GEOLOCATING THE HIGGS

James S. "Jamie" Gainer
Brookhaven Forum

University of Florida

May 1, 2013

GEOLOCATING THE HIGGS

- arXiv:1304.4936
- JG, Lykken, Matchev, Mrenna, Park

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.

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

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)

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

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

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

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

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.

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

- These operators cover all possible Lorentz structures in the amplitude

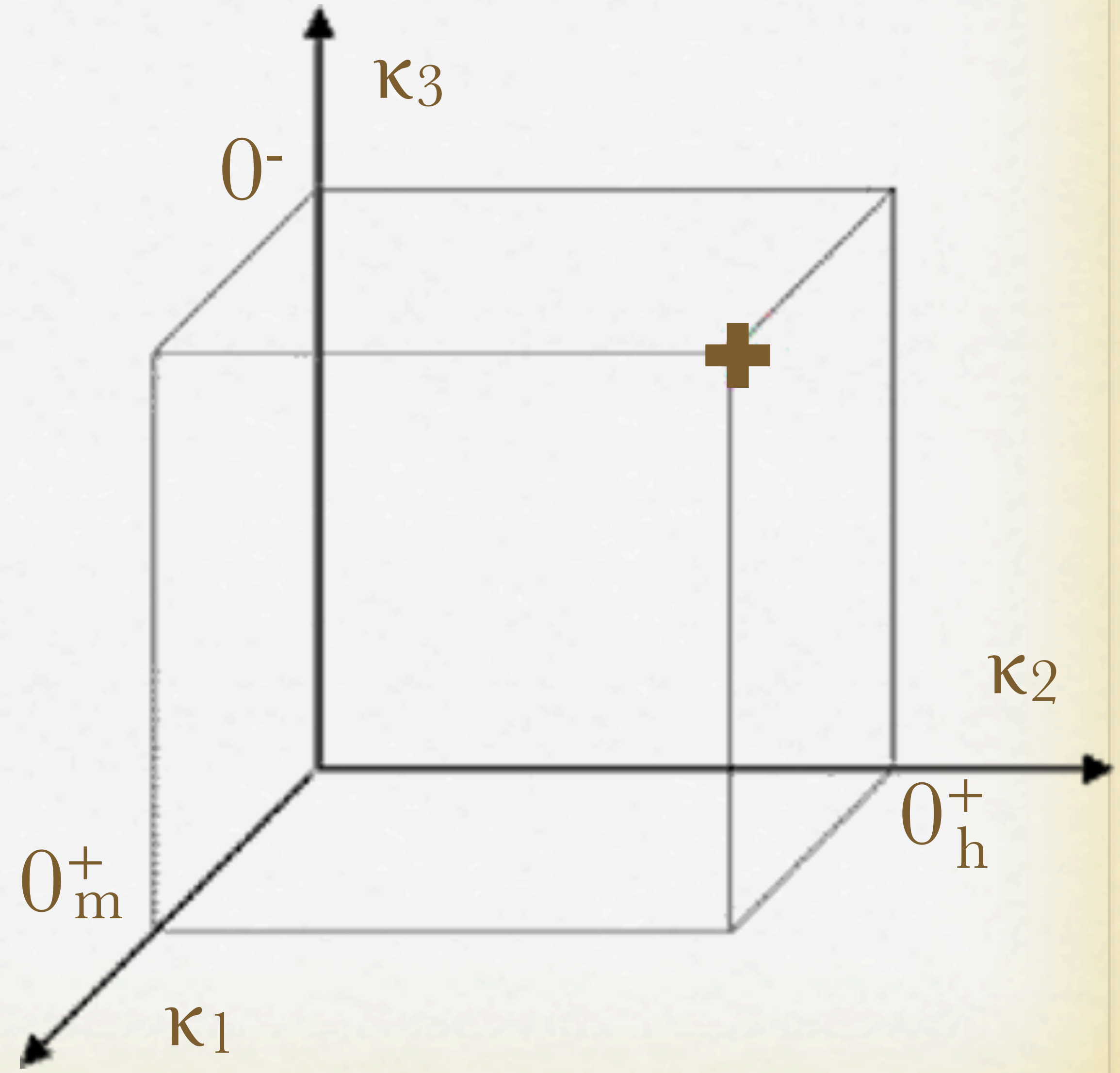
$$A(X \to V_1 V_2) = v^{-1} \epsilon_1^{*\mu} \epsilon_2^{*\nu} \left(a_1 g_{\mu\nu} m_x^2 + a_2\, q_\mu q_\nu + a_3 \epsilon_{\mu\nu\alpha\beta}\, q_1^\alpha q_2^\beta \right)$$

Gao, Gritsan, Guo, Melnikov, Schulze, Tran (2010)
De Rújula, Lykken, Pierini, Rogan, Spiropulu (2010)

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

REAL OR COMPLEX: THAT IS THE QUESTION

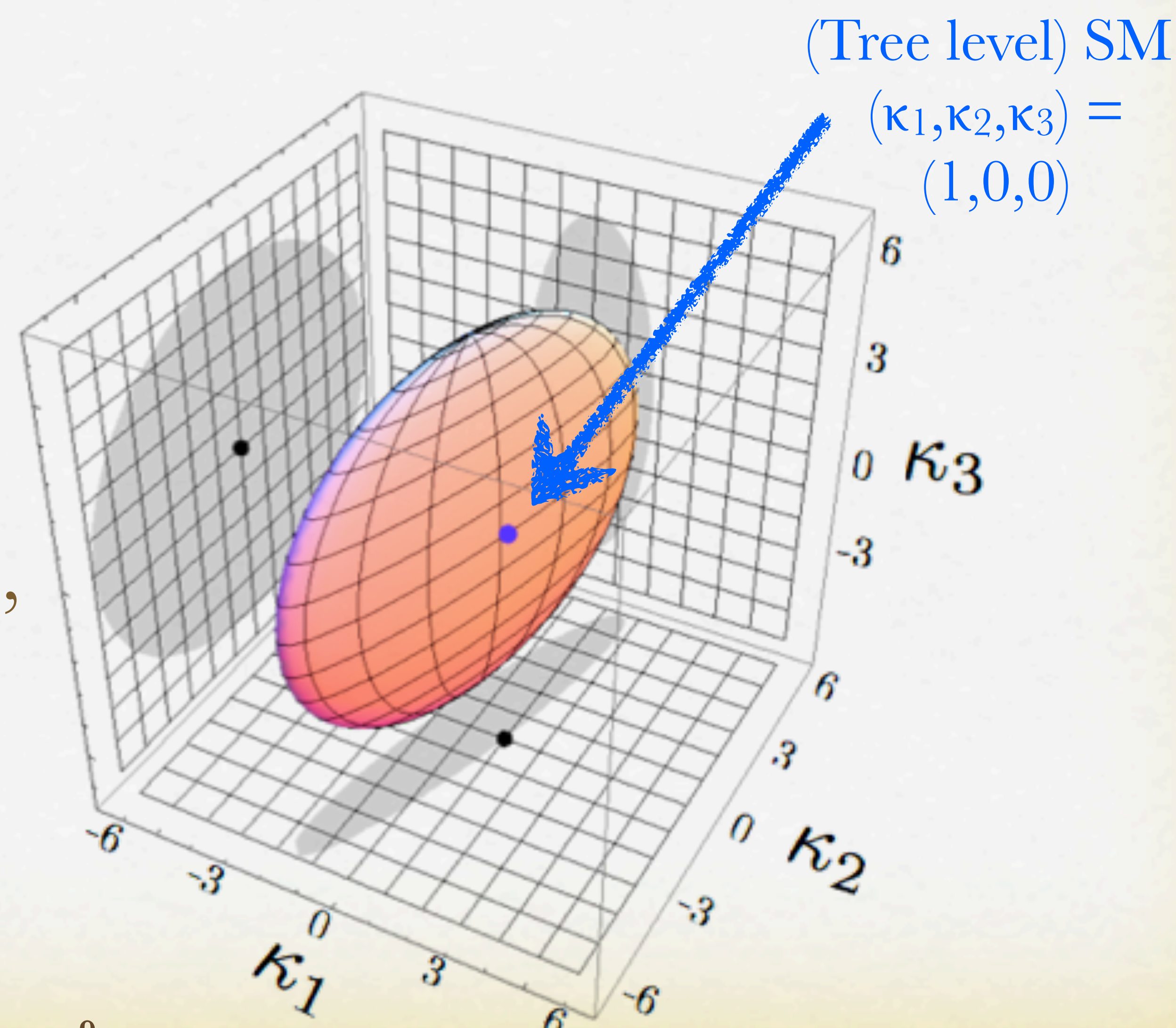
- Lagrangians must be real, so the κ's must be real
- The amplitude receives corrections from loops
  - ★ Contributions from heavy particle loops are real
  - ★ Contributions from light particle loops are complex
    - • These complex contributions can be mimicked with complex κ's



RATE CONSTRAINT

- Consider κ_1, κ_2, κ_3 real
- Measured rate implies correlations among couplings
  - ★ Defines an ellipsoidal "pancake" in κ space
  - ★ Larger (smaller) total rate: pancake inflated (deflated), but shape stays the same
- Removes one degree of freedom

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

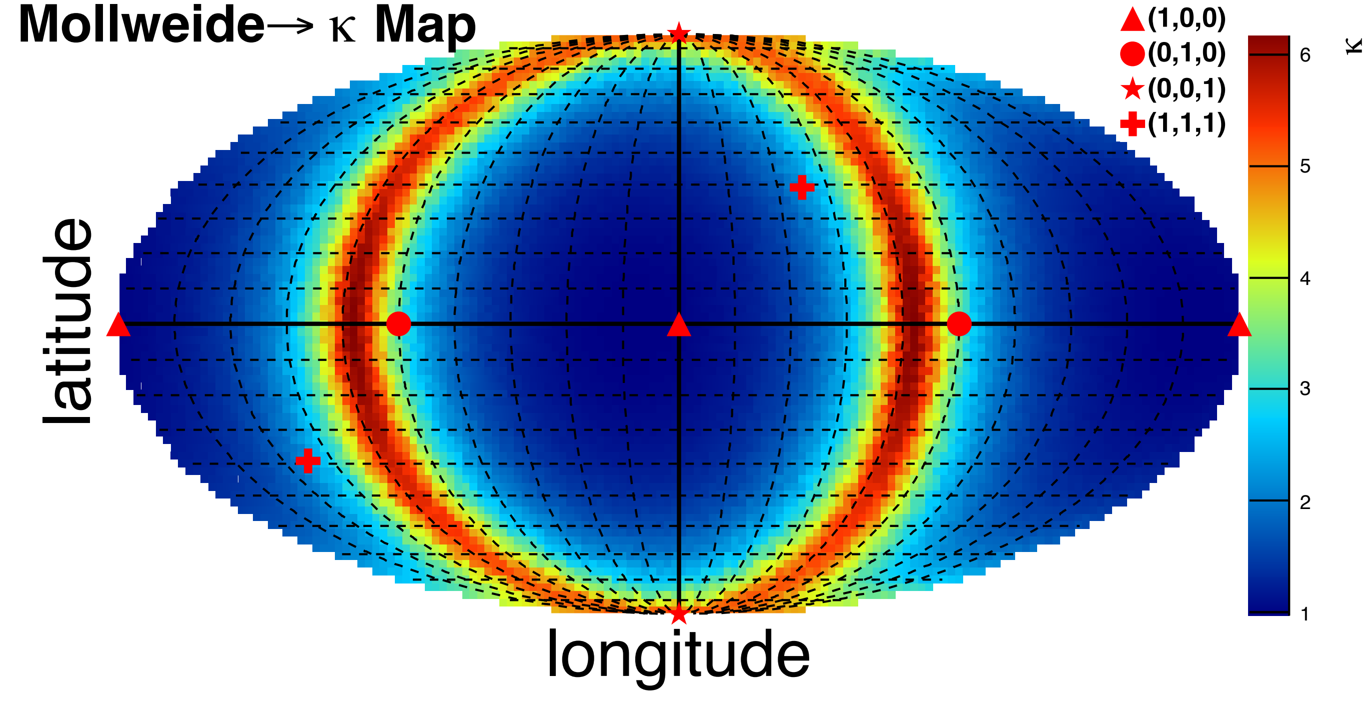


PARAMETRIZING THE PANCAKE 1

- 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

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

Map of κ as function of θ and ϕ



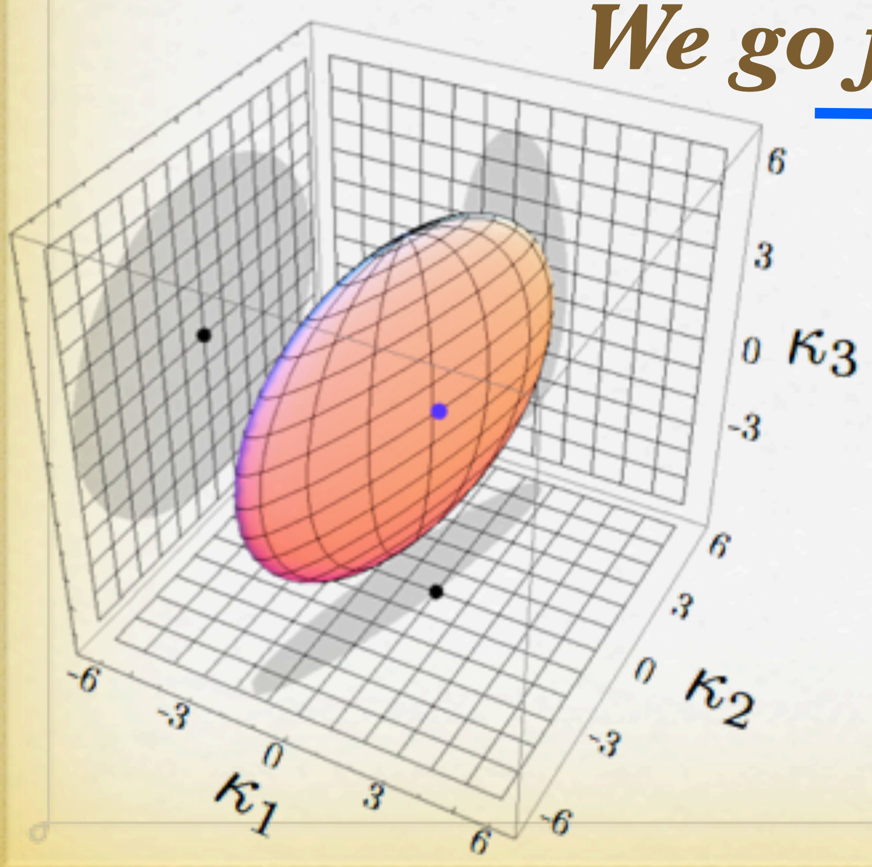
PARAMETRIZING THE PANCAKE 2

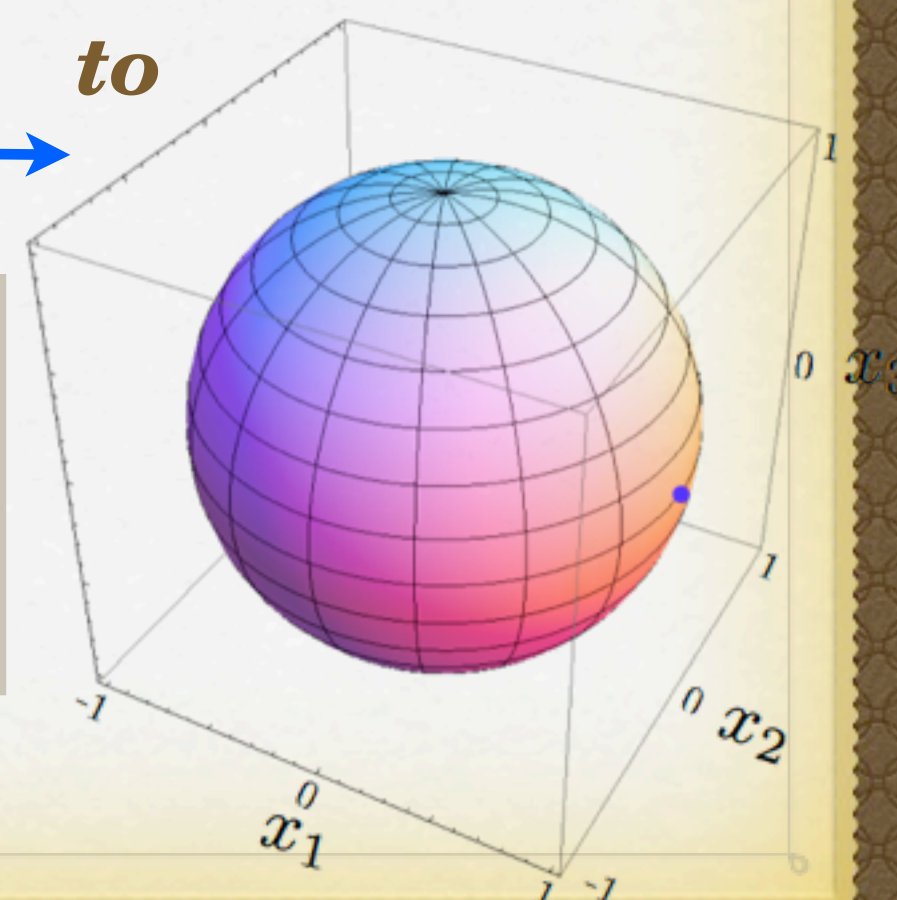
- Alternatively one can change variables to deform the pancake into an “equal rate sphere”
- This involves a linear transformation:

We go from ***to***

using

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





DF, before cuts

GEOLOCATING THE HIGGS

- Any given value of $(\kappa_1, \kappa_2, \kappa_3)$, corresponding to a given rate, maps to a point on the sphere

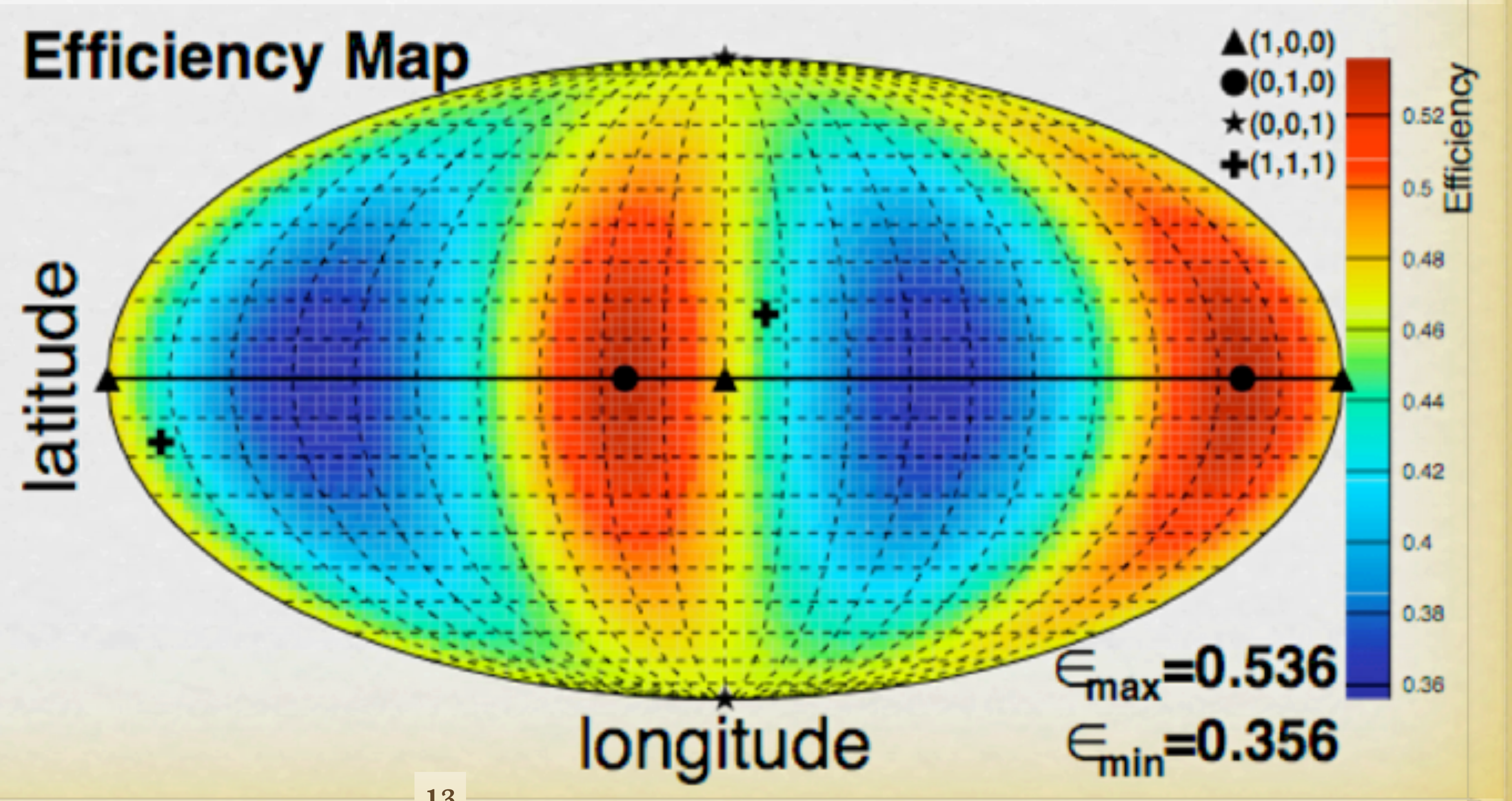
$(-0.945804, -3.88525, 2.44522)$

$(\phi, \lambda) = (29.64945, -82.3486)$

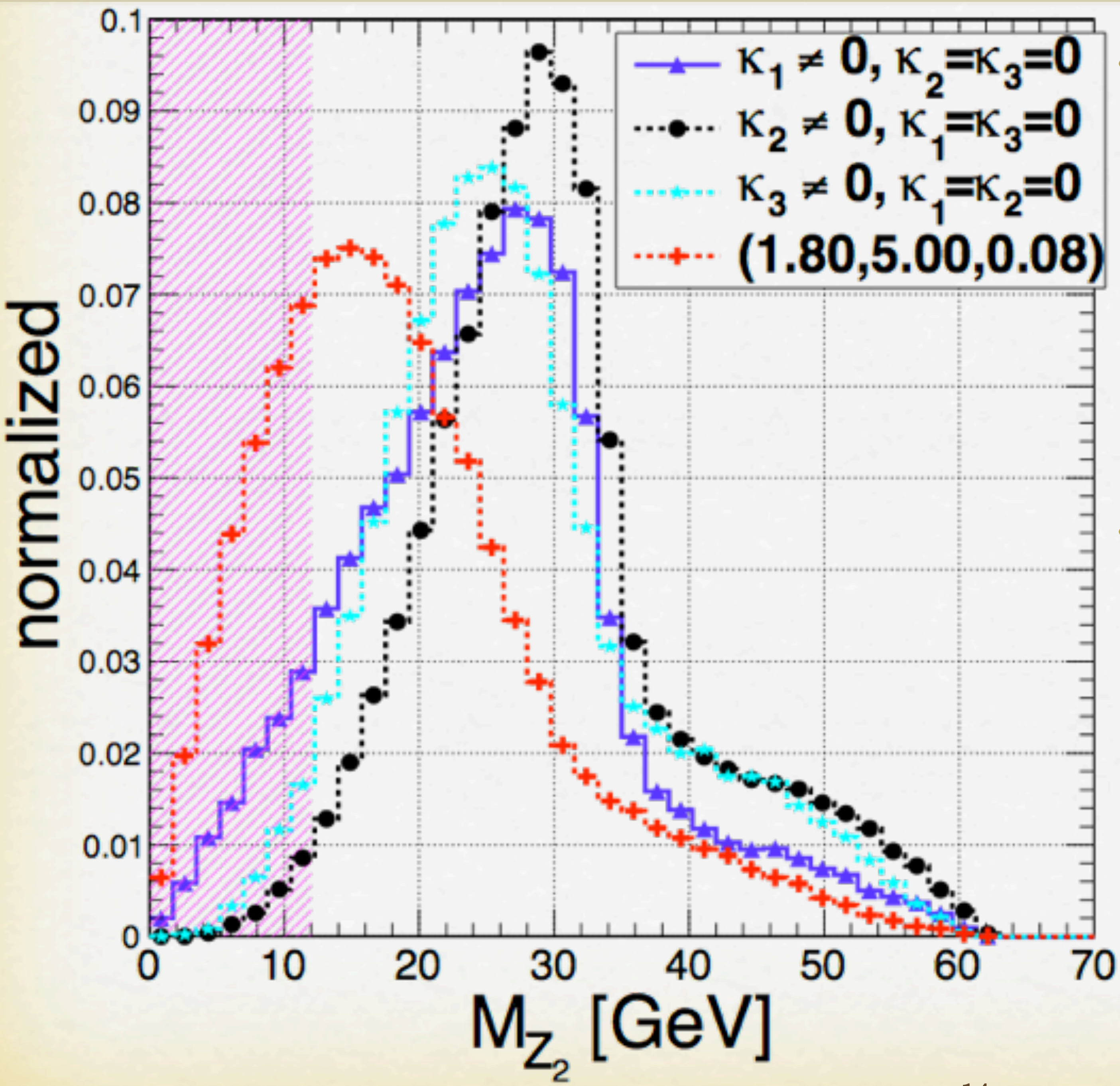
CUTS AND EFFICIENCIES

- 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%
- $p_T > 7$ GeV
  $|\eta| < 2.5$ for electrons
- $p_T > 5$ GeV
  $|\eta| < 2.4$ for muons
- $M_1 > 40$ GeV
- $M_2 > 12$ GeV



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^*

- (Choi, Miller, Muhlleitner, and Zerwas, 2003),

  (Godbole, Miller, and Muhlleitner, 2007),

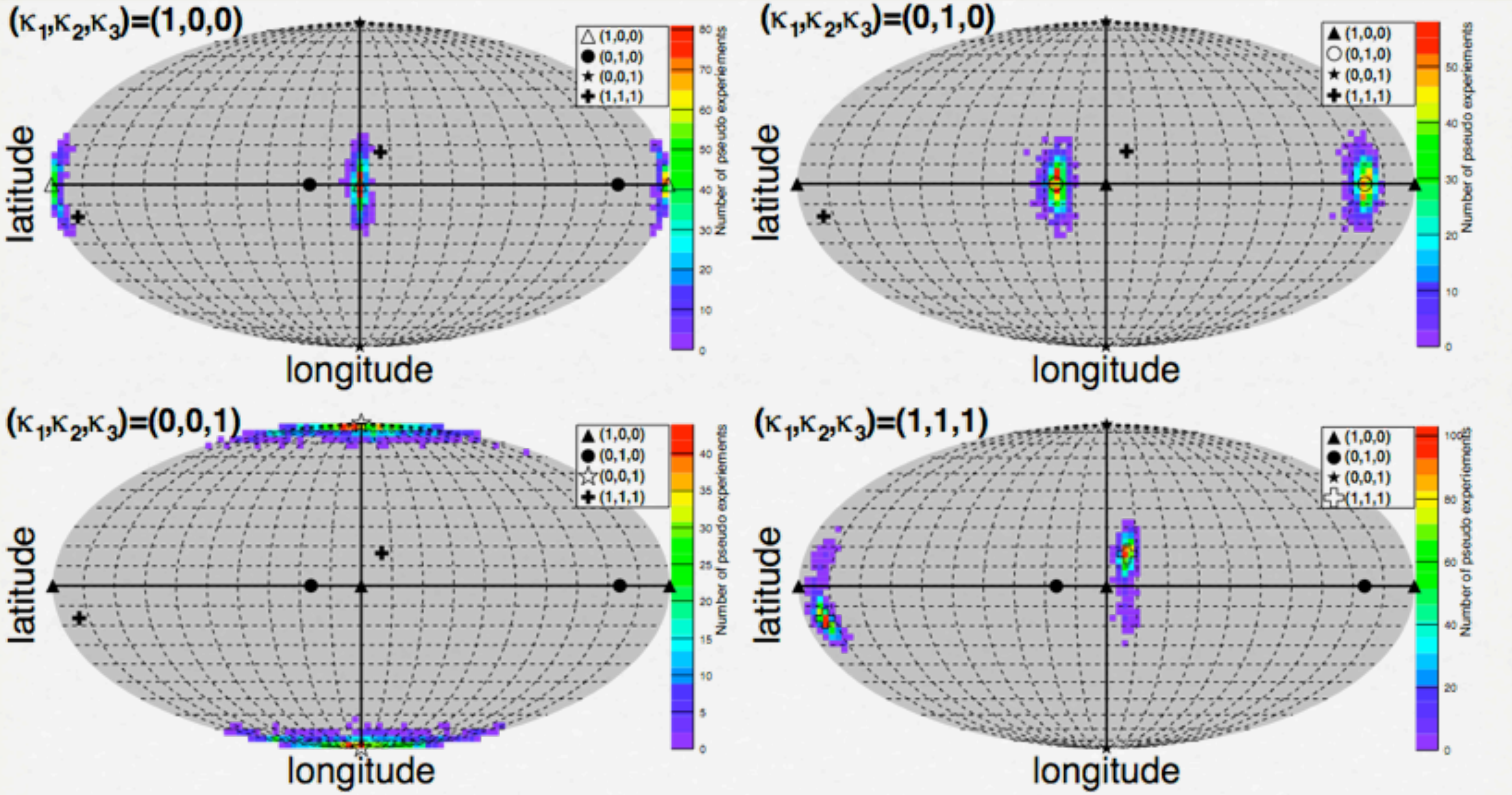
  (Boughezal, LeCompte, and F. Petriello, 2012),

  etc.

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

EXAMPLE ANALYSIS



- Note: a point and its antipode are effectively equivalent

OTHER SPHERES

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

- Scenario 1: $\kappa_1 = 0$. κ_2 and κ_3 arbitrary and complex. Coupling can be gauge invariant.
  Example: X is SM singlet.

- Scenario 2: $\kappa_2 = 0$. Mixing of SM scalar and pseudoscalar.

- Scenario 3: $\kappa_3 = 0$. Arbitrary CP-even scalar.

EXAMPLE: SCENARIO 2

- Now we allow κ_1, κ_3 to be complex

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

- 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

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

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^-)
  - $\kappa_1 = 0$, κ_2, κ_3 complex: θ_{23}, ϕ_{23}
  - $\kappa_2 = 0$, κ_1, κ_3 complex: θ_{13}, ϕ_{13}
  - $\kappa_3 = 0$, κ_1, κ_2 complex: θ_{12}, ϕ_{12}

- We look forward to locating the Higgs on the sphere!

BACKUP SLIDES

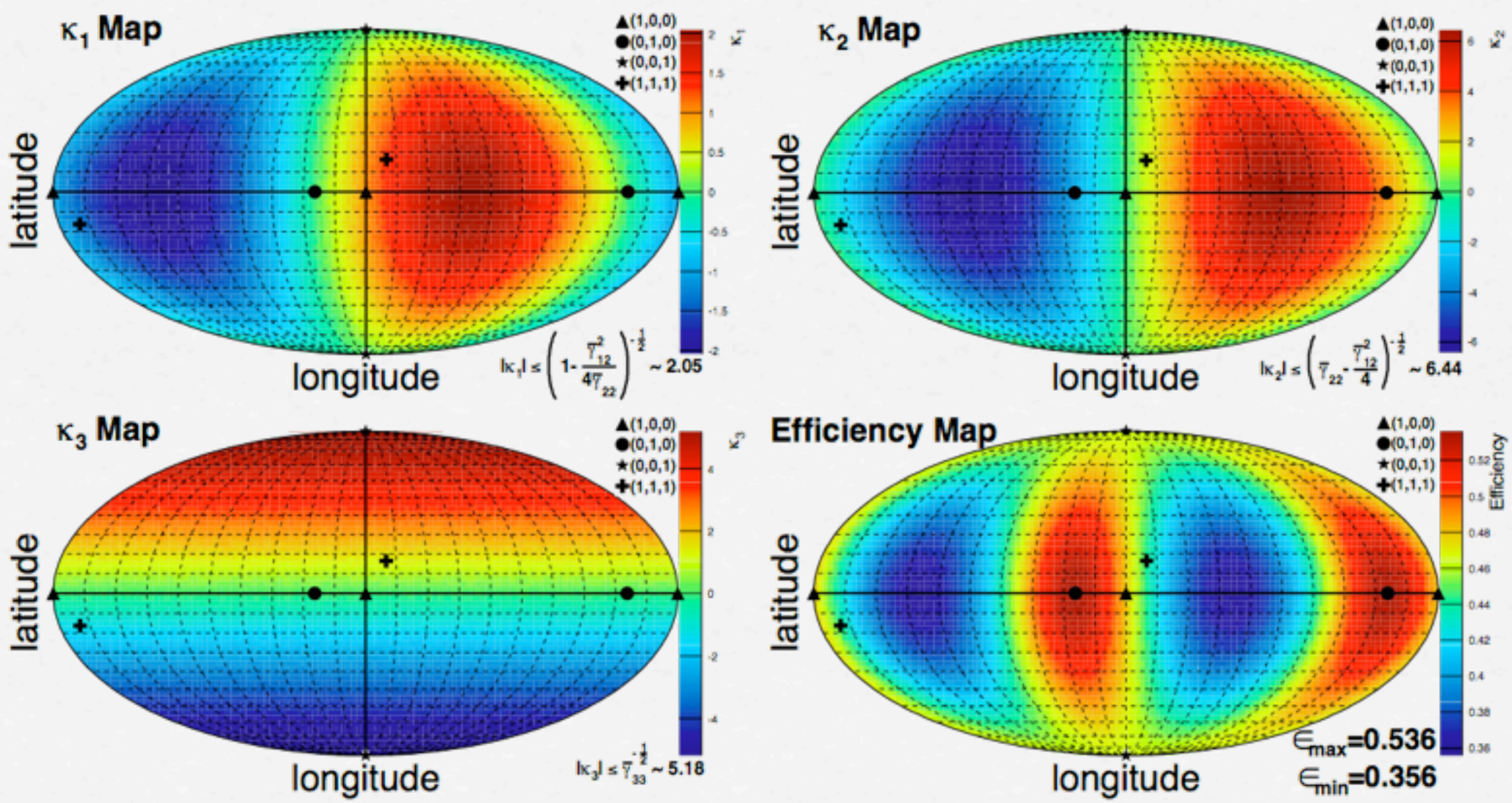
EXPRESSIONS FOR CHANGE OF VARIABLES

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

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