A History of CTEQ: The Coordinated Project on Theoretical and Experimental Studies of QCD

The CTEQ Collaboration
Editor: Jeff Owens

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1 Introduction

Editor: Jeff Owens

The CTEQ Collaboration had its start in 1990 when a proposal was submitted to the Texas National Laboratory Research Commission for a project to study issues related to the use of Quantum Chromodynamics (QCD) in order to understand data expected from the Superconducting Super Collider that was under construction in Waxahatchie, Texas. From the outset, the project was designed to bring together theorists and experimentalists with the aim of addressing fundamental issues relating to the structure of the nucleon from lepton-nucleon deep-inelastic scattering and, in particular, understanding large momentum transfer processes as measured in high energy experiments. This document describes the history of the project and summarizes its accomplishments over a span of several decades.

In order to understand how CTEQ came about, it is useful to step back and take a brief look at some developments in high energy physics that preceded its formation. With the development of the Electroweak theory in 1967 and of Quantum Chromodynamics (QCD) in 1973, the basic elements of the Standard Model were in place. The search for higher center-of-mass energy collisions led to the development of high energy colliders - the CERN ISR with proton-proton collisions with $\sqrt{s}$ up to 62.4 GeV in the 1970s and the CERN SPS proton-antiproton collider with $\sqrt{s}$ up to over 600 GeV in the 1980s. By the mid-1980s there was a basic understanding of how to apply QCD to the description of large momentum transfer processes, at least using the lowest order matrix elements. However, more theoretical input was needed for precision predictions. For example, precise parton distribution functions were needed to connect perturbative QCD predictions at the parton level to measurements at the hadron level. Higher order calculations were needed to improve the accuracy of the theoretical predictions. Perhaps most importantly, a better understanding of what observables should be measured was needed along with an understanding of how they should be defined in order that meaningful perturbative predictions should be made.

During the 1980s there was much activity on the theoretical side on topics such as string theory and lattice field theory. Neither of these areas were developed to the point where they would be relevant for predictions of observables in large momentum transfer processes. A report commissioned by the Division of Particles and Fields (the Peccei Report) advocated a return to "physics in four dimensions" specifically addressing issues related to collider physics. Simultaneously in the 1980s a series of Fermilab-organized "Snowmass" workshops were held that included working groups of theorists and experimentalists, many of them future CTEQ members. These working groups were considering the then-current lepton-nucleon/nucleus deep-inelastic scattering experiments and how to best encompass their global results within a common description of the structure of the nucleon.

At this time a competition was underway to determine the eventual site for the SSC. In the end, Waxahatchee Texas was chosen. As part of its proposal, the State of Texas allocated $100 million for the support of high energy collider physics groups outside of Texas. In response to a call for proposals, a proposal was submitted by Wu-Ki Tung together with about a dozen other physicists, a group that included both theorists and experimentalists. A copy of that proposal is included on the CTEQ History website and it can be accessed here.

This proposal was ultimately chosen for funding at the level of $250,000 per year and a meeting of the participants was held at a hotel located at O'Hare Airport in 1991. At this formative meeting the basic concept for CTEQ was developed. Although the main focus was to improve the communication between theorists and experimentalists involved in the study of large momentum transfer processes, improved communication in the study of nucleon structure with lower-energy experiments was also important. The participation of both theorists and experimentalists was thought to be key in order for everyone to better understand what could be measured, what could be calculated, and how best to compare the two. Several key decisions were made:

- There should be a Summer School designed for advanced graduate students and post-docs in order to present essential fundamentals of high-energy interactions as well as to disseminate the results of CTEQ-led investigations
- There should be topical workshops to bring together experts on various topics in a venue where they could share questions and ideas
- There should be quarterly meetings to develop the reports needed for continued funding from The Texas National Laboratory Research Commission.
- It was envisioned that subgroups within CTEQ would be formed to investigate interesting issues as they came up. By including both theorists and experimentalists in these subgroups, good communication would be ensured so that meaningful results and their applications could be developed.

The above list of CTEQ activities has carried through to the present day, although the quarterly meetings soon became a single annual meeting. And with the cancellation of the SSC project the funding from the State of Texas ceased after two years. The National Science Foundation and the Department of Energy have both contributed to the funding of the Summer Schools, as have various National Laboratories including Fermilab, Brookhaven National Lab, and DESY. Other funding has come from the research grants of the CTEQ members.

The remainder of this document will be used to describe the history of our Summer Schools, our Workshops, and some of the physics projects in which CTEQ members have participated.

2 Summer Schools

Editors: Jorge Morfin, Zack Sullivan, and Fred Olness

CTEQ Summer Schools Since 1992, over one thousand physicists have attended the CTEQ Summer Schools which have played a seminal role promoting the knowledge of quantum chromodynamics (QCD), its applications to electroweak precision measurements, and new physics searches. Certainly the discovery of the Higgs Boson at the LHC highlights the need to better understand these tools as we investigate whether this is purely a Standard Model (SM) Higgs or an admixture with an exotic component. Some of the early students have returned as lecturers at more recent schools.[1] The CTEQ schools have proven to be extremely useful for students involved at both the Intensity Frontier and the Energy Frontier. In particular for many of the experimentalist students, the CTEQ schools offered a first exposure to the deeper theoretical concepts important for understanding the results of their experiments.

The schools consist of eight days of lectures and discussion where students interact closely with distinguished experts with a broad range of expertise. The audience for these schools is primarily the younger generation of high energy elementary particle physicists—typically advanced graduate students and postdocs, and are roughly evenly divided between experimental and theoretical disciplines.

This school provides the participants with a deeper understanding and improved competency of the fundamental ideas, tools, and techniques that serve as the foundation for all our current investigations of the Standard Model (SM) and beyond. The broader impact is conveyed through the students' strengthened awareness of the context of their research in the overall endeavor of fundamental physics. The interactive nature of the schools encourages the skills necessary for communicating the excitement and results within the diverse community of collaborations, and also to the wider public.

Past Schools: Since 1992, twenty-five of these CTEQ Summer Schools have been held: fourteen in the United States, eight in Europe, one in Mexico, one in South America, and one in China. In recent years, the school alternates between a US and a foreign location. The US based schools were hosted at the UW-Madison campus during 2002-2011 and have been hosted at the University of Pittsburgh since 2013. The schools have been funded by DOE and NSF.

For the US-based schools, we typically had 60 to 70 students; the number for the foreign schools varies from 60 to 90 depending on the venue and other constraints.[2]

[1] Examples include: Ingo Schienbein (LPSC), Andrzej Siodmok (Cracow INP), Simon Platzer (Vienna U), Mike Seymour (Manchester), Günther Dissertori (ETH), Voica Radescu (DESY), Fernando Febres Cordero (Freiburg), Burkhard Reisert (MPI Munich).

[2] Specifically, the 2014 school in Beijing had 90 students, and the 2016 school in Hamburg had 80 students.

List of CTEQ Summer Schools

	Year	Location	Date	Notes
1	1992	Mackinac Island, MI	27 May - 3 June	
2	1993	Lake Monroe, IN	25 July - 3 August	
3	1994	Lake Ozark, MO	10 - 18 August	
4	1995	Bad Lauterberg	17 - 25 July	DESY[a]
5	1997	Lake Como, WI	27 May - 4 June	
6	1998	Courmayeur, Italy	8-16 July	INFN[b]
7	2000	Lake Geneva, WI	30 May - 7 June	
8	2001	St. Andrews, Scotland	17 - 26 June	IPPP[c]
9	2002	UW-Madison, WI	2 - 10 June	
10	2003	Sant Feliu, Spain	22-30 May	IFAE[d]
11	2004	UW-Madison, WI	22-30 June	
12	2005	Puebla, Mexico	19-27 May	BUAP[e]
13	2006	Rhodes, Greece	1 - 9 July	
14	2007	UW-Madison, WI	30 May - 7 June	
15	2008	Debrecen, Hungary	8 - 16 August	with MCnet[f]
16	2009	UW-Madison, WI	24 June - 2 July	
17	2010	Lauterbad, Germany	26 July - 4 August	with MCnet
18	2011	UW-Madison, WI	10 - 20 July	
19	2012	Lima, Peru	30 July - 9 August	Fermilab & PUCP[g]
20	2013	Pittsburgh, PA	7 - 17 July	PITT-PACC[h]
21	2014	Beijing, China	8-18 July	University of Beijing
22	2015	Pittsburgh, PA	7 - 17 July	PITT-PACC
23	2016	Hamburg, Germany	6 - 16 July	DESY with MCnet
24	2017	Pittsburgh, PA	18-28 July	PITT-PACC
25	2018	Puerto Rico	18-28 June	U. of Mayagëz
26	2019	Pittsburgh, PA	22 July - 1 August	PITT-PACC
–	2020[i]	Karlsruhe, Germany	2 - 12 August	with MCnet
27	2021	Dresden, Germany *(Virtual)*	6-16 September	with MCnet
28	2022	Pittsburgh, PA	6-16 July 2022	PITT-PACC

[a] Deutsches Elektronen-Synchrotron (DESY).
[b] Istituto Nazionale di Fisica Nucleare (INFN), Italy.
[c] Institute for Particle Physics Phenomenology (IPPP), University of Durham.
[d] Institut de Fisica d'Altes Energies (IFAE), Universitat Autonoma de Barcelona.
[e] Benemerita Universidad Autonoma de Puebla (BUAP)
[f] MCnet is a European Union funded Marie Curie Research Training Network.
[g] Pontificia Universidad Católica del Perú (PUCP) Lima, Peru
[h] University of Pittsburgh Particle physics, Astrophysics, and Cosmology Center (PITT PACC).
[i] Canceled due to COVID-19.

Table 1: List of CTEQ Summer Schools.

CTEQ has collaborated with the MCnet[3] collaboration for a number of our schools. In particular, the 2008, 2010 and 2016 summer schools were hosted jointly by CTEQ and MCnet, and featured very popular "hands-on" tutorial sessions working with the Pythia, Herwig, and Sherpa Monte Carlo programs.

The Students:

Most participants at these schools are advanced graduate students (beyond their course work) and postdocs. The international reputation of the School is evidenced by the substantial participation from Europe and Asia, and by the desire of other countries/institutions to host future schools; typically, one third of the students come from abroad for schools held in the United States.

Interaction with Lecturers

An essential element of the CTEQ Schools is complete immersion in the topics. Everyone—both students and lecturers—participates in the lectures, meals, recitations, and evening session. This interaction provides the students with an opportunity to think and discuss the day's lecture topics in an informal setting where they can revisit points that may be confusing, and dig into questions that are relevant for their own research. This interaction between students and lecturers is one of the hallmarks of the CTEQ summer schools.[4] This project enables the CTEQ School to provide access to a diverse group of expertise from outside the CTEQ Collaboration.

Following the School, we ask the students for feedback regarding the lectures; many students commented about the interaction with the lecturers.

Sample Agenda: The 2019 School The 2019 CTEQ Summer School followed the very successful format of previous schools consisting of 8 days of lecture, split into two 4-day halves with one free day in the middle. A typical day consists of 4 full hours of lecture, a 1.5 hour "recitation" session where students can ask questions they typically are reluctant to ask during lectures, and a concluding 1.5 hour "nightcap" where all participants mix in a relaxed setting to continue discussions on a personal level one-on-one or in small groups. Including arrival and departure days this calls for a ten night span of the school.

The physics program for 2019 followed the lines of previous schools. A series of introductory lectures on fundamentals of perturbative QCD was followed by a more advanced component of specialized and contemporary topics–a format

[3]MCnet is a European Union funded Marie Curie Research Training Network dedicated to developing the next generation of Monte Carlo event generators and providing training of a wide selection of its user base, particularly through funded short-term residencies and Annual Schools. `http://www.montecarlonet.org/`

[4]An interesting anecdote came from the 2009 summer school. A student asked a question of one of the lecturers (Scott Dodelson) during a recitation; Scott said that this was a fairly basic question, but one which no one had thought to ask before. The resultant paper based on the question has now been published in PRL. (Dodelson & Vesterinen, Phys. Rev. Lett. 103 (2009) 171301.)

which has proven to be extremely effective. Slides of lectures from the previous schools are available at the CTEQ web page during and after the schools and illustrate the careful presentation by the lectures as well as the breadth and depth of the content.

In 2019 we also included a hands-on tutorial sessions on Monte Carlo event generator programs. These sessions have been well received at past schools, and we coordinate with the members of the MCnet Collaboration. These lectures complement and broaden the discussion of hadron collider topics.

Lecturers are invited from the CTEQ Collaboration and from the worldwide QCD communities. This mix has proven effective to ease the pedagogical integration of the lectures, in particular at the introductory level.

Value of the School Since 1992, the CTEQ Summer School on QCD Analysis and Phenomenology has provided a unique opportunity for young experimentalists and theorists to learn the important ideas, tools, and techniques from experts in the field.

Intellectual Merit:

Physicists analyzing data from high energy elementary particle experiments require a good working knowledge of QCD. This is inevitable, because the constituent particles of hadrons, quarks and gluons, have strong interactions, and many of the new particles that we would like to find are also strongly interacting. For all high-energy experiments initiated by a hadron or nucleus (including those at the Tevatron, RHIC, JLAB, HERA, LBNF, LHC), an understanding of PDFs and associated QCD issues is absolutely indispensable. Equally important for experimentalists and theorists alike is a familiarity with calculations that account for the emission and exchange of quarks and gluons. The role of the CTEQ Schools is even more critical as we advance the frontiers and seek breakthroughs in our understanding of the basic nature of matter and energy, at the highest energies and densities. Adequate training of young experimentalists and theorists will be critical for the success of these programs.

Broader Impact:

The CTEQ Schools address the pressing educational needs of junior physicists involved in front-line search to incisively test the Standard Model and search for new physics, and demonstrates the inextricable role of QCD in their experimental results. The format of this educational enterprise fosters student–lecturer interaction and provides the students a deeper understanding of the fundamental physics. We believe this experience benefits our students both as they complete their experimental/theoretical analysis and toward their pursuits outside of science.

3 Workshops

Editor: Jeff Owens

From the outset CTEQ was envisioned as a collaborative effort between theorists and experimentalists. In the early 1990s there were many questions about what to measure and how to calculate relevant, precise predictions. It was felt that such a collaborative effort would lead to substantial progress as the experimentalists could tell the theorists what they could measure and the theorists could tell the experimentalists what they could calculate. Initially, CTEQ members met quarterly, although in later years the meetings would be held on an annual basis. These meetings were characterized by lively discussions which often led to progress in how best to compare theory and experiment. Rather naturally, these results led to the idea of expanding the discussions to include a wider audience by holding workshops where, again, theorists and experimentalists could devise strategies for making the best use of the latest collider results.

The CTEQ Collaboration has hosted twenty-three such workshops as of 2020, covering a wide range of topics. A complete list can be found at the main CTEQ web site located at here. Today, the concept of workshops is quite common, with many held in any given year covering a wide range of topics. But in the early 1990s when CTEQ was formed, such workshops were not at all common. In fact, the most common forum for such discussion was large summer studies such as those held at Snowmass or Les Houches. The idea of topical workshops of one or two days duration was not as common.

The first such workshop was held in 1993 at Michigan State University. It was titled QCD2TEV and was devoted to a discussion of both theoretical and experimental issues relevant to the collider program at Fermilab which was then operating at $\sqrt{s} = 1.8$ TeV. A glance at the list of workshops shows that the subject matter of each was focused on issues where there were questions about what was being measured, how it was to be compared to theory, etc. Subsequent workshops touched on topics such as Higgs boson production, Drell-Yan and vector boson production, unanswered questions related to QCD, and more. As time progressed, some of the workshops were held in conjunction with the annual CTEQ meeting with the workshops being one or two days followed by a day for the general CTEQ business meeting. And some workshops, such as that in 2016 with the POETIC Collaboration, have been held in conjunction with other collaborations.

4 Physics Projects

4.1 QCD Handbook

With the creation of the first CTEQ Summer School, it was realized that a general reference on QCD and its applications would be beneficial for the students. Accordingly, CTEQ members set out to create such a handbook. The final product, published in Reviews of Modern Physics in 1995 [1] proved to be very useful for both students and practitioners in the field. Starting with the basic QCD Lagrangian, the Handbook reviewed the basics of the parton model and then showed how QCD added new elements to this starting point. Applications to deeply inelastic lepton nucleon scattering, electron-positron annihilation, hadron-hadron scattering, and the determination of parton distribution functions were all discussed. PDF and Postscript versions are available here.

4.2 CTEQ Parton Distribution Functions

Editors: Fred Olness, Jorge Morfin

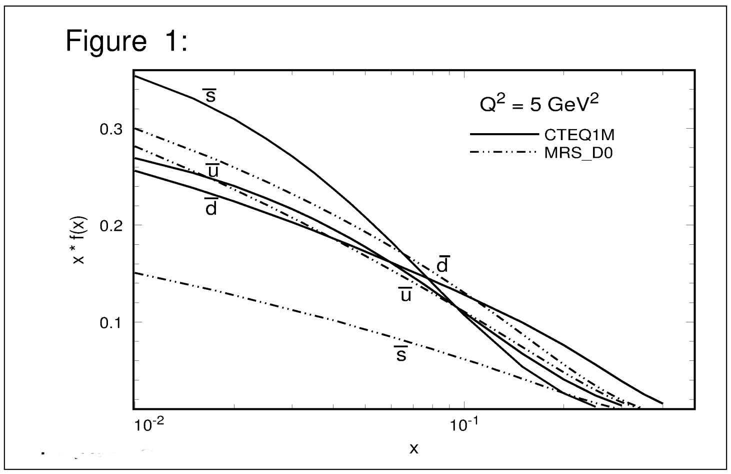


Figure 1: Plot of the CTEQ1 PDFs. We observe the large value of the $\bar{s}(x, Q)$ quark at small x.

Introduction: In the several "Snowmass" workshops preceding the establishment of the CTEQ collaboration, a collaborative effort of theorists and experimentlists (many of them future members of CTEQ) formed to combine results from various types of experiments with techniques then recently introduced [2] to better understand what these results implied for the structure of the nucleon. Several of these reports contained in the Snowmass proceedings led to more formal publications. In particular, a preliminary exercise of the CTEQ collaborative theorist/experimentalist concept was an early global fit [3] of experimental data that yielded a set of pre-CTEQ Parton Distribution Functions. Methods and techniques introduced in this effort were then improved and perfected by the CTEQ collaboration in their global fits.

CTEQ1: Ref. [4] (March 1993)

The CTEQ1 analysis was based on data on cross-sections and structure

Process	Experiment	Observable	Data Points	$\Delta\sigma$	Set
DIS	BCDMS	$F^{\mu}_{2\ H}$	168	.02	1
		$F^{\mu}_{2\ D}$	156	.02	1
	NMC	$F^{\mu}_{2\ H}$	52	.02	1
		$F^{\mu}_{2\ D}$	52	.02	1
	H1	$F^{\mu}_{2\ H}$	21	.04	2
	ZEUS	$F^{\mu}_{2\ H}$	56	.03	2
	CCFR	$F^{\nu}_{2\ Fe}$	63	.02	1
		$x\ F^{\nu}_{3\ Fe}$	63	.02	1
	NMC	F^n_2/F^p_2	89	-	1
Drell-Yan	E605	$sd\sigma/d\sqrt{\tau}dy$	119	.1	1
	CDF	$sd\sigma/d\sqrt{\tau}dy$	8	.1	2
	NA-51	A_{DY}	1	-	3
W-prod.	CDF	Lepton asym.	9	-	3
Direct γ	WA70	$Ed^3\sigma/d^3p$ $1.0 \geq y \geq -.75$	39	.10	1
	E706	$Ed^3\sigma/d^3p$ $y = 0$	8	.15	1
	UA6	$Ed^3\sigma/d^3p$ $y = .3$	16	.10	1

Table 1: The data sets used in the CTEQ global analyses. Data sets marked with 1 in the final column were used for the CTEQ1 and later fits. Those with a 2 or 3 were added for the CTEQ2 and CTEQ3 analyses respectively. The column labelled $\Delta\sigma$ gives the overall normalization systematic error used in defining the χ^2, as discussed in the text.

Figure 2: Table showing the input data for the {CTEQ1, CTEQ2, CTEQ3} sets.

functions available at the end of 1992 for DIS and Drell-Yan data, and was focused to improve sensitivity of the sea quark PDFs. Very good fits to this wide range of data were obtained—both the overall χ^2 and the χ^2 distribution among the experimental data sets indicated a remarkable degree of consistency.

The CTEQ1 analysis highlighted two main observations. i) The strange quark PDF was softer than the non-strange sea quarks, and rose quickly at small x; the fact that $s(x) > \bar{d}, \bar{u}$ was striking. ii) The difference $(\bar{d} - \bar{u})$ changed sign as a function of x.

One disturbing feature of the CTEQ1 parton distributions was that the strange quark distribution $s(x, Q)$ obtained was considerably larger in the $x < 0.1$ region then those obtained from leading-order parton model analysis of the neutrino dimuon production data. It was pointed out that this $s(x, Q)$ behavior followed from the high precision input data sets on total inclusive DIS structure functions through the familiar ("charge ratio") parton model identity $s(x, Q) = \frac{5}{6} F_2^{\nu N} - 3F_2^{\mu N}$. This combination of structure functions entails using the (small) difference between two larger numbers to play a decisive role in the determination of $s(x, Q)$.

CTEQ2: (No separate publication; only a PDF release.)

Shortly after the release of the CTEQ1 paper and PDFs, the CTEQ2 PDF sets were released; there was not an accompanying paper, but the details are described in the CTEQ3 paper.

The CTEQ2 analysis was initiated after the first measurement of $F_2^{ep}(x, Q)$ from HERA became available. These new data not only extended the measured range of x by two orders of magnitude; they also offered the possibility of formulating the global analysis in an alternative way in the face of the dilemma exposed by the CTEQ1 study. The HERA data provide very useful constraints on the small-x behavior of the parton distributions even with their relatively large initial errors because of the extended reach down to $x \sim 10^{-4}$.

CTEQ2 modified the input used in the CTEQ1 analysis by adding the new HERA data in conjunction with: (i) using a parametrized function $s(x, Q_0)$; (ii) removing the conflicting DIS F2 data between $x = 0.01$ and $x = 0.09$ which drove the large strange sea through the charge ratio relation; (iii) including the CTEQ1 fixed-target lepton-pair and direct photon production data sets; and (iv) adding the new collider data on lepton-pair production obtained by CDF.

CTEQ3: Ref. [5] (October 1994)

CTEQ3 extended the CTEQ2 analysis by including data from the Tevatron Collider for the first time; especially, the new CDF data on the W-asymmetry. This, together with the NA51 Drell-Yan asymmetry measurement provided new constrains on the u and d quarks.

CTEQ4: Ref. [6] (June 1996)

CTEQ4 PDFs added the Tevatron jet measurements $(d\sigma/dE_T)$ to the collection of data sets. Preliminary comparisons found that the jet cross sec-

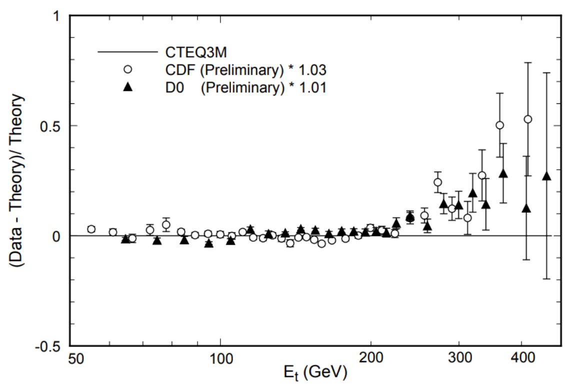


Figure 9 : Inclusive jet cross-section measured by the CDF and D0 collaborations in Run-IB at the Tevatron normalized to NLO QCD calculations based on CTEQ3M PDF's. The difference in rapidity coverage of the two experiments is taken into account.

Figure 3: Comparison with the Tevatron jet data showing the differences at high E_T values.

Process	Experiment	Measurable	Data Points	Ref.
DIS	BCDMS	$F_2^\mu{}_H, F_2^\mu{}_D$	324	[26]
	NMC	$F_2^\mu{}_H, F_2^\mu{}_D, F_2^\mu{}_{n/p}$	297	[18]
	E665	$F_2^\mu{}_H, F_2^\mu{}_D$	70	[21]
	H1	$F_2^e{}_H$	172	[19]
	ZEUS	$F_2^e{}_H$	179	[20]
	CCFR	$F_2^\nu{}_{Fe}, x\ F_3^\nu{}_{Fe}$	126	[27]
Drell-Yan	E605	$sd\sigma/d\sqrt{\tau}dy$	119	[28]
	NA-51	A_{DY}	1	[29]
W-prod.	CDF	Lepton asym.	9	[30]
Direct γ	WA70	$Ed^3\sigma/d^3p$	8	[3]
	UA6	$Ed^3\sigma/d^3p$	16	[31]
Incl. Jet	CDF	$d\sigma/dE_t$	36	[7]
	D0	$d\sigma/dE_t$	26	[8]

Table 2: List of processes and experiments used in the Global analysis.

Figure 4: Table showing the input data for the CTEQ4 set.

tions exceeded the theory predictions in the highest few E_T bins in the region $E_T \gtrsim 300$ GeV, and this could be interpreted as a signal for quark or gluon compositeness—certainly a very intriguing possibility.

Instead, the resolution was that a modified gluon PDF could accommodate the excess, and the paper stated: "The observed high E_T 'excess' jet cross-section can be accommodated by a modified gluon distribution, represented by the CTEQ4HJ set, since no other independent measurement constrains it in this range."

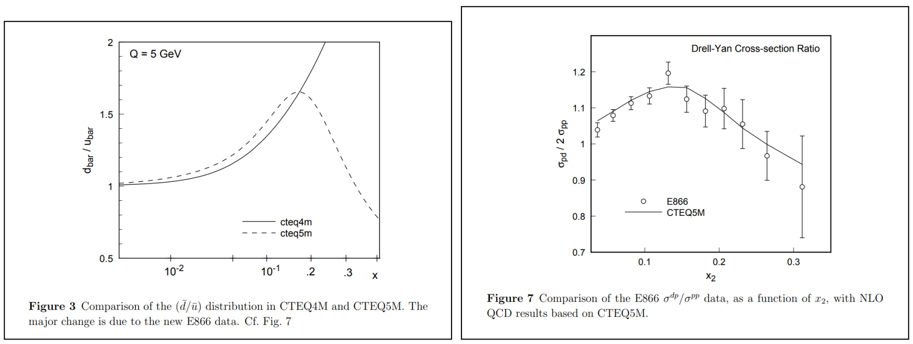


Figure 5: Figures showing the (left) comparison of the $\bar{d}/\bar{u}$ CTEQ4 and CTEQ5 PDFs, and the E866 data that drove the change.

CTEQ5: Ref. [7] (May 1999)

The CTEQ5 PDFs added the E866 Drell-Yan data. The paper states: "Lepton-pair production (p/d) asymmetry: The E866 collaboration has measured the ratio of lepton-pair production (Drell-Yan process) in *pp* and *pd* collisions over the x range 0.03–0.35, thus expanding greatly the experimental constraint on the ratio of parton distributions $\bar{d}/\bar{u}$ (compared to the single point of NA51 at $x = 0.18$). This data set has the most noticeable impact on the new round of global analysis."

The lepton pair production data uniquely provides strong constraints on the $\bar{d}/\bar{u}$ ratio. In the CTEQ4 fit, only the single NA51 data point was available; when this was included in the CTEQ4 fit, the extrapolation of the $\bar{d}/\bar{u}$ ratio increased at large x values (*c.f.*, Fig. 5-a).

The E866 σ^{dp}/σ^{pp} data exhibited a distinctive turn-over for $x_2 \sim 0.15$ and this resulted in the CTEQ5 $\bar{d}/\bar{u}$ turning over and decreasing at large values of x—in contrast to the CTEQ4 extrapolation, (*c.f.*, Fig. 5-b). To model this effect accurately, the underlying PDF parametrization was modified to better capture these features.

CTEQ6: Ref. [8] (Nov. 2002)

The CTEQ6 PDFs extended the previous analysis by including PDF uncertainties utilizing the Hessian eigenvectors as the coordinate basis in the parameter space. It also included a study of higher twist effects and parametrization impact.

Beyond CTEQ6: As the CTEQ PDF global analysis effort evolved, it branched into three separate projects. The "CT" effort extended the analysis of proton PDFs along the lines of the previous work. A joint collaboration between CTEQ and the JLab scientists resulted in the "CJ" project which extended the analysis into the large-x region explored by the JLab experiments. Prompted by the extensive data on nuclear targets (e.g., from the νN experiments), the "nCTEQ" project extended the analysis to include the nuclear dimension and produced a full range of nuclear PDFs. All three of these projects are currently ongoing.

4.3 CJ: CTEQ–JLab Parton Distribution Functions

Editor: Jeff Owens

Long baseline neutrino experiments involve both a near and a far detector. It is of paramount importance to understand the nature of deep inelastic and so-called shallow inelastic neutrino events in order to understand the response of each detector to the neutrino beams. Simulating these often involves the use of PDFs at lower values of Q^2 and higher values of x than most PDF sets provide. Jorge Morfin, in particular, repeatedly emphasized the need for such PDFs. The problem is that as one goes to such regions of Q^2 and x various power suppressed contributions become increasingly important. Higher Twist (HT) contributions and Target Mass Corrections (TMC) must be taken into account, introducing model dependence and thereby complicating PDF analyses that traditionally only included leading twist contributions [5]. Furthermore, one needs data in these extended kinematic regions. Traditional high energy deep inelastic experiments tend to concentrate on Q^2 values above about 4 GeV and x values below about 0.7. However, data from Jefferson Lab do cover the necessary kinematic regions. Accordingly, CTEQ members Alberto Accardi and Cynthia Keppel from Jefferson Lab, Jorge Morfin from Fermilab, and Jeff Owens from Florida State University teamed up with scientists from Jefferson Lab to form the CJ (CTEQ-Jefferson Lab) Collaboration to explore this expanded kinematic region. In addition to the four CTEQ members listed above, CJ initially included Eric Christy, Wally Melnitchouk, and Peter Monaghan from Jefferson Lab.

Of particular interest to the CJ members is the behavior of the d/u ratio in the region $x \to 1$. The standard method of studying this ratio involves the use of deuterium targets to obtain information on the neutron structure function. Since the valence content of the proton is uud and that of the neutron is ddu, comparing F_2^p and F_2^n provides information on the behavior of the d quark

[5] Leading twist refers to PDFs that have the characteristic logarithmic Q^2 dependence predicted by QCD. Higher twist contributions are suppressed by one or more powers of Q^2. In the CJ work HT contributions proportional to Q^{-2} are included

PDF. In order to perform fits including the deuteron structure function one must include effects due to the nuclear structure of the deuteron. Traditional high energy experiments using deuteron targets are usually limited to the region $x < 0.7$ where such nuclear effects are small. However, interest in the large-x region necessitated the use of a model for the nuclear corrections.

The first CJ analysis [9] included HT, TMC, and deuterium nuclear corrections in a traditional fit to DIS, lepton pair production, and high-p_T jet production data. The main conclusion was that the model dependence of the nuclear corrections was largely compensated by the parametrized HT contributions, thereby yielding twist-2 PDFs that were relatively stable to model variations. This was an excellent result in that it showed that one could achieve extractions of the leading twist PDFs over the extended kinematic regions in x and Q^2. This was by no means guaranteed since the power suppressed $1/Q^2$ contributions could mask the QCD predicted logarithmic dependence in Q^2 over a limited region in Q^2.

The next CJ analysis [10] focused on studying sources of uncertainty in the extraction of PDFs, specifically that of the d quark. The impact of different choices of nuclear correction models was closely studied. It was pointed out that the rapidity charge asymmetry of $W^{\pm}$ vector bosons at colliders provides constraints on the d PDF that are not dependent on nuclear corrections. Therefore, constraints form these data provide constraints on the nuclear correction model that is used. This is an interesting interplay between high energy and low energy phenomenology. This interplay was further explored in [11]

The previous two analyses concentrated on the corrections used to extend the analyses to lower regions of Q^2 and higher regions of x. The next publication [12] focused on extracting parametrizations of the PDFs themselves. This first set of PDFs is referred to the CJ12 PDFs and may be found in the LHAPDF repository. Refinements to this analysis [13] were subsequently developed and resulted in the CJ15 PDF set which is also included in the LHAPDF repository.

Most recently a study of the shape of the $\bar{d} - \bar{u}$ asymmetry [14] has been published. This study made use of the constraints on the antiquark PDFs that are provided by the interplay of DIS and lepton pair production data.

CJ activities are continuing with the current focus being on benchmarking the program package against those of other groups and studies of the contraints on the s quark PDF provided by LHC vector boson production data, and on the light antiquark sea by vector boson production at RHIC.

4.4 nCTEQ: nuclear CTEQ

Editors: Fred Olness, Jorge Morfín, and Jeff Owens

Many types of high energy experiments have been performed on nuclear targets in order to increase the measured event rates. Neutrino experiments in particular have often utilized heavy targets such as iron, lead, or tungsten. It has been known for some time that the PDFs in nuclei differ from those in single nucleons, thereby making the interpretation of the results of experiments using nuclear targets in terms of nucleon PDFs somewhat problematic.

The nCTEQ project is an extension of the CTEQ collaborative effort to determine nuclear parton distribution functions (nPDFs). It generalizes the free-proton PDF framework to the nuclear case by computing the densities of a proton within the nuclear environment. Hence nCTEQ, which stands for "nuclear CTEQ." These nPDFs are actually effective parton distributions since, in several cases, the interaction takes place with multiple nucleons within the nucleus.

To date a number of such fits have been performed and sets of nuclear PDFs have been produced. Details of these releases can be found at **www.ncteq.org**. A number of publications have been produced detailing the PDF sets and their impact on analyzing nuclear target data. These nCTEQ publications include the following [15, 16, 17, 18, 19, 20].

The DIS processes are crucial for this analysis, and the the charged-current νN data is especially valuable as it provides four observables $\{F_2^{\nu}, F_2^{\bar{\nu}}, F_3^{\nu}, F_3^{\bar{\nu}}\}$ which can be used to disentangle the parton flavors. Due to the small neutrino cross section, this data is typically performed on heavy targets (Fe, Pb) so it is necessary to apply nuclear corrections to extract the proton PDFs. While there have been attempts to determine the proton PDF without the nuclear data, a recent analysis demonstrates the PDF central value and uncertainties are significantly impacted when this data is neglected. Thus, the data from nuclear targets is absolutely essential to the extraction of the proton PDFs; this is the motivation behind the nCTEQ project which extends the pioneering work of the CTEQ by incorporating the nuclear degrees of freedom. This can improve theoretical predictions for both the proton and nuclei, and extend the reach for new discoveries.

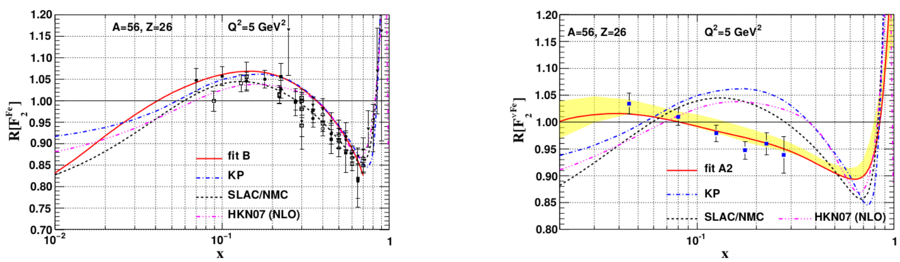
Prior to the nCTEQ work, a "frozen" nuclear correction was applied to the nuclear data to "convert" this into proton data. In contrast, the nCTEQ project integrated the nuclear degrees of freedom into the fit dynamically on an equivalent footing to the proton parameters providing the ability to study the interdependence between the proton and nuclear PDFs. Thus, when one observed a tension between two data sets, it was possible to modify *both* the underlying proton PDFs and the nuclear corrections to search for a resolution; this feature is especially crucial for investigating the strange PDF.

The nCTEQ framework allows the correction factors to be integrated *dynamically* into the fit to better identify tensions between data sets, and to extract more accurate PDF error sets for both protons and nuclei.

nCTEQ15: The first nCTEQ publication was Ref. [15] "Nuclear PDFs from neutrino deep inelastic scattering" with authors I. Schienbein, J.Y. Yu, C. Keppel, J.G. Morfin, F. I. Olness, & J.F. Owens.

The nCTEQ15 PDF set was the first complete release with nuclear uncertainties. [18] These PDFs provided a more precise analysis of the heavy target DIS and DY data which enter the fit, and thus improved the constraints on the separate flavor components of the PDF.

The uncertainties were determined using the Hessian method with an optimal rescaling of the eigenvectors to accurately represent the uncertainties for the chosen tolerance criteria. In addition to the Deep Inelastic Scattering (DIS) and Drell-Yan (DY) processes, the fit included inclusive pion production data to help constrain the gluon PDF. Furthermore, the correlation of the data sets with specific flavor components was investigated to asses the impact of individual experiments. These PDFs have been used for a variety of analyses by the community.[18]



(a) (b)

Figure 6: Figure from Ref. [16]. The computed nuclear correction ratio, F_2^{Fe}/F_2^D, as a function of x for $Q^2 = 5\ GeV^2$. Figure-a) shows the fit using charged-lepton–nucleus ($\ell^{\pm}A$) and DY data, whereas Figure-b) shows the fit using neutrino-nucleus (νA) data. Both fits are compared with the SLAC/NMC parameterization, as well as fits from Kulagin-Petti (KP) and Hirai et al. (HKN07). The data points displayed in Figure-a) are from SLAC and BCDMS data, and those displayed in Figure-b) come from the NuTeV experiment.

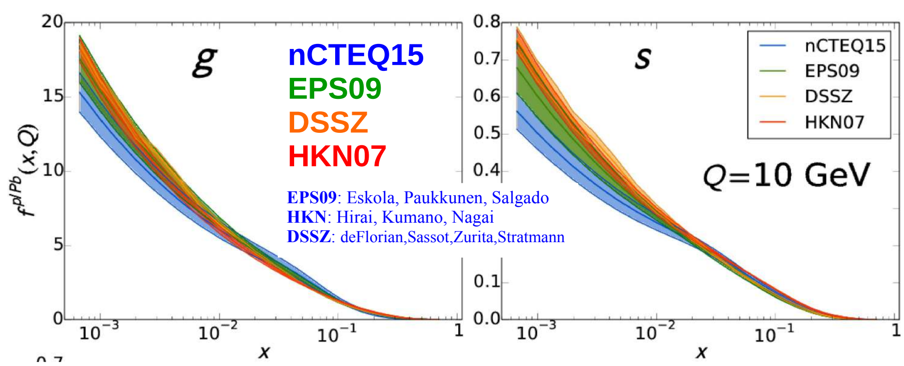


Figure 7: Selected flavors of nCTEQ15 from Ref. [18] compared with other results from the literature.

5 Wu-Ki Tung Award

Editor: Jeff Owens

In 2014 the CTEQ Collaboration created the Wu-Ki Tung Award for Early-Career Research on QCD. The Wu-Ki Tung award is to recognize outstanding contributions made by early-career physicists on experimental or theoretical research on Quantum Chromodynamics. The award is given annually and consists of a certificate citing the contributions of the recipient and support for travel to a CTEQ Summer School to deliver an invited lecture. Nominees must have received a Ph.D. in experimental or theoretical particle physics within the last seven years, excluding any career breaks, by the time of nomination. The Wu-Ki Tung Award web page is located here.

Past Recipients:

2021: Phiala Shanahan, Massachusetts Institute of Technology Citation: "For pioneering studies of long-wavelength and nuclear nonperturbative QCD effects in discretized space and time, and for applications of machine learning to lattice field theory."

2020: Bernhard Mistlberger, SLAC National Accelerator Laboratory Citation: "For pioneering theoretical computations of multi-loop radiative contributions for precision Higgs and electroweak physics at hadron colliders."

2019: Valerio Bertone, University of Pavia Citation: "For innovative contributions to the precise determination of parton distribution and fragmentation functions, and for the development of cutting-edge software to perform global fits."

2018: Benjamin Nachman, Lawrence Berkeley National Laboratory Citation: "For significant contributions to experimental studies of jet substructure, and for the discrimination of possible new physics signatures from QCD backgrounds using jet substructure."

2017: Andrew Larkoski, Reed College Citation: "For seminal contributions to the theoretical understanding of jet substructure and to the application of that understanding to the analysis of experimental data."

2016: Ciaran Williams, State University of New York, Buffalo Citation: "For significant contributions to higher-order QCD calculations for hadron scattering processes, and for their practicable implementation for the analysis of hadron collider data."

2015: Mikko Voutilainen, Helsinki Institute of Physics Citation: "For outstanding contributions to the development of innovative techniques for jet energy calibration and the measurement of the inclusive jet cross section at the D-Zero and CMS experiments."

2014: Stefan Hoeche, SLAC National Accelerator Laboratory Citation: "For seminal contributions to the advancement of parton-shower event generators and the development of novel matching schemes to exploit higher-order QCD calculations."

6 Members

6.1 Spokespersons

CTEQ has traditionally had two spokespersons - one theorist and one experimentalist. These are chosen by vote of the membership and each spokesperson serves a two year term. The theoretical and experimental positions are filled in alternate years so that there is an overflap should a new spokesperson be elected.

Experimental Spokespersons

- Jorge Morfin (1991-2000)
- Steve Kuhlmann (2001-2006)
- Joey Huston (2007-2012)
- Nikos Varelas (2013-2016)
- Cynthia Keppel (2017-2021)
- Paul Reimer (2022-)

Theory Spokespersons

- Wu-Ki Tung (1991-2001)
- George Sterman (1995-2001)
- Dave Soper (2001-2005)
- Jeff Owens (2006-2010)
- Fred Olness (2011-2014)
- Frank Petriello (2014-2016)
- Pavel Nadolsky (2016-2021)
- Doreen Wackeroth (2022-)

Member	Institution	Exp/Th	Date Joined & Status
Alberto Accardi	Hampton/JLab	Theory	2012
Edmond Berger	Argonne	Theory	1990 FM
Raymond (Chip) Brock	Michigan State University	Experiment	1990 FM, EM
John Campbell	Fermilab	Theory	2012
John Collins	Pennsylvania State University	Theory	1990 FM, EM
Bill Gary	Univ. of California, Riverside	Experiment	1999 EM
Walter Giele	Fermilab	Theory	???
Tao Han	U Pittsburgh	Theory	???
Kenichi Katakeyama	Baylor	Experiment	2014
Stefan Höche	SLAC	Theory	2015
Joey Huston	MSU	Experiment	1990 FM
Cynthia Keppel	JLab	Experiment	2003
Michael Klasen	Universität Müenster	Theory	2016
Karol Kovarik	Universität Müenster	Theory	2012
Steve Kuhlmann	ANL	Experiment	1993 EM
Hung-Liang Lai	Michigan State University	Theory	2007 EM
Tom LeCompte	ANL	Experiment	2003
Huey-Wen Lin	MSU	Theory	2018
Bruce Mellado	University of Witwatersrand	Experiment	2014
Sanjib Mishra	Columbia University	Experiment	1990 FM, EM
Jorge Morfin	Fermilab	Experiment	1989 FM
Steve Mrenna	Fermilab	Theory	2001
Pavel Nadolsky	SMU	Theory	2009
Fred Olness	SMU	Theory	1991 FM
Joseph Owens	FSU	Theory	1990 FM
Frank Petriello	ANL, Northwestern	Theory	2011
Jon Pumplin	MSU	Theory	1990 FM, DM
Jianwei Qiu	Jefferson Lab	Theory	1990 FM
Paul Reimer	Argonne	Experiment	2016 CS
Laura Reina	FSU	Theory	2008
Heidi Schellman	Oregon State	Experiment	???
Ingo Schienbein	LPSC, Grenoble	Theory	2018
Reinhard Schwienhorst	Michigan State University	Experiment	2020
Jack Smith	SUNY Stony Brook	Theory	1990 FM, DM
Davison Soper	U. of Oregon	Theory	1990 FM
George Sterman	Stony Brook	Theory	1990 FM
Dan Stump	MSU	Theory	???
Zack Sullivan	IIT	Theory	2008
Wu-Ki Tung	Michigan State University	Theory	1989 FM, DM
Nikos Varelas	U. Illinois, Chicago	Experiment	1998
Werner Vogelsang	Universität Tübingen	Theory	2006
Doreen Wackeroth	SUNY at Buffalo	Theory	2008 CS
Harry Weerts	ANL	Experiment	1990 FM, EM
Jim Whitmore	DESY	Experiment	??? EM
C. P. Yuan	MSU	Theory	1992
Dieter Zeppenfeld	Karlsruhe	Theory	1996
Marek Zielinski	Rochester	Experiment	2006

†Founding Member (FM); Emeritus Member (EM);
Co-Spokesperson (CS); Deceased Member (DM).

Table of CTEQ Members

7 Future

It has been more than thirty years since the CTEQ Collaboration was founded. At the time of its founding there were many questions about how to use QCD to obtain precise predictions for high energy hard scattering processes. The state-of-the-art in many cases was still the leading-log approximation. The Tevatron Collider experiments were just coming online and there were profound questions as to what should be measured and how best to compare theory and experiment. In the intervening years the development of next-to-leading-order calculations followed by next-to-next-to-leading-order calculations has led to precision predictions for a wide variety of hard scattering processes. The energy frontier has moved from center-of-mass energies of 1 to 2 TeV at Fermilab to nearly 14 TeV at the LHC. To many physicists QCD is viewed as simply a tool to be used in probing for "new physics." If this is true, then it appropriate to consider what role CTEQ can play in future developments.

Certainly, one aspect of CTEQ that has stood the test of time is the CTEQ Summer School. Each year it is necessary to bring along new students and post-docs and to demonstrate to them the techniques and tools used in comparing theory and experiment. To this end, the Summer School curricula have evolved to include topics such as lattice field theory and event generators. Keeping the curricula up to date and relevant is an ongoing task.

Recruitment of new members is also an ongoing task. As time passes many of the early members of the collaboration have retired - you can see their names listed as Emeritus Members in the Members section. To keep CTEQ current in both theoretical and experimental developments it is necessary to bring in new members - something that is done on a continuing annual basis.

The LHC program is scheduled to run through 2040. As the integrated luminosity is increased and the capabilities of the detectors are expanded there will surely be new discoveries and, it is hoped, surprises. CTEQ will have a role in these developments. But beyond that, there will be new experimental facilities - The Electron Ion Collider (EIC) at Brookhaven is one such facility and continued experimental work at Jefferson lab with its 12 GeV program is another. The EIC will be a dedicated "QCD machine" designed to explore the structure of matter at very short distances, a study that will require QCD as a tool and will also shed light on how QCD generates the structure of both nucleons and nuclei. Future recruitment will no doubt see new members working in topics related to both Jefferson Lab and EIC physics programs.

In short, it is anticipated that CTEQ will continue to evolve as new facilities, new experimental results, and new theoretical results are developed. Members of CTEQ will continue to play leading roles in all these endeavors.

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A Photo Gallery

Editors: Fred Olness, + ...

Figure 8: CTEQ Summer School 2012: Pontificia Universidad Católica del Perú, Lima, Peru 30 July - 9 August 2012.

Figure 9: CTEQ Summer School 2013: PITTsburgh Particle physics, Astrophysics, and Cosmology Center (PITT PACC), University of Pittsburgh, Pennsylvania, USA. 7 - 17 July 2013.

Figure 10: CTEQ Summer School 2015: PITTsburgh Particle physics, Astrophysics, and Cosmology Center (PITT PACC), University of Pittsburgh, Pennsylvania, USA. 7 - 17 July 2015

Figure 11: CTEQ Summer School 2015: Collins Soper Sterman (CSS) Celebration, 12 July 2015.

Figure 12: Joint POETIC 7 & CTEQ Workshop, Jeff Owens Celebration, 17 November 2016. Temple University, Philadelphia, PA.

Figure 13: CTEQ Summer School 2017: PITTsburgh Particle physics, Astrophysics, and Cosmology Center (PITT PACC), University of Pittsburgh, Pennsylvania, USA. 18 - 28 July 2017.

Figure 14: CTEQ Summer School 2018: 18 - 28 June 2018; Mayaguez, Puerto Rico, USA

B Summer School Posters

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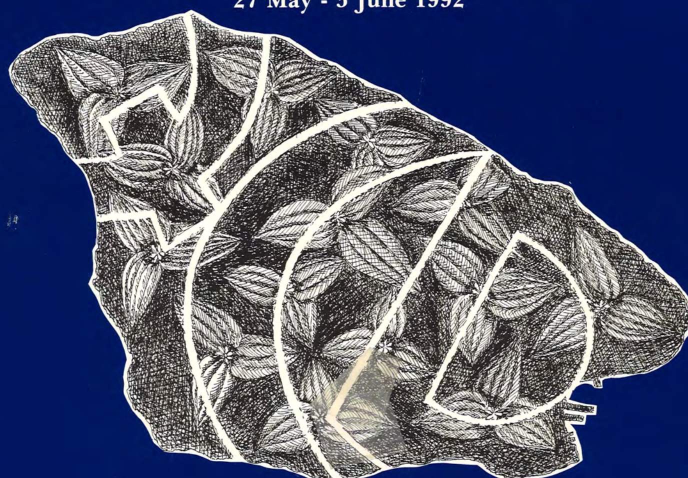

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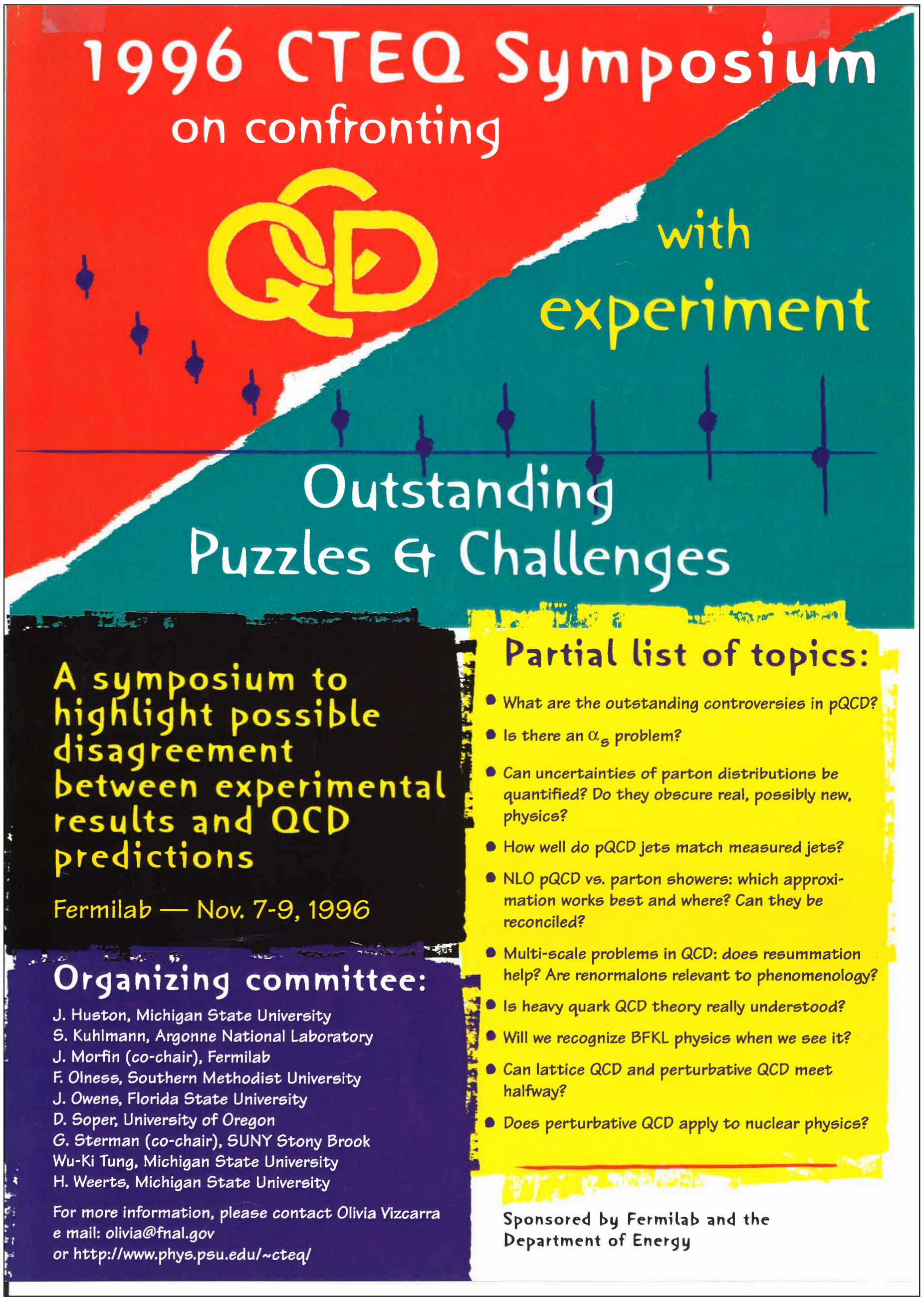
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J. Morfin (co-chair), Fermilab
F. Olness, Southern Methodist University
J. Owens, Florida State University
D. Soper, University of Oregon
G. Sterman (co-chair), SUNY Stony Brook
Wu-Ki Tung, Michigan State University
H. Weerts, Michigan State University
For more information, please contact Olivia Vizcarra
e mail: olivia@fnal.gov
or http://www.phys.psu.edu/~cteq/
Partial list of topics:
What are the outstanding controversies in pQCD?
Is there an α_s problem?
Can uncertainties of parton distributions be quantified? Do they obscure real, possibly new, physics?
How well do pQCD jets match measured jets?
NLO pQCD vs. parton showers: which approximation works best and where? Can they be reconciled?
Multi-scale problems in QCD: does resummation help? Are renormalons relevant to phenomenology?
Is heavy quark QCD theory really understood?
Will we recognize BFKL physics when we see it?
Can lattice QCD and perturbative QCD meet halfway?
Does perturbative QCD apply to nuclear physics?
Sponsored by Fermilab and the Department of Energy

The Project on Collaborative Theoretical and Experimental Studies of QCD (CTEQ) will conduct its fifth annual

CTEQ Summer School on QCD Analysis and Phenomenology

at

Interlaken Resort, Lake Como, Wisconsin

May 27 - June 4, 1997

Topics

Introduction to the Parton Model and Perturbative QCD,
QCD Phenomenology and Experimental Reviews of Basic Processes:
Deep Inelastic Scattering; Lepton-pair/W,-Z-Production; Photo-production and Direct Photon Production; Jet Physics; Heavy Quark and Quarkonium Production;
QCD in e+e- Interactions,

Special Topics and Techniques:
Physics and Techniques of Event Generators; Small x and Diffractive Physics;
Higher Twist Effects and the Perturbative-non-perturbative Interface;
Spin/Polarization Physics in QCD; QCD and Precision Tests of the Standard Model;
Physics of High Energy Nuclear Collisions and Targets

Instructors: Members of CTEQ and Guest Lecturers (To Be Announced)

Members of the CTEQ Collaboration:

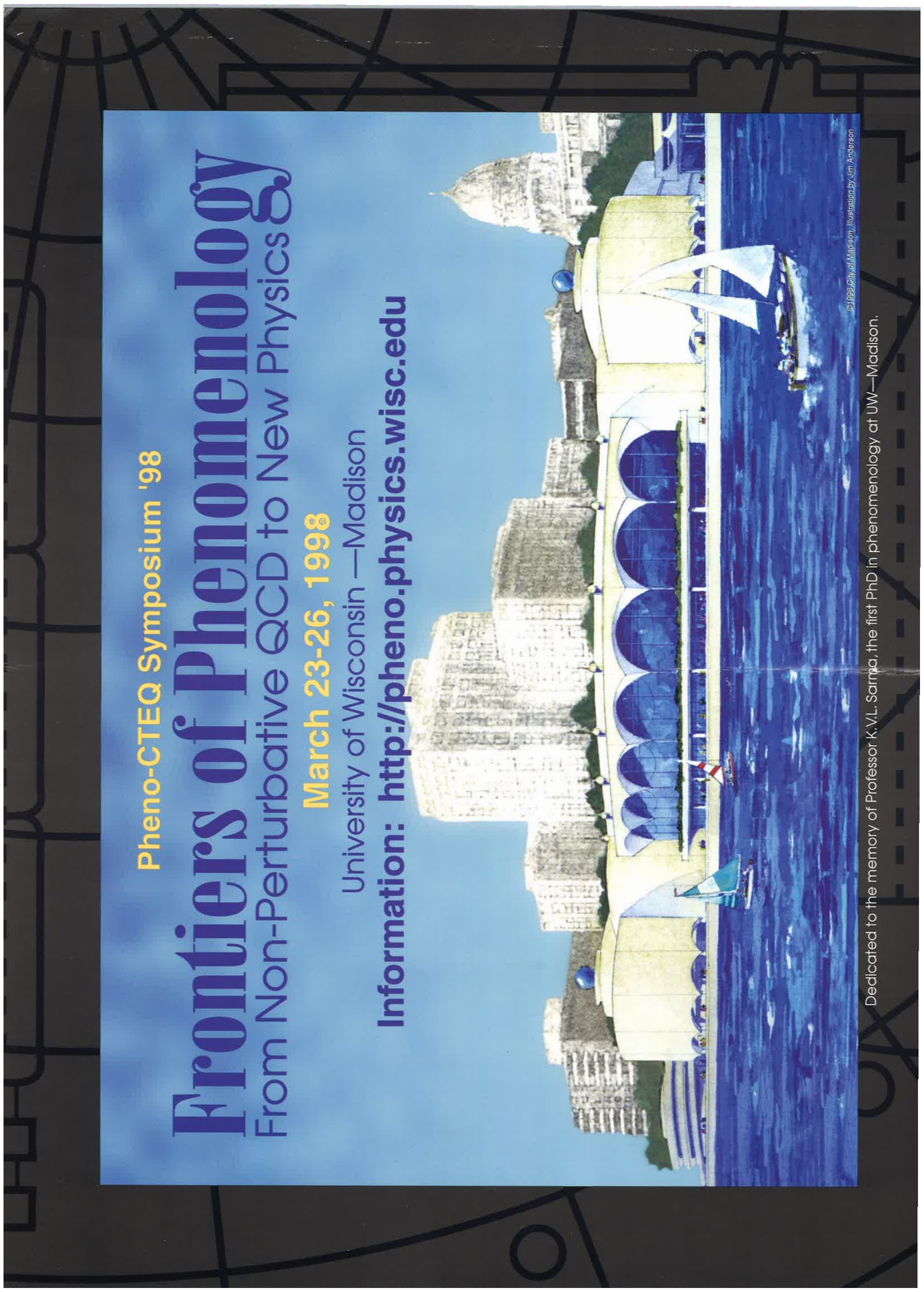
R. Brock - Michigan State U.
J. Huston - Michigan State U.
S. Mishra - Harvard U.
F. Olness - Southern Methodist U.
J. Pumplin - Michigan State U.
J. Smith - SUNY Stony Brook
G. Sterman - SUNY Stony Brook
H. Weerts - Michigan State U.
C.P. Yuan - Michigan State U.
J. Collins - Penn State U.
S. Kuhlmann - Argonne National Lab.
J. G. Morfín - Fermilab
J. Owens - Florida State U.
J. Qiu - Iowa State U.
D. Soper - U of Oregon
W.K. Tung - Michigan State U.
J. J. Whitmore - Penn State U.

Organizing Committee

T. L. Grozis and J. G. Morfín, Fermilab

Further information and registration procedures can be obtained via WWW at:
http://www.phys.psu.edu/~cteq/schools/summer97/
or by contacting:
Terry L. Grozis, CTEQ School, Fermilab M.S. 205
P.O. Box 500, Batavia, IL 60510, Telefax: 630-840-2194
TGROZIS@FNAL.GOV

Sponsored by
Deutsches Elektronen-Synchrotron, Fermi National Accelerator Laboratory
National Science Foundation and U.S. Department of Energy



This 1998 CTEQ workshop was joint with the Pheno98 meeting in Madison WI.

The Project on Collaborative
Theoretical & Experimental Studies of QCD (CTEQ)
Will Organize and Conduct the Seventh

CTEQ Summer School on QCD Analysis & Phenomenology

Lake Geneva, Wisconsin | May 30 – June 7, 2000

TOPICS TO BE COVERED

Introduction to the Parton Model & Perturbative QCD

QCD Phenomenology & Experimental Reviews of Basic Processes

- *Deep-inelastic Scattering*
- *Lepton pair / W,-Z-Production*
- *Direct Photon Production*
- *Jet Physics and Fragmentation*
- *Heavy Quark and Quarkonium Production*
- *Heavy Quarks, CP and CKM*
- *QCD and the Search for New Physics*

Special Topics & Techniques

- *Global Determination and Error Estimates for Parton Distributions*
- *Spin and Skewed Distributions*
- *The Lattice Approach to QCD*
- *Nuclear Collisions and QCD in Extreme Conditions*
- *Neutrinos in Space, the Atmosphere and Nuclei*
- *High energy Diffraction and Rapidity Gaps*
- *BFKL Evolution: What & Where?*
- *Large Extra Dimensions: String Theory at Accelerator Energies?*

Instructors: Guest Lecturers & Members of CTEQ (To Be Announced)

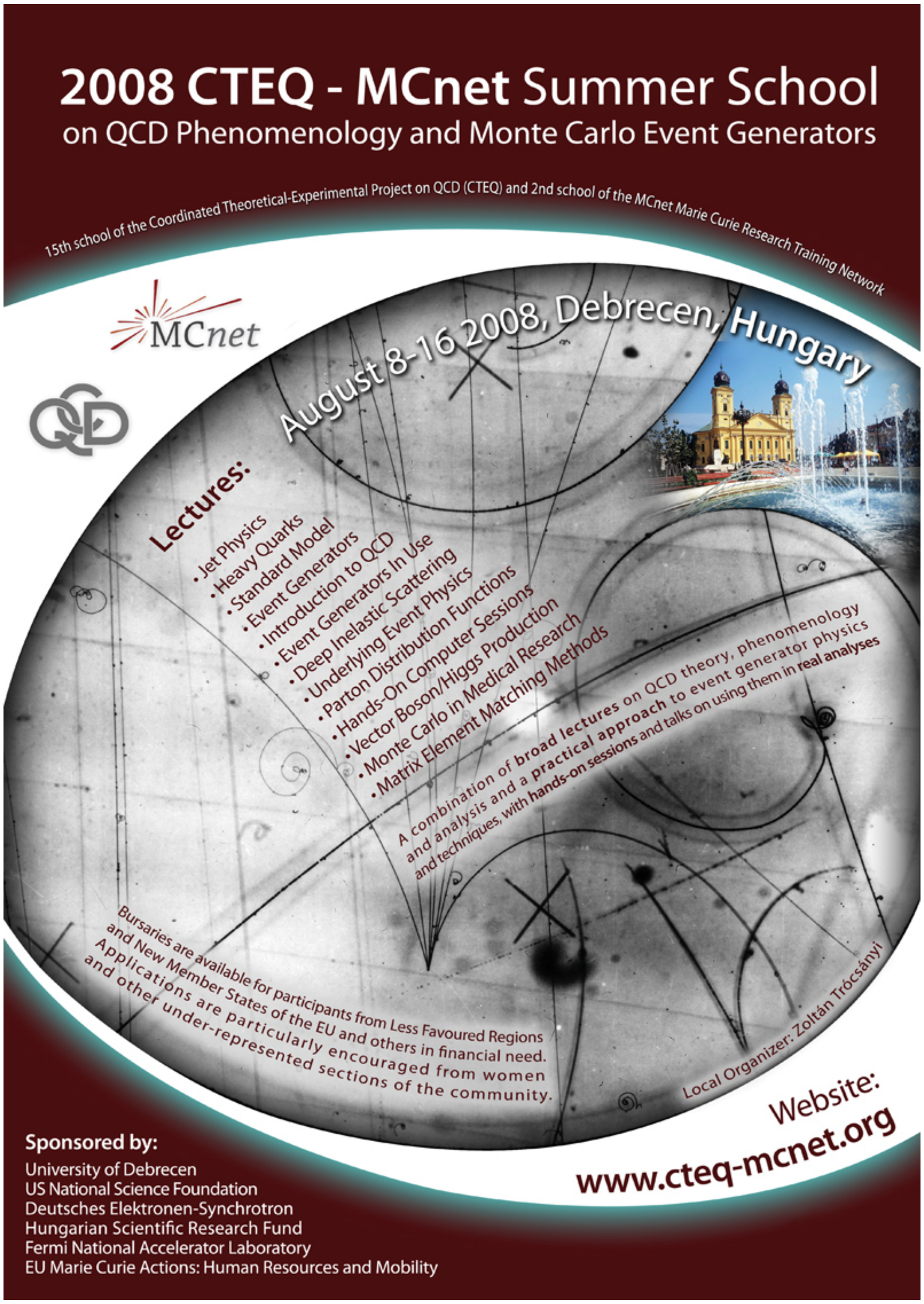
PROGRAM COMMITTEE: Members of the CTEQ Collaboration
E. Berger - Argonne Lab. | R. Brock - Michigan State U. | J. Collins - Penn State U. | J. Conrad - Columbia U | J. Huston - Michigan State U. | S. Kuhlmann - Argonne Lab. | J. G. Morfin - Fermilab | F. Olness - Southern Meth. U. | J. Owens - Florida State U. | J. Pumplin - Michigan State U. | J. Qiu - Iowa State U. | H. Schellman Northwestern U. | J. Smith - SUNY Stony Brook | D. Soper - U of Oregon | G. Sterman - SUNY Stony Brook | W.K. Tung - Michigan State U. | N. Varelas - U. Illinois/Chi. | H. Weerts - Michigan State U. | J. J. Whitmore - Penn State U. | C.P. Yuan - Michigan State U. | D. Zeppenfeld - U. of Wisconsin

ORGANIZING COMMITTEE: Terry L. Grozis and Jorge G. Morfin, Fermilab

Further information and application procedures can be obtained at the CTEQ Summer School WWW Page: http://www.phys.psu.edu/~cteq/schools/summer00/

OR BY CONTACTING: Ms. Terry L. Grozis | CTEQ School | Fermilab M.S. 205 | P.O. Box 500 | Batavia, Il 60510 | Fax (630) 840-2194 | TGROZIS@FNAL.GOV

Sponsored by: Argonne National Laboratory, Deutsches Elektronen-Synchrotron, Fermi National Accelerator Laboratory, the National Science Foundation, and the U.S. Department of Energy



Poster design by Andrzej Siodmok.

Poster design by Andrzej Siodmok.

2013 CTEQ School

The Coordinated Theoretical-Experimental Project on QCD (CTEQ)
will organize and conduct the

2013 CTEQ School

on

QCD and Electroweak Phenomenology

at

University of Pittsburgh, PA, USA
7 - 17 July 2013

The school will be locally hosted by **PITT PACC**, and the Monte Carlo Tutorial Sessions will be organized with the cooperation of the **MCnet Collaboration**.

The School is ideally suited for advanced graduate students and recent PhDs.

Topics to be covered:

Focused Introductory Reviews:

- Introduction to the Parton Model & Perturbative QCD
- Monte Carlo Introduction
- Deeply Inelastic Scattering
- Higgs at Hadron Colliders
- Vector Bosons / Direct Photons
- Production and Structure of High Energy Jets
- Heavy Quarks

In-depth Analysis and Phenomenology:

- Monte Carlo Tutorial
- Experimental Results from LHC
- QCD/EWK/Top Searches at Hadron Colliders
- PDFs and Global Fits
- Intensity Frontier: Neutrino Physics
- Intensity Frontier: Muon Physics
- The Standard Model and Beyond
- NLO Computation and Matching/Merging

Application Deadline: 30 March 2013

Website: **www.cteq.org** E-mail: **cteq2013@list.smu.edu**

Sponsors: Fermi National Accelerator Laboratory, National Science Foundation, U.S. Department of Energy, University of Wisconsin, MC-Net, & PITTsburgh Particle physics, Astrophysics, & Cosmology Center (PITT-PACC)

Organizing Committee: Ed Berger and Tom LeCompte (Argonne), Jorge Morfin (Fermilab), Jeff Owens (FSU), Nikos Varelas (UI-Chicago), Zack Sullivan (IIT), Stefan Gieseke (KIT), Joey Huston and C.-P. Yuan (MSU), Davison Soper (Oregon), Tao Han, Cynthia Cercone & Adam Leibovich (Pittsburgh), Fred Olness and Randall J. Scalise (SMU), Stefan Hoeche (SLAC), Werner Vogelsang (Tubingen), Bruce Mellado (Wisconsin).

2014 CTEQ School

The Coordinated Theoretical-Experimental Project on QCD (CTEQ)
will organize and conduct the

2014 CTEQ School

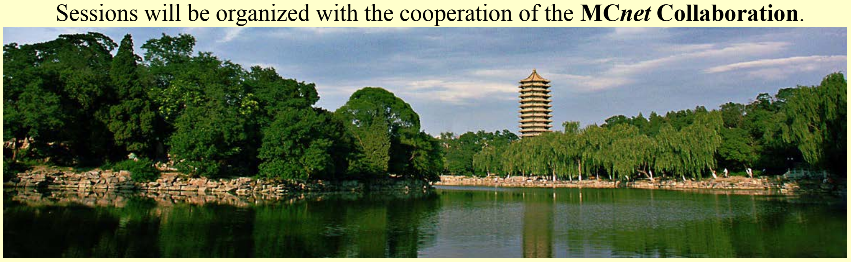
on

QCD and Electroweak Phenomenology

at

Peking University, Beijing, China
8 - 18 July 2014

The school will be locally hosted by **PKU ITP**, and the Monte Carlo Tutorial Sessions will be organized with the cooperation of the **MC*net* Collaboration**.



The School is ideally suited for advanced graduate students and recent PhDs.

Topics to be covered:

Focused Introductory Reviews:

- Introduction to the Parton Model & Perturbative QCD
- Deeply Inelastic Scattering
- Higgs Boson
- Vector Bosons / Direct Photons
- Production and Structure of High Energy Jets
- Heavy Quarks
- Monte Carlo Introduction & Tutorials

In-depth Analysis and Phenomenology:

- QCD/EWK/Higgs/Top
- New Physics Searches
- PDFs and Global Fits
- Transverse Momentum Dependent PDFs
- Neutrino Physics
- High Intensity Muon & Kaon Physics
- Low Energy Spectroscopy
- NLO Computation and Matching/Merging

Application Deadline: 1 March 2014

Website: **www.cteq.org** E-mail: **cteq2014@list.smu.edu**

Sponsors: Fermi National Accelerator Laboratory, National Science Foundation, U.S. Department of Energy, MC*net*, National Science Foundation of China, State Key Laboratory for Nuclear Science and Technology at PKU, Institute of Theoretical Physics at PKU, Center of High Energy Physics at PKU, Graduate School of PKU

Organizing Committee: Ed Berger and Tom LeCompte (Argonne), Jorge Morfin (Fermilab), Jeff Owens and Laura Reina (FSU), Nikos Varelas (UI-Chicago), Zack Sullivan (IIT), C.-P. Yuan (MSU), Davison Soper (Oregon), Qing-Hong Cao and Shou-hua Zhu (PKU), Tao Han (Pittsburgh), Stefan Hoeche (SLAC), Fred Olness (SMU), George Sterman (SUNY), Bruce Mellado (Witwatersrand).

2015 CTEQ School

The Coordinated Theoretical-Experimental Project on QCD (CTEQ)
will organize and conduct the

2015 CTEQ School

on

QCD and Electroweak Phenomenology

at

University of Pittsburgh, PA, USA
7 - 17 July 2015

The school will be locally hosted by **PITT PACC**, and the Monte Carlo Tutorial Sessions will be organized with the cooperation of the **MCnet Collaboration**.

The School is ideally suited for advanced graduate students and recent PhDs.

Topics to be covered:

Focused Introductory Reviews:

- Introduction to the Parton Model & Perturbative QCD
- Monte Carlo Introduction
- Deeply Inelastic Scattering
- Higgs at Hadron Colliders
- Vector Bosons / Direct Photons
- Production and Structure of High Energy Jets
- Heavy Quarks

In-depth Analysis and Phenomenology:

- Monte Carlo Tutorial
- Experimental Results from LHC
- QCD/EWK/Top at Hadron Colliders
- PDFs and Global Fits
- Intensity Frontier: Neutrino Physics
- Intensity Frontier: Muon Physics
- The Standard Model and Beyond
- NLO Computation and Matching/Merging

Final Application Deadline: 20 April 2015

Website: **www.cteq.org** E-mail: **cteq2015@gmail.com**

Sponsors: Fermi National Accelerator Laboratory, National Science Foundation, U.S. Department of Energy, University of Wisconsin, MC-Net, & PITTsburgh Particle physics, Astrophysics, & Cosmology Center (PITT-PACC)

Organizing Committee: Ed Berger and Tom LeCompte (Argonne), Jorge Morfin (Fermilab), Laura Reina and Jeff Owens (FSU), Nikos Varelas (UI-Chicago), Frank Petriello (Northwestern/ANL), Zack Sullivan (IIT), Davison Soper (Oregon), Tao Han, Cynthia Cercone and Ayres Freitas (Pittsburgh), Fred Olness and Randall J. Scalise (SMU), Stefan Hoeche (SLAC), Joey Huston (MSU)

CTEQ/MCnet School 2016
QCD and Electroweak Phenomenology
6-16 July 2016
DESY, Hamburg
Program:
• Introductions to QCD and electroweak theory
• Introduction to Monte Carlo generators
• Parton densities: introduction and tutorial
• Monte Carlo tutorials
• Matching and merging higher orders
• W, Z and Higgs production at the LHC
• Heavy quarks
• Jet physics
• BSM searches at the LHC
• Dark matter and Astroparticle physics
• Future colliders
DFG
DESY
MCnet
Particles, Strings, and the Early Universe
Collaborative Research Center SFB 676
Local organising committee:
Markus Diehl, Judith Katzy, Katerina Lipka, Sven-Olaf Moch
CTEQ organising committee:
Ed Berger, Joey Huston, Karol Kovarik, Tom LeCompte, Jorge Morfin, Pavel Nadolsky, Fred Olness, Frank Petriello, Zack Sullivan, Dave Soper, Nikos Varelas, Werner Vogelsang
MCnet organising committee:
Stefan Gieseke, David Grellscheid, Stefan Hoeche, Frank Krauss, Peter Richardson, Mike Seymour
http://qcd2016.desy.de

2017 CTEQ School

The Coordinated Theoretical-Experimental Project on QCD (CTEQ)
will organize and conduct the

2017 CTEQ School

on

QCD and Electroweak Phenomenology

at the

University of Pittsburgh, PA, USA
18 – 28 July 2017

The school will be locally hosted by **PITT PACC**, and the Monte Carlo Tutorial Sessions will be organized with the cooperation of the **MCnet Collaboration**.

The School is ideally suited for advanced graduate students and recent PhDs.

Topics to be covered:

Focused Introductory Reviews:
- Introduction to the Parton Model & Perturbative QCD
- Monte Carlo Introduction
- Deeply Inelastic Scattering
- Higgs at Hadron Colliders
- Vector Bosons / Direct Photons
- High Energy Jets
- Heavy Quarks

In-depth Analysis and Phenomenology:
- Monte Carlo Tutorial
- Experimental Results from LHC
- QCD/EWK/Top at Hadron Colliders
- PDFs and Global Fits
- The Intensity Frontier: Neutrino & Muon Physics
- EIC & Related Topics
- The Standard Model and Beyond
- NLO/NNLO Computation & Matching/Merging

Review of Applications Begins: 1 March 2017

Website: **www.cteq.org** E-mail: **cteq.school@gmail.com**

Sponsors: U.S. Department of Energy, National Science Foundation, Fermi National Accelerator Laboratory, MCnet, Pittsburgh Particle physics, Astrophysics, & Cosmology Center (PITT PACC)

Organizers: Brian Batell, Cindy Cercone, Tao Han, Ken Hatakeyama, Stefan Hoeche, Joey Huston, Cynthia Keppel, Tom LeCompte, Jorge Morfin, Pavel Nadolsky, Fred Olness, Jeff Owens, Dave Soper, Zack Sullivan, Nikos Varelas

2018 CTEQ School

The Coordinated Theoretical-Experimental Project on QCD (CTEQ)
will organize and conduct the

2018 CTEQ School

on

QCD and Electroweak Phenomenology

at the

University of Puerto Rico, Mayaguez, USA
18 – 28 June 2018

The school will be locally hosted by **University of Puerto Rico, Mayaguez**

The School is ideally suited for advanced graduate students and recent PhDs.

Topics to be covered:

Focused Introductory Reviews:
- Introduction to the Parton Model & Perturbative QCD
- Deeply Inelastic Scattering
- Higgs Boson Physics
- Vector Bosons / Direct Photons
- Jets & Jet Substructure
- Heavy Quarks

In-depth Analysis and Phenomenology:
- Experimental Results from LHC
- QCD/EWK/Top Studies
- Monte Carlo Event Generators
- PDFs and Global Fits
- Neutrino & Muon Physics
- Machine Learning
- The Standard Model and Beyond

Review of applications begins: 1 March 2018

Website: `www.cteq.org`   E-mail: `cteq.school@gmail.com`

Sponsors: University of Puerto Rico, Mayaguez, Colegio De Fisica Fundamental E Interdiciplinaria De Las Americas (COFI), U.S. Department of Energy, National Science Foundation, Fermi National Accelerator Laboratory, Jefferson Lab, MCnet, Pittsburgh Particle Physics, Astrophysics, & Cosmology Center (PITT PACC)

Organizers: Tao Han, Kenichi Hatakeyama, Stefan Hoeche, Joey Huston, Cynthia Keppel, Sudhir Malik, Jorge Morfin, Fred Olness, Pavel Nadolsky, Paul Reimer, Dave Soper, Zack Sullivan, Nikos Varelas, Mayda Velasco, C.P. Yuan

2019 CTEQ School

The Coordinated Theoretical-Experimental Project on QCD (CTEQ)
will organize and conduct the

2019 CTEQ School

on

QCD and Electroweak Phenomenology

at the

University of Pittsburgh, PA, USA

16-26 July 2019

The school will be locally hosted by **PITT PACC**, and the Monte Carlo Tutorial Sessions will be organized with the cooperation of the **MCnet Collaboration**.

The School is ideally suited for advanced graduate students and recent PhDs.

Topics to be covered:

Focused Introductory Reviews:

- Introduction to the Parton Model & Perturbative QCD
- Deeply Inelastic Scattering
- Vector Bosons / Direct Photons
- High Energy Jets
- Heavy Quarks
- Neutrinos

In-depth Analysis and Tutorials:

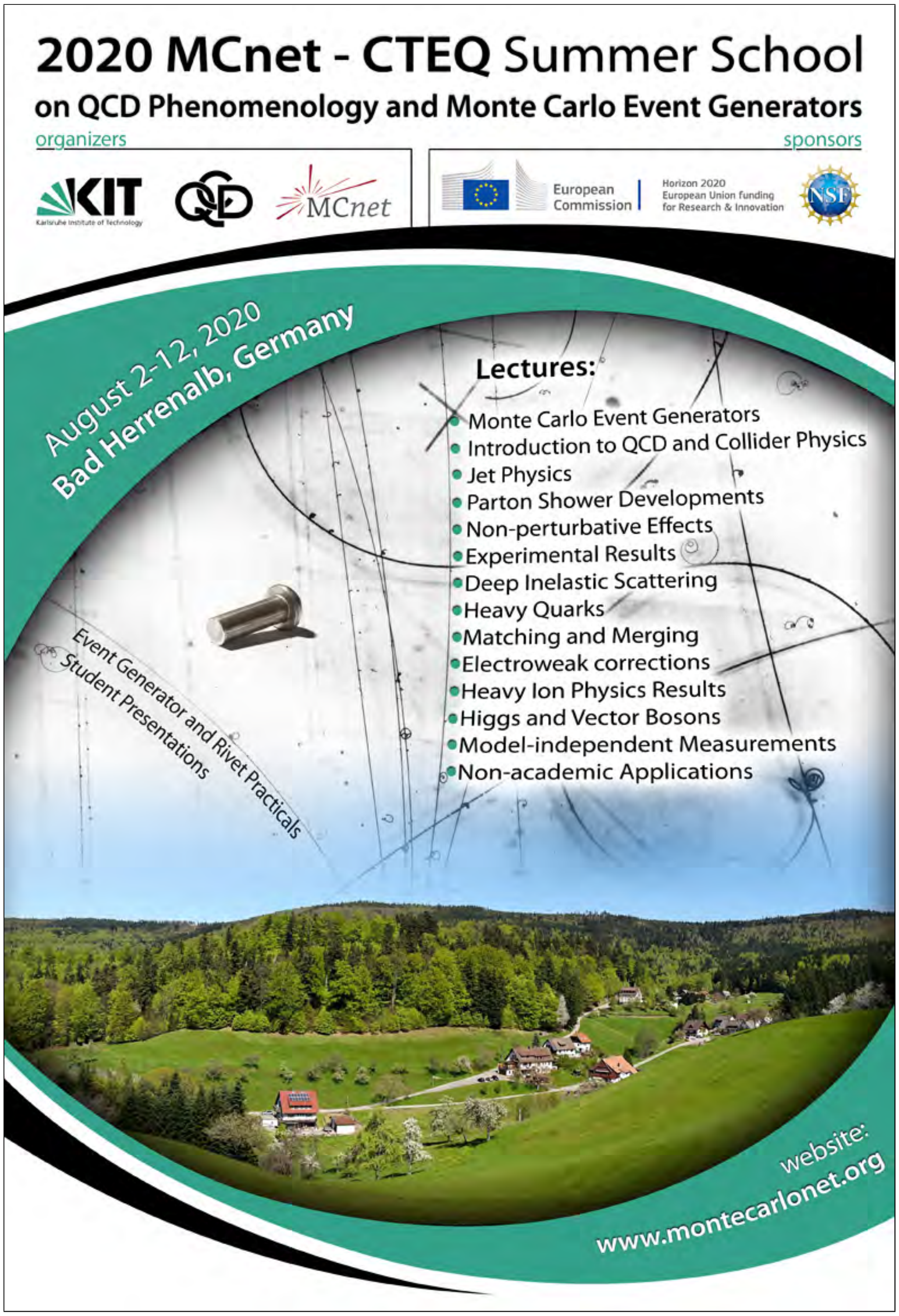
- **Machine Learning Techniques & Tutorial**
- **Monte Carlo Introduction & Tutorial**
- Higgs at Hadron Colliders
- Experimental Results from QCD/EWK/Top
- PDFs and Global Fits
- Dark Matter
- The Standard Model and Beyond

Review of Applications Begins: 1 March 2019

Website: `www.cteq.org` E-mail: `cteq.school@gmail.com`

Sponsors: U.S. Department of Energy, National Science Foundation, Fermi National Accelerator Laboratory, MCnet, Pittsburgh Particle physics, Astrophysics, & Cosmology Center (PITT PACC)

Organizers: Brian Batell, Tao Han, Ken Hatakeyama, Stefan Hoeche, Joey Huston, Cynthia Keppel, Huey-Wen Lin, Jorge Morfin, Pavel Nadolsky, Fred Olness, Jeff Owens, Paul Reimer, Ingo Schiengein, Dave Soper, George Sterman, Zack Sullivan, Nikos Varelas



Poster design by Andrzej Siodmok.

The 2020 School was canceled due to COVID-19; instead a virtual school was held 6-16 September 2021 organized with U. Dresden.

MCnet

MCnet-CTEQ Summer School 2021 VIRTUAL

5–16 Sep 2021

America/Chicago timezone

Enter your search term

- Overview
- 2021 Schedule Overview
- Timetable
- Participant List
- MCnet Schools

Local Organisers

frank.siegert@cern.ch

school@montecarlonet....

olness@smu.edu

Zack.Sullivan@IIT.edu

The 2021 CTEQ-MCnet Summer School will be held **ONLINE only in a virtual format.** The lectures will be presented Monday–Thursday September 6–9 and 13–16.

YouTube Channel (Collected videos of lectures)

It is the 14th MCnet Summer School and 27th CTEQ School.

The school provides training on the physics at high energy colliders, particularly the LHC. We will have series of lectures on basic and more advanced topics, practical sessions, and evening discussions with the lecturers. The school is aimed at advanced doctoral students and young postdocs.

Our core sessions comprise a series of introductory lectures on the physics of Monte Carlo event generators, Electroweak Physics and Quantum Chromodynamics, further lectures on a wider range of associated topics, a series of hands-on tutorials using all of the MCnet event generators for LHC physics, and evening discussion sessions with all lecturers.

There is NO fee for the virtual school.

Topics covered in the school will include the following.

Focused Introductory Reviews:

- Introduction to Monte Carlo Event Generators
- Introduction to QCD in the Standard Model
- Deeply Inelastic Scattering
- Higgs Boson Physics
- Vector Bosons / Direct Photons
- Production and Structure of High Energy Jets
- Heavy Quarks

In-depth Analysis and Phenomenology:

- Monte Carlo Tutorials
- Higgs at Hadron Colliders
- QCD/EWK/Top/Searches at Hadron Colliders
- Non-perturbative/soft physics
- Heavy Ions and Min Bias
- Higher-order QCD and EW Calculations
- Matching/Merging to Parton Showers

Organised by:

MCnet NSF TECHNISCHE UNIVERSITÄT DRESDEN

2022 CTEQ School

The Coordinated Theoretical-Experimental Project on QCD (CTEQ)
will organize and conduct the

2022 CTEQ School

on

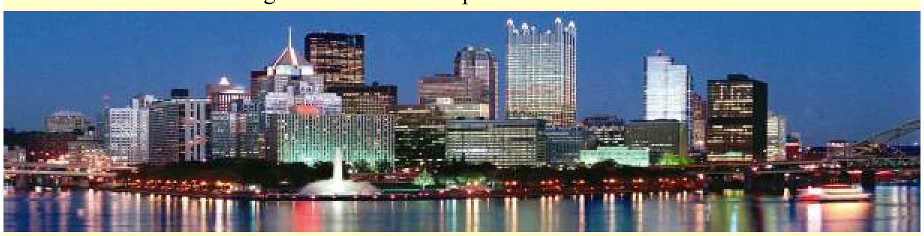
QCD and Electroweak Phenomenology

at the

University of Pittsburgh, PA, USA

06-16 July 2022

The school will be locally hosted by **PITT PACC**, and the Monte Carlo Tutorial Sessions will be organized with the cooperation of the **MCnet Collaboration**.



The School is ideally suited for advanced graduate students and recent PhDs.

Topics to be covered:

Focused Introductory Reviews:
- Introduction to the Parton Model & Perturbative QCD
- Deeply Inelastic Scattering
- Vector Bosons / Direct Photons
- High Energy Jets
- Neutrinos

In-depth Analysis and Tutorials:
- Monte Carlo Introduction & Tutorial
- Machine Learning Techniques
- Higgs at Hadron Colliders
- Experimental Results from QCD/EWK/Top
- PDFs and Global Fits
- Dark Matter

Review of Applications Begins: 31 March 2022

Website: **www.cteq.org** E-mail: **cteq.school@gmail.com**

Sponsors: U.S. Department of Energy, National Science Foundation, Fermi National Accelerator Laboratory, MCnet, Pittsburgh Particle physics, Astrophysics, & Cosmology Center (PITT PACC)

Organizers: Brian Batell, Tao Han, Joni George, Ken Hatakeyama, Stefan Hoeche, Joey Huston, Cynthia Keppel, Huey-Wen Lin, Jorge Morfin, Pavel Nadolsky, Fred Olness, Paul Reimer, Ingo Schiengein, Dave Soper, George Sterman, Zack Sullivan, Doreen Wackeroth