QCD with Zoltan

Giulia Zanderighi

Max Planck Institute for Physics & Technische Universität München

TECHNISCHE UNIVERSITÄT MÜNCHEN

Symposium in the honour of Zoltan Kunszt's 80th birthday

Plan

- We are here to celebrate Zoltan's 80th birthday. Approximately, this means more than 50 years of physics!

- In fact, first papers of Zoltan indeed appeared in the late 60s. Very influential papers with Riccardo Barbieri very early on

- Aim of this talk: look back at the incredible progress done in the past 50 years in pQCD and at Zoltan's role in this endeavour

The talk will revolve around the dichotomy:
what has changed dramatically in this time
and what has remained essentially the same

Early stages of QCD

Perturbative calculations:

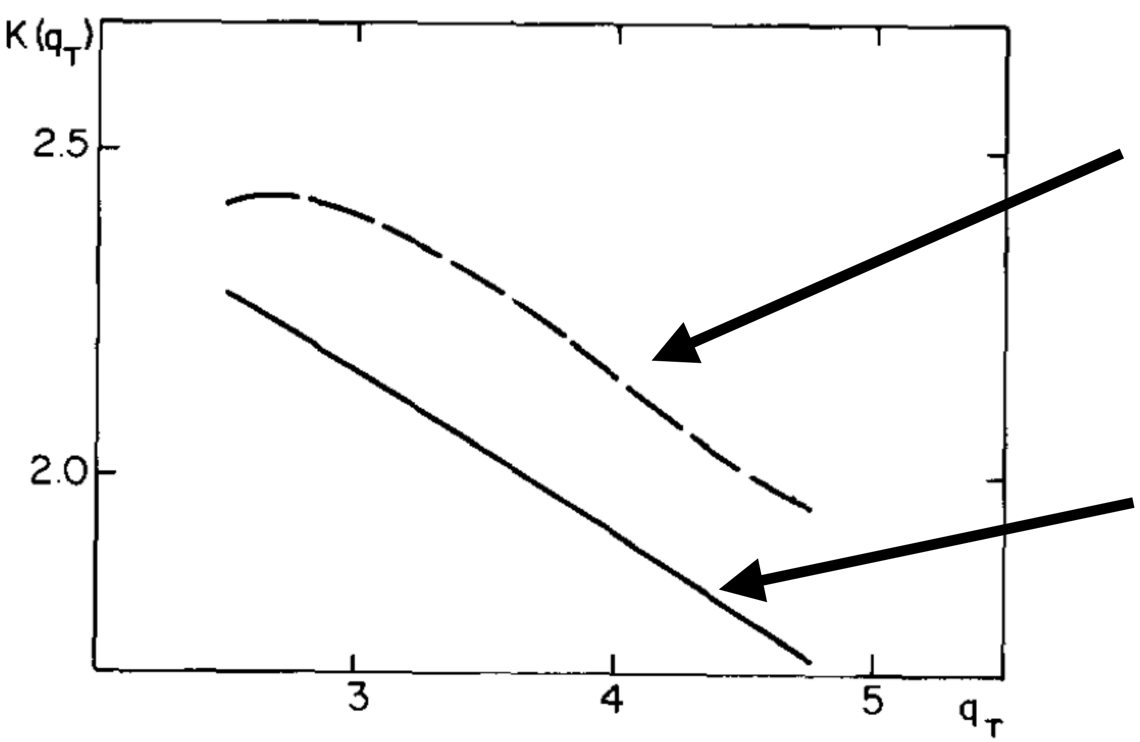
- Calculations done mostly analytically by hand (no big computer at the time)

- First few phenomenological milestones:
  - NLO calculation of three-jet production in e^+e^- collisions
    Ellis, Ross, Terrano '80
  - Drell-Yan at NLO
    Altarelli; Ellis, Martinelli, Petronzio '81

NB: Calculations already done in $\overline{\text{MS}}$ scheme using dimensional regularisation

Z+0 jets

K-factor for Z-boson transverse momentum



With intrinsic k_t

Without intrinsic k_t

Accurate modelling of intrinsic k_t extremely relevant today (see e.g. W-mass measurement from transverse momentum distributions)

$$K(q_T) = \left(\frac{1}{q_T}\frac{d\sigma}{dQ\,dq_T}\right)_{[O(\alpha_s)+O(\alpha_s^2)]} \Bigg/ \left(\frac{1}{q_T}\frac{d\sigma}{dQ\,dq_T}\right)_{[O(\alpha_s)]},$$

K-factors ubiquitous today

Ellis, Martinelli, Petronzio '81

Z+0 jets

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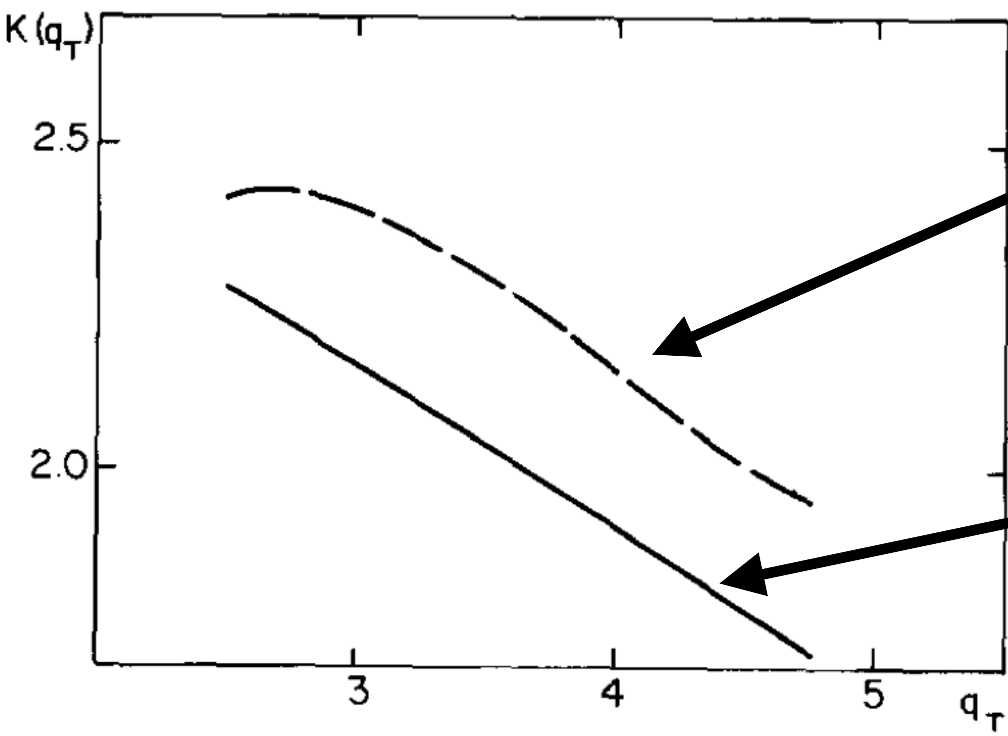

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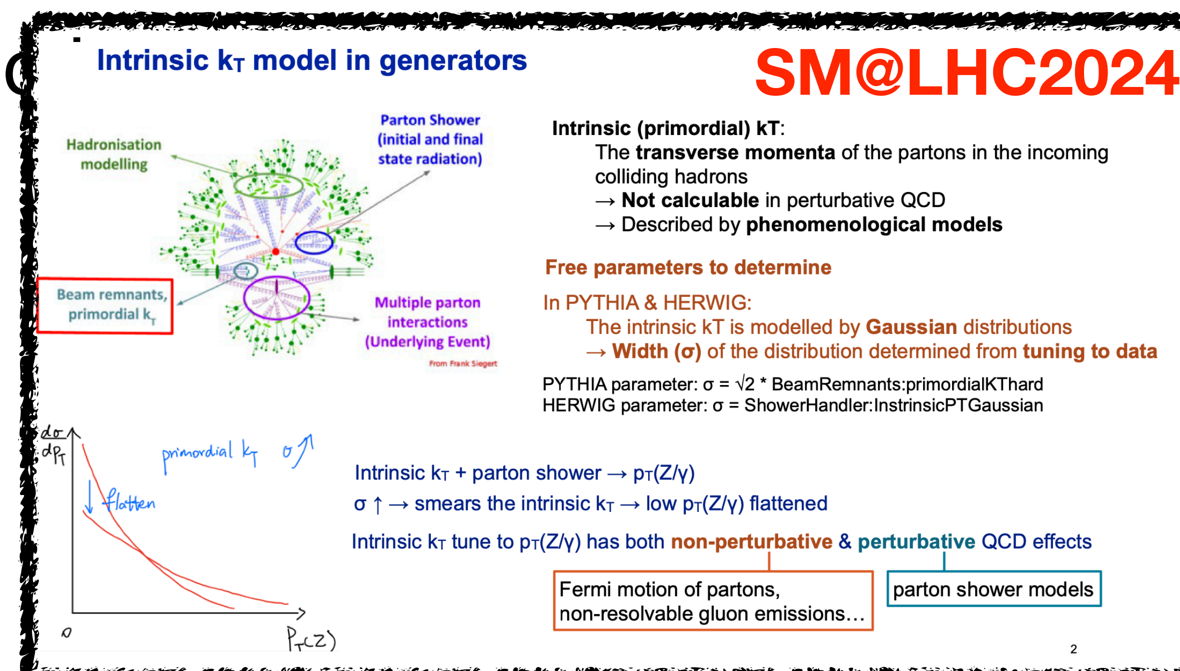
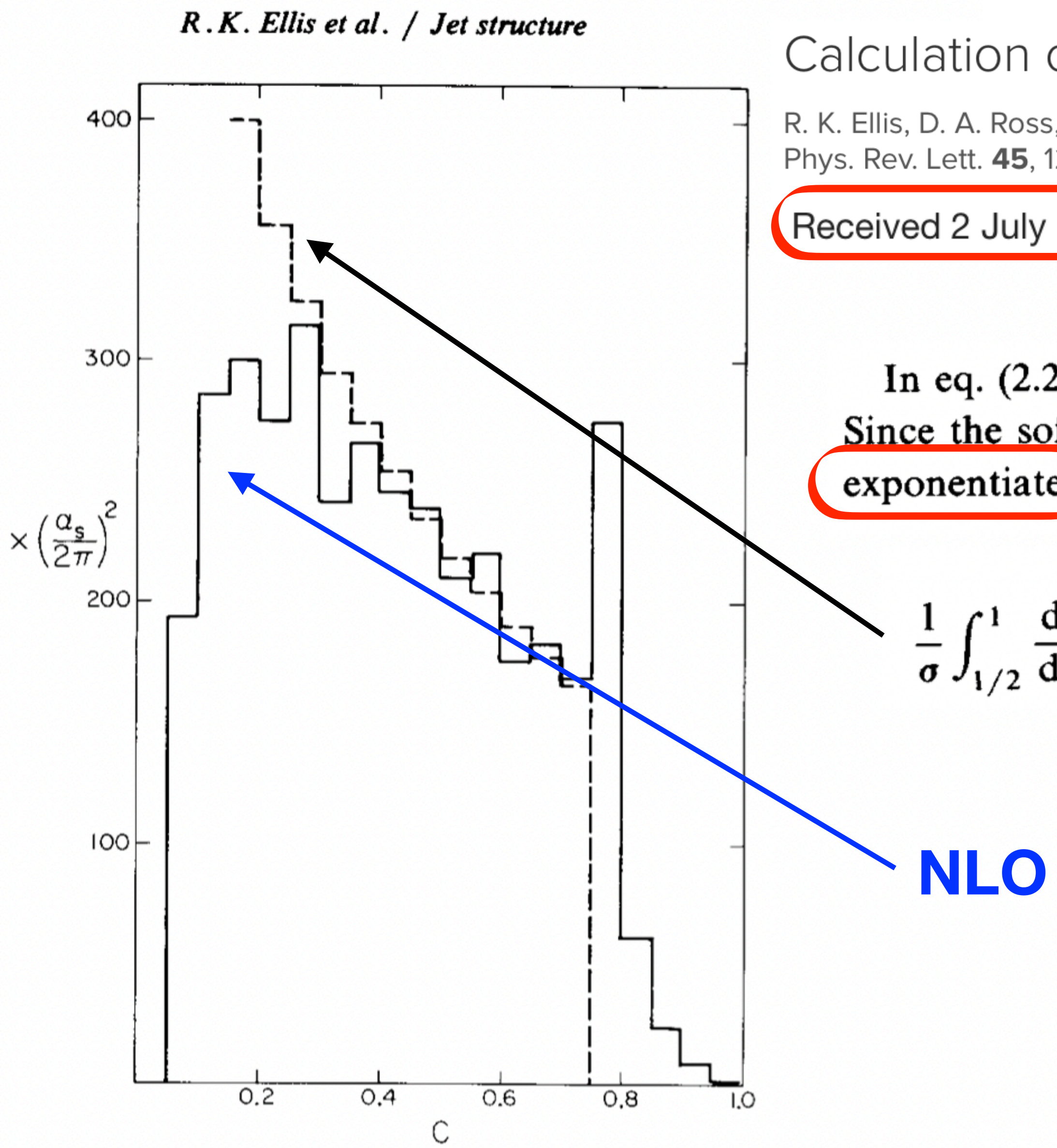


Ellis, Martinelli, Petronzio '81

C-parameter in e+e-



Ellis, Ross, Terrano '80

Calculation of Event-Shape Parameters in e^+e^- Annihilation

R. K. Ellis, D. A. Ross, and A. E. Terrano

Phys. Rev. Lett. **45**, 1226 – Published 13 October 1980

Received 2 July 1980

In eq. (2.24) we noted the appearance of π^2 terms related to the soft singularity. Since the soft logarithms exponentiate it is presumably true that the π^2 terms also exponentiate. Under this assumption eq. (4.5) becomes

$$\frac{1}{\sigma}\int_{1/2}^{1}\frac{d\sigma}{dC}\,dC \sim \exp\left(\frac{\alpha_s(Q^2)}{2\pi}\left(C_F+\tfrac{1}{2}N_C\right)\pi^2\right)2.8\left(\frac{\alpha_s(Q^2)}{2\pi}\right)\left(1+9\frac{\alpha_s(Q^2)}{2\pi}\right).$$

Many debates on π² resummation even today

MACSYMA still used by Keith today!

We are pleased to acknowledge useful discussions with R. P. Feynman, R. D. Field, T. Goldman, Z. Kunszt, H. D. Politzer, and S. Wolfram. We thank the MATHLAB at MIT for the use of MACSYMA.

COMMENT ON THE $O(\alpha_s^2)$ CORRECTIONS TO JET-PRODUCTION IN e^+e^- ANNIHILATION

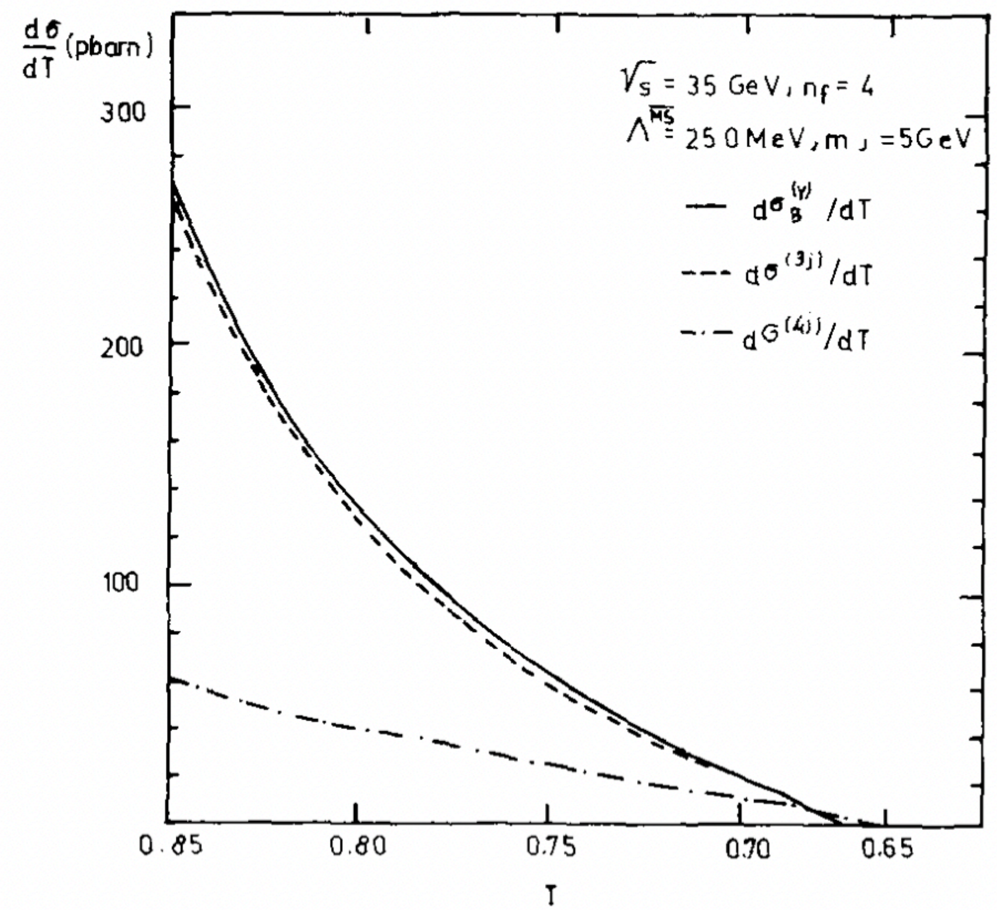
Zoltán KUNSZT
Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany
and L. Eötvös University, Budapest, Hungary

Received 28 August 1980

Using recent results of Ellis et al. I calculate the $O(\alpha_s^2)$ corrections to thrust distribution in e^+e^- annihilation. The numerical importance of the change of the four-momentum squared which determines the strength of the running coupling constant is studied in detail.

In ref. [1], however, all the important details are published so the above mentioned minor shortcomings can be easily eliminated. First of all with a slight modification of the pole terms (which have been subtracted from the four-jet matrix elements to regularize the infrared and mass singularities), any distribution can be calculated with high accuracy.

The same modification leads to formulae where jet fragmentation can be trivially introduced.



I am pleased to acknowledge illuminating discussions with R.K. Ellis and T. Walsh.

Many debates on choice of the scale in the running coupling even today

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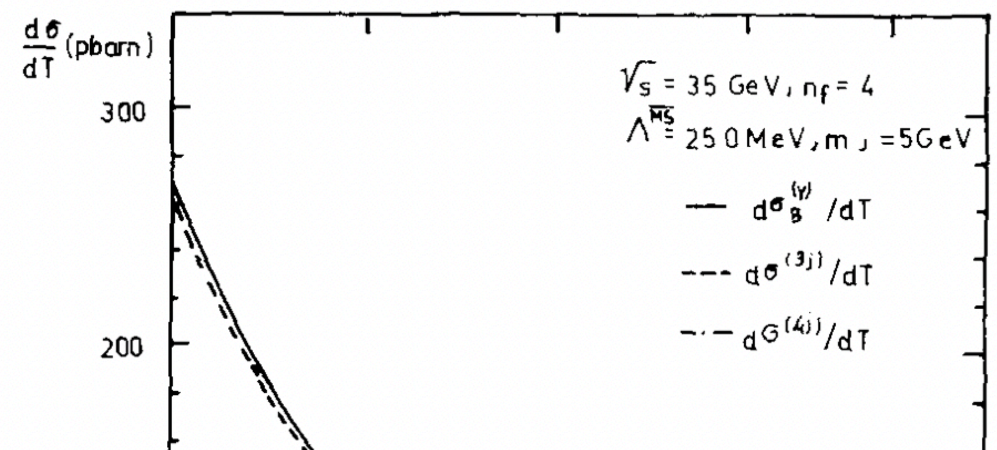


Typical of Zoltan:

- Follow closely recent progress
- Find clever ways to improve on already very hard calculations and exploit them more widely, effectively contributing to improving theory predictions

Many debates on choice of the scale in the running coupling even today

I am pleased to acknowledge illuminating discussions with R.K. Ellis and T. Walsh.

10 years before the discovery of the top-quark …

ASSOCIATED PRODUCTION OF HEAVY HIGGS BOSON WITH TOP QUARKS

Z. KUNSZT* **

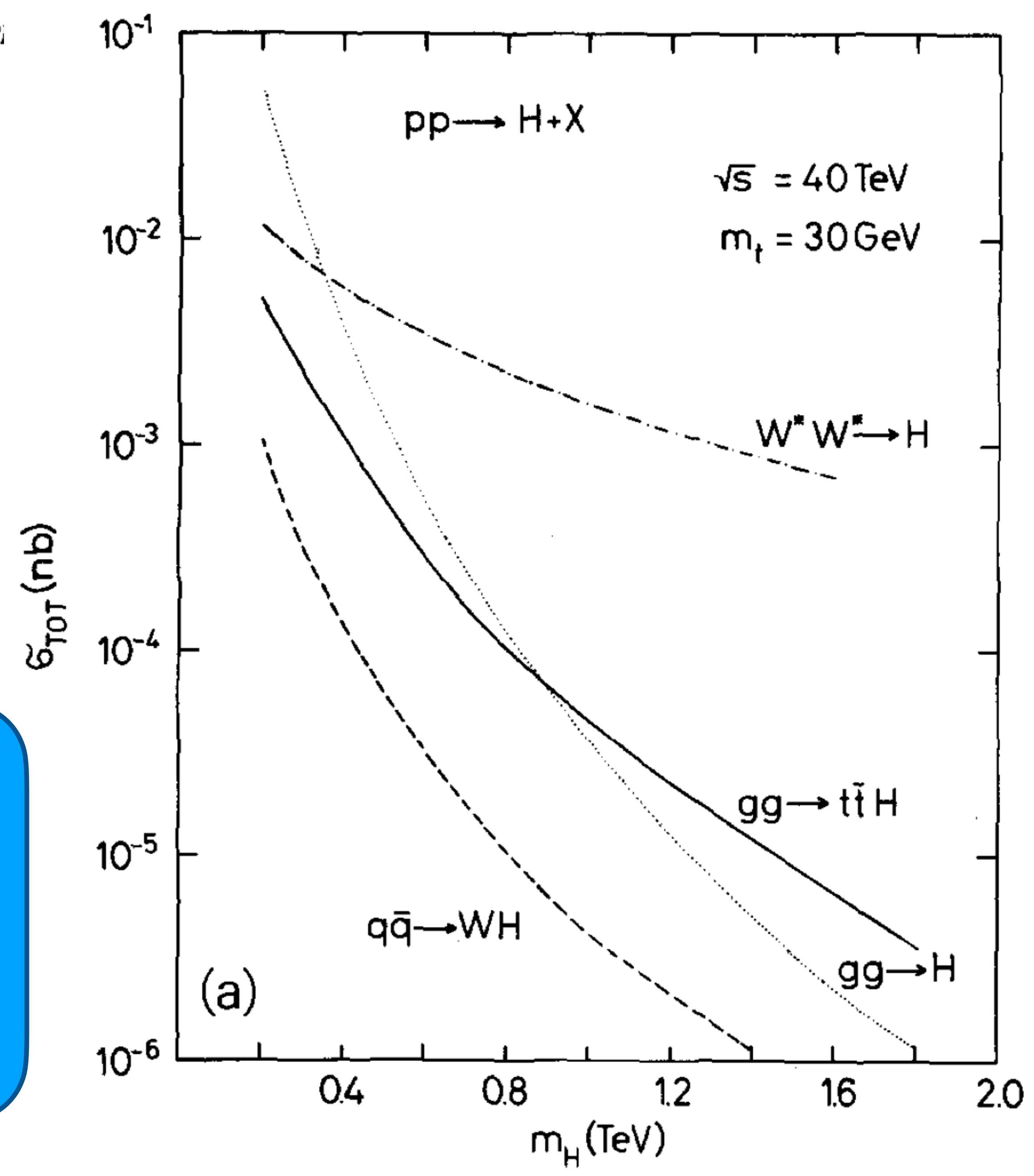
Institute for Theoretical Physics, University of Bern, Bern, Switze

Received 13 June 1984

Typical of Zoltan:

- Close connection to phenomenology
- Focus of paper is on backgrounds as well

What I found however most astonishing: third solo paper I found of Zoltan during those years. I cannot imagine Zoltan working alone (without anybody to talk to!). Something must have changed over time!



IMPROVED ANALYTIC TECHNIQUES FOR TREE GRAPH CALCULATIONS AND THE $ggq\bar{q}\ell\bar{\ell}$ SUBPROCESS

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Received 14 June 1985

We demonstrate further improvements in the CALCUL approach to tree graph calculations. We employ polarization vectors referenced to a single momentum and obtain expressions in terms of spinor inner products. The method is crossing symmetric and can be easily implemented as an algebraic computer program. As an illustration we present an analytic calculation of the $ggq\bar{q}'\ell\bar{\ell}'$ subprocess in the standard model where $\ell\bar{\ell}'$ can be in either the charged or the neutral channel.

- Paper pioneers the development of state-of-the art methods for the efficient calculation of LO high-multiplicity processes
- Use of “modern” computers to handle complex algebra

In conclusion we remark that numerical programs based on our expressions for the $ggq\bar{q}\ell\bar{\ell}$ process are both shorter and faster than those based on spin summed matrix elements squared computed by traditional trace techniques in terms of subprocess invariants. No sacrifice of numerical accuracy occurs; for example, the numerical gauge invariant check produces a result nineteen orders of magnitude smaller than the actual cross section (on an IBM 3081). Thus a wide variety of calculations involving massless external fermions may be usefully and economically performed using the techniques of this paper.

IMPROVED ANALYTIC TECHNIQUES FOR TREE GRAPH CALCULATIONS AND THE $gg q\bar{q} \ell\bar{\ell}$ SUBPROCESS

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Typical of Zoltan:

- Seek simplicity and analytic elegance
- Practical attitude: shorter and faster means more applications

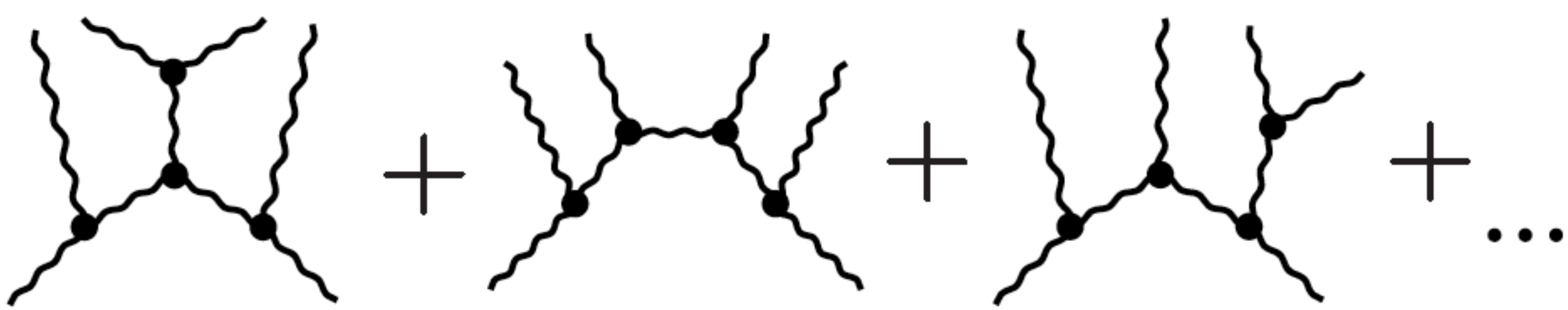
- Paper pioneers the development of state-of-the art methods for the efficient calculation of LO high-multiplicity processes
- Use of “modern” computers to handle complex algebra

In conclusion we remark that numerical programs based on our expressions for the $gg q\bar{q} \ell\bar{\ell}$ process are both shorter and faster than those based on spin summed matrix elements squared computed by traditional trace techniques in terms of subprocess invariants. No sacrifice of numerical accuracy occurs; for example, the numerical gauge invariant check produces a result nineteen orders of magnitude smaller than the actual cross section (on an IBM 3081). Thus a wide variety of calculations involving massless external fermions may be usefully and economically performed using the techniques of this paper.

$gg \to gggg$

Consider the amplitude for two gluons to collide and produce four gluons: $gg \to gggg$

Before modern computers, this would have been barely tractable even at leading order (LO)



217 diagrams

gg → gggg

background to the detection of W^+W^- pairs in their nonleptonic decays. The cross sections for the elementary two→four processes have not been calculated, and their complexity is such that they may not be evaluated in the foreseeable future. It is worthwhile to seek estimates of the four-jet cross sections, even if these are only reliable in restricted regions of phase space.

Supercollider physics

(1984)

E. Eichten

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Lawrence Berkeley Laboratory, Berkeley, California 94720

K. Lane

The Ohio State University, Columbus, Ohio 43210

C. Quigg

Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, Illinois 60510

Eichten *et al.* summarize the motivation for exploring the 1-TeV ($=10^{12}$ eV) energy scale in elementary particle interactions and explore the capabilities of proton-(anti)proton colliders with beam energies between 1 and 50 TeV. The authors calculate the production rates and characteristics for a number of conventional processes, and discuss their intrinsic physics interest as well as their role as backgrounds to more exotic phenomena. The authors review the theoretical motivation and expected signatures for several new phenomena which may occur on the 1-TeV scale. Their results provide a reference point for the choice of machine parameters and for experiment design.

TeV. From Fig. 78 we find the corresponding two-jet cross section (at $p_\perp = 0.5$ TeV/c) to be about 7×10^{-2} nb/GeV, which is larger by an order of magnitude. Let us next consider the cross section in the neighborhood of the peak in Fig. 102. The integrated cross section in the bin ... is approximately 0.1 nb/GeV, with transverse energy ... by $\langle E_T\rangle \approx (1\text{ TeV}) \times \langle\cos\theta\rangle = 350$ GeV. The corresponding two-jet cross section, again from Fig. 78, is approximately ... which is larger by 2 orders of magnitude. In fact, we have certainly underestimated $\langle E_T\rangle$ and thus somewhat overestimated the two-jet/three-jet ratio in this second case.

We draw two conclusions from this very casual analysis:

At least at small-to-mod... values of E_T, two-jet events should ... for most of the cross section.

... three-jet cross section is large enough that a detailed study of this topology should be possible.

It is apparent that these questions are amenable to detailed investigation with the aid of realistic Monte Carlo simulations. Given the elementary two→three cross sections and reasonable parametrizations of the fragmentation functions, this exercise can be carried out with some degree of confidence.

For multijet events containing more than three jets, the theoretical situation is considerably more primitive. A specific question of interest concerns the QCD four-jet background to the detection of W^+W^- pairs in their nonleptonic decays. The cross sections for the elementary two→four processes have not been calculated, and their complexity is such that they may not be evaluated in the foreseeable future. It is worthwhile to seek estimates of the four-jet cross sections, even if these are only reliable in restricted regions of phase space.

Another background source of four-jet events is double parton scattering, as shown in Fig. 103. If all the parton momentum fractions are small, the two interactions may be treated as uncorrelated. The resulting four-jet cross section with transverse energy E_T may then be approximated by

$$\sigma_4(E_T) = \int_\epsilon^{E_T-\epsilon} dE_{T1} \int_\epsilon^{E_T-\epsilon} dE_{T2} \frac{\sigma_2(E_{T1})\sigma_2(E_{T2})\delta(E_{T1}+E_{T2}-E_T)}{\sigma_{\text{total}}}, \quad (3.47)$$

where $\sigma_2(E_{T1})$ is the two-jet cross section and ϵ denotes the minimum E_T required for a discernable two-jet event. For a recent study of double parton scattering at $Sp\bar{p}S$ and Tevatron energies, see Paver and Treleani (1983).

In view of the promise that multijet spectroscopy holds, improving our understanding of the QCD background is an urgent priority for further study.

D. Summary

We conclude this section with a brief summary of the ranges of jet energy which are accessible for various beam energies and luminosities. We find essentially no differences between pp and $\bar{p}p$ collisions, so only pp results will be given except at $\sqrt{s} = 2$ TeV where $\bar{p}p$ rates are quoted. Figure 104 shows the E_T range which can be explored at the level of at least one event per GeV of E_T per unit rapidity at 90° in the c.m. (compare Figs. 77–79 and 83). The results are presented in terms of the transverse energy per event E_T, which corresponds to twice the transverse momentum $p_\perp$ of a jet. In Fig. 105 we plot the values of E_T that distinguish the regimes in which the two-gluon, quark-gluon, and quark-quark final states are dominant. Comparing with Fig. 104, we find that while the accessible ranges of E_T are impressive, it seems extremely difficult to obtain a clean sample of quark jets. Useful for estimating trigger rates is the total cross section for two jets integrated over $E_T(=2p_\perp) > E_{T_0}$ for both jets in a rapidity interval of -2.5 to $+2.5$. This is shown for pp collisions in Fig. 106.

IV. ELECTROWEAK PHENOMENA

In this section we discuss the supercollider processes associated with the standard model of the weak and electromagnetic interactions (Glashow, 1961; Weinberg, 1967; Salam, 1968). By "standard model" we understand the $SU(2)_L \otimes U(1)_Y$ theory applied to three quark and lepton doublets, and with the gauge symmetry broken by a single complex Higgs doublet. The particles associated with the electroweak interactions are therefore the (left-handed) charged intermediate bosons $W^\pm$, the neutral intermedi-

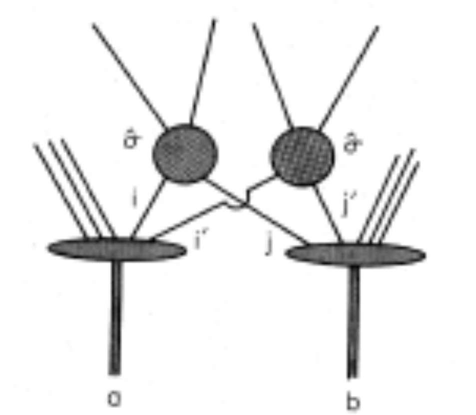


FIG. 103. Four-jet topology arising from two independent parton interactions.

gg → gggg

In 1985 Parke and Taylor took up the challenge, using

✓ the most advanced theoretical tools available

✓ the world best computers

they produced a final formula that would fit in **8 pages**

THE CROSS SECTION FOR FOUR-GLUON PRODUCTION BY GLUON–GLUON FUSION

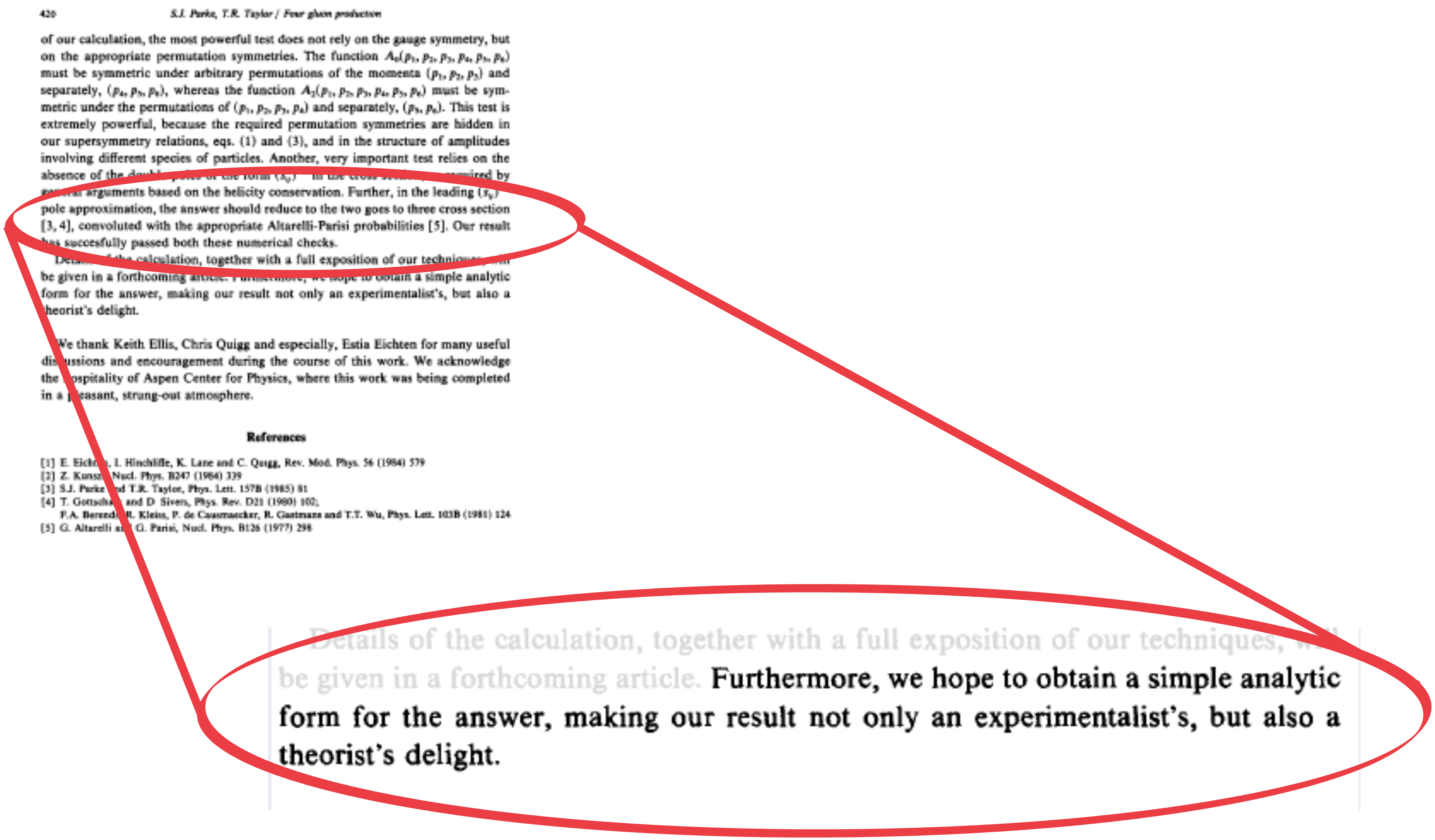
Stephen J. PARKE and T.R. TAYLOR

Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, IL 60510 USA

Received 13 September 1985

The cross section for two-gluon to four-gluon scattering is given in a form suitable for fast numerical calculations.

Parke-Taylor



of our calculation, the most powerful test does not rely on the gauge symmetry, but on the appropriate permutation symmetries. The function $A_6(p_1, p_2, p_3, p_4, p_5, p_6)$ must be symmetric under arbitrary permutations of the momenta (p_1, p_2, p_3) and separately, (p_4, p_5, p_6), whereas the function $A_2(p_1, p_2, p_3, p_4, p_5, p_6)$ must be symmetric under the permutations of (p_1, p_2, p_3, p_4) and separately, (p_5, p_6). This test is extremely powerful, because the required permutation symmetries are hidden in our supersymmetry relations, eqs. (1) and (3), and in the structure of amplitudes involving different species of particles. Another, very important test relies on the absence of the [illegible] required by [illegible] arguments based on the helicity conservation. Further, in the leading (s_{ij}) pole approximation, the answer should reduce to the two goes to three cross section [3, 4], convoluted with the appropriate Altarelli-Parisi probabilities [5]. Our result has succesfully passed both these numerical checks.

Details of the calculation, together with a full exposition of our techniques, will be given in a forthcoming article. Furthermore, we hope to obtain a simple analytic form for the answer, making our result not only an experimentalist's, but also a theorist's delight.

We thank Keith Ellis, Chris Quigg and especially, Estia Eichten for many useful discussions and encouragement during the course of this work. We acknowledge the hospitality of Aspen Center for Physics, where this work was being completed in a pleasant, strung-out atmosphere.

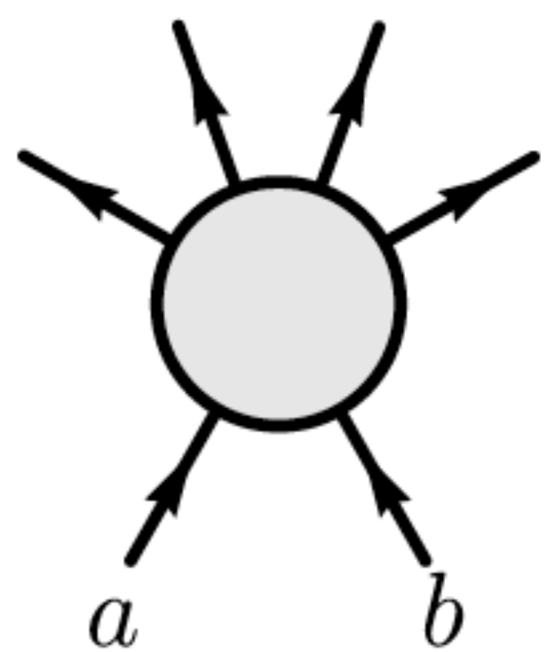
References

[1] E. Eichten, I. Hinchliffe, K. Lane and C. Quigg, Rev. Mod. Phys. 56 (1984) 579
[2] Z. Kunszt, Nucl. Phys. B247 (1984) 339
[3] S.J. Parke and T.R. Taylor, Phys. Lett. 157B (1985) 81
[4] T. Gottschalk and D. Sivers, Phys. Rev. D21 (1980) 102;
F.A. Berends, R. Kleiss, P. de Causmaecker, R. Gastmans and T.T. Wu, Phys. Lett. 103B (1981) 124
[5] G. Altarelli and G. Parisi, Nucl. Phys. B126 (1977) 298

Details of the calculation, together with a full exposition of our techniques, will be given in a forthcoming article. Furthermore, we hope to obtain a simple analytic form for the answer, making our result not only an experimentalist's, but also a theorist's delight.

Game-changer

Soon afterwards they could guess an incredible, unanticipated simple form (for a fixed helicity configuration) …



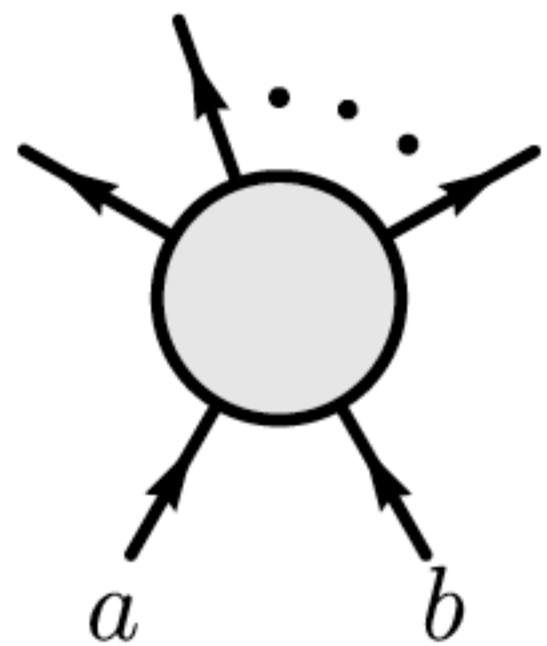
$$= \frac{\langle a\, b\rangle^4}{\langle 1\,2\rangle\langle 2\,3\rangle\langle 3\,4\rangle\langle 4\,5\rangle\langle 5\,6\rangle\langle 6\,1\rangle}$$

Parke and Taylor, Phys. Rev. Lett 56 (1986) 2459

Game-changer

… which naturally suggested the result for an arbitrary number of gluons

Parke and Taylor, Phys. Rev. Lett 56 (1986) 2459



$$= \frac{\langle a\, b\rangle^4}{\langle 1\, 2\rangle\langle 2\, 3\rangle\langle 3\, 4\rangle\langle 4\, 5\rangle \cdots \langle n\, 1\rangle}$$

The surprise about this result is that all denominators are simple dot products of two momenta. The Feynman diagrams for n ($>$ 5) gluon scattering contain propagators $(p_i + p_j + p_k)^2$, $(p_i + p_j + p_k + p_m)^2$, $\ldots$. These propagators must cancel for eqn(3) to be correct; this occurs for n=6. Of course, Altarelli and Parisi have taught us that many cancellations are expected.

COMBINED USE OF THE CALKUL METHOD AND $N = 1$ SUPERSYMMETRY TO CALCULATE QCD SIX-PARTON PROCESSES

Z. KUNSZT[1]

CERN, Geneva, Switzerland

Received 23 December 1985

Concise expressions are presented for the two independent helicity amplitudes of the subprocess 4g2q. The result has been derived using the improved CALKUL method and is given in terms of spinor inner products in manifestly covariant and crossing symmetric forms. Changing the color factors of the quarks from the fundamental to the adjoint representation we obtain the helicity amplitudes of the four-gluon-two-gluino subprocess. Simple $N = 1$ supersymmetric relations have been found which express the helicity amplitudes of the six gluon parton process in terms of the helicity amplitudes of the $4g2\tilde{g}$ process. In this way we have avoided the direct calculation of 220 Feynman diagrams. Gauge invariance and the validity of the supersymmetric relations have been tested with an independent numerical calculation.

In order to check the results I also have calculated the amplitudes and cross sections for the 6g, 4g2q and 4g2$\tilde{g}$ subprocesses with a completely numerical program. This way I have checked gauge invariance and the validity of the supersymmetry relations. The numerical program is about 10 times slower than the Fortran program based on the formulae presented in this paper.

Phenomenological implications of the results of this paper will be discussed in a forthcoming publication [14]. Here I would like only to emphasize that we are finally in a position to carry out the phenomenological cross section calculations based on all subprocesses without resorting to any approximations.

Note added

After completing this work I have been informed by S. Parke and T. Taylor that they have also computed the amplitudes of the 4g2q subprocesses [15]. We have compared our results numerically for both the subprocesses involving six gluons and four gluons plus two quarks and we have found complete agreement. I thank S. Parke for correspondence. The six-gluon amplitude has been also calculated recently by the helicity method [16].

Kunszt, Nucl. Phys. B 271 (1986) 333

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The One-Jet Inclusive Cross Section at Order α_s^3 : Quarks and Gluons

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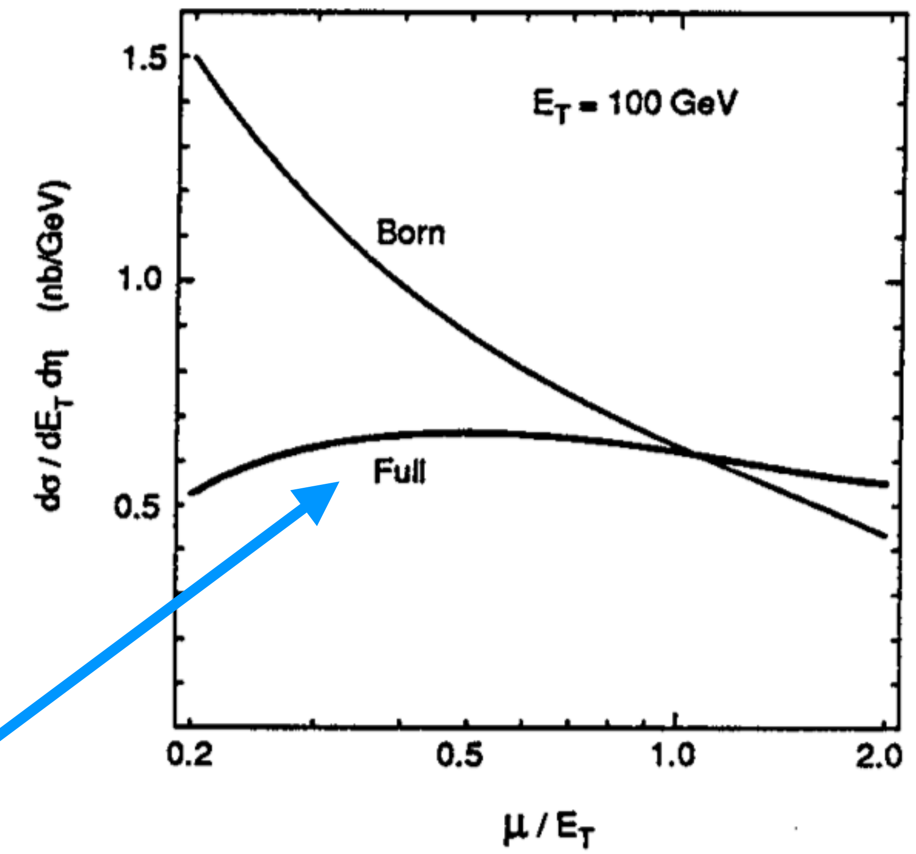
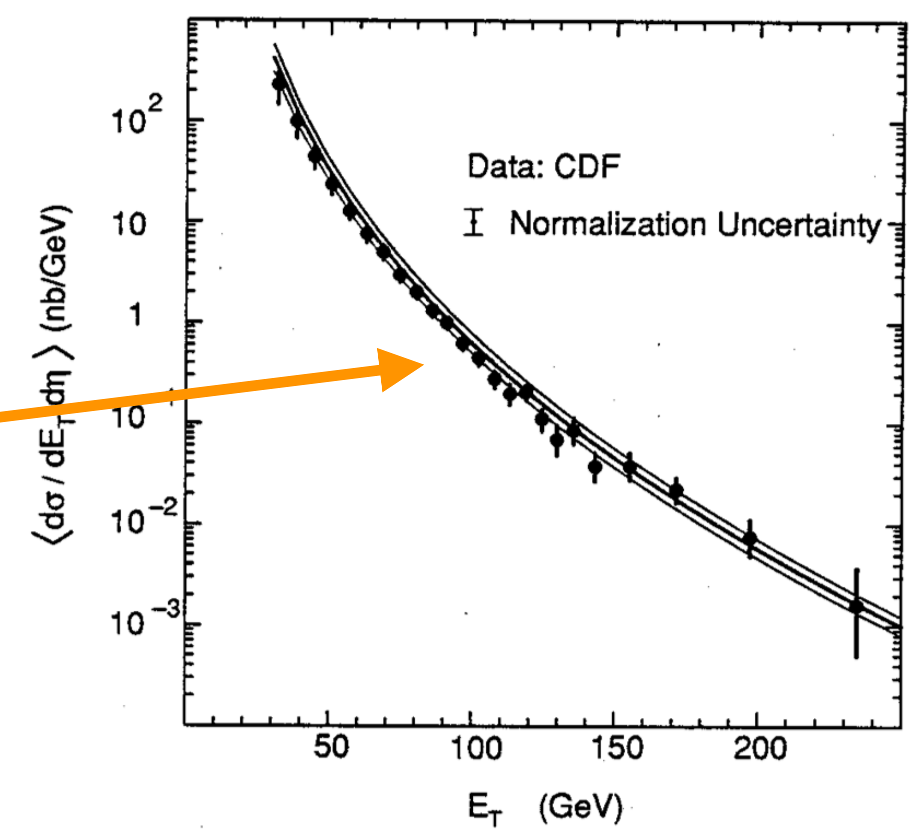


Pioneering full NLO calculation
Characteristic shapes of LO and NLO scales dependencies



Validation of NLO through comparison to data

NB: no k_t-algorithm, cone algorithm still used

New clustering algorithm for multijet cross sections in e^+e^- annihilation☆

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Received 2 August 1991

$$y_{kl} = 2(1-\cos\theta_{kl})\,\min(E_k^2, E_l^2)/s\,,$$

Longitudinally-invariant $k_\perp$-clustering algorithms for hadron–hadron collisions *

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Accepted for publication 5 April 1993

$$d_{kB} \simeq E_k^2\theta_{kB}^2 \simeq k_{\perp kB}^2, \qquad \text{for } \theta_{kB}\to 0,$$

$$d_{kl} \simeq \min(E_k^2, E_l^2)\theta_{kl}^2 \simeq k_{\perp kl}^2, \qquad \text{for } \theta_{kl}\to 0.$$

New jet cluster algorithms: next-to-leading order QCD and hadronization corrections

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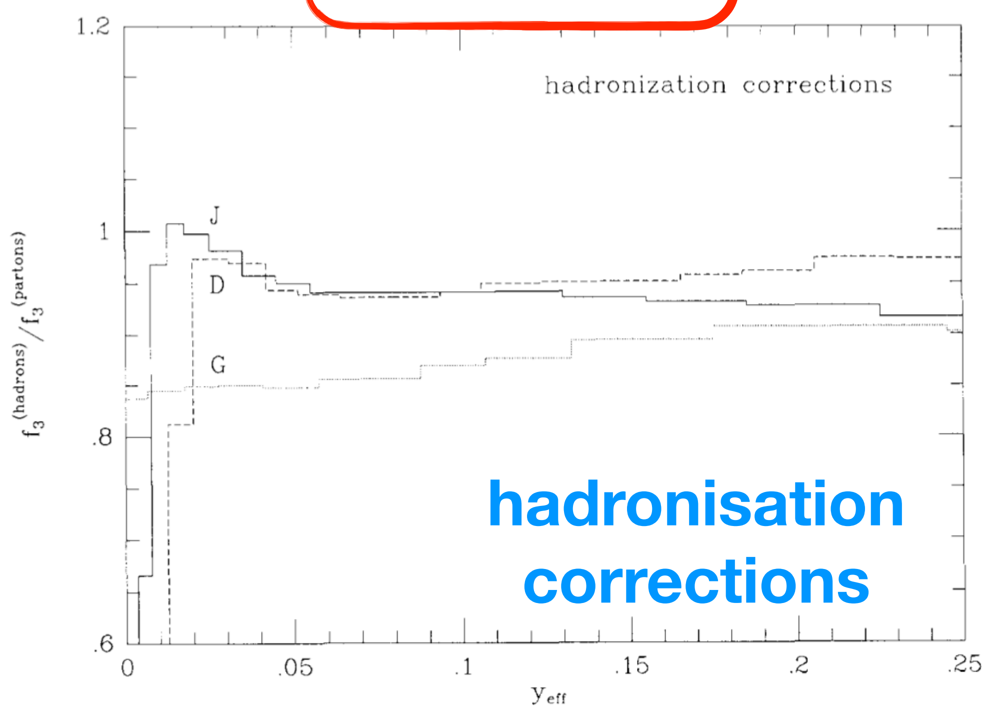
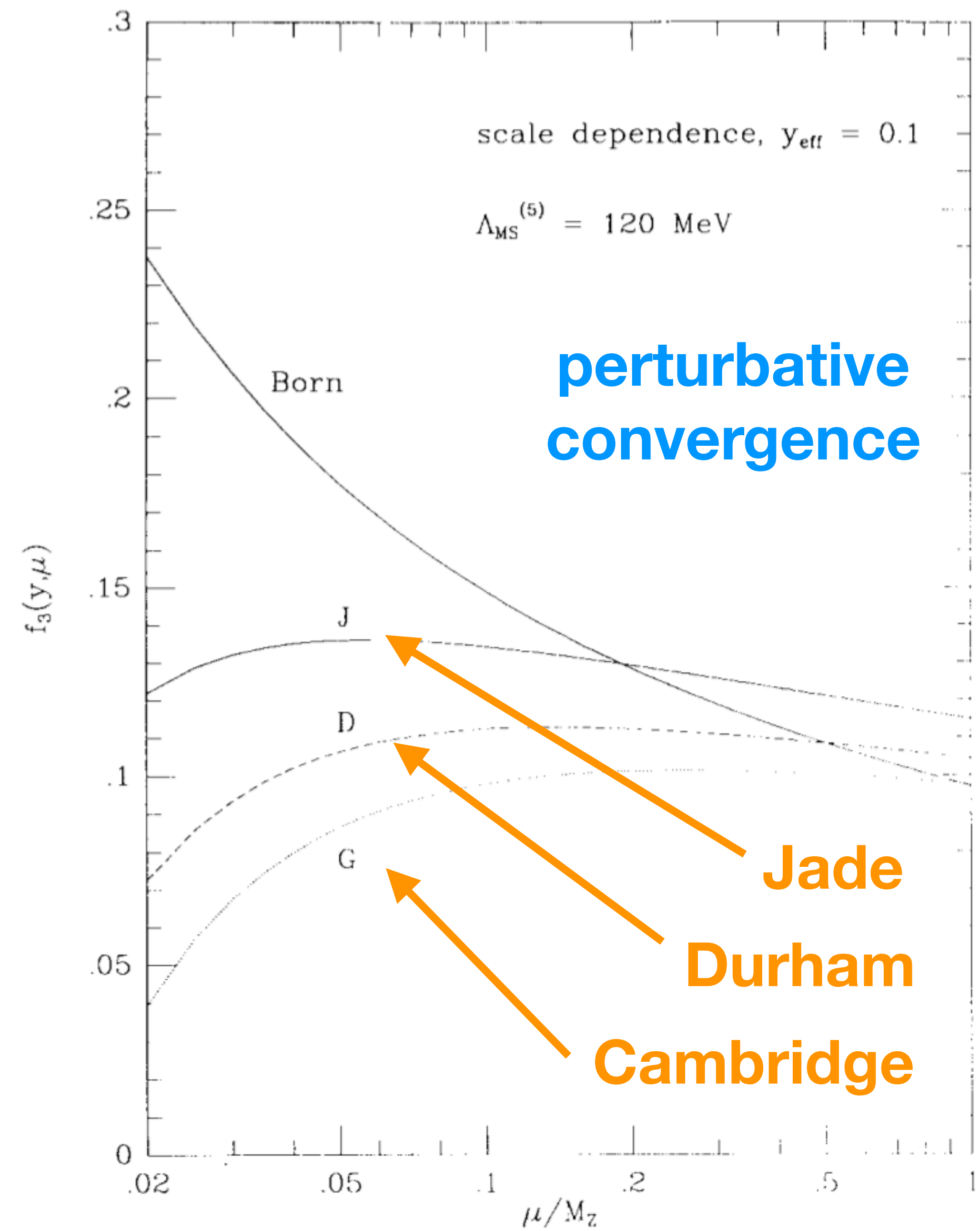




Our study also raises some wider questions about the QCD perturbation theory.

...

With these issues of the behaviour of the perturbation series at large y, resummability at small y, and non-perturbative hadronization effects, there is clearly much interesting and important work still to be done in this area of jet physics.

Other “pheno” highlights of the 90s

Calculation of jet cross-sections in hadron collisions at order alpha-s3**

Zoltan Kunszt (Zurich, ETH), Davison E. Soper (Oregon U.) (Jan, 1992)

Published in: *Phys.Rev.D* 46 (1992) 192-221

pdf DOI cite claim reference search 339 citations

Two jet production in hadron collisions at order alpha-s3 in QCD**

Stephen D. Ellis (Washington U., Seattle), Zoltan Kunszt (Zurich, ETH), Davison E. Soper (Oregon U.) (Jul, 1992)

Published in: *Phys.Rev.Lett.* 69 (1992) 1496-1499

pdf DOI cite claim reference search 222 citations

Jets at hadron colliders at order $\alpha - s^{3:}$ A Look inside

Stephen D. Ellis (Washington U., Seattle), Zoltan Kunszt (Zurich, ETH), Davison E. Soper (Oregon U.) (Aug, 1992)

Published in: *Phys.Rev.Lett.* 69 (1992) 3615-3618 • e-Print: hep-ph/9208249 [hep-ph]

pdf DOI cite claim reference search 230 citations

Higgs production with large transverse momentum in hadronic collisions at next-to-leading order

D. de Florian (Zurich, ETH), M. Grazzini (Zurich, ETH), Z. Kunszt (Zurich, ETH) (Feb, 1999)

Published in: *Phys.Rev.Lett.* 82 (1999) 5209-5212 • e-Print: hep-ph/9902483 [hep-ph]

pdf DOI cite claim reference search 226 citations

“Amplitudes” highlights of the 90s

One loop radiative corrections to the helicity amplitudes of QCD processes involving four quarks and one gluon

Zoltan Kunszt (Zurich, ETH), Adrian Signer (Zurich, ETH), Zoltan Trocsanyi (Zurich, ETH and Kossuth Lajos U., Debrecen) (May, 1994)

Published in: *Phys.Lett.B* 336 (1994) 529-536 • e-Print: hep-ph/9405386 [hep-ph]

pdf DOI cite claim reference search 116 citations

Singular terms of helicity amplitudes at one loop in QCD and the soft limit of the cross-sections of multiparton processes

Zoltan Kunszt (Zurich, ETH), Adrian Signer (Zurich, ETH), Zoltan Trocsanyi (Zurich, ETH) (Jan, 1994)

Published in: *Nucl.Phys.B* 420 (1994) 550-564 • e-Print: hep-ph/9401294 [hep-ph]

pdf DOI cite claim reference search 150 citations

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

Zoltan Kunszt (Zurich, ETH), Adrian Signer (Zurich, ETH), Zoltan Trocsanyi (Zurich, ETH) (May, 1993)

Published in: *Nucl.Phys.B* 411 (1994) 397-442 • e-Print: hep-ph/9305239 [hep-ph]

Helicity amplitudes for O(alpha-s) production of W^+W^-, $W^\pm Z$, ZZ, $W^\pm\gamma$, or $Z\gamma$ pairs at hadron colliders

Lance J. Dixon (SLAC), Z. Kunszt (Zurich, ETH), A. Signer (CERN) (Mar, 1998)

Published in: *Nucl.Phys.B* 531 (1998) 3-23 • e-Print: hep-ph/9803250 [hep-ph]

pdf links DOI cite claim reference search 188 citations

The game-changer: FKS

Three jet cross-sections to next-to-leading order

S. Frixione (Zurich, ETH), Z. Kunszt (Zurich, ETH), A. Signer (SLAC) (Dec, 1995)

Published in: *Nucl.Phys.B* 467 (1996) 399-442 • e-Print: hep-ph/9512328 [hep-ph]

The subtraction method presented in the literature is based on a systematic use of boost-invariant kinematical variables, and therefore its application to three-jet production is quite cumbersome. In this paper we re-analyze the subtraction method and point out the advantage of using angle and energy variables. This leads to simpler results and it has complete generality, extending its validity to n-jet production. The formalism is also applicable to n-jet production in e^+e^- annihilation and in photon-hadron collisions. All the analytical results necessary to construct an efficient numerical program for next-to-leading order three-jet inclusive quantities in hadroproduction are given explicitly. As new analytical result, we also report the collinear limits of all the two-to-four processes.

The game-changer: FKS

Three jet cross-sections to next-to-leading order

S. Frixione (Zurich, ETH), Z. Kunszt (Zurich, ETH), A. Signer (SLAC) (Dec, 1995)

Published in: *Nucl.Phys.B* 467 (1996) 399-442 • e-Print: hep-ph/9512328 [hep-ph]

pdf   links   DOI   cite   claim   reference search   1,009 citations

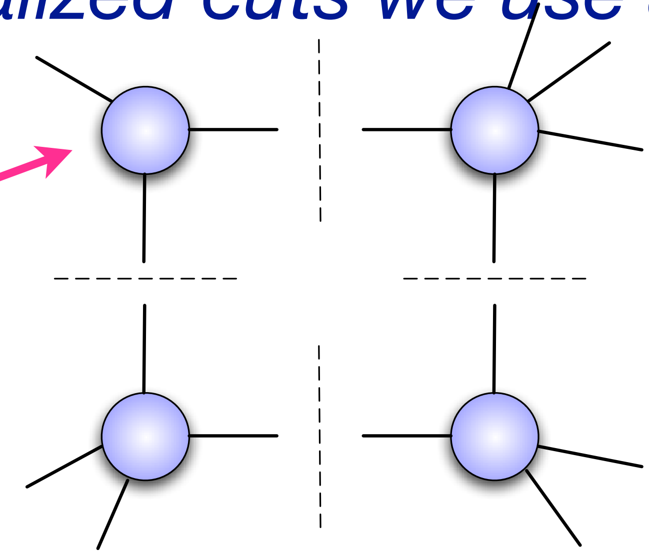
- 😄 Together with Catani-Seymour, one of the two subtraction methods used in virtually all NLO calculations
- 😄 Implemented e.g. in POWHEG, MC@NLO, …
- 😄 Precursor of NNLO subtraction methods
- 😕 But …

NLO revolution

Two breakthrough ideas:

1) "... we show how to use generalized unitarity to read off the (box) coefficients. The generalized cuts we use are quadrupole cuts ..."

NB: non-zero because cut gives complex momenta



Britto, Cachazo, Feng '04

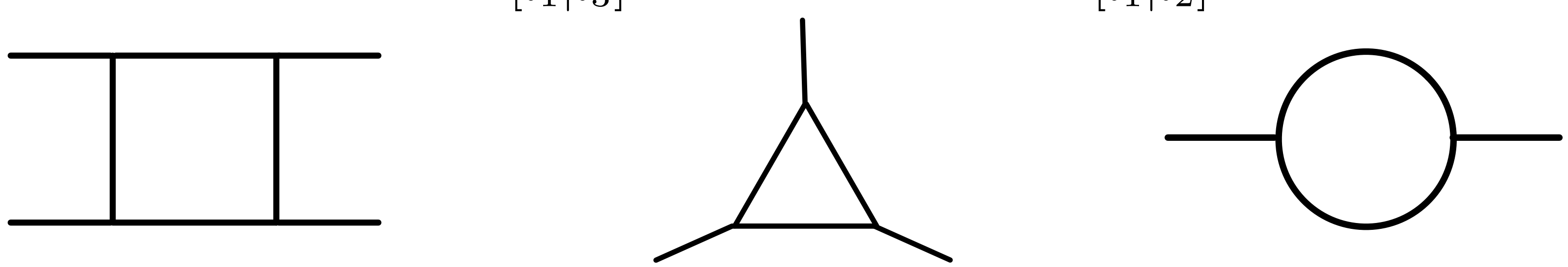
Quadrupole cuts: four on-shell conditions on four dimensional loop momentum freezes the integration. Rational part of the amplitude, computed separately

NLO revolution

Two breakthrough ideas:

2) The OPP method: "We show how to extract the coefficients of 4-, 3-, 2- and 1-point one-loop scalar integrals...."

$$\mathcal{A}_N = \sum_{[i_1|i_4]} \left(d_{i_1 i_2 i_3 i_4} \; I^{(D)}_{i_1 i_2 i_3 i_4} \right) + \sum_{[i_1|i_3]} \left(c_{i_1 i_2 i_3} \; I^{(D)}_{i_1 i_2 i_3} \right) + \sum_{[i_1|i_2]} \left(b_{i_1 i_2} \; I^{(D)}_{i_1 i_2} \right) + \mathcal{R}$$



Ossola, Pittau, Papadopolous '06

Coefficients can be determined by solving a system of equations

Highlights after 2000

With a series of seminal papers on D-dimensional unitarity, Zoltan played a key role in the development of the so-called NLO revolution

D-dimensional unitarity cut method

Charalampos Anastasiou (Zurich, ETH), Ruth Britto (Amsterdam U.), Bo Feng (Imperial Coll., London and Zhejiang U.), Zoltan Kunszt (Zurich, ETH), Pierpaolo Mastrolia (Zurich U.) (Sep, 2006)

Published in: *Phys.Lett.B* 645 (2007) 213-216 • e-Print: hep-ph/0609191 [hep-ph]

pdf DOI cite claim reference search 267 citations

Unitarity cuts and Reduction to master integrals in d dimensions for one-loop amplitudes

Charalampos Anastasiou (CERN), Ruth Britto (Amsterdam U.), Bo Feng (Imperial Coll., London and Zhejiang U.), Zoltan Kunszt (Zurich, ETH), Pierpaolo Mastrolia (Zurich U.) (Dec, 2006)

Published in: *JHEP* 03 (2007) 111 • e-Print: hep-ph/0612277 [hep-ph]

pdf links DOI cite claim reference search 184 citations

A Numerical Unitarity Formalism for Evaluating One-Loop Amplitudes

R.Keith Ellis (Fermilab), W.T. Giele (Fermilab), Z. Kunszt (Zurich, ETH) (Aug, 2007)

Published in: *JHEP* 03 (2008) 003 • e-Print: 0708.2398 [hep-ph]

pdf links DOI cite claim reference search 314 citations

Highlights after 2000

With a series of seminal papers on D-dimensional unitarity, Zoltan played a key role in the development of the so-called NLO revolution

Full one-loop amplitudes from tree amplitudes

Walter T. Giele (Fermilab), Zoltan Kunszt (Zurich, ETH), Kirill Melnikov (Hawaii U.) (Jan, 2008)

Published in: *JHEP* 04 (2008) 049 • e-Print: 0801.2237 [hep-ph]

pdf links DOI cite claim reference search 356 citations

Masses, fermions and generalized D-dimensional unitarity

R.Keith Ellis (Fermilab), Walter T. Giele (Fermilab), Zoltan Kunszt (Zurich, ETH), Kirill Melnikov (Hawaii U.) (Jun, 2008)

Published in: *Nucl.Phys.B* 822 (2009) 270-282 • e-Print: 0806.3467 [hep-ph]

pdf links DOI cite claim reference search 244 citations

One-loop amplitudes for W^+ 3 jet production in hadron collisions

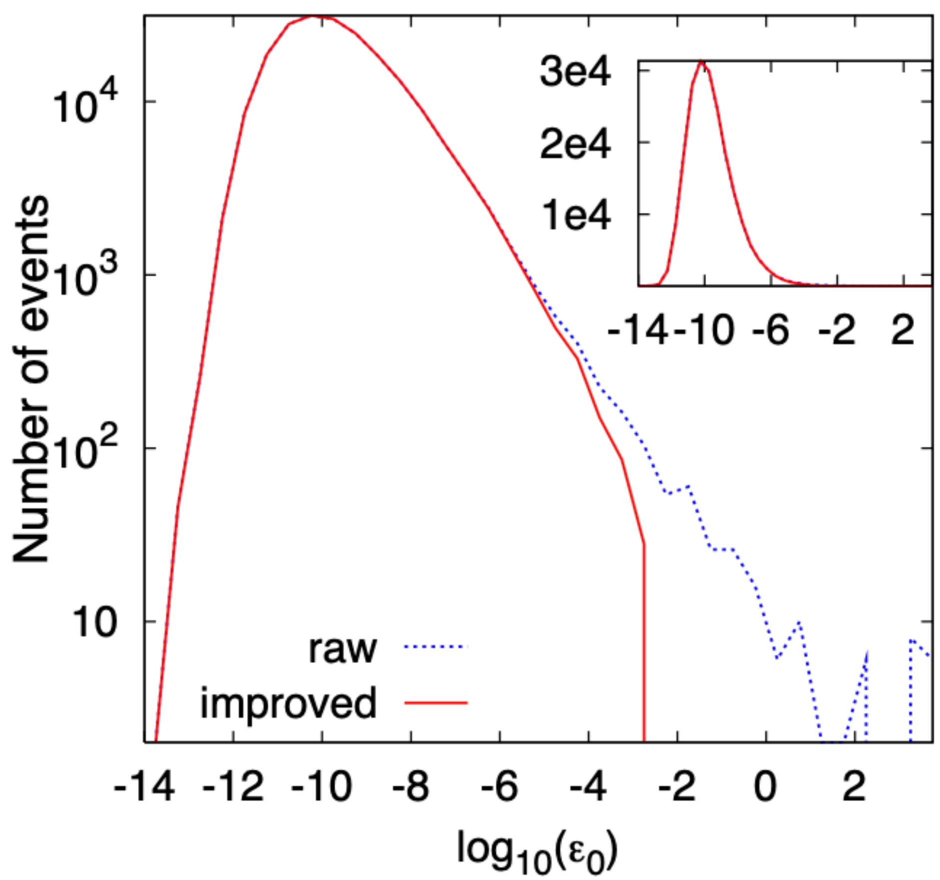
R.Keith Ellis (Fermilab), W.T. Giele (Fermilab), Zoltan Kunszt (Zurich, ETH), Kirill Melnikov (Johns Hopkins U.), Giulia Zanderighi (Oxford U., Theor. Phys.) (Oct, 2008)

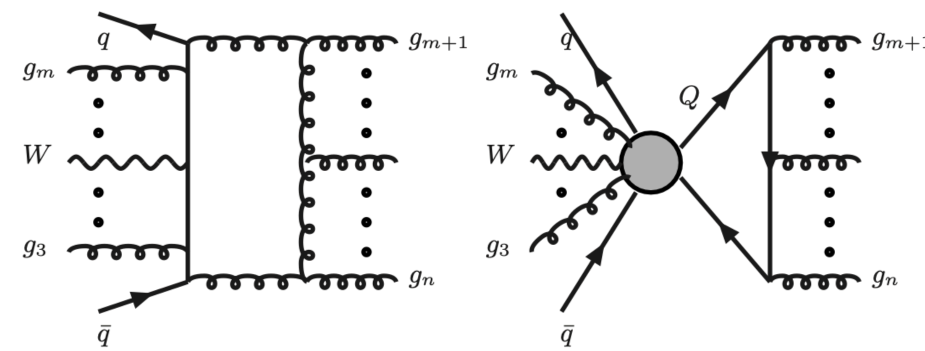
Published in: *JHEP* 01 (2009) 012 • e-Print: 0810.2762 [hep-ph]

pdf links DOI cite claim reference search 128 citations

W+3 jets

accuracy for one primitive amplitude





Helicity	$1/\epsilon^2$	$1/\epsilon$	ϵ^0
$A^{\rm tree}(1_{\bar q}^+ 2_q^- 3_g^+ 4_g^+ 5_g^+ 6_{\bar l}^+ 7_l^-)$			$-0.006873 + i\,0.011728$
$r_L^{[1]}(1_{\bar q}^+ 2_q^- 3_g^+ 4_g^+ 5_g^+ 6_{\bar l}^+ 7_l^-)$	-4.00000	$-10.439578 - i\,9.424778$	$5.993700 - i\,19.646278$
$A^{\rm tree}(1_{\bar q}^+ 2_q^- 3_g^+ 4_g^+ 5_g^- 6_{\bar l}^+ 7_l^-)$			$0.010248 - i\,0.007726$
$r_L^{[1]}(1_{\bar q}^+ 2_q^- 3_g^+ 4_g^+ 5_g^- 6_{\bar l}^+ 7_l^-)$	-4.00000	$-10.439578 - i\,9.424778$	$-14.377555 - i\,37.219716$
$A^{\rm tree}(1_{\bar q}^+ 2_q^- 3_g^- 4_g^+ 5_g^+ 6_{\bar l}^+ 7_l^-)$			$0.495774 - i\,1.274796$
$r_L^{[1]}(1_{\bar q}^+ 2_q^- 3_g^- 4_g^+ 5_g^+ 6_{\bar l}^+ 7_l^-)$	-4.00000	$-10.439578 - i\,9.424778$	$-1.039489 - i\,30.210418$
$A^{\rm tree}(1_{\bar q}^+ 2_q^- 3_g^- 4_g^+ 5_g^- 6_{\bar l}^+ 7_l^-)$			$-0.294256 - i\,0.223277$
$r_L^{[1]}(1_{\bar q}^+ 2_q^- 3_g^- 4_g^+ 5_g^- 6_{\bar l}^+ 7_l^-)$	-4.00000	$-10.439578 - i\,9.424778$	$-1.444709 - i\,26.101951$

Paper written in the phase when unitarity methods were still being tested and validated; all ingredients provided for the computation of the full NLO cross section

Ellis, Giele, Kunszt, Melnikov, GZ, 0810.2762

Review on unitarity

Contents

⇨ **Very pedagogical, many worked out examples. Input and contributions of Zoltan absolutely crucial**

Ellis, Kunszt, Melnikov, GZ, 1105.4319

Conclusions

The field of perturbative computations for multi-particle processes went through a remarkable transformation in the past few years. During these years, the ability to perform specific computations that are of importance for the Tevatron and the LHC physics program has increased beyond the most optimistic expectations. The improvement in our understanding of perturbative quantum field theory – that is a byproduct of these exciting developments – gives us hope that the momentum of the past several years can be carried forward, so that even more complicated physics – both in terms of the number of external particles and in terms of the number of loops – can be addressed.

Ellis, Kunszt, Melnikov, GZ, 1105.4319

A few personal recollections

Looking for pictures of Zoltan …

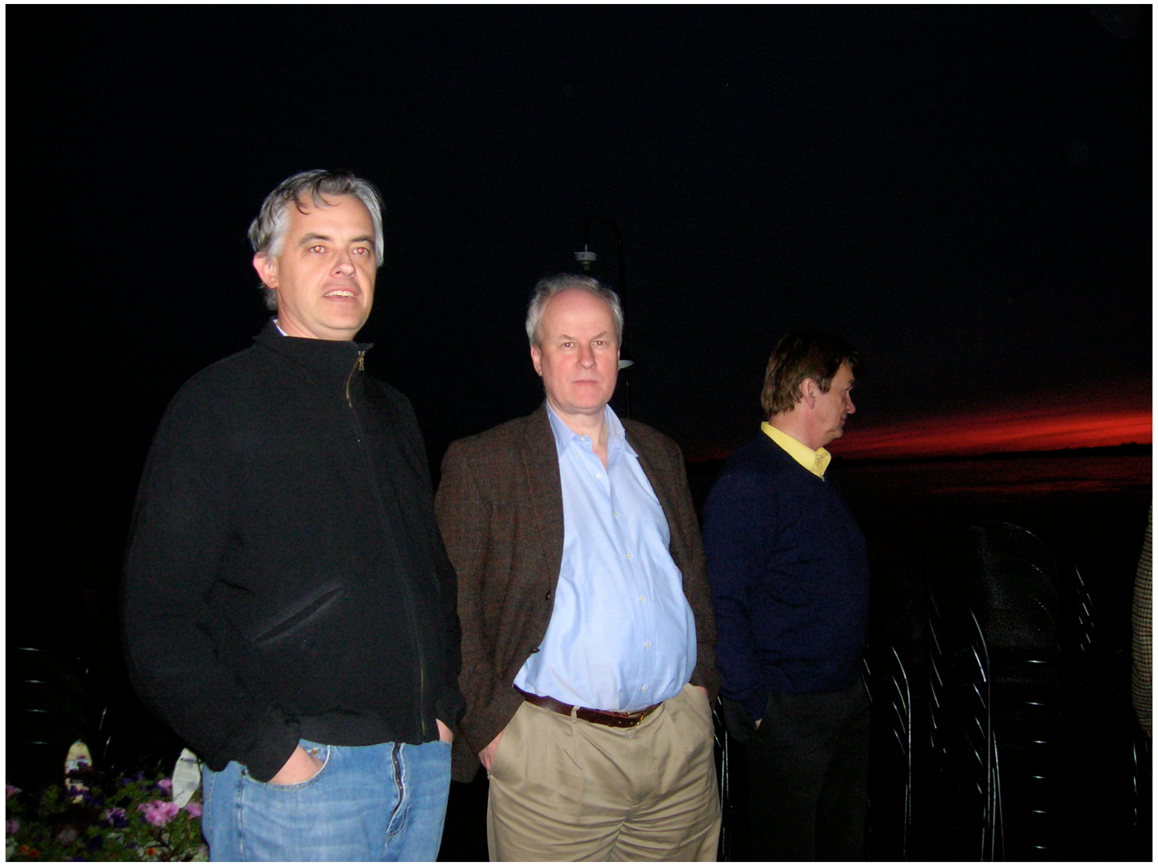
Looking for pictures of Zoltan …

Santa Barbara 2004!?

Santa Barbara 2004!?

Santa Barbara 2004!? Crazy times, but no pictures of Zoltan ...

Loopfest in Buffalo in 2006!!!



Zoltan’s free time at Loopfest …

Zoltan’s free time at Loopfest …


The Marriage
of
and

Happy Birthday Zoltan!