15-th Lomonosov Conference

on Elementary Particle Physics

August 18-24, 2011   Moscow, Russia

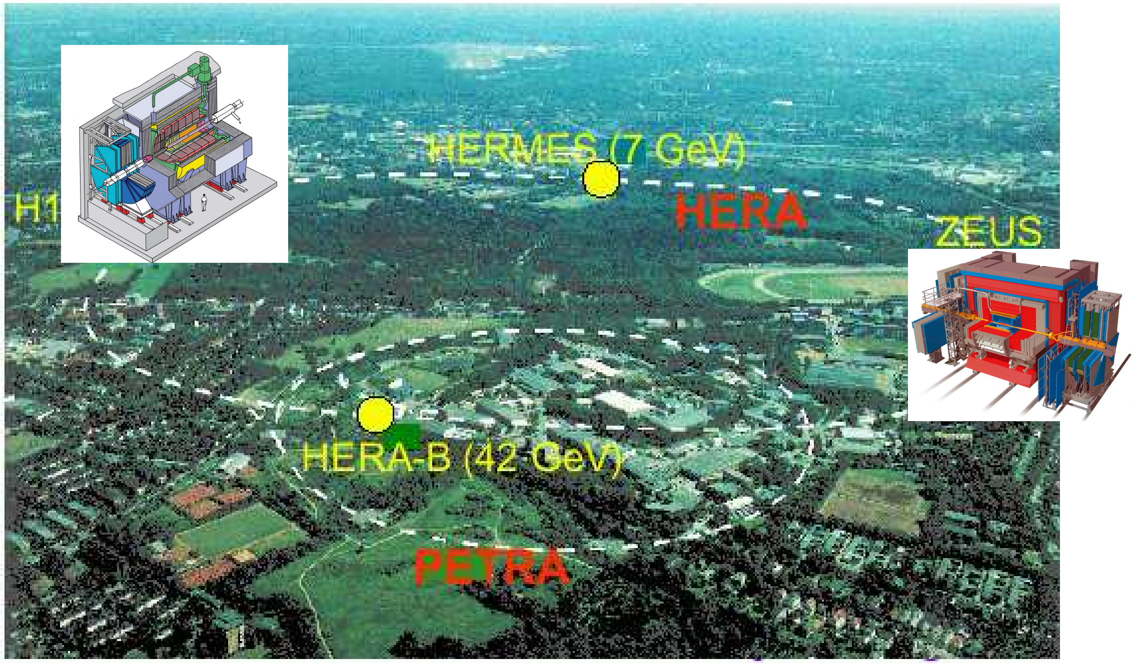
Recent Results from HERA Collider

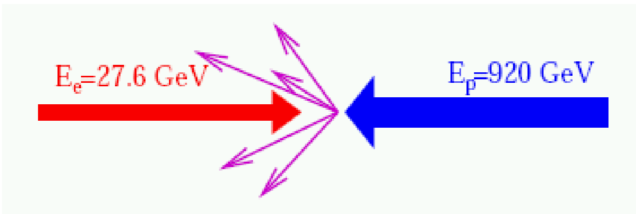
S. Levonian (DESY)

representing

H1 and ZEUS

HERA: The World's Only ep Collider





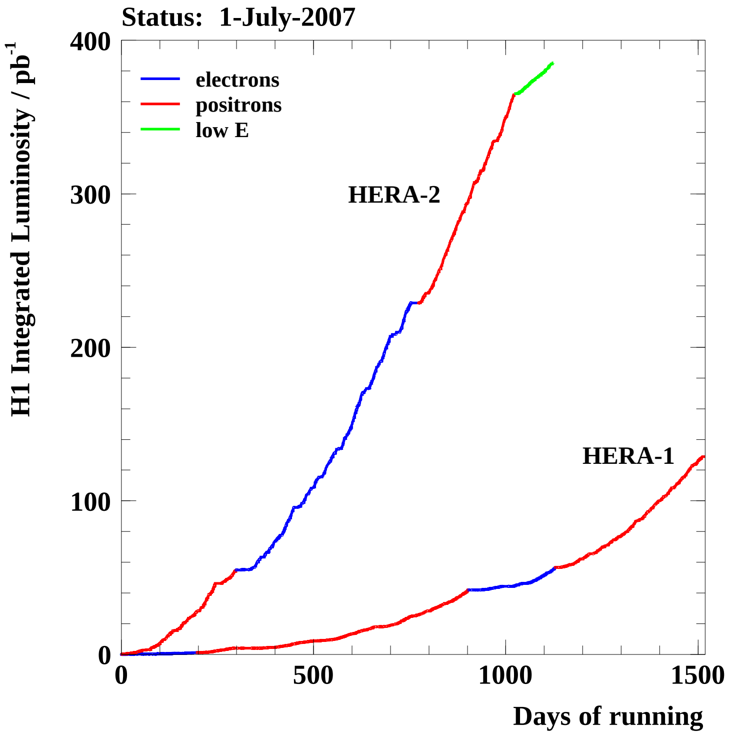
- 1998 E_p upgrade: $820 \Rightarrow 920$ GeV
  ($\sqrt{s}$: $301 \Rightarrow 319$ GeV)
- 2001 HERA-2 upgrade: $\mathcal{L} \times 3$, Polarised e^+/e^-
  ($\langle P \rangle = 40\%$)

HERA-1 (1993-2000) $\simeq 120$ pb^{-1}

HERA-2 (2003-2007) $\simeq 380$ pb^{-1}

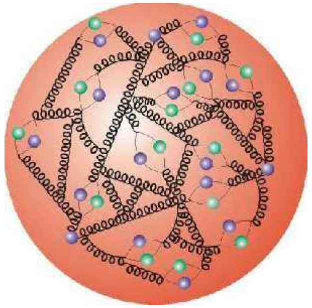
Final Data samples

H1+ZEUS: 2×0.5 fb^{-1}

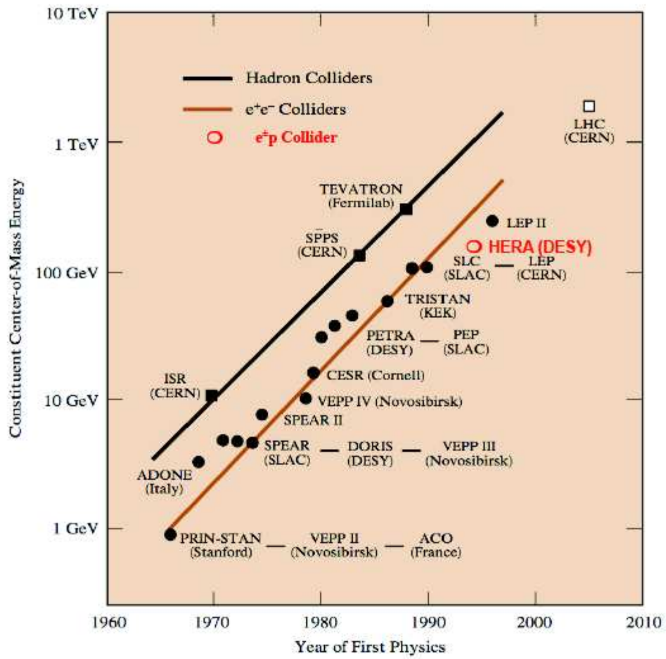


Physics at HERA

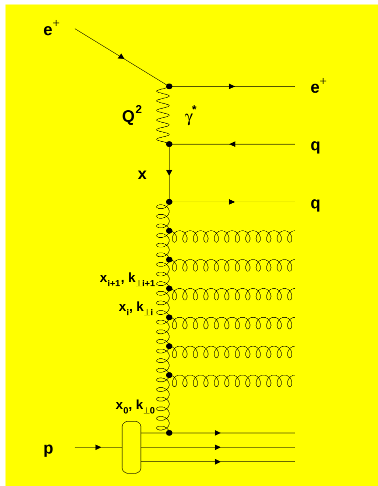
- **HERA as Super-microscope**
  - ▷ Proton structure at high resolution
  - ▷ Impact for LHC



- **HERA as Energy frontier machine**
  - ▷ Electroweak unification at work
  - ▷ Anything beyond the Standard Model?

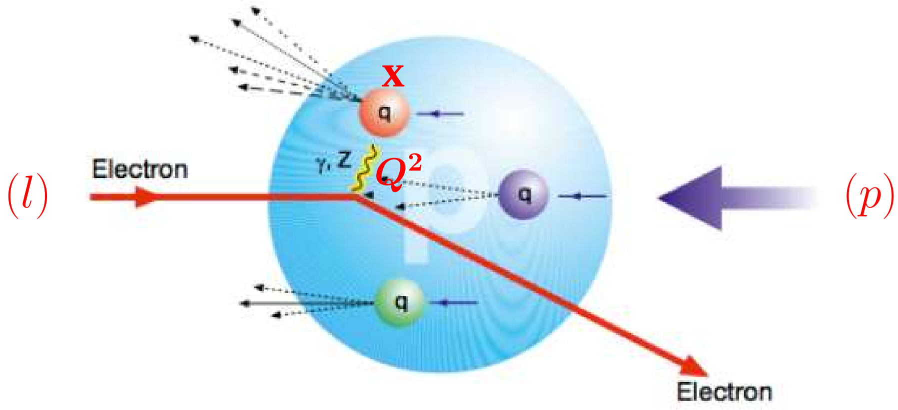


- **HERA as QCD laboratory**
  - ▷ Putting QCD in stringent tests with:
    - ◦ Jets (parton evolution schemes, NLQ QCD, α_s)
    - ◦ Diffraction (interplay of soft and hard physics)
    - ◦ Heavy flavor sector (multiscale problem: Q^2, M_Q, E_t)
    - ◦ Particle production (parton dynamics and fragmentation)
  - ▷ HERA specifics: low x phenomena

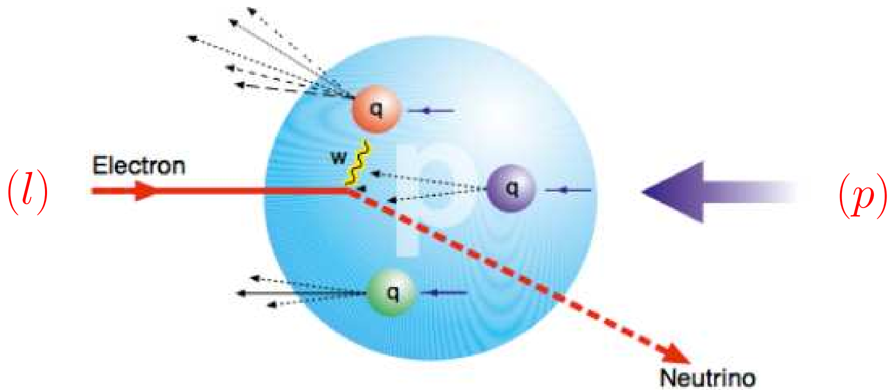


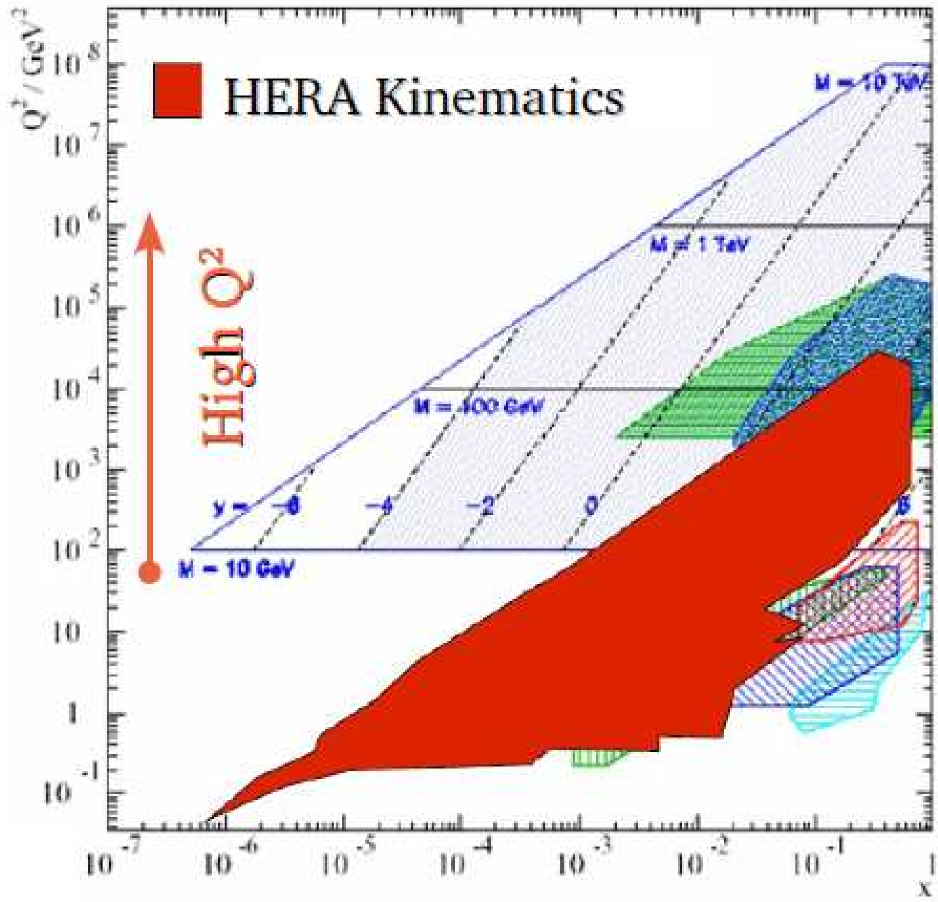
Deep-Inelastic Scattering at HERA

Neutral Current DIS: ep $\to$ e$'$X



Charged Current DIS: ep $\to \nu$X





Kinematics:

Momentum transfer: $Q^2 = -q^2$

Bjorken x: $x = Q^2/(2p \cdot q)$

Inelasticity: $y = (p \cdot q)/(p \cdot l)$

DIS: Cross sections and Structure Functions

NC
$$\frac{d\sigma^{\pm}_{NC}}{dxdQ^2} = \frac{2\pi\alpha^2}{x}\left[\frac{1}{Q^2}\right]^2\left[Y_+\tilde{F}_2 \mp Y_- x\tilde{F}_3 - y^2\tilde{F}_L\right]$$

CC
$$\frac{d\sigma^{\pm}_{CC}}{dxdQ^2} = \frac{G_F^2}{4\,\pi\,x}\left[\frac{M_W^2}{M_W^2+Q^2}\right]^2\left[Y_+\tilde{W}_2^{\pm} \mp Y_- x\tilde{W}_3^{\pm} - y^2\tilde{W}_L^{\pm}\right]$$

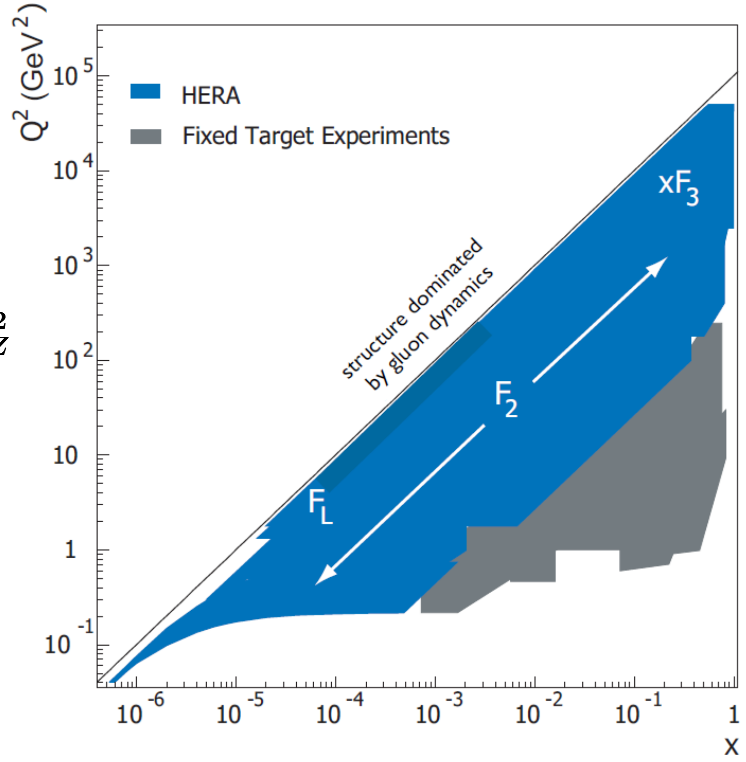
$$Y_{\pm} = 1 \pm (1-y)^2$$

$$\tilde{F}_2 \propto \sum (xq_i + x\overline{q}_i)$$ Dominant contribution

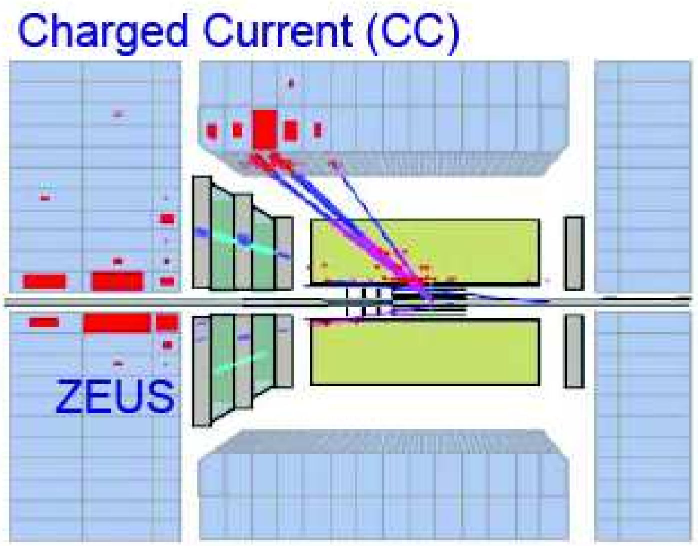
$$x\tilde{F}_3 \propto \sum (xq_i - x\overline{q}_i)$$ Only sensitive at high $Q^2 \sim M_Z^2$

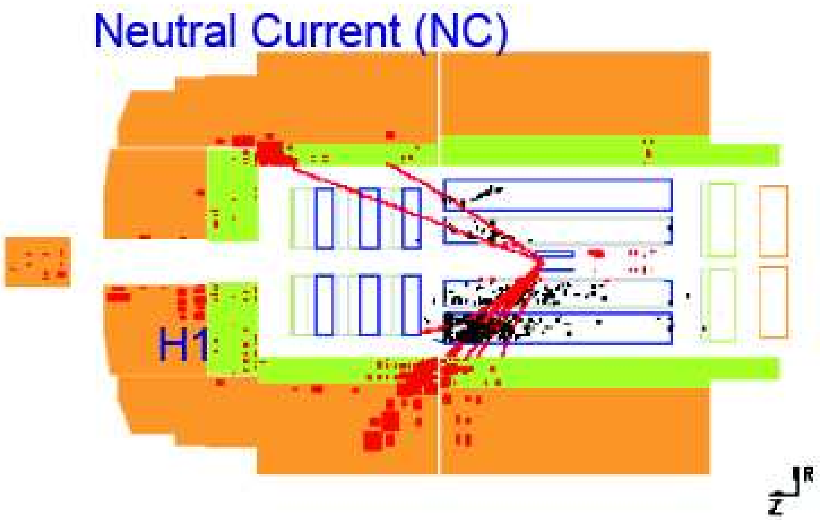
$$\tilde{F}_L \propto \alpha_s \cdot xg(x,Q^2)$$ Only sensitive at high y

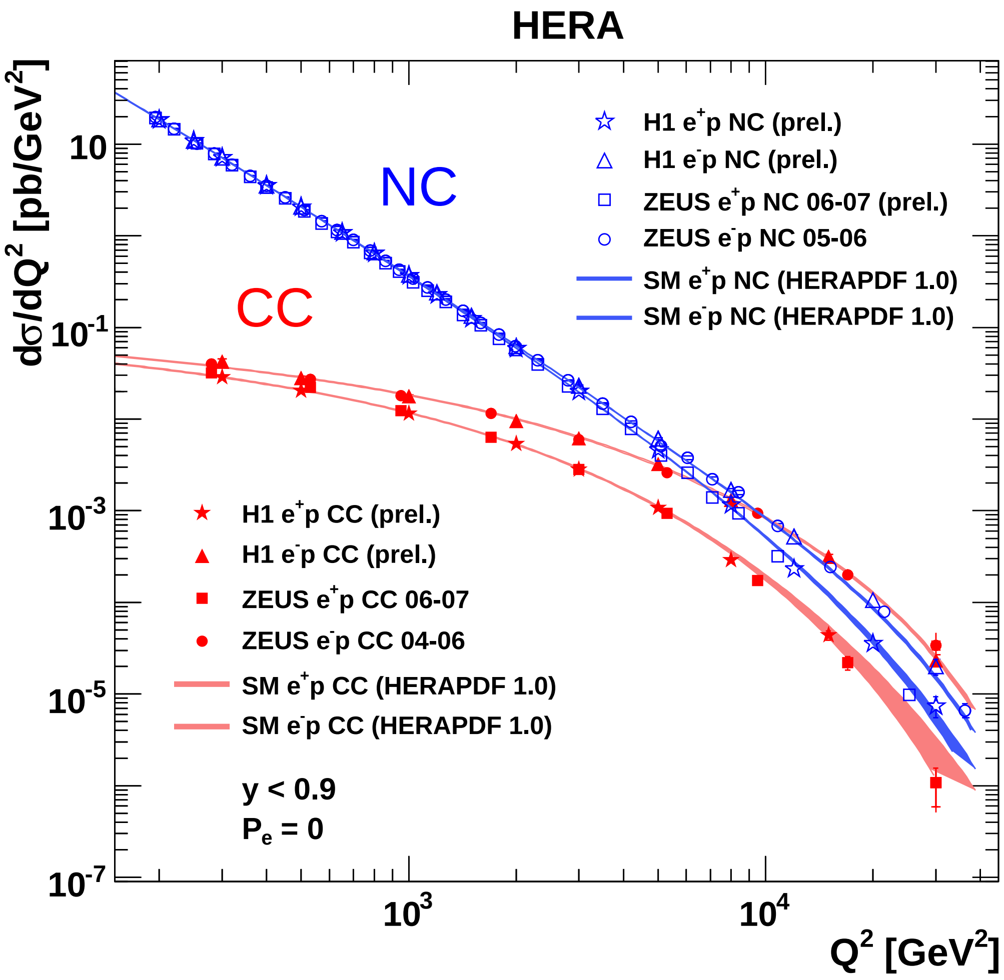
(similarly for pure weak CC analogues: $W_2^{\pm}, xW_3$ and $W_L^{\pm}$)



DIS at HERA: Unpolarised NC and CC cross sections





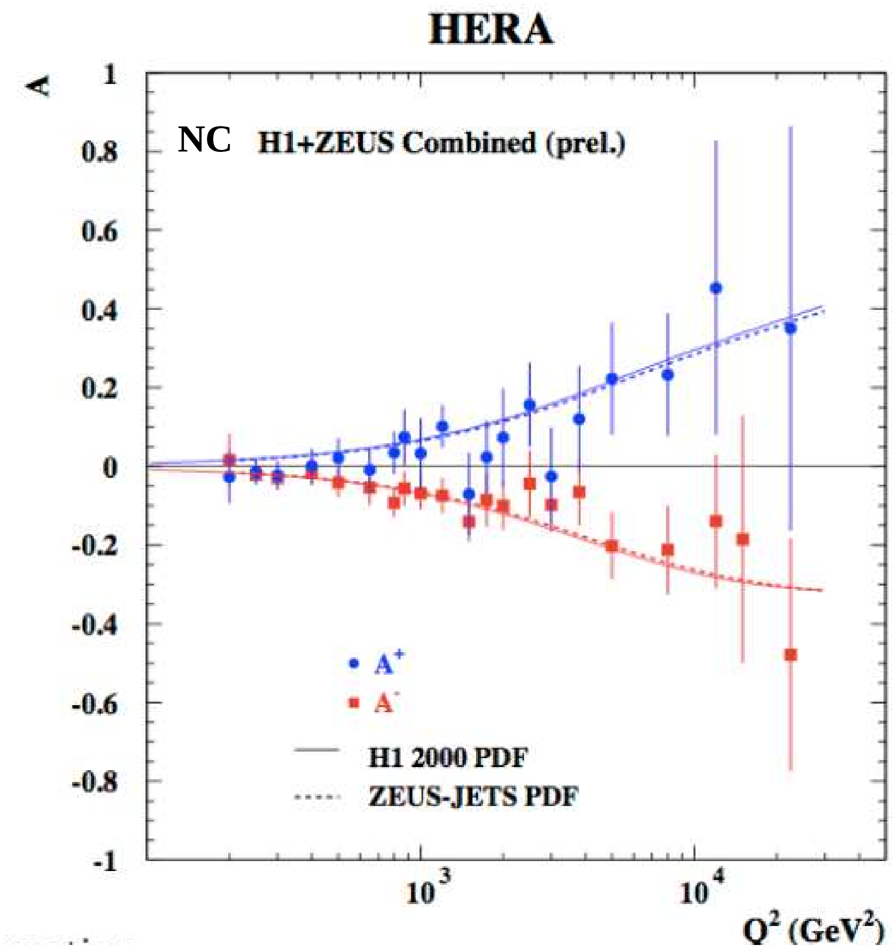


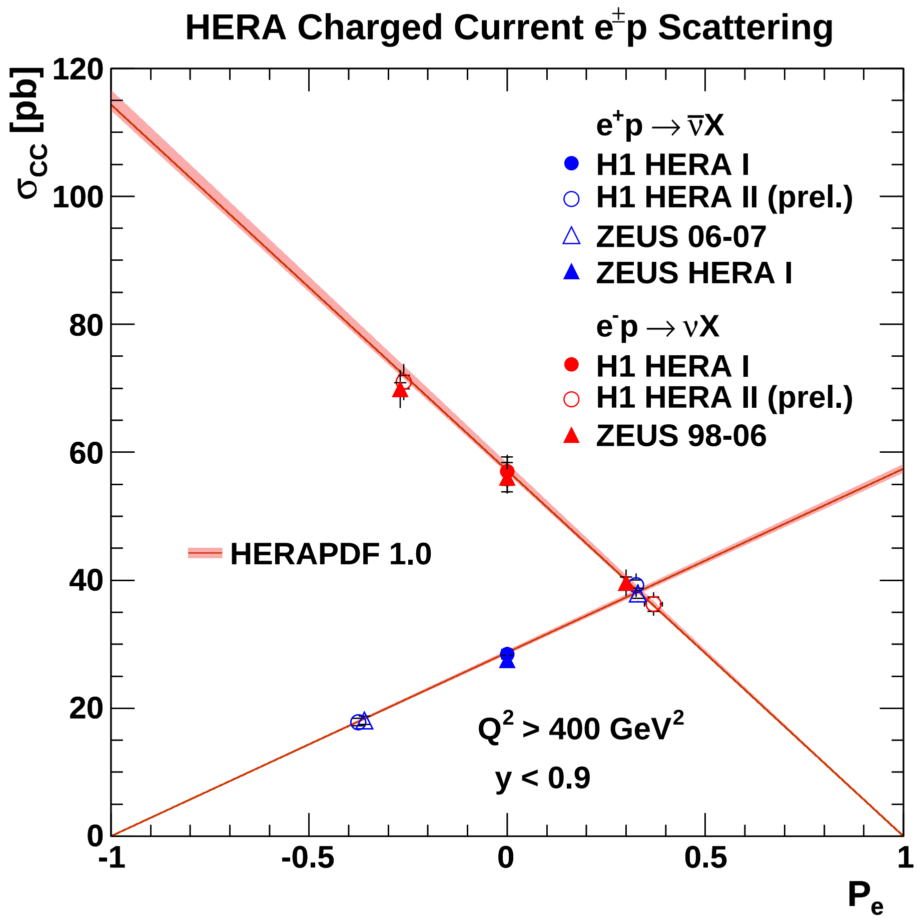
Electro-Weak Unification

Parity violation in polarised NC and CC DIS

$$A = \frac{2}{P_R - P_L} \cdot \frac{\sigma^{\pm}(P_R) - \sigma^{\pm}(P_L)}{\sigma^{\pm}(P_R) + \sigma^{\pm}(P_L)}$$

$$\sigma^{CC}_{\mathrm{pol}}(\mathrm{e}^{\pm}\mathrm{p}) = (1 \pm \mathrm{P}) \cdot \sigma^{\mathrm{CC}}_{\mathrm{unpol}}(\mathrm{e}^{\pm}\mathrm{p})$$

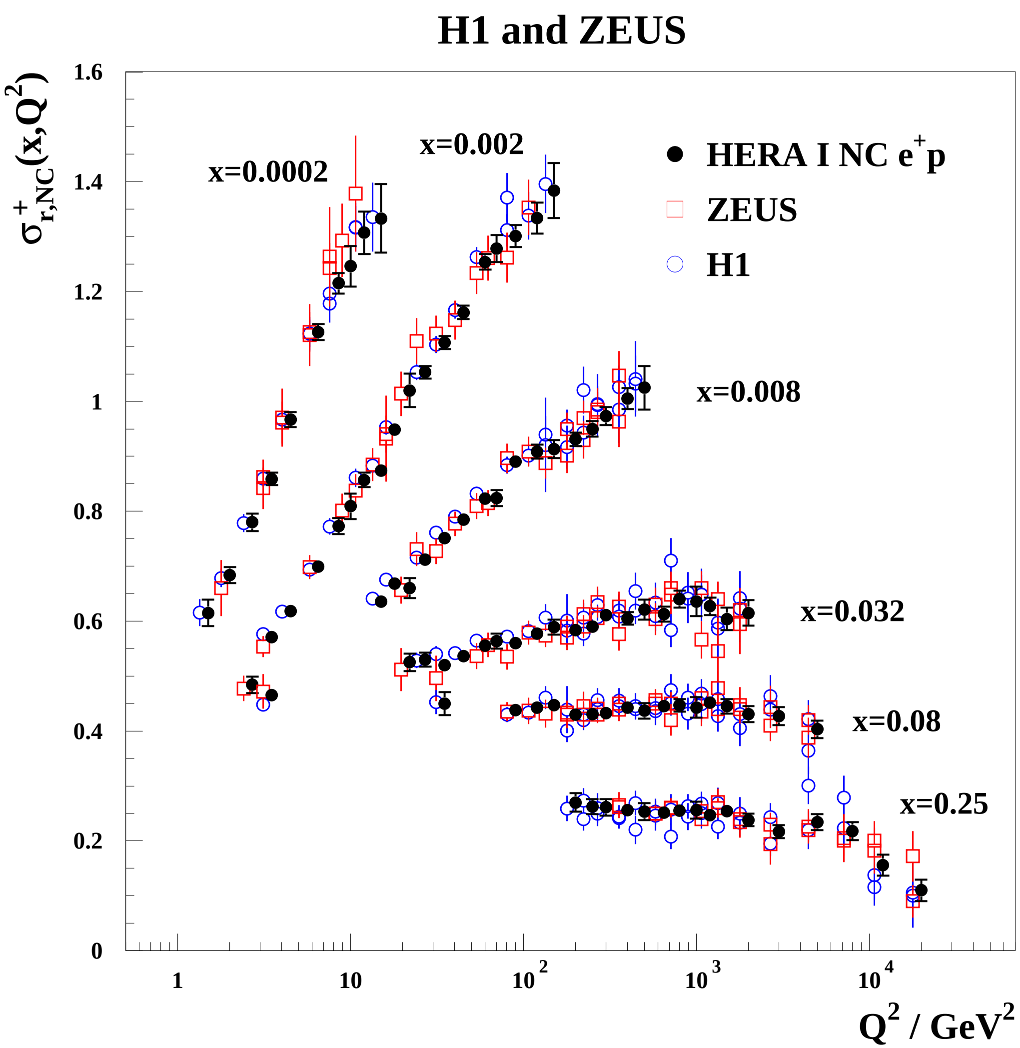




SM expectation is in agreement with data

Absence of weak right-handed currents verified

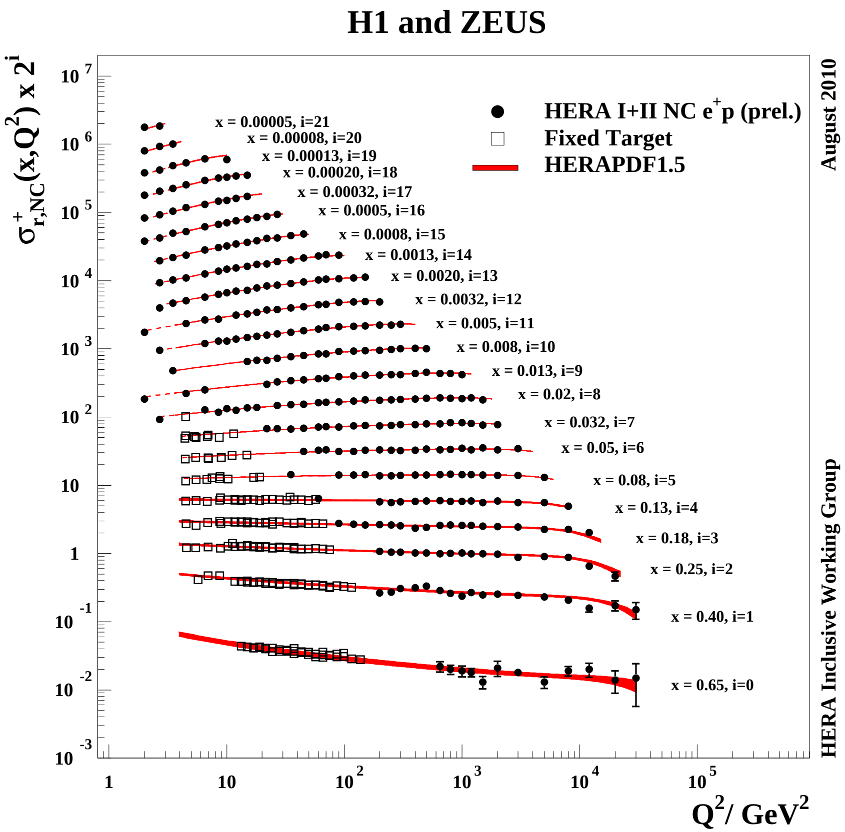
Combination of H1 and ZEUS data

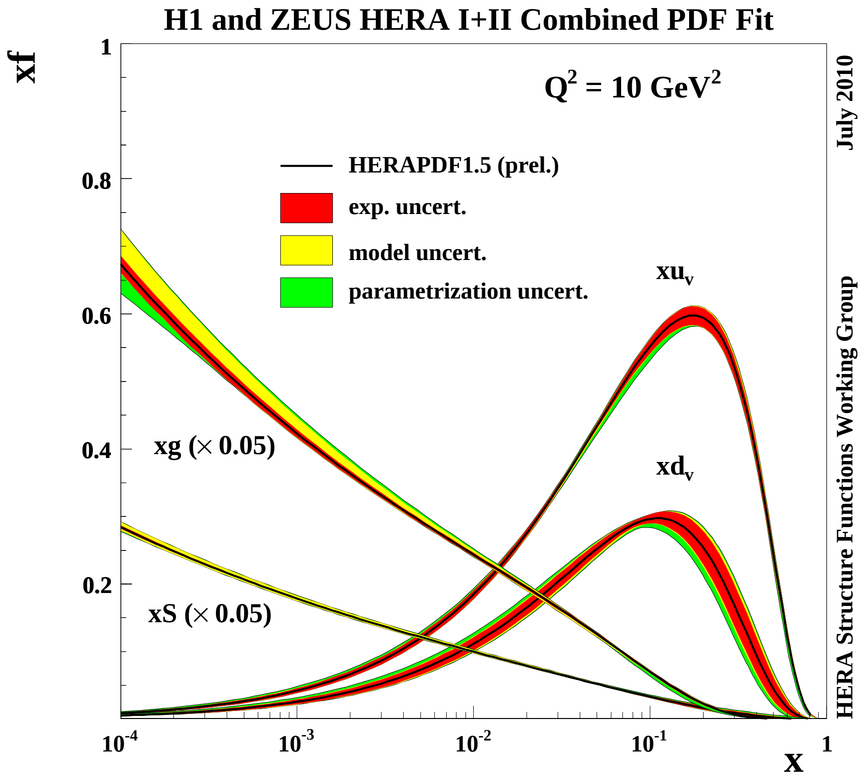


- H1 and ZEUS data are fully consistent ($\chi^2/DOF = 637/656$)
- Cross calibrate each other (via correlated systematics)
- Precision improved, reaching 1% in the bulk region

HERAPDF: QCD fits using HERA data only

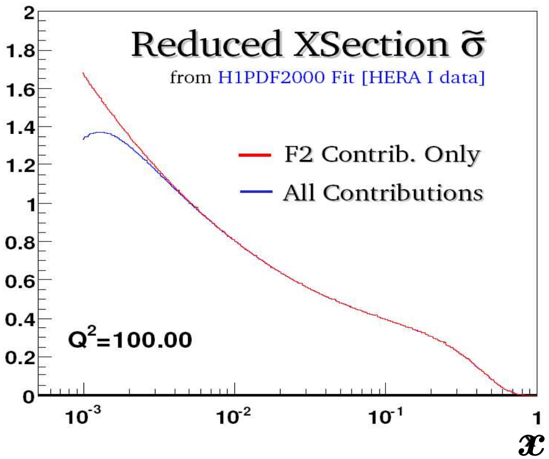
QCD factorisation: $\sigma_{DIS} \sim \sum_a C_a \otimes f_{a/p}$ allows to determine non-pert. pdf, $f_{a/p}(x, Q^2)$



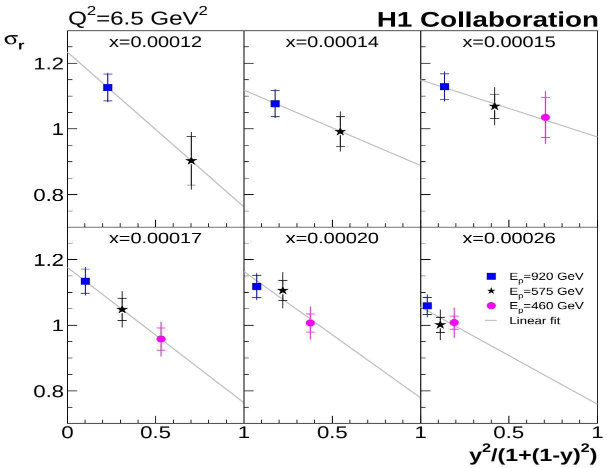


- Perfect desciption of the data by NLO QCD over many orders in x and Q^2
- Good agreement with fixed target data
- Universal parton distribution functions determined with associated error bands

Longitudinal SF: F_L vs QCD predictions

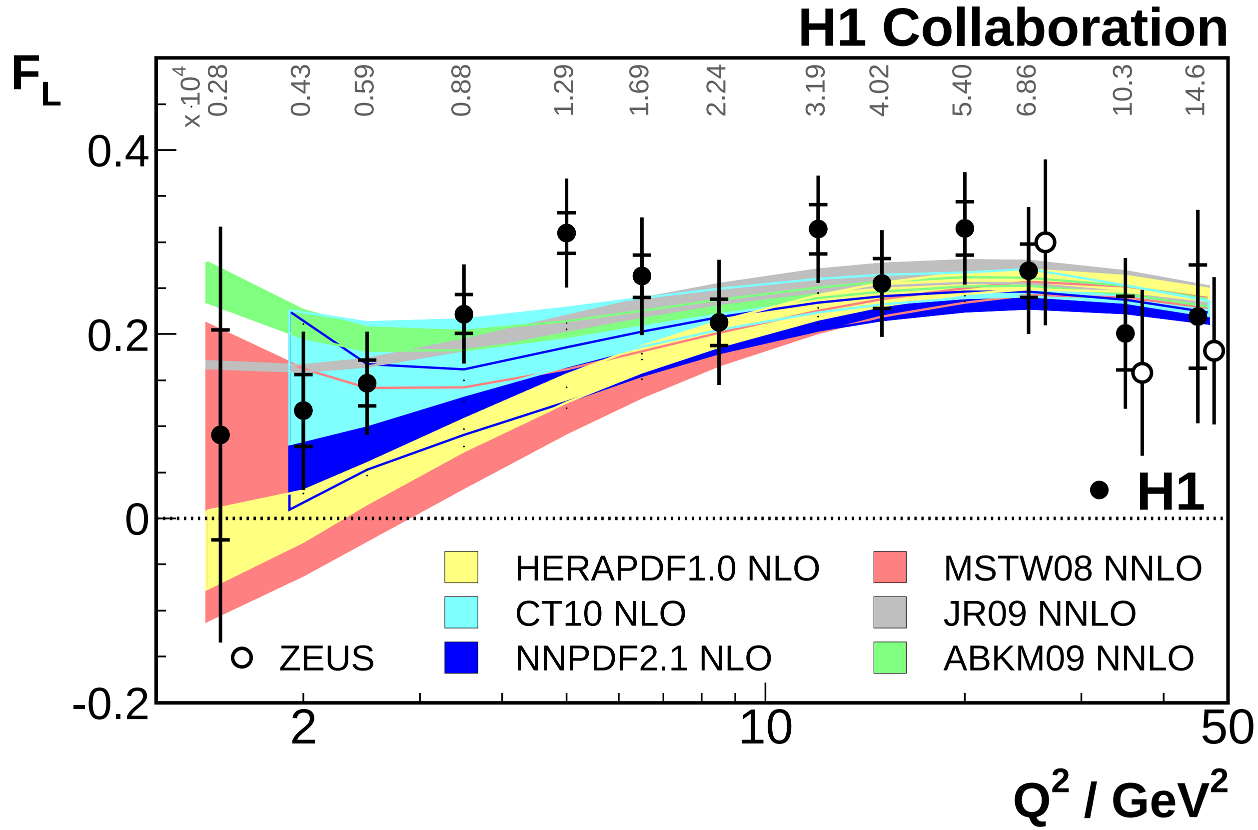


$$\sigma_{NC} = F_2 - (y^2/Y_+) \cdot F_L$$



y^2/Y_+

EPJ C71 (2011) 1579

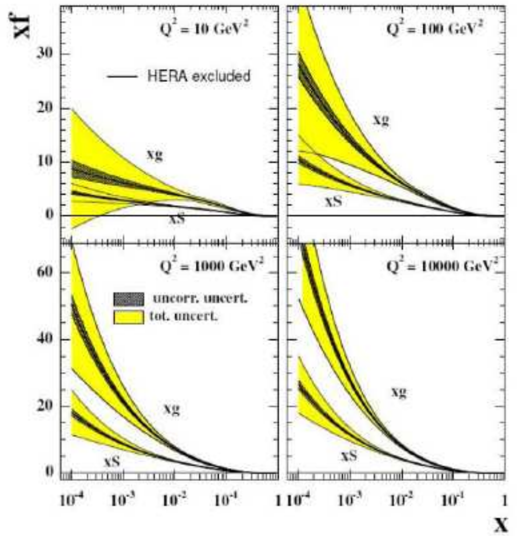


- good description by QCD for $Q^2 \geq 10$ GeV^2
- large spread in predictions for low Q^2

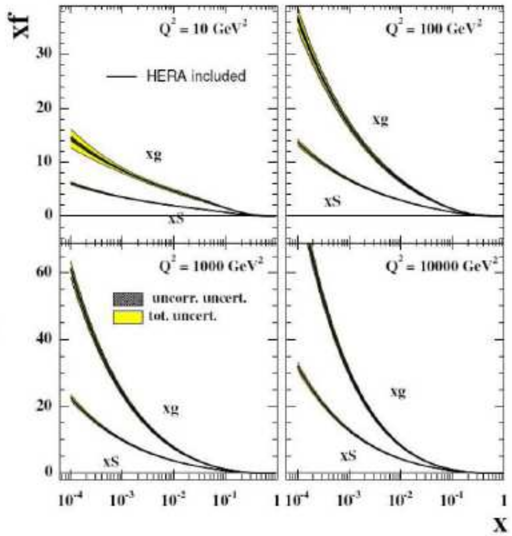
$\Rightarrow$ F_L data represent a valuable input for QCD fits

HERAPDF for LHC

Knowledge of gluon without HERA data.

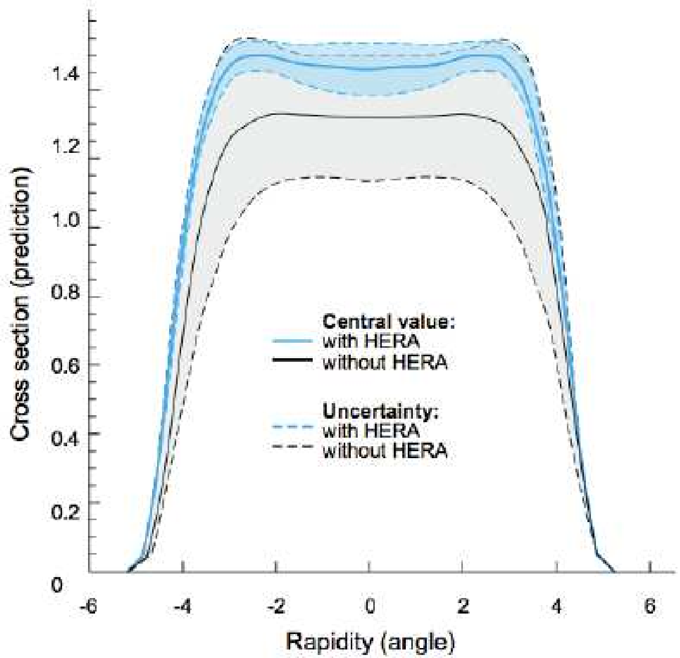


Knowledge of gluon with HERA

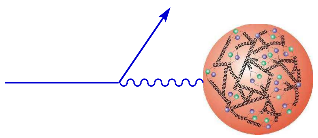


Cooper-Sarkar et al. : HERA-LHC workshop 2009

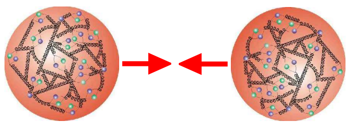
W^+ cross-section



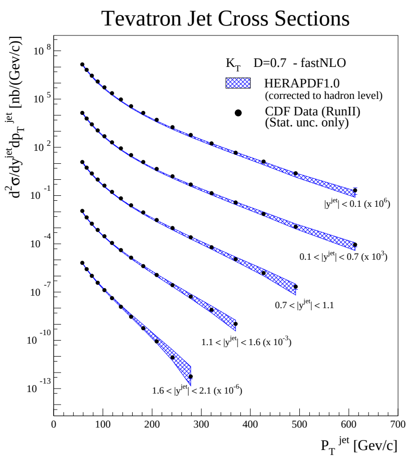
HERA

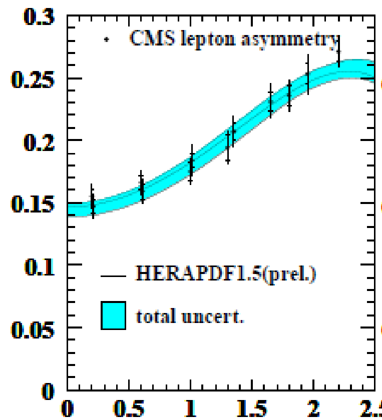


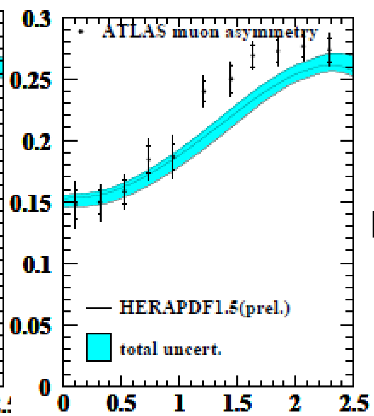
LHC



CDF Data (Run II)







2011 LHC Data

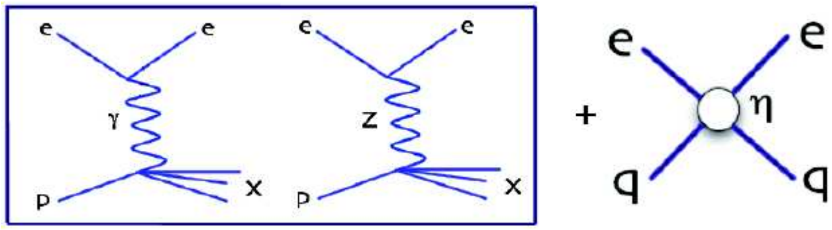
Any sign for New Physics?

So far all NC and CC HERA data were in good agreement with SM.
Try now to look more carefully at the tails, using two strategies:

1. Specific BSM signals search (LQ, LFV, SUSY, ...) – guided by theory

2. Model independent generic search (data vs SM) – guided by data

Search for Contact Interactions at HERA



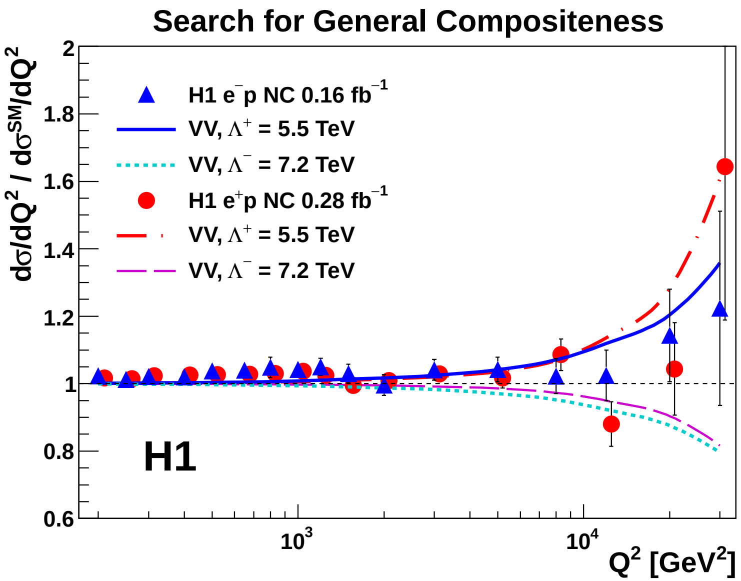
$$L = L_{SM} + L_{CI}$$

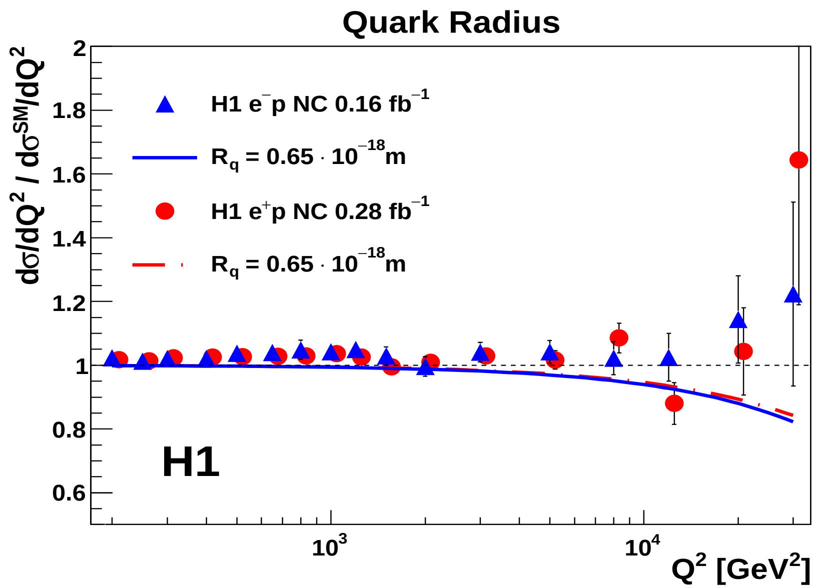
$$L_{CI} = \sum_{i,j=L,R} \eta_{ij}^{eq} (\overline{e}_i \gamma_\mu e_i)(\overline{q}_j \gamma^\mu q_j)$$

4 possible couplings for each q flavor

$$\eta_{ab}^{eq} = \frac{\pm 4\pi}{\Lambda^2}$$

$$\frac{d\sigma}{dQ^2} = \frac{d\sigma_{SM}}{dQ^2} \cdot \left(1 - \frac{R^2}{6} \cdot Q^2\right)^2$$





Limit on effective mass scale:

$\Lambda > 3.2 - 7.2$ TeV

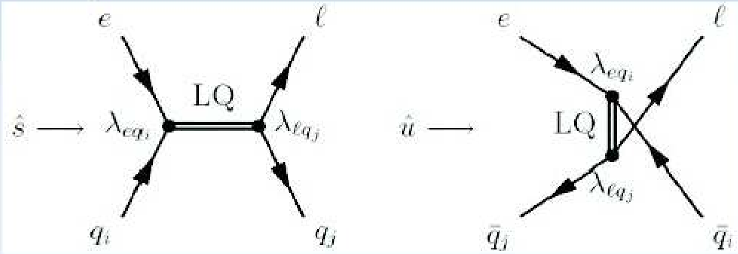
Upper limit on quark radius:

$R < 0.65 \cdot 10^{-18}$ m

Search for Leptoquarks at HERA

- Leptoquarks ***(LQ),*** compound states of leptons and quarks

  Fermion number *F = L+3B* *F = 2 (e^-p)* *F = 0 (e^+p)*
- ***Buchmüller-Rückl-Wyler*** framework: 14 different types (7 scalar, 7 vector)
- LQ at HERA:



1st gen: eq → LQ → e(ν)q ***(LFC)***

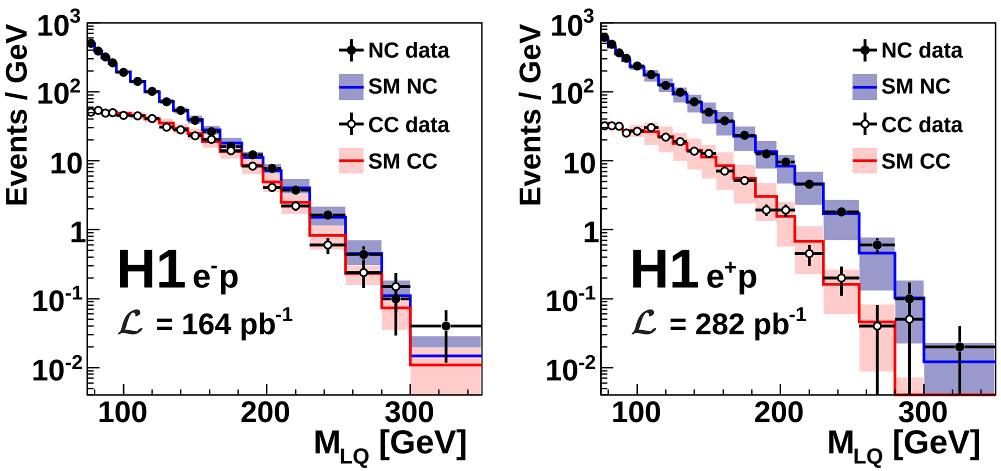
2nd gen: eq → LQ → μ(ν)q ***(LFV)***

3rd gen: eq → LQ → τ(ν)q ***(LFV)***

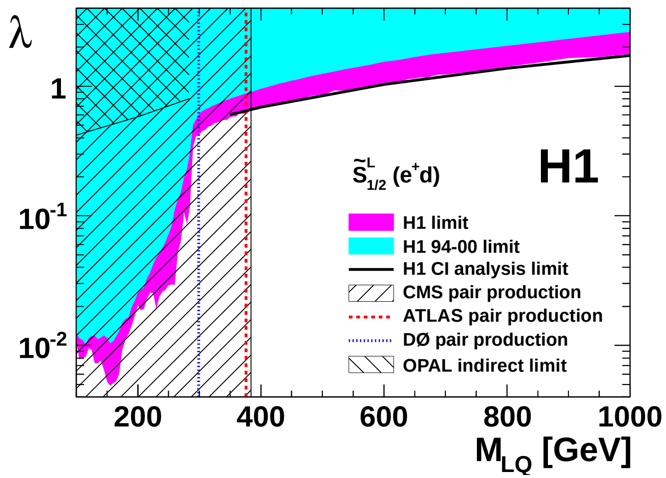
s-channel: (resonant production)

u-channel: (LQ exchange)

H1 Search for First Generation Leptoquarks



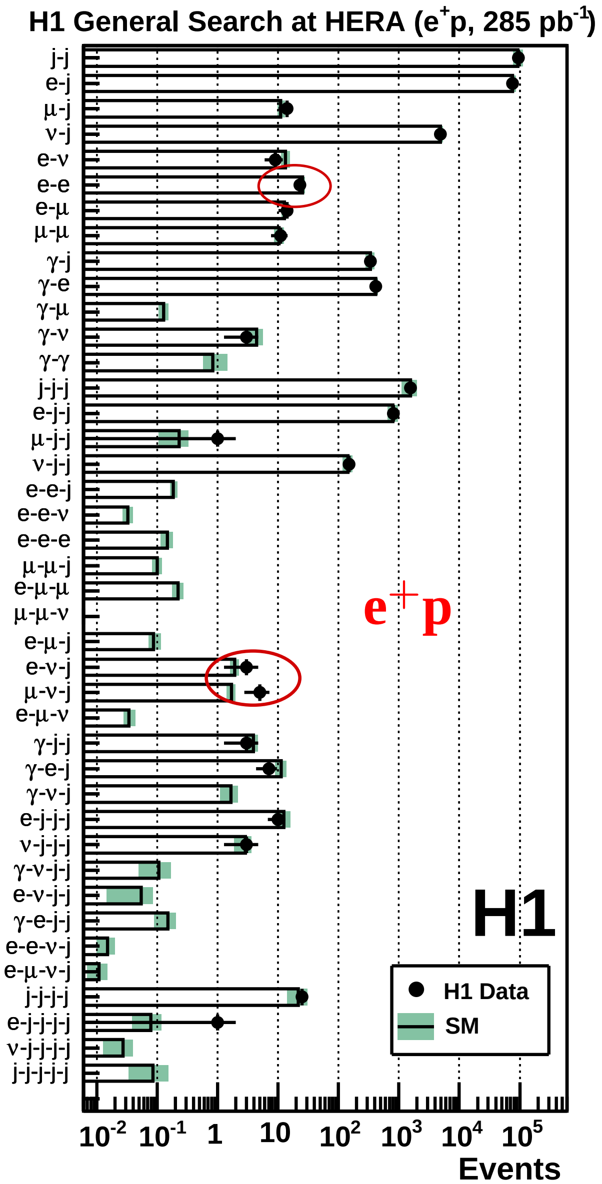
H1 Search for First Generation Scalar Leptoquarks



Model independent search for New Phenomena

- Identify isolated ($D(\eta\phi) > 1$) particles (objects): e, μ, γ, j, ν
- Select events, having at least two objects with high $P_T > 20$GeV in the detector acceptance ($10^o < \theta < 140^o$)
- Classify into exclusive channels containing from 2 to 5 objects
- Compare with SM predictions
  $\Rightarrow$ **good overall agreement**
- Find interesting regions with greatest deviations from SM in kin. distributions ($M_{\rm all}$, ΣP_T)

  $\Rightarrow$ **Combine H1 and ZEUS data**



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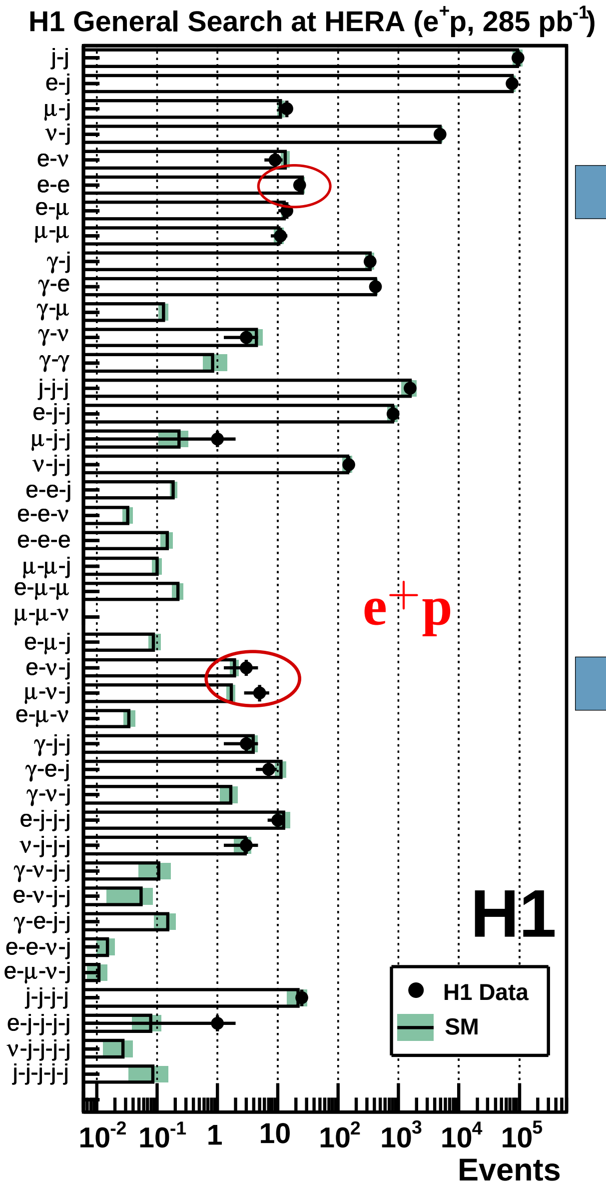
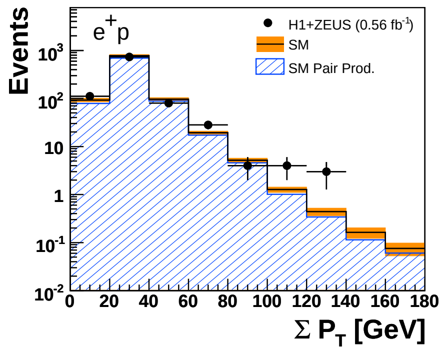
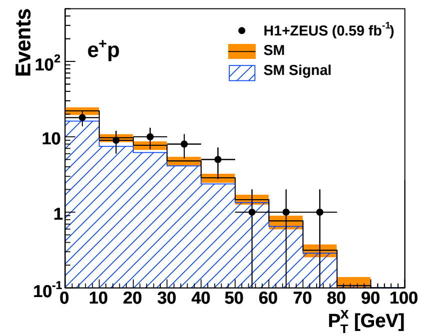


H1+ZEUS, $0.59\ \text{fb}^{-1}$



2.6σ

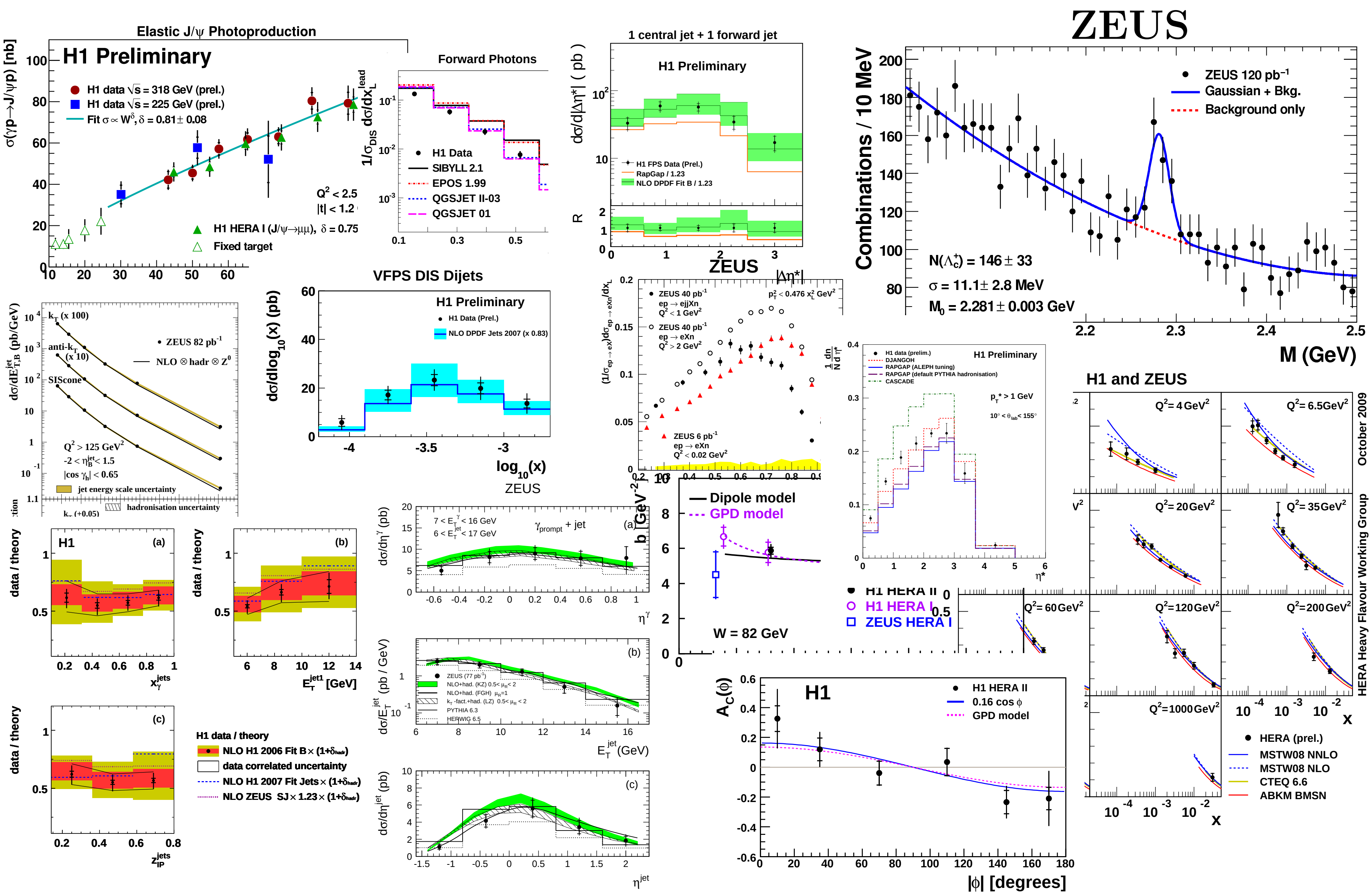


1.9σ

Largest observed deviations from the SM at HERA

JHEP 0910:013 (2009)
JHEP 1003:035 (2010)

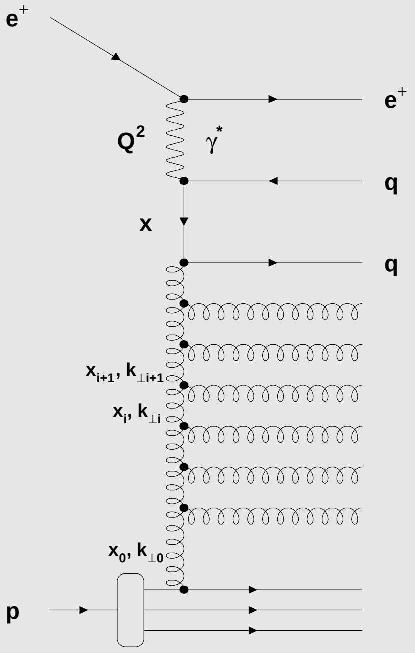
HERA as QCD factory



QCD at low x

Lots of glue in the proton $\Rightarrow$ long gluon cascade at low x. Perturbative expansion of evolution equations $\sim \sum_{mn} A_{mn} \ln(Q^2)^m \ln(1/x)^n$ hard to calculate explicitely

$\Rightarrow$ approximations needed



DGLAP: resums $\ln(Q^2)^n$ terms, neglecting $\ln(1/x)^n$ terms
strong k_T ordering in partonic cascade

BFKL: resums $\ln(1/x)^n$ terms
no k_T ordering in partonic cascade $\Rightarrow$ more hard gluons are radiated far from the hard interaction vertex

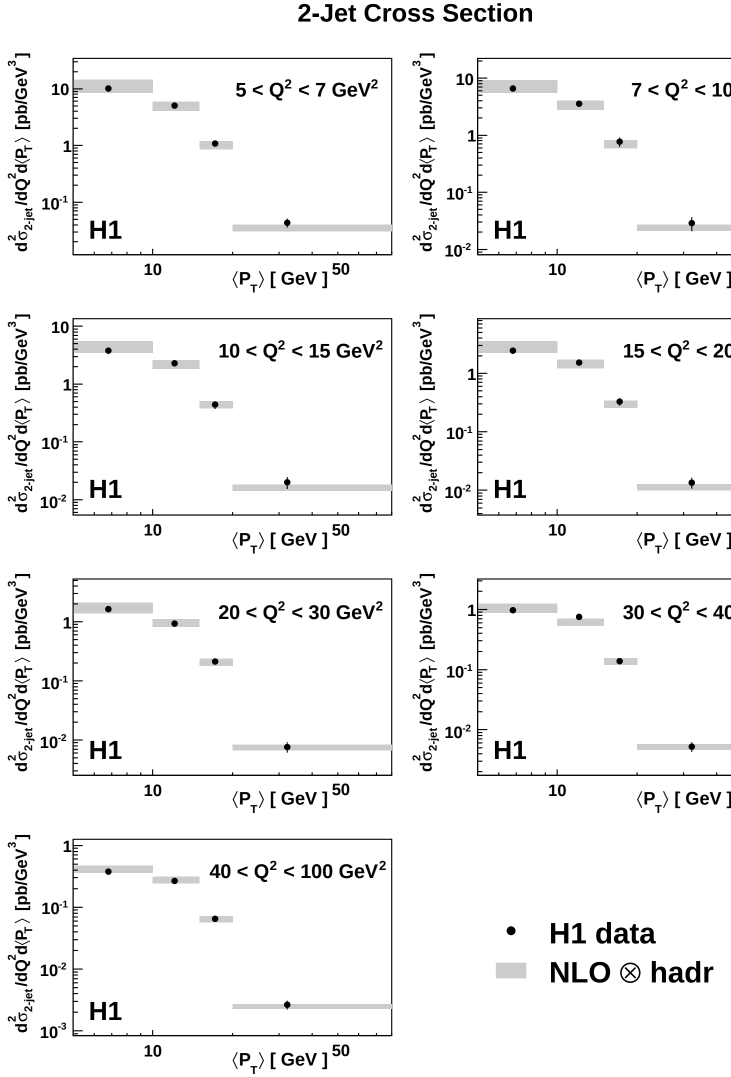
CCFM: angular ordered parton emission $\Rightarrow$
reproduces DGLAP at large x and BFKL at $x \rightarrow 0$

- How long is partonic cascade at HERA, at small x?
- Do the $\ln(1/x)^n$ terms play a major role in parton dynamics as suggested by BFKL?

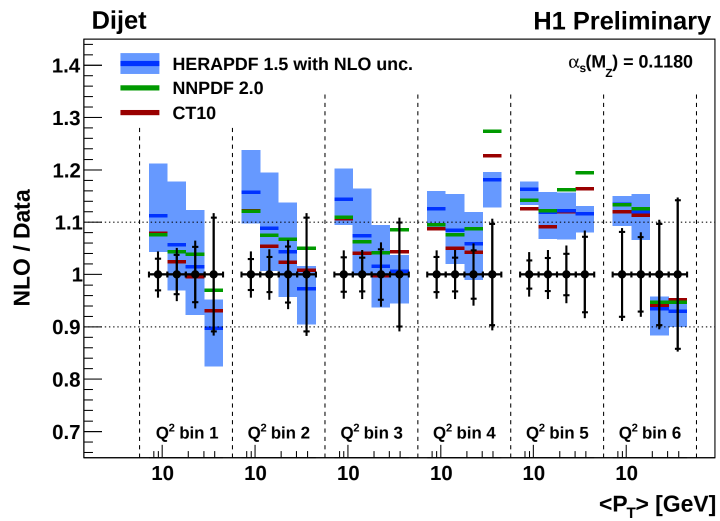
$\Rightarrow$ Look at (multi)jet final states at low x in different configurations

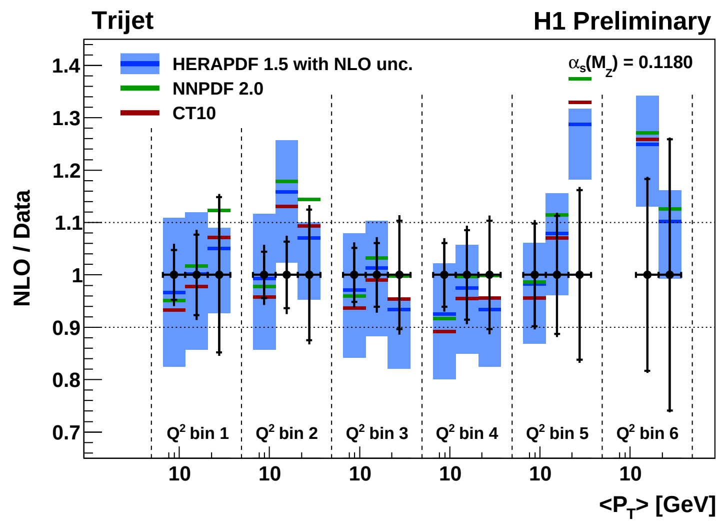
Jet Production at HERA in DIS regime

Low Q^2 : $5 < Q^2 < 100$ GeV^2



High Q^2 : $150 < Q^2 < 15000$ GeV^2

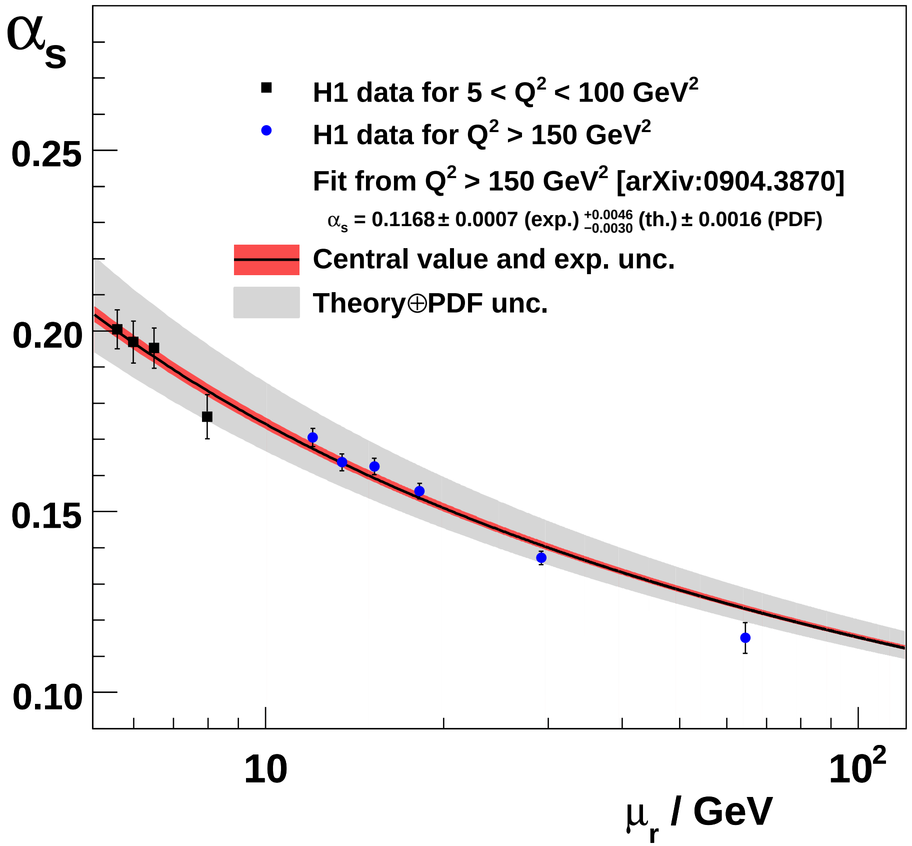


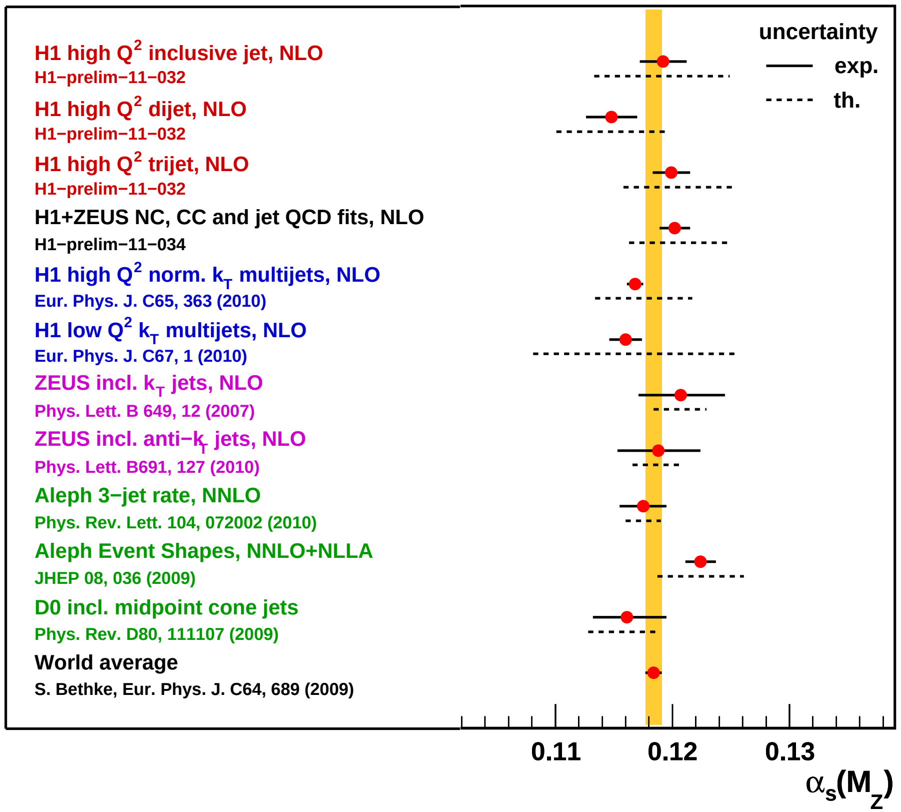


Good description by NLO QCD in DGLAP formalizm

Strong Force Coupling measurement at HERA

α_s from Jet Cross Sections in DIS



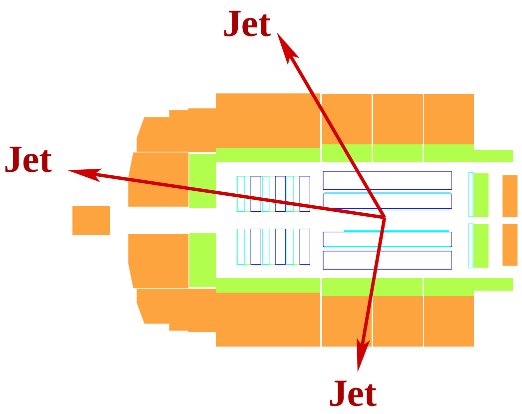


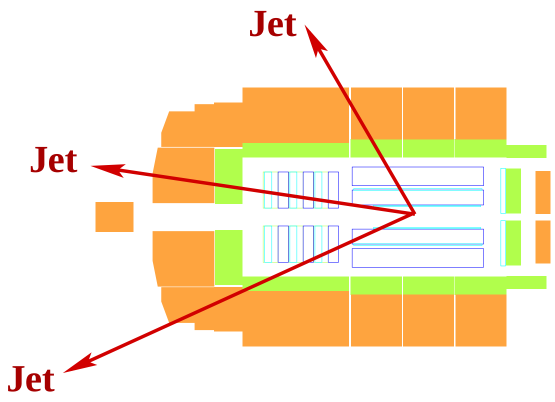
Running of α_s in a single experiment

$\alpha_s(M_Z)$ from different measurements

- Remarkable agreement between different datasets and methods
- Precision is limited by theory error $\Rightarrow$ need to include terms beyond NLO

3-jet samples with different topologies





Central jets:

$-1 < \eta_{jet} < 1$

Forward jets:

$\eta_{fj1} > 1.73$

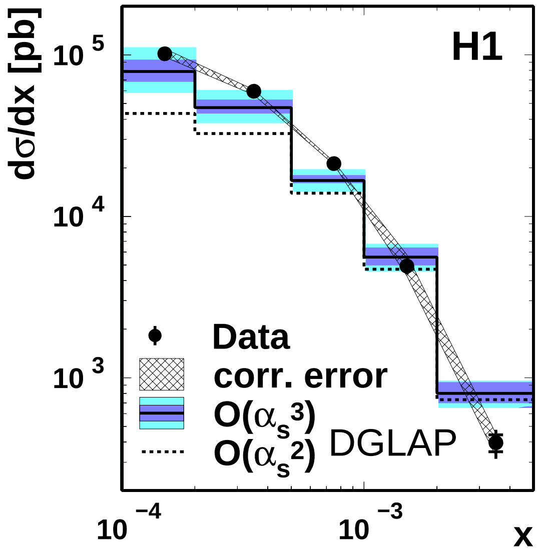
$x_{fj1} > 0.035$

$\eta_{fj2} > 1$

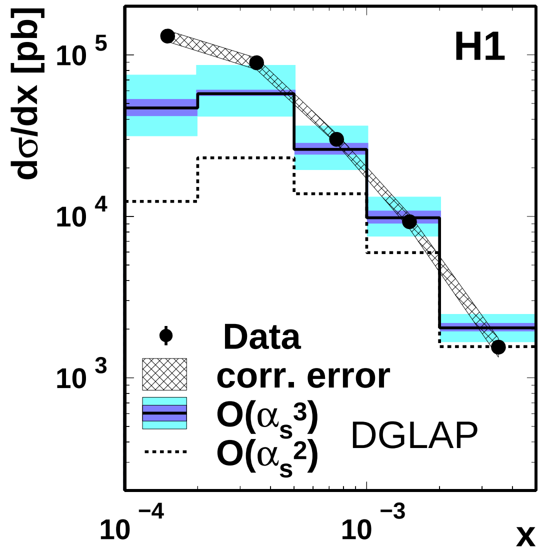
All jets:

$E^*_{t,jet} > 4$ GeV

1 forward jet + 2 central jets



2 forward jets + 1 central jet



- **Large deficit at small x for 2-forward jet topology! There $\mathcal{O}(\alpha_s^3)$ calculation is insufficient**

⇒ room for non-DGLAP dynamics!

Summary

- Standard Model survived $1\ \text{fb}^{-1}$ of **HERA** data and is still in a good shape. Next challenge will come from the **LHC** - stay tuned!

- Combining H1 and ZEUS data allowed proton structure to be measured with unprecedental precision

- NLO DGLAP is surprisingly successful down to low Q^2 and low x in describing bulk of HERA data. Although some room for parton evolution beyond DGLAP is found at specific phase space corners, there are no unumbiguous evidence for parton saturation at low x yet.

- Gained new insights into high energy diffraction: Pomeron under the HERA microscope (large wealth of data)

- Is this the end of DIS experiments at the colliders? Or what's next?

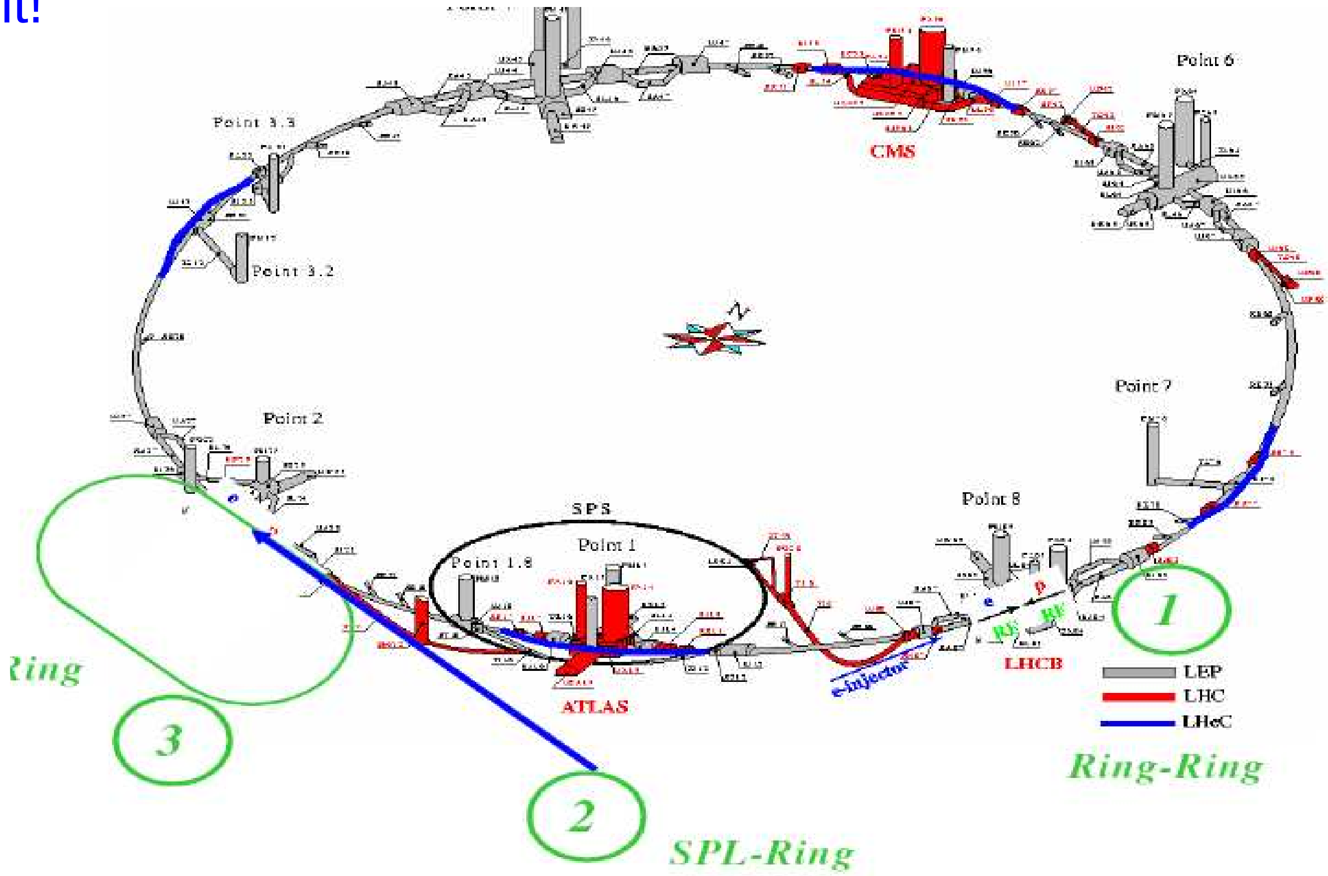
LHeC

Project under discussion

Support it!

For late LHC period:

$\sim \mathbf{2022-2032}$



$$e^{\pm}p$$

$(60-140)$GeV $\times$ 7000 GeV