Selected topics
in
High-energy QCD physics

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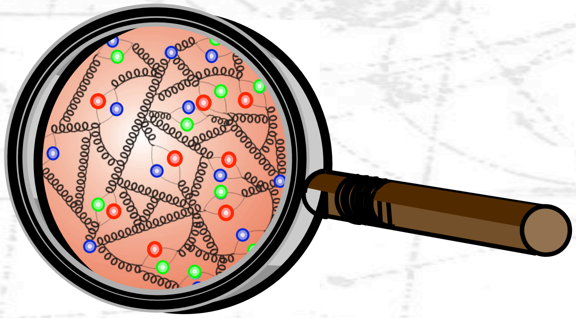
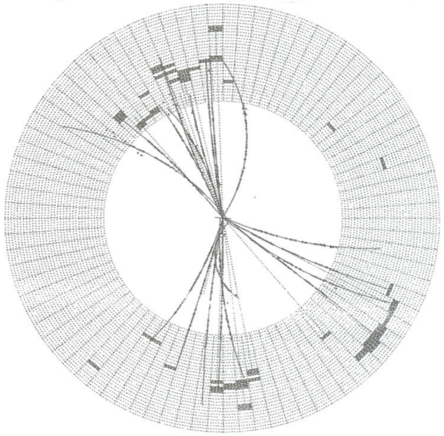
Outline

- Introduction

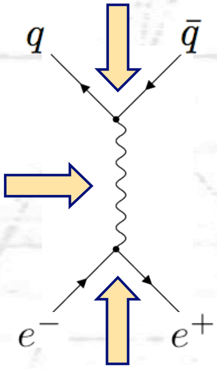


- QCD basics

- Experimental aspects



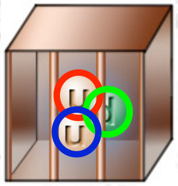
- Selected QCD topics at high-energy collider experiments
  - Electron - Positron
  - Electron - Proton
  - Proton - Anti-proton / Proton - Proton



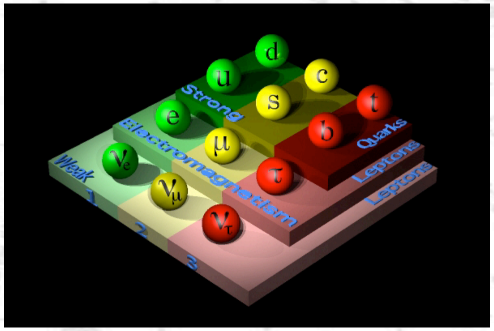
- Summary and Outlook

Introduction

- Quantum Chromo Dynamics

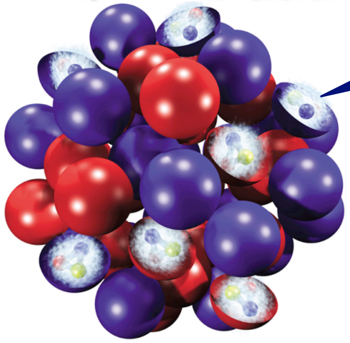


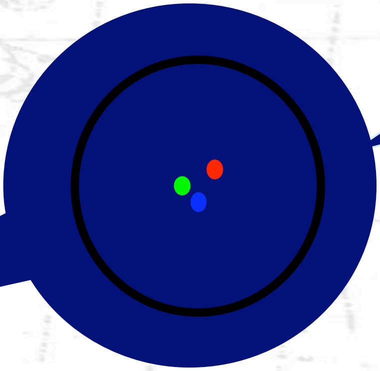
Proton=uud



Visible Universe

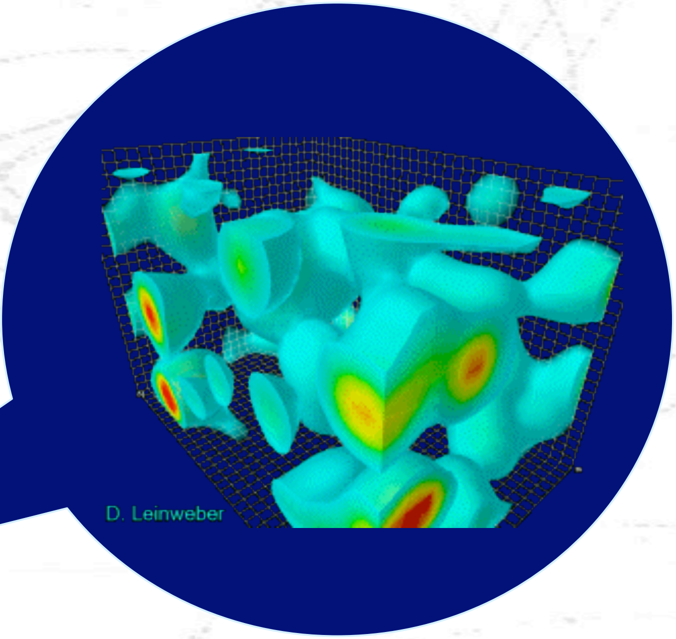
Galaxies, stars, people,...





Protons & Neutrons

3 valence quarks +...


D. Leinweber

Silent Partners:

Virtual quark-antiquark pairs $(\Delta E\ \Delta t \sim h)$

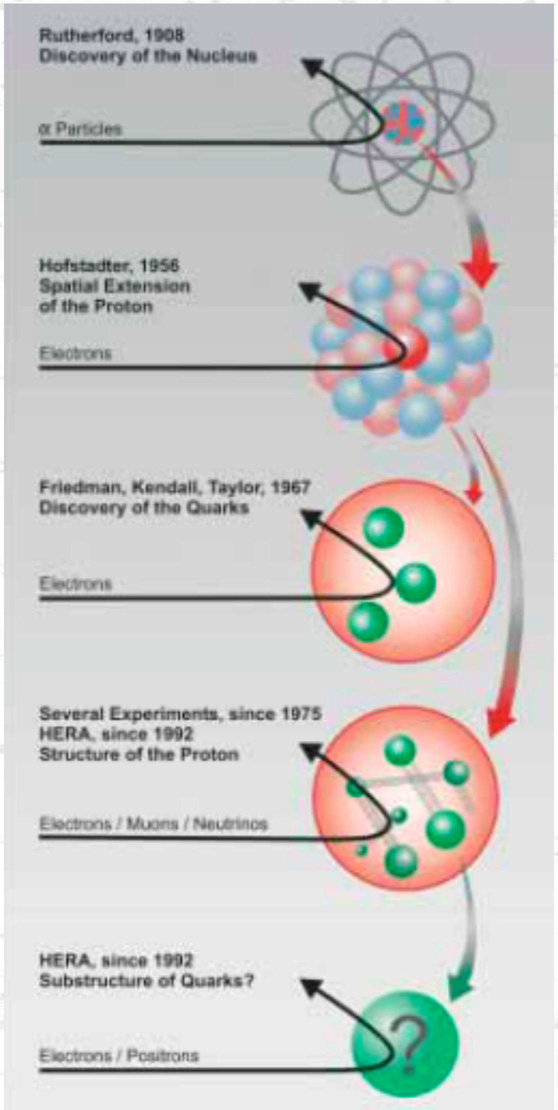
Gluons!

Structure and dynamics of proton (mass) (→ visible universe) originates from QCD-interactions!

What about spin as another fundamental quantum number?

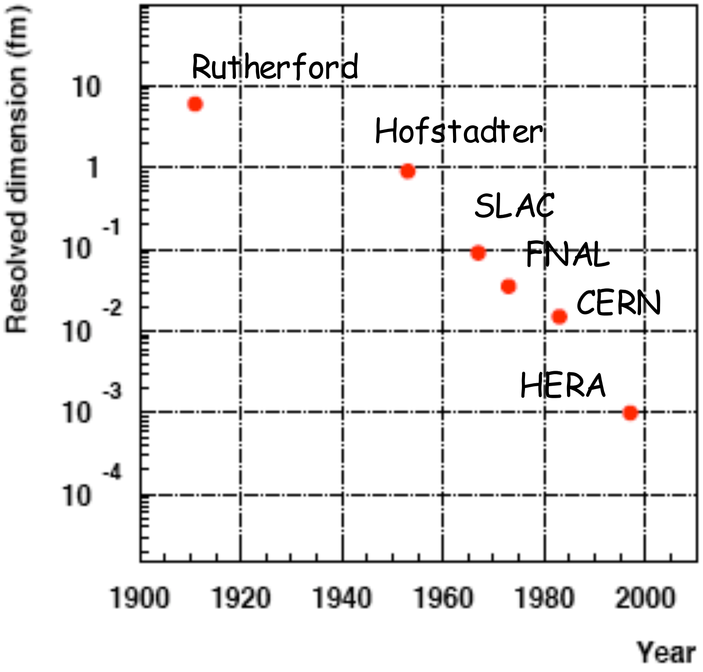
Introduction

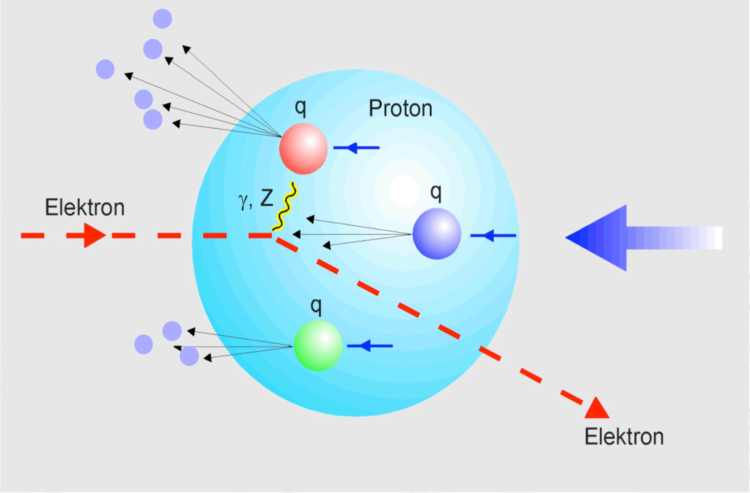
- General considerations on scattering experiments



Probing smaller distances requires larger momentum transfer q (small wavelength λ)

- Measurement of the final-state (**scattered electron**): ⇒ Structure of **target**!
- Scatter point-like **probe** onto object (**target**)





Introduction

- Exploring nuclear structure - elastic electron-nucleus scattering
  - Scattering of electron (Spin 1/2) on point-charge charge (Spin 0): Mott cross-section

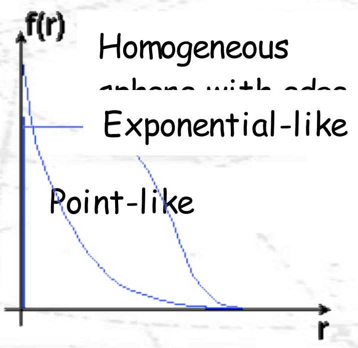
$$\left(\frac{d\sigma}{d\Omega}\right)^{*}_{Mott} = \left(\frac{d\sigma}{d\Omega}\right)_{Rutherford} \cdot \cos^2(\theta/2)$$

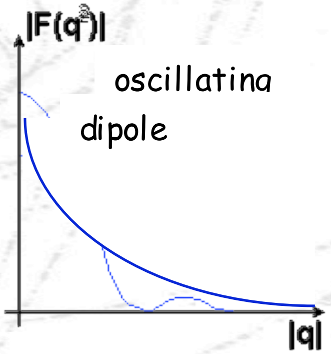
  - Take into account finite charge distribution: Form factor

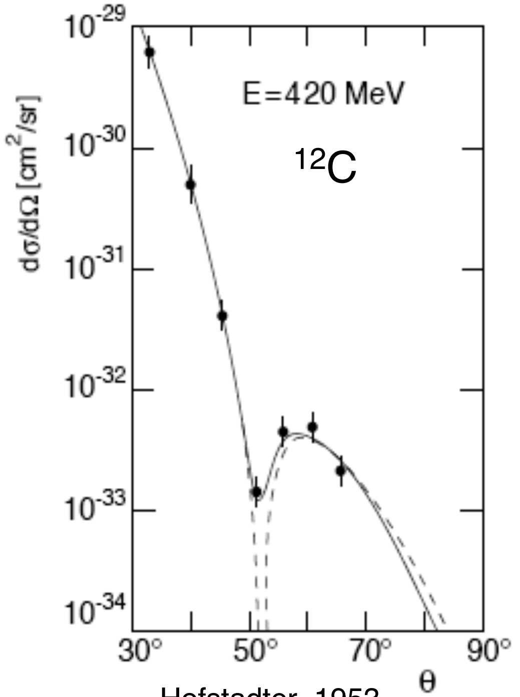
$$\left(\frac{d\sigma}{d\Omega}\right)_{exp} = \left(\frac{d\sigma}{d\Omega}\right)^{*}_{Mott} \cdot \left|F(q^2)\right|^2$$

$$\left(\frac{d\sigma}{d\Omega}\right)_{Mott} = \left(\frac{d\sigma}{d\Omega}\right)^{*}_{Mott} \frac{E'}{E}$$

Ignore recoil!







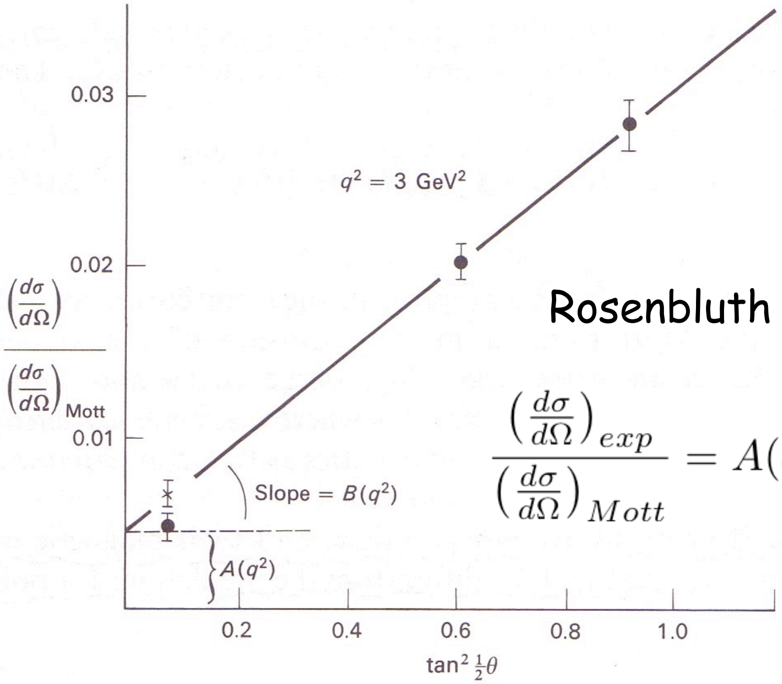
Hofstadter, 1953

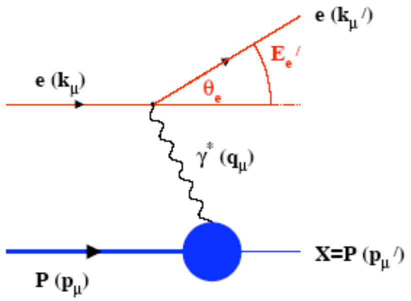
Introduction

- Exploring the Proton structure - elastic ep scattering
  - Scattering of electron (Spin 1/2) on proton (Spin 1/2)

$$\left(\frac{d\sigma}{d\Omega}\right)_{point} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \{1 + 2\tau \tan^2(\theta/2)\}$$

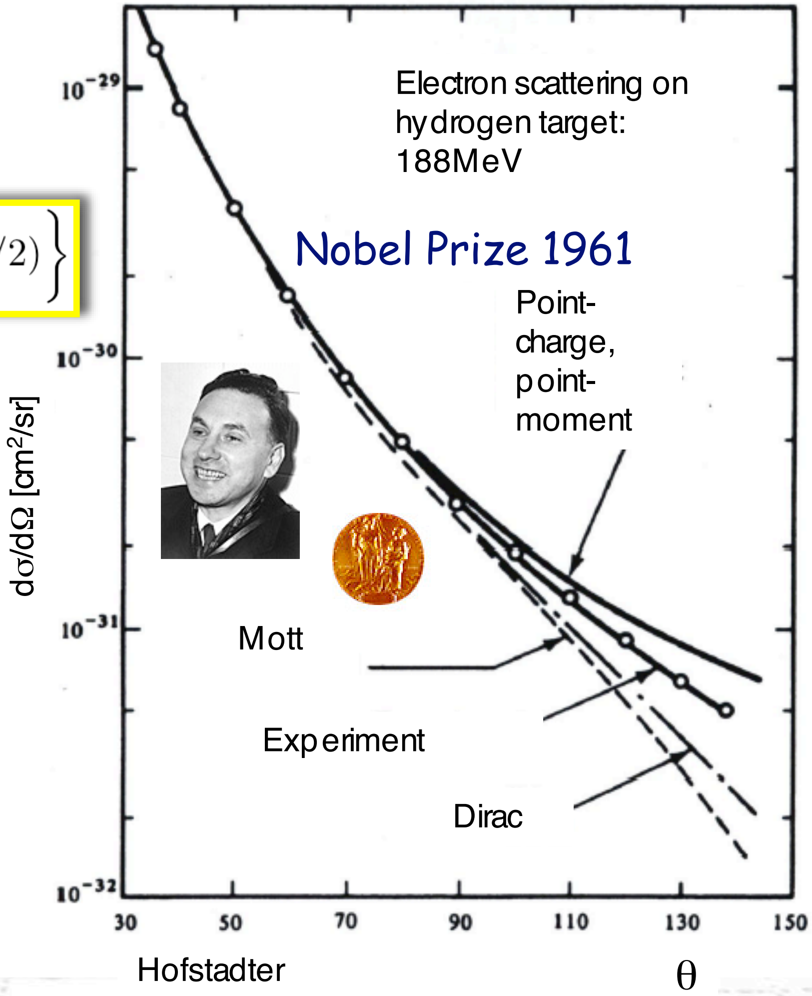
$$\left(\frac{d\sigma}{d\Omega}\right)_{exp} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \left\{\frac{G_E^2(q^2) + \tau G_M^2(q^2)}{1+\tau} + 2\tau G_M^2(q^2)\tan^2(\theta/2)\right\}$$





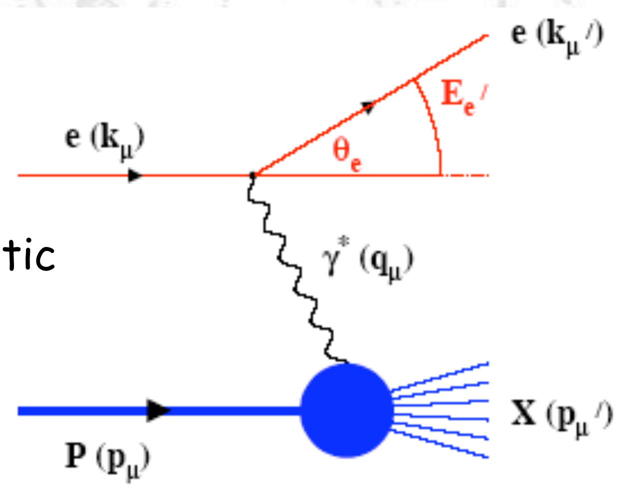
Rosenbluth separation method:

$$\frac{\left(\frac{d\sigma}{d\Omega}\right)_{exp}}{\left(\frac{d\sigma}{d\Omega}\right)_{Mott}} = A(q^2) + B(q^2)\tan^2(\theta/2)$$



Introduction

- Exploring the Proton structure - inelastic ep scattering
  - Scattering of electron (Spin 1/2) on proton (Spin 1/2)

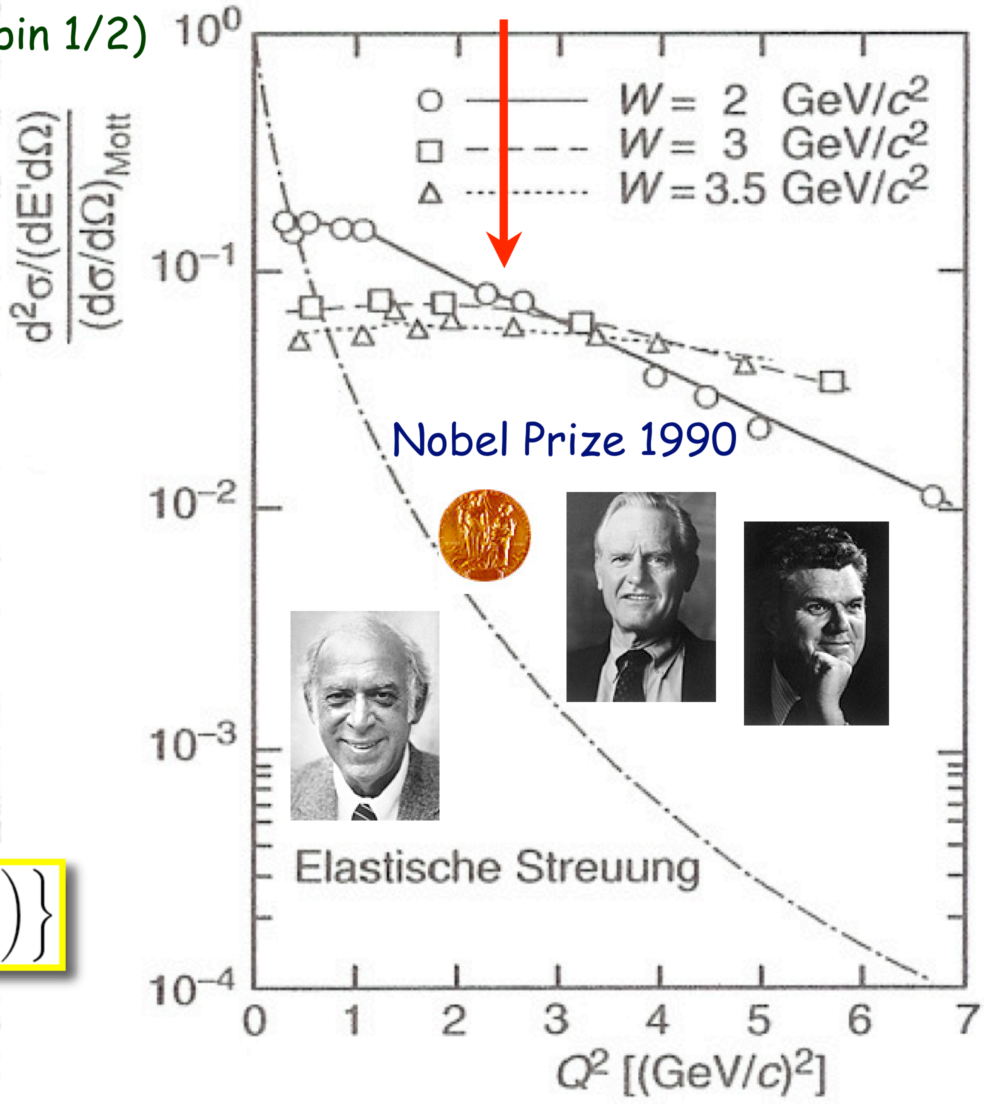


Here: Deep-inelastic scattering (DIS)

$$\left(\frac{d\sigma}{d\Omega}\right) = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \frac{E'}{E}\left\{1+2\tau\tan^2\left(\frac{\theta}{2}\right)\right\}$$

$$\left(\frac{d^2\sigma}{dE'd\Omega}\right) = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \left\{W_2(Q^2,x)+2W_1(Q^2,x)\tan^2\left(\frac{\theta}{2}\right)\right\}$$

Scattering on point-like objects: Quarks!



Nobel Prize 1990

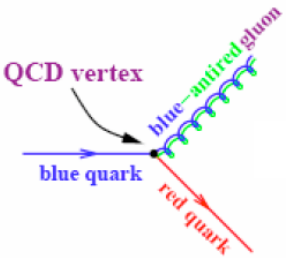
Friedman, Kendall and Taylor

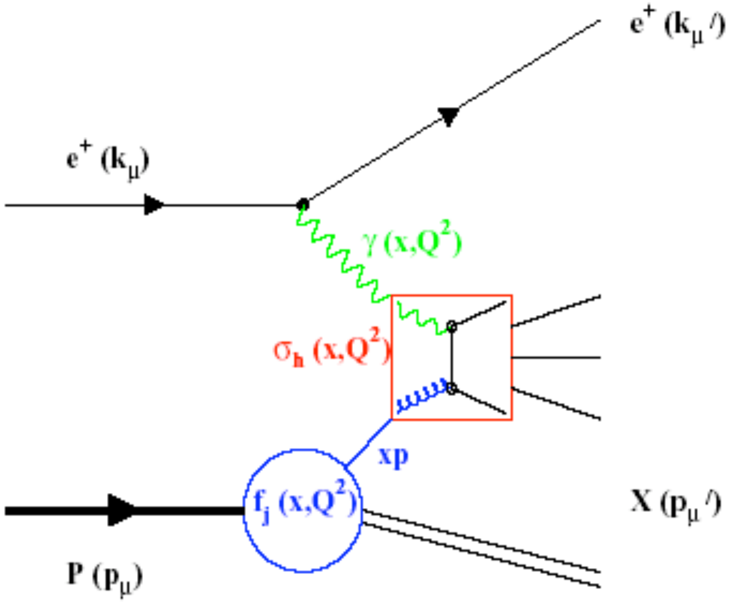
QCD basics

- Fundamental QCD ingredients
  - Asymptotic freedom:

$\alpha_s \rightarrow 0$ at short distances:
$\Rightarrow$ perturbatve QCD

α_s large at long distances:
$\Rightarrow$ non-perturbative QCD





  - Factorization: hard scale Q^2, m_c, m_b

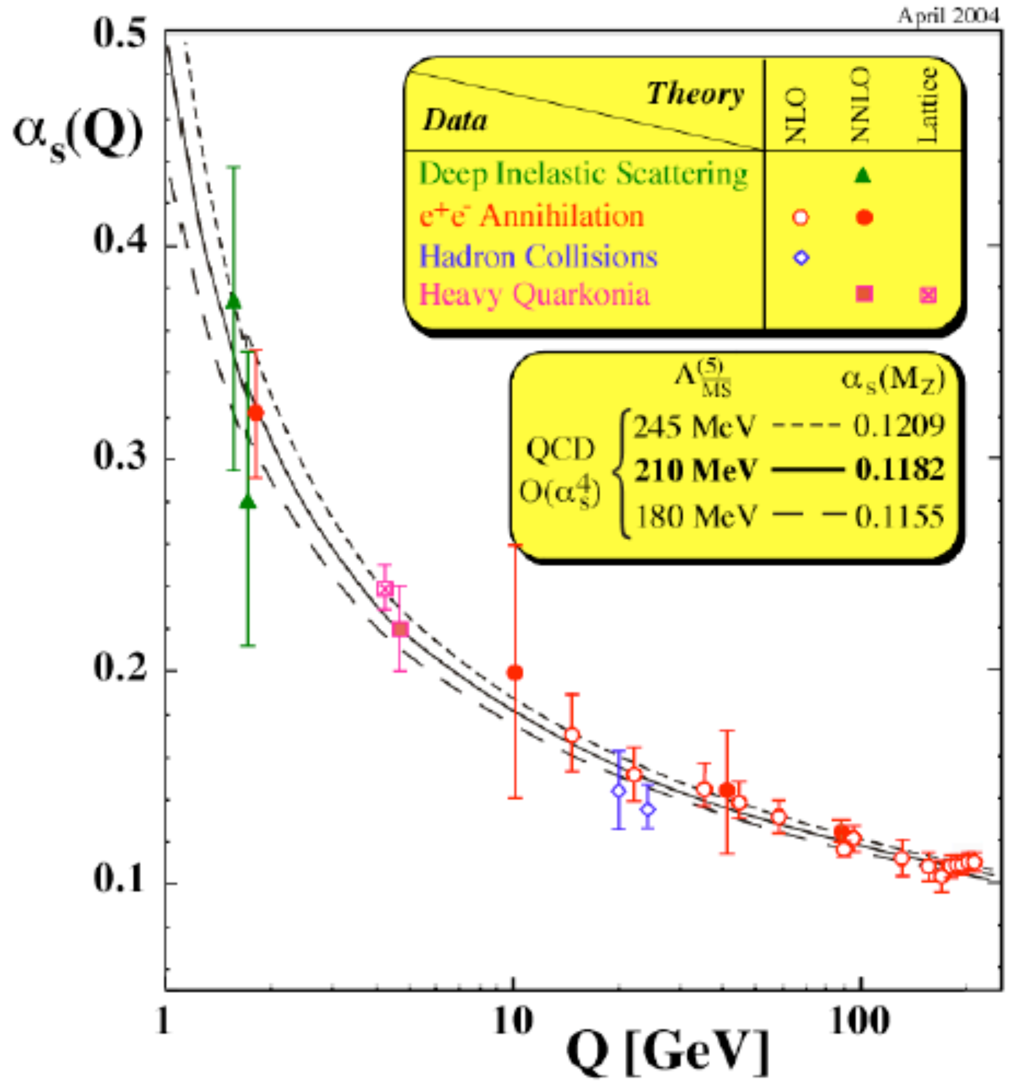
$$\sigma^{ep} = \gamma(x, Q^2) \times f_j(x, Q^2) \times \sigma_h(x, Q^2)$$

non-perturbative part

  - Evolution:
    - Beyond Quark-Parton model, Parton densities become functions of Q^2
    - Predict Q^2 dependence of parton distribution functions (DGLAP evolution equations)

QCD basics

- Asymptotic freedom



Leading-log approximation:

$$\alpha_s(Q) = \frac{12\pi}{(11n_c - 2n_f)\ln(Q^2/\Lambda^2)}$$

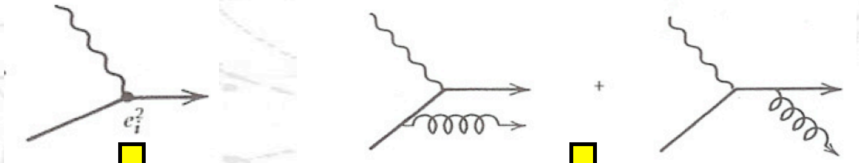
$$11n_c > 2n_f$$

Discovery of asymptotic freedom in the theory of strong interaction (Quantum Chromo Dynamics): Nobel prize in physics 2004

QCD basics

- Evolution (1)
  - ❑ The presence of QCD related diagrams leads to a modification of F_2

$$\begin{aligned} F_2 &= \nu W_2 \\ \nu &= \frac{p \cdot q}{m_p} \end{aligned}$$



$$\frac{F_2(x,Q^2)}{x} = \sum_i Q_i^2 \int_0^1 \left(\frac{dy}{y}\right) q(y) \left\{ \underbrace{\delta\left(1-\frac{x}{y}\right)}_{\text{Parton model}} + \underbrace{\left(\frac{\alpha_s}{2\pi}\right) P_{qq}\left(\frac{x}{y}\right) \log\frac{Q^2}{\mu^2}}_{\text{Gluon radiation}} \right\}$$

Logarithmic violation of scaling

Splitting function

$$q(y) \equiv f_q(y)$$

$$\frac{F_2(x,Q^2)}{x} = \sum_i Q_i^2 \int_0^1 \left(\frac{dy}{y}\right) \{q(y) + \Delta q(y,Q^2)\}\, \delta\left(1-\frac{x}{y}\right) =$$

$$\sum_i Q_i^2 \left(q(x) + \Delta q(x,Q^2)\right)$$

Quark densities depend on x and Q^2: →

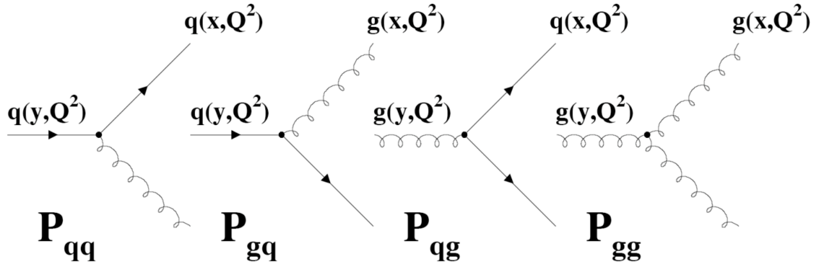
$$\Delta q(x,Q^2) = \left(\frac{\alpha_s}{2\pi}\right) \log\left(\frac{Q^2}{\mu^2}\right) \int_x^1 \left(\frac{dy}{y}\right) q(y) P_{qq}\left(\frac{x}{y}\right)$$

QCD basics

Evolution (2)

- Consider the change of the quark density Δq(x,Q²) over an interval of ΔlogQ²

$$\frac{d}{d\log Q^2}q(x,Q^2)=\left(\frac{\alpha_s}{2\pi}\right)\int_0^1\left(\frac{dy}{y}\right)q(y,Q^2)P_{qq}\left(\frac{x}{y}\right)$$



- General including other types of splitting functions:

Singlet distribution $\Sigma(x,Q^2)=\sum_{i=1}^{n_f}[q_i(x,Q^2)+\bar{q}_i(x,Q^2)]$

Gluon distribution $g(x,Q^2)$

$$\frac{d\Sigma(x,Q^2)}{d\ln Q^2}=\frac{\alpha_s(Q^2)}{2\pi}\int_x^1\frac{dz}{z}\left[P_{qq}\left(\frac{x}{z}\right)\Sigma(z,Q^2)+P_{qg}\left(\frac{x}{z}\right)g(z,Q^2)\right]$$

$$\frac{dg(x,Q^2)}{d\ln Q^2}=\frac{\alpha_s(Q^2)}{2\pi}\int_x^1\frac{dz}{z}\left[P_{gq}\left(\frac{x}{z}\right)\Sigma(z,Q^2)+P_{gg}\left(\frac{x}{z}\right)g(z,Q^2)\right]$$

Probability of finding a parton of type i with momentum fraction x which originated from parton j having momentum fraction y!

$$P_{ij}\left(\frac{x}{y}\right)$$

DGLAP evolution equations:

G. Altarelli and G. Parisi, Nucl. Phys. B 126 (1977) 298; V. Gribov and L.N. Lipatov, Soc. J. Nucl. Phys. 15 (1972) 438; L.N. Lipatov, Soc. J. Nucl. Phys. 20 (1975) 96; Y.L. Dokshitzer, Soc. Phys. JETP 46 (1977) 641.

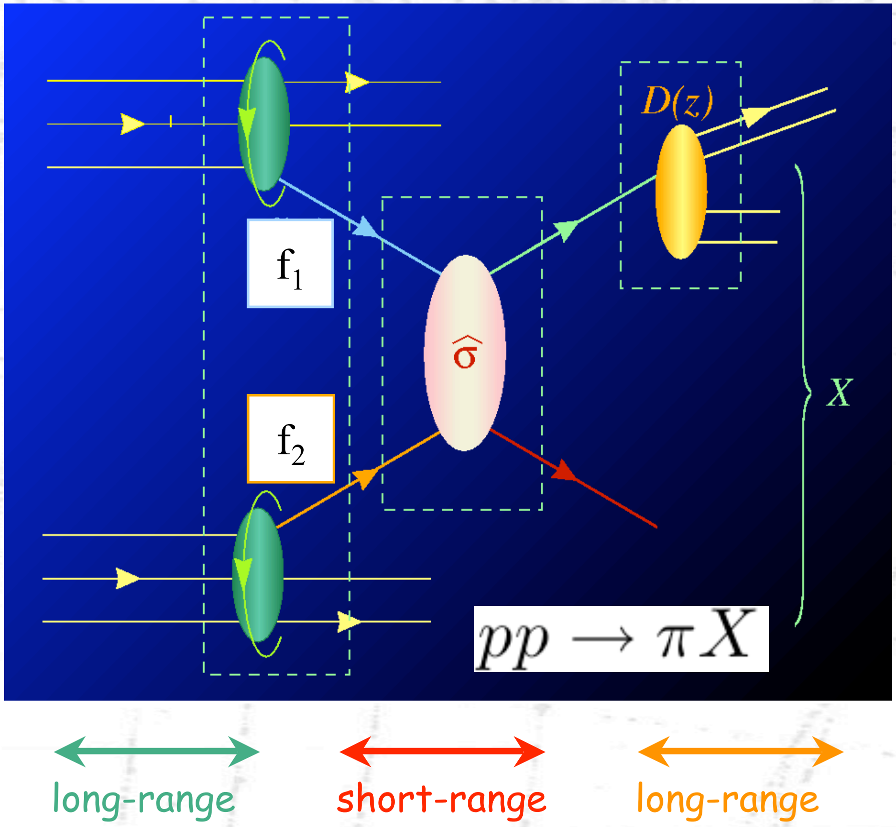
QCD basics

- **Factorization**
  - Unpolarized proton structure:

$$f(x) =$$

$f^{+}(x)$ $f^{-}(x)$

$$F_2 = \sum_q x e_q^2 q$$



$$\sigma_{pp\rightarrow\pi X} = \sum_{f_1,f_2} f_1 \otimes f_2 \otimes \hat{\sigma} \otimes D_f^{\pi}$$

- Three step process:
  - Partons (quarks/gluons) in initial state: Long distance (non-perturbative QCD domain)

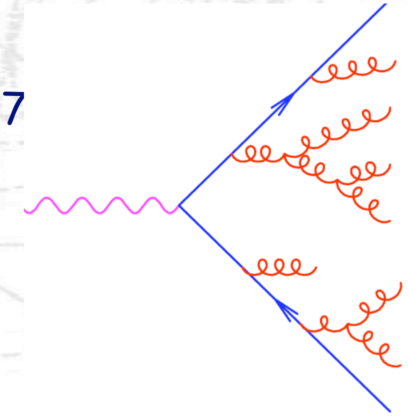
    ⇒ Parton (quarks/gluons) distribution functions
  - Hard interaction: Small distances (high energies) (perturbative QCD domain)

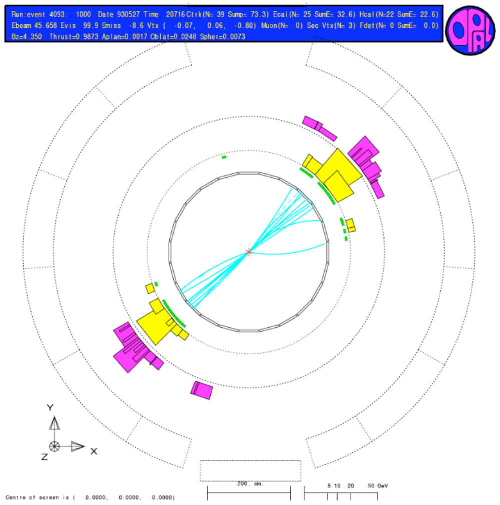
    ⇒ Cross-section prediction (LO,NLO,NNLO)
  - Quarks in final state: Long distance (non-perturbative QCD domain):

    ⇒ Quarks fragment into observable hadrons described by fragmentation functions

QCD basics

- QCD at work: Jet production
  - ☐ First observation: SLAC-SPEAR (197
  - ☐ Discovery of gluon: PETRA (1979)





```
Run:event 4093:  1000  Date 930527 Time  20716 Ctrk(N= 39 Sump= 73.3) Ecal(N= 25 SumE= 32.6) Hcal(N=22 SumE= 22.6)
Ebeam 45.658 Evis  99.9 Emiss  -8.6 Vtx (  -0.07,   0.06,  -0.80) Muon(N=  0) Sec Vtx(N= 3) Fdet(N= 0 SumE=  0.0)
Bz=4.350  Thrust=0.9873 Aplan=0.0017 Oblat=0.0248 Spher=0.0073
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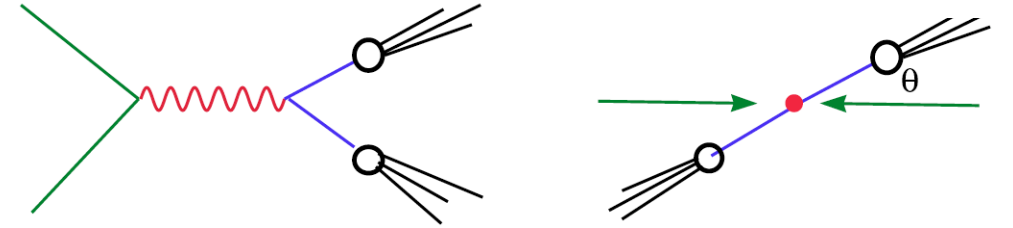
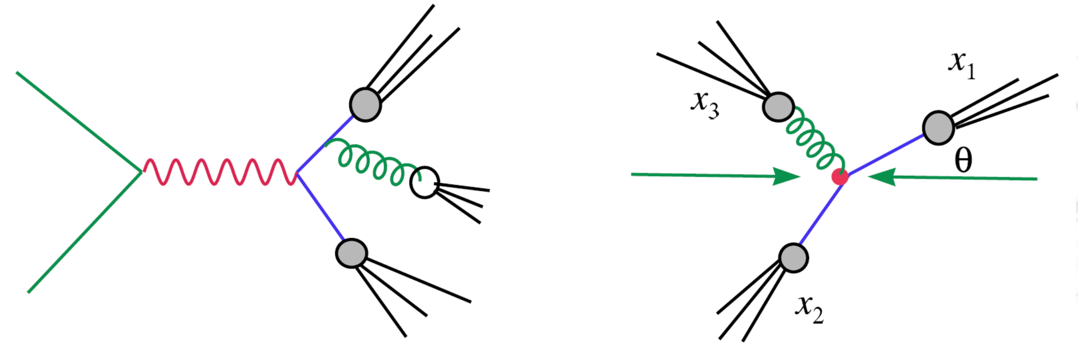
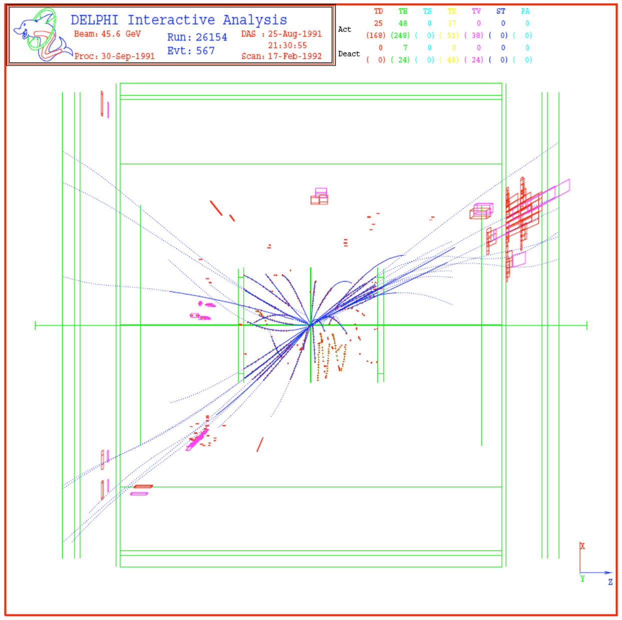




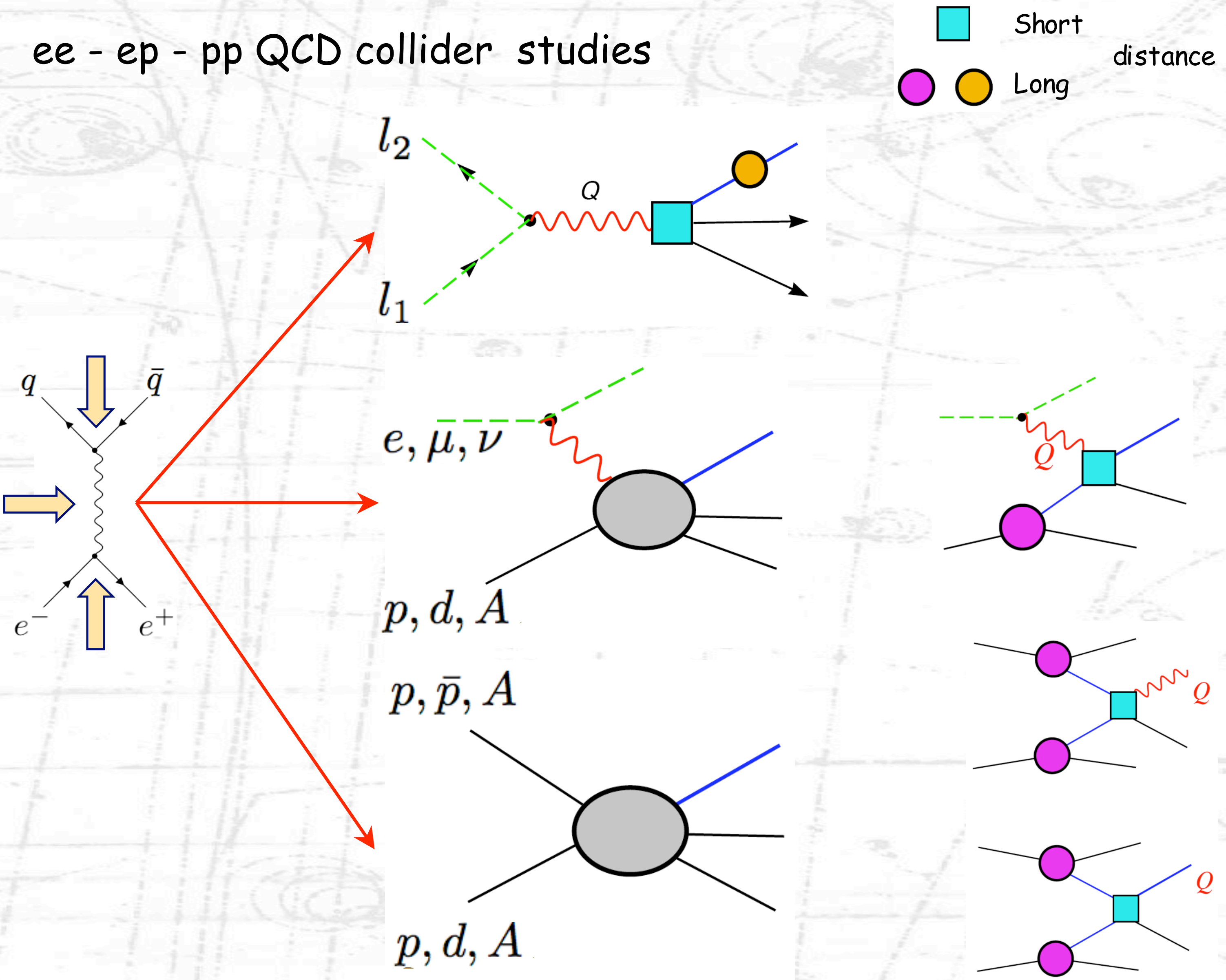


```
DELPHI Interactive Analysis
Beam: 45.6 GeV     Run: 26154   DAS : 25-Aug-1991
                   Evt: 567           21:30:55
Proc: 30-Sep-1991               Scan: 17-Feb-1992

         TD     TE     TS     TK     TV     ST     PA
Act      25     48      0     37      0      0      0
       (168)  (248)  (  0)  ( 51)  ( 38)  (  0)  (  0)
Deact     0      7      0      0      0      0      0
       (  0)  ( 24)  (  0)  ( 48)  ( 24)  (  0)  (  0)
```

Experimental aspects

- ee - ep - pp QCD collider studies



Q: large momentum scale

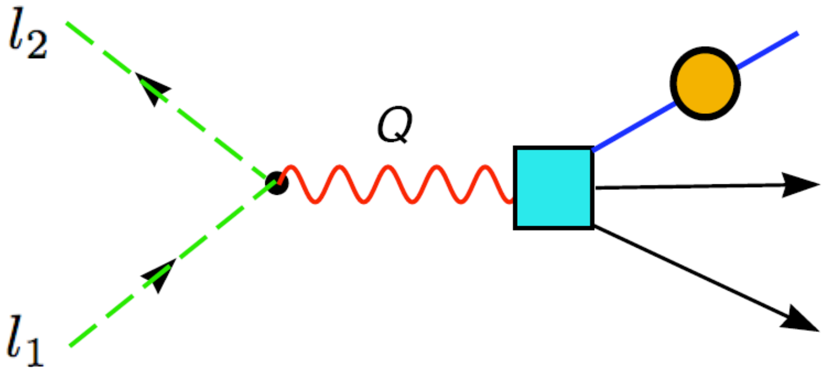
PEP,
PETRA,
Cornell,
LEP,
SLD,
NLC

SLAC,
FNAL,
CERN,
HERA,
eRHIC

FNAL,
CERN,
Tevatron,
RHIC,
RHICII,
LHC

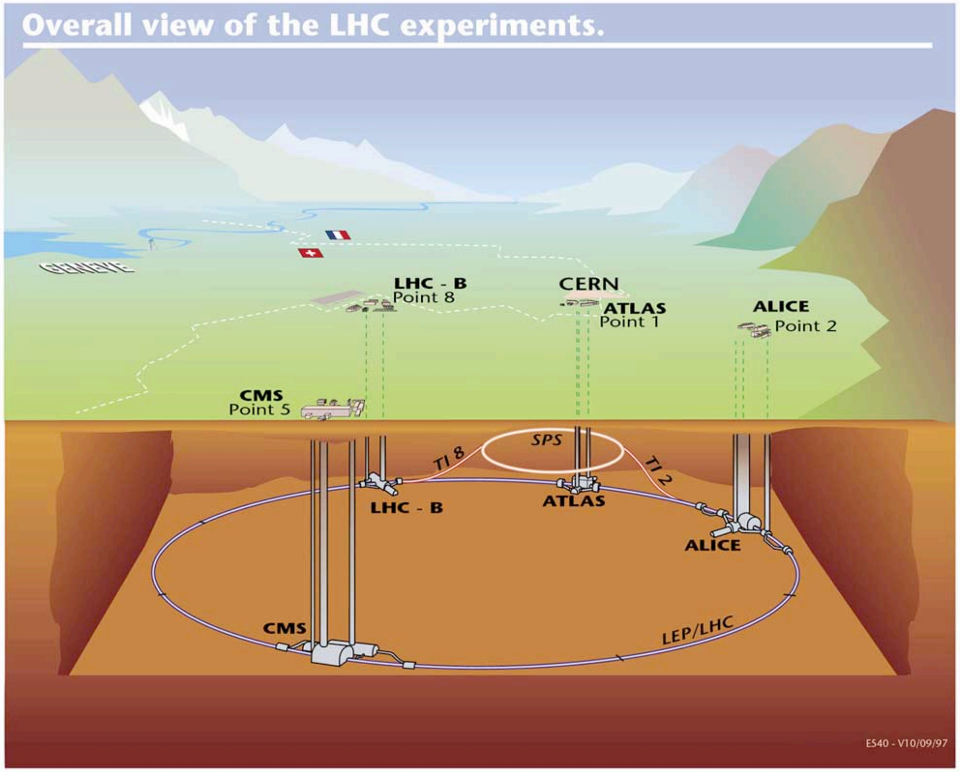
Experimental aspects

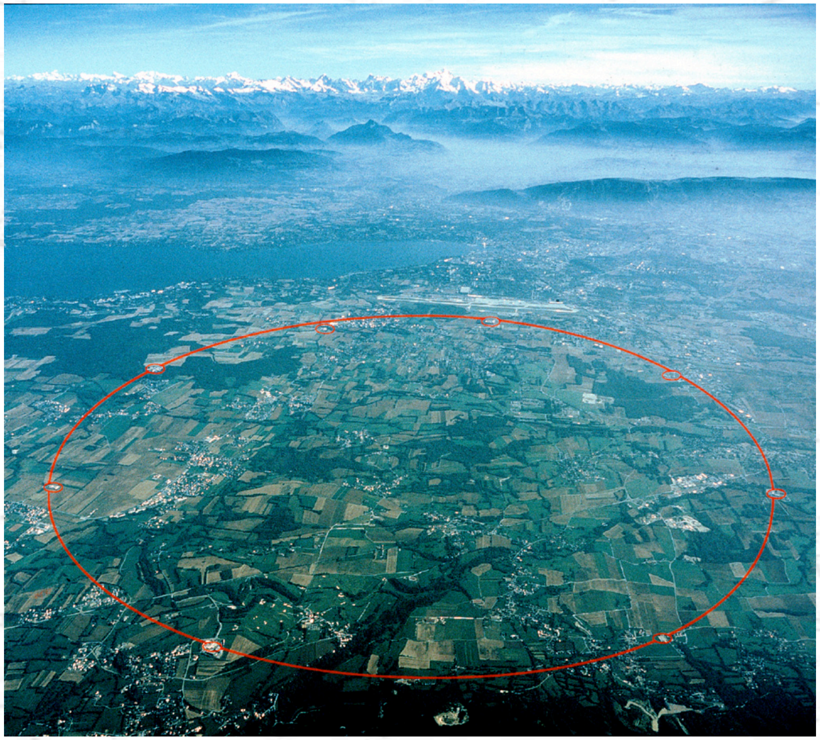
- Experimental QCD tests in ee
  - ☐ Measurement of α_s
  - ☐ Fragmentation functions
  - ☐ Color/spin dynamics
  - ☐ Quark-Gluon jet properties
  - ☐ Event shape variables (Sphericity, thrust, …)



Experimental aspects

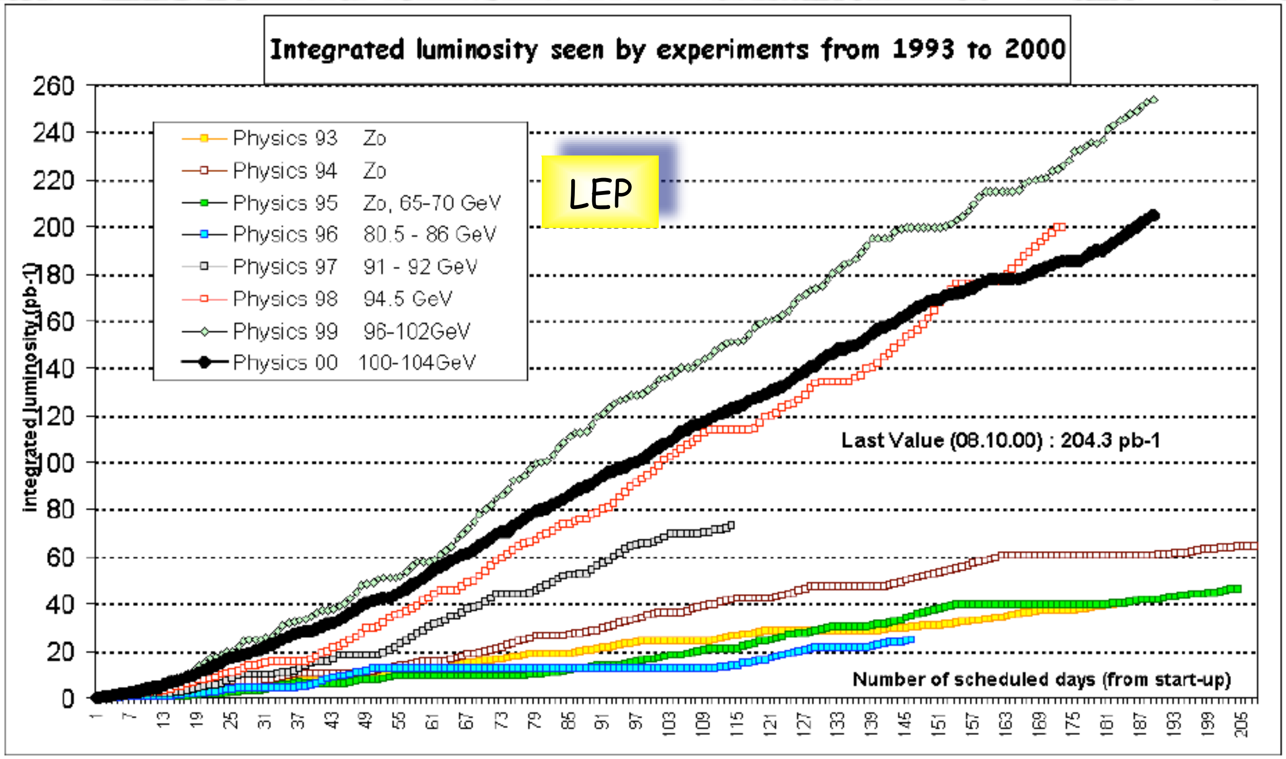
- LEP and LHC at CERN, Geneva
  - ☐ LEP: Centre-of-mass energy (e^+e^-) up to 205GeV
  - ☐ LHC: Centre-of-mass energy (pp): 14000GeV = 14TeV
  - ☐ Circumference: 27km



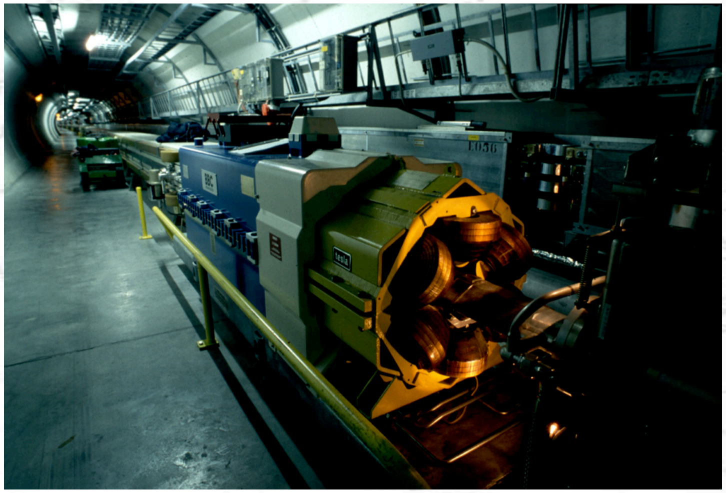


Experimental aspects

- LEP and LHC at CERN, Geneva
  - ☐ Luminosity

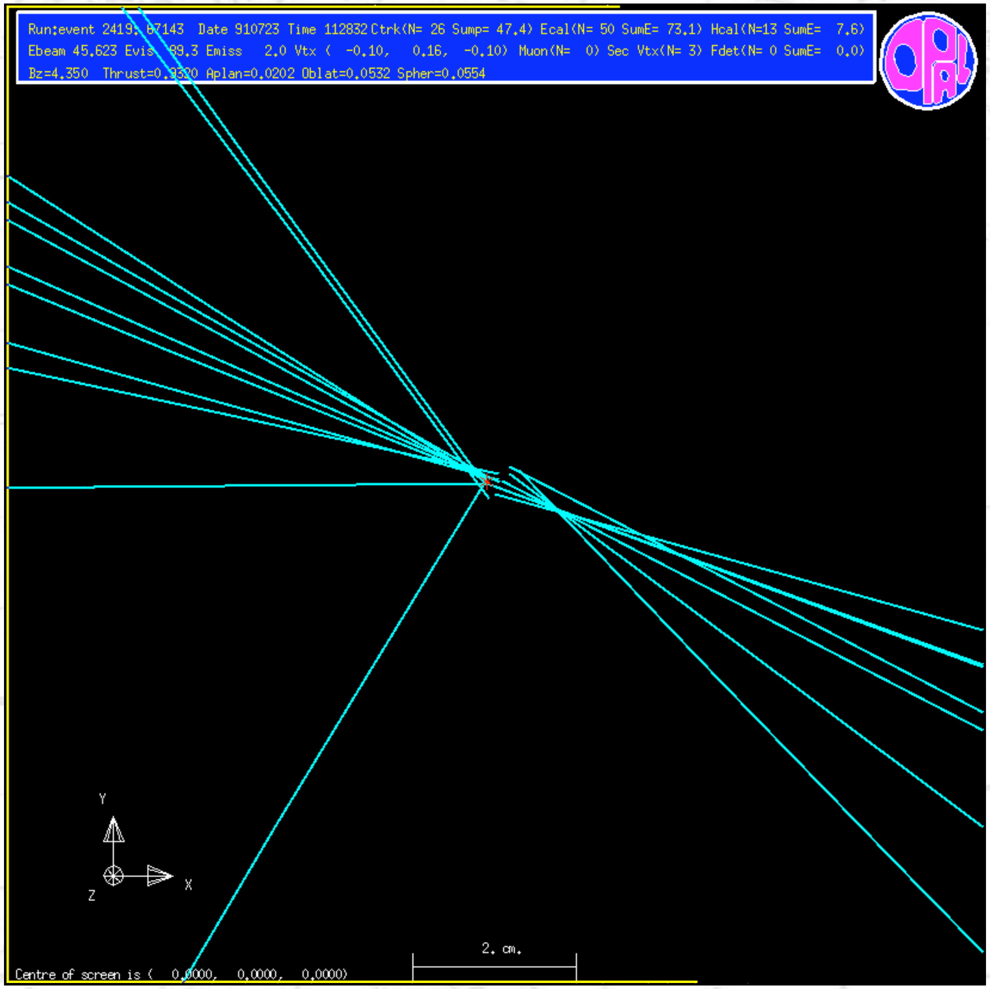


10 weeks



Experimental aspects

- e^+e^- collisions: Here OPAL at LEP



```
Run:event 2419: 67143  Date 910723 Time 112832 Ctrk(N= 26 Sump= 47.4) Ecal(N= 50 SumE= 73.1) Hcal(N=13 SumE=  7.6)
Ebeam 45.623 Evis  89.3 Emiss   2.0 Vtx (  -0.10,   0.16,  -0.10) Muon(N=  0) Sec Vtx(N= 3) Fdet(N= 0 SumE=  0.0)
Bz=4.350  Thrust=0.9320 Aplan=0.0202 Oblat=0.0532 Spher=0.0554
Centre of screen is (  0.0000,  0.0000,  0.0000)
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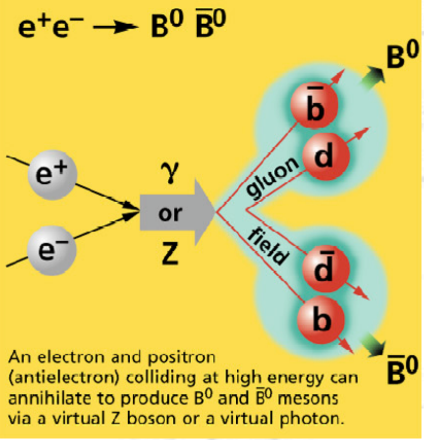
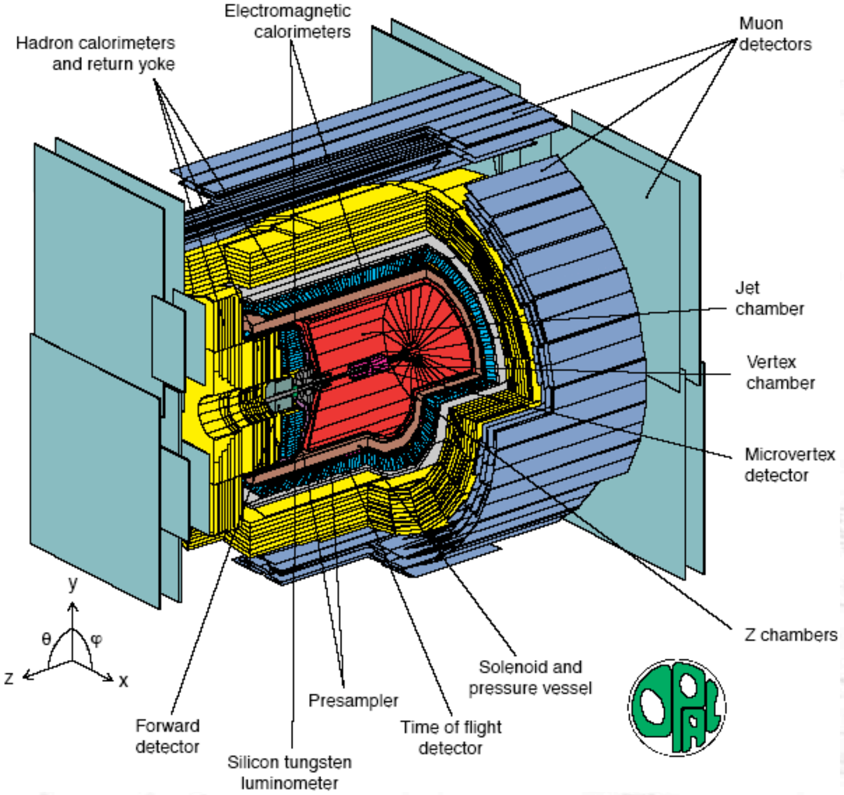
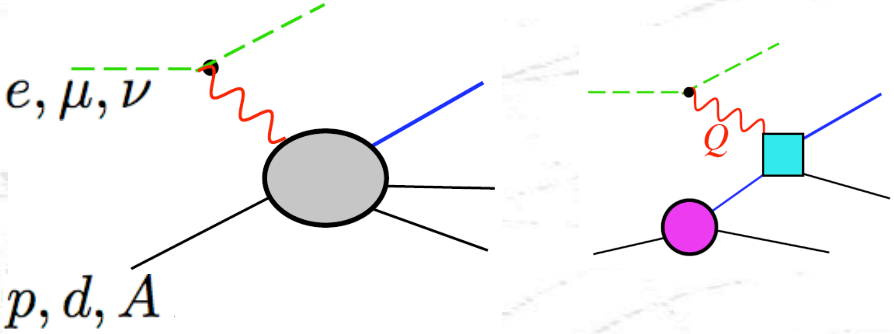


An electron and positron (antielectron) colliding at high energy can annihilate to produce B^0 and $\bar{B}^0$ mesons via a virtual Z boson or a virtual photon.



Experimental aspects

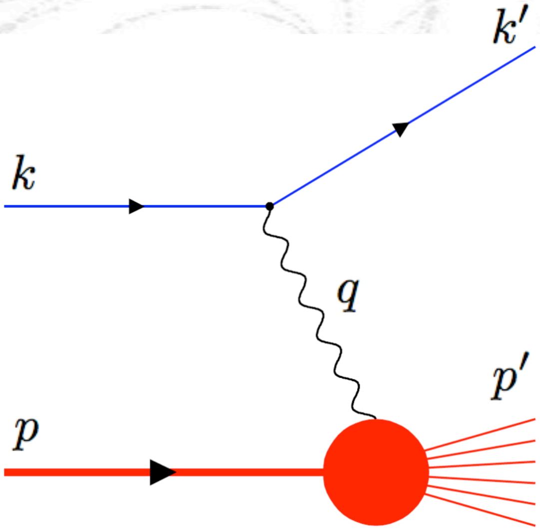
- Experimental QCD tests in ep
  - ☐ Measurement of α_s
  - ☐ Fragmentation functions
  - ☐ Extraction of parton distribution functions
  - ☐ Color/spin dynamics
  - ☐ Quark-Gluon jet properties
  - ☐ Event shape variables (Sphericity, thrust, …)
  - ☐ Diffraction



Experimental aspects

- ep kinematics (1)

$$e(k) + P(p) \rightarrow l(k^{'}) + X(p^{'})$$

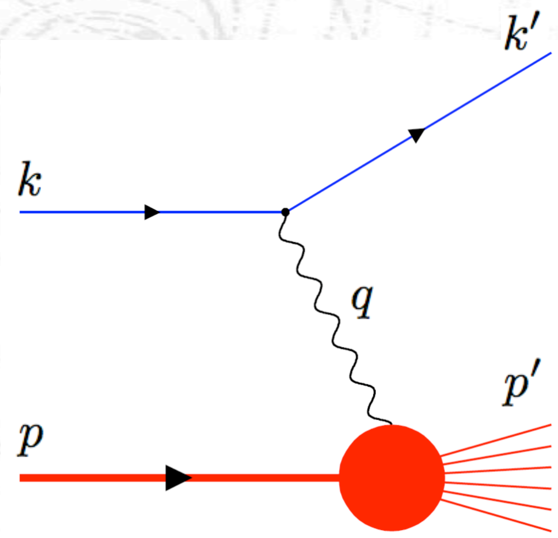


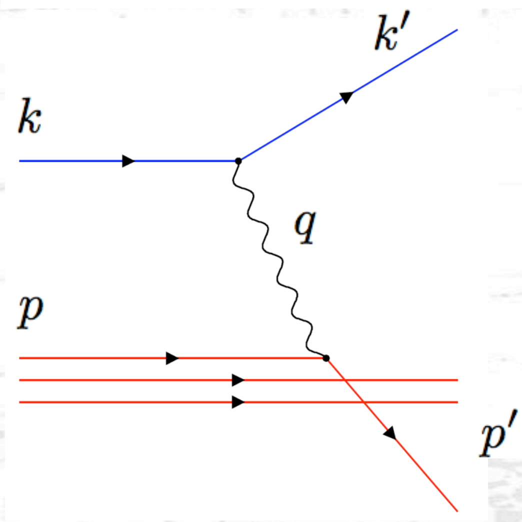
- ☐ Four vectors: $k, \;\; p, \;\; k', \;\; p'$
- ☐ Neutral current exchange (NC): γ^{*}, Z^{0}
- ☐ Charged current exchange (CC): $W^{\pm}$
- ☐ Measurement of structure functions:
  - NC: Scattered electron and/or hadronic final state
  - CC: Hadronic final state (neutrino escapes detection)

} Determine kinematics!

Experimental aspects

- Kinematic variables





$$Q^2 = -(k-k^{'})^2 = -(p-p^{'})^2 = -t = -q^2$$

(momentum transfer)^2
virtuality of γ^*, Z^0, $W^\pm$

⇒ ("size" of the probe)$^{-1}$

$$x = \frac{Q^2}{2(p\cdot q)} \simeq -\frac{t}{u+s} \qquad 0 \leq x \leq 1$$

fraction of the proton momentum carried by the charged parton

$$y = \frac{p\cdot q}{p\cdot k} \simeq \frac{u+s}{s} \qquad 0 \leq y \leq 1$$

fraction of the electron energy carried by the virtual photon ("inelasticity")

$$s = (k+p)^2 \simeq 4E_eE_P$$

center of mass energy of ep system

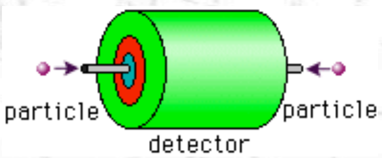
(mass)^2 of $\gamma^* p$ system

$$W^2 = (p+q)^2 = (p^{'})^2 = m_p^2 + \frac{Q^2}{x}(1-x) \simeq s+t+u$$

$$Q^2 \simeq s\cdot x\cdot y$$

Experimental aspects

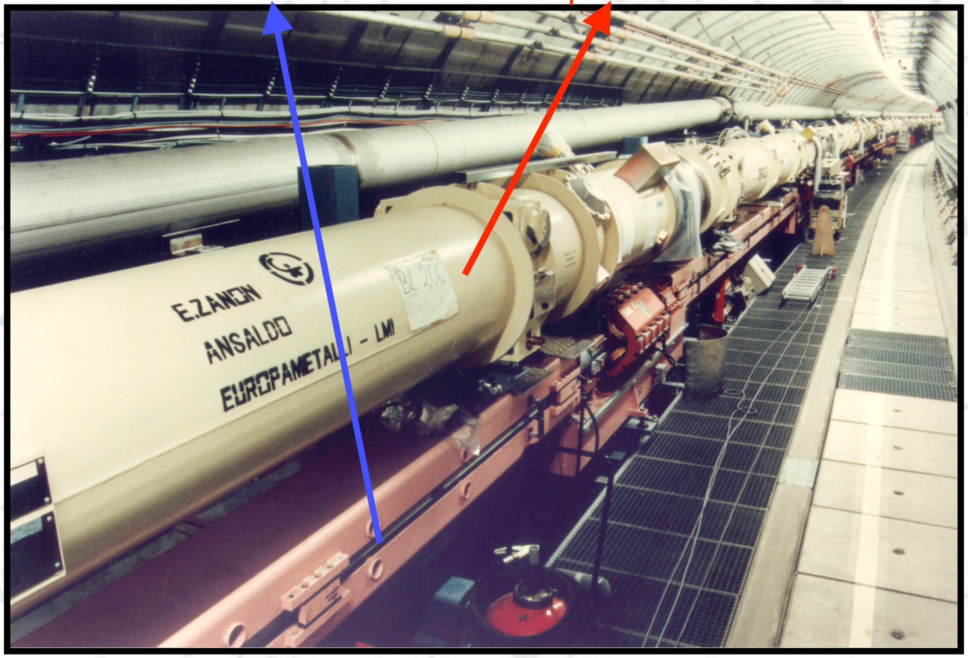
- Collider experiment: Electron-Proton collisions at HERA (DESY, Hamburg, Germany)



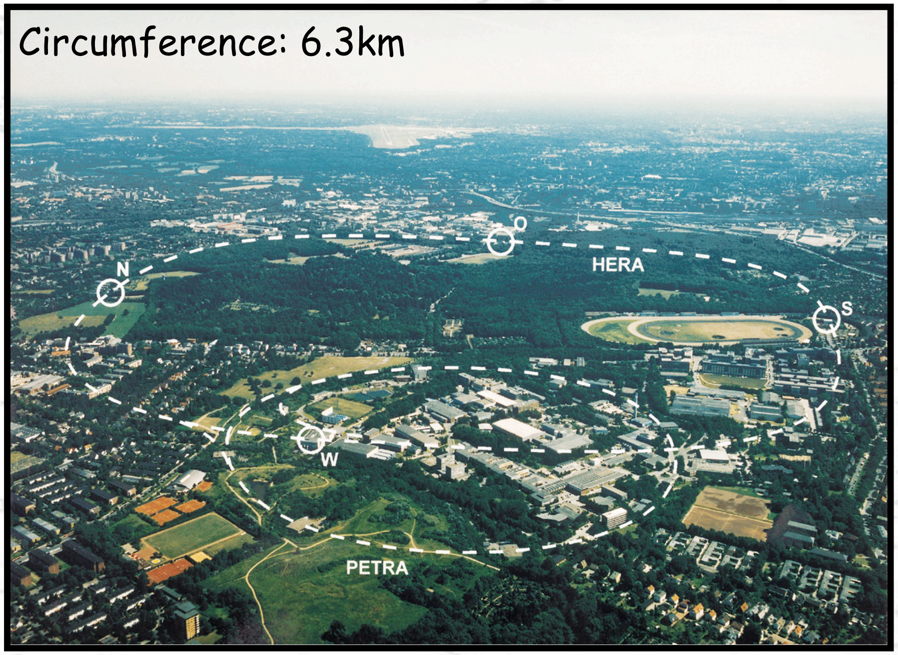
Equivalent to fixed target of
E_e = 50600 GeV:

E_e = 27.5 GeV

E_p = 920 GeV

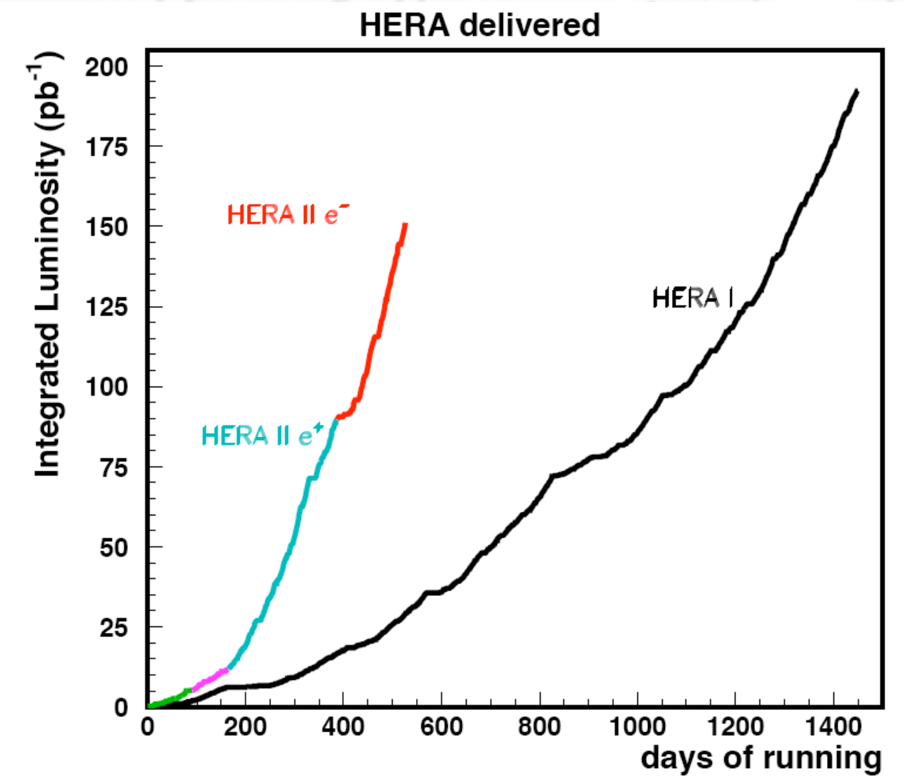


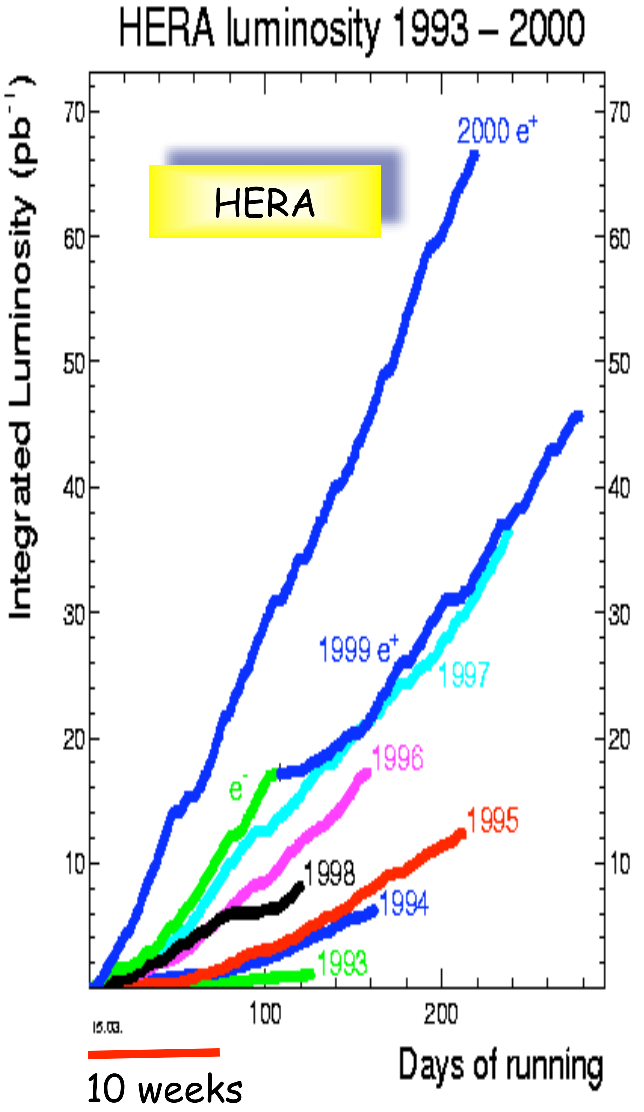
Circumference: 6.3km



Experimental aspects

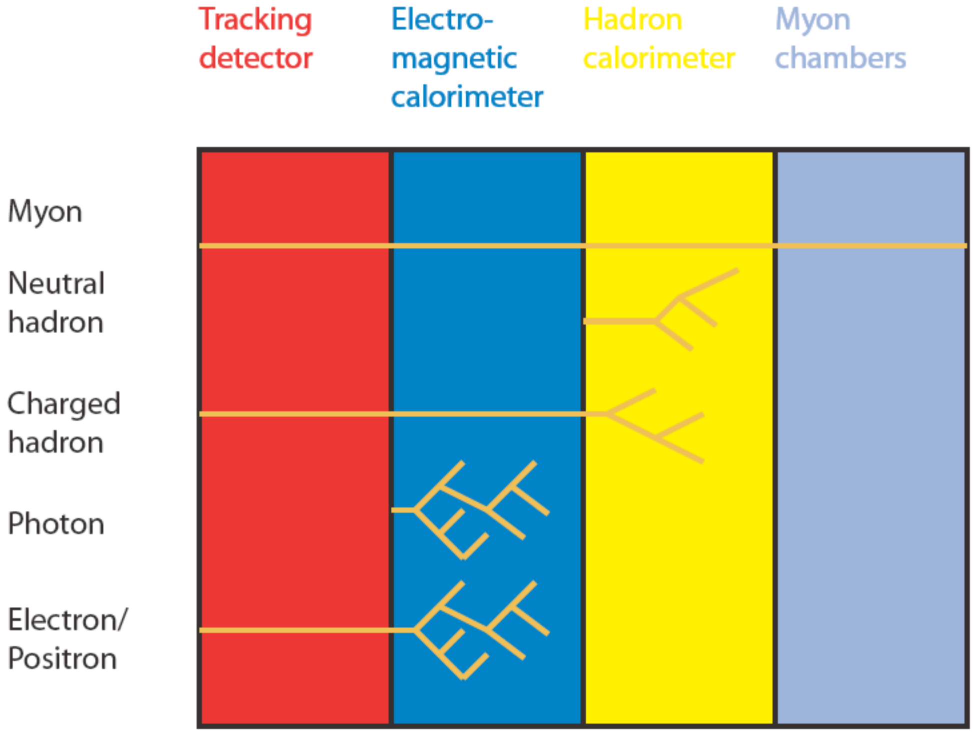
- Collider experiment: Electron-Proton collisions at HERA (DESY, Hamburg, Germany)
  - ❑ Luminosity:

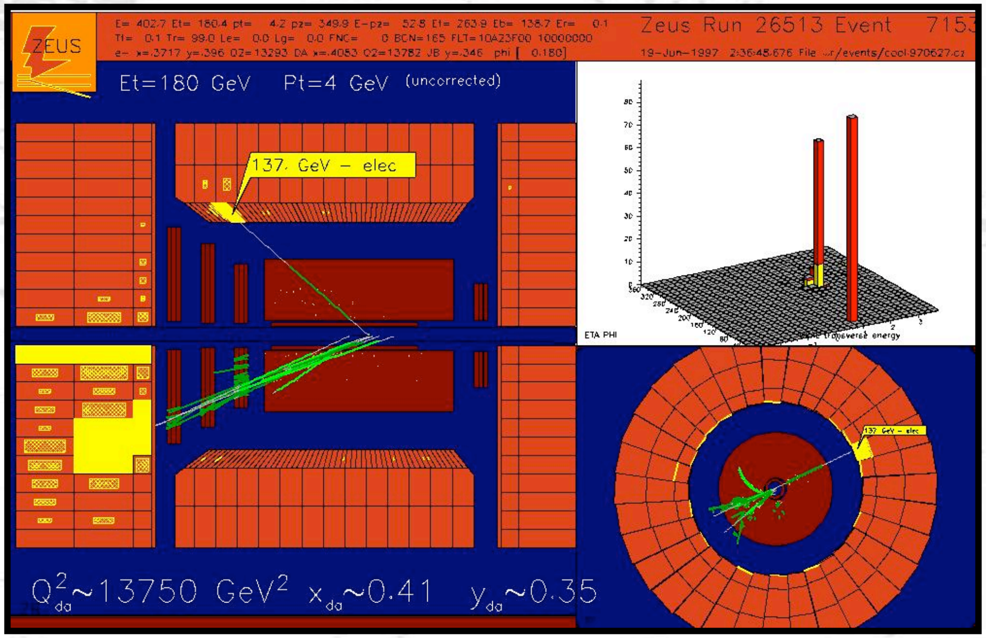


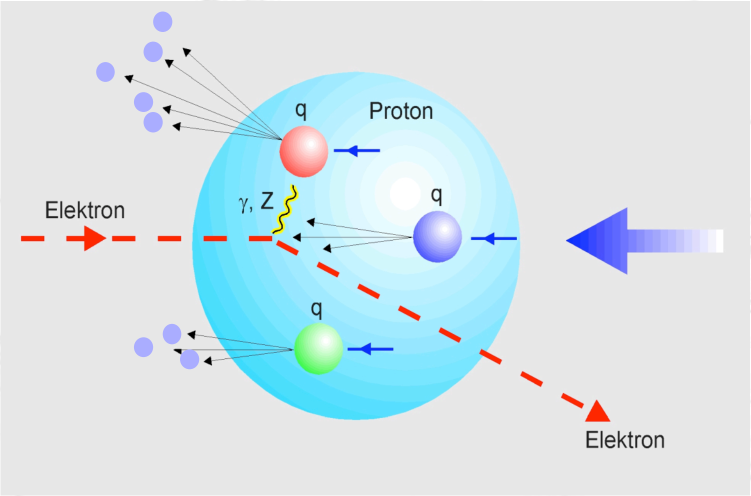


Experimental aspects

- ep collisions: Here ZEUS at HERA
  - Onion-shell structure of various detector systems around the collision point:
    - Energy measurement
    - Momentum measurement
    - Particle identification

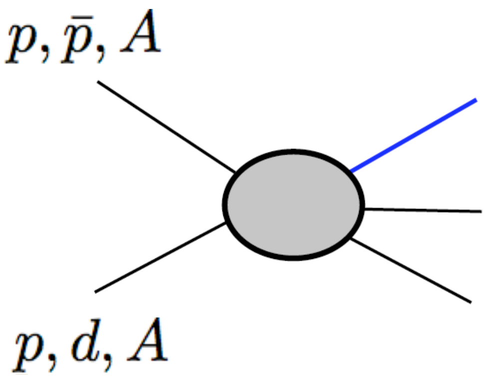


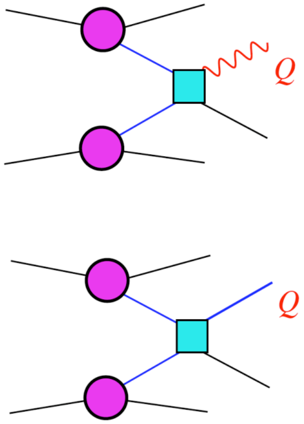




Experimental aspects

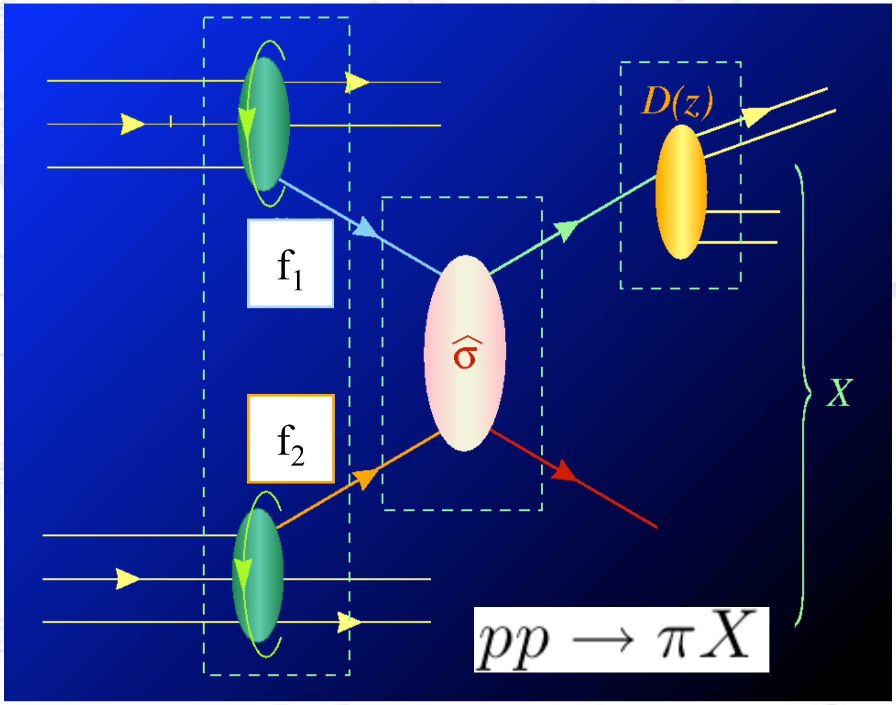
- Experimental QCD tests in pp
  - Measurement of α_s
  - Fragmentation functions
  - Extraction of parton distributionfunctions
  - Color/spin dynamics
  - Quark-Gluon jet properties
  - Event shape variables (Sphericity, thrust, …)
  - Diffraction





Experimental aspects

- pp kinematics (1)
  - ❑ Two incoming hadron beams:
    - Spectrum of longitudinal momenta determined by parton distribution functions
    - Centre-of-mass of parton-parton system is boosted with respect to two incoming hadrons, i.e. $x_1 \neq x_2$
    - Therefore: Classify final state using variables that transform simply under longitudinal boosts:
      - Rapidity: y
      - Transverse momentum: p_T
      - Azimuthal angle: ϕ
    - Four-vector formulation: $p^{\mu} = (E, p_x, p_y, p_z)$



$$m_T = \sqrt{p_T^2 + m^2} \qquad y = \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right)$$

$$= (m_T \cosh\ y, p_T \sin\phi, p_T \cos\phi, m_T \sinh\ y)$$

Experimental aspects

- pp kinematics (2)
  - ❑ Property of rapidity:
    - Additive under the restricted class of Lorentz transformations corresponding to a boost along the z direction.
    - Therefore: Rapidity differences (Δy) are boost invariant!
    - Pseudorapidity: y for m → 0

$$\eta = \frac{1}{2}\ln\frac{|\vec{p}| + p_z}{|\vec{p}| - p_z} = -\ln\tan\frac{\theta}{2}$$

$$p_z = |\vec{p}|\cos\theta$$

- Transverse energy: Measured quantity in a calorimeter system, rather than p_T!

$$E_T = E\sin\theta$$

Jet definition: Cone jet finder

Concentration of transverse energy E_T in a cone of radius R:

$$R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$$

- Invariant under longitudinal boost!
- In the two-dimensional plane, curves of constant R are circles around the jet axis!

Experimental aspects

- pp kinematics (3)
  - ☐ Partonic centre-of-mass energy:

$$\hat{s} = (x_1 p_1 + x_2 p_2)^2 \qquad s = (p_1 + p_2)^2$$

  - ☐ Bjorken x_1 and x_2 and rapidity y:

$$x_1 = \frac{1}{2} x_T (e^{y_3} + e^{y_4})$$

$$x_T = 2p_T/\sqrt{s}$$

$$x_2 = \frac{1}{2} x_T (e^{-y_3} + e^{-y_4})$$

$$\bar{y} = (y_3 + y_4)/2$$

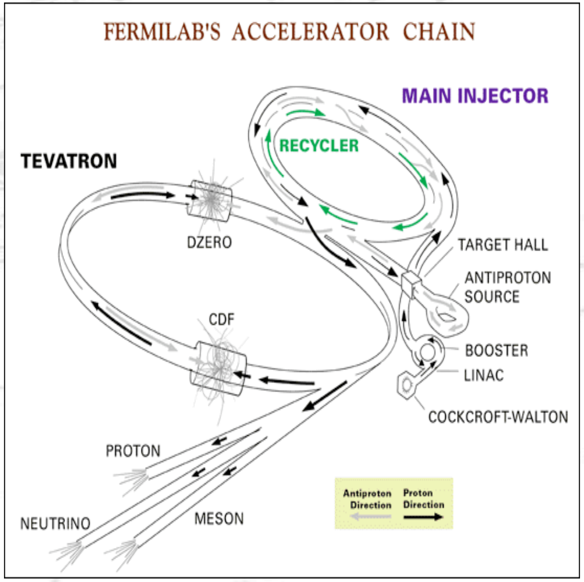
$$\bar{y} = \frac{1}{2} \ln \left(\frac{x_1}{x_2} \right)$$

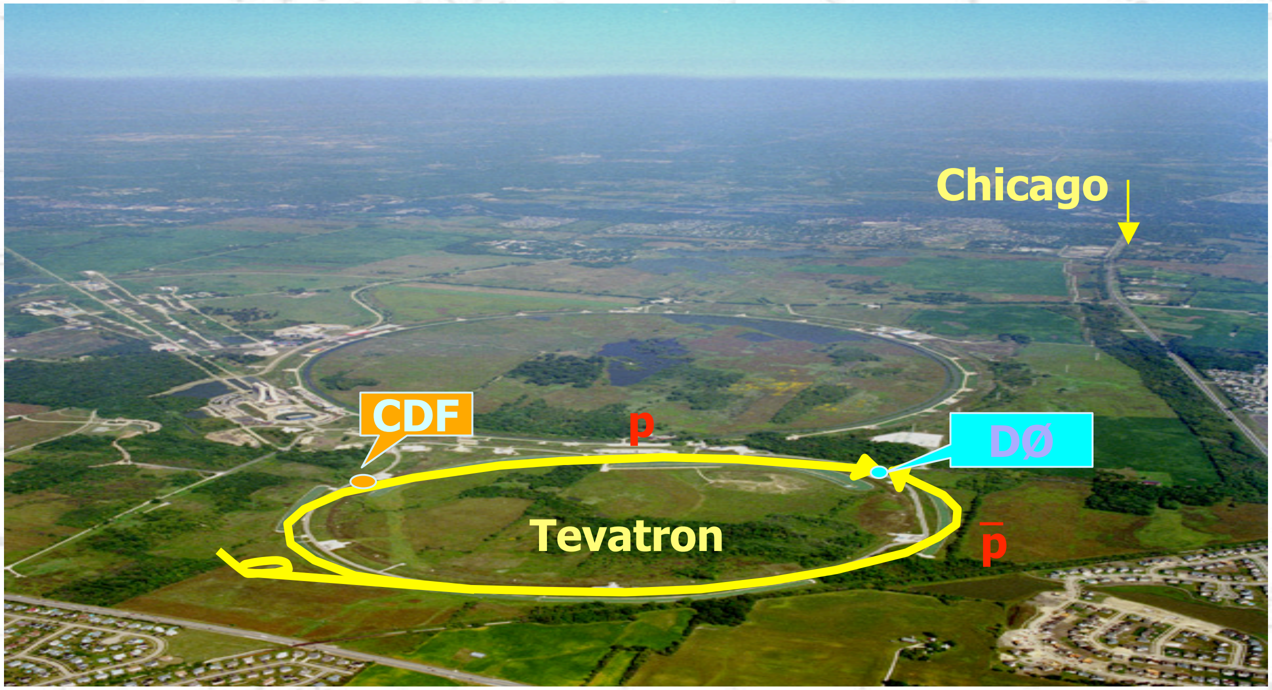
$$\cos\theta^* = \frac{p_z^*}{E^*} = \frac{\sinh y^*}{\cosh y^*} = \tanh\left(\frac{y_3 - y_4}{2}\right)$$

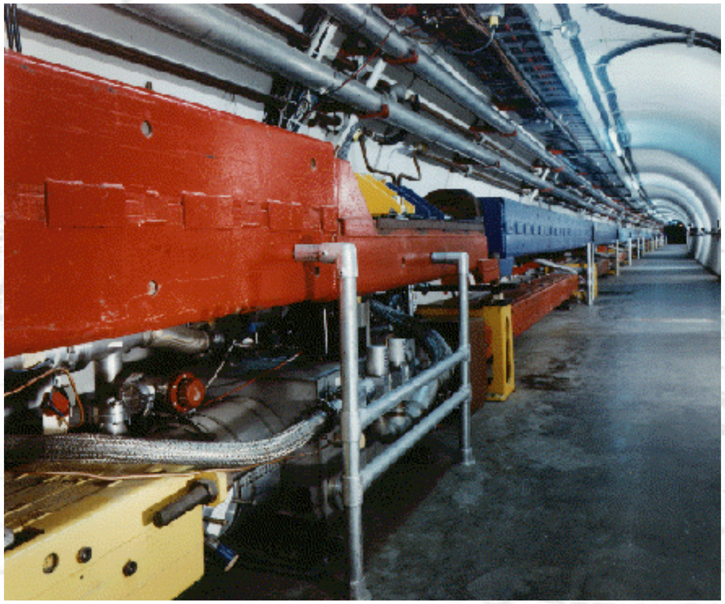
Partonic centre-of-mass angle!

Experimental aspects

- World’s Highest Energy proton-anti-proton collider - Tevatron (1)
  - Centre-of-Mass Energy: E_{cm}=1.96 TeV
  - Circumference: 6.85km

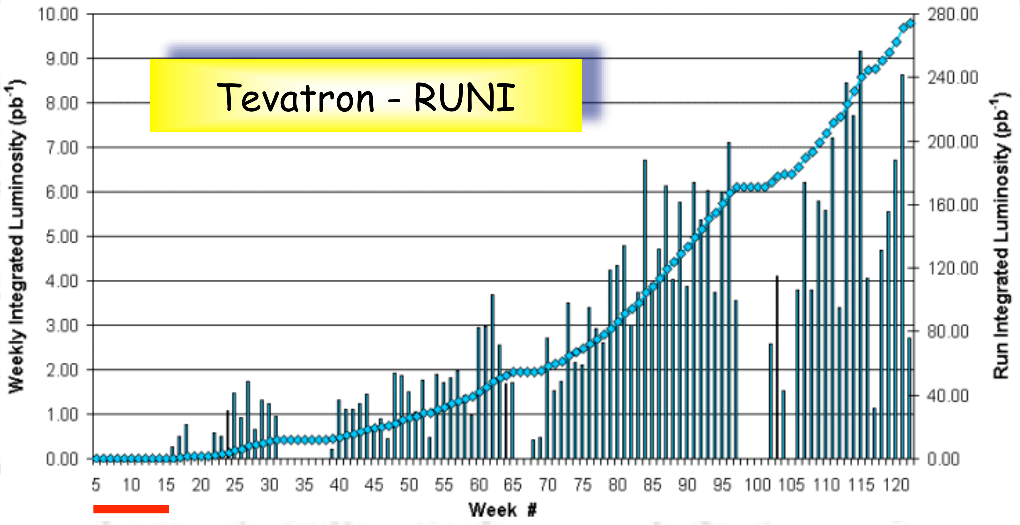




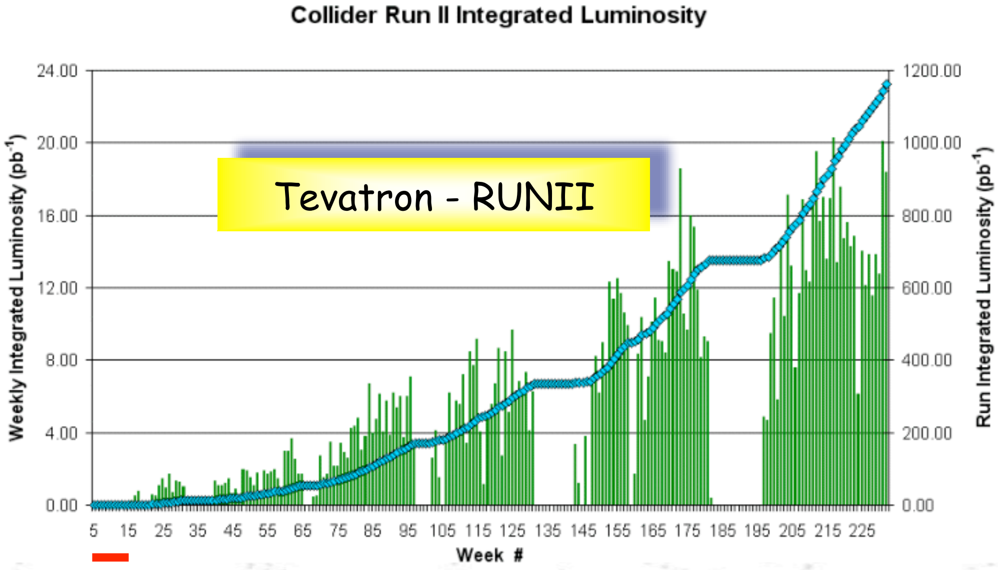


Experimental aspects

- World's Highest Energy proton-anti-proton collider - Tevatron (2)
  - ❑ $\sqrt{s}$ = 1.96 TeV (Run I → 1.8 TeV)
  - ❑ Peak luminosity is now ~ 10^{32} cm^{-2} s^{-1}



10 weeks

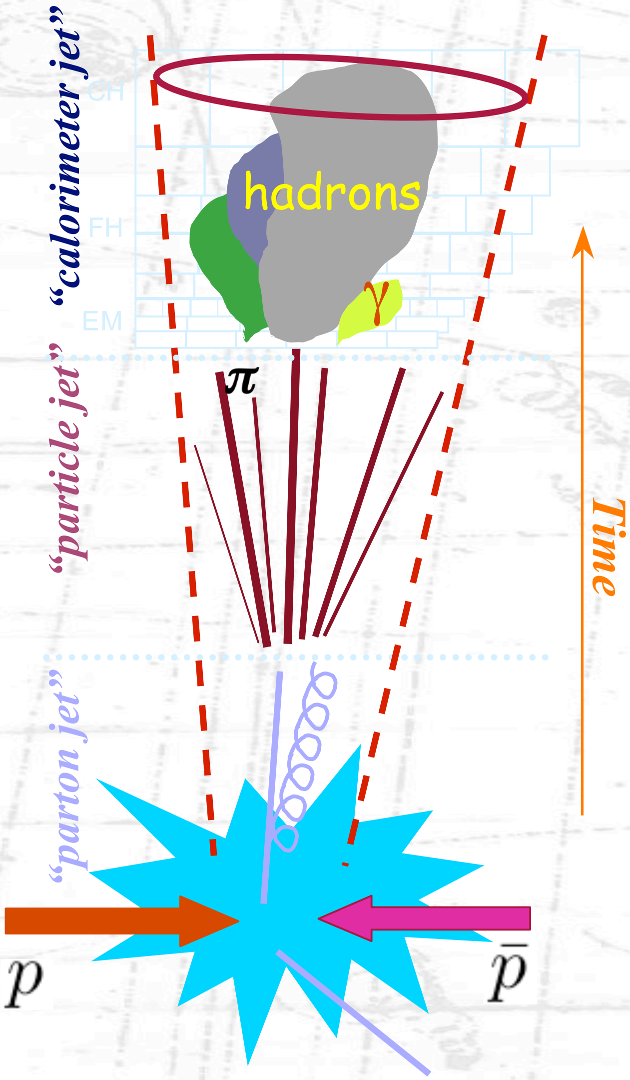


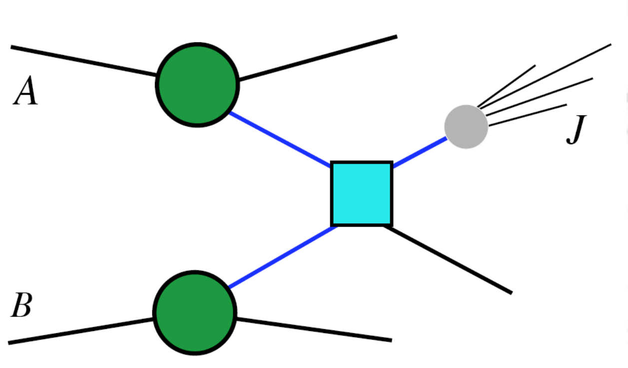
10 weeks

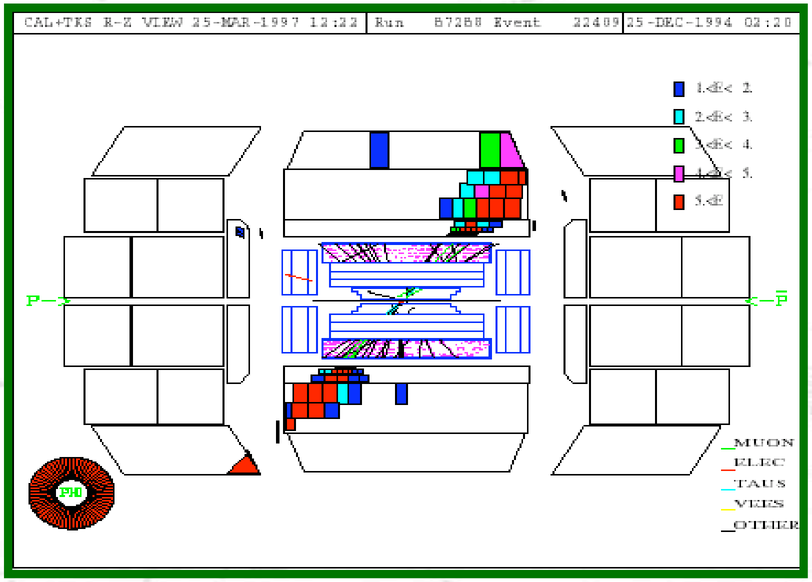
- RUNII Long term luminosity goal
  - Base 4.4 fb^{-1}
  - Design 8.5 fb^{-1} by the end of 2009

Experimental aspects

- Proton - Anti-Proton collisions: Here D0 at the Tevatron







Dijet event at DØ

Selected QCD topics at high-energy collider experiments

- Structure function measurement: Formalism
  - ❑ In terms of laboratory variables:

$$\left(\frac{d\sigma}{d\Omega}\right)_{Mott} = \left(\frac{d\sigma}{d\Omega}\right)_{Rutherford} \cdot \cos^2(\theta/2)$$

$$\left(\frac{d^2\sigma}{dE'd\Omega}\right) = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \left\{W_2(Q^2,x) + 2W_1(Q^2,x)\tan^2\left(\frac{\theta}{2}\right)\right\}$$

$$\left(\frac{d\sigma}{d\Omega}\right)_{Rutherford} = \frac{4\alpha^2 E'^2}{q^4}$$

  - ❑ Formulate this now in relativistic invariant quantities:

$$\theta'_e, \quad E'_e \rightarrow y_e, \quad Q^2_e$$

  - ❑ Instead of W_1 an

$$F_1 = m_p W_1 \qquad F_2 = \nu W_2$$

Longitudinal structure function: F_L

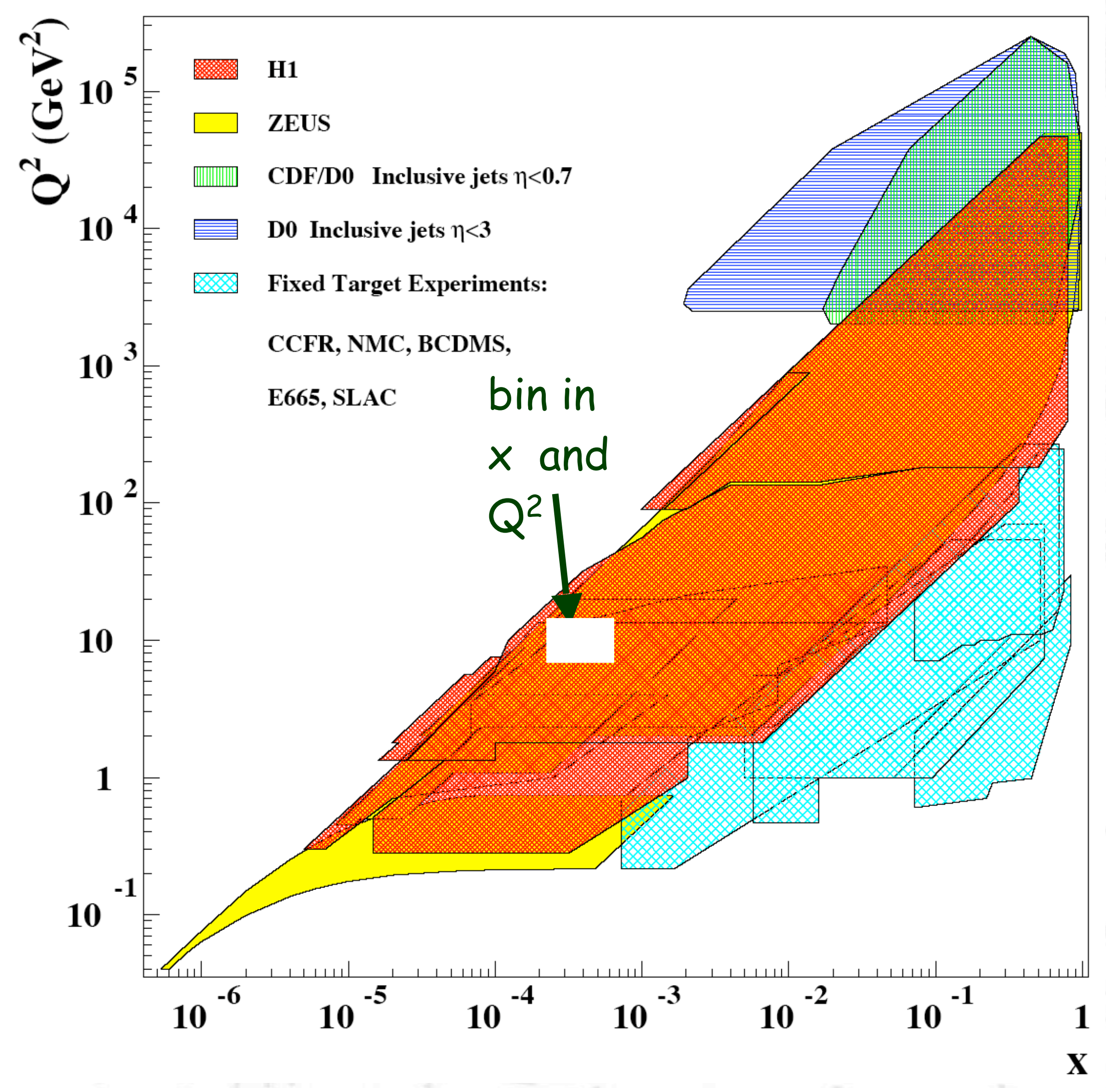
$$\left(\frac{d^2\sigma}{dydQ^2}\right) = \frac{2\pi\alpha^2 Y_+}{yQ^4}\left(F_2 - \frac{y^2}{Y_+}F_L\right)$$

$$F_L = F_2 - 2xF_1$$

$$Y_+ = 1 + (1-y)^2$$

Selected QCD topics at high-energy collider experiments

- Structure function measurement: Kinematic coverage and measurement

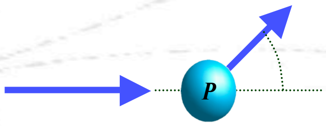


1. Determination of kinematics (e.g. electron method):

$$Q^2 = 4E'_e E_e \sin^2\left(\frac{\vartheta'_e}{2}\right)$$

$$y = 1 - \frac{E'_e}{E_e}\cos^2\left(\frac{\vartheta'_e}{2}\right)$$

$$x = \frac{Q^2}{sy}$$



2. Determination of cross-section and extraction of F_2:

Number of selected events

Background

$$\frac{d^2\sigma}{dxdQ^2} = \frac{(N-B)}{L\cdot\varepsilon} \propto F_2$$

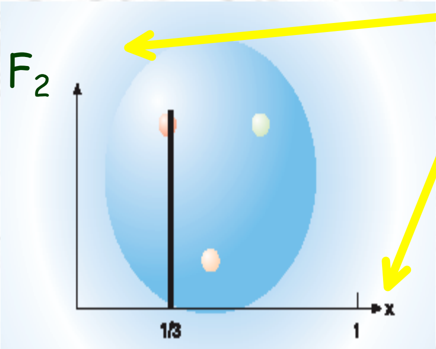
Luminosity

Efficiency

Selected QCD topics at high-energy collider experiments

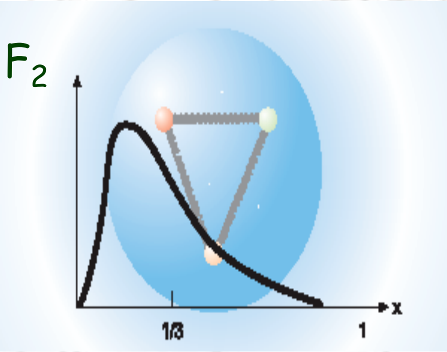
- Structure function measurement: Picture of the Proton

Three valence quarks



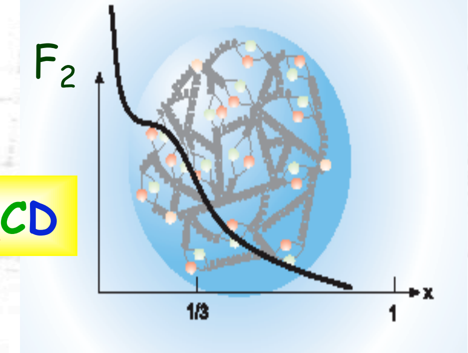
x: Momentum fraction of struck quark

Three bound valence quarks

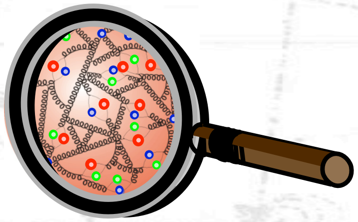


Three valence quarks and sea quarks + gluons

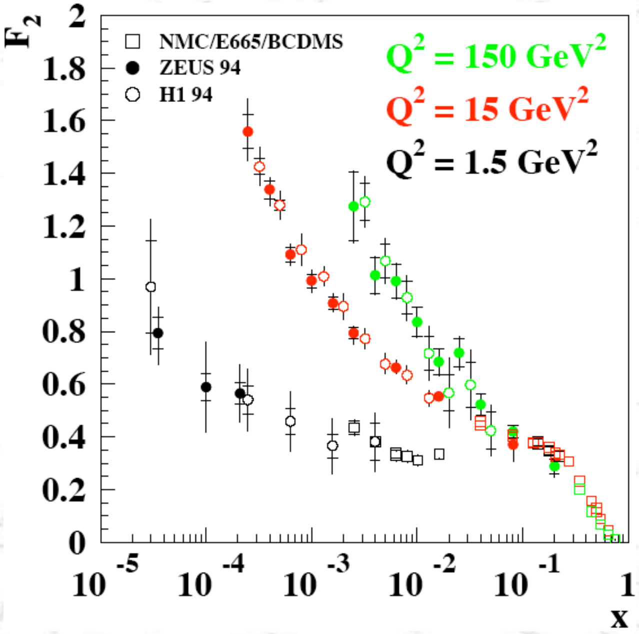
QCD



Valence quarks and QCD sea

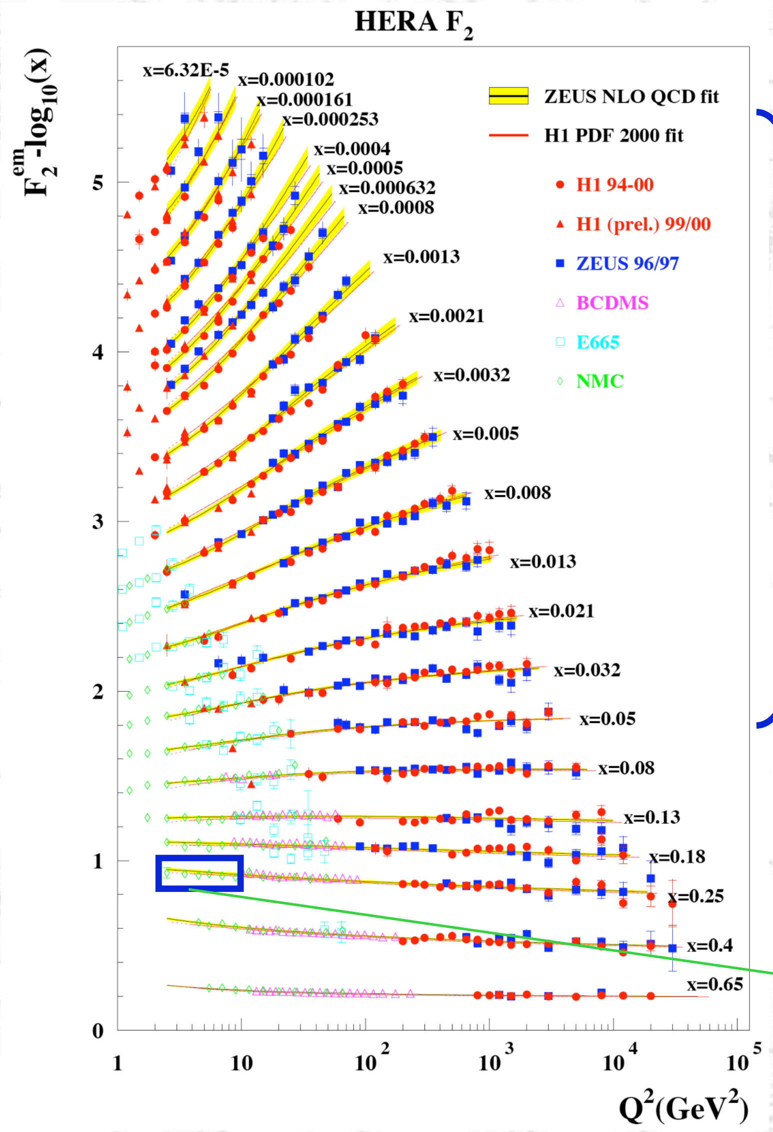


Proton = valence quarks + QCD sea



Selected QCD topics at high-energy collider experiments

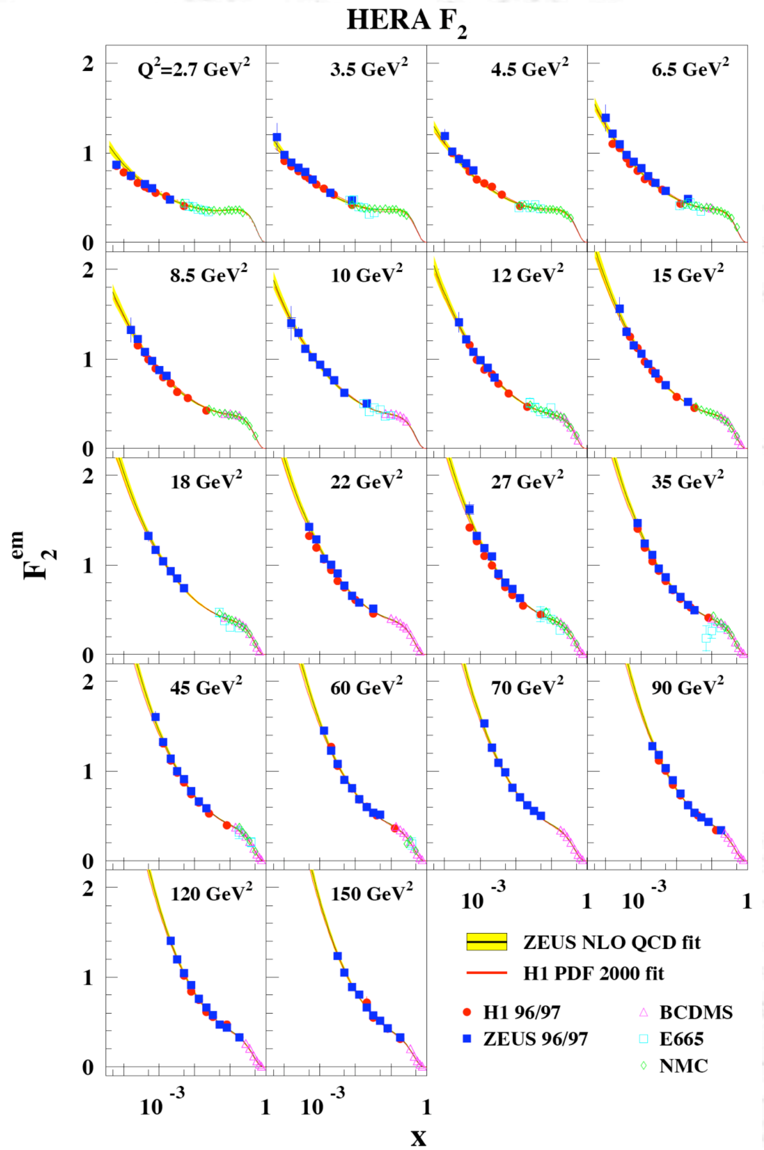
- Structure function measurement: Q^2 and x dependence



Strong violation of scaling at low x and high Q^2

In contrast to:

Low Q^2 high x!



- Global fits - Basics
  - Starting point: DGLAP evolution equations

$$\frac{d\Sigma(x,Q^2)}{d\ln Q^2} = \frac{\alpha_s(Q^2)}{2\pi}\int_x^1 \frac{dz}{z}\left[P_{qq}\left(\frac{x}{z}\right)\Sigma(z,Q^2) + P_{qg}\left(\frac{x}{z}\right)g(z,Q^2)\right]$$

$$\frac{dg(x,Q^2)}{d\ln Q^2} = \frac{\alpha_s(Q^2)}{2\pi}\int_x^1 \frac{dz}{z}\left[P_{gq}\left(\frac{x}{z}\right)\Sigma(z,Q^2) + P_{gg}\left(\frac{x}{z}\right)g(z,Q^2)\right]$$

  - Strategy to extract parton densities from a measurement of F_2
  - Specify a set of parton distribution functions as a function of x
    - Starting scale Q^2
    - Take into account flavor sum rule and momentum sum rule!

$$xf_i = A_i x^{-\lambda_i}(1-x)^{\eta_i}F(x)$$

$$\int_0^1 f_u(x,Q_0^2)dx = 2 \qquad \int_0^1 f_d(x,Q_0^2)dx = 1 \qquad \int_0^1[xf_u(x,Q_0^2) + xf_d(x,Q_0^2) + xf_s(x,Q_0^2) + xf_g(x,Q_0^2)]dx = 1$$

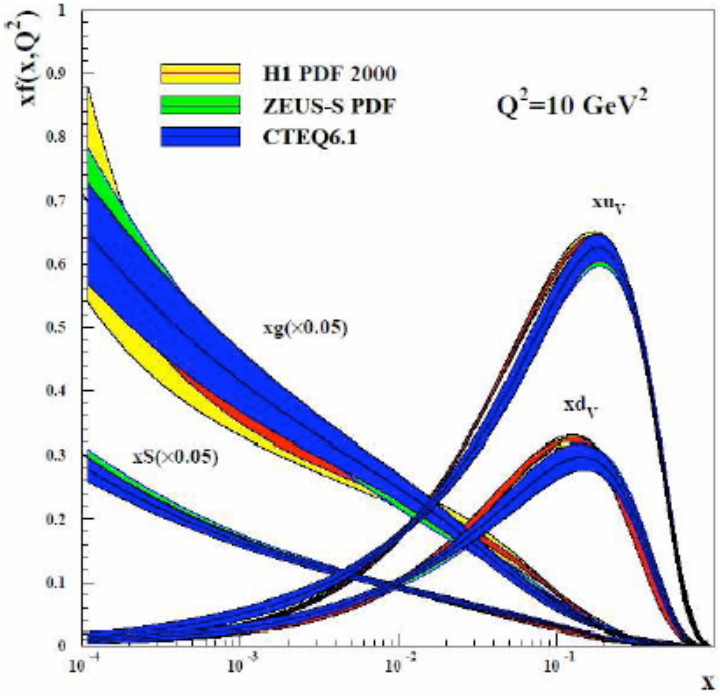
i: valence (u,d), sea (s) and gluon (g)

Selected QCD topics at high-energy collider experiments

- Global fits results from ZEUS
  - ☐ Determine F_2^{QCD} in terms of parton distribution functions
  - ☐ Evolve F_2^{QCD} through parton distribution functions based on evolution equations
  - ☐ Minimize χ^2 in terms of F_2^{QCD} and F_2^{data} by adjusting parameters in $xf_i(x,Q^2)$
  - ☐ Net result: QCD prediction for $xf_i(x,Q^2)$ and therefore $F_2(x,Q^2)$
  - ☐ Various global pdf analysis:
    - GRV
    - CTEQ
    - MRST
    - ZEUS/H1

i: valence (u,d), sea (s) and gluon (g)

$$xf_i = A_i x^{-\lambda_i}(1-x)^{\eta_i}F(x)$$

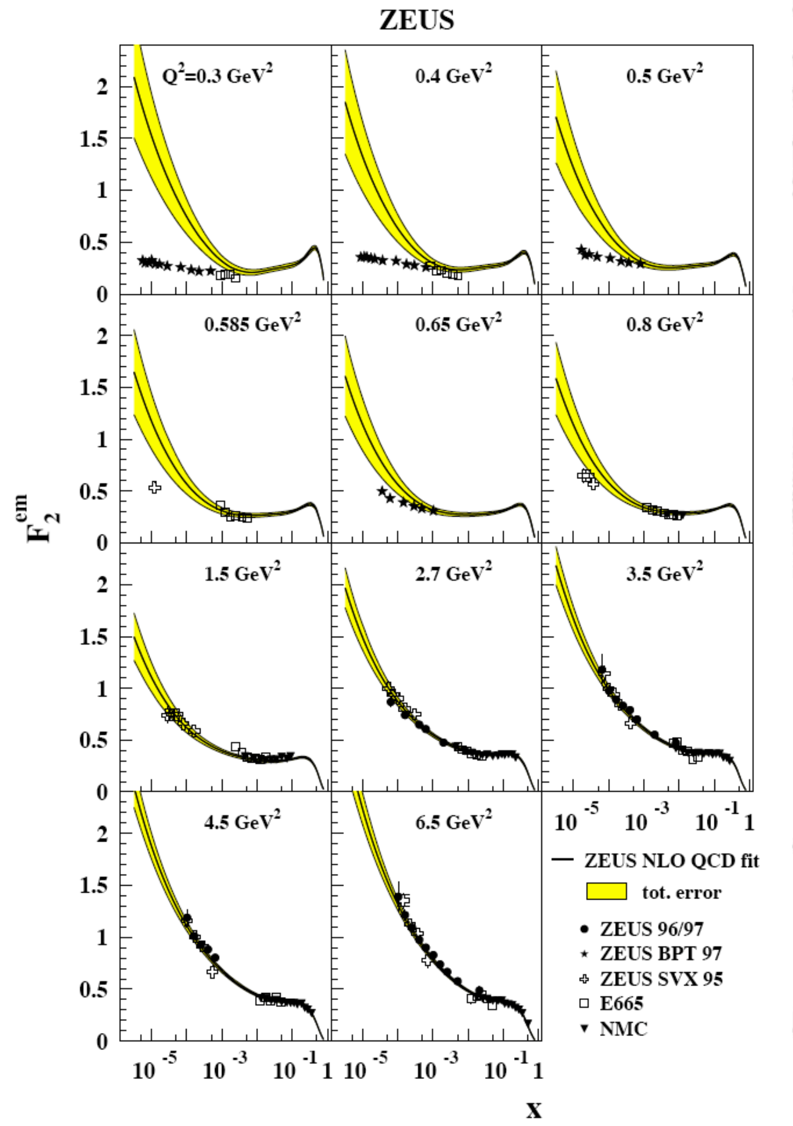


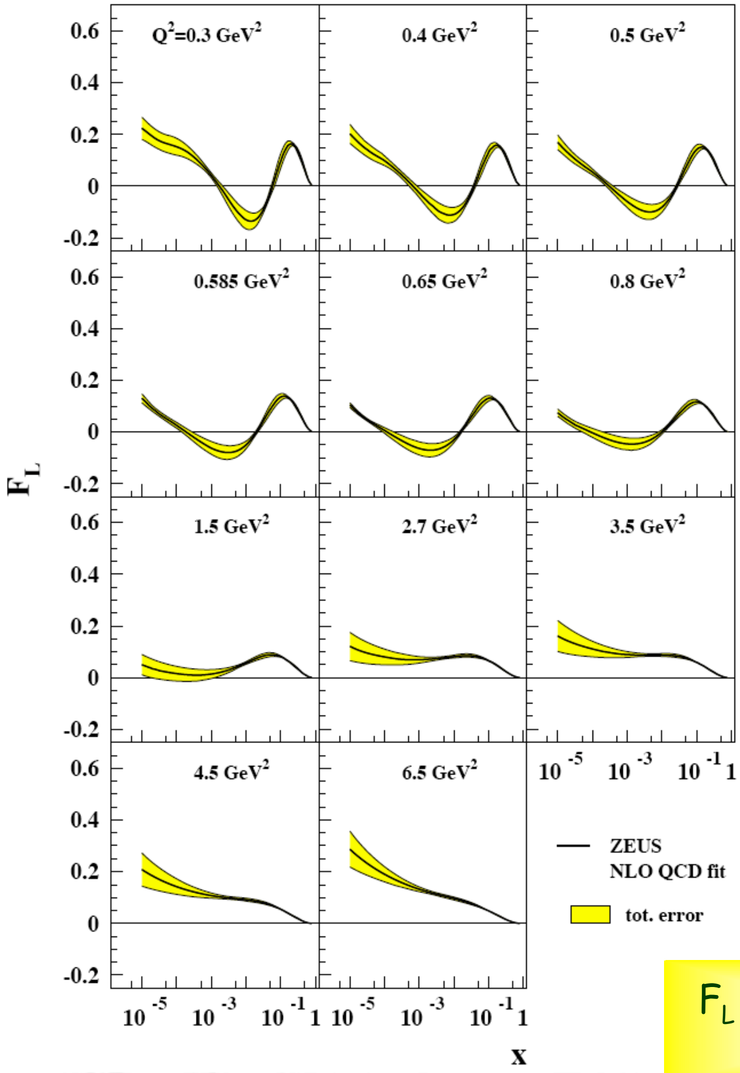
Low x: λ_i

High x: η_i

Selected QCD topics at high-energy collider experiments

- Extrapolation of ZEUS NLO DGLAP fit towards low Q2





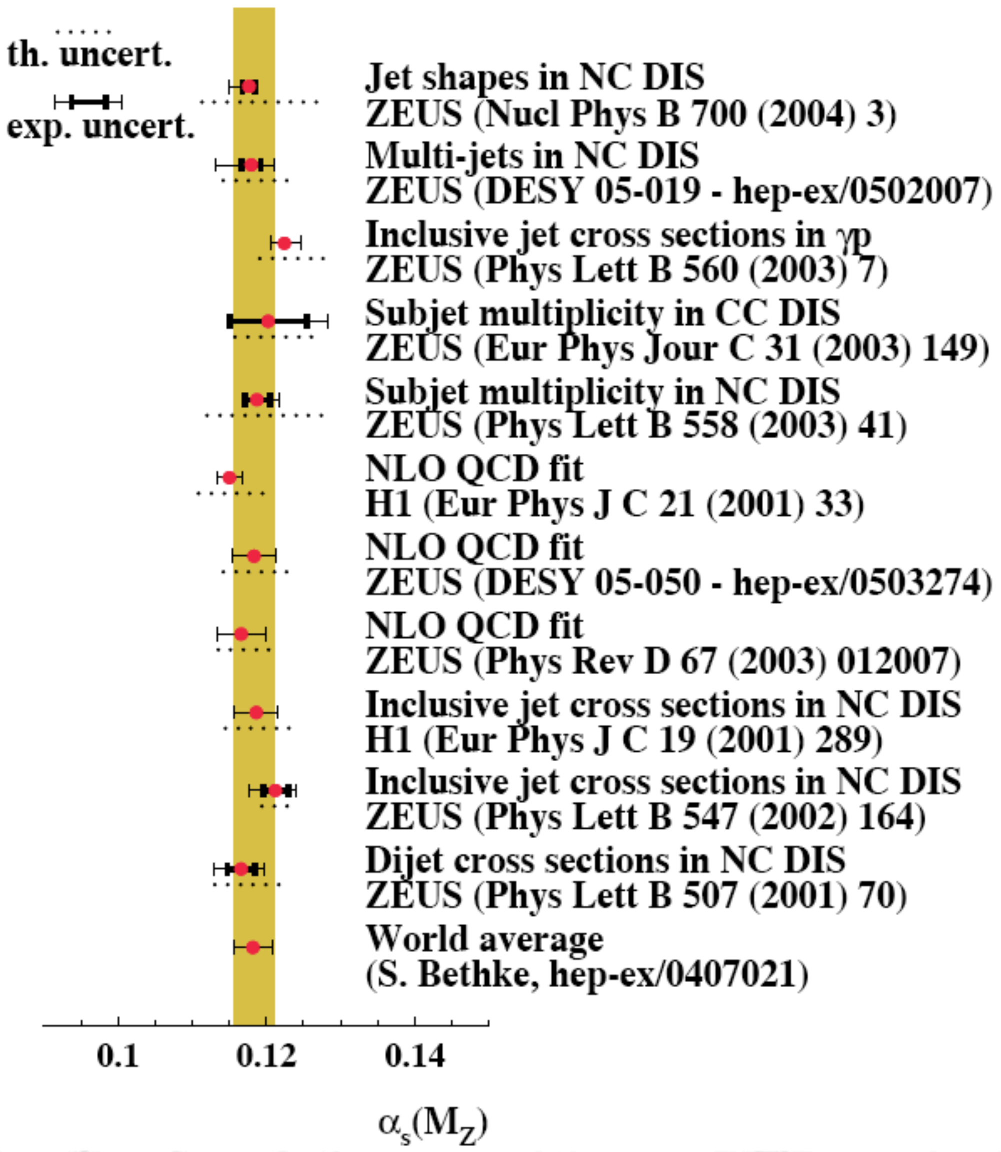
F_L negative at low Q2 and low x!

Selected QCD topics at high-energy collider experiments

- Measurement of α_s
  - The success of perturbative QCD lies on the precise determination of α_s from diverse phenomena
  - There is a wealth of determinations of α_s at HERA from a variety of observables (jets, structure functions, …)
  - Good agreement with current world average:

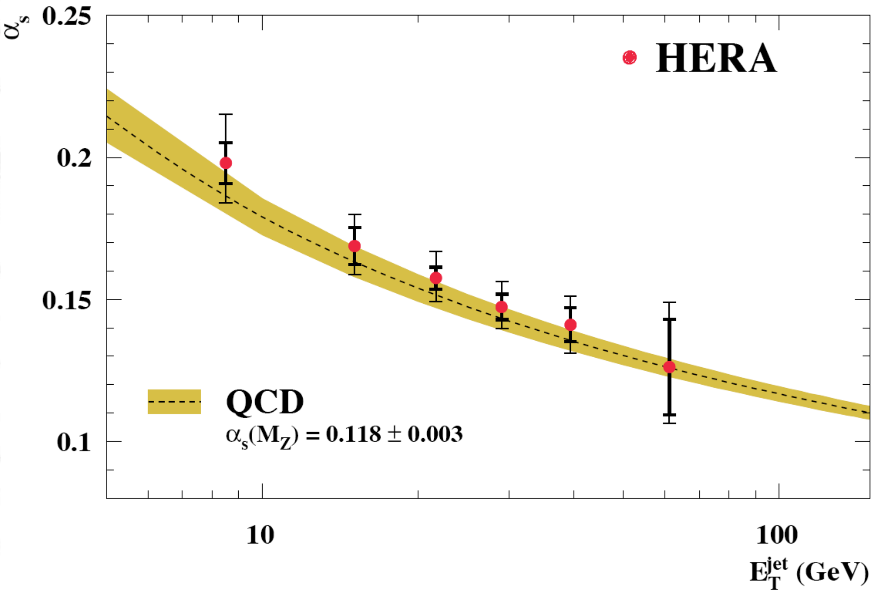
    0.1182 ± 0.0027

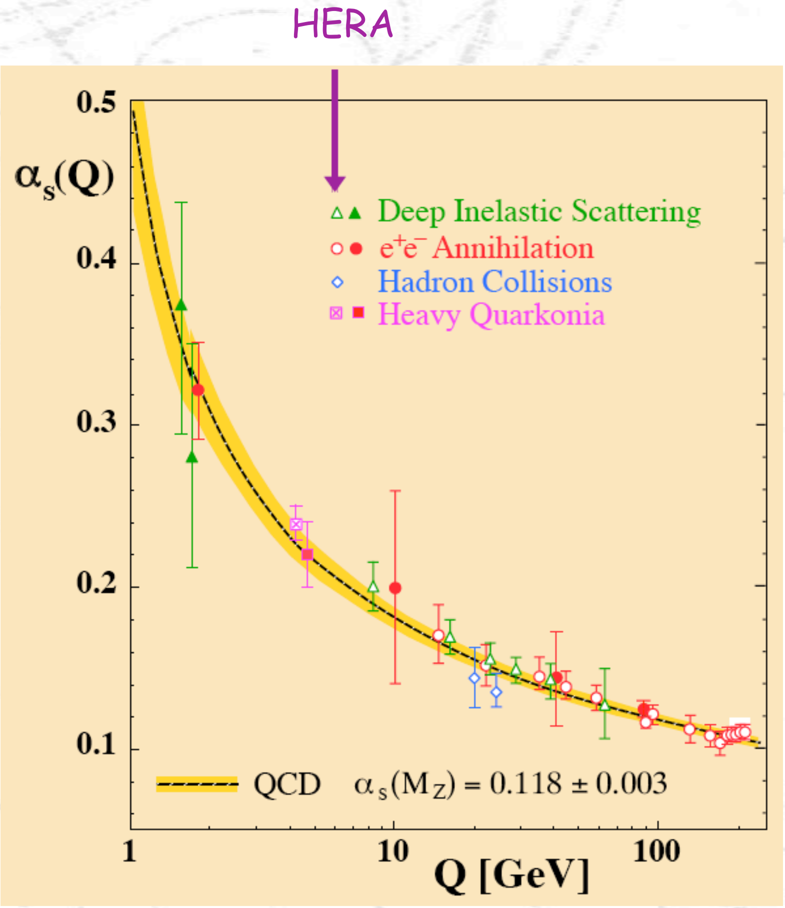
    S Bethke, hep-ex/0407021
  - HERA jet measurements are by now as precise as more inclusive measurements such as those from τ decays



Selected QCD topics at high-energy collider experiments

- Measurement of α_s
  - ☐ The HERA determinations are consistent with the running of α_s over a large range in E_T
  - ☐ Dominant uncertainties are:
    - Experimental (jet energy scale): ~0.9%
    - Theoretical uncertainties (parton distribution functions, hadronization corrections, terms beyoind NLO): ~4%

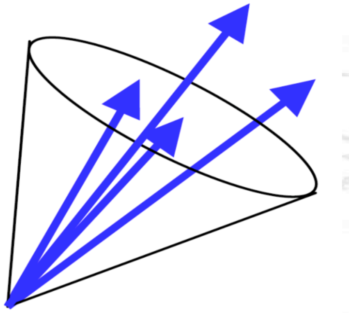




Selected QCD topics at high-energy collider experiments

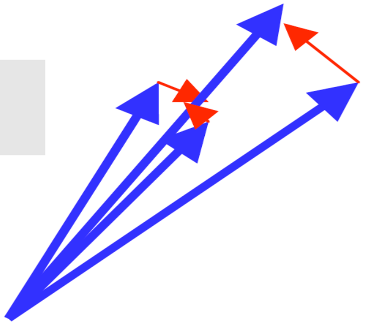
- Jet production: Jet reconstruction
  - ☐ Traditional choice at hadron colliders: cone algorithm

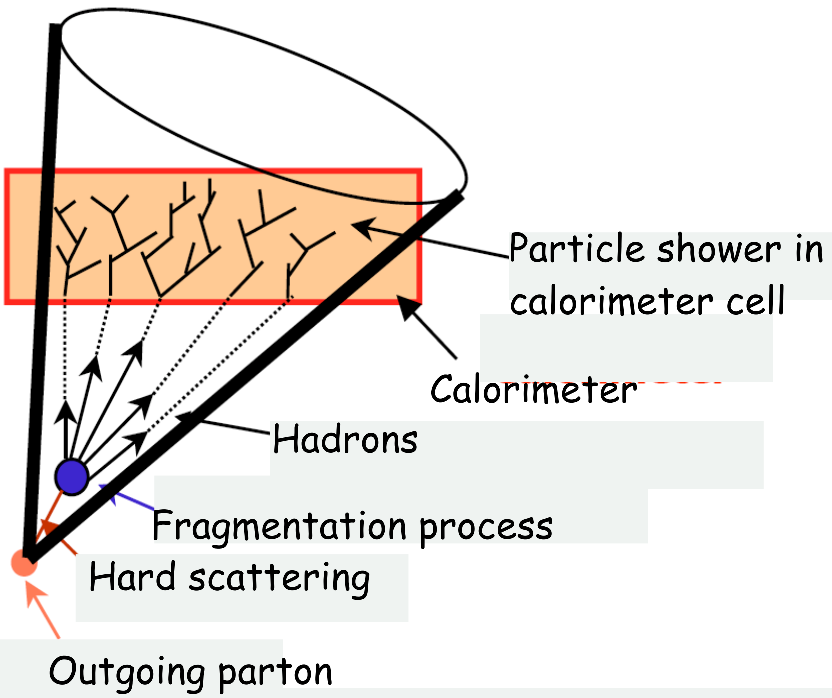
    Sum up energy inside cone



  - ☐ Traditional choice in e+e-: successive recombination algorithms (k_T algorithm)

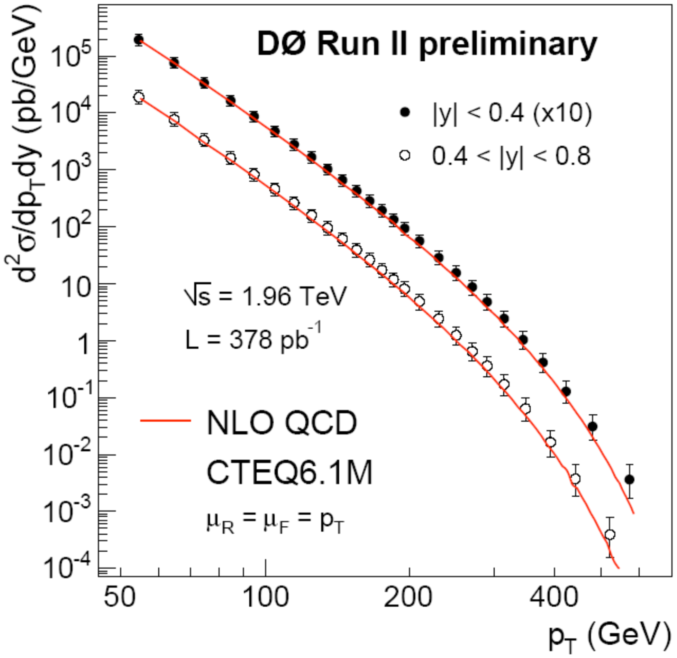
    Sum of particles/cells close in relative k_T

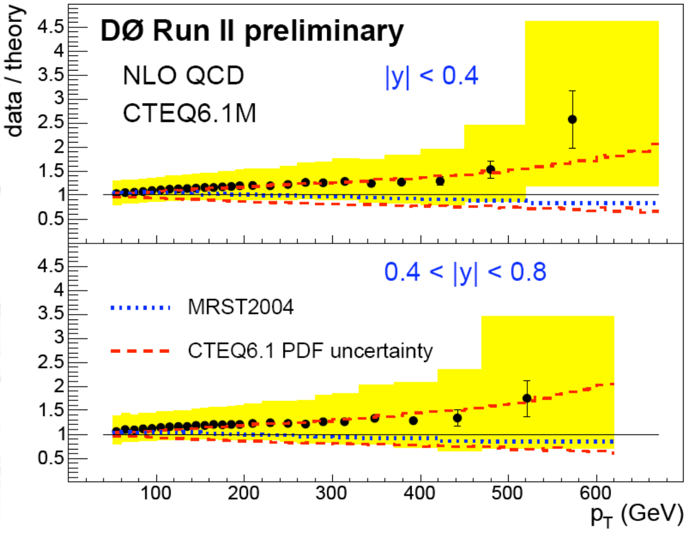




Selected QCD topics at high-energy collider experiments

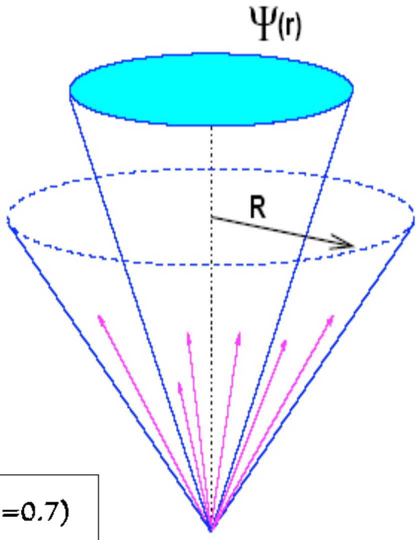
- Jet production: Inclusive jet cross-section
  - ❑ Inclusive jet cross section @ Tevatron
    - Stringent test of pQCD
    - Tail sensitive to new physics
    - PDFs at high Q^2 & high
  - ❑ Direct comparison with NLO
    - QCD Hadronization / Underlying Event corrections small
  - ❑ Good data-theory agreement
    - Experimental uncertainty dominated by jet energy scale
    - Largest theoretical error from PDFs (gluon at high x)

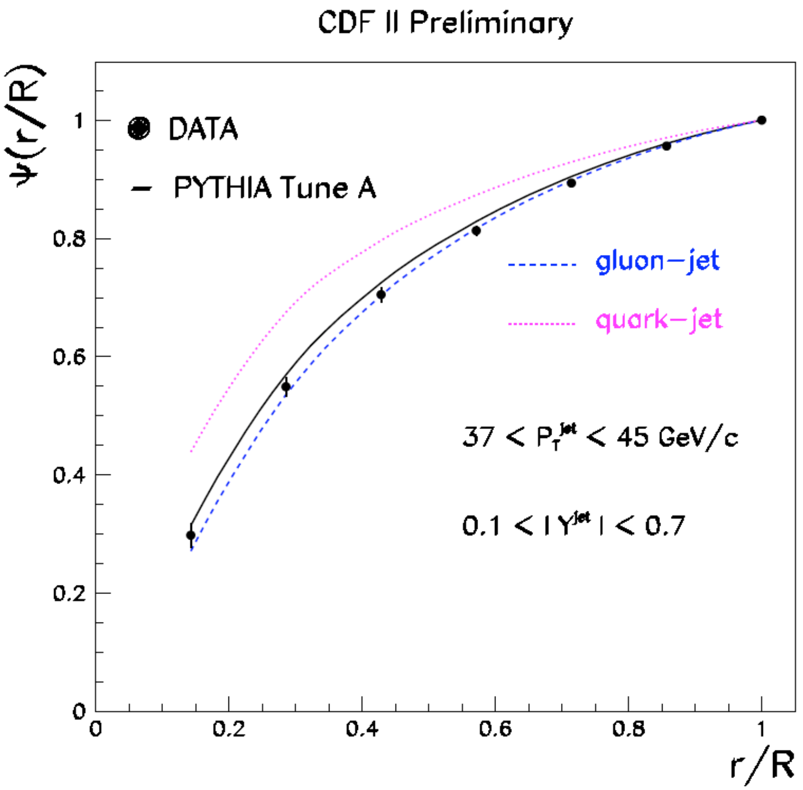


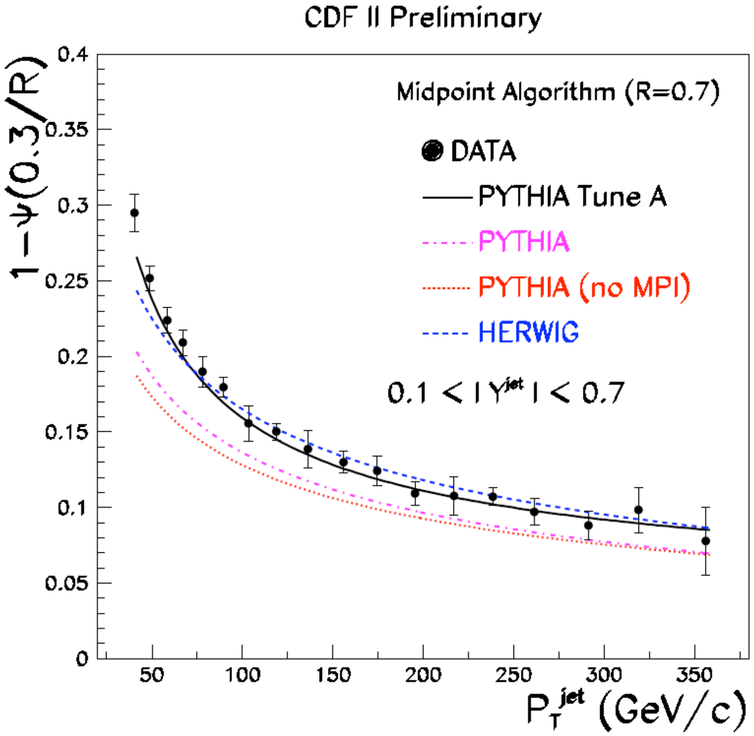


Selected QCD topics at high-energy collider experiments

- Jet production: Jet shapes
  - Jet shapes governed by multi-gluon emission from primary parton
    - Test of parton shower models
    - Sensitive to underlying event structure
    - Sensitive to quark and gluon mixture in the final state







Selected QCD topics at high-energy collider experiments

- Helicity average and helicity difference parton distribution functions

- Unpolarized proton structure:

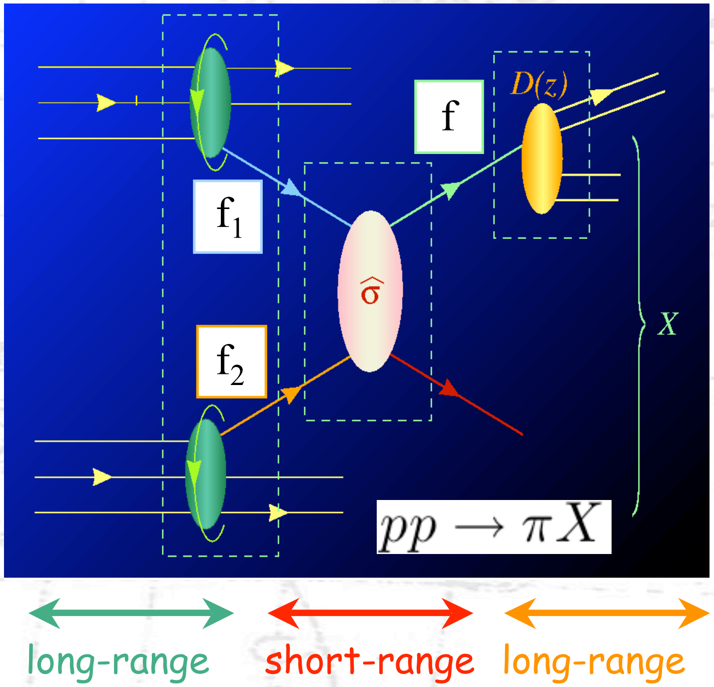
$$f(x) =$$

$f^+(x)$ $f^-(x)$

$$F_2 = \sum_q x e_q^2 q$$

Quark (q) distribution and
Gluon (g) distributions:
Well known experimentally!

Quarks and Gluons carry
50% of the proton
momentum, respectively!



$$A_{LL} = \frac{d\Delta\sigma_{pp\to\pi+X}}{d\sigma_{pp\to\pi+X}}$$

$$\hat{a}_{LL} = \frac{d\Delta\hat{\sigma}}{d\hat{\sigma}}$$

f_1 f_2

$$= \frac{\sum_{f_1,f_2} \Delta f_1 \otimes \Delta f_2 \otimes d\hat{\sigma}^{f_1 f_2 \to fX} \cdot \hat{a}_{LL}^{f_1 f_2 \to fX} \otimes D_f^{\pi}}{\sum_{f_1,f_2} f_1 \otimes f_2 \otimes d\hat{\sigma}^{f_1 f_2 \to fX} \otimes D_f^{\pi}}$$

- Polarized proton structure:

$$\Delta f(x) =$$

$f^+(x)$ $f^-(x)$

$$g_1 = \frac{1}{2}\sum_q e_q^2 \Delta q$$

Quark (Δq) distributions:
Known only at high x.
Gluon (Δg) distributions:
Poorly constrained!

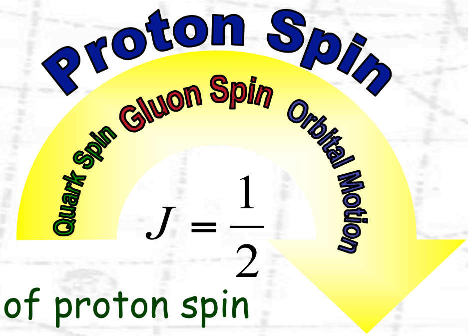
How do quarks and gluons
make up the proton spin?

Selected QCD topics at high-energy collider experiments

- RHIC SPIN program (e.g. ΔG)

- Fundamental question: How is the proton spin made up (helicity)?

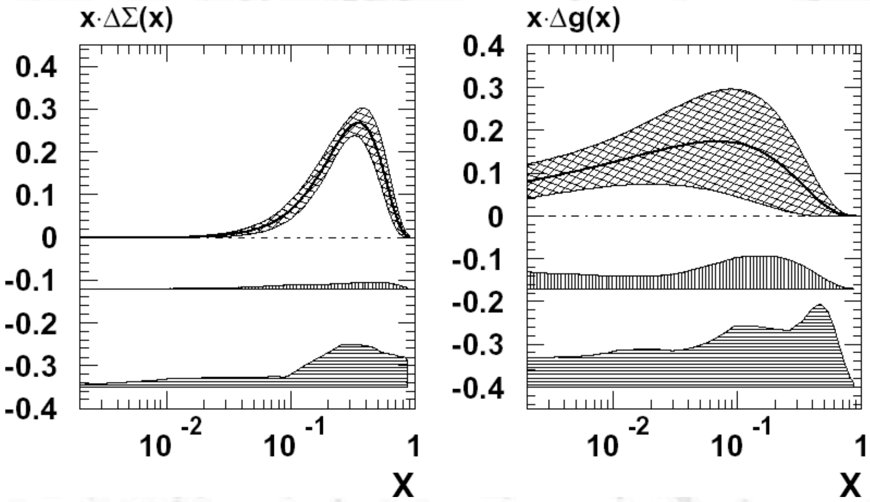
$$J = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_z^q + L_z^g$$



- EMC/SMC result: Fraction of proton spin carried by quarks is small:

$$\Delta\Sigma_{(AB)} = 0.38 \, {}^{+\,0.03}_{-\,0.03} \quad \text{at} \quad Q_i^2 = 1\text{GeV}^2$$

- Where is the spin of the proton? $\Delta G \;\text{and}\; (L_z^q + L_z^g)$
- SMC QCD-analysis:



- At present: ΔG is only poorly constrained from scaling violations in fixed target DIS experiments

$$\Delta G_{(AB)}\left(Q^2 = 1GeV^2\right) = 0.99 \, {}^{+\,1.17}_{-\,0.31} \quad \text{at} \quad Q_i^2 = 1\text{GeV}^2$$

B. Adeva et al., SMC Collaboration, Phys. Rev. D58 (1998) 112002.

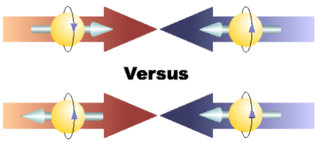
- Need: New generation of experiments to explore the spin structure of the proton: polarized proton-proton collisions at RHIC

RHIC spin program:

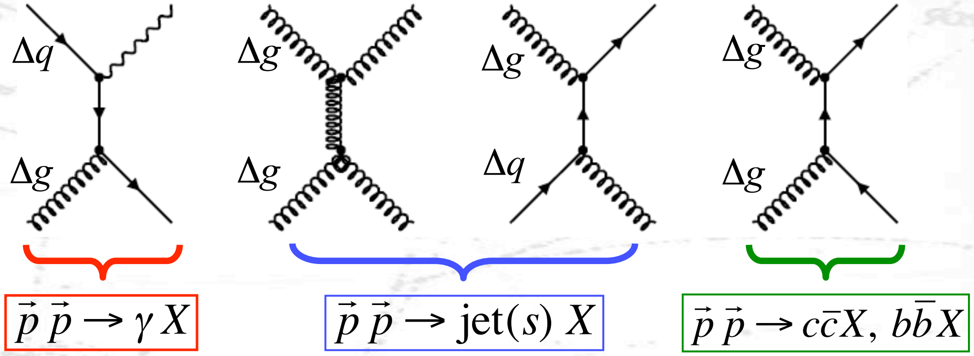
- Unique multi-year program which has just started…!
- Explore various aspects on the spin structure and dynamics of the proton in a new domain:
    - Spin structure of the proton (Transverse spin dynamics and transversity, Gluon polarization and Flavor decomposition of quark/anti-quark polarization)
    - Spin dependence of fundamental interactions
    - Spin dependence of fragmentation
    - Spin dependence in elastic polarized pp collisions

Selected QCD topics at high-energy collider experiments

- Access helicity difference distribution functions (gluon and quark/anti-quark)
  - At RHIC, any combination of beam polarization (longitudinal (+/-) /transverse (↑/↓)) is possible, which allows to access different aspects of the proton spin structure
  - Double longitudinal-spin asymmetry:



$$A_{LL} = \frac{(\sigma_{++} + \sigma_{--}) - (\sigma_{+-} + \sigma_{-+})}{(\sigma_{++} + \sigma_{--}) + (\sigma_{+-} + \sigma_{-+})}$$



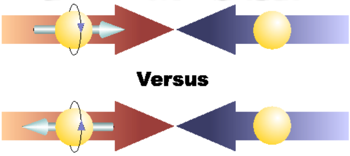
$\vec{p}\,\vec{p} \rightarrow \gamma\, X$

$\vec{p}\,\vec{p} \rightarrow \mathrm{jet(s)}\; X$

$\vec{p}\,\vec{p} \rightarrow c\bar{c}X,\; b\bar{b}X$

☐ Study helicity dependent structure functions (Gluon polarization)!

- Single longitudinal-spin asymmetry:



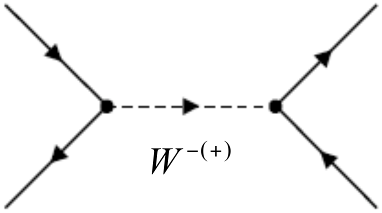
$$A_L = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$

$\Delta d + \bar{u} \rightarrow W^-$

$\Delta \bar{u} + d \rightarrow W^-$

$\Delta \bar{d} + u \rightarrow W^+$

$\Delta u + \bar{d} \rightarrow W^+$



$\boxed{W^{-(+)} \rightarrow l^- + \bar{\nu}_l\; (l^+ + \nu_l)}$

$l = e, \mu$

☐ Study parity violation effects (Flavor decomposition Quark/Anti-Quark polarization)!

- Statistical significance (FOM=figure-of-merit):

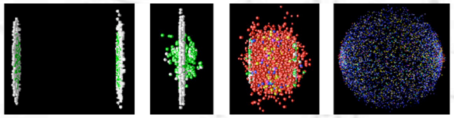
☐ Single spin asymmetry: $P^2 \cdot \int Ldt$

☐ Double spin asymmetry: $P^4 \cdot \int Ldt$

Selected QCD topics at high-energy collider experiments

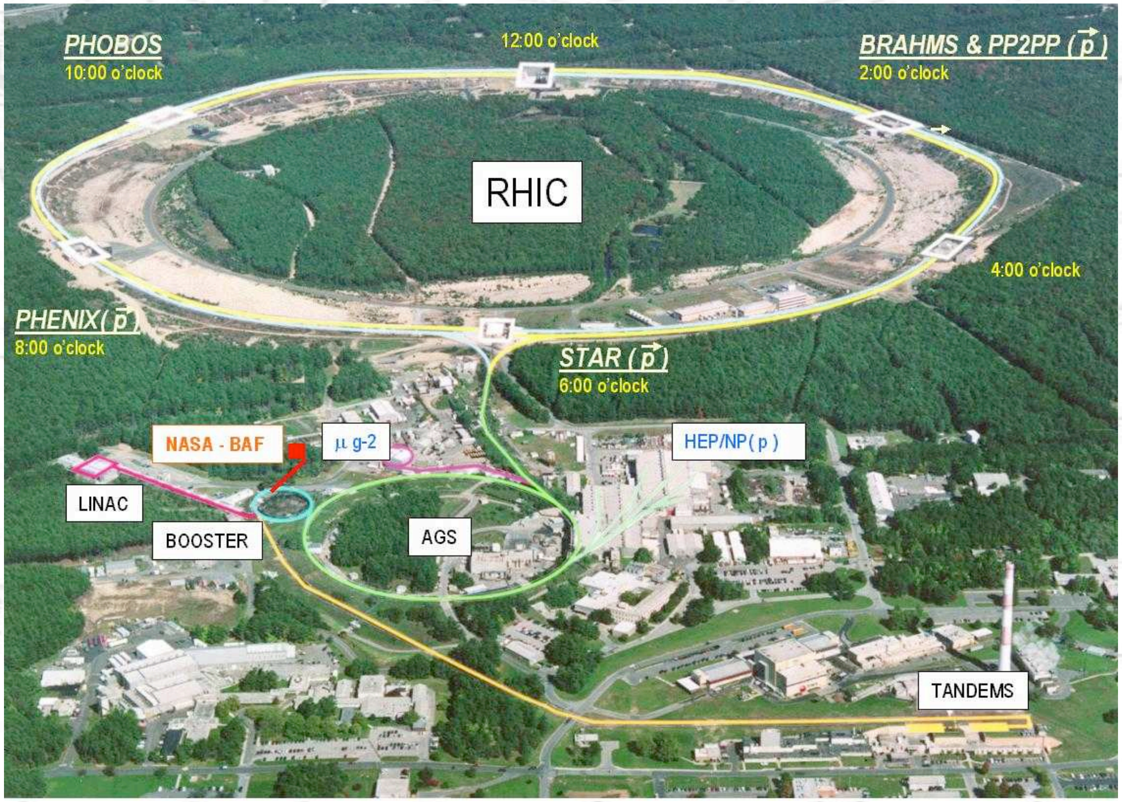
- Dedicated high-energy QCD physics program at Brookhaven National Laboratory

Au+Au (d+Au)

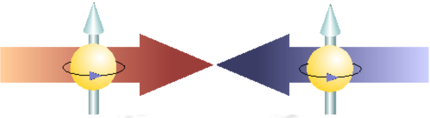


Experiments:

- PHENIX
- STAR
- BRAHMS
- PHOBOS



p+p (trans. polarized)



p+p (long. polarized)

Experiments:

- PHENIX
- STAR
- BRAHMS

- RHIC facility: Unique collider facility which allows to collide different species (Au-Au and d-Au as well as polarized p-p) at variable beam energy
- Explore the nature of matter under extreme conditions (Relativistic-heavy ion program)
- Explore the nature of the proton spin (High energy spin physics program)

Unique
QCD
lab!

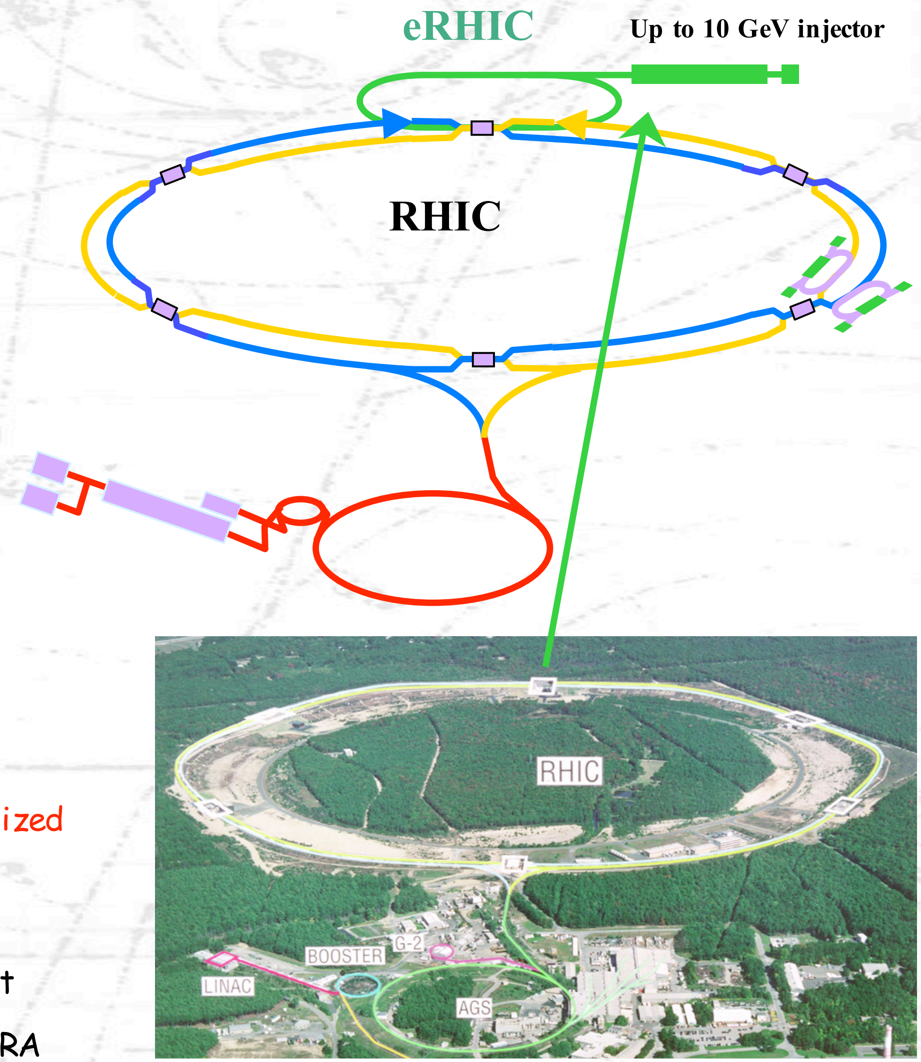
Summary and Outlook

Summary

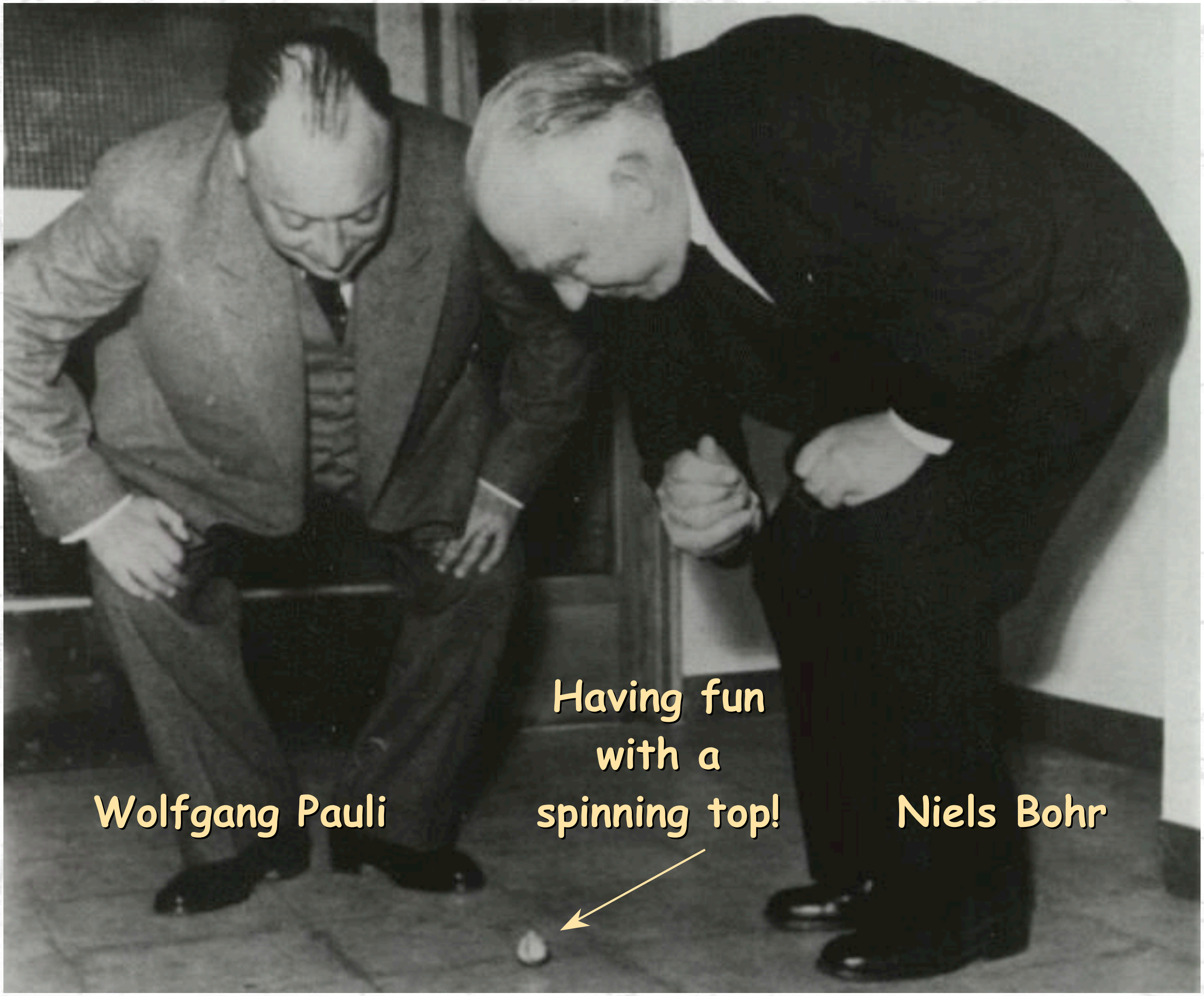
- Wealth of QCD data from high-energy QCD collider experiments
- Parton distributions functions are known over a large range in Bjorken-x with large uncertainties at high-x
- LEP/HERA/Tevatron will provide critical input for LHC QCD background studies
- After 2010, RHIC and LHC will be the only high-energy hadron collider facilities for the foreseeable future

Outlook

- LHC will allow to probe distance scales (high E_T) beyond the current reach
- Explore new QCD regime in eAu (high parton density) and polarized ep scattering (complement ongoing RHIC physics activities)
- Unique opportunity to establish such a QCD facility (eRHIC) at BNL ⇒ Continuation of collider based DIS program beyond HERA



Fun with SPIN in the Past and the Future



Having fun with a spinning top!

Wolfgang Pauli

Niels Bohr

Backup

- Machine performance overview (FY02-FY05)
  - Overview of performance parameters

	$\sqrt{s}$ [GeV]	Lpeak $[10^{30}]$ $cm^{-2}\,s^{-1}$	L $[pb^{-1}]$	Polarization [%]
FY02	200	2	0.35	15
FY03	200	6	1	30
FY04	200	6	0.4	40
FY05	200 (410)	9	9	50

  - Status

☑ Siberian snake and spin rotator magnets

☑ Fast polarimeters in AGS/RHIC

☑ Local polarimeters at STAR/PHENIX

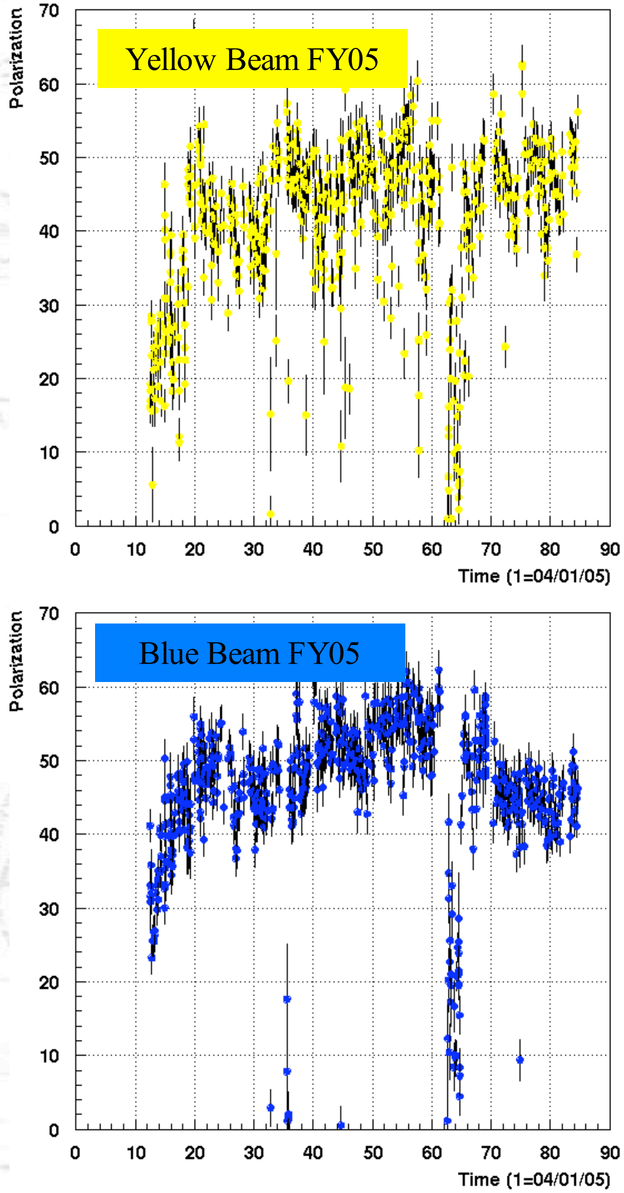
☑ Spin transfer AGS to RHIC

☑ Polarized gas-jet target

☑ Warm AGS Siberian snake

☑ Installation of cold AGS Siberian snake magnet and commissioning started

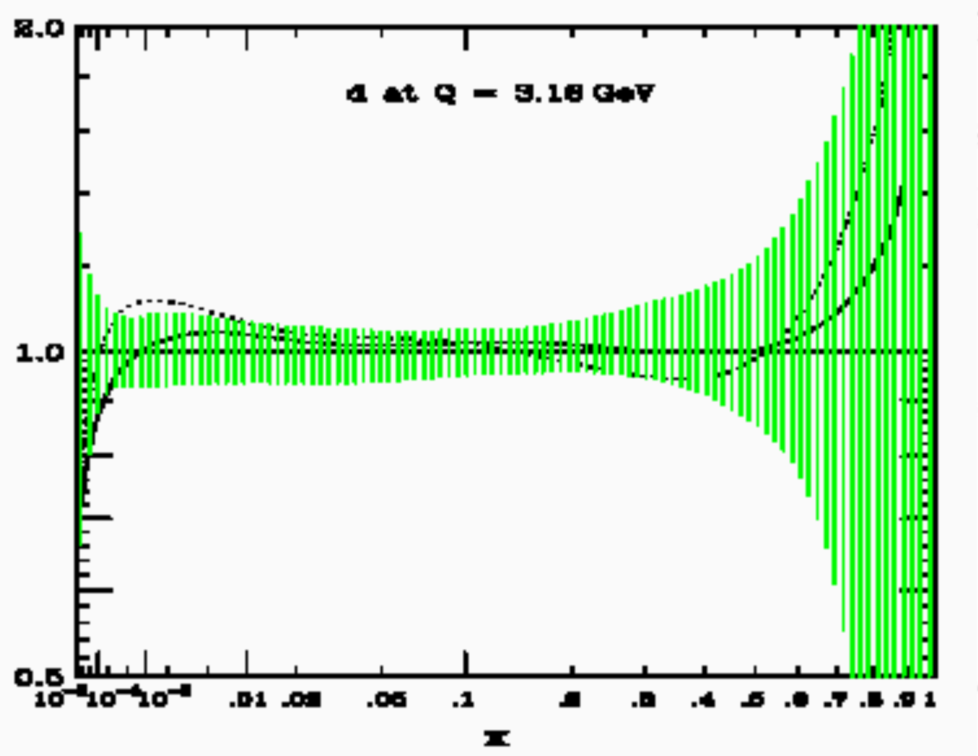
☑ Commissioning towards 250GeV ramp started (At 205GeV)

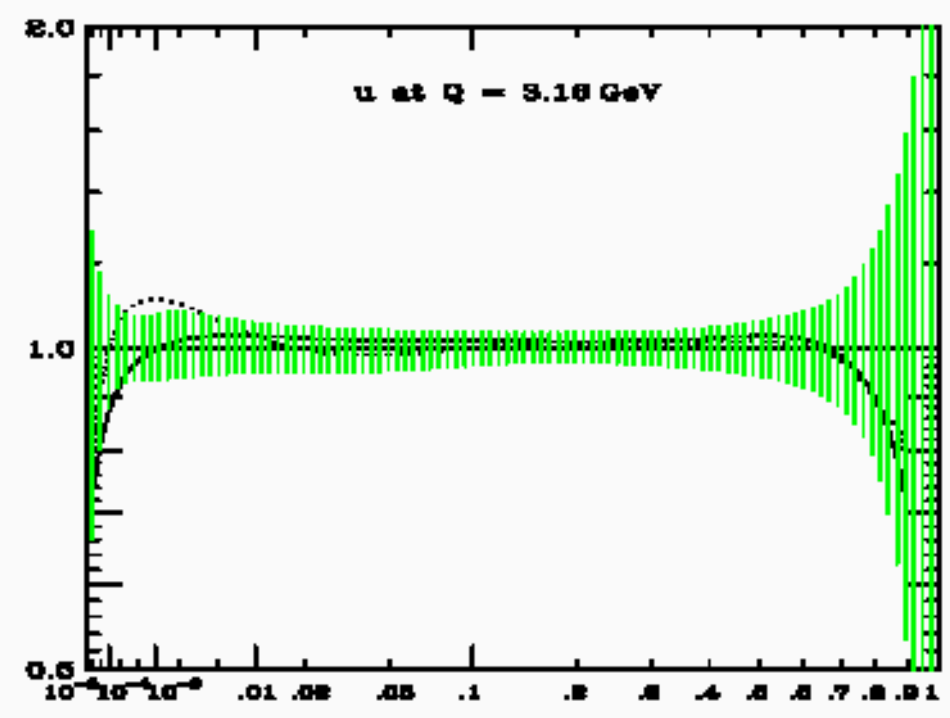


Blue and Yellow Beam polarization

Backup

- PDF uncertainty (Ratio to CTEQ6)





- ☐ RHIC can reduce errors of valence PDFs at large x!

Backup

- Comparison of kinematic coverage
  - ☐ RHIC
  - ☐ Tevatron
  - ☐ LHC