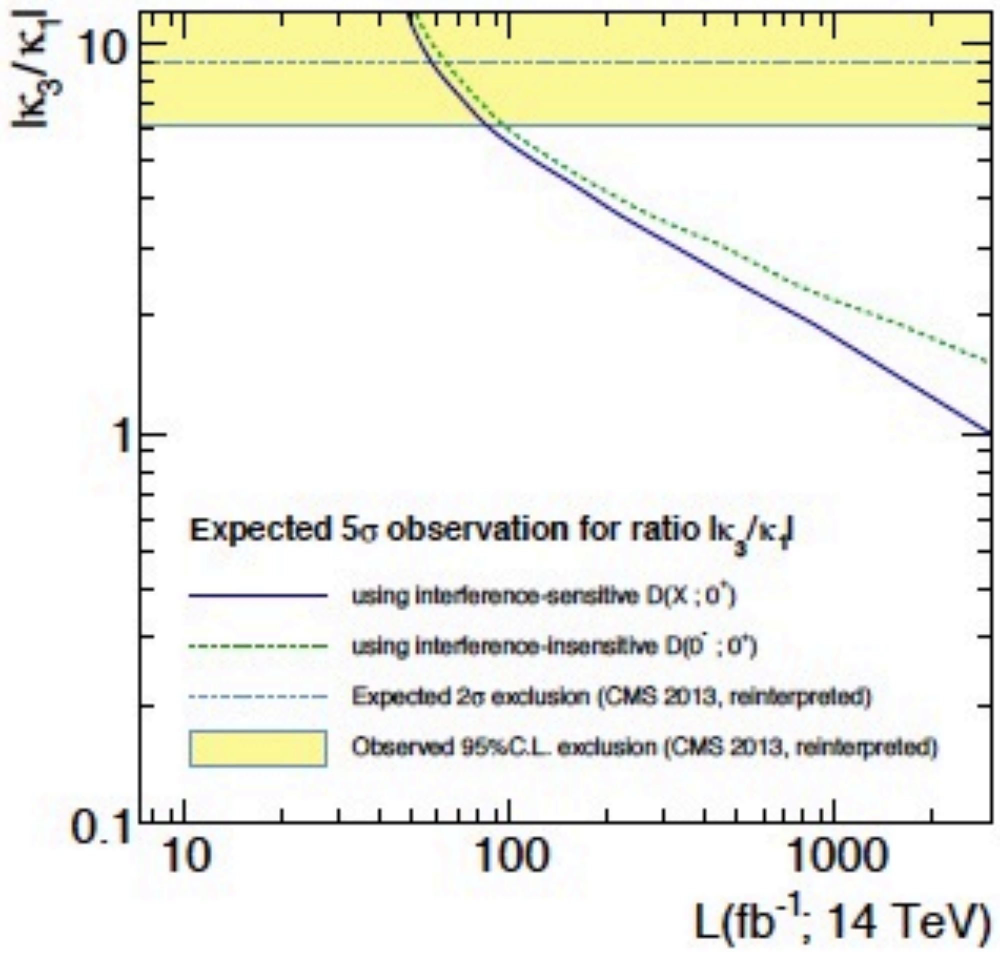


$\theta = \arctan(\varkappa_2/\varkappa_1)$

Projections

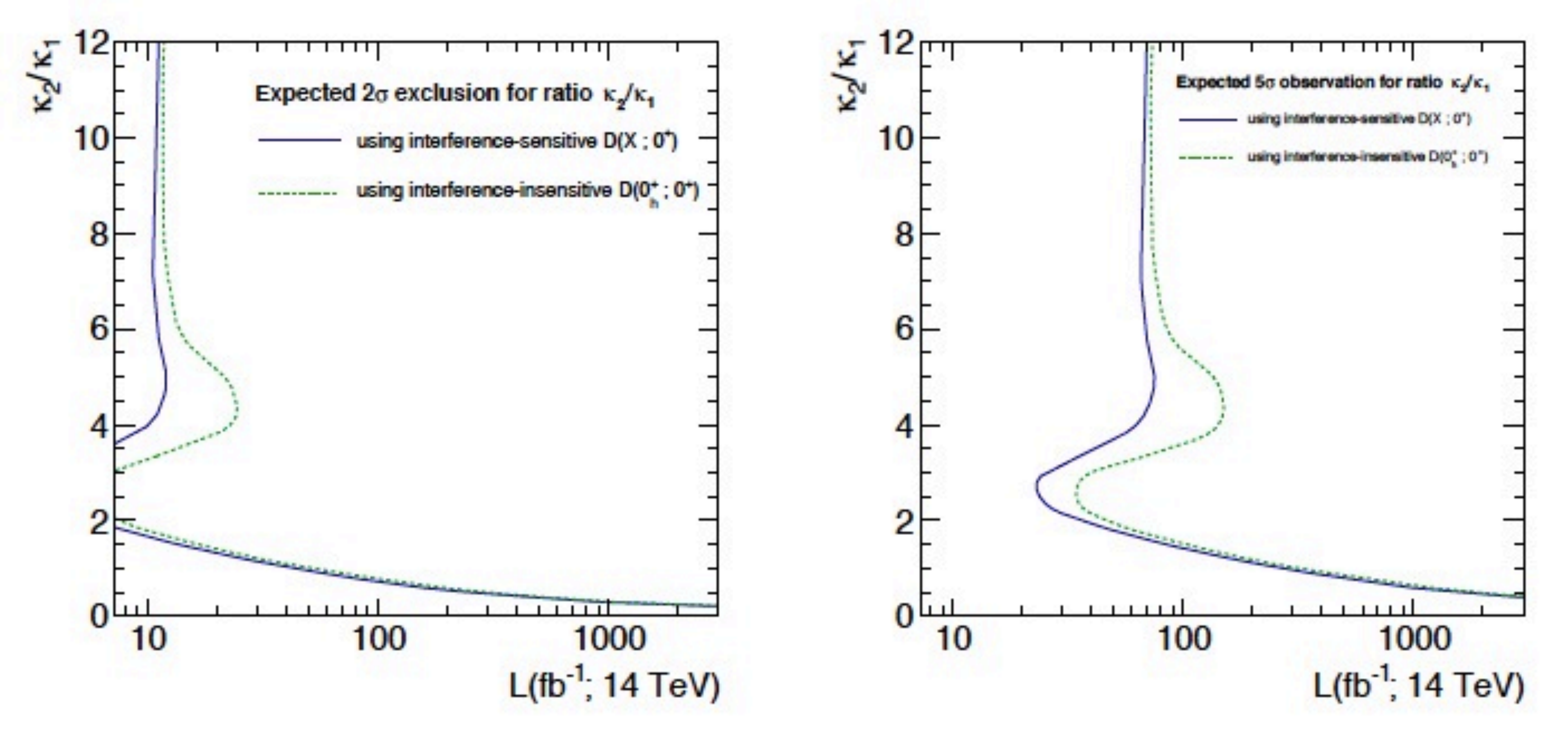


(a)



(b)

Projections



Brief Conclusions

- “Golden” $H \to ZZ^* \to 4\ \ell$ useful channel both in Higgs discovery and in the measurement of Higgs properties
- The Matrix Element Method has been useful for optimizing sensitivity in this channel. Physically transparent (for an MVA).
- I’ve described a public tool for golden channel analyses and presented a useful framework for the interpretation of results
- Exciting times are also ahead as we measure the couplings of the Higgs!

Thanks!!!

backup slides

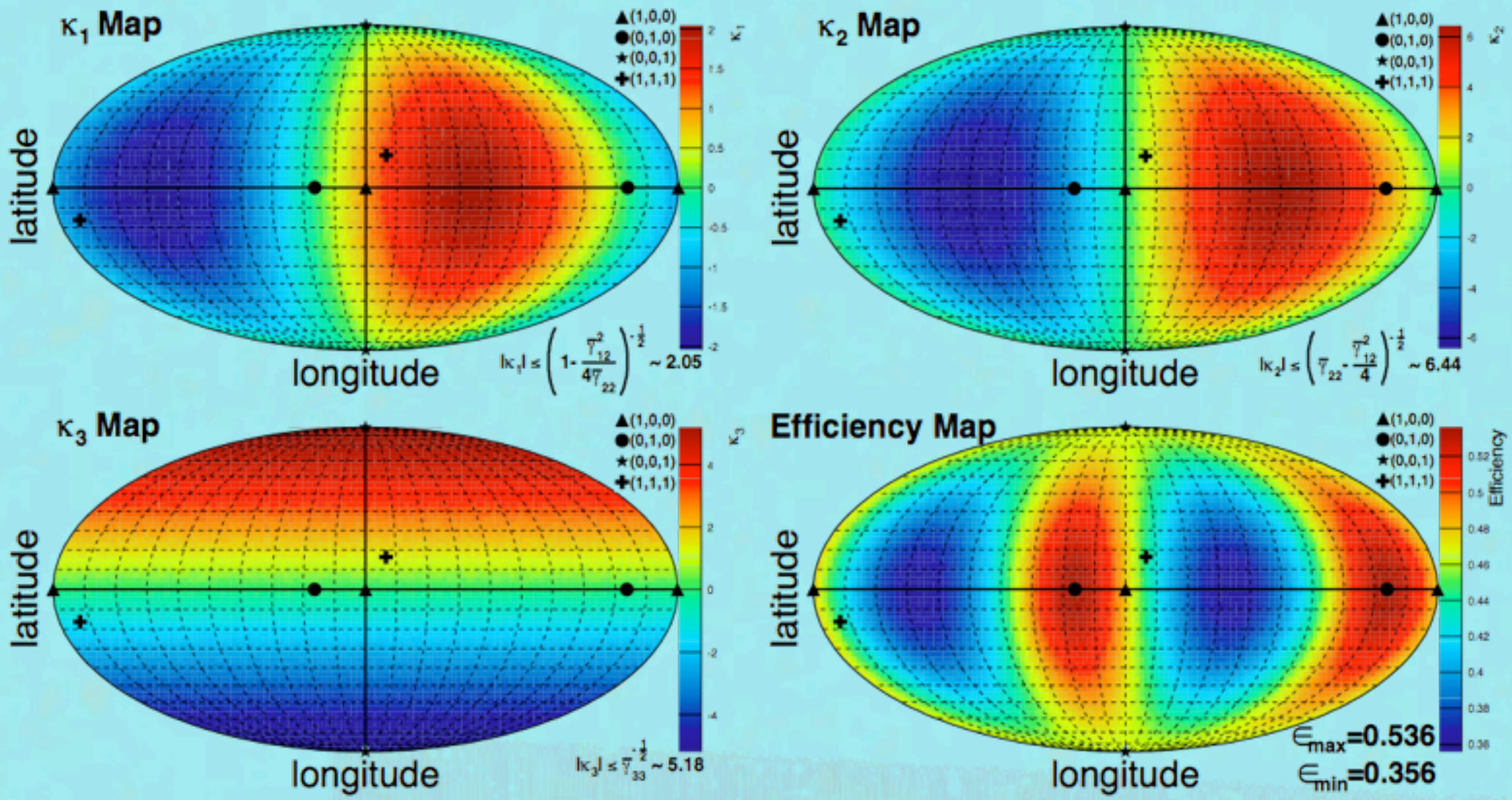
Expressions for change of variables

$$x_i = \sum_j O_{ij} \kappa_j$$

where $O_{21} = O_{31} = O_{32} = 0$ and

$$\begin{aligned}
O_{1i} &= \gamma_{1i}/\sqrt{\gamma_{11}}, \quad (i = 1, 2, 3) \\
O_{2i} &= \frac{\gamma_{11}\gamma_{2i} - \gamma_{12}\gamma_{1i}}{\sqrt{(\gamma_{11}\gamma_{22} - \gamma_{12}^2)\gamma_{11}}}, \quad (i = 2, 3) \\
O_{33} &= \sqrt{\det ||\gamma_{ij}|| / (\gamma_{11}\gamma_{22} - \gamma_{12}^2)}
\end{aligned}$$

More Mollweide



Top two and bottom left plots show ϰ values on the sphere.

Rates for various processes

Process	γ_{11}	γ_{22}	γ_{33}	γ_{12}
$X \to ZZ$ (DF)	1	0.090	0.038	−0.250
$X \to ZZ$ (SF)	1	0.081	0.032	−0.243
$X \to \gamma\gamma$	0	1	1	0
$X \to WW$	1	0.202	0.084	−0.379
after cuts				
$X \to ZZ$ (DF)	1	0.101	0.037	−0.277

- Avoid variable efficiencies: use γ_{ij} after cuts
- Note also that γ_{ij} are substantially different in the same flavor and different flavor cases

Matrix Element Method

- In particle physics, the likelihood/ probability function P(**α**, **x**) is the differential cross section

$$\mathcal{P}(\mathbf{p}_i^{\mathsf{vis}}|\alpha) = \frac{1}{\sigma_\alpha}\int dx_1 dx_2 \frac{f_1(x_1)f_2(x_2)}{2sx_1x_2} \times \left[\prod_{i\in\mathsf{final}}\int\frac{d^3p_i}{(2\pi)^3 2E_i}\right]|M_\alpha(p_i)|^2 \prod_{i\in\mathsf{vis}}\delta(\mathbf{p}_i - \mathbf{p}_i^{\mathsf{vis}})$$

Only LO here: for extension to extra radiation/ NLO/ parton showers see

Alwall, Freitas, Mattelaer (2010)

Soper, Spannowsky (2011) (2012)

Campbell, Giele, Williams (2012)[2]

Campbell, Ellis, Giele, Williams (2013)