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FORMAL REPORT

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Global Analysis of Polarized Parton Distributions in the RHIC Era

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Organizers:

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Preface to the Series

The RIKEN BNL Research Center (RBRC) was established in April 1997 at Brookhaven National Laboratory. It is funded by the "Rikagaku Kenkyusho" (RIKEN, The Institute of Physical and Chemical Research) of Japan. The Center is dedicated to the study of strong interactions, including spin physics, lattice QCD, and RHIC physics through the nurturing of a new generation of young physicists.

The RBRC has both a theory and experimental component. The RBRC Theory Group and the RBRC Experimental Group consist of a total of 25-30 researchers. Positions include the following: full time RBRC Fellow, half-time RHIC Physics Fellow, and full-time, post-doctoral Research Associate. The RHIC Physics Fellows hold joint appointments with RBRC and other institutions and have tenure track positions at their respective universities or BNL. To date, RBRC has ~50 graduates of which 14 theorists and 6 experimenters have attained tenure positions at major institutions worldwide.

Beginning in 2001 a new RIKEN Spin Program (RSP) category was implemented at RBRC. These appointments are joint positions of RBRC and RIKEN and include the following positions in theory and experiment: RSP Researchers, RSP Research Associates, and Young Researchers, who are mentored by senior RBRC Scientists. A number of RIKEN Jr. Research Associates and Visiting Scientists also contribute to the physics program at the Center.

RBRC has an active workshop program on strong interaction physics with each workshop focused on a specific physics problem. Each workshop speaker is encouraged to select a few of the most important transparencies from his or her presentation, accompanied by a page of explanation. This material is collected at the end of the workshop by the organizer to form proceedings, which can therefore be available within a short time. To date there are eighty-five proceeding volumes available.

A 10 teraflops RBRC QCDOC computer funded by RIKEN, Japan, was unveiled at a dedication ceremony at BNL on May 26, 2005. This supercomputer was designed and built by individuals from Columbia University, IBM, BNL, RBRC, and the University of Edinburgh, with the U.S. D.O.E. Office of Science providing infrastructure support at BNL. Physics results were reported at the RBRC QCDOC Symposium following the dedication. QCDSP, a 0.6 teraflops parallel processor, dedicated to lattice QCD, was begun at the Center on February 19, 1998, was completed on August 28, 1998, and was decommissioned in 2006. It was awarded the Gordon Bell Prize for price performance in 1998.

N. P. Samios, Director
March 2007

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– Introduction –

The determination of the polarized gluon distribution is a central goal of the RHIC spin program. Recent achievements in polarization and luminosity of the proton beams in RHIC, has enabled the RHIC experiments to acquire substantial amounts of high quality data with polarized proton beams at 200 and 62.4 GeV center of mass energy, allowing a first glimpse of the polarized gluon distribution at RHIC. Short test operation at 500 GeV center of mass energy has also been successful, indicating absence of any fundamental roadblocks for measurements of polarized quark and anti-quark distributions planned at that energy in a couple of years. With this background, it has now become high time to consider how all these data sets may be employed most effectively to determine the polarized parton distributions in the nucleon, in general, and the polarized gluon distribution, in particular. A global analysis of the polarized DIS data from the past and present fixed target experiments jointly with the present and anticipated RHIC Spin data is needed.

The one-day RBRC workshop on "Global Analysis of Polarized Parton Distributions in the RHIC Era" marked the beginning of this effort. It brought together a few of the leading theorists and experimentalists interested in becoming involved in this effort. The morning of the workshop day featured presentations that reviewed past efforts in this area. Jeff Owens (Florida State) and Jon Pumplin (Michigan State) presented the techniques used by the CTEQ collaboration, and described the experience made. CTEQ serves as a model for the global analysis we have in mind for RHIC Spin. Lara de Nardo gave an account of the analyses of polarized DIS data by the HERMES collaboration, and Jechiel Lichtenstadt discussed the SMC/COMPASS analysis. The final talk of the morning was given by a theorist again, Shunzo Kumano (KEK), who has been leading the Japanese AAC parton distribution collaboration in the past. Particular emphasis was put in the morning on the treatment of theoretical and experimental uncertainties in the analysis, which is of course a vital issue.

In the afternoon, we had focused presentations and discussions on the actual global analysis of DIS and RHIC-Spin data. Marco Stratmann (RIKEN) reviewed the Mellin-technique, which will be central for incorporating the RHIC data in the analysis. Daniel de

Florian and Rodolfo Sassot (Buenos Aires U.) presented analyses of fragmentation functions and spin-dependent parton distributions that use the Mellin technique and serve as "proof-of-principle" that the technique can be used in a practical application. The day was topped off by a round-table discussion, in which concrete plans for future collaboration were made.

This one-day workshop marked the starting point for the endeavor of global analysis of spin-dependent parton distributions, which is vital for fully realizing the potential of the RHIC Spin program. We believe the workshop was a great success. We are grateful to all participants for coming to the Center, and for their dedicated efforts relating to the RHIC program. We are grateful for the support provided for this workshop by Dr. N. Samios and the RIKEN-BNL Research Center. Sincere thanks go to Pamela Esposito for her invaluable help in organizing and running the workshop on a relatively short time-scale.

BNL, October 2007

A. Deshpande and W. Vogelsang

The CTEQ Global Fitting Project

J.F. Owens
Physics Department
Florida State University

Summary

Some projects carried out by the Global Fitting Group within the CTEQ Collaboration are listed. Organizational considerations and operational procedures are also presented and some considerations for forming a similar group for polarized PDFs are listed.

CTEQ Global Fitting Group

Group Members: J. Huston, J. Pumplin, D. Stump; J. Morfín (FNAL); S. Kuhlmann (ANL); F. Olness (SMU); J.F. Owens (FSU); W-K. Tung (U. Wash., ret)

Program Packages

- MSU Evolution and Fitting package

    - Developed by Wu-Ki Tung; extended/modified by others
    - Main package used for CTEQ pdfs
    - Now archived at SMU and maintained in CVS form by F. Olness
    - Wu-Ki Tung has his own extensively revised package

- Fitting and Evolution package originally developed by Duke and Roberts; extended and maintained by JFO.

    - Used for early LO fits and DIS analyses
    - Core for original MRS pdfs
    - Maintained to use as a cross check on the CTEQ fits
    - Also used for CCFR and NuTeV DIS analyses

CTEQ Project Procedures

- Each new project has a designated "leader"
  - Responsible for setting up phone conferences
  - Maintains web site for displaying notes, figures, etc during phone conferences
  - Coordinates tasks
- CVS Code Management
  - Fred maintains the current version
  - Others can contribute additions or changes needed for a particular project
- There have been several projects following the latest CTEQ6.1 PDFs
  - NuTeV/Chorus/E-866 data
  - More on $s - \overline{s}$
  - Nuclear PDFs
  - Topics involving heavy quarks
- Typically different author sets appear on the smaller analyses

Organizational Considerations

- Project leader needed to keep each analysis moving
- All too easy to fall prey to other distractions
  - Group includes an Associate Dean, a Department Chair (now on sabbatical after completing his term), the spokesperson for MINOS, and several faculty members
  - Many other duties/distractions, so weekly meetings keep us on task
  - Sure would be nice to have a post-doc ...
- Language of choice is FORTRAN
  - Historical - the existing packages have all been developed over many years/decades
  - FORTRAN is what we all grew up with and understand (look again at the group composition)
  - It is a language which all new members of various projects understand, so the learning curve is not so steep

Recent Work - inclusion of NuTeV, CHORUS, and E-866 data in the Global Fits

- New NuTeV and CHORUS neutrino and antineutrino cross section data on Fe and Pb, respectively
  - NuTeV data higher then the older CCFR data at high values of x
  - Need nuclear corrections for both data sets (used Kulagin-Petti model)
  - Expect the NuTeV data to pull the valence PDFs up at large x
- New E-866 pp and pd data for dimuon pair production
  - Data tend to pull the valence PDFs lower at high values of x

Conclusions

- Have tested a reference fit against three new data sets
- Have examined how each data set pulls the reference fit and how the data sets pull against each other
- If state of the art nuclear corrections are used it appears that the NuTeV and E-866 data sets pull against each other and the fitting program finds a solution with a significantly enhanced d/u ratio in the large-x region
- This conclusion can be altered by varying the weight given to each experiment in the fit
- The conclusion also depends on the precise nuclear correction model used
- There is some suggestion that the nuclear corrections used may be too large and that the corrections should be similar for both ν and $\overline{\nu}$ processes

Other Projects

- Nuclear PDFs - goal is to determine a self-consistent set of iron PDFs using the NuTeV data and calculate nuclear correction factors for various observables by comparing to the free nucleon values - this is essentially complete (Schienbein/Olness)
- NLO $s - \bar{s}$ analysis - in progress (Olness)
- Large-x PDFs using new W-lepton asymmetry data and new BONUS d/u data when it becomes available (Owens)

Comments

- Preceding examples show how we have organized various projects within the global fitting group
- Individuals contribute to those projects they are interested in
- Major projects such as new PDF versions have more inclusive author lists
- Past experience shows that without a designated "lead" person little progress will be made
- It helps to have a single person dedicated to the project (postdoc) - we have not had that in CTEQ since the mid 1990's

Techniques in Global Fitting

Jon Pumplin – October 8, 2007

BNL Workshop on Global Analysis for Polarized Parton Distributions

The goal of this talk is to give an overview of techniques used to measure Parton Distribution Functions by the CTEQ group, with an eye toward extending those techniques to measure polarized Parton Distributions using data from RHIC.

Topics discussed: Introduction to PDFs; results from the unpolarized analysis; Handling correlated experimental errors; Eigenvector PDF sets to estimate uncertainties; Steps needed to obtain polarized PDFs.

The original slides may more readable than this summary, since they contain some useful graphs and make use of color.

Introduction to PDFs

High energy hadrons interact through their quark and gluon constituents. At short distance scales—e.g. large momentum transfer—QCD interactions become weak due to asymptotic freedom, which allows us to apply perturbation theory to a rich variety of experiments. The complicated nonperturbative long-distance nature of the proton then shows itself only through the Parton Distribution Functions $f(Q, x)$ of momentum scale Q and light-cone momentum fraction x for each flavor. It is convenient to think of these loosely as "one-particle" probability distributions; although that is not strictly correct beyond leading order, where their definition requires singularity management choices such as $\overline{\text{MS}}$.

The goals of the global analysis are three-fold: (1) testing QCD; (2) PDFs are needed for Signal and Background calculations at colliders; and (3) PDFs measure fundamental aspects of proton structure that may be tested against moments of distributions that can be calculated in lattice gauge theory. This third motivation is particularly strong for the case of exploring the spin dependence.

Global QCD analysis

The dependence of the PDFs on Q is determined perturbatively by QCD renormalization group equations (DGLAP). Hence $f(Q, x)$ can be characterized by functions $f_a(Q_0, x)$ at a fixed small Q_0, where $a = g, u, \bar{u}, d, \ldots$. Those functions are measured by a QCD *global analysis*: simultaneously fitting a wide range of data from different experiments at $Q \geq Q_0$.

Key points:

- *Factorization Theorem:* Short distance and long distance are separable, PDFs are process independent
- *Asymptotic Freedom:* Hard scattering is perturbatively calculable
- *DGLAP Evolution:* Evolution in Q is perturbatively calculable, so the functions to be measured depend only on x.

If the hard-scattering data include polarization information, it should be possible to extend the PDF formalism to allow separate PDFs for polarization states of each flavor.

CTEQ6.6 Global analysis

Input from Experiment:

- $\sim$ 2700 data points with $Q > 2\,\text{GeV}$ from e, μ, ν DIS; lepton pair production (DY); lepton asymmetry in W production; high p_T inclusive jets; dimuon production in neutrino scattering; HERA c and b production; HERA charged current. $\alpha_s(M_Z)$ obtained from LEP.

Data cuts:

- $Q^2 > 4\text{GeV}^2$, $W^2 > 12\text{GeV}^2$

Input from Theory:

- NLO QCD evolution and hard scattering

Assumptions:

- Parametrize at Q_0: $A_0\, x^{A_1}\,(1-x)^{A_2}\, e^{A_3 x}\,(1+A_4 x+A_5 x^2)$ with $A_4 = 0$ and/or $A_5 = 0$ for flavors that are less well constrained by data.
- $s = \bar{s}$ with $A_4 = A_5 = 0$;
- No intrinsic b or c

Method

- Construct effective $\chi^2_{\text{global}} = \sum_{\text{i=expts}} W_i\, \chi_i^2$
- Minimize χ^2_{global} to find "Best Fit" PDFs.
- Use χ^2_{global} in neighborhood of the minimum to define uncertainty limits.
- Weights W_i are chosen so that all experiments (including experiments with few data points) are fit well.

The PDF Paradigm

1. Parameterize x-dependence of each flavor at fixed small Q_0 (1.3 GeV) (parameters $A_1, \ldots, A_N$) $N \sim 20$
2. Compute PDFs $f_a(x, Q)$ at $Q > Q_0$ by DGLAP
3. Compute cross sections for DIS(e,μ,ν), Drell-Yan, Inclusive Jets, ... by perturbation theory (NLO or NNLO — LO is not good enough, gives much worse χ^2)
4. Compute "χ^2" measure of agreement between predictions and measurements:

$$\chi^2 = \sum_i W_i \left(\frac{\text{data}_i - \text{theory}_i}{\text{error}_i} \right)^2$$

or generalizations to include correlated systematic errors.

5. Minimize χ^2 with respect to the shape parameters $\{A_i\}$ to find Best Fit PDFs

6. PDF Uncertainty Range is the region in $\{A_i\}$ space where χ^2 is sufficiently close to minimum that all experiments are fit tolerably well.

7. Weight factors W_i are needed to force the fit to pay attention to small data sets.

Minimizing χ^2

The PDFs are determined by finding the fitting parameters $\{A_i\}$ that minimize χ^2. This job is nontrivial because

1. There are lots of parameters — currently 22.

2. To reduce the dependence on parametrization assumptions, new parameters are included in the fit until it is barely stable. Hence there are some "nearly flat" directions, which leaves the χ^2 surface quadratic only very close to the minimum.

3. The parameters are highly correlated.

4. Evaluation of χ^2 for a single choice of $\{A_i\}$ takes a few seconds, so efficiency is needed.

I have extended the classic Minuit to include an iterative method that converges to obtain the eigenvectors of the Hessian matrix. Other groups restrict the number of parameters (10–15) to avoid convergence problems at the cost of more dependence on the assumed parametrization.

In the neighborhood of the minimum, χ^2 can be approximated by a quadratic form

$$\chi^2 = \chi_0^2 + \sum_{ij} H_{ij}\,(A_i - A_i^{(0)})\,(A_j - A_j^{(0)})$$

where the Hessian matrix H is the inverse of error matrix.

After the iteration has converged, this is expressed in a diagonal form by making use of the eigenvectors of H:

$$\chi^2 = \chi_0^2 + \sum_i z_i^2$$

$$A_i = A_i^{(0)} + \sum_j w_{ij}\, z_j$$

In this way, χ^2 is probed in each eigenvector direction at the appropriate scale of $\Delta\chi^2$. The distances moved in parameter space range from very small ("steep directions", well-determined features) to very large ("flat" directions).

The ratio of these distances corresponds to the spectrum of eigenvalues of the Hessian, which span a range of many orders of magnitude.

Uncertainties from eigenvector sets

The uncertainty of PDFs can be characterized by a collection of fits that are created by stepping away from the minimum of χ^2 along each eigenvector direction of the local quadratic form (Hessian matrix). The distance to go along each direction must be such that the fit remains "acceptable". In CTEQ6.1, this was estimated to be $\Delta\chi^2 = 100$ for 90% confidence. (1811 data points) The current CTEQ6.6 fits have 22 free parameters and hence 44 "Eigenvector uncertainty sets".

The PDF uncertainty for any predicted quantity is obtained by evaluating that quantity with each of the eigenvector sets and then applying a simple asymmetric formula: the square root of the sum of the squares of the upward (downward) deviations from the value given by the central fit gives the estimated upper (lower) limit.

Outlook for Spin-dependent PDFs

- The standard PDF analysis already deals with quantities that are very well determined, such as $u(x)$ at moderate x, along with quantities that correspond to "flat" directions, such as $g(x)$ at large x. Hence no problem is anticipated in extracting information on quantities like spin dependence that are not strongly constrained.
- Rather than making a new full global fit that includes all of the current unpolarized data set used in the CTEQ fit, together with the polarized data to constrain the spin-dependent degrees of freedom, it may be possible to do a good job much more easily by freezing the unpolarized PDFs at their current forms in the CTEQ fit, and just fitting the new helicity-dependent functions to the polarized data.

What needs to be done?

The following issues need to be handled to extract spin-dependent PDFs from the polarized data. Perhaps some of these have already by solved by the Spin Experts.

1. What are the spin-dependent PDFs that one can hope to extract? — is it just replacing each unpolarized parton distribution (d, u, s, $\bar{d}$, $\bar{u}$, $\bar{s}$, g) by a pair of functions with helicity parallel or antiparallel to the proton helicity?
2. How should these functions be parametrized at Q_0? — models will be needed at first to keep the number of new fitting parameters small enough to be determinable by the data.
3. Is a NLO DGLAP evolution package available for the polarized PDFs?

4. What data sets are or will be available? — can we afford the luxury of cuts like $Q^2 > 4\,\mathrm{GeV}^2$ to suppress non-leading twist effects?

5. Are NLO calculations of the relevant polarization-dependent observables available — or might LO calculations be good enough for this sector?

QCD fits to the g_1 world data and uncertainties

Lara De Nardo
TRIUMF/DESY

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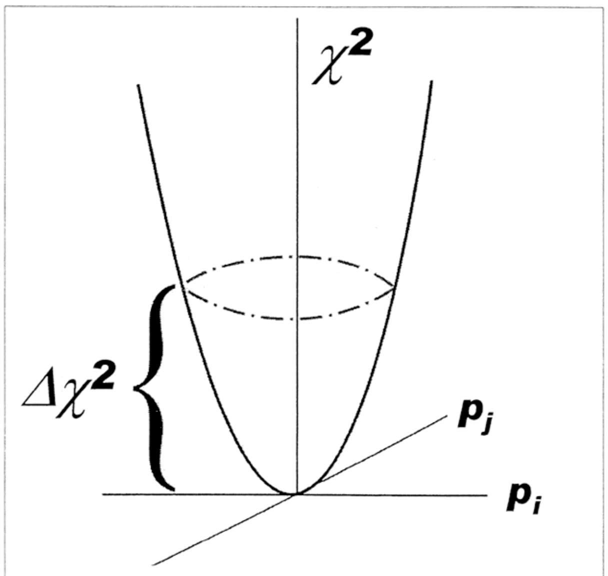
In my talk I will mainly focus on the calculation of uncertainties in polarised parton distributions obtained by QCD fits to g_1 world data. I will discuss how some published results on statistical uncertainties cannot be readily compared with results from other papers, because of different interpretations of these uncertainties; from this it follows that sometimes opposite conclusions are reached based on similar results.

Statistical Uncertainties

- *At least two groups (BB and AAC) report statistical uncertainties inflated by* $\approx \sqrt{NPAR}$
- *They cannot be directly compared to those of other groups.*

(These inflated uncertainties do not correspond to what is normally understood as statistical uncertainty, obtained as the ***standard deviation of the distribution of results*** *derived by fitting a large number of MC data sets resembling the experimental data sets, but with* ***each data point fluctuating independently*** *according to the experimental statistical uncertainty)*



- $\Delta\chi^2$**=1** *defines the 1σ uncertainty for single parameters*

- $\Delta\chi^2$**~NPAR** *is the 1σ uncertainty for the NPAR parameters to be* ***simultaneously*** *located inside the hypercontour (normally used for* ***unknown systematics****, see CTEQ, MRST….)*

NPAR=number of parameters

Evolution of Statistical Uncertainties

Statistical uncertainties are given by: ***X-space***

$$(\sigma_{\Delta q})^2(x,Q^2) = \sum_{ij} \frac{d\Delta q}{dp_i}(x,Q^2)\frac{d\Delta q}{dp_j}(x,Q^2)\,\mathrm{cov}(p_i,p_j)$$

❖ *Calculable exactly at Q^2_0 since the functional form of Δq is known at Q^2_0.*

$$\frac{d}{dp_k}\left[\begin{aligned} \frac{d}{dt}\Delta q_{NS} &= P_1 \otimes \Delta q_{NS} \\ \frac{d}{dt}\Delta\Sigma &= P_2 \otimes \Delta\Sigma + P_3 \otimes \Delta G \\ \frac{d}{dt}\Delta G &= P_4 \otimes \Delta\Sigma + P_5 \otimes \Delta G \end{aligned}\right] \Rightarrow \begin{aligned} \frac{d}{dt}\frac{d\Delta\Sigma}{dp_{\Sigma_i}} &= P_2 \otimes \frac{d\Delta\Sigma}{dp_{\Sigma_i}} + P_3 \otimes \frac{d\Delta G}{dp_{\Sigma_i}} \\ \frac{d}{dt}\frac{d\Delta G}{dp_{\Sigma_i}} &= P_4 \otimes \frac{d\Delta\Sigma}{dp_{\Sigma_i}} + P_5 \otimes \frac{d\Delta G}{dp_{\Sigma_i}} \end{aligned}$$

❖ *The derivatives of the distributions* ***evolve just like the distributions****!*

Evolution of Statistical Uncertainties

$$\frac{d}{dt}\frac{d\Delta\Sigma}{dp_{\Sigma_i}} = P_2 \otimes \frac{d\Delta\Sigma}{dp_{\Sigma_i}} + P_3 \otimes \cancel{\frac{d\Delta G}{dp_{\Sigma_i}}}$$

$$\frac{d}{dt}\frac{d\Delta G}{dp_{\Sigma_i}} = P_4 \otimes \frac{d\Delta\Sigma}{dp_{\Sigma_i}} + P_5 \otimes \cancel{\frac{d\Delta G}{dp_{\Sigma_i}}}$$

Parameter of $\Delta\Sigma(x, Q^2_0)$

At initial $Q^2 = Q^2_0$

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- *Only at Q^2_0 ΔG does not depend on the $\Delta\Sigma$ parameters!*
- ***ΔG acquires a dependence on the $\Delta\Sigma$ parameters** in Q^2*
- *The same is true for $\Delta\Sigma$ (it depends on the ΔG parameters through the evolution)*
- *The **NS evolves independently** from the other distributions*
- *For details on the unc. calculations in Mellin space see BB paper (*Nucl.Phys.**B636**(2002)225)

Normalization Uncertainties

❖*Account for the (substantial) syst. unc. common to an entire data set for one experiment by adding it incoherently in quadrature to the uncertainty in each data point.*

❖*Done with a* χ^2 ***penalty term,*** *see BB:*

Fitted normalization

$$\chi^2 = \sum_{i=1}^{n^{exp}} \left[\frac{(N_i - 1)^2}{(\Delta N_i)^2} + \sum_{j=1}^{n^{data}} \frac{\left(N_i g_{1,j}^{data} - g_{1,j}^{theor}\right)^2}{\left(N_i \Delta g_{1,j}^{data}\right)^2} \right]$$

Norm. unc. quoted by expt.

❖*The normalizations can also be calculated* ***analytically*** *at each step, without increasing the number of parameters in the fit:*

$$\left(\frac{\partial \chi^2}{\partial N_i} = 0\right) \Rightarrow N_i = 1 + \frac{\sum_{k=1}^{n^{data}} g_{1,k}^{theor}\left(g_{1,k}^{theor} - g_{1,k}^{data}\right)/\left(\Delta g_{1,k}^{data}\right)^2}{\left(\frac{1}{\Delta N_i}\right)^2 + \sum_{j=1}^{n^{data}} \left(g_{1,j}^{theor}\right)^2 / \left(\Delta g_{1,k}^{data}\right)^2}$$

Systematic uncertainties

One can get even more fancy and consider the experimental systematic uncertainties:

$$g_{1,k}^{data} \Rightarrow g_{1,k}^{data} + S_i \cdot \Delta_{sys} g_{1,k}^{data}$$

S_i *can also be calculated analytically at each step*

$$\chi^2 = \sum_{i=1}^{n^{\exp}} \left[\sum_{j=1}^{n^{data}} \frac{\left(g_{1,j}^{data} + S_i \cdot \Delta_{sys} g_{1,j}^{data} - g_{1,j}^{theor}\right)^2}{\left(\Delta g_{1,j}^{data}\right)^2} + S_i^2 \right]$$

$$\left(\frac{\partial \chi^2}{\partial S_i} = 0 \right) \quad \Longrightarrow \quad S_i = \frac{\sum_{k=1}^{n^{data}} \left(g_{1,k}^{theor} - g_{1,k}^{data}\right) \Delta_{sys} g_{1,k}^{theor} / \left(\Delta g_{1,k}^{data}\right)^2}{1 + \sum_{j=1}^{n^{data}} \left(\Delta_{sys} g_{1,j}^{theor}\right)^2 / \left(\Delta g_{1,j}^{data}\right)^2}$$

QCD analysis of spin structure function data: The polarized gluon distribution in the nucleon from present and prospective future measurements

Jechiel LICHTENSTADT

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New experiments have been set up to measure the gluon polarization, $\Delta G(x)$, from asymmetries in semi-inclusive DIS processes involving photon-gluon fusion. The HERMES experiment at DESY and the SM Collaboration at CERN have obtained values of $\Delta G/G$ from asymmetries in photo-production of high p_T hadron pairs. More recently the COMPASS Collaboration measured such asymmetries at low Q^2, and presented preliminary values for $\Delta G/G$ from asymmetries of high p_T hadron pairs at high Q^2, and from the much cleaner process of open charm production open charm production. In particular, measurements of double-helicity asymmetries in hadron production from $\vec{p}\vec{p}$ collisions at RHIC provide data which are sensitive to the polarized gluon distribution. The PHENIX measurements of double helicity asymmetries for π^0 production put significant constraints on the polarized gluon distributions constraining their integral over relatively small regions of x.

It is thus interesting to see how these new measurements agree with the results obtained from the QCD analysis in NLO of the g_1 data, which is more 'sensitive' to the polarized-gluon first moment rather than to values at a given x_g. Such a comparison would show the regions where new data will provide very important information on the polarized gluon distribution in the nucleon, and will pin down its shape.

The QCD analysis included the updated g_1 data from EMC, SMC, SLAC-E142,E143, E154, E155, and JLAB - Hall A for the proton, deuteron and neutron, as well as the recent COMPASS deuteron data. The extended CLAS data set at low x was not yet incorporated in the analysis.

We follow Altarelli, Ball, Forte and Ridolfi, and utilize the AB scheme in the analysis. Using the DGLAP equations, parton distributions parameterized at an initial scale Q_0^2 are evolved to the Q^2 value of the experimental data at the measured x, thereby fitting the initial parameterization to the data. Four parton distributions were used for the quark singlet and non-singlet distributions and for the gluon distribution. The non-singlet distribution was allowed to have a different parameterization for the proton and the neutron. The form for each parton distribution at the initial scale (Q_0^2=1 GeV^2) was taken as:

$$\Delta f = N\eta_f x^{\alpha_f}(1-x)^{\beta_f}(1+a_f x+\rho_f\sqrt{x})$$

where N is a normalization factor ($\int_0^1 Nx^\alpha(1-x)^\beta(1+ax+\rho\sqrt{x})\mathrm{d}x = 1$) and η_f is the first moment of the Δf. The first moment of the non-singlet distribution was fixed by $\pm\frac{3}{4}\frac{g_A}{g_V}+\frac{1}{4}a_8$. Not all 18 parameters were fitted, and the best fit was obtained with a 12 parameter fit. The high x behavior of the gluon distribution is determined by β_G, which was set at $\beta_G = 8$ to avoid large violations of the positivity limit $\Delta G/G$.

The best fit polarized gluon distributions are shown in Fig. 1 for Q^2 scales of 1 and 3 (GeV/c)^2. The first moment of the polarized gluon distribution ati $Q^2 = 1$ (GeV/c)^2 is $\eta_G = 0.62^{+0.13}_{-0.12}$ (*stat.*) Errors are statistical only.

The total χ^2 of the fit is: $\Sigma\chi^2 = 251$ for 286 data points and 12 fitted parameters which corresponds to a very high confidence level (C.L.) of about 85%.

The significance of the node in the gluon distribution (shown in Fig. 1). was tested by repeating the fit with 11 parameters (setting $\rho_G = 0$ in the fit). The resulting polarized gluon distribution is shown in Figure 2. The first moment of the gluon distribution is reduced to $\eta_G = 0.48^{+0.20}_{-0.13}$ (*stat.*) The fit yields $\Sigma\chi^2 = 261$ for 286 data points and 11 fitted i parameters which reduces the C.L. to about 72%.

The compatibility of the resulting polarized gluon distribution with the measured values of $\Delta G/G$ by HERMES, SMC and COMPASS was tested by including these values as $\Delta G(x, Q^2)$ values in the fit. Due to the large errors in these measurements, they hardly affect the results of the fit. The fits which include these data are shown in Figs. 3 and 4. However one should note that while the ΔG measurement seem compatible with the best fit, we obtain for the 11 parameter fit $\Sigma\chi^2 = 269$ for 291 D.o.F with C.L. = 67%.

The best fit was compared also to measured π^0 asymmetries of the PHENIX Collaboration at RHIC. The double helicity asymmetries were calculated using the best-fit polarized gluon distribution, and compared to the Run-5 results in Fig. 5.

The systematic errors were not determined. A rough estimate of the total systematic error due to the systematic errors in the data ($\approx \pm 0.10$), the functional form ($\approx \pm$ 0.15) and the factorization and renormalization scales ($\approx \pm 0.05$) gives $\delta(\Delta G) \approx \pm$ 0.20.

An electron-ion collider (EIC) with polarized beams of 10 and 250 GeV respectively will extend significantly the kinematic range for measurements of g_1. The best fit distribution from the QCD fits were used to calculate A_1 asymmetries over the EIC kinematic range. These values were randomized and the QCD fit was repeated to evaluate the effect of the prospective future data on the polarized gluon distribution. The error (statistical) on the polarized-gluon first moment drops to about 0.05. The simulated data are shown with the existing data in Figure 6. The error on the polarized gluon first moment drops significantly to about 0.05.

In conclusion, it is clear from these results that more g_1 data are critically needed at low x for the proton and the deuteron. Precise ΔG data is also essential to pin down the shape of the polarized gluon distribution. In the future, one should try to utilize 'model-independent' parton distributions in the QCD analysis. Thus, determination of the few parameters of each parton distribution over a rather limited x range, will not give a false impression of good knowledge of δG in the *unmeasured* low x region. Using series expansions of the parton distributions will result also in realistic errors along x.

Incorporating RHIC data and ΔG measurements in the analysis with their actually measured cross section asymmetries will make the QCD analysis fully self-consistent.

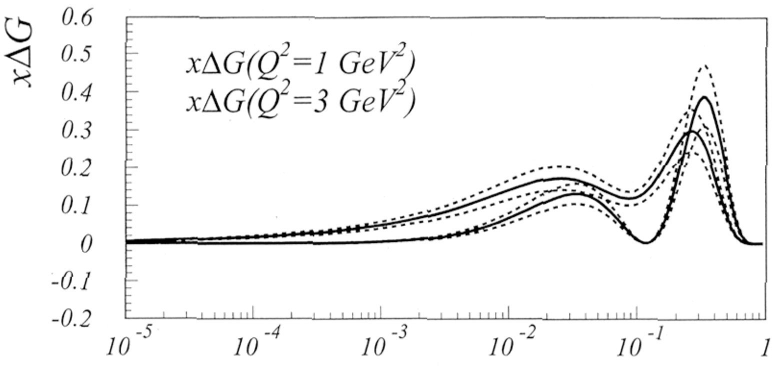


Figure 1

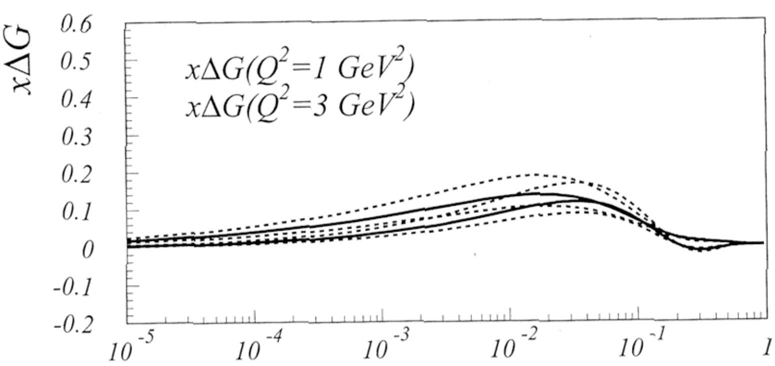


Figure 2

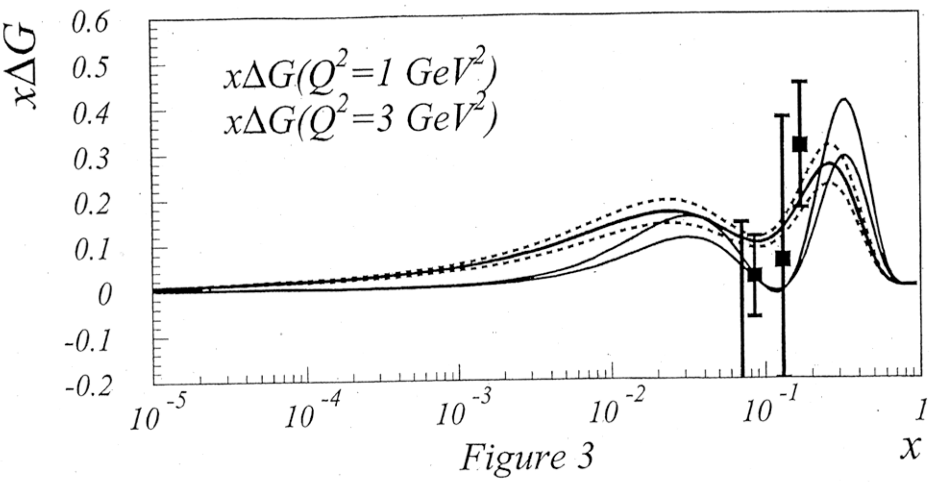


Figure 3

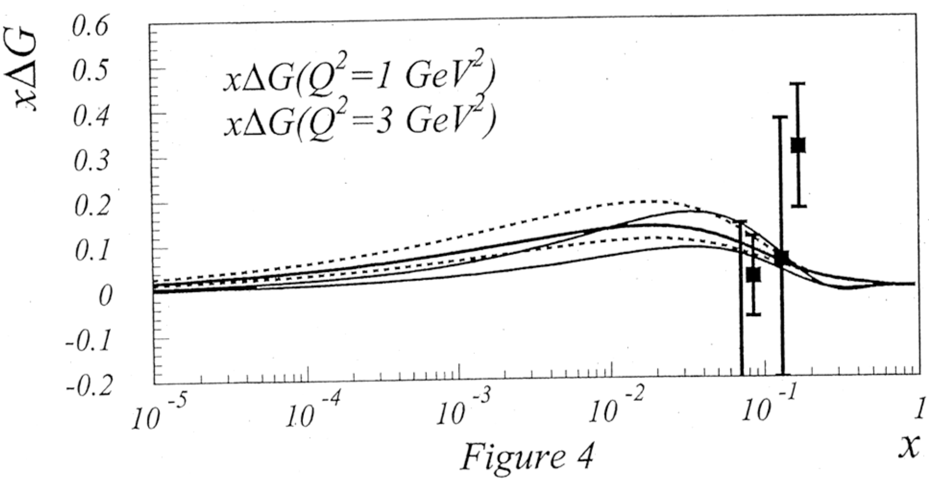
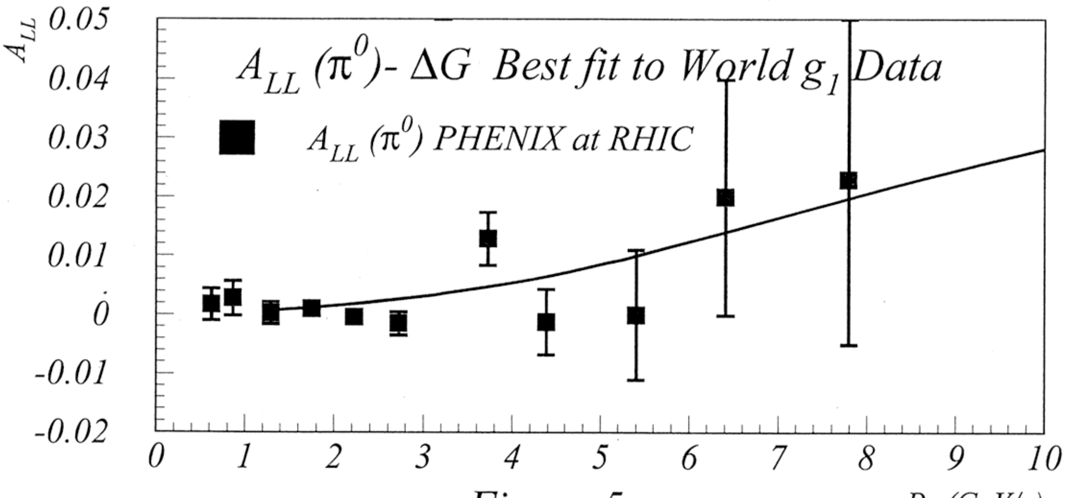


Figure 4



A_{LL}
0.05
0.04
0.03
0.02
0.01
0
-0.01
-0.02
A_{LL} (π^0)- ΔG Best fit to World g_1 Data
A_{LL} (π^0) PHENIX at RHIC
0
1
2
3
4
5
6
7
8
9
10
P_T (GeV/c)

Figure 5

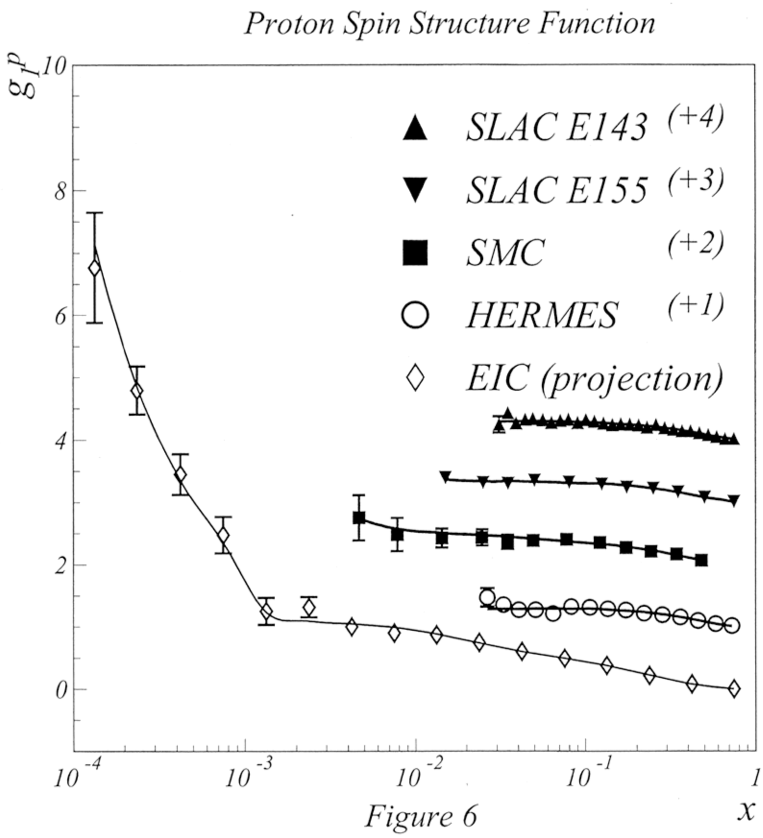

Proton Spin Structure Function
g_1^p
10
8
6
4
2
0
SLAC E143 (+4)
SLAC E155 (+3)
SMC (+2)
HERMES (+1)
EIC (projection)
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
x

Figure 6

Global Analysis of Polarized Parton Distribution Functions by Asymmetry Analysis Collaboration

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High Energy Accelerator Research Organization (KEK)
and Department of Particle and Nuclear Studies
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ABSTRACT

I explain global analysis results on polarized parton distribution functions (PDFs) by the Asymmetry Analysis Collaboration (AAC) [1–3]. The polarized PDFs have been determined by using world data from the longitudinally polarized deep inelastic scattering experiments [1,2] together with π^0-production measurements at RHIC [3].

In our first analysis [1], we pointed out that the quark spin content ($\Delta\Sigma$) depends much on the small-x behavior of the polarized antiquark distributions. The results indicated that the quark spin content is $\Delta\Sigma$ =0.20 and 0.05 in the leading order (LO) and the next-to-leading-order (NLO) $\overline{\rm MS}$ scheme, respectively. However, if x dependence of the antiquark distribution is fixed at small x by "perturbative QCD" and Regge theory, it becomes $\Delta\Sigma = 0.24 \sim 0.28$ in the NLO. The small-x behavior cannot be uniquely determined by the existing data, which indicated the importance of future measurements.

In the second version [2], we estimated uncertainties of the polarized PDFs by the Hessian method. The results suggested that the up and down valence-quark distributions are determined well; however, the antiquark distributions have large uncertainties and it is particularly difficult to determine the gluon distribution. We showed that even $\Delta g(x) = 0$ could be allowed if the uncertainty is taken into account although a positively polarized gluon distribution is favored. It was also found that accurate E155 data improve the determination of the polarized PDFs, especially the polarized antiquark distributions. We also investigated error correlation effects between the antiquark and gluon distributions by showing global analysis results with the condition $\Delta g(x) = 0$ at the initial scale, $Q^2 = 1$ GeV^2.

In the third version [3], the polarized PDFs were determined by adding new data, which include JLab, HERMES, and COMPASS measurements on spin asymmetry A_1 for the neutron and deuteron. In addition, we included double-spin asymmetry data for π^0 production in polarized pp collisions, $A_{LL}^{\pi^0}$, measured by the PHENIX collaboration. Because of these new data, uncertainties of the polarized PDFs were reduced. In particular, the PHENIX π^0 data significantly reduced the uncertainty of $\Delta g(x)$. Furthermore, we discussed a possible constraint on $\Delta g(x)$ at large x by using the HERMES data on g_1^d in comparison with the COMPASS ones at $x \sim 0.05$. Obtained distributions can be calculated by using codes at our web site [4].

References

[1] Y. Goto *et al.*, Phys. Rev. D62 (2000) 034017.
[2] M. Hirai, S. Kumano, and N. Saito, Phys. Rev. D69 (2004) 054021.
[3] M. Hirai, S. Kumano, and N. Saito, Phys. Rev. D74 (2006) 014015.
[4] Polarized-PDF subroutines could be obtained from http://spin.riken.bnl.gov/aac/.

* http://research.kek.jp/people/kumanos/

Gluon polarization at large x

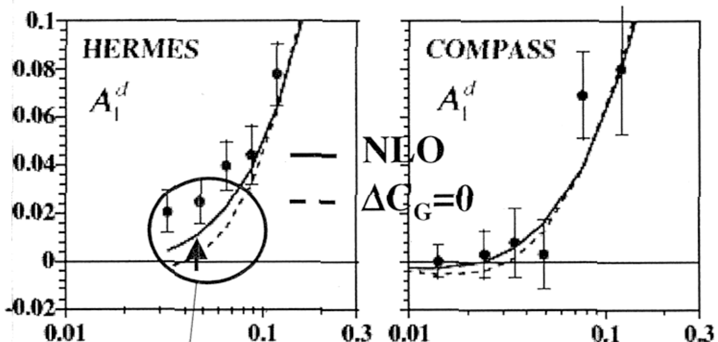
$$g_1(x,Q^2)=\frac{1}{2}\sum_q e_q^2\int_x^1\frac{dz}{z}\left[\Delta q(x/z,Q^2)+\Delta\bar{q}(x/z,Q^2)\right]\times\left[\delta(1-z)+\frac{\alpha_s(Q^2)}{2\pi}\Delta C_q(z)+\cdots\right]$$

$$+\frac{1}{2}\langle e_q^2\rangle\int_x^1\frac{dz}{z}\Delta g(x/z,Q^2)\left[n_f\,\frac{\alpha_s(Q^2)}{2\pi}\Delta C_g(z)+\cdots\right]$$

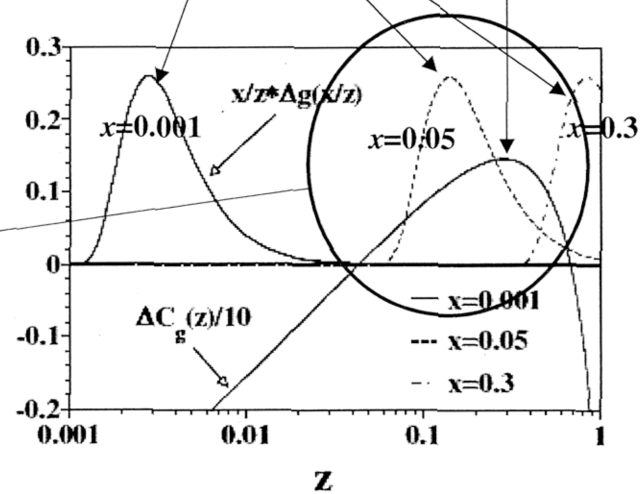
This term is terminated.

AAC, PRD74 (2006) 014015:

Analysis without higher-twist effects



$Q^2_{HERMES}\sim 1\ \text{GeV}^2$ $Q^2_{COMPASS}\sim 6\ \text{GeV}^2$



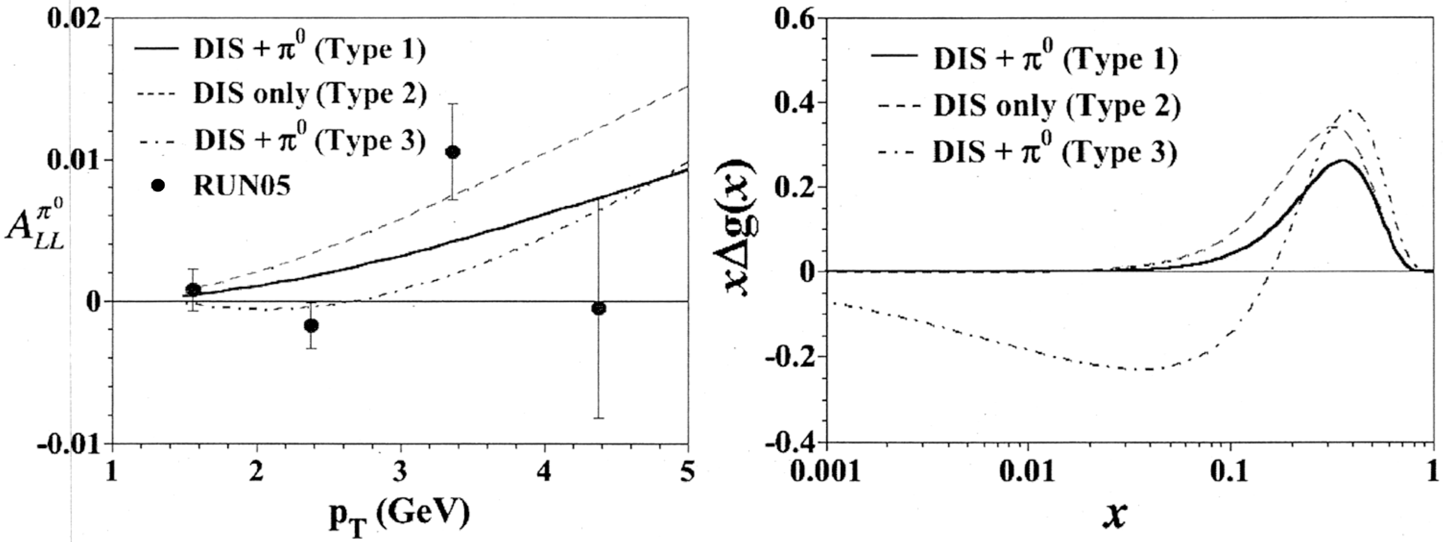
Positive contribution to A_1 comes from $\Delta C_G\otimes\Delta g$ at $x\sim 0.05$.

Note: $\Delta C_G\otimes\Delta g>0$ if $\Delta g(0.05/0.2=0.25)>0$

Gluon polarization is positive at large x.

Possibility of negative gluon polarization $\Delta g < 0$

π^0 production data do not distinguish between $\Delta g < 0$ and $\Delta g > 0$



Error estimation

Hessian method

The error of a distribution $F(x)$ is given by

$$[\delta F(x)]^2 = \Delta\chi^2 \sum_{i,j} \frac{\partial F(x)}{\partial \xi_i} H_{ij}^{-1} \frac{\partial F(x)}{\partial \xi_j}$$

$\chi^2 (= s)$ distribution with N degrees of freedom

$$P(s) = \frac{1}{2^{N/2}\Gamma(N/2)} s^{N/2-1} \exp(-s/2)$$

(1) $N = 1$ case, $\Delta\chi^2 = 1$

$$\int_0^{\Delta\chi^2=1} ds\, P(s)_{n=1} = \mathrm{erf}\,(1/\sqrt{2}) = 0.6826...$$

where $\mathrm{erf}\,(z) = \frac{2}{\sqrt{\pi}} \int_0^z dt\, e^{-t^2}$

(2) our $N = 11$ case, $\Delta\chi^2 = ?$

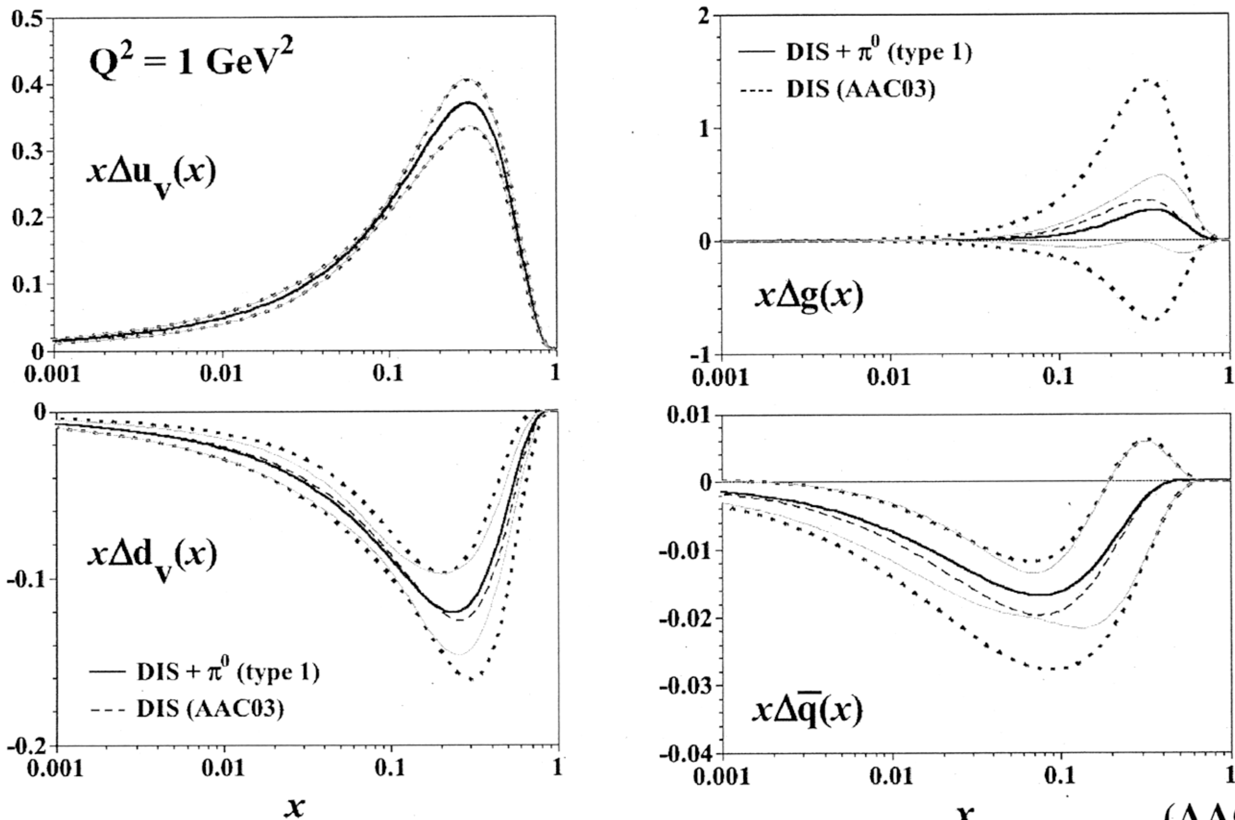
$$\int_0^{\Delta\chi^2} ds\, P(s)_{n=11} = \int_0^{\Delta\chi^2} ds \frac{s^{9/2} e^{-s/2}}{2^{11/2}\Gamma(11/2)} = 0.6826...$$

Solving this equation, we have $\Delta\chi^2 = 12.64...$

Refs. http://wwwasdoc.web.cern.ch/wwwasdoc/minuit/node33.html
http://www.library.cornell.edu/nr/bookfpdf/f15-6.pdf
http://ccwww.kek.jp/pdg/2005/reviews/statrpp.pdf

Roles of RHIC-pion data

Polarized PDFs, especially Δg, are better determined by the additional RHIC-π^0 data.



(AAC06)

Summary of the AAC analysis

(AAC00) Y. Goto *et al.*, Phys. Rev. D62 (2000) 034017.

(AAC03) M. Hirai, S. Kumano, N. Saito, Phys. Rev. D69 (2004) 054021;

(AAC06) M. Hirai, S. Kumano, N. Saito, D74 (2006) 014015.

- **Global analysis for polarized PDFs**
  - $\Delta u_v(x)$, $\Delta d_v(x)$ **are determined well**
  - $\Delta\Sigma = 0.27 \pm 0.07$ ($Q^2 = 1$ GeV^2)
  - $\Delta g(x)$ **could not be well constrained**

AAC03
- **Uncertainties of polarized PDFs**
- **Effects of E155-proton data**
- **Global analysis also with $\Delta g=0$**
- **Error correlation between Δg and $\Delta\bar{q}$**

AAC06
- **Better Δg determination by RHIC-pion**
- **Δg determination at large x by scaling violation (HERMES, COMPASS)**

AAC03-polarized-pdfs code could be obtained from http://spin.riken.bnl.gov/aac/

Global Analysis Toolbox: Mellin Technique

Marco Stratmann

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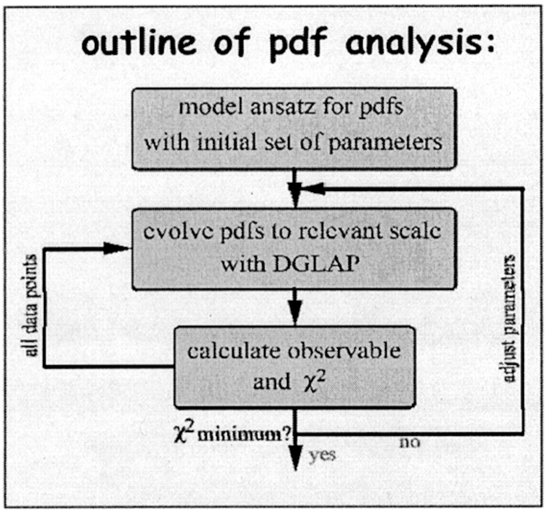
We present a technique [1] for implementing in a fast way, and without any approximations, higher-order calculations of partonic cross sections into global analyses of parton distribution or fragmentation functions. The approach, which is set up in Mellin-moment space, is particularly suited for analyses of present and upcoming data from unpolarized and polarized hadron-hadron collisions, but not limited to this case.
The technical details of the Mellin technique and the requirements in terms of CPU time are discussed in quite some detail. Possible future improvements to speed up the pre-analysis stage of a global analysis are mentioned.
The practicability of this method was recently demonstrated in a global analysis of fragmentation functions, and the Mellin technique is currently being used in a first global analysis of helicity-dependent parton densities.

References:

[1] M. Stratmann and W. Vogelsang, Phys. Rev. **D64** (2001) 114007

the way to do it: global χ^2 minimization



involves multi-parameter fitting

→ **1000's of evaluations of NLO cross sections needed**

(a proper error analysis adds to this)

the problem:

NLO expressions are fairly complex and numerically very time-consuming

computing time for a global analysis at NLO becomes excessive

4

19th century math comes to help ...

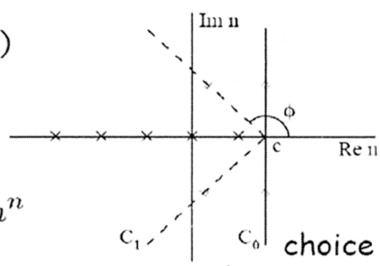
R.H. Mellin
Finnish mathematician

integral transformation: **Mellin n-moments**

$$h^n \equiv \int_0^1 dx\, x^{n-1}\, h(x)$$

↕ inverse

$$h(x) \equiv \frac{1}{2\pi i}\int_{\mathcal{C}_n} dn\, x^{-n}\, h^n$$



choice of contour → later

crucial property: convolutions factorize into simple products

$$\int_0^1 dx\, x^{n-1}\int_x^1 \frac{dy}{y} h(y) g(x/y)$$

$$= \int_0^1 dx\, x^{n-1}\left[\int_0^1 dy \int_0^1 dz\ h(y) g(z) \delta(x - zy)\right]$$

$$= \int_0^1 dy\, y^{n-1} h(y) \int_0^1 dz\, z^{n-1} g(z) = h^n \cdot g^n$$

well-known application: DGLAP evolution

Bjorken-x space: integro-differential equations → no analytical solution

e.g. LO non-singlet (valence) evolution
$$\frac{dq(x,Q^2)}{d\ln Q^2} = \frac{\alpha_s(Q^2)}{2\pi}\int_x^1 \frac{dy}{y}\, q(y,Q^2) P_{qq}(x/y)$$
known up to NNLO

full singlet evolution more complicated: coupled equations

Mellin-n space: ordinary differential equations → analytical solution

$$\frac{dq^n(Q^2)}{d\ln Q^2} = \frac{\alpha_s(Q^2)}{2\pi}\, q^n(Q^2)\; P^n_{qq}$$
n-moments known analytically

solve analytically (to all orders !):

$$q^n(Q^2) = q^n(Q_0^2)\left(\frac{\alpha_s(Q^2)}{\alpha_s(Q_0^2)}\right)^{-2P^n_{qq}/\beta_0}$$
input (fitted) — pQCD scaling viol.

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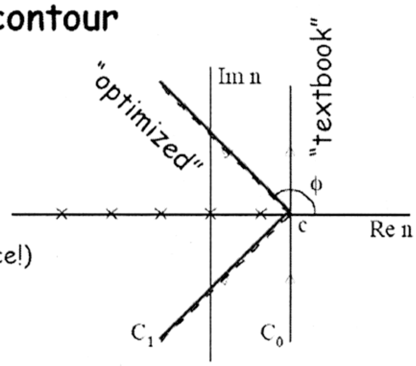
back into x-space: optimizing the contour

$$f(x,Q^2) \equiv \frac{1}{2\pi i}\int_{C_n} dn\, x^{-n} f^n(Q^2)$$



c: to the right of rightmost pole (convergence!)

f(x) are real functions: $(f^n)^* = f^{n^*}$

→ parametrize contour to integrate over real variable z

$$f(x,Q^2) = \frac{1}{\pi}\int_0^\infty dz\,\mathrm{Im}\left[e^{-i\phi}\, x^{-c-ze^{i\phi}}\, f^{n=c+ze^{i\phi}}(Q^2)\right]$$

receipe for numerical fast but reliable inversion: see, e.g., A. Vogt "QCD-PEGASUS" code

C_1 contour with $\phi=3\pi/4$: exp. dampening for large $|n|$ → can use small z_{max}

in practice: z_{max} adaptive depending on x (large x more costly!)
choose n as supports for Gaussian integration **VERY FAST!**

NLO expressions in pp are *much more* complicated than in (SI)DIS

→ Mellin moments cannot be taken analytically & numerically very slow

idea: re-organize multi-convolutions by taking Mellin moments

example: pp→ π X

$$d\Delta\sigma = \sum_{abc} \int \Delta f_a \, \Delta f_b \, d\Delta\hat{\sigma}_{ab\to cX} \, D_c \, dx_a dx_b dz_c$$

express pdfs by their Mellin inverses $\frac{1}{2\pi i}\int_{C_n} dn \, x_a^{-n} \, \Delta f_a^n$ $\quad \frac{1}{2\pi i}\int_{C_m} dm \, x_b^{-m} \, \Delta f_b^m$

$$= \frac{1}{(2\pi i)^2} \sum_{abc} \int_{C_n} dn \int_{C_m} dm \, \Delta f_a^n \Delta f_b^m \int x_a^{-n} x_b^{-m} d\Delta\hat{\sigma}_{ab\to cX} \, D_c \, dx_a dx_b dz_c$$

$$\equiv d\Delta\tilde{\sigma}_{ab\to cX}(n,m)$$

$\int_{C_n} dn \int_{C_m} dm$	$\Delta f_a^n \Delta f_b^m$	$\int x_a^{-n} x_b^{-m} d\Delta\hat{\sigma}_{ab\to cX} \, D_c \, dx_a dx_b dz_c \equiv d\Delta\tilde{\sigma}_{ab\to cX}(n,m)$
standard Mellin inverse	fit	can be pre-calculated on grids!

applicability: completely general, tested for pp→γX, pp→πX, pp→jetX

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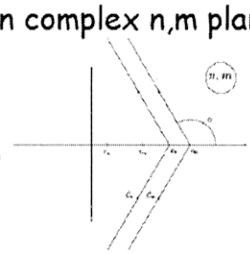
Mellin technique in-depth: the ingredients

$d\Delta\tilde{\sigma}_{ab\to cX}(n,m)$

- contains all time-consuming integrations
- calculated once and forever before the fit
- stored in large n×m grids

$\int_{C_n} dn \int_{C_m} dm$

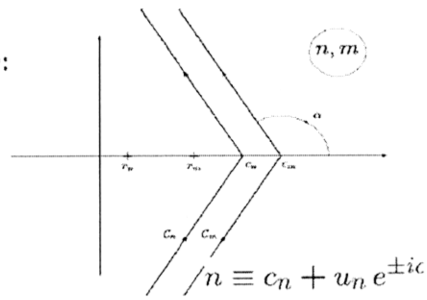
- fast numerical Mellin inverse in complex n,m plane
- exponential fall-off of x^{-n}, x^{-m} along contour optimal
- integration = summation in n,m



$\Delta f_a^n \Delta f_b^m$

- Mellin moments of ansatz for pdfs in x-space, e.g., $f_a(x,\mu_0) = N x^{\alpha} (1-x)^{\beta}$
- parameters determined in standard χ^2 analysis

Mellin technique in-depth: taking the inverse



straightforward extension to double contour:

use that pdfs are real and parametrize contour with 2 real parameters u_n and u_m

find:

$$d\Delta\sigma = -\frac{1}{2\pi^2}\sum_{a,b} \mathrm{Re}\Big[\int_0^\infty du_n \int_0^\infty du_m\, \Delta f_a^n \times \Big\{ e^{2i\alpha}\, \Delta f_b^m\, d\Delta\tilde{\sigma}_{ab}(n,m) - (\Delta f_b^m)^*\, d\Delta\tilde{\sigma}_{ab}(n,m^*) \Big\} \Big]$$

again, choose n,m as supports for Gaussian integration → num. fast!

bookkeeping: for *each subprocess* we need two grids: (n,m) and (n,m*)

[in fact this requires four runs (!!) of the NLO codes since -- so far -- they cannot handle complex valued "pdfs" x^{-n}]

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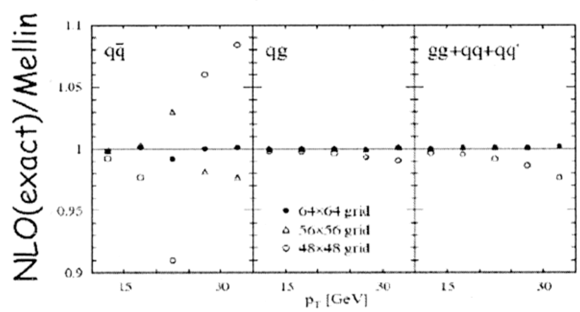
Mellin technique in-depth: performance & accuracy

precision: usually, 64×64 grids sufficient for less than 0.5% deviation



example: prompt photons

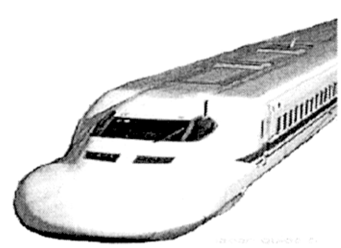
performance:

"**before**": typ. NLO code O(30sec/p_T value)

"after Mellin tune-up": bullet-train performance

100 evaluations of x-sec take a few seconds

ideal tool for multidim. fitting beyond LO



Mellin technique in-depth: pre-calculated grids

how long does it take?

example: pp $\to$ jet X (to analyse STAR data for A_{LL})

6 different subprocesses to consider: gg, qg, 4* "qq'"

$\to 6 \times 4 \times 64 \times 64 \simeq 10^5$ calls of the NLO code per data point

$\to$ current # data points keep 4 dual-core CPU's busy for a week

example: pp $\to$ hadron X (to analyse PHENIX & STAR data for A_{LL})

many more grids since fragmentation distinguishes flavors !!

example: pp $\to \gamma$ X (future)

somewhat less demanding than jets ✓

sufficient computing power is essential for the pre-analysis stage

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Mellin technique in-depth: improvements

good news: grids only "know about" the kinematics of the exp. bins

$\to$ if binning & kinematics (e.g. η-range) remains unchanged
we can simply add more bins if they become available

Mellin technique has passed an important stress test in
global analyses of fragmentation functions   de Florian, Sassot, MS

improvements: codes not really optimized for speed

parallelization possible

user intervention still required $\to$ automatization

currently, changing $\mu_{r,f}$ requires new grids
$\to$ separate grids for the few terms which depend on $\mu_{r,f}$

Global Analysis of Fragmentation Functions

Daniel de Florian
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Argentina

Summary : We present new sets of pion, kaon, proton and charge hadrons fragmentation functions obtained in NLO combined analyses of single-inclusive hadron production in electron-positron annihilation, proton-proton collisions, and deep-inelastic lepton-proton scattering. At variance with all previous fits, the present analyses take into account data where hadrons of different electrical charge are identified, which allow to discriminate quark from anti-quark fragmentation functions without the need of non trivial flavor symmetry assumptions.
An extensive use of the Lagrange multiplier technique is made in order to assess the uncertainties in the extraction of the fragmentation functions and the synergy from the complementary data sets in our global analysis

Fragmentation functions

Represent the probability that a parton hadronizes in h

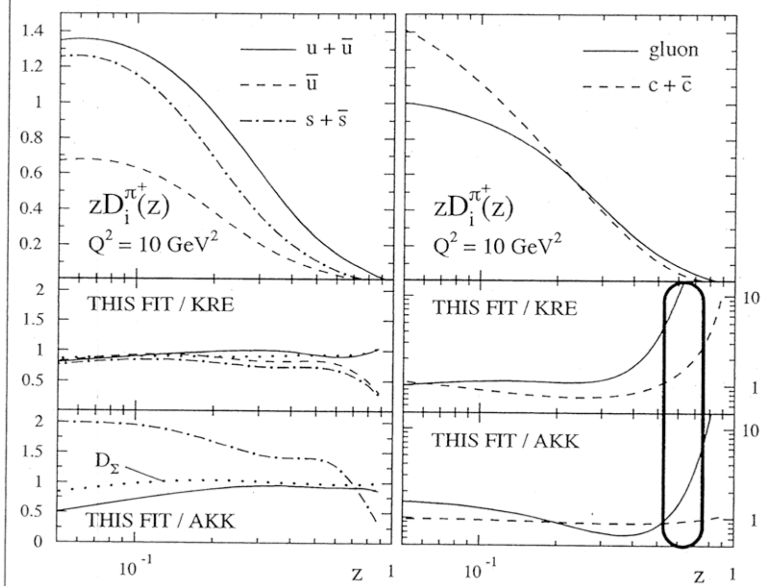
From TH point of view at the same level of pdfs

Relevant any time a hadron is produced in high energy collisions

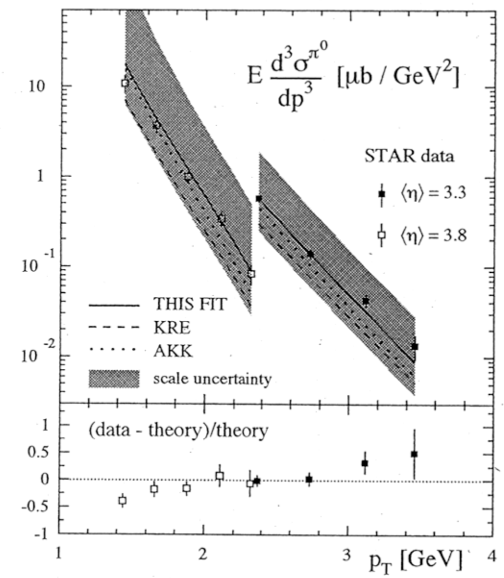
- e+e- : primary "source"
- SIDIS : complement DIS to allow flavor separation
- pp collisions: signal and "background" for a lot of physics

Heavy Ions
polarized pdfs

Distributions (pions)



large rapidity at STAR



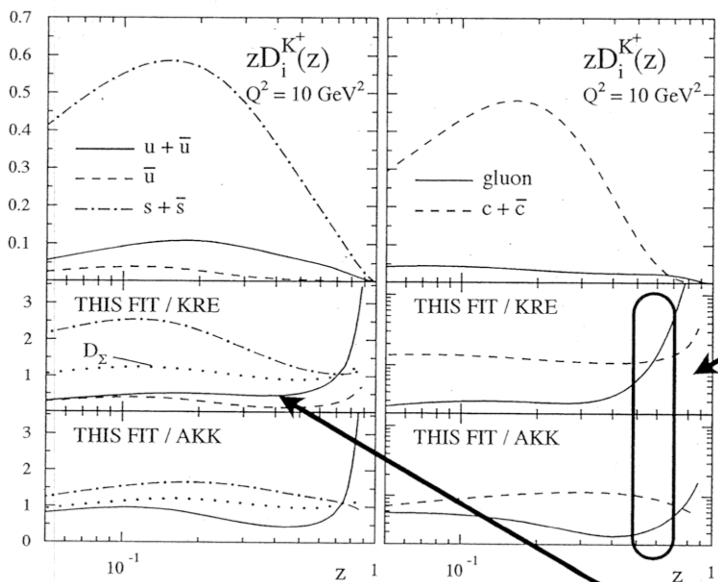
Large differences visible in the gluon at large z : explains pp

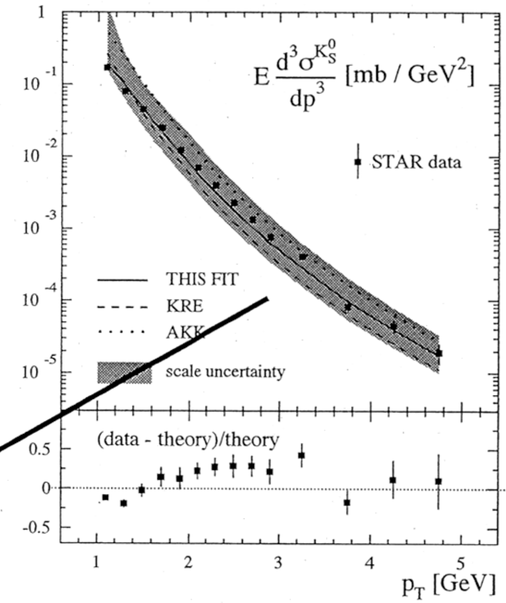
Large differences in unfavored distributions : explains SIDIS and pp

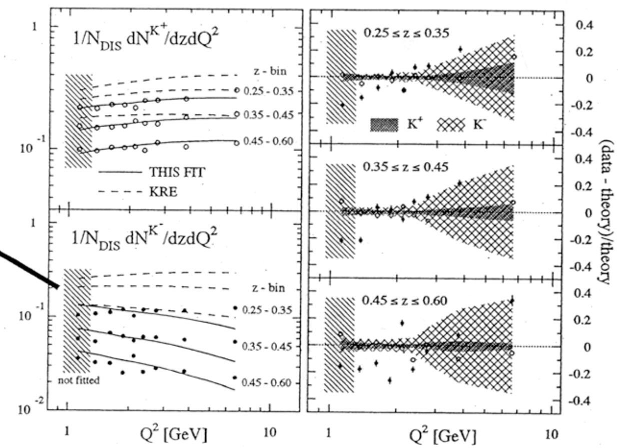
For pions u fragmentation smaller than AKK : required by SIDIS and compensated in SIA by larger s

Similar singlet

Distributions (Kaons)







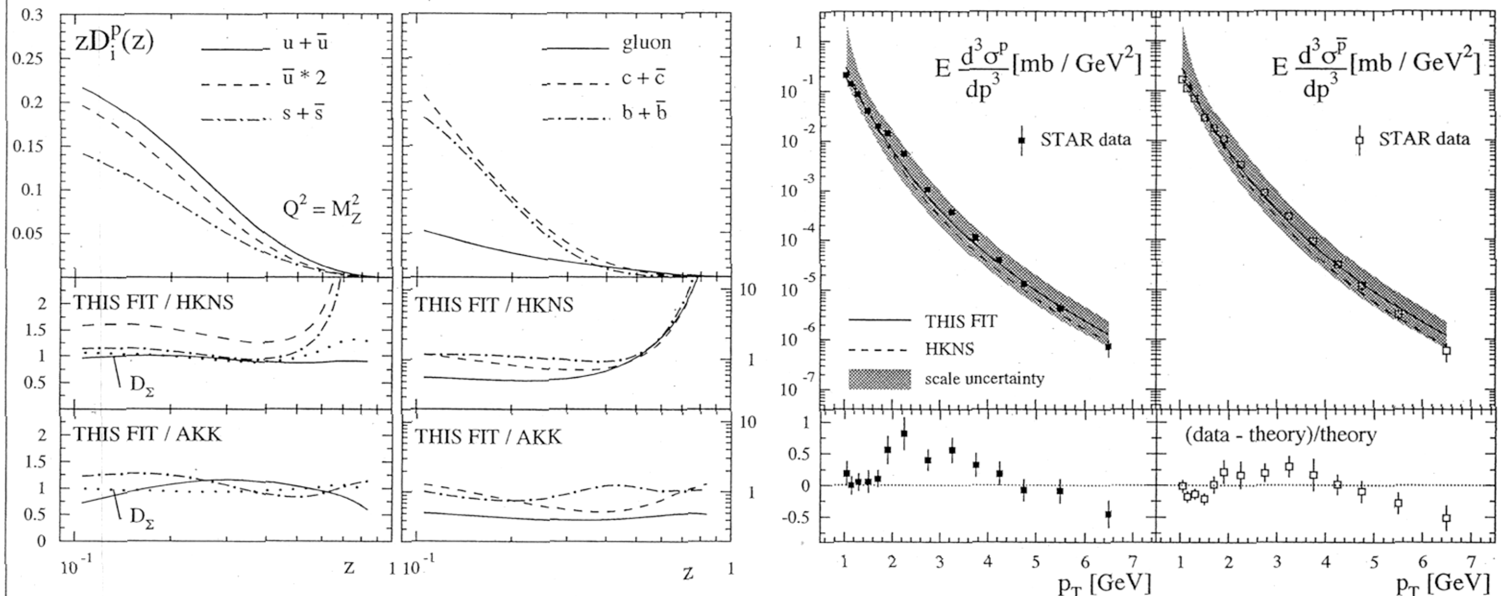
Smaller u required by SIDIS

VERY different gluon by pp

Similar singlet (larger dominant s)

Issues for K- (s and $\overline{u}$ in proton at large x)

Distributions (protons)



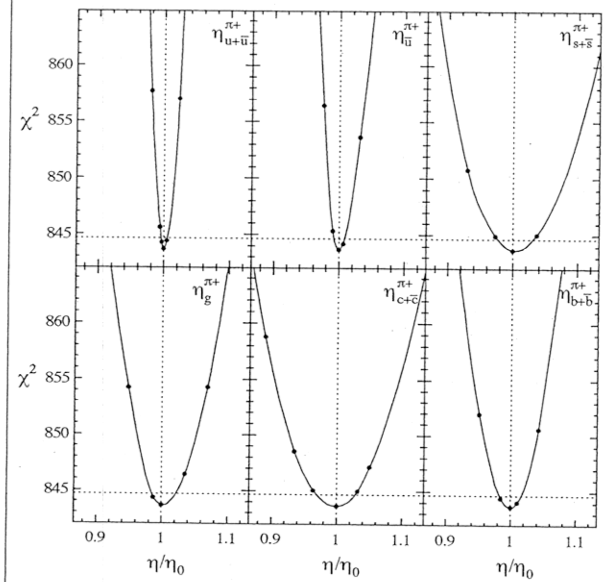
Differences with HKNS also sizeable : gluons, unfavored and large z (pp)

Similar singlet, but large diff. between HKNS and AKK (using same data)

In general differences look much larger than for pdf fits :
comparison between GLOBAL fits

To "estimate" uncertainties using different sets (like MRST vs CTEQ), more global fits needed

Uncertainties

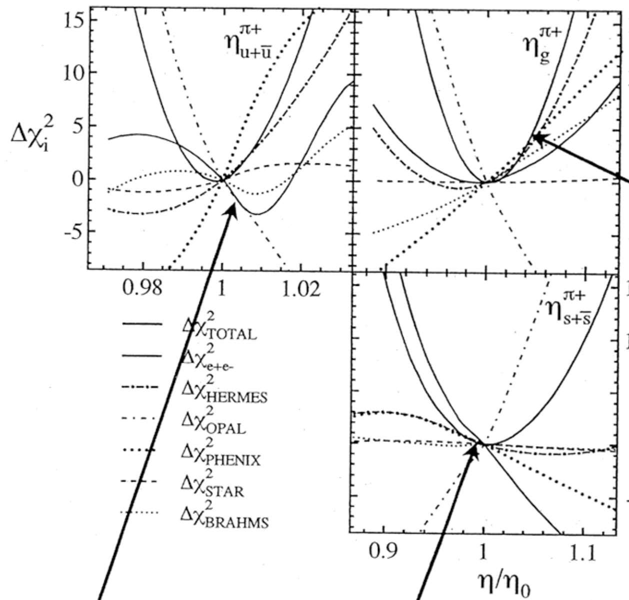


$$\Delta\chi^2 = 15(\sim 2\%)$$

u < 5%
s ~ 10 %

dominated by z~0.2

Individual profiles



Precision RHIC

Tension

Complementarity

Constrained parabola as a result of global fit

NLO QCD fits to polarized DIS & SIDIS data

Rodolfo Sassot
Universidad de Buenos Aires

Global Analysis Workshop, RIKEN-BNL October 8, 2007

why polarized SIDIS?

- flavor and quark-antiquark discriminatrion,
- increasead statistics, new/forthcoming data
- sea quarks and flavor dependence in hadronization.

what do we get from data?

- fits to inclusive/semi-inclusive polarized data.
- uncertainties in pPDFs: $\Delta\bar{q}$, Δg.
- impact "direct" Δg measurements.

how can we improve the present picture?

- further constraints from forthcoming data.
- fragmentation functions.

The case for pSIDIS: Flavor decompositon in pSIDIS

$$g_1^{N\,h} = \frac{1}{2}\Sigma\, e_q^2 \left\{\Delta q\, D^h + \frac{\alpha_s}{2\pi}\left[C_{qq}\otimes\Delta q\otimes D_q^h + C_{qg}\otimes\Delta q\otimes D_g^h + C_{gq}\otimes\Delta g\otimes D_q^h\right]\right\}$$

$$D_u^{\pi^+} = D_{\overline{d}}^{\pi^+} = D_d^{\pi^-} = D_{\overline{u}}^{\pi^-} \equiv D_1^\pi$$
$$D_{\overline{u}}^{\pi^+} = D_d^{\pi^+} = D_{\overline{d}}^{\pi^-} = D_u^{\pi^-} \equiv D_2^\pi$$
$$D_s^{\pi^+} = D_s^{\pi^-} \equiv D_s^\pi$$

$$2\, g_1^{p\,\pi^{+(-)}} \sim \frac{4}{9}(\Delta u + \Delta\overline{u})\, D^\pi_{1(2)} + \frac{1}{9}\left(\Delta d + \Delta\overline{d}\right) D^\pi_{2(1)} + \frac{1}{9}\left(\Delta\overline{d} - 4\Delta\overline{u}\right)\left(D^\pi_{1(2)} - D^\pi_{2(1)}\right) + \frac{1}{9}(\Delta s + \Delta\overline{s})\, D_s^\pi + \mathcal{O}(\alpha_s)$$

$\Delta\overline{u},\ \Delta\overline{d}$

$\Delta u_V,\ \Delta d_V$

$(\Delta u + \Delta\overline{u}) \qquad \left(\Delta d + \Delta\overline{d}\right)$

DNS NLO combined analysis: parameterizations

pDIS can probe:

$$x(\Delta q + \Delta\overline{q}) = N_q \frac{x^{\alpha_q}(1-x)^{\beta_q}(1+\gamma_q x^{\delta_q})}{B(\alpha_q+1,\beta_q+1)+\gamma_q B(\alpha_q+\delta_q+1,\beta_q+1)}, \quad q = u, d$$

$$x(\Delta s + \Delta\overline{s}) = 2N_s \frac{x^{\alpha_s}(1-x)^{\beta_s}}{B(\alpha_s+1,\beta_s+1)},$$

$$x\Delta g = N_g \frac{x^{\alpha_g}(1-x)^{\beta_g}}{B(\alpha_g+1,\beta_g+1)}.$$

$$N_u - N_d = (F+D)(1+\epsilon_{Bj})$$

$$N_u + N_d - 4N_s = (3F-D)(1+\epsilon_{SU(3)})$$

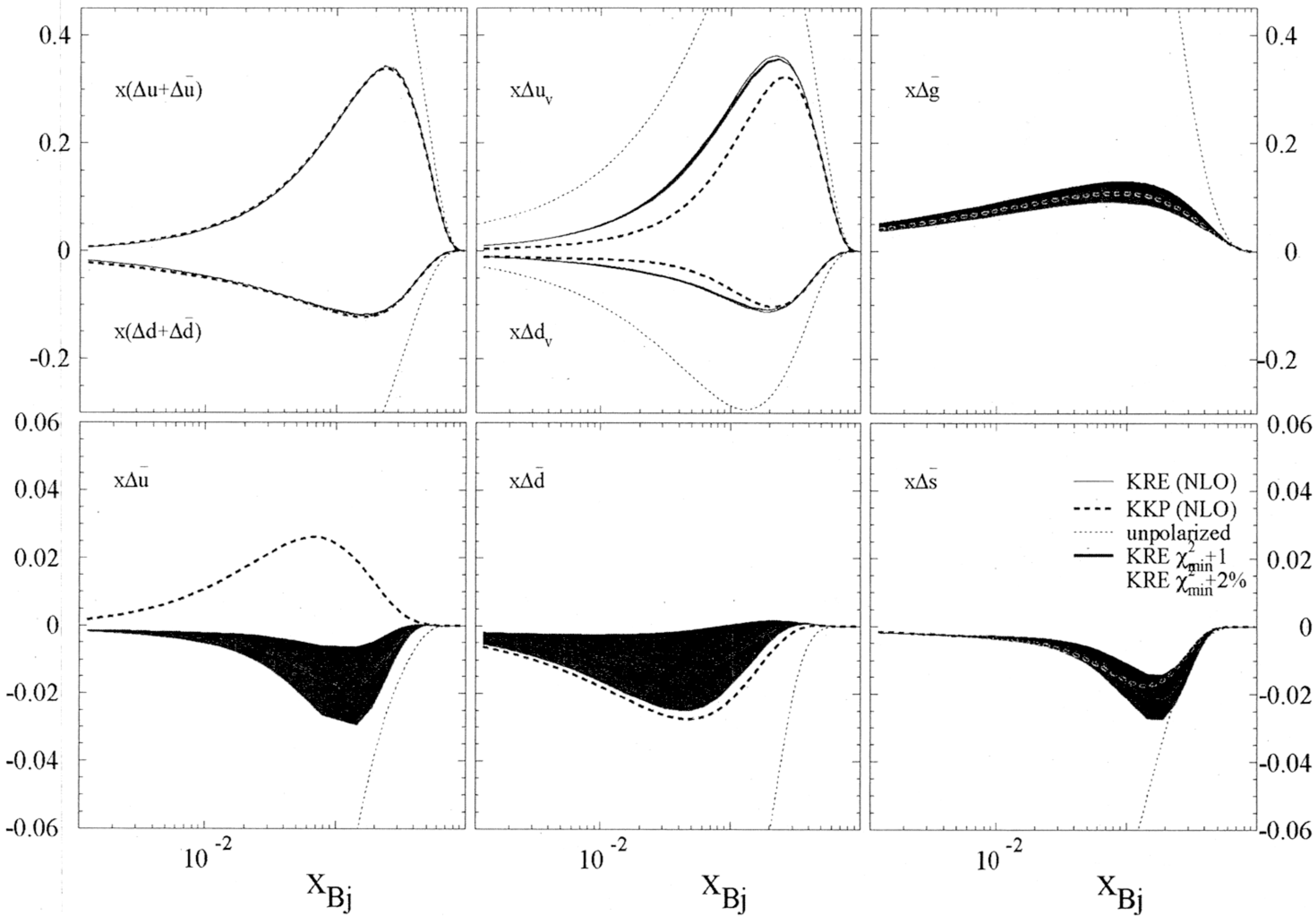
pSIDIS give access to:

$$x\Delta\overline{q} = N_{\overline{q}} \frac{x^{\alpha_{\overline{q}}}(1-x)^{\beta_{\overline{q}}}}{B(\alpha_{\overline{q}}+1,\beta_{\overline{q}}+1)}, \quad \overline{q} = \overline{u}, \overline{d}$$

➡ 20 parameters

positivity relative to MRST02: $|\Delta q| \leq q$

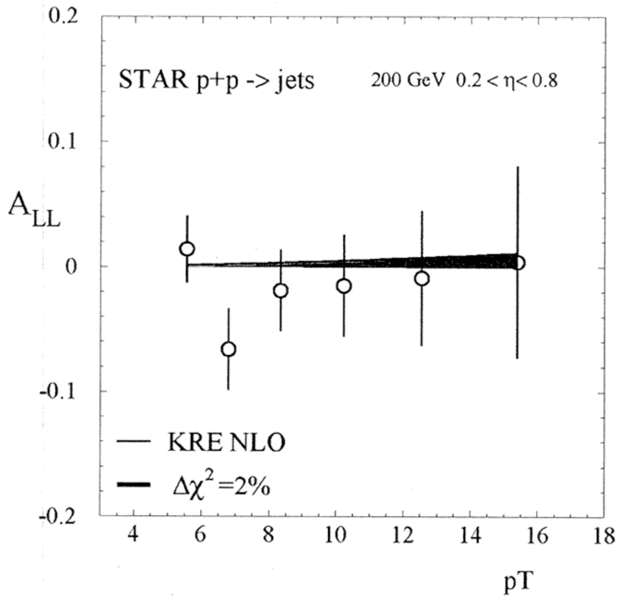
A.D. Maritn et al. Eur.Phys.J.C28 (2002) 455

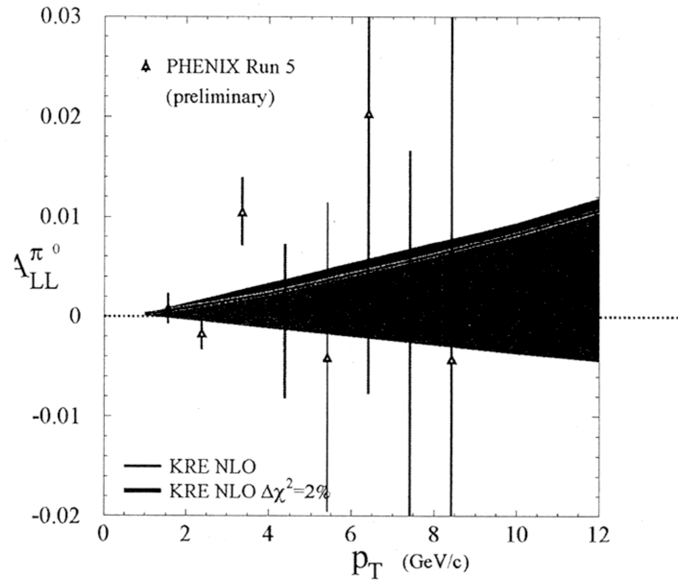


0.4
0.2
0
-0.2
$x(\Delta u+\Delta \bar{u})$
$x(\Delta d+\Delta \bar{d})$
$x\Delta u_v$
$x\Delta d_v$
$x\Delta g$
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
$x\Delta \bar{u}$
$x\Delta \bar{d}$
$x\Delta \bar{s}$
KRE (NLO)
KKP (NLO)
unpolarized
KRE $\chi^2_{min}+1$
KRE $\chi^2_{min}+2\%$
10^{-2}
x_{Bj}

Consistency with independent measurements:

G. Navarro R.S hep-ph/0605266





R. Sassot BNL, October 8, 2007

Discussion

Global Analysis of Polarized RHIC and DIS data:

How do we get there?

Abhay Deshpande(SBU/RBRC) & Werner Vogelsang(BNL)

RBRC Workshop at BNL
October 8, 2007

Disclaimer:
No decisions
Only thoughts and proposals.

For every one to get involved and participate

Aim today is to plan:
how we start off and get there…

Observations

- Need for a global analysis using the most advanced experimental data and theoretical techniques is beyond argument
- There is ample experience in un-polarized DIS and p-p/p-pbar data set:
  - Ample guidance
  - Open questions
  - Food for thought

A Minimum Aim

- To include polarized DIS data and the new RHIC data (present and future) to determine the best possible *polarized gluon* distribution and its first moment
- In future when W physics comes of age we should be able to include them consistently in the analysis to extract the flavor *separated quarks and anti-quarks distributions*
- Adding new DIS data is straight forward at this stage, but
  - issues of handling HT corrections, target mass corrections, radiative corrections may need to be thought through…(?)

Technical Issues

- Getting a consistent fitting code at NLO that reliably determines the pdfs
  - *Mainly a theoretical effort at the moment to be led by the theorists amongst us*
- Do a systematic uncertainty analysis including statistical and systematic uncertainties and their correlations
  - *Mainly a project in which experimentalists will contribute principally*

A semi-proposal:

- Theorists who did this full time, did not get future jobs, despite their significant contribution
  - Can not expect a full time theorist to do this
- How about an experimentalist + backing from theorists and experimentalists on various technical issues
  - Supported as well by experimental collaborations (STAR, PHENIX, DIS-exp.s)
    - Contribution is not only welcome, but *essential*
  - *We propose to start something like the "RHIC Spin Collaboration"*
  - This is the assumption we are starting off with

Technical Theoretical Issues

- Theorists and basic structures to start this work already exists at NLO
- Players: *theorists around the table today*
- Analysis:
  - *NLO analysis for DIS + SIDIS exists in some form (Usable?)*
  - *Basic technical ideas and demonstrations on how to include RHIC (pp) data also exist*
  - Our theory friends will of course lead this effort, keeping us all involved and informed in the discussions
  - Need of CPUs/Computing power

Experimental Issues

- Beyond the fitting method, jump in to help with:
  - At the beginning "Computing"
    - Help with CPU for grid calculations
    - Lead effort for multi-user user possibility
    - Help with automation
  - Handling of *uncertainties* in a technically consistent way
  - Study and understanding of theoretical and experimental uncertainty correlations with consultation with experimentalists and theorists
  - Uncertainty analysis with large computing farms

Correlated with these are issues of actually working on these issues:

- A core group starts off with the basic NLO fit development
  - a "coordinator-group" for analysis
- A computing coordinator at an appropriate time:
  - Initial grid computation issues: plan this according to what is expected from the data in future from RHIC (Inclusive pi0s, jets, then direct photon, gamma-Jet, Jet-Jet… then W physics)
- Always overseen by our theory friends:
  - A new data set coordinator like the one in CTEQ "project coordinator" to include each of the pi0, jets…DIS data….
  - Optimally chosen from EXPERIMENTAL collaborations

Mode of operation I

- Lets start with assumption: group will be here or around here or meet here
  - Theorists local or/and visit as necessary
  - PHENIX and STAR experimentalists visit often
    - Short or long term stays of experimentalists envisioned and we should try to support
  - Facilities for small informal meetings easily available (BNL and some times change of venue at SBU)
- Multiple, frequent visits by theorists to be supported by local support (BNL, RBRC, DOE, NSF, *any* other…)
- Post doctoral fellows, students lead the actual work with supervision from groups around them here.
  - Experimentalists will necessarily do experimental work with collaborations.

Mode of operation II

- Monthly, bi-monthly, weekly meetings as seen appropriate
- Couple with big RHIC spin meeting(?) or separately as twice "collaboration" meeting a year
- Use phone, video, skype, personal visits across the groups contributing and institutions
- Communicate on regular basis on email (setup a email list for open discussion at BNL?)
  - Suggestion: spinpdfs-l-lists@bnl.gov or something like this….

Results & publish them?

(my personal opinion)

- Theoretically all new results or methods if appropriate should be published by the theorists as *they* please
- Uncertainty analyses comes from experimental issues, and their proper handling: will have to be decided up on within the "Global Fit Collaboration"
  - *Possibility of a GFC-fit result in long time future to explain all methods, archive the physics and methods*
  - *This may include all of us who have contributed in some way to this effort*
- Experimental collaborations(PHENIX, STAR, COMPASS…) may chose to use and publish subset of these data for their publication… its their discretion…
- We would try to keep the analysis in focus to get the best PDFs

Summary

- We need to do *this*, no matter what
- All are welcome to join and contribute
  - We expect we need a lot of help at *various stages*, perhaps not start right away: …This is not to exclude some one but only to organize this work
- Work could start with 1 post doctoral fellow supported by all of us. (We have a candidate with unique background , expect students to jump in and help with technical details very soon)
  - New post doctoral fellow at SBU: *Dr. Swadhin Taneja*
- Last but not the least: When should we have the next meeting? *About three months from today.*

Global Analysis of Polarized Parton Distribtuions in the RHIC Era

October 8, 2007

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PARTICIPANTS

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Global Analysis of Polarized Parton Distributions in the RHIC Era

October 8, 2007

Physics Department
Room 2-111

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09:00 - 10:00 ....Registration

10:00 - 10:30 ....The CTEQ pdf Analyses.......................................J. Owens
10:30 - 11:00 ....Error Analysis in CTEQ ....J. Pumplin
11:00 - 11:30 ....HERMES Experience ....L. de Nardo
11:30 - 12:00 ....COMPASS/SMC Experience ....J. Lichtenstadt
12:00 - 12:30 ....The AAC Analysis ....S. Kumano

12:30 - 13:30 ....Lunch (will be provided)

13:30 - 14:00 ....Global Analysis Toolbox - Mellin Technique......M. Stratmann
14:00 - 14:30 ....Global Analysis of Fragmentation Functions .....D. deFlorian
14:30 - 15:00 ....Fits to Polarized DIS and SIDIS Data ....R. Sassot

15:00 - 15:30 ....Coffee Break

15:30 - 18:00 ....Discussion/Plans

19:00 - 21:00 ....Dinner

Additional RIKEN BNL Research Center Proceedings:

Volume 85 – Parity-Violating Spin Asymmetries at RHIC-BNL, April 26-27, 2007 – BNL-79146-2007
Volume 84 – Domain Wall Fermions at Ten Years, March 15-17, 2007 – BNL 77857-2007
Volume 83 – QCD in Extreme Conditions, July 31-August 2, 2006– BNL-76933-2006
Volume 82 – RHIC Physics in the Context of the Standard Model, June 18-23, 2006 – BNL-76863-2006
Volume 81 – Parton Orbital Angular Momentum (Joint RBRC/University of New Mexico Workshop) February 24-26, 2006 – BNL-75937-2006
Volume 80 – Can We Discover the QCD Critical Point at RHIC?, March 9-10, 2006 – BNL-75692-2006
Volume 79 – Strangeness in Collisions, February 16-17, 2006 – BNL-
Volume 78 – Heavy Flavor Productions and Hot/Dense Quark Matter, December 12-14, 2005 – BNL-76915-2006
Volume 77 – RBRC Scientific Review Committee Meeting – BNL-52649-2005
Volume 76 – Odderon Searches at RHIC, September 27-29, 2005 – BNL-75092-2005
Volume 75 – Single Spin Asymmetries, June 1-3, 2005 – BNL-74717-2005
Volume 74 – RBRC QCDOC Computer Dedication and Symposium on RBRC QCDOC, May 26, 2005 – BNL-74813-2005
Volume 73 – Jet Correlations at RHIC, March 10-11, 2005 – BNL-73910-2005
Volume 72 – RHIC Spin Collaboration Meetings XXXI(January 14, 2005), XXXII (February 10, 2005), XXXIII (March 11, 2005) – BNL-73866-2005
Volume 71 – Classical and Quantum Aspects of the Color Glass Condensate – BNL-73793-2005
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Volume 68 – Workshop on the Physics Programme of the RBRC and UKQCD QCDOC Machines – BNL-73604-2004
Volume 67 – High Performance Computing with BlueGene/L and QCDOC Architectures – BNL-
Volume 66 – RHIC Spin Collaboration Meeting XXIX, October 8-9, 2004, Torino Italy – BNL-73534-2004
Volume 65 – RHIC Spin Collaboration Meetings XXVII (July 22, 2004), XXVIII (September 2, 2004), XXX (December 6, 2004) - BNL-73506-2004
Volume 64 – Theory Summer Program on RHIC Physics – BNL-73263-2004
Volume 63 – RHIC Spin Collaboration Meetings XXIV (May 21, 2004), XXV (May 27, 2004), XXVI (June 1, 2004) – BNL-72397-2004
Volume 62 – New Discoveries at RHIC, May 14-15, 2004 – BNL- 72391-2004
Volume 61 – RIKEN-TODAI Mini Workshop on "Topics in Hadron Physics at RHIC", March 23-24, 2004 – BNL-72336-2004
Volume 60 – Lattice QCD at Finite Temperature and Density – BNL–72083-2004
Volume 59 – RHIC Spin Collaboration Meeting XXI (January 22, 2004), XXII (February 27, 2004), XXIII (March 19, 2004)– BNL-72382-2004
Volume 58 – RHIC Spin Collaboration Meeting XX – BNL-71900-2004
Volume 57 – High pt Physics at RHIC, December 2-6, 2003 – BNL-72069-2004

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Volume 56 – RBRC Scientific Review Committee Meeting – BNL-71899-2003
Volume 55 – Collective Flow and QGP Properties – BNL-71898-2003
Volume 54 – RHIC Spin Collaboration Meetings XVII, XVIII, XIX – BNL-71751-2003
Volume 53 – Theory Studies for Polarized pp Scattering – BNL-71747-2003
Volume 52 – RIKEN School on QCD "Topics on the Proton" – BNL-71694-2003
Volume 51 – RHIC Spin Collaboration Meetings XV, XVI – BNL-71539-2003
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Volume 49 – RBRC Scientific Review Committee Meeting – BNL-52679
Volume 48 – RHIC Spin Collaboration Meeting XIV – BNL-71300-2003
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Volume 43 – RIKEN Winter School – Quark-Gluon Structure of the Nucleon and QCD – BNL-52672
Volume 42 – Baryon Dynamics at RHIC – BNL-52669
Volume 41 – Hadron Structure from Lattice QCD – BNL-52674
Volume 40 – Theory Studies for RHIC-Spin – BNL-52662
Volume 39 – RHIC Spin Collaboration Meeting VII – BNL-52659
Volume 38 – RBRC Scientific Review Committee Meeting – BNL-52649
Volume 37 – RHIC Spin Collaboration Meeting VI (Part 2) – BNL-52660
Volume 36 – RHIC Spin Collaboration Meeting VI – BNL-52642
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Volume 33 – Spin Physics at RHIC in Year-1 and Beyond – BNL-52635
Volume 32 – RHIC Spin Physics V – BNL-52628
Volume 31 – RHIC Spin Physics III & IV Polarized Partons at High Q^2 Region – BNL-52617
Volume 30 – RBRC Scientific Review Committee Meeting – BNL-52603
Volume 29 – Future Transversity Measurements – BNL-52612
Volume 28 – Equilibrium & Non-Equilibrium Aspects of Hot, Dense QCD – BNL-52613
Volume 27 – Predictions and Uncertainties for RHIC Spin Physics & Event Generator for RHIC Spin Physics III – Towards Precision Spin Physics at RHIC – BNL-52596
Volume 26 – Circum-Pan-Pacific RIKEN Symposium on High Energy Spin Physics – BNL-52588
Volume 25 – RHIC Spin – BNL-52581
Volume 24 – Physics Society of Japan Biannual Meeting Symposium on QCD Physics at RIKEN BNL Research Center – BNL-52578
Volume 23 – Coulomb and Pion-Asymmetry Polarimetry and Hadronic Spin Dependence at RHIC Energies – BNL-52589
Volume 22 – OSCAR II: Predictions for RHIC – BNL-52591

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Volume 15 – QCD Phase Transitions – BNL-52561
Volume 14 – Quantum Fields In and Out of Equilibrium – BNL-52560
Volume 13 – Physics of the 1 Teraflop RIKEN-BNL-Columbia QCD Project First Anniversary Celebration – BNL-66299
Volume 12 – Quarkonium Production in Relativistic Nuclear Collisions – BNL-52559
Volume 11 – Event Generator for RHIC Spin Physics – BNL-66116
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Volume 9 – High Density Matter in AGS, SPS and RHIC Collisions – BNL-65762
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Volume 7 – RHIC Spin Physics – BNL-65615
Volume 6 – Quarks and Gluons in the Nucleon – BNL-65234
Volume 5 – Color Superconductivity, Instantons and Parity (Non?)-Conservation at High Baryon Density – BNL-65105
Volume 4 – Inauguration Ceremony, September 22 and Non -Equilibrium Many Body Dynamics –BNL-64912
Volume 3 – Hadron Spin-Flip at RHIC Energies – BNL-64724
Volume 2 – Perturbative QCD as a Probe of Hadron Structure – BNL-64723
Volume 1 – Open Standards for Cascade Models for RHIC – BNL-64722

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RIKEN BNL RESEARCH CENTER

Global Analysis of Polarized Parton Distributions in the RHIC Era

October 8, 2007

Li Keran

Nuclei as heavy as bulls
Through collision
Generate new states of matter.
T.D. Lee

Speakers:

Daniel de Florian	Lara De Nardo	Shunzo Kumano	Jechiel Lichtenstadt
Jeff Owens	Jon Pumplin	Rodolfo Sassot	Marco Stratmann

Organizers: Abhay Deshpande and Werner Vogelsang