# PARTICLE PRODUCTION AND FRAGMENTATION

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Recent results from HERA are presented on a range of topics: charged multiplicities, production of non-strange mesons and strange particles, charm fragmentation, baryons decaying to strange particles, antideuteron production, Bose-Einstein correlations, and new interpretations of results on prompt photon production in DIS.

## 1. Charged particle multiplicities in DIS and DDIS.

Historically, charged particle multiplicities have been measured in DIS in the current region of the Breit frame - defined as the frame in which there is no energy transfer in the collision. In zeroth order perturbative QCD this corresponds to a quark-parton jet with energy $Q/2$ and can be compared to a half-event in $e^+e^-$ annihilation. Early ZEUS results covered the range $10 < Q^2 < 4000\ \mathrm{GeV}^2$ with rather large errors at the high end. The results lie mostly on top of $e^+e^-$ annihilation but fall below those at $Q^2 < 50\ \mathrm{GeV}^2$. New analyses in the Breit frame using $2E_{current}$ as the scale instead of $Q/2$ fix this problem at low energy - see figure 1.

Using one hemisphere of the Breit frame offers a rapidity range of only $\ln(Q/m)$ where $m$ is the pion mass. Instead we can work in the $\gamma^* p$ centre-of-mass frame using the hadronic energy $W$ as the scale and access instead a larger rapidity range of $\ln(W/m)$ (recall $W^2 \simeq Q^2/x$.) These results are also shown in figure 1 and show excellent agreement between DIS and $e^+e^-$, and with calculations using LEPTO and ARIADNE.

ZEUS have also looked at an alternative approach, which is to use only the best part of the tracker ($20^\circ < \theta < 160^\circ$) where the tracking efficiencies are high and well-known and to plot the multiplicity (excluding the recoil electron) as a function of $M^2_{\mathrm{eff}} = (\Sigma E)^2 - (\Sigma \mathbf{p})^2$. The results cover the range $5 < M_{\mathrm{eff}} < 40$ GeV and agree well with ARIADNE. There is a weak Bjorken-$x$ dependence across the range $0.006 < x < 0.1$.

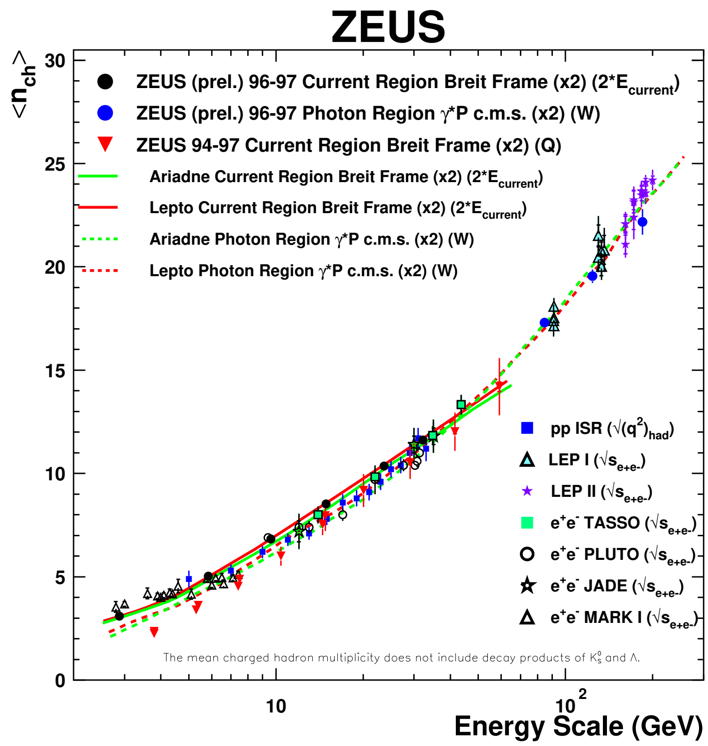


Figure 1. Charged particle multiplicities.

H1 have compared multiplicities in DIS and DDIS. The variable used to characterise the DDIS event is the mass of the diffractively produced hadronic system, $M_x$, giving a rapidity range of $\ln(M_x/m)$. Many comparison plots are made of mean multiplicity versus $W$ or $Q^2$ for different $M_x$ ranges. As $M_x$ increases, the DDIS mean multiplicities, and their rapidity spectra, smoothly approach the DIS values from below. This is as one might expect naively in a colour-string approach where what matters is the number of units of rapidity of colour-string available to fragment into hadrons.

## 2. Non-strange inclusive meson photoproduction

H1 have analysed the $\pi^+\pi^-$ mass spectrum in photoproduction. Mass peaks for $\rho^0$, $f_0$ and $f_2$ are identified over a large and steeply falling background.

They plot (see figure 2) a universal curve of spin-weighted rate against $p_T + m$. Within the discrimination of a log-log plot, these mesons and $\eta$ and $\pi^+$ lie on the same line and follow a power law over six orders of magnitude.

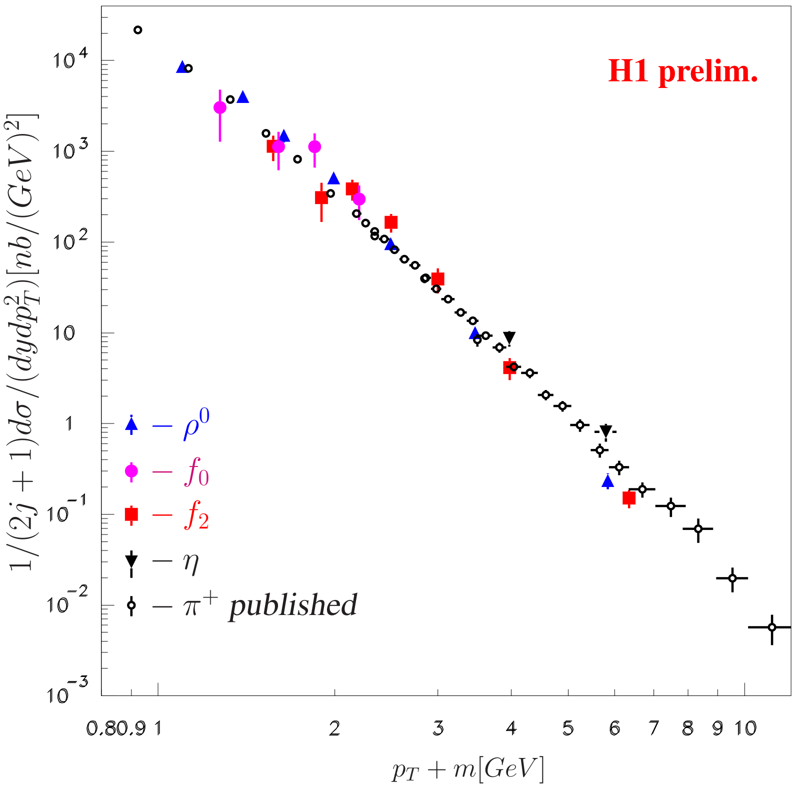


Figure 2. Meson production rates.

## 3. $K^0, \Lambda^0$ and $\overline{\Lambda}^0$ production in DIS.

ZEUS present clean mass peaks for these strange particles and plot the $p_T, \eta, Q^2$ and $x$ distributions for $K_s^0$, $\Lambda^0 + \overline{\Lambda}^0$, and the ratios $(\Lambda^0 + \overline{\Lambda}^0)/K_s^0$, and $(\Lambda^0 - \overline{\Lambda}^0)/(\Lambda^0 + \overline{\Lambda}^0)$ for $Q^2 > 25$ GeV$^2$. The error bars (see figure 3) are small and there is mostly very pleasing agreement with the predictions of Ariadne. Ariadne tends to overestimate the $K^0$ production rate, suggesting that a lower value of $s/u \simeq 0.22$ may be appropriate. No significant difference is found between $\Lambda^0$ and $\overline{\Lambda}^0$. The $\Lambda/K$ ratio is underestimated by ARIADNE for $x < 0.003$, as shown in figure 3.

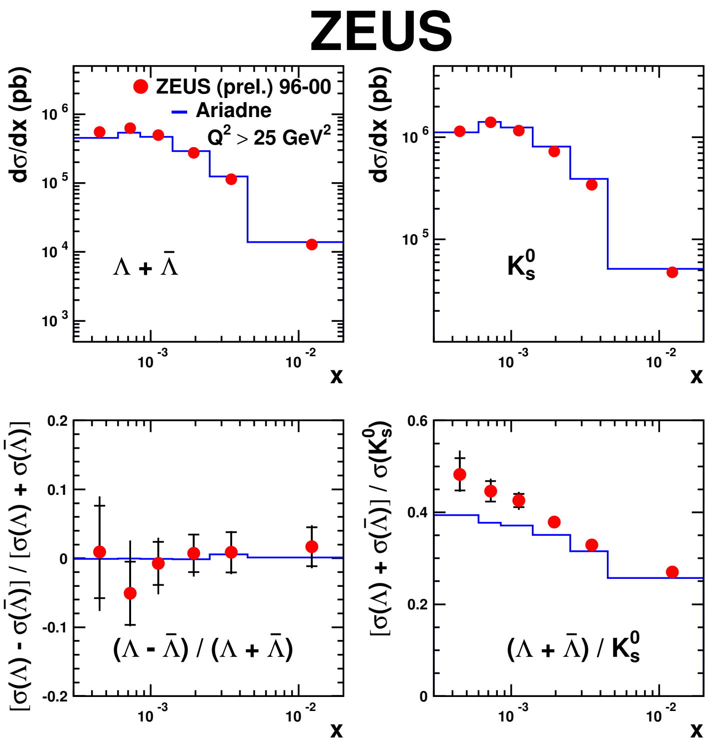


Figure 3. Strange particle production compared to predictions of ARIADNE.

$\Lambda^0$ and $\overline{\Lambda}^0$ polarisations are measured using the $\Lambda \to \pi^- p$ decay as analyser. In the $\Lambda^0$ rest frame the decay angular distribution with respect to a chosen axis is proportional to $(1 + \alpha P \cos\theta)$ with $\alpha = 0.642$. Using unpolarised $e^\pm$ beams no significant polarisations are observed either normal to the production plane (with 6% errors) or along the $\Lambda$ flight path (with 12% errors). They have thus demonstrated the ability to measure these polarisations, with possible application to polarised $e^\pm$ running at HERA-II.

**4. Charm fragmentation.**

Results from H1 and ZEUS measure the production rates of $D^{*+}, D^+, D^0, D_s^+$ and $\Lambda_c^+$. $D^{*+}$ are measured by the traditional decay chain $D^{*+} \to D^0\pi^+$, $D^0 \to K^-\pi^+$. H1 use vertex detector signatures to isolate the decays $D^+ \to K^-\pi^+\pi^+$ and $D^0 \to K^-\pi^+$ with relatively small backgrounds. They also use vertex tagging to measure $D_s^\pm$ production via the decay chain $D_s^\pm \to \phi\pi^\pm$, $\phi \to K^+K^-$. ZEUS observe the same channel and also find a signal of $(1440 \pm 220)$ $\Lambda_c^+$ events on a background of some 20000 events in the $pK^-\pi^+$ decay channel.

This allows them to compare fragmentation fractions such as $f(c \to D^0)$ in photoproduction, DIS (using both H1 and ZEUS data) and $e^+e^-$ annihilation. There is good agreement on the fractions in all cases, though there is a hint that ZEUS find a somewhat lower value for $f(c \to D^{*+})$ than $e^+e^-$ annihilation.

**5. Baryons decaying to strange particles.**

The search for pentaquarks has revived interest in baryons decaying to strange particles. We do not cover pentaquark issues here but look at other particles whose production has now been observed, often small but significant signals on large backgrounds. Both ZEUS and H1 identify protons and antiprotons by $dE/dx$ information, restricted to momenta below 1.5 GeV/c. ZEUS demand that charged tracks emerge from the primary production vertex and identify $K_s^0$ via a $\pi^+\pi^-$ secondary vertex, selecting $p_T(K_s^0) > 0.3$ GeV/c and $-1.5 < \eta(K_s^0) < 1.5$ to use the best part of the tracker. Additional cuts exclude Dalitz pairs, $\gamma$-conversions and $\Lambda^0$ candidates. Their $(K_s^0 p)$ mass resolution is 2.4 MeV.

Three data samples are used: photoproduction, DIS for $Q^2 > 1$ GeV$^2$, and DIS for $Q^2 > 25$ GeV$^2$. The particle multiplicities, and hence the backgrounds, are highest in photoproduction and lowest in the high-$Q^2$ sample. In the $K_s^0 p(\overline{p})$ mass spectrum, as well as a pentaquark candidate, $\Theta(1530)$, in DIS a clear $\Lambda_c(2286)$ is seen in all three samples with a width of typically $5.3 \pm 3.0$ MeV (see figure 4.) The most prominent signal is $(278 \pm 67)$ events in low-$Q^2$ DIS. It is seen equally in $K_s^0 p$ and $K_s^0 \overline{p}$ $(162 \pm 36$ and $116 \pm 38$ events) and equally at forward and backward lab rapidity $(131 \pm 40$ and $145 \pm 34$ events.) This is consistent with expectations for $\gamma g \to c\overline{c}$ production.

A clear $\Lambda(1520)$ signal is seen equally in both $K^-p$ and $K^+\overline{p}$ mass spectra in all three data samples: in photoproduction they observe $(13526 \pm$

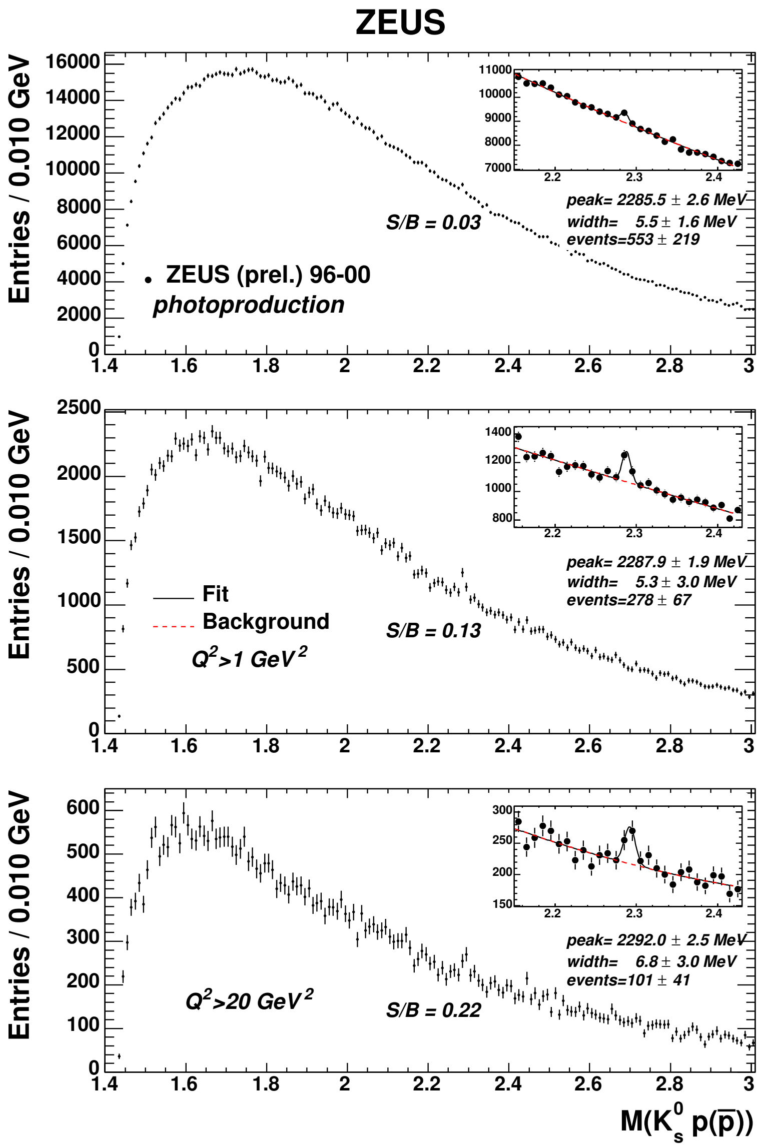


Figure 4. Observation of $\Lambda_c(2286)$ production.

561) events giving $S/B = 0.05$ with errors of 0.4 MeV on both mass and width. Again the production is the same at forward and backward rapidity, again consistent with photon-gluon fusion.

In the $\Lambda\pi^{\pm}$ spectrum one searches for $\Xi, \Sigma^*$ and pentaquark production. $\Xi(1320)$ and $\Sigma^*(1385)$ production are seen but there is no peak in the $\Theta^+(1530)$ region. There is a 4.6 $\sigma$ peak near 1600 MeV in the $Q^2 > 1\mathrm{GeV}^2$ sample, which might be $\Sigma(1580)$ or $\Sigma(1620)$ production.

Very clean peaks of $(1561 \pm 46)$ events in $\Xi^- \to \Lambda\pi^-$ and the same number in $\overline{\Xi}^+$ decay are seen after cuts are made to ensure a clean $\Lambda$ decay vertex. These in turn lead to a clear narrow $\Xi^0(1530)$ signal in the $\Xi^-\pi^+$ (and antiparticle) mass spectrum.

## 6. Antideuteron production and heavy particle search.

H1 have used their excellent $dE/dx$ resolution to measure the photoproduction of $K, p, d, t$ and antiparticles for $\langle W(\gamma p)\rangle = 200$ GeV, $0.2 < p_T/M < 0.7$, $-0.4 < y_{lab} < 0.4$, using 5.5 pb$^{-1}$ of data. Clear peaks are observed for $K^+, p, d, t, K^-$ and $\overline{p}$ with 7% mass resolution, and a clean cluster of 45 antideuterons is observed, corresponding to a cross section of $(2.7 \pm 0.5 \pm 0.2$ nb). There are no candidates for heavier negative particles.

Antideuteron production is beyond standard fragmentation models. H1 compare their results to $pp$ collisions at the ISR and to $AuAu$ collisions in STAR at RHIC as a function of $p_T/M$. Plotting the cross-section/total cross-section and the $\overline{d}/\overline{p}$ ratio the photoproduction and $pp$ data are in good agreement but the $AuAu$ data are much higher. The data are also tested against a coalescence model, which favours $d$ production if $p$ and $n$ are produced very close together. Heavy ion collisions have a much larger production volume and hence a much smaller chance of overlap. Again we find agreement between $\gamma p$, $pp$ and $pA$ over a wide c.m. energy range, but very heavy ions $NeAu$, $AuPt$ and $PbPb$ give much lower coalescence probabilities, falling rapidly as the c.m. energy increases.

## 7. Bose-Einstein correlations in $K^0_s K^0_s$ and $K^{\pm}K^{\pm}$.

ZEUS have performed a Bose-Einstein analysis for charged and neutral kaons. The correlation function used for two particles is $R(p_1, p_2) = \rho(p_1, p_2)/\rho(p_1)\rho(p_2)$ . We set $Q_{12} = p_1 - p_2$ and fit the data to the form

$$R(Q_{12}) = \alpha(1 + \delta Q_{12})(1 + \lambda \exp[-r^2 Q_{12}^2])$$

where the physics interest lies in the source radius, $r$, and the incoherence parameter, $(0 < \lambda < 1)$. $R(Q_{12})$ is measured in the data by the double ratio

$$R = [P(\text{data})/P_{mix}(\text{data})]/[P(\text{MC})/P_{mix}(\text{MC})]$$

all evaluated at the same $Q_{12}$, where the suffix *mix* implies that the two particles are taken from different events. The Monte-Carlo has no Bose-Einstein correlations.

Looking at $K^{\pm}K^{\pm}$ in DIS events ($Q^2 > 2$ GeV$^2$) ZEUS find $r = (0.57 \pm 0.09 + 0.15 - 0.06)$ fm in good agreement with LEP and with charged pions. The $\lambda$ value, $(0.31 \pm 0.06 + 0.09 - 0.06)$, is less than half that at LEP. The reason is unclear, though we note that the fragmentation may be different in the proton region of the c.m. frame and that $\phi(1020)$ decay may therefore play a different role.

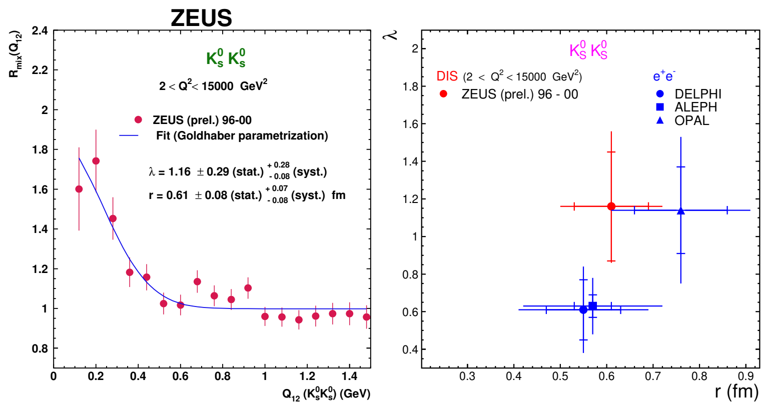


Figure 5. Bose-Einstein correlations.

In $K^0_s K^0_s$ ZEUS find a very similar value for $r$, in contrast with LEP results where there is a hierarchy, $r(\pi^{\pm}) > r(K^{\pm}) > r(\Lambda)$. (See figure 5.) ZEUS find $\lambda \simeq 1.2$, similar to OPAL but well above values from ALEPH and DELPHI who have removed $f_0(980) \to K^0_s K^0_s$ effects. Correction for this may bring the results into agreement.

## 8. Prompt photon emission.

We are looking here for hard photons emitted from the quark line in photoproduction or DIS. The experimental definition of photoproduction demands that the electron be lost down the beam pipe, so that a photon observed in the detector with $p_T > 5$ GeV must be far from it. We demand that the photon be isolated from all other outgoing particles by drawing a cone of radius 1 in $(\Delta\eta, \Delta\phi)$ around it and demanding that the electromagnetic cluster identified with the photon contain at least 90% of the energy found in the isolation cone. In DIS the photon is therefore far from both electron and quark.

$\pi^0$ and $\eta^0$ decay to photons provide major backgrounds to prompt photon signals. Both ZEUS and H1 have used transverse shower shape to discriminate these. In the ZEUS barrel calorimeter $(-0.7 < \eta < 0.9)$ the fine segmentation means that photons predominantly illuminate only 1 $z$-strip, $\pi^0$ decay mostly two strips amd $\eta$ decay fills one to many strips. A photon signal is extracted statistically from fitting the shape distributions.

Photoproduction of prompt photons is rather well described by both PYTHIA (shape OK, normalisation a bit low) and by NLO QCD. H1 measurements of $E_T^\gamma, \eta^\gamma$ and $\eta^{\rm jet}$ for accompanying jets are all described well. Corrections to NLO for multiple interactions (as estimated by PYTHIA) improve the fit, but there are no surprises.

Deep inelastic scattering turns out to be more of a challenge. ZEUS have published measurements of inclusive prompt photon emission and of the (photon+jet) final state, and they compared these to two Monte Carlo calculations (PYTHIA v6.206 and HERWIG v6.1) and to NLO, that is $O(\alpha^3\alpha_s)$, calculations by Kramer and Spiesberger. The data are shown in figure 6. PYTHIA and HERWIG get the normalisation wrong, by factors (in the inclusive case) of 2.4 and 8.3 respectively, and HERWIG gets too low a mean $Q^2$, while PYTHIA gets the slope of the rapidity spectrum wrong. A similar story holds in the case of prompt photon plus one jet.

Comparisons with NLO calculations, only available for the photon plus jet case, are more encouraging. The normalisation and mean $Q^2$ are good, (within 1.7 S.D. for cross-section) as are the photon rapidity and $E_T^{\rm jet}$ distribution. But the jet rapidity is predicted to be more forward peaked than the data and the photon $E_T$ spectrum is more steeply falling than the data. More statistics will obviously help to clarify whether these issues are significant or not.

After these results were published, Martin, Roberts, Stirling and Thorne produced a different approach, in which the outgoing hard photon is emitted by the electron, which in turn scatters off a photon which is a constituent of the proton, produced by QED/QCD evolution of the proton structure function. The high $Q^2$ in the event (averaging 85 GeV$^2$) in the data is carried by the exchanged electron. MRST calculate the photon structure of the proton $x\gamma_p(x, Q^2)$ to be about 0.03 at $x \simeq 0.005$, (i.e. about 300 times

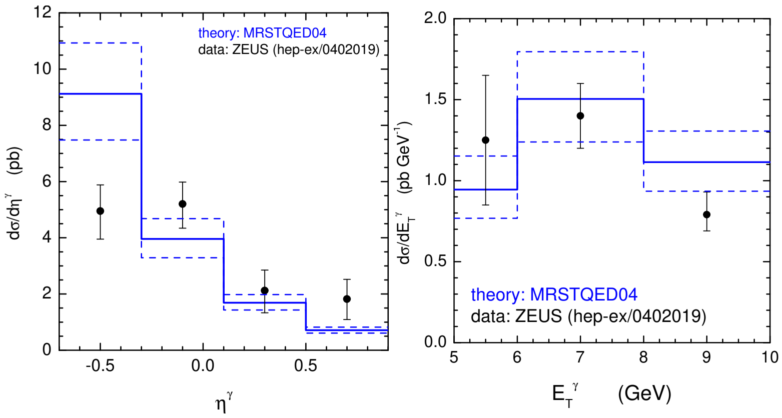


Figure 6. Inclusive prompt photon production in DIS compared to MRST predictions (absolute normalisation).

lower that the gluon content. This in turn gives a cross-section prediction similar to the data (well within 1 S.D.). The predictions for inclusive photon production (they do not calculate photon+jet) are overlaid on the data in figure 6.

The upshot is in some sense intriguing. Both the NLO and the structure approach are presumably valid and naively should be added together. Yet both explain to some extent the whole signal, in one case for inclusive photons and in the other in the sub-domain of photon plus jet. It is not clear how to reconcile these, and we await further developments.

## References

Most of the work described here can be found at
http://www-zeus.desy.de/physics/phch/conf/lp05_eps05/ and
http://www-h1.desy.de/h1/www/general/home/intra_home.html.
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