Report on Experimental Measurements and Observables for EFT Interpretations

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based on recent WG note by

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December 2, 2022

5th General Meeting of LHC EFT WG
CERN, Geneva, Switzerland

Area 3: Experimental Measurements and Observables

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(theory) (ATLAS) (CMS)

CERN-LHCEFTWG-2022-001
CERN-LPCC-2022-05

November 15, 2022

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- Started with dedicated meetings

  kick-off 11 January 2021

- Several iterations

  LHCEFTWG-2022-001

- Submitted to arXiv

  15 November 2022

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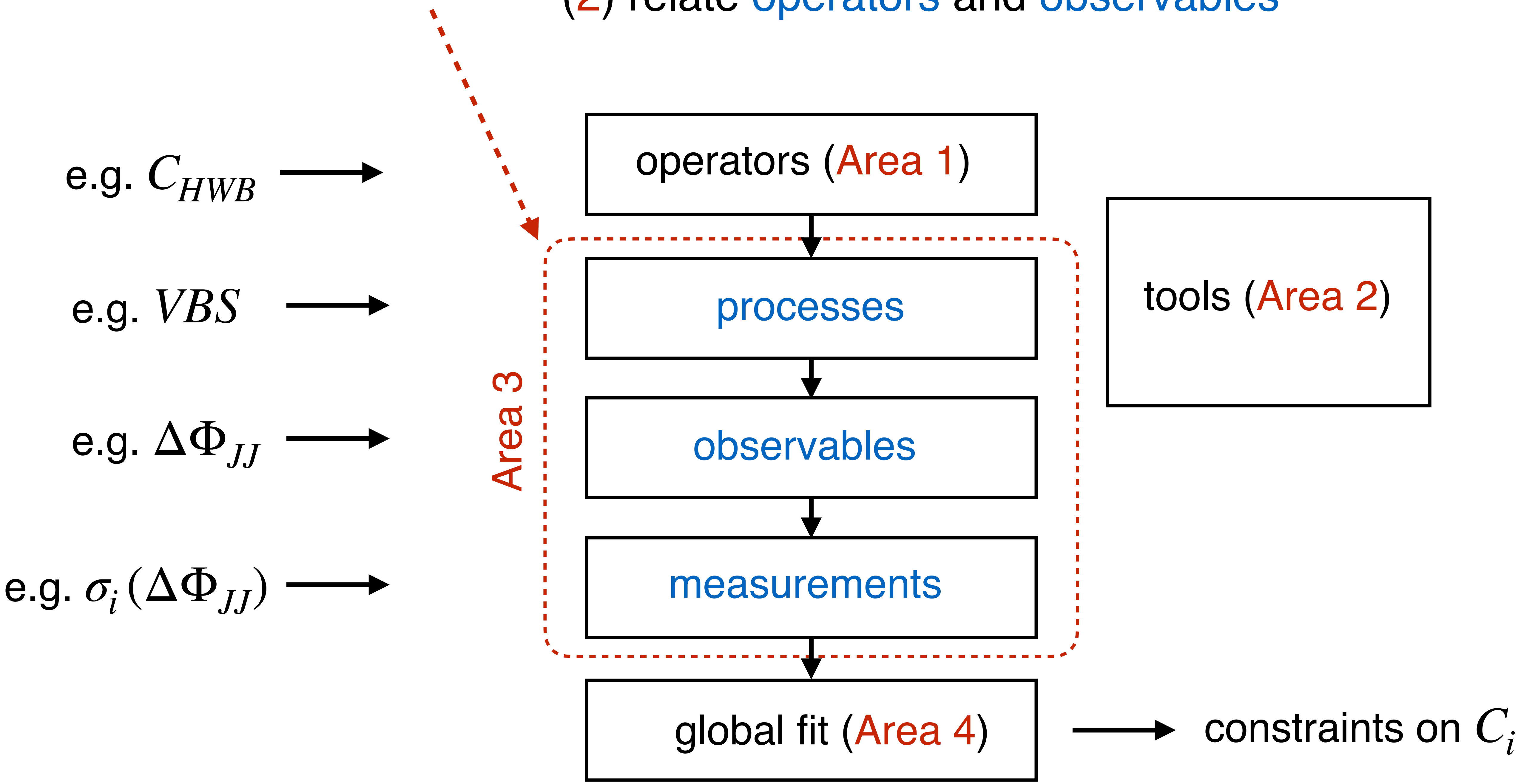
Abstract
The LHC effective field theory working group gathers members of the LHC experiments and the theory community to provide a framework for the interpretation of LHC data in the context of EFT. In this note we discuss experimental observables and corresponding measurements in analysis of the Higgs, top, and electroweak data at the LHC. We review the relationship between operators and measurements relevant for the interpretation of experimental data in the context of a global SMEFT analysis. One of the goals of ongoing effort is bridging the gap between theory and experimental communities working on EFT, and in particular concerning optimised analyses. This note serves as a guide to experimental measurements and observables leading to EFT fits and establishes good practice, but does not present authoritative guidelines how those measurements should be performed.

Area 3: Experimental Measurements and Observables

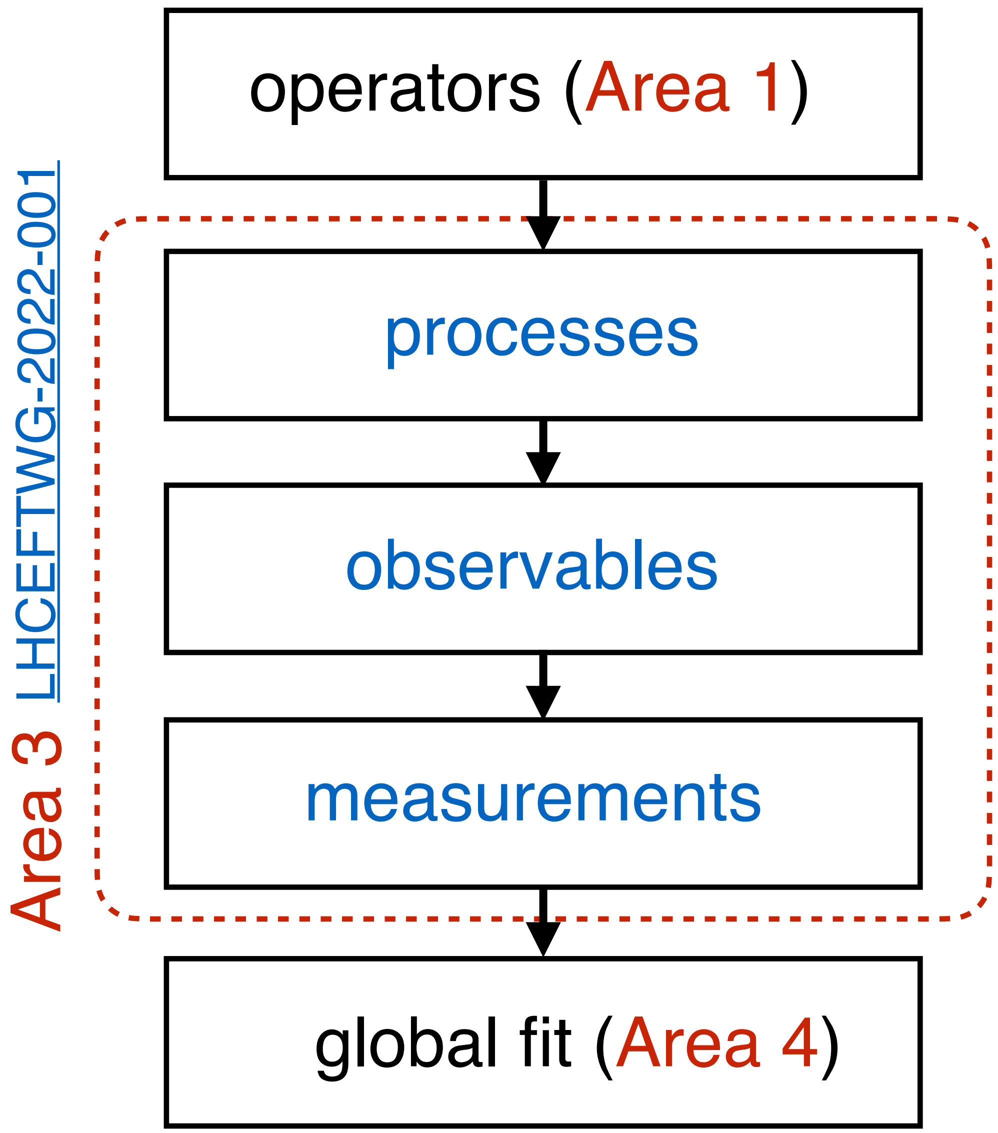
Area 3: measurements and observables

(1) define observables and measurements

(2) relate operators and observables



Outline



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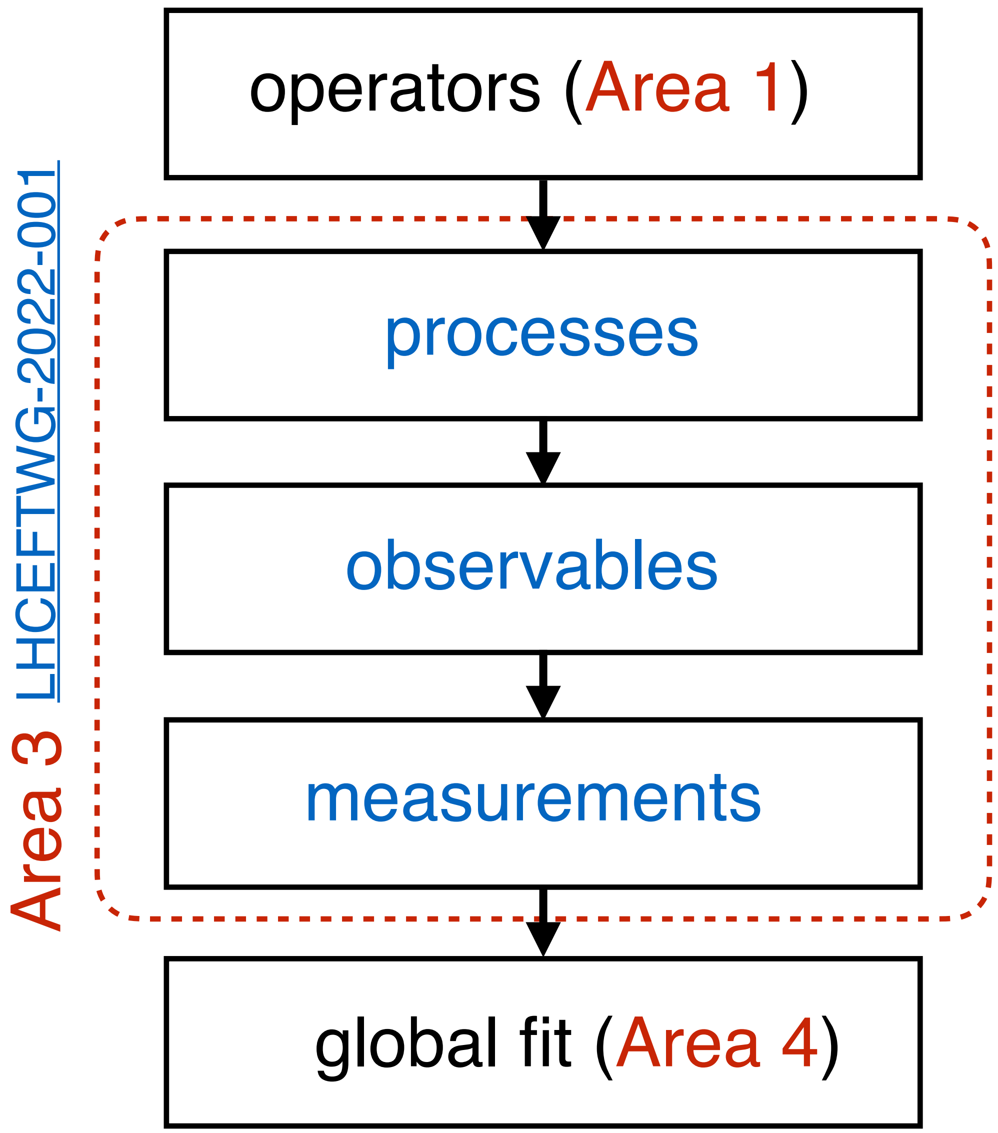
Outline



Chapter III

(2) relate operators and observables

Chapter II

(1) define observables and measurements

touched in Ch.II, but need “ future work ”

communicate measurements

(1) Measurements and Observables

measurements ← observables ← processes

$$\mathscr{P}(\vec{x}_{\rm reco}\,|\,\vec{\theta}) = \int d\vec{x}_{\rm part} \quad p(\vec{x}_{\rm reco}\,|\,\vec{x}_{\rm part}) \quad \mathscr{P}(\vec{x}_{\rm part}\,|\,\vec{\theta})$$

reco observables

$\vec{x}_{\rm reco}$

measurement

parton shower

detector effects

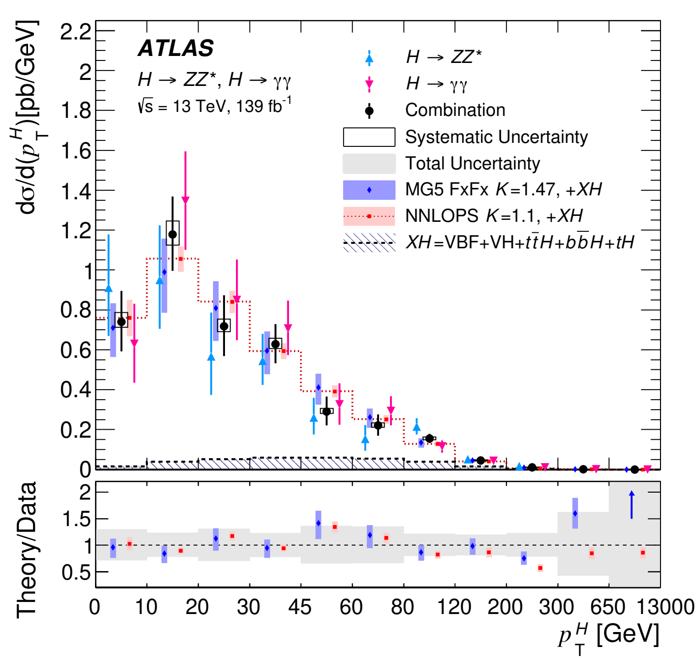
reconstruction

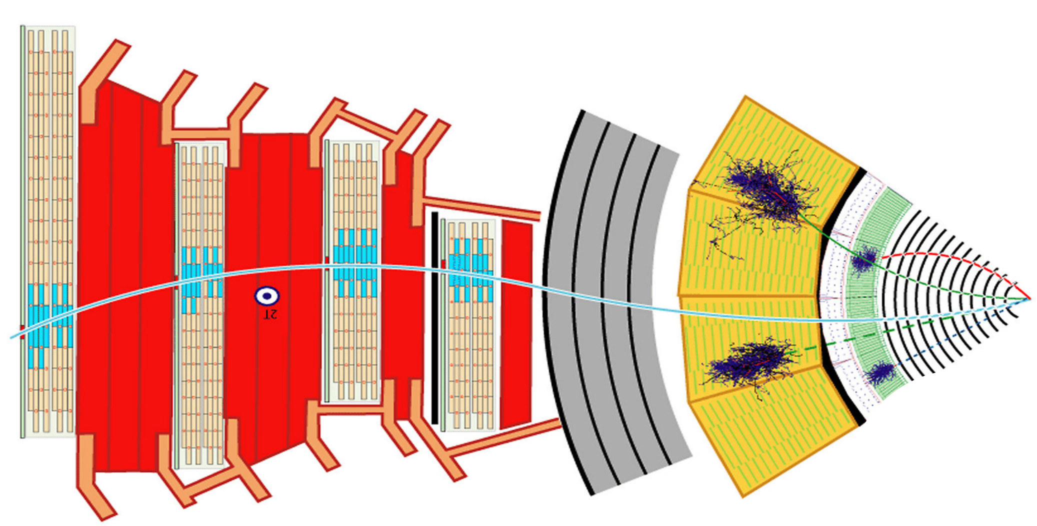
hard process

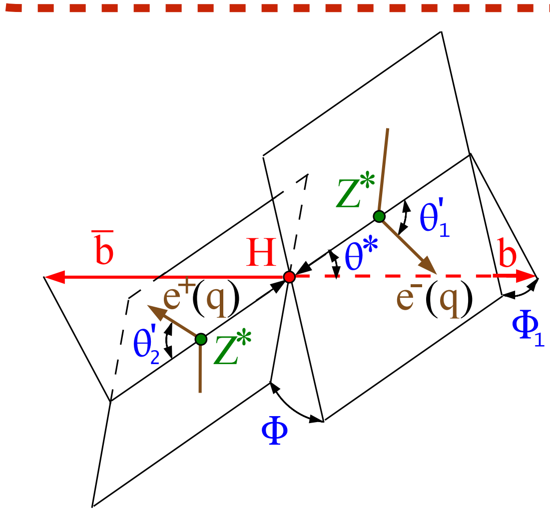
matrix elements

EFT params $\vec{\theta}$

parton mom $\vec{x}_{\rm part}$

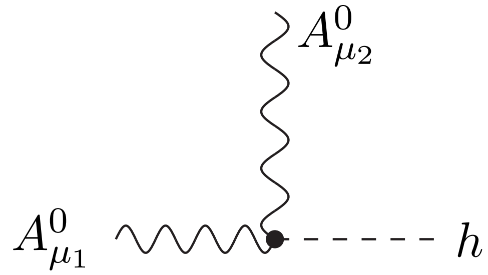






(2) Operators and Processes / Observables

- Feynman rules for SMEFT (Area 1)
  - relate processes and operators



$$
\begin{aligned}
&+\frac{4i\bar{g}'^2 v}{\bar{g}^2+\bar{g}'^2} C^{\varphi W}\left(p_1^{\mu_2} p_2^{\mu_1} - p_1\cdot p_2 \eta_{\mu_1\mu_2}\right)\\
&+\frac{4i\bar{g}^2 v}{\bar{g}^2+\bar{g}'^2} C^{\varphi B}\left(p_1^{\mu_2} p_2^{\mu_1} - p_1\cdot p_2 \eta_{\mu_1\mu_2}\right)\\
&-\frac{4i\bar{g}\bar{g}' v}{\bar{g}^2+\bar{g}'^2} C^{\varphi WB}\left(p_1^{\mu_2} p_2^{\mu_1} - p_1\cdot p_2 \eta_{\mu_1\mu_2}\right)\\
&+\frac{4i\bar{g}'^2 v}{\bar{g}^2+\bar{g}'^2} C^{\varphi\widetilde{W}} p_1^{\alpha_1} p_2^{\beta_1}\epsilon_{\mu_1\mu_2\alpha_1\beta_1} + \frac{4i\bar{g}^2 v}{\bar{g}^2+\bar{g}'^2} C^{\varphi\widetilde{B}} p_1^{\alpha_1} p_2^{\beta_1}\epsilon_{\mu_1\mu_2\alpha_1\beta_1}\\
&-\frac{4i\bar{g}\bar{g}' v}{\bar{g}^2+\bar{g}'^2} C^{\varphi\widetilde{W}B} p_1^{\alpha_1} p_2^{\beta_1}\epsilon_{\mu_1\mu_2\alpha_1\beta_1}
\end{aligned}
$$

arXiv:1704.03888

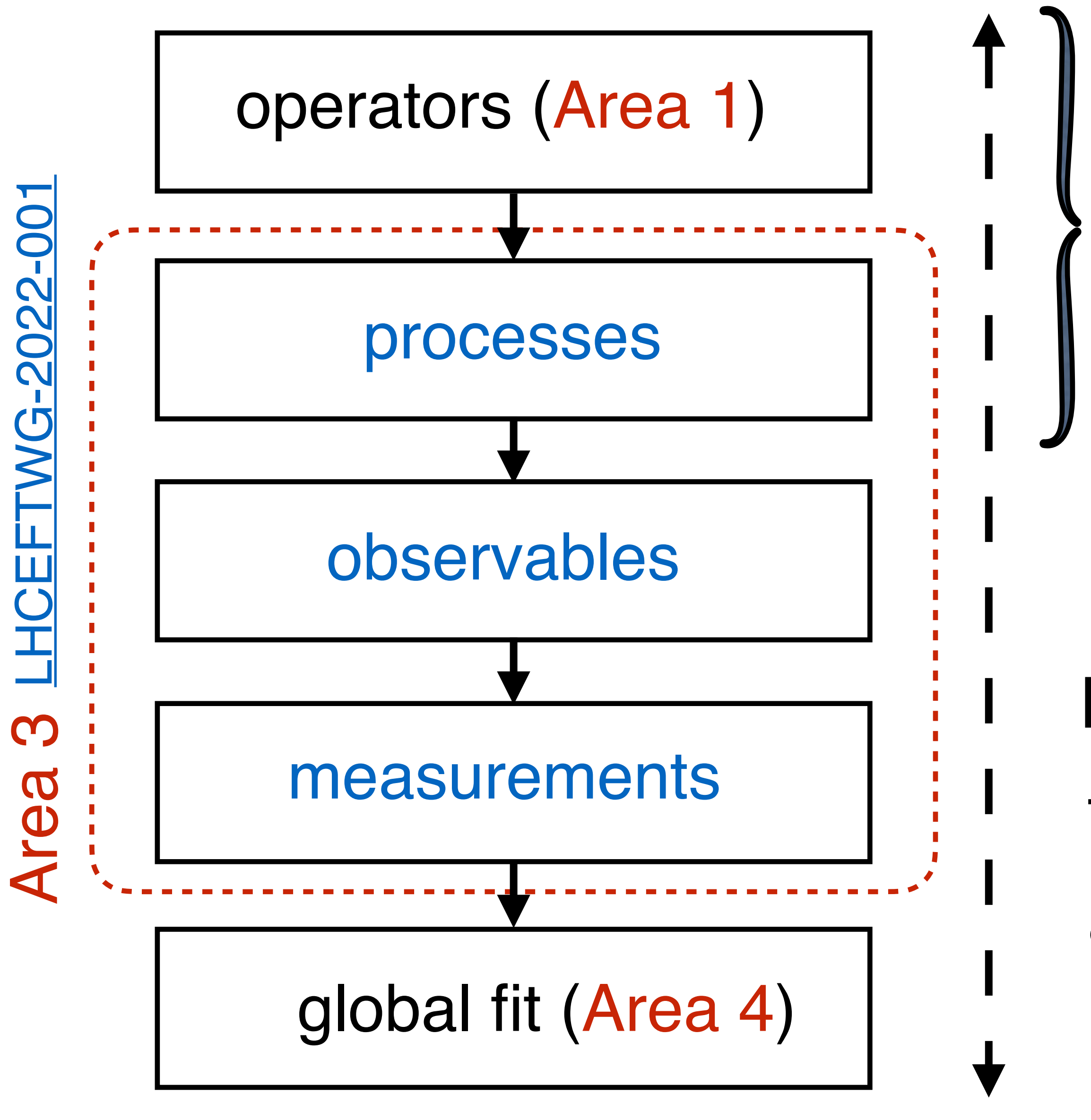
- In the end relate to observables $\vec{x}_{\text{reco}}$
  - kinematic effects
  - experimental choice

  } affect sensitivity to EFT parameters $\vec{\theta}$

$$
\mathscr{P}(\vec{x}_{\text{reco}}\,|\,\vec{\theta}) \propto \mathscr{P}_0(\vec{x}_{\text{reco}}) + \sum_k \left(\frac{2\theta_k}{\theta_0}\right)\mathscr{P}_{0k}(\vec{x}_{\text{reco}}) + \sum_k \left(\frac{\theta_k}{\theta_0}\right)^2 \mathscr{P}_k(\vec{x}_{\text{reco}}) + \sum_{i<j}\left(\frac{2\theta_i\theta_j}{\theta_0^2}\right)\mathscr{P}_{ij}(\vec{x}_{\text{reco}})
$$

SM — linear terms — quadratic terms

Part 2 (Chapter III)



Lets discuss this connection

But we may need the full chain
to understand sensitivity to operators
assuming reasonably optimal analysis

(III) Operators and Measurements

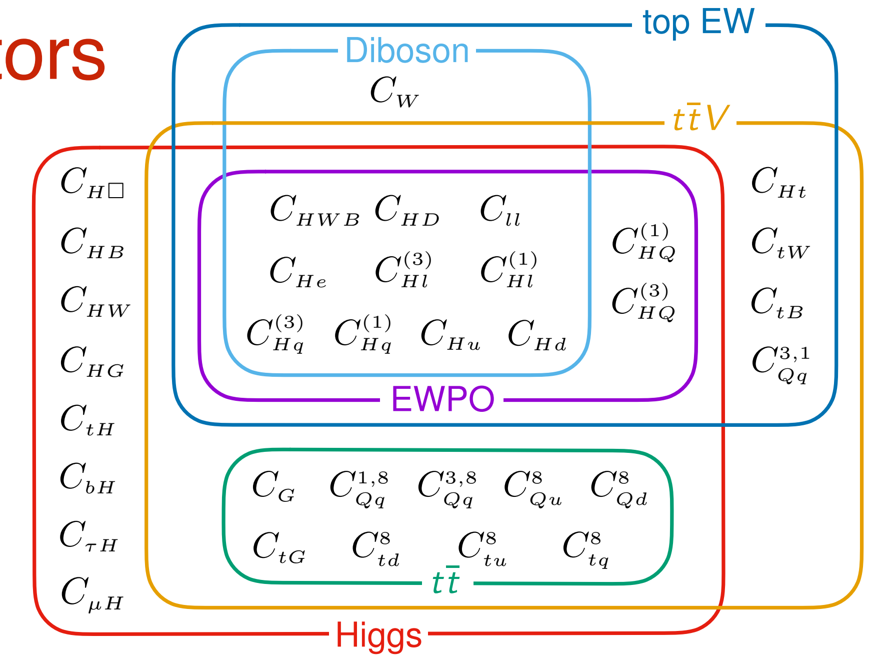
- Which measurements are sensitive to which operators

  based on SMEFiT and Fitmaker global fits

  — limited to the choice of 20–50 operators

  (e.g. only heavy flavor Yukawa couplings)

  Note: separate note on flavor assumptions…



— limited to the choice of ATLAS+CMS inclusive and differential measurements

- Extract sensitivity:

  — Linear dependence on operators

  — Fisher information matrix

  — Global fit with one operator

Category	Processes	$n_{\rm dat}$
Top quark production	$t\bar{t}$ (inclusive)	94
	$t\bar{t}Z$, $t\bar{t}W$	14
	single top (inclusive)	27
	tZ, tW	9
	$t\bar{t}t\bar{t}$, $t\bar{t}b\bar{b}$	6
	Total	**150**
Higgs production and decay	Run I signal strengths	22
	Run II signal strengths	40
	Run II, differential distributions & STXS	35
	Total	**97**
Diboson production	LEP-2	40
	LHC	30
	Total	**70**
Baseline dataset	**Total**	**317**

(III) Operators and Measurements

	4H	AC	Hdiff	HrunI	HrunII	VV	t	tV	tt	ttV
$c_{\varphi Q}^{(-)}$					21.4					64.4
$c_{\varphi Q}^{3}$							71.0	23.2		
$c_{\varphi t}$					10.0					83.9
c_{tW}			16.7	15.8	59.5					
c_{tG}			23.7		24.8				41.4	
$c_{t\varphi}$			43.2	14.7	42.1					
c_{tZ}			18.2	17.1	64.7					
c_{QQ}^{1}	100.0									
c_{QQ}^{8}	100.0									
c_{Qt}^{1}	100.0									
c_{Qt}^{8}	100.0									
c_{tt}^{1}	100.0									
$c_{qq}^{1,8}$		33.1							39.4	26.6
$c_{qq}^{1,1}$		73.6							26.0	
$c_{qq}^{8,3}$		49.1					16.6		10.1	23.6
$c_{qq}^{1,3}$							83.9	16.1		
c_{qt}^{8}		27.4							31.4	39.5
c_{qt}^{1}		77.9							21.9	
c_{ut}^{8}		54.4							42.8	
c_{ut}^{1}		79.6							20.1	
c_{qu}^{8}		58.5							31.1	
c_{qu}^{1}		61.3							38.6	
c_{dt}^{8}		42.6							52.4	
c_{dt}^{1}		57.9							41.7	
c_{qd}^{8}		35.5							48.2	13.3
c_{qd}^{1}		60.9							38.9	
$c_{\varphi G}$			43.4	14.9	41.7					
$c_{\varphi B}$			18.2	17.2	64.7					
$c_{\varphi W}$			18.2	17.2	64.5					
$c_{\varphi WB}$			19.3	17.0	63.5					
$c_{\varphi \Box}$			43.7	16.6	39.7					
$c_{\varphi D}$			70.2		14.4					
$c_{b\varphi}$			14.7	22.7	62.5					
$c_{c\varphi}$			13.3	23.2	63.5					
$c_{\tau\varphi}$				38.8	60.4					
c_{WWW}						100.0				

- Fisher information matrix $I_{ij}(\boldsymbol{c}) = -\mathrm{E}\left[\frac{\partial^2 \ln f(\boldsymbol{\sigma}_{\exp}|\boldsymbol{c})}{\partial c_i \partial c_j}\right]$

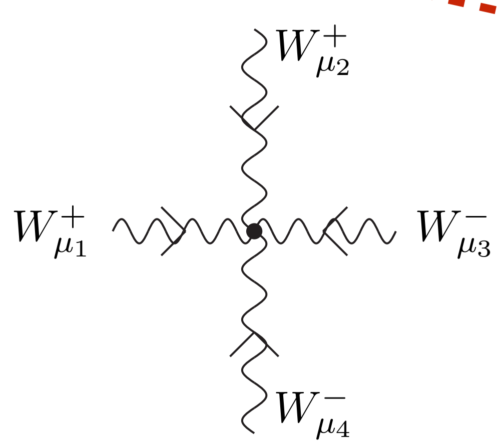
  (SMEFiT approach)

two-fermion operators from Higgs / top data

four-fermion operators from top data

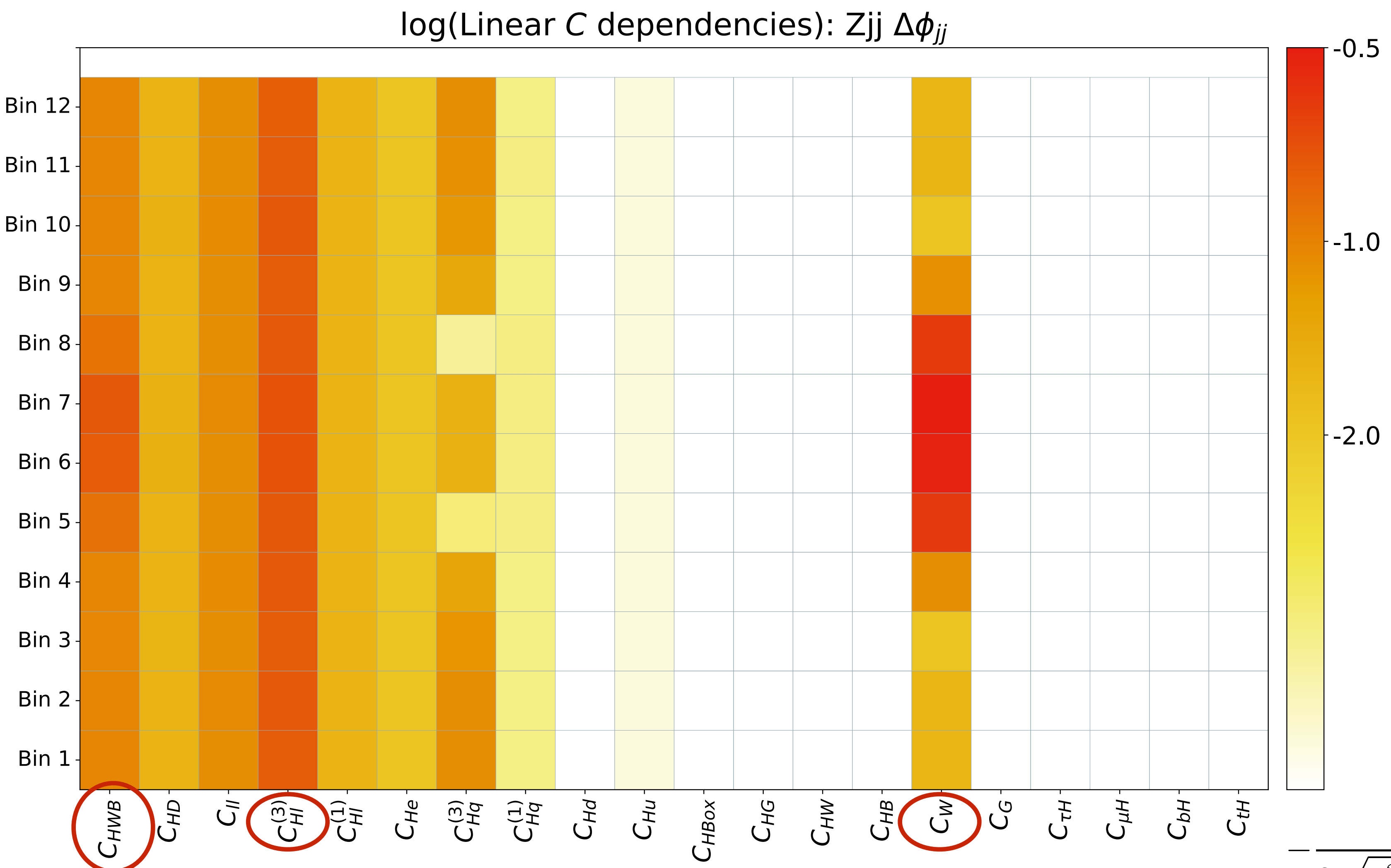
Higgs operators

VV data



$$
\begin{aligned}
&-i\bar{g}^2\left(\eta_{\mu_1\mu_4}\eta_{\mu_2\mu_3} + \eta_{\mu_1\mu_3}\eta_{\mu_2\mu_4} - 2\eta_{\mu_1\mu_2}\eta_{\mu_3\mu_4}\right)\\
&+ 6i\bar{g}C^W\Big(\eta_{\mu_1\mu_3}(p_3^{\mu_2}p_1^{\mu_4} - p_1^{\mu_2}p_3^{\mu_4} - p_4^{\mu_2}p_1^{\mu_4} - p_3^{\mu_2}p_2^{\mu_4})\\
&+ \eta_{\mu_1\mu_4}(p_4^{\mu_2}p_1^{\mu_3} - p_1^{\mu_2}p_4^{\mu_3} - p_3^{\mu_2}p_1^{\mu_3} - p_4^{\mu_2}p_2^{\mu_3})\\
&+ \eta_{\mu_2\mu_3}(p_3^{\mu_1}p_2^{\mu_4} - p_2^{\mu_1}p_3^{\mu_4} - p_4^{\mu_1}p_2^{\mu_4} - p_3^{\mu_1}p_1^{\mu_4})\\
&+ \eta_{\mu_2\mu_4}(p_4^{\mu_1}p_2^{\mu_3} - p_2^{\mu_1}p_4^{\mu_3} - p_3^{\mu_1}p_2^{\mu_3} - p_4^{\mu_1}p_1^{\mu_3})\\
&- \eta_{\mu_1\mu_2}(p_4^{\mu_3}(p_3+p_4)^{\mu_4} + (p_3+p_4)^{\mu_3}p_3^{\mu_4})\\
&- \eta_{\mu_3\mu_4}(p_2^{\mu_1}(p_1+p_2)^{\mu_2} + (p_1+p_2)^{\mu_1}p_1^{\mu_2})\\
&+ \eta_{\mu_1\mu_3}\eta_{\mu_2\mu_4}(p_1\cdot p_4 + p_2\cdot p_3) + \eta_{\mu_1\mu_4}\eta_{\mu_2\mu_3}(p_1\cdot p_3 + p_2\cdot p_4)\\
&- \eta_{\mu_1\mu_2}\eta_{\mu_3\mu_4}(p_1\cdot p_3 + p_1\cdot p_4 + p_2\cdot p_3 + p_2\cdot p_4)\Big)
\end{aligned}
$$

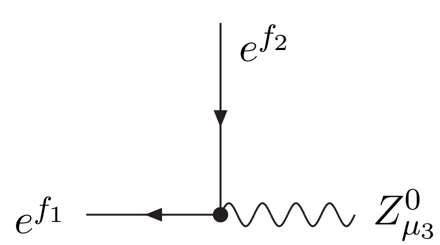
(III) Operators and Measurements



- Linear dependence

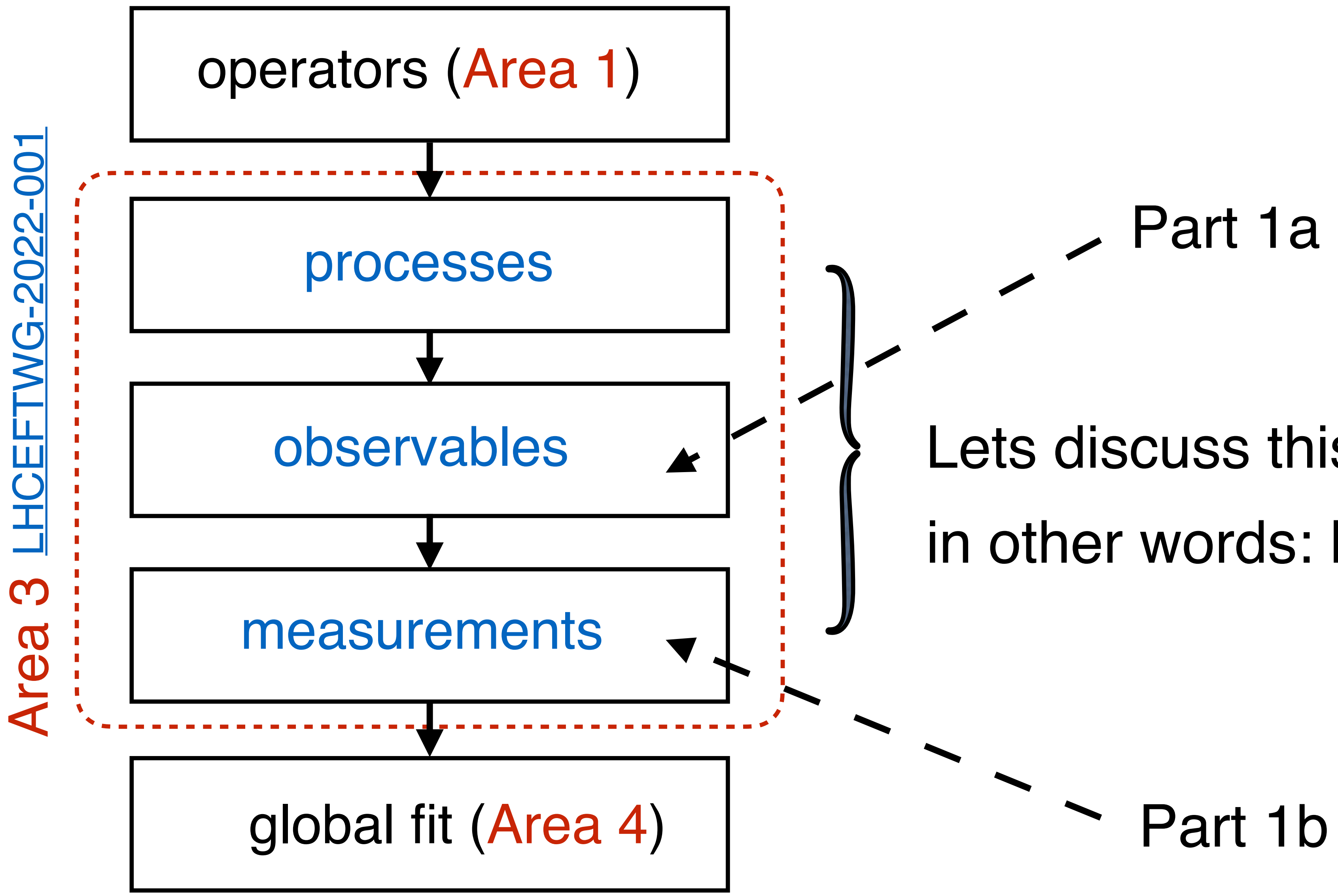
  (Fitmaker approach)

$$\mu_X \equiv \frac{X}{X_{SM}} = 1 + \sum_i a_i^X \frac{C_i}{\Lambda^2} + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)$$



$$
\begin{aligned}
&-\frac{i}{2\sqrt{\bar{g}^2+\bar{g}'^2}}\delta_{f_1 f_2}\left(\left(\bar{g}'^2-\bar{g}^2\right)\gamma^{\mu_3}P_L + 2\bar{g}'^2\gamma^{\mu_3}P_R\right)\\
&+\frac{i\bar{g}\bar{g}'v^2}{2\left(\bar{g}^2+\bar{g}'^2\right)^{3/2}}\delta_{f_1 f_2}C^{\varphi WB}\left(\left(\bar{g}'^2-\bar{g}^2\right)\gamma^{\mu_3}P_L - 2\bar{g}^2\gamma^{\mu_3}P_R\right)\\
&+\frac{\sqrt{2}\bar{g}v}{\sqrt{\bar{g}^2+\bar{g}'^2}}p_3^\nu\left(C^{eW*}_{f_2 f_1}\sigma^{\mu_3\nu}P_L + C^{eW}_{f_1 f_2}\sigma^{\mu_3\nu}P_R\right)\\
&+\frac{\sqrt{2}\bar{g}'v}{\sqrt{\bar{g}^2+\bar{g}'^2}}p_3^\nu\left(C^{eB*}_{f_2 f_1}\sigma^{\mu_3\nu}P_L + C^{eB}_{f_1 f_2}\sigma^{\mu_3\nu}P_R\right)\\
&+\frac{1}{2}iv^2\sqrt{\bar{g}^2+\bar{g}'^2}C^{\varphi l1}_{f_1 f_2}\gamma^{\mu_3}P_L + \frac{1}{2}iv^2\sqrt{\bar{g}^2+\bar{g}'^2}C^{\varphi l3}_{f_1 f_2}\gamma^{\mu_3}P_L\\
&+\frac{1}{2}iv^2\sqrt{\bar{g}^2+\bar{g}'^2}C^{\varphi e}_{f_1 f_2}\gamma^{\mu_3}P_R
\end{aligned}
$$

Part 1 (Chapter II)



Lets discuss this connection

in other words: how to build a data analysis (on LHC)

(II) Observables (1a)

$$\mathscr{P}(\vec{x}_{\rm reco}\,|\,\vec{\theta}) = \int d\vec{x}_{\rm part}\; p(\vec{x}_{\rm reco}\,|\,\vec{x}_{\rm part})\; \mathscr{P}(\vec{x}_{\rm part}\,|\,\vec{\theta})$$

reco observables

Part 1a

- typical SM observables (to suppress background)
- EFT-sensitive observables (e.g. angular, q^2, etc)
- optimized observables (matrix element, machine learning)
- full accessible information $\vec{x}^{\rm full}_{\rm reco}$ (e.g. all four-vectors)

Example: VBF $\Delta\Phi_{JJ}$ (EFT-sensitive)

EFT:

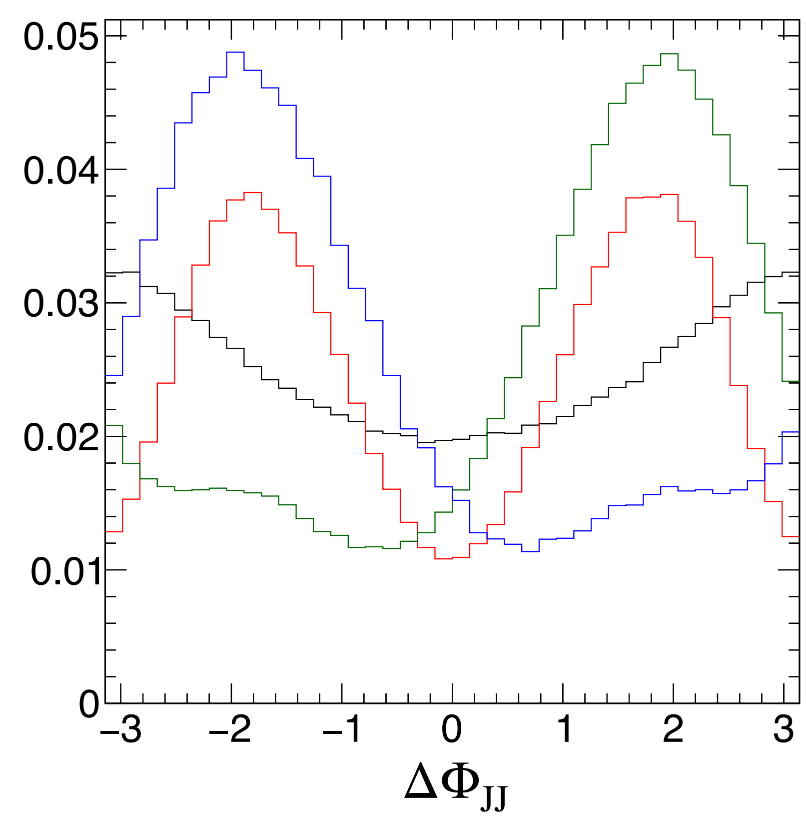
- new tensor structures
- higher q dimensions

SM — $(\theta_0, 0\,)$

CP-odd — $(\,0\,, \theta_1)$

+mix — $(\theta_0, +\theta_1)$

- mix — $(\theta_0, -\theta_1)$



(II) Observables (1a)

$$\mathscr{P}(\vec{x}_{\mathrm{reco}}\,|\,\vec{\theta}) \;=\; \int \mathrm{d}\vec{x}_{\mathrm{part}} \quad p(\vec{x}_{\mathrm{reco}}\,|\,\vec{x}_{\mathrm{part}}) \quad \mathscr{P}(\vec{x}_{\mathrm{part}}\,|\,\vec{\theta})$$

reco observables

Part 1a

- typical SM observables (to suppress background)
- EFT-sensitive observables (e.g. angular, q^2, etc)
- optimized observables (matrix element, machine learning)
- full accessible information $\vec{x}_{\mathrm{reco}}^{\mathrm{full}}$ (e.g. all four-vectors)

— full information is the best, but hard to deal with $ND, N \gg 1$

— optimized observables: pack full information in $1D$ optimal for one target
works if the number of targets is small

— observable choice does not limit its usage
(e.g. differential measurement of an optimized observable is an option)

(II) Optimized Observables

$$\mathscr{P}(\vec{x}_{\rm reco}\,|\,\vec{\theta}) \propto \mathscr{P}_0(\vec{x}_{\rm reco}) + \sum_k \left(\frac{2\theta_k}{\theta_0}\right)\mathscr{P}_{0k}(\vec{x}_{\rm reco}) + \sum_k \left(\frac{\theta_k}{\theta_0}\right)^2 \mathscr{P}_k(\vec{x}_{\rm reco}) + \sum_{i<j}\left(\frac{2\theta_i\theta_j}{\theta_0^2}\right)\mathscr{P}_{ij}(\vec{x}_{\rm reco})$$

$$\mathcal{R}_{\rm opt,1} = \frac{2\mathcal{P}_{01}(\vec{x}^{\,\rm full}_{\rm reco})}{\mathcal{P}_0(\vec{x}^{\,\rm full}_{\rm reco}) + c\cdot\mathcal{P}_1(\vec{x}^{\,\rm full}_{\rm reco})} \qquad \mathcal{R}_{\rm opt,2} = \frac{\mathcal{P}_1(\vec{x}^{\,\rm full}_{\rm reco})}{\mathcal{P}_0(\vec{x}^{\,\rm full}_{\rm reco}) + c\cdot\mathcal{P}_1(\vec{x}^{\,\rm full}_{\rm reco})}$$

- Two types from first principles:
  (matrix elements for models θ_0, θ_1)
- Machine learning equivalent
  (parton shower, detector effects)

  $\mathscr{R}_{\rm opt,1}$: train +mix vs -mix

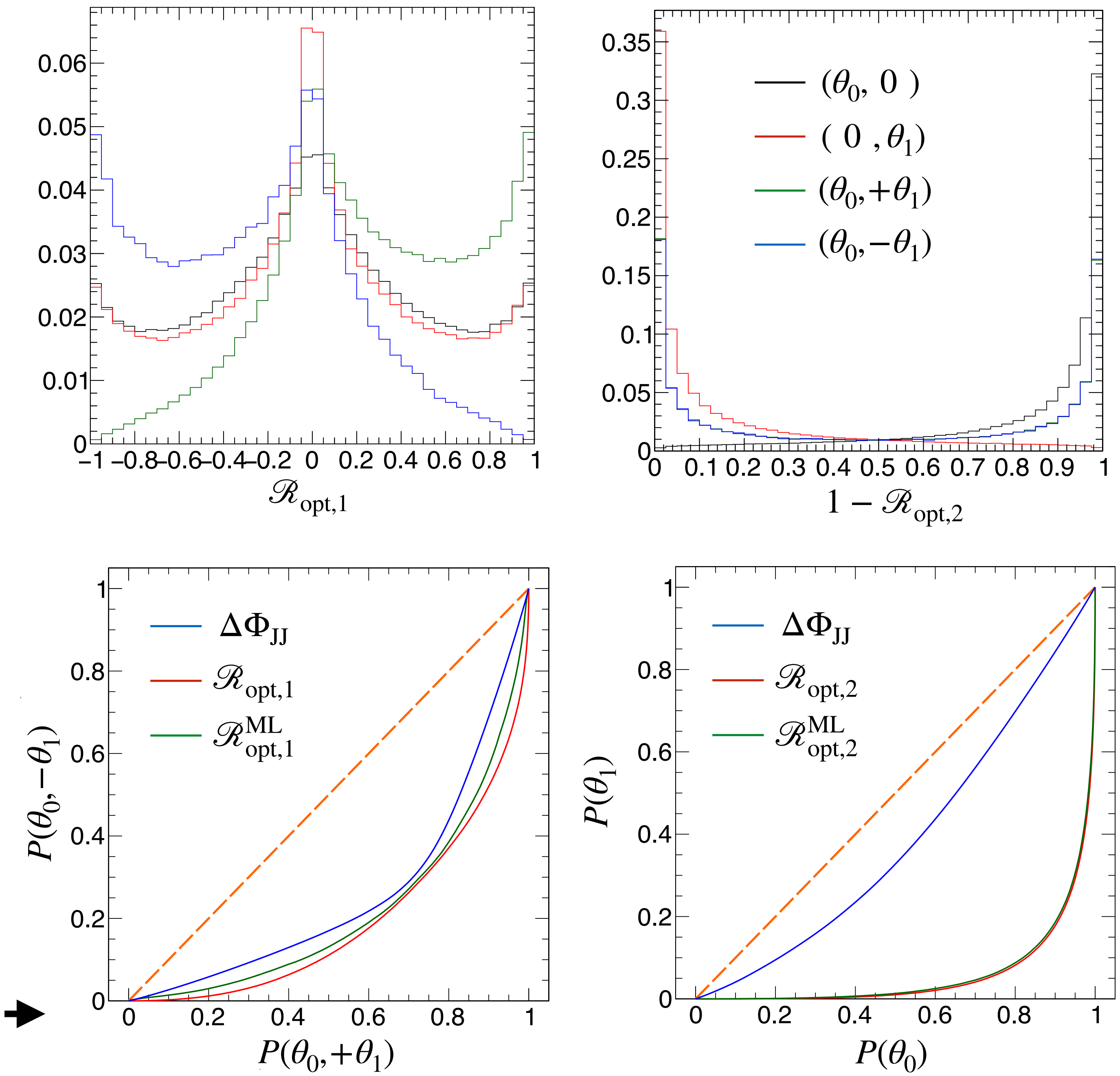
  $\mathscr{R}_{\rm opt,2}$: train θ_1 vs θ_0 (SM)

- Essential to limit the set of θ_i

— determine sensitive θ_i in advance

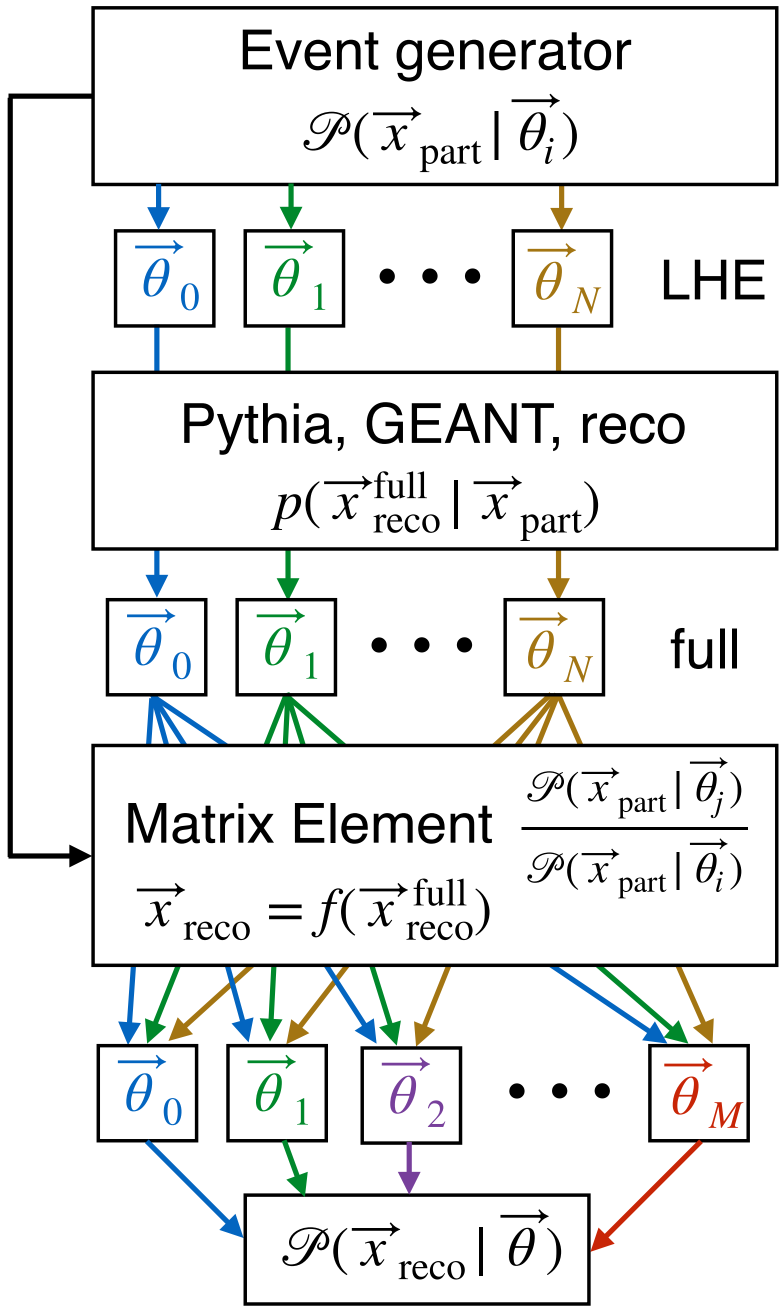
— rotate basis to remove flat directions

e.g. in VBF: rotate to $\theta_1 = \tilde{c}_{zz}$



(II) Two Types of Measurements (2b)

- Single-step approach (folded)



- Two-step approach (unfolded)

— step 1: “unfold” to parton-level distribution

$\vec{x}'_{\rm part} \subset \vec{x}_{\rm part}$

$$\mathcal{P}(\vec{x}_{\rm reco}|\vec{\theta}) = \int d\vec{x}'_{\rm part}\; p'(\vec{x}_{\rm reco}|\vec{x}'_{\rm part};\vec{\theta})\,\mathcal{P}(\vec{x}'_{\rm part}|\vec{\theta})$$

usually assume SM θ_0

— step 2: (re)interpretation - global fit

- Single-step (folded)

— can be optimal and unbiased

— most difficult and no re-interpretation

- Two-step (unfolded)

— easier and open for re-interpretation

— not full information, SM assumption

$$\mathscr{P}(\vec{x}_{\rm reco}\,|\,\vec{\theta}) \propto \mathscr{P}_0(\vec{x}_{\rm reco}) + \sum_k \left(\frac{2\theta_k}{\theta_0}\right)\mathscr{P}_{0k}(\vec{x}_{\rm reco}) + \sum_k \left(\frac{\theta_k}{\theta_0}\right)^2 \mathscr{P}_k(\vec{x}_{\rm reco}) + \sum_{i<j}\left(\frac{2\theta_i\theta_j}{\theta_0^2}\right)\mathscr{P}_{ij}(\vec{x}_{\rm reco})$$

(II) Differential cross sections (unfolding)

unfolding: $$\frac{d\sigma_{t\bar{t}}}{dX^i} = \frac{1}{\mathscr{L} \cdot \Delta X^i \cdot \epsilon^i_{eff}} \cdot \sum_j R^{-1}_{ij} \cdot f^j_{acc} \cdot (N^j_{obs} - N^j_{bkg})$$

Integrated luminosity; bin width; Response Matrix; Data Events; Expected Background Events

reverse

$$\mathcal{P}(\vec{x}_{\rm reco}|\vec{\theta}) = \int {\rm d}\vec{x}\,'_{\rm part}\; p'(\vec{x}_{\rm reco}|\vec{x}\,'_{\rm part};\vec{\theta}\,)\mathcal{P}(\vec{x}\,'_{\rm part}|\vec{\theta})$$

- Differential cross sections — detector corrected measurement

— historically tools for theorists to test calculations and MC tuning

— more recently EFT applications — shape dependence

- Potential concerns:

— unfolding procedure — best with diagonal response matrix

— biased to SM in unfolding — often small, best with flat acceptance effects

— EFT effect in background — best with high S/B

- STXS: “sort-of” differential measurement, likelihood-based fits (may use OO)

— unique to Higgs: multiple production, multiple decay modes

(II) MEM and ML likelihood inference

- not the same as optimized observables (though can be used to compute):
  — ME or ML observables can be used in any approach (e.g. differential)

- Matrix Element Method (MEM) — compute the likelihood from first principles

$$\mathscr{P}(\vec{x}_{\rm reco}\,|\,\vec{\theta}) = \int {\rm d}\vec{x}_{\rm part}\, p(\vec{x}_{\rm reco}\,|\,\vec{x}_{\rm part})\,\mathscr{P}(\vec{x}_{\rm part}\,|\,\vec{\theta})$$

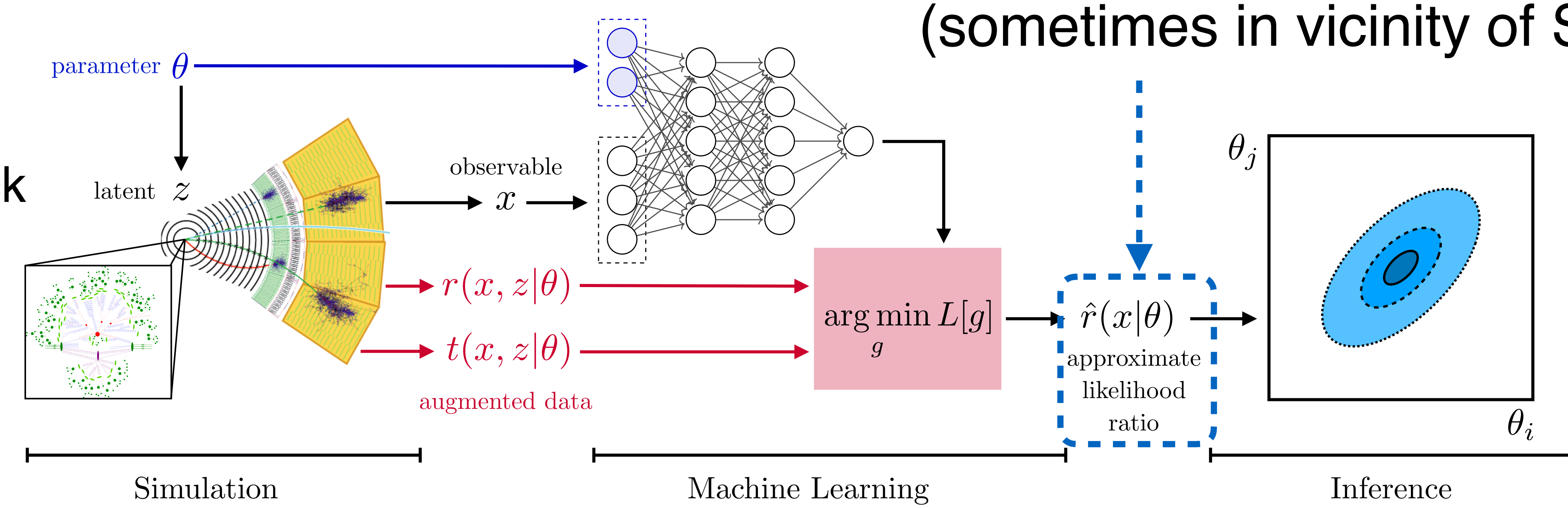
full info

ideal for EFT, but: hard to model transfer function p, ME not available for all processes…
(e.g. backgrounds)

few examples in Higgs, top, EW

- Machine Learning (ML) inference — learn the full likelihood ratio (sometimes in vicinity of SM)

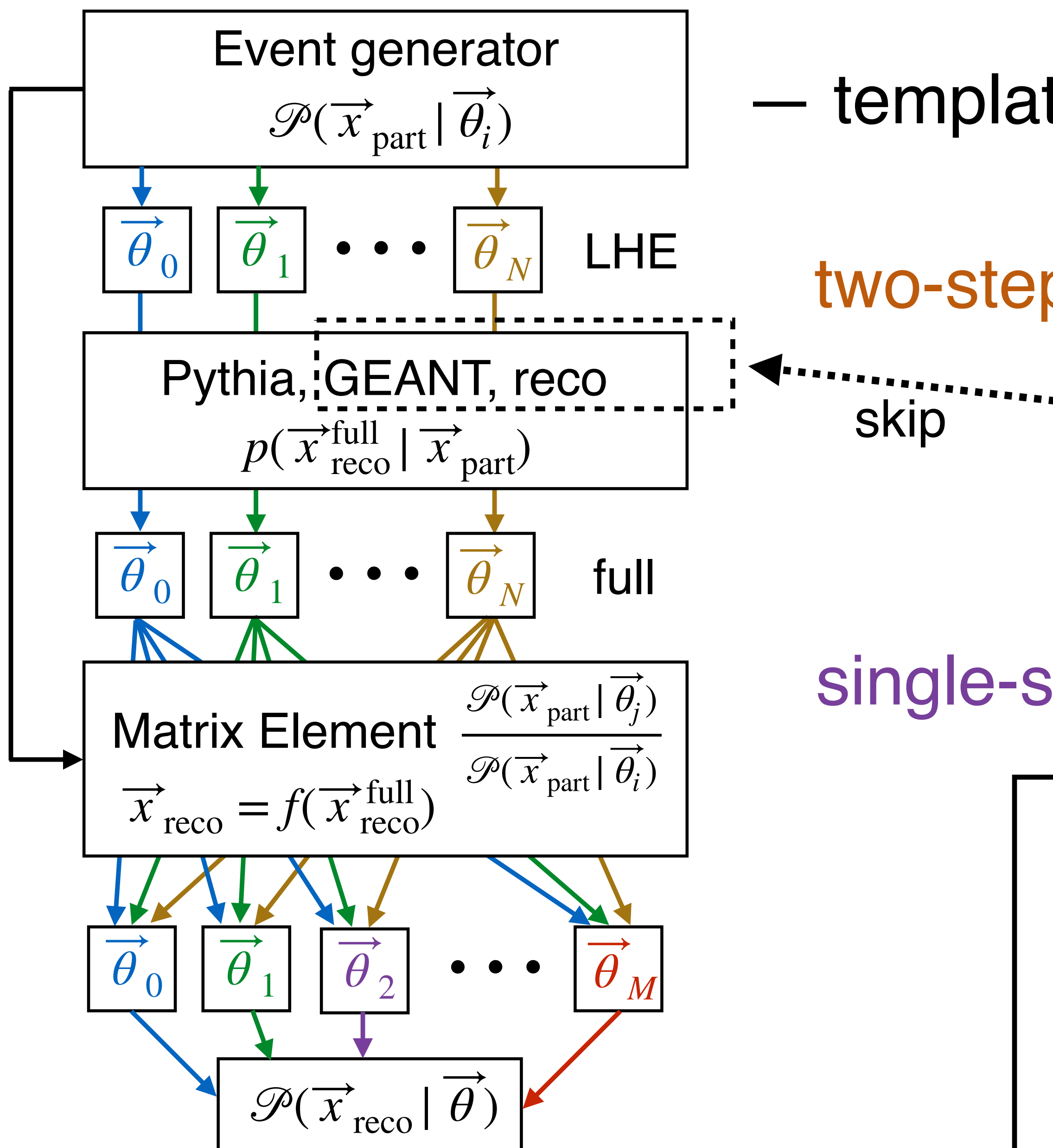
see next talk by Robert Schoefbeck



(II) Template likelihood fit

- Most common fit approach is based on "templates"

$$\mathscr{P}(\vec{x}_{\mathrm{reco(part)}}\,|\,\vec{\theta}) \propto \mathscr{P}_0(\vec{x}_{\mathrm{reco}}) + \sum_k \left(\frac{2\theta_k}{\theta_0}\right)\mathscr{P}_{0k}(\vec{x}_{\mathrm{reco(part)}}) + \sum_k \left(\frac{\theta_k}{\theta_0}\right)^2 \mathscr{P}_k(\vec{x}_{\mathrm{reco(part)}}) + \sum_{i<j}\left(\frac{2\theta_i\theta_j}{\theta_0^2}\right)\mathscr{P}_{ij}(\vec{x}_{\mathrm{reco(part)}})$$



— templates in bins of observables / measurements

two-step: first SM templates with full simulation

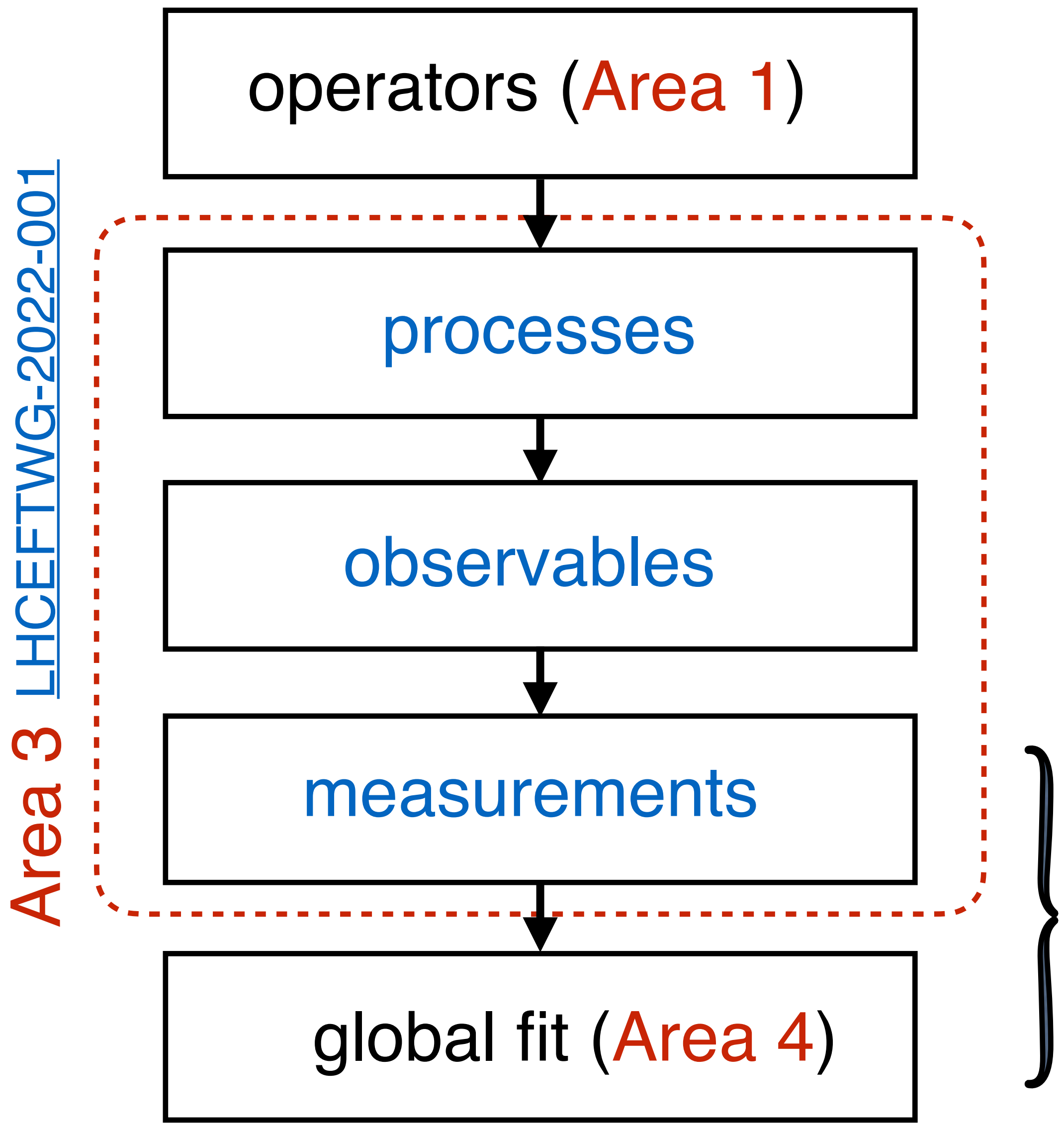
second EFT templates without detector

(e.g. globals fits in Area 4)

single-step: make EFT templates with full simulation

- Bottom line: variety of approaches
  no unique recommendation
  awareness of pros / cons, tools
  practical choices

Final step in measurements: communicate results



We need to discuss this connection

Final step in measurements: communicate results

measurements

↓

global fit (Area 4)

} We need to discuss this connection

- How to communicate systematics, bias, and with all correlations
- How to communicate dedicated measurements (single-step)

— approximate likelihood (Gaussian assumptions break, correlations lost…)

— direct fits by LHC collaborations (+ theorists, activity by this WG)

— report "full likelihood" — no practical EFT examples yet, but works in exotica

HEPData supports HistFactory model (full-blown workspaces)

limited to template fits currently, equivalent to fits by collaborations

— report experimental EFT templates with full simulation + observation

(kind of "STXS" at detector level)

Summary: EFT Measurements and Observables

- Observables for EFT

LHC EFT WG Area 3

LHCEFTWG-2022-001

  — from "simple" to optimized observables

  — clear prescription if optimization is desired

  needed: clear shared target

- Measurements for EFT global fits

  — unfolded (two-step) { easier and open for re-interpretation
not full information, SM assumption

  inclusive, differential, and STXS used in global EFT fits

  challenges: uncertainties, correlations, EFT in backgrounds…

  — folded (single-step) { can be optimal and unbiased
most difficult and no re-interpretation

  MEM, ML inference, template fit with OO

  we are still to successfully interface these to the global EFT fits…