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Generative Adversarial Neural Networks in Parton Distribution Functions (PDFs)

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UNIVERSITÀ DEGLI STUDI DI MILANO

DIPARTIMENTO DI FISICA

Istituto Nazionale di Fisica Nucleare

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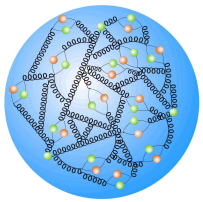
What are PDFs

Definition of Parton Distribution Functions (PDFs):

The **probability** of finding a constituent of the proton, commonly known as **parton** (gluons, quarks, and anti-quarks), with a momentum fraction x and momentum transfer Q^2.



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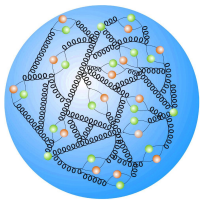
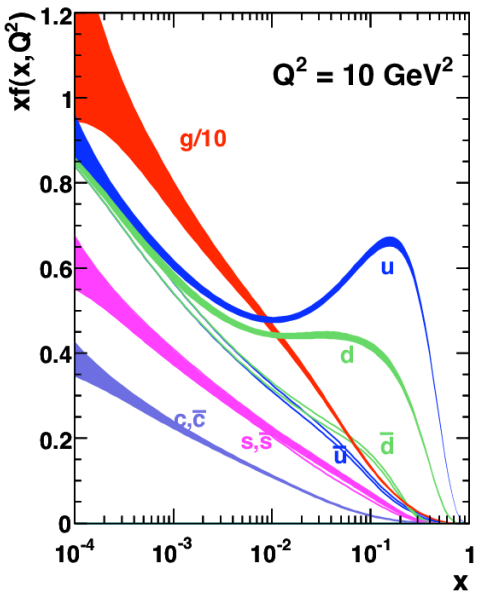


PDFs Snapshot



$g(x, Q^2)$: Probability of finding a gluon, carrying a fraction x of the proton momentum when probed with energy Q^2.

x: Fraction of the proton momentum carried out by the gluon.

Q^2: Energy of the hard-scattering reaction (inverse of the resolution length)

What do we need PDFs for?

PDFs are crucial for Theoretical Predictions!

The **Factorization Theorem** in QCD is a main guiding principle that studies the **interplay** between the **perturbative** and **non-perturbative** regime in order to make meaningful theoretical predictions.

$$\sigma_H(Q^2) \sim \sum_{i,j} f_{i/A}(Q^2) \otimes f_{j/B}(Q^2) \otimes \hat{\sigma}_P(Q^2)$$

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- $\sigma_H(Q^2)$: Hadronic cross-section
- $f_{i/A}(Q^2) \otimes f_{j/B}(Q^2)$: PDFs containing the non-perturbative efffects
- $\hat{\sigma}_P(Q^2)$: Partonic cross-section

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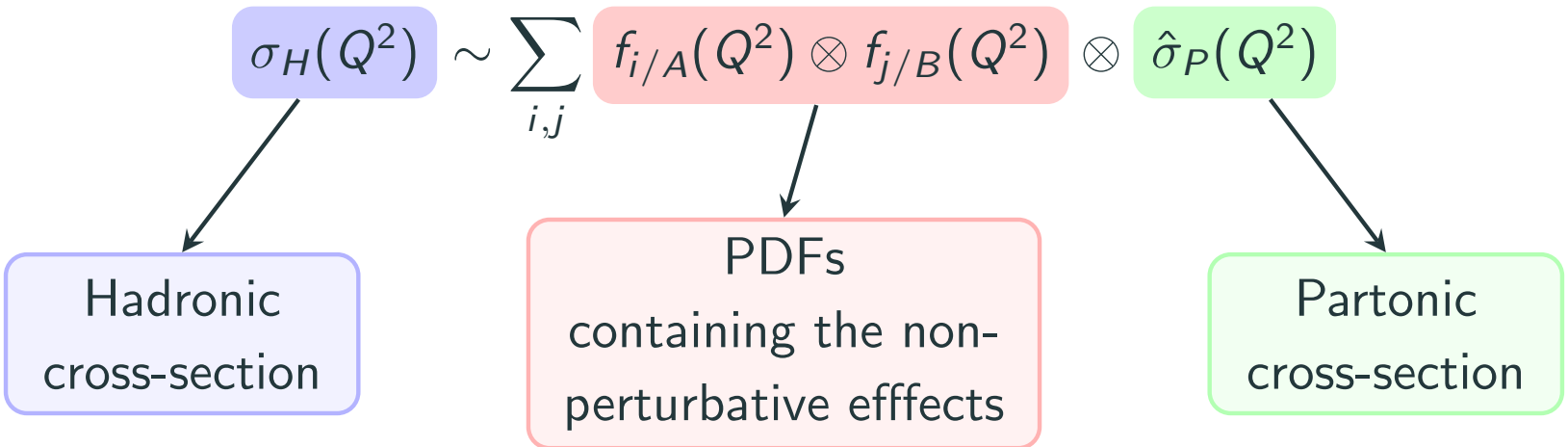
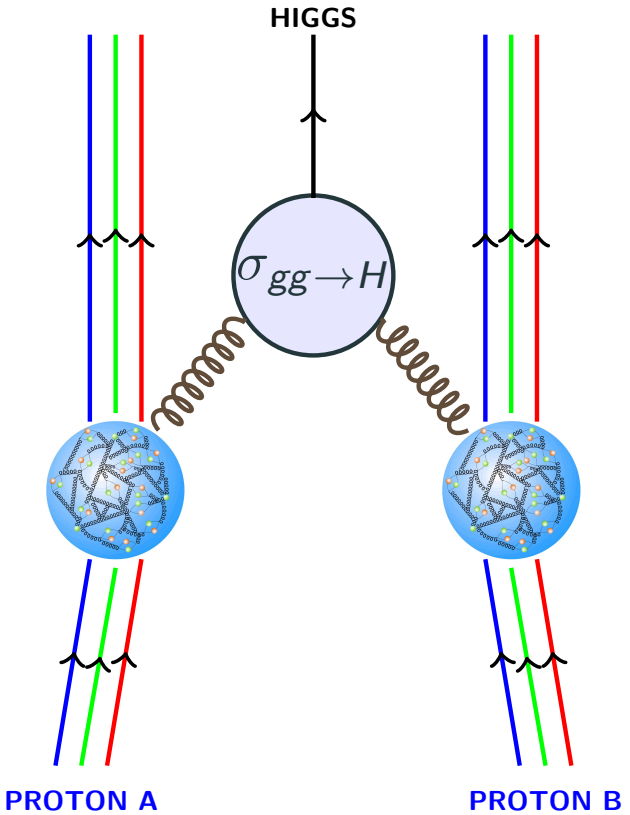


Warning ⚠

PDF **cannot** be computed from 1st principle due to **confinement**. It has to be extracted from experimental data using a global QCD analysis.

What do we need PDFs for?

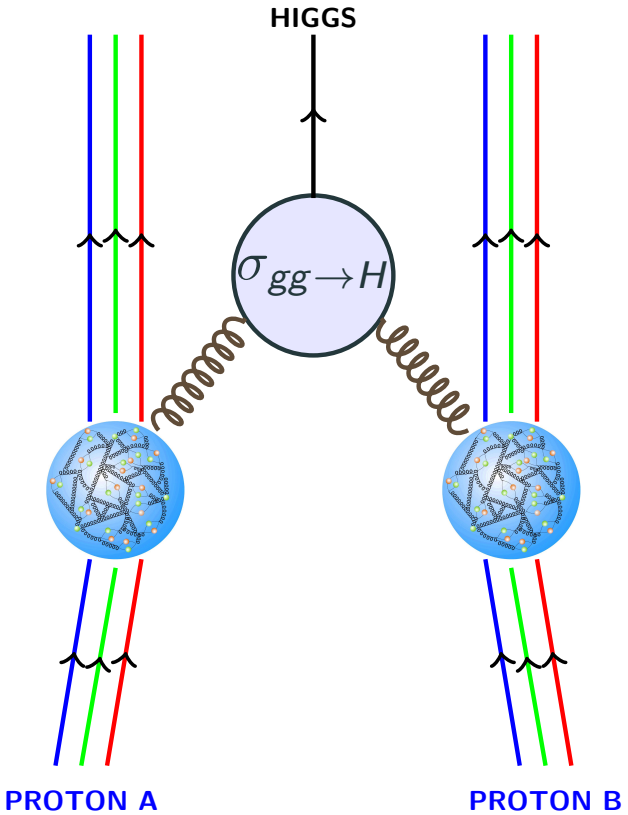
Example: Higgs Production from gluon-gluon fusion

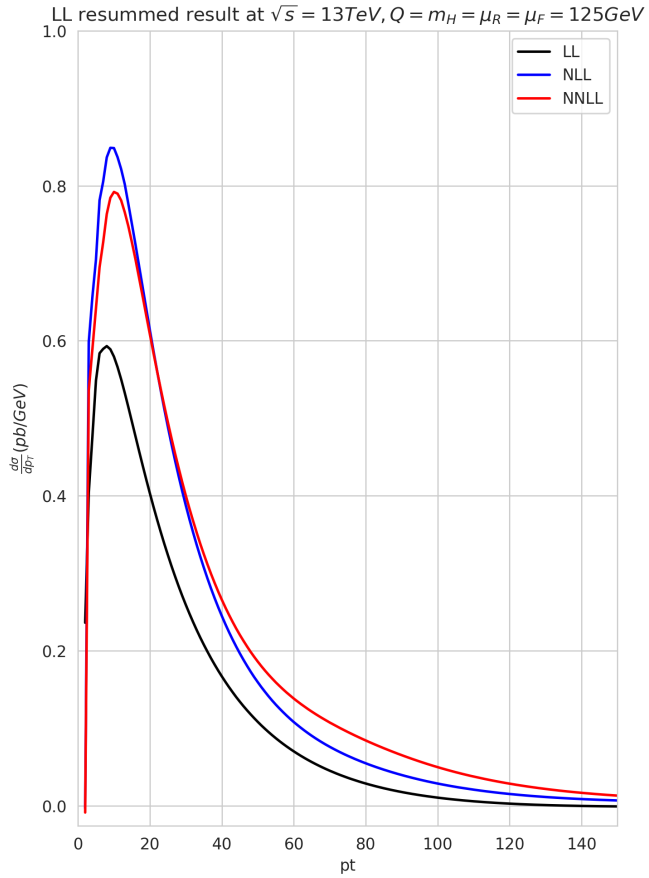


$\Longrightarrow$

What do we need PDFs for?

Example: Higgs Production from gluon-gluon fusion





PDFs and New Physics

Can new physics hide inside a proton?

σ	$\delta(\text{PDF})$	$\delta(\alpha_s)$	$\delta(\text{scale})$	$\delta(\text{trunc})$	$\delta(\text{PDF-TH})$	$\delta(\text{EW})$	$\delta(tbc)$	$\delta(1/m_t)$	
48.58	± 0.90	$^{+1.27}_{-1.25}$	$^{+0.10}_{-1.15}$	± 0.18	± 0.56	± 0.49	± 0.40	± 0.49	pb
	± 1.86	$^{+2.61}_{-2.58}$	$^{+0.21}_{-2.37}$	± 0.37	± 1.16	± 1	± 0.83	± 1	%

$$\sigma = 48.58\,\text{pb}^{+2.22\,\text{pb}\,(+4.56\%)}_{-3.27\,\text{pb}\,(-6.72\%)}(\text{theory}) \pm 1.56\,\text{pb}\,(3.20\%)(\text{PDF} + \alpha_s)$$

REDUCE PDF **UNCERTAINTIES** $\Longrightarrow$ **PRECISION PHYSICS**

Solutions:

- Adding more data: for example, top quark pairs production constrains the gluon PDF
- Improving the methodology: robust and flexible framework, future-proof for future data

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NNPDF status & Achievements

PDF Fitter Groups:

- **Functional form approach:** uses specific polynomials to fit experimental data **(How to define the polynomials?)**

  CTEQ **MMHT** **MSTW** **HERAPDF**

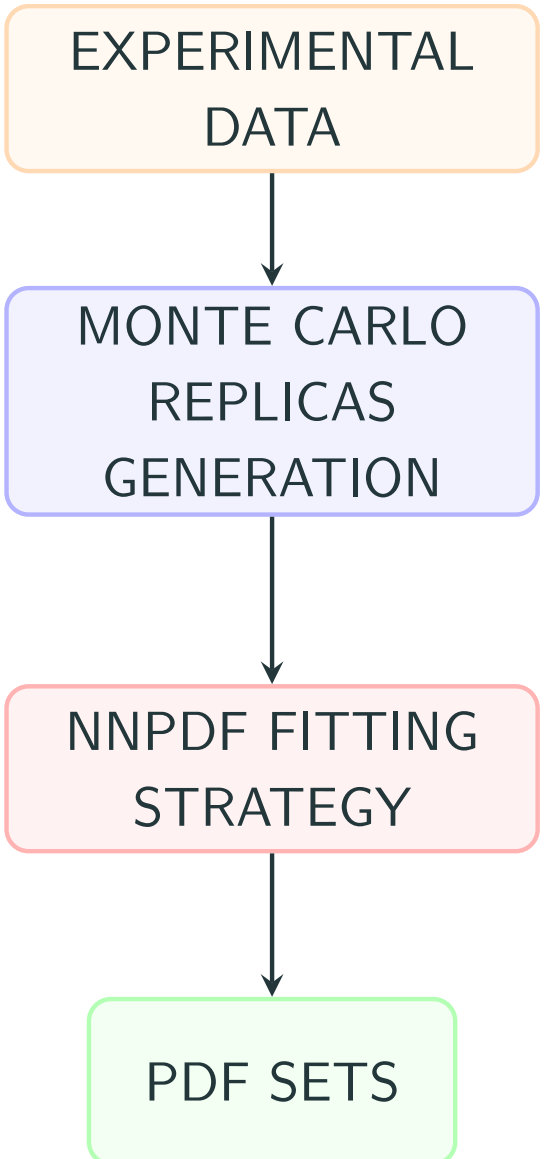
- **Neural Network approach:** uses techniques from machine learning and Artificial Intelligence to reduce all sources of theoretical biases

  NNPDF

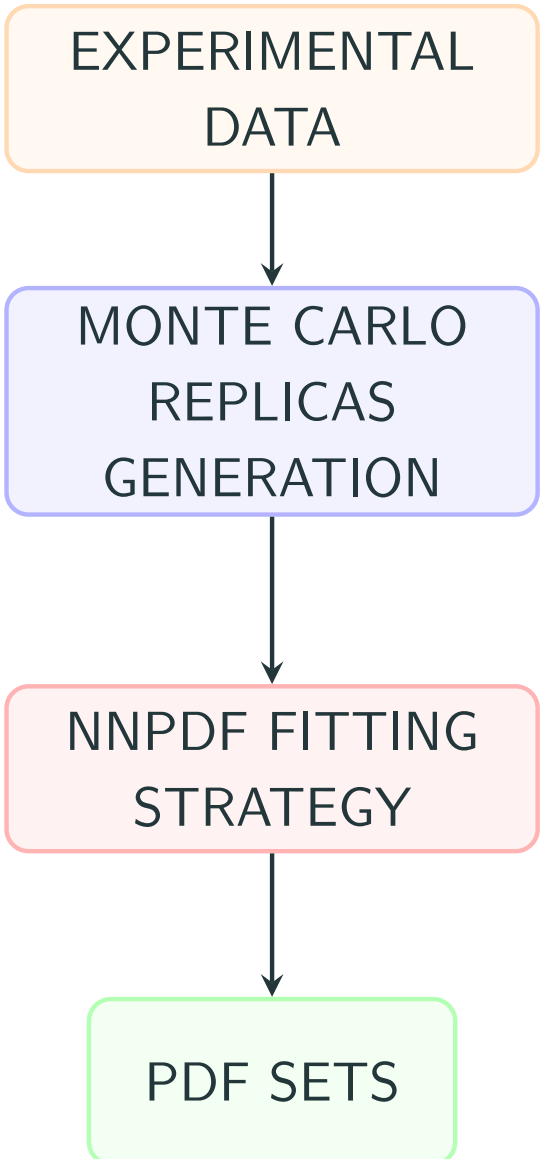
NNPDF's Features:

- Robust and reliable methodology (under upgrade)
- Only fitter group to include Theory Uncertainties in the PDF [1] [2]

NNPDF Workflow



NNPDF Workflow



The total number of replicas is chosen in such a way that it is **large enough** to produce the statistical properties of the original data to the desired accuracy. Generating Replicas is time consuming.
$\Longleftrightarrow$ 1 Replicas takes about 40 Hours

Fits each generated replicas with a PDF parametrized by an Artificial Neural Network. The training is controlled by a Genetic Algorithm (GA).

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Overview of GANs

Definition

GANs are deep neural network architectures comprised of two networks competing against each other: a **generative** model **G** that creates object instances (e.g., images, sentences) while capturing the data distribution, and a **discriminative** model **D** that estimates the probability that a sample came from the training data rather than **G**. `[Ian Goodfellow, 2014]`

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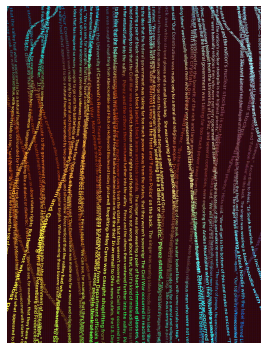
THE FOLLOWING PERSONS DO NOT ACTUALLY EXIST!

Overview of GANs

Examples of generative model applications from **OpenAI** :

Transformer from GPT-2 (Text Generator)

Doing a PhD in physics isn't easy because you're always trying to do too much. For people who have a strong passion for physics, it'll be really helpful to be able to think in a more abstract mathematical fashion. Then it will be a lot easier to work on papers that make sense.



Musenet

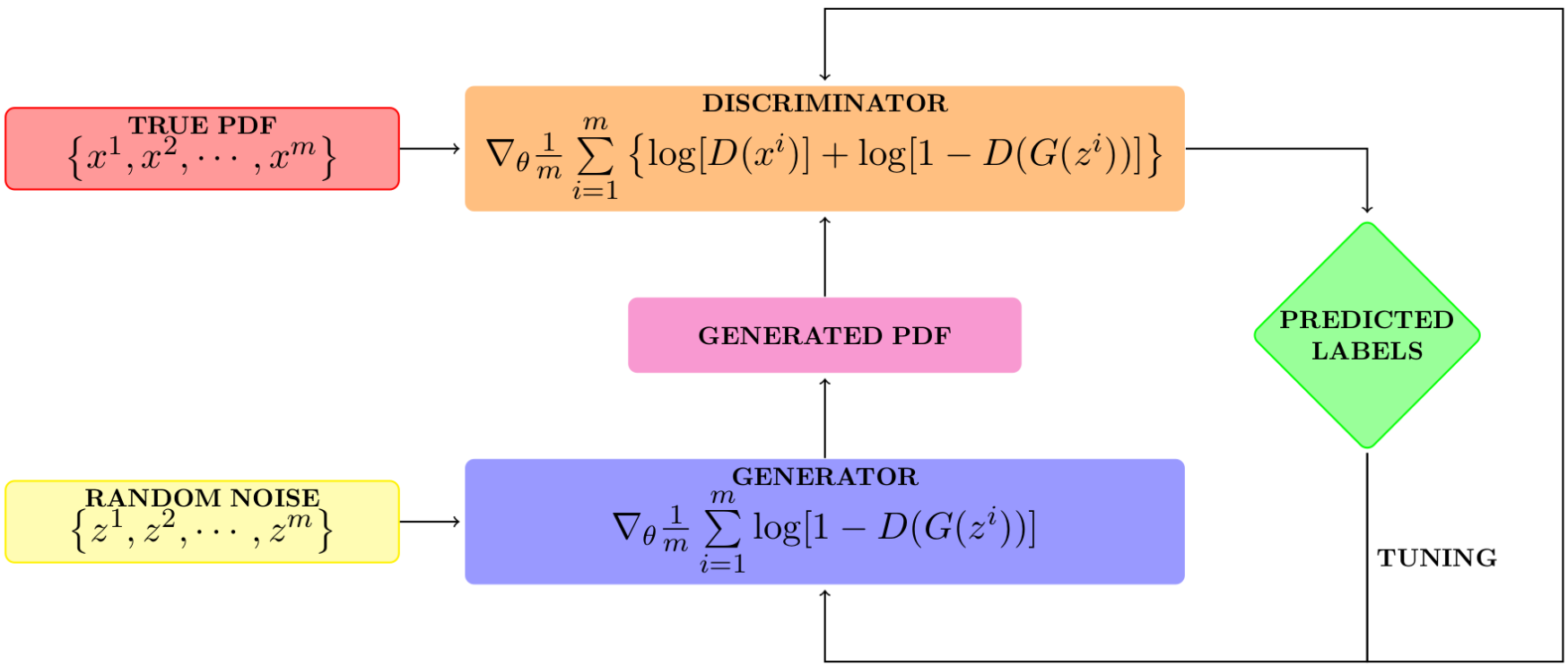
Musenet is a deep neural network that can generate 4-minute musical compositions with 10 different instruments, and can combine styles from country to Mozart to the Beatles. The following composition improvises Chopin from Mozarts Rondo alla Turca.

GANs for Replicas Generation

Why the need of GANs?

By-pass the need of generating large sample of Monte Carlo Replicas

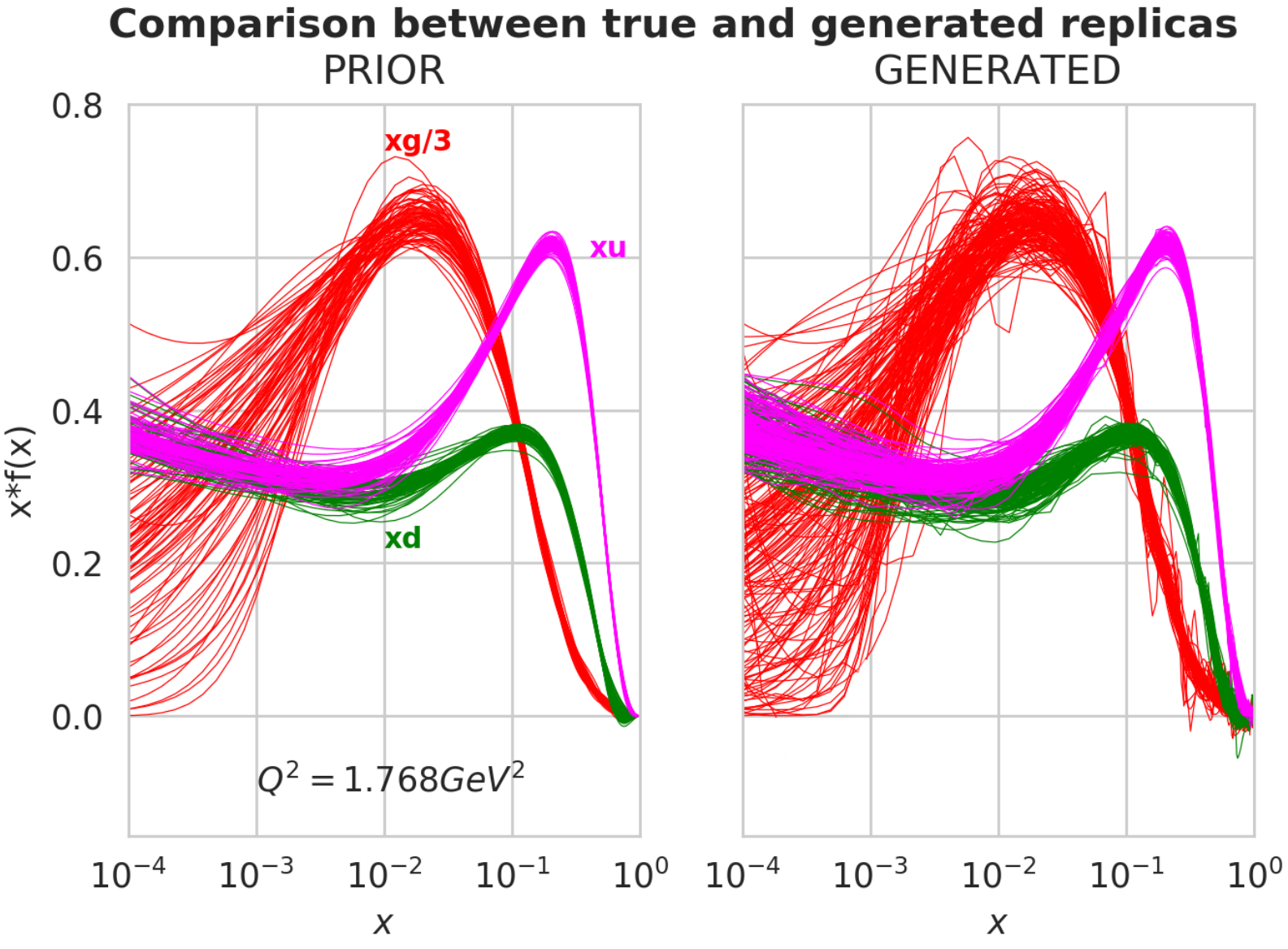
Workflow layout of our GAN model:



Preliminary Results

- We chose `PN3_GLOBAL_NNPDF31_nnlo_as_0118_070219-001` from N3FIT with 80 replicas as the prior and generated 160 output replicas
- We compare the probability distribution of the real and generated data for a given value of x

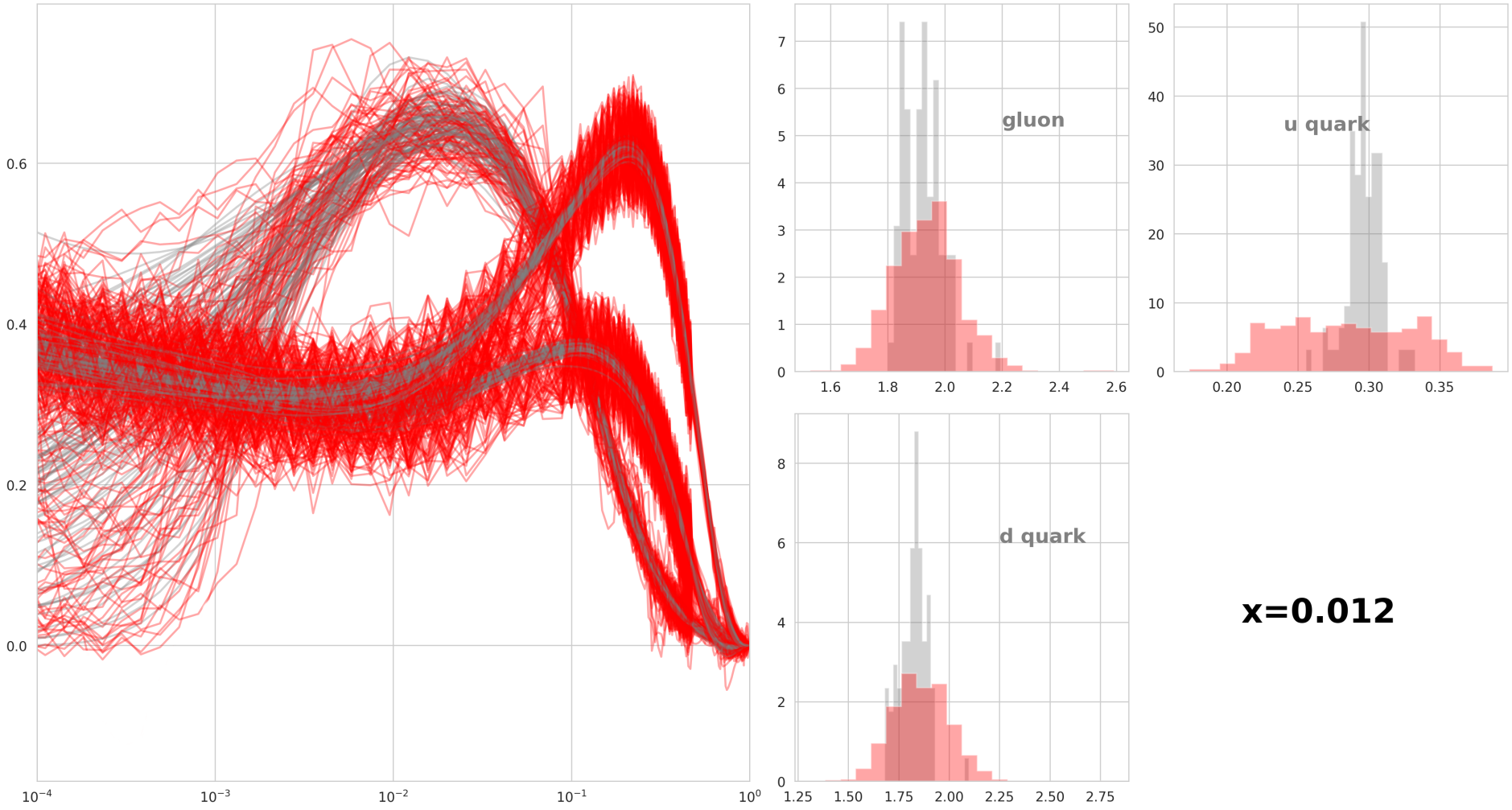
Preliminary Results



Preliminary Results

Evolution of the training ...

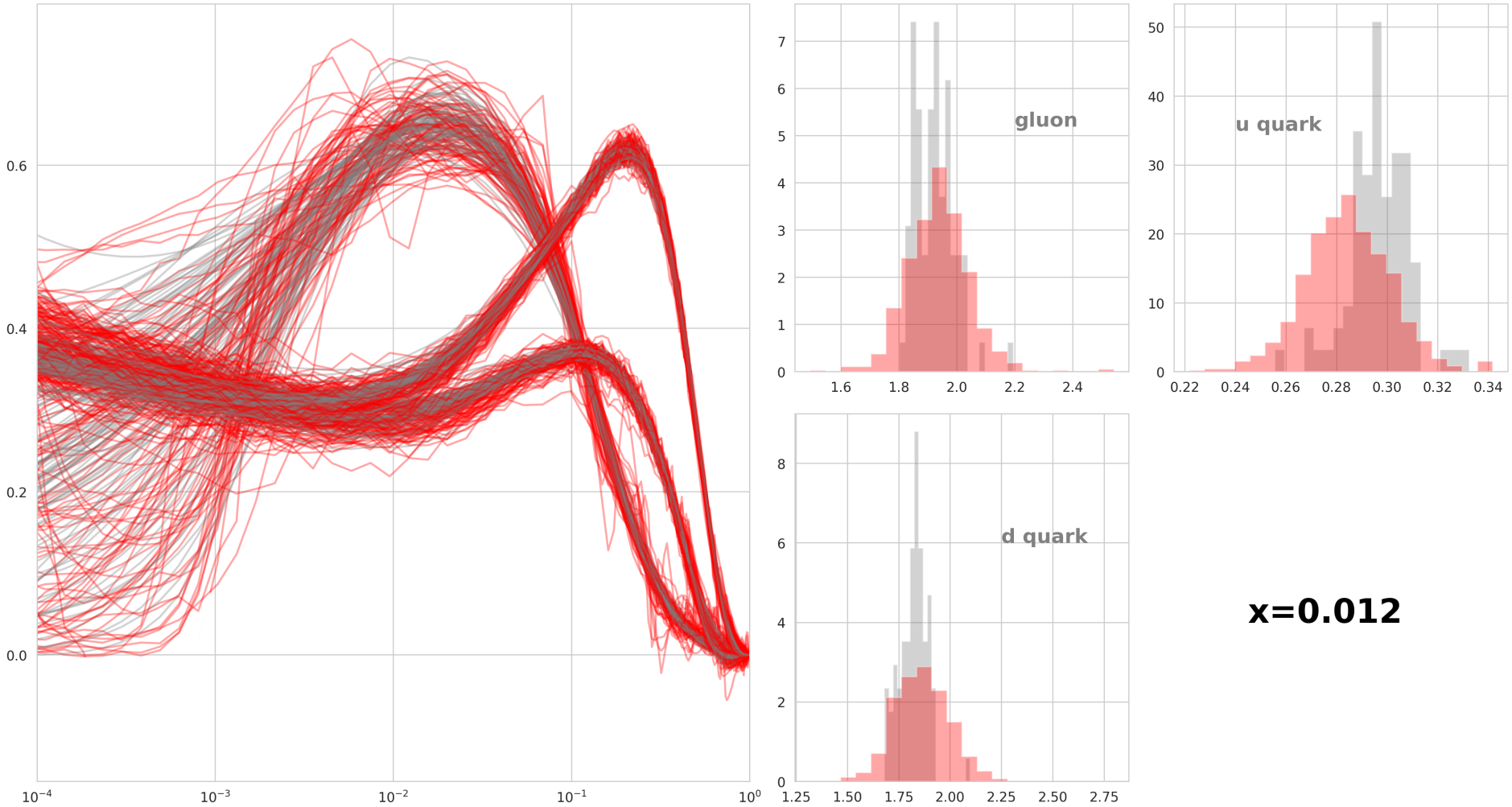
generated_replicas_at_1000_iteration.png



Preliminary Results

Evolution of the training ...

generated_replicas_at_7000_iteration.png

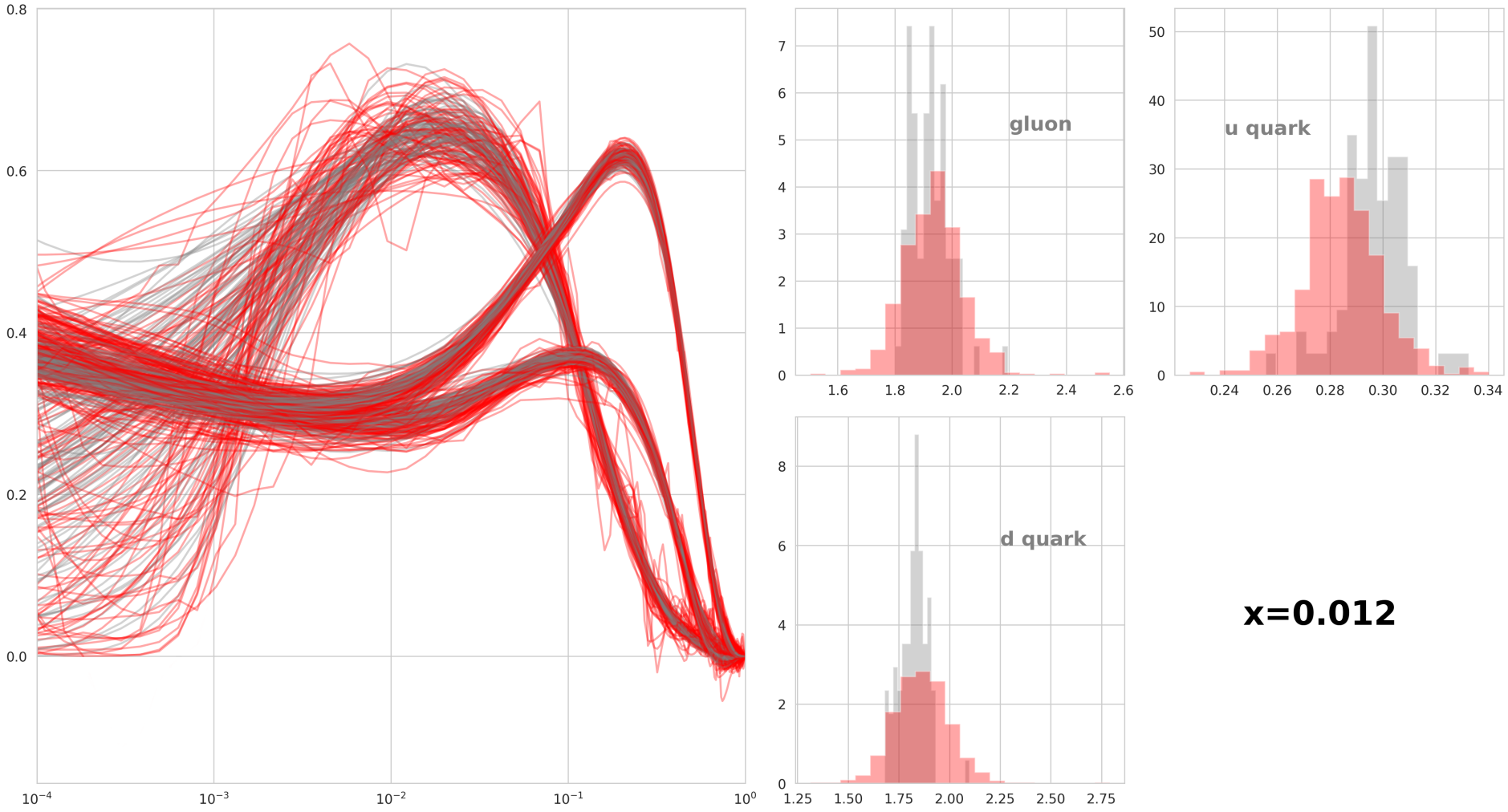


x=0.012

Preliminary Results

Evolution of the training ...

generated_replicas_at_10000_iteration.png



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Summary and Outlook

- **What we have achieved so far with GANs**:
  - ✔ Custom and flexible framework
  - ✔ Model that is able to learn the underlying distribution of the original replicas
  - ✔ Generate a large (as much as one want) sample of PDF replicas
- **Ongoing and future works**:
  - ✗ Perform statistical tests to assess performance & efficiency (compare the real and generated distribution)
  - ✗ Extend the model to include all flavors
  - ✗ Modify the model to take into account the momentum sum rules

THANK YOU

BACKUP SLIDES

Here are the backups