# Polarized Drell Yan and Double Photon Production to NLO QCD

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**based on joint work with L. Gordon and with S.Chang, R. Field and L. Gordon** (ARGONNE) (U.FLORIDA)

I present results for the NLO (order $\alpha_s^2$) corrections to 2 polarized cross sections: double prompt photon production and production of a Drell Yan pair in polarized pp collisions. In both cases I wil go through a detailed analysis of the structure of the radiative corrections and I will try to underline the differences between the calculations of the radiative corrections in the polarized case compared to the the unpolarized one. In the case of double photon, I will consider a very special cross section -at large $p_T$ of the photon pair- and study the dependence of the cross section with NLO evolved structure functions. I will show that the asymmetries are sizeable (L. Gordon and C.C. PRD).

Then I will move to the Drell Yan case. I give complete NLO results for the nonsinglet (order $\alpha_s^2$) cross section for the *distributions*. (S.Chang, R. D. Field, L, Gordon, C.C., to appear)

Spin physics is a very important avenue for QCD. There are many reasons to believe that the interest in the field will grow even more in the next few years and we have the hope that some of the phenomenological work that many people are doing will be eventually measured (at RHIC and at HERA).

The chapter of the "radiative corrections" is still at its infancy. If we move from DIS to polarized pp colliders, then the story of this corrections may become important. The work, as usual, in this direction, goes through factorization theorems and resummation in order to predict the cross sections with good accuracy.

*What is known to NLO at pp colliders*

Most of the work has focussed on single and double prompt photon (Gordon and Vogelsang; Gordon and C.C.). Some important features of these calculations have been noticed, especially in the non singlet sector.

The analysis involves the so called "initial state asymmetries". Basically there is no work to NLO for the "transmitted asymmetrics". Also the study of the transversities at pp colliders is at its beginning and work is in progress (S. Chang et al.).

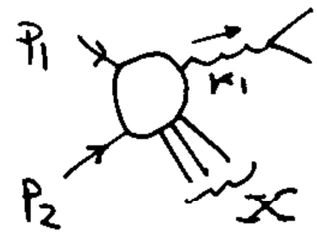
*Why do we need a hadron colliders*

- At hadron colliders we can definitively set the issue of the gluon polarization, so important after the results of the EMC collaboration.
- We can try to unveil the mystery about the so called transversity distributions (such as $h_1$), some of them which are Leading twist (twist 2) ( Ralston and Soper, Qiu and Sterman, Jaffe and Ji). Drell Yan is the natural process to study these distributions and therefore it is crucial to have complete NLO studies of both the longitudinal and of the transverse asymmetries.
- The calculation are notoriously difficult and extremely time consuming because of the presence of chiral projectors in the initial state.
- Factorization theorems help in "guessing" the structure of the answer, but, as we will see, the structure of the finite contributions to the crosss sections are non-trivial.
- In the non singlet sector Drell Yan polarized has a strong resemblence to the corresponding unpolarized.

# The DY mechanism

We intend to study the cross section

$$\frac{d\sigma}{dQ^2\,dt\,du}$$



$t = (p_1 - k_1)^2$
$u = (p_2 - k_1)^2$
$k_1^2 \equiv Q^2$

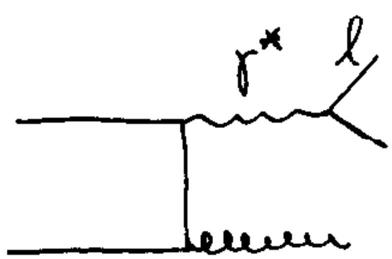
this cross section starts at $O(\alpha_s)$
Since we are assuming that at least one jet

is in the final state

Originally studied by Ellis Martinelli and Petronzio

in the unpolarized case.

The calculation originally was a study of the large $p_T$ behaviour of the process



Born level contribution

since the lepton pair is emitted with a large $p_T$ (non-zero).

This cross section is of course, related to the total cross section $\frac{d\sigma}{dQ^2} \equiv \sigma_{total}$ which is only a function of $x \equiv Q^2/s$

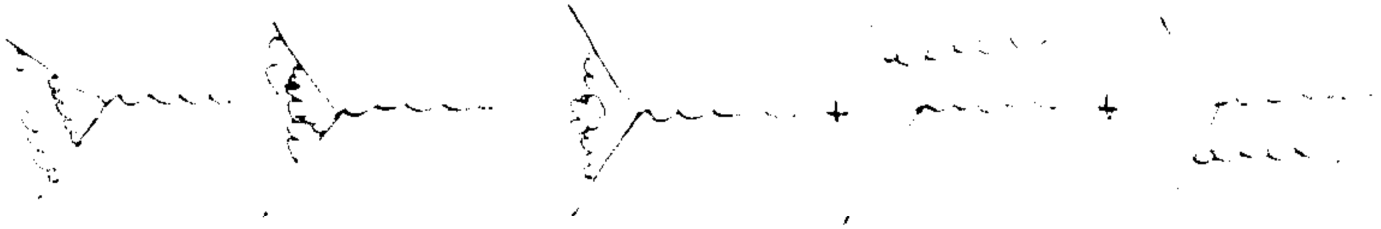
$\sigma_{total}$ has been studied up to $O(\alpha_s^2)$ by Van Neerven and collaborators (unpolarized) and up to $O(\alpha_s)$ in the polarized case by Ratcliffe (NP B223 (1983)). More recently Gehrmann has studied the $y - x_F$ distribution to $O(\alpha_s)$.

$O(\alpha_s)$ [illegible]

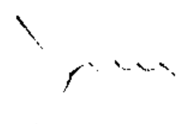

[illegible]

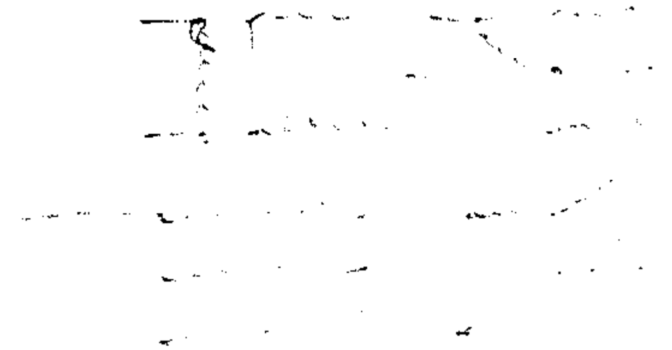
The small-$x$ limit also requires resummation. (Van Neerven et al.). Work on the resummation of the large $\ln x$ contributions.

$O(\alpha_s^2)$ corrections to $d\sigma/dQ^2$



interfere with





new contributions, the same as in $d\sigma/dt\,du$

therefore, by u-t integration of our result one gets the total $\sigma(Q^2,s)$ cross section

In principle one does not need to resum to small $p_T$ the result to obtain $\sigma(Q^2,s)$, but just embeds in Dim. Reg.

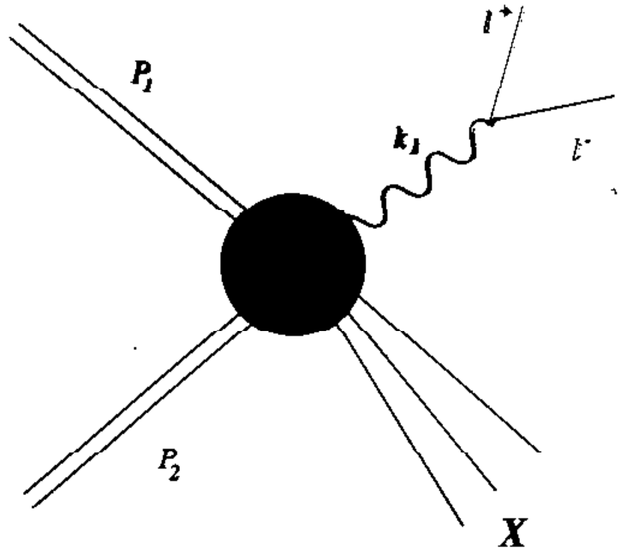



Figure 1: Drell-Yan process

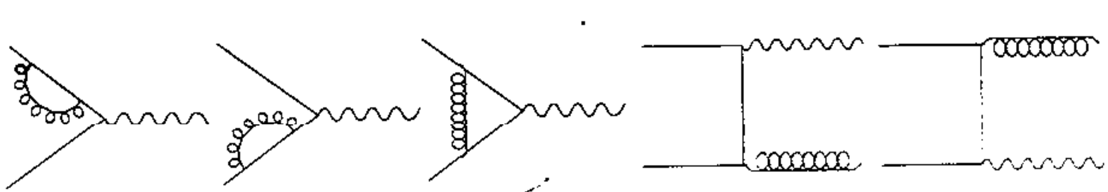


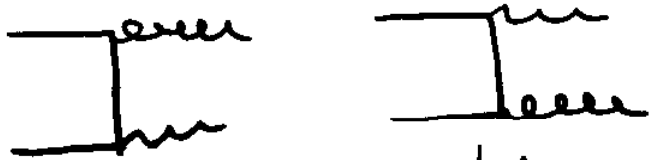

Figure 2: $\alpha_s$ order contributions

$d\sigma/dQ^2$

interfering with

Contributing as $|L_1 + L_2|^2$

Virtual Corrections up to $\alpha_s^2$



$L_2$ $\qquad$ $L_1$

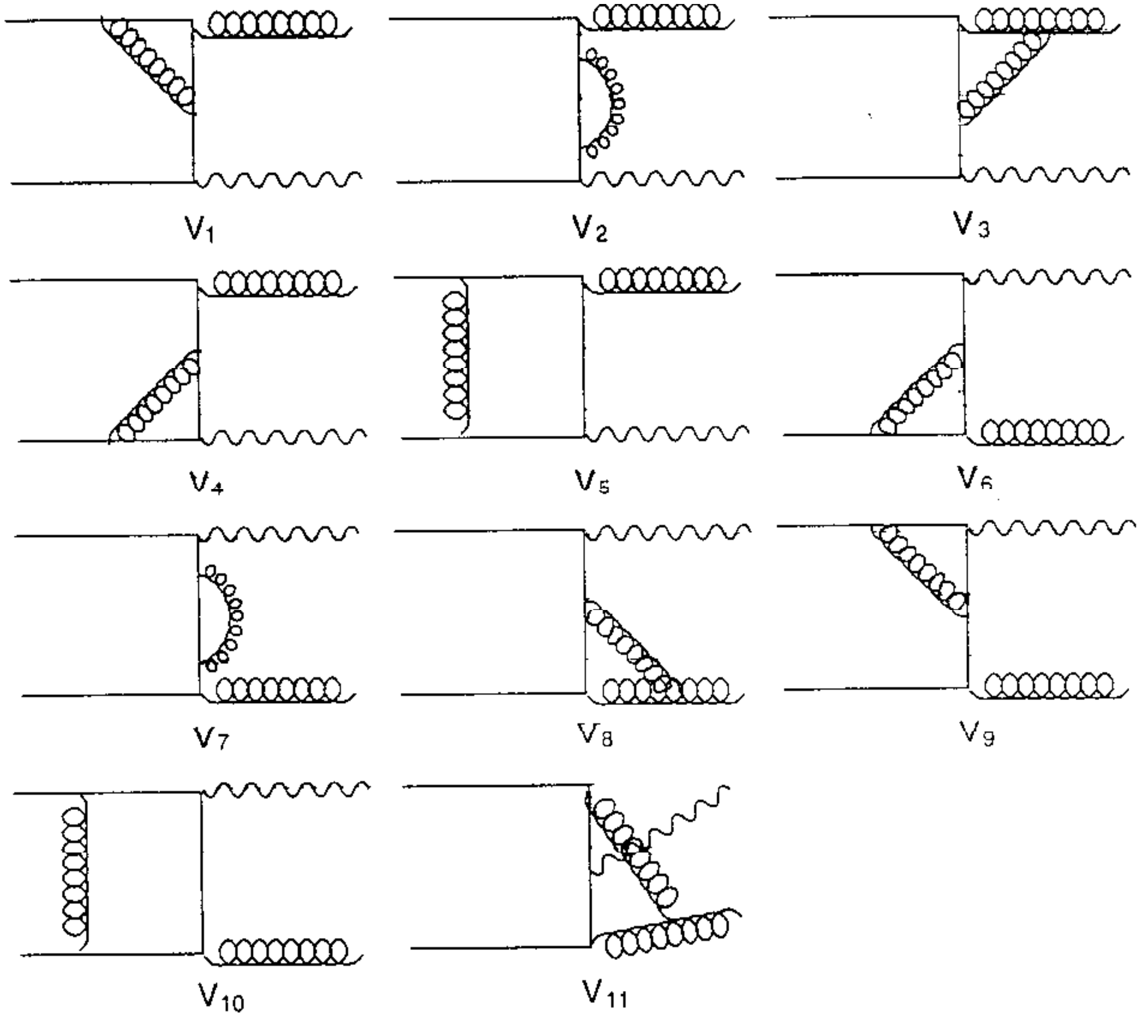
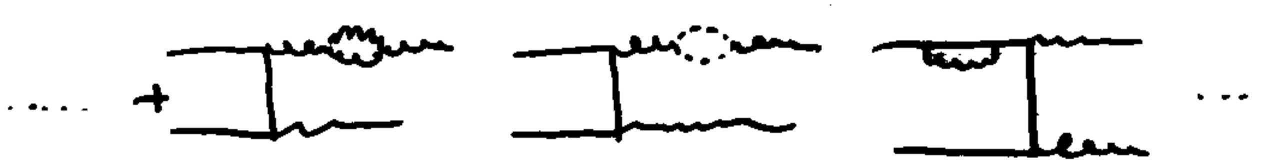



Figure 6: Diagrams which contribute to the process $q + \bar{q} \to \gamma^* + G$

+ self energy insertions



# Scheme dependence

As we are going to see

there are subtle issues connected to the Renormalization Scheme dependence ( $\overline{MS}$ and $\overline{MS}_p$ ) to be

considered. Therefore, we are going to calculate again both the unpolarized and the polarized contributions. The EMP result has never been checked before (the virtuals) We are in complete agreement with EMP in the unpolarized limit of our results. The reals have been checked against Gonsalves et al. in complete agreement.

We employ Dimensional Reg. to control both the UV and IR singularities and enforce a

t'Hooft Veltman prescription for $\gamma_5$

$\gamma_5 \to$ <u>anticommuting</u> with $\gamma_\mu$ in $D=4$

in the remaining $D-4$ dimensions

$\gamma_5$ <u>is commuting</u>

Virtuals

Off-shell Renormalization and tensor reductions

(method of [illegible] in QCD)

Renormalization is enforced in the usual way since no $\gamma_5$ is present. No problem with anomalies since $\gamma_5$ appears only from the helicity of the initial state.

We use the P.V. reduction procedure

tensor $\rightarrow$ scalar loop integrals.

We've developed a method - which can be easily implemented in symbolic manipulations - to obtain the scalar expansion of the 1-loop tensor integrals in the presence of massless states

prescription for massless tadpoles.

example

[illegible]

$B(p^2)$

[illegible] we use the PV reduction method

[illegible] $B(0)$ [illegible]

[illegible]

They are intrinsically ambigous.
Usually in DR

$$B(0) \equiv 0.$$

This not <u>correct</u> in general within the Passarino - Veltman reduction.

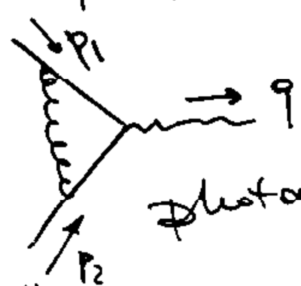
then we observe that $B(0)$ is intrinsically ambigous

we interpret $$\underbrace{B(0) = \lim_{q^2 \to 0} B(q^2)}_{\text{UV Renormalized (off-shell)}}$$

① $\longrightarrow B^R(q^2) \to B(0) \equiv \frac{1}{\omega} = \frac{1}{D-4}$

② while $\to W \; B^R(0) \equiv 0$

We then obtain all the QCD vertices in a single stroke by symbolic manipulation




photon vertex

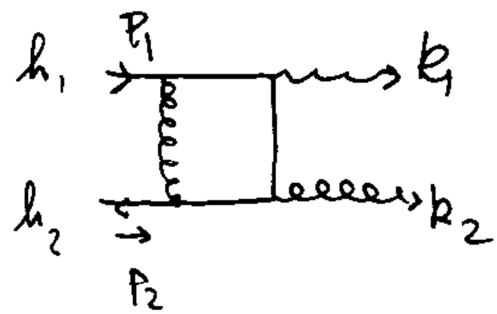
$$
\begin{aligned}
V = \frac{\gamma^\mu}{(t-q^2)^2} \Big\{ & \frac{2}{\omega}\Big[ (L_t - L_{q^2} - 1) q^4 + (L_{q^2} - L_t) q^2 t + t^2 \Big] \\
& + (4 - 3L_{q^2} - L_{q^2}^2 + 2L_t + L_t^2) q^4 + (L_{q^2}^2 - 3L_{q^2} + 3L_t - L_t^2) q^2 t \\
& + (L_t - 4) t^2 \Big\} \quad + \frac{2 p_1^\mu \not{p}_2}{(t-q^2)^3} \Big\{ \frac{2}{\omega}\Big[ (L_t - 1 - L_{q^2}) q^4 + (L_{q^2} - L_t) q^2 t \\
& + t^2 \Big] \\
& + (5 - 5L_{q^2} - L_{q^2}^2 + 3L_t + L_t^2) q^4 \\
& + (L_{q^2}^2 - 5L_{q^2} + 5L_t - L_t^2) q^2 t \\
& + (2L_t - 5) t^2 \Big\} \quad + \frac{2 p_2^\mu \not{p}_2}{t - q^2} (L_t - L_{q^2})
\end{aligned}
$$

for instance, in the total cross section, we need an expansion up to $O(\epsilon^2)$ of vertices, boxes, etc.

With our prescription, this is very easy to obtain.

For any QCD Diagram at 1 loop we generate immediately the Renormalized expressions of the DV coefficients and implement them in actual calculations.

Another example

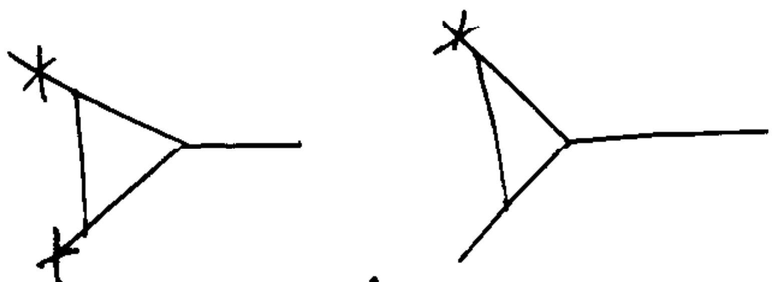



$h_1 \rightarrow$ helicities
$h_2$

We generate after loop-integration Rank 1, Rank 2 and Rank 3 tensor integrals.

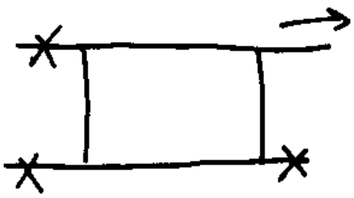
$D^{\mu}, D^{\mu\nu}, D^{\mu\nu\rho}$

Using the PV procedure we introduce a huge # of massless tadpoles. Also a large # of triangle type contributions are generated (of various type)



We use our renormalization prescriptions for

$\omega B(0)$, $B(0)$, $B(q^2)$ and the Renormalized expressions of all the vertices $\Rightarrow$ Renormalized PV coefficients massive scalar box



$k_1^2 = Q^2 \neq 0$

$$I_4(s,t,Q^2) = -i\,(4\pi)^{-n/2}\,\frac{2}{\epsilon^2}\,C_\Gamma \left\{ \frac{(-Q^2)^{-\epsilon}}{st} F\left[1,-\epsilon,1-\epsilon,\frac{-uQ^2}{st}\right] - \frac{(-s)^{-\epsilon}}{st} F\left[1,-\epsilon,1-\epsilon,-u/t\right] - \frac{(-t)^{-\epsilon}}{st} F\left[1,-\epsilon,1-\epsilon,-u/s\right] \right\}$$

(Van Neerven)

(in the Euclidean Region $s<0,\ t>0$)

$$(-s)^{-\epsilon} \to |s|\,e^{i\pi\theta(s)}$$

$$\ln(-s) \to \ln|s| - i\pi\,\theta(s)$$

For calculations of the total cross section $I_4$ is not expanded in $\epsilon$. Since the integrals for $\sigma_{total}$ can be done at finite $\epsilon$.

For the distributions instead, we expand up to $O(1)$

$$I_4(s,t,Q^2) = \frac{i\,(4\pi)^{-n/2}}{st}\,C_\Gamma \left\{ \frac{2}{\epsilon^2}\left[-(-Q^2)^{-\epsilon} + (-s)^{-\epsilon} + (-t)^{-\epsilon}\right] - 2\,\mathrm{Li}_2\left[1-Q^2/s\right] - 2\,\mathrm{Li}_2\left[1-Q^2/t\right] - \ln^2\left(\frac{|s|}{|t|}\right) + \frac{2}{3}\pi^2 \right\}$$

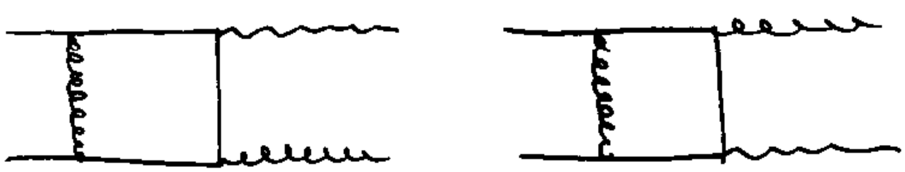
Direct, exchange etc. require different analytic continuations

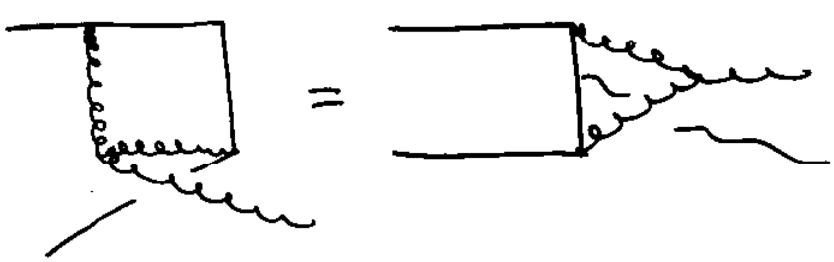
$$
\begin{array}{lll}
Q^2<0 & \to Q^2>0 & \\
s<0 & \phantom{\to} s>0 & \\
t>0 & \to t<0 &
\end{array}
$$

physical region of Drell Yan process

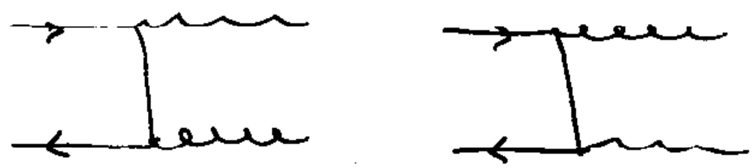
$$(-s)^{-\epsilon} \to |s|^{\epsilon} e^{i\pi}$$
$$(-Q^2)^{-\epsilon} \to (Q^2)^{\epsilon} e^{i\pi}$$

exchanged diagrams





interference with



Tree level amplitudes and helicity violations

the t'Hooft-Veltman scheme induces helicity violations for IR-sensitive contributions.

$$u(p,s)\bar{u}(p,s) = \tfrac{1}{2}\not{p}\left[1+\gamma_5\not{s}\right] \qquad \underline{m=0}$$

$$v(p,s)\bar{v}(p,s) = \tfrac{1}{2}\not{p}\left[1+\gamma_5\not{s}\right]$$

$$u(p,h)\bar{u}(p,h) = \tfrac{1}{2}\not{p}\left[1-\gamma_5 h\right]$$

$$v(p,h)\bar{v}(p,h) = \tfrac{1}{2}\not{p}\left[1+\gamma_5 h\right]$$

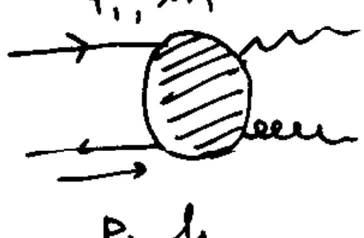
"helicity averages"

$S\cdot p = 0 \quad , S^2 = -1$

$\sigma(h)$ is only a function of the <u>product</u> of $h_1$ and $h_2$

$h = h_1 \cdot h_2$

$p_1, h_1$



$p_2, h_2$

$\rightarrow (1+h)\,\sigma^{\text{unpol.}}$

helicity conservation if $\{\gamma_5, \gamma_\mu\} = 0$ completely helicity + (fermion) $\rightarrow h_1 = +1$

helicity + (antifermion) $\rightarrow h_2 = -1$

$(1+h) = 0$

therefore for the virtual corrections one would expect that $|M(+,+)|^2 = 0 \rightarrow |M(-,-)|^2 = 0$

Now

$$\Delta \overline{M}^2 \equiv \frac{1}{2}\left[|M(+,+)|^2 - |M(+,-)|^2\right]$$

$$\sigma^{unp} = \frac{1}{4}\left\{|M(+,+)|^2 + |M(+,-)|^2 + |M(-,+)|^2 + |M(-,-)|^2\right\}$$

$$|M(+,-)|^2 = |M(-,+)|^2$$

whence $\sigma^{unp} = -\sigma^{pol} = -\Delta \overline{M}^2$

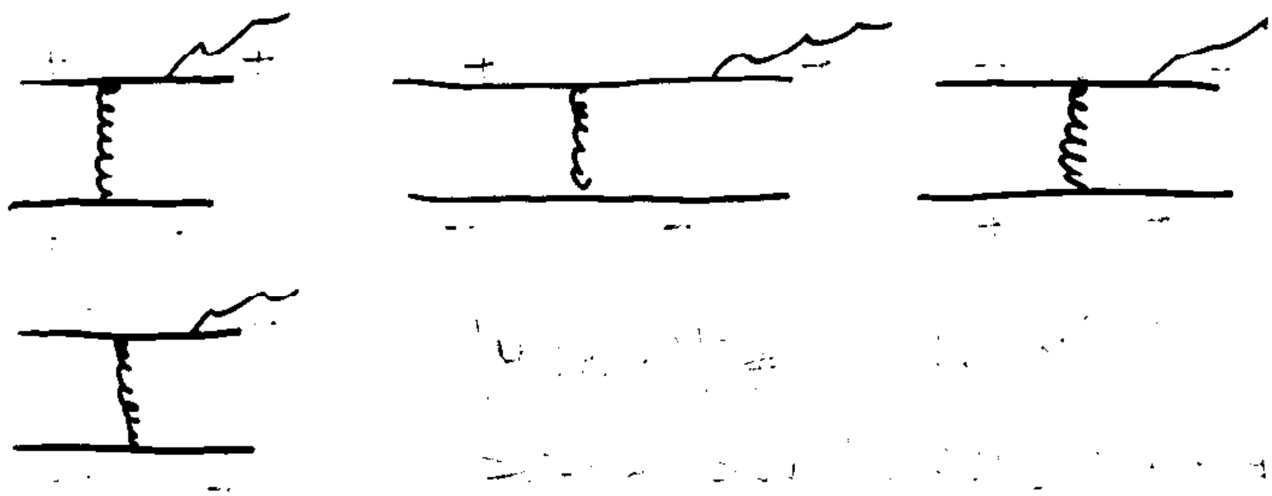
Asymmetry $= \sigma^{pol}/\sigma^{unp} = -1$

therefore $|M(+,+)|^2$

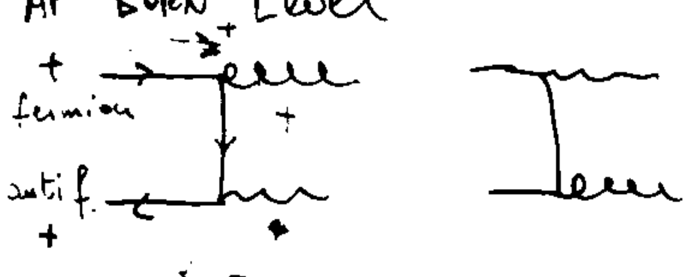
"measures" the helicity violating part of the

$|\text{Amplitude}|^2$

Notice that for scattering contributions (real emissions



At BORN Level




$\rightarrow |M(+,+)|^2 = 0$

now, since there are not singularities the helicity violation, in the HVBM scheme is $\epsilon$-Dependent.

Consider 

now to $O(\epsilon^2)$

$$|\overline{M}|^2 = \frac{1}{4} \sum_{h_1 h_2} |M(h_1, h_2)|^2$$

$$\Delta \overline{M}^2 = \frac{1}{2}\left( |M_{++}|^2 - |M_{+-}|^2 \right)$$

$$|M(h_1, h_2)|^2 = |M(h)|^2 = |\overline{M}|^2 - h\, \Delta\overline{M}^2 \qquad \text{(CCFG)}$$

with

$$|\overline{M}|^2 = e_f^2 g^2 g_s^2 \frac{C_F}{N_c} \frac{2}{tu} \left\{ (1-\epsilon)\left(2Q^2 s + (1-\epsilon)(t^2+u^2)\right) - 2\epsilon tu \right\}$$

Therefore : since the result is IR safe

$\epsilon \to 0$

then $|M_{++}|^2 \to 0$ and $\Delta|M|^2 = -|\overline{M}|^2$

In the factorization formula for the non-singlet EMP factorize $|\overline{M}|^2$ up to $O(\epsilon^2)$

$$K_2 T_B(Q^2, u, t) = K\, T_0(Q^2, u, t) \leftarrow (\text{EMP})$$

$$K = 2\pi\alpha \frac{C_F}{N_c} \frac{(1-\epsilon)}{\Gamma[1-\epsilon]} \left(\frac{4\mu^2\pi}{Q^2}\right)^{\epsilon} \left(\frac{sQ^2}{ut}\right)^{\epsilon}$$

Therefore : [illegible] terms arise [illegible]

[illegible] Dimensional Regularization in the $\overline{MS}$ scheme

and are not present "naturally" in the [illegible] schemes.

The structure of the result for the virtual contributions in EMP (unpolarized non singlet)

$$s\frac{d\sigma}{dt\,du} = e_f^2 K_2 \frac{\alpha_s}{s}\delta(s+t+u-Q^2)\Big\{ \underbrace{\text{BORN LEVEL}}_{T_B} \otimes$$

$$\otimes \left[ \left\{ \frac{c_1}{\epsilon^2} + \frac{c_2}{\epsilon} \right\} \right] + O(\alpha_s) \Big\}$$

complex expression, finite.

in $\overline{MS}$

$$\frac{c_1}{\epsilon^2} = \frac{2C_F + N_c}{\epsilon^2}\ , \quad \frac{c_2}{\epsilon} = \frac{1}{\epsilon}\Big\{ 3C_F - 2C_F \ln s/Q^2 + \frac{11}{6}N_c + N_c \ln sQ^2/ut - \tfrac{1}{3}N_F \Big\}$$

\# of flavours

Double poles and single poles correctly factorize and $T_B$ is the

$O(\epsilon^2)$ Born level 2-to-2- cross section

Virtuals in the non-singlet

$$\frac{s\, d\sigma^V}{dt\, du}(s,t,u,h) = e_f^2 K_2 \frac{\alpha_s}{s}\delta(s+t+u-Q^2)\left\{\left((1+hT_B)+h\epsilon A_B\right)\times\right.$$

$$\left[1-\frac{\alpha_s}{2\pi}\frac{\Gamma(1-\epsilon)}{\Gamma[1-2\epsilon]}\left(\frac{4\pi\mu^2}{Q^2}\right)^\epsilon\left(\frac{2C_F+N_c}{\epsilon^2}+\frac{1}{\epsilon}\left(3N_c-2C_F\ln s/Q^2+\frac{11}{6}N_c+N_c\ln\frac{sQ^2}{ut}-\frac{1}{3}N_F\right)\right)\right]$$

$$-\frac{\alpha_s}{2\pi}(1+h)\left[\pi^2(4C_F+N_c)\frac{2Q^2s+t^2+u^2}{3tu}-2(2C_F-N_c)\frac{Q^2(t^2+u^2)}{tu(t+u)}\right.$$

$$-2C_F\left(\frac{8(2Q^2s+t^2+u^2)}{tu}-\frac{Q^4s(t+u)}{tu(Q^2-u)(Q^2-t)}-\frac{t^2+u^2}{(Q^2-u)(Q^2-t)}\right)$$

$$-2\left(\mathrm{Li}_2\left(\frac{t}{t-Q^2}\right)+\frac{1}{2}\ln^2\left(1-\frac{Q^2}{t}\right)\right)\left(N_c\frac{2s+u}{t}+2C_F\frac{s^2+(s+u)^2}{tu}\right)$$

$$-2\left(\mathrm{Li}_2\left(\frac{u}{u-Q^2}\right)+\frac{1}{2}\ln^2\left(1-Q^2/u\right)\right)\left(N_c\frac{2s+u}{t}+2C_F\frac{s^2+(s+t)^2}{tu}\right)$$

$$+2(2C_F-N_c)\left(\mathrm{Li}_2\left(-\frac{t+u}{s}\right)\frac{2Q^2s+u^2+t^2+2s^2}{ut}\right.$$

$$+\left(2\ln(s/Q^2)\frac{Q^4-(t+u)^2}{(t+u)^2}+\ln^2(s/Q^2)\,s^2/tu\right)$$

$$-\left(\ln|t|/Q^2\,\ln s/Q^2-\frac{1}{2}\ln^2|t|/Q^2\right)\frac{s^2+(s+u)^2}{tu}$$

$$\left.-\left(\ln s/Q^2\,\ln|u|/Q^2-\frac{1}{2}\ln^2|u|/Q^2\right)\frac{s^2+(s+t)^2}{tu}\right)$$

$$+2\ln|u|/Q^2\left(C_F\frac{4Q^2s-2su+tu}{(Q^2-u)^2}+\frac{N_c u}{Q^2-u}\right)$$

$$+2\ln|t|/Q^2\left(C_F\frac{4Q^2s-2st+tu}{(Q^2-t)^2}+\frac{N_c}{Q^2-t}\right)-2\ln|t|/Q^2\,\ln|u|/Q^2\,N_c\frac{2Q^2s+t^2+u^2}{tu}$$

where we have factorized the lowest order spin-dependent cross section

$$\frac{d\sigma}{dt}(s,t,h) = e_q^2 K_2 \frac{\alpha_s}{s}\left[(1+h)T_B(Q^2,u,t) + h\epsilon A_B(Q^2,u,t)\right]$$

if we send $\epsilon \to 0$ and $h \to 0$ $\Rightarrow$ EMP result never checked before

$\underline{\underline{h\epsilon A_B(Q^2,u,t)}}$ generates an helicity violating contribution

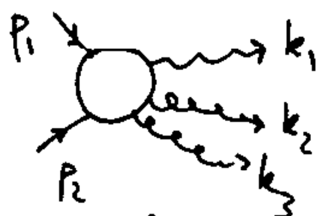
$$\frac{s\,d\sigma^{++}}{dt} = -e_q^2 K_2 \frac{\alpha_s}{2\pi s} A_B(s,t)\left\{3C_F - 2C_F \ln s/Q^2 + \frac{11}{6}N_c + N_c \ln sQ^2/ut - \frac{1}{3}N_F\right\}$$

We have to look at the real emission diagrams.

# Collinear initial and final state factorization

– distributions appear in the real emission

$\left(\frac{1}{s_{23}}\right)_+$ and $\left(\frac{\ln(s_{23})}{s_{23}}\right)_+$




$$s_{23} = (k_2 + k_3)^2$$

Bare vs Renormalized structure functions

$$f_j^A(x, M^2) = \int_x^1 \frac{dz}{z} \left\{ \delta_{ij}\, \delta(z-1) - \frac{\alpha_s}{2\pi} R_{j\to i}(z, M^2) \right\}_\epsilon f^A_{j,\text{bare}}(x/z)$$

$$R_{j\to i} = -\frac{1}{\epsilon} P_{i\to j}(z) \frac{\Gamma[1-\epsilon]}{\Gamma[1-2\epsilon]} \left(\frac{4\pi\mu^2}{M^2}\right)^\epsilon + C_{j\to i}(z)$$

$$P_{qq} = C_F \frac{(1+z^2)}{(1-z)_+} - \epsilon(1-z)$$

$P_{qg}$

$P_{gq}$

$P_{gg}$

$$\frac{s\, d\tilde{\sigma}_{ij}}{dt\, du} = \frac{s\, d\sigma_{ij}}{dt\, du} - \frac{\alpha_s}{2\pi} \sum_k \int_0^1 dz_1\, R_{i\to k}(z_1, M^2)\, \frac{s\, d\sigma_k}{dt\, du}\bigg|_{p_1 \to z_1 p_1}$$

$$- \frac{\alpha_s}{2\pi} \sum_k \int_0^1 dz_2\, R_{j\to k}(z_2, M^2)\, \frac{s\, d\sigma_k}{dt\, du}\bigg|_{p_2 \to z_2 p_2}$$

IR sensitive

Sets of diagrams

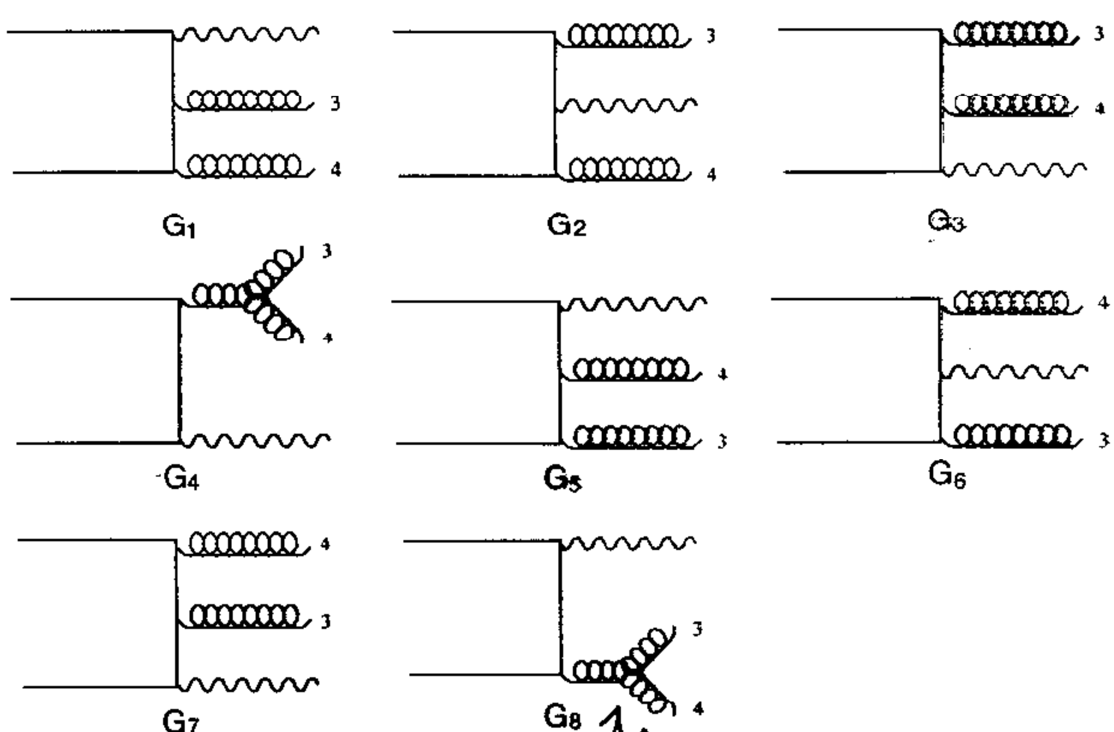
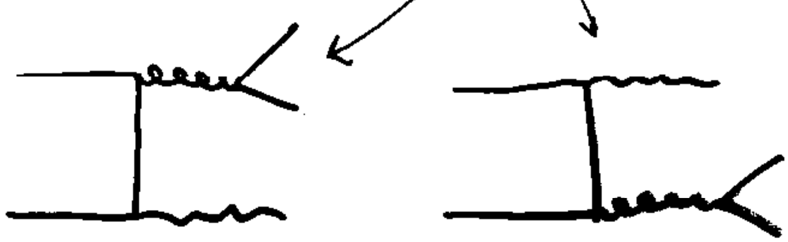



Figure 4: Diagrams which contribute to the process $q + \bar{q} \to \gamma^* + G + G$



F1 F2

included with the Ci's

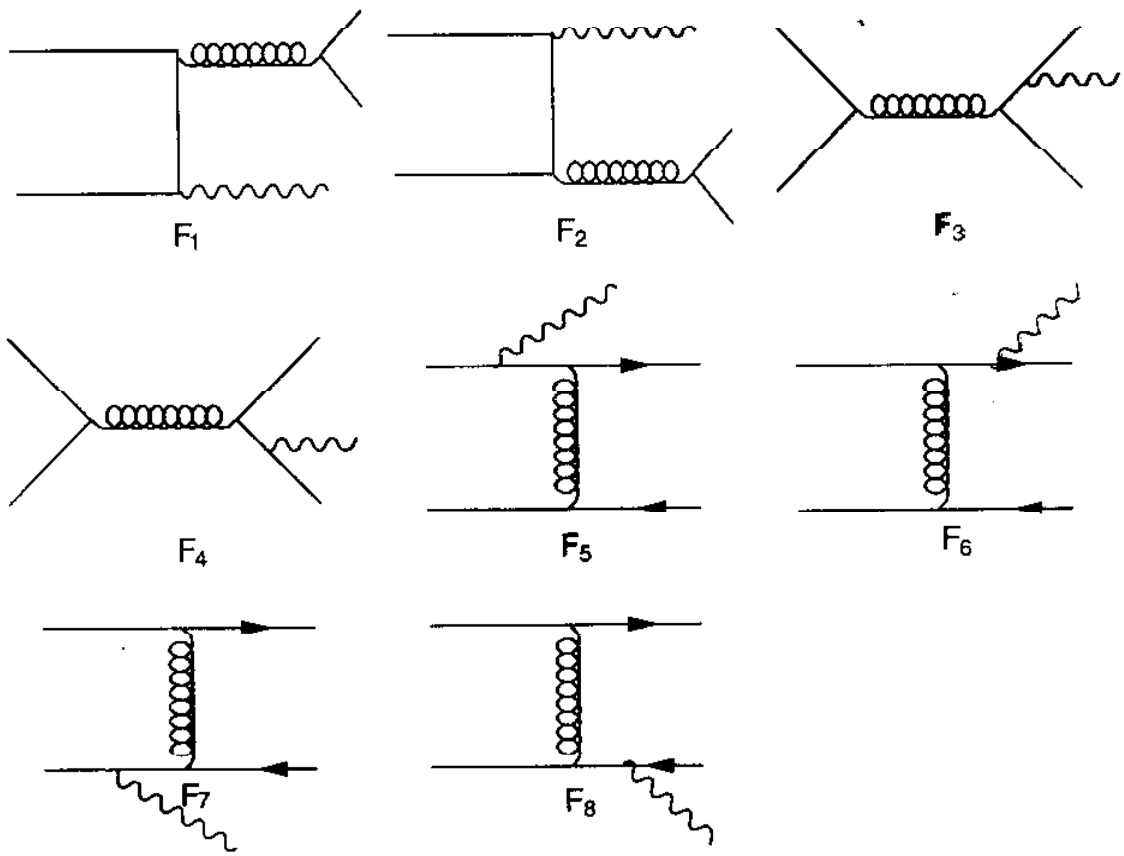



Figure 3: Diagrams which contribute to the process $q + \bar{q} \to \gamma^{*} + q + \bar{q}$

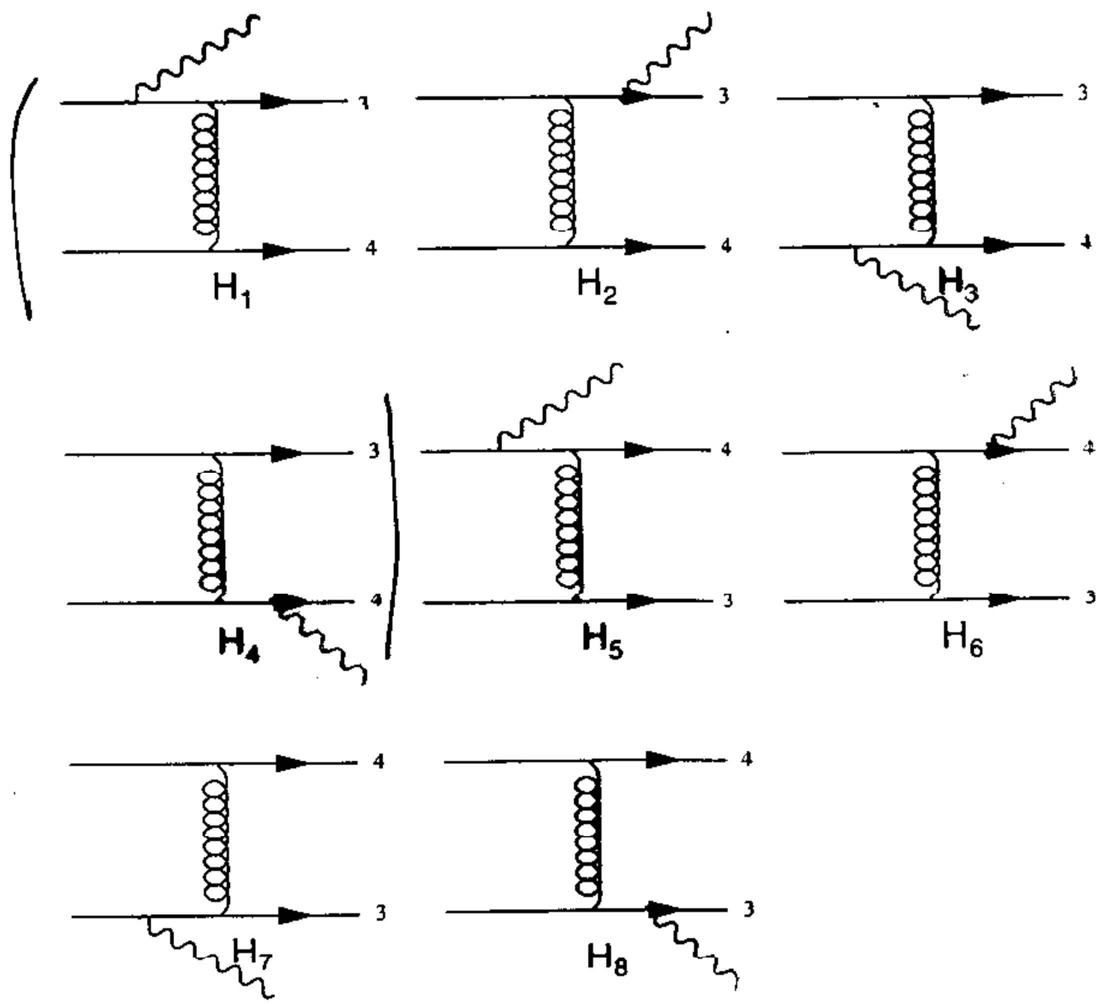



Figure 5: Diagrams which contribute to the process $q + q \to \gamma^* + q + q$

Hat-momenta integrations and helicity violation

$$\gamma_\mu = \underbrace{\hat{\hat{\gamma}}_\mu}_{4\,\text{Dim}} \oplus \underbrace{\hat{\gamma}_\mu}_{n-4\,\text{Dim.}}$$

$$k = \hat{\hat{k}} + \hat{k}$$

non-hat momenta

$$PS_3 = \frac{(4\pi)^{2\epsilon}}{2^8\pi^4 s\,\Gamma[1-2\epsilon]}\left\{\frac{s}{s_{23}(tu - Q^2 s_{23})}\right\}^{\epsilon} \times I_{1,2}$$

$\frac{1}{\epsilon^2} + \frac{1}{\epsilon} + \cdots$

$O(1)$

hat-momenta

$$PS_2 = \int d^n k_2\, \delta(k_2^2)\, \delta\left((k_{23} - k_2)^2\right)\ \hat{k}_2^{\,2}$$

we can remove only $\underline{3}$ hat momenta, by choosing a suitable ref. frame, but $\underline{1}$ is left.

$O(\epsilon)$

$\frac{1}{\epsilon^2} + \frac{1}{\epsilon} + \cdots$

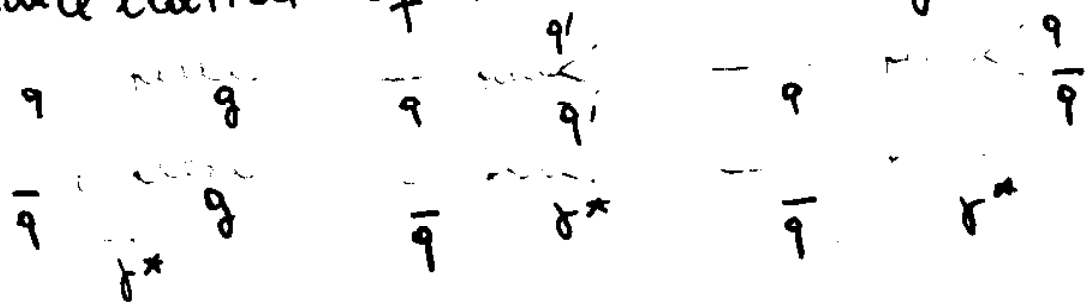
interference contributions contain hat-momenta give $1/\epsilon$ and $O(1)$ terms responsible of helicity violation (in the real emission).

the collinear and soft divergences of the two unobserved jets are described by the limit

$$s_{23} \to 0$$

$$\frac{1}{s_{23}^{1+\epsilon}} = -\frac{1}{\epsilon}\delta(s_{23})\left\{1-\epsilon \ln A + \tfrac{1}{2}\epsilon^2 \ln^2 A\right\} + \left(\frac{1}{s_{23}}\right)_{A+} - \epsilon\left(\frac{\ln s_{23}}{s_{23}}\right)_{A+}$$

Cancellation of the collinear singularities



$\left|\sum_i G_i\right|^2 + \left|F_1+F_2\right|^2$ are IR sensitive

polarized and unpolarized are now different

the difference comes in part from hat-momenta contributions

and in part from 3-body contributions $\sim \frac{1}{(s_2)^{1+\epsilon}} \otimes$ Trace

3-body contributions

(1) $$\delta\sigma \sim 4N_f\,\delta(s_2)\,\frac{Q^4 - Q^2 t + 2t^2 - Q^2 u + 2tu + 2u^2}{3tu}$$

(2) hat momenta

If we use the $\overline{MS}$ scheme then

$$\underbrace{\text{Virtual}}_{\sigma_V} + \underbrace{|C_1 + \dots + C_8|^2 + |F_1 + F_2|^2}_{\sigma_I} \to \text{IR [illegible] and finite}$$

But due to an overall helicity violating term [illegible]

$$\left(\sigma_V + \sigma_I\right)^{pol}_{Fact.} = (1+h)\,\sigma^{unp}_{EMP} + h H_t$$

However, in the $\overline{MS}$ scheme

$$\underset{\text{unpol}}{P_{qq}} = \underset{\text{polarized}}{\Delta P_{qq}} = C_F \frac{(1+z^2)}{(1-z)_+} - \epsilon(1-z$$

It has been noted before

Gordon and [illegible], Florian and De [illegible]

that if

$$\Delta P_{qq} = C_F \frac{(1+z^2)}{(1-z)_+} - \epsilon(1-z) + [illegible] \qquad \overline{MS}_p$$

$$\left(\sigma_V + \sigma_R\right)^{pol}_{Fact} = (1+h)\,\sigma^{unp}$$

However, we truly need the $\overline{MS}$ scheme

since the evolution equations are studied in this scheme usually

$\Rightarrow$ it is crucial to know the helicity violating contributions at parton level .. or $H_t$.

Question

if we modify $\Delta P_{qq}$ from $\overline{MS}$ to $\overline{MS}_p$

what is the structure of $\sigma_V + \sigma_R \equiv \sigma_V + \sigma_I + \sigma_{II} + \sigma_{III} - \sigma_{IV}$

$$\left. \sigma_V + \sigma_I \right|_{\overline{MS}_p} = (1+h)\, \sigma^{[illegible]}_{EMF}$$

[illegible] check the validity of [illegible] formulae in this modified scheme [illegible]

$$\frac{s\, d\sigma_I^R}{dt\, du} = e_f^2 K_2 \frac{\alpha_s}{s} \Big((1+h) T_B + h\epsilon A_B\Big) \delta(s_{23}) \frac{\alpha_s}{2\pi} \frac{\Gamma[1-\epsilon]}{\Gamma[1-2\epsilon]} \left(\frac{4\pi\mu^2}{Q^2}\right)^\epsilon \otimes$$

double / single

$$\otimes \Bigg( \frac{2C_F + N_c}{\epsilon^2} + \frac{1}{\epsilon}\Big(3C_F - 2C_F \ln s/Q^2 + \frac{11}{6} N_c + N_c \ln \frac{sQ^2}{ut} - \frac{1}{3} N_F$$

$$+ \frac{\alpha_s}{2\pi} \Bigg\{ \Big(\frac{11}{6} N_C - \frac{1}{3} N_F\Big) \ln\left(Q^2/A\right) + \Big(\frac{67}{18} N_C - \frac{5}{9} N_F\Big) + N_C \ln\left(Q^2/A\right)^2$$

$$+ \Big(C_F - \frac{1}{2} N_C\Big)\left(\frac{\pi^2}{3} + \ln\left(\frac{A^2 s}{Q^2 ut}\right)^2\right) \Bigg\} + \frac{\alpha_s}{2\pi} (1+h) T_B \Bigg[ \frac{2N_F - 11 N_C}{6\,(s_2)_{A+}}$$

$$+ (2C_F - N_C)\left\{ 2\left(\frac{\ln(s_2/A)}{s_2}\right)_{A+} + \left(\frac{1}{s_2}\right)_{A+} \ln \frac{s^2 A^2}{(u-s_2)(t-s_2)(ut - Q^2 s_2)} \right\}$$

$$+ \frac{2C_F}{(s_2)_{A+}} \ln \frac{ut - Q^2 s_2}{(u-s_2)(t-s_2)} + 4 C_F \left(\frac{\ln s_2/Q^2}{s_2}\right)_{A+} \Bigg] \Bigg\}$$

[illegible]

# Drell Yan Summary.

[illegible]

[illegible] the $\overline{MS}$ $\overline{MS}_p$ schemes.

clear scheme dependence.

$$\sigma^{pol} = (1+h)\,\sigma^{unp}_{EMP} + h H_t + H_{234} + h H'_{234}$$

$\left.\begin{matrix} H_{234} \\ H'_{234} \end{matrix}\right\}$ Closely related to the EMP result for the [illegible]

$\hookrightarrow$ IR finite contributions coming from

[illegible]

$q\bar{q}$ scattering [illegible]

as $h \to 0$ we recover for $H_{234}$ and $H'_{234}$ the EMP result.

[illegible]

[illegible] (non singlet virtual)

[illegible] a multiple [illegible]

[illegible]

$$[illegible] = T_E + [illegible] A + [illegible]$$

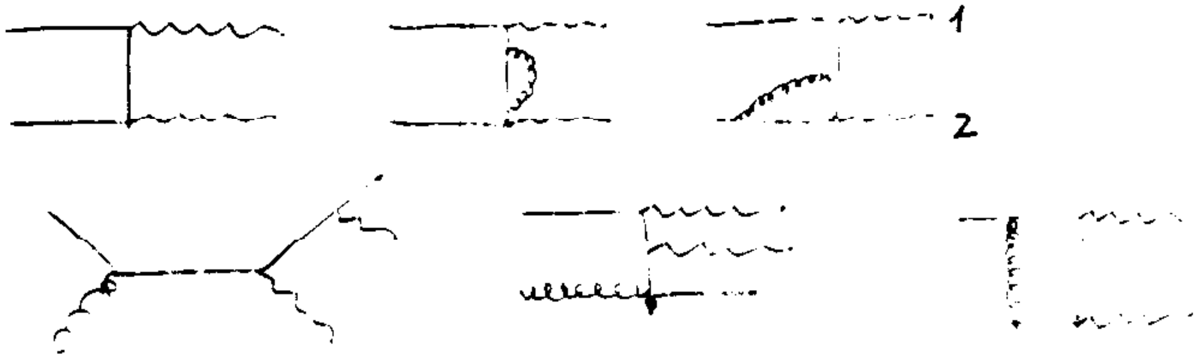
new structures
due to transverse spin

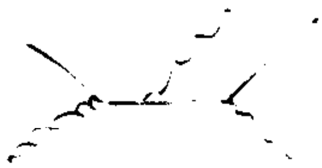
[illegible]

the longitudinal qg sector of DY
for longitudinally polarized contributions
from the initial state is also in progress

[illegible]

Double prompt photon production to NLO
(GORDON and C.C.)



sensitive to $\Delta G$, gluon polarization

(Aurenchie et al. unpolarized)

$$\underbrace{\frac{d\sigma}{dk_t^1\, dy^1\, dz}}_{\text{photon 1}} \qquad z = -k_t^1 \cdot k_t^2 / |k_t^1|^2$$

differential in the transverse momentum and rapidity of one of the photons

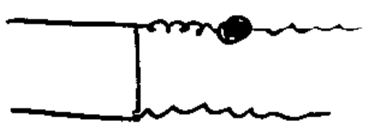
$z$ → information about the $k_t$ of ... but not its rapidity

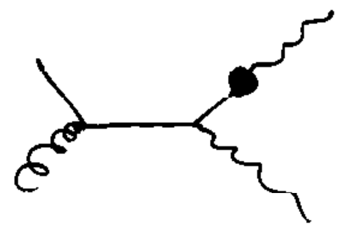
lowest order $\rightarrow$ $z = 1$ back to back
$w = 1$

$$\frac{d\sigma}{dv\,dw\,dz}(q\bar{q} \to \gamma\gamma) = \frac{2\pi\alpha_{em}^2}{3s}\, e_q^4\, \frac{1-2v+2v^2}{v(1-v)}\,\delta(1-z)\,\delta(1-w)$$

$$\frac{d\sigma}{dk_t^1\, dy_1\, dz} = \frac{2\pi k_t^1}{\pi S}\int_{VW}^{V}\frac{dv}{(1-v)}\, f_q^A(x_1, M^2)\, f_{\bar{q}}^B(x_2, M^2)\,\frac{d\hat{\sigma}}{dv\,dw\,dz} + (q\bar{q}$$

there are also fragmentation contributions





fragmentation scale

$$\Delta f_a^A(x, Q^2) = f_{a,+}^A(x, Q^2) - f_{a,-}^A(x, Q^2)$$

The real emissions are calculated in the C.M. frame of the photon-gluon pair.

All the calculation can be done analytically

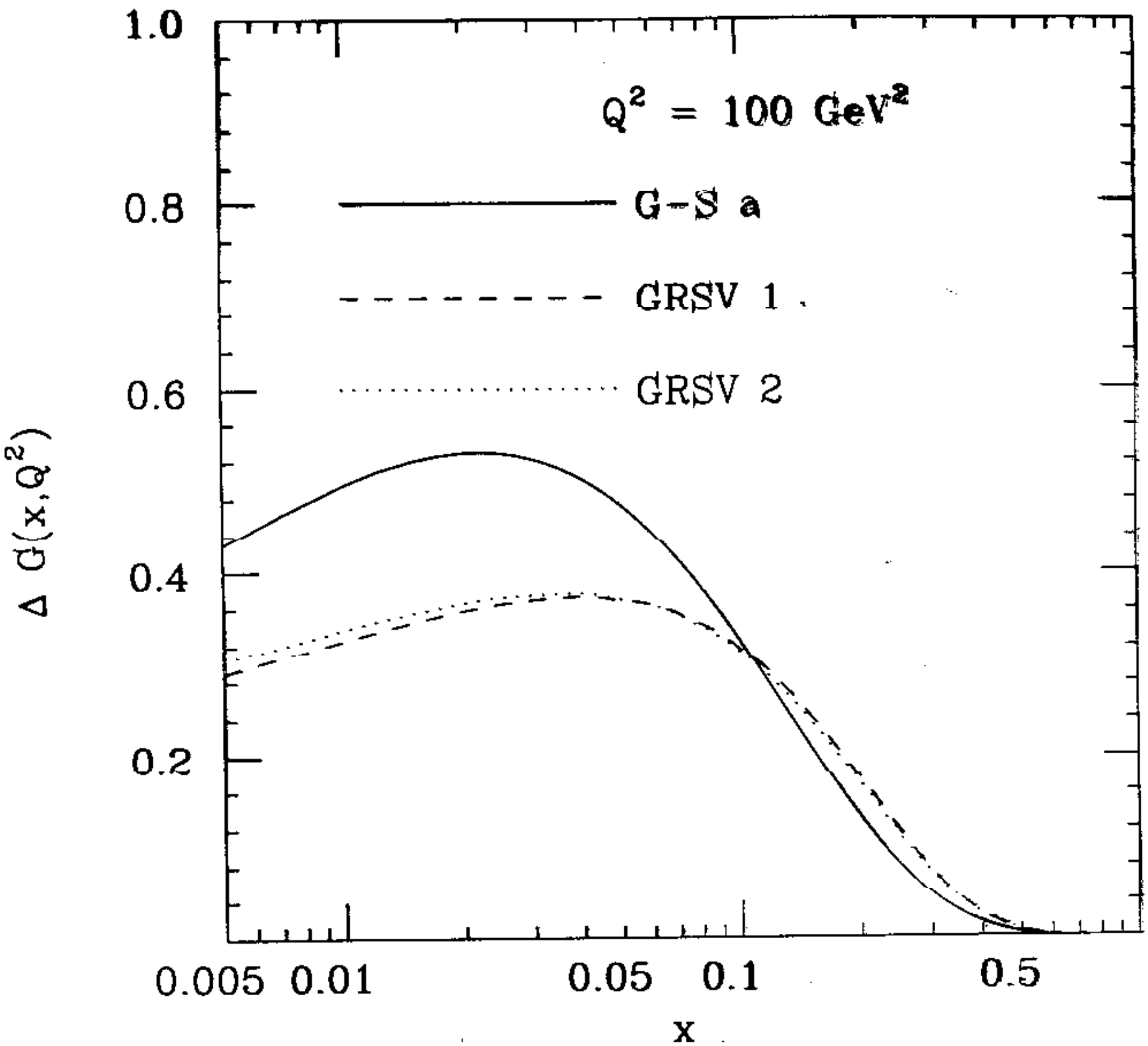
$$\hat{PS}_3 = C_\epsilon \left(\frac{-\epsilon}{1-\epsilon}\right) \int dv\, dw\, (1-v)^{-\epsilon} (1-w)^{1-\epsilon} v^{2-2\epsilon} w^{-\epsilon}$$
$$\times \int_0^\pi d\theta_2\, dz\, \delta(z - m\cdot k_2)\, \sin\theta_2^{\,2-2\epsilon} \int_0^\pi d\theta_1 \sin\theta_1^{\,3-2\epsilon}$$

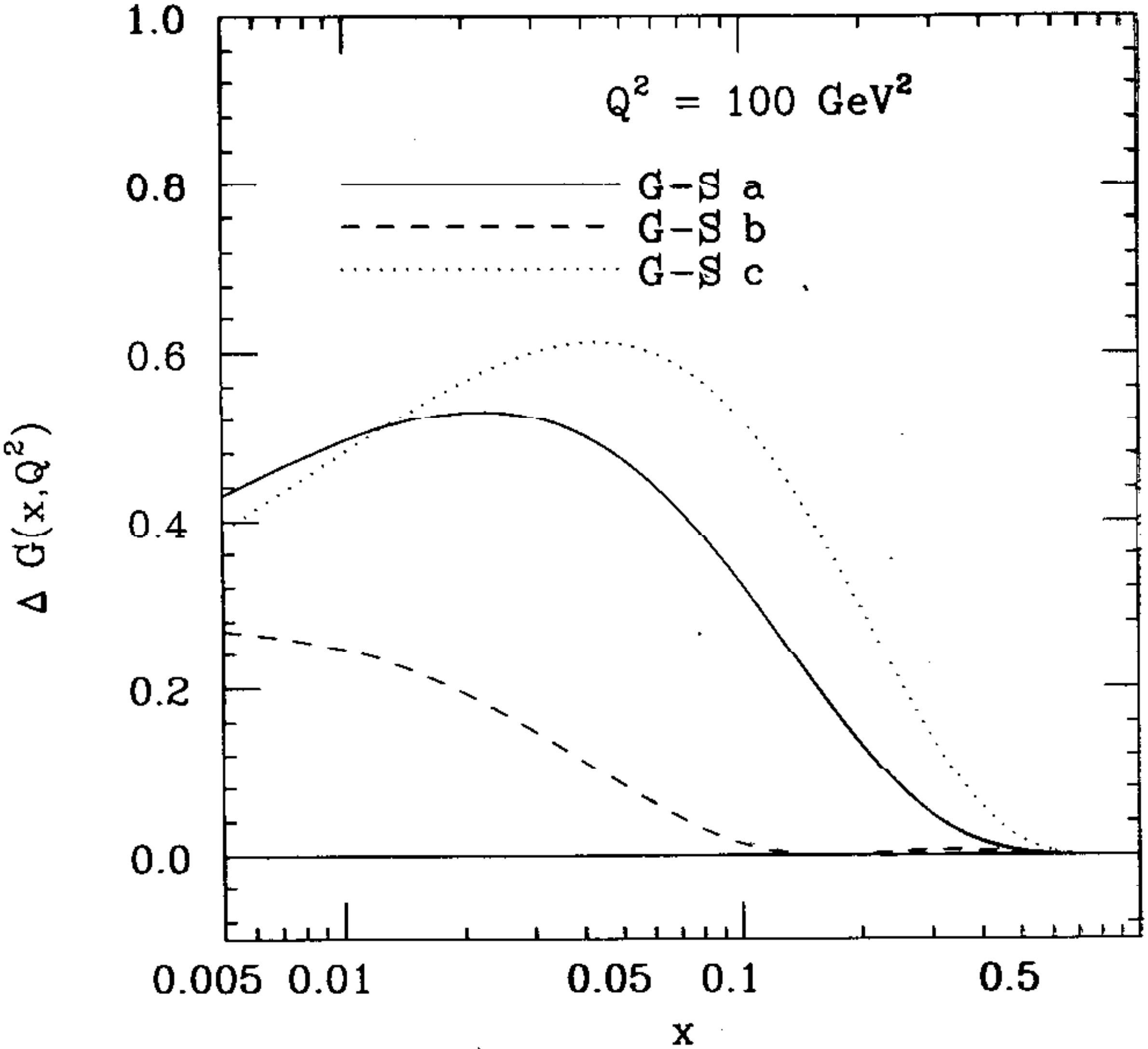
$m = (s k_3 + t p_2 + u p_1)/tu$

again : in the $\overline{HS}_p$ scheme

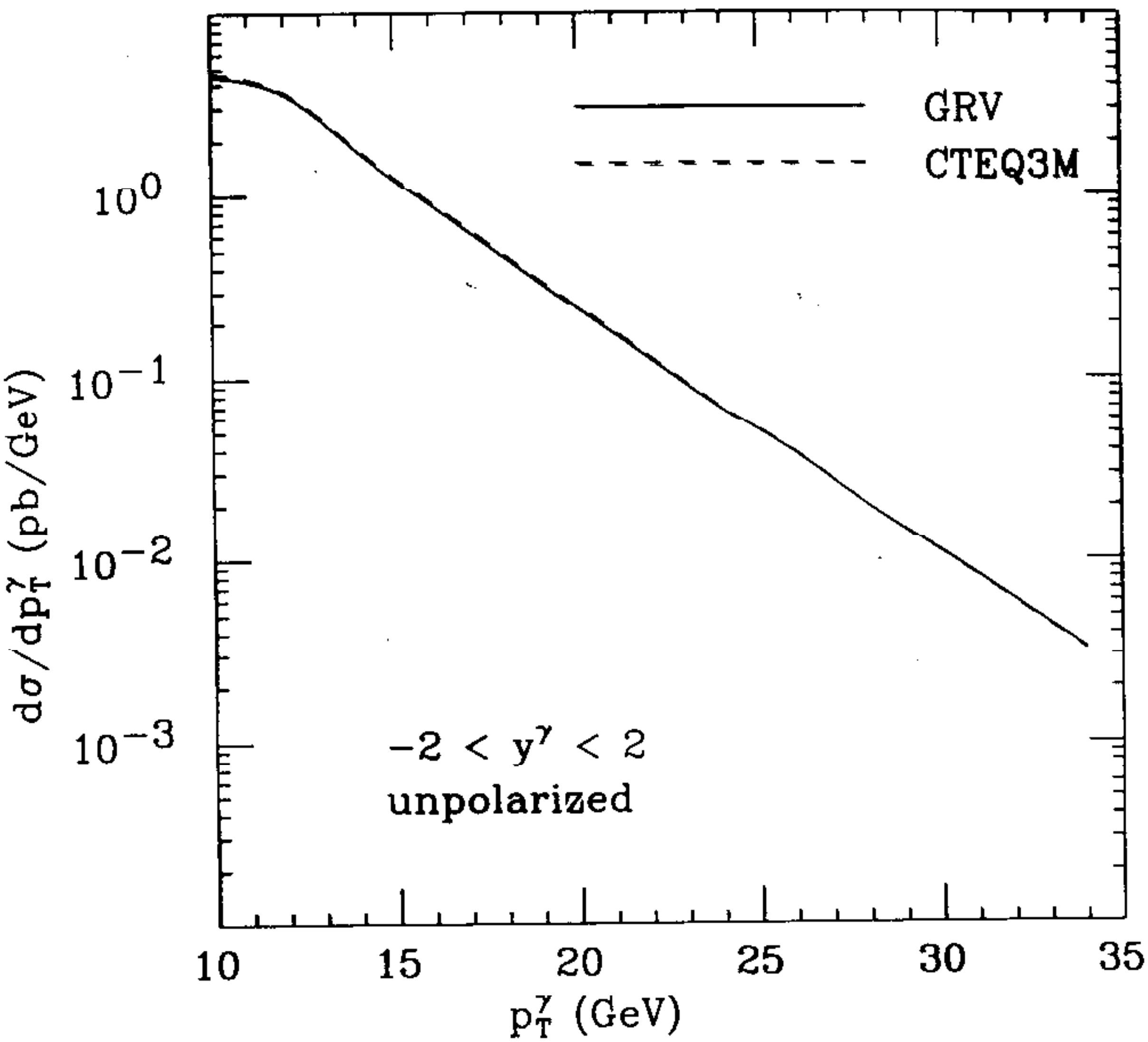
$\sigma^{pol} - \sigma^{unp}$ and helicity is conserved

(Aurenche et al)

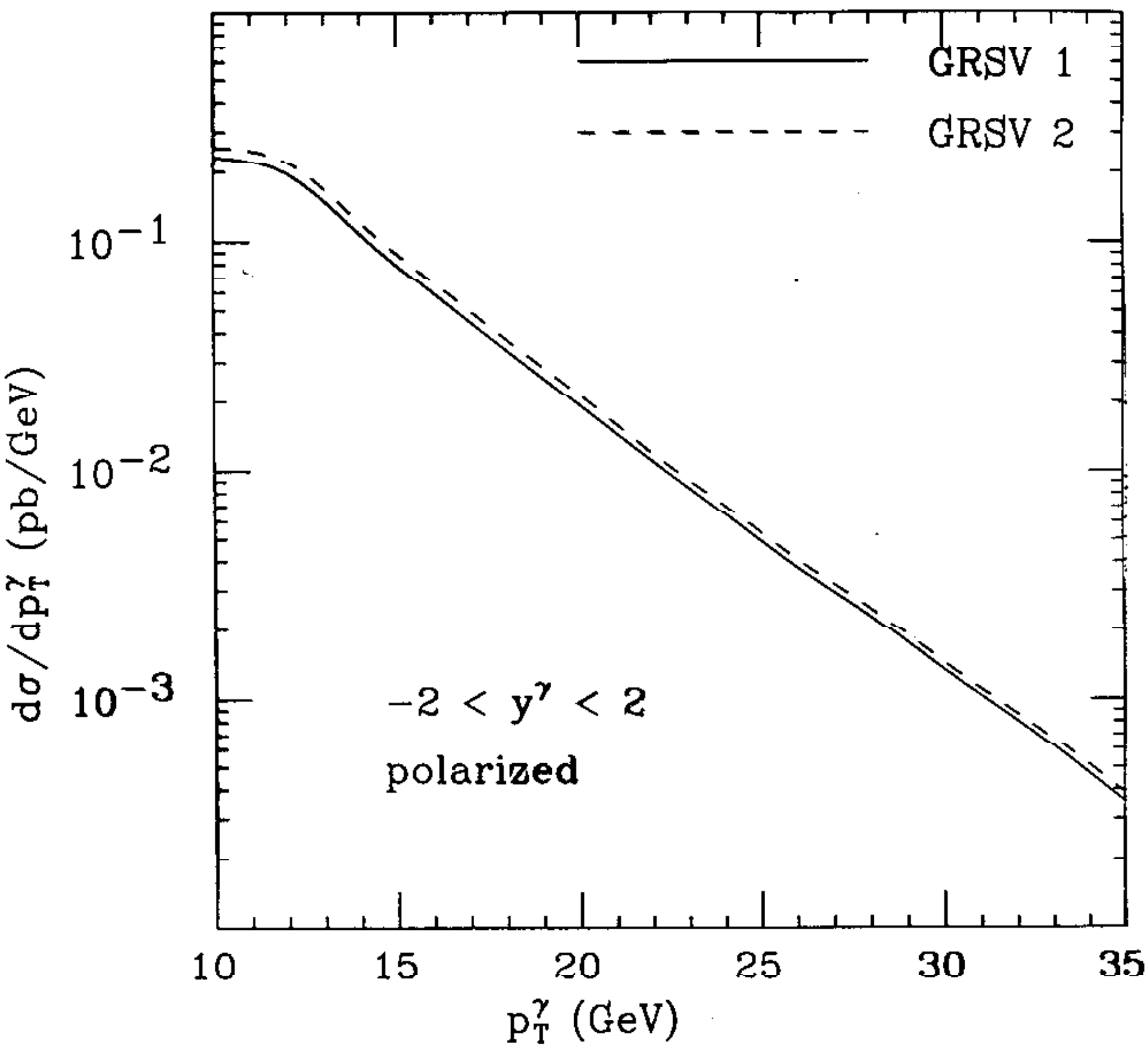

$Q^2 = 100\ GeV^2$
G-S a
GRSV 1
GRSV 2
$\Delta\ G(x,Q^2)$
1.0
0.8
0.6
0.4
0.2
0.005
0.01
0.05
0.1
0.5
x

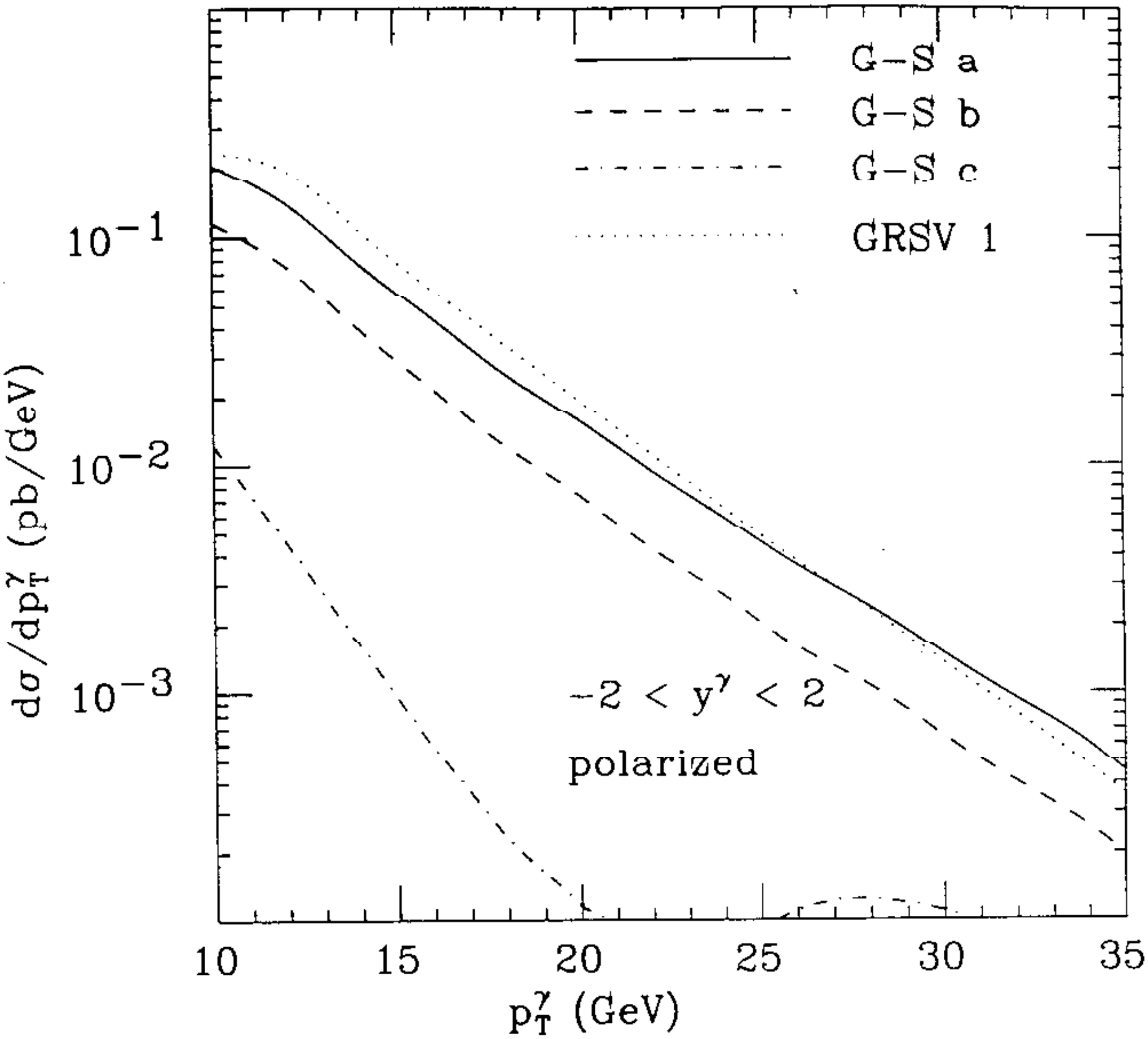


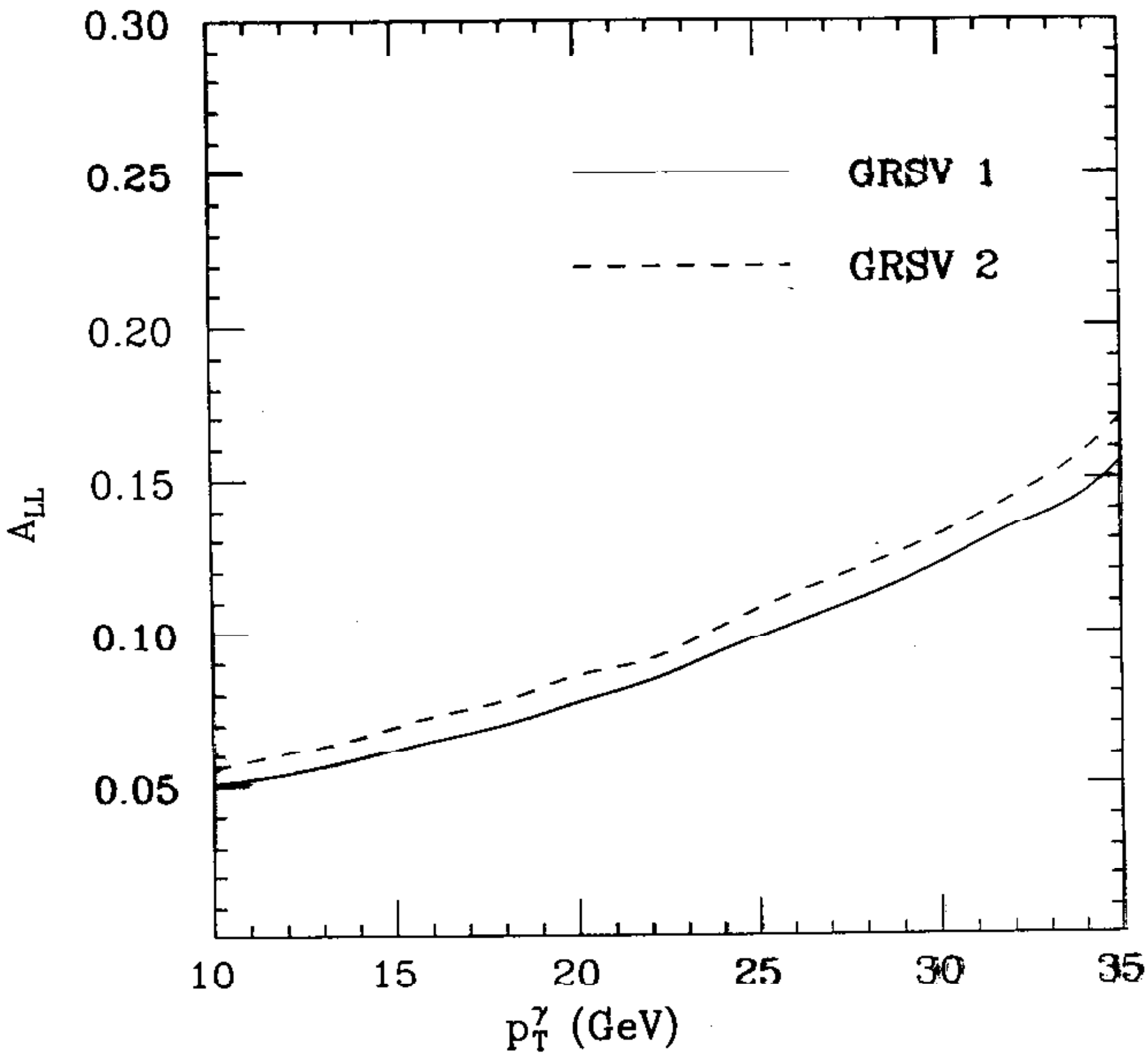
$Q^2 = 100\ GeV^2$
G-S a
G-S b
G-S c
$\Delta G(x,Q^2)$
1.0
0.8
0.6
0.4
0.2
0.0
0.005
0.01
0.05
0.1
0.5
x

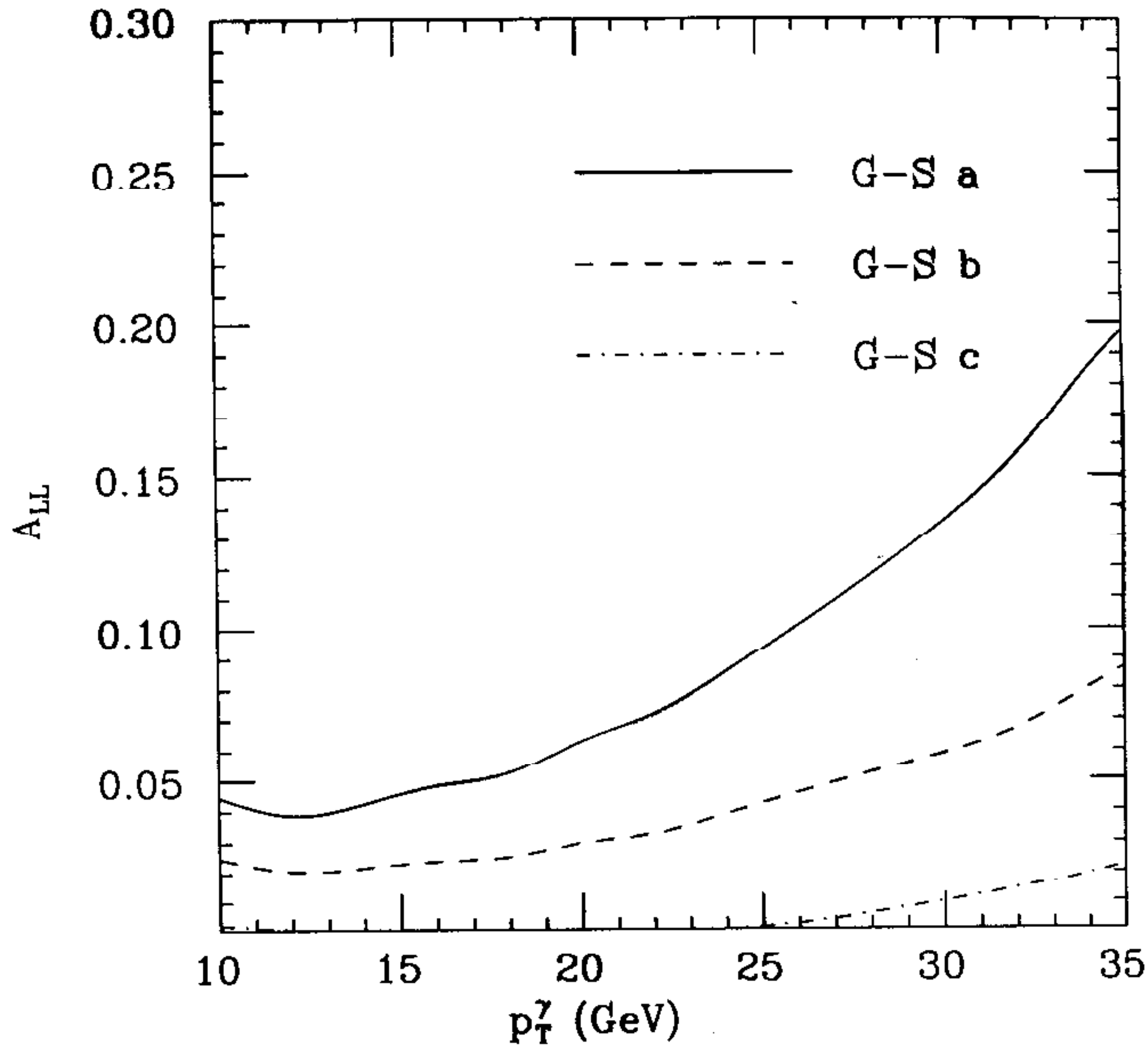


GRV
CTEQ3M
$10^0$
$10^{-1}$
$10^{-2}$
$10^{-3}$
$d\sigma/dp_T^\gamma$ (pb/GeV)
$-2 < y^\gamma < 2$
unpolarized
10
15
20
25
30
35
$p_T^\gamma$ (GeV)

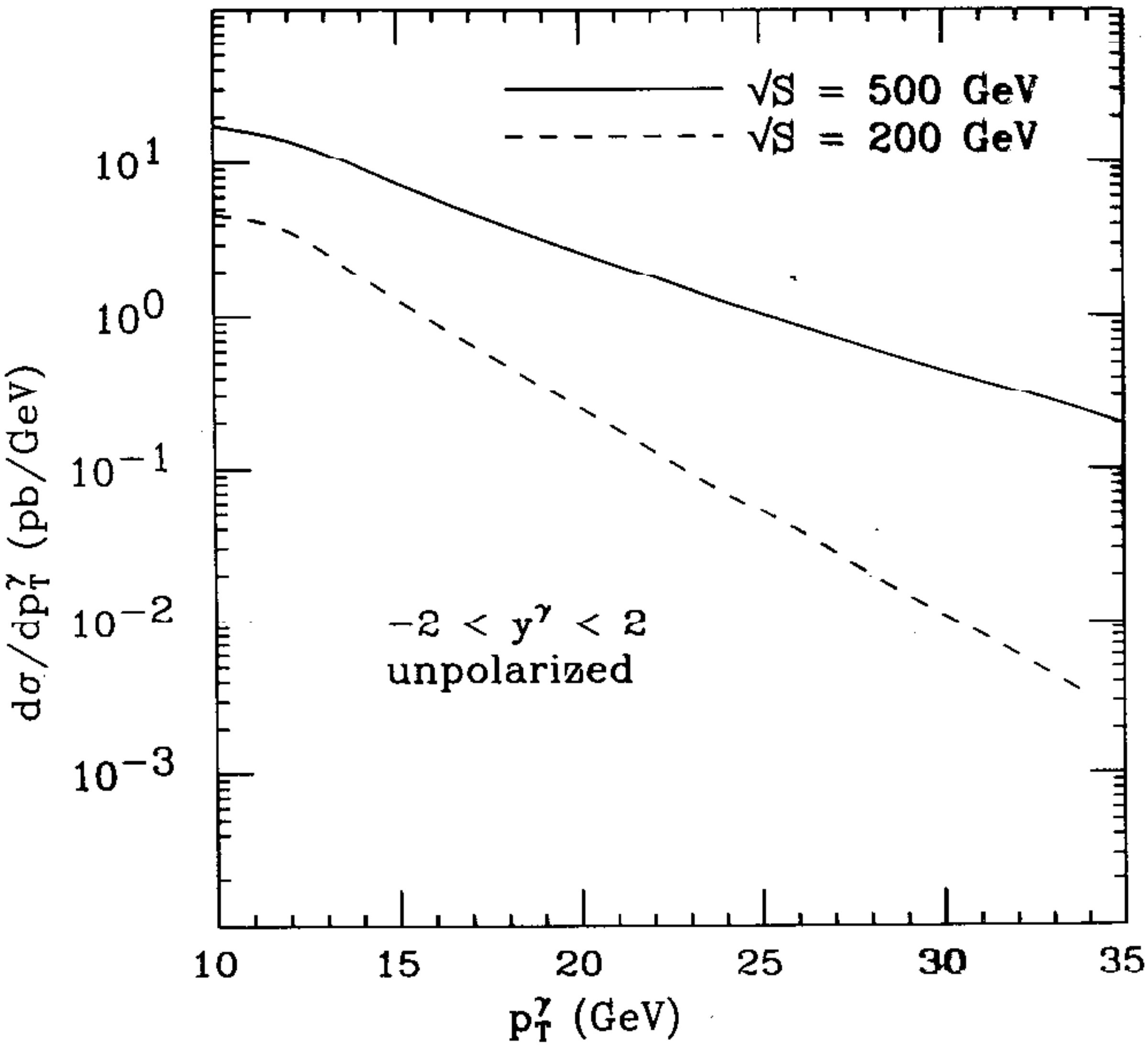

GRSV 1
GRSV 2
$10^{-1}$
$10^{-2}$
$10^{-3}$
$d\sigma/dp_T^\gamma$ (pb/GeV)
$-2 < y^\gamma < 2$
polarized
10
15
20
25
30
35
$p_T^\gamma$ (GeV)


G−S a
G−S b
G−S c
GRSV 1
−2 < y^γ < 2
polarized
10^−1
10^−2
10^−3
dσ/dp_T^γ (pb/GeV)
10
15
20
25
30
35
p_T^γ (GeV)

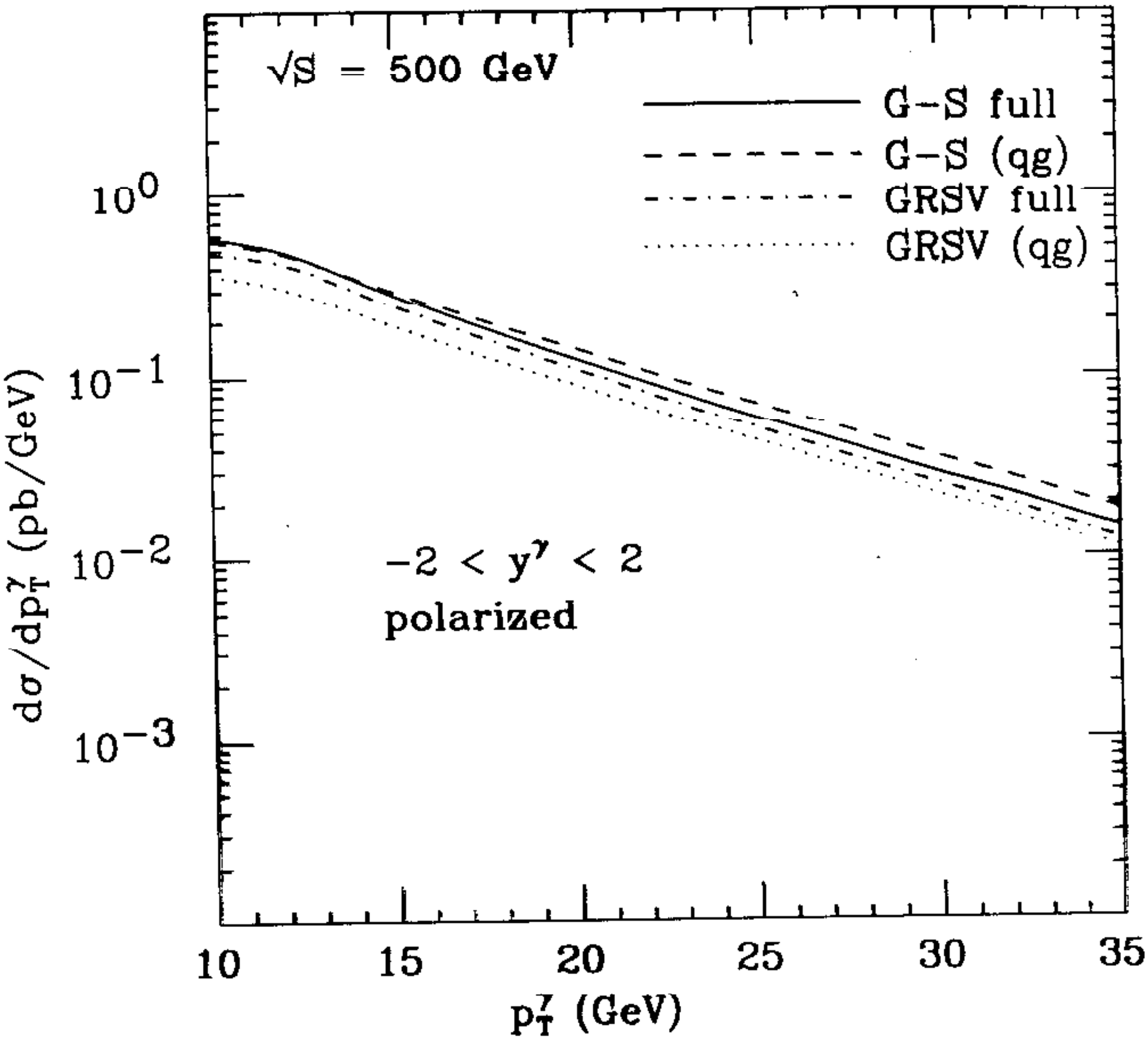

0.30
0.25
0.20
0.15
0.10
0.05
$A_{LL}$
GRSV 1
GRSV 2
10
15
20
25
30
35
$p_T^\gamma$ (GeV)



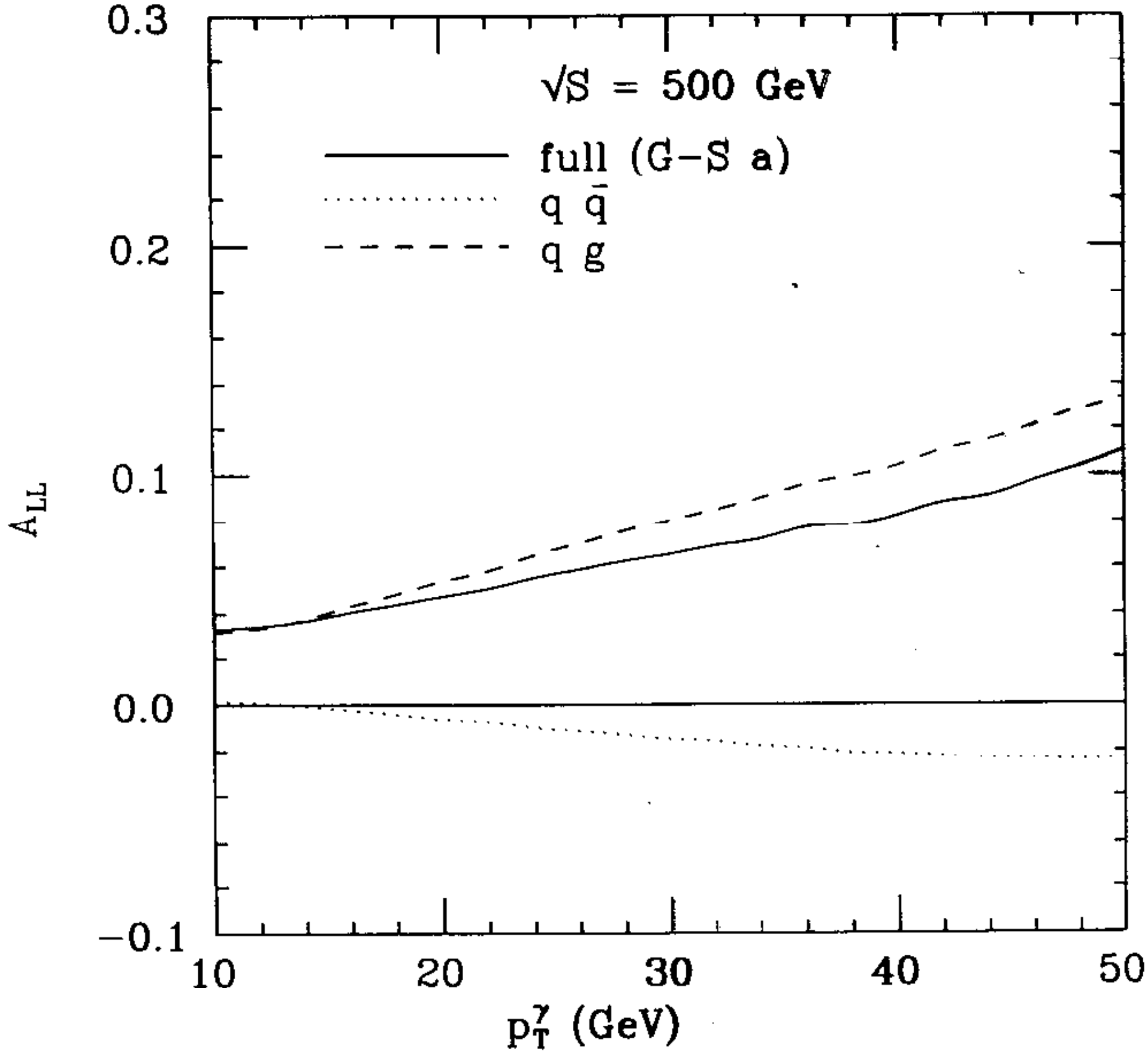
0.30
0.25
0.20
0.15
0.10
0.05
$A_{LL}$
G−S a
G−S b
G−S c
10
15
20
25
30
35
$p_T^\gamma$ (GeV)

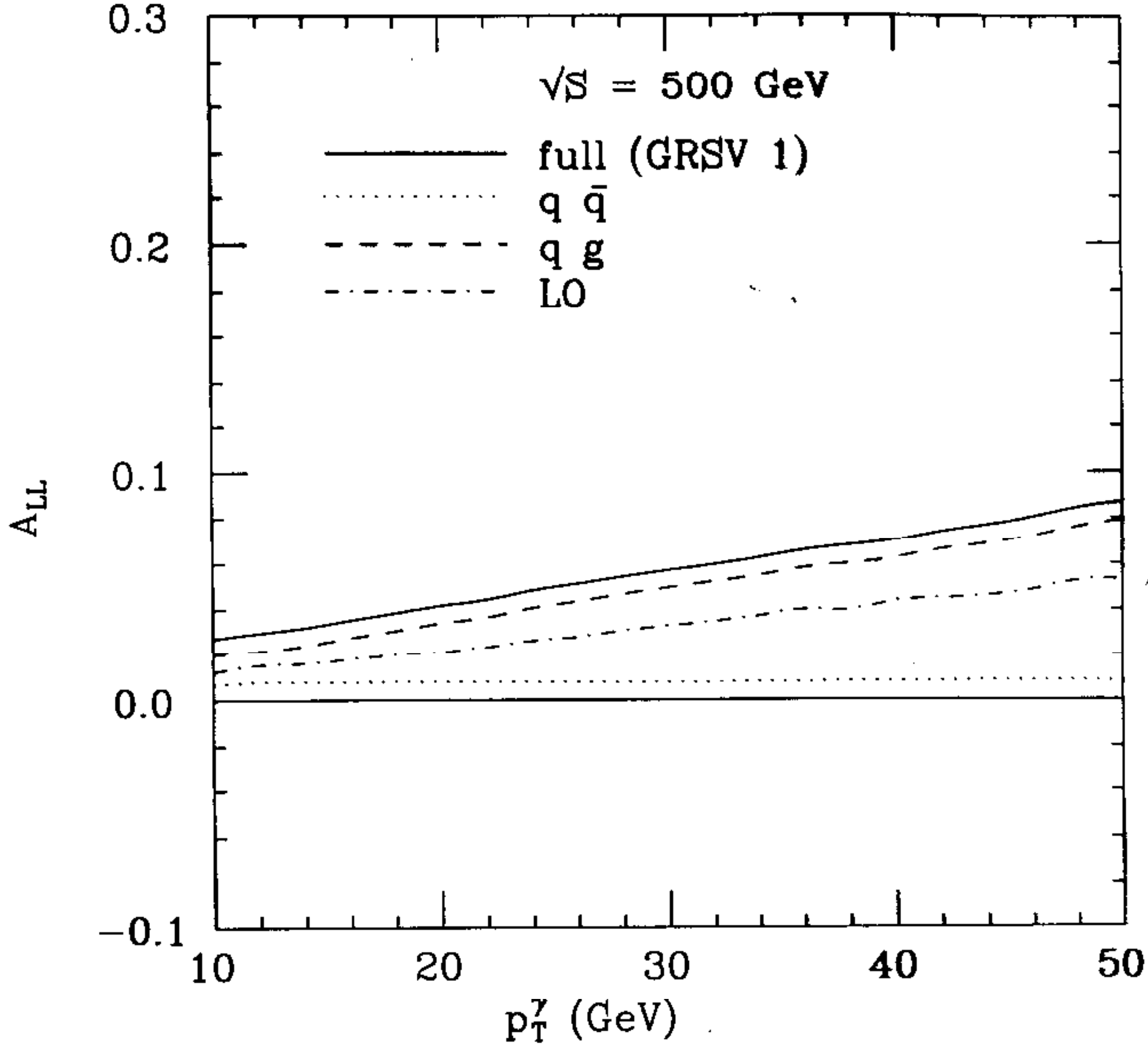


$\sqrt{S}$ = 500 GeV
$\sqrt{S}$ = 200 GeV
$10^1$
$10^0$
$10^{-1}$
$10^{-2}$
$10^{-3}$
$d\sigma/dp_T^\gamma$ (pb/GeV)
$-2 < y^\gamma < 2$
unpolarized
10
15
20
25
30
35
$p_T^\gamma$ (GeV)

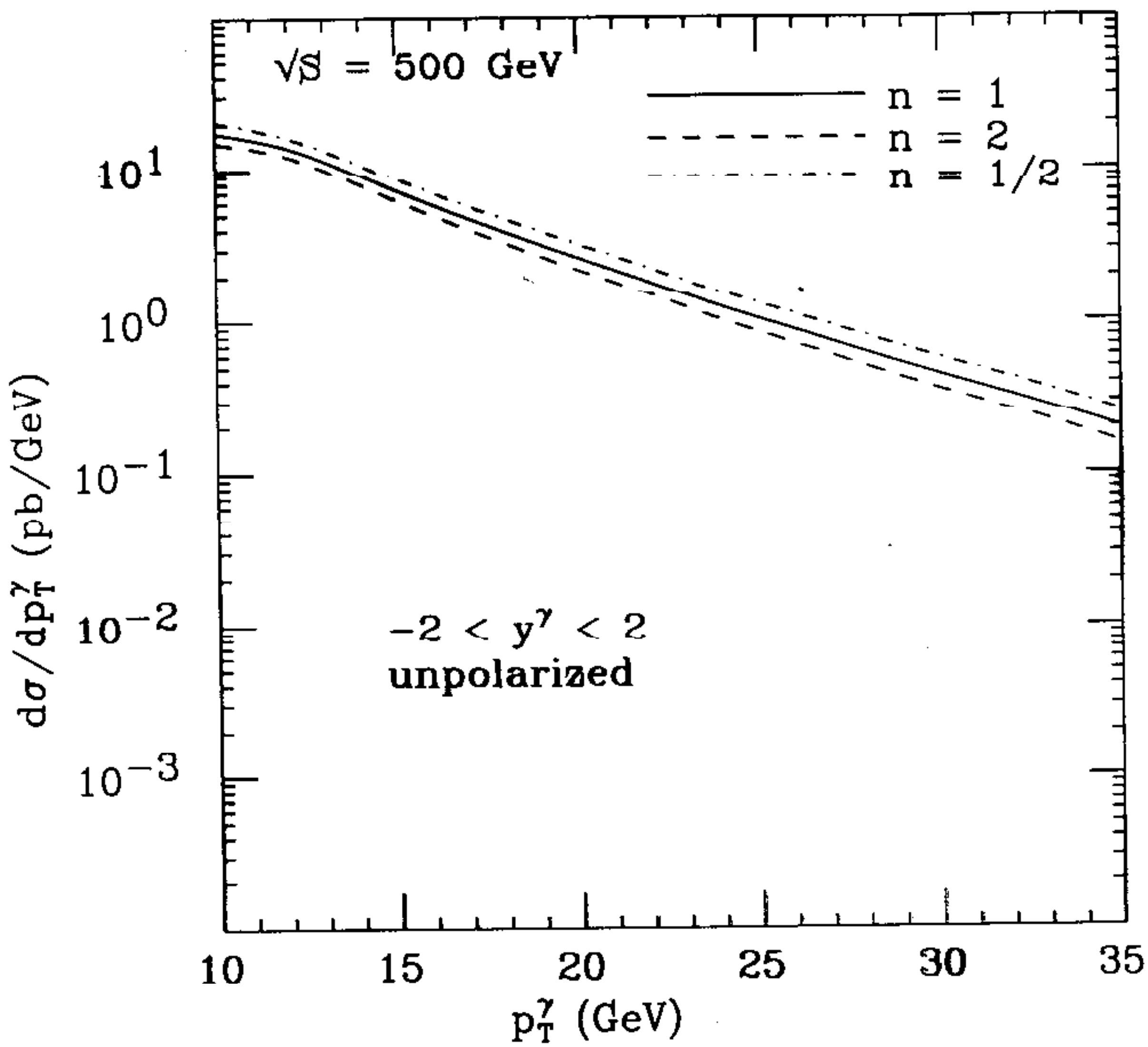


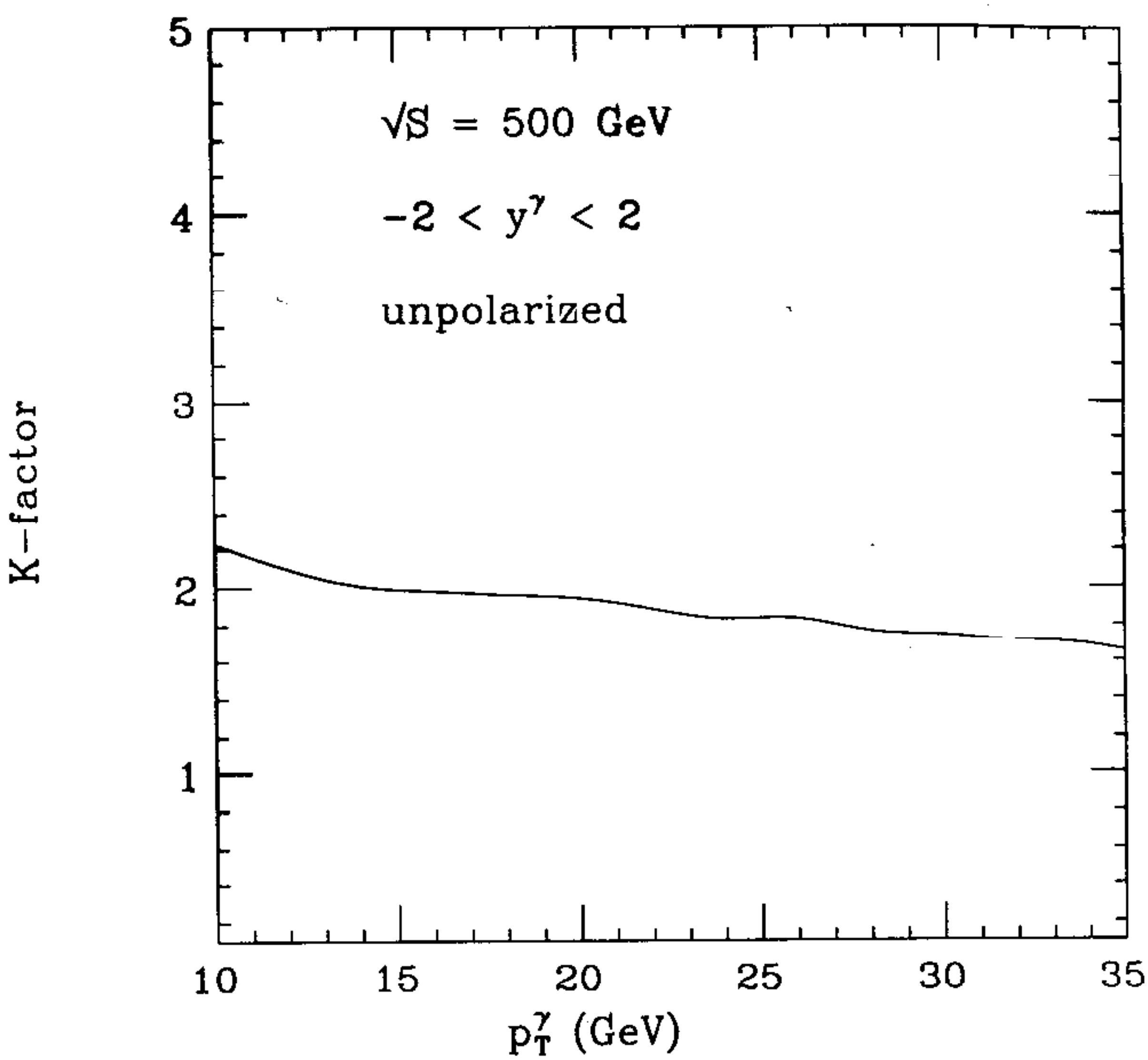
$\sqrt{S}$ = 500 GeV
G–S full
G–S (qg)
GRSV full
GRSV (qg)
$10^{0}$
$10^{-1}$
$10^{-2}$
$10^{-3}$
$d\sigma/dp_T^\gamma$ (pb/GeV)
$-2 < y^\gamma < 2$
polarized
10
15
20
25
30
35
$p_T^\gamma$ (GeV)


0.3
0.2
0.1
0.0
−0.1
10
20
30
40
50
$\sqrt{S}$ = 500 GeV
full (G−S a)
q $\bar{q}$
q g
$A_{LL}$
$p_T^\gamma$ (GeV)



0.3
0.2
0.1
0.0
−0.1
$A_{LL}$
$\sqrt{S}$ = 500 GeV
full (GRSV 1)
$q\ \bar{q}$
q g
LO
10
20
30
40
50
$p_T^\gamma$ (GeV)


√S = 500 GeV
n = 1
n = 2
n = 1/2
-2 < y^γ < 2
unpolarized
dσ/dp_T^γ (pb/GeV)
p_T^γ (GeV)
10^1
10^0
10^-1
10^-2
10^-3
10
15
20
25
30
35



$\sqrt{S}$ = 500 GeV
$-2 < y^\gamma < 2$
unpolarized
K–factor
$p_T^\gamma$ (GeV)
5
4
3
2
1
10
15
20
25
30
35

What needs to be done

1. Total cross section
2. Isolation cuts for DY
3. Transversities

Nice Signal

Work in progress

Signal

Chang, Gordon, Field, C.C.