JHU generator framework: new features for Higgs boson studies

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~~Pittsburgh, PA~~ Your house
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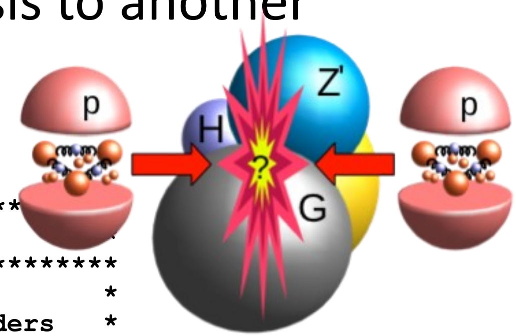
https://arxiv.org/abs/2002.09888

JHU Generator and MELA package

- JHU Generator
  - Designed to simulate a wide range of processes involving spin 0, 1, 2 particles with a general coupling model
- JHUGen MELA—Matrix Element Likelihood Approach
  - Calculate discriminants to optimally isolate processes or operators
  - Reweight generated samples from one hypothesis to another
- https://spin.pha.jhu.edu/

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*                                JHU Generator                                  *
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*   Spin and parity determination of single-produced resonances at hadron colliders   *
*                                                                               *
*            I. Anderson, S. Bolognesi, F. Caola, Y. Gao, A. Gritsan,           *
*        Z. Guo, C. Martin, K. Melnikov, R. Rontsch, H. Roskes, U. Sarica,      *
*               M. Schulze, N. Tran, A. Whitbeck, M. Xiao, Y. Zhou              *
*            Phys.Rev. D81 (2010) 075022;  arXiv:1001.3396  [hep-ph],           *
*            Phys.Rev. D86 (2012) 095031;  arXiv:1208.4018  [hep-ph],           *
*            Phys.Rev. D89 (2014) 035007;  arXiv:1309.4819  [hep-ph],           *
*            Phys.Rev. D94 (2016) 055023;  arXiv:1606.03107 [hep-ph].           *
*                                          arXiv:2002.09888 [hep-ph].           *
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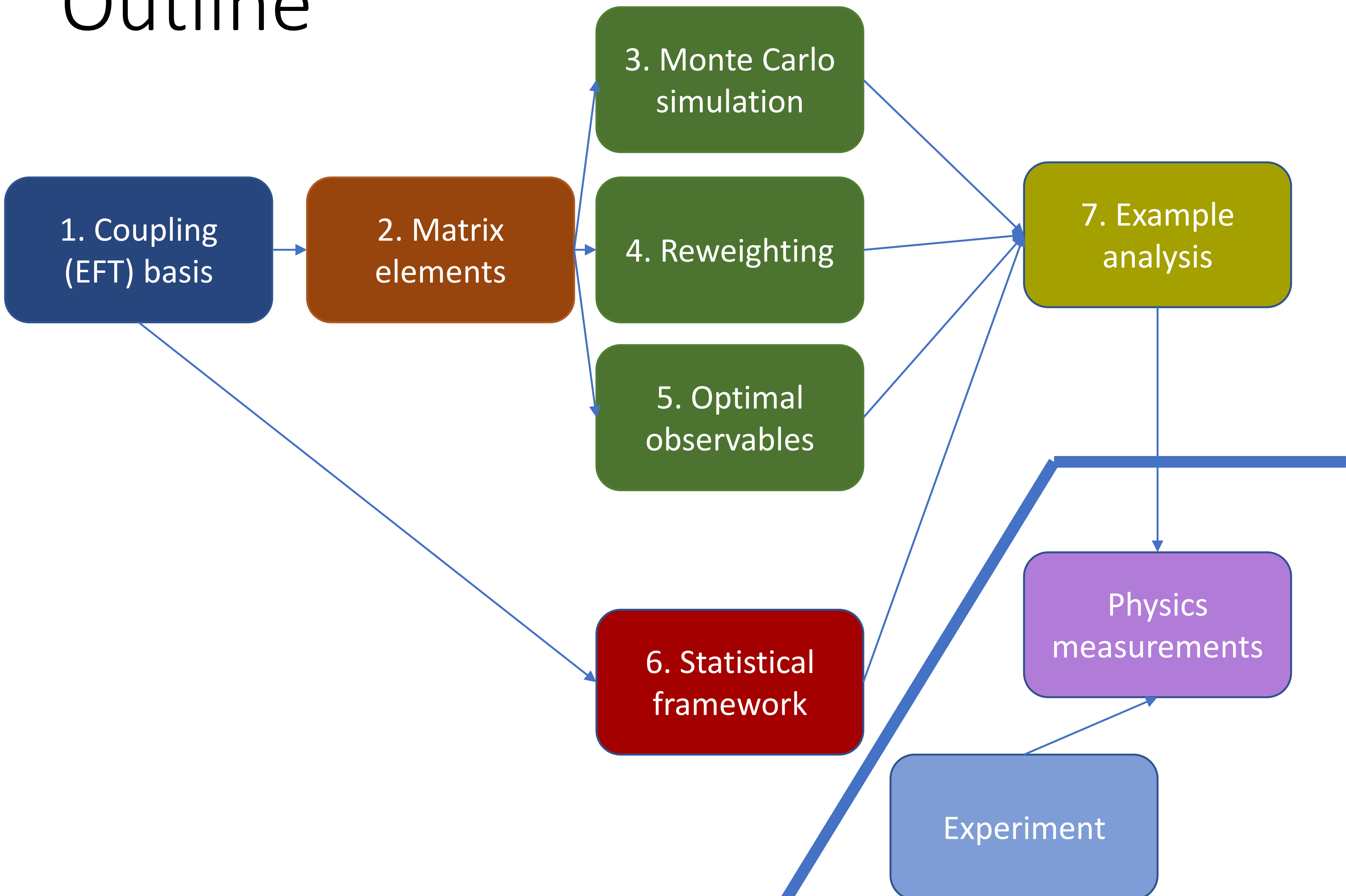
Outline



1. Coupling (EFT) basis
2. Matrix elements
3. Monte Carlo simulation
4. Reweighting
5. Optimal observables
6. Statistical framework
7. Example analysis
Physics measurements
Experiment

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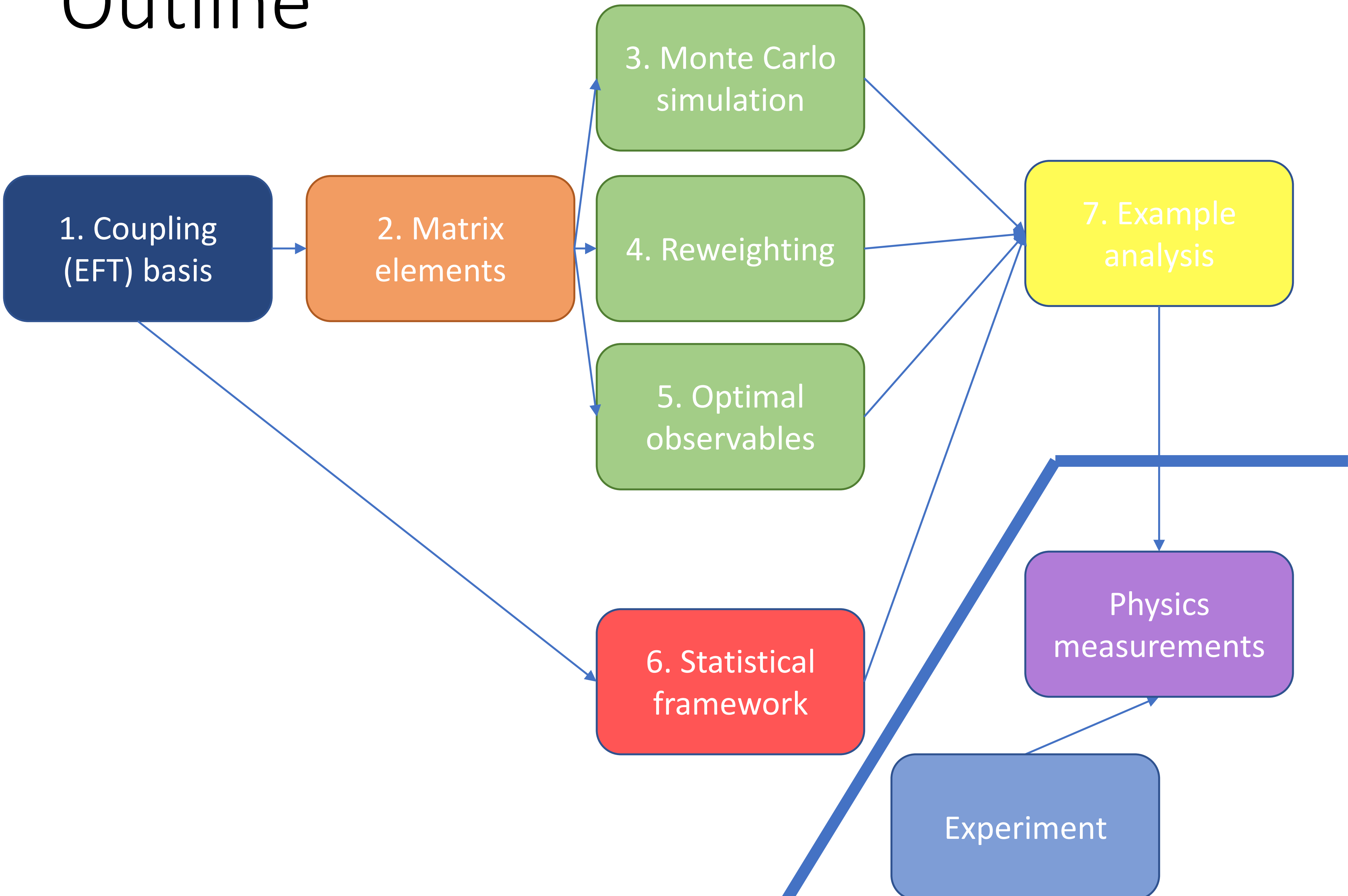
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SM

CP-odd

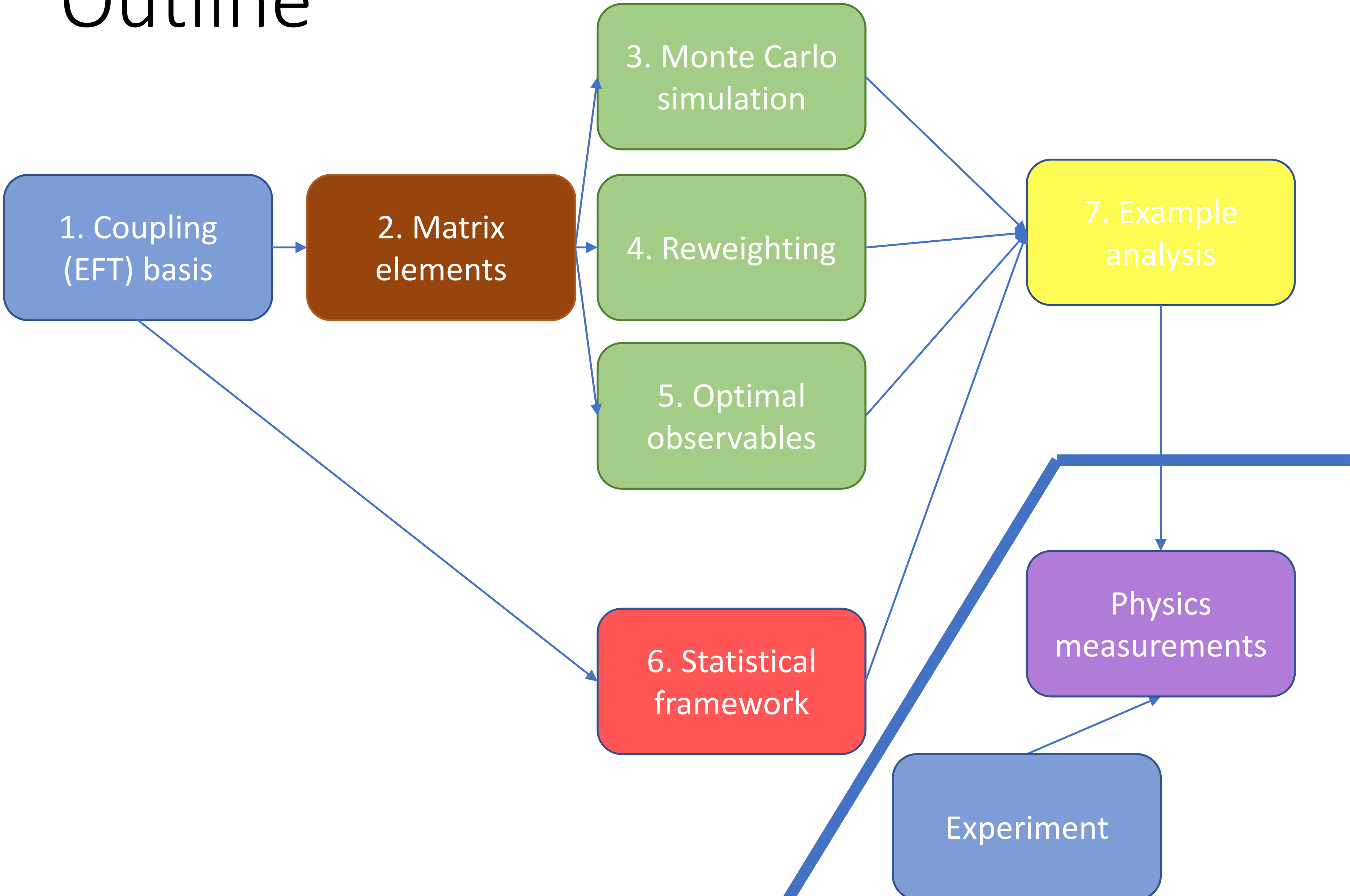
Coupling parameterization

- $A(HVV) = \frac{1}{v}\left[g_1^{VV} + \frac{\kappa_1^{VV} q_1^2 + \kappa_2^{VV} q_2^2}{\left(\Lambda_1^{VV}\right)^2} + \frac{\kappa_3 (q_1+q_2)^2}{\left(\Lambda_Q^{VV}\right)^2}\right] m_{V1}^2 (\epsilon_1 \cdot \epsilon_2) + 2g_2^{VV}[(q_1 \cdot q_2)(\epsilon_1 \cdot \epsilon_2) - (\epsilon_1 \cdot q_2)(\epsilon_2 \cdot q_1)] - 2g_4 \epsilon^{\epsilon_1 \epsilon_2 q_1 q_2}$

- $A(Hff) = -\frac{m_f}{v} \bar{\psi}_f \left(\kappa_f + i\tilde{\kappa}_f \gamma_5\right) \psi_f$

- General coupling model – easy to relate to other models, e.g. Higgs basis of EFT
  - See paper for details of the relationship
  - E.g., $c_{zz} \sim -g_2^{ZZ}, c_{z\Box} \sim -\kappa_1^{ZZ}, \tilde{c}_{zz} \sim -g_4^{ZZ}$
  - EFT implies relationships between couplings, e.g. g_2^{WW} is a linear combination of $g_2^{ZZ,Z\gamma,\gamma\gamma}$

Outline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Production
Decay
Propagator

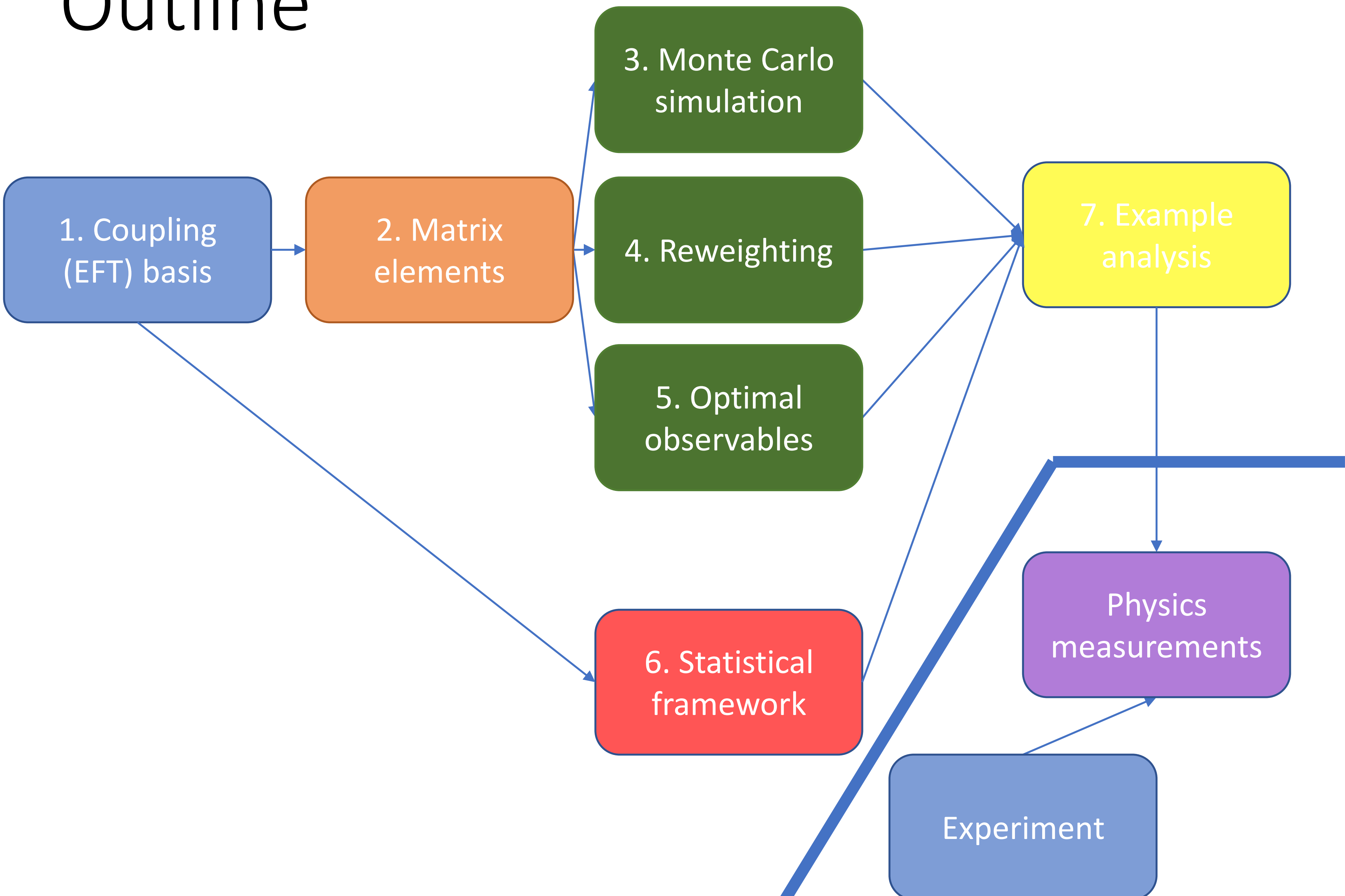
Matrix elements

- Characterize the probability of an event based on kinematics $\vec{\Omega}$
  - Based on couplings $\vec{a}$
  - $\vec{a}$ includes g_i, κ_i for bosons or c_i in EFT, κ and $\tilde{\kappa}$ for fermions

$$\frac{d\sigma}{d\vec{\Omega}}(i \to H \to f) \sim \frac{\left(\sum_{i,j} a_i\, a_j \alpha_{i,j}^{(i)}\left(\vec{\Omega}^{(i)}\right)\right)\left(\sum_{i,j} a_i\, a_j \alpha_{i,j}^{(f)}\left(\vec{\Omega}^{(f)}\right)\right)}{(s-m_H^2)^2 + m_H^2\Gamma^2}$$

- Usually components factorize – can calculate each one separately
- (Except when calculating interference between signal and background)

Outline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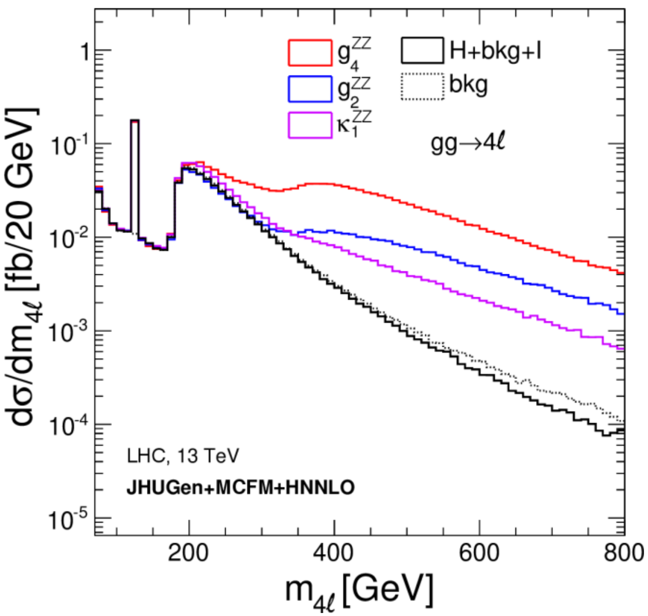
Sample generation and reweighting

- Generate samples according to the coupling model presented earlier
- Output in LHE format: can interface to parton showering and detector simulations
- Use the matrix elements to *reweight* samples to each other to increase statistics
  - Not an approximation: if the same matrix element is used for generation and reweighting, the results are equivalent (in the limit of infinite statistics)
  - Also needed for practical reasons when analysis needs hundreds of samples, as is the case here

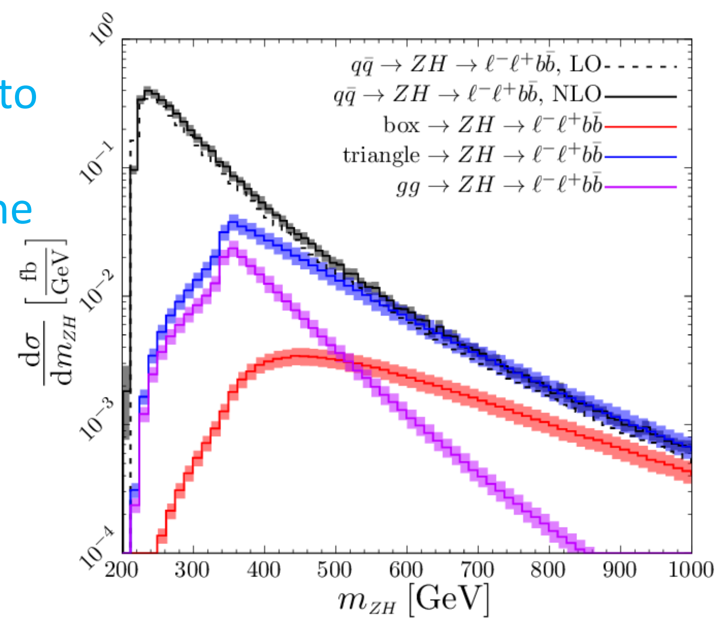
Special features: off-shell generation and NLO VH production

- Gluon fusion (shown here) and electroweak production off-shell ($m_{4f} \gtrsim 2m_V \sim 200$ GeV)
  - Sensitive to Γ_H and anomalous couplings

Used in analysis: 1 2

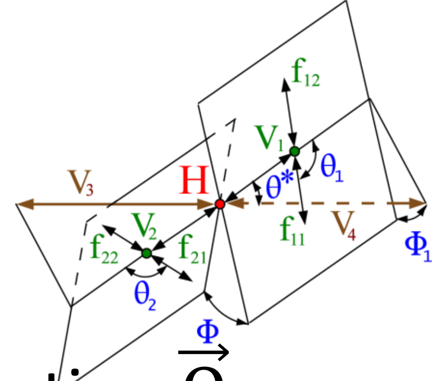


I'm not doing justice to either of these in the limited time. Read the paper for more!



- VH production at NLO in both gg and qq initial states
  - See paper for methods to detect and analyze $gg \to ZH$

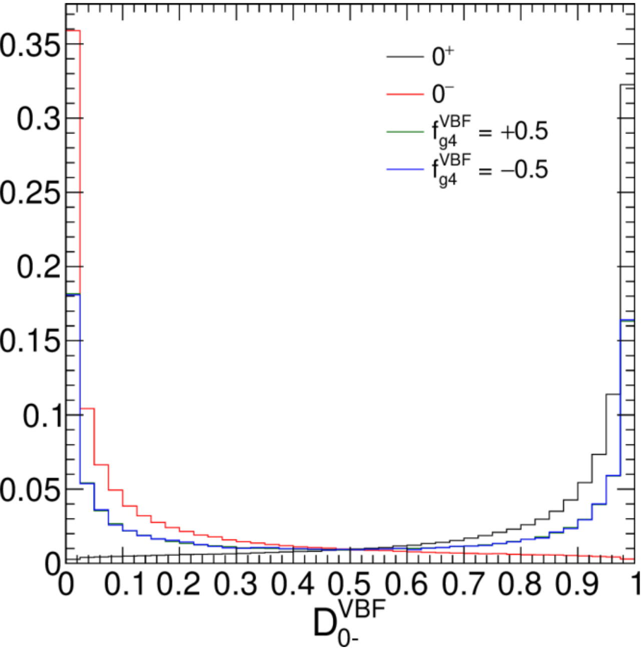
Optimal observables



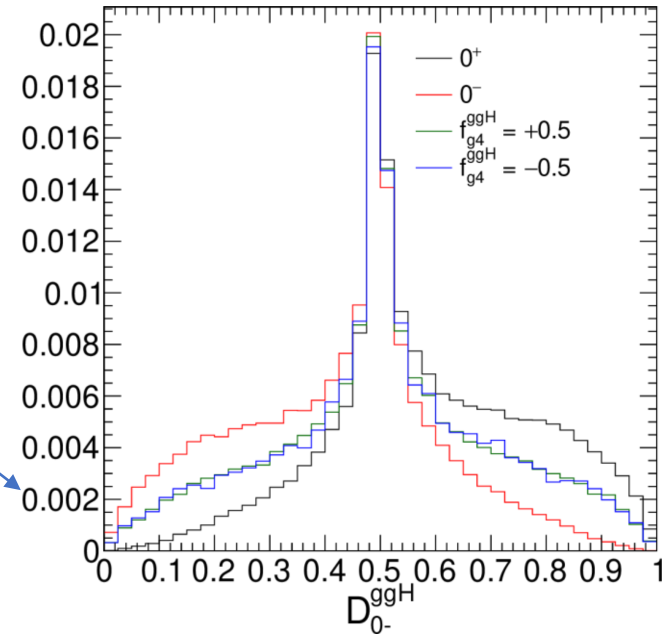
- Parameterize events in terms of kinematics $\vec{\Omega}$
- For $VV \to H$ with 2 jets or $H \to VV \to 4f$, 5 angles and 2 V invariant masses, plus H invariant mass
- ttH: even more angles and masses
  - also complicated because we can't tell which jet is which, or in the leptonic case we have missing neutrinos
  - arXiv: 1606.03107 [hep-ex]
- Can't deal with so many dimensions: construct observables that use all this information

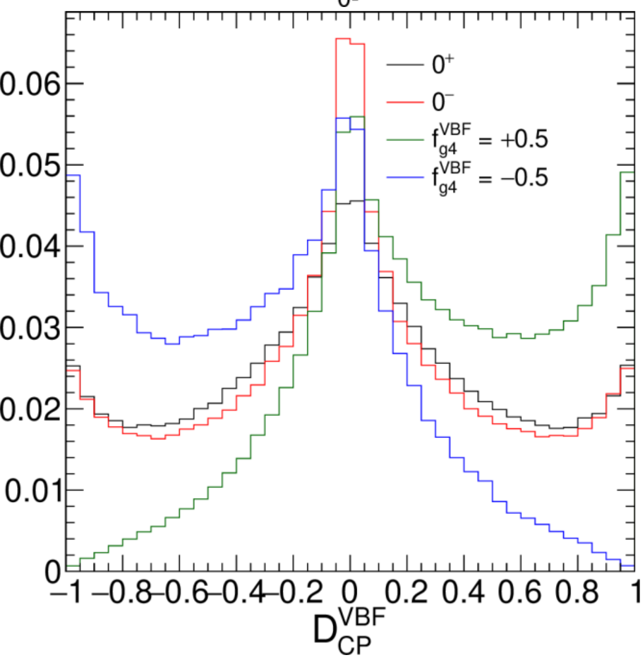
$$D_{alt}(\vec{\Omega}) = \frac{p_{sig}(\vec{\Omega})}{p_{sig}(\vec{\Omega}) + p_{alt}(\vec{\Omega})} \qquad D_{int}(\vec{\Omega}) = \frac{p_{int}(\vec{\Omega})}{2\sqrt{p_{sig}(\vec{\Omega})\,p_{alt}(\vec{\Omega})}}$$

Optimal observables

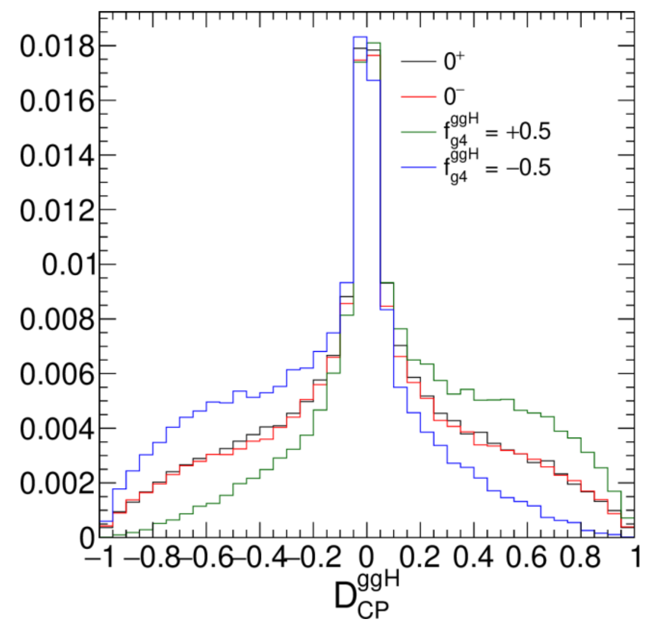


- Example: D_{0-} and D_{CP} (=p_{alt} and p_{int} for g_1 vs. g_4) in VBF with weak bosons or gluons



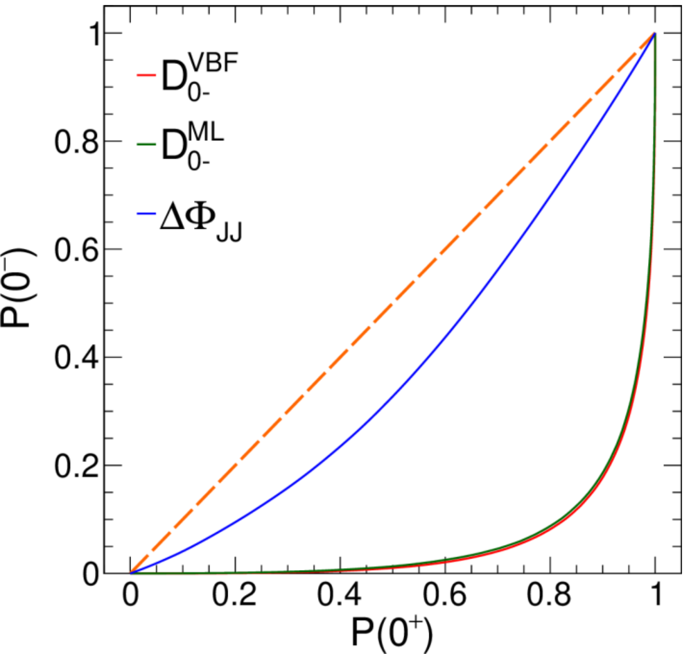


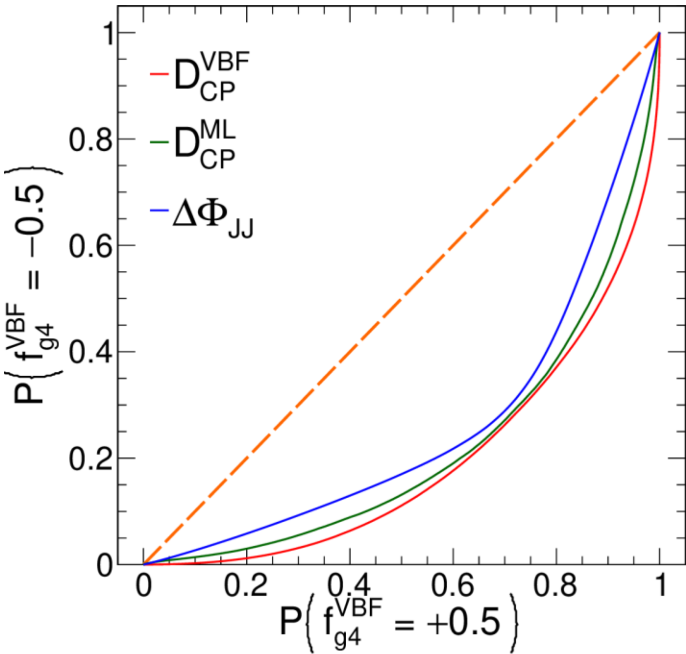
- D_{0-} separates pure hypotheses
- D_{CP} measures interference sign for mixture



Machine learning

- Before NLO and detector effects, MELA contains full information: no other observable can do better
- In the limit of perfect training, machine learning (ML) can give equivalent results
  - Difficult in practice in the case of D_{CP}
- If detector effects are large or some particles are lost, can e.g. integrate or use transfer functions in MELA, or use ML





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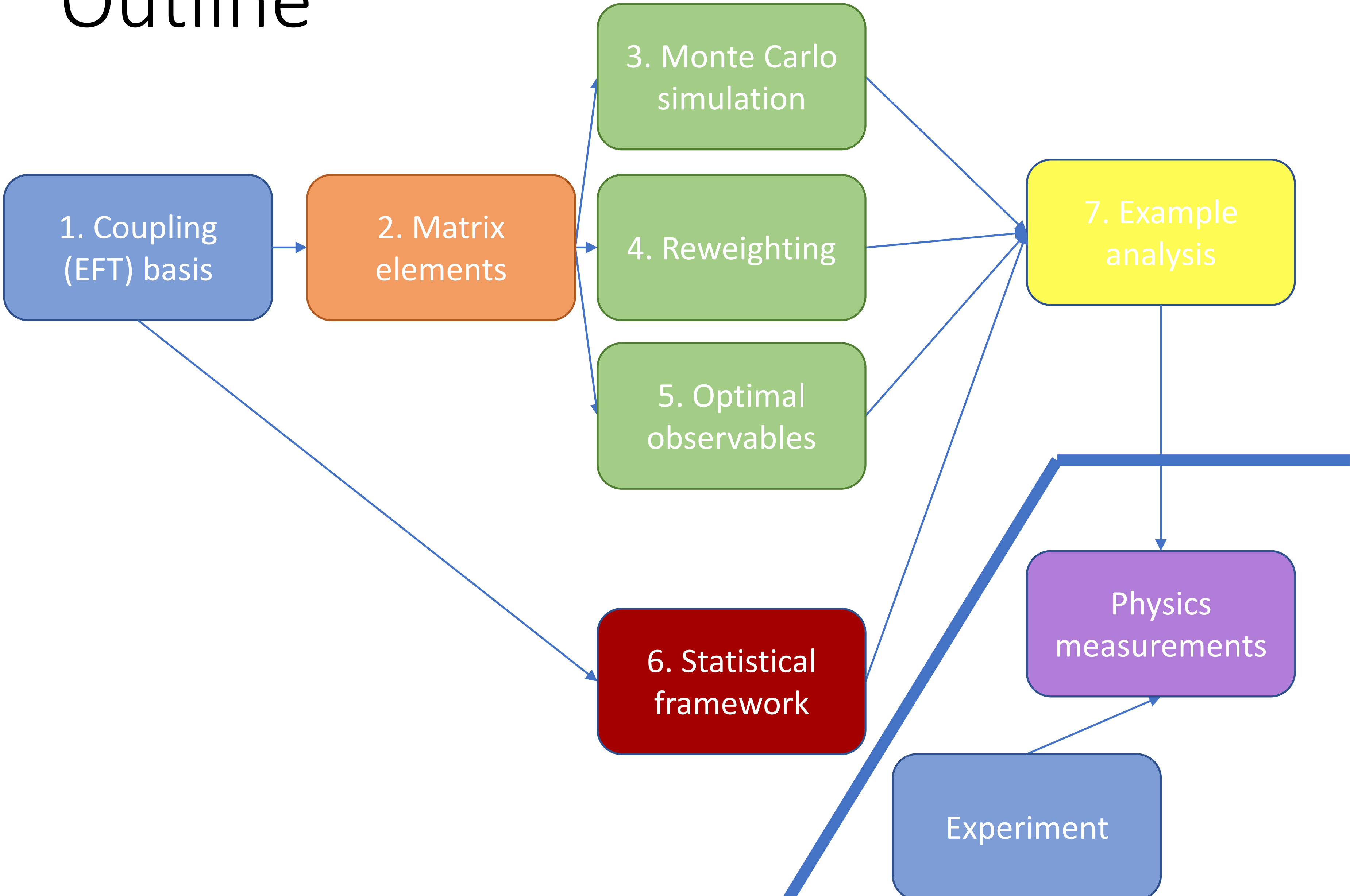
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Statistical framework

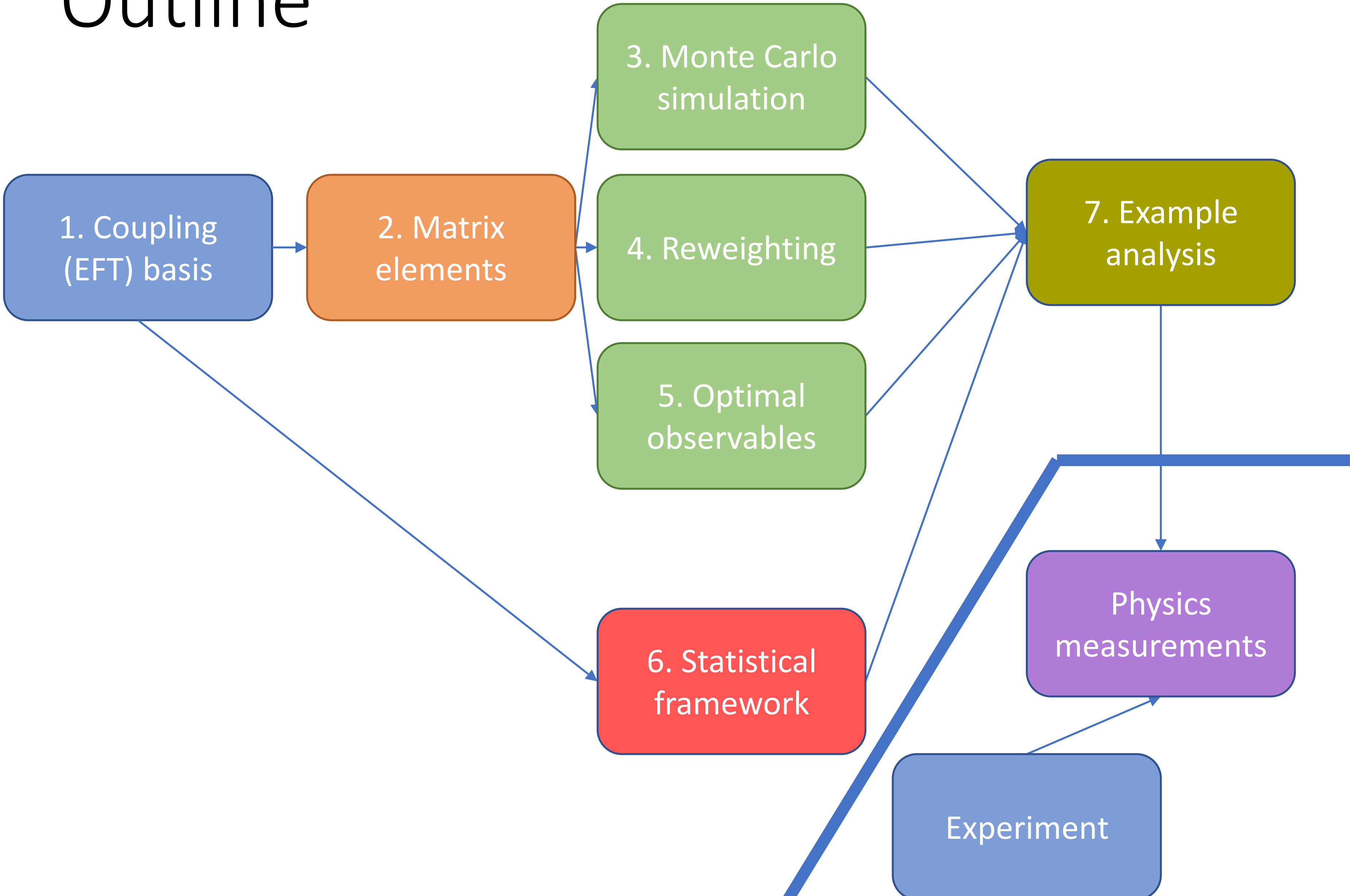
$$\mathcal{P}(\vec{\Omega};\vec{a}) \sim \frac{\left(\sum_{i,j} a_i\, a_j \alpha_{i,j}^{(i)}\left(\vec{\Omega}^{(i)}\right)\right)\left(\sum_{i,j} a_i\, a_j \alpha_{i,j}^{(f)}\left(\vec{\Omega}^{(f)}\right)\right)}{(s-m_H^2)^2 + m_H^2\Gamma^2}$$

- Polynomial in $\vec{a}$
- When we look at only production or decay (e.g. $gg \to H \to ZZ$), $N = 2$ powers of a; when they have the same couplings (e.g. $\mathrm{VBF} \to H \to ZZ$), $N = 4$
- For K couplings, have $\binom{N+K-1}{N}$ terms to parameterize
    - E.g. $N = 4, K = 5 \Rightarrow 70$ terms
- Need to either simulate each one or reweight

Parameterization

- Can either float couplings $\vec{a}$ and width Γ_H directly, or reparameterize in terms of $\vec{f}_a$ and μ
- $f_{ai} = \frac{a_i^2 \sigma_i}{\sum_j a_j^2 \sigma_j} \operatorname{sgn} a_i$
  - Bounded between -1 and 1
  - σ_i depends on the process – have to specify a convention
  - By default for HZZ couplings we use $H \to ZZ \to 2e2\mu$
- $\vec{f}_a$ is independent of overall scaling (including Γ_H), which is absorbed by μ

Outline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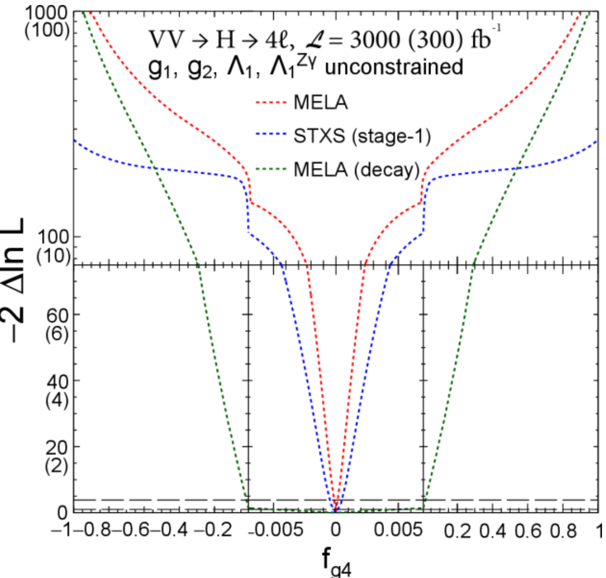
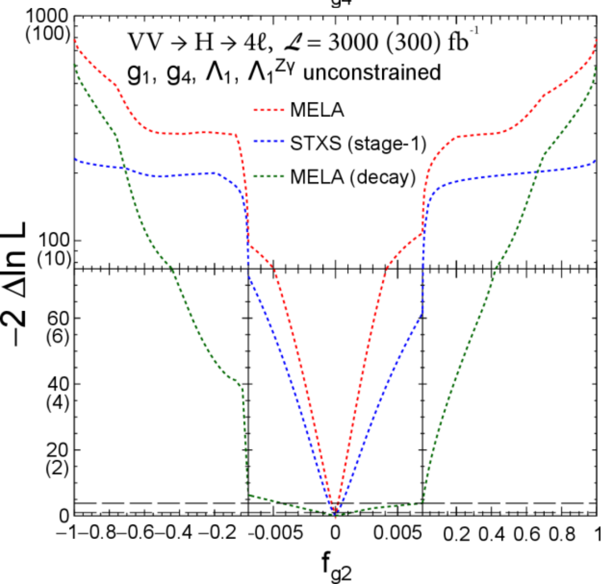
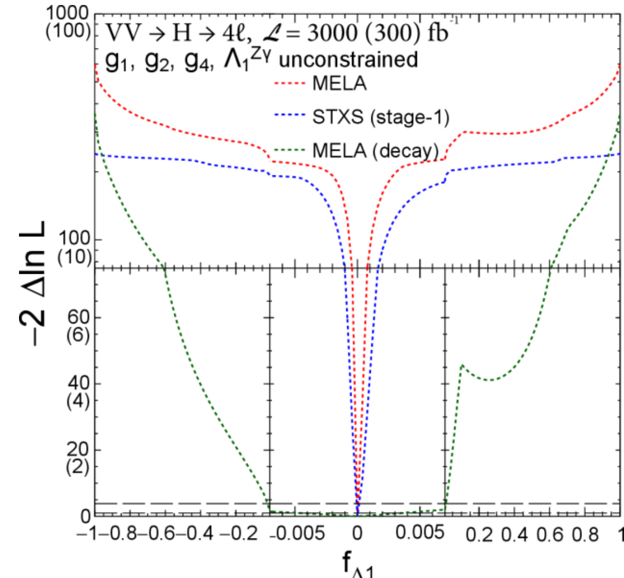
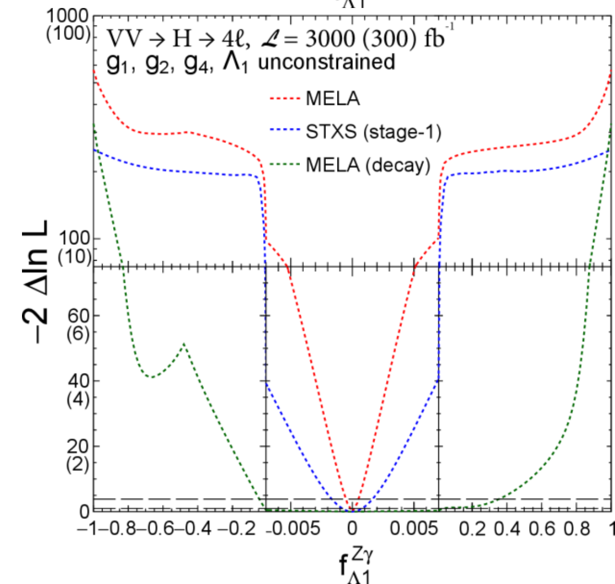
Example analysis: search for g_4, g_2, Λ_1, and $\Lambda_1^{Z\gamma}$



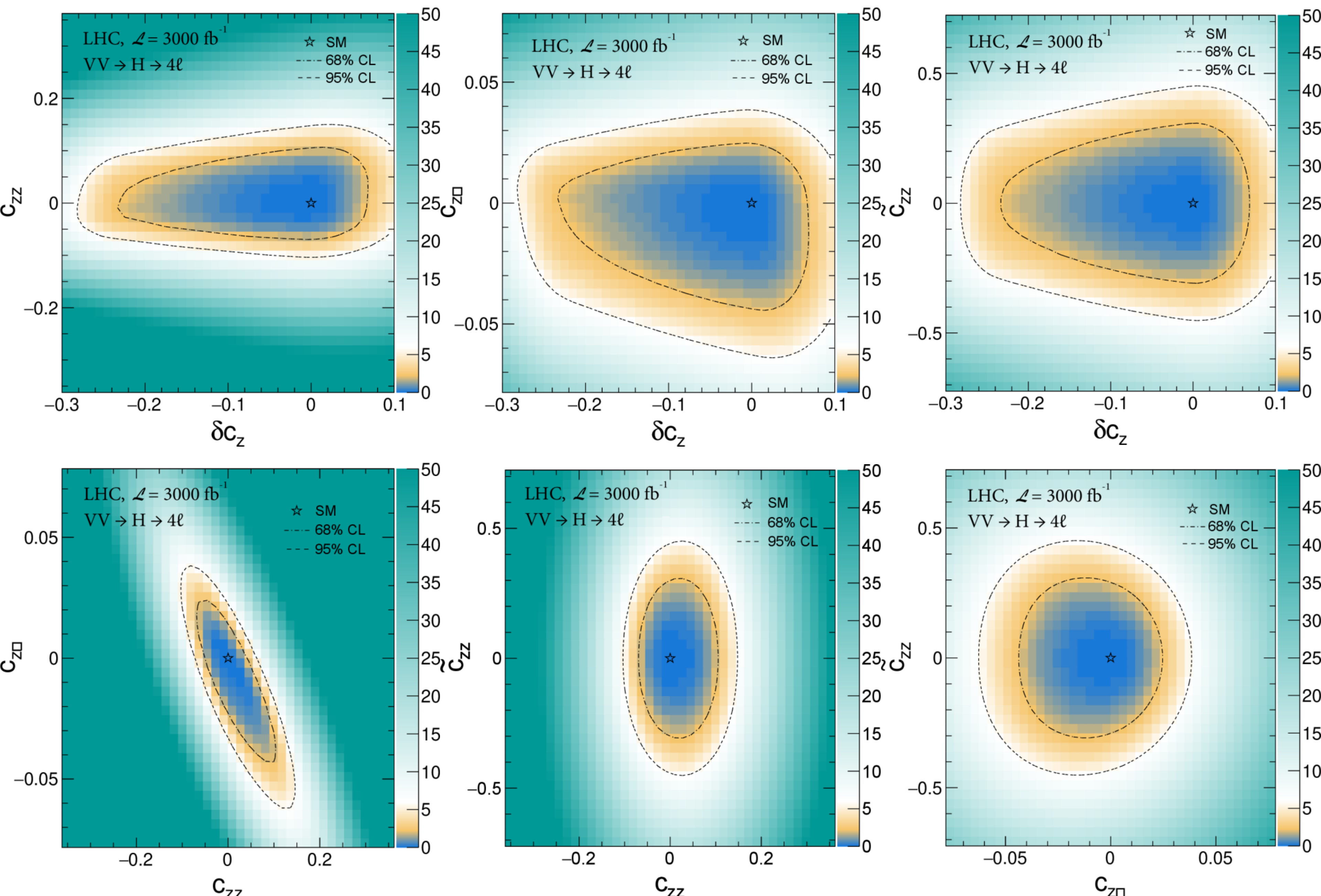


- Floating SM and 4 anomalous couplings simultaneously
- Expected constraints at 300 and 3000 fb^{-1}
- Full MELA approach
- Using simplified template cross section (STXS) discriminants
- Use information from decay only
  - More model independent (no high q^2 regime)



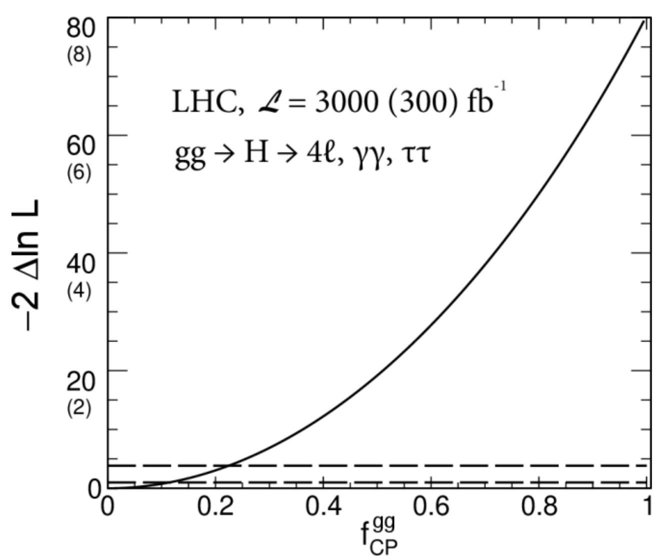


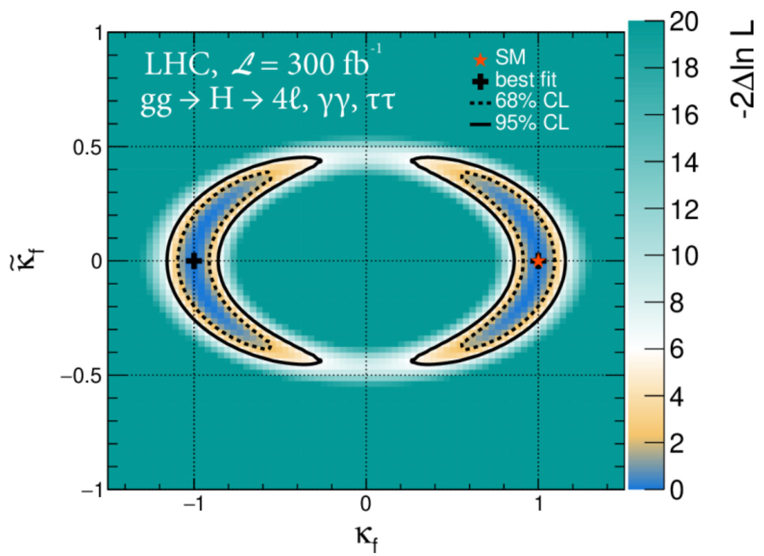
Example analysis: EFT: δc_z, c_{zz}, $c_{z\Box}$, $\tilde{c}_{zz}$



Example analysis: anomalous ggH

- Can measure CP in ggH using the MELA approach and discriminants
- Requires events with 2 jets (small fraction of ggH), and even then only VBF-like topology is sensitive
- Electroweak VBF forms a background
- Can start constraining now, tighter constraints at HL-LHC





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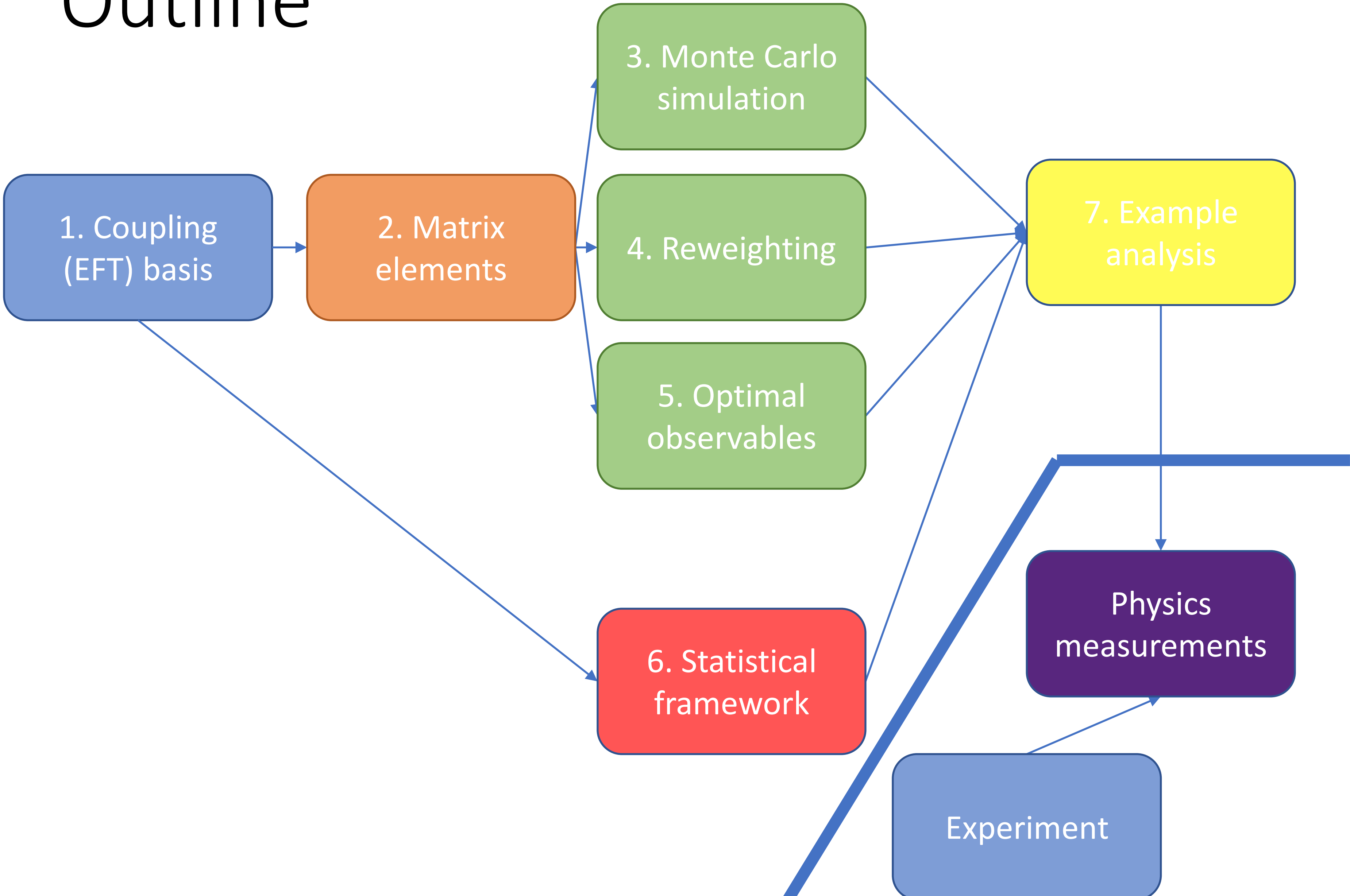
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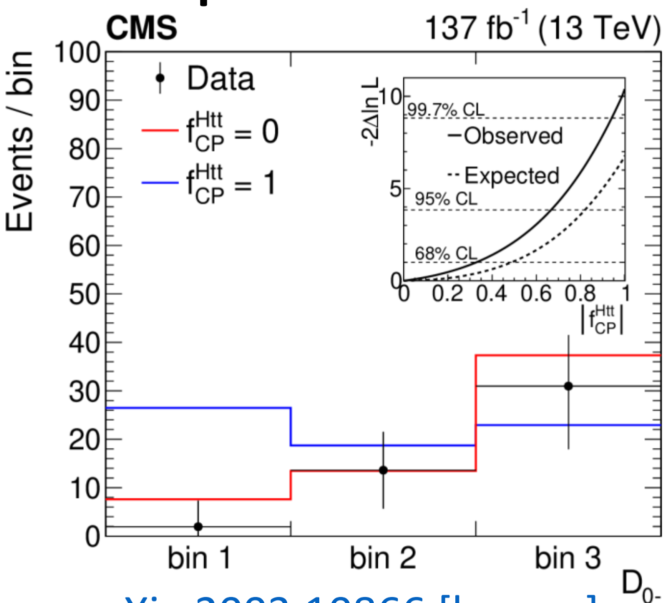
Experimental results using JHUGen



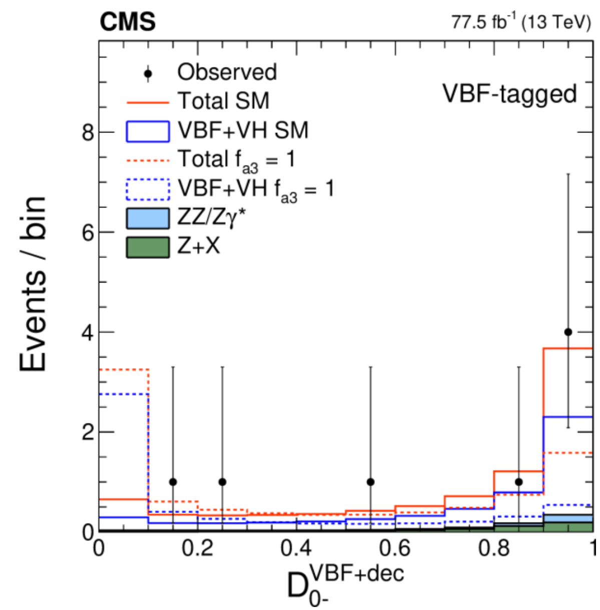
arXiv:2003.10866 [hep-ex]
CMS measurement of anomalous couplings in ttH using $H \to \gamma\gamma$

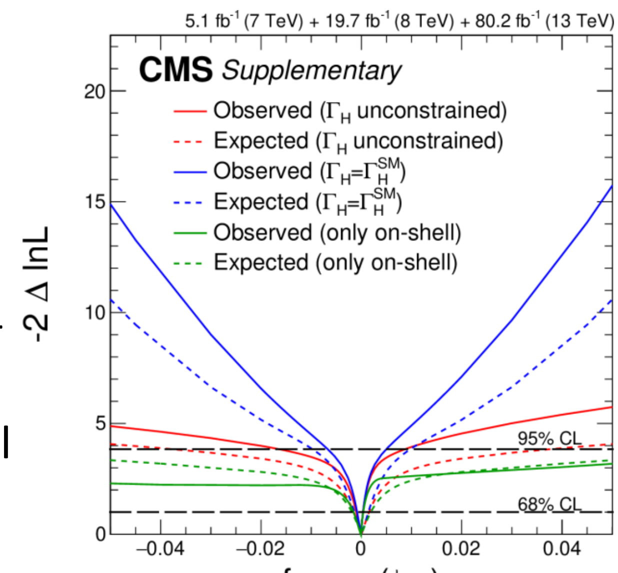
D_{0-} is calculated here using machine learning due to the complicated jet correlations and missing neutrinos. Samples are produced with JHUGen

arXiv:2003.10866 [hep-ex]
CMS measurement of anomalous couplings in on-shell and off-shell production and decay $H \to 4\ell$

D_{0-} is calculated using VBF production and $H \to 4\ell$ decay and provides strong separation between g_1 and g_4

Likelihood scans for $f_{a3}(= f_{g4})$ using on-shell production and two possible off-shell scenarios





Summary

- Coherent framework for measuring Higgs boson anomalous couplings using a general model
- The tools, framework, and methods are general enough to build analyses for any convention you like – our anomalous couplings, EFT, pseudo-observables, …
- The most general analysis will float more couplings at once, and then the results (not only the analysis methods) are independent of notation as well
  - Limited only by available data and CPU
- Sample analysis and approximate sensitivity for HL-LHC
- Has been used extensively for CMS and ATLAS analyses
- Please see the paper for more