Phenomenological analysis of the internal structure of hadrons by photon production at NLO QCD + LO QED

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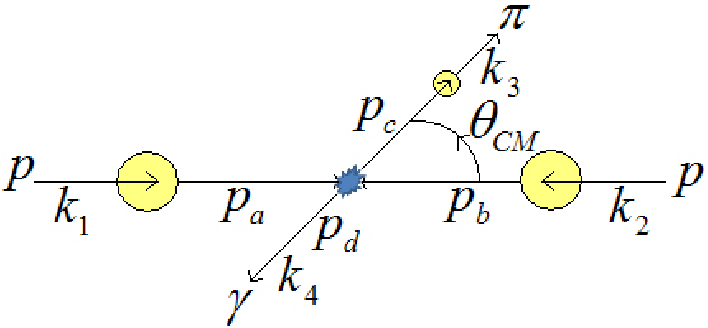
Motivation

- Understanding the internal structure of non-fundamental particles implies dealing with complex mathematics models.
- The solutions of these models cannot be easily obtained and, they are mainly solved by using approximeted methods.
- Detecting a hard photon in final state, is a method that allows characterise the kinematics of the partons hadrons.
- Due to low interaction of photons with the medium generated in high energy collisions, the identification of a hard photon in the final state could help to understand the physics in heavy ion collisions.

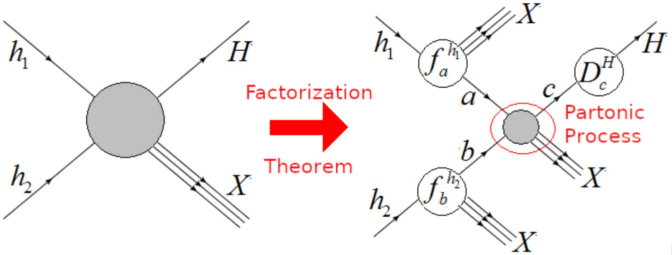
- $p\,p \to h + \gamma$ process.



Parton Model

In hadron-hadron collisions, the cross section is described by the convolution between PDFs, FFs, and the partonic cross section

$$d\sigma^{h_1 h_2 \to HX} = \sum_{a,b,c} \int_0^1 dx \int_0^1 dy \int_0^1 dz\, f_a^{h_1}(x, \mu_I) f_b^{h_2}(y, \mu_I) d_c^H(z, \mu_F) \times d\hat{\sigma}_{ab \to cX} \tag{1}$$



PDF and FF

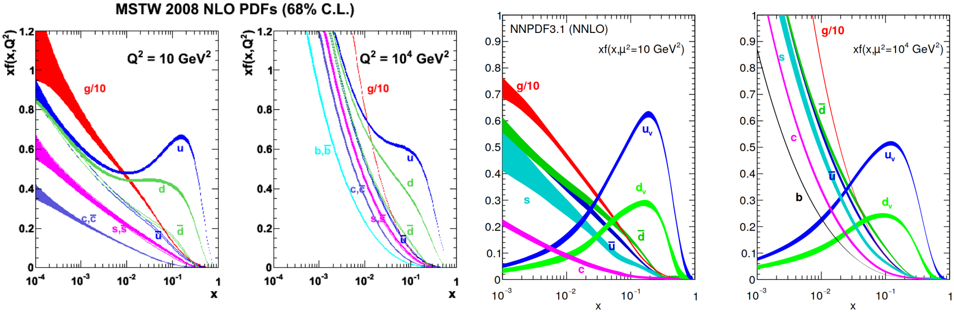
- Parton Distribution Function $f_a^h(x)$ is the probability density to find a parton a, with momentum fraction x inside h.

$$\sum_a \int dx\, x\, f_a^h(x) + \int dx\, x\, f_g^h(x) = 1 \tag{2}$$

- Fragmentation Function $d_b^h(z)$ is the density probability function to generate a hadron h with momentum fraction z from the parton b.

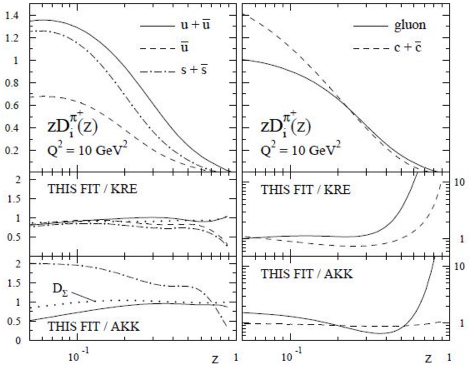
$$\sum_h \int dx\, x\, d_b^h(z) = 1 \tag{3}$$

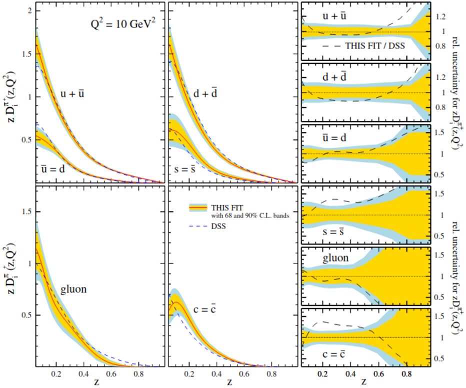
PDF and FF



In this work we are interested on the impact of the new set of PDFs and FFs. For this reason, we will present comparisons between MSTW2008 and NNPDF3.1.

PDF and FF

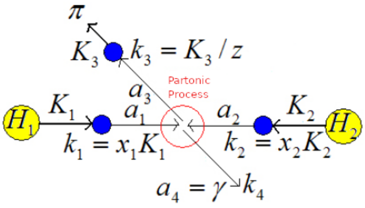




For FF, we have compare DSS-2007 and DSS-2014.

In the case of the hadron-photon production we have two different mechanism to produce this final state.
i) Directly from the hard process

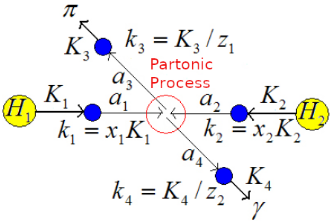
$$d\sigma^{DIR}_{H_1H_2\to h\gamma} = \sum_{a_1,a_2,a_3} \int_0^1 dx_1\, dx_2\, dz\, f^{H_1}_{a_1}(x_1,\mu_I) f^{H_2}_{a_2}(x_2,\mu_I) d^h_{a_3}(z,\mu_F) \times d\hat{\sigma}^{DIR}_{a_1a_2\to a_3\gamma} \quad (4)$$



Cross section NLO computation

ii) when the photon is generated from the fragmentation of a parton, the so-called resolved contribution.

$$d\sigma^{RES}_{H_1 H_2 \to h\gamma} = \sum_{a_1,a_2,a_3,a_4} \int_0^1 dx_1\, dx_2\, dz\, dz'\, f^{H_1}_{a_1}(x_1,\mu_I) f^{H_2}_{a_2}(x_2,\mu_I) d^h_{a_3}(z,\mu_F) \times d^{\gamma}_{a_4}(z',\mu_F) d\hat{\sigma}^{RES}_{a_1 a_2 \to a_3 a_4} \tag{5}$$

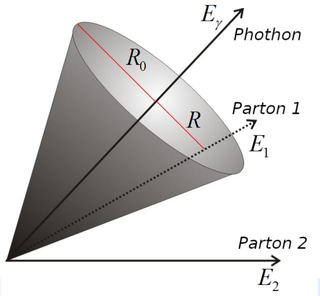


- **Characterization of events**

  Usually, distances are measured within the rapidity–azimuthal plane: if $a = (\eta_1, \phi_1)$ and $b = (\eta_2, \phi_2)$, then:

$$\Delta r_{ab} = \sqrt{(\eta_1 - \eta_2)^2 + (\phi_1 - \phi_2)^2}, \tag{6}$$

represents the distance between these two points.



Selection of events

- The selection procedure is given by the smooth cone isolation algorithm
  1. Identify each photonic signal in the final state, and draw a cone of radius r_0 around it.
  2. If there are not QCD partons inside the cone, the photon is isolated.
  3. If there are QCD partons inside the cone, we calculate their distance to the photon and then we define the total transverse hadronic energy for a cone of radius r as:

$$E_T(r) = \sum_j E_{T_j} \Theta(r - r_j). \tag{7}$$

  4. Define an arbitrary smooth function $\xi(r)$ that satisfies $\xi(r) \to 0$ for $r \to 0$.
  5. If $E_T(r) < \xi(r)$ for every $r < r_0$, then the photon is isolated.

This prescription completely eliminates the collinear quark radiation, which implies that the *resolved* contribution $\sigma^{RES}_{H_1 H_2 \to h\gamma}$ can be neglected. In this way,

$$d\sigma_{H_1 H_2 \to h\gamma} = \sum_{a_1, a_2, a_3} \int_0^1 dx_1\, dx_2\, dz\, f^{H_1}_{a_1}(x_1, \mu_I) f^{H_2}_{a_2}(x_2, \mu_I) d^h_{a_3}(z, \mu_F) d\hat{\sigma}^{ISO}_{a_1 a_2 \to a_3 \gamma} \quad (8)$$

Cross section NLO computation

The QCD corrections to the process $\gamma + h$, up to NLO accuracy:

$$
\begin{aligned}
d\hat{\sigma}^{\mathrm{ISO}}_{a_1\, a_2 \to a_3\, \gamma} = {} & \frac{\alpha_s}{2\pi}\frac{\alpha}{2\pi} \int d\mathrm{PS}^{2\to 2}\, \frac{|\mathcal{M}^{(0)}|^2(x_1 K_1, x_2 K_2, K_3/z, K_4)}{2\hat{s}}\, \mathcal{S}_2 \\
& + \frac{\alpha_s^2}{4\pi^2}\frac{\alpha}{2\pi} \int d\mathrm{PS}^{2\to 2}\, \frac{|\mathcal{M}^{(1)}|^2(x_1 K_1, x_2 K_2, K_3/z, K_4)}{2\hat{s}}\, \mathcal{S}_2 \\
& + \frac{\alpha_s^2}{4\pi^2}\frac{\alpha}{2\pi} \sum_{a_5} \int d\mathrm{PS}^{2\to 3}\, \frac{|\mathcal{M}^{(0)}|^2(x_1 K_1, x_2 K_2, K_3/z, K_4, k_5)}{2\hat{s}}\, \mathcal{S}_3
\end{aligned}
\tag{9}
$$

Cross section NLO computation

- Where $\hat{s}$ is the partonic center-of-mass energy, $|\mathcal{M}^{(0)}|^2$ the squared matrix-element at Born level and $|\mathcal{M}^{(1)}|^2$ the corresponding one-loop one. $\mathcal{S}_2$ and $\mathcal{S}_3$ are the measure functions that implements the experimental cuts and the isolation prescription for the $2 \to 2$ and $2 \to 3$ sub-processes, respectively.
- There are two partonic channels contributing at LO:

$$q\bar{q} \to \gamma g\,, \quad qg \to \gamma q \tag{10}$$

- The QCD channels contributing at NLO:

$$\begin{gathered} q\bar{q} \to \gamma gg\,, \quad qg \to \gamma gq\,, \quad gg \to \gamma q\bar{q}\,, \\ q\bar{q} \to \gamma Q\bar{Q}\,, \quad qQ \to \gamma qQ \end{gathered} \tag{11}$$

Adding LO QED corrections

If we want to consider QED corrections, we should add:

$$d\hat{\sigma}^{\mathrm{ISO,QED}}_{a_1\, a_2 \to a_3\, \gamma} = \frac{\alpha^2}{4\pi^2} \int d\mathrm{PS}^{2\to 2}\, \frac{|\mathcal{M}^{(0)}_{QED}|^2(x_1 K_1, x_2 K_2, K_3/z, K_4)}{2\hat{s}}\, \mathcal{S}_2 \tag{12}$$

- In this case, the new partonic channels are:

$$q\gamma \to \gamma q\,, \quad q\bar{q} \to \gamma\gamma \tag{13}$$

- For the isolation algorithm, we use the function:

$$\xi(r) = \epsilon_\gamma E_T^\gamma \left(\frac{1-\cos(r)}{1-\cos r_0}\right)^4 \tag{14}$$

- The average of the photon and hadron transverse energy was used as the typical energy scale of the process:

$$\mu \equiv \frac{p_T^h + p_T^\gamma}{2} \tag{15}$$

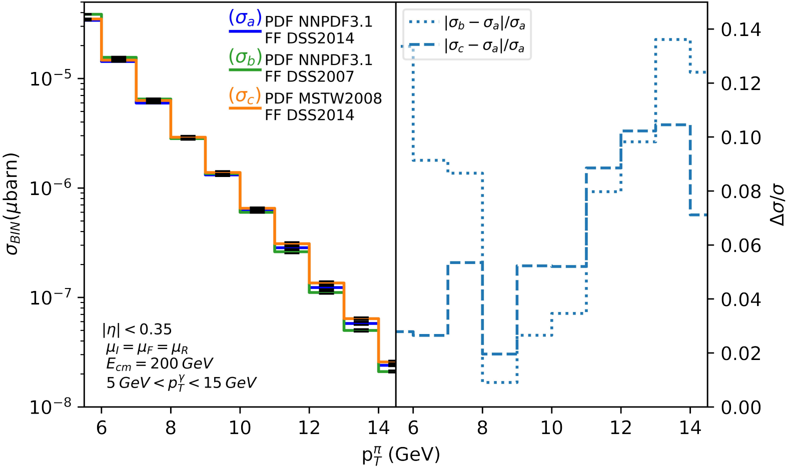
and we set by default $\mu_I = \mu_F = \mu_R \equiv \mu$.

Numerical simulation and results

Numerical cuts

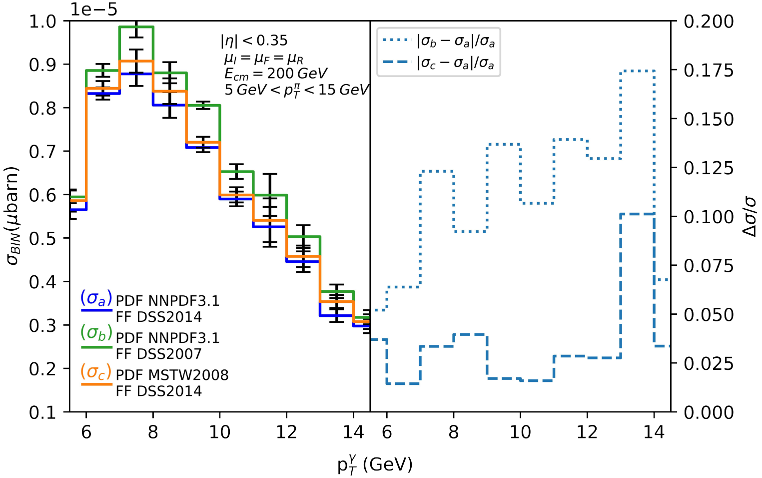
- Our default configuration corresponds to the one used by the PHENIX detector:
  1. Pion and photon rapidities are restricted to $|\eta| \leq 0.35$.
  2. The photon transverse momentum fulfills $5\,\mathrm{GeV} \leq p_T^{\gamma} \leq 15\,\mathrm{GeV}$.
  3. Pion transverse momentum must be larger than 2 GeV.
  4. We consider full azimuthal coverage, i.e. no restriction on $\{\phi^{\pi}, \phi^{\gamma}\}$, as a simplification of the real detectors.
  5. The center-of-mass energy of the hadron collisions, we use by default $E_{CM} = 200$ GeV.
  6. Although we also explored the TeV region accessible by LHC, setting $E_{CM} = 13$ TeV.
  7. We restrict $\Delta\phi = |\phi^{\pi} - \phi^{\gamma}| \geq 2$.

- We consider three configurations:
  1. σ_a: `NNPDF3.1` and `DSS2014` (default up-to-date simulation)
  2. σ_b: `NNPDF3.1` and `DSS2007` (effects in the hadronization)
  3. σ_c: `MSTW2008` and `DSS2014` (effects in the parton distributions)


(σ_a) PDF NNPDF3.1 FF DSS2014
(σ_b) PDF NNPDF3.1 FF DSS2007
(σ_c) PDF MSTW2008 FF DSS2014
$|\eta| < 0.35$
$\mu_I = \mu_F = \mu_R$
$E_{cm} = 200\, GeV$
$5\, GeV < p_T^{\gamma} < 15\, GeV$
$\sigma_{BIN}(\mu\mathrm{barn})$
10^{-5}
10^{-6}
10^{-7}
10^{-8}
$|\sigma_b - \sigma_a|/\sigma_a$
$|\sigma_c - \sigma_a|/\sigma_a$
$\Delta\sigma/\sigma$
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
6
8
10
12
14
p_T^{π} (GeV)

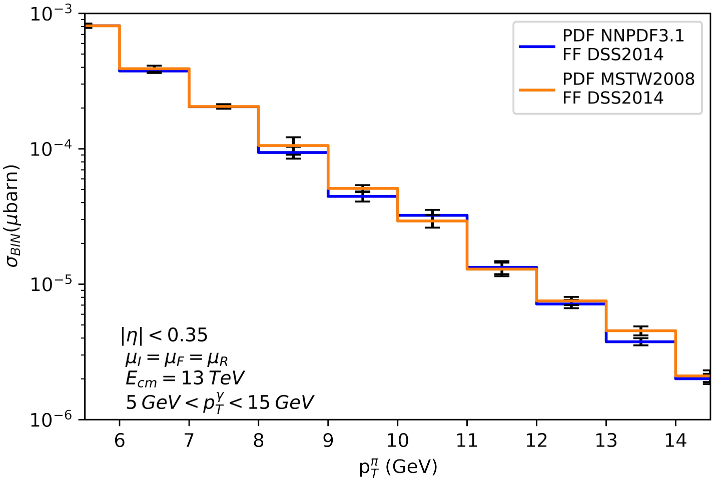
Numerical simulation and results

PHENIX results



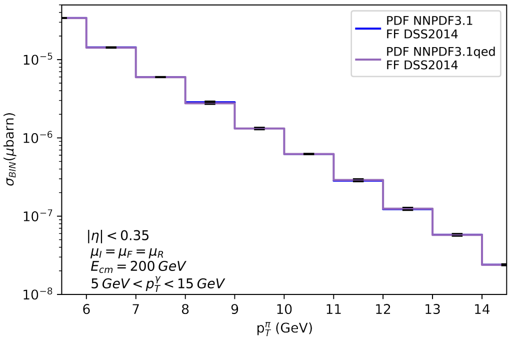
Numerical simulation and results

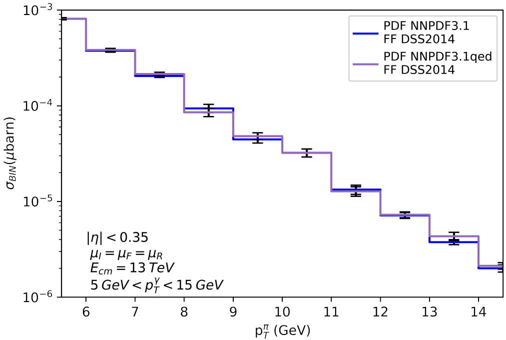
LHC results



Numerical simulation and results

PHENIX and LHC results with QED corrections





Conclusion

- We found reasonable deviations (i.e. $\mathcal{O}(10\,\%)$ on average), although our preliminary studies suggest a stronger sensibility in the p_T^γ distribution.
- By including LO QED corrections (using `NNPDF3.1luxQEDNLO`), we found small but still non-negligible corrections: $\mathcal{O}(2\,\%)$ for PHENIX and $\mathcal{O}(8\,\%)$ for LHC center-of-mass energies.
- The results presented in this study suggest that hadron+photon production might be a useful process to impose tighter constraints on both PDFs and FFs.

Thank you!