Highlights of HERA-I results

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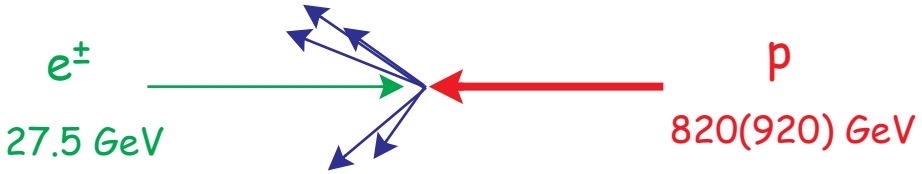
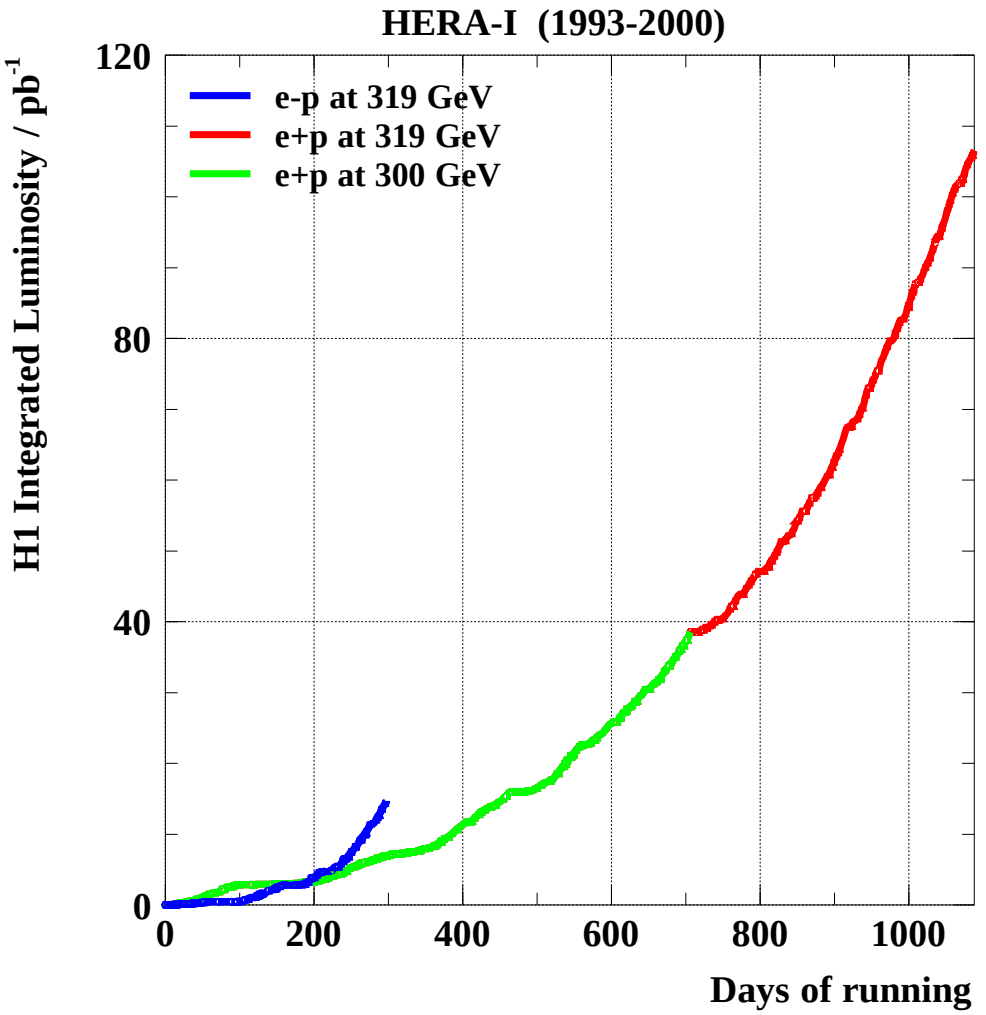
DESY

Available Data Sets from HERA I

HERA – the world's only ep collider

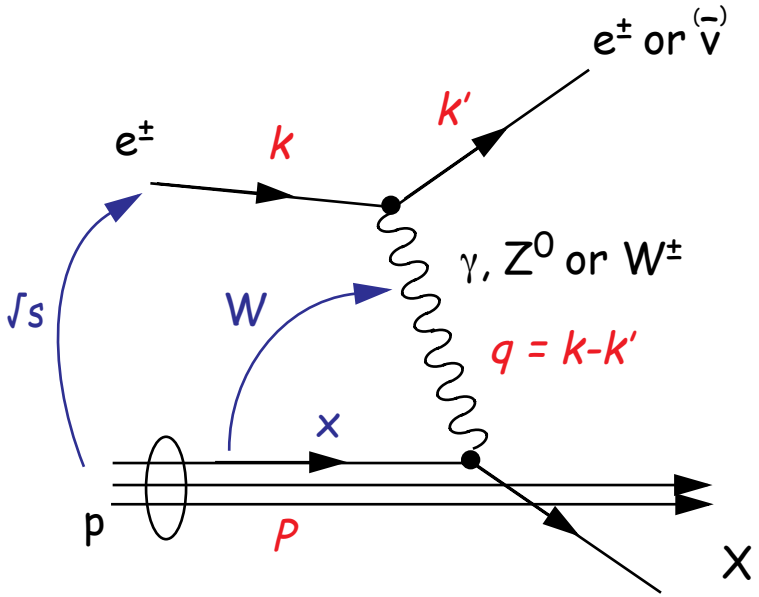


equivalent to 50 TeV fixed target



more than 100 pb^{-1} per experiment

DIS Kinematics



Kinematic variables:

- $Q^2 = -(k-k')^2 = -q^2$
  four momentum transfer squared
- $x = -\frac{q^2}{2P \cdot q}$
  momentum fraction of struck quark
- $y = \frac{q \cdot P}{k \cdot P}$
  $e^{\pm}$ energy fraction carried by γ : "inelasticity"
- $s = (k+P)^2 = \frac{Q^2}{x \cdot y}$
  ep center of mass energy squared
- $W^2 = (q+P)^2 = Q^2\frac{(1-x)}{x} + m_p^2 = M_X^2$
  mass squared of γ*p system

Inclusive DIS cross sections for $e^{\pm}p$

Neutral Current

$$\frac{d^2\sigma_{NC}^{e^{\pm}p}}{dxdQ^2} = \frac{2\pi\alpha^2}{x} \cdot \frac{1}{Q^4} \cdot \left[Y_+ \tilde{F}_2(x,Q^2) \mp Y_- x\tilde{F}_3(x,Q^2) - y^2 \tilde{F}_L(x,Q^2) \right]$$

$$\tilde{F}_2 \equiv F_2 - v_e \frac{\kappa_w Q^2}{Q^2+M_Z^2} F_2^{\gamma Z} + (v_e^2 + a_e^2)\left(\frac{\kappa_w Q^2}{Q^2+M_Z^2}\right)^2 F_2^Z = x\sum_i A_i(q_i + \bar{q}_i)$$

$$x\tilde{F}_3 \equiv -a_e \frac{\kappa_w Q^2}{Q^2+M_Z^2} xF_3^{\gamma Z} + (2v_e a_e)\left(\frac{\kappa_w Q^2}{Q^2+M_Z^2}\right)^2 xF_3^Z = x\sum_i B_i(q_i - \bar{q}_i)$$

Charged Current

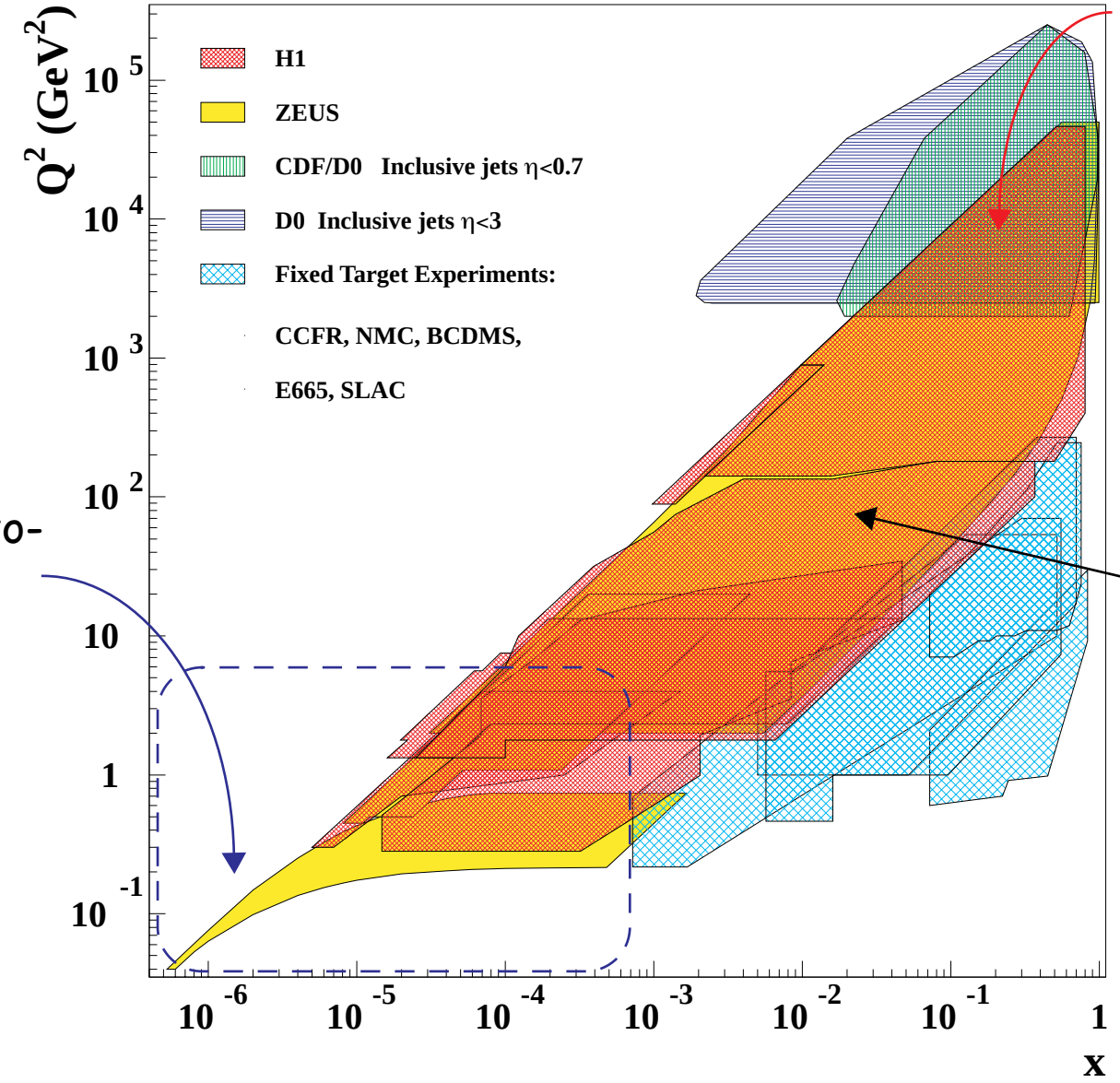
$$Y_{\pm} = (1 \pm (1-y)^2)$$

$$\frac{d^2\sigma_{CC}^{e^{\pm}p}}{dxdQ^2} = \frac{G_F^2}{2\pi x} \cdot \frac{M_W^4}{(Q^2+M_W^2)^2} \cdot \phi_{CC}^{\pm}(x,Q^2)$$

$$\phi_{CC}^{+} = x[(\bar{u}+\bar{c}) + (1-y)^2(d+s)]$$

$$\phi_{CC}^{-} = x[(u+c) + (1-y)^2(\bar{d}+\bar{s})]$$

Kinematic Reach of HERA



small Q^2:
DIS → photo-production

high Q^2 , x:

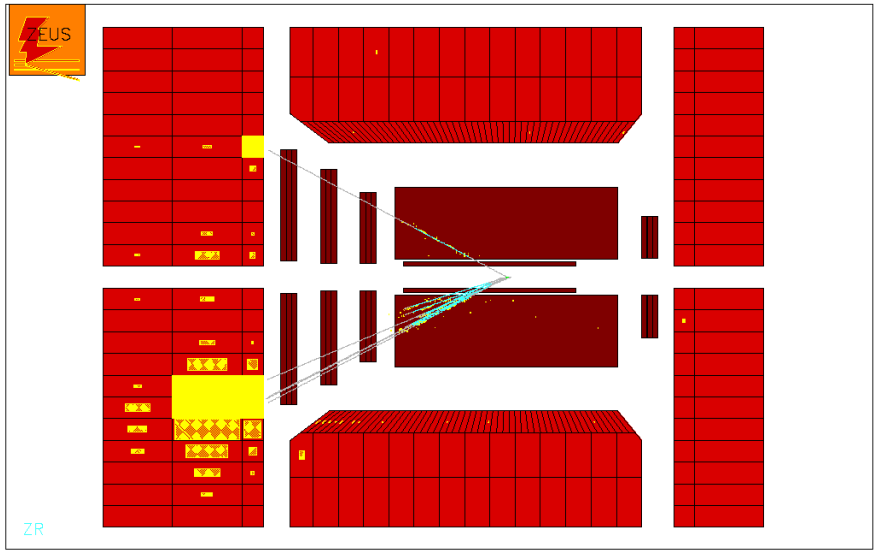
- electroweak effects
- valence quarks
- xF_3
- BSM physics

medium Q^2 :

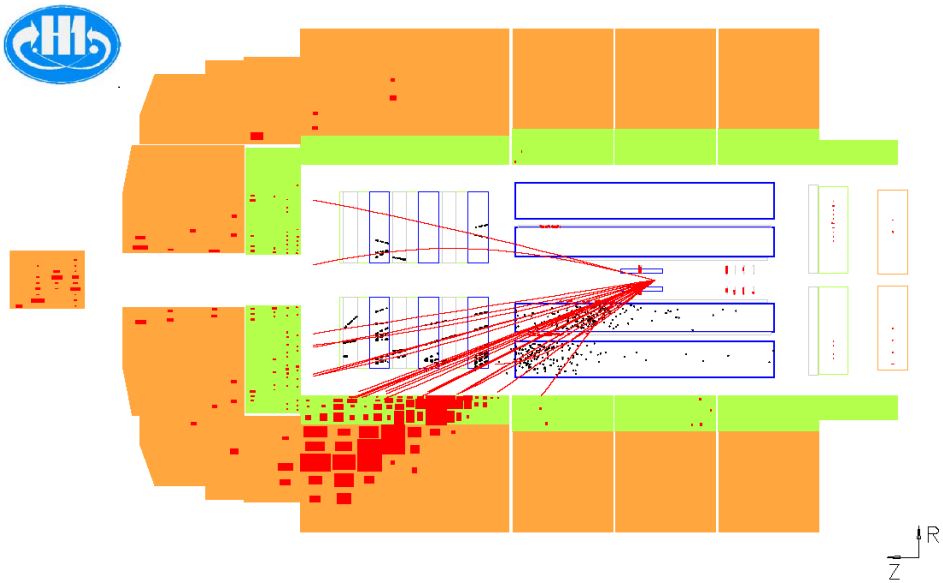
- F_2, F_L
- gluon pdf
- α_s

The Detectors: H1 and ZEUS

Neutral Current Event

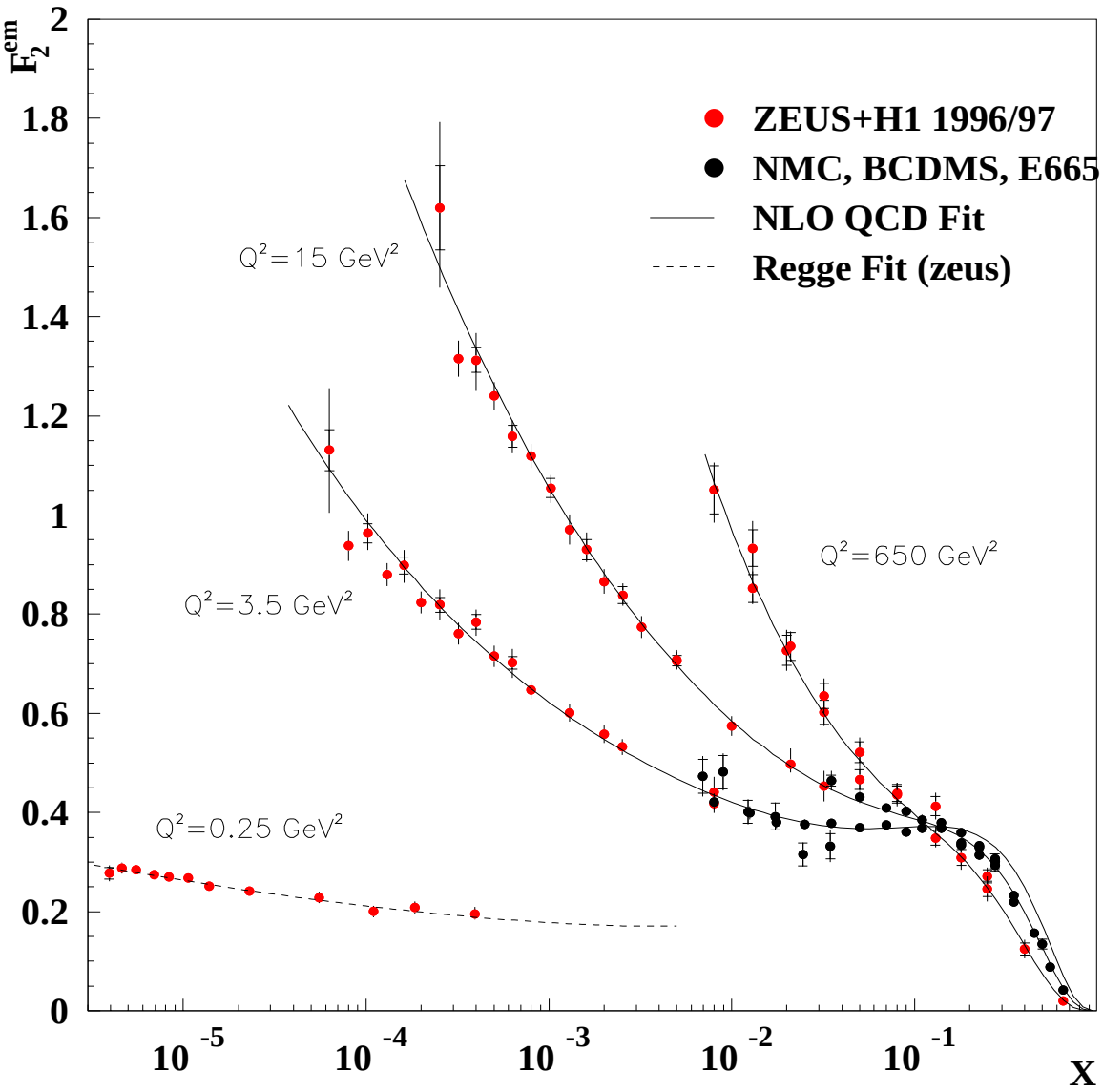


Charged Current Event



Calo	Nr. of Cells	σ_{θ_e} (mrad)	$\frac{\sigma}{\sqrt{E}}$ (e)	$\frac{\sigma}{\sqrt{E}}$ (had)	$\frac{\Delta E}{E}$
Uran. Sc.	6000	3	18 %	35 %	1 - 3 %
Liq. Ar	44000	2 - 5	12 %	50 %	1 - 3 %

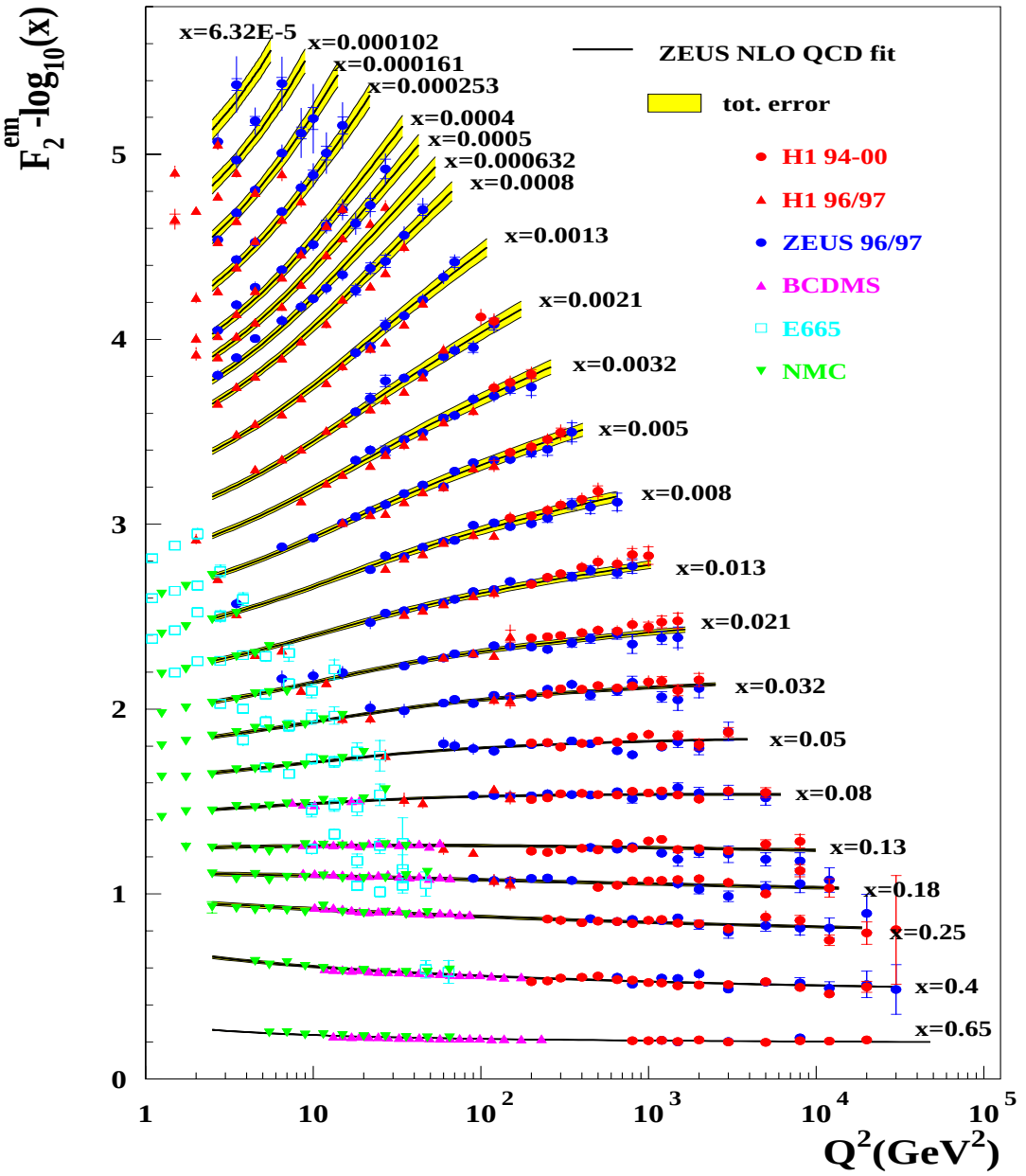
Rise of F_2



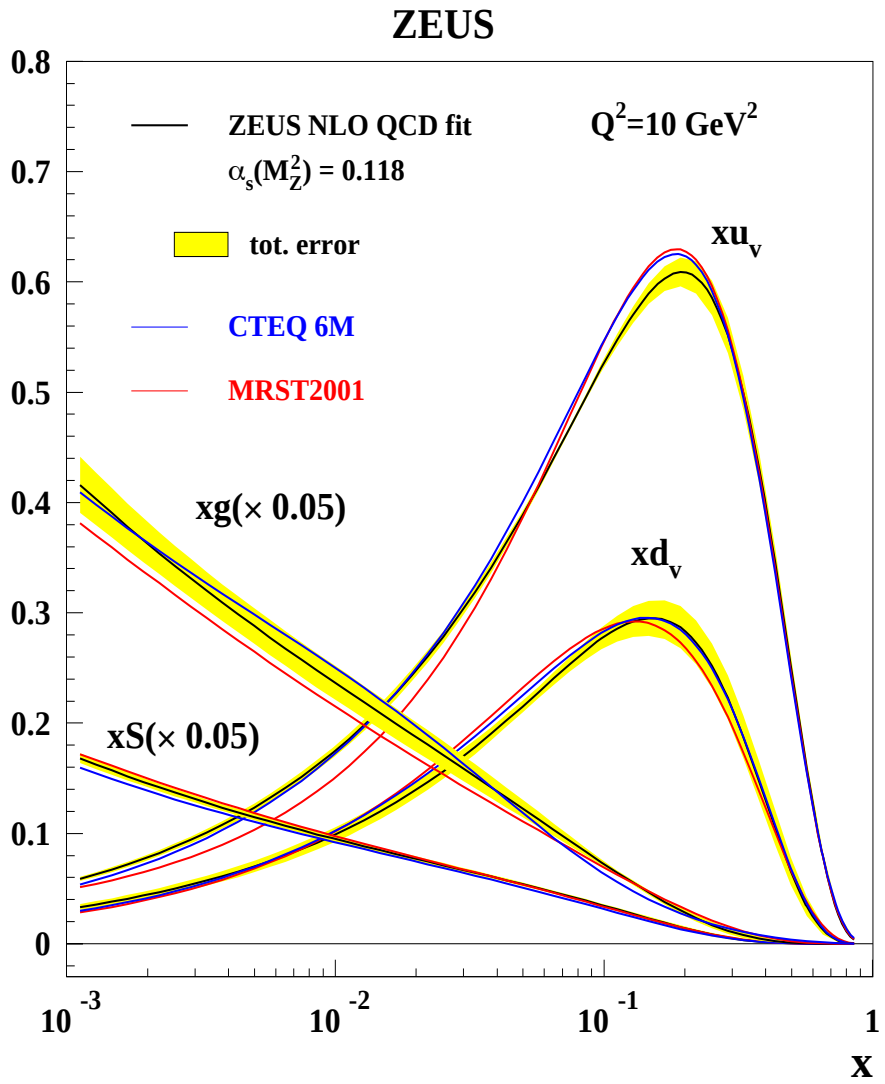
- first discovery at HERA
- strong rise at low x ($F_2 \sim x^{-\lambda}$)
- good agreement between H1 and ZEUS
- overlap with fixed target experiments
- high precision reached:
  ~1% (stat) ⊕ 2-3% (syst)

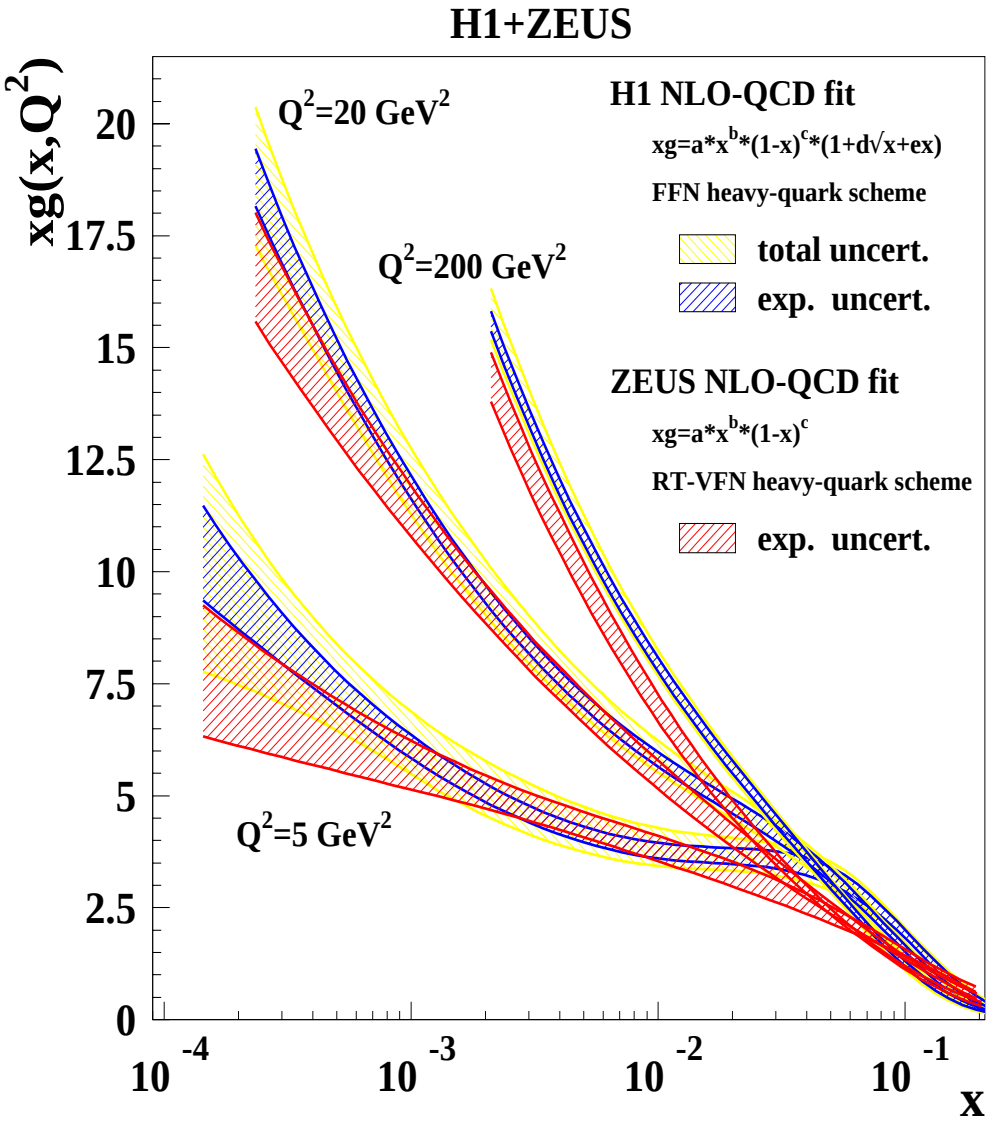
F_2 Scaling Violation

- H1 and ZEUS give consistent results
- positive and negative scaling violations clearly observed
- NLO QCD able to describe data over >4 orders of magnitude
- fit works even for Q^2 down to $O(1\ GeV)$



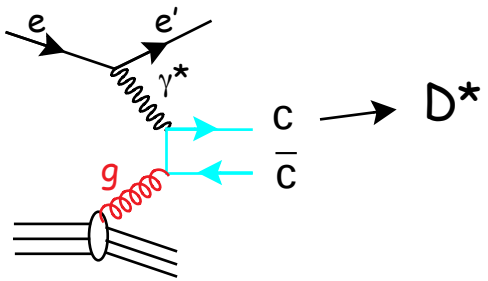
Quark & Gluon Distributions from HERA

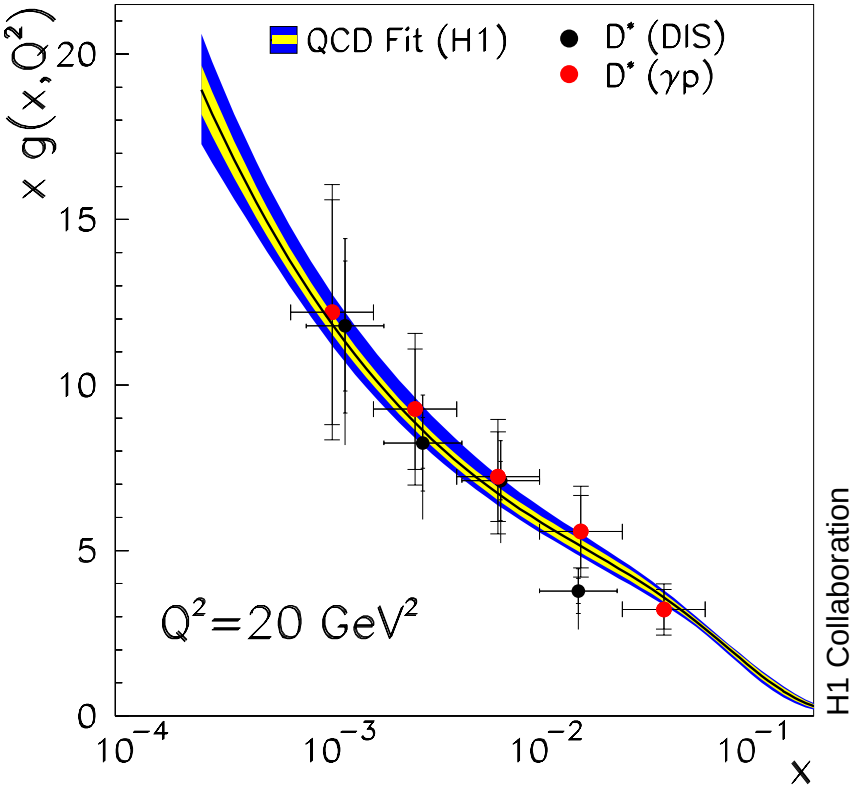




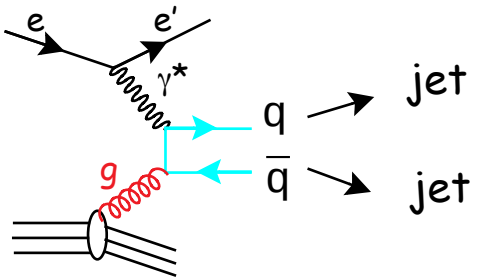
Universality of Gluon Determination at HERA

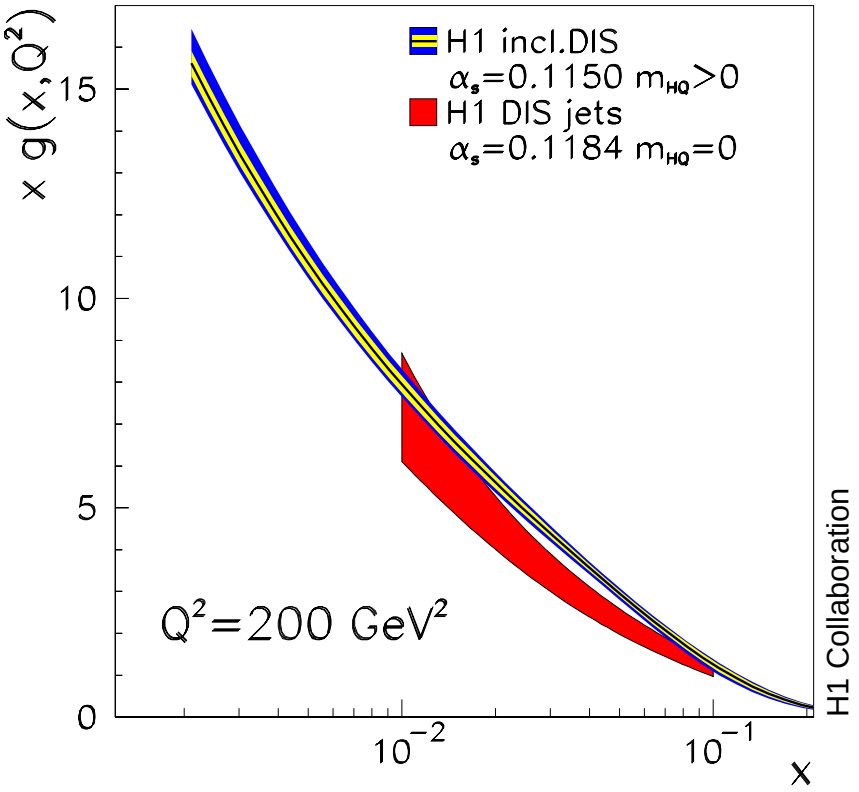
inclusive DIS vs D*



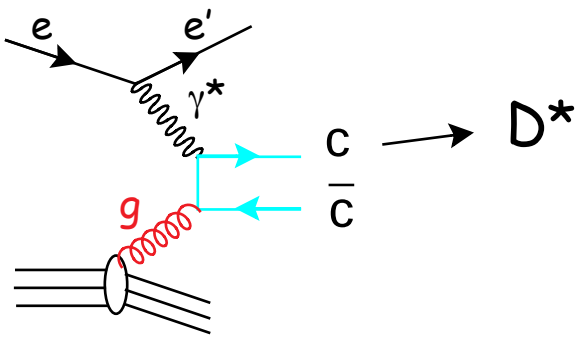


inclusive DIS vs DIS jets

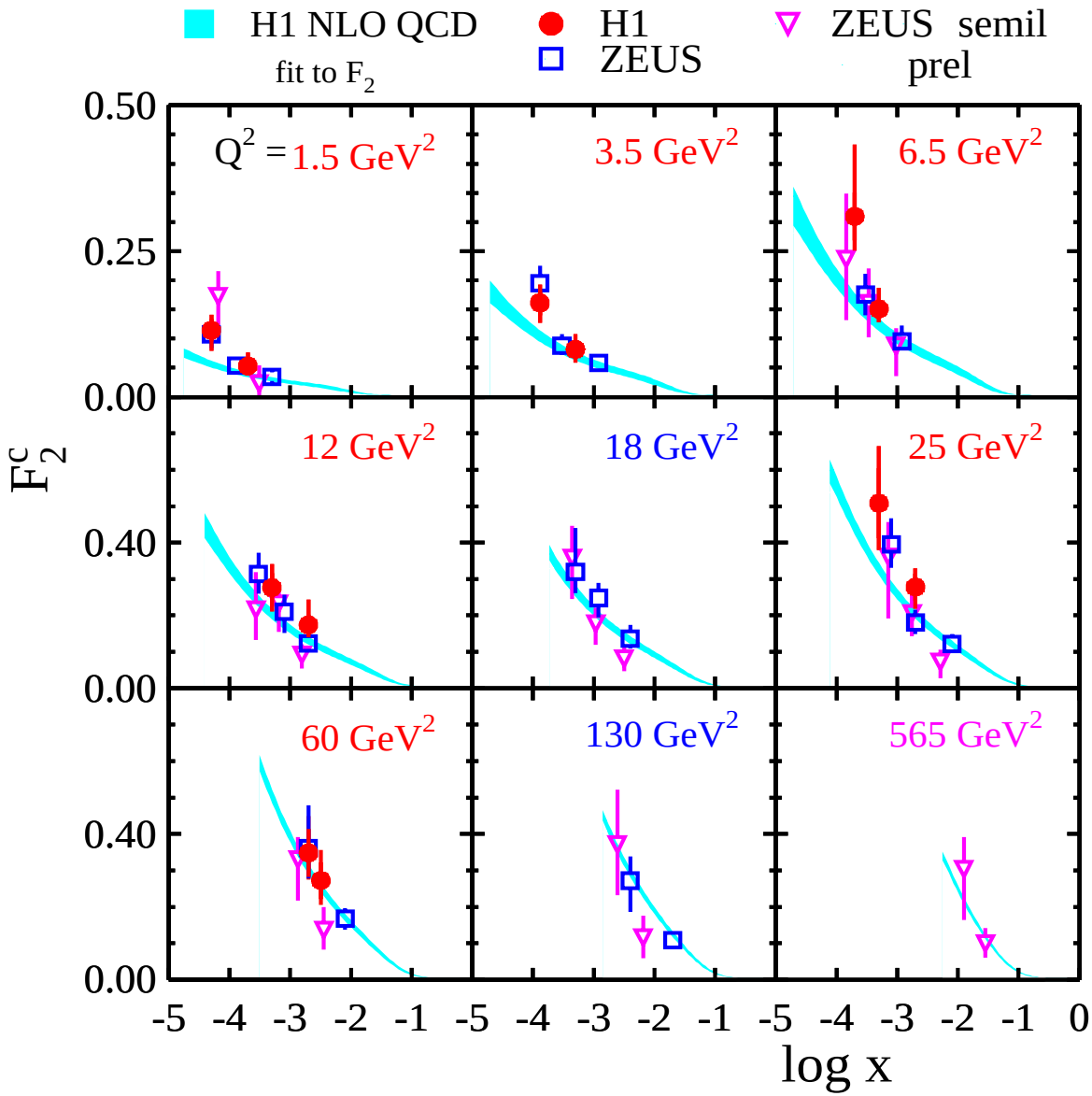




Charm contribution to F_2

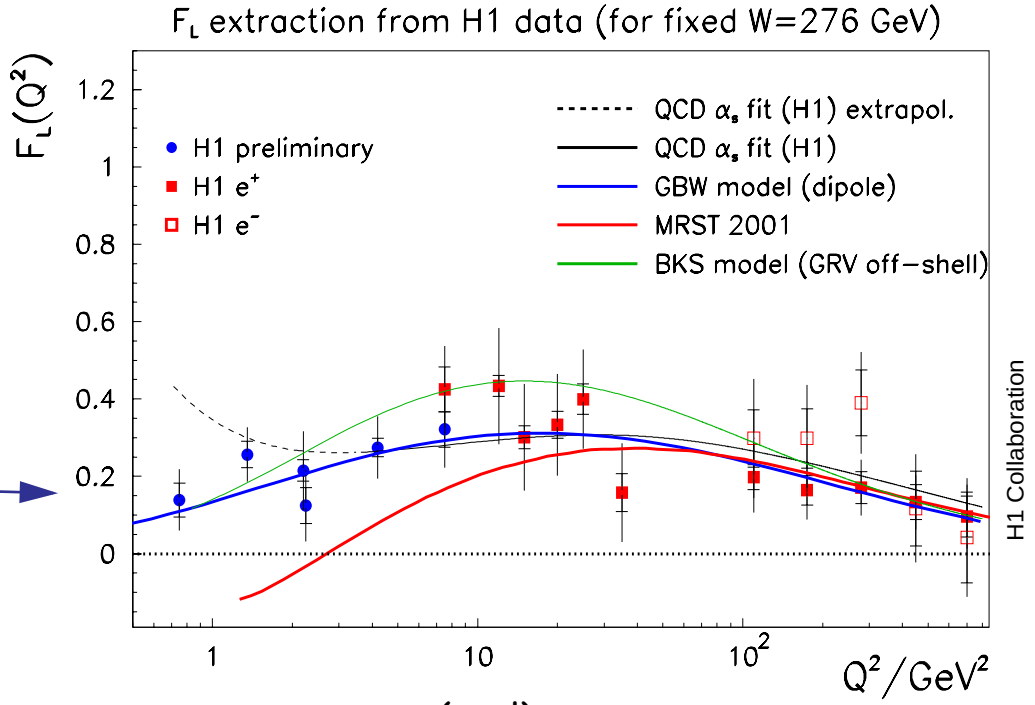


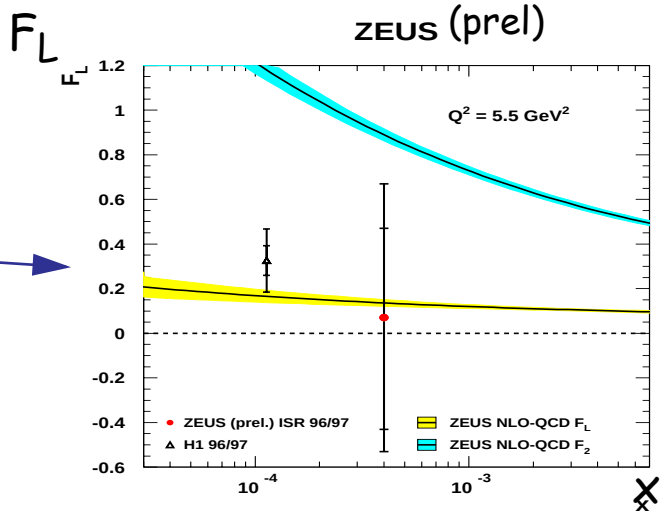
- Boson Gluon Fusion process gives direct handle on the gluon density
- D* as charm tag
- measured F_2^c consistent with NLO fit to inclusive data
- substantial charm contribution at HERA:
- at small x and $Q^2 > 10\ GeV^2$ $F_2^c/F_2 \approx 0.3$



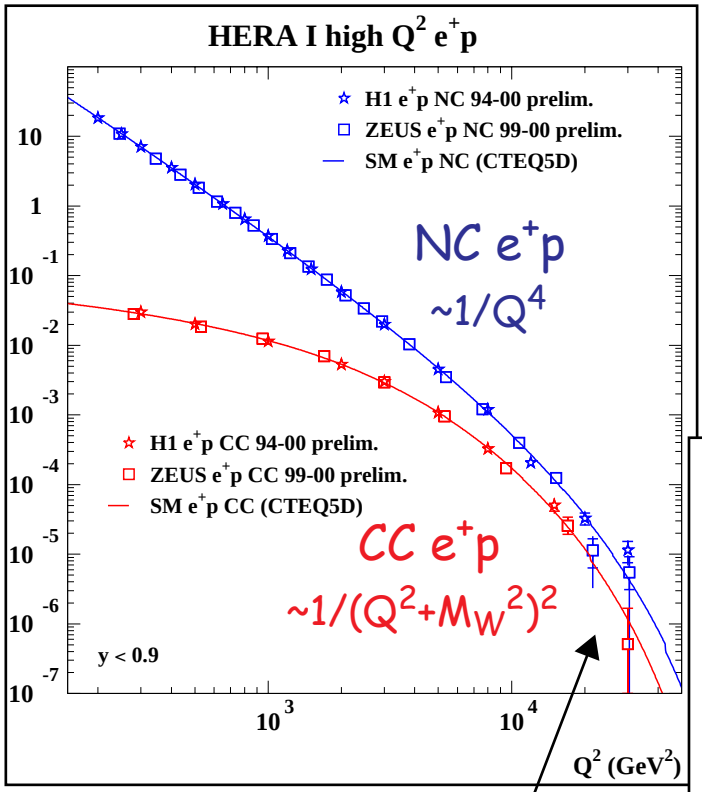
Longitudinal Structure Function F_L

- F_L = 0 in Quark Parton Model
  ⇒ important handle on Gluon
- Contribution to cross section damped by $\sim y^2$
- Indirect extraction methods (H1):
  - extrapolation method
  - derivative method
- Measurements so far well in agreement with QCD fit
- Some discriminating power at low Q^2
- For model independent analysis need data at different $\sqrt{s}$:
  - radiative events ISR (ZEUS)
  - run HERA-p at lower energies
    → HERA-II



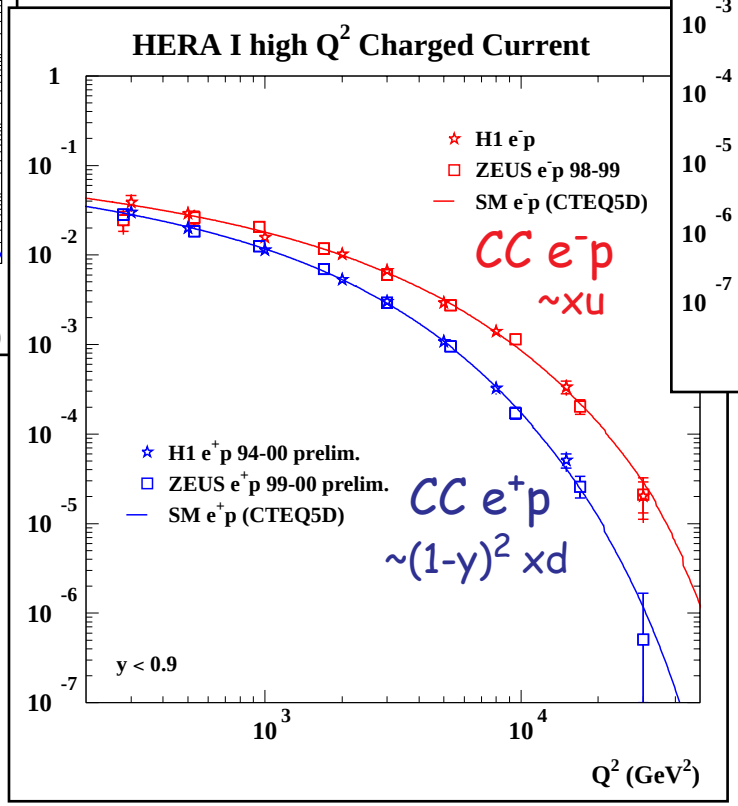


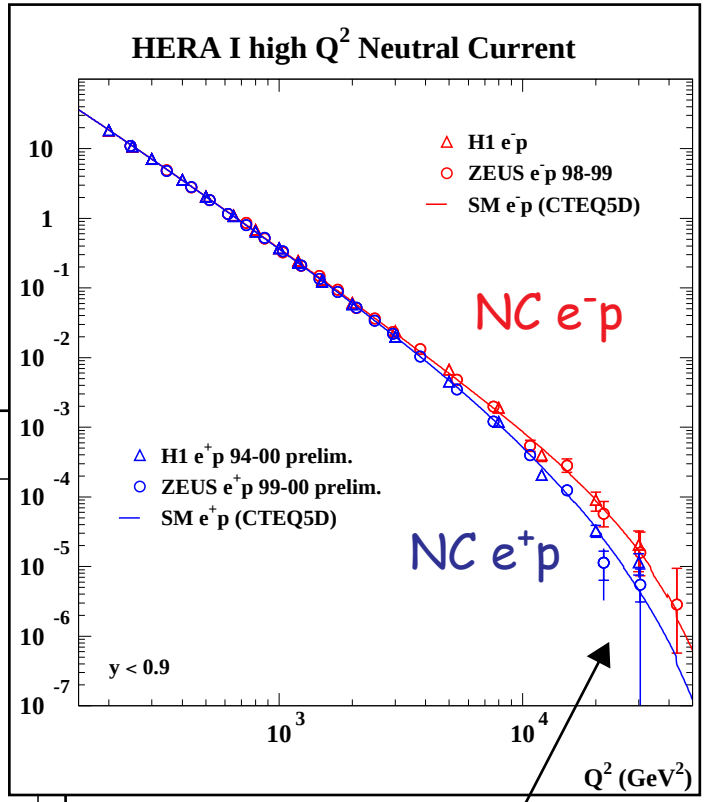
NC and CC cross section $d\sigma/dQ^2$ for e^+p and e^-p



$Q^2 \gg M_W^2 \rightarrow$ electroweak unification

- H1 and ZEUS agree
- data consistent with SM over >6 orders of magnitude





γZ interference $\rightarrow xF_3$

need more e^-p data !

Extraction of $xF_3^{\gamma Z}$

- Interference between photon and Z exchange → difference in cross section between e^+p and e^-p NC at high Q^2

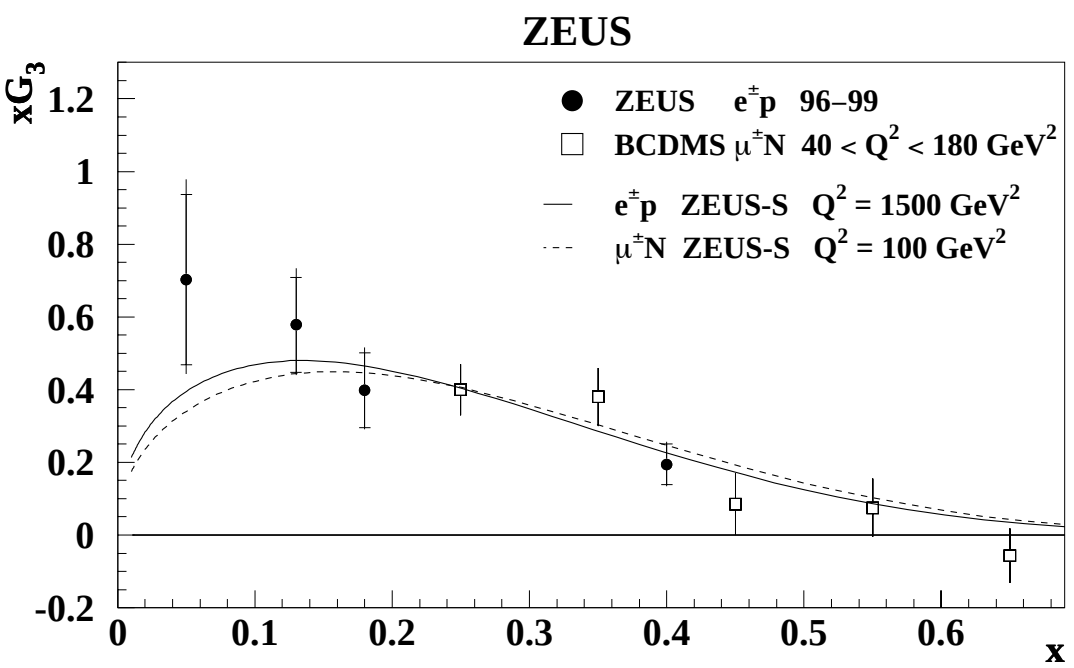
- $x\tilde{F}_3 = \frac{1}{2Y_-}[\phi_{NC}^- - \phi_{NC}^+]$

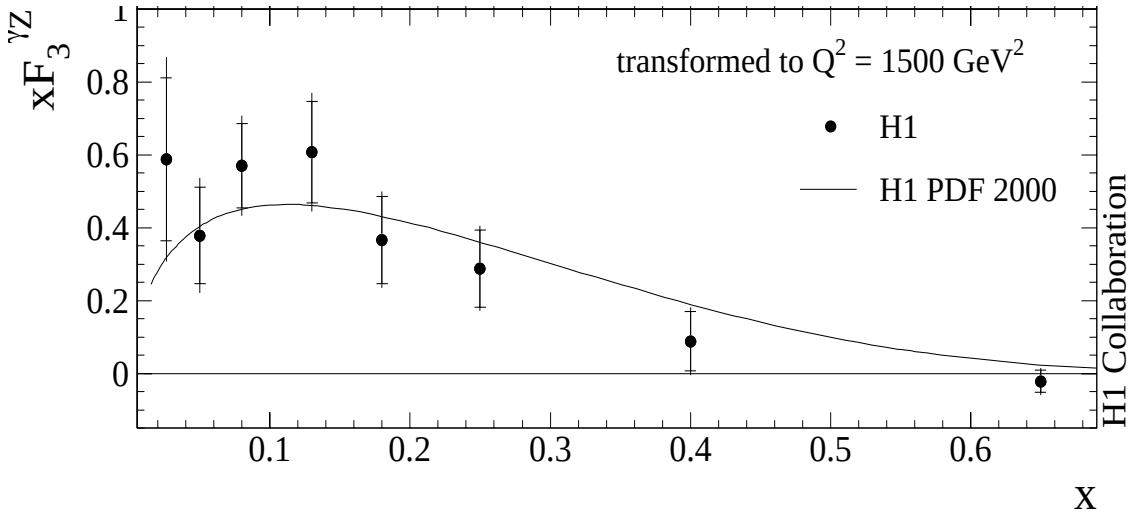
  neglect pure Z exchange

  → extract $xF_3^{\gamma Z} \equiv xG_3$

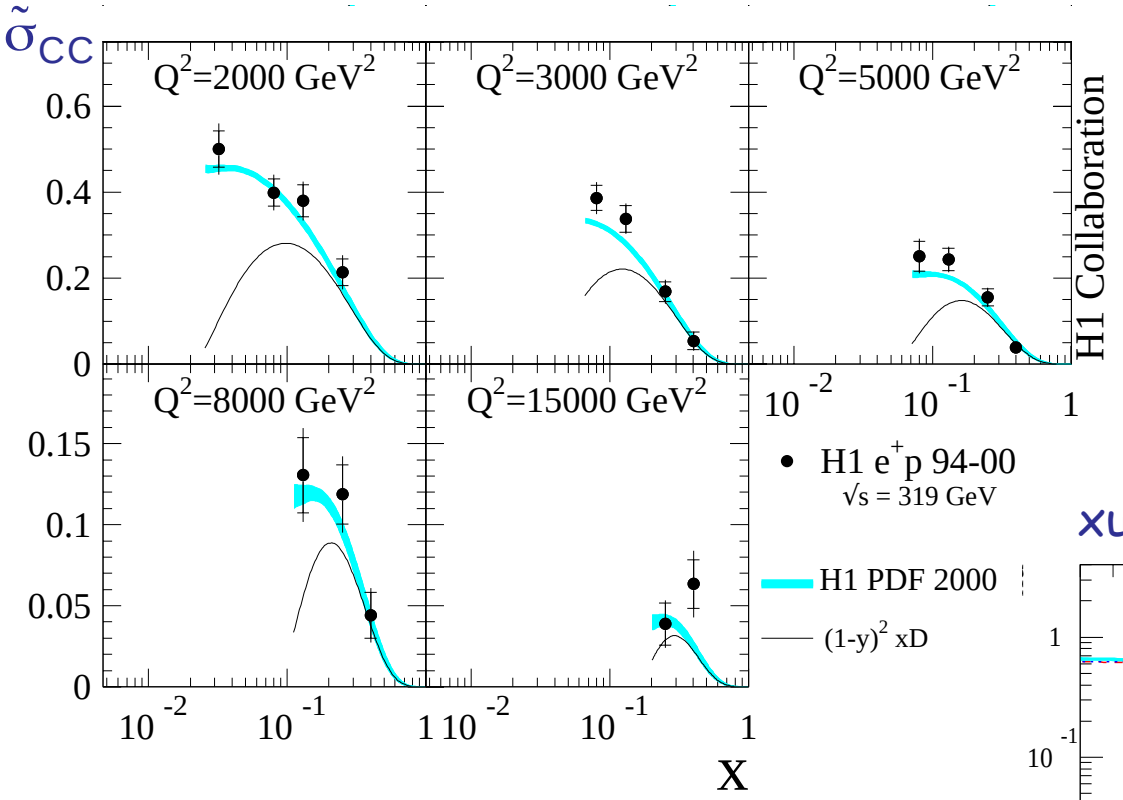
- statistical errors large, dominated by small e^-p statistics

- within errors good agreement with
  - fixed-target BCDMS data
  - QCD fits

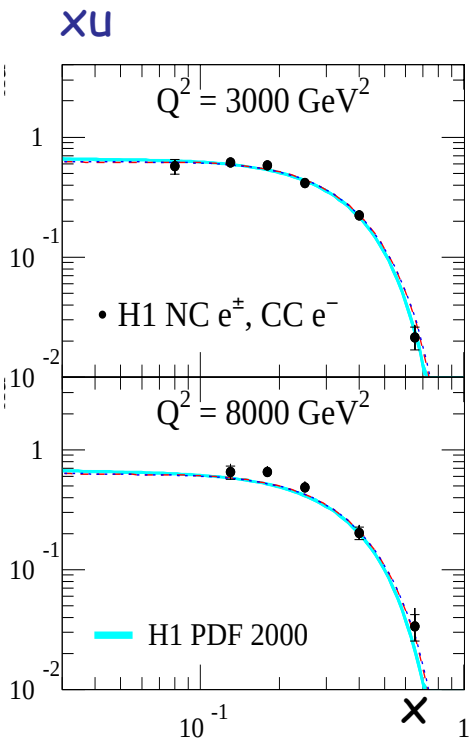


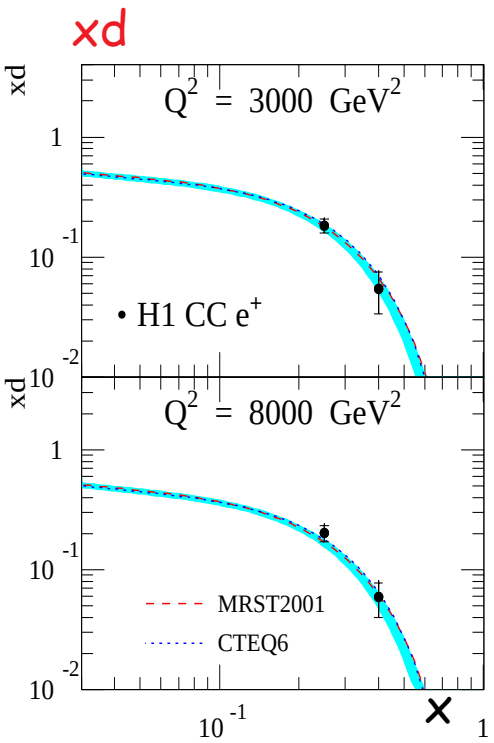


xu and xd at high x from CC



- xd dominates e^+p CC
- xu dominates e^-p CC and $e^\pm p$ NC
- local extraction where contribution to cross section is >70%



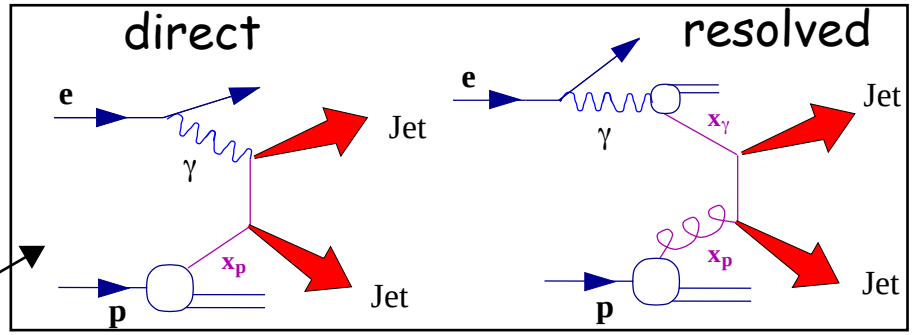


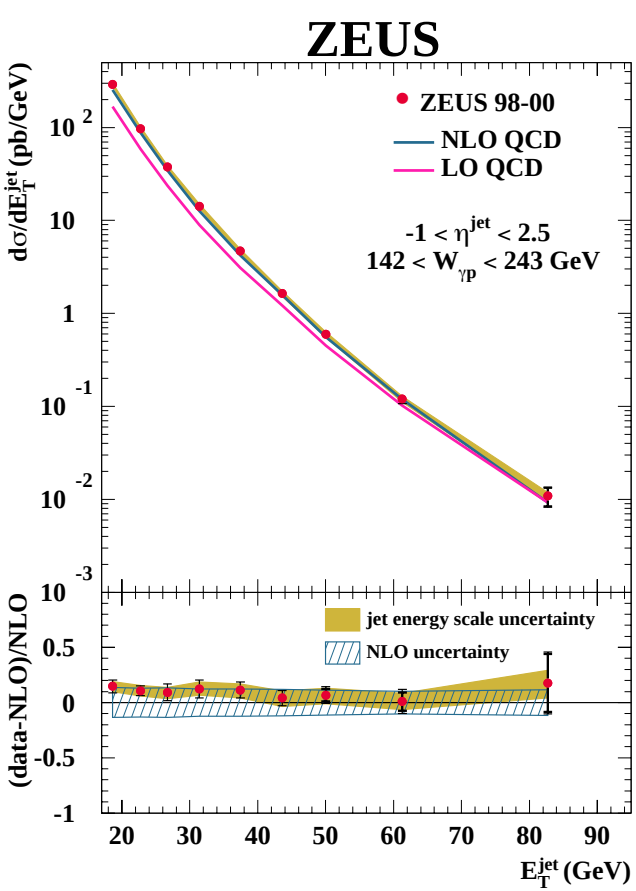
reduced cross section:

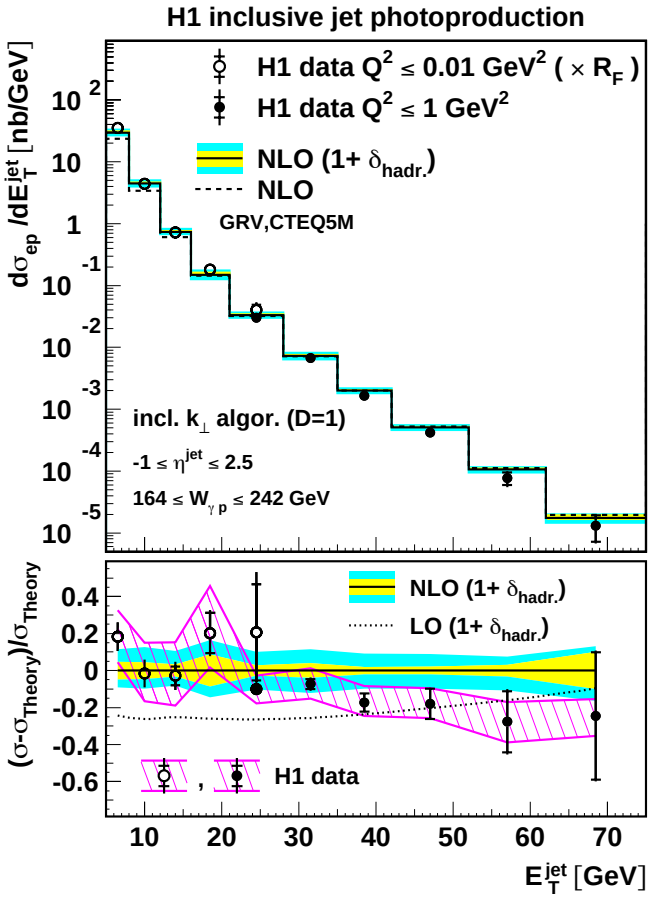
$$\tilde{\sigma}_{CC} = \frac{2\pi x}{G_F^2}\left[\frac{M_W^2 + Q^2}{M_W^2}\right]^2 \frac{d^2\sigma_{CC}}{dxdQ^2}$$

Inclusive Jets in Photoproduction

- hard scale provided by high transverse energy jet
- two types of processes contribute to high E_T jet production $O(\alpha\alpha_s)$
  - direct
  - resolved
- precise test of NLO QCD calculations
  - test of parametrisations of
    - proton pdfs
    - photon pdfs
- determination of α_s and its scale dependence

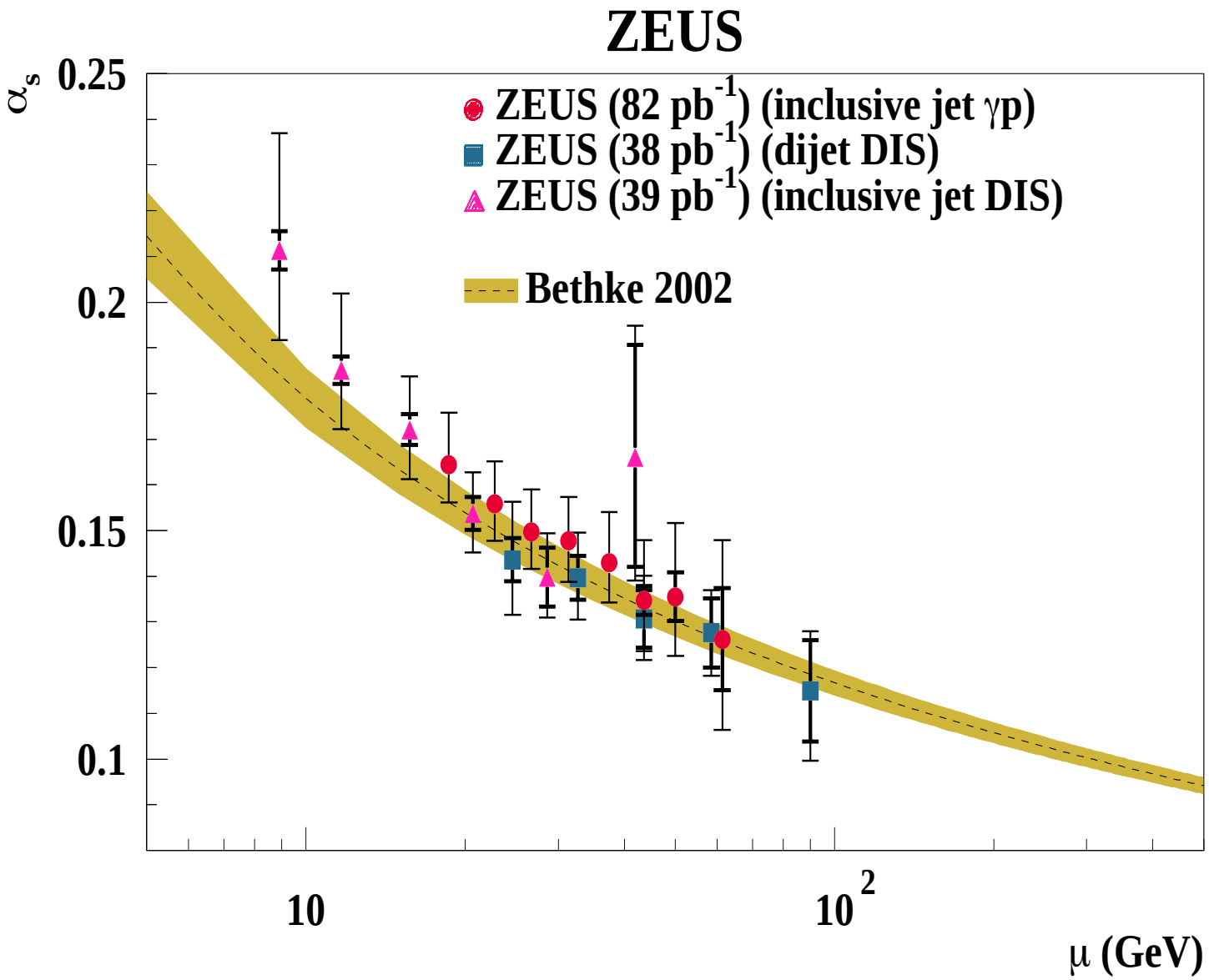




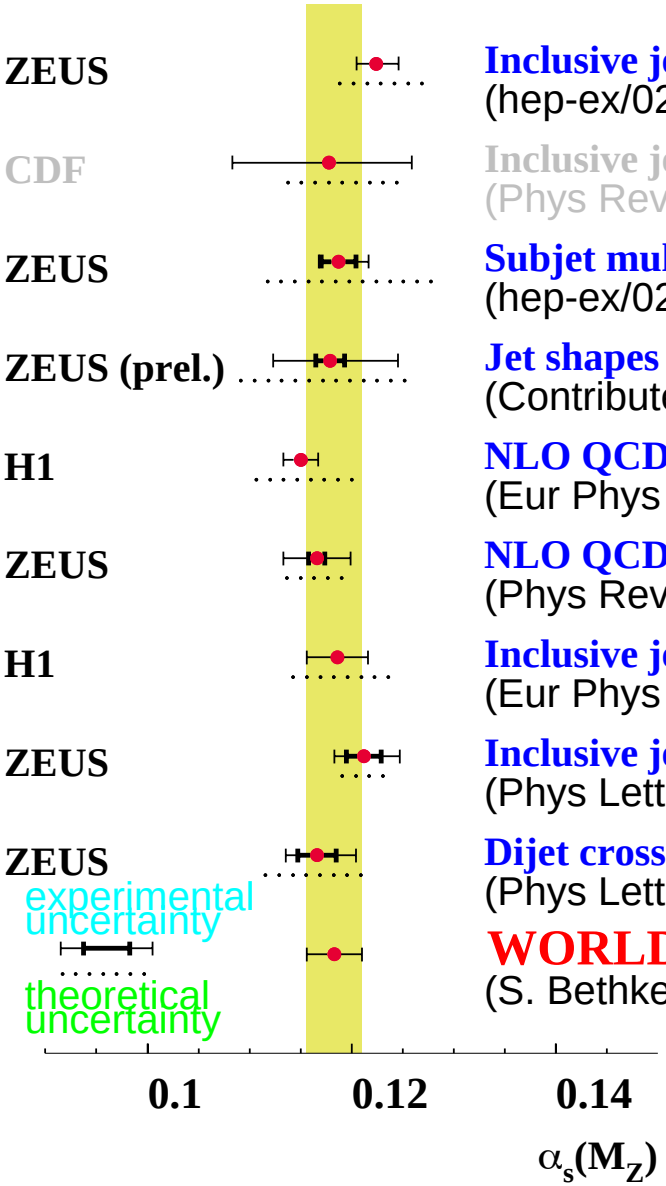


Running of α_s in a single Experiment

- running of α_s clearly observed over an order of magnitude in scale variation within a single experiment
- consistency between different analyses



Summary of α_s measurements at HERA I



Inclusive jet cross sections in γp
(hep-ex/0212064)

Inclusive jet cross sections in pp
(Phys Rev Lett 8 (2002) 042001)

Subjet multiplicity in DIS
(hep-ex/0212030)

Jet shapes in DIS
(Contributed paper to ICHEP01)

NLO QCD fit
(Eur Phys J C 21 (2001) 33)

NLO QCD fit
(Phys Rev D 67 (2003) 012007)

Inclusive jet cross sections in DIS
(Eur Phys J C 19 (2001) 289)

Inclusive jet cross sections in DIS
(Phys Lett B 547 (2002) 164)

Dijet cross sections in DIS
(Phys Lett B 507 (2001) 70)

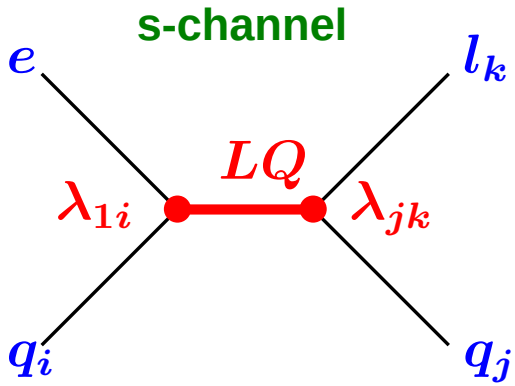
WORLD AVERAGE
(S. Bethke, hep-ex/0211012)

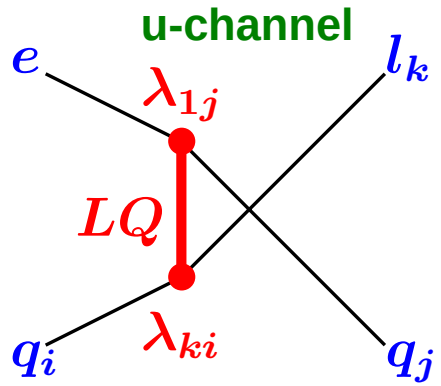
- very different measurements agree with each other within errors
- measurements from HERA are consistent with world average
- precision competitive with world data
- in most cases experimental errors smaller than theoretical errors
- need higher orders
- NNLO calculation under way ...

Search for Leptoquarks: Resonances

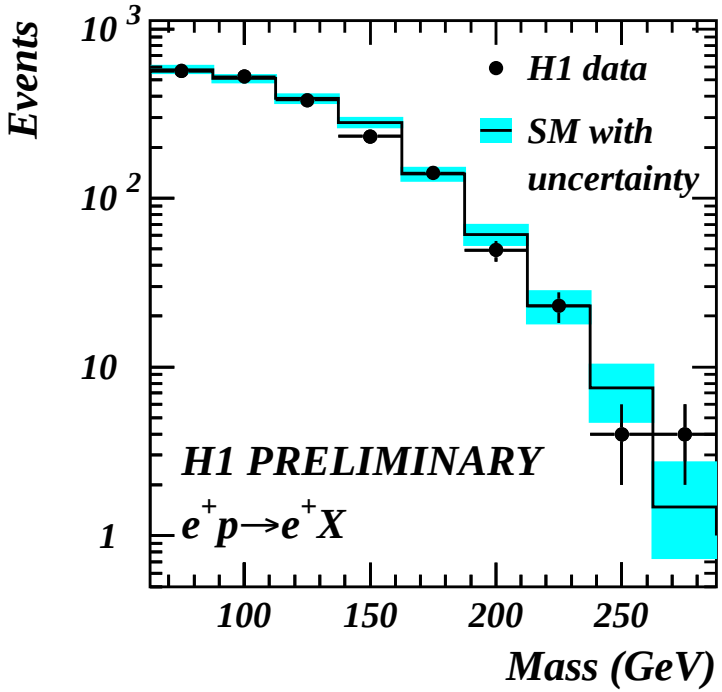
Leptoquark production at HERA:

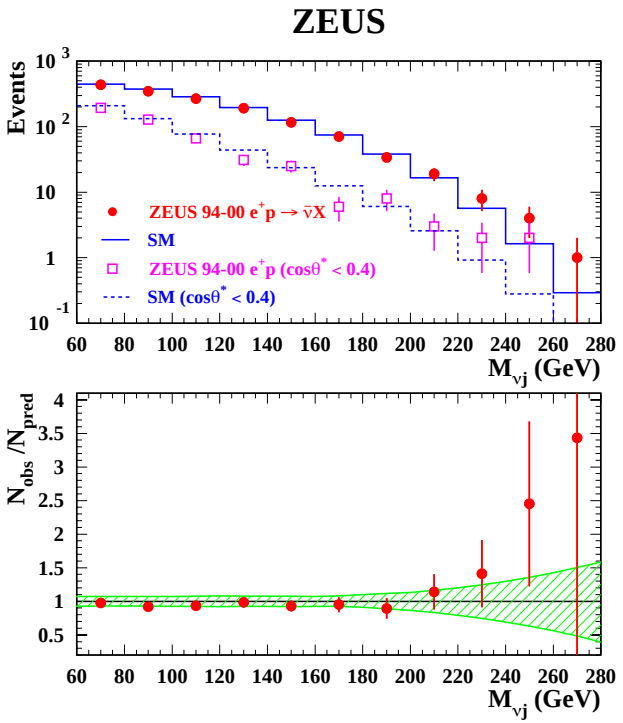
$\sigma \sim f(\lambda, M_{LQ})$



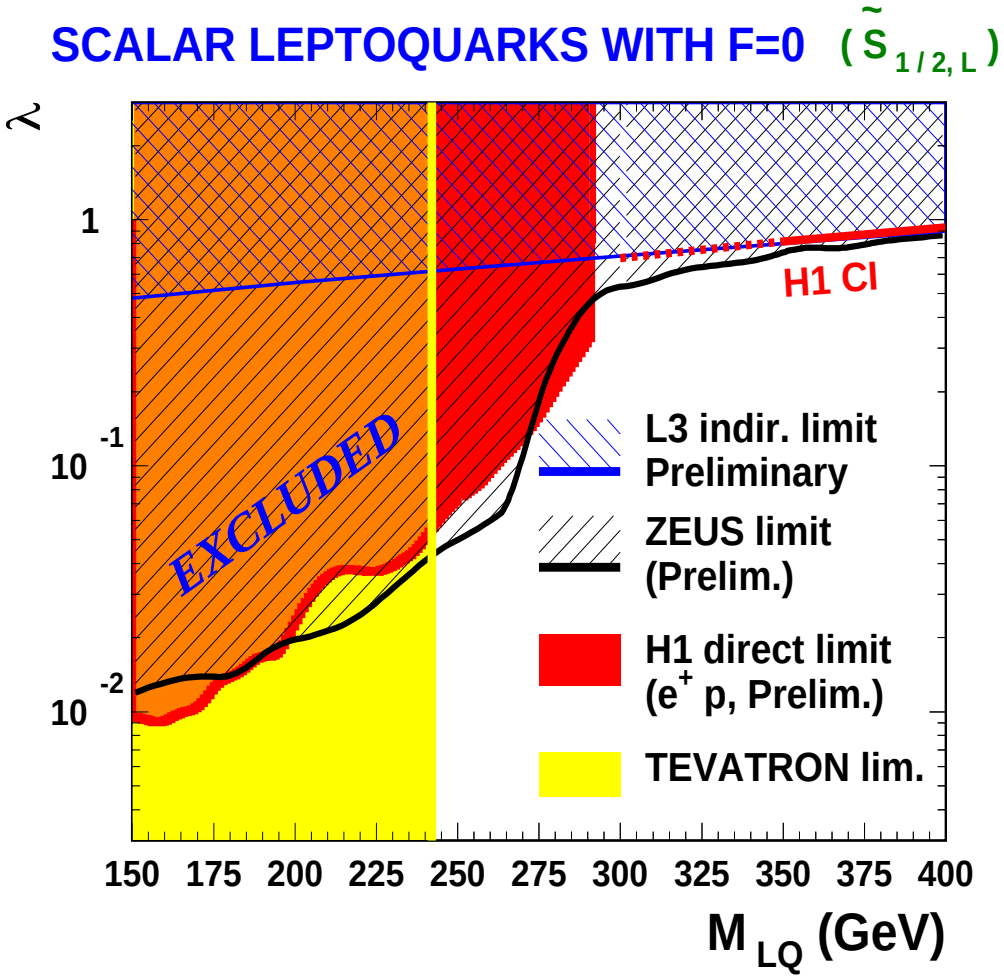


- Scalar or Vector color triplet bosons
- Carry both Lepton and Baryon number
- Fractional electric charge
- Appear in many extensions of SM





Leptoquark Limits from HERA



No excess seen over SM expectation

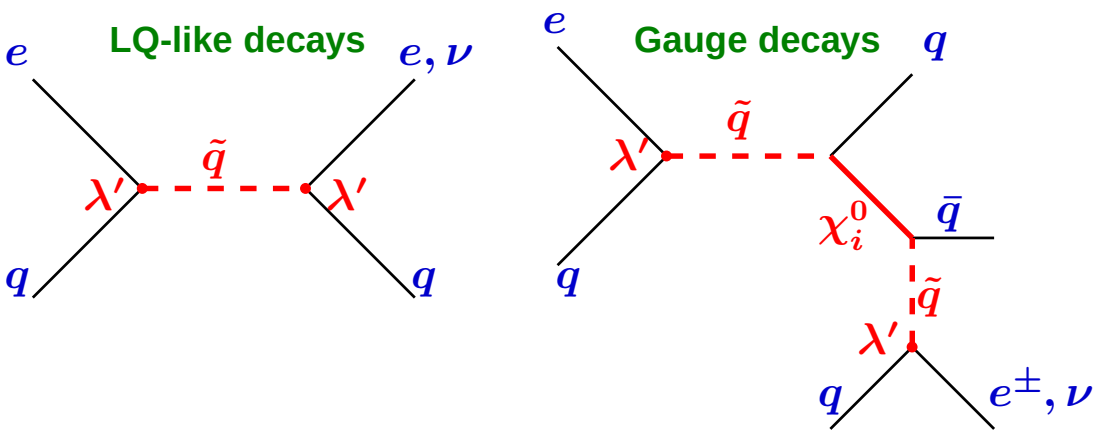
Evaluate in Buchmüller-Rückl-Wyler model (β fixed to 0 / 0.5 / 1) and derive limits on λ vs M_{LQ}

Compare results with other experiments:

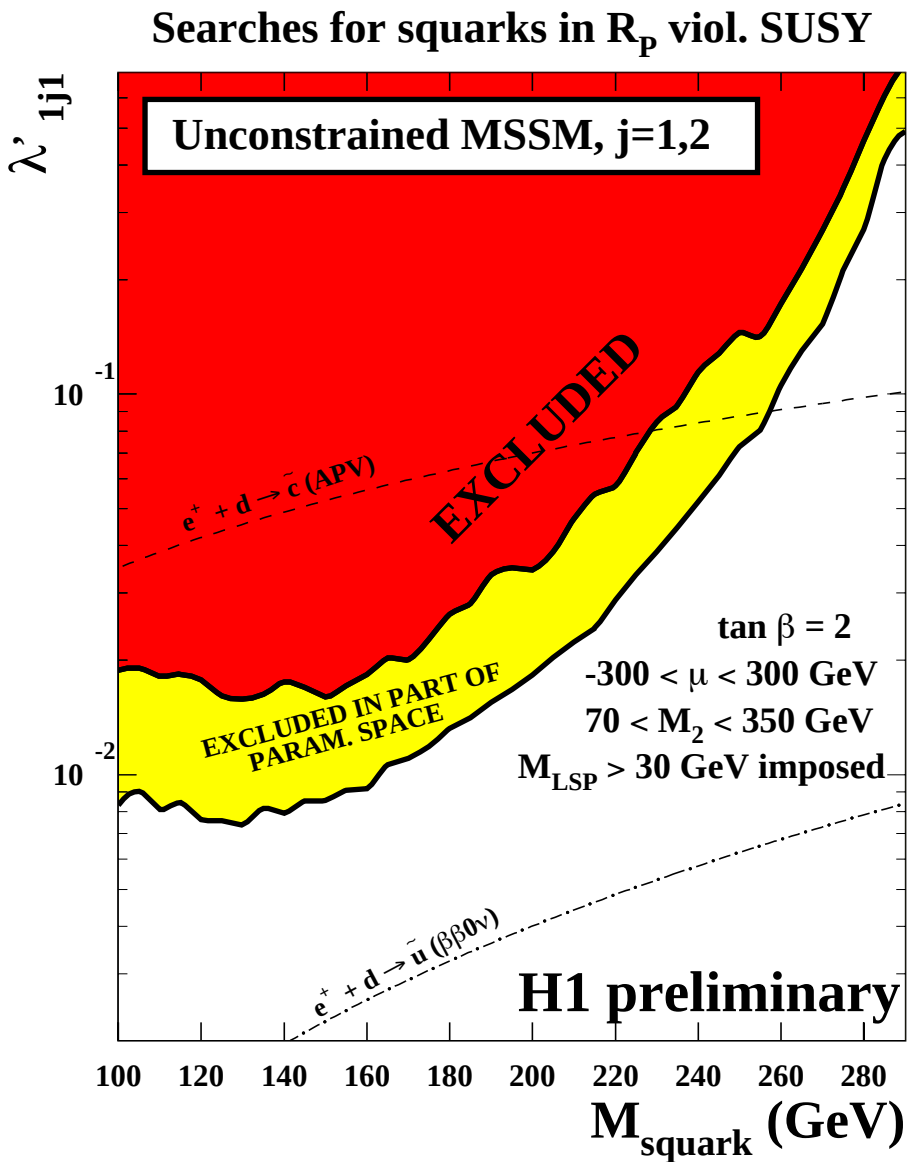
- Tevatron:
  pair production, independent of λ
- LEP:
  t-channel contribution to $e^+e^- \rightarrow$ hadrons, strong λ dependence

R_p violating MSSM from HERA

$R_p = (-1)^{3B+L+2S}$ +1 for SM particles
-1 for SUSY particles



- R_p violation ⇒ SUSY particles can be singly produced & LSP not stable
- no excess seen in any channel ⇒ limits
- analysis in unconstrained MSSM - free variation of parameter
- limits rather insensitive to these variations
- masses up to 270 GeV excluded for $\lambda' = 0.3$

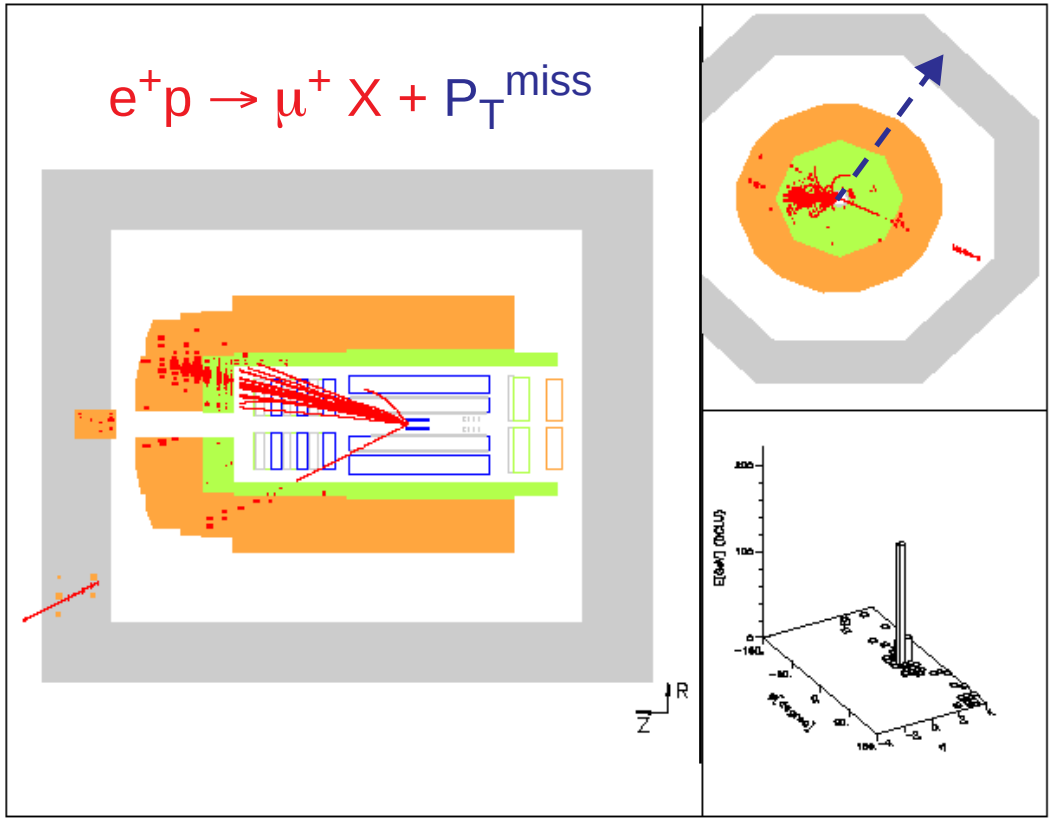


Other Searches

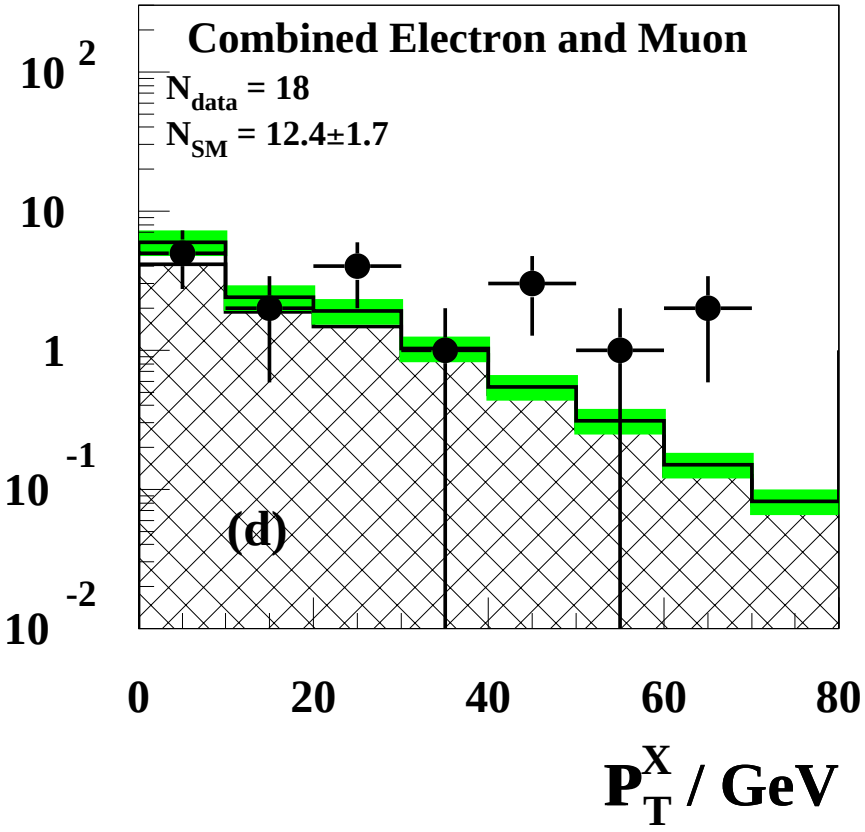
Many other analyses performed. No signal found and limits derived for several models beyond the SM

- Leptoquarks
- Lepton Flavour Violation
- R_p violating supersymmetric models
- Excited Fermions
- Contact Interaction, Compositeness, Large Extra Dimensions
- Anomalous top production and FCNC
- Search for Monopoles

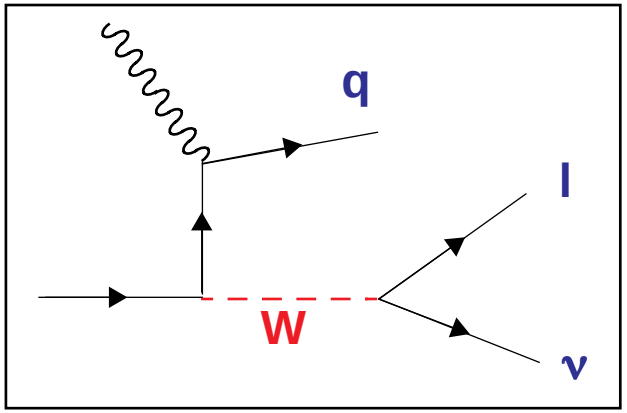
Unexpected Events at HERA: Lepton & P_T^{miss}



P_T^{μ}=28 GeV, P_T^{X}=67 GeV, P_T^{miss}=43 GeV



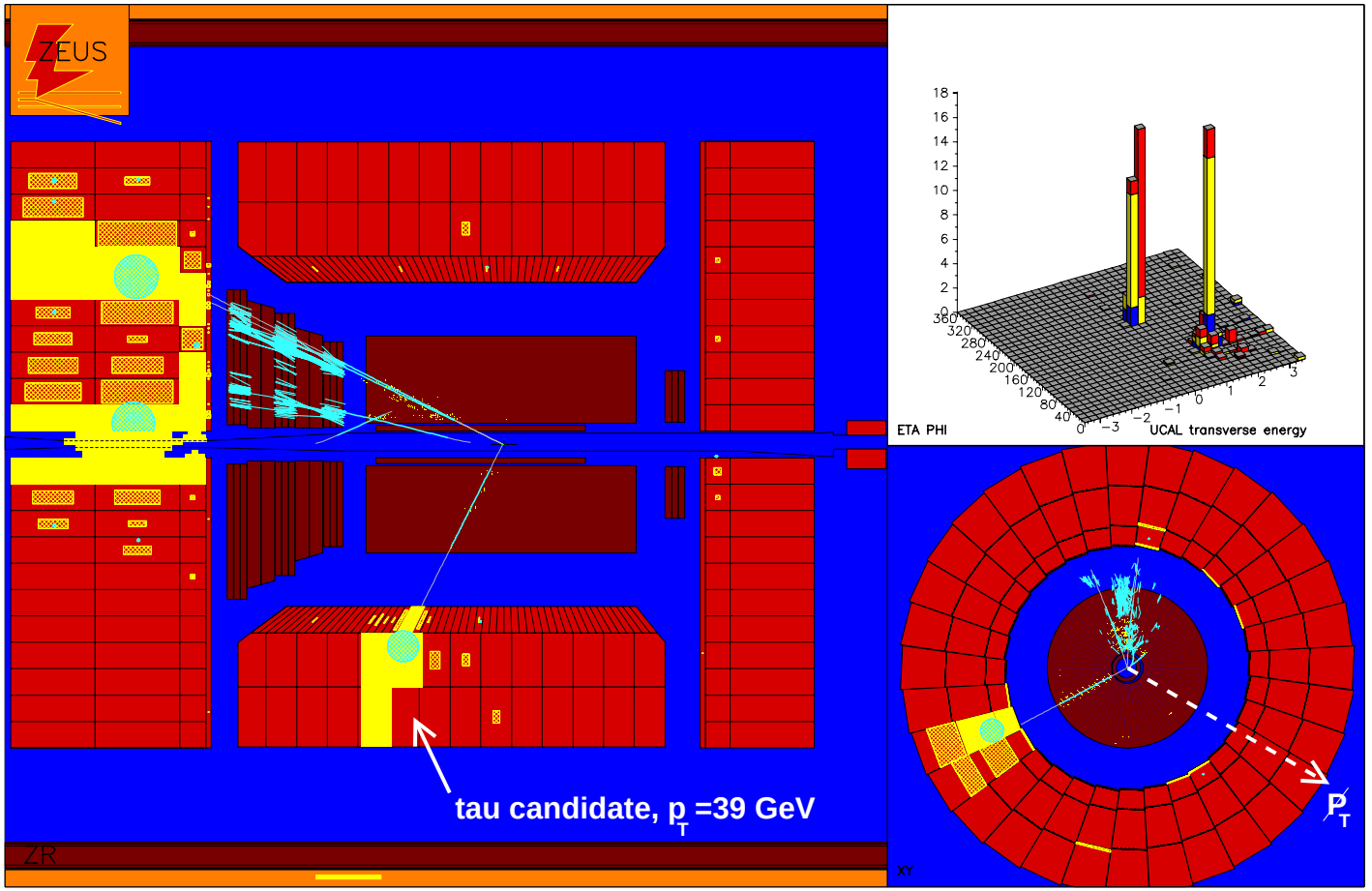
- Only significant SM process is W production
- NLO corrections under control
  - residual scale dependence O(10%)



Isolated τ candidate in ZEUS

Look also for events with isolated τ :

- ZEUS finds 2 candidates with $p_T^X > 25$ GeV ; SM expectation : 0.12 ± 0.02
- H1 analysis ongoing, no results yet



Summary on isolated Leptons at HERA

electron + muon channel

	H1		ZEUS	
P_T^X cut	Data	SM	Data	SM
0	18	12.4 ± 1.7	36	32.6 ± 3.8
25	10	2.9 ± 0.5	7	5.7 ± 0.6
40	6	1.1 ± 0.2	0	1.9 ± 0.2

tau channel

	ZEUS (prel.)	
P_T^X cut	Data	SM
0	–	–
25	2	0.12 ± 0.02
40	1	0.06 ± 0.01

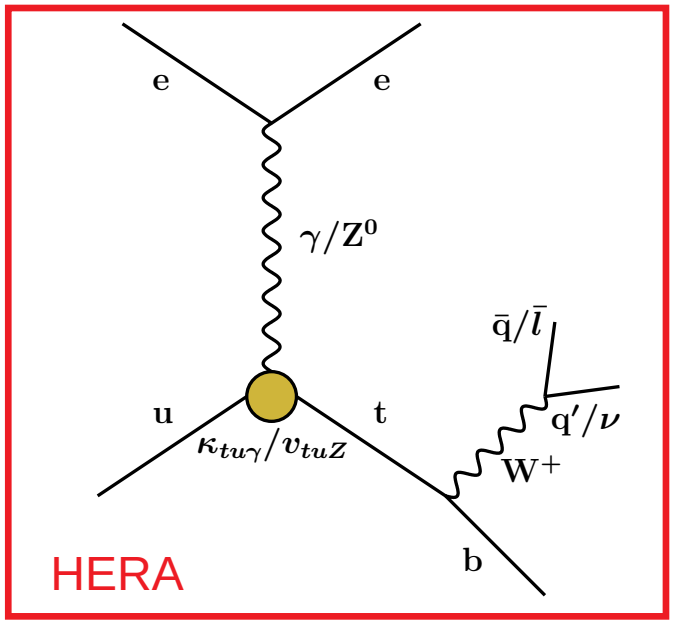
- electron and muon channel:
  - H1 sees excess
  - ZEUS agrees with SM expectation
- tau channel
  - ZEUS sees excess
  - H1 no results yet

For $p_T^X > 25$ GeV:

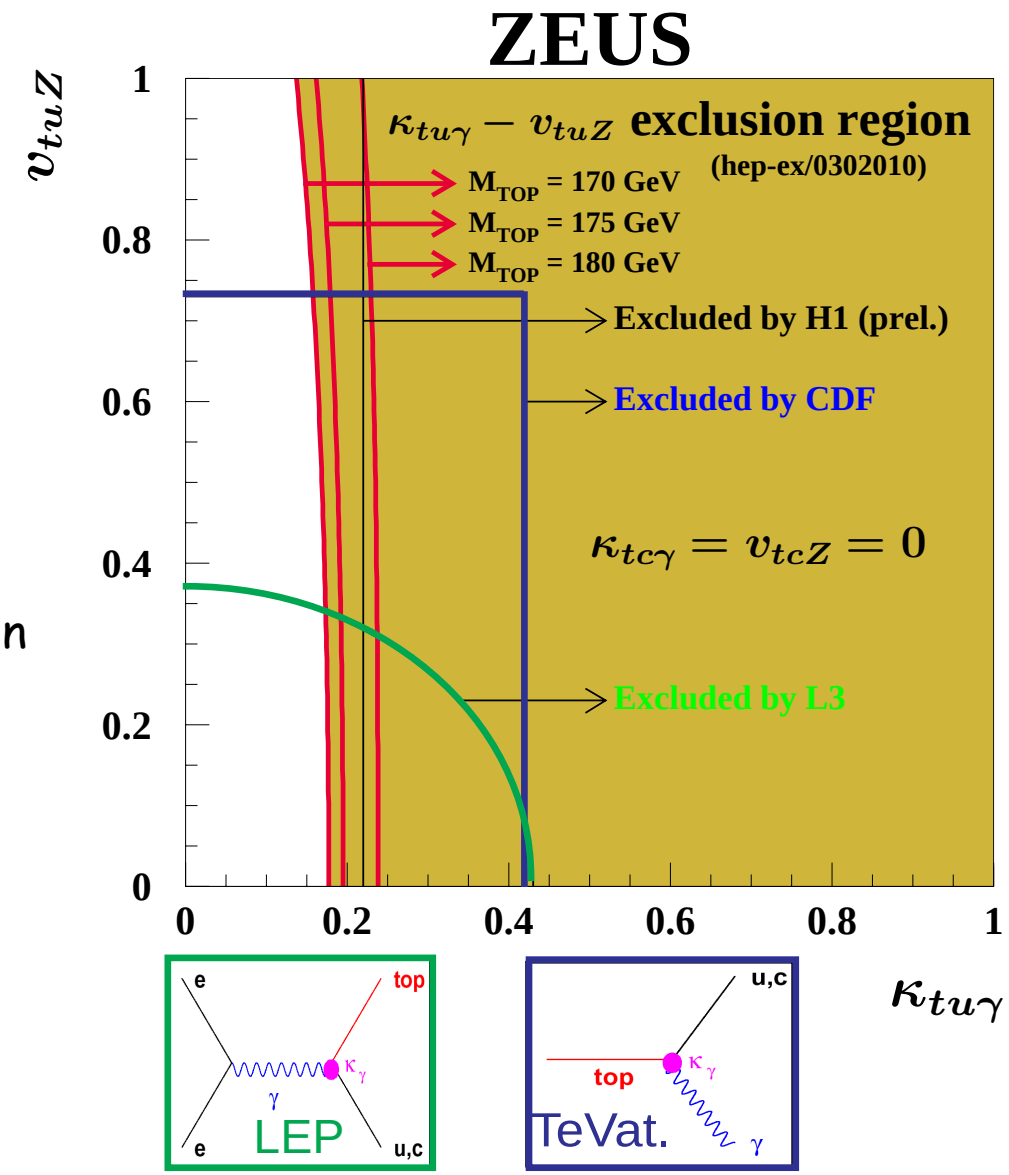
- in total 19 events seen in data ($e+\mu+\tau$, H1+ZEUS)
- SM expectation is 8.8 events

  $\Rightarrow$ overall probability P = 0.44%
- no firm conclusion possible now
- need HERA II data ($1 fb^{-1}$)

Search for single Top Production

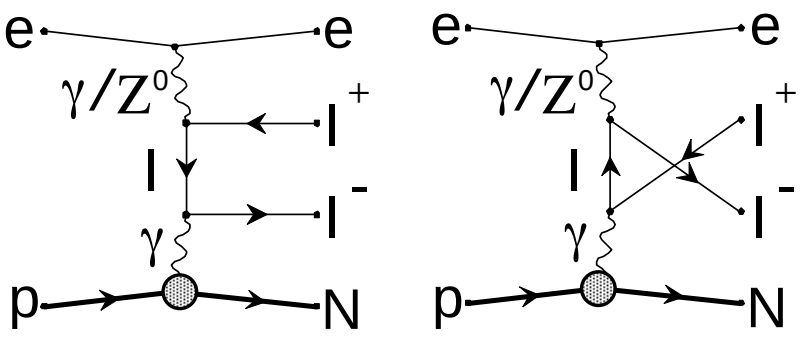


- can anomalous single top production explain excess of isolated lepton events?
- SM rate negligible due to FCNC vertex
- dedicated top search by ZEUS and H1
  - semileptonic and
  - hadronic channel
- no excess over SM
  ⇒ stringent limits on anomalous magnetic coupling $\kappa_{tu\gamma}$

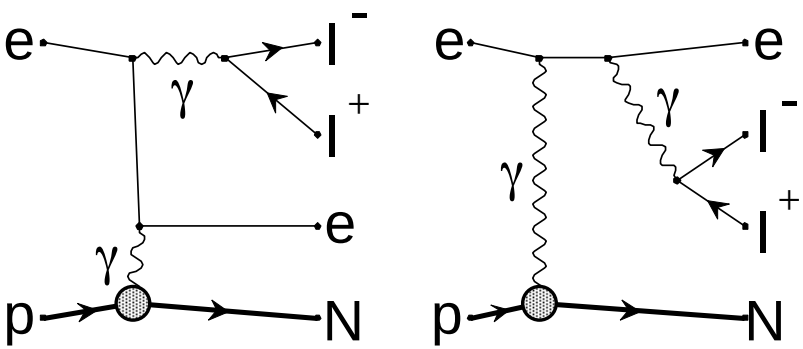


Another Puzzle: Multi-Lepton Events at HERA

Grape:



(a) Bethe-Heitler type diagrams

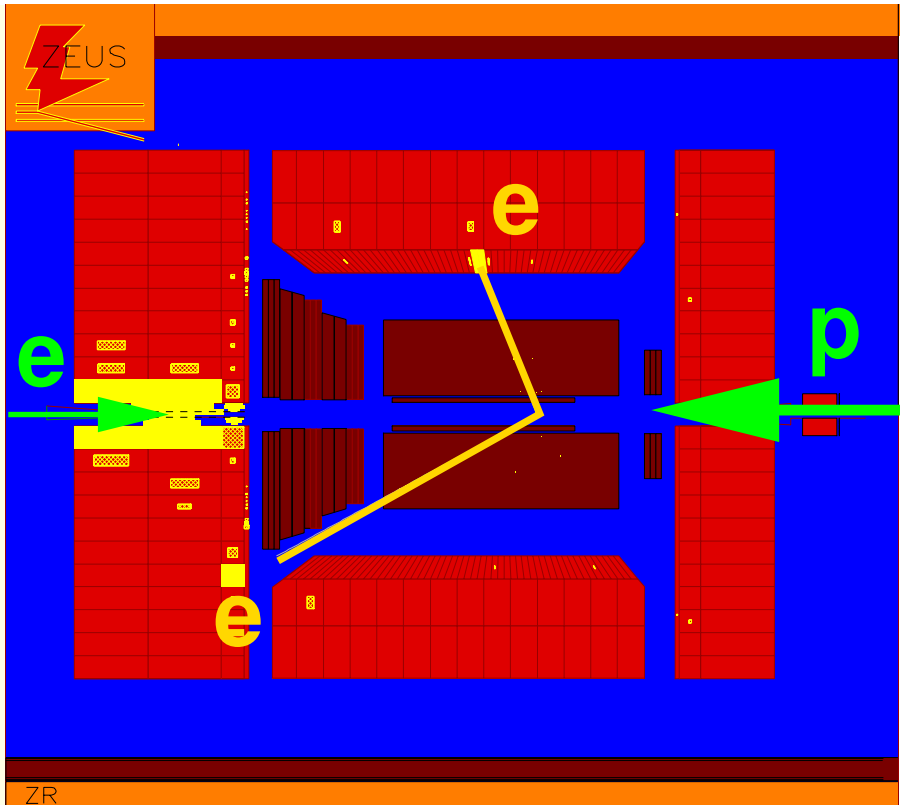


(b) QED-Compton type diagrams

\+ electroweak diagrams

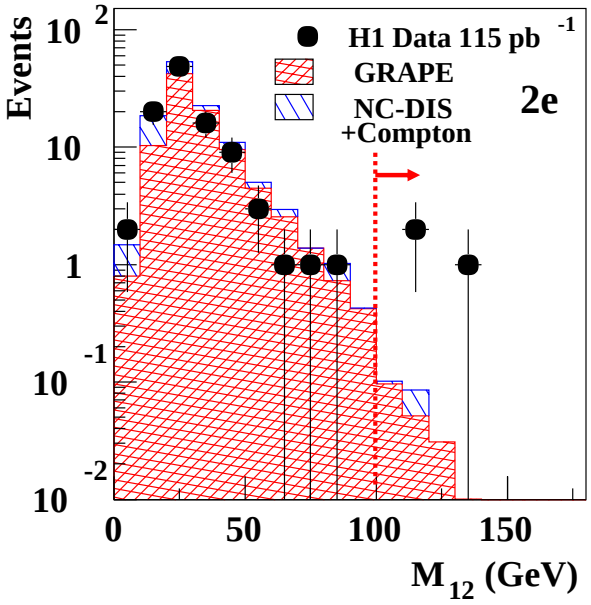
Two isolated electrons with $E_T > 10$ GeV

- H1 $20° < \theta_e < 150°$
- ZEUS $17° < \theta_e < 164°$
- both allow for third electron in: $5° < \theta_e < 175°$

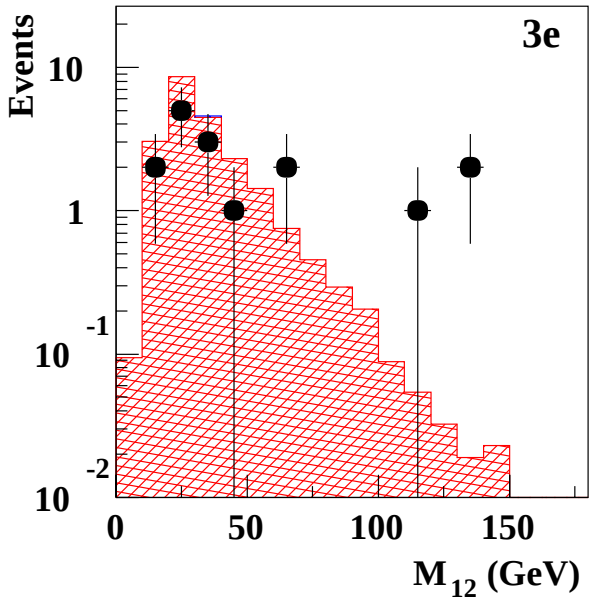


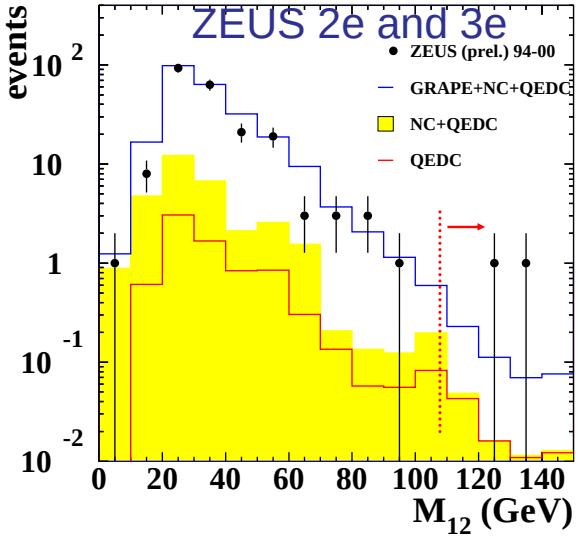
Preliminary Results for 2e, 3e and 2μ

Two Electron: H1 2e



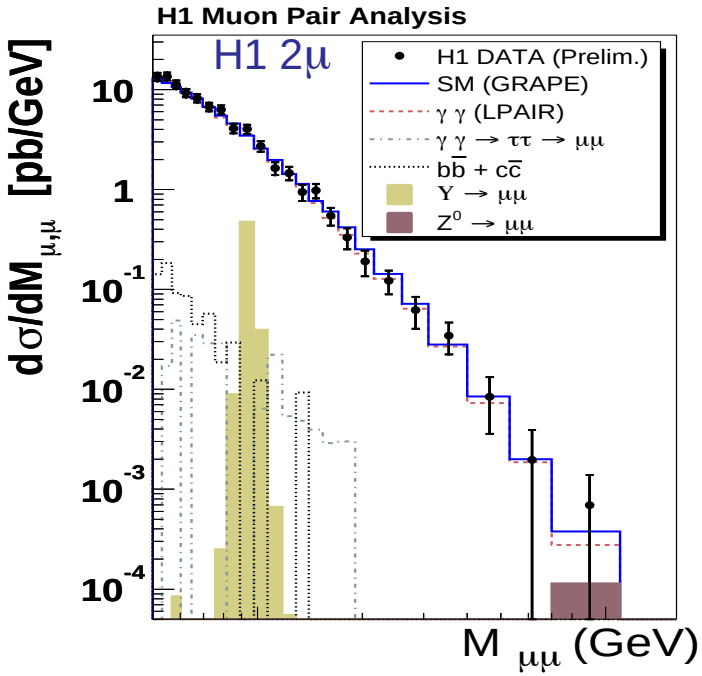
Three Electron: H1 3e





Multielectrons: M_{12} > 100 GeV [$E_{T,1}$> 30 GeV (ZEUS 3e)]

	H1		ZEUS	
	Data	SM	Data	SM
2 $e^{\pm}$	3	0.25 ± 0.05	2	0.8 ± 0.1
3 $e^{\pm}$	3	0.23 ± 0.04	2	1.4 ± 0.1



Muon data do not show any excess → not conclusive

Summary and Conclusions

- High precision data emerging from HERA
  - SF measurements at the ~2% level
  - Jet production meas. at the ~5% level
  - gluon, α_s

- HERA has some windows for discoveries
  - LQ, Rp violating SUSY, excited fermions
  - some unexplained lepton events

- Many aspects not covered in this talk
  - Diffraction, Vector Mesons — Talk by I.Gialas
  - Charm & Beauty production
  - Photon structure
  - small x, novel parton dynamics
  - DVCS
  - Instantons
  - ...

- HERA II
  - higher luminosity $\rightarrow$ 1 fb^{-1}
  - longitudinally polarised $e^{\pm}$ beam

  Talk by R. Yoshida

Further extentions of physics programme being discussed:

- HERA III
  - Deuterons in HERA
  - A>2
  - Spin

  Talks by D.Pitzl (Physics) and I.Abt (Mach.&Det.)