The top quark legacy of the LHC Run II for PDF and SMEFT analyses

for HEFT 2023, in Manchester

James Moore, University of Cambridge

PBSP: Physics Beyond the Standard Proton

- The **PBSP group** is based at the **University of Cambridge**, and is headed by **Maria Ubiali**; the project is **ERC-funded.**
- The aim is to **investigate interplay between BSM physics and proton structure** - the subject of the rest of this talk!
- The team members are:
  - *Postdocs:* Zahari Kassabov, Maeve Madigan, Luca Mantani
  - *PhD students:* Mark Costantini, Shayan Iranipour (*former*), Elie Hammou, **James Moore**, Manuel Morales, Cameron Voisey (*former*)

Talk overview

1. Joint PDF-SMEFT fits

2. The SIMUnet methodology

3. The top quark legacy of the LHC Run II for PDF and SMEFT analyses

1. - Joint PDF-SMEFT fits

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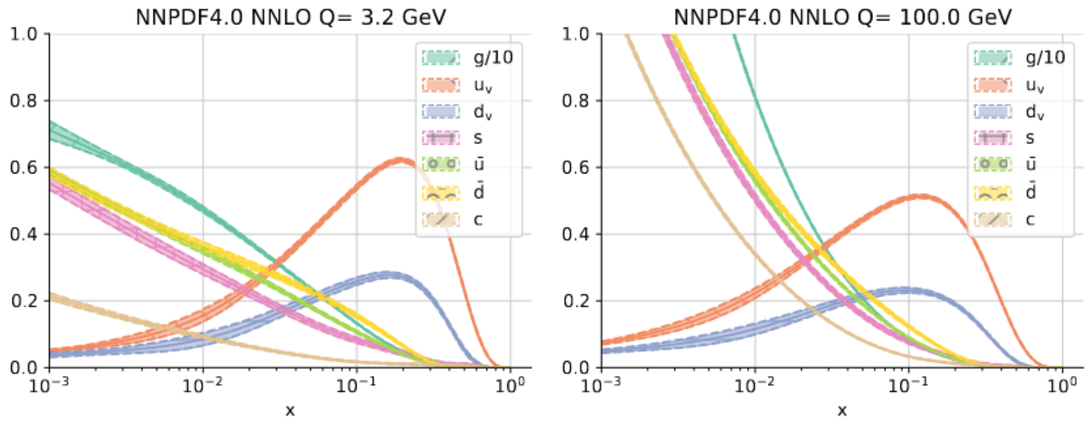

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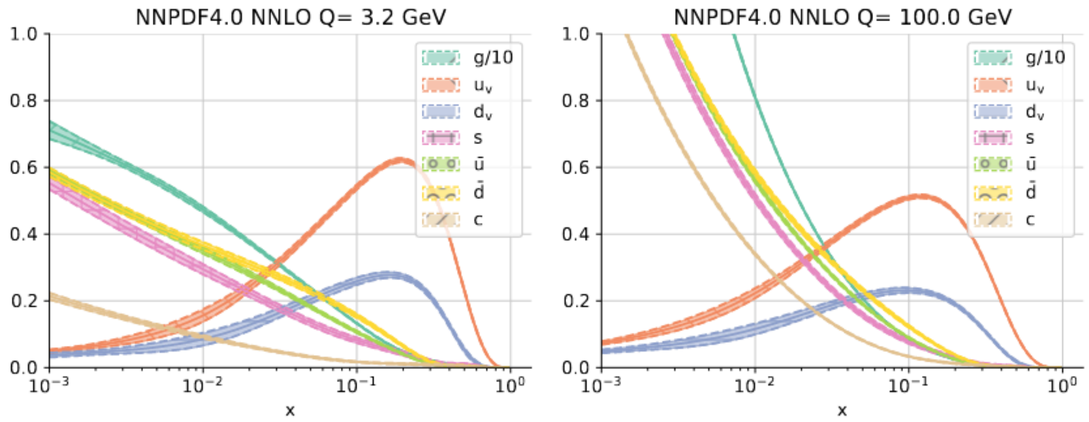

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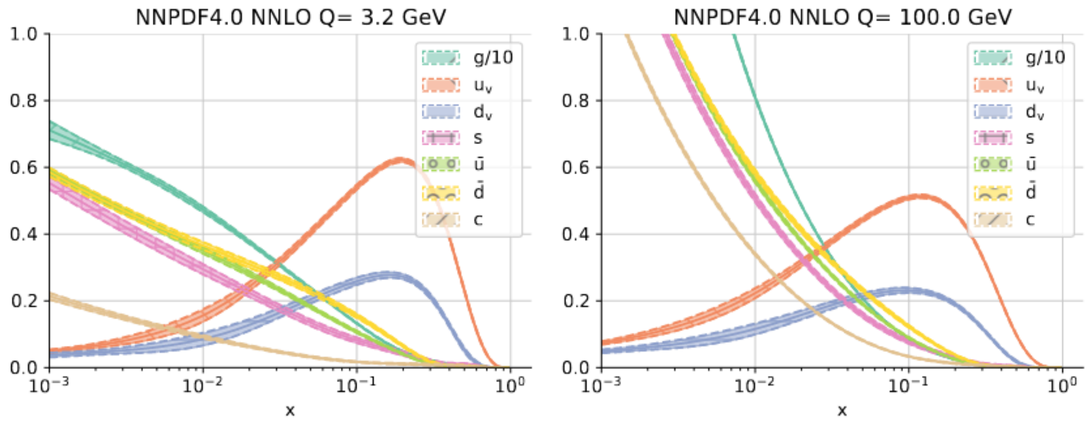

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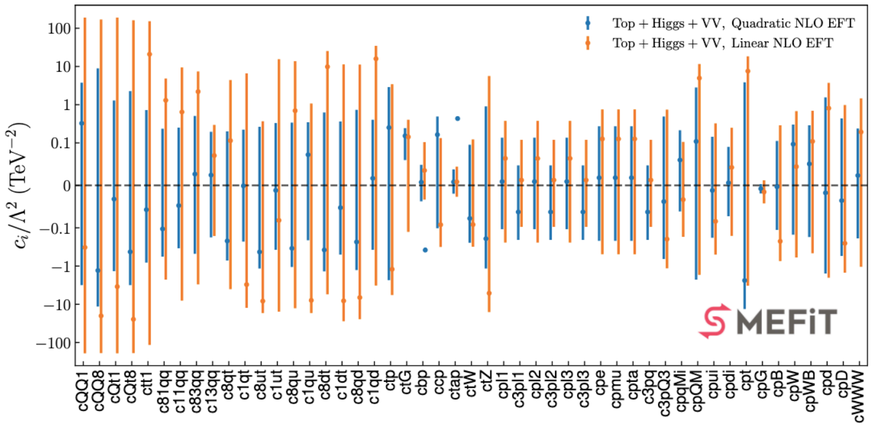

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- In particular, if we fit PDFs **assuming all SMEFT couplings are zero**, but then **use those PDFs in a fit of SMEFT couplings**, our resulting bounds **could be misleading**. The same applies to SM parameters.
- We could even **miss New Physics**, or **see New Physics that isn't really there**!

PDF-SMEFT interplay: natural questions

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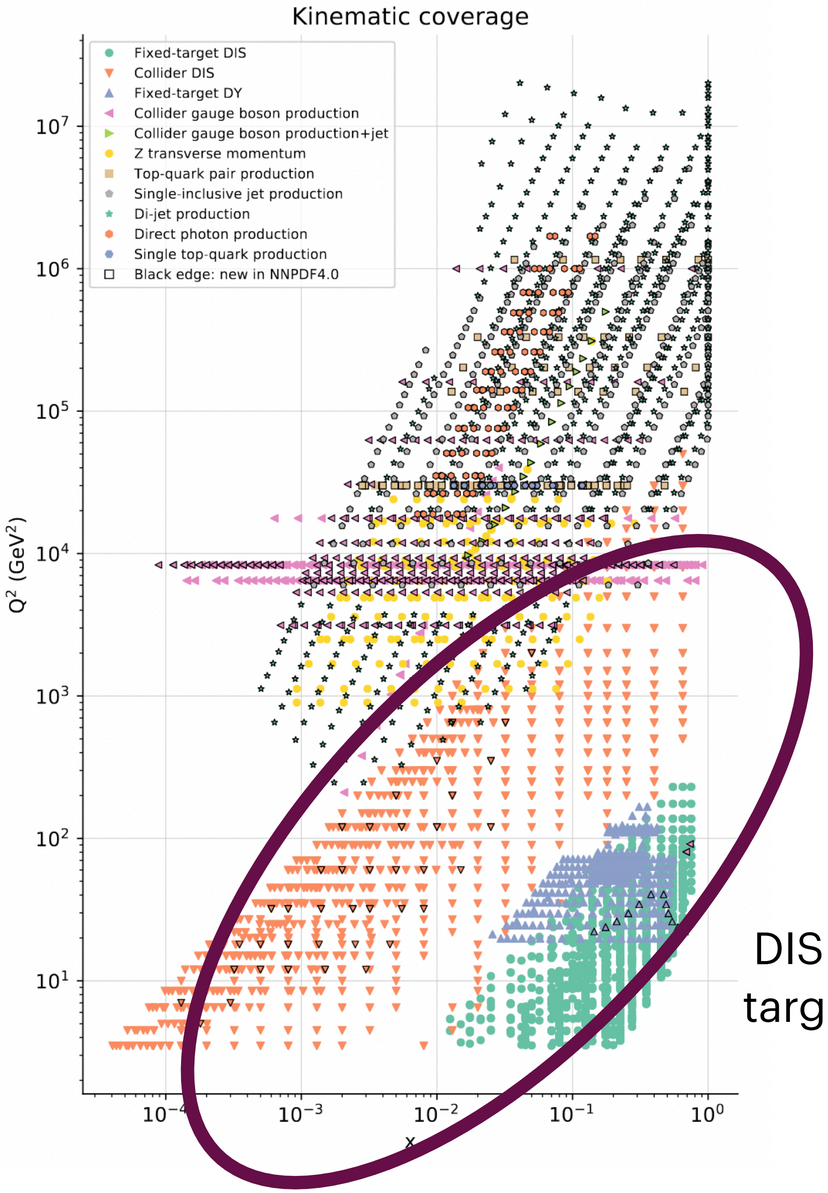
  - It depends on the SMEFT operators. Some operators (e.g. four-fermion operators) will **contaminate DIS and DY data**, which comprise the majority of the data going into PDF fits. So often '*uncontaminated PDFs' don't exist*!
  - Right: kinematic coverage of NNPDF4.0 by dataset.



DIS and fixed target DY data

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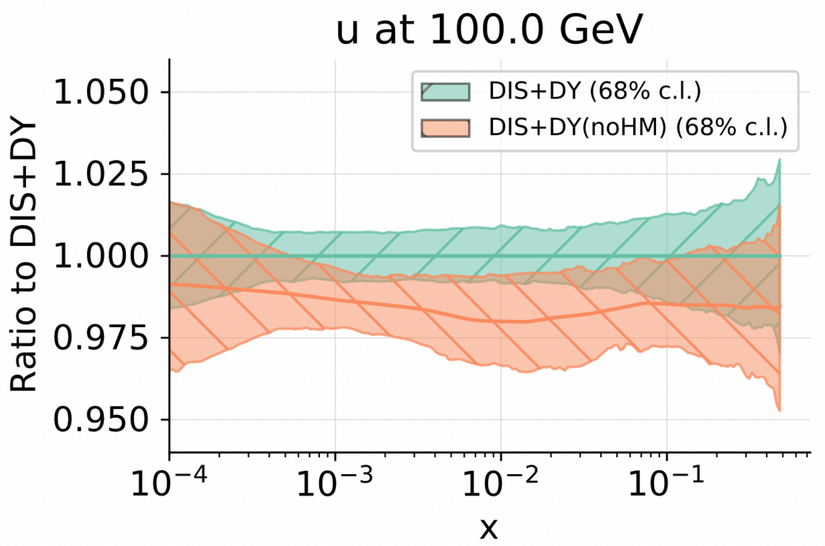
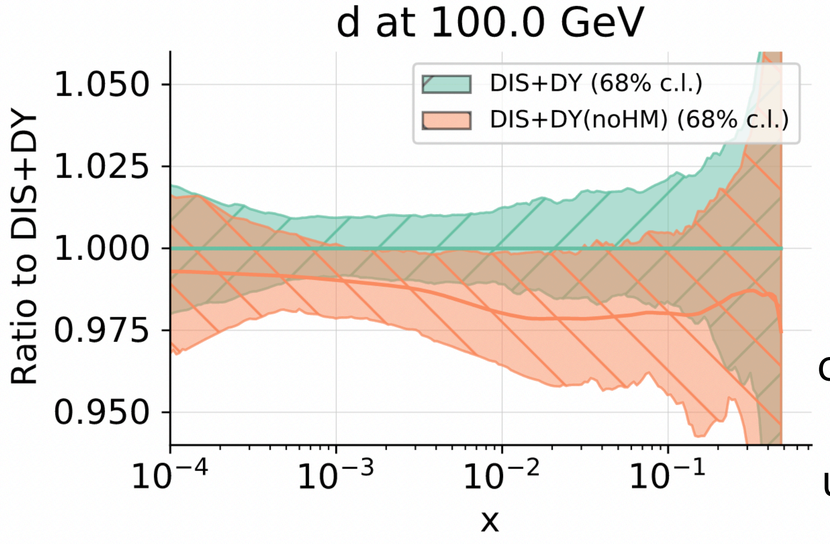
- *Question 1:* **Can't I just use PDF sets which are fitted using data that is not affected by SMEFT operators?**

  - Furthermore, if we include more data in a PDF fit, we obtain **better quality fits**. Therefore, we expect that using 'uncontaminated PDFs' will result in **poorer quality SMEFT fits**; we won't be using the 'best quality' PDFs that are available - this is shown explicitly in *Greljo et al., 2104.02723*, where PDF sets including and excluding high-mass DY data are compared.





without certain DY data points, high-x uncertainty increases

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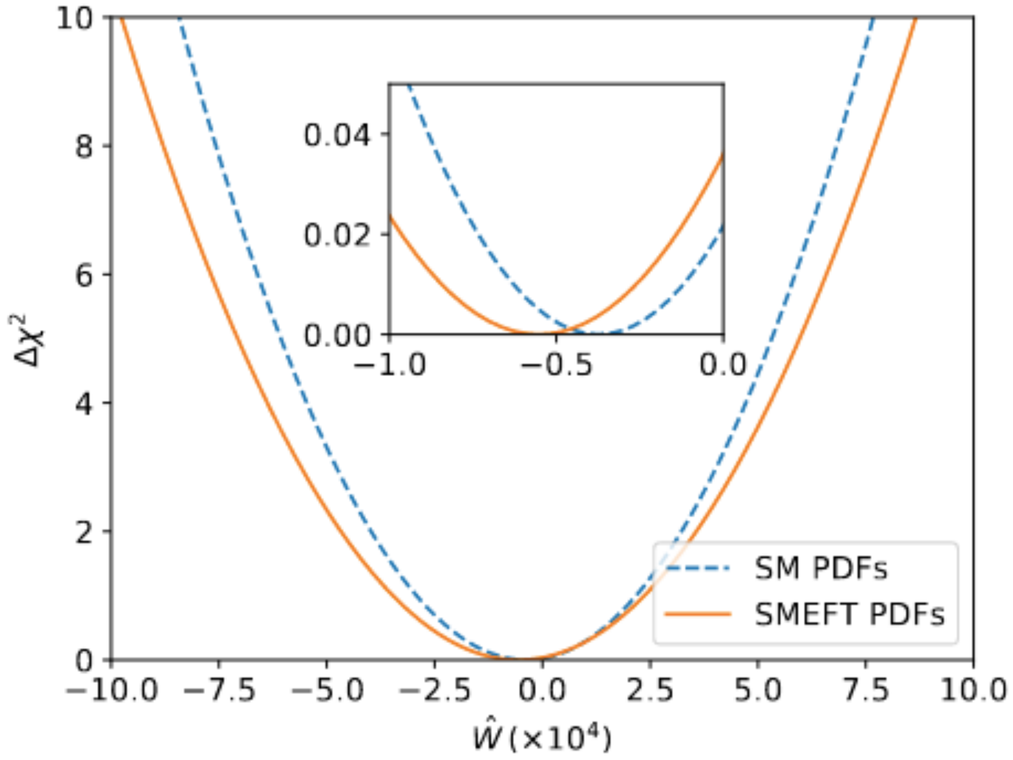
  - It depends on the scenario!
  - It was shown in *Carrazza et al., 1905.05215*, that interplay is very mild in the case of simultaneous extractions of four-fermion operators and PDFs using DIS-only data.
  - Similarly, it was shown in the PBSP team's earlier study, *Greljo et al., 2104.02723*, that interplay is mild between the $\hat{W}$, $\hat{Y}$ operators and PDFs using current DIS and DY data.



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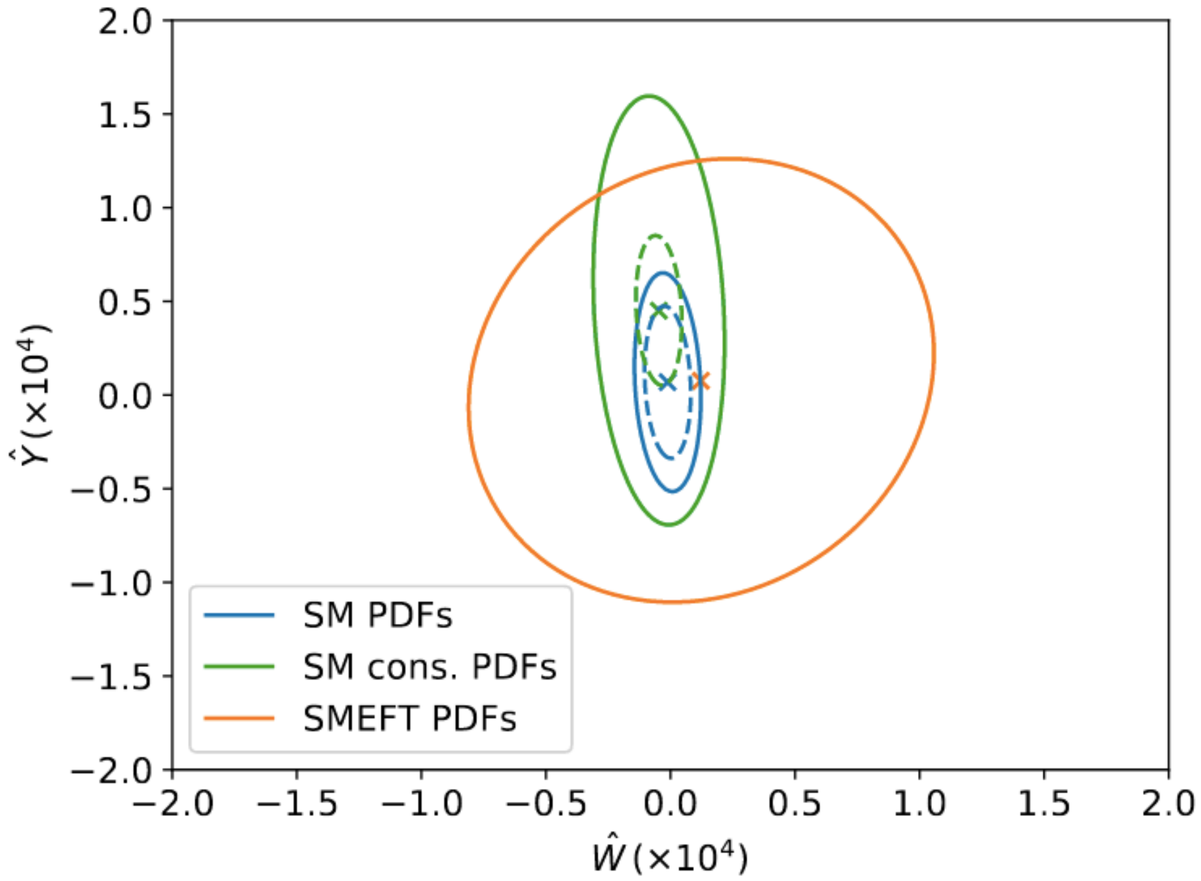
- *Question 2*: **Won't the PDF-SMEFT interplay be negligible?**
  - *However,* it was also shown in *Greljo et al., 2104.02723*, that interplay is **very significant** between the $\hat{W}$, $\hat{Y}$ operators and PDFs using **projected high-luminosity DY data**.



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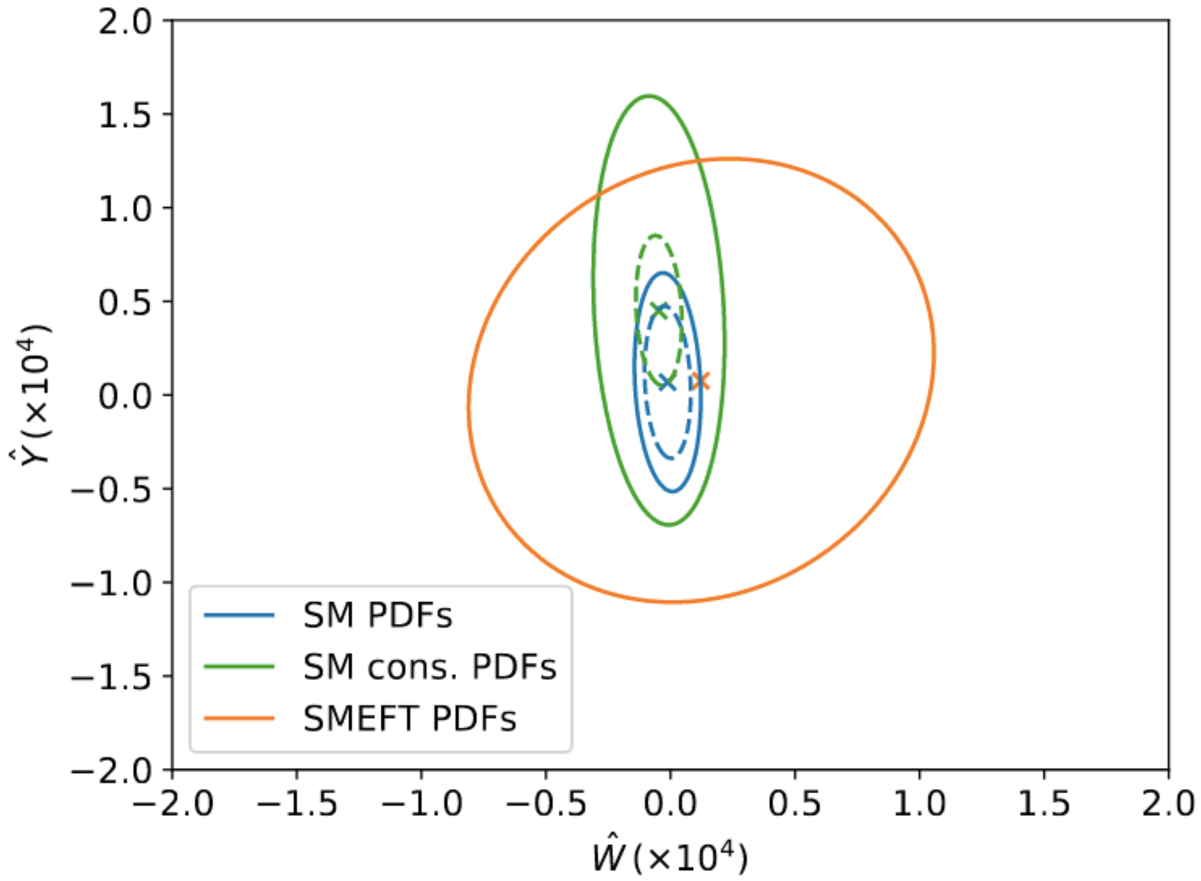
  - We see that using fixed PDFs results in a **significant underestimation** of uncertainties on the WCs - we might wrongly conclude **New Physics**!



2. - The SIMUnet methodology for joint PDF-SMEFT fits

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- There are three main methodologies available: (i) a **scan** in Wilson coefficient space (see 1905.05215 and 2104.02723); (ii) the **CTEQ-TEA** methodology (see 2201.06586 and 2211.01094); (iii) the **SIMUnet** methodology (see 2201.07240).

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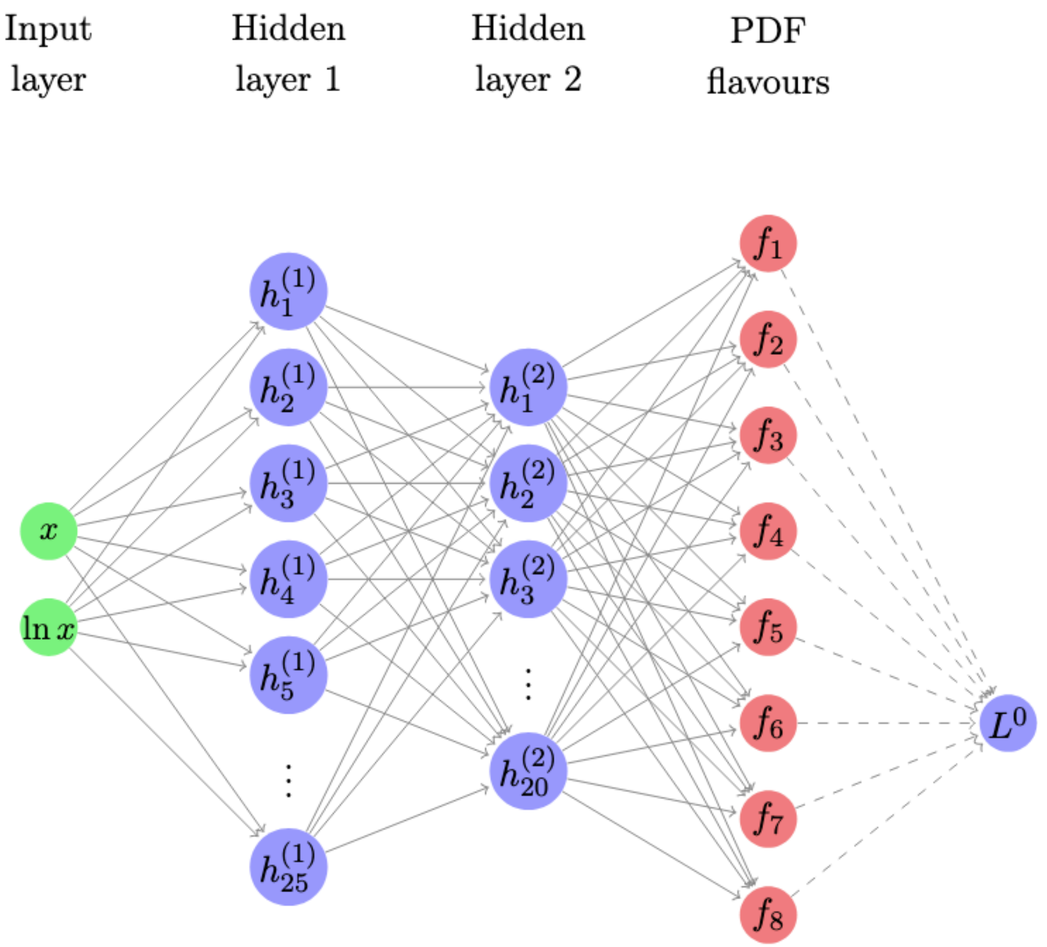
- We will focus only on **SIMUnet**.

The SIMUnet methodology: details

- The SIMUnet methodology **extends the existing NNPDF neural network** with an additional **convolution layer**.



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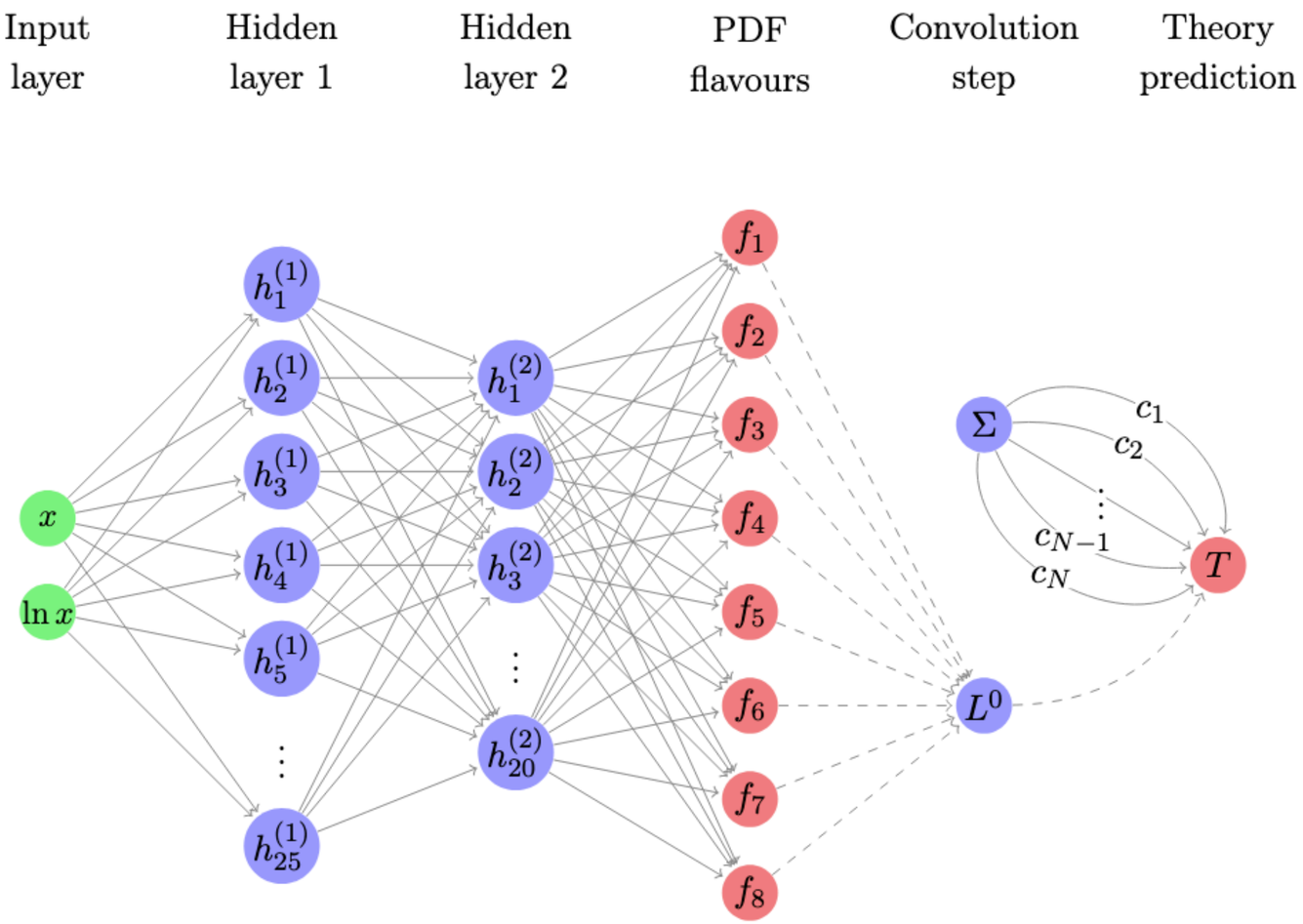

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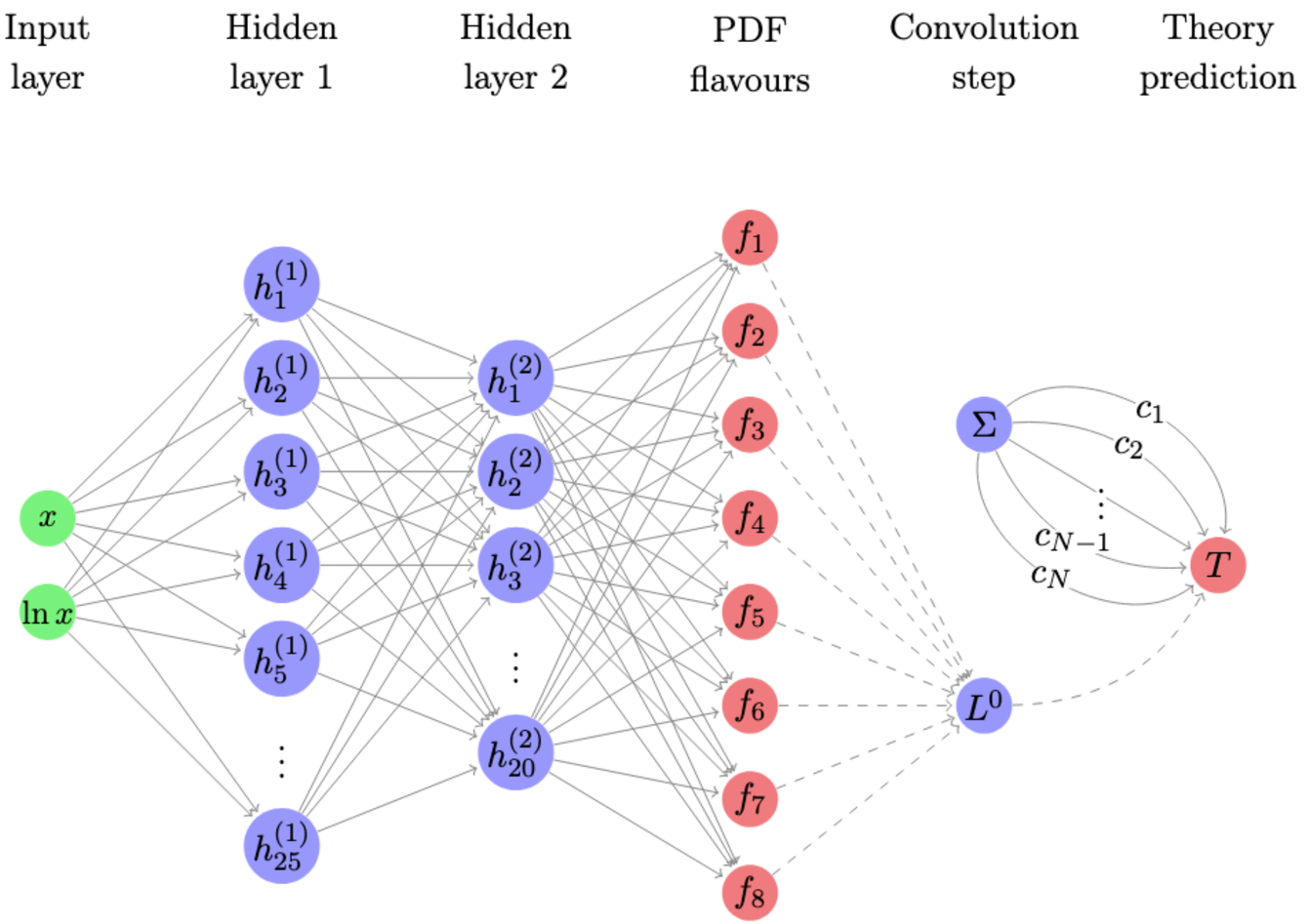

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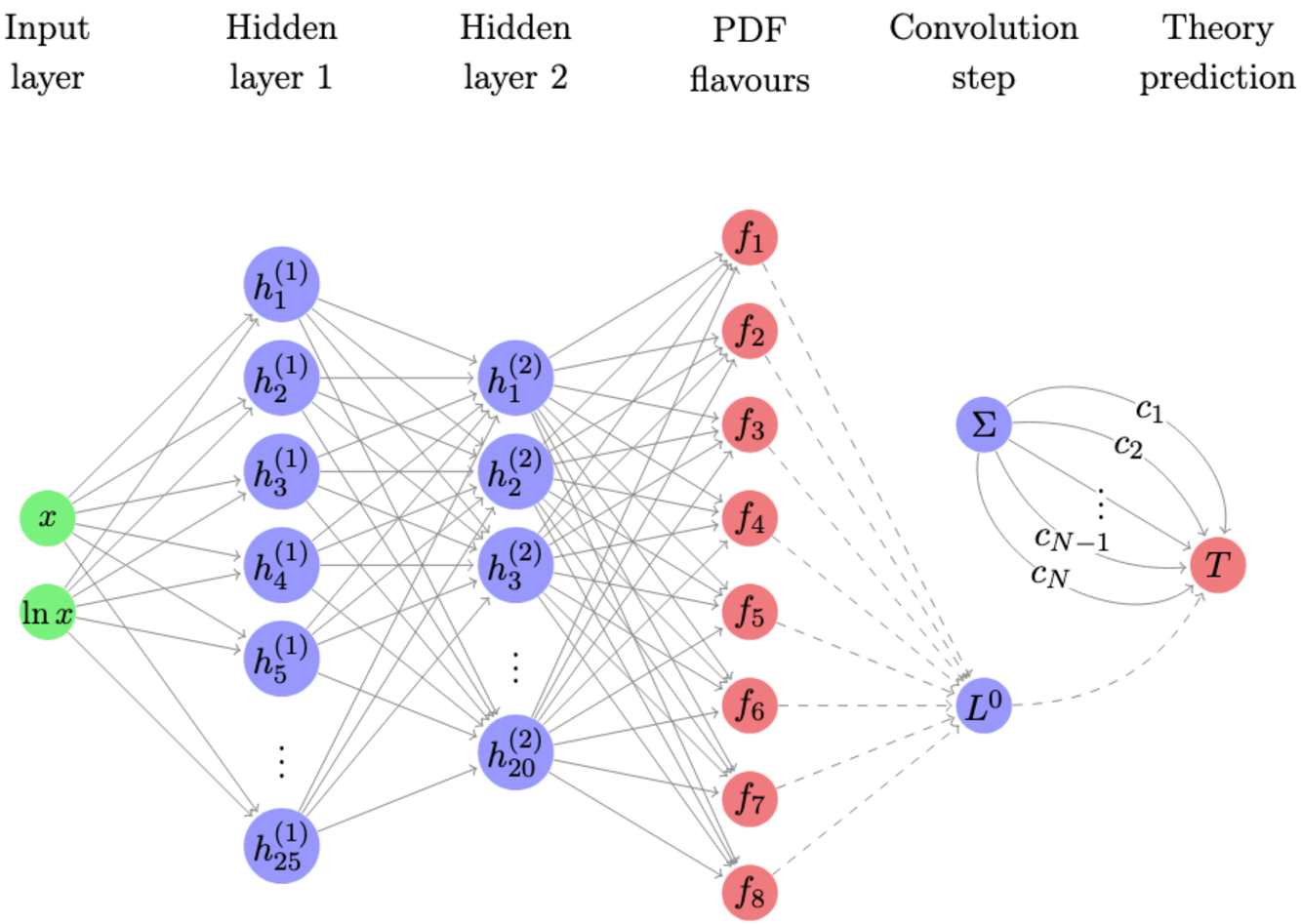

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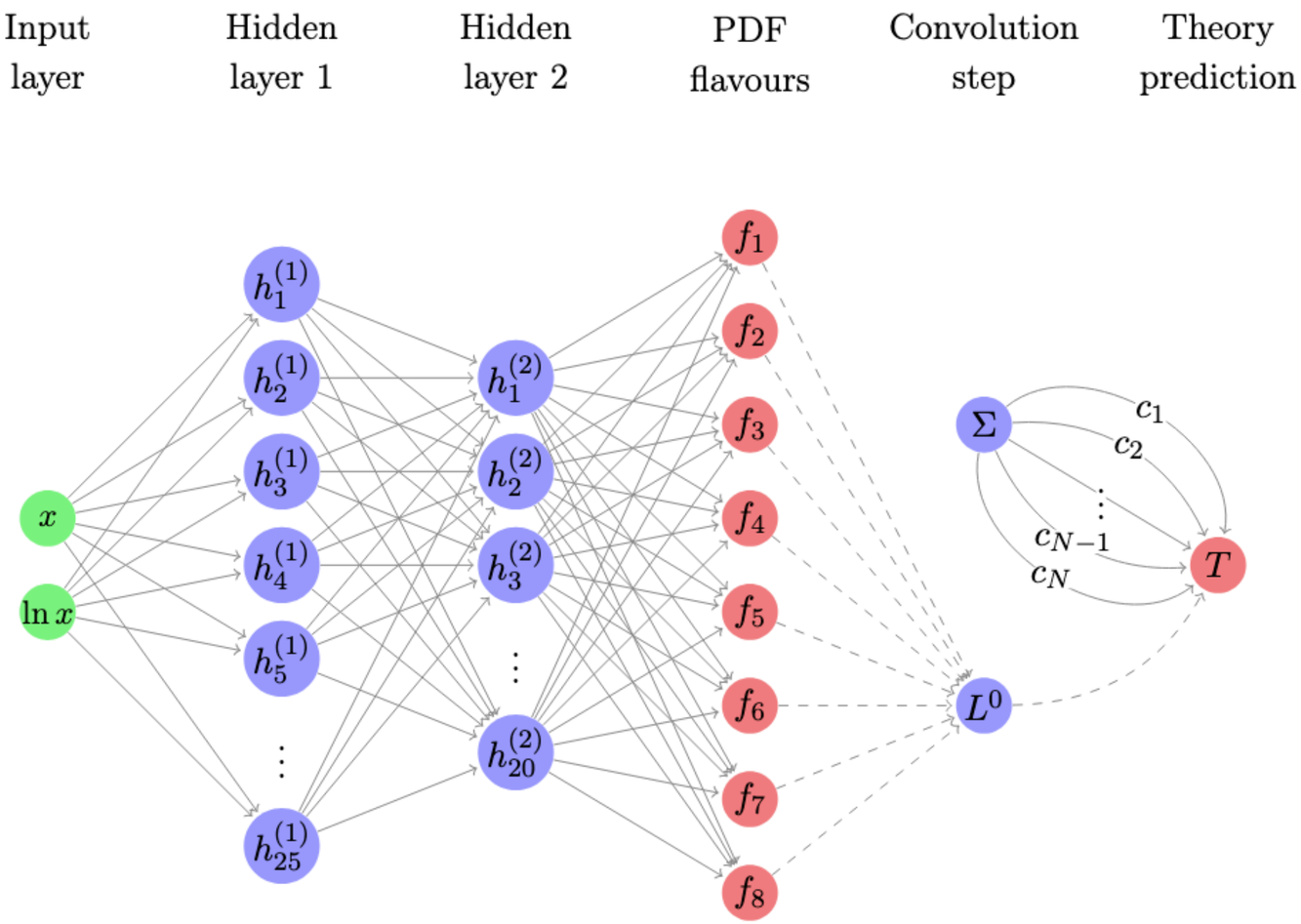

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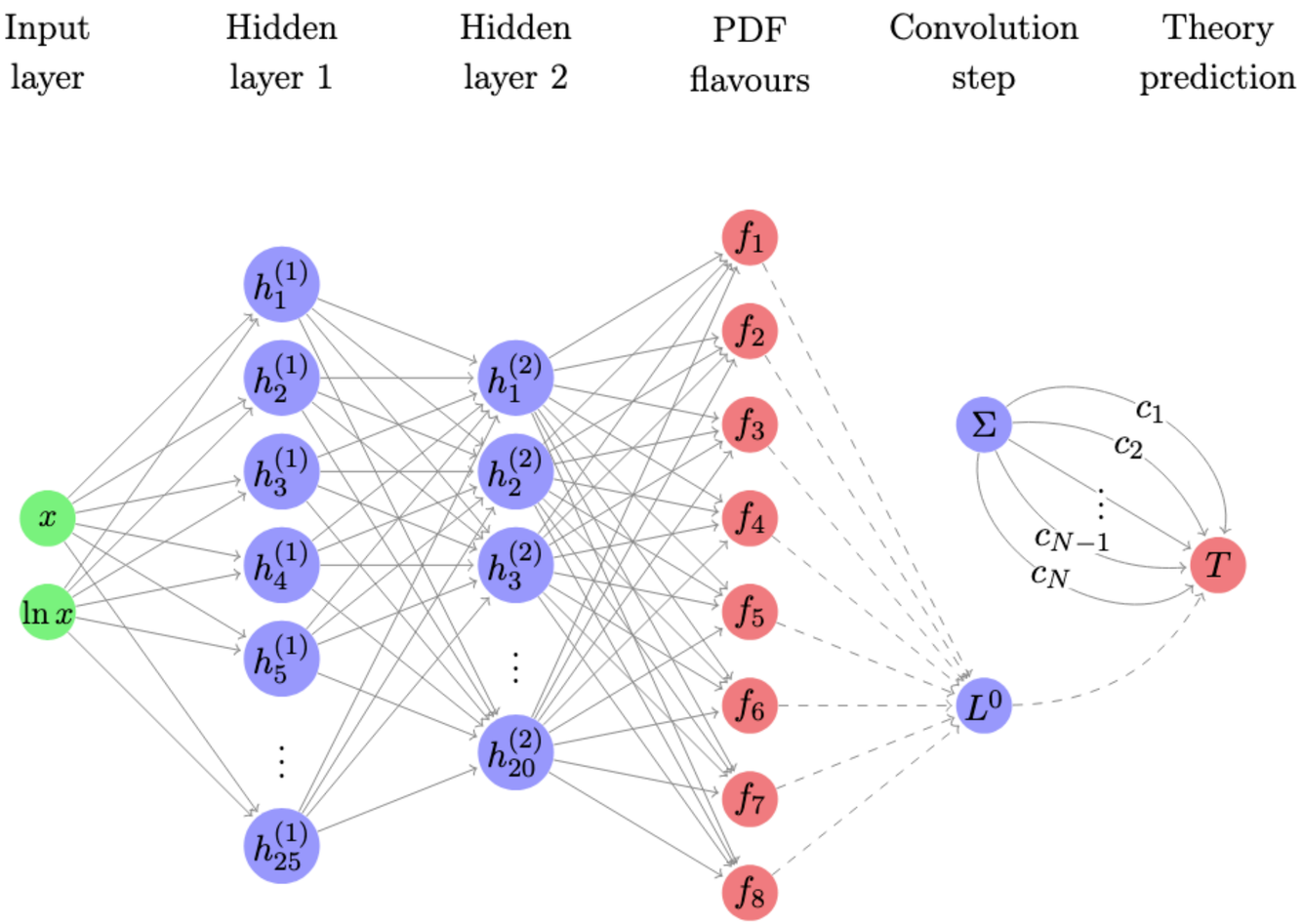

3. - The top quark legacy of the LHC Run II for PDF and SMEFT analyses

Based on 2303.06159

Run II top quark data

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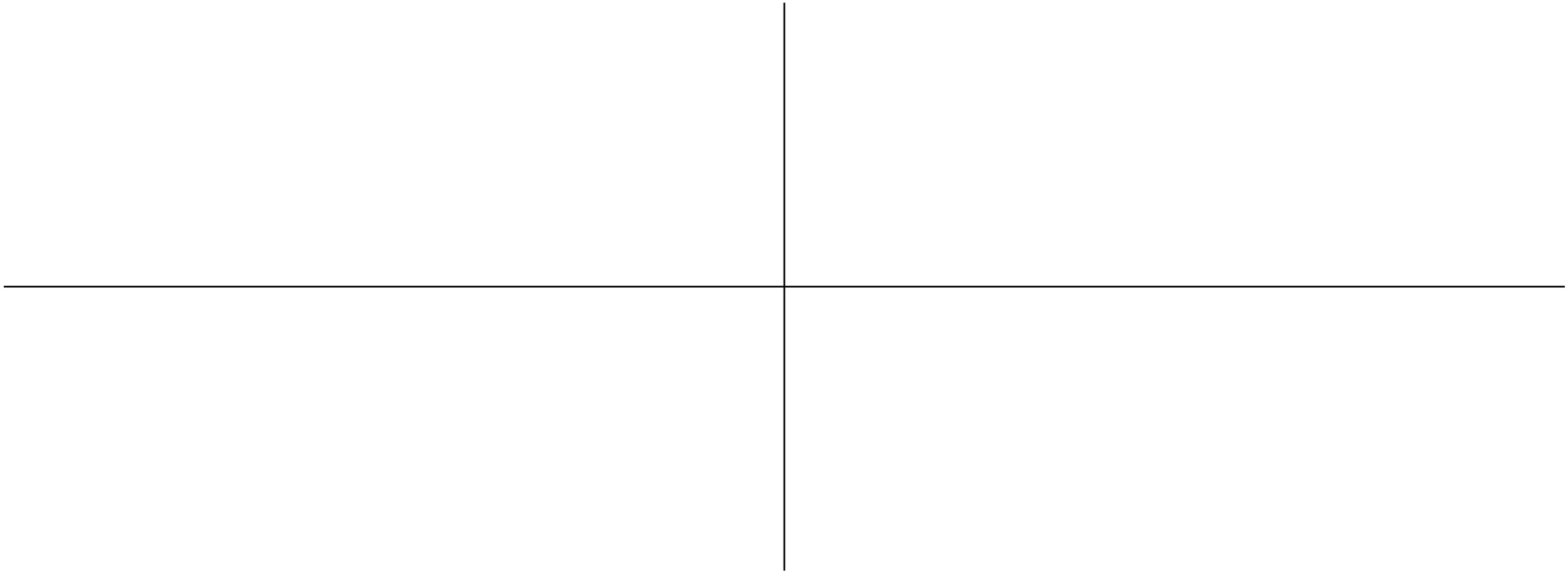

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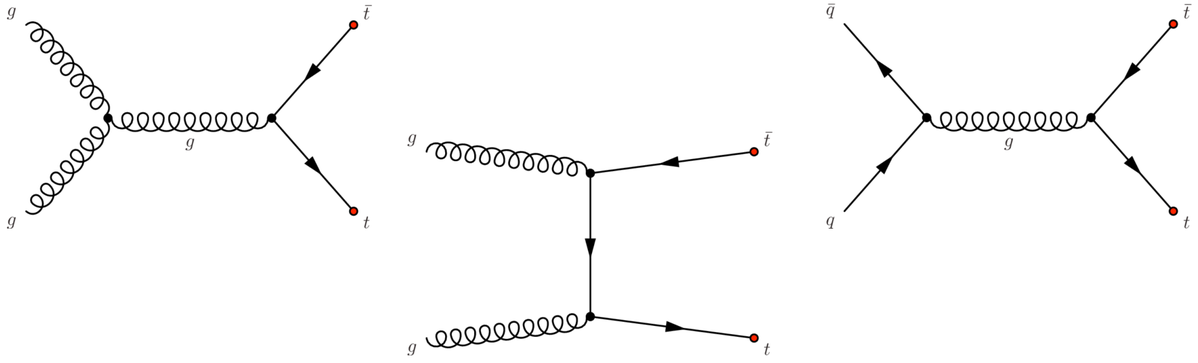

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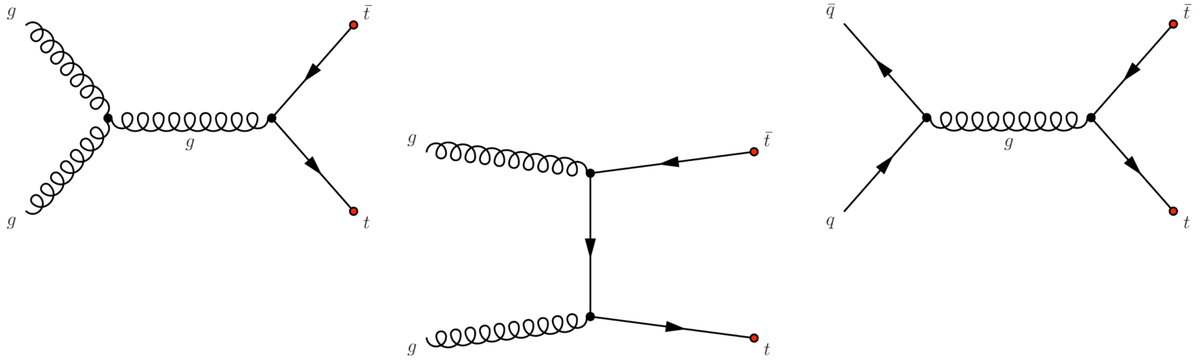

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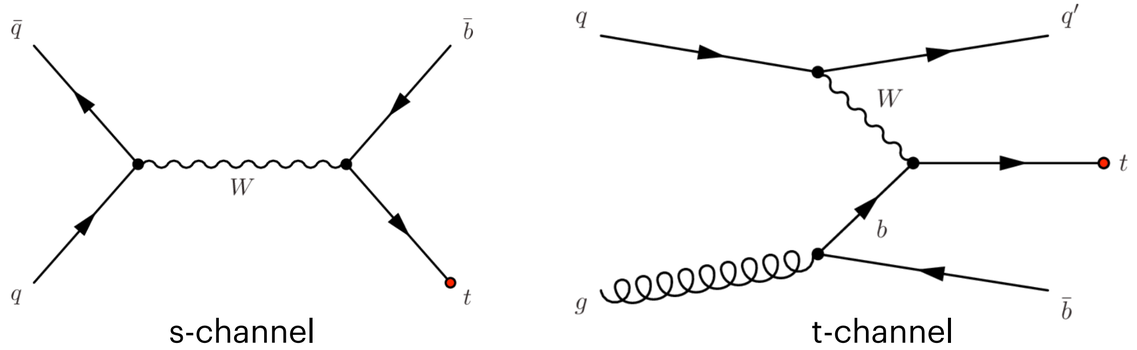

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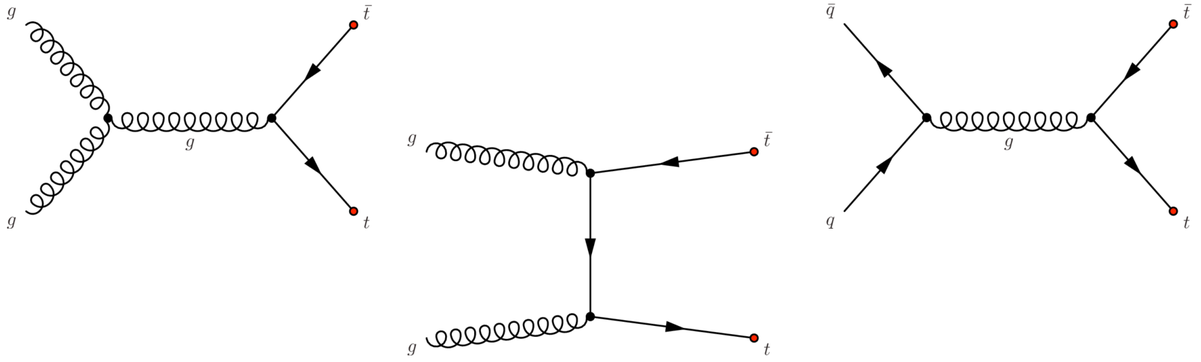

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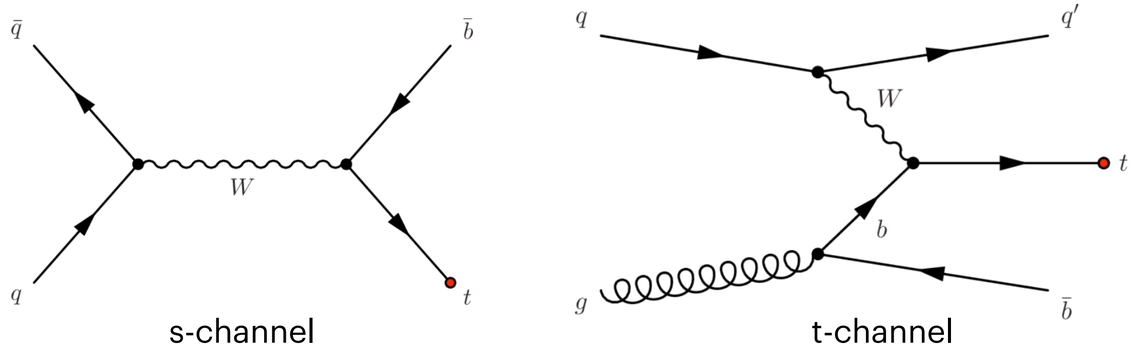

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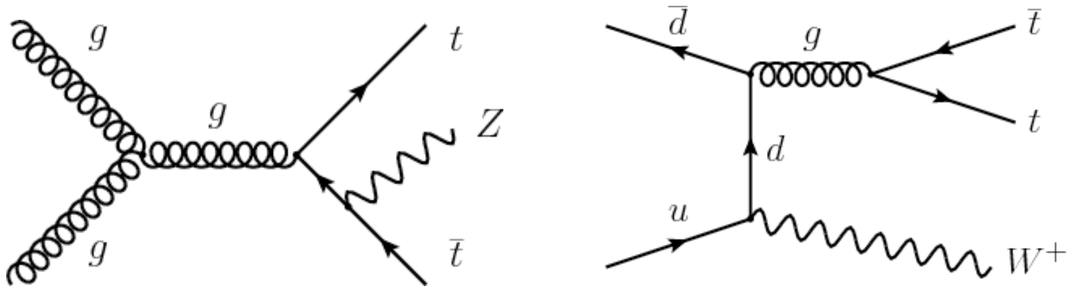

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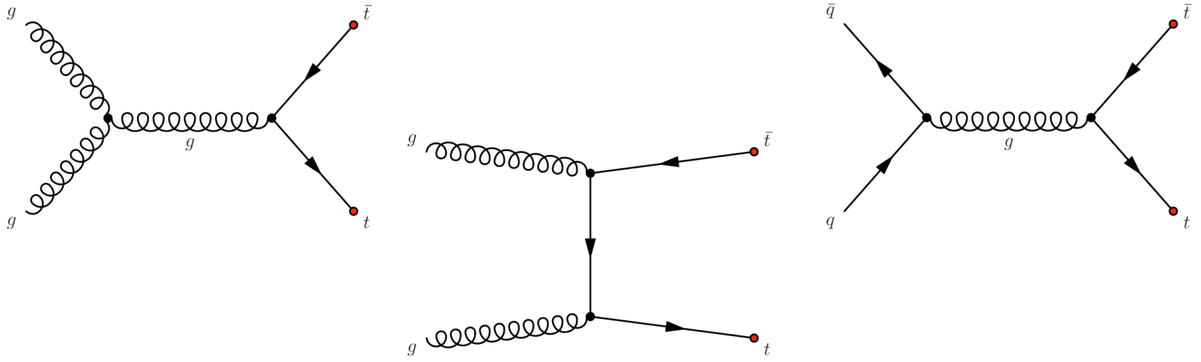

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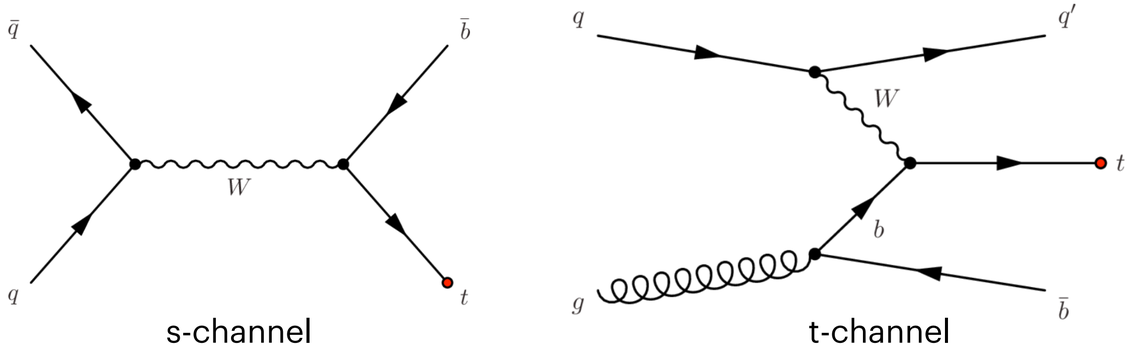

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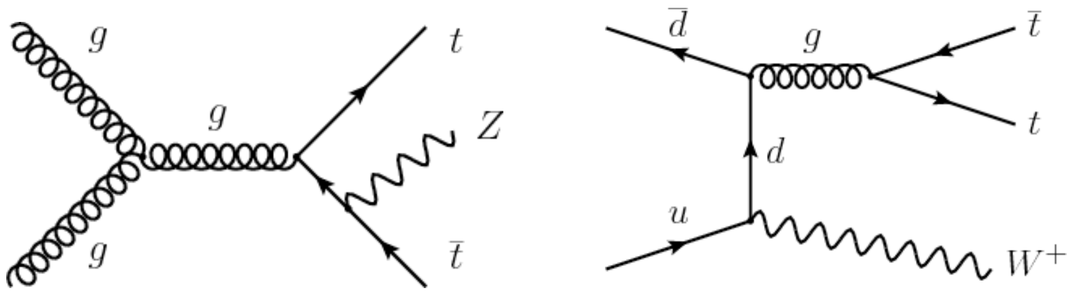

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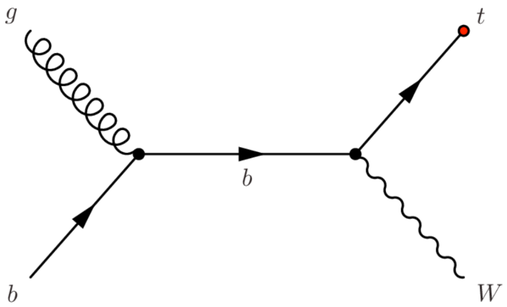

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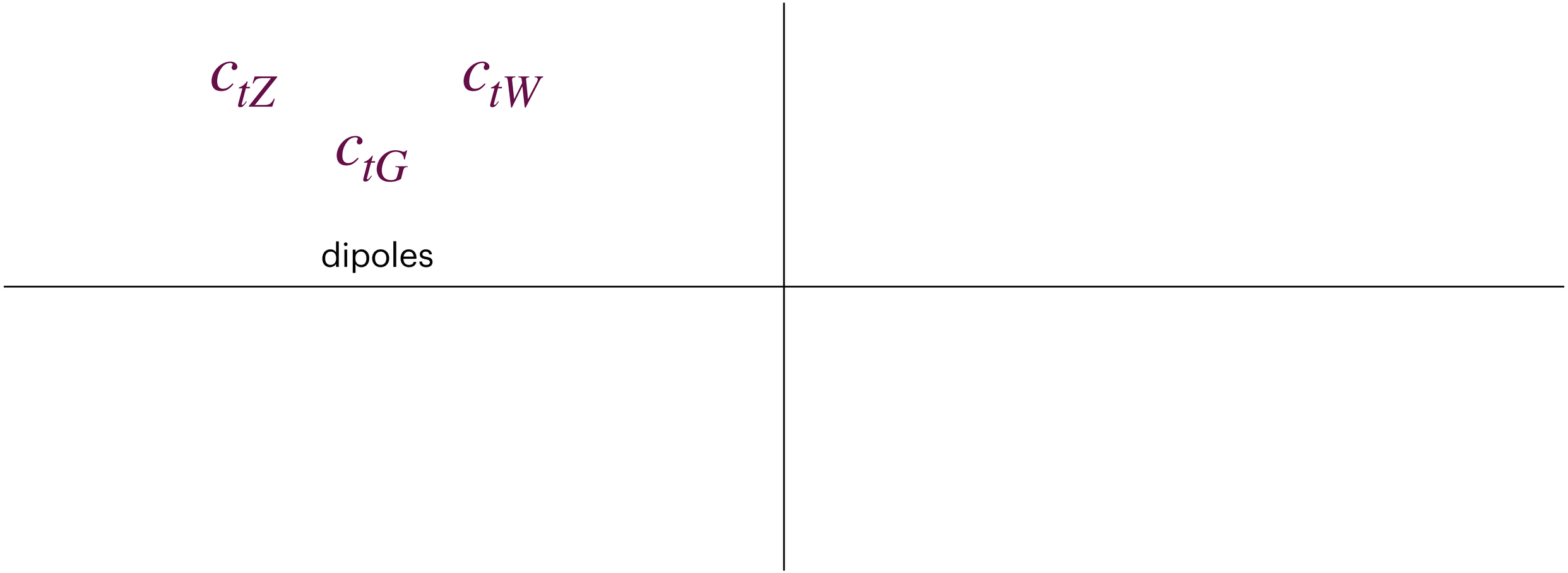

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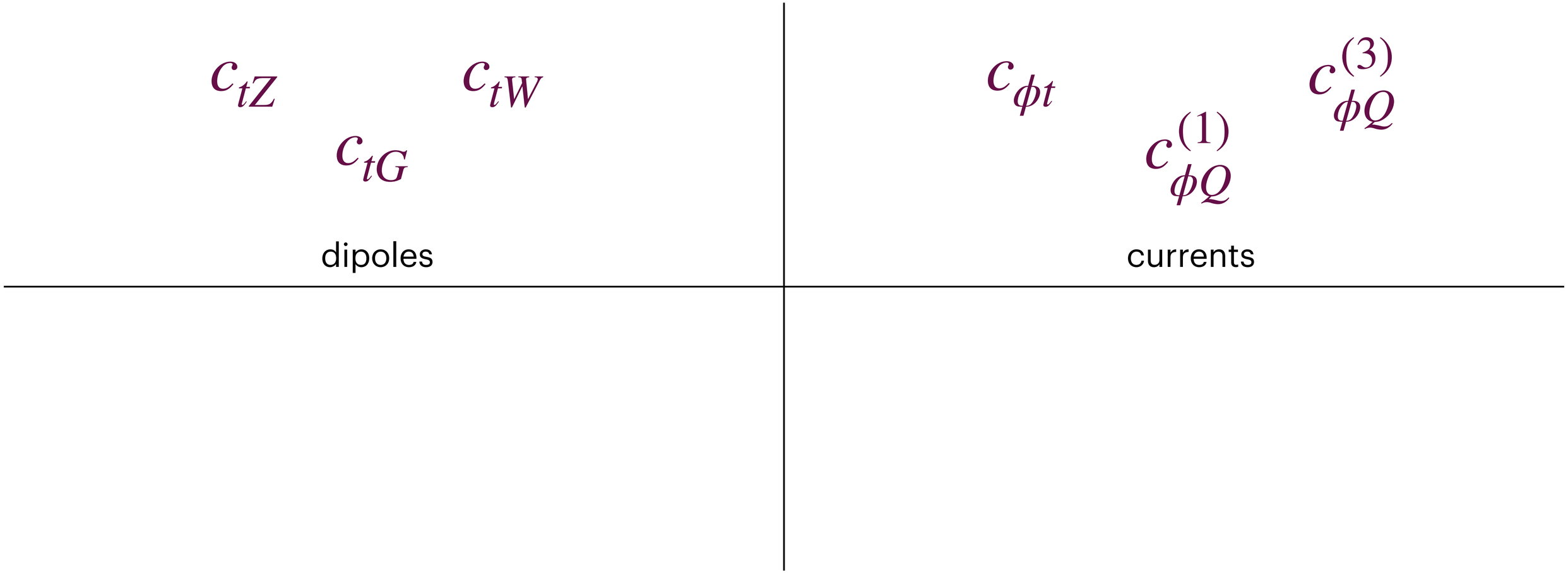

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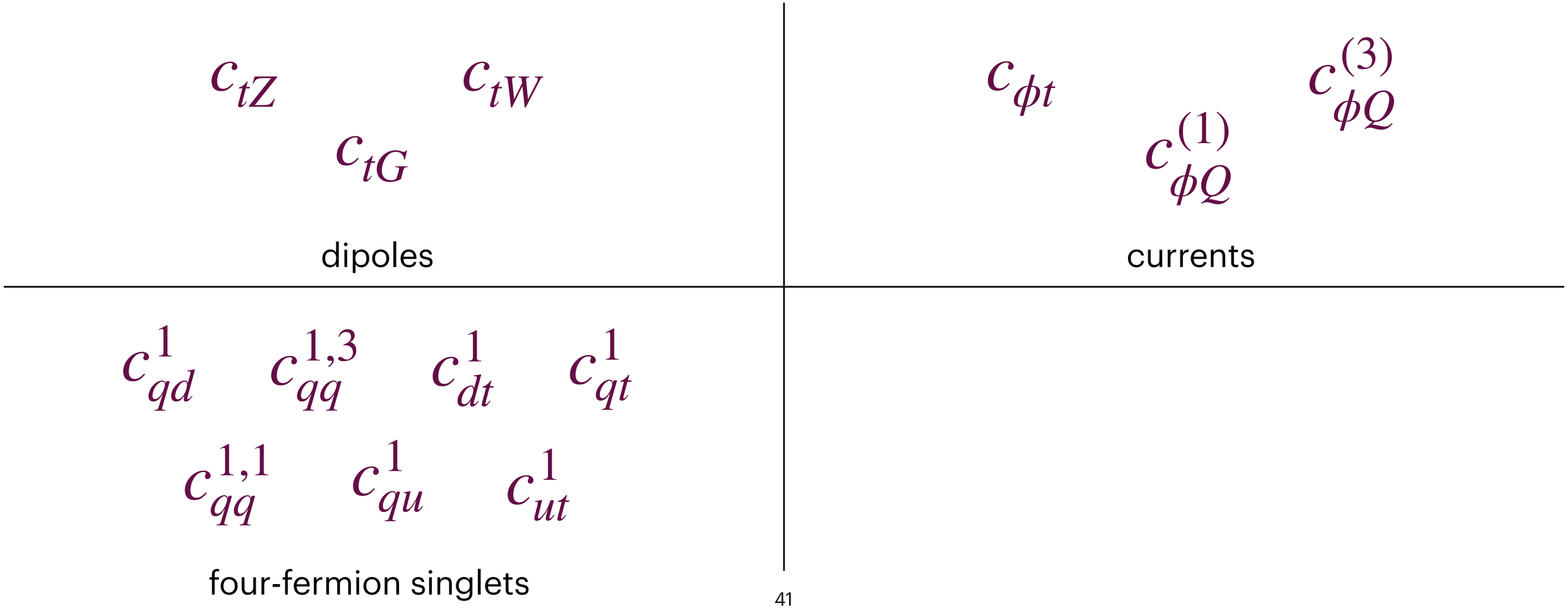

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c_{tZ} c_{tW} c_{tG}

dipoles

$c_{\phi t}$ $c_{\phi Q}^{(3)}$ $c_{\phi Q}^{(1)}$

currents

c_{qd}^{1} $c_{qq}^{1,3}$ c_{dt}^{1} c_{qt}^{1} $c_{qq}^{1,1}$ c_{qu}^{1} c_{ut}^{1}

four-fermion singlets

c_{qd}^{8} $c_{qq}^{8,3}$ c_{dt}^{8} c_{qt}^{8} $c_{qq}^{8,1}$ c_{qu}^{8} c_{ut}^{8}

four-fermion octets

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  - Fitmaker (137 top data points)

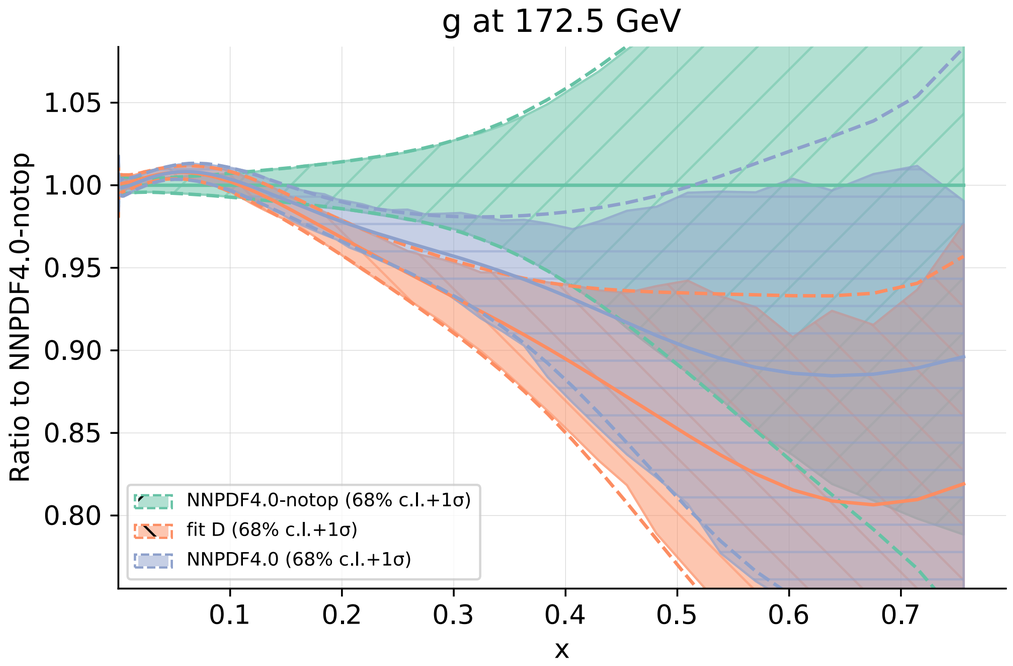
Fit settings

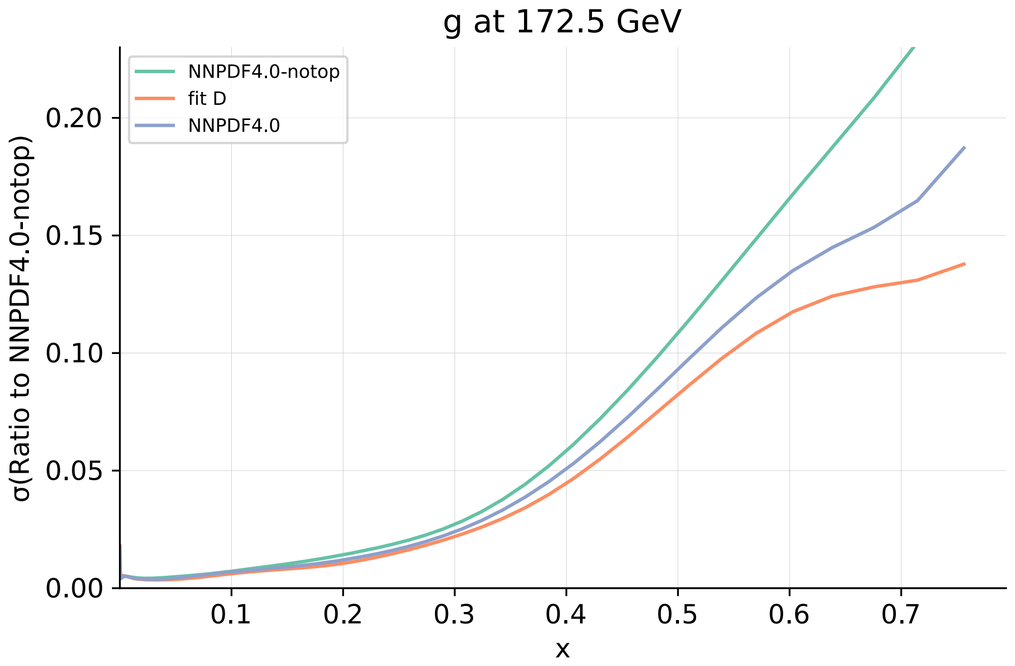
- Using the SIMUnet methodology, we have performed simultaneous determinations of PDFs and top-sector WCs using the **most comprehensive** and **up-to-date** LHC top dataset possible.
- We use **175 top data points** from ATLAS and CMS, for the four top processes described above, which comprise a superset of the measurements used in:
  - NNPDF4.0 (84 top data points, inclusive $t\bar{t}$ and single top only)
  - SMEFiT (143 top data points)
  - Fitmaker (137 top data points)
- We work with theory predictions accurate to **NNLO in QCD in the SM**, and include **NLO QCD in the SMEFT**. Some fits are **linear in the SMEFT**, some are **quadratic** - a point we will return to.

Let’s start the results with the PDF-only fits…

PDFs in the SM - impact of inclusive $t\bar{t}$ and single-top

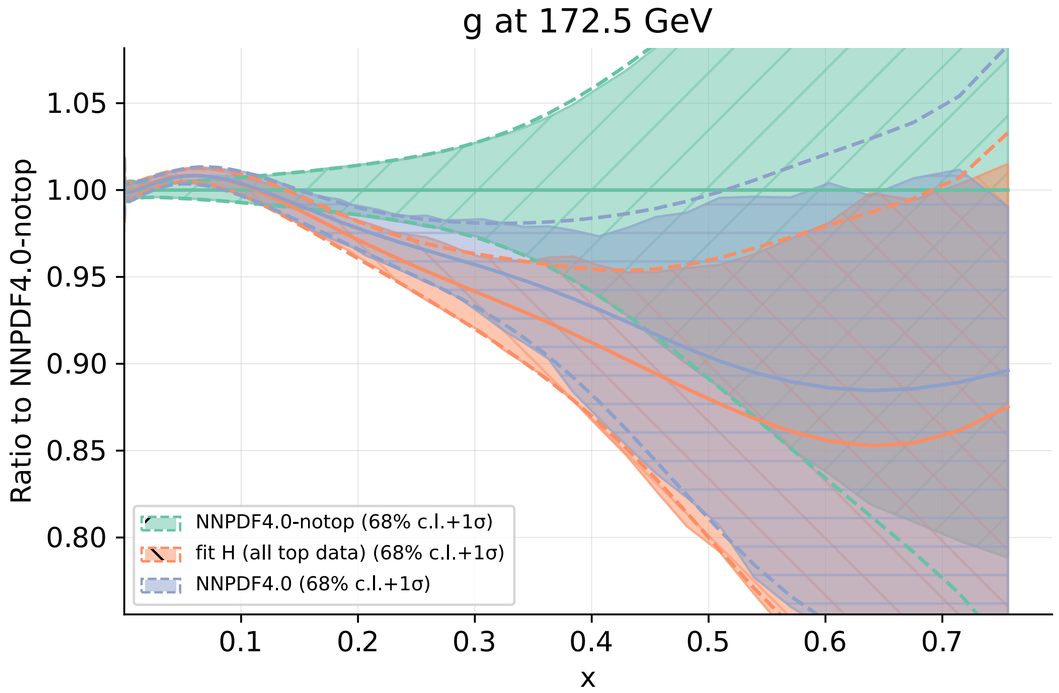
- First, we consider the impact of our dataset on PDFs **in the SM**.
- Begin by considering the updates to the **inclusive** $t\bar{t}$ and **single-top** dataset relative to NNPDF4.0. If we perform a SM PDF fit using only our new inclusive $t\bar{t}$ and single-top data, we see a more pronounced effect on the **large-x gluon** relative to NNPDF4.0. The **uncertainty** is also **further reduced**.

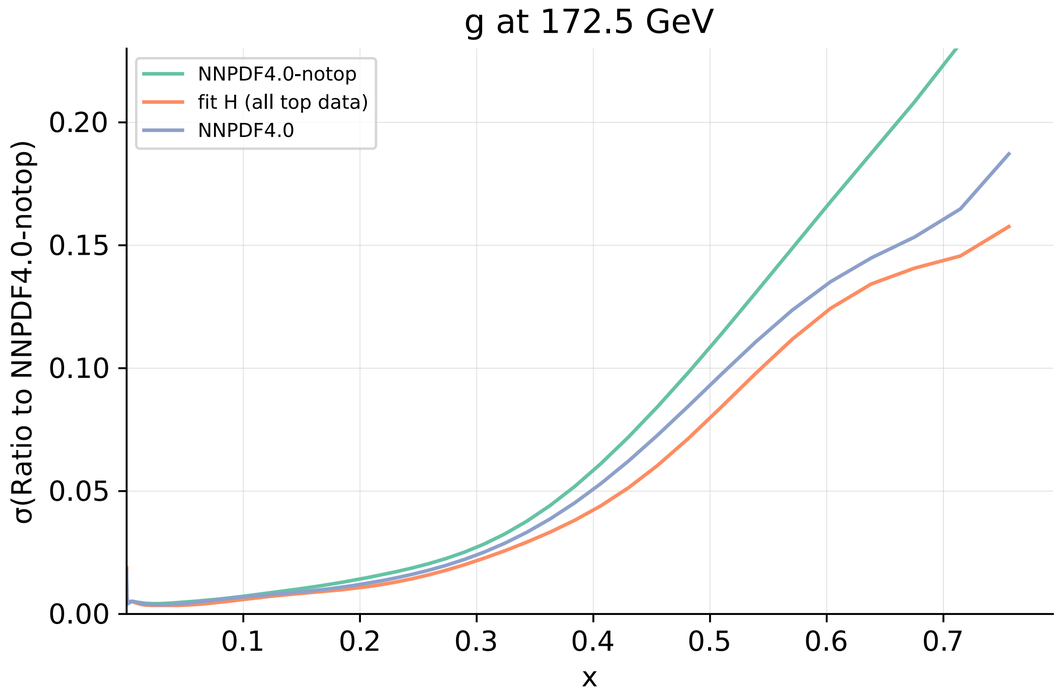




PDFs in the SM - impact of all new top data

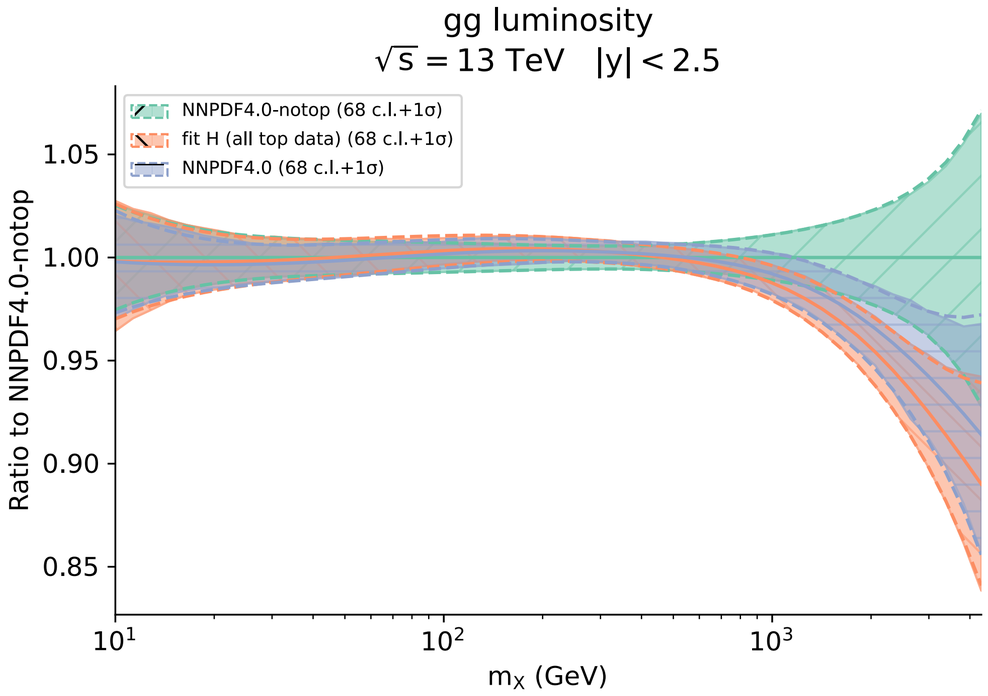
- Finally, we present the results of a **complete PDF fit** including **all our new top data**. As expected, the effect on the large-x gluon is broadly the same as the effect of just including the inclusive $t\bar{t}$ and single-top data, but is mildly tempered by the associated top data.

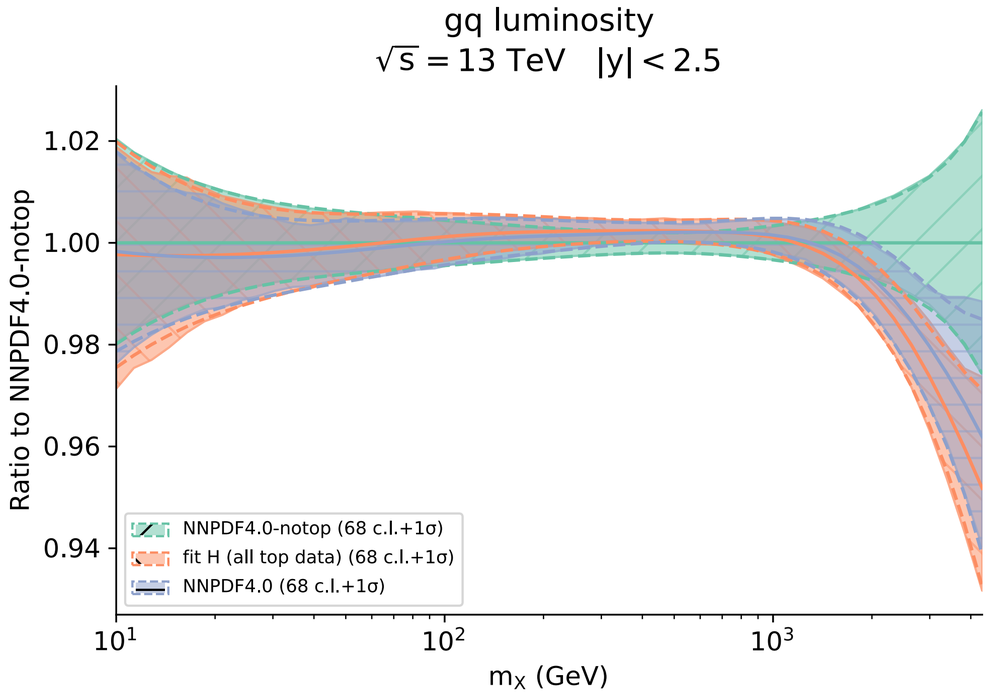




PDFs in the SM - impact of all new top data

- A similar trend holds for the **PDF luminosities**, with our new updated fit compatible with NNPDF4.0, but with the central luminosity reduced relative to NNPDF4.0 at very large invariant mass.



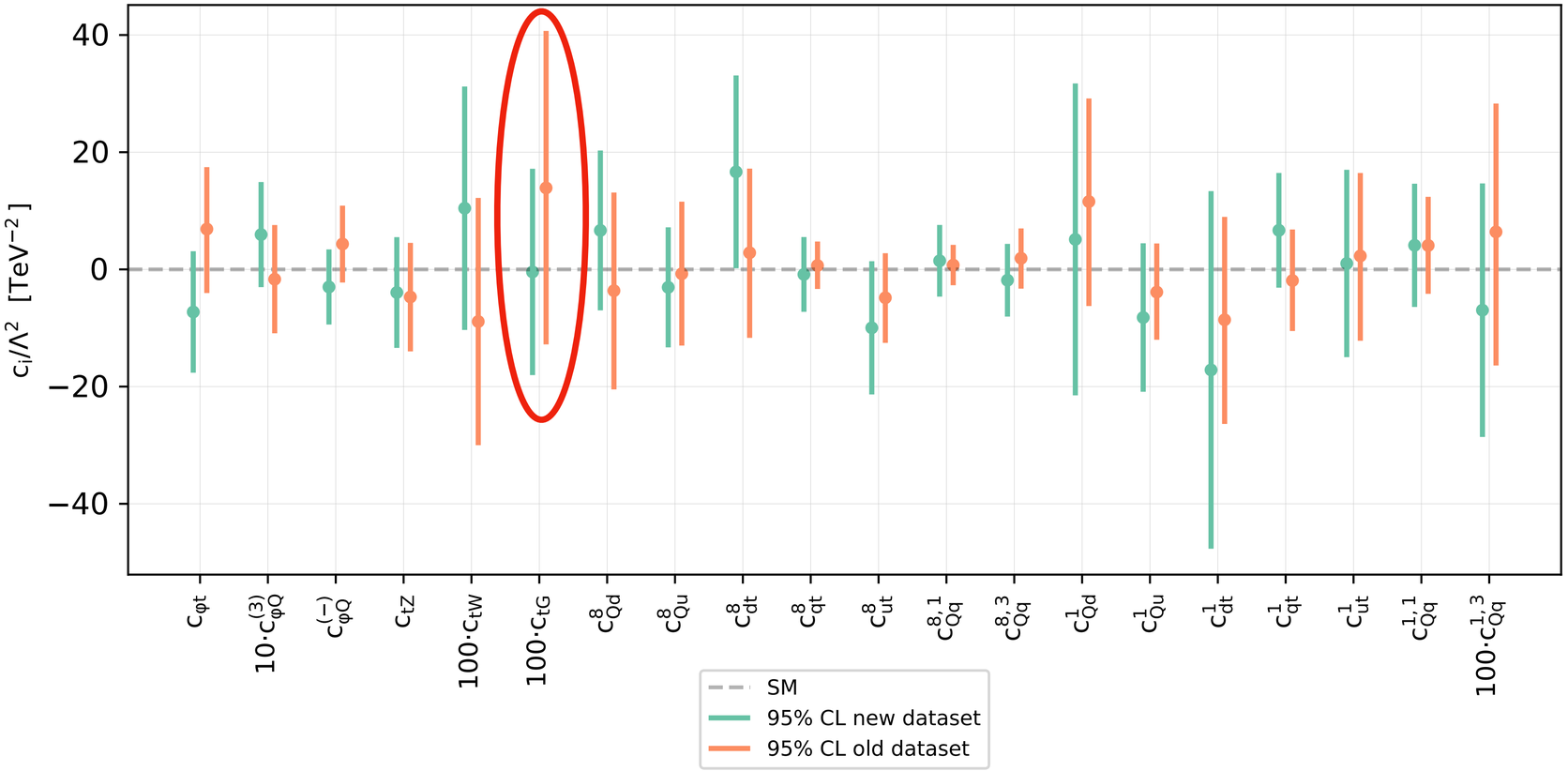


Now let’s see the SMEFT-only fits…

SMEFT-only fits: linear SMEFT

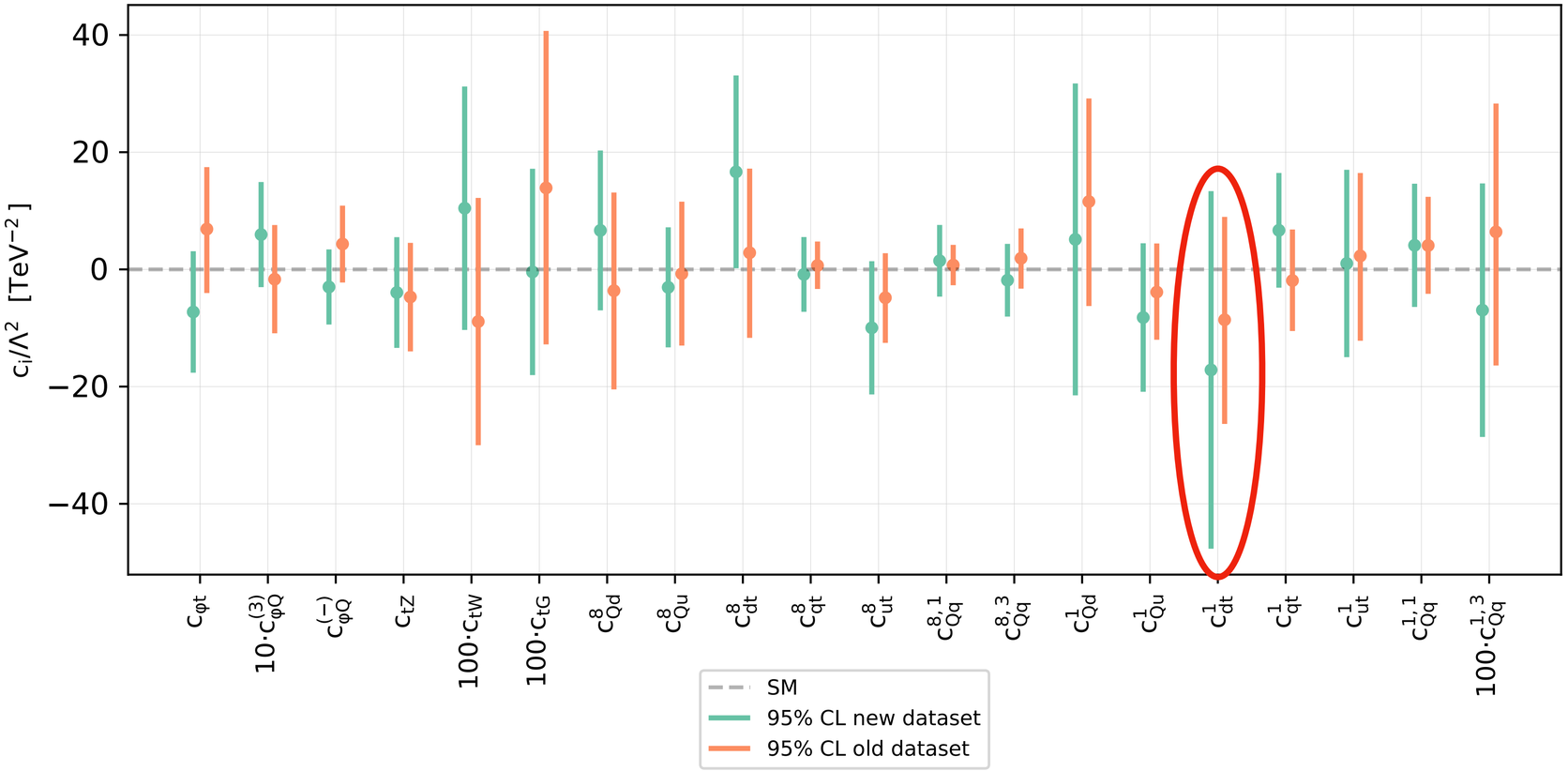
- We have also performed SMEFT-only fits to see the impact of our new dataset relative to previous SMEFT-fits, namely **SMEFiT**.

- At the **linear level** in the SMEFT, best improvement is seen in c_{tG}, whose bound undergoes a 35% tightening - this is traced to more precise total $t\bar{t}$ measurements.



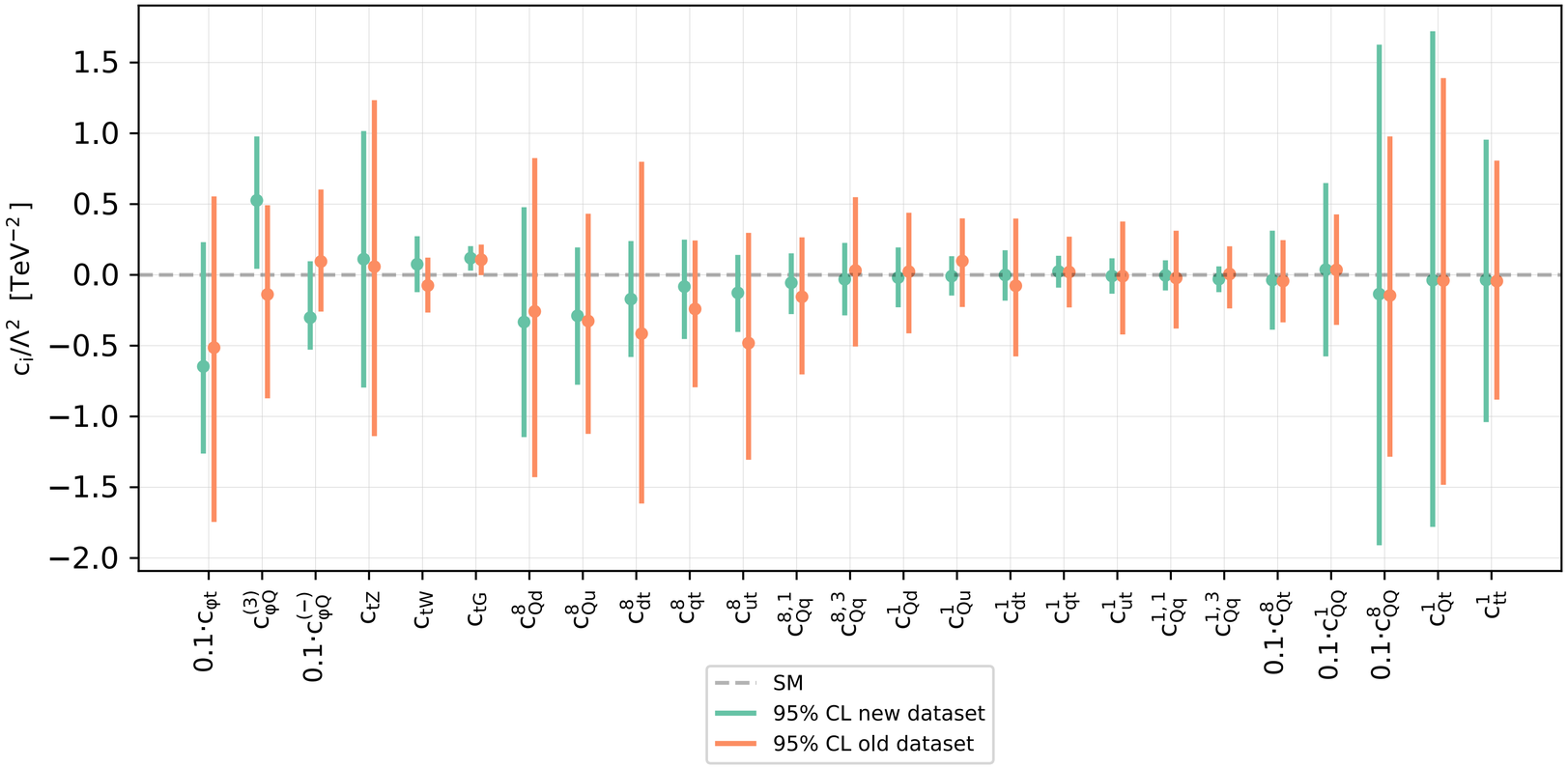
SMEFT-only fits: linear SMEFT

- Some other coefficients undergo a **shift in the central value**, but no tightening or broadening of the constraint.
- Some coefficients have **broader bounds** than previously obtained, in particular some of the four-fermion operators.
- However, bounds are very weak here anyway, and likely challenge EFT validity.



SMEFT-only fits: quadratic SMEFT

- Results are **much more promising** when **quadratic SMEFT effects** are included. A **significant tightening** of bounds is seen for most operators.
- Only the five **four-heavy operators** experience broadening relative to the old dataset. This could point to some inconsistency in the $t\bar{t}t\bar{t}$ and $t\bar{t}b\bar{b}$ data, but with such large uncertainties, it is difficult to be precise.



PDF-SMEFT correlation

- We can try to get intuition for the result of the **joint PDF-SMEFT** fit by considering the **PDF-SMEFT correlation** in the SMEFT-only fits.

PDF-SMEFT correlation

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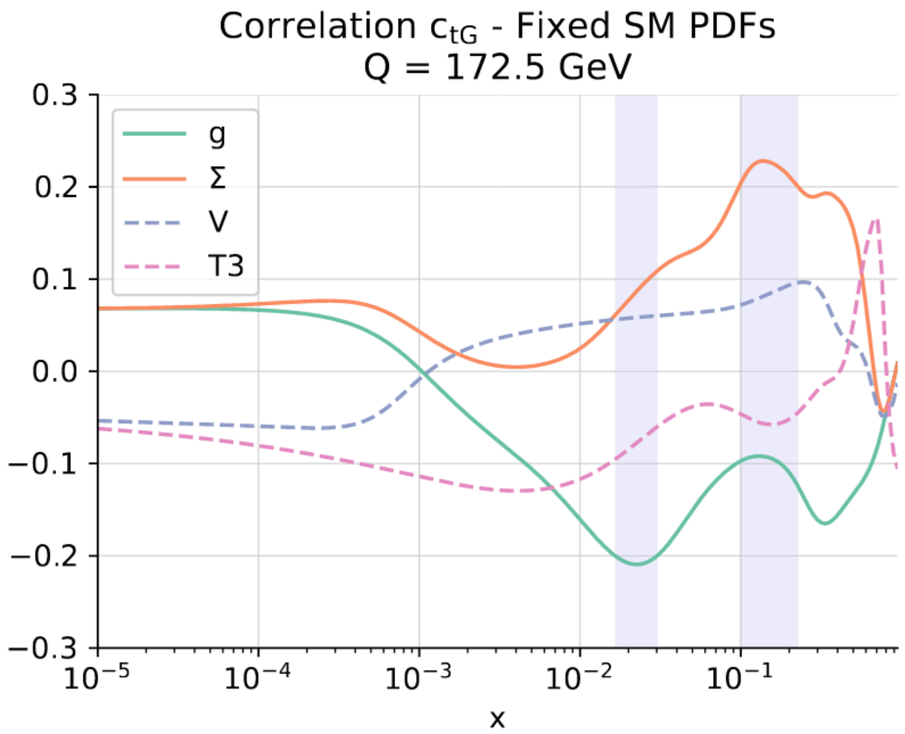
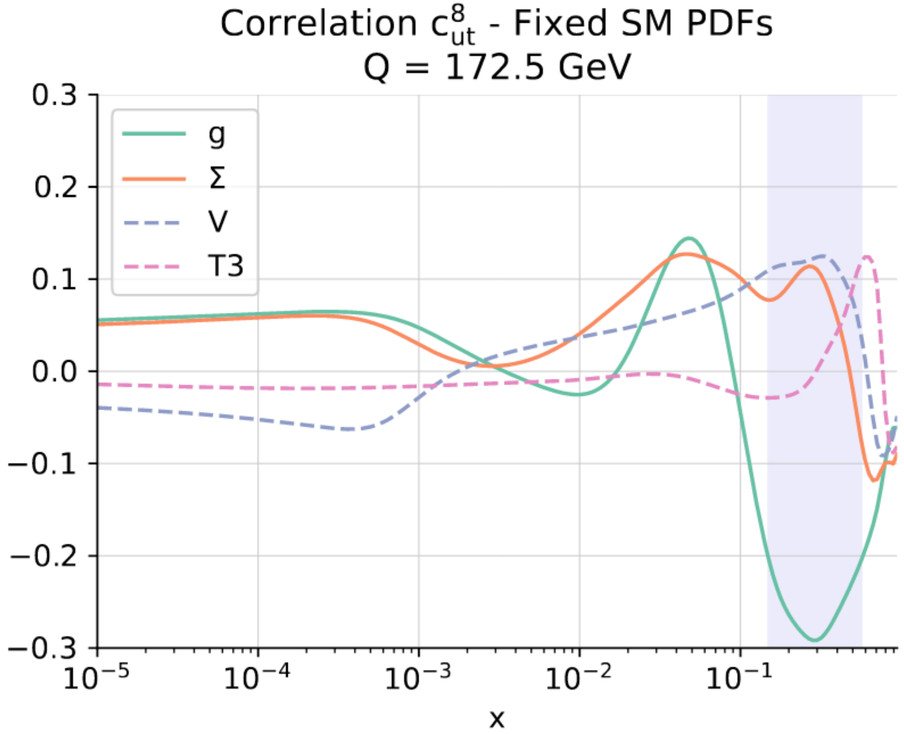
- This is defined for each Wilson coefficient and each PDF flavour by:

$$\rho\left(c, f(x,Q^2)\right) = \frac{\left\langle c^{(k)} f^{(k)}(x,Q^2)\right\rangle_k - \left\langle c^{(k)}\right\rangle_k \left\langle f^{(k)}(x,Q^2)\right\rangle_k}{\sqrt{\left\langle (c^{(k)})^2\right\rangle_k - \left\langle c^{(k)}\right\rangle_k^2}\sqrt{\left\langle \left(f^{(k)}(x,Q^2)\right)^2\right\rangle_k - \left\langle f^{(k)}(x,Q^2)\right\rangle_k^2}}$$

PDF-SMEFT correlation

- We see the **strongest correlation** between the Wilson coefficients and the gluon PDF at high-x, as to be expected. The correlation is still **mild** though, suggesting that the interplay will also be **relatively mild**.

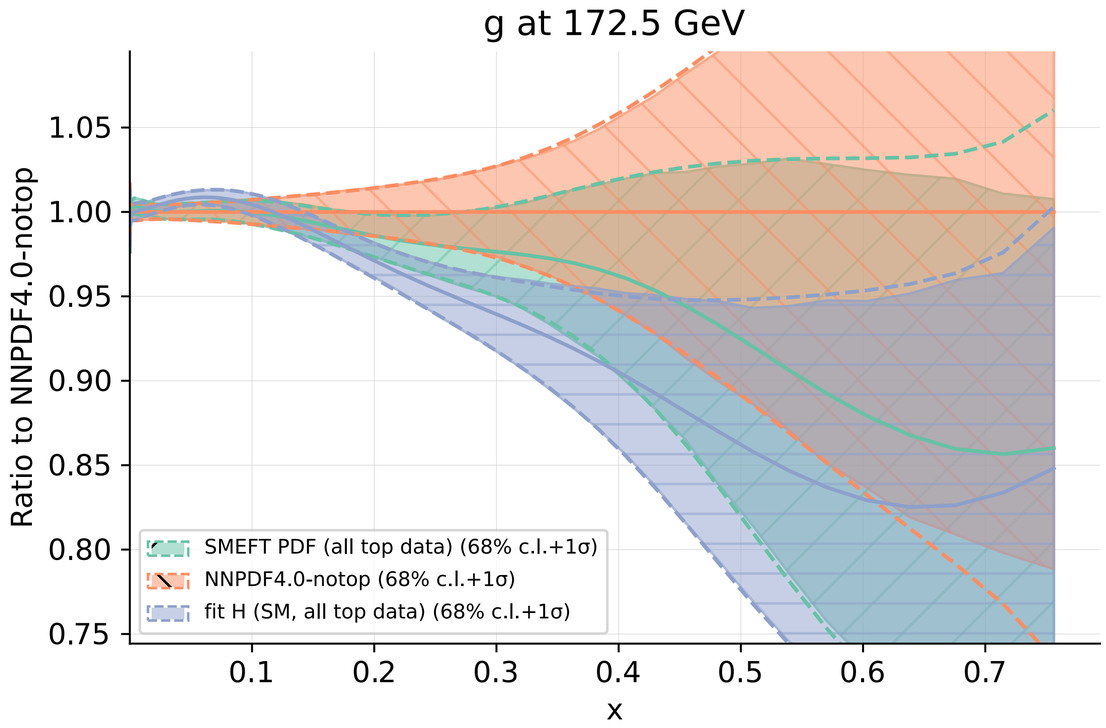


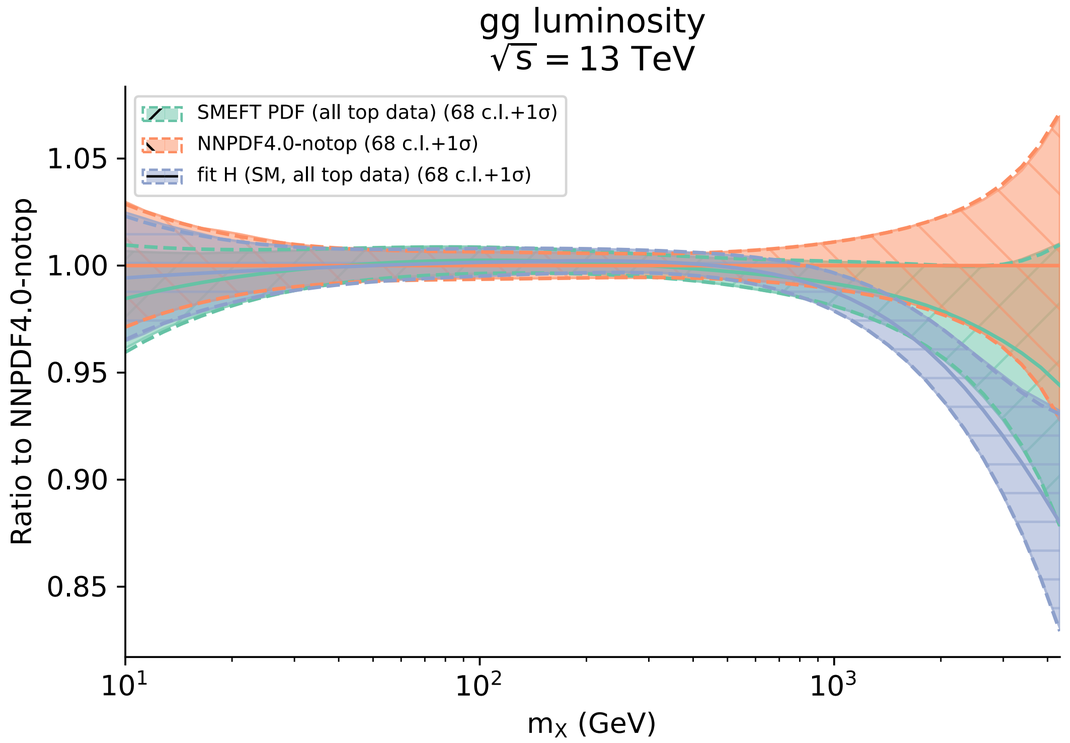


Now, let’s do the joint fit…

Joint PDF-SMEFT fits: linear SMEFT

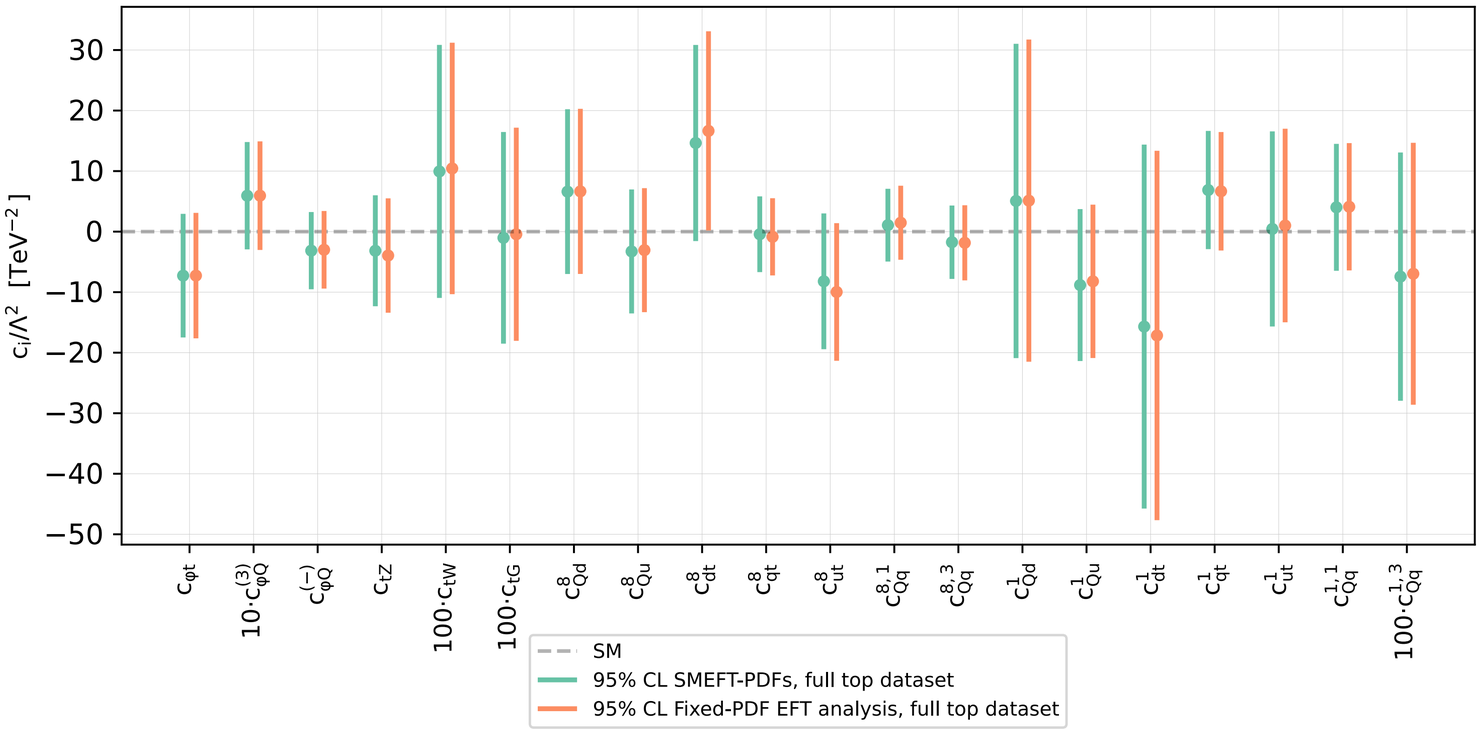
- Finally, we present the key result of the work: a **simultaneous** determination of PDFs and SMEFT Wilson coefficients. We start assuming **linear SMEFT**.
- In terms of the gluon PDFs and luminosities, we find that a simultaneous determination **reduces the pull** of the top data from the **non-top baseline**.





Joint PDF-SMEFT fits: linear SMEFT

- On the other hand, we find that the bounds on the Wilson coefficients are **very stable** between a simultaneous PDF-SMEFT fit and a SMEFT-only fit.



- This indicates that within a **linear EFT interpretation** of the top data, the PDF effects are **currently subdominant**.

Joint PDF-SMEFT fits: quadratic SMEFT

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Joint PDF-SMEFT fits: quadratic SMEFT

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- However... during the course of our study, we discovered an important problem with the **Monte Carlo replica method** used to propagate uncertainties in the SIMUnet methodology.

- The issue is such that quadratic results with the SIMUnet methodology (and indeed with any methodology that uses the Monte Carlo replica method) are **currently unreliable**.

Joint PDF-SMEFT fits: quadratic SMEFT

- **Next obvious fit…** joint PDF-SMEFT fit using **quadratic SMEFT contributions?** Could interplay be more pronounced there … ?

- However… during the course of our study, we discovered an important problem with the **Monte Carlo replica method** used to propagate uncertainties in the SIMUnet methodology.

- The issue is such that quadratic results with the SIMUnet methodology (and indeed with any methodology that uses the Monte Carlo replica method) are **currently unreliable**.

- An **upcoming publication** will describe the issue in more detail; for now, here's the basics…

Pitfalls of the Monte-Carlo replica method

- For simplicity, consider a single data point d with experimental variance σ^2, which we attempt to describe using the **quadratic** theory, involving a single theory parameter c:

$$t(c) = t^{\mathrm{SM}} + t^{\mathrm{lin}}{}_c + t^{\mathrm{quad}}{}_{c^2}$$

- The Monte-Carlo replica method propagates the uncertainty from the data to the theory parameter by fitting to **pseudodata**. We sample lots of pseudodata replicas from a normal distribution based on the data, $d_p \sim N(d, \sigma^2)$, and define the corresponding **parameter replicas** to be a random function of the pseudodata given by minimising the χ^2-statistic:

$$c_p(d_p) = \arg\min_c \left(\frac{(t(c) - d_p)^2}{\sigma^2} \right)$$

Pitfalls of the Monte-Carlo replica method

- In this very simple example, one can compute the distribution function of the parameter replicas analytically; it is given by:

$$P_{c^{(i)}}(c) \propto \delta\left(c + \frac{t^{\text{lin}}}{2t^{\text{quad}}}\right) \int_{-\infty}^{t_{\text{min}}} dx \ \exp\left(-\frac{1}{2\sigma^2}(x-d)^2\right) + \frac{2}{|2ct^{\text{quad}} + t^{\text{lin}}|} \exp\left(-\frac{1}{2\sigma^2}(d - t(c))^2\right)$$

- Here, t_{min} is the minimum value of the theory (which is a parabola).

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- **Key features to note:**
  - Part of the distribution looks like a **scaled version** of what we would expect from a **Bayesian method with uniform prior**.

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- Here, t_{min} is the minimum value of the theory (which is a parabola).

- **Key features to note:**
  - Part of the distribution looks like a **scaled version** of what we would expect from a **Bayesian method with uniform prior**.
  - There is also a **delta function spike** in the distribution - interesting to ask: why...?

Pitfalls of the Monte-Carlo replica method

- The **minimum of the theory** can result in many pseudodata replicas falling **below the range of the theory**.

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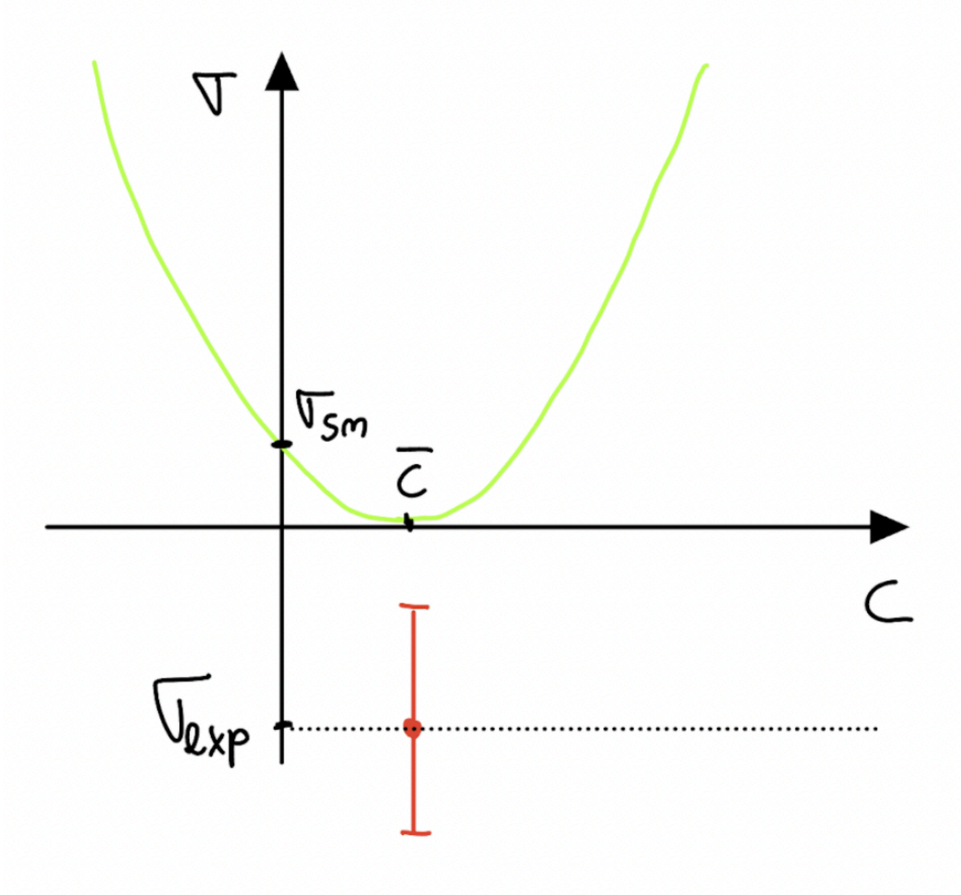

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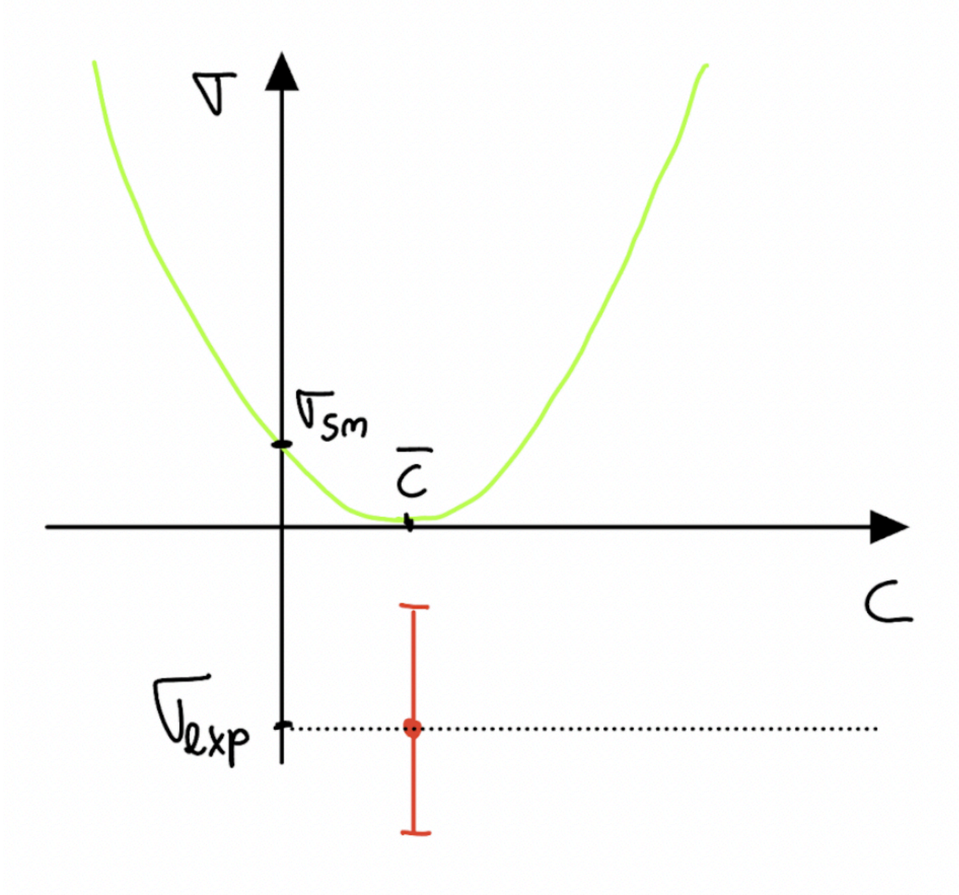

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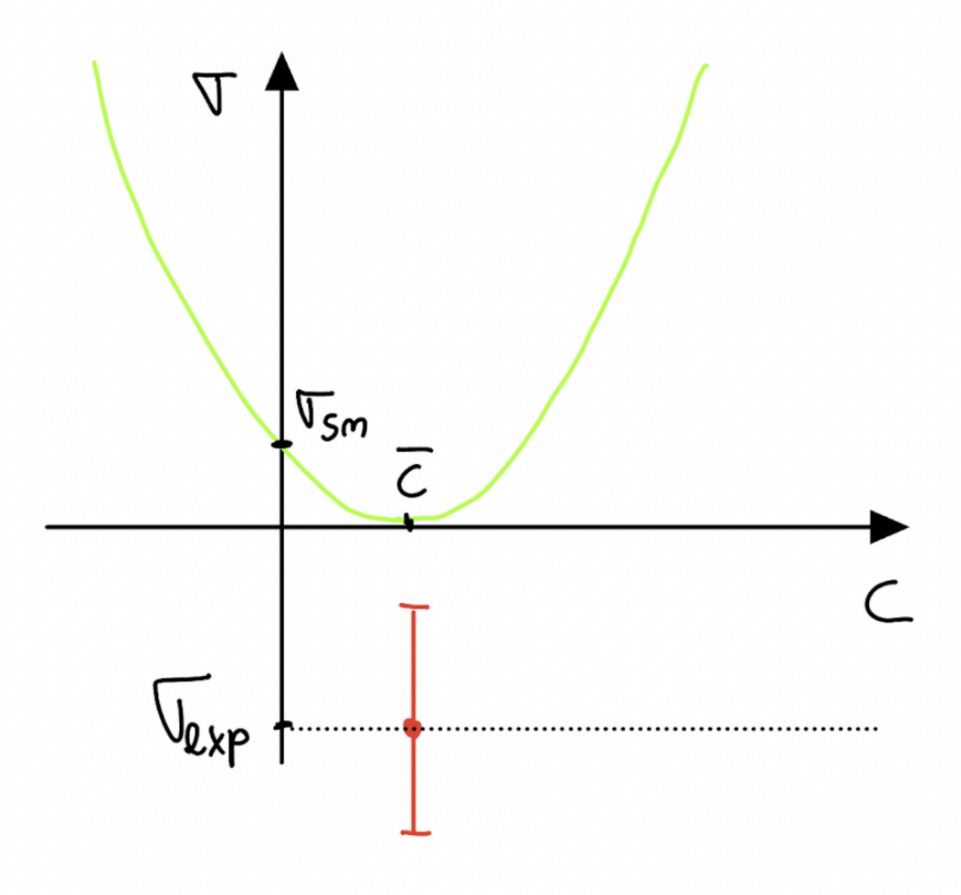

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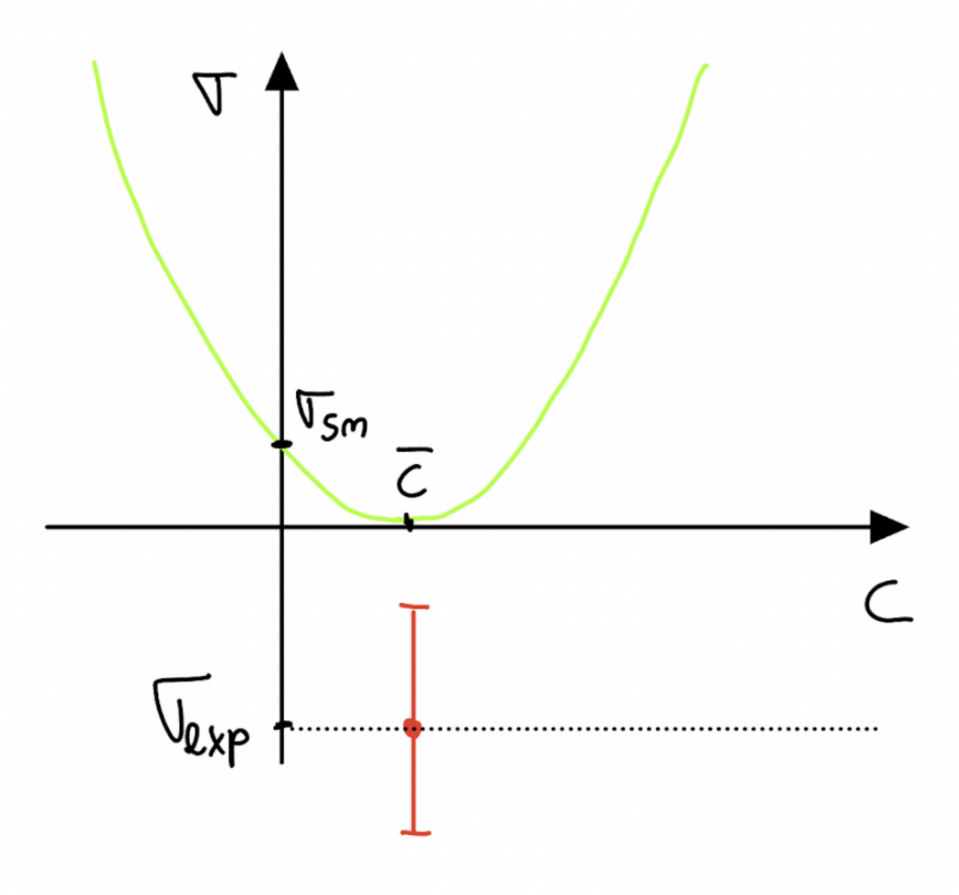
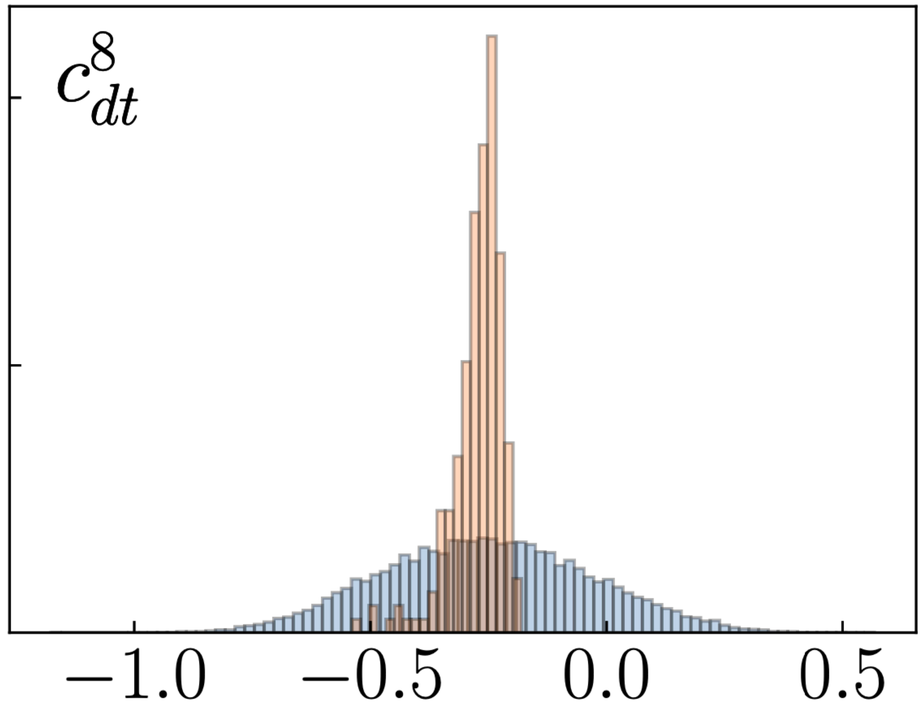


- This occurs if the experimental data falls **below the minimum** of the theory, or **above but close** to the minimum.
- Any pseudodata replica that falls below the minimum results in the **same parameter replica**, corresponding to the parameter value that gives the minimum.
- This gives rise to the spike in the distribution at $c = -t^{\text{lin}}/2t^{\text{quad}}$.

Pitfalls of the Monte-Carlo replica method

- These problems extend to our top fit... for example in a **realistic quadratic fit** of one operator $c_{dt'}^8$, we get the following comparison between the Monte-Carlo method (orange) and a Bayesian method with uniform prior (blue).
- We see that **Monte-Carlo massively underestimates uncertainties.**



Key questions for the future:

Can the MC replica method be modified to agree with Bayesian methods?

To what extent do existing fits (in the SMEFT world, PDF world, and beyond) that use the MC replica method underestimate uncertainties?

Conclusions

Conclusions

- **Simultaneous determination of PDFs and BSM parameters**, will be **very important in future analyses** (especially as we enter Run III).

- Members of the **PBSP team** have already produced three works in the direction of simultaneous PDF-SMEFT fits: (i) a **phenomenological study** 2104.02723 showing the need for simultaneous extraction; (ii) a **methodology** (SimuNET, 2201.07240) capable of **fast simultaneous fitting**; (iii) a **comprehensive simultaneous extraction** of PDFs and SMEFT couplings from the **full LHC Run II top dataset**, 2303.06159.

Thanks for listening!
Questions?