Kunsztwerk und Wissenschaft*

Keith Ellis
Fermilab

* Art and Science of Zoltan Kunszt

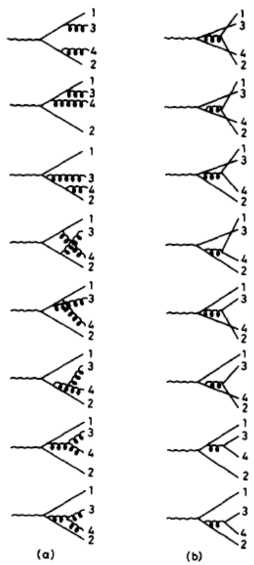
Colloquium in honour of the retirement of Zoltan Kunszt

In the beginning....

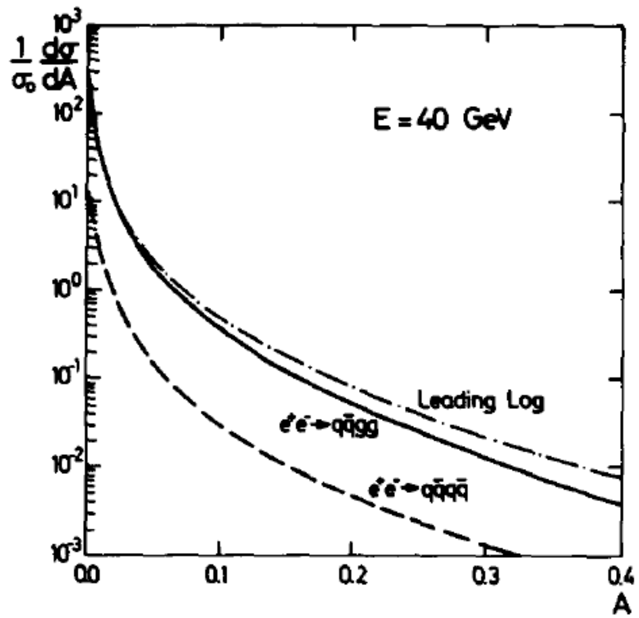
- I met Zoltan in 1979 when he visited Caltech
- Later in June 1980 I met him again at DESY
- This was the beginning of a professional relationship and friendship which has spanned three decades.

Jets

- 1978-1979 was a period of intense activity at the e^+e^- colliders, DORIS and PETRA.
- Establish the quark and gluon degrees of freedom. If there were three jet events, then there should also be four jet events....
- Ali et al, provided a tree graph calculation of $e^+e^- \rightarrow$ qqgg and qqqq
- Shown is the prediction for the Acoplanarity, showing that the branching into gluons pairs is much more copious than in to quark pairs.



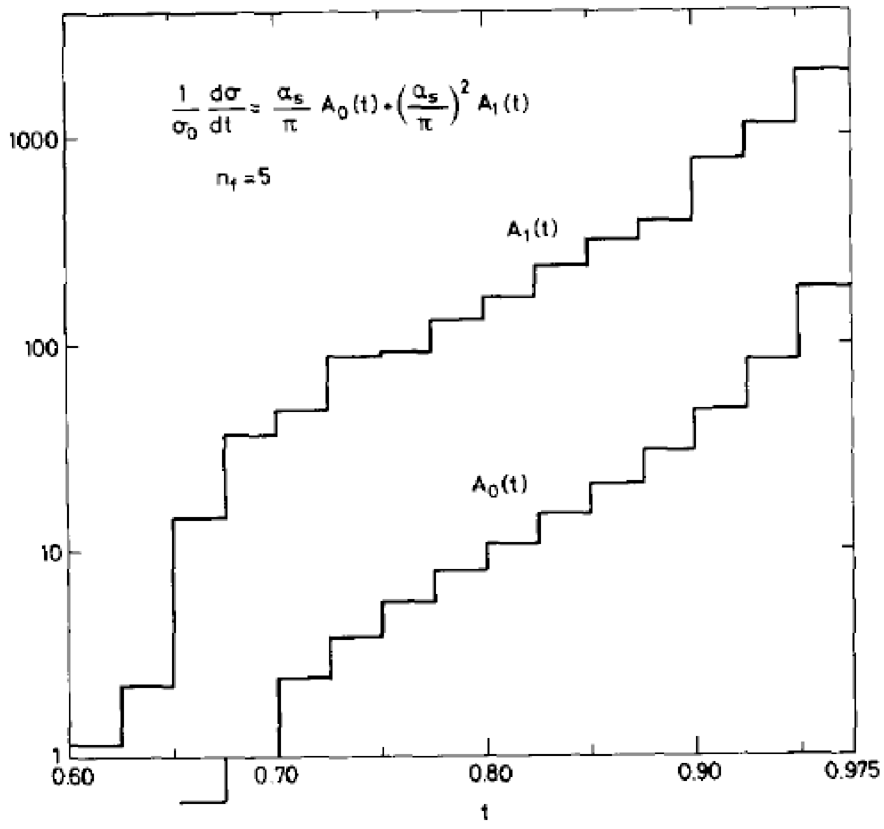
A. Ali et al. / QCD predictions



[1] On leave from L. Eötvös University, Budapest.

Thrust distribution in e^+e^-

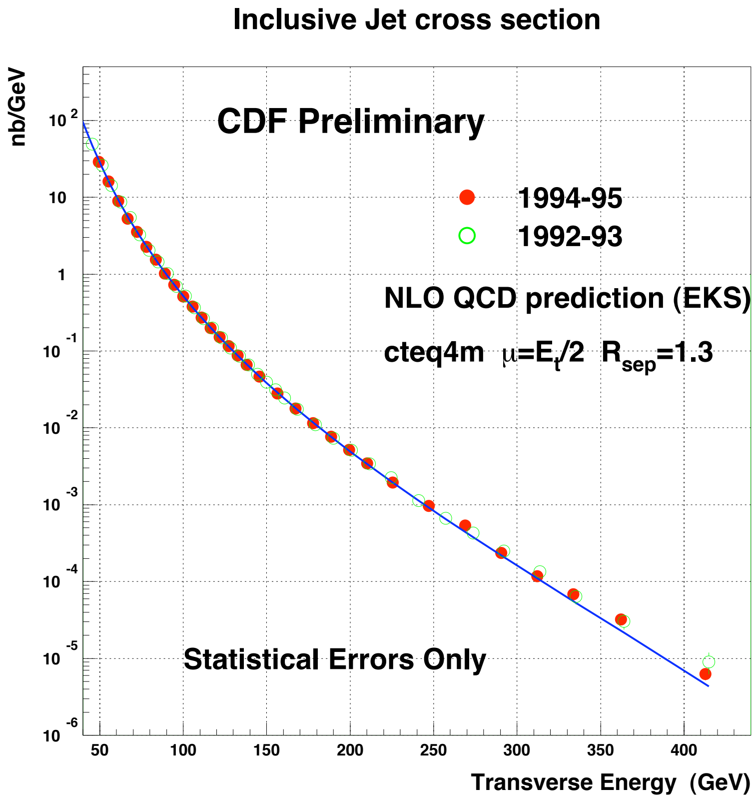
- Use the precision jet data at colliders to make QCD measurements, eg α_s.
- In June 1980 Ross, Terrano and I finished our NLO calculation of the C parameter in e^+e^- annihilation.
- Zoltan was the first to calculate the NLO thrust distribution in e^+e^- and it confirmed that the corrections were large.



ZK PL107B, 1981

Jets in hadron-hadron collisions

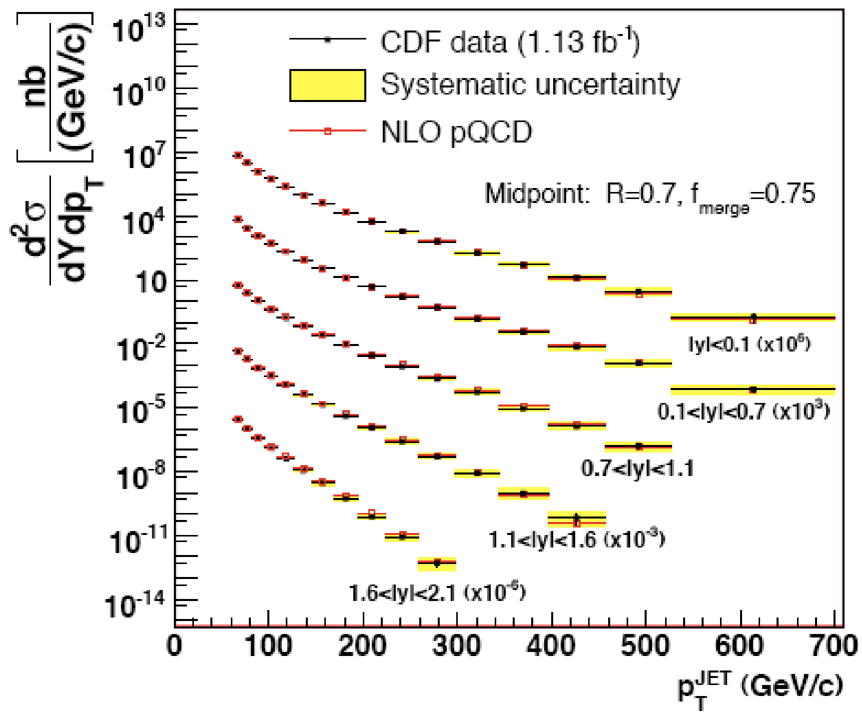
- (Steve)Ellis, ZK and Soper took results from RKE & Sexton and came up with a way to make NLO predictions for a physical jet cross section.



EKS Phys.Rev.Lett 62:726,1989

Jet physics 2009

- In the intervening 20 years, jet physics has become more sophisticated.
- No longer compared with the EKS code, instead it is compared with the NLO++ code of Zoltan Nagy.



Predictions for Physics at LEP

Cern yellow report 1989

- A comprehensive treatment. Laid out the full program of QCD measurements at LEP.
- The beginning of NLO parton integrators.
- NLO predictions for Thrust, oblateness, C-parameter and energy-energy correlation.
- Would certainly have 1000's of citations if it had been published.

QCD

Conveners: Z. Kunszt and P. Nason

Working Group: G. Marchesini and B.R. Webber

I. Introduction

II. The running coupling constant

III. The total hadronic width

IV. Three jet like quantities
(1) Thrust as an illustration. (2) Oblateness. (3) The C parameter. (4) Energy-energy correlation. (5) Heavy jet mass. (6) Jet clusters. (7) Calorimetric jet definition.

V. Multijet effects

VI. Sensitivity of infrared finite quantities to parton showering and hadronization

VII. Infrared sensitive quantities and coherence
(1) Multiplicity. (2) Small relative momenta (small x). (3) Heavy and light quark jet shapes.

VIII. Conclusions

Next-to-leading Monte Carlo

- Generically all radiative corrections can be considered as a plus distribution.
- Realization that NLO correction formula could be included in a Monte Carlo as event and counter-event.

event

$$\int_0^1 dx \frac{f(x)}{(1-x)_+} = \int_0^1 dx \frac{f(x) - f(1)}{(1-x)}$$

counterevent

Frixione, Kunszt, Signer

FKS subtraction

- Development of experience with Soper and Frixione, MNR experience with NLO Heavy quarks.
- Introduce a set of FKS pairs P_{FKS} which induce soft or collinear in the n+1 dimensional matrix elements.
- Partition the phase space so that in each partition at most one soft and one collinear singularity are present.
- Introduce S_{ij}, a positive definite partition function, such that each term only contains singularities for i || j or i soft.

$$\mathcal{M}^{(n+1,0)}(r) = \sum_{(i,j)\in\mathcal{P}_{\rm FKS}} \mathcal{S}_{ij}(r)\mathcal{M}^{(n+1,0)}(r)\,.$$

Method of choice for POWHEG (Nason) and MadFKS (Frederix)

CS subtraction

- Partial fractioning of eikonal expression to associate soft singularities with a particular emitter. Subtraction valid throughout phase space.
- Exact factorization of n+1 dimensional phase space

$$\frac{p_i \cdot p_j}{p_i \cdot k \, p_j \cdot k} = \frac{p_i \cdot p_j}{p_i \cdot k + p_j \cdot k} \, \frac{1}{p_i \cdot k} + \frac{p_i \cdot p_j}{p_i \cdot k + p_j \cdot k} \, \frac{1}{p_j \cdot k}$$

Spinor techniques

- Modern version of spinor techniques began with PL 103B, 1981 CALKUL collaboration.

$$\not\epsilon^{\pm}(k) = \frac{N}{2\sqrt{2}}\Big[\not k \not q_- \not q_+ (1 \pm \gamma_5) - \not k \not q_- \not q_+ \not k (1 \mp \gamma_5)\Big]$$

$$N = \Big[2(q_+ \cdot q_-)\,(k \cdot q_-)\,(k \cdot q_+)\Big]^{-\frac{1}{2}}$$

- Making a particular choice of phase, dependence on the second gauge vector drops out. Xu, Zhang and Chang, preprint TUTP-84/3. Not published until NPB 291, 392 (1987)!

$$\not\epsilon^{\pm}(k) = \sqrt{2}\Big[|k_\mp\rangle\langle q_\mp| + |q_\pm\rangle\langle k_\pm|\Big]/\langle q_\mp|k_\pm\rangle$$

- Useful because the spinor products make manifest the square root singularities of QCD.

Applications to six jet processes

- In a series papers with Jack Gunion, explicit expressions for qqqqqq and ggqqqq processes were presented.
- Using the supersymmetry trick of Grisaru, Pendleton and van Nieuwenhuizen (1977) 6g processes were related to processes with 4g and 2 gluinos

$$A^{6g}(1_g^+,2_g^+,3_g^+,4_g^-,5_g^-,6_g^+) = -\frac{\langle 45\rangle}{\langle 46\rangle} A^{4g2\tilde{g}}(1_g^+,2_g^+,3_g^+,4_{\tilde{g}}^-,5_{\tilde{g}}^+,6_g^+)$$

↑ ↑
g̃

"In this way we have avoided the direct calculation of 220 Feynman diagrams"

ZK, NPB271, 1986 , (see also Parke & Taylor)

And on to MHV...

$$A^{4g}(1_g^-, 2_g^-, 3_g^+, 4_g^+) = \frac{\langle 12\rangle^4}{\langle 12\rangle\langle 23\rangle\langle 34\rangle\langle 41\rangle}$$

$$A^{5g}(1_g^-, 2_g^-, 3_g^+, 4_g^+, 5_g^+) = \frac{\langle 12\rangle^4}{\langle 12\rangle\langle 23\rangle\langle 34\rangle\langle 45\rangle\langle 51\rangle}$$

$$A^{6g}(1_g^-, 2_g^-, 3_g^+, 4_g^+, 5_g^+, 6_g^+) = \frac{\langle 12\rangle^4}{\langle 12\rangle\langle 23\rangle\langle 34\rangle\langle 45\rangle\langle 56\rangle\langle 61\rangle}$$

With confirmed numerical results in hand, Parke and Taylor conjectured that this pattern would hold for all n

Arsenal of tools for tree amplitude

- Helicity methods, spinor products
- Supersymmetry
- Colour stripped amplitudes (Chan-Paton)
- Recursion relations (eg. Berends & Giele)

All of the techniques which were useful at tree graph level would prove invaluable as one went on to loops.

One-loop helicity amplitudes

- One loop 4-parton scattering matrix elements squared (gggg, qqgg, qqqq) were calculated in 1986 (RKE, Sexton)
- One-loop gggg helicity amplitudes Bern, Kosower 1990
- Remaining qqgg, qqqq helicity amplitudes obtained by (ZK, Signer and Trocsanyi, 1993
- Provided the structure and confidence in the methods to go onto 5 partons (Bern, Dixon and Kosower, ZK, Signer, Trocsanyi)(1993-1994)

One-loop four parton processes

- Extremely simple formula for one-loop amplitudes revealing simplicity in supersymmetric limit.

$$c_{4;1}^{\rm HV}(+,+;+,-) = -\frac{\rm i}{48\pi^2}\frac{\langle 34\rangle[12][13][23]}{s_{12}s_{14}}\left[\frac{3}{2}\frac{N_c^2+1}{N_c}+(N_c-N_f)\frac{s_{14}}{s_{12}}\right].$$

$$c_{4;1}^{\rm HV}(-,-;+,-) = \frac{\rm i}{48\pi^2}\frac{\langle 12\rangle\langle 14\rangle\langle 24\rangle[34]}{s_{12}s_{14}}\left[\frac{3}{2}\frac{N_c^2+1}{N_c}+(N_c-N_f)\frac{s_{14}}{s_{12}}\right].$$

ETH-TH/93-11
May 5 1992

One-loop helicity amplitudes for all 2 → 2 processes in QCD and N=1 supersymmetric Yang-Mills theory [1]

Zoltan Kunszt, Adrian Signer and Zoltán Trócsányi
Theoretical Physics, ETH,
Zürich, Switzerland

Abstract

Unitarity and one-loop diagrams

- Important steps include:-
- First modern use of the idea Bern, Dixon,Kosower
- Cuts w.r.t. to loop momenta give (box) coefficients directly Cachazo, Britto, Feng
- OPP tensor reduction scheme, Ossola, Pittau, Papadopoulos
- Integrating the OPP procedure with unitarity Ellis, Giele, Kunszt
- D-dimensional unitarity Giele, Kunszt, Melnikov

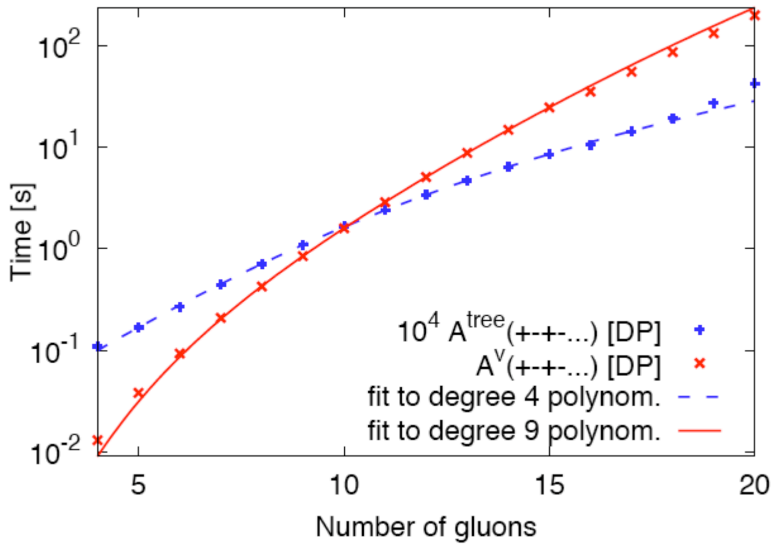
Giele, Kunszt,Melnikov, arXiv 0801.2237

Unitarity in D-dimensions

- The theory contains divergences which we regulate dimensionally. Divergences give poles as =(4-D)/2 ->0
- Calculate the unitarity cuts numerically in integer dimensions D>4. Internal degrees of freedom are taken to be D_s dimensional.
- Dependence on D_s is linear so we calculating in a two different integer dimensions and extrapolate to 0
- Only the length of the loop momentum in the extra dimension is relevant so we can treat the loop momentum as five-dimensional.

One-loop: the extension to n-legs

- Time to calculate one-loop amplitude scales as N^9 as expected.
- For small numbers of legs N=4,5,6 the times are of the order of 10's of milliseconds



4g:Ellis-Sexton(1985)
5g:Bern-Dixon-Kosower(1993)
6g:Ellis-Giele-Zanderighi(2006)

Zoltan and ETH

- For 23 years Zoltan has kept the flame of accelerator-based particle physics alive at ETH Zurich.
- He has nurtured students: Peter Bamert, Stefan Beerli, Stefan Bucherer, Gudrun Heinrich,Francesco Knechtli, Martin Puchwein, Adrian Signer (→ Darren Forde, scientific grandchild)
- Many of us have been happy to accept the hospitality at ETH, for example ESW to write parts of our book, QCD and Collider physics

Zoltan's secret

- Zoltan has an infectious sense of excitement about physics, which he communicates to others.
- He knows that the ultimate arbiter of all that we do is experiment, and that until a theory makes a prediction for the experiment, nothing has really been done.

Key ideas of perturbative QCD

- Asymptotic Freedom
- Factorization/Resummation
- DGLAP evolution
- Parton Shower Monte Carlo
- Jets
- Monte Carlo programs beyond leading order
- Spinor methods
- Unitarity for loop diagrams

Zoltan has been a prime mover in half of these...and it ain't over yet

So please join with me in wishing Zoltan and Marika many happy years hiking through life together.