Photons, Regge Poles, QCD, and PDFs

– A Retrospective –

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Transverse Spin Phenomena and Their Impact on QCD

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Outline

- Introduction
- My work with Gary
- QCD and PDFs
- Some recent results
- Concluding remarks

Background

- Graduate student at Tufts University: 1968-1973
- Started research with Gary in 1969
- Post-doc at Case Western Reserve University: 1973-1976
- Post-doc at Florida State University: 1976-1980
- Faculty position at Florida State University: 1980-present
- Wrote eight papers with Gary: 1972-1977

Photons and Regge Poles: 1969-1977

- Regge models for two-body processes
  - A new Regge absorption model
  - $\gamma p \to K^+ \Lambda/\Sigma$
  - $\gamma p \to \pi^0 p$
  - $\gamma N \to \pi N, \pi\Delta$
  - *Modeling photon processes*
  - *Creating codes for fitting a wide range of observables*

- Inclusive processes
  - Natural extension from few-body processes as accelerator energies increased
  - Application of Regge ideas
  - Polarization in inclusive processes
- Amplitudes and spin observables
  - Constraints on amplitudes from existing spin observables
  - Model dependent amplitude analyses

Common theme: *Art of relating observables to the parameters of the models*

Transition to QCD - 1977

- Application of Regge ideas limited in the era of higher energies (ISR, Fermilab)
- Perturbative QCD offered a new avenue for describing the data
- How to get started? Write a fitting program to fit deep inelastic data!
- Visit of Ewald Reya to FSU in the summer of 1977 - resulted in three papers

  - J/ψ production
  - Υ productions and PDFs
  - High-p_T particle production

- Brought together familiar ideas
  - Underlying theory of QCD could be applied to many observables
  - Still required the modeling of the PDFs
  - Combination of phenomenology and testing of the underlying theoretical framework
- Era of testing QCD
  - Role of the gluon PDF
  - DIS scaling violations
  - High-p_T phenomenology
  - Need PDFs/FFs for most calculations, but few were available, so "roll your own"
  - Also needed higher order calculations to test the theory
- Quite natural for me to consider processes with photons!

Two Examples

Hadroproduction of photons and photoproduction of hadrons

Global fits for PDFs

- Although seemingly quite different, there is a theme which can be traced to my studies with Gary
- Photons
- Amplitude analysis/phenomenology
- Modeling and fitting

Hadroproduction of photons and photoproduction of hadrons

- $pp(\overline{p}) \rightarrow \gamma + X$
- $\gamma p \rightarrow jet + X$
- Both processes use an *electromagnetic* probe to study the hard scattering interaction
- In lowest order there are only two subprocesses

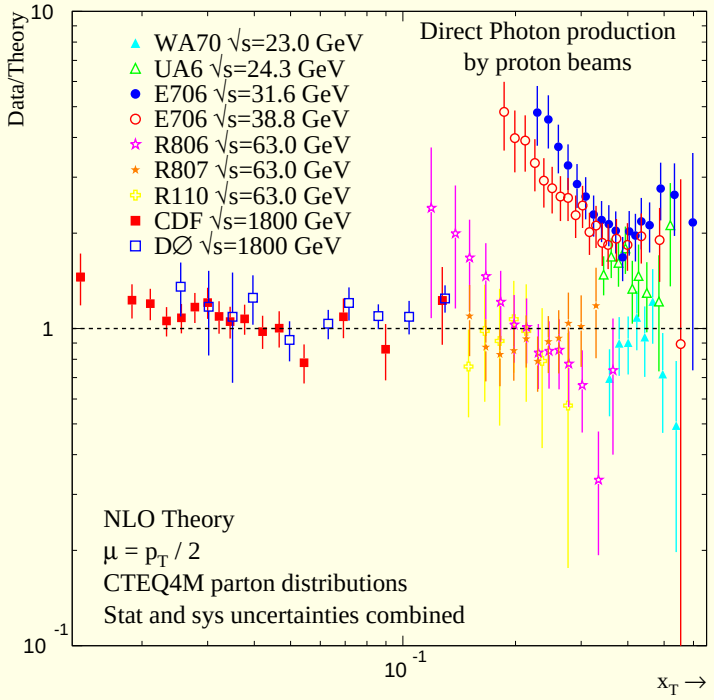
  - $gq \rightarrow \gamma q$
  - $q\overline{q} \rightarrow \gamma g$

- Simplest process where the gluon enters in lowest order
- Responsible for the early interest in these processes
- Good testing ground for QCD

A little study showed that things were a bit more complicated

- Photons couple to $q\overline{q}$ pairs
- Quarks can emit photons (bremsstrahlung)
- Thus, there is a hadronic component to the photon (familiar to those who remember vector dominance)
- Collinear singularities must be resummed - use the DGLAP equations and generate photon PDFs
- In direct photon production the bremsstrahlung process leads to photon fragmentation functions
- Again, can use modified DGLAP equations to study the photon FFs

End result - photons have all of the complications of hadrons (PDFs, FFs) plus they have their own pointlike interaction!



Data/theory plot shows several key features

- Plotted versus $x_T = 2p_T/\sqrt{s}$
- Low x_T data described reasonably well
- Scatter in high x_T data - fixed target experiments
- Some apparent disagreement between data sets
- Room for improvement in the theoretical description

However, many other features of the data are well described

- Photon-jet angular distribution
- Photon-jet mass plot
- Photoproduction of jets at HERA also well described by the theory

Aside - these results were obtained at next-to-leading order and required a new means of calculating two-particle correlations at NLO with experimental cuts. I developed the two cut-off phase space slicing approach to do this.

So, after nearly thirty years of direct photons, what is the answer? Does the theory work? The answer appears to be "yes"

At least part of what was missing was soft gluon resummation for the fragmentation (or bremsstrahlung) component.

- High-p_T fragmentation photons take most of the energy of the parent parton (high momentum fraction z)
- There are large logarithmic enhancements going as $\ln^n(1-z)$ which must be resummed
- Net result increases the fragmentation component
- Largest effect is at the fixed target energies

Work is continuing - a comprehensive study has not been done, but the initial results are positive

An understanding of photon production in the context of QCD is vital for new physics searches at the LHC

Some Recent Work on PDFs

Cast of characters - Alberto Accardi, Eric Christy, Cynthia Keppel, Simona Malace, Wally Melnitchouk, Peter Monaghan, Jorge Morfín, JFO, and Lingyan Zhu

Goals:

- Overall goal - Improve the precision of the d PDF
- Extend PDF fits to larger values of x and lower values of Q
- Wealth of data from older SLAC experiments and newer JLAB experiments
- Study effects of different target mass correction methods
- Explore role of higher twist contributions
- Quantify the uncertainty due to nuclear corrections for deuteron targets
- Study the parametrization dependence of the results

Previous analysis (Phys. Rev. **D81**:034016, 2010) showed the following

- Good fits could be obtained using the lower Q and W cuts on the DIS data
- Different target mass correction prescriptions gave equivalent fits as long as a simple parametrization of higher twist contributions was added
- Leading twist PDF was stable as the TMC prescription was varied

Residual questions:

- How do the results depend on the models used for the nuclear corrections for DIS data from deuterium targets (deuteron wavefunction, offshell corrections)?
- How do the results depend on the parametrization used for the d PDF?

Information on the d PDF

DIS

- $F_2^P(x,Q^2) \sim 4u + d$
- $F_2^d(x,Q^2) \sim 5(u+d)$, but requires nuclear corrections

Lepton Pair Production

- $x_1 x_2 = \frac{M^2}{s}$ and $x_F = x_1 - x_2$
- Can get to large x_1 if high-x_F data are available
- E-866 reaches to $x \approx .8$
- $\sigma_{pp} \sim \overline{u}(x_2)[4u(x_1) + d(x_1)\overline{d}(x_2)/\overline{u}(x_2)]$
- $\sigma_{pn} \sim \overline{d}(x_2)[4u(x_1) + d(x_1)\overline{u}(x_2)/\overline{d}(x_2)]$
- At large $x_F, x_1 \gg x_2$
- To the extent that $\overline{u}(x_2) \simeq \overline{d}(x_2)$, which is roughly satisfied for small x_2, one is still sensitive to $4u + d$

Nuclear Corrections

- Fermi motion smearing done using the Weak Binding Approximation (WBA)
- Various choices of wavefunctions explored
- Include model-dependent offshell corrections
- Corrections are very important in the large-x region since the d PDF is a rapidly falling function
- u PDF is already well constrained, so the d PDF adjusts to whatever nuclear corrections are used

Fitting Package

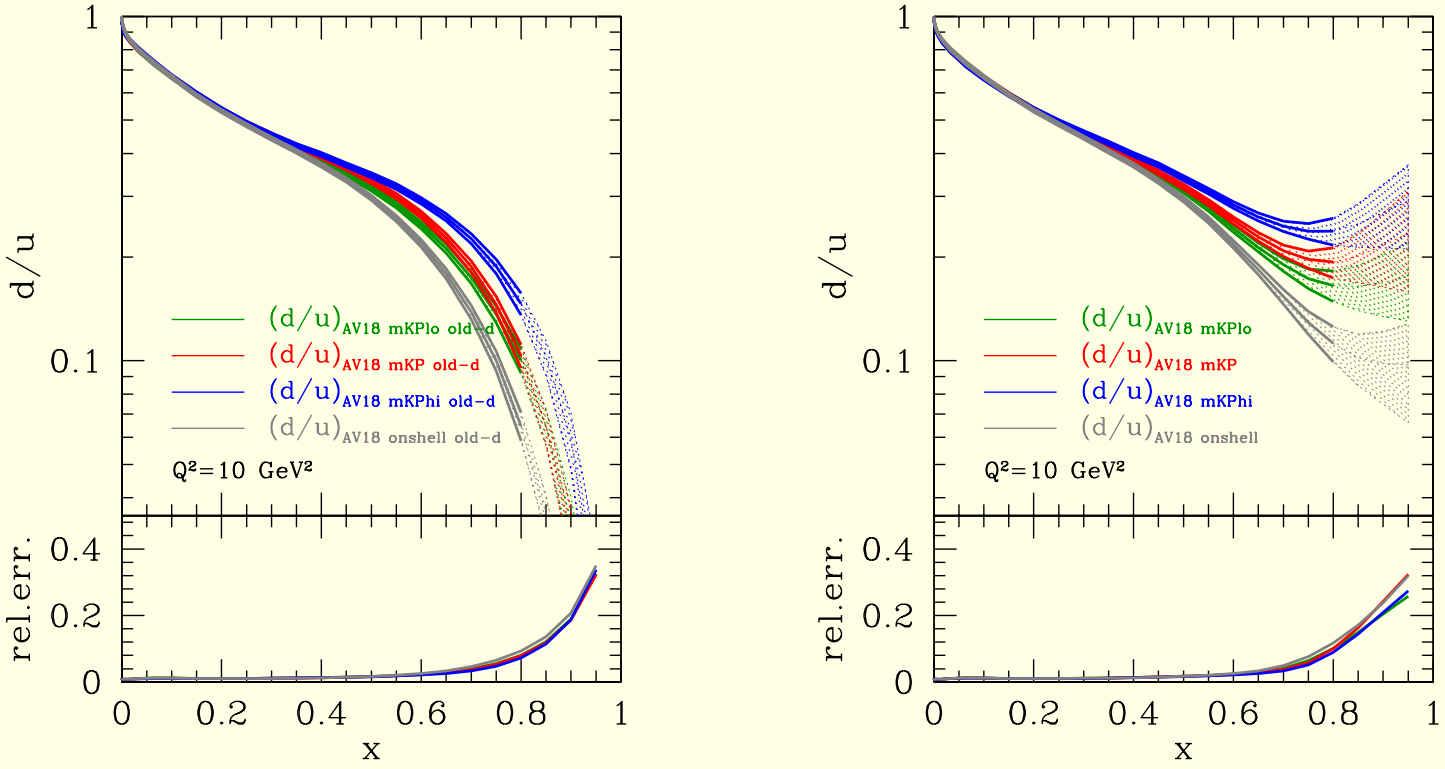
We are using my NLO DGLAP fitting package which I have continued to update and extend

- Can fit DIS, Drell-Yan, W lepton asymmetry, jets, and γ + jet
- W lepton asymmetry routine allows for a single p_T cut, but a generalization to allow for multiple p_T cuts has been developed
- Added PDF errors (Hessian method)
- Multiple TMC and HT terms added (Alberto Accardi)
- Some correlated errors added
- Options for nuclear corrections added (Wally Melnitchouk, Alberto Accardi)

Results

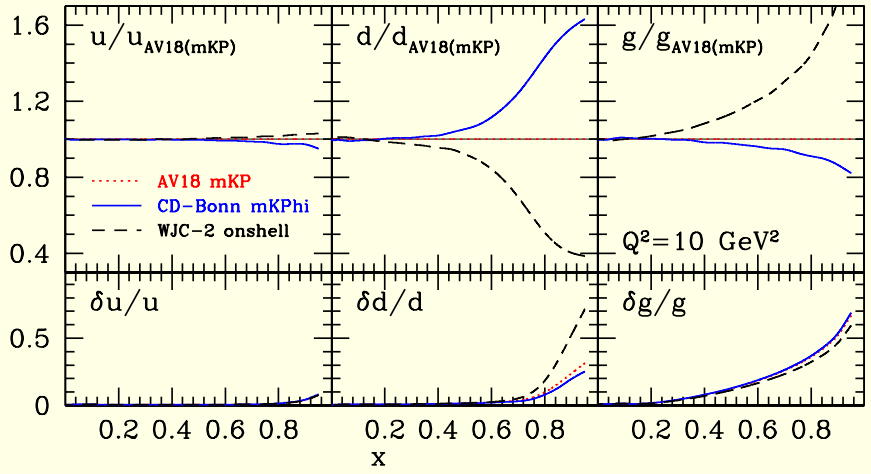
- Summarize results by showing d/u ratios
  - The u PDF is already well constrained
  - The different nuclear corrections have the largest effect on the d PDF
  - Basically, the d PDF shifts to accommodate whatever nuclear model is used and the other PDFs adjust to compensate for the shift
- Consider first a traditional parametrization where the d PDF vanishes as $x \to 1$
- Then, compare to a parametrization where $d \to d + c * u * x^b$ so that $d/u \to c$ in the limit that $x = 1$
- For clarity, the bands denote the PDF uncertainty resulting from the experimental errors with $\Delta\chi = 1$

Sample results obtained using the AV18 wavefunction



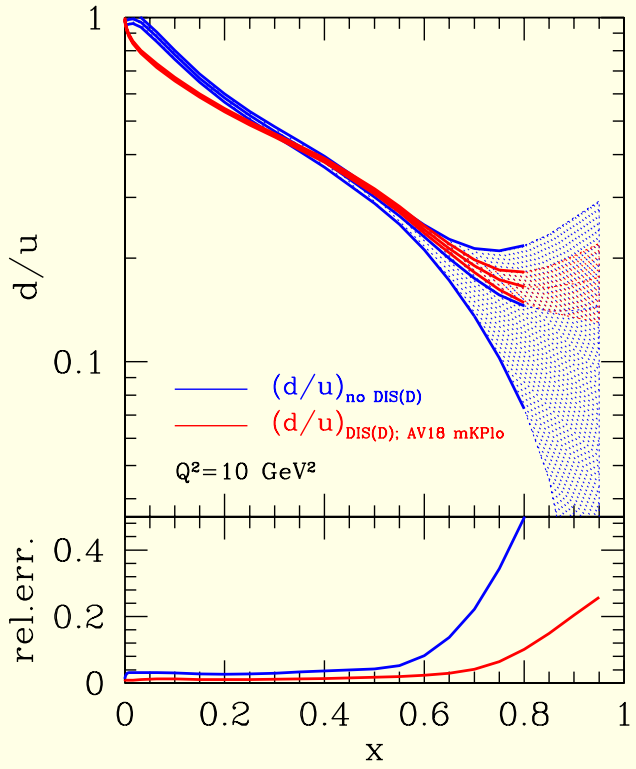
Either parametrization gives good fits, with a very slight chi square preference existing for the right-hand plots ($d/u \to c$ at $x = 1$)

Compare the PDFs resulting from the upper and lower extremes of the d/u ratios



- Center panels show the d PDFs for the upper and lower extremes
- A very small shift (few percent) in the u PDF compensates
- Primarily because the DIS and Drell Yan data are sensitive to $4u + d = u(4 + d/u)$ in a region where d/u is already small
- Gluon PDF compensates the change in the d PDF for the jet data
- Uncertainty in the d PDF due to the variation of the nuclear corrections feeds into increased uncertainty in the large-x gluon PDF

The figure below shows the result of removing the deuterium DIS data from the fit.



- For a fixed choice of the nuclear models the uncertainty on the d PDF is decreased.
- Notice the relatively large shift in the d/u ratio at low values of x
- Shift is unexpected based on standard error propagation

What have we learned?

- Need more observables which are less sensitive to nuclear corrections
- Examples include the BONUS, MARATHON, and PVDIS experiments at Jefferson Lab
- Can learn about nuclear models if the uncertainties on the d PDF are reduced
- Decisions regarding the use of deuterium data sets and choices for nuclear corrections can affect PDFs in regions which are relevant for collider physics

Concluding Remarks

Much of my current work traces its roots back to things I learned working with Gary

- Modeling underlying amplitudes or functions
- The art of relating observables to the underlying amplitudes or functions
- Learning to recognize and interpret the correlations that exist between observables
- Working with extensive and diverse data sets
- The art of fitting

Gary - Thanks for the preparation and the lessons you provided!