QCD and hadronic final states at HERA

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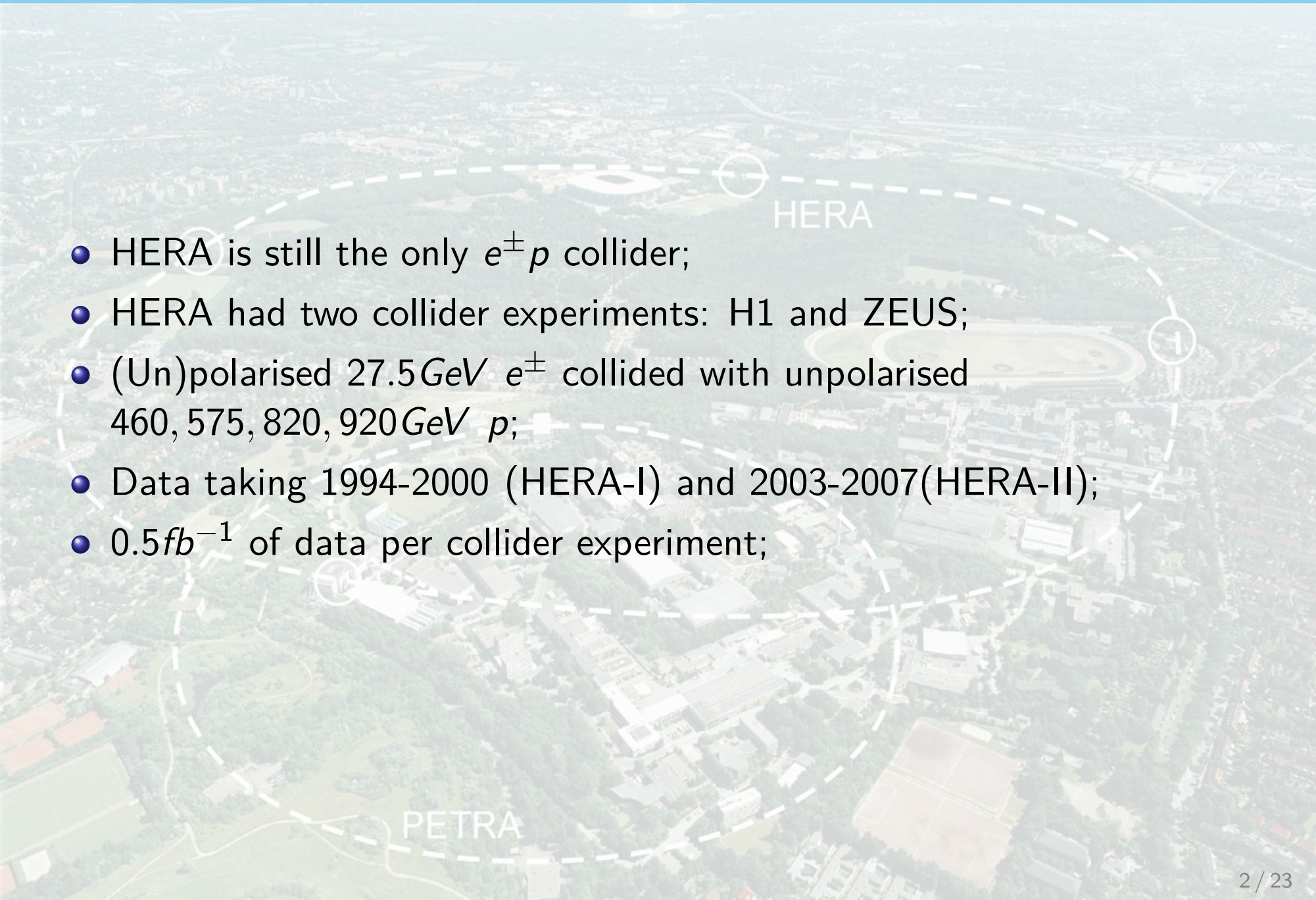
HERA, H1 and ZEUS

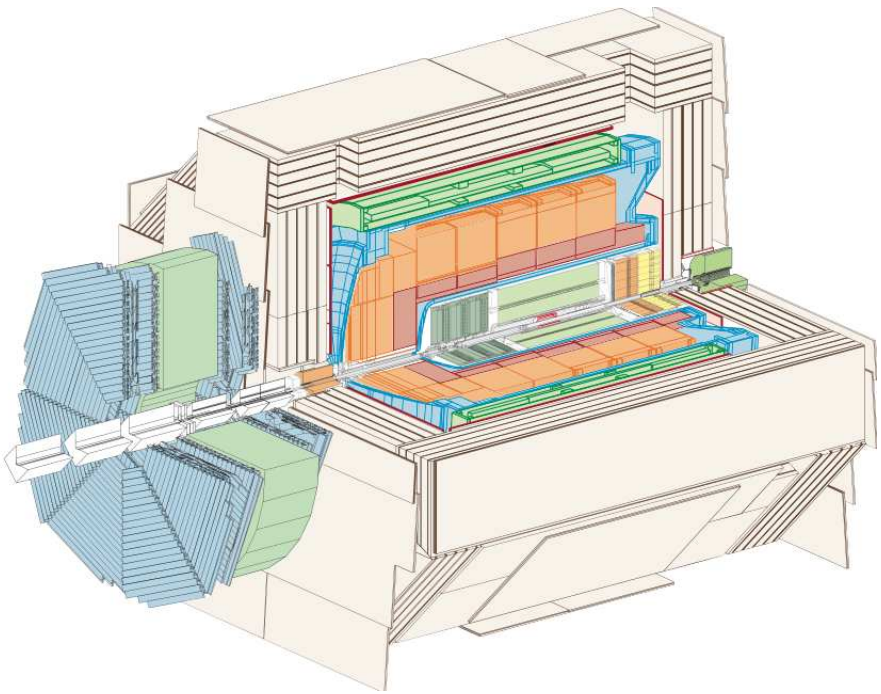


- HERA is still the only $e^{\pm}p$ collider;
- HERA had two collider experiments: H1 and ZEUS;
- (Un)polarised $27.5 GeV$ $e^{\pm}$ collided with unpolarised $460, 575, 820, 920 GeV$ p;
- Data taking 1994-2000 (HERA-I) and 2003-2007(HERA-II);
- $0.5 fb^{-1}$ of data per collider experiment;

H1 and ZEUS

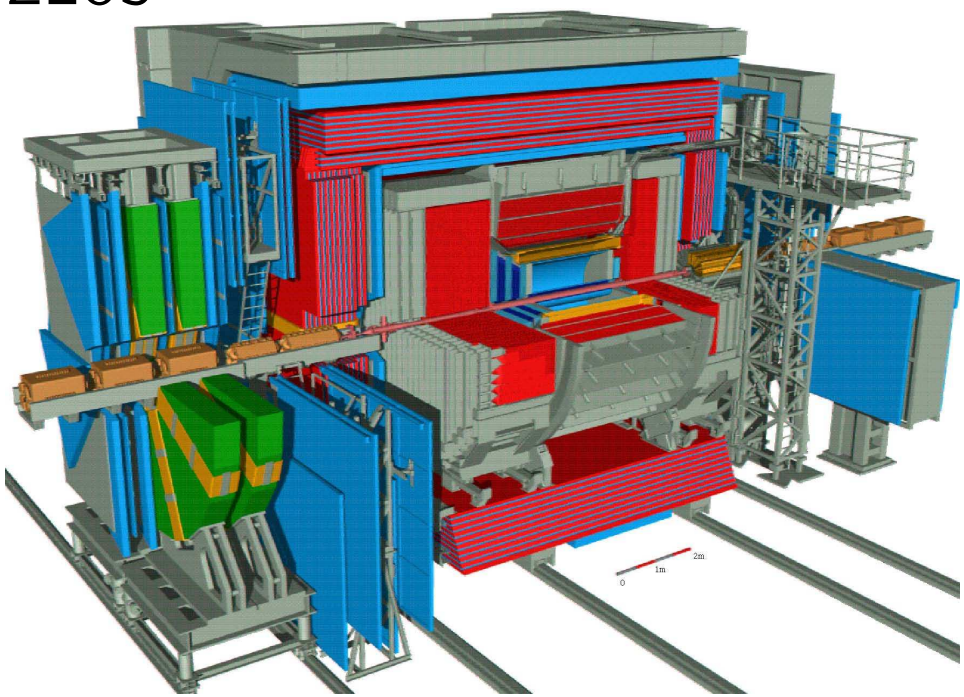
- (Un)polarised $e^{\pm}$ are collided with unpolarized protons;
- Almost 4π solid angle coverage, asymmetric design, muon detection systems, precise tracking;

H1



- Liquid argon sampling and scintillating fiber calorimeters.

ZEUS



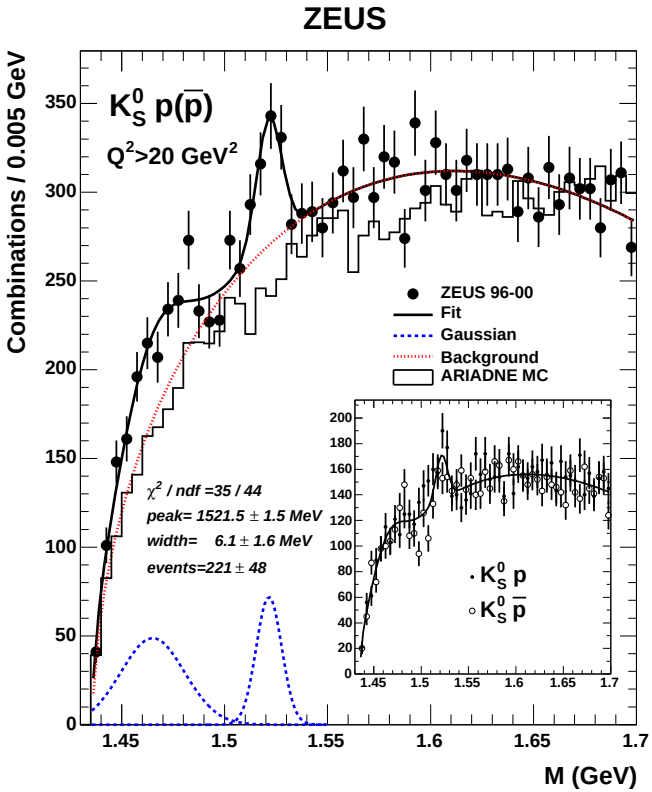
- High resolution compensating uranium-scintillator calorimeter.

Topics

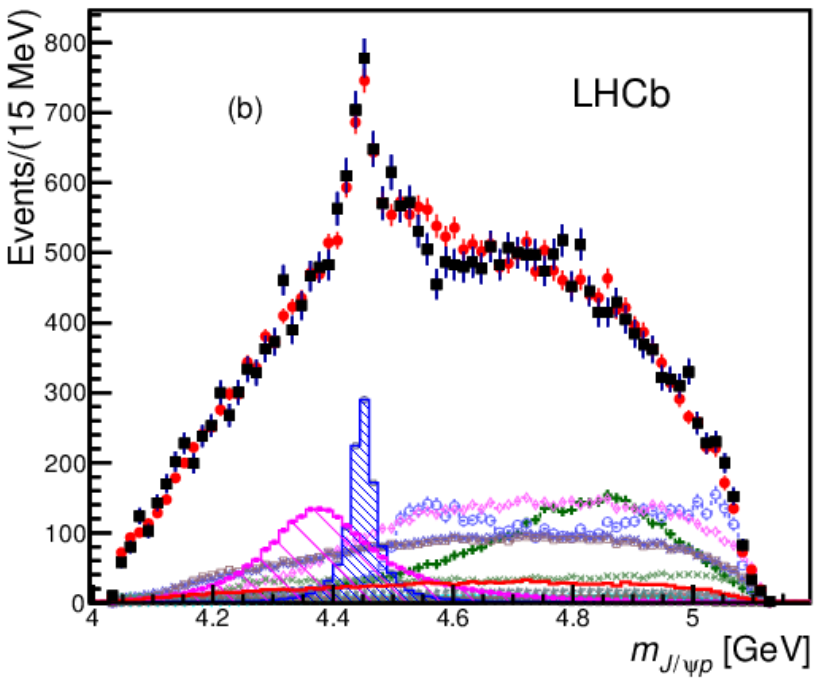
- Search for a narrow baryonic state decaying to pK_S^0 and $\bar{p}K_S^0$ in deep inelastic scattering at HERA
- Search for QCD instanton-induced processes at HERA in the high-Q^2 domain
- Further measurements of isolated photons accompanied by jets in deep inelastic ep scattering
- Measurement of multijet production in $e^{\pm}p$ collisions at low Q^2 at HERA

Search for a narrow baryonic state decaying to pK_S^0 and $\bar{p}K_S^0$ in deep inelastic scattering at HERA

A candidate for a $uudd\bar{s}$ state Θ^+ was observed at HERA-I in $M(pK_S^0)$ spectrum,
Phys. Lett. B **591** (2004) 7

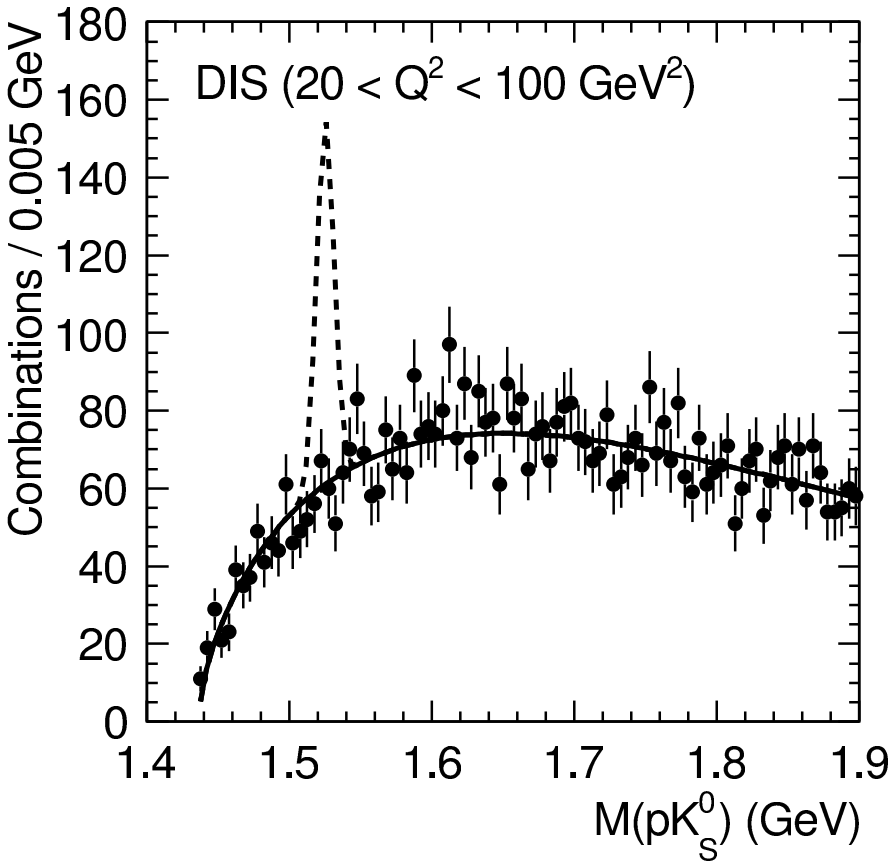


The recent observation of LHCb can be considered as a strong evidence of existence of $5q$ states,
Phys. Rev. Lett. **115** (2015) 072001.



A clear motivation to look for the Θ^+ signal in HERA-II data.

Search for a narrow baryonic state decaying to pK^0_S and $\bar{p}K^0_S$ in deep inelastic scattering at HERA



Data(dots), fit(solid line) and simulated signal(dashed line).

Deep-inelastic scattering (DIS) and photoproduction samples from HERA-II are analysed.

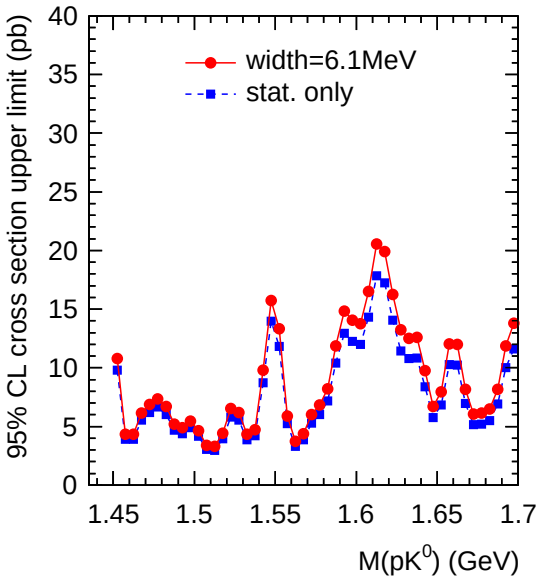
- dE/dx cuts to select high purity sample of p;
- Reconstruction of K^0 with high purity;
- The $\Lambda_c^+(2286) \to pK^0$ as a check;
- Search for $\Theta^+ \to pK^0$ signal.

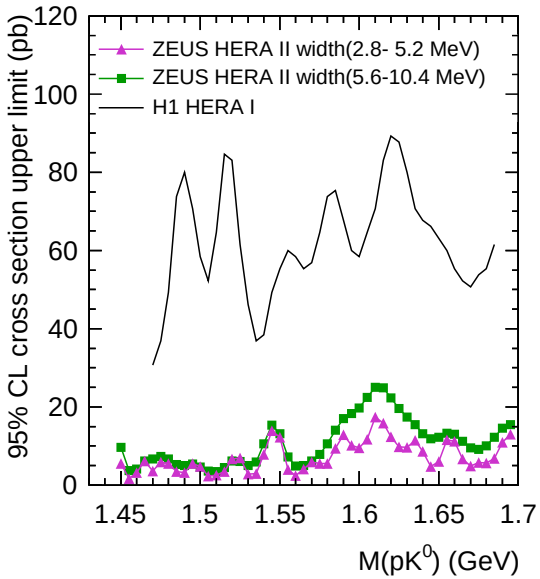
Search for a narrow baryonic state decaying to pK_S^0 and $\bar{p}K_S^0$ in deep inelastic scattering at HERA

As no clear signal is seen, the limits on the production cross-section of $\Theta^{\pm}$ is set.

- $\mathcal{B}(\Theta \to pK_S^0) = 1$ is assumed;
- Different widths hypotheses are tested;
- Results are compared with H1.

ZEUS

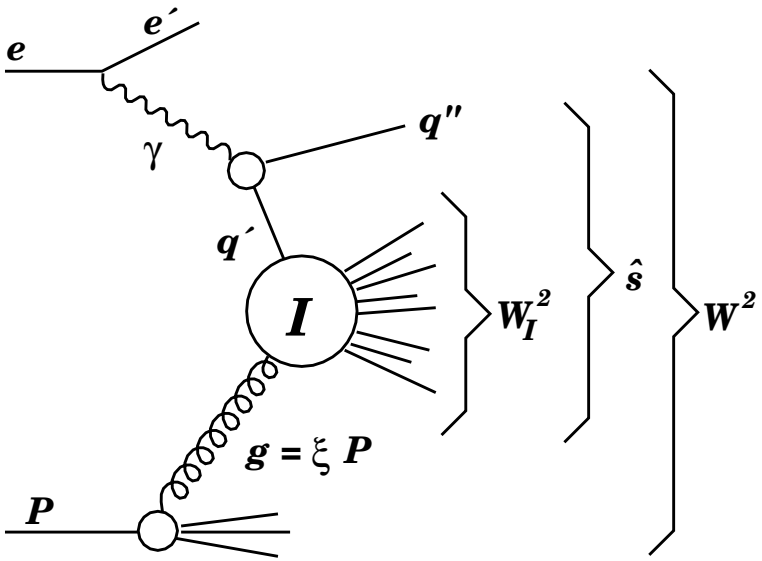




The search contributes to the $5q$ state puzzle.

Accepted by Phys. Lett. B.

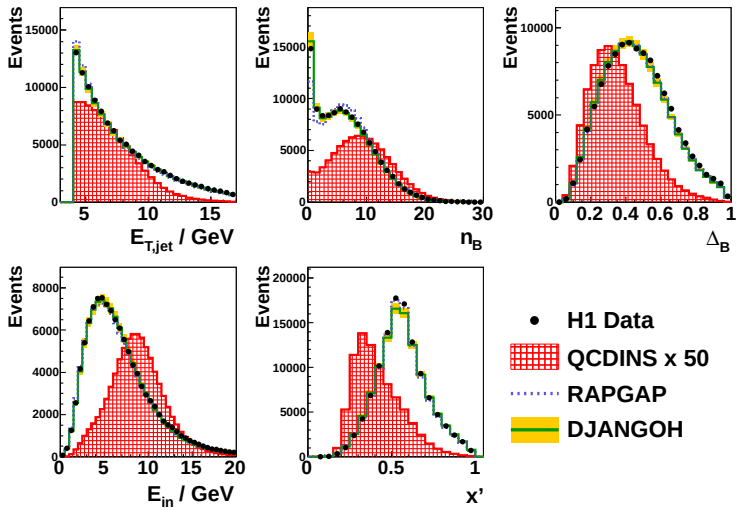
Search for QCD instanton-induced processes at HERA in the high-Q^2 domain

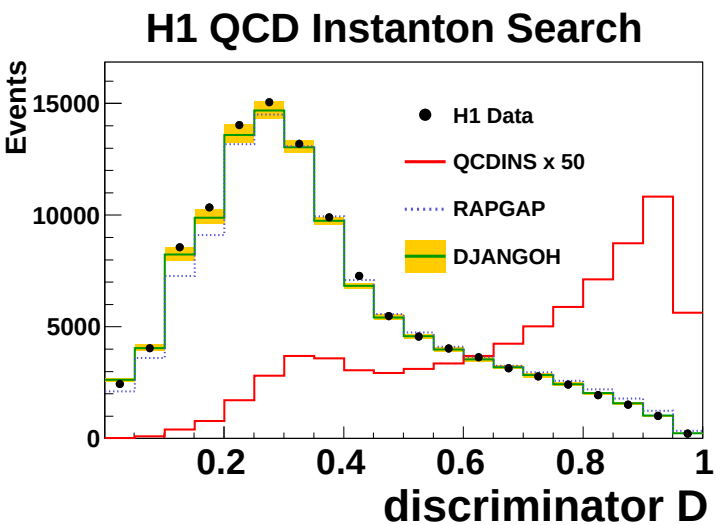


Instantons induce processes with violating conservation of baryon and lepton numbers.
A. Ringwald and F. Schrempp [hep-ph/9411217].
Expected signatures at HERA:

- Hard jet;
- Densely populated narrow band in η, isotropic in ϕ;
- Isotropy in instanton rest frame;
- High charged particles multiplicity;
- Large total transverse energy.

Search for QCD instanton-induced processes at HERA in the high-Q^2 domain

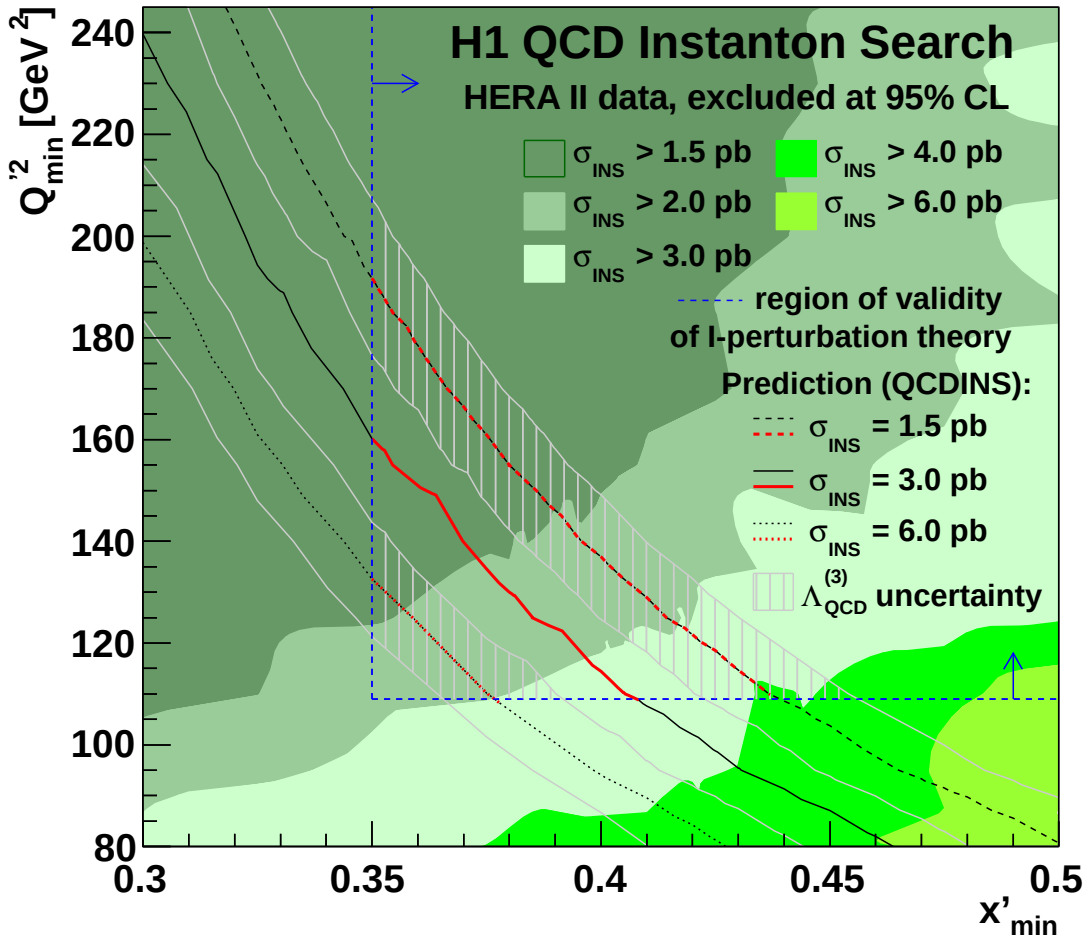




- DIS events with hard jets are selected;
- Constituents of hard jets are removed from the event;
- The rest within $|\eta_{jet} - \eta| < 1.1$ is considered as an instanton candidate;
- Instanton observables are calculated and used to discriminate the signal:
  - E_T^{jet};
  - number of charged particles;
  - "Event shape" like observables (Fox-Wolfram moments).

MWA with training on QCDINS Monte Carlo results in the discriminator D.

Search for QCD instanton-induced processes at HERA in the high-Q^2 domain



Theory predicts $\sigma \approx 10 \pm 3pb$ with an uncertainty coming from Λ_{QCD}. As no clear signal is seen, the upper limit on the instanton cross-section at 95% C.L. is set.

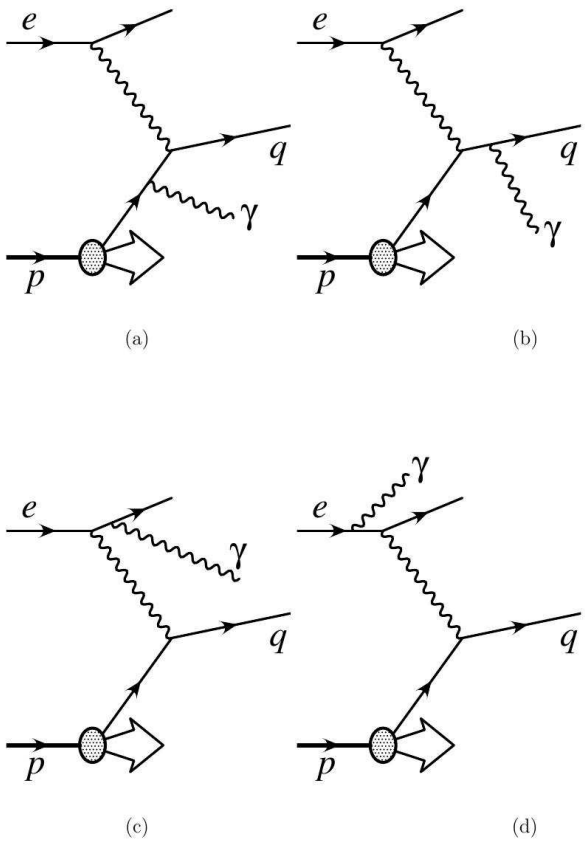
Here:

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

$x' \equiv Q'^2 \; / \; (2\, g \cdot q')$

Exploration of fundamental properties of QCD.
Submitted to Eur.Phys.J.C, arXiv:1603.05567 [hep-ex].

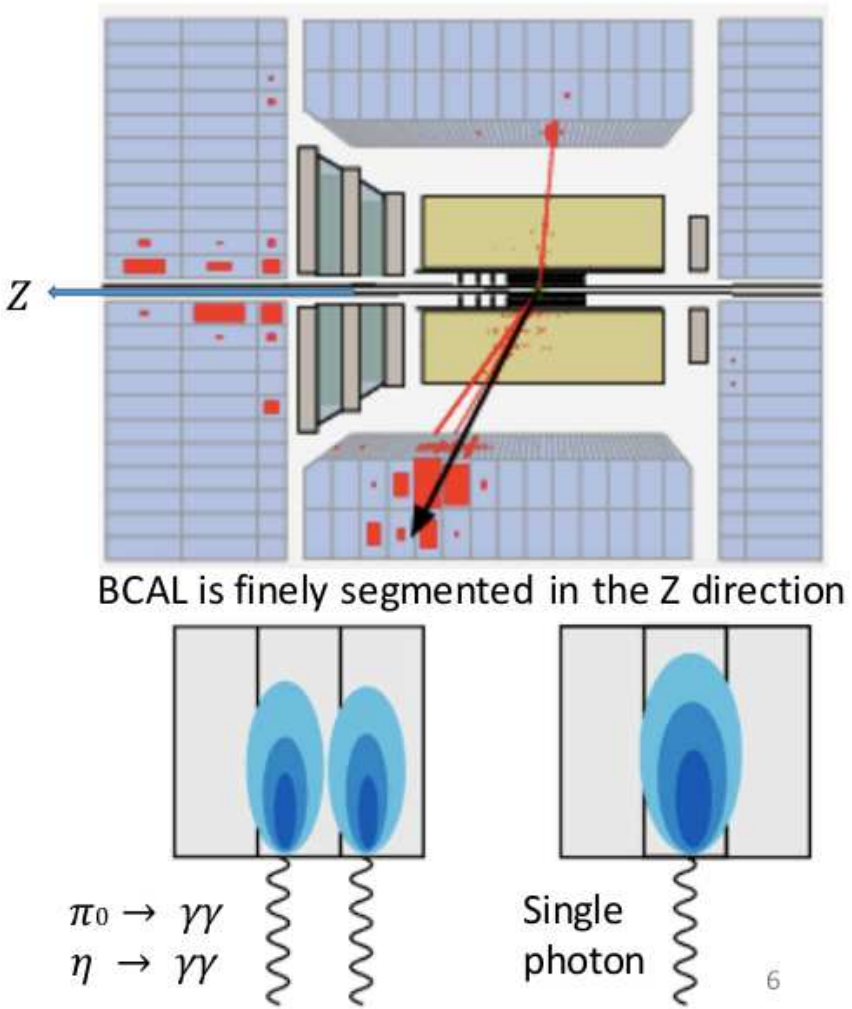
Further measurements of isolated photons accompanied by jets in deep inelastic $e^{\pm}p$ scattering



Isolated (prompt) photons:

- Produced in the hard process.
- From **quarks (QQ photons)** and leptons (LL photons), interference (LQ photons) is negligible.
- Produced photons are largely insensitive to the effects of final-state hadronization.
- Provides an access to the on the structure of the proton.

Further measurements of isolated photons accompanied by jets in deep inelastic $e^{\pm}p$ scattering



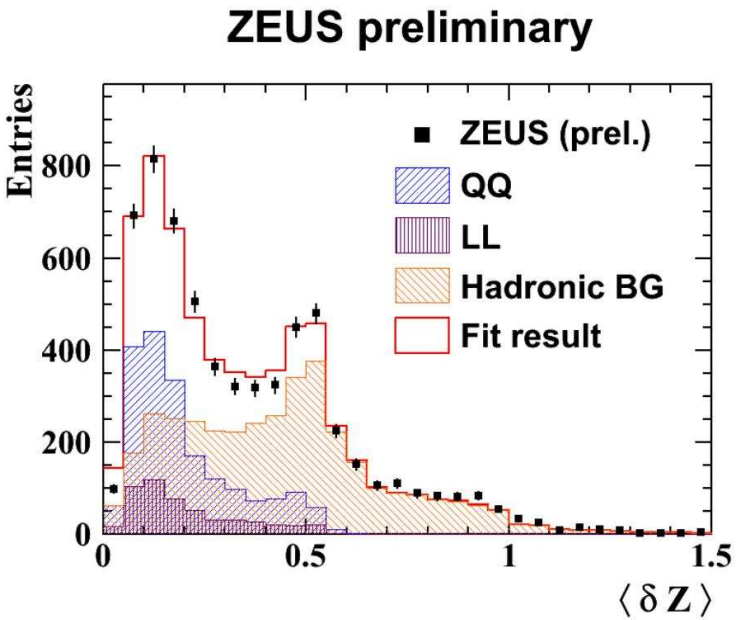
- DIS selection with electron.
- $10 < Q^2 < 350\,GeV^2$
- $4 < E_T^{\gamma} < 15\,GeV$
- $-0.7 < \eta^{\gamma} < 0.9$
- $2.5\,GeV < E_T^{jet}$
- $-1.5 < \eta^{jet} < 1.8$

Dominant BG from π^0 can be rejected with an analysis of EMC cluster shapes.

Further measurements of isolated photons accompanied by jets in deep inelastic $e^{\pm}p$ scattering

Cross-sections from fraction fit: $\frac{d\sigma}{dY} = \frac{N(QQ)}{A_{QQ} \cdot \mathcal{L} \cdot \Delta Y} + \frac{d\sigma_{LL}^{MC}}{dY}$ with discriminator $\langle \delta Z \rangle = \frac{\sum_i |z_i - z_{cluster}| E_i}{width\ of\ cell \cdot \sum_i E_i}$ using $\frac{d\sigma_{LL}^{MC}}{dY}$ from Monte Carlo.

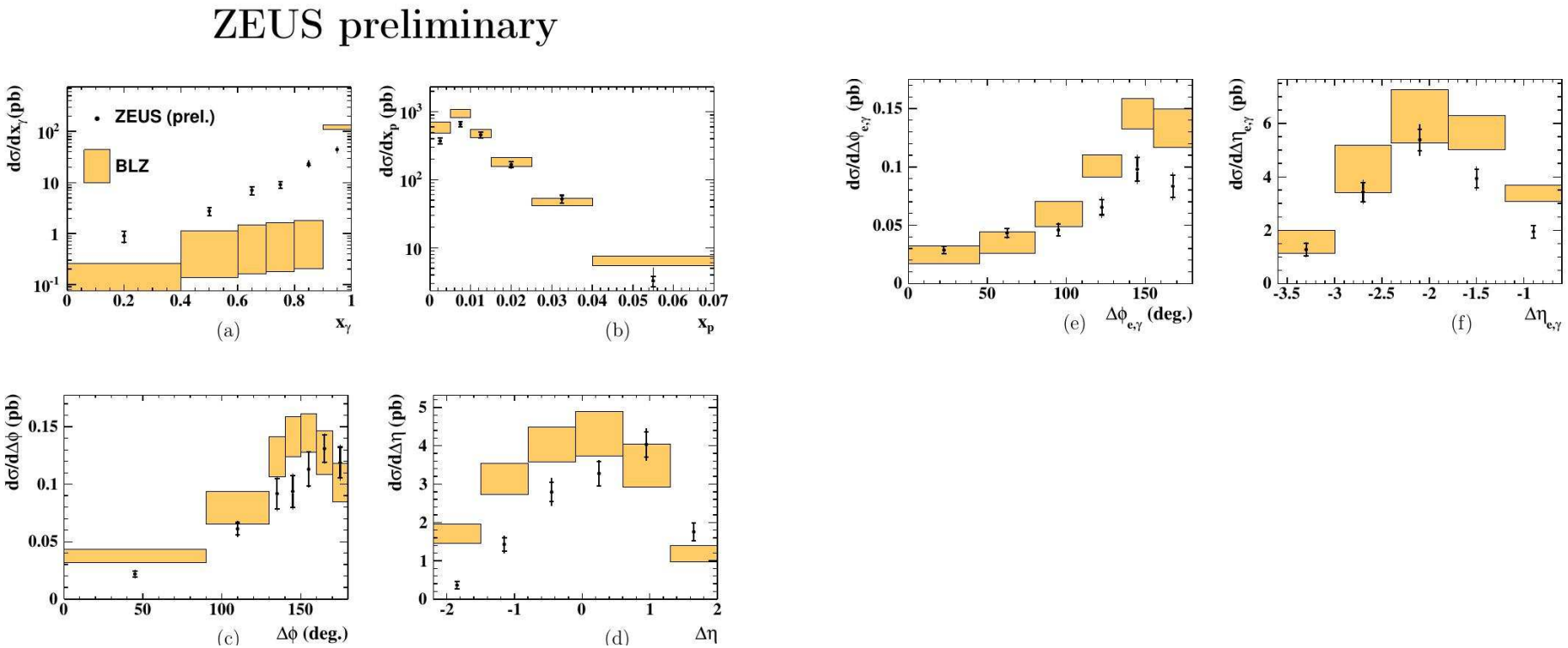
Phys. Lett. B **715** (2012) 88 covered Q^2, η_{jet}, η_γ, ϕ_{jet}, ϕ_γ.



Theoretical studies in progress, for the better understanding, in this analysis:

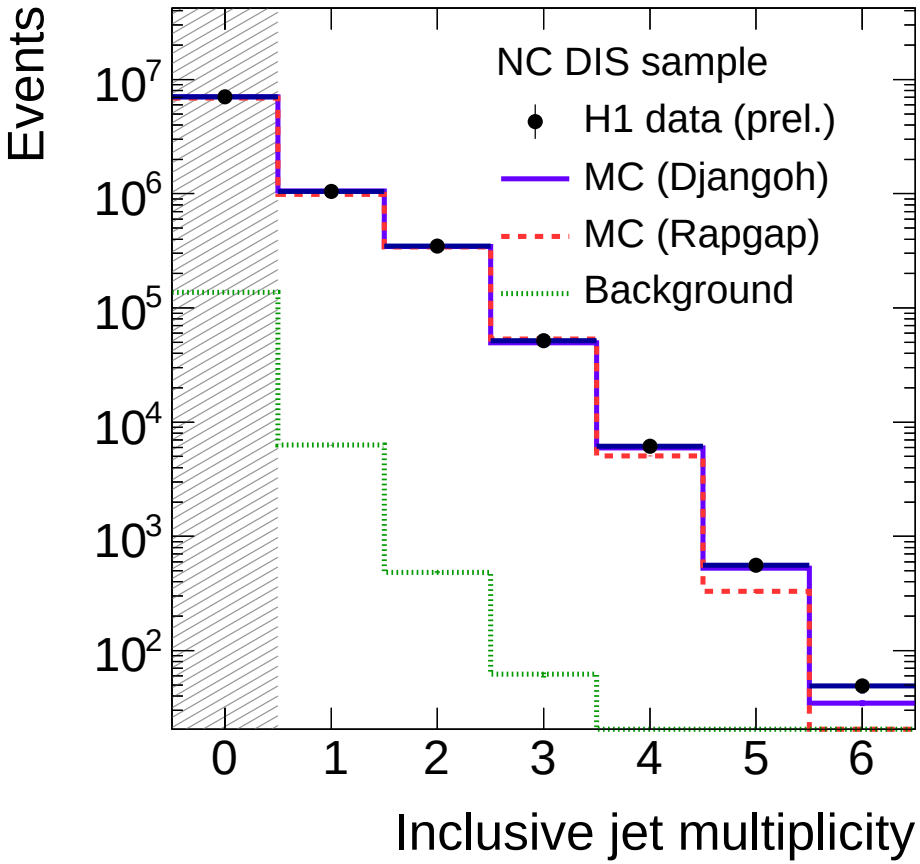
- $\Delta\eta = \eta_{jet} - \eta_\gamma$; $\Delta\phi = \phi_{jet} - \phi_\gamma$;
- $\Delta\eta_{e,\gamma} = \eta_e - \eta_\gamma$; $\Delta\phi_{e,\gamma} = \phi_e - \phi_\gamma$;
- $x_\gamma = \frac{\Sigma_{jet,\gamma}(E - p_z)}{2 y_{JB} E_e}$; $x_p = \frac{\Sigma_{jet,\gamma}(E - p_z)}{2 E_p}$.

Further measurements of isolated photons accompanied by jets in deep inelastic $e^{\pm}p$ scattering



- Compared to BLZ model: Phys. Rev. D **81** (2010) 094034;
- Test of recent theoretical models (Eur. Phys. J. C **75** (2015) no.2, 64) with direct, resolved and fragmentation.

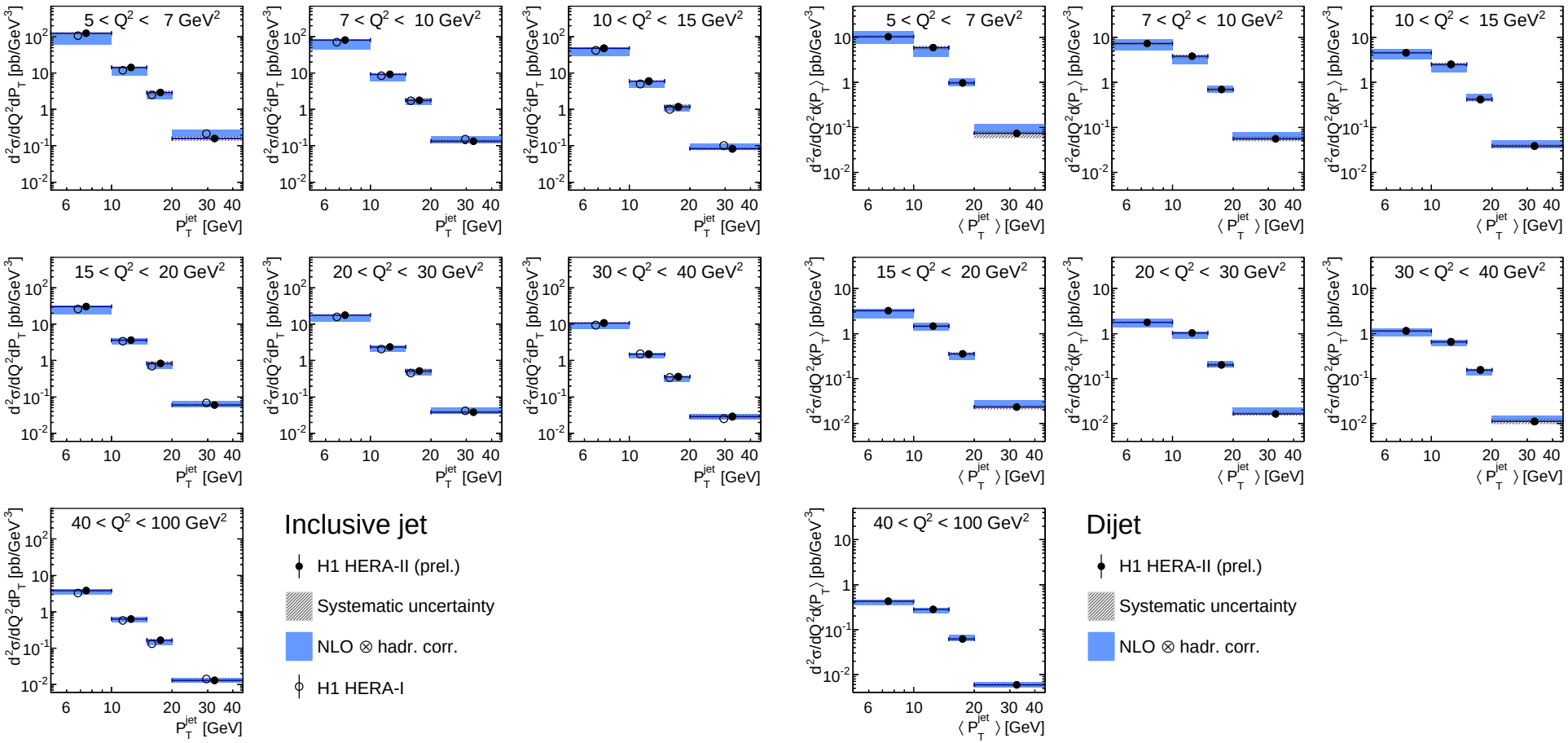
Further contribution to an important topic that can be studied on HERA with a good precision.
Preliminary, ZEUS-prel-16-001



- Jets is a nice way to study QCD;
- Studied inclusive, 2- and 3- k_T jets;
- $5 < Q^2 < 100 GeV^2$, $0.2 < y < 0.65$;
- Studied jet production in the bins of average P_T of leading jet(s).

Clear motivation to study QCD and get α_s

Measurement of multijet production in $e^{\pm}p$ collisions at low Q^2 at HERA



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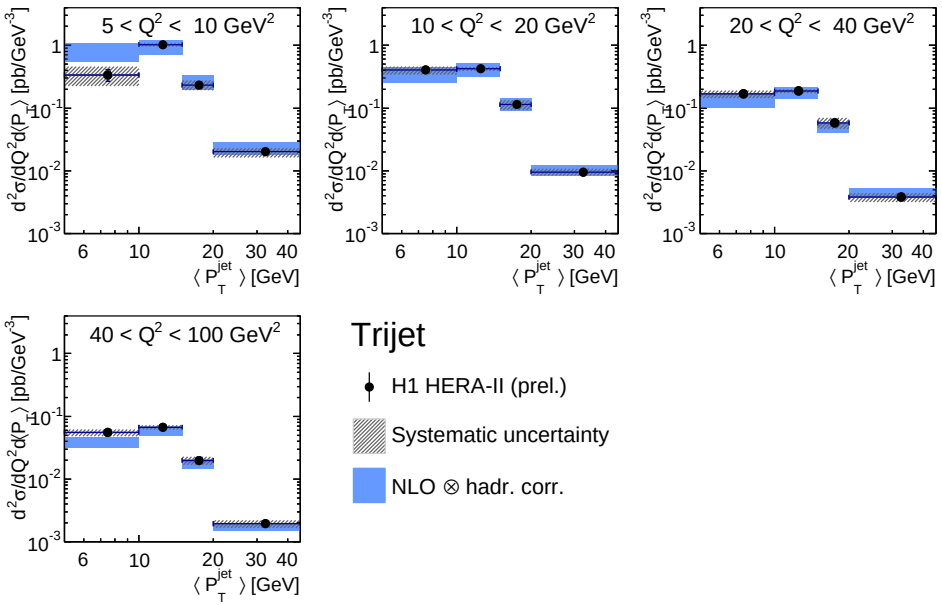
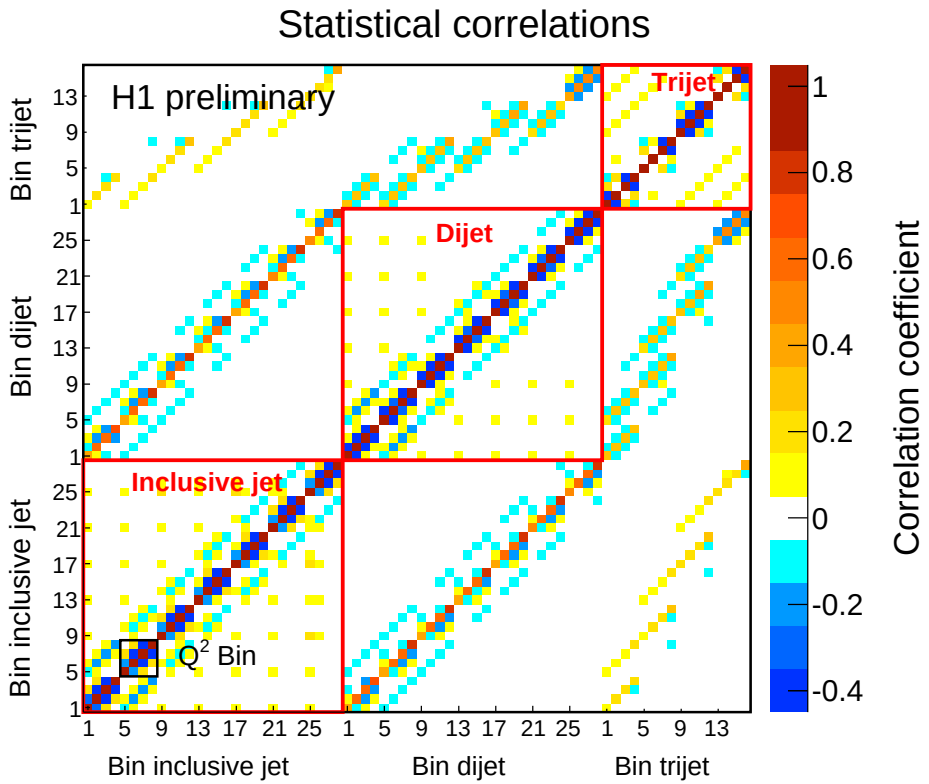




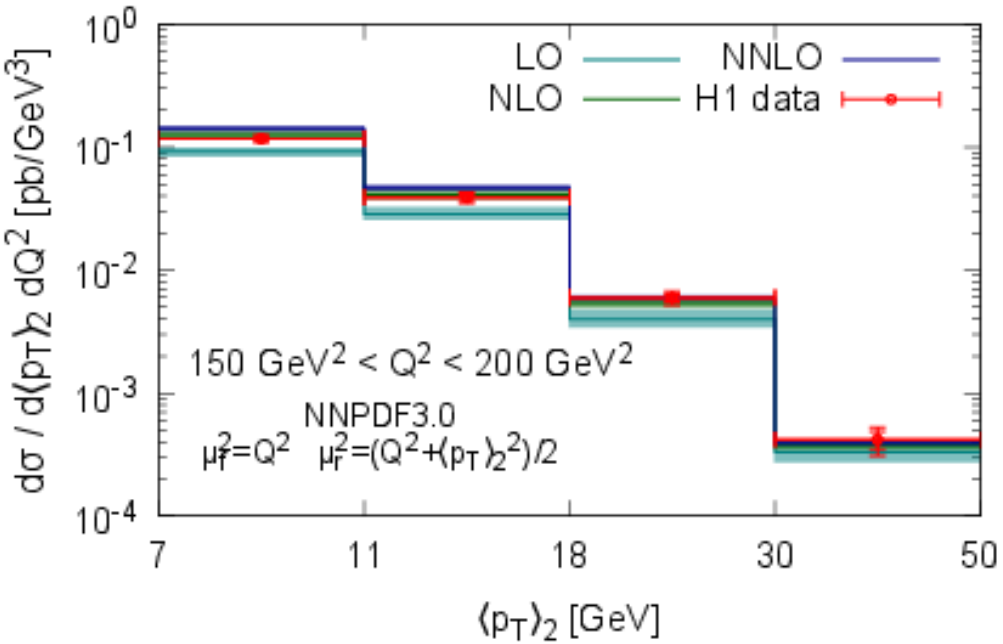
The cross-sections are obtained with regularised unfolding, deriving the **full correlation matrix for the results**.

The results, together with other HERA measurements, can be used for the first α_s extraction at NNLO (2-jets) in DIS.

Dijet predictions:

- aNNLO T. Biekötter, M. Klasen and G. Kramer, Phys. Rev. D **92** (2015) no.7, 074037
- NNLO J. Currie, T. Gehrmann and J. Niehues, arXiv:1606.03991 [hep-ph].

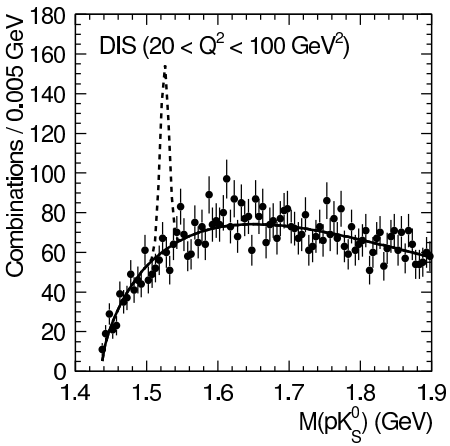
NLO vs. Eur. Phys. J. C **67** (2010) 1.

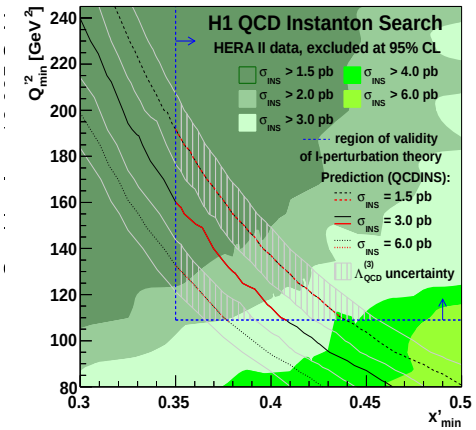


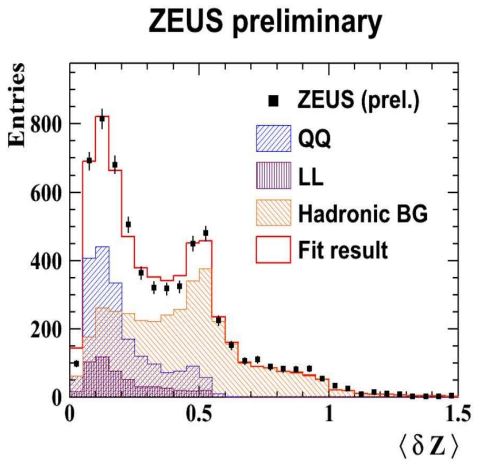
Extremely valuable input for the α_s extraction in DIS.
Preliminary, H1prelim-16-061

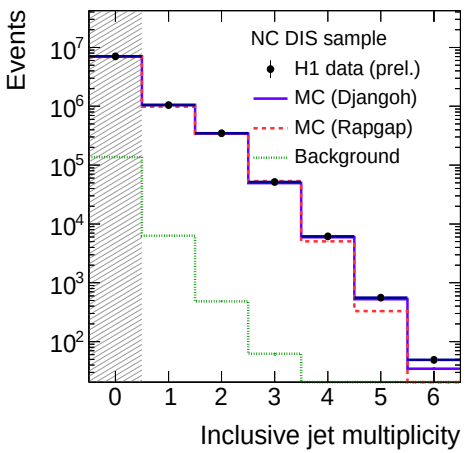
Summary

- Nine years after the end of data taking, HERA experiments continue to deliver innovative, valuable physics results;
- Some of these will remain the only source for the tests of state-of-the-art theoretical predictions for a long time;









Pentaquarks: no signal of Θ^+.

Instantons: no signal of R.S. instanton.

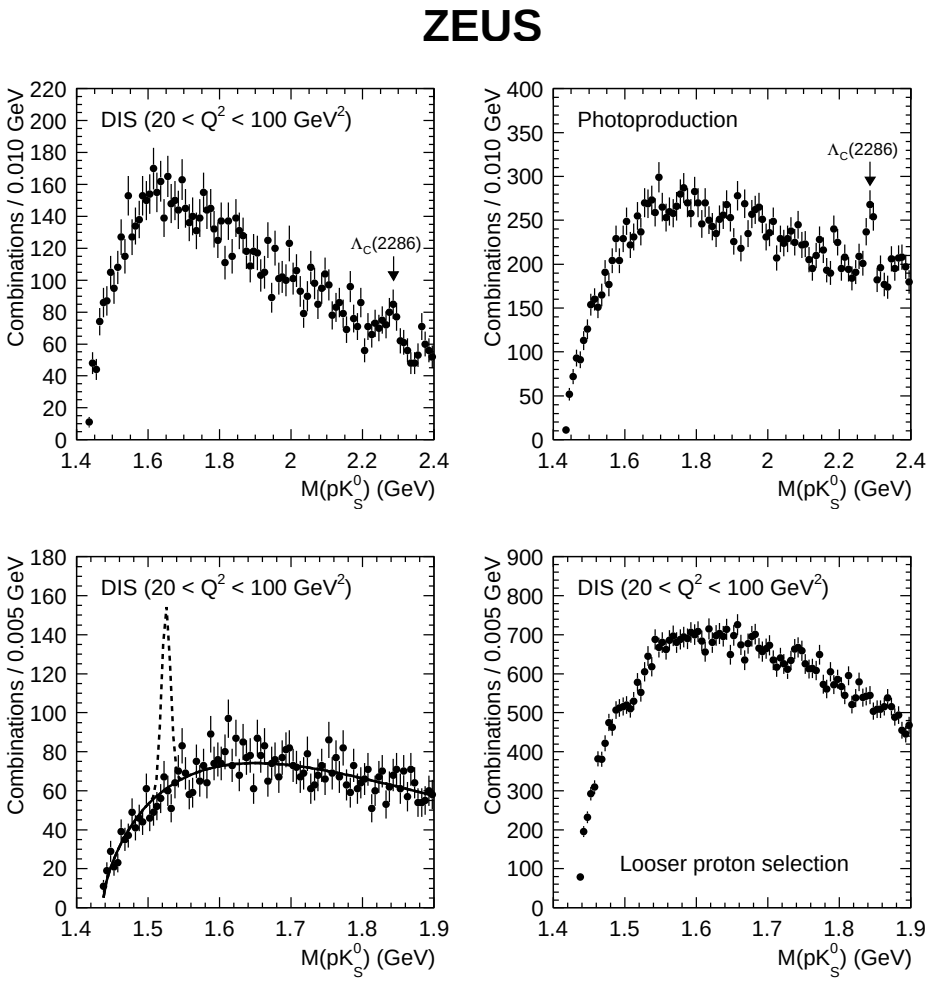
Prompt photons: better understanding.

Precise jets: input for the precise QCD.

- H1 and ZEUS are active. More results will come.

BACKUPS

Search for a narrow baryonic state decaying to pK^0_S and $\bar{p}K^0_S$ in deep inelastic scattering at HERA



Deep-inelastic scattering (DIS) and photoproduction samples from HERA-II are analysed.

- dE/dx cuts to select high purity sample of p;
- Reconstruction of K^0 with high purity;
- The $\Lambda_c^+(2286) \to pK^0$ as a check;
- Search for $\Theta^+ \to pK^0$ signal.

Instanton variables

NC DIS variables:

$s = (e + P)^2$

$Q^2 = -\gamma^2 = -(e - e')^2$

$x = Q^2 / (2P \cdot \gamma)$

$y = Q^2 / (s\, x)$

$W^2 = (\gamma + P)^2 = Q^2(1 - x)/x$

$\hat{s} = (\gamma + g)^2$

$\xi = x\,(1 + \hat{s}/Q^2)$

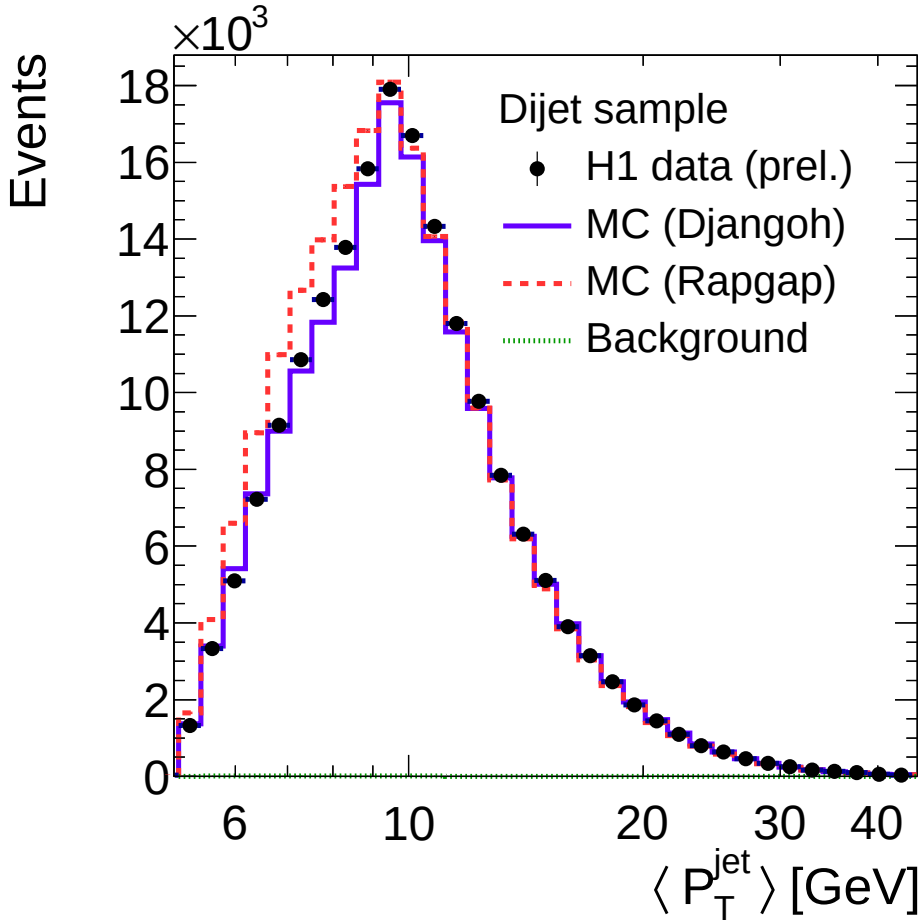
Variables of the instanton subprocess:

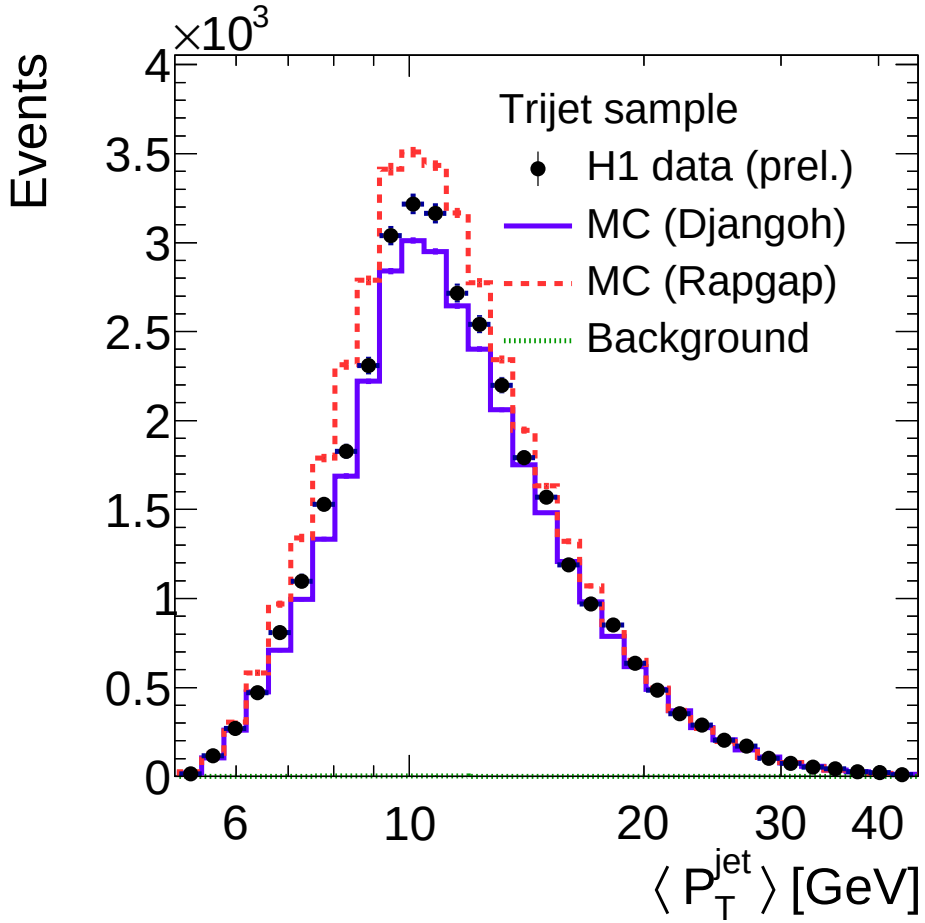
$Q'^2 \equiv -q'^2 = -(\gamma - q'')^2$

$x' \equiv Q'^2 \,/\, (2\, g \cdot q')$

$W_I^2 \equiv (q' + g)^2 = Q'^2\,(1 - x'\,)/x'$

Measurement of multijet production in $e^{\pm}p$ collisions at low Q^2 at HERA





Fair description with Djangoh and Rapgap.