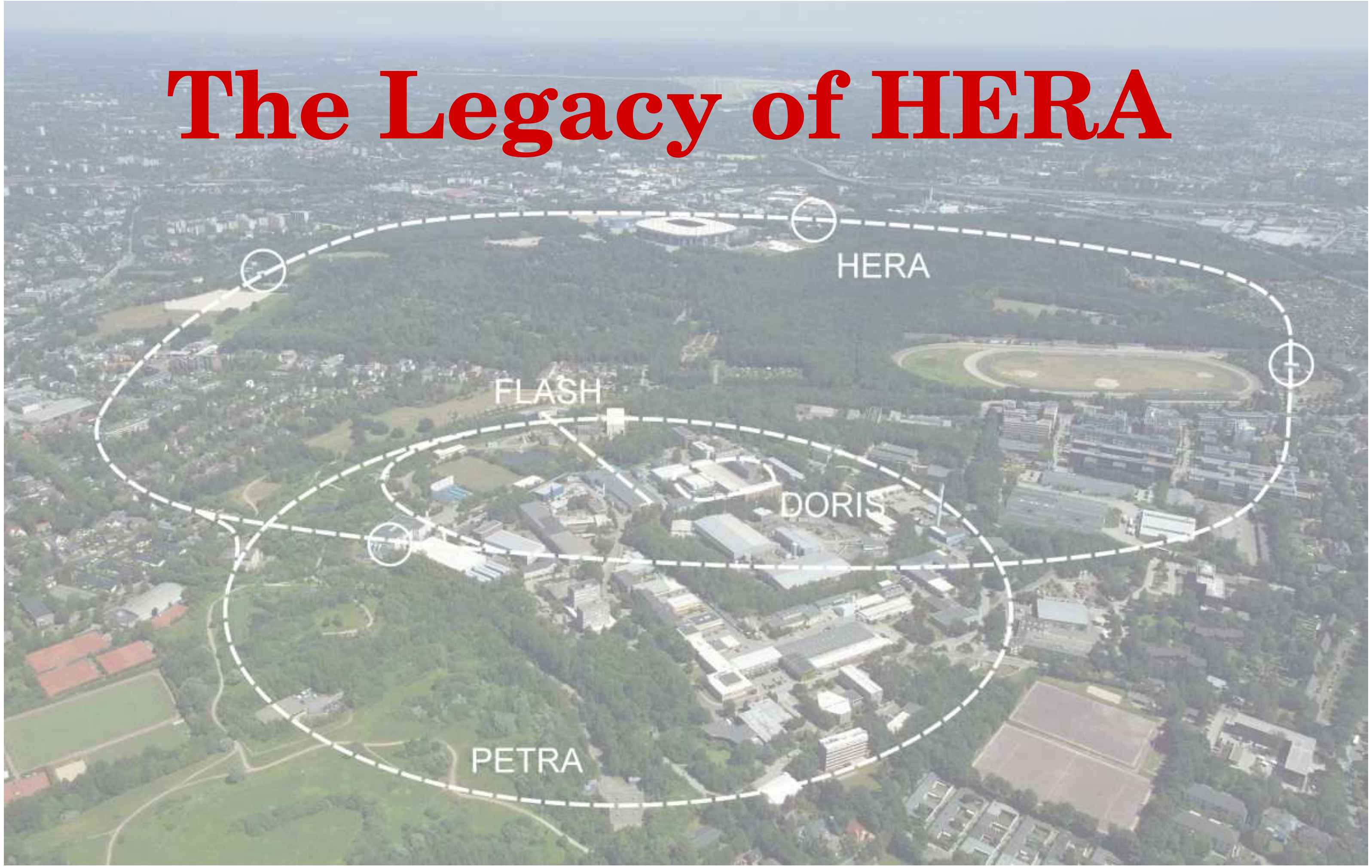
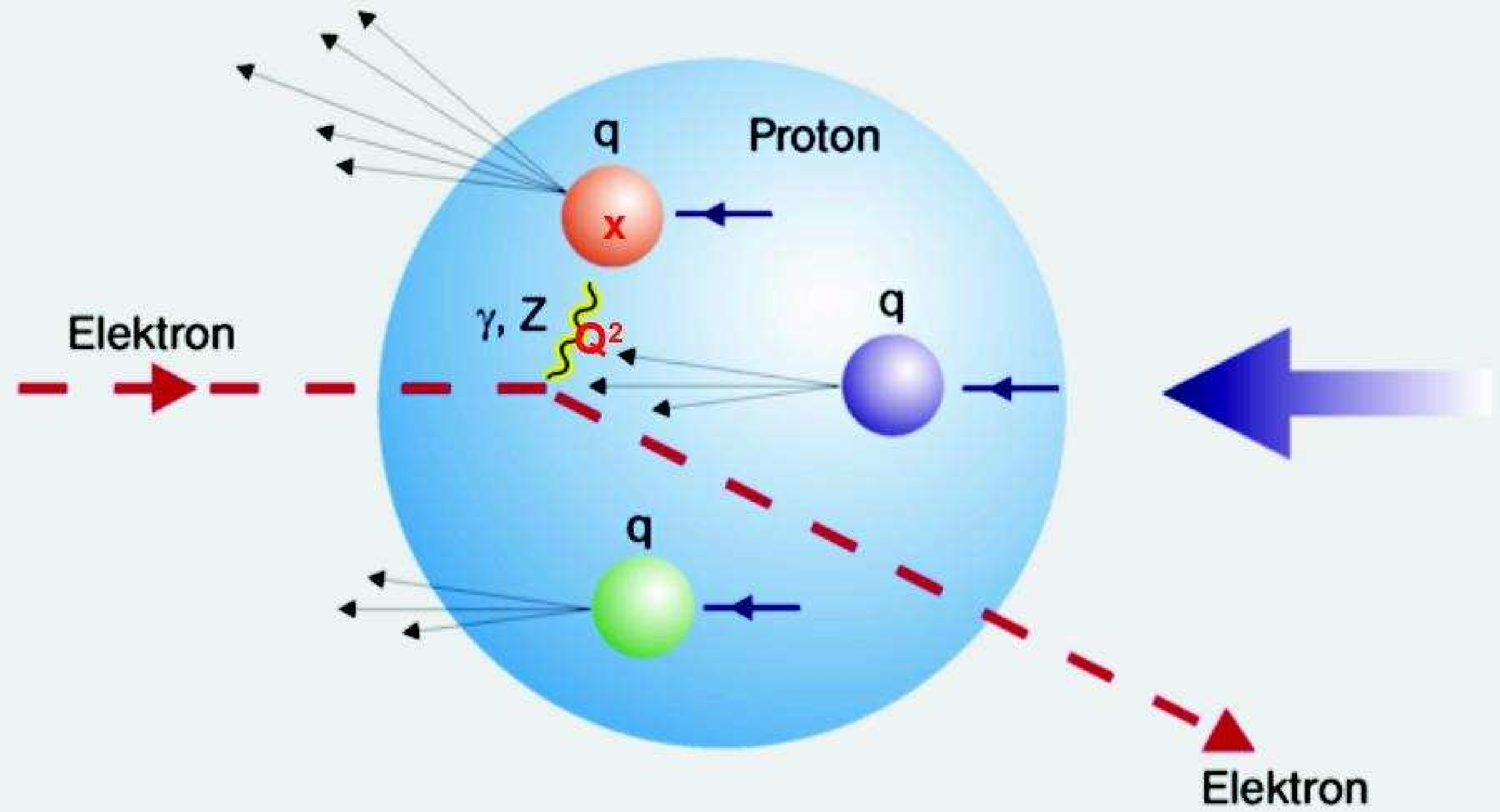
Sergey Levonian
DESY, Hamburg

The Legacy of HERA



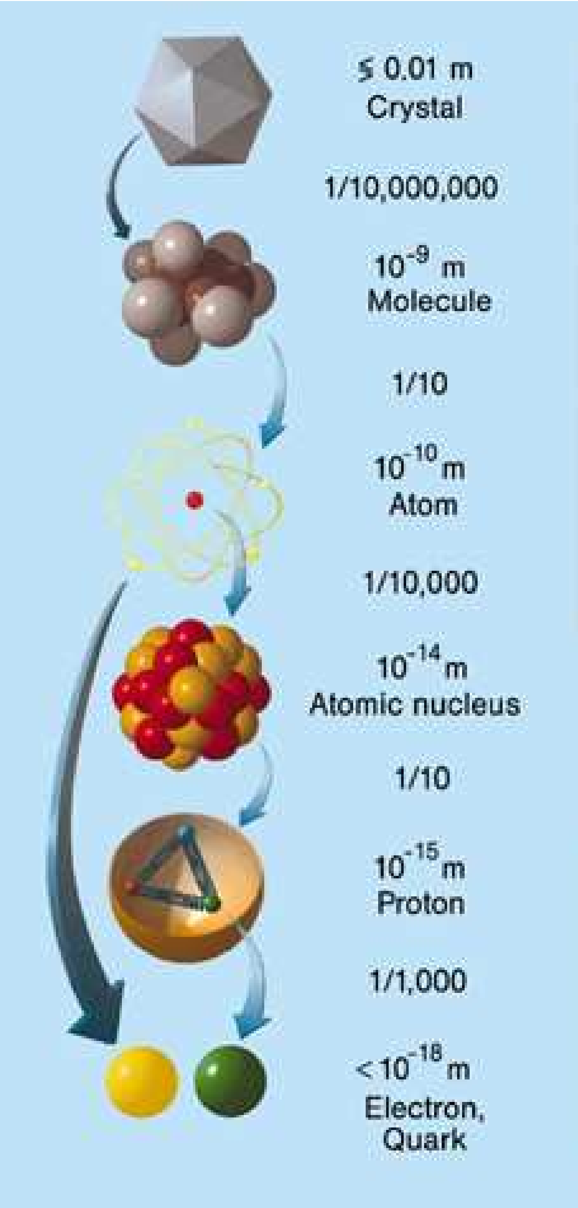
Deep-Inelastic Scattering



Kinematics x, Q2 can be measured from the detected particles

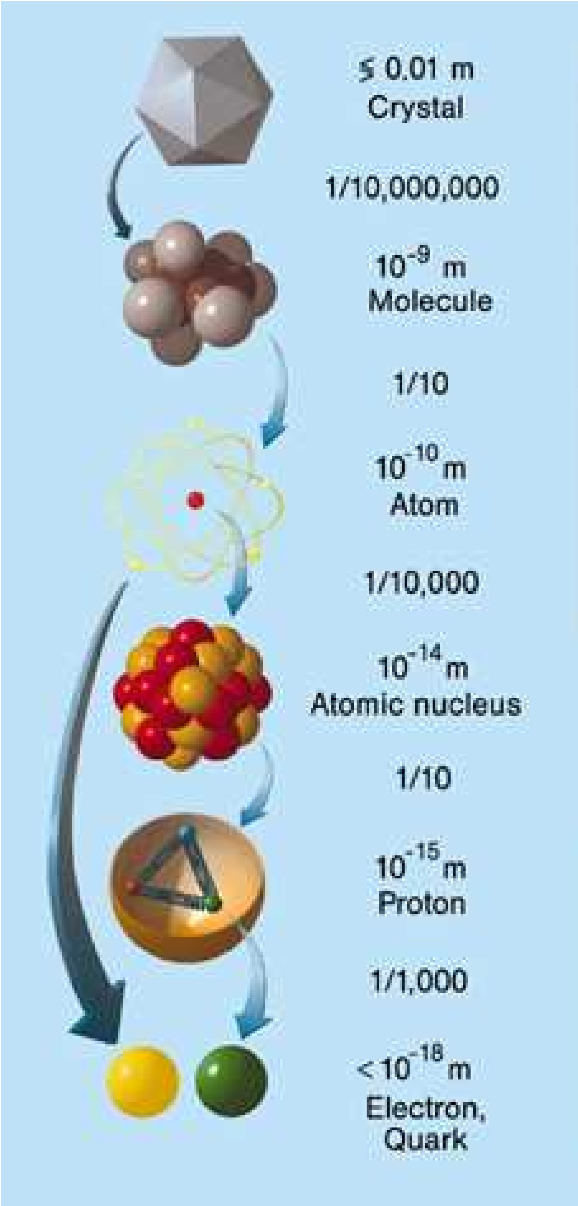
Charged current interactions also accessible (neutrino in the final state)

Looking deeper inside matter



$$\lambda = h/p \sim \frac{1}{E}$$

Looking deeper inside matter



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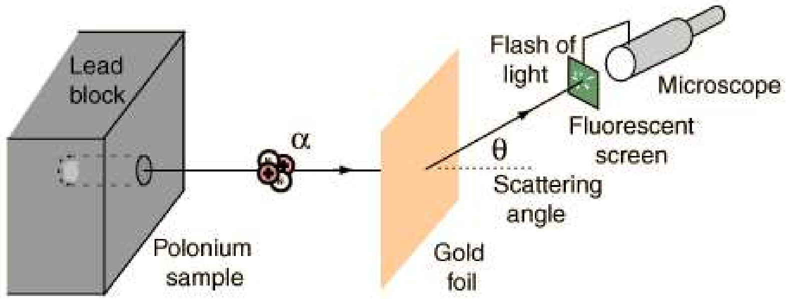
Rutherford (1911)

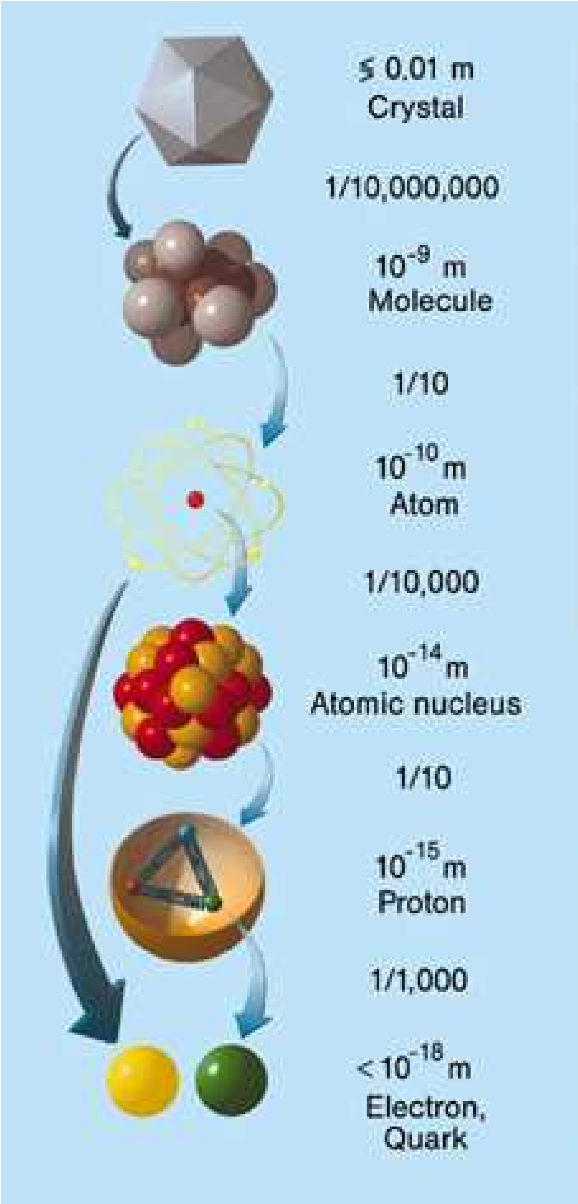
– elastic (Coulomb) scattering of 7 MeV α on Au

– planetary model of atom $\Rightarrow$ QM



$$\frac{d\sigma}{d\ \cos\theta} = \frac{\pi}{2} z^2 Z^2 \alpha^2 \left(\frac{\hbar c}{KE}\right)^2 \frac{1}{(1-\cos\theta)^2} \ ; \quad N(\theta) \sim \frac{1}{\sin^4(\theta/2)}$$

Looking deeper inside matter



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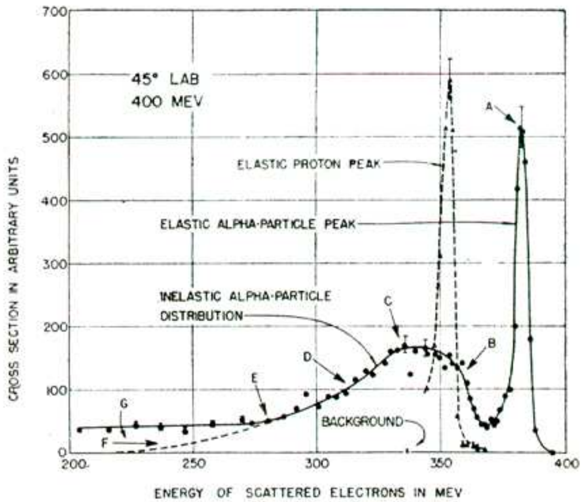
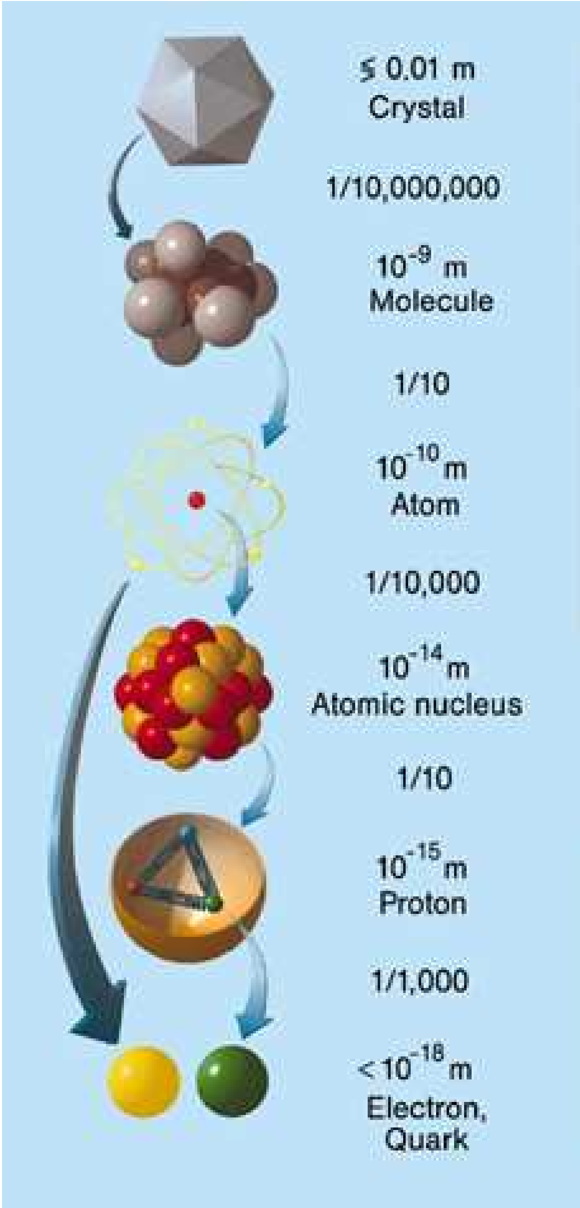
- (in)elastic eN scattering of 400 MeV electrons
- Nucleus structure; size of A,p



Looking deeper inside matter



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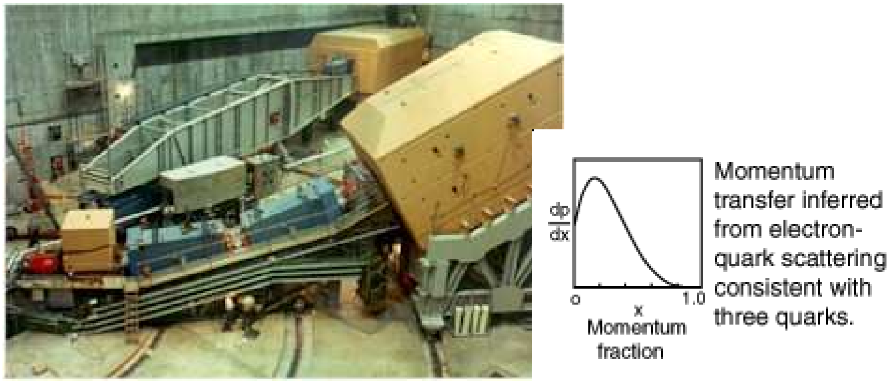
– Fixed target DIS with 20 GeV electron beam

– internal structure of hadrons

– experimental evidence for quarks



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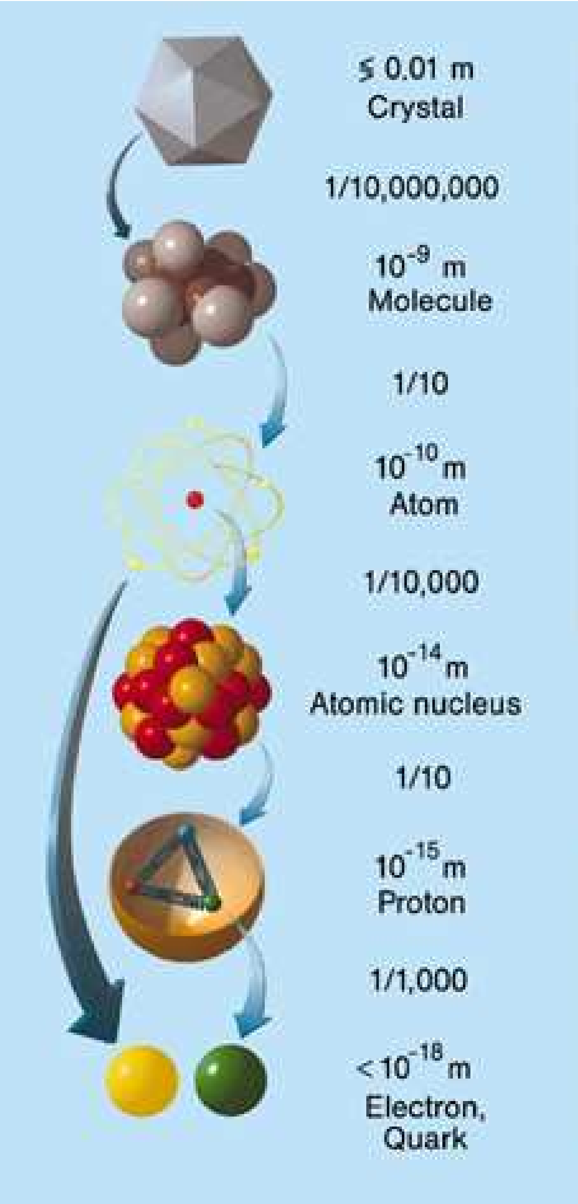

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HERA (1992 – 2007)

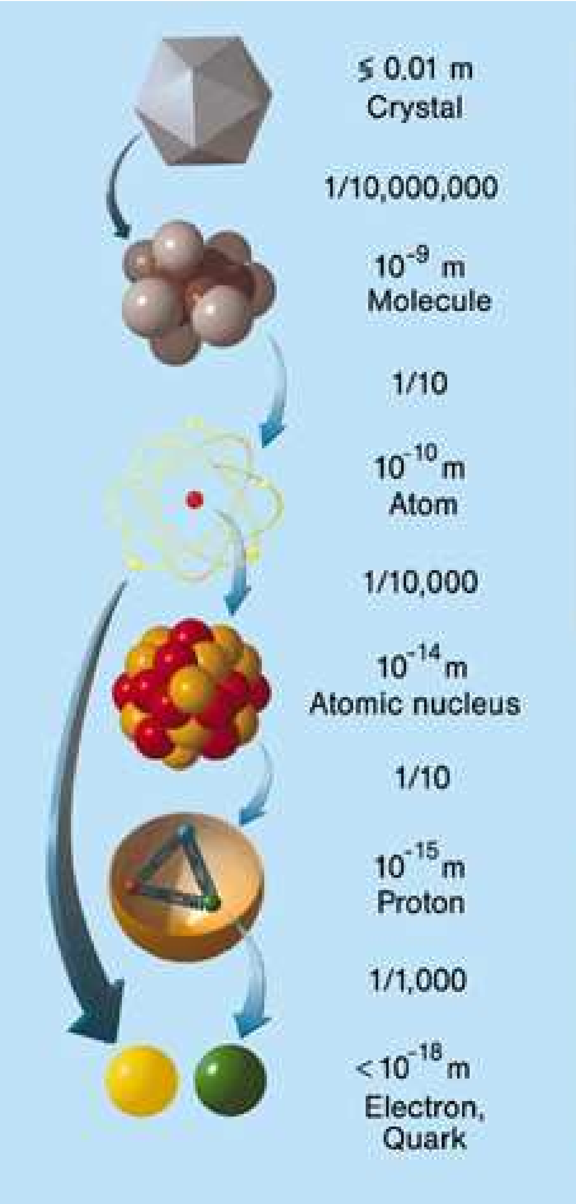
– first (and so far the only) ep collider

– energy frontier: $\sqrt{s} = 319$ GeV

– resolution power down to 10^{-18}m

– QCD in low x regime ($x > 10^{-5}$)

Looking deeper inside matter



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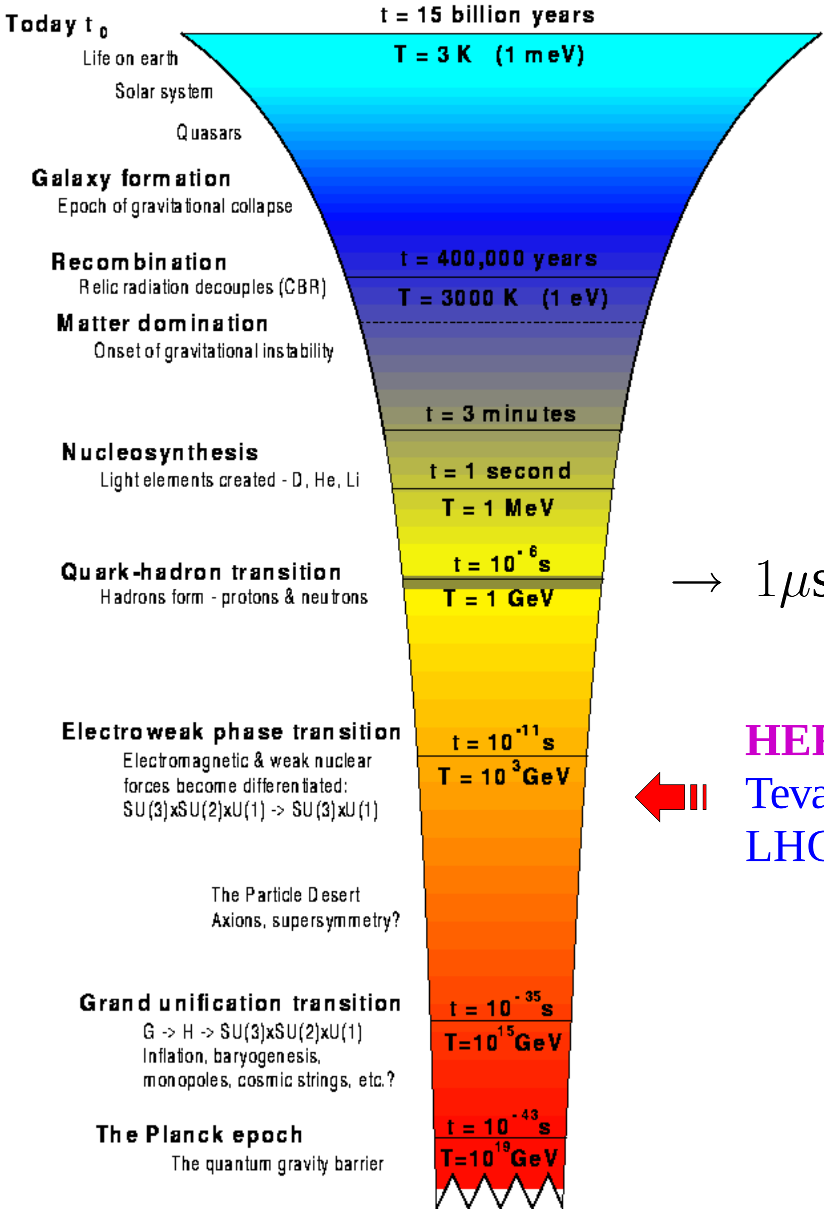
Restoring Universe Evolution

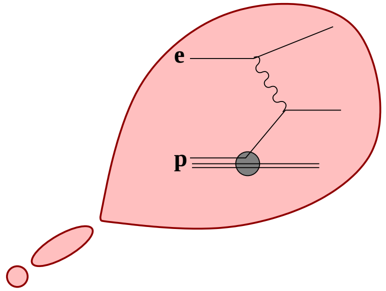


$\rightarrow 1\mu\text{sec}$

HERA
Tevatron
LHC

$$E \sim T$$

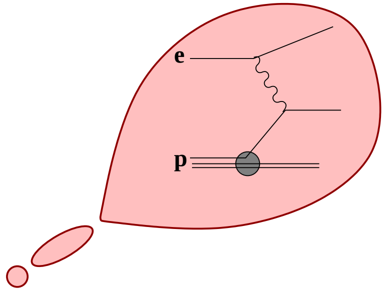
In the beginning the was the Idea...



1979

...then a lot of Hard Work...

1984-1991



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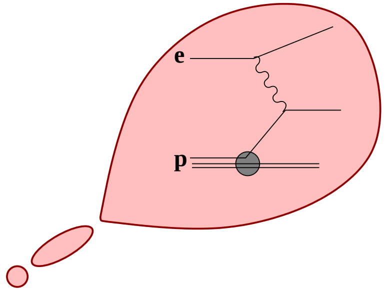

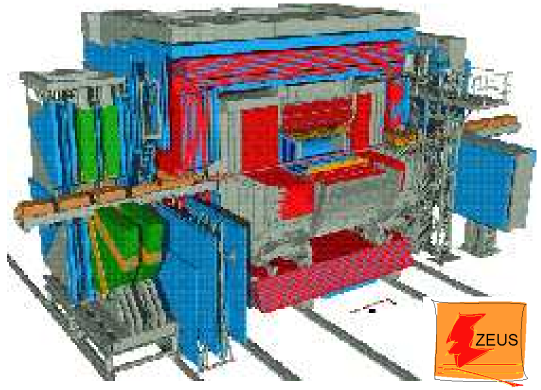

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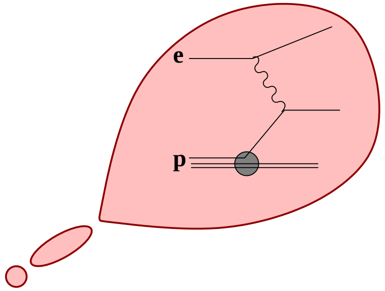

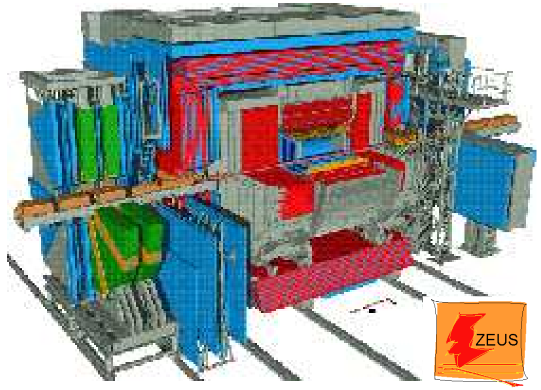

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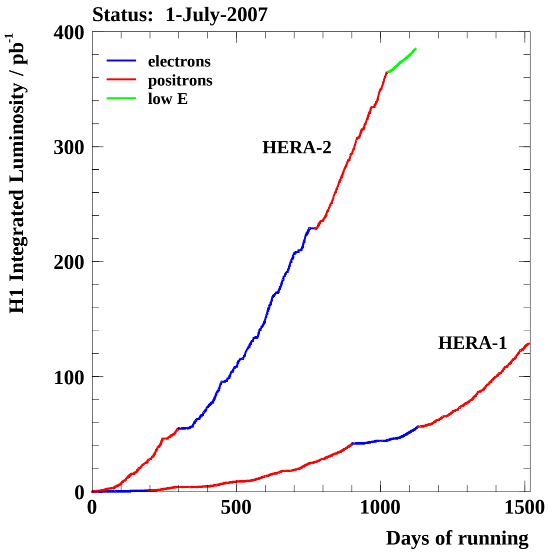
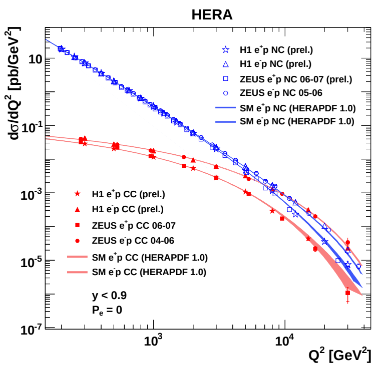
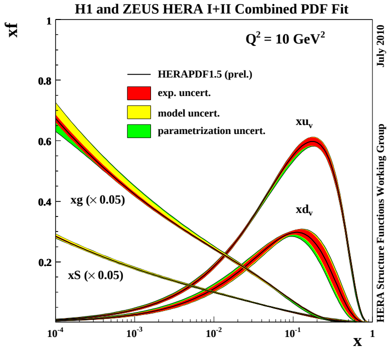


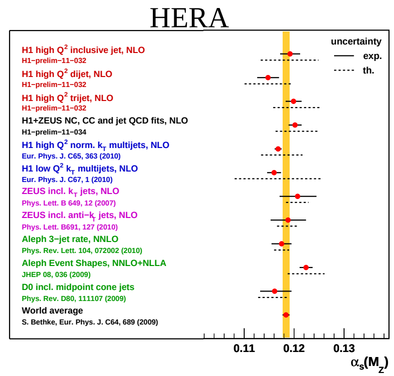
1992-2007

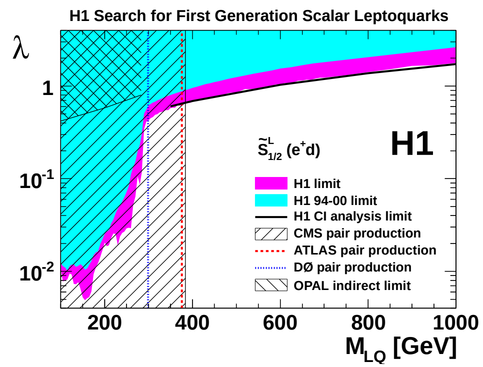
1979

...and finally...

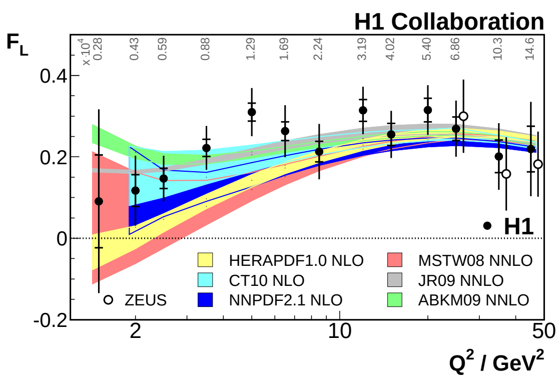


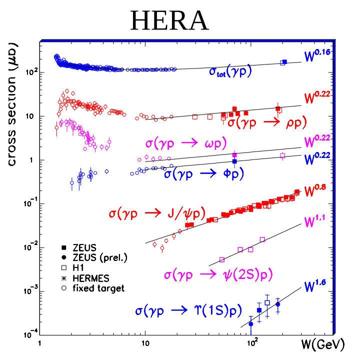


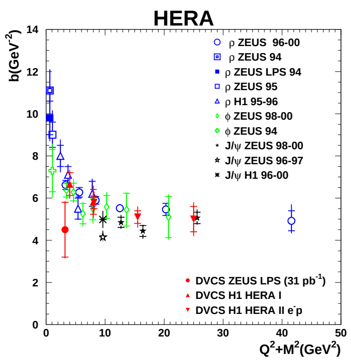


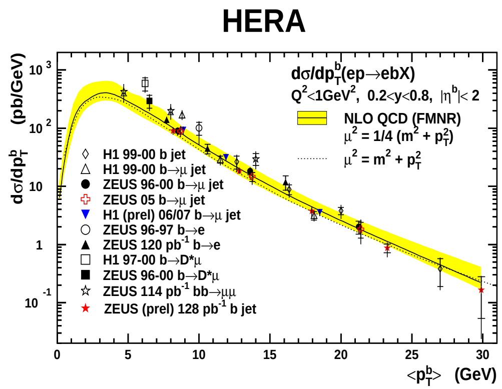


Lots of Textbook results

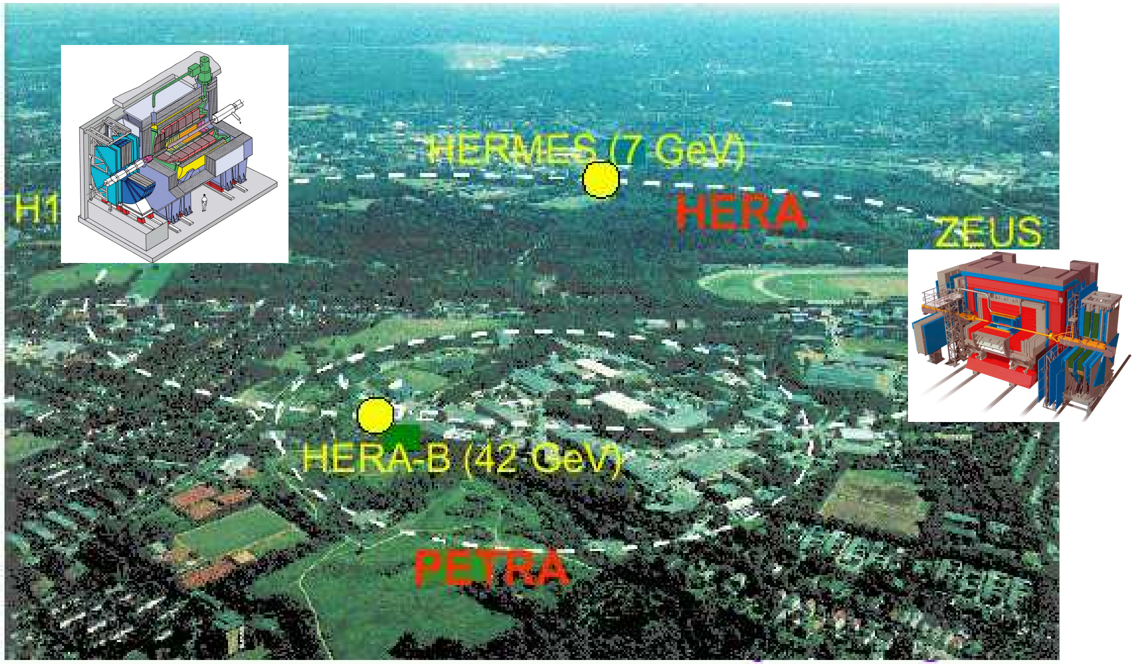


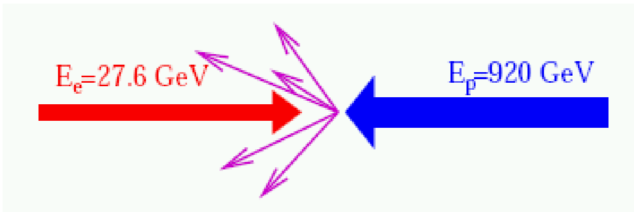






HERA: The World's Only ep Collider



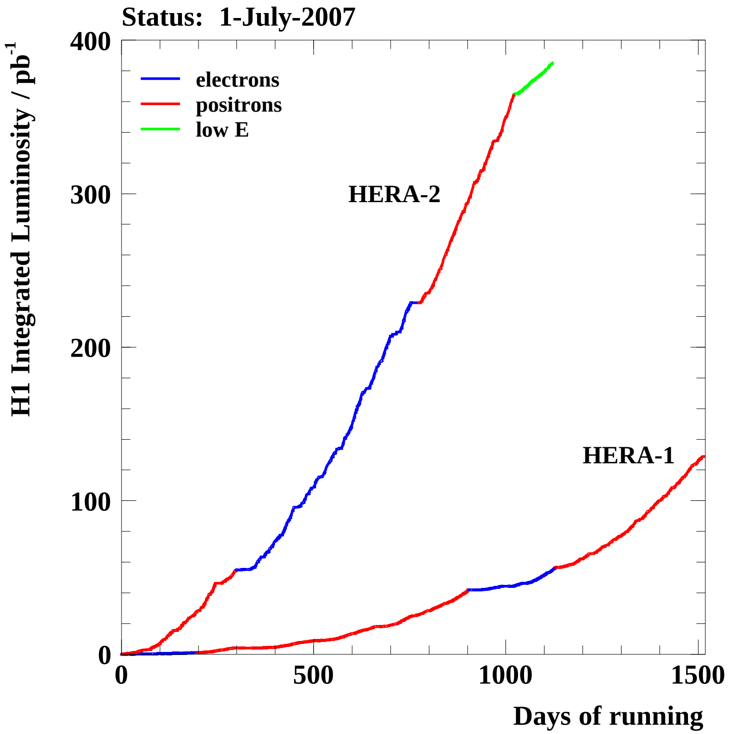


HERA-1 (1993-2000) $\simeq 120$ pb^{-1}

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

Final Data samples

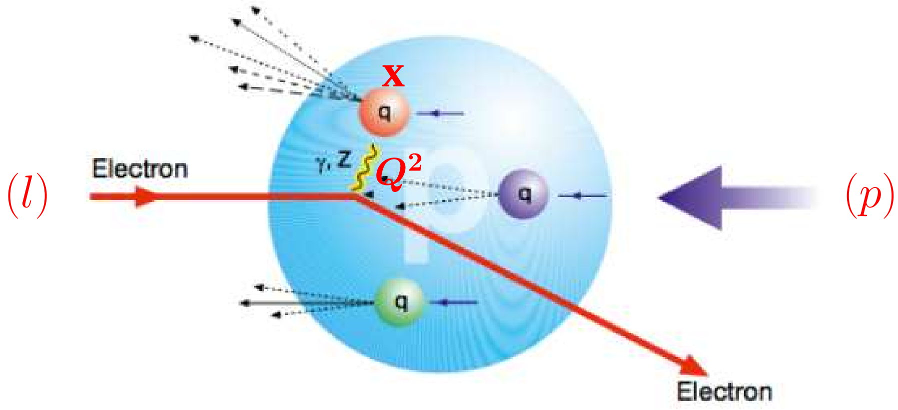
H1+ZEUS: 2×0.5 fb^{-1}



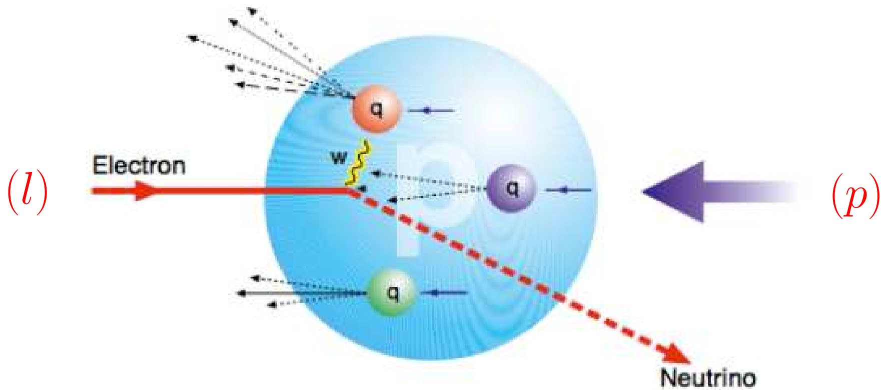
- 1998 E_p upgrade: $820 \Rightarrow 920$ GeV
  ($\sqrt{s}$: $301 \Rightarrow 319$ GeV)
- 2001 HERA-2 upgrade: $\mathcal{L} \times 3$, Polarised e^+/e^-
  ($\langle P \rangle = 40\%$)

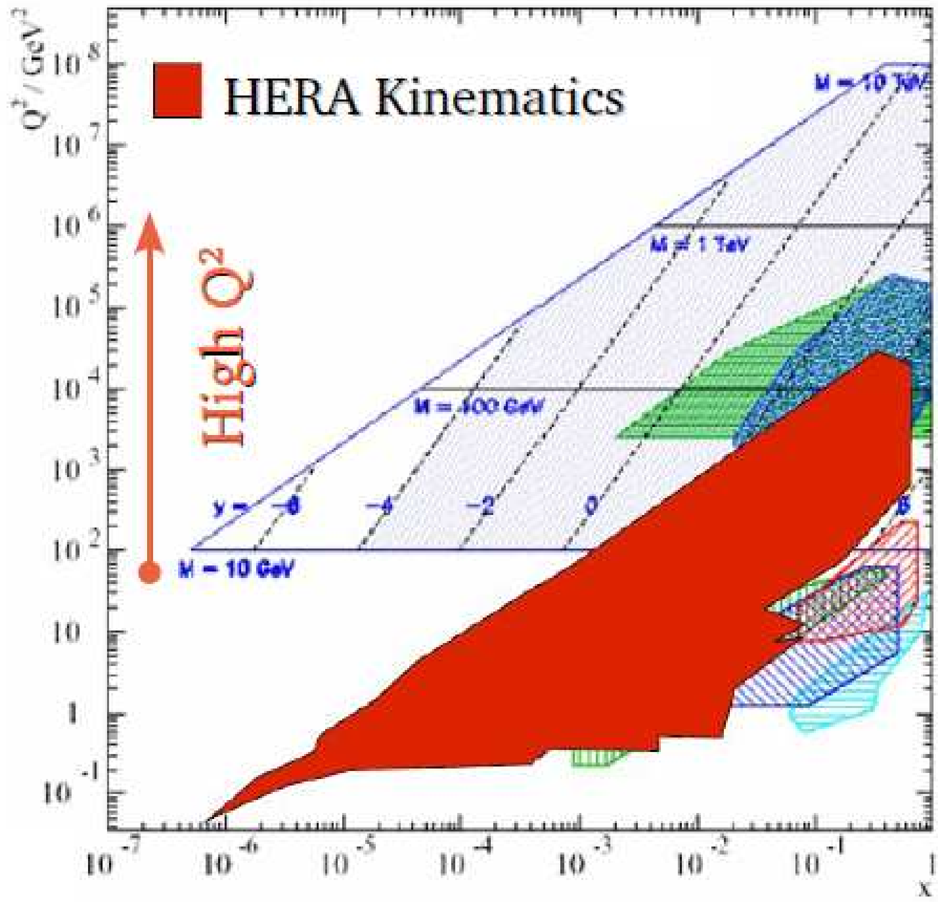
Deep-Inelastic Scattering at HERA

Neutral Current DIS: ep $\rightarrow \mathrm{e}'$X



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





Kinematics: (Momentum transfer)^2: $Q^2 = -q^2$

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

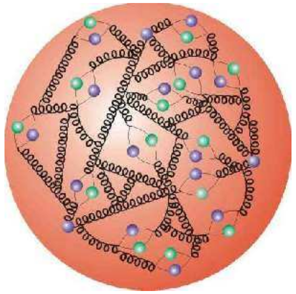
Inelasticity: $y = (p \cdot q)/(p \cdot l)$

(Total hadronic energy)^2: $W^2 = (p+q)^2$

$W^2 \simeq Q^2/x$

Physics landscape at HERA

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



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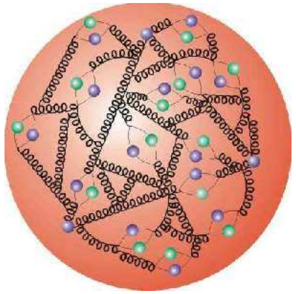
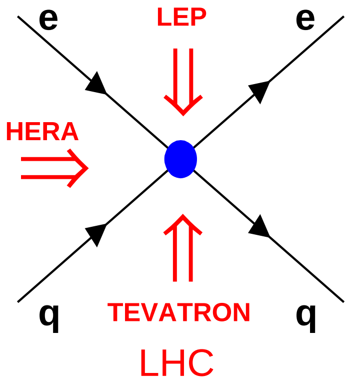


- **HERA as Energy frontier machine**
  - ▷ Electroweak unification at work
  - ▷ Anything beyond the Standard Model?



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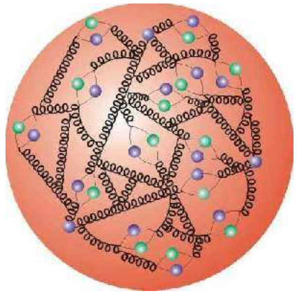

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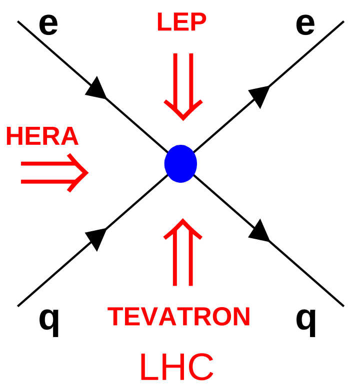
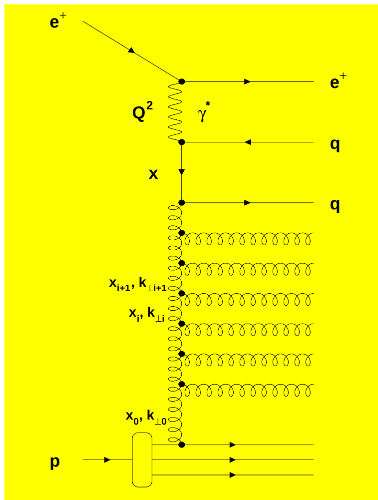


- **HERA as QCD laboratory**
  - ▷ Putting QCD in stringent tests with:
    - ∘ Jets (parton evolution schemes, NLO QCD, α_s)
    - ∘ Heavy flavor sector (multiscale problem: Q^2, M_Q, E_t)
    - ∘ Diffraction (interplay of soft and hard physics)
  - ▷ HERA specifics: lox x physics



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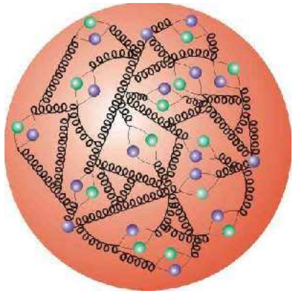

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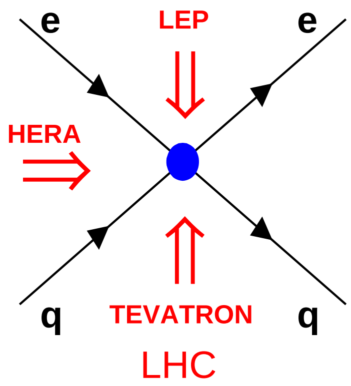

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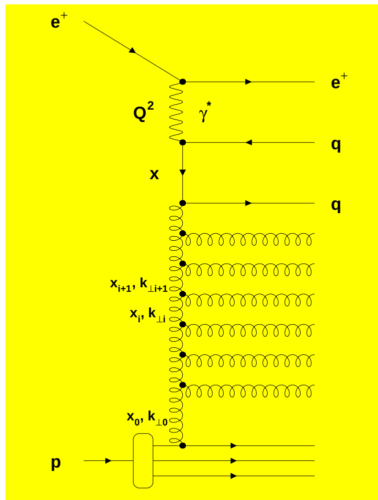


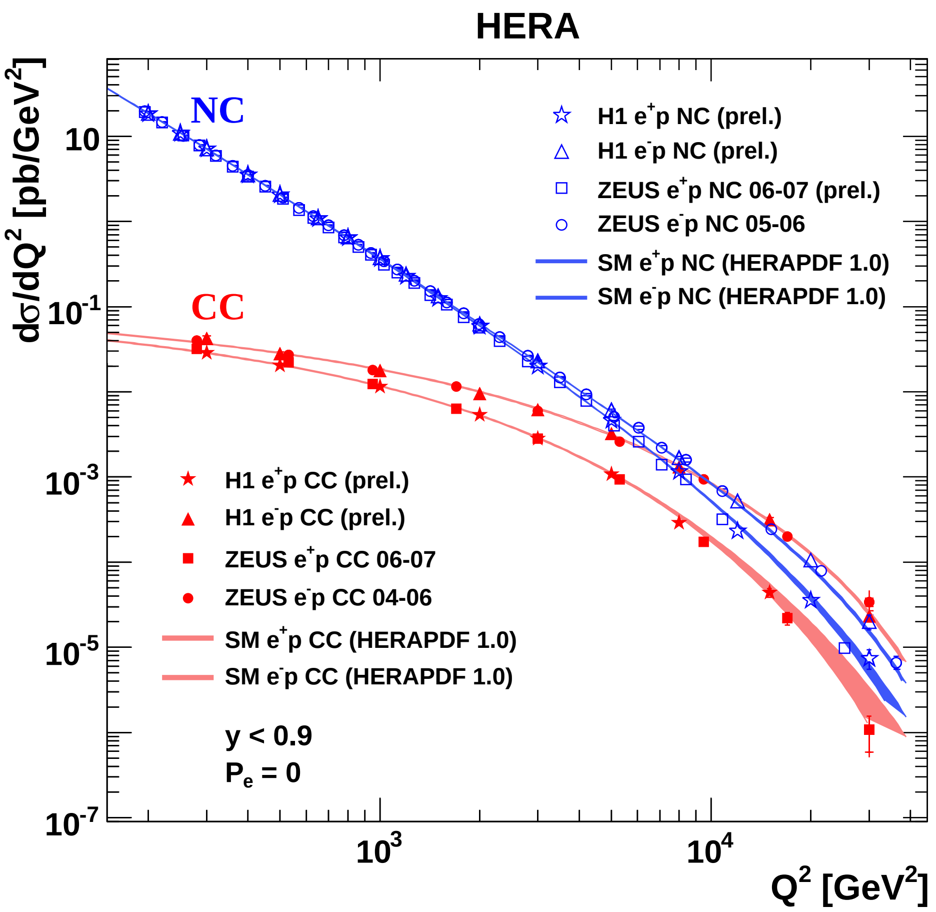
➡ **Search for Novel Phenomena**

➡ **Precision Measurements**

HERA as Energy Frontier Machine

HERA at Energy Frontier

Unpolarized DIS cross sections



Electro-Weak Unification

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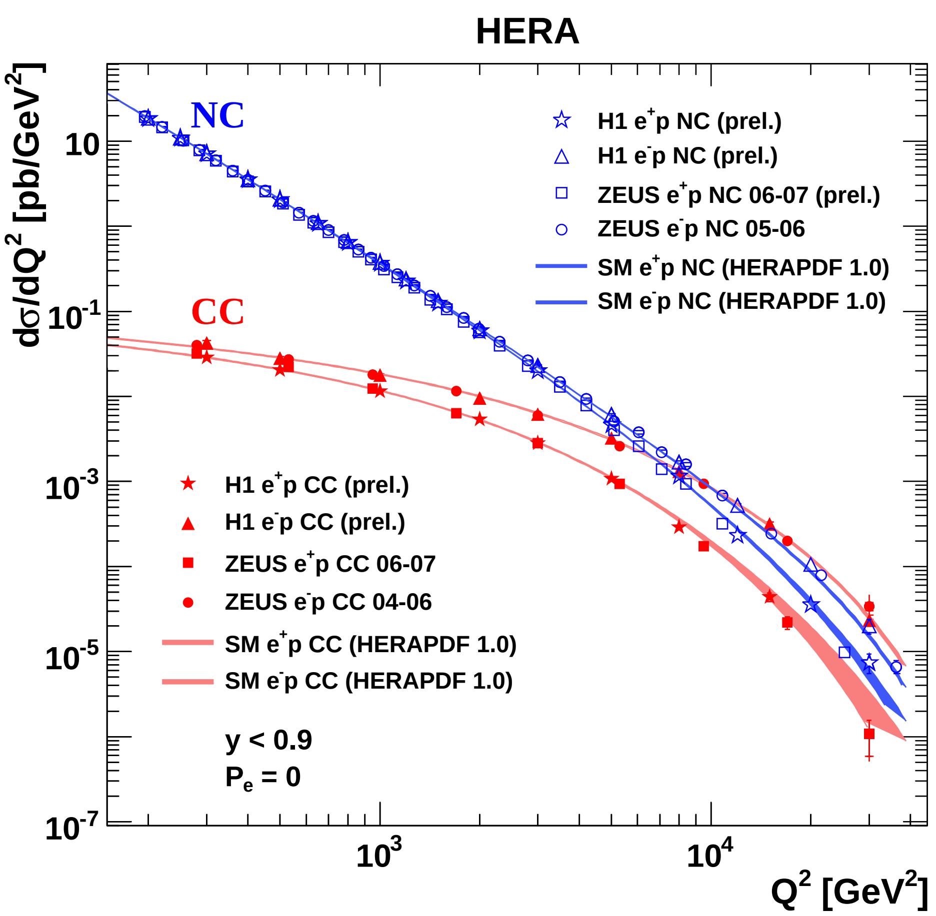
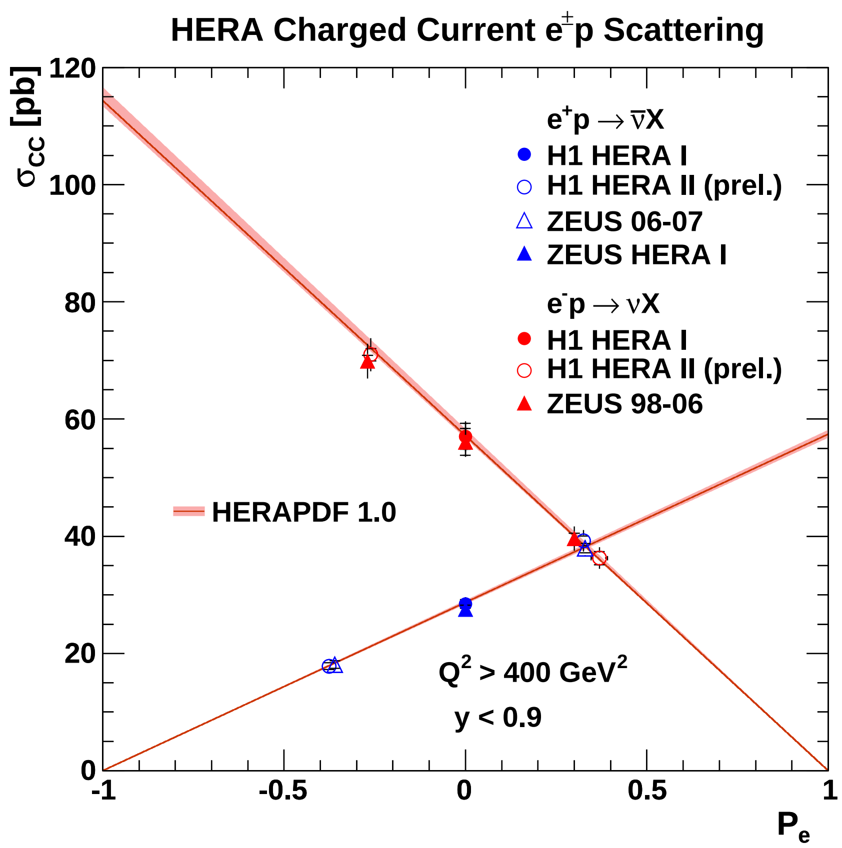
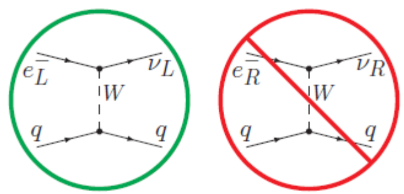


Electro-Weak Unification

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

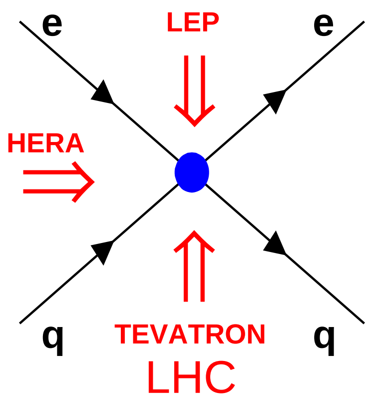




No W coupling to e^-_R and e^+_L

Anything beyond the SM ?

$\sqrt{s} = 319$ GeV

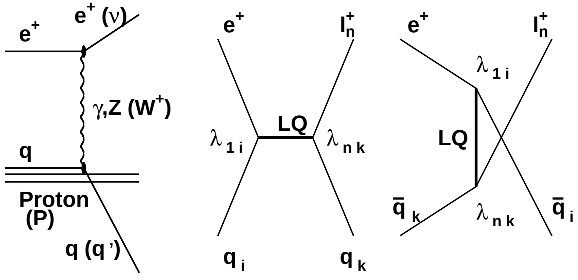


So far all NC and CC HERA data were in good agreement with the SM.
Try to look more carefully at the tails, using two strategies:

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

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

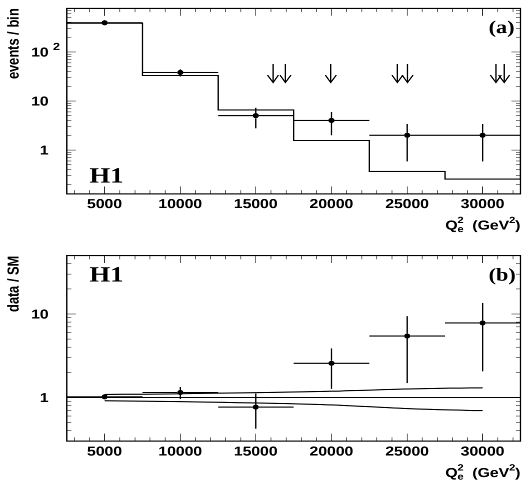
Leptoquarks ?

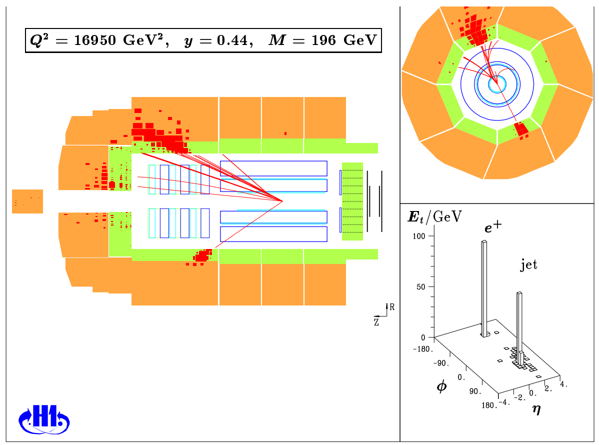


(a) (b) (c)

1994-97: High Q^2 events.

Rate in excess of Standard Model!





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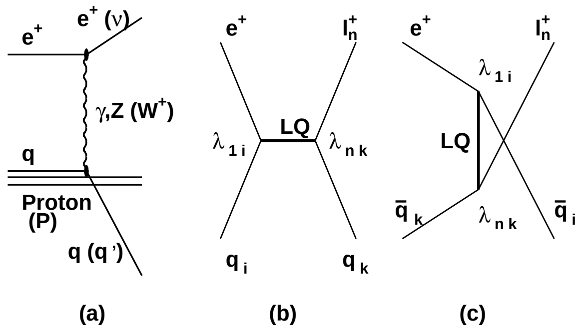

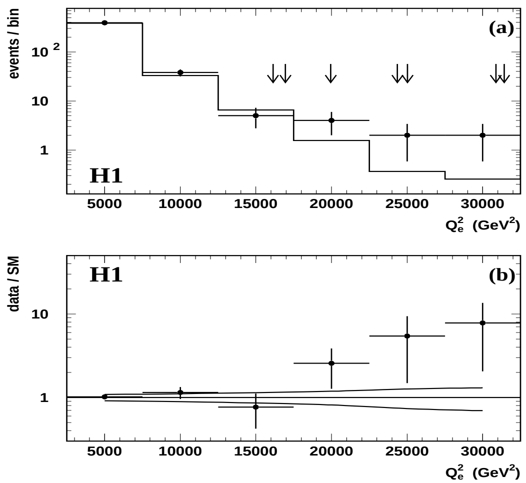

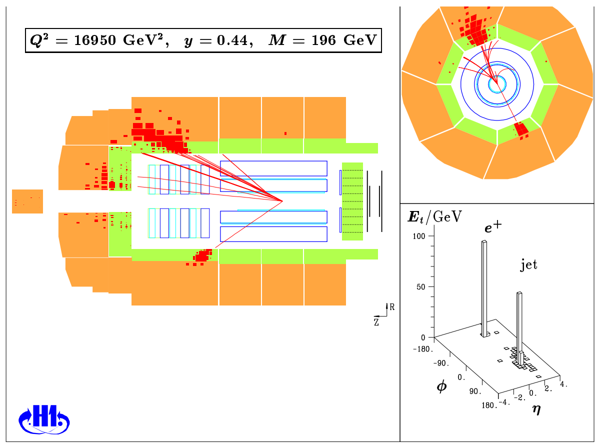

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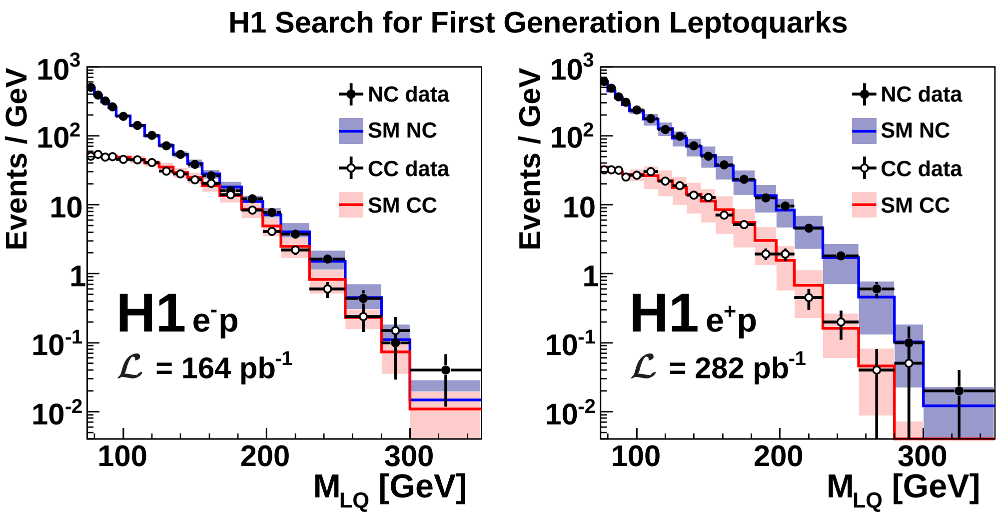
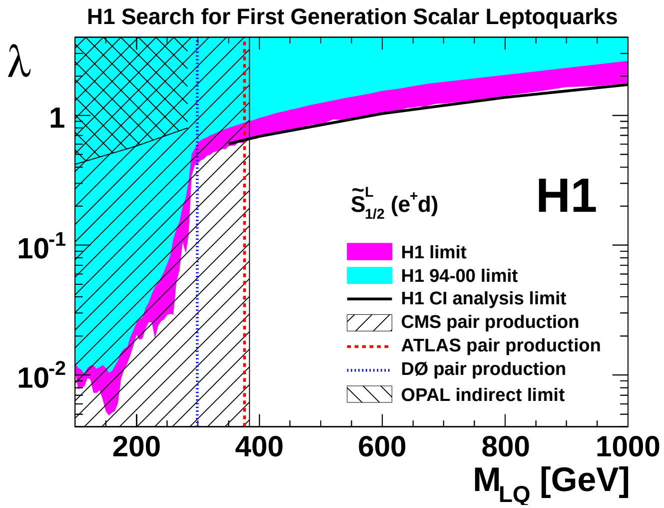
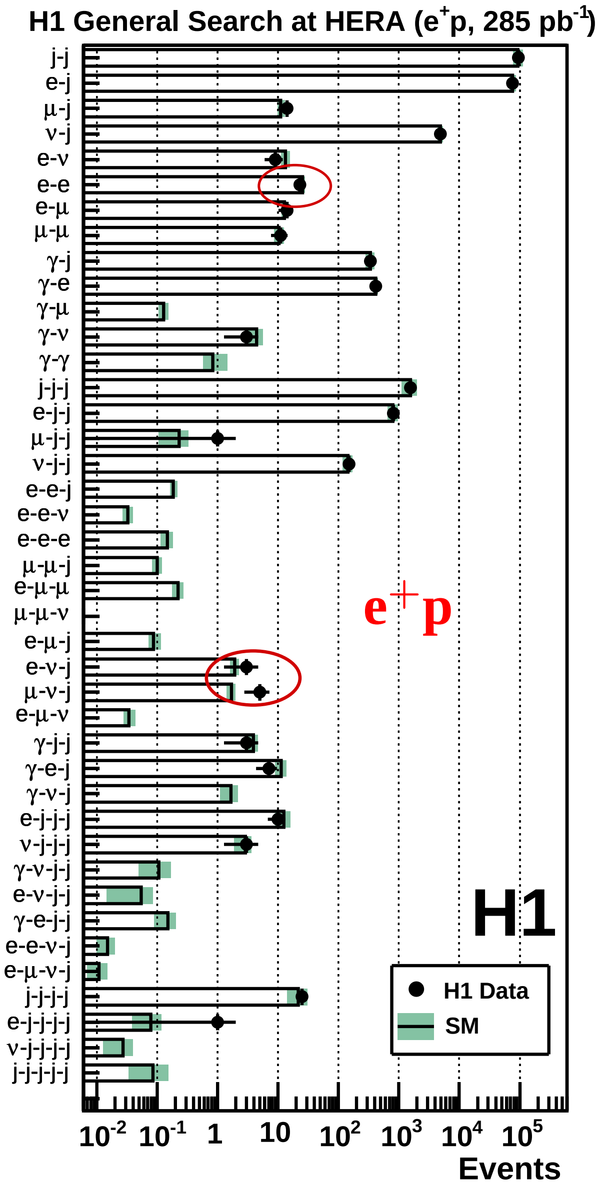
2011: Final status





Model independent search for New Phenomena

- Identify isolated objects:
  e, μ, γ, j, ν
- Select events, having at least two objects with high $P_T > 20$GeV
- 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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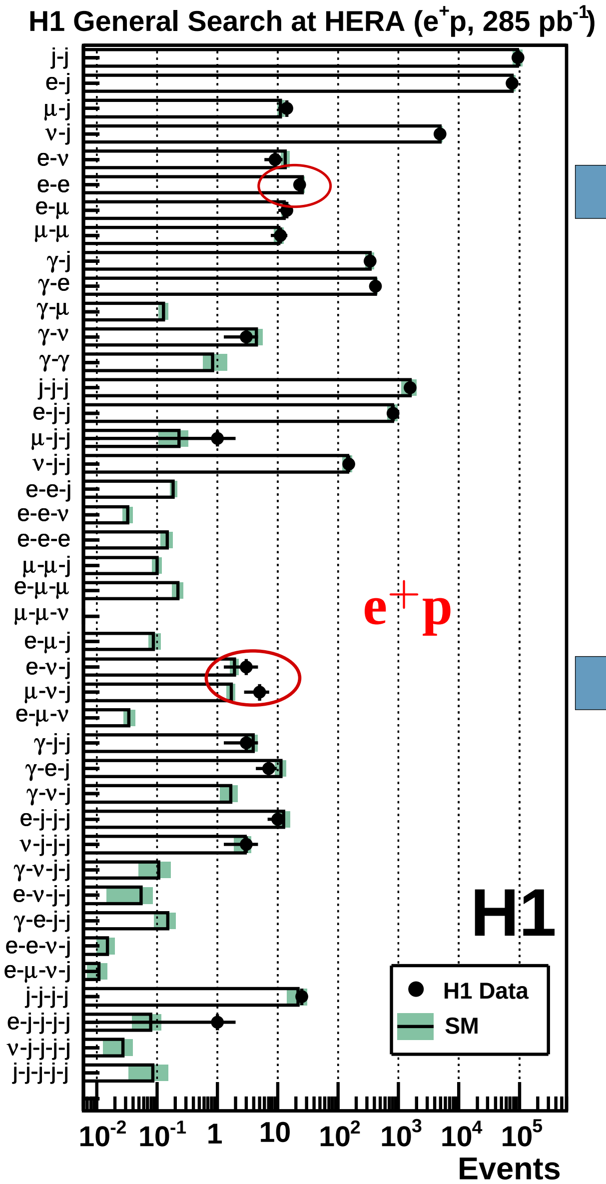
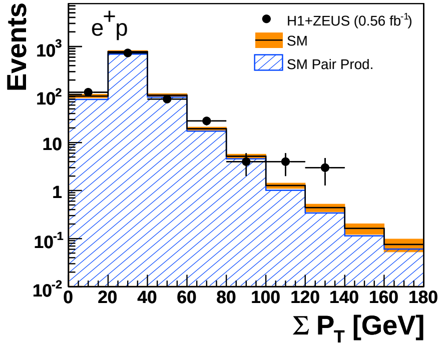
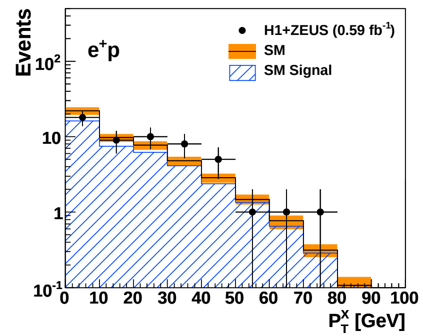


H1+ZEUS, 0.59 fb^{-1}



2.6σ



1.9σ

Largest observed deviations from the SM at HERA

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

HERA at Energy Frontier:

Standard Model is still in excellent shape!

HERA as Super–microscope

DIS: Cross sections and Structure Functions

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

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

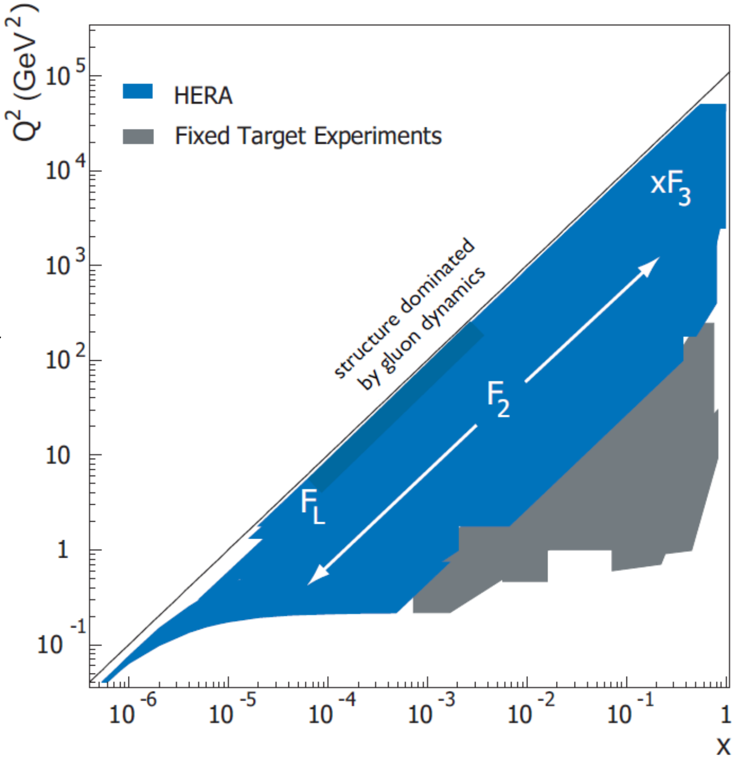
$$Y_{\pm} = 1 \pm (1-y)^2$$

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

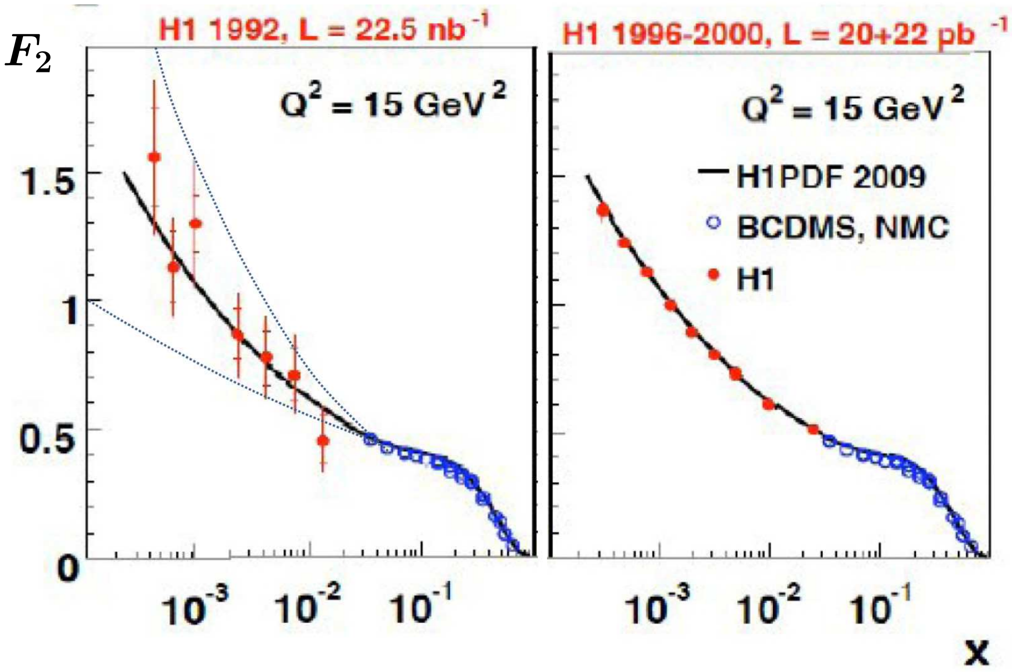
$$x\tilde{F}_3 \propto \sum (xq_i - x\bar{q}_i)$$ Only sensitive at high $Q^2 \sim M_Z^2$

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

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

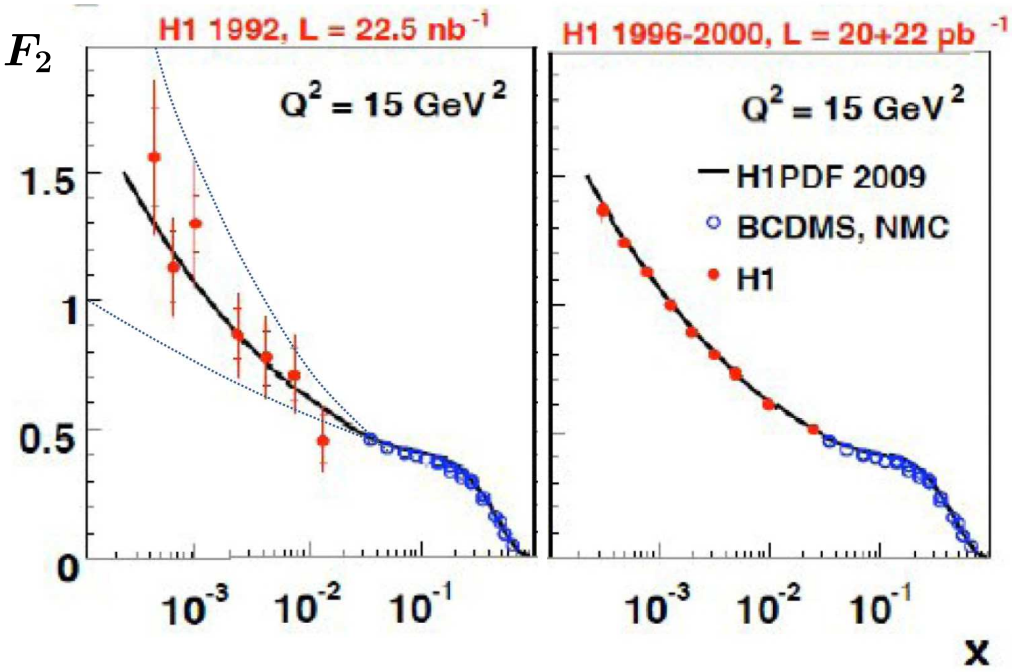


Structure of the proton



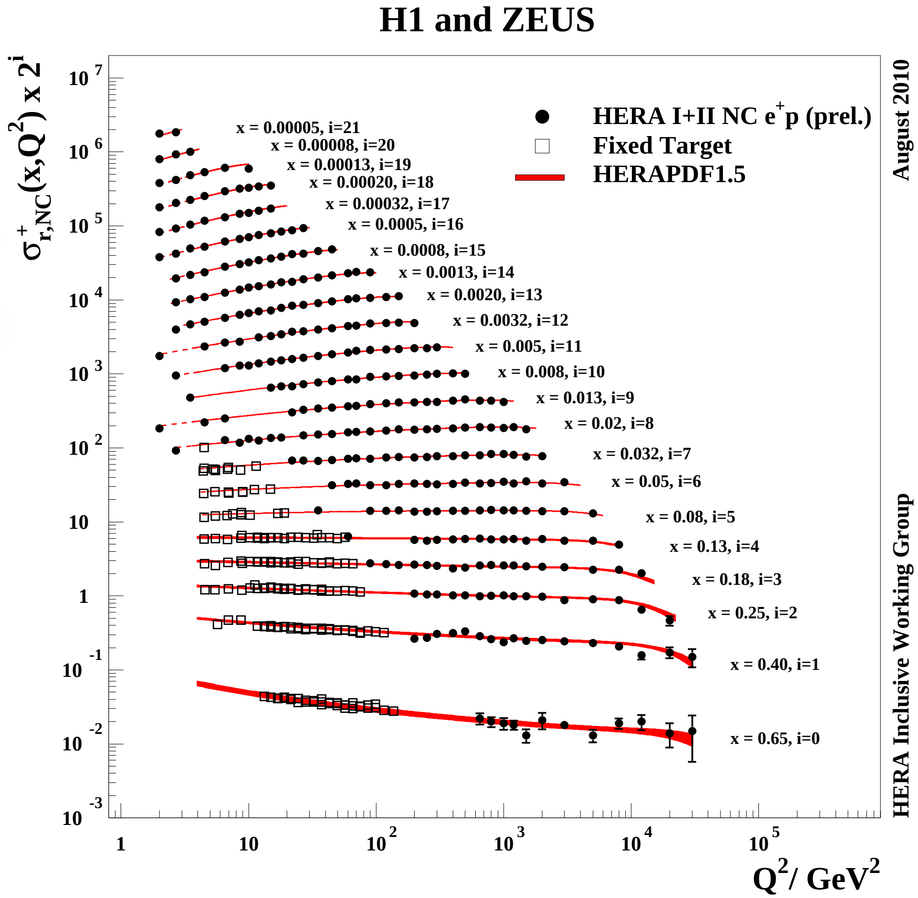
dotted lines show the spread in predictions
prior to HERA startup (1992)

Structure of the proton



dotted lines show the spread in predictions prior to HERA startup (1992)

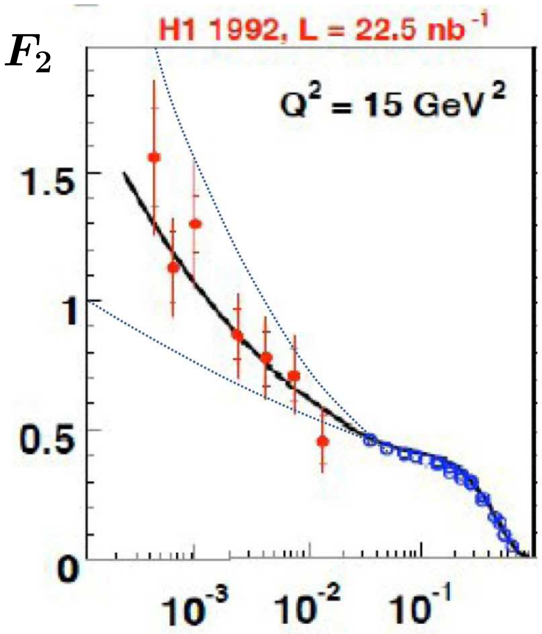
Combined HERA e^+p data
($\mathcal{L} = 2 \times 250$ pb^{-1})

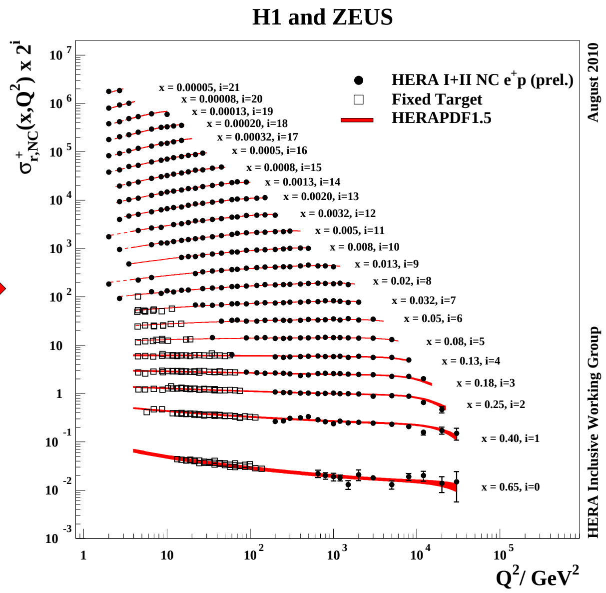


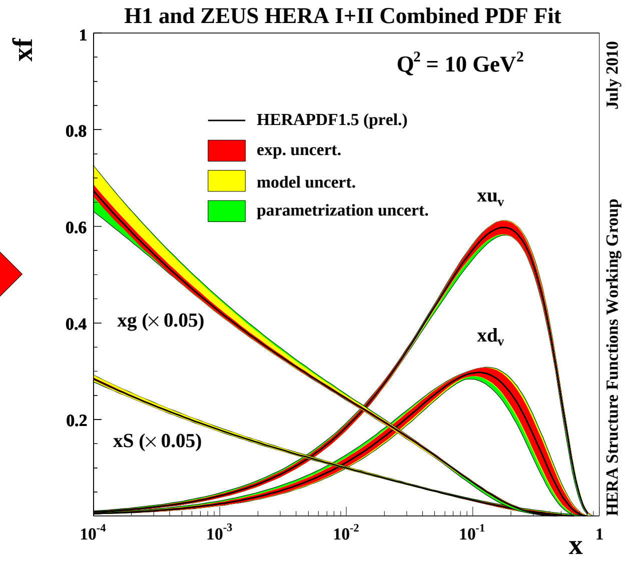
➡ *Bjorken scaling* regime at $x > 0.05$

➡ Large *scaling violation* at $x < 0.01$

Structure of the proton



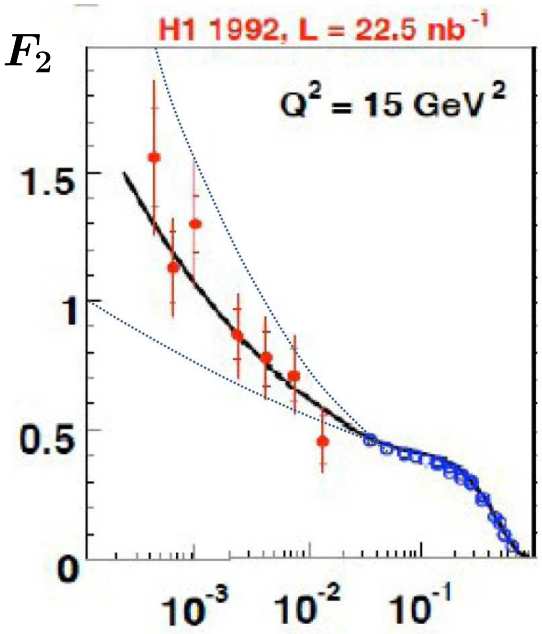


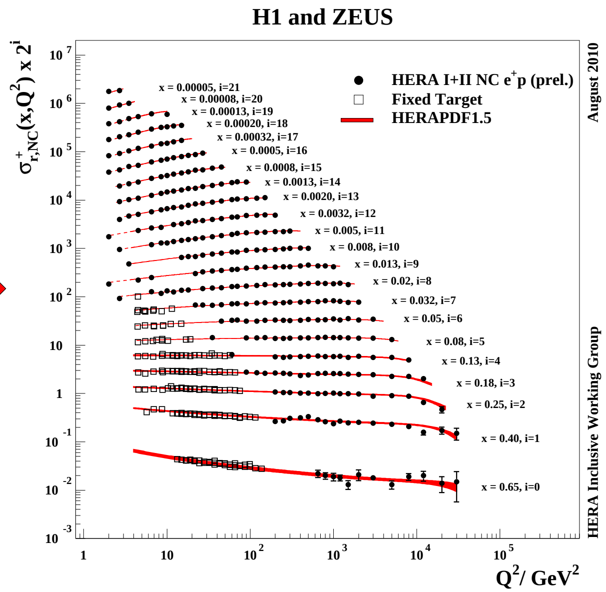


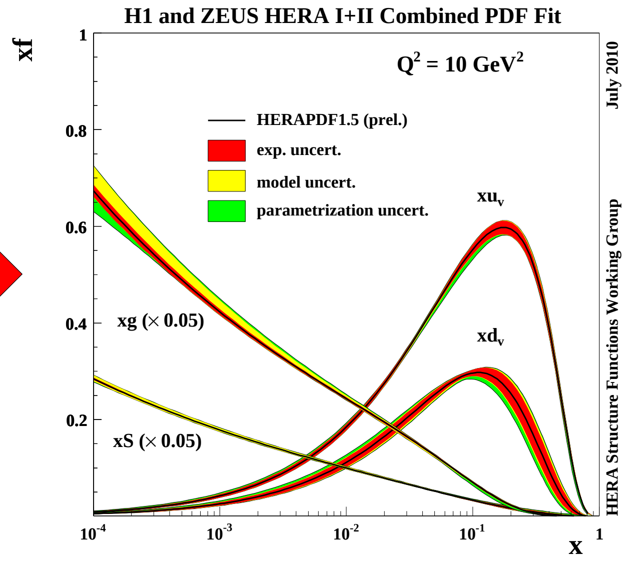
- Precision of $(1-2)\%$ in the bulk region
- Perfect desciption of the data by NLO QCD over many orders in x and Q^2
- using QCD factorisation: $\sigma_{DIS} \sim \sum_a C_a \otimes f_{a/p}$ universal PDFs, $f_{a/p}$, determined with error bands

⇒ Any substructures at 10^{-18}m ?

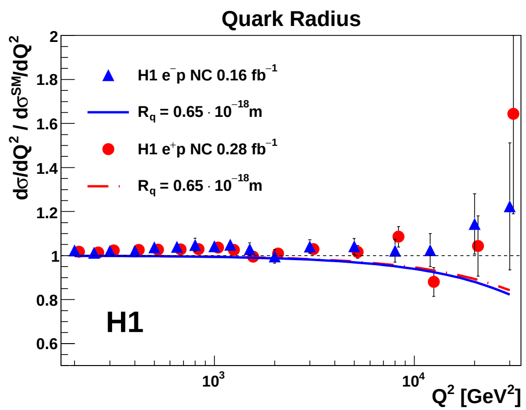
Structure of the proton







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



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Any substructures at 10^{-18}m ?

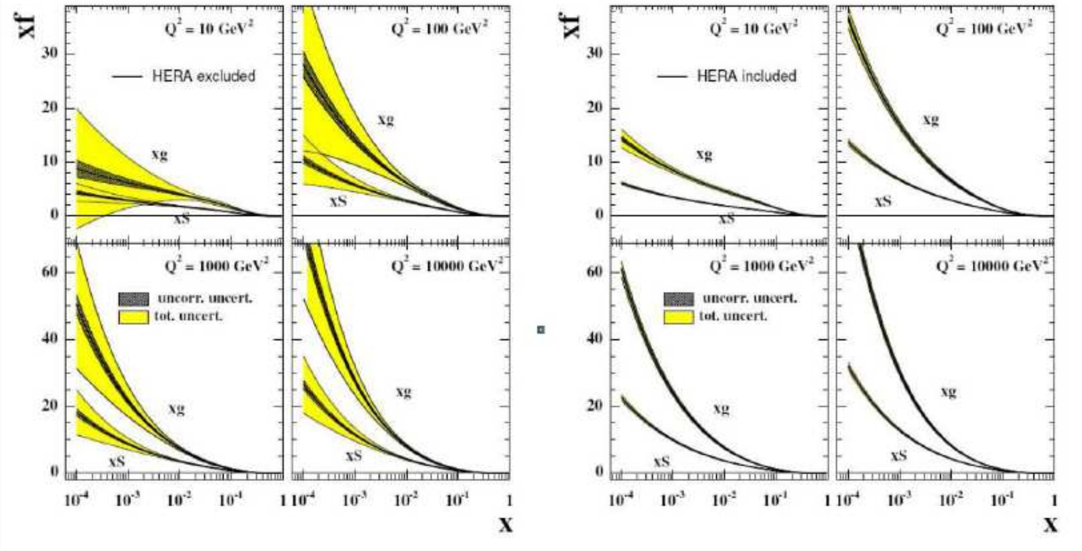
No. Quarks are still pointlike

Upper limit: $R_q < 0.65 \cdot 10^{-3}$ **fm**

HERAPDF for LHC

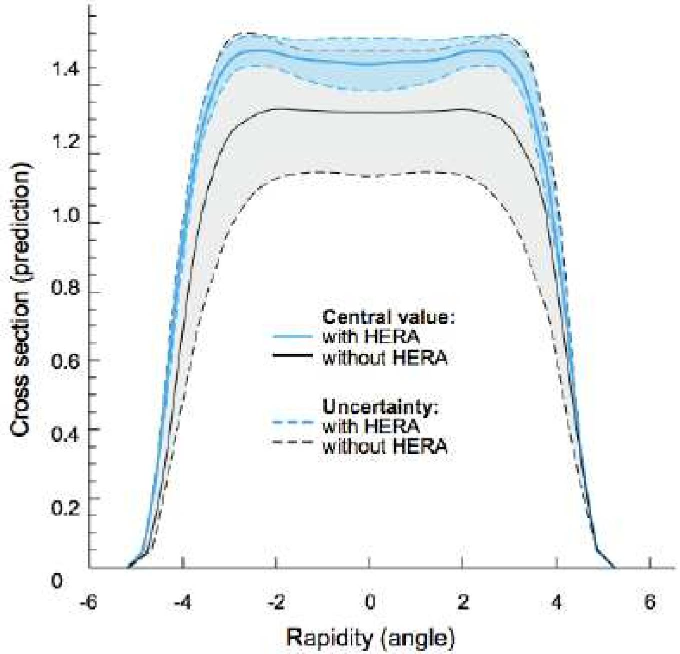
Knowledge of gluon without HERA data.

Knowledge of gluon with HERA

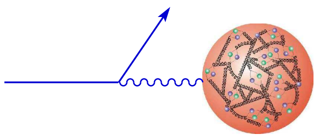


Cooper-Sarkar et al. : HERA-LHC workshop 2009

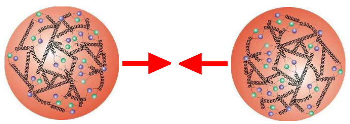
W^+ cross-section



HERA

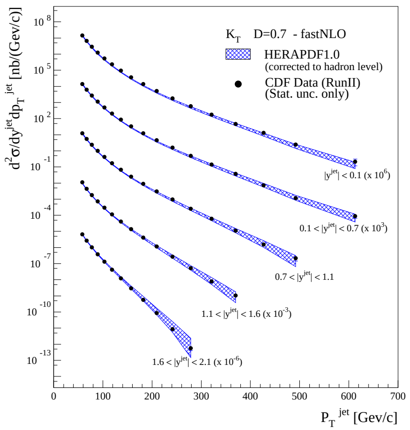


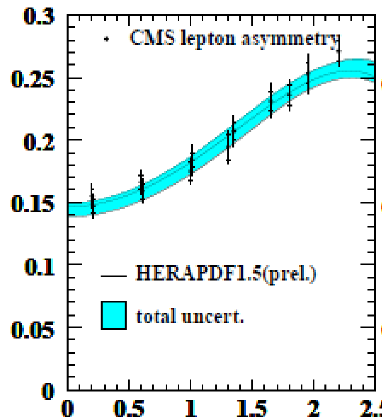
LHC

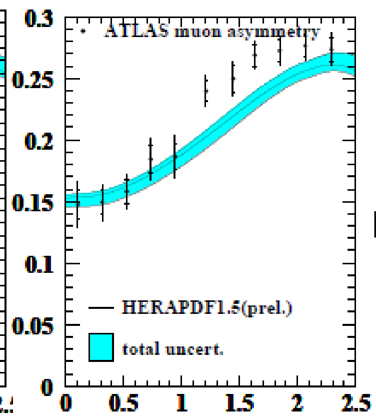


CDF Data (Run II)

Tevatron Jet Cross Sections







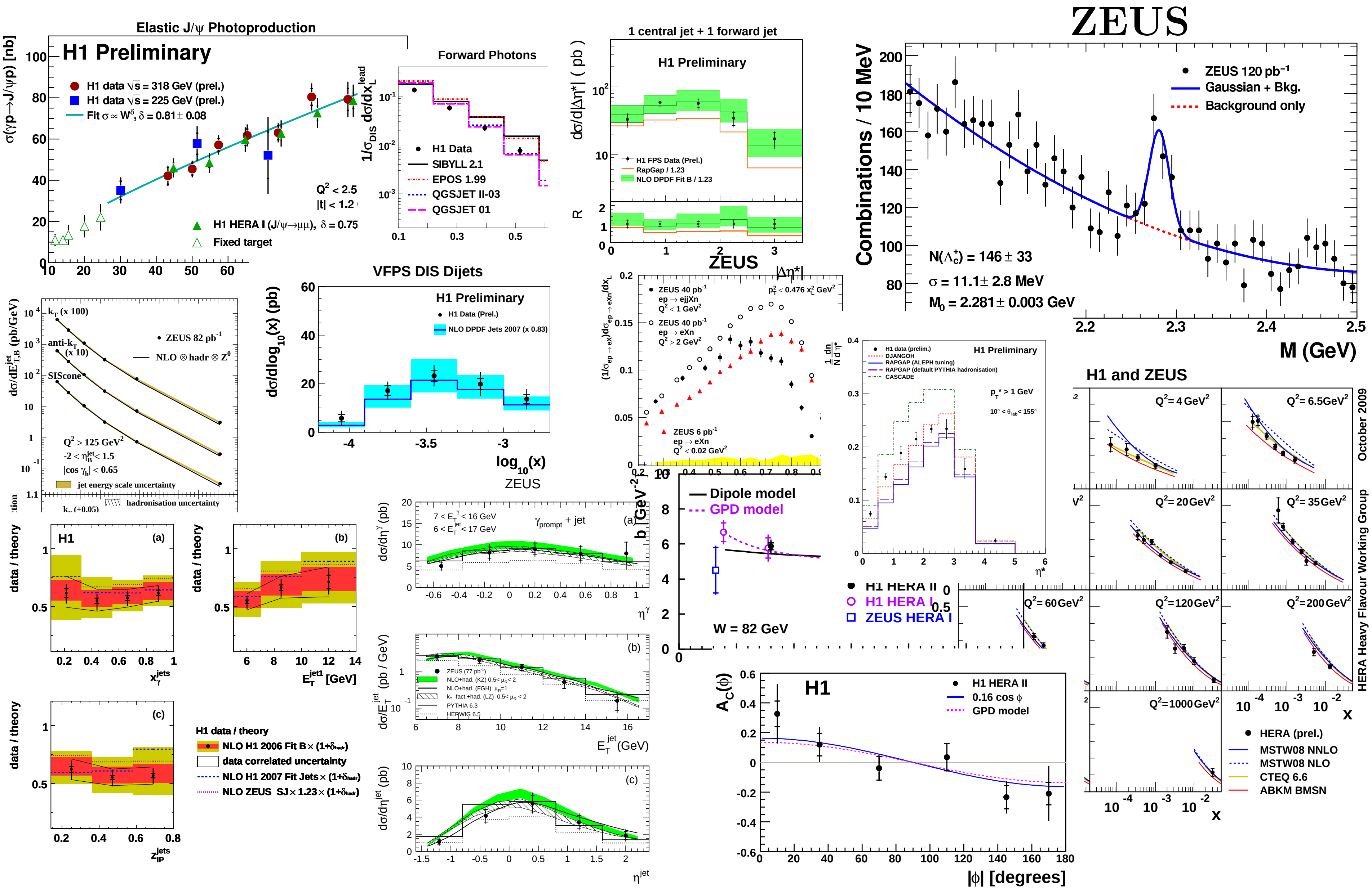
2011 LHC Data

HERA as a Super-microscope:

- best ever measurement of the proton structure down to $\mathbf{0.001}$ fm ($\boldsymbol{F_2}$, $\boldsymbol{F_L}$, $\boldsymbol{xF_3}$)
- lots of glue at low $\boldsymbol{x}$ $\Rightarrow$ in high enery limit QCD processes are gluon-driven

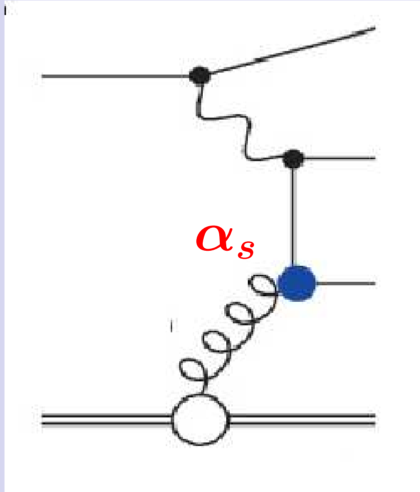
HERA as QCD factory

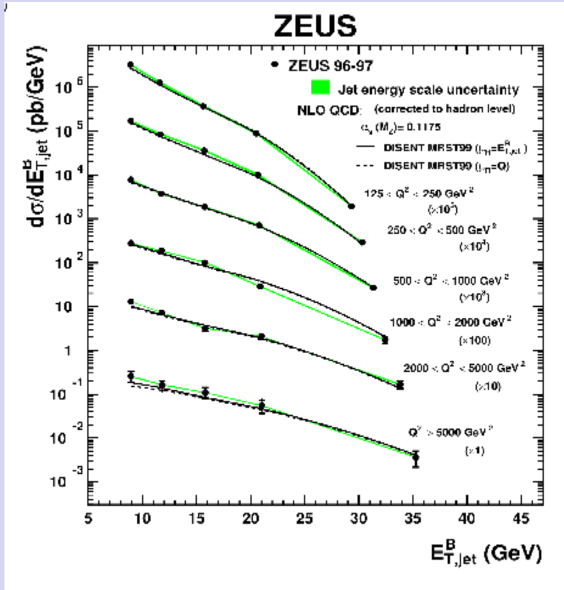
HERA as QCD factory

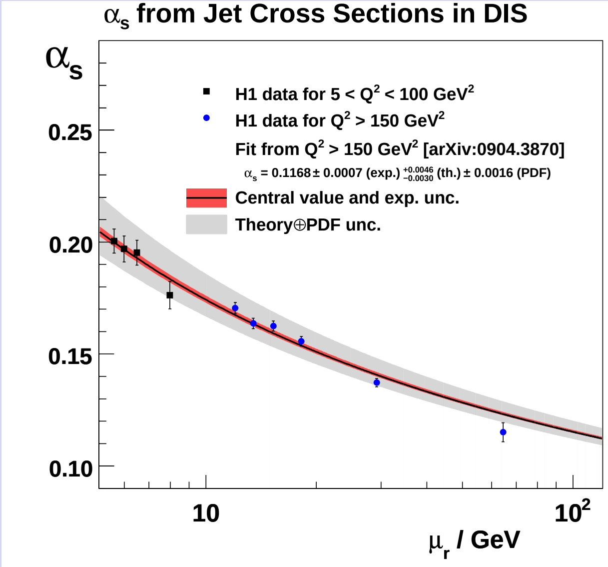


Jets at HERA

Precision QCD



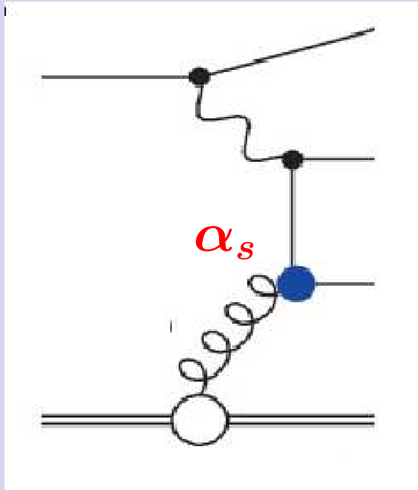


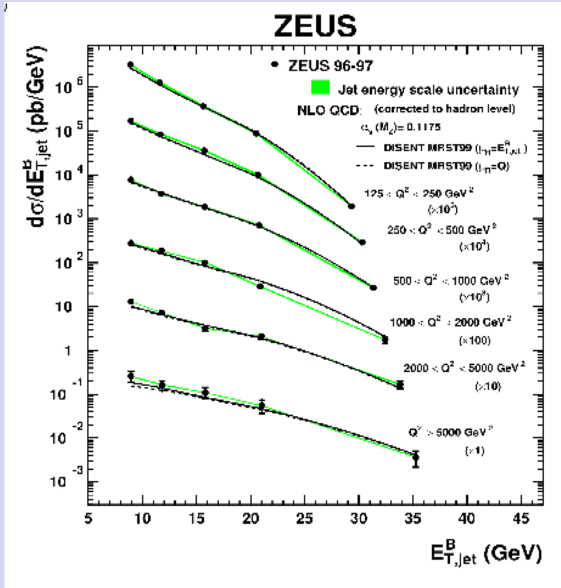


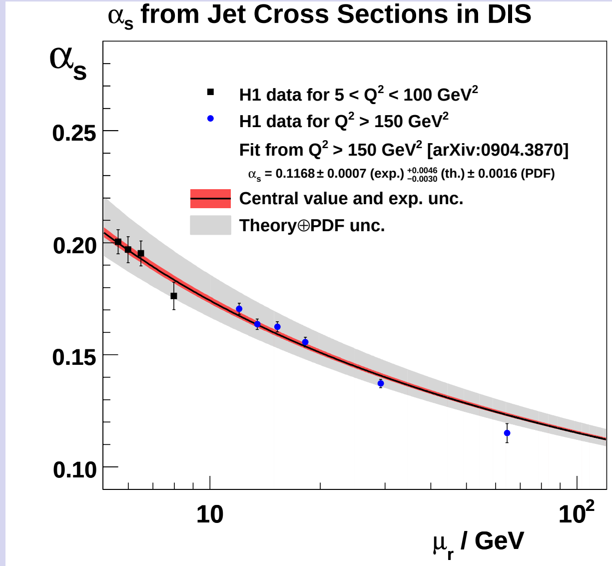
Running α_s in a single experiment!

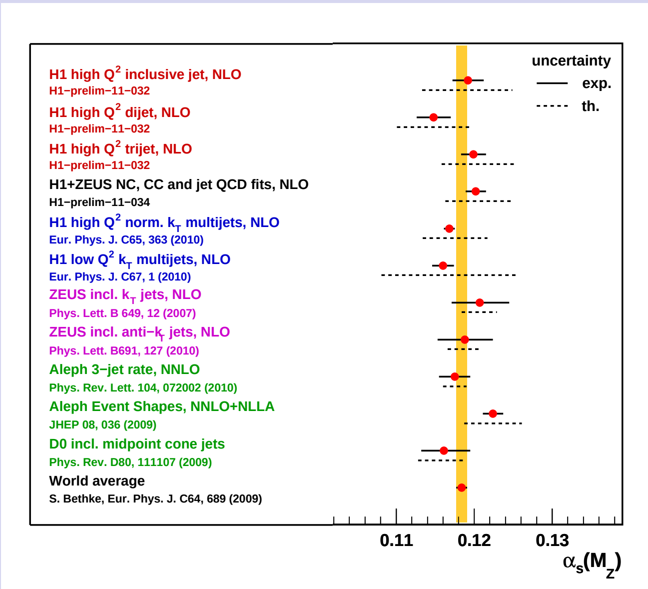
Jets at HERA

Precision QCD









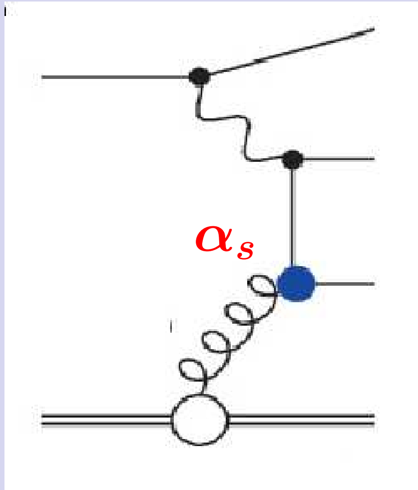
Running α_s in a single experiment!

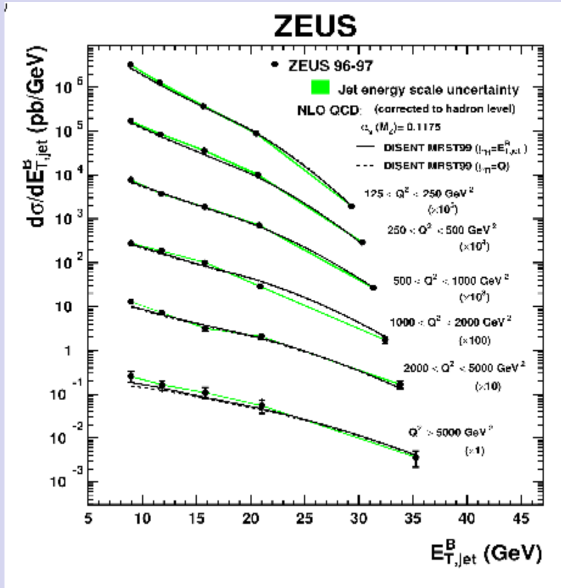
HERA results are comparable (and competetive) with the world average

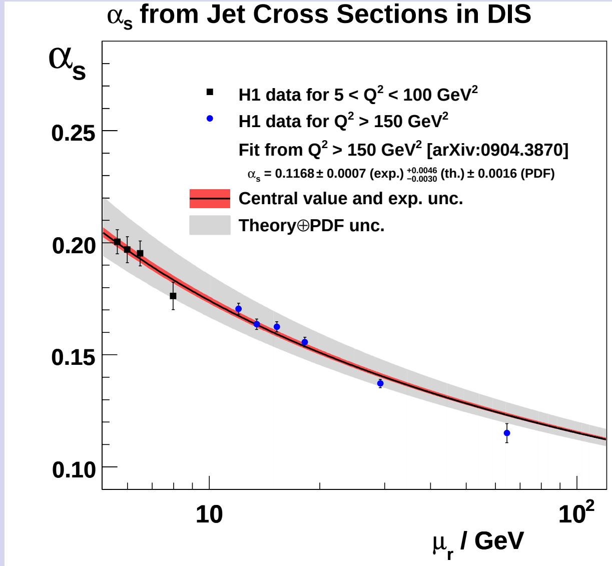
Errors are dominated by theoretical uncertainties (calculations are lacking HO (NNLO) terms)

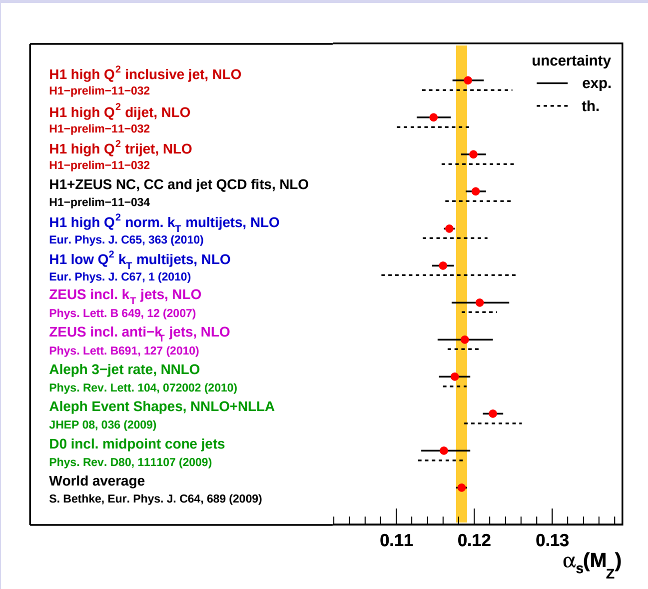
Jets at HERA

Precision QCD



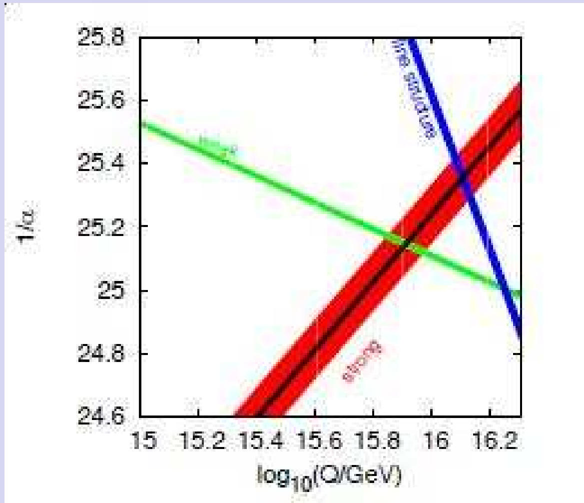






?

Grand Unification?

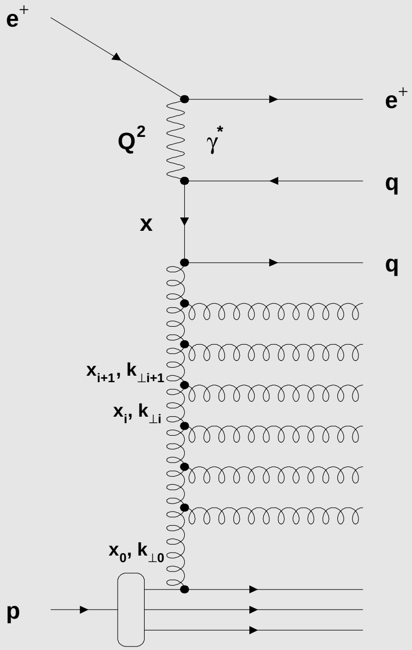


Precision does matter!

QCD at low x

Lots of glue in the proton ⇒ 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

⇒ approximations needed



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

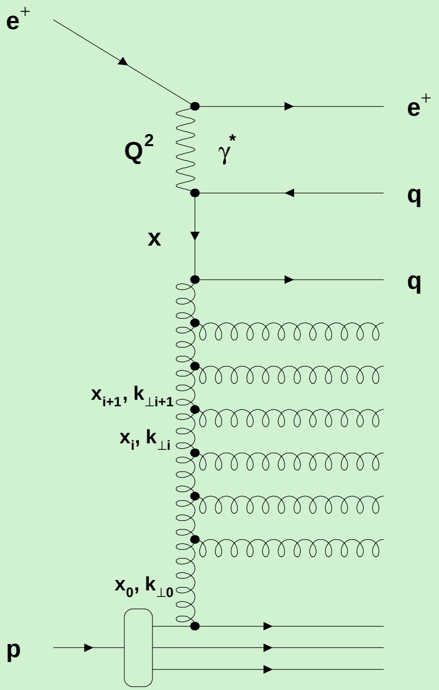
BFKL: resums $\ln(1/x)^n$ terms
no k_T ordering in partonic cascade ⇒ more hard gluons are radiated far from the hard interaction vertex

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

- 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?

⇒ Look at (multi)jet final states at low x in different configurations

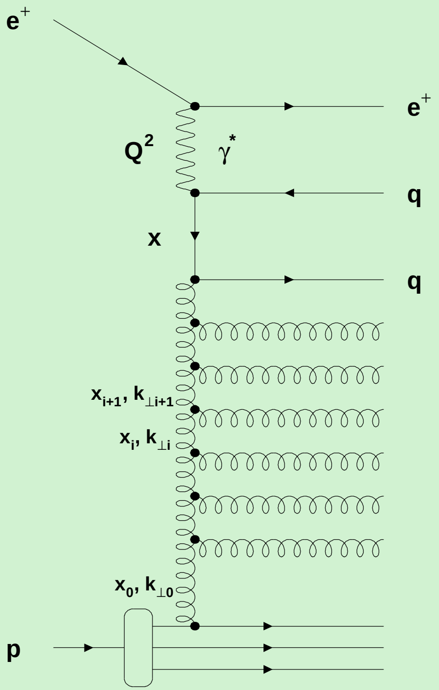
Jets at HERA: New dynamics?

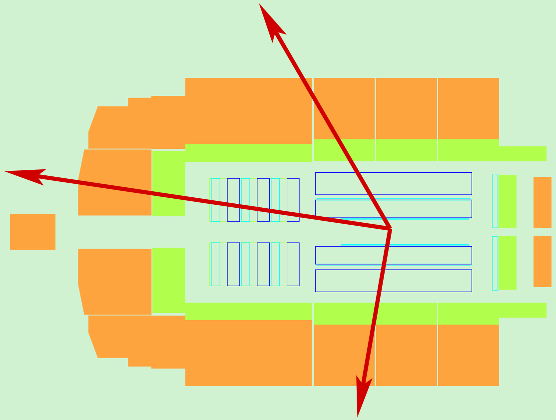


look at different topologies

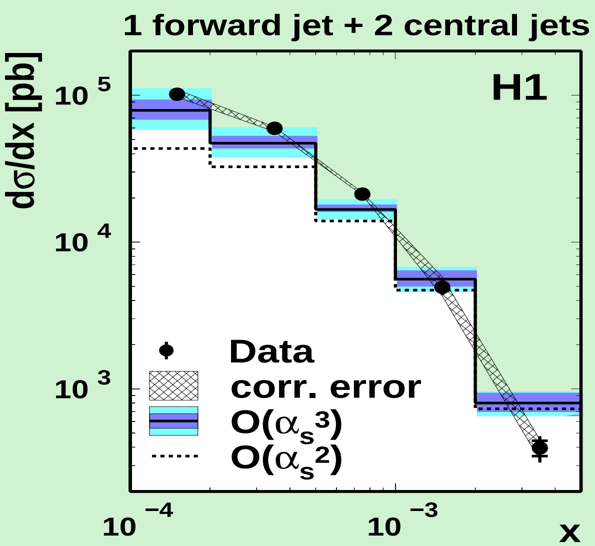
especially with forward jets

Jets at HERA: New dynamics?





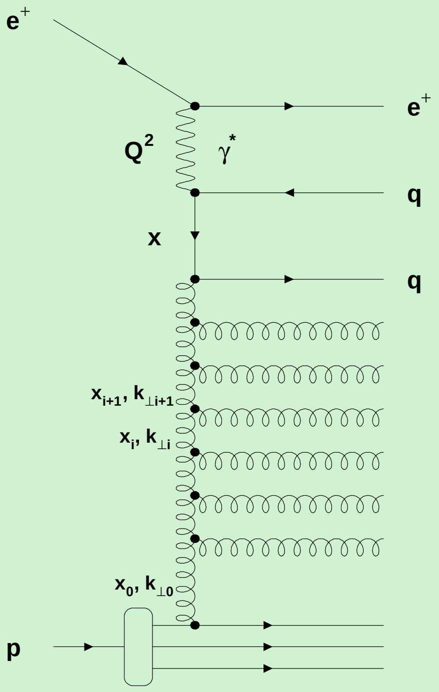
NLO DGLAP is OK

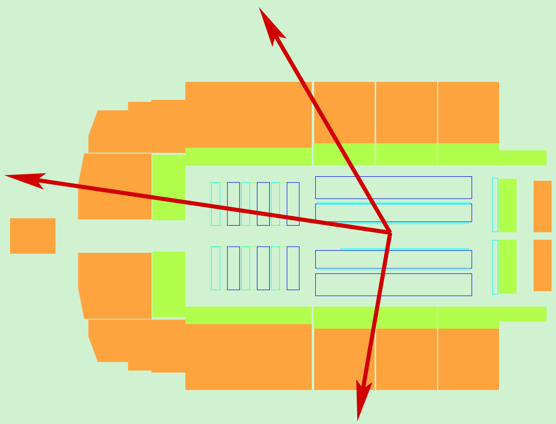


look at different topologies

especially with forward jets

Jets at HERA: New dynamics?





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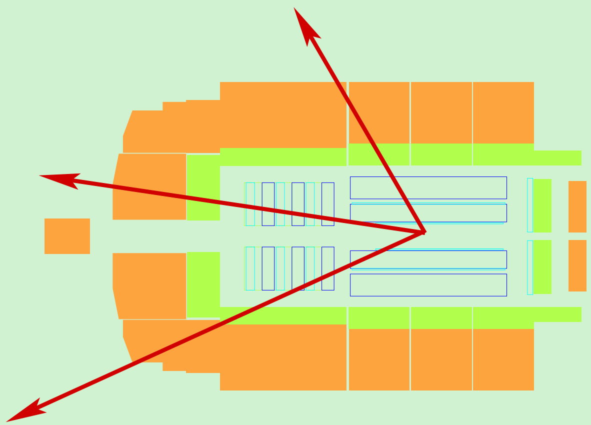
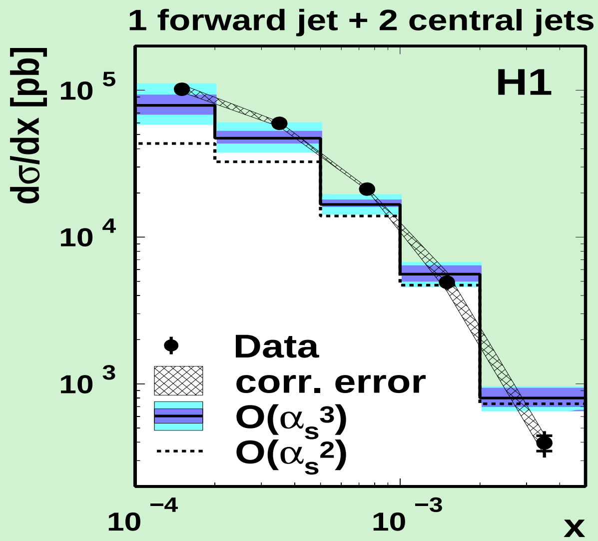
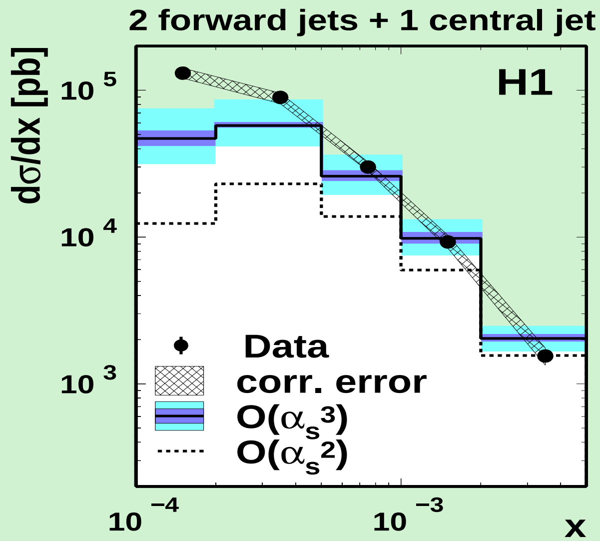


NLO DGLAP fails at low x

look at different topologies

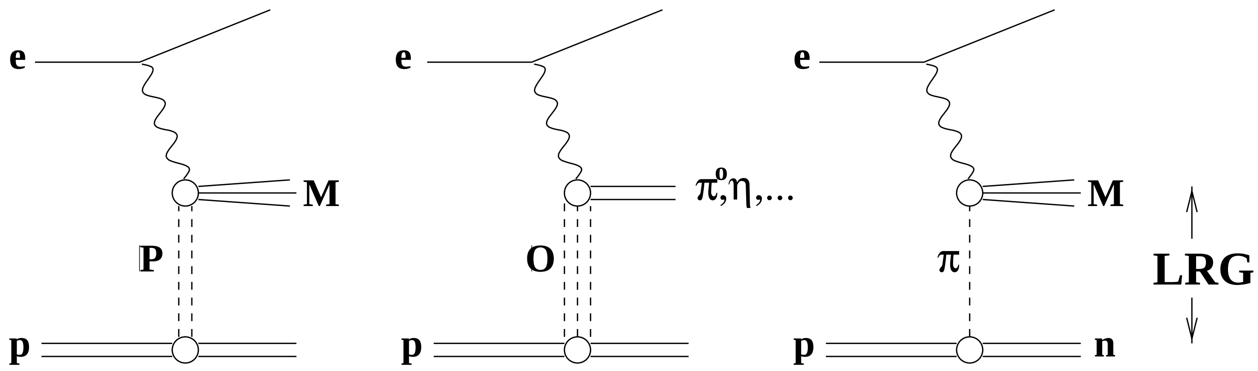
especially with forward jets



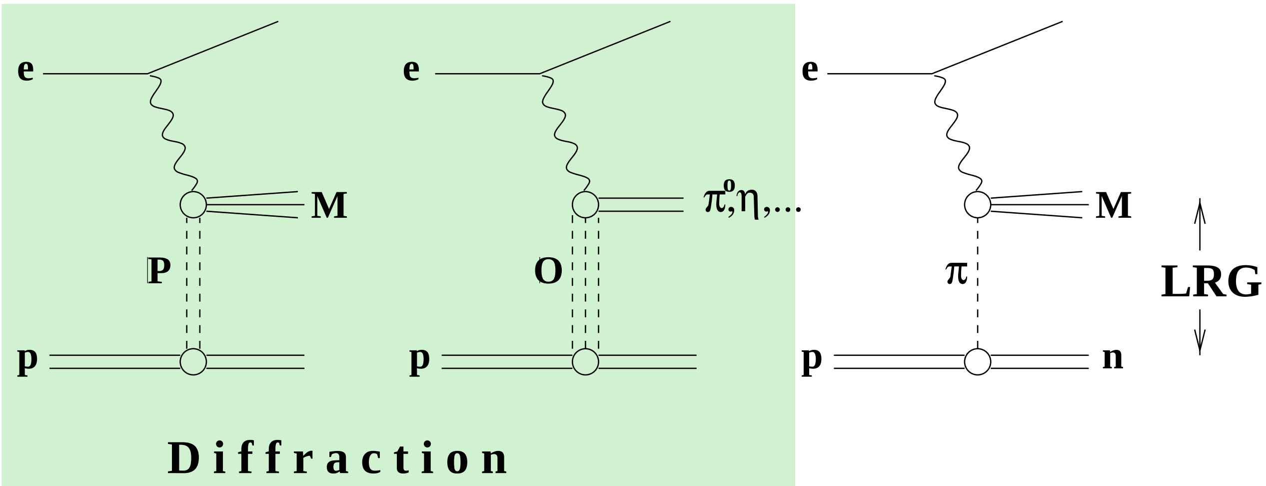


⇒ NLO DGLAP insufficient at low x $\Rightarrow$ **Room for non-DGLAP dynamics!**

Diffraction



Diffraction

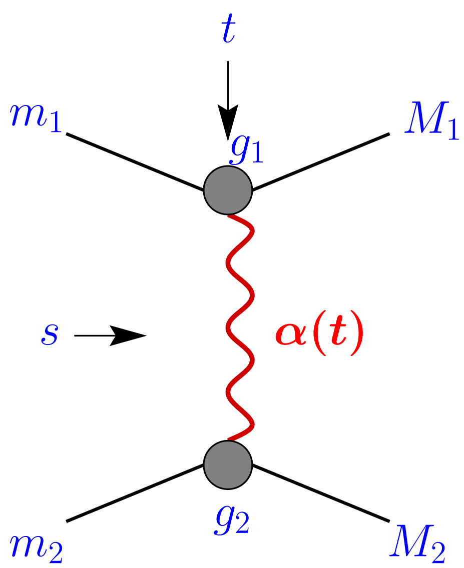


Diffraction in HEP =

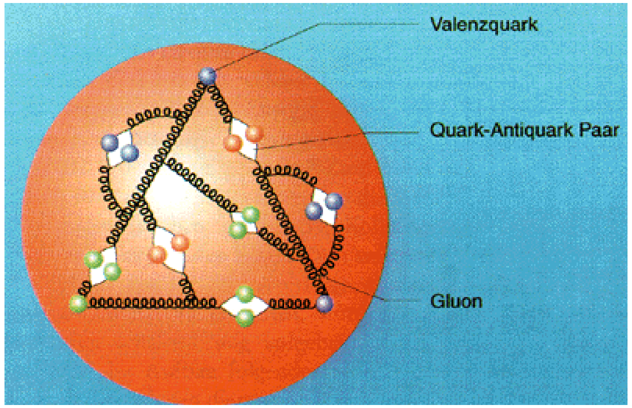
Colorless exchange carrying vacuum quantum numbers

Two approaches to Strong Interactions

1. Regge Pole Model ⇒ RFT



2. Quark-Parton Model ⇒ QCD



$$A(s,t) =$$

$$g_1(m_1, M_1, t) g_2(m_2, M_2, t) \frac{s^{\alpha(t)} \pm (-s)^{\alpha(t)}}{\sin(\pi\alpha(t))}$$

hadronic language

$$\sigma_{ab} =$$

$$\int f_{i/a}(x_i, \mu^2) \cdot f_{j/b}(x_j, \mu^2) \cdot \hat{\sigma}_{ij}(x_i, x_j, \mu^2)$$

sub-hadronic language

Ultimate goal: derive (1) from (2)

RFT: soft hh scattering vs QCD: deep inelastic ep scattering

RFT: soft hh scattering

- Hadronic degrees of freedom
- Validity: large $s \gg t$
- $I\!P$ dominates: $\alpha_{I\!P}(0) > \alpha_{I\!R}(0)$
  $\longrightarrow \sigma_{\rm tot} \propto s^{\alpha_{I\!P}(0)-1}$
- Unitarity corrections unavoidable
  ($\sigma_{\rm tot} \leq \ln^2(s/s_0)$ at $s \to \infty$)
- When? $s_{sat} = ?$
- First to be seen in diffraction: $\sigma_D \propto s^{2(\alpha-1)}$

QCD: deep inelastic ep scattering

- Partonic degrees of freedom
- Low x: $W^2 \gg Q^2, t$ $(Q^2/W^2 \simeq x \ll 1)$
- gluons dominate: $xg(x) \gg xq_{val}(x)$
  $F_2(x,Q^2) \propto xg(x) \sim x^{-\lambda}$
- Saturation of the $xg(x)$
  (non-linear effects, shadowing, ...)
- $x_{sat}(Q_{sat}) = ?$
- First to be seen in diffraction: $\sigma_D \propto |xg(x)|^2$

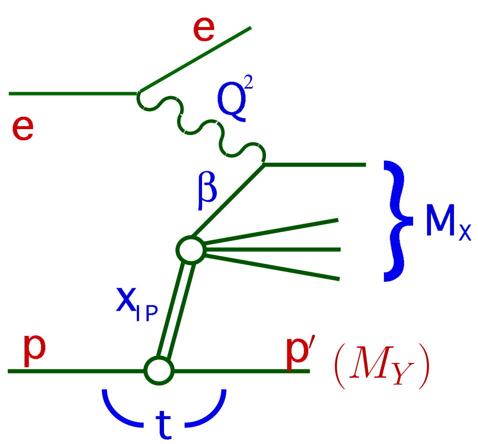
$\Rightarrow$ Diffraction $\equiv$ Physics of the Pomeron,
the essence of strong interactions

$\Rightarrow$ Diffraction $\equiv$ Gluodynamics,
the essence of QCD

(in high energy limit)

Diffraction at HERA

- Fundamental aim: understand high energy limit of QCD (gluodynamics; CGC ?)
- Novelty: for the first time probe partonic structure of diffractive exchange
- Practical motivations: study factorisation properties of diffraction; try to transport to hh scattering (e.g. predict diffractive Higgs production at LHC)



$$x_{I\!P} = \xi = \frac{Q^2+M_X^2}{Q^2+W^2}$$

(momentum fraction of colour singlet exchange)

$$\beta = \frac{Q^2}{Q^2+M_X^2} = x_{q/I\!P} = \frac{x}{x_{I\!P}}$$

(fraction of exchange momentum, coupling to γ^*)

$$t = (p - p')^2$$

(4-momentum transfer squared)

Experimental methods:

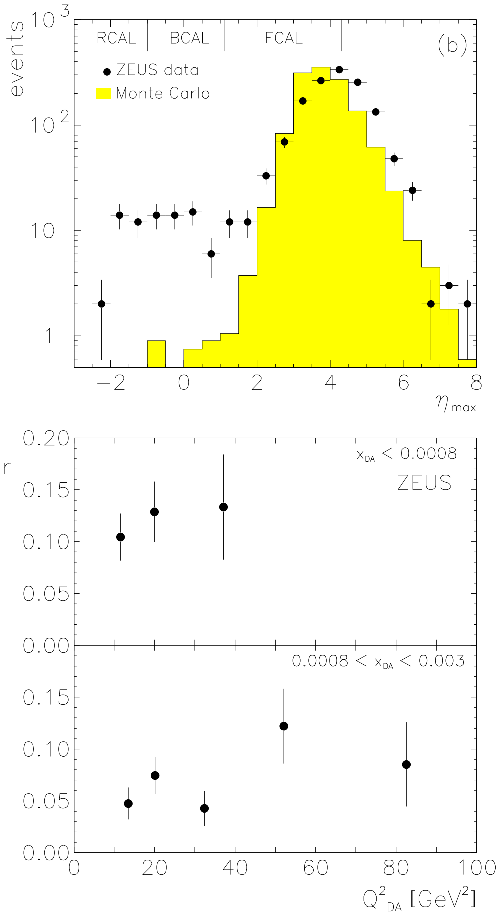
1) selecting LRG events

2) detecting p in Roman Pots

FPS, VFPS

Inclusive Diffraction in DIS

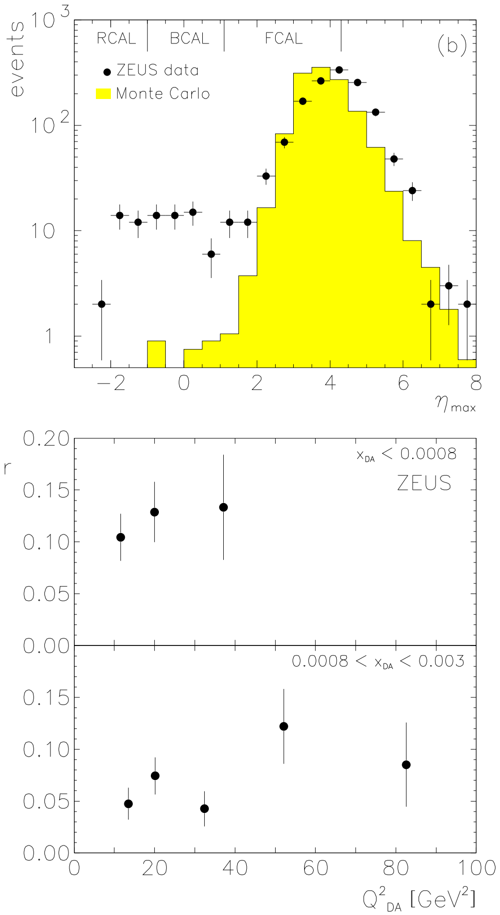
ZEUS-1993



First observation
of diffraction in DIS
1992 data, 24.7 nb^{-1}

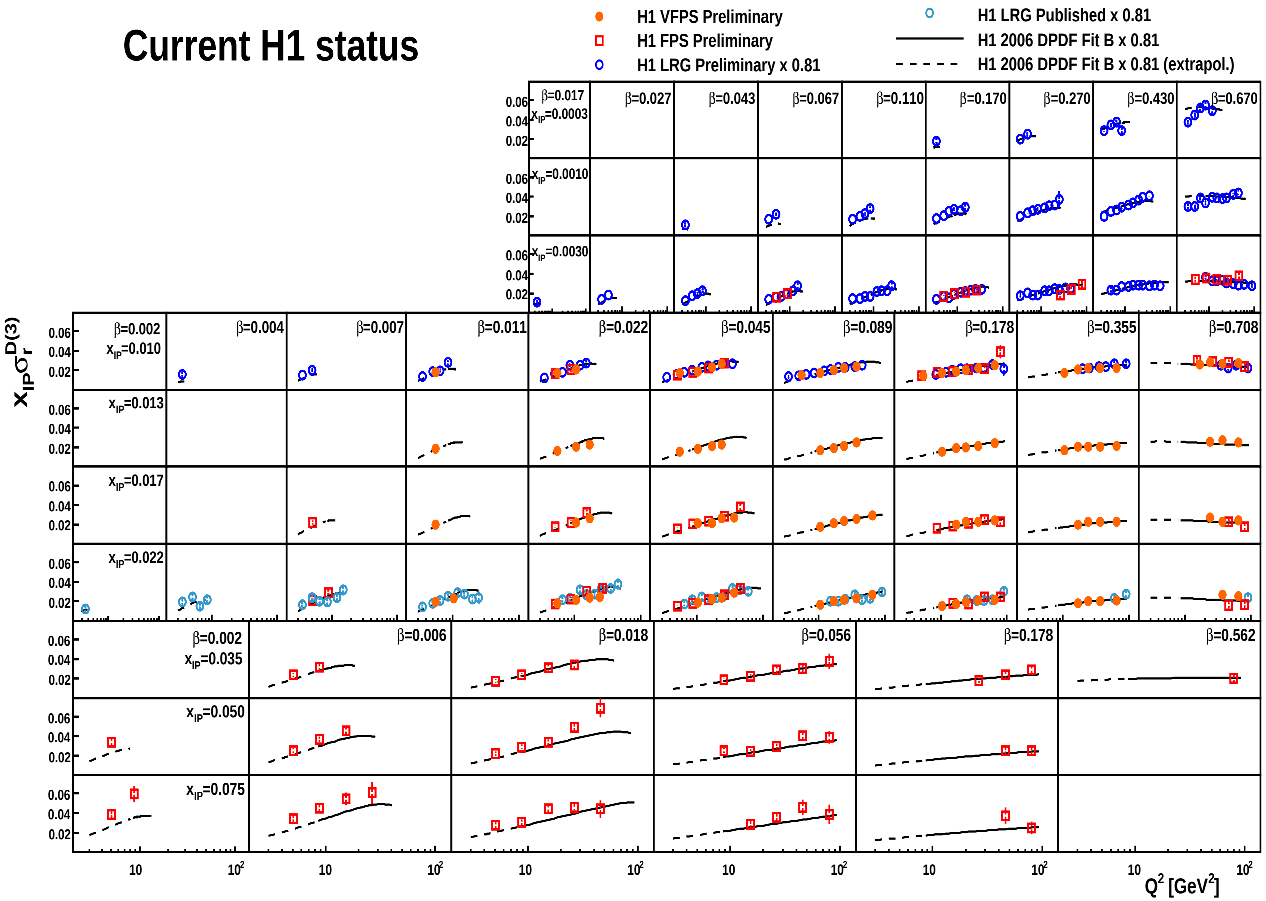
Inclusive Diffraction in DIS

ZEUS-1993



First observation
of diffraction in DIS
1992 data, 24.7 nb^{-1}

Current H1 status



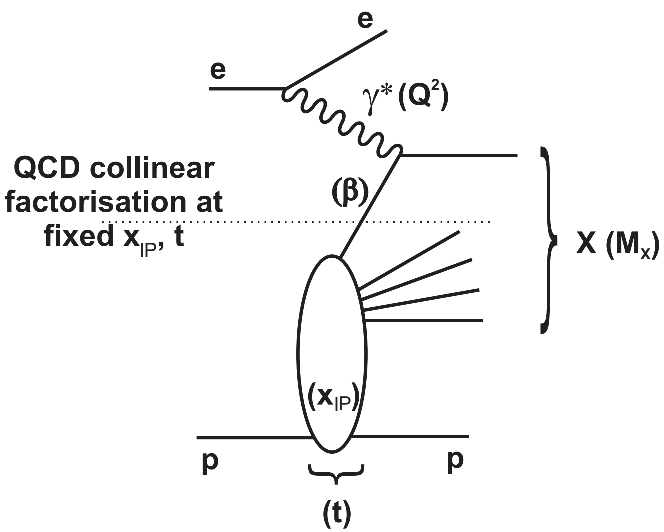
LRG

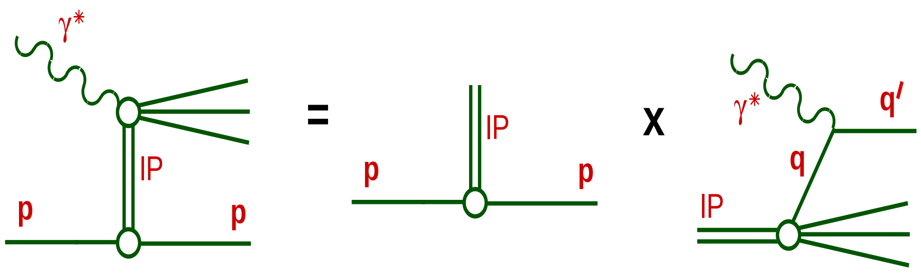
VFPS

FPS

- Compelling confirmation of the NLO QCD picture of diffraction over a wide kinematic range. Clear candidate for the textbook!
- Diffractive PDFs are determined from these data. Are they universal?

Factorisation properties in diffraction





QCD versus Regge factorisation

QCD factorisation

(rigorously proven for DDIS by Collins et al.):

$$\sigma_r^{D(4)} \propto \sum_i \hat{\sigma}^{\gamma^* i}(x, Q^2) \otimes f_i^D(x, Q^2; x_{I\!P}, t)$$

- $\hat{\sigma}^{\gamma^* i}$ – hard scattering part, same as in inclusive DIS
- f_i^D – diffractive PDF's, valid at fixed $x_{I\!P}, t$ which obey (NLO) DGLAP

Regge factorisation

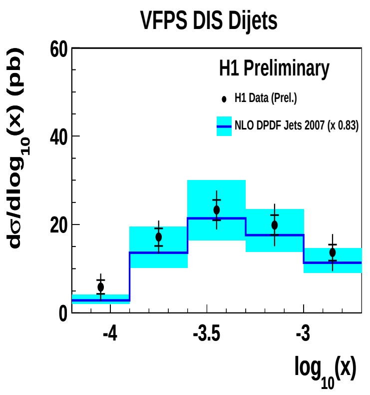
(conjecture, e.g. RPM by Ingelman,Schlein):

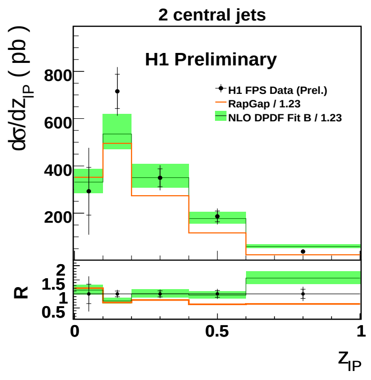
$$F_2^{D(4)}(x_{I\!P}, t, \beta, Q^2) = \Phi(x_{I\!P}, t) \cdot F_2^{I\!P}(\beta, Q^2)$$

- In this case shape of diffractive PDF's is independent of $x_{I\!P}, t$ while normalization is controlled by Regge flux $\Phi(x_{I\!P}, t)$

QCD Factorisation Tests in Diffraction at HERA

QCD Factorisation holds in DIS regime, e.g.:





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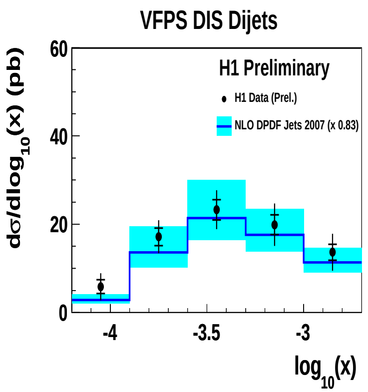
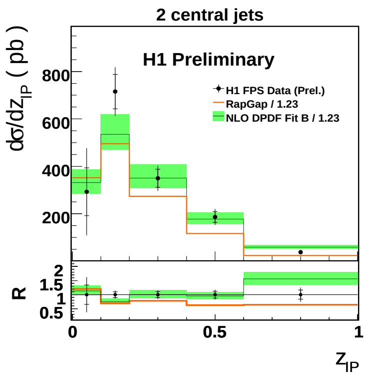
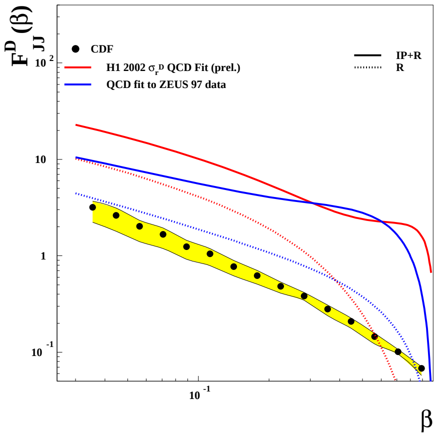
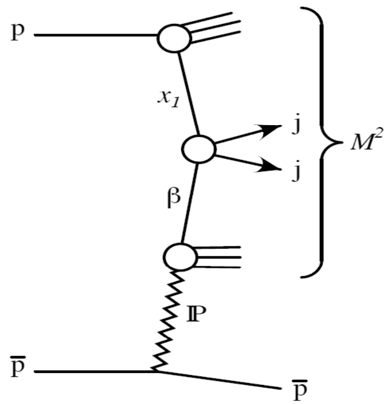




However, it breaks down at Tevatron ...

Tevatron vs HERA





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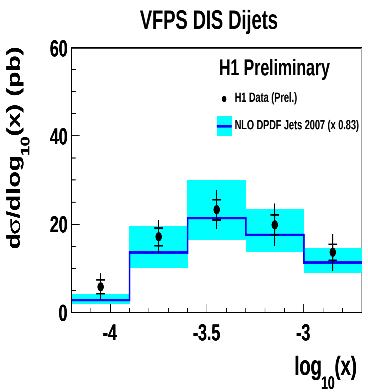

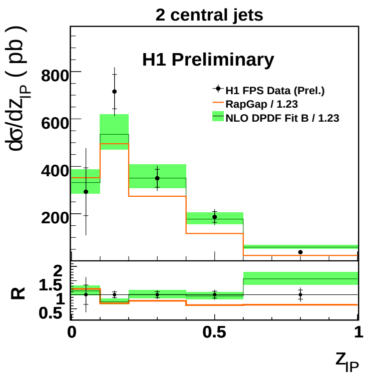

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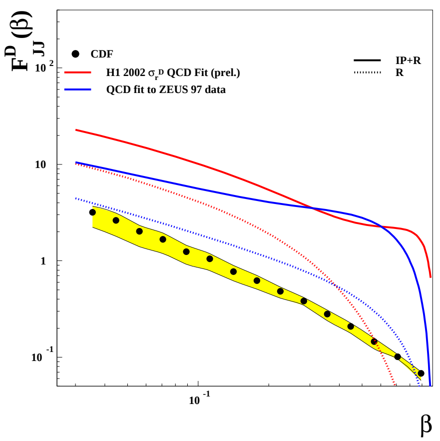
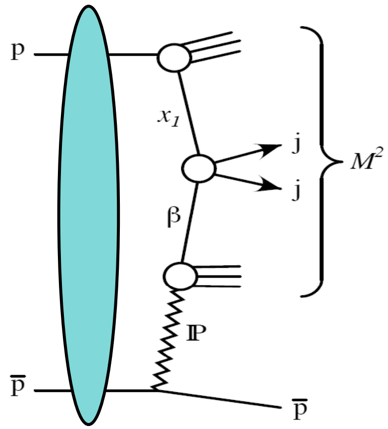
...due to soft remnant rescattering ($S \sim 0.15$)

Tevatron vs HERA





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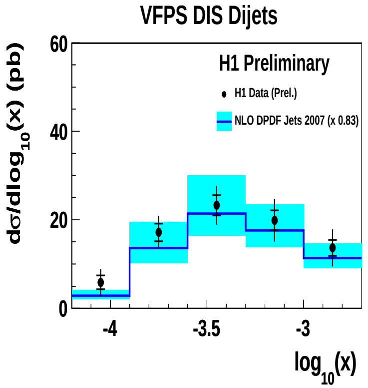

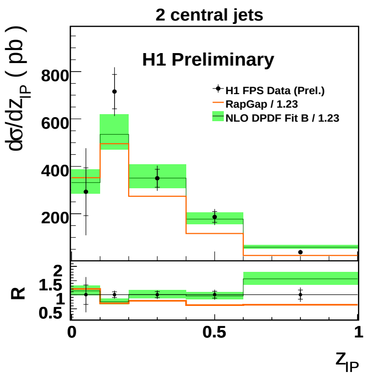

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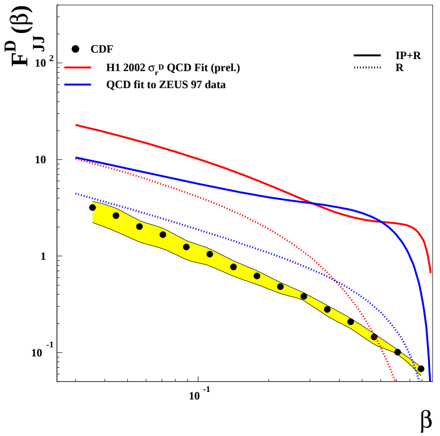
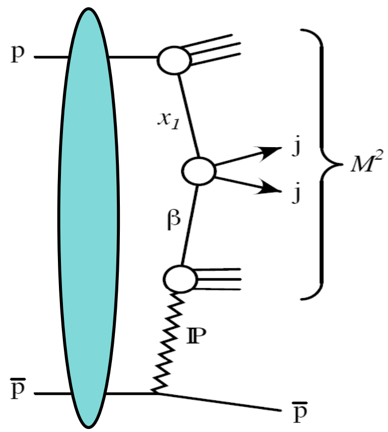
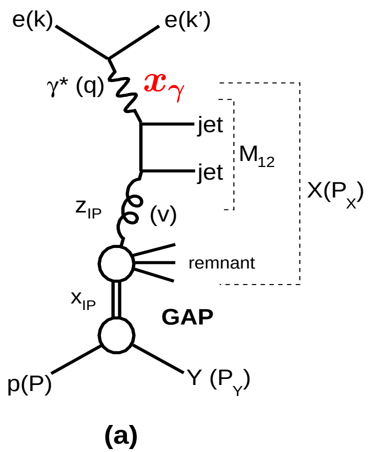
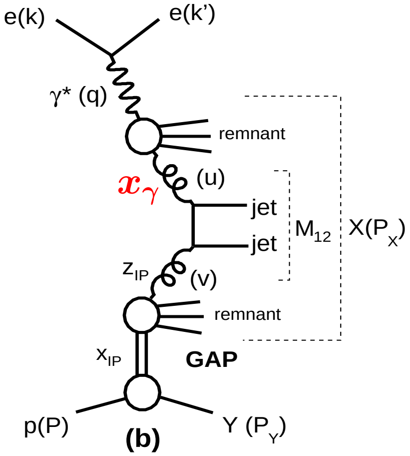




⇒ Test it in photoproduction:





direct, $x_\gamma = 1$ (DIS-like) resolved, $x_\gamma < 1$ (hadron-like)

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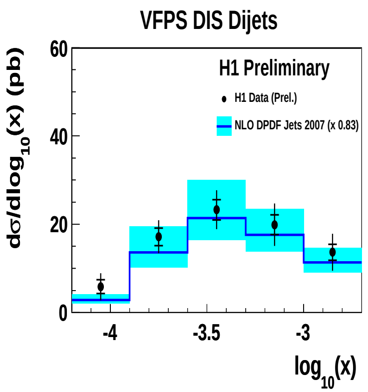
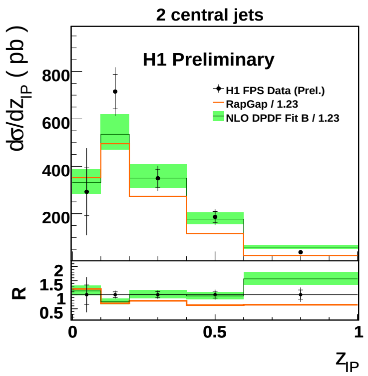
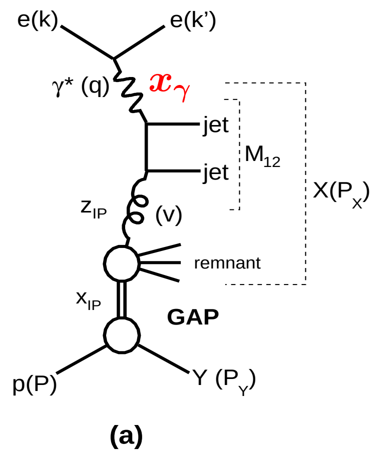
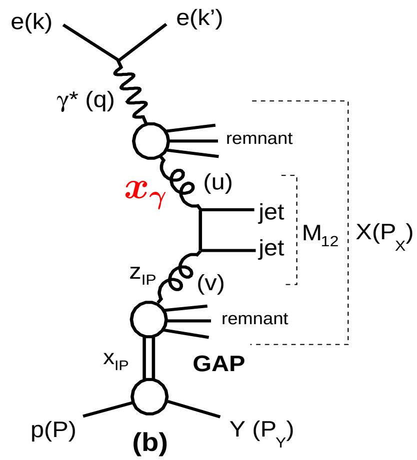




$\Rightarrow$ Test it in photoproduction:





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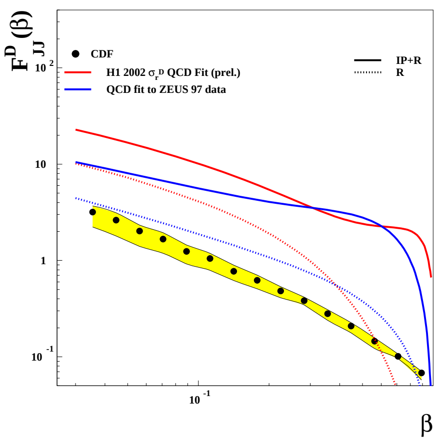
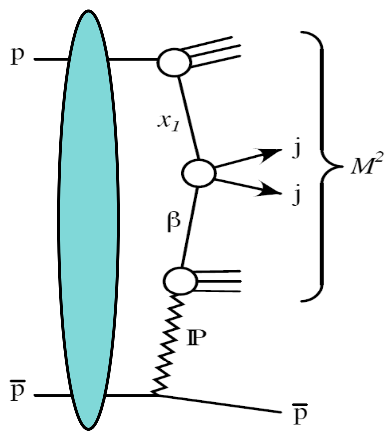
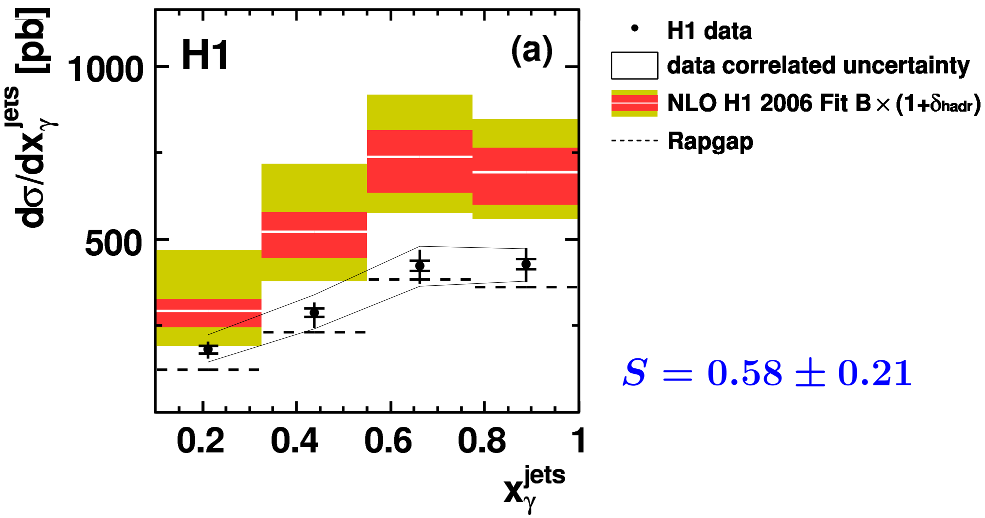






$S = 0.58 \pm 0.21$

- Global, x_γ-independent suppresion factor is observed – somewhat unexpected

$\Rightarrow$ Details of factorisation breaking mechanism in γp at HERA are not fully understood yet

Summary

- Standard Model survived $1\ \text{fb}^{-1}$ of **HERA** data and is still in a good shape. Next challenge is now coming 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. However, some room for parton evolution beyond DGLAP is found at specific phase space corners $\Rightarrow$ important message for LHC

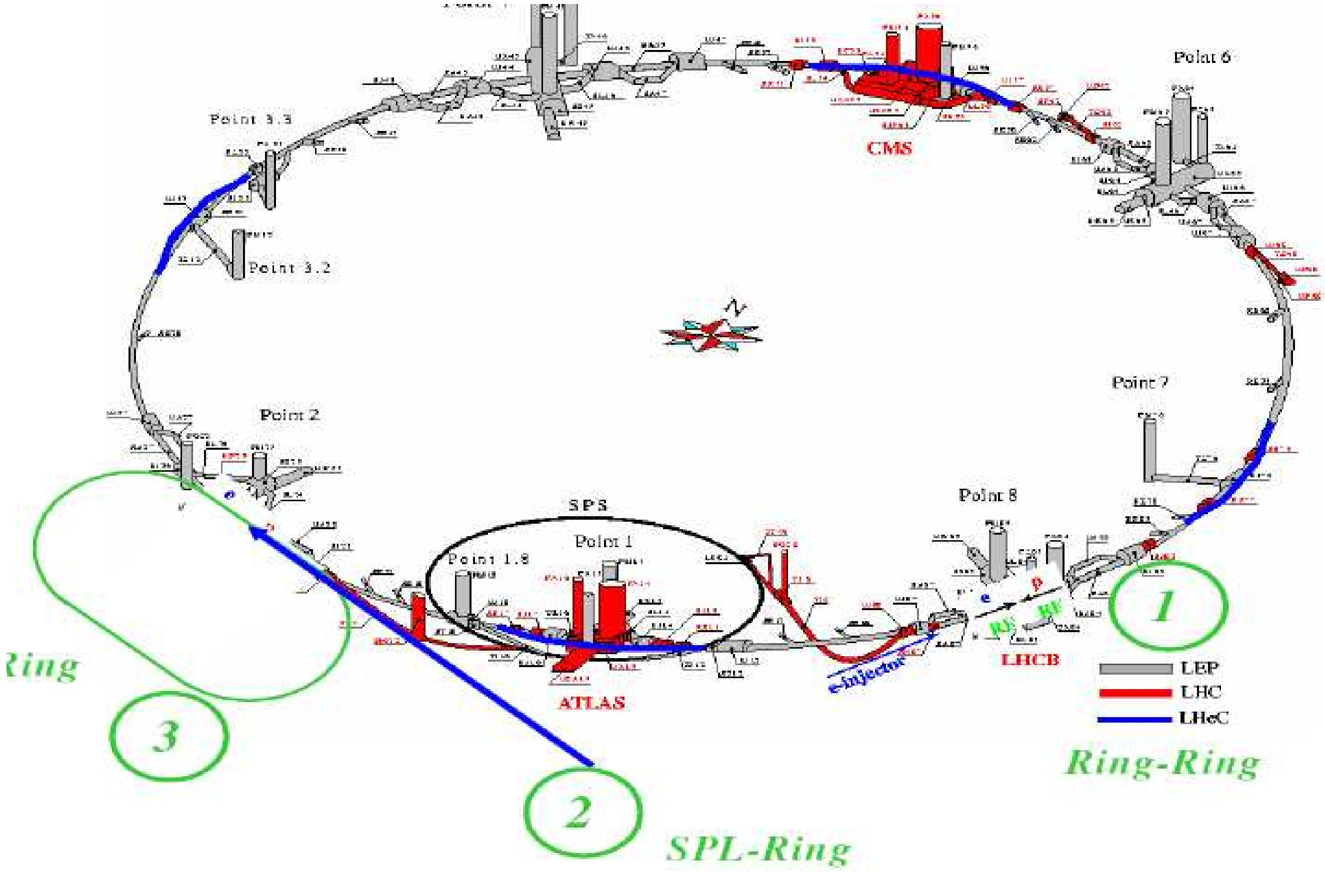
- Gained new insights into high energy diffraction: Pomeron under the HERA microscope shows complicated interplay of soft and hard phenomena. Understanding colour singlet exchange remains a major challenge in QCD

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

Project under discussion

For late LHC period:

$\sim 2022 - 2032$



$$e^{\pm}p$$

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

100 years of studying the structure of matter

■ Fixed target experiments

- ▷ Rutherford – 1911 (7 MeV, αAu)
  structure of atoms ⇒ planetary model ⇒ quantum mechanics
- ▷ Hofstadter – 1953 (400 MeV, eA)
  structure of the nucleus; determination of the size of A and p
- ▷ SLAC – 1968 (20 GeV, ep)
  structure of the proton ⇒ quarks ⇒ QPM
- ▷ SPS@CERN – 1976 (EMC, NA4, etc. studying DIS with μ beam)

■ Collider experiments

- ▷ HERA – 1992 (27.5×920 GeV ep)
  gluon dominated proton (and Pomeron); low x QCD; EW sector of SM
- ▷ LHeC – 2022 (60×7000 GeV, ep/eA) – *not approved yet*
  non-linear QCD? Strong parton saturation? BSM phenomena?