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WINO AND ZINO PRODUCTION IN $p\bar{p}$ COLLISIONS:
FIRST ORDER SUPERSYMMETRIC QCD CORRECTIONS

P. Chiappetta

CERN - Geneva

Y. Gabellini

Laboratoire de Physique Théorique ^{*)}
Nice, France

and

F.M. Renard ⁺⁾

Laboratoire de Physique Mathématique ^{&)}
Montpellier, France

ABSTRACT

We compute the first order supersymmetric QCD corrections to wino ($\tilde{W}$) and zino ($\tilde{Z}$) production in $p\bar{p}$ collisions via subprocesses involving two massless partons inside the nucleon or one massless parton and a massive SUSY parton (squark or gluino). The first order SQCD corrections to the rapidity dependence at CERN collider and Tevatron energies are found large ($K \sim 2$). The rates are important ($\sim 10^{-2}$ nb at $\sqrt{s} = 630$ GeV and $\sim 10^{-1}$ nb at $\sqrt{s} = 2$ TeV), as soon as the $\tilde{W}$ and $\tilde{Z}$ production by squarks is allowed. Transverse momentum distributions are also given and their shape is found very sensitive to the presence of SUSY partons inside the nucleon.

^{*)} Unité associée au CNRS.

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^{&)} Unité associée au CNRS No.040768.

1. - INTRODUCTION

In our present knowledge, supersymmetry is one of the most elegant approaches to unify the fundamental particles and their interactions¹⁾. More recently, attempts²⁾ to link the superstrings with physics at low energy from the Calabi-Yau compactification mechanism favour an effective $N = 1$ supergravity model.

The fact that, up to now, no SUSY particles have been found, although disappointing, is not that catastrophic since all experimental limits on SUSY partner masses are far below the TeV scale which is the energy scale needed to solve the hierarchy problem³⁾. By looking at monojet events at the CERN $p\bar{p}$ collider, the squark and gluino masses have been pushed⁴⁾ up to 70 GeV and from the absence of a new sequential lepton, the wino mass to 41 GeV⁵⁾. This implies that in $N = 1$ SUSY, the photino is massive ($m_{\tilde{\gamma}} > 10$ GeV). The most stringent limit on selectron masses⁶⁾ comes from the reaction $e^+e^- \rightarrow \tilde{\gamma}\tilde{\gamma}$ at PEP giving $m_{\tilde{e}} > 50$ GeV.

It has been pointed out several years ago that the existence of SUSY partners for quarks and gluons would change the QCD picture of the hadrons at short distances⁷⁾. This affects squarks production⁸⁾ and one jet cross-sections⁹⁾. Search for $\tilde{W}$ and $\tilde{Z}$ from massless partons has been extensively studied¹⁰⁾ and production of gauginos from the $q\bar{q}$ subprocess is possible. A first estimate¹¹⁾ at the Born level seemed very promising, since as soon as squarks are present inside the nucleon, the production rates are greater than those obtained from $q\bar{q}$ and qg subprocesses. Their detection by the Jacobian peak method through their decay modes offers a very clean signature. Since the production via a $q\bar{q}$ subprocess is similar to W and Z production in which first order corrections are large^{12),13)} (about 40%), we expect the SQCD corrections to give a similar enhancement for gaugino production. They will also sensibly modify the wino and zino rapidity and transverse momentum distributions. These effects will then be important in order to extract from experiment either a signal or a bound on the possible existence of these particles. The purpose of this paper is the evaluation of these first order SQCD corrections to the processes $p\bar{p} \rightarrow \tilde{W}^+ + X$ and $p\bar{p} \rightarrow \tilde{Z}_0 + X$.

In Section 2 we give the analytical expressions for the various subprocesses ($q\bar{q} \rightarrow \tilde{W}$, $q\bar{q} \rightarrow \tilde{W}+g$, $g\bar{q} \rightarrow \tilde{W}+q$, $q\bar{g} \rightarrow \tilde{W}+q$, $q\bar{q} \rightarrow \tilde{W}g$, $qg \rightarrow \tilde{W}q$). In Section 3 we establish the physical cross-sections for the wino and zino production, $d\sigma/dy$ where y is the gaugino rapidity and $d\sigma/dp_{\perp}dy$ where $p_{\perp}$ is the transverse momentum of the gaugino. We give our set of structure functions in Section 4 and display the numerical results. Actually, we find that when gaugino production from SUSY

partons is allowed, the $q\tilde{q}$ subprocess is the dominant one and first order SUSY QCD corrections are large, giving a K factor of the order of two. Production rates for a gaugino of 140 GeV are roughly 10^{-2}nb at $\sqrt{s} = 630\text{ GeV}$ and 10^{-1}nb at $\sqrt{s} = 2\text{ TeV}$ and therefore much more important than the magnitude 10^{-4}nb found for a gaugino of 80 GeV at 630 GeV and 10^{-2}nb at 2 TeV (for which only $q\bar{q}$ and qg subprocesses are allowed). The shape of the transverse momentum distribution is very different: for gaugino masses lower than squark and gluino ones, $d\sigma/dp_{\perp}dy$ is maximal for $p_{\perp} \sim m_{\tilde{q}}/2$ whereas for subprocesses involving a SUSY parton the cross-section decreases. We give our conclusions in Section 5.

2. - PARTONIC CROSS-SECTIONS

We will compute the first order SQCD corrections to the processes $p\bar{p} \rightarrow \tilde{W}^+X$ and $p\bar{p} \rightarrow \tilde{Z}_0 + X$. In this section we will concentrate on the $\tilde{W}^-$ production only, the application to the $\tilde{Z}_0$ case being straightforward.

We will use the same scheme as the authors of Ref. 11) who computed the Born term, namely the simplest supersymmetric extension of the standard model $SU(3)_C \times SU(2) \times U(1)$ with pure winos. For physical winos, one has to take into account the mixing with Higgsinos. We have mainly to deal with reactions of the type: $A(p_1) + B(p_2) \rightarrow C(p_3) + D(p_4)$. As usual, we define the Mandelstam variables: $\hat{s} = (p_1 + p_2)^2$, $\hat{t} = (p_1 - p_3)^2$, $\hat{u} = (p_1 - p_4)^2$. We will work with massless quarks and call λ the gluon mass with which we will keep trace of the infra-red and collinear singularities. We call M , m and $\tilde{m}$ the masses of the gaugino, squark and gluino respectively.

The partonic cross-section for the Born diagram $q\tilde{q} \rightarrow \tilde{W}$ (depicted in Fig. 1a) reads:

$$\frac{d\hat{\sigma}}{d\hat{t}} = \frac{2\pi^2\alpha}{3\sin^2\theta_w} S(\hat{s}-M^2) S(\hat{t}-m^2) \quad (1)$$

There are five partonic subprocesses contributing to the first order corrections to the gaugino production involving a real particle associated to the wino and four one-loop diagrams, the amplitudes of which have to be squared with the Born term amplitude. We have not taken into account one-loop corrections involving squarks and gluinos since they are not singular and because one can include them inside the global uncertainty in squark and gluino distribution functions. Let us give the five real reaction cross-sections $(d\sigma/d\hat{t})(\hat{s}, \hat{t}, \hat{u})$. The cross-sections for the five subprocesses ($q\tilde{q} \rightarrow \tilde{W}g$, $g\tilde{q} \rightarrow \tilde{W}q$, $q\tilde{g} \rightarrow \tilde{W}q$, $q\bar{q} \rightarrow \tilde{W}g$, $qg \rightarrow \tilde{W}q$) whose

graphs are depicted in Figs.1b-f read respectively:

$$\frac{d\hat{\sigma}^1}{d\hat{E}} = \frac{4\pi\alpha d_s}{9\sin^2\theta_w} \frac{1}{(\hat{s}-m^2)^2} \left[1 + \frac{2\hat{E}(m^2-M^2)}{(\hat{E}-m^2)^2} + \frac{\lambda^2}{\hat{U}^2} (m^2-M^2) + \frac{(\hat{E}-M^2)^2 + (M^2-m^2)^2}{\hat{U}(\hat{E}-m^2)} \right] \quad (2)$$

$$\frac{d\hat{\sigma}^2}{d\hat{E}} = \frac{\pi\alpha d_s}{6\sin^2\theta_w} \frac{1}{(\hat{s}-m^2)^2} \left[1 - \frac{\hat{s}+M^2}{\hat{s}-m^2} + \frac{(\hat{s}-M^2)(\hat{s}+m^2)}{(\hat{s}-m^2)^2} + \frac{1}{\hat{U}} \left(\hat{s}-m^2 + 2 \frac{(\hat{s}-M^2)(m^2-M^2)}{(\hat{s}-m^2)} \right) + \frac{\lambda^2(m^2-M^2)}{\hat{U}^2} \right] \quad (3)$$

$$\frac{d\hat{\sigma}^3}{d\hat{E}} = \frac{\pi\alpha d_s}{12\sin^2\theta_w} \frac{1}{(\hat{s}-m^2)^2} \left[\frac{(m^2-\hat{E})(M^2-\hat{E})}{(\hat{E}-m^2)^2} + \frac{(\hat{m}^2-\hat{s})(M^2-\hat{s})}{(\hat{s}-m^2)^2} - \frac{2\hat{m}M\hat{u}}{(\hat{E}-m^2)(\hat{s}-m^2)} \right] \quad (4)$$

$$\frac{d\hat{\sigma}^4}{d\hat{E}} = \frac{2\pi\alpha d_s}{9\sin^2\theta_w} \frac{1}{\hat{s}^2} \left[\frac{(M^2-\hat{U})(\hat{m}^2-\hat{U})}{(\hat{U}-\hat{m}^2)^2} + \frac{(M^2-\hat{E})(\hat{m}^2-\hat{E})}{(\hat{E}-\hat{m}^2)^2} - \frac{2\hat{m}M\hat{s}}{(\hat{E}-\hat{m}^2)(\hat{U}-\hat{m}^2)} \right] \quad (5)$$

$$\frac{d\hat{\sigma}^5}{d\hat{t}} = \frac{\pi \alpha_s}{12 \sin^2 \theta_w} \frac{1}{\hat{s}^2} \left[\frac{(\hat{t}-M^2)(\hat{t}+m^2)}{(\hat{t}-m^2)^2} + \frac{M^2 - \hat{u}}{\hat{s}} + \frac{2(\hat{t}-M^2)(m^2-M^2) - \hat{s}(\hat{t}+M^2)}{\hat{s}(\hat{t}-m^2)} \right] \quad (6)$$

These formulae apply separately to $\tilde{W}^-$, $\tilde{W}^+$ or $\tilde{Z}$ production using in each case the corresponding charge states for quarks and squarks. Cross-sections for subprocesses 1 and 2 are singular when $\lambda \rightarrow 0$. The first one contains both infra-red singularities (i.e., terms like $\ln^2 M^2/\lambda^2$) and mass singularities (i.e., terms like $\ln M^2/\lambda^2$). The second subprocess contains only mass singularities. The cross-section for subprocess 3 is regular provided $M > m$ and $m > \tilde{m}$. Cross-sections for subprocesses 4 and 5 are regular.

The four one-loop diagrams are depicted in Fig. 2. Their contribution is given by:

$$\frac{d\hat{\sigma}^V}{d\hat{t}} = \frac{d\hat{\sigma}^0}{d\hat{t}} 2 \operatorname{Re}(V) \quad (7)$$

with

$$V = (-V^g - V^{\tilde{g}} + \sum \sigma + \sum \tilde{\sigma}) \frac{d_s}{3\pi} \quad (8)$$

V^g , obtained from the vertex involving a gluon, reads:

$$V^g = -\frac{1}{2} - 3 \zeta(2) - 2 L_{12}\left(\frac{M^2}{M^2-m^2}\right) - \frac{1}{2} \log^2 \frac{m^2}{\lambda^2} - \log^2 \frac{\lambda^2}{M^2-m^2} + \log m^2 + 2 \log \frac{\lambda^2}{M^2-m^2} + 2 \log^2 \frac{\lambda^2}{M^2-m^2} \quad (9)$$

where $L_{12}(x)$ is the dilogarithm function. $V^{\tilde{g}}$, obtained from the vertex involving a gluino, reads:

$$\begin{aligned}
 V_{\tilde{g}} = & \frac{-2\hat{m}M}{M^2-m^2} \left\{ \log \frac{M^2}{m^2} + \frac{m^2}{M^2} \log \frac{m^2}{M^2} + \frac{M^2-m^2}{M^2} \log \frac{M^2-m^2}{M^2} \right. \\
 & - \frac{\hat{m}^2}{m^2} \log \frac{m^2}{m^2} - \frac{m^2-\hat{m}^2}{m^2} \log \frac{m^2-\hat{m}^2}{m^2} \\
 & - \frac{2m^2-\hat{m}^2-M^2}{M^2-m^2} \left[\log \frac{M^2}{m^2} \log \frac{m^2-\hat{m}^2}{2m^2-\hat{m}^2-M^2} + \log \frac{m^2}{M^2} \log \frac{M^2(m^2-\hat{m}^2)}{m^2-M^2\hat{m}^2} \right. \\
 & - \log \frac{m^2-M^2}{M^2} \log \frac{M^2(2m^2-\hat{m}^2-M^2)}{m^4-M^2\hat{m}^2} - \log \frac{\hat{m}^2}{m^2} \log \frac{m^2(m^2-\hat{m}^2)}{m^4-M^2\hat{m}^2} \\
 & + \log \frac{\hat{m}^2-m^2}{m^2} \log \frac{m^2(2m^2-\hat{m}^2-M^2)}{m^4-M^2\hat{m}^2} + \text{Li}_2 \left(\frac{m^2(m^2-M^2)}{m^4-M^2\hat{m}^2} \right) \\
 & \left. \left. - \text{Li}_2 \left(\frac{(M^2-m^2)^2}{m^4-M^2\hat{m}^2} \right) - \text{Li}_2 \left(\frac{\hat{m}^2(m^2-M^2)}{m^4-M^2\hat{m}^2} \right) + \text{Li}_2 \left(\frac{(m^2-\hat{m}^2)(M^2-m^2)}{m^4-M^2\hat{m}^2} \right) \right] \right\} \quad (10)
 \end{aligned}$$

The quark self-energy via the gluon reads:

$$\Sigma^g = \frac{1}{2} \left(\frac{1}{2} - \log \frac{\Delta^2}{\mu^2} \right) \quad (11)$$

where μ is the renormalization mass. The quark self-energy via the gluino reads:

$$\begin{aligned}
 \Sigma^{\tilde{g}} = & -\frac{1}{2} \left[\frac{\hat{m}^4}{(\hat{m}^2-m^2)^2} \log \frac{\hat{m}^2}{\mu^2} + \frac{m^2(m^2-2\hat{m}^2)}{(\hat{m}^2-m^2)^2} \log \frac{m^2}{\mu^2} \right. \\
 & \left. - \frac{3}{2} - \frac{m^2}{(\hat{m}^2-m^2)} \right] \quad (12)
 \end{aligned}$$

Infra-red singularities cancel when one adds these virtual corrections to the real emission diagrams and the mass singularities will be absorbed into the structure functions which become evolved. We have first to extract the singularities for the real emission diagrams. Therefore, we will now express the cross-section $d\hat{\sigma}/d\hat{t}$, like for Drell-Yan processes¹⁴⁾, in terms of the scaling variables $z_i = x_i/t_i$ where t_i are the fractional momenta defined by $p_i^0 = (\sqrt{s}/2)t_i$ and $x_i = (M/\sqrt{s})e^{\pm y}$.

Here, the situation is more complicated since we have to handle massive SUSY partners in the initial state. For a parton of four momentum p ($E, \vec{0}, p$) collinear to the hadron of four momentum P ($\epsilon, \vec{0}, P$), we define the t variable as the light-

like energy-momentum fraction:

$$t = \frac{E + |p|}{E + |p|} \quad (13)$$

In the hadronic centre-of-mass frame, if particle 1 corresponds to a massless parton and particle 2 to a massive SUSY one of mass m the four momenta of the partons read:

$$\begin{aligned} p_1 &= \left(t_1 \frac{\sqrt{s}}{2}, \vec{0}, t_1 \frac{\sqrt{s}}{2} \right) \\ p_2 &= \left(\frac{\sqrt{s}}{2} t_2 \left(1 + \frac{m^2}{s t_2^2} \right), \vec{0}, -\frac{\sqrt{s}}{2} t_2 \left(1 - \frac{m^2}{s t_2^2} \right) \right) \end{aligned} \quad (14)$$

One gets

$$\hat{s} = t_1 t_2 s + m^2 \quad (15)$$

It is convenient to introduce the variables:

$$T_1 = t_1 + \frac{m^2}{s t_2} \quad T_2 = t_2 \quad (16)$$

Equation (15) becomes:

$$\hat{s} = T_1 T_2 s \quad (17)$$

At the Born level one has:

$$\hat{s} = M^2 \quad (18)$$

Besides $x_i = (M/\sqrt{s})e^{\pm y}$, we also define

$$x_1 = X_1 \left(1 - \frac{m^2}{M^2} \right) \quad X_2 = x_2 \quad (19)$$

The scaling variables are:

$$Z_i = \frac{X_i}{T_i} \quad , \quad \beta_i = \frac{x_i}{t_i} \quad (20)$$

Using the same techniques as for Drell-Yan processes¹⁴⁾, we will express the

partonic cross-sections in terms of δ distributions after use of the inequality:

$$\frac{(1-z_1)(1-z_2)}{z_1 z_2} \gg \frac{m_4^2}{M^2} \quad (21)$$

The hadronic cross-section is obtained as a convolution of the partonic one with the structure functions. If $P_\perp$ and y are the transverse momenta and rapidity of the gaugino, the invariant cross-section is given by:

$$\frac{d\sigma}{dP_\perp dy} = \int_{\Delta} dt_1 dt_2 f_{P_1/P}(t_1) f_{P_2/\bar{P}}(t_2) \frac{S t_1 t_2}{\pi} \frac{d\hat{\sigma}}{d\hat{t}} \left(\hat{s} + \hat{t} + \hat{u} - \sum_{i=1}^4 m_i^2 \right) \quad (22)$$

where Δ is defined by Eq. (21).

In order to cancel the mass singularities, we have to compute the first order corrections to the quark and gluon structure functions. One gets:

$$\begin{aligned} q(z, Q^2) = & \delta(1-z) + \frac{\alpha_s C_F}{2\pi} \left\{ \left(\frac{1+z^2}{1-z} \right)_+ \log \frac{Q^2}{\lambda^2 z^2} - \frac{3}{2(1-z)_+} \right. \\ & \left. + (1+z^2) \left(\frac{\log(1-z)}{1-z} \right)_+ + 1 + 4z - \delta(1-z) \left(\frac{2\pi^2}{3} + \frac{9}{4} \right) \right\} \end{aligned} \quad (23)$$

and

$$g(z, Q^2) = \delta(1-z) + \frac{\alpha_s}{4\pi} \left\{ (z^2 + (1-z)^2) \log \frac{Q^2}{\lambda^2 z^2} - 6\delta(1-z) - 2 \right\} \quad (24)$$

Next-to-leading corrections to squark and gluino structure functions have been neglected with respect to the uncertainties in the input distributions. Let us recall that since SUSY partons are massive, they are free of mass singularities. Once these corrections have been added, mass singularities cancel and Eq. (22) becomes:

$$\frac{d\sigma}{dP_\perp dy} = \int_{\Delta} \frac{dz_1}{z_1} \frac{dz_2}{z_2} f_{P_1/P}(t_1, M^2) f_{P_2/\bar{P}}(t_2, M^2) \frac{S(t_1 t_2)^2}{\pi} \frac{d\hat{\sigma}}{d\hat{t}}(z_1, z_2) S(\hat{s} + \hat{t} + \hat{u} - \sum m_i^2) \quad (25)$$

We will now give the expressions of the physical cross-sections.

3. - PHYSICAL CROSS SECTIONS

The first cross-section we deal with is the rapidity dependence. It is given by:

$$\frac{d\sigma}{dy} = \int_{x_1}^{x_1^{\max}} \frac{dz_1}{z_1} \int_{x_2}^{x_2^{\max}} \frac{dz_2}{z_2} f_{p_1/p} \left(\frac{x_1}{z_1}, M^2 \right) f_{p_2/\bar{p}} \left(\frac{x_2}{z_2}, M^2 \right) \frac{d\hat{\sigma}}{dy} (z_1, z_2) \quad (26)$$

with

$$\begin{aligned} \frac{d\hat{\sigma}}{dy} = & \frac{d\hat{\sigma}^0}{dy} + \frac{d\hat{\sigma}^V}{dy} - \frac{d\hat{\sigma}^{DIS}}{dy} + \frac{d\hat{\sigma}^1}{dy} + \frac{d\hat{\sigma}^2}{dy} + \frac{d\hat{\sigma}^3}{dy} \\ & + \frac{d\hat{\sigma}^4}{dy} + \frac{d\hat{\sigma}^5}{dy} \end{aligned} \quad (27)$$

$$\frac{d\hat{\sigma}^0}{dy} = \frac{2\pi^2 \alpha}{3 \sin^2 \theta_w} \frac{1}{S} \delta(1-z_1) \delta(1-z_2) \quad (28)$$

$$\begin{aligned} \frac{d\hat{\sigma}^V}{dy} = & -\frac{4\pi \alpha d_S}{9 S \sin^2 \theta_w} \delta(1-z_1) \delta(1-z_2) \left\{ \Sigma \tilde{q} - V \tilde{q} - \frac{3}{4} - 3 Z(2) \right. \\ & \left. - 2 \text{Li}_2 \left(\frac{M^2}{M^2 - m^2} \right) - \frac{1}{2} \log^2 m^2 - 2 \log(M^2 - m^2) + \log^2(M^2 - m^2) \right. \\ & \left. + \log \frac{m^2}{\mu^2} \right\} \end{aligned} \quad (29)$$

We will choose $\mu = M$

$$\begin{aligned} \frac{d\hat{\sigma}^{DIS}}{dy} = & \frac{4\pi \alpha d_S}{9 S \sin^2 \theta_w} \left[\frac{1+z_1^2}{(1-z_1)_+} \log \frac{1}{z_1^2} + (1+z_1^2) \left(\frac{\log(1-z_1)}{1-z_1} \right)_+ \right. \\ & \left. - \frac{3}{2(1-z_1)_+} + 1 + 4z_1 \right] \delta(1-z_2) + \frac{2\pi^2 \alpha}{3 S \sin^2 \theta_w} \delta(1-z_1) \left[1 + \frac{d_S}{2\pi} C_F \right. \\ & \left. \left(-\frac{2\pi^2}{3} - \frac{9}{4} + \frac{3}{2} \log M^2 \right) \right] \delta(1-z_2) - \frac{8\pi \alpha d_S}{9 S \sin^2 \theta_w} \log M^2 \log \frac{M^2 - m^2}{M^2} \\ & \cdot \delta(1-z_2) \delta(1-z_1) \end{aligned} \quad (30)$$

$$\frac{d\hat{\sigma}^1}{d\gamma} = \frac{8\pi\alpha d_s}{9S\sin^2\theta_W} \frac{Z_1\beta_2(1+Z_1\beta_2)}{(Z_1+\beta_2)^2} (1 + I'_1 + I'_2 + I'_3) \quad (31)$$

with

$$\begin{aligned} I'_2 = & 2\hat{t}(m^2-M^2) \left[\frac{\beta_0(1-Z_1)+\gamma_0(1-\beta_2)}{\beta(1-Z_1)+\gamma(1-\beta_2)} \right]^2 \left\{ \left(\frac{1}{[M^2(1-Z_1)+m^2(1-\beta_2)]^2} \right)_{++} \right. \\ & + \delta(1-Z_1) \left(\frac{1}{m^2(1-\beta_2)(M^2+m^2(1-\beta_2))} \right)_{++} + \delta(1-\beta_2) \left(\frac{1}{M^2(1-Z_1)(m^2+M^2(1-Z_1))} \right)_{++} \\ & \left. - \frac{\delta(1-Z_1)\delta(1-\beta_2)}{2m^2M^2} \log \frac{(M^2+m^2)^2}{M^4m^2} \right\} \end{aligned} \quad (32)$$

$$\begin{aligned} I'_2 = & \left[(\hat{t}-M^2)^2 + (M^2-m^2)^2 \right] \frac{\beta_0(1-Z_1)+\gamma_0(1-\beta_2)}{\beta(1-Z_1)+\gamma(1-\beta_2)} \frac{1}{\theta} \frac{1-\beta_2+\eta_0}{1-\beta_2+\eta} \\ & \left\{ - \left(\frac{1}{(\beta_0(1-Z_1)+\gamma_0(1-\beta_2))(1-\beta_2)} \right)_{++} + \delta(1-Z_1) \left(\frac{1}{M^2(1-\beta_2)} \log \frac{m^2(1-\beta_2)}{M^2+m^2(1-\beta_2)} \right)_{++} \right. \\ & + \delta(1-\beta_2) \left(\frac{1}{M^2(1-Z_1)} \log \frac{Z_1(3M^2-m^2)-(M^2+m^2)}{2(M^2+m^2)(1-Z_1)} \right)_{++} \\ & + \frac{\delta(1-Z_1)\delta(1-\beta_2)}{M^2} \left[-\frac{Z_1(2)}{2} + \frac{1}{4} \log^2 m^2 + \log M^2 \log \left(-\frac{M^2+m^2}{2M^2(M^2-m^2)} \right) \right. \\ & + Li_2 \left(-\frac{m^2}{M^2} \right) + \log \frac{3M^2-m^2}{2M^2(M^2-m^2)} \log \left(-\frac{M^2+m^2}{2M^2(M^2-m^2)} \right) - Li_2 \left(\frac{M^2+m^2}{3M^2-m^2} \right) \\ & \left. \left. - \frac{1}{2} \log^2 \frac{(3M^2-m^2)}{2M^2(M^2-m^2)} \right] \right\} \end{aligned} \quad (33)$$

$$I'_3 = \delta(1-\beta_2) \frac{-M^2(1-Z_1^2)}{2Z_1(M^2-m^2Z_1)} \quad (34)$$

In Eqs. (32) and (33) one has to replace β , γ , β_0 , γ_0 and $\hat{t}$ by:

$$\beta = \frac{M^2(1+Z_1)}{Z_1(\beta_2+Z_1)}, \quad \gamma = \frac{m^2Z_1(1+\beta_2)}{(Z_1+\beta_2)}, \quad \beta_0 = M^2, \quad \gamma_0 = m^2, \quad \hat{t} = m^2 - \beta(1-Z_1) - \gamma(1-\beta_2)$$

$$\theta = -\frac{(M^2 - m^2 Z_1 \beta_2)}{(Z_1 + \beta_2) \beta_2} (1 + \beta_2), \quad \eta = -\frac{(M^2 + m^2 \beta_2) Z_1 \beta_2 \lambda^2}{(1 + \beta_2) M^2 (M^2 - m^2 Z_1 \beta_2)} \quad \eta_0 = -\frac{(M^2 + m^2) \lambda^2}{2 M^2 (M^2 - m^2)}$$

$$\frac{d\sigma^2}{dy} = \frac{\pi d d_s}{3 S \sin^2 \theta_w} \frac{Z_1 \beta_2 (1 + Z_1 \beta_2)}{(Z_1 + \beta_2)^2} \left\{ 1 - \frac{\beta + M^2}{\beta - m^2} + \frac{(\beta - M^2)(\beta + m^2)}{(\beta - m^2)^2} \right. \quad (35)$$

$$+ \left[\frac{M^2 - m^2 Z_1 \beta_2}{Z_1 \beta_2} + \frac{2 M^2 (1 - Z_1 \beta_2) (m^2 - M^2)}{(M^2 - m^2 Z_1 \beta_2)} \right] \frac{1}{\theta} \frac{1 - \beta_2 + \eta_0}{1 - \beta_2 + \eta} \frac{1}{(1 - \beta_2)_+}$$

$$+ \frac{\delta(1 - \beta_2)}{2(M^2 + m^2) Z_1 (M^2 - m^2 Z_1)} \left\{ -\frac{\pi d d_s}{6 S \sin^2 \theta_w} \left\{ \frac{M^4 (1 - Z_1)^2 + Z_1^2 (M^2 - m^2)^2}{(M^2 - m^2 Z_1)^2} \right. \right.$$

$$\cdot \left[\log \left(-\frac{M^2 + m^2}{2 M^2 (M^2 - m^2)} \right) + \log \frac{M^2}{Z_1^2} \right] + 6 \beta_1 (1 - \beta_1) - 2 \left. \right\} \delta(1 - \beta_2)$$

with

$$\theta = -\frac{(1 + \beta_2) (M^2 - m^2 Z_1 \beta_2)}{\beta_2 (Z_1 + \beta_2)}, \quad \eta_0 = -\frac{\lambda^2 (M^2 + m^2)}{2 M^2 (M^2 - m^2)}$$

$$\eta = -\frac{\lambda^2 (M^2 + m^2 \beta_2) Z_1 \beta_2}{M^2 (1 + \beta_2) (M^2 - m^2 Z_1 \beta_2)} \quad \hat{\lambda} = \frac{M^2}{Z_1 \beta_2}$$

$$\frac{d\sigma^3}{dy} = \frac{\pi d d_s}{6 S \sin^2 \theta_w} \frac{Z_1 \beta_2 (1 + Z_1 \beta_2)}{(Z_1 + \beta_2)^2} \left\{ \frac{(\hat{m}^2 - \hat{\beta}) (M^2 - \hat{\beta})}{(\hat{\beta} - m^2)^2} \right.$$

$$+ \frac{(\hat{m}^2 - \hat{\beta}) (M^2 - \hat{\beta})}{(\hat{\beta} - m^2)^2} - \frac{2 M \hat{m} \hat{\alpha}}{(\hat{\beta} - m^2) (\hat{\beta} - m^2)} \left. \right\} \quad (36)$$

with

$$\hat{\beta} = \frac{\hat{m}^2 \beta_2 (1 + Z_1 \beta_2)}{Z_1 + \beta_2} + \frac{M^2 (Z_1^2 - 1)}{Z_1 (Z_1 + \beta_2)}$$

$$\hat{u} = (1 - \beta_2^2) \frac{(\hat{m}^2 \beta_1 \beta_2 - M^2)}{\beta_2 (\beta_1 + \beta_2)}$$

For these three processes, the upper limits of integration in Eq. (26) are one.

$$\begin{aligned} \frac{d\hat{\sigma}^4}{d\hat{E}} = & \frac{4\pi\alpha d_S}{9\sin^2\Theta_W} \frac{1}{S} \frac{\beta_1 \beta_2 (M^2(1 + \beta_1 \beta_2) - \hat{m}^2 \beta_1 \beta_2)}{M^2 (\beta_1 + \beta_2)^2} \left\{ \frac{(M^2 - \hat{U})(\hat{m}^2 - \hat{u})}{(\hat{u} - m^2)^2} \right. \\ & \left. + \frac{(M^2 - \hat{E})(\hat{m}^2 - \hat{E})}{(\hat{E} - m^2)^2} - \frac{2 M \hat{m} \hat{S}}{(\hat{E} - m^2)(\hat{u} - m^2)} \right\} \quad (37) \end{aligned}$$

and $\hat{E} = \frac{M^2(\beta_1^2 - 1) + \hat{m}^2 \beta_1 \beta_2}{\beta_1(\beta_1 + \beta_2)}, \quad \hat{u} = \frac{M^2(\beta_2^2 - 1) + \hat{m}^2 \beta_1 \beta_2}{\beta_2(\beta_1 + \beta_2)}$

$$\begin{aligned} \frac{d\hat{\sigma}^5}{d\hat{E}} = & \frac{\pi\alpha d_S}{6\sin^2\Theta_W} \frac{1}{S} \frac{\beta_1 \beta_2 (M^2(1 + \beta_1 \beta_2) - m^2 \beta_1 \beta_2)}{M^2 (\beta_1 + \beta_2)^2} \left\{ \right. \\ & \left. \frac{(\hat{E} - M^2)(\hat{E} + m^2)}{(\hat{E} - m^2)^2} + \frac{M^2 - \hat{U}}{\hat{S}} + 2 \frac{(\hat{E} - M^2)(m^2 - M^2) - \beta(\hat{E} + M^2)}{\hat{S}(\hat{E} - m^2)} \right\} \quad (38) \end{aligned}$$

with $\hat{E} = \frac{M^2(\beta_1^2 - 1) + m^2 \beta_1 \beta_2}{\beta_1(\beta_1 + \beta_2)}$

and $\hat{u} = \frac{M^2(\beta_2^2 - 1) + m^2 \beta_1 \beta_2}{\beta_2(\beta_1 + \beta_2)}$

For processes 4 and 5, the limits of integration in Eq. (26) are

$$x_1 \leq z_1 \leq \frac{1-x_2}{1-x_2+\frac{m_4^2}{M^2}x_2} \quad \text{and} \quad x_2 \leq z_2 \leq \frac{1-z_1}{1-z_1+z_1\frac{m_4^2}{M^2}}$$

The expression of the + distributions is given in Appendix I.

We will now give the expression of the transverse momentum distribution $d\sigma/dp_\perp^2 dy$ at fixed rapidity. The transverse momentum distribution at first QCD order is singular for $p_\perp \rightarrow 0$. Since we will not attempt to use soft gluon resummation techniques¹²⁾ in order to keep track of this singularity, our results will be valid only for large $p_\perp$. Consequently, only regular terms will contribute, since singular terms are proportional to $\delta(p_\perp^2)$. The transverse momentum distribution reads:

$$\begin{aligned} \frac{d\sigma}{dp_\perp^2 dy} = & \frac{\pi}{2M^2 \sqrt{1+\frac{p_\perp^2}{M^2}}} \left[\int_{\left(\frac{M_\perp+m_{4\perp}}{\sqrt{s}}\right)e^{-\gamma}}^1 dT_1 \frac{1}{t_1 t_2} f_{p_1/p}(t_1, M^2) \right. \\ & \cdot f_{p_2/\bar{p}}(t_2, M^2) \frac{(T_1 x_2 + T_2 x_1)^2}{x_2(T_1^2 - x_1^2) + x_1 \frac{m_4^2}{s}} \left. \left(\frac{d\hat{\sigma}}{dy} \right)_1 \right. \\ & + \int_{\left(\frac{M_\perp+m_{4\perp}}{\sqrt{s}}\right)e^{-\gamma}}^1 dT_2 \frac{1}{t_1 t_2} f_{p_1/p}(t_1, M^2) f_{p_2/\bar{p}}(t_2, M^2) \\ & \left. \frac{(T_1 x_2 + T_2 x_1)^2}{x_1(T_2^2 - x_2^2) + x_2 \frac{m_4^2}{s}} \left(\frac{d\hat{\sigma}}{dy} \right)_2 \right] \end{aligned} \quad (39)$$

with

$$M_\perp = \sqrt{M^2 + p_\perp^2} \quad m_{4\perp} = \sqrt{m_4^2 + p_\perp^2}$$

in the first integral
$$T_2 = \frac{M^2 - m_4^2 - M_\perp \sqrt{s} e^{-\gamma} T_1}{M_\perp \sqrt{s} e^{\gamma} - T_1 s}$$

in the second integral
$$T_1 = \frac{M^2 - m_4^2 - M_\perp \sqrt{s} e^{\gamma} T_2}{M_\perp \sqrt{s} e^{-\gamma} - T_2 s}$$

$(d\hat{\sigma}/dy)_1$ for processes 3, 4 and 5 are given by equations (36), (37) and (38).

For process 1 one gets:

$$\left(\frac{d\hat{\sigma}}{dy}\right)_1 = \frac{8\pi\alpha\alpha_s}{9\sin^2\theta_W} \frac{1}{S} \frac{Z_1\beta_2(1+Z_1\beta_2)}{(Z_1+\beta_2)^2} \left\{ 1 + \frac{2\hat{t}(m^2-M^2)}{(\hat{t}-m^2)^2} + \frac{(\hat{t}-M^2)^2 + (M^2-m^2)}{\hat{u}(\hat{t}-m^2)} \right\} \quad (40)$$

For process 2 one gets:

$$\left(\frac{d\hat{\sigma}}{dy}\right)_2 = -\frac{\pi\alpha\alpha_s}{3\sin^2\theta_W} \frac{1}{S} \frac{Z_1\beta_2(1+Z_1\beta_2)}{(Z_1+\beta_2)^2} \left\{ 1 - \frac{\hat{s}+M^2}{\hat{s}-m^2} + \frac{(\hat{s}-M^2)(\hat{s}+m^2)}{(\hat{s}-m^2)^2} + \frac{1}{\hat{u}} \left[\hat{s}-m^2 + 2 \frac{(\hat{s}-M^2)(m^2-M^2)}{(\hat{s}-m^2)} \right] \right\} \quad (41)$$

$(d\sigma^1/dy)_2$ is obtained from $(d\sigma/dy)_1$ by interchange of indices 1 and 2 and $t \leftrightarrow u$. Cross-sections for processes involving a massive SUSY parton inside the proton and a massless one in the antiproton are obtained by the interchanges $1 \leftrightarrow 2$, $t \leftrightarrow u$, $y \leftrightarrow -y$. The combinations of structure functions for $\tilde{W}^-$ production are given in Appendix II. $\tilde{W}^+$ production is obtained by the interchange $y \leftrightarrow -y$. We will take into account six quark flavours and assume that the Kobayashi-Maskawa matrix elements for quark-squark couplings are the same as for quark-quark weak couplings. For simplicity, we will use a diagonal matrix.

The cross-sections for the $\tilde{Z}^0$ case differ from the $\tilde{W}^-$ by the factor

$$\alpha_q = \frac{a_q^2 + b_q^2}{4\cos^2\theta_W} \quad (42)$$

with $a_q = 1 - 8/3 \sin^2\theta_W$, $b_q = 1$ for quarks of charge $2/3$ and $a_q = -1 + 4/3 \sin^2\theta_W$, $b_q = -1$ for quarks of charge $-1/3$. The combinations of structure functions are given in Appendix III.

4. - NUMERICAL RESULTS

We will now discuss the implications of the SUSY QCD corrections for gaugino production. We will restrict ourselves to $\tilde{W}^-$ and $\tilde{Z}^0$ production at the CERN $p\bar{p}$ collider energy ($\sqrt{s} = 630$ GeV) and at the Tevatron energy ($\sqrt{s} = 2$ TeV).

We have first to specify our choice for the structure functions at a given Q^2 . For the usual quark densities we take the parametrization of Duke-Owens¹⁵⁾ at $Q_0^2 = 4$ GeV². For $Q^2 < m^2$ and $\tilde{m}^2$, we perform the evolution of the structure functions at the leading logarithmic approximation by direct resolution of Altarelli-Parisi equations¹⁶⁾. For $Q^2 > m^2, \tilde{m}^2$, we solve, using the same method¹⁷⁾, the SUSY extension of Altarelli-Parisi equations. For $Q^2 = m^2$ and $Q^2 = \tilde{m}^2$, the input squark and gluino structure functions are directly generated from quarks and gluons according to SUSY QCD bremsstrahlung. Since the direct resolution method is not valid for small x values, we will not give reliable predictions for $x < 0.025$. This will exclude very high energies like the LHC and SSC ones. According to UA1 limits on the SUSY particle spectrum, we will take $m = \tilde{m} = 85$ GeV. The squark and gluino distributions inside the proton are much weaker than the quark and gluon ones. They come mainly from gluons whose structure function becomes less important than if SUSY partons were not present according to the energy-momentum sum rule. We show in Figs. 3a and 3b the various structure functions for $Q = 100$ GeV and $Q = 140$ GeV. The SUSY parton distributions are peaked to small x values. A comment is in order here. The squark and gluino structure functions have been extracted in the range $m^2 < Q^2 < 4m_{q,g}^2$ which is sensitive to threshold effects. Therefore, our numerical results have to be taken as an orientation but not as firm and definite predictions.

We will now give our predictions for the rapidity cross-section $d\sigma/dy$ at several gaugino masses. We show in Fig. 4 the rapidity dependence at $\sqrt{s} = 630$ GeV for winos of 65 and 80 GeV and a zino of 80 GeV. The cross-section for $\tilde{W}$ production is maximal around $y = -0.25$ and decreases more rapidly for large positive rapidities than for negative ones. The production rate decreases when the gaugino masses becomes higher. The cross-section for $\tilde{Z}$ production is symmetric around $y = 0$ and of the same order of magnitude. As shown in Fig. 5, for $\sqrt{s} = 2$ TeV, the production rate increases with the energy: we gain roughly a factor 20 between the CERN collider energy and the Tevatron one. The decrease with rapidity is less important at $\sqrt{s} = 2$ TeV, as expected.

We will now give our results for gaugino masses M greater than the squark

and gluino masses (we have chosen $m = \tilde{m} = 85$ GeV as an illustration). In this case, the subprocesses involving a massive SUSY parton will contribute. We have computed the rapidity dependence for a gaugino of mass 100 GeV at $\sqrt{s} = 630$ GeV. The rate for $\tilde{W}$ production is much more important than for lower masses: we gain two orders of magnitude. The $g\tilde{q}$ subprocess gives a negative contribution of roughly 15%. The $\tilde{g}q$ subprocess and those involving massless partons ($q\bar{q}$ and qg) are quite negligible. Therefore, the first order SQCD is big: $K = 1.75$ at $y = 0$ and reaches 1.86 at $y = 0.55$. This slight increase of the SQCD corrections with rapidity is not surprising since when the argument of the structure function increases, the $g\tilde{q}$ contributions become less important. In the rapidity range we have explored (which is limited by our confidence in structure functions only for $x > 0.025$) the y dependence is quite flat with $d\sigma/dy \approx 0.041 \pm 0.44$ nb for $-0.6 < y < 0.6$. The cross-section for zino production is also quite flat with $d\sigma/dy = 0.07 \pm 0.075$ nb in the same rapidity range. The shape is symmetric around $y = 0$. The first order correction is important: $K = 1.7$ at $y = 0$ and reaches 1.8 at $y = 0.55$. The $g\tilde{q}$ contribution is somewhat larger than for $\tilde{W}^-$ production (around 20% at $y = 0$ and 14% at $y = 0.6$).

We give in Fig. 6 the rapidity dependence for a gaugino of 140 GeV at $\sqrt{s} = 630$ GeV. As expected, the production rate decreases when the gaugino becomes more massive. The first order SUSY QCD corrections are important. At $y = 0$, $K = 2.07$. It is bigger than for a wino of 100 GeV since when M increases, the argument of the structure functions becomes larger and therefore the $g\tilde{q}$ contribution is very small ($\sim 2\%$) and is cancelled by the $q\tilde{g}$ contribution. The cross-section is maximal for negative y with $d\sigma/dy \sim 10^{-2}$ nb and decreases faster at large positive rapidities. The K factor increases slightly with y . Similar conclusions for the K factor apply to $\tilde{Z}$ production. The cross-section is 70% higher than for $\tilde{W}^-$ production.

Finally, we have considered the case of a gaugino of mass 140 GeV at $\sqrt{s} = 2$ TeV. The production rate is higher; we gain a factor 6 between the CERN $p\bar{p}$ collider and the Tevatron energy. The K factor decreases $K \approx 1.9$. This result is not surprising since when $\sqrt{s}$ increases, the argument of the structure functions moves to smaller values. Therefore, the gluon structure functions become more important (see Fig. 3b) increasing the magnitude of the $g\tilde{q}$ subprocess. A comment is in order here: its magnitude is strongly dependent upon the choice of the scale of evolution for the structure functions since the second order correction has not been computed. Since we have taken Q^2 for scale, we maximize the magnitude of the contribution. In the rapidity range ($-0.6 < y < +0.6$) we have explored $d\sigma/dy$ is flat and of the order of 0.07 nb. The rate for $\tilde{Z}$

production is higher. The K factor is important ($K \sim 1.85$). It decreases with energy for the same reasons as for the wino case. The rapidity shape is quite flat and $d\sigma/dy$ is of the order of 0.1nb .

The cross-sections for gaugino production are less important than the estimates for W and Z production^{13),17)}: we are down by roughly two orders of magnitude. Moreover, we should not forget that the Higgsino content of physical gauginos not considered here (since it is model-dependent) will reduce the gaugino production rates.

We will now give our results for the large transverse momentum distribution $d\sigma/dp_{\perp}dy|_{y=0}$ at fixed rapidity. Since we have not taken into account soft gluon resummation, we cannot be confident in the small $p_{\perp}$ behaviour of the cross-section. Therefore, the minimal $p_{\perp}$ value we consider is $p_{\perp} = 15\text{ GeV}$. We show in Fig. 7 the cross-section $d\sigma/dp_{\perp}dy|_{y=0}$ for a $\tilde{W}^-$ of 80 GeV at $\sqrt{s} = 630$ and 2 TeV. Since the SUSY parton in the final state is massive, the $p_{\perp}$ spectrum is maximal around $p_{\perp} = 40\text{ GeV}$. The situation is very different for large gaugino masses as can be seen from inspection of Figs. 8a and 8b for $M = 100\text{ GeV}$ and $M = 140\text{ GeV}$ respectively. The cross-section is a decreasing function of $p_{\perp}$. The contribution of $q\bar{q}$ and qg subprocesses is dominant in the high $p_{\perp}$ range ($p_{\perp} > 60\text{--}70\text{ GeV}$). The intermediate $p_{\perp}$ range is driven by the subprocesses involving a massive SUSY parton inside the proton. At fixed mass $d\sigma/dp_{\perp}dy|_{y=0}$ increases with $\sqrt{s}$. It decreases by roughly a factor of 2 when the gaugino mass becomes larger at fixed energy. At $\sqrt{s} = 630\text{ GeV}$ the shape of $\tilde{Z}$ production is similar to the $\tilde{W}^-$ case whereas at $\sqrt{s} = 2\text{ TeV}$, the $p_{\perp}$ decrease is much pronounced.

This very different shape of the $p_{\perp}$ cross-section should give a clear indication on the squark and gluino contents inside the proton.

5. - CONCLUSIONS

We have done a more refined calculation of $\tilde{W}$ and $\tilde{Z}$ production in $p\bar{p}$ collisions including first order SUSY QCD corrections. Squark and gluino structure functions were directly evaluated from the SUSY extension of Altarelli-Parisi equations. We have carefully treated the effects of having massive partons both in the kinematics of the parton model and in the analytical properties of the amplitude of the subprocesses.

Results are very strongly dependent upon the values of squark, gluino and $\tilde{W}^{\pm}$ or $\tilde{Z}$ masses. In particular, they depend essentially on whether $\tilde{W}^{\pm}$ or $\tilde{Z}$ are heavier or lighter than squarks or gluinos. Our results confirm that as soon as there is a squark and gluino content inside the proton, the subprocesses involving SUSY partons are dominant. The first order QCD corrections, which have been computed keeping the SUSY parton masses, are found very large: at $\sqrt{s} = 630$ GeV the K factor is roughly equal to 2. It decreases with energy. For example, cross-sections at $\sqrt{s} = 630$ GeV are of the order of a few 10^{-3} nb for $m_{\tilde{W},\tilde{Z}} < m_{q,g}$ (taken at 85 GeV) but become close to 0.1 nb for $m_{\tilde{W},\tilde{Z}} > m_{q,g}$. Rapidity distributions $d\sigma/dy$ for $\tilde{W}^{\pm}$ or $\tilde{Z}$ have been computed in the central region (around $y = 0$). They decrease for large $|y|$ values especially for "light" winos or zinos. Transverse momentum distributions $d\sigma/dydp_{\perp}|_{y=0}$ are also very much dependent on the wino and zino masses. As soon as $m_{\tilde{W},\tilde{Z}} > m_{q,g}$ the presence of the Born term ($q\bar{q} \rightarrow \tilde{W}^{\pm}$ or $\tilde{Z}$) leads to a strong enhancement of the low $p_{\perp}$ domain which does not exist if the mass inequality is reversed.

These properties are crucial for an experimental search of winos and zinos in $p\bar{p}$ collisions, in particular in order to produce reliable limits on the existence of these particles. In practice, the search will proceed through the leptonic decays of the $\tilde{W}^{\pm}$ and $\tilde{Z}$. The transverse momentum distributions of the leptons issued from the decays will present a Jacobian peak. The branching ratios depend on the supersymmetric scheme and more precisely on the choice of the lightest SUSY particle and the SUSY mass spectrum contrarily to the first order corrections we have computed which are quite model independent. Such a study needs also a detailed treatment of detector acceptances and will be the subject of a forthcoming publication.

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APPENDIX I

We give in this appendix the expressions of the + distributions

$$\int_x^1 dz \frac{f(z)}{(1-z)_+} = \int_x^1 dz \frac{f(z) - f(1)}{1-z} + f(1) \ln(1-x) \quad (\text{A.1})$$

$$\begin{aligned} \int_x^1 dz f(z) \left(\frac{\ln(1-z)}{(1-z)_+} \right) &= \int_x^1 dz (f(z) - f(1)) \frac{\ln(1-z)}{(1-z)} \\ &+ f(1) \ln^2(1-x) \end{aligned} \quad (\text{A.2})$$

$$\begin{aligned} \int_{x_1}^1 dz_1 \int_{x_2}^1 dz_2 \frac{f(z_1, z_2)}{[M^2(1-z_1) + m^2(1-z_2)]_+^2} &= \\ \int_{x_1}^1 dz_1 \int_{x_2}^1 dz_2 \frac{f(z_1, z_2) - f(1, 1)}{[M^2(1-z_1) + m^2(1-z_2)]^2} & \quad (\text{A.3}) \\ - \frac{f(1, 1)}{m^2 M^2} \ln \frac{M^2(1-x_1) + m^2(1-x_2)}{(M^2 + m^2)(1-x_1)(1-x_2)} \end{aligned}$$

$$\begin{aligned} \int_{x_1}^1 dz_1 \int_{x_2}^1 dz_2 \frac{f(z_1, z_2)}{[M^2(1-z_1) + m^2(1-z_2)]_+ (1-z_2)_+} &= \\ \int_{x_1}^1 dz_1 \int_{x_2}^1 dz_2 \frac{f(z_1, z_2) - f(z_1, 1) - f(1, z_2) + f(1, 1)}{[M^2(1-z_1) + m^2(1-z_2)] (1-z_2)} & \\ - \frac{1}{M^2} \int_{x_2}^1 dz_2 \ln \left(\frac{m^2(1-z_2) + M^2}{M^2(1-x_1) + m^2(1-z_2)} \right) \frac{(f(1, z_2) - f(1, 1))}{(1-z_2)} & \quad (\text{A.4}) \\ + \frac{1}{M^2} \int_{x_1}^1 dz_1 \frac{(f(z_1, 1) - f(1, 1))}{(1-z_1)} \left[\ln(1-x_2) + \ln \left(\frac{M^2(1-z_1) + m^2}{M^2(1-z_1) + m^2(1-x_2)} \right) \right] \\ + \frac{f(1, 1)}{M^2} \left\{ \ln(1-x_1) \ln(1-x_2) - \text{Li}_2 \left(-\frac{m^2}{M^2} \right) + \text{Li}_2 \left(-\frac{m^2}{M^2(1-x_1)} \right) + \text{Li}_2 \left(-\frac{m^2(1-x_2)}{M^2} \right) \right\} \end{aligned}$$

$$- \operatorname{Li}_2 \left(-\frac{m^2(1-x_2)}{M^2(1-x_1)} \right) \}$$

$$\int_{x_1}^1 dz_1 \frac{f(z_1)}{[(1-z_1)(m^2+M^2(1-z_1))]} = \quad (A.5)$$

$$\int_{x_1}^1 dz_1 \frac{f(z_1)-f(1)}{(1-z_1)[m^2+M^2(1-z_1)]} + \frac{f(1,1)}{m^2} \log \left(\frac{(1-x_1)(m^2+M^2)}{m^2+M^2(1-x_1)} \right)$$

$$\int_{x_1}^1 dz_1 f(z_1) \left(\frac{1}{(1-z_1)} \log \frac{z_1(3M^2-m^2)-(M^2+m^2)}{2(M^2+m^2)(1-z_1)} \right) =$$

$$\int_{x_1}^1 dz_1 \frac{(f(z_1)-f(1))}{1-z_1} \log \left(\frac{z_1(3M^2-m^2)-(M^2+m^2)}{2(M^2+m^2)(1-z_1)} \right) \quad (A.6)$$

$$- f(1) \left[\frac{1}{2} \ln^2(1-x_1) + \ln(1-x_1) \ln \left(\frac{M^2+m^2}{M^2-m^2} \right) - \operatorname{Li}_2 \left(\frac{3M^2-m^2}{2(M^2-m^2)} \right) \right. \\ \left. + \operatorname{Li}_2 \left(\frac{(3M^2-m^2)(1-x_1)}{2(M^2-m^2)} \right) \right]$$

$$\int_{x_2}^1 dz_2 f(z_2) \left[\frac{1}{(1-z_2)} \log \left(\frac{m^2(1-z_2)}{M^2+m^2(1-z_2)} \right) \right] =$$

(A.7)

$$\int_{x_2}^1 dz_2 \frac{(f(z_2)-f(1))}{(1-z_2)} \log \frac{m^2(1-z_2)}{M^2+m^2(1-z_2)}$$

$$+ f(1) \left[\frac{1}{2} \ln^2(1-x_2) + \log \frac{m^2}{M^2} \log(1-x_2) \right. \\ \left. - \operatorname{Li}_2 \left(-\frac{m^2}{M^2} \right) + \operatorname{Li}_2 \left(-\frac{m^2(1-x_2)}{M^2} \right) \right]$$

APPENDIX II

We give in this appendix the combination of structure functions for $\tilde{W}^-$ production, assuming SU(6) symmetry for the sea

For process 1

$$\begin{aligned} d(t_1) \tilde{u}_L(t_2) + 5 \tilde{s}(t_1) \hat{\tilde{s}}_L(t_2) \\ \tilde{d}_L(t_1) u(t_2) + 5 \tilde{s}_L(t_1) \tilde{s}(t_2) \end{aligned}$$

For process 2

$$\begin{aligned} g(t_1) (\tilde{u}_L(t_2) + 5 \tilde{s}_L(t_2)) \\ g(t_2) (\hat{\tilde{d}}_L(t_1) + 5 \tilde{s}_L(t_1)) \end{aligned}$$

For process 3

$$\begin{aligned} \tilde{g}(t_2) (5 \tilde{s}(t_1) + d(t_1)) \\ \tilde{g}(t_1) (u(t_2) + 5 \tilde{s}(t_2)) \end{aligned}$$

For process 4

$$\begin{aligned} d(t_1) u(t_2) + 2 \tilde{s}(t_1) \tilde{s}(t_2) \\ 3 \tilde{s}(t_1) \tilde{s}(t_2) \end{aligned}$$

For process 5

$$\begin{aligned} g(t_2) (d(t_1) + 5 \tilde{s}(t_1)) \\ g(t_1) (5 \tilde{s}(t_2) + u(t_2)) \end{aligned}$$

APPENDIX III

We give in this appendix the combinations of structure functions for zino production assuming squarks degenerate in mass

For process 1

$$2[\alpha_u u(t_1) \hat{u}_L(t_2) + \alpha_d d(t_1) \hat{d}_L(t_2) + 5(\alpha_u + \alpha_d) \zeta(t_1) \hat{\zeta}_L(t_2)]$$

$$2[\alpha_u u(t_2) \hat{u}_L(t_1) + \alpha_d d(t_2) \hat{d}_L(t_1) + 5(\alpha_u + \alpha_d) \hat{\zeta}_L(t_1) \zeta(t_2)]$$

For process 2

$$2g(t_1) [\alpha_u \tilde{u}_L(t_2) + \alpha_d \hat{d}_L(t_2) + 5(\alpha_u + \alpha_d) \hat{\zeta}_L(t_2)]$$

$$2g(t_2) [\alpha_u \tilde{u}_L(t_1) + \alpha_d \hat{d}_L(t_1) + 5(\alpha_u + \alpha_d) \hat{\zeta}_L(t_1)]$$

For process 3

$$\hat{g}(t_2) [\alpha_u u(t_1) + \alpha_d d(t_1) + 5(\alpha_u + \alpha_d) \zeta(t_1)]$$

$$\hat{g}(t_1) [\alpha_u u(t_2) + \alpha_d d(t_2) + 5(\alpha_u + \alpha_d) \zeta(t_2)]$$

For process 4

$$\alpha_u u(t_1) u(t_2) + \alpha_d d(t_1) d(t_2) + 2(\alpha_u + \alpha_d) \zeta(t_1) \zeta(t_2)$$

$$3(\alpha_u + \alpha_d) \zeta(t_1) \zeta(t_2)$$

For process 5

$$g(t_2) [\alpha_u u(t_1) + \alpha_d d(t_1) + 5(\alpha_u + \alpha_d) \zeta(t_1)]$$

$$g(t_1) [\alpha_u u(t_2) + \alpha_d d(t_2) + 5(\alpha_u + \alpha_d) \zeta(t_2)]$$

where α_u and α_d are defined in Eq. (42).

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FIGURE CAPTIONS

Fig. 1 : Real diagrams contributing to wino production

- a) $q\bar{q}_L$ Born subprocess;
- b) $q\bar{q}_L \rightarrow \tilde{W}g$ subprocess;
- c) $g\bar{q}_L \rightarrow \tilde{W}q$ subprocess;
- d) $q\bar{g} \rightarrow \tilde{W}q$ subprocess;
- e) $q\bar{q} \rightarrow \tilde{W}g$ subprocess;
- f) $qg \rightarrow \tilde{W}q$ subprocess.

Fig. 2 : Virtual diagrams contributing to wino production.

Fig. 3 : a) Quark, antiquark, gluon, squark and gluino distribution functions inside the proton evaluated at $Q = 100$ GeV.
b) Same as in Fig. 3a for $Q = 140$ GeV.

Fig. 4 : The rapidity cross-section $d\sigma/dy$ at $\sqrt{s} = 630$ GeV for several wino and zino masses. Full curve: $m_{\tilde{W}} = 65$ GeV. Dot dashed curve: $m_{\tilde{W}} = 80$ GeV. Dashed curve: $M_{\tilde{Z}} = 80$ GeV.

Fig. 5 : The same as Fig. 4 at $\sqrt{s} = 2$ TeV.

Fig. 6 : The rapidity cross-section $d\sigma/dy$ at $\sqrt{s} = 630$ GeV for winos and zinos of mass 140 GeV. Full curve: first order cross-section for the wino production. Dashed curve: Born contribution. Small dashed curve: first order cross-section for the zino production. Dot-dashed curve: Born contribution.

Fig. 7 : The transverse momentum distribution $d\sigma/dp_{\perp} dy \Big|_{y=0}$ for a wino mass of 80 GeV. Full curve: $\sqrt{s} = 630$ GeV. Dashed curve: $\sqrt{s} = 2$ TeV.

Fig. 8 : a) The transverse momentum distribution $d\sigma/dp_{\perp} dy \Big|_{y=0}$ for winos and zinos of mass 100 GeV. Full curve: wino production at $\sqrt{s} = 630$ GeV. Dashed curve: wino production at $\sqrt{s} = 2$ TeV. Small dashed curve: zino production at $\sqrt{s} = 630$ GeV. Dot dashed curve: zino production at $\sqrt{s} = 2$ TeV.
b) The same as Fig. 8a for winos and zino of mass 140 GeV.

FIG. 1a

+

FIG. 1b

+

FIG. 1c

+

FIG. 1d

+

FIG. 1e

+

FIG. 1f

FIG. 2

Fig. 3a

Fig. 3b

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8a

Fig. 8b