Hide and Seek: Can PDFs fit away New Physics signals?

For PDF4LHC 2023, CERN, based on 2307.10370
(by the PBSP team + Michelangelo Mangano)

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 (*former*), Maeve Madigan, Luca Mantani, **James Moore**
  - *PhD students:* Mark Costantini, Shayan Iranipour (*former*), Elie Hammou, Manuel Morales, Cameron Voisey (*former*)

PBSP

European Research Council
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The talk in a nutshell...

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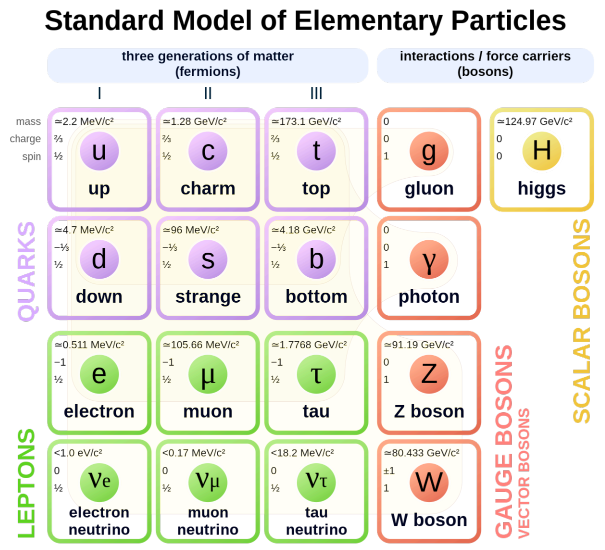
Imagine Nature is described by SM + some New Physics



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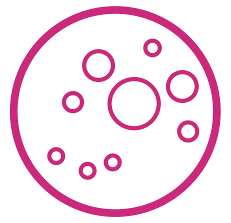

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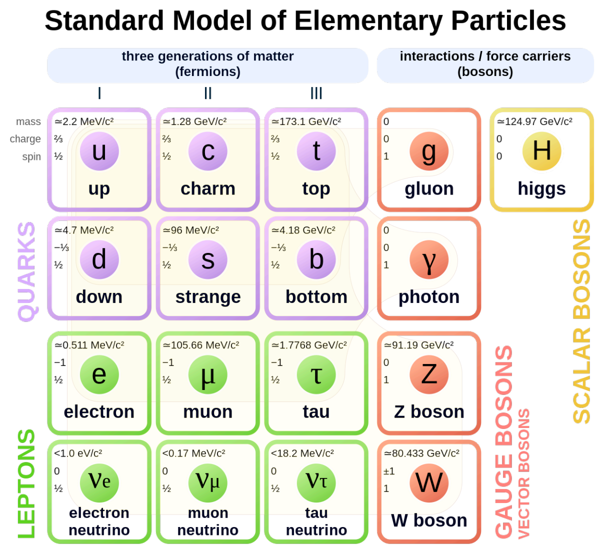

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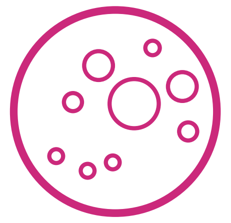

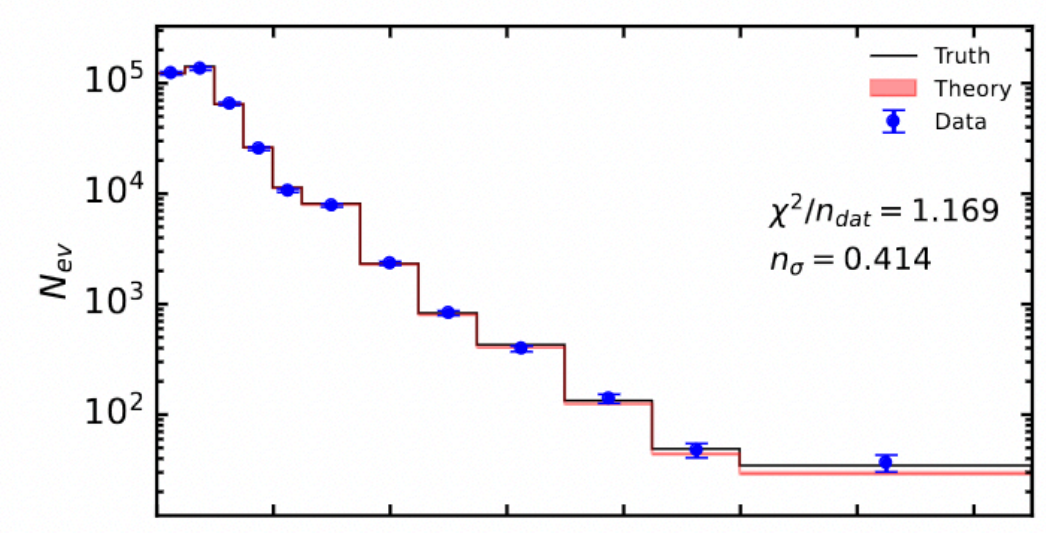

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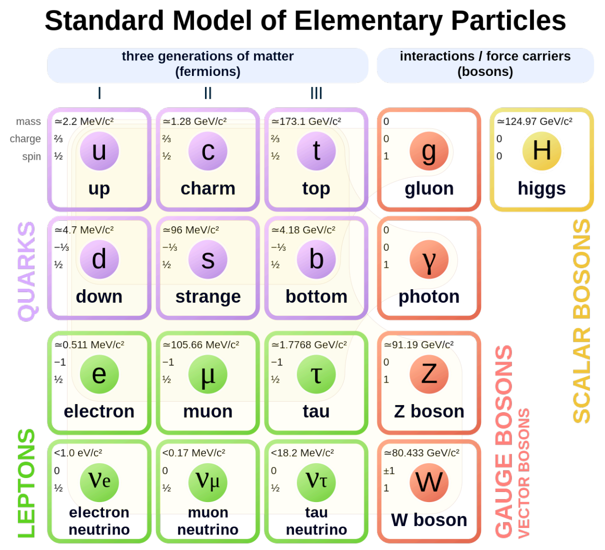

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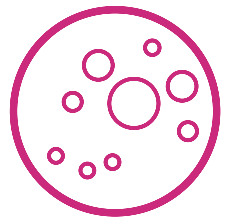

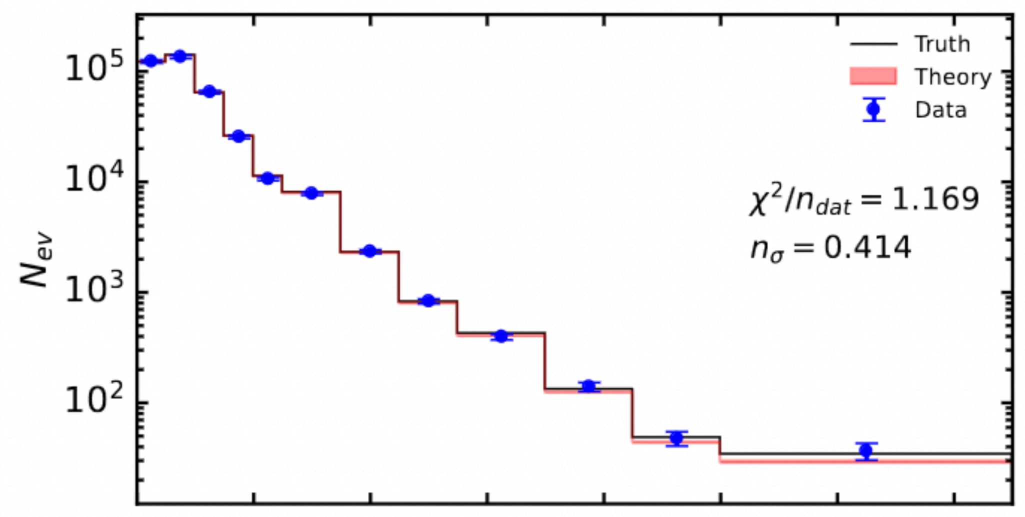

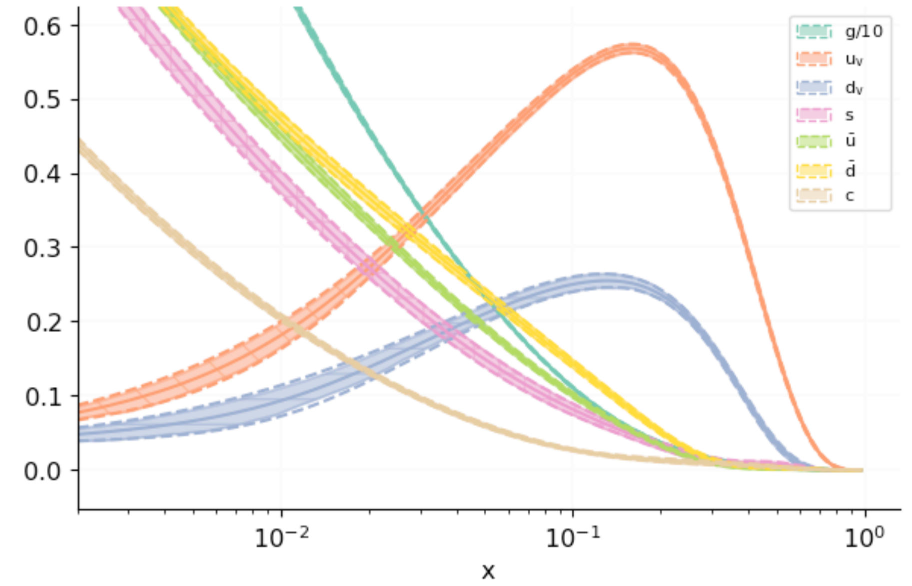

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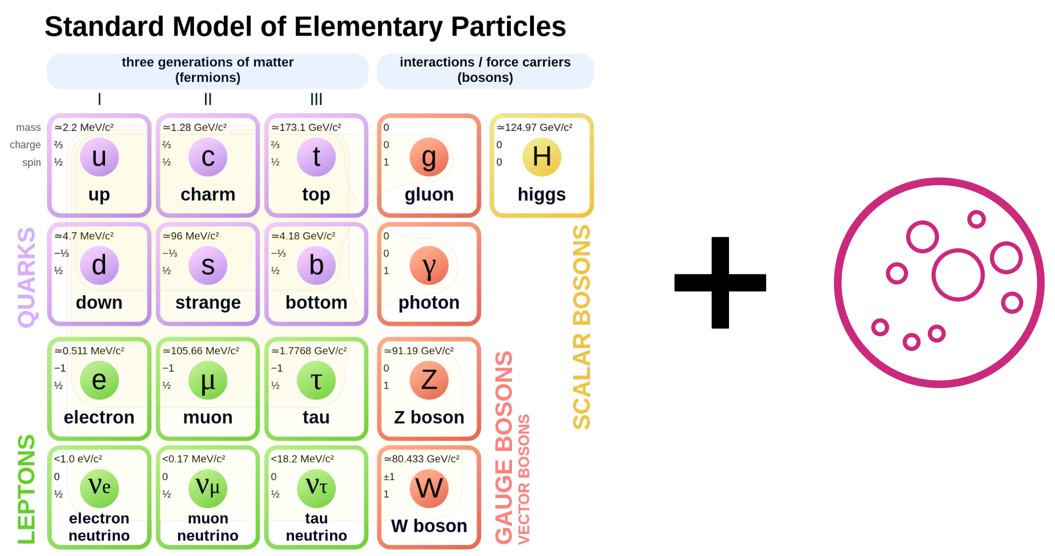

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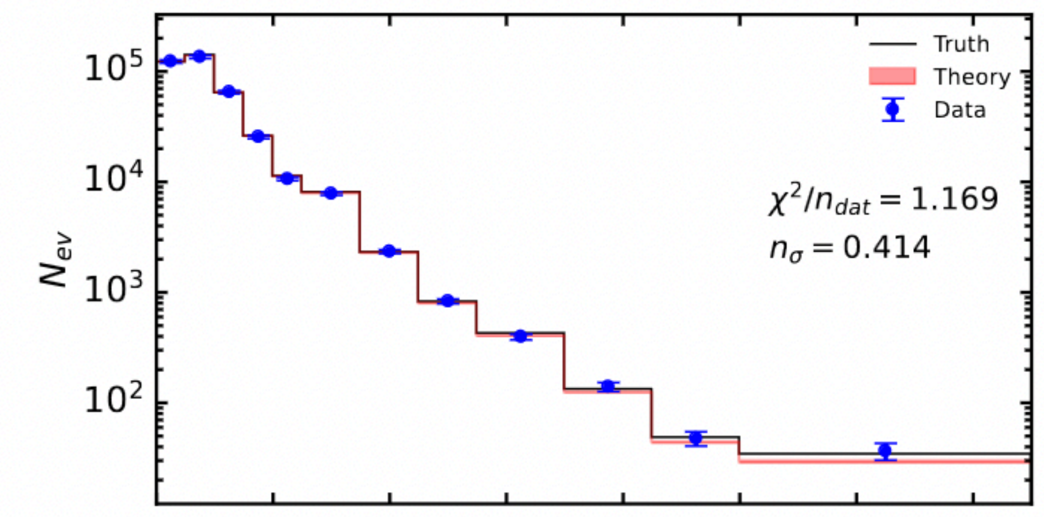

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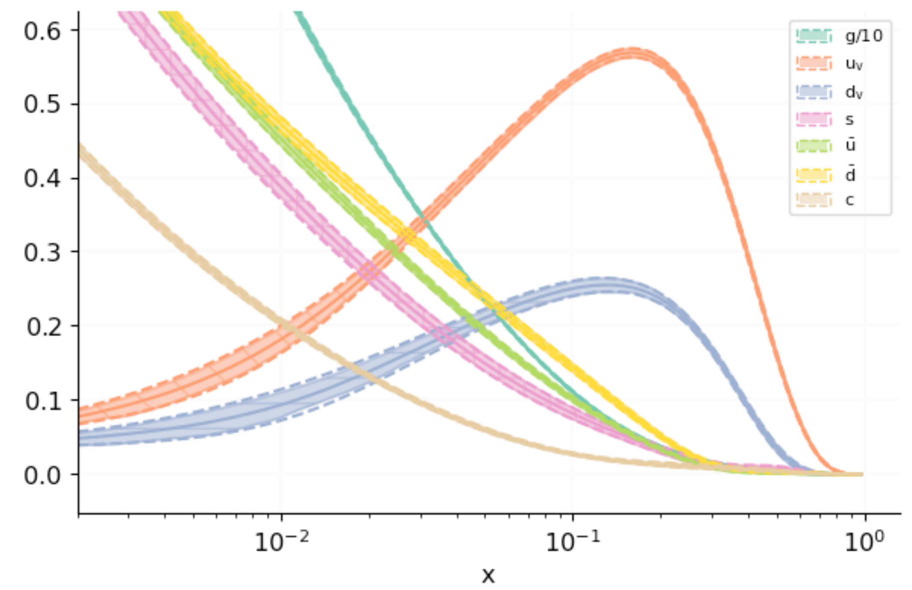

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- Predictions are formed from **TRUE** PDFs, and **TRUE** New Physics parameters:

$$\sigma = \hat{\sigma}_{\text{SM+NP}} \otimes f_{\text{true}}$$

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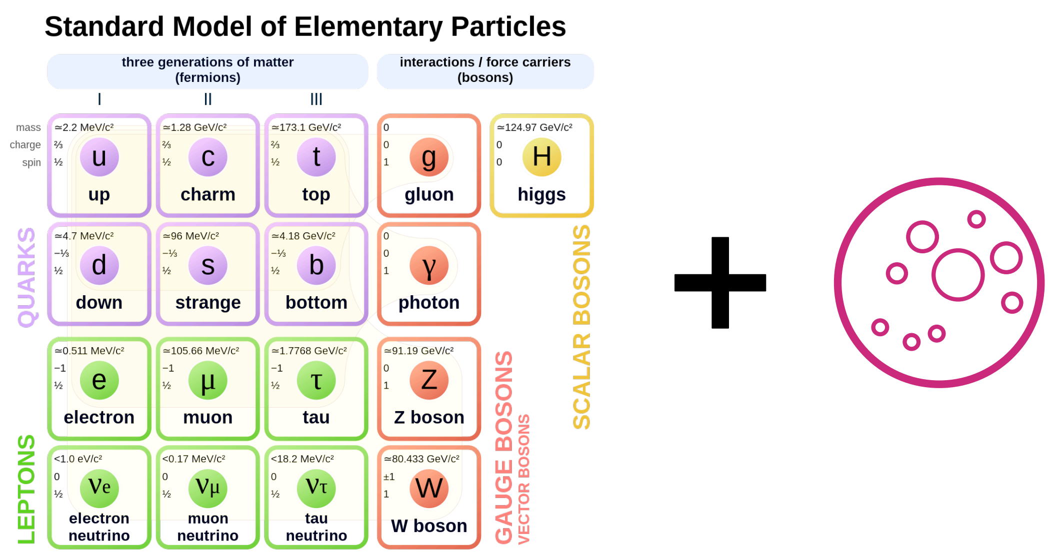

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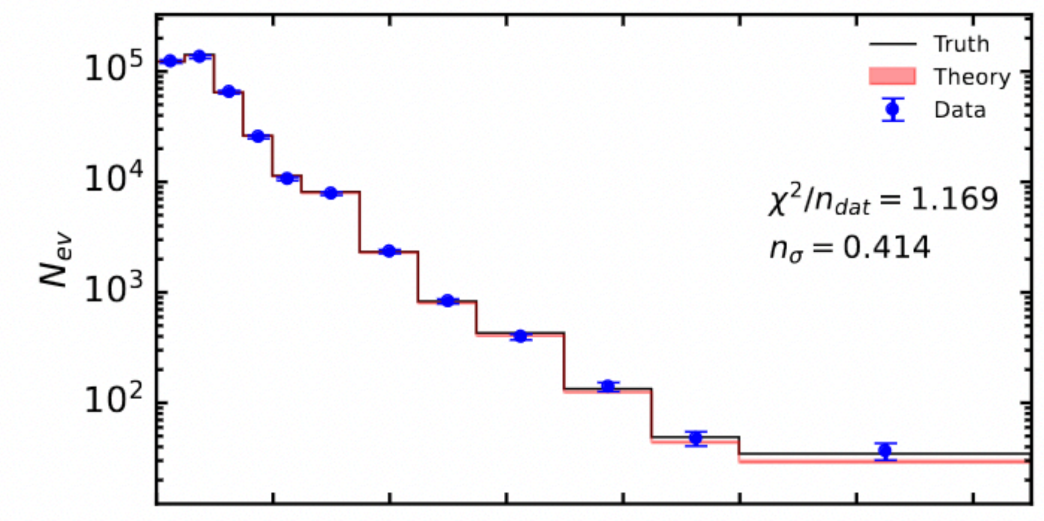

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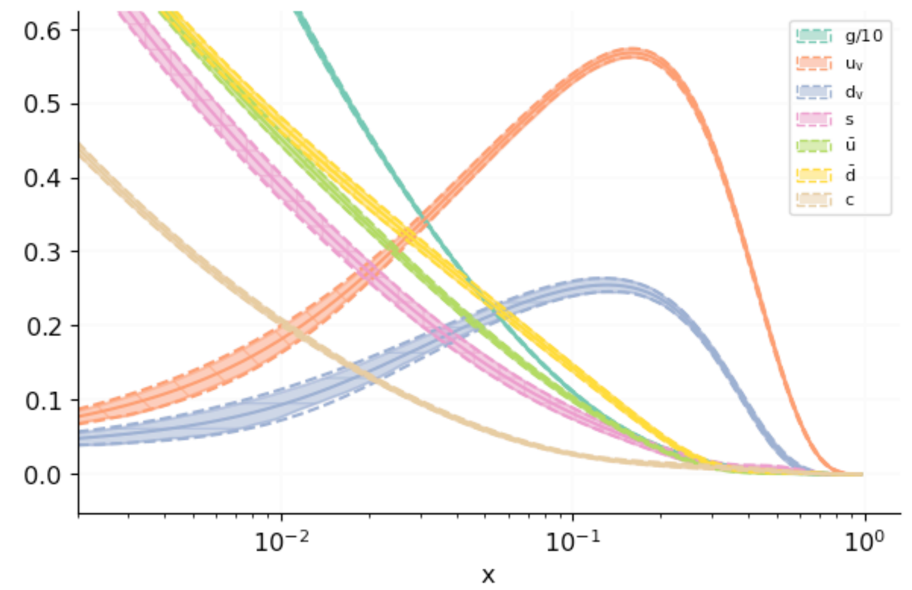

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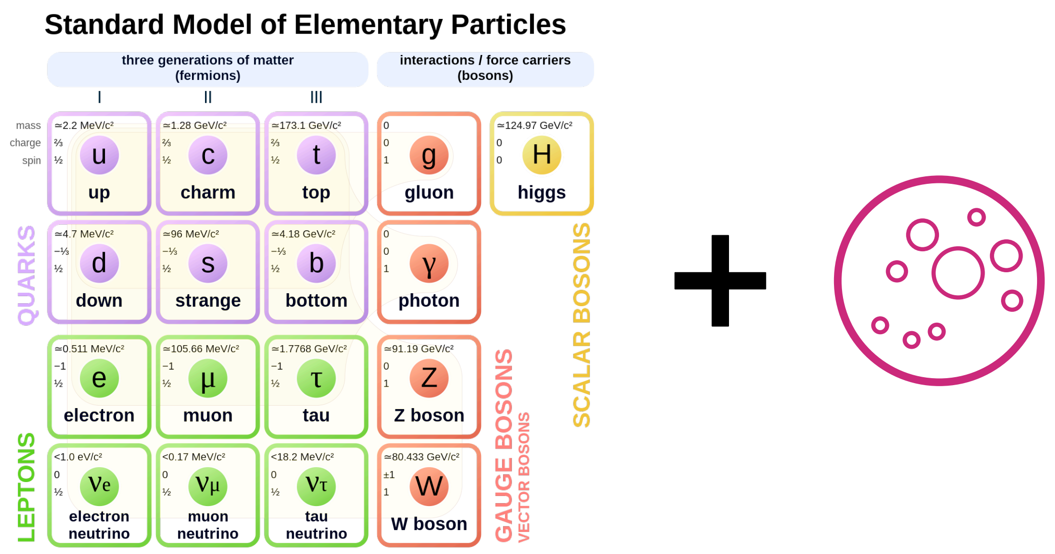

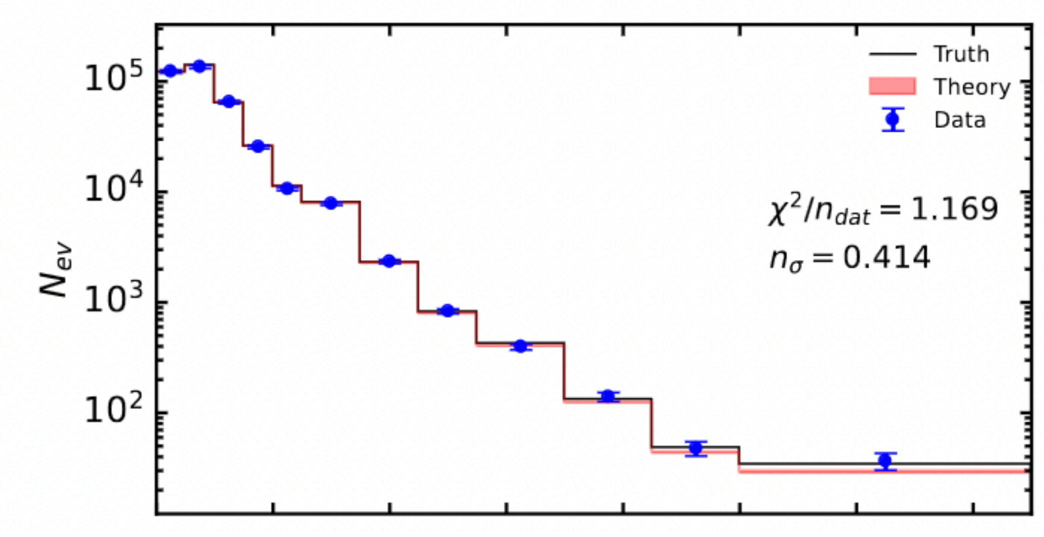

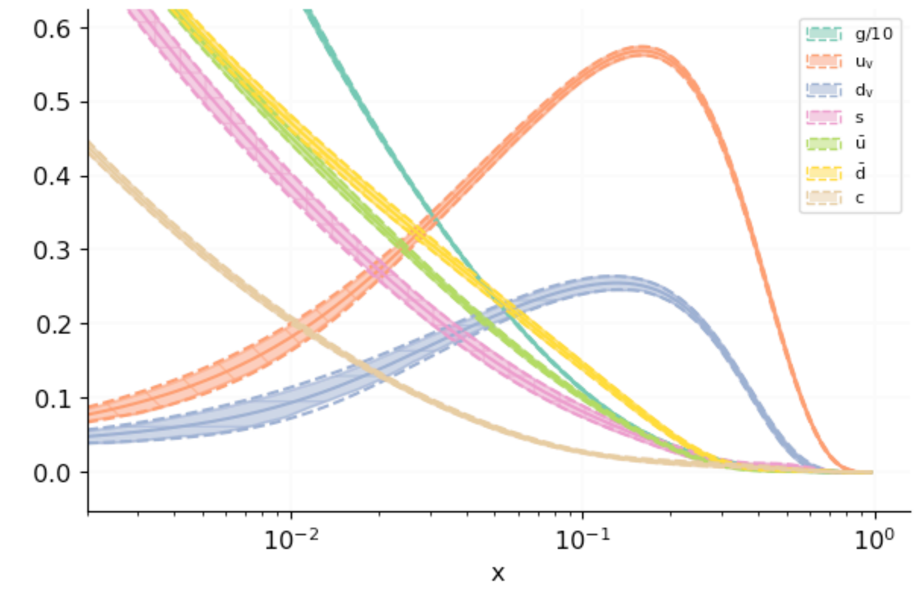

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$\approx$

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Key idea: If the fit quality is good, these are approximately equal for the fit dataset, and the PDFs have 'fitted away' the New Physics.

Key questions for the talk…

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1. Does there exist a New Physics model which can be ‘absorbed’ by the PDFs in this way? (Spoiler alert: yes!)

2. Given a ‘contaminated’ PDF fit, what are the effects of using the PDF on out-of-fit datasets? Could we see New Physics that isn’t really there? (Spoiler alert: yes!)

1. - Contaminated fits for a W' model

Model details

- Let's suppose that the **true theory of Nature** is the SM plus some new W' -boson:

$$\mathcal{L}_{\text{UV}}^{W'} = \mathcal{L}_{\text{SM}} - \frac{1}{4} W'^{a}_{\mu\nu} W'^{a,\mu\nu} + \frac{1}{2} M_{W'}^2 W'^{a}_{\mu} W'^{a,\mu} - g_{W'} W'^{a,\mu} \sum_{f_L} \bar{f}_L T^a \gamma^\mu f_L - g_{W'} (W'^{a,\mu} \varphi^\dagger T^a i D_\mu \varphi + \text{h.c.})$$

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- For **large** W' **masses**, an EFT approach is valid, and the 'strength of New Physics' can be characterised entirely by a **single parameter**:

$$\hat{W} = \frac{\sqrt{2} g_{W'}^2}{8 G_F M_{W'}^2}$$

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- The existence of the W'-boson induces **four-fermion interactions** which affect both **deep-inelastic scattering** and **Drell-Yan** observables entering a PDF fit.

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	n_{dat}
ATLAS DY high-mass 7 TeV	13
ATLAS DY high-mass 8 TeV	46
CMS DY high-mass 7 TeV	117
CMS DY high-mass 8 TeV	41
CMS DY high-mass 13 TeV	43
Total DY (HM-only)	**260**

- There are **five high-mass DY sets** that can be included in PDF global fits, shown above.

Model details

- … and we **additionally** use four **projected** HL-LHC high-mass Drell-Yan datasets, generated as in 1810.03639, which are also affected.

HL-LHC HM DY 14 TeV - neutral current - electron channel
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Total HL-LHC: 56 points

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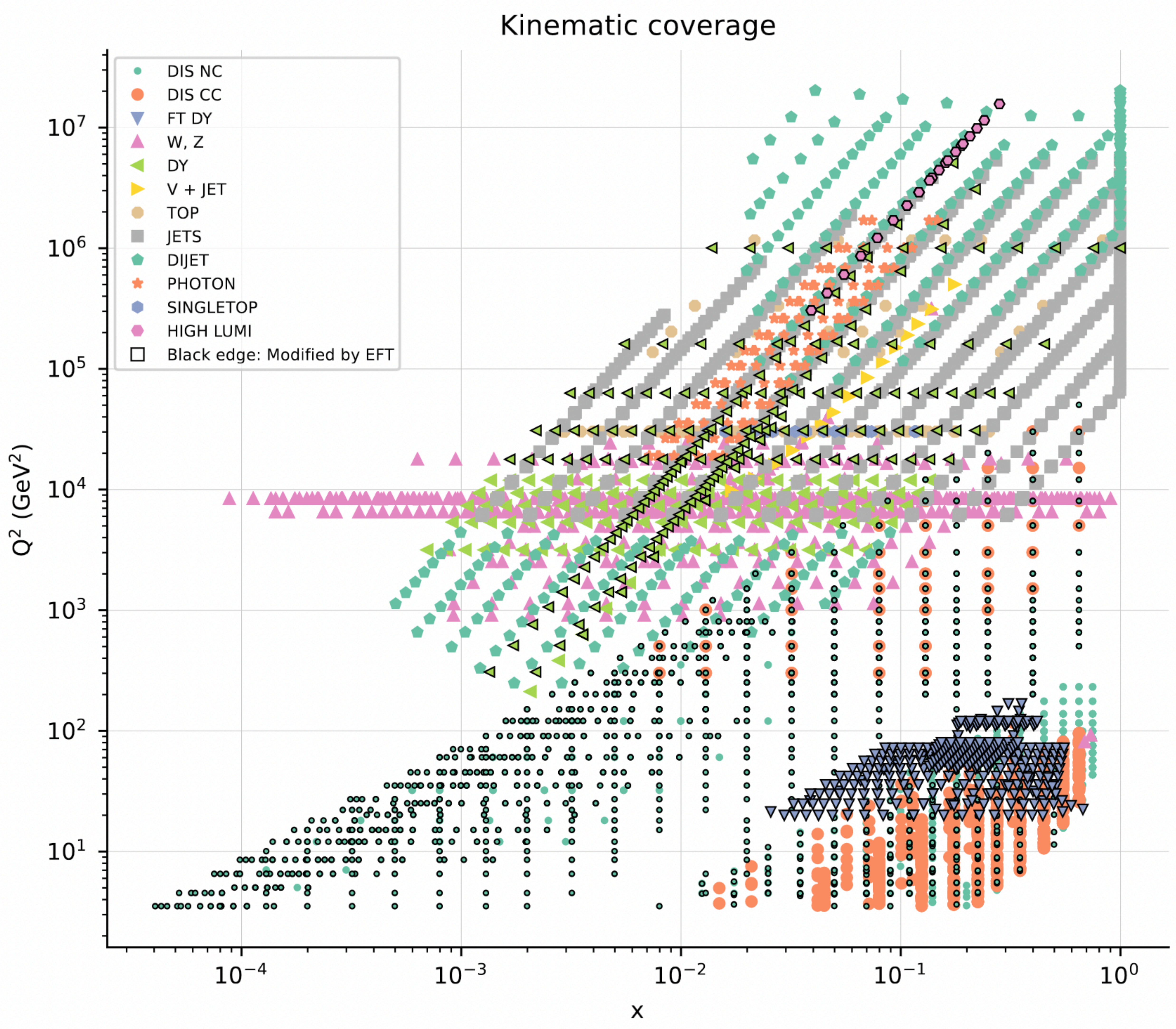
- *Right*: the kinematic coverage of our fit, with the **New-Physics 'contaminated' points** shown with **bold outline**.



Contaminated PDF fits

- We generate **fake data** according to three different interaction strengths for the W'-model: $\hat{W} = 0.00003$, $\hat{W} = 0.00008$, $\hat{W} = 0.00015$. The first two are **allowed within current constraints**.

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- Using the contaminated PDF to make predictions for **out-of-fit SM-like datasets**, get **poor** data-theory agreement, ***erroneously indicating NP!***

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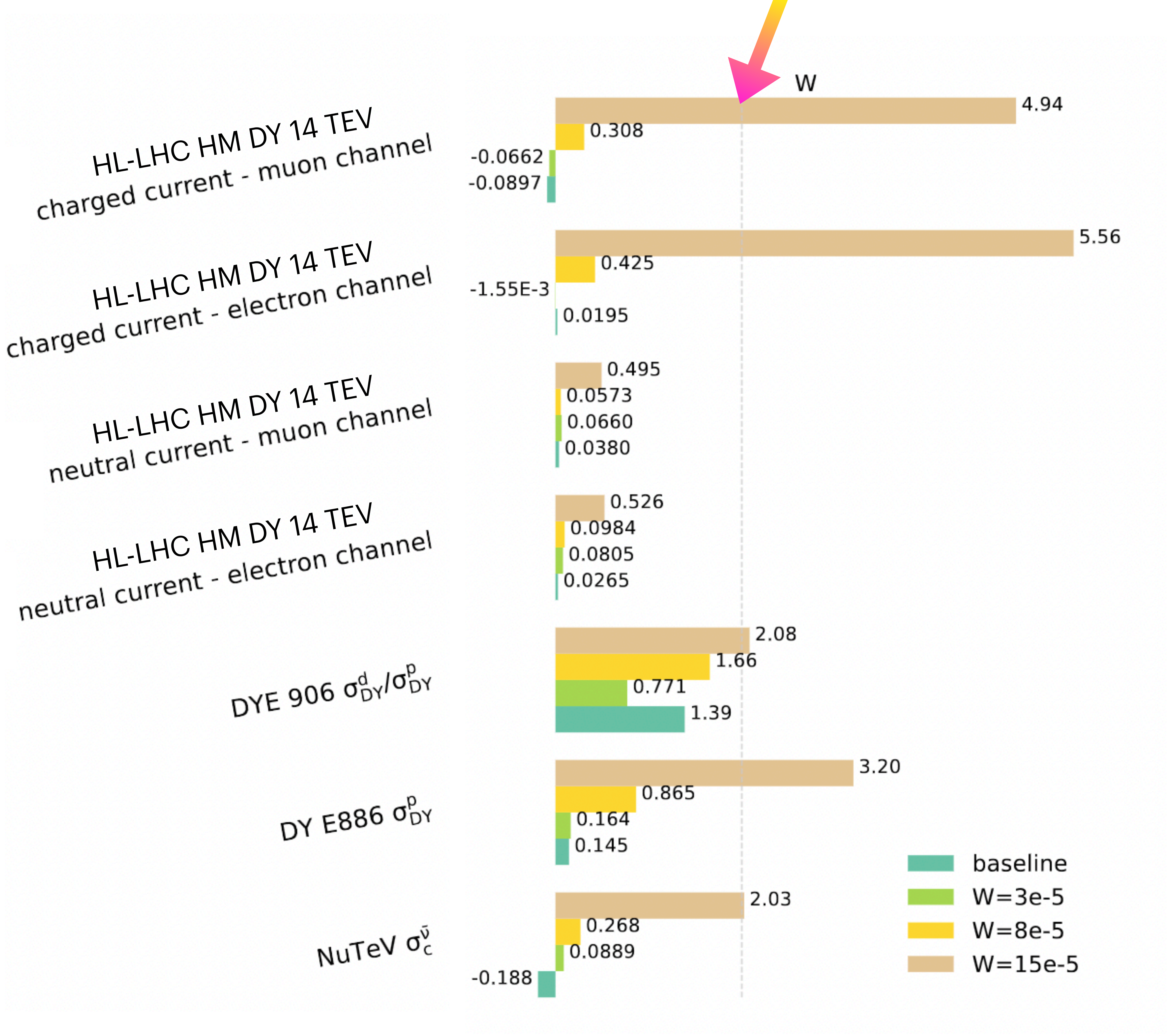
- If datasets are flagged, the **weighted fit** method is applied, and depending on its success, the flagged datasets are either judged **consistent/inconsistent** with the global dataset, and **included/excluded** on that premise.

Fit quality

$n_\sigma = 2$, the critical rejection value for NNPDF



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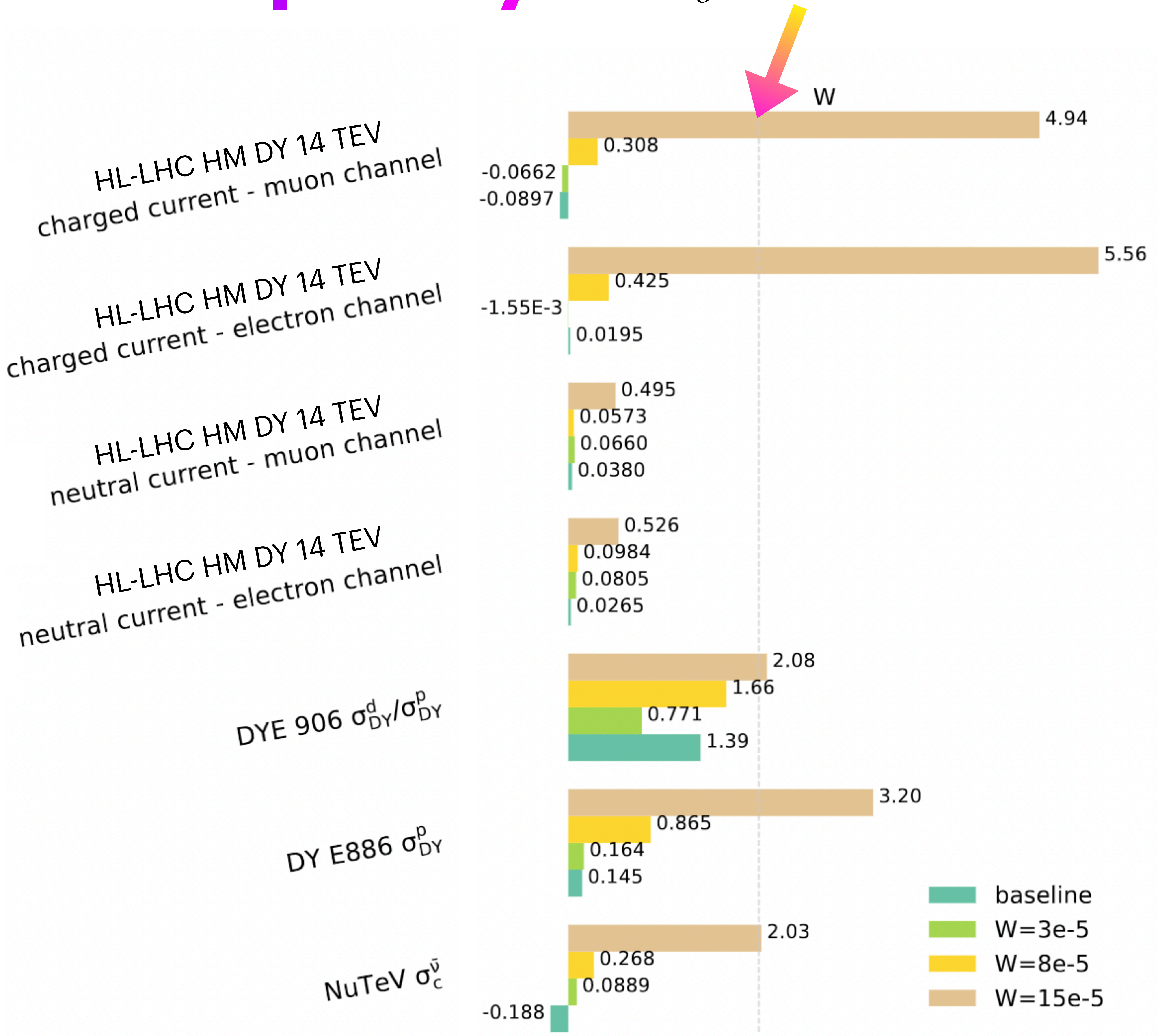

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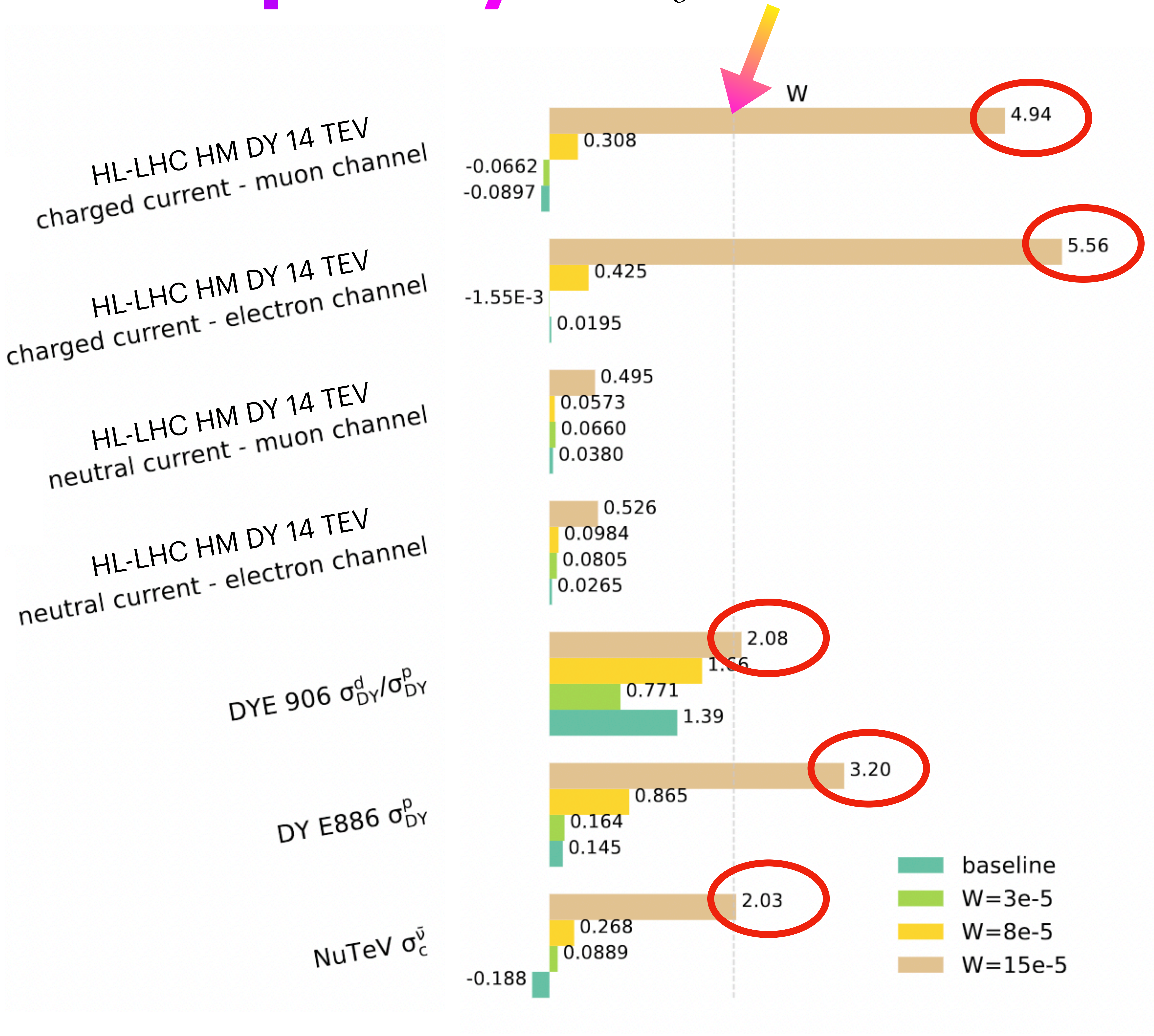

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- As promised, fit quality **doesn't show anything unusual** for $\hat{W} = 0.00003$ and $\hat{W} = 0.00008$.
- For relatively 'strong' New Physics though, we start to get **flagged sets** amongst the **contaminated HL-LHC CC datasets**, and amongst **low-energy SM-like fixed target DY datasets**, indicating a **tension**.

Why the tension? - Look at the PDFs!

- The predictions for the high mass DY datasets that are ‘contaminated’ by New Physics come from the $q\bar{q}$ **PDF luminosity** in the case of **neutral current DY** and from the qq **PDF luminosity** in the case of **charged current DY**.

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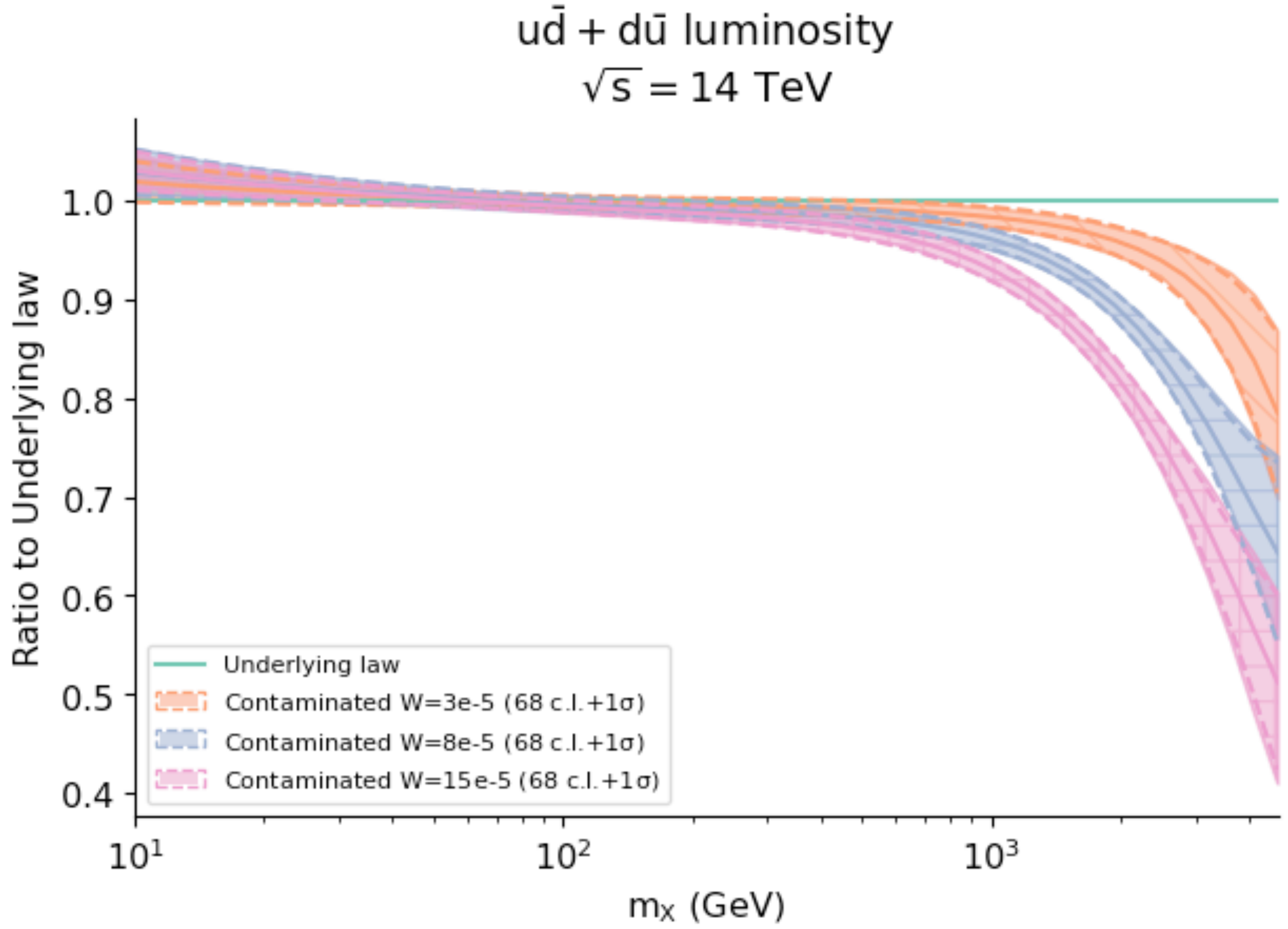
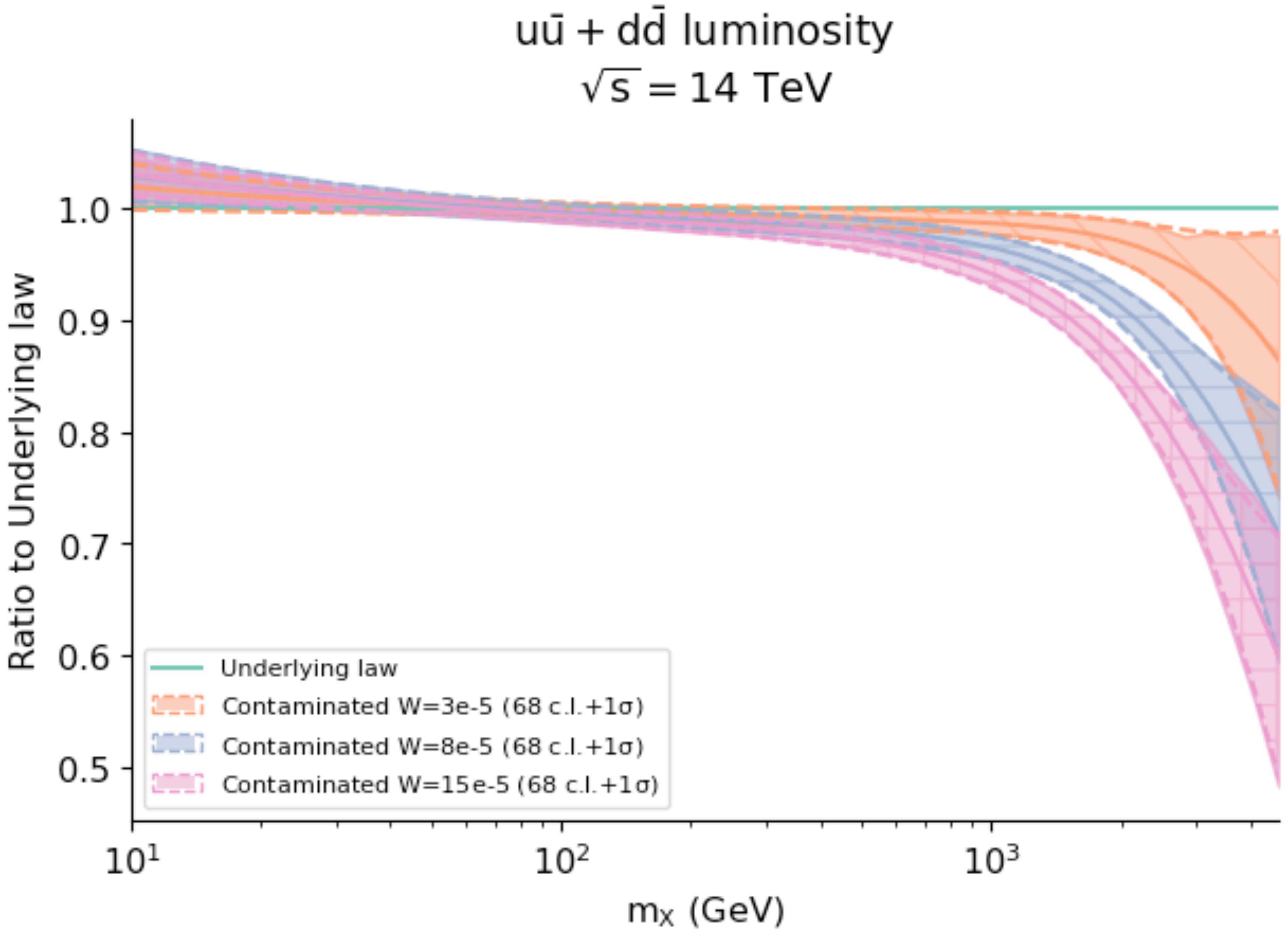
- The predictions for the high mass DY datasets that are 'contaminated' by New Physics come from the $q\bar{q}$ **PDF luminosity** in the case of **neutral current DY** and from the qq **PDF luminosity** in the case of **charged current DY**.
- As the interaction strength of the New Physics increases, a **larger shift** is required in **both luminosities** at **smaller invariant masses**:





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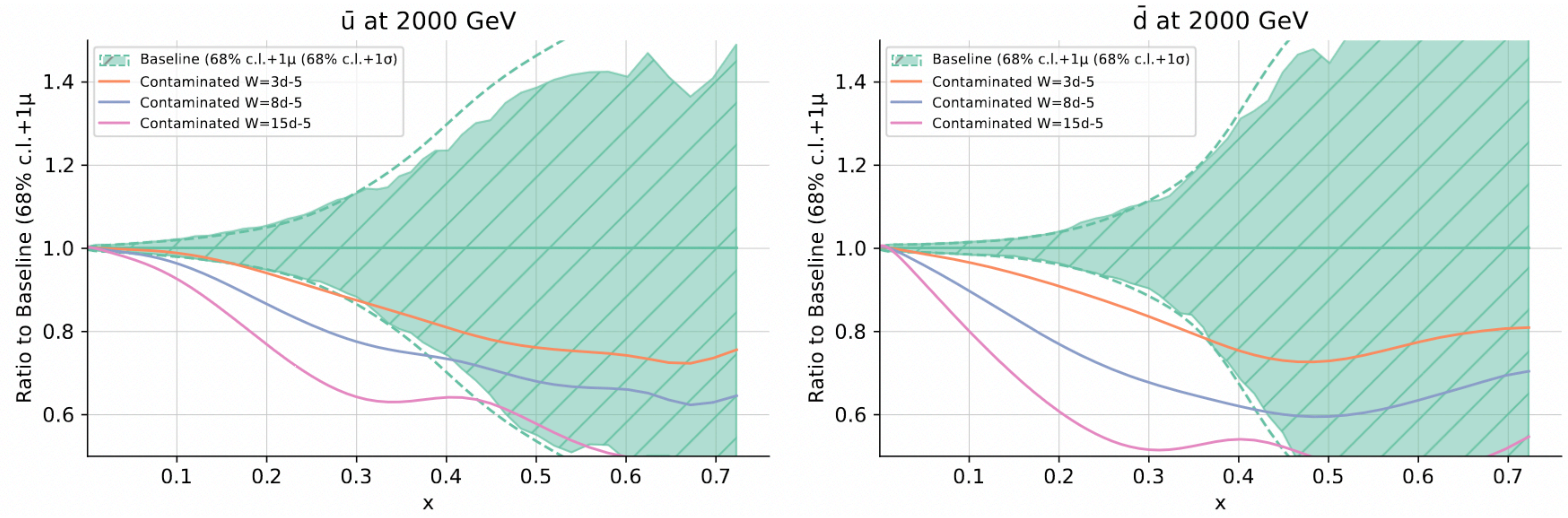

- In the $\hat{W} = 0.00003$ and $\hat{W} = 0.00008$ scenarios, the **large-x regions** of the **anti-quark PDFs** (which contribute to the large invariant mass regions where the shift is required) are otherwise **unconstrained** in the PDF fit; hence, they can move to accommodate the New Physics.

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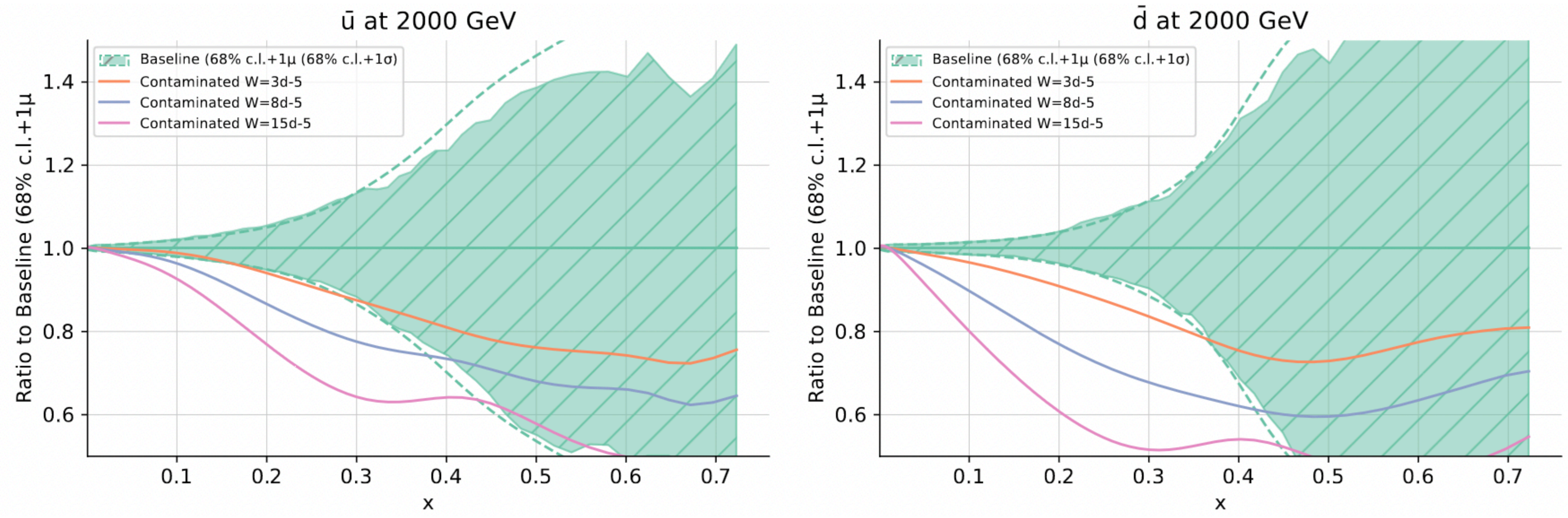

- In the $\hat{W} = 0.00015$ scenario however, the luminosity shift is required at a **sufficiently low invariant mass** such that other datasets (notably **low-energy fixed target DY**) begin to constrain the corresponding region of x-space that the anti-quark PDFs had **previously exploited**. This points to the need for **better knowledge of the large-x anti-quark PDFs**, e.g. from the **EIC** or proposed **Forward Physics Facility** at CERN.

2. - Consequences of using a contaminated fit

Predictions for SM-like out-of-sample sets

- So far, we have concentrated on whether **New Physics** can **pass undetected** through a PDF fit - in our W'-model, this is possible for a **sufficiently low interaction strength** by **exploiting a lack of constraints** on the **large-x anti-quark PDFs**.

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- *Next natural question*: Is there a value of $\hat{W}$ for which the PDFs **absorb the New Physics**, but give **wrong conclusions** when applied to **out-of-fit datasets**? As promised earlier, **yes**.

W^+W^- production

- Consider W^+W^- production, an observable **not usually included in PDF fits**. This observable is **unaffected** by New Physics in our W'-model, therefore if we **generate fake data**, it will be **SM-like**.

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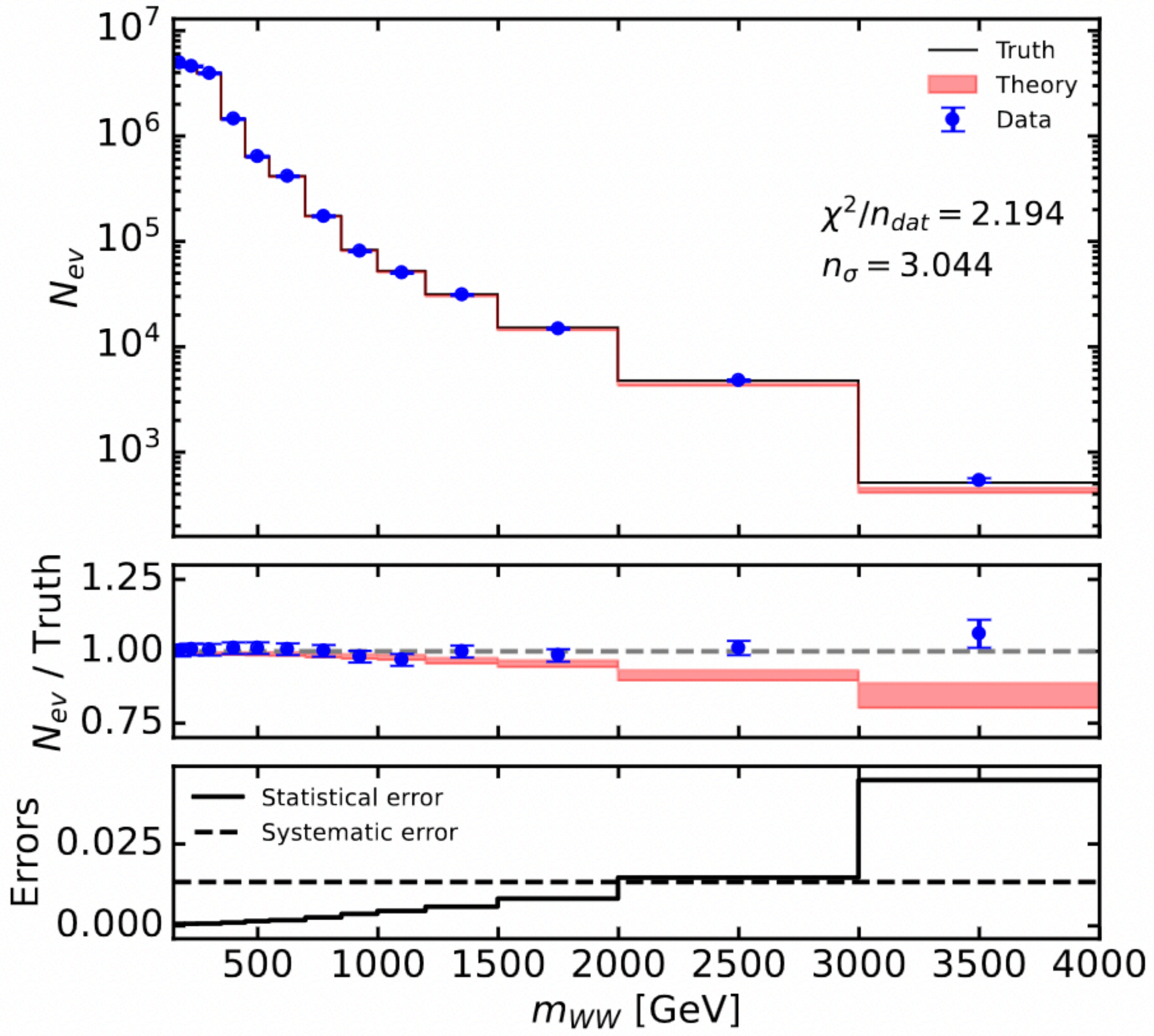
- Generating a fake **HL-LHC** W^+W^- **dataset**, shown right in **blue**, we compare with predictions obtained from the 'contaminated' PDFs.



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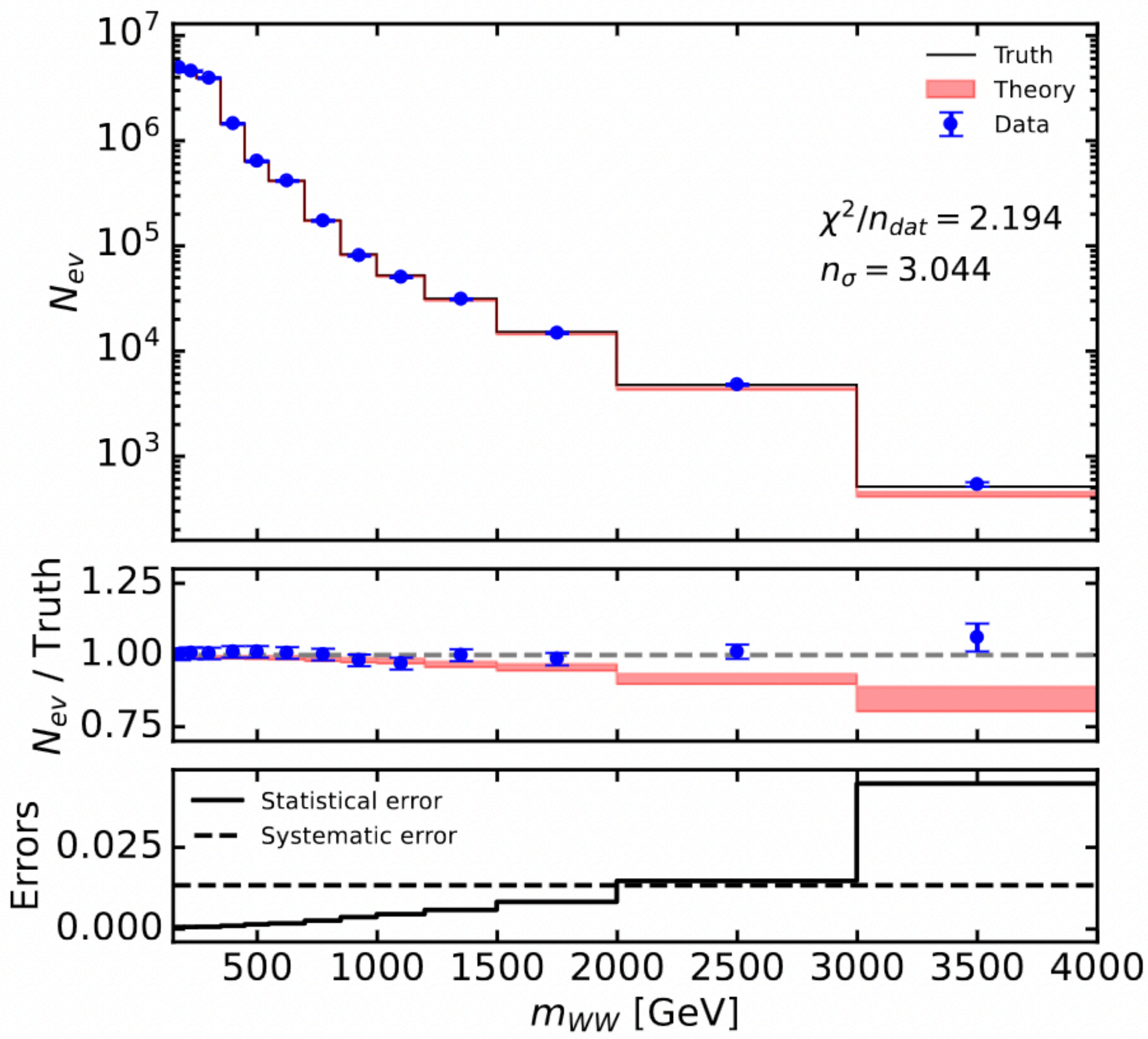
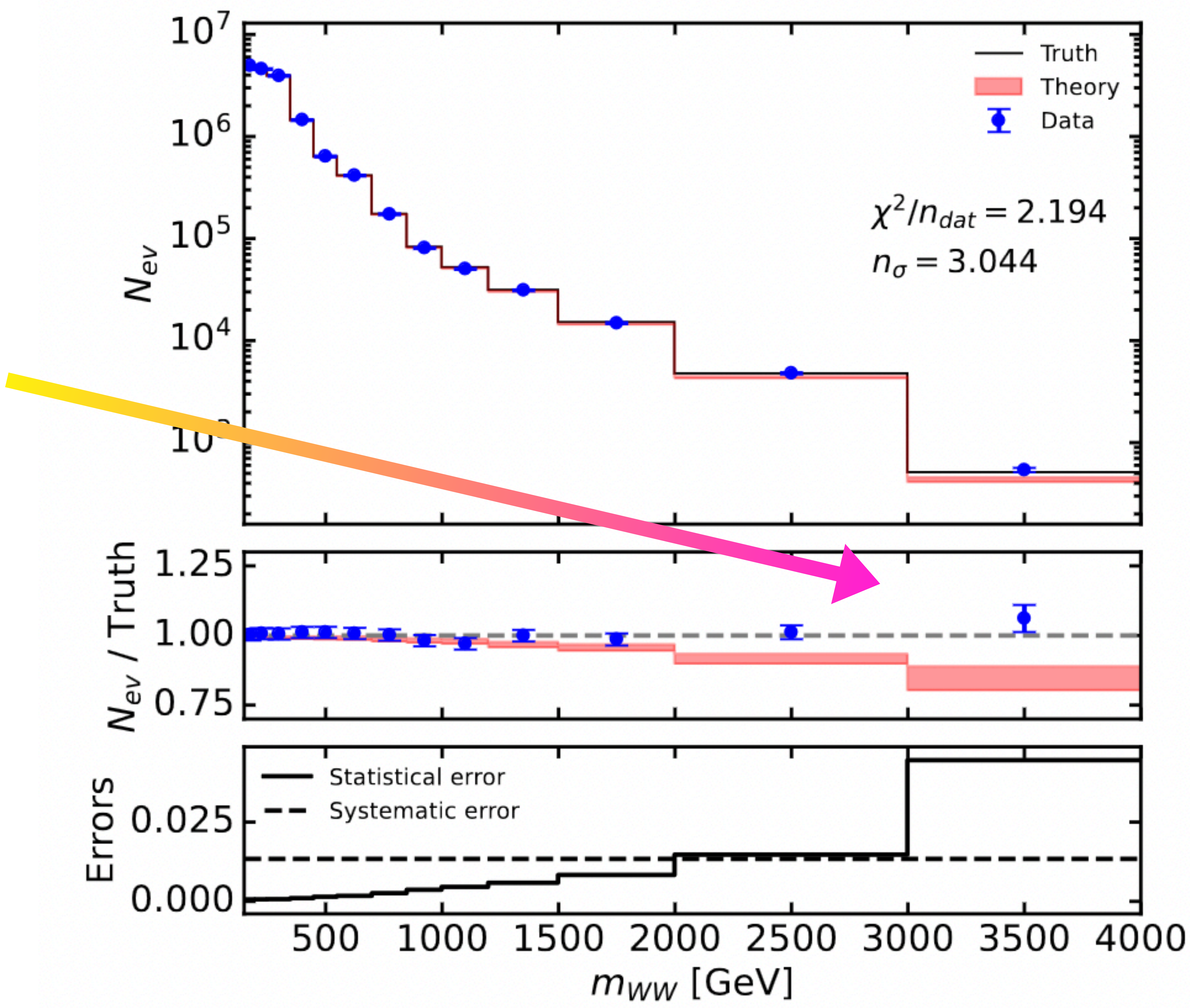
- Generating a fake **HL-LHC** W^+W^- **dataset**, shown right in **blue**, we compare with predictions obtained from the 'contaminated' PDFs.

- For $\hat{W} = 0.00003$, **predictions are consistent**, but for $\hat{W} = 0.00008$ **a deviation of 3σ is observed** (shown in **red**)!



W^+W^- production

To the naïve BSM practitioner, who simply uses PDFs as given to them by the fitting collaborations, this looks like New Physics!



3. - Disentangling PDFs and New Physics

Disentangling strategies

- We have now seen that there exists a **real danger** for PDFs to **inadvertently absorb New Physics effects**, which can lead to **erroneous discoveries** of **New Physics**.

Key question for last part of talk:

Can we do anything about this?

Disentangling strategies

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- We explored several strategies for **disentangling PDFs and New Physics** as part of our paper. In this talk we mention **only two**:

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1. Obvious first choice: include **more low-energy SM-like data** which probes the **large-x anti-quarks**.
2. Using **observable ratios** to remove PDF dependence when **searching for New Physics.**

If you can think of other strategies, let us know!

New data from LHCb?

- Future precision data from LHCb might be expected to **better constrain** the **large-x anti-quark PDFs** whose freedom was exploited to absorb the New Physics earlier.

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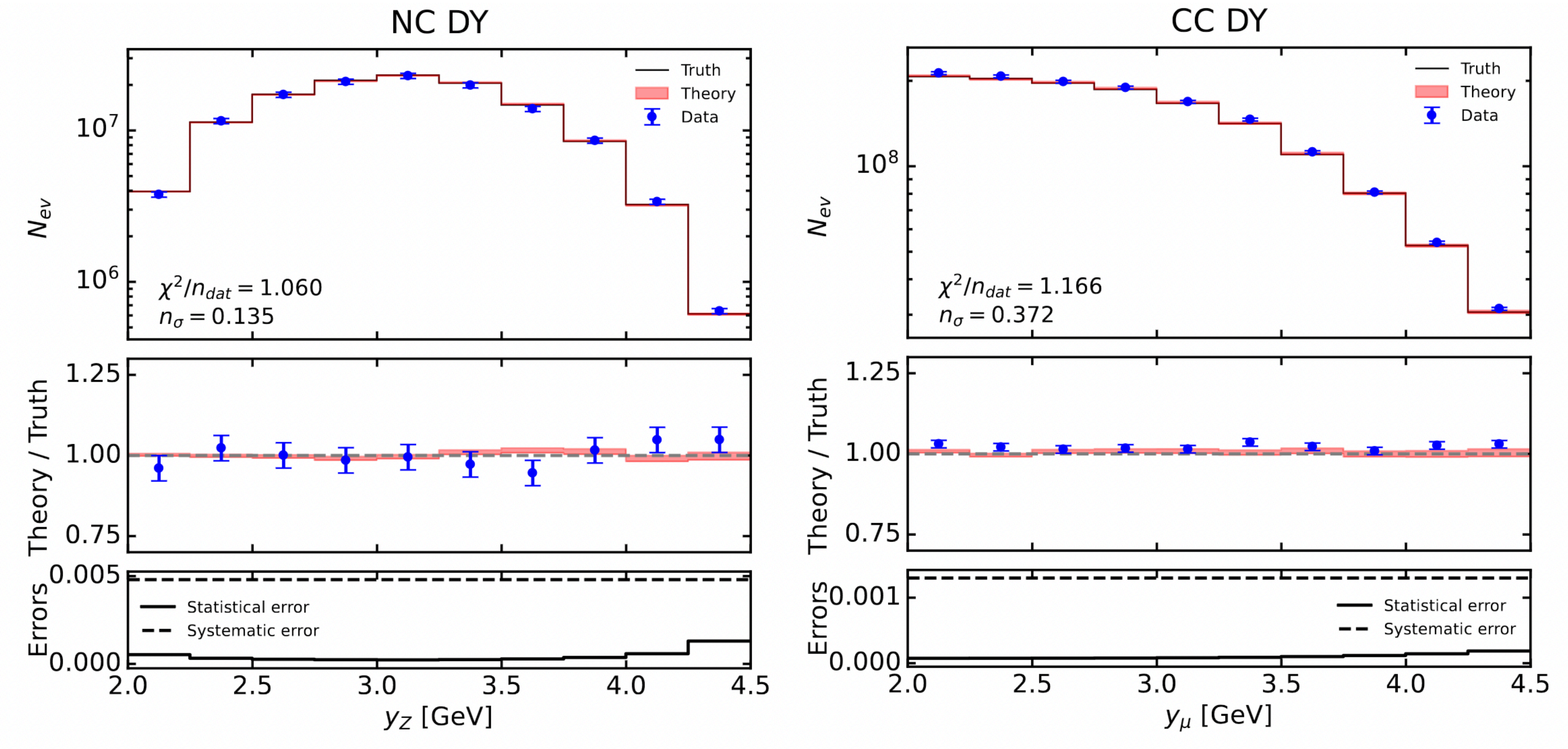
- Future precision data from LHCb might be expected to **better constrain** the **large-x anti-quark PDFs** whose freedom was exploited to absorb the New Physics earlier.

- In particular, measurement of **on-shell forward W and Z production** at the **HL-LHC** might be hoped to provide these constraints.

- We generate **fake data** for these observables, as they would be measured by LHCb, and check the **quality of predictions** from the $\hat{W} = 0.00008$ PDFs, hoping they will **perform badly**.

New data from LHCb?

- We see that the agreement is **excellent**.



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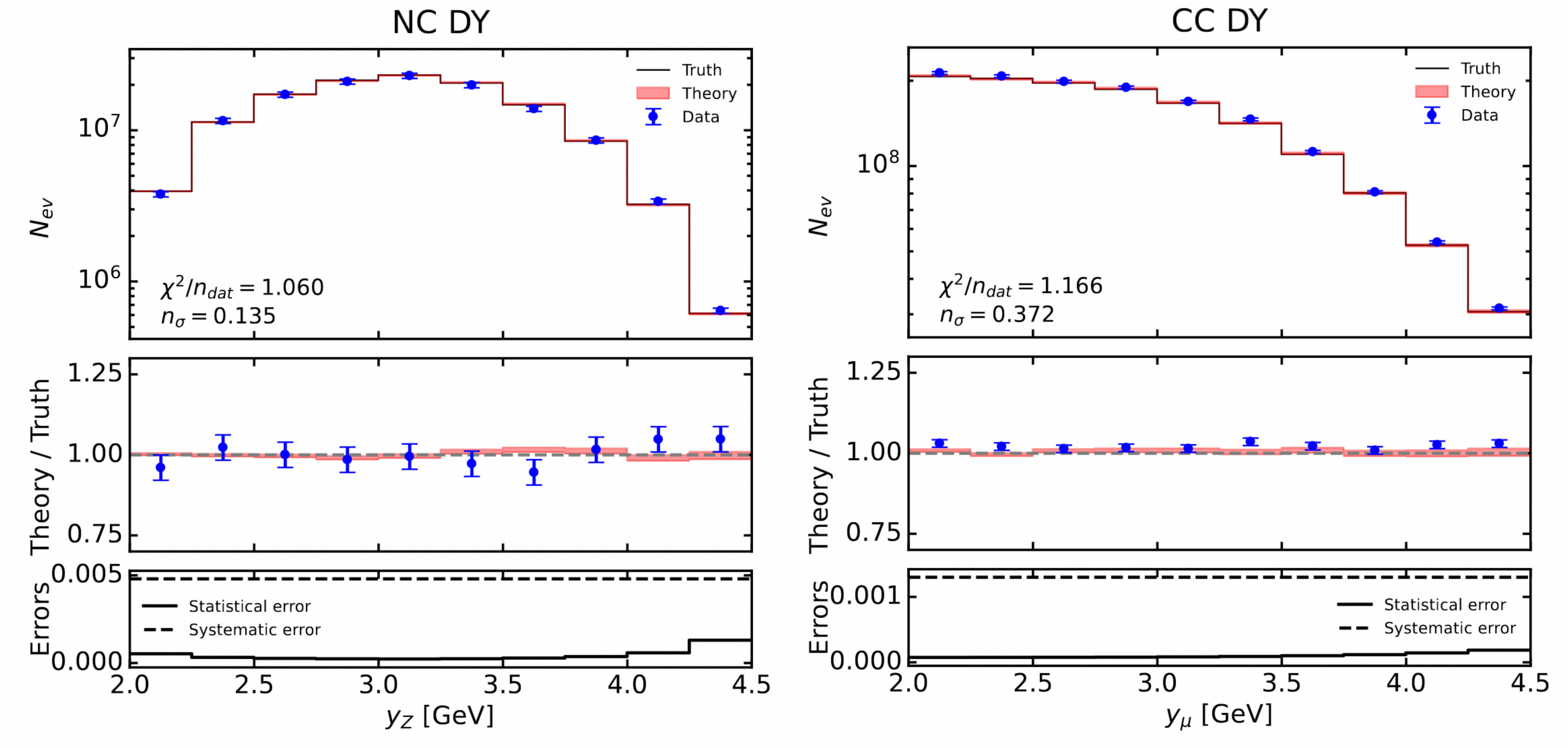

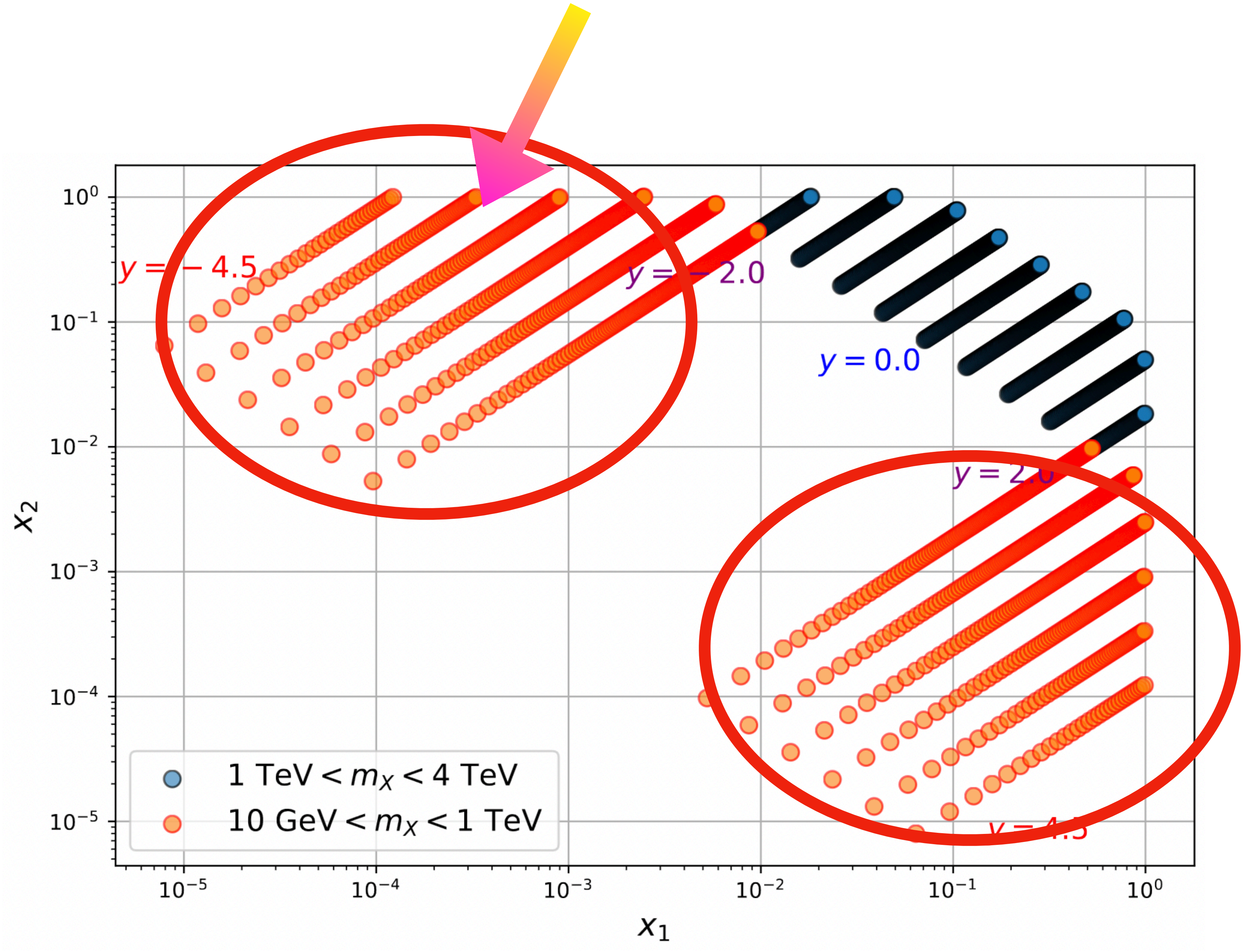

- Why? In the **forward region** probed by LHCb, one parton has **very large** x, but the other has **very small** x. Since **valence quarks** at large-x are **much more abundant**, in the vast majority of collisions we end up probing the **large-**x **quarks** instead of the **large-**x **anti-quarks.**

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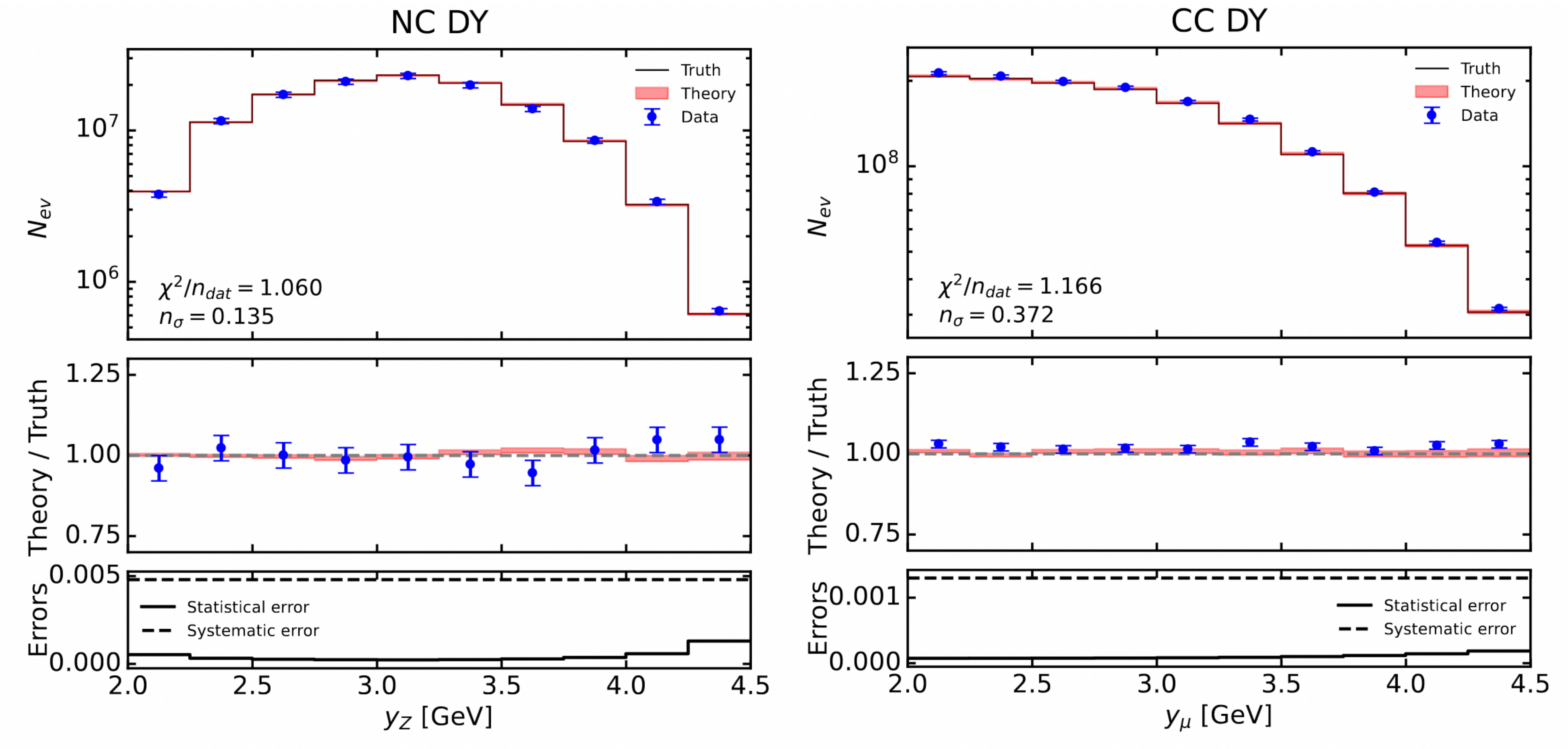

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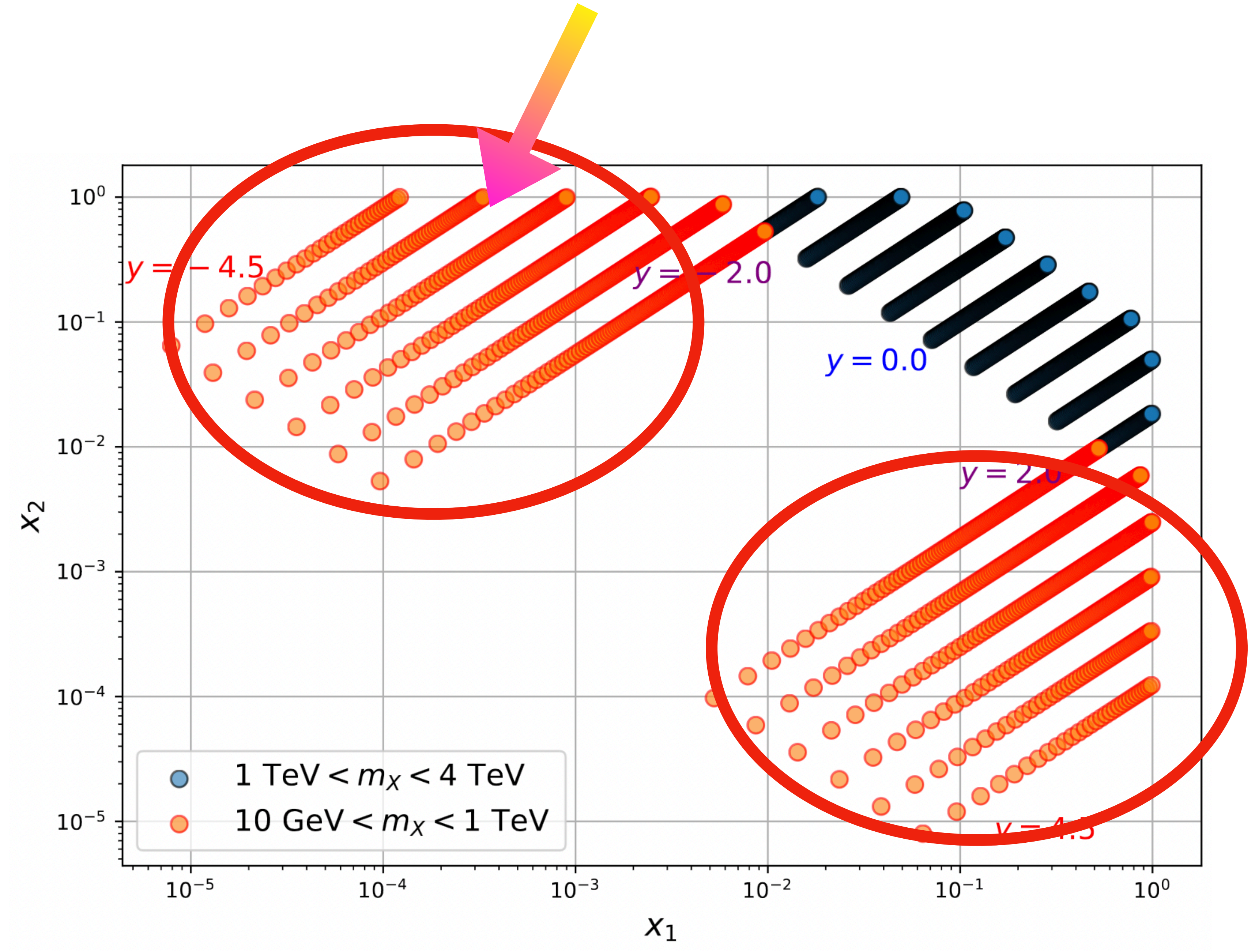

- Other observables might be useful from LHCb though - we have yet to explore the **forward/ backward asymmetry** and **differential angular distributions**, which may provide useful constraints.

Observable ratios

- Including **new low-energy data** will hopefully **protect the PDF fit from contamination**. However, **even if the PDF is contaminated**, BSM practitioners can still make reliable conclusions about New Physics by **limiting the PDF dependence** of the observables they study.

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Observable ratios

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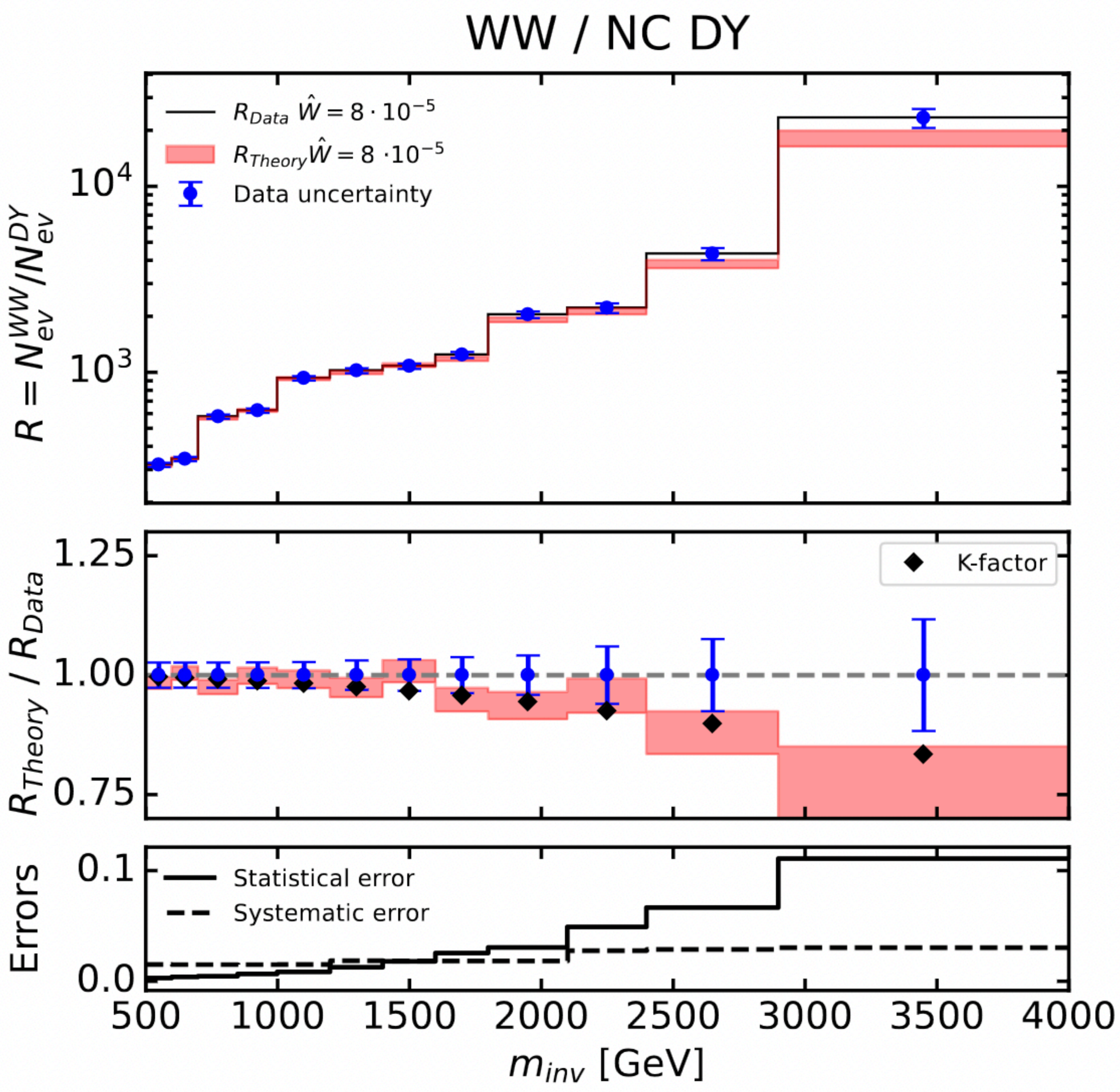
- Suppose that instead of studying W^+W^- earlier and **erroneously** discovering New Physics there, a BSM practitioner studies the ratio W^+W^-/(NC DY) to **neutral-current DY**.

- Here, the **PDF dependence mostly cancels in the ratio**, keeping us **safe** from contamination effects.

Observable ratios

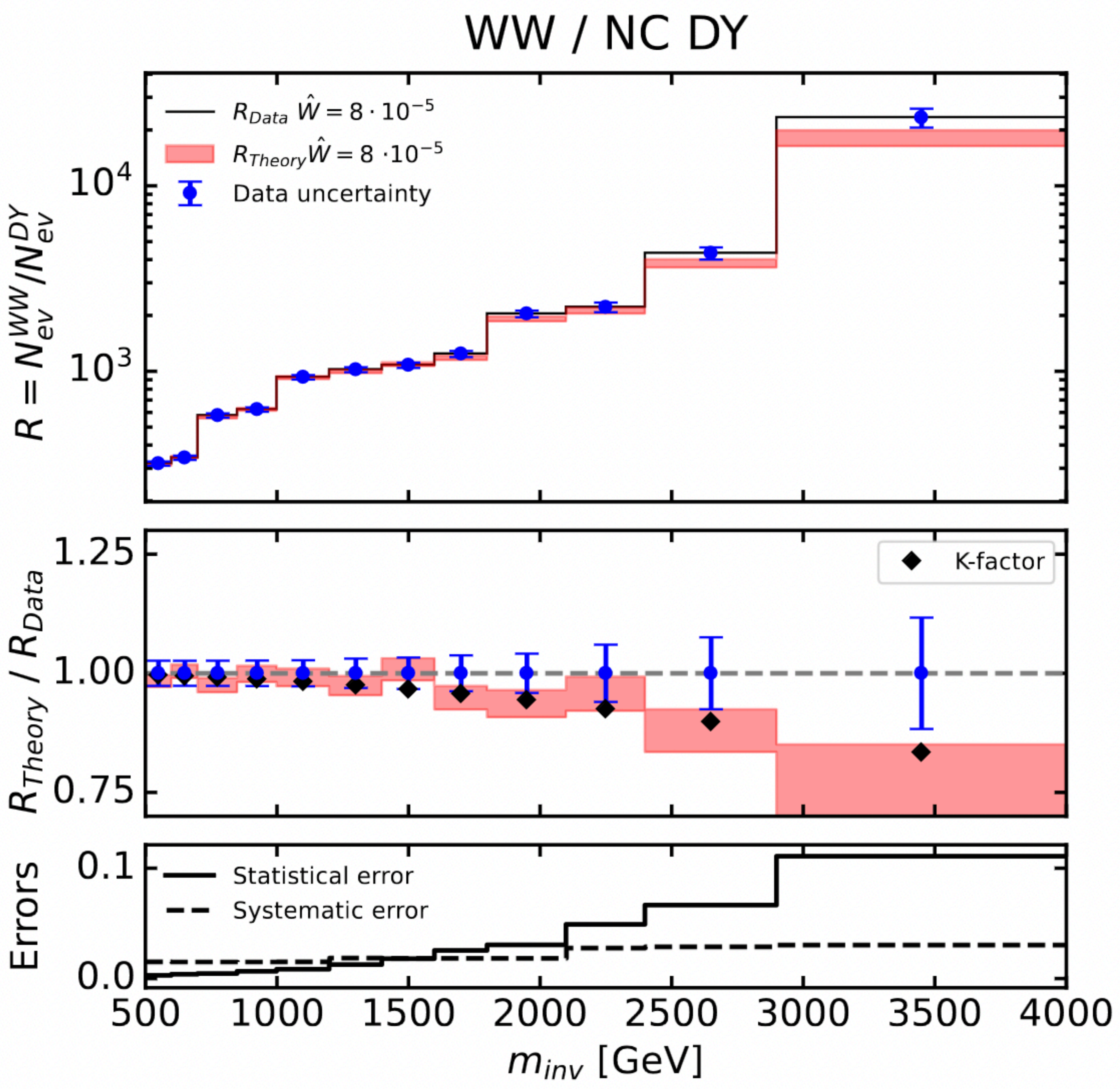
- Indeed, we see that studying this ratio, the BSM practitioner would **correctly** conclude New Physics in **either** W^+W^- **or** NC DY in this case (or both).



Observable ratios

- Indeed, we see that studying this ratio, the BSM practitioner would **correctly** conclude New Physics in **either** W^+W^- **or** NC DY in this case (or both).

- If the **observables** are studied **independently**, they would **wrongly** conclude New Physics in W^+W^- as we saw above.



Conclusions

Conclusions

- There exist New Physics scenarios which can be **'fitted away'** into the PDFs.

- If these PDFs are **used for BSM searches**, we might **erroneously** see New Physics.

- PDF fits should aim to include **more low-energy SM-like data** to guard against contamination from New Physics.

- BSM practitioners should aim to study **PDF-independent observables** to **avoid wrong conclusions** about New Physics.

Future work (advertisements)

- The **best-case scenario** for BSM studies would be to **simultaneously extract PDFs** and **BSM parameters**. This has previously been studied in 2303.06159, for example. The **PBSP group** will shortly release a **public code** which allows BSM practitioners to do this for **linear BSM models**:

SIMUnet

- This public code will **also** support the reproduction of the results of this talk, and allow for users to **assess the possibility of PDF contamination** for their own **user-defined models** (which are **not** restricted to the linear case).

Thanks for listening!
Questions?

Backup A: Validity of the SMEFT approach

Is the SMEFT approach valid?

- We approximated the W'-model with a **linear EFT approach**. This is useful because the New Physics contamination to observables is then given by **linear K-factor multiplication**, allowing us to scan many more scenarios than if we used the UV model.

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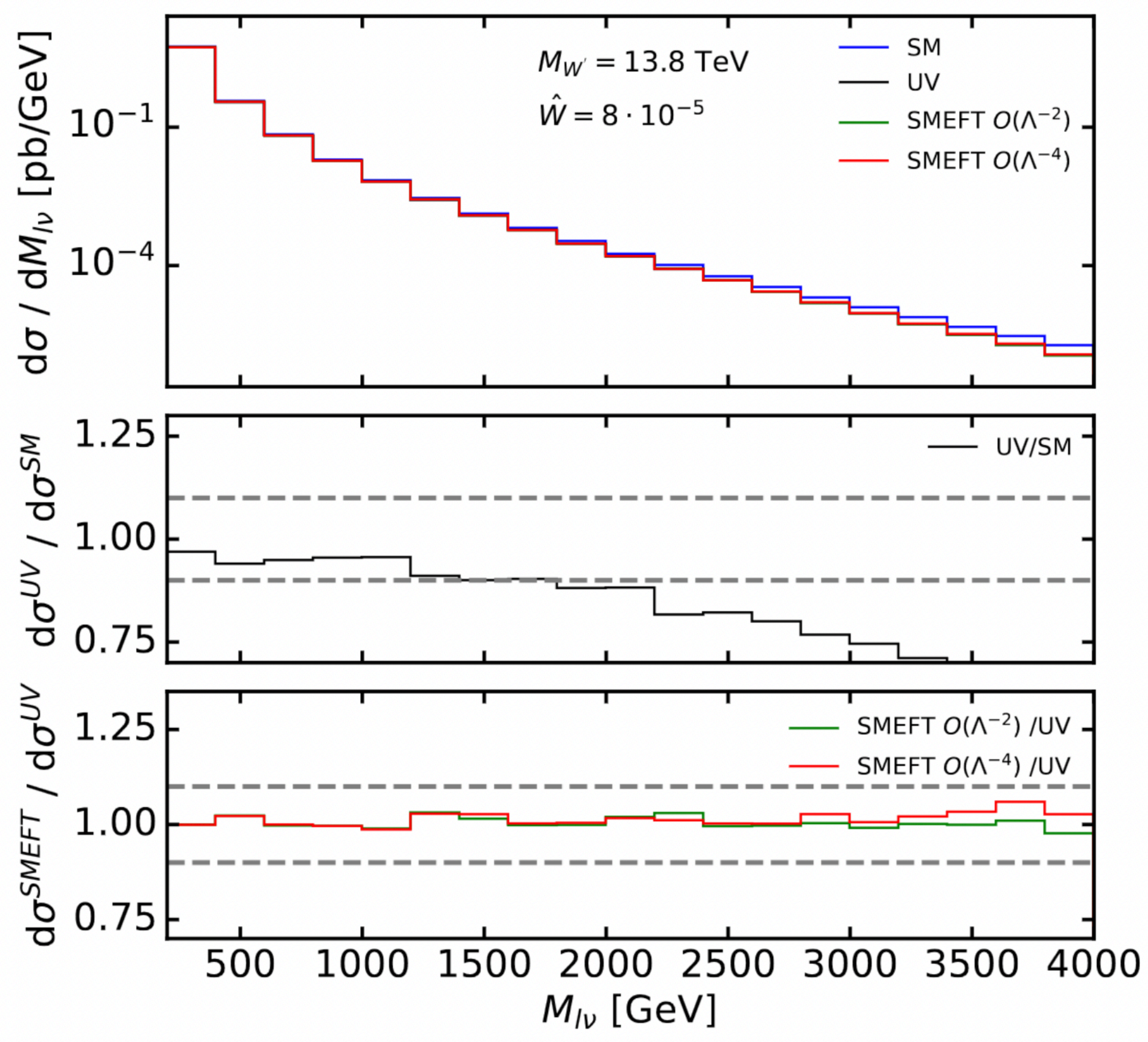
- *Right*: For the $\hat{W} = 0.00008$ scenario, we show the **SM**, the **UV model**, and the **SMEFT approximation** (at linear and quadratic order) for CC DY.



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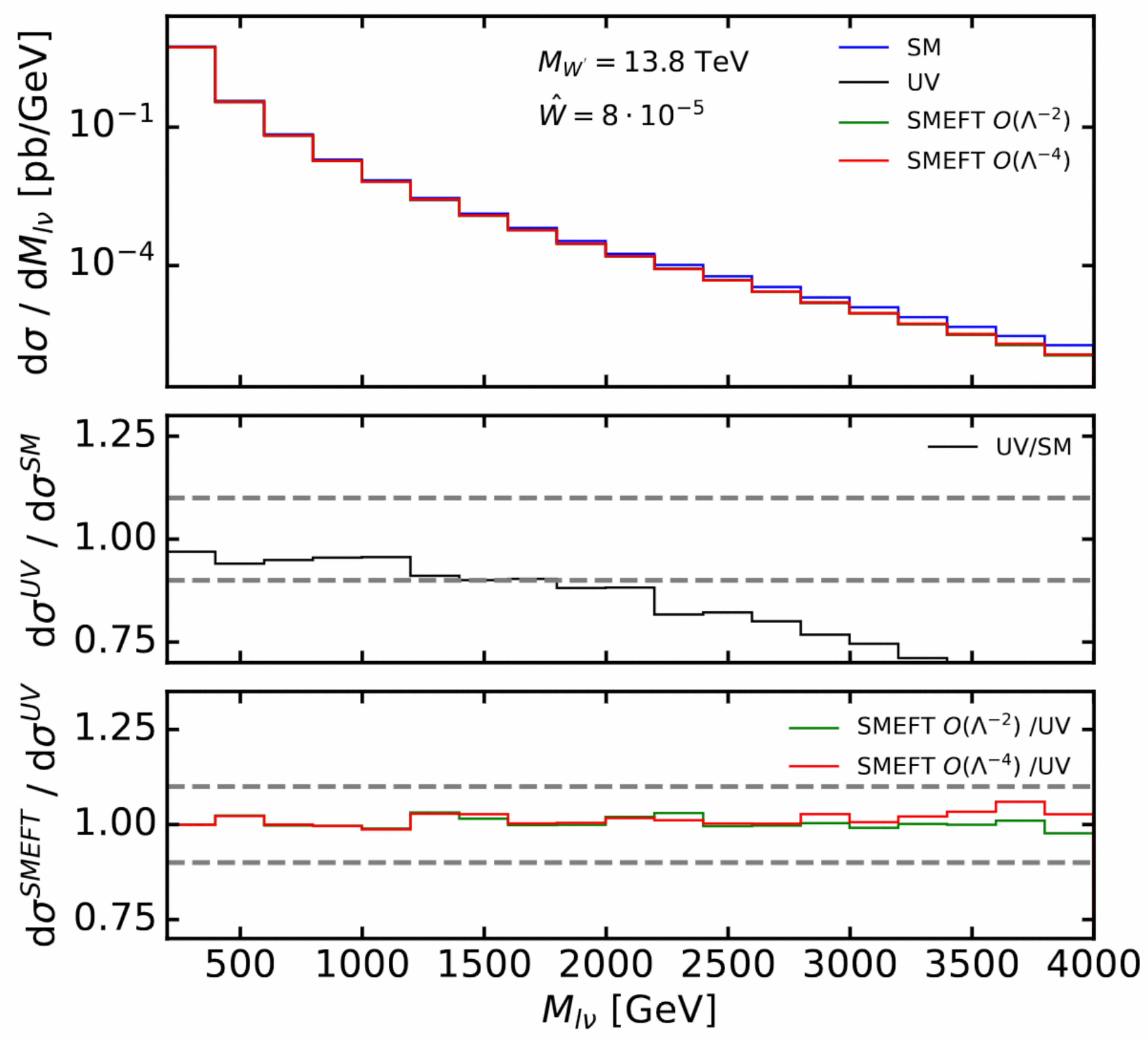
- *Right*: For the $\hat{W} = 0.00008$ scenario, we show the **SM**, the **UV model**, and the **SMEFT approximation** (at linear and quadratic order) for CC DY.

- The UV model deviates from the SM implying **interesting New Physics**. The linear SMEFT **agrees well with the UV**.



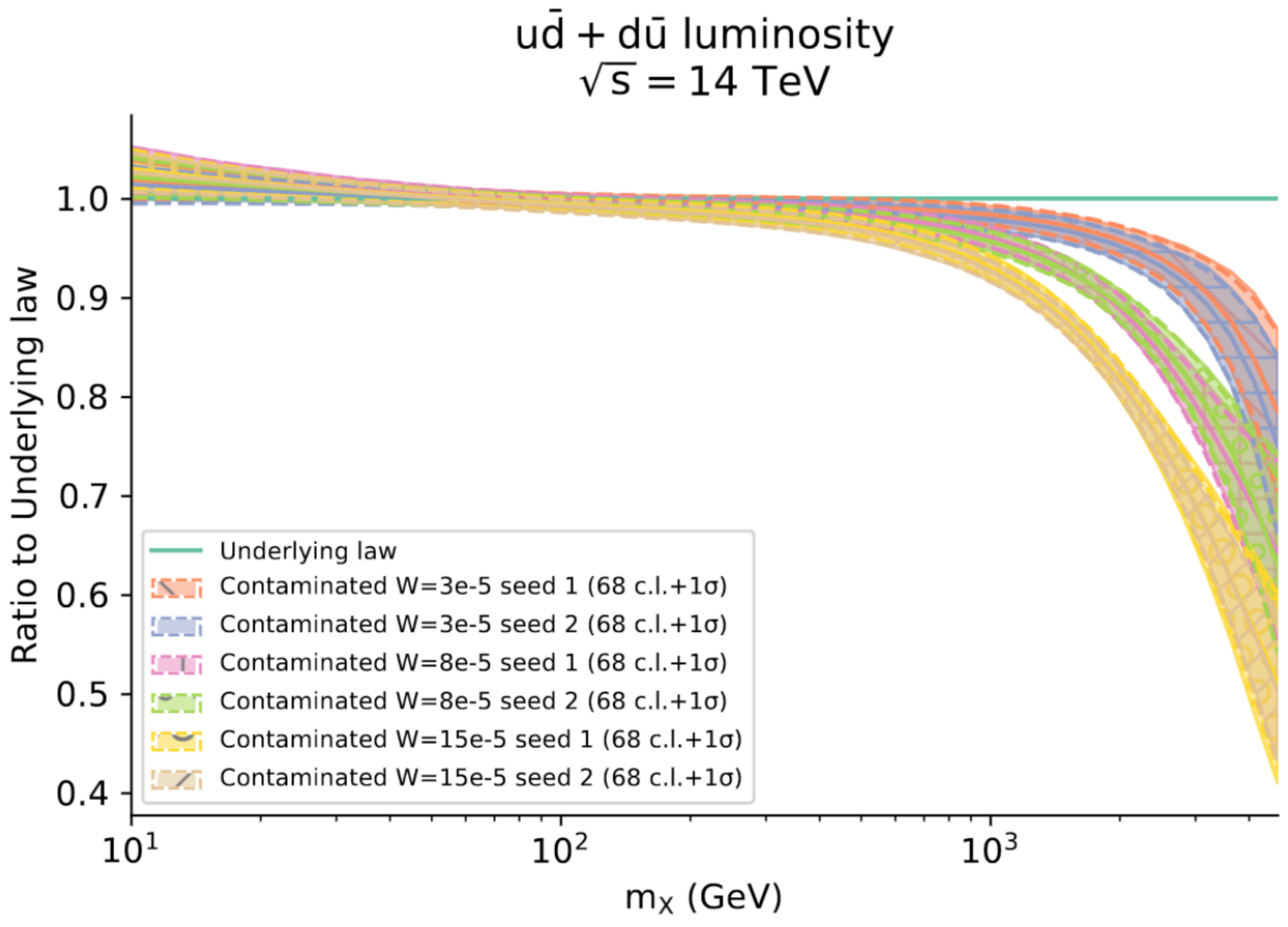
Backup B: Random seed dependence

Random seed dependence

- When we generate **fake data** in this study, it is possible that the results might **depend on the random seed** that was used to make the fake data. We have **verified extensively** that this is not the case.

Random seed dependence

- When we generate **fake data** in this study, it is possible that the results might **depend on the random seed** that was used to make the fake data. We have **verified extensively** that this is not the case.
- At the PDF level, the choice of random seed is **much less important** than the **strength of the New Physics** that is used to generate the fake data.
- *Right:* Comparison of the CC luminosity for the three $\hat{W}$-values, across **two different choices** of **random seed**.



Random seed dependence

- In terms of **fit quality**, on the right we display a comparison of the n_σ to the two most interesting datasets for a **range of fits** performed using **many different random seeds**.

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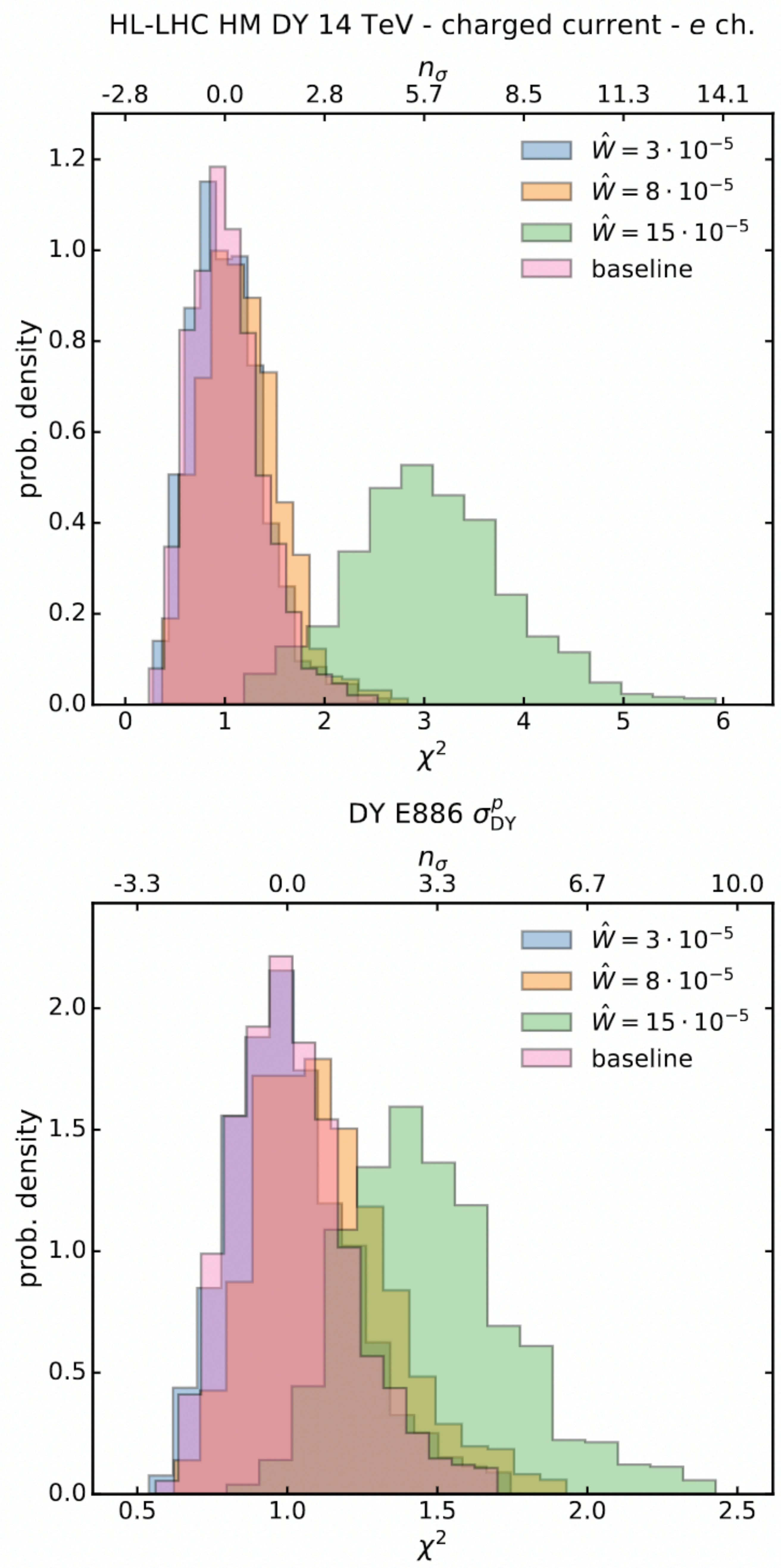

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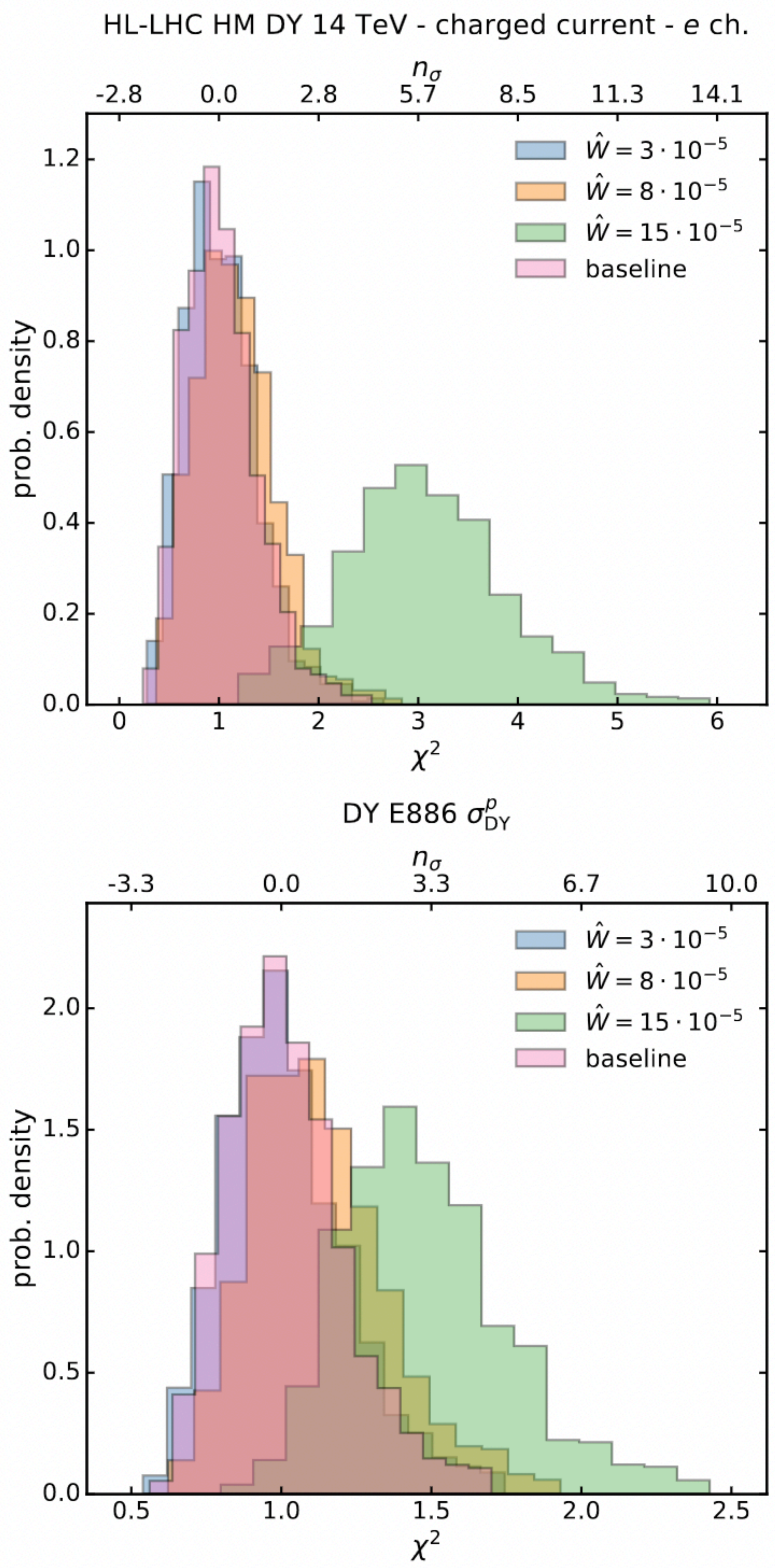
- On the other hand, for $\hat{W} = 0.00015$, the distribution is **skewed** to **higher** n_σ**s**.



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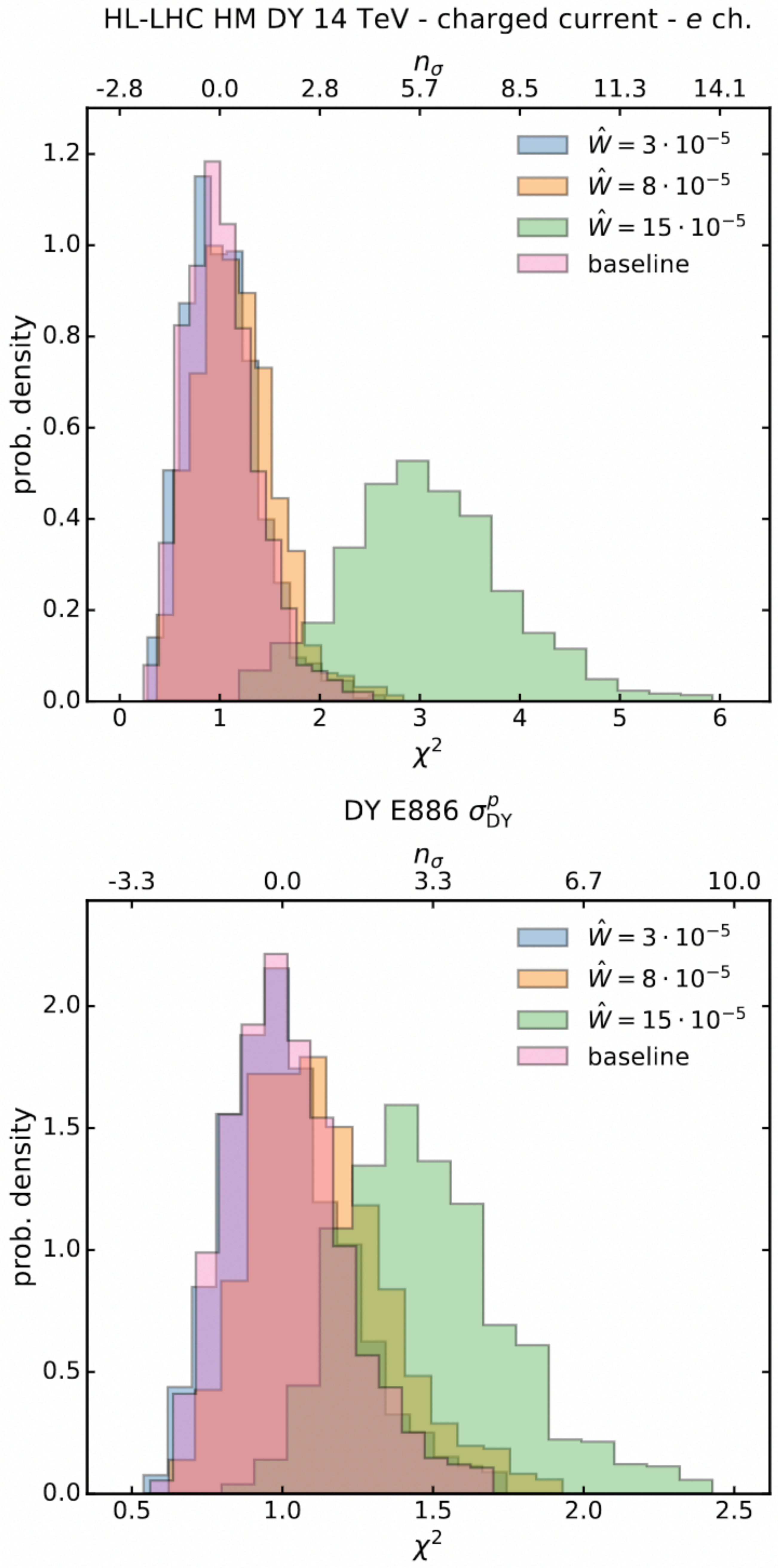
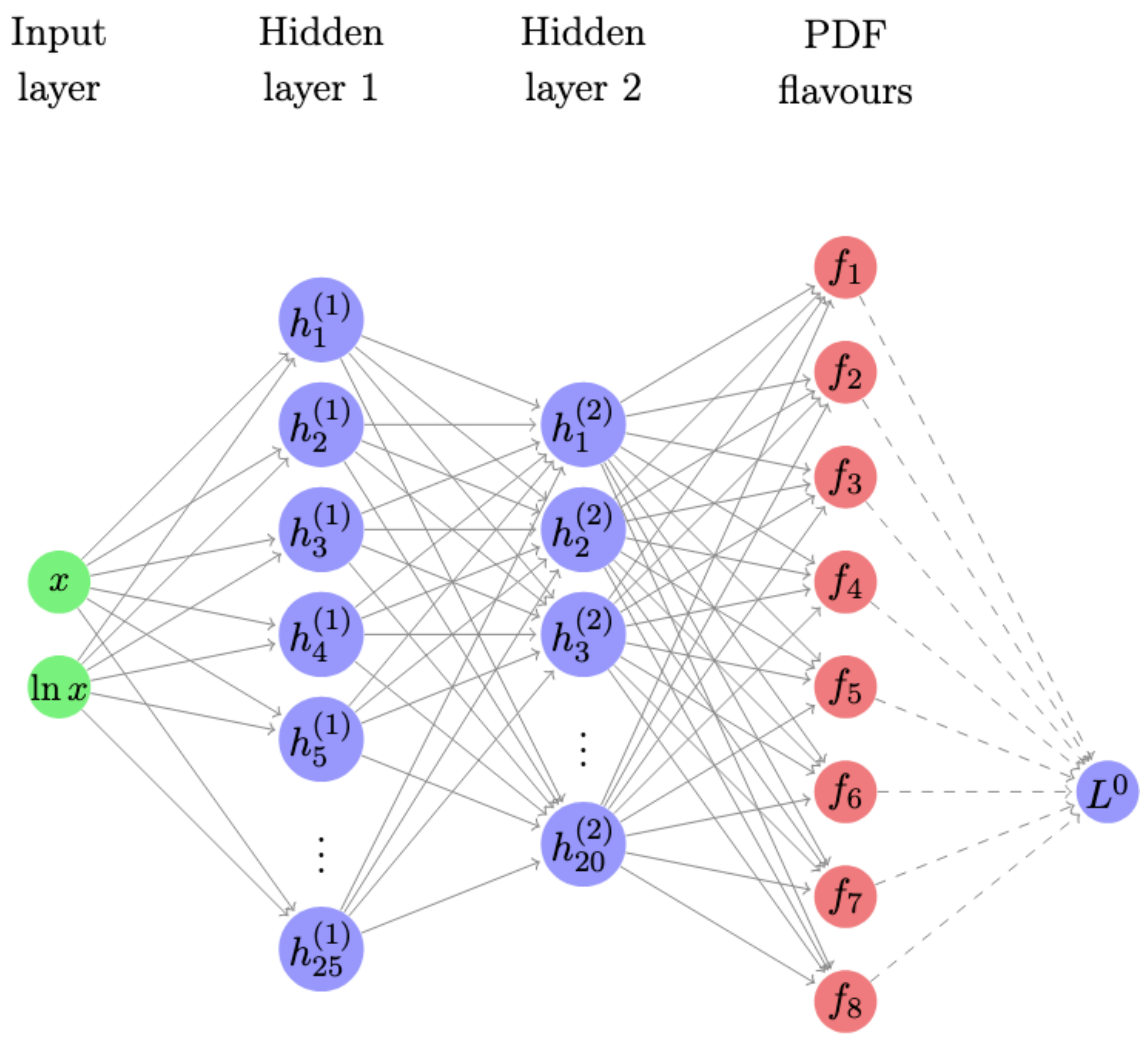
- On the other hand, for $\hat{W} = 0.00015$, the distribution is **skewed** to **higher n_σs**.
- This shows that **on average**, we would not flag datasets for the lower interaction strengths, but we would for the highest interaction strength.



Backup C: The SIMUnet methodology

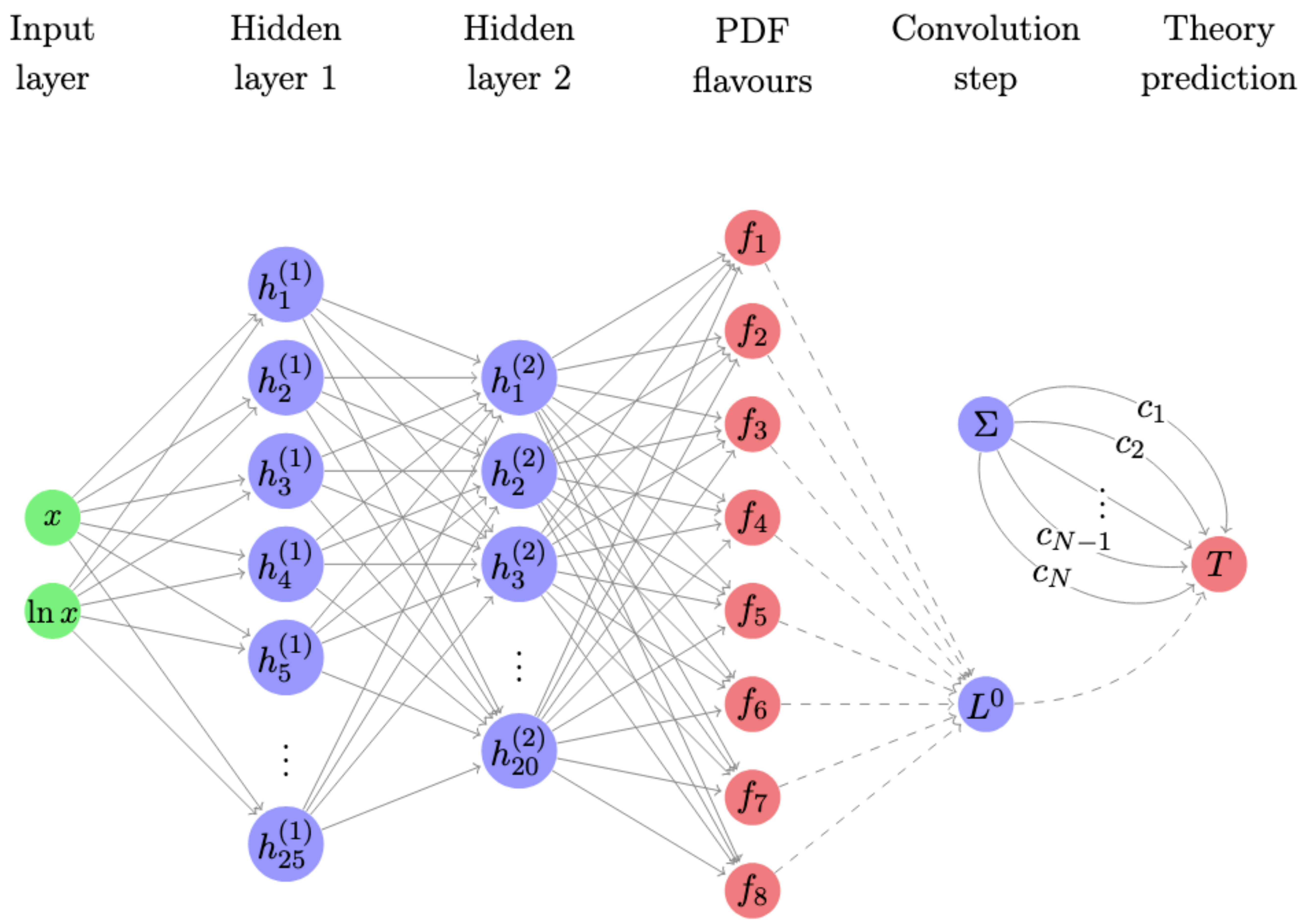
The SIMUnet methodology: details

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



The SIMUnet methodology: details

- The SIMUnet methodology **extends the existing NNPDF neural network** with an additional **convolution layer**.
- The SMEFT couplings are added as **weights of neural network edges**, and are **trained alongside the PDFs**.



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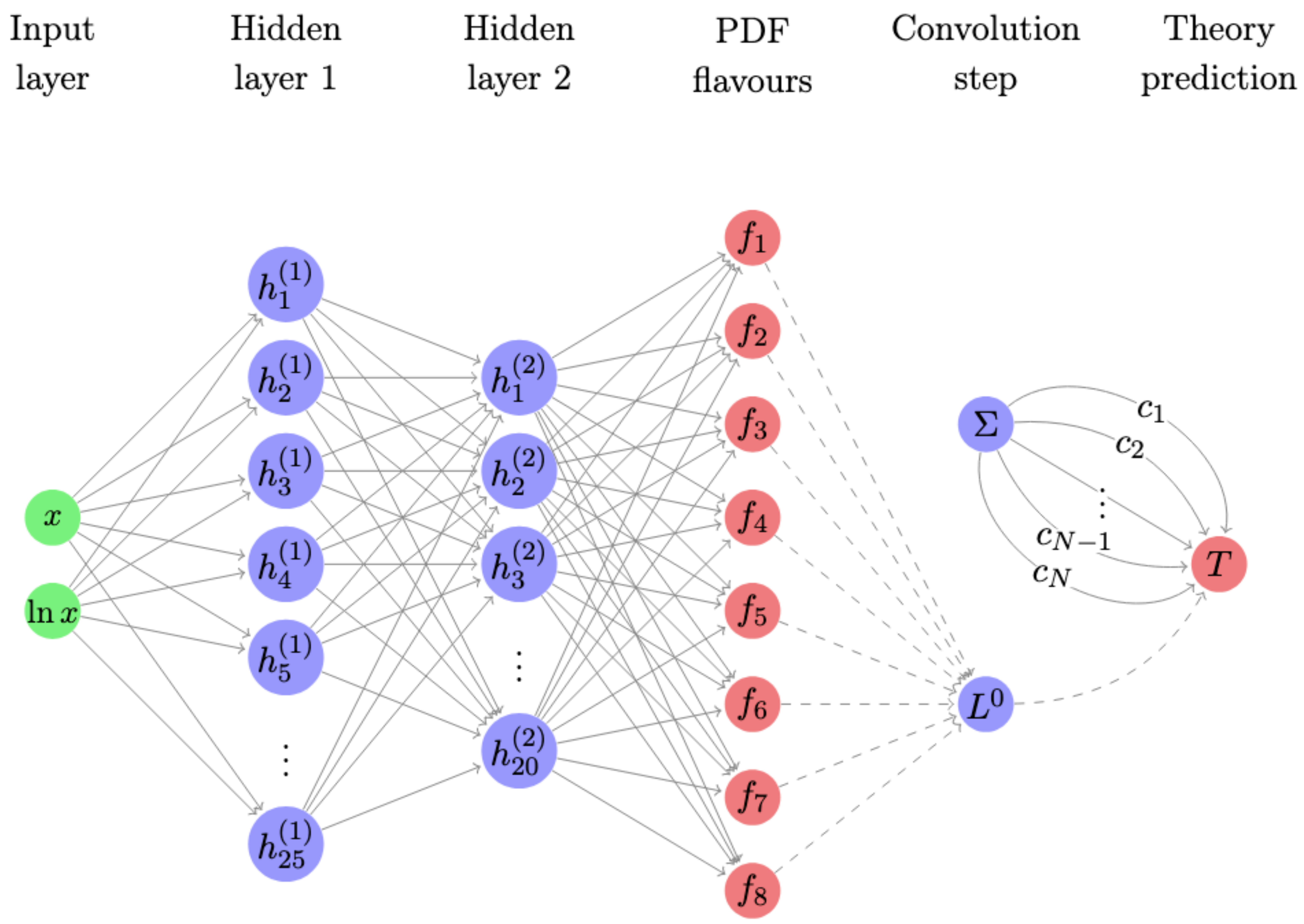

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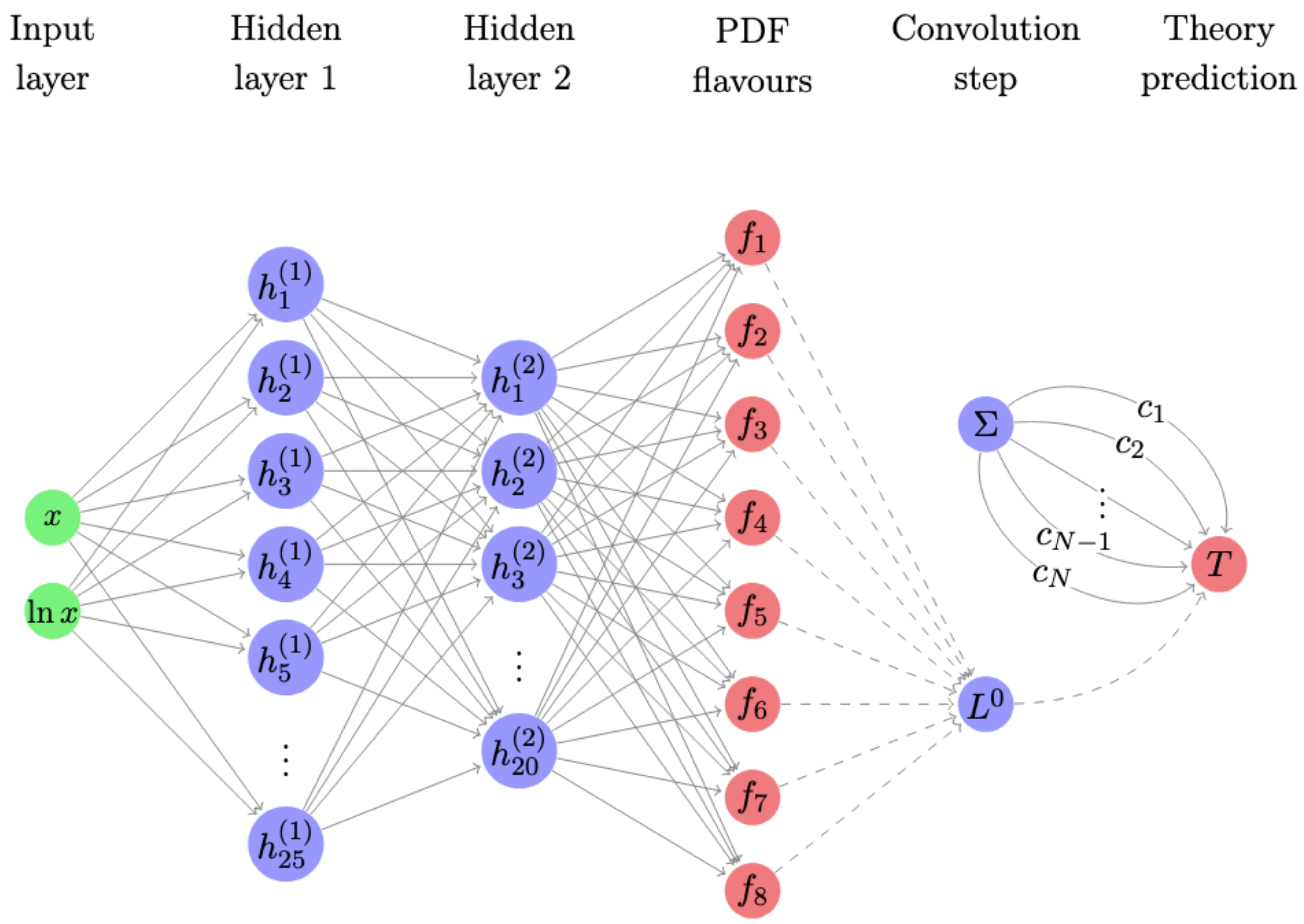

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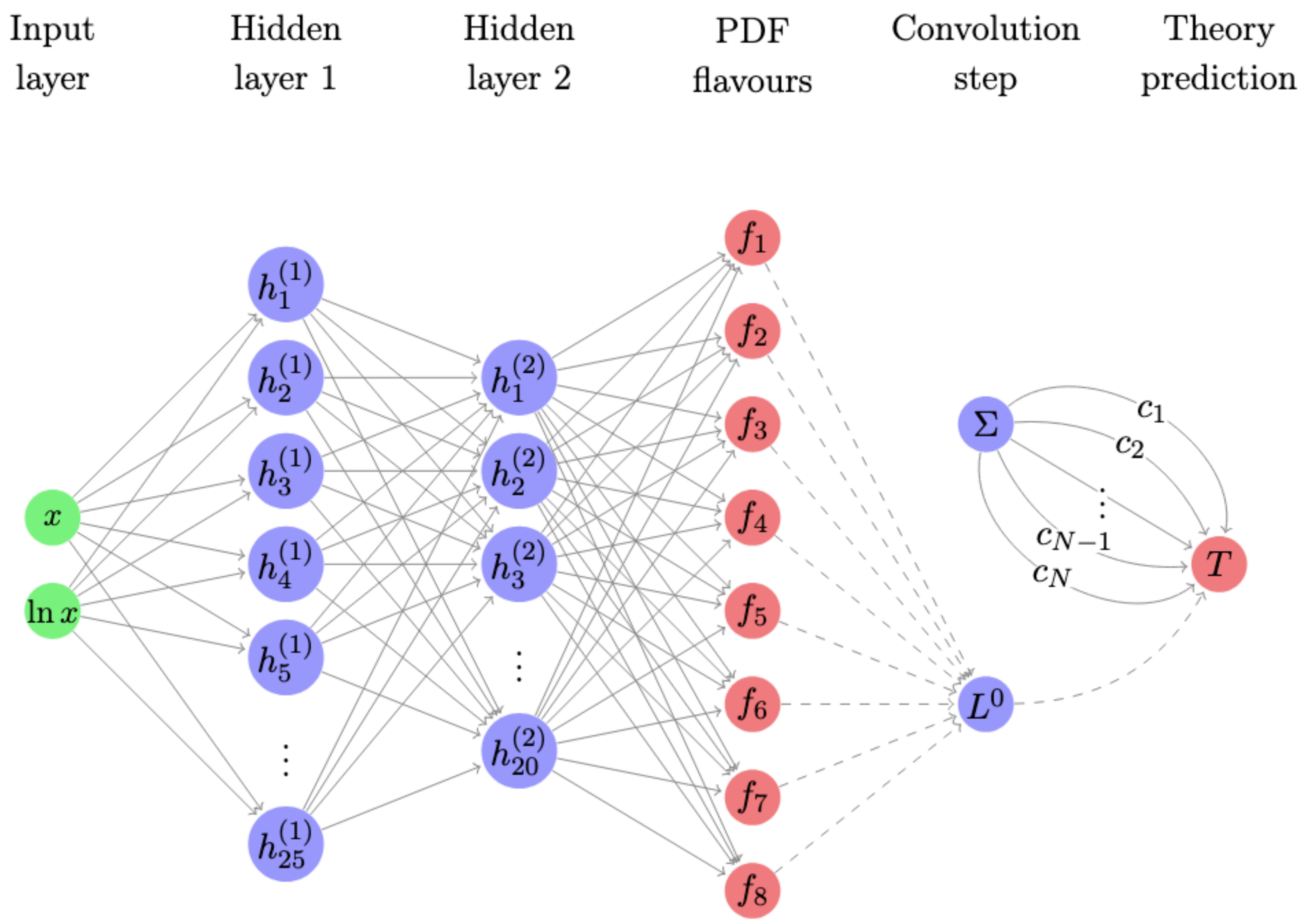
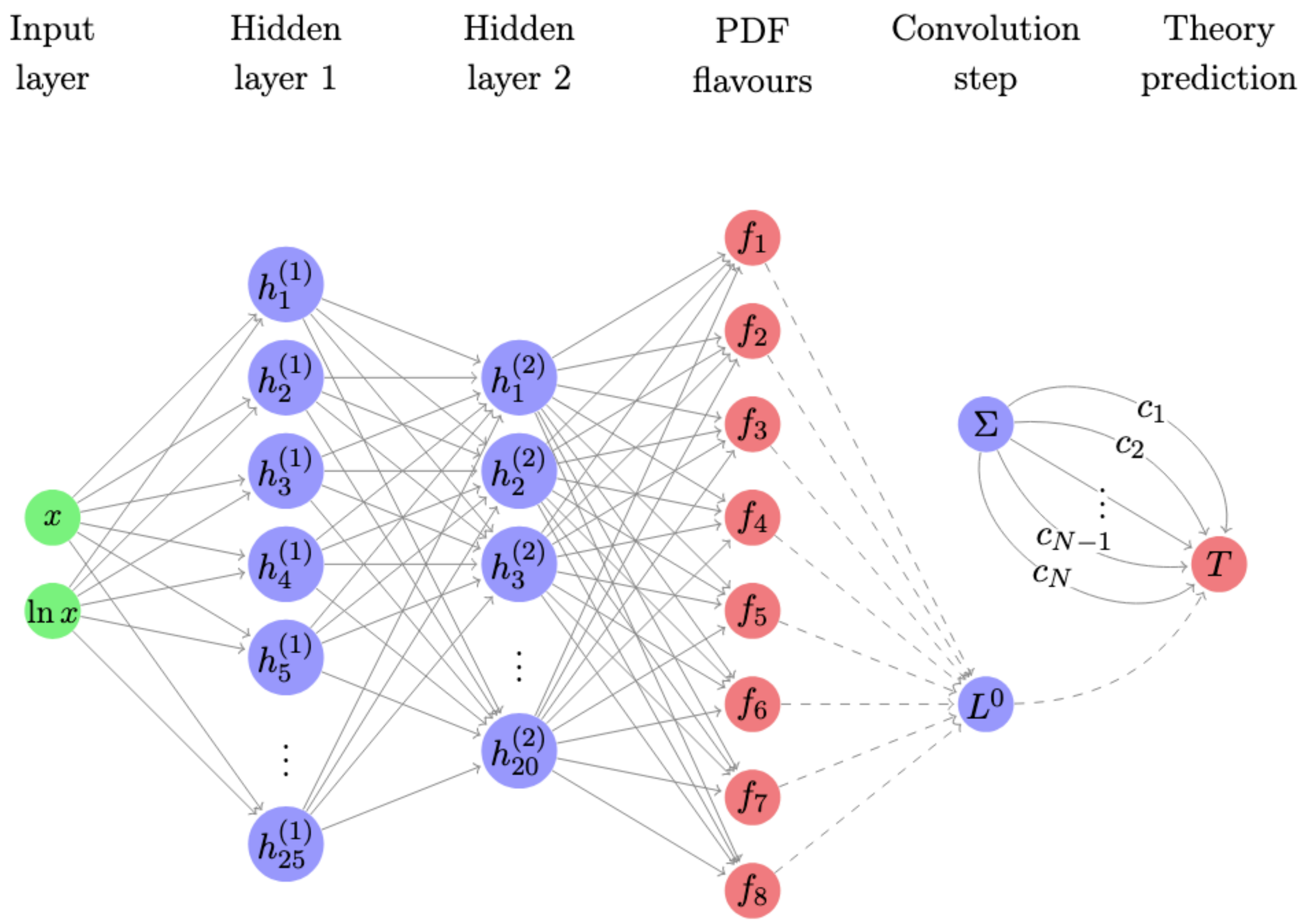


The SIMUnet methodology: details

- The SIMUnet methodology allows for **a lot of flexibility**:
    - Can easily include **PDF-independent observables**.
    - Can perform **fixed PDF fits** by **freezing the PDF part of the network**.
- The **code release** will also provides the ability to perform **contaminated fits**, like those presented in this talk.



Backup D: Pitfalls of the Monte Carlo Replica method

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:

$$t(c) = t^{\text{SM}} + t^{\text{lin}}c + t^{\text{quad}}c^2$$

- 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:

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

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$$P_{c^{(i)}}(c) \propto \delta\left(c + \frac{t^{\text{lin}}}{2t^{\text{quad}}}\right) \int_{-\infty}^{t_0} dx\ \exp\left(-\frac{1}{2\sigma^2}(x-d)^2\right) + 2\,|\,2ct^{\text{quad}} + t^{\text{lin}}\,|\exp\left(-\frac{1}{2\sigma^2}(d - t(c))^2\right)$$

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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_0 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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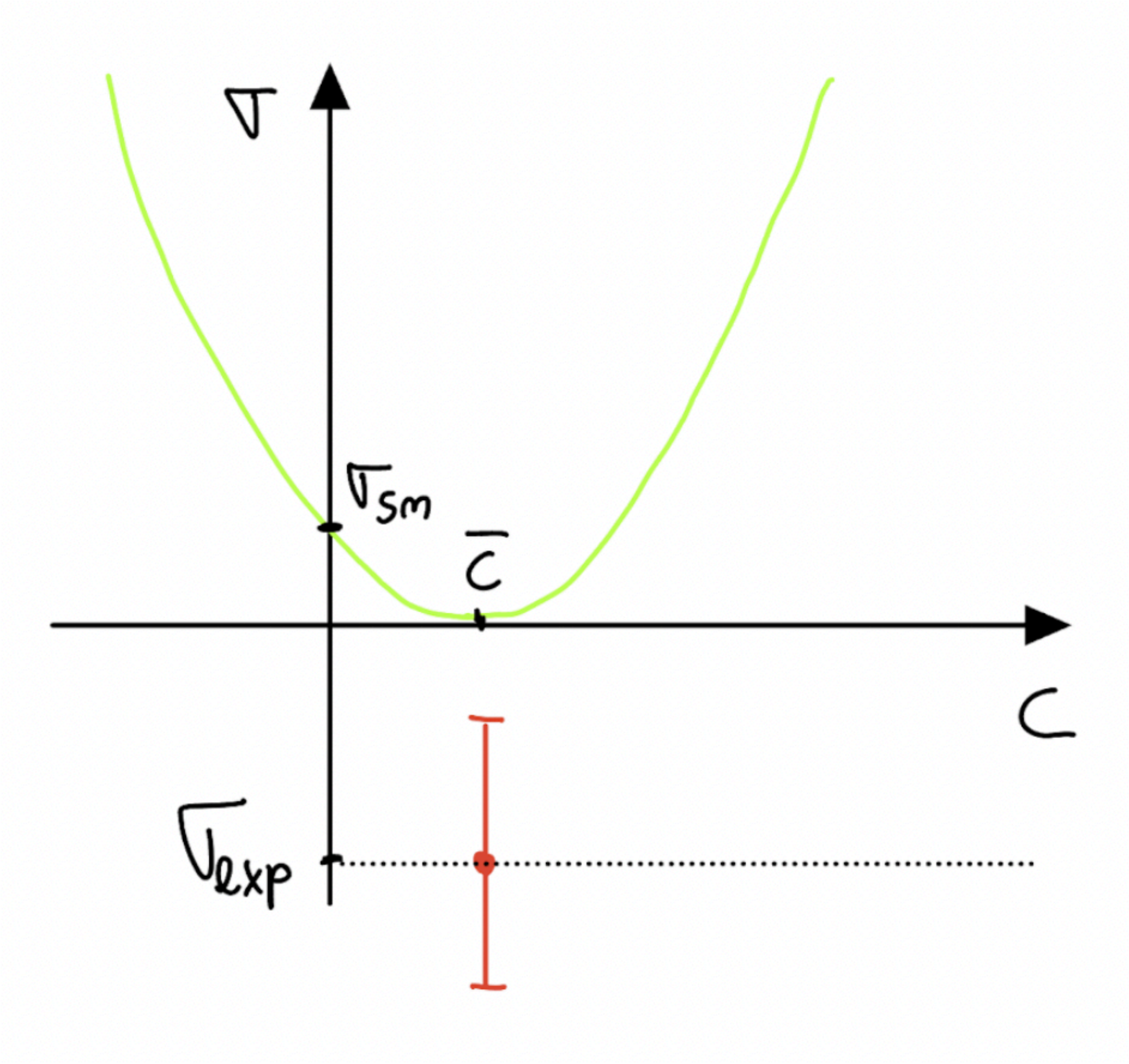

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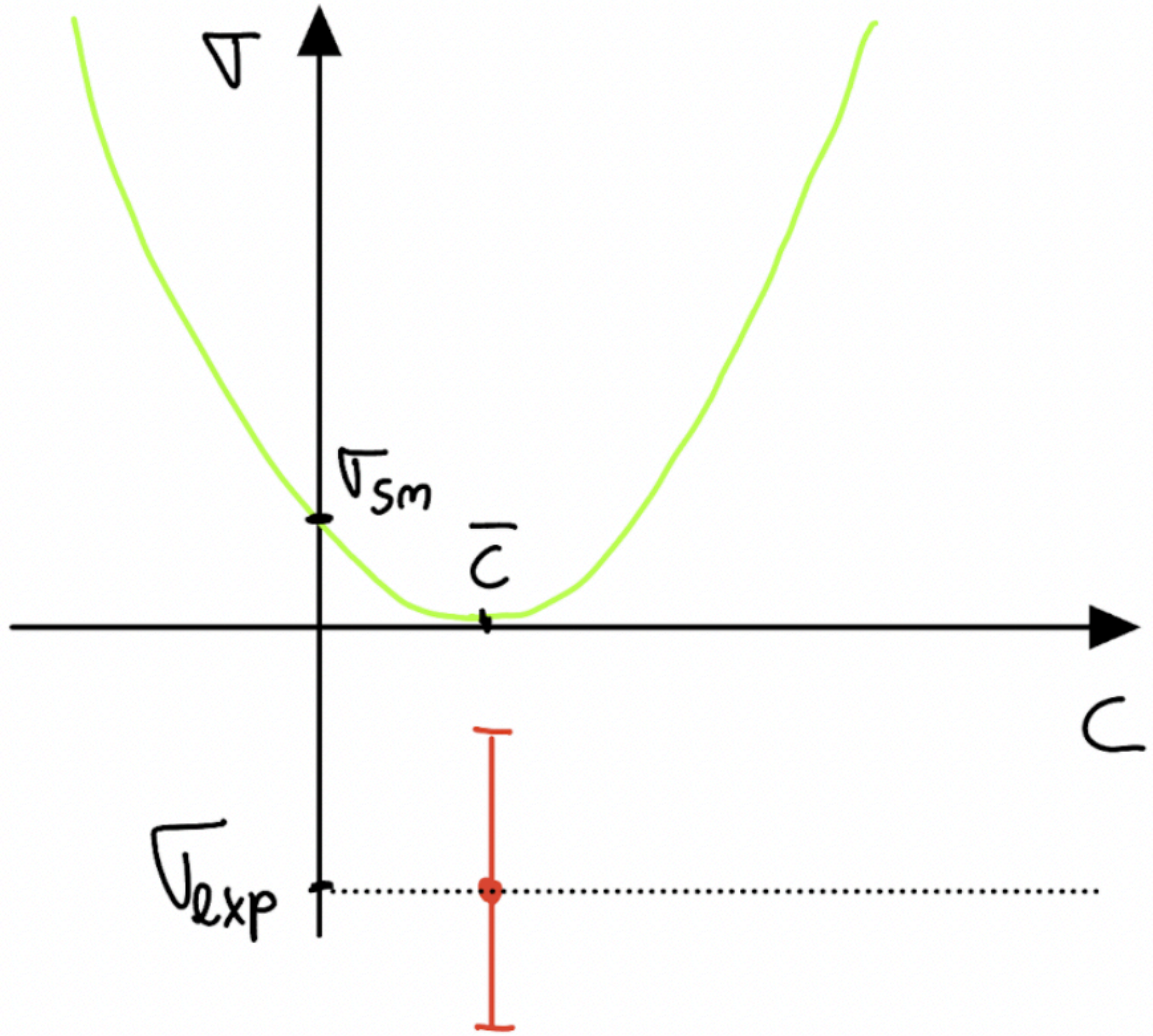

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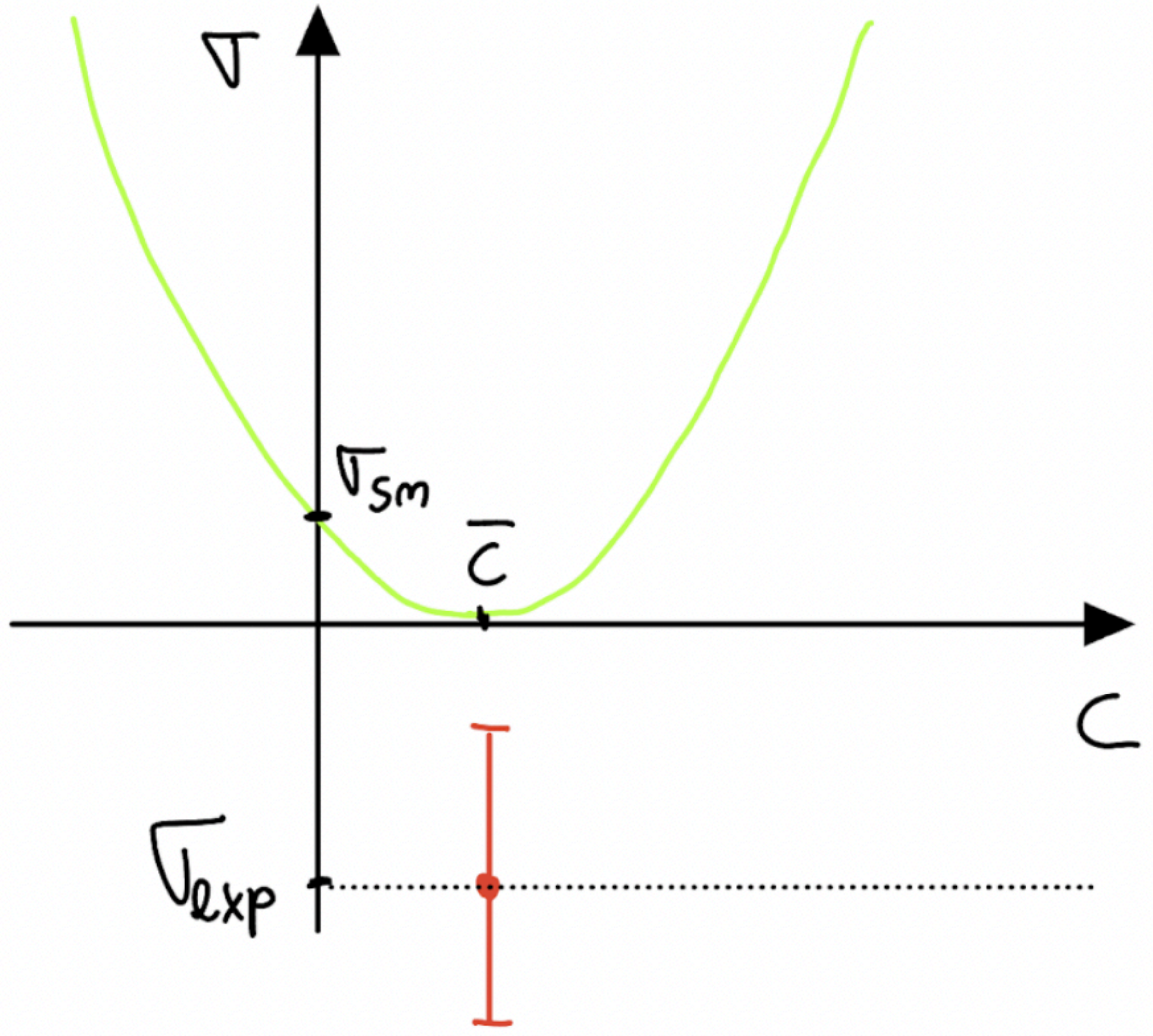

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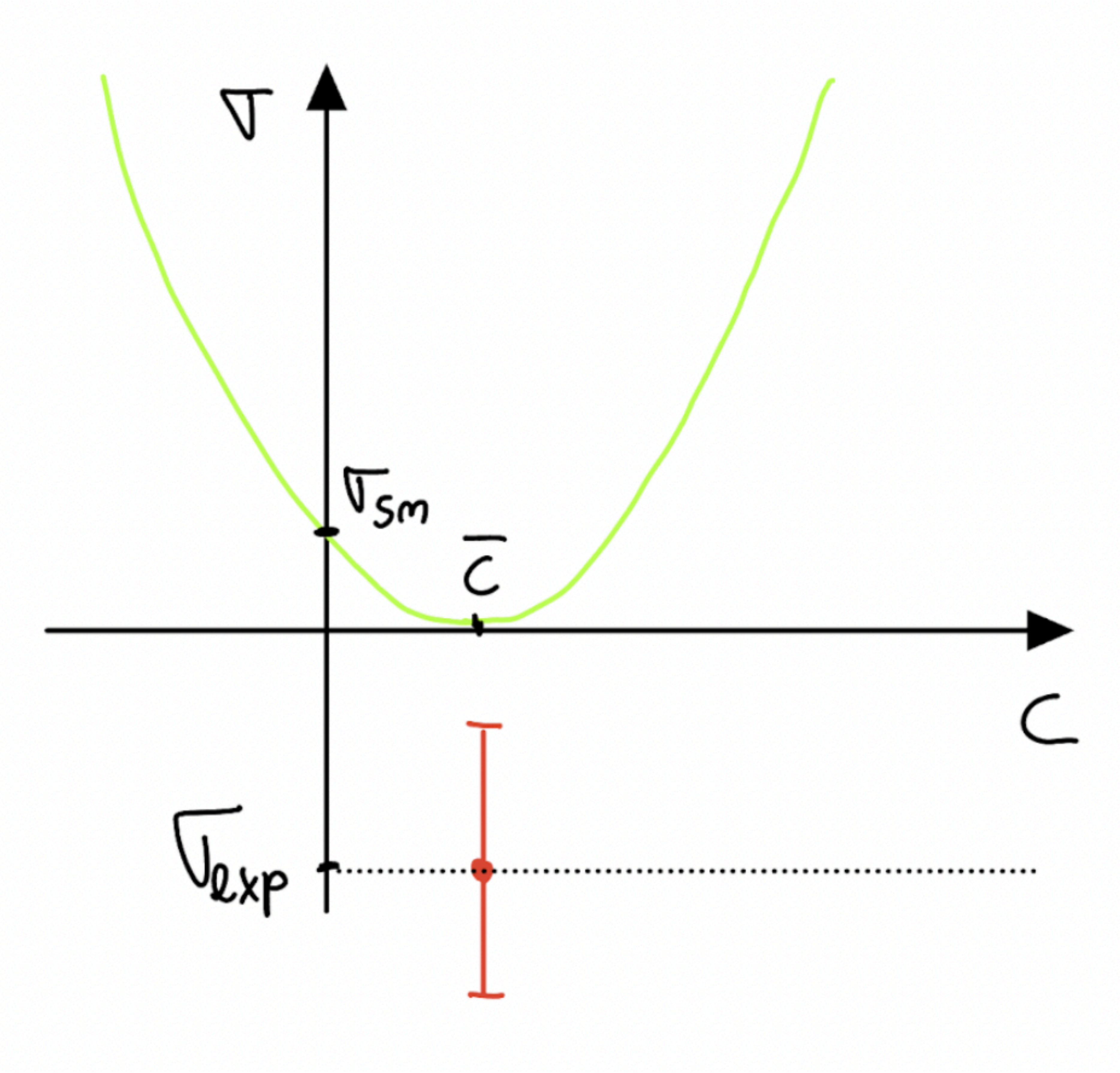

- This occurs if the experimental data falls **below the minimum** of the theory, or **above but close** to the minimum.
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- This gives rise to the spike in the distribution at $c = -t^{\text{lin}}/2t^{\text{quad}}$.

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.**