MAX-BORN-PREIS

Partons and the LHC

Alan D. Martin

We discuss the partonic structure of the proton, and outline how the parton densities may be determined. We use them to predict the event rates of various processes which may be observed at the forthcoming Large Hadron Collider at CERN. We briefly discuss how to observe a „light“ Higgs boson (of mass less than 140 GeV), and emphasize the advantages of an exclusive Higgs signal.

I feel greatly honoured to receive the Max Born Medal. I am doubly delighted since Max Born is one of my heroes. He is seated in the photograph of **Fig. 1** with two other Nobel prize winners, Niels Bohr and James Franck, behind him, and Oscar Klein, of Klein-Gordon and Kaluza-Klein fame, to his left.

An over-simplified description of particle physics is that it is the search for the fundamental constituents of matter and, more importantly, the interaction(s) between them. At present we have the amazingly successful Standard Model (SM) for the strong and electroweak interactions based on $SU(3)_{QCD} \times SU(2)_L \times U(1)_Y$ local gauge symmetries, which, with decreasing energy, is spontaneously broken to $SU(3)_{QCD} \times U(1)_{QED}$ at a scale of order of the mass of the W boson, M_W. The fundamental particles are the six quarks (u, d, s, c, b, t) and the six leptons $(e, \mu, \tau, \nu_e, \nu_\mu, \nu_\tau)$ and their antiparticles, interacting via the gauge particles (the gluons g, the weak bosons, $W^\pm$, Z, and the photon, γ). The only missing ingredient is the Higgs boson. The Higgs mechanism is believed to be responsible for electroweak symmetry breaking, $SU(2)_L \times U(1)_Y \rightarrow U(1)_{QED}$, which gives mass to the weak bosons (and other particles). There could be a Higgs field, with a non-zero vacuum-expectation-value pervading all of space, without there being a Higgs boson. On the other hand, if supersymmetry is true, there will be several Higgs bosons. Indeed there is a plethora of ideas taking us beyond the Standard Model. Experiments at the LHC (and maybe the Tevatron) should show us the direction that Nature takes.

The Standard Model is in remarkable agreement with experiment. Why go beyond it? The most compelling reason is that it does not include gravity. Moreover it contains three independent gauge couplings. Perhaps even worse it offers no explanation for family replication. Finally it has too many free parameters, which has been made even worse with the observation of non-zero neutrino masses and the consequent lepton mixing parameters.

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Fig. 1 Max Born, seated, at the Bohr Festspiele held in Göttingen in June 1922, with (from left) Carl Wilhelm Oseen, Niels Bohr, James Franck, and Oskar Klein.

It is informative to trace the route by which quark constituents were revealed. We start with electron-nucleus scattering. Essentially we are probing the nucleus with a virtual photon of 4-momentum q (**Fig. 2**). The invariant mass W of the outgoing system satisfies

$$W^2 = (p + q)^2 = M^2 + 2p \cdot q + q^2, \qquad (1)$$

where M is the mass of the nucleus. A probing photon of long wavelength sees only a point nucleus; so we

IN BRIEF

- Electron-proton scattering revealed that the proton consists – in accordance with QCD – of valence quarks, sea quarks and gluons.
- This partonic substructure comes along with the so called scaling violation which was precisely confirmed at the HERA accelerator.
- Using the known structure functions it is possible to predict the rates at which so far undiscovered particles like the Higgs boson or supersymmetric particles will be produced at the Large Hadron Collider LHC.

Prof. Alan D. Martin, Department of Physics and Institute for Particle Physics Phenomenology, University of Durham, DH1 3LE, UK – Plenary talk on the occasion of the conferment of the Max Born Prize 2007 at the DPG Conference in Heidelberg.

have elastic electron-nuclear scattering with $W=M$. Thus it follows that

$$x_N \equiv Q^2/2p\cdot q = 1, \text{ where } Q^2 \equiv -q^2. \qquad (2)$$

As we increase Q we start to excite nuclear states, for which $x_N < 1$. Eventually, when $Q^2R^2 \gg 1$, the photon probes deep into the nucleus and elastically scatters off one of the proton constituents, which leads to a peak at $x_N \sim p_p/p \sim m_p/M \sim 1/A$, but smeared out by the Fermi momentum distribution of the confined proton. These effects of increasing Q are depicted in **Fig. 2**. We see the suppression of the elastic electron-nuclear peak; for large values of Q, the chance of the A–1 spectator nucleons being aligned with the struck proton and re-forming the nucleus is very small. In summary, high-Q electron-nuclear scattering reveals the composition of the nucleus; the area under the elastic electron-proton peak gives the number, Z, of protons in the nucleus and the position of the peak gives $A = N + Z$.

If we increase Q further, then electron-proton scattering turns out to be a replay of the electron-nuclear case (**Fig. 3**). Here, the cross section (essentially the structure function F_2) is plotted versus the Bjorken scaling variable $x = Q^2/2p\cdot q$, where now p is the proton 4-momentum. With the increase of Q, the elastic electron-proton scattering peak is suppressed and, instead, there is an elastic electron-quark scattering peak at $x \sim 1/3$ corresponding to the three constituent quarks which make up the proton, but smeared by the struck quark's Fermi momentum. If the quarks were truly elementary, then for higher values of Q^2, F_2 would be only a function of the variable x, that is the ratio of the variables Q^2 and $2p\cdot q$, and not as a function of both of them independently. The dependence on only the dimensionless ratio x is known as *scaling*, since no energy or length scale controls the scattering. This would be the case if the quarks were truly point-like. In passing, we note that the experiments indicated that the struck quark acts as if it were *free*. Yet it has never been *observed*. The struck quark appears to be confined within the proton and yet behaves as if it were free! This was a big puzzle around 1970. We will return to this dilemma in a moment.

If, with an even further increase of Q^2, the photon probe were to reveal that the quarks themselves have structure, then the scaling behaviour would be broken. Suppose, indeed, that history were to repeat itself, and that at some high Q^2 the photon probe were to reveal that each quark was itself composed of n_q constituents, then the peak in F_2 would move to $x \sim 1/(3n_q)$. However there is no evidence of quark substructure. Instead evidence was found for QCD, the $SU(3)$ gauge theory of strong interactions, based on the colour attribute of quarks which had been introduced earlier as an ad hoc way to patch up their statistics. According to QCD, the photon probe may interact with a "sea" quark of a $q\bar{q}$ pair created by a gluon which had been radiated from a "valence" quark (**Fig. 3**). So as we look deeper into the proton we experience more and more partonic constituents, that is quarks and gluons. If the photon strikes a quark containing a fraction ξ of the proton's momentum, then $(\xi p + q)^2 = m_q^2 \simeq 0$, and so $\xi \simeq x$.

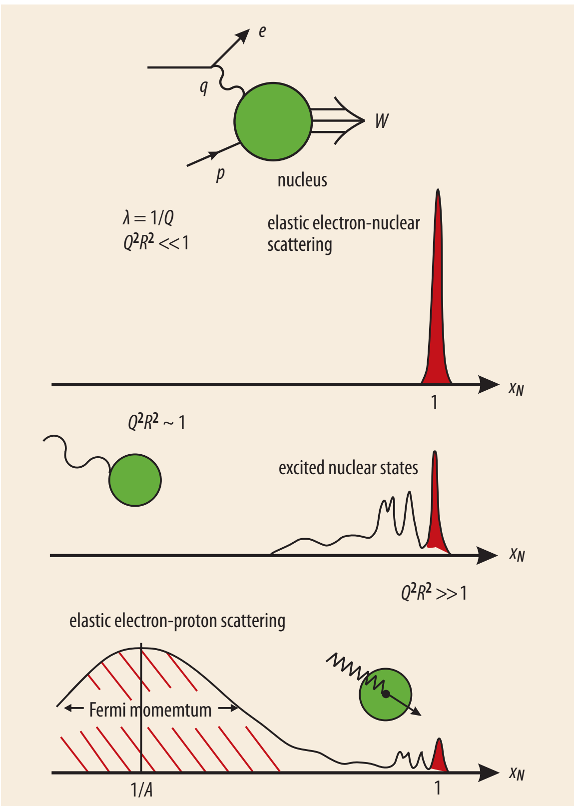

Fig. 2 Electron-nucleus scattering, where p and q are the 4-momenta of the incoming nucleus and virtual photon respectively, and W is the invariant mass of the outgoing hadronic system. The lower three plots are a schematic illustration of the cross section for electron-nucleus scattering, $eN \to eX$, at three different values of Q^2. The wavelength λ of the virtual photon probe is much less than the nuclear radius R in the lower plot, and the photon probes a constituent proton of the nucleus.

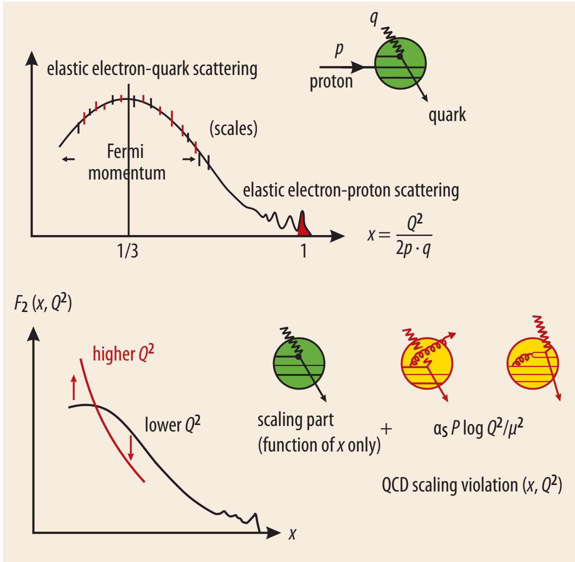

Fig. 3 The cross section for deep inelastic electron-proton scattering, $ep \to eX$. The second plot shows, in addition to scaling elastic eq scattering, the effects of QCD scaling violations. The scaling contribution and the lowest-order diagrams in the QCD coupling, α_s, are sketched to the right of the plot. The $O(\alpha_s)$ contributions have a log Q^2 behaviour and are proportional to the appropriate partonic splitting function P_{ij}.

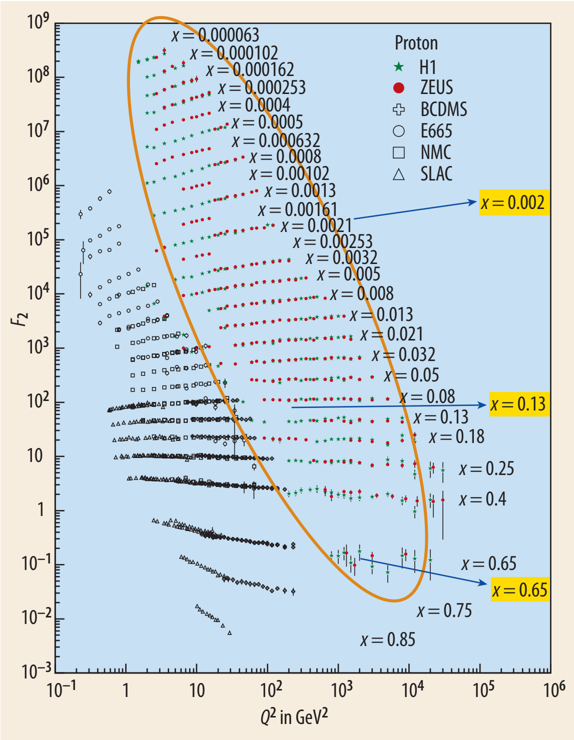

Fig. 4 World data for the proton structure function $F_2(x,Q^2)$ shown as a function of Q^2 for fixed values of x. The data at the different x values have been displaced for clarity. The HERA data, which are enclosed by the ellipse, allow small x values to be probed. The QCD scaling violations are emphasized by the arrows which indicate the behaviour of the data at $x = 0.002$, 0.13 and 0.65.

Thus, as Q^2 increases, more and more partons become involved, and as a consequence each parton must, on average, have smaller x. So, as a result, scaling is indeed broken. However these QCD scaling violations, as indicated in the bottom half of **Fig. 3**, are predicted to have a log Q^2 type of behaviour. When QCD was discovered, a famous experimentalist said to Wilczek (one of the discoverers) "You expect us to measure logarithms!? Not in your lifetime, young man!". Yet, today, we have the precise data shown in **Fig. 4**, behaving just as QCD anticipated.

Moreover, since QCD is a non-Abelian gauge theory, the gauge particles, the gluons, couple to themselves. This is unlike QED. In QED, the coupling, α_{QED}, increases with Q^2 since the photon penetrates more deeply through the virtual e^+e^- pairs which screen the bare electric charge. On the contrary, the QCD coupling, α_S, decreases with increasing Q^2 since the virtual gluon pairs antiscreen the bare colour charge and dominate the screening due to the virtual $q\bar{q}$ pairs. The small coupling at large Q^2 means that the quark acts as if it is *free*, yet the large coupling at hadronic scales leads to the possibility of *confinement* of the quark within the hadron. The big puzzle of 1970 has the possibility of being completely resolved.

Since the QCD coupling α_S becomes small at high Q^2 we can use (truncated) perturbation series in α_S to calculate the experimental observables. The details are shown in **Fig. 5** for the observable structure functions describing "deep inelastic scattering", $ep \to eX$, that is $\gamma p \to X$. It shows, first pictorially, and then as an equation, how the observable structure functions F_a of the proton may be factorized into

- *universal* parton densities (of the proton), f_i, which absorb the *long-distance* singularities. They cannot be calculated in perturbative QCD (pQCD), but their Q^2 dependence is given by DGLAP evolution equations[1], in which the partonic splitting functions P_{ij} are known as power series in α_S,
- coefficient functions, $C_{a,i}$, which describe the *short-distance* subprocess. They are calculable from perturbative QCD as a power series in α_S, but are unique to the particular observable, F_a. Only the Q^2 dependence of the parton densities $f_i(x,Q^2)$ is given by pQCD, in terms of the DGLAP equations for $\partial f_i/\partial \log Q^2$. Therefore we need to input the values of the f_i at some low scale Q_0^2, but which is still in the perturbative domain.

A similar factorization applies to inclusive "hard" hadron-hadron collisions. For instance, consider the LHC process $p(p_1) + p(p_2) \to H(Q,..) + X$, where H denotes the triggered hard system, such as a weak boson, a pair of jets, a Higgs boson, etc. The typical hard scale Q could be the invariant mass of H or the transverse momentum of a jet. Then according to the factorization theorem the cross section is of the form

$$\sigma = \sum_{i,j} \int_{x_{\min}}^{1} dx_1 dx_2\, f_i(x_1,Q^2)\, f_j(x_2,Q^2)\, \hat{\sigma}_{ij}(x_1p_1, x_2p_2, Q^2), \tag{3}$$

where $\hat{\sigma}_{ij}$ is the cross section for the partonic subprocess $i + j \to H$.

To determine the parton densities, f_i, we perform a "global" fit to all available hard scattering data involving incoming protons (and antiprotons). The procedure is to parametrize the x dependence of $f_i(x,Q_0^2)$ at

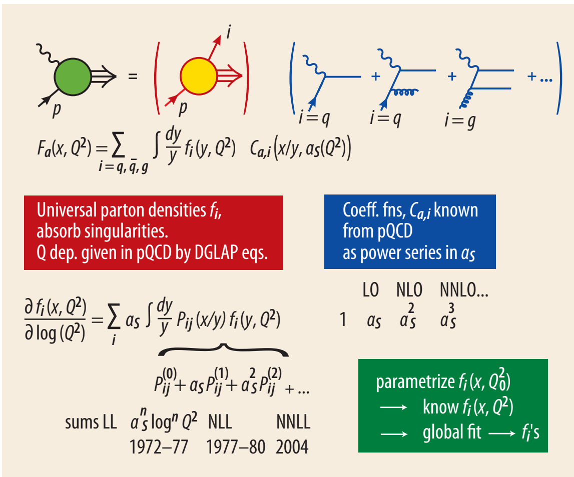

Fig. 5 The factorization theorem, which expresses the observable structure functions, F_a, in terms of universal parton distributions, f_i, and known coefficient functions, $C_{a,i}$. The variable y is the fraction of the proton's momentum carried by the quark when it is struck. Only the Q^2 dependence of the f_i are calculable in pQCD via the DGLAP evolution equations for $\partial f_i/\partial \log Q^2$; rather, the $f_i(x,Q^2)$ are determined by a global fit to all available high Q data, as indicated in the lower box and explained in the text. [The state-of-the-art is the expression for the splitting function $P_{gg}^{(2)}$, which sums the next-to-next leading logs (NNLL), $\alpha_S^n \log^{n-2} Q^2$, and which covers 8 journal pages!]

1) These equations are named after the authors Dokshitzer, Gribov, Lipatov, Altarelli and Parisi.

some low, yet perturbative, scale Q_0^2. Then to use the DGLAP equations to evolve the f_i up in Q^2, and to fit to all the available data (proton structure functions, Drell-Yan production, Tevatron jet and W production…) to determine the values of the input parameters. In principle, if we neglect the distribution of the very heavy top quark, there are 11 parton distributions ($f_i = u, \bar{u}, d, \bar{d}, s, \bar{s}, c, \bar{c}, b, \bar{b}, g$). However m_c, $m_b \gg \Lambda_{\mathrm{QCD}}$, where $\Lambda_{\mathrm{QCD}} \sim 0.2$ GeV determines the scale where α_s becomes large. So $c = \bar{c}$ and $b = \bar{b}$ are calculated from perturbative QCD via $g \to Q\bar{Q}$. Also the evidence from neutrino-produced dimuon data, $\nu N \to \mu^+\mu^- X$, is that $s \simeq \bar{s} \simeq 0.2(\bar{u} + \bar{d})$ at $Q^2 \simeq 1$ GeV^2. Typical results at two different values of Q are shown in **Fig. 6**. The u and d valence distributions, u–$\bar{u}$ and d–$\bar{d}$, are clearly seen. Note the enormous size of the gluon distribution (shown divided by 10) at small x. The transition $g \to q\bar{q}$ drives all the quark and antiquark distributions at small x, which are only distinguished by the masses of the quarks, with the distinction decreasing with increasing Q. Moreover we see that $\bar{d}$ exceeds $\bar{u}$, as would be anticipated by a virtual pion cloud surrounding the proton.

We may use the parton distributions to predict the rates of various processes at the Large Hadron Collider (LHC) which is due to be commissioned next year at CERN. **Fig. 7** shows the cross section, in nb, of several processes at both the Tevatron energy (1.96 TeV) and the LHC energy (14 TeV). If we assume that the LHC has a luminosity of 10^{33} cm^{-2}s^{-1}, which in practice should be exceeded, then the scale simply translates into the number of events expected each second. The numbers are given for some individual processes, together with the type of physics that they will illuminate. The values of M_W, m_t, Γ_W are important to increase the precision of the electroweak sector of the SM, and to predict the mass of the Higgs, should it exist.

Note that the discovery channels for supersymmetric particles (squarks, gluinos, etc.) and Higgs (of mass about 150 GeV) contain a few events per minute. However their discovery will be challenging, because the branching ratio of the decay channel to be observed is not included in the event rate and, more important, no allowance has been made for extracting the signal from potentially huge backgrounds. For example if the Higgs is relatively light, $M_H < 140$ GeV, the dominant $H \to b\bar{b}$ decay is completely swamped by the huge QCD $b\bar{b}$ background. The conventional discovery channel is $H \to \gamma\gamma$ with a branching ratio of 2×10^{-3}. Even here, the signal will be a small peak sitting on a large $\gamma\gamma$ background. Detection will require a very precise measurement of the $\gamma\gamma$ mass, with an accuracy of 1 GeV or less. An alternative is to observe the exclusive process, $pp \to p + H + p$, with the outgoing very forward protons detected far from the interaction point (ideally some 400 m away). In principle, the process has some advantages (Khoze-Martin-Ryskin). A $J_z = 0$ selection rule greatly suppresses the QCD $b\bar{b}$ background. The missing mass to the measured protons gives a precise measurement of the Higgs mass. There is a very clean environment with a signal-to-background ratio of about 1. The price is that the observed rate (after allowing for detection efficiencies and acceptance cuts) is only a handful of events for an integrated LHC luminosity of 50 fb^{-1}. However the exclusive signals for the 0^{++} Higgs bosons are considerably enhanced in certain parameter regions of supersymmetric models, particularly in the large $\tan\beta$ domain.

Of course, it would be even more exciting if the LHC were to find something totally unexpected. Referring back to the photograph of Max Born and his

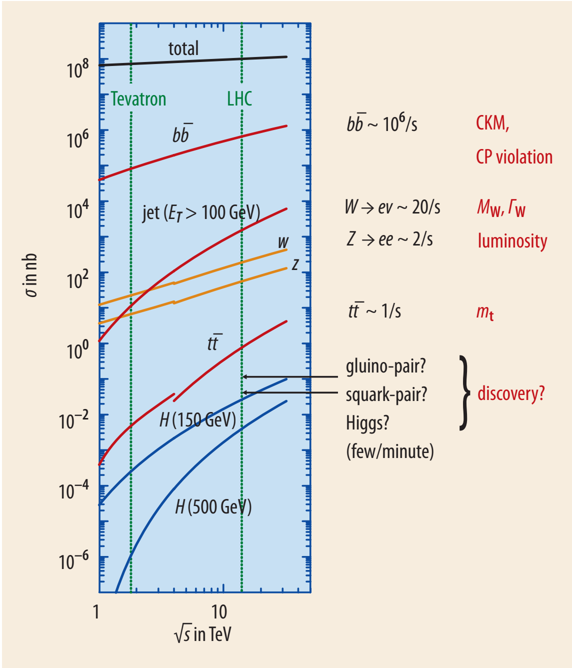

Fig. 7 The cross sections (in nb) for some relevant processes in the Tevatron-LHC energy range. The event rates at the LHC are also shown (if the luminosity L of the LHC is 10^{33} cm^{-2}s^{-1}), together with the physics they will illuminate, shown in red type. The luminosity L, which is a measure of the rate of proton-proton collisions, may be determined in terms of the accurately known rates of W and Z boson production. The event rate of a process with cross section σ is $L\sigma$.

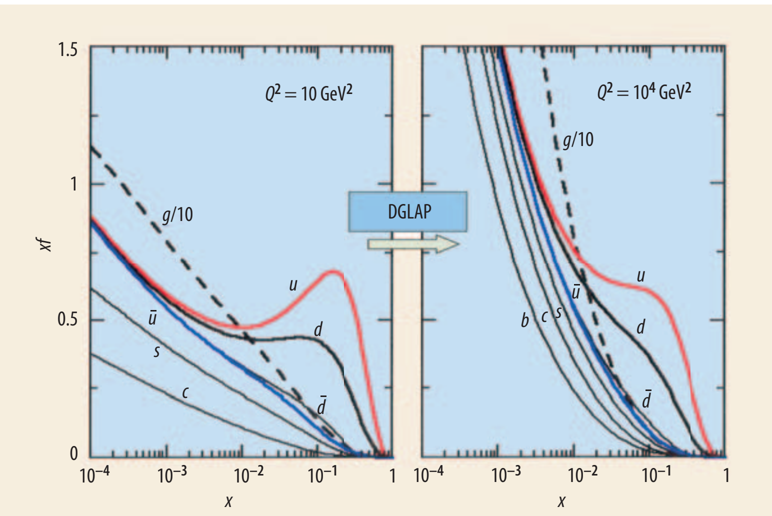

Fig. 6 Parton distributions at Q^2=10 and 10^4 GeV^2 obtained using NLO DGLAP evolution in the Martin-Stirling-Thorne-Watt global analysis.

colleagues, **Fig. 1**, my dream is that one of you may in this way get the Nobel Prize, and even that two others standing behind may also be so honoured. Would it not be wonderful if we had another quantum mechanics type of revolution?

Acknowledgements

I thank all my colleagues for so many enjoyable research collaborations and from whom I have learnt so much. Here it is appropriate to especially thank those involved with theoretical analyses relevant to HERA: Krzysztof Golec-Biernat, Victor Fadin, Aliosha Kaidalov, Valery Khoze, the late Jan Kwieciński, Genya Levin, Dick Roberts, Misha Ryskin, Andrez Shuvaev, Anna Stasto, James Stirling, Thomas Teubner, Robert Thorne and Mark Wüsthoff; together with research students Adrian Askew, Peter Harriman, Martin Kimber, Sabine Lang, Claire Lewis, John Outhwaite, Peter Sutton and Graeme Watt. Indeed, Graeme Watt has replaced Dick Roberts in MRST, and he and Robert Thorne now provide the driving force behind the global analyses.

THE AUTHOR

Alan D. Martin (here at the prize ceremony in Heidelberg) is a theoretical physicist distinguished for his pivotal contributions to our understanding of the hadronic interaction. From his Durham University base he has developed close working links with many accelerator laboratories worldwide like HERA in Hamburg. He is also well known for his textbooks.

Alexander Müller

