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EFTS AND MACHINE LEARNING

OUTLINE

- Introduction:
  - ➡ Machine learning applications on indirect searches for new physics
  - ➡ Machine learning in SMEFT fits
  - ➡ Simultaneous fits of SMEFT Wilson coefficients and PDFs

- Machine learning for simultaneous fits of EFT WCs and PDFs
  - ➡ The SimuNET methodology and applications

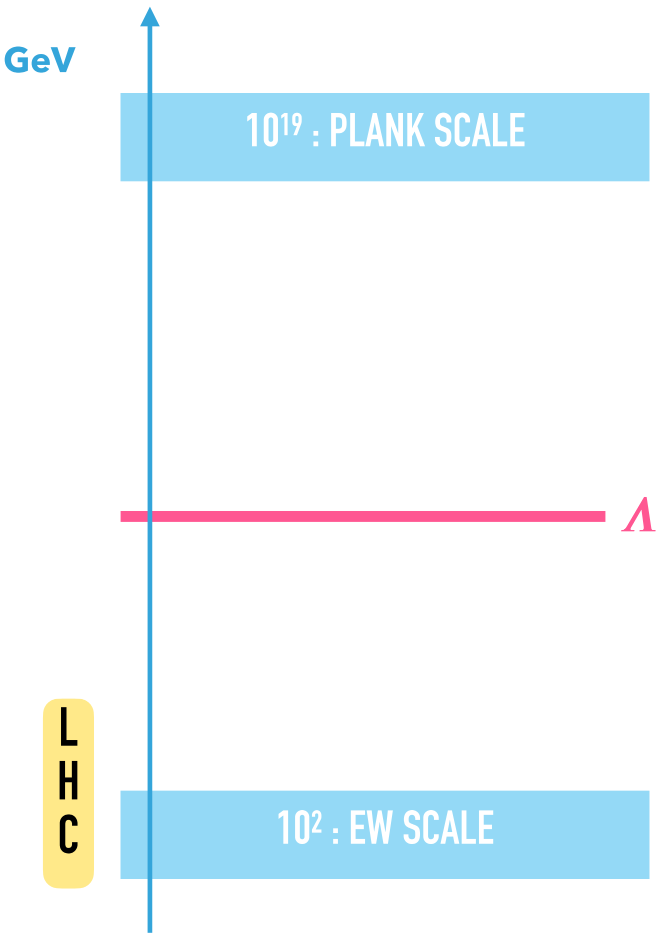
    based on: S. Iranipour, MU (arXiv:2201.07240)
    Z. Kassabov, L. Mantani, M. Madigan, J. Moore, M. Morales, J. Rojo, MU (in progress)

- Conclusions and outlook

INTRODUCTION

MACHINE LEARNING AND EFFECTIVE FIELD THEORIES

✓ Machine-Learning techniques widely applied to boost colliders' performance in the indirect searches for new physics within EFT framework



➡ Increase sensitivity to new physics effects in kinematic distributions and determine statistically optimal observables
[Freitas et al 1902.05803, De Simone et al 1807.06038…]

➡ Devise model-independent searches for new physics
B. Nachman's talk
[D'Agnolo et al 1806.02350, Cerri et al 1811.10276…]

➡ Link SMEFT fit to UV models
[D'Agnolo et al 1806.02350

➡ Explore large Wilson coefficient's parameter space using wide range of data (global SMEFT analyses)

$$\mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{\text{SM}} + \sum_i^{N_{d6}} \frac{c_i}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_j^{N_{d8}} \frac{b_j}{\Lambda^2}\mathcal{O}_i^{(8)} + \dots$$

EXTRACTING PHYSICS PARAMETERS FROM LHC DATA

✓ Abundance of precise LHC data allows to extract info on SM parameters and non-pert. objects such as PDFs as well as WCs of EFT expansion

$$\chi^2 = \frac{1}{N_{\rm dat}} \sum_{i=1}^{N_{\rm dat}} (T_i(\{\theta\},\{c\}) - D_i)\, {\rm cov}_{ij}^{-1}\, (T_j(\{\theta\},\{c\}) - D_j)$$

$$T_i(\{\theta\},\{c\}) = {\rm PDFs}(\{\theta\},\{c\}) \otimes \hat{\sigma}_i(\{c\})$$

(B)SM parameters: $\alpha_s(M_z)$, M_w, θ_w ,SMEFT WCs…..

Parameters determining PDFs at initial scale

NNPDF4.0, Ball et al, arXiv: 2109.02653

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The NNPDF approach

- Generate MC replicas of data
- Parametrize PDFs with deep NN and get best fit for each replica (stopping training with cross-validation)
- Use ML hyper-optimisation techniques to “learn” fitting methodology and NN architecture
- Obtain a MC sample in PDF space

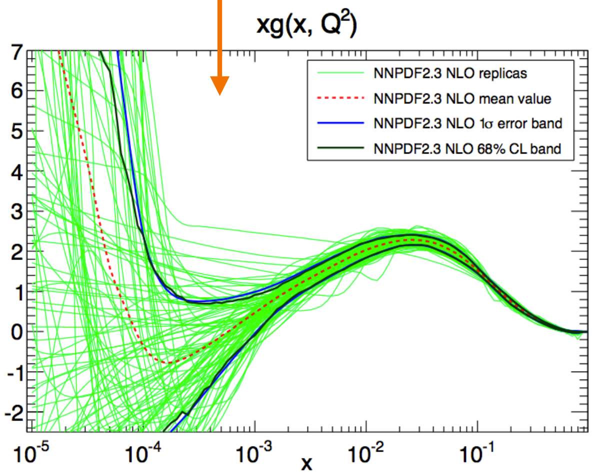
$$T_i(\{\theta\},\{c\}) = {\rm PDFs}(\{\theta\},\{c\}) \otimes \hat{\sigma}_i(\{c\})$$

(B)SM parameters: $\alpha_s(M_z)$, M_w, θ_w ,SMEFT WCs…..

Parameters determining PDFs at initial scale

✓ In a PDF fit typically

$$T_i(\{\theta\}) = {\rm PDFs}(\{\theta\},\{\bar{c}\}) \otimes \hat{\sigma}_i(\{\bar{c}\})$$



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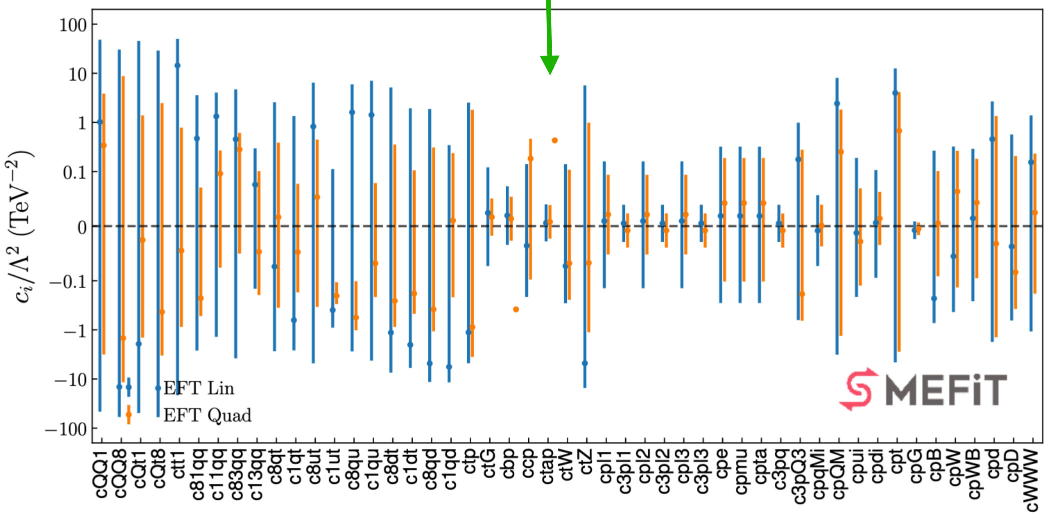
$$\chi^2 = \frac{1}{N_{\rm dat}} \sum_{i=1}^{N_{\rm dat}} (T_i(\{\theta\},\{c\}) - D_i)\,{\rm cov}^{-1}_{ij}\,(T_j(\{\theta\},\{c\}) - D_j)$$

The SMEFiT approach

- Generate MC replicas of data
- Include linear and quadratic SMEFT corrections (analytic)
- Minimisation in the WCs parameters space
- MC sample in WC's space



$$T_i(\{\theta\},\{c\}) = {\rm PDFs}(\{\theta\},\{c\}) \otimes \hat\sigma_i(\{c\})$$

(B)SM parameters: $\alpha_s(M_z)$, M_w, θ_w ,SMEFT WCs…..

Parameters determining PDFs at initial scale

✓ In a PDF fit typically

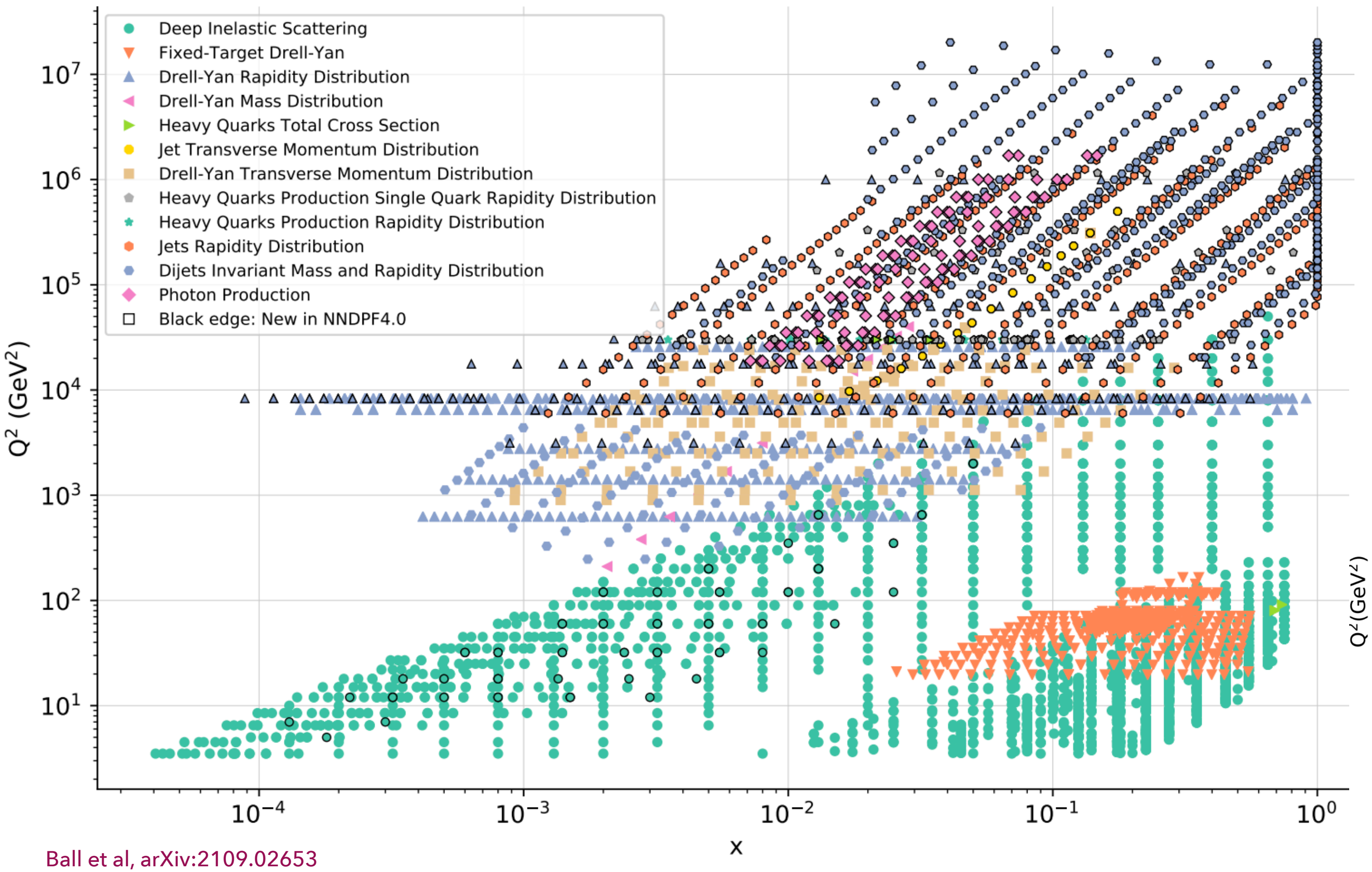
$$T_i(\{\theta\}) = {\rm PDFs}(\{\theta\},\{\bar c\}) \otimes \hat\sigma_i(\{\bar c\})$$

✓ In a fit of SMEFT Wilson coefficients

$$T_i(\{c\}) = {\rm PDFs}(\{\bar\theta\},\{\bar c\}) \otimes \hat\sigma_i(\{c\})$$

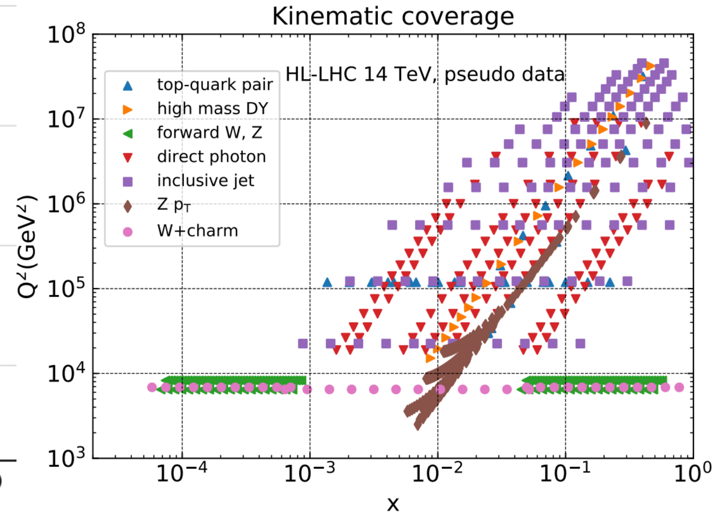
Ethier et al, arXiv: 2105.00006 - Hartland et al, arXiv:1901.05965

INTERPLAY BETWEEN PDF FITS AND SMEFT FITS



Ball et al, arXiv:2109.02653

- ➡ Top pair production and single top data included in SMEFT analysis [Hartland et al 1901.05965] [Ellis et al 2012.02779]
- ➡ Dijets data in [Bordone et al 2103.10332] [Alioli et al 1706.03068]
- ➡ Drell-Yan data in [Farina et al 1609.08157] [Torre et al 2008.12978]
- ➡ Inclusive jets in [Alte et al 1711.07484]
- ➡ Overlap enhanced in HL-LHC projections [Abdul Khalek et al,1810.03639]



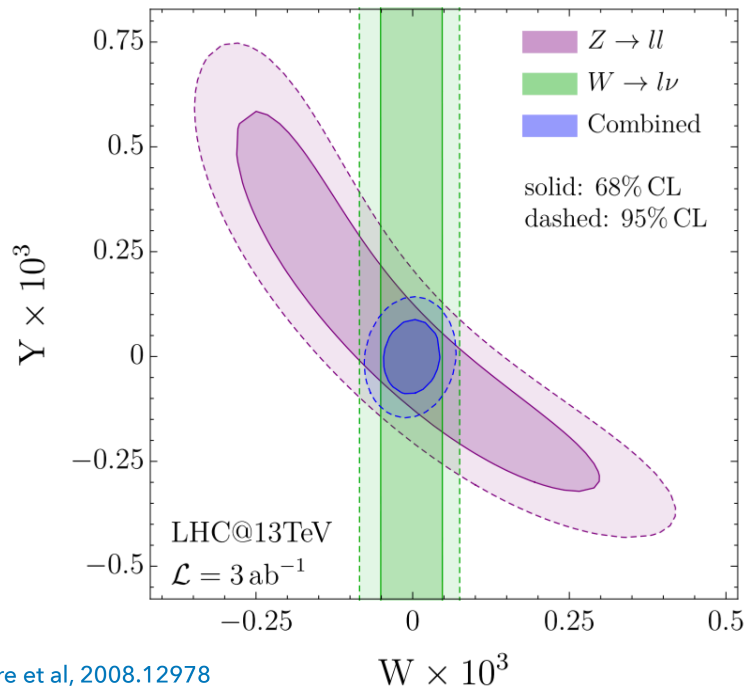
Abdul Khalek et al, arXiv:1810.03639

THE CASE OF HIGH MASS DRELL-YAN DISTRIBUTIONS

OBLIQUE PARAMETERS AND HIGH-MASS DY TAILS

- Case study at higher energy: EW oblique corrections in high-mass NC and CC Drell-Yan tails.
- W and Y parametrise the self-energy of gauge bosons and are powerful probes of quark-lepton contact interactions that produce effects that grow with energy [Torre et al, 2008.12978]

$$\mathscr{L}_{\rm SMEFT} \supset -\frac{\hat{W}}{4m_W^2}(D_\rho W^a_{\mu\nu})^2 - \frac{\hat{Y}}{4m_W^2}(\partial_\rho B_{\mu\nu})^2$$



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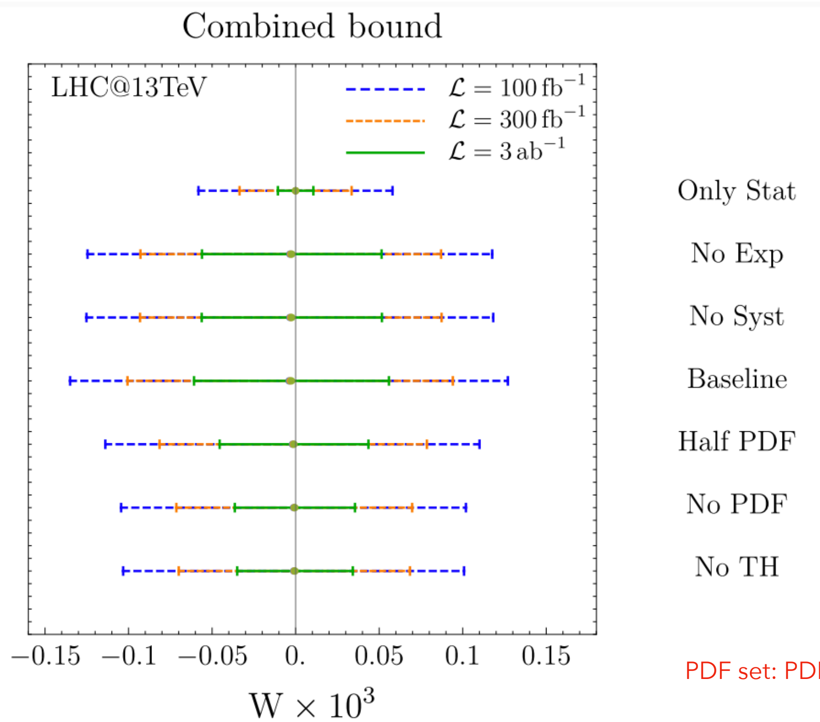


PDF set: PDF4LHC15_nlo_30_pdfas

PDF-SMEFT INTERPLAY IN HIGH-MASS DY TAILS

- We performed a similar analysis as in Torre et al, now with emphasis on PDF and their interplay with bounds on oblique operators
  [Greljo, Iranipour, Kassabov, Madigan, Moore, Rojo, MU, Voisey: 2104.02723]
  [Iranipour, MU, Voisey: 2201.07240]

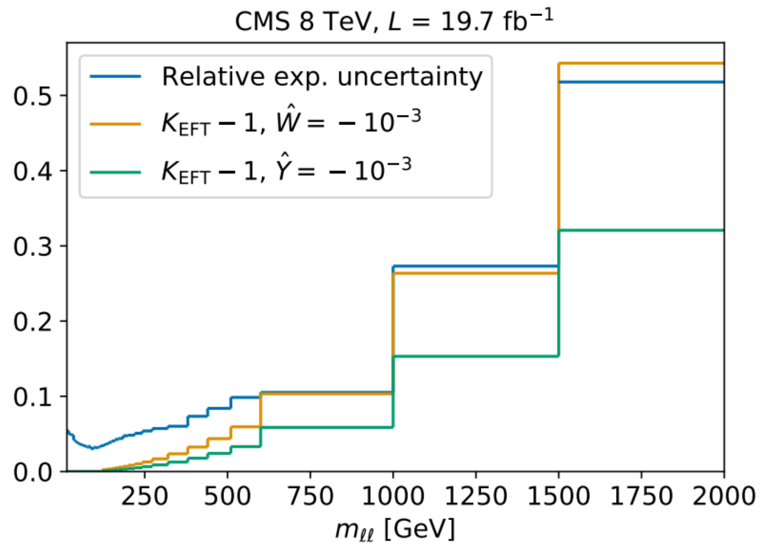
- Settings:
  - ➡ PDF fit based on DIS (~3000 data points), Drell-Yan on-shell and low-mass data from ATLAS, CMS and LHCb (~600 data points)
  - ➡ + Run I and II ATLAS and CMS high mass NC Drell-Yan data (~300 data points)
  - ➡ SM predictions at NNLO QCD + NLO EW
  - ➡ SMEFT corrections added via local K-factors

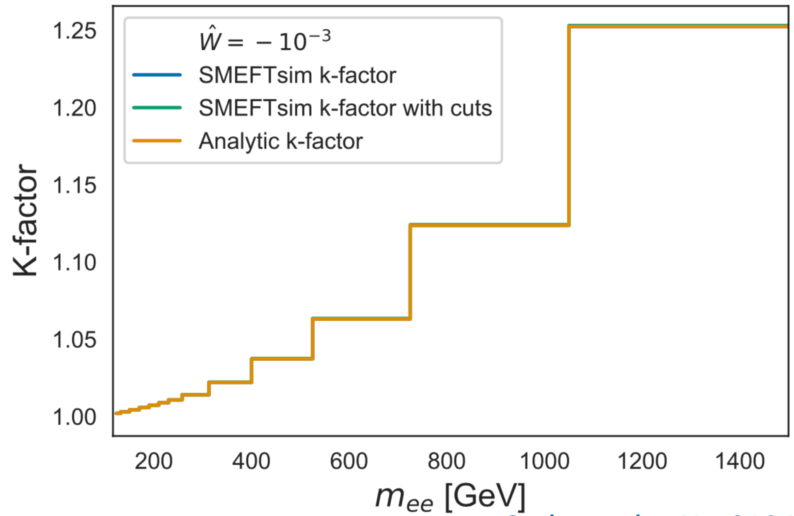
$$d\sigma_{\rm SMEFT} = d\sigma_{\rm SM} \times K_{\rm EFT}$$

$$K_{\rm EFT} = 1 + \sum_{n=1}^{n_{\rm op}} c_n R^{(n)}_{\rm SMEFT} + \sum_{n,m=1}^{n_{\rm op}} c_n c_m R^{(n,m)}_{\rm SMEFT}$$

$$R^{(n)}_{\rm SMEFT} \equiv \left(\mathcal{L}^{\rm NNLO}_{ij} \otimes d\widehat{\sigma}^{(n)}_{ij,\rm SMEFT}\right) / \left(\mathcal{L}^{\rm NNLO}_{ij} \otimes d\widehat{\sigma}_{ij,\rm SM}\right) , \quad n = 1 \ldots , n_{\rm op}$$

$$R^{(n,m)}_{\rm SMEFT} \equiv \left(\mathcal{L}^{\rm NNLO}_{ij} \otimes d\widehat{\sigma}^{(n,m)}_{ij,\rm SMEFT}\right) / \left(\mathcal{L}^{\rm NNLO}_{ij} \otimes d\widehat{\sigma}_{ij,\rm SM}\right) , \quad n,m = 1 \ldots , n_{\rm op}$$





Greljo et al, arXiv:2104.02723

PDF-SMEFT INTERPLAY IN HIGH-MASS DY TAILS

- A scan in the (W,Y) parameter space was made
  [Greljo, Iranipour, Kassabov, Madigan, Moore, Rojo, MU, Voisey: 2104.02723]

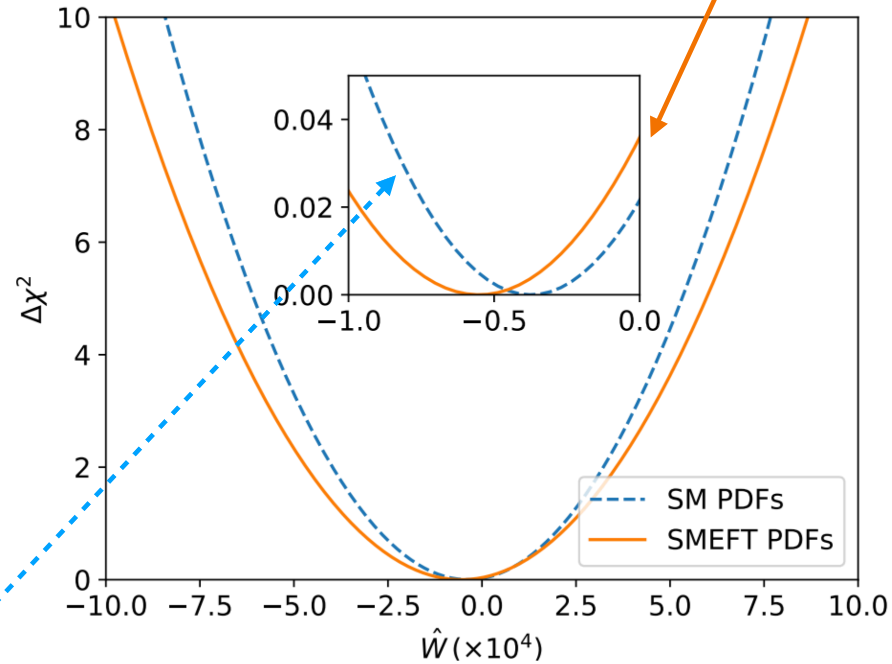
1. Take data, make theoretical predictions accounting for operator in partonic cross section and PDFs.
2. Compute chi2 as a function of WCs (Wilson Coefficients)
3. Minimise chi2 and find best-fit and C.L.s of WCs
4. Extract bounds

$$T = f_{1,\mathrm{BSM}} \otimes f_{2,\mathrm{BSM}} \otimes \hat{\sigma}_{\mathrm{BSM}}$$

SMEFT PDFs / Simultaneous fit

$$\chi^2 = \frac{1}{n_{\mathrm{dat}}} \sum_{i,j=1}^{n_{\mathrm{dat}}} (D_i - T_i)\,(\mathrm{cov}^{-1})_{ij}\,(D_j - T_j)$$

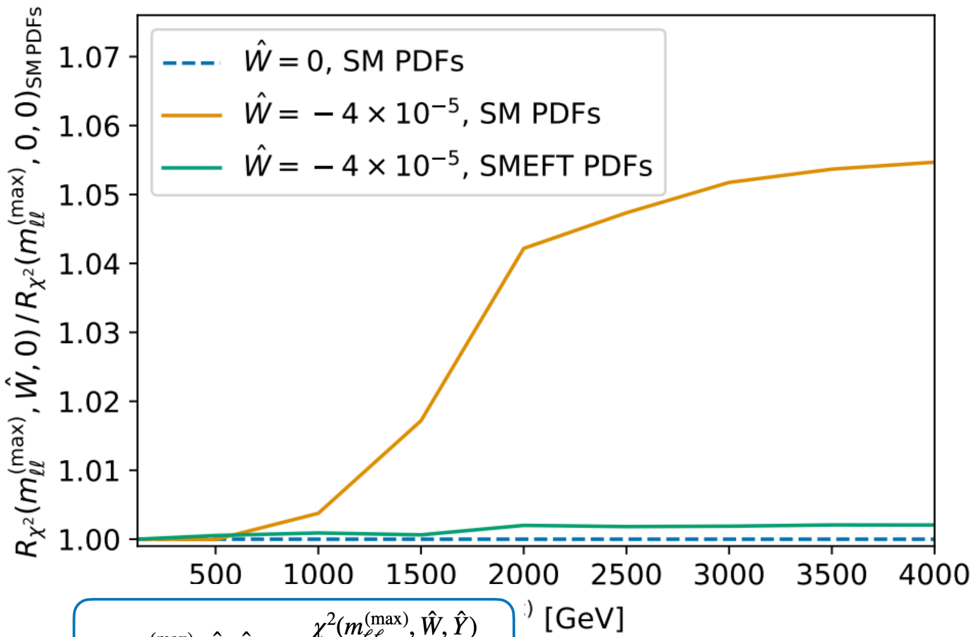
$$T = f_1(\hat{W}) \otimes f_2(\hat{W}) \otimes \hat{\sigma}(\hat{W})$$



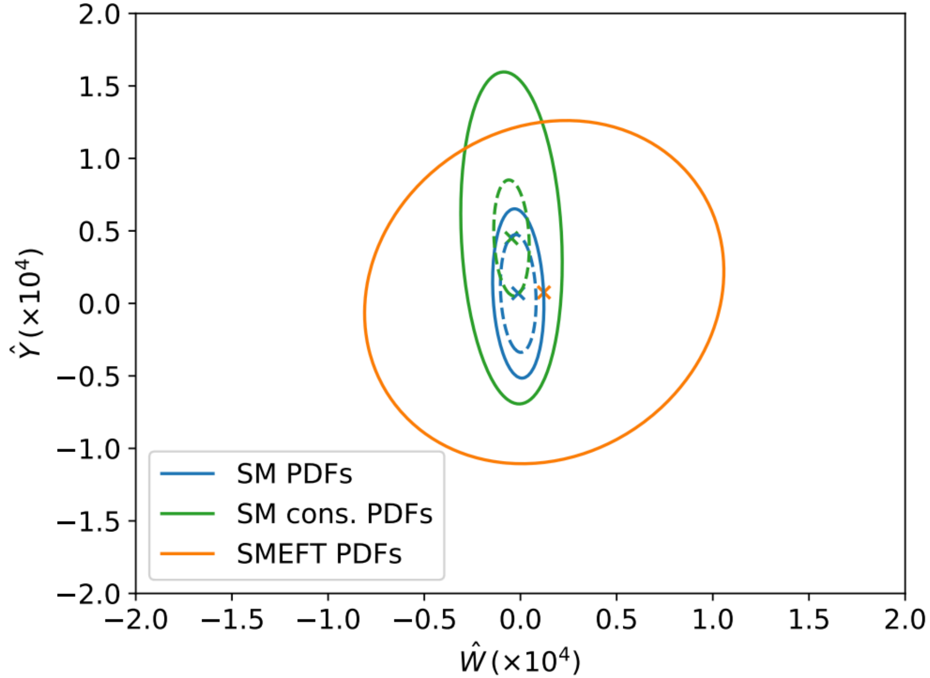
$$T = f_1(\hat{W}=0) \otimes f_2(\hat{W}=0) \otimes \hat{\sigma}(\hat{W})$$

PDF–SMEFT INTERPLAY IN HIGH-MASS DY TAILS

Greljo et al, 2104.02723



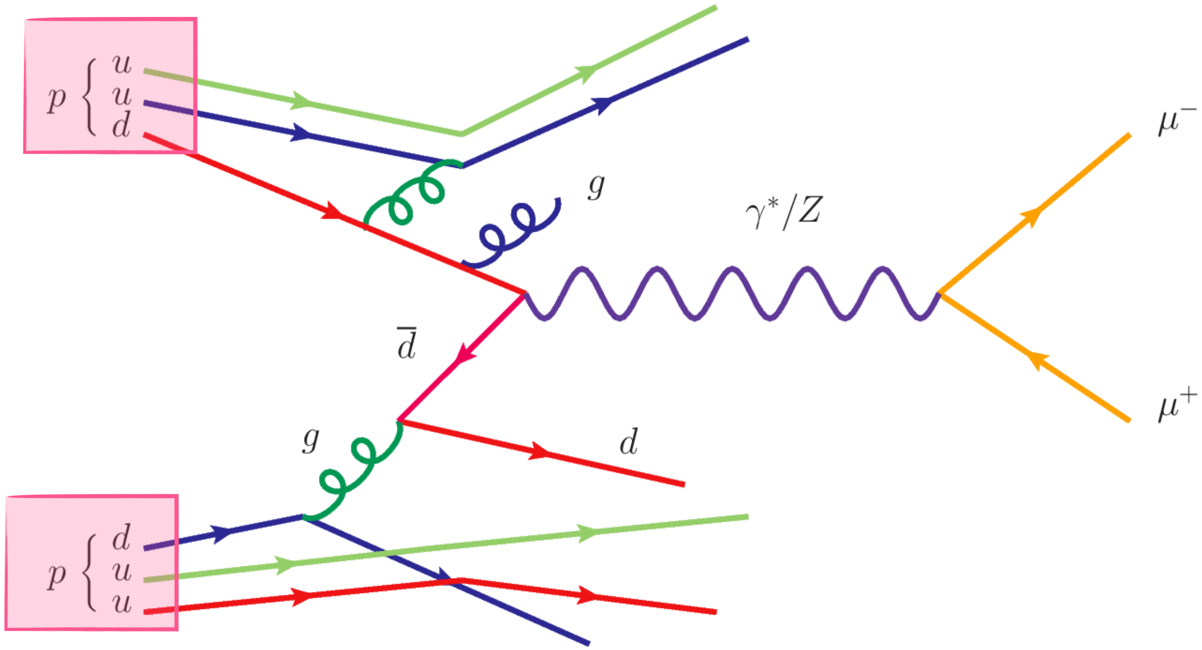
$$R_{\chi^2}(m_{\ell\ell}^{(\max)}, \hat{W}, \hat{Y}) \equiv \frac{\chi^2(m_{\ell\ell}^{(\max)}, \hat{W}, \hat{Y})}{\chi^2(120\ \mathrm{GeV}, \hat{W}, \hat{Y})}$$



- Compare Wilson coefficients bounds from HL-LHC projections assuming SM PDFs (including NC+CC data) to the bounds on the same Wilson coefficients obtained from a simultaneous scan of PDFs and WCs
- Not accounting for interplay (using PDFs as a black box) leads to over-constrained bounds
- PDFs do absorb effect of new physics in this case!
- CMS analysis on inclusive jet cross section points to a non-negligible interplay [CMS collaboration, 2111.10431]

MACHINE LEARNING FOR SIMULTANEOUS FITS

FROM INDIVIDUAL FITS…



$$d\sigma^{pp\to ab} = \sum_{i,j} f_i \otimes f_j \otimes d\hat{\sigma}^{ij\to ab} + \ldots$$

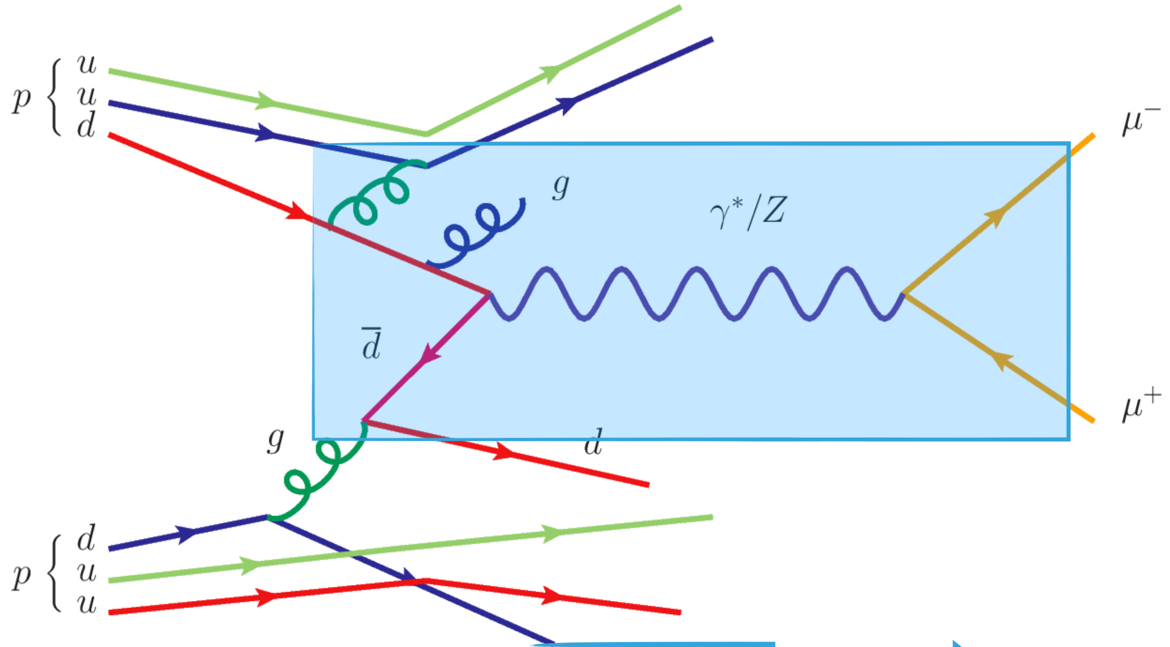
Fit of PDF
$\{\theta_i\}$

LHC Data

$f_i(\{\theta_k\})$

Assuming all data are
described by SM predictions

FROM INDIVIDUAL FITS…



$$d\sigma^{pp\to ab} = \sum_{i,j} f_i \otimes f_j \otimes d\hat{\sigma}^{ij\to ab} + \ldots$$

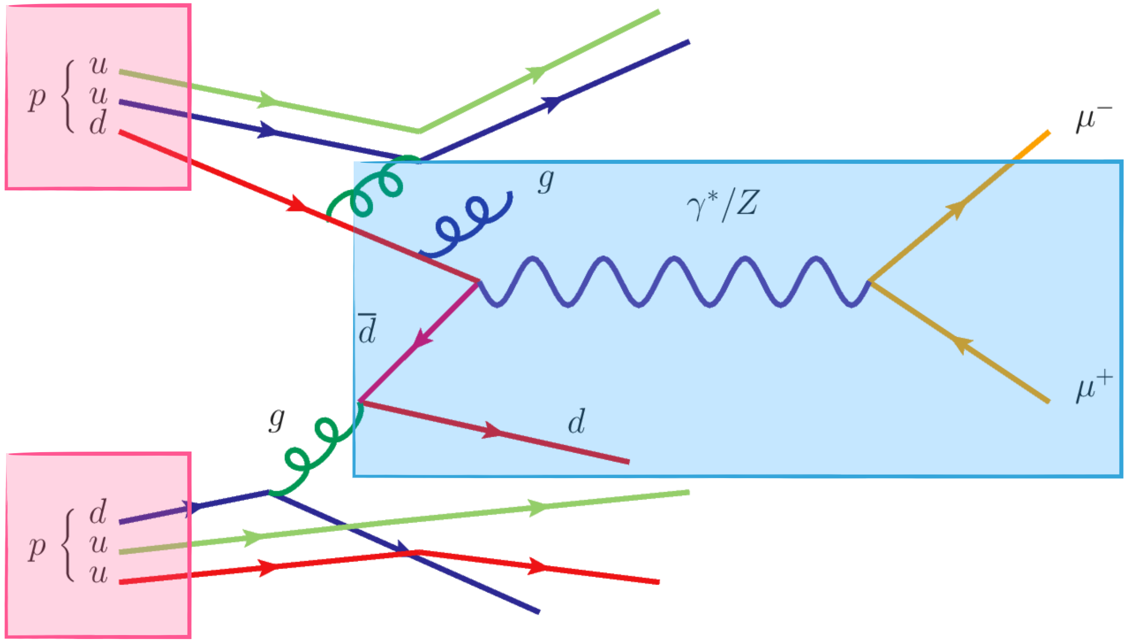
Fit of Wilson Coefficients $\{c_i\}$

LHC Data

Assuming PDFs are unaffected by non-zero c_i

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i^{(6)} + \cdots$$

. . . TO SIMULTANEOUS FITS?



$$d\sigma^{pp\to ab} = \sum_{i,j} f_i \otimes f_j \otimes d\hat{\sigma}^{ij\to ab} + \ldots$$

Simultaneous fits?

$$f_i(\{\theta_k\}) \qquad \mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i^{(6)} + \cdots$$

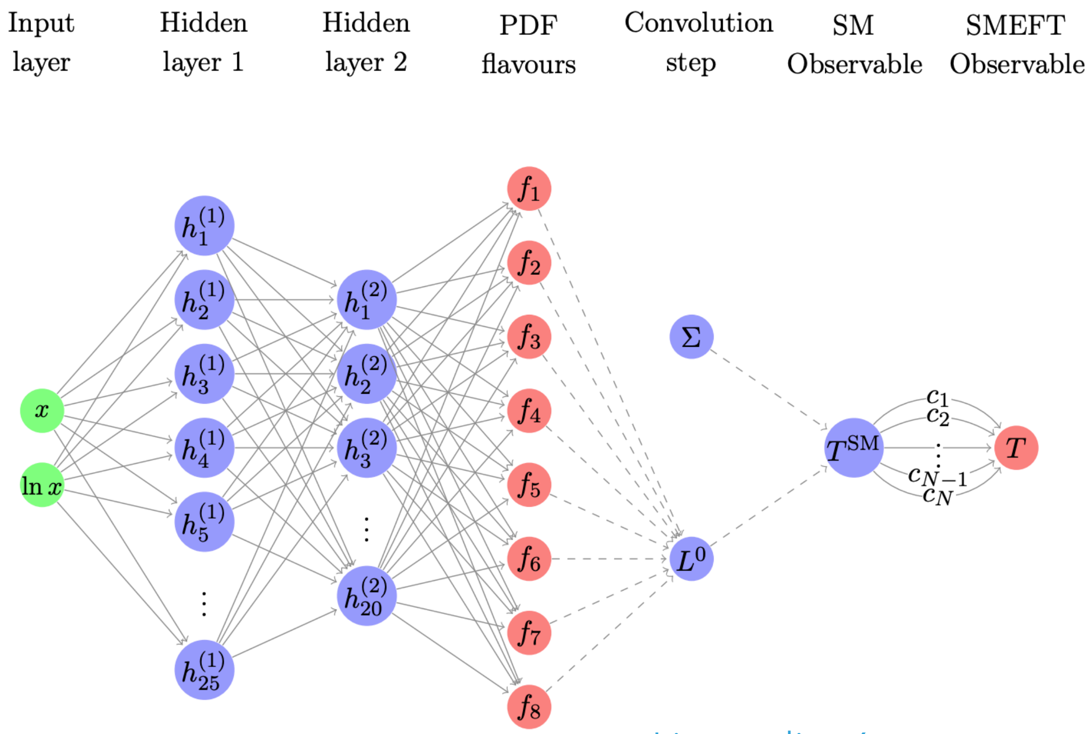
SIMUNET: A DEEP-LEARNING BASED SIMULTANEOUS FIT

- The idea: take a PDF fit based on NNPDF4.0 methodology and make dependence of observables on physics parameters $\{c_i\}$ explicit via fast interface before computing the loss function (e.g. adding SMEFT corrections, expanding observables in terms of SM precision parameters)

- Perform minimisation of loss function over

$$\hat{\theta} = \theta \bigcup \{c_i\}$$

by adding new layer to the deep neural network used in NNPDF4.0



Linear dim-6 operator

$$T(\hat{\theta}) = \Sigma(\{c_n\}) \cdot L^0(\theta) = T^{\rm SM}(\theta) \cdot \left(1 + \sum_{n=1}^{N} c_n R^{(n)}_{\rm SMEFT}\right)$$

S. Iranipour, MU - arXiv: 2201.07240

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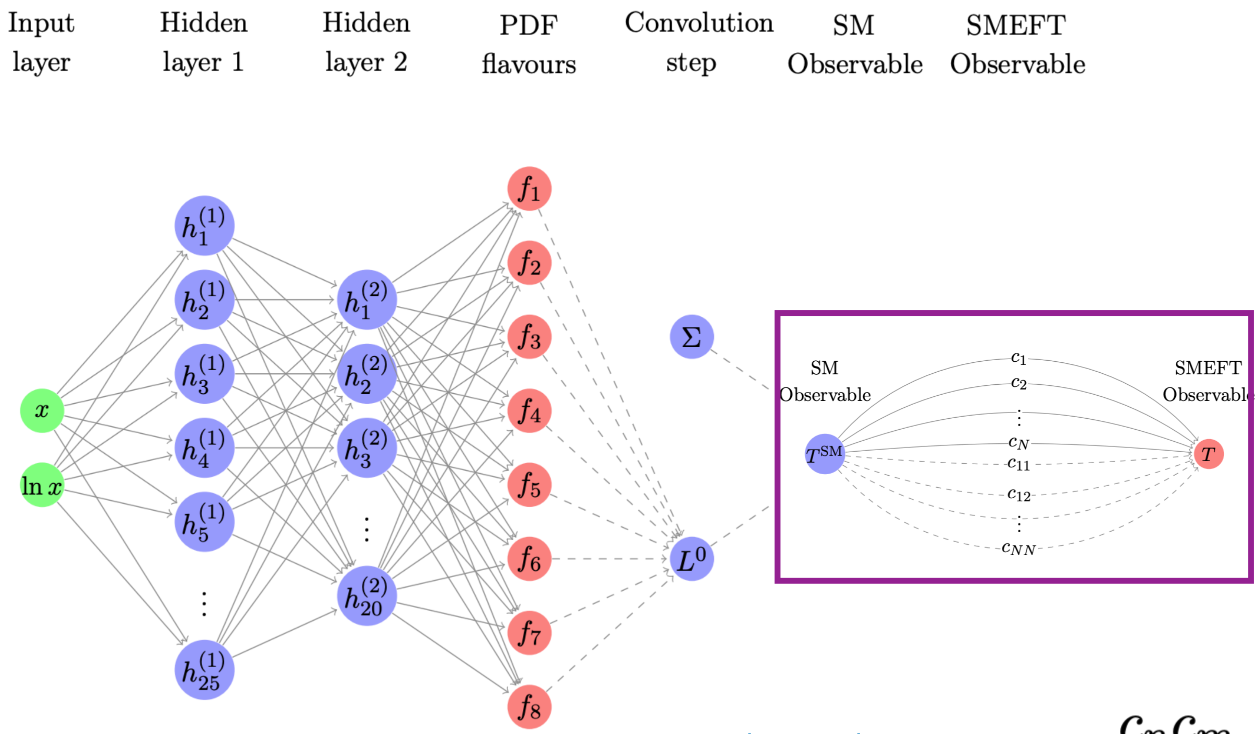
- The idea: take a PDF fit based on NNPDF4.0 methodology and make dependence of observables on physics parameters $\{c_i\}$ explicit via fast interface before computing the loss function (e.g. adding SMEFT corrections, expanding observables in terms of SM precision parameters)

- Perform minimisation of loss function over

$$\hat{\theta} = \theta \bigcup \{c_i\}$$

by adding new layer to the deep neural network used in NNPDF4.0

- Can expand dependence on c_i beyond linear terms in T (up to generic power in polynomial expansion) by adding non-trainable edges

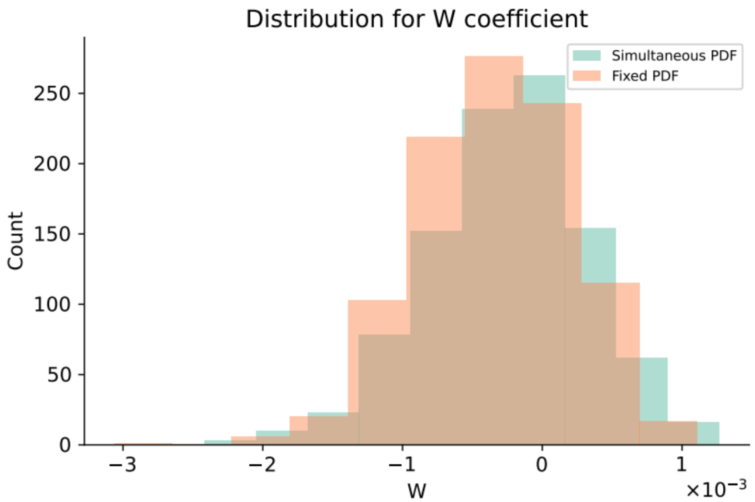


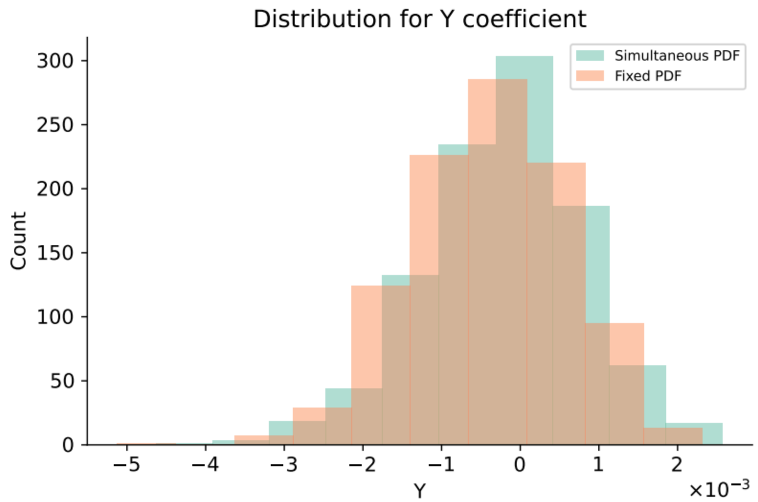
Quadratic dim-6 operator $c_n c_m$

$$T(\hat{\theta}) = T^{\rm SM}(\theta) \cdot \left(1 + \sum_{n=1}^{N} c_n R^{(n)}_{\rm SMEFT} + \sum_{1 \le n \le m \le N} c_{nm} R^{(n,m)}_{\rm SMEFT}\,,\right)$$

S. Iranipour, MU - arXiv: 2201.07240

RESULTS: DRELL-YAN DATA @RUN1 AND RUN2

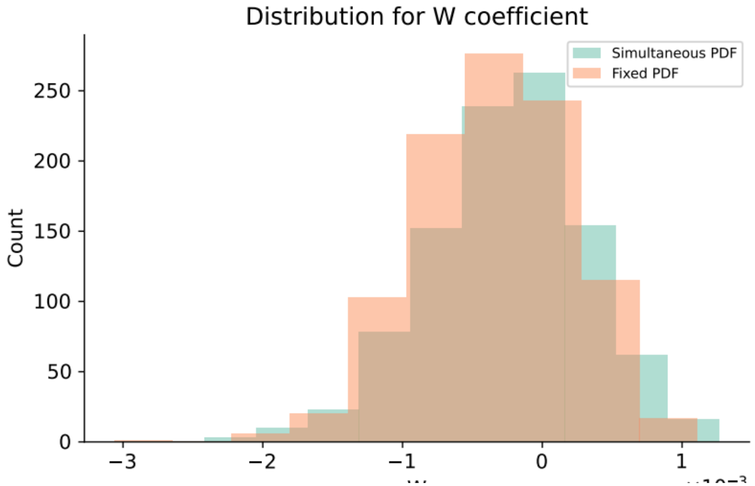


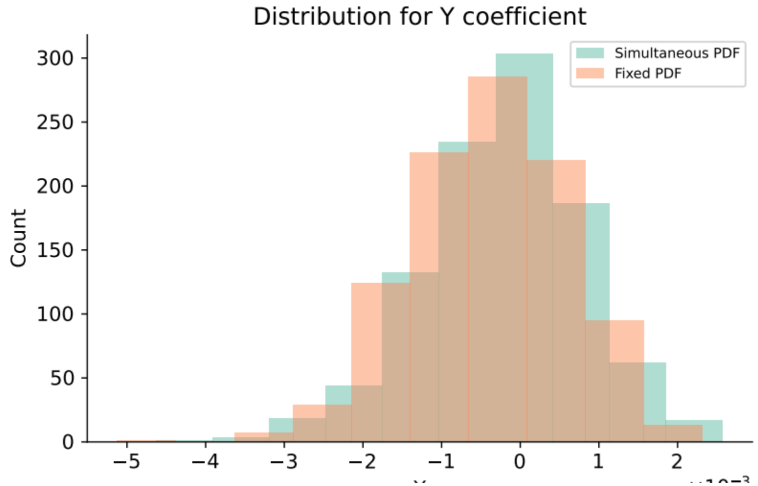


Distribution of W & Y best fits over MC reps with fixed SM PDFs (baseline)

Distribution of W & Y best fits over MC reps with PDFs fitted alongside them

RESULTS: DRELL-YAN DATA @RUN1 AND RUN2





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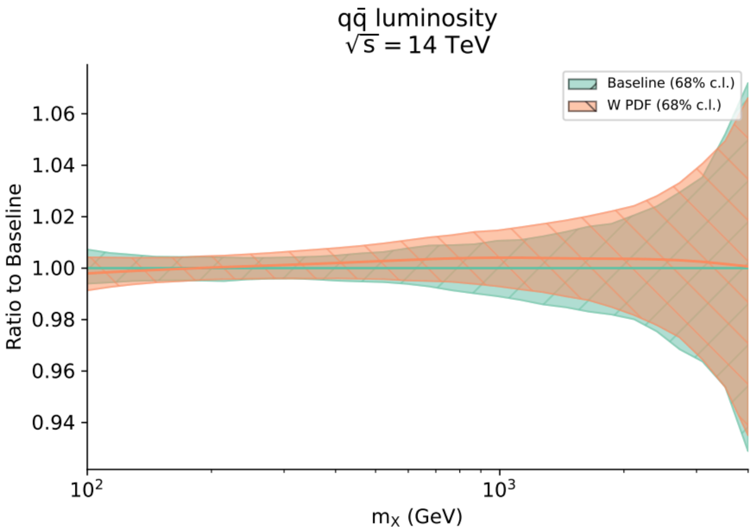
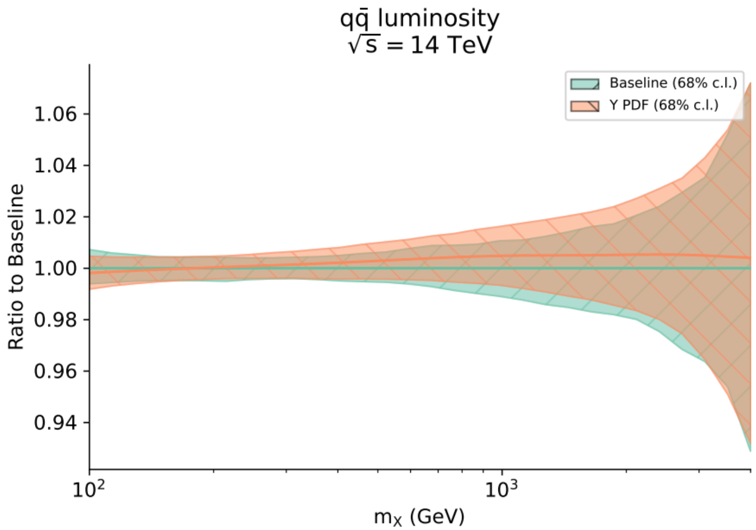
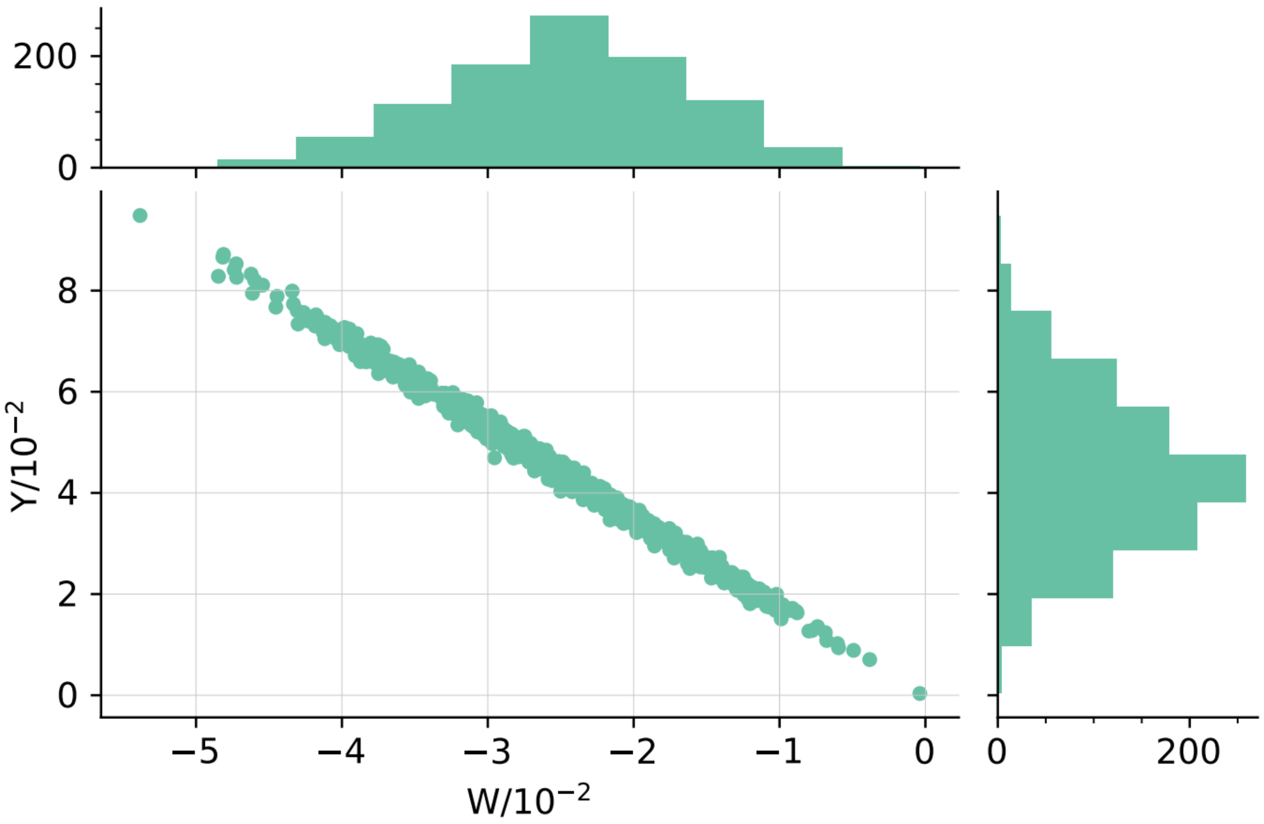




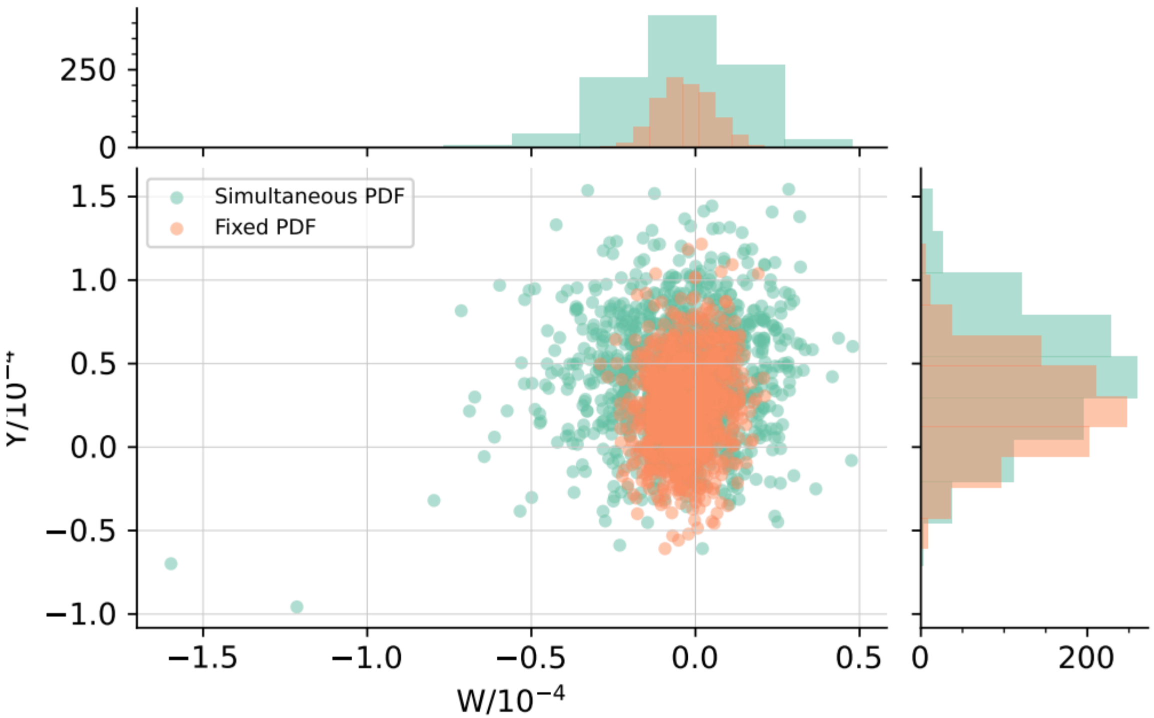
Same comparison for quark-antiquark luminosity

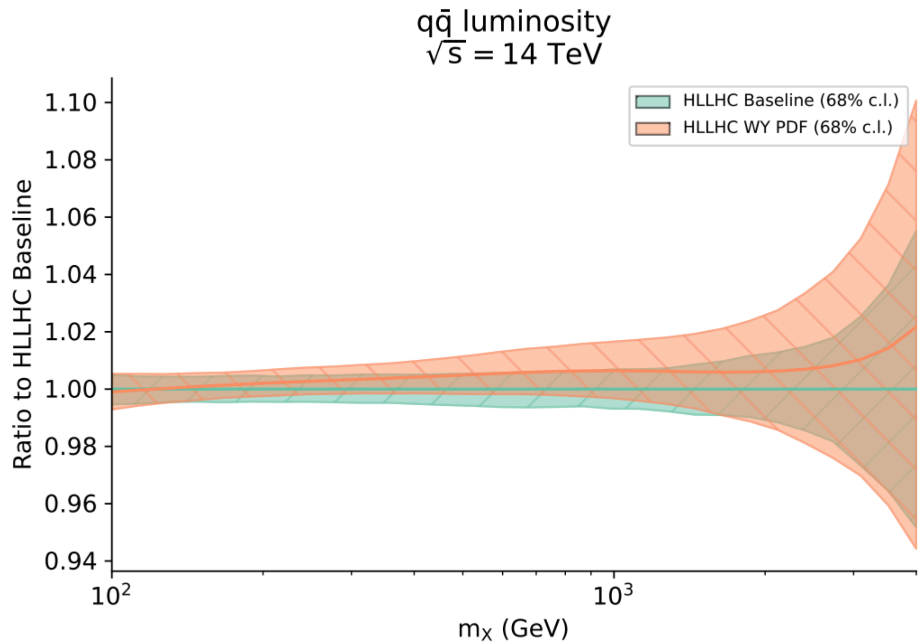
RESULTS: DRELL-YAN DATA @RUN1 AND RUN2



- ✓ Simultaneous analysis confirms results of previous study based on scan on benchmark points in the SMEFT space: with current data effect is not-negligible but small compared to PDF uncertainties
- ✓ Methodology able to find flat direction in W-Y parameter space
- ✓ To eliminate it, need Drell-Yan charged current data

RESULTS: DRELL-YAN DATA @HL-LHC





✓ When adding HL-LHC projections in the Neutral- Current and Charged-Current channels, W and Y can be fitted simultaneously without any flat directions

✓ Simultaneous analysis confirms results of previous study based on scan on benchmark points in the SMEFT space: at HL-LHC the effect of interplay becomes important as WCs bounds broaden and PDFs change significantly once SMEFT effects allowed in theory predictions entering PDF fit

✓ Stress-tested and shown robustness with closure tests

CONCLUSIONS AND OUTLOOK

- While huge progress made in determining key ingredients of theoretical predictions from the data, PDFs, α_s, SMEFT WCs coefficients, it is not yet evident how to combine all these partial fits into a global interpretation of the LHC data
- Time to wok on new generation of global fits, in which all ingredients that enter theoretical predictions are treated consistently.
- SimuNET methodology based on an extension of the NNPDF4.0 NN architecture, allows the addition of an extra layer to simultaneously determine PDFs alongside an arbitrary number of physics parameters that enter predictions.
- Proof-of-concept on simultaneous determination of W and Y oblique parameters and PDFs from DIS+DY fit

- Lots of exciting avenues being explored:
  - ➡Determination of PDFs and SMEFT coefficients in the top sector (Kassabov, Madigan, Mantani, Moore, Morales, Rojo, MU)
  - ➡Systematic study of new physics contamination in PDF fits
  - ➡ Inclusion of light new physics particle (McCullogh, Moore, MU arXiv:2203.12628)

THANK YOU FOR YOUR ATTENTION!

EXTRA MATERIAL

ANALYSIS METHODOLOGY

- We performed a similar analysis as in Torre et al, now with emphasis on PDF and their interplay with bounds on oblique operators
  [Greljo, Iranipour, Kassabov, Madigan, Moore, Rojo, MU, Voisey: 2104.02723]

$$\chi^2 = \frac{1}{n_{\rm dat}} \sum_{i,j=1}^{n_{\rm dat}} (D_i - T_i)\,({\rm cov}^{-1})_{ij}\,(D_j - T_j)$$

1. Take data, make theoretical predictions accounting for operator in partonic cross section with fixed SM PDFs.
2. Compute chi2 as a function of WCs (Wilson Coefficients)
3. Minimise chi2 and find best-fit and C.L.s of WCs
4. Extract bounds

$$T = f_{1,\rm SM} \otimes f_{2,\rm SM} \otimes \hat{\sigma}_{\rm BSM}$$

SM PDFs

1. Take data, make theoretical predictions accounting for operator in partonic cross section and PDFs.
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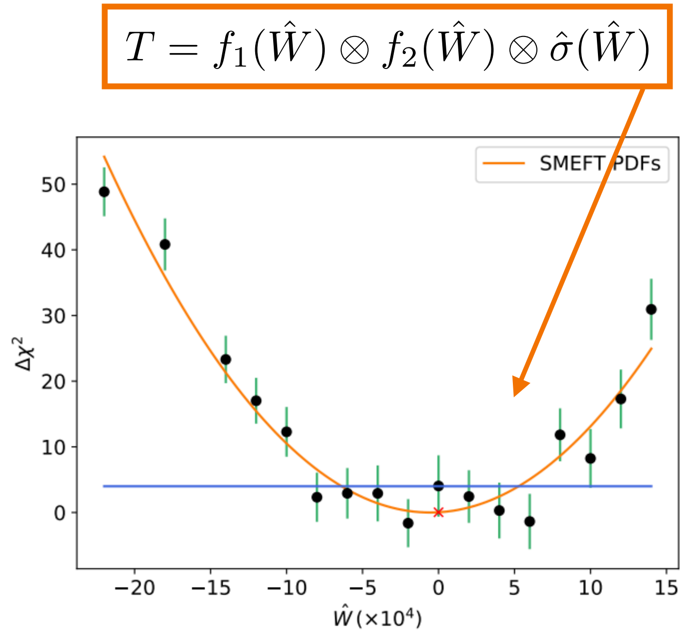
SMEFT PDFs / Simultaneous fit

ANALYSIS METHODOLOGY

- We performed a similar analysis as in Torre et al, now with emphasis on PDF and their interplay with bounds on oblique operators
[Greljo, Iranipour, Kassabov, Madigan, Moore, Rojo, MU, Voisey: 2104.02723]

- Methodology for simultaneous fit is similar to the one adopted in fits of α_S from a global fit of PDFs

$$\chi^2 = \frac{1}{n_{\rm dat}} \sum_{i,j=1}^{n_{\rm dat}} (D_i - T_i)\,({\rm cov}^{-1})_{ij}\,(D_j - T_j)$$



Greljo et al, 2104.02723

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SM PDFs

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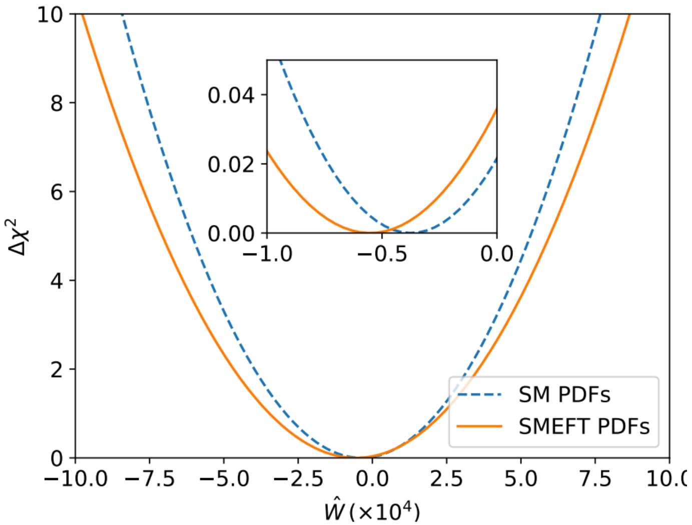
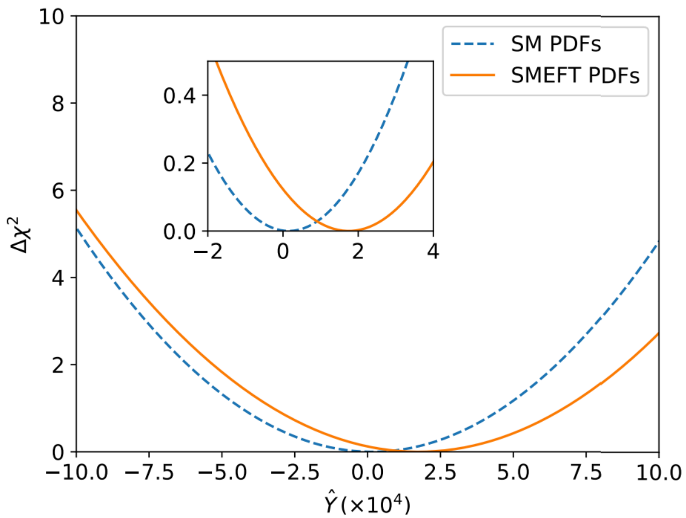
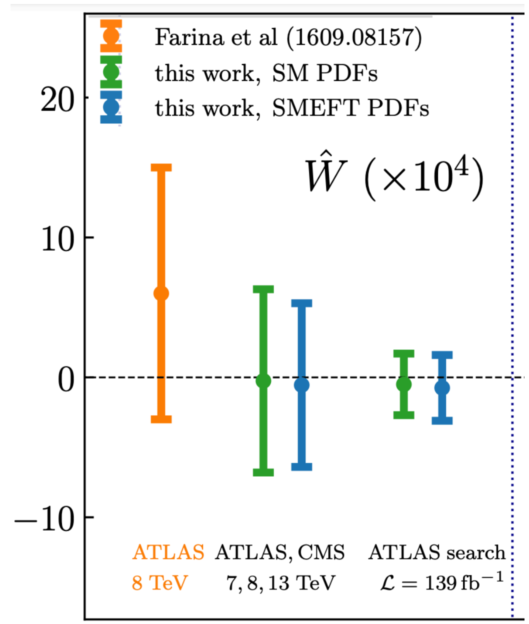
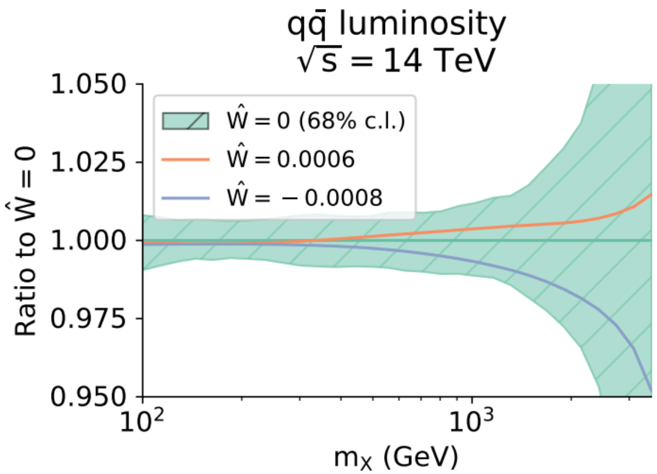
SMEFT PDFs / Simultaneous fit

INTERPLAY @ RUN I AND RUN II







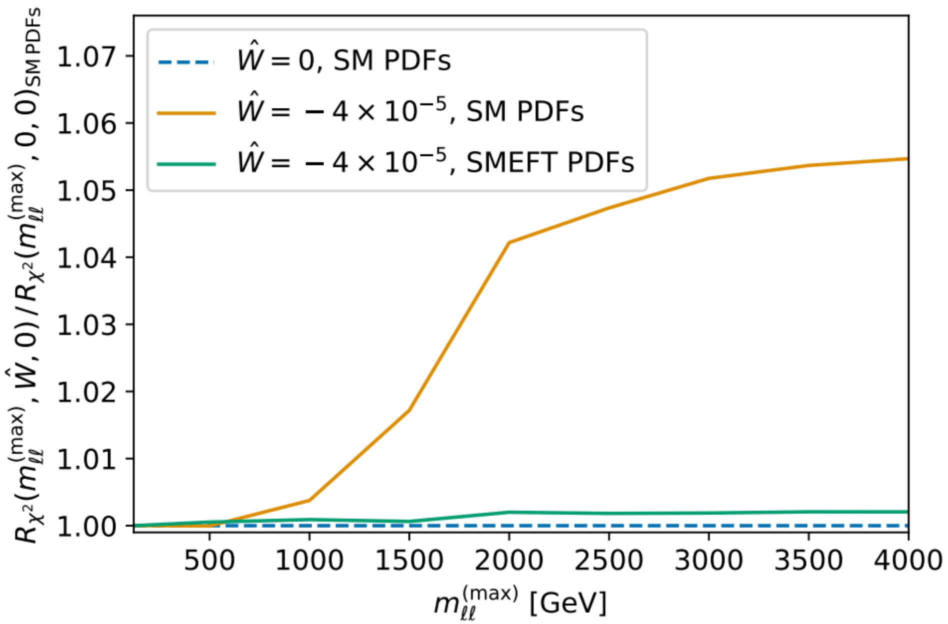


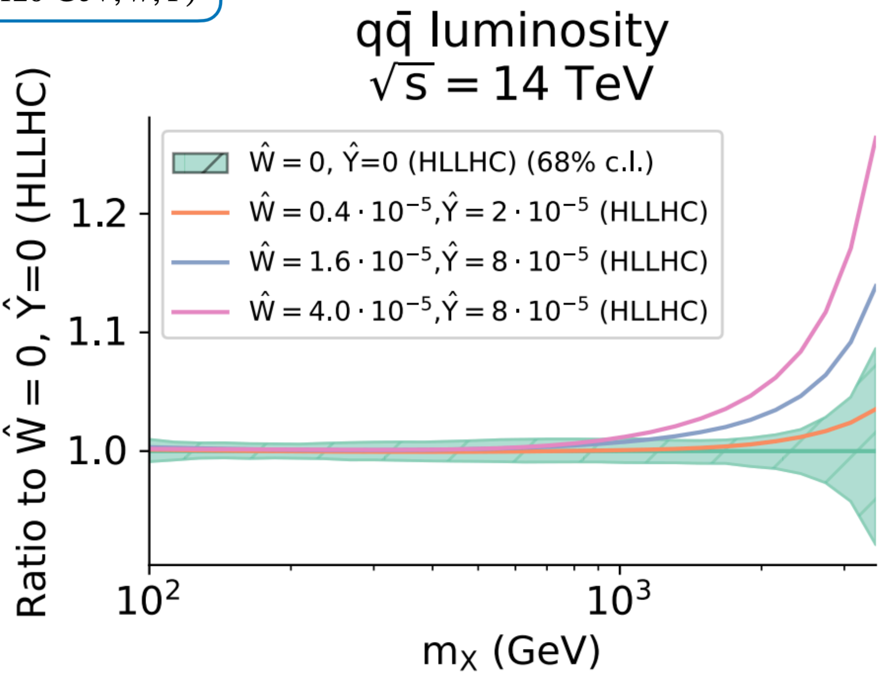
- With current data, PDFs are moderately affected by inclusion of non-zero W and Y coefficients in the fit, mostly quark-antiquark luminosity within uncertainties
- Broadening of individual bounds on W and Y once SMEFT PDFs are used (i.e. PDFs that have been fitted with consistent values of W and Y) is not negligible, but still within PDF uncertainties
- If SMEFT PDFs are used in determining bounds from ATLAS search same mild broadening (larger than PDF uncertainties)

INTERPLAY @ HL-LHC

- Compare Wilson coefficients bounds from HL-LHC projections assuming SM PDFs (that include NC+CC data) to the bounds on the same Wilson coefficients obtained from a simultaneous fit of PDFs and Wilson coefficients
- Not accounting for interplay (using PDFs as a black box) leads to over-constrained bounds
- PDFs do absorb effect of new physics in this case!

$$R_{\chi^2}(m_{\ell\ell}^{(\max)}, \hat{W}, \hat{Y}) \equiv \frac{\chi^2(m_{\ell\ell}^{(\max)}, \hat{W}, \hat{Y})}{\chi^2(120\ \text{GeV}, \hat{W}, \hat{Y})}$$





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