Large Transverse Momentum

Physics at the ISR

Pierre Darriulat
CERN, January 2011

By chance, the life time of the ISR, roughly speaking the seventies, coincides with a giant leap in our understanding of particle physics. Those of us who have worked at the ISR remember these times with the conviction that we were not merely spectators of the ongoing progress, but also – admittedly modest – actors. The ISR contribution, it seems to us, is too often unjustly forgotten in the accounts that are commonly given of the progress of particle physics during this period.

David Gross reminds us that, quoting Emerson, *“There is properly no history; only biography”*

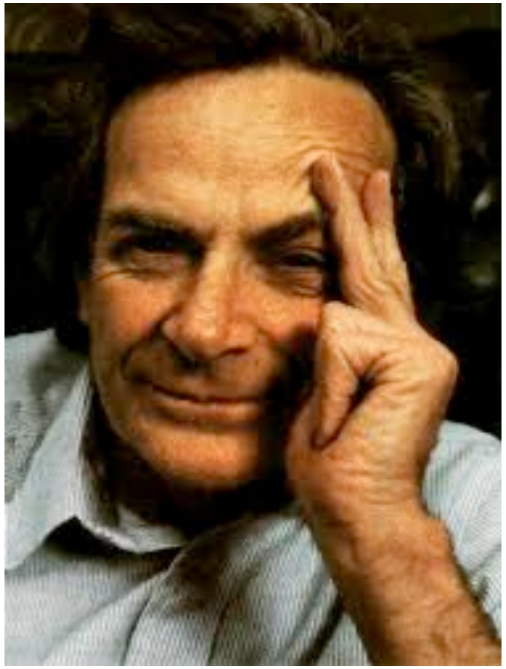
In physics, this is particularly true when discoveries and new ideas occur at a rapid pace, as was the case in the seventies.

As instructive examples, see accounts by D. Gross, S. Weinberg, J. Friedman, G. ‘t Hooft.

The same kind of disparity that exists between the visions of different individuals also occurs between the visions of different communities.

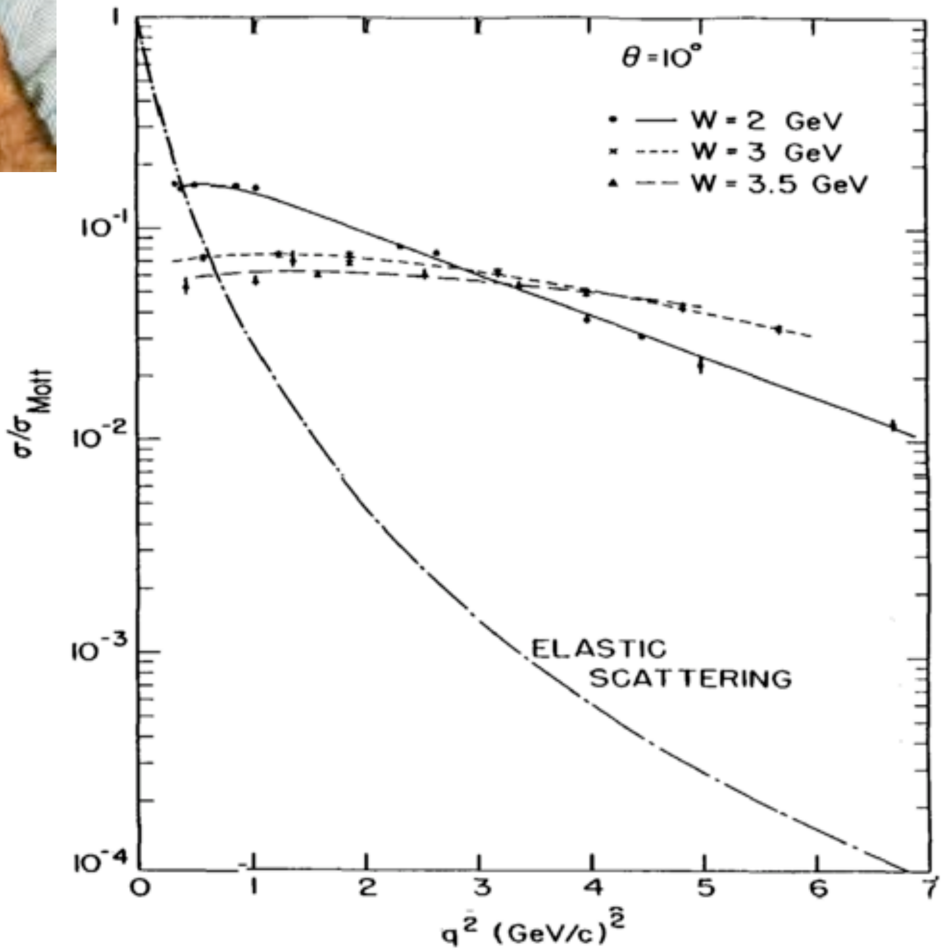
In December 1965 Vicky Weisskopf, in his last Council session as Director-General, obtained approval for the construction of the ISR to explore the *terra incognita* of higher centre of mass energy collisions.

At that time the strong interaction was perceived as a complete mystery; SU(3) flavour symmetry was thought to have no dynamical implication (no free quark, wrong statistics of Δ^{++}).



1968-1969 at SLAC discovery of an important continuum in the deep inelastic region of electron proton scattering.

From the very beginning, experimenters and theorists were in close contact, feeding each other with new data and new ideas, starting with Bjorken's ideas on scaling and Feynman's ideas on partons.




Jerome Friedman
1930–


Henry Kendall
1926–1999

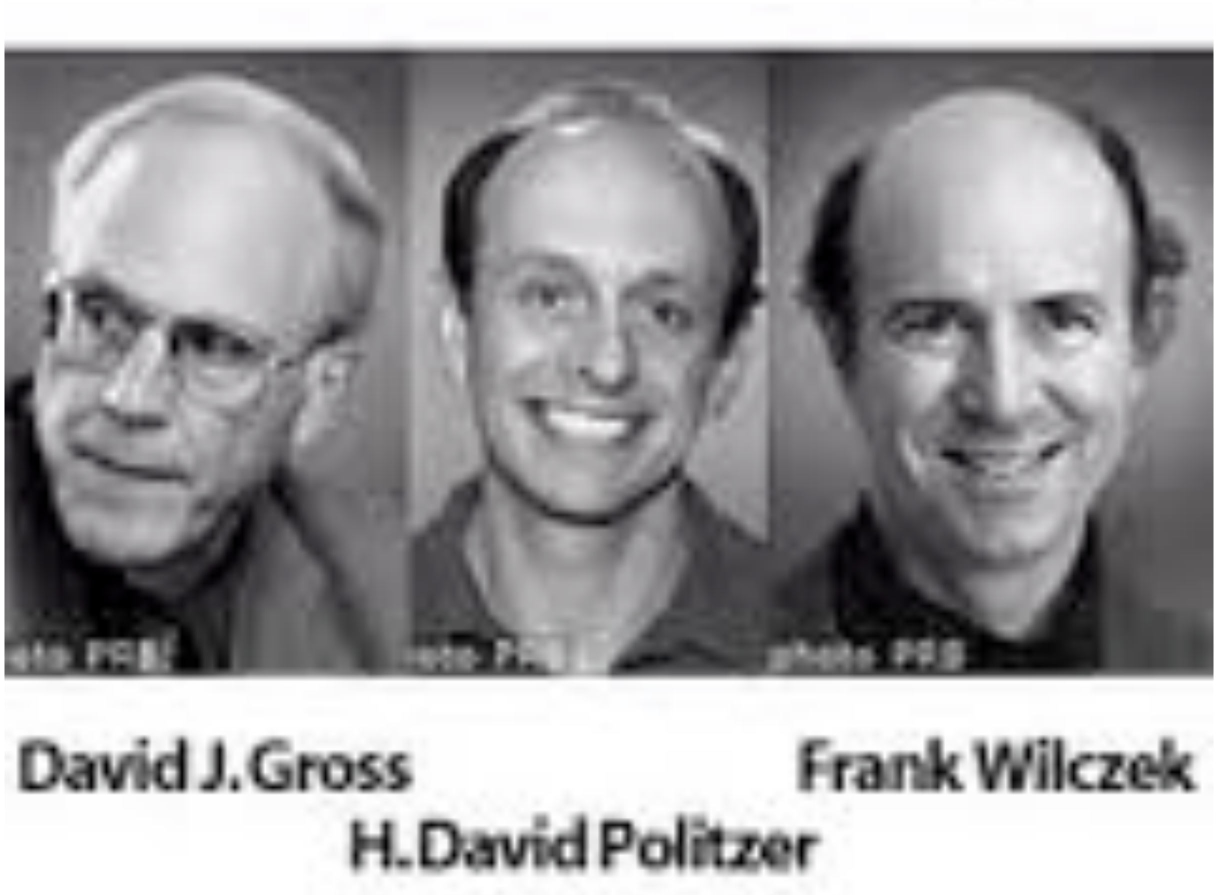

Richard Taylor
1929–


Andre Lagarrigue


D. H. Perkins

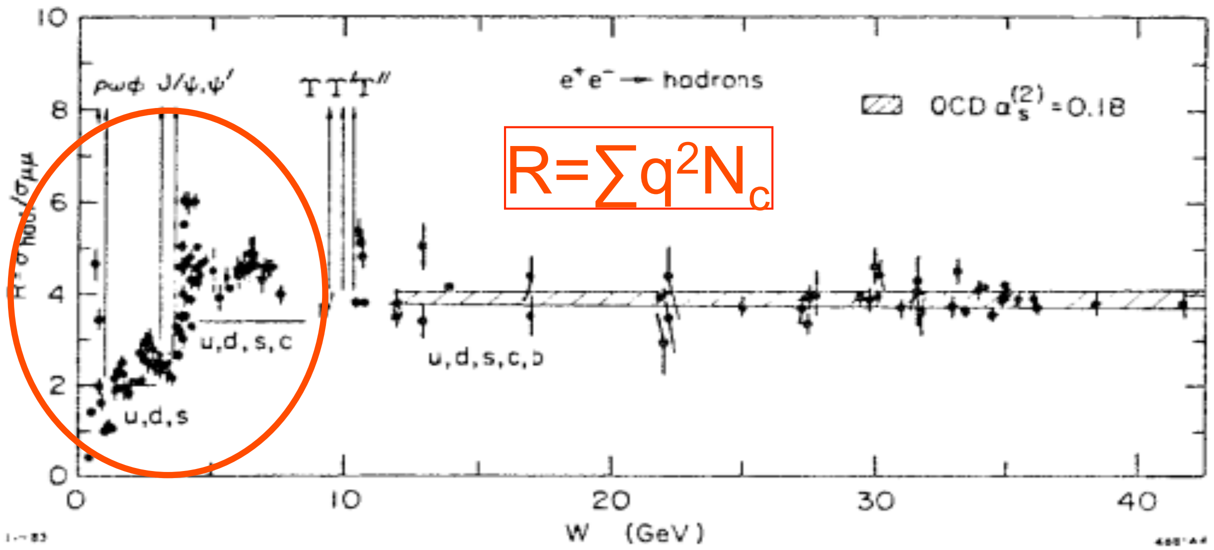
Perkins DH. 2005.
Annu. Rev. Nucl. Part. Sci. 55:1–26

By 1972, the case for a quark model had become strong: scaling had been established; the measurement of a small *R* value (the ratio of the absorption cross sections of transverse and longitudinal virtual photons) had eliminated competitors such as the then popular VDM; deuterium data had been collected allowing for a comparison between the proton and neutron structure functions; a number of sum rules had been tested; evidence for the quarks to carry but a part of the proton longitudinal momentum had been obtained; the first neutrino deep-inelastic data from Gargamelle had become available.



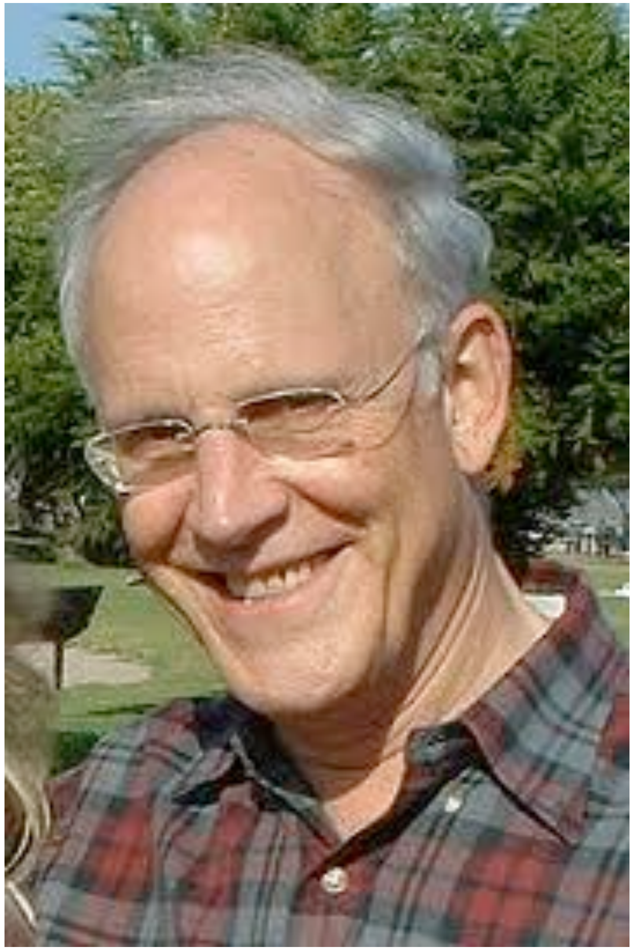
By the end of 1972, the way was traced for Gross, Wilczek and Politzer to conceive the idea of asymptotic freedom and thereby explain why one could not see free quarks. By the end of 1973, the connection with non-abelian gauge theories had been established and the “advantages of the colour-octet gluon picture”, including the solution of the Fermi statistics puzzle, had been presented by Fritzsch, Gell-Mann and Leutwyler. QCD was born and, by 1974, was starting to be accepted by the whole community as ***the*** theory of the strong interaction. It took another three to four years for it to come of age.

By mid 1972, SPEAR had begun operation. November 1974 Revolution: discovery of the *Ψ* (and of the *J* at Brookhaven). It immediately exploited its ability to produce pure quark-antiquark final states to measure the number of colours. However, it took some time to understand what was going on. By the end of the decade, scaling violations had been studied both in neutrino interactions and in electron-proton annihilations.



$R=\sum q^2 N_c$

QCD had reached maturity and the only puzzling questions that remained unanswered, the absence of a CP violating phase and our inability to handle the theory at large distances, are still with us today.



Question: *Were you aware of the results obtained at the ISR and did they have an impact on the development of QCD?*

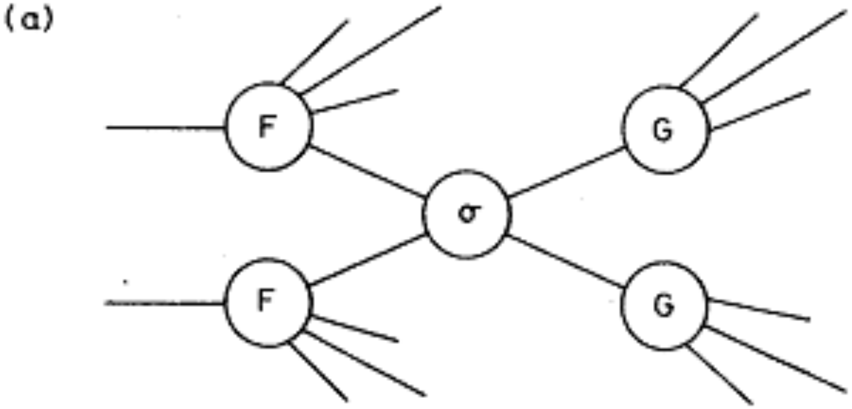
David Gross: *"Every one was aware of the qualitative phenomena observed in hadronic physics at large p_T, which were totally consistent with simple scattering ideas and parton model ideas […] The tests were not as clean as in deep inelastic scattering, the analysis was more difficult and deep inelastic scattering was much cleaner in the beginning of perturbative QCD […] Parton ideas did not test QCD at all, they simply tested the idea that there were point-like constituents but not the dynamics."*

Alvaro de Rujula, who witnessed from Boston "the maiden years of QCD": *"I do not know the answer to this question, I am not an historian"*.

David Gross could have returned the question to me: *“How aware were you, the ISR community, of the experimental progress at SLAC and of the new ideas in theory?”*

Following a stay at SLAC, Maurice Jacob organized a lively series of discussions between ISR experimenters and theorists that proved to be extremely successful in permeating our community with the progress in deep-inelastic scattering and, later, in electron-positron collisions.

At that time, our community was small enough to fit in the ISR auditorium. Maurice was gifted with an unusual talent to make theoretical ideas accessible to us. We all remember these seminars as a most profitable experience that brought coherence and unity in our community. For this reason, it makes sense to talk about a common ISR culture.



In particular, by 1972, we were aware of the basic parton ideas and of the picture of large transverse momentum production factorized in three steps: singling out a parton in each proton, making them interact (how was often unclear) in a binary collision and letting the final state partons fragment into hadrons. There were a few papers in support of such a picture which most of us had read and which were our basic reference. Yet, in these early days, there was a typical delay of nearly one year between SLAC and us for a new idea to be digested. There was even more delay, for most of us, to digest the more subtle development of non abelian gauge theories: we only knew about it from our theorist friends.

<table>
<tr><td colspan="4">Electron-positron annihilations</td></tr>
<tr><td>1</td><td></td><td>$e^+e^->\gamma<q^+q^-$</td><td>α^2G^2</td></tr>
<tr><td colspan="4">Deep-inelastic electron scattering</td></tr>
<tr><td>2</td><td></td><td>$\mathrm{eq]}\gamma\mathrm{[eq}$</td><td>$\alpha^2\mathrm{FG}$</td></tr>
<tr><td colspan="4">Deep-inelastic neutrino scattering</td></tr>
<tr><td>3</td><td>Neutral currents</td><td>$vq]Z[vq$</td><td>$\alpha_n{}^2FG$</td></tr>
<tr><td>4</td><td>Charged currents</td><td>$vq]W[lq$</td><td>$\alpha_{ch}{}^2FG$</td></tr>
<tr><td colspan="4">Proton-proton collisions (ISR)</td></tr>
<tr><td>5</td><td>Drell Yan</td><td>$q^+q^->\gamma<l^+l^-$</td><td>α^2F^2</td></tr>
<tr><td>6</td><td rowspan="2">Direct photons</td><td>$q^+q^-]q[\gamma g$</td><td rowspan="2">$\alpha\alpha_sF^2G$</td></tr>
<tr><td>7</td><td>$qg]q[\gamma q$</td></tr>
<tr><td>8</td><td rowspan="12">Large p_T hadrons</td><td>$qq]g[qq$</td><td rowspan="12">$\alpha_s{}^2F^2G^2$</td></tr>
<tr><td>9</td><td>$qq]q[gg$</td></tr>
<tr><td>10</td><td>$q^+q^->g<gg$</td></tr>
<tr><td>11</td><td>$q^+q^->g<q^+q^-$</td></tr>
<tr><td>12</td><td>$qg]q[qg$</td></tr>
<tr><td>13</td><td>$qg]g[qg$</td></tr>
<tr><td>14</td><td>$qg>q<qg$</td></tr>
<tr><td>15</td><td>$gg>g<q^+q^-$</td></tr>
<tr><td>16</td><td>$gg>g<gg$</td></tr>
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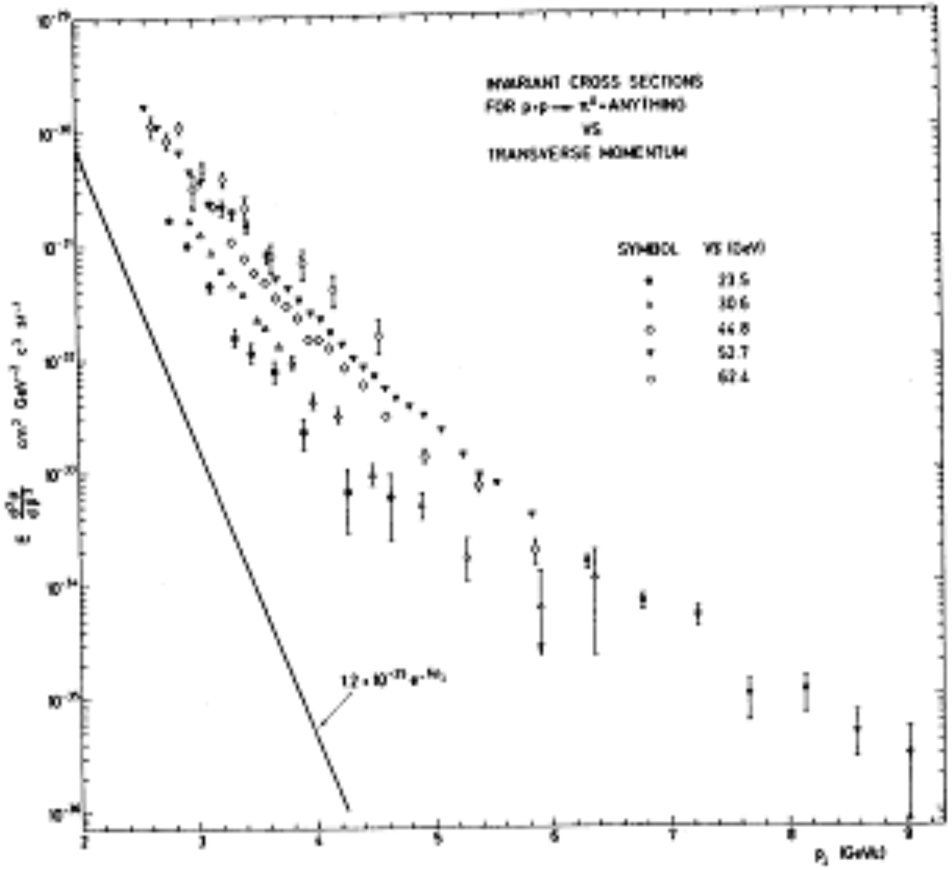
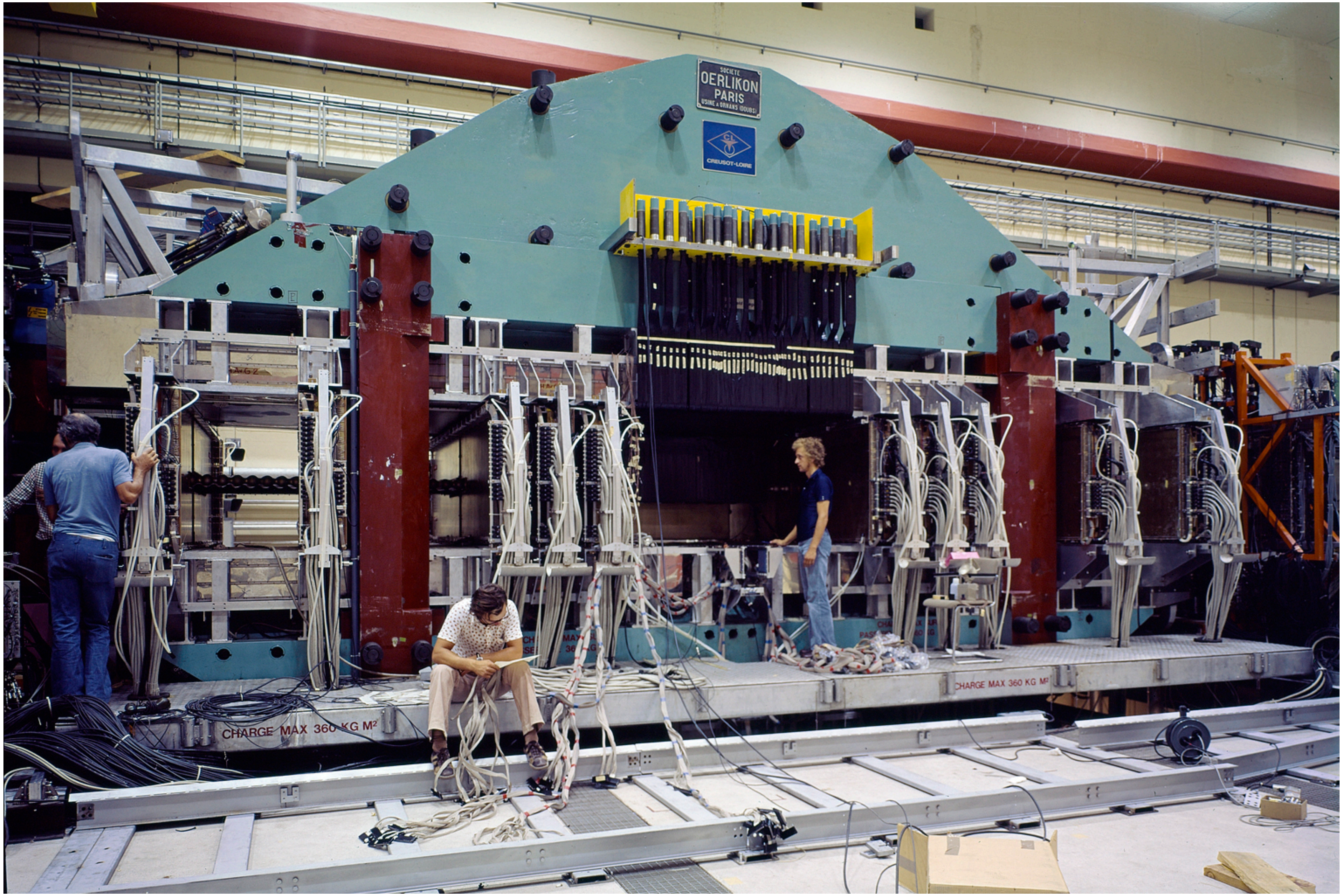
At the ISR, gluons contribute to leading order. In electron-proton annihilations and deep inelastic scattering, gluons contribute to next to leading order only, in the form of radiative corrections associated with a bremsstrahlung gluon radiated from a quark line. This does not mean that such gluon contributions are unimportant: the scaling violations which they induce have been one of the most powerful tool in the development of our understanding of QCD. But, at the ISR, gluons not only contribute to leading order but indeed dominate the scene: in the low x regime characteristic of the ISR, collisions involving gluons, either gluon-gluon or quark-gluon, account for most of the high p_T cross-section. Gluon interactions being a privileged domain of the ISR, and gluons having been the last component of the theory to be understood and digested, it seems difficult to argue that the ISR have played but a minor role. The more so when one considers that the ISR had exclusive access to the three and four gluon vertices, which are a specific expression of QCD as a non abelian gauge theory.

In 1972-1973, three ISR teams announced the observation of an unexpectedly copious pion yield at large transverse momenta, orders of magnitude above the extrapolation of the exponential distribution observed at lower energies ~$exp(–6p_T)$.

Experiments had been designed under the assumption that all hadrons would be forward produced. This first discovery opened the ISR to high p_T studies providing a new short distance probe. But the background that had been anticipated in the search for new particles had been strongly underestimated and such searches were now becoming much more difficult than had been hoped for.

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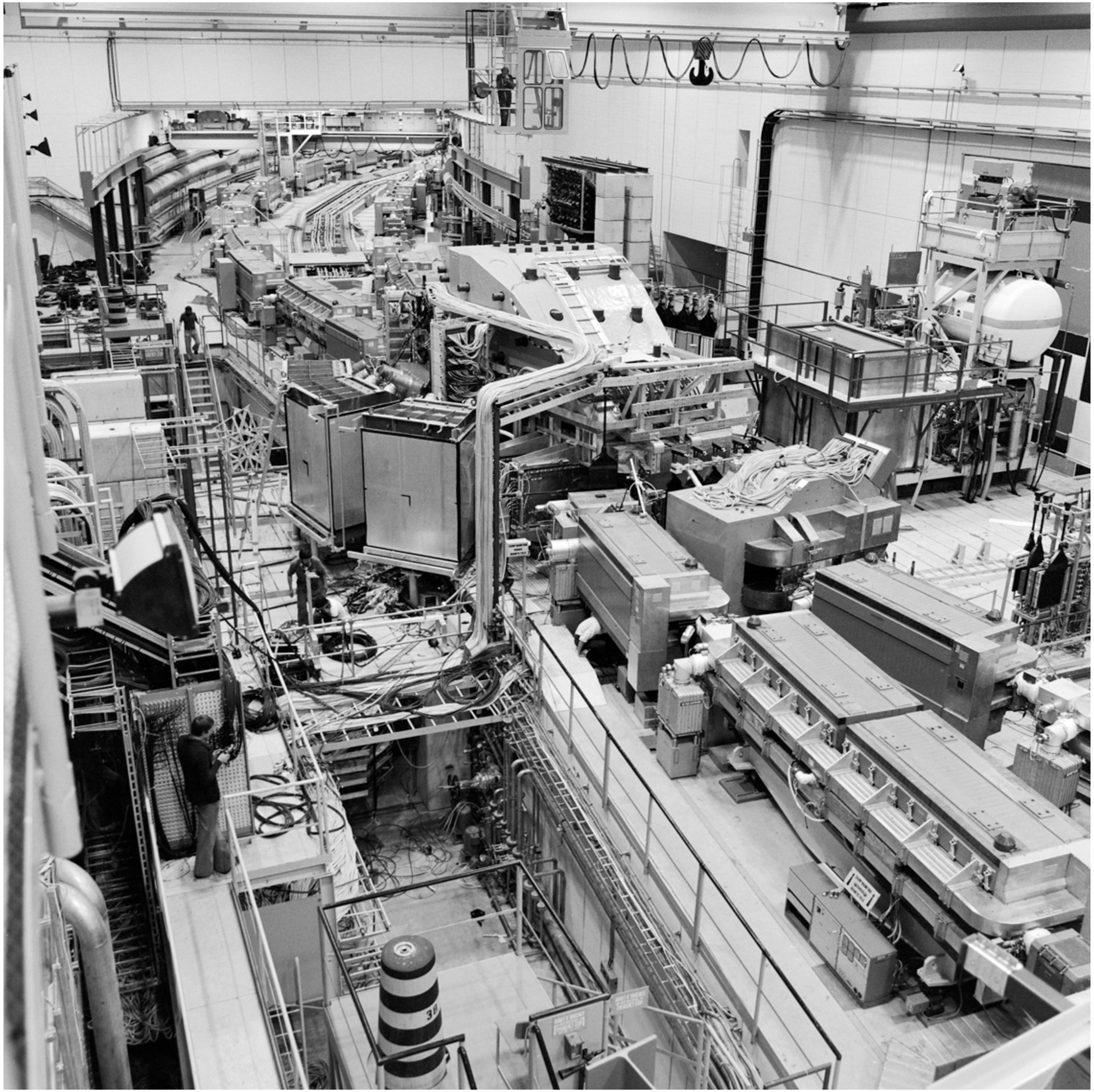
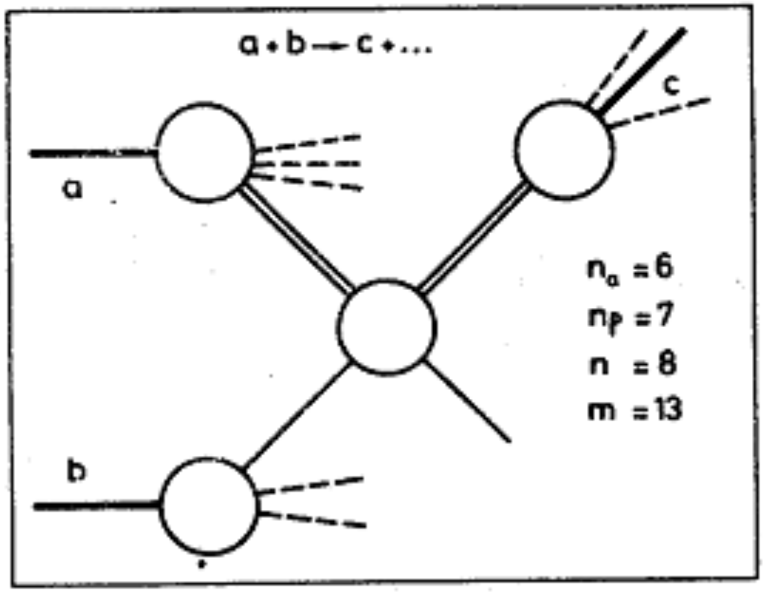
CHARGE MAX 360 KG M²

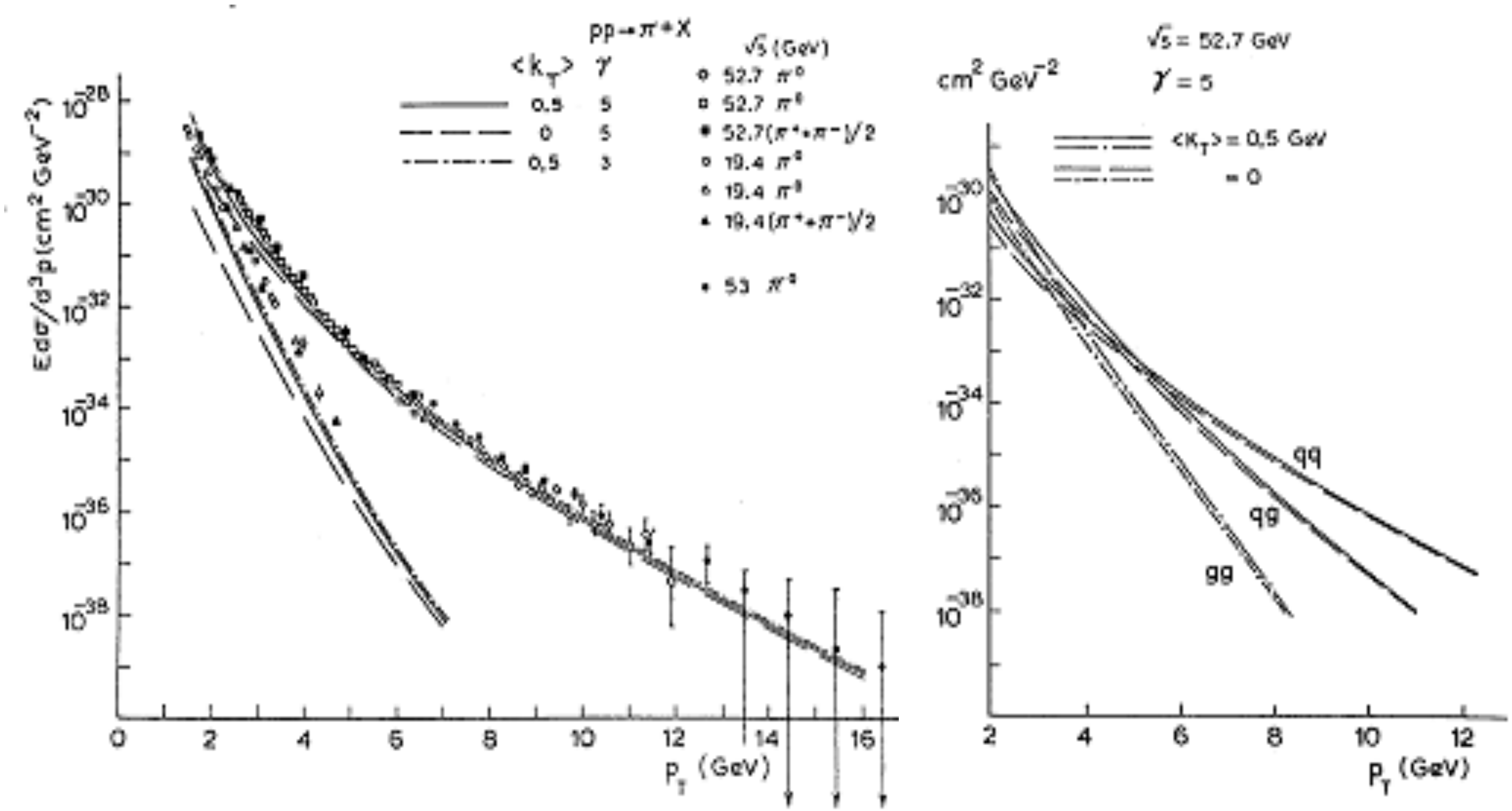


Bjorken scaling was found to apply, in support of the parton picture, $p_T^{-n}exp(-kx_T)$ $x_T=2p_T/\sqrt{s}$, but $n=8.24\pm0.05$ instead of 4 expected for quark partons. The constituent interchange model includes mesons in addition to quarks among the parton constituents: deep-inelastic scattering would be blind to such mesons because of their form factor but hadron interactions would allow for quark rearrangements such as $\pi^{+}+d \rightarrow \pi^{0}+u$. At large x_T, $p_T^{-2(n-2)}(1-x_T)^{2m-1}$ where n stands for the number of "active quark lines" taking part in the hard scattering and m stands for the number of "passive" quark lines wasting momentum in the transitions between hadrons and quarks.

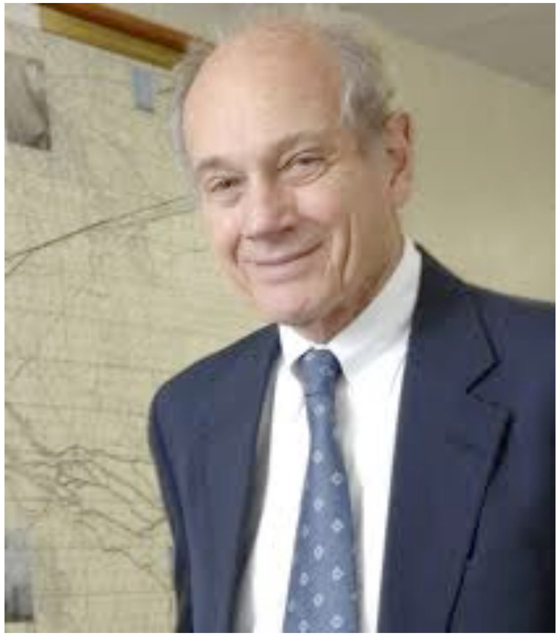
The model had many successes but did not stand the competition with early QCD models that were starting to be developed: they got relegated to the rank of "higher twist corrections" to the leading order perturbative QCD regime.



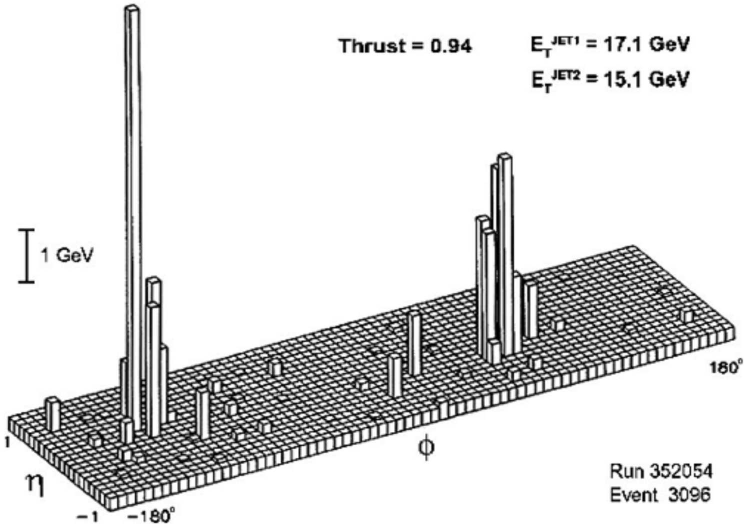
QCD models gave evidence for important quark-gluon and gluon-gluon contributions beside the quark-quark term. By then, the inclusive production of charged pions, kaons, protons and antiprotons as well as η mesons had been studied at the ISR, and at Fermilab where a π^- beam had also been used, providing decisive evidence in favour of QCD. It was then understood that the p_T power law was indeed evolving to p_T^{-4} at high values of x_T accessible to larger cm energy collisions.



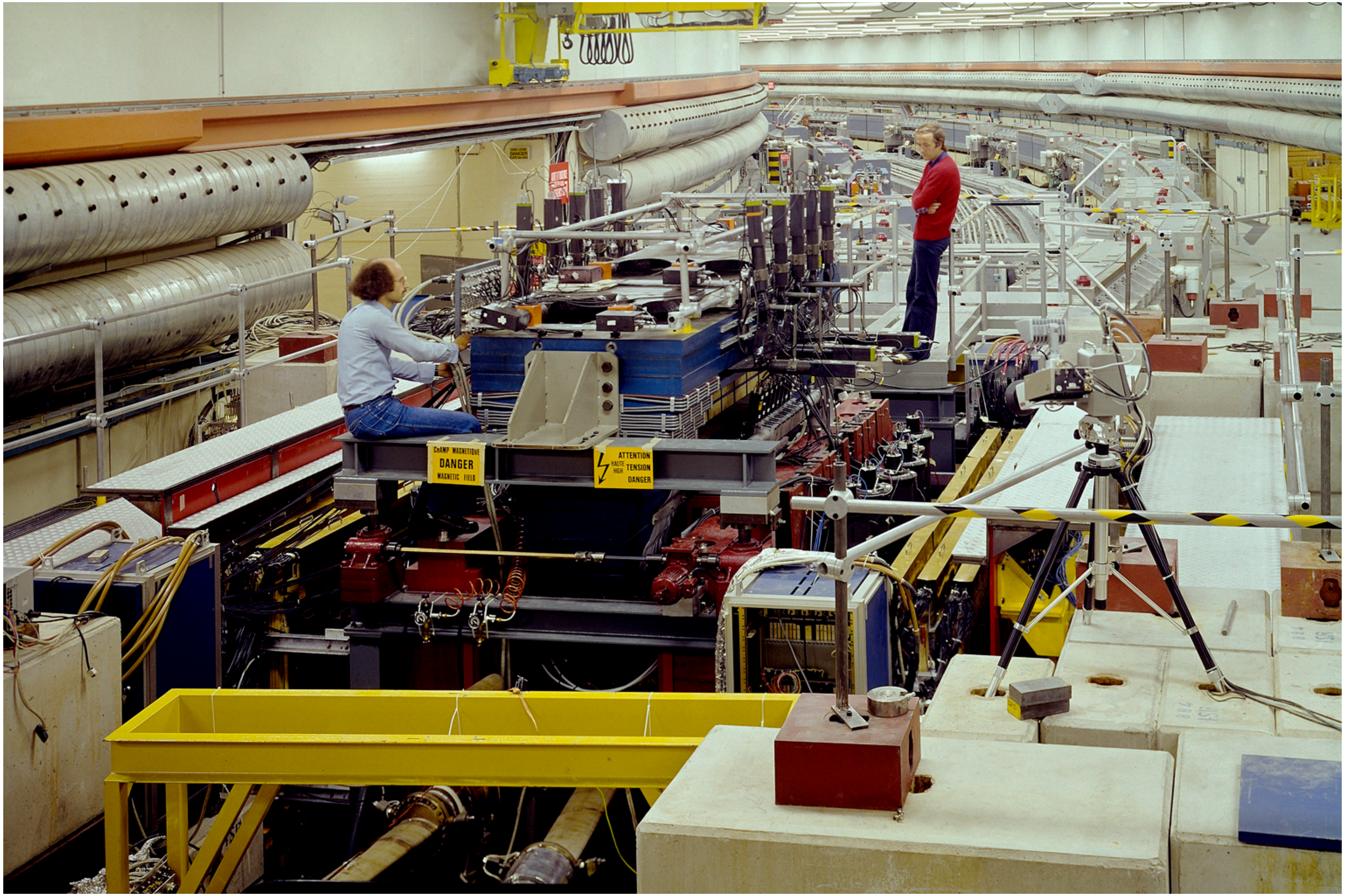
Between 1973 and 1978, inclusive high p_T single hadron production in hadron collisions had given exclusive contributions to the establishment of QCD as the theory of the strong interaction in a domain where other experiments – deep inelastic scattering and electron-positron annihilations – could not contribute: that of short distance collisions involving gluons to leading order of the perturbative expansion. In this domain, the data collected at the CERN ISR – at the higher centre of mass energies – and at Fermilab – with a variety of beams and targets – nicely complemented each other. As the results were confirming the validity of QCD, and as there were so many important events happening elsewhere in physics, people have tended to neglect or forget these important contributions.



The early evidence in favour of the parton picture encouraged studies of the global event structure and, in particular, experiments aiming at the detection of the hadron jets into which the hard scattered partons were supposed to fragment. Unfortunately, none of the existing ISR detectors was matched to the task. A large magnetic detector was proposed in March 1975 and definitively turned down in November 1976 in spite of considerable support. Meanwhile, step by step, the existing ISR experiments had upgraded their set ups as well as they could but one had to wait until the eighties, with the Axial Field Spectrometer in I8 and the Superconducting Solenoid in I1 to see detectors having large calorimeter coverage.



When the ISR closed down in 1984, a rich set of important results had been obtained by these two groups, with two-jet events dominating the scene for transverse energies in excess of 35 GeV but the CERN proton-antiproton collider, which had published its first jets in 1982, had already taken the limelight away from the ISR.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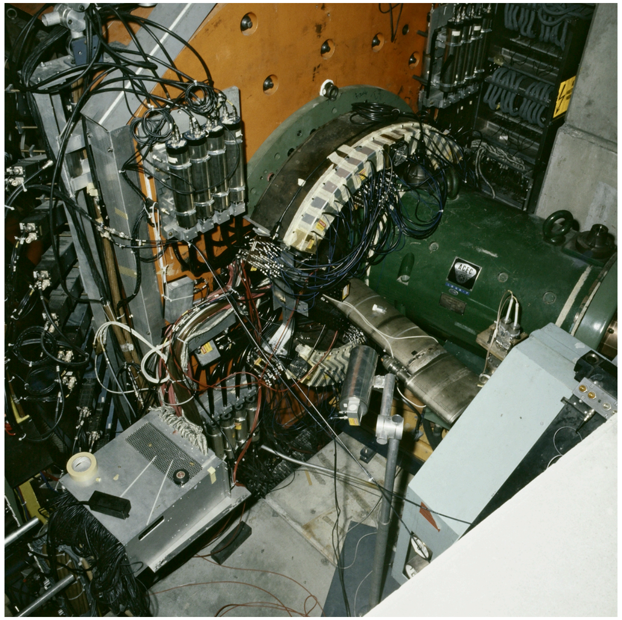
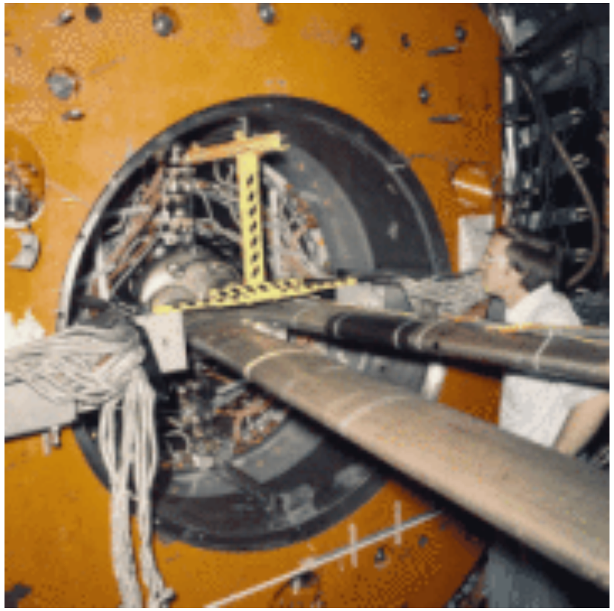
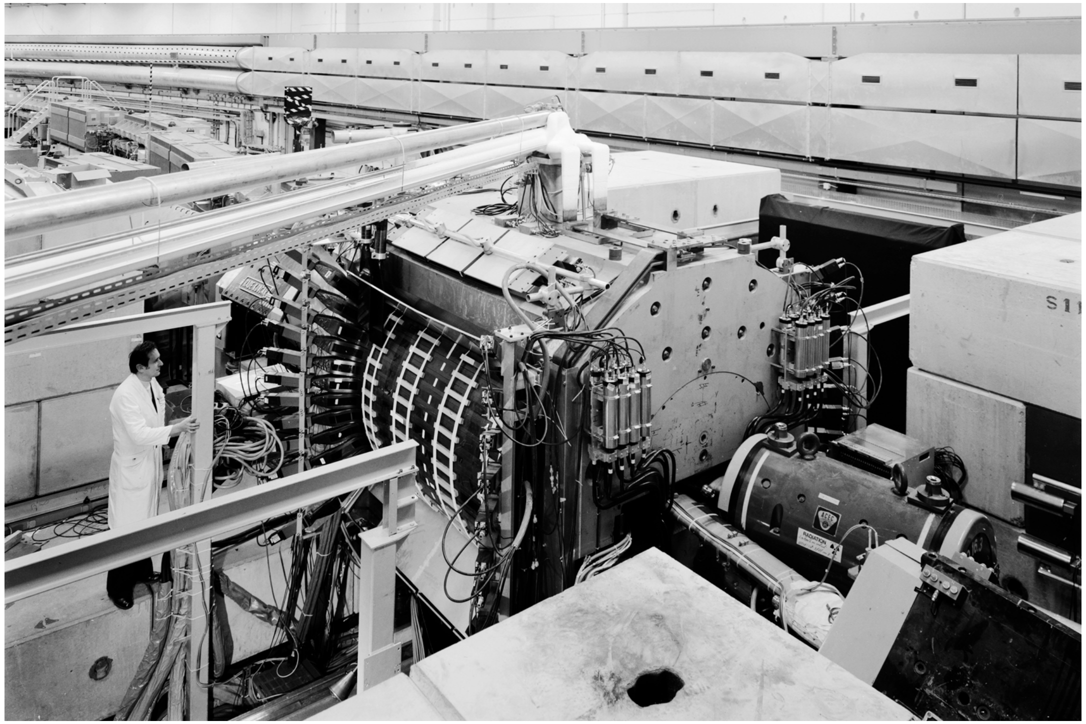
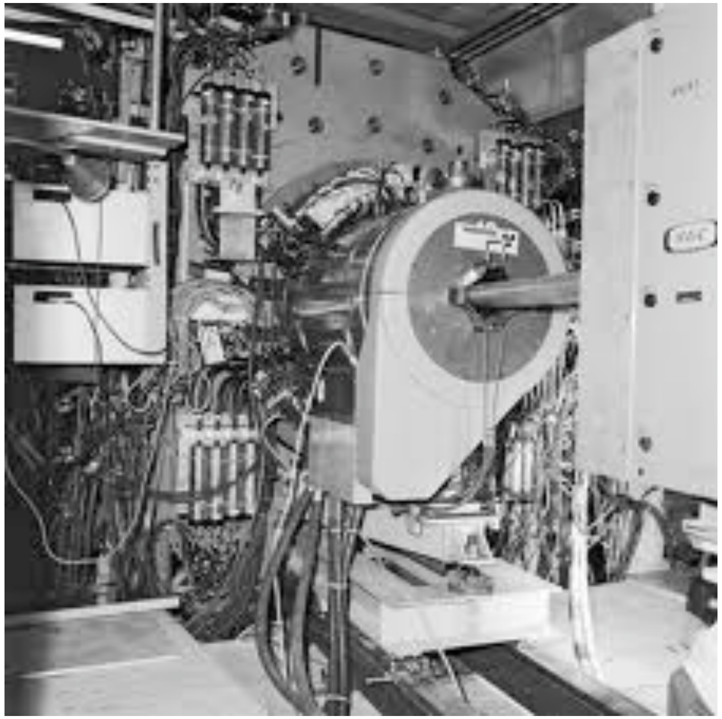
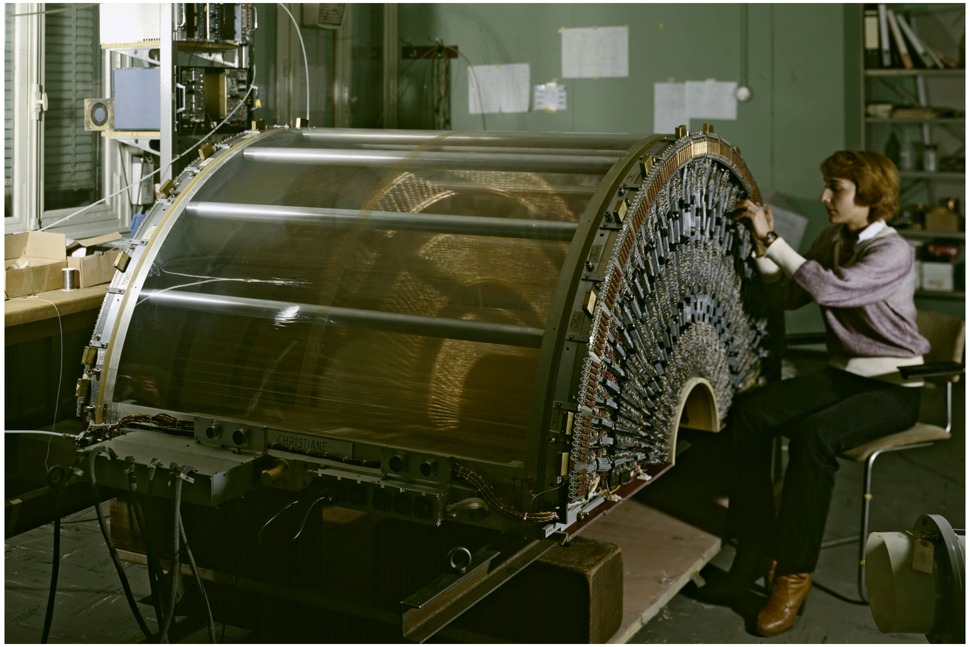
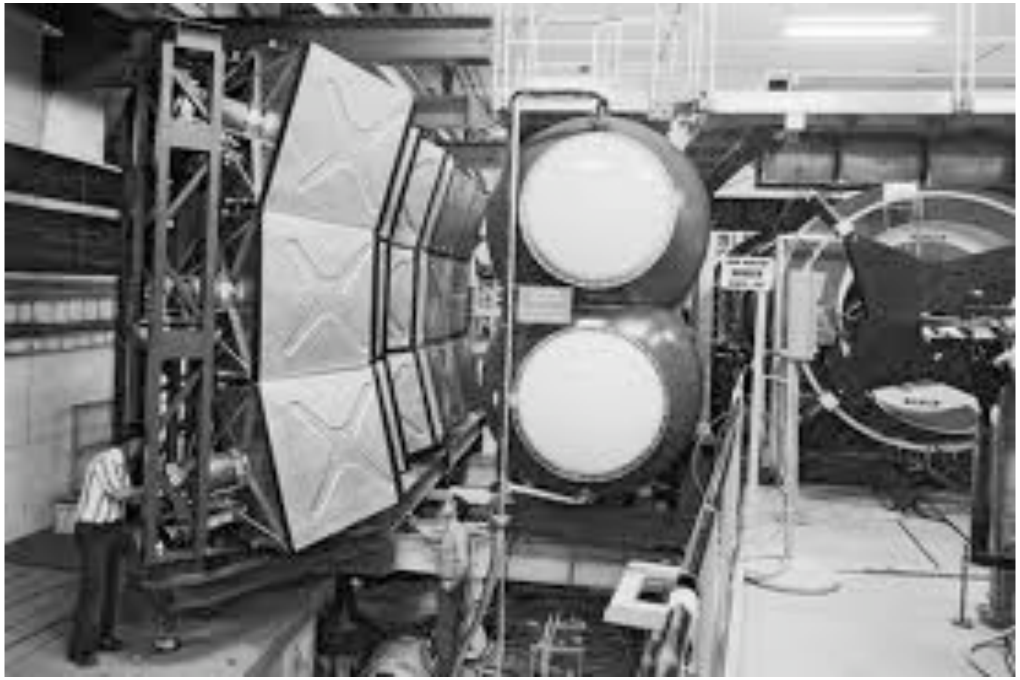






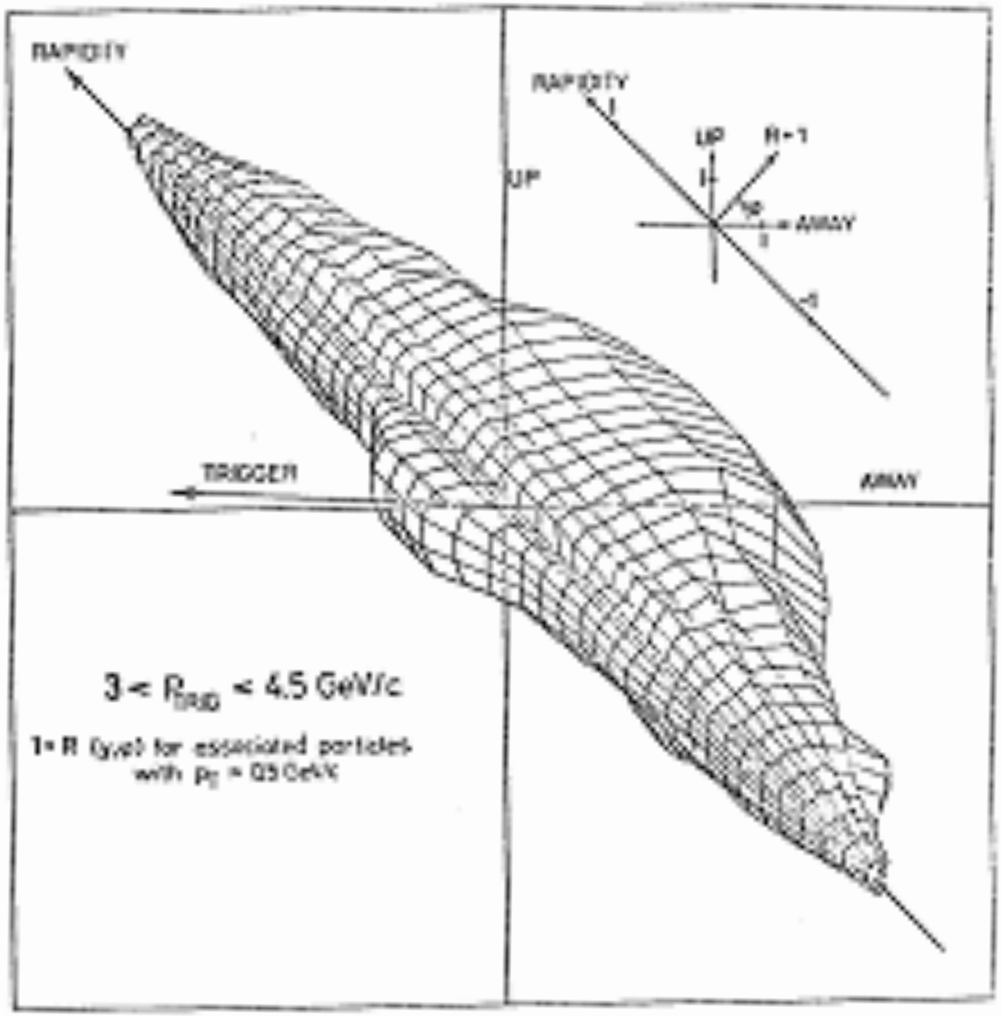






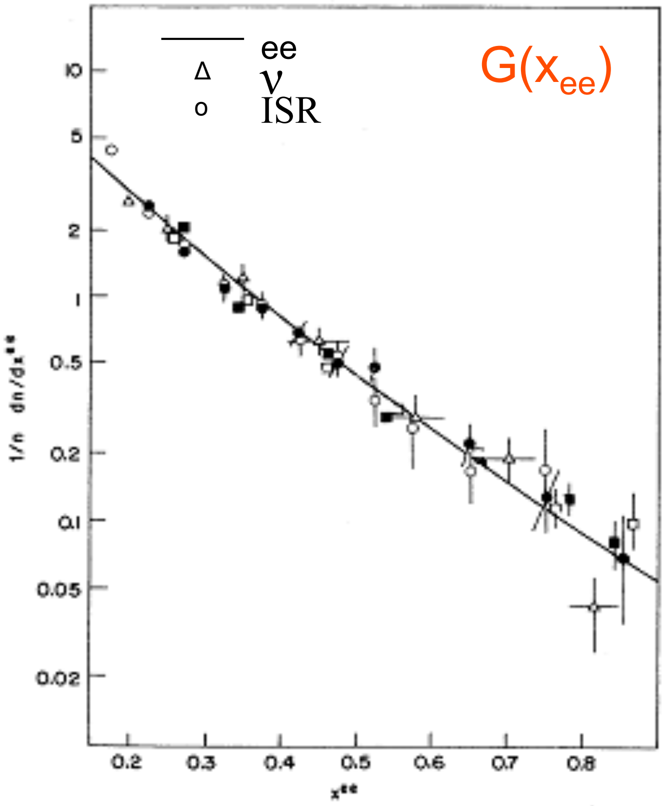
Between 1973 and 1978, several ISR experiments completed studies of the event structure and the evidence for hard jets in the final state, already clear in 1976, had become very strong.

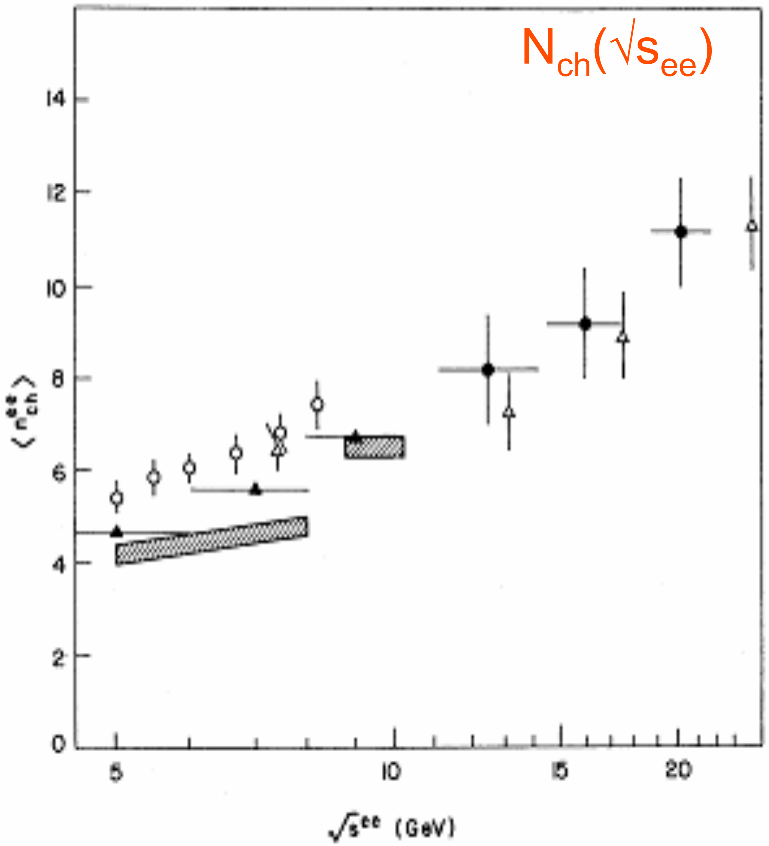
Diffraction is suppressed at large rapidities, a "same-side" jet is present alongside the trigger and "away-side jets", at opposite azimuth to the trigger, cover a broad rapidity range.

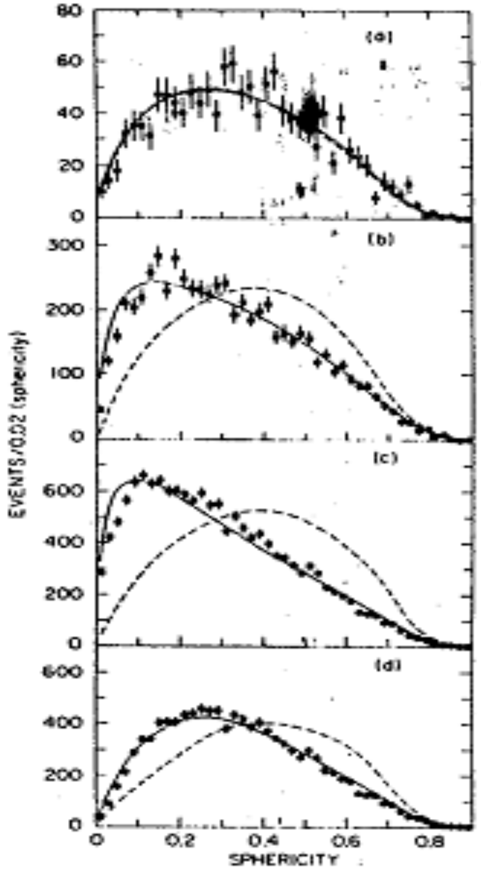


The "underlying event" implies a transverse momentum threshold, ½ to 1 GeV, below which a particle cannot be unambiguously identified as being a fragment of a hard scattered parton. Single particle triggers distort the "same-side" jet fragmentation: An ideal experiment should trigger on the total transverse energy E_T using calorimetric devices.

Evidence for an excess of particles at opposite azimuth to the trigger had been obtained very early and it had soon been recognized that it was due to a collimated jet produced at a rapidity which was different from event to event. The away-jet multiplicity could then be measured and compared to that of quark jets observed in deep inelastic and electron-positron annihilations. ISR jets being dominantly gluon jets, one could expect to see a difference but the p_T range accessible to the ISR was still too low to reveal significant differences in the fragmentation functions of quark and gluon jets.

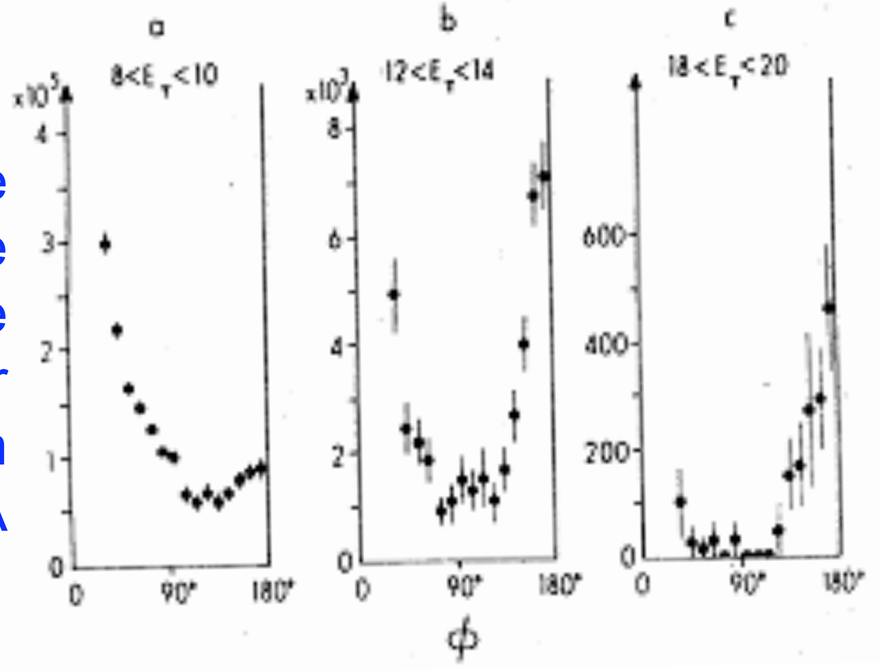


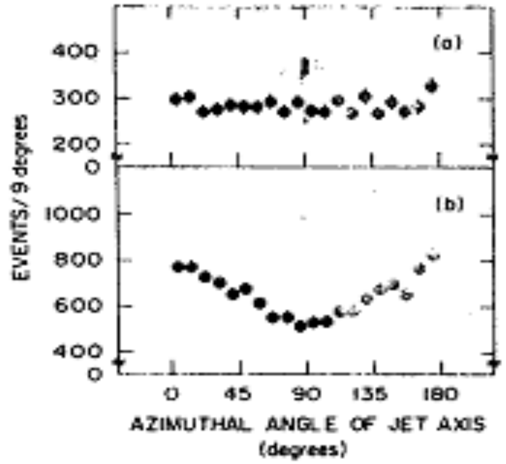




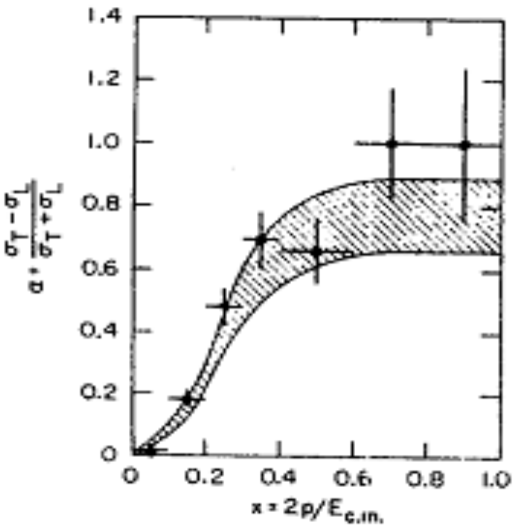
In electron-positron collisions, the first evidence for quark jets came from SPEAR in 1975 and the first evidence for gluon jets came from PETRA in 1979-1980. The former were 4 GeV quark jets, PETRA’s gluon jets were typically 6 GeV, ISR jets – mostly gluon jets – were at least 10 GeV. The e^+e^- data were analysed in terms of event shapes: sphericity, oblateness, thrust, triplicity, etc… There was no doubt that, without any theoretical preconception, the evidence for ISR jets was stronger than the evidence for quark jets at SPEAR in 1975 and the evidence for gluon jets at PETRA in 1979-1980;

The ISR physicists who studied large transverse momentum production were rightly feeling frustrated with the relative lack of public recognition given to their data compared with the enthusiasm generated by the SPEAR and PETRA results.

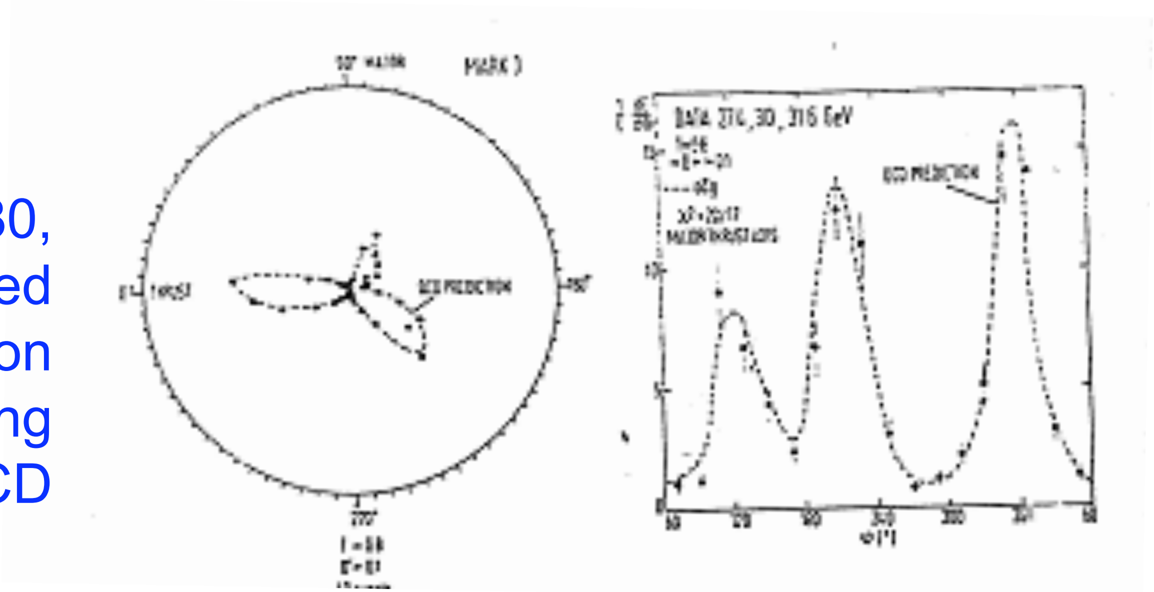




Part of the imbalance in the reception given to ISR data compared with SPEAR and PETRA data was subjective: the analysis of ISR data was too complicated, which for many meant “was not clean”. But, one must recognize that a good part was objective. The SPEAR and PETRA detectors were better fit to these studies and, more importantly, their data were easier to interprete. In the SPEAR case, the azimuthal distribution of the jet axis displayed the behaviour expected from the known beam polarization and its polar angle distribution obeyed the *$1+cos^2\theta$* law expected in the case of spin ½ partons.

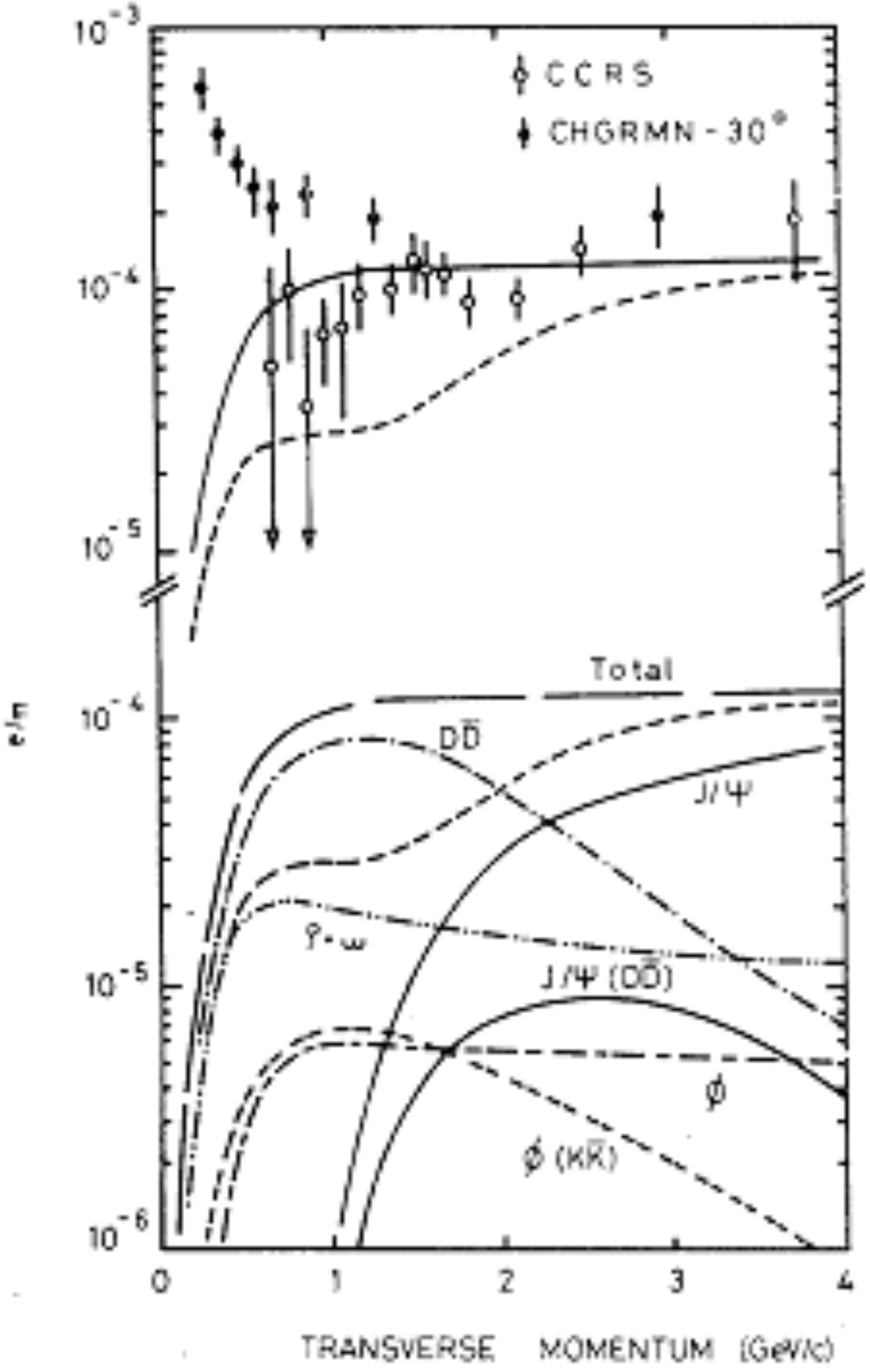


In the PETRA case, by mid-1980, all four experiments had presented clear evidence for gluon bremsstrahlung, including convincing comparisons with QCD predictions.

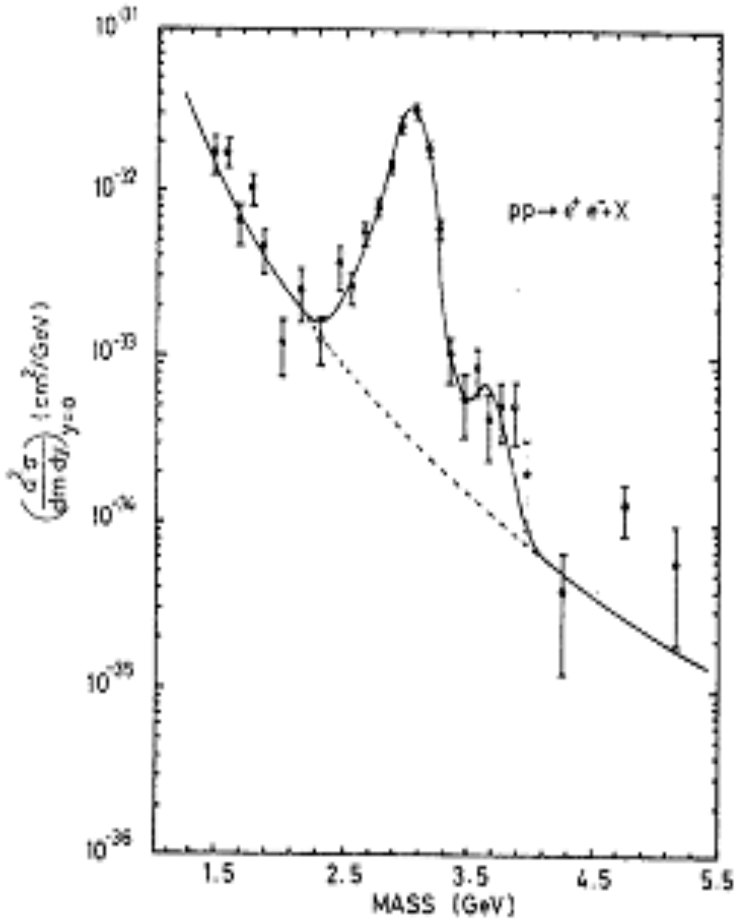


At the ISR, the complexity of the physics processes at stake was undoubtedly much larger than at electron-positron colliders, making it difficult to devise decisive QCD tests independent from what had been learned at other accelerators. But, once again, ISR data were exploring elementary processes which were not accessible to other accelerators and were shown to nicely fit in a coherent QCD picture embedding deep-inelastic as well as e^+e^- annihilation results. This was clearly an independent and essential contribution to the validation of QCD.

The worse sceptics were to be found in the fixed target community where too low values of the centre of mass energy prevented jets to be revealed. There were exceptions, however. I remember Walter Selove spending the Summer months at CERN and scanning with us our streamer chamber data collected with a high p_T π^0 trigger at 90°: each time he would see some kind of a jet, he would exult and copy its configuration in a notebook…

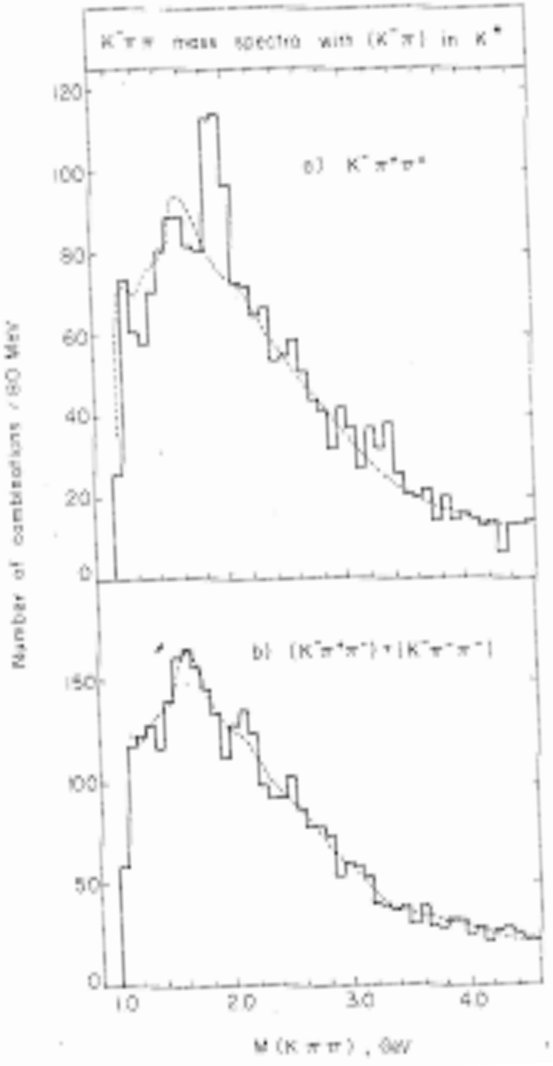


Leptons were produced at the ISR either as decay products of other particles or as a continuum of opposite charge pairs coupled to a quark-antiquark pair in the initial state via a virtual photon in the *s* channel, the so-called Drell-Yan process. In the first half of the decade, the e/π ratio had been measured by several experiments to be of the order of 10^{-4} over a broad range of transverse momenta and was understood as being the result of a “cocktail” of different sources, including, among others, open charm and charmonium.

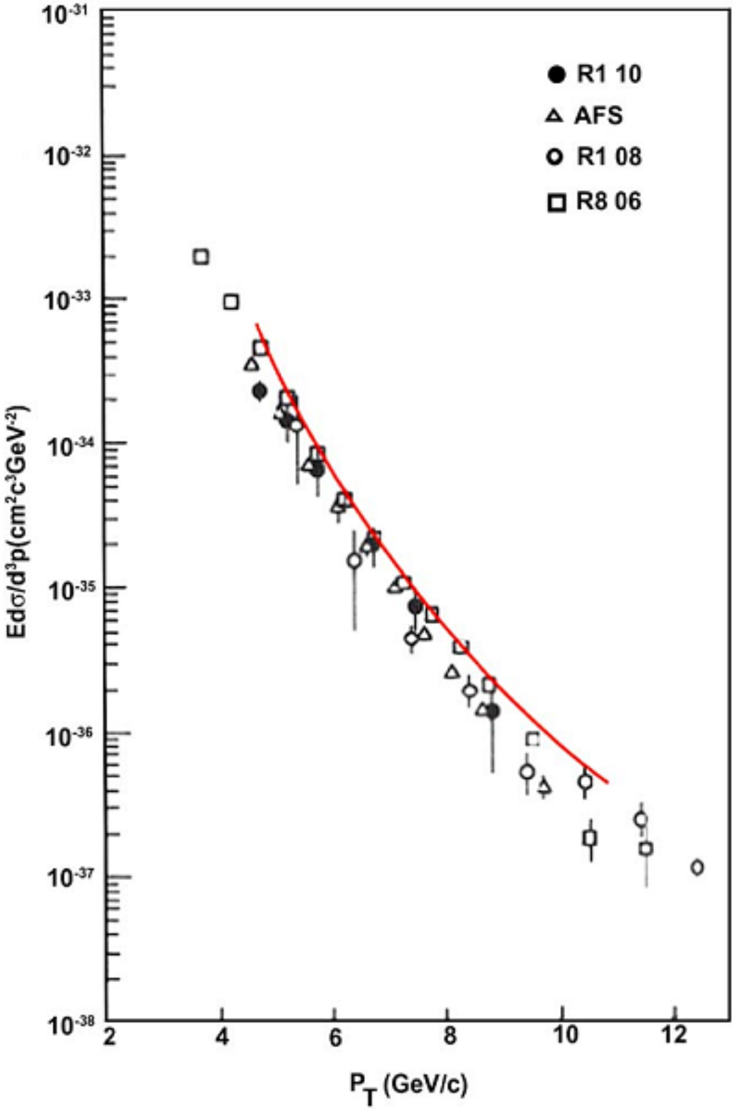


By the end of the decade, the *J/Ψ* and the *Y* had been detected and their production cross-section had been measured.

Moreover, a clear evidence for *D* production had been obtained at the Split Field Magnet – for the first time in hadron interactions.



Dilepton masses up to 20 GeV have been ultimately studied, giving evidence for strong next to leading order corrections to the Drell-Yan leading order diagram.



At the ISR, direct photon production proceeds mainly by Compton interaction between a quark and a gluon producing a quark and a photon. The photon is produced alone and its transverse momentum is balanced by a hadron jet. It provides information on the gluon structure function as well as a measurement of α_s, the quark fragmentation being borrowed from e^+e^- data. In the first half of the decade, pioneering measurements have established the existence of a signal and identified backgrounds, the main source being π^0 and η decays. At the end of the decade, clear signals were observed and a series of measurements followed, which, together with fixed target data, provided a very successful laboratory for QCD.

Once again, hadronic interactions, both on fixed target machines and at the ISR, had made use of their unique ability to study gluon collisions and to give essential contributions to the study of the strong interaction in the QCD perturbative regime.

I hope that this brief review of ISR contributions to the new physics that was born in the seventies, and specifically to QCD, has convinced you that they were more than a mere *“test of the idea that there were point-like constituents inside the proton*”. Together with hard hadron interactions on fixed target machines, they made optimal use of their exclusive property to study the gluon sector of QCD to leading order. The ISR had the privilege of a higher centre of mass energy, fixed target machines had the privilege of versatility, their respective virtues nicely complemented each other.

Many factors have contributed to the relative lack of recognition which has been given to ISR physics results: the absence, for many years, of detectors optimized for the study of hard processes, the fact that the weak sector, which during the decade was the scene of as big a revolution as the strong sector, was completely absent from the ISR landscape and, may be most importantly, the fact that hard hadron collisions imply complex processes which may seem “dirty” to whom does not make the effort to study them in detail.

We, who worked at the ISR, tend not to attach much importance to this relative lack of recognition because for us, their main legacy has been to have taught us how to make optimal use of the proton-antiproton collider, which was soon to come up. They had given us a vision of the new physics and of the methods to be used for its study which turned out to be extremely profitable. They had played a seminal role in the conception of the proton-antiproton collider experiments, they were the first hadron collider ever built in the world, they were the machine where a generation of physicists learned how to design experiments on hadron colliders. We tend to see the ISR and the proton-antiproton collider as a lineage, father and son, the success of the latter being indissociable from the achievements of the former.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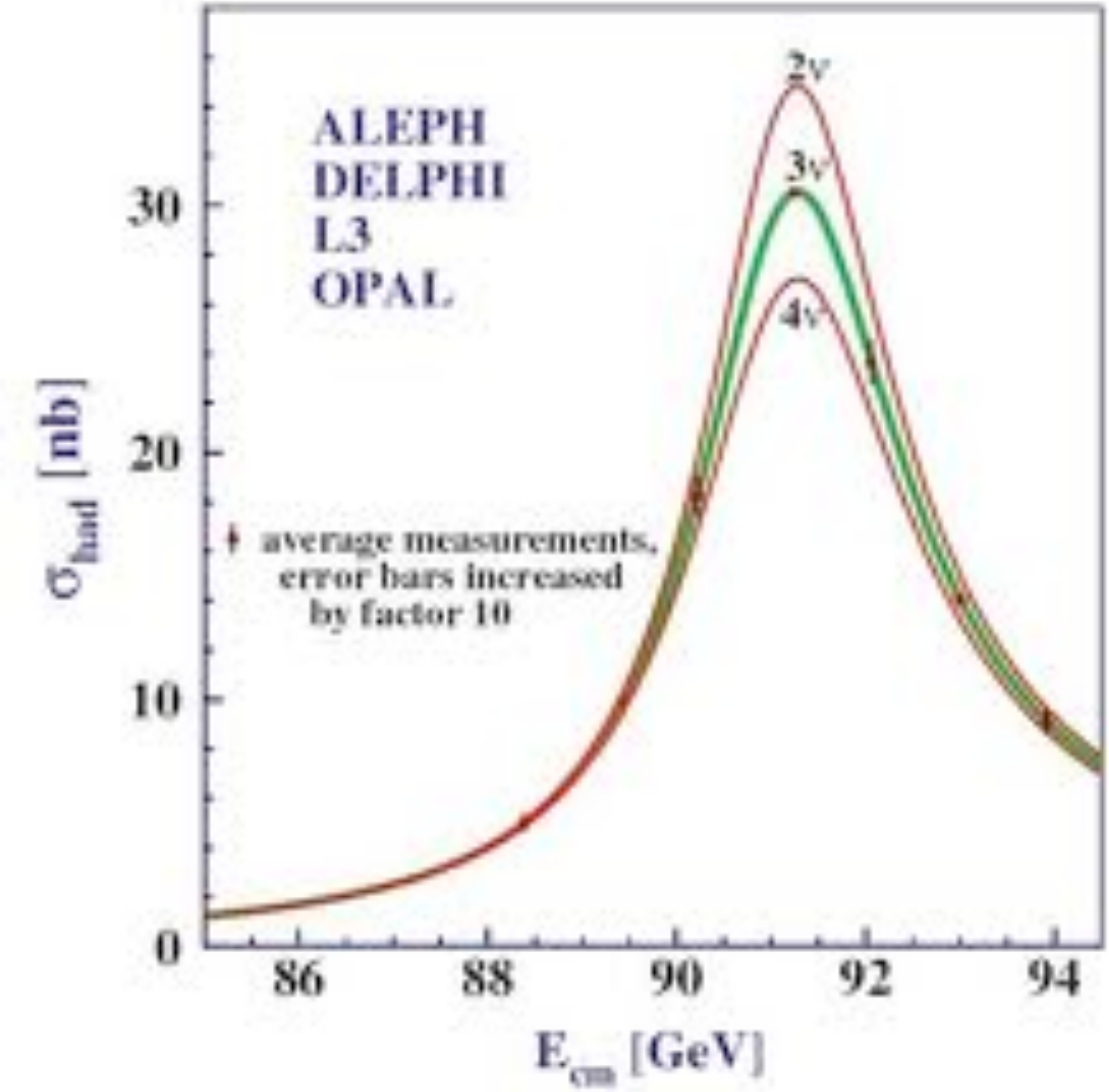
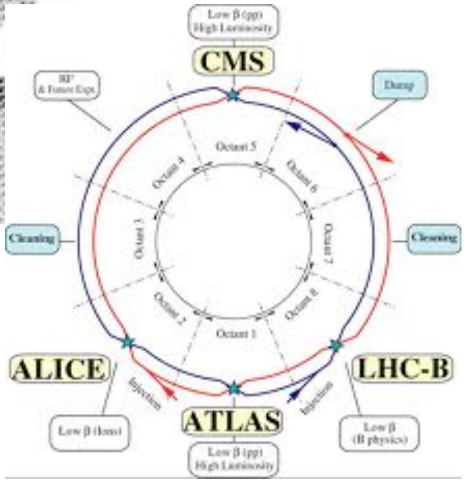


ALEPH
DELPHI
L3
OPAL
2ν
3ν
4ν
average measurements, error bars increased by factor 10
σ_had [nb]
0
10
20
30
86
88
90
92
94
E_cm [GeV]

THREE GENERATIONS OF HADRON COLLIDERS



We were young then, this may be another reason why we remember these times with affection… The lineage has now extended to a third generation and we look at the future with the eyes of grand parents, full of tenderness and admiration for their grand son whom we wish fame and glory.