WI Group Physics on ZEUS at the HERA *ep* Collider

Anna Goussiou

University of Washington

Wesley Fest

Madison, August 30, 2019

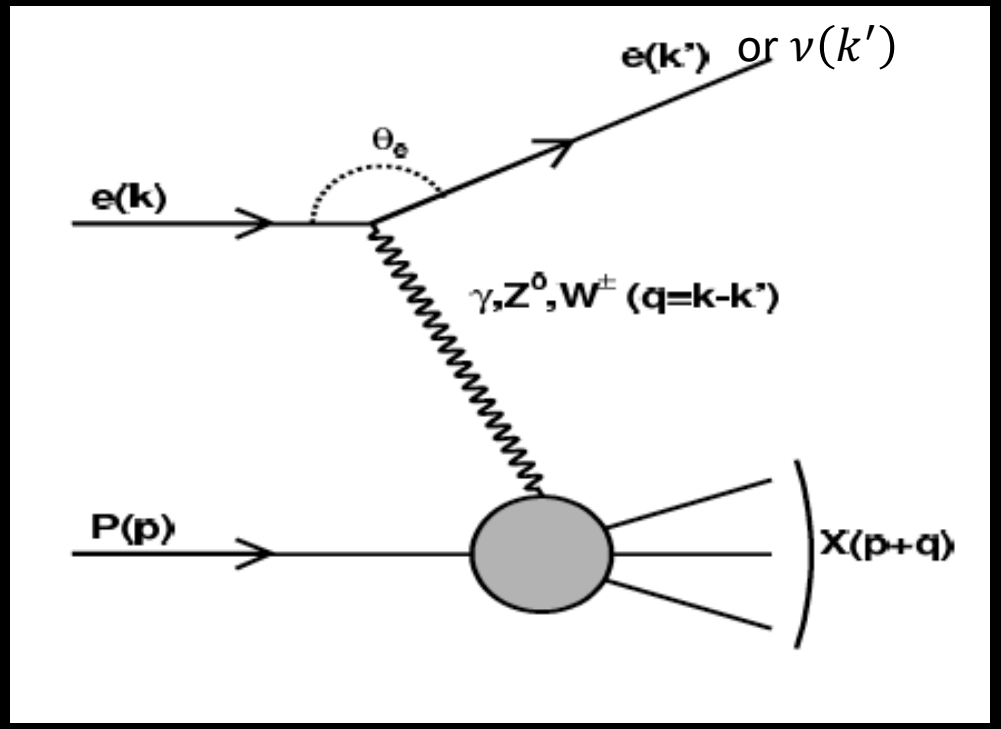
Extensive Contributions to ZEUS Physics

- 19 PhD students graduated from 1995-2008
  - Some jointly with Don Reeder and Sridhara Dasu
- Wide range of physics topics
  - Total & Differential DIS Cross Sections
  - Proton Structure Function and Gluon Distribution
  - Event shapes & multiplicities in DIS
  - Multi-jet production
  - Photoproduction
  - Search for Leptoquarks

$e^{\pm}p$ collider

1992-
2007

Deep Inelastic Scattering (DIS)



- Virtuality of the exchange boson

$$Q^2 \equiv -q^2 = -(k - k')^2$$

- Bjorken x: fraction of proton's momentum carried by struck parton

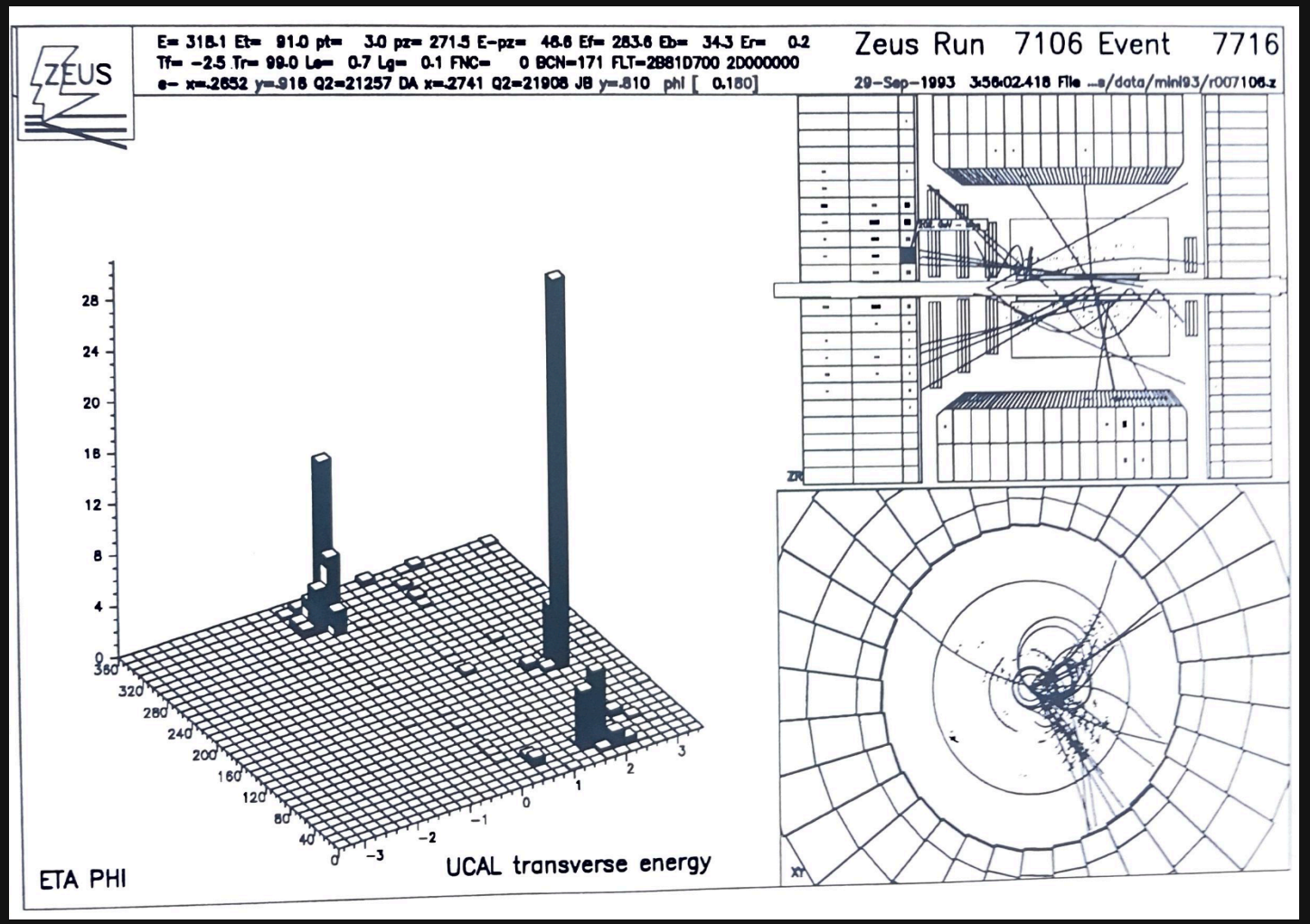
$$x = \frac{Q^2}{2p \cdot q}$$

Measurement of Neutral and Charged Current DIS Cross Sections at Very High Q^2

Issam Ali

1995

A Neutral Current data event with Q^2=20000 GeV^2 and x=0.27



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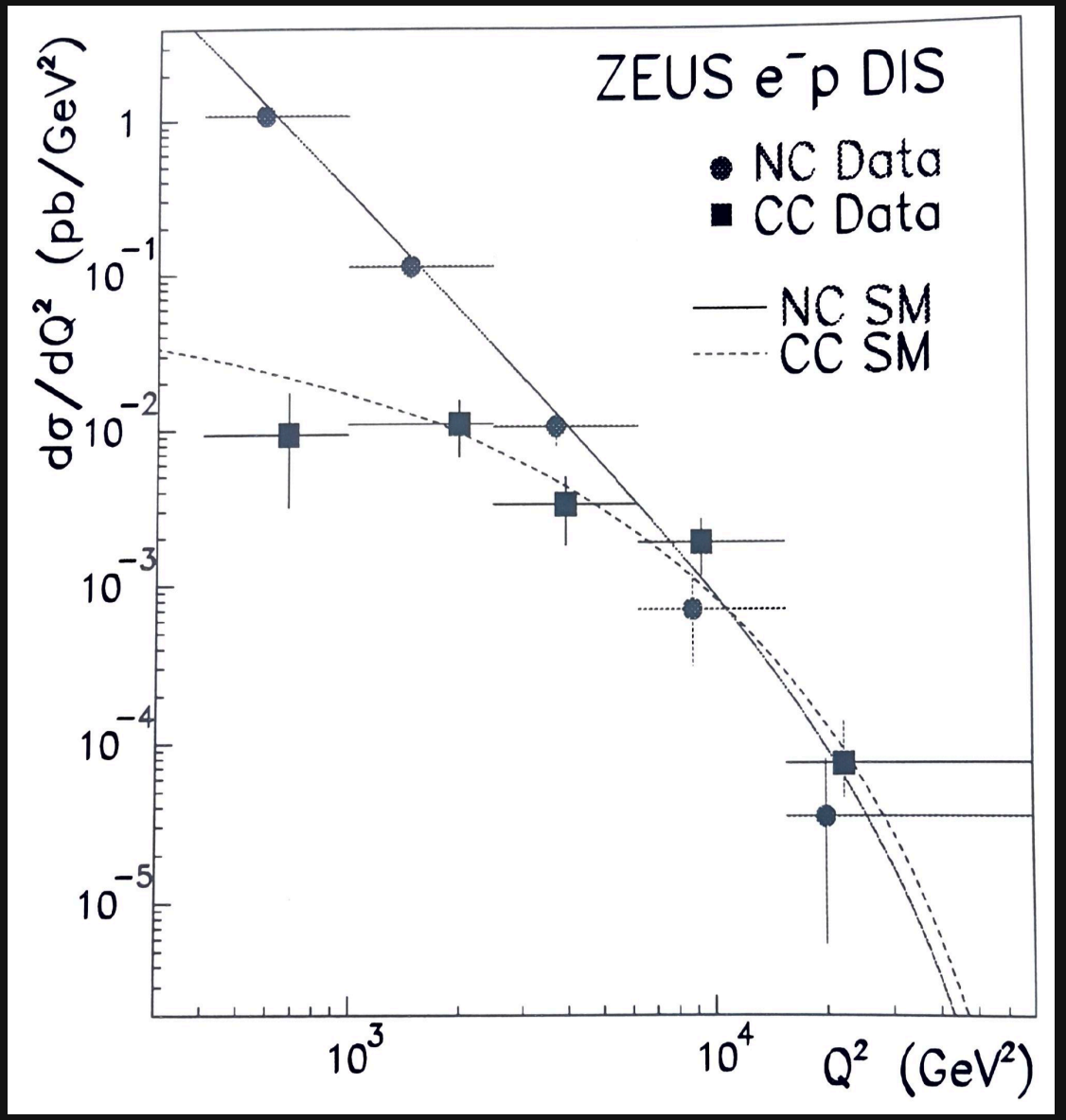


Measurement of the Proton Structure Function F_2 and Extraction of the Gluon Density of the Proton at Low x

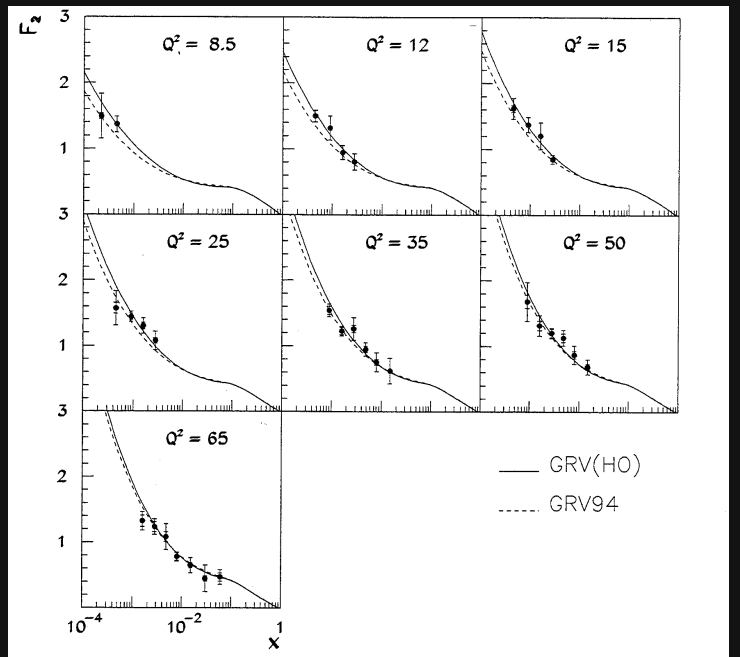
Anna Goussiou
1995

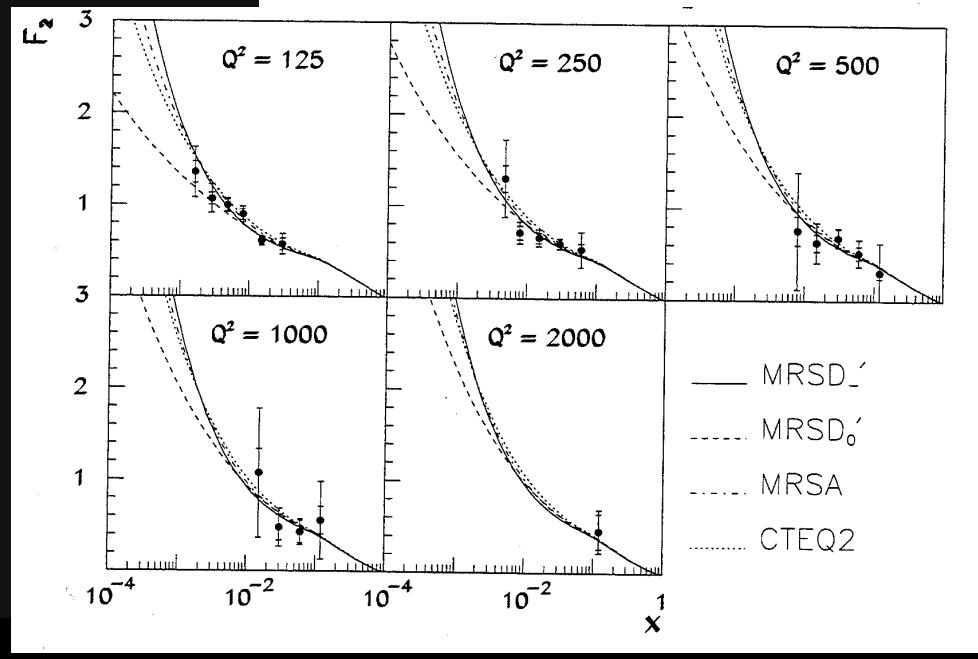
$$F_2(x, Q^2) = \sum_i e_i^2 x f_i(x, Q^2)$$

Probability that parton i carries momentum fraction x

extracted from:

$$\frac{d^2\sigma}{dx\, dQ^2}$$





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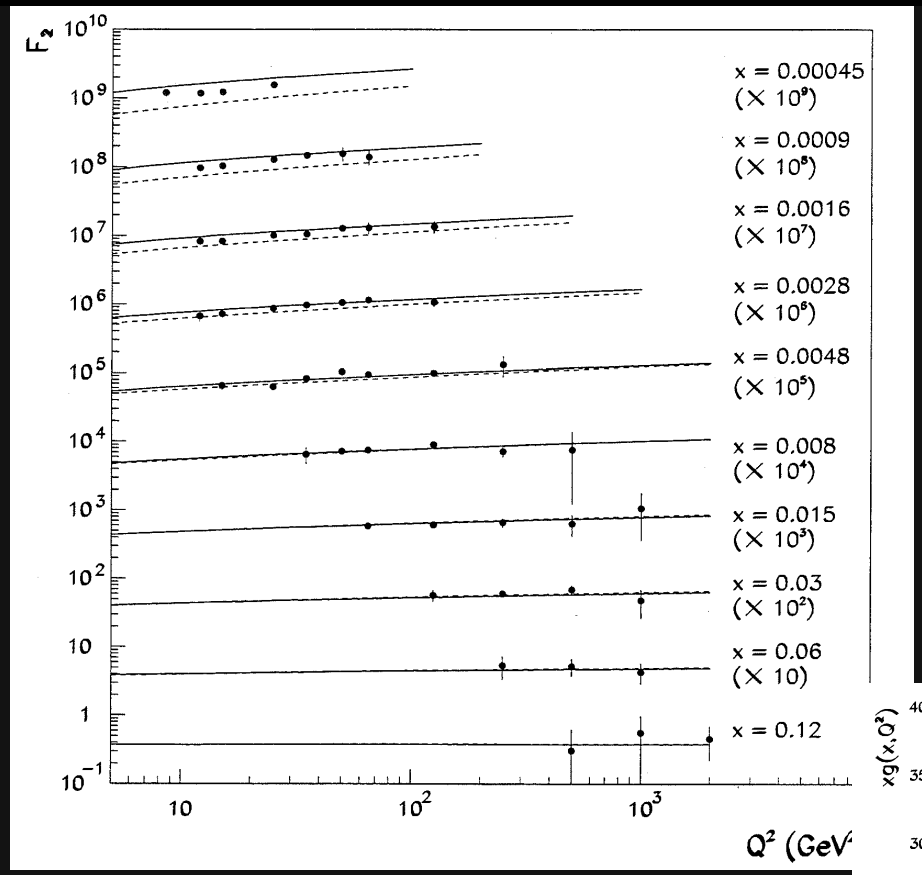
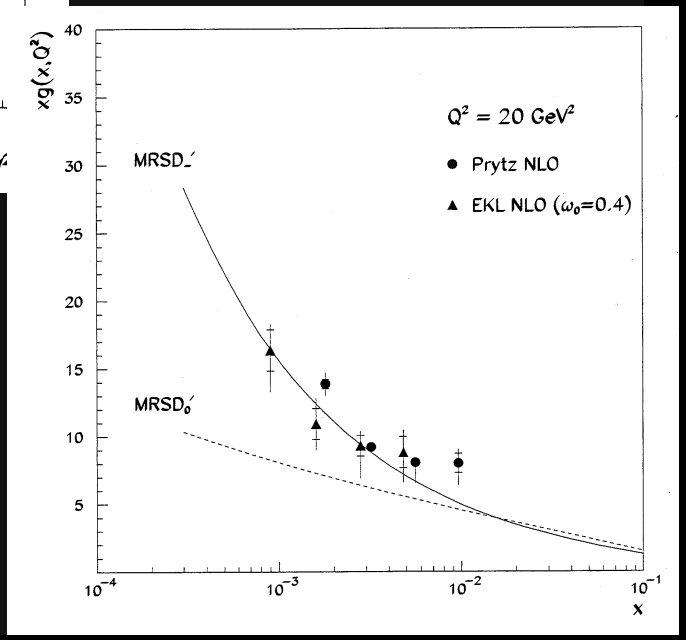


$$\frac{dF_2(x,Q^2)}{d\,lnQ^2}$$



Gluon momentum density

A Search for Non-Resonant Effects of Leptoquarks in Electron-Proton Collisions

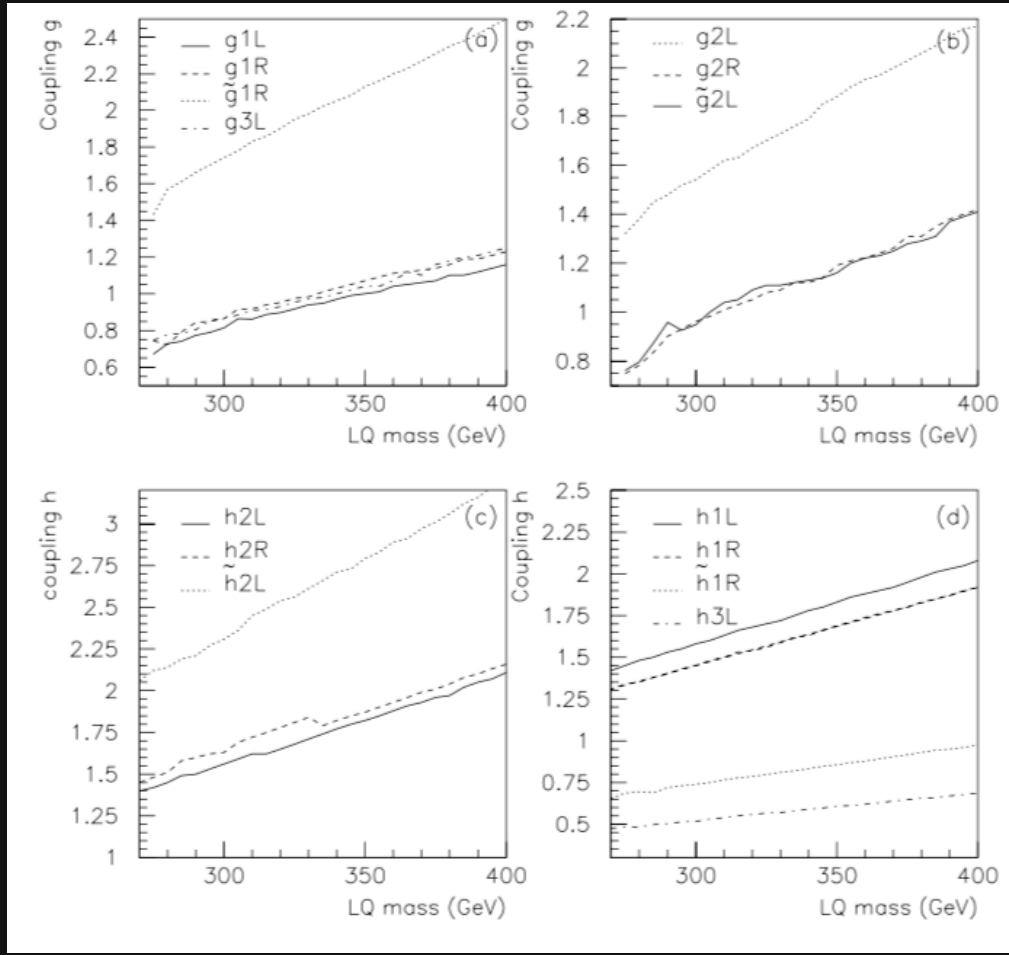
Sam Silverstein
1996

- Leptoquarks: hypothetical particles carrying both baryon number (B) and lepton number (L)
- They appear in various BSM models:
  - Compositeness of quarks and leptons
  - SUSY with R-parity violation
  - GUTs
- In DIS: $e + q \rightarrow LQ$
- Look for enhancement in high-Q^2 cross section
- Set limits using LQ Monte Carlo Generator (LQMGEN) for 14 LQ types

A Search for Non-Resonant Effects of Leptoquarks in Electron-Proton Collisions

Sam Silverstein
1996

Mass/Coupling limits for 14 LQ types



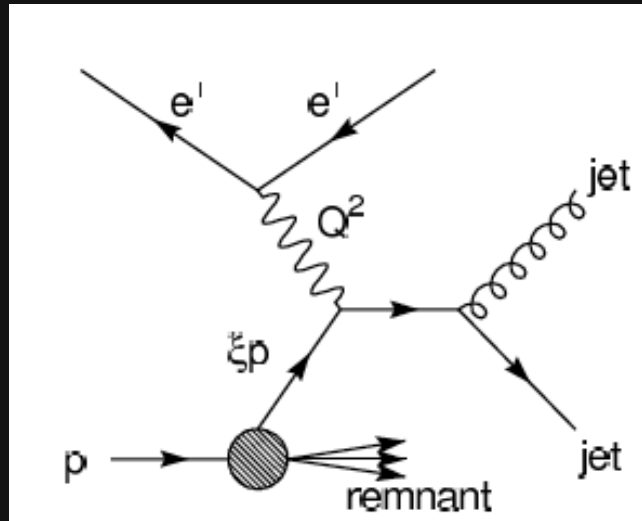
Electron beam data 1993-94

Multi-Jet Production at Low x

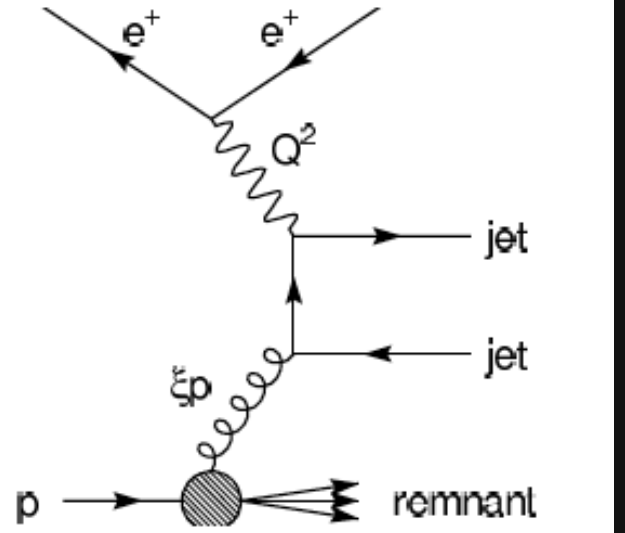
Tom Danielson
2007

Di-Jet Production in DIS at LO

QCD Compton



Boson Gluon Fusion



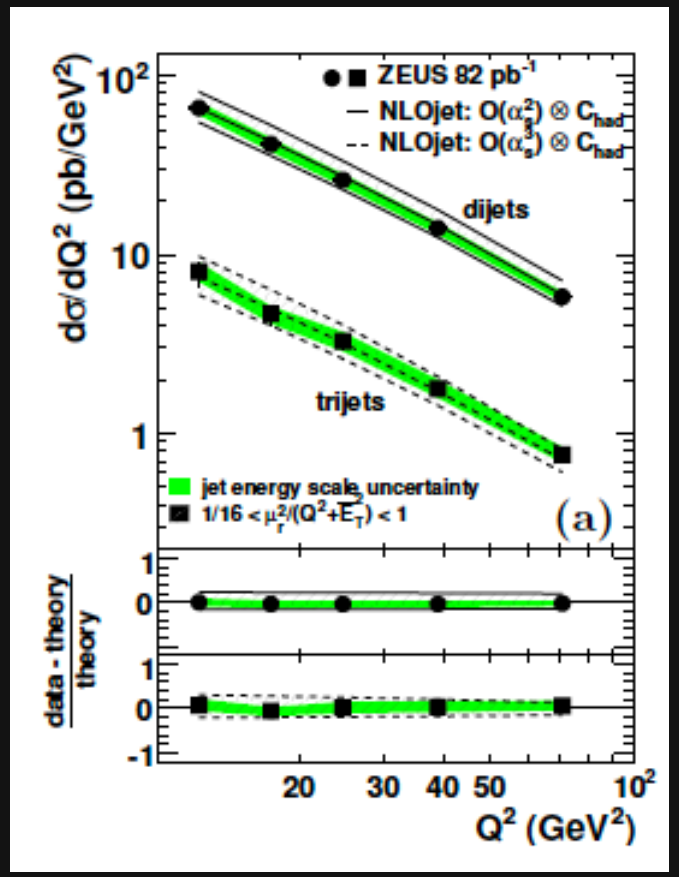
Now, momentum fraction of incident parton is:

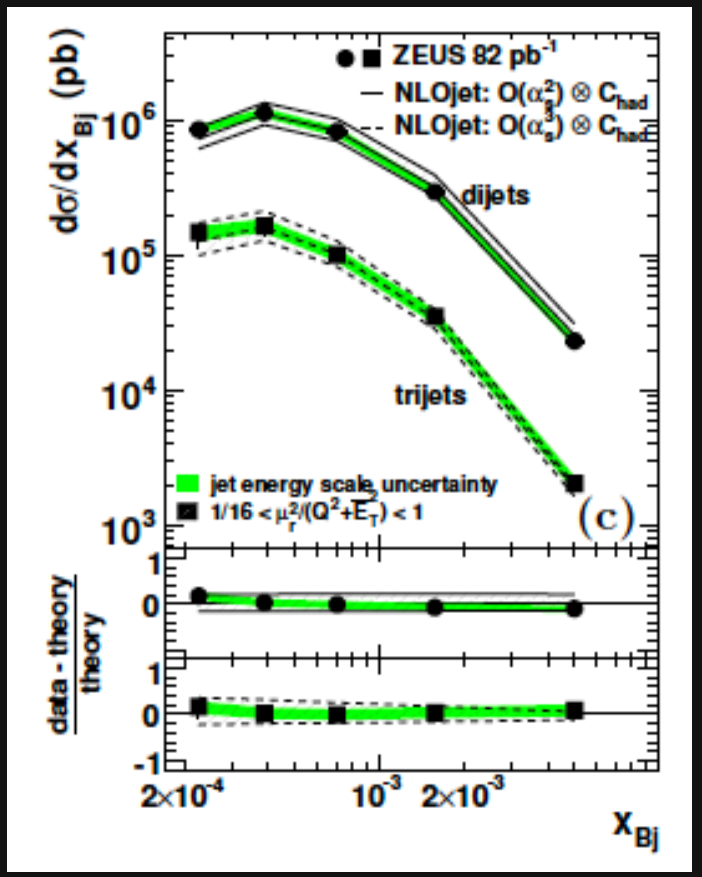
$\xi = x\left(1 + \frac{M_{jj}^2}{Q^2}\right)$ where M_{jj} = di-jet mass

Multi-Jet Production at Low x

Tom Danielson
2007

Inclusive Differential Di-Jet & Tri-Jet Cross Sections (Neutral Current DIS)





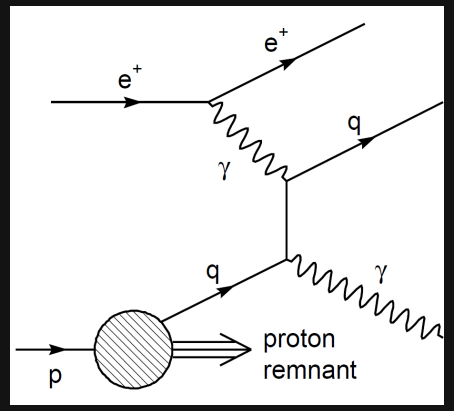
Data agree with NLO QCD predictions

Prompt Photons in Photoproduction and DIS

Eric Brownson
2008

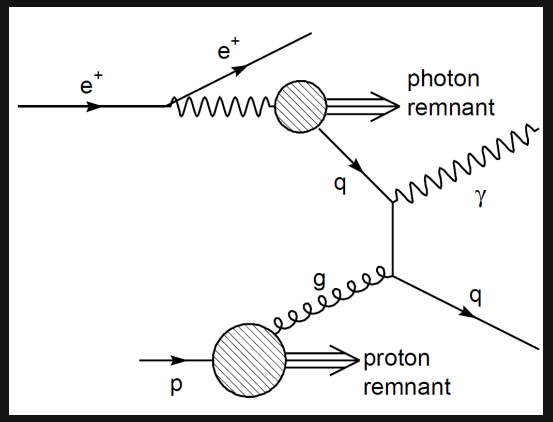
For $Q^2 \approx 0$, interaction predominantly electromagnetic, photon almost real: Photoproduction

Direct



Entire photon interacts in the hard scatter

Resolved

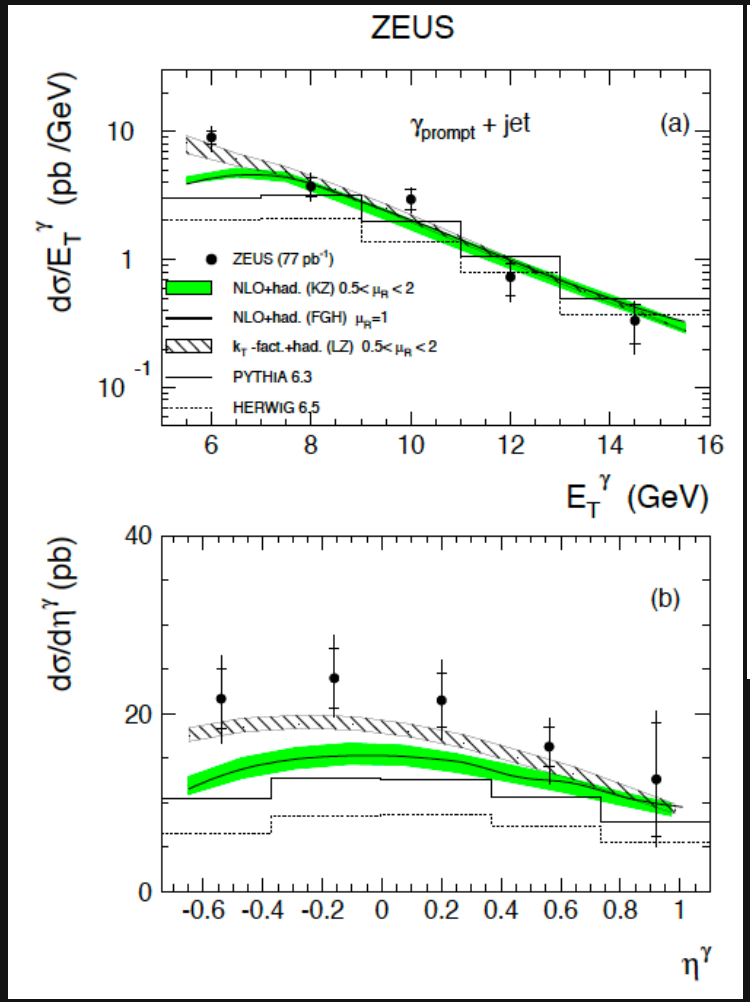


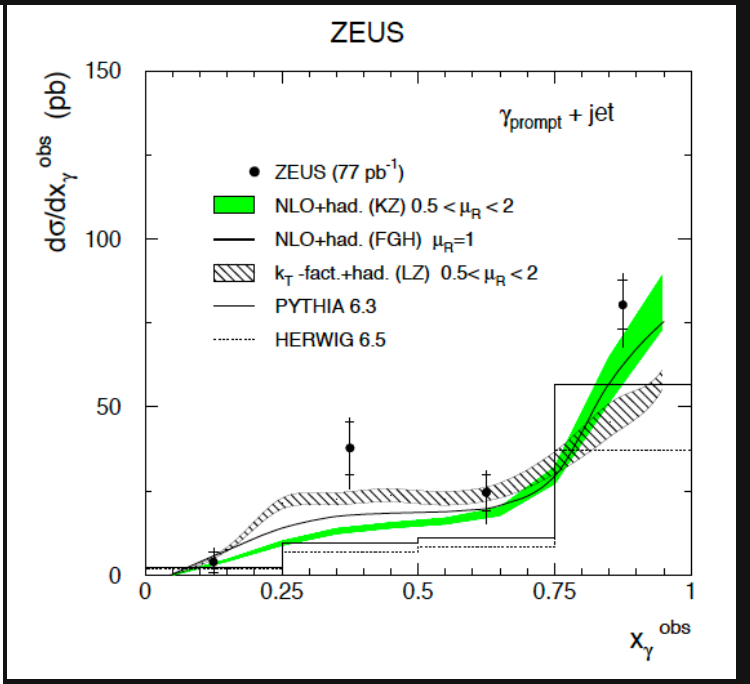
Photon briefly fluctuates into hadronic state

Prompt Photons in Photoproduction and DIS

Eric Brownson 2008

Prompt photons (from hard scatter) test quark and gluon content of proton

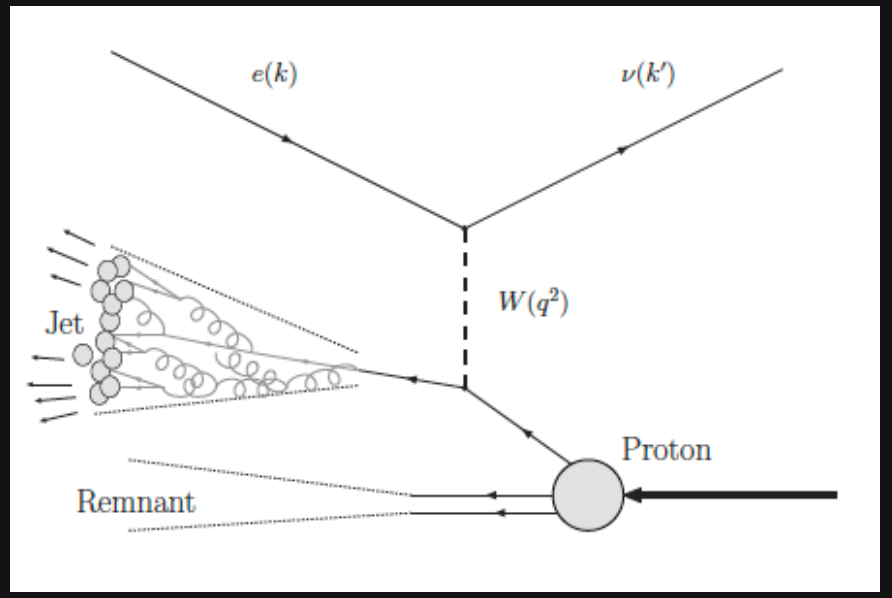




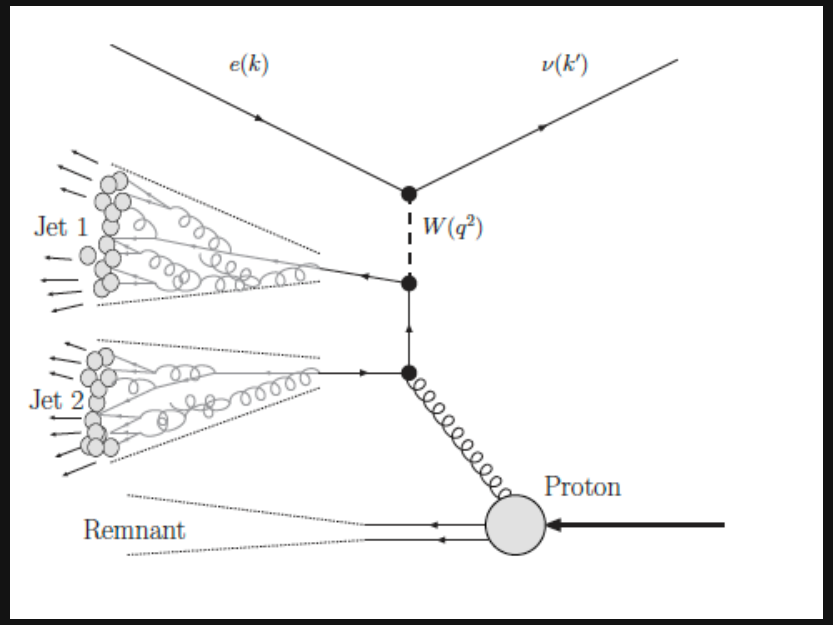
x_γ = fraction of the exchange photon's momentum involved in the hard scatter

Multi-Jet Production in Charged Current DIS

Homer Wolfe 2008



Leading Order

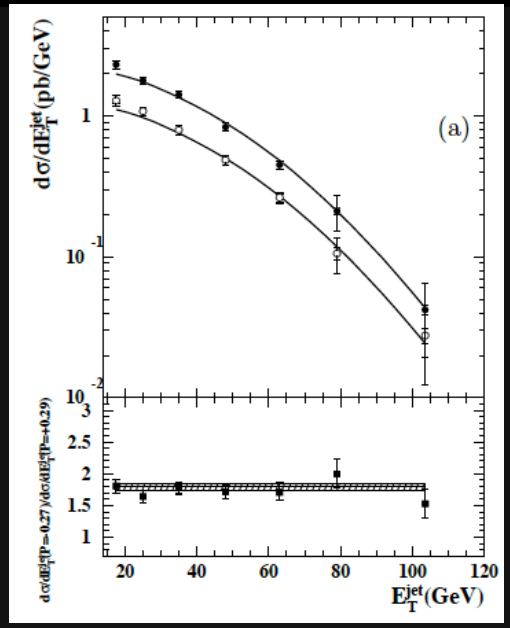


Leading Order Boson-Gluon Fusion

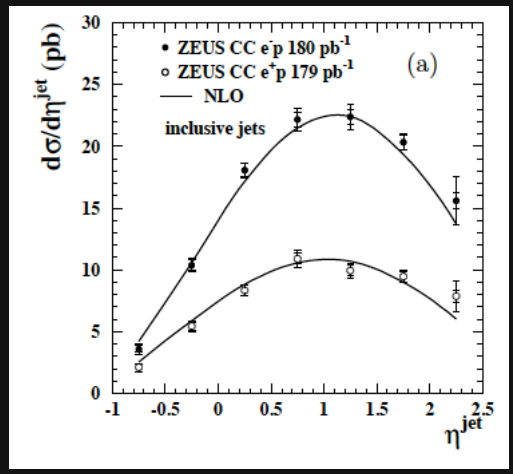
Multi-Jet Production in Charged Current DIS

Homer Wolfe
2008

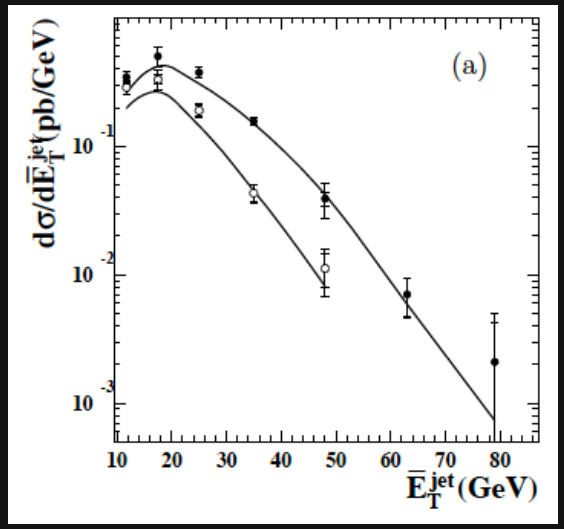
Inclusive Jet Polarized e^-p

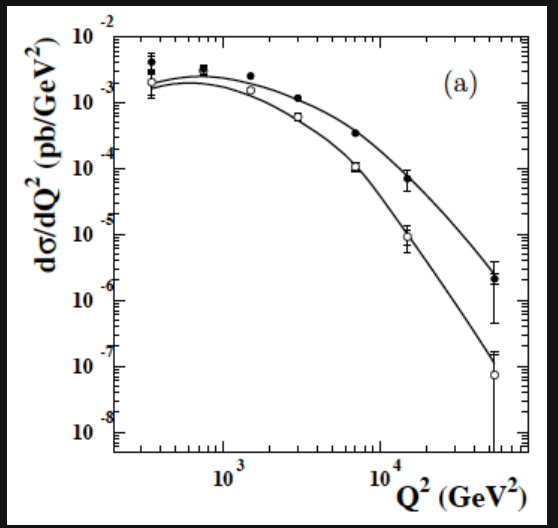


Inclusive Jet Unpolarized e^-p and e^+p



Three-Jet Unpolarized e^-p and e^+p





In conclusion…

- Wesley's group on ZEUS was instrumental not only for the Calorimeter First Level Trigger, but also for a wide range of physics contributions, over the whole life span of the experiment
- A personal note: Wesley gave me complete freedom in selecting my thesis topic and absolute support in pursuing my research. And has also eagerly supported me through every step of my career.

Thank you!!!

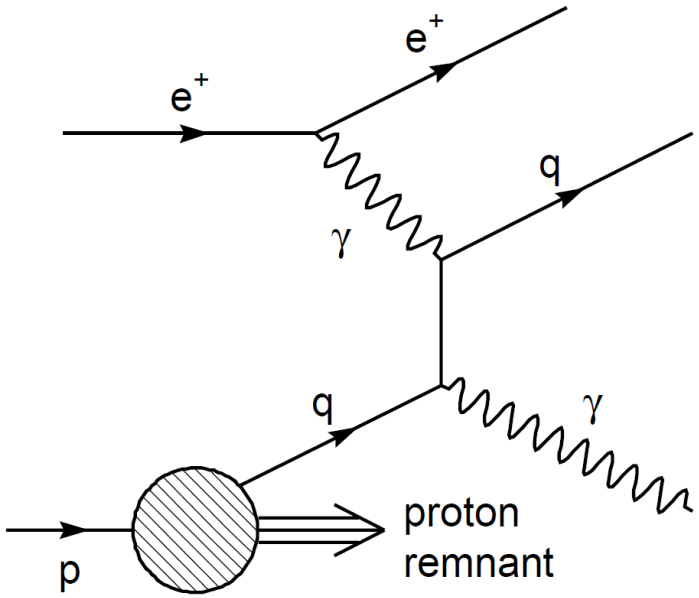
Tony Vaiciulis, 1999

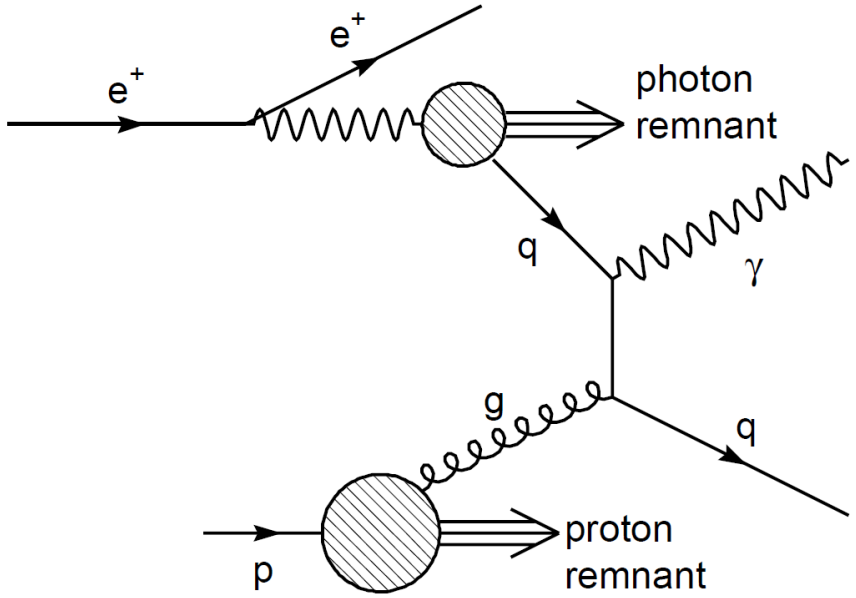
Observation of Isolated High-ET Photons in Photoproduction at HERA

Observation of Isolated High Transverse Energy Photons in Photoproduction at HERA
Anthony Vaiciulis (ZEUS Collaboration, 1999)

27.5 Gev x 820 GeV e x p

Photon is generated as part of the hard scatter, not from fragmenting partons
Direct link to parton level of interaction – no ambiguities from jet identification



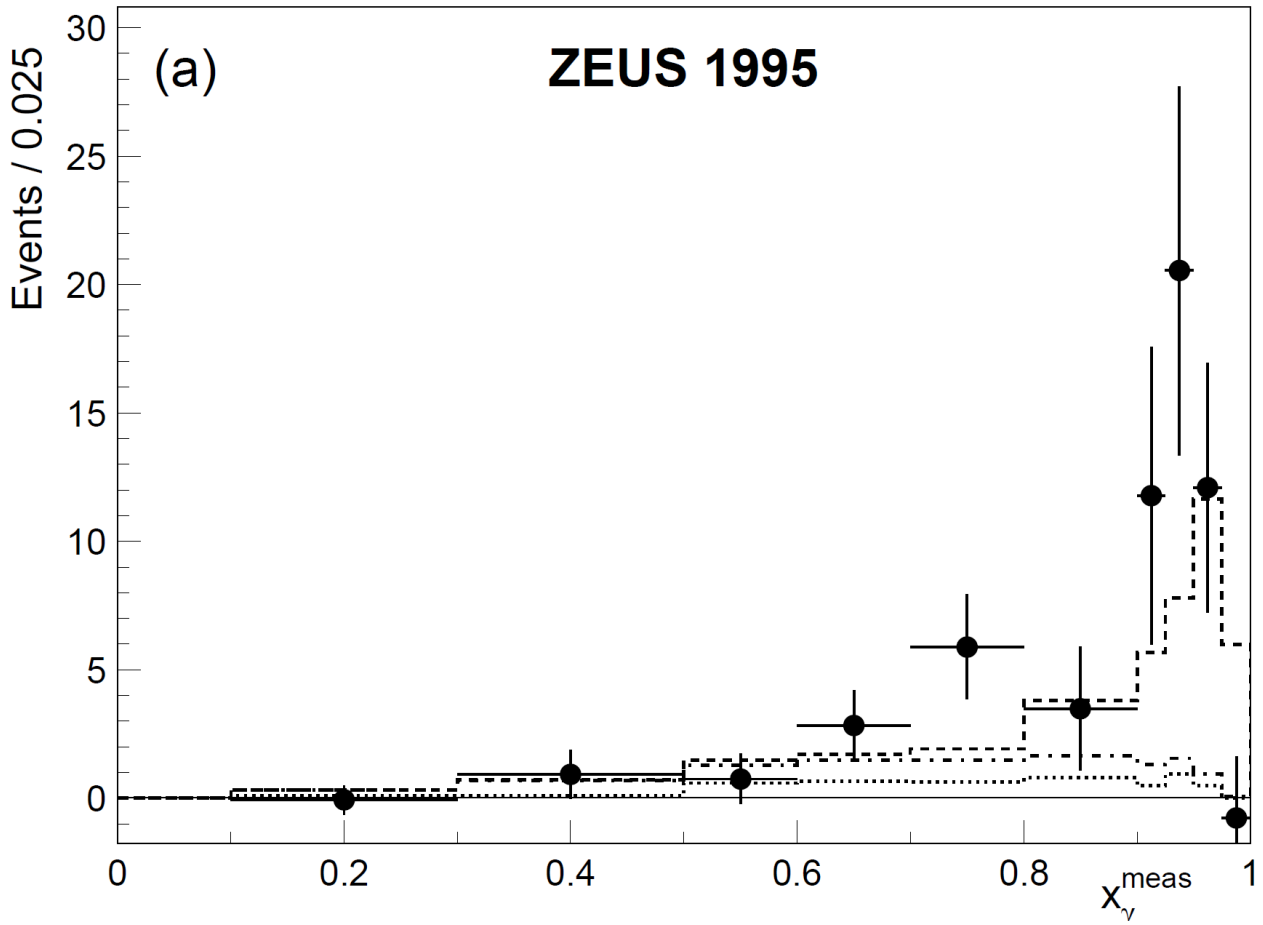


Xγ is fraction of photon momentum involved in hard scatter

"direct" process: entire photon interacts

"resolved" process: photon provides quark or gluon which interacts

Result agrees with LO QCD expectations (Pythia Monte Carlo)



Cross section measurement

$$ep \rightarrow e + \gamma_{prompt} + jet + X$$

σ = 15.3 +/- 3.8 (stat.) +/- 1.8 (sys.) pb

NLO calculation ranges from 13 to 18 pb, depending on assumptions for photon parton density (L. Gordon)

Experimental result agrees with theory

Figure 4: (a) Distribution in x_γ^{meas} of prompt photon events after background subtraction. Points = data; dotted histogram = MC radiative contribution; dash-dotted = radiative + resolved; dashed = radiative + resolved + direct. Plotted values represent numbers of events per 0.025 interval of x_γ^{meas}; i.e. total number of events in bin = plotted value × bin width / 0.025. Errors are statistical only and no corrections have been applied to the data.

Dijets at HERA: A QCD Story

Douglas Chapin
University of Wisconsin–Madison
15 May 2001

OUTLINE

HERA and ZEUS

Deep Inelastic Scattering and pQCD

Structure functions and the gluon

Dijets and pQCD

Dijet cross section measurement

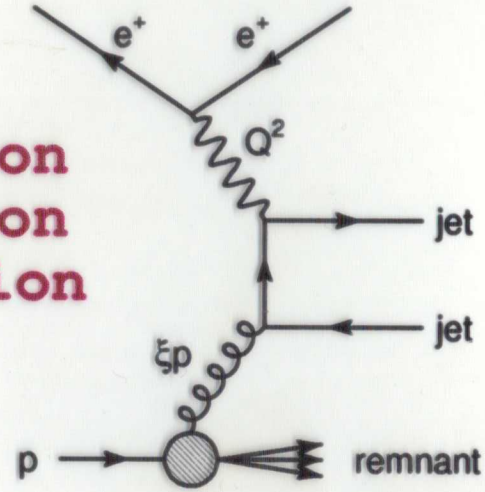
The Future

Dijet Production at HERA

Why settle for one jet, when you can have two!

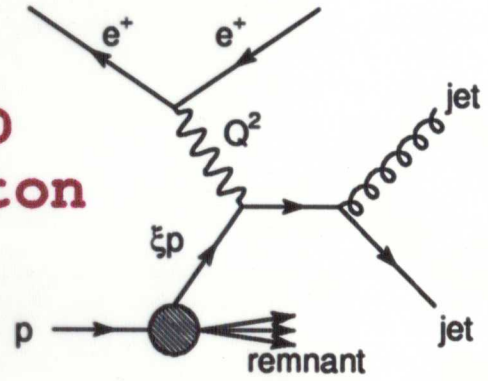
HERA √s provides high E_T final hadronic state

Boson Gluon Fusion



(2+1) event

QCD Compton



(2+1) event

DIS variables still apply

$$Q^2 = -q^2 = -(k - k')^2$$

$$y = \frac{p \cdot q}{p \cdot k} \qquad x = \frac{Q^2}{2p \cdot q}$$

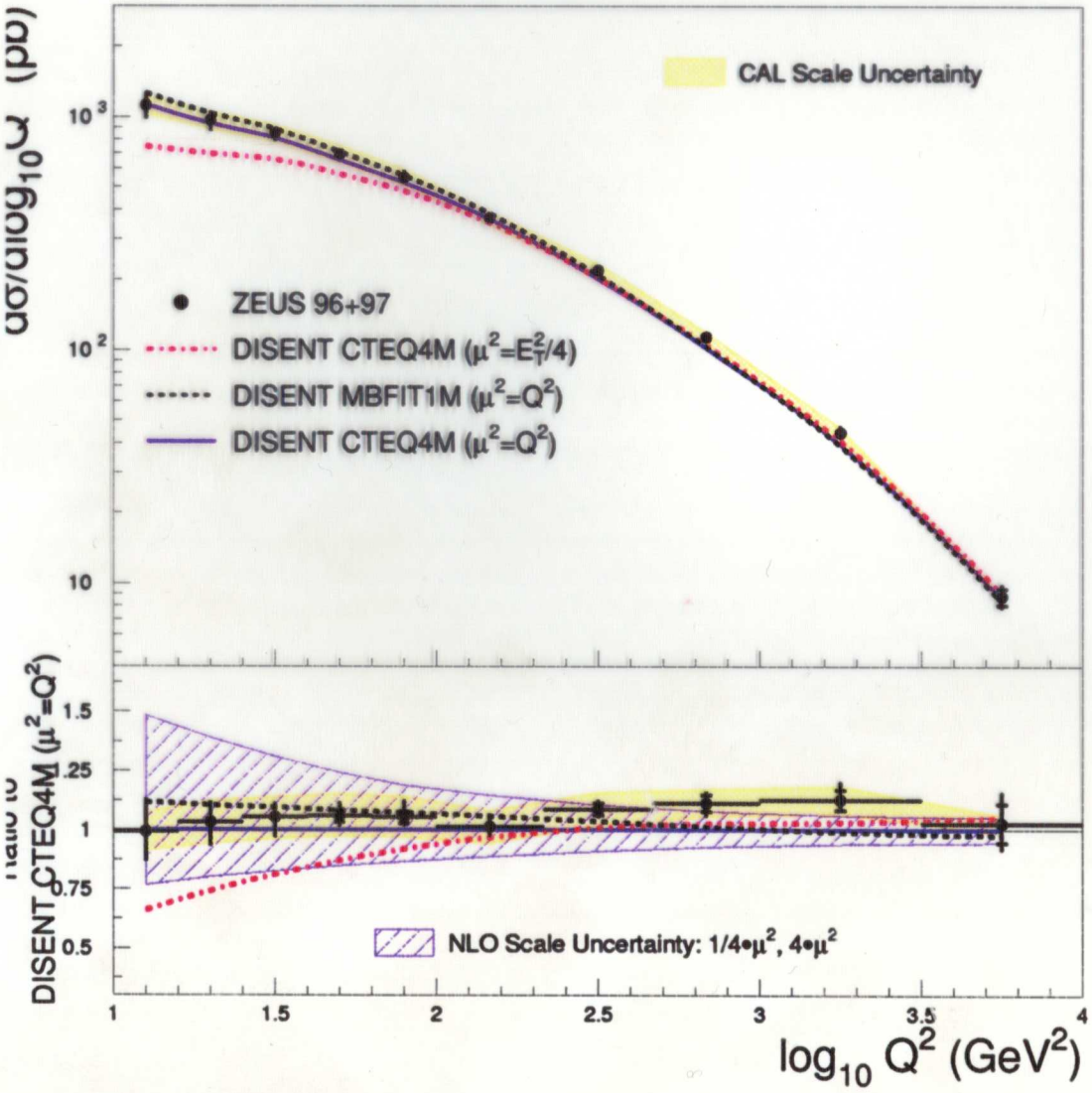
But now the momentum fraction of the incident parton (at LO) is

$$\xi = x\left(1 + \frac{M_{jj}^2}{Q^2}\right)$$

M_{jj}=dijet mass

Inclusive Dijet Cross Section vs Q^2

Asymmetric jet cut: 5, 8GeV; E_e>10, y>0.04



NLO Comparison

Success for pQCD!

Within NLO scale uncertainty estimate, NLO calculations reproduce measured cross section to within 10%

- over three orders of magnitude in Q^2
- over 2 orders of magnitude in value

For Q^2<~200 measurement uncertainties less than renormalization scale uncertainty

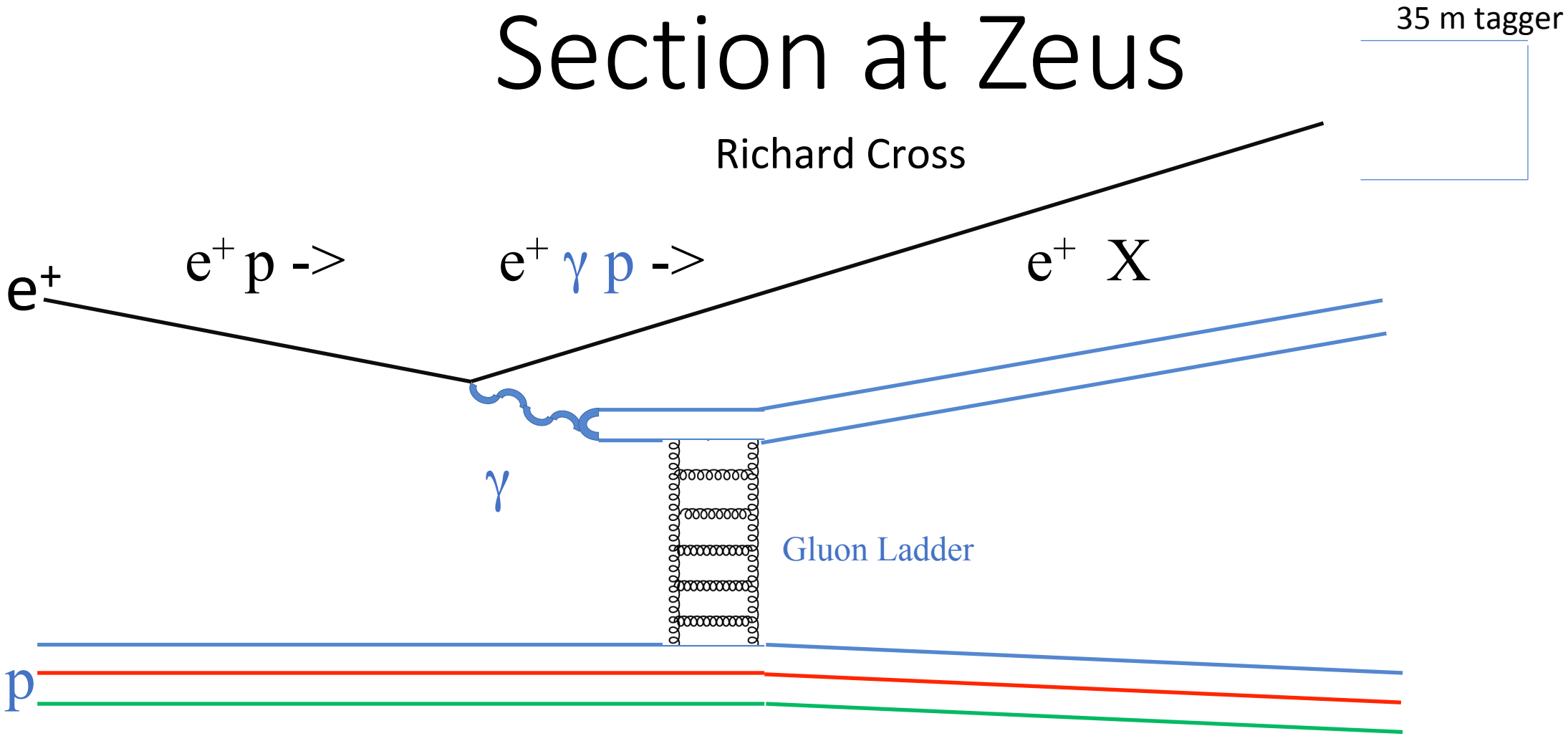
- Need improved theoretical calculations with reduced renormalization scale dependence

A Few Lessons Learned

- It’s OK to let things go
  - Circular logic
  - Bucky Bus
- But don’t let everything go
  - Teleconferences
  - Slide titles
- People, then results
  - Personalities
  - Summer students
  - Ski trips
  - PhD -> Industry

Total Photon-Proton Cross Section at Zeus

Richard Cross



Total Photon-Proton Cross Section Measurement Method

- Treat the e^+ as a photon source, 35 m Tagger measured energy tells you how much energy the photon has
  - e^+ (initial) = γ + e^+(35 m tagger)

- Trigger was 35 m tagger signal + some sort of signal in the calorimeter.
  - These events were normally thrown out as background "junk" during regular runs.
  - (35 m tagger signal was a veto for most Zeus physics)

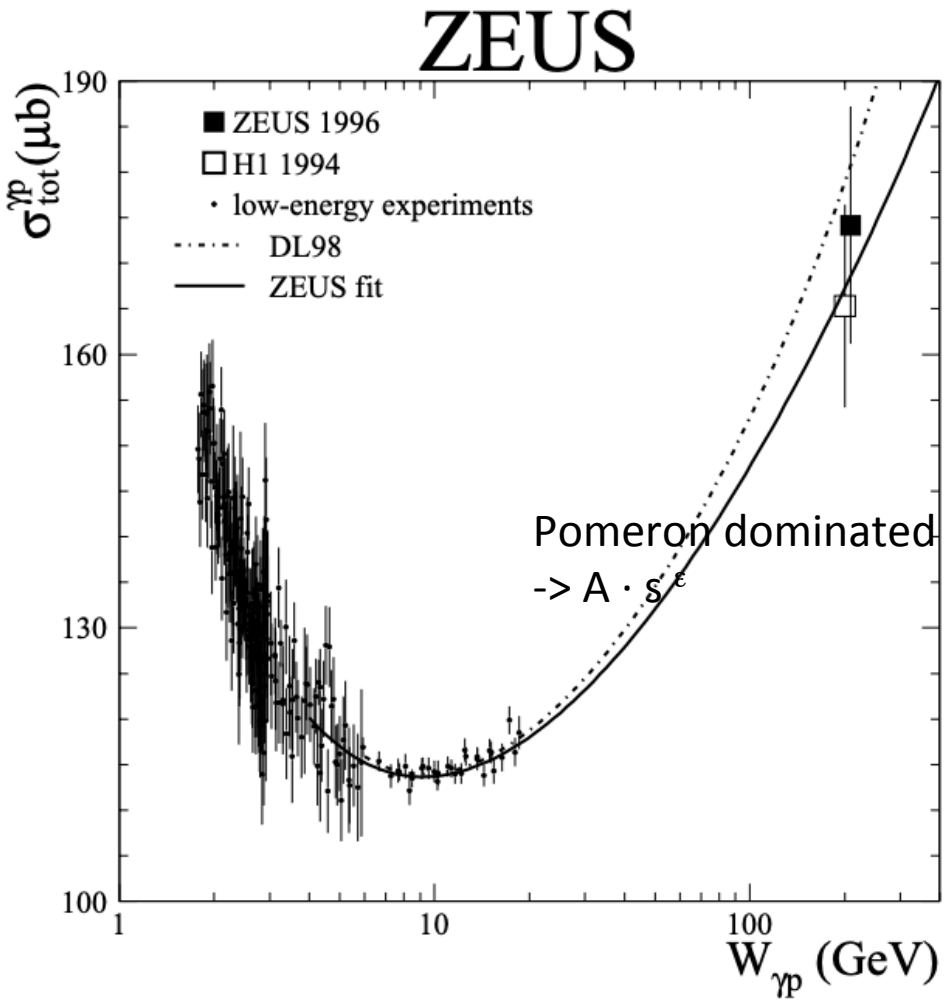
- $W\gamma p$ = 209 GeV measured in a dedicated **8 hour** run

- That run gave integrated luminosity of 49 nb^{-1}

- Dedicated run yielded a measurement of $\sigma^{\gamma p}_{tot} = 174 \pm 1(stat.) \pm 13(syst.)$ μb

Regge Theory, the physics

- Regge Theory parameterized several hadronic cross sections as
  - $\sigma_{tot} = A \cdot s^{\varepsilon} + B \cdot s^{-\eta}$. Where s center of mass energy…
- Does a Proton – Photon interaction behave hadronically?
  - Yes, we showed that
- s^{ε} Is the "Pomeron term", a term that rises with increasing energy
  - What is it, really?
  - A colorless mess (~nonlocalized) of something that transfers momentum
- Recall, dedicated run yielded a measurement of $\sigma^{\gamma p}_{tot}$ = 174 ± 1(stat.) ± 13(syst.) μb
  - Would be almost 0 if proton-photon interaction did not behave **hadronically**
  - And/Or if the Pomeron term was small
- Conclusions:
  - At high energy, the photon behaves hadronically
  - A colorless soft interaction dominates the proton-photon interaction
  - **Gluon ladder** is the best interpretation

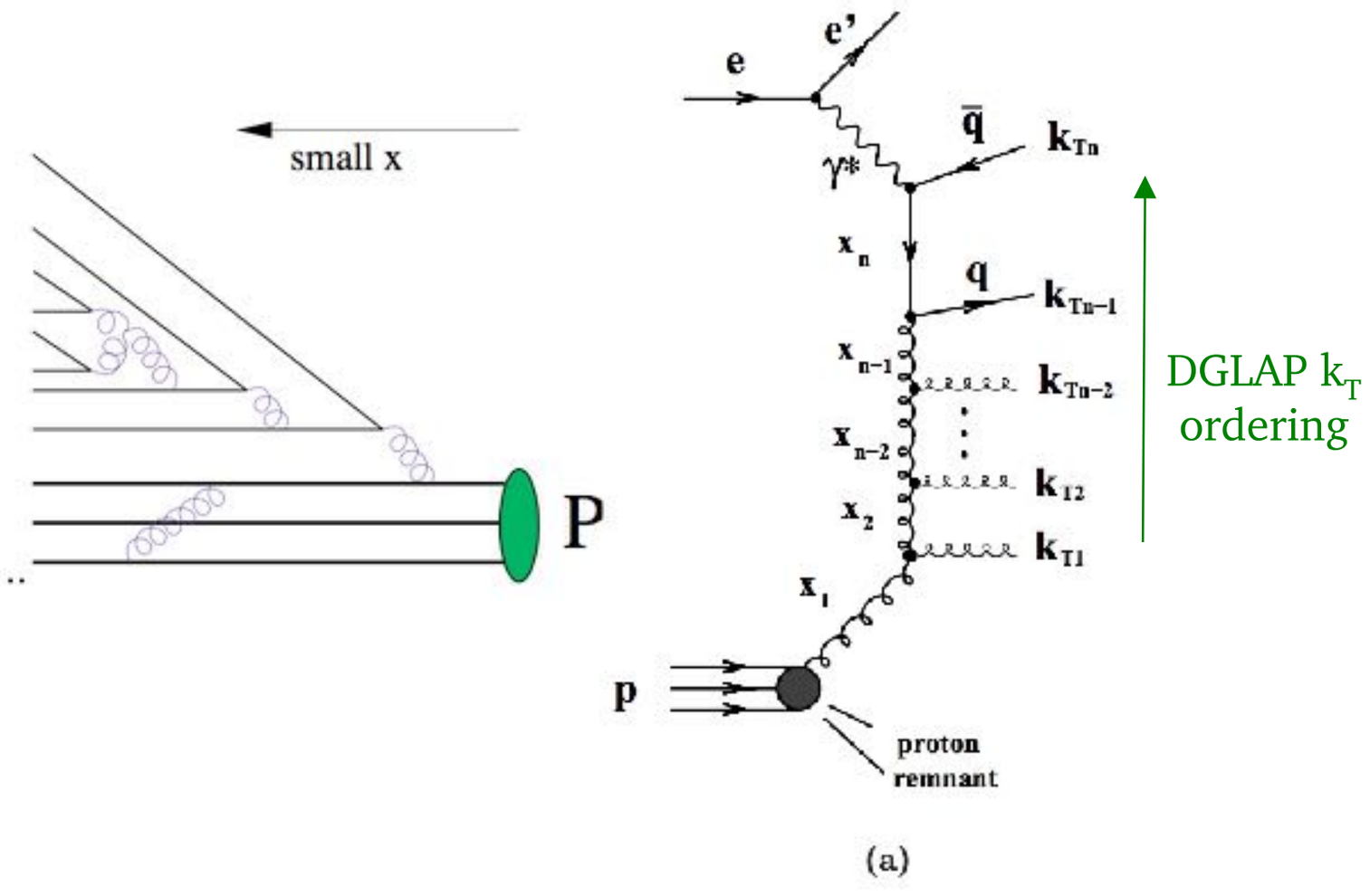


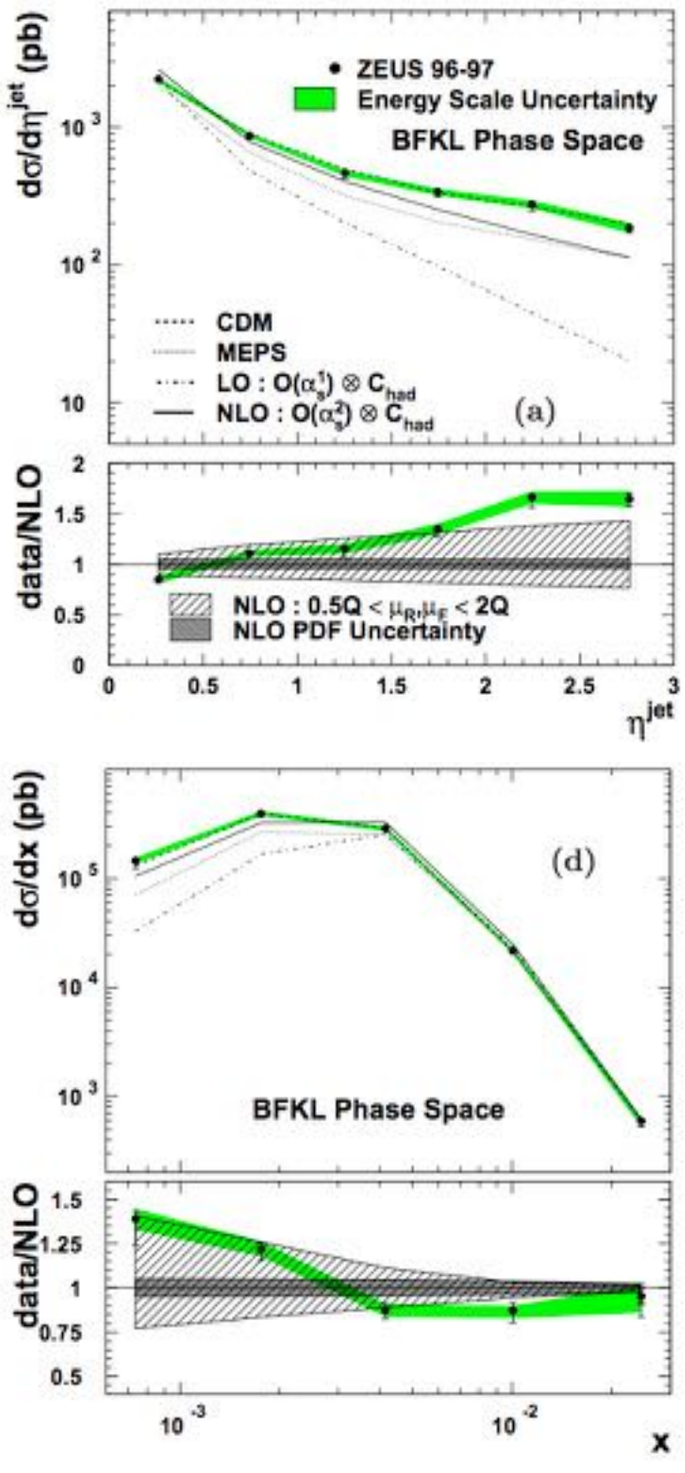
Sabine Lammers, 2004

Thesis: A Study of Parton Dynamics at Low x with ZEUS at HERA

Forward Jet Production in DIS and low-x parton dynamics

DGLAP: $x = x_n < x_{n-1} < \ldots < x_1$, $Q^2 = k^2_{T,n} >> \ldots >> k^2_{T,1}$
BFKL : $x = x_n << x_{n-1} << \ldots << x_1$, no ordering in k_T





Forward Jet Production in Deep Inelastic ep Scattering and low-x Parton Dynamics at HERA, S. Chekanov, *et al.*, Phys. Lett. **B632** 13, 2005.

Liang Li, 2005

Three Jet Production in NC DIS with Zeus at HERA

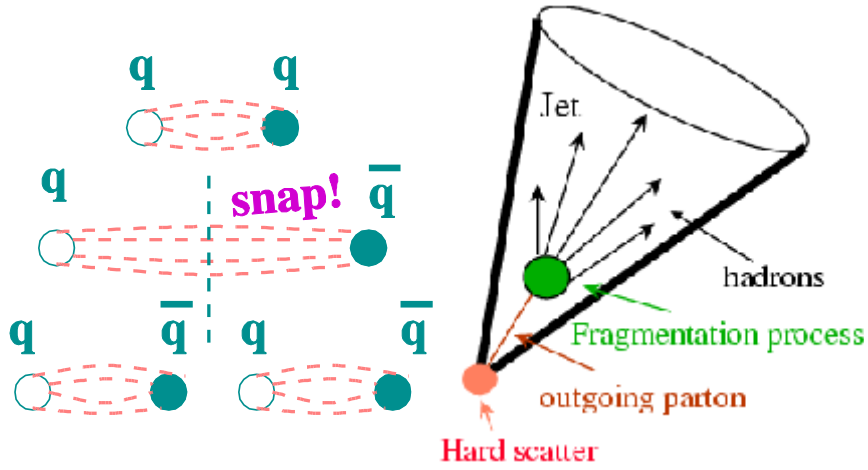
Ph.D. Thesis

- Three Jet Production in Neutral Current Deep Inelastic Scattering with ZEUS at HERA
- Liang Li: graduated in 2005
- Thesis work published at Eur. Jour. Phys. C44 ,183
  - Alive and kicking after 14 years, latest citation in 2019
  - Total citation 51 (INSPIRES)
  - Owe great gratitude to Wesley: babysitting the analysis from the beginning
- Hardware and service work
  - Worked on ZEUS Calorimeter First Level Trigger (CFLT) and Data Quality Monitoring System (DQM)
  - CFLT: Wesley's oyster!

Why Jets?

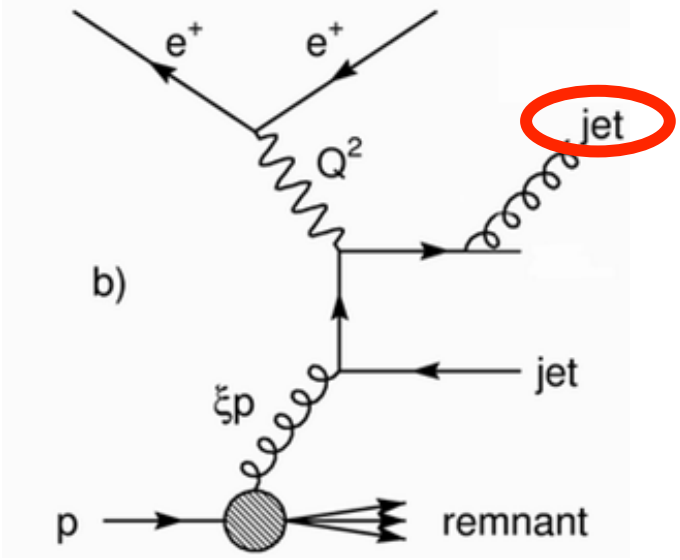
Quarks and gluons cannot be observed directly by detector

- They interact by strong interactions
  - Hadrons: molecules of strong interactions
  - Jet: "spray" of hadrons
- Jet: experimental observables
  - What we "see" are all jets
  - Theory calculation made possible by renormalization and perturbative QCD calculations



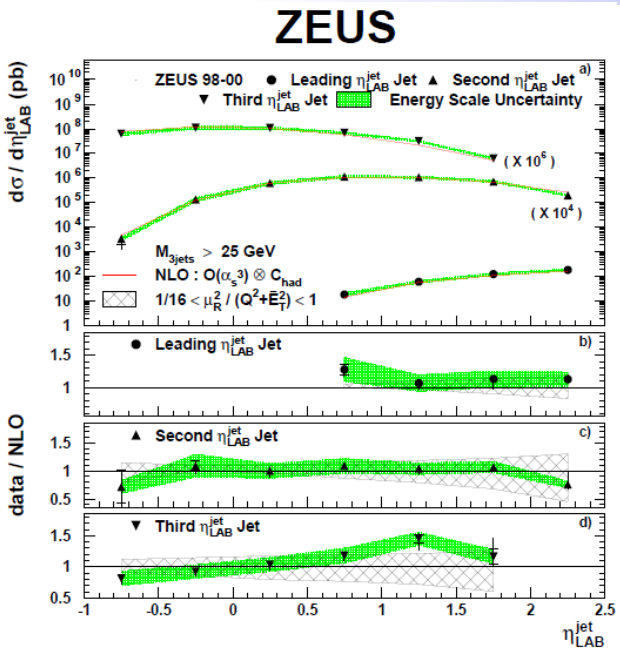
Direct test to QCD calculations

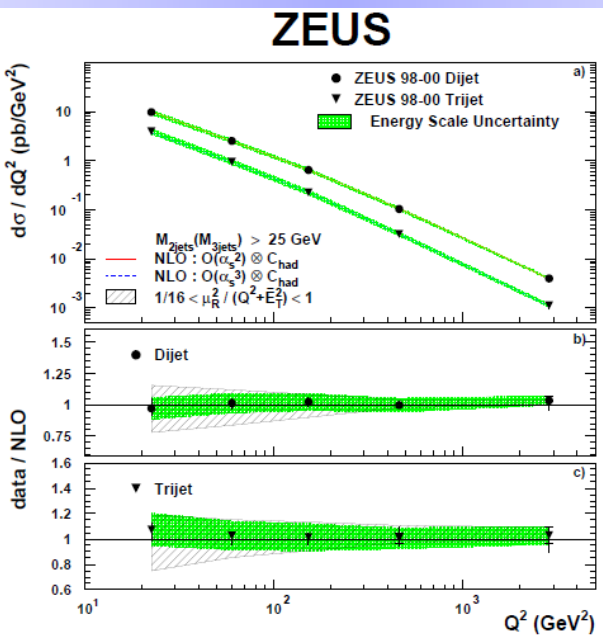
- Precise tests
  - Multiple (N) jet calculation ~ α_s^N
- Ratio $\sigma_{3jet}/\sigma_{2jet} = O(\alpha_s)$ some uncertainties cancel -- more precise measurement of strong interaction constant

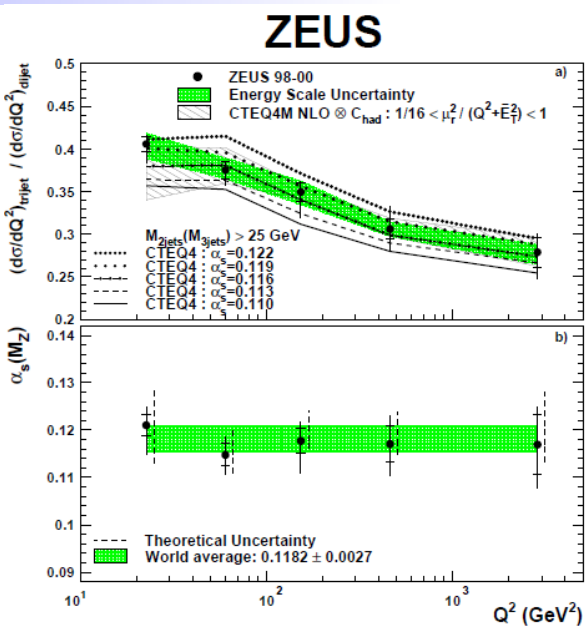


Foundation work for new physics searches

Multijets Measurement







Precise tests across wide kinematic ranges

- High order calculation (α_s^3)

First measurement on α_s in multijets environment at HERA

- First experimental results using jet(α_s^2) cross section to extract α_s

Eur. Jour. Phys. C44, 183 (2005) 50+

$$\alpha_s(M_Z) = 0.1179 \pm 0.0013(\text{stat.}) \,^{+0.0028}_{-0.0046}(\text{syst.}) \,^{+0.0064}_{-0.0046}(\text{th.})$$