High energy reactions

and the

QCD vacuum structure

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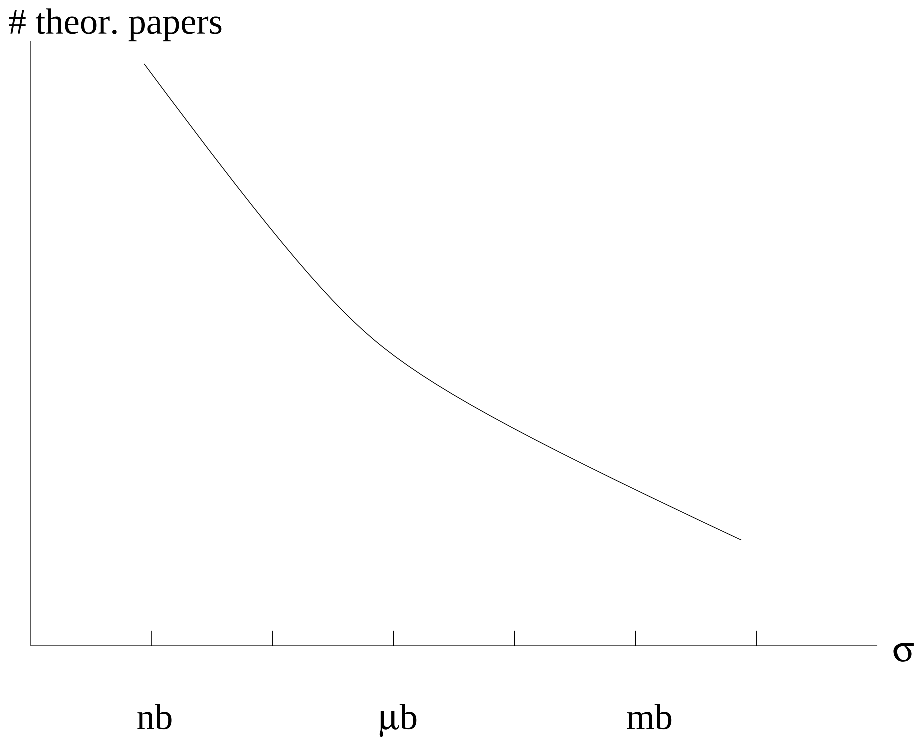
DESY THEORY WORKSHOP, 25. Sept. 2002

Inverse correlation between number of observed events and number of theoretical papers.



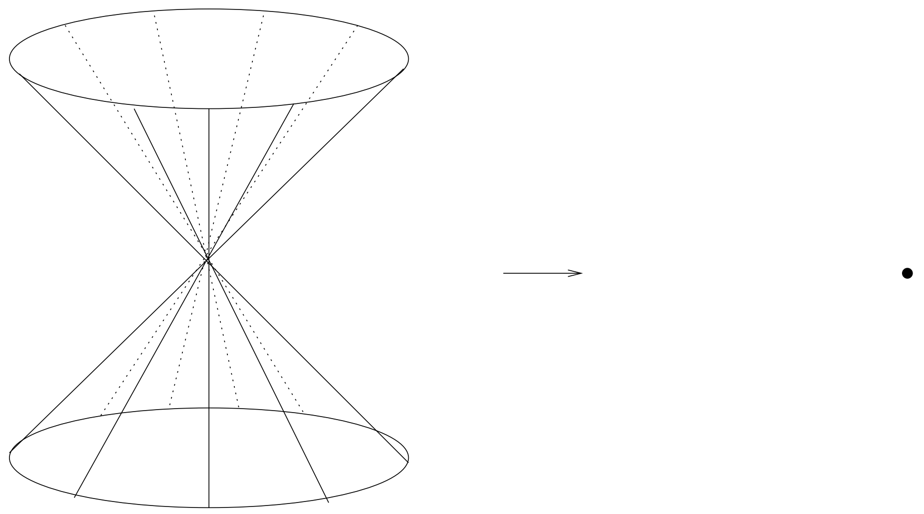
Reason: Nonperturbative effects become more and more important.

Lattice gauge theory

High energy scattering on Euclidean lattice difficult:

$$\vec{x}^2 - c^2t^2 = 0 \quad \rightarrow \quad \vec{x}^2 - (ict)^2 = 0$$

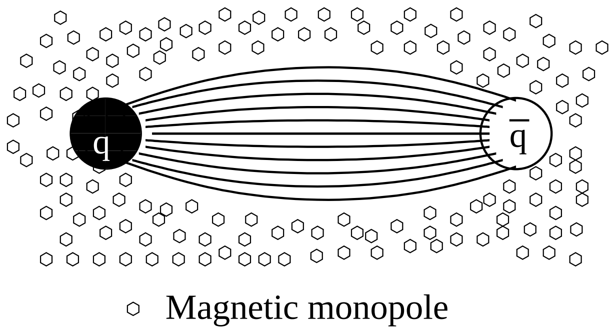
Lightcone in Minkowski shrinks to point in Euclidean:



Novel feature of QCD : **confinement**

t'Hooft-Mandelstam picture: Condensation of colour-electric field in flux tube due to magnetic Monopole condensation.

Analogous to magnetic flux tubes in type-II superconductors due to Cooper-pair condensation



Complicated ground state in effective theory:
QCD vacuum.

What do we know about the QCD vacuum?

Confinement picture of t'Hooft Mandelstam essentially confirmed by lattice simulations. *Di Giacomo*

Analytical results:

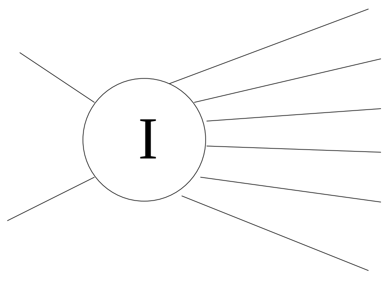
Instantons

Minima of the (Euclidean) QCD Lagrangian ($N_c = 2$), certainly contribute to vacuum structure.

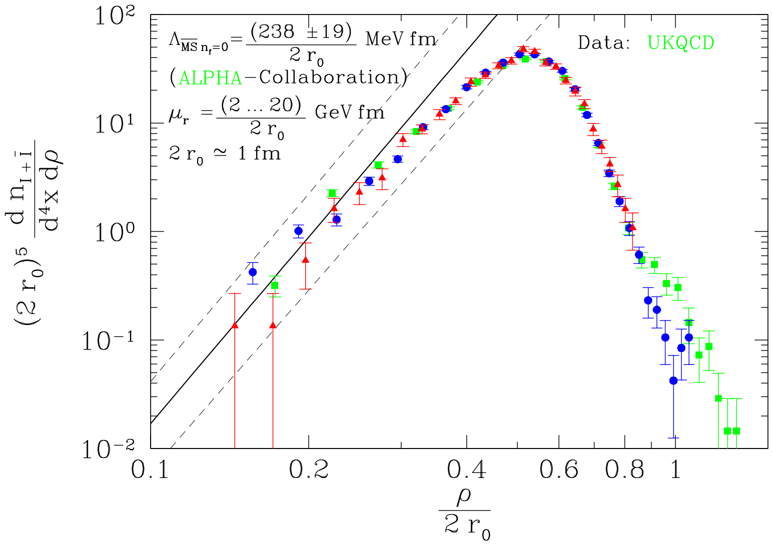
$$\mathbf{A}_\mu = \frac{x^2}{x^2+\rho^2}\partial_\mu g(x) g^{-1}(x) \quad g(x) = \frac{x_0 + i\vec{\sigma}.\vec{x}}{\sqrt{x^2}}$$

ρ Instanton size.

Effect of instantons: Interaction amplitudes small ($O(e^{-\pi/\alpha_s})$, but high multiplicities : no α_s factor for additionally produced parton.



Small size instantons: model independent contributions. Instanton distribution function can be calculated perturbatively up to $\rho \leq 0.4$ fm.



From Ringwald and Schrempp, 1999

Effects on H E scattering by small size instantons:

Balitzky and Braun, 1993; Ringwald and Schrempp 95 ff

Experiments: *H1 2002, Ringwald und Schrempp 2000*

Instanton contributions compatible with experiment, but not absolutely necessary.

Apart from own interest: Feasability of B and L violating accelerator experiments. see *Ringwald 2002*

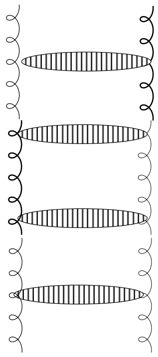
Large size instantons: models necessary. Instanton liquid (Shuryak)

Shuryak, Zahed 2000, Kharzeev, Kovchegov, Levin 2001, Schrempp, Utermann 2002

Soft energy dependence and instantons

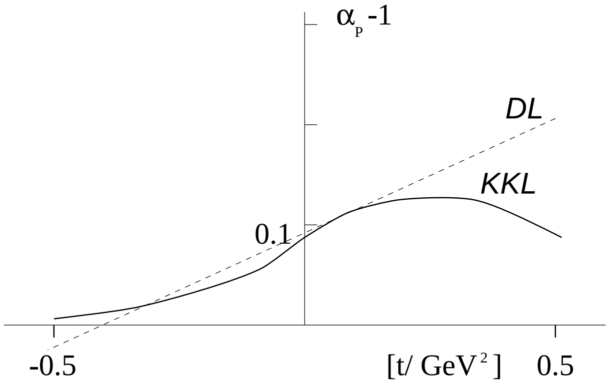
Energy dependence through multiparticle production through increase of phase space.

BFKL-type argument, but rungs of BFKL ladder are corlour singlet states produced by instanton interactions.



They find a Regge trajectory with maximal intercept $\epsilon = \alpha_P(0) - 1 = 0.08$ (!) at $\alpha_s = 0.8$

Trajectory has peculiar form:



The Pomeron trajectory of *Kharzeev, Kovchegov and Levin 2001*

Other effects (confinement) important for $t \geq 0$

Condensates

Information mainly from QCD Sum Rules.

Shifman,Vainshtein, Zakharov 1979

Power corrections due to condensates of quarks, gluons – or both – in the (physical) vacuum. Based on OPE, proven in pQCD.

Gluon condensate:
$\langle : g^2/2 \text{ Tr } \mathbf{F}_{\mu\nu}\mathbf{F}^{\mu\nu} : \rangle = (1 \pm 0.15\,\text{GeV})^4 \gg \Lambda^4_{\text{QCD}}$

Pragmatically defined since short distant physics even in QCD not uniquely defined (renormalons).

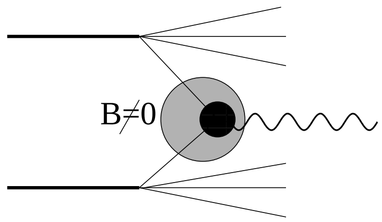
Notation: $\mathbf{F}_{\mu\nu} = \sum_c F_{\mu\nu}\lambda_c/2$

Direct application to high energy scattering:
Violation of factorisation in Drell-Yan processes.

Nachtmann, Reiter 1984,

Brandenburg, Nachtmann, Mirkes 1993

$\pi^- p \to X \gamma^*_{\hookrightarrow \mu^+ \mu^-}$



The spin of the two partons participating in the hard process is correlated through the movement in the same magnetic field.

Confinement ?

Go deeper into models.

Stochastic **V**acuum **M**odel

Simonov, D. 1987

Functional integral approach (Feynman):

$$\langle f(\mathbf{A})\rangle = \int \mathcal{D}\mathbf{A} f(\mathbf{A}) \exp(-iS_{QCD}[\mathbf{A}]) \tag{1}$$

stochastic prozess with **A** as stochastic variable.

Only well understood for Gaussian measure:
Action S quadratic in stochastic variable.
Methods to treat other processes:

- Numerical evaluation on lattice.

- Perturbation theory:

$$S_{QCD}[\mathbf{A}] = S_0[\mathbf{A}] + ig_s S_{\text{int}}[\mathbf{A}] \tag{2}$$

$S_0[\mathbf{A}]$ quadratic in gluon potential **A**; Gaussian prozess
Expand exponential in g_s, perform Gaussian integrals.

- SVM: The long range part of QCD can be approximated by a **Gaussian** stochastic process in the **Gluon Field Strength** $\mathbf{F}_{\mu\nu}$

Cumulant (linked cluster) expansion.

$\langle \ \mathrm{Tr}\ e^{-ig\int_{\mathcal{F}} d\sigma_{\mu\nu}\mathbf{F}_{\mu\nu}(x)}\rangle \ =$

$$\exp\Big[-\frac{1}{2}g^2\int_{\mathcal{F}}\int_{\mathcal{F}} d\sigma_{\mu\nu}d\sigma'_{\kappa\lambda}\langle\ \mathbf{F}_{\mu\nu}(x)\mathbf{S}(x,x')\mathbf{F}_{\kappa\lambda}(x')\rangle + \text{higher cumulants}\Big]$$

$$\mathbf{S}(x,x') = \exp\big(-ig\int_x^{x'} dz.\mathbf{A}\big) \text{ for gauge invariance}$$

Higher cumulants =0 $\leftrightarrow$ **Gaussian** process
the long range part of QCD is determined by the non-local correlator of two gluon fields, all gauge invariant expressions factorise into products of these correlators.

Convenient to evaluate Wegner-Wilson loops:

$$\langle\ \mathrm{Tr}\ e^{-ig\int_C \mathbf{A}_\mu(x)\,dx_\mu}\rangle \overset{n.A.Stokes}{=}$$
$$\langle\ \mathrm{Tr}\ e^{-ig\int_W \mathbf{F}_{\mu\nu}(x)\,d\sigma_{\mu\nu}}\rangle \overset{Gaussian}{=}$$
$$e^{-\frac{g^2}{2}\int_W\int_W\langle\mathbf{F}_{\mu\nu}(x)\,\mathcal{S}\mathbf{F}_{\kappa\lambda}(x')\rangle d\sigma_{\mu\nu}\,d\sigma'_{\kappa\lambda}}$$

Nice features of SVM:

1)Semiclassical, but genuine approximation to Functional Integral approach to QFT

2)Yields **confinement** for **non**-Abelian gauge theories and for
Abelian theories with magnetic monopoles
$\sigma = 0.17\,\mathrm{GeV}^2$ if correlator of LQCD (*Di Giacomo a. coworkers*) is inserted.

3)Resulting dynamical picture: **String** formation in conformity with the t'Hooft-Mandelstam picture
Rueter, D. 1995

4) Yields Casimir scaling for loops in different representations of $SU(3)$, confirmed by lattice results
Bali 2000, Simonov, Shevchenko 2000

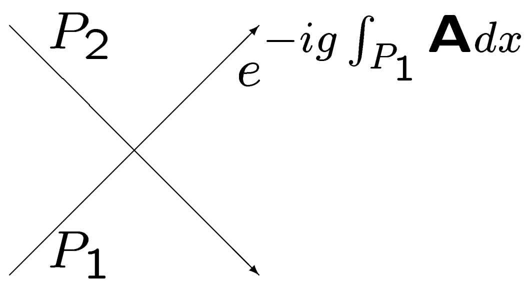
Unpleasant feature:

Gaussian process for **non-commuting** variables not uniquely defined. Path dependence of correlator.

Application to soft high energy scattering

Functional approach to HES *Nachtmann 1991*:

Scattering of fast q on (lightlike) path P_1 in external colour field, picks up WKB phase:



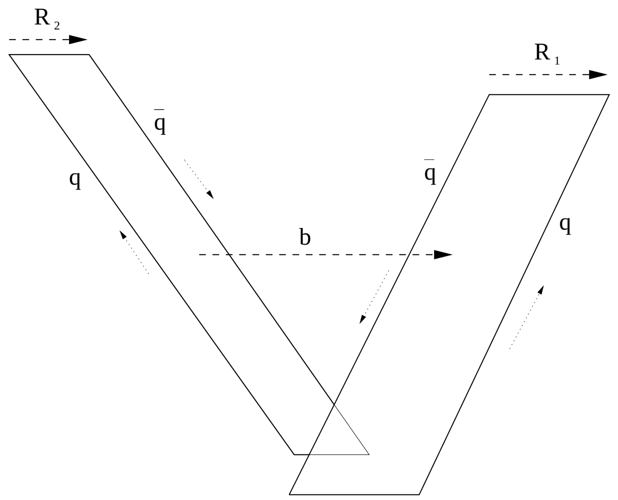
Scattering of two quarks in QFT: Functional integration over colour field:

$$\langle e^{-ig\int_{P_1}\mathbf{A}dx}e^{-ig\int_{P_2}\mathbf{A}dx}\rangle$$

Goal: Apply SVM to perform $\langle\cdot\rangle$.

Not gauge invariant, no Stokes theorem !

Hadron-hadron scattering: With q goes an $\bar{q}$ coupled to colour singlet: Wilson lines to Wegner-Wilson loops:



Scattering amplitude of two dipoles with vectors $\vec{R}_1,\ \vec{R}_2$ and impact parameter $\vec{b}$:

$$J(\vec{b}, \vec{R}_1, \vec{R}_2, z_1, z_2)$$

determined by vev of **two** loops:

$$\langle \text{ Tr } e^{-ig\int_{W_1}\mathbf{A}dx} \text{ Tr } e^{-ig\int_{W_2}\mathbf{A}dx}\rangle$$

Krämer, D. 1991; D., Ferreira Krämer 1994

In principle clear: Apply SVM to this expression.

Similar approach: Cosider one loop in the colour field of the **proton**

Buchmüller, Hebecker 1995

Problems:

Non-Abelian Stokes theorem . Find “best” surface having the loops as borders. Several possibilities. Pragmatic solutions.

How to treat traces:

a) Pedestrian way: Expand exponentials and apply Gaussian factorisation.

b) More refined method, matrix cumulants
Berger, Nachtmann 1998

Express the product of **two** traces, each in $SU(3)$ in **one** TRACE in $SU(3) \otimes SU(3)$, assume factorisation of stochastic variables in $SU(3) \otimes SU(3)$

Guaranties unitarity of hadronic cross sections.

Both methods need an extension of the SVM.
One loop: factorisation of **matrices** $\mathbf{F}_{\mu\nu}$
two or more loops:
factorisation of **matrix elements** $F^c_{\mu\nu}$.

Model in Euclidean space! Easy to continue to Minkowski space. *Dosch 1997*

General results

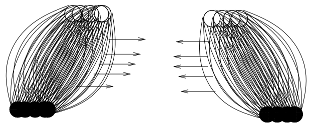
Model yields amplitudes in impact parameter representation, therefore total and differential cross sections can be calulated.

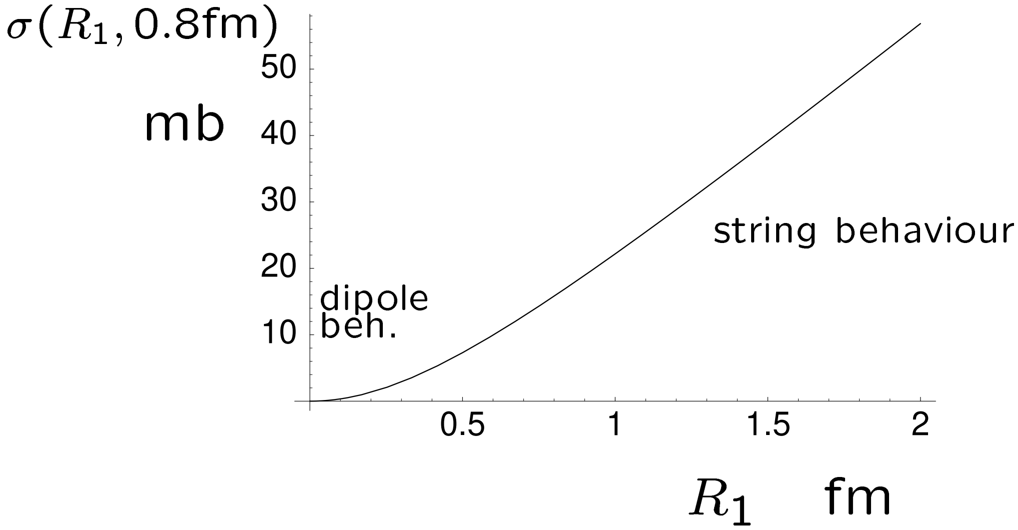
Example: Dipole-dipole cross section:
$\sigma(R_1, R_2) = \int d^2b \int \frac{d\phi_1}{2\pi}\frac{d\phi_2}{2\pi} J(\vec{b}, \vec{R}_1, \vec{R}_2)$

Resulting dipole-dipole cross section factorises to good approximation. Convenient parametrization of $\sigma(R_1, R_2)$

$$\begin{aligned}\sigma(R_1, R_2) &= 0.67 \frac{1}{4\pi^2} (< g^2 FF > a^4)^2 \\ &\quad \times R_1 (1 - e^{-\frac{R_1}{3.1a}}) \, R_2 (1 - e^{-\frac{R_2}{3.1a}})\end{aligned}$$

Using lattice results for the parameters





The same mechanism which leads to confinement also leads to **string-string interaction in high energy scattering.**

but **Note**: Internal fermion loops will lead eventually to string breaking and cross section will level off (like the confining potential) $1/N_c$

Only low energy input(QCD SR and spectroscopy or lattice calculations)
Cross sections of hadrons have right order of magnitude

QCD Factorisation:

If one dipole is very small factorisation should hold. But even for a very small dipole scattering off a large one the string contribution of the small one is still important!

Does string-string interaction violation factorisation ? No

It has been shown recently, that the string part of the interaction can be pushed into the nonperturbative part of the large dipole.
Shoshi,Steffen,Pirner, D. 2002

Contribution of A. Shoshi (Sept. 26, 2, 17.15)

If both dipoles are small, string contribution negligible.

Energy dependence

Model yields constant cross sections, directly applicable at ISR energies . Energy dependence has to be put in by hand.

Comparison with experiment

Application to hadron-hadron scattering: Superposition of dipole-dipole amplitudes with light-cone wave functions as weights.

Choice of wave functions: Gaussian, normalised to one (necessary for consistency) and width adjusted to measurable quantities: e.m. radius, decay constant ...

$\gamma^{(*)}$: perturbative wave function, with quark mass $m(q^2)$, adjusted to two point function.
D.,Gousset,Pirner 1998

Model applied to calculate total and differential cross sections for

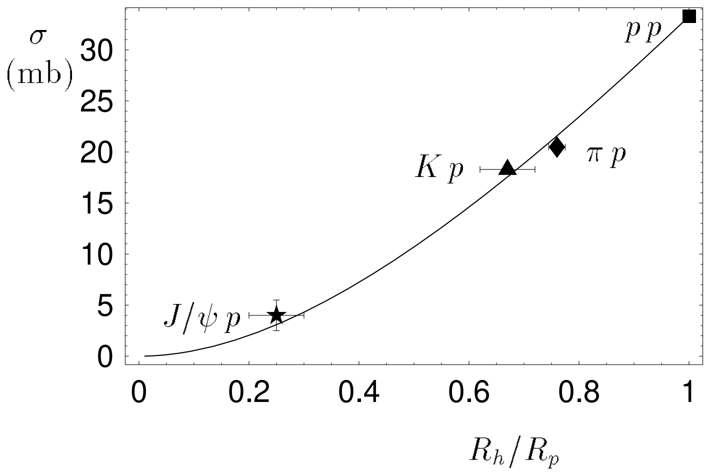
$pp,\ \pi p,\ Kp,\ J/\psi p$

$\gamma p,\ \gamma^* p,\ \gamma^{(*)}\gamma^{(*)}$

$\gamma^* p \to \gamma p,\ \gamma^{(*)} p \to \mathsf{VM}p$

Two examples of applications:

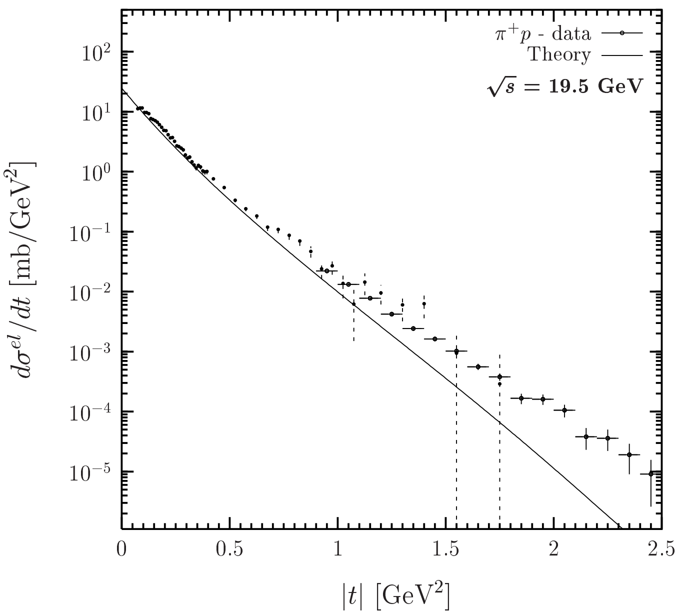
Pomeron contribution to total Hadron-hadron cross sections at $\sqrt{s} \approx 20\,\text{GeV}$.

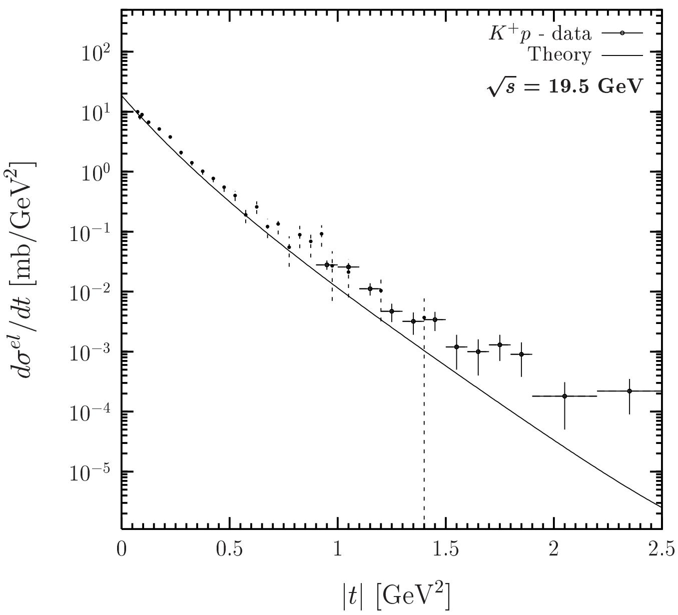


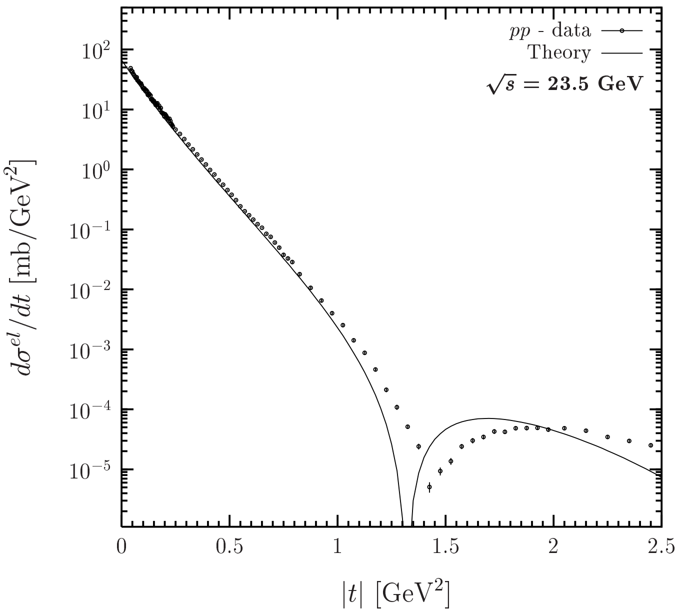
from *Donnachie, D., Landshoff, Nachtmann* Pomeron Physics and QCD, CUP 2002

No quark counting rule, but
$\sigma_{\pi N} : \sigma_{NN} \approx 2 : 3$ correctly predicted.
Even $\sigma_{KN} : \sigma_{\pi N} \approx 0.85$

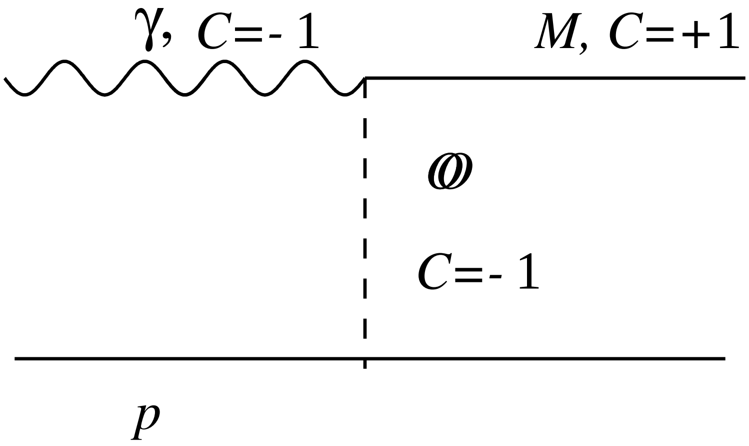
For differential cross sections for $|t| > 0.5$ GeV^2 matrix cumulant method of *Berger and Nachtmann* is essential.
Shoshi,Steffen,Pirner 2002:







Failure of the model Photoproduction of pseudoscalar and tensor mesons, dominated by Odderon exchange.



Theory: *Berger, Donnachie, D., Kilian, Nachtmann, Rueter 1999,2000*

Experiment: *Golling 2001, H1 2002*

Reaction	**H1***	BDDNR
$\gamma p \to \pi^0 N^*$	$<$ **38**	294 $\pm$ 150
$\gamma p \to f_2 N^*$	$<$ **12**	21 $\pm$ 10
$\gamma p \to a_2^0 N^*$	$<$ **62**	190 $\pm$ 100

Summary and conclusions

Nonperturbative input needed if at least one hadron (size $\sim 1/\Lambda_{QCD}$) is involved.

,,Perturbative" methods: distribution functions at given scale are taken as nonperturbative input.

Lattice calculations difficult for kinematical reasons, but nevertheless relevant for:

• Regge trajectories for $t > 0$
• critical exponents leading to intercepts

Hebecker, Meggiolaro, Nachtmann 2000, Pirner 2001, Nachtmann 2002

• also for models they give important imput: Instanton ditribution function, gauge invariant gluon corrrelator.

Instantons

• small size: a priori calculations, at the edge of observability.

• large size: models needed (instanton liquid)

Interesting possibility: yield soft energy dependence

• can they explain bulk ?

Vacuum models

- Connect high energy scattering with low energy physics.
- Yield string-string interaction (confinement).
- Successfull phenomenological description of many diffractive interactions.
- Pragmatically defined, many theoretical questions open.
- Odderon problem (not present for instantons).

Connection between Instantons and vacuum models

• Philosophy similar. Both insist of nonperturbative scale $>> \Lambda_{QCD}$.

Point on possibly deceptive feature: Perturbative and non-perturbative methods have phenomenologically a large region of overlap.

• Crucial input of SVM can be calculated in Instanton model, but:
Gaussian assumption not valid in Instanton model (no confinement) Semiclassical solutions to orderly.

• My preferred scenario: Bulk at ISR energies comes from semiclassical string-string interaction, energy dependent terms from instanton-induced interactions.

Specific literature

• A. Ringwald and F. Schrempp, "Towards the phenomenology of QCD instanton induced particle production at HERA," arXiv:hep-ph/9411217.

• A. Ringwald and F. Schrempp, "Zooming-in on instantons at HERA," Phys. Lett. B **503** (2001) 331 [arXiv:hep-ph/0012241].

• A. Ringwald and F. Schrempp, "QCD-instantons at HERA: An introduction," J. Phys. G **25** (1999) 1297 [arXiv:hep-ph/9812359].

• C. Adloff *et al.* [H1 Collaboration], "Search for QCD instanton-induced processes in deep-inelastic scattering at HERA," arXiv:hep-ex/0205078.

• A. Ringwald and F. Schrempp, "QCDINS 2.0: A Monte Carlo generator for instanton-induced processes in deep-inelastic scattering," Comput. Phys. Commun. **132** (2000) 267 [arXiv:hep-ph/9911516].

• I. I. Balitsky and V. M. Braun, "Instanton induced contributions to structure functions of deep inelastic scattering," Phys. Lett. B **314** (1993) 237 [arXiv:hep-ph/9305269].

• E. V. Shuryak and I. Zahed, "Instanton-induced effects in QCD high-energy scattering," Phys. Rev. D **62** (2000) 085014 [arXiv:hep-ph/0005152].

• D. E. Kharzeev, Y. V. Kovchegov and E. Levin, "QCD instantons and the soft pomeron," Nucl. Phys. A **690** (2001) 621 [arXiv:hep-ph/0007182].

• F. Schrempp and A. Utermann, "QCD instantons and high-energy diffractive scattering," Phys. Lett. B **543** (2002) 197 [arXiv:hep-ph/0207300].

• O. Nachtmann and A. Reiter, "The Vacuum Structure In QCD And Hadron - Hadron Scattering," Z. Phys. C **24** (1984) 283.

• A. Brandenburg, O. Nachtmann and E. Mirkes, "Spin Effects And Factorization In The Drell-Yan Process," Z. Phys. C **60** (1993) 697.

• H. G. Dosch and Y. A. Simonov, "The Area Law Of The Wilson Loop And Vacuum Field Correlators," Phys. Lett. B **205** (1988) 339.

• H. G. Dosch, "Gluon Condensate And Effective Linear Potential," Phys. Lett. B **190** (1987) 177.

• M. D'Elia, A. Di Giacomo and E. Meggiolaro, "Gauge-invariant nonlocal quark condensates in QCD," Nucl. Phys. Proc. Suppl. **73** (1999) 515 [arXiv:hep-lat/9811017].

• G. S. Bali, "Casimir scaling of SU(3) static potentials," Phys. Rev. D **62** (2000) 114503 [arXiv:hep-lat/0006022].

• V. I. Shevchenko and Y. A. Simonov, "Casimir scaling as a test of QCD vacuum," Phys. Rev. Lett. **85** (2000) 1811 [arXiv:hep-ph/0001299].

• O. Nachtmann, "Considerations Concerning Diffraction Scattering In Quantum Chromodynamics," Annals Phys. **209** (1991) 436.

• A. Kraemer and H. G. Dosch, "Nonperturbative Contributions To High-Energy Hadron-Hadron Scattering," Phys. Lett. B **272** (1991) 114.

• H. G. Dosch, E. Ferreira and A. Kramer, "Nonperturbative QCD Treatment Of High-Energy Hadron Hadron Scattering," Phys. Rev. D **50** (1994) 1992 [arXiv:hep-ph/9405237].

• W. Buchmuller and A. Hebecker, "A Parton model for diffractive processes in deep inelastic scattering," Phys. Lett. B **355** (1995) 573 [arXiv:hep-ph/9504374].

• W. Buchmuller, T. Gehrmann and A. Hebecker, "Inclusive and diffractive structure functions at small x," Nucl. Phys. B **537** (1999) 477 [arXiv:hep-ph/9808454].

• E. R. Berger and O. Nachtmann, “Differential cross sections for high energy elastic hadron hadron scattering in nonperturbative QCD,” Eur. Phys. J. C **7** (1999) 459 [arXiv:hep-ph/9808320].

• T. Golling [H1 Collaboration], “Investigation of pomeron and odderon induced photoproduction of mesons decaying to pure multiphoton final states at HERA,” *Prepared for International Europhysics Conference on High-Energy Physics (HEP 2001), Budapest, Hungary, 12-18 Jul 2001*.

• C. Adloff *et al.* [H1 Collaboration], “Search for odderon-induced contributions to exclusive pi0 photoproduction at HERA,” Phys. Lett. B **544** (2002) 35 [arXiv:hep-ex/0206073].

• E. R. Berger, A. Donnachie, H. G. Dosch and O. Nachtmann, “Observing the odderon: Tensor meson photoproduction,” Eur. Phys. J. C **14** (2000) 673 [arXiv:hep-ph/0001270].

• E. R. Berger, A. Donnachie, H. G. Dosch, W. Kilian, O. Nachtmann and M. Rueter, “Odderon and photon exchange in electroproduction of pseudoscalar mesons,” Eur. Phys. J. C **9** (1999) 491 [arXiv:hep-ph/9901376].

• O. Nachtmann, “Effective field theory approach to structure functions at small x(Bj),” arXiv:hep-ph/0206284.

• A. Hebecker, E. Meggiolaro and O. Nachtmann, “Structure functions at small x(Bj) in a Euclidean field theory approach,” Nucl. Phys. B **571** (2000) 26 [arXiv:hep-ph/9909381].

• H. J. Pirner, “Low x-scattering as a critical phenomenon,” Phys. Lett. B **521** (2001) 279 [arXiv:hep-ph/0108243].

Reviews:

• H. G. Dosch, V. I. Shevchenko and Y. A. Simonov, “Field correlators in QCD: Theory and applications,” arXiv:hep-ph/0007223.

• O. Nachtmann, “High energy collisions and nonperturbative QCD,” arXiv:hep-ph/9609365.

• H. G. Dosch, “Non-Perturbative Diffractive Scattering,” Acta Phys. Polon. B **30** (1999) 3813.

• H. G. Dosch, “Non-perturbative Methods in QCD” Hadron Physics 96, Ed. E. Ferreira et al., Singapore 1997

Applications of the model :

• A. Donnachie and H. G. Dosch, “A comprehensive approach to structure functions,” Phys. Rev. D **65** (2002) 014019 [arXiv:hep-ph/0106169].

• H. G. Dosch, O. Nachtmann, T. Paulus and S. Weinstock, “Inelastic diffractive scattering in nonperturbative QCD,” Eur. Phys. J. C **21** (2001) 339 [arXiv:hep-ph/0012367].

• A. Donnachie and H. G. Dosch, “Diffractive exclusive photon production in deep inelastic scattering,” Phys. Lett. B **502** (2001) 74 [arXiv:hep-ph/0010227].

• A. Donnachie, H. G. Dosch and M. Rueter, “gamma* gamma* reactions at high energies,” Eur. Phys. J. C **13** (2000) 141 [arXiv:hep-ph/9908413].

• H. G. Dosch, F. S. Navarra, M. Nielsen and M. Rueter, “Charmonium-hadron cross section in a nonperturbative QCD approach,” Phys. Lett. B **466** (1999) 363 [arXiv:hep-ph/9908274].

• G. Kulzinger, H. G. Dosch and H. J. Pirner, “Diffractive photo- and leptoproduction of vector mesons rho, rho' and rho”,” Eur. Phys. J. C **7** (1999) 73 [arXiv:hep-ph/9806352].

• H. G. Dosch, T. Gousset and H. J. Pirner, “Nonperturbative gamma* p interaction in the diffractive regime,” Phys. Rev. D **57** (1998) 1666 [arXiv:hep-ph/9707264].

• H. G. Dosch, T. Gousset, G. Kulzinger and H. J. Pirner, “Vector meson leptoproduction and nonperturbative gluon fluctuations in QCD,” Phys. Rev. D **55** (1997) 2602 [arXiv:hep-ph/9608203].

• A. I. Shoshi, F. D. Steffen and H. J. Pirner, "S-matrix unitarity, impact parameter profiles, gluon saturation and high-energy scattering," arXiv:hep-ph/0202012.

• F. Pereira and E. Ferreira, "Zeros, dips and signs in p p and p anti-p elastic amplitudes," Phys. Rev. D **61** (2000) 077507 [arXiv:hep-ph/9907415].

• F. Pereira and E. Ferreira, "Eikonal profile functions and amplitudes for p p and anti-p p scattering," Phys. Rev. D **59** (1999) 014008 [arXiv:hep-ph/9811496].

• E. Ferreira and F. Pereira, "Hadronic sizes and observables in high-energy scattering," Phys. Rev. D **56** (1997) 179 [arXiv:hep-ph/9705278].