HERA – a Theory Perspective

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What are my qualifications for giving this summary talk on HERA.

Started working on HERA physics (small-x structure functions) at RAL in 1995 – along with J. Forshaw and R.G. Roberts.

Continued to work in this general field ever since.

However, wasn't involved directly at very being, or before turn-on.

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Actually latter not true.

Undergraduate summer student at Oxford in 1989 working on HERA development.

Given "HERA: Physics, Machine and Experiments" (G. Wolf) as bedtime reading.

Interesting to look back.

First interesting feature, presentation of kinematics – compare with standard LHC presentation (MRST99).

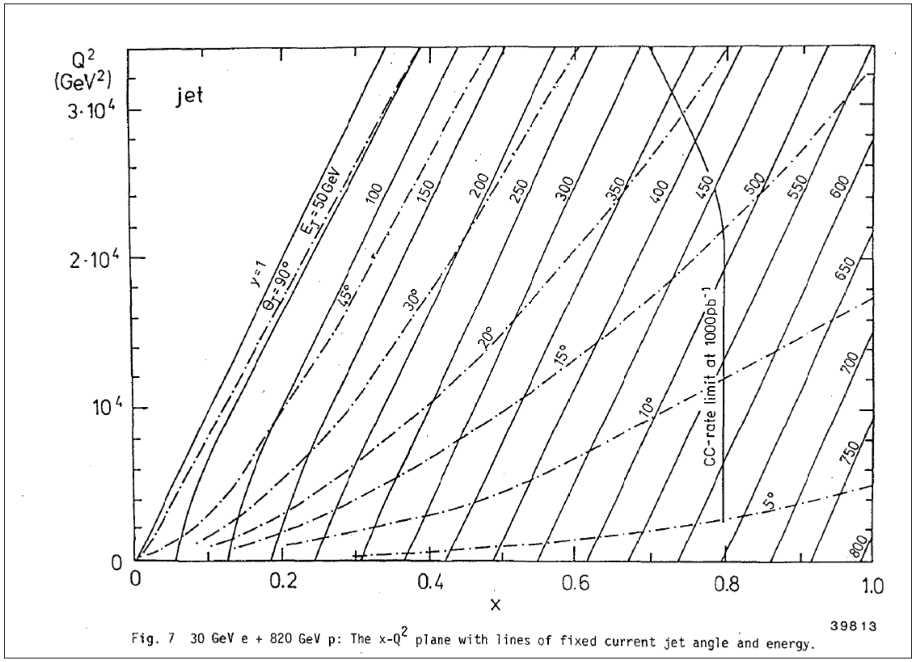
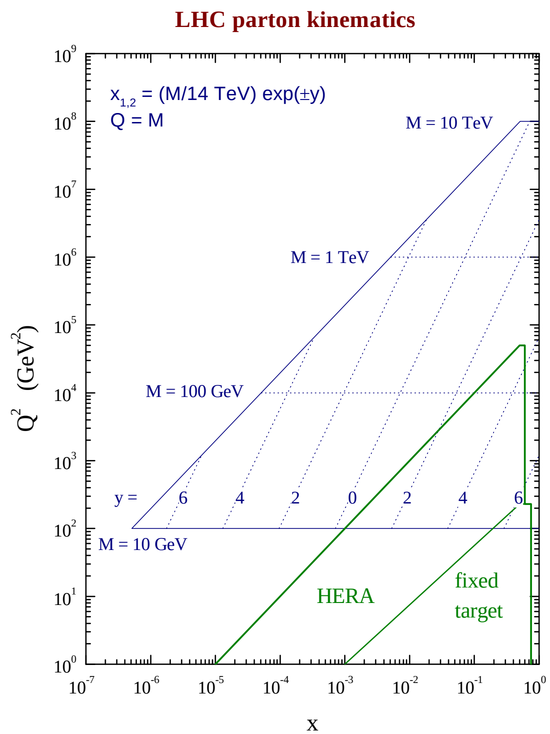


Fig. 7 30 GeV e + 820 GeV p: The x-Q^2 plane with lines of fixed current jet angle and energy.



Partially for convenience for kinematics presented, but discussion of physics fits fairly uniformly over phase space shown, not concentrated into tiny part of of bottom left.

Physics that was to be covered at HERA.

Structure functions - particularly comparison of neutral and charged currents (electroweak "unification"). Also, some investigation of scaling violations. Large Q^2 range test $\alpha_S(M_Z^2)$ to ~ 0.003 and look at power corrections.

In structure functions look for evidence of contact interactions, new intermediate bosons.

Lots of emphasis on production of new particles.

Quarks. Possibly top (if $m_t \leq 100 GeV$) and important to look for intrinsic charm!

Technicolour leptoquarks up to $180\mathrm{GeV}$.

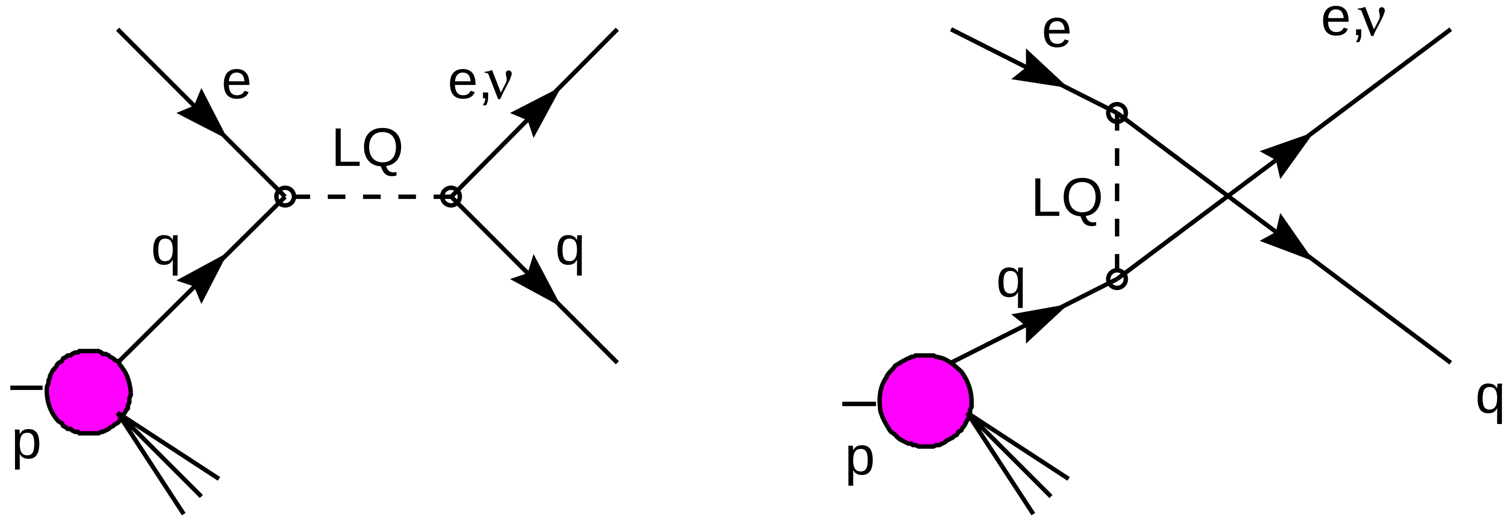
Supersymmetric particles for $M \leq 100 GeV$. No mention of R-parity violation though.

With benefit of hindsight how has HERA done with respect to these goals?

Beyond the Standard Model Physics.

HERA could never beat the straight centre-of-mass energy production prowess of the Tevatron.

Always going to contribute most for a particular type of BSM physics.



Most particularly leptoquark generation. Probably most likely candidate is similar R_P-violating but lepton+baryon conserving Supersymmetry.

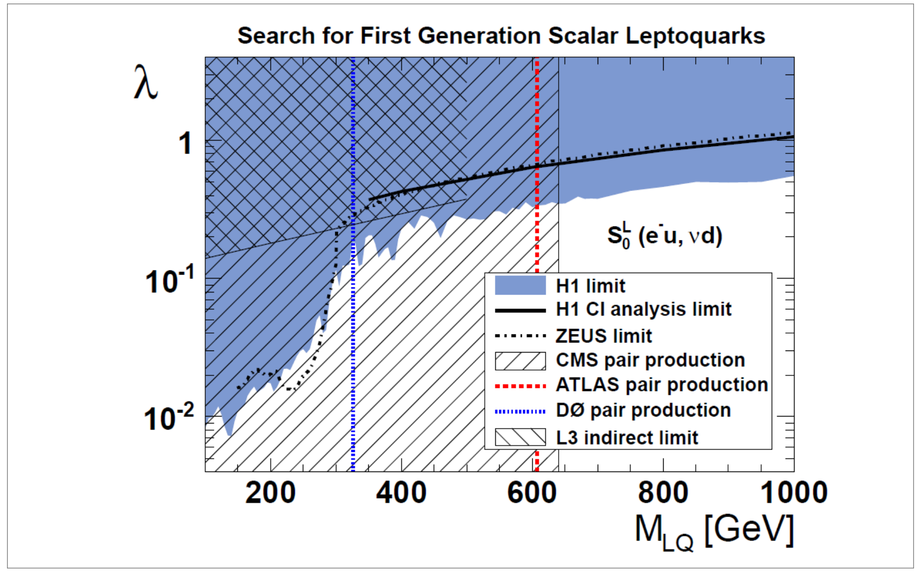
Those with long memories remember hint for this type of event in both H1 and ZEUS in 1997.

Ultimately nature did not choose this so HERA obtains bounds rather than signal.

Leptoquark searches compared to Tevatron, LEP and LHC.

Tevatron and LHC limit from pair production. Determined just by mass.

LEP production from virtual effects on precision measurements, determined by coupling λ and log of mass.

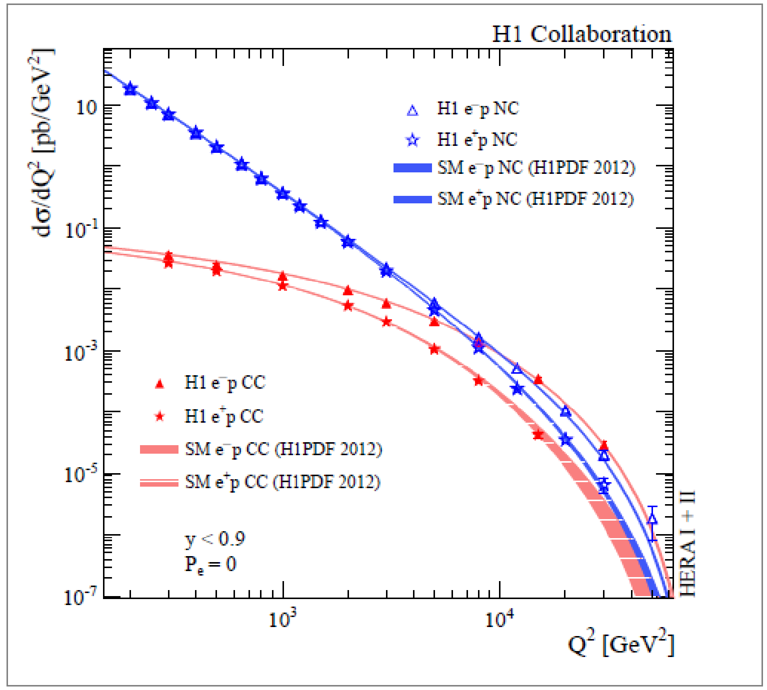


HERA from λM^2 (until very high mass). All three constrain search space in different way. Combination gives best chance of discovery, and of information if discovery made.

Electroweak Physics

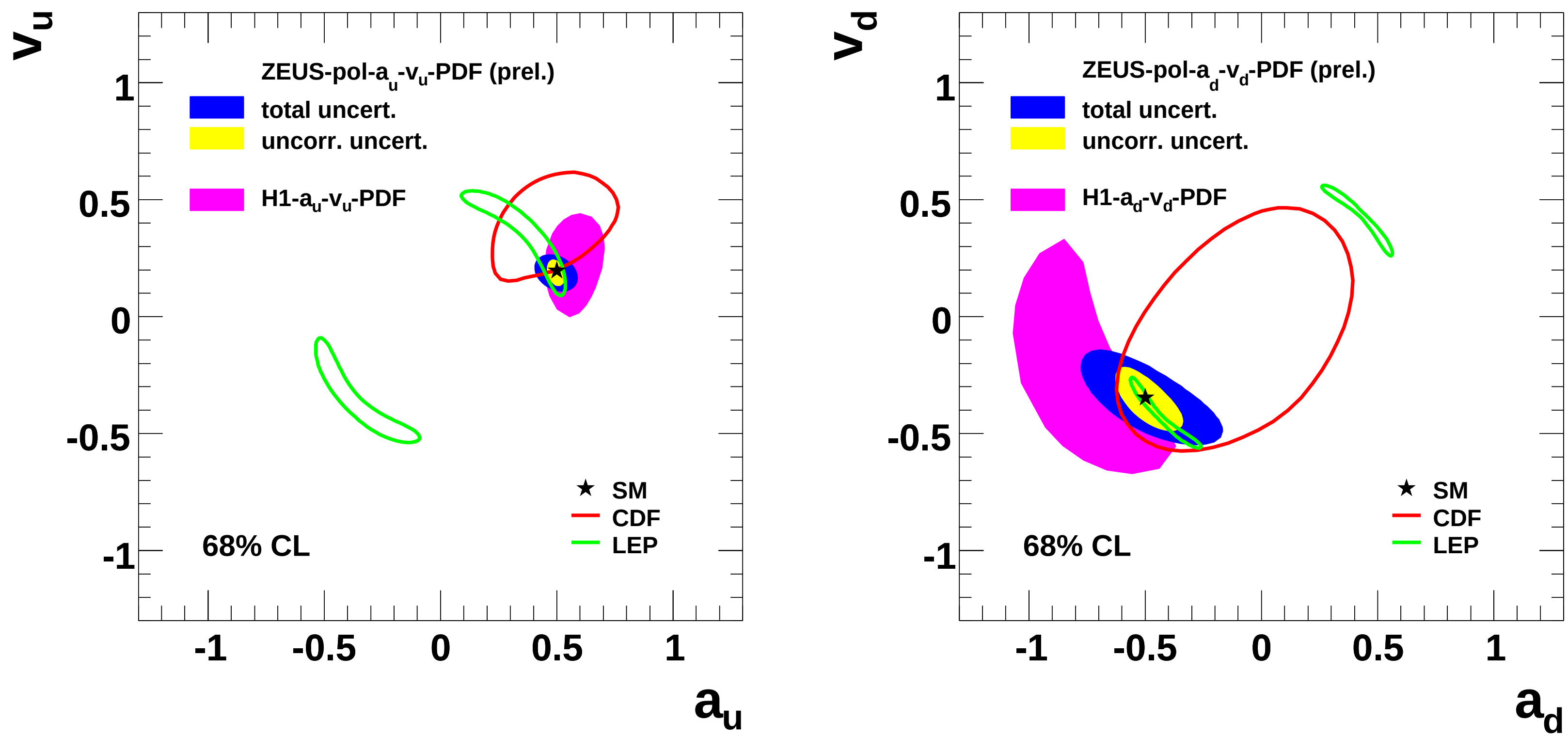
Again, in many ways HERA could never compete with the precision of LEP-type experiments. But again can provide its own unique contribution to our understanding.

Electroweak *unification*.
No “discovery”, but comparison of charged coupling and neutral coupling show restoration of symmetry in electroweak theory at high scales.



Cross-sections not identical.
Not *unification*. $\alpha_W \sim 3\alpha_{em}$ with opposite sign of running.

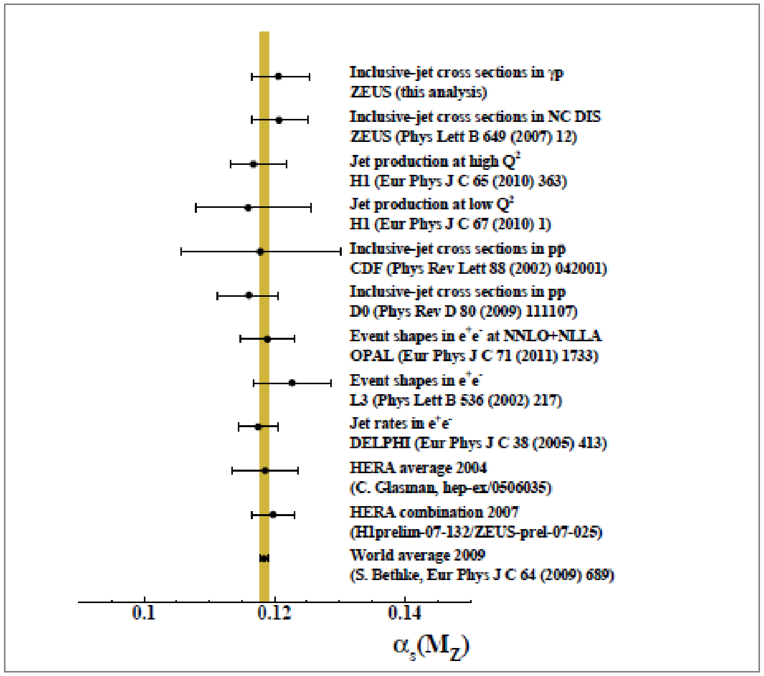
Measurement of sign and size of vector and axial quark couplings from $\gamma - Z$ interference and lepton polarisation.

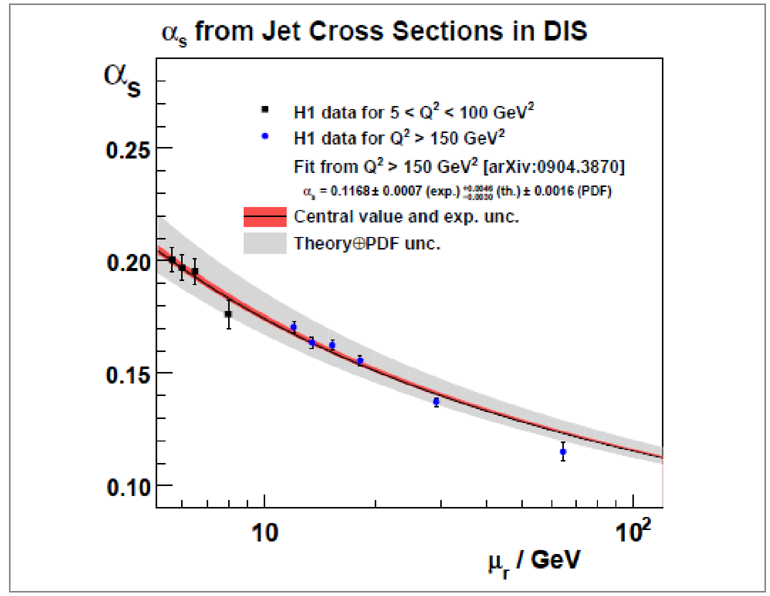


Similar to searches for BSM physics. Complementary behaviour.

Cannot beat precision in LEP runs at Z pole, but easily superior to forward-backward asymmetry determination at Tevatron.

Tests of QCD – many places where HERA is at least as good as any other experiment, including, so far, the LHC.





For example, the measurements of $\alpha_S(\mu^2)$ are of comparable accuracy to those of any other measurement.

However, no other single experiment illustrates the evolution of the coupling over a range of scales in nearly such a graphic way.

Jets

HERA has also made a major contribution to the field of jet physics.

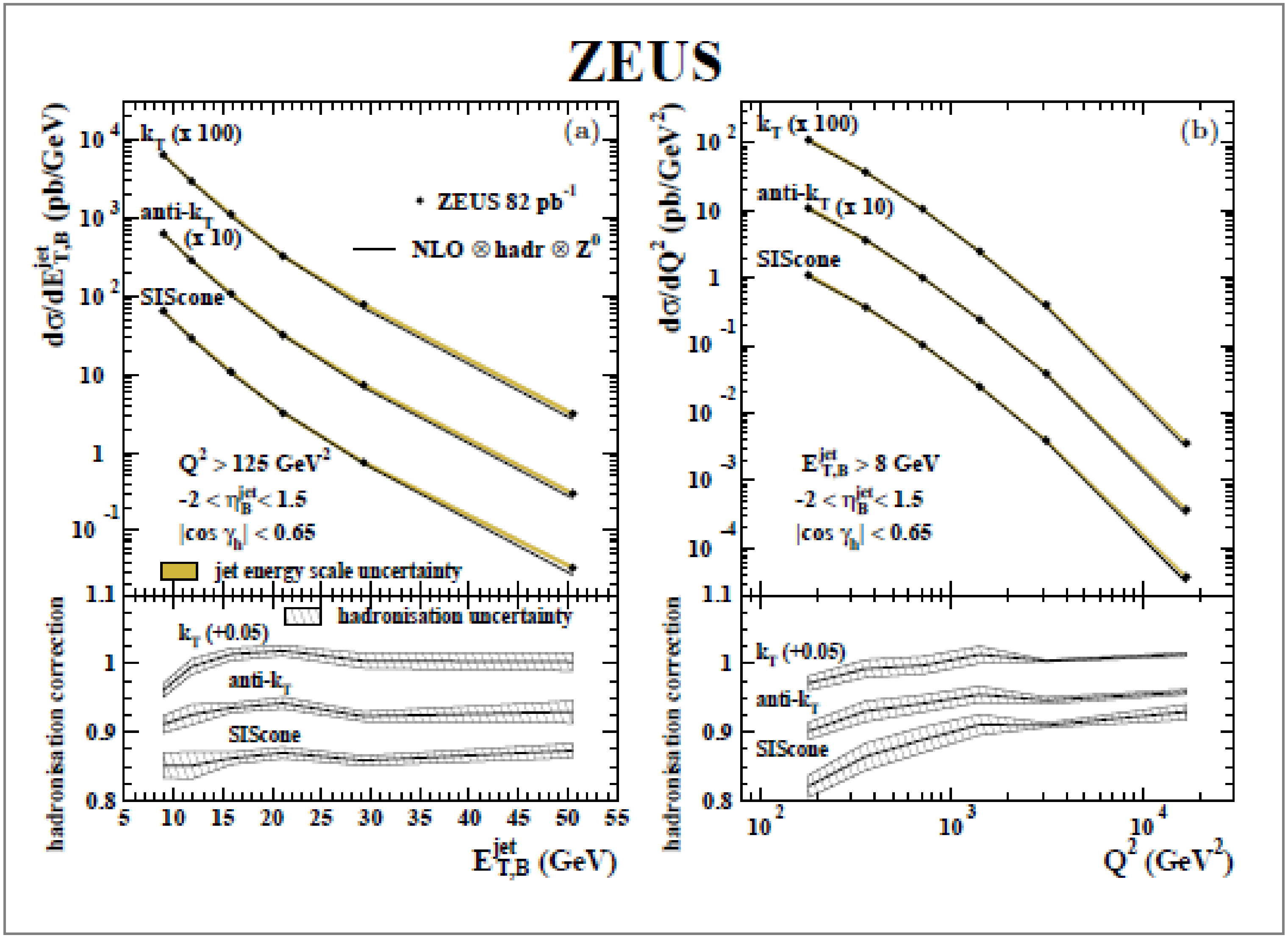
Two competing types of algorithm – cone-like and k_T-like. Latter more generally theoretically robust. Former more conceptually simple, but simplest versions infrared-sensitive.

At LEP-like colliders relatively clean events and fairly easy to use k_T-like algorithms.

At hadron colliders much more messy, with dangers from proton remnants, multiple interactions *etc.*. Run-I Tevatron used simple cone algorithms in the main.

HERA pioneered use of more sophisticated k_T-like algorithms in more complex situations, showing that they could work.

For example, HERA studies of comparions of algorithms



Now being used at LHC, decisions helped by HERA investigations.

Factorization Theorem and Perturbative QCD.

For real precision HERA is certainly Queen.

Cross-sections described by factorization theorem

$$\sigma(ep \to eX) = \sum_i C_i^P(x, \alpha_s(Q^2)) \otimes f_i(x, Q^2, \alpha_s(Q^2)) + \mathcal{O}(\Lambda^2_{\mathrm{QCD}}/Q^2),$$

where the coefficient functions $C_i^P(x, \alpha_s(Q^2))$ are process dependent (new physics) but are calculable as a power-series in $\alpha_s(Q^2)$.

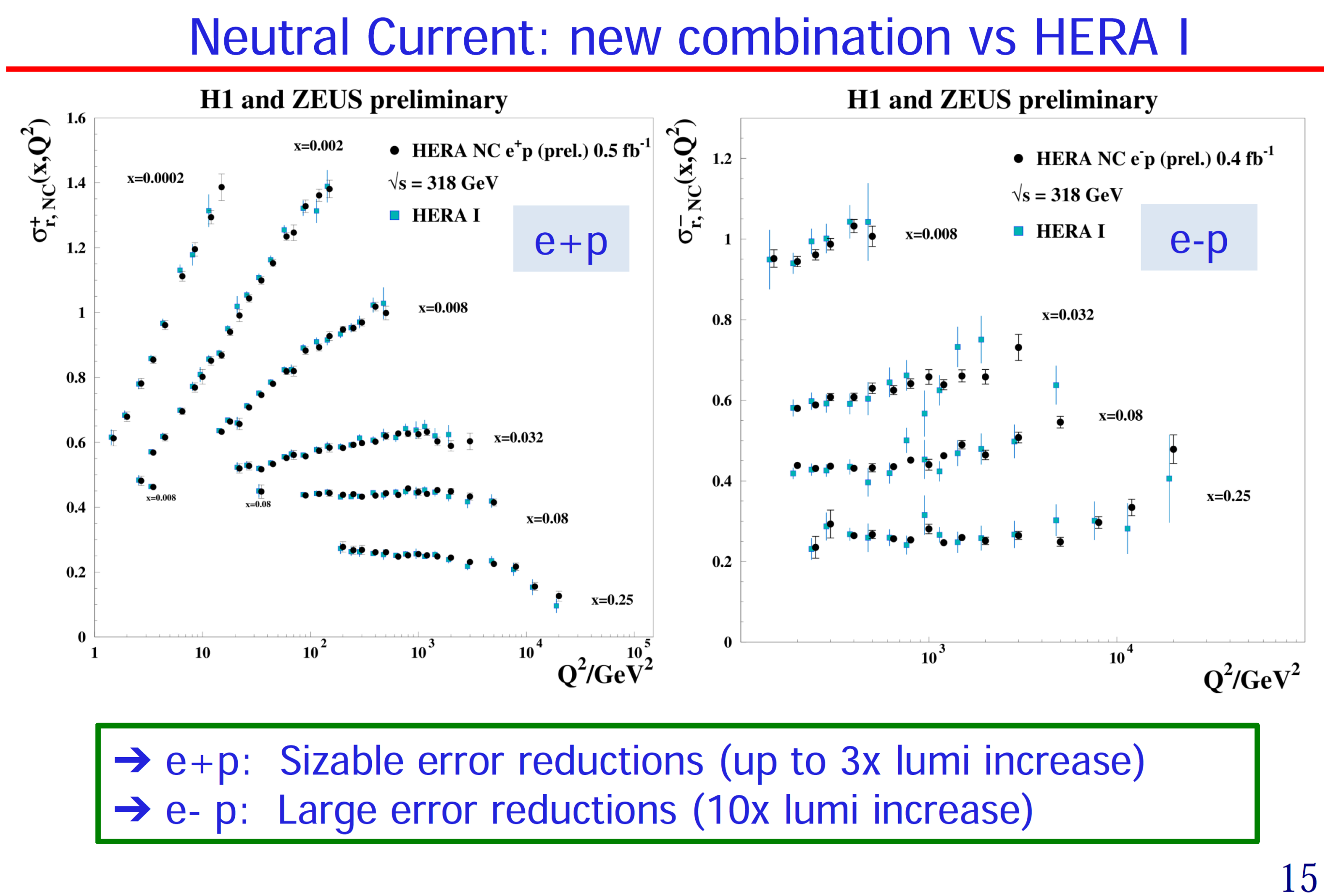
$$C_i^P(x, \alpha_s(Q^2)) = \sum_k C_i^{P,k}(x)\alpha_s^k(Q^2).$$

The parton distributions $f_i(x, Q^2, \alpha_s(Q^2))$ are intrinsically nonperturbative. However, once Q^2 is large enough they do evolve with Q^2 in a perturbative manner.

$$\frac{df_i(x, Q^2, \alpha_s(Q^2))}{d\ln Q^2} = \sum_j P_{ij}(x, \alpha_s(Q^2)) \otimes f_j(x, Q^2, \alpha_s(Q^2))$$

where the splitting functions $P_{ij}(x, Q^2, \alpha_s(Q^2))$ are calculable order by order in perturbation theory.

HERA measurement of total inclusive cross-section to at best $1-2\%$ over enormous range of both x and Q^2 best test of factorization and perturbative QCD that we have.



Will come back to fits of this precise data.

However, HERA has made more contribution to factorization theorems.

Diffraction

Much more direct impact from diffractive processes.

In this case also have factorization.

$$\sigma^D = \sum_i C_i^P(x, \alpha_s(Q^2)) \otimes f_i^D(x_P, \beta, Q^2) \;+ \mathcal{O}(\Lambda^2_{\rm QCD}/Q^2),$$

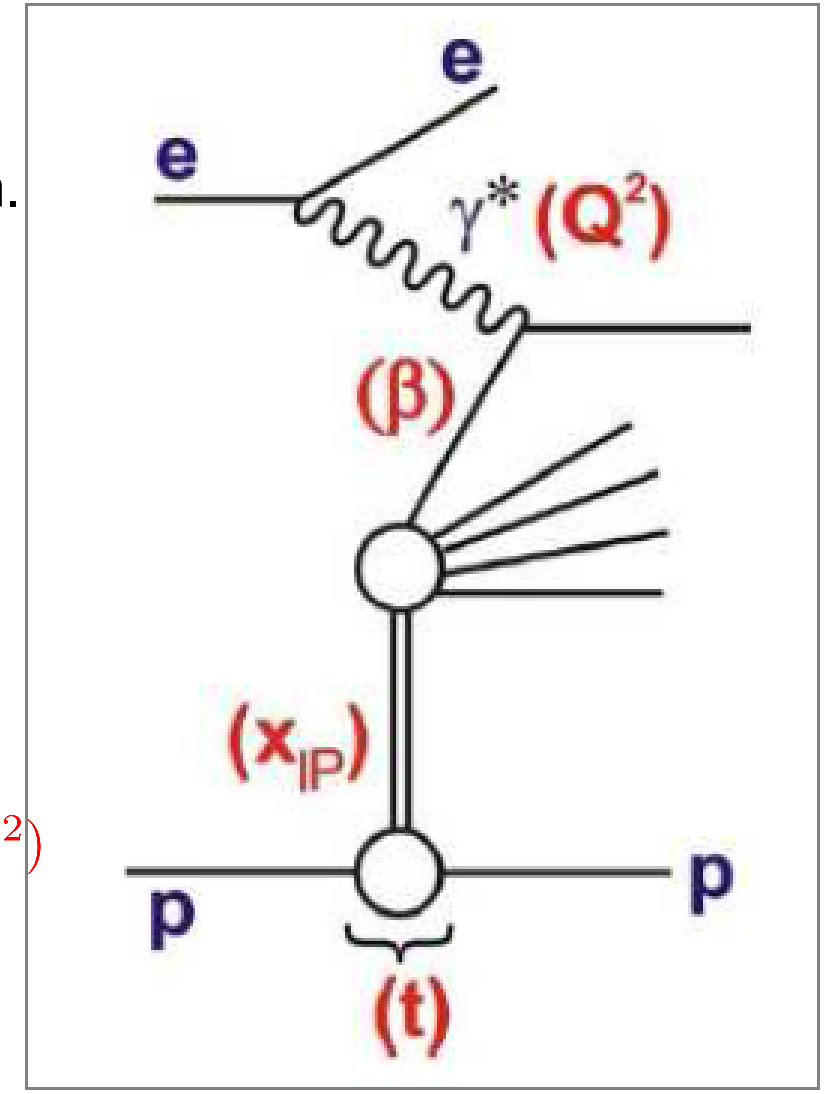
Only proved after HERA turn on by Collins.

Usually assume additional factorization

$$f_i^D(x_P, \beta, Q^2) = {\rm Flux}(x_P) f_i^P(\beta, Q^2)$$

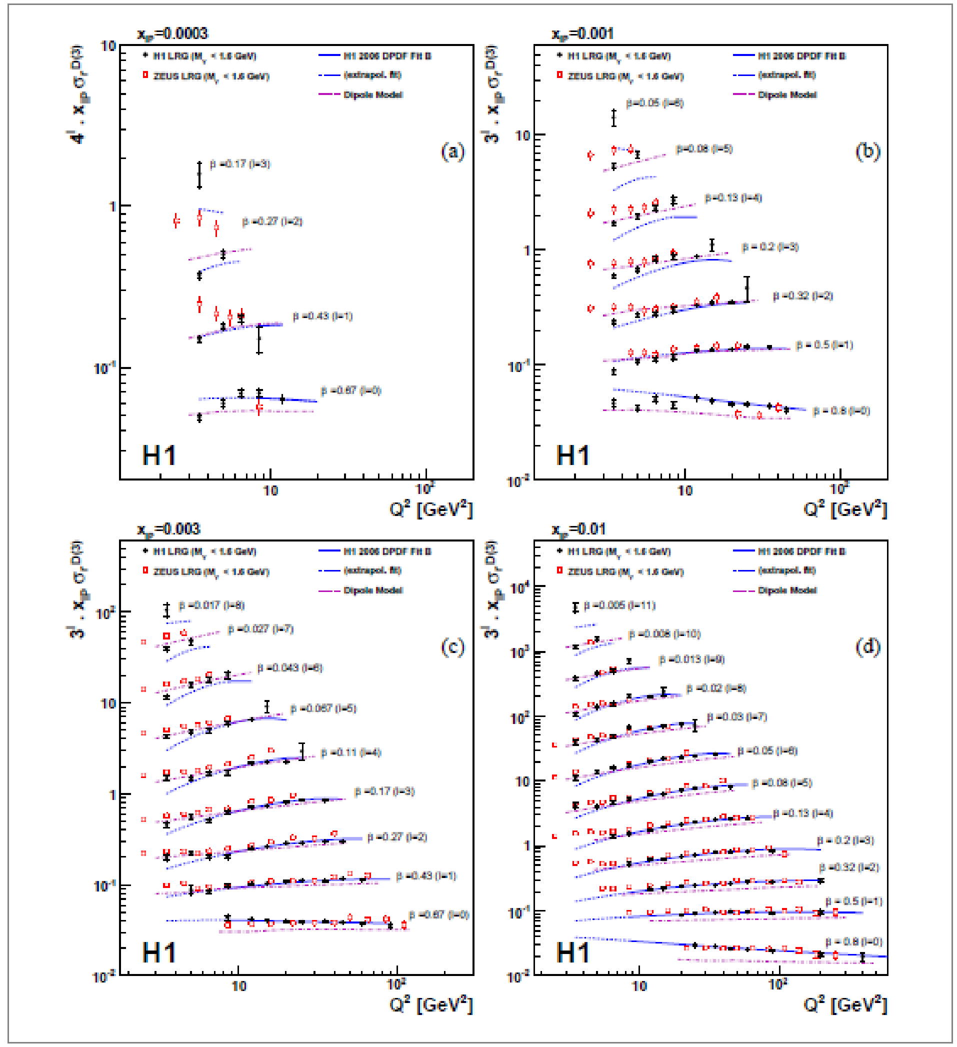
Though there can also be a Reggeon contribution.

Diffractive pdfs satisfy usual DGLAP evolution.

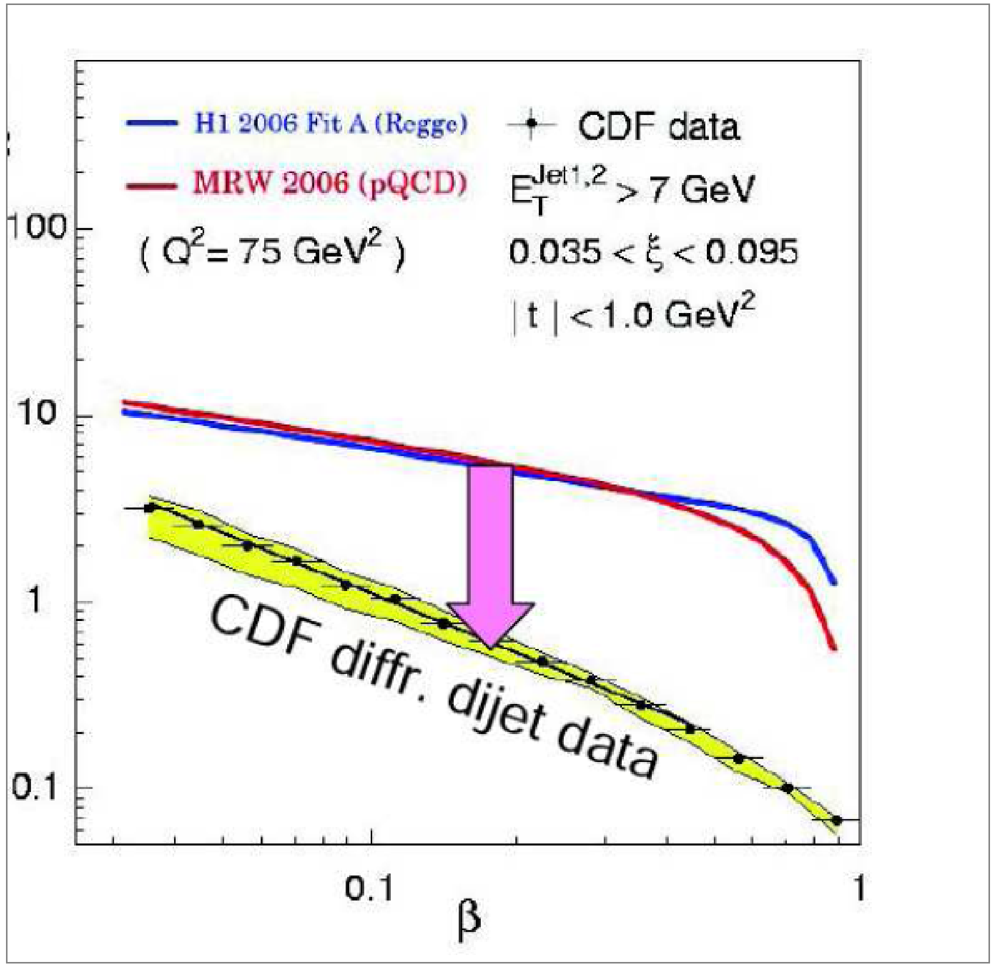


The final data on the diffractive structure function is almost as impressive as that on the total inclusive cross-section.

Has led to a lot of analysis.



However, while diffractive pdfs obey factorization, i.e. can determine evolution and combine with hard coefficient functions, the factorization is not like that for normal pdfs. It is not inclusive.



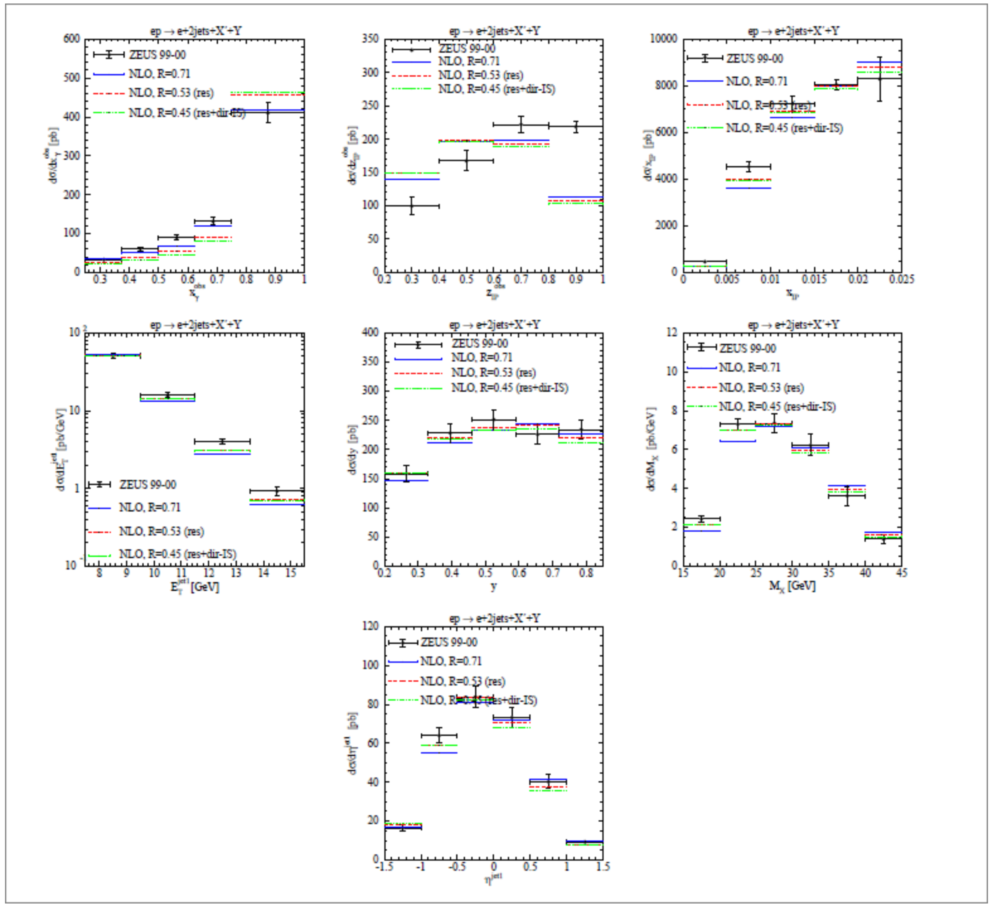
Very simple application of extracted pdfs to Tevatron data does not, and was never expected to work.

Factorization known to be broken in hadronic diffraction due to soft interaction filling in gaps in both initial and final states.

Interpreted as *phenomenological* “gap survival” probability. Can give some reasonable accuracy for prediction of LHC processes.

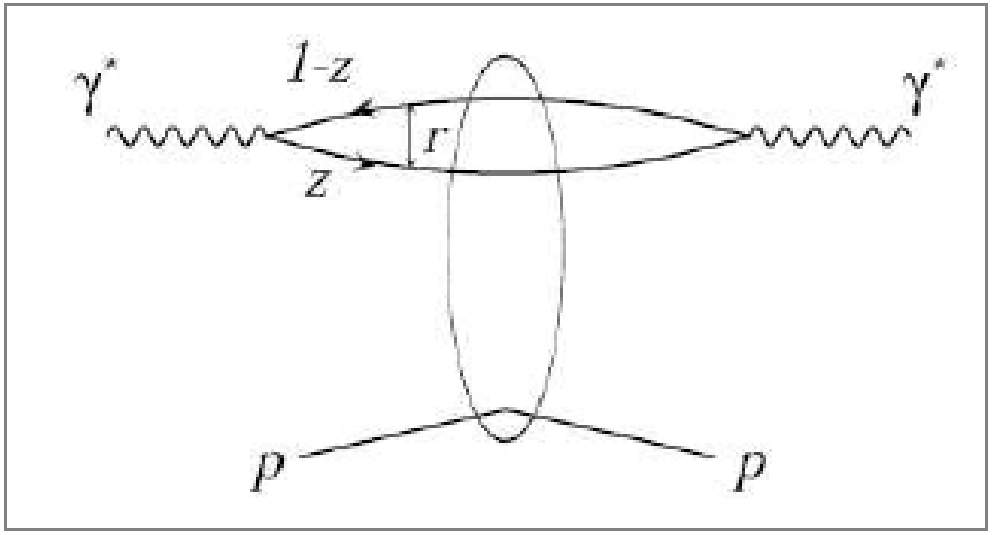
Interesting test of factorisation in context of diffractive dijet photoproduction. Does this obey universal factorization?

Naive guess – yes for direct contribution (like DIS no for resolved (like hadronic) – gap survival ~ 0.3 (Khoze, Martin ...)).



Appears that suppression (gap survival) factor of $\sim 0.4 - 0.5$ works independent of x_γ (Klasen, Kramer), but not fully determined.

Dipole Picture



Unification of total cross-section and diffractive cross-section achieved in dipole formulation.

Alternative picture where view photon as fluctuating into quark-antiquark dipole pair and use dipole cross-section with proton.

$$\sigma_{Tot} = \frac{2\pi}{3} \int_0^1 dz \int d^2r |\Psi(r, z, Q)|^2 \hat{\sigma}(x, r^2).$$

and from the optical theorem

$$\left.\frac{d\sigma_D}{dt}\right|_{t=0} = \frac{1}{16\pi} \int_0^1 dz \int d^2r |\Psi(r, z, Q)|^2 \hat{\sigma}^2(x, r^2).$$

Originally Nikolaev, Zakharov, but pushed by Golec-Biernat, Wusthöff, in context of small-x saturation of $\hat{\sigma}^2(x, r^2)$.

This picture can be related to the standard partonic picture via the relationship.

$$\hat{\sigma}(x,r^2) = \frac{2\pi}{3}\int \frac{d^2k}{k^4}\alpha_S f(x,k^2)(1-J_0(kr))$$

In the small r^2 limit it is often written as

$$\hat{\sigma}(x,r^2) = \frac{2\pi}{3}r^2\int \frac{d^2k}{k^2}\alpha_S f(x,\mu^2) \sim \frac{2\pi\alpha_S}{3}r^2 g(x,\mu^2), \qquad \mu^2 \approx 10/r^2.$$

This combines an inclusion of a small-x resummation and some higher twist terms, but is only correct at LO, up to leading $\ln(1/x)$ and does not include quark contributions.

Good qualitative fit to total structure function data and simultaneously to diffractive data with saturation model.

When done properly (heavy quarks, impact parameter dependence, ...) implies saturation implied at HERA for $Q^2 \leq 1GeV^2$ at $x = 10^{-5}$, i.e. in nonperturbative regime.

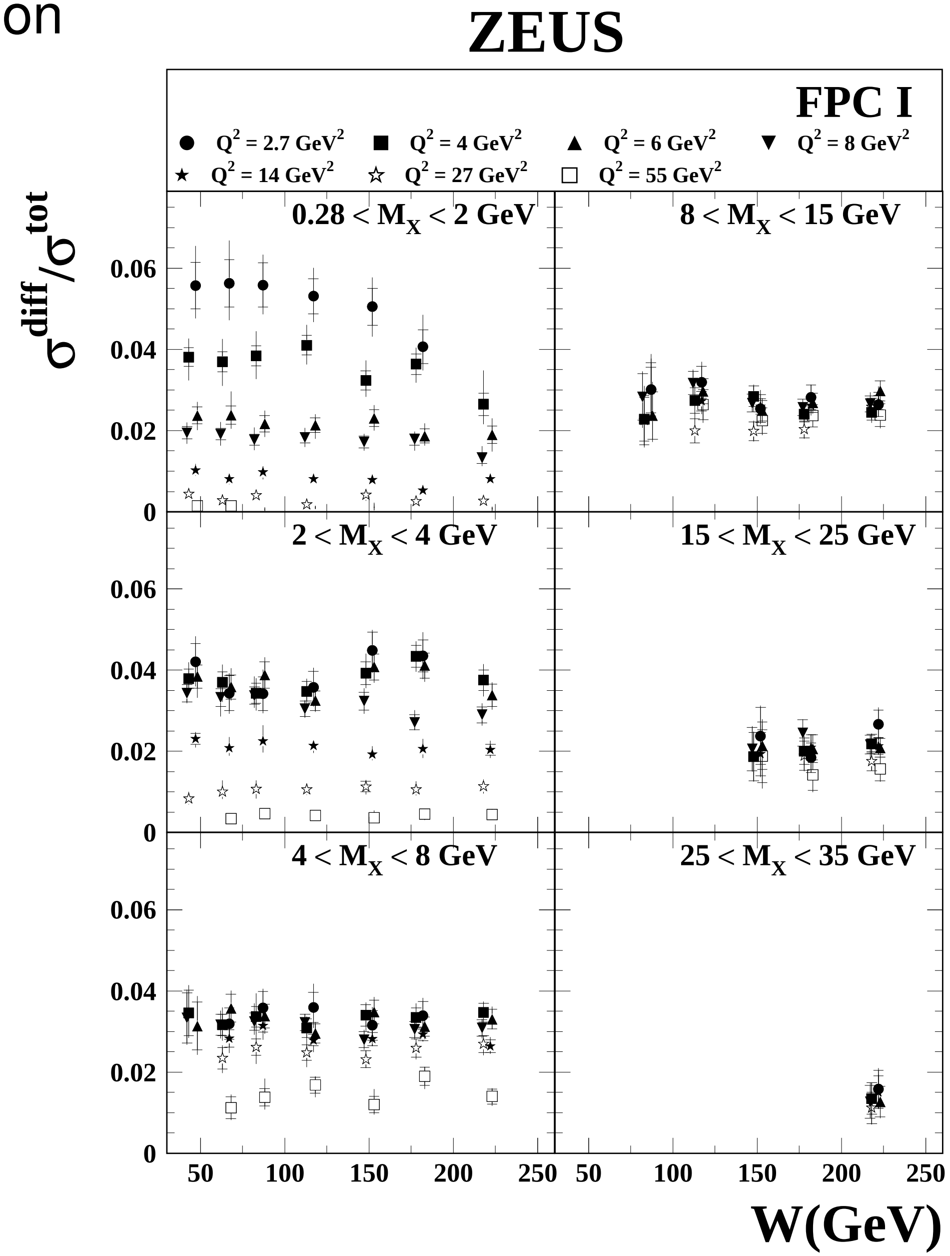
Gives good qualitative explanation of roughly constant σ_D/σ_{Tot}.

In diffraction probes $\hat{\sigma}^2(x, r^2)$ not $\hat{\sigma}(x, r^2)$.

But $\hat{\sigma}^2(x, r^2)$ peaks at larger $r^2 \rightarrow$ smaller Q^2.

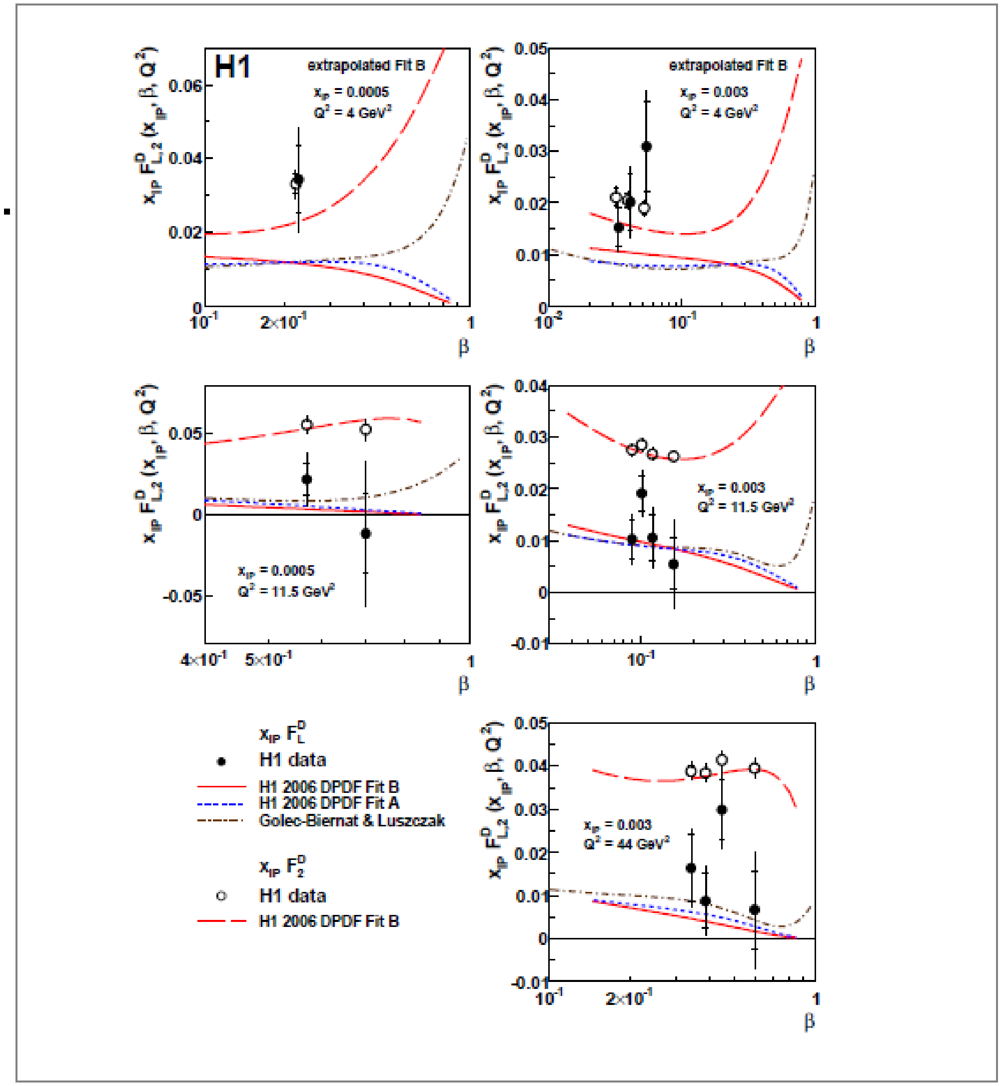
$\sigma_D/\sigma_{Tot} \sim g^2(x, Q_1^2)/g(x, Q_2^2)$, where $Q_2^2 \gg Q_1^2$.

Steepening of perturbative gluon with Q^2 explains main points.



Makes fairly sucessfully predictions for diffractive longitudinal structure function recently measured.

However, not obviously better than standard factorisation theorem with extracted PDFs.



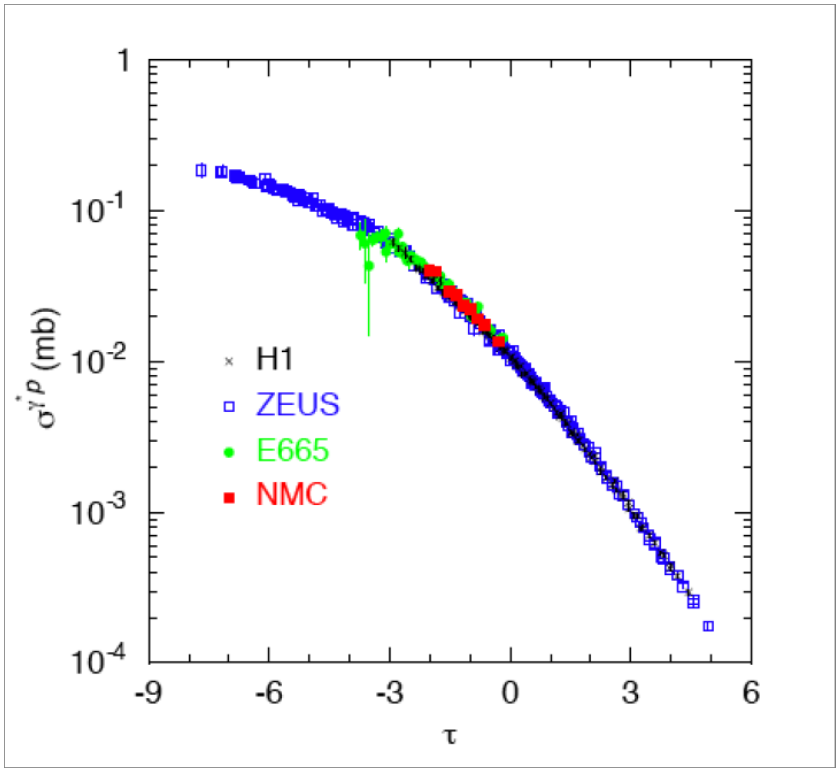
Taken further to predict that total cross-section function

$\tau = \ln(Q^2/Q_S^2), Q_S^2 = Q_0^2(x/x_0)^\lambda,$

and more complex extensions.

Very qualitative, e.g. broken by $F_2^{c\bar{c}}(x, Q^2)$ which is $0 \rightarrow 40\%$ of total.

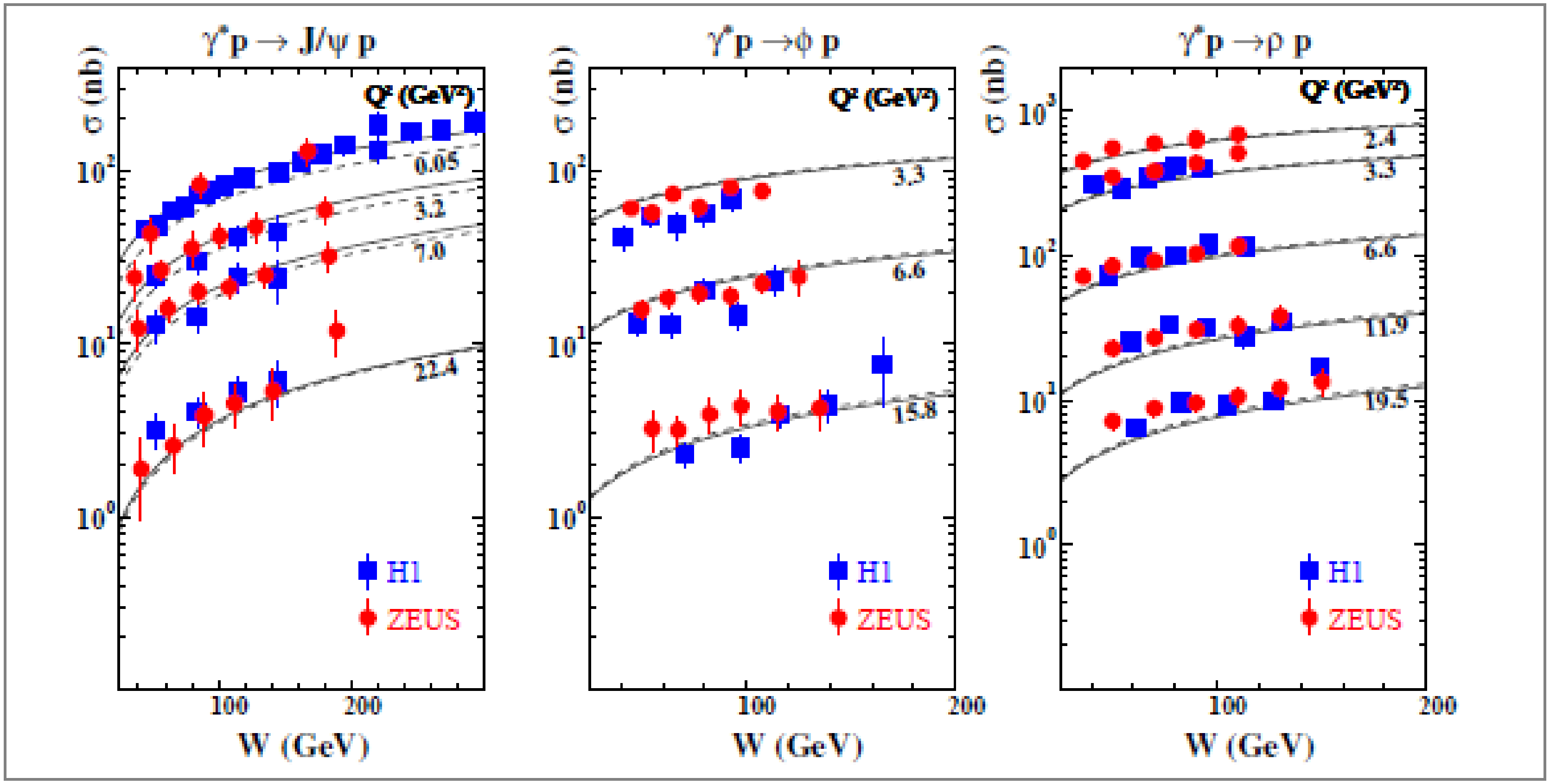
Moreover satisfied by MRST and CTEQ parameterisations (Salek), which fit data but certainly don't have saturation.



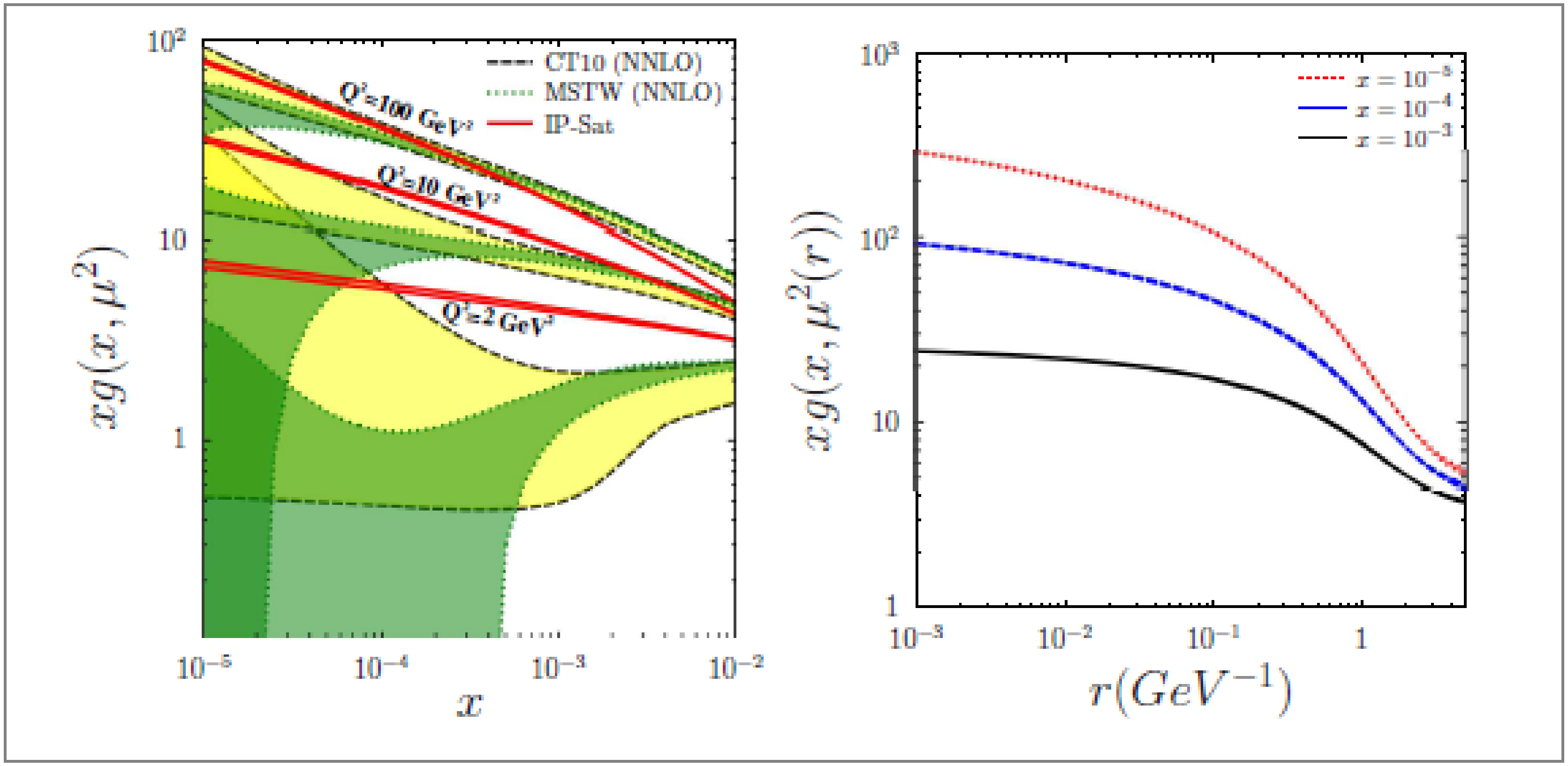
Similar in some senses to **Double Asymptotic Scaling** (Ball, Forte), data function of $\sigma * \rho, \sigma/\rho,$ where ($\sigma = \sqrt{\ln(1/x)}, \rho = \sqrt{\ln(\ln(Q^2/\Lambda^2)/\ln(Q_0^2/\Lambda^2))}$, which fit early data very well, and other, less justified parameterisations which give qualitative descriptions.

DAS is representation of LO perturbation theory at small x. Not sure if anything really in **Geometric Scaling**.

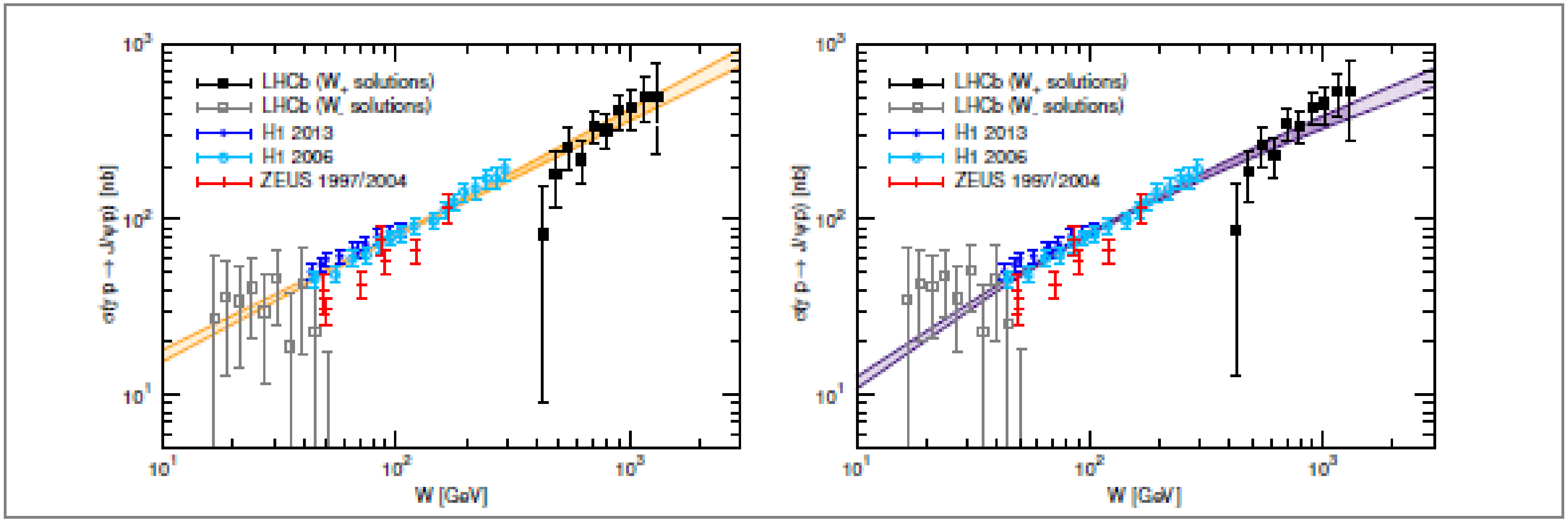
New saturation inspired theories (e.g. Rezaeian et al.) based on dipole model with impact parameter dependence fit to a variety of HERA data, including exclusive vector meson production.



Results in an effective gluon distribution rather different to those in fixed-order perturbative QCD.

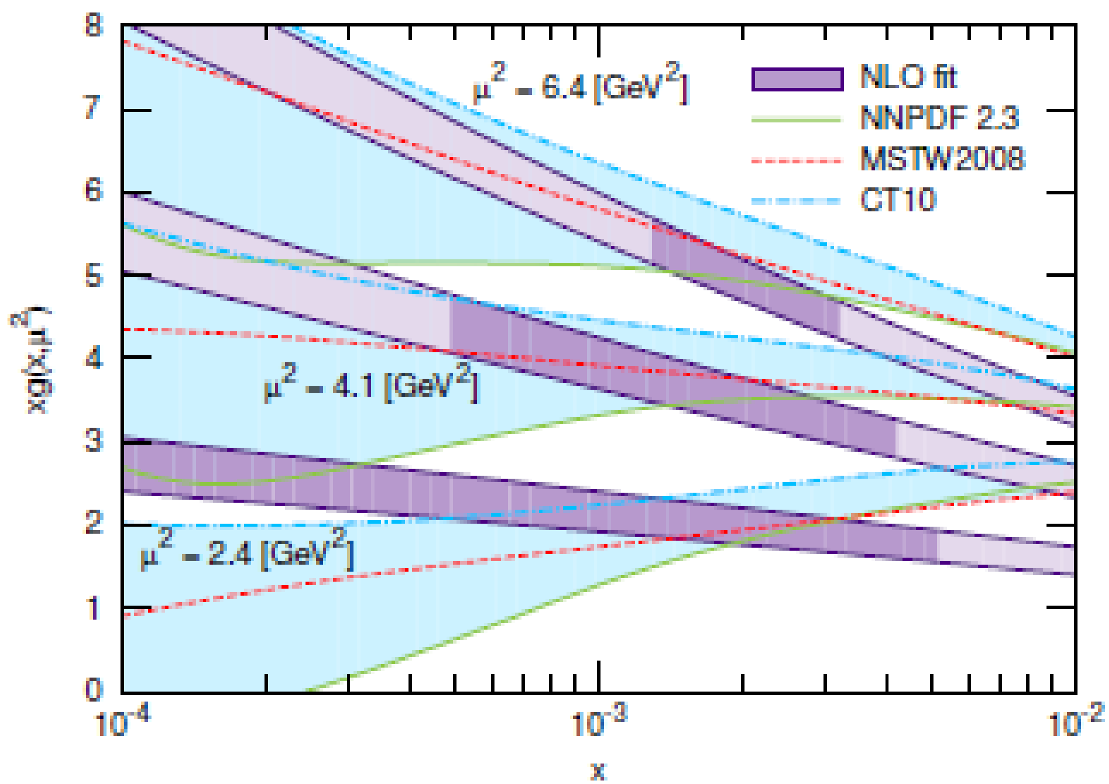


Similar analysis of exclusive vector meson production ($J/\psi, \upsilon$) at HERA and LHCb in rather different framework of cross section in terms of skewed PDFs by Jones, et al.



(Inclusive vector meson production data also used in extraction of long-distance matrix elements in non-relativistic QCD approach (Butenschön et al))

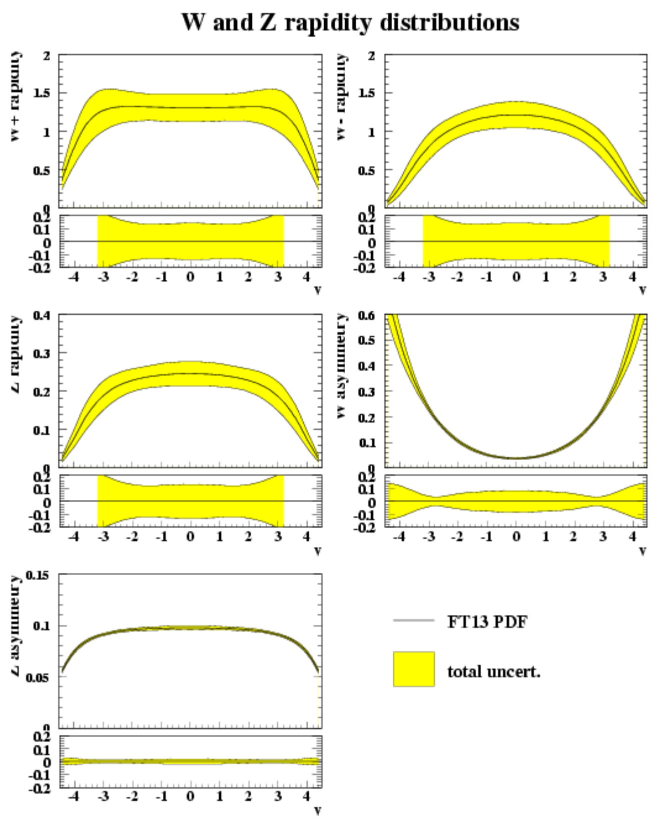
Also results in gluon distribution rather different to those in fixed-order perturbative QCD.

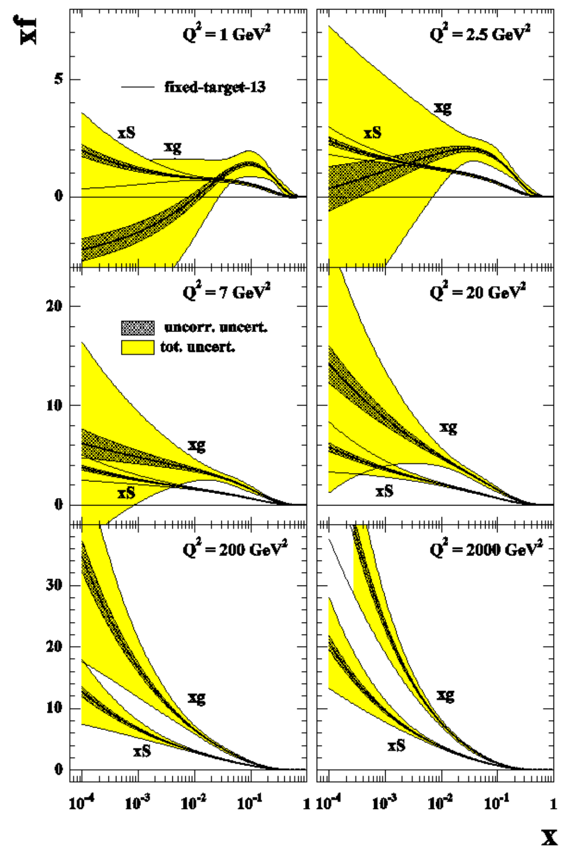


rather similar in many respects to results in dipole/saturation model. Suspect high-x limit shortcomings similar in both.

Precision QCD.

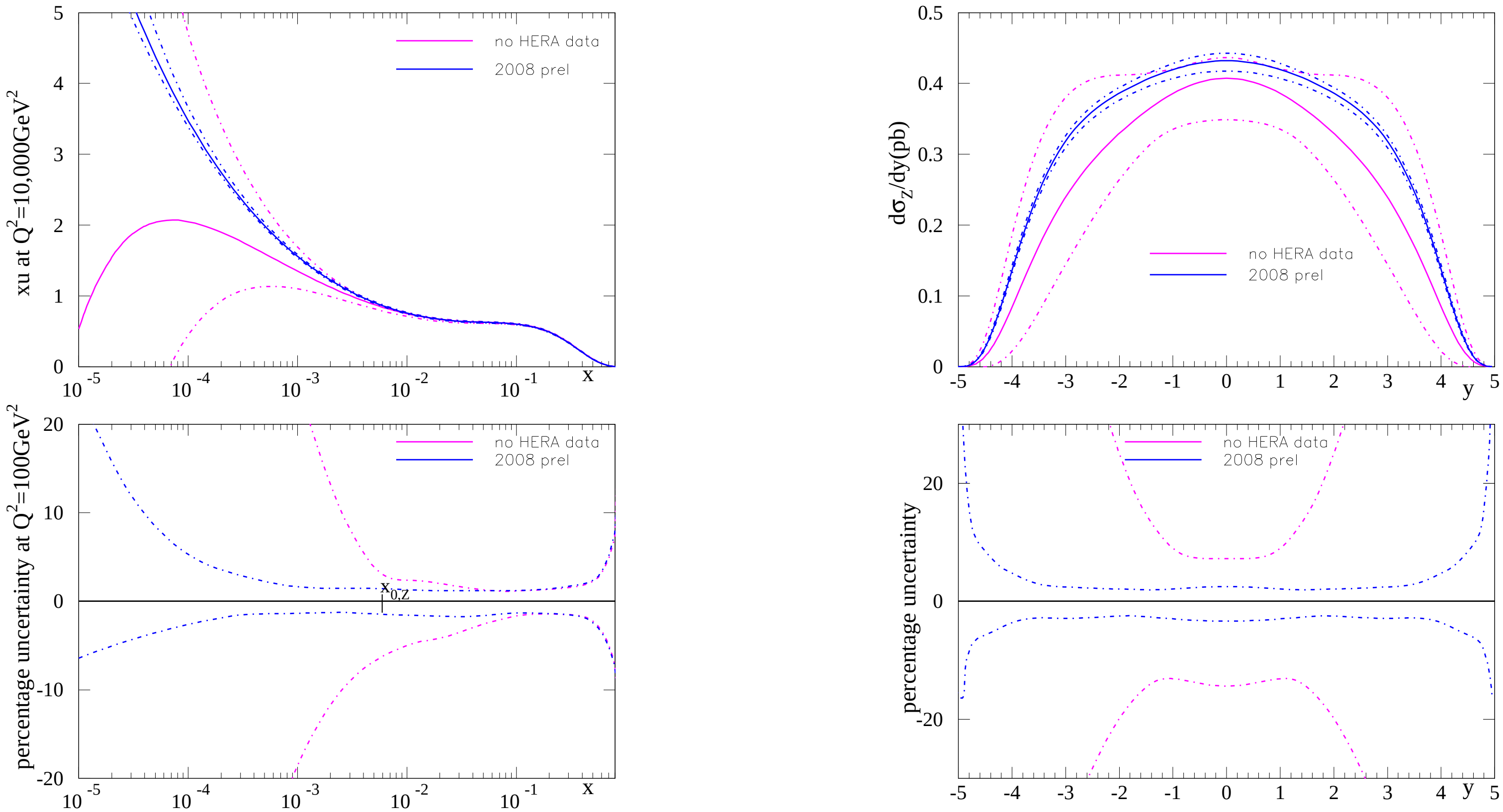
Look at effect of leaving HERA data out of global fit on pdfs and LHC prediction.



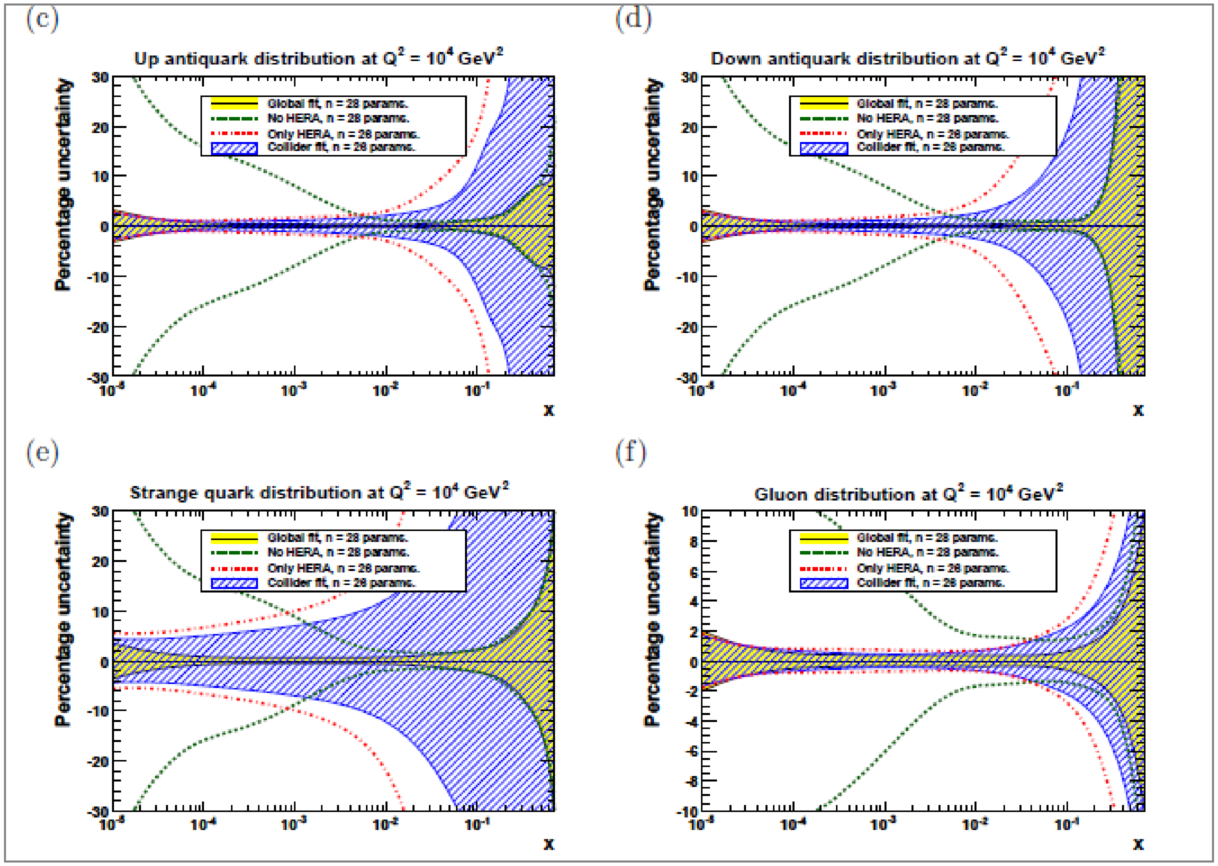


HERA analysis with no-HERA fits (Cooper-Sarkar).

Also investigated by MSTW with more flexible parameterisation and more other data.



Perhaps best seen with PDFs themeselves.



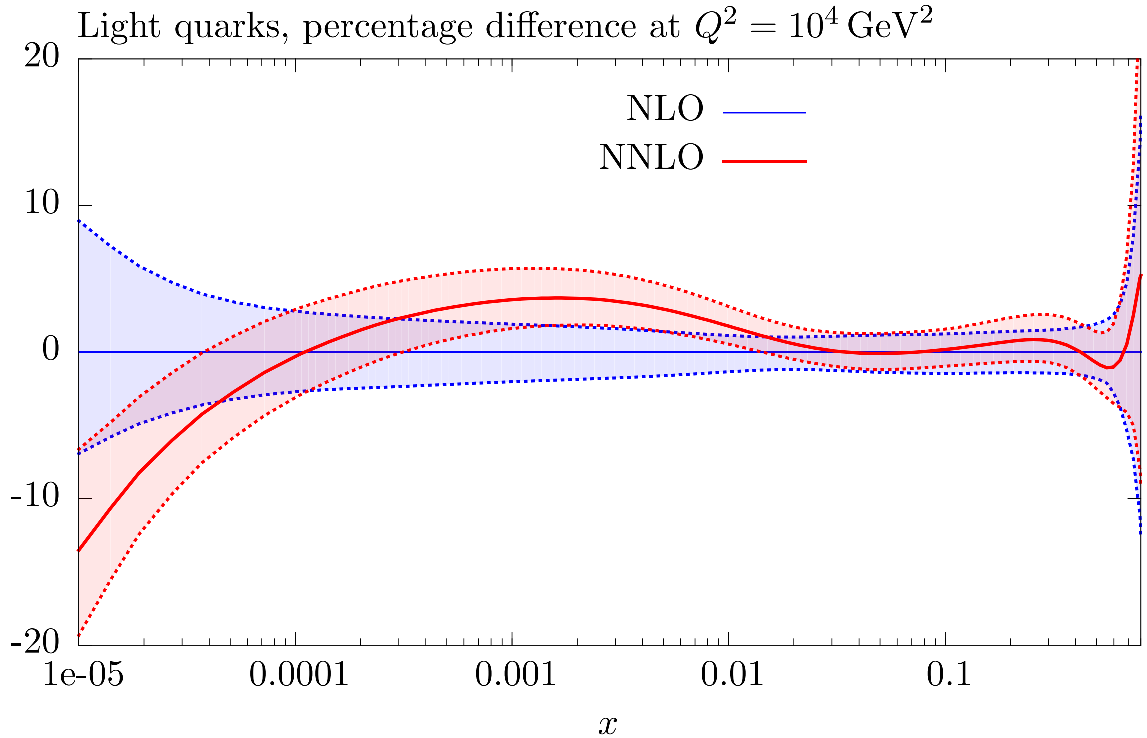
HERA (run I at least), not the dominant constraint at highest x.

Even for the gluon benefits from additional info for $x \sim 0.05$ and above.

However, absolutely overwhelming costraint at small x, vital for Higgs predictions.

NNLO corrections

HERA data down to $1-2\%$ uncertainties. NLO QCD working perfectly at this level? Even using evolution from $Q_0^2 = 1\mathrm{GeV}^2$.

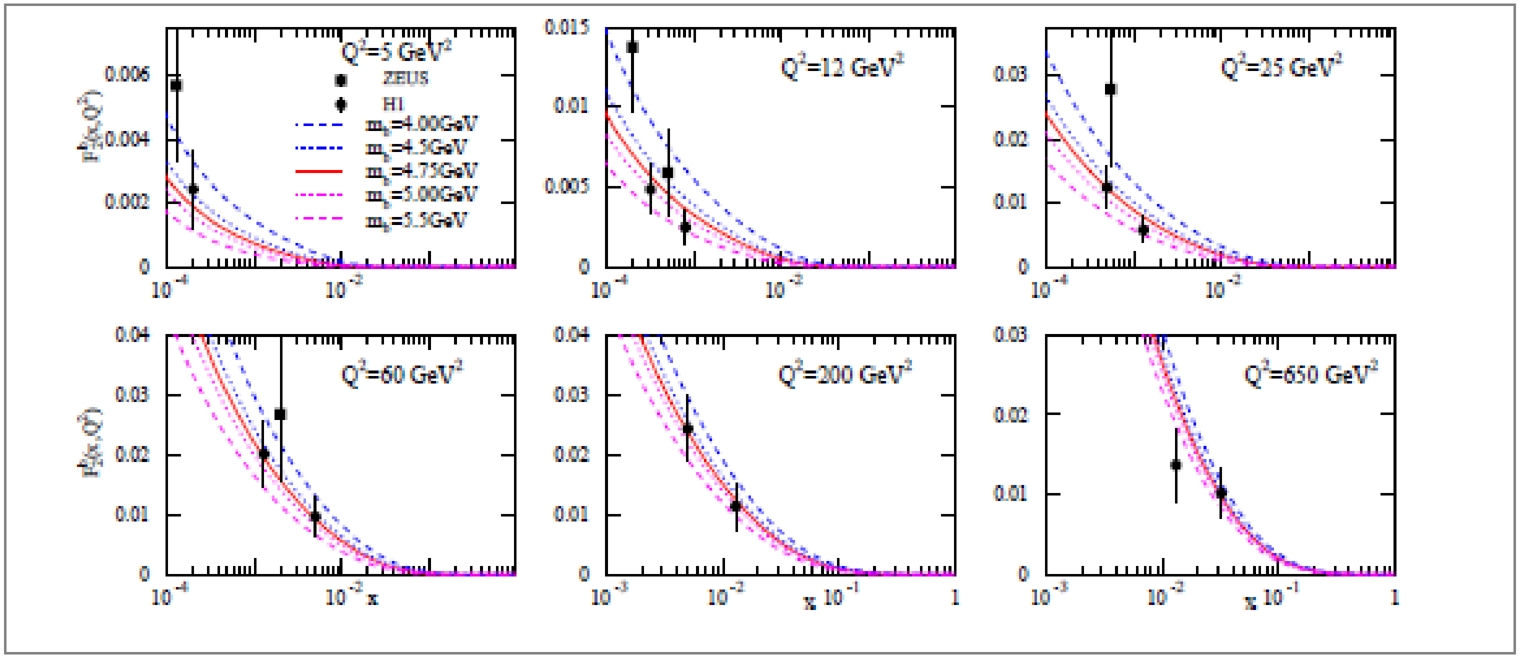


HERA results major impetus in calculation of NNLO splitting functions (Moch, Vermaseren and Vogt).

Enables global fits for pdfs, now all groups.

Example, light quark distribution at NNLO compared to NLO. Change from NLO to NNLO greater than uncertainty in each ($\sim 2\%$).

Heavy Flavours – Beauty



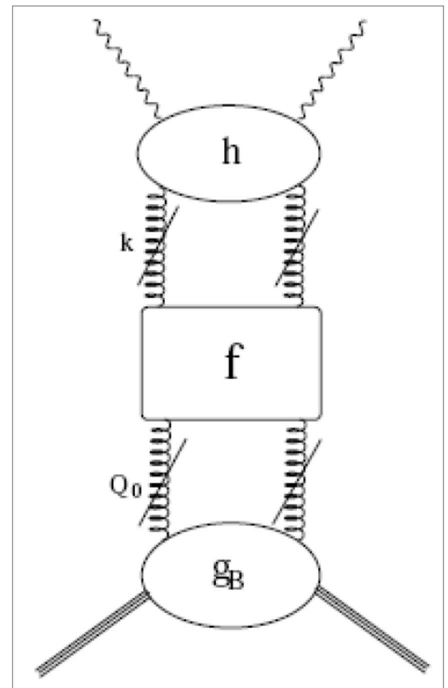
Combined charm structure function data starting to act as a real constraint on the gluon (particularly at NNLO in MMHT14), and allows accurate extraction of m_c (Alekhin, et al.).

Beauty data will never constrain PDFs, but on the edge of providing a good measurement of m_b.

Small-x corrections.

For a long time a dominant area of research for theorists working on HERA physics.

Look at a brief history. Development as long as any experiment.



Late 1970s, LO BFKL equation for high energy limit in QCD - related to gluon ladders

$\sigma(x, Q^2)$ and later $xP_{ij}(x), C_{i,j}(x) \sim x^{-\lambda}$ – where in each $\lambda = 12/\pi \ln 2\, \alpha_S \approx 2.7\alpha_S$.

Early-mid 1990s analysis of structure function impact by may groups

Also look for signs in jets, Orr-Stirling, $+\cdots$, onium-onium Salam, i.e. where $Q_0^2 \sim k^2$.

Showed matching onto normal perturbative expansion possible. Growth really too steep, $\sim x^{-0.5}$ asymptotically.

OK, in some respects good, but became harder to fit to data as it improved.

However, in early 1998 data pressure overtaken by theory disaster – NLO calculation Fadin and Lipatov, Camici and Ciafaloni.

$$\lambda = 2.7\alpha_S * (1 - 6.4\alpha_S + \cdots),\ \text{i.e. unstable.}$$

At NLO fundamentally more complicated. Cannot ignore running coupling or dependence on scales at each end of gluon ladder, i.e. is variable $s/k^2, s/Q_0^2$ or $s/(kQ_0)$.

In 1998 essentials of importance of running coupling and change of scales (collinear resummation) presented.

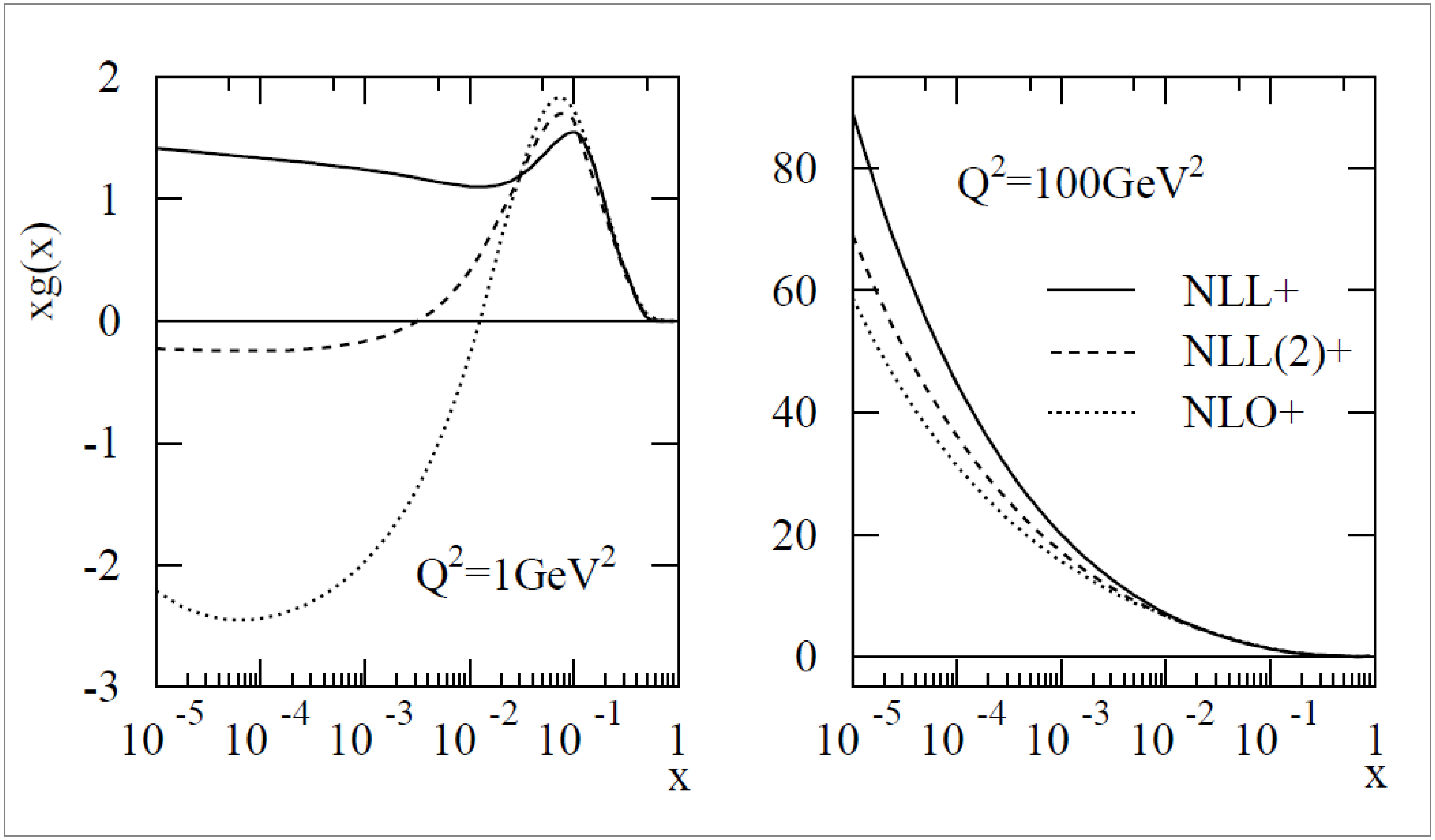
Large part of NLO correction to kernel due to large logs inherent in scale change. Can be resummmed to all orders.

Factorization $\rightarrow$ evolution with Q^2 in BFKL equation sensitive to UV diffusion – coupling weaker more convergent expansion. Normalization/input sensitive to IR diffusion – coupling stronger.

Also duality of splitting functions between high Q^2 and small x proposed.

BFKL physics in jets etc. messy theoretically unless scales fairly large. Work by Andersen, Sabio-Vera $\cdots$ Results in HEJ program.

In 2006 enough finally worked out (heavy quarks a complication) for a fit with NLO plus NLO resummation (White, RT).

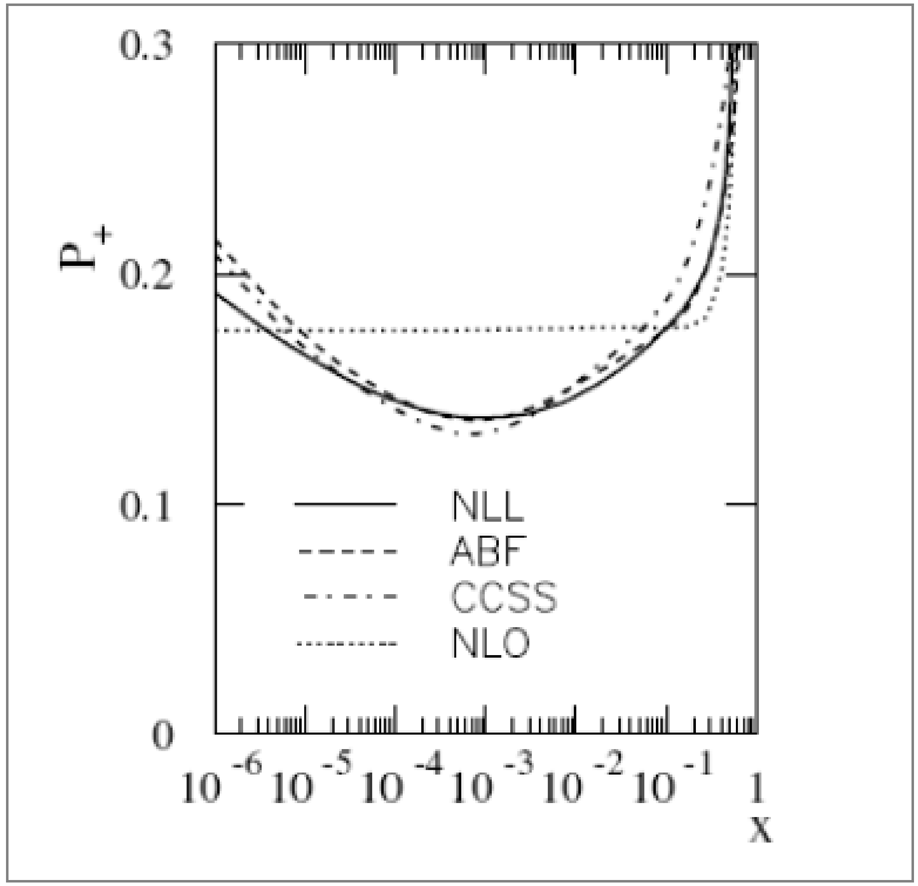


$\rightarrow$ moderate improvement in fit to HERA data within global fit, and moderate change in extracted gluon (more like quarks at low Q^2).

By 2008 very similar results coming from the White-RT, Ciafaloni-Colferai-Salam-Stasto and the Altarelli-Ball-Forte procedures, despite some differences in technique.

Full set of coefficient functions still to come in many cases.

Note NLO corrections lead to dip in functions below fixed order values until slower growth (running coupling effect) at very small x.

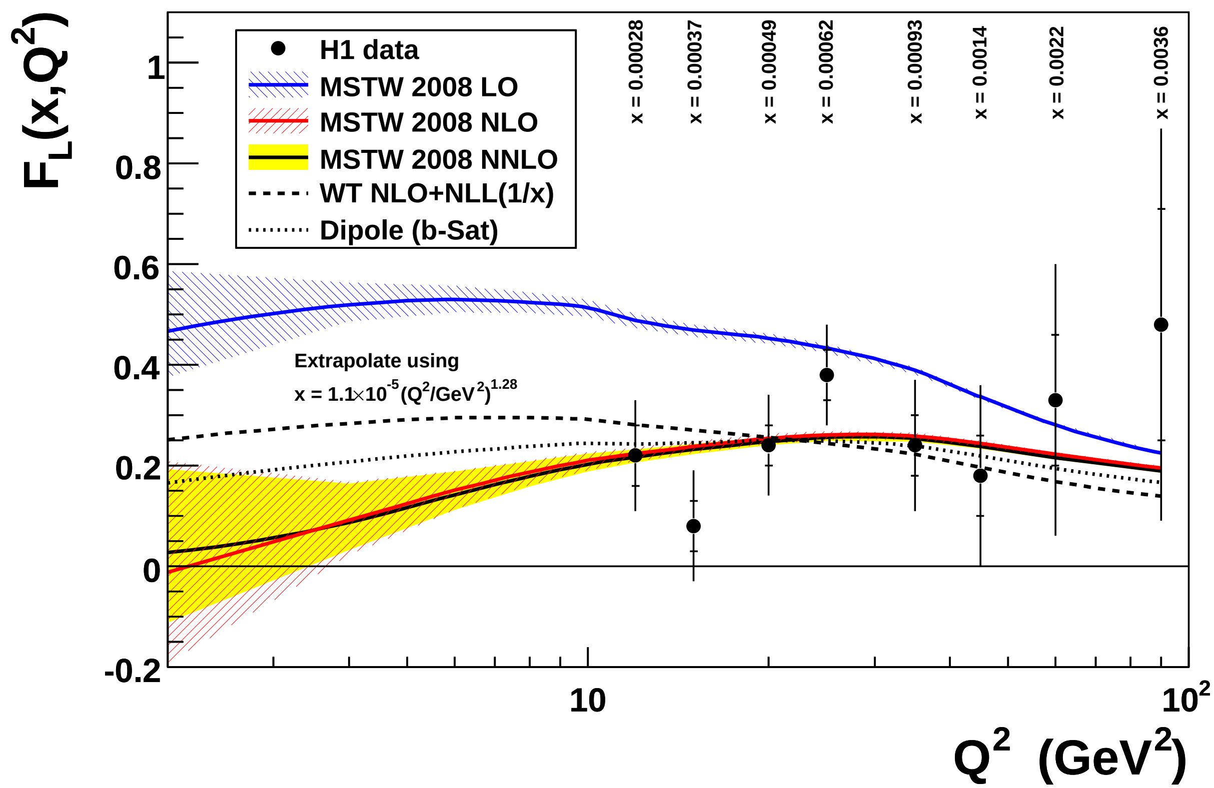


May possibly be significant to small x details, and spoil $3-4\%$ theoretical accuracy.

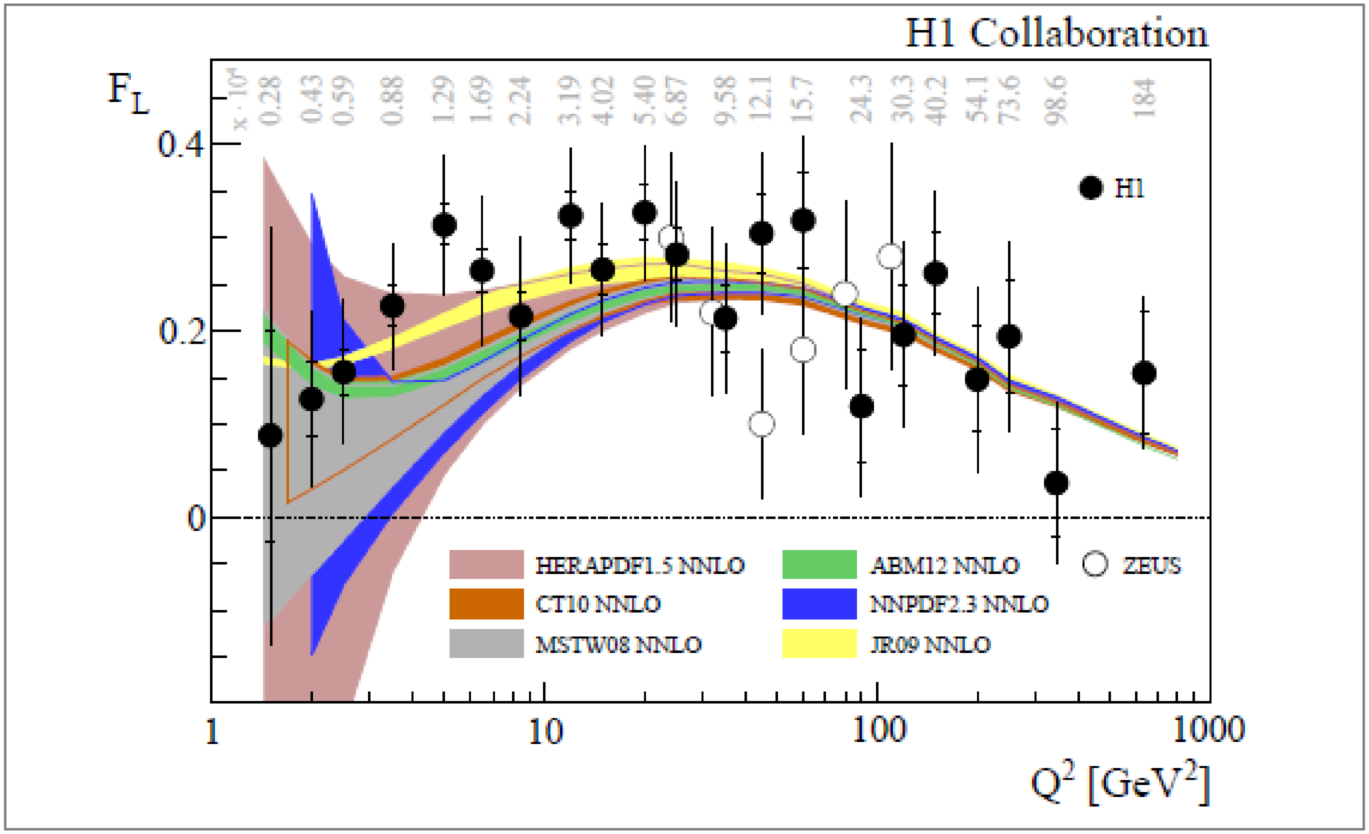
Need to fit to more than just $F_2(x,Q^2)$ and highly correlated $F_2^{c\bar{c}}(x,Q^2)$, to check. Need another prediction, gluon can change to mask theoretical corrections with just one variable to fit.

Measurement of $F_L(x, Q^2)$ with the final low-energy running have been coming out in recent years – last H1 data shown.

Reasonably consistent with – NLO, NNLO, dipole model predictions and resummed fits. Some possibiilities (LO QCD) ruled out.



Much improved recent data.



Still matched well with fixed-order predictions in general.

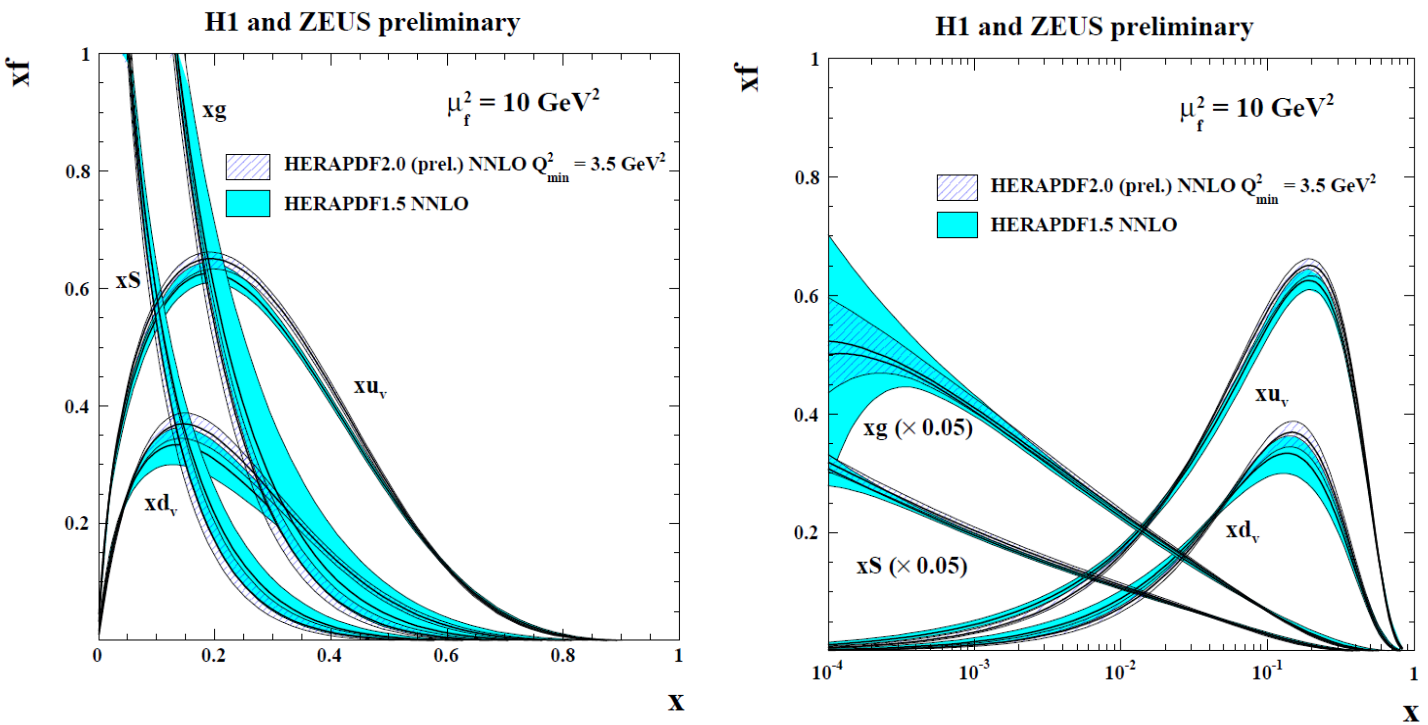
However, some signs of inconsistency at lower Q^2 – may suggest resummation or other effects.

Final Combined Structure Function Data

Showed final data earlier. Improved precision of HERAPDFs

Now make the same comparison by overlaying

NNLO
$Q^2 > 3.5$ GeV^2



Reduction in gluon uncertainty both at low-x and high-x.

A lot of this reduction is because the effect of the Q2 cuts is not as dramatic now that we have more data.

(NOTE: HERAPDF2.0 has smaller uncertainty on the high-x g-g luminosity and hence on top predictions!)

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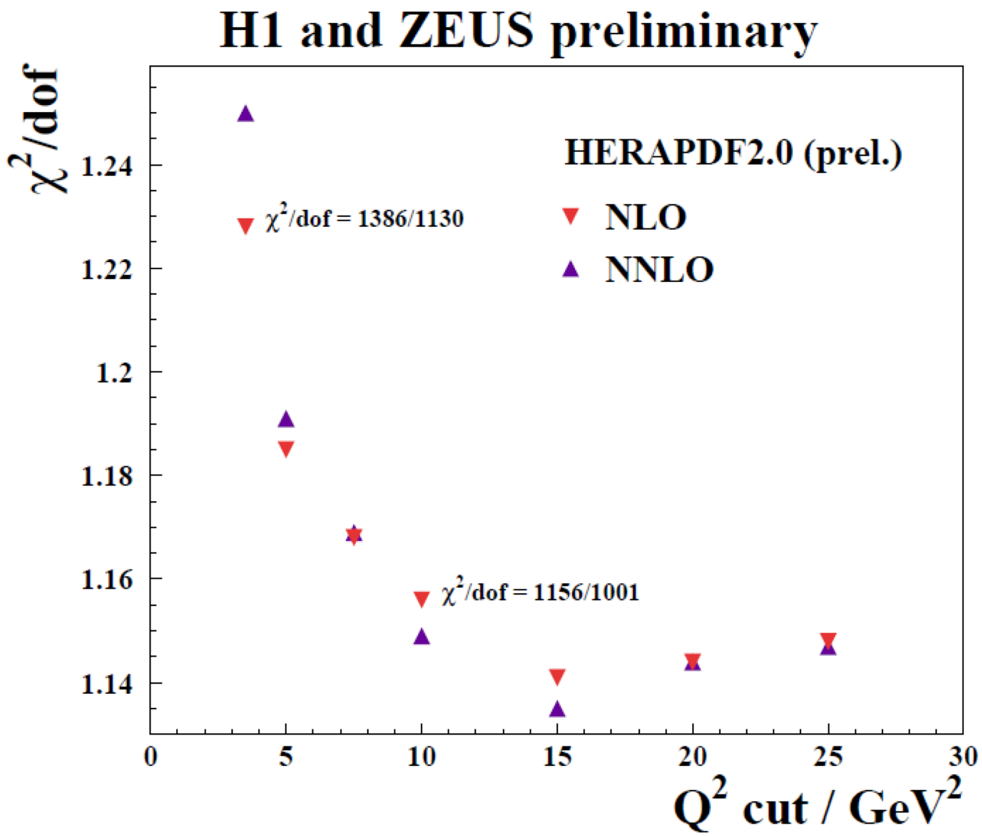
Reconsider the Q2 cut on the data

Traditionally Q2>3.5 GeV2



For Q^2_{min}= 3.5 GeV^2

Chi2/dof (NLO) = 1386/1130

Chi2/dof(NNLO)= 1414/1130

For Q^2_{min}= 10 GeV^2

Chi2/dof (NLO) = 1156/1001

Chi2/dof(NNLO)= 1150/1001

Dependence of fit quality on Q^2_{cut} – correlated with x. Not yet clear if present in global fits. Possible sign of nonstandard QCD effects.

Conclusion

Have tried to cover interaction between particle theory and HERA physics.

HERA has made significant contributions to our understanding of electroweak and BSM physics, and very large parts of QCD. These contributions highlight the continuing need for complementary experiments for a full investigation of most particle physics.

HERA has made a fundamental contribution to our understanding of precision strong interaction physics, and we would be able to do very little at LHC without this.

Has provided us theorists with the potential of doing and testing QCD to $\sim 2\%$. However, we still are still uncertain whether we are quite this precise.

Hopefully the best structure function data yet to to the general community will help us convince ourselves, or show us what improvements are still necessary.

HERA has given us a much more complete understanding of QCD and is certainly leading us to this extreme precision, which is/will be one of the major triumphs of particle physics in itself, as well as intrinsically linked to any future discoveries. Future improvements from HERA data to come.