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A STATISTICAL APPROACH TO HIGGS COUPLINGS IN THE SMEFT

based on 1710.02008

IS ANOTHER SMEFT FIT NECESSARY?

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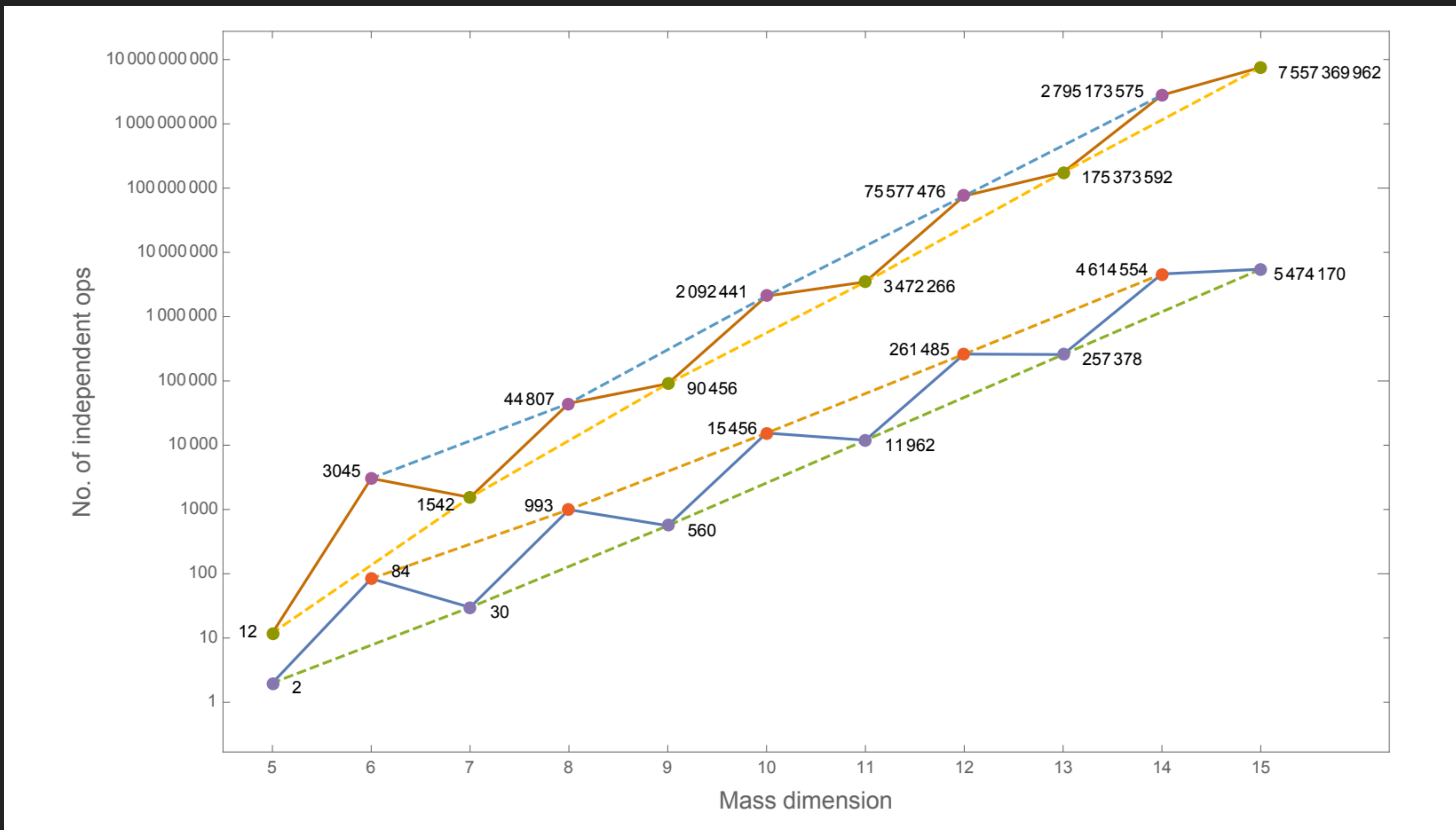
probably an incomplete list

LARGE NUMBER OF PARAMETERS IN SMEFT



Henning, Lu, Melia, Murayama 1512.03433

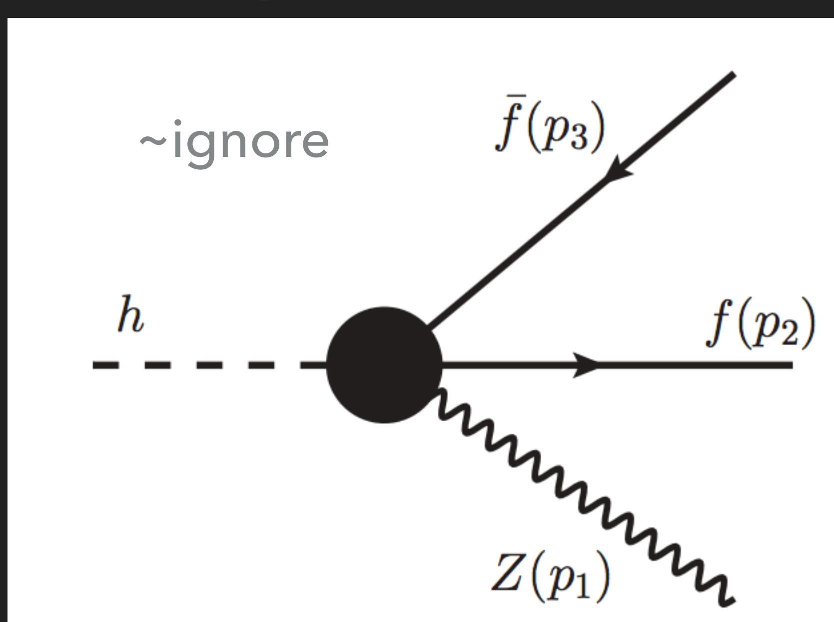
2,499 *B#* conserving at dimension-6: Alonso, Jenkins, Manohar, Trott 1312.2014

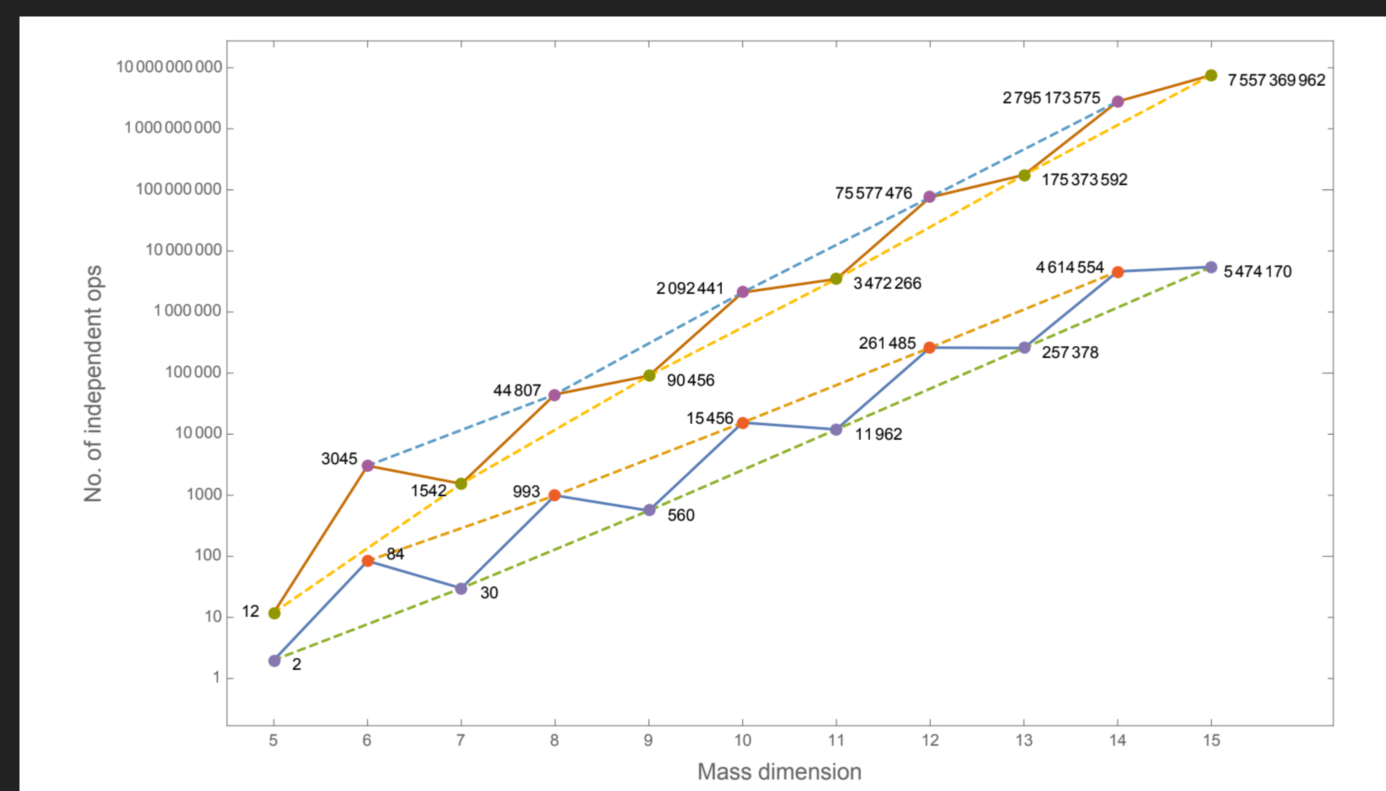
OUTLINE

- Regularized linear regression / cross-validation
- Eigensystem of covariance matrix – (more) model independent
- Predictions, constraints, future measurements

SMEFT HIGGS SECTOR

- 18 parameters that can interfere w/ LO SM Higgs diagrams with $U(2)^5$ flavor symmetry
- proof of principle – assume VBF, *Vh* production; *h* decay to *VV** are independent of the fermions associated w/ *V*
    - 12 parameters





SMEFT HIGGS SECTOR

$$\Delta\mathcal{L}^{(6)} = \frac{c_H}{v^2}\partial_\mu\left(H^\dagger H\right)\partial^\mu\left(H^\dagger H\right) + \frac{c_T}{v^2}\left|H^\dagger \overleftrightarrow{D}_\mu H\right|^2 + \frac{c_6}{v^2}\left(H^\dagger H\right)^3$$
$$+ \frac{\left(H^\dagger H\right)}{v^2}\left[c_b\left(\bar{q}_{L3} d_{R3} H\right) + c_t\left(\bar{q}_{L3} u_{R3}\tilde{H}\right) + c_\tau\left(\bar{\ell}_{L3} e_{R3} H\right) + \text{h.c.}\right]$$
$$+ \frac{i c_W}{v^2}\left(H^\dagger \sigma^i \overleftrightarrow{D}^\mu H\right)\left(D^\nu W_{\mu\nu}\right)^i + \frac{i c_B}{v^2}\left(H^\dagger \overleftrightarrow{D}^\mu H\right)\left(D^\nu B_{\mu\nu}\right)$$
$$+ \frac{i c_{HW}}{v^2}\left(D^\mu H\right)^\dagger \sigma^i \left(D^\nu H\right) W^i_{\mu\nu} + \frac{i c_{HB}}{v^2}\left(D^\mu H\right)^\dagger\left(D^\nu H\right) B_{\mu\nu}$$
$$+ \frac{c_\gamma}{v^2} H^\dagger H B_{\mu\nu} B^{\mu\nu} + \frac{c_g}{v^2} H^\dagger H G^a_{\mu\nu} G^{a\mu\nu},$$

3rd generation only:
$U(2)^5$ symmetry

$$H^\dagger \overleftrightarrow{D}_\mu H \equiv H^\dagger D_\mu H - (D_\mu H^\dagger) H$$

SMEFT HIGGS SECTOR

- Compute observables to linear order in c_i
- Include NLO contribution of Higgs trilinear coupling - 1607.04251

$$\frac{\Gamma(h \to WW^*)}{\Gamma_{SM}(h \to WW^*)} \simeq 1 - 2.02c_H + 0.72c_W + 0.61c_{HW} - 0.057c_6$$

REGULARIZED LEAST SQUARES

- Augment standard chi-squared function w/ positive definite regulation term

$$\chi^2(\mathbf{c}) = (\mathbf{y} - \boldsymbol{\mu}(\mathbf{c}))^\top V^{-1} (\mathbf{y} - \boldsymbol{\mu}(\mathbf{c})) + \mathbf{c}^\top \kappa\, \mathbf{c}$$

take $\kappa_{ij} = \kappa\delta_{ij}$ $\qquad$ $\mu_i = H_{ij} c_j$

$$\hat{\mathbf{c}} = \left(H^\top V^{-1} H + \kappa\mathbb{1}\right)^{-1} H^\top V^{-1}\mathbf{y}$$

$$U = \left(H^\top V^{-1} H + \kappa\mathbb{1}\right)^{-1}$$

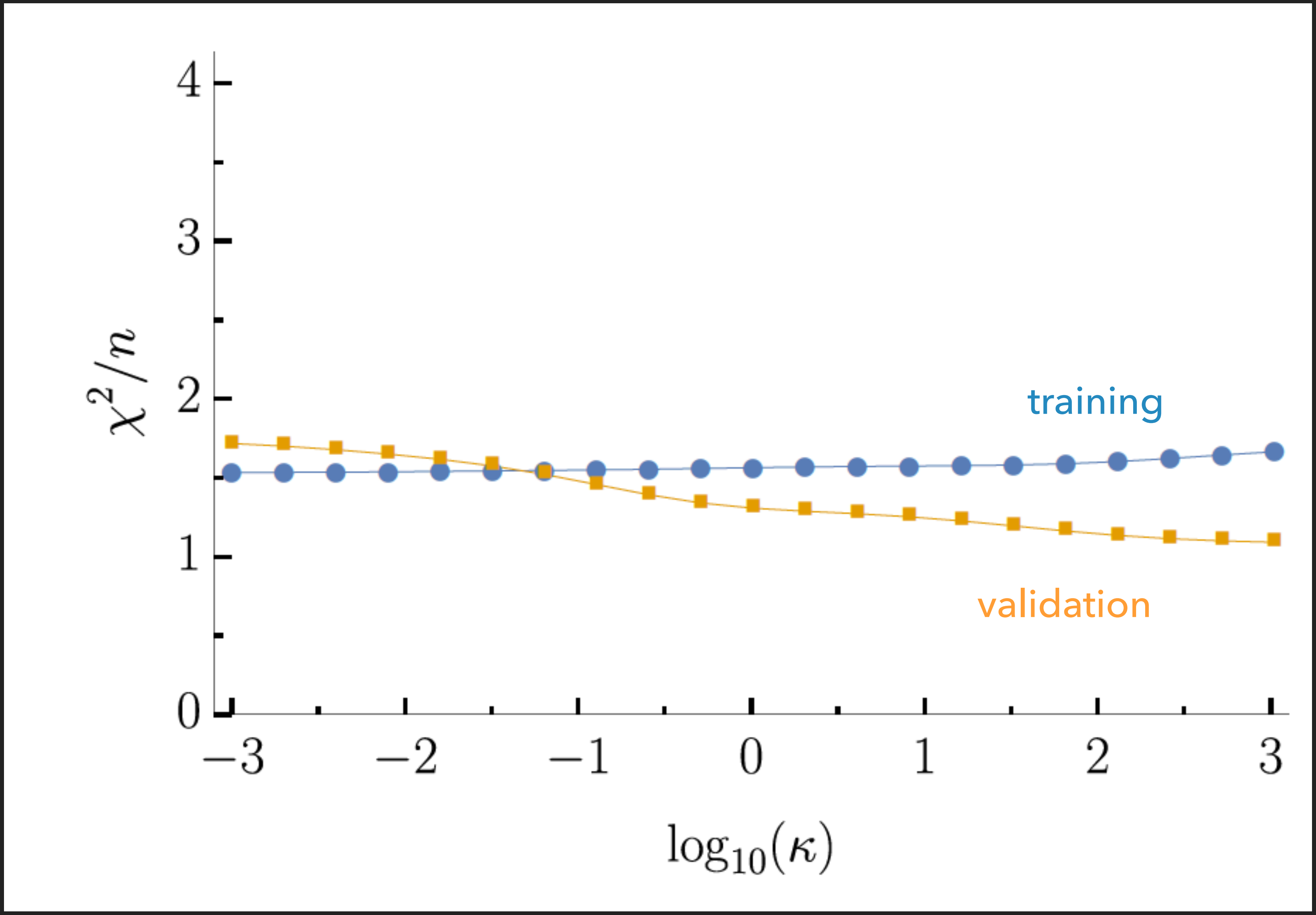
MEASUREMENTS USED

- Higgs Results:
  - 22 Run-1 signal strengths (mostly ATLAS+CMS combined)
  - 33 Run-2 signal strengths
  - no differential/boosted measurements
- no EWPD, triple gauge couplings, flavor measurements

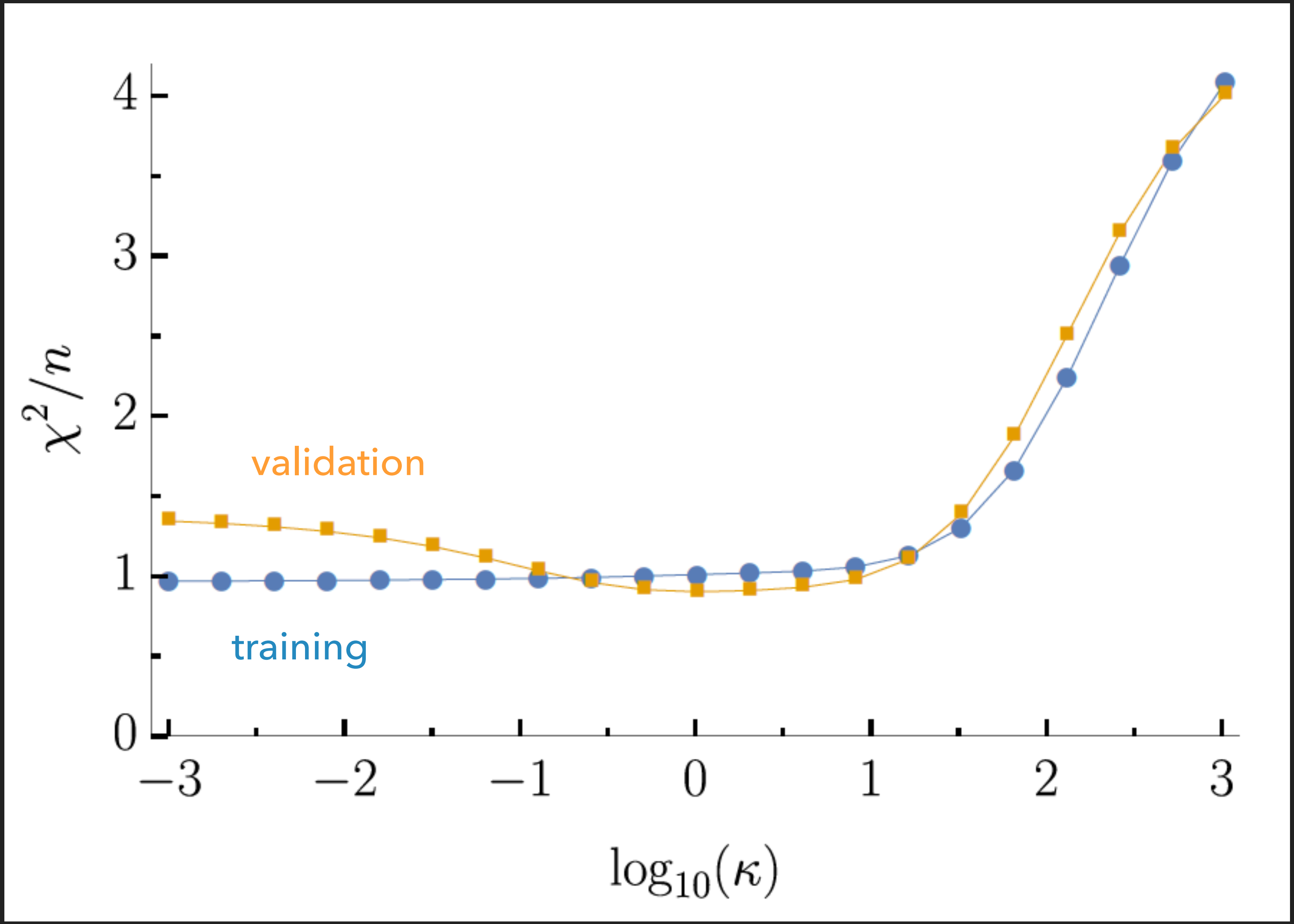
CROSS-VALIDATION

- Split data into training and validation sets
- Optimize parameters using training data w/ regularized linear regression
- Compute χ^2 w/ optimized parameters w/o regularization
- Optimal regularization parameter minimizes this χ^2 / n

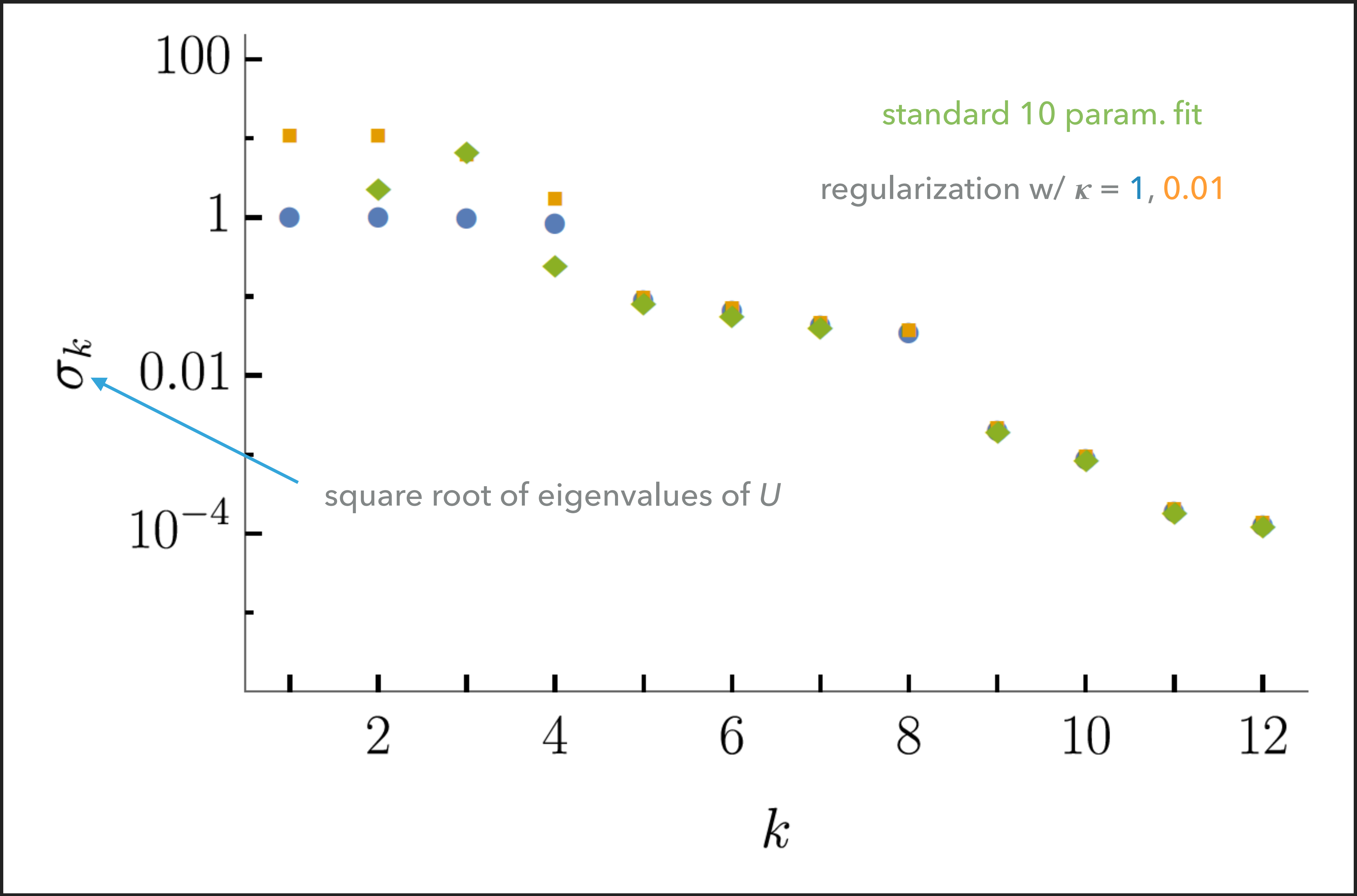
CROSS-VALIDATION



CROSS-VALIDATION - HYPOTHETICAL BSM SIGNAL

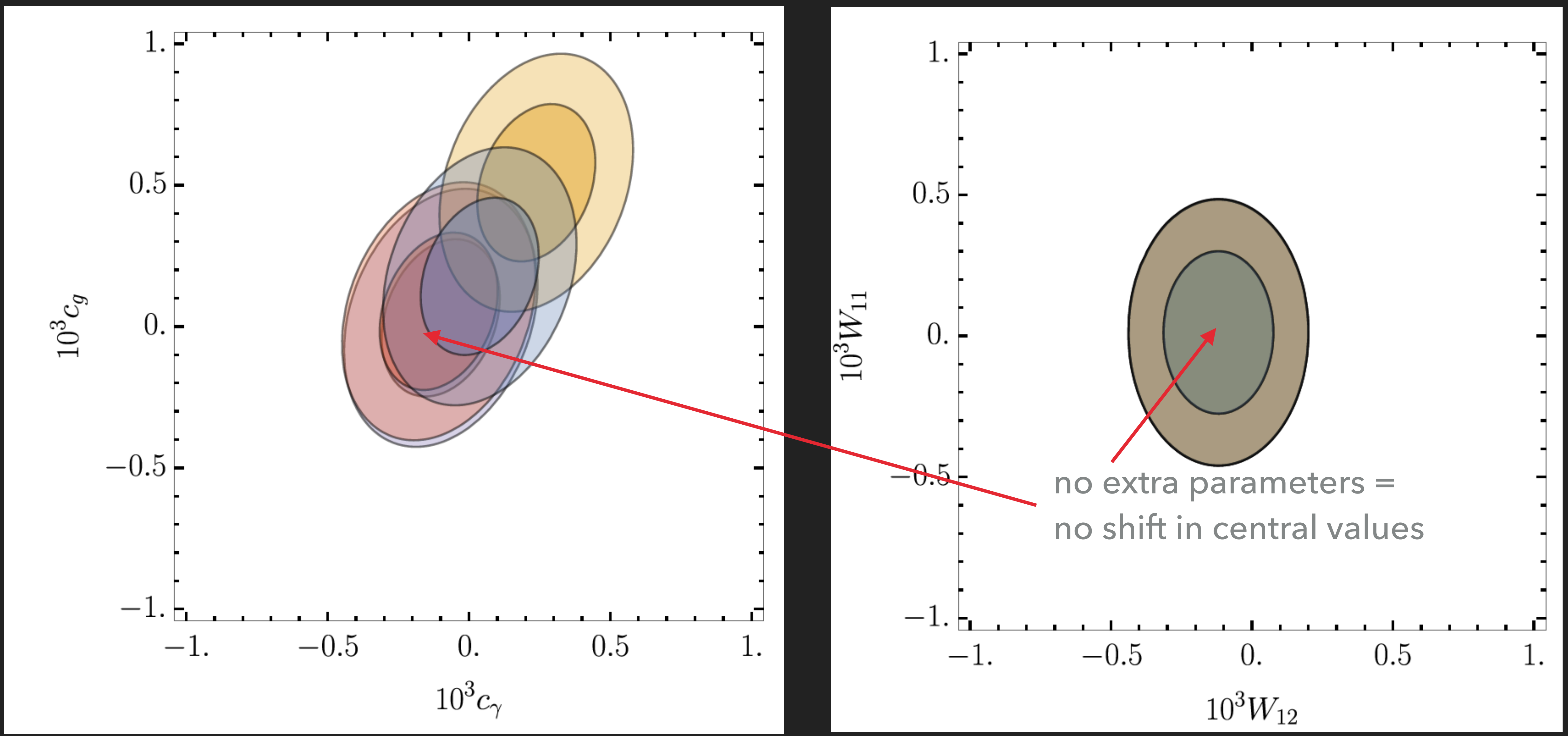


ONE SIGMA LIMITS ON EIGENVECTORS

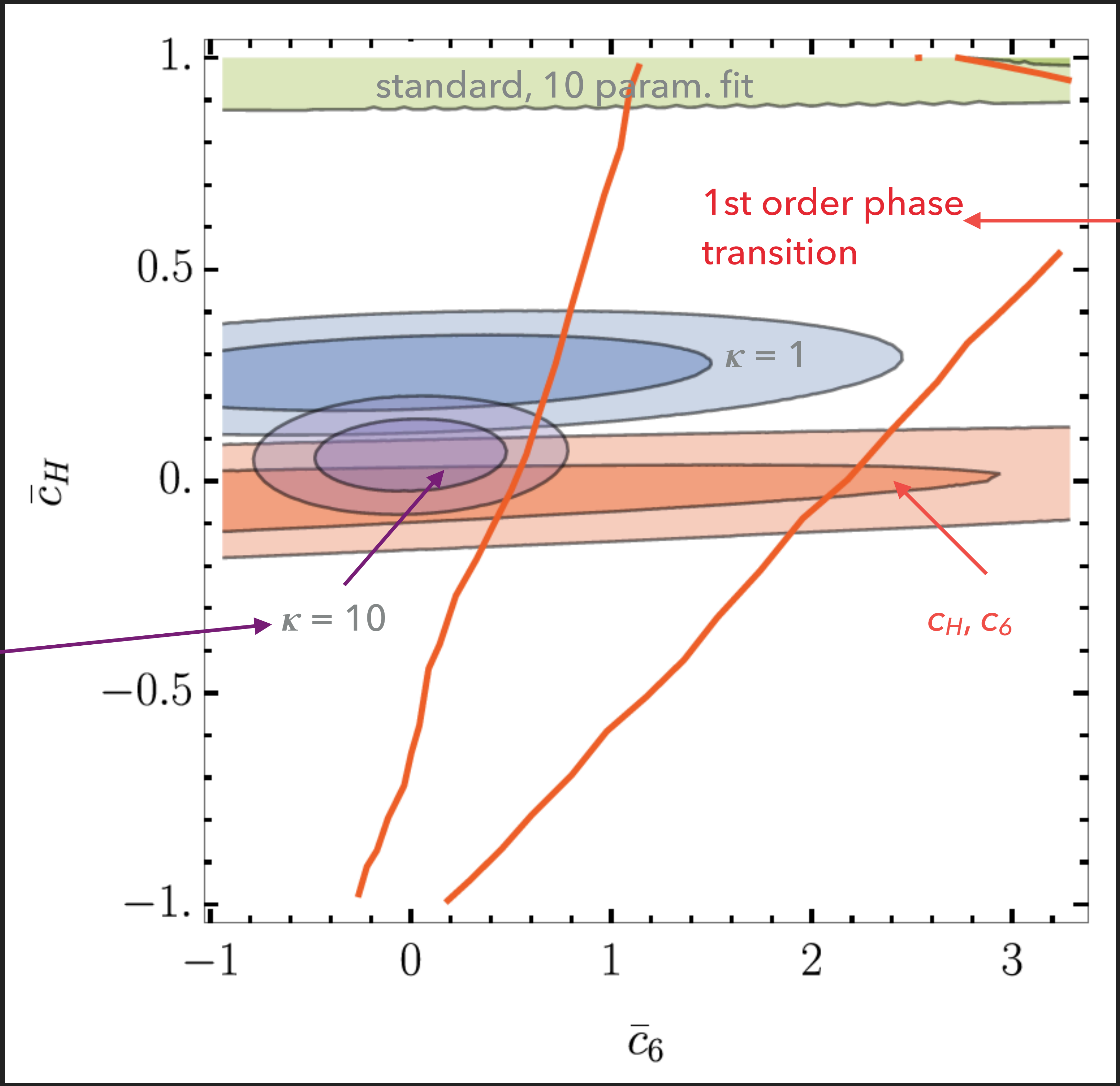


TWO-DIMENSIONAL PROFILES

- Presence of extra parameters/flat directions shift central values of c_γ, c_g, from central values of W_{12}, W_{11}



IMPLICATIONS FOR EW BARYOGENESIS IN SMEFT



1512.01963

effective scale ~800 GeV – need lower scale BSM

GUIDANCE FOR FUTURE MEASUREMENTS

- Which measurements would improve the global constraints the most?
- Quantify using the global determinant parameter - 1704.02333

$$\mathrm{GDP} = \left(\prod_{j \subseteq k} \sigma_j^2 \right)^{\frac{1}{m}}$$

GUIDANCE FOR FUTURE MEASUREMENTS

- Add one hypothetical signal strength of 1.0 ± 0.1 to the global fit
- Compute GDP ratio with/without additional measurement

Observable	GDP ratio	Observable	GDP ratio
$gg \to hh$	0.37	$Wh,\ h \to ZZ^*$	0.96
$h \to Z\gamma$	0.71	VBF, $h \to b\bar{b}$	0.98
$h \to c\bar{c}$	0.80	Γ_h	0.98
$h \to \mu^+\mu^-$	0.80	$Zh,\ h \to \tau^+\tau^-$	0.99
$tth,\ h \to ZZ^*$	0.93	$tth,\ h \to b\bar{b}$	0.99
$Zh,\ h \to ZZ^*$	0.94	ggF, $h \to b\bar{b}$	0.99

SUMMARY

- Regularized linear regression prevents a fit from falling into an overfit solution
  - Applications beyond Higgs signal strengths
- Eigensystem of the covariance matrix – model-independent
- If all parameters known predictions can be made
- EW Baryogenesis in SMEFT is constrained, but not ruled out
- Studied which future measurements would improve the constraints the most

BACKUP SLIDES

HOW SHOULD WE INTERPRET NULL RESULTS?

- No evidence of other new particles
  - implies a separation of scales, $v < \Lambda$
  - use effective field theory approach

$m_h \approx 125$ GeV

$$V_{SM} = \frac{1}{2} m_h^2 h^2 + \lambda_{SM} v h^3 + \frac{\lambda_{SM}}{4} h^4$$

$v \approx 246$ GeV

STANDARD MODEL EFFECTIVE FIELD THEORY

- expansion in E^2 / Λ^2

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \mathcal{L}^{(5)} + \mathcal{L}^{(6)} + \dots$$

$$\mathcal{L}^{(n)} = \Sigma_i \frac{c_i^{(n)}}{v^{n-4}} O_i^{(n)}$$

STANDARD MODEL EFFECTIVE FIELD THEORY

- Advantages of SMEFT
  - consistently incorporate higher-order corrections
  - describe differential distributions
  - combine w/ measurements from other sectors: EWPD, triple gauge couplings, …

VALIDITY OF THE EFFECTIVE THEORY

- Must be careful to respect the expansion in E^2 / Λ^2

REVIEW OF LEAST SQUARES

- chi-squared function $$\chi^2(\mathbf{c}) = (\mathbf{y} - \boldsymbol{\mu}(\mathbf{c}))^\top V^{-1} (\mathbf{y} - \boldsymbol{\mu}(\mathbf{c}))$$
- predicted values linear functions of parameters $\mu_i = H_{ij} c_j$
- estimators for central values $$\hat{\mathbf{c}} = \left(H^\top V^{-1} H\right)^{-1} H^\top V^{-1} \mathbf{y}$$
- covariance matrix for estimators $$U = \left(H^\top V^{-1} H\right)^{-1}$$
- U exists if
  - # measurements > # parameters
  - H_i sufficiently unique

PREDICTIONS

- Total width of Higgs boson

$$\frac{\Gamma_{SMEFT,h}}{\Gamma_{SM,h}} \simeq 0.5 \pm 0.4 \quad \text{(Run-1)}$$

$$\frac{\Gamma_{SMEFT,h}}{\Gamma_{SM,h}} \simeq 0.9 \pm 0.3 \quad \text{(Run-1+Run-2)}$$

PREDICTIONS

- Double Higgs boson production
  - CMS upper limit 19x SM rate (ATLAS 29x)
  - In most general case SMEFT bounds not competitive
  - Particular scenarios can be highly restricted, *e.g.* $c_6 = 0$:

$$\sigma_{SMEFT}(gg \to hh)/\sigma_{SM}(gg \to hh) \simeq 1.4 \pm 0.4$$

IMPLICATIONS FOR EW BARYOGENESIS IN SMEFT

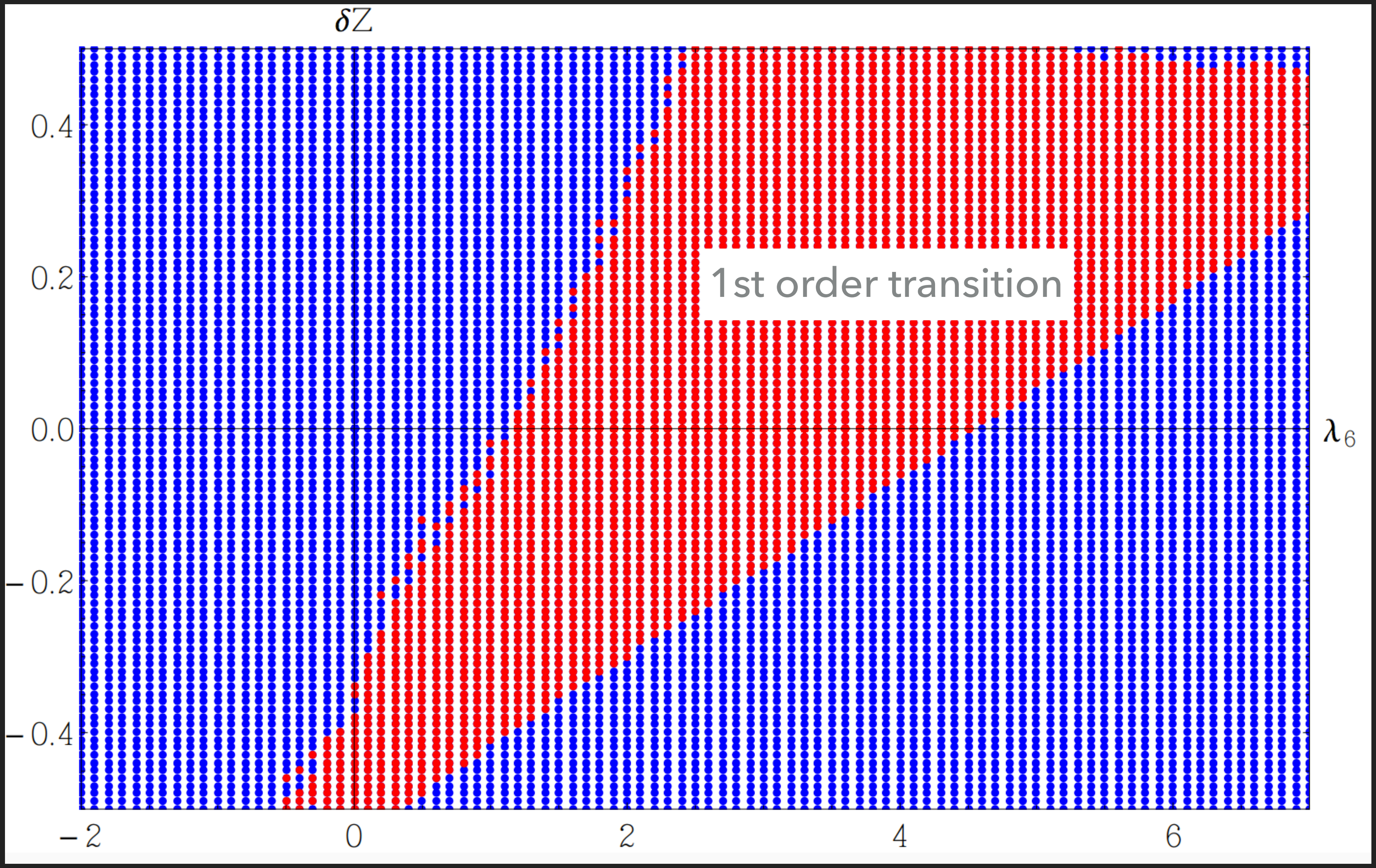
- assuming temperature dependence only in Higgs mass parameter
- 1st order transition if $\frac{2}{3} < \bar{c}_6 < 2$

$$c_H = \frac{1}{2}\bar{c}_H, \quad c_6 = -\frac{m_h^2}{2v^2}\bar{c}_6$$

hep-ph/0407019, 1512.00068, 1512.08922, 1709.03232

IMPLICATIONS FOR EW BARYOGENESIS IN SMEFT

$\propto \bar{c}_H$

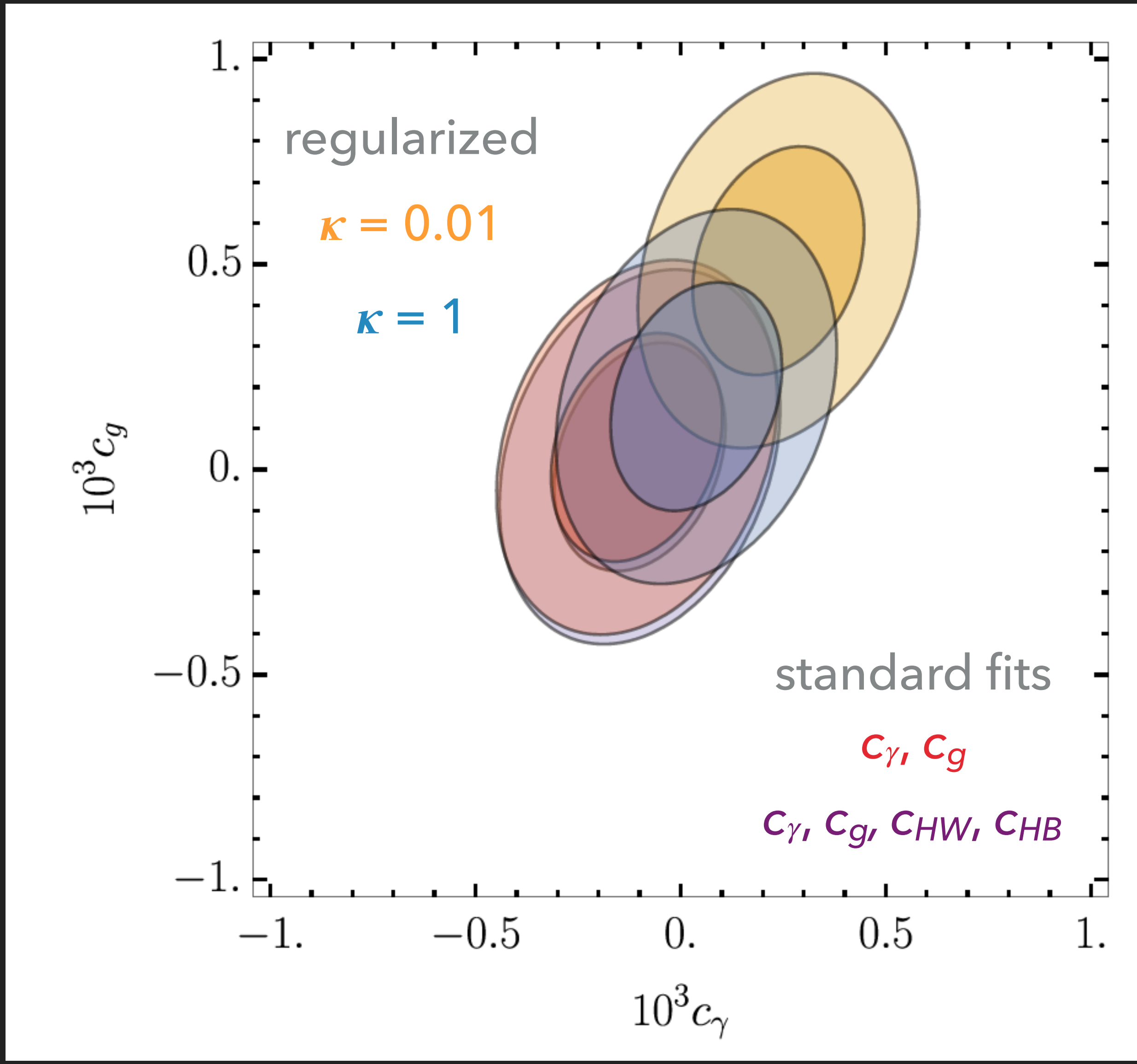


$\propto \bar{c}_6$

1512.01963

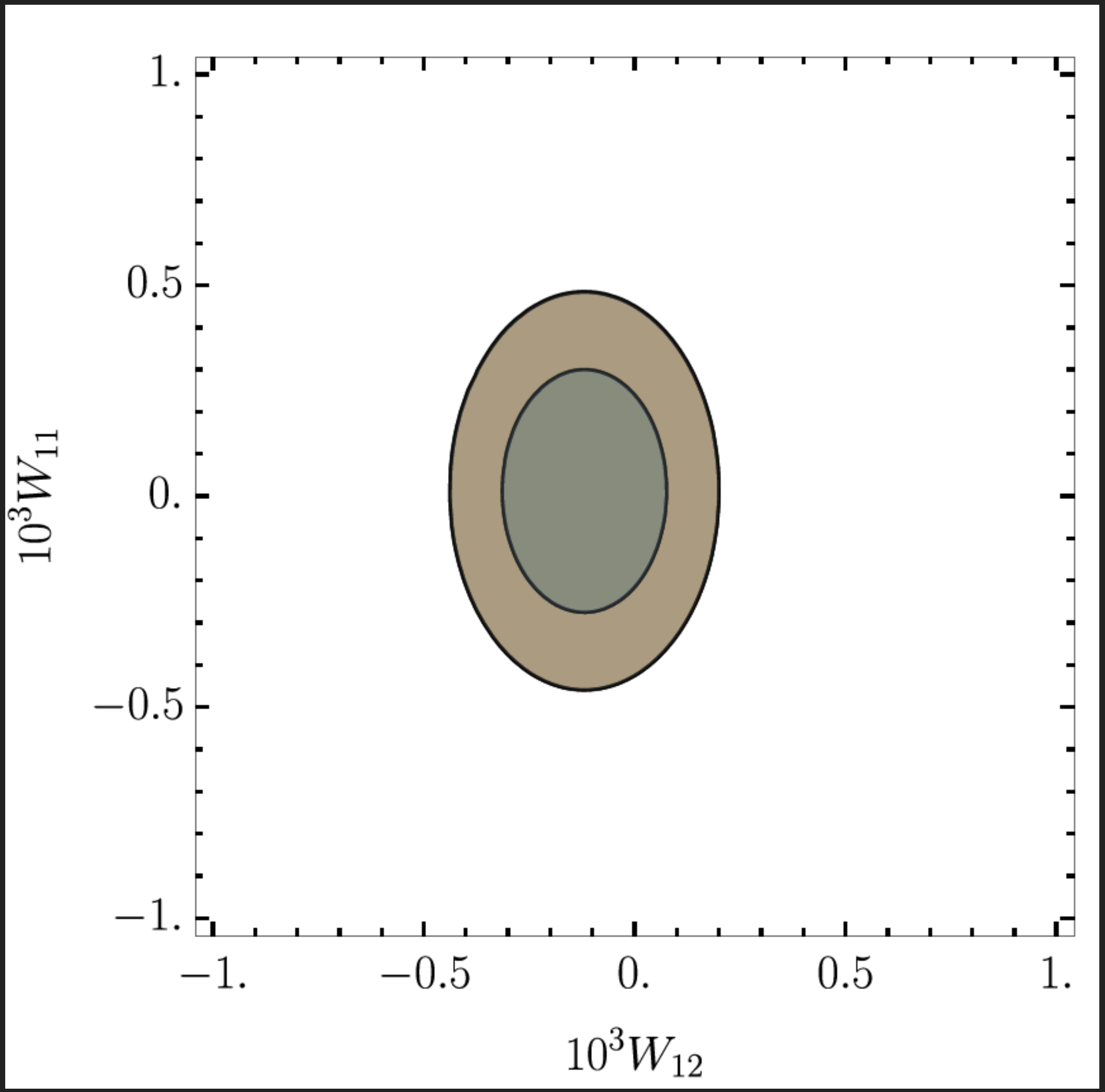
TWO-DIMENSIONAL PROFILES

- variances, correlation agree
- central values differ



TWO-DIMENSIONAL PROFILES

- All scenarios agree perfectly
- Largely model-independent



INTERPRETATION OF κ ?

- $\kappa < 1$: enforce experimental upper limit ($pp \to hh$, $h \to Z\gamma$)
- $\kappa \geq 1$: set lowest BSM scale of $\Lambda_{min} \sim v/\sqrt{\kappa}$

$$\Delta c_i \lesssim \frac{1}{\sqrt{\kappa}}$$

    - normalization dependent
- Regularization matrix in general not proportional to identity
- *e.g.* if strongly coupled theory assumed, relate entries of κ_{ij} to size of coefficients expected from NDA?

SMEFT DECAY RATES

$$\frac{\Gamma(h \to \tau\tau)}{\Gamma_{SM}(h \to \tau\tau)} \simeq 1 - 2c_H - 196c_\tau,$$
$$\frac{\Gamma(h \to \mu\mu)}{\Gamma_{SM}(h \to \mu\mu)} \simeq 1 - 2c_H,$$
$$\frac{\Gamma(h \to bb)}{\Gamma_{SM}(h \to bb)} \simeq 1 - 2c_H - 83c_b - 0.0085c_t,$$
$$\frac{\Gamma(h \to cc)}{\Gamma_{SM}(h \to cc)} \simeq 1 - 2c_H - 0.015c_t,$$

$$\frac{\Gamma(h \to WW^*)}{\Gamma_{SM}(h \to WW^*)} \simeq 1 - 2.02c_H + 0.72c_W + 0.61c_{HW} - 0.057c_6,$$
$$\frac{\Gamma(h \to ZZ^*)}{\Gamma_{SM}(h \to ZZ^*)} \simeq 1 - 2.02c_H - 4c_T + 0.66c_W + 0.34c_B + 0.49c_{HW}$$
$$+ 0.26c_{HB} - 0.24c_\gamma - 0.064c_6,$$
$$\frac{\Gamma(h \to Z\gamma)}{\Gamma_{SM}(h \to Z\gamma)} \simeq 1 - 2c_H + 0.12c_t - 0.12c_b - 0.0088c_\tau + 1.38c_W$$
$$+ 151\,(0.16c_{HW} - 0.32c_{HB} + 1.58c_\gamma)\,,$$
$$\frac{\Gamma(h \to \gamma\gamma)}{\Gamma_{SM}(h \to \gamma\gamma)} \simeq 1 - 2.01c_H + 0.54c_t - 0.29c_b - 0.69c_\tau + 1.66c_W$$
$$- 863c_\gamma - 0.038c_6,$$
$$\frac{\Gamma(h \to gg)}{\Gamma_{SM}(h \to gg)} \simeq 1 - 2.02c_H - 2.13c_t + 4.17c_b + 589c_g - 0.051c_6.$$

$$\frac{\Gamma_h}{\Gamma_{SM,h}} \simeq 1 - 2.007c_H - 0.11c_T - 1.61c_\gamma + 12.3c_g + 0.18c_{HW} - 0.067c_{HB}$$
$$+ 0.18c_W + 0.009c_B - 0.187c_t - 47.4c_b - 12.3c_\tau - 0.018c_6.$$

SMEFT CROSS SECTIONS

$$\frac{\sigma(gg \to h)}{\sigma_{SM}(gg \to h)} \simeq \frac{\Gamma(h \to gg)}{\Gamma_{SM}(h \to gg)},$$

$$\frac{\sigma(pp \to jjh)}{\sigma_{SM}(pp \to jjh)} \simeq 1 - 2.02c_H - c_T - 0.06c_\gamma + 0.58c_{HW} + 0.085c_{HB} + 0.71c_W + 0.085c_B - 0.05c_6,$$

$$\frac{\sigma(pp \to Wh)}{\sigma_{SM}(pp \to Wh)} \simeq 1 - 2.03c_H + 0.61c_{HW} + 0.72c_W - 0.081c_6,$$

$$\frac{\sigma(pp \to Zh)}{\sigma_{SM}(pp \to Zh)} \simeq 1 - 2.04c_H - 4c_T - 0.24c_\gamma + 0.49c_{HW} + 0.34c_{HB} + 0.66c_W + 0.34c_B - 0.095c_6,$$

$$\frac{\sigma(pp \to t\bar{t}h)}{\sigma_{SM}(pp \to t\bar{t}h)} \simeq 1 - 2.11c_H - 2.01c_t - 0.29c_6.$$

RUN-1 MEASUREMENTS

Production	Decay	Signal Strength	Production	Decay	Signal Strength
ggF	$\gamma\gamma$	$1.10^{+0.23}_{-0.22}$	Wh	bb	1.0 ± 0.5
ggF	ZZ	$1.13^{+0.34}_{-0.31}$	Zh	$\gamma\gamma$	$0.5^{+3.0}_{-2.5}$
ggF	WW	0.84 ± 0.17	Zh	WW	$5.9^{+2.6}_{-2.2}$
ggF	$\tau\tau$	1.0 ± 0.6	Zh	$\tau\tau$	$2.2^{+2.2}_{-1.8}$
VBF	$\gamma\gamma$	1.3 ± 0.5	Zh	bb	0.4 ± 0.4
VBF	ZZ	$0.1^{+1.1}_{-0.6}$	tth	$\gamma\gamma$	$2.2^{+1.6}_{-1.3}$
VBF	WW	1.2 ± 0.4	tth	WW	$5.0^{+1.8}_{-1.7}$
VBF	$\tau\tau$	1.3 ± 0.4	tth	$\tau\tau$	$-1.9^{+3.7}_{-3.3}$
Wh	$\gamma\gamma$	$0.5^{+1.3}_{-1.2}$	tth	bb	1.1 ± 1.0
Wh	WW	$1.6^{+1.2}_{-1.0}$	pp	$\mu\mu$	0.1 ± 2.5
Wh	$\tau\tau$	-1.4 ± 1.4	pp	$Z\gamma$	$2.7^{+4.6}_{-4.5}$

TABLE II: Run-1 experimental results used in this work. The $Z\gamma$ result is from ATLAS [64]. CMS does not provide a signal strength for $h \to Z\gamma$ although their 95% CL upper limit is stronger [65] than the ATLAS Run-1 result. All other results are taken from the combined ATLAS+CMS analysis of Ref. [1] with correlations taken into account.

RUN-2 ATLAS MEASUREMENTS

Production	Decay	Signal Strength	Reference	Production	Decay	Signal Strength	Reference
pp	$\mu\mu$	-0.1 ± 1.4	[66]	ggF	ZZ	$1.11^{+0.25}_{-0.22}$	[67]
Wh	bb	$1.35^{+0.68}_{-0.59}$	[68]	VBF	ZZ	$4.0^{+1.8}_{-1.5}$	[67]
Zh	bb	$1.12^{+0.50}_{-0.45}$	[68]	VBF	WW	$1.7^{+1.2}_{-0.9}$	[69]
ggF	$\gamma\gamma$	$0.80^{+0.19}_{-0.18}$	[70]	Wh	WW	$3.2^{+4.4}_{-4.2}$	[69]
VBF	$\gamma\gamma$	2.1 ± 0.6	[70]	tth	$2\ell\,0\tau_h$	$4.0^{+2.1}_{-1.7}$	[71]
Vh	$\gamma\gamma$	$0.7^{+0.9}_{-0.8}$	[70]	tth	$2\ell\,1\tau_h$	$6.2^{+3.6}_{-2.7}$	[71]
tth	$\gamma\gamma$	0.5 ± 0.6	[70]	tth	3ℓ	$0.5^{+1.7}_{-1.6}$	[71]
pp	$Z\gamma$	1.3 ± 2.6	[72]				

TABLE III: Run-2 ATLAS results used in this work. We estimate the signal strength for $h \to Z\gamma$ from Ref. [72], which states the upper limit for this process is 6.6 times the SM rate at 95% CL and that the significance of the measurement is 0.5σ.

RUN-2 CMS MEASUREMENTS

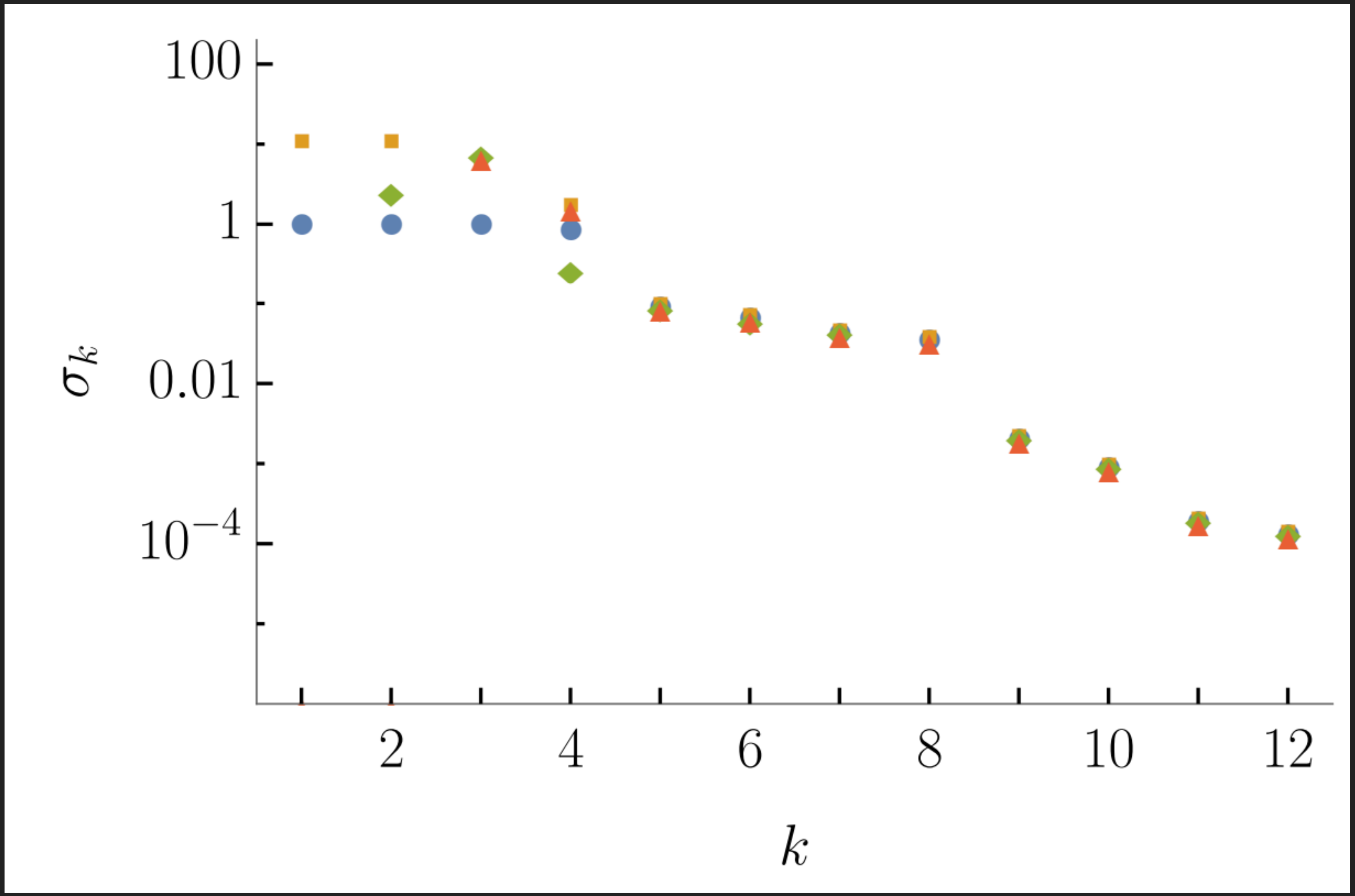
Production	Decay	Signal Strength	Reference	Production	Decay	Signal Strength	Reference
ggF	ZZ	1.20 ± 0.20	[73]	ggF	$\gamma\gamma$	$1.11^{+0.19}_{-0.18}$	[74]
0-jet	$\tau\tau$	0.84 ± 0.89	[75]	VBF	$\gamma\gamma$	$0.5^{+0.6}_{-0.5}$	[74]
VBF	$\tau\tau$	$1.11^{+0.34}_{-0.35}$	[75]	Vh	$\gamma\gamma$	$2.3^{+1.1}_{-1.0}$	[74]
tth	2ℓ	$1.7^{+0.6}_{-0.5}$	[76]	tth	$\gamma\gamma$	$2.2^{+0.9}_{-0.8}$	[74]
tth	3ℓ	$1.0^{+0.8}_{-0.7}$	[76]	0-jet	WW	$0.9^{+0.4}_{-0.3}$	[77]
tth	4ℓ	$0.9^{+2.3}_{-1.6}$	[76]	VBF	WW	1.4 ± 0.8	[77]
tth	$\tau\tau$	$0.72^{+0.62}_{-0.53}$	[78]	Wh	WW	-1.4 ± 1.5	[77]
Wh	bb	1.7 ± 0.7	[79]	Vh	WW	$2.1^{+2.3}_{-2.2}$	[77]
Zh	bb	0.9 ± 0.5	[79]	tt	bb	$-0.19^{+0.82}_{-0.81}$	[80]

TABLE IV: Run-2 CMS results used in this work.

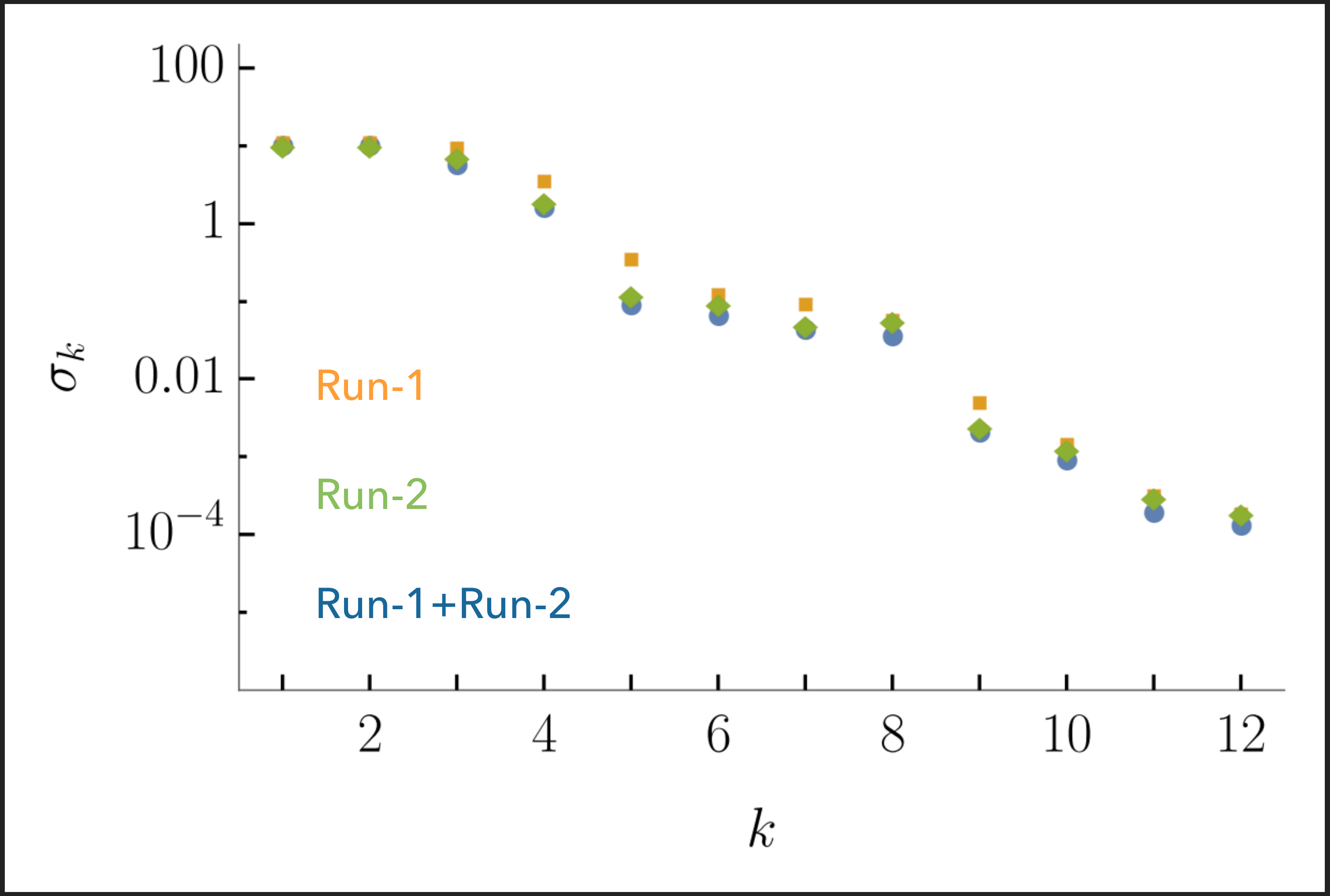
PSEUDOINVERSE

- defined by $A\,A^p\,A = A$ rather than $A^{-1}\,A = 1$
- exists for any matrix
- if (genuine) inverse exists, then $A^p = A^{-1}$

FIT USING PSEUDOINVERSE



RUN-1 VS. RUN-2



EIGENVECTOR COMPOSITION

$$
\begin{aligned}
W_1 &\simeq 0.99c_B + 0.09c_{HW} + 0.09c_T - 0.08c_W + 0.05c_{HB}, \qquad \text{(B1)}\\
W_2 &\simeq 0.67c_{HW} - 0.56c_W - 0.36c_B + 0.33c_{HB} - 0.02c_T,\\
W_3 &\simeq 0.99c_6 - 0.13c_t + 0.05c_W + 0.03c_{HW} + 0.02c_{HB} - 0.01c_H,\\
W_4 &\simeq 0.67c_W + 0.45c_{HW} + 0.38c_H - 0.38c_t + 0.24c_{HB} - 0.09c_6,\\
W_5 &\simeq 0.76c_t + 0.40c_W - 0.32c_H + 0.24c_{HW} + 0.22c_T + 0.20c_{HB} + 0.06c_6 - 0.02c_B,\\
W_6 &\simeq 0.78c_H + 0.51c_t - 0.32c_T - 0.10c_W + 0.08c_6 - 0.07c_{HB} - 0.05c_{HW} + 0.03c_b + 0.03c_B,\\
W_7 &\simeq 0.87c_{HB} - 0.48c_{HW} + 0.09c_H + 0.09c_T - 0.06c_W - 0.03c_t + 0.01c_b,\\
W_8 &\simeq 0.91c_T + 0.34c_H - 0.16c_{HB} - 0.11c_W - 0.08c_B - 0.03c_{HW} + 0.03c_b + 0.01c_6,\\
W_9 &\simeq 0.97c_b + 0.24c_\tau - 0.07c_g + 0.04c_\gamma - 0.03c_H + 0.02c_W + 0.01c_{HW} - 0.01c_t - 0.01c_T,\\
W_{10} &\simeq 0.97c_\tau - 0.24c_b + 0.05c_g,\\
W_{11} &\simeq 0.93c_g + 0.35c_\gamma + 0.06c_b - 0.03c_\tau,\\
W_{12} &\simeq 0.93c_\gamma - 0.35c_g - 0.07c_b.
\end{aligned}
$$

PREDICTIONS

- Double Higgs boson production