EFT methodology
– a general introduction –

Ecole de Gif 2023 -- Annecy

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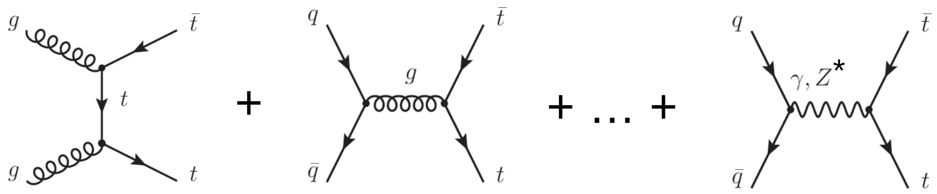
Introduction

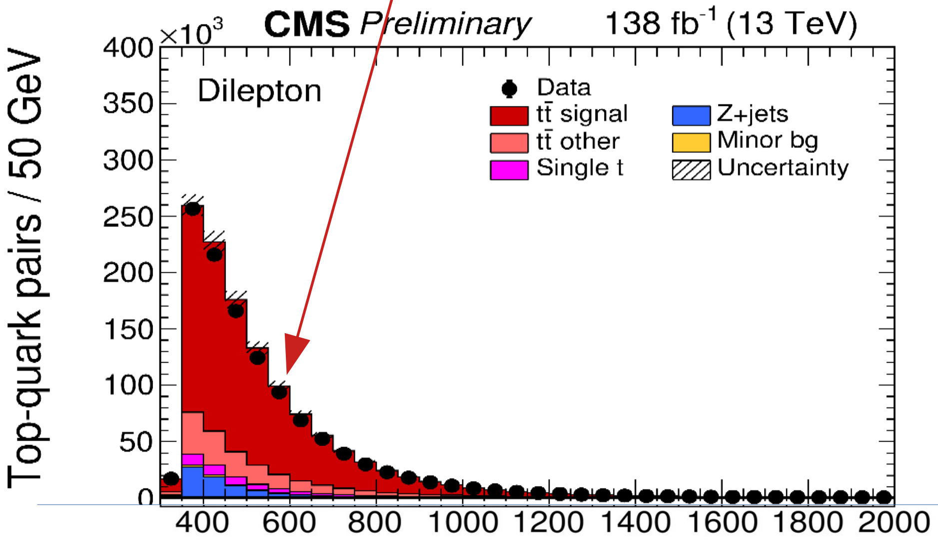
- Standard Model (SM): good description of elementary particles and their interactions (at "low" energy scale)
- Long history of discovering it's particles & interactions, measuring free parameters and probe its predictions
  - So far, good agreement in most measurements, but we know that new physics is needed to explain some observations (neutrino masses, dark matter,…)
  - Continue searching for hints: searching for new particles, new interactions and deviations
  - Start looking into more and more extreme corners of phase space and tails of distributions
- Maybe new physics is (for now) beyond our reach for direct observation
  - Still could leave some measurable trace in our observations → should look at very small deviations in a systematic way, combining information from many measurements
  - Avoid looking at many different models (maybe the right one is not even in the list!) → need a way to interpret measurements in generic (model independent) way to hopefully get a hint where to look

Example: ttbar production at the LHC

ttbar production at LHC:

SM





m(tt̄) [GeV]

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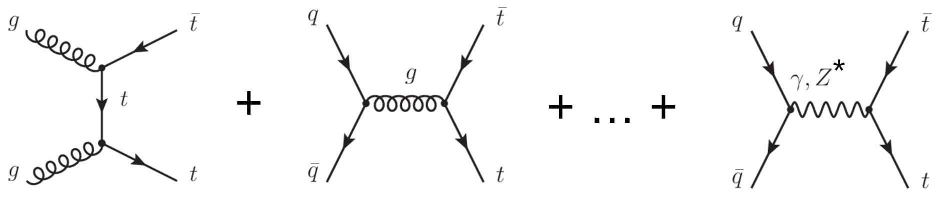
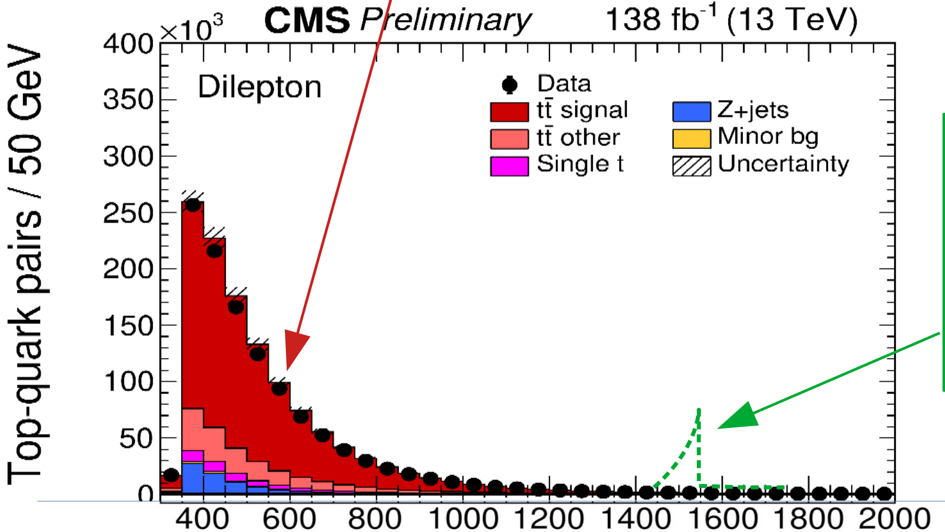
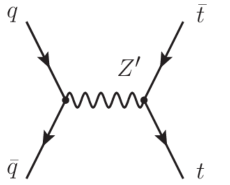




Resonant BSM production



$M_{Z'}$

m($t\bar{t}$) [GeV]

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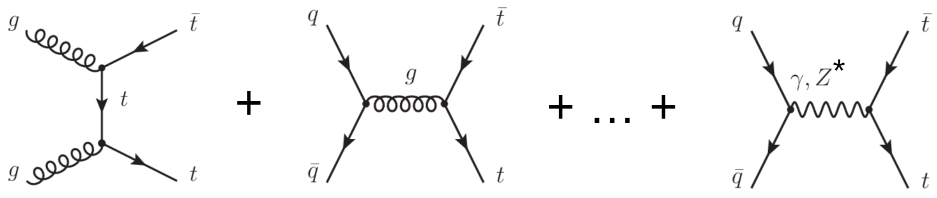

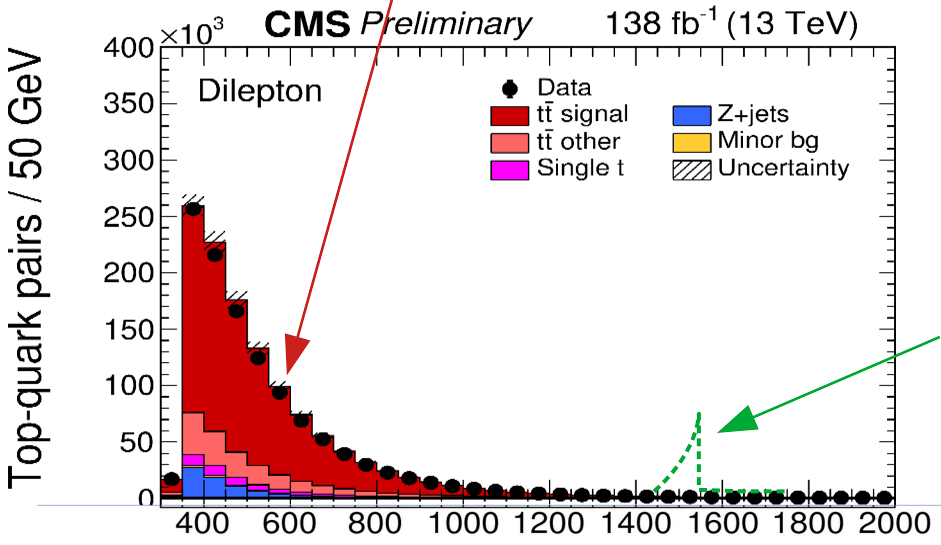

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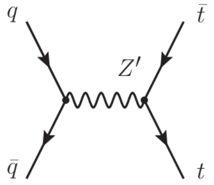

We did not find it (yet); possible reasons

→ it does not exist

→ it couples very weakly to SM particles

→ it is too heavy to be produced at LHC

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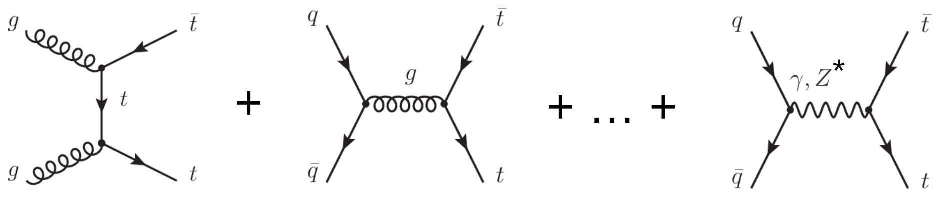

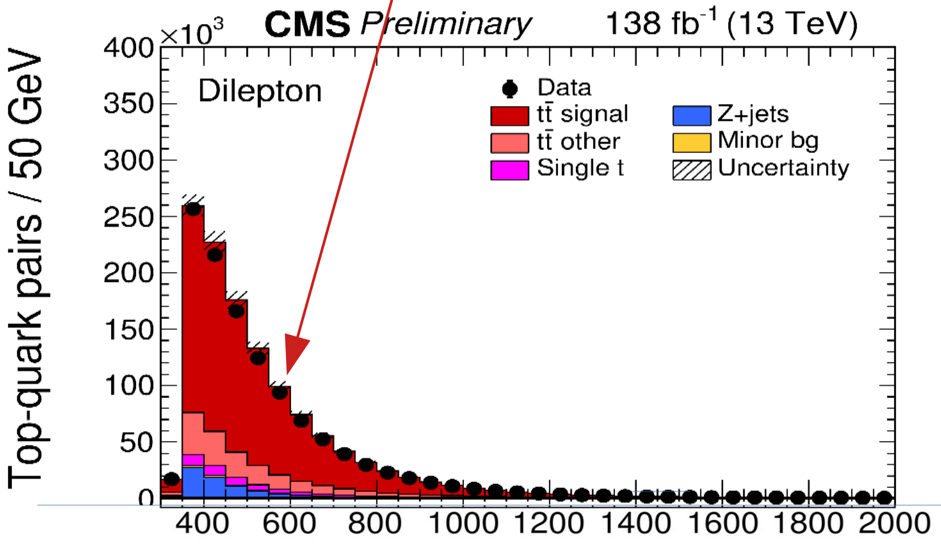

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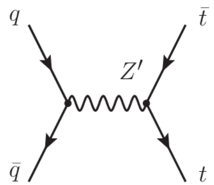
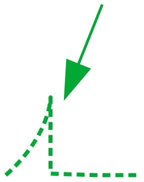
Let's assume...

Resonant BSM production





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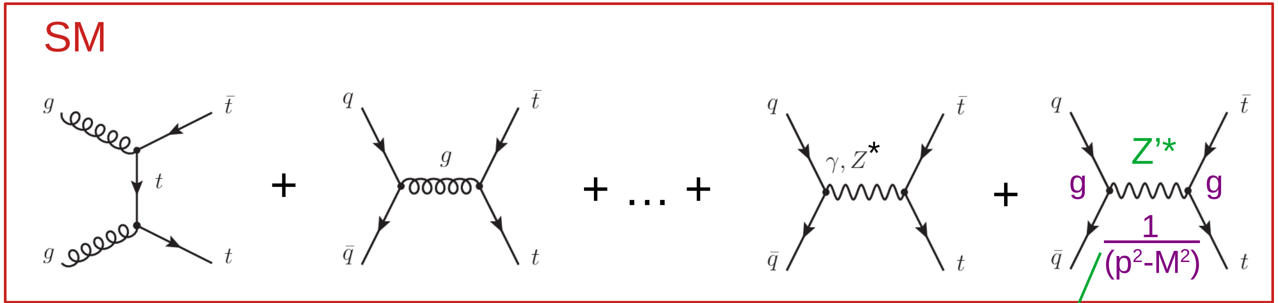

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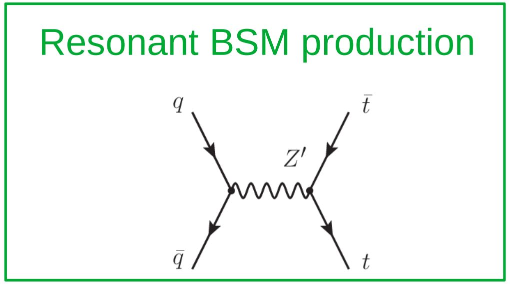

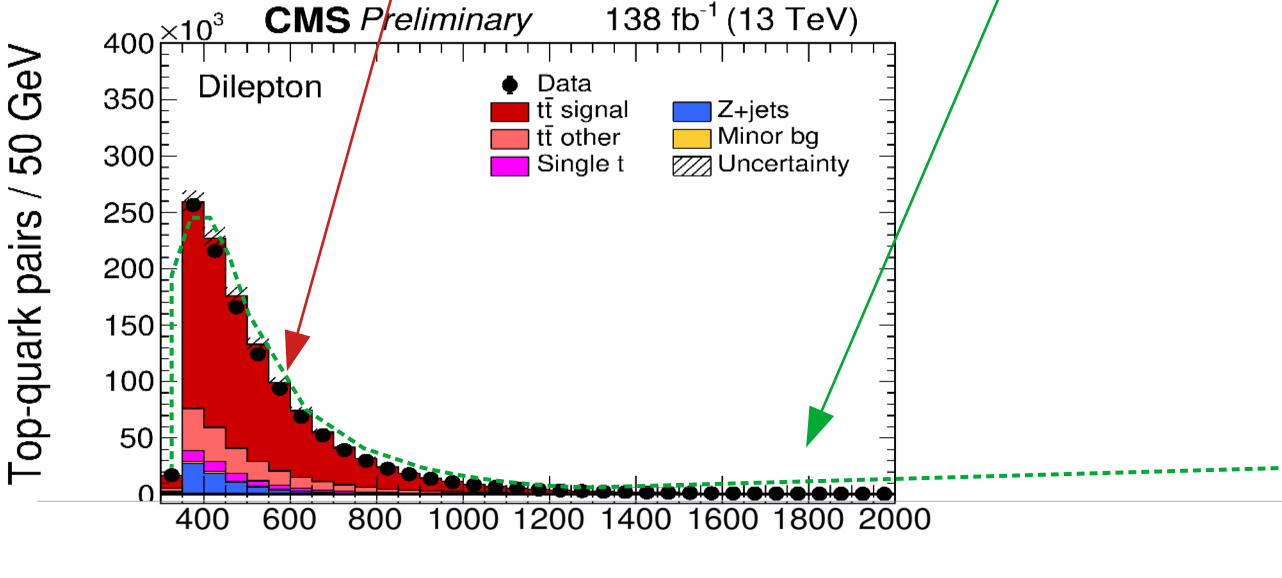

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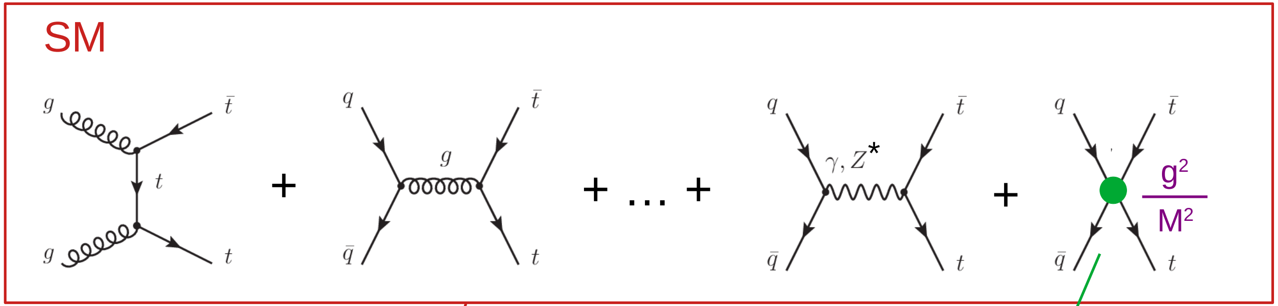

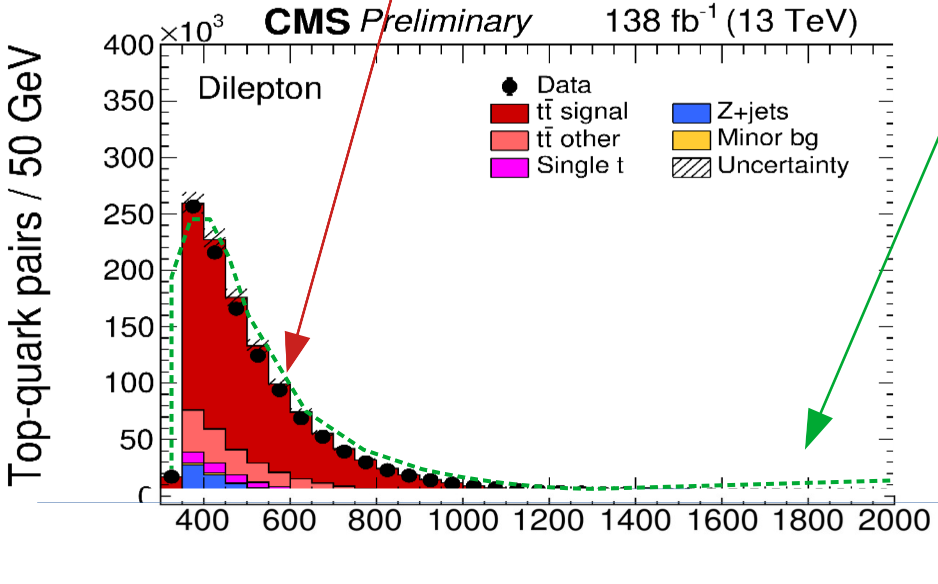

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Let's assume...

- Observe effective coupling that could be explained by many models
- CAVEAT: still assuming here that this is the only modified coupling in this process!

Example: ttbar production at the LHC

ttbar production at LHC:

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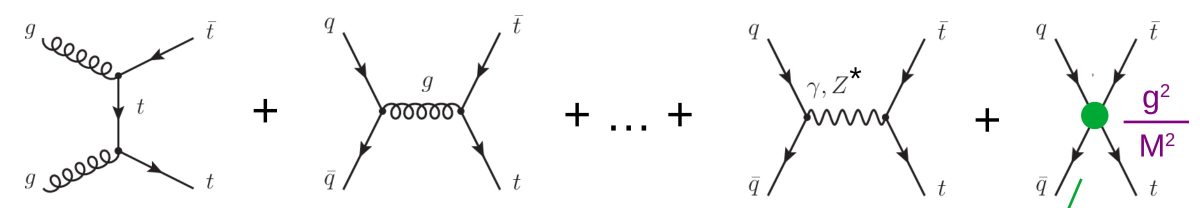

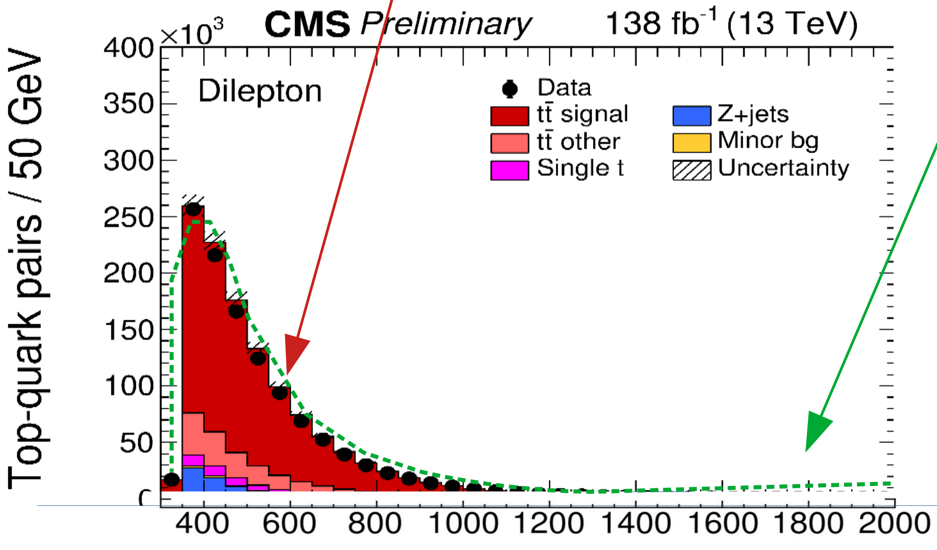

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Let's assume...

Let's generalise & formalise this!
→ Effective Field Theory (EFT)

(theory details in Nazila's lecture)

Content

- Ingredients for EFT fits
  - Input measurements – experiments, observables, etc.
- EFT constraints from experimental data
  - Setup: model, basis, input parameters, symmetries
  - EFT in the analysis: simulation and parametrisation
  - Working with a real detector
  - Validity considerations and theory uncertainties: limitations and work arounds
- Global EFT fits
  - Benefits and challenges of combined fit
  - Limitations and perspectives for EFT fits – towards HL-LHC and beyond

Note: This lecture is quite technical; more details on application of these concepts in dedicated sessions (EFT in Higgs + EW and in flavour physics)

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EFT in 2 sentences

- EFT is “just” an approximation of a theory at a given energy scale, allowing to “integrate out” contributions from higher scales – we are using it all the time
  - example 1: QED is an effective theory integrating out everything but photon and electron
  - example 2: Heavy Quark Effective Theory (HQET) assumes infinite b- and top mass to model B decays
- If BSM scale is significantly higher than measured energy scale at experiment, the Lagrangian can be expanded:

$$\mathscr{L}_{\mathrm{EFT}} = \mathscr{L}_{\mathscr{D}\leq 4} + \frac{\mathscr{L}_5}{\Lambda} + \frac{\mathscr{L}_6}{\Lambda^2} + \ldots$$

- $\mathscr{L}_{\mathrm{D}}$ are linear combinations of all dim-D operators within a set of assumptions -- this allows for a relatively easy interpretation

EFT in HEP in 2 sentences

- EFT used to constrain BSM at high energy scales in many experiments
  - Requirement: c/Λ<<1 – probed BSM scale much higher than experimental scale ($\sim q^2$), i.e. probing BSM via indirect loop effects (e.g. at B-factories, LHC,…)
  - Sensitive BSM scale probed with EFT depends on experiment – possibility to match EFT results with direct searches for BSM (e.g. constraints from B decays with searches at the LHC)
- Will concentrate on accelerator based particle physics

	Intensity frontier	Energy frontier
Main characteristics	• Medium energies, clean environment, high intensity (i.e. large integrated lumi) • High precision measurements with indirect probe of BSM • Example: Belle 2	• High center of mass energies • Usually hadrons → dirty environment • Direct search of BSM, still possible to make precision measurements • Example: LHC experiments
Measurements for EFT interpretation	Rare B decays, differential cross sections	(Differential) cross sections of Higgs production, rare SM processes, top quark production, etc.

Typical analysis workflow

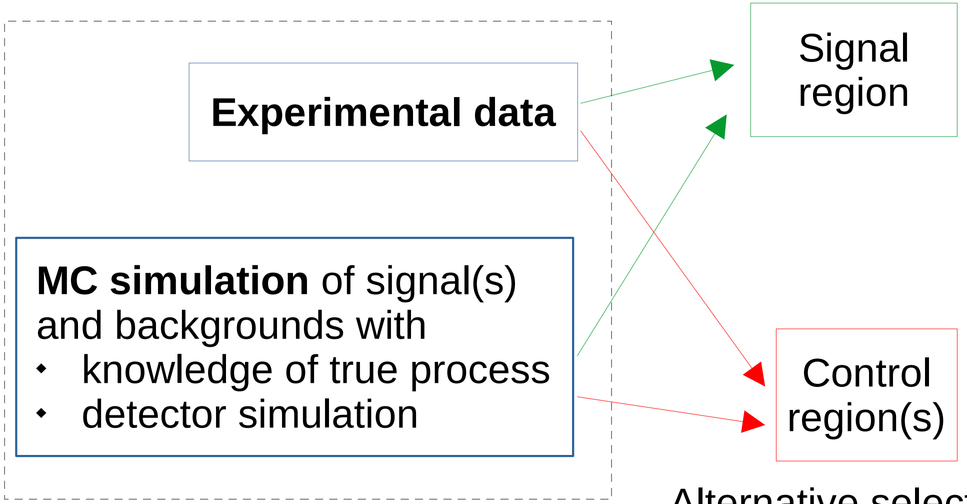
Experimental data

MC simulation of signal(s) and backgrounds with
- knowledge of true process
- detector simulation

- Object / particle reconstruction
- MC calibration / correction

Typical analysis workflow

Basic event selection
(cut-based or using ML)



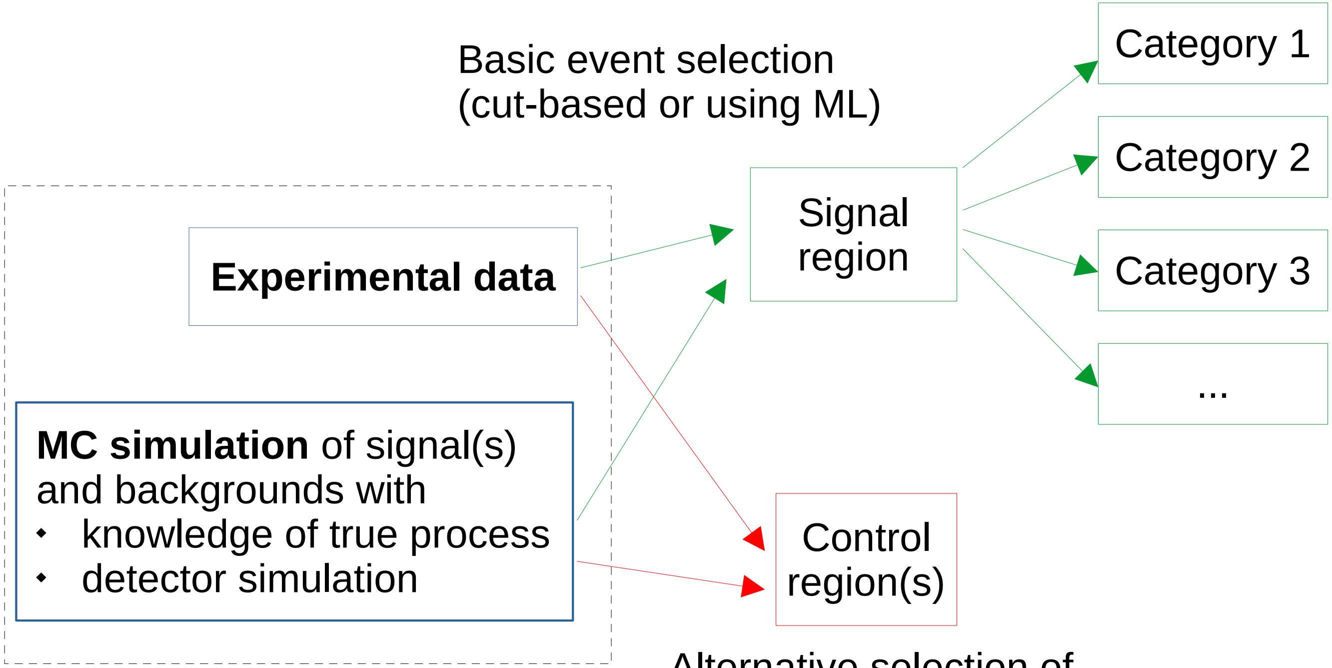
- Object / particle reconstruction
- MC calibration / correction

Alternative selection of
background enriched regions
for data driven estimate

Typical analysis workflow

Event categorisation to:

- Split experimental signatures
- Def. regions with good signal significance or resolution
- Target different POIs



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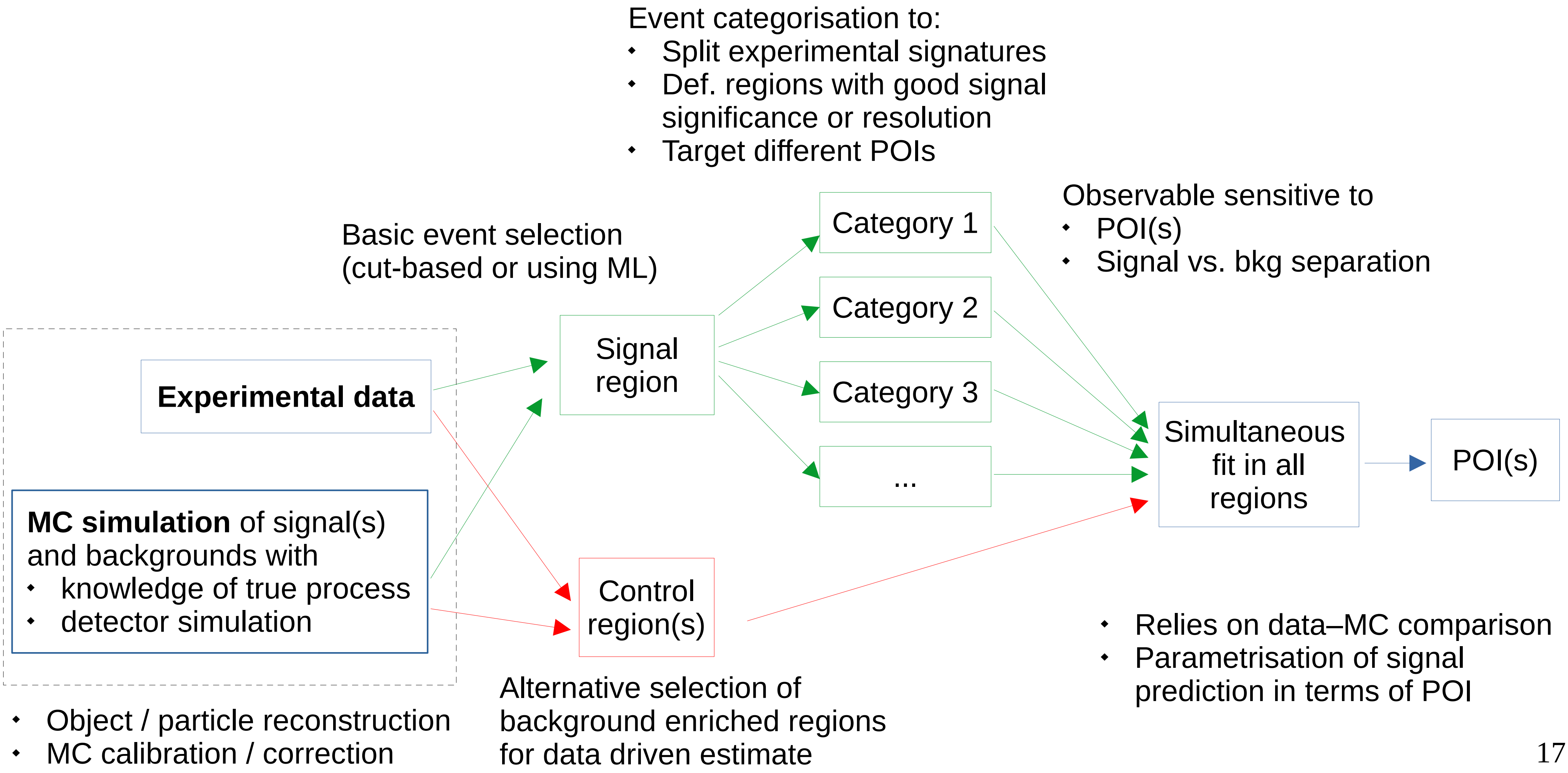

Typical analysis workflow

Impacted by systematic uncertainties (theoretical + experimental) propagated through each step

Event categorisation to:
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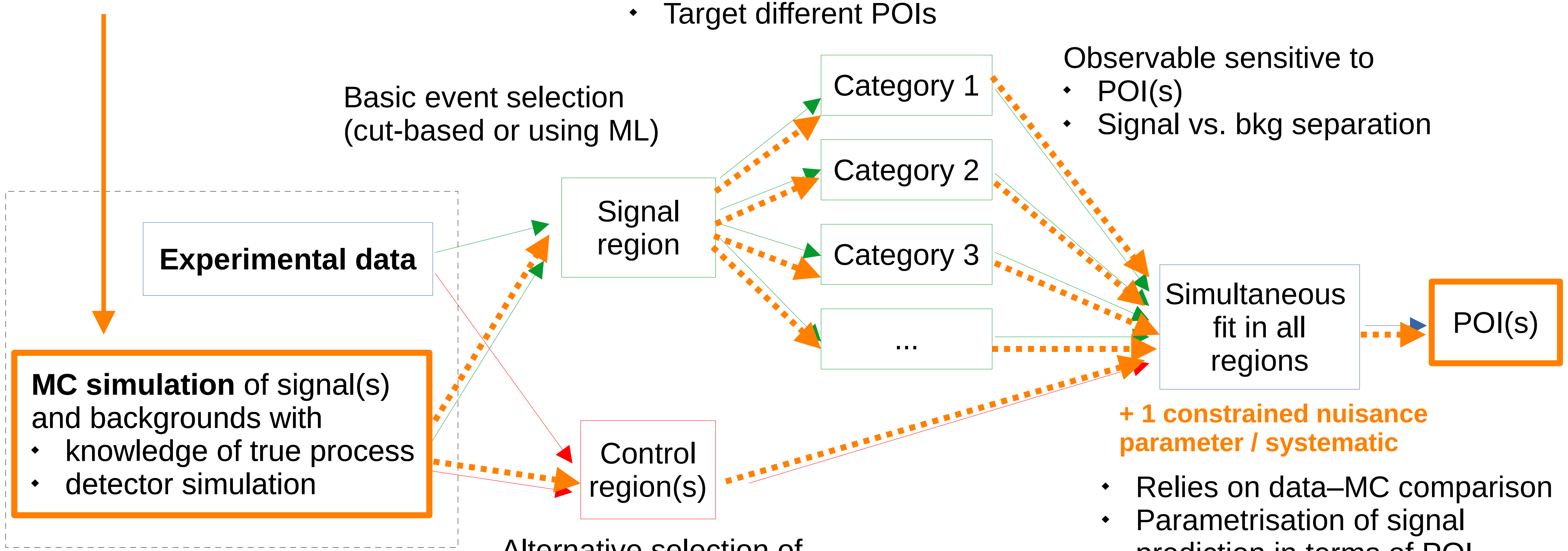

- Object / particle reconstruction
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Alternative selection of background enriched regions for data driven estimate

Interlude -- profile likelihood fit

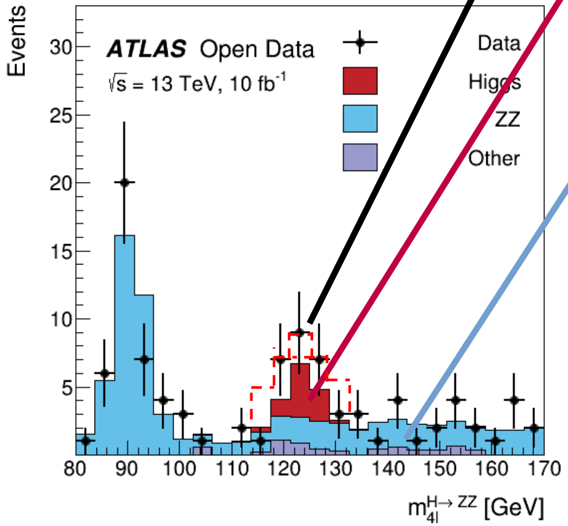
Poisson

$$\mathcal{L}(\boldsymbol{n}|\mu, \boldsymbol{\theta}) = \prod_{i \in bins} \mathcal{P}(n_i|\mu \cdot S_i(\boldsymbol{\theta}) + B_i(\boldsymbol{\theta}))$$

observed bin contents

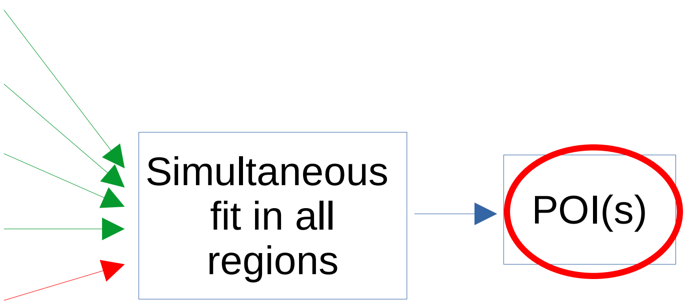
parameters

S+*B* prediction in bin *i*



Here: POI = signal strength μ

Observable sensitive to
- POI(s)
- Signal vs. bkg separation



- Relies on data–MC comparison
- Parametrisation of signal prediction in terms of POI

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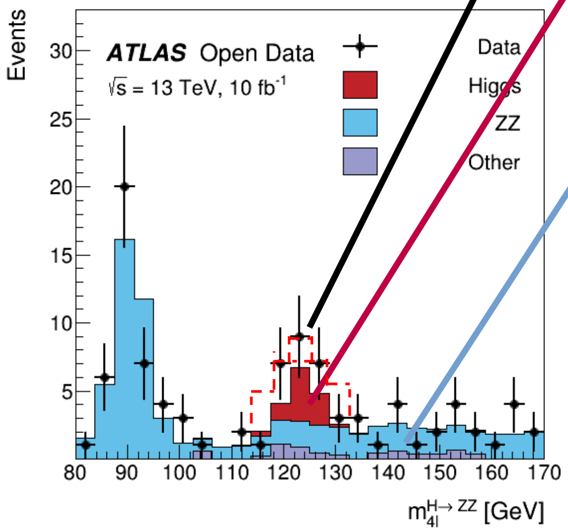

Here: POI = signal strength μ

Here: 4-lepton invariant mass used to identify signal vs. background

Observable sensitive to
- POI(s)
- Signal vs. bkg separation

Simultaneous fit in all regions

POI(s)

- Relies on data–MC comparison
- Parametrisation of signal prediction in terms of POI

Interlude -- profile likelihood fit

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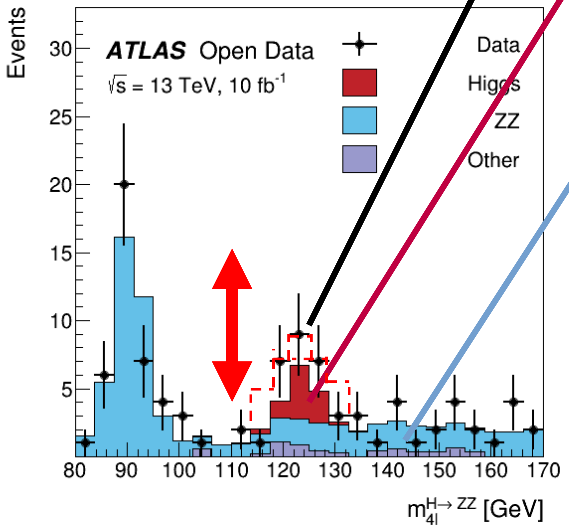
Poisson

observed bin contents

parameters

S+*B* prediction in bin *i*

Minimisation of -2lnL



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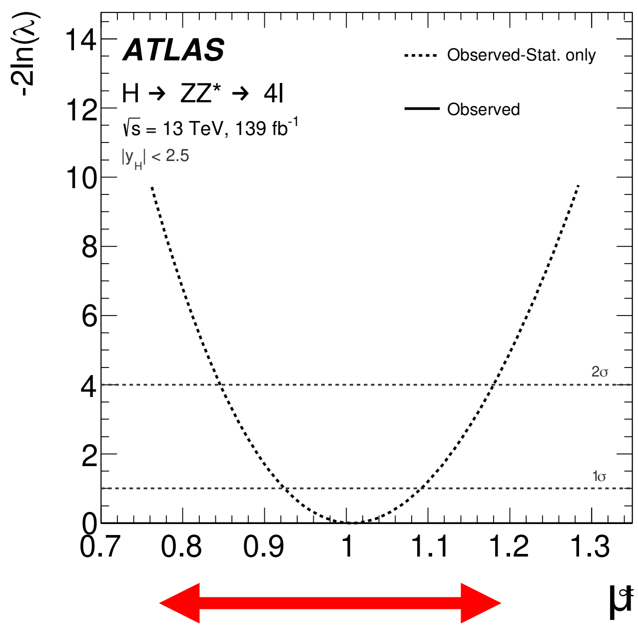

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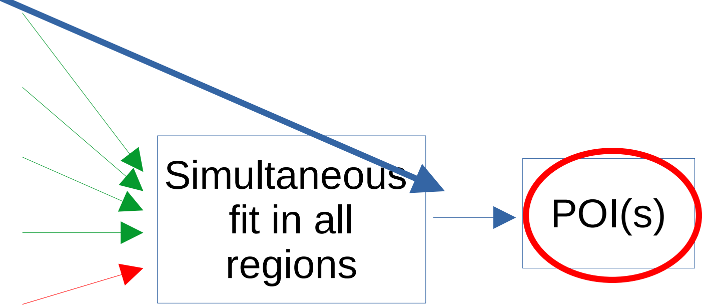

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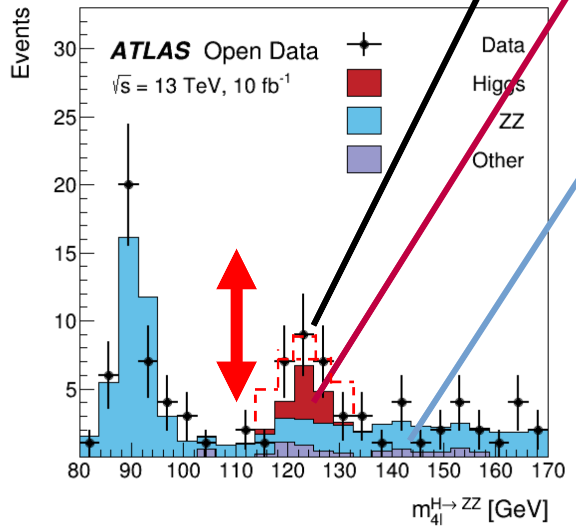

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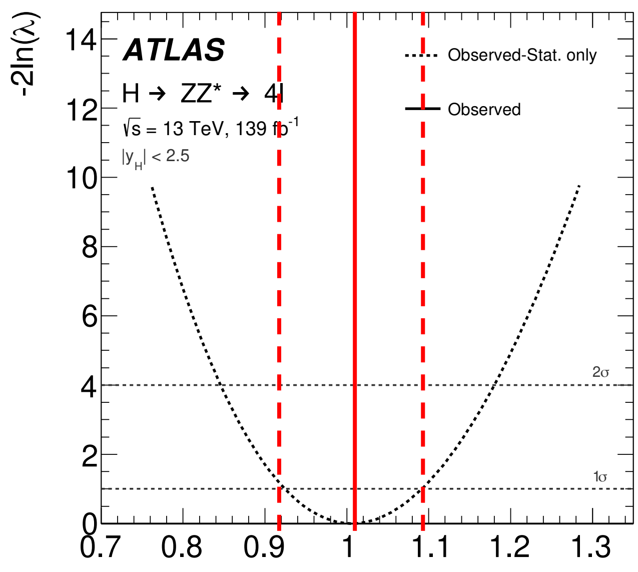

Best fit value +/- statistical uncertainty

Observable sensitive to

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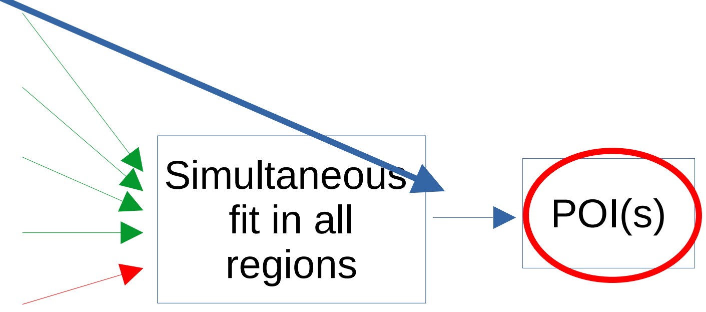
- Signal vs. bkg separation



- Relies on data–MC comparison
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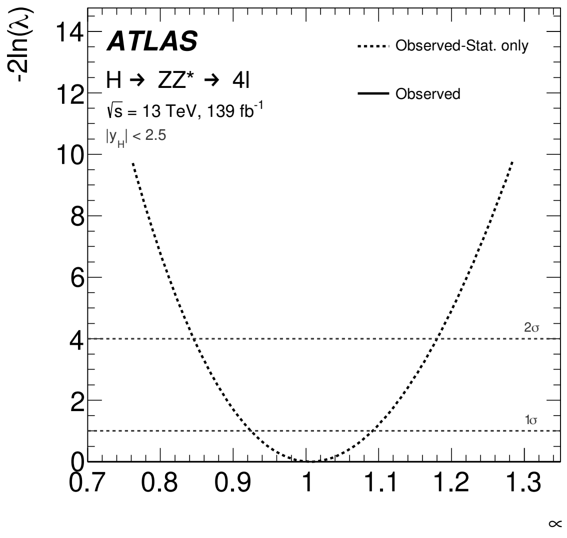
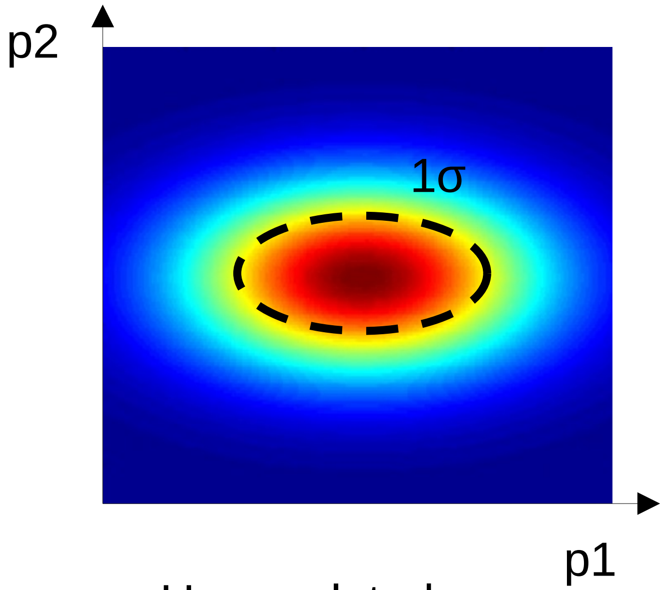
Interlude -- profile likelihood fit

1 parameter (POI) → 2 parameters (POIs or nuisance parameters) → ... → N parameters





Uncorrelated

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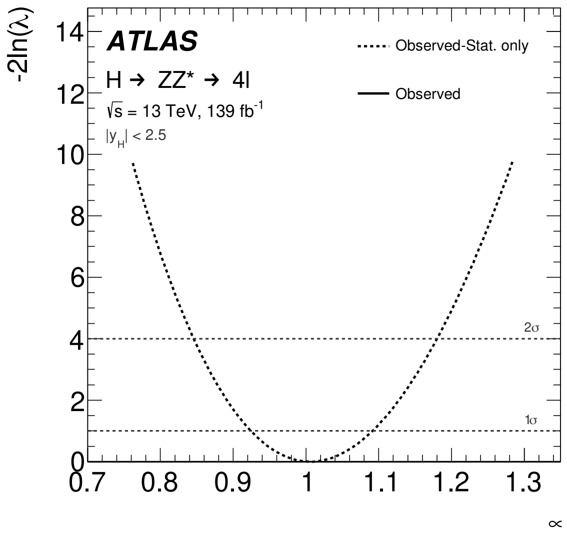

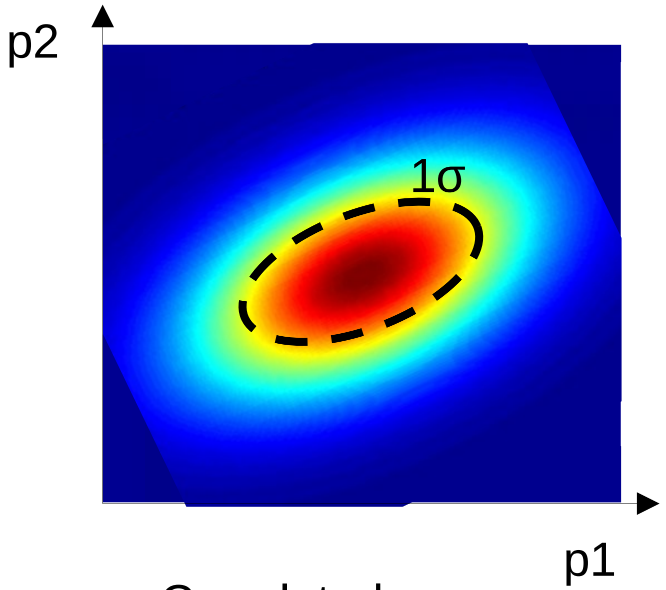

Correlated

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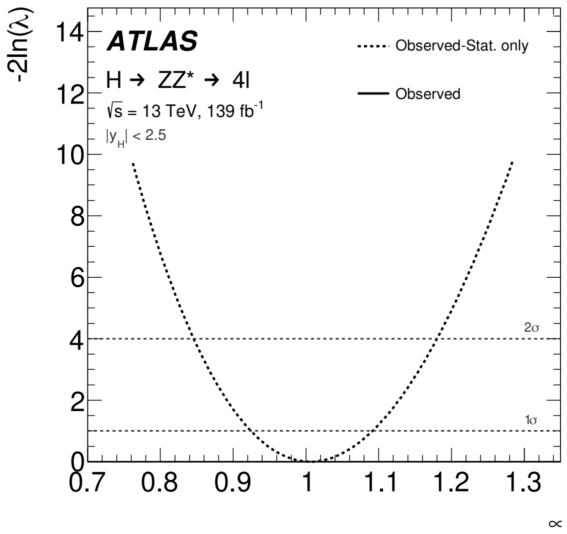

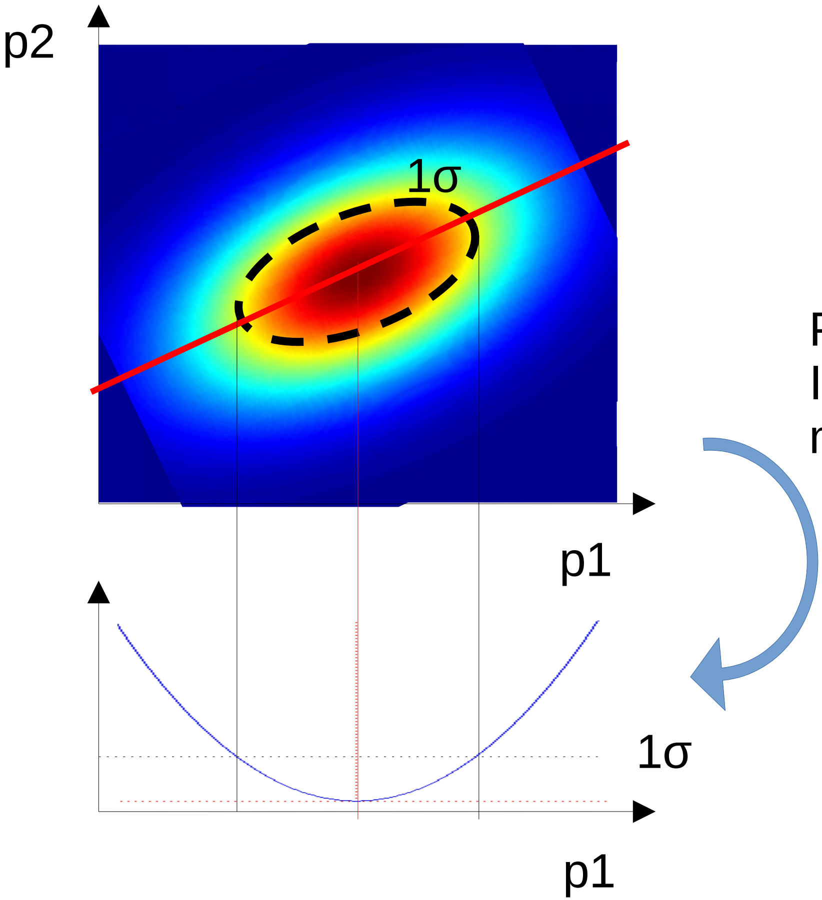

Profile likelihood scan of p1:
In each value of p1,
minimise likelihood w.r.t. p2

Interlude -- profile likelihood fit

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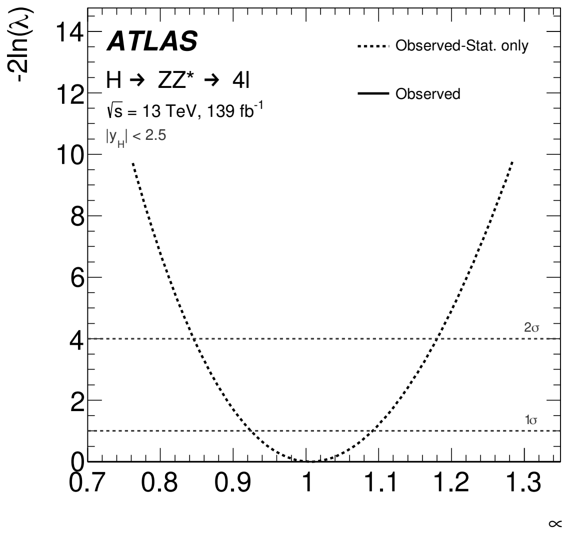

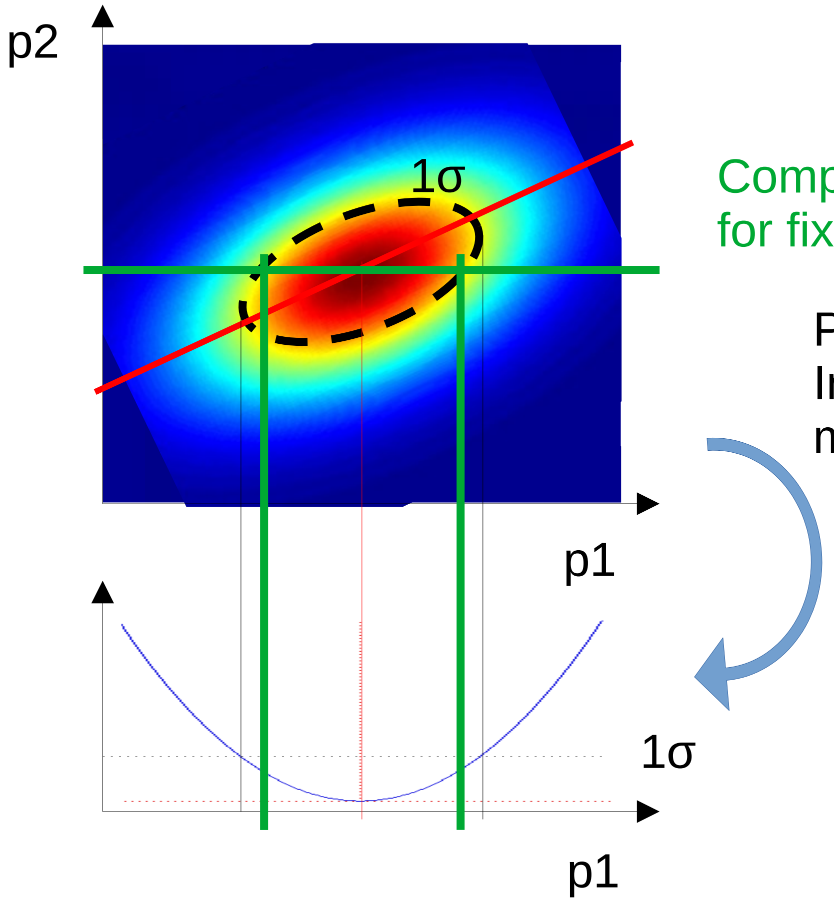

Compare: Simple scan of p1 for fixed value of p2

Profile likelihood scan of p1:
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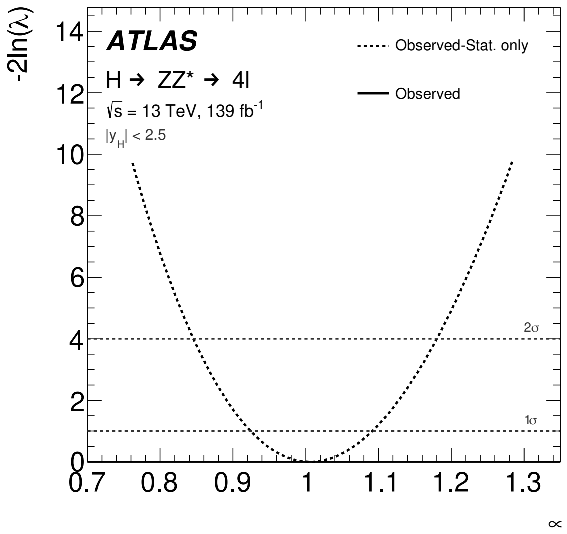
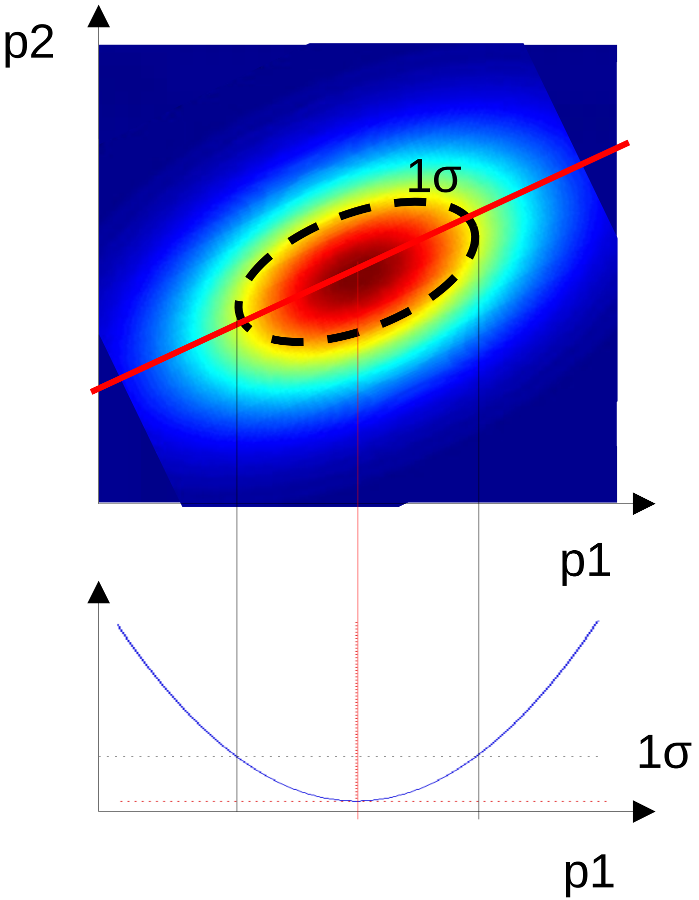




Note:

- P2 can be another POI or a nuisance parameter, e.g. systematic uncertainty
- 2D contour is nice ellipse in case of all-Gaussian behaviour – can have other shape in case of more complicated dependences (quadratic terms etc.)

Interlude -- profile likelihood fit

Poisson

$$\mathcal{L}(\boldsymbol{n}|\mu,\boldsymbol{\theta}) = \prod_{i\in bins} \mathcal{P}(n_i|\mu\cdot S_i(\boldsymbol{\theta})+B_i(\boldsymbol{\theta})) \times \prod_{j\in syst} \mathcal{G}(\theta_j^0|\theta_j,\Delta\theta_j)$$

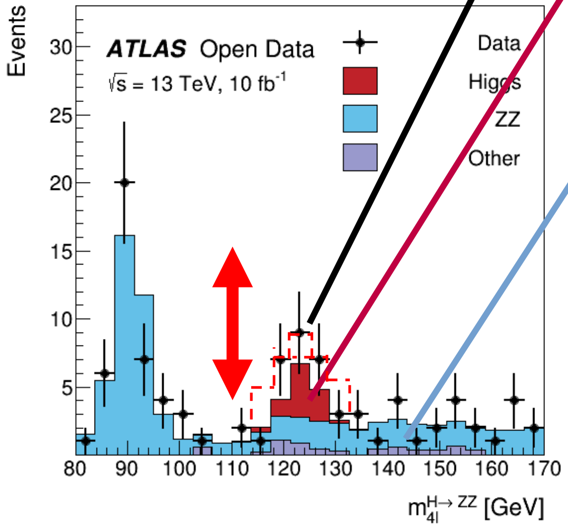
observed bin contents

parameters

$S+B$ prediction in bin i

Additional freedom in likelihood allowing prediction to vary within uncertainties with Gaussian distribution

Minimisation of -2lnL



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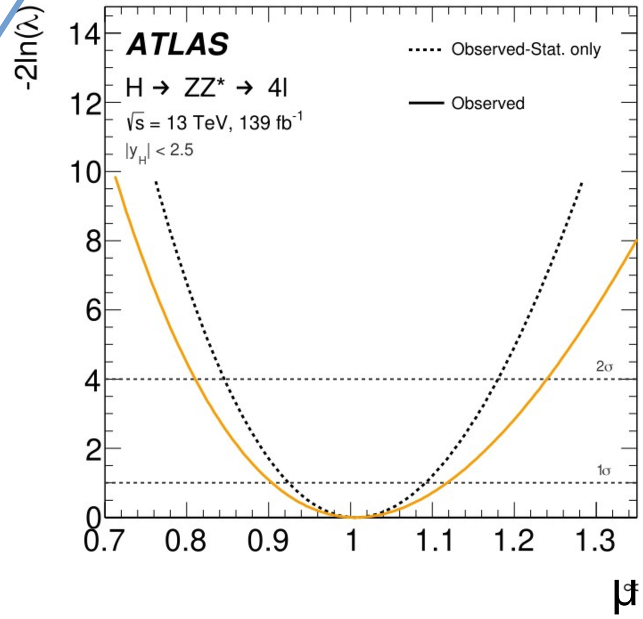

Observable sensitive to
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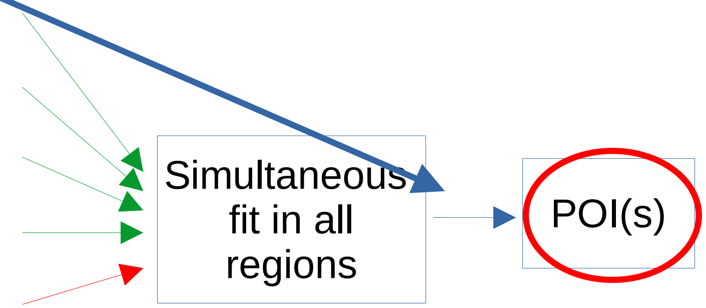

- Relies on data–MC comparison
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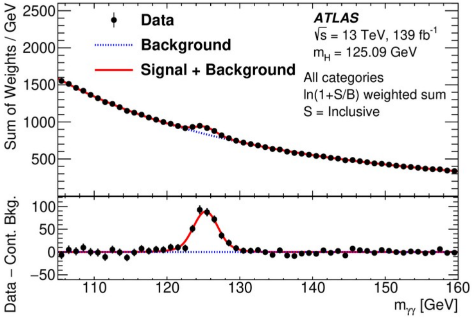
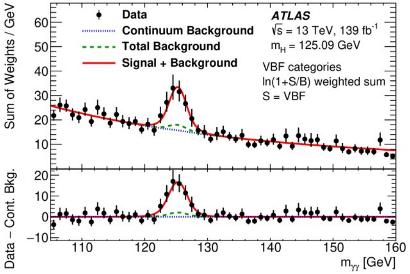
Example: Higgs to diphoton

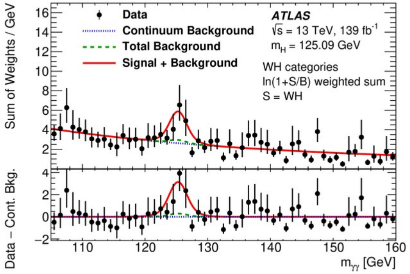
Basic reconstruction & selection of photon pair



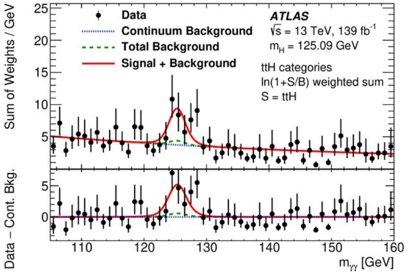
Event categorised to target Higgs production mode



VBF ~ Higgs + 2 forward jets



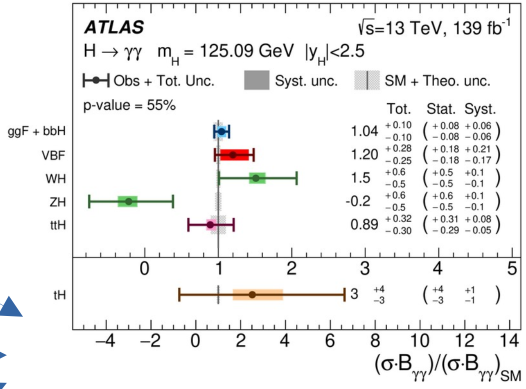
WH ~ Higgs + 2 leptons

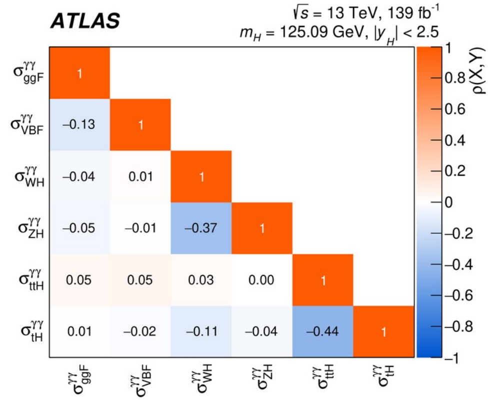


ttH ~ Higgs + 2 tops

Simultaneous fit to diphoton mass

Result: cross section of Higgs decaying to 2 photons in different production modes + associated correlation matrix





Content

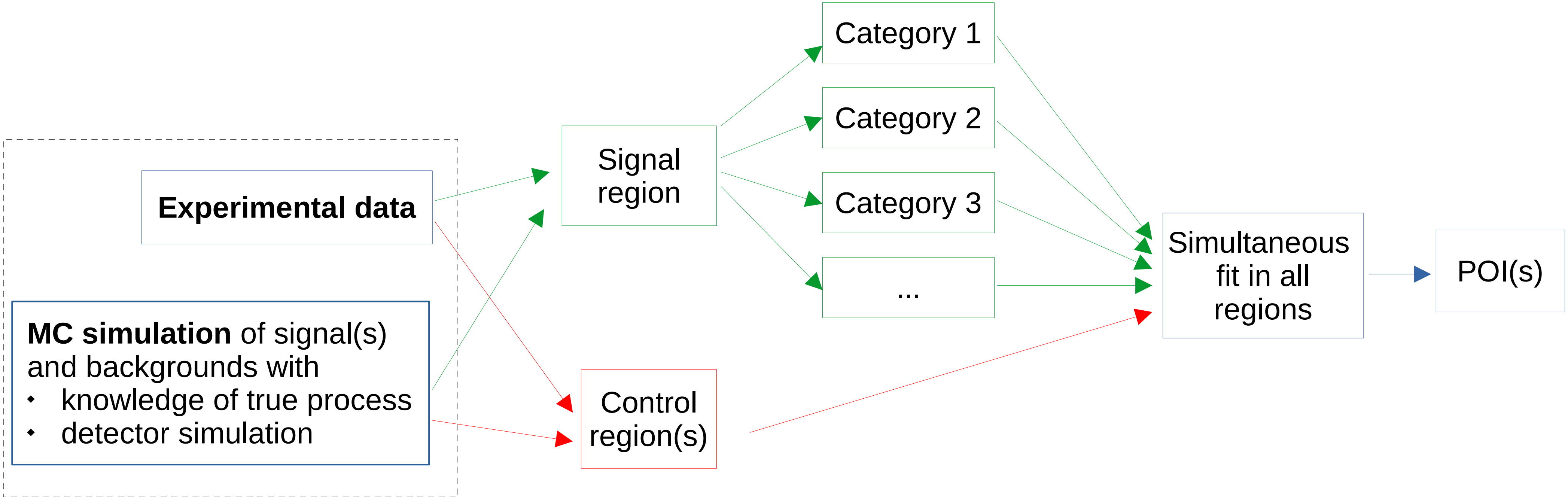
- Ingredients for EFT fits
  - Input measurements – experiments, observables, etc.
- EFT constraints from experimental data
  - Setup: model, basis, input parameters, symmetries
  - EFT in the analysis: simulation and parametrisation
  - Working with a real detector
  - Validity considerations and theory uncertainties: limitations and work arounds
- Global EFT fits
  - Benefits and challenges of combined fit
  - Limitations and perspectives for EFT fits – towards HL-LHC and beyond

Note: This lecture is quite technical; more details on application of these concepts in dedicated sessions (EFT in Higgs + EW and in flavour physics)

EFT model and basis

- Several different EFT models with different underlying assumptions: SMEFT, HEFT,…
  - Choice depending on physics models to be probed (Higgs physics, B physics, etc.)
- Described by complete and orthogonal basis of operators; several bases possible
  - In principle, can easily convert one to the other
  - Basis choice depends on measured processes – basis can be defined such that operators correspond to modifications of physical couplings, or, in contrary, should be general and useful for all measurements
- Operator set might be reduced by requiring additional symmetries, if measurement is not sensitive e.g. to flavour etc.
- More details in theory introduction and dedicated lectures on Higgs+EW and flavour physics
  - Overview of (equivalent) bases in this LHCXSWG note

Where do EFT enter in the analysis?



Where do EFT enter in the analysis?

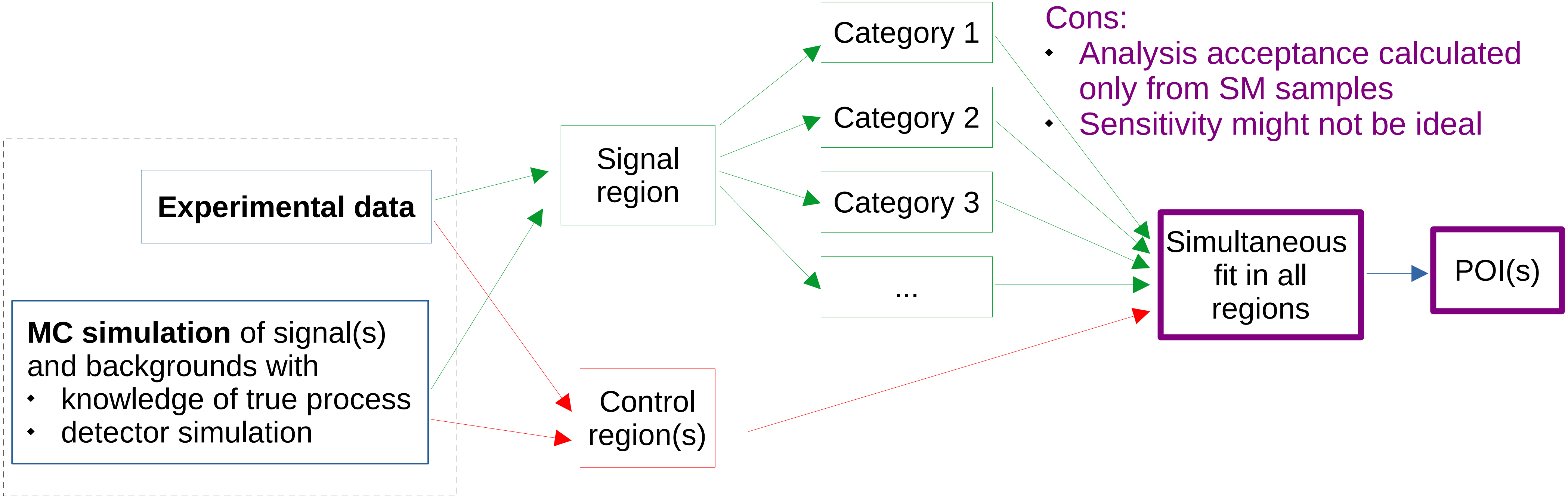
<u>**Option 1**: Parametrisation of results</u>

Pros:

- Fast and exact EFT impact computed at truth level
- Straight forward to handle interference between operators

Cons:

- Analysis acceptance calculated only from SM samples
- Sensitivity might not be ideal



Where do EFT enter in the analysis?

Option 2: Use alternative signal model with EFT contributions

Pros:
- Propagation through full analysis procedure
- Possibility to optimise analysis for EFT sensitivity
- Suited for single EFT operator fit

Cons:
- Heavy due to full detector simulation
- Interpolation between values of Wilson coefficients
- Becomes very complex for global EFT fit

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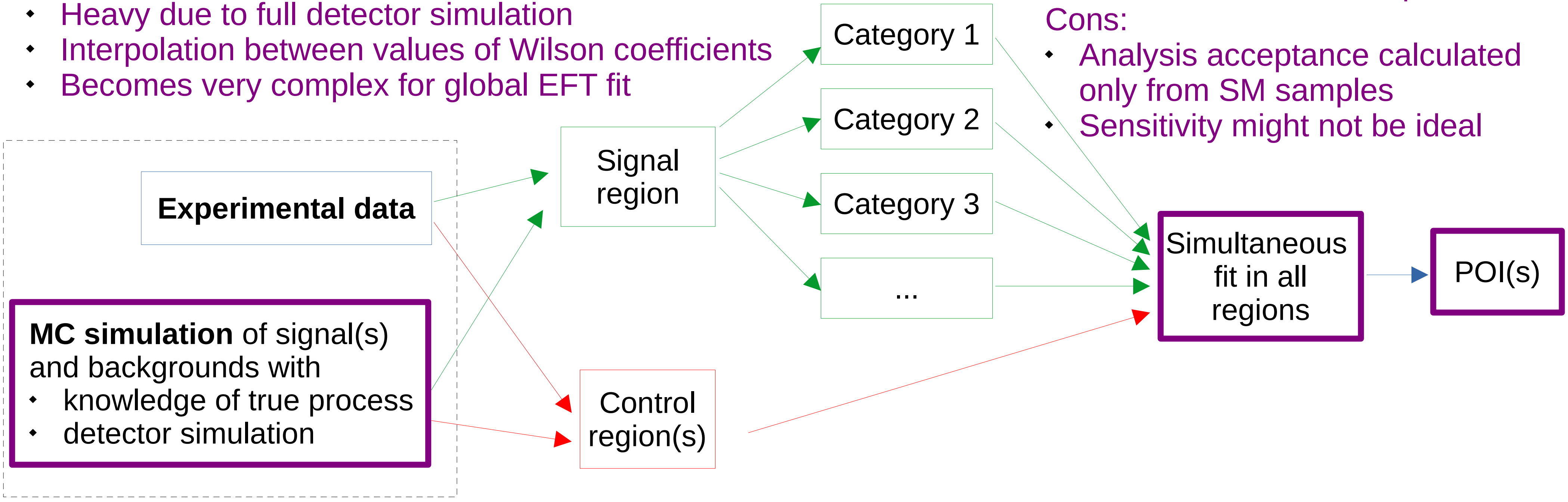

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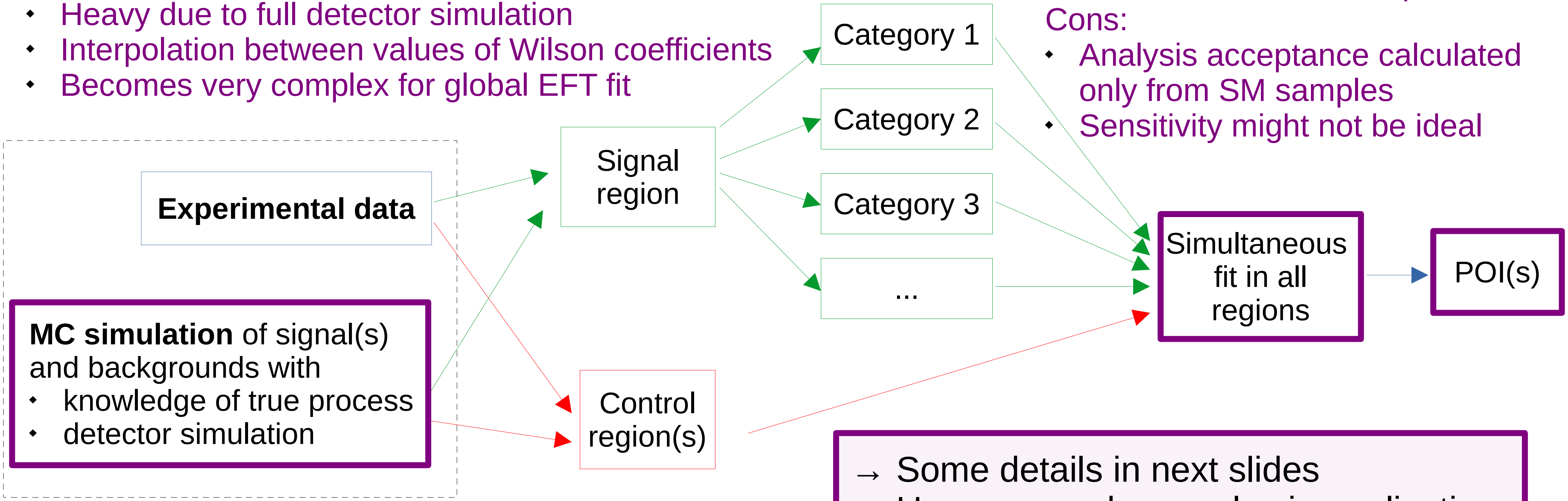

→ Some details in next slides
→ Use case and examples in applications for Higgs+EW & flavour

Building the EFT parametrisation

- Numerous tools on the market to simulate EFT impact on specific processes
- Implemented e.g. as MadGraph UFOs -- allowing to generate MC with EFT contribution

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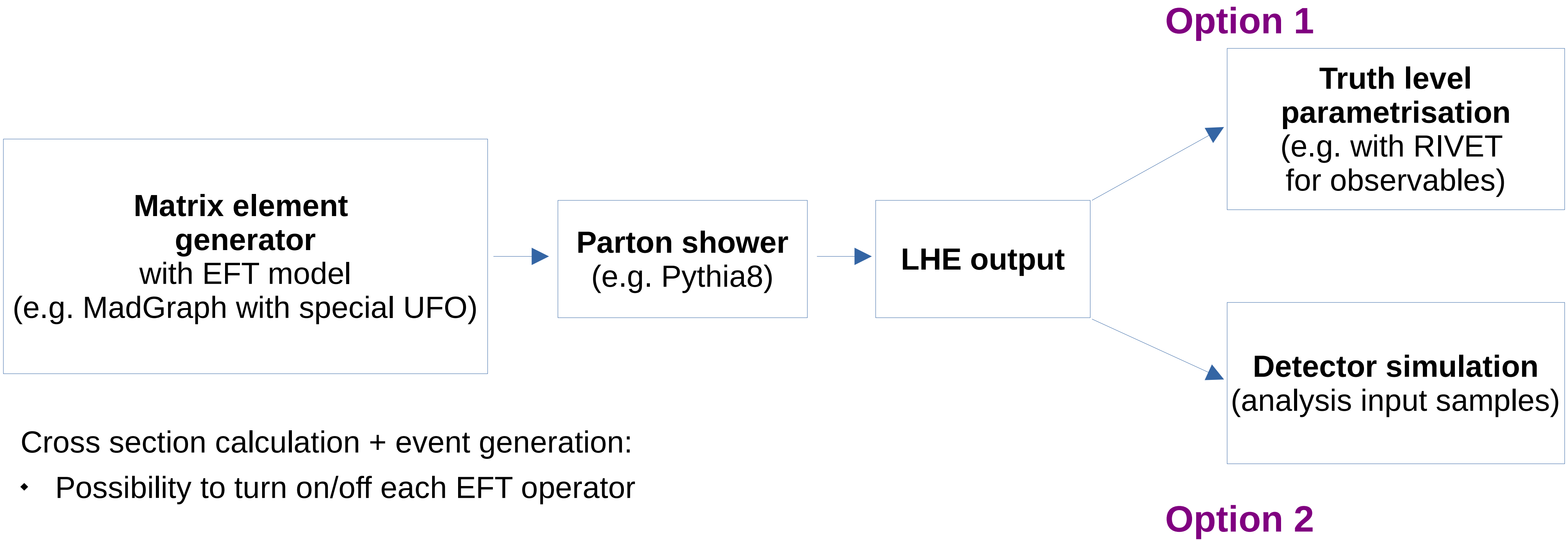

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- Possibility to turn on/off each EFT operator

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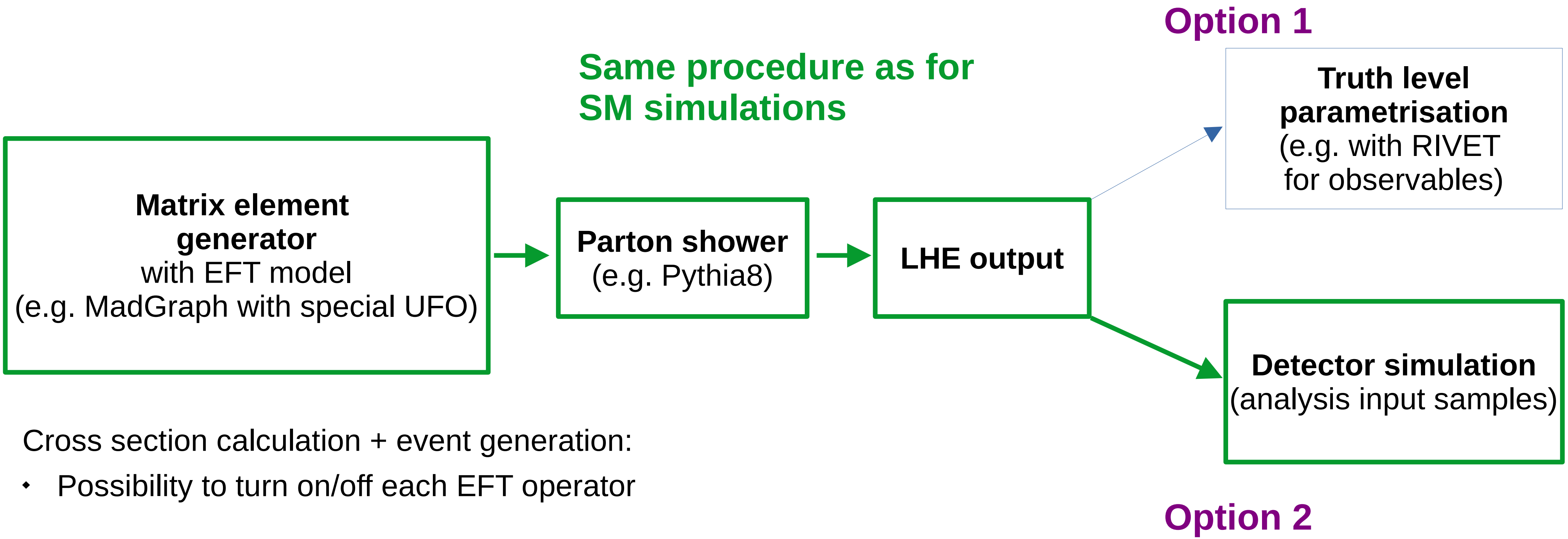

Cross section calculation + event generation:

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Step-by-step: event generation

Dimension and order – example SMEFT

The general SMEFT Lagrangian contains the SM (dim-4 operators) + higher (even) order operators (odd dimension operators are lepton number violating)

$$\mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{\text{SM}}^{(4)} + \frac{1}{\Lambda^2}\sum_{i}^{N_6} c_i \mathcal{O}_i^{(6)} + \frac{1}{\Lambda^4}\sum_{j}^{N_8} c_j \mathcal{O}_j^{(8)} + \dots$$

Leading BSM → often only consider dim-6 operators

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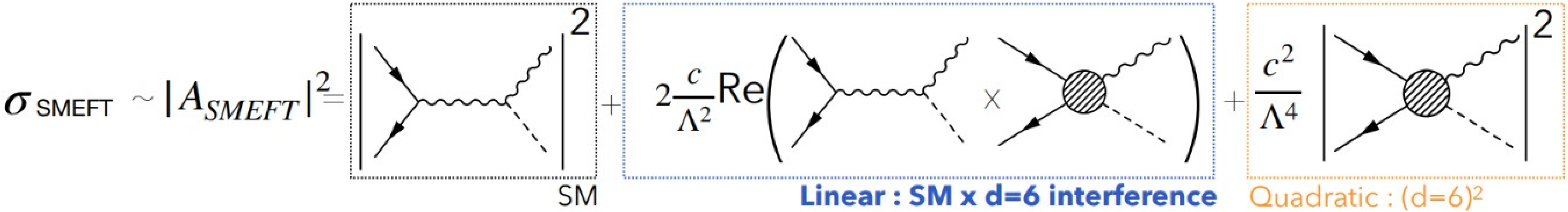

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$|\;|^2$

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$$|\mathscr{M}_{\text{SMEFT}}|^2 \sim \sigma = \sigma_{\text{SM}} + \sigma_{\text{int}} + \sigma_{\text{BSM}}$$

$\sim 1/\Lambda^2$ for dim-6 EFT

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Leading BSM → often only consider dim-6 operators

Theory calculations ongoing, but heavy dominant BSM contribution to certain processes

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Input parameters & symmetries

Input parameters

- The SM depends on a set of free parameters that need to be measured (masses, widths, QCD constants, mixing angles, etc.) – need to define minimal complete set of free parameters
- Additional free parameters in EFT: energy scale Λ and Wilson Coefficients c_i – in practice, hard to make simultaneous measurement of Wilson Coefficients and SM parameters → need input values
- Choice of input parameter set & measurements can depend on use case and should fulfill some criteria (e.g. on precision, decorrelation from EFT contributions, etc.)
- Note: for a global EFT combination, input parameter choice needs to be consistent

Symmetries

- Full EFT formulation yields large number of independent operators – not all of them can be constrained by every analysis
- Number of operators can be reduced a priori in some cases by requiring certain symmetries, e.g. $U(3)^5$ flavour symmetry – e.g. VH production in $H \to bb$ decay has no sensitivity to discriminate between fermion generations

EFT calculation order

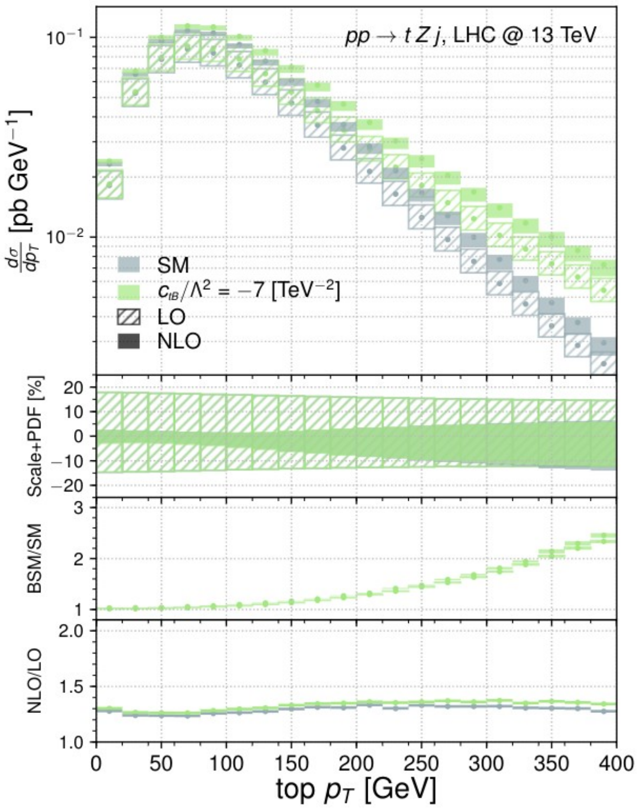
- For some processes, SM calculations available at high order (NNLO, N3LO,…)
- EFT models often “only” available at LO or NLO

Solution: assume k-factor between LO and higher order is similar for SM and EFT
→ compute relative EFT correction to SM prediction

$$\sigma = \sigma_{\mathrm{SM}}^{\mathrm{(N)NLO}} \cdot \left(1 + \frac{\sigma_{\mathrm{int}}^{\mathrm{LO}}}{\sigma_{\mathrm{SM}}^{\mathrm{LO}}} + \frac{\sigma_{\mathrm{BSM}}^{\mathrm{LO}}}{\sigma_{\mathrm{SM}}^{\mathrm{LO}}}\right)$$

Note:
- not ideal for every process
- should know EFT at least at leading order of specific process

Example: transverse top momentum in pp→tZj production



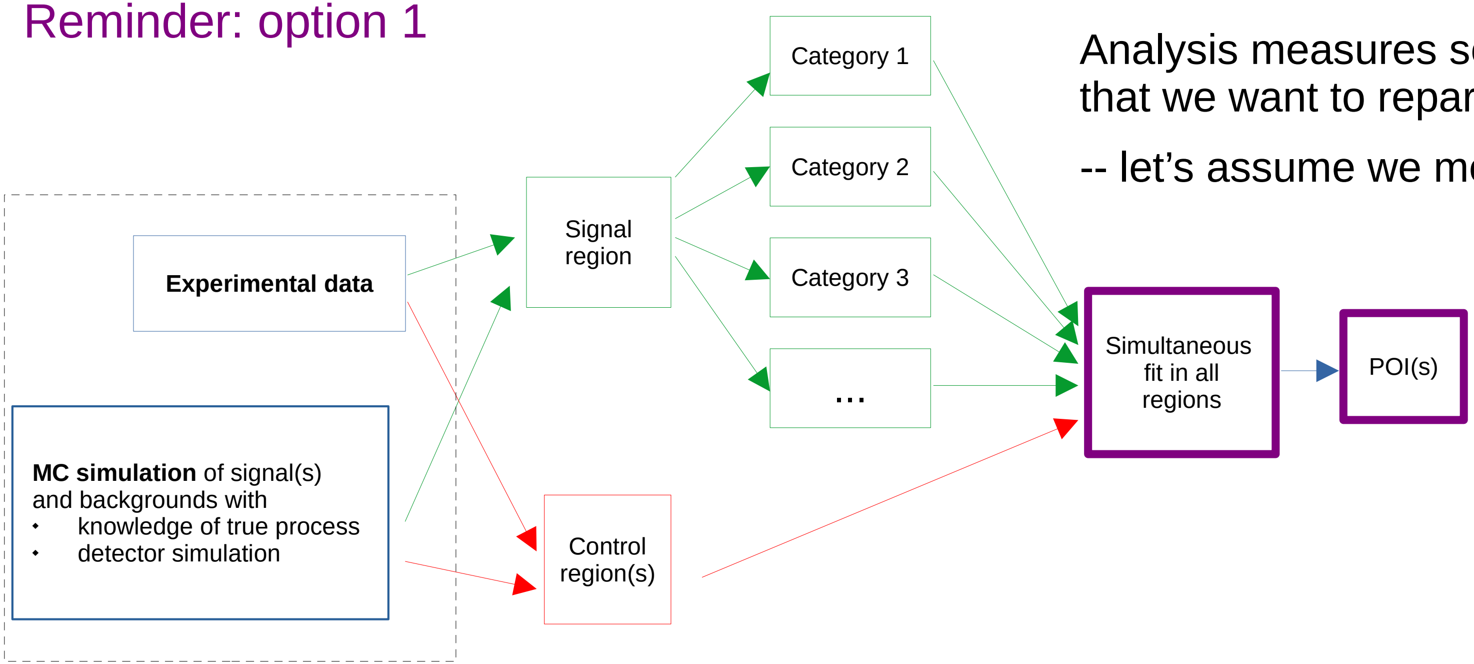
C. Degrande, F. Maltoni, K. Mimasu, E. Vryonidou, C. Zhang

Step-by-step: parametrisation

Building the EFT parametrisation

Building the EFT parametrisation

Reminder: option 1



Analysis measures some observable / parameter that we want to reparametrise in terms of EFT

-- let's assume we measure a **cross section σ**

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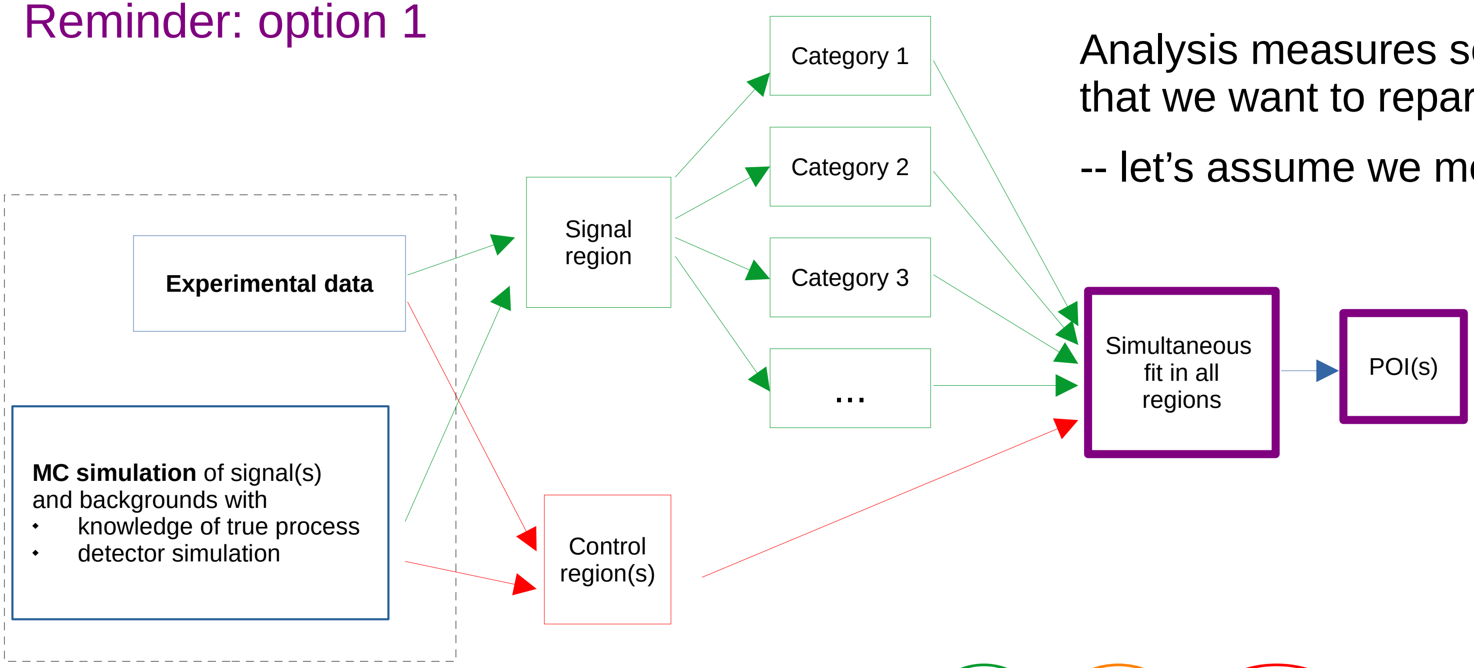

$$\sigma = \sigma_{\mathrm{SM}} + \sigma_{\mathrm{int}} + \sigma_{\mathrm{BSM}}$$

Value observed in data

SM prediction

EFT-SM interference

EFT-EFT interference

Building the EFT parametrisation

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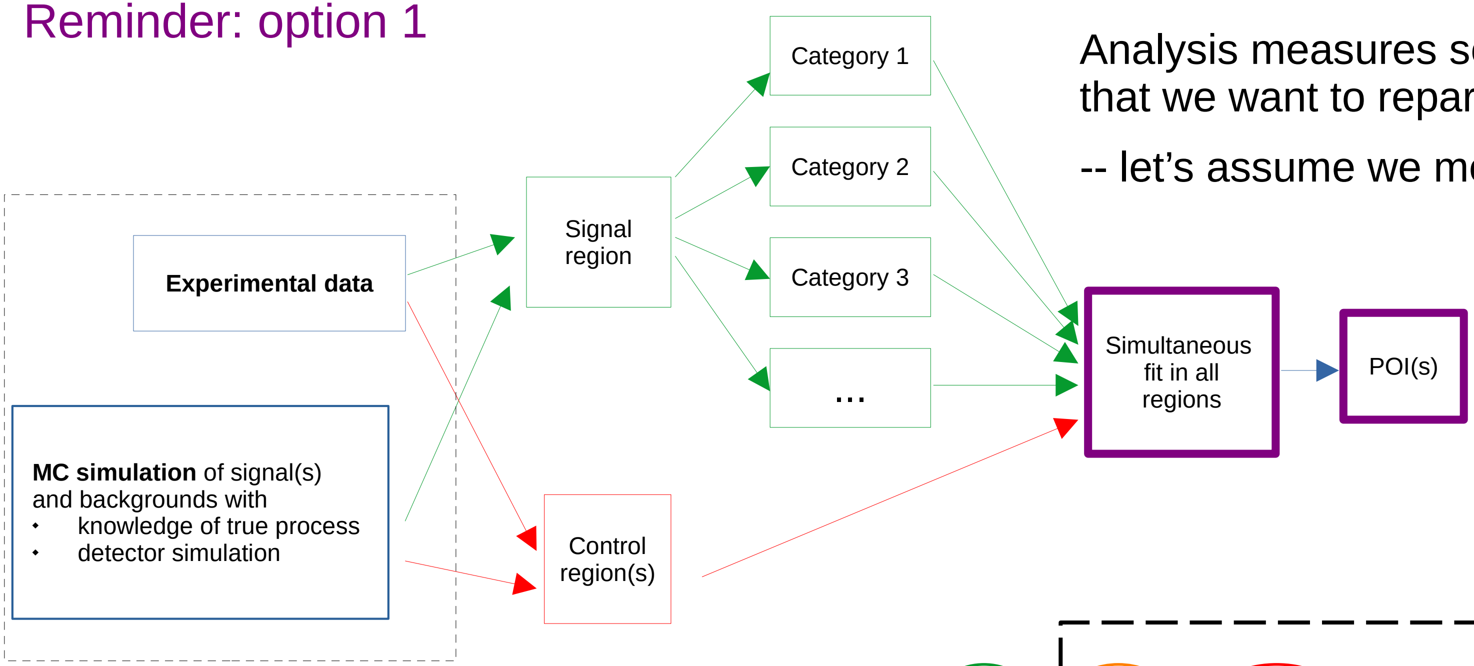

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BSM contributions that we want to constrain

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Relative effect of BSM model (EFT operator) on σ: **constant factors computed from MC simulation**

Wilson coefficients (coupling strength associated to EFT operator): **POI of the fit**

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Relative effect of BSM model (EFT operator) on σ: **constant factors computed from MC simulation**

Wilson coefficients (coupling strength associated to EFT operator): **POI of the fit**

Some generators allow to simulate EFT-SM interference and pure EFT terms separately

Simple linear or quadratic dependence on Wilson coefficients

→ simulation for a few values of c_i sufficient to compute constant coefficients A_i and B_{ij}

Building the EFT parametrisation

$$\sigma = \sigma_{\mathrm{SM}} + \sigma_{\mathrm{int}} + \sigma_{\mathrm{BSM}}$$

- σ: Value observed in data
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- σ_{int}: EFT-SM interference
- σ_{BSM}: EFT-EFT interference

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A_i, B_{ij}: Relative effect of BSM model (EFT operator) on σ: **constant factors computed from MC simulation**

c_i, c_j: Wilson coefficients (coupling strength associated to EFT operator): **POI of the fit**

<u>Example</u>

Using MadGraph with separate simulation of σ_{int} and σ_{BSM}, need:

- SM: 1 sample
- A_i: 1 sample / operator (e.g. $c_i = 1$)
- B_{ii}: 1 sample / operator (e.g. $c_i = 1$)
- B_{ij}: 1 sample / operator pair (e.g. $c_i = c_j = 1$)

Simple linear or quadratic dependence on Wilson coefficients

→ simulation for a few values of c_i sufficient to compute constant coefficients A_i and B_{ij}

Option 1 -- application

- Example on previous slide is basic example with one input measurement -- in practice, usually use differential cross sections and/or input from several analyses
- Under fully Gaussian assumption, can work with public results: measurement results with corresponding covariance matrix

$$\chi^2 = (P\text{-}\mu)\ \ C^{-1}\ (P\text{-}\mu)^T$$

Measurement covariance matrix

Measurement vector

Prediction vector:

$$P^{\,i} = \sigma_r^i\ x\ \ \left(1 + \sum_i A_i c_i + \sum_{ij} B_{ij} c_i c_j\right)$$

Option 1 -- application

Example: Higgs to diphoton differential cross sections

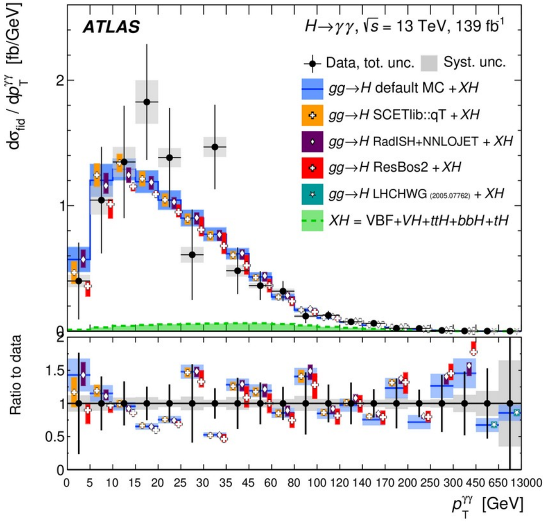
$$\chi^2 = (P-\mu)\ \ C^{-1}\ (P-\mu)^T$$

Measurement vector

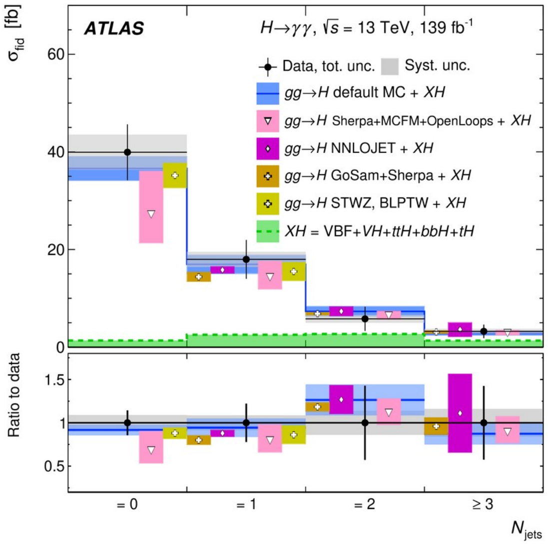
Input measurements:

Differential cross section as a function of several kinematic quantities of the diphoton system or associated particles

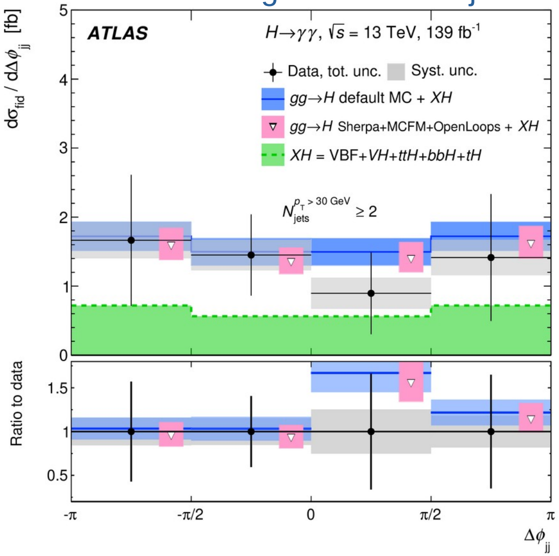
Transverse momentum of the reco Higgs



Number of jets in the event



Azimuthal angle between 2 jets



+ ...

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Measurement covariance matrix

Measurement vector

<u>Covariance matrix:</u>

Correlations between measurements, i.e. between bins of each differential distribution and between distributions

Transverse momentum of the reco Higgs

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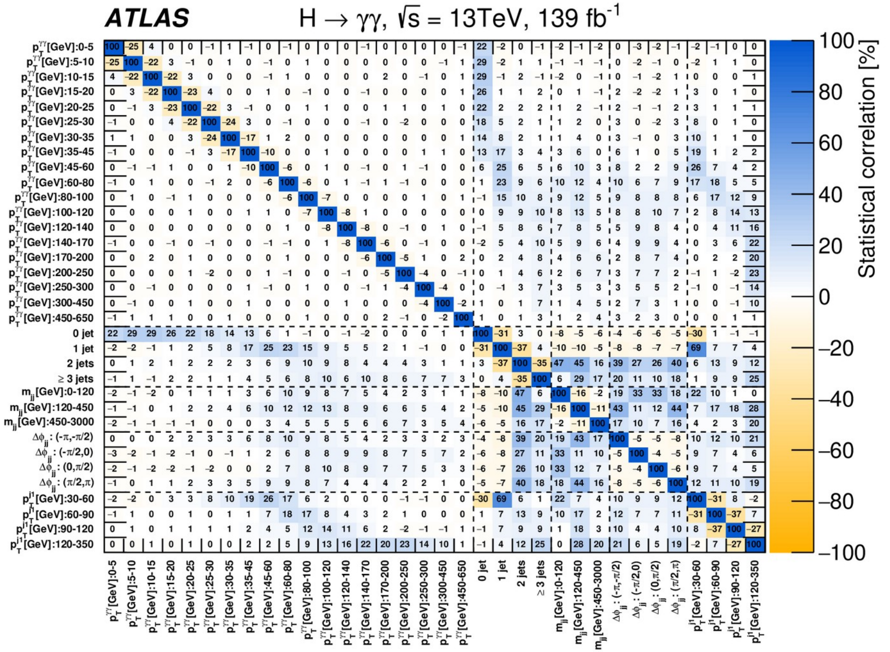

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Prediction vector

Measurement covariance matrix

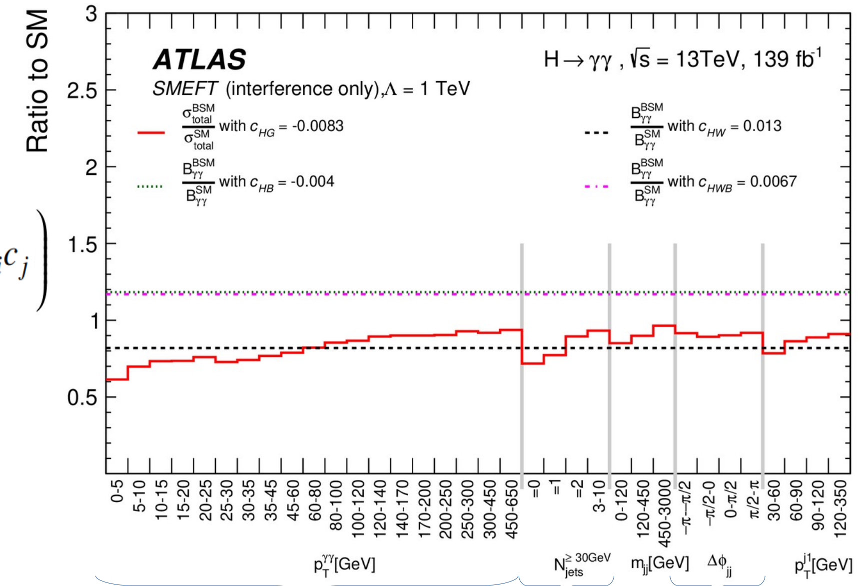
Measurement vector

Prediction:

Parametrisation in terms of EFT operators from truth level MC simulation for chosen operators

$$P^i = \sigma_r^i\ x\ \left(1 + \sum_i A_i c_i + \sum_{ij} B_{ij} c_i c_j\right)$$

Similar parametrisation for corresponding CP-odd operators



Transverse momentum of the reco Higgs

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Option 1 -- application

Example: Higgs to diphoton differential cross sections

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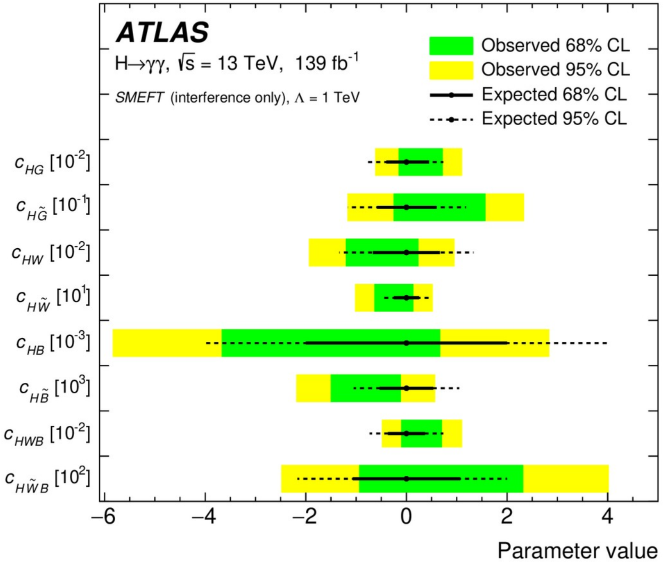
Prediction vector:

Measurement covariance matrix

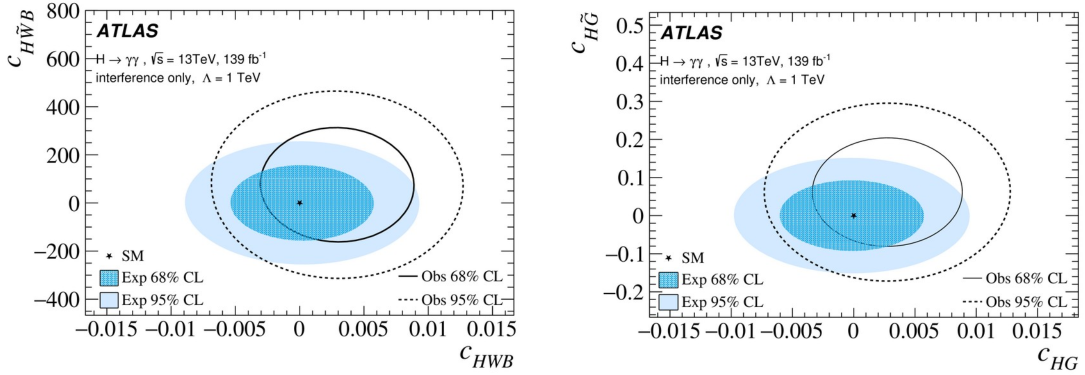
Measurement vector

Results from chi2 minimisation:

Adding 1 operator at the time



2-dimensional optimisation constraining CP-odd versus CP-even couplings in Higgs decay (left) and production (right)



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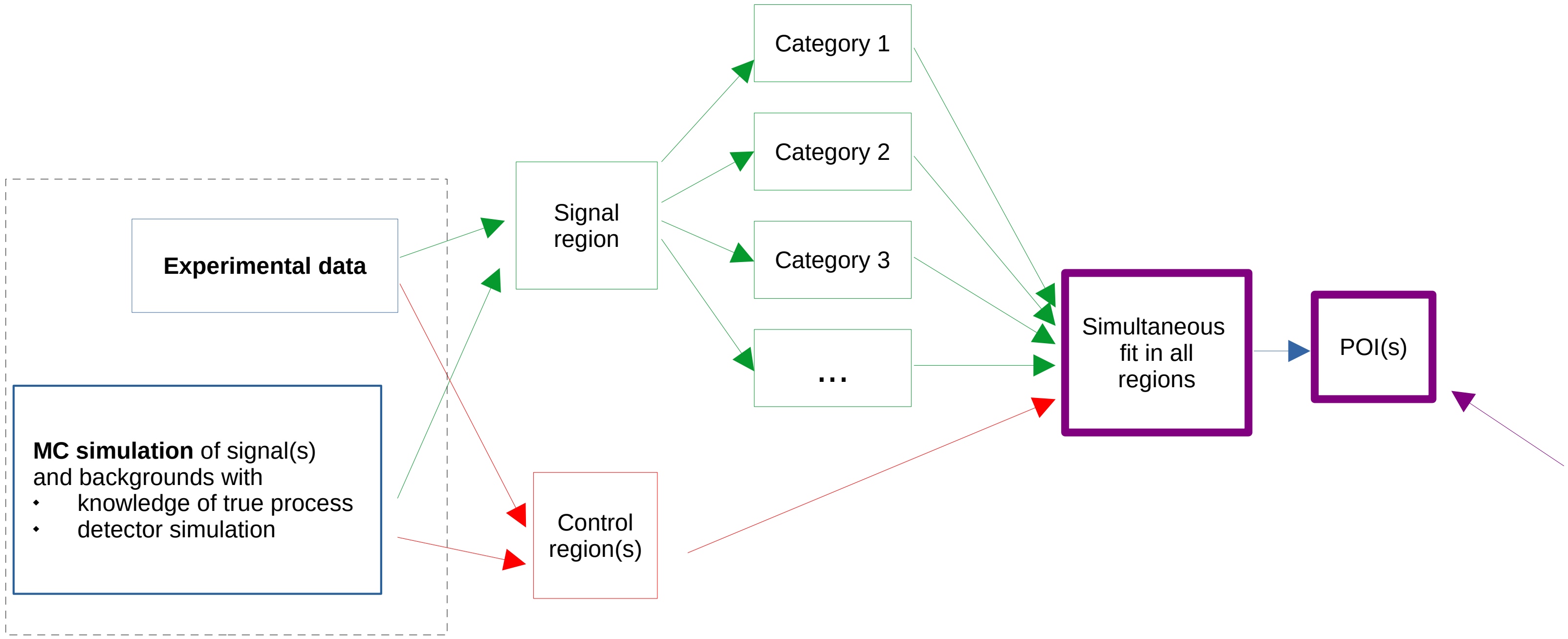
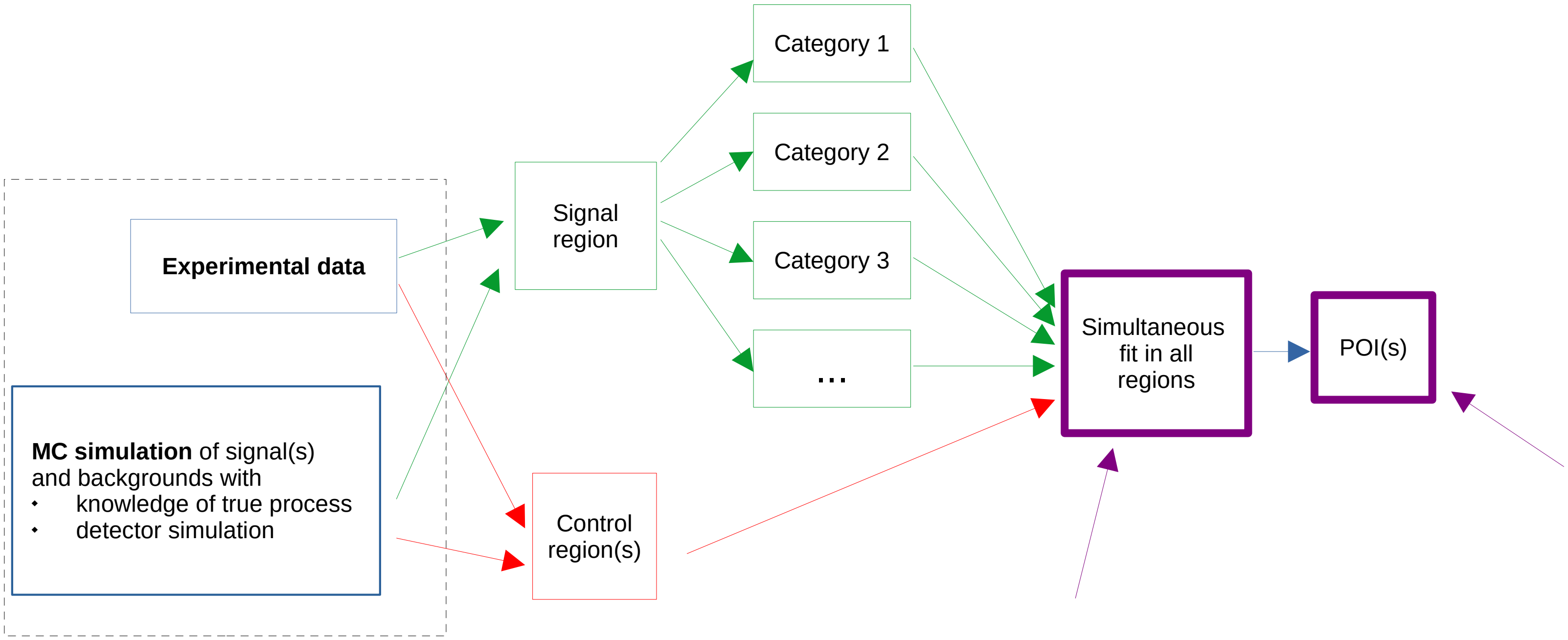


Example from previous slide using published results (measurements + covariance matrix)

Option 1 -- application



Example from previous slide using published results (measurements + covariance matrix)

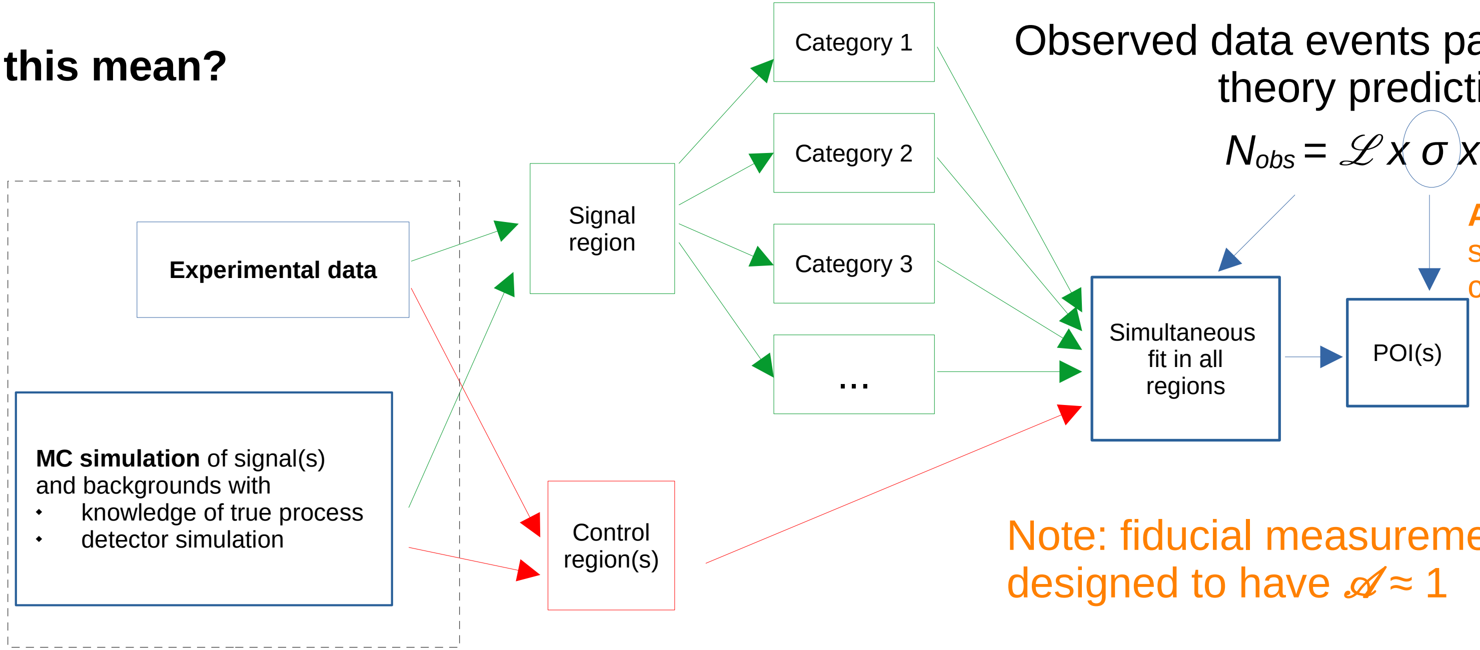
As experimentalist, have the possibility to go one step back and insert **EFT parametrisation into likelihood** (working in very similar way):

- Better treatment of non-Gaussian contributions
- Correlation of systematic uncertainties between measurements
- Correlations between signal and backgrounds

Option 1 – working with a real detector

- Using experimental data requires reconstruction and event selection – to optimise the sensitivity and reject backgrounds, specific phase spaces are selected by analysis cuts
- Analysis strategy should be independent on input model – in many analyses, phase space extrapolations are made using acceptance calculations based on SM samples

What does this mean?



Observed data events parametrised by theory prediction:

$$N_{obs} = \mathscr{L} \times \sigma \times \mathscr{A}$$

Acceptance (reco, selection,…) computed **from MC**

Note: fiducial measurements designed to have $\mathscr{A} \approx 1$

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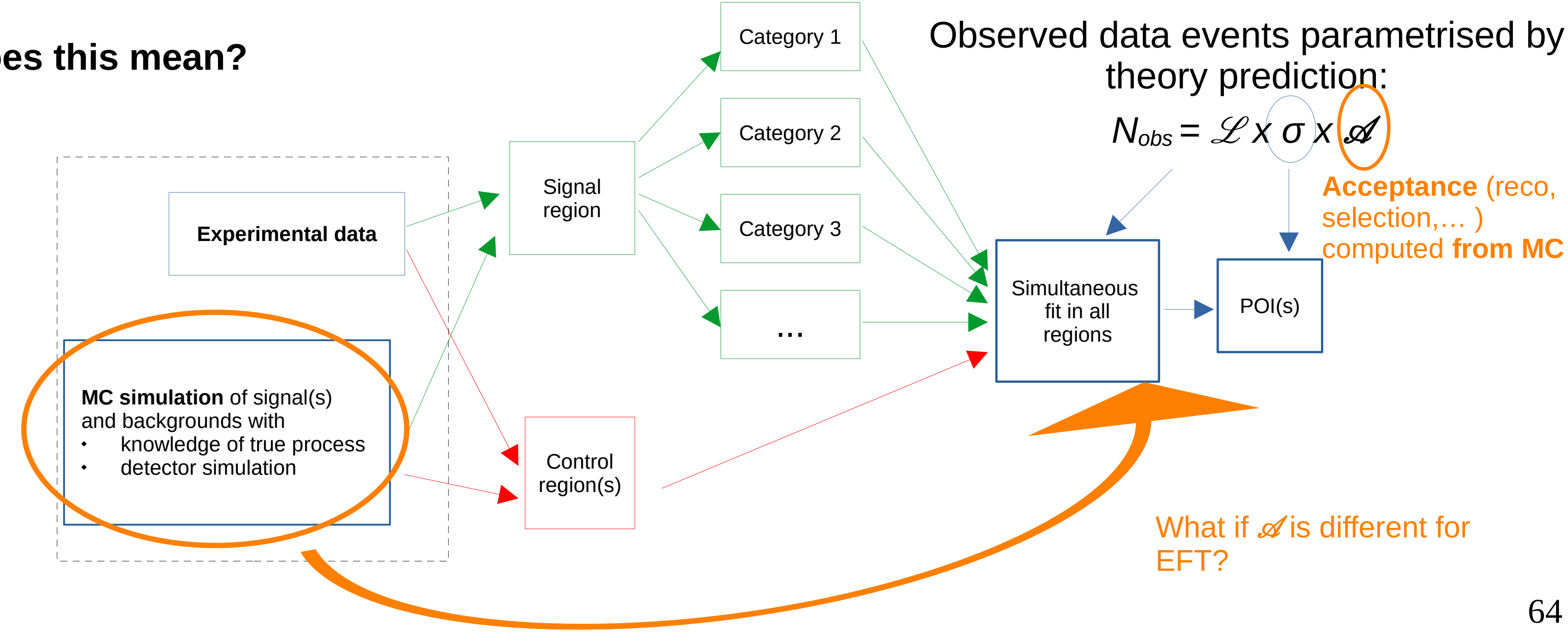

This is SM!

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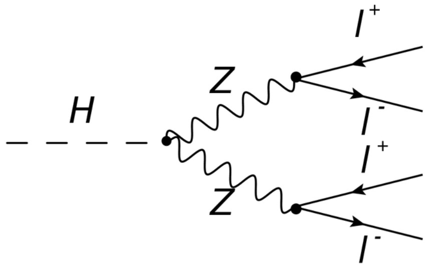
Example: $H \rightarrow ZZ^* \rightarrow 4l$ measurement



- Final state with 2 lepton pairs (e^+e^- or $\mu^+\mu^-$)
- Selection of Higgs based on dilepton mass:
  - Leading pair from Z: $50 < m_{12} < 106$ GeV
  - Subleading pair from off-shell Z: $m_{min} < m_{34} < 115$ GeV ($12 < m_{min} < 50$ GeV)

$$N^i_{obs} = \mathscr{L} \times \sigma^i \times BR(H \rightarrow ZZ^*) \times \mathscr{A}$$

Selected data events in given p_T^H bin i | Integrated luminosity | POI | Acceptance factor

$$\mathscr{A} = \frac{N_{sel}}{(N_{sel} + N_{cut})}$$

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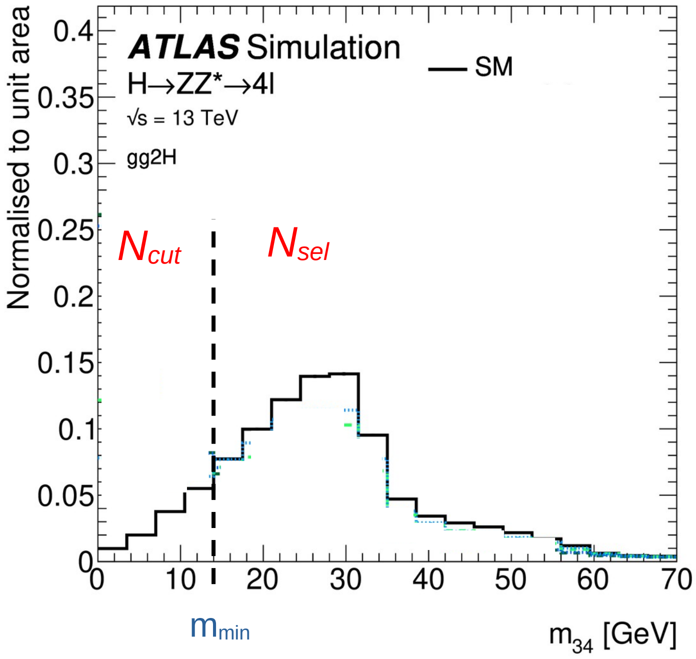

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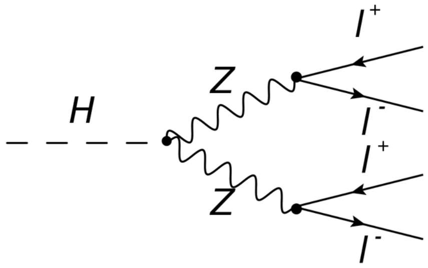
- Using experimental data requires reconstruction and event selection – to optimise the sensitivity and reject backgrounds, specific phase spaces are selected by analysis cuts

- Analysis strategy should be independent on input model – in many analyses, phase space extrapolations are made using acceptance calculations based on SM samples

Example: $H \to ZZ^* \to 4l$ measurement



- Final state with 2 lepton pairs (e^+e^- or $\mu^+\mu^-$)
- Selection of Higgs based on dilepton mass:
  - Leading pair from Z: $50 < m_{12} < 106$ GeV
  - Subleading pair from off-shell Z: $m_{min} < m_{34} < 115$ GeV ($12 < m_{min} < 50$ GeV)

$$N^i_{obs} = \mathcal{L} \times \sigma^i \times BR(H \to ZZ^*) \times \mathcal{A}$$

Selected data events in given p_T^H bin i

Integrated luminosity

POI

Acceptance factor

$$\mathcal{A} = \frac{N_{sel}}{(N_{sel} + N_{cut})}$$

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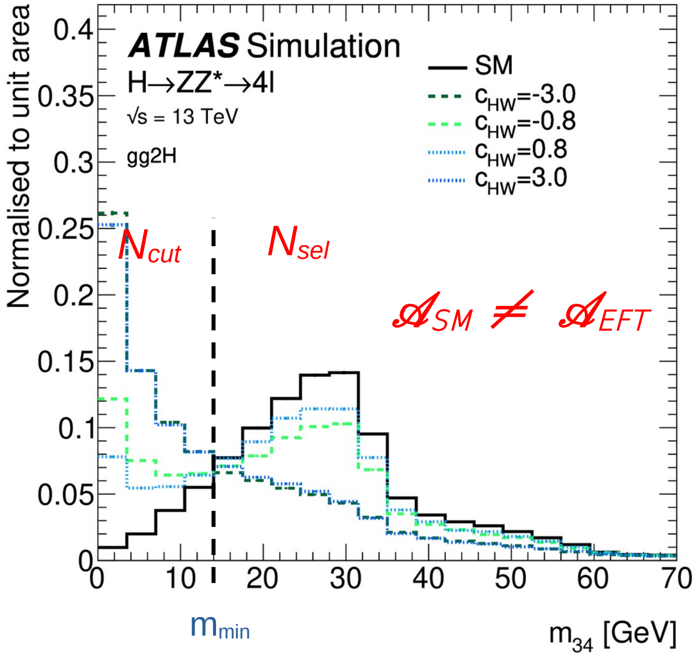


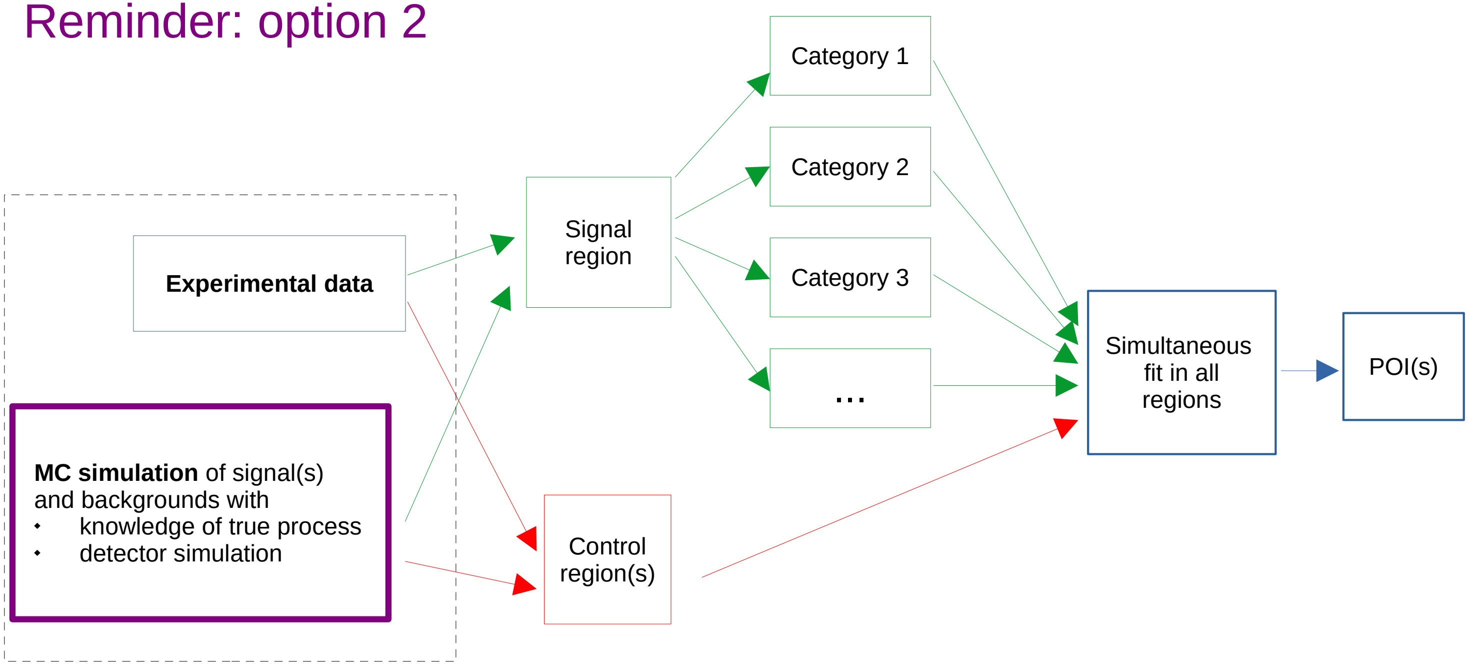
Option 1 – working with a real detector

- One solution: fiducial measurements ↔ measure cross section in phase space close to analysis selection

- Else, possibility to overcome acceptance effects using explicit parametrisation as a function of Wilson coefficients
    - Parametrisation with “arbitrary” function – working well for small deviations of c_i (within EFT validity)
    - Can become heavy if taking into account many operators and quadratic terms
    - Analysis design might be suboptimal for sensitivity to EFT operators (e.g. cutting away phase space with large EFT effects)

Building the EFT parametrisation

Reminder: option 2

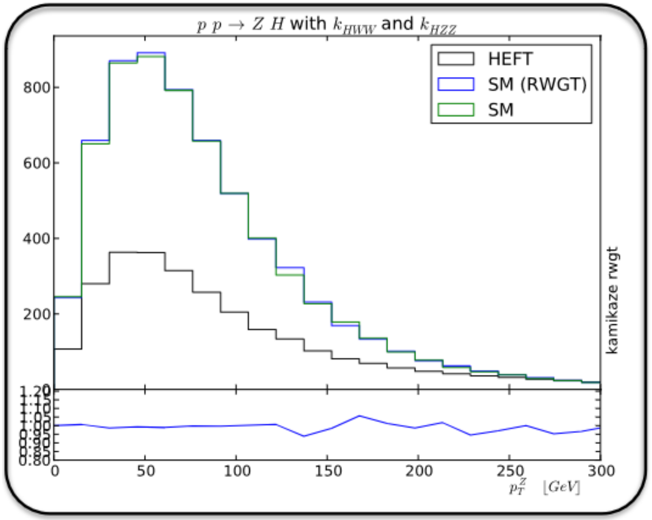


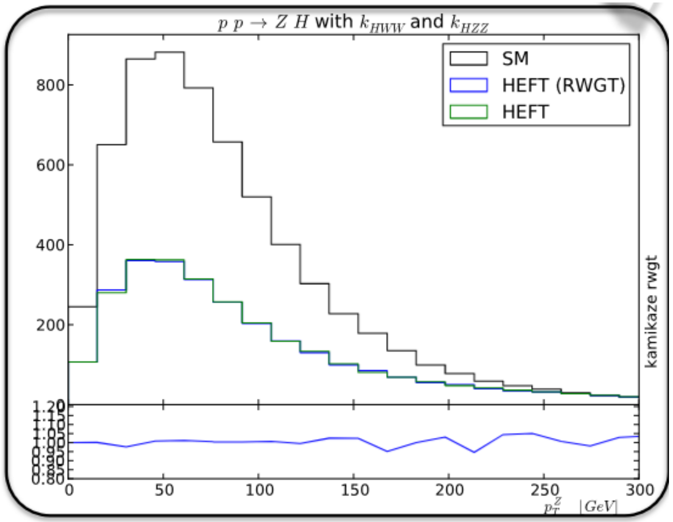
Full analysis chain performed (or at least cross checked) using EFT samples with different values of Wilson coefficients

- Automatically taking into account acceptance effects
- Possibility to optimise analysis towards EFT sensitivity

Option 2 – MC production

- Requiring full simulation (ME, PS & detector) for many values of each Wilson coefficients → very heavy
- Solution: reweighting
  - Generate one high statistics sample
  - Reweight events at truth level (matrix element ratios) to EFT predictions for several values of different Wilson coefficient (combinations)
  - Only need to run parton shower + detector simulation ones for these events
  - Initial samples should cover the same (or larger) phase space than alternative models
  - Need many events to avoid large statistical uncertainties (for weights > 1) and problems due to correlations



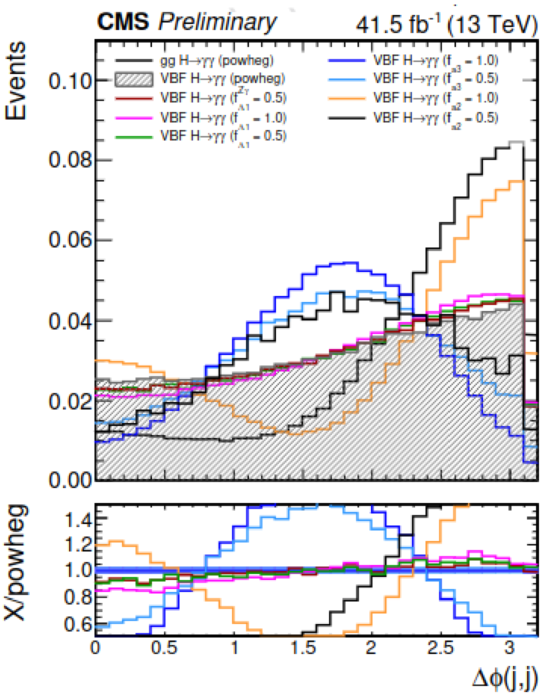


O. Mattelaer (https://indico.cern.ch/event/458670/#4-mc-ac-reweighting-and-nlo-ew)

Option 2 -- EFT optimised analyses

- Possibility to build analysis for optimal EFT sensitivity
  - Categorisation to target specific couplings
  - Design of observables with good separation of model hypothesis (“simple” kinematic observables, matrix element approximations, machine learning techniques…)

Example 1: kinemetic variable sensitive to Higgs CP nature



Example 2: Matrix Element Likelihood Approach

$$\mathcal{D}_{\text{alt}}(\boldsymbol{\Omega}) = \frac{\mathcal{P}_{\text{sig}}(\boldsymbol{\Omega})}{\mathcal{P}_{\text{sig}}(\boldsymbol{\Omega}) + \mathcal{P}_{\text{alt}}(\boldsymbol{\Omega})}$$

$$\mathcal{D}_{\text{int}}(\boldsymbol{\Omega}) = \frac{\mathcal{P}_{\text{int}}(\boldsymbol{\Omega})}{2\sqrt{\mathcal{P}_{\text{sig}}(\boldsymbol{\Omega})\ \mathcal{P}_{\text{alt}}(\boldsymbol{\Omega})}}$$

- “sig”: SM Higgs signal (possibly specific production mode)
- “alt”: background, production modes or BSM
- “int”: interference terms
- Ω: full kinematic description of process

Option 2 – limitations

- Perform analysis for descrete values of c_i; to fit these on data, need fine granularity or some interpolation (morphing)
  - Feasible for linear terms, varying 1 Wilson coefficient at the time
  - Becoming very difficult when including quadratic terms (with interference between different operators)
- Optimised analysis working well in case o a few, well defined operators impacting analysed process – not suited for global EFT fit
- Detailed analysis examples in dedicated lectures (flavour + Higgs / EW physics)

Building the EFT parametrisation

Option 1

- Simple approach – re-parametrisation of analysis results
- Fast to simulate – only require truth level simulation for a few Wilson coefficients values
- Might compromise on sensitivity due to non-optimised analysis regarding EFT effects
- Might require separate (ad-hoc) parametrisation of EFT acceptance compared to SM acceptance – can introduce large uncertainties or biases
- Often assume SM backgrounds or analysis results assumed to be uncorrelated to background modelling

Option 2

- Full consideration of EFT effects in analysis design to obtain optimal sensitivity
- Automaticly taking into account acceptance effects
- Heavy simulation (at detector level), limiting number of considered operators – partially solved using ME reweighting
- Need interpolation between simulated points – difficult to treat quadratic terms (interference between EFT operators)
- Potentially more complicated to treat interplay between signal and backgrounds

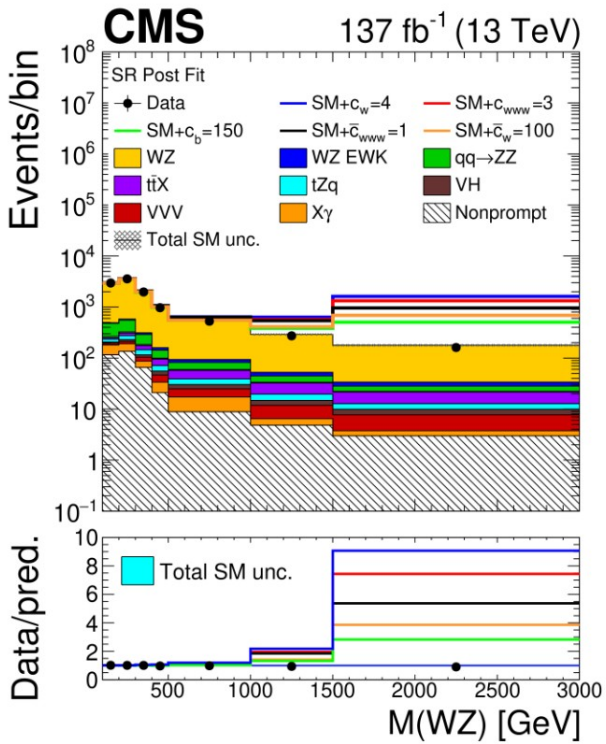
Making physics with EFT

- Up to now, have measured some physics quantities and re-parametrised in terms of EFT – on a very technical basis…
- Main goal: learn something about physics!
- Need to ask several questions:
  - What is the BSM scale that we are sensitive to? Is the EFT approach valid in the regime we are probing? ↔ choice of new physics scale Λ
  - Which EFT operators should be considered? How do we treat correlations between them? ↔ choice of fit parameters – more details in global EFT fit discussion
  - What do these results tell us in terms of “real” physics models?

Choice of BSM scale Λ

- Main assumption in EFT formalism: $c/\Lambda^2 \ll 1$ → naively, best to consider higher scale & small coupling
- Often Λ=1TeV; historical choice from flavour physics (studying meson decays with low $q^2 \sim 10$ GeV^2)
- Larger impact from BSM at “not so large” scale → better sensitivity
- But often, high energy tails most affected by EFT; containing events with high q^2

Example: WZ production @ LHC



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Content

- Ingredients for EFT fits
  - Input measurements – experiments, observables, etc.
- EFT constraints from experimental data
  - Setup: model, basis, input parameters, symmetries
  - EFT in the analysis: simulation and parametrisation
  - Working with a real detector
  - Validity considerations and theory uncertainties: limitations and work arounds
- Global EFT fits
  - Benefits and challenges of combined fit
  - Limitations and perspectives for EFT fits – towards HL-LHC and beyond

Note: This lecture is quite technical; more details on application of these concepts in dedicated sessions (EFT in Higgs + EW and in flavour physics)

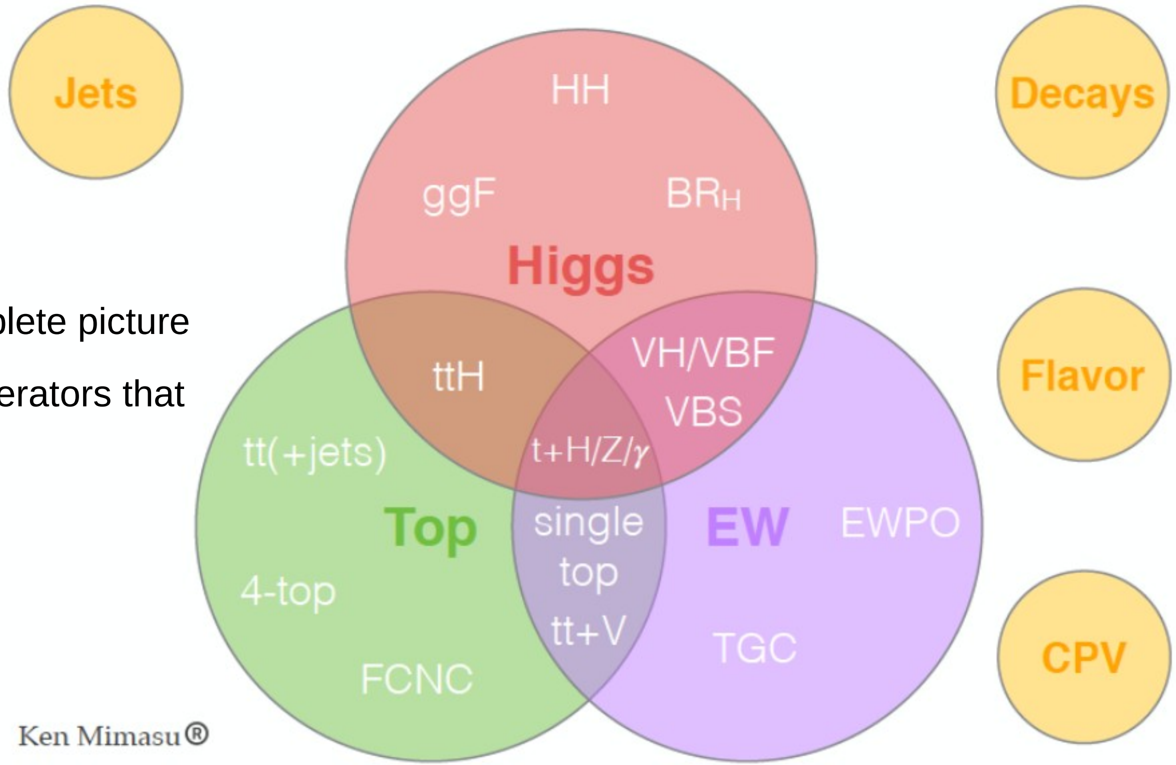
Why doing a global fit?

BSM can be in several EFT operators at the same time

→ should fit simultaneously all EFT operators to ensure model-independence

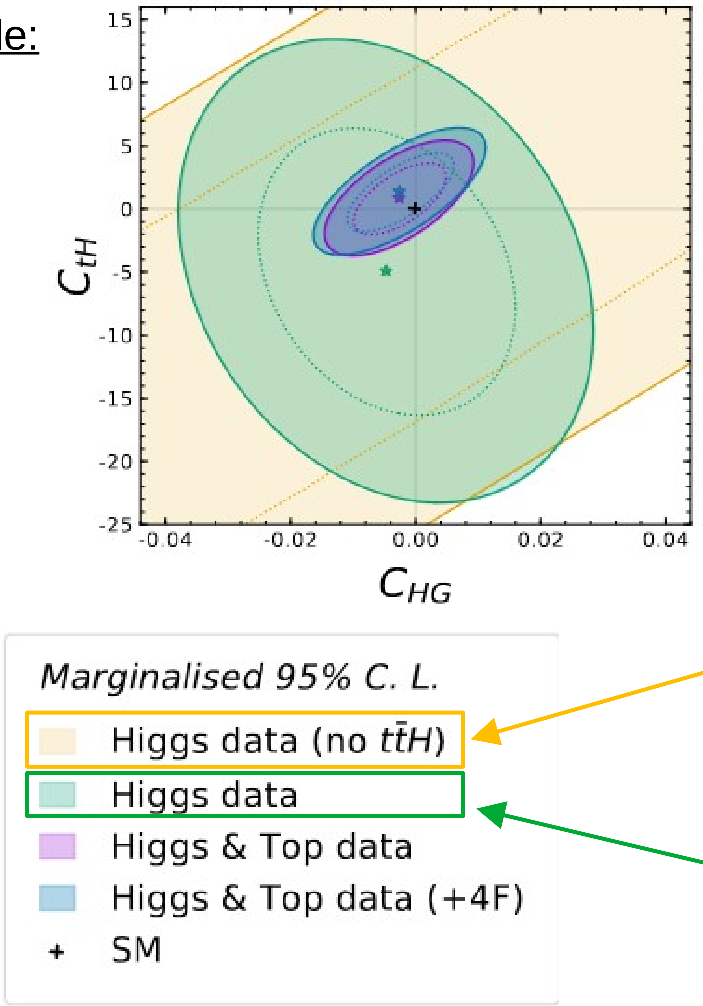
Use complementarity of physics processes:

- sensitive to different EFT operators – get complete picture
- overlapping couplings – help to decorrelate operators that affect single processes in a similar way



Decorrelating operators through combination

Example:



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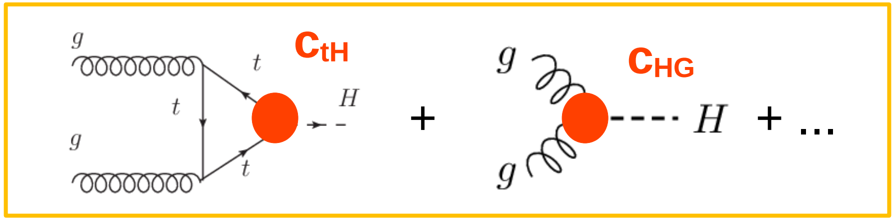
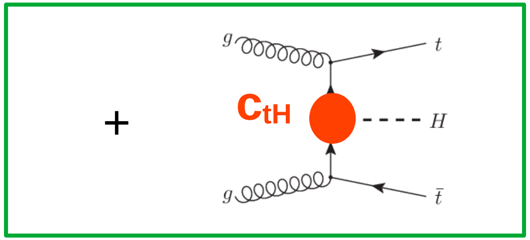
c_{tH}: top Yukawa coupling modifier

c_{HG}: effective Higgs-gluon coupling





Global EFT fit – a broad picture

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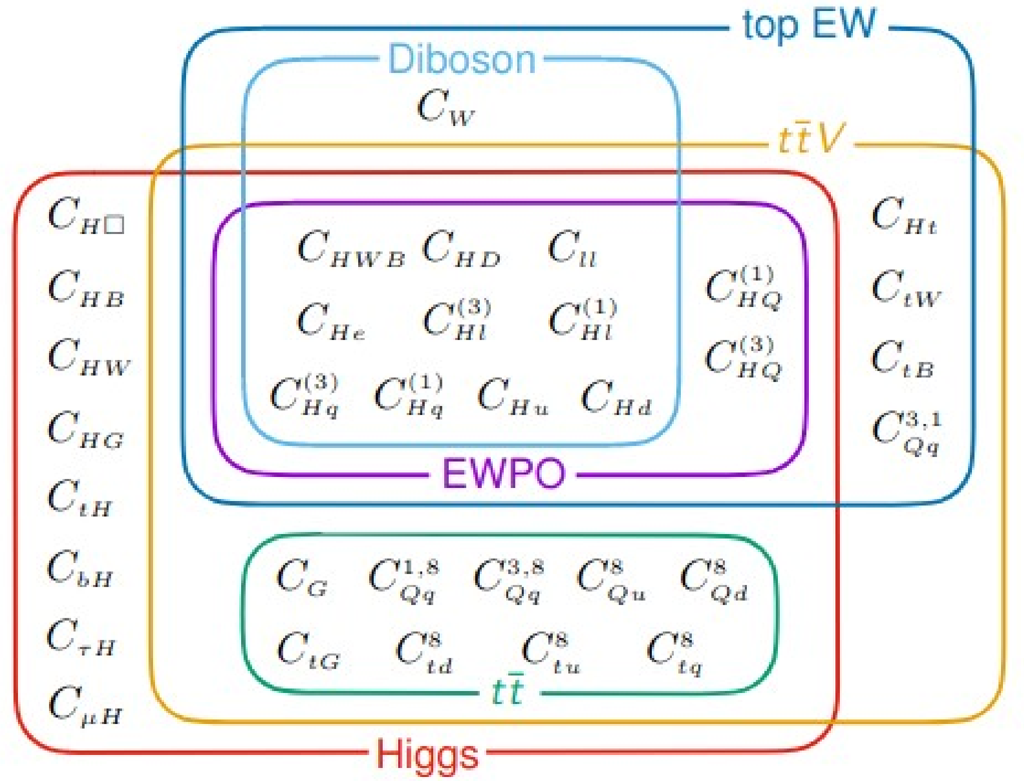
- Input: as many as possible orthogonal measurements from different experiments:
  - EW precision observables
  - Diboson measurements from LEP & LHC
  - Higgs measurements from LHC Run 1+2
  - Top measurements from Tevatron & LEP
- Good complementarity of analyses to constrain Wilson coefficients



Global EFT fit – flat directions

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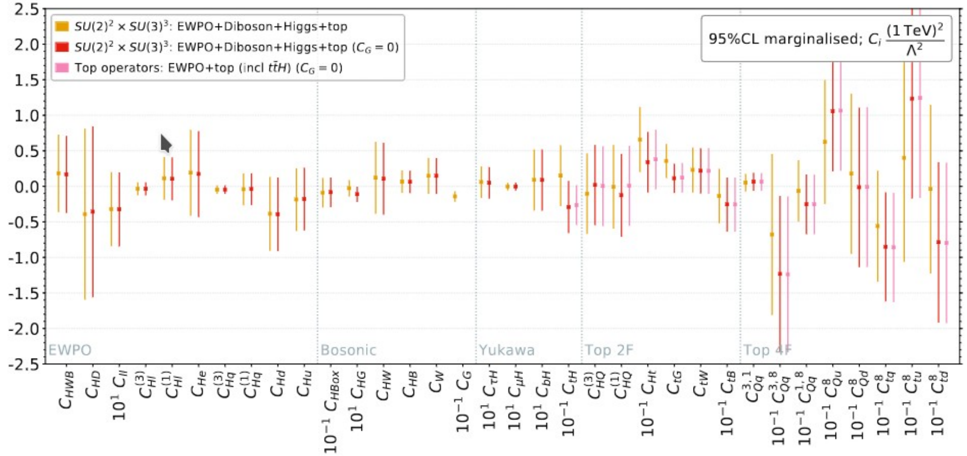
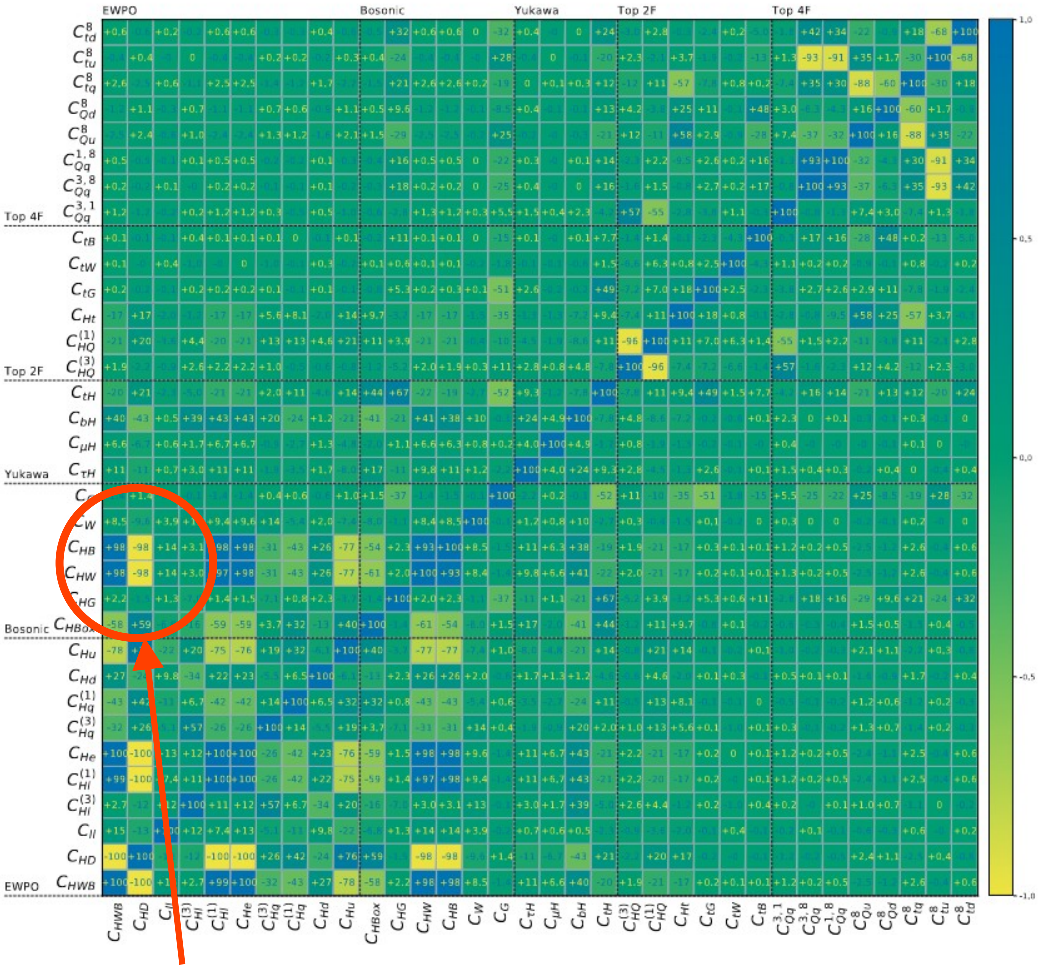
Constraining a large set of operators simultaneously



Still, large correlations between some operators: so-called flat directions, where we are only sensitive to linear combinations of several operators

Solution: principle component analysis
-- more details in Higgs+EW lecture



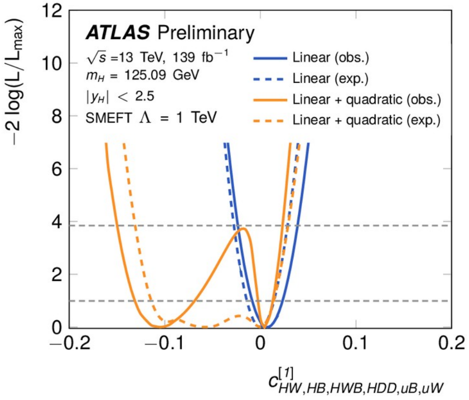
Example: these cHB and cHW are only constrained from bosonic Higgs couplings

Reasons to do global EFT fit within experiments

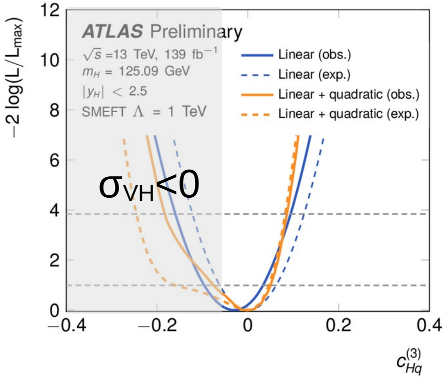
- Correlation of measured signal with background processes
  - Usually assume background to be SM-like in EFT fits -- might be affected by BSM as well
  - Signal and background measurements might be correlated (e.g. VH→llbb, dominant systematics from background modeling)
- Orthogonality between analyses
  - Several analyses can target overlapping signal, i.e. same signal but optimised for different measurement, or one analysis is subset of the other
  - Backgrounds of one analysis might be signals of another analysis
  - Can be avoided at experiment level from beginning on or statistical correlations can be inferred through bootstrapping
  - Might happen at the price of sensitivity – choice to be made
- Proper correlation of systematic uncertainties between analyses (e.g. jet energy scale calibration is the same in all analyses containing jets)

EFT limitations and uncertainties

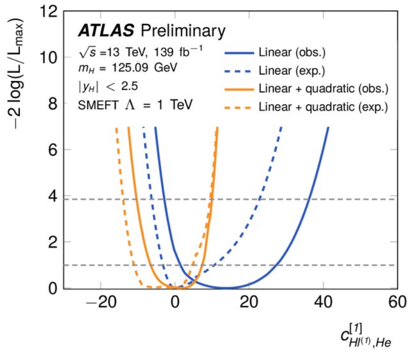
Quadratic terms can be important; interpretation?
→ also check linear dim-8 -- same order in $1/\Lambda^2$



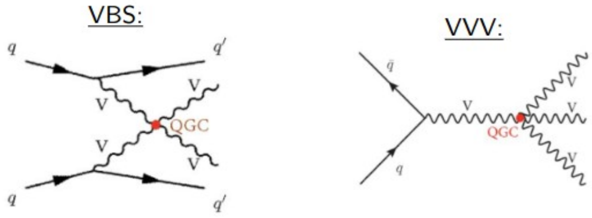
Linear-only parametrisation might lead to unphysical, negative cross section predictions



Which operators can be safely ignored?
→ 1σ bound can be far outside valid range
→ significant correlation to other, thus can not be ignored



Some BSM occuring at dim-8, e.g. aQGC
→ how to make consistent interpretation in global fit?



Huge effort going on in theory + experiment to solve these problems, calculate uncertainties, etc.

Conclusion

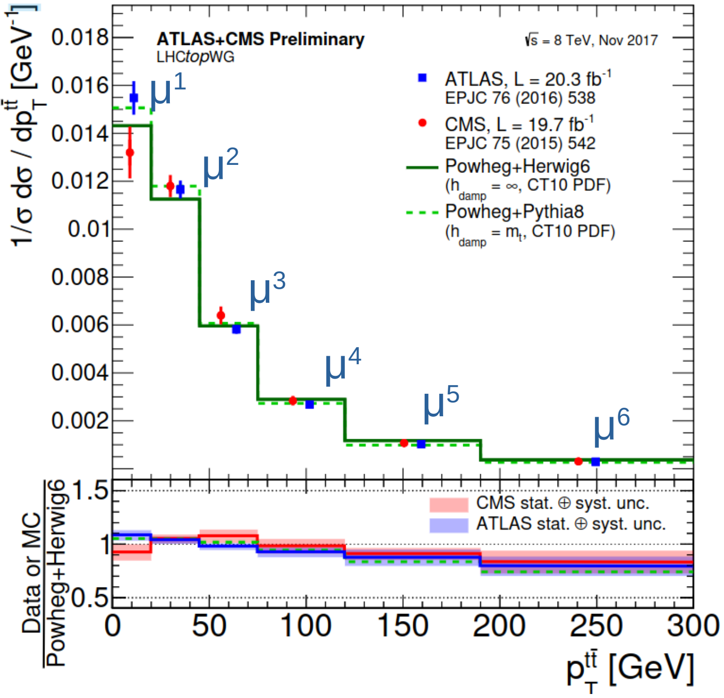
- EFT interpretations becoming more and more important at LHC and beyond
- Allow to search for new physics in model independent way
  - Including constraints from all fields
  - Without probing a concrete model – (mostly) any model can be matched to EFT results
- Active field – many ongoing developments (both from theory and experiment)
  - A lot of exchange ongoing to optimise and synchronise efforts to learn as much as possible from the available data
  - Some unsolved limitations – need to find solutions and sometimes be pragmatic

THANKS FOR YOUR ATTENTION

BACKUP

Option 1 -- application

Example: ttbar production @ LHC



Input measurement:

Differential cross section as a function of p_T of ttbar system

- cross section in each p_T^{tt} bin (+ uncertainty)
- possible correlation between bins

$$\chi^2 = (P-\mu)\ C^{-1}\ (P-\mu)^T$$

Measurement covariance matrix

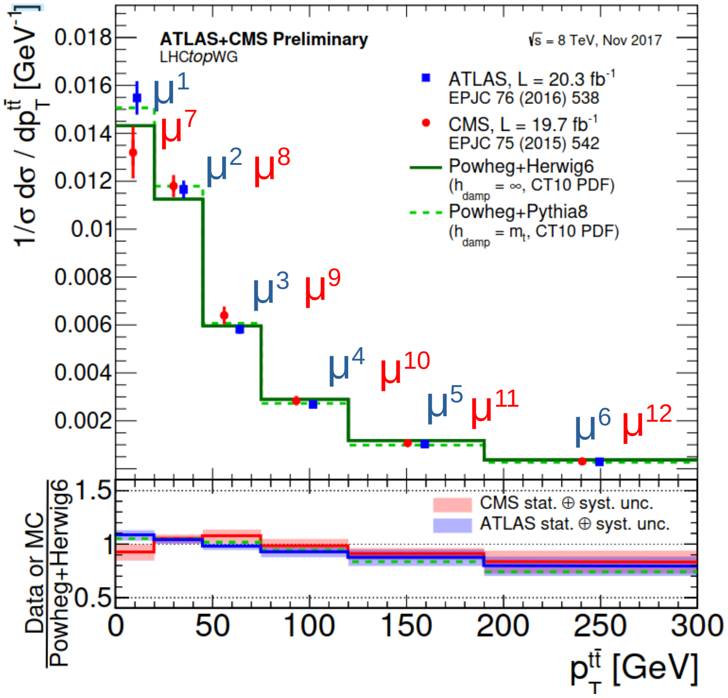
Measurement vector

Prediction vector:

$$P^i = \sigma_{ttbar}{}^i \ x \left(1 + \sum_i A_i c_i + \sum_{ij} B_{ij} c_i c_j\right)$$

Option 1 -- application

Example: ttbar production @ LHC



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Measurement covariance matrix

Measurement vector

Prediction vector:

$$P^i = \sigma_{ttbar}{}^i \ x \left(1 + \sum_i A_i c_i + \sum_{ij} B_{ij} c_i c_j\right)$$

Straight forward to combine, e.g., ATLAS & CMS results, assuming no correlation between experiments / measurements