$48^{\rm th}$ Session of the Extended Scientific Council
DESY, Hamburg, October 28, 1999

HERA at the turn of the Millenium

S. Levonian

DESY, Hamburg and LPI, Moscow

representing

Outline

– What have we learnt so far?
– What is the best way to proceed?

- **HERA performance:**
  1280 days of ep collisions

- **Structure of the Matter:**
  What is going on at 10^{-16} cm?

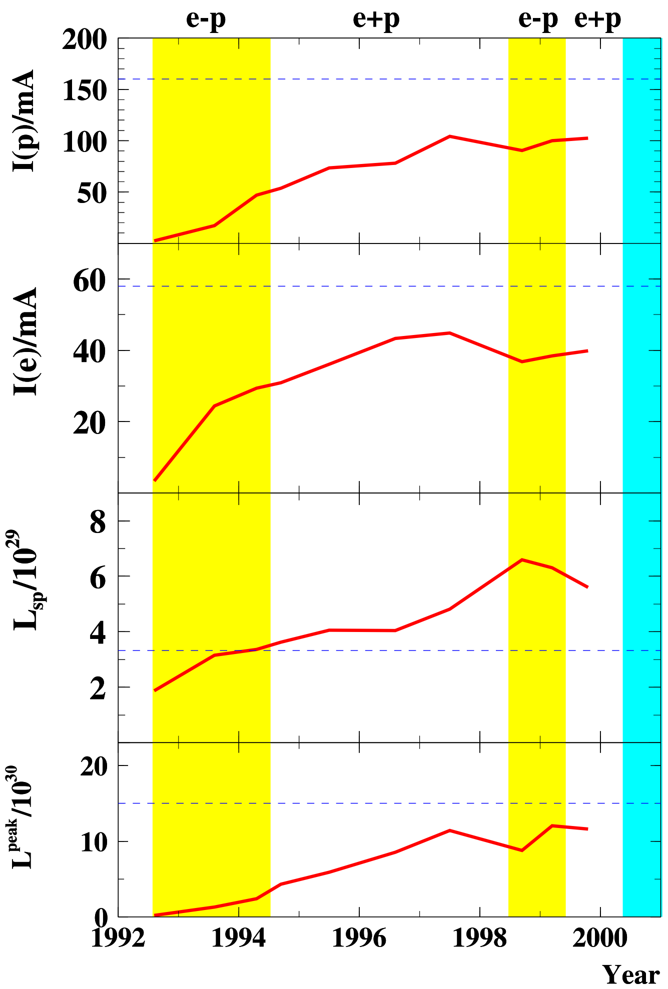
- **QCD at short and long distances:**
  Any surprises?

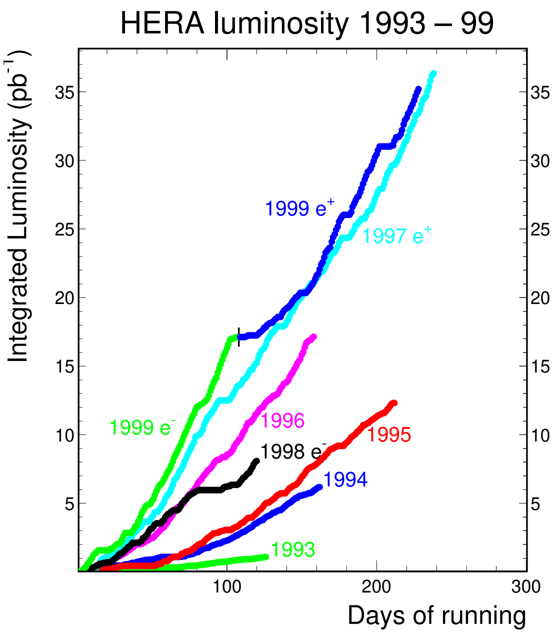
- **Discovery potential:**
  Is there a life beyond the Standard Model?

- **Summary and Outlook**

HERA performance

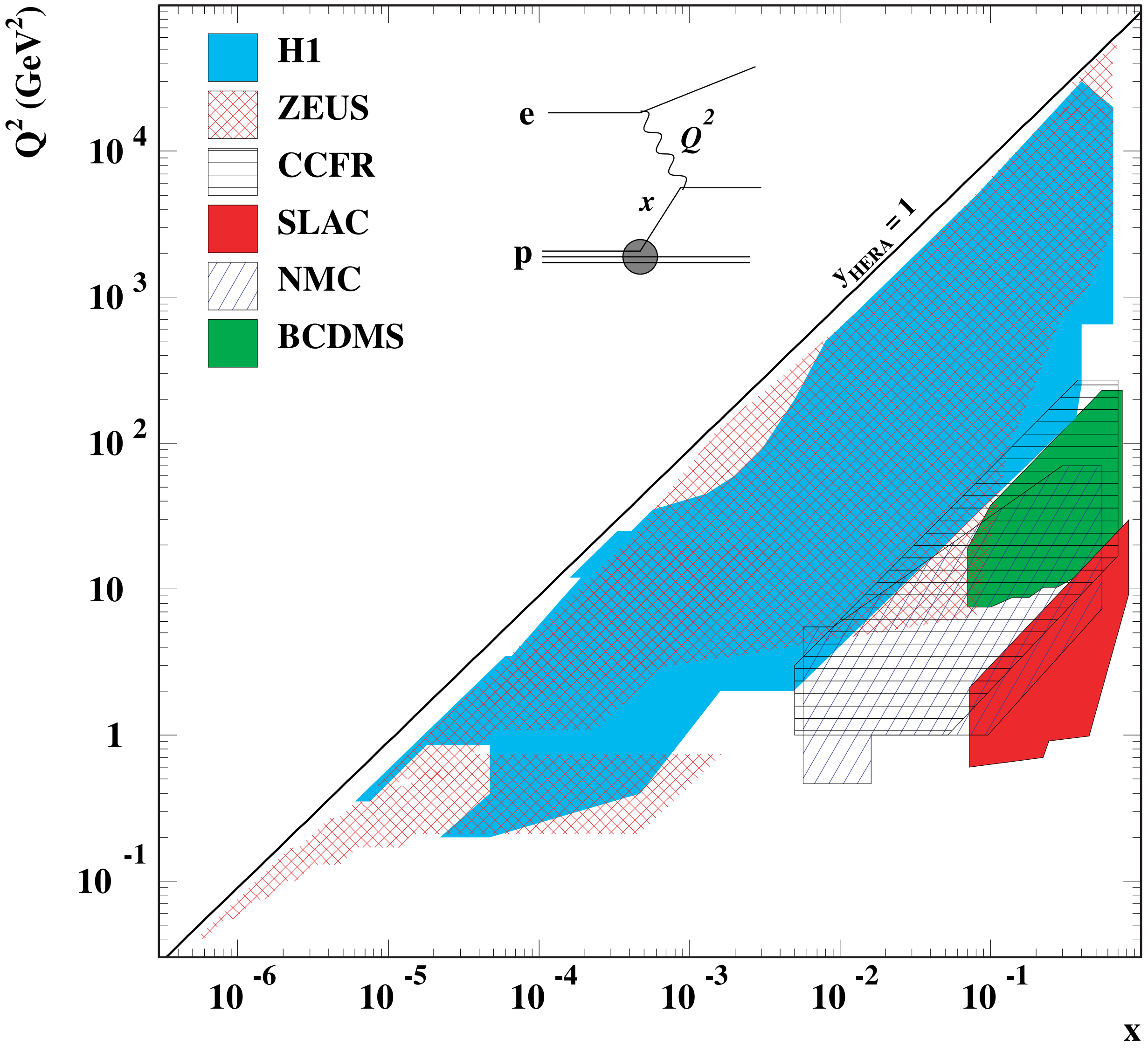
- **Difficult machine, requires skilled shift crew**
  - ▷ **many subtle effects**
  - ▷ **conflicting demands from the experiments**
  - ▷ **complicated environment (LPS, FPS, e-taggers internal targets)**
- **e^+ is easier to run than e^- (life time, efficiency, background)**
- **Upgrade is a real challenge... ... but realistic !**





L/pb^{-1}	H1	ZEUS	Total
e- p	16	17	33
e+p	37	48	85
	12	12	24
	25	25	50
>2001	150	150	300/Y

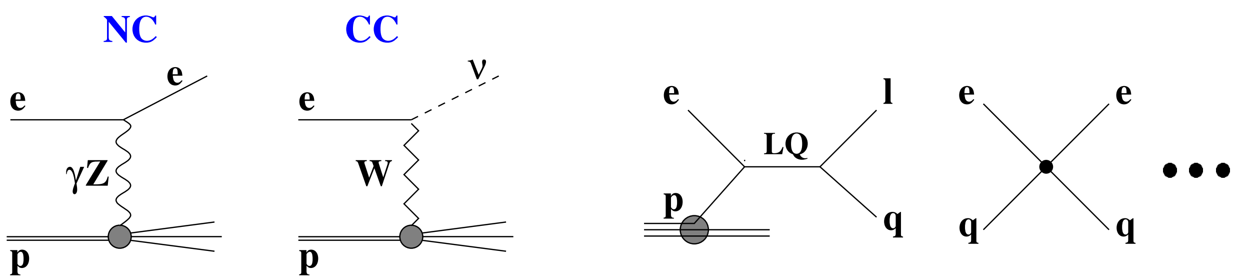
HERA kinematic range

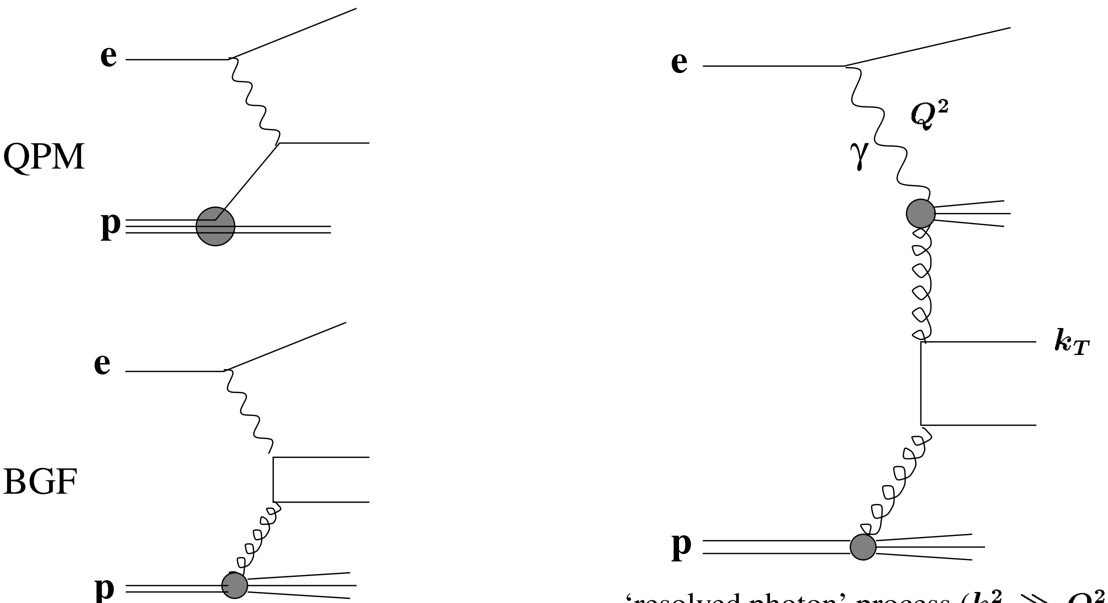


x/Q^2	$\rightarrow 10^{-5}$	$\Rightarrow$	low x limit of pQCD
y	$\rightarrow 0.005$	$\Rightarrow$	overlap with fixed target experiments
y	$\rightarrow 0.82$	$\Rightarrow$	sensitivity to F_L
Q^2	$\rightarrow 0.045$ GeV^2	$\Rightarrow$	transition to γp
Q^2	$\rightarrow 50000$ GeV^2	$\Rightarrow$	EW sector, (new physics?)
			Emphasized by the Upgrade-2000

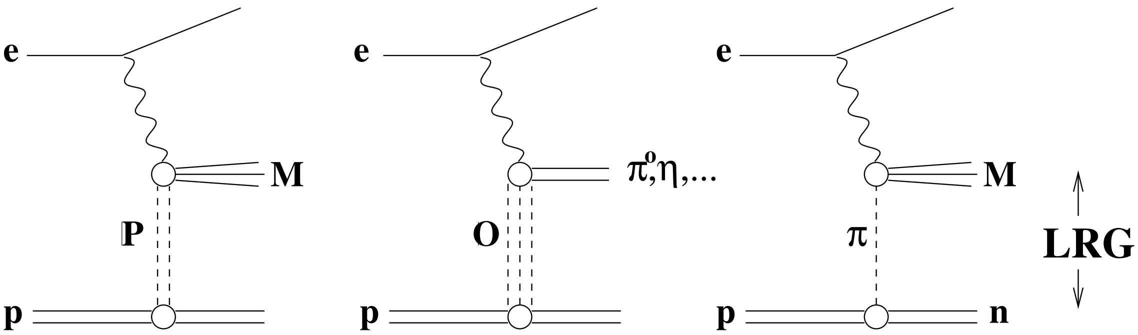
HERA Physics

SM **BSM**





‘resolved photon’ process ($k_T^2 \gg Q^2$)

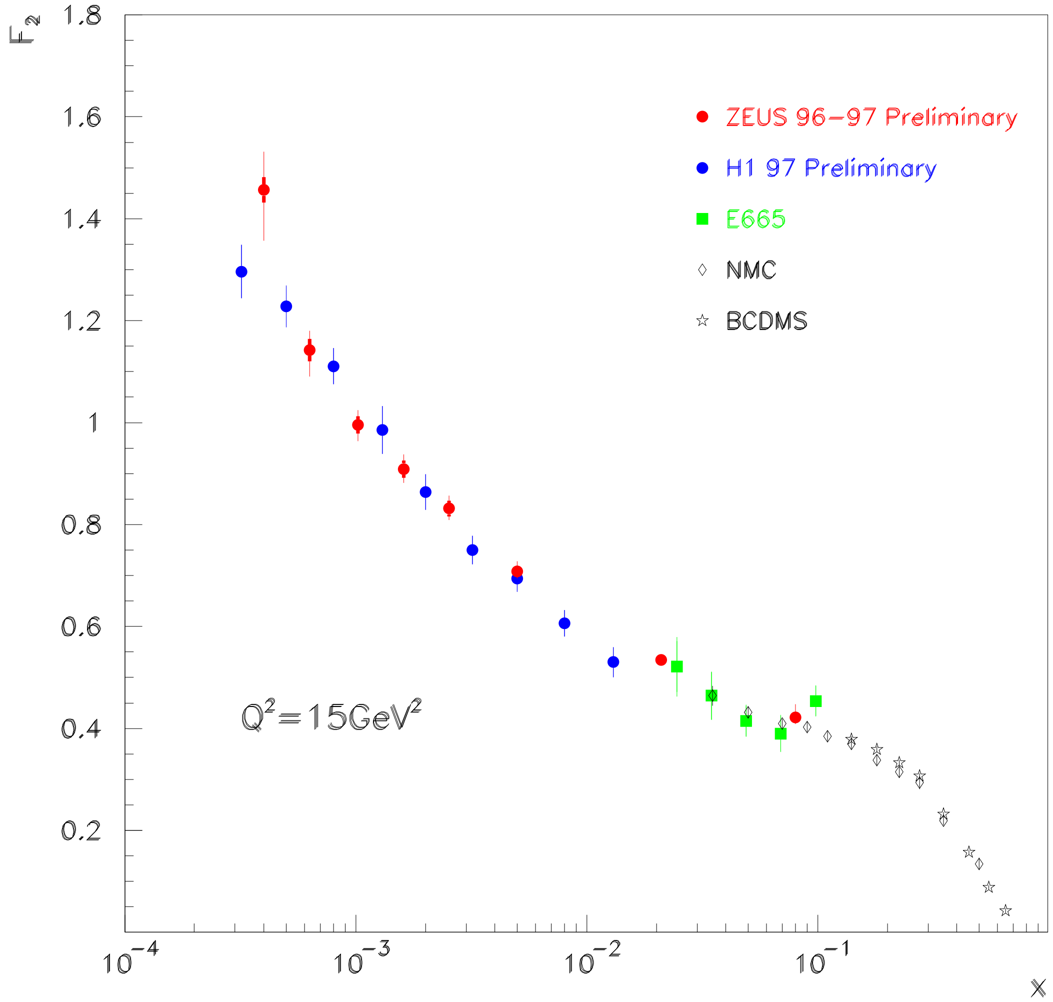


Diffraction

Structure of the Proton: F_2

$$\frac{d^2\sigma^{NC}}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4} Y_+ \underbrace{\left(F_2 - \frac{y^2}{Y_+} F_L\right)}_{\sigma_r \equiv \tilde{\sigma}} \qquad Q^2 << M_Z^2; \quad Y_+ = 1 + (1-y)^2$$

– 'reduced cross section'



★ High precision: 1%(stat) $\oplus$ 3-4%(syst)

★ Good agreement between H1 and ZEUS

★ Overlap is achieved with fixed target experiments

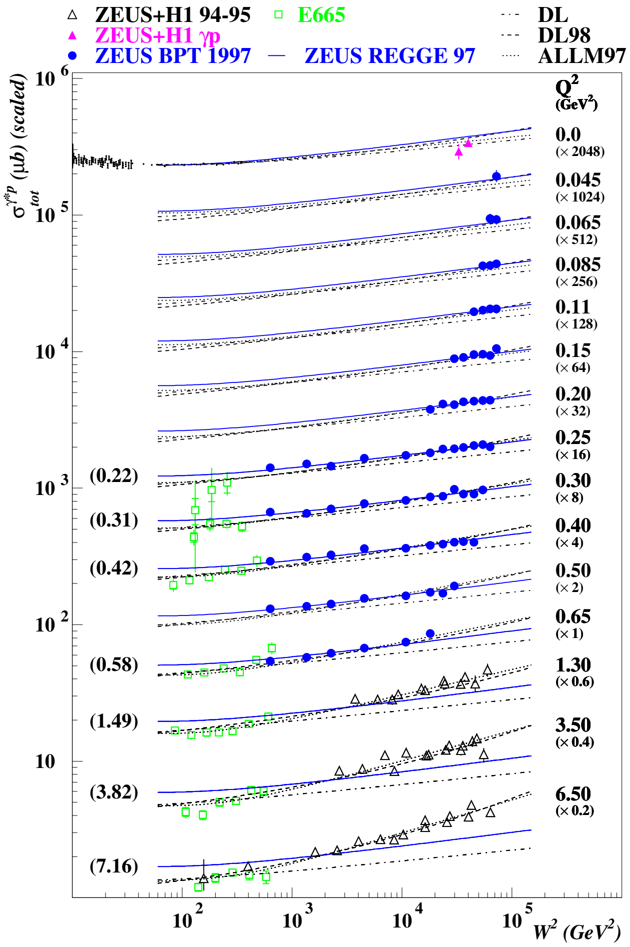
★ Strong rise at low x

F_2 scaling violation

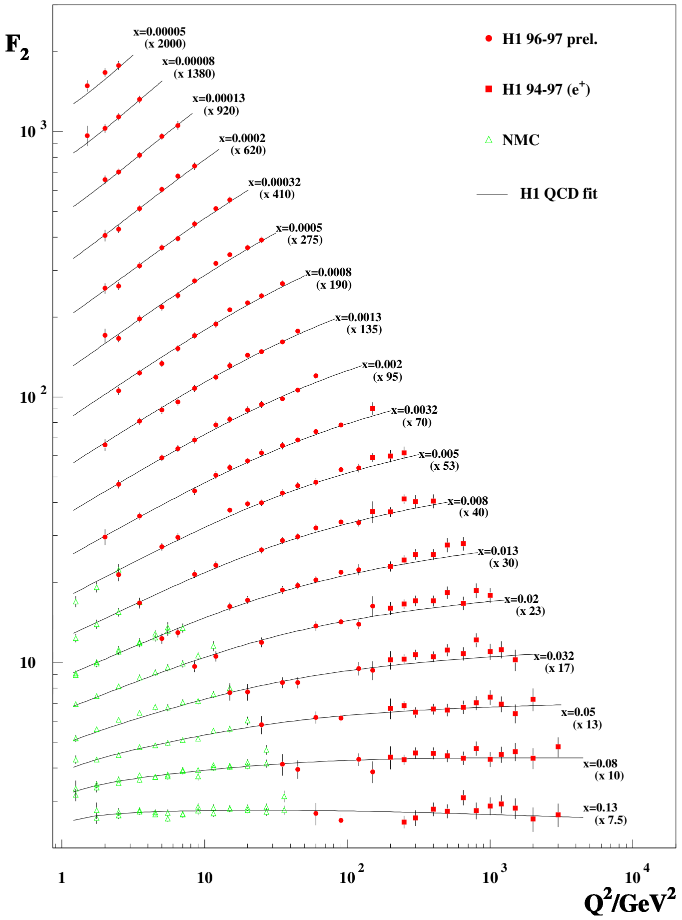
QCD

transition to soft physics | **perturbative regime**

ZEUS 1997 (Preliminary)



H1 low x



★ **Excellent agreement with NLO QCD down to surprisingly low Q^2, $\mathcal{O}(1\text{GeV}^2)$**

★ **Smooth transition from partonic to hardonic degrees of freedom at $Q^2 \to 0$**

Structure of the Proton: F_L

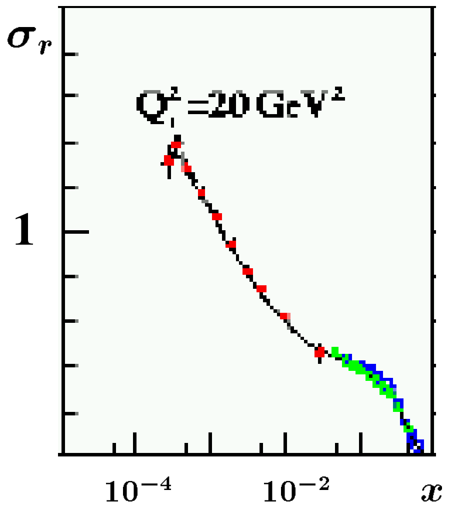
$$\sigma_{\rm r} = \left(F_2 - \frac{y^2}{Y_+} F_L\right) \quad \rightarrow \quad F_L \text{ gets important at high } y \quad (x = \frac{Q^2}{ys})$$

- **Methods**

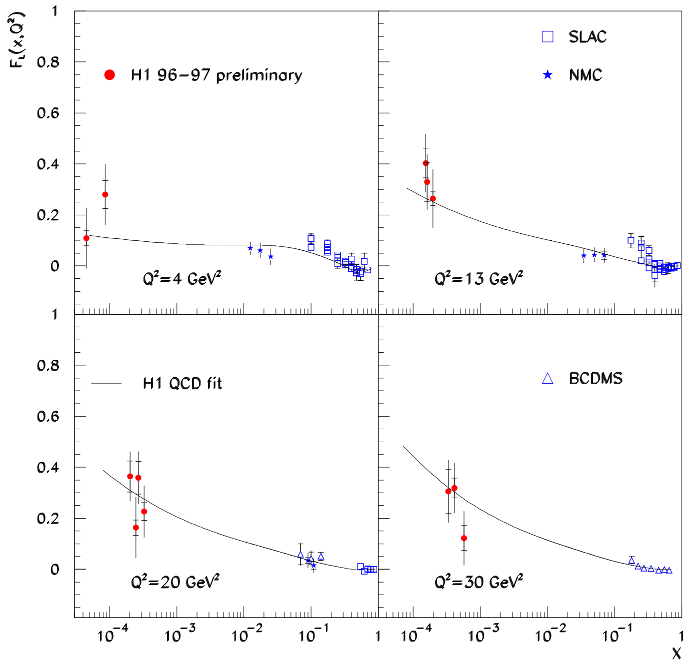
1. **QCD extrapolation** ($Q^2 > 10$ GeV^2)
   $F_L = F_2^{QCD} - \frac{Y+}{y^2}\sigma_r^{exp}$

2. **Derivative** ($Q^2 < 10$ GeV^2)
   $\frac{\partial \sigma_r}{\partial \log y} = \frac{\partial F_2}{\partial \log y} - F_L 2y^2 \frac{(2-y)}{Y_+^2} - \ldots$

3. **ISR events** (all Q^2)
   (varying "e beam" energy)



- **Results**



★ **For better precision have to use "classical" method (varying collision energy) ⇒ After upgrade ...**

QCD studies

Using those precise data we can go on and

$\Rightarrow$ **extract gluon density in the proton**

$\Rightarrow$ **determine α_s $\quad\rightarrow\quad$ precision test of pQCD**

$\Rightarrow$ **search for new dynamics in the limit of low x**

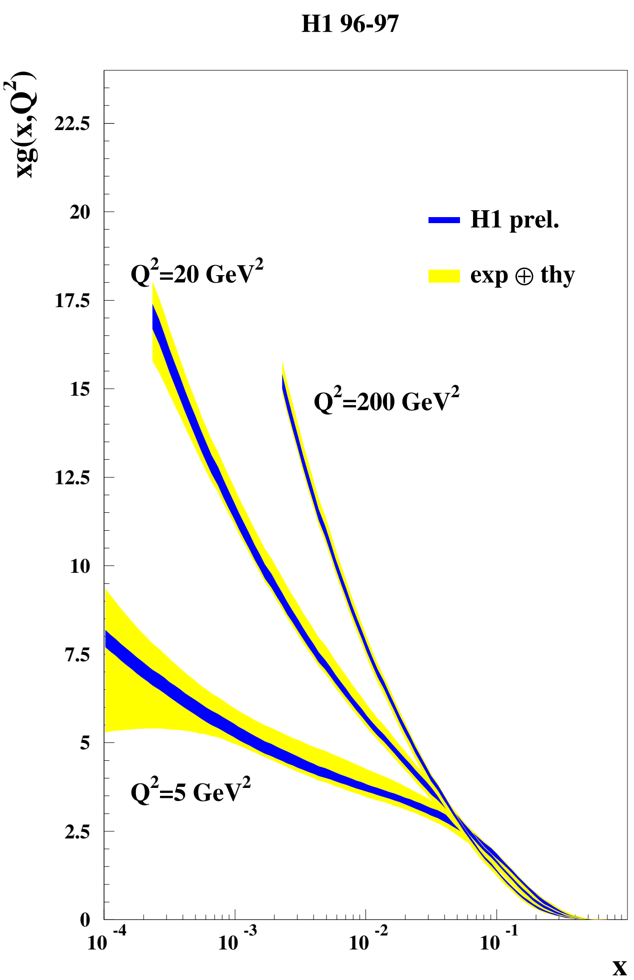
$\Rightarrow$ **study the transition to non-perturbative γp regime**

★ **For most of these tasks statistics, collected until the Upgrade, $\mathcal{O}(100\ \mathrm{pb}^{-1})$ is adequate**

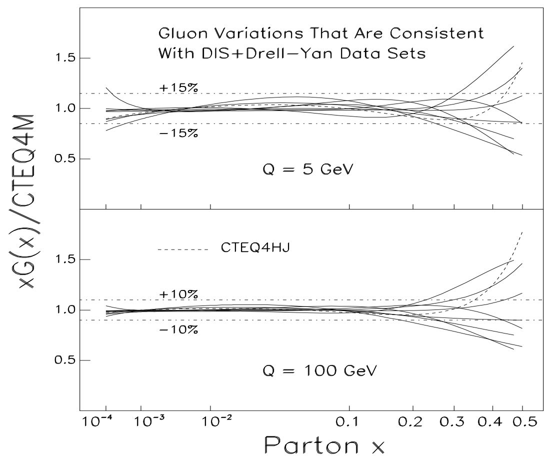
Gluon density in the proton

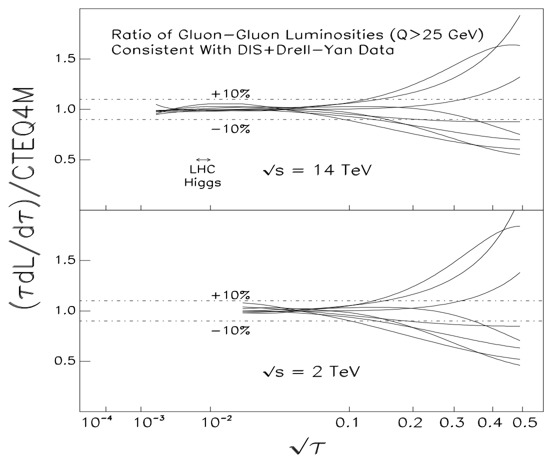
From F_2 scaling violation

$$\frac{dF_2}{d\log Q^2} \propto xg(x)\cdot\alpha_s$$



Impact on LHC physics



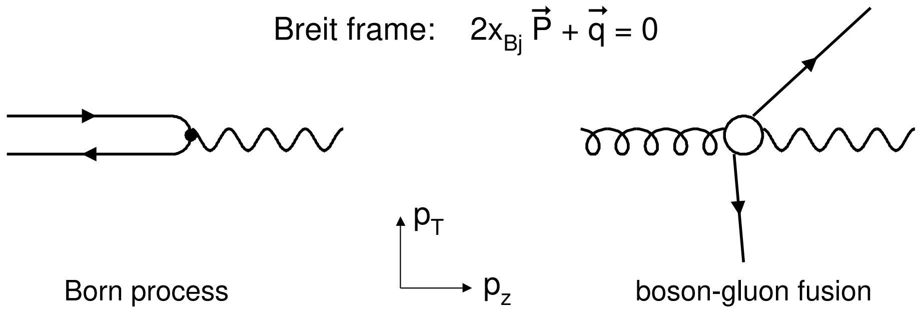


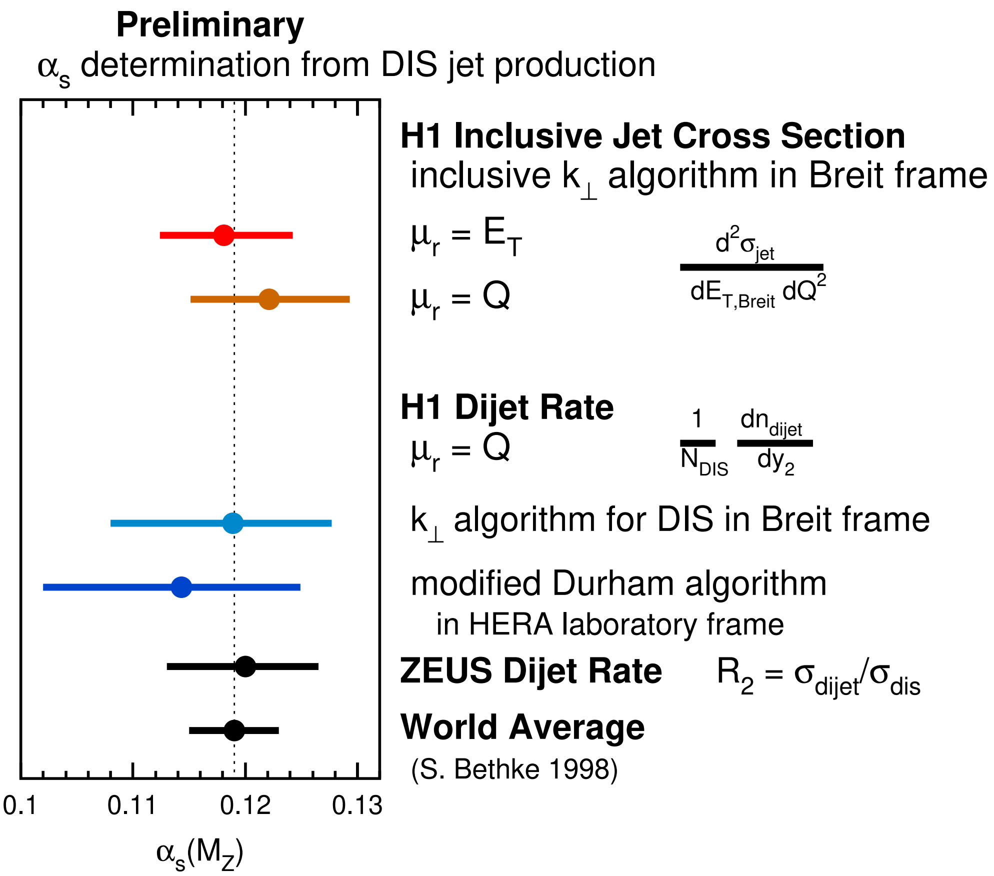
★ **Results are in a good agreement with other methods: jets, charm from BGF (not shown) ⇒ universality**

★ **Gluon density at low $x < 0.1$ is constrained within 10% ⇒ good control for Higgs production at LHC**

Precision QCD: α_s measurement

From jet production in DIS





★ **Precision is comparable to the best world result**

Low x regime: BFKL dynamics?

How to distinguish different parton evolution schemes?

DGLAP resums $\log(\frac{Q^2}{Q_0^2})$ terms

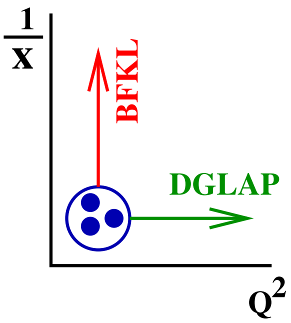
with $k_{Tk}^2 \gg k_{Tk-1}^2 \gg \ldots,$

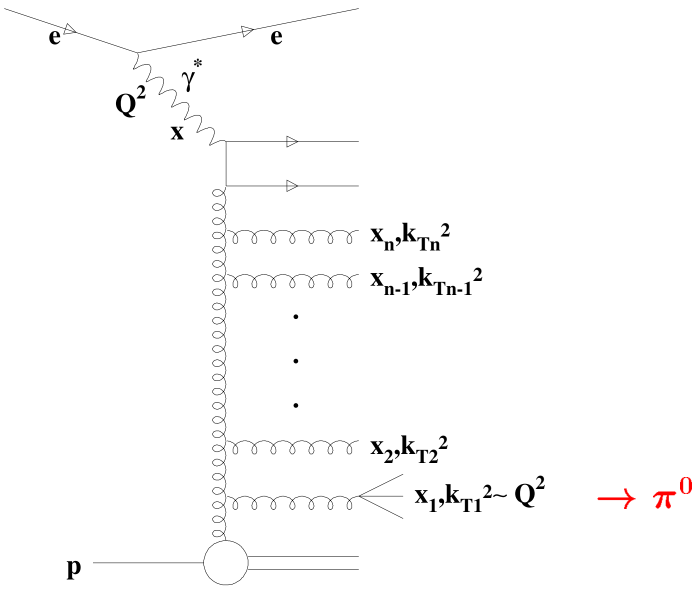
and $x_1 > x_2 > \ldots$

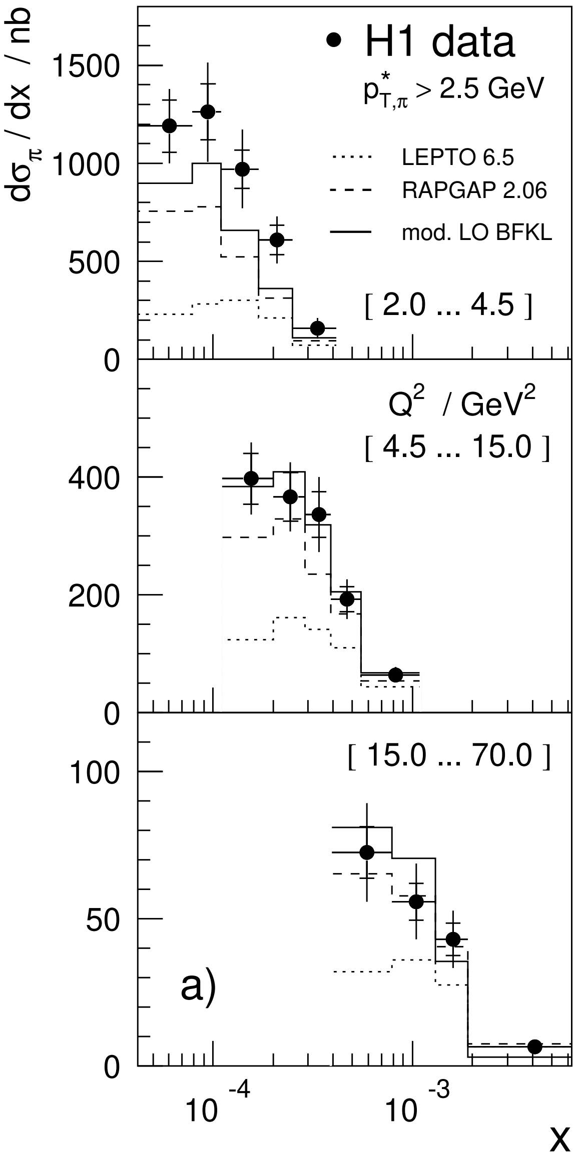
BFKL resums $\log(\frac{1}{x})$ terms

with $k_{Tk}^2 \sim k_{Tk-1}^2$

and $x_1 \gg x_2 \gg \ldots$







★ **DGLAP evolution can't describe the data**

★ **Resolved photon component helps**

★ **BFKL calculation comes closest to the experiment**

⇒ **Conseptual problem? – Theory gurus, your turn...**

Diffraction at HERA

Diffraction in HEP =
Colorless exchange carrying vacuum quantum numbers
$\Rightarrow$ Physics of the Pomeron

To understand Pomeron means
to understand Strong Interactions

There were two partly successful attempts undertaken:

1. Regge phenomenology (60's)
2. QCD (80's)

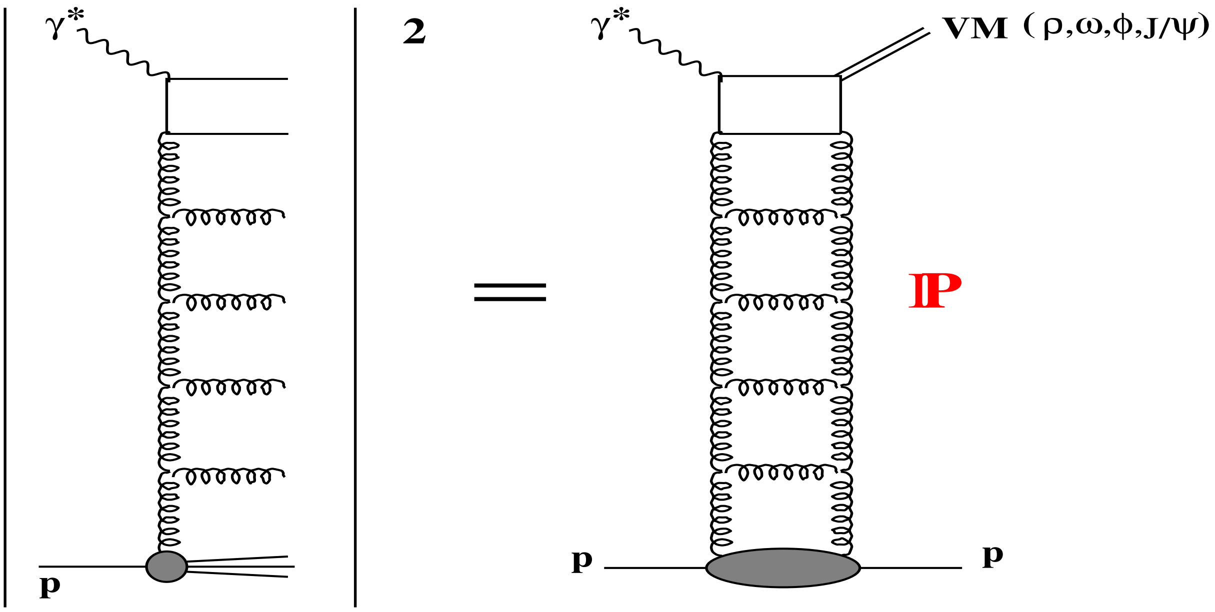
Goal: To finalize these attempts
(Ex: Effective field theory of reggeized gluons – L.Lipatov et al.)

RFT:	**Universal ('soft') $I\!P$** (phenomenological D-L fit)	$\alpha(t) = 1.08 + 0.25t$
QCD:	**? ... trying hard ...**	$\alpha(t) = 1.2\pm$?

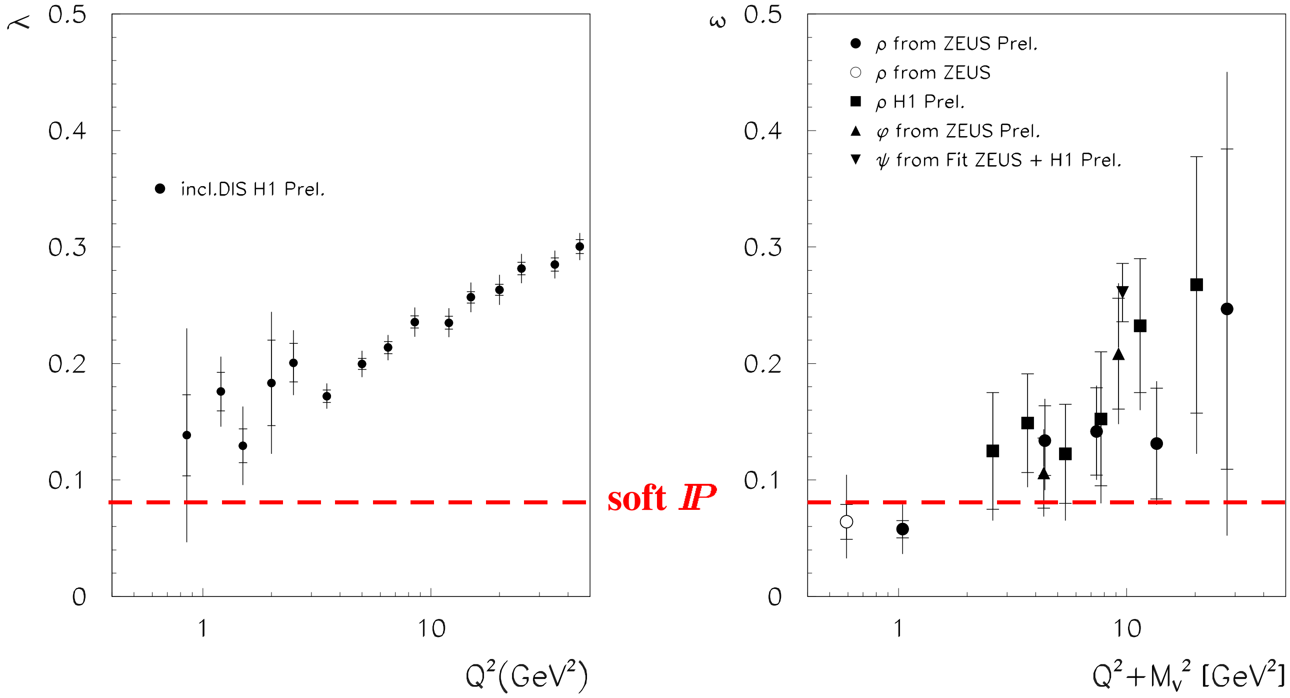
★ **Due to its unique possibilities HERA is presently leading this field of research**

Low x physics and the Pomeron

Relating $F_2^p(s,Q^2) \sim \sigma_{tot}^{\gamma^* p}$ with elastic scattering via optical theorem:



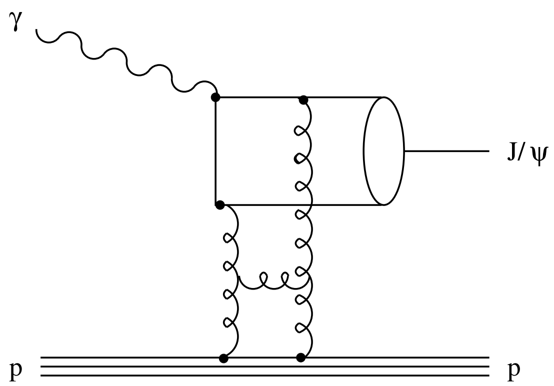
$\sigma_{tot}^{\gamma^* p} \sim s^{\epsilon}$ $\sigma_{el}(\gamma^* p \to V p) \sim s^{2\epsilon}$

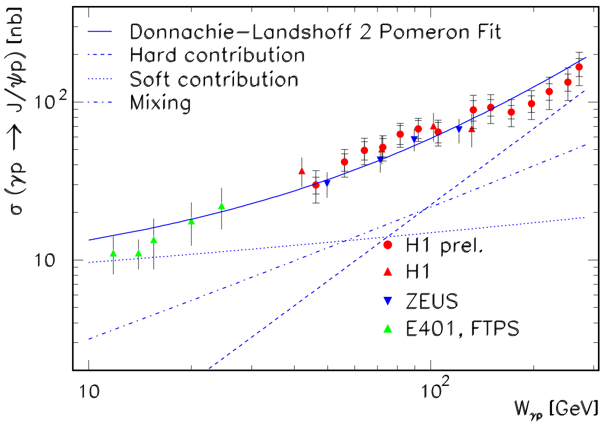


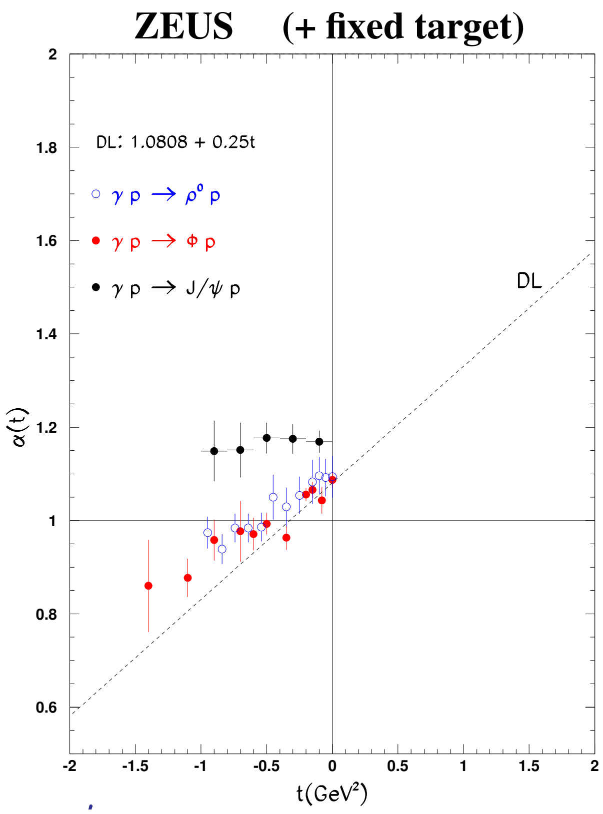
★ **Striking similarity !**

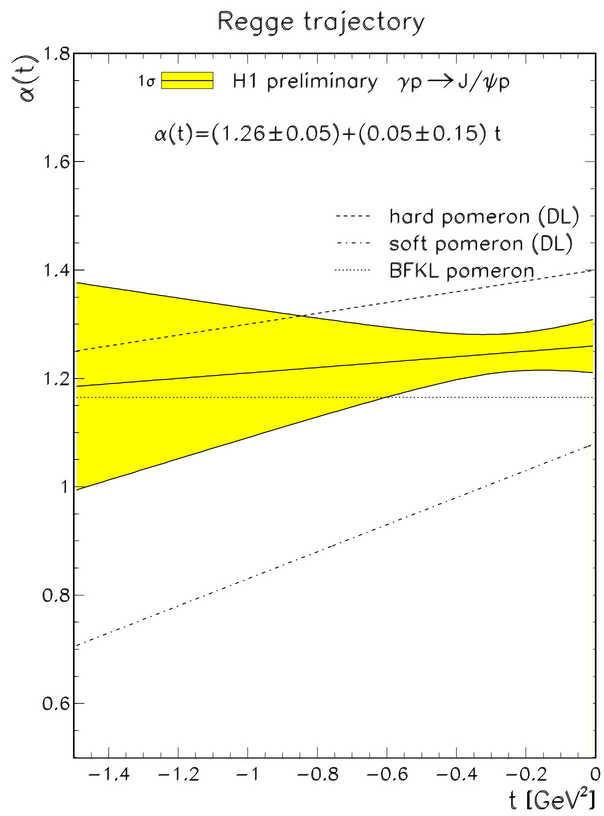
Elastic J/ψ photoproduction

Soft $I\!P$ trajectory: $\alpha(t) = 1.08 + 0.25t$ **(e.g. hh scattering)**
Hard $I\!P$ trajectory: $\alpha(t) = 1.2 \pm ?$ **(pQCD expectation)**









★ **So far the best possibility to isolate hard Pomeron**

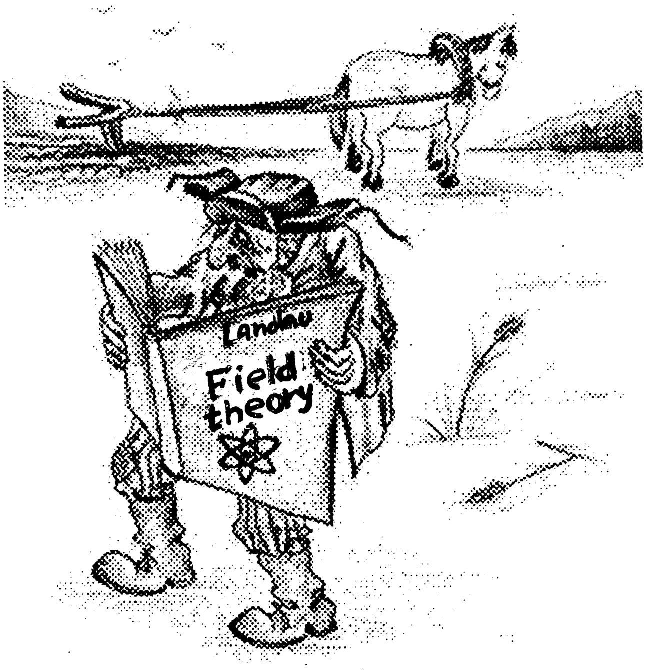
QCD at HERA: Summary

★ In QCD sector HERA becomes a leading facility

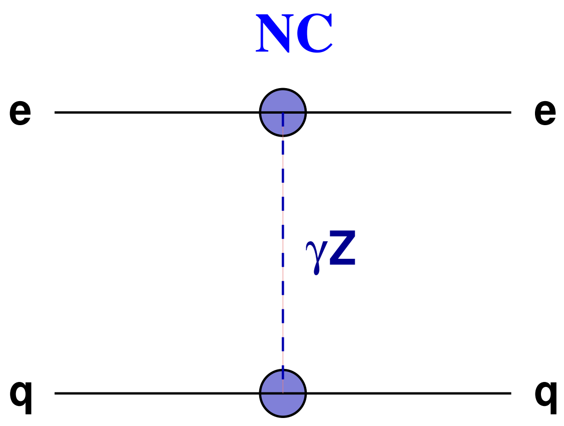
With high statistics available, of order $10^6 \div 10^7$ events one can

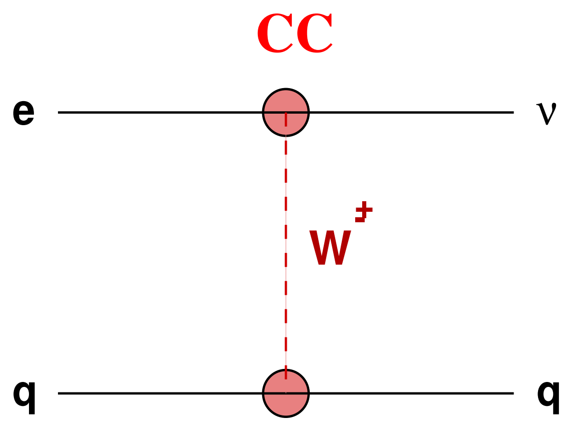
- **measure partonic structure of the hardonic matter down to 10^{-16} cm ($p, \gamma, \pi, I\!P$)**
- **perform precision tests: $\delta\alpha_s^{\mathrm{HERA}} \simeq \delta\alpha_s^{\mathrm{world\ av.}}$**
- **gain new insigt into diffractive phenomena and the quest of the Pomeron**
- **possibly establish new dynamics at low $x/Q^2 \sim 10^{-5}$**
- **study the transition between perturbative and non-perturbative regimes**

**★ For further improvement –
to take a good crop from this field -
we need yet better support
from theory side**



Testing the SM in electroweak sector

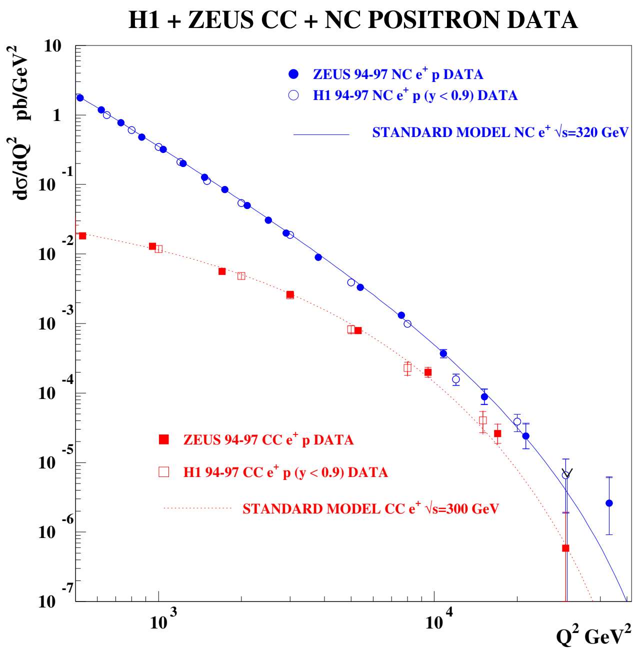


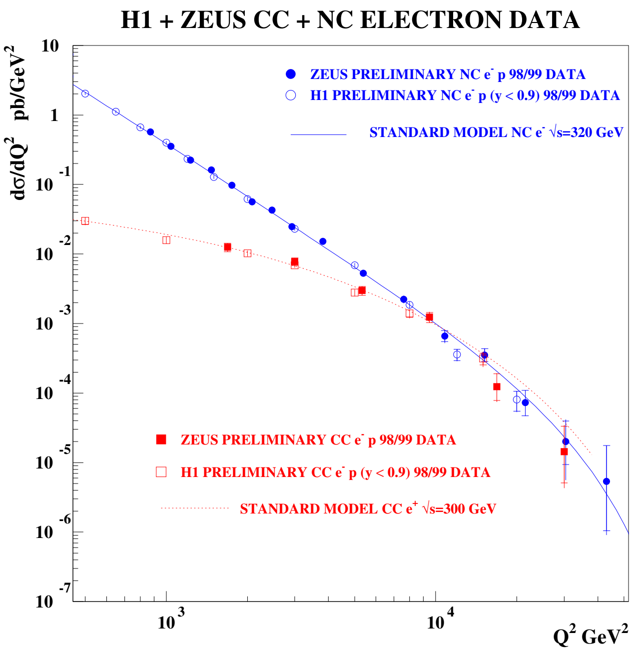


$$\tilde{\sigma}_{NC}(e^{\pm}p) = F_2 + a_e^2\kappa_w^2\left[\frac{Q^2}{Q^2+M_Z^2}\right]^2 F_2^Z \mp 2a_e\kappa_w\left[\frac{Q^2}{Q^2+M_Z^2}\right] xF_3$$

$$(\tilde{\sigma}_{CC}^{e^+p})_{LO} = x[(\bar{u}+\bar{c}) + (1-y^2)(d+s)]$$

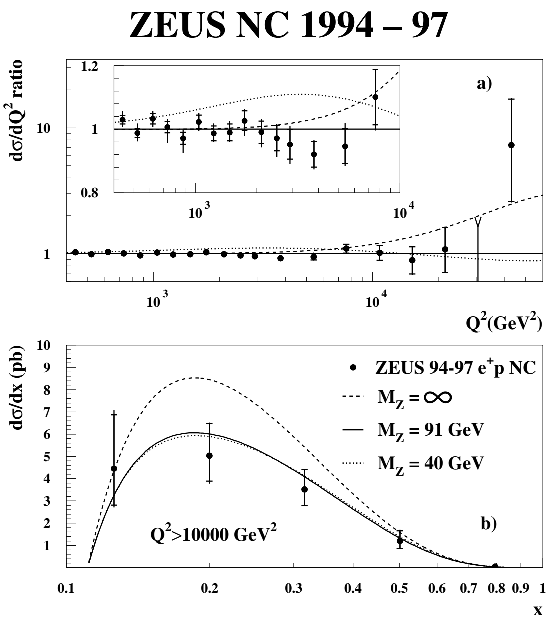
$$(\tilde{\sigma}_{CC}^{e^-p})_{LO} = x[(u+c) + (1-y^2)(\bar{d}+\bar{s})]$$

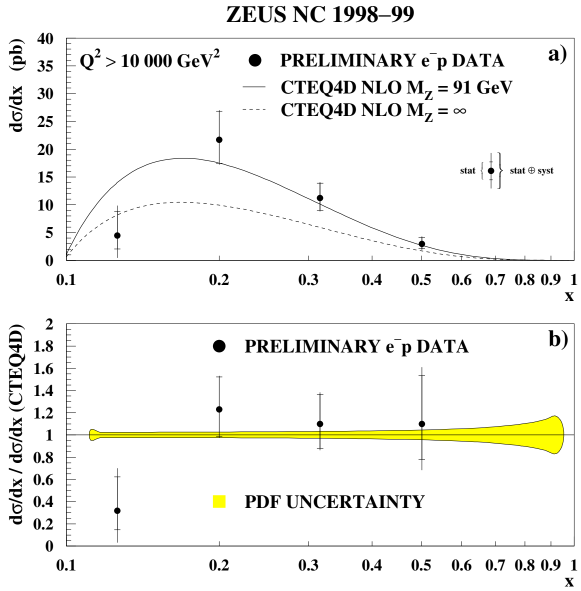


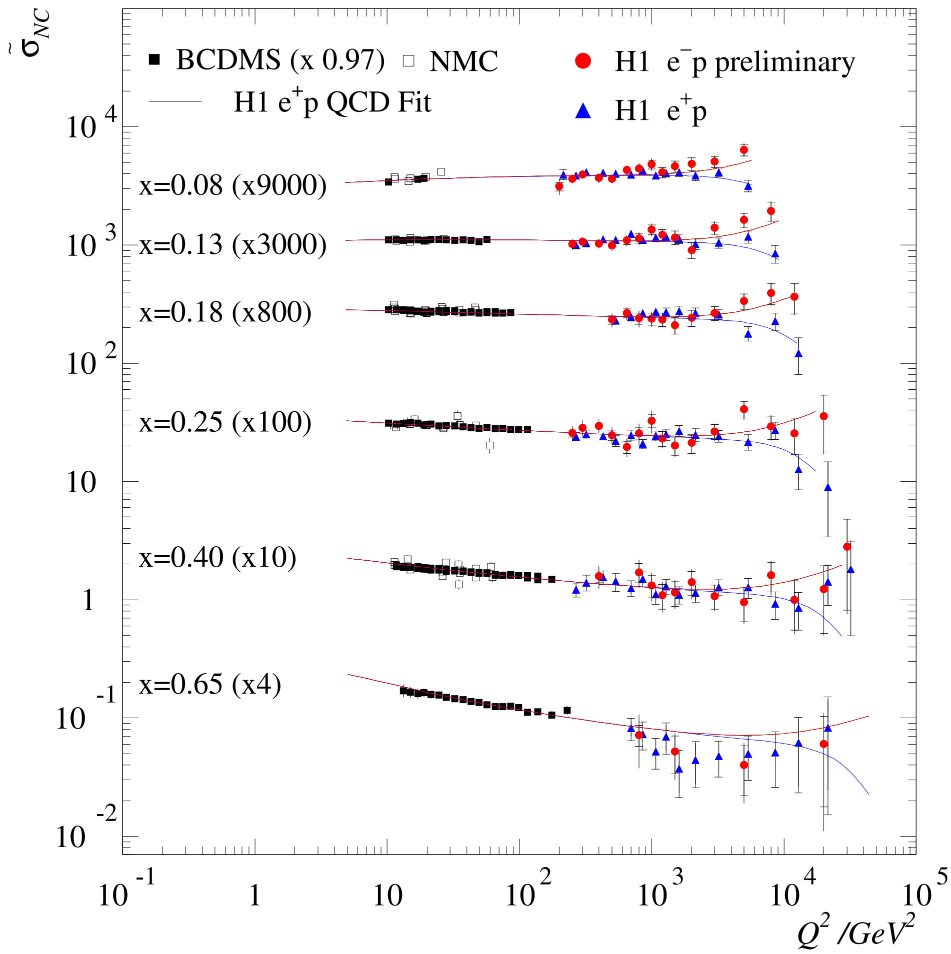


★ **Elecroweak unification at a scale of $\sim 10^4$ GeV^2**

High Q^2 NC cross sections







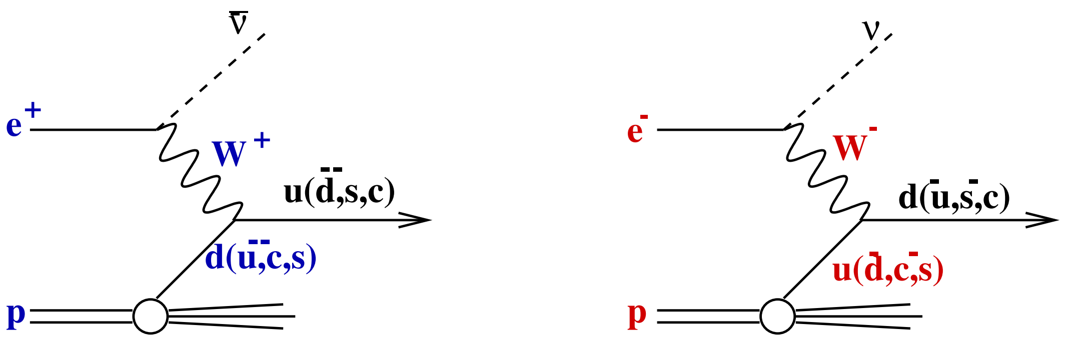
★ High Q^2, high x 'anomaly' is still there ($\sim$ 2σ level)

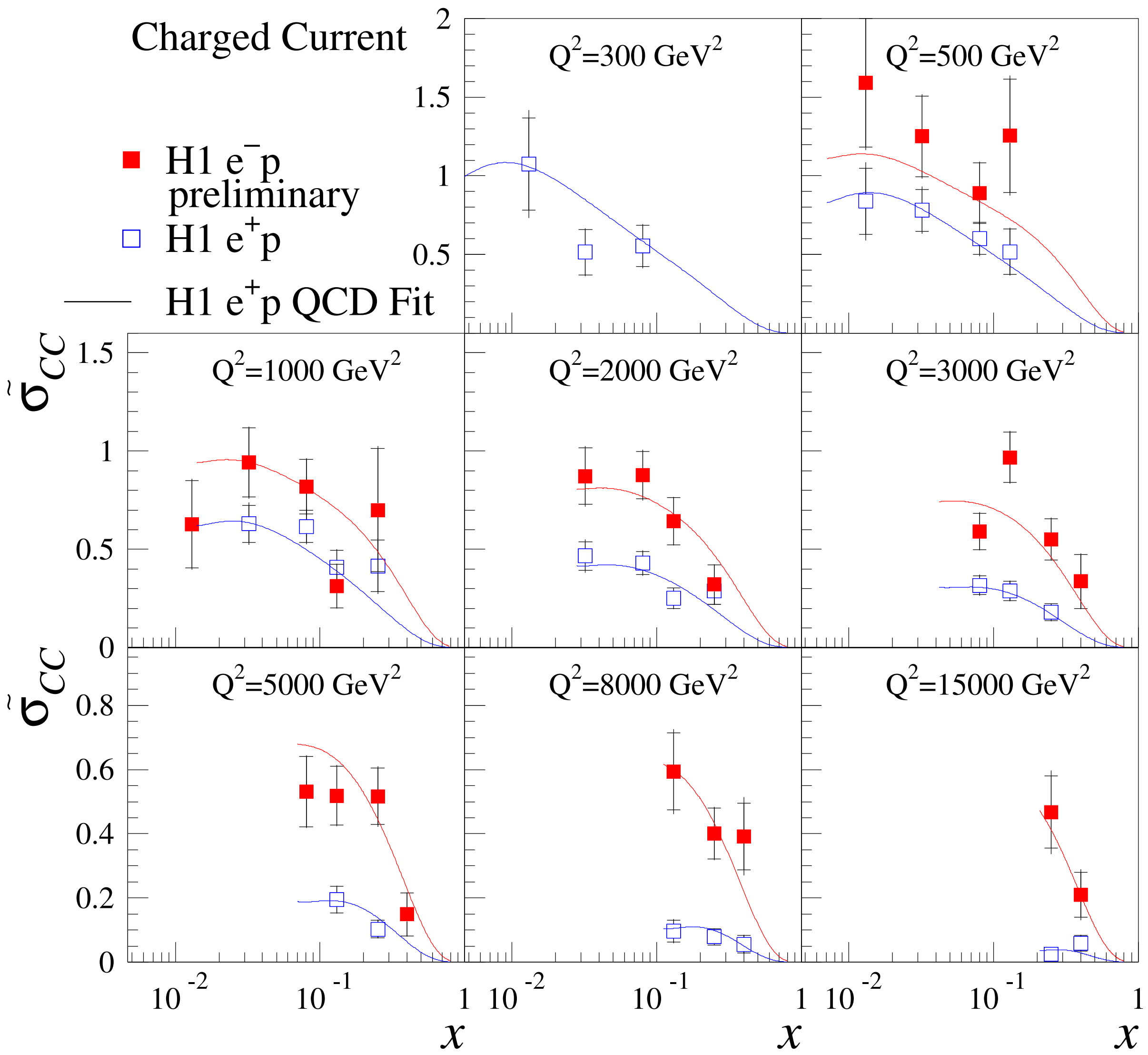
To clarify the situation:

$\Rightarrow$ double e^+p data sample before the upgrade

$\Rightarrow$ run HERA in high $\mathcal{L}$ mode in the next millenium

CC cross section: probing quark densities





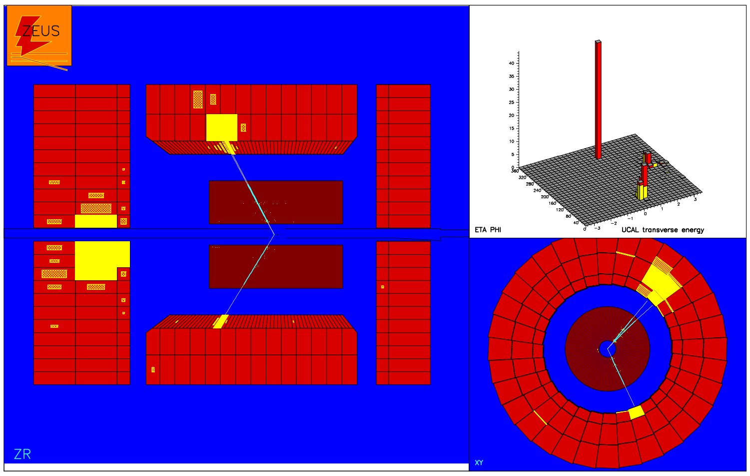
$$\bigstar \quad \sigma^- \propto u + (1-y)^2\bar{d} \rightarrow u_v$$

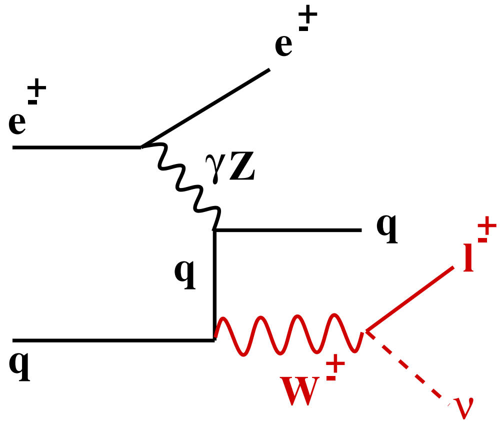
$$\bigstar \quad \sigma^+ \propto \bar{u} + (1-y)^2 d \rightarrow (1-y)^2 d_v$$

Isolated Lepton Events

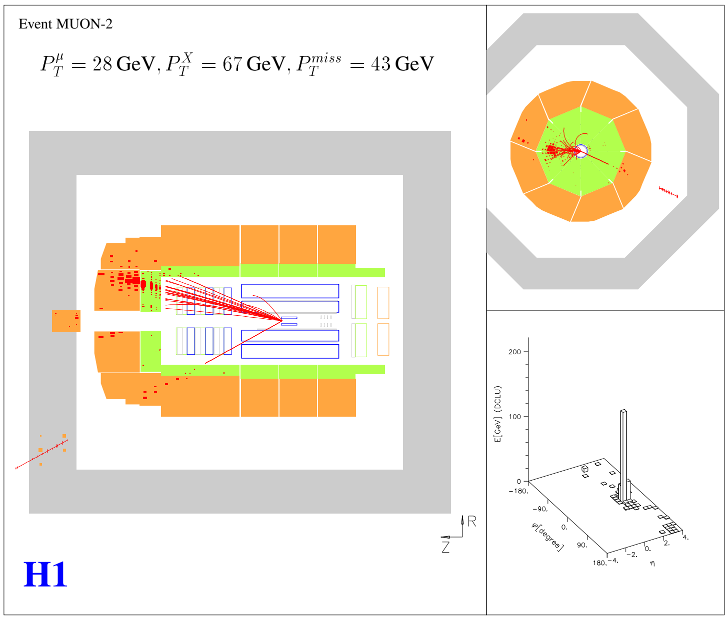
Potential source of new physics, clean signature

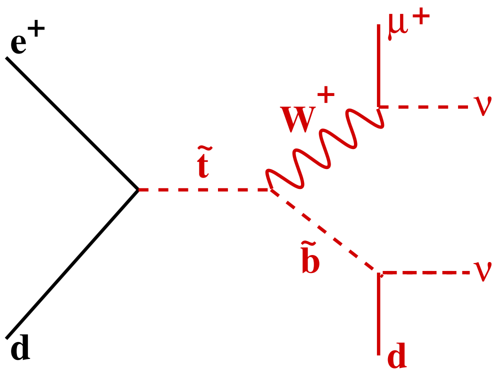
W candidate ($M_T = \mathbf{81.4 \pm 3.2}$ GeV)





$e^+p \rightarrow \mu^+X$





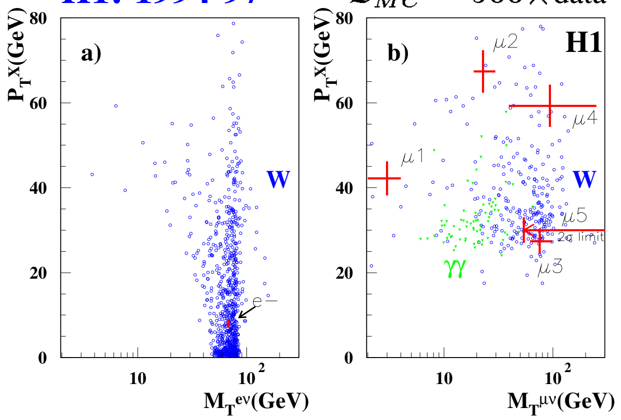
Signature: **lepton + jet +** $\not{p}_T$

Rate: $W^{\pm} \rightarrow l^{\pm}\nu$ – $\mathcal{O}$(0.3 pb)

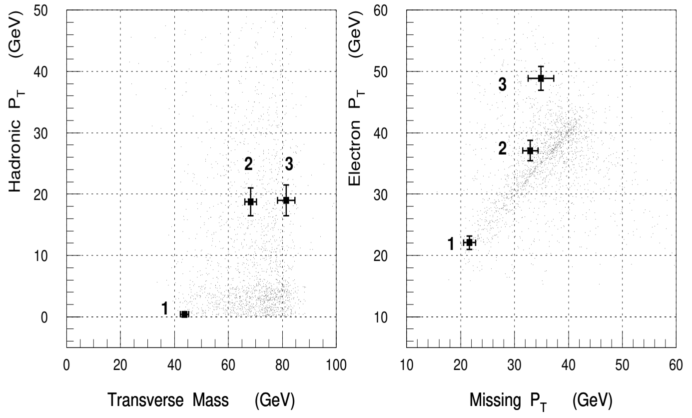
SUSY ($\tilde{t}$, $\tilde{b}$) – $\mathcal{O}$(? pb)

Isolated Leptons: Results

H1: 1994-97 $\mathcal{L}_{MC} = 500\times$data



ZEUS: 1994-97 $\mathcal{L}_{MC} = 1000\times$data



H1 e^+p 1994-1997

e:

P_T^X	Data	SM	W
> 0 GeV	3	3.12 ± 0.70	2.24 ± 0.67
> 12 GeV	1	1.15 ± 0.25	0.78 ± 0.23
> 25 GeV	0	0.50 ± 0.12	0.38 ± 0.11
> 40 GeV	0	0.16 ± 0.04	0.14 ± 0.04

μ:

P_T^X	Data	SM	W	
> 12 GeV	5	1.01 ± 0.28	0.87 ± 0.26	
> 25 GeV	5	0.56 ± 0.15	0.49 ± 0.15	
> 40 GeV	3	0.21 ± 0.06	0.19 ± 0.06	$\Leftarrow$!

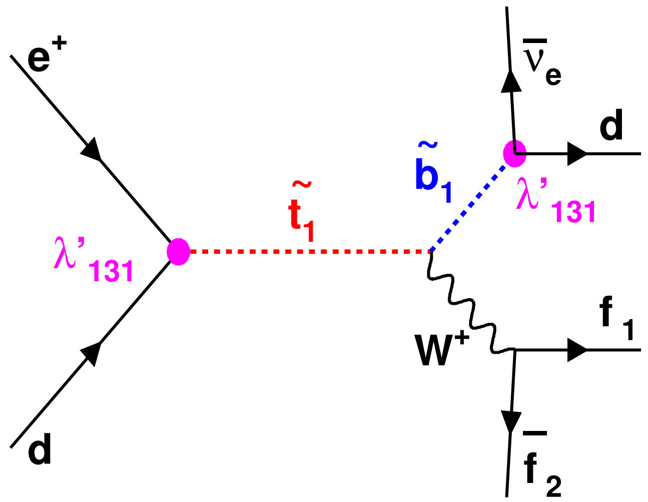
ZEUS e^+p 1994-1997

Channel	Data	SM expectation	W
Electron	3	3.5 ± 0.7	0.9
Muon	0	2.0 ± 0.4	0.4

- ★ ZEUS results in agreement with SM
- ★ H1 observes 3 outstanding μ events, no simple SM explanation
- ★ No excess over SM in e^-p data (1998-99) of H1 and ZEUS

H1 isolated μ events: SUSY?

$\boxed{\tilde{b} + \text{W Production}}$



Model : $R\!\!\!/_p$ SUSY
$\lambda'_{131} \neq 0$

Assumptions :
$\tilde{b}_1$ is the LSP
$M_{\tilde{b}_1} < M_{\tilde{t}_1} < M_{\chi_1^+}$

cf T.Kon et al

Existing limits $\Rightarrow M_{\tilde{b}_1} \gtrsim 90$ GeV, sizeable $\sigma \Rightarrow M_{\tilde{t}_1} \gtrsim 180$ GeV
Only decay mode for $\tilde{b}_1$: $\tilde{b}_1 \to d\bar{\nu}_e$

- $W \to e\nu$: 1 event in H1 (e^-)
- $W \to \mu\nu$: 4 events in H1 (2 μ^+, 1 μ^-, 1 $\mu^\pm$)

cf Events with an isolated high p_T lepton and $P_{T,miss}$
Euro. Phys. J. C5 (1998) 575.

- $W \to had.$: cf $\tilde{q} \to q\chi \to \nu q q' q''$; here : P_T(both jets) > 25 GeV

$$\boxed{N_{obs} = 3 \text{ evts}, \quad N_{SM} = 4.7 \pm 0.7 \text{ evts}}$$

For $M_{\tilde{t}_1} \sim 200$ GeV, $M_{\tilde{b}_1} \sim 100$ GeV :

Using $\left\{ \begin{array}{l} \text{efficiencies } (\varepsilon(W \to had.) \simeq \varepsilon(W \to \mu\nu) \simeq 50\%) \\ BR(W \to \mu\nu)/BR(W \to had.), \\ N_{obs}(W \to had.) \text{ and } N_{SM}(W \to had.) \end{array} \right.$

$\Longrightarrow N_{obs}(W \to \mu) < 0.36$ at 90% C.L.

★ **No excess over the SM in hadronic decay mode of *W***

BSM: LFV leptoquarks

$$M_{LQ} >> \sqrt{s_{ep}} \Rightarrow \sigma \propto (\lambda_{1i}\lambda_{3j}/M^2_{LQ})^2$$

$e \longleftrightarrow \tau$ **F = 0**

BEST EXCLUSION UPPER LIMITS ON $\frac{\lambda_{1i}\ \lambda_{3j}}{M^2_{LQ}}$ (in 10^{-4} GeV^{-2})

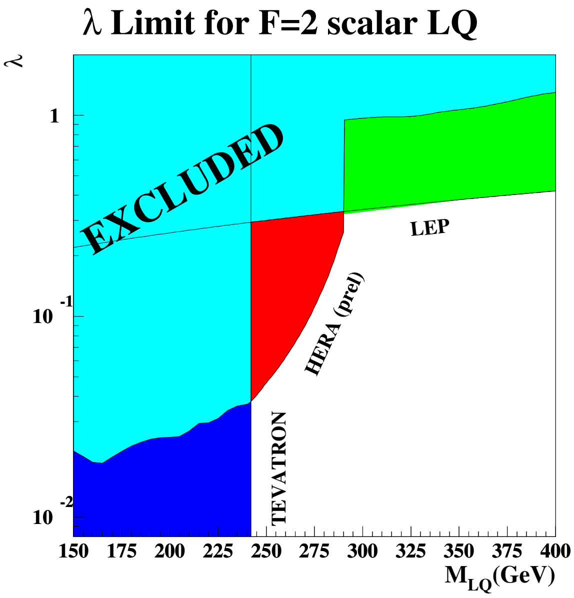
FOR LEPTON FLAVOUR VIOLATING LEPTOQUARKS

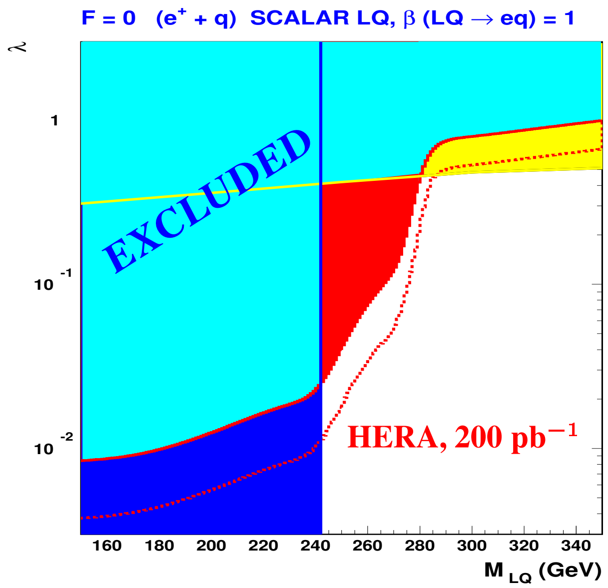
$q_i\ q_j$	$S_{1/2,L}$	$S_{1/2,R}$	$\tilde{S}_{1/2,L}$	$V_{0,L}$	$V_{0,R}$	$\tilde{V}_{0,R}$	$V_{1,L}$
1 1	$\tau \to \pi e$ 0.0032 H1: 0.046	$\tau \to \pi e$ 0.0016 H1: 0.037	$\tau \to \pi e$ 0.0032 H1: 0.062	G_F 0.002 H1: 0.015	$\tau \to \pi e$ 0.0016 H1: 0.015	$\tau \to \pi e$ 0.0016 H1: 0.013	G_F 0.002 H1: 0.0060
1 2	ZEUS: 0.12 H1: 0.047	$\tau \to K e$ 0.05 H1: 0.038	$\tau \to K e$ 0.05 H1: 0.063	$\tau \to K e$ 0.03 H1: 0.017	$\tau \to K e$ 0.03 H1: 0.017	ZEUS: 0.10 H1: 0.014	$K \to \pi \nu \bar{\nu}$ 2.5×10^{-6} H1: 0.0065
1 3	*	$B \to \tau \bar{e} X$ 0.08 H1: 0.065	$B \to \tau \bar{e} X$ 0.08 H1: 0.065	$B \to l \nu X$ 0.02 H1: 0.020	$B \to \tau \bar{e} X$ 0.04 H1: 0.020	*	$B \to l \nu X$ 0.02 H1: 0.020
2 1	ZEUS: 0.34 H1: 0.15	$\tau \to K e$ 0.05 H1: 0.095	$\tau \to K e$ 0.05 H1: 0.12	$\tau \to K e$ 0.03 H1: 0.020	$\tau \to K e$ 0.03 H1: 0.020	ZEUS: 0.10 H1: 0.023	$K \to \pi \nu \bar{\nu}$ 2.5×10^{-6} H1: 0.010
2 2	$\tau \to e \gamma$ 0.03 H1: 0.18	$\tau \to e \gamma$ 0.02 H1: 0.10	ZEUS: 0.48 H1: 0.13	ZEUS: 0.25 H1: 0.024	ZEUS: 0.25 H1: 0.024	ZEUS: 0.31 H1: 0.034	ZEUS: 0.13 H1: 0.014
2 3	*	$B \to \tau \bar{e} X$ 0.08 H1: 0.14	$B \to \tau \bar{e} X$ 0.08 H1: 0.14	$B \to l \nu X$ 0.02 H1: 0.035	$B \to \tau \bar{e} X$ 0.04 H1: 0.035	*	$B \to l \nu X$ 0.02 H1: 0.035
3 1	*	$B \to \tau \bar{e} X$ 0.08 H1: 0.16	$B \to \tau \bar{e} X$ 0.08 H1: 0.16	V_{ub} 0.002 H1: 0.022	$B \to \tau \bar{e} X$ 0.04 H1: 0.022	*	V_{ub} 0.002 H1: 0.022
3 2	*	$B \to \tau \bar{e} X$ 0.08 H1: 0.19	$B \to \tau \bar{e} X$ 0.08 H1: 0.19	$B \to l \nu X$ 0.02 H1: 0.026	$B \to \tau \bar{e} X$ 0.04 H1: 0.026	*	$B \to l \nu X$ 0.02 H1: 0.026
3 3	*	ZEUS: 0.72 H1: 0.23	ZEUS: 0.72 H1: 0.23	$\tau \to e \gamma$ 0.51 Z H1: 0.045	$\tau \to e \gamma$ 0.51 Z H1: 0.045	*	ZEUS: 0.38 H1: 0.045

★ **High discovery potential for LFV LQ at HERA**

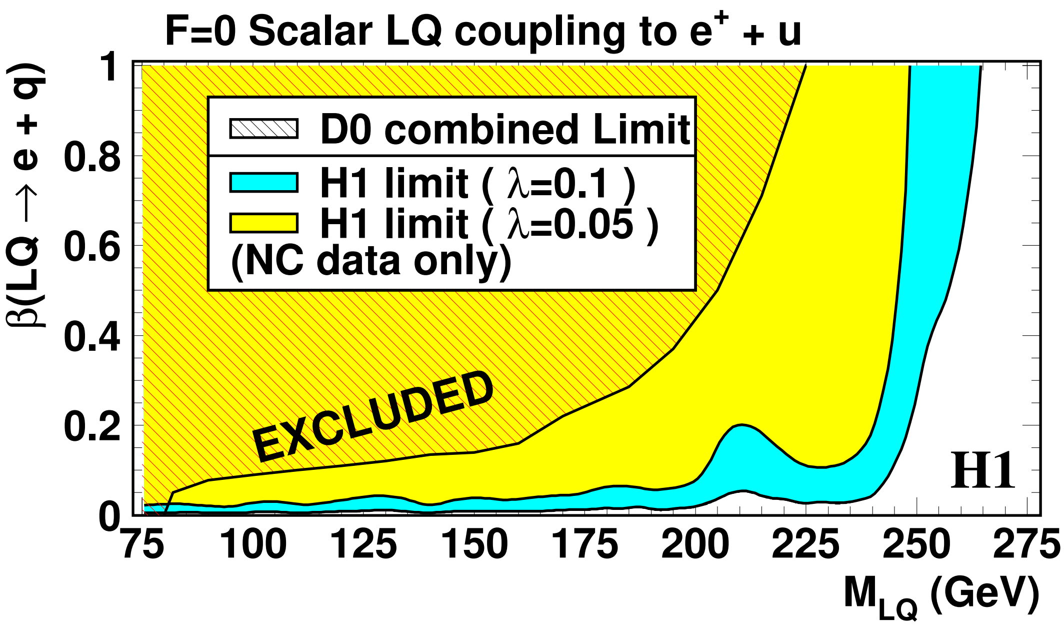
BSM: First generation leptoquarks

ZEUS: $e^{-}p$, 16 pb^{-1} | **HERA: $e^{+}p$, 40 pb^{-1}**





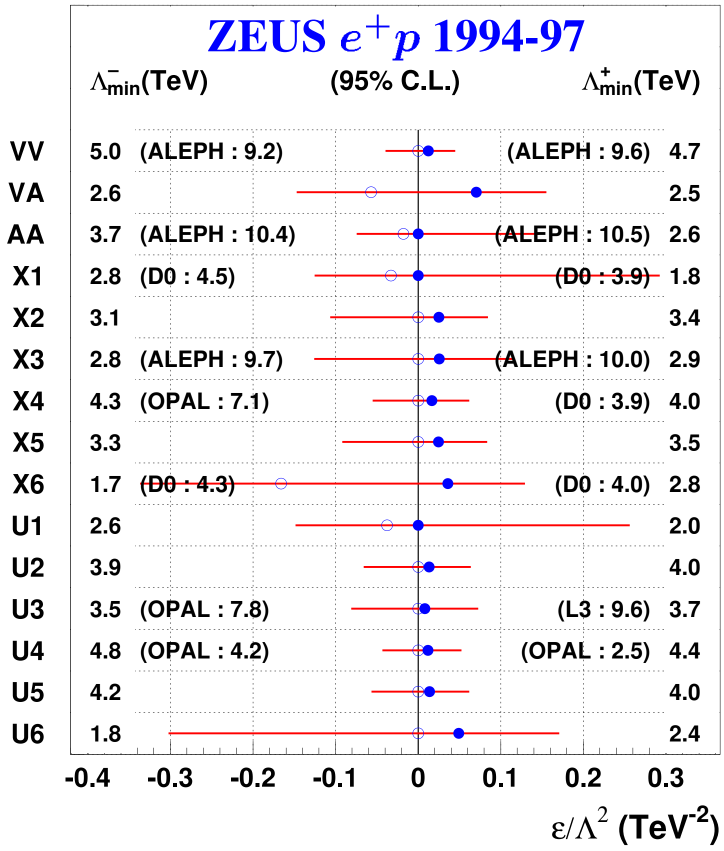
★ **Strong competition with Tevatron-II !**



★ **Still high discovery potential for small β !**

BSM: Contact Interactions

- “New Physics” processes with characteristic scale $>> \sqrt{s}$
- CI interfere with DIS, affecting $d\sigma/dQ^2, \;\; d\sigma/dx$



- 15 $(\times 2)$ scenarios constrained by ZEUS
- horizontal bars show 95% CL limits

- limits range **from 1.7 TeV to 5 TeV**

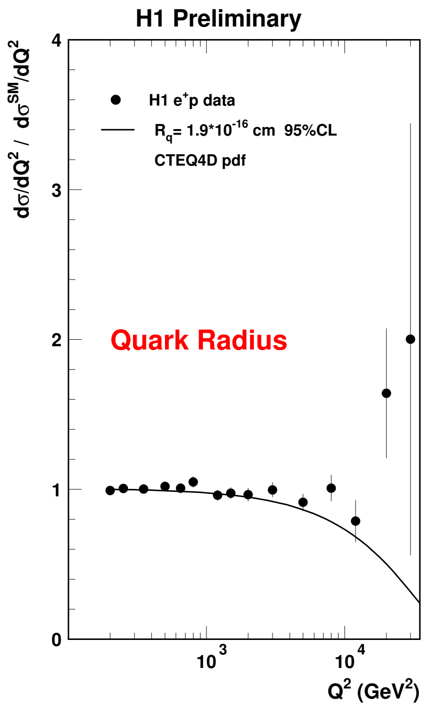
- NB : LEP (EPS’99) limits rely on flavor symmetry hypothesis

H1 results interpreted in terms of quark radius by using form factors:

$$d\sigma/dQ^2 = d\sigma^{SM}/dQ^2 \times f_q(Q^2)$$

with $f_q(Q^2) = 1 - \frac{1}{6}R_q^2 Q^2$

$$R_q < 1.9 \cdot 10^{-3} \text{ fm}$$



Summary

★ **HERA becomes a leading facility for studies in QCD sector**

★ **Standard Model is still in a very good shape**

★ **Although there are no clear evidence for new physics beyond the SM, we do see an intriguing effects at very large Q^2 and transverse momenta**

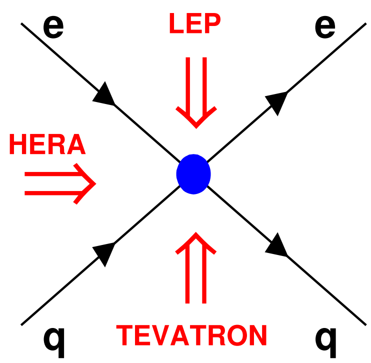
★ **Running HERA after the Upgrade will clarify questions about outstanding events with isolated leptons and exess of the NC events at large Q^2 and large x in e^+p collisions**

★ **To optimally exploit discovery potential at HERA we expect the upgrade to come on schedule...**

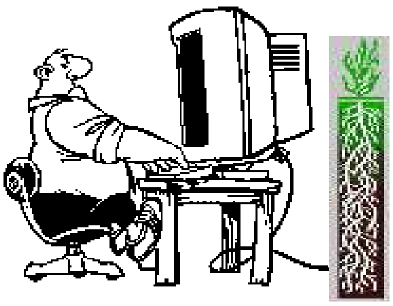
Outlook

Curiosity is a driving force of the intellectual progress
Three main ingredients to maintain this progress:

- Competition
  - ▷ Tevatron / LEP / HERA
  - ▷ Tevatron-II / HERA-2000
  - ▷ LHC / TESLA ...



- Laziness
  (OO technologies:
  complete analysis within 10 clicks?)



RooT

- Resources
  - ▷ get support from the community
  - ▷ attract and recruit new personpower
    (fill the gap between LEP and LHC)
  - ▷ improve public relations

Outlook

1999

20 . .

Here

could be

Your Image

It's up to us
to convert the dreams into reality ...

Dixi