Selected Recent Highlights from

Lepton-Nucleon Scattering at HERA

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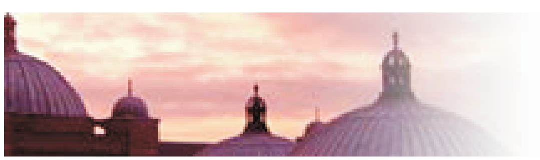
- *Introduction*
- *Inclusive Data*
- *Charm and Beauty*
- *High p_T Signals*
- *Pentaquarks*

IoP Particle Physics Conference, 6 April 2004



Institute *of* **Physics**
High Energy *Particle Physics* Group

HERA: High Energy Electron-Proton Scattering

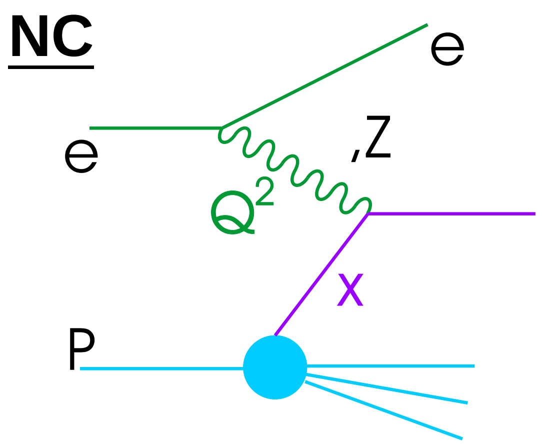
Strong sector of Standard Model much more poorly understood than Electroweak . . .

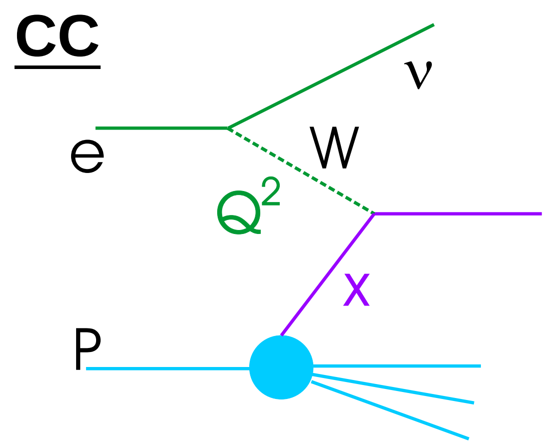
In high energy ep Collisions, electron probes the strong interaction at work in the proton

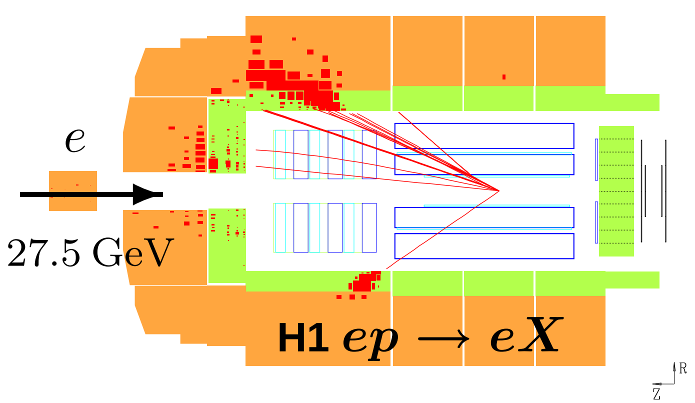
. . . Measure the quark and gluon content of the proton

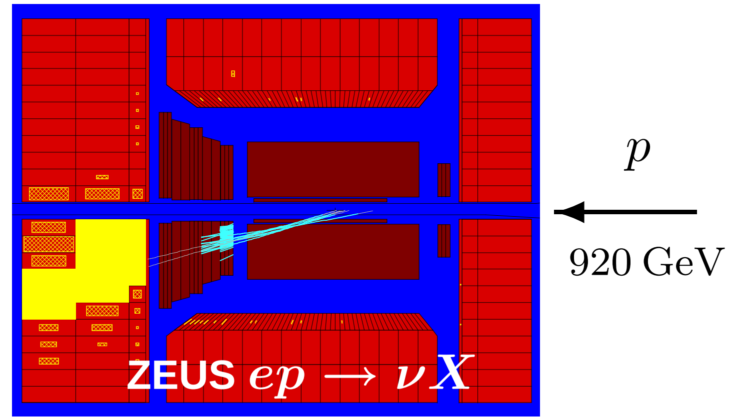
. . . Test our understanding of Strong Interaction dynamics

. . . Search for new physics e.g. in mixed states, eq, eg

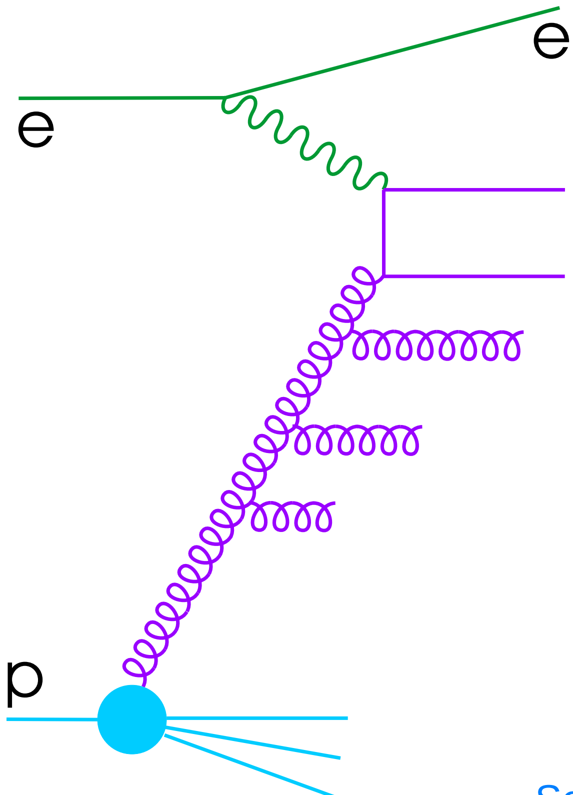


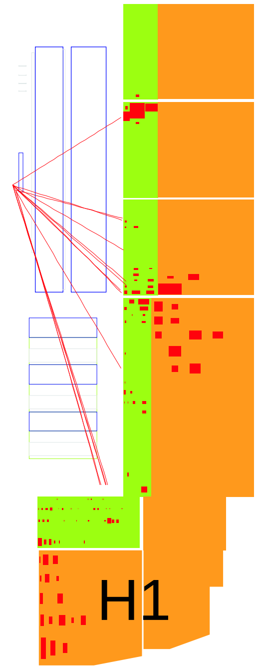






HERA: QCD from the established to the exploratory





Structure Functions

Precision QCD tests

Parton dynamics

Rapidity Gaps, Diffraction

Searches at highest $\sqrt{s}$ with initial state lepton

$s = (e + p)^2$ $\quad (\sqrt{s} = 300 - 320\ \mathrm{GeV})$

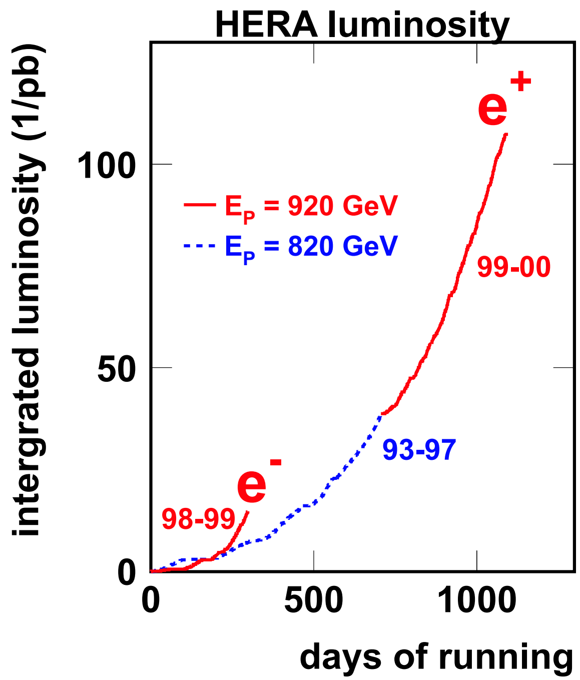
$Q^2 = -(e - e')^2$ $\quad (0 < Q^2 < 10^5\ \mathrm{GeV}^2)$

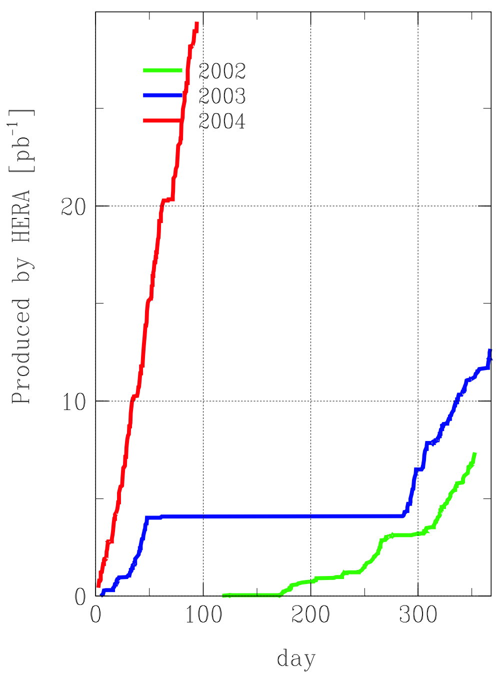
$x = Q^2 \,/\, (2p \cdot e)$ $\quad (10^{-6} < x < 1)$

$y = (p \cdot \gamma) \,/\, (p \cdot e)$

Sensitive to new physics on scales $\gtrsim 10^{-18}\ \mathrm{m}$

HERA Status and Plans





HERA-I run, 1992-2000

$\sim 100\ \mathrm{pb}^{-1}\ e^+p\ ,\ \sim 15\ \mathrm{pb}^{-1}\ e^-p$ per experiment.

Sufficient for precision measurements at low/medium Q^2, x

Glimpse at potential of highest Q^2, x region

Final HERA-I data published in many areas

Upgrade 2000-2002

Focusing magnets to improve luminosity

Spin rotators $\longrightarrow$ Longitudinally polarised leptons

Many detector upgrades $\longrightarrow$ extended phase space, precision

HERA-II run, 2003-2007(?)

$\longrightarrow 1\ \mathrm{fb}^{-1}$, shared equally between $e^{\pm}$ with $\pm$ helicity

$\longrightarrow$ Precision era for high x, high Q^2 physics, heavy flavours . . .

Reduced E_p running for F_L, high x & moderate Q^2

HERA performing well . . . First results with polarised leptons

HERA-II Charged Currents with Polarised Leptons

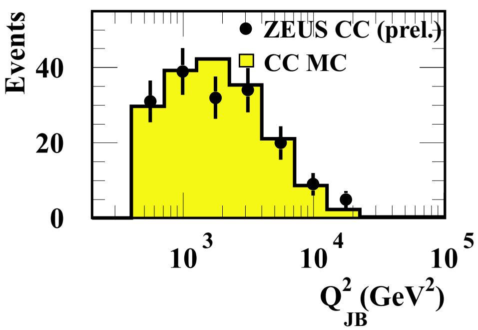
Polarisation expected to have largest effect on CC cross section . . . Linear dependence in SM

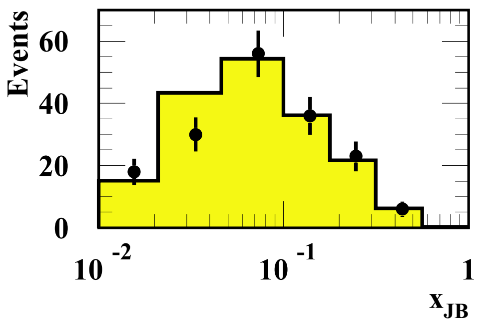
First measurements of influence of lepton helicity on CC interactions in ep scattering

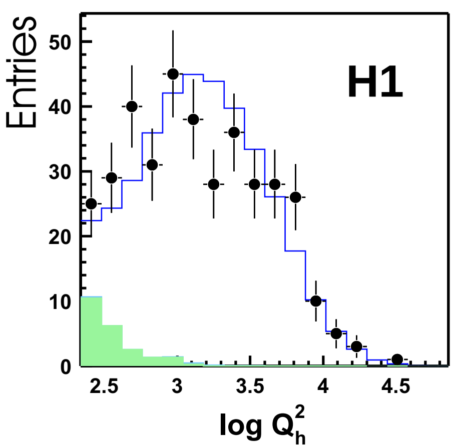
Polarisation $\sim 30\%$

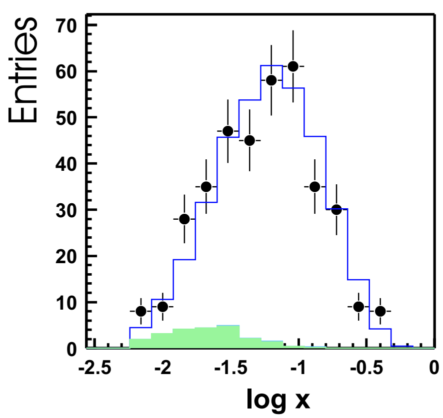
Effect established at $\sim 2\sigma$ per expt.

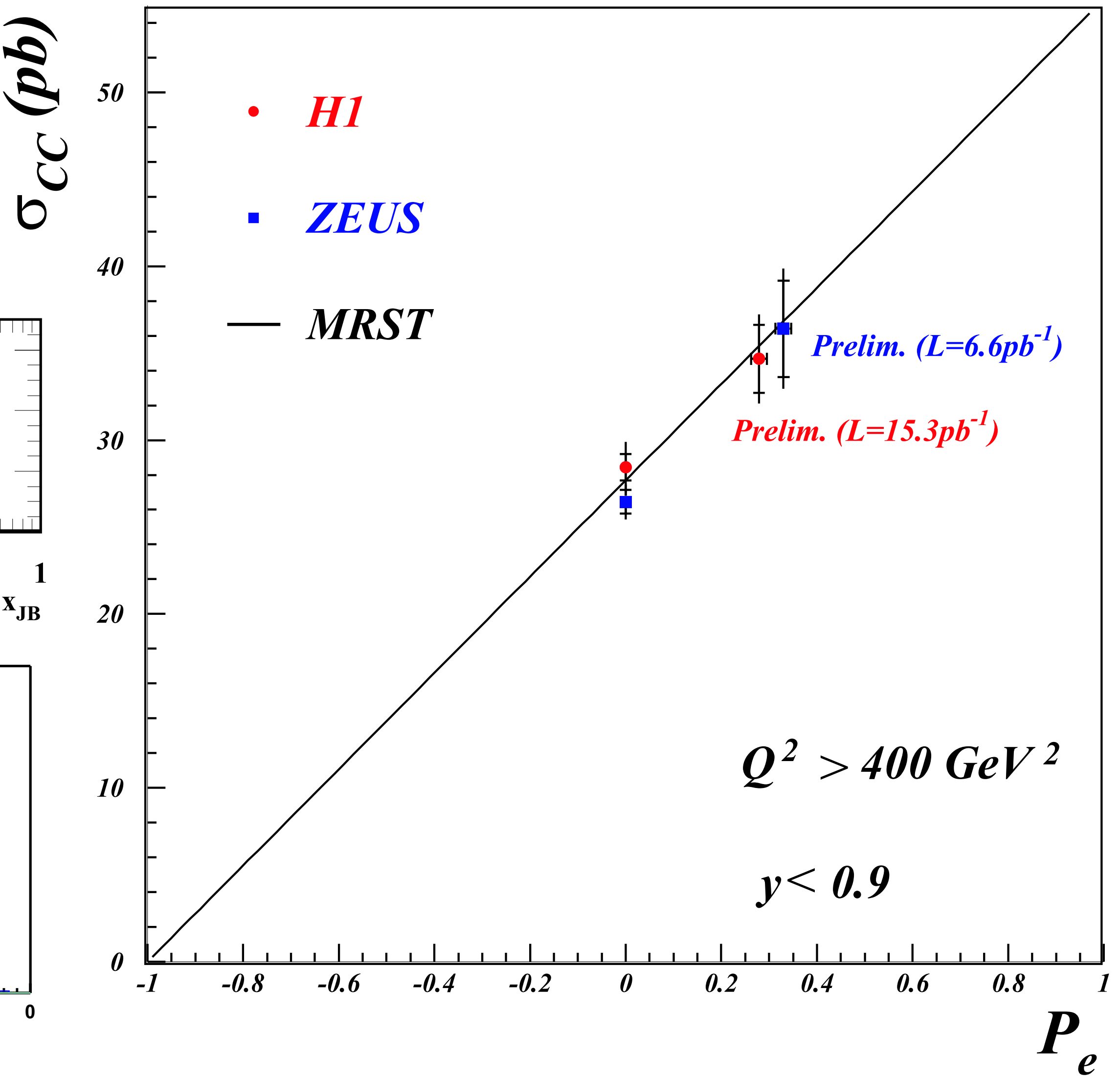
. . . much more to come from NC and CC!



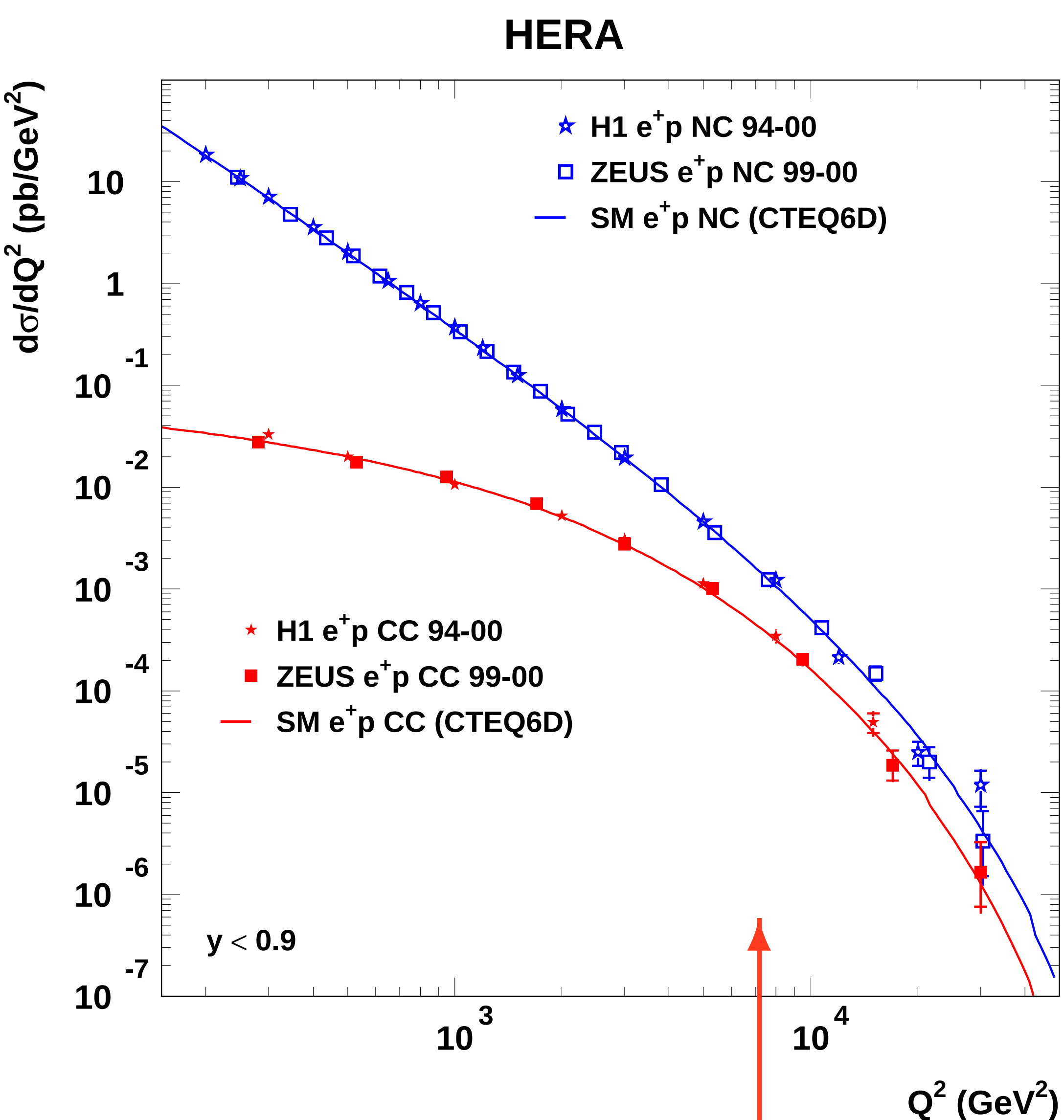








HERA-I: High Q^2 and Electroweak Unification



$Q^2 \sim M_W^2, M_Z^2$

Neutral current cross sections

$$\frac{d\sigma^{NC}}{dx dQ^2} \sim \frac{\alpha^2}{x} \cdot \left(\frac{1}{Q^2}\right)^2 \cdot \tilde{\sigma}_{NC}$$

Charged current cross sections

$$\frac{d\sigma^{CC}}{dx dQ^2} \sim \frac{G_F^2 M_W^4}{x} \cdot \left(\frac{1}{Q^2+M_W^2}\right)^2 \cdot \tilde{\sigma}_{CC}$$

Coupling

Propagator

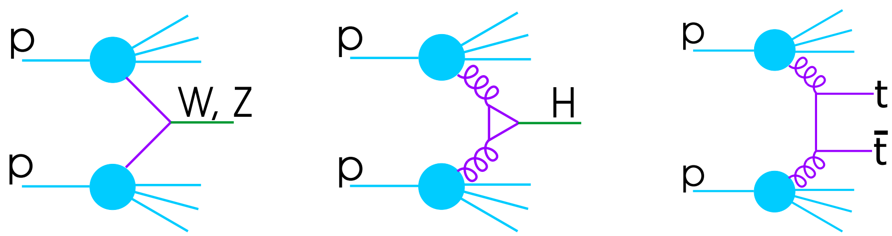
Quark Densities

NC and CC cross sections become comparable at EW unification scale

Illustration of electroweak unification with space-like gauge bosons, in beautiful agreement with Standard Model

HERA Data as an Input to LHC

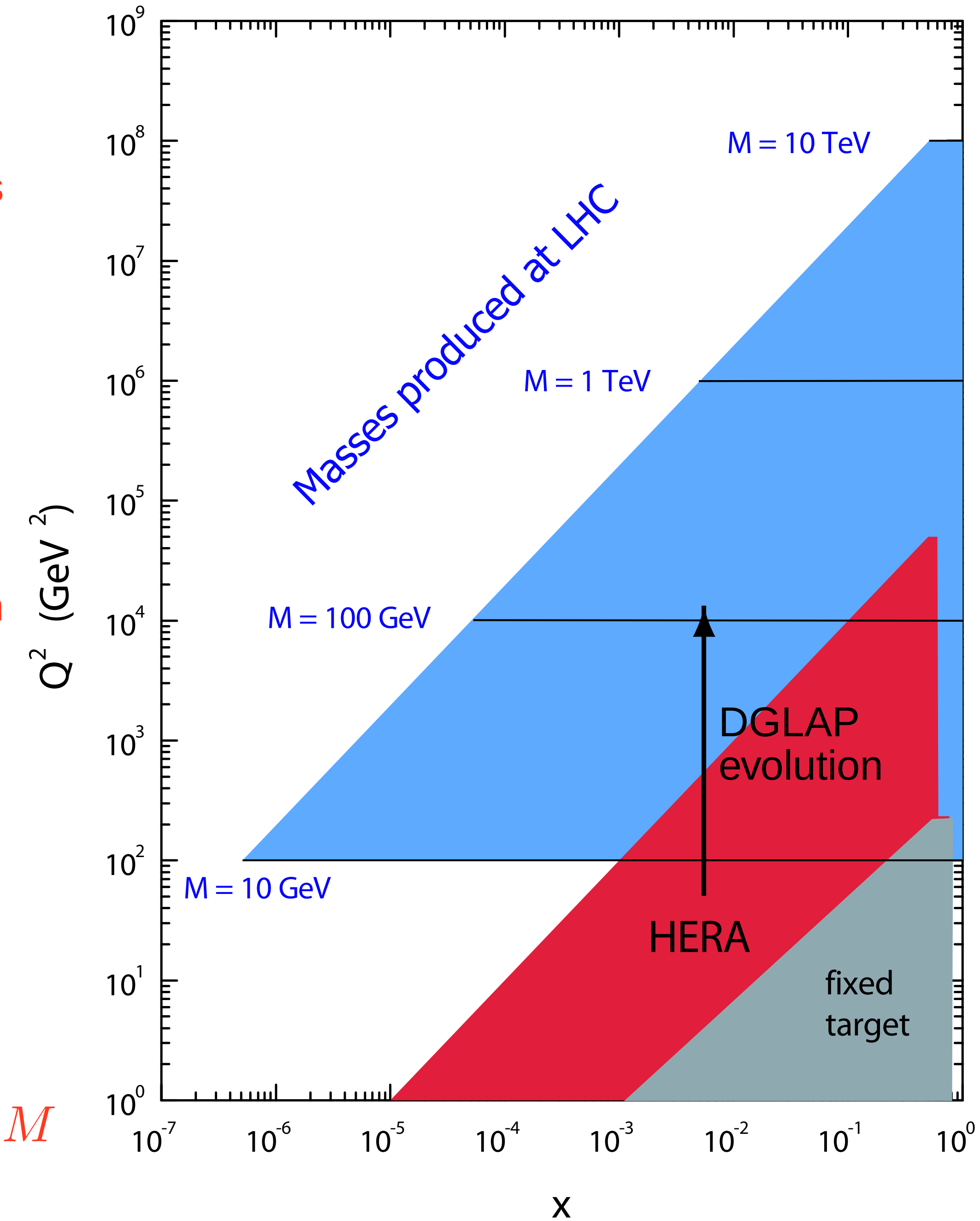
Understanding signals and background at the LHC requires detailed knowledge of the quark and gluon composition of the incoming protons



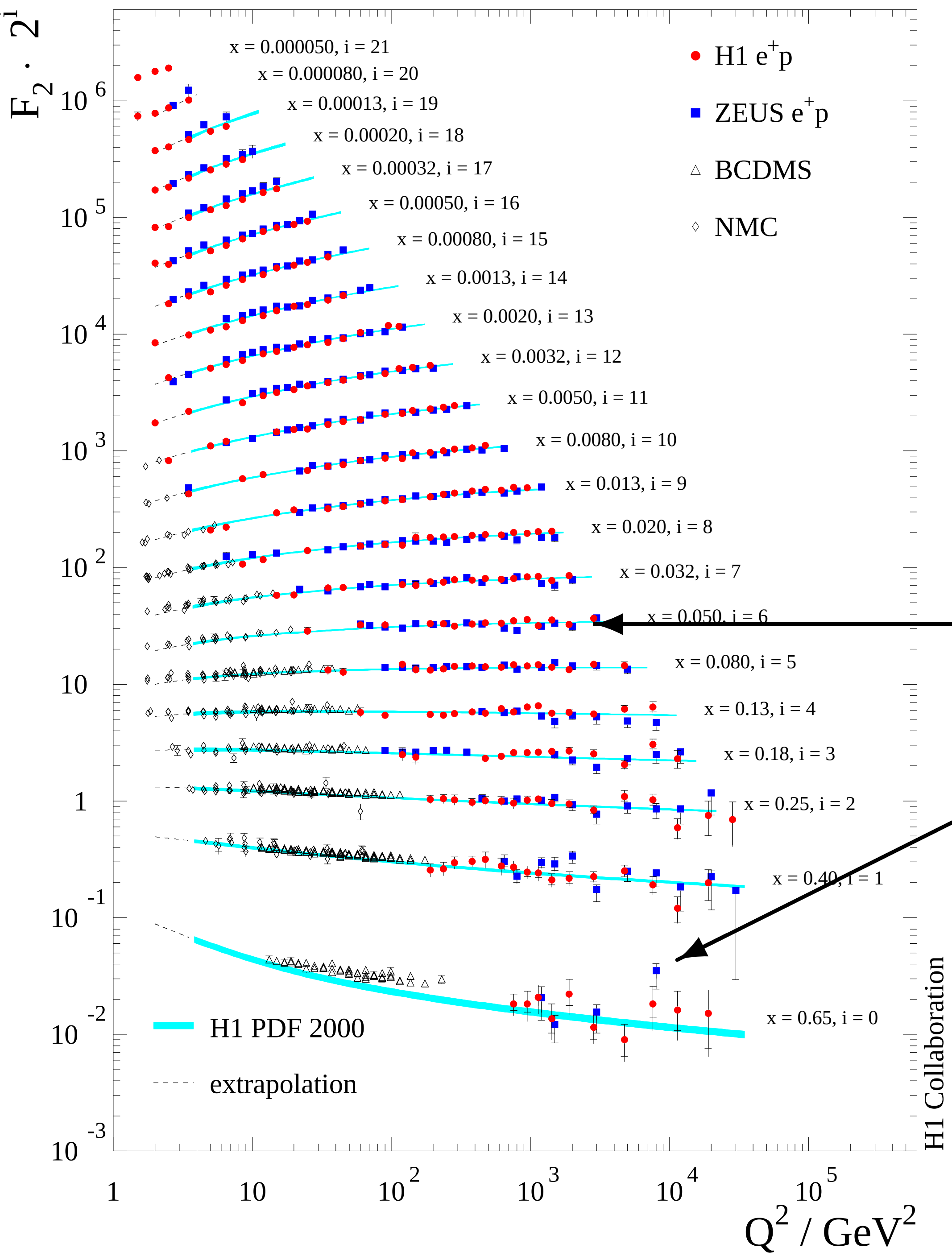
If x dependence of parton densities are known at one Q^2 value, DGLAP evolution allows us to obtain them at arbitrary Q^2

HERA data constrains quark densities over most of x range for LHC to a few $\%$ and tests the applicability of DGLAP

Larger uncertainties on gluon and at high x or M



$F_2(x, Q^2)$



$$\tilde{\sigma}^{\pm}_{\mathrm{NC}} = F_2 \mp \frac{Y_-}{Y_+} xF_3 - \frac{y^2}{Y_+} F_L$$

$$F_2(x, Q^2) \sim x \sum_q e_q^2 (q + \bar{q})$$

…dominates in most of phase space

Measured over huge kinematic range

2-3% precision in bulk of phase space

Highest x region requires much more luminosity and / or reduced E_p running

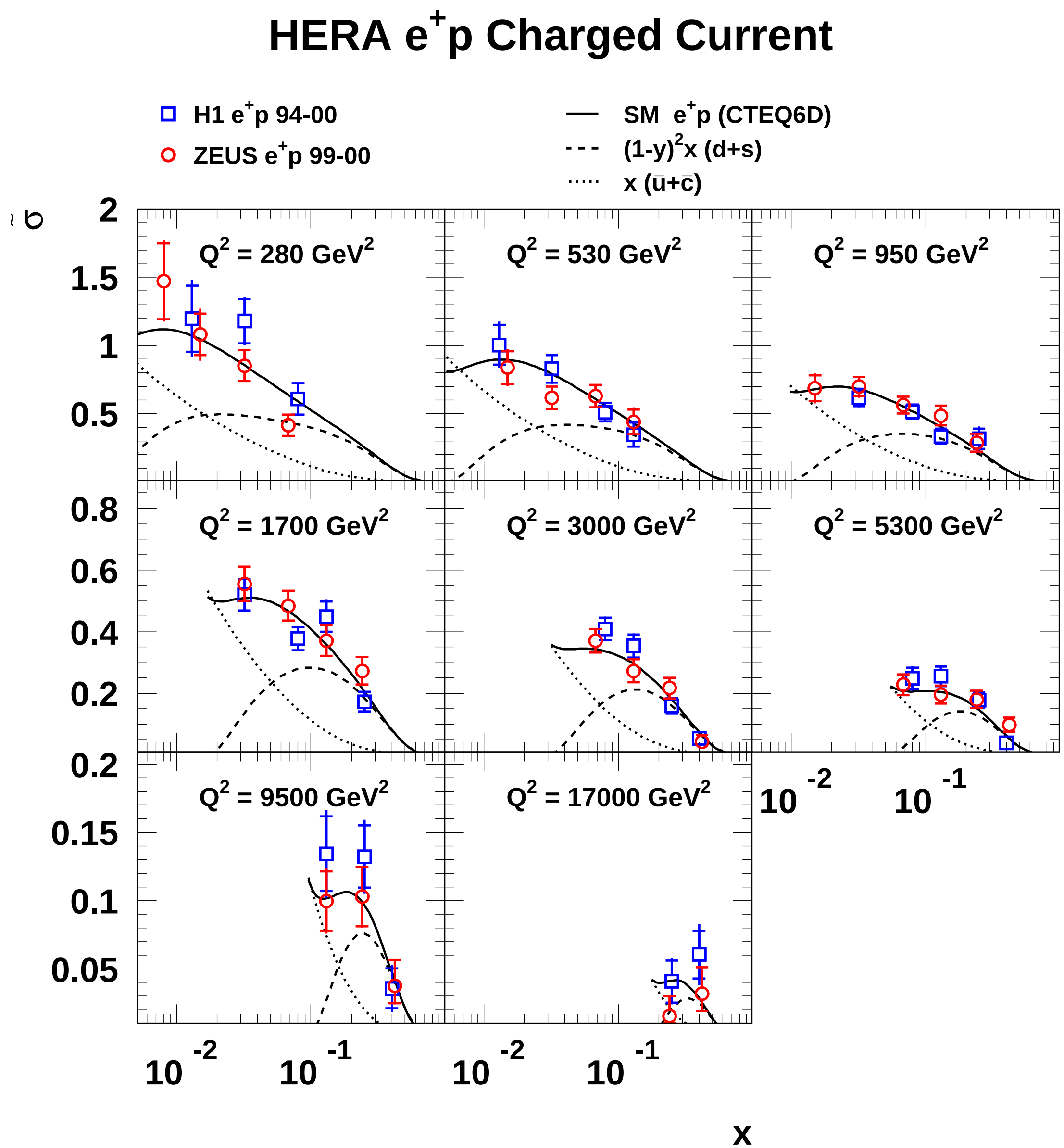
Beautifully described by QCD fits

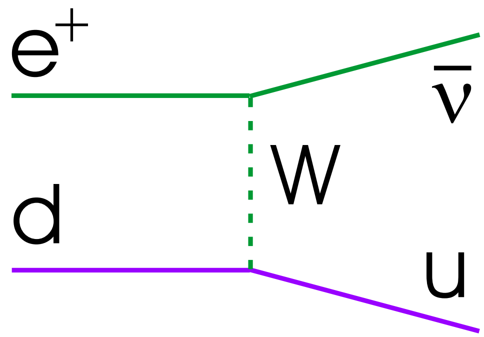
$\rightarrow$ strongest constraint on u, $\bar{u}$

Constrains gluon and α_s

via $\frac{\partial F_2}{\partial \ln Q^2} \sim \alpha_s x g(x)$

e^+p Charged Current Cross Sections





$$\tilde{\sigma}^{+}_{\rm CC} \sim x(\bar{u}+\bar{c}) \; + \; (1-y)^2\, x(d+s)$$

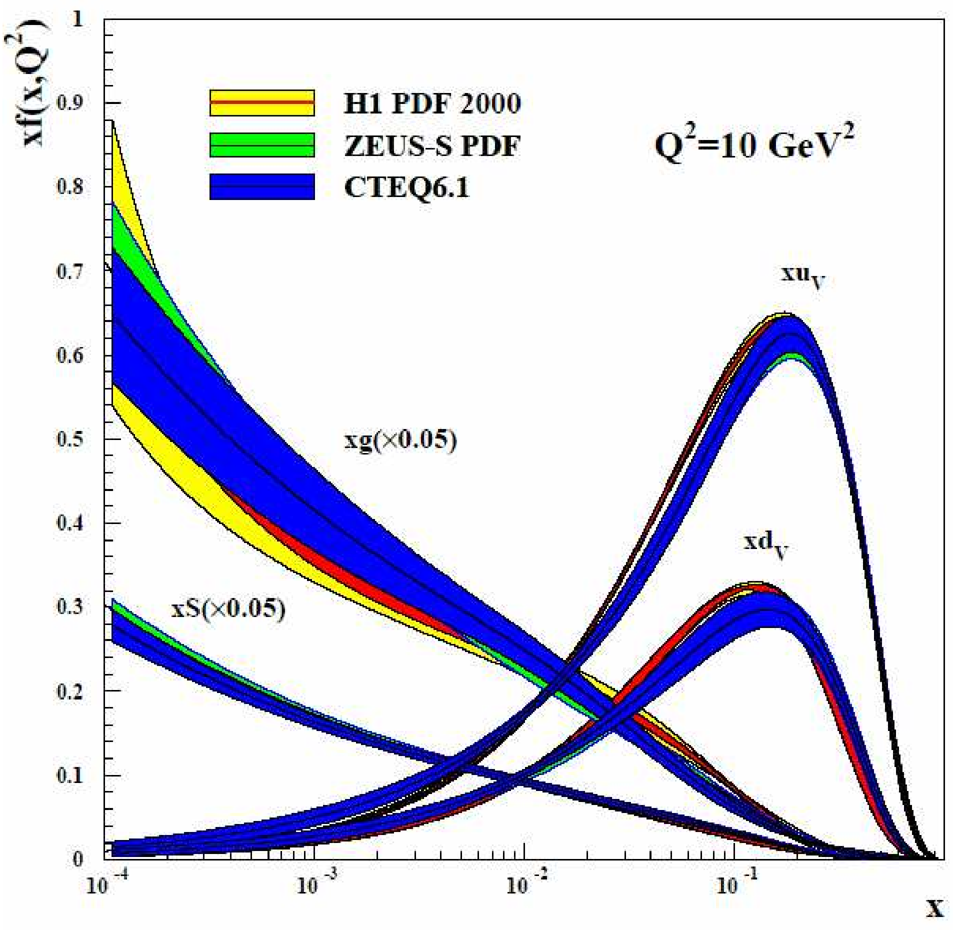
Promising for d density at high x

More data will help a lot

Still large errors at $x \gtrsim 0.5$ with $1\ {\rm fb}^{-1}$

eD data would constrain d/u at large x

Parton Density Extractions from HERA Data alone



NLO DGLAP fits to HERA NC, CC data

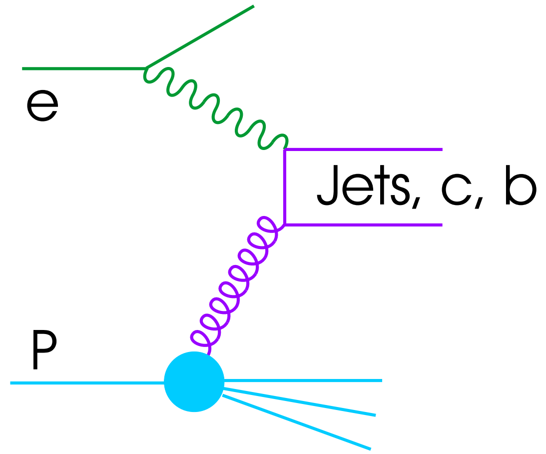
u, d densities to few % for $10^{-4} < x < 10^{-1}$

Uncertainties much larger at highest x

Indirect sensitivity to gluon

$\sim 3\%$ *experimental* uncertainty at low x

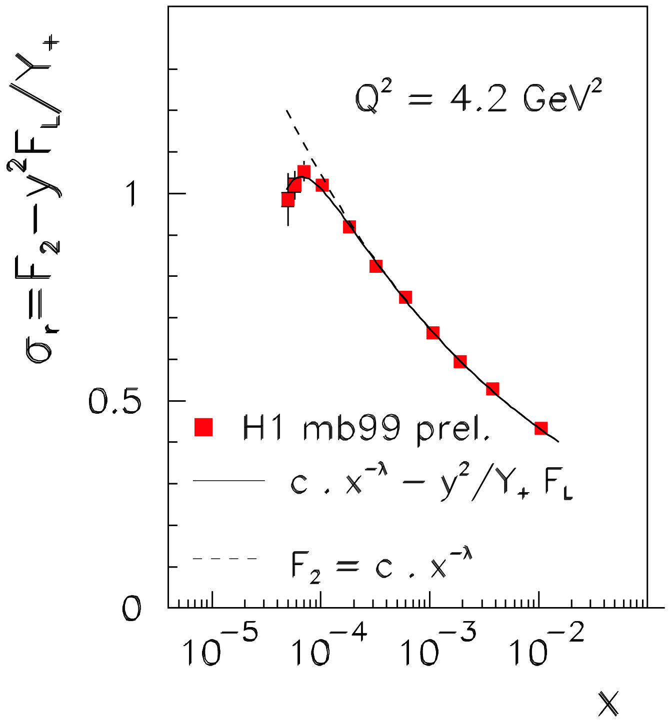
Very large gluon density at low x . . . DGLAP sufficient? . . . unitarity? . . . $gg \to g$? . . .



More direct gluon constraints from other observables . . .

$\sigma(\text{jets})$, $\sigma(\text{charm})$, $F_L \sim \alpha_s \, xg(x)$ (LO QCD)

e.g. HERA jet data sensitive up to $x \sim 0.8$



F_L Determinations

$F_L \neq 0$ at $\mathcal{O}(\alpha_s^1)$ due to gluon radiation

Ideal observable for gluon at lowest x, Q^2

beyond kinematic range of jet / charm data

$$\tilde{\sigma} = F_2 - (y^2/Y_+)\, F_L$$

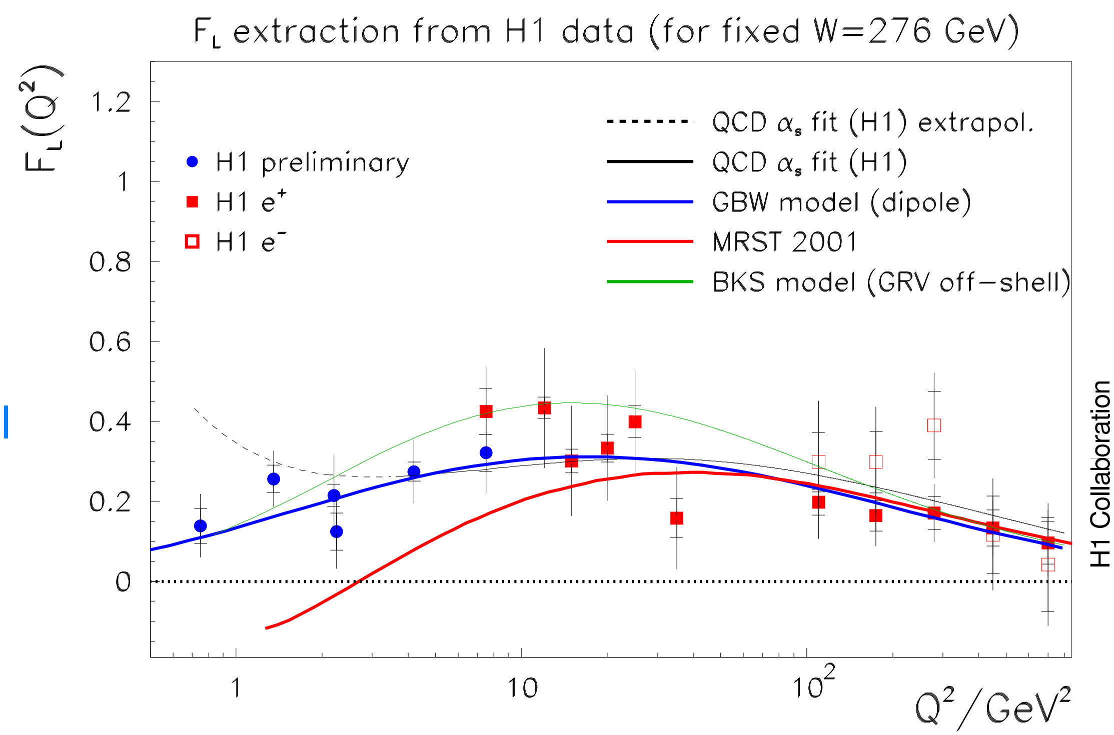
Sensitivity at highest $y \to 0.9 \quad (E'_e \to 3\,\mathrm{GeV})$

F_L determination spans 3 orders of magnitude in Q^2

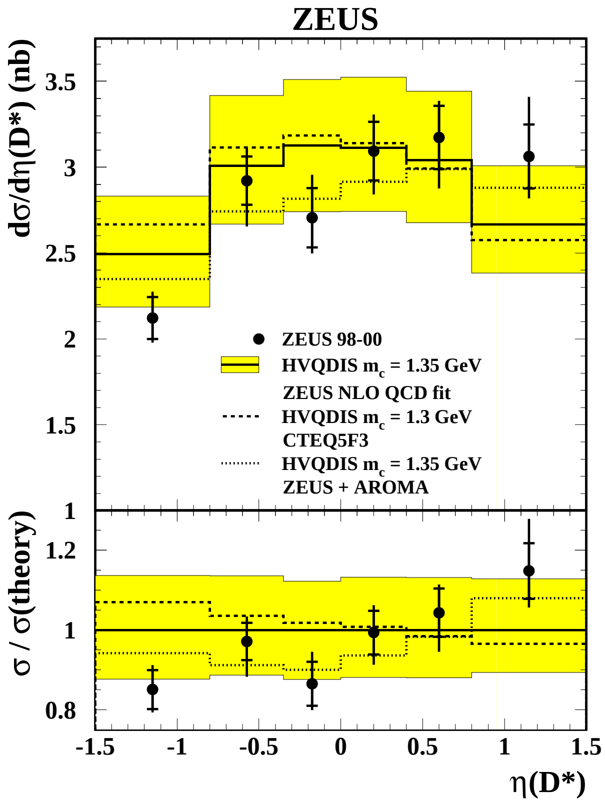
Distinguishes between DGLAP and other approaches at low Q^2

. . . but measurements of x dependence still required to see the full picture

. . . Requires reduced E_p running



Charm and the Gluon



Charm from $\sigma(D^*)$

v NLO QCD $\otimes\ xg(x)$

Beautiful confirmation

of gluon from scaling

violations at 10% level

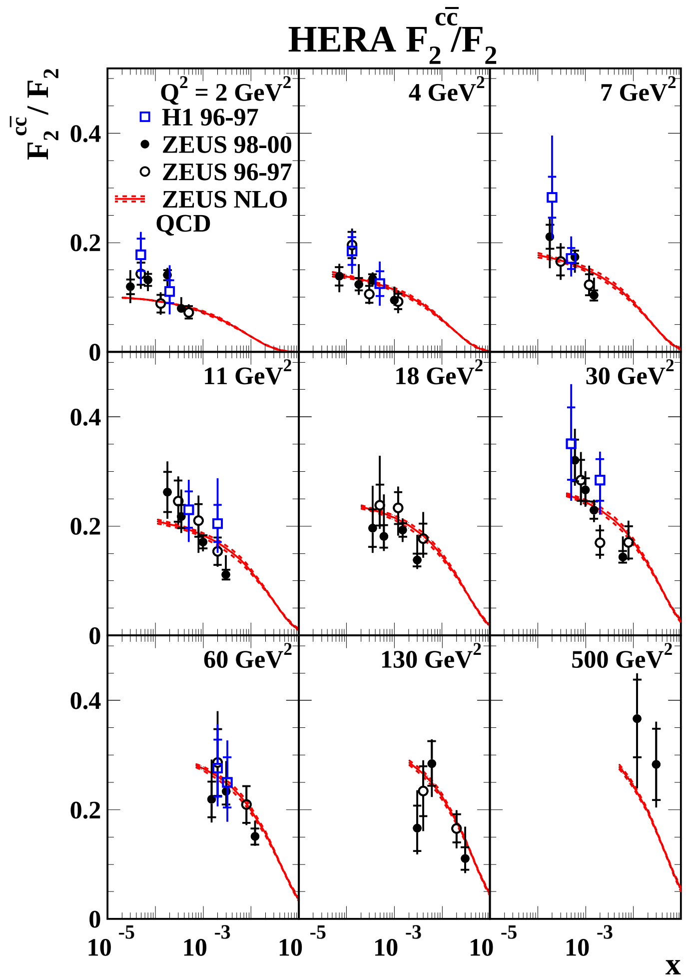
Sensitive to differences

between fitted gluons

Theoretical uncertainties

dominate $\longrightarrow\ m_c, \mu_r, \mu_f$

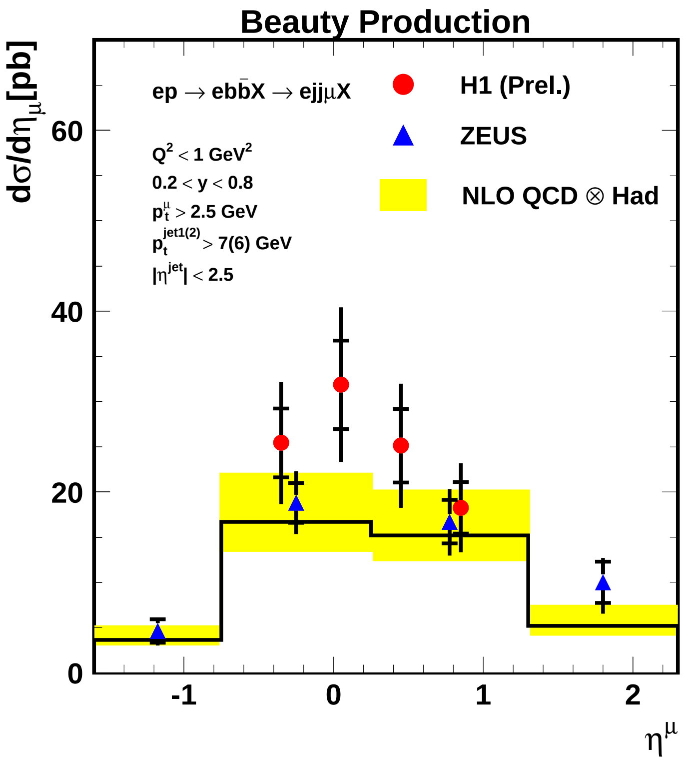
ϵ_c, HF scheme

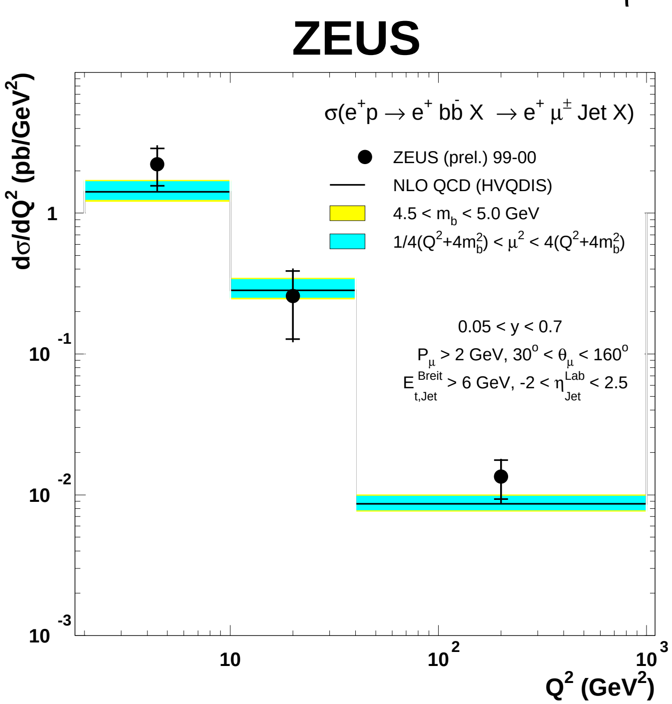


$F_2^{c\bar{c}}$ obtained with extrapolation in η, p_t (NLO HVQDIS)

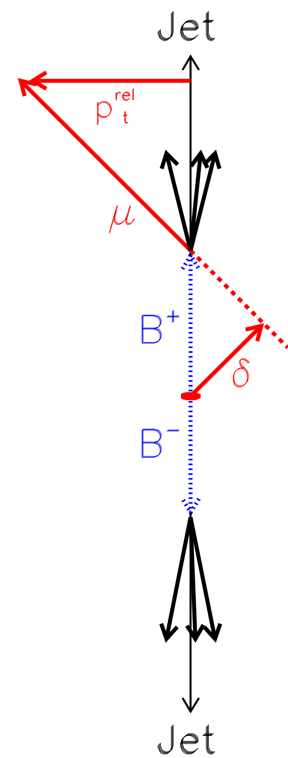
Well above threshold, for massless charm, $\frac{F_2^{c\bar{c}}}{F_2} \longrightarrow \frac{e_c^2}{e_u^2+e_d^2+e_s^2+e_c^2} = \frac{4}{10}$

Upgraded Silicon detectors, triggers $\longrightarrow$ big charm future at HERA-II





Beauty Production



$\sigma(b) \ : \ \sigma(c) \ \sim \ 1 \ : \ 200$

- Understanding parton dynamics and multi-scale QCD
- Previously reported HERA, Tevatron beauty “anomalies” . . .

Measure using $b \longrightarrow c\nu\mu$

Unfold from charm, uds using δ (Si) and $p_T^{\rm rel}(\mu - jet)$

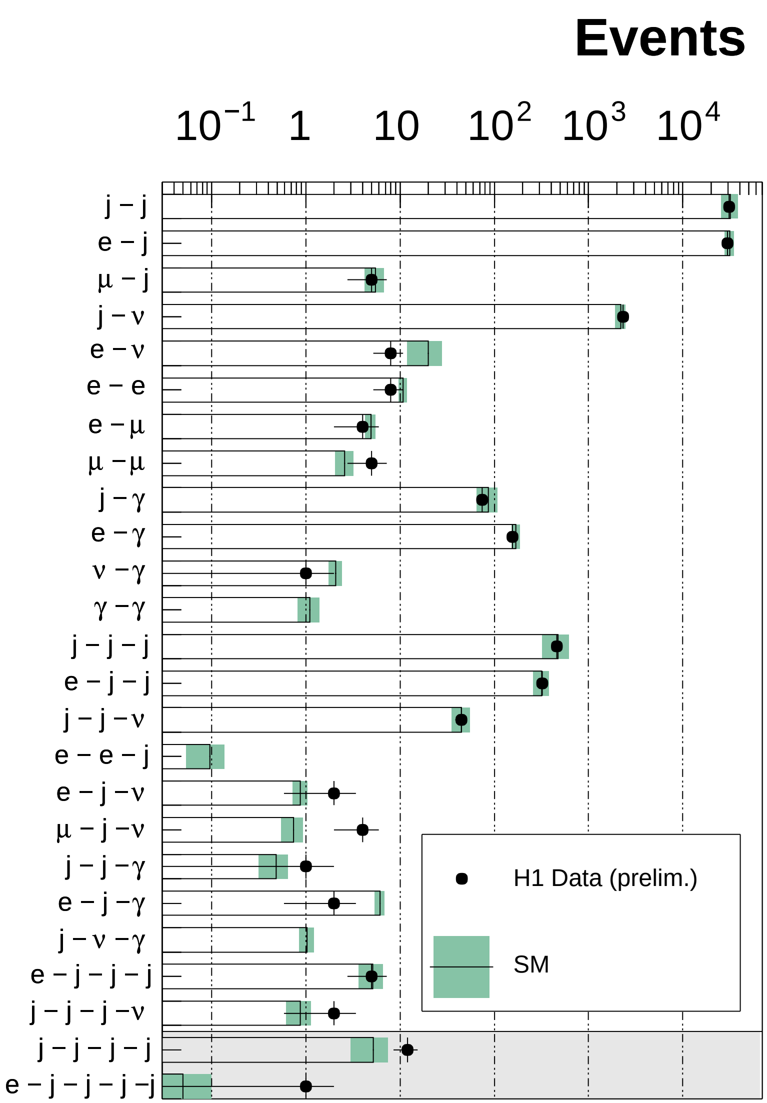
Compare with NLO QCD directly in measured range

Good agreement at large Q^2, p_T

Data $>$ theory at $Q^2 = 0 \ \ (1.5\sigma)$

Larger statistics and more Si in future $\longrightarrow F_2^{b\bar{b}}$

Systematic Search for New Physics



H1 General Search

How compatible is HERA data with the Standard Model overall?

Investigation of all multi-object final states with

$j,\ e,\ \mu,\ \gamma,\ \nu\ \ldots$

. . . isolated

$\ldots p_T > 20\ \mathrm{GeV}$

$\ldots 10^\circ < \theta < 140^\circ$

23+2 channels!

Compare with Standard Model using Monte Carlos to $\mathcal{O}(\alpha_s)$ in QCD, with parton showers

Impressive agreement for most channels!

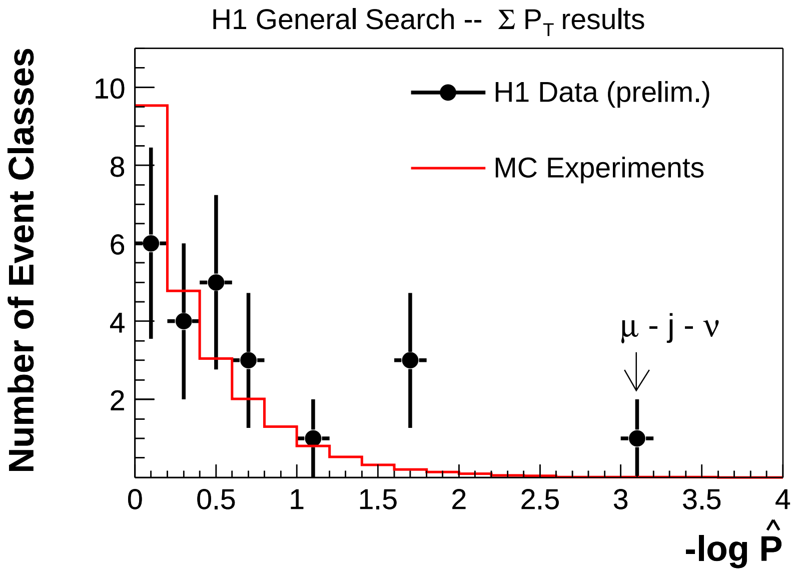
Looking in more Detail

For each channel, scan all possible connected regions in Σp_T and M_{all} to find most significant deviation

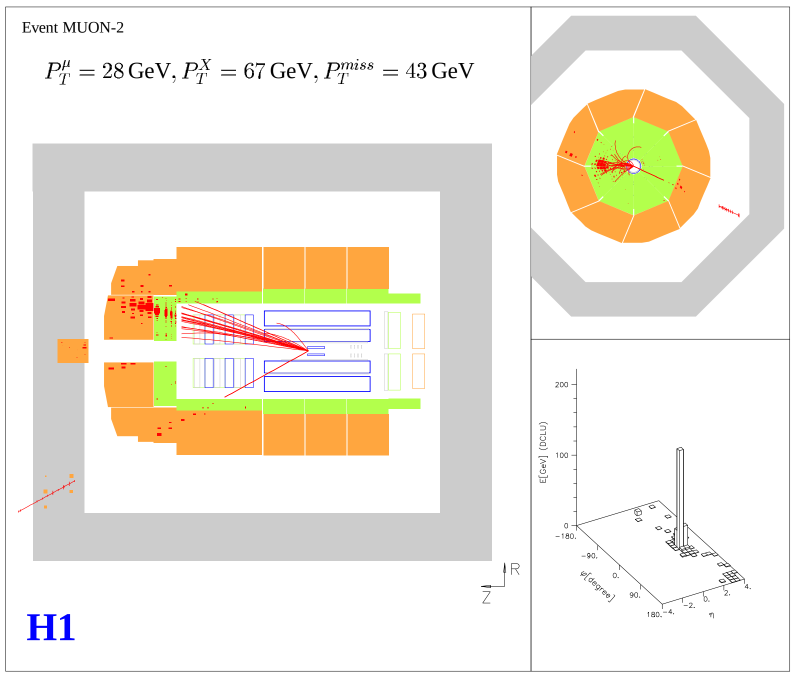
Use MC experiments to determine probability $\hat{P}$ of finding a more significant excess somewhere in distribution

Most significant effect at large Σp_T for $\mu j \nu$ events

Probability for one of the 23 studied channels to give a more significant excess in $\Sigma p_T \sim 2\%$



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



Dedicated Studies of Isolated Leptons with Missing p_T

Study events containing an isolated high p_T μ, e or τ, a high p_T jet and missing p_T

Dominant Standard Model Process is W radiation

	Observation / Standard Model Prediction				
	H1 μ	H1 e	ZEUS μ	ZEUS e	ZEUS τ
$p_T^X > 25$ GeV	6 / 1.44	4 / 1.48	5 / 2.75	2 / 2.90	2 / 0.20
$p_T^X > 40$ GeV	3 / 0.55	3 / 0.54	0 / 0.95	0 / 0.94	1 / 0.07

Spectacular μ and e events observed by H1

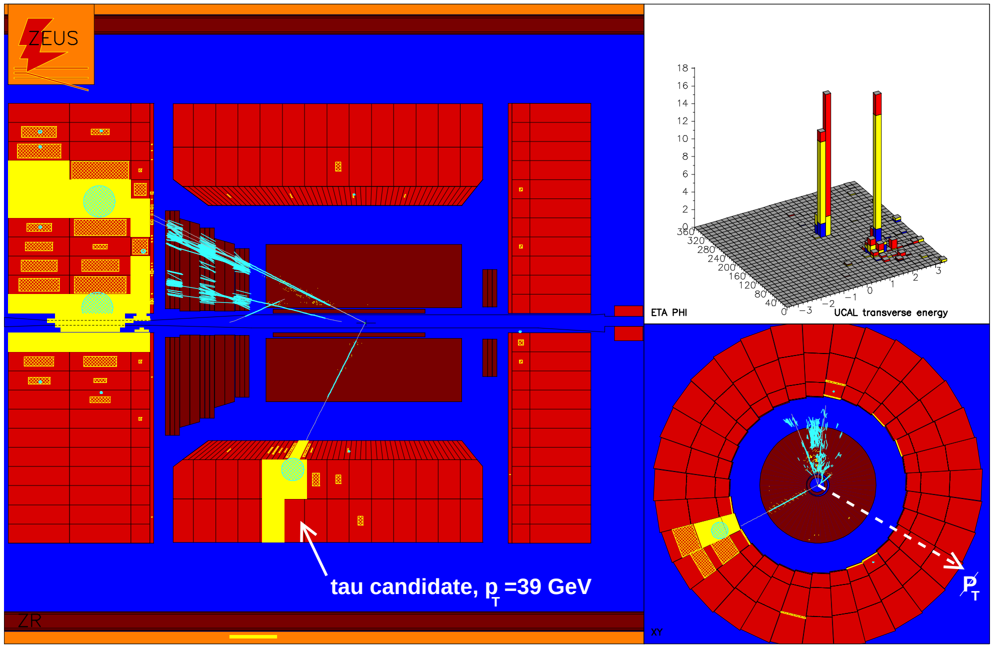
Spectacular τ events observed by ZEUS

Many possible explanations

eg FCNC top production with $t \to bW$

. . . or just a fluctuation?

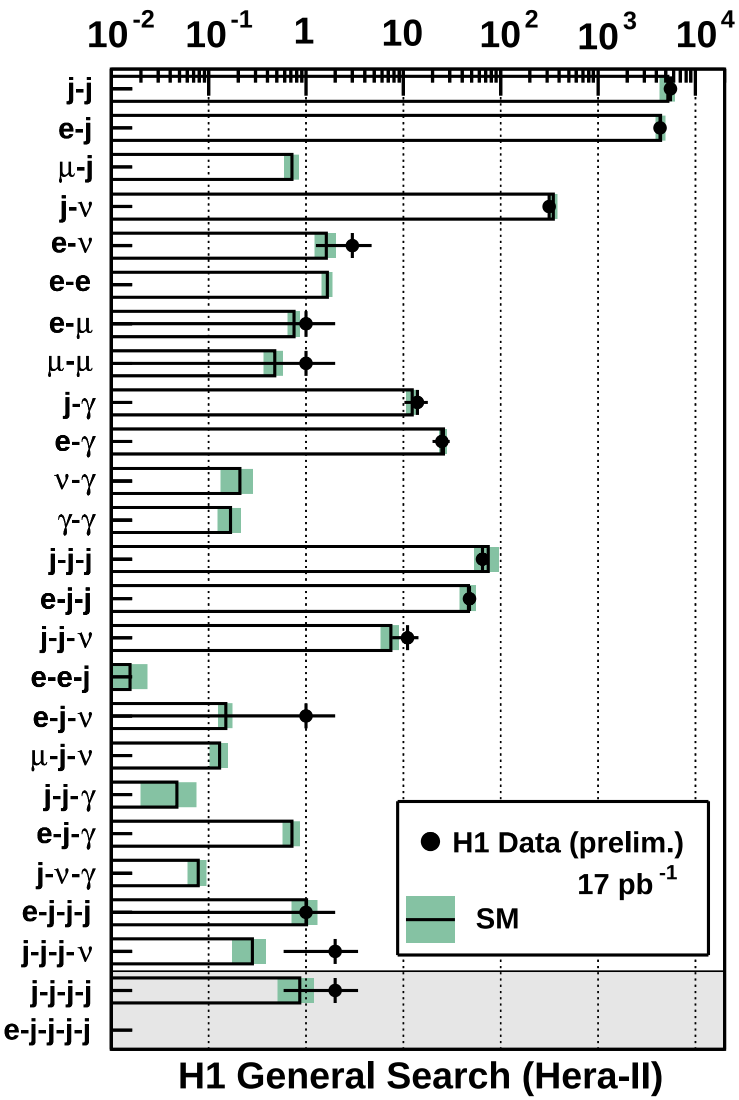
HERA-II data will clarify



First Searches with HERA-II Data

H1 generic search repeated with $17\ \mathrm{pb}^{-1}$ of HERA-II data

Overall good agreement with SM . . . upgraded detector well understood

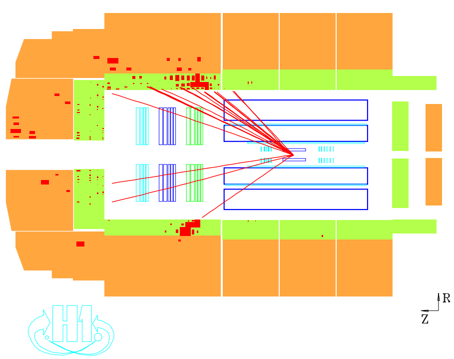


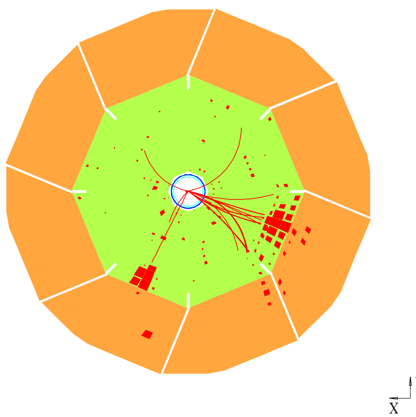
Events with isolated leptons and

missing p_T continue to show up . . .

	Obs. / SM Prediction	
	H1 μ	H1 e
All p_T^X	0 / 0.44	3 / 1.60
$p_T^X > 25$ GeV	0 / 0.29	2 / 0.34

$p_T^e = 37\ \mathrm{GeV},\ p_T^{miss} = 44\ \mathrm{GeV},\ p_T^X = 29\ \mathrm{GeV}$





Pentaquarks at HERA

HERA is a copious producer of strange and charm quarks

. . . Study spectroscopy of strange and charmed hadrons

Current hot topic:- PENTAQUARKS

Resonances in K^+n and $K_s^0 p$ reported by fixed target expts

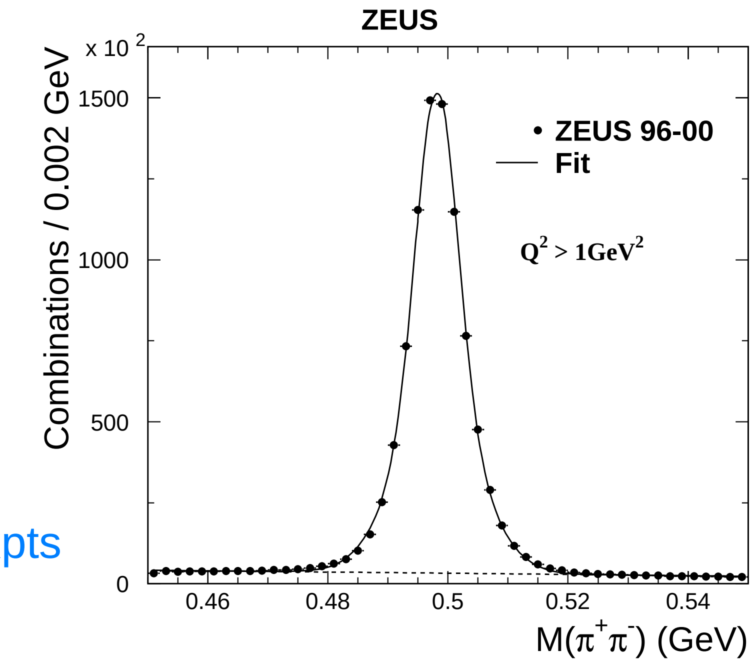
Minimal constituent quark composition $uudd\bar{s}$

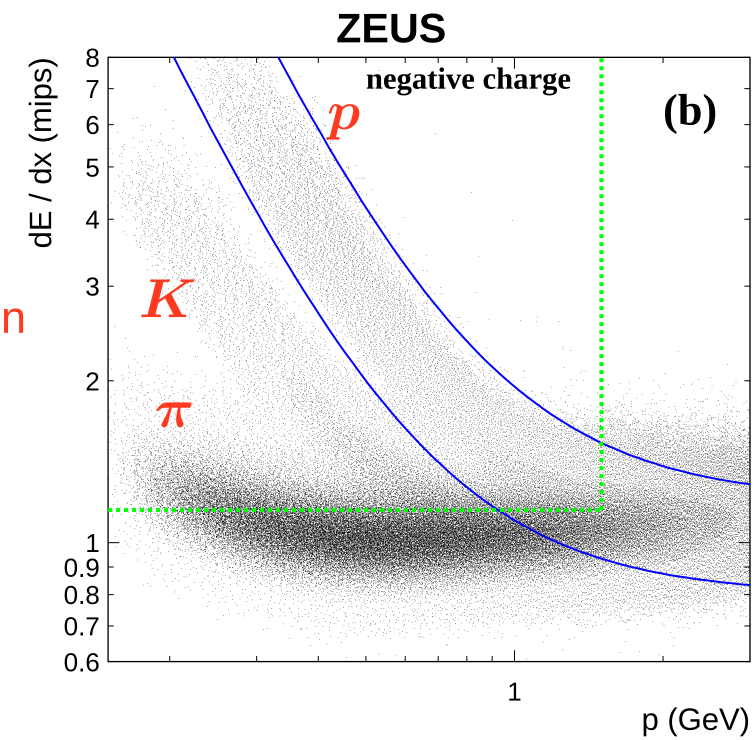
. . . $\theta^+(1540)$ pentaquark?

New evidence in $K_s^0 p$ and $K_s^0 \bar{p}$ from ZEUS

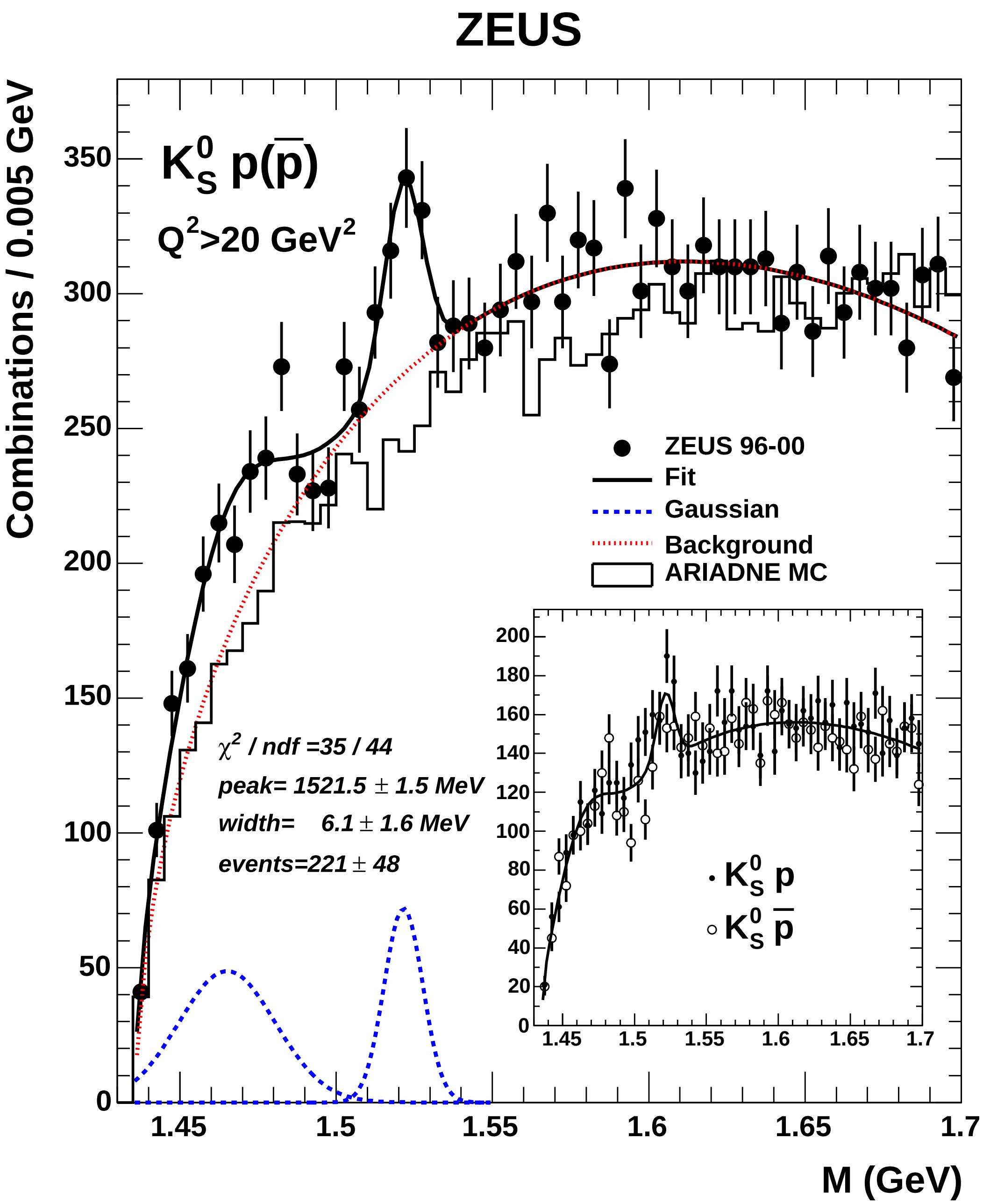
Clean kaon selection with $K_s^0 \to \pi^+\pi^-$

Ionisation energy loss $\mathrm{d}E/\mathrm{d}x$ assists proton track selection





Evidence for θ^+ Pentaquark



Clearest signal for $Q^2 > 20\ \mathrm{GeV}^2$

$1521.5 \pm 1.5\ (\mathrm{stat.})^{+2.8}_{-1.7}\ (\mathrm{syst.})\ \mathrm{MeV}$

221 ± 48 events (4.6σ)

Width consistent with resolution of $\sim 2\ \mathrm{MeV}$

First observation at colliding beam experiment

Suggestion of $\Sigma(1480)$ bumps?

No evidence for related states

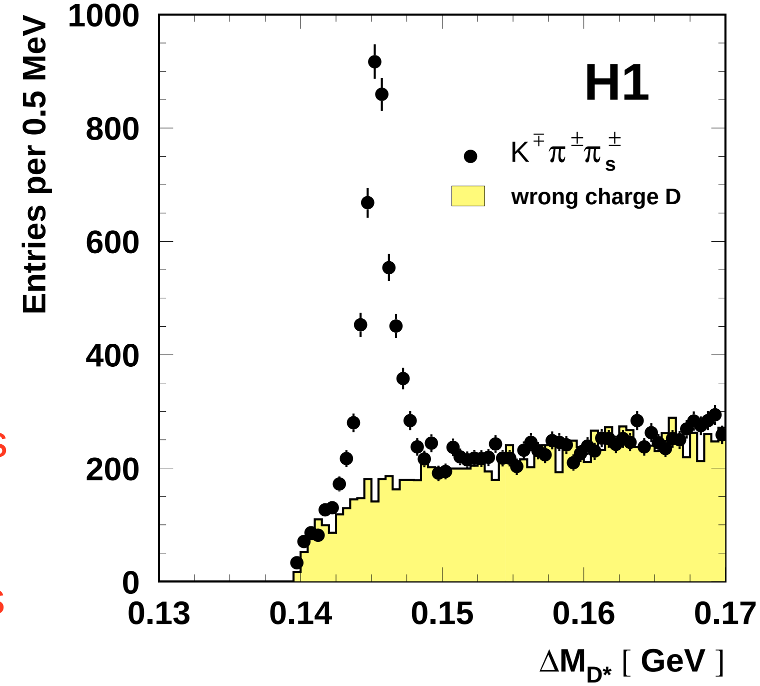
(θ^{++}?) in K^+p

θ^+ isosinglet rather than isotensor?

Charmed Pentaquarks

If strange pentaquarks exist, what about charm?

Replacing $\bar{s} \longrightarrow \bar{c}$ could give $D^{(*)}p$ final states



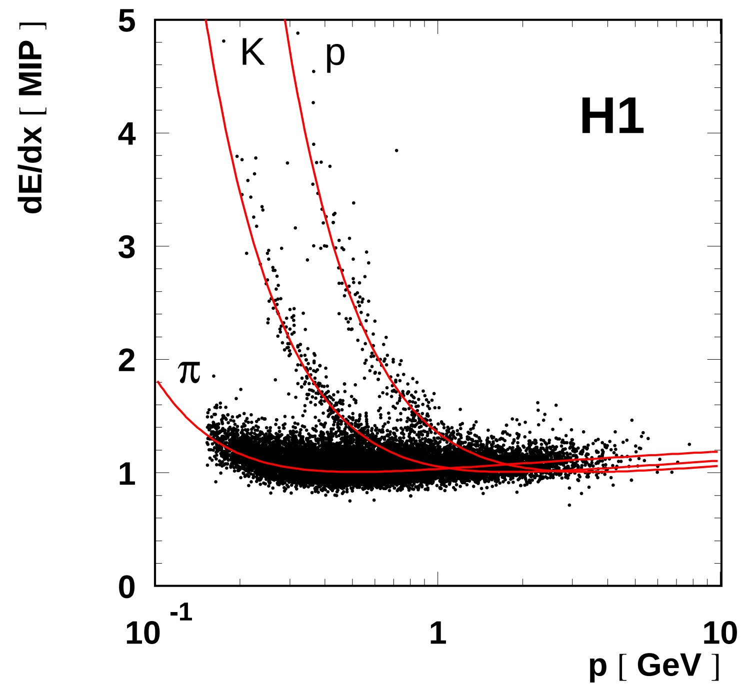
D^* mesons experimentally much easier than D mesons

'Golden' channel $D^{*-} \longrightarrow \bar{D}^0\pi_s^- \longrightarrow K^+\pi^-\pi_s^-$ & c.c.

…Use $m(K\pi)$ and $m(K\pi\pi_s) - m(K\pi)$ constraints

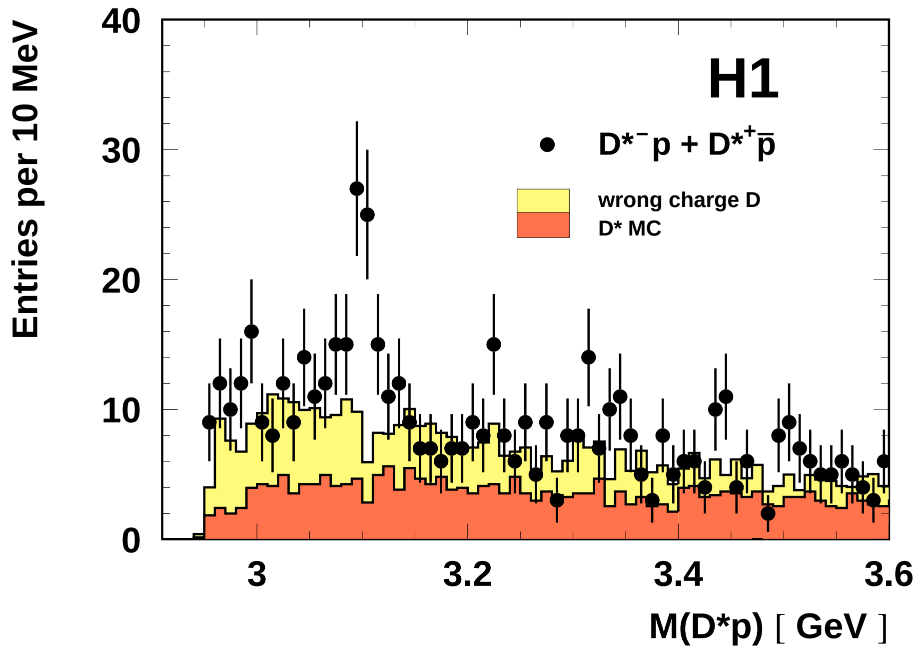
Cuts on $p_T(D^*)$, $\eta(D^*)$, $z(D^*)$ to improve purity

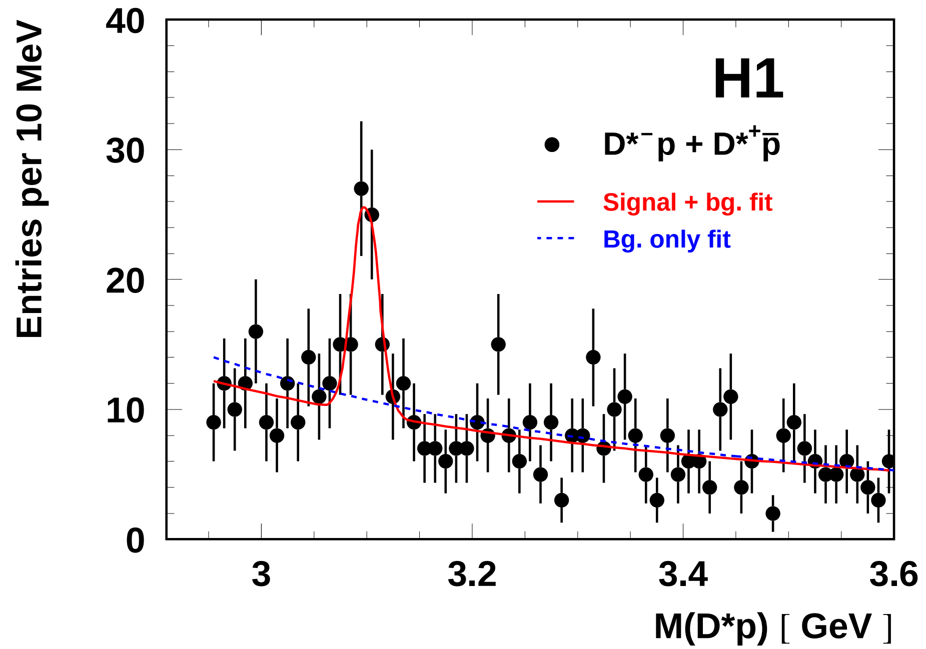
Use $\mathrm{d}E/\mathrm{d}x$ to select proton candidates based on proximity to K, π and p parameterisations



Evidence for a new state observed in both photoproduction and DIS …

Charmed Pentaquarks





Clear signal with mass $3099 \pm 3\,(\mathrm{stat.}) \ \pm 5\,(\mathrm{syst.})\ \mathrm{MeV}$

Background well modelled by wrong charge $K^{\pm}\pi^{\pm}$ combinations and D^{*} Monte Carlo

51 ± 11 events (6.2σ from change in fit likelihood with(out) signal component)

As in strange case, width compatible with experimental resolution ($\sim 7\ \mathrm{MeV}$)

Minimal constituent quark composition $uudd\bar{c}$ . . . strong evidence for a charmed pentaquark

Not yet confirmed . . . no signal visible in preliminary ZEUS analysis

Summary

- **Ongoing analysis of HERA-I data**

  Ever stronger constraints on PDFs from inclusive data ($10^{-4} \lesssim x \lesssim 10^{-1}$)

  Final states test QCD and give competitive information on gluon

  Competitive searches . . . tantalising $l\nu j$ signals

  Strong evidence for strange and charmed pentaquarks

- **HERA-II has begun**

  First results obtained with polarised leptons

  High luminosity $\longrightarrow$ improved high x, Q^2

  Polarised leptons $\longrightarrow$ chiral structure

  Detector upgrades $\longrightarrow$ precision HF era

  Reduced E_p $\longrightarrow$ high x, medium Q^2, F_L

  . . . watch this space . . .

Simulation with $1\ \mathrm{fb}^{-1}$ at HERA-II