Groupe d'Annecy

Laboratoire
d'Annecy-le-Vieux de
Physique des Particules

ENSLAPP

Groupe de Lyon

Ecole Normale
Supérieure de Lyon

DO WE UNDERSTAND THE HADROPRODUCTION OF PROMPT PHOTONS ?

COMPRENONS NOUS LA PRODUCTION DE PHOTONS DIRECTS DANS LES COLLISIONS HADRONIQUES ?

E. Pilon
LPTHE[1] , Université Paris XI, F-91405 Orsay cedex
and
ENSLAPP[2], B.P. 110, F-74941 Annecy-le-Vieux cedex

Abstract

We review the present theoretical problems which spoil the quantitative understanding of the production of high $p_\perp$ prompt photons in hadronic collisions.

Résumé

Nous passons en revue les divers problèmes théoriques qui pénalisent actuellement la compréhension quantitative de la production de photons directs à grande impulsion transverse dans les collisions hadroniques.

LPTHE-ORSAY 96/47
ENSLAPP-A-596/96
June 96

Invited talk given at the *XXXI Rencontres de Moriond on QCD and High Energy Hadronic Interactions*, Les Arcs, France - March 23-30, 1996

[1] URA 0063 du CNRS associée à l'Université Paris XI
[2] URA 1436 du CNRS associée à l'ENS de Lyon et à l'Université de Savoie

1 Introduction

Schematically, a high $p_\perp$ photon is said to be prompt (or direct) if it is produced in a short distance subprocess, i.e. before the hadronization stage of the outgoing partons, contrarily to "secondary photons" which come from decays of hadrons, mainly π^0, and η. The production of high $p_\perp$ prompt photons in hadronic collisions has been motivating much activity, both experimentally [1]-[2] and theoretically [4]-[8] since

it allows us to test our understanding of QCD at work in a way complementary to jet physics;

it provides us with an *a priori* privileged mean of determining the gluon densities in the colliding hadrons, e.g. in the proton, since this process is sensitive to these quantities already at the leading order;

pairs of photons produced at large invariant mass will be the so-called irreducible background to the search of neutral Higgs bosons in the mass range 90 $GeV \leq M_h \leq$ 150 GeV at LHC through their $h \to \gamma\gamma$ decays. This background is huge, so an accurate understanding is required in order to disantangle a possible signal from background fluctuations.

2 Standard theoretical framework

Our theoretical understanding of high $p_\perp$ prompt photon hadroproduction relies on the calculation of the cross section at Next to Leading Logarithmic (NLL) accuracy in the framework of the QCD improved parton model, schematically

$$\begin{aligned} p_\perp^4 \frac{d\sigma^{AB\to\gamma X}}{d^2p_\perp dy} &= G_{a/A}(x_a, M^2) \otimes G_{b/B}(x_b, M^2) \otimes \hat{\sigma}^{ab\to\gamma x} \\ &+ G_{a/A}(x_a, M^2) \otimes G_{b/B}(x_b, M^2) \otimes D_{\gamma/c}(z_c, M_f^2) \otimes \hat{\sigma}^{ab\to cx} \quad (1) \\ \text{where} \quad \hat{\sigma}^{ab\to\gamma x} &= \alpha_s(\mu^2)\alpha_{em} \left[\hat{\sigma}_{Born}^{ab\to\gamma x} + \alpha_s(\mu^2) \hat{\kappa}_{NLO}^{ab\to\gamma x} \left(x_a, x_b, \frac{p_\perp^2}{\mu^2}, \frac{p_\perp^2}{M^2} \right) \right] \\ \hat{\sigma}^{ab\to cx} &= \alpha_s^2(\mu^2) \left[\hat{\sigma}_{Born}^{ab\to cx} + \alpha_s(\mu^2) \hat{\kappa}_{NLO}^{ab\to cx} \left(x_a, x_b, z_c, \frac{p_\perp^2}{\mu^2}, \frac{p_\perp^2}{M^2}, \frac{p_\perp^2}{M_f^2} \right) \right] \quad (2) \end{aligned}$$

The parameters μ^2 and M^2 are respectively the arbitrary renormalization scale, and the arbitrary scale introduced to factorize the initial state collinear singularities, which appear in the perturbative calculation of the QCD corrections to the Born subprocess due to collinear branchings of the incoming massless partons, and absorb them into the (bare) parton densities of the incoming hadrons according to the factorization property. The induced M^2 dependence of the densities $G_{a/A}(x_a, M^2)$ is governed by the Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) equations. Among what is thought to be next to leading order QCD corrections to the Born contribution, there appears actually the leading order term of a new type of production mechanism by which, instead of being produced directly in the hard subprocess, the photon is emitted almost collinearly by a parton itself produced at large $p_\perp$. The proper account for this fragmentation mechanism relies also on the factorization of the final state mass singularities accompaying the collinear emission of the photon, and implies the introduction of inclusive fragmentation functions of partons into a photon $D_{\gamma/c}(z_c, M_f^2)$ obeying inhomogeneous DGLAP equations. The factors $\hat{\sigma}^{ab\to\gamma x}$ and $\hat{\sigma}^{ab\to cx}$ which remain are "cross sections" for short distance subprocesses of two massless on-shell partons collinear to the incoming hadrons.

Were the calculation performed to all orders in α_s, the obserbable cross section $p_\perp^4 d\sigma/d^2p_\perp dy$ would not depend on the unphysical parameters μ^2, M^2 and M_f^2. The truncation of the expansion at any finite order is responsible for such a remnant, unavoidable dependence. The higher the order of the expansion is, the flater is the remnant dependence, so that a NLL calculation is necessary. Renormalization group arguments suggest that these scales have to be chosen *of the order of* the hard scale of the process, here the $p_\perp$ of the emitted photon, so that the perturbative expansion of the hard partonic cross section in powers of α_s be not plagued by large logarithms of $p_\perp^2/\mu^2$, $p_\perp^2/M^2$ or $p_\perp^2/M_f^2$. However the statement "*of the order of*" is not quantitative and does not remove the scale ambiguities, which, as it is the case for any other process, can affect both normalization and slope of the computed cross section quite sensitively.

3 The fragmentation contribution at fixed targets

A crude estimate of the magnitude of the fragmentation contribution using the Leading Log (LL) set of fragmentation functions of [3] gives a small contribution to the cross section in the range covered by fixed targets experiments [1], suggesting that a LL approximation for it would be enough there. Yet notice that this LL statement is strongly scale dependent. The computer codes of [4] (which relies on an analytic calculation) and of [5] (in which phase space integrations are done by Monte Carlo) are working at this accuracy. However fragmentation functions also contain non-perturbative components not incorporated in [3]. At fixed target energies, the average value $< z_c >$ of the fragmentation variable is close to 1, so that these non perturbative parts are not important, but they become so at collider energies, where $< z_c >$ is smalller and the fragmentation contribution dominates. These non-perturbative (unpredictable yet) components spoil the predictive power of the theory, unless they are measured elsewhere (e.g. at LEP), or modelized as best as one can. An improved version [7] of [4], and [8] (which rely on an analytic calculation) are NLL for both direct and fragmentation parts, although they use NLL fragmentation functions whose non perturbative components are questionable. The determination of a set of more realistic NLL fragmentation functions is in progress [9].

4 The mismatch fragmentation/isolation at colliders

Actually, eqs.(1) and (2) are suited to the *inclusive* prompt photon cross section measured at fixed target experiments. Collider experiments [2] cannot measure the inclusive prompt photon production: they have to require experimentally that the measured photon be *isolated* in order to reject the background of secondary photons. A photon is said to be isolated if it is accompanied by less than a specified amount of hadronic energy in a cone about the direction of the photon momentum. This request for isolation supresses also a part of the prompt photon signal itself, and especially it drastically reduces the fragmentation contribution which dominates the inclusive production. Isolation, especially its effects on the fragmentation contribution, has thus to be taken carefully into account in the theoretical calculation, but this is rather tricky.
The authors of [6] proposed to define a fragmentation function of a parton into an isolated photon as the inclusive fragmentation function of this parton minus a "fragmentation function into an photon accompanied by a jet energetic enough". The latter was claimed to be simply given by the same inclusive fragmentation function where the scale M_f would be fixed to $\sim \delta p_\perp$, δ being the opening angle of the isolation cone. This prescription was used in [8] who claimed to provide a complete NLL calculation for both direct and fragmentation parts.
However the ansatz of [6] is erroneous. The isolation constraint, which restricts the phase

space available for real gluon emission, makes the cross section infrared sensitive, and causes the appearence of large logarithms of infrared (IR) nature. This was ignored in the ansatz proposed in [6], and has been recognized recently in [10] in the context of prompt photon production in hadronic e^+e^- annihilation. These IR logarithms need to be resummed if possible in order to restore a factorized form for the cross section and to properly identify semi inclusive fragmentation functions of partons into an isolated photon. As a simpler example [11], if, instead of using a criterion in terms of cone and energy, one considers that a parton is said to accompany the photon if its relative transverse momentum with respect to the photon is $k^2_{\perp\, rel} \leq p^2_{max}$, the LL analysis which leads to the DDT formula [12] shows that the IR logarithms exponentiate in a form factor of Sudakov type, $S(p^2_{\perp\,\gamma}, p^2_{max})$, resulting from the mismatch between the deepest rung of the ladder and the hard subprocess, so that in this case the corresponding erroneous ansatz of [6] for the accompanied fragmentation:

$$D_\gamma^{accompanied} = D_\gamma^{inclusive}(z, p^2_{max}) \tag{3}$$

has to be corrected into

$$D_\gamma^{accompanied} = D_\gamma^{inclusive}(z, p^2_{max}) \exp\left[-S\left(p^2_{\perp\,\gamma}, p^2_{max}\right)\right] \tag{4}$$

which does have a factorized form, typical of IR sensitive quantities. Concerning the criterion in terms of cone and energy experimentally used, a correct treatment of the effect of isolation constraint on the fragmentation part is still lacking at present, even at the LL level.

5 The issue of extra $k_\perp$ - effect

The comparison by [13] between data and theory using the ratio "(data - theory)/theory" as a function of the photon's $x_\perp = 2p_\perp/\sqrt{S}$ seems to indicate a quantitative discrepancy between data and theory in the form of a systematic slope in the data for all experiments. The conclusion drawn by [13] is that the NLL QCD improved partonic framework which treats the incoming partons in the collinear approximation, misses an important effect kicking the photon's $p_\perp$ upwards.

Motivated by this conclusion, an empirical smearing of the standard prediction with an *ad hoc* gaussian distribution $\propto \exp\left(-k^2_\perp/\sigma^2\right)$ is sometimes used to kick it up towards experimental data. This could be naively thought as an effective intrinsic $k_\perp$ distribution of partons inside the incoming hadrons. However this empirical procedure raises more problems than it cures. Firstly the fitted width of the *ad hoc* gaussian happens to increase with the hadronic c.m.s. energy of the collision, from $\sigma \sim 1GeV$ for WA70 to $\sigma \sim 3-4GeV$ for the Tevatron experiments, so one should wonder why. Moreover, if this gaussian is really considered as a $k_\perp$ distribution of partons inside the incoming hadrons, this is not only ad hoc but seems inconsistent with the standard partonic framework which relies on the treatment of the incoming hadron as a flux of on-shell collinear partons. Considering unintegrated $\vec{k}_\perp$-parton distributions consistently would require a more involved "$k_\perp$ factorization" procedure such as the one suited for "small x physics" [14] and it would imply considering off-shell incoming partons - although the values of $x_\perp$ reached so far at colliders suggest that the incoming momentum fractions $x_a \gtrsim O(x_\perp)$ are not yet in what is considered as the so-called small x range, so that this sophisticated factorization algorithm is usually not thought to be required. This is even more true for fixed target experiments.

A source of $k_\perp$ effect which may be not accounted accurately in NLL calculations is a consequence of multi-parton radiation on the kinematics of the hard process : this showering transfers

some $k_\perp$ to the hard partons so that the hard subprocess is somehow boosted transversally. This effect is expanded in series of α_s in standard calculations, whose NLL truncations keep only its first order term in the term $\hat{\kappa}_{NLO}$ of eq.(2). However a misleading argument has been argued in favour of the need for going beyond the standard NLL treatment for single photon production, relying on the transverse momuntum spectrum of high mass photon pairs [15]. For this observable the NLL calculation gives a distribution qualitatively badly behaved at small $p_\perp$ and too narrow at larger $p_\perp$. This is indeed understood as a soft gluon multiradiation effect, unaccurately treated in the NLL calculation, and which is expected because of the semi inclusive, infrared sensitive character of this observable. For a photon pair produced at small $p_\perp$, the phase space available for real gluon emission in the initial state is squeezed so that the effect of soft gluon emision is enhanced [16] - as it is for the $p_\perp$ spectrum of large mass lepton pairs or weak bosons in the Drell-Yan process, and for the $p_\perp$ spectrum of *a pair photon-jet* at large invariant mass. On the other hand, the *single photon* $p_\perp$ spectrum is not so: the phase space available for gluon emission is not the same - it is not squeezed that way since the momentum of the away side jet is integrated out, so that soft multigluon effects are not so enhanced.
A more suggestive indication may be given by the exploratory work by [17] in which the $k_\perp$ effect of multiparton emission is qualitatively accounted by matching initial state parton showers on the hard partonic subprocess, calculated at next to leading order, in a Monte Carlo. However the quantitative nature of this matching is somewhat hybrid: the parton showers, working at a LL accuracy but resumming leading kinematical effects to all orders, are switched on parton densities determined in the standard NLL framework; different unphysical parameters introduced to slice the phase space or control several technical aspects such as starting and end scales for the showering, a minimal hardness to be imposed by hand on the subprocess, ... have to be tunned and can increase the importance of multiparton emission artificially. A quantitative procedure would be to identify the terms responsible for this $k_\perp$ effect in the NLL calculation and resum them "analytically" to all orders in α_s. This has not been done yet.
A poor man's way of implementing such a resummation consists in "playing with the arbitrary scales" and looking for an optimum of stability of the NLL calculation with respect to changes in these parameters [18] [4]. The need for going beyond NLL appears through instabilities about the "orthodox" scale choice $\mu^2 \sim M^2 \sim p_\perp^2$ which drive the "optimal" scales away from these values. Although it may be considered as "heterodox", the use of such optimized scales happens to effectively resum contributions Beyond Leading Logarithms - actually this has been seen [19] in the case of the mass distribution in the Drell Yann process near the elastic phase space boundary, while here we mainly worry about the "lower x-range" of the photon $p_\perp$ spectrum. This freedom has been taken recently in [8] which shows a much reduced discrepancy between data and NLL calculations than magnified in [13].

6 Conclusion

The theoretical understanding of prompt photon production has made continuing progress, relying on calculations at Next to Leading Logarithmic accuracy. However several issues still limit the quantitativeness of this undertanding. The proper account for isolation, especially on the fragmentation contribution, which happens to be infrared sensitive, has not been correctly implemented yet in theoretical calculations. This spoils our understanting of isolated photon production at colliders, and has to be tackled carefully. The systematic discrepancy between data and NLL calculations exhibited for orthodox choices of scales suggests the need for going beyond NLL to account for the $k_\perp$ kick due to multiparton radiation, an effect which is (only) qualitatively accounted by matching a Monte Carlo parton shower on a Next to Leading Order calculation. The discrepancy can be partialy reduced using optimized scales which can be seen as an effective way to resum some kinematical effects. A better approach would consist in identifying and explicitly resumming of the leading terms responsible for the $k_\perp$ kick. These theoretical concerns have to be addressed before we can claim to fully understand the production of prompt photons in hadronic collisions.

References

[1] WA70 Collab., *Z. Phys.* **C 38** (1988) 371; **C 38** (1989) 591
M.Werlen, UA6 Collab., *EPS Conference* 1993, ed. J. Carr and M.Perrottet.
T.Ferbel, E706 Collab., this conference.

[2] UA2' Collaboration, *Phys. Lett.* **263 B** (1991) 544; see also M.Bourliaud, PhD Thesis, Universite de la Méditerrannée 1995
S.Kuhlmann and A.Maghakian, CDF collab., this conference.
D.Buchholz, D0 Collab., this conference.

[3] J.Owens, *Rev. Mod. Phys.* **59** (1987) 465

[4] P.Aurenche et al, *Nucl. Phys.* **B 286** (1987) 533; *Phys. Rev.* **D 42** (1991) 1440

[5] H.Baer et al, *Phys. Rev.* **D 42** (1990) 61

[6] E.L. Berger and J. Qiu, *Phys. Rev.* **D 44** (1991) 2002

[7] P. Aurenche et al, *Nucl. Phys* **B 399** (1993) 34

[8] M. Gluck et al, *Phys. Rev. Lett.* **73** (1994) 388 ; A. Vogt and W. Vogelsang, *Nucl. Phys* **B 453** (1995) 334

[9] L. Bourhis, this conference.

[10] E.L. Berger et al, *Phys. Rev. Let.* **76** (1996) 2234

[11] P.Aurenche et al, preprint hep-ph/9606287; M.Fontannaz, *les Rencontres du Val d'Aoste*, La Thuile, March 1996, ed. M.Greco

[12] Y.Dokshitzer, D.I.Dyakonov and S.I.Troyan, *Phys. Rep.* **58** (1980) 265
G.Parisi and R.Petronzio, *Nucl. Phys.* **B 154** (1979) 427

[13] J. Huston et al, *Phys. Rev.* **D 51** (1995) 6159

[14] S. Catani et al, *Nucl. Phys.***B 366** (1990) 135

[15] J.Owens, *Workshop DIS 95*, Paris, 24-28 April 1995, ed. J.F.Laporte and Y.Sirois.

[16] P. Chiappetta et al, *Phys. Lett.* **236 B** (1995) 646

[17] H. Baer and M.H. Reno, preprint FSU-HEP-951229 / UIOWA-95-07

[18] P.M.Stevenson and H.D.Politzer , *Nucl. Phys.* **B 277** (1986) 758
P.Aurenche et al, *Nucl. Phys.* **B 286** (1987) 509

[19] P.Aurenche et al, *Z. Phys* **C 48** (1990) 143