Constraining the Trilinear and Quartic Higgs Self-Coupling through Triple Higgs Production

Summer Student Project

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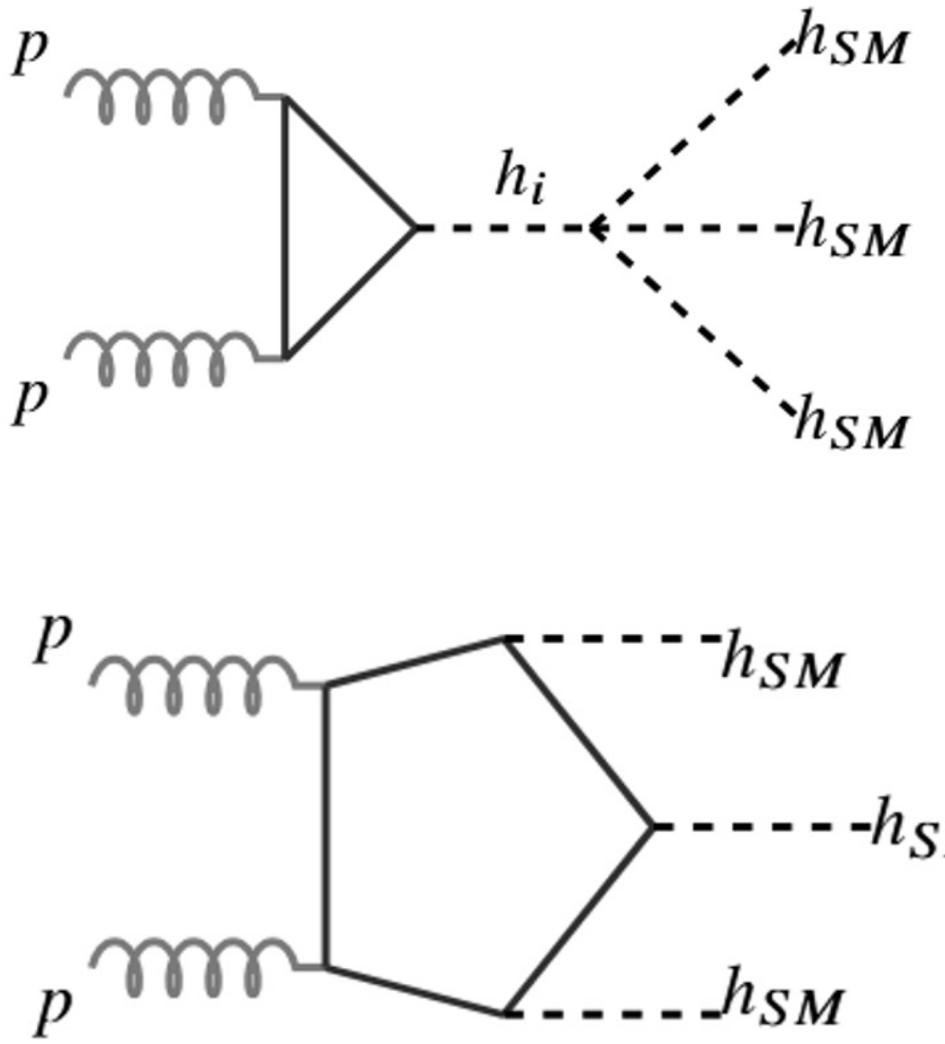
HELMHOLTZ

ATLAS EXPERIMENT

DESY.

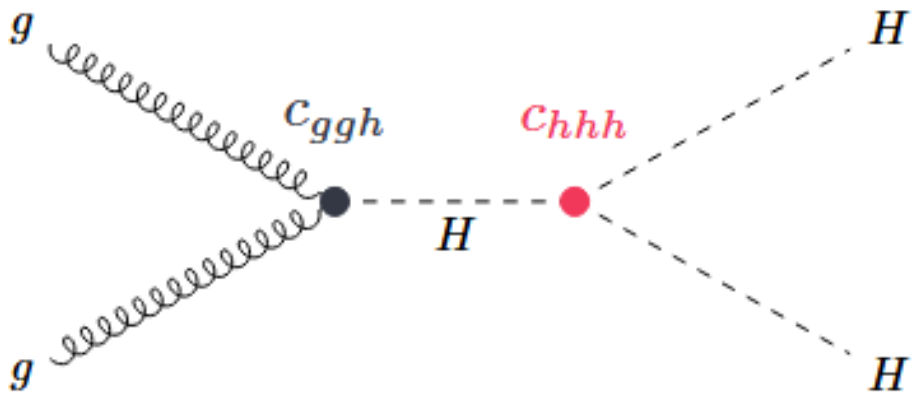
Motivation

- Reveal insights into the shape of the Higgs potential
- Crucial for drawing conclusions about the electroweak phase transition
- Could show significant deviations from SM (even if other Higgs couplings align with it)
- Probe deviations expected by BSM models that introduce new scalar fields (e.g. TRSM, X or S)
- Loose constraints can already have big impact on theories around early universe
- Georg Weiglein [arXiv:2312.04646]

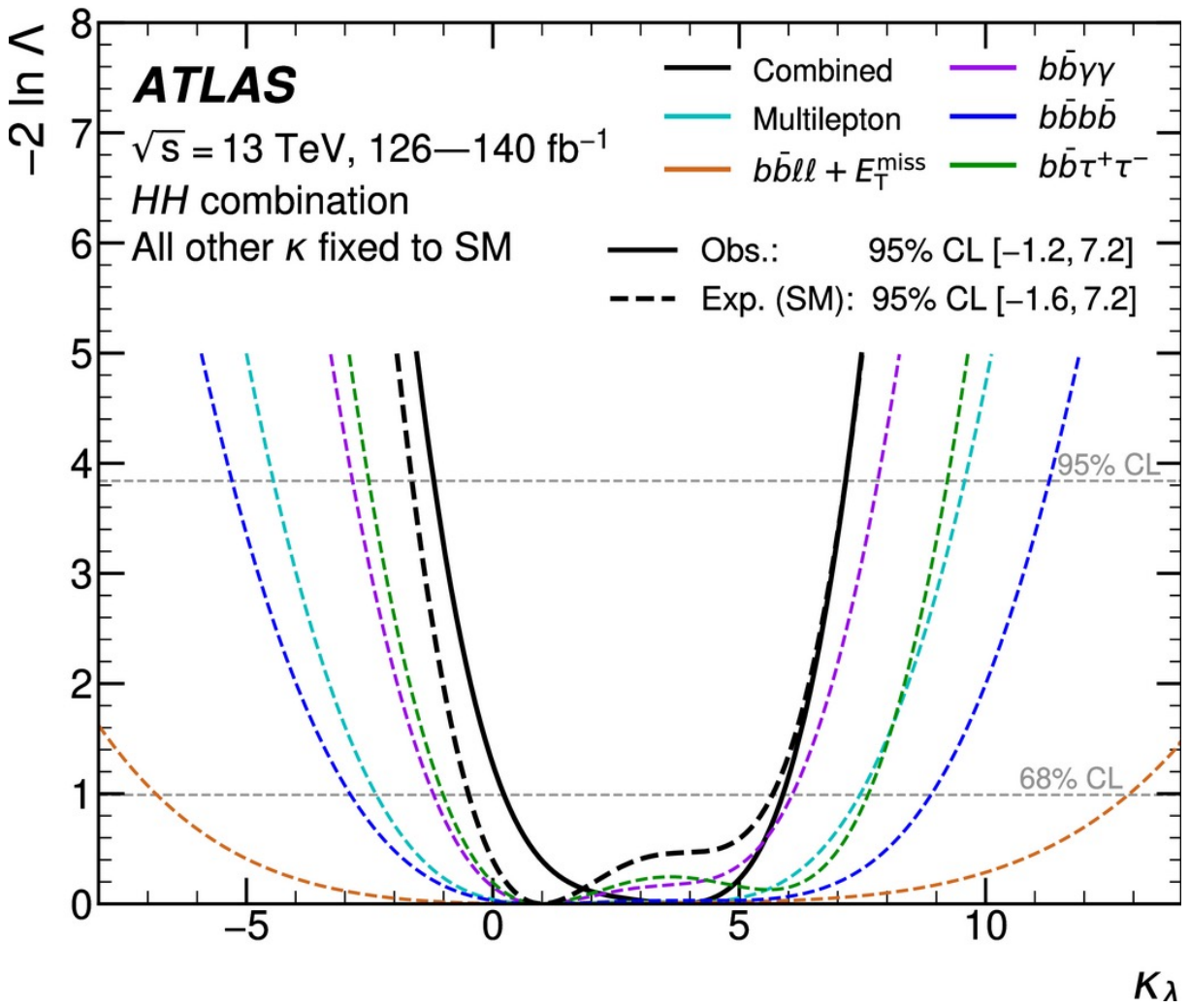


Trilinear and Quartic Higgs Self-Coupling

- $V(\Phi) = \lambda\, v^2 h^2 + \lambda_3\, v^2 h^3 + \frac{1}{4}\lambda_4\, h^4$
- Define κ_i as $\kappa_i = \frac{\lambda_i}{\lambda_i^{SM}}$, $i = 3,4$
- ATLAS set previous limits on κ_3 from Higgs boson pair production: $-1.2 < \kappa_3 < 7.2$ at 95% CL



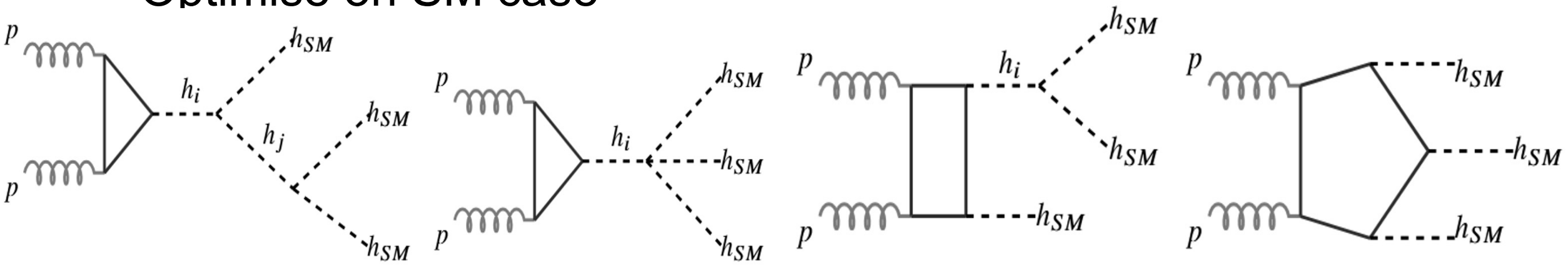
arXiv:2406.09971



Triple Higgs Production

- No experimental measurement yet
- Unique sensitivity to κ_4 (very loose constraints so far)
- Also sensitive to $\kappa_3 \rightarrow$ 2D scan?
- SM HHH production cross section = 0.08 fb

  → $0.08fb * 140fb^{-1} \cong 11$ expected events before selection
- Optimise on SM case



Signal Definition

Tiny cross section → Need enough statistics → 6b channel

BR~19.5%

$0.08 * 140 * 0.2 \cong 2!$

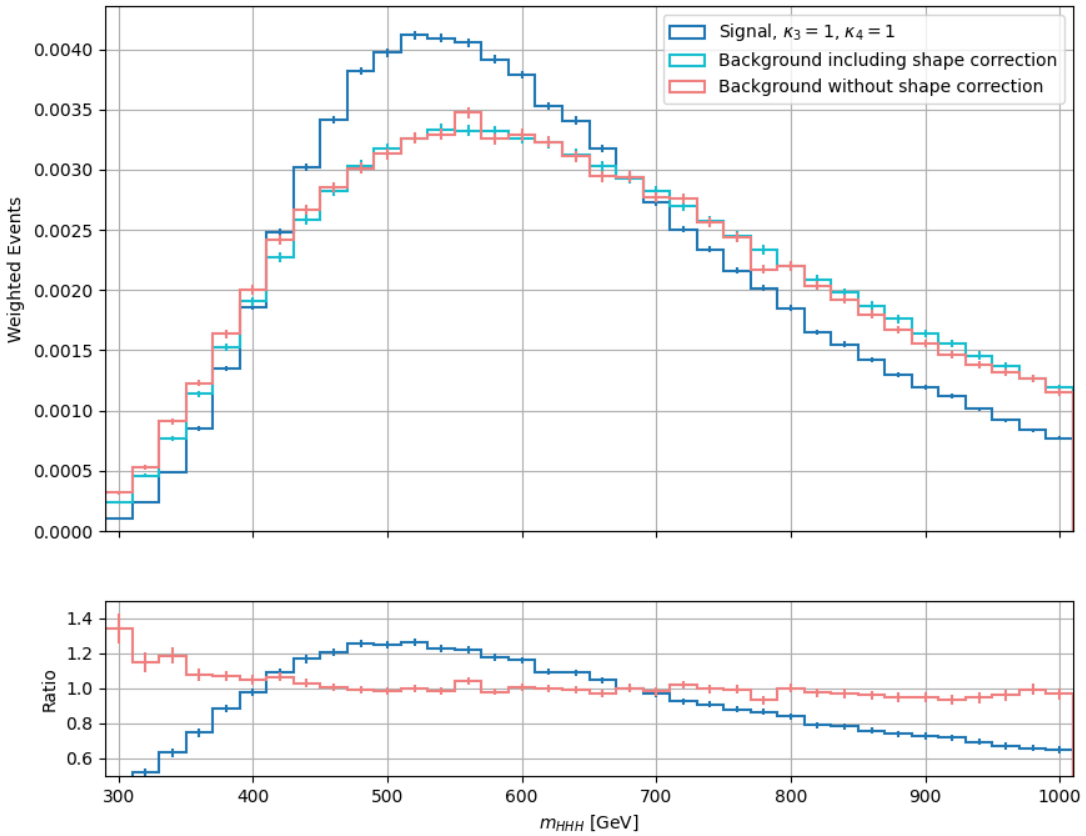
	6b region	5b region	4b region
b-Jets	≥ 6	$= 5$	$= 4$

At least 6 Jets with $p_T > 20$ GeV
At least 4 Jets with $p_T > 40$ GeV
$|\eta| < 2.5$

6b is signal region
4b and 5b region are needed for background estimation

Background Estimation

- Background dominated by QCD multijet production
- 6b background estimation can be extrapolated from 5b yields, which can be extrapolated from 4b
- $bkg_i = 5b_i \, R_{(5b_i|4b_i)} \, / R_{(5b|4b)}$
- Method validated on 4b to 5b
- First extrapolation gives necessary shape correction

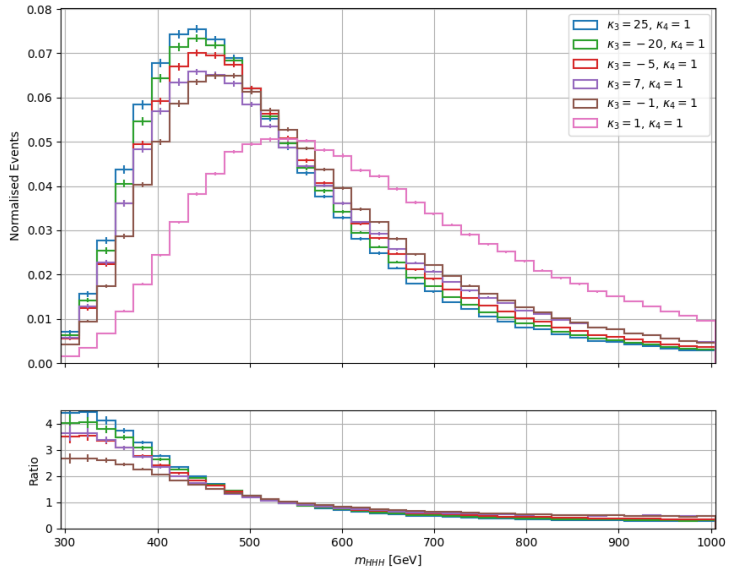


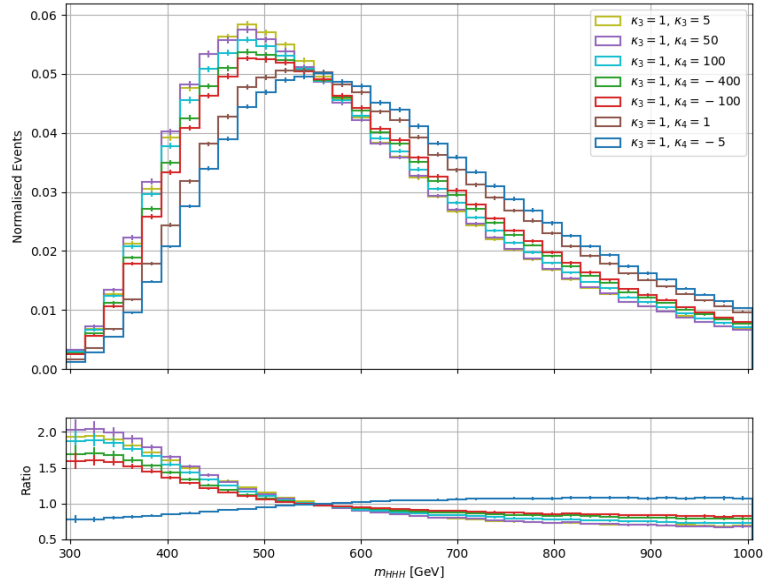
Reweighting for different values of κ_3 and κ_4

$$\begin{bmatrix} \kappa_{3,1}=0, \kappa_{4,1}=0 \\ \kappa_{3,2}=1, \kappa_{4,2}=-1 \\ \kappa_{3,3}=-1, \kappa_{4,3}=1 \\ \kappa_{3,4}=1, \kappa_{4,4}=0 \\ \kappa_{3,5}=0, \kappa_{4,5}=1 \\ \kappa_{3,6}=-1, \kappa_{4,6}=0 \\ \kappa_{3,7}=0, \kappa_{4,7}=-1 \\ \kappa_{3,8}=\frac{1}{2}, \kappa_{4,8}=0 \\ \kappa_{3,9}=-\frac{1}{2}, \kappa_{4,9}=0 \end{bmatrix}$$

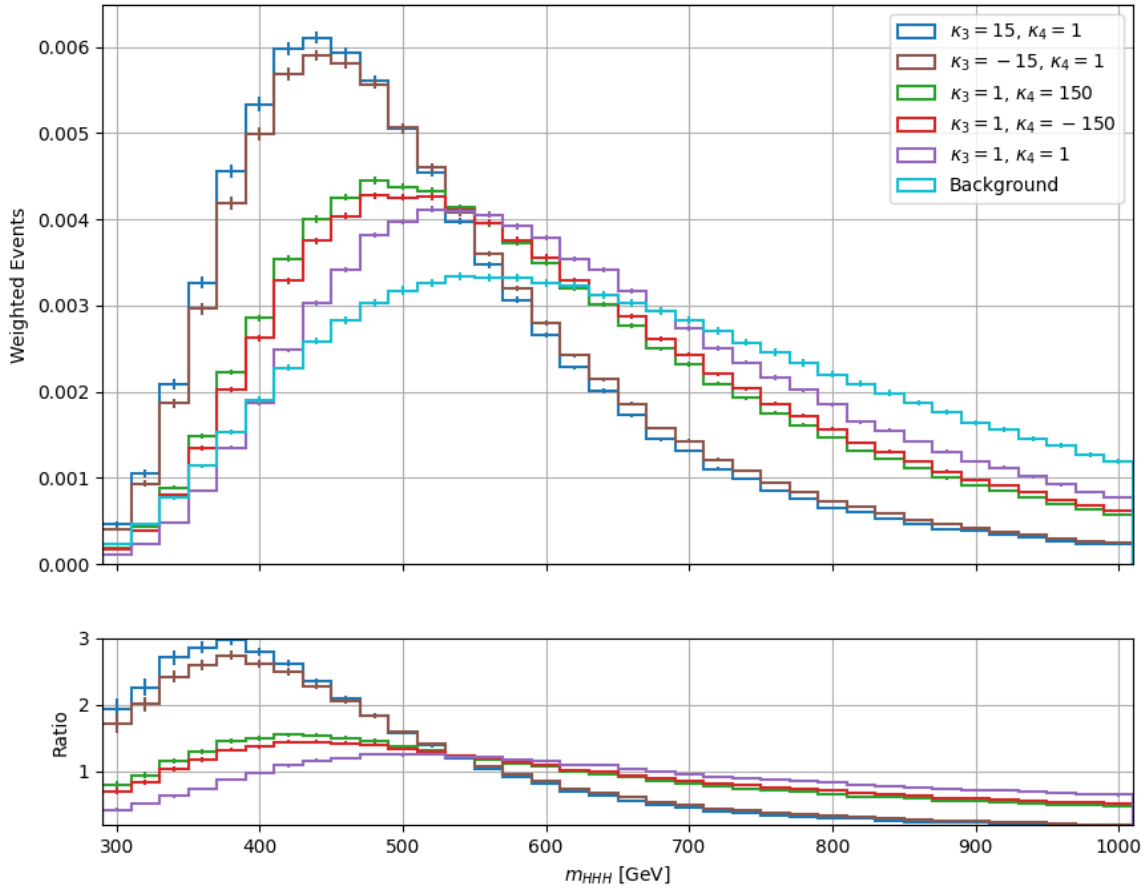
- Reweighting using 9 base vectors
- Formula based on analytic dependence of cross section on κ_3 and κ_4

$$w_{\text{total}}(\kappa_3,\kappa_4) = \begin{bmatrix} 1 \\ \kappa_3^2 \\ \kappa_3^4 \\ \kappa_4^2 \\ \kappa_3 \\ \kappa_4 \\ \kappa_3^3 \\ \kappa_3\kappa_4 \\ \kappa_3^2\kappa_4 \end{bmatrix} \cdot \left(\begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -5 & 0 & 0 & -\frac{1}{6} & 0 & -\frac{1}{6} & 0 & \frac{8}{3} & \frac{8}{3} \\ 4 & 0 & 0 & \frac{2}{3} & 0 & \frac{2}{3} & 0 & -\frac{8}{3} & -\frac{8}{3} \\ -1 & 0 & 0 & 0 & \frac{1}{2} & 0 & \frac{1}{2} & 0 & 0 \\ 0 & 0 & 0 & -\frac{1}{6} & 0 & \frac{1}{6} & 0 & \frac{4}{3} & -\frac{4}{3} \\ 0 & 0 & 0 & 0 & \frac{1}{2} & 0 & -\frac{1}{2} & 0 & 0 \\ 0 & 0 & 0 & \frac{2}{3} & 0 & -\frac{2}{3} & 0 & -\frac{4}{3} & \frac{4}{3} \\ -1 & -\frac{1}{2} & -\frac{1}{2} & \frac{1}{2} & \frac{1}{2} & \frac{1}{2} & \frac{1}{2} & 0 & 0 \\ 0 & -\frac{1}{2} & \frac{1}{2} & \frac{1}{2} & -\frac{1}{2} & -\frac{1}{2} & \frac{1}{2} & 0 & 0 \end{bmatrix} \begin{bmatrix} w_{\text{total}}(\kappa_{3,1},\kappa_{4,1}) \\ w_{\text{total}}(\kappa_{3,2},\kappa_{4,2}) \\ w_{\text{total}}(\kappa_{3,3},\kappa_{4,3}) \\ w_{\text{total}}(\kappa_{3,4},\kappa_{4,4}) \\ w_{\text{total}}(\kappa_{3,5},\kappa_{4,5}) \\ w_{\text{total}}(\kappa_{3,6},\kappa_{4,6}) \\ w_{\text{total}}(\kappa_{3,7},\kappa_{4,7}) \\ w_{\text{total}}(\kappa_{3,8},\kappa_{4,8}) \\ w_{\text{total}}(\kappa_{3,9},\kappa_{4,9}) \end{bmatrix} \right)$$





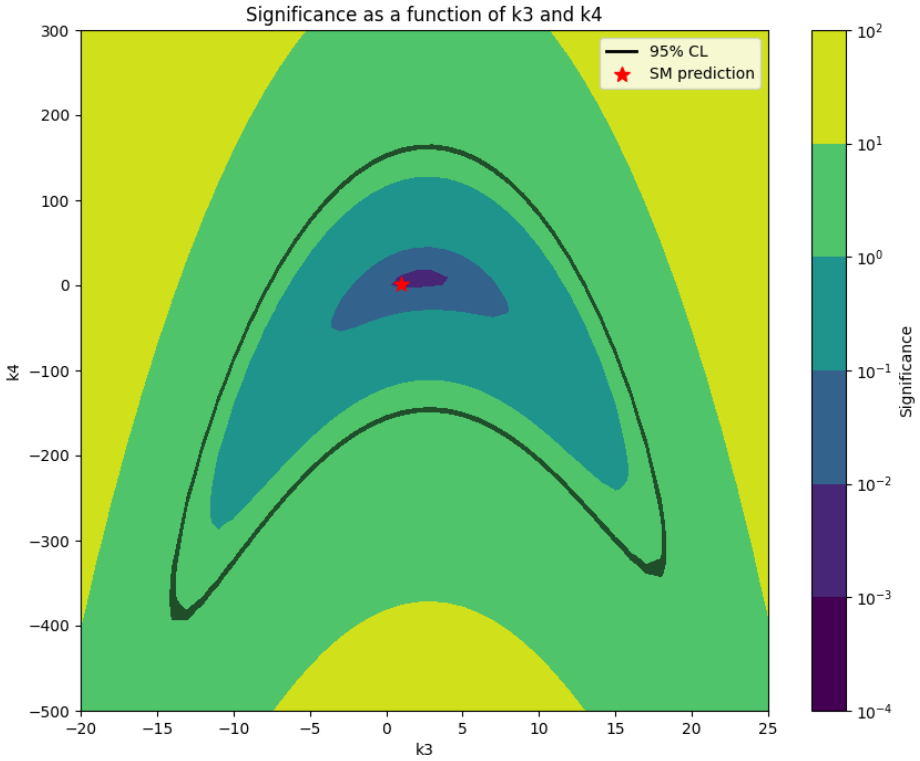
Signal vs Background



- High level variables to separate signal and background
- mHHH shows largest discrimination

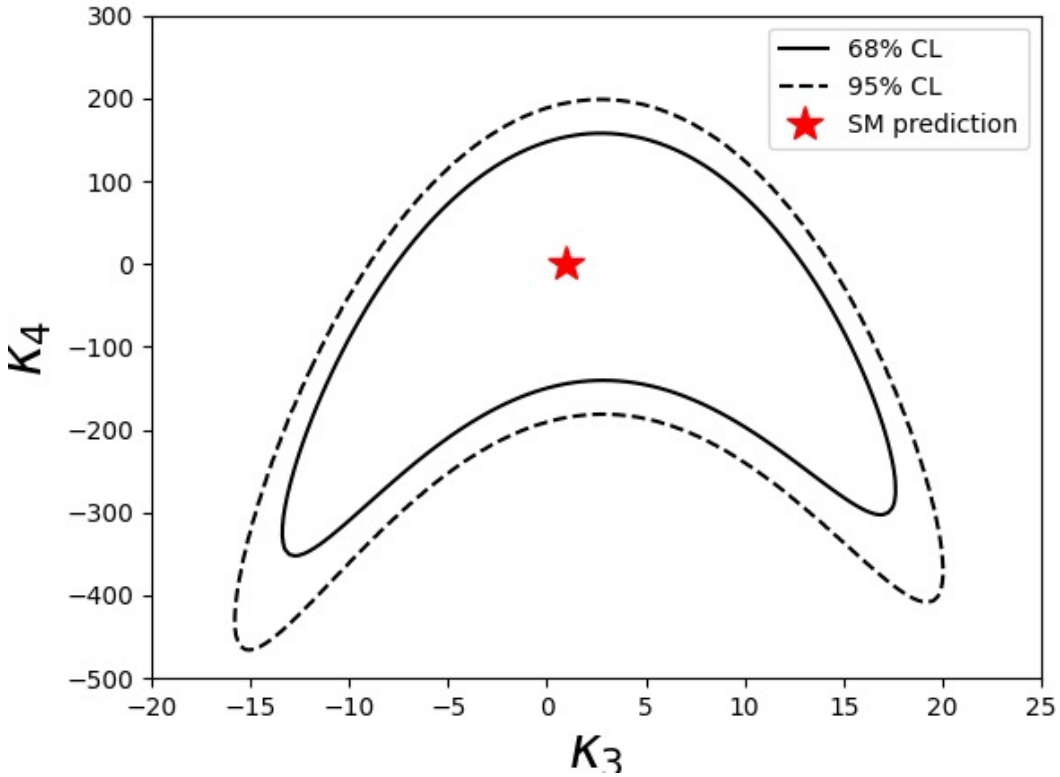
Likelihood and Significance

Looking at likelihood scan for limits shows far more conservative limits than significance scan



2D significance scan

$$\frac{S}{\sqrt{(B)}}$$



Log-likelihood scan

Is the pheno study too optimistic?

DNN - work-in-progress

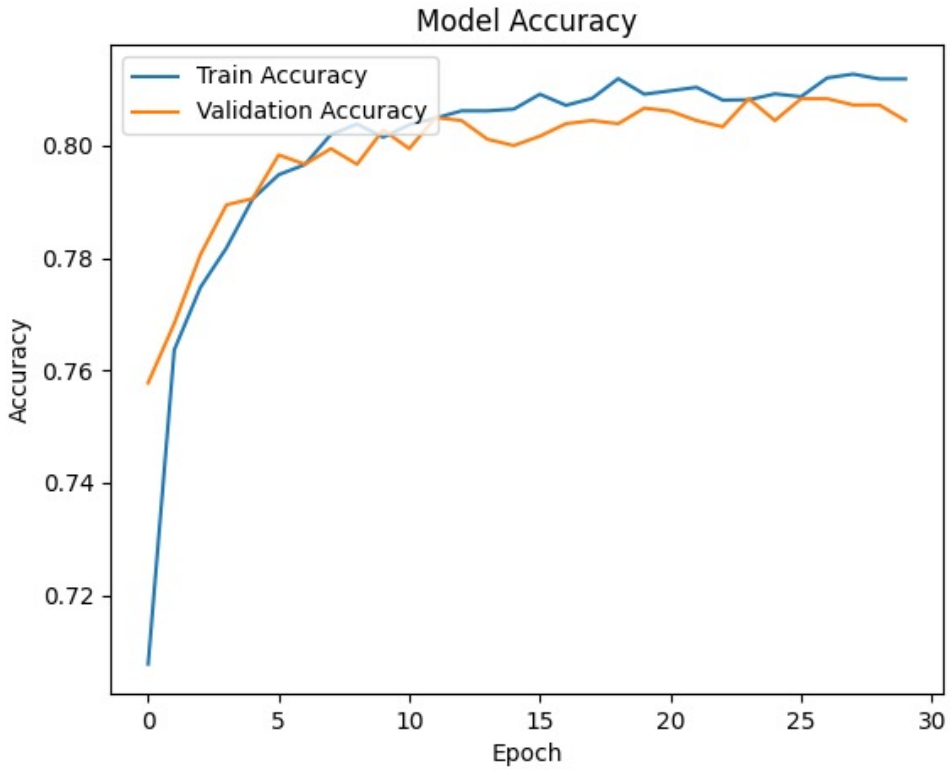
- Multivariate analysis: combine high level variables into DNN
- Start with simple architecture to separate signal and background
- Goal: Refining limits by implementing cuts on DNN score
- Trained on one κ variation but has to work on all

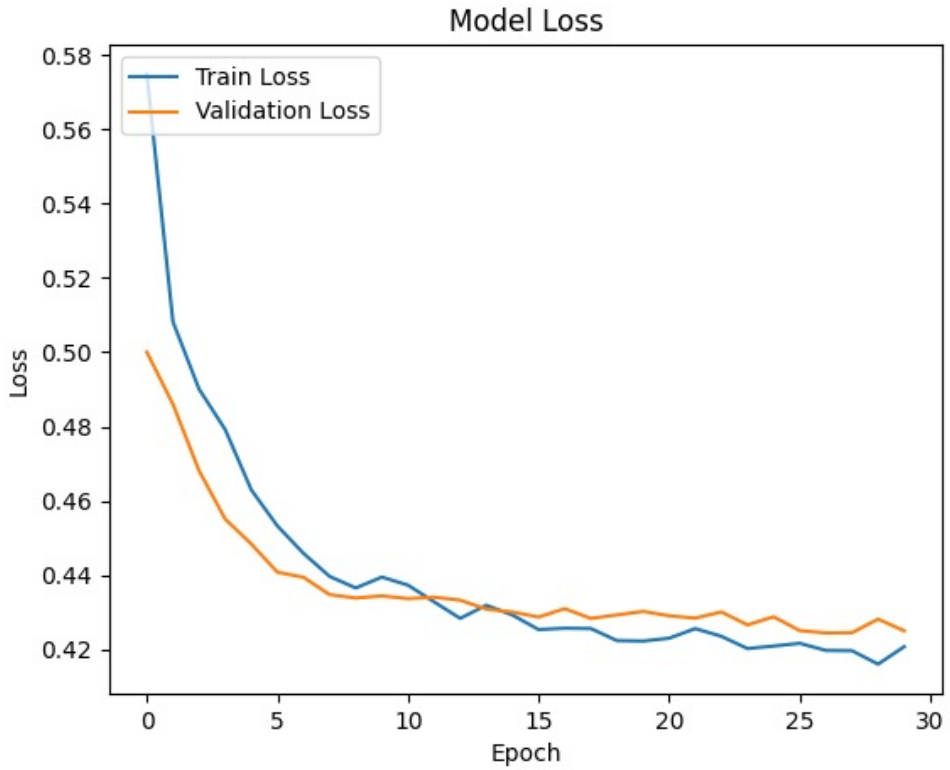
```
# define DNN model
model = models.Sequential()
model.add(layers.Dense(64, activation='relu'))
model.add(layers.Dropout(0.5))
model.add(layers.Dense(32, activation='relu'))
model.add(layers.Dropout(0.5))
model.add(layers.Dense(1, activation='sigmoid'))

# compile model
model.compile(optimizer=tf.keras.optimizers.Adam(learning_rate=0.0001), loss='binary_crossentropy', metrics=['accuracy'])

history = model.fit(X_train, y_train, epochs=50, batch_size=32,
                    validation_data=(X_val, y_val, weights_val),
                    verbose=2,
                    callbacks=[tf.keras.callbacks.EarlyStopping(patience=10, restore_best_weights=True)], class_weight=dict(enumerate(class_weights)))
```

Performance so far





Trained on 16 high level variables

Still very rudimentary but already learning something

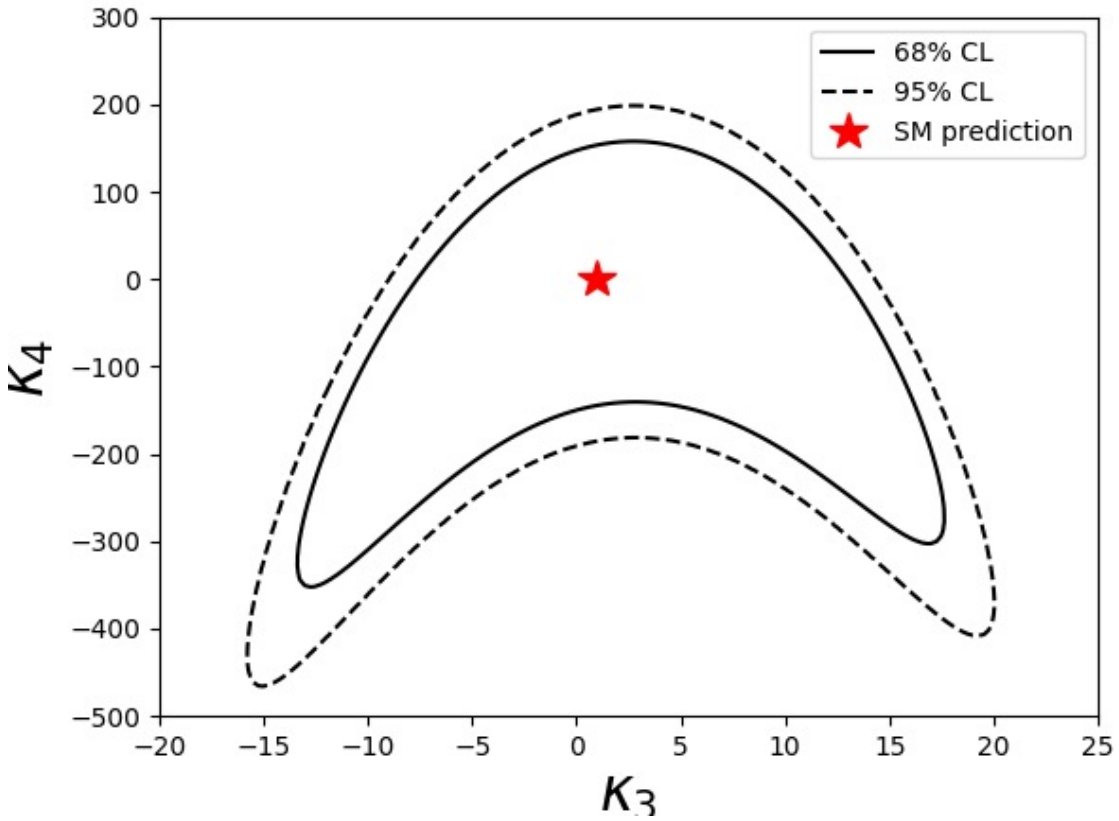
Outlook

- Implementing DNN score cuts
- Refining confidence levels of likelihood fit

- Exploring transformers (existing setup)
- High potential by learning from low level variables
- Testbed for researching other machine learning solutions

Conclusion

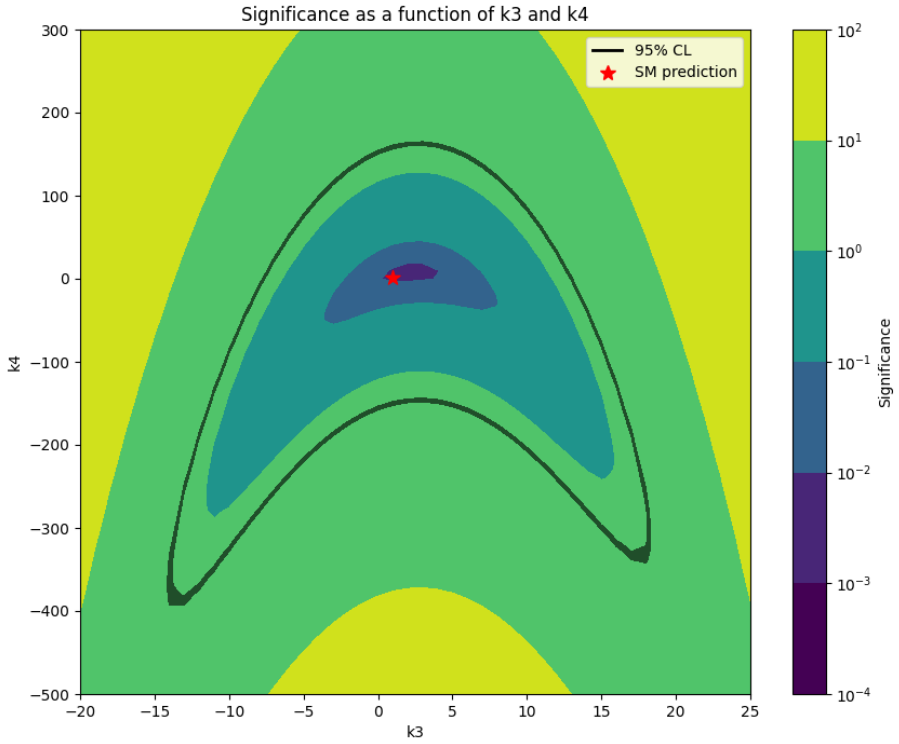
- New grounds with triple Higgs production
- Exciting possibilities for BSM physics
- Build on on-going HHH6b search targeting BSM physics
- Limited by statistics
- DNN shows promising performance
- Possible improvements with transformer setup?



Thank you

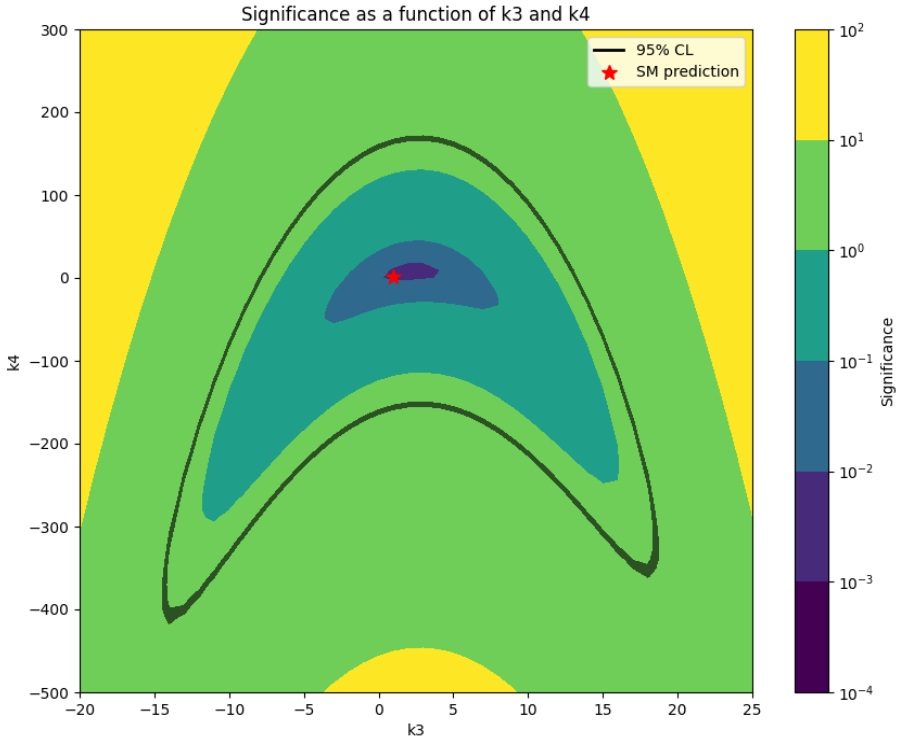
Backup

2D Significance Scan



Significance calculated via S/sqrt(B)

Slightly more optimistic but not a big difference



Significance calculated via
sqrt(2*((S+B)*ln(1+S/B)-S))
More accurate for smaller statistics

List of Variables used in DNN

- mHHH
- njets
- htbjet
- ht
- mH1, mH2, mH3
- dRH1, dRH2, dRH3
- meanmH
- meanEta
- rmsEta
- skewnessEta
- kurtosisEta
- pTHHH