α_s Determinations from Jets and Scaling Violations at HERA

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Buzios, Brazil

on behalf of the H1 and ZEUS Collaborations

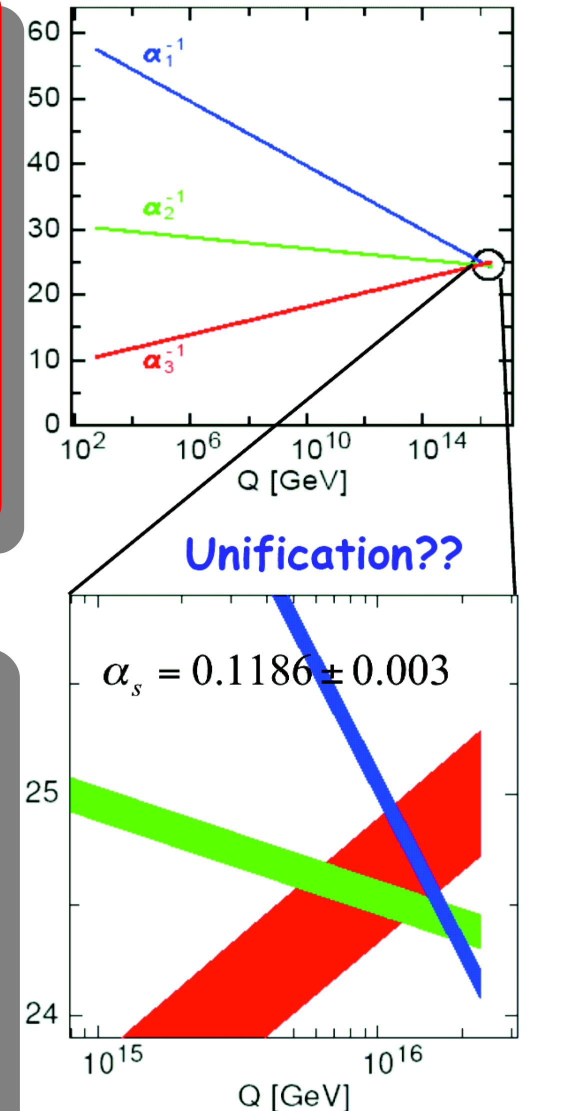
The Strong Coupling

Why is it so important to know α_s precisely?

- ✗ Single free parameter of QCD
- ✗ Affects almost any cross section in high energy collisions
- ✗ Need to know QCD “background” precisely to discover new physics
- ✗ Unification of forces valid?

Features

- ✗ Asymptotic freedom
- ✗ Strong force for partons: (10^2x EM, 10^{14}x weak, 10^{40}x gravitation)
- ✗ Less precisely known compared to other forces
- ✗ Cannot get hold of partons (confinement)

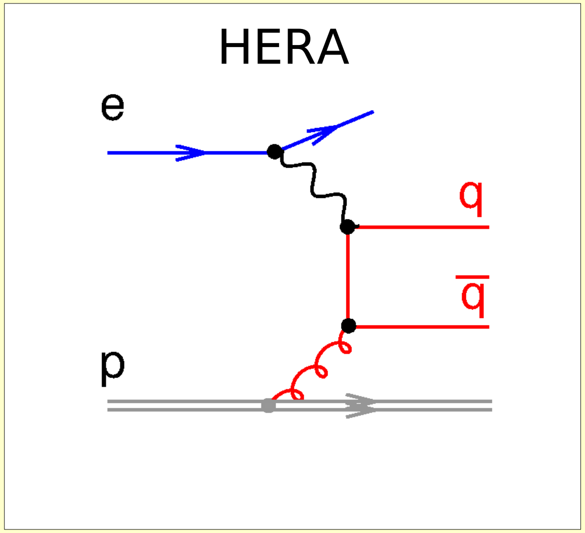


hep-ph/0407067 B.Allanach ... P.Zerwas

Determinations

How to determine α_s?

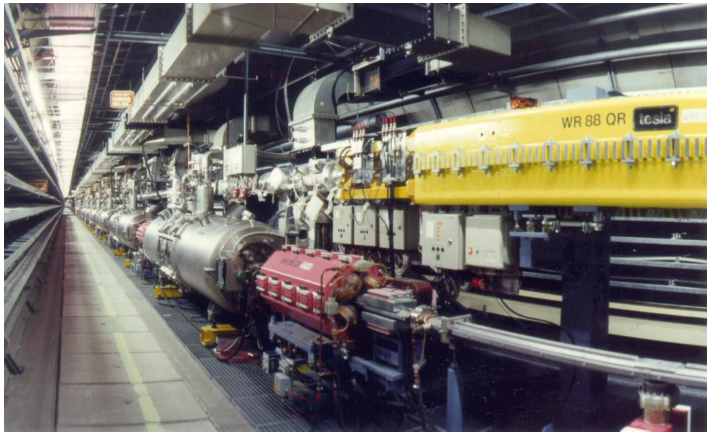
- Processes which involve gluon vertices
  - electron-nucleon scattering
  - e^+e^- annihilation
  - hadron-hadron collisions
  - decays

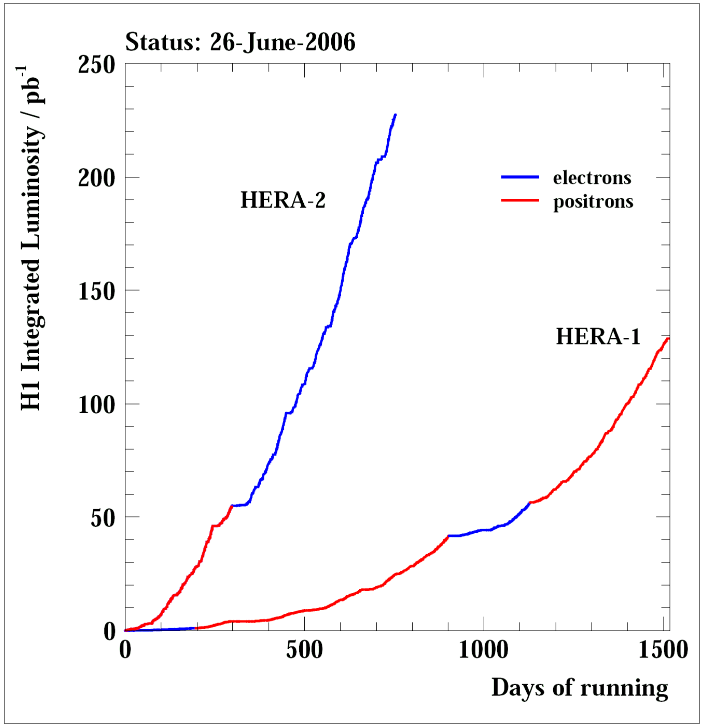


World averages

- 1989: $\alpha_s(m_Z) = 0.11 \pm 0.01$ only at 10%!
- Now world means from PDG and Bethke, constantly updated
- Making use of lots of measurements from different processes

HERA at DESY

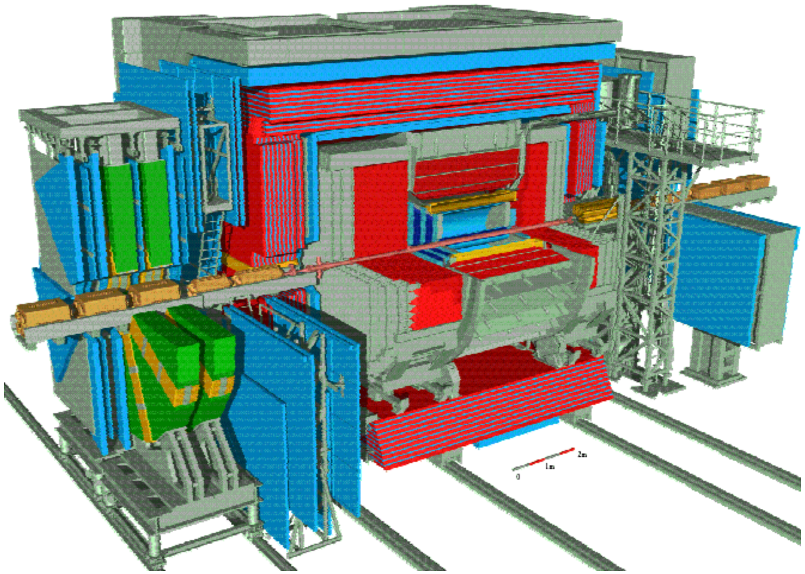


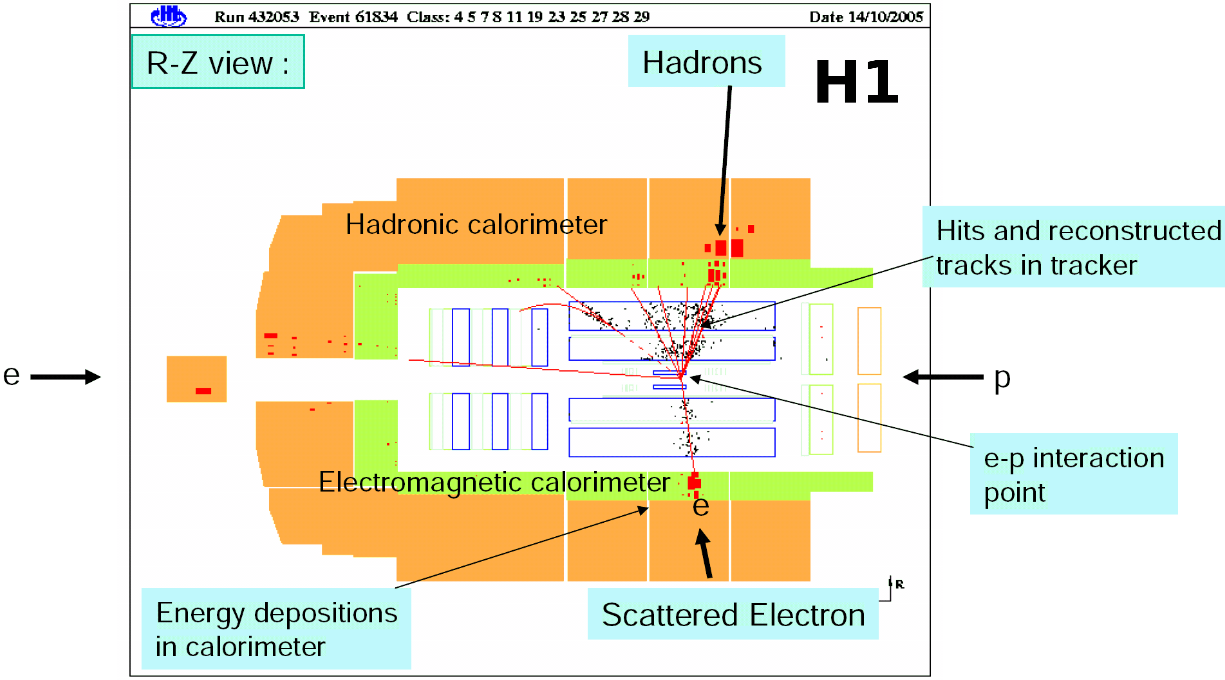


- Unique facility: separate storage rings for $e^{\pm}$ and p
- 27.5 GeV electrons on 920 GeV protons
- HERA II (2002..):
  - longitudinally polarised electrons
  - inst. luminosity x5
  - 2006: best performance ever
- In the following: analyses with HERA I data

The H1 and ZEUS Experiments

ZEUS





- ✗ Two general purpose 4π detectors
- ✗ Scattered electron measured at 1% level
- ✗ Use electron to calibrate jets
- ✗ Major upgrades with HERA II:
  - ✗ More silicon detectors
  - ✗ Trigger
  - ✗ .....

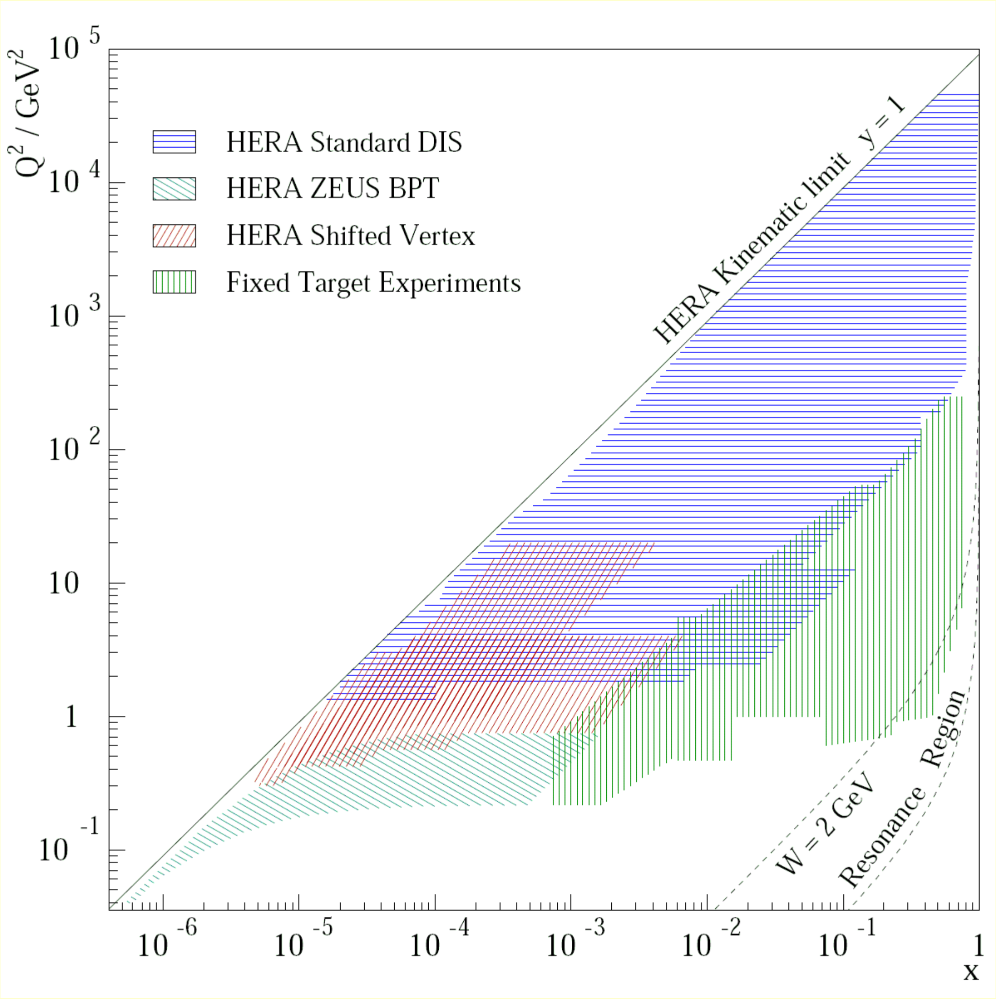
HERA's Contribution to α_s

How can HERA contribute?

- Competitive precision, enters world averages
- Complementary information:
  - Incompatible α_s from ep and e^+e^- $\Rightarrow$QCD broken!
- Two approaches:
  - Scaling violation of F_2
    - ☺ very precise measurement and theory
    - ☹ indirect sensitivity
  - Observation of Jets
    - ☹ more difficult measurement and theory
    - ☺ direct sensitivity
  - Want both!

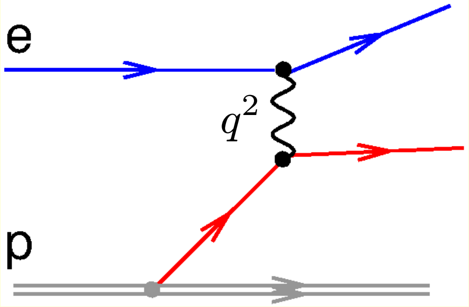
Factorisation: $$\sigma = \left[\sum_{i=g,q,\bar{q}} \int dx\, f_i(x, \mu_f, \underline{\alpha}_s(\mu_f))\, \hat{\sigma}_{\mathrm{pQCD}}(x, \mu_f, \mu_r, \underline{\alpha}_s(\mu_r)) \right] (1 + \delta_{\mathrm{had}})$$

Kinematic Coverage



✗ Large range in x and Q^2

Essential to establish scaling violations



Center of mass energy

$$\sqrt{s} = 319\,\mathrm{GeV}$$

Four momentum transfer

$$Q^2 = -q^2$$

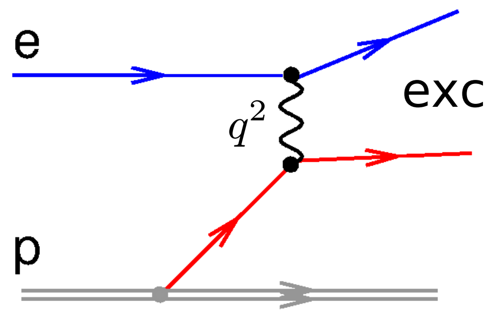
Bjorken scaling variable

$$x = \frac{Q^2}{2p \cdot q}$$

Inelasticity

$$y = \frac{Q^2}{sx}$$

Determination of F_2



exchanged photon=NC

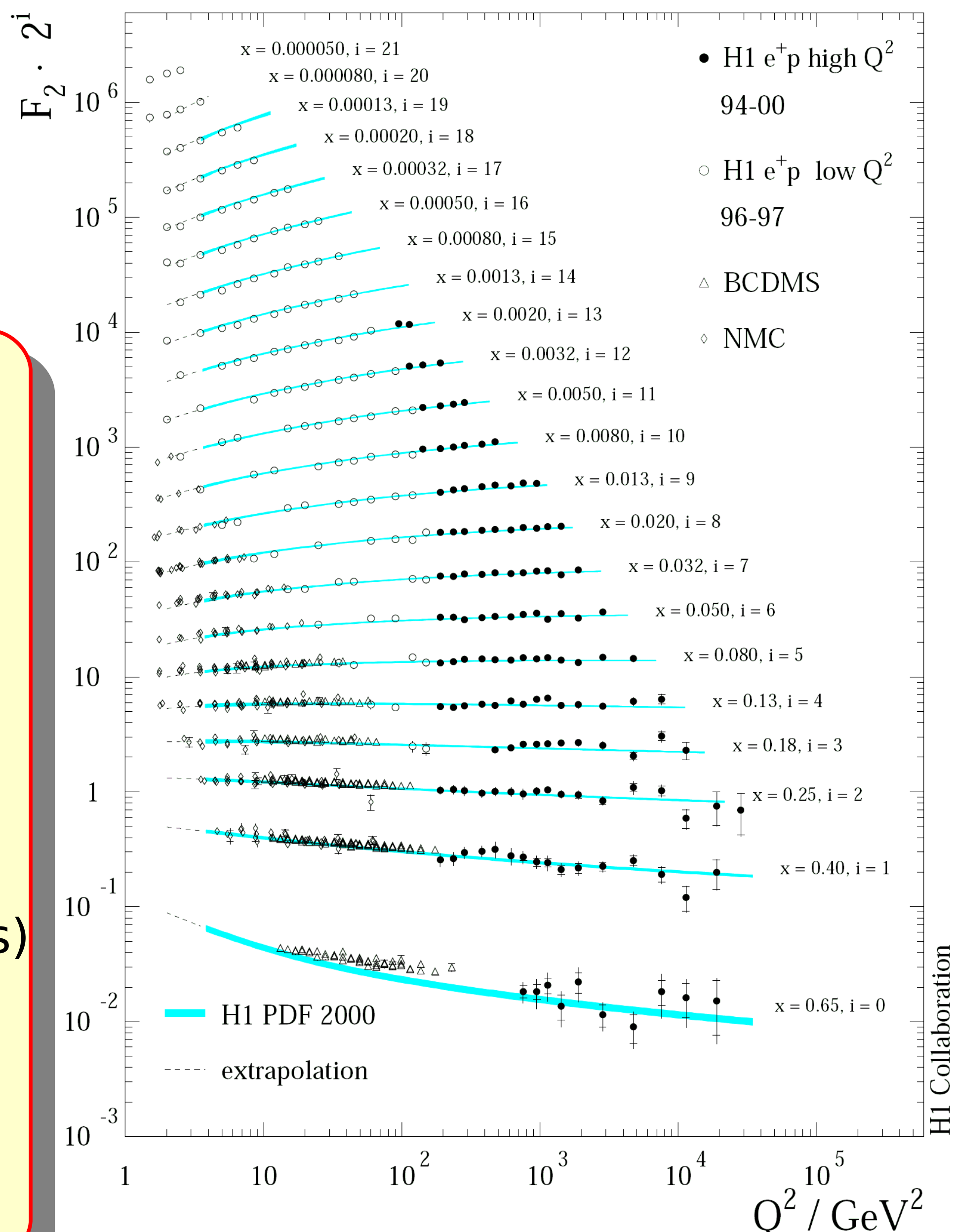
$$\frac{d^2\sigma_{NC}^{e^{\pm}p}}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4}$$

$$\left[\left(1+(1-y)^2\right)\tilde{F}_2(x,Q^2) - \frac{y^2}{2}\tilde{F}_L(x,Q^2) \mp \left(y-\frac{y^2}{2}\right)x\tilde{F}_3(x,Q^2)\right]$$

- ✗ In large part of phase space: cross section dominated by electromagnetic structure function F_2
- ✗ F_2 related to parton density functions(pdfs) in QPM:

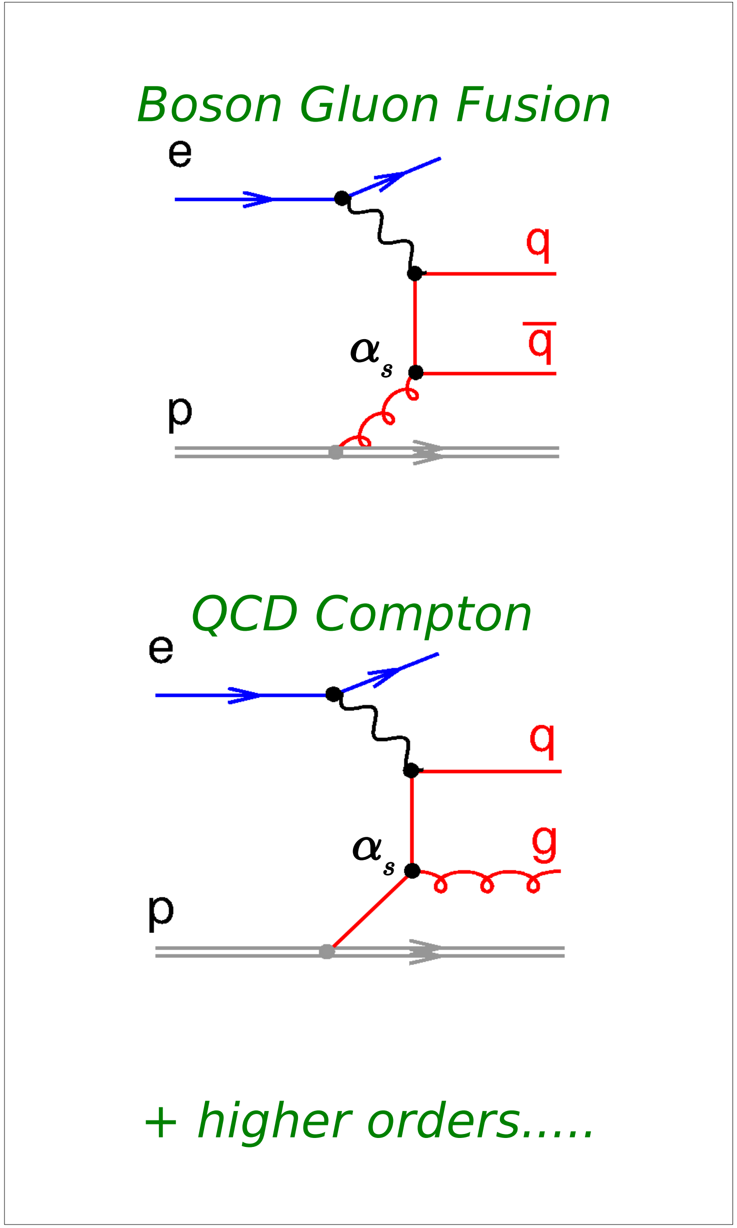
$$F_2 = x\sum_q e_q^2(q+\bar{q})$$

does not depend on $Q^2 \Rightarrow$ scaling



α_s Extraction with F_2

- Higher order QCD processes introduce scaling violations $\frac{\partial F_2}{\partial \ln Q^2} \neq 0$
- Magnitude given by gluon density and α_s
- Evolution of the pdfs with Q^2 by DGLAP equations
- In a fit, the gluon density and $\alpha_s(m_Z)$ can be simultaneously determined

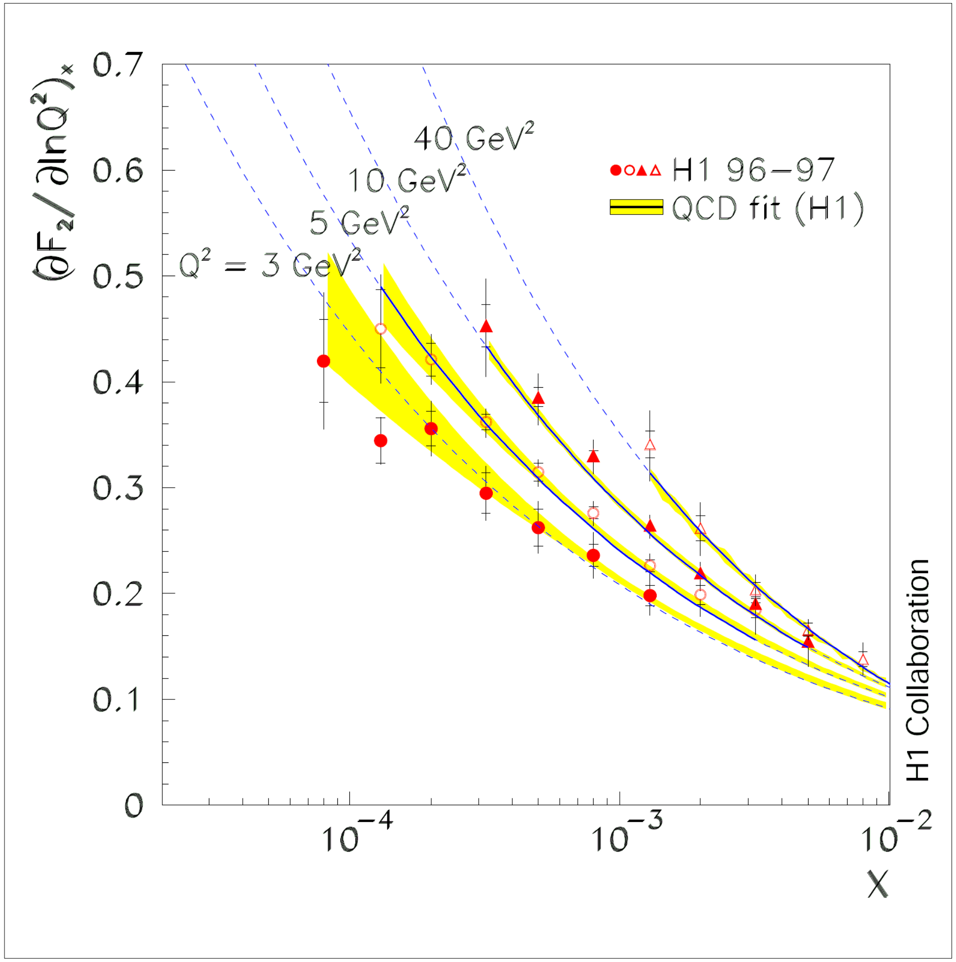


α_s Extraction with F_2

- Structure functions data from H1 and BCDMS (high x, muon) used
- Determination of the pdfs: gluon, up-type, down-type
- Best fit:

$$\alpha_s(m_Z) = 0.1150 \pm 0.0017(\text{exp})$$
$$^{+0.0009}_{-0.0005}(\text{model}) \pm 0.0050(\text{th.})$$

- Compatible with world mean, small experimental error



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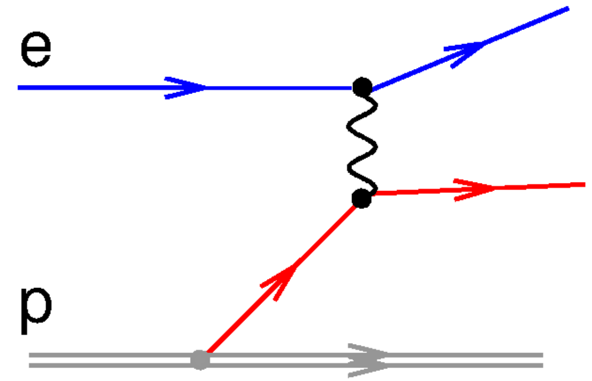
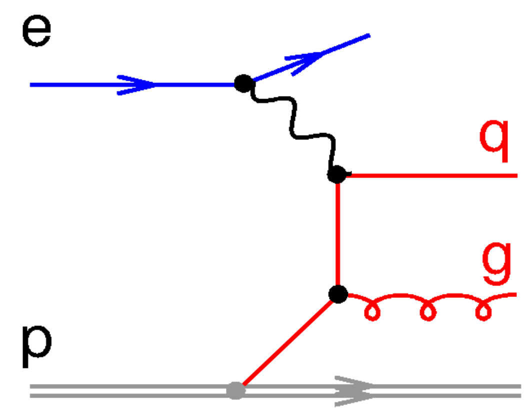
Jet Measurements

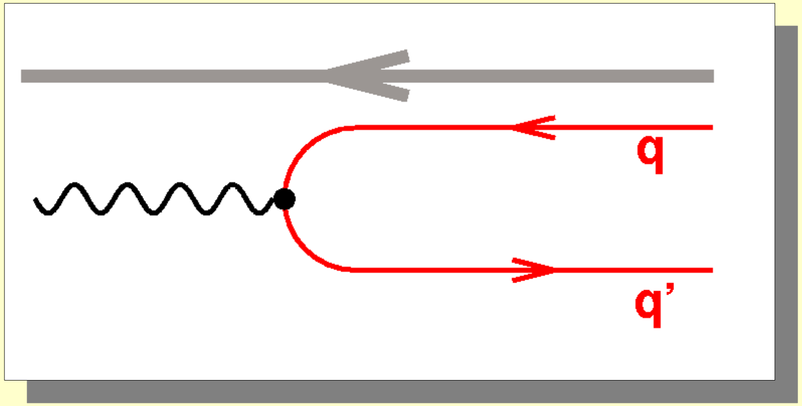
- ✗ To obtain direct sensitivity: observable which vanishes for the Born graph
- ✗ Final state with multiple partons
- ✗ Correspondence jet↔ parton at high E_t
- ✗ No unique definition of a jet, here **incl. k_t cluster algorithm**
  - ✗ similar to e^+e^- algorithms
  - ✗ favoured by theory over cone algorithms
    - ✗ infrared and collinear safe at all orders
    - ✗ factorisable
- ✗ For DIS: the E_t of jets in the laboratory frame not QCD driven: recoil of the scattered electron! ⇒ boost to **Breit frame** of reference



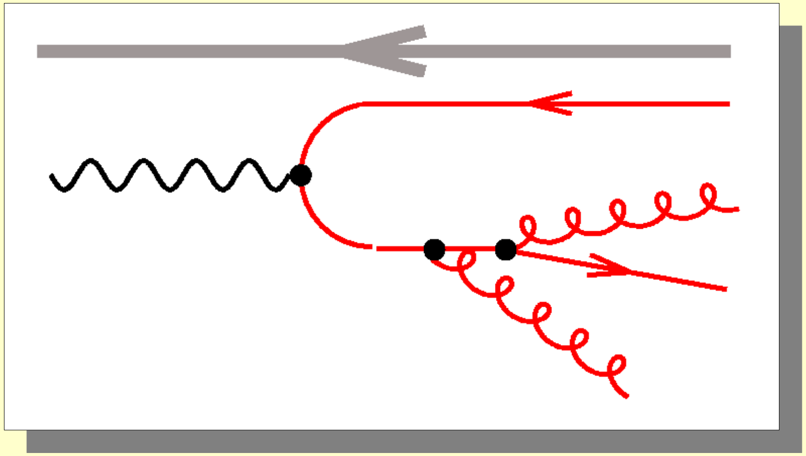


Breit Reference Frame

- ✗ Virtual photon and incoming parton: head-on
- ✗ Calculated using kinematic variables



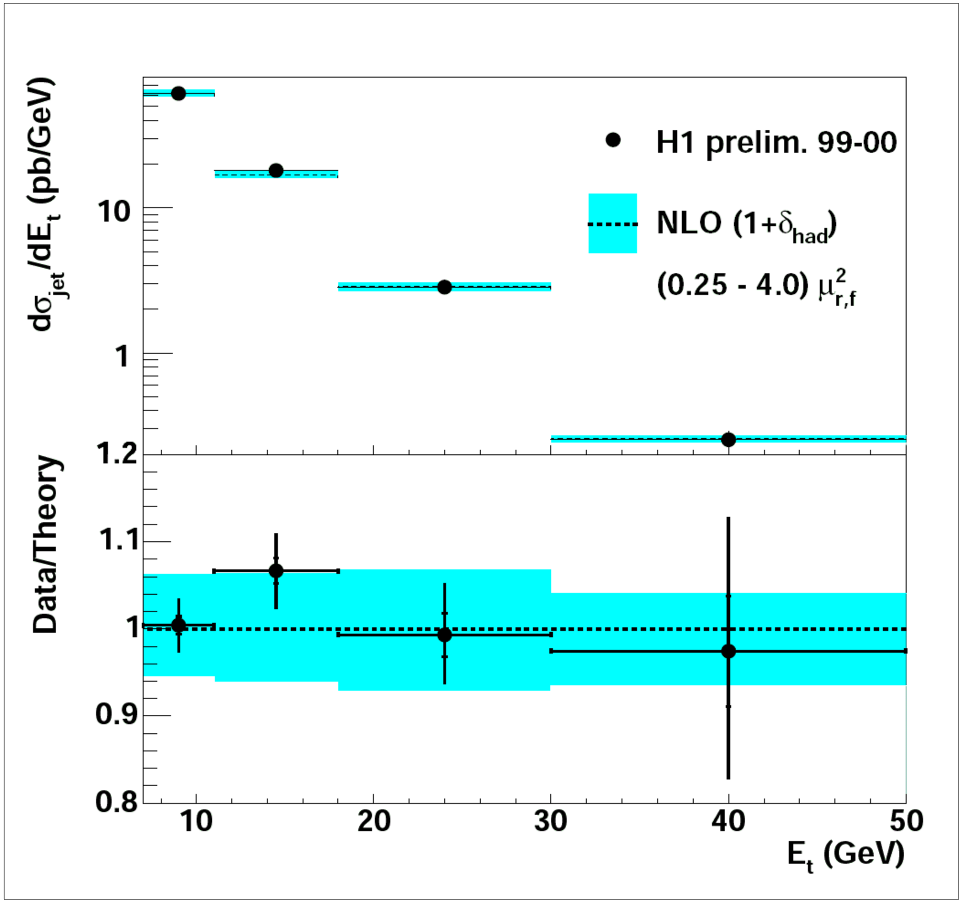
Breit frame: jet at Born level has no E_t
may have high E_t in lab. frame



require minimum E_t in Breit frame ->
pQCD reliable

Inclusive Jets at High Q^2

- “inclusive”: each jet of an event contributes to the cross section
- High Q^2: 150 GeV^2...5000 GeV^2
- Exp. error ~5%, mainly due to hadronic energy scale
- Theory prediction:
  - NLOJET++, CTEQ5M1
  - Hadronisation corrections <10% (obtained with MC generators)
  - $\mu_R = E_t$, $\mu_F = Q$, varied by factor 2 to estimate uncertainty
- Data well reproduced over E_t range



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Inclusive Jets at High Q^2

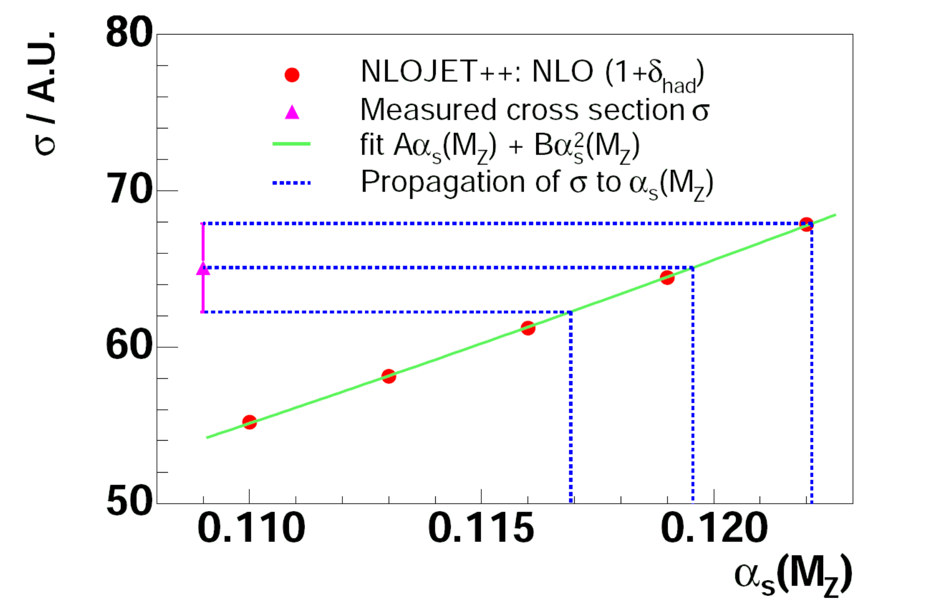
Method to extract α_s

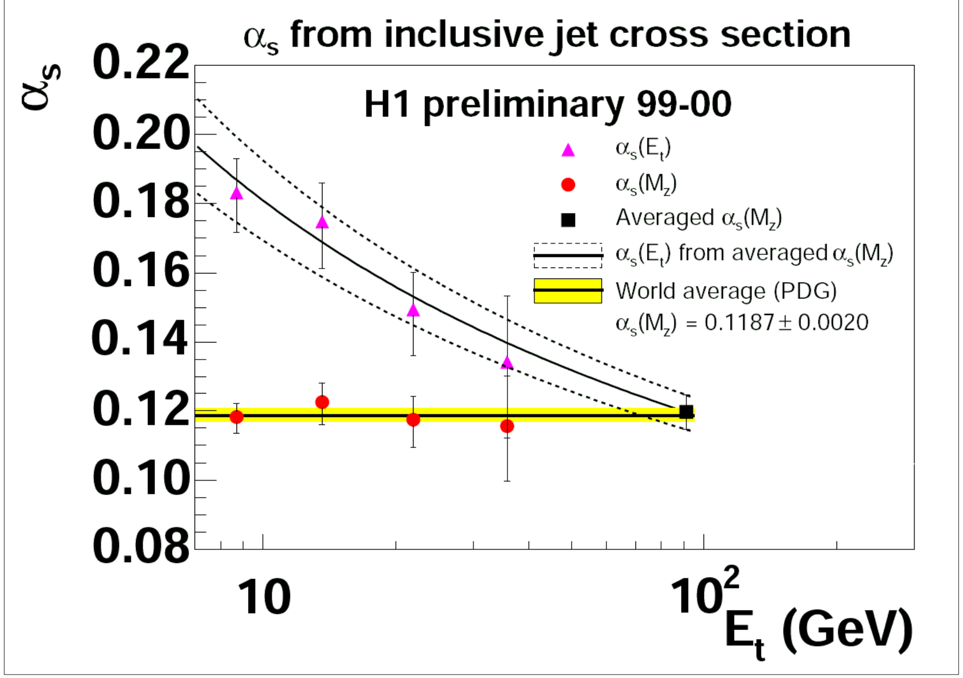
- Calculate each cross section for some values of $\alpha_s(m_Z)$, matched with pdfs
- Interpolate between points
- Map measured cross section with error onto $\alpha_s(m_Z)$ axis
- Using **R**enomalisation **G**roup **E**quation obtain "running" $\alpha_s(\mathrm{E}_t)$
- Average (with correlated systematics):

$$\alpha_s(m_Z) = 0.1197 \pm 0.0016(\text{exp.})^{+0.0046}_{-0.0048}(\text{th.})$$

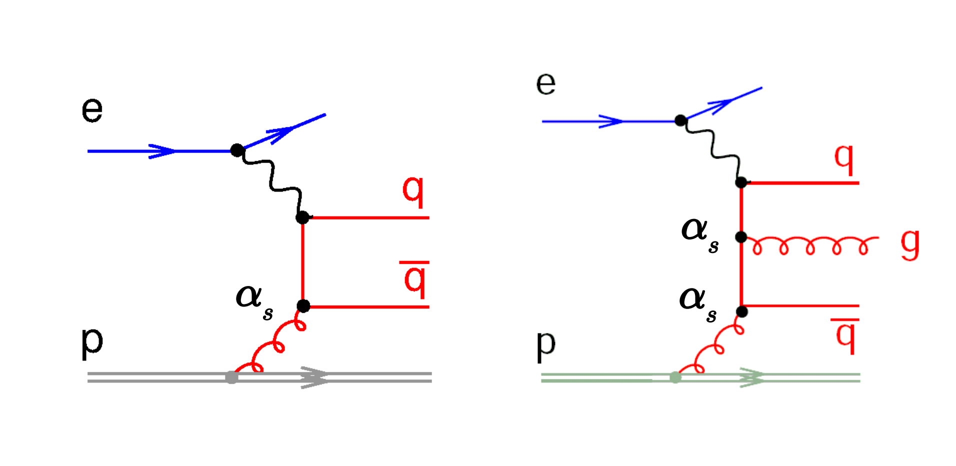
theory error dominating

- Precision comparable with F_2 analysis, compatible within errors

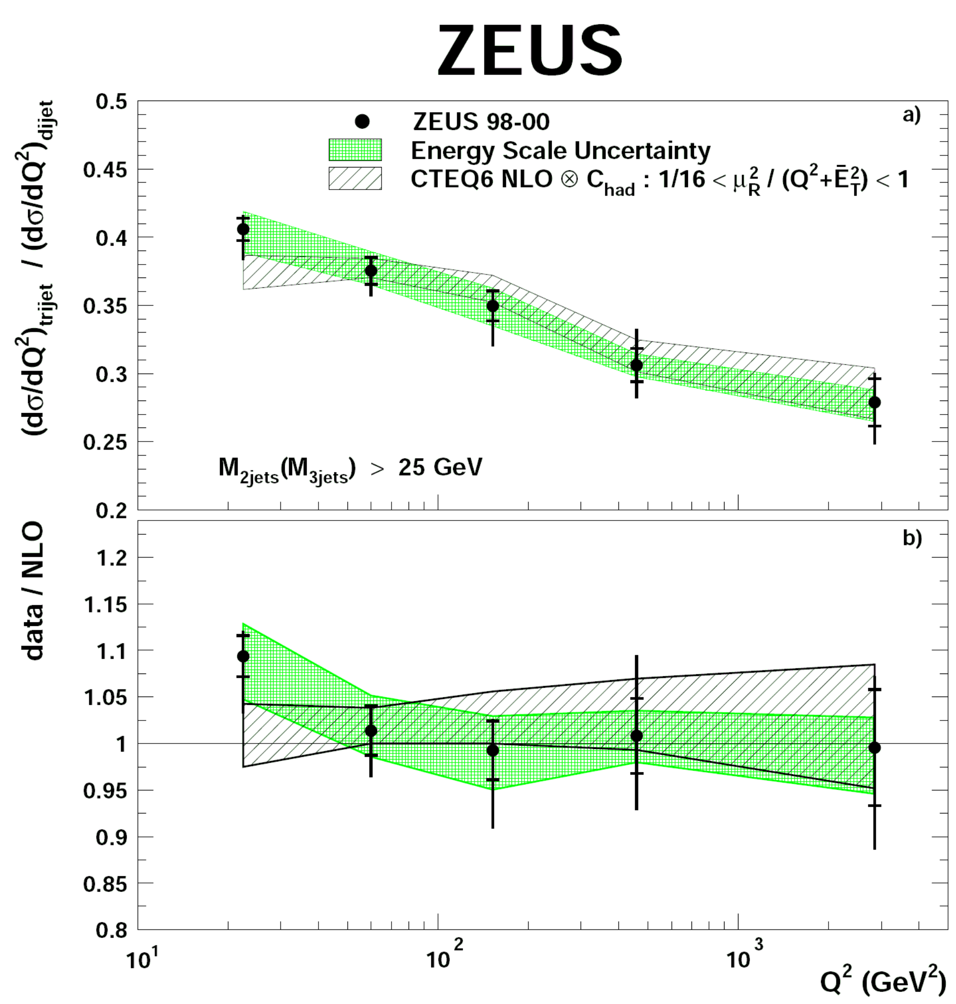




Multi Jets at High Q²



- ✗ Build a ratio 3-jet/2-jet
- ☺ Partial cancellation of uncertainties (e.g. on gluon density)
- ☹ But: less statistics, more constrained phase space
- ✗ An alternative
- ✗ Good description of Q^2 dependence by NLOJET++ and CTEQ6 pdfs



Eur. Phys. J. C 44, 183-193 (2005)

Multi Jets at High Q^2

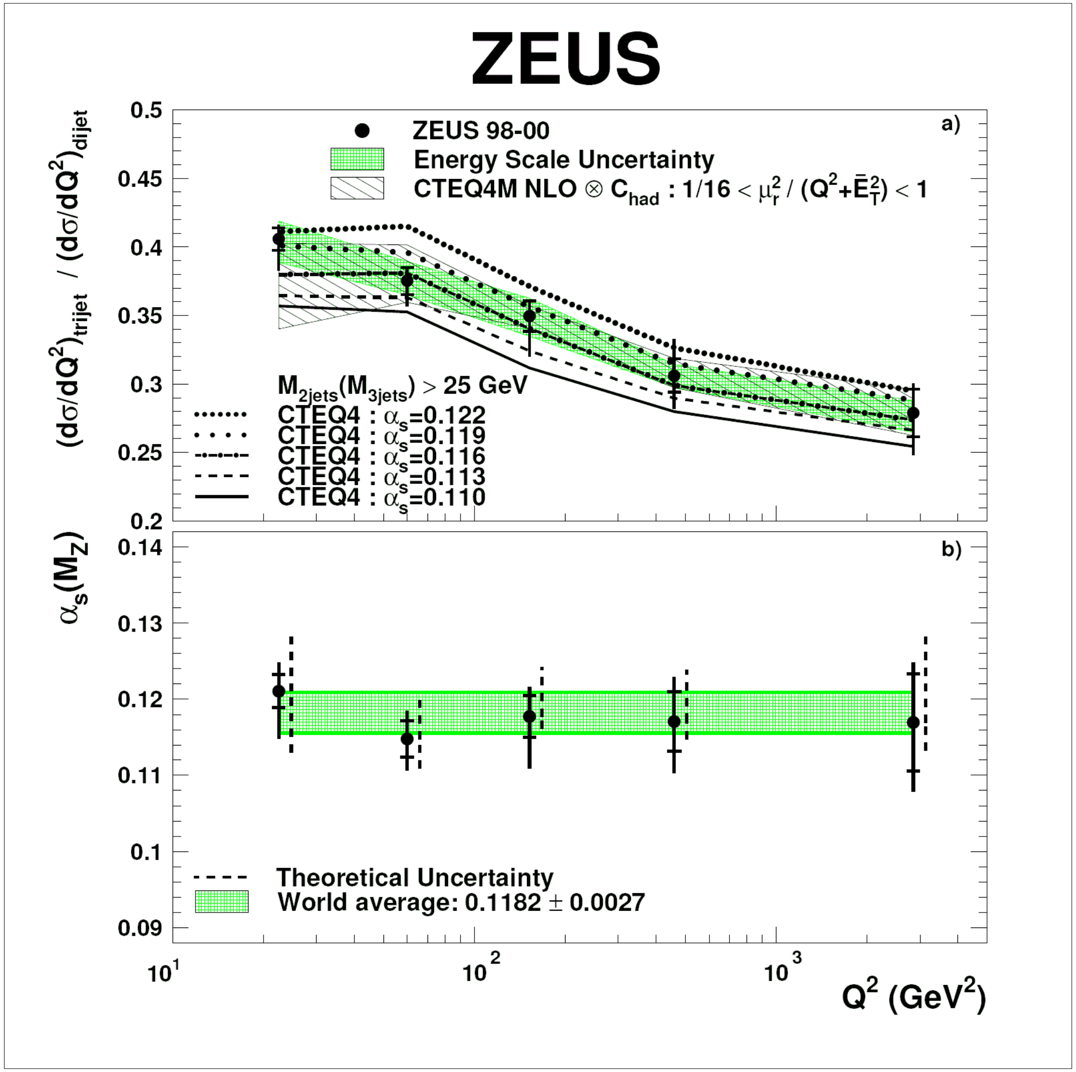
✗ Same method to extract $\alpha_s(m_Z)$ as for incl. jets

✗ Extension to lower Q^2 :
10 GeV^2...5000 GeV^2 possible due to reduced theory uncertainty

✗ Average value consistent with the other determinations

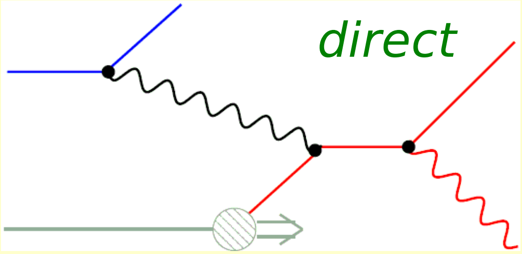
$$\alpha_s(m_Z) = 0.1179 \pm 0.0013(\text{stat.})^{+0.0028}_{-0.0046}(\text{exp.})^{+0.0064}_{-0.0046}(\text{th.})$$

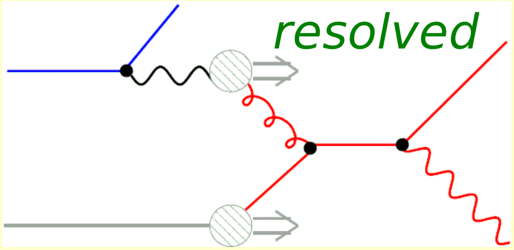
again theory largest uncertainty



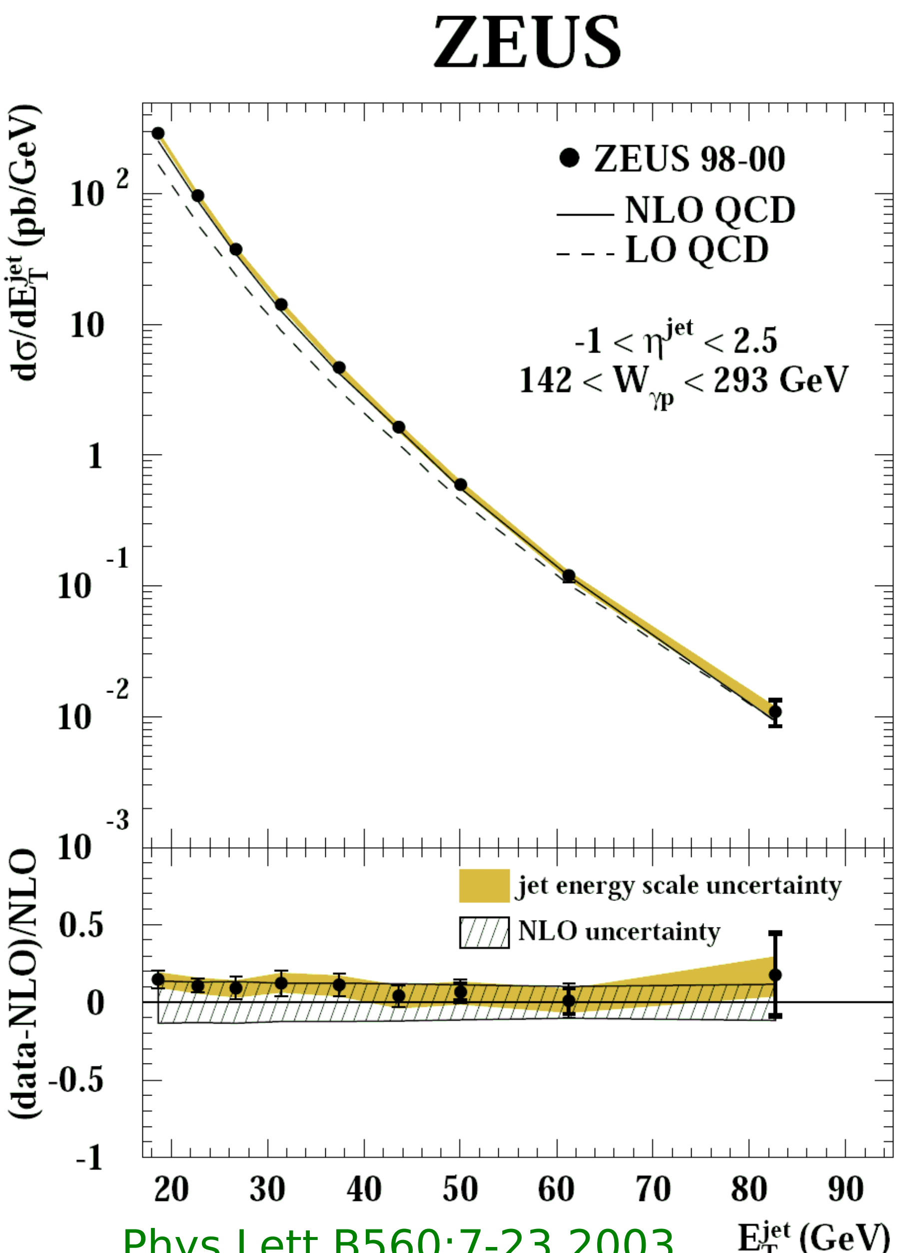
Inclusive Jets in γp

- Photoproduction: quasi real photons, scattered electron stays in beampipe
- Resolved photon process, similar to hadron-hadron (RHIC energies)





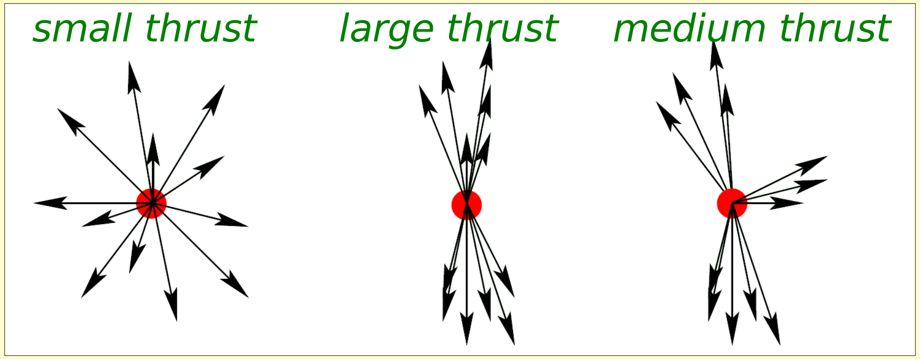
- Large cross section, can go to high jet E_t
- NLO (Klasen et al.), $\mu_R=\mu_F=E_t$, MRST99 (proton), GRV (photon)
- Fitted $\alpha_s(m_Z) = 0.1224 \pm 0.0001\,(\text{stat.})\,^{+0.0022}_{-0.0019}\,(\text{exp.})\,^{+0.0054}_{-0.0042}\,(\text{th.})$
- Consistent value (different process!)



Phys.Lett.B560:7-23,2003

Event Shapes

- ✗ Introduced historically before jets: event shapes
- ✗ Calculate from 4-vectors of HFS a real number, topological feature



- ✗ QCD sensitive, more inclusive than jets: no E_t cut ⇒ large statistics
- ✗ Ratio of momenta ⇒ had. energy scale cancels (largest exp. uncert. for jets!)
- ✗ But: hadronisation effects very large (upto 100%)

⇒ application for ansatz beyond models: **Power Corrections**

Thrust

$$T_C = \max_{\vec{n}_T} \frac{\sum |\vec{p}_h \cdot \vec{n}_T|}{\sum |\vec{p}_h|}$$

Jet Mass

$$\rho = \frac{(\sum E_h)^2 - (\sum \vec{p}_h)^2}{(2 \sum |\vec{p}_h|)^2}$$

C-Parameter

$$C = \frac{3}{2} \frac{\sum_{h,i} |\vec{p}_h||\vec{p}_i| \sin^2 \theta_{hi}}{(\sum |\vec{p}_h|)^2}$$

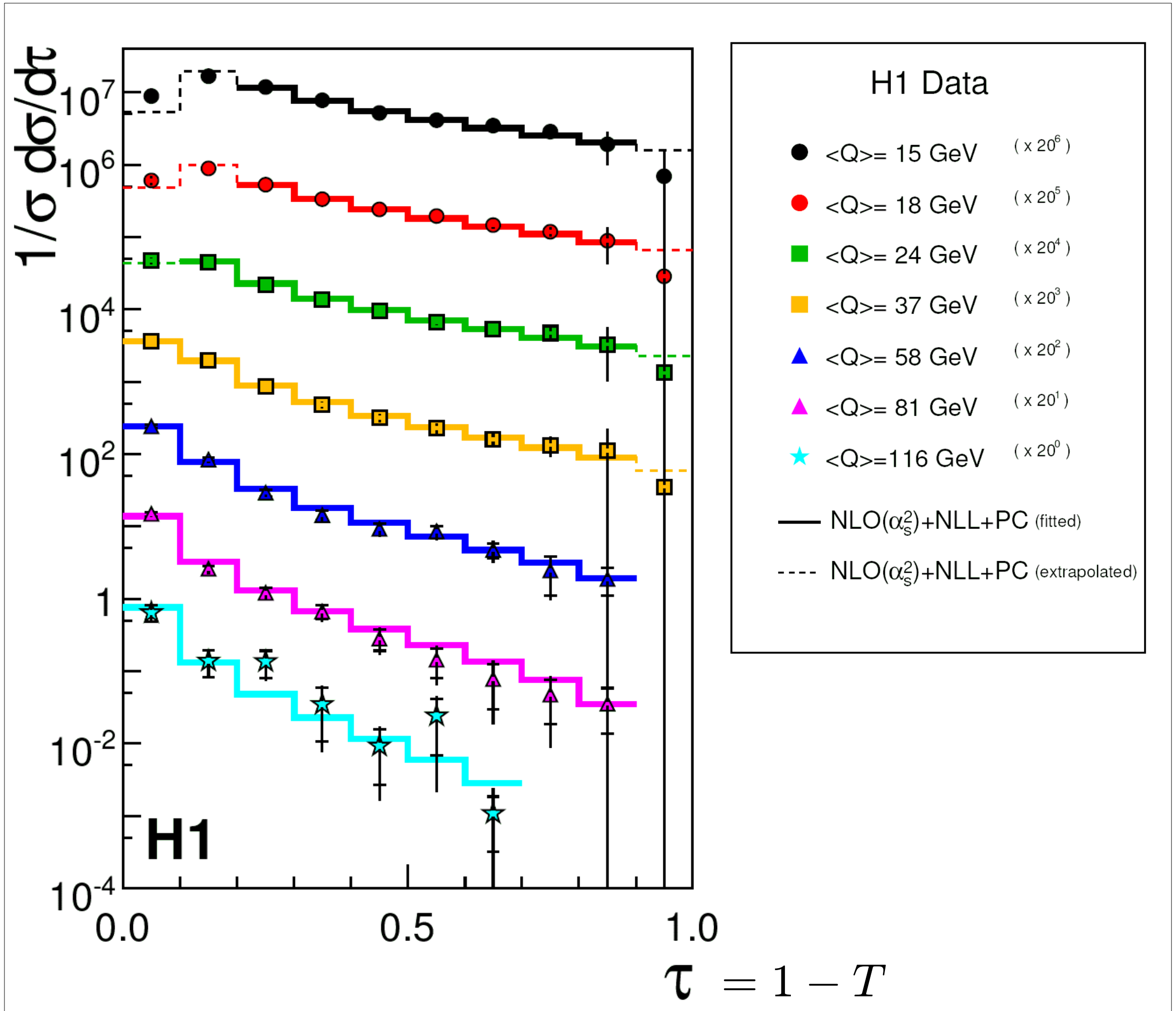
Thrust , Broadening (boson axis)

$$T = \frac{\sum |\vec{p}_{z,h}|}{\sum |\vec{p}_h|} \qquad B = \frac{\sum |\vec{p}_{\perp h}|}{2 \sum |\vec{p}_h|}$$

- ✗ Sum over particles in current hemisphere (reject remnant)

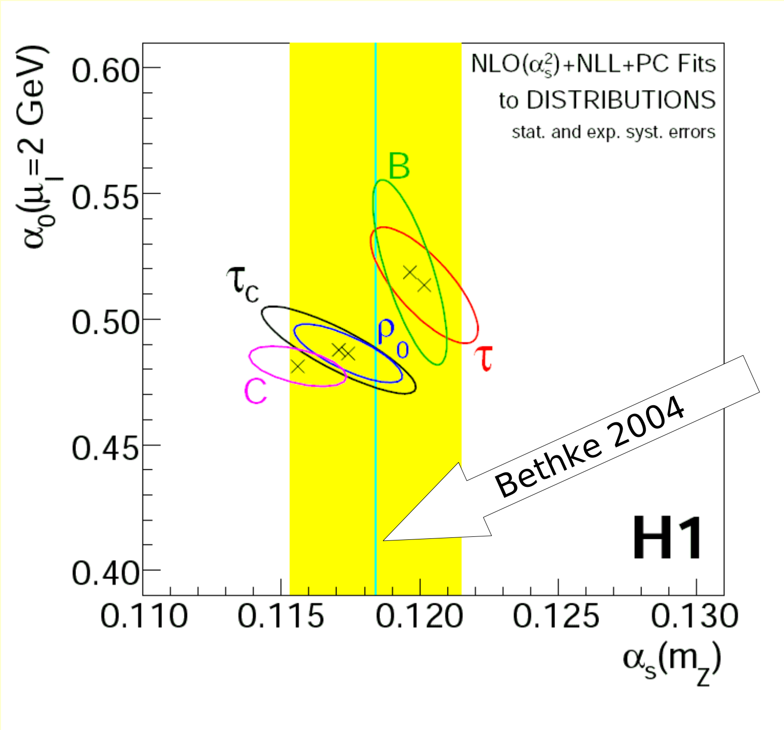
Event Shapes

- ✗ Differential distributions as function of scale Q
- ✗ Not statistically limited (except highest Q)
- ✗ Asymptotic freedom: higher scales ⇒ smaller α_s ⇒ collimated HFS ⇒ τ peaks at 0
- ✗ Theory:
  - ✗ DISASTER++ (Graudenz)
  - ✗ Soft gluon resummation at NLL (Dasgupta, Salam)
  - ✗ Power corrections (Dokshitzer, Webber)
- ✗ Good description over full Q range, but not valid everywhere
- ✗ Also available: τ_c,B,ρ,C



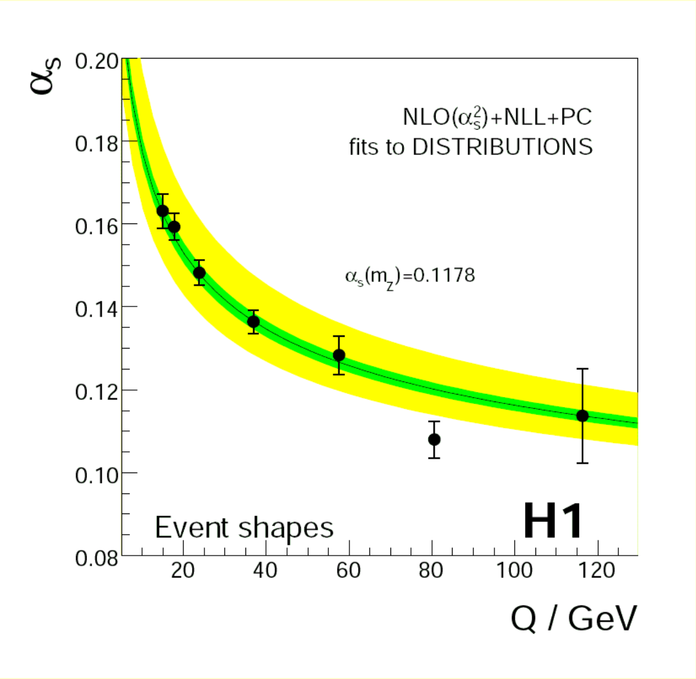
Eur.Phys.J.C46:343-356,2006

Event Shapes



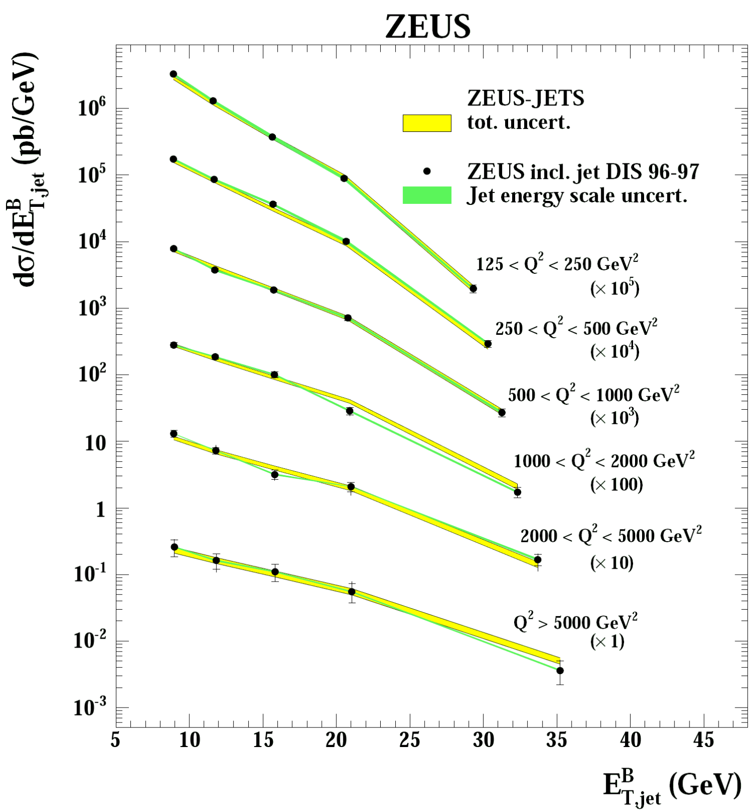
- ✗ Simultaneous fit of $\alpha_s(m_Z)$ and power correction parameter $\alpha_0(2\text{GeV})$
- ✗ Universal $\alpha_0 = \mu_I^{-1}\int_0^{\mu_I} \alpha_{\text{eff}}(k)dk$ required for power corrections, similar value in e^+e^-
- ✗ Combine 5 event shapes into average:

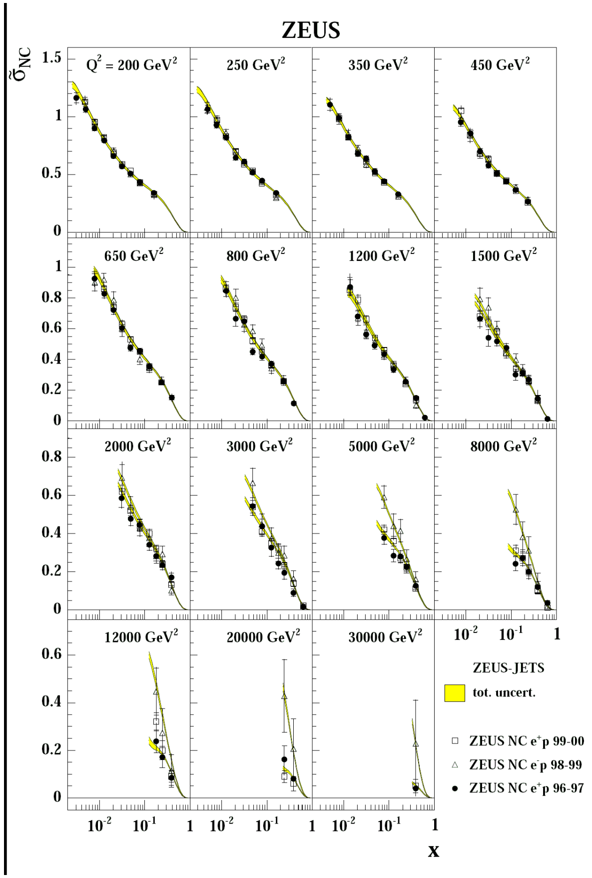
$$\alpha_s(m_Z) = 0.1198 \pm 0.0013(\text{exp.})^{+0.0056}_{-0.0043}(\text{th.})$$



- ✗ Asymptotic freedom clearly demonstrated, huge range in Q

Merging F_2 and Jets in a Fit

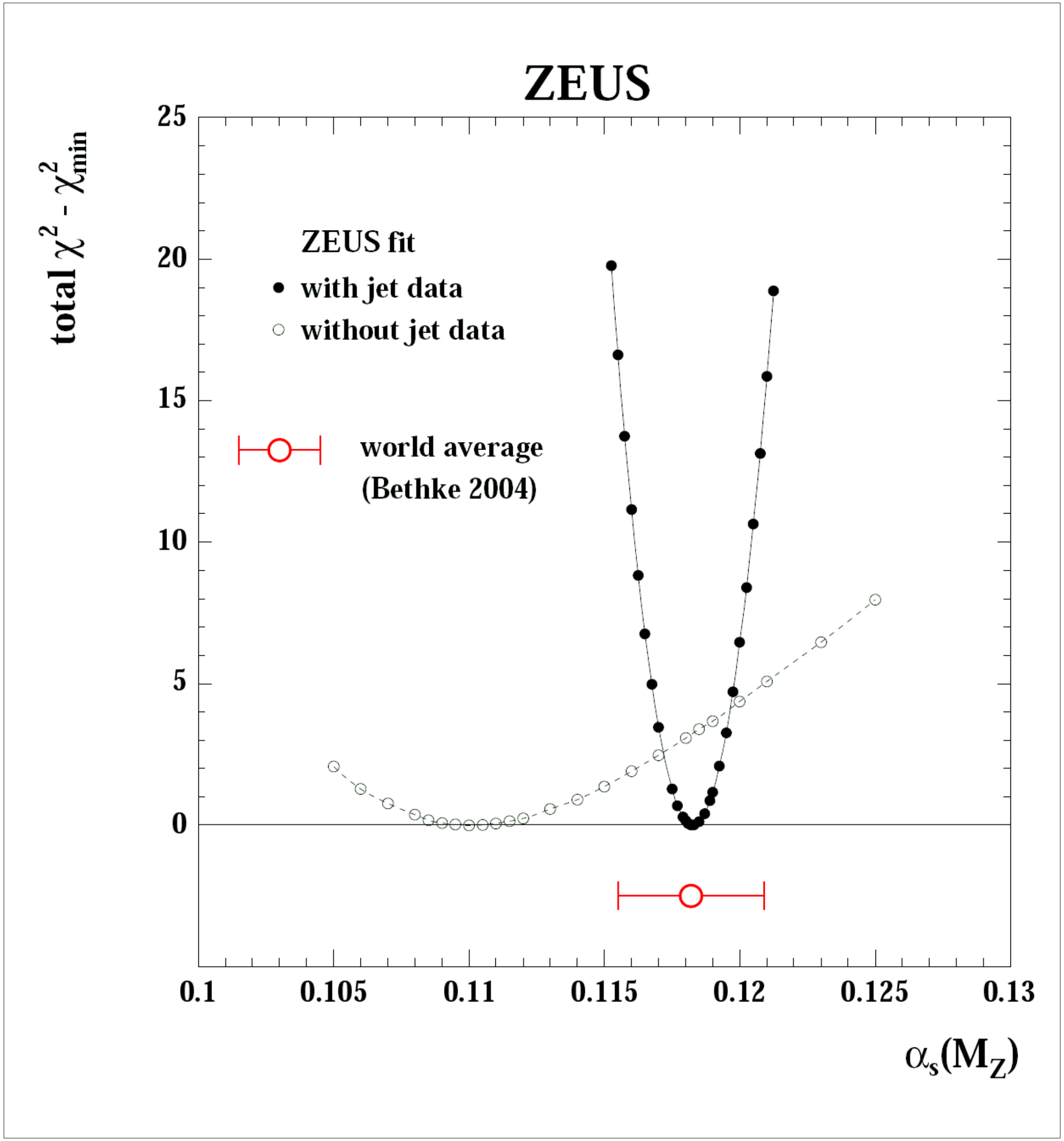




Eur.Phys.J.C42:1-16,2005

- ✗ ZEUS-JETS QCD fit: inclusive cross sections +incl. jets in DIS + dijets in γp
- ✗ Take care of correlated experimental uncertainties
- ✗ Jets improve gluon at higher x

Combining F_2 and Jets in a Fit



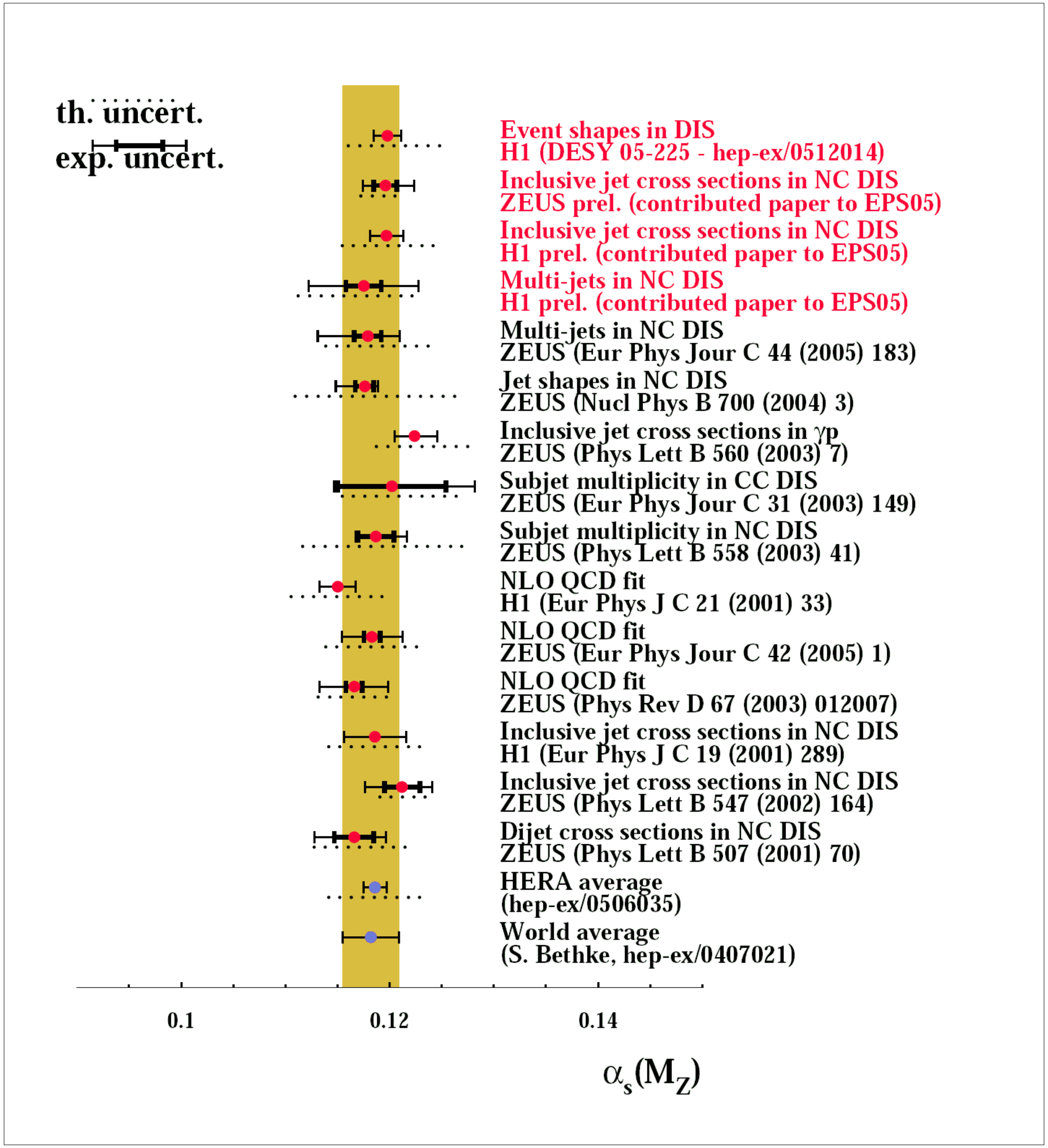
- Jets constrain $\alpha_s(m_Z)$
- Inclusive data alone prefer low value of strong coupling
- Compare to other incl. fits:
  H1: $\alpha_s(m_Z)$ = 0.1151
  BCDMS: $\alpha_s(m_Z)$ = 0.1107
- General issue? More data and improved theory will tell....

HERA Average

- Great diversity in determinations of $\alpha_s(m_Z)$ at HERA
- Consistent with each other
- Theoretical uncertainties dominant
- Build HERA average (without red ones)

$$\alpha_s(m_Z) = 0.1186 \pm 0.0011\,(\text{exp.}) \pm 0.0050\,(\text{th.})$$

- Compatible with Bethke2004
- With competitive precision



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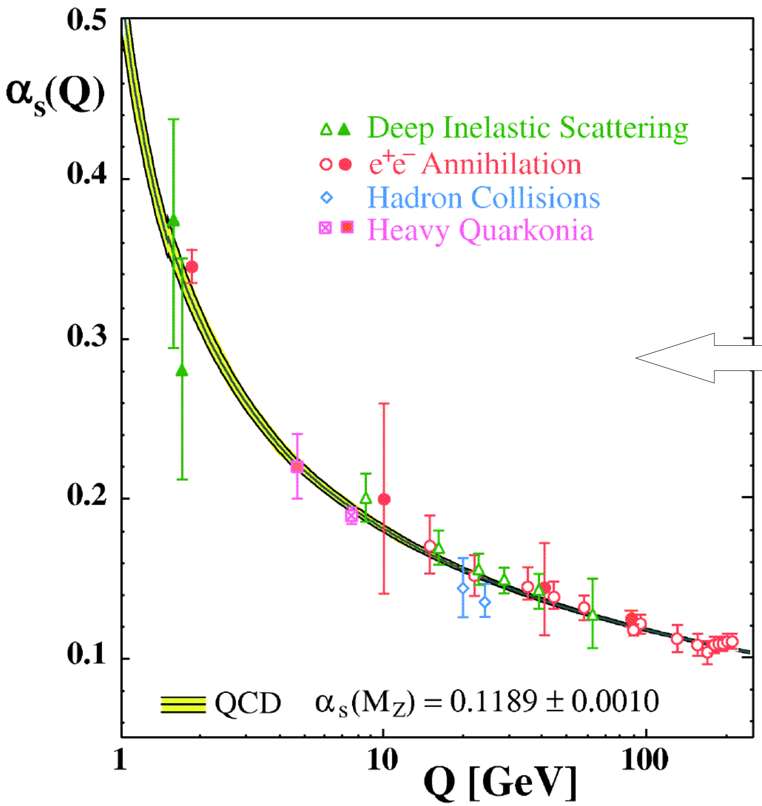
World average



hep-ex/0606035

- ✗ The world averages used to include only incl. DIS data
- ✗ Brand new determination from Bethke incorporates the HERA average (with jets)

$$\alpha_s(m_Z) = 0.1189 \pm 0.0010$$

- ✗ Compare to 2004:

  Bethke $\alpha_s(m_Z) = 0.1183 \pm 0.0027$

  PDG $\alpha_s(m_Z) = 0.1187 \pm 0.002$

- ✗ Big improvement in uncertainty mainly due to new data: τ decays and lattice theory of heavy hadron masses
- ✗ After 30 years of QCD: better than 1%!

Summary

- Plenty of α_s determinations from **HERA** available
- The **precision** is competitive to e^+e^- annihilation analyses
- **Diversity** important to test universality of QCD
- Precision needed for QCD itself and for background predictions e.g. at **LHC**
- Still: theory at NLO induces large **theory errors**
- Looking forward to **NNLO** calculations on the way...
- ... and to fits to the wealth of **HERA II** data still to come!

Nobelprize.org

The Nobel Prize in Physics 2004

David J. Gross
Kavli Institute for Theoretical Physics
University of California, Santa Barbara, USA

H. David Politzer
California Institute of Technology (Caltech), Pasadena, USA

Frank Wilczek
Massachusetts Institute of Technology (MIT), Cambridge, USA

“the discovery of asymptotic freedom in the theory of the strong interaction”