Spin correlations in the Drell-Yan process, parton entanglement, and other unconventional QCD effects

Otto Nachtmann, Univ. Heidelberg

1 Introduction and motivation

2 Spin correlations in the Drell-Yan process

3 Soft photons in hadron-hadron collisions

4 Conclusions

1 Introduction and motivation

In this talk we want to discuss unconventional QCD effects in hadron-hadron collisions, in particular for:

Drell-Yan (DY) $\quad h_1 + h_2 \longrightarrow \gamma^* + X$

$\hookrightarrow l^+ l^-$

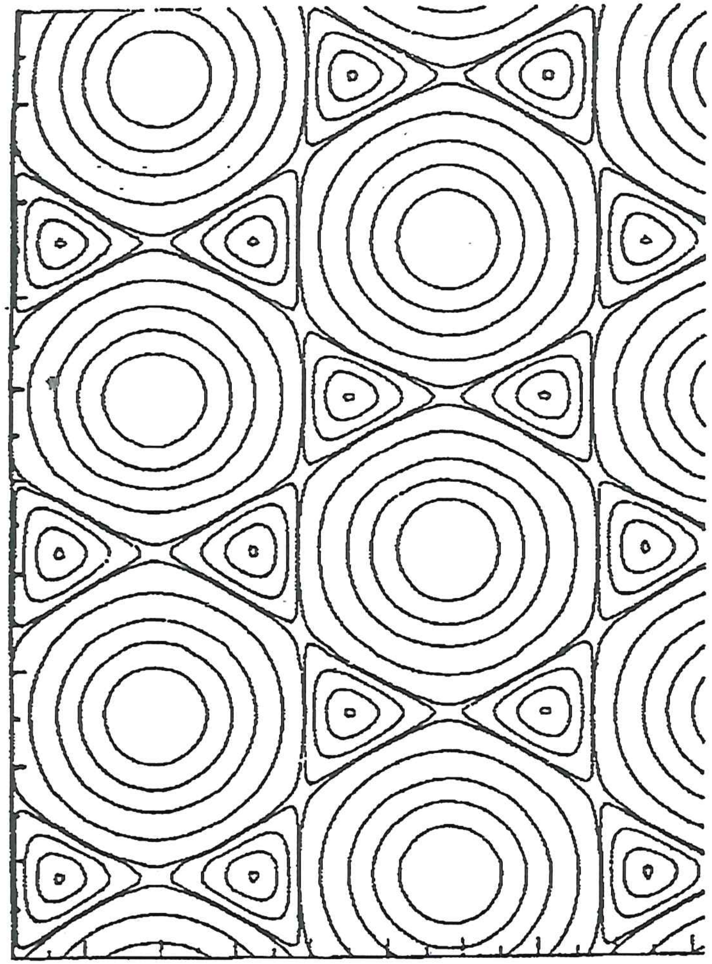
soft photon prod. $\quad h_1 + h_2 \longrightarrow \gamma(\text{soft}) + X$

Predictions for such effects were made in papers of 1984 to 1996.

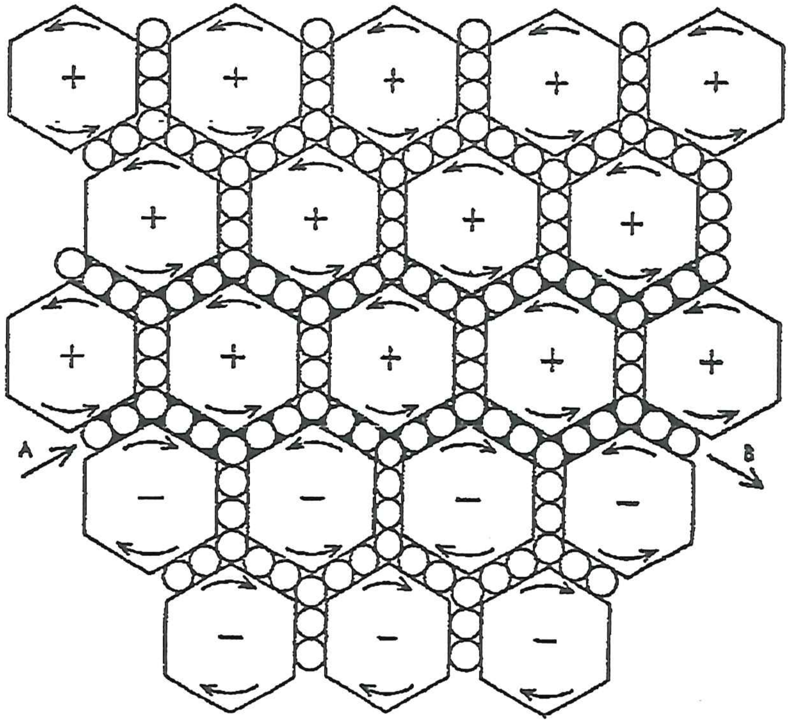
- O. N., A. Reiter, "The vacuum structure in QCD and hadron-hadron scattering", Z. Phys. C 24, 283 (1984)
- A. Brandenburg, O.N., E. Mirkes, "Spin effects and factorization in the Drell-Yan process", Z. Phys. C 60, 697 (1993)
- G. W. Botz, P. Haberl, O. N., "Soft photons in hadron - hadron collisions: synchrotron radiation from the QCD vacuum?", Z. Phys. C 67, 143 (1995)
- O. N., "The QCD vacuum structure and its manifestations", in "Confinement Physics", eds. S. D. Bass, P. A. M. Guichon, Editions Frontières, 1996

Our motivation derived from the discussions of the QCD vacuum structure in the 1970s, 1980s.

- Instantons (Belavin et al. 1975, 't Hooft 1976)
- Savvidy (1977): a chromomagnetic field lowers the vacuum energy
- Shifman, Vainshtein, Zakharov (SVZ): gluon condensate G_2 (1978)
- Spaghetti vacuum, ...



QCD vacuum
Ambjørn, Olesen 1980



Ether
Maxwell 1861

The gluon condensate of SVZ:

$$\langle 0| \frac{g^2}{4\pi^2} : G^a_{\mu\nu}(x)\, G^b_{\rho\sigma}(x): |0\rangle = \frac{1}{96}\, \delta^{ab} \left(g_{\mu\rho} g_{\nu\sigma} - g_{\mu\sigma} g_{\nu\rho} \right) G_2$$

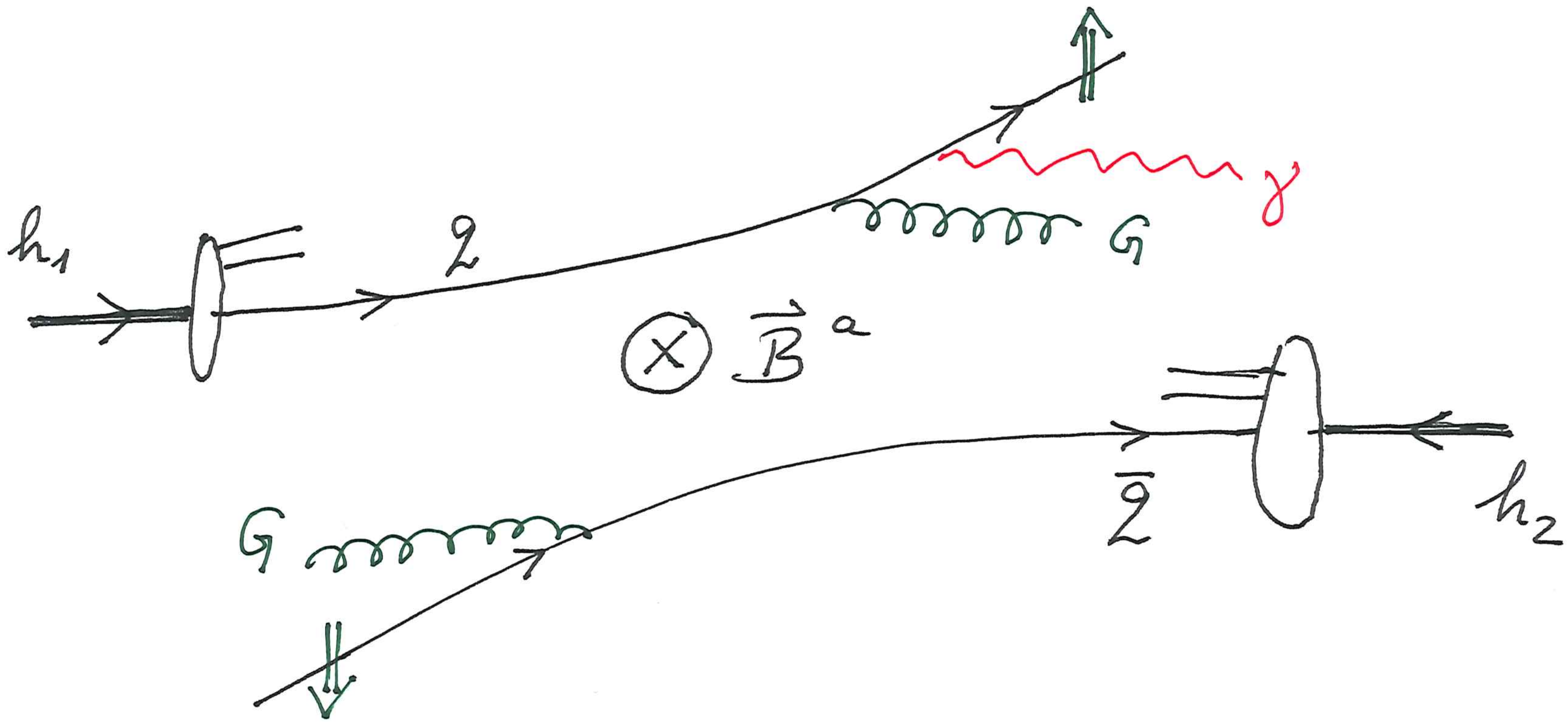
$$G_2 = \frac{1}{4\pi^2} \left(0.95 \pm 0.45 \right) \mathrm{GeV}^4$$

$\Longrightarrow$

$$\langle 0| g^2 : \vec{B}^a(x)\, \vec{B}^a(x): |0\rangle = - \langle 0| g^2 : \vec{E}^a(x)\, \vec{E}^a(x): |0\rangle = \pi^2 G_2 \cong (700\,\mathrm{MeV})^4$$

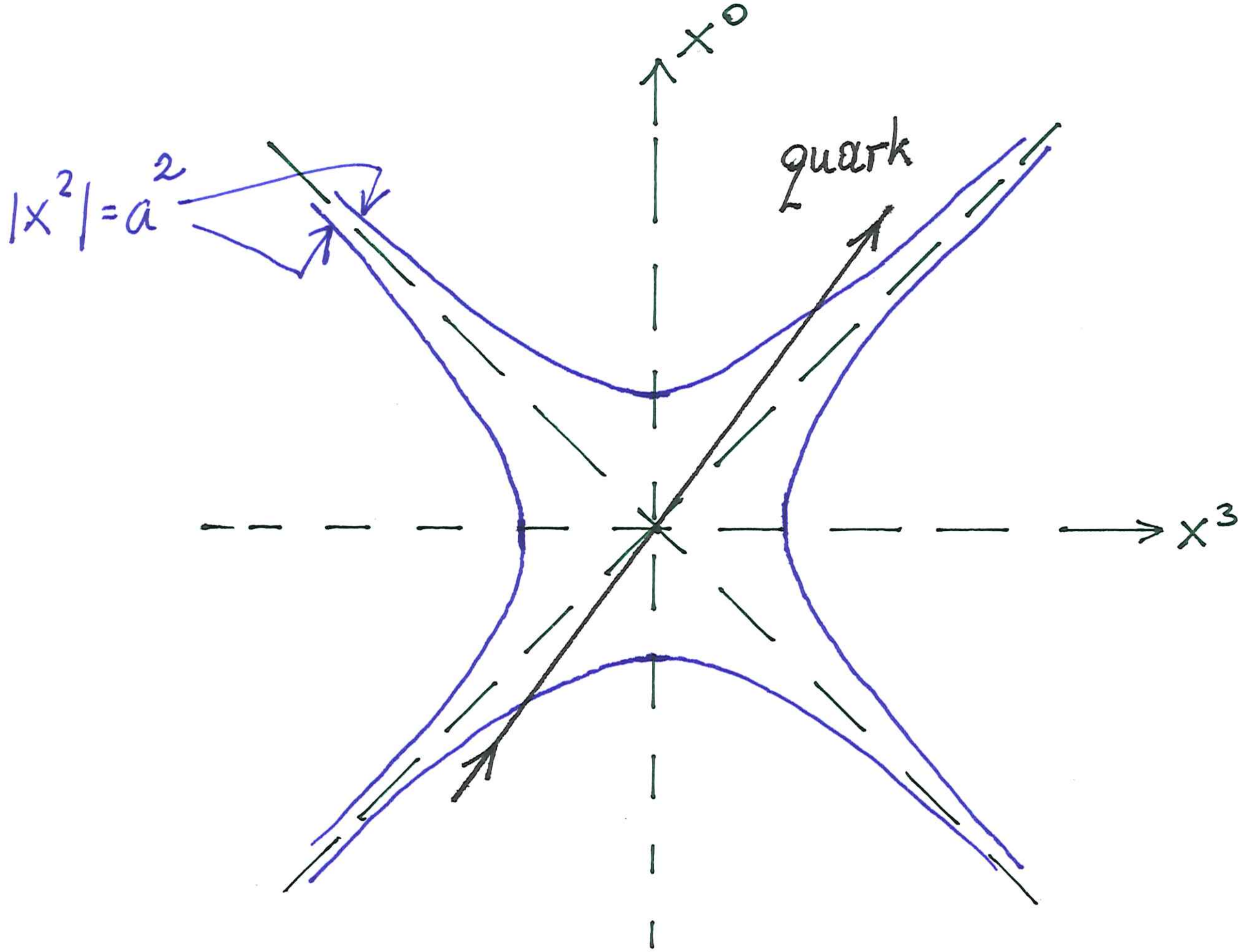
In the physical vacuum the chromomagnetic field fluctuates with larger amplitude than in the pert. vacuum.

What may happen in a high-energy collision to quarks and antiquarks travelling through these strong chromomagnetic background fields?



- Deflection due to chromomagnetic Lorentz force
- Synchrotron emission of gluons and photons
- Spin-flip gluon synchrotron emission leading to a correlated polarisation of q and $\bar{q}$ (Chromomagnetic Sokolov-Ternov effect).
  In electrodynamics this effect is well known, leading to the transverse polarisation of e^- and e^+ in storage rings.

Of course, there can be no constant chromomagn. field in the vacuum. But there can be correlation regions of fields.



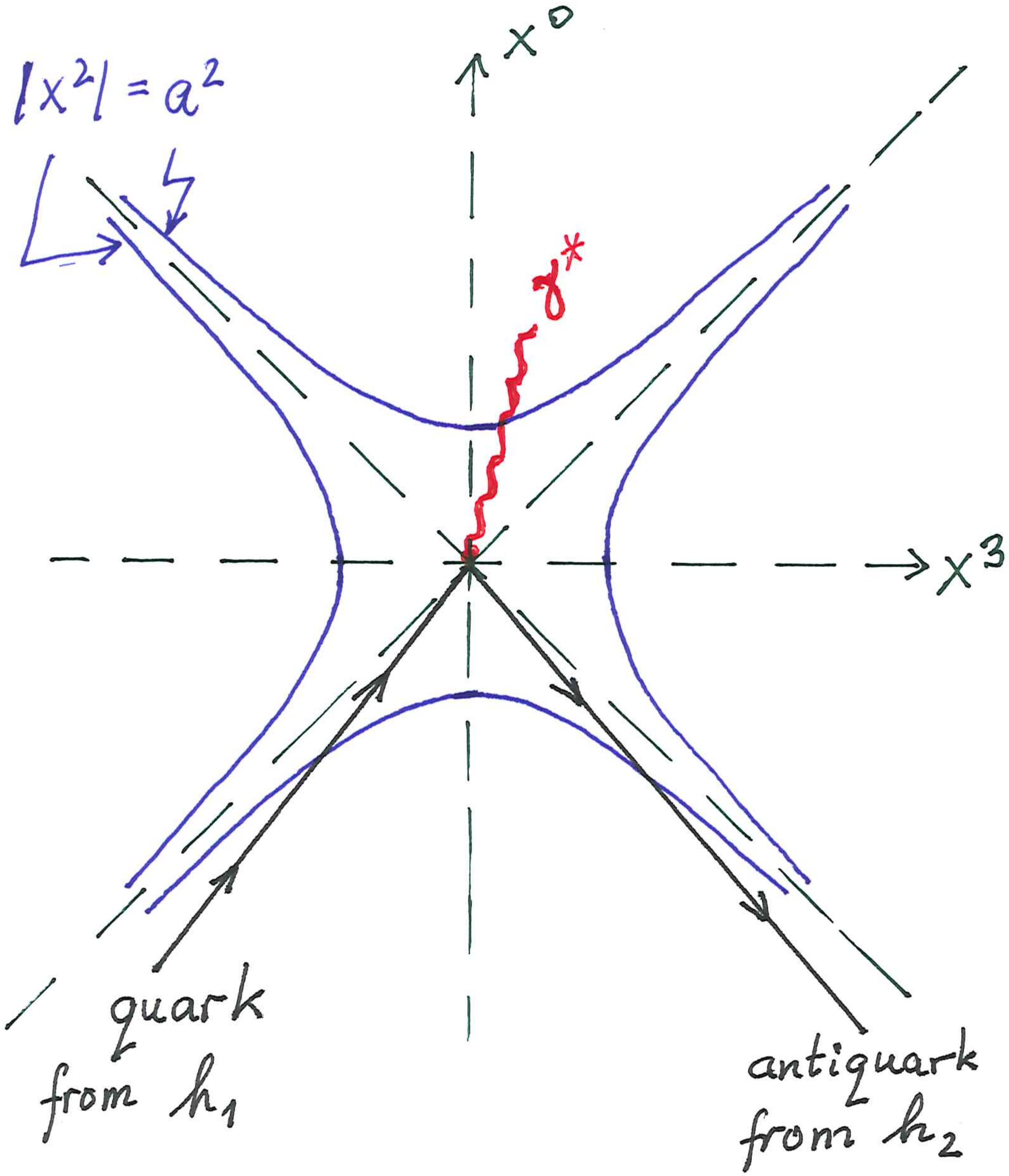
correlation region of $x = 0$:

$$|x^2| \lesssim a^2$$

$a = 0.2$ to 0.3 fm

from lattic QCD;

Instantons: "typical" size



A quark from a fast hadron can spend a long time in a correlation region.

In the Drell-Yan process the annihilating quark and antiquark can spend a long time in the <u>same</u> correlation region.

Summary of our picture, developed in 1984 - 1996

(i) quarks and gluons ~~of~~ of a fast hadron travel in a chromomagnetic background field: strength $\approx g B_c$. Wiggling due to chromomagn. Lorentz force. Ordinary and spin-flip synchrotron gluons and photons are part of the cloud of virtual particles around an isolated hadron h.

(ii) Different hard partons of the same hadron h travel in general in uncorrelated field regions since $a^2 \ll R^2_{hadron}$.

(iii) In a hadron-hadron collision the cloud of synchrotron photons may be shaken off, giving rise to soft photons with a characteristic energy spectrum. From a comparison of our prediction with the exp. results of J. Antos et al., Z. Phys. C59, 547 (1993) we got for the effective field in a hadron

$$gB_c \cong (44\ \mathrm{MeV})^2 \ll gB_{vac} \cong (700\ \mathrm{MeV})^2$$

Vacuum fields in a fast hadron must be shielded, may be by our synchrotron gluons. This gives an important dynamical role to gluons in a fast hadron.

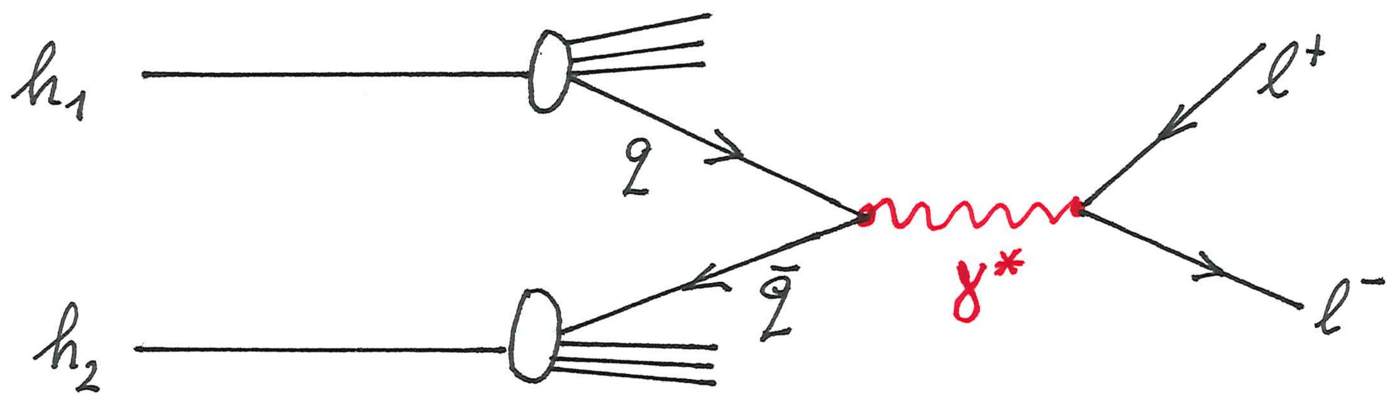
(iv) Gluonic spin-flip synchrotron radiation of quarks may be of relevance for the proton spin puzzle.

(v) For the Drell-Yan process spin correlations of the annihilating $q\bar{q}$ pair are predicted due to the chromomagnetic Sokolov - Ternov effect.

2 Spin correlations in the Drell-Yan process

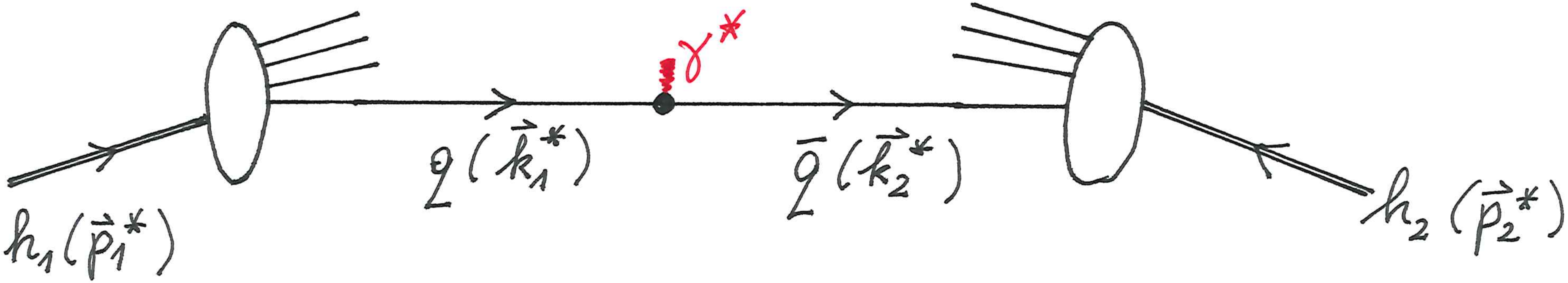
$$h_1(p_1) + h_2(p_2) \longrightarrow \gamma^*(k) + X$$
$$\hookrightarrow \ell^+ + \ell^-$$

Leading order diagram : $q + \bar{q} \rightarrow \gamma^*$



Extension to Z and $W^{\pm}$ production is straightforward.

In the γ^* rest system $=$ $q\bar{q}$ c.m. system:



$$\vec{k}_1^{\,*} + \vec{k}_2^{\,*} = 0$$

Def.:

$$\vec{e}_1^{\,*} = \frac{(\vec{p}_1^{\,*} + \vec{p}_2^{\,*}) \times \vec{k}_1^{\,*}}{|(\vec{p}_1^{\,*} + \vec{p}_2^{\,*}) \times \vec{k}_1^{\,*}|} \;, \quad \vec{e}_3^{\,*} = \frac{\vec{k}_1^{\,*}}{|\vec{k}_1^{\,*}|} \;, \quad \vec{e}_2^{\,*} = \vec{e}_3^{\,*} \times \vec{e}_1^{\,*}$$

In our paper of 1993 we made the most general ansatz for the $q\bar{q}$ density matrix

$$\rho^{(q\bar{q})}(\vec{k}_1^{\,*}, \vec{p}_1^{\,*}, \vec{p}_2^{\,*}) = \frac{1}{4}\{ \mathbb{1} \otimes \mathbb{1}$$

$$+ (\vec{F} \cdot \vec{\sigma}) \otimes \mathbb{1} + \mathbb{1} \otimes (\vec{G} \cdot \vec{\sigma}) + H_{ij} (\vec{e}_i^{\,*} \cdot \vec{\sigma}) \otimes (\vec{e}_j^{\,*} \cdot \vec{\sigma}) \}$$

From P invariance of strong interactions:

$$\left.\begin{aligned} \vec{F} &= F_j \vec{e}_j^{\,*} = \vec{F}(\vec{k}_1^{\,*}, \vec{p}_1^{\,*}, \vec{p}_2^{\,*}) = \vec{F}(-\vec{k}_1^{\,*}, -\vec{p}_1^{\,*}, -\vec{p}_2^{\,*}) \\ \vec{G} &= G_j \vec{e}_j^{\,*} = \vec{G}(\vec{k}_1^{\,*}, \vec{p}_1^{\,*}, \vec{p}_2^{\,*}) = \vec{G}(-\vec{k}_1^{\,*}, -\vec{p}_1^{\,*}, -\vec{p}_2^{\,*}) \end{aligned}\right\} \text{pseudo-vectors}$$

$$\underline{H} = H_{ij} \vec{e}_i^{\,*} \otimes \vec{e}_j^{\,*} = \underline{H}(\vec{k}_1^{\,*}, \vec{p}_1^{\,*}, \vec{p}_2^{\,*}) = \underline{H}(-\vec{k}_1^{\,*}, -\vec{p}_1^{\,*}, -\vec{p}_2^{\,*})$$

Standard theory : $\vec{F} = 0$, $\vec{G} = 0$, $\underline{H} = 0$.

The challenge for experimentalists is to determine all parameters of $\rho^{(q,\bar{q})}$. Is it factorising

$$\rho^{(q,\bar{q})} = \rho^{(q)} \otimes \rho^{(\bar{q})}$$ standard? non stand.?

or is there $q\bar{q}$ entanglement?

The Drell-Yan reaction without measurement of ℓ^+, ℓ^- polarisation is only sensitive to

$$1 + H_{33} \quad , \qquad H_{22} - H_{11} .$$

Def.: $$\varkappa = \frac{H_{22} - H_{11}}{1 + H_{33}}$$

The overall rate is sensitive to $1 + H_{33}$,

the ℓ^+ angular distribution to $\varkappa$.

The Collins - Soper basis vectors in the γ^* rest system:

$$\vec{e}_1{}' = \frac{\hat{p}_1' + \hat{p}_2'}{|\hat{p}_1' + \hat{p}_2'|} \, , \quad \vec{e}_2{}' = \frac{\hat{p}_1' \times \hat{p}_2'}{|\hat{p}_1' \times \hat{p}_2'|} \, , \quad \vec{e}_3{}' = \frac{\hat{p}_1' - \hat{p}_2'}{|\hat{p}_1' - \hat{p}_2'|}$$

$$\hat{p}_i' = \vec{p}_i{}' / |\vec{p}_i{}'| \, .$$

Angular distribution of ℓ^+ momentum

$$\frac{1}{\sigma} \frac{d\sigma}{d\Omega_+} = \frac{3}{4\pi(3+\lambda)} \Big\{ 1 + \lambda \cos^2\vartheta + \mu \sin(2\vartheta) \cos(\varphi) + \frac{1}{2} \nu \sin^2\vartheta \cos(2\varphi) \Big\}$$

In the standard theory one has the Lam-Tung relation, valid to order α_s, practically unchanged to order $(\alpha_s)^2$:

$$1 - \lambda - 2\nu = 0$$

With our ansatz we get

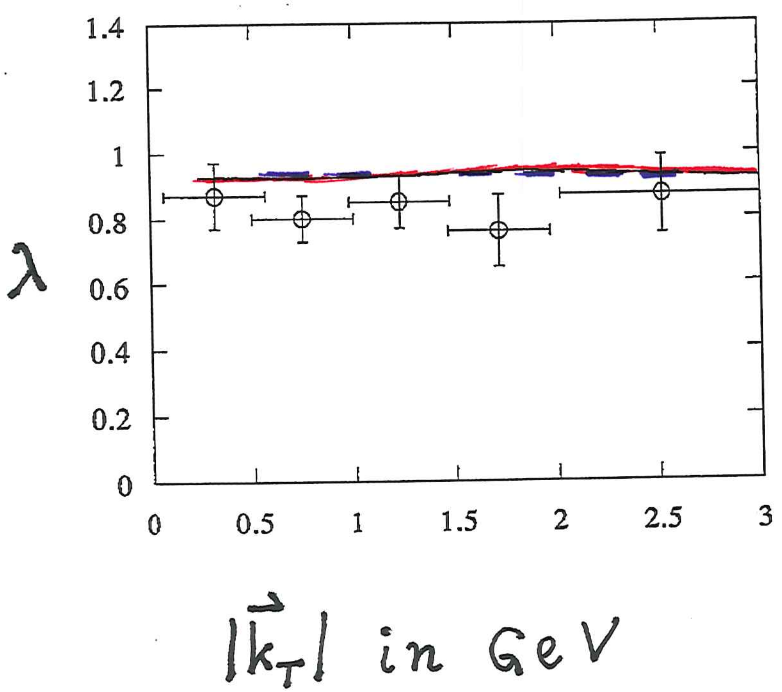
$$1 - \lambda - 2\nu \approx -4\varkappa$$

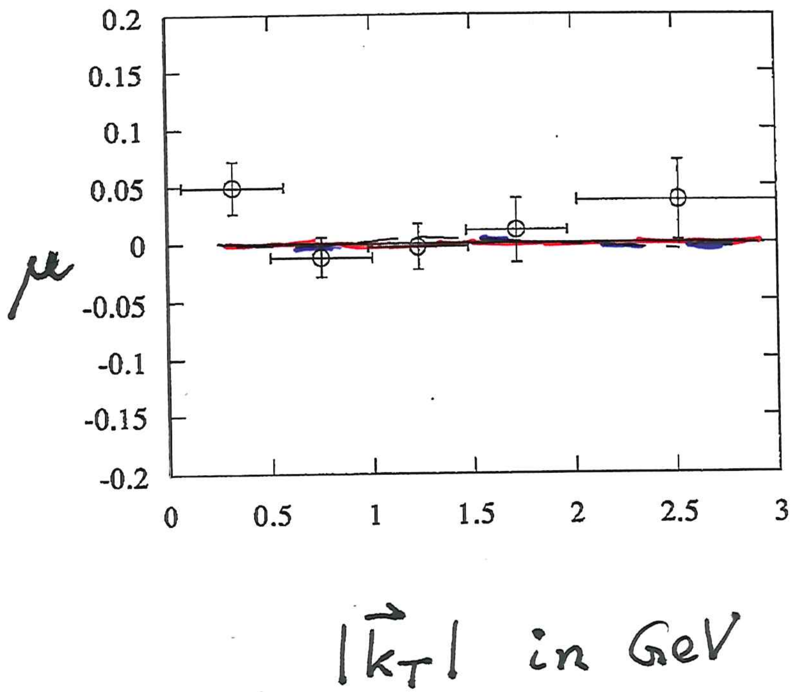
Good description of the NA10 data with

$$\varkappa = \varkappa_0 \frac{|\vec{k}_T|^4}{|\vec{k}_T|^4 + m_T^4}, \quad \varkappa_0 = 0.17, \quad m_T = 1.5\ \mathrm{GeV}$$

$\varkappa > 0$ is expected from the chromomagn. Sokolov-Ternov effect!

Data: NA 10, $\pi^- N$, 194 GeV/c, $\eta = 0$, $m_{\gamma^*} = 8\,\text{GeV}$
(1988)

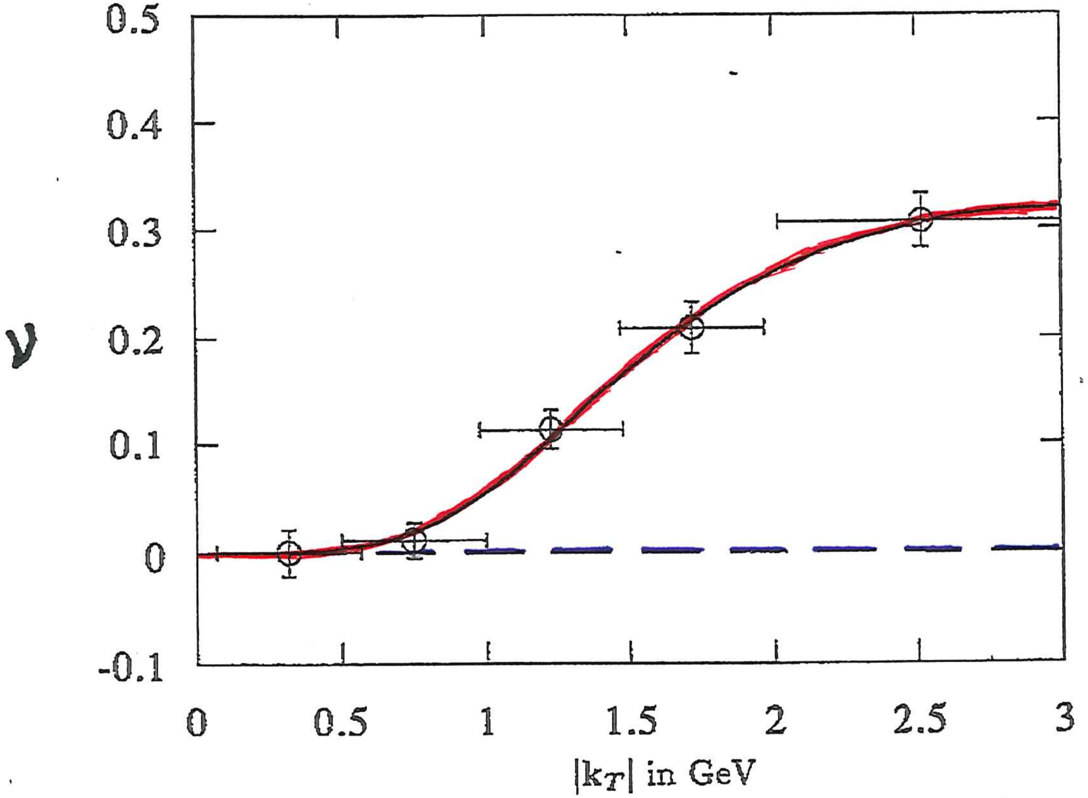




- - - - $\varkappa = 0$

——— $\varkappa = \varkappa_0 \dfrac{|\vec{k}_T|^4}{|\vec{k}_T|^4 + m_T^4}$

Data : NA 10 , Theory : Brandenburg, O. N., Mirkes, 1993



- - - - $\varkappa = 0$ ——— $\varkappa = \varkappa_0 \dfrac{|\vec{k}_T|^4}{|\vec{k}_T|^4 + m_T^4}$

When we discussed our theory with experimental and theoretical colleagues there was no great interest generated. Most theorists made it clear to us that they considered our ideas to be crazy...

Then, in 2003 I attended a workshop at Ringberg castle where I met D. Boer who told me that he was interested in our work. I thought the best way to understand what they were doing was to write a paper together:

- D. Boer, A. Brandenburg, O.N., A. Utermann, "Factorisation, parton entanglement and the Drell-Yan process", Eur. Phys. J. C40, 55 (2005)

In the approach of Boer and Mulders (1999, ...) a factorising density matrix is assumed:

$$\rho^{(q,\bar{q})} = \rho^{(q)} \otimes \rho^{(\bar{q})}$$

$$= \frac{1}{2}\left(\mathbb{1} + \vec{F}^{BM} \cdot \vec{\sigma}\right) \otimes \frac{1}{2}\left(\mathbb{1} + \vec{G}^{BM} \cdot \vec{\sigma}\right)$$

$$\vec{F}^{BM} = \frac{h_1^{\perp}}{f_1} \frac{x_1}{m_{h_1}} \vec{e}_3^{\,*} \times \vec{p}_1^{\,*}$$

$$\vec{G}^{BM} = -\frac{\bar{h}_1^{\perp}}{\bar{f}_1} \frac{x_2}{m_{h_2}} \vec{e}_3^{\,*} \times \vec{p}_2^{\,*}$$

For the Drell-Yan process the BM ansatz is a special case of our general approach.

For BM: $F_3 = 0 \quad , \quad G_3 = 0 \, ,$

$$H_{ij} = F_i \, G_j \quad , \quad \text{in particular: } H_{33} = 0$$

$\rho^{(q)}$ depends only on $\vec{p}_1^{\,*}, \vec{k}_1^{\,*}$, $\rho^{(\bar{q})}$ only on $\vec{p}_2^{\,*}, \vec{k}_2^{\,*}$.

F_3, G_3 are pseudoscalars, must be proportional to

$$\det(p_1, p_2, k_1, k_2).$$

$F_3, G_3 \neq 0$ need correlation of all 4 momenta.

In our approach H_{33} is in general unrelated to $F_3 G_3$.

Summary on the Drell-Yan process:

- Spin correlations for $q\bar{q}$ were introduced by A. Reiter and O.N. in 1984. The most general $q\bar{q}$ spin density matrix was first discussed in 1993 by A. Brandenburg, E. Mirkes and O.N. The results of the NA10 experiment were found to be consistent with the expectation from the chromomagnetic Sokolov-Ternov effect.
- A factorised density matrix $\rho^{(q,\bar{q})} = \rho^{(q)} \otimes \rho^{(\bar{q})}$ as assumed by Boer, Mulders et al. is a special case of our general ansatz.

- In our approach $\rho^{(q,\bar{q})}$ need not be universal in strength of H_{33}, $H_{22}-H_{11}$ etc. for different collisions $h_1 + h_2$. The vacuum colour-fields may be shielded to a different extent in different hadrons.
- Further experiments, confirming NA10 results

  Conway et al. (1989); Heinrich et al. (1991)

  $\pi^- + W$ at 252 GeV/c
- Only a very small effect if any is found by Zhu et al. (2007) in $p + d$ at 800 GeV/c.

  No problem for us: stronger shielding for sea antiquarks!

- Instanton effects are expected to be very important in the Drell-Yan process. Already in Ellis, Gaillard, Zakrzewski, Phys. Lett. B81, 224 (1979) instantons were found to affect the rate in DY.

  $\Rightarrow \quad H_{33} \neq 0 \quad \Rightarrow \quad \rho^{(q,\bar{q})}$ is not factorisable àla BM,

  $\Rightarrow$ most probably $q\ \bar{q}$ are entangled.

- Further discussions of instanton effects in DY:

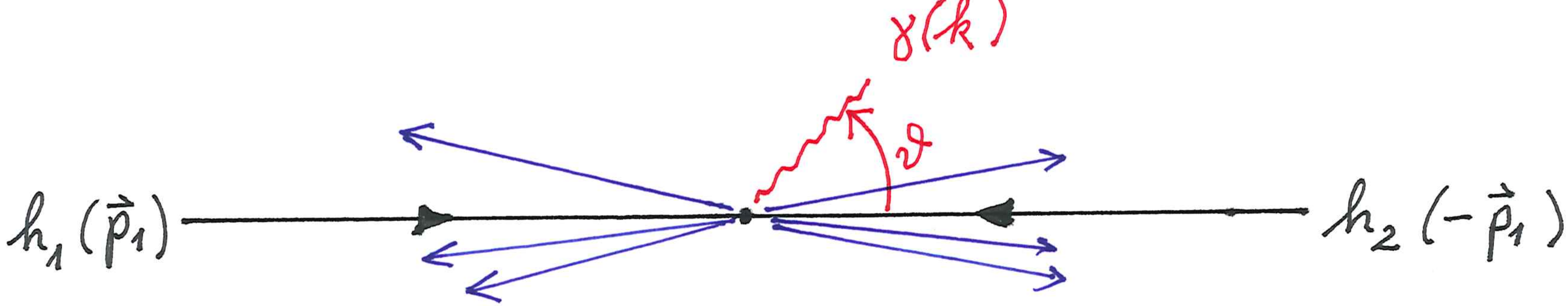
  A. Brandenburg, A. Ringwald, A. Utermann, N.P. B754, 107 (2006)

  DY may be a good place to look for instanton effects!

3 Soft photons in hadron-hadron collisions

$$h_1(p_1) + h_2(p_2) \longrightarrow \gamma(k) + X$$

c.m. system:



$|\vec{k}| = \omega$

Low's theorem holds for $\omega \to 0$. Bremsstrahlung from the hadrons.

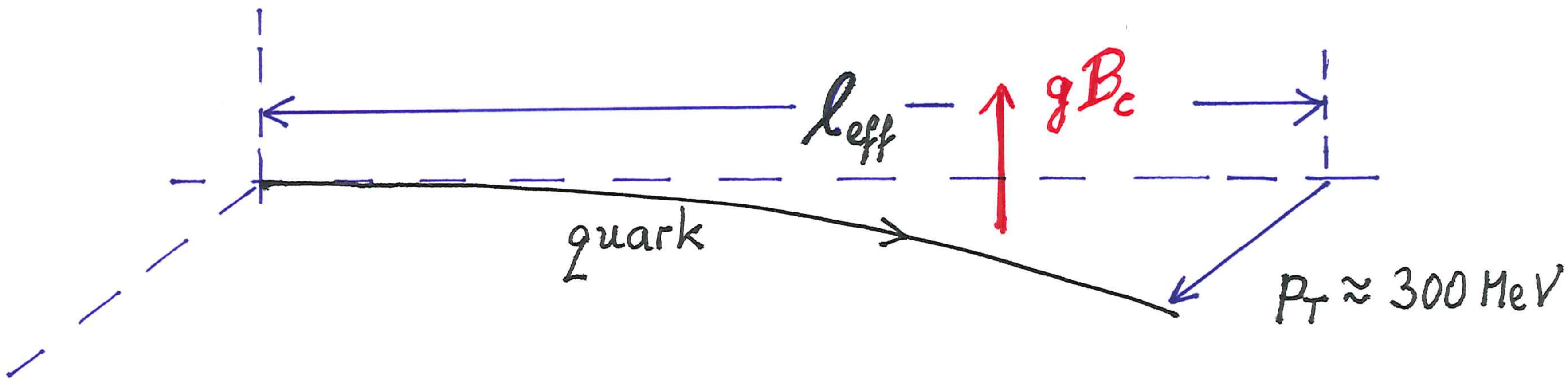
$$\omega \frac{d^3 n_\gamma^{(br)}}{d^3 k} \propto \frac{1}{\omega^2 \sin^2\vartheta} \qquad \text{(Rückl 1976)}$$

"Synchrotron" photons from quarks and antiquarks

$$\omega \frac{d^3 n_\gamma^{(syn)}}{d^3 k} = \frac{\alpha}{\omega^{4/3}} \left(l_{eff}\right)^{2/3} \Sigma(\cos\vartheta)$$

$$\Sigma(\cos\vartheta) \quad \propto \quad (\sin\vartheta)^{-2/3}$$ approximately

(Reiter, O.N. 1984 ; Botz, Haberl, O.N. 1995)



$$l_{eff} = p_T / (gB_c)$$

- Experiments show conflicting results:

  Bremsstrahlung only : Goshaw et al. 1979

  huge excess over bremsstrahlung: e.g. Chliapnikov et al. 1984

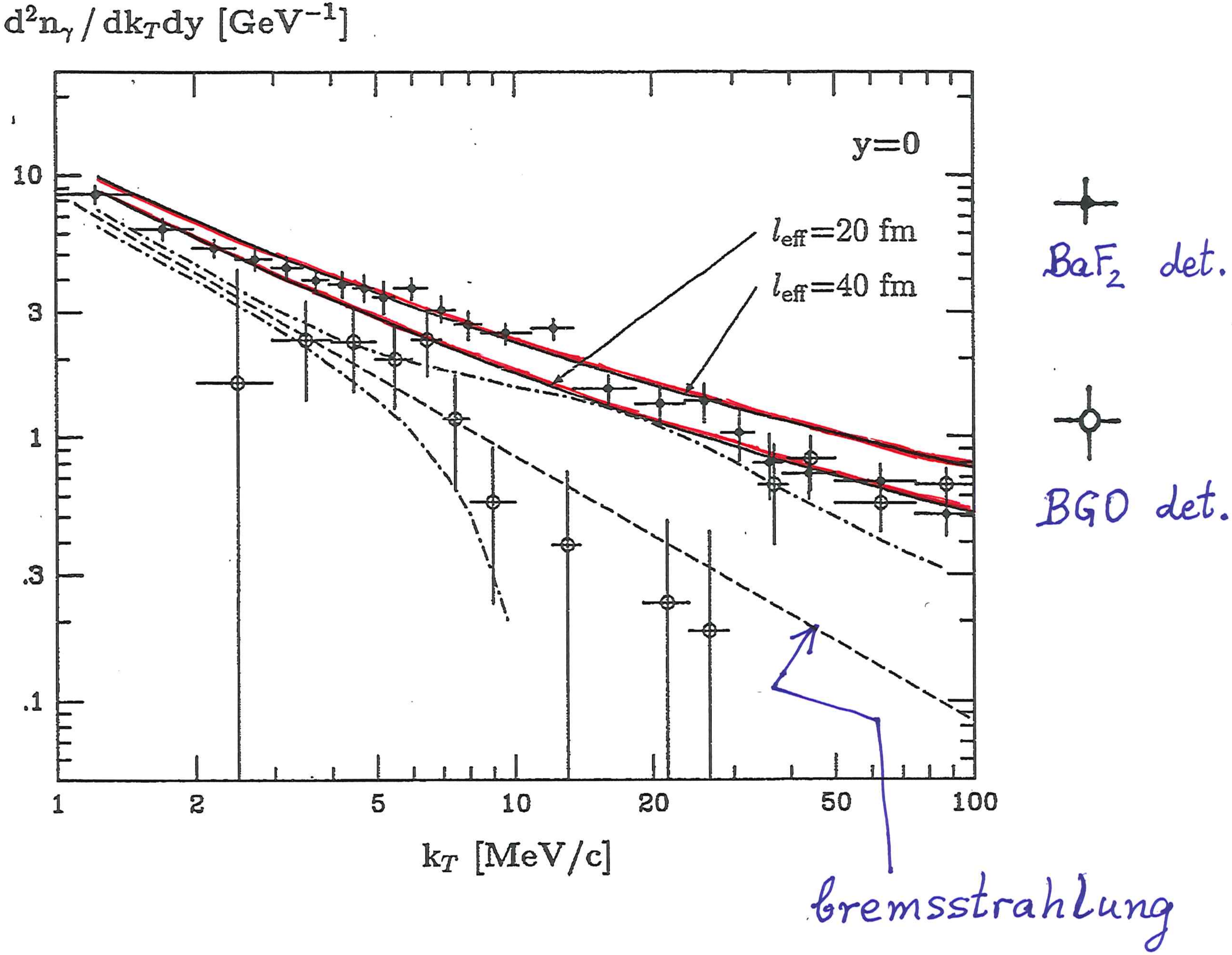
  moderate excess : e.g. Antos et al. 1993

$$p + Be \longrightarrow \gamma + X$$

at 450 GeV/c incident proton momentum

soft photons : $\omega \lesssim 100$ MeV

Data: Antos et al., normalisation: H. Specht, priv. comm.



4 Conclusions

- We have argued that the QCD vacuum structure leads to unconventional effects in hadronic reactions:
- spin correlations of $q\bar{q}$ in Drell-Yan processes, were introduced in theory by us in 1984 and 1993 and confirmed by the NA10 exp. in 1986 and 1988
- Instanton calculations suggest that $q\bar{q}$ are entangled
- Our theory predicts soft "synchrotron" photons in addition to bremsstrahlung ones. Experimental results are conflicting among each other. Clarification from the experimental side would be most welcome.