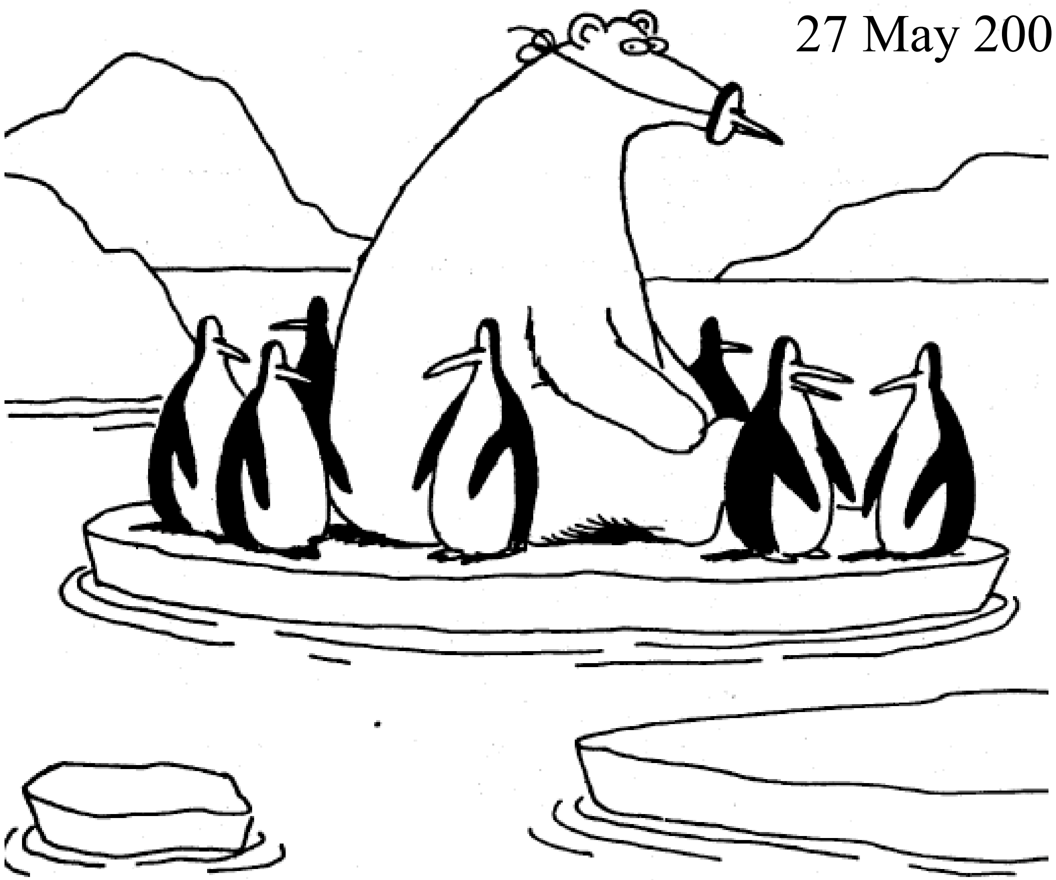
Hadron scattering and QCD

Paul Hoyer
University of Helsinki

GSI Colloquium
27 May 2008



"And now Edgar's gone. ... Something's going on around here."

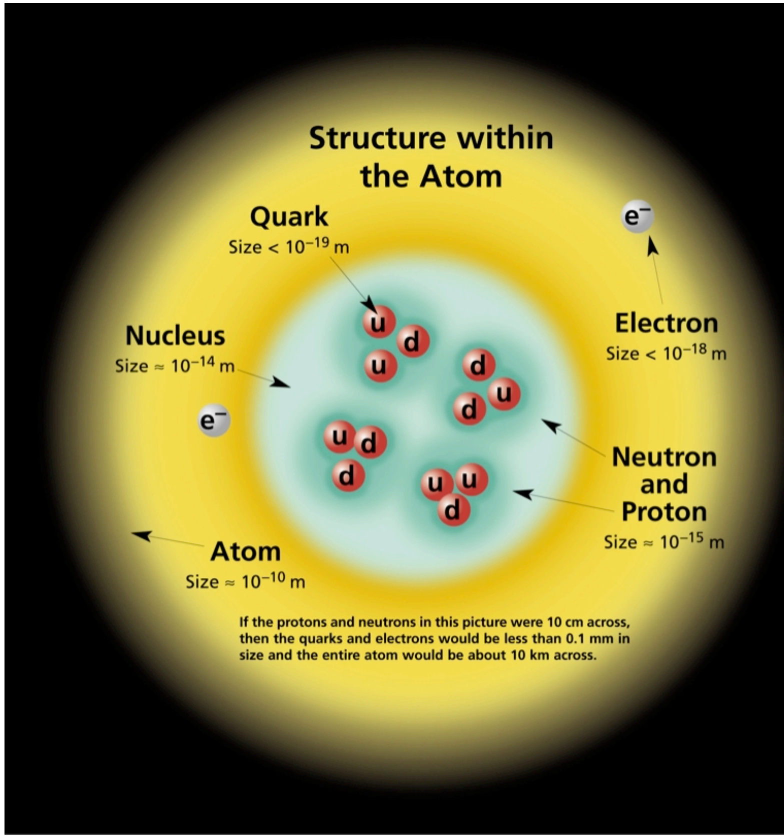
Gary Larson, The Far Side

The divisibility of matter

Since ancient times we have wondered whether matter can be divided into smaller parts *ad infinitum*, or whether there is a smallest constituent.

Democritus, ~ 400 BC
Vaisheshika school

Common sense suggest that these are the two possible alternatives. However, physics requires us to refine our intuition.



Quantum mechanics shows that atoms (or molecules) are the identical smallest constituents of a given substance – yet they can be taken apart into electrons, protons and neutrons.

Hadron physics gives a new twist to this age-old puzzle: Quarks can be removed from the proton, but cannot be isolated.

Relativity – particle creation from energy – is the new feature which makes this possible.

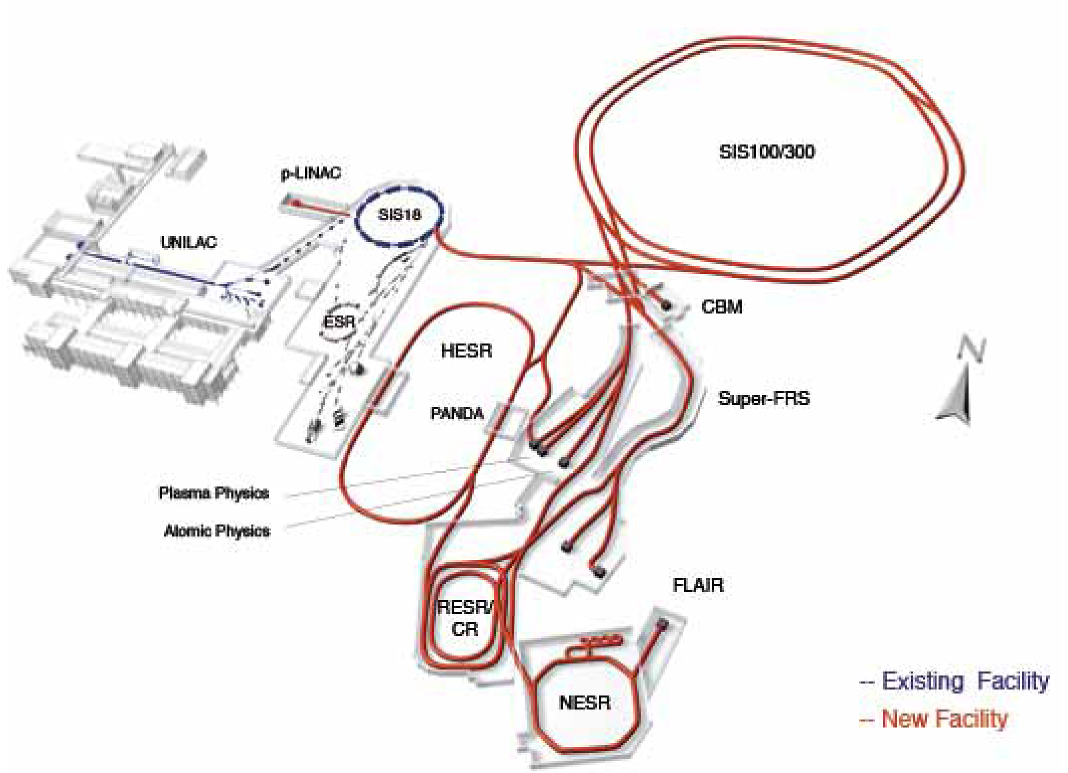
We are fortunate to be here to address – and hopefully develop an understanding of – this essentially novel phenomenon!

Hadrons are within "easy" reach of experiments

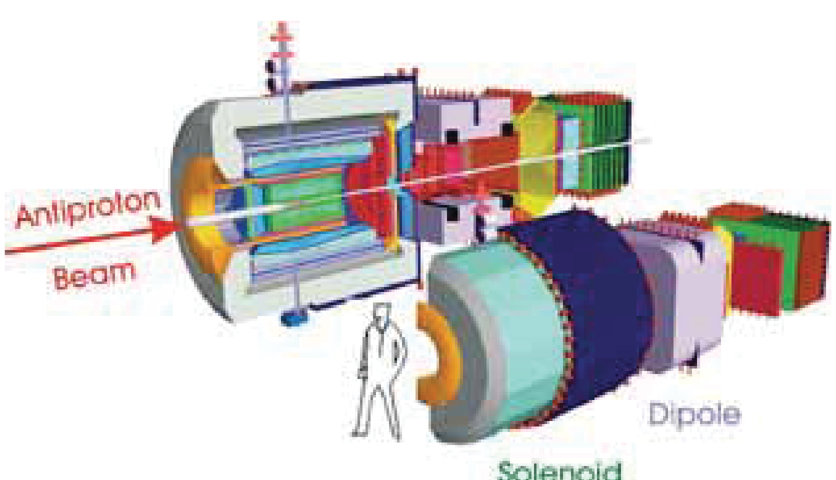
Dedicated hadron facilities
FAIR in Europe
... and particle physics facilities

Moderate energies:
strong interaction scale ~ 200 MeV

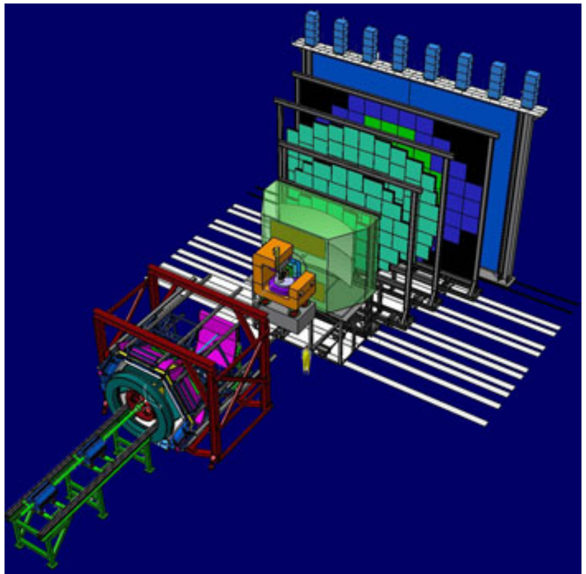
Hints from data:
Quark model, low energy scaling,...



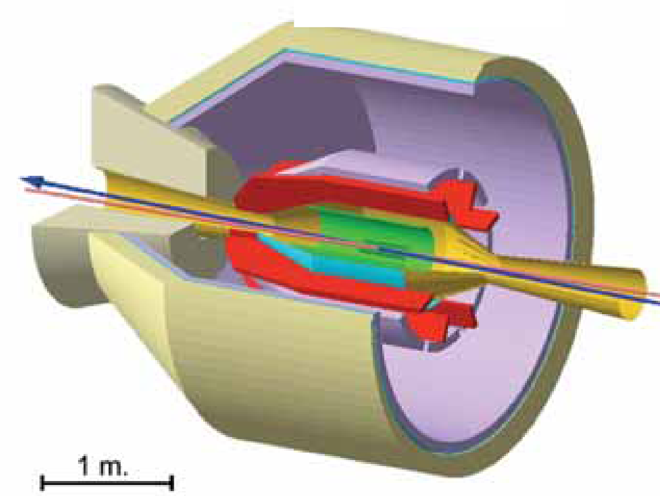
PANDA



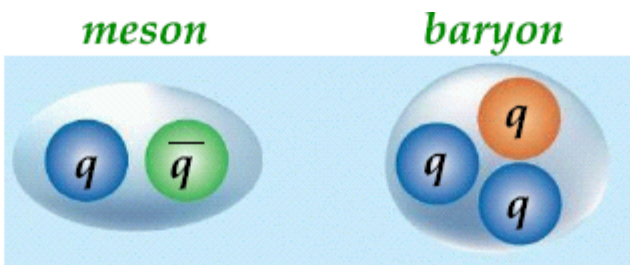
CBM



PAX



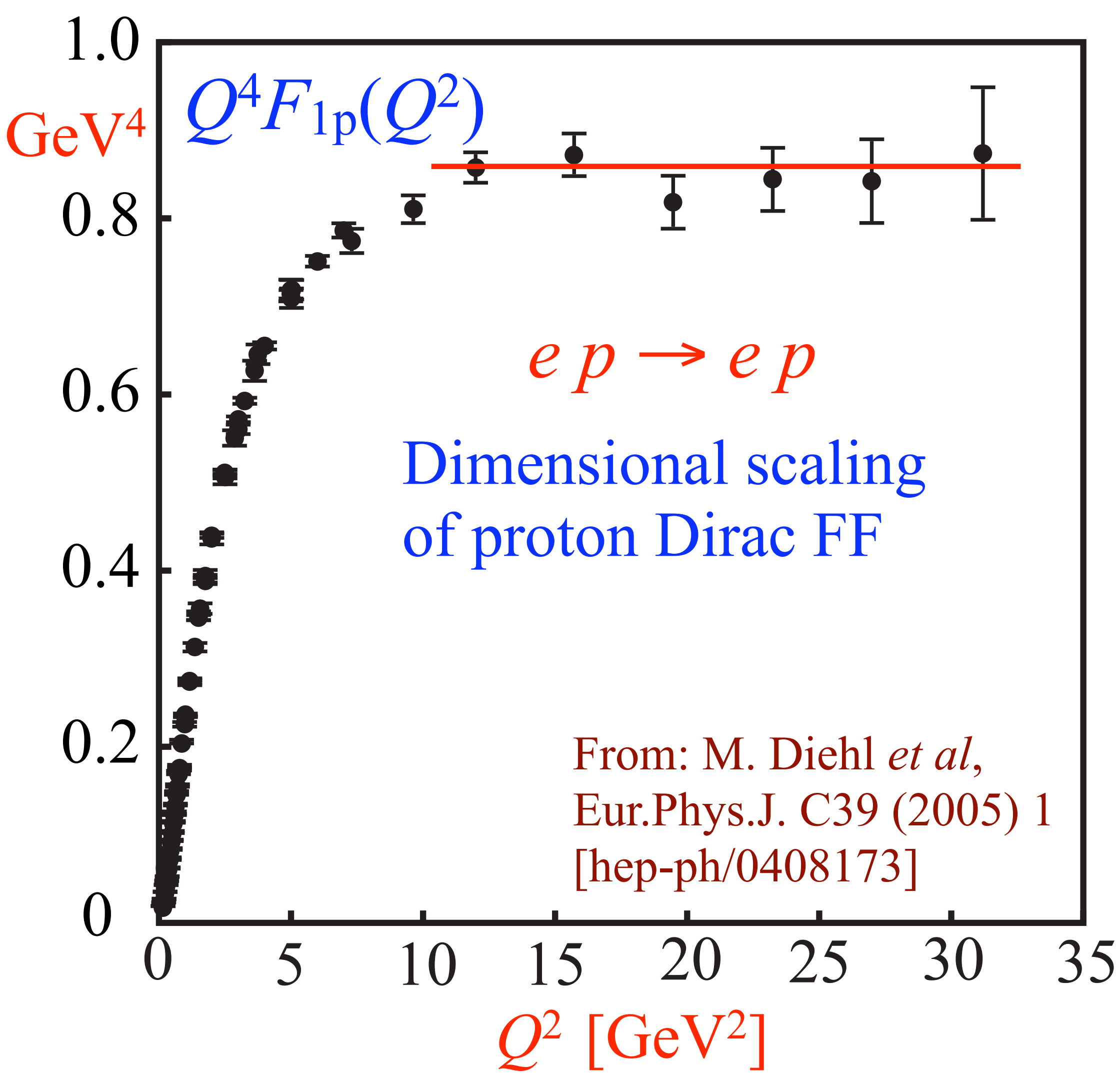
Hint from experiments:
The Constituent Quark Model

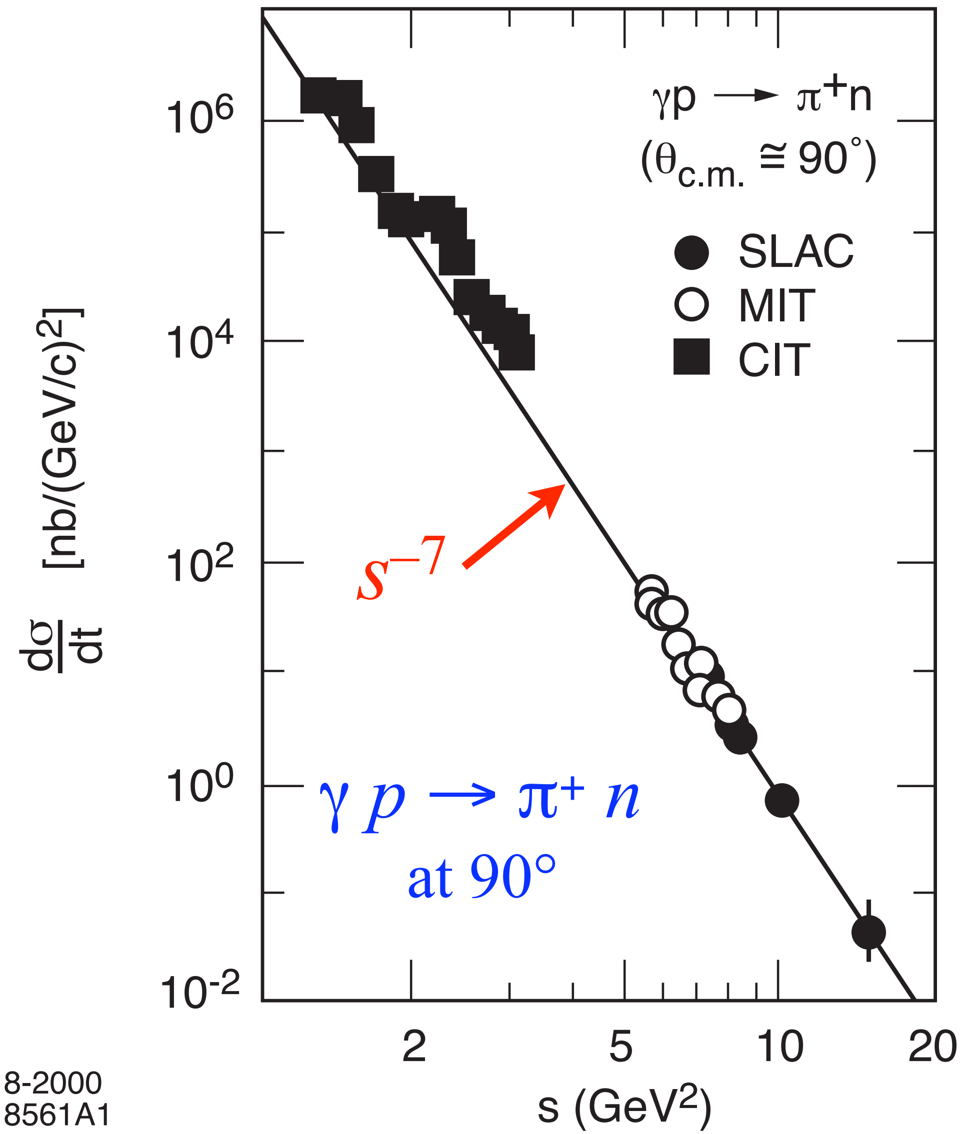


Hadrons can be classified as $q\bar{q}$ or qqq bound states, using non-relativistic *n, L, S* quantum numbers, as for QED atoms

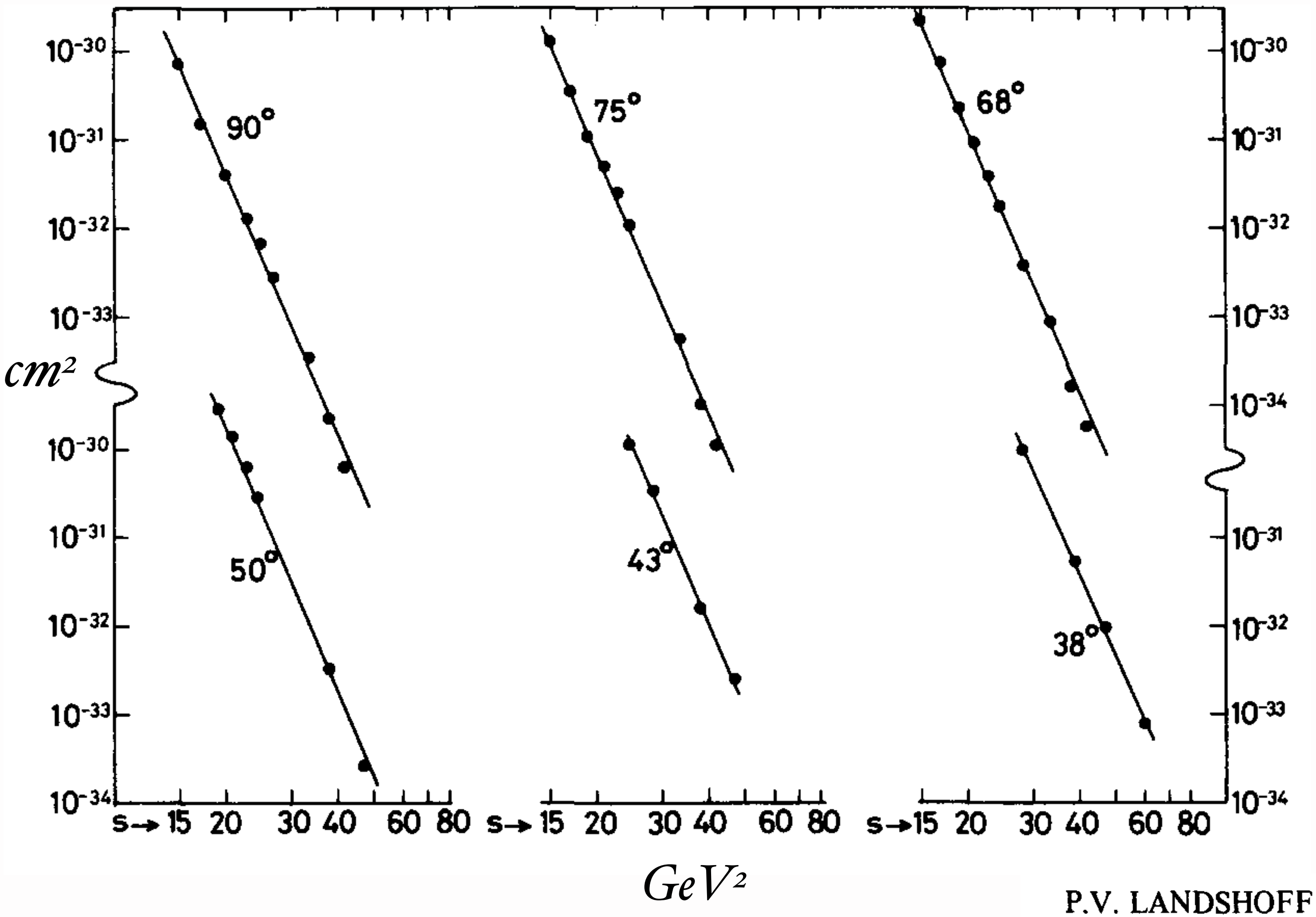
$n\ ^{2s+1}\ell_J$	J^{PC}	I = 1 ud, $\overline{u}d$, $\frac{1}{\sqrt{2}}(d\overline{d} - u\overline{u})$
$1\ ^1S_0$	0^{-+}	π
$1\ ^3S_1$	1^{--}	$\rho(770)$
$1\ ^1P_1$	1^{+-}	$b_1(1235)$
$1\ ^3P_0$	0^{++}	$a_0(1450)$
$1\ ^3P_1$	1^{++}	$a_1(1260)$
$1\ ^3P_2$	2^{++}	$a_2(1320)$
$1\ ^1D_2$	2^{-+}	$\pi_2(1670)$
$1\ ^3D_1$	1^{--}	$\rho(1700)$
$1\ ^3D_2$	2^{--}	
$1\ ^3D_3$	3^{--}	$\rho_3(1690)$
$1\ ^3F_4$	4^{++}	$a_4(2040)$
$1\ ^3G_5$	5^{--}	$\rho_5(2350)$
$1\ ^3H_6$	6^{++}	$a_6(2450)$
$2\ ^1S_0$	0^{-+}	$\pi(1300)$
$2\ ^3S_1$	1^{--}	$\rho(1450)$

Early onset of Dimensional Scaling





Quark-Counting : $\frac{d\sigma}{dt}(pp \to pp) = \frac{F(\theta_{CM})}{s^{10}}$ $\quad n = 4 \times 3 - 2 = 10$



P.V. LANDSHOFF and J.C. POLKINGHORNE

Best Fit

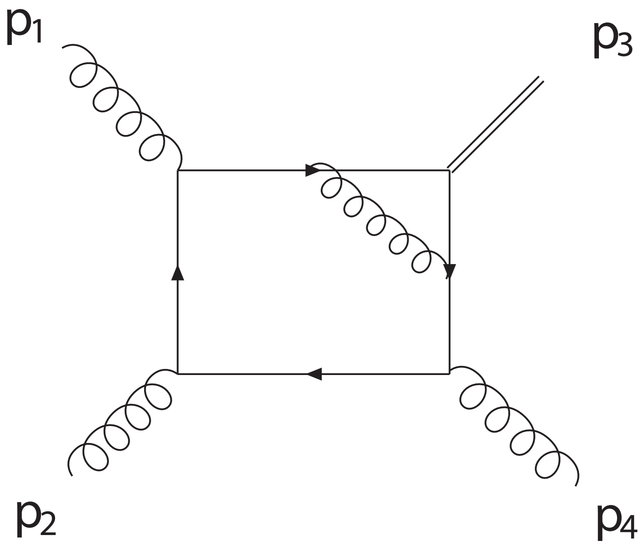
$n = 9.7 \pm 0.5$

Reflects underlying conformal scale-free interactions

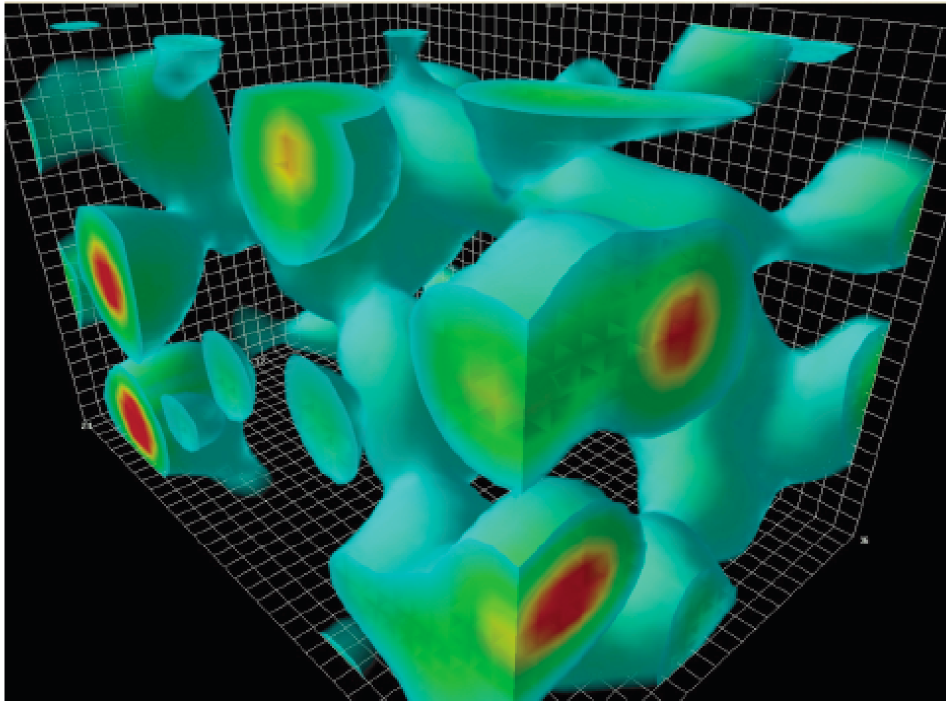
We know the theory of hadron physics

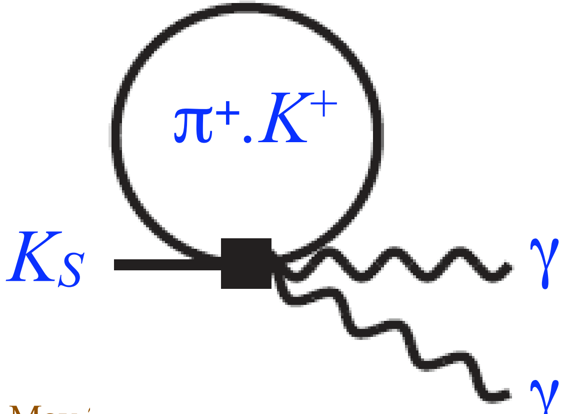
$$\mathcal{L}_{QCD} = \bar{\psi}(i\partial\!\!\!/ - gA\!\!\!/ - m)\psi - \frac{1}{4}F^{\mu\nu}F_{\mu\nu}$$

Perturbative calculations at short distance



Lattice calculations at long distance





Chiral expansions at low energy

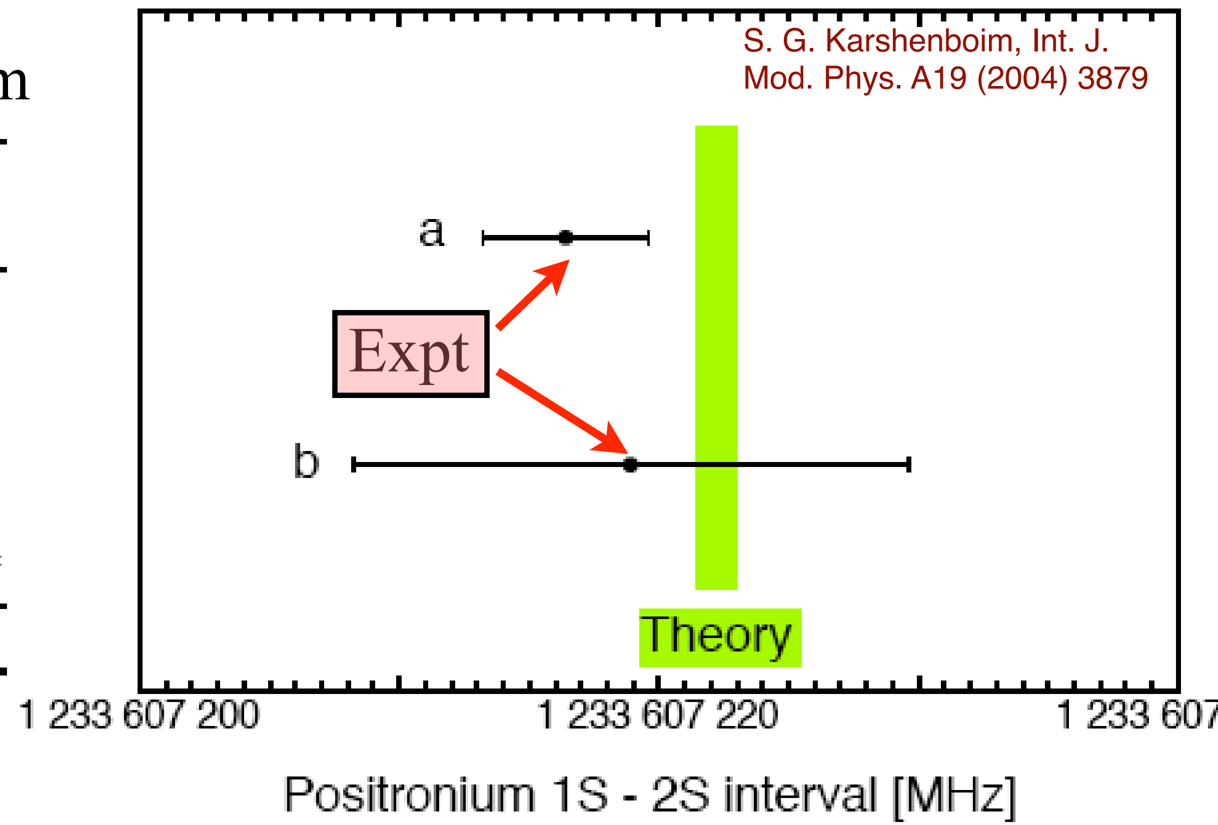
Theory needs data, and vice versa

Some of the most accurate predictions in physics are obtained in QED by expanding in $\alpha = e^2/4\pi \approx 1/137.035\,999\,11(46)$.

1^3S_1 - 2^3S_1 interval in positronium

QED

Term	ΔE [MHz]
$\alpha^2 mc^2$	1 233 690 735.1
$\alpha^4 mc^2$	-82 005.6
$\alpha^5 mc^2$	-1 501.4
$\alpha^6 mc^2$	-7.1[23]
$\alpha^7 mc^2$	1.2(6)[24]
Total	1 233 607 222.2(6)



However, the QED series must diverge since for any $\alpha = e^2/4\pi < 0$ the electron charge e is imaginary: The Hamiltonian is not hermitian and probability not conserved. The calculations would be void without experimental confirmation.

F. Dyson

Hadrons are ultra-relativistic

Compare the excitation energies of atoms, nuclei and hadrons

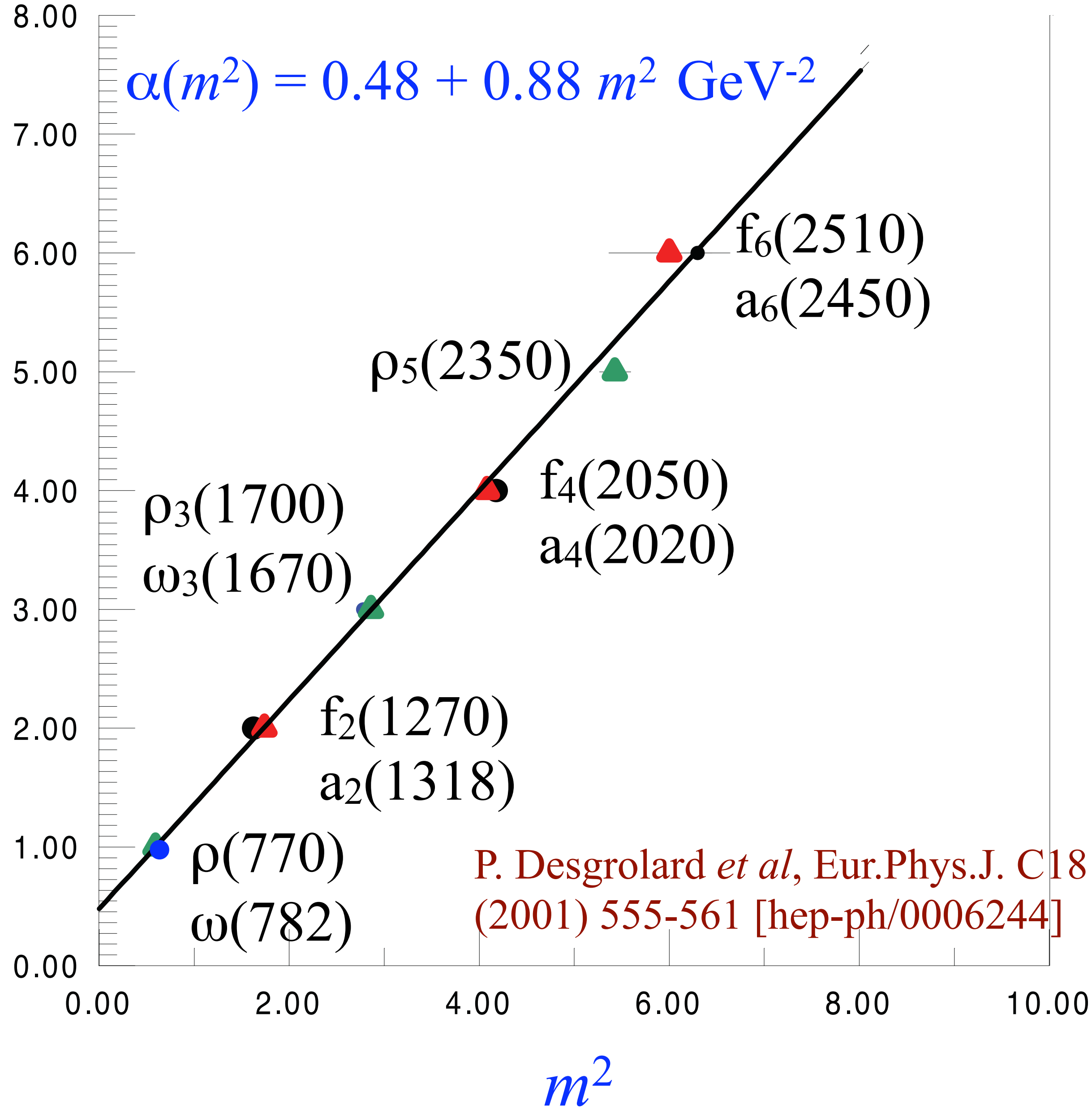
Atoms: $\Delta E/mc^2 \sim 10^{-5}$

Nuclei: $\Delta E/mc^2 \sim 10^{-3}$

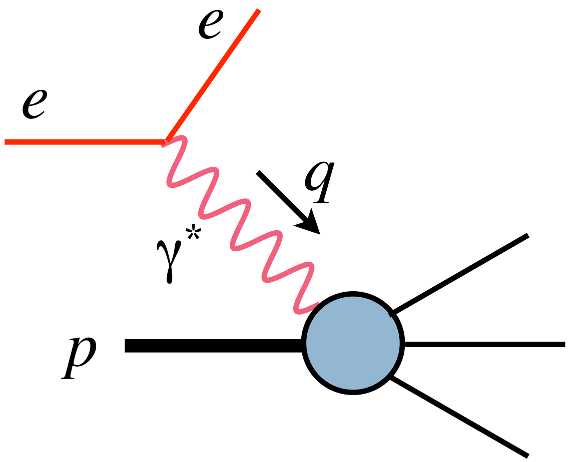
Hadrons: $$\frac{m_\rho - m_\pi}{m_\pi} \simeq 4.5$$

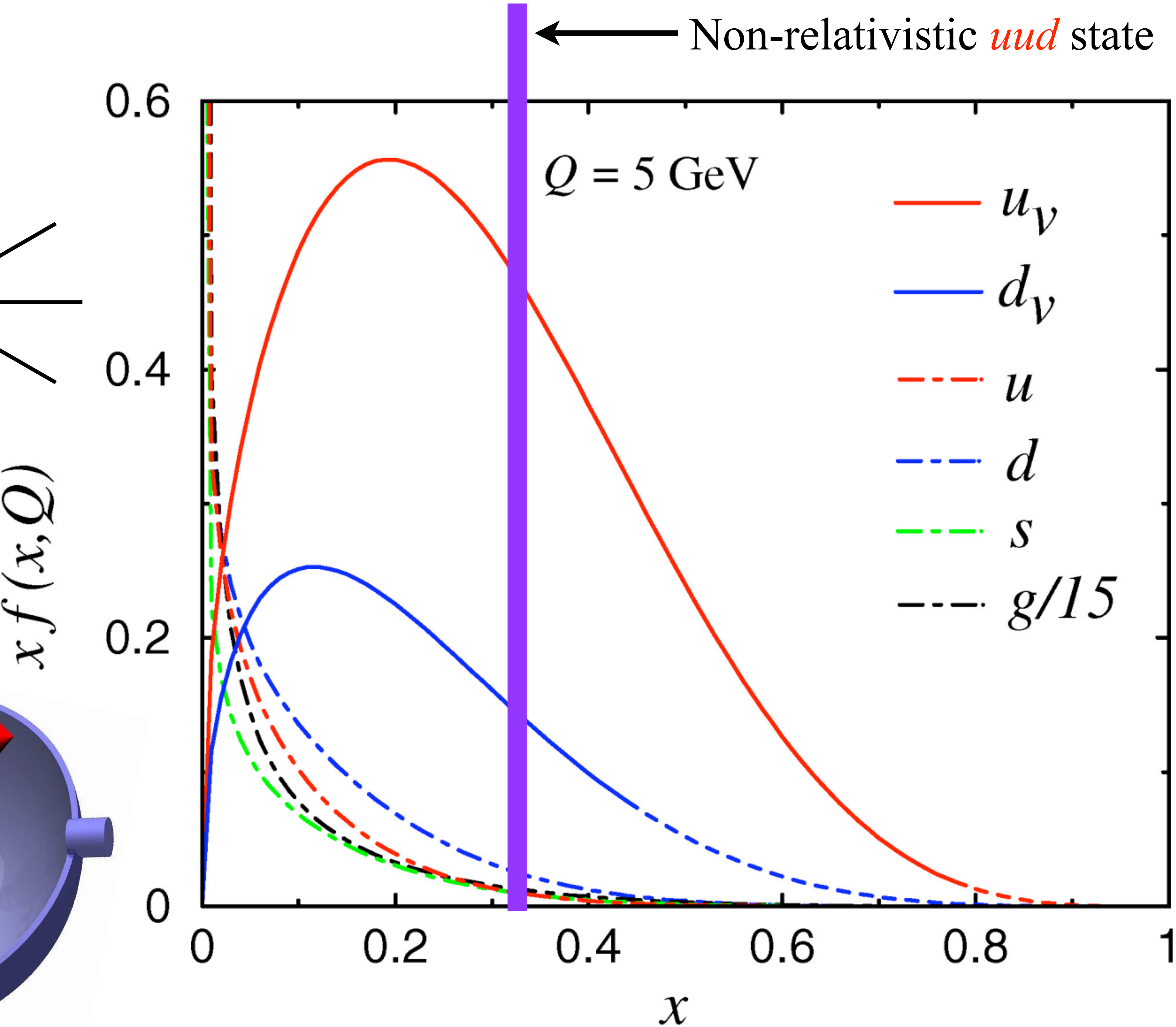
Linear Regge trajectories:

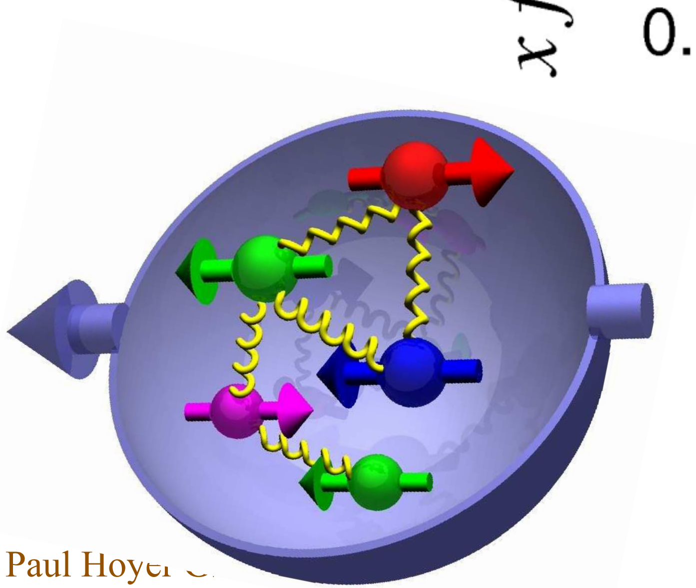
$$\frac{\Delta m^2}{m^2} \simeq 1$$



Relativity revealed by parton distributions in proton







A closer look at the proton…

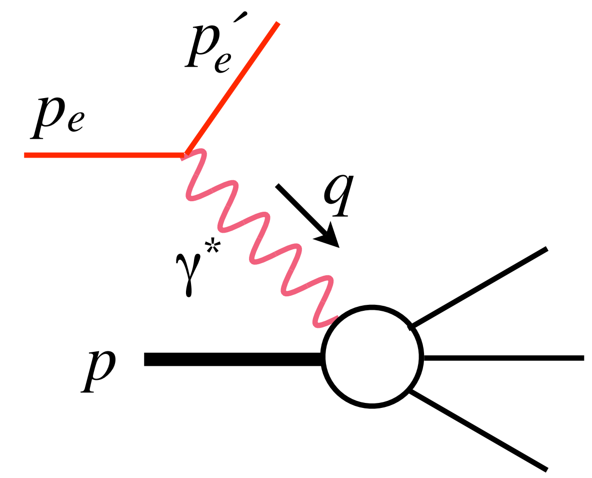
The NR quark model, precocious scaling, soft hadronization,...
suggest that a simple, approximative description of hadrons may be feasible.

Experiment and theory must work together to establish how such a description can arise from the QCD lagrangian.

Understanding precisely how hard scattering data relates to hadron structure is non-trivial, taking relativistic field theory into account.

Which target matrix elements can be measured
– and with what resolution?

Effects of relativity on resolution of hard probes



In the target proton rest frame the beam may be taken to move along the $-z$ direction

$$p_e = (\sqrt{p_z^2 + m_e^2}, 0, 0, -p_z)$$

For fixed angle scattering in CM the photon virtuality

$$Q^2 \equiv -q^2 \sim (E_{CM}^{ep})^2$$

and $q_\perp \sim Q$ whereas $q^0 \simeq -q^z \sim Q^2$

Hence the γ^* resolution is different in the directions transverse and longitudinal to the beam.

The spatial resolution in the transverse direction is

$\Delta x_\perp \sim 1/q_\perp \sim 1/Q$ (uncertainty relation)

E.g.: $\Delta x^\perp \sim 0.1$ fm for $Q^2 = 4$ GeV^2

Transverse structure of the nucleon
Elastic Form Factors

The proton charge density ρ^N as a function of impact parameter $\boldsymbol{b} = \boldsymbol{x}_\perp$ is given by the elastic $ep \to ep$ form factors $F_1(Q^2)$ and $F_2(Q^2)$, which measure the quark charge density

M. Burkardt (2000)
G. A. Miller (2007)
C. E. Carlson and M. Vanderhaeghen (2008)

$$J_q^+ = 2e_q\, q_+^\dagger q_+ \quad \text{where} \quad q_+ \equiv \frac{1}{4}\gamma^-\gamma^+ q \qquad \gamma^\pm = \gamma^0 \pm \gamma^3$$

☆ The charge density of an unpolarized nucleon is given by $F_1(Q^2)$

$$\rho_0^N(\boldsymbol{b}) = \int_0^\infty \frac{d^2\boldsymbol{q}_\perp}{(2\pi)^2} e^{i\boldsymbol{q}_\perp\cdot\boldsymbol{b}}\, \frac{1}{2P^+}\langle P^+, \tfrac{1}{2}\boldsymbol{q}_\perp, \lambda|J^+(0)|P^+, -\tfrac{1}{2}\boldsymbol{q}_\perp, \lambda\rangle$$

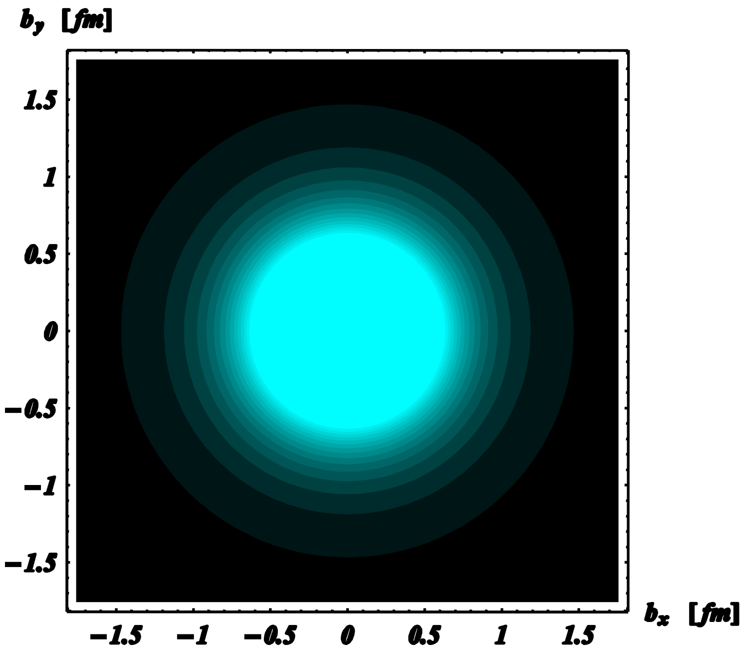
$$= \int_0^\infty \frac{dQ}{2\pi} Q\, J_0(bQ)\, F_1(Q^2)$$

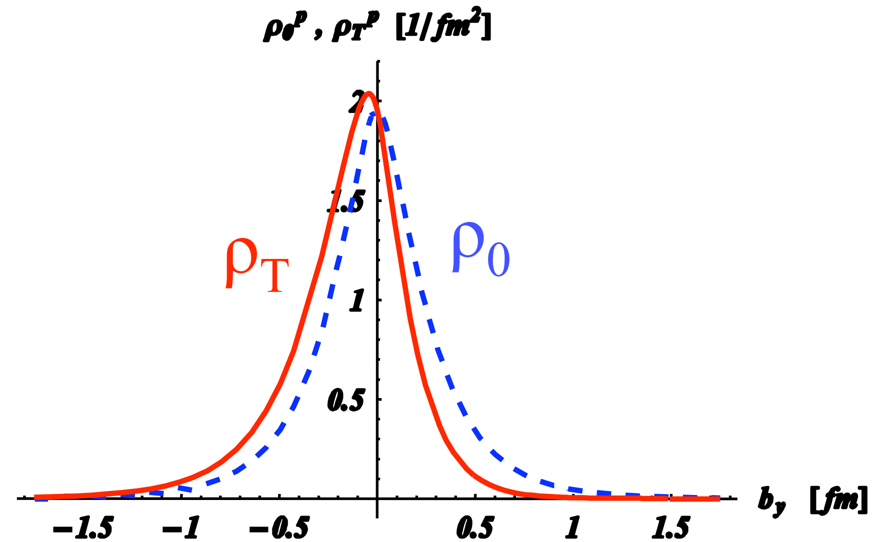
☆ The charge density of a transversely polarized nucleon depends on the angle between the spin and the impact parameter, and is given by $F_2(Q^2)$

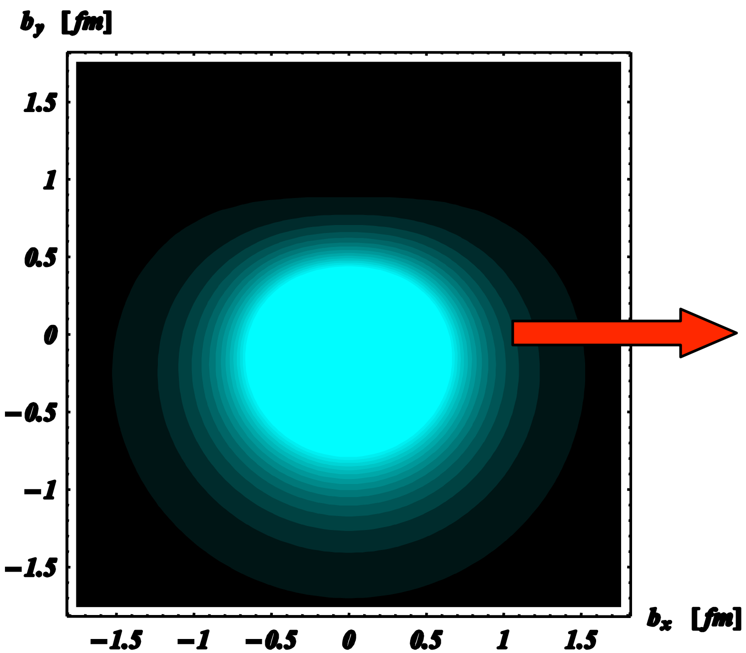
$$\rho_T^N(\boldsymbol{b}) = \int_0^\infty \frac{d^2\boldsymbol{q}_\perp}{(2\pi)^2} e^{i\boldsymbol{q}_\perp\cdot\boldsymbol{b}}\, \frac{1}{2P^+} \langle P^+, \tfrac{1}{2}\boldsymbol{q}_\perp, s_\perp = \tfrac{1}{2} | J^+(0) | P^+, -\tfrac{1}{2}\boldsymbol{q}_\perp, s_\perp = \tfrac{1}{2}\rangle$$

$$= \rho_0^N(b) - \sin(\phi_b - \phi_S) \int_0^\infty \frac{dQ}{2\pi} \frac{Q^2}{2m_N}\, J_1(bQ)\, F_2(Q^2)$$

empirical quark transverse densities in proton







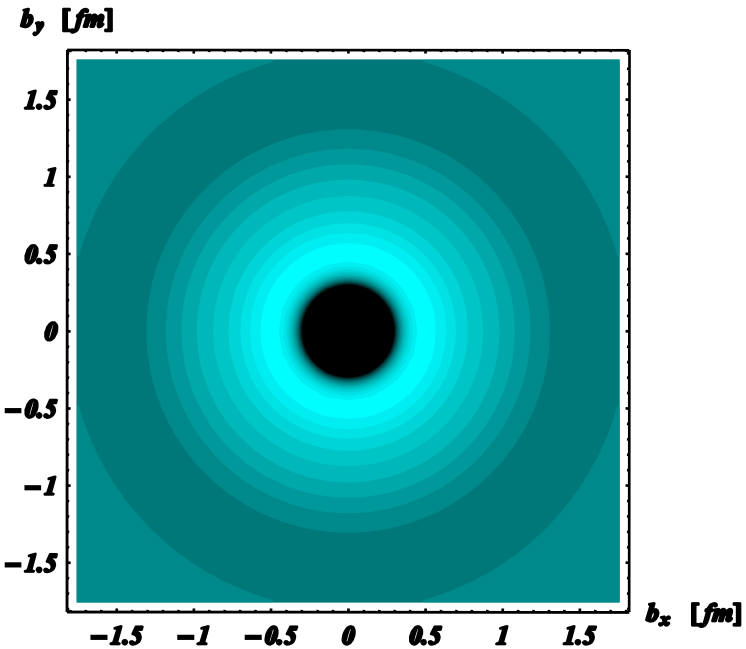
induced EDM : $d_y = - F_{2p}(0) \cdot e / (2 M_N)$

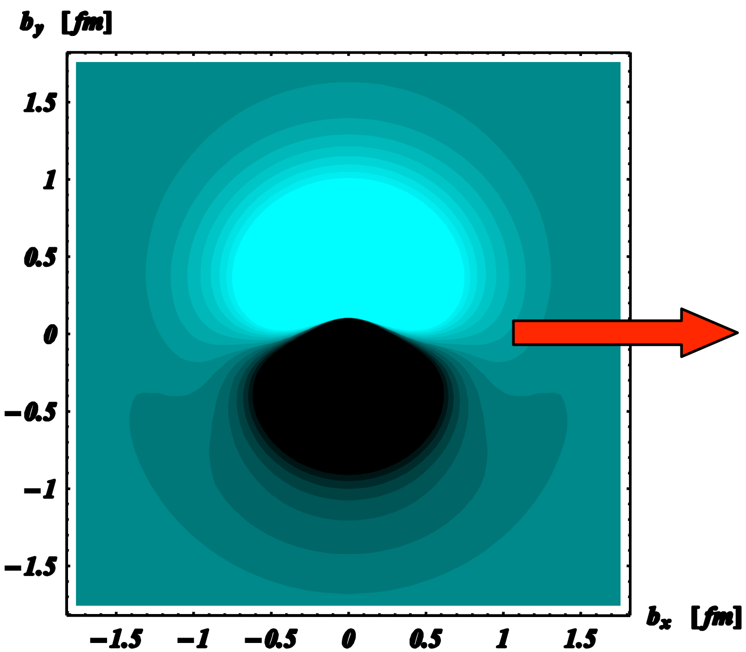
data : Arrington, Melnitchouk, Tjon (2007)

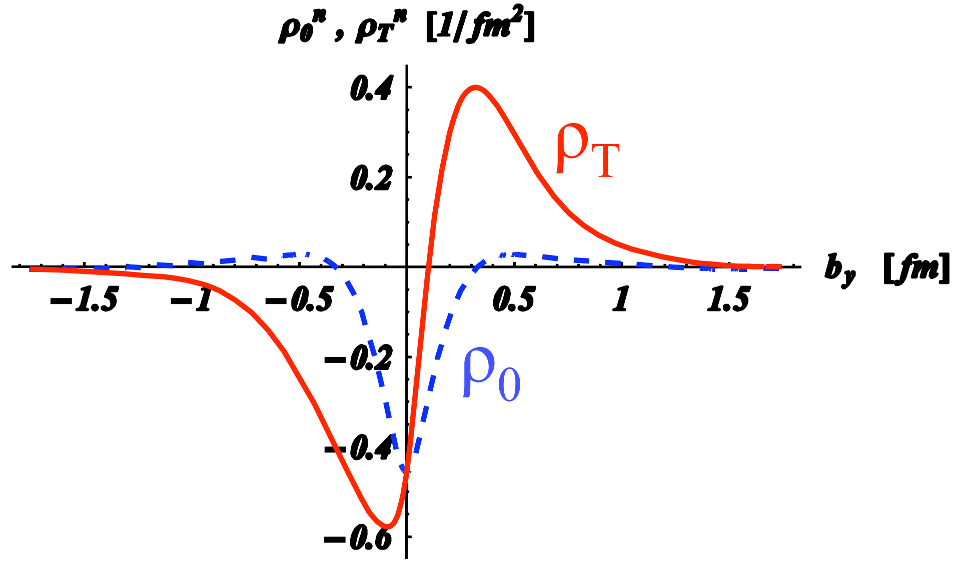
densities : Miller (2007); Carlson, Vdh (2007)

M. Vanderhaeghen, ECT* May 2008

empirical quark transverse densities in neutron







induced EDM : $d_y = - F_{2n}(0) \,.\, e / (2 M_N)$

data : Bradford, Bodek, Budd, Arrington (2006)

densities : Miller (2007); Carlson, Vdh (2007)

M. Vanderhaeghen, ECT* May 2008

Longitudinal resolution in hard scattering

At high $p_e = (\sqrt{p_z^2 + m_e^2}, 0, 0, -p_z)$ it is instructive to use

Light-Front coordinates $q = (q^+, q^-, \boldsymbol{q}^\perp)$

$$p^\pm = E \pm p^z$$

$$\boldsymbol{p}^\perp = (p^x, p^y)$$

$$q \cdot x = \tfrac{1}{2}(q^+ x^- + q^- x^+) - \boldsymbol{q}^\perp \cdot \boldsymbol{x}^\perp$$

☆ The resolution in "Light Front time" $x^+ = t + z \sim 1/q^-$:

$$\Delta x^+ \sim \frac{2m_N x_B}{Q^2}$$

where the Bjorken variable $x_B = \frac{Q^2}{2p \cdot q} = \frac{Q^2}{2m\nu}$

Hence: The photon "measures" the proton at equal x^+ as $Q^2 \to \infty$
(also known as the "infinite momentum frame")

☆ The resolution " along the light cone" $x^- = t - z \sim 1/q^+$:

$$\Delta x^- \sim \frac{1}{2m_N x_B}$$

Note: This "Ioffe" distance remains finite as $Q^2 \to \infty$

Longitudinal structure of the nucleon

Parton distributions

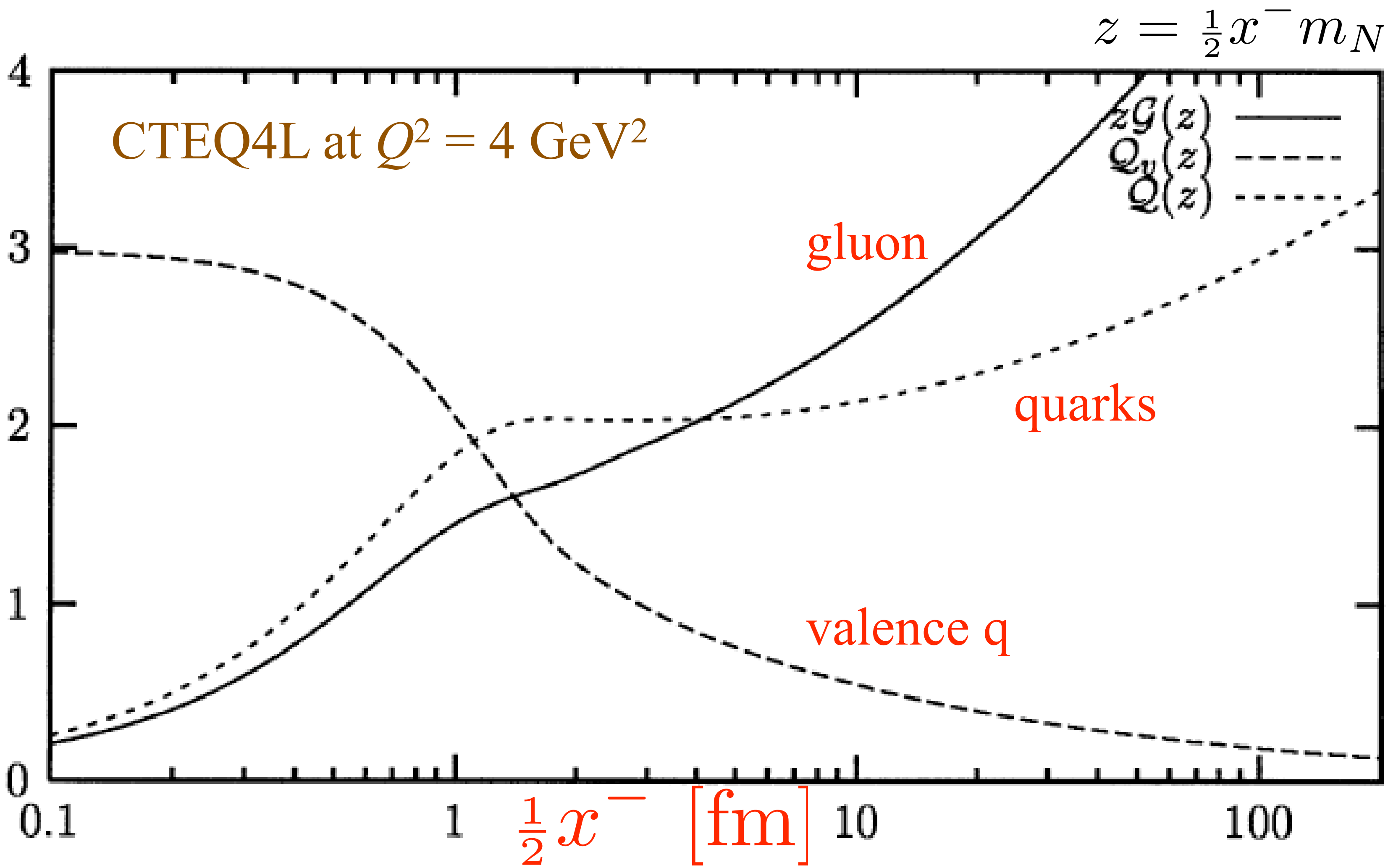
The longitudinal x^- distribution of partons in the proton is given by the parton distributions measured in inclusive $ep \to e\, X$

$$f_{q/N}(x_B) = \frac{1}{8\pi}\int dx^- \exp(-\tfrac{1}{2} i m_N x_B x^-) \times \langle N(p)|\bar{q}(x^-)\gamma^+ q(0)|N(p)\rangle\Big|_{\substack{x^+=0\\ x_\perp=0}}$$

The quark operators are displaced by $x^- \sim 1/m_N x_B$, due to the finite resolution of the photon as we noted above.

We can Fourier transform the data from momentum (x_B) to coordinate (x^-) space. This gives us an idea of how "long" the proton is:

Parton distributions of nucleon in coordinate space

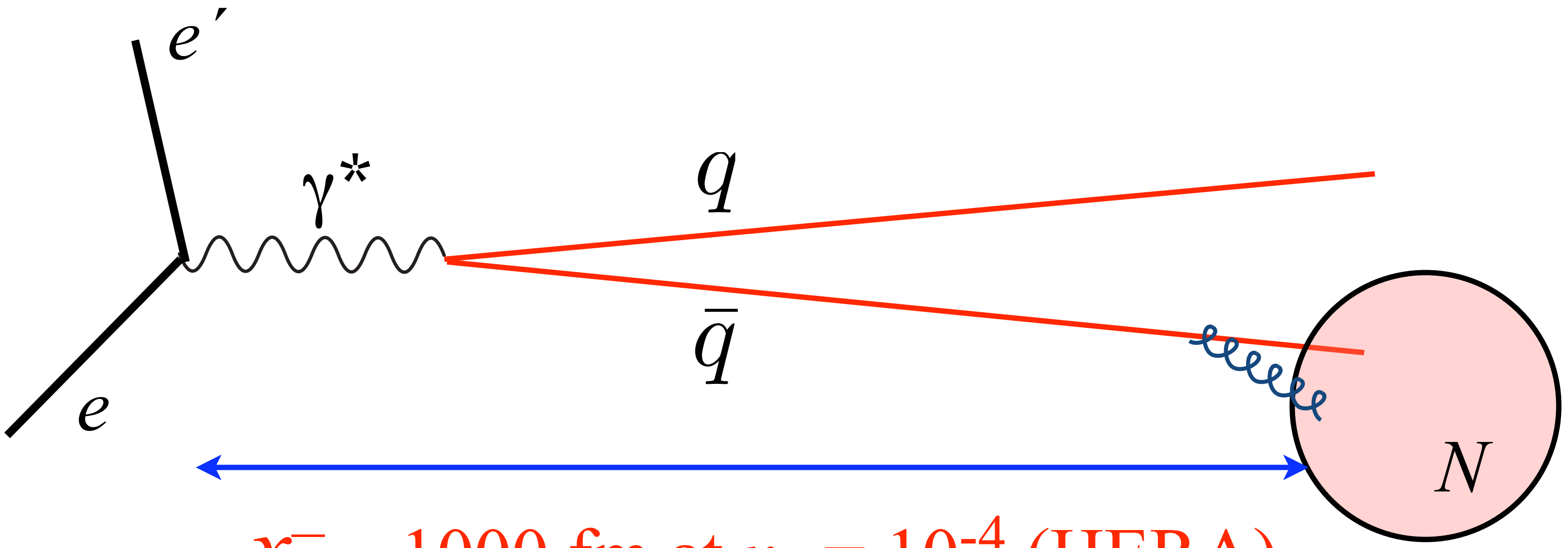


M. Vänttinen, G. Piller, L. Mankiewicz, W. Weise, K.J. Eskola, Eur. Phys. J. A3 (1998) 351.

Large gluon and (sea) quark distributions at long distances (~ small x_B) reflect parton distributions of the photon, not those of the nucleon!

Coordinate space view of low x_B events

$\gamma^* \to q\bar{q}$ long before the target

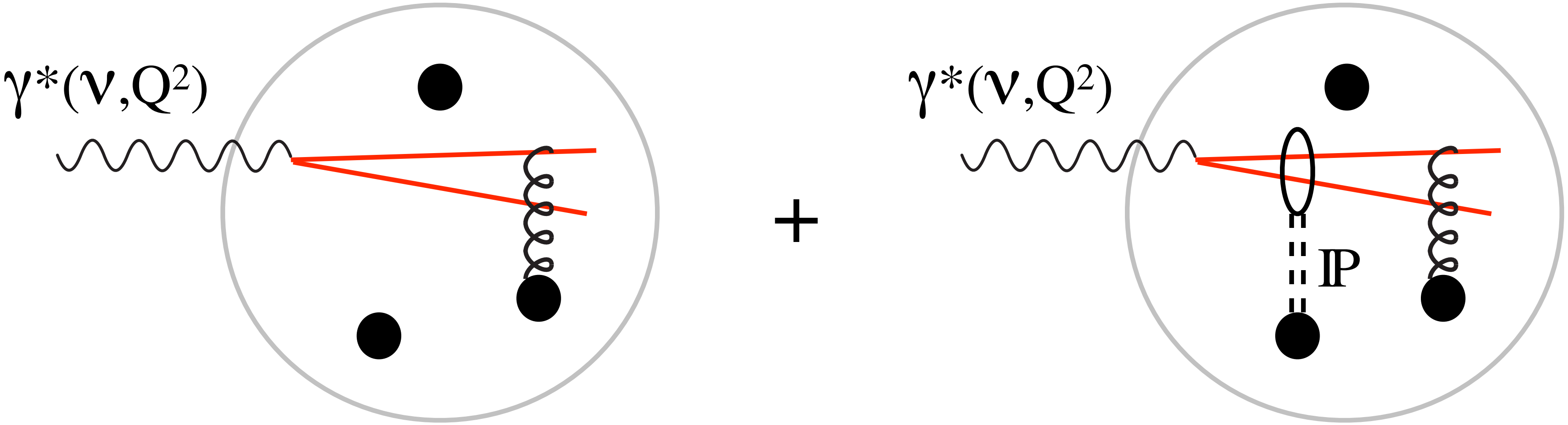


$x^- \sim 1000$ fm at $x_B = 10^{-4}$ (HERA)

$\sigma_{DIS} \propto \sigma(q\bar{q} + N)$ DIS cross section determined by scattering in the target of partons in the photon

Multiple scattering leads to shadowing in nuclear targets...

Shadowing dynamics

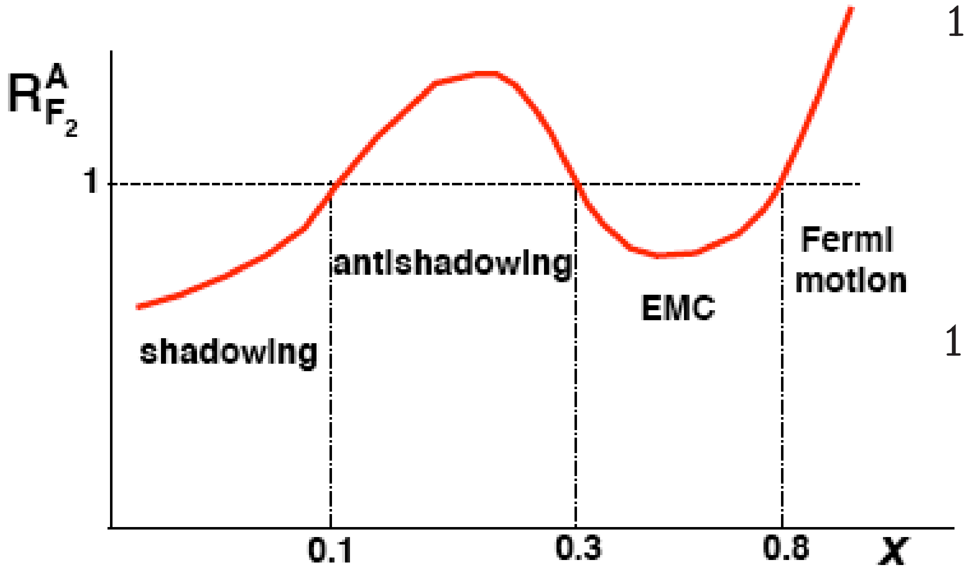


M_{single} $\qquad\qquad$ $M_{double} \sim i \cdot i\, M_{single}$

Negative interference between single and double scattering due to factor $i^2 = -1$ from elastic scattering and on-shell intermediate state

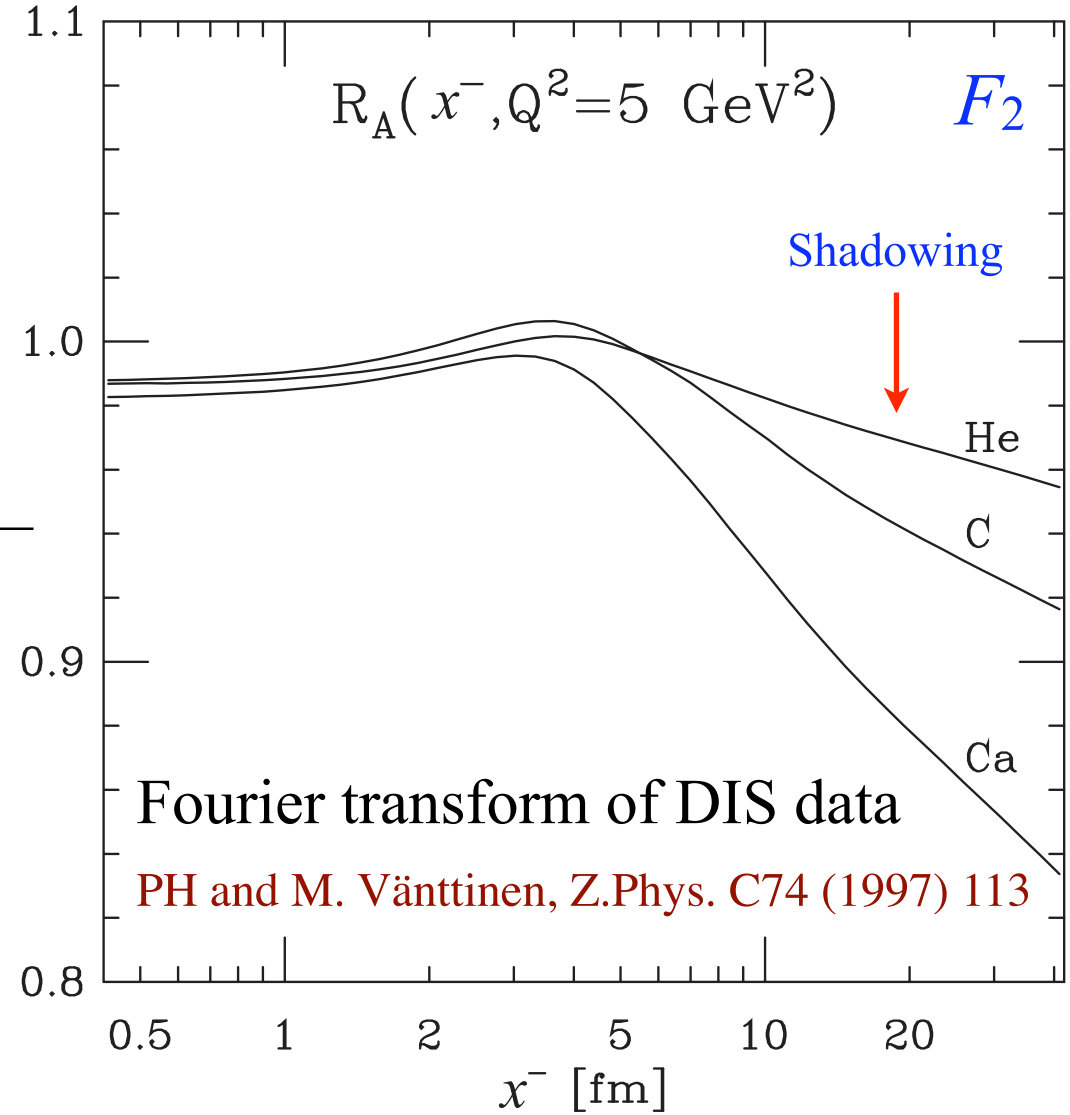
Coordinate space view of nuclear shadowing (I)

The parton distribution in momentum space $f_{q/A}(x_B)$ has a complicated A-dependence:



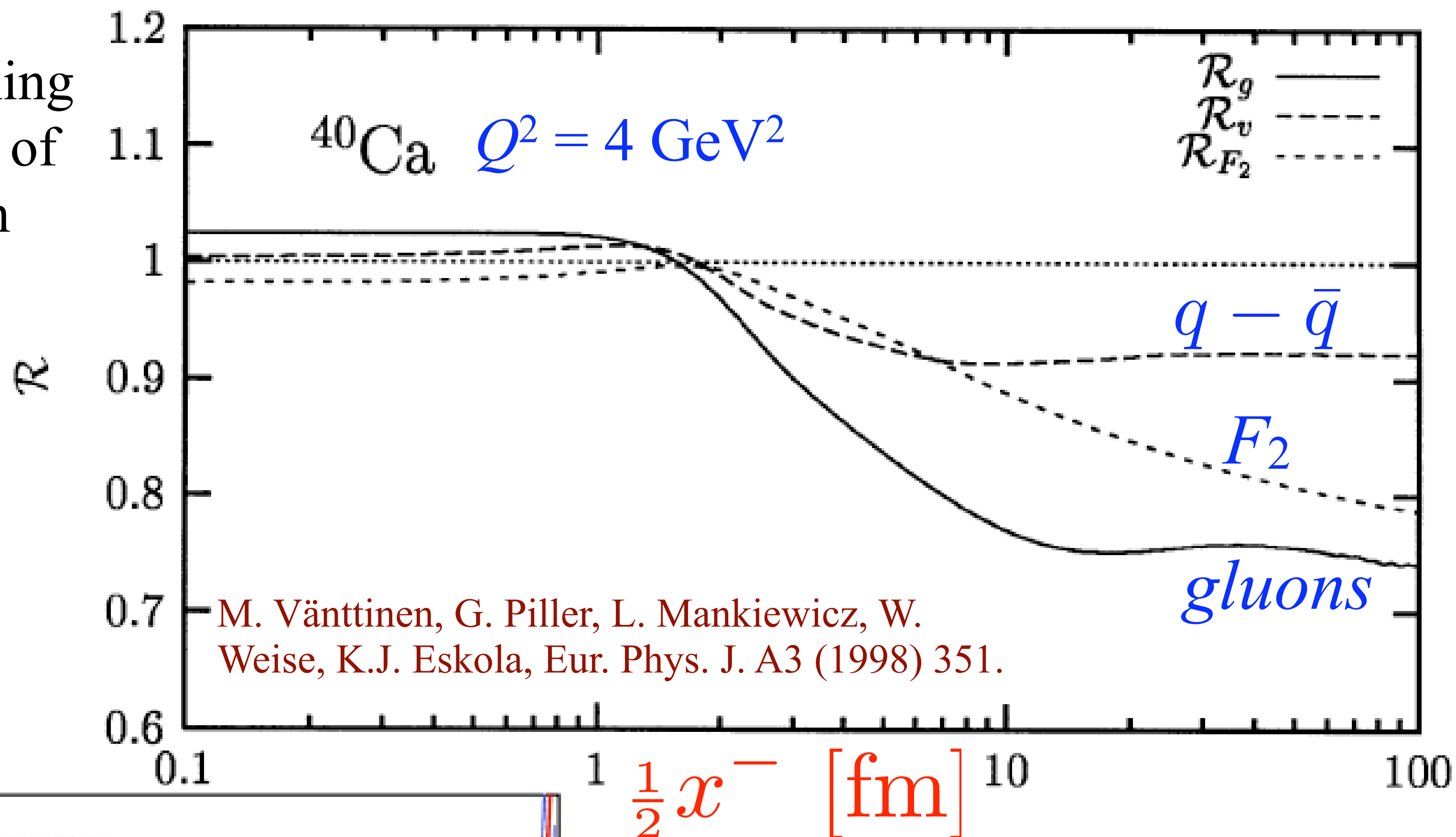
Within the experimental resolution (~ 2%) there is only shadowing is seen in coordinate space!

When transformed to coordinate (x^-) space the *A*-dependence is simple:



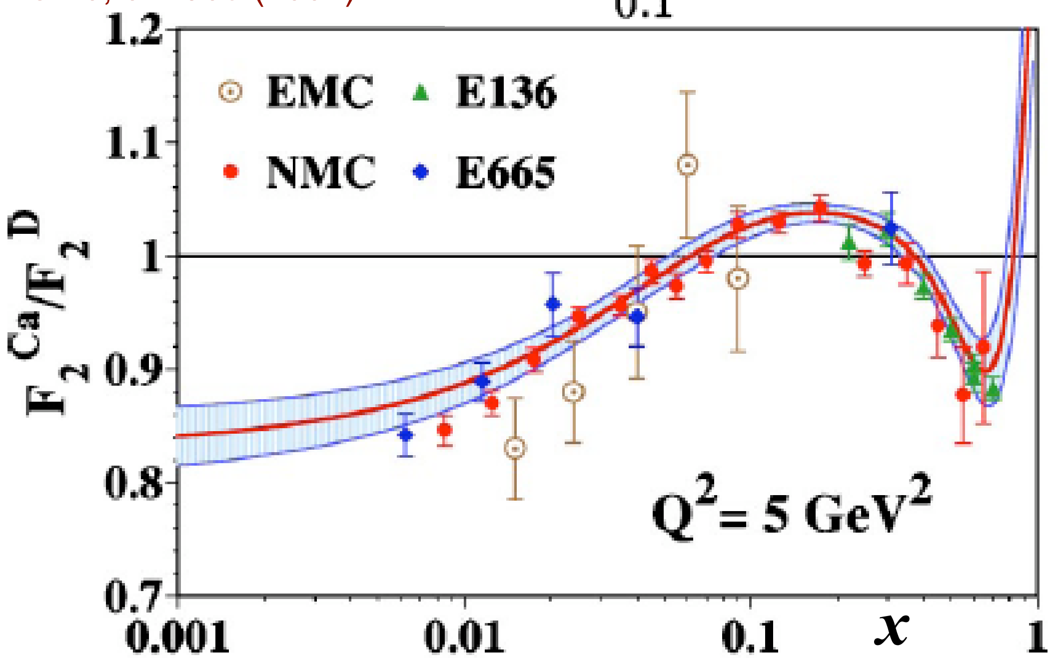
Coordinate space view of nuclear shadowing (II)

Fourier transforming a parametrization of the nuclear parton distributions:



M. Vänttinen, G. Piller, L. Mankiewicz, W. Weise, K.J. Eskola, Eur. Phys. J. A3 (1998) 351.

M. Hirai, S. Kumano and T. H. Nagai, Phys. Rev. C 70, 044905 (2004)



The EMC and antishadowing effects may be viewed as a consequence of the Fourier transform from coordinate to momentum space.

Shadowing as rescattering of the struck quark

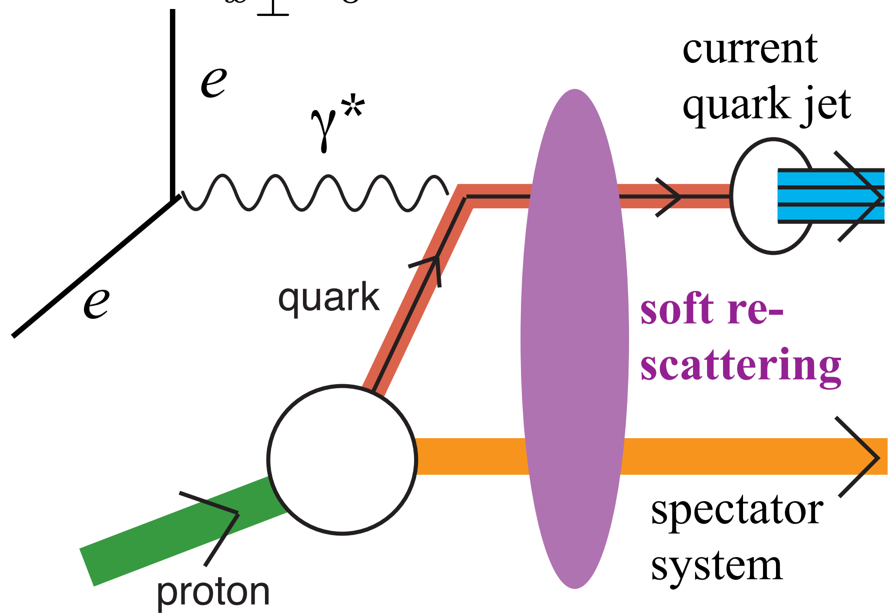
Due to the finite resolution $\Delta x^- \sim 1/2m_N x_B$ the soft rescattering of the struck quark with spectators in the target is coherent with the hard γ^* interaction

⇒ Parton distributions depend on spectators in the whole target.
This effect is hidden in the "gauge link" of the target matrix element

$$f_{q/N}(x_B) = \frac{1}{8\pi}\int dx^- \exp(-\tfrac{1}{2} i m_N x_B x^-)$$
$$\times \langle N(p)|\bar{q}(x^-)\gamma^+ W[x^-,0] q(0)|N(p)\rangle\Big|_{\substack{x^+=0\\ x_\perp=0}}$$

Brodsky, P.H., Marchal, Peigné, Sannino (2002)

$$W[x^-,0] \equiv \mathrm{P}\exp\left[\tfrac{1}{2} i g \int_0^{x^-} dx'^- A^+(x'^-)\right]$$



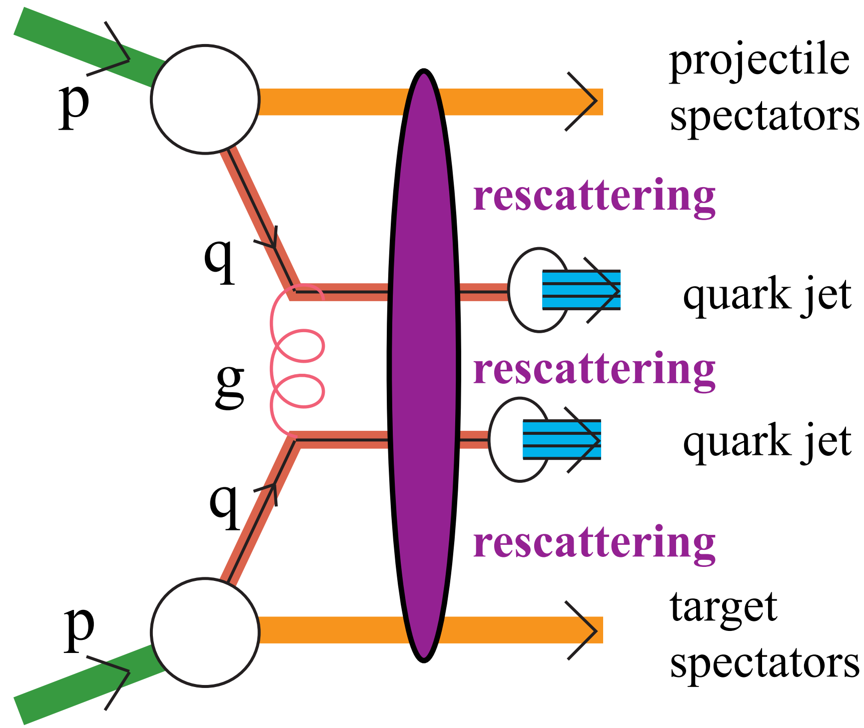
Physical effects of the gauge link include shadowing and diffraction

Breakdown of factorization in hadron collisions?

The color field environment is different in *NN* collisions, as compared to *eN*

Parton distributions depend on the environment due to rescattering.
Is this consistent with universality?

A breakdown of factorization has been demonstrated for k_T-dependent parton distributions, the case for k_T-integrated distributions is still pending.



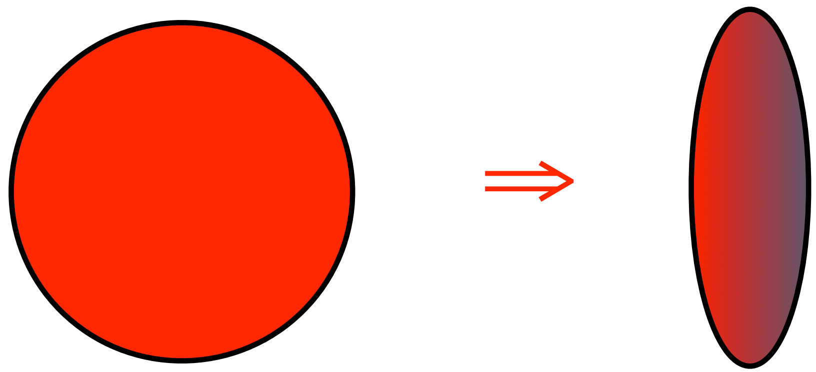
Factorization is violated in production of high-transverse-momentum particles in hadron-hadron collisions

John Collins*
Physics Department, Penn State University, 104 Davey Laboratory, University Park PA 16802, U.S.A.

Jian-Wei Qiu†
Department of Physics and Astronomy, Iowa State University, Ames IA 50011, U.S.A. and High Energy Physics Division, Argonne National Laboratory, Argonne IL 60439, U.S.A.

(Dated: 15 May 2007)

Do hadrons and nuclei Lorentz contract?



$\boldsymbol{p} = 0$ $\Rightarrow$ $\boldsymbol{p} >> m$?

... and if so, does this refer to wave functions at equal LF time

$$x^+ = t + z = 0$$

or equal ordinary time

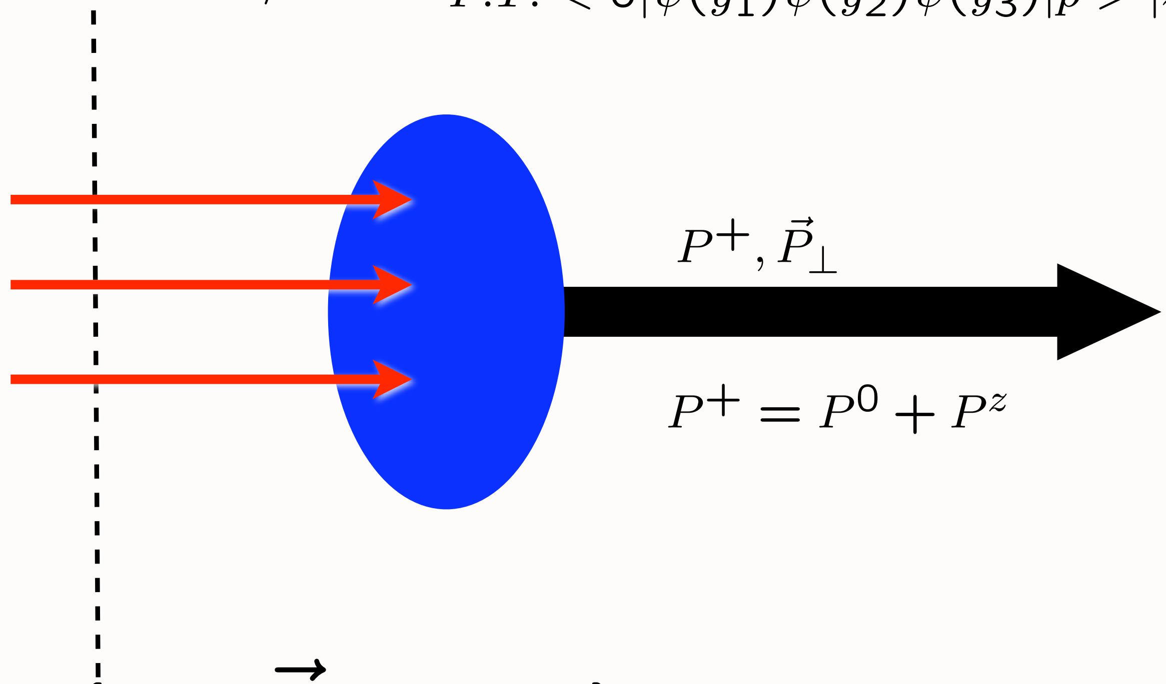
$$t = 0$$

?

Light-Front Wavefunctions

Fixed $\tau = t + z/c$

$F.T. < 0|\psi(y_1)\psi(y_2)\psi(y_3)|p > |_{\tau_i=0}$



$x_i P^+, x_i \vec{P}_\perp + \vec{k}_{\perp i}$

$\sum_i^n x_i = 1$

$\sum_i^n \vec{k}_{\perp i} = \vec{0}_\perp$

$P^+, \vec{P}_\perp$

$P^+ = P^0 + P^z$

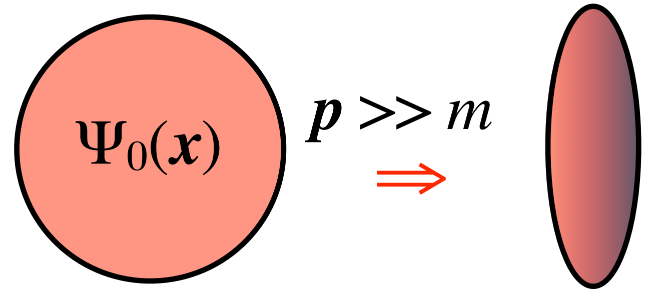
$$\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$$

Invariant under boosts! Independent of P^μ

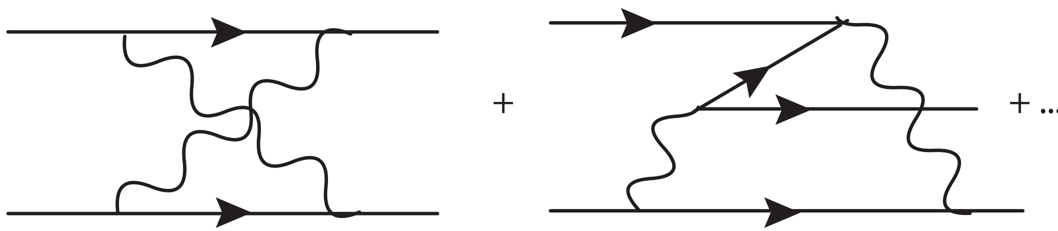
Lorentz contraction at equal ordinary time?

In analogy to classical relativity, the equal time w.f. $\Psi_0(\boldsymbol{x})$ might Lorentz contract in a moving frame.

Observers measure endpoints at equal times in their respective frames.

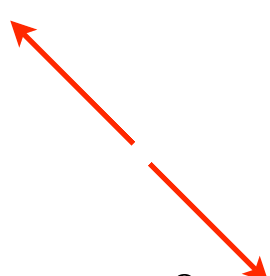


But: Time-ordered Feynman diagrams are not individually boost invariant

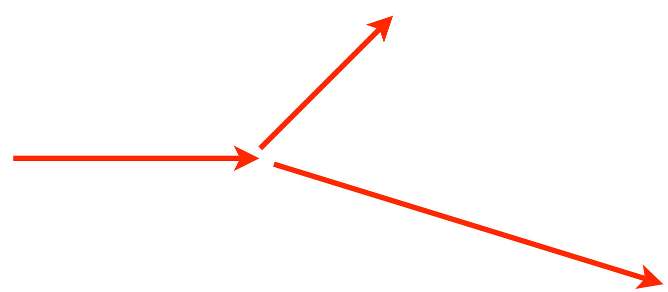


Fock state content is frame dependent

Decay angles are not boost invariant: More than just contraction is involved:



$\boldsymbol{p} = 0$



$\boldsymbol{p} >> m$

Does the Hydrogen atom Lorentz contract?

Calculate the $t = 0$ Positronium wave function at lowest order, for arbitrary CM momentum $\boldsymbol{p}$.

Matti Järvinen, Phys. Rev. D71, 085006 (2005)

- ☆ Find that both the $|e^+ e^-\rangle$ and $|e^+ e^- \gamma\rangle$ Fock components contribute for $\boldsymbol{p} \neq 0$, giving (non-trivially)

$$E(\boldsymbol{p}) = \sqrt{(2m_e c^2 - E_b)^2 + \boldsymbol{p}^2 c^2}$$

where E_b is the binding energy in the rest frame.

- ☆ Find that the $|e^+ e^- \gamma\rangle$ Fock amplitude does not simply contract.

Angular distribution of the photon in positronium $|e^+ e^- \gamma\rangle$

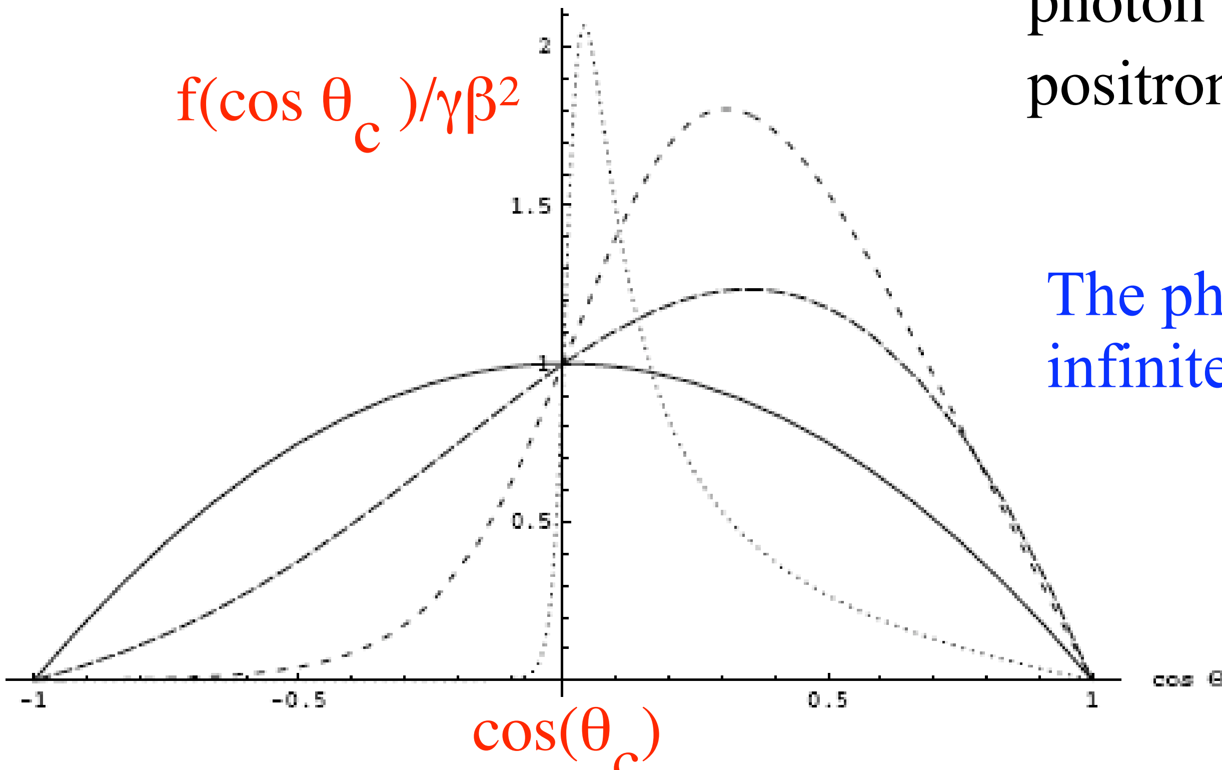


FIG. 8. The angular dependence the contracted and integrated photon distribution (53) in the positronium ground state. The lines show the angular distribution $f(\cos\theta)/(\gamma\beta^2)$ [defined in (56)] for $\beta = 0.001, 0.5, 0.9$ and 0.999. For $\beta = 0.001$ (solid line) the distribution is close to the symmetric limit (58). For $\beta = 0.999$ (dotted line) the distribution approaches the limit (59).

Plot of the angular distribution of the photon in the $|e^+ e^- \gamma\rangle$ Fock state of positronium for various $\beta = |\boldsymbol{p}|/E$.

The photon goes only forward in the infinite momentum frame, $\beta \to 1$

Summary

Hadrons are the only truly relativistic bound states found in Nature

This makes their study both challenging and rewarding

Data must guide us to the proper approximation scheme for QCD

Just as in QED

Hadrons are studied both in dedicated (FAIR!) and other acclerator facilities

The variety of beams, targets, energies and polarizations is important.

We are still learning precisely what aspects of hadron wave functions are measured by high resolution (hard scattering) data

Form factors, Parton distributions, Generalized parton distributions