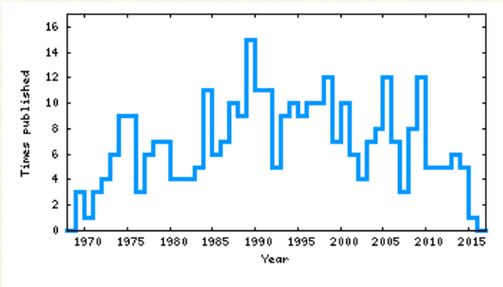
CERN June 2016

The Standard Model at the SPS collider: Guido Altarelli Memorial Symposium

Keith Ellis
IPPP, Durham

At the vanguard of science



Place of Work

Paris

CERN

US

RomaIII

Florence

Roma La Sapienza

Research topics

Higgs

Duality /Sigma model

Partons and QCD

Small x

Heavy Flavour/Charm

Precision EW

Neutrino Physics

1960 1965 1970 1975 1980 1985 1990 1995 2000 2005 2010 2015

Sppbar

LEP

LHC

ISR

Adone

Tevatron

Machines

Hera

SLAC ep

Spear

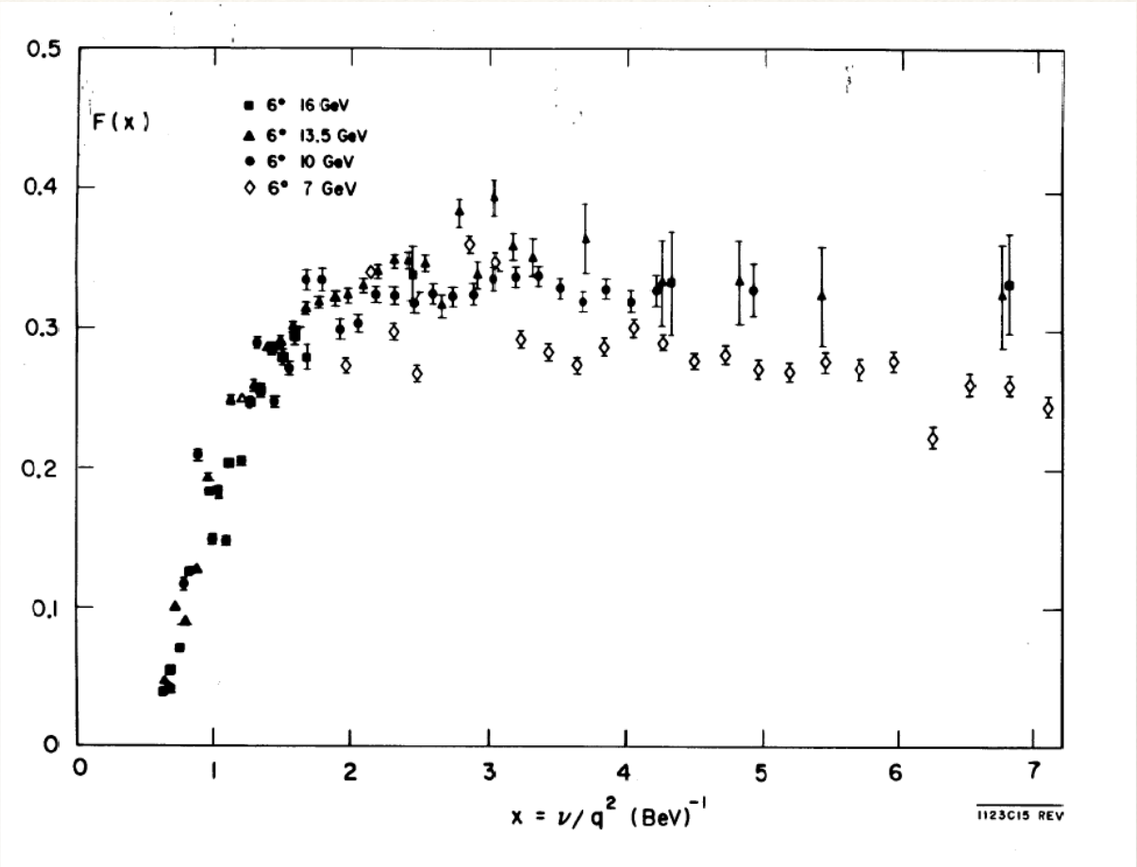
SLC

Timeline

	1969	Parton model
	1970	
	1971	Cornell conference
	1972	Photon-hadron interactions
Annus mirabilis	1973	Asymptotic freedom
	1974	
	1975	
	1976	
Annus mirabilis	1977	DGLAP, Demise of the transverse momentum cutoff, Infrared safety
	1978	
Annus semi-mirabilis	1979	NLO QCD for Drell Yan
	1980	Factorisation beyond leading logs,
	1981	
	1982	
Annus mirabilis	1983	W and Z discovery, Jets
	1984	W and Z distributions, Monojets,
	1985	SppS collider shutdown

Life before QCD

- Feynman wrote his book on Photon-hadron Interactions in response to the 1971 Cornell conference (the precursor to Lepton Photon).
- Approximate scaling in Deep Inelastic Scattering was known.
- Theoretical explanations in vogue were:-
  - the light cone expansion, that somehow produced free field behaviour on the light cone, but was strongly interacting off the light cone
  - The parton model that required an *ad hoc* cut on the transverse momentum of the partons to explain the scaling behaviour.
- At the Cornell conference, gluons were mentioned in the talk of Bjorken, but they were labelled as speculative and no details of their couplings were given.
- The fractional charges of the quarks were still speculative.



Approximate scaling was established

The “Drell-Yan” process

- The production of muon pairs at the AGS was first observed by Christenson et al. and first presented at the Spring APS meeting, (PRL Sept 1970)
- Drell and Yan wrote a theory paper (May 1970) expressing the cross section in terms of DIS structure functions F_2

Leon Lederman

$$\frac{d\sigma}{dQ^2} = \left(\frac{4\pi\alpha^2}{3Q^2}\right)\left(\frac{1}{Q^2}\right)\mathcal{F}(\tau) = \left(\frac{4\pi\alpha^2}{3Q^2}\right)\left(\frac{1}{Q^2}\right)\int_0^1 dx_1 \int_0^1 dx_2\, \delta(x_1 x_2 - \tau) \sum_a \lambda_a^{-2} F_{2a}(x_1) F_{2\bar{a}}'(x_2),$$

- Nowadays this formula would have a colour averaging factor, ie. the rate would be a factor of 3 smaller.

Sidney Drell+Tung-Mow Yan

Altarelli, Brandt and Preparata

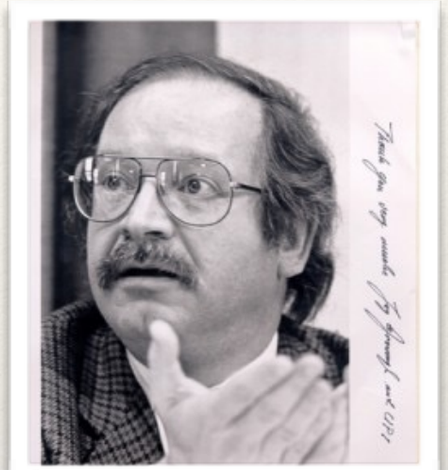
VOLUME 26, NUMBER 1 PHYSICAL REVIEW LETTERS 4 JANUARY 1971

Light-Cone Analysis of Massive μ-Pair Production*

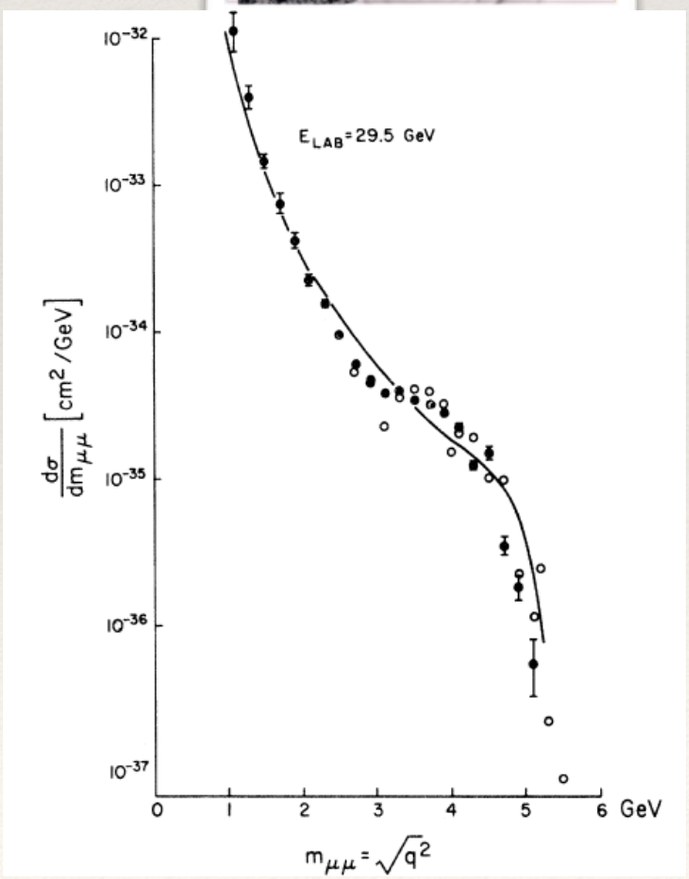
Guido Altarelli,† Richard A. Brandt,‡ and Giuliano Preparata†
Rockefeller University, New York, New York 10021
(Received 9 September 1970)

An operator representation for the behavior of the product of two electromagnetic currents near the light cone is used to discuss massive μ-pair production in hadron-hadron interactions. Restrictions from the Stanford Linear Accelerator Center electroproduction experiments and from Regge theory are incorporated. Our predictions are in agreement with the recent Columbia–Brookhaven National Laboratory experiment.

Giuliano Preparata 1942-2000

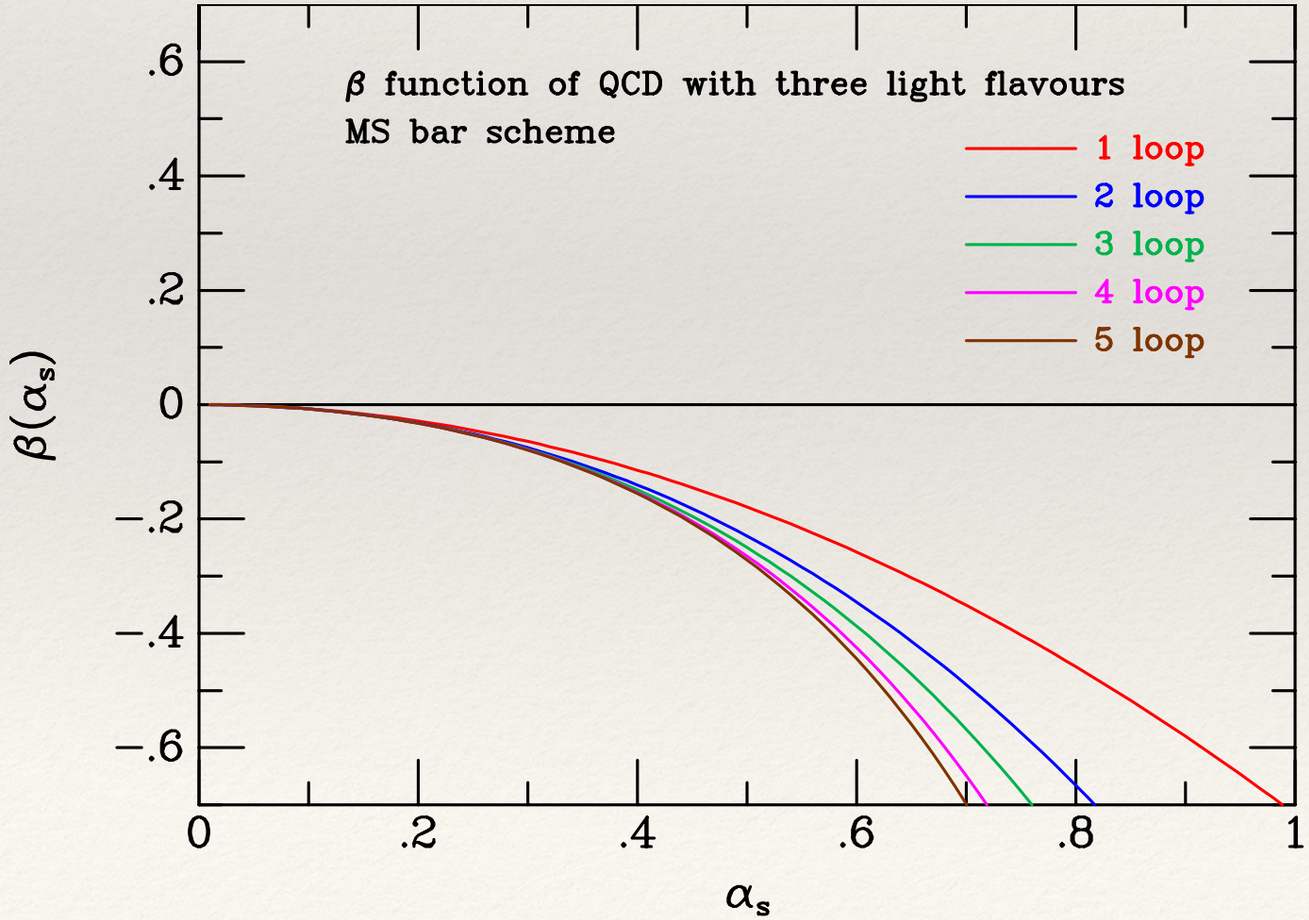


- Almost contemporaneous with the paper of Drell and Yan.
- Guido was at NYU as a Fulbright fellow and evidently had extensive conversations with the group of Lederman.
- The ABP model was an amalgam of Regge theory and the parton model.
- Unlike Drell and Yan, ABP actually tried to fit the Lederman data.

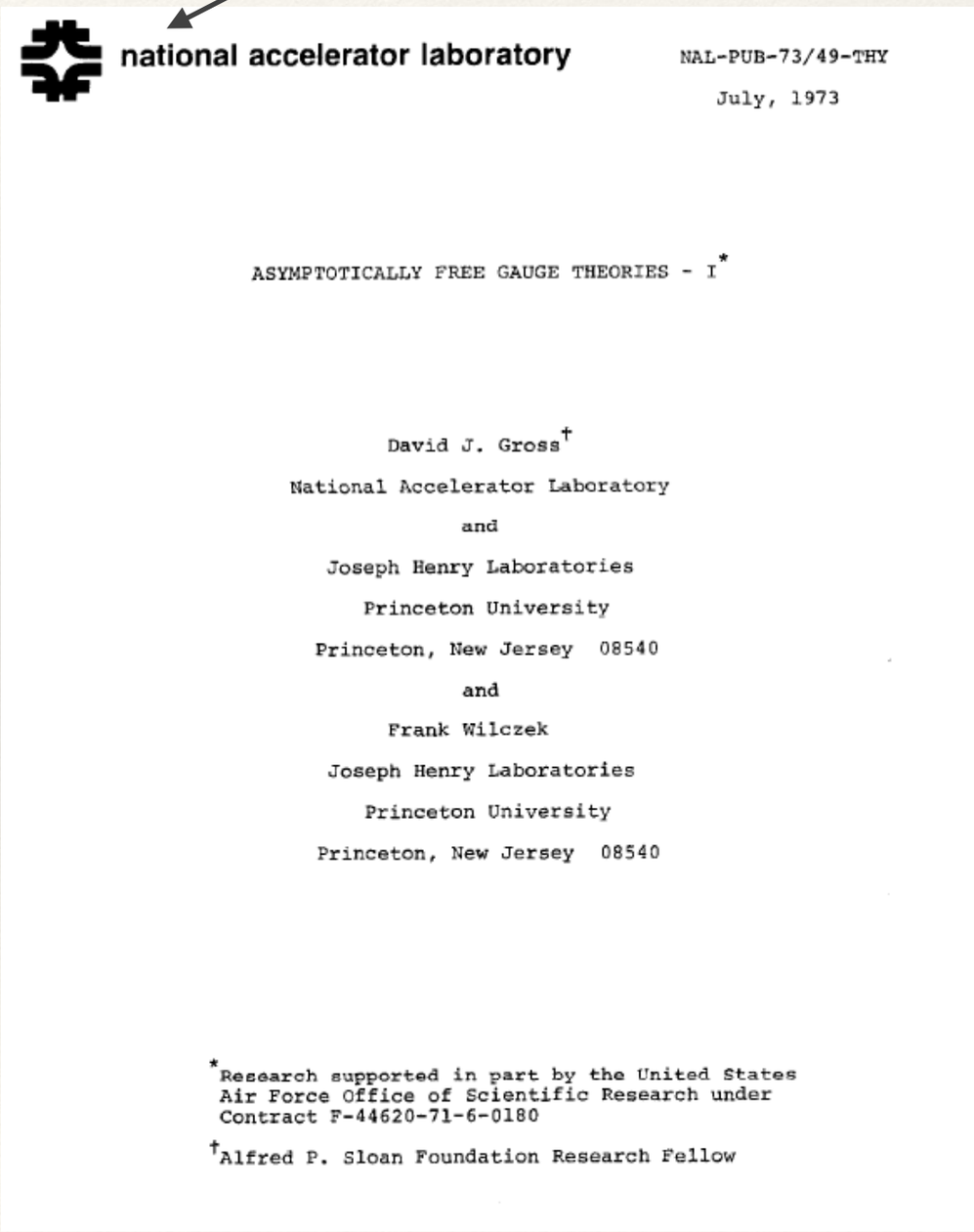


Asymptotic freedom

- The game changed with the discovery of asymptotic freedom.
- The beta function is negative (and now known to 5 loops!)
- How and what to calculate with this theory?



Shows importance of lab summer programs!



national accelerator laboratory

NAL-PUB-73/49-THY

July, 1973

ASYMPTOTICALLY FREE GAUGE THEORIES - I*

David J. Gross†

National Accelerator Laboratory

and

Joseph Henry Laboratories

Princeton University

Princeton, New Jersey 08540

and

Frank Wilczek

Joseph Henry Laboratories

Princeton University

Princeton, New Jersey 08540

*Research supported in part by the United States Air Force Office of Scientific Research under Contract F-44620-71-6-0180

†Alfred P. Sloan Foundation Research Fellow

Life before the AP equation

- "In spite of the relative simplicity of the final results, their derivation, although theoretically rigorous, is somewhat abstract and formal, being formulated in the language of renormalisation group equations for the coefficient functions of the local operators which appear in the light cone expansion for the product of two currents." (AP, Nuclear Phys. B)

Georgi Politzer Phys. Rev. D9 (1974) 416
685
Gross-Wilczek, Phys. Rev. D9 (1974) 980
1131

Lepton pair production

- Given the previous experience with lepton pair production, it was natural to try and apply QCD to this process.
- The first order of business was the establish whether the transverse momentum was limited (parton model) or grew with Q^2 (at fixed $\tau = Q^2/s$) as predicted by QCD.
- Real experiments do not have fixed τ.
- The second paper showed that the data could be fitted with an intrinsic transverse momentum of 500-600MeV.

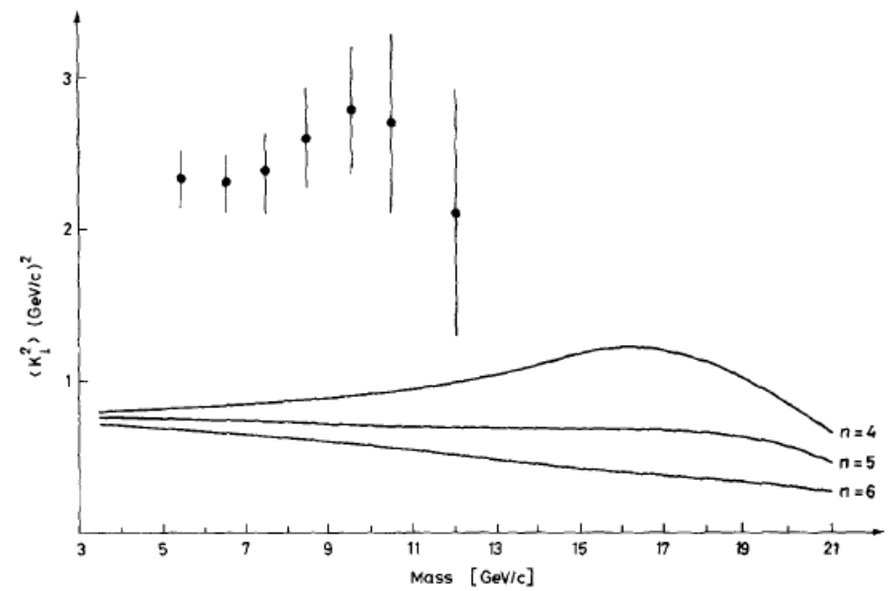


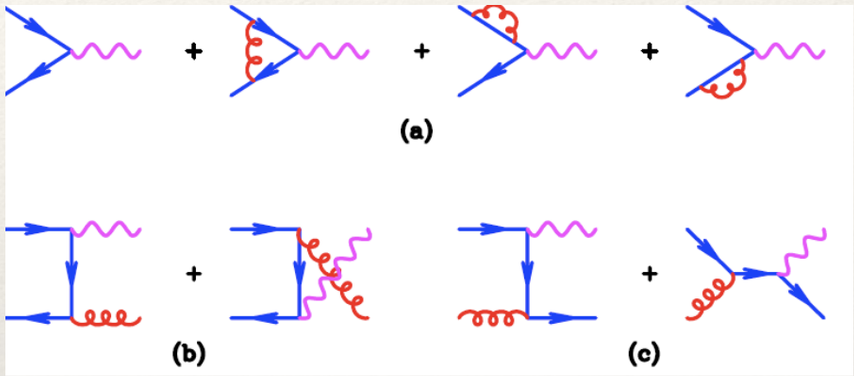
Fig. 3. The hard component of the $\langle k_\perp^2 \rangle$ of the muon pair as a function of their invariant mass is compared with the experimental points taken from ref. [9] for three different powers $n = 4, 5, 6$ of the gluon distribution, following the procedure described in the text.

Altarelli, Parisi and Petronzio, PL 76B, 351
Altarelli, Parisi,Petronzio, PL76B 356

Corrections to Lepto-production and to Drell-Yan

- The principle benefit of QCD is that it gives a procedure for systematically improving the predictions using perturbation theory.
- Technical problem to resolve was the regulation of soft and collinear singularities. The first paper used the off-shellness of the quarks, the second paper used dimensional regularization, (which worked much better).
- This is now a text-book calculation which is used as an exercise, e.g. at the CTEQ schools.

Diagrams for NLO prediction

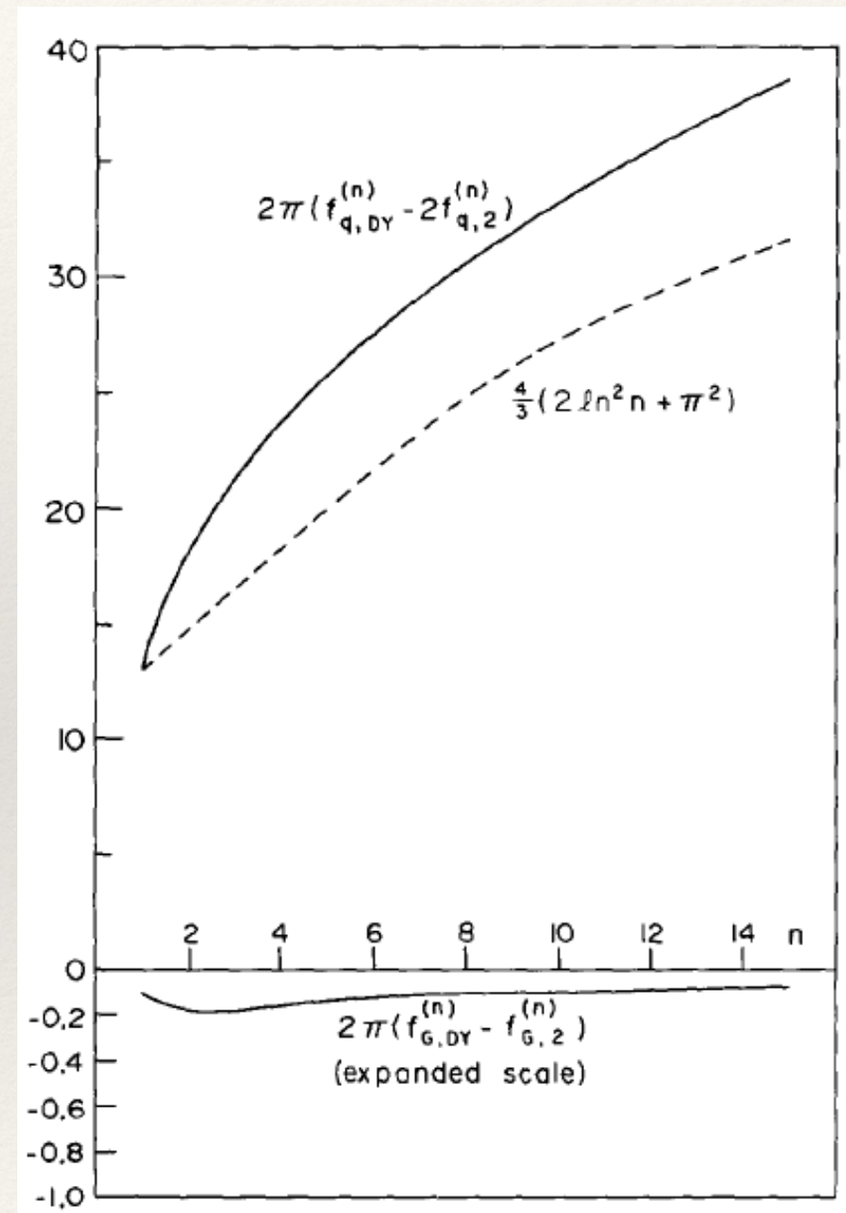


Altarelli,Ellis, Martinelli, NPB157 (1979) 461
NPB143 (1978) 521, NPB146(1978)544(E)

Corrections to Drell- Yan (the K-factor)

$$\alpha_s(f_{q,\mathrm{DY}} - 2f_{q,2})$$
$$= \frac{\alpha_s}{2\pi}\frac{4}{3}\left[\frac{3}{(1-z)_+} - 6 - 4z + 2(1+z^2)\left(\frac{\ln(1-z)}{1-z}\right)_+ + (1+\tfrac{4}{3}\pi^2)\,\delta(1-z)\right].$$

- Taking the notional value $\alpha_s/(2\pi)=1/20$ we see that the corrections are not small.
- Helpful in accommodating data.
- Since in a coloured quark theory a red quark can only annihilate with an anti-red quark suppression by 3.
- Feynman-Field recalculation at Caltech.



Experimental results from NA3

Table 2
$K = (d^2\sigma/dx_1 dx_2)_{exp}/(d^2\sigma/dx_1 dx_2)_{DY\ model}$

Reaction	pN	$\bar{p}N$	$\pi^- N$	$\pi^+ N$	$\pi^- H_2$	$(\pi^- - \pi^+)N$
K	2.2 ± 0.4	2.4 ± 0.5	2.2 ± 0.3	2.4 ± 0.4	2.4 ± 0.4	2.2 ± 0.4
Events	960	44	5607	2073	138	–

PL 89B 145 (1979)

- Experiments with various beams all showed that the cross-section was too large compared to the Drell-Yan formula, where the factor of 3 for colour averaging is now included.

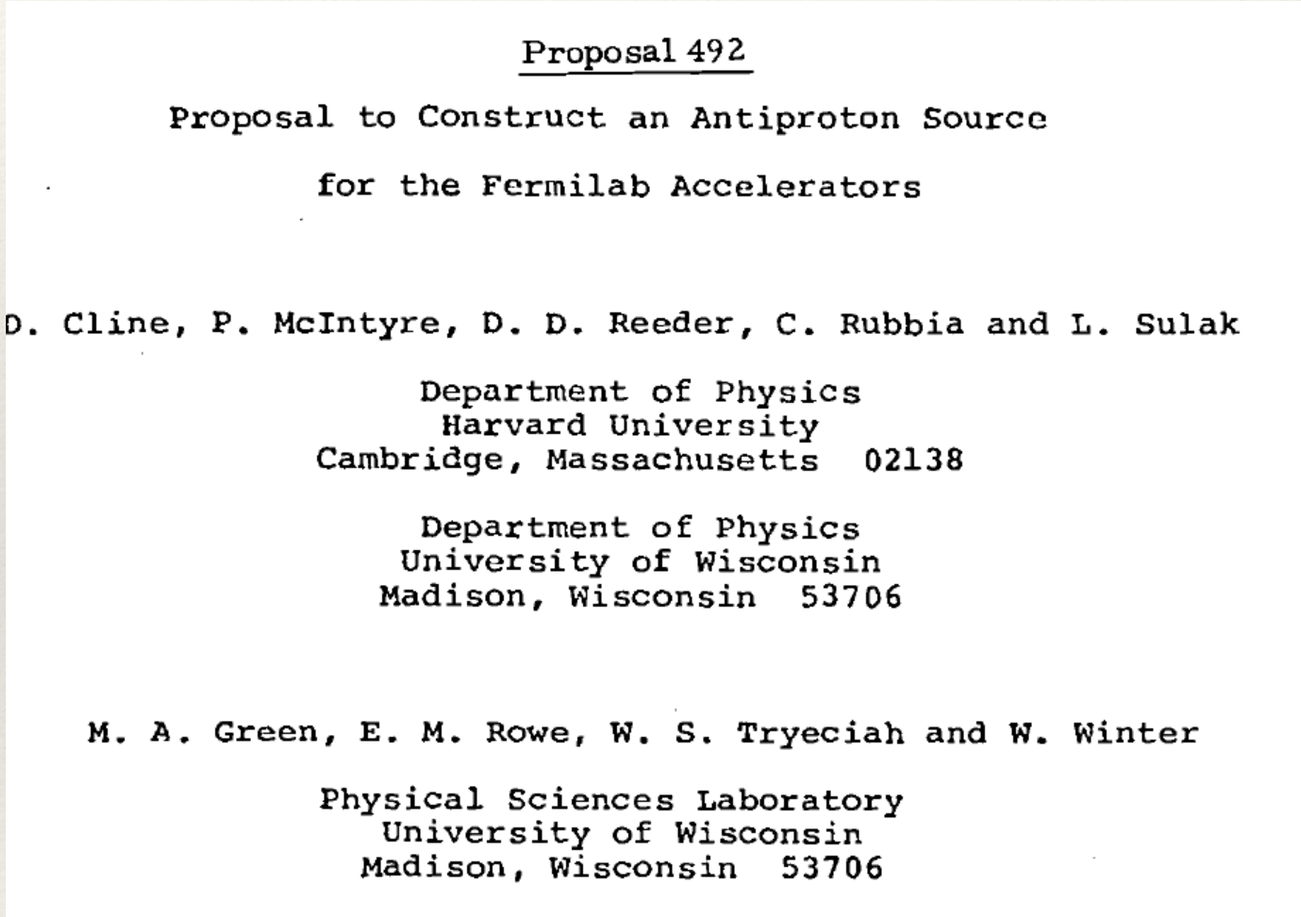
$$\frac{d\sigma^{DY}}{dQ^2} = \frac{4\pi\alpha^2}{9SQ^2}\int \frac{dx_1\, dx_2}{x_1 x_2}\left[\sum_f e_f^2 q_{0f}^{(1)}(x_1)\,\bar{q}_{0f}^{(2)}(x_2) + (1 \leftrightarrow 2)\right]\delta\left(1 - \frac{\tau}{x_1 x_2}\right)$$

- An early triumph for the application of perturbative QCD to hadron-hadron processes.

Discovery of the W and Z

- 1983 discovery of the W and the Z
- Consternation in the USA. Should the Rubbia proposal have been implemented in the main ring as outlined in proposal 492?
- Considered "wisdom" in the Fermilab cafeteria was that the right decision was taken.
- Because of the poor vacuum system and the magnets unable to operate DC at more than 200 GeV, it would have been at best ppbar at 400GeV and low luminosity.
- The Rome group (Altarelli, Ellis, Greco, Martinelli, Parisi, Petronzio) were well placed to respond to the discovery, because of our experience with Drell-Yan

Proposal May 1976



Proposal 492

Proposal to Construct an Antiproton Source for the Fermilab Accelerators

D. Cline, P. McIntyre, D. D. Reeder, C. Rubbia and L. Sulak

Department of Physics
Harvard University
Cambridge, Massachusetts 02138

Department of Physics
University of Wisconsin
Madison, Wisconsin 53706

M. A. Green, E. M. Rowe, W. S. Tryeciah and W. Winter

Physical Sciences Laboratory
University of Wisconsin
Madison, Wisconsin 53706

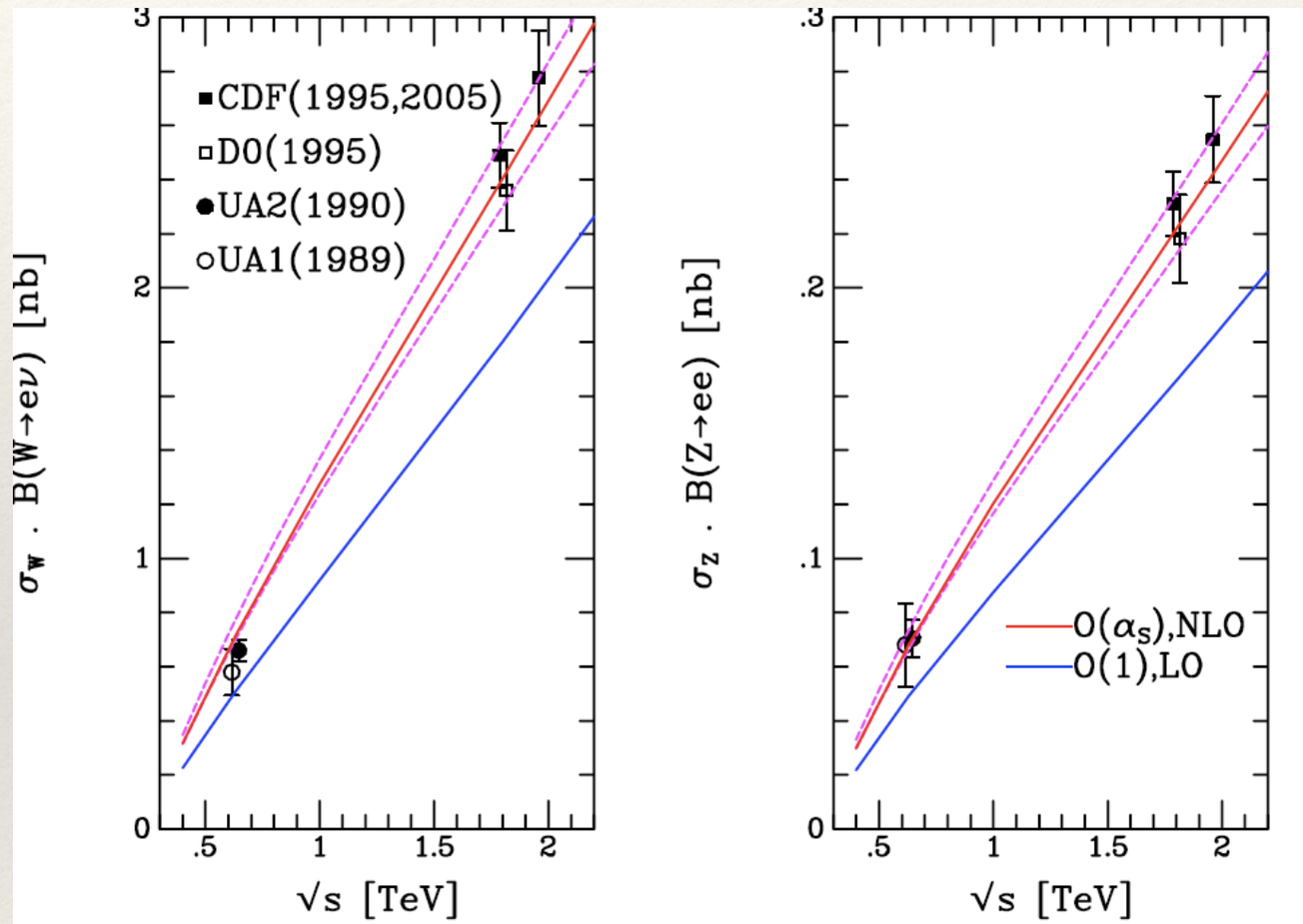
Drell-Yan type processes (γ^*,W,Z)

QCD provides a systematic way of improving the calculations of cross sections

$$\hat{\sigma}(z) = \delta(1-z) + \frac{\alpha_s}{2\pi} f_1(z) + \left(\frac{\alpha_s}{2\pi}\right)^2 f_2(z) + \ldots$$

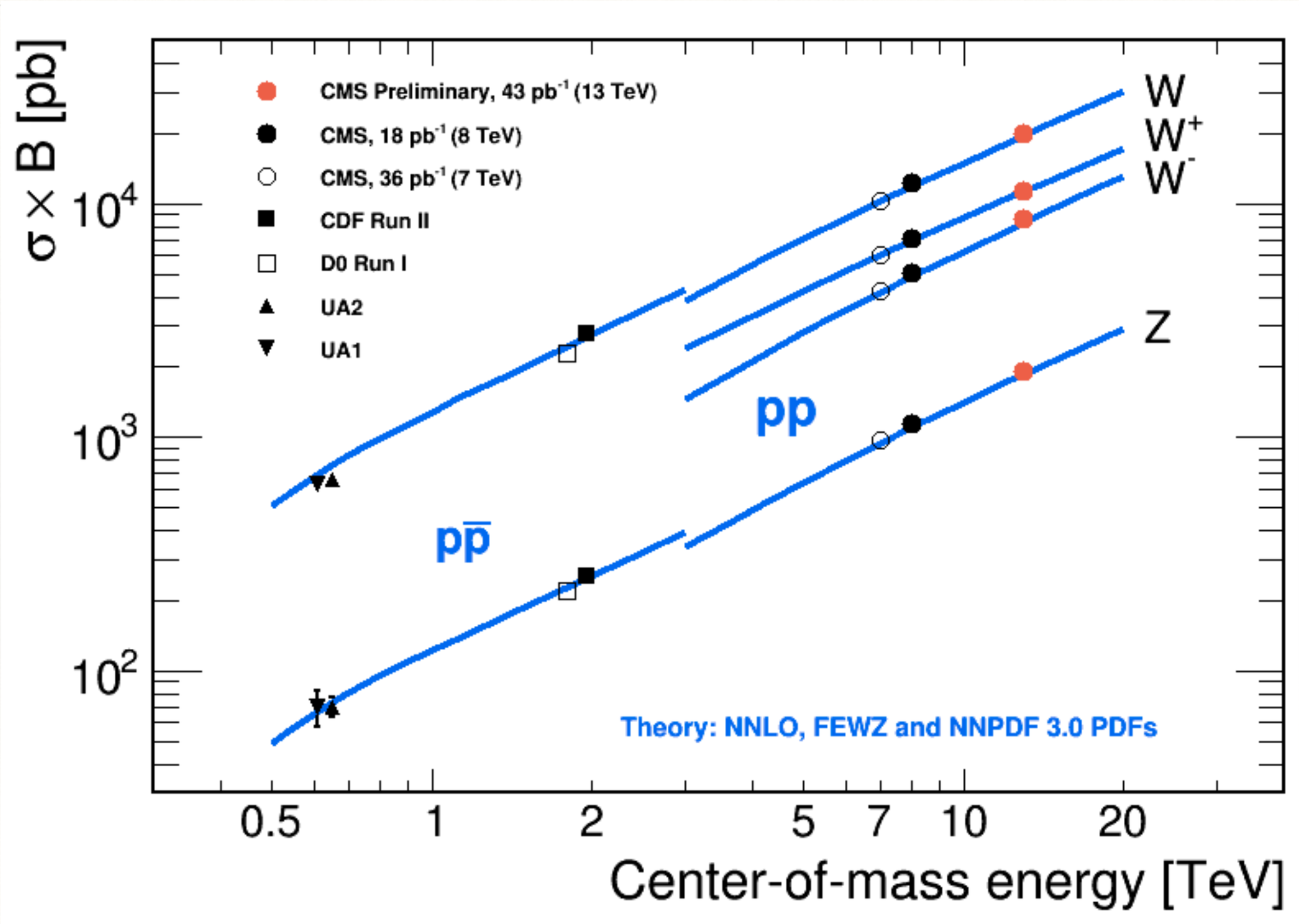
by expanding in the small coupling α_S. Corrections are large at $O(\alpha_S)$ but needed to needed to achieve agreement with data.

(α_S^2 corrections also known and lead to a further modest increase.)

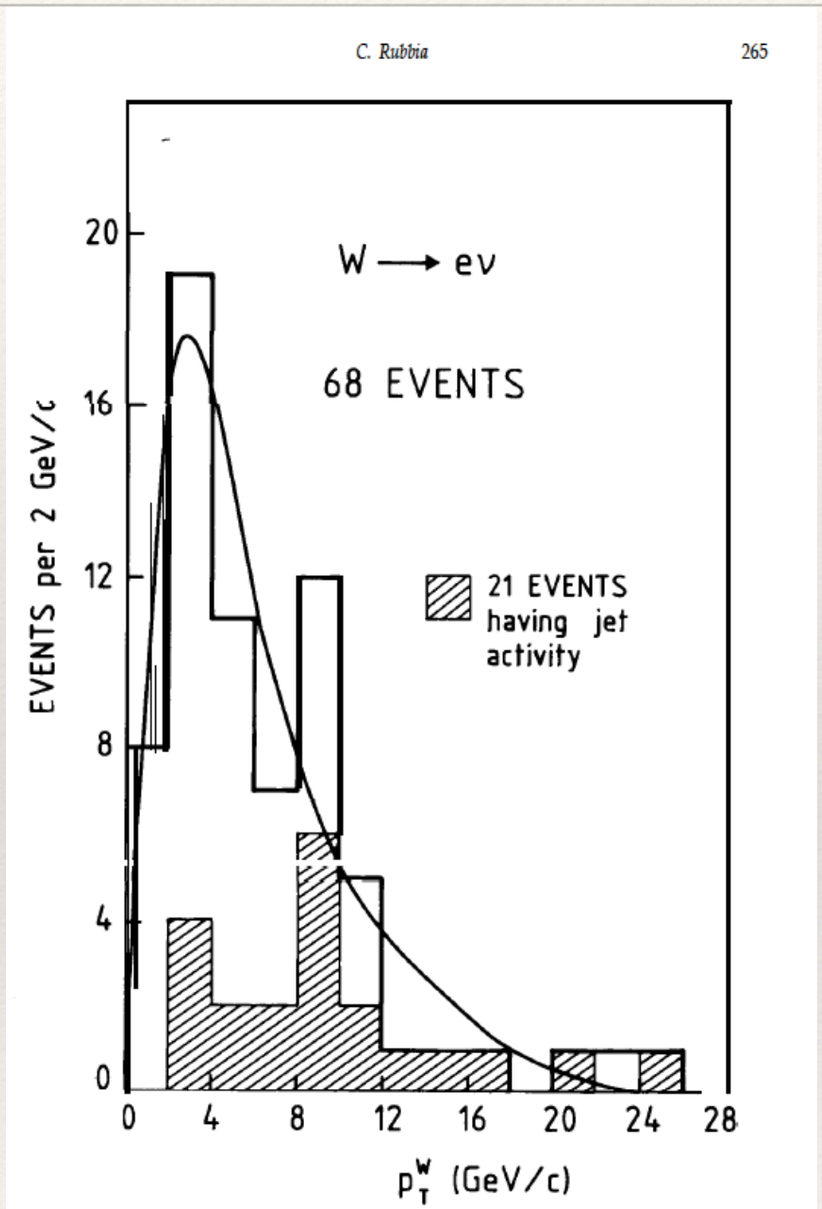


Moral: at least next-to-leading order (NLO) corrections are needed.

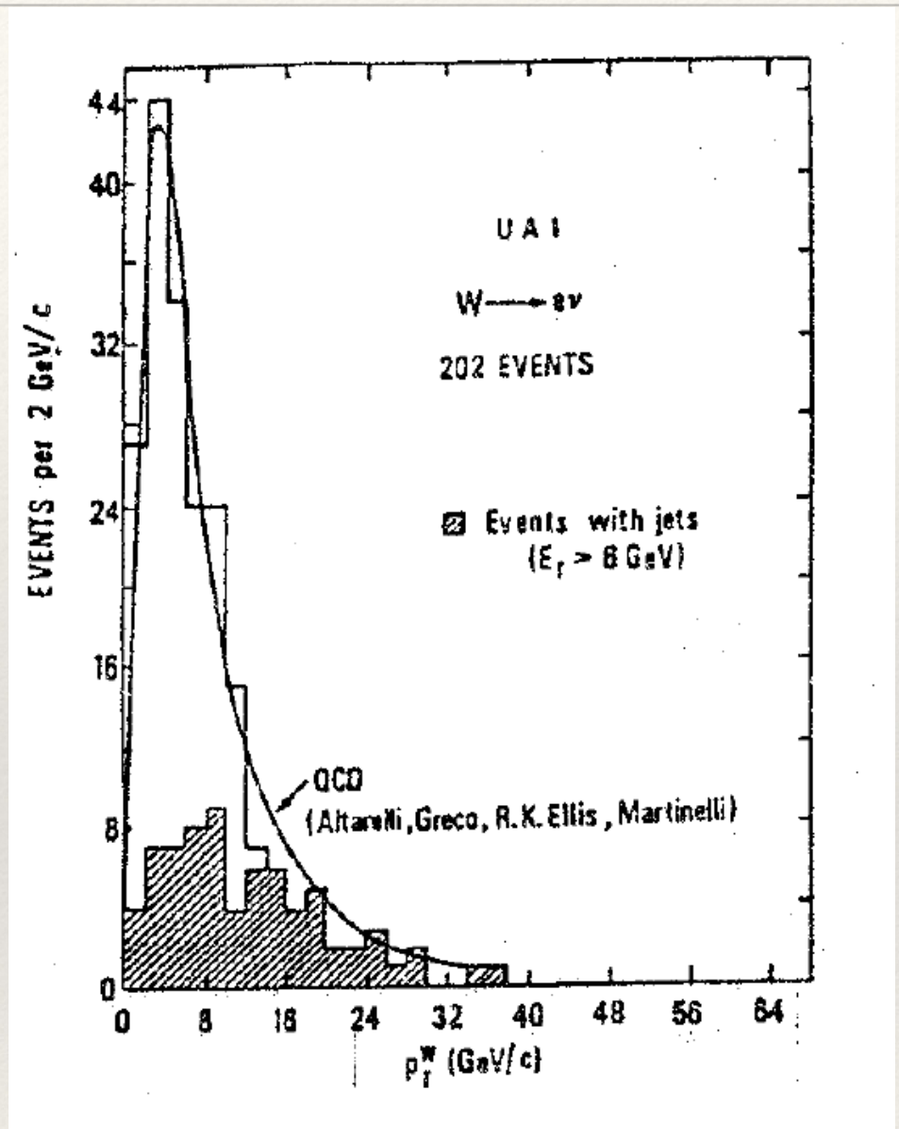
Results at 0.54→13 TeV



Early measured W-p_T distributions

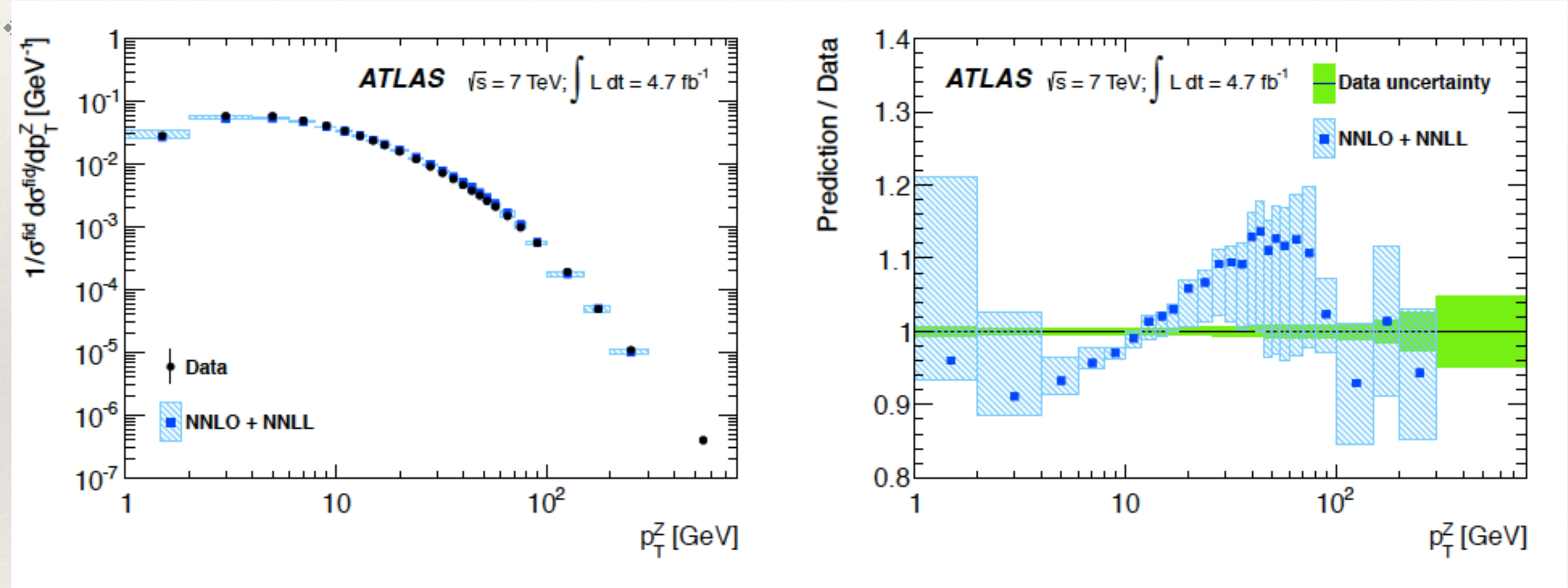


Curves from Altarelli et al in the Nobel Lecture of Carlo Rubbia, December 1984.



"Note that there are no adjustable parameters. Of course there are the same ambiguities on parton densities, on the value of Λ and on the choice of scale as for the total cross sections," (GA, October 1985)

Current results on Z pt



- This is the ATLAS result for Z production at √s=7 TeV compared to theory (Banfi, Dasgupta, Marzani, Tomlinson, 1205.4760)

Missing E_T events (Bern, 1984)

EXPERIMENTAL OBSERVATION OF EVENTS WITH LARGE MISSING TRANSVERSE ENERGY ACCOMPANIED BY A JET OR A PHOTON(S) IN $p\bar{p}$ COLLISIONS AT $\sqrt{s}$ = 540 GeV

UA1 Collaboration, CERN, Geneva, Switzerland

Presented by C. Rubbia, CERN

No written contribution received

Abstract from Physics Letters, 139B, 115 (1984)

We report the observation of five events in which a missing transverse energy larger than 40 GeV is associated with a narrow hadronic jet and of two similar events with a neutral electromagnetic cluster (either one or more closely spaced photons). We cannot find an explanation for such events in terms of backgrounds or within the expectations of the Standard Model.

Missing ET events (St Vincent, 1985)

UA1 UPDATE*

C. Rubbia

CERN, Geneva
SWITZERLAND

and

Harvard University
Cambridge, MA 02138
USA

* Lecture reproduced with copies of original transparencies.

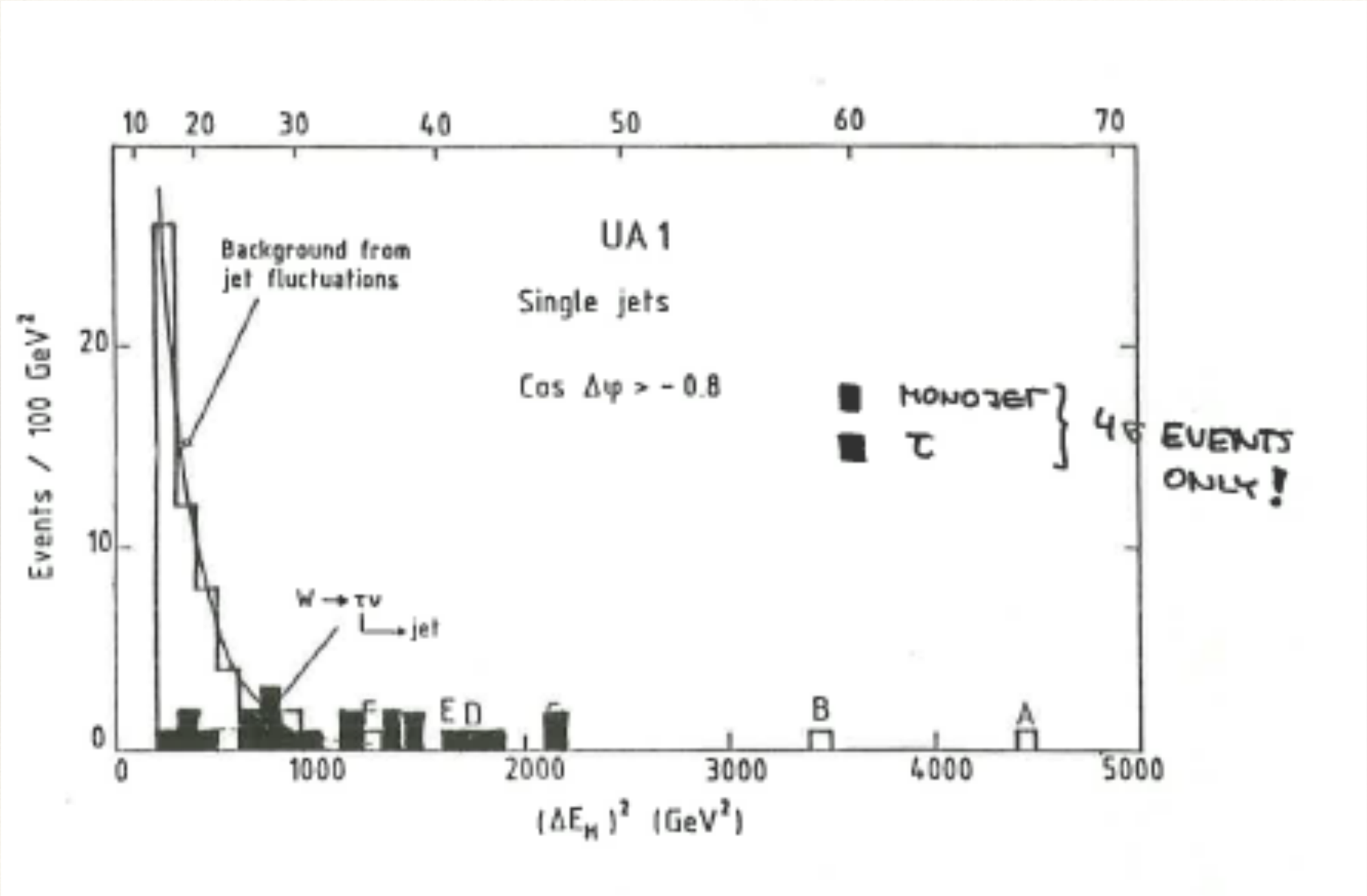
UA1 UPDATE

ON

- MISSING E_T EVENTS (*)
- SEARCHES FOR SUSY
- $W \to t\bar{b}$ DECAYS (*)

WARNING: THESE (*) ARE RAW DATA THEY SHOULD NOT BE USED IN FITS SINCE THERE IS (1) NO EFFICIENCY CORRECTION; (2) NO BACKGROUND(S) SUBTRACTIONS.

G. KANE ⇒ PLEASE TAKE NOTE !


UA 1
Single jets
Cos Δφ > - 0.8
Background from jet fluctuations
W → τν
jet
monojet
τ
4τ EVENTS ONLY!
Events / 100 GeV²
(ΔE_H)² (GeV²)
0
10
20
30
40
50
60
70
1000
2000
3000
4000
5000
A
B
C
D
E
F

The Altarelli cocktail

- The calculation of the splitting functions rapidly gave rise to shower Monte Carlos
- Importantly, without matrix element corrections, these give a good description of collinear emission, but seriously underestimate events at large p_T
- This was probably originally responsible for the underestimate of standard model backgrounds for mono jets.
- Eventually explained by Guido as a "cocktail" of Z(→ν ν)+jet events, misidentified electron, cracks, jet fluctuations,W->tau ν events….at St. Vincent.

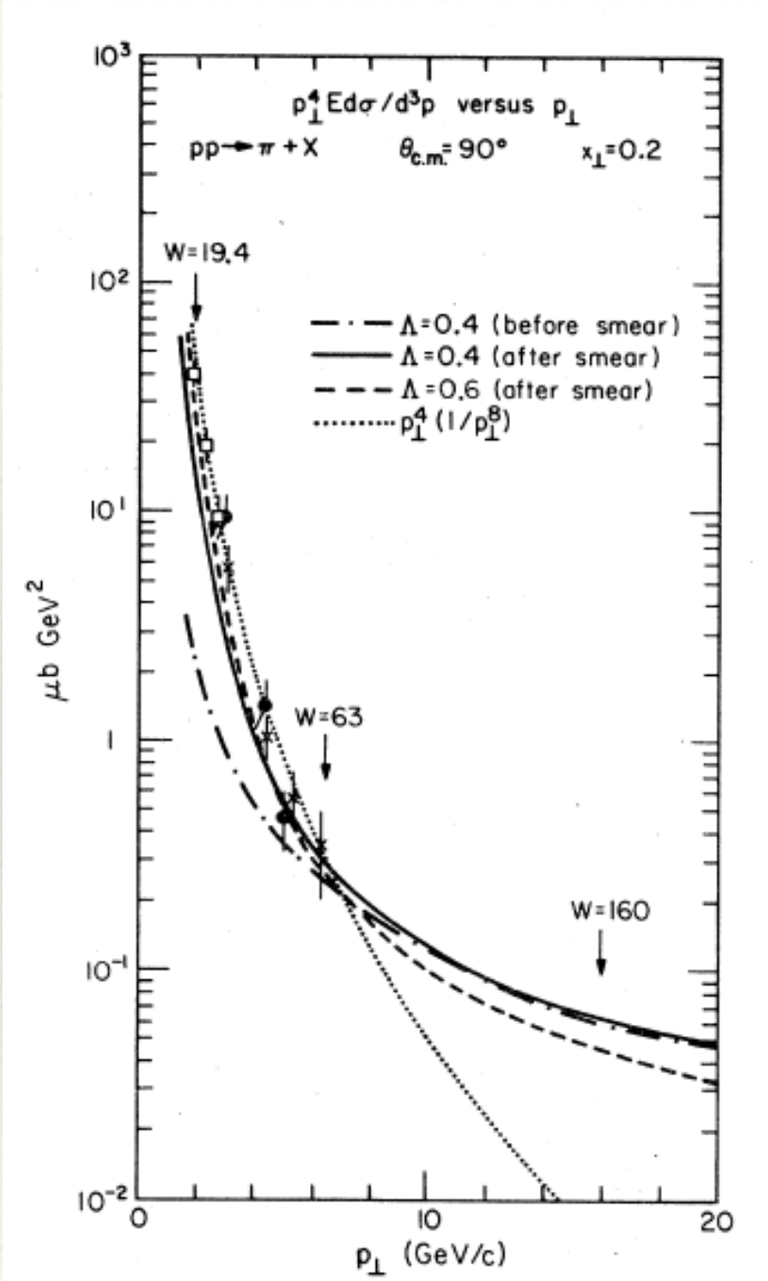
QCD-the candidate theory

"Although QCD imposes itself as the only theory of strong interactions within reach of the weapons of conventional quantum field theory, yet it is still the least established sector of the standard model. Testing QCD is, in fact, more difficult than testing the electroweak sector. In the latter domain the theory is more explicit because perturbation theory can always be applied. Besides that, the leptons and the weak gauge bosons are at the same time the fields in the Lagrangian and the particles in our detectors. On the other hand, QCD is the theory of quarks and gluons while only hadrons are observable; also, perturbation theory can only be applied in that particular domain of the strong interactions where approximate freedom, which is only asymptotic, can be reached."

G. Altarelli Erice 1983.

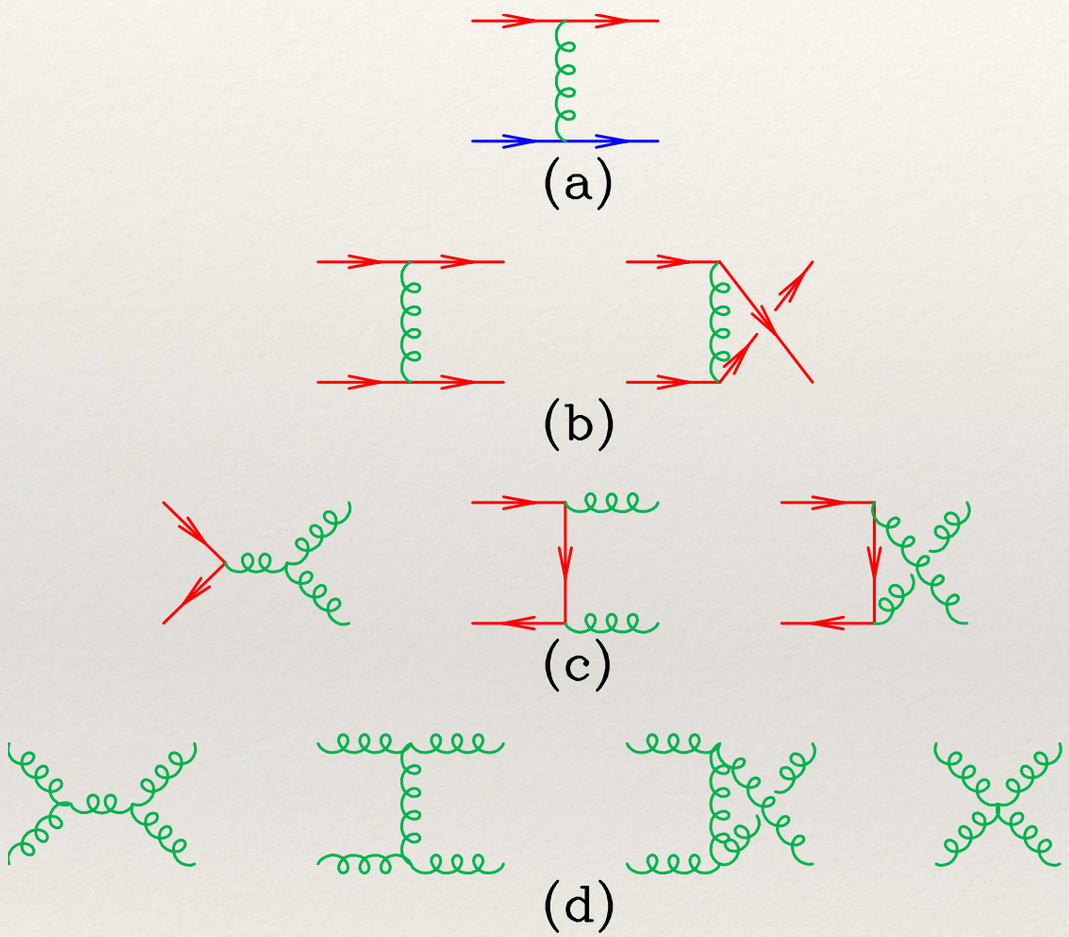
Jets studies (pre-)QCD

- Before jet studies at the SppS collider it was hard to distinguish the QCD, with a transverse momentum smearing from a phenomenological model, falling like $1/p_T^8$



Feynman, Field, Fox PRD18 (1978) 3320

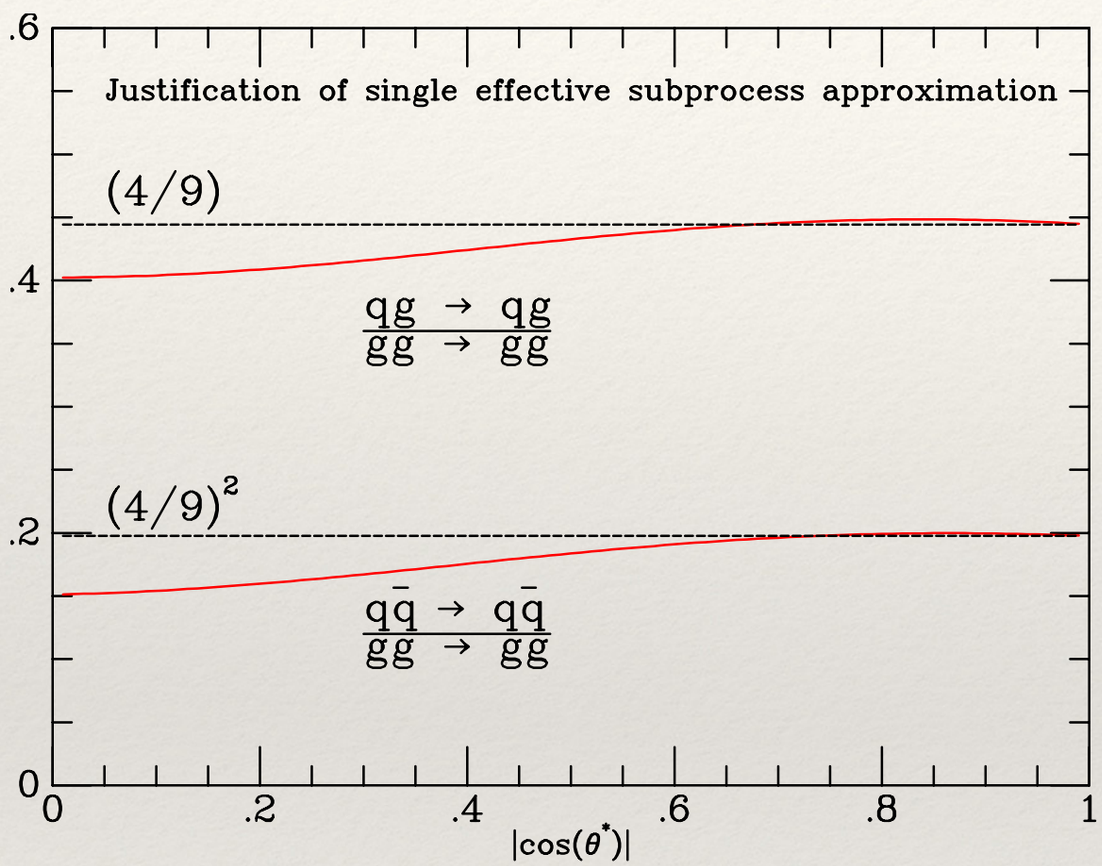
Parton cross sections



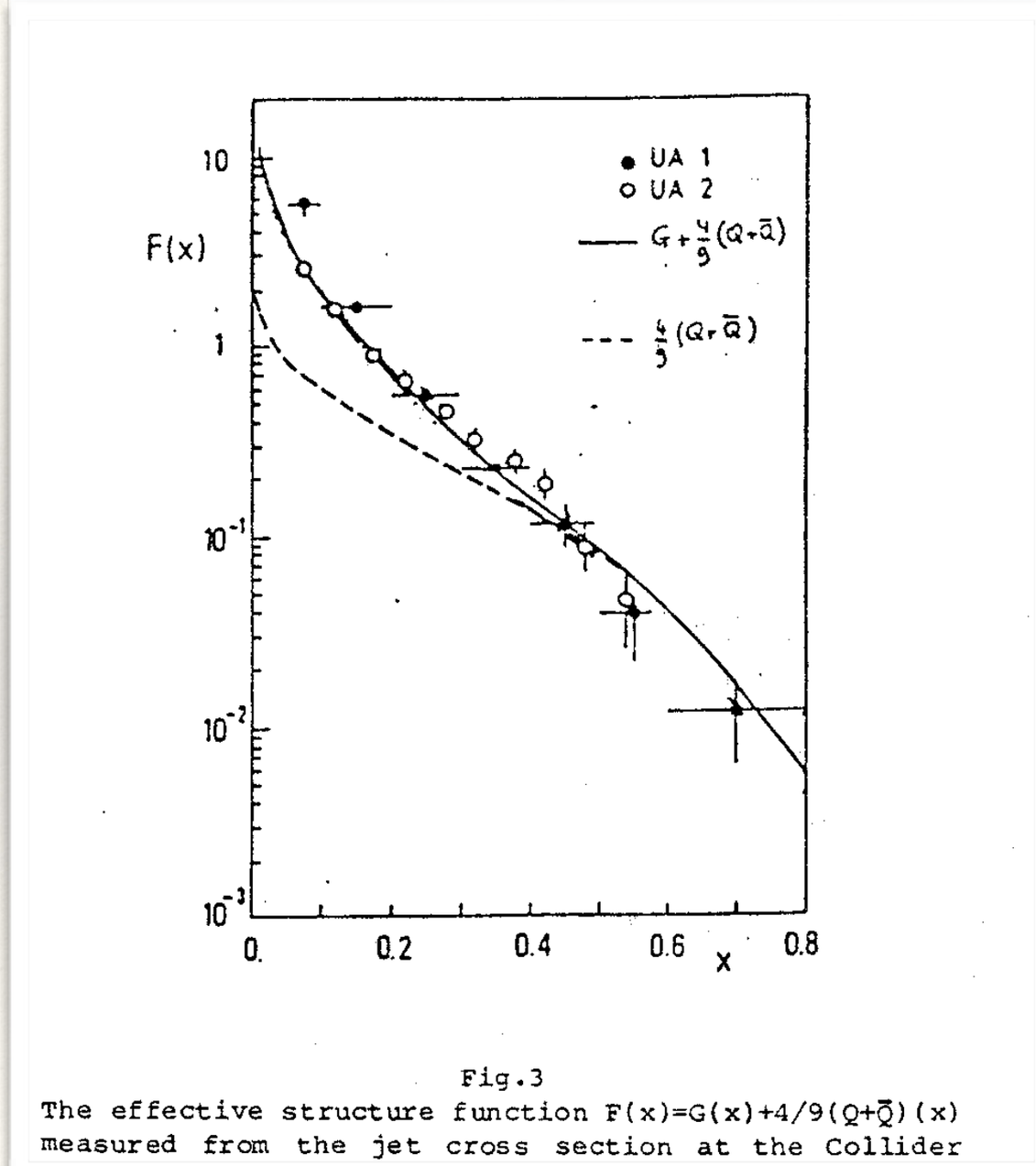
Process	$\overline{\sum}\lvert\mathcal{M}\rvert^2/g^4$	$\theta^* = \pi/2$
$q\,q' \to q\,q'$	$\frac{4}{9}\,\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}$	2.22
$q\,\overline{q}' \to q\,\overline{q}'$	$\frac{4}{9}\,\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}$	2.22
$q\,q \to q\,q$	$\frac{4}{9}\,(\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}+\frac{\hat{s}^2+\hat{t}^2}{\hat{u}^2})-\frac{8}{27}\,\frac{\hat{s}^2}{\hat{u}\hat{t}}$	3.26
$q\,\overline{q} \to q'\,\overline{q}'$	$\frac{4}{9}\,\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}$	0.22
$q\,\overline{q} \to q\,\overline{q}$	$\frac{4}{9}\,(\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}+\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2})-\frac{8}{27}\,\frac{\hat{u}^2}{\hat{s}\hat{t}}$	2.59
$q\,\overline{q} \to g\,g$	$\frac{32}{27}\,\frac{\hat{t}^2+\hat{u}^2}{\hat{t}\hat{u}}-\frac{8}{3}\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}$	1.04
$g\,g \to q\,\overline{q}$	$\frac{1}{6}\,\frac{\hat{t}^2+\hat{u}^2}{\hat{t}\hat{u}}-\frac{3}{8}\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}$	0.15
$g\,q \to g\,q$	$-\frac{4}{9}\,\frac{\hat{s}^2+\hat{u}^2}{\hat{s}\hat{u}}+\frac{\hat{u}^2+\hat{s}^2}{\hat{t}^2}$	6.11
$g\,g \to g\,g$	$\frac{9}{2}\,(3-\frac{\hat{t}\hat{u}}{\hat{s}^2}-\frac{\hat{s}\hat{u}}{\hat{t}^2}-\frac{\hat{s}\hat{t}}{\hat{u}^2})$	30.4

- First calculated correctly by Combridge, Kripfganz, Ranft, CERN-TH-2343 , 1977

Identifying the gluon component of the proton



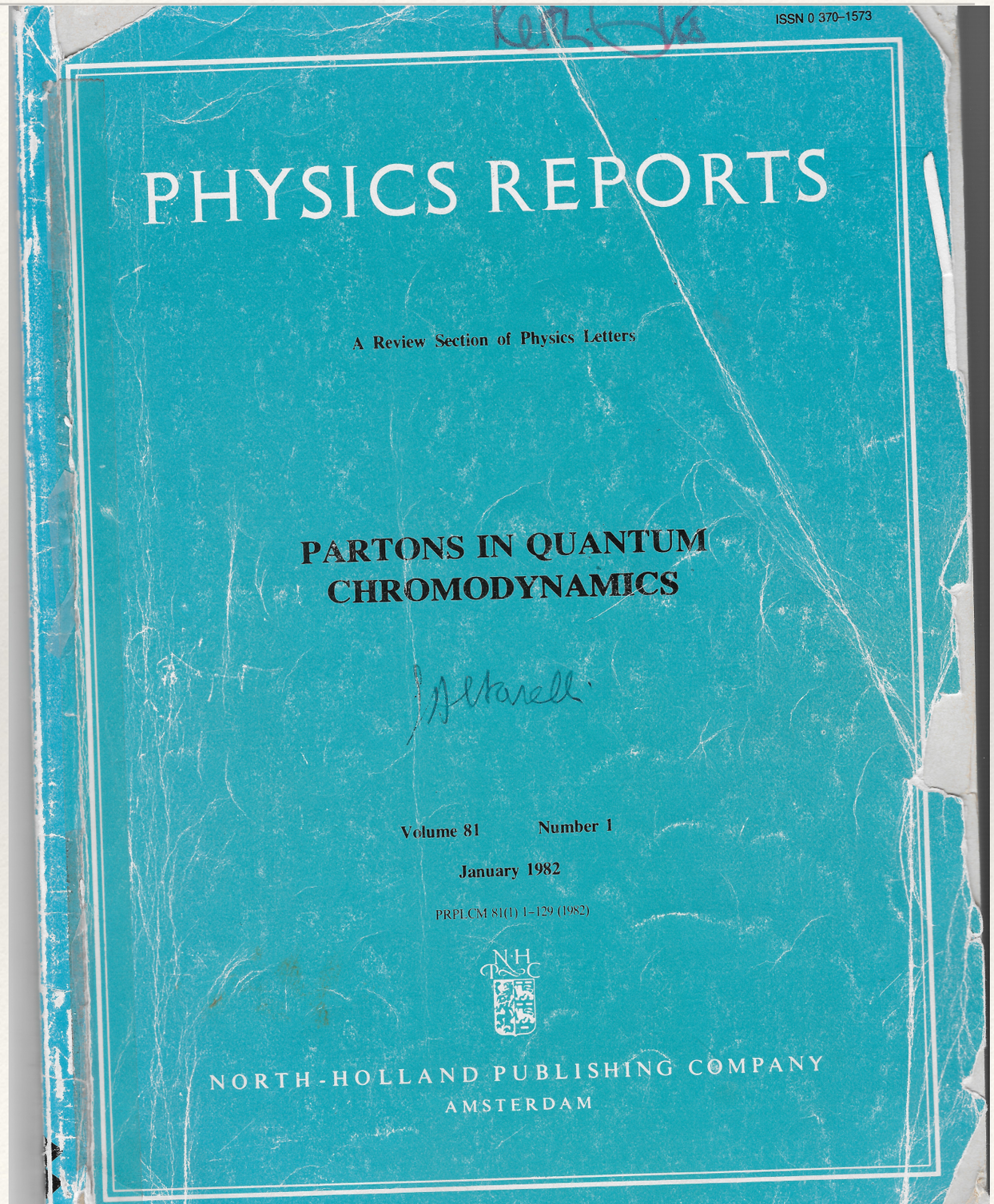
- Extraction of the single effective structure function showed the necessity of gluons at small x.



G. Altarelli EPS Talk Bari 1985

Partons in Quantum Chromodynamics

- The definitive text for the 80-90's on QCD.
- As you can see my copy is much used (and abused).
- Written, for the most part, in the library at CERN as a visitor (1982).
- By an unacknowledged author!



Language

- As well as my thesis advisor, Guido was my also my Italian language (Roman dialect) instructor.
- Royal Society
- “the normal Evolution Equation”
- Il senso del gioco

Radiative Corrections to $e^+e^- \to \mu^+\mu^-$ near a Narrow Vector Resonance.

G. Altarelli, R. K. Ellis (*) and R. Petronzio

Istituto di Fisica dell'Università - Roma
Istituto Nazionale di Fisica Nucleare - Sezione di Roma

(ricevuto il 2 Maggio 1975)

In this note we evaluate the forward-backward asymmetry in $e^+e^- \to \mu^+\mu^-$ in the vicinity of a narrow resonance such as the recently discovered ([1]) $\psi(3100)$ or the $\psi'(3700)$. Since we assume that the ψ and ψ' are pure $J^P = 1^-$ states, this asymmetry is due to radiative corrections. We consider only the case of nonpolarized beams. Although it is likely that the ψ and ψ' are coupled to leptons via the photon, it is entirely equivalent for our purposes to assume an effective universal vector coupling of the form $gR^\mu(\bar{e}\gamma_\mu e + \bar{\mu}\gamma_\mu\mu)$ with $g^2/4\pi = \tilde{\alpha}$ for ψ and $\tilde{\alpha}'$ for ψ'. The computation of the cross-section to order α^3 in pure quantum electrodynamics has been presented in ref. ([2,3]). Near a narrow resonance terms proportional to $\tilde{\alpha}$ can become comparable or larger than terms of order α. We therefore calculate the cross-section to third order in both α and $\tilde{\alpha}$. The diagrams which give significant contributions are shown in Fig. 1. In view

(*) Royal Society European Exchange Fellow.

Letters

- Estimation of Cabibbo and Letter from Cabibbo
- My thesis was supervised by Guido and Luciano Maiani

  "To this last paper also contributed Keith Ellis, a Scottish PhD student of Cabibbo, who was to stay with us in Rome for a few years, eventually speaking a very good Italian and fully understanding the roman way of living." GA 1106.3189
- I had a very prolonged post-doc career (six post-docs!); at every stage Guido wrote letters of recommendation for me.
- So it was a great pleasure to return the favour, in supporting his nomination for the Sakurai Prize, (although I had the impression that the tail was wagging the dog).

Fermilab

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Fax 630-840-5435

Joseph Lykken,
Chair, 2011 Sakurai Prize Committee
MS 106
Fermilab
Batavia, IL 60510

Dear Joe,

It is a great pleasure to support the nomination of Guido Altarelli for the Sakurai Prize. Guido has been an influential and authoritative figure in our field from the invention of the Standard model in the early seventies until the present day.

Although the jewel in the crown of his production is the Altarelli-Parisi (AP) equation, it is my opinion that his achievements over the years would merit the award of the Sakurai prize, even if the AP paper had never been written.

I am referring in particular to his work transverse momentum distributions in Drell-Yan processes, a key element of distinction between the parton model and QCD; to his work on higher order corrections to the Drell Yan process (where I was a co-author) that calculated the first K factor; to his work on the small x evolution of the structure functions that emphasizes the tempering role that momentum conservation has on the growth of parton distributions at small x. I am also referring to his work on the interpetation of precision electroweak data from LEP, that provides important constraints on physics beyond the standard model. I am referring to his work on the Delta I = 1/2 rule, showing that hard QCD effects were responsible for part of the enhancement. Also noteworthy is his work on neutrino mixing based on the flavor group A_4, that provides an appealing explanation for the tri-bimaximal structure of the neutrino mixing matrix. The tri-bimaximal structure provides a convenient lowest order prediction for the observed structure of the neutrino mixing matrix. Lastly, I am referring to his work on the polarized structure function, suggesting that a sizeable fraction of the spin of the proton is carried by the gluons. Although Nature appears not to have availed herself of this possibility it remains an extremely elegant solution.

Guido's work on the Altarelli-Parisi equation was tremendously influential; the new result of that paper was the calculation of splitting functions for polarized targets. But much more importantly the work of Altarelli and Parisi gave a physical picture, which allowed the union of the parton model with QCD. Prior to the appearance work of AP the treatment of deep inelastic scattering was done using the operator product expansion and the renormalization group. However, at the time there was little understanding of the classes of diagrams

- Students
  - Keith Ellis
  - Guido Martinelli (Parisi)
  - Barbara Mele
  - Marco Ciuchini
  - Roberto Franceschini
  - Emilio Gabrielli
  - Sandro Ambrosiano
  - +many younger collaborators

that were summed by the renormalization group, or of the importance of a physical gauge to simplify the QCD treatment. The simple physical picture of the AP paper begged the question of the extension to other processes such as Drell-Yan that ultimately led to proofs of factorization.

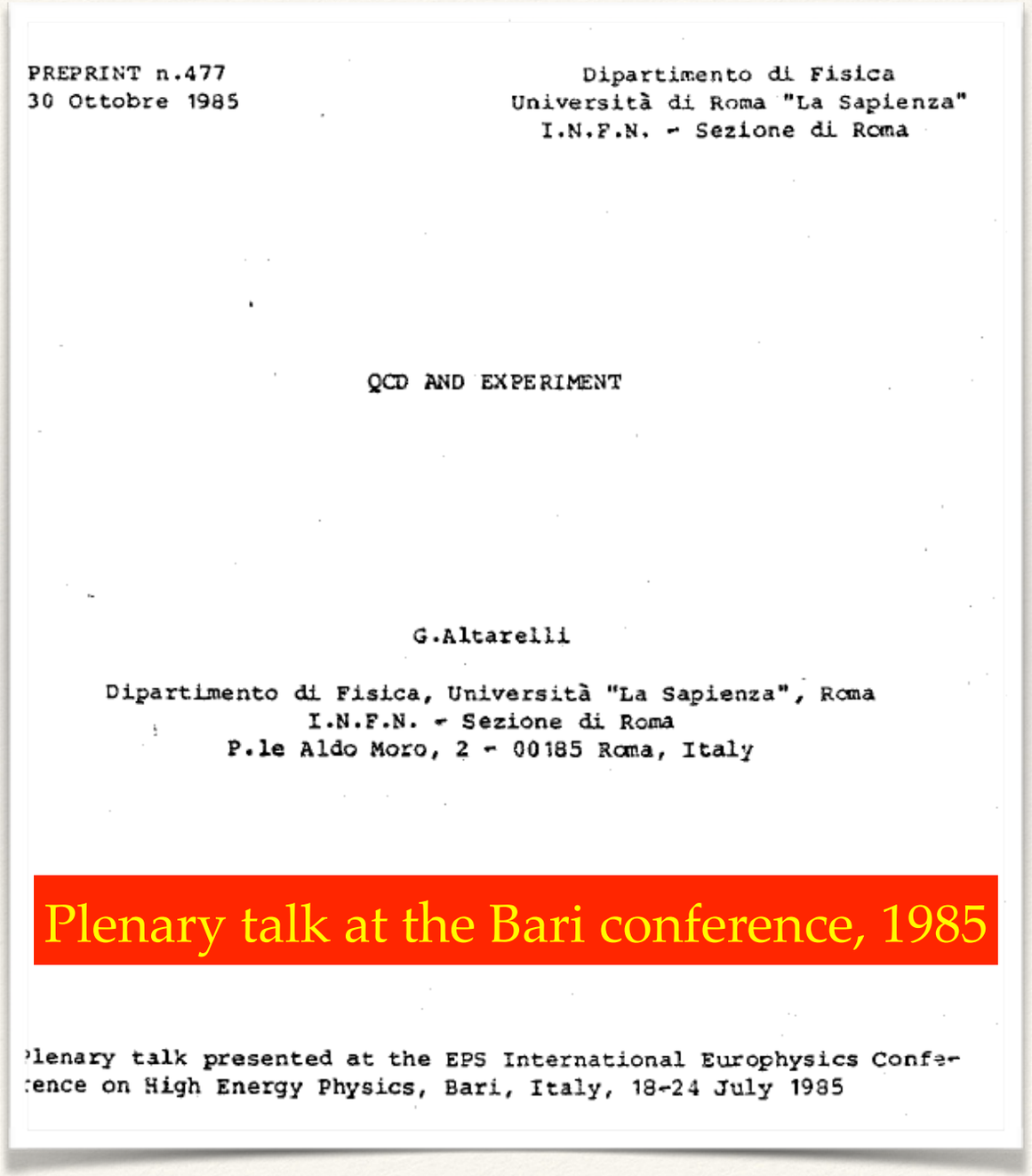
I believe that his intensely physical approach, communicated through his papers, and perhaps more importantly through his influence on students and junior collaborators, has had a profound effect on our field. I am happy to recommend the award of the Sakurai prize without reservation.

Yours sincerely,

R. Keith Ellis

In conclusion…..

- The last word, on this glorious period (1973-1985), should go to Guido.
- "The beautiful 'naive' parton model of Bjorken, Feynman and others has by now evolved into the 'QCD improved' parton model. This powerful language has become such a familiar and and widespread tool for everyday practice in high energy physics that one is led to take all its new successes as granted and in a way obvious."



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QCD AND EXPERIMENT

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Plenary talk at the Bari conference, 1985

Plenary talk presented at the EPS International Europhysics Conference on High Energy Physics, Bari, Italy, 18-24 July 1985