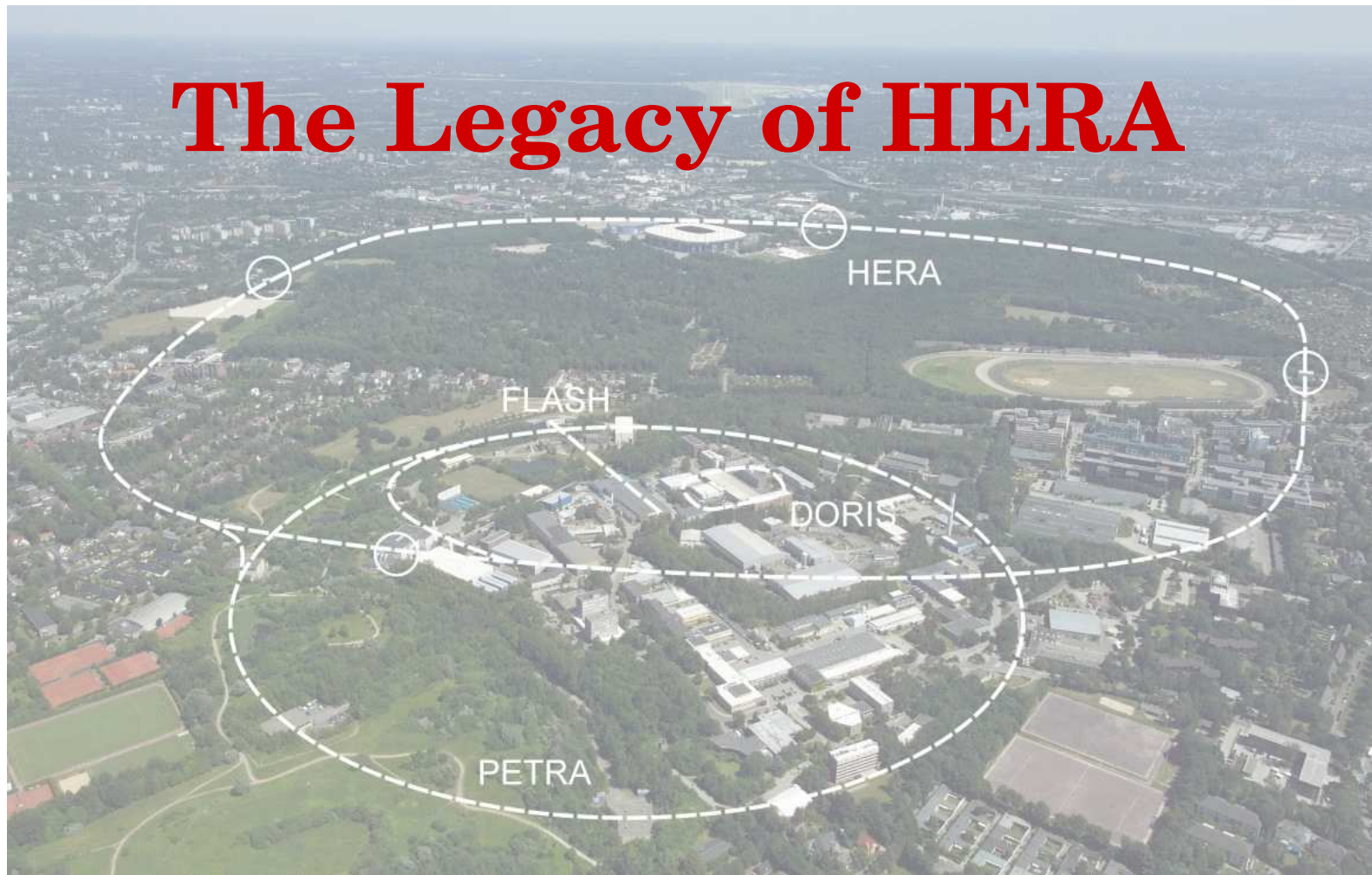


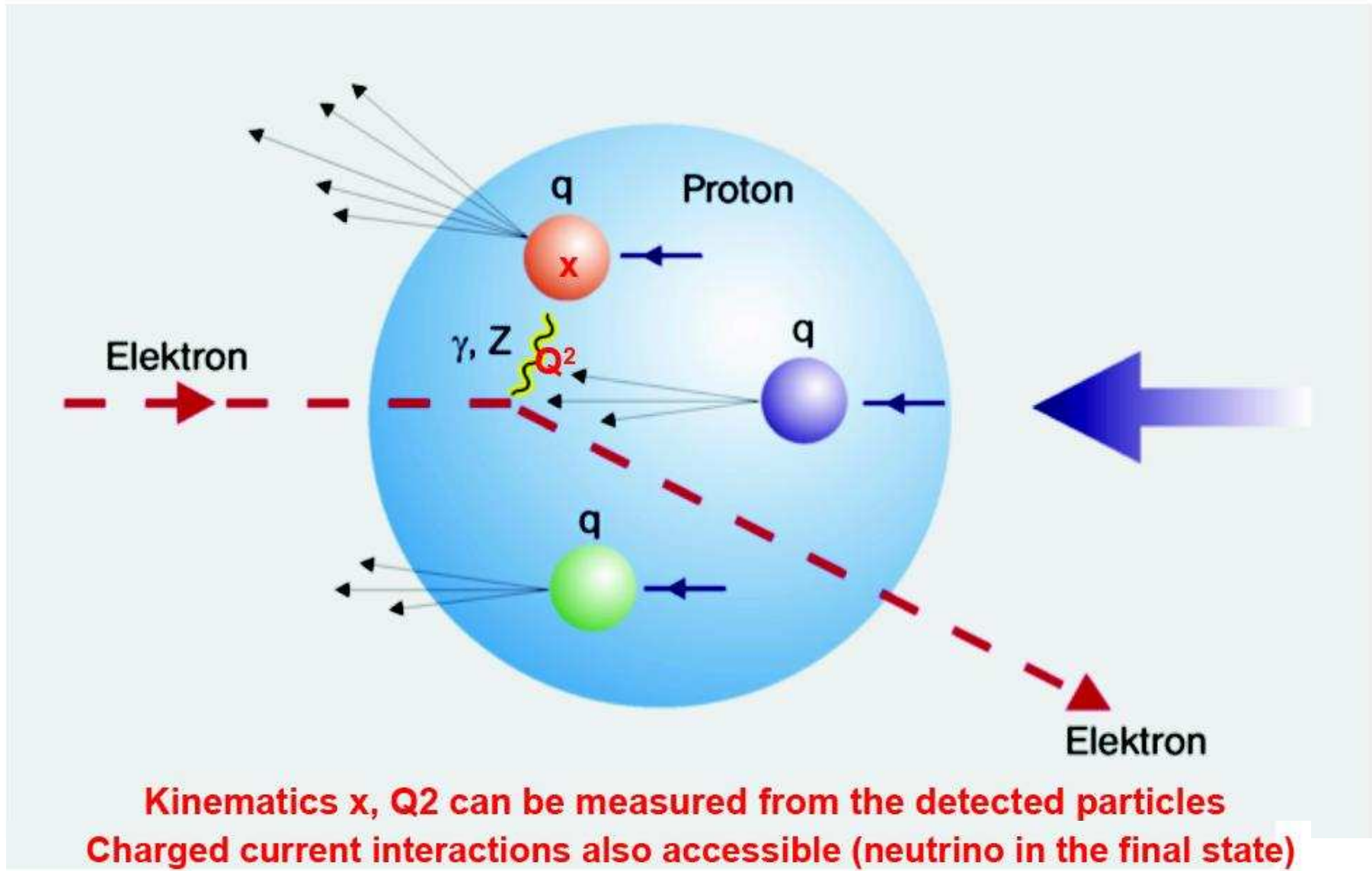


Sergey Levonian
DESY, Hamburg

The Legacy of HERA



Deep-Inelastic Scattering



Looking deeper inside matter

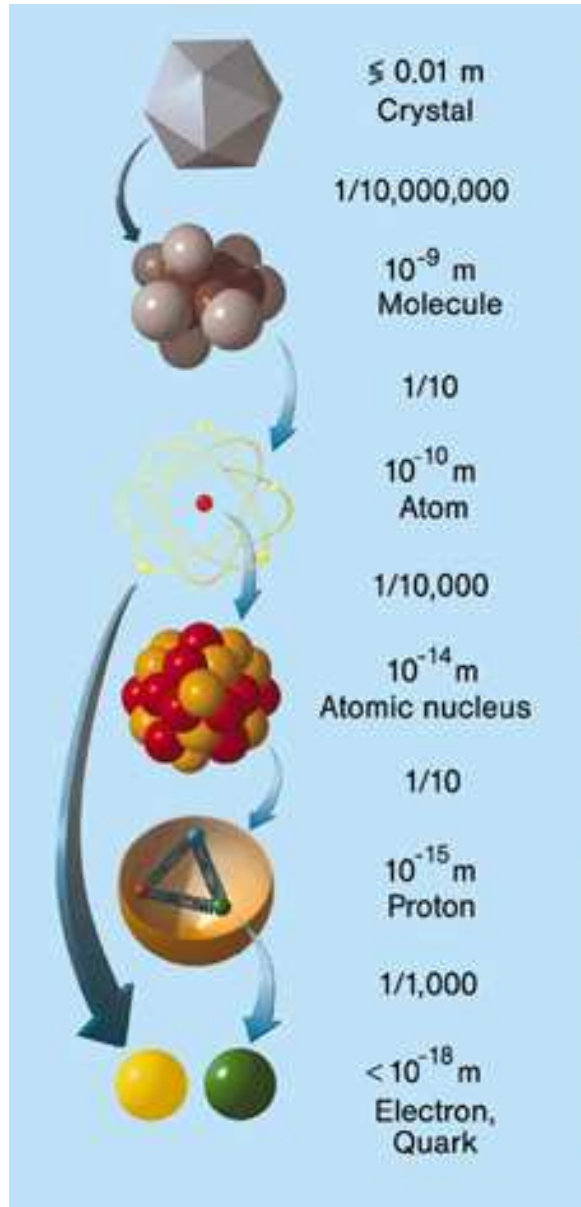
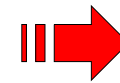


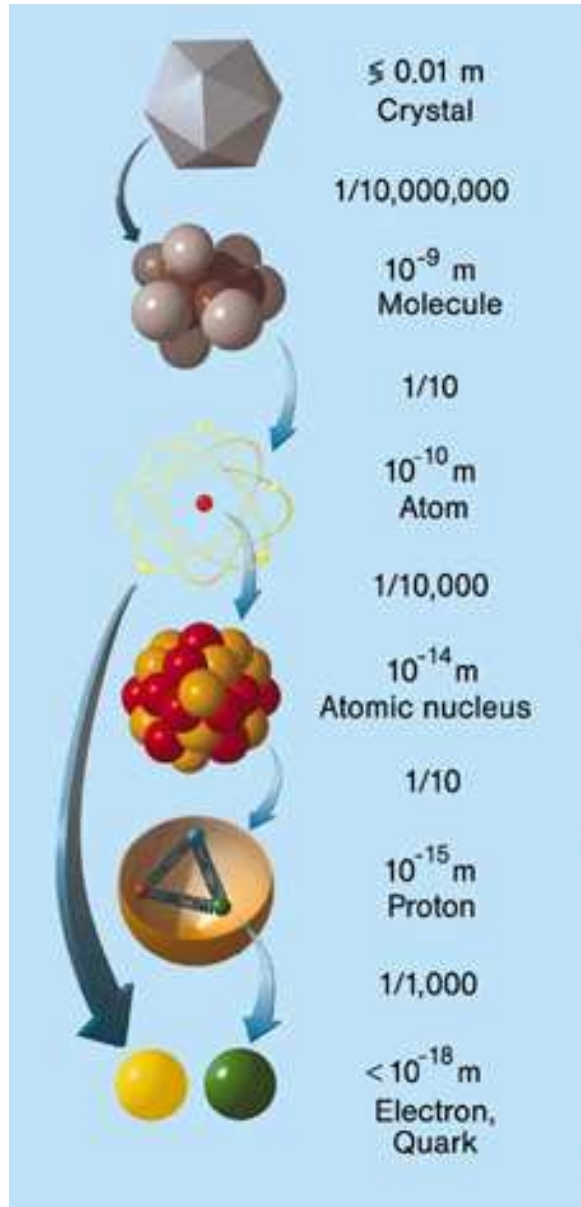
Illustration of improved understanding of the structure of matter with time (and with increasing resolution power)

High energy scattering process has been the basic tool during last 100 years



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

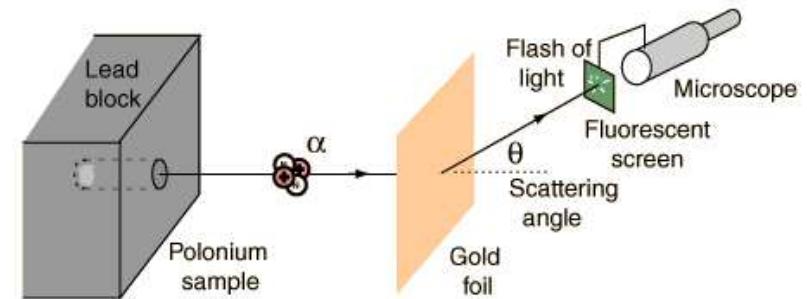
Looking deeper inside matter



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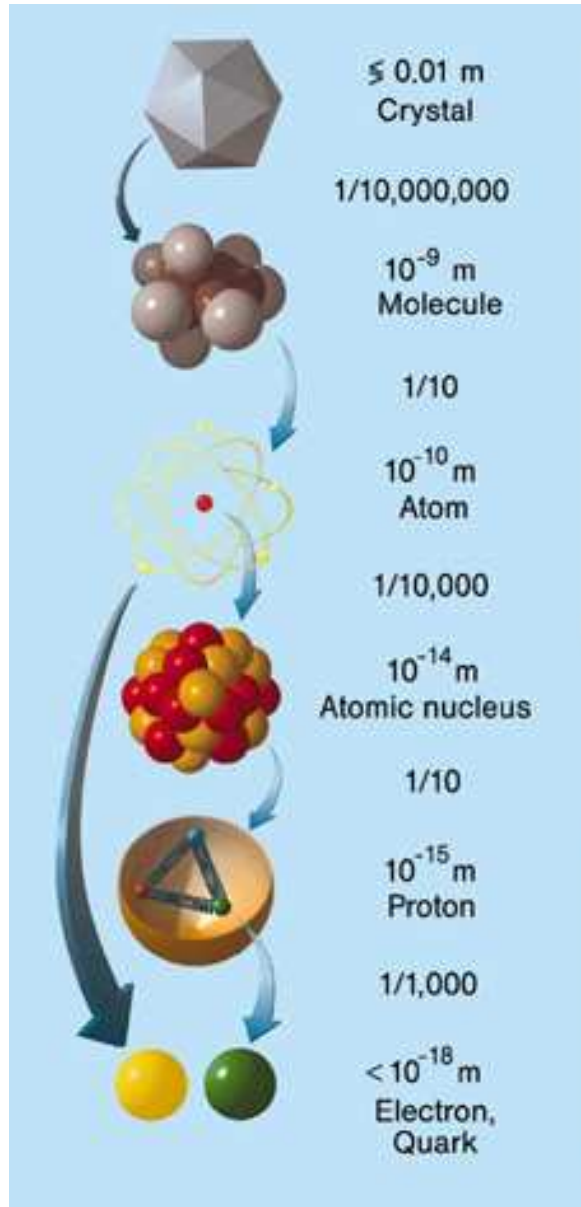
Rutherford (1911)

- 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



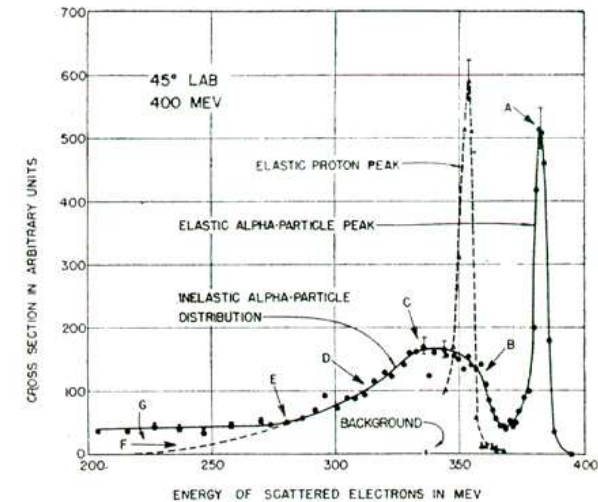
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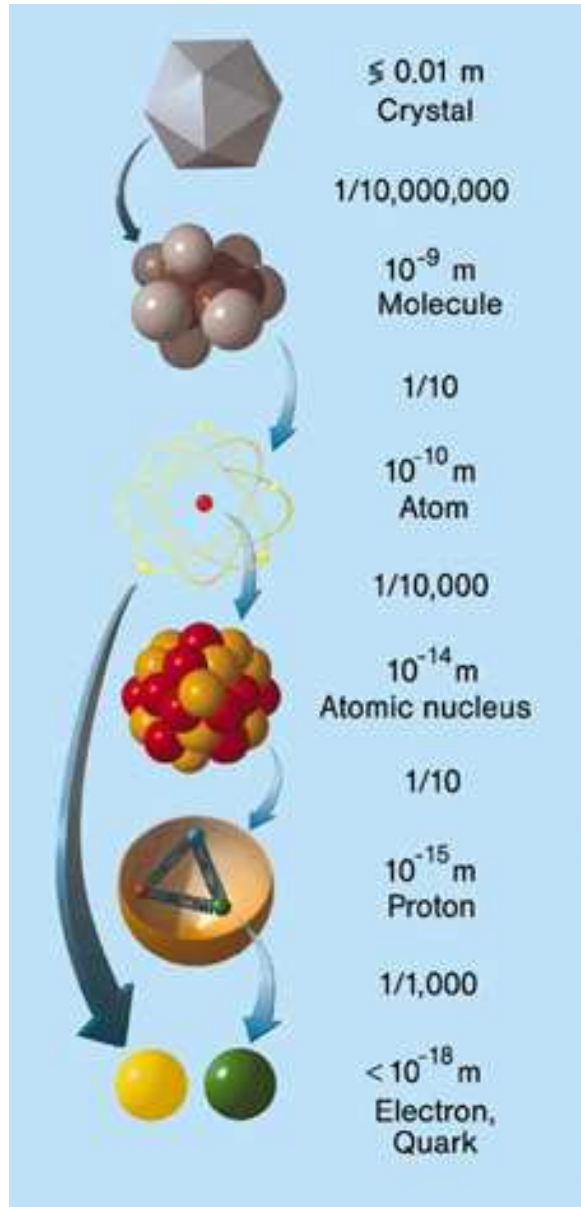
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- (in)elastic eN scattering of 400 MeV electrons
- Nucleus structure; size of A,p



Looking deeper inside matter



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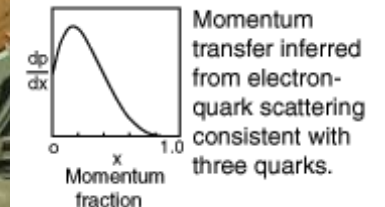
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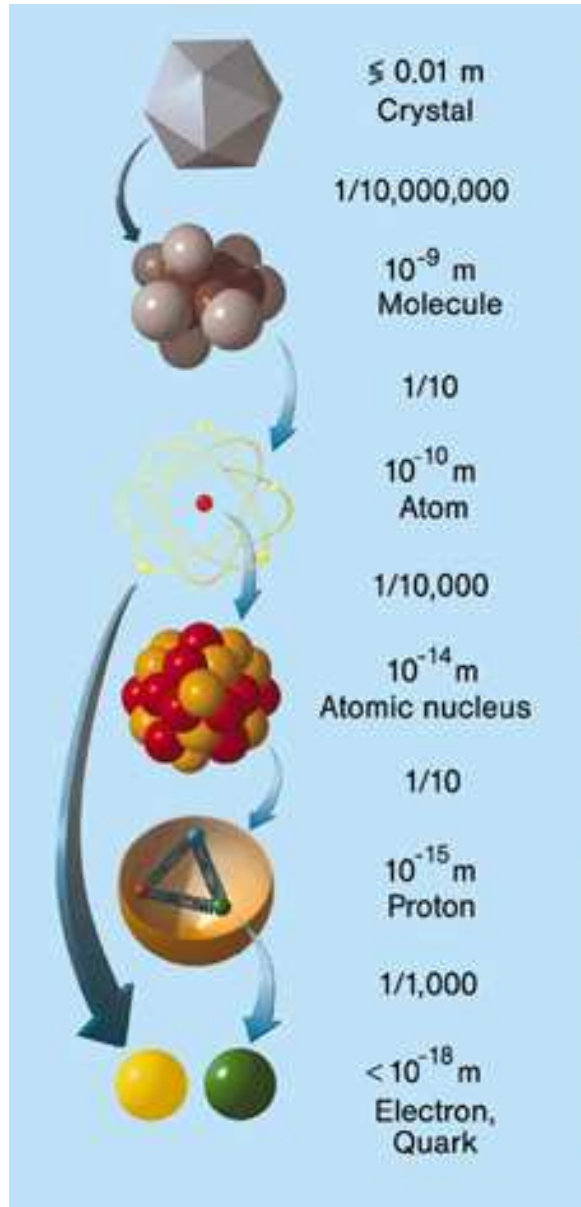
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- Fixed target DIS with 20 GeV electron beam
- internal structure of hadrons
- experimental evidence for quarks



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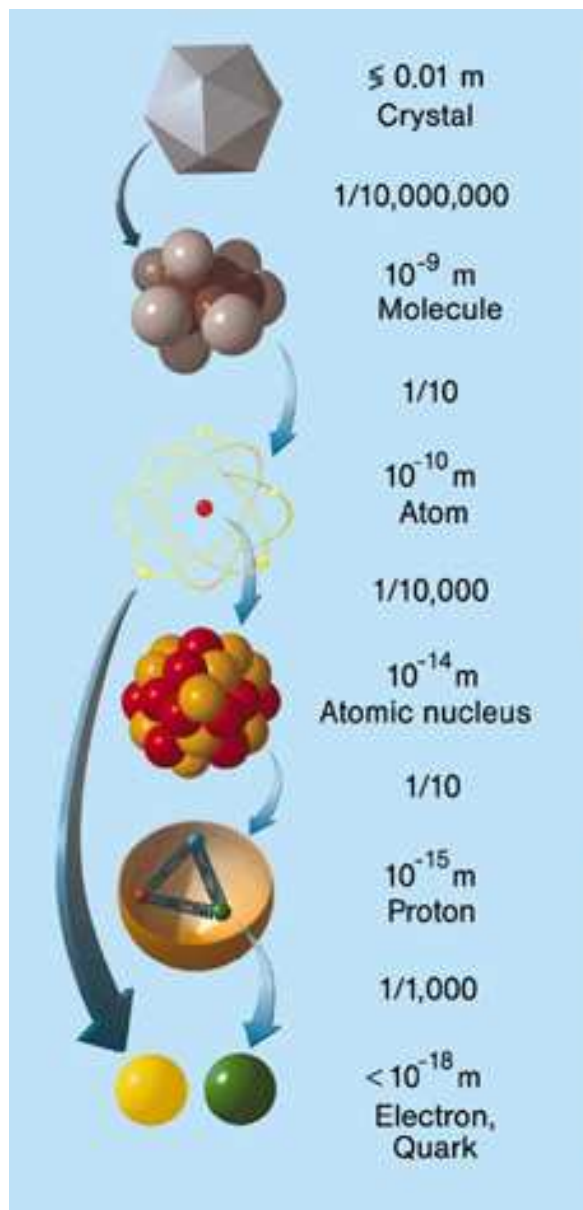
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HERA (1992 – 2007)

- 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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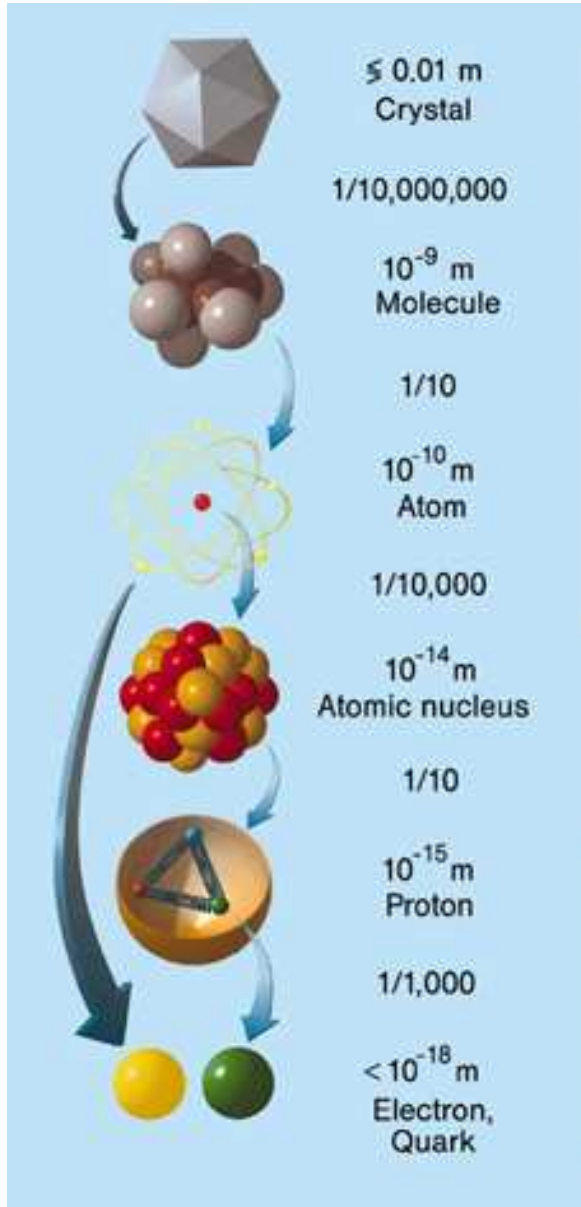
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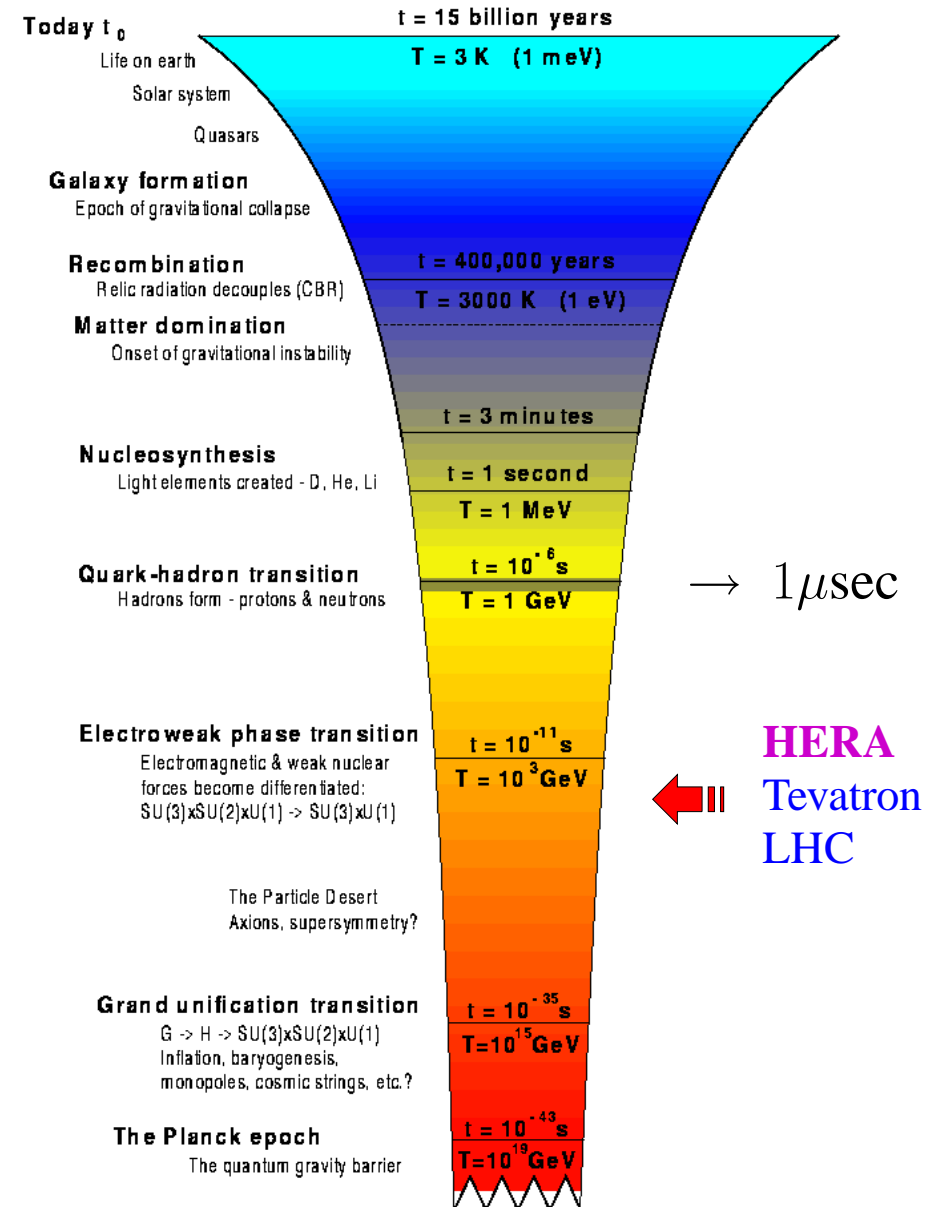
By increasing E we are not only looking deeper into matter, but also perform 'backward evolution' of the Universe in attempt to understand better fundamental forces of nature \Rightarrow

Looking deeper inside matter



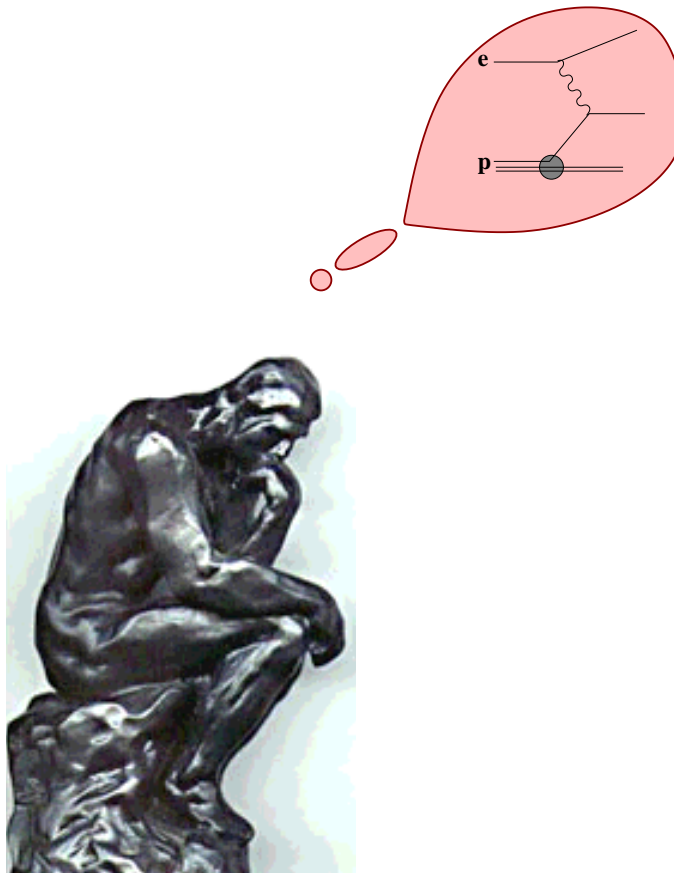
$$\lambda = h/p \sim \frac{1}{E}$$

Restoring Universe Evolution



$$E \sim T$$

In the beginning there was the Idea...

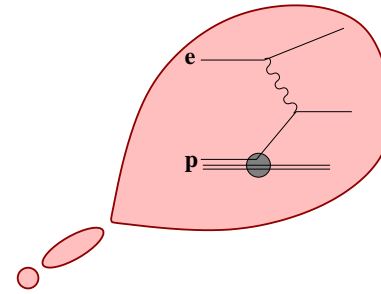


1979

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



1984-1991

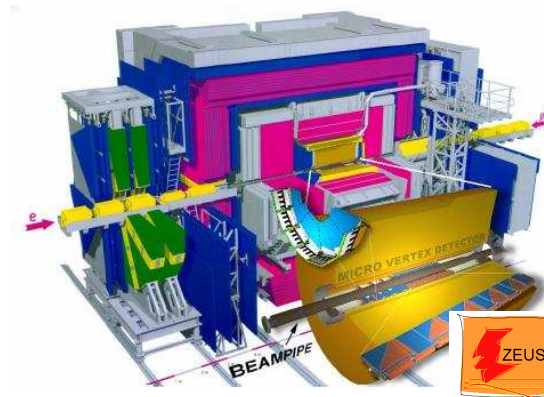
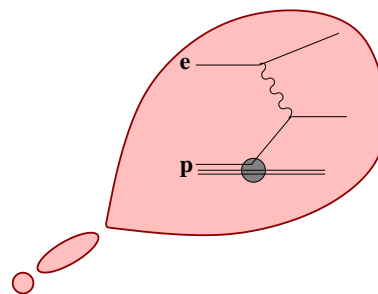


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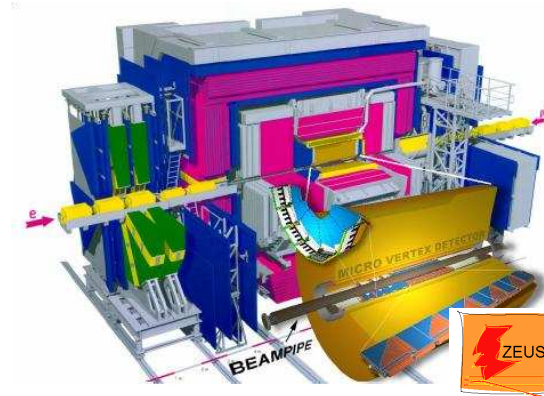
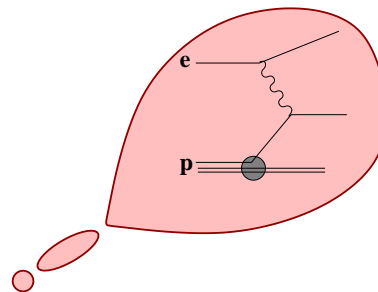
1979



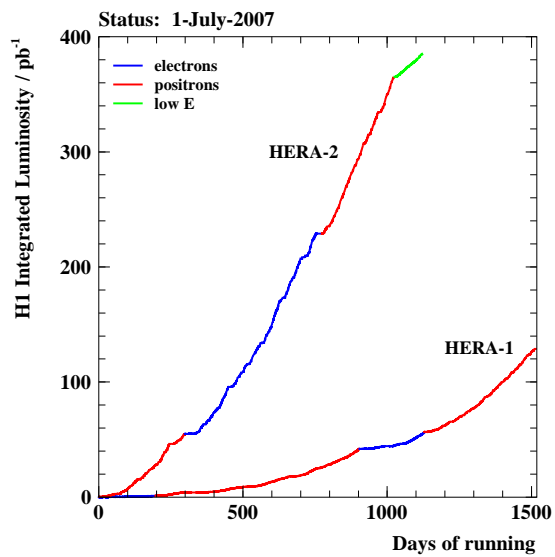
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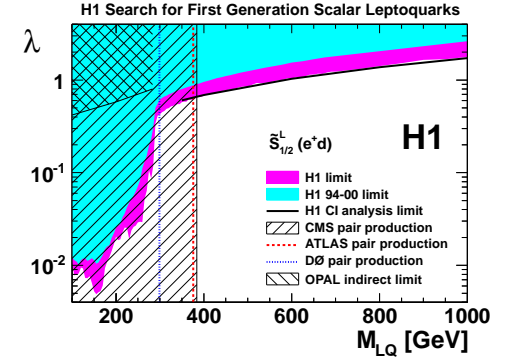
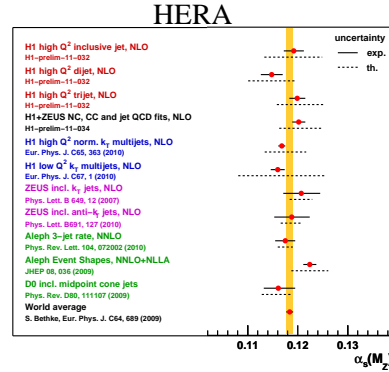
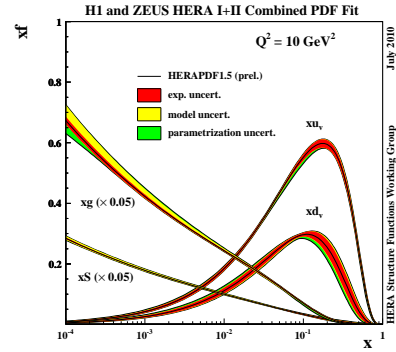
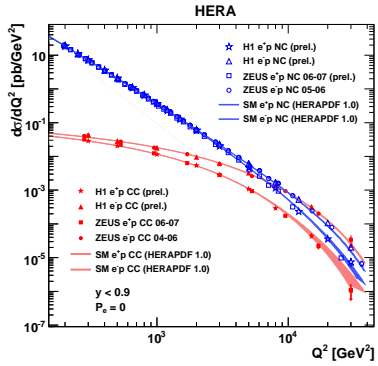
1992-2007



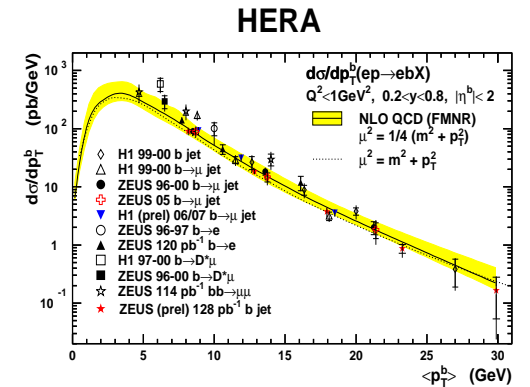
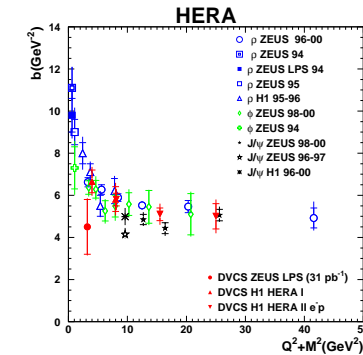
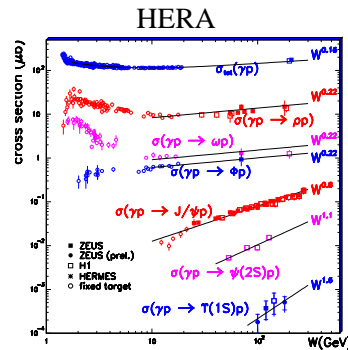
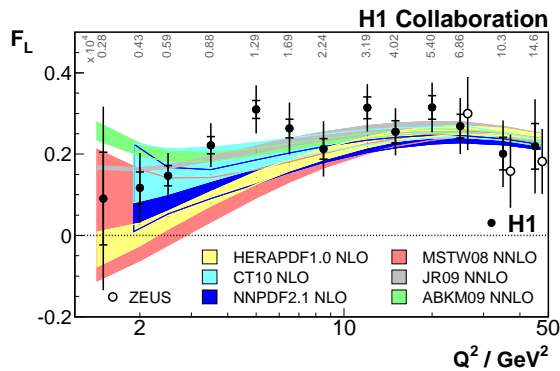
1979



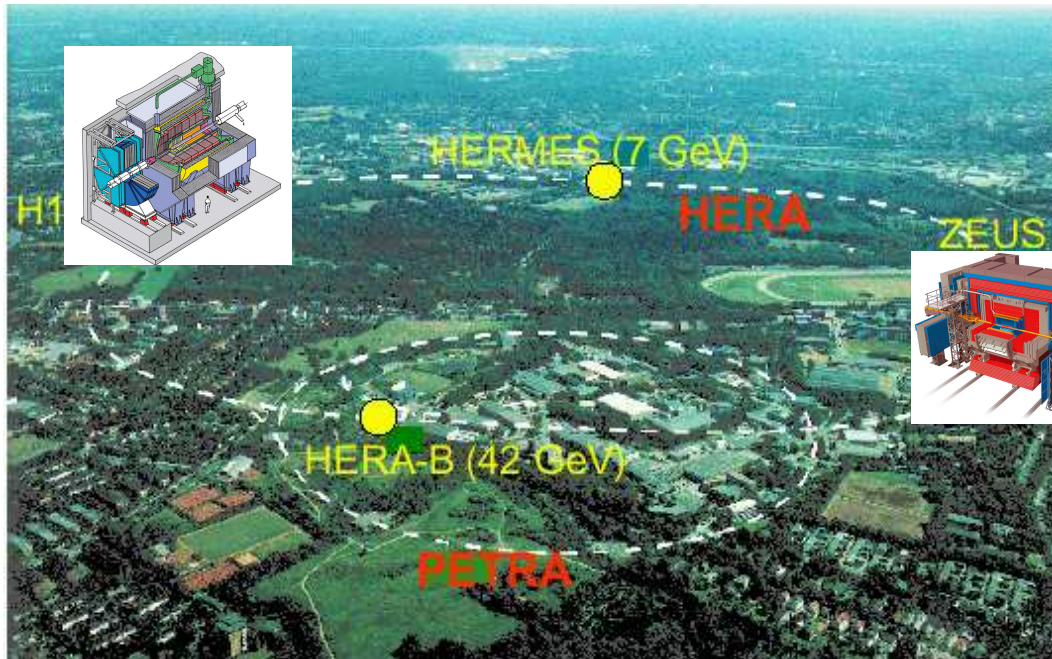
...and finally...



Lots of Textbook results



HERA: The World's Only ep Collider

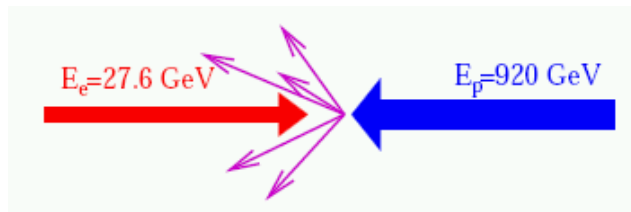


HERA-1 (1993-2000) $\simeq 120 \text{ pb}^{-1}$

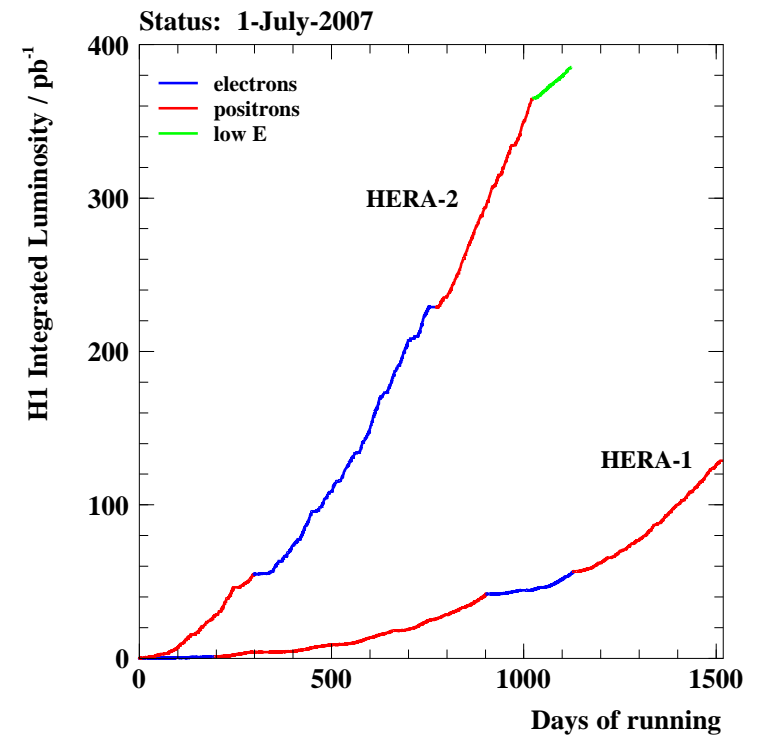
HERA-2 (2003-2007) $\simeq 380 \text{ pb}^{-1}$

Final Data samples

H1+ZEUS: $2 \times 0.5 \text{ fb}^{-1}$

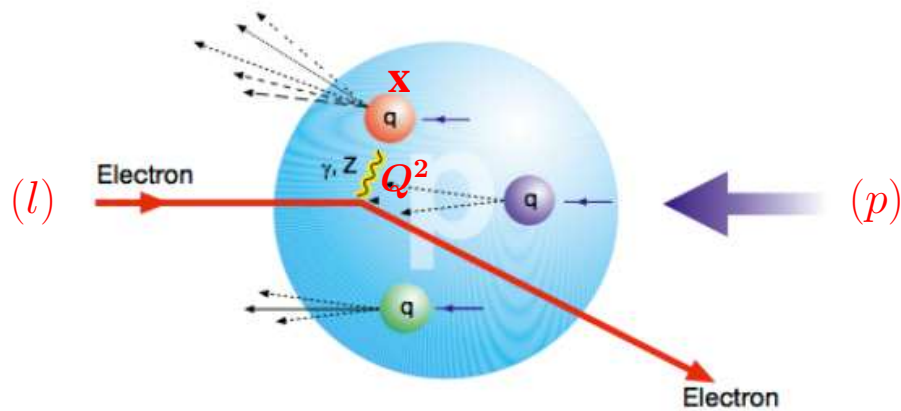


- 1998 E_p upgrade: $820 \Rightarrow 920 \text{ GeV}$
(\sqrt{s} : $301 \Rightarrow 319 \text{ GeV}$)
- 2001 HERA-2 upgrade: $\mathcal{L} \times 3$, Polarised e^+/e^-
($\langle P \rangle = 40\%$)

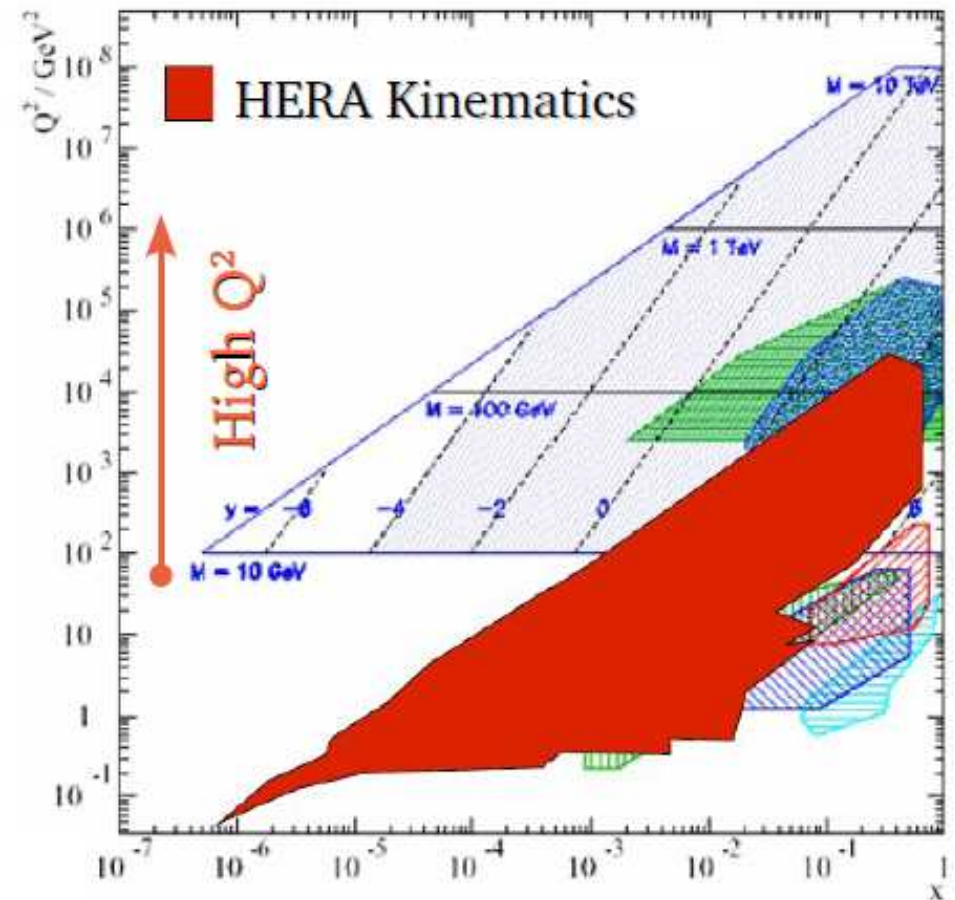
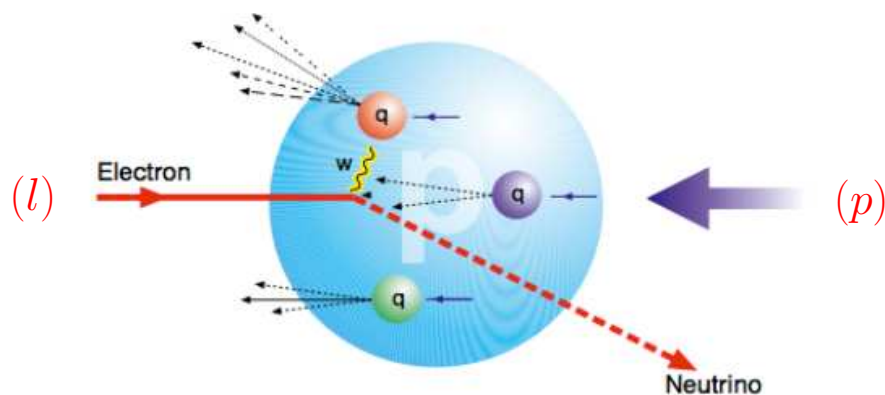


Deep-Inelastic Scattering at HERA

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



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

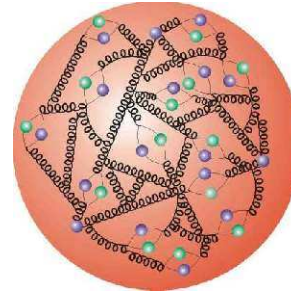


Kinematics: (Momentum transfer)²: $Q^2 = -q^2$
 Bjorken x : $x = Q^2 / (2p \cdot q)$
 Inelasticity: $y = (p \cdot q) / (p \cdot l)$
 (Total hadronic energy)²: $W^2 = (p + q)^2$
 $W^2 \simeq Q^2 / x$

Physics landscape at HERA

- **HERA as Super-microscope**

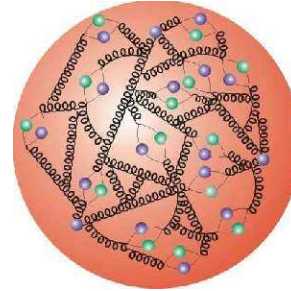
- ▷ Proton structure at high resolution
- ▷ Impact for LHC



Physics landscape at HERA

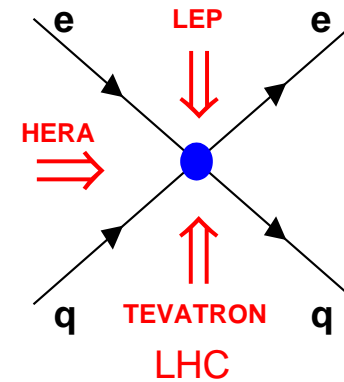
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- **HERA as Energy frontier machine**

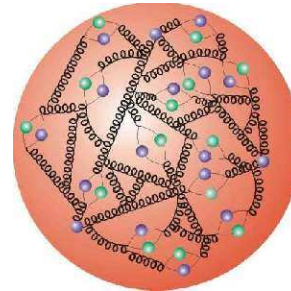
- ▷ Electroweak unification at work
- ▷ Anything beyond the Standard Model?



Physics landscape at HERA

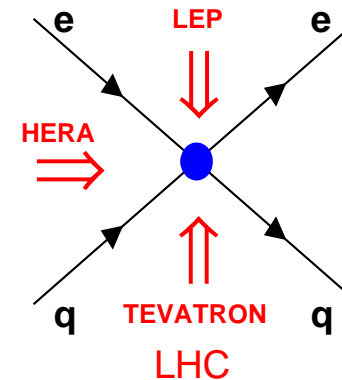
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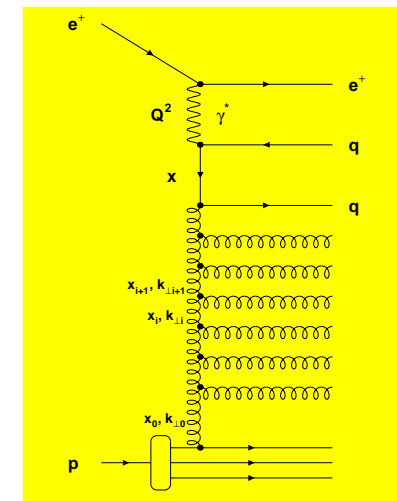
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• HERA as QCD laboratory

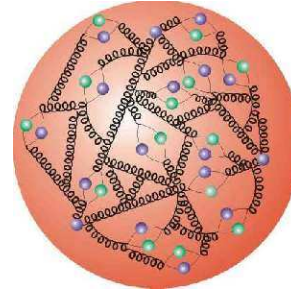
- ▷ Putting QCD in stringent tests with:
 - Jets (parton evolution schemes, NLO QCD, α_s)
 - Heavy flavor sector (multiscale problem: Q^2 , M_Q , E_t)
 - Diffraction (interplay of soft and hard physics)
- ▷ HERA specifics: $\log x$ physics



Physics landscape at HERA

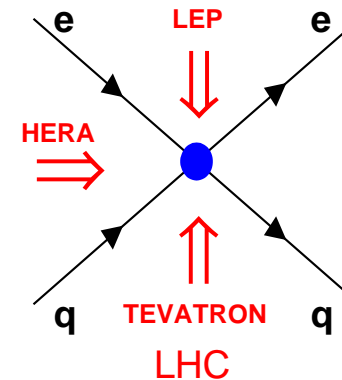
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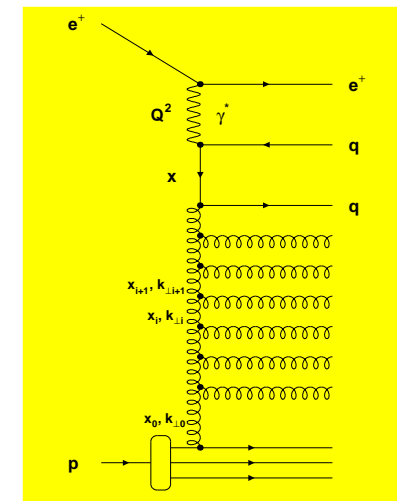


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⇒ Search for Novel Phenomena

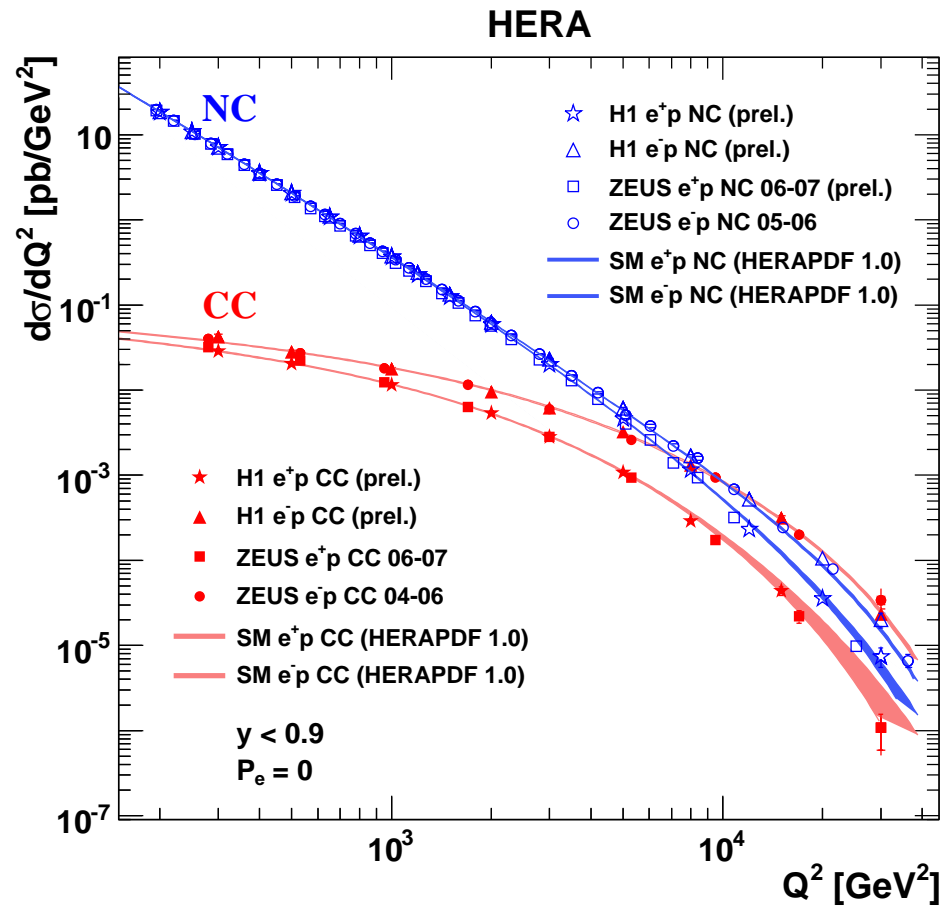
⇒ Precision Measurements



HERA as Energy Frontier Machine

HERA at Energy Frontier

Unpolarized DIS cross sections

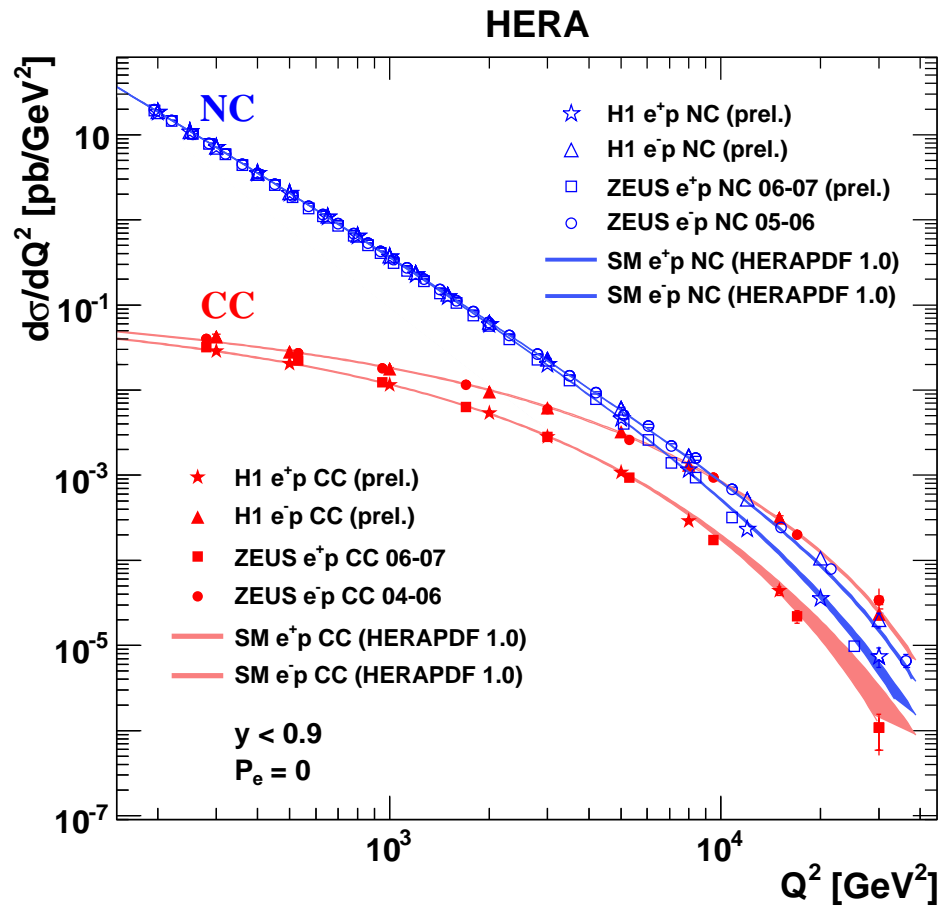


Electro-Weak Unification

HERA at Energy Frontier

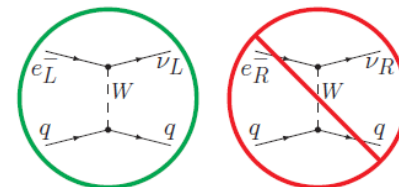
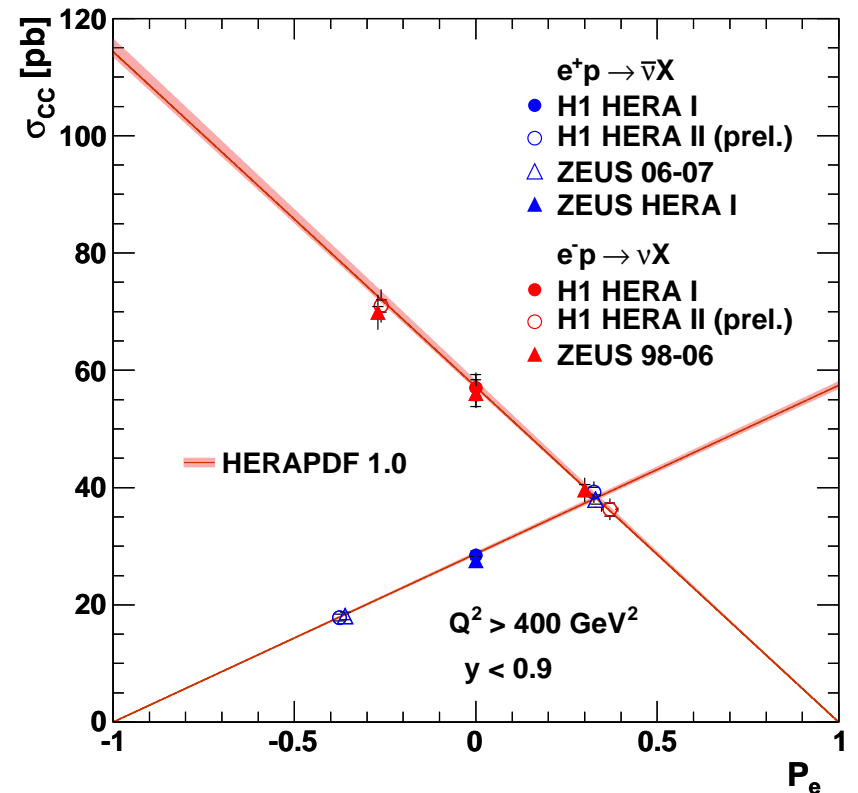
Unpolarized DIS cross sections

$$\sigma_{\text{pol}}^{CC}(e^\pm p) = (1 \pm P_e) \cdot \sigma_{\text{unpol}}^{CC}(e^\pm p)$$



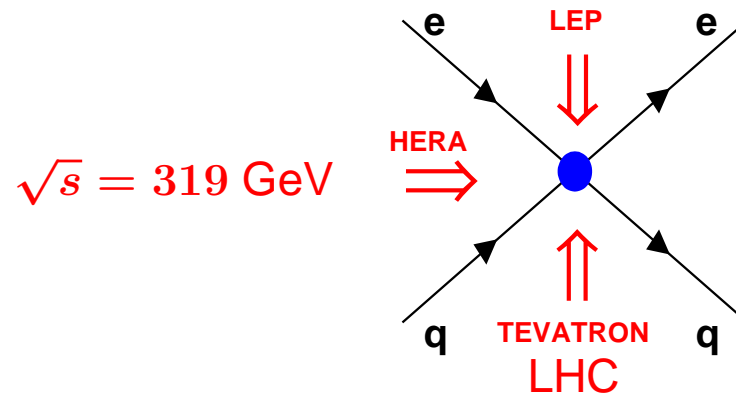
Electro-Weak Unification

HERA Charged Current e[±]p Scattering



No W coupling
to e_R^- and e_L^+

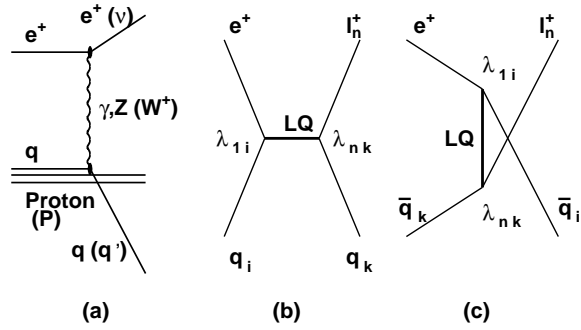
Anything beyond the SM ?



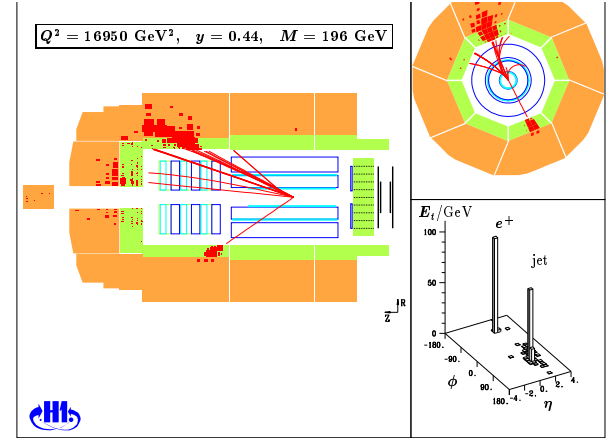
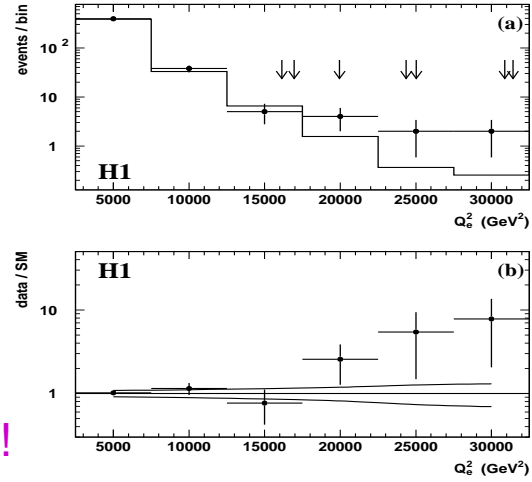
So far all NC and CC HERA data were in good agreement with the SM.
Try to look more carefully at the tails, using two strategies:

1. Specific BSM signals search (LQ, LFV, SUSY, ...) – guided by theory
2. Model independent generic search (data vs SM) – guided by data

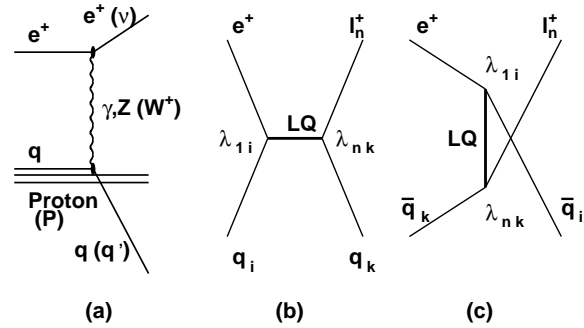
Leptoquarks ?



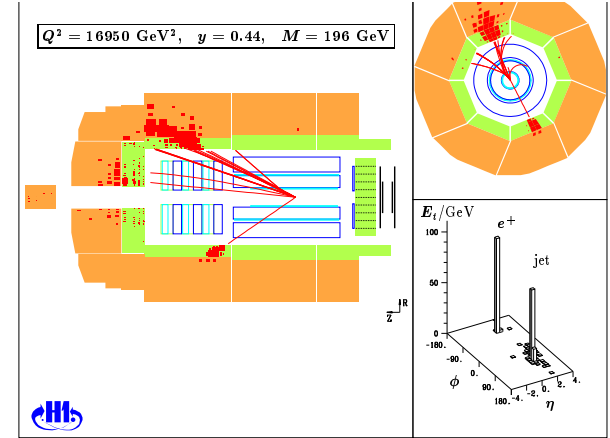
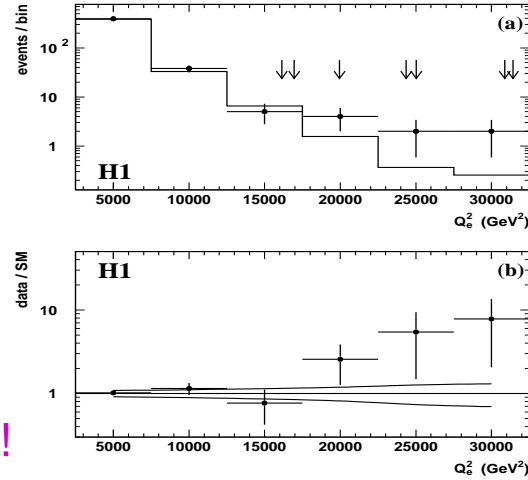
1994-97: High Q^2 events.
 Rate in excess of Standard Model!



Leptoquarks ?

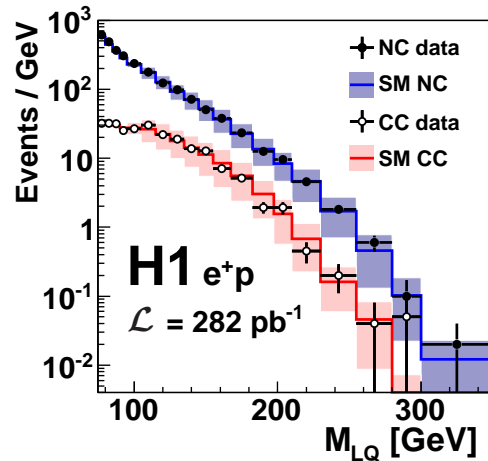
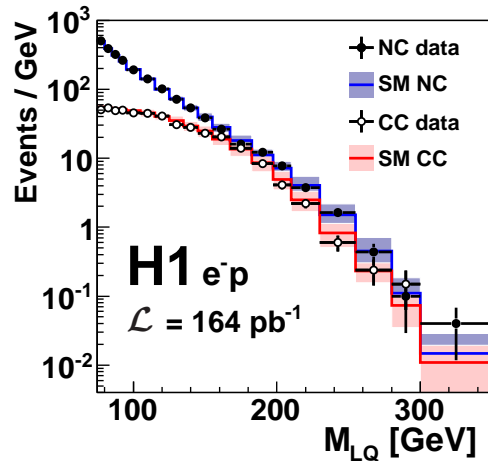


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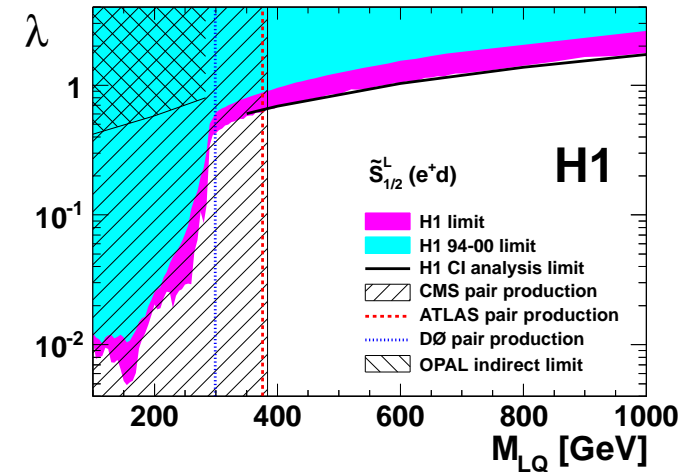


2011: Final status

H1 Search for First Generation Leptoquarks

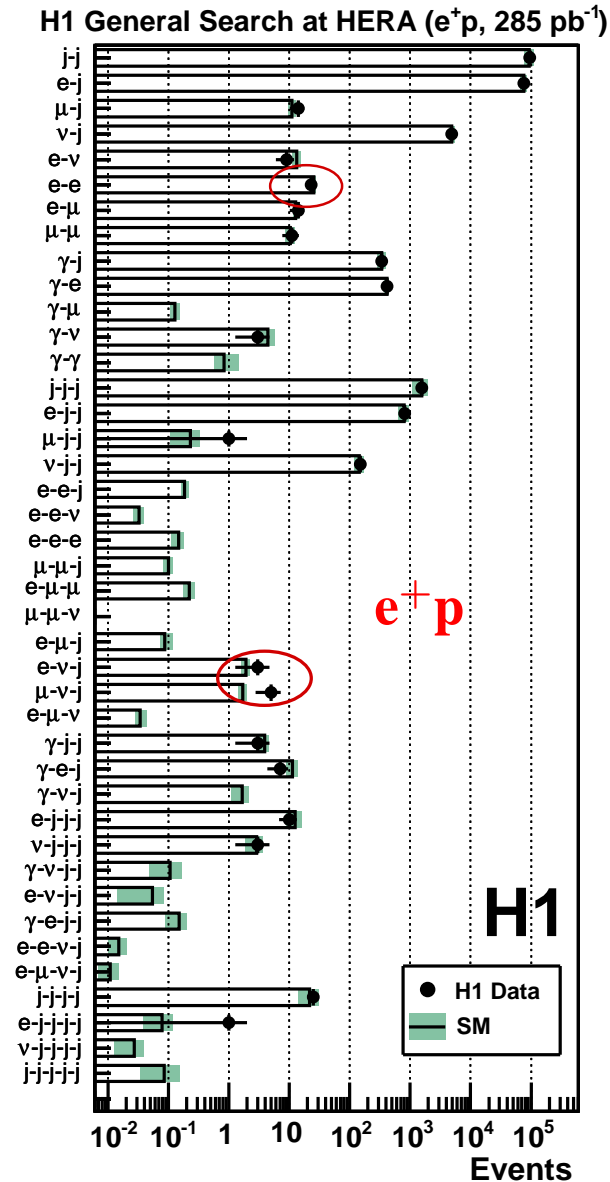


H1 Search for First Generation Scalar Leptoquarks



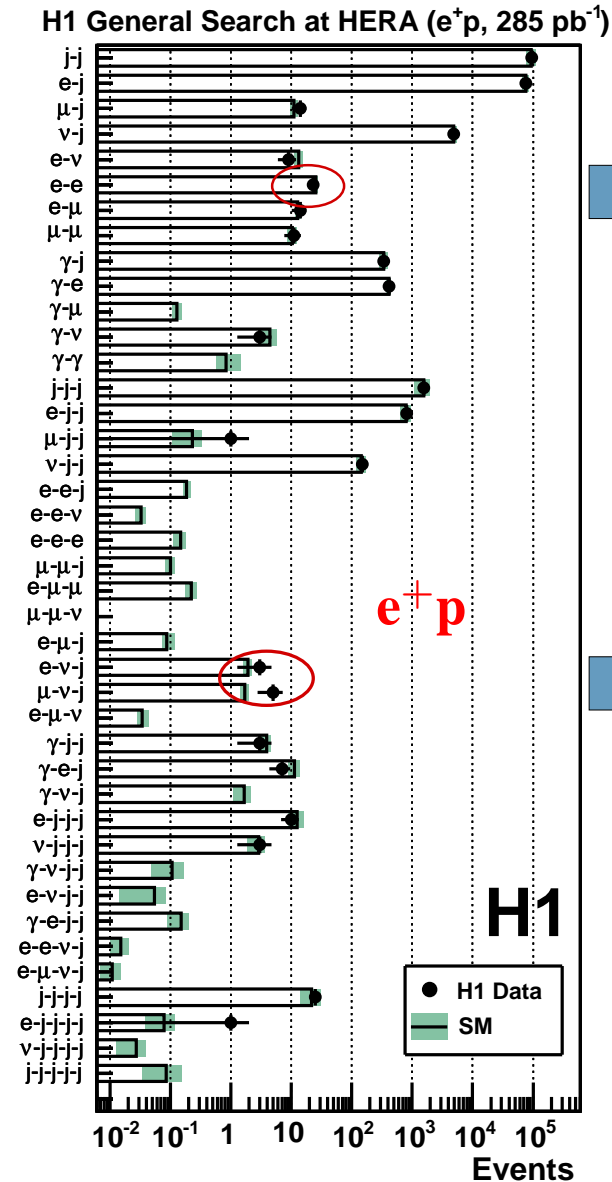
Model independent search for New Phenomena

- Identify isolated objects:
 e, μ, γ, j, ν
- Select events, having at least two objects with high $P_T > 20\text{GeV}$
- 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 ($M_{\text{all}}, \Sigma P_T$)
 \Rightarrow **Combine H1 and ZEUS data**

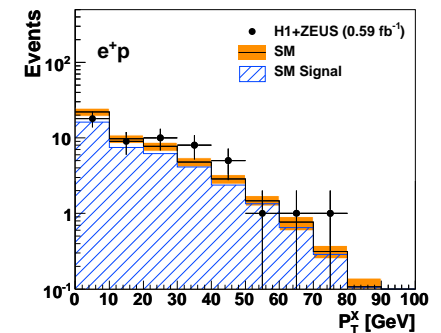
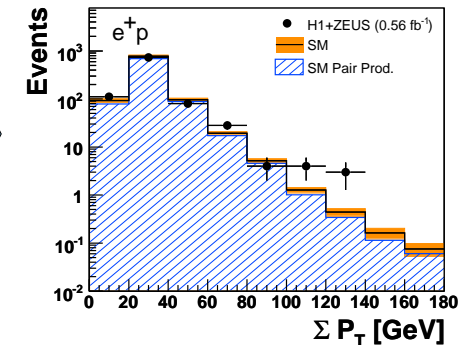


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H1+ZEUS, 0.59 fb^{-1}



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

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

CC

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

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

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

Dominant contribution

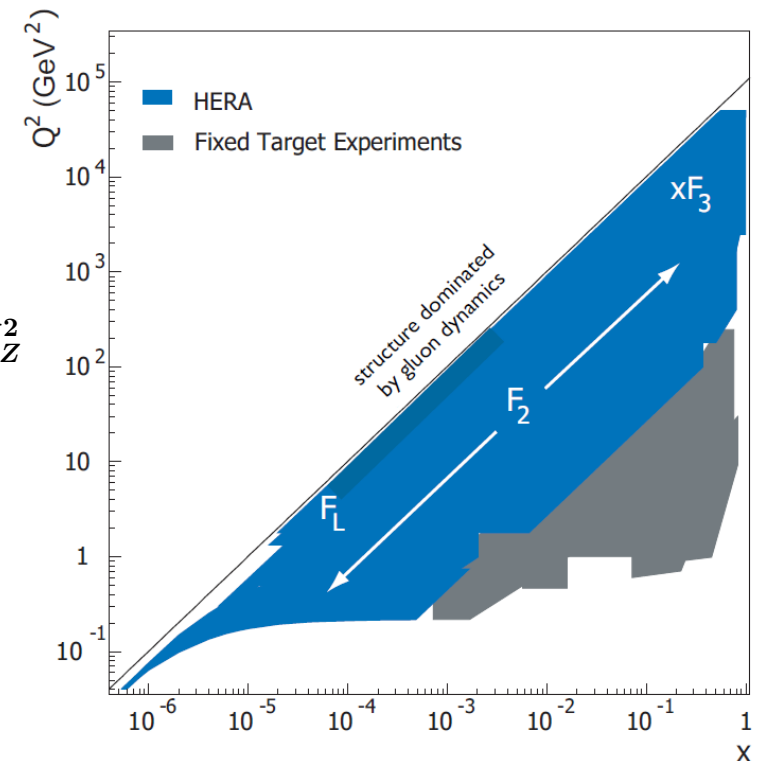
$$x\tilde{F}_3 \propto \sum (xq_i - x\bar{q}_i)$$

Only sensitive at high $Q^2 \sim M_Z^2$

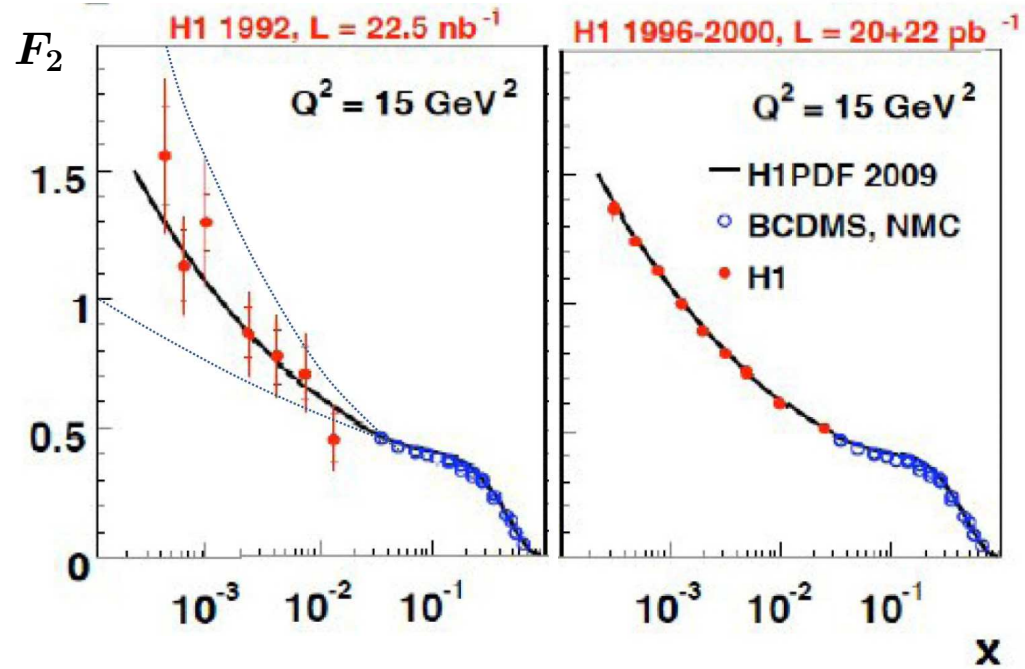
$$\tilde{F}_L \propto \alpha_s \cdot xg(x, Q^2)$$

Only sensitive at high y

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

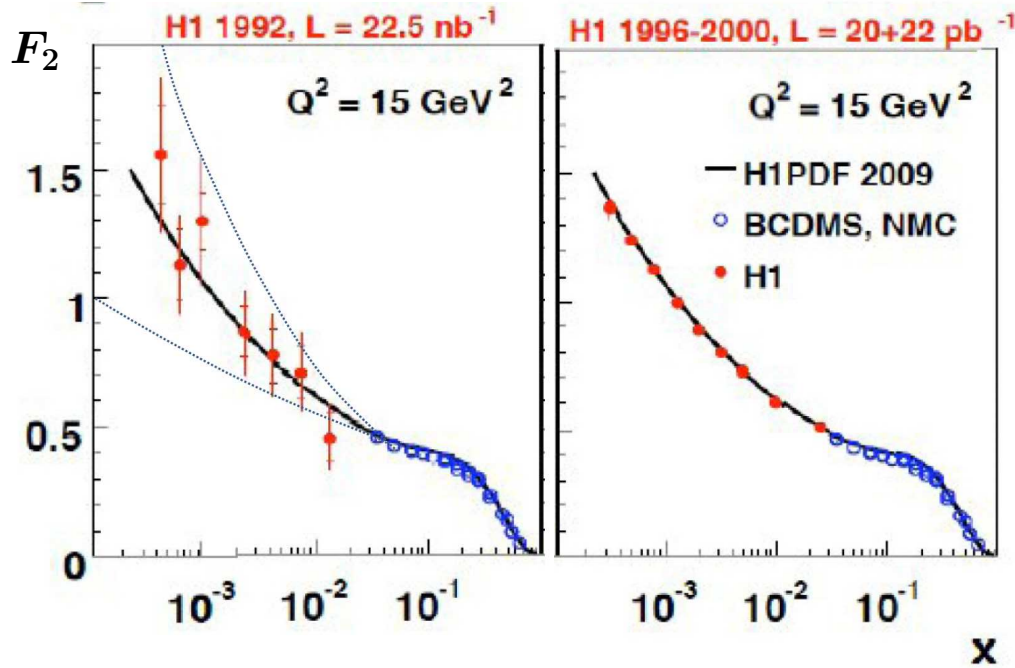


Structure of the proton



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

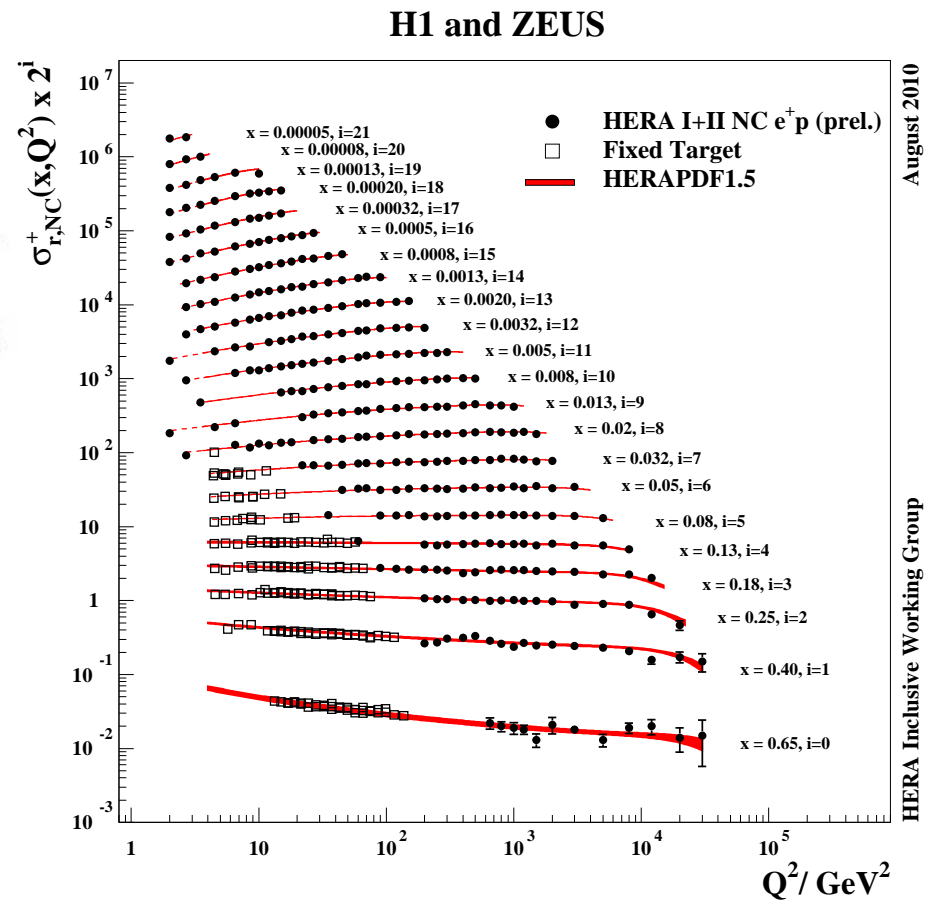
Structure of the proton



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

- ⇒ Bjorken scaling regime at $x > 0.05$
- ⇒ Large scaling violation at $x < 0.01$

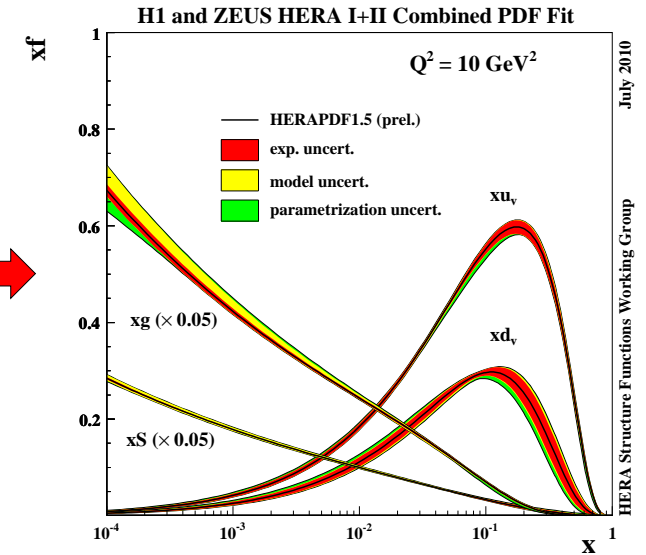
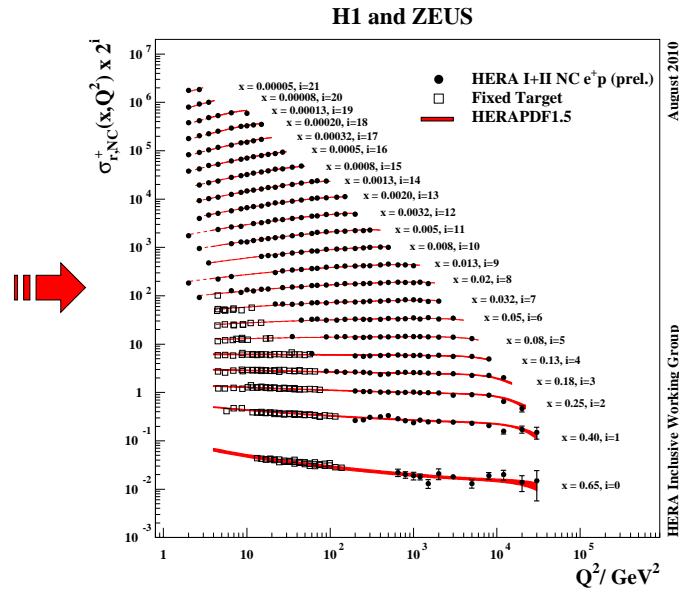
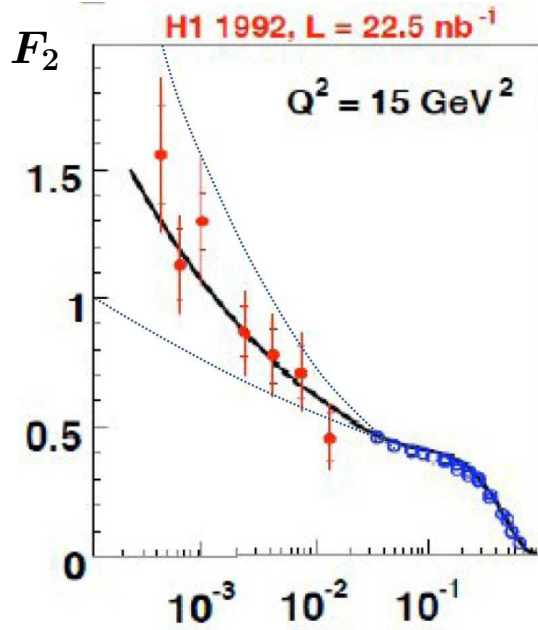
Combined HERA e^+p data
($\mathcal{L} = 2 \times 250 \text{ pb}^{-1}$)



August 2010

HERA Inclusive Working Group

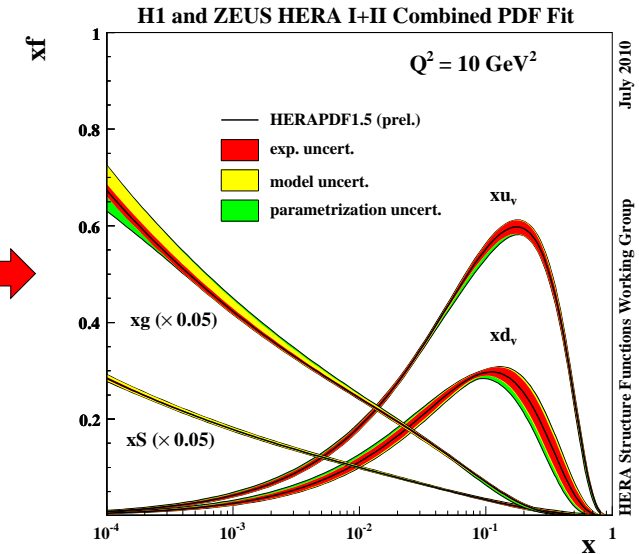
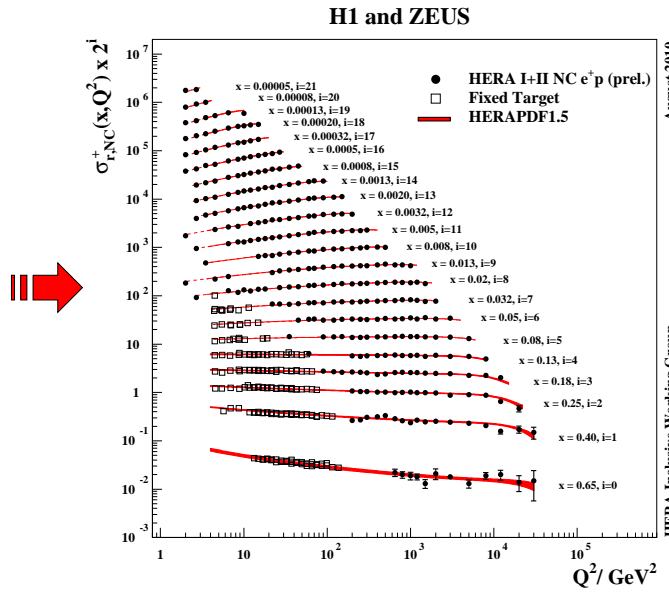
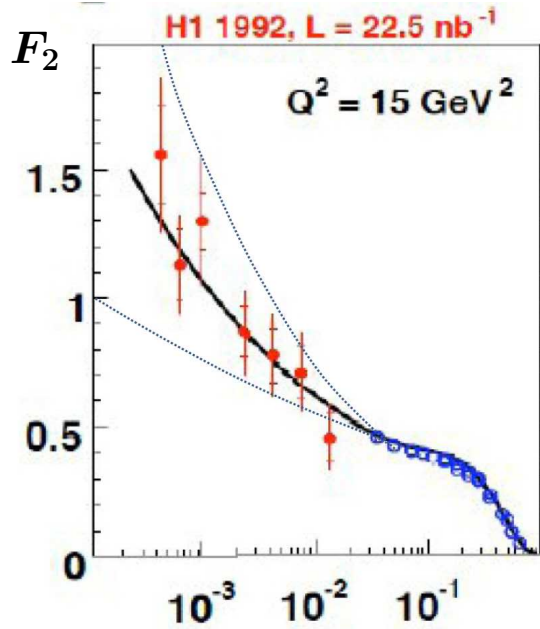
Structure of the proton



- Precision of (1 – 2)% in the bulk region
- Perfect description 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 ?

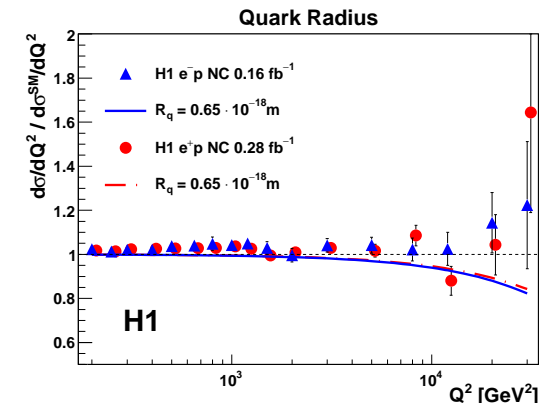
Structure of the proton



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⇒ Any substructures at $10^{-18}m$?
 No. Quarks are still pointlike

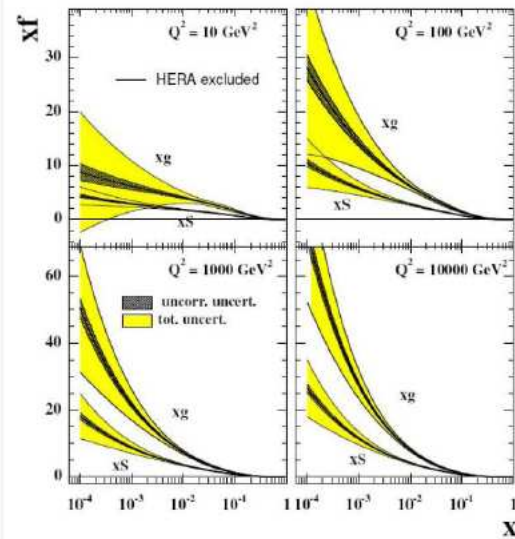
$$\frac{d\sigma}{dQ^2} = \frac{d\sigma_{SM}}{dQ^2} \cdot \left(1 - \frac{R^2}{6} \cdot Q^2\right)^2$$



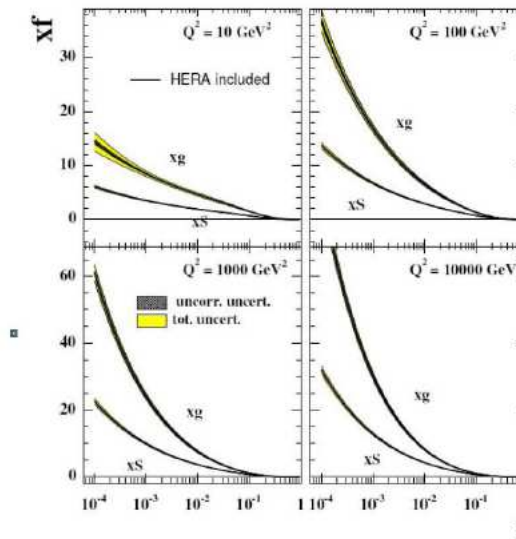
Upper limit: $R_q < 0.65 \cdot 10^{-3} \text{ fm}$

HERAPDF for LHC

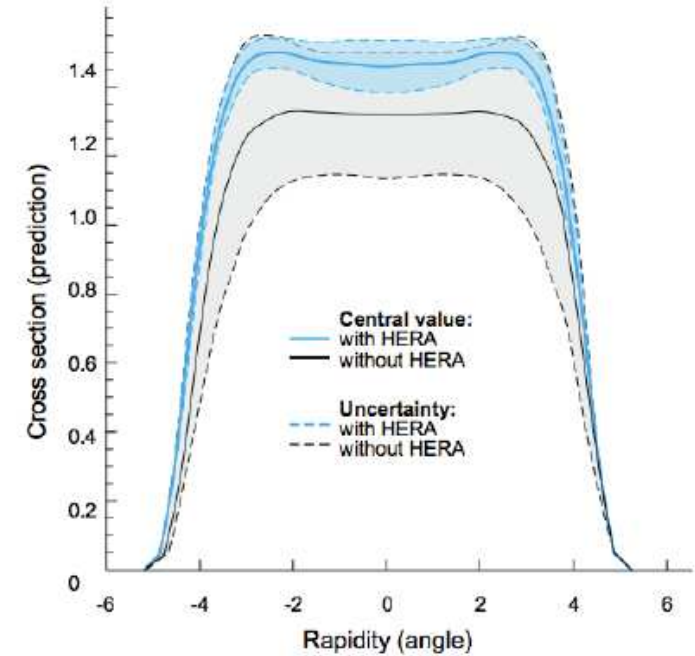
Knowledge of gluon without HERA data.



Knowledge of gluon with HERA

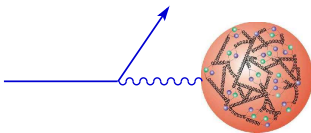


W⁺ cross-section

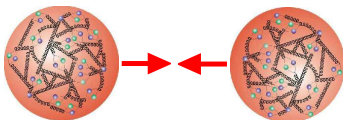


Cooper-Sarkar et al. : HERA-LHC workshop 2009

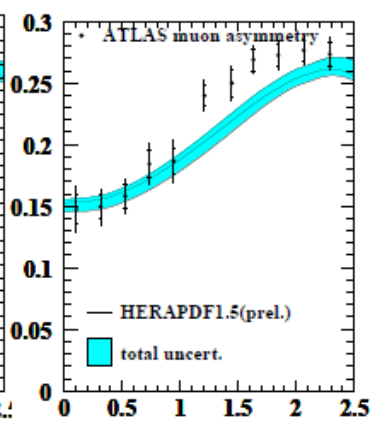
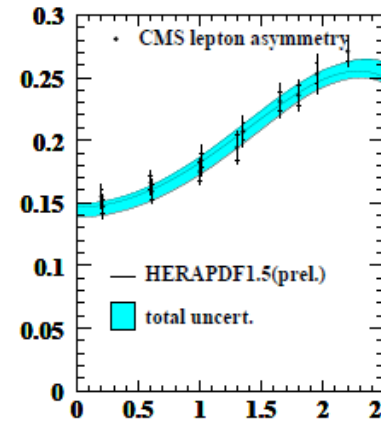
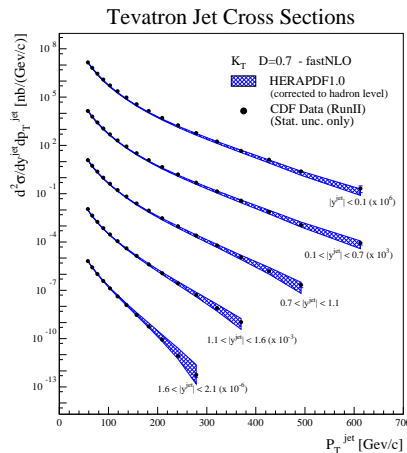
HERA



LHC



CDF Data (Run II)



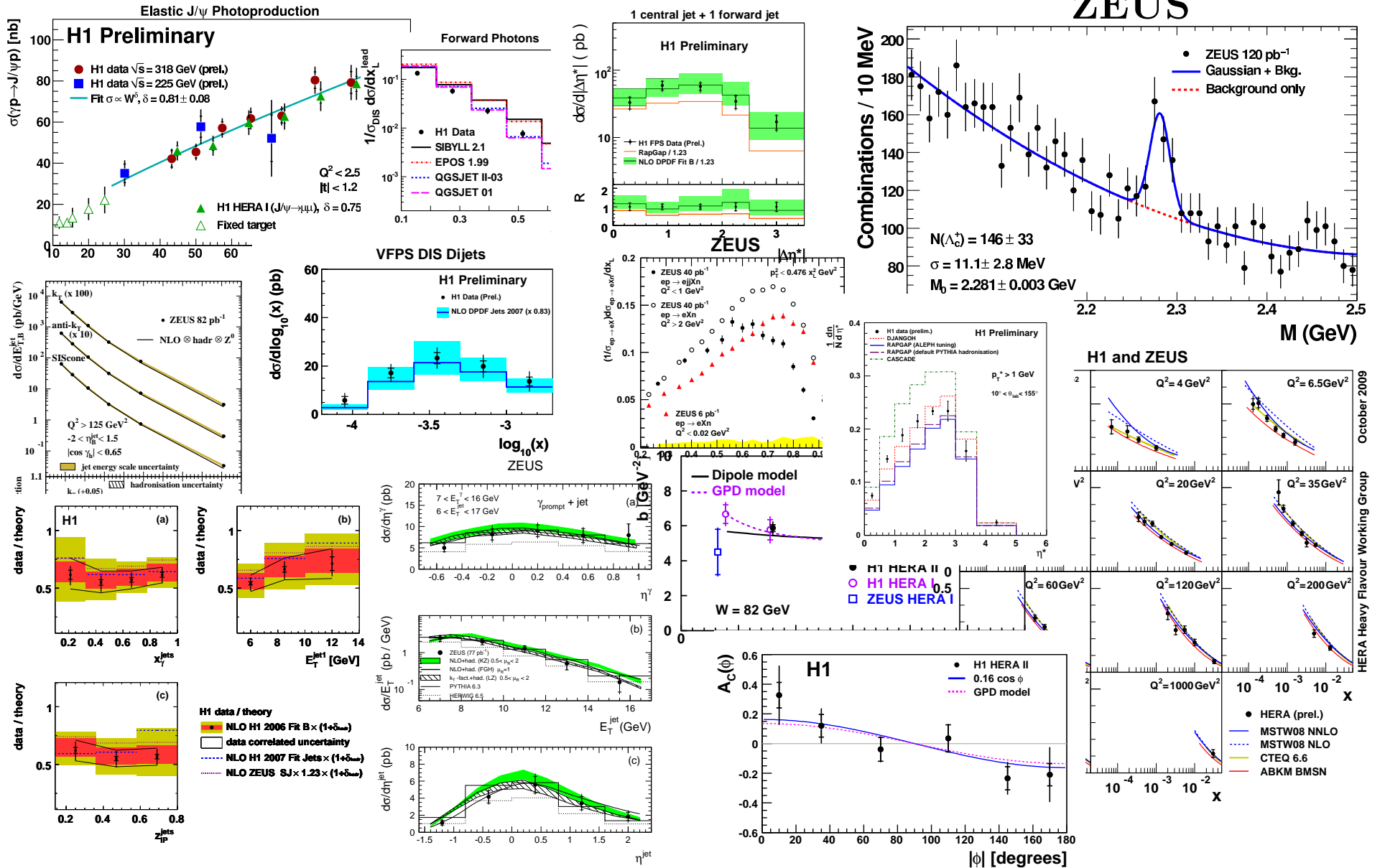
2011 LHC Data

HERA as a Super-microscope:

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

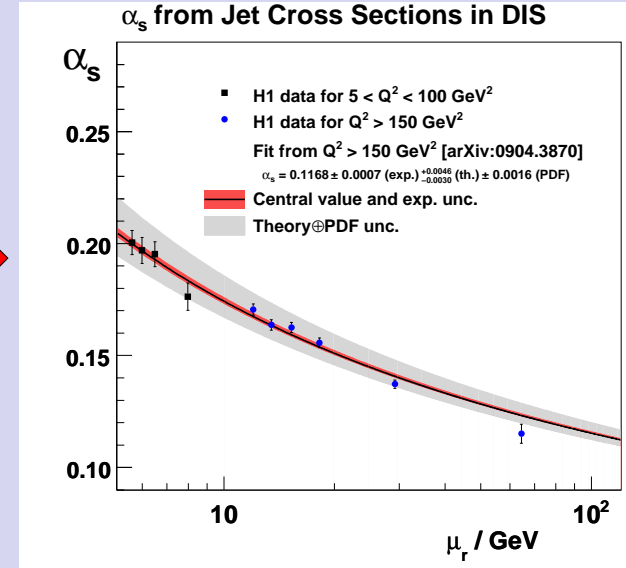
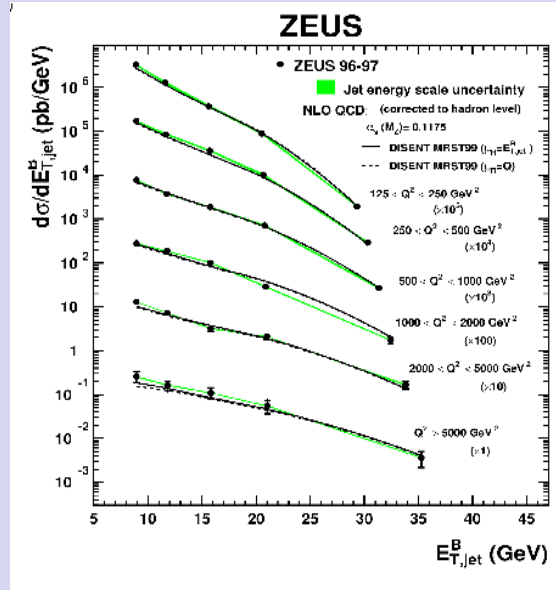
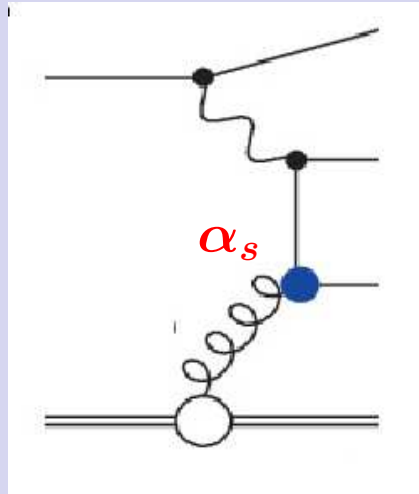
HERA as QCD factory

HERA as QCD factory



Jets at HERA

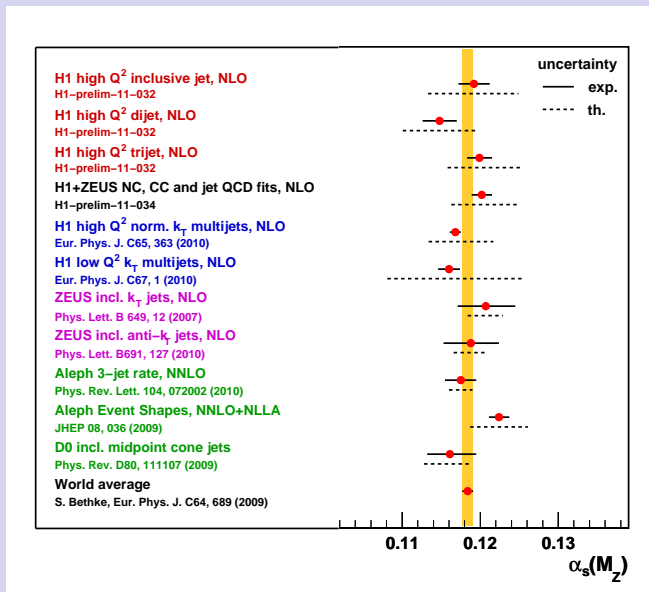
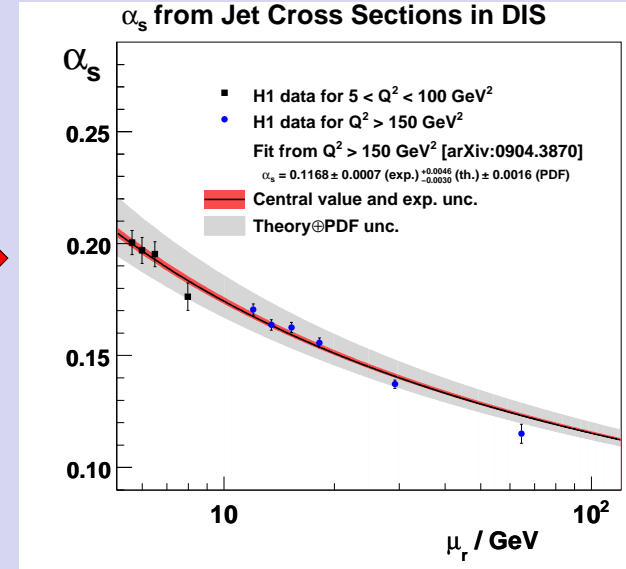
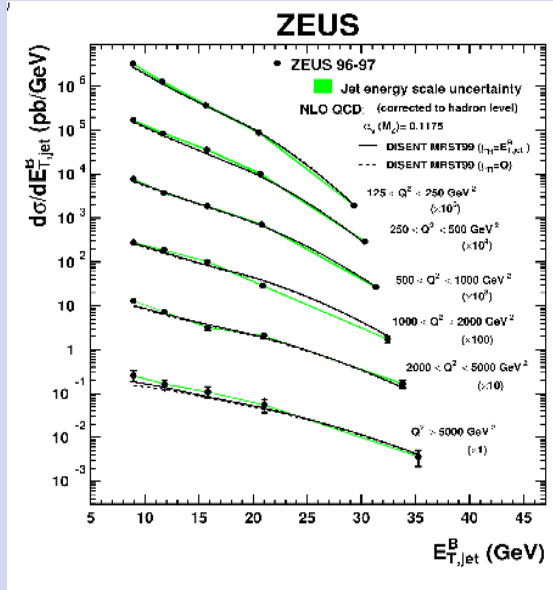
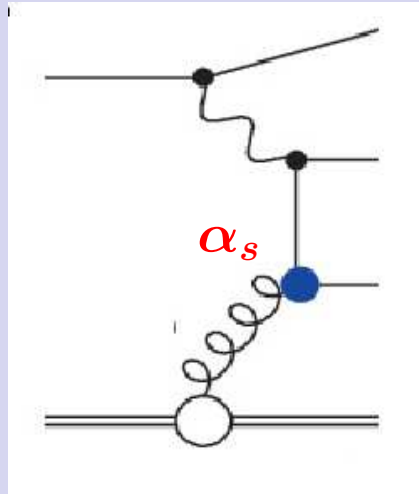
Precision QCD



Running α_s in a single experiment!

Jets at HERA

Precision QCD



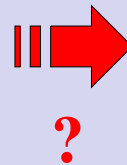
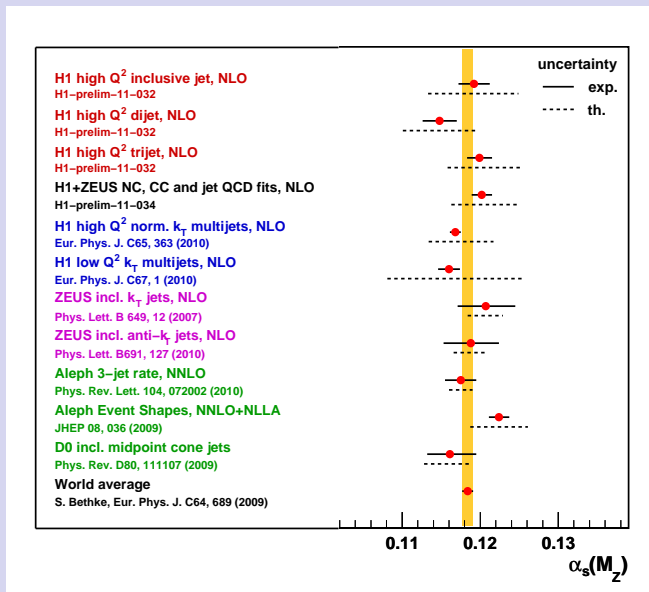
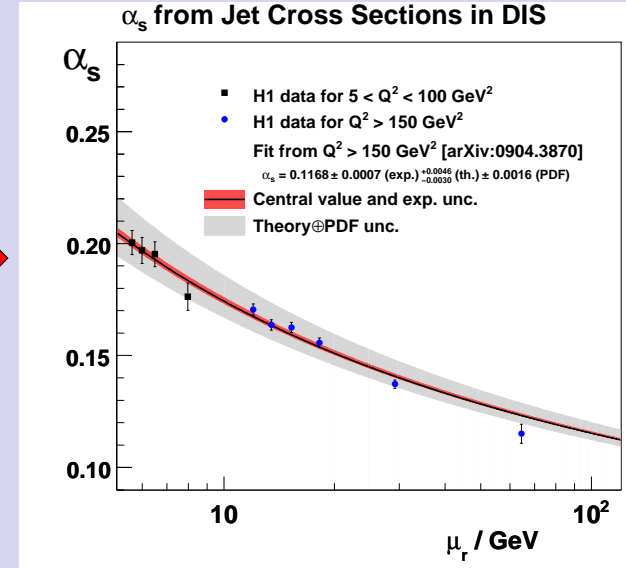
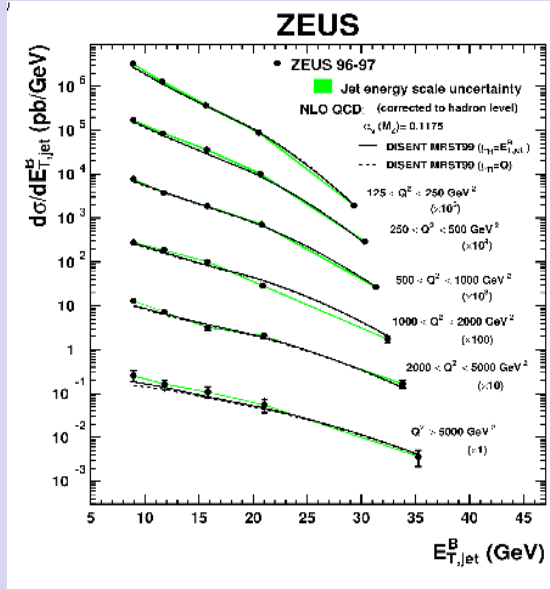
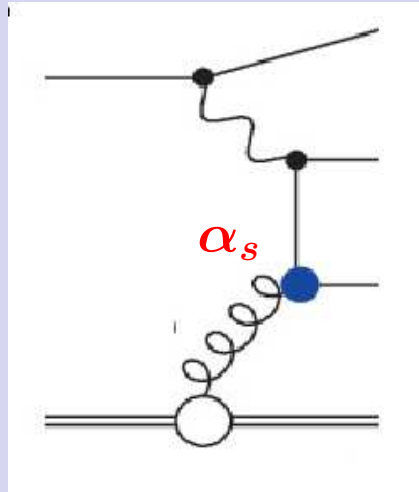
Running α_s in a single experiment!

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

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

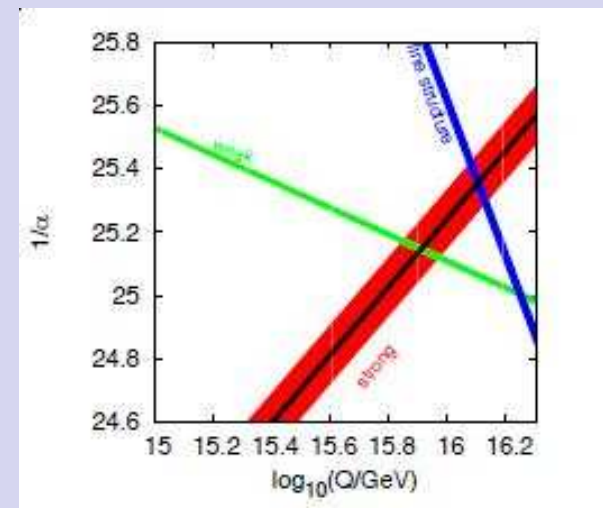
Jets at HERA

Precision QCD



Precision does matter!

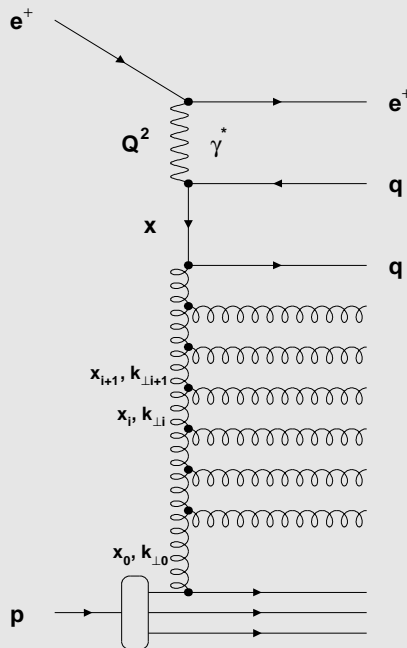
Grand Unification?



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 explicitly

\Rightarrow approximations needed



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

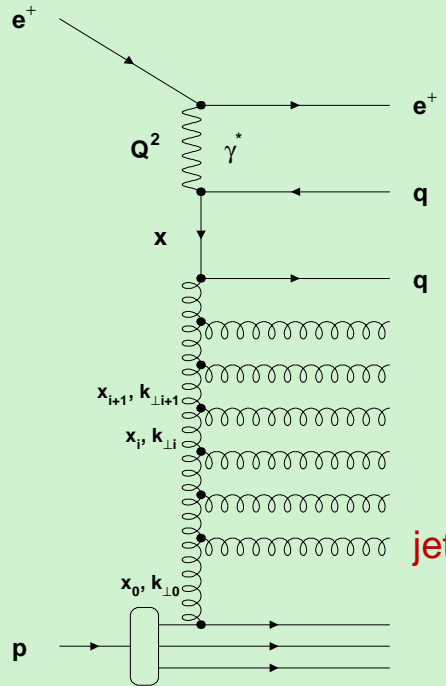
BFKL: resums $\ln(1/x)^n$ terms
no k_T ordering in partonic cascade \Rightarrow more hard gluons are radiated far from the hard interaction vertex

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

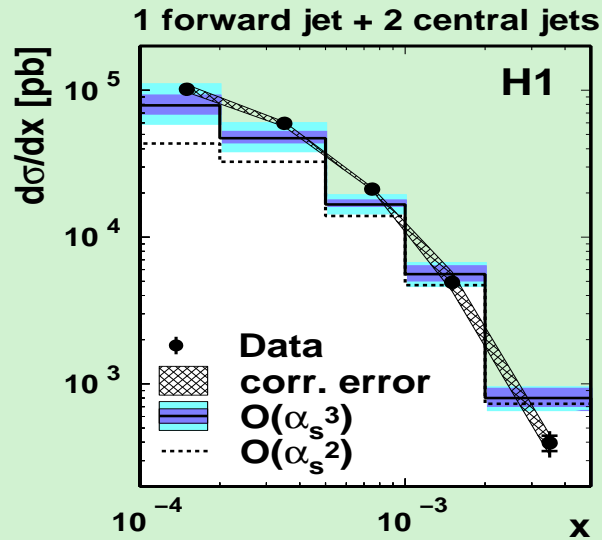
Jets at HERA: New dynamics?



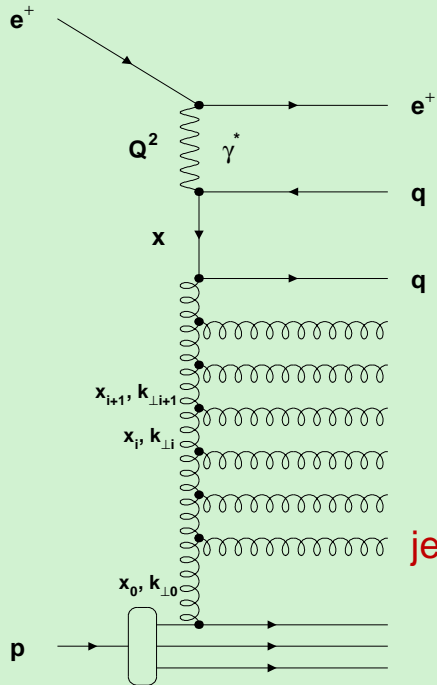
jet, $E_t > 4$ GeV

NLO DGLAP is OK

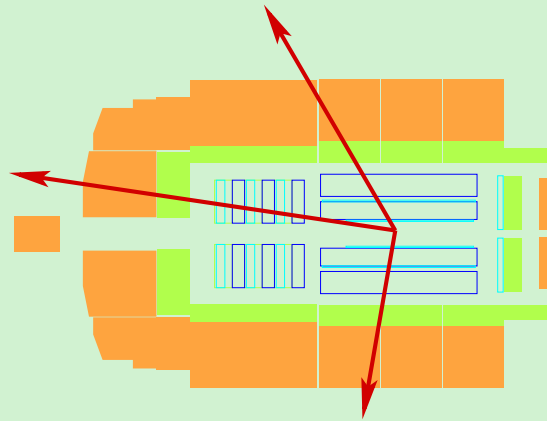
look at different topologies especially with forward jets



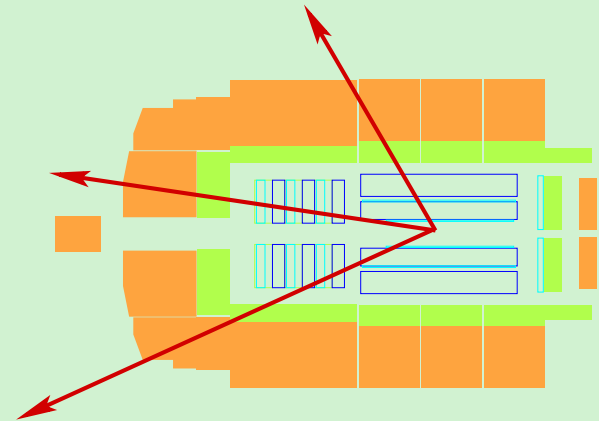
Jets at HERA: New dynamics?



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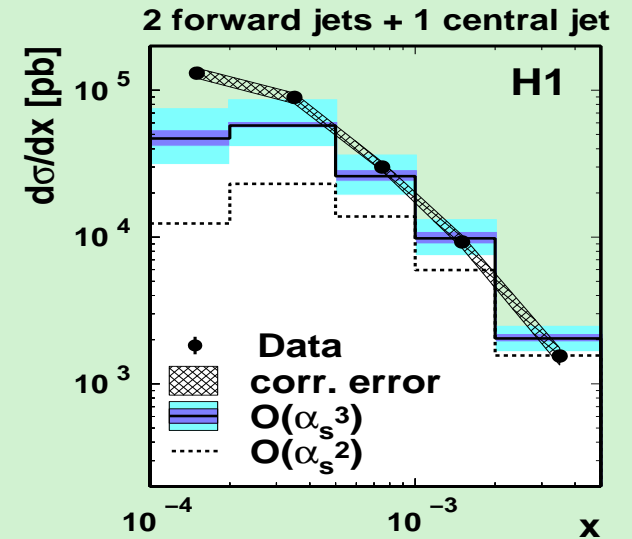
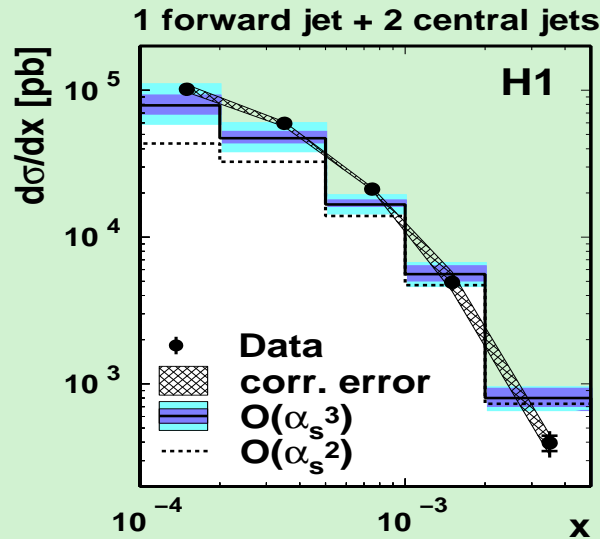
NLO DGLAP is OK



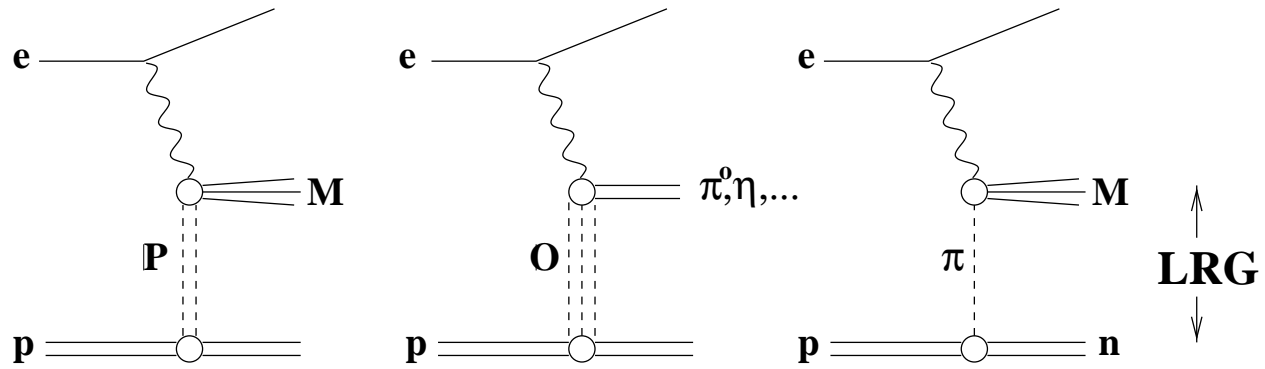
NLO DGLAP fails at low x

look at different topologies especially with forward jets

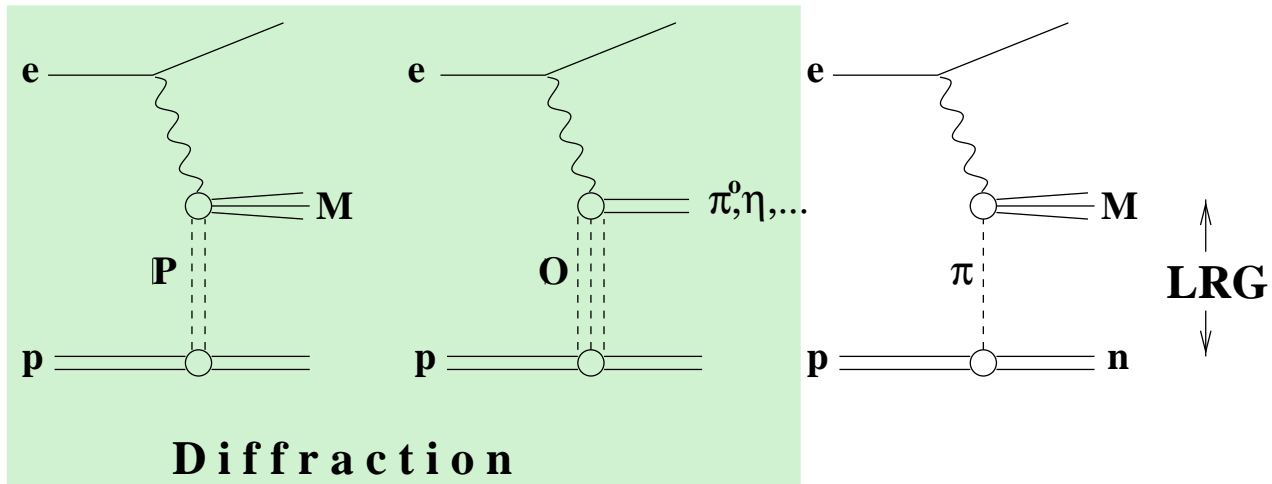
⇒ NLO DGLAP insufficient at low x ⇒ Room for non-DGLAP dynamics!



Diffraction



Diffraction

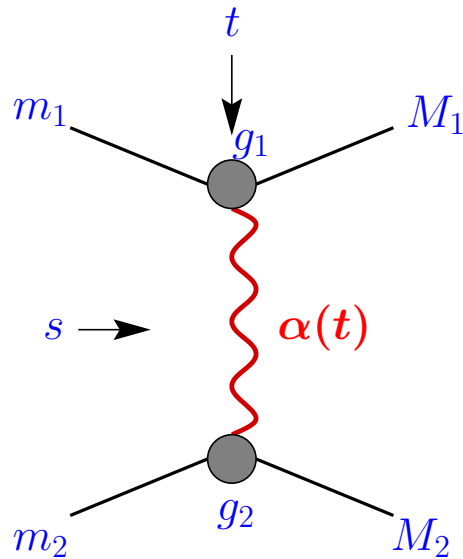


Diffraction in HEP =

Colorless exchange carrying vacuum quantum numbers

Two approaches to Strong Interactions

1. Regge Pole Model \Rightarrow RFT

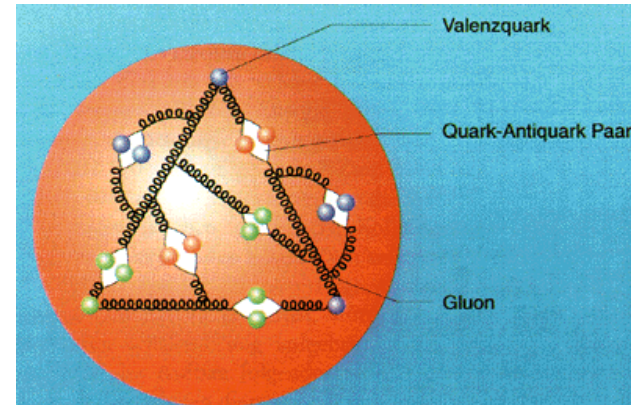


$$A(s, t) =$$

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

hadronic language

2. Quark-Parton Model \Rightarrow QCD



$$\sigma_{ab} =$$

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

sub-hadronic language

Ultimate goal: derive (1) from (2)

- **Hadronic** degrees of freedom
 - Validity: large $s \gg t$
 - \mathbb{P} dominates: $\alpha_{\mathbb{P}}(0) > \alpha_{\mathbb{R}}(0)$
 $\rightarrow \sigma_{\text{tot}} \propto s^{\alpha_{\mathbb{P}}(0)-1}$
 - Unitarity corrections unavoidable
 $(\sigma_{\text{tot}} \leq \ln^2(s/s_0) \text{ at } s \rightarrow \infty)$
 - When? $s_{\text{sat}} = ?$
 - First to be seen in diffraction: $\sigma_D \propto s^{2(\alpha-1)}$
- **Partonic** degrees of freedom
 - Low x : $W^2 \gg Q^2, t$ ($Q^2/W^2 \simeq x \ll 1$)
 - gluons dominate: $xg(x) \gg xq_{\text{val}}(x)$
 $F_2(x, Q^2) \propto xg(x) \sim x^{-\lambda}$
 - Saturation of the $xg(x)$
(non-linear effects, shadowing, ...)
 - $x_{\text{sat}}(Q_{\text{sat}}) = ?$
 - First to be seen in diffraction: $\sigma_D \propto |xg(x)|^2$

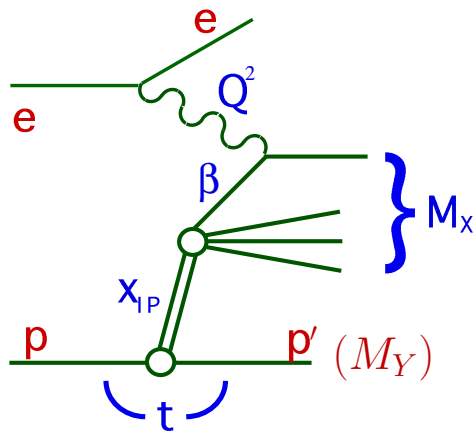
\Rightarrow Diffraction \equiv Physics of the Pomeron,
the essence of strong interactions

\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)



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

(momentum fraction of colour singlet exchange)

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

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

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

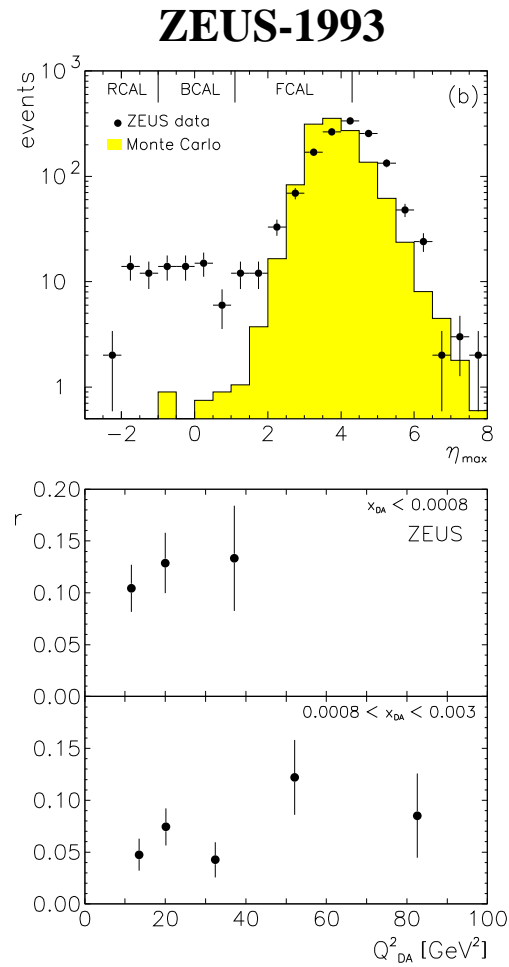
(4-momentum transfer squared)

Experimental methods:

- 1) selecting LRG events
- 2) detecting p in Roman Pots (60 – 220 m from IP)

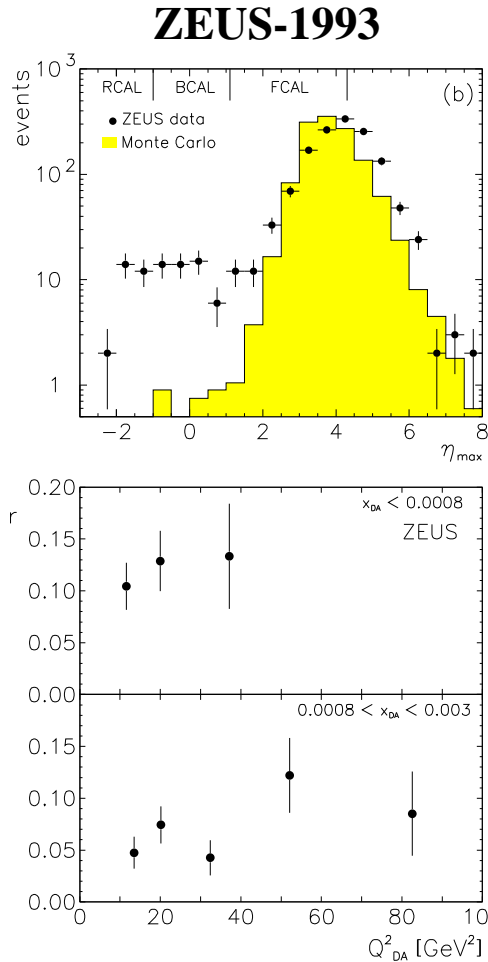


Inclusive Diffraction in DIS



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

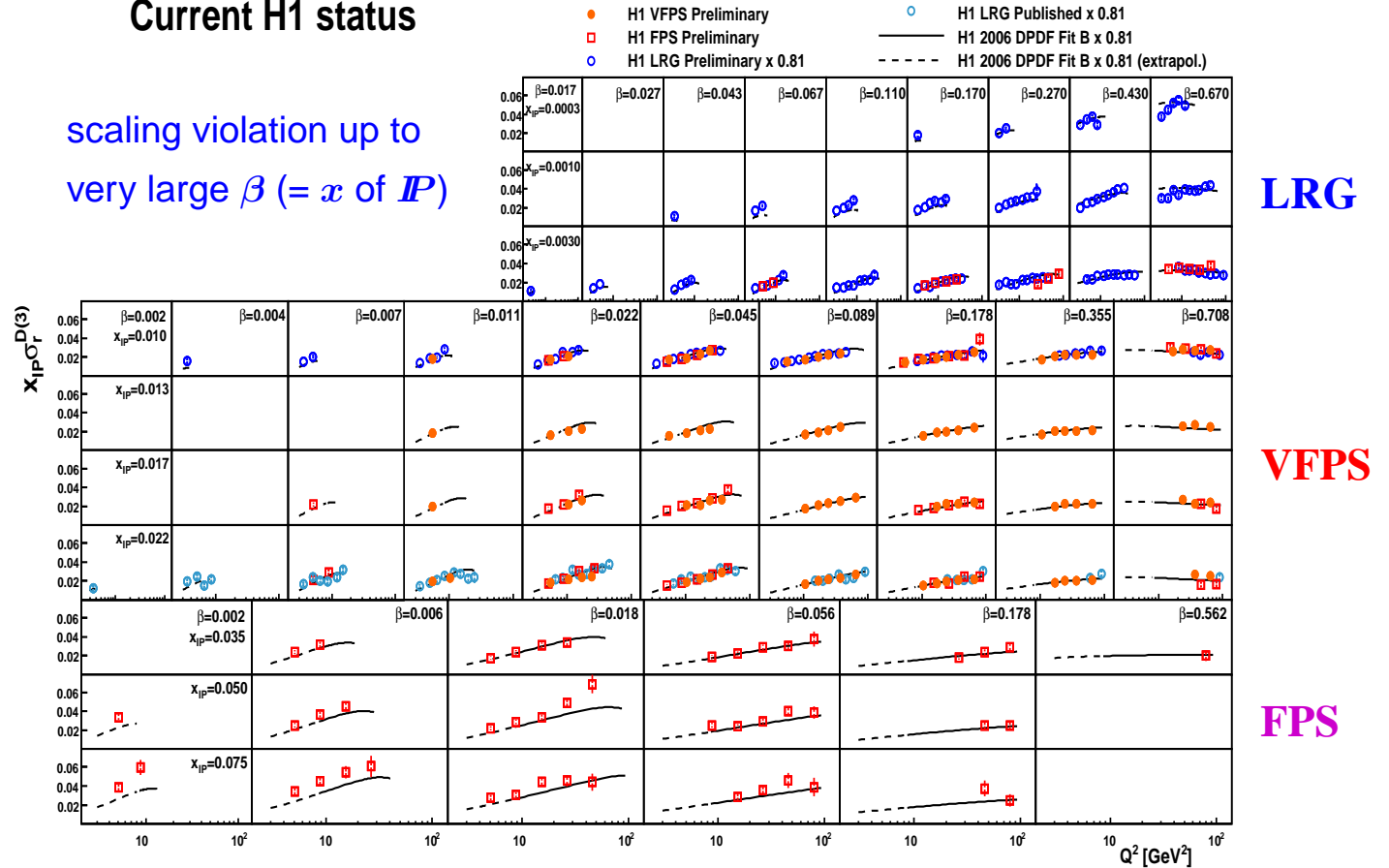
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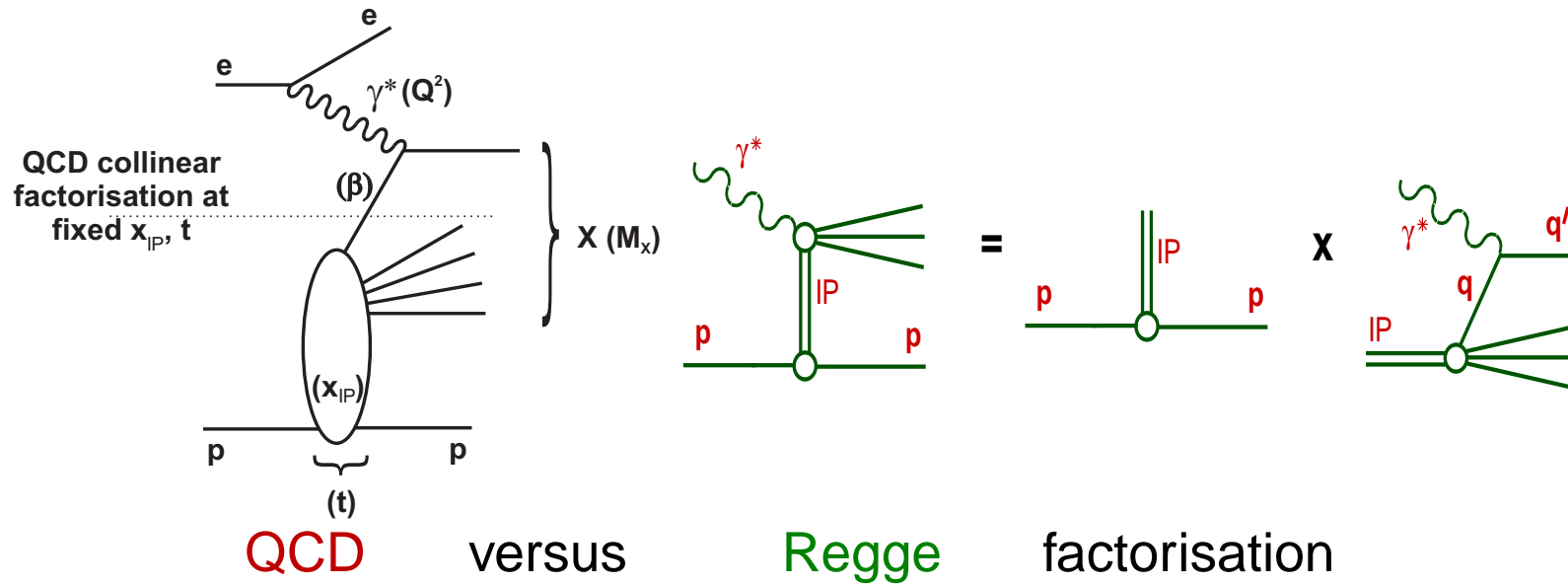
Current H1 status

scaling violation up to
very large $\beta (= x \text{ of } IP)$



- 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 factorisation

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

Regge factorisation

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

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

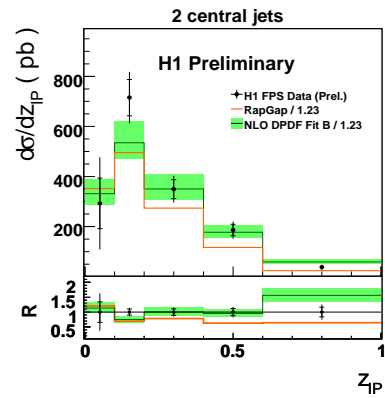
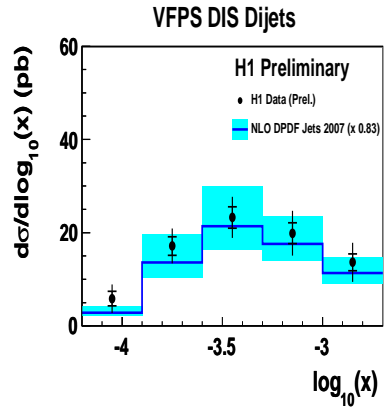
- $\hat{\sigma}^{\gamma^*i}$ – hard scattering part, same as in inclusive DIS
- f_i^D – diffractive PDF's, valid at fixed x_{IP}, t which obey (NLO) DGLAP

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

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

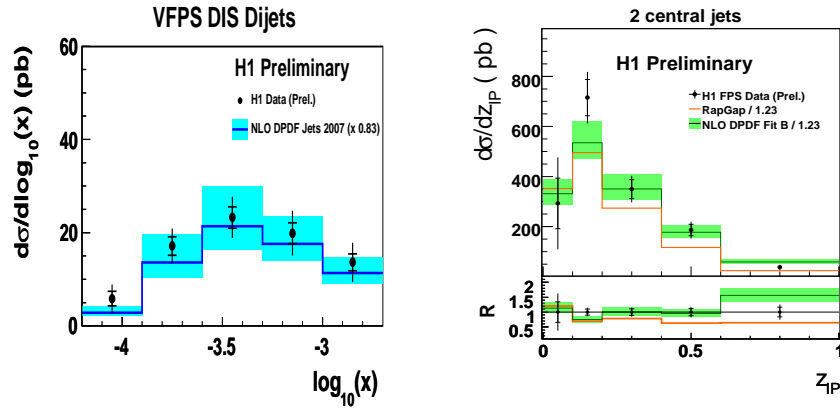
QCD Factorisation Tests in Diffraction at HERA

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

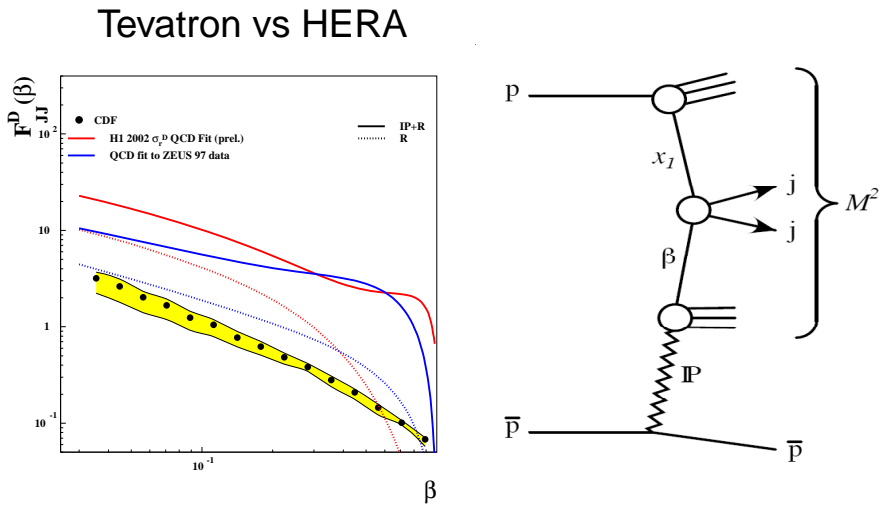


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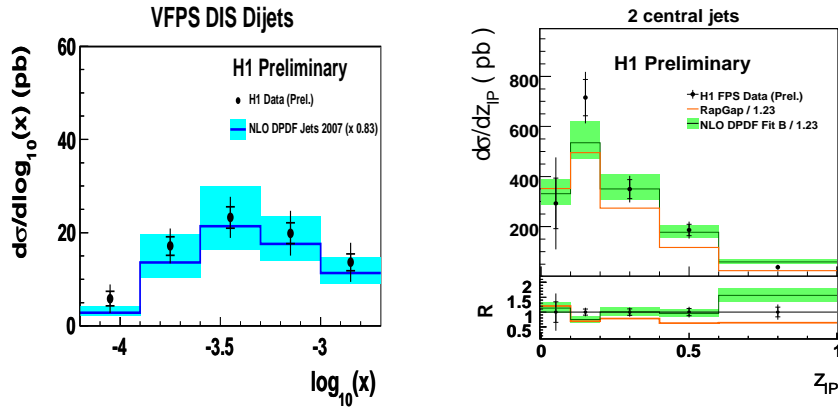


However, it breaks down at Tevatron ...



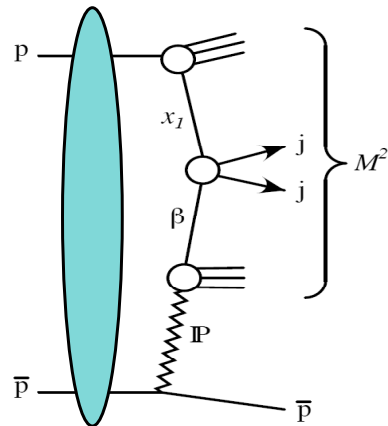
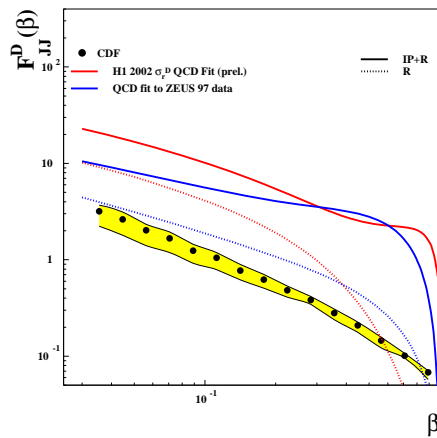
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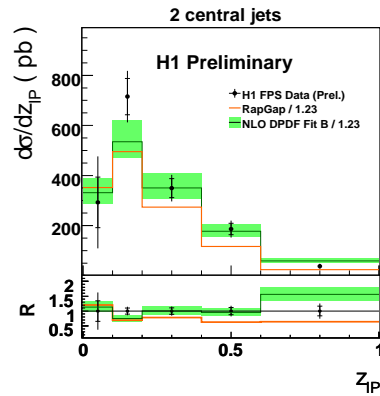
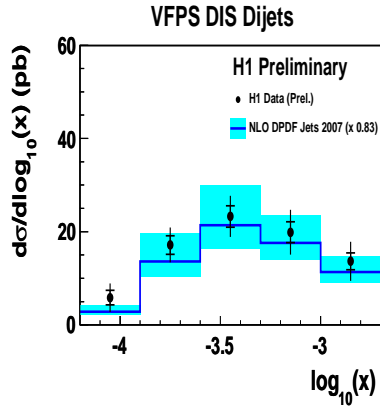
However, it breaks down at Tevatron ...
 ...due to soft remnant rescattering ($S \sim 0.15$)

Tevatron vs HERA



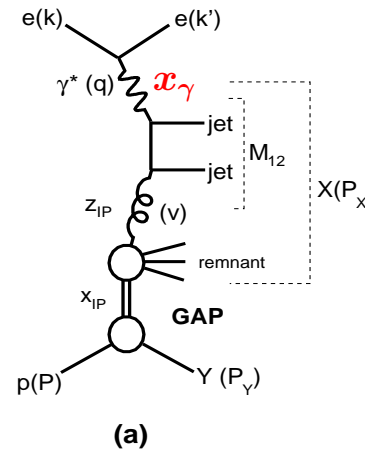
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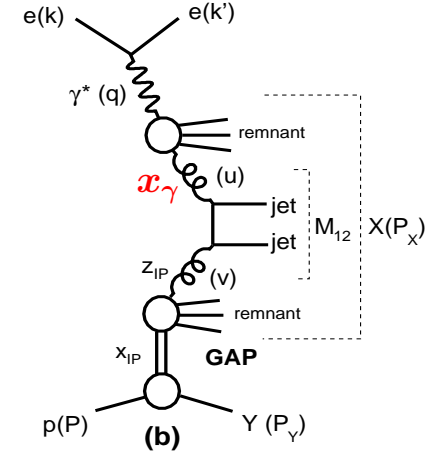


However, it breaks down at Tevatron ...
 ...due to soft remnant rescattering ($S \sim 0.15$)

⇒ Test it in photoproduction:

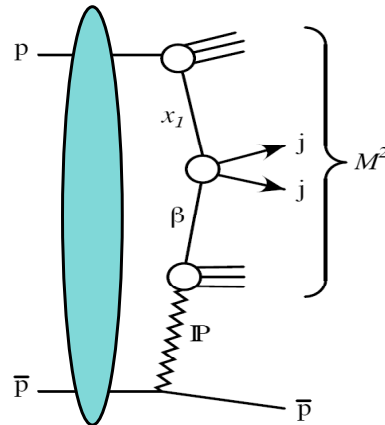
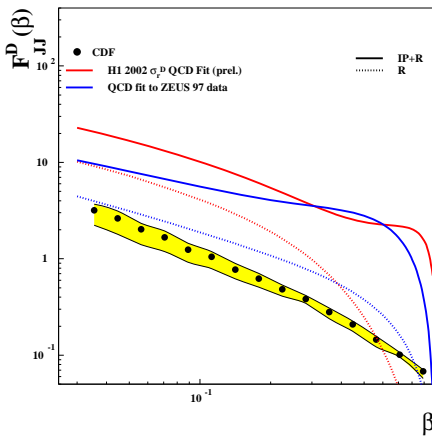


(a) direct, $x_\gamma = 1$ (DIS-like)



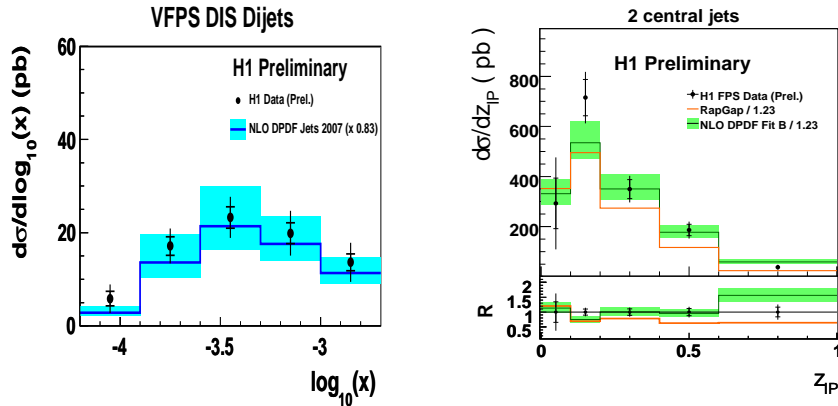
(b) resolved, $x_\gamma < 1$ (hadron-like)

Tevatron vs HERA



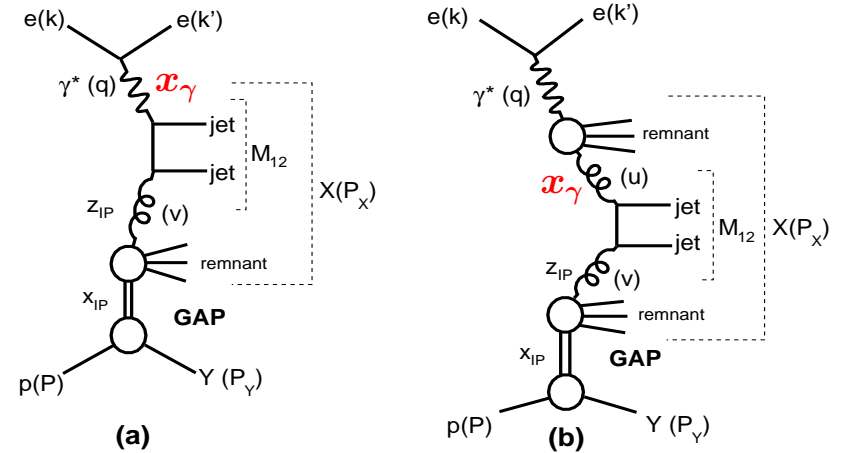
QCD Factorisation Tests in Diffraction at HERA

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



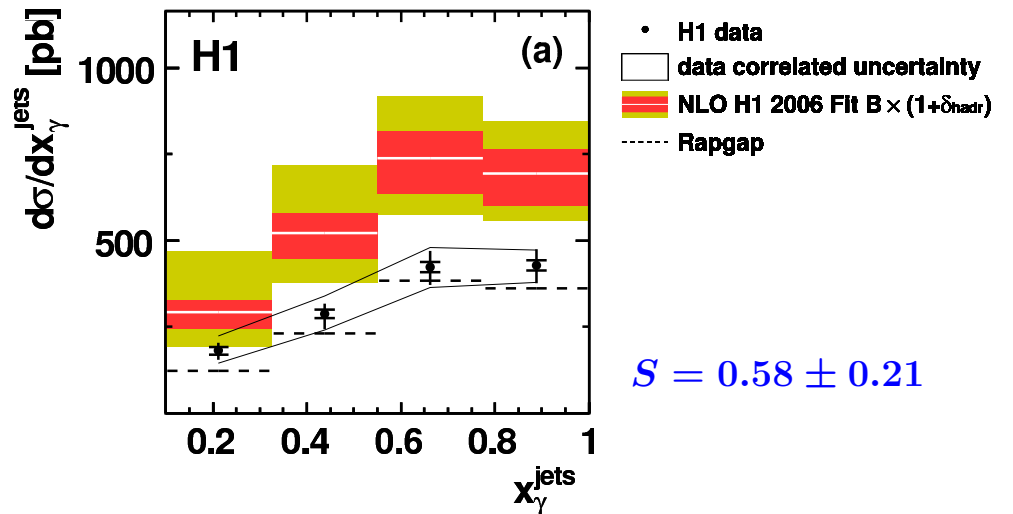
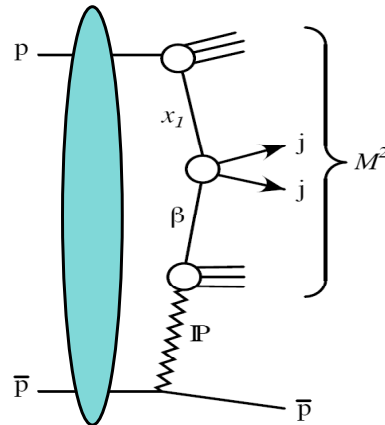
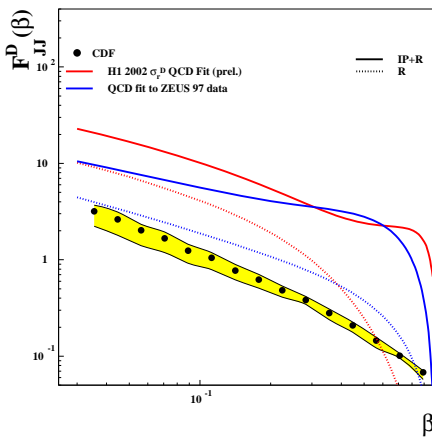
However, it breaks down at Tevatron ...
 ...due to soft remnant rescattering ($S \sim 0.15$)

⇒ Test it in photoproduction:



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

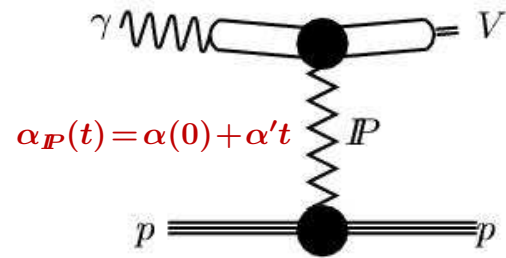
Tevatron vs HERA



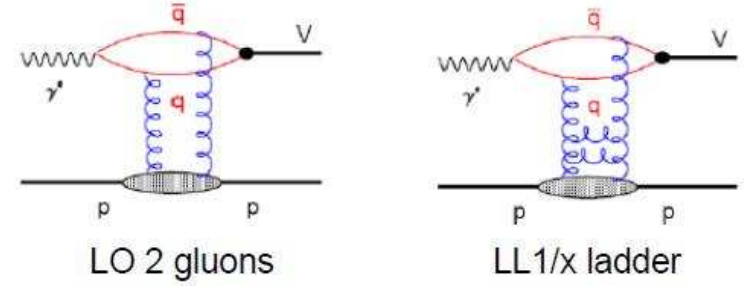
- Global, x_γ -independent suppression factor is observed – somewhat unexpected
- ⇒ Details of factorisation breaking mechanism in γp at HERA are not fully understood yet

Vector Mesons at HERA

soft \mathbb{P} omeron exchange

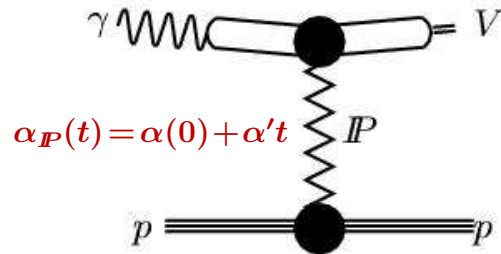


hard \mathbb{P} omeron diagrams



Vector Mesons at HERA

soft \mathbb{P} omeron exchange



Hard scales: Q^2, M_V, t

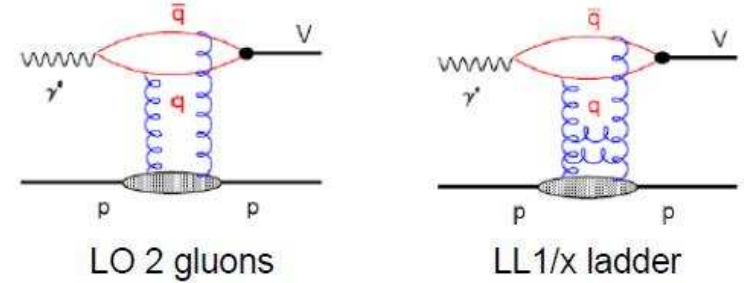
Predictions

$$\alpha_{\mathbb{P}}(0) \simeq 1.08 / 1.20$$

$$\alpha'_{\mathbb{P}} \simeq 0.25 / 0.0$$

$$\text{Universal scale } \mu^2 = (Q^2 + M_V^2)/4$$

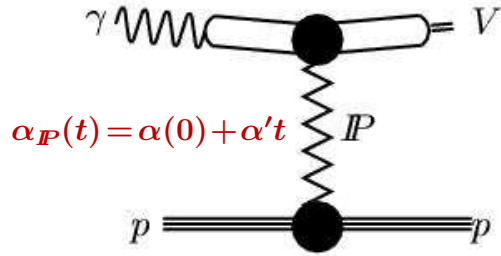
hard \mathbb{P} omeron diagrams



Exclusive VM production at HERA – a nice tool to study ‘soft’ vs ‘hard’ Pomeron regimes

Vector Mesons at HERA

soft \mathbb{P} omeron exchange



Hard scales: Q^2, M_V, t

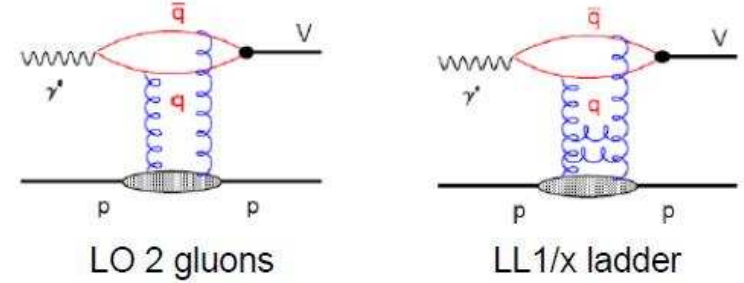
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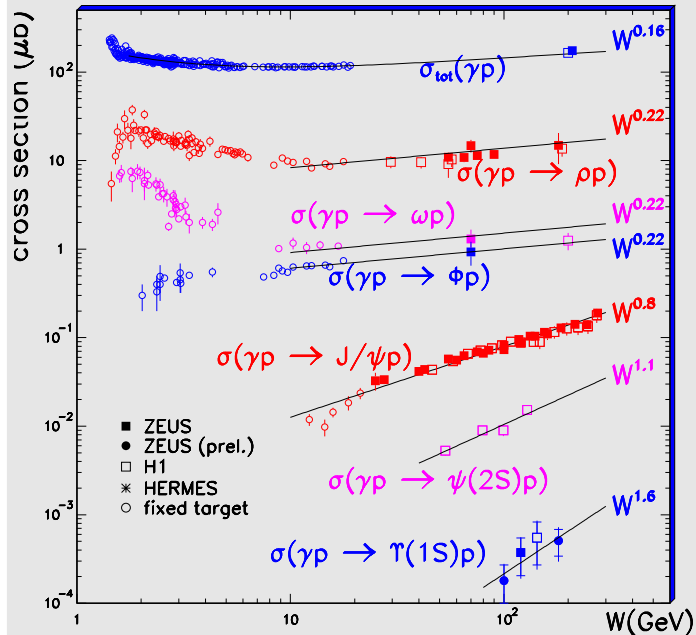
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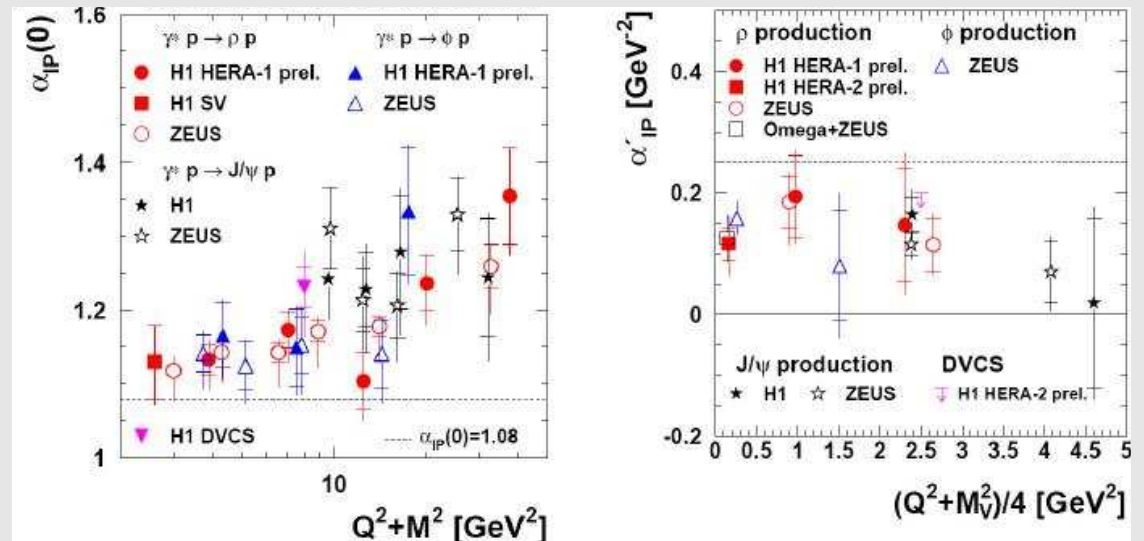
hard \mathbb{P} omeron diagrams



Exclusive VM production at HERA – a nice tool to study ‘soft’ vs ‘hard’ Pomeron regimes



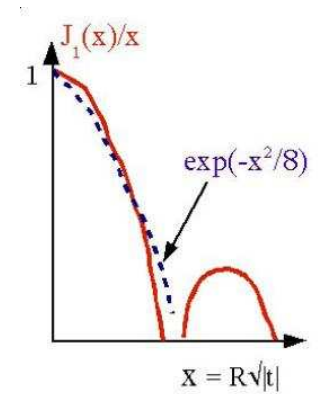
transition from soft to hard regime at $\mu^2 \simeq 4 \div 5 \text{ GeV}^2$



Vector Mesons at HERA: t –dependence

$d\sigma/dt \sim e^{-b|t|} \rightarrow$ diffractive peak (approximated from Bessel function)

$b = (R/2)^2 \rightarrow$ transverse size of the target (geometric picture)



Vector Mesons at HERA: t -dependence

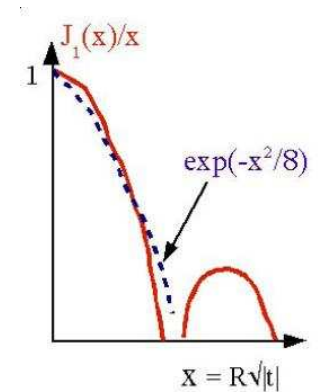
$d\sigma/dt \sim e^{-b|t|} \rightarrow$ diffractive peak (approximated from Bessel function)

$b = (R/2)^2 \rightarrow$ transverse size of the target (geometric picture)

Predictions: $b = b_0 + 4\alpha'_{\mathbb{P}} \ln(W/W_0);$

soft \mathbb{P} : shrinkage of diffractive peak ($\alpha'_{\mathbb{P}} = 0.25$); large $b_0 \approx 10 \text{ GeV}^{-2}$

hard \mathbb{P} : no (or small) shrinkage ($\alpha'_{\mathbb{P}} < 0.1$); small $b_0 \approx 5 \text{ GeV}^{-2}$



Vector Mesons at HERA: t -dependence

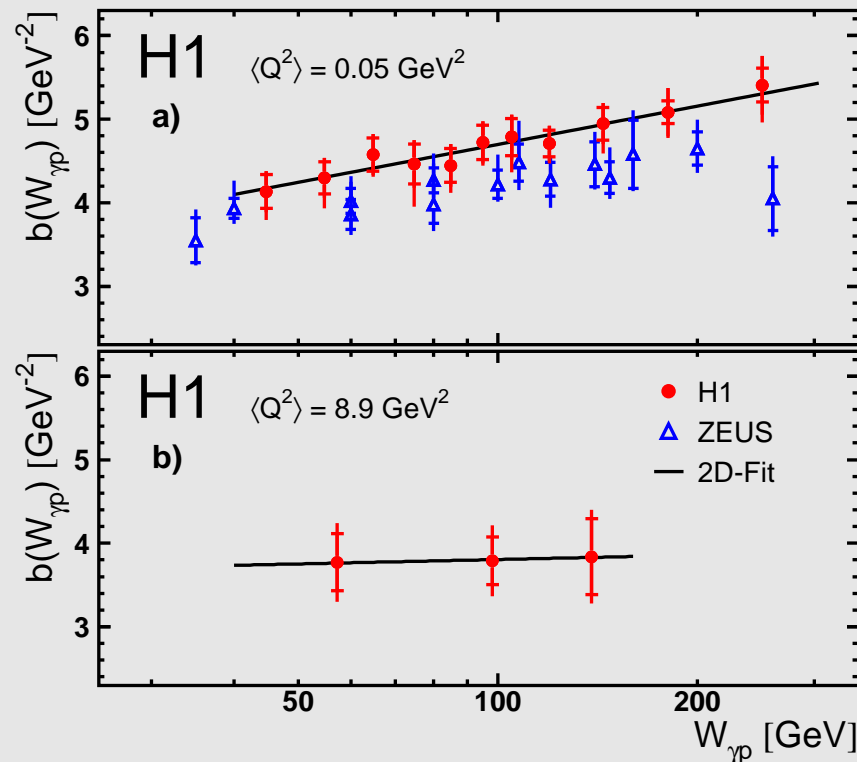
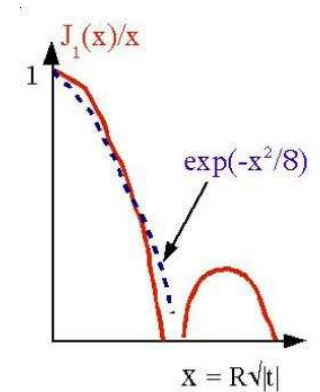
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Example: shrinkage in $\gamma^*p \rightarrow J/\psi p$

$Q^2 < 1 \text{ GeV}^2:$

$\alpha'_{\mathbb{P}} = 0.164 \pm 0.028 \pm 0.030$

$Q^2 = 2 - 80 \text{ GeV}^2:$

$\alpha'_{\mathbb{P}} = 0.019 \pm 0.139 \pm 0.076$

Vector Mesons at HERA: t -dependence

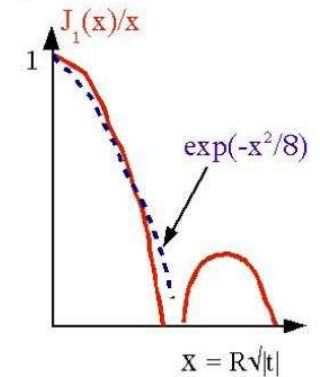
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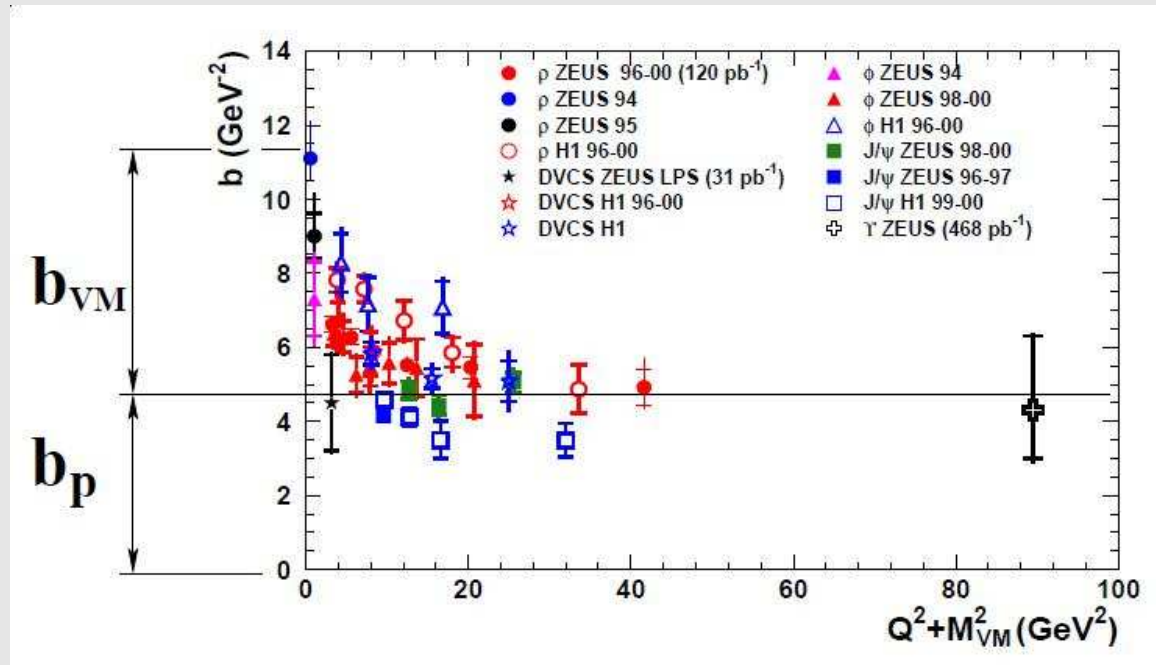
Dipole picture interpretation:

$$b = b_{VM} + b_p$$

$$b_{VM} \sim 1/(Q^2 + M_{VM}^2)$$

$b_p \rightarrow$ size of the gluons area:

$$\langle r^2 \rangle = 2b_p \cdot (\hbar c)^2 \simeq 0.6 \text{ fm}$$



⇒ Gluons confinement area (0.6 fm) is smaller than the proton size (0.8 fm)

Summary

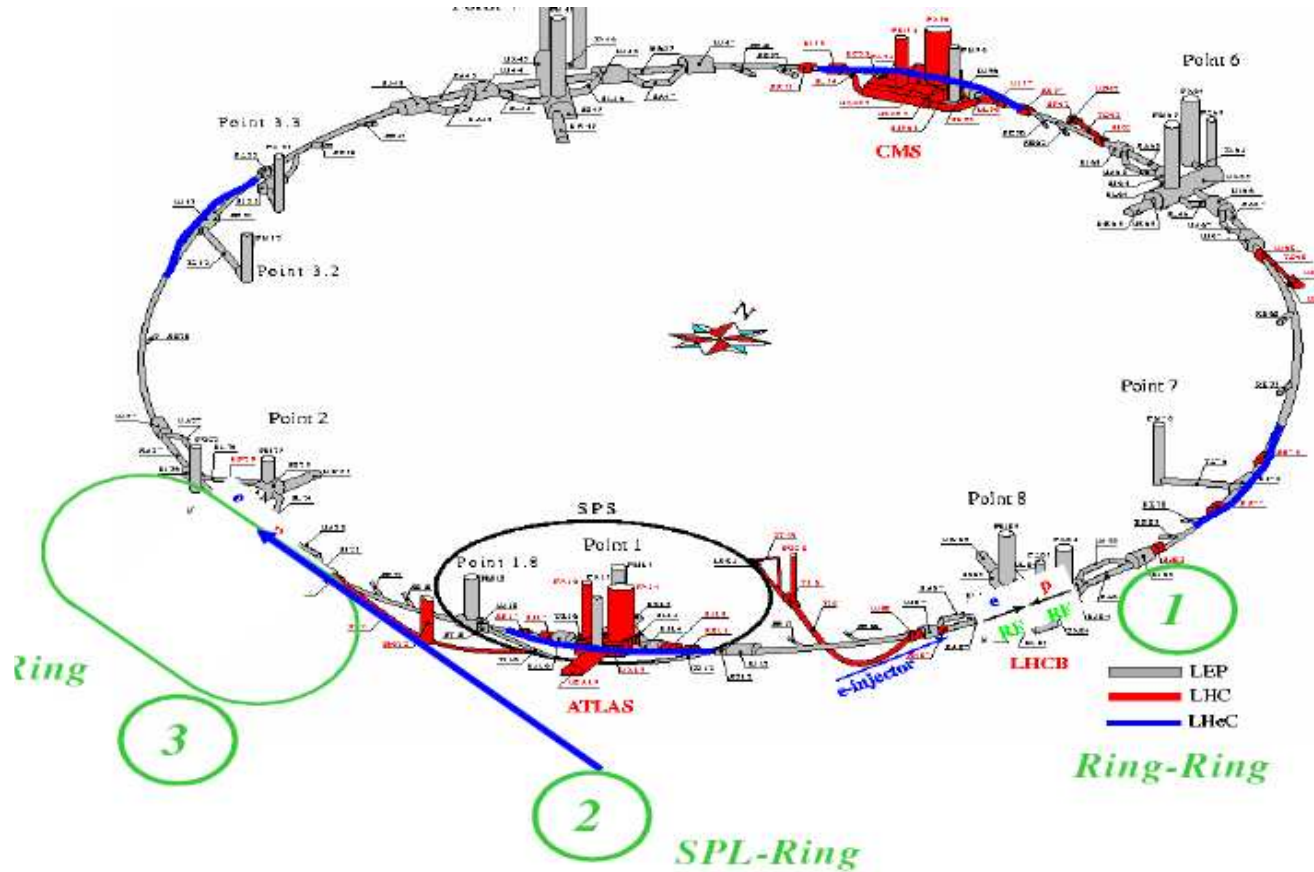
- Standard Model survived 1 fb^{-1} of **HERA** data and is still in a good shape. Next challenge is now coming from the **LHC** - stay tuned!
- Combining H1 and ZEUS data allowed proton structure to be measured with unprecedented precision
- NLO DGLAP is surprisingly successful down to low Q^2 and low 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:

~ 2022 – 2032



$$e^{\pm}p$$

$$(60 - 140)\text{GeV} \times 7000 \text{ GeV}$$

$$\sqrt{s} \approx (4 - 6) \times \text{HERA}$$

$$\mathcal{L} \approx (50 - 100) \times \text{HERA}$$

■ Fixed target experiments

- ▷ **Rutherford** – 1911 (7 MeV, αAu)
structure of atoms \Rightarrow planetary model \Rightarrow 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 \Rightarrow quarks \Rightarrow 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?