Can New Physics Hide inside the Proton?

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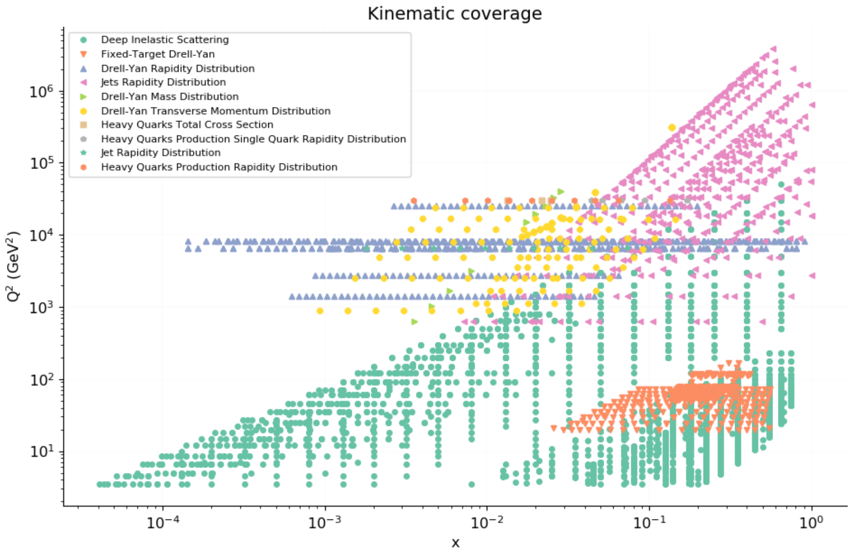
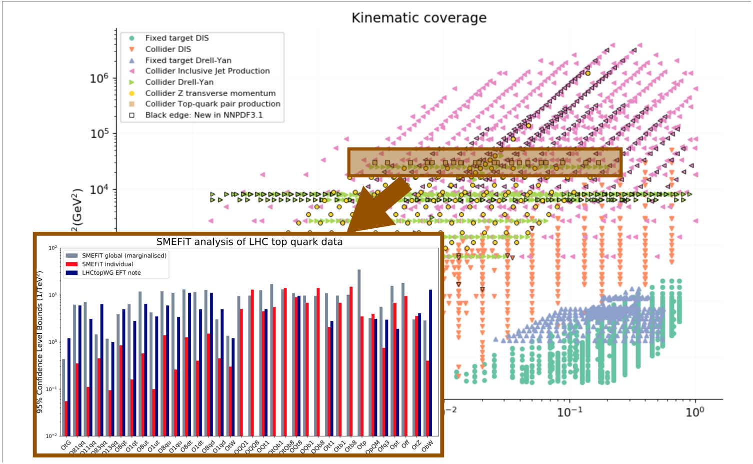
S. Carrazza, C. Degrande, S. Iranipour, J. Rojo, and M. Ubiali, "Can New Physics hide inside the proton?," *Phys. Rev. Lett.*, vol. 123, p. 132001, 2019

Motivation

- Need to assess if BSM effects can be absorbed into PDFs during fitting
- State of the art Parton Distribution Functions (PDFs) now using high Q^2 data from LHC. With increasing kinematic coverage (LHeC, FCC), need to consider the validity of using SM for PDFs.
- Contrast bounds on BSM degrees of freedom using PDFs fitted with BSM operators with bounds obtained by using fixed SM PDFs.
- High energy degrees of freedom become important at large Q^2.


Kinematic coverage
Deep Inelastic Scattering
Fixed-Target Drell-Yan
Drell-Yan Rapidity Distribution
Jets Rapidity Distribution
Drell-Yan Mass Distribution
Drell-Yan Transverse Momentum Distribution
Heavy Quarks Total Cross Section
Heavy Quarks Production Single Quark Rapidity Distribution
Jet Rapidity Distribution
Heavy Quarks Production Rapidity Distribution
Q² (GeV²)
x



Hartland et al 1901.05965. Image credit: Maria Ubiali (HEFT 2019)

- Important to fully probe a multi-dimensional parameter space to see effects of having several BSM degrees of freedom present together.
- Want to include data sets that constrain BSM and PDF simultaneously.

See arXiv: 1902.03048 and 1107.2478 alongside earlier talks for analyses using xFitter studies restricted to H1 and ZEUS data.

NNPDF Methodology

Obtain PDFs ($q(x,Q^2)$) by fitting to experimental data.

- Data provided by experimental collaborations
- Generate *pseudodata* replicas of original data, with the same statistical properties
- Use pseudodata to train and validate a neural network by minimizing χ^2 cost function against theory predictions

$$\chi^2 = (\text{data} - \text{theory})^T \text{cov}^{-1} (\text{data} - \text{theory})$$

Where cov^{-1} is the inverse covariance matrix provided by experimentalists.

- Generate one PDF replica per pseudodata replica (typically 100 replicas).
- Cascade experimental error to the PDF fit level due to finite ensemble size.
- For analysis use central value from the 100 replicas (central replica).

Standard Model as an EFT

Treat the Standard Model as the low energy, IR limit of some UV complete theory.

$$\mathcal{L} = \mathcal{L}_{\mathsf{SM}} + \sum_{d \geq 5} \sum_{i=1}^{N_d} \frac{a_i}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$$

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Ignore odd d values. Violate baryon/lepton number conservation. First non-trivial contribution at $d = 6$

Convenient because:

- Model independent. Uses same matter fields and gauge symmetry as the SM.
- For $d = 6$ and 3-flavours, minimal $\{\mathcal{O}_i^{(6)}\}$ basis fully determined (Warsaw basis[1]).
- Encompasses *any* UV complete theory that has SM as an IR limit.

[1] arXiv:1008.4884

As a proof of concept consider only the subset of the Warsaw basis:

$$\mathcal{O}_{lu} = \left(\bar{l}_R \gamma^\mu l_R\right)\left(\bar{u}_R \gamma_\mu u_R\right) \quad , \quad \mathcal{O}_{ld} = \left(\bar{l}_R \gamma^\mu l_R\right)\left(\bar{d}_R \gamma_\mu d_R\right)$$
$$\mathcal{O}_{lc} = \left(\bar{l}_R \gamma^\mu l_R\right)\left(\bar{c}_R \gamma_\mu c_R\right) \quad , \quad \mathcal{O}_{ls} = \left(\bar{l}_R \gamma^\mu l_R\right)\left(\bar{s}_R \gamma_\mu s_R\right)$$

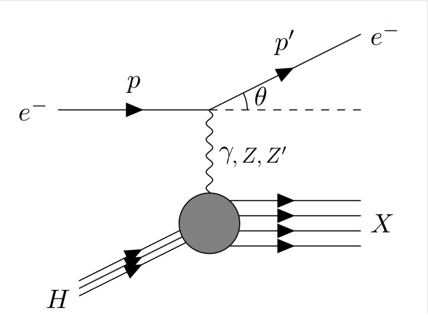
For l either an electron or muon.

Wish to find a confidence interval on the Wilson Coefficients for these operators using DIS data.

Hadronic Structure Functions

- Can think of these 4 SMEFT operators as low energy limit of some heavy Z' coupling to right handed leptons/quarks.
  - Allows for easier computation of modified structure functions, by drawing analogy to the SM computation

New Z' contributes to the NC DIS process:



This alters the NC DIS observable:

$$\frac{d^2\sigma^{\mathrm{NC},l^\pm}}{dxdQ^2}(x,Q^2) = \frac{2\pi\alpha^2}{xyQ^4}\left[Y_+\, F_2^{\mathrm{NC}}(x,Q^2) \mp Y_-\, xF_3^{\mathrm{NC}}(x,Q^2) - y^2\, F_L^{\mathrm{NC}}(x,Q^2)\,\right]$$

Note $F_L = F_L^{\mathsf{SM}}$ since it is only non-zero for NLO QCD.

Requires a modification of the APFEL program (arXiv:1310.1394). In turn alters the theory input in the NNPDF methodology.

Dimension 6 operators modify hadronic structure functions.

$$F_2(x,Q^2) = F_2^{\mathrm{SM}}(x,Q^2) + \frac{x}{12e^4}\left[\left(4a_u e^2 \frac{Q^2}{\Lambda^2}(\overbrace{1}^{Z'/\gamma} + \overbrace{4K_Z s_W^4}^{Z'/Z}) + \overbrace{3a_u^2 \frac{Q^4}{\Lambda^4}}^{Z'/Z'}\right)\left(u(x,Q^2) + \bar{u}(x,Q^2)\right) + \cdots\right]$$

$$F_3(x,Q^2) = F_3^{\mathrm{SM}}(x,Q^2) + \frac{1}{12e^4}\left[\left(4a_u e^2 \frac{Q^2}{\Lambda^2}(1 + 4K_Z s_W^4) + 3a_u^2 \frac{Q^4}{\Lambda^4}\right)\left(u(x,Q^2) - \bar{u}(x,Q^2)\right) + \cdots\right]$$

Where

$$K_Z = \frac{Q^2}{4c_W^2 s_W^2 (Q^2 + M_Z^2)} \qquad c_W^2 = 1 - s_W^2 = \cos^2\theta_W.$$

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Main analysis done up to $\mathcal{O}\left(\frac{1}{\Lambda^2}\right)$ because:

- Subleading compared to Z'/SM
- Will be corrected by $\mathcal{O}^{(8)}$ operators
- Results largely unchanged if you include them for a 1 dimensional analysis

Fixed PDF analysis

- Initially, keep PDF fixed using the NNPDF31 NNLO DIS only PDF set.
- Scan the SMEFT operator phase space by sampling (a_u, a_d, a_s, a_c).
- Then obtain a χ^2 value for how well modified DIS observable fits data.

Results look like:

(a_u, a_d, a_s, a_c)	χ^2
$(0, 0, 0, 0)$	3568.915
$(-0.18, 0, 0, 0)$	3571.693
$(0.9, 0.9, 0, 0)$	3583.612
$\vdots$	$\vdots$

Since structure functions are linear in Wilson Coefficient (a_i), the χ^2 is quadratic in a_i. Can represent the χ^2 as a quadratic form.

$$\chi^2(a;\beta) = \chi_0^2 + \frac{1}{2}(a - a_0)^T H (a - a_0)$$

H the Hessian, a_0 position of minimum and χ_0^2 value at minimum. Fit to χ^2 values using least squares to obtain fit parameters β ($\dim \beta = 15$).

Minimize, w.r.t β

$$\sum_{i}^{N_{BP}} ||y_i - \chi^2(a_i;\beta)||^2$$

Can obtain analytic solution for β, since functional form is polynomial in fit parameters:

$$\beta = (X^T X)^{-1} X^T \vec{y}$$

for X the design matrix and $\vec{y}$ the vector of data to fit to.

Confidence Intervals

A 90% CI is defined by the region:

$$\Delta\chi^2 = \frac{1}{2}(a - a_0)^T H (a - a_0) = 7.779$$

Defines a $\dim 3$ ellipsoid embedded in $\mathbb{R}^4$.

Extremes of this ellipsoid give 90% CI on Wilson Coefficients.

Fitting PDFs in the presence of BSM operators

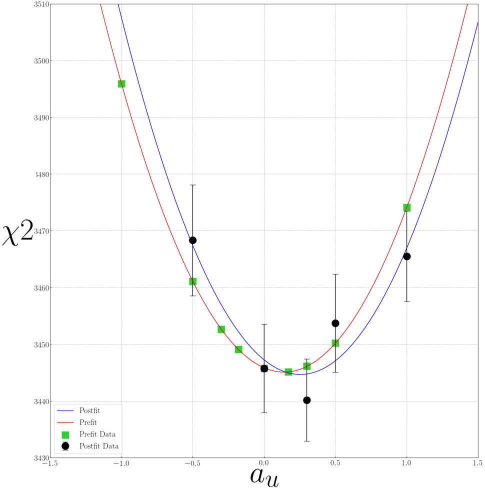
Now allow the PDF to change in the presence of SMEFT operators. Requires employing NNPDF methodology to fit PDFs from scratch.

- Modify theory prediction ($d^2\sigma$) with BSM operators (generated by APFEL)
- Use NNPDF methodology to obtain PDF fits using the modified theory.

One dimensional analysis

Choose BPs along each of the principal axes, e.g $(a_u, 0, 0, 0)$

One dimensional analysis



Error bars due to finite number of replicas.

Four Dimensional Analysis

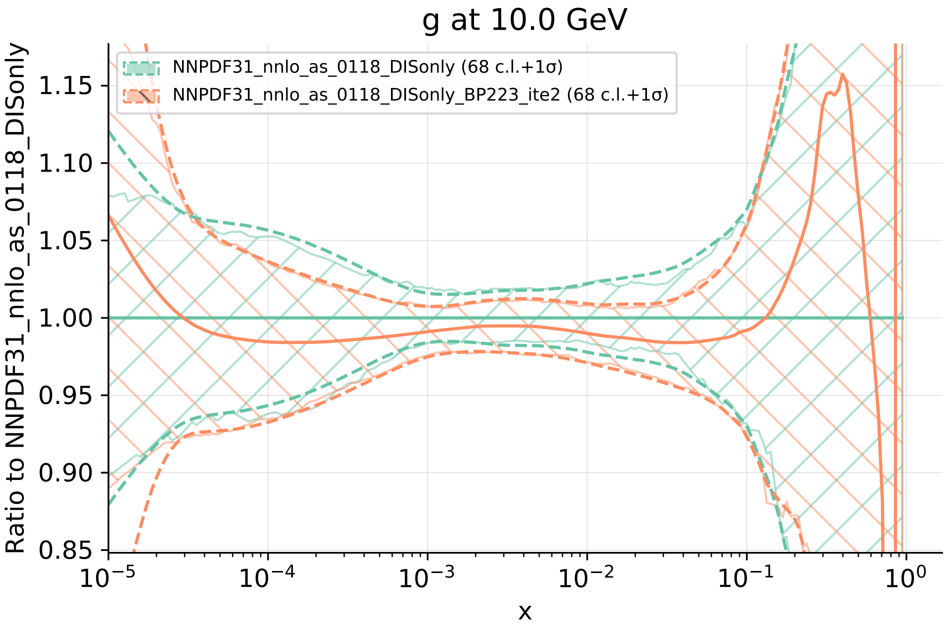
Perform the analysis in the presence of all 4 SMEFT operators (marginalized bounds) and compare with individual bounds.

Flavour	Individual Bounds	Marginalized Bounds
up	$[-0.1, +0.4]$	$[-2.3, +1.4]$
down	$[-1.6, +0.4]$	$[-13, +3.9]$
strange	$[-2.8, +4.2]$	$[-18, +29]$
charm	$[-2.6, +1.2]$	$[-13, +7.0]$

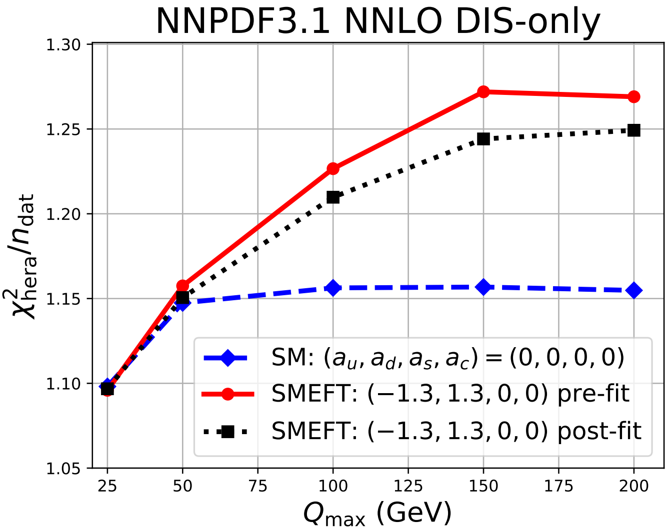
Four Dimensional Analysis

Bounds obtained with PDFs fitted with SMEFT operators

Flavour	Individual Bounds	Marginalized Bounds
up	$[0.0, +0.5]$	$[-0.4, +2.4]$
down	$[-1.1, +0.8]$	$[-4.4, +4.5]$
strange	$[-4.5, +3.6]$	$[-61, +39]$
charm	$[-2.4, +0.7]$	$[-29, +2.7]$


g at 10.0 GeV
NNPDF31_nnlo_as_0118_DISonly (68 c.l.+1σ)
NNPDF31_nnlo_as_0118_DISonly_BP223_ite2 (68 c.l.+1σ)
Ratio to NNPDF31_nnlo_as_0118_DISonly
1.15
1.10
1.05
1.00
0.95
0.90
0.85
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
x

Variaton of PDF χ^2 for (-1.3, 1.3, 0, 0)



Outlook

- Fitting more SMEFT operators for more processes e.g NLO DIS and DY.
- Use higher energy data in PDF fits e.g high mass DY.
- Simultaneous fit of PDF and BSM dynamics. Requires updated methodology.

Conclusions

- Demonstration of proof of concept. Can systematically disentangle BSM physics and PDFs.
- Demonstrates feasibility of constraining PDF and Wilson Coefficients simultaneously.
- Paves the way for future studies involving higher energy data.