Constraining Fragmentation Functions through photon-hadron production

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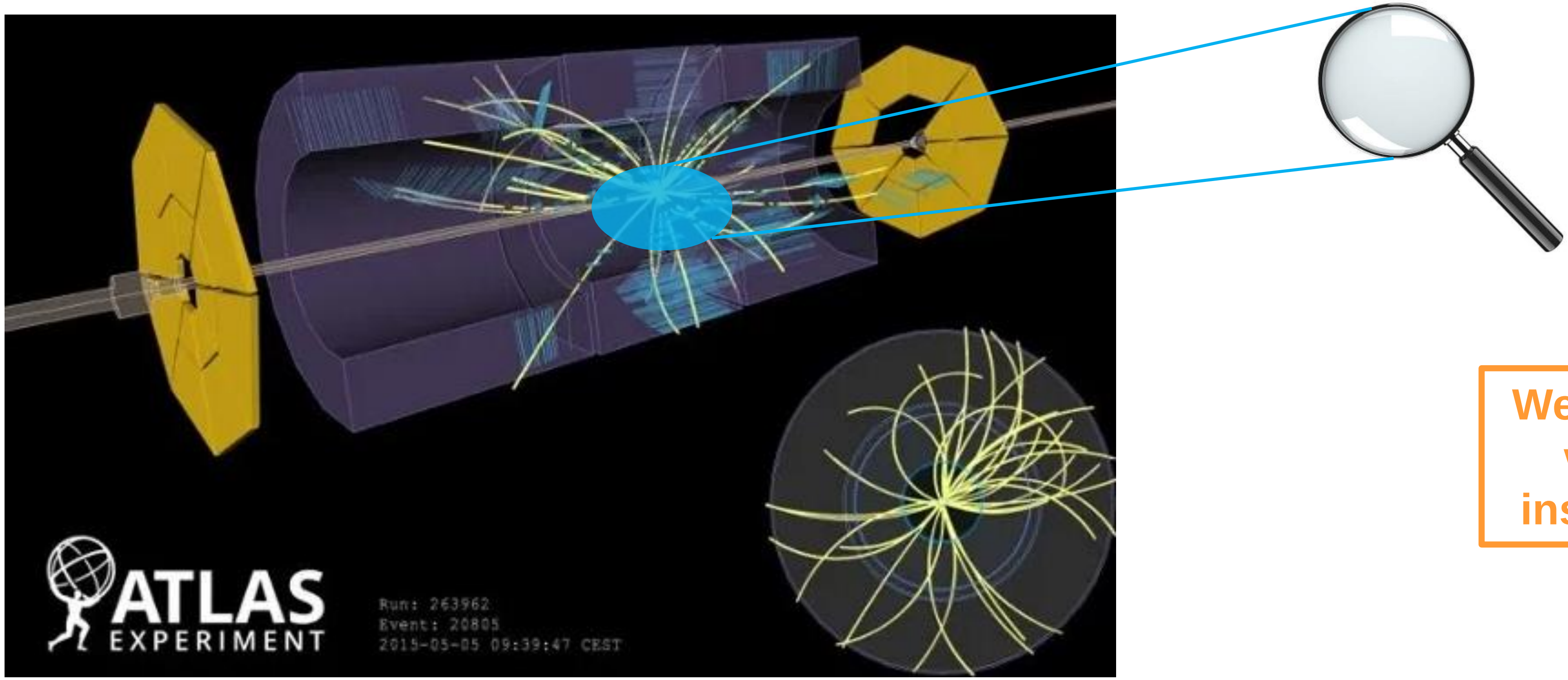
Based on the following published articles:

- **1011.0486 (inspiration)**
- **2104.14663**
- **2112.05043**
- **2303.04965 (new)**

- Experiments are collecting more and more data
- **More data available** ⇨ **More accurate results!!**
- Hadrons are composite states ⇨ **Non-perturbative description**
- Several aspects must be explored, but we must **enter into their internal structure**

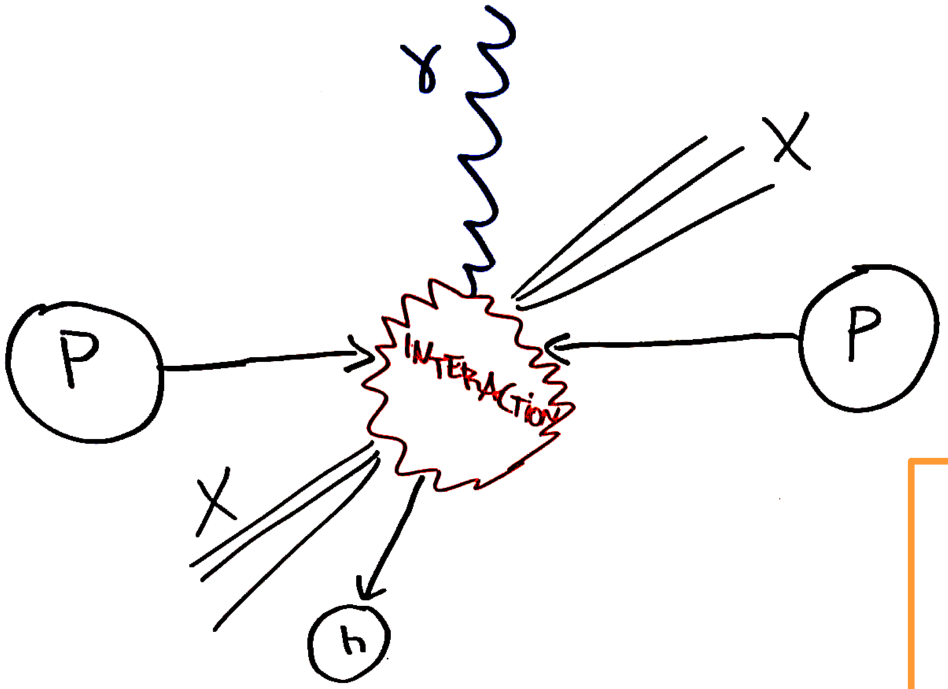


We must reconstruct what's going on inside the collisions

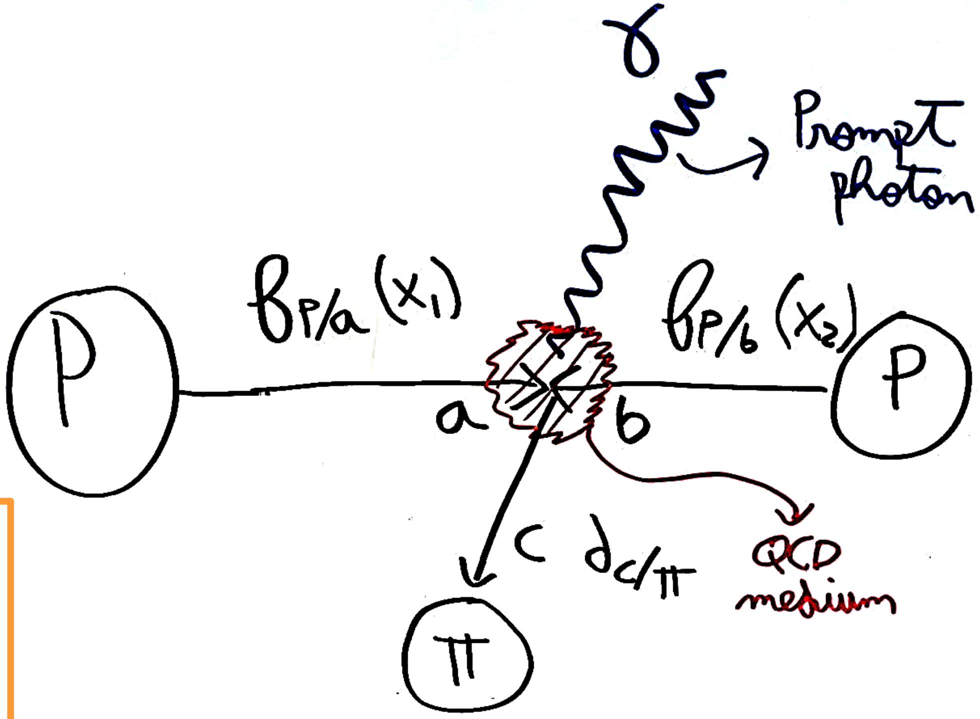
Motivation

- **Process of interest:** photon-**hadron** production at colliders
- **Why?** ⇨ Photon acts as a clean probe of the parton collision
- We can access information regarding PDFs and FFs
- **Hadron = Pion** (higher-production rates, more statistics)
- **Use to impose restrictions on heavier hadron FF!**

The photon is our "magnifying glass"



We rely on the factorization theorem and the parton model

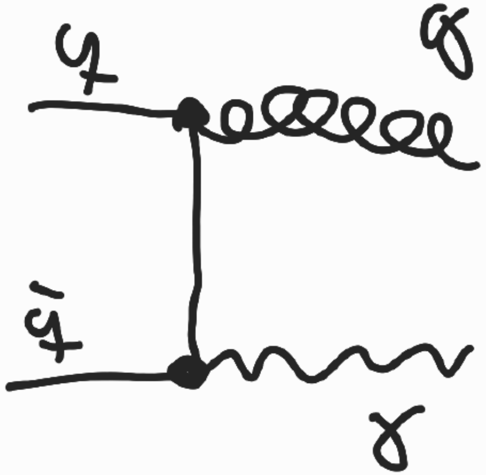


Computational details

- **Idea:** LO vs NLO
- Higher-orders contain unresolved (not measurable) particles
- Loops are quantum fluctuations of vacuum; real emission includes extra-particles (not considered as part of the observable)

$$P+P \to \gamma+\pi+X$$

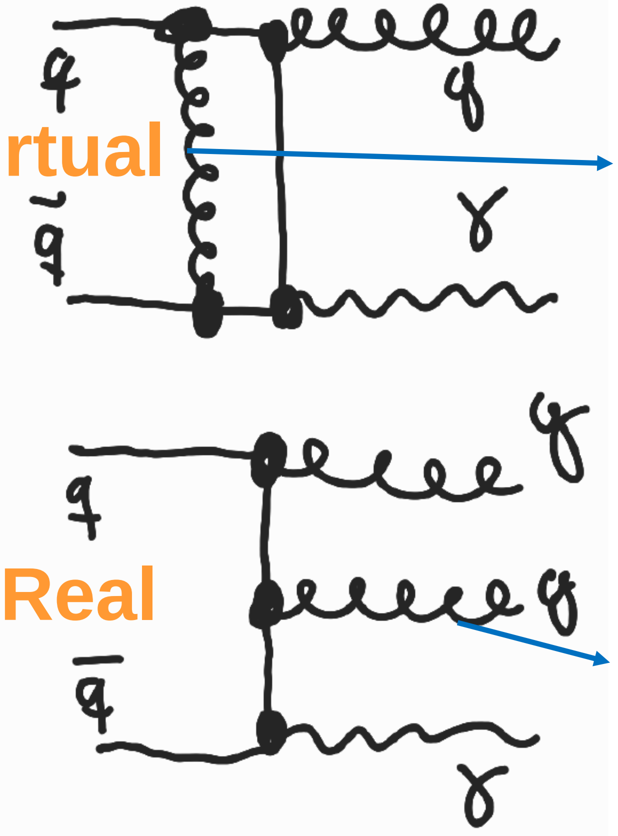
g hadronizes into a pion



γ directly observable

LO

Virtual



Real

Virtual g (“invisible”)

Extra g included in X

NLO

Computational details

- **Framework:** Higher-order contributions implemented in **FKS** (virtual + real + UV counter-terms + ISR counter-terms) ⇒ **Separated integrations!**

Hadronic cross-section

$$d\sigma_{H_1 H_2 \to h\gamma} \approx \sum_{a_1 a_2 a_3} \int dx_1\, dx_2\, dz\, f_{H_1/a_1}(x_1,\mu_I)\, f_{H_2/a_2}(x_2,\mu_I)\, D_{a_3/h}(z,\mu_F) \times d\hat{\sigma}^{(ISO)}_{a_1\, a_2 \to a_3 \gamma}(x_1 P_1, x_2 P_2, P^h/z, P^\gamma; \mu_I, \mu_F, \mu_R)$$

Partonic cross-section

$$d\hat{\sigma}^{\text{ISO},(1),\text{finite}}_{a_1\, a_2 \to a_3\, \gamma} = d\hat{\sigma}^{\text{ISO},(1),\text{ren.}}_{a_1\, a_2 \to a_3\, \gamma} - \frac{C^{\text{UV}}_{a_1\, a_2 \to a_3\, \gamma}}{\epsilon} \times d\hat{\sigma}^{\text{ISO},(0)}_{a_1\, a_2 \to a_3\, \gamma} - d\hat{\sigma}^{\text{ISO},\text{cnt},(I)}_{a_1\, a_2 \to a_3\, \gamma} - d\hat{\sigma}^{\text{ISO},\text{cnt},(F)}_{a_1\, a_2 \to a_3\, \gamma}$$

f_{H_1/a_1} NNPDF 3&4 $D_{a_3/h}$ DSS2014

- **Isolation:** smooth isolation criteria $\xi(r) = E_T^\gamma \left(\frac{1-\cos(r)}{1-\cos(r_0)}\right)^4$

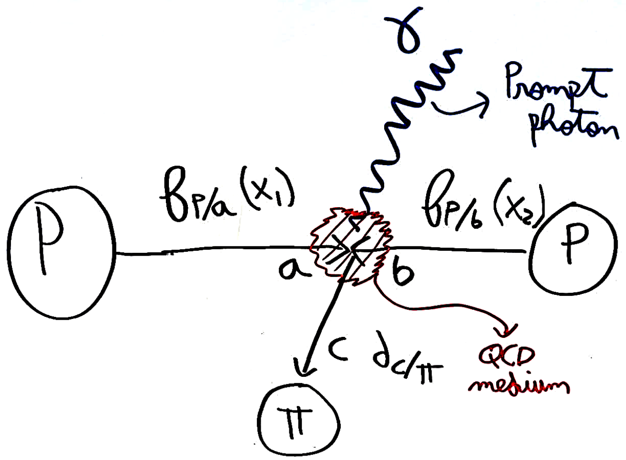
More details: 2112.05043 [hep-ph]

- **Cuts** (*used by STAR/PHENIX @ RHIC*):

$$|\eta^h| \le 0.35\,, \quad |\eta^\gamma| \le 0.35\,, \quad p_T^h \ge 2\,\text{GeV}\,, \quad 5\,\text{GeV} \le p_T^\gamma \le 15\,\text{GeV} \quad + \quad |\phi^h - \phi^\gamma| > 2$$

Reconstructing the partonic kinematics

- Momentum fractions are not “physical” (consequence of parton model)
- **Still, they allow to understand what’s going on inside hadrons**
- **Experimentally accessible quantities:**



$$\mathcal{V}_{\rm Exp} = \{p_T^\gamma, p_T^\pi, \eta^\gamma, \eta^\pi, \cos(\phi^\pi - \phi^\gamma)\}$$

- **Analytic formulae (exact only at LO – Born kinematics)**

SET 1

$$X_{1,\rm REC} = \frac{p_T^\gamma \exp(\eta^\pi) + p_T^\gamma \exp(\eta^\gamma)}{\sqrt{S_{CM}}}$$

$$X_{2,\rm REC} = \frac{p_T^\gamma \exp(-\eta^\pi) + p_T^\gamma \exp(-\eta^\gamma)}{\sqrt{S_{CM}}}$$

$$Z_{\rm REC} = \frac{p_T^\pi}{p_T^\gamma}$$

SET 2

$$X_{1,\rm REC} = \frac{p_T^\gamma \exp(\eta^\pi) - \cos(\phi^\pi - \phi^\gamma)\, p_T^\gamma \exp(\eta^\gamma)}{\sqrt{S_{CM}}}$$

$$X_{2,\rm REC} = \frac{p_T^\gamma \exp(-\eta^\pi) - \cos(\phi^\pi - \phi^\gamma)\, p_T^\gamma \exp(-\eta^\gamma)}{\sqrt{S_{CM}}}$$

$$Z_{\rm REC} = -\cos(\phi^\pi - \phi^\gamma)\, \frac{p_T^\pi}{p_T^\gamma}$$

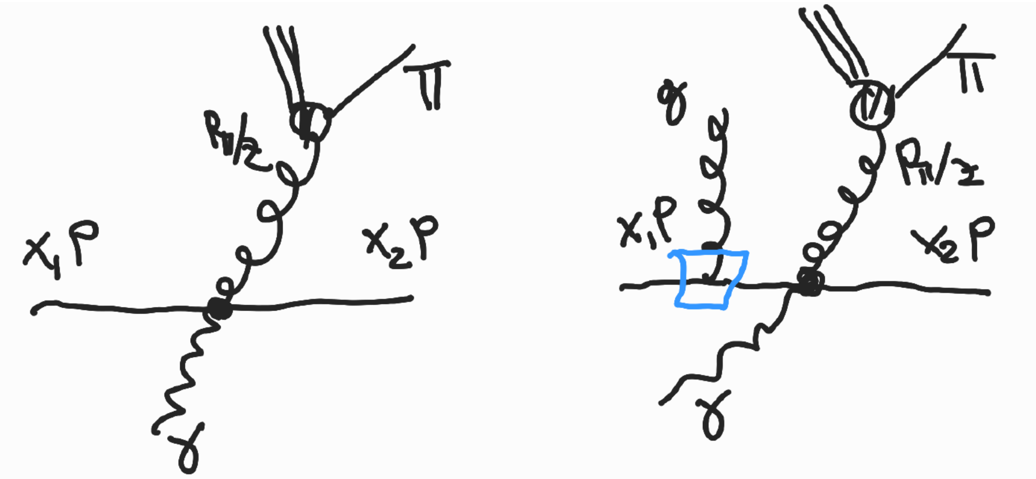
These expressions are equivalent at LO, but differ at NLO (due to real radiation)

Reconstructing the partonic kinematics

Dealing with higher-orders: binning

- NLO corrections involve: real (2-to-3), virtual (2-to-2), counterterms (2-to-2)
- **Create “bins” in the external variables and compute the cross-section**
- NLO events don’t have a unique momentum fraction *(x,z)* ⇨ **Weight contributions!**

Hadron & photon momenta fixes (x,z)



Extra-radiation integrated (included in “X”, not resolved)

⇩

(x,z) can not be exactly identified

- **Goal:** find the maps

$$X_{1,\mathrm{REC}} := \bar{\mathcal{V}}_{\mathrm{Exp}} \longrightarrow \bar{X}_{1,REAL} = \{(x_1)_j\}$$
$$Z_{\mathrm{REC}} := \bar{\mathcal{V}}_{\mathrm{Exp}} \longrightarrow \bar{Z}_{REAL} = \{(z)_j\}$$

Renteria-Estrada et al, arXiv:2112.05043 [hep-ph]

Reconstructing the partonic kinematics

Dealing with higher-orders: binning

- NLO corrections involve: real (2-to-3), virtual (2-to-2), counterterms (2-to-2)
- **Create "bins" in the external variables and compute the cross-section**

$$p_j = \{\bar{p}_T^\gamma, \bar{p}_T^\pi, \bar{\eta}^\gamma, \bar{\eta}^\pi, \overline{\cos}(\phi^\pi - \phi^\gamma)\} \in \bar{\mathcal{V}}_{\rm Exp} \quad \textbf{Grid}$$

$$\sigma_j(\bar{p}_T^\gamma, \bar{p}_T^\pi, \bar{\eta}^\gamma, \bar{\eta}^\pi, \overline{\cos}(\phi^\pi - \phi^\gamma)) = \int_{(p_T^\gamma)_{j,{\rm MIN}}}^{(p_T^\gamma)_{j,{\rm MAX}}} dp_T^\gamma \int_{(p_T^\pi)_{j,{\rm MIN}}}^{(p_T^\pi)_{j,{\rm MAX}}} dp_T^\pi \int dx_1 dx_2 dz\, d\bar{\sigma}$$

- Weight the MC momentum fractions with the cross-section per bin:

$$(x_1)_j = \sum_i (x_1)_i \frac{d\sigma_j}{dx_1}(p_j; (x_1)_i) \qquad (z)_j = \sum_i z_i \frac{d\sigma_j}{dz}(p_j; z_i)$$

- **Goal:** find the maps

$$X_{1,{\rm REC}} := \bar{\mathcal{V}}_{\rm Exp} \longrightarrow \bar{X}_{1,REAL} = \{(x_1)_j\}$$
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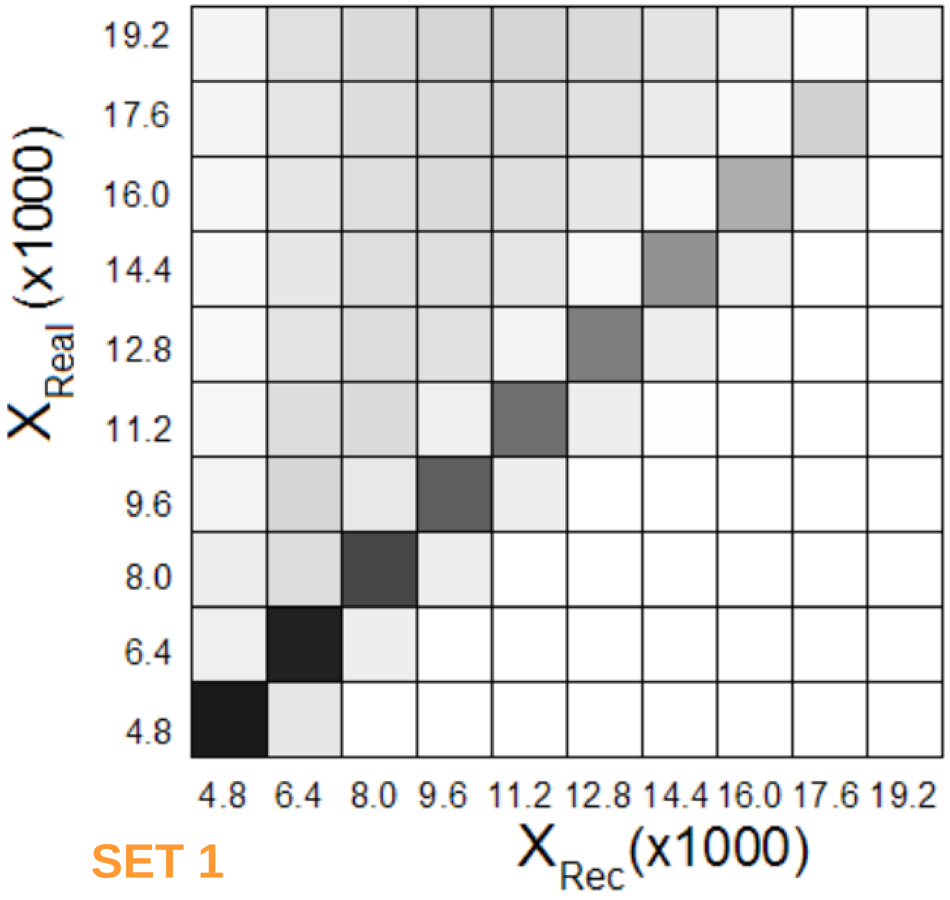
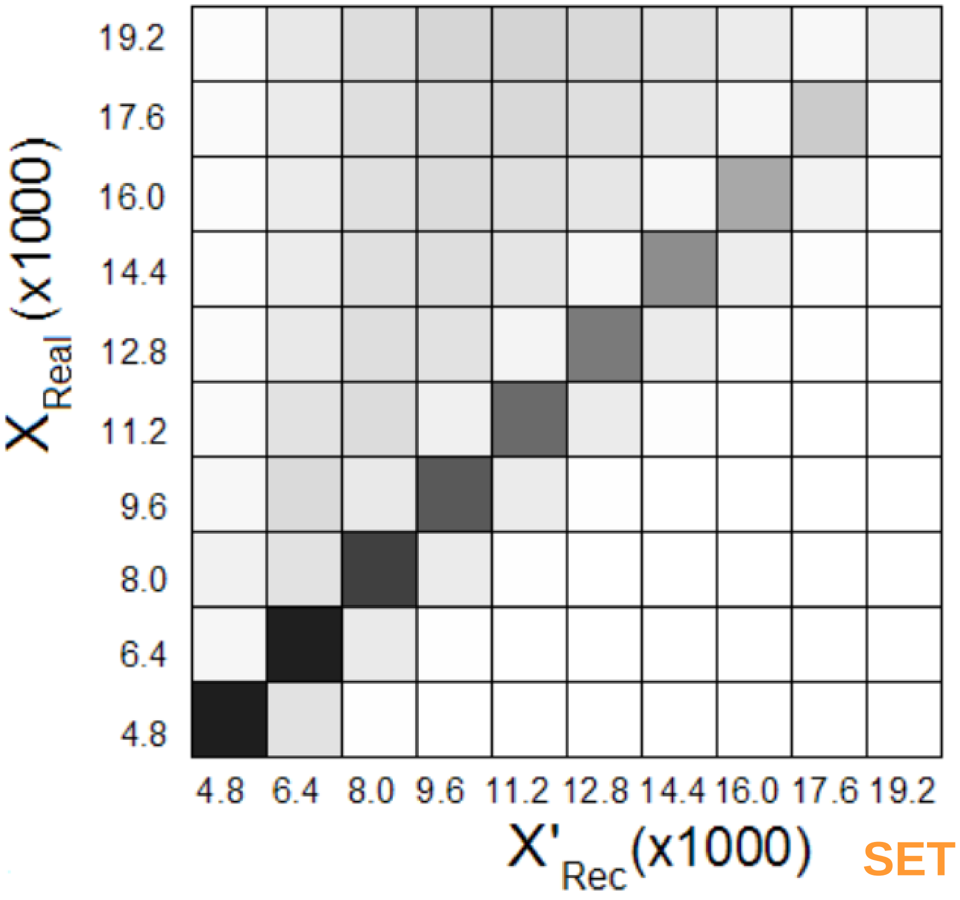
Previous results (from 2011)

- **SET 1** and **SET 2** tested against real Monte-Carlo momentum fractions
- **Good agreement for low x region; dispersion increases at larger values**



SET 1



SET 2

NLO

De Florian and Sborlini, arXiv:1011.0486 [hep-ph]

Previous results (from 2011)

- **SET 1** and **SET 2** tested against real Monte-Carlo momentum fractions
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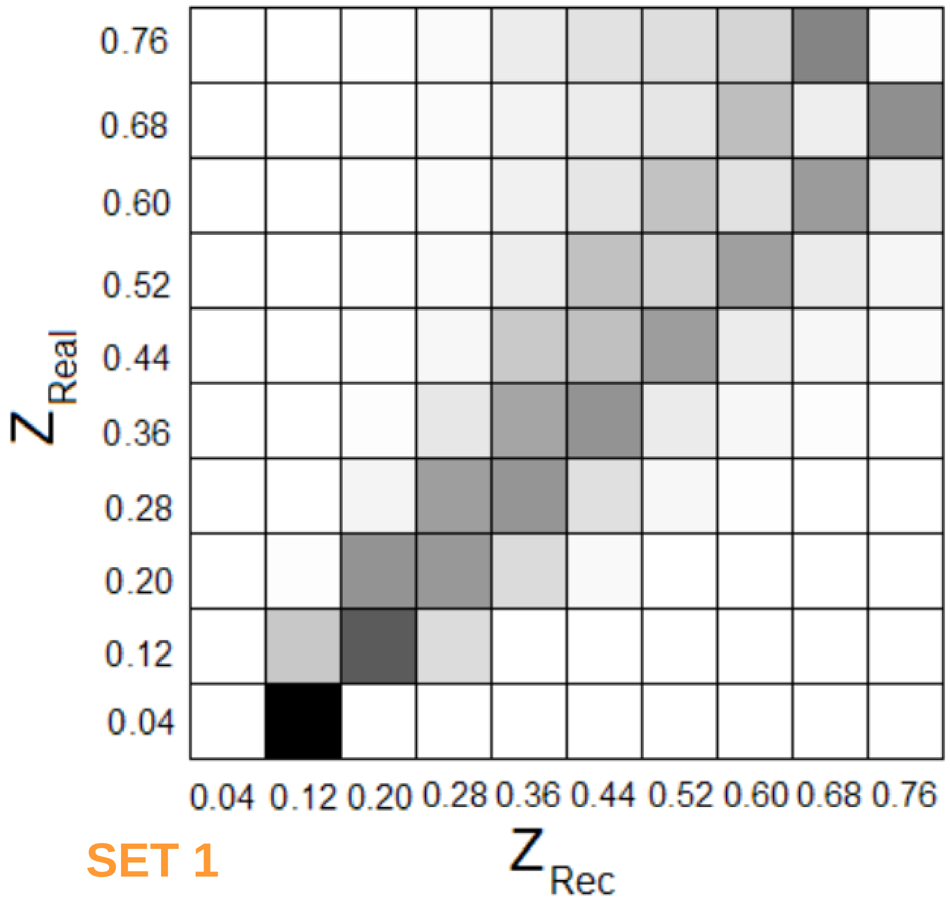
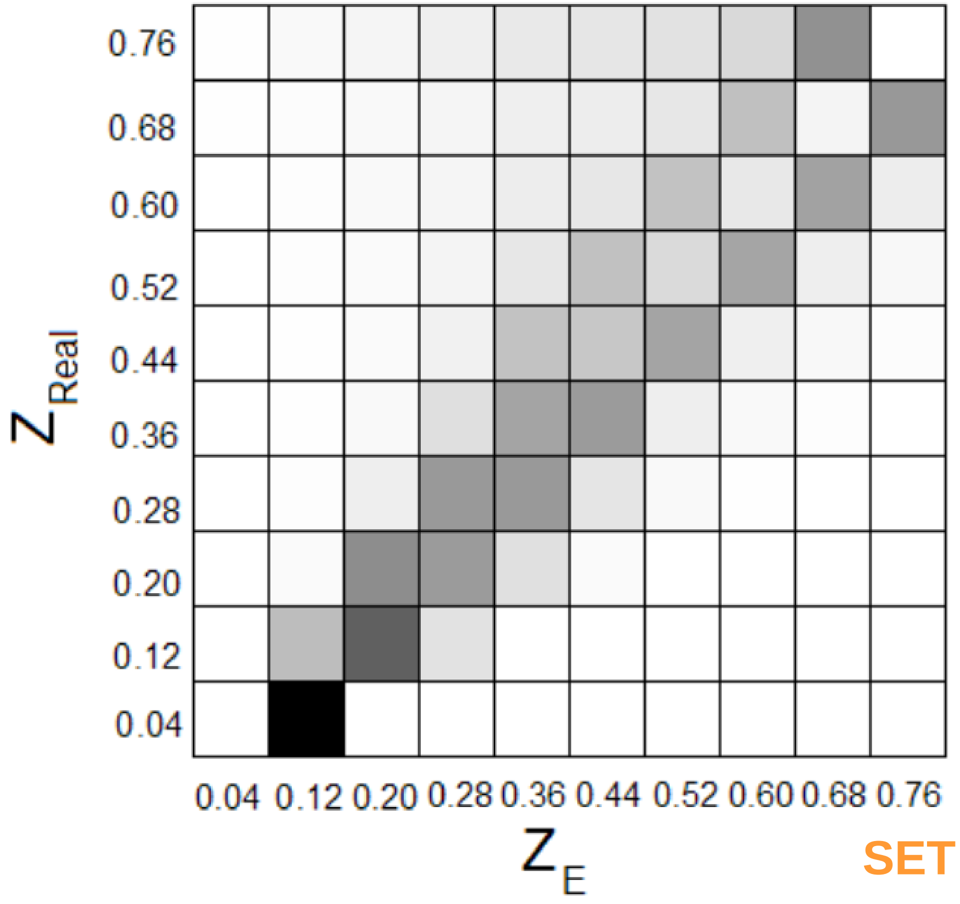


SET 1



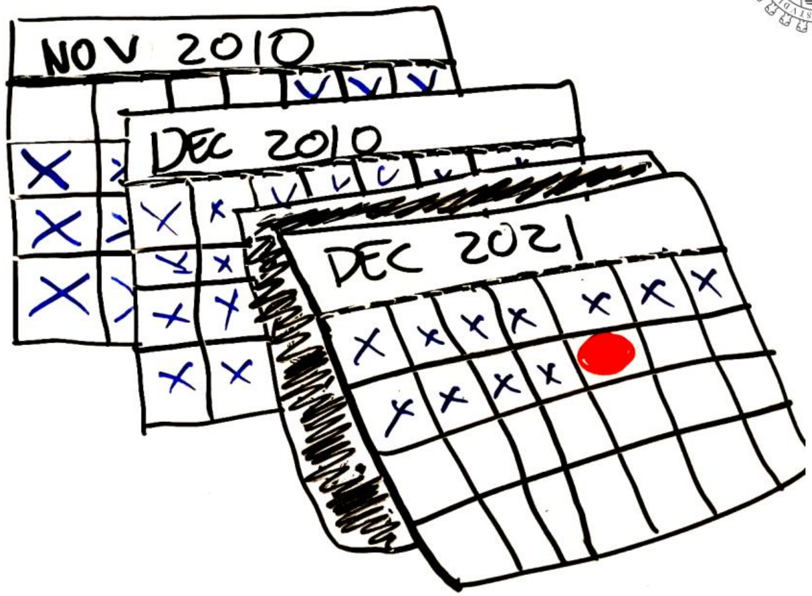
SET 2

NLO

De Florian and Sborlini, arXiv:1011.0486 [hep-ph]

But 11 years after…

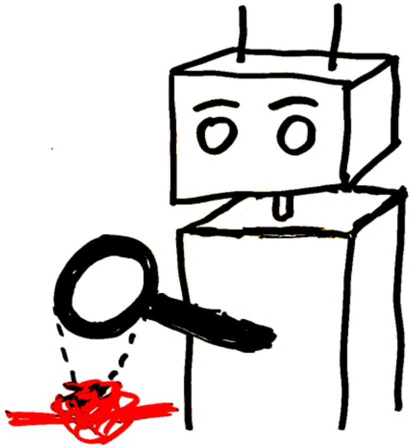
- New technologies are easier to use (even for non-experts)
- Computing the NLO corrections is faster (better hardware)
- New high-precision PDFs and FFs are available
- **Machine learning (ML) is becoming a crucial discovery tool for HEP!**



So…

- We updated our 2011 MC code, **including QED corrections**
- We adapted it to the **LHAPDF framework** (with the latest PDFs)

NNPDF3.1QED; NNPDF4.0



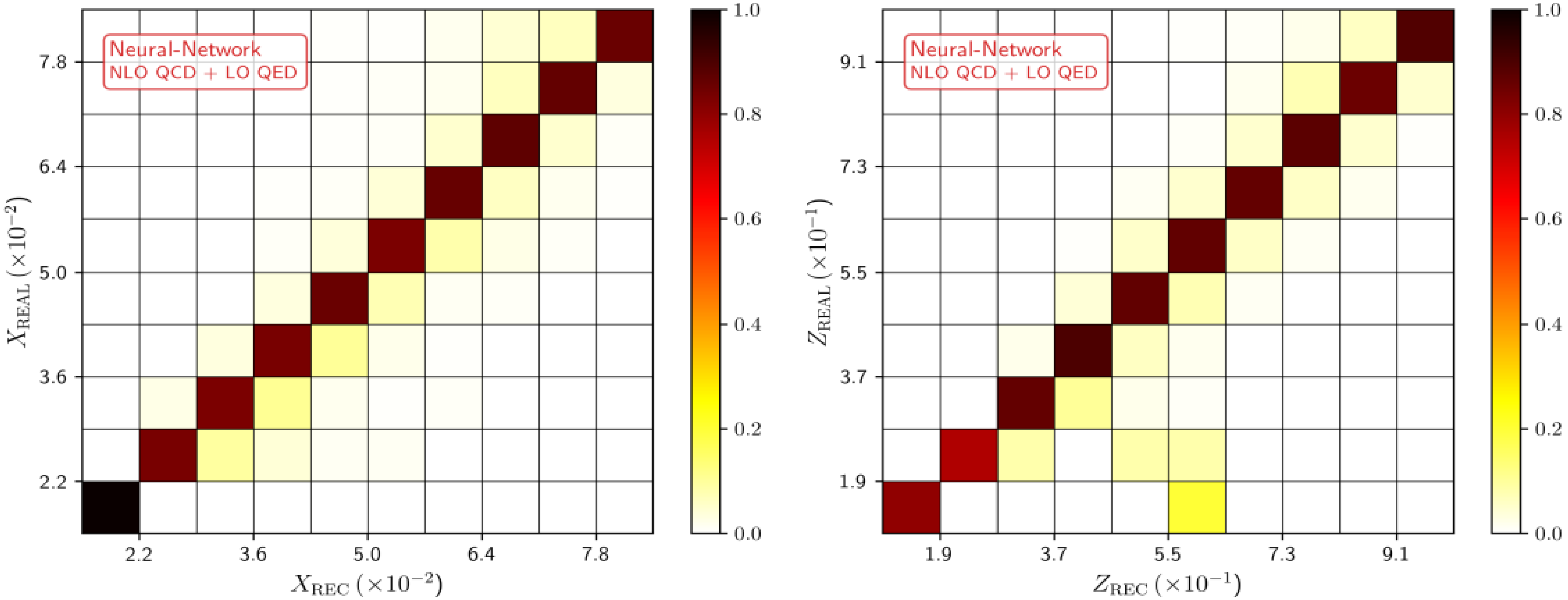
In order to…

- **Apply ML to discover new approximations to the real MC momentum fractions (with less assumptions)**

Renteria-Estrada et al, arXiv:2112.05043 [hep-ph]

Dealing with higher-orders: neural networks (NN)

Uses a Multilayer Perceptron (more details in the paper!!!)



NLO

Renteria-Estrada et al, arXiv:2112.05043 [hep-ph]

Advantages

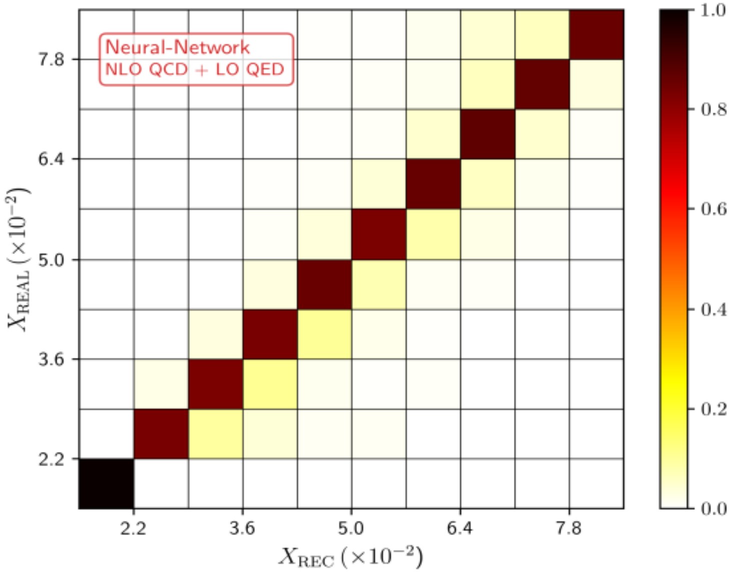
- No need to define an specific basis (**only input variables & architecture**)
- **Minimal human intervention**, with **better reconstruction quality**

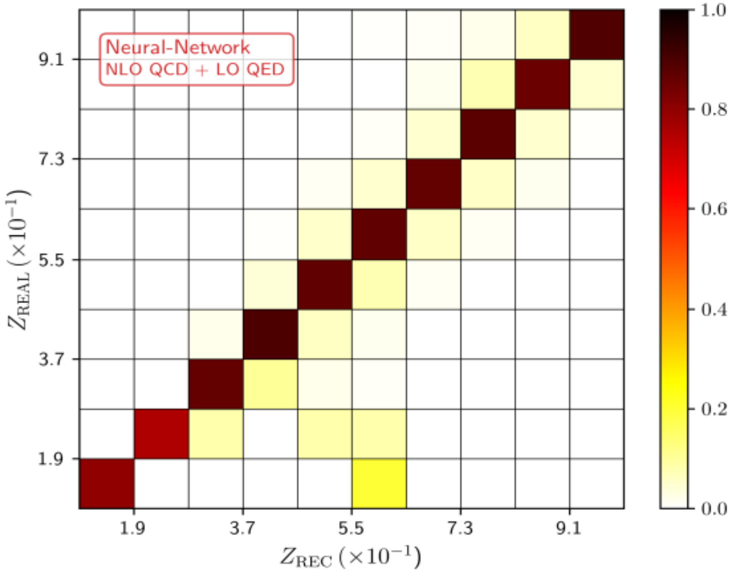
Disadvantages

- Complicated architectures take **more time** to be trained

Reconstructing the partonic kinematics

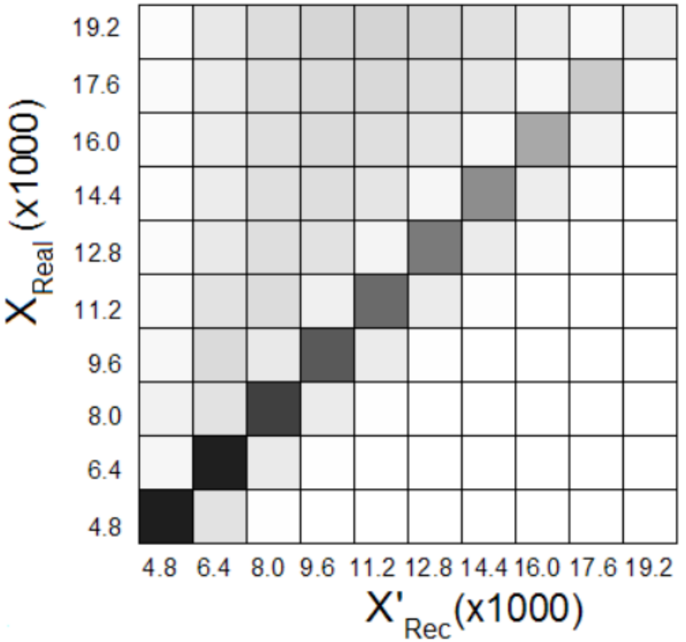
More than 10 years in a single slide…

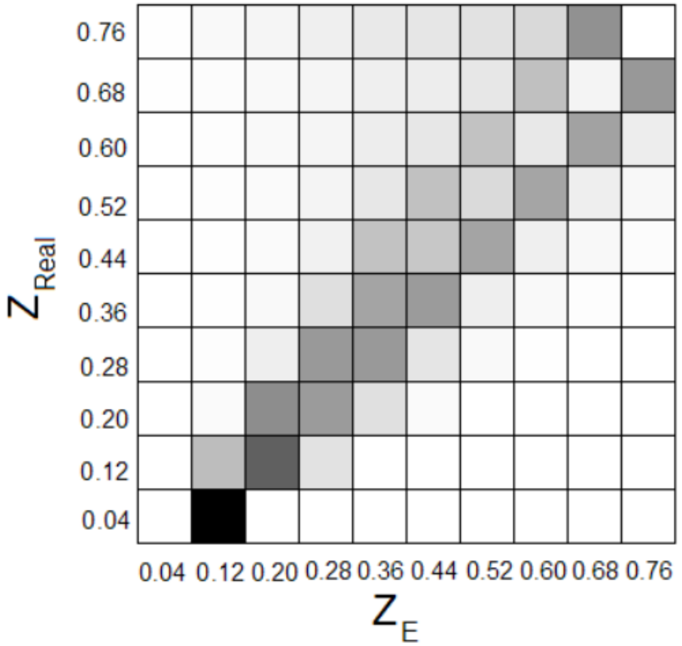


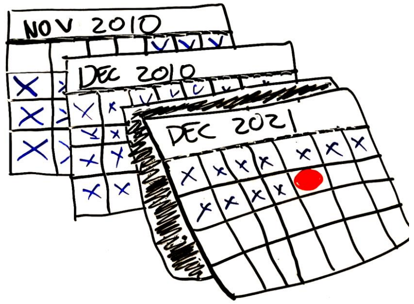


Human criteria + machine power

Renteria-Estrada et al, arXiv:2112.05043 [hep-ph]







De Florian and Sborlini, arXiv:1011.0486 [hep-ph]

Human intuition + creativity

Error estimation for the reconstruction

How to estimate errors when reconstructing X and Z?

- Several possibilities explored!
- Propagate scale-dependence of partonic cross-section, PDF and FF ⟹ $\xi = \{1/2, 1, 2\}$
- For each scale, a training-set is defined and the associated reconstruction functions are obtained

Kinematical points

$$(p_j, x_1, x_2, z, \sigma) \in \mathcal{D}^{(\xi)}$$

The cross-sections depends on the scale

⟹

$$X_{1,\mathrm{REC}}^{(\xi)} := \bar{\mathcal{V}}_{\mathrm{Exp}}^{(\xi)} \longrightarrow \bar{X}_{1,REAL}^{(\xi)} = \{(x_1)_j\} \subset \mathcal{D}^{(\xi)}$$

$$X_{2,\mathrm{REC}}^{(\xi)} := \bar{\mathcal{V}}_{\mathrm{Exp}}^{(\xi)} \longrightarrow \bar{X}_{2,REAL}^{(\xi)} = \{(x_2)_j\} \subset \mathcal{D}^{(\xi)}$$

$$Z_{\mathrm{REC}}^{(\xi)} := \bar{\mathcal{V}}_{\mathrm{Exp}}^{(\xi)} \longrightarrow \bar{Z}_{REAL}^{(\xi)} = \{(z)_j\} \subset \mathcal{D}^{(\xi)}$$

Scale-dependent mappings (reconstructed variables)

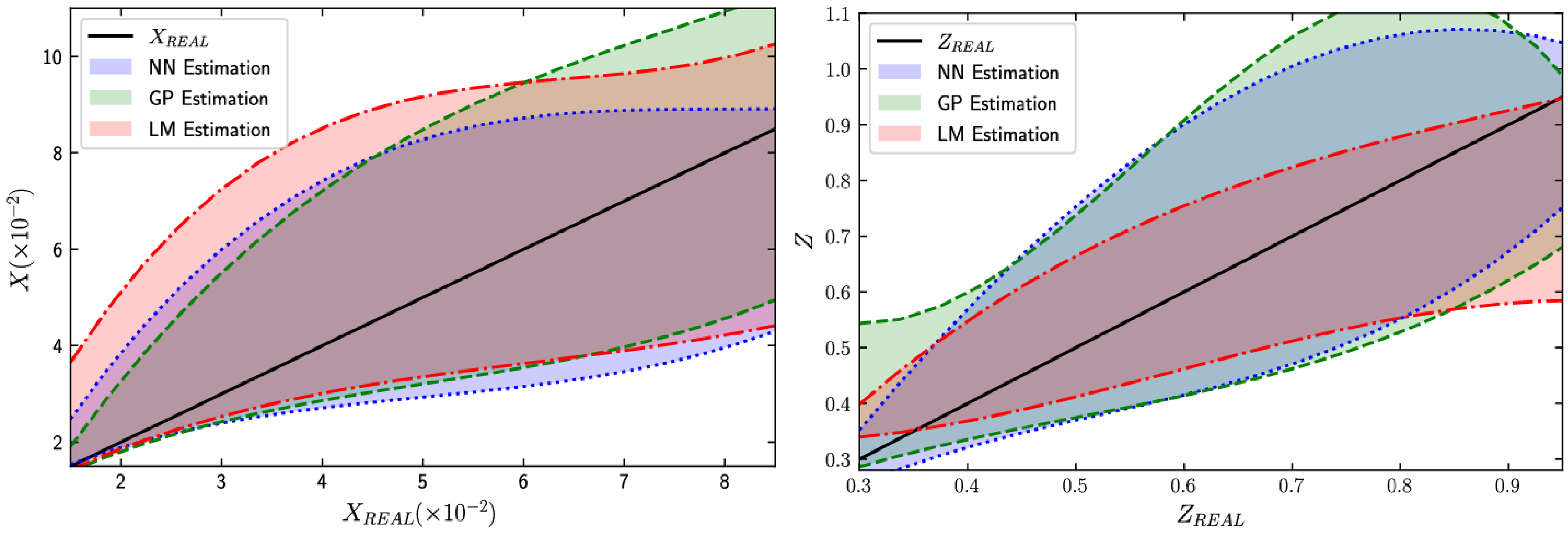
- **Then, we can provide error estimation!**

$$X_{\mathrm{REC}}(p_j) = \overline{X(p_j)} \pm \frac{\max(X(p_j)) - \min(X(p_j))}{2} \equiv \overline{X(p_j)} \pm \Delta X(p_j)$$

Avg. error estimated over the complete dataset!

Renteria-Estrada et al, arXiv:2112.05043 [hep-ph]

How to estimate errors when reconstructing X and Z?



Renteria-Estrada et al, arXiv:2112.05043 [hep-ph]

Error bands

- We evaluate three reconstruction functions over the complete training-set
- Correlation plots are obtained, showing **smaller error for low x/z values**

Global error

- With our method, **avg. error is 7% and 5% for x_1 and z, respectively!**

Using photon+hadron to constrain FF

Imposing constraints on FFs through cross-section ratios

We can rewrite the hadronic cross-section for this process as:

$$\frac{d\sigma^{h_i}}{dz} = \sum_{a_3} d_{a_3}^{h_i}(z) \times \left[\sum_{a_1,a_2} \int dx_1 dx_2\, f_{a_1}^{H_1}(x_1)\, f_{a_2}^{H_2}(x_2)\, d\hat{\sigma}_{a_1 a_2 \to a_3 \gamma}\right]$$
$$= \sum_{a_3} d_{a_3}^{h_i}(z) \times g_{a_3}(z)$$

The function *g* is independent of the FS-hadron!

Kinematics restrictions

- We impose |η| < 0.5 to (mainly) retain those events that are closer to the Born-level kinematic.
- We notice that ***qg-channel*** is **~**10 times larger than the others (mainly due to PDFs).
- As a consequence of EM-coupling, the U-channels are dominant w.r.t. D-channels. This leads to:

$$|\mathcal{M}_{ug\to u\gamma}|^2 = 4|\mathcal{M}_{dg\to d\gamma}|^2$$

u-quark dominant w.r.t. c, t quarks (PDF effect)

Goal: Relate cross-section and FF ratios, for different hadrons in final state:

$$R^{K/\pi}(d\sigma) = \frac{d\sigma^K/dz_{\mathrm{REC}}}{d\sigma^\pi/dz_{\mathrm{REC}}} \approx \frac{d_u^K(z_{\mathrm{REC}})}{d_u^\pi(z_{\mathrm{REC}})} = R^{K/\pi}(d_u)$$

where $z_{\mathrm{REC}} = \frac{p_T^\pi}{p_T^\gamma}$

Ochoa-Oregon et al, arXiv:2303.04965 [hep-ph]

Cross-section vs FFs ratios

We present a comparison between the FFs and the cross-section ratios for positive hadron production. In concrete, we restrict to pion and kaon production (higher cross-section).

Two different approaches:

1) Using the reference energy scale (upper plot):

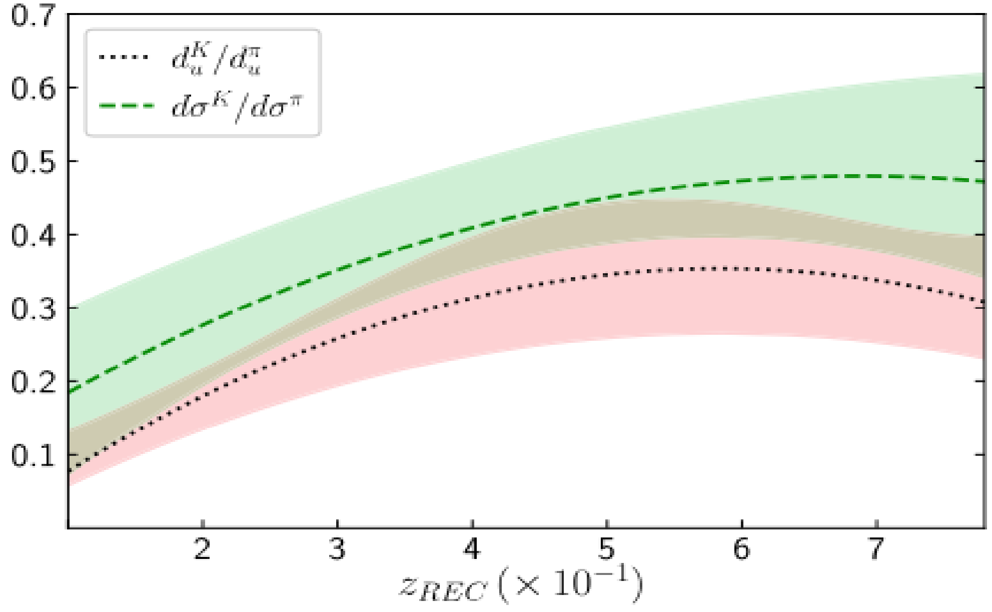
$$\mu = \frac{p_T^\gamma + p_T^h}{2}$$

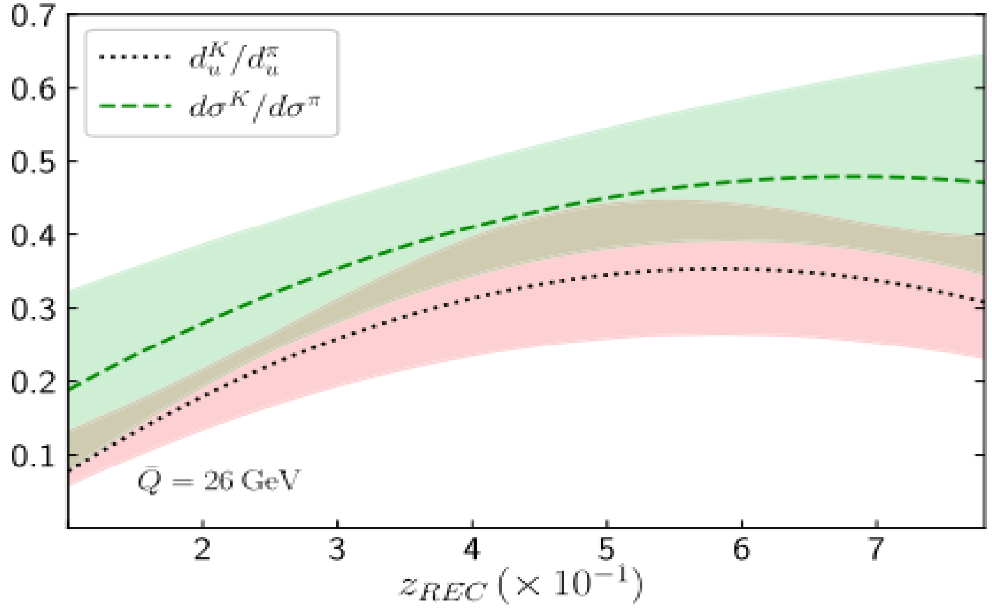
2) Fixing the reference energy scale (lower plot):

$$\mu = \bar{Q} = 26\,\mathrm{GeV}$$

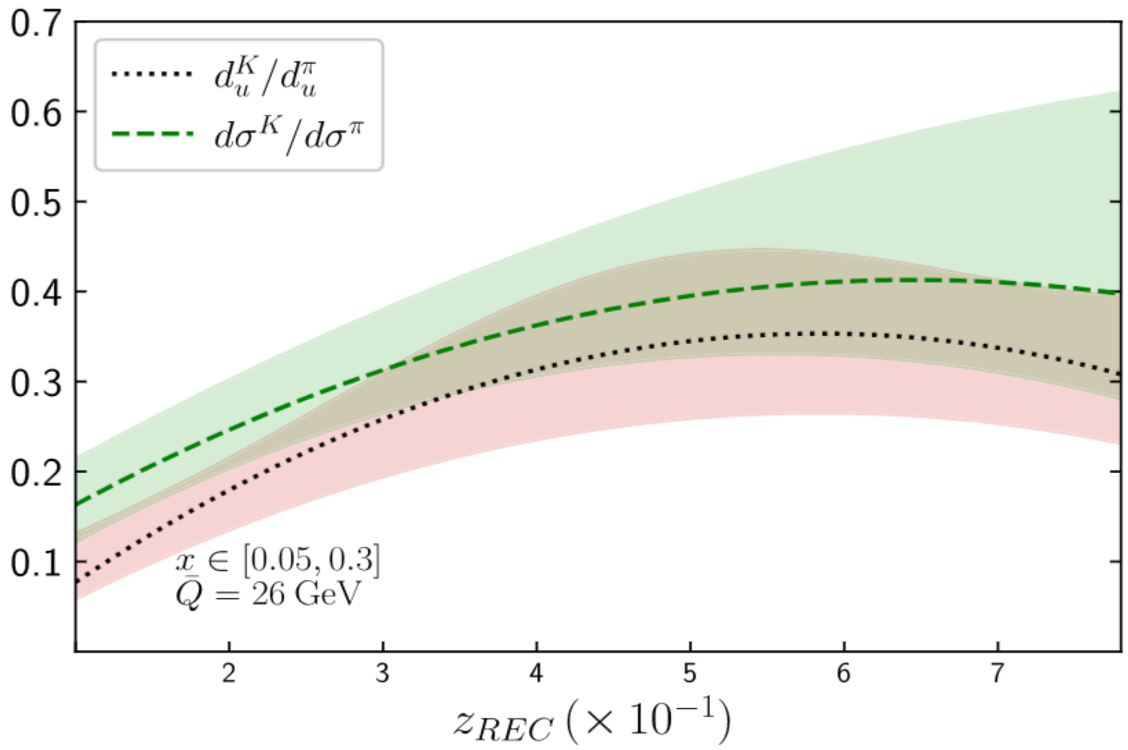
Motivation: Reduce the impact of the scale dependence of FFs (improves the validity of the approximation)

$$R^{K/\pi}(d\sigma) = \frac{d\sigma^K/dz_{\mathrm{REC}}}{d\sigma^\pi/dz_{\mathrm{REC}}} \approx \frac{d_u^K(z_{\mathrm{REC}})}{d_u^\pi(z_{\mathrm{REC}})} = R^{K/\pi}(d_u)$$





Improved analysis with physically motivated cuts



1) To remove the scale-induced effects (improve the approximation), we fix:

$$\bar{Q} = \frac{\sum_i \mu(p_T^\gamma, p_T^h)_i (\sigma_{\mathrm{BIN}})_i}{\sigma_{\mathrm{TOTAL}}}$$

2) To enhance even more the weight of u-started processes, we look into the region where u-PDF dominates and impose the cut:

$$0.03 \leq \{(x_1)_{\mathrm{REC}}, (x_2)_{\mathrm{REC}}\} \leq 0.5$$

with

$$X_{1,\mathrm{REC}} = \frac{p_T^\gamma \exp(\eta^\pi) + p_T^\gamma \exp(\eta^\gamma)}{\sqrt{S_{CM}}}$$

$$X_{2,\mathrm{REC}} = \frac{p_T^\gamma \exp(-\eta^\pi) + p_T^\gamma \exp(-\eta^\gamma)}{\sqrt{S_{CM}}}$$

- We notice that $\frac{d\sigma^K/dz_{REC}}{d\sigma^\pi/dz_{REC}}$ and $\frac{d_u^K(z_{REC})}{d_u^\pi(z_{REC})}$ are much closer than in the previous scenarios, **particularly in the range z∈(0.35,0.65)**.
- More stringent constraints can be imposed from the ratio of the cross sections, *paving the road for a more precise determination of heavy-meson FFs from experimental data.*

Conclusions

- *Photon-hadron production is an interesting process to access to the parton-level kinematics (presence of prompt-photon in final state)*

- **Reconstruction of partonic momentum fractions:** *Validity of analytical approximations confirmed against machine-learning analysis.*

- **Constraining FFs:**
  - Use approximations to relate cross-section and FF ratios for different hadrons.
  - Consider z_{REC} spectrum and impose cuts in x_{REC}.

- **Outlook:** *Use ML-assisted optimization of kinematical cuts (as well as NN for parton momentum fraction approximations) to better constrain FFs.*

THANKS!