The EFT measurement problem

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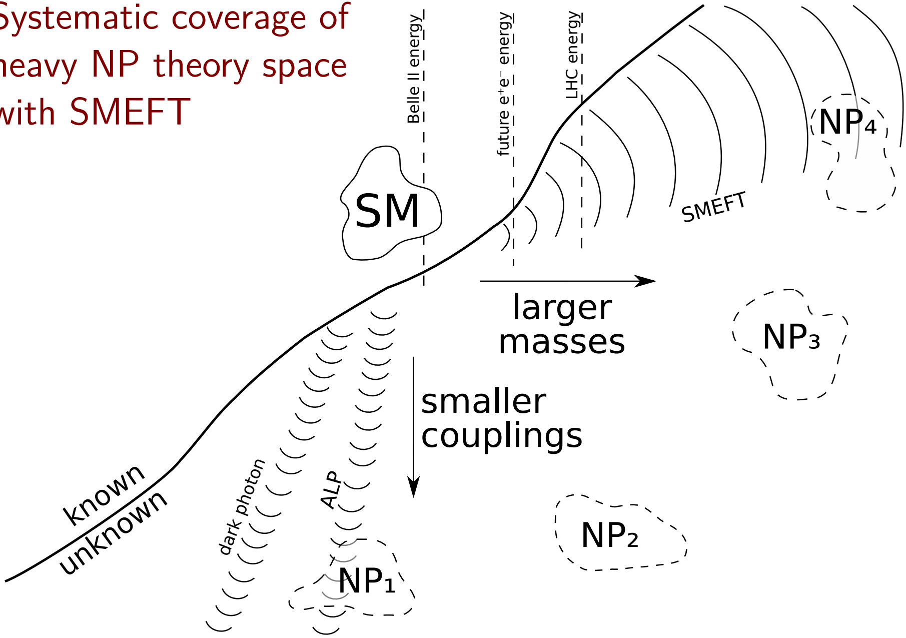
LHC EFT WG webpage, mailing list, agenda

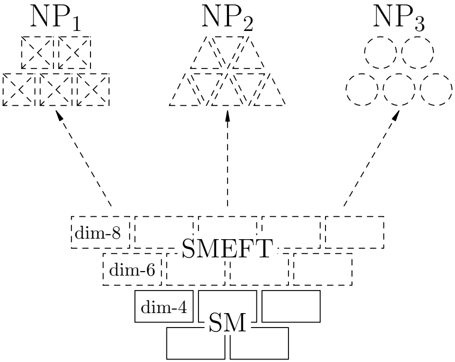
see Jan 11 meeting: *Experimental measurements and observables*

IML meeting
13 July 2021

Systematic coverage of heavy NP theory space with SMEFT



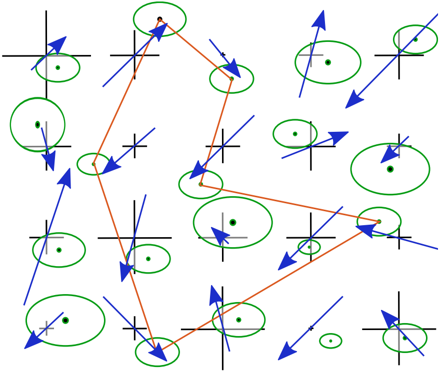
Taking the SM to higher dimensions



- using established bricks (fields and symmetries)
- deformations organised in layers (by dimension)
- including all deformations (theory space coverage)

→ a global approach

Identifying the pattern of new physics



design sensitive observables

- precise SM predictions
- precise SMEFT predictions
- precise measurements

→ leverage correlations

EFT measurement challenges

- multidimensional parameter space

  expensive optimization at every point

- suppressed linear sensitivities

  $d\sigma \sim |A_{SM}|^2 + 2C_i\,\mathrm{Re}\{A^*_{SM}A_i\} + C_iC_j\,A^*_iA_j + \dots$
  with intricate kinematics & impacting validity

- re-interpretability

  more operators, or more precise EFT predictions

- global combinations

$\rightarrow$ compromise btw sensitivity, practicality and usefulness

Statistical optimality

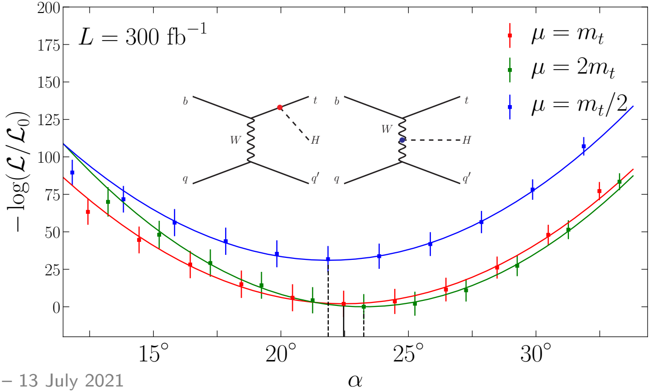
Matrix element method

[Kondo ’88], [...]
[Kraus, Martini, Peitzsch, Uwer ’19]

$$L(\theta|\{x_n\}) = \prod_{n=1}^{N} p(x_n|\theta) \qquad \text{with} \qquad p(x|\theta) = \frac{1}{\sigma(\theta)} \int dz \frac{d\sigma(z|\theta)}{dz} W(z,x)$$

possibly adding total rate information

Mostly 1D parameter space
Demanding when $W(z,x) \neq \delta(z,x)$: partial or imperfect measurements
Make the most of limited data, without training samples



fNLO QCD corrections to event weights

[Kraus, Martini, Uwer '19]
[see also Figy, Giele '18]

- fNLO = Born + Virtual + Real

  with virtual and real occupying different phase-spaces (n vs. $n+1$)
  and IR divergences cancelling between them

- 'jet events' instead of parton events

  intrinsic inclusiveness guaranteeing IR safety
  for a given jet clustering algorithm
  integrating out soft and collinear radiations

$$\frac{d^r\sigma^{\text{NLO}}}{dx_1\dots dx_r} = \frac{d^r\sigma^{\text{BV}}}{dx_1\dots dx_r} + \sum_i \sum_{\substack{j \\ j\neq i}} \frac{d^r\sigma^{\text{R}}_{\mathcal{R}_{ij}}}{dx_1\dots dx_r} + \sum_i \frac{d^r\sigma^{\text{R}}_{\mathcal{R}_i}}{dx_1\dots dx_r} + \sum_i \frac{d^r\sigma^{\text{R}}_{\tilde{\mathcal{R}}_i}}{dx_1\dots dx_r}$$

- phase space parametrization with variables

  already non-trivial at LO
  not allowing reconstruction of
  - jet invariant masses
  - overall transverse momentum

fNLO QCD corrections to event weights

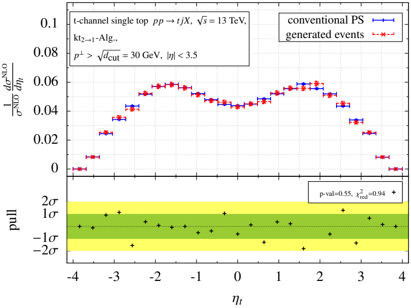
[Kraus, Martini, Uwer '19]

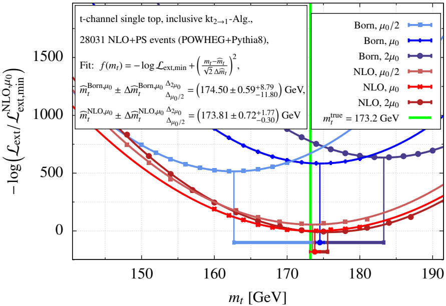
e.g. in $pp \to t\, j$ use $x = \{\eta_t,\, E_j,\, \eta_j,\, \phi_j\}$

$$J_t = \left(E_t,\, -J^\perp \cos\phi_j,\, -J^\perp \sin\phi_j,\, J^\perp \sinh\eta_t\right)$$
$$J_j = \left(E_j,\, J^\perp \cos\phi_j,\, J^\perp \sin\phi_j,\, J^\perp \sinh\eta_j\right)$$

with

$$J^\perp = J^\perp_t = J^\perp_j = \frac{\sqrt{{E_j}^2 - {J_j}^2}}{\cosh\eta_j}$$
$$E_t = \sqrt{{J^\perp}^2 \cosh^2\eta_t + {J_t}^2}$$





Addressing multidimensionality

Statistically optimal observables

[Atwood,Soni '92]
[Diehl,Nachtmann '94]

- discrete set (one number per $\{x_n\}$ for each C_i)
- amenable to usual studies
  - higher-order effects
  - systematic uncertainties

  most easily on LO parton-level definition (i.e. optimization)
- optimized at one point (e.g. $\{C_i = 0\,\forall i\}$)
- for linear sensitivity

- used for $ee \to WW$ at LEP2 [Opal, L3, ALEPH, DELPHI]
- similar to MELA discriminant averages

Statistically optimal observables

minimize the one-sigma ellipsoid in target parameter space

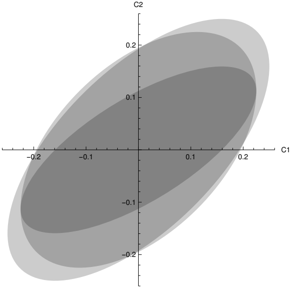
(*joint efficient* set of estimators, saturating the Cramér-Rao bound: $V^{-1} = I$)

For small C_i, with a phase-space distribution $\sigma(x) = \sigma_{\text{SM}}(x) + \sum_i C_i\, \sigma_i(x)$,

The stat. optimal observables: $OO_i \equiv \Big\langle n\, \sigma_i(x)/\sigma_{\text{SM}}(x) \Big\rangle_{\{x_n\}}$

The associated covariance:

$$\text{cov}(C_i, C_j)^{-1} = \epsilon\mathcal{L} \int \!\text{d}x\, \frac{\sigma_i(x)\sigma_j(x)}{\sigma_{\text{SM}}(x)} + \mathcal{O}(C_k).$$



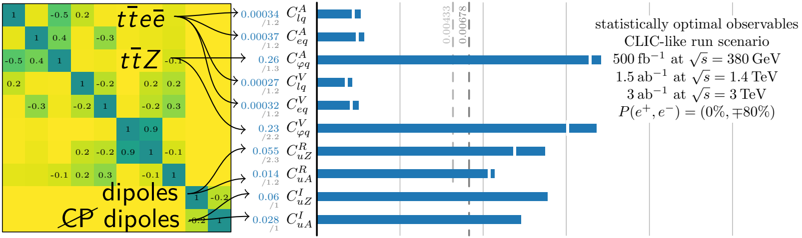
e.g. $\sigma(\phi) = 1 + \cos(\phi) + C_1 \sin(\phi) + C_2 \sin(2\phi)$

1. asymmetries $\sim \big\langle\, \text{sign}\{\sin(i\phi)\} \big\rangle$
2. moments $\sim \big\langle\, \sin(i\phi) \big\rangle$
3. statistically optimal $\sim \Big\langle \dfrac{\sin(i\phi)}{1 + \cos\phi} \Big\rangle$

$\Longrightarrow$ area ratios 1.9 : 1.7 : 1

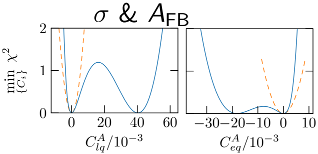
$e^+e^- \to t\bar{t}$ application

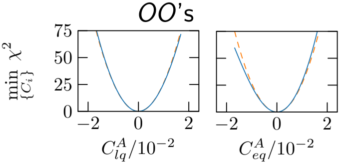
[Grzadkowski, Hioki '00], [Janot '15]
[GD, Perelló, Vos, Zhang '18]
[CLICdp '18]

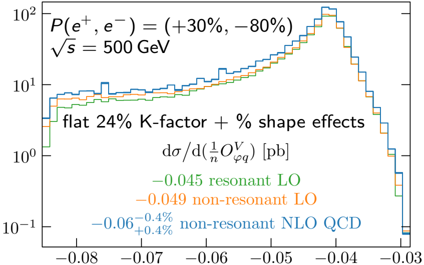


7.8% efficiency vs. A_{FB} : 4.7% (σ : 12.9%)

semileptonic $t\bar{t}$, $\sqrt{s} = 380$ GeV, $P(e^-) = -80\%$





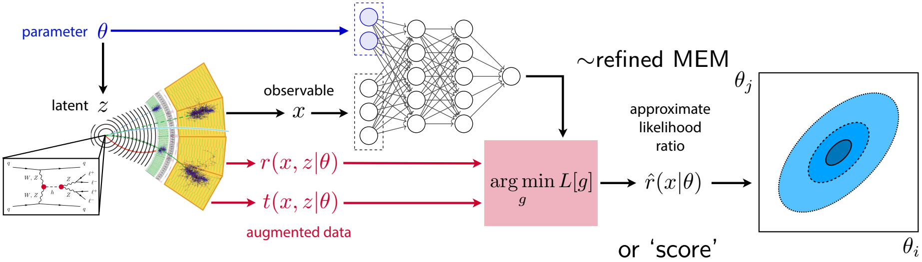


Integration, shower and detector

Integration, shower and detector

[DNN integration for MEM: Bury, Delaere '20]
[K. Cranmer 11 Jan '21]

- extrapolate from truth to reco, from training sample
- avoid integration over unmeasured phase-space and transfer fct.
- include shower, hadronization and detector effects



or 'score'

$$t(x) = \nabla_\theta \log p(x|\theta)\Big|_{\theta_{SM}}$$

$\sim$ refined optimal observables: $\langle t(x) \rangle_{\{x_n\}}$

Re-interpreting

see also LHC Re-interpretation Forum

Reweighting

Full truth distribution $p_0(z)$
Reconstructed distributions $p_0(x)$
Abstract *folding* operator $W(x|z)$

$$p_0(x) = \int \mathrm{d}z\ p_0(z)\ W(x|z) \qquad \text{through MC sampling}$$

Reweighting from theory hypothesis 0 to 1
given a set of pre-folded events (x_k, z_k) distributed following $p_0(z)$

$$p_1(x) = \int \mathrm{d}z\ p_0(z)\ \frac{p_1(z)}{p_0(z)}\ W(x|z)$$

Recipe:

1. take events $\{x_k, z_k, p_0(z_k)\}$ (published?!)
2. reweight by $p_1(z_k)/p_0(z_k)$ (no new sample generation)
3. get arbitrarily fine-grained and multidimensional reco. $p_1(x)$
4. change observable too, if x is rich enough

The EFT measurement problem

Compromise btw sensitivity, practicality, usefulness?

Cover multidimensional spaces?

Re-interpretability?

Global combinations?

Use of reweighting and fNLO weights?

Enhanced EFT validity?