# DIRECT PHOTON PRODUCTION IN WA70

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Abstract:

Direct photon cross sections with high integrated luminosity in $\pi^- p$ (3.5 $pb^{-1}$), $\pi^+ p$ (1.3 $pb^{-1}$) and $pp$ (5.2 $pb^{-1}$) collisions have been measured by the WA70 collaboration in the transverse momentum range $4.0 < p_T < 7.0$ GeV/c and Feynman x range $-0.45 < x_F < 0.55$ with 280 GeV/c beams at the CERN SPS. A consistent approach, at next-to-leading order for the prompt photon diagrams and the parton densities, allows a determination of the proton and pion gluon structure function and of the QCD scale parameter $\Lambda_{\overline{MS}}$.

Essentially two QCD subprocesses, at leading order, contribute to prompt photon production: the Compton graph $qg \to \gamma q$, dominant in pp and $\pi^+p$ collisions and the annihilation graph $q\bar{q} \to \gamma g$, important in $\pi^-p$ and $\bar{p}p$ collisions at large $x_T(=2p_T/\sqrt{s})$. Using new precise deep inelastic scattering (DIS) data, a beyond leading log fit, including the parton structure functions (SF), to $pp \to \gamma X$ determines the proton gluon structure function. A similar fit to $\pi^\pm p \to \gamma X$ allows a precise determination of the pion SF and of the QCD scale parameter $\Lambda_{\overline{MS}}$.

## 1. Optimized perturbative QCD theory

Full next-to-leading order calculations of the direct photon cross sections have recently become available [1]. The cross section at $O(\alpha_s{}^2)$ can be written as [2]

$$\sigma^{(2)} = Ed^3\sigma/dp^3 = F(M) \otimes F(M)\alpha_s(\mu)[\sigma_{BORN} + \alpha_s(\mu)/\pi \; R(\mu,M,..)]$$

where M is the factorization scale (SF evolution) and $\mu$ the renormalization scale.

To resolve scale ambiguities, the Principle of Minimum Sensitivity (PMS [3]) $d\sigma^{(2)}/d\ln M = d\sigma^{(2)}/d\ln\mu = 0$ is applied. It leads to a saddle point at the "optimized scales" $\mu^{opt}(s,y,p_T)$ and $M^{opt}(s,y,p_T)$ around which the cross section is stable.

Different SF conventions, different optimization methods such as the fastest apparent convergence method [4] (setting higher order to zero) and PMS with only one scale, yield cross sections within 10% of $\sigma^{(2)}(\mu^{opt},M^{opt})$. The small remaining theoretical uncertainties in this next-to-leading perturbative QCD calculation should allow experimentalists to test the theoretical assumptions.

## 2. WA70 experiment

Taking advantage of the Ω′ spectrometer to allow a study of the event structure, the WA70 experiment uses 280 GeV/c proton and pion beams on an hydrogen target. The large acceptance (4m×4m at 10m), fine grained (1 cm) electromagnetic calorimeter [7] consits of a sandwich of liquid-scintillator in teflon tubes and 4.2 mm lead-plates. Two showers are resolved down to a distance of 2.7 cm and the energy threshold is 250 MeV with 50% efficiency at 1 GeV [8]. Prompt photons are identified with a residual background from electromagnetic decay of mesons of about 10% (20%, 30%) at high $p_T$ in the $\pi^-$ (p, $\pi+$) sample.

The analysis is presented in detail in Ref. 5−6. Systematic errors are mainly due to uncertainties in the absolute energy scale (≈7%), inhomogeneity of the calorimeter (8% increasing to 16% at the edges of acceptance), background (4% to 14%) and efficiency (5% to 15%). Added in quadrature, the systematic errors amount to 15% in the range $4.5 < p_T < 5.5$ GeV/c. The maximum overall normalization uncertainty (adding linearly all the errors in the above range) is about 30%.

The cross sections are shown as a function of $p_T$ for pp (Fig. 1), $\pi^-p$ (Fig. 2) and $\pi^+p$ (Fig. 3). In the optimized perturbation theory (PMS) framework, the cross sections are compatible [8] with Duke-Owens [9, 10] SF set 1 ($\Lambda = 200$ MeV, soft gluon) and exclude set 2 ($\Lambda = 400$ MeV, harder gluon).

### 3. Probing the gluon beyond leading order with real $\gamma$ [11]

Implementing beyond leading log evolution [12] for the SF, we fit the preliminary DIS $\mu$p data ($F^2_p$ and $F^2_p/F^2_n$) from the BCDMS collaboration [13]. With a simple form for the gluon distribution, $xG(x) = A_g(1-x)^\eta$ at $Q_0^2 = 2$ (GeV/c)$^2$, the best fit gives $\eta = 7.92 \pm 1.57$ and $\Lambda_{\overline{MS}} = 188 \pm 20$ MeV (statistical errors only). Such a gluon distribution produce too small a cross section for $pp \to \gamma X$ as shown in the table below giving results of fits to direct photon data of WA70 as well as NA24 [15] and R806 [16]. Including only statistical errors, the $\chi^2$ and the ratio R (=data/predictions) are given below for various ranges of $x_T$ ($\approx$x). The fit gets worse with increasing $x_T$, where DIS data do not constrain the gluon SF [14].

| | $\chi^2$/points | $x_T$ | R |
|---|---|---|---|
| WA70 [6] | 390.5/7 | 0.38→0.61 | 3.→15. |
| NA24 [15] | 39.4/5 | 0.27→0.59 | 2.→16. |
| R806 [16] | 411.4/10 | 0.18→0.365 | 1.6 |

#### *3.1 The gluon structure function from a fit to pp→γX (WA70)*

Sets of SF and corresponding $\Lambda$ in the SF evolution, derived from fits to BCDMS data for a range of $\eta$ values, are used to fit the WA70 cross section with two free parameters, $\eta$ and $\Lambda(\alpha_s)$. The best estimate are $\eta = 3.82 \pm 0.32$ and $\Lambda = 200 \pm 55$ MeV ($\chi^2 = 7.67$, statistical errors only) with a strong correlation (0.948). The systematic errors in $\eta$ and $\Lambda$ are evaluated in several different ways: 1) with systematic errors added in quadrature to the statistical errors, 2) comparing fits to different data taking periods, 3) shifting the overall normalization by $\pm 30\%$. These evaluations lead to:

$$\eta = 3.82 \pm 0.32 \pm 0.62 \quad \text{and} \quad \Lambda(\alpha_s) = 200 \pm 55 \pm 142 \text{ MeV},$$

where the errors are statistical and systematic respectively. The sensitivity to $\Lambda$ in the SF evolution is small: a variation of $\Lambda$ by $\pm 80$ MeV (the errors quoted in the BCDMS scaling violation analysis [18]), affects the mean gluon density ($\Lambda = 223$ MeV) within the statistical errors.

Doing the same procedure using EMC hydrogen data rather than BCDMS yield a nearly identical gluon density [2] while fits to EMC alone give $4.5 < \eta < 10$ (with $40 < \Lambda < 150$, statistical errors only).

The gluon SF and $\Lambda(\alpha_s)$ derived above fits well NA24 data giving a $\chi^2$ of 5.64 (statistical errors only), but badly the R806 data. If one now tries to get the gluon SF using R806 data, the best estimates are $\eta = 7.07 \pm 0.3$ and $\Lambda = 374.8 \pm 9.5$ MeV. With total errors, the results are $\eta = 8.27 \pm 1.6$ and $\Lambda = 480. \pm 160.$ MeV. Error ellipses are shown on Fig. 4 for R806, WA70 and BCDMS. With the simple gluon shape, WA70 agrees with the precise $\Lambda$ determination from BCDMS, but implies a harder gluon density. Although R806 agrees with a gluon as soft as BCDMS, it favors a higher value of $\Lambda$. As the probed x ranges are different, we are currently testing gluon shapes like $xG(x) = A_g(1-x)^{\eta(x)}$. With $\eta(x) = 2.75 - 4.5 \times \ln\{\ln[(1/(1-x)]\}$

and $\eta(x>0.5)=\eta(0.5)$, a compromise between WA70 and R806 ($x_T<0.33$) may be found while it seems more difficult to accommodate BCDMS.

*3.2 Gluon density in the proton*

The WA70 determination of the gluon SF is compared on Fig. 5 to the CHARM parametrization [17] at $\Lambda=310$ MeV and to the BCDMS best fit, all at $Q^2=10\ (\mathrm{GeV/c})^2$. The determination from prompt $\gamma$ data (WA70 for $x>0.38$, NA24 for $x>0.27$) exclude a gluon as soft as favoured by the indirect [14] DIS methods (CHARM for $x<0.35$ or BCDMS for $x<0.25$). However, the CHARM result [19], with $\Lambda$ uncertainties included, overlaps the WA70 determination within statistical errors. Systematics errors are not yet taken into account for BCDMS.

**4. Beyond leading order fit to $\pi^{\pm}p\rightarrow\gamma X$ (WA70)**

We perform a joint fit to the $\pi^-p\rightarrow\gamma X$ and $\pi^+p\rightarrow\gamma X$ cross sections (Fig. 2 and 3, $p_T>4.25$ GeV/c, 12 points). The proton SF are derived from fits to BCDMS and WA70. The pion valence SF has the form $xV_\pi(x)\sim x^\alpha(1-x)^\beta$. The NA10 collaboration have fitted their di-muon data at $Q^2_0=25(\mathrm{GeV/c})^2$ and parametrized the $Q^2$ dependence [20]. We use their parametrization extrapolated to $Q^2=2(\mathrm{GeV/c})^2$ as our starting values. This gives: $\alpha=0.45\pm0.03$ and $\beta=0.70\pm0.04$ corresponding to $<x_V>=\int xV_\pi(x)dx=0.42$. For the $\pi$ gluon density, we assume a simple form $xG_\pi(x)\sim(1-x)^{\eta_\pi}$.

*4.1 Determination of $\Lambda(\alpha_S)$ and $\eta_\pi$*

The best fit, with statistical errors only ($\chi^2=9.45$), gives $\Lambda(\alpha_S)=225.4\pm17.9$ MeV and $\eta_\pi=2.08\pm0.27$ with a strong correlation (0.886). The effect of the proton gluon SF is small: a variation of $\pm0.3$ in $\eta(p)$ changes $\Lambda$ by $\pm1.2$MeV and $\eta_\pi$ by $\pm0.1$. A change of $\Lambda$ in the SF evolution by $\pm50$MeV increases the $\chi^2$ by at most one unit. Systematic errors are evaluated following the same procedure as for the proton fits. In particular, fits to different data taking periods (including 1986 preliminary $\pi^-$ data, 7.7 $\mathrm{pb}^{-1}$) yield mean values for $\Lambda$ within $\pm50$ MeV and mean values for $\eta_\pi$ within $\pm0.45$. These evaluations lead to:

$$\Lambda=225\pm18\pm60\ \mathrm{MeV}\ \text{and}\ \eta_\pi=2.08\pm0.27\pm0.70,$$

where the errors are statistical and systematic respectively.

The results of this fit are in good agreement with NA24. The $\pi$ gluon density is softer than that found by Owens using a leading log fit [10] based on $J/\Psi$ production [21].

*4.2 Pion valence structure function*

Fits with $\beta$ and $<x_V>$ free yield compatible results ($\Lambda$ within 5 MeV, $\eta_\pi$ within 0.04) to the previous fit while $<x_V>$ changes by 0.002 and $\beta$ by $-0.1$ compared to the NA10 input values. The best WA70 fit, evolved to $Q^2=25(\mathrm{GeV/c})^2$, is in good agreement with the NA10 fit. This provides an independent determination of the $\pi$ valence SF from prompt $\gamma$ production which, although less accurate, is in good agreement with NA10 Drell-Yan fits [20].

## 5. Summary

Inclusive cross sections for direct photon production have been measured by the WA70 collaboration in $\pi^{\pm}p$ and pp collisions with high statistics in the range $0.3 < x_T < 0.6$ with 280 GeV/c beams.

A consistent next-to-leading order perturbative QCD calculation of prompt photon cross sections, using BCDMS DIS recent hydrogen data, leads to this preliminary set of parameters at $Q_0^2 = 2(\mathrm{GeV/c})^2$ for $0.3 < x_T < 0.6$:

- $\Lambda(\alpha_S) = 225 \pm 18 \pm 60$ MeV, statistically compatible with the precise BCDMS determination from scaling violations analysis [18].
- Proton gluon structure function: $xG(x) \approx 2.1 \times (1-x)^4$, harder than DIS parametrizations [17, 18] but statistically compatible to DFLM belt [19].
- $\pi$ gluon structure function: $xG(x) \approx 1.5 \times (1-x)^2$, softer than Owens leading log fit [10] based on J/$\Psi$ production [21].
- $\pi$ valence structure function: $< x_V > = 0.42$ and $\beta = 0.6$, in agreement with di-muon fits [20, 10].

It is a pleasure to acknowledge the fruitfull collaboration with P.Aurenche, M.Fontannaz and R.Baier, the warm hospitality of LAPP, the enthusiastic support of WA70 colleagues and more particularly M.N.Kienzle-Focacci and finally a careful reading of the manuscript from C.Dukes.

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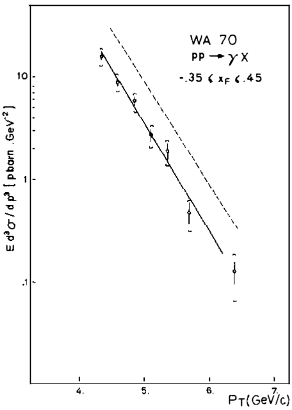


FIG. 1

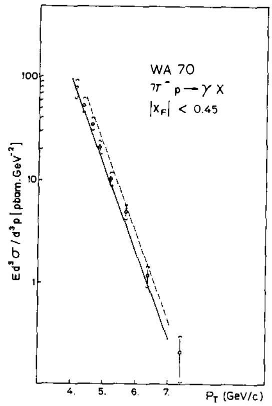


FIG.2

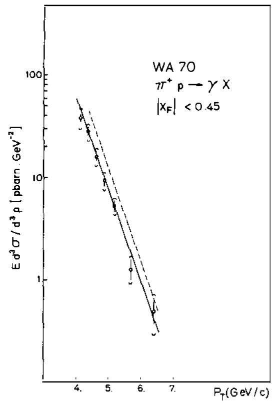


FIG.3

Cross section for 1. pp→γX, 2. $\pi^-$p→γX and 3. $\pi^+$p→γX. Statistical error bars are drawn and total errors combining systematic in quadrature are shown. Lines are optimized next-to-leading QCD predictions [1] with Duke-Owens structure function set 1 (full) and set 2 (dashed).

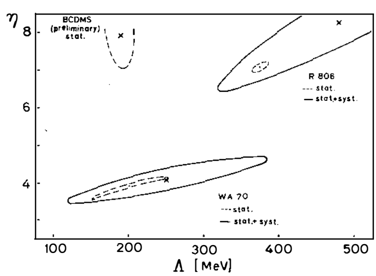


FIG. 4

Error ellipses η/Λ (1 standard deviation) for WA70, R806 and BCDMS.

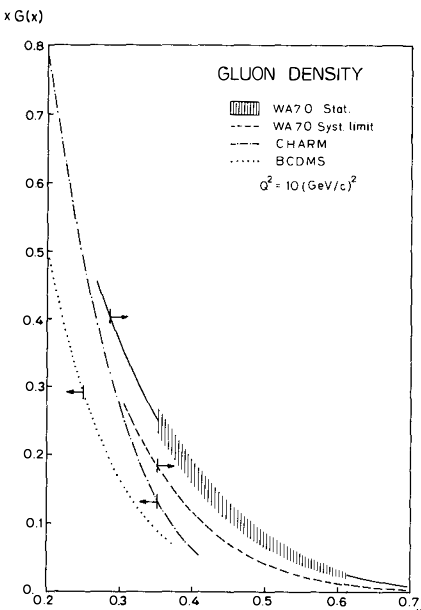


FIG. 5

Fig.5. Gluon density in the proton determined from WA70 and compatible to NA24 direct photon cross sections compared at $Q^2 = 10$ (GeV/c)$^2$ to DIS parametrizations. Limits of the x ranges probed are shown with bars.