Experimental results - summary

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• Introduction/guide
• Diffraction
• Multiple interactions
• Forward physics
• Total/elastic cross section
Introduction

- There were about 24 experimental talks and many theoretical ones of direct interest to experiments
- Represented were in alphabetical order EAS, HERA, FNAL, LHC, RHIC
- Common themes are proton structure and QCD - mainly gluodynamics
- At least three different frameworks/different degrees of freedom
  - quarks and gluons
  - dipoles/color glass condensate (CGC)
  - Regge language
Guide - traveling salesman problem

Diffraction
HERA, FNAL, LHC

Heavy ions
RHIC, LHC

New Physics
EAS, LHC

Multiple interact.
HERA, FNAL, LHC

Forward Physics
HERA, FNAL, LHC

Total/el x-section
EAS, LHC

Higgs

leading proton

high density g

factorisation

QGP/CGC

unitarity

MSSM

modeling

unitarity

modeling

gluons

unitarity

QGP/CGC

unitarity

modeling

unitarity

modeling

9/05/07
Signs of problems: Diffraction

- Large fraction of DIS events have LRG (visible 10%)

\[ Q^2 = -q^2 = -(k - k')^2 \]
\[ x = \frac{Q^2}{2P \cdot q} \]
\[ y = \frac{q \cdot P}{k \cdot P} \]
\[ W^2 = (q + P)^2 \]

LRG cannot be generated by DGLAP. Maybe it is there in the initial condition?
Diffraction soft/hard?

- Extraction of $\alpha_{IP}$ from DIS diffraction
  \[ f^D_i(x, Q^2, x_{IP}, t) = f_{IP/p}(x_{IP}, t) \cdot f^{IP}_i(\beta = \frac{x}{x_{IP}}, Q^2) \]

Indication that $\alpha_{IP}$ in DIS harder than in hadron-hadron

Compatible with LRG in initial condition

Indication that $\alpha_{IP}$ in DIS harder than in hadron-hadron
QCD factorisation holds for diffractive PDF (DPDF)

\[ \text{DPDF} = \text{fraction of proton PDF that lead to LRG events} \]
Diffractive factorisation in DIS

\[ z_{ip} = \frac{Q^2 + M_{X}^2}{Q^2 + M_{X}^2} \]

\[ Q^2 = 35 \text{ GeV}^2 \]

\[ x_{ip} = 0.018 \]

H1 Preliminary

H1 2006 DPDF Fit (scale err.)

H1 2006 DPDF Fit B (scale err.)

H1 Displaced Track Data

H1 D' Data

ZEUS D'

H1 2006 DPDF Fit A

H1 2006 DPDF Fit B
Why do we care about DPDFs

MC models notoriously get the baryon spectra wrong
DPDFS are perfect tools to get it right!

Diffraction as elastic
$\gamma^* p \rightarrow \gamma^* p$

$$P_g^D(x, Q^2) = \frac{\int_{x/0.01}^1 d\beta \frac{1}{\beta} f_{FP}(\frac{x}{\beta}) g^P(\beta, Q^2)}{g^P(x, Q^2)},$$

$$P_q^D(x, Q^2) = \frac{\sum_i \int_{x/0.01}^1 d\beta \frac{1}{\beta} f_{FP}(\frac{x}{\beta}) q_i^P(\beta, Q^2)}{\sum_i q_i^P(x, Q^2)},$$

New parametrisations do not have this problem

Possible meter for signs of black body limit ???

Pumplin's limit
The diffractive structure function measured on the proton side in events with a leading antiproton is NOT suppressed relative to predictions based on DDIS.
Uniform suppression?

- Suppression seems independent of final state
- Possibly dependent on the diffracted particle

**Old results**

ZEUS and H1 measurements cover different kinematic ranges
- H1: \( E_T > 5 \text{ GeV}, x_\perp < 0.030 \)
- ZEUS: \( E_T > 7.5 \text{ GeV}, x_\perp < 0.025 \)

x2 too high
res. \( \gamma \times 0.34 \)
Role of inclusive diffraction

• There is a set of DPDF which may be used to model forward protons, provided gap survival probability is understood.
• HERA measurements may be used to describe through fracture functions leading protons and neutrons (not discussed in this meeting).
• Gap survival and its dependence on the projectile size may turn out to be important for multiple interactions.
Hard diffraction - exclusive reactions

\[ \sigma(W) \propto W^\delta \]

\[ \frac{d\sigma}{dt} \propto e^{-b|t|} \]

- Expect \( \delta \) to increase from soft (~0.2, from 'soft Pomeron' value) to hard (~0.8, from \( xg(x,Q^2)^2 \))
- Expect \( b \) to decrease from soft (~10 GeV\(^{-2}\)) to hard (~4-5 GeV\(^{-2}\))

*C. Royon, hep-ph/0308283*
*B. Cox, A. Pilkington, PRD 72, 094024 (2005)*

**OTHER...**

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Exclusive processes in DIS

\[ \gamma p \rightarrow V(\rho, \phi, \omega^0, J/\psi, \Upsilon)p \]

H1 DVCS Analysis HERA II

- H1 HERA II e^+p (prelim.)
- H1 HERA II e^+p (prelim.)
- H1 HERA I
- ZEUS HERA I

Q^2 = 8 GeV^2

H1 DVCS Analysis HERA II

- H1 HERA II e^+p (prelim.)
- H1 HERA II e^+p (prelim.)
- H1 HERA I
- ZEUS HERA I

Q^2 = 8 GeV^2

σ_dvcs M nb

σ \propto W^\delta

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Slope of $t$ - size of interaction region

\[ \frac{d\sigma}{dt} \propto e^{-b|t|} \]

The $t$ distribution becomes universal - gluon formfactor

\[ r_p = 0.8\text{fm} > r_g = 0.6\text{fm} \]
Exclusive processes - GPDs

\[ \frac{x + \eta}{2} p^+ \quad \frac{x - \eta}{2} p^+ \]

GPDs

PDF

Forward limit \( \Delta \to 0 \)

\( \Delta = P_2 - P_1 \)

\( \eta = -\frac{\Delta^+}{p^+} \) (skewedness)

Hard Exclusive Photon Production

Form Factors

Orbital Angular Momentum \( L_{\text{quark}} \)

Hard Exclusive Meson Production

Parton Distribution Functions

DVCS

ep \to e'p'\gamma
DVCS with polarized electrons - HERMES

- Beam-charge asymmetry $A_C(\phi)$ (BCA):
  \[ d\sigma(e^+;\phi) - d\sigma(e^-;\phi) \propto Re[\mathcal{H}] \cdot \cos(\phi) \]

- Beam-spin asymmetry $A_{LU}(\phi)$ (BSA):
  \[ d\sigma(e^-;\phi) - d\sigma(\bar{e}^-;\phi) \propto Im[\mathcal{H}] \cdot \sin(\phi) \]

- Longitudinal target-spin asymmetry $A_{UL}(\phi)$ (LTSA):
  \[ d\sigma(P;\phi) - d\sigma(\bar{P};\phi) \propto Im[\tilde{\mathcal{H}}] \cdot \sin(\phi) \]

- BCA: $A_C(\phi) \propto Re[\mathcal{H}] \cdot \cos(\phi)$

- BSA: $A_{LU}(\phi) \propto Im[\mathcal{H}] \cdot \sin(\phi)$

- LTSA: $A_{UL}(\phi) \propto Im[\tilde{\mathcal{H}}] \cdot \sin(\phi)$

- Vector mesons ($\rho^0$): $\mathcal{H}, \mathcal{E}$ (flavor singlet)

- $f$-meson family ($f_0, f_2$): $\mathcal{H}, \mathcal{E}$ (flavor non-singlet)

- Pseudoscalar mesons ($\pi^+$): $\tilde{\mathcal{H}}, \tilde{\mathcal{E}}$
NLO&beyond fits to DVCS/inclusive

Three-dimensional image of a proton

Quarks:

Gluons:

Kornelija Passek-Kumerički: Fitting DVCS at NLO and beyond...
Exclusive diffraction in $pp$

Search for exclusive dijets

$R_{jj} = \frac{M_{jj}}{M_X \text{(all calorimeters)}}$

Exclusive b-jets are suppressed by $J_Z = 0$ selection rule
Exclusive dijets

Two MC programs

ExHuME (KMR): $gg \rightarrow gg$ process $\Rightarrow$ uses LO pQCD

Exclusive DPE (DPEMC) $\Rightarrow$ non-pQCD based on Regge theory

CDF Run II Preliminary

Data corrected to the hadron level

Exclusive DPE (DPEMC)

ExHuME

Jet $E_T^{\text{min}}$ (GeV)

Jet $E_T^{\text{min}} > 5$ GeV

$|\eta_1^{\text{jet1}}, \eta_2^{\text{jet2}}| < 2.5$

$3.6 < \eta_{\text{gap}} < 5.9$

$0.03 < \zeta_{T} < 0.08$

stat. error

syst. error

$|\eta_1^{\text{jet1}}, \eta_2^{\text{jet2}}| < 2.5$

$3.6 < \eta_{\text{gap}} < 5.9$

$0.03 < \zeta_{T} < 0.08$

Systematic Uncertainty

$\sigma_{\text{excl}}^{\text{hadron level}} (E_T^{\text{min}})$

$\frac{d\sigma_{\text{excl}}}{dM_{jj}}$ (GeV/c$^2$)
Diffractive Higgs at LHC

\[ M_H^2 = (p + \bar{p} - p' - \bar{p}')^2 \]

Roman pots

Totem/CMS

9/05/07

EDS07
Diffractive Higgs at LHC

SM Higgs - good mass determination, spin information, background suppression

MSSM \( h, H \Rightarrow b\bar{b} \) enhanced

NMSSM Higgs

\[ pp \rightarrow p + h_1 + p \]

\[ a_1 \rightarrow T^+ + T^- \]
Forward detectors for ATLAS/CMS

Cold region of LHC
Too far for L1
Fast timing
ATLAS rapidity coverage

ATLAS Forward Detectors

- LUCID
- ALFA RP
- ATLAS-ZDC
CMS rapidity coverage

Forward Detectors at CMS IP :: Overview

- CMS Central
- TOTEM-T2
- CMS-CASTOR
- ZDC
- TOTEM-RP

CMS+TOTEM have the largest acceptance ever at a hadron collider
Rapidity coverage

- model predictions of particle multiplicity and energy flow differ by factor $\sim 2$

[R. Engel]
Underlying event and MPIs

The harder the collision, the bigger the probability of another collision.
Underlying event/MPIs

- $P_T^{jet} > 5$ GeV
- Mini-jets have $P_T^{jet} > 3$ GeV
Forward physics and high gluon density

RHIC data

pp at 200 GeV

NLO dominance of $gq$ and $gg$

Red: proton/$\pi^+$
Blue: antiproton/$\pi^-$

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**dAu at 200 GeV**

**Clear suppression as \( \eta \) increases**
- Cronin effect ?
- Nuclear shadowing?
- Gluon saturation?
- Suppression due to dominance of \( q_v \), energy loss, coherent multiple scat., parton recombination, energy conservation...

\[
R_{dAu} = \frac{1}{<N_{coll}>} \frac{d^2N^{d+Au}}{dp_Td\eta} / \frac{d^2N^{pp}_{inel}}{dp_Td\eta}
\]

where \( <N_{coll}> = 7.2\pm0.3 \)

**Nuclear Modification Factor**

AuAu at 200 GeV

No change of $R_{\text{AuAu}}$ with rapidity

- dAu suppression at high rapidity consistent with saturation picture, but at RHIC energy, $x$ and $p_T$ reach may be too small to decisively settle this
Underlying event/MPIs

- Complexity of the problem and lack of theory requires measurements for tuning - minimum bias
- Efforts are underway to define minimum bias triggers
- The wider the phase space coverage the better
- Theoretical efforts are also under way

### MB Triggers - ATLAS

<table>
<thead>
<tr>
<th>Coincidence Logic</th>
<th>Counter Threshold [pC]</th>
<th>Trigger Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>900 GeV</td>
<td>14 TeV</td>
</tr>
<tr>
<td>1+1</td>
<td>10.75</td>
<td>98%</td>
</tr>
<tr>
<td>2+2</td>
<td>7.75</td>
<td>97%</td>
</tr>
<tr>
<td>3+3</td>
<td>6.25</td>
<td>94%</td>
</tr>
<tr>
<td>4+4</td>
<td>5.25</td>
<td>90%</td>
</tr>
<tr>
<td>5+5</td>
<td>4.50</td>
<td>85%</td>
</tr>
<tr>
<td>6+6</td>
<td>4.00</td>
<td>79%</td>
</tr>
</tbody>
</table>
Total cross section

COMPETE fits:

- Current predictions for LHC: 90 – 130 mb
- Final aim of TOTEM: ~1% accuracy
Totem detector configuration

T1: $3.1 < \eta < 4.7$
T2: $5.3 < \eta < 6.5$

$\mathcal{L} \sigma_{tot}^2 = \frac{16\pi}{1 + \rho^2} \frac{dN_{el}}{dt} \bigg|_{t=0}$

$\mathcal{L} \sigma_{tot} = N_{el} + N_{inel}$

$\sigma_{tot} = \frac{16\pi}{1 + \rho^2} \frac{dN_{el}}{dt} \bigg|_{t=0}$

$\mathcal{L} = \frac{1 + \rho^2}{16\pi} \left( N_{el} + N_{inel} \right)^2$

$N_{el}$, $dN_{el}/dt$ : elastic rate

$N_{inel}$ : inelastic rate

$\rho = \Re f(0) / \Im f(0)$ : external input (small effect)
Level-1 Trigger Schemes

Whenever possible, use 2-arm coincidence to suppress background.

- **Elastic Trigger:**
  \[ \sigma \approx 30 \text{ mb} \]

- **Single Diffractive Trigger:**
  \[ \sigma \approx 14 \text{ mb} \]

- **Double Diffractive Trigger:**
  \[ \sigma \approx 7 \text{ mb} \]

- **Central Diffractive Trigger**
  (Double Pomeron Exchange DPE)
  \[ \sigma \approx 1 \text{ mb} \]

- **Non-diffractive Inelastic Trigger:**
  \[ \sigma \approx 58 \text{ mb} \]

**Total Cross Section:**
\[ \sigma_{\text{tot}} \approx 110 \text{ mb} \]
Combined Uncertainty in $\sigma_{\text{tot}}$

$$\sigma_{\text{tot}} = \frac{16\pi}{1 + \rho^2} \left. \frac{dN_{\text{el}}}{dt} \right|_{r=0} / \left( N_{\text{el}} + N_{\text{inel}} \right)$$

$$\mathcal{L} = \frac{1 + \rho^2}{16\pi} \left( \frac{N_{\text{el}} + N_{\text{inel}}}{dN_{\text{el}} / dt} \right)^2_{r=0}$$

At $\beta^* = 90$ m:
- Extrapolation of elastic cross-section to $t = 0$: ± 4 %
- Total elastic rate (strongly correlated with extrapolation): ± 2 %
- Total inelastic rate:
  (error dominated by Single Diffractive trigger losses) ± 1 %
- Error contribution from $(1+\rho^2)$
  using full COMPETE error band $\delta\rho/\rho = 33$ % ± 1.2 %

=>$ \text{Total uncertainty in } \sigma_{\text{tot}} \text{ including correlations in the error propagation: } \pm 5 \%$

Slightly worse in $\mathcal{L}$ ($\sim$ total rate squared!): ± 7 %

Later improvement to ~ 1 % with $\beta^* = 1540$ m requires:
- improved knowledge of optical functions
- alignment precision < 50 μm
Cosmic ray link

\[ X_{\text{max}} \propto \lambda_{\text{inel}} + \lambda_{\text{e.m.}} \cdot \ln \left( \frac{E_0}{n_{\text{mult}} E_c} \right) \]

Main shower ingredients
- Electromagnetic bulk
- Penetrating muons
- Hadronic core
- Invisible (neutrinos)
- Fluorescence/Cherenkov photons

\[ \lambda_{\text{int}} = k \cdot \Lambda_{\text{obs}} = \frac{\langle M \rangle}{\sigma_{\text{int}}} \]

all detector effects and fluctuations are contained in \( k \)
Proton air cross section
Air shower development

Much modeling to get energy and cross sections - HEP measurements are an important ingredient (LHCf exp.)
Summary

• There is this fundamental area of strong interactions which is far from being understood from first principles
• There is a steady influx of new experimental results to guide the theoretical concepts
• The experimental environment is as difficult as the underlying theory
• The fundamental nature of the questions and their impact on many other aspects of physics is such that they deserve their own experimental facility - EIC, LeHC?
• In the mean time we have to rely on the ingenuity of experimentalists (vide LHC!!!)