HERA operated during 1992 - 2007 with:

- \( e^\pm \) energy of 27.5 GeV;
- \( p \) energies of 920, 820, 575 and 460 GeV.

**H1** and **ZEUS** - two general purpose collider experiments at HERA:

\(~0.5 \text{ fb}^{-1}\) of luminosity were recorded by each experiment.

\[
Q^2 = -\left(k - k'\right)^2 \\
x_{Bj} = \frac{Q^2}{2P \cdot q} \\
y = \frac{P \cdot q}{P \cdot k}
\]
2015 - early 2016:

\(~3.5\ \sigma\) excess of the di-photon events for the resonance mass:

\[ m_X = 750\sim 760 \text{ GeV} \]

observed in both, \textit{Atlas} and \textit{CMS}, experiments.

\[ \sigma_1 = 3.3 \text{ fb}^{-1} \text{ (13 TeV)} + 19.7 \text{ fb}^{-1} \text{ (8 TeV)} \]

\[ \frac{\Gamma_X}{m_X} = 1.4 \times 10^4, J=0 \]

\[ \gamma = 13 \text{ TeV}, 3.2 \text{ fb}^{-1} \]

\[ \Gamma_X/m_X = 2\% \]

\[ \text{Spin-0 Selection} \]

\[ \text{Observed} \]

\[ \sim 600 \text{ theory papers.} \]
2003 - 2004:

\(\sim 4\) \(\sigma\) evidence at CERN SPS

\[\Xi^- (1860) \rightarrow uudds, \quad \Xi^+ (2070) \rightarrow uussd, \quad \Sigma (1890) \rightarrow ddssu, \quad N (1710) \rightarrow \Xi^+ (1530) \rightarrow uuudd\]

\(\sim 4.5\) \(\sigma\) evidence of \(\Theta^+\) at LEPS,
followed by \(\sim 4\) \(\sigma\) reports from 9 more experiments
2003 - 2004:

- \( \approx 4 \sigma \) evidence at CERN SPS

\[ \Xi^- (1860) \, Z. \, Phys. \, A \, 359 \, (1997) \, 305 \quad \Xi^+ (2070) \]

- \( \approx 4.5 \sigma \) evidence of \( \Theta^+ \) at LEPS, followed by \( \approx 4 \sigma \) reports from 9 more experiments

- \( \approx 4 \sigma \) evidence at HERMES

2003 - 2004:

~4 \sigma evidence at CERN SPS

\[ M = 1527 \pm 2.3\text{ (stat)} \text{ MeV} \]
\[ \sigma = 9.2 \pm 2\text{ (stat)} \text{ MeV} \]

~4.5 \sigma evidence of \( \Theta^+ \) at LEPS, followed by ~4 \sigma reports from 9 more experiments

~4 \sigma evidence at HERMES


~5.5 \sigma evidence at H1

2003 - 2004:

~4 σ evidence at CERN SPS

~4.5 σ evidence of Θ+ at LEPS, followed by ~4 σ reports from 9 more experiments

~4 σ evidence at HERMES


~4 σ evidence at ZEUS


~5.5 σ evidence at H1

2003 - 2004:

~4 σ evidence at CERN SPS

\[ \Xi^-(1860) \quad \Xi^+(2070) \]

\[ \text{ddss}_{\bar{u}} \quad \Sigma(1890) \quad \text{uuss}_d \]

~4.5 σ evidence of \( \Theta^+ \) at LEPS, followed by ~4 σ reports from 9 more experiments

~4 σ evidence at ZEUS

\[ \Theta^+(1530) \]

uudd_s

\[ \Theta^+ \]

the status of ★★★☆☆

~5.5 σ evidence at H1

\[ \Theta^0_c \quad \text{uudc} \]

\[ \sqrt{s} > 20 \text{ GeV}^2 \]

\[ K^+_S p(\bar{p}) \]

\[ D^*+ p + D^0 p \]

\[ D^0 p + D^0 p \]

PDG14 set \( \Theta^+ \)

\[ \text{Entries per 10 MeV} \]

\[ \text{FWHM [MeV]} \]

\[ \text{Mass value [MeV]} \]

\[ \text{Events / (8 MeV)} \]

\[ M=1527 \pm 2.3\text{(stat)} \text{MeV} \]

\[ \sigma=9.2 \pm 2\text{(stat)} \text{MeV} \]

\[ M=1528 \pm 2.6\text{(stat)} \text{MeV} \]

\[ \sigma=8 \pm 2\text{(stat)} \text{MeV} \]

\[ M(\pi^+ + \pi^- p) \text{[GeV]} \]

\[ \text{Signal + bg. fit} \]

\[ \text{Bg. only fit} \]

\[ \text{Signal} + \text{bg. fit} \]

\[ \text{Bg. only fit} \]

\[ \text{Entries per 10 MeV} \]

\[ \text{FWHM [MeV]} \]

\[ \text{Mass value [MeV]} \]

\[ \text{Events / (8 MeV)} \]

\[ M(\pi^+ + \pi^- p) \text{[GeV]} \]

\[ \text{Signal + bg. fit} \]

\[ \text{Bg. only fit} \]

\[ \text{Signal} + \text{bg. fit} \]

\[ \text{Bg. only fit} \]

\[ \Theta^0_c \quad \text{uudc} \]

\[ \Theta^+ \]

\[ \text{uudd}_c \]

\[ \Theta^0_c \quad \text{uudc} \]

\[ \Theta^+ \]

\[ \text{uudd}_c \]

\[ \Theta^0_c \quad \text{uudc} \]

\[ \Theta^+ \]

\[ \text{uudd}_c \]

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\[ \text{uudd}_c \]

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\[ \text{uudd}_c \]

\[ \Theta^0_c \quad \text{uudc} \]

\[ \Theta^+ \]

\[ \text{uudd}_c \]

\[ \Theta^0_c \quad \text{uudc} \]

\[ \Theta^+ \]

\[ \text{uudd}_c \]

\[ \Theta^0_c \quad \text{uudc} \]

\[ \Theta^+ \]

\[ \text{uudd}_c \]

\[ \Theta^0_c \quad \text{uudc} \]

\[ \Theta^+ \]

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\[ \Theta^+ \]

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\[ \Theta^0_c \quad \text{uudc} \]

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\[ \Theta^+ \]

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\[ \Theta^0_c \quad \text{uudc} \]

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\[ \Theta^+ \]

\[ \text{uudd}_c \]

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\[ \Theta^+ \]

\[ \text{uudd}_c \]

\[ \Theta^0_c \quad \text{uudc} \]

\[ \Theta^+ \]

\[ \text{uudd}_c \]
No $\Theta^+$ or $\Xi^{--}$ observed by HERA-B

Beyond the Standard Model searches at HERA

No $\Theta^+$ or $\Xi^{--}$ observed by HERA-B


No $\Theta^0_c$ peak observed in ZEUS data

2004 - 2005: No \( \Xi^{-} \) peak observed by HERMES


No \( \Xi^{-} \) peak observed by HERMES


No \( \Theta^{+} \) or \( \Xi^{-} \) observed by HERA-B


No \( \Theta^{0}_{c} \) peak observed in ZEUS data


Oleksii Turkot
Beyond the Standard Model searches at HERA
No $\Theta^+$ peak observed by Belle, later CLAS analysis and several other experiments.
2006 - 2016:

No $\Theta^+$ peak observed by Belle, later CLAS analysis and several other experiments

No $\Xi^{--}$ peak observed by H1

No $\Theta^+$ peak in H1 data

Oleksii Turkot

Beyond the Standard Model searches at HERA
2006 - 2016:

- No $\Theta^+$ peak observed by Belle, later CLAS analysis and several other experiments

- No $\Xi^{--}$ peak observed by H1

- No $\Theta^+$ peak in H1 data

- No $\Xi^{--}$ peak observed by ZEUS in HERA II data

- No $\Theta^+$ peak observed by ZEUS in HERA II data

- No $\Theta^+$ peak observed by H1 in H1 data

- Looser proton selection

- H1 data

- H1 data

- bgr fit

- $20 < Q^2 < 100 \text{ GeV}^2$

- $M(K_{SP}\pi)(\text{GeV})$

- $\sigma^\Theta_{ul}$

- 95 % C.L.
The prospect of hadrons with more than the minimal quark content (by the diagram in Fig. 1(b), that could result in resonant structures in the precise measurement of the distinctive signatures [10]. States would not be surprising. States that decay into charmonium may have particularly observed in be spurious [6], although there is at least one viable tetraquark candidate, the idea was expanded upon [4] proposed by Gell-Mann in 1964 [1] and Zweig [2], followed by a quantitative model for two large yields of

\[ \Lambda_b^0 \left\{ \begin{array}{c} b \\ u \\ c \\ d \\ u \\ c \\ u \\ d \end{array} \right\} P_c^+ \]

Discovery of the \( P^+_c \) (ccccud) pentaquark states at LHCb
Isolated Leptons

In case of events excess, some of the possible interpretations:

- Isolated high-\(P_T\) lepton, high \(P_T^{\text{miss}}\) and \(P_{T_X}\)
- Anomalous single-top production
- Stop production in the R-parity breaking SUSY
Isolated Leptons

Bin-to-bin combination of the data from H1 and ZEUS - 1 fb⁻¹ of data.

In total, 23 events with \( P_T^X > 25 \) GeV observed, \( 14.0 \pm 1.9 \) expected.
Multi-Leptons

Bin-to-bin combination of the data from H1 and ZEUS - 1 fb⁻¹ of data.

0 events with \( \sum P_T > 100 \text{ GeV} \) observed, 1.19 ± 0.12 expected.

7 events with \( \sum P_T > 100 \text{ GeV} \) observed, 1.94 ± 0.17 expected.

At least 2 high-\( P_T \) leptons

\[ \begin{align*}
\text{e}^+ & \rightarrow \gamma \rightarrow e^+ / \mu^+ / \tau^+ \\
\text{e}^- \text{p} & \rightarrow \Sigma P_T [\text{GeV}] \\
\text{e}^+ \text{p} & \rightarrow \Sigma P_T [\text{GeV}]
\end{align*} \]

JHEP 0910 (2009) 013
HERA inclusive DIS data combination

- 2927 data point combined to 1307
- up to 8 data points combined to 1
- impressive improvement of precision due to:
  - increased statistics
  - better understanding of systematics
  - cross-calibration of the data from two experiments

QCD analysis of the combined DIS data

Parton Density Functions

Parameterised at the starting scale of $Q_0^2 = 1.9$ GeV$^2$:

$$xg(x) = A_g x^{B_g} (1-x)^{C_g} - A_g' x^{B_g'} (1-x)^{C_g'}$$

$$xu_v(x) = A_{u_v} x^{B_{u_v}} (1-x)^{C_{u_v}} (1 + E_{u_v} x^2)$$

$$xd_v(x) = A_{d_v} x^{B_{d_v}} (1-x)^{C_{d_v}}$$

$$x\bar{U}(x) = A_{\bar{U}} x^{B_{\bar{U}}} (1-x)^{C_{\bar{U}}} (1 + D_{\bar{U}} x)$$

$$x\bar{D}(x) = A_{\bar{D}} x^{B_{\bar{D}}} (1-x)^{C_{\bar{D}}}$$

Evolve to any $Q^2 > Q_0^2$ with DGLAP.

BSM signal in the data could affect the PDF fit and result in biased PDFs.

This could affect all available high-precision PDFs (MMHT2014, NNPDF 3.0, etc.) - they all include HERA DIS data in the fit.

Proper procedure for a BSM analysis of the HERA data - global QCD analysis which includes a possible contribution from BSM processes.
Simultaneous PDF + $R_q$ analysis

Wide kinematic range of the HERA data allows determination of PDFs simultaneously with BSM searches.

For example - quark form-factor:

$$\frac{d\sigma}{dQ^2} = \frac{d\sigma^{SM}}{dQ^2} \times \left(1 - \frac{R_q^2}{6} Q^2\right)^2$$

Frequentist analysis - generate MC replicas and simultaneously fit PDFs and $R_q$:

$$\mu_i = [m_{i0}^2 + \delta_{i,stat}^2 + \delta_{i,uncor}^2 \cdot \mu_{i0}^2 \cdot r_i] \cdot \left(1 + \sum_j \gamma_j^i \cdot r_j\right)$$

Previous results:

- H1 (446 pb$^{-1}$): $R_q \leq 0.65 \cdot 10^{-16}$ cm
- ZEUS (128 pb$^{-1}$): $R_q \leq 0.85 \cdot 10^{-16}$ cm

Conclusions from simultaneous analysis

➤ BSM signal in the data affects the PDF fit and results in biased PDFs.

➤ Use of the biased PDFs in the BSM analysis results in overestimated limits.

Pseudodata generated for values of $R^2_q = R^2_q^{\text{True}}$

$R^2_q + \text{PDF fit}$

$R^2_q^{\text{only fit after SM PDF fit}}$

$\chi^2$

Pseudodata generated for value of $R^2_q = 0$

$R^2_q + \text{PDF } \chi^2 \text{ scan}$

$R^2_q^{\text{only } \chi^2 \text{ scan}}$

$R^2_q + \text{PDF procedure provides unbiased results of } R^2_q^{\text{Fit}}$

$R^2_q^{\text{only } \text{procedure results in too strong limits}}$
General contact interactions and leptoquarks

Low-energy effects due to physics at much higher energy scales can be described with the four-fermion contact interactions (CI):

\[ \mathcal{L}_{\text{CI}} = \sum_{k,j=L,R}^{u,d,s,c,b} \eta_{k,j}^{eq} (\bar{e}_k \gamma^\mu e_k)(\bar{q}_j \gamma_\mu q_j) \]

All up- or down-type quarks were assumed to have the same contact-interaction couplings:

\[ \eta_{k,j}^{eq} = \epsilon_{k,j} \frac{g^2}{\Lambda^2} \]

\[ \epsilon_{k,j}^{eq} = \pm 1; 0 \]

In the limit of heavy leptoquarks (\(M_{LQ} \gg \sqrt{s}\)), the effect of \(s\)- and \(t\)-channel LQ exchange is equivalent to a vector-type \(eeqq\) CI with the coupling of:

\[ \eta_{k,j}^{eq} = a_{k,j} \left( \frac{\lambda_{LQ}}{M_{LQ}} \right)^2 \]

ZEUS

Data \(\eta^1\) vs Fit \(\eta^1\) Prob(

95\% CL limit

Prob(\(\eta^{\text{fit}}<\eta^{\text{Data}}\))

Prob(\(\eta^{\text{fit}}<\eta^{\text{SM}}\))

Prob(\(\eta^{\text{fit}}<\eta^{\text{SM}}\))

Z_0 \text{ model}

2 Data \(\eta^1\) vs Fit \(\eta^1\) Prob(\(\eta^{\text{fit}}<\eta^{\text{Data}}\))

95\% CL limit

Prob(\(\eta^{\text{fit}}<\eta^{\text{Data}}\))

Prob(\(\eta^{\text{fit}}<\eta^{\text{SM}}\))
### General contact interactions

<table>
<thead>
<tr>
<th>Coupling structure</th>
<th>$p_{SM}$ (%)</th>
<th>$\Lambda^-$</th>
<th>$\Lambda^+$</th>
<th>$\Lambda^-$</th>
<th>$\Lambda^+$</th>
<th>$\Lambda^-$</th>
<th>$\Lambda^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>LL</strong></td>
<td>7.0</td>
<td>12.8</td>
<td>4.5</td>
<td>5.9</td>
<td>6.3</td>
<td>4.0</td>
<td>4.2</td>
</tr>
<tr>
<td><strong>RR</strong></td>
<td>5.9</td>
<td>14.7</td>
<td>4.4</td>
<td>5.7</td>
<td>6.1</td>
<td>3.9</td>
<td>4.4</td>
</tr>
<tr>
<td><strong>LR</strong></td>
<td>34</td>
<td>4.7</td>
<td>5.5</td>
<td>5.7</td>
<td>6.3</td>
<td>3.7</td>
<td>4.8</td>
</tr>
<tr>
<td><strong>RL</strong></td>
<td>42</td>
<td>5.0</td>
<td>5.3</td>
<td>5.6</td>
<td>6.5</td>
<td>3.8</td>
<td>4.8</td>
</tr>
<tr>
<td><strong>VV</strong></td>
<td>25</td>
<td>13.9</td>
<td>9.0</td>
<td>11.2</td>
<td>11.4</td>
<td>7.2</td>
<td>5.6</td>
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<tr>
<td><strong>AA</strong></td>
<td>0.6</td>
<td>15.7</td>
<td>4.2</td>
<td>7.9</td>
<td>7.8</td>
<td>5.1</td>
<td>4.4</td>
</tr>
<tr>
<td><strong>VA</strong></td>
<td>2.5 (5.8)</td>
<td>3.6</td>
<td>3.5</td>
<td>4.2</td>
<td>4.2</td>
<td>3.6</td>
<td>3.8</td>
</tr>
<tr>
<td><strong>X1</strong></td>
<td>0.4</td>
<td>–</td>
<td>3.2</td>
<td>5.4</td>
<td>5.5</td>
<td>3.6</td>
<td>2.6</td>
</tr>
<tr>
<td><strong>X2</strong></td>
<td>24</td>
<td>10.4</td>
<td>6.4</td>
<td>7.8</td>
<td>8.3</td>
<td>3.9</td>
<td>4.0</td>
</tr>
<tr>
<td><strong>X3</strong></td>
<td>7.3</td>
<td>17.9</td>
<td>6.2</td>
<td>8.3</td>
<td>8.7</td>
<td>5.1</td>
<td>5.3</td>
</tr>
<tr>
<td><strong>X4</strong></td>
<td>39</td>
<td>7.2</td>
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<td>8.0</td>
<td>8.6</td>
<td>4.8</td>
<td>5.4</td>
</tr>
<tr>
<td><strong>X5</strong></td>
<td>27</td>
<td>9.5</td>
<td>6.4</td>
<td>7.7</td>
<td>7.7</td>
<td>4.0</td>
<td>4.0</td>
</tr>
<tr>
<td><strong>X6</strong></td>
<td>0.3</td>
<td>3.1</td>
<td>–</td>
<td>5.3</td>
<td>5.5</td>
<td>2.5</td>
<td>3.5</td>
</tr>
</tbody>
</table>

For AA, VA, X1 and X6 models QCD+CI fits provide improved description of the data, with up to 2.7$\sigma$ difference.
# Leptoquarks

95% C.L. $\lambda_{LQ}/M_{LQ}$ upper limits (TeV$^{-1}$)

<table>
<thead>
<tr>
<th>Model</th>
<th>Coupling structure</th>
<th>$\hat{\rho}_{SM}$ (%)</th>
<th>H1 + ZEUS data (1 fb$^{-1}$)</th>
<th>H1(446 pb$^{-1}$)</th>
<th>ZEUS (128 pb$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_{0}^{L}$</td>
<td>$\alpha_{LL}^{e} = +\frac{1}{2}$</td>
<td>9.0</td>
<td>0.28</td>
<td>0.56</td>
<td>0.91</td>
</tr>
<tr>
<td>$S_{0}^{R}$</td>
<td>$\alpha_{RR}^{e} = +\frac{1}{2}$</td>
<td>5.5</td>
<td>1.03</td>
<td>0.72</td>
<td>0.91</td>
</tr>
<tr>
<td>$\overline{S}_{0}^{L}$</td>
<td>$\alpha_{LR}^{e} = +\frac{1}{2}$</td>
<td>1.8</td>
<td>-</td>
<td>1.71</td>
<td>2.44</td>
</tr>
<tr>
<td>$S_{\frac{1}{2}}^{L}$</td>
<td>$\alpha_{LR}^{e} = -\frac{1}{2}$</td>
<td>43</td>
<td>0.83</td>
<td>0.76</td>
<td>1.15</td>
</tr>
<tr>
<td>$S_{\frac{1}{2}}^{R}$</td>
<td>$\alpha_{RL}^{e} = \alpha_{RL}^{a} = -\frac{1}{2}$</td>
<td>39</td>
<td>1.04</td>
<td>0.92</td>
<td>1.69</td>
</tr>
<tr>
<td>$\overline{S}_{\frac{1}{2}}^{L}$</td>
<td>$\alpha_{RL}^{e} = -\frac{1}{2}$</td>
<td>38</td>
<td>1.66</td>
<td>1.39</td>
<td>1.52</td>
</tr>
<tr>
<td>$S_{1}^{L}$</td>
<td>$\alpha_{LL}^{e} = +1, \alpha_{LL}^{a} = +\frac{1}{2}$</td>
<td>$&lt;0.01$</td>
<td>1.18</td>
<td>0.62</td>
<td>1.41</td>
</tr>
<tr>
<td>$V_{0}^{L}$</td>
<td>$\alpha_{LL}^{e} = -1$</td>
<td>0.5</td>
<td>-</td>
<td>0.44</td>
<td>0.94</td>
</tr>
<tr>
<td>$V_{0}^{R}$</td>
<td>$\alpha_{RR}^{e} = -1$</td>
<td>1.8</td>
<td>1.47</td>
<td>0.99</td>
<td>1.10</td>
</tr>
<tr>
<td>$\overline{V}_{0}^{L}$</td>
<td>$\alpha_{RR}^{e} = -1$</td>
<td>5.5</td>
<td>0.18</td>
<td>0.53</td>
<td>0.74</td>
</tr>
<tr>
<td>$V_{\frac{1}{2}}^{L}$</td>
<td>$\alpha_{LR}^{e} = +1$</td>
<td>38</td>
<td>1.19</td>
<td>1.29</td>
<td>1.96</td>
</tr>
<tr>
<td>$V_{\frac{1}{2}}^{R}$</td>
<td>$\alpha_{RL}^{e} = \alpha_{RL}^{a} = +1$</td>
<td>39</td>
<td>0.67</td>
<td>0.57</td>
<td>0.69</td>
</tr>
<tr>
<td>$\overline{V}_{\frac{1}{2}}^{L}$</td>
<td>$\alpha_{RL}^{e} = +1$</td>
<td>43</td>
<td>0.59</td>
<td>0.49</td>
<td>0.63</td>
</tr>
<tr>
<td>$V_{1}^{L}$</td>
<td>$\alpha_{LL}^{e} = -1, \alpha_{LL}^{a} = -2$</td>
<td>32</td>
<td>0.41</td>
<td>0.25</td>
<td>0.54</td>
</tr>
</tbody>
</table>

For $S_{1}^{L}$ and $V_{0}^{R}$ models the difference from SM predictions is about $4\sigma$ and $2\sigma$, respectively.
BSM weak couplings

\[ g_A = \sqrt{\rho_{NC,q}^I \rho_{NC,q}^I} I_{L,q}^3 \]

\[ g_V = \sqrt{\rho_{NC,q}^I \rho_{NC,q}^I (I_{L,q}^3 - 2Q_q \kappa_{NC,q} \sin^2 \theta_W)} \]
Scale dependance of $\rho'_{NC}$, $\kappa'_{NC}$ and $\rho'_{CC}$

For the first time the scale dependence of $\rho'_{NC}$, $\kappa'_{NC}$ and $\rho'_{CC}$ has been studied:

No significant deviation from the SM expectation is observed

Summary

- Experiments at HERA have a rich history of BSM searches.

- Standard Model provides a good description of the HERA data, though some interesting effects are seen and studied.

- Wide kinematic range of the HERA data provides an unique opportunity to perform the simultaneous BSM and PDF analyses.