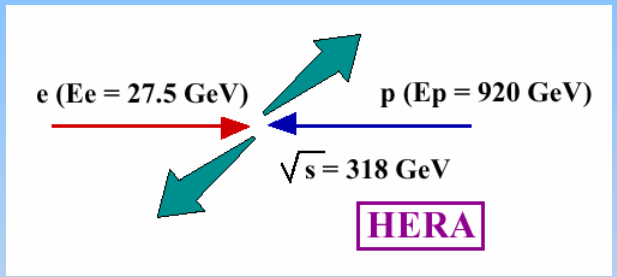
LISHEP 2006 Workshop
Rio de Janeiro, April 3-7, 2006

pQCD ∩ JETS

(AND)

at HERA



Luca Stanco – INFN Padova

on behalf of
H1 and ZEUS collaborations

more or less…

…
Single particles production
Charged multiplicities
Bose-Einstein correlation
Neutral, strange, Baryons
Charm fragmentation
Remnant/Multiple interactions
Prompt Photon
Resolved-Direct γ–production
Parton Evolutions
Color dynamics, Energy flow
Multiscale
Strong coupling
Dijets, Trijets
Inclusive Jets production
Forward Jets production
Heavy Quarks Jets
Diffractive Jets
…

AND

QCD items

JETS items

QCD:

- WHAT ? ⟶ Partons/JETS
- WHY ?
- HOW ?

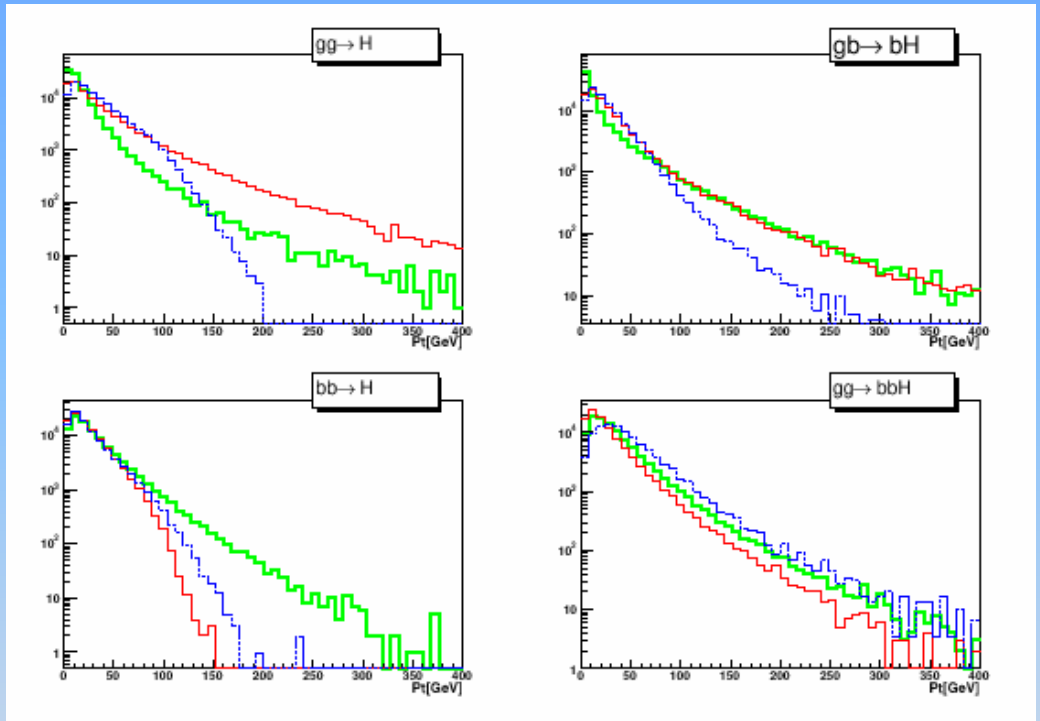
WHY ?

at least 3 answers:

1. NOT TRUE it is so well understood ..
2. Strong coupling, α_S, measurement
3. Parton Density Functions measurements *(see previous talk)*

From recent HERA-LHC workshop, examples of uncertainties,

Z.Czyczula et al., p_T of Higgs (120 GeV) from different Parton-Showers (PS) models and QCD scale choices



Uncertainties:

- **up to 170% due to PS** *(which evolution type ? which ordering ?)*
- **up to 100% due to the choice of QCD scale** *(Q^2, m^2, $\hat{s}$ etc.)*

⇒ low-x and forward jets…

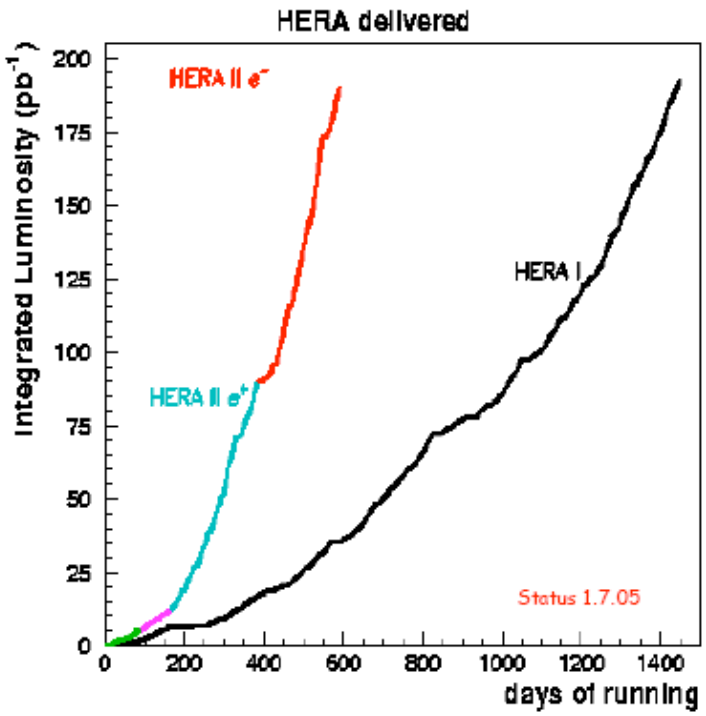
HOW ?

Outline of the talk:

- Inclusive Jets in DIS
- Multi-Jet production in DIS
- α_s measurements
- Jets in γ-production (resolved/direct photon)
- Gluon PDF
- Color and sub-jets dynamics
- Forward Jets

before going into physics, let us look at environment...

Luminosity development at HERA (I: 92-00, II: 03-07)



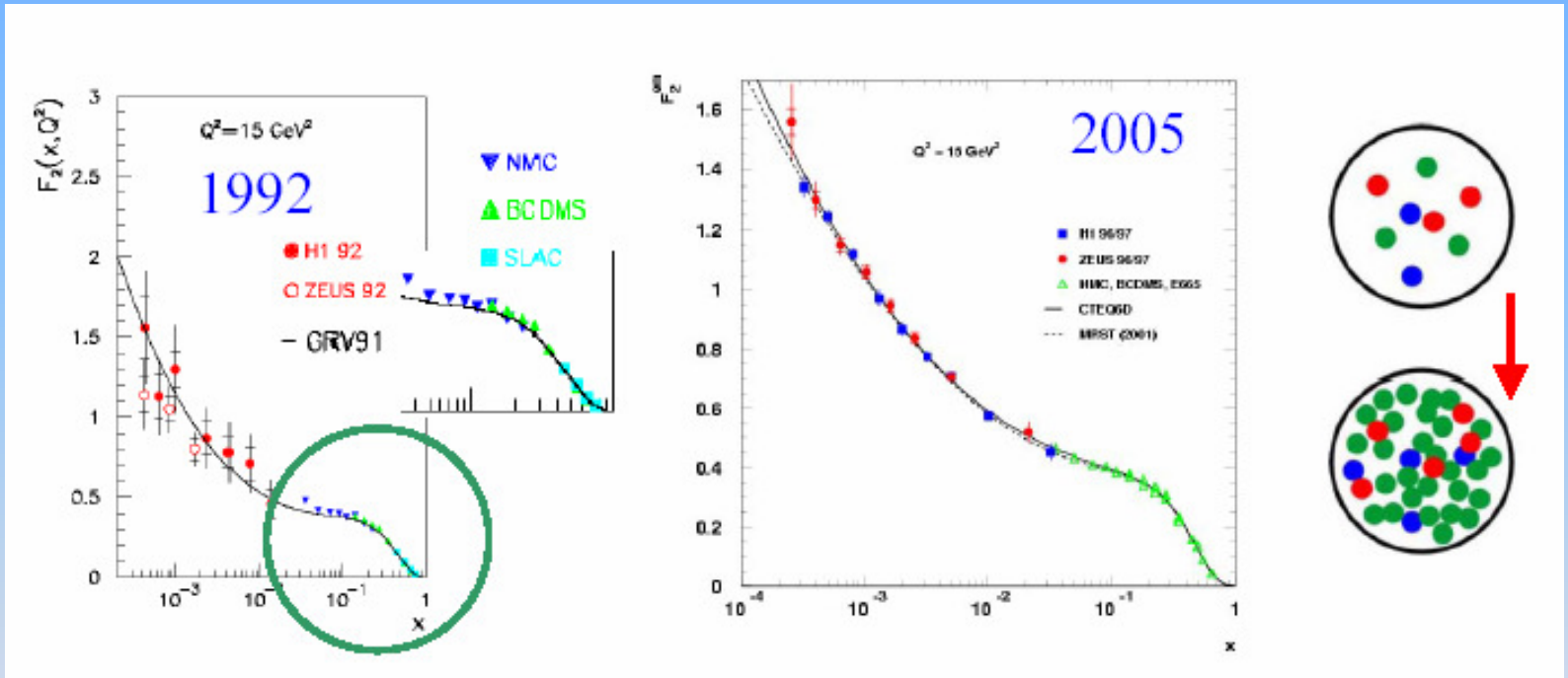
HERA delivering 1pb^{-1} /day and HV on feasible

- HERAI: H1 and ZEUS took about 130pb^{-1} (1992-2000)
- 2001 "luminosity upgrade"
- 2002/03 background problems
- 2004: positrons (50 pb^{-1})
- 2005: electrons: so far 55 (H1) 75 (ZEUS)
- One further shutdown Nov05/Jan06
- 2007: scheduled end of HERA: PETRA III

Results on pQCD∩JETS only from HERA-I *(up till now)*

...if nobody else has already shown ...

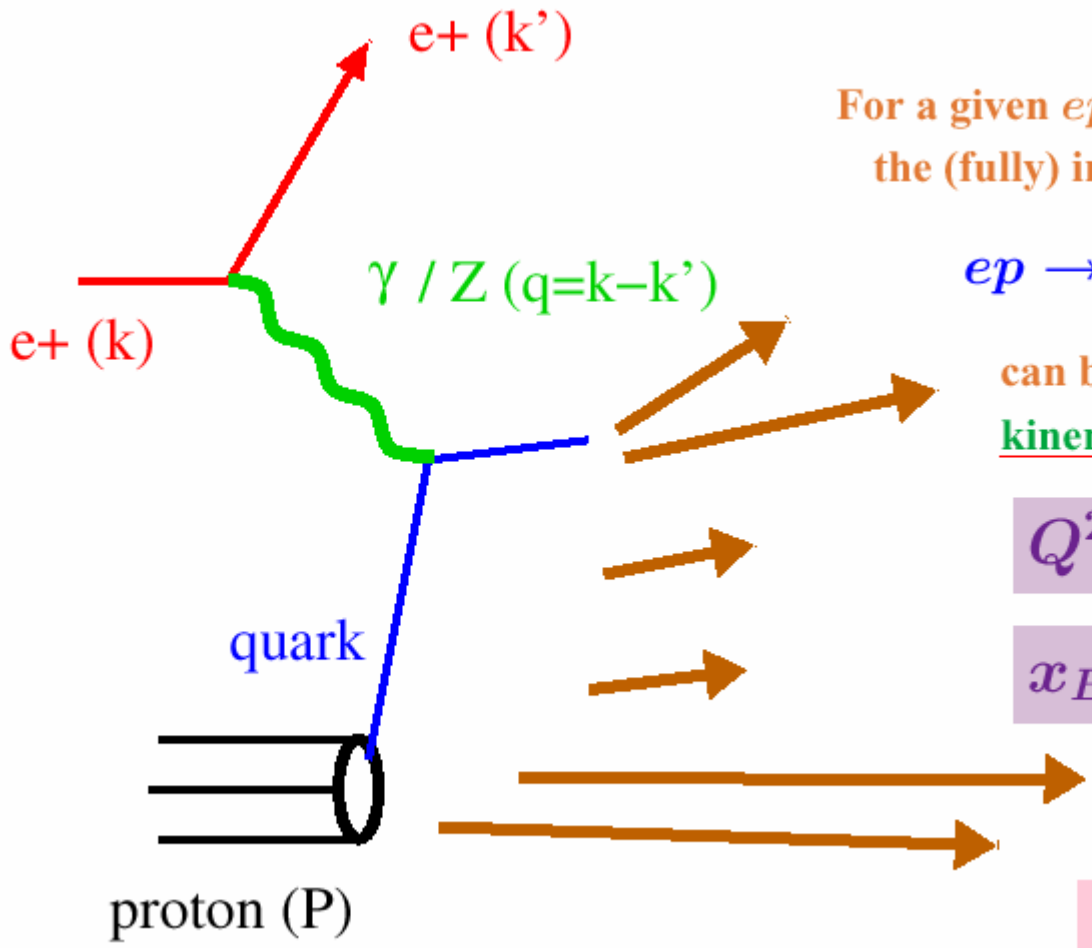
HERA: the QCD machine



... The most dramatic of these (experimental consequences), that protons viewed at ever higher resolution would appear more and more as field energy (soft glue), was only clearly verified at HERA twenty years later. ...

Frank Wilczek

Kinematics of Neutral Current (NC) Deep Inelastic Scattering (DIS)



For a given ep centre-of-mass energy, $\sqrt{s}$, the (fully) inclusive cross section for

$$ep \to e + X$$

can be described by two independent kinematic variables, e.g.

$$Q^2 = -(k - k')^2$$

$$x_{Bj} = Q^2/(2P \cdot q)$$

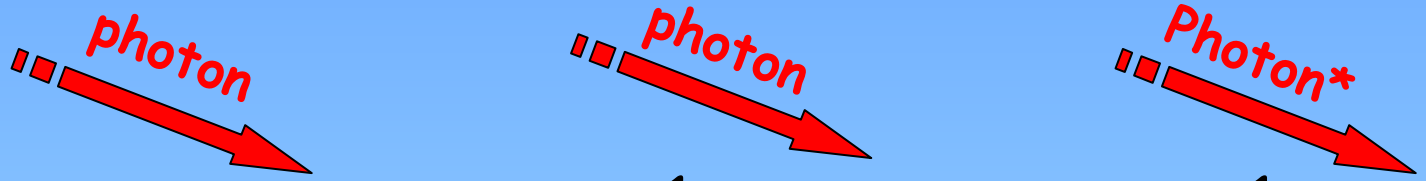
→ Inelasticity variable

$$y = Q^2/(x_{Bj} s)$$

Processes at HERA *(defined by Initial States of HARD Scattering)*

DIRECT γ-PRODUCTION

Electron beam



$x_\gamma < 1$

$x_\gamma = 1$
$Q^2 = 0$

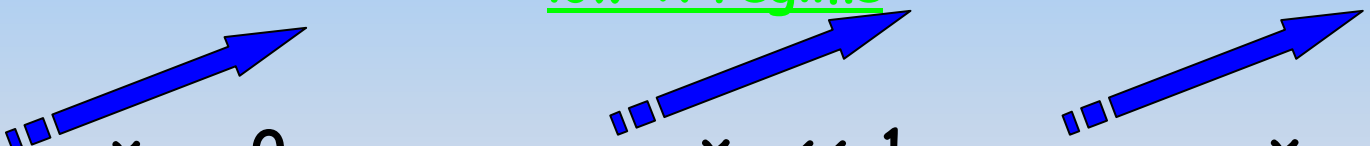
$x_\gamma = 1$
$Q^2 > 0$

RESOLVED γ-PRODUCTION

DIS

low-x regime

Proton beam



$x_{Bj} \sim 0$

$x_{Bj} << 1$

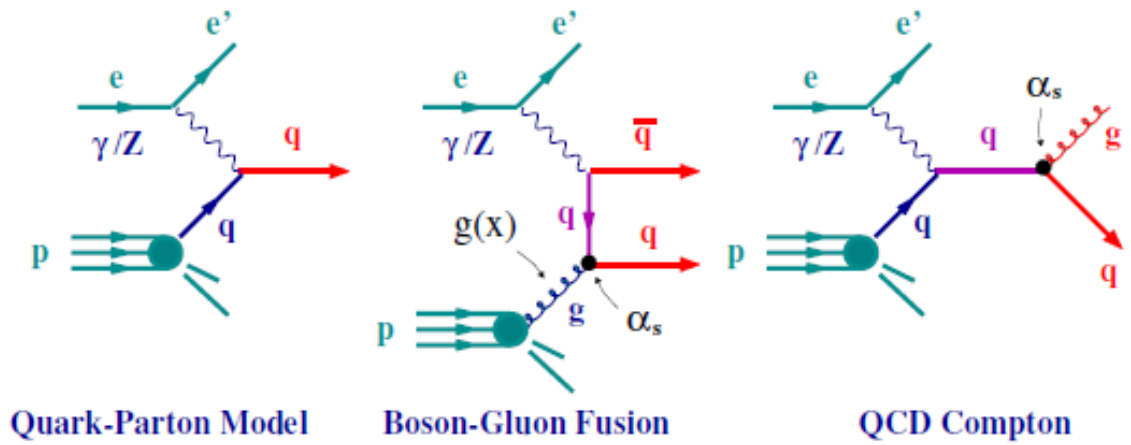
$x_{Bj} < 1$

DIFFRACTION

quark/gluon PARTONS

Jets Production in NC Deep Inelastic Scattering

- Jet production in neutral current deep inelastic scattering up to $\mathcal{O}(\alpha_s)$:

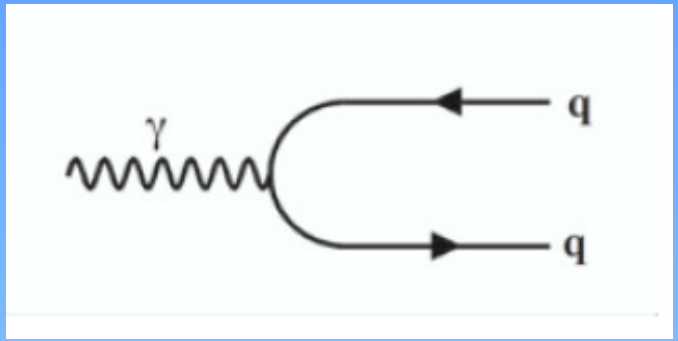


- Perturbative QCD calculations of jet cross sections:

$$d\sigma_{jet} = \sum_{a=q,\bar{q},g} \int dx\, f_a(x,\mu_F^2)\, d\hat{\sigma}_a(x,\alpha_s(\mu_R),\mu_R^2,\mu_F^2)$$

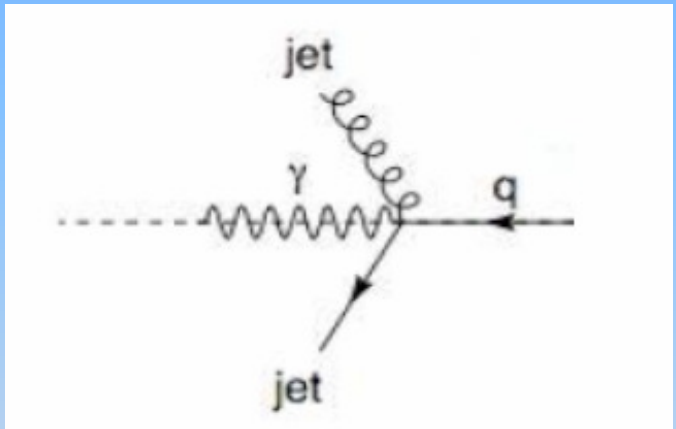
  - f_a: parton a density in the proton, determined from experiment; long-distance structure of the target
  - $\hat{\sigma}_a$: subprocess cross section, calculable in pQCD; short-distance structure of the interaction

Inclusive JETS in DIS



The BREIT frame !

- Frame where virtual boson is enterely spacelike
- At lowest order, quark is back scattered



In pratice, high Et jet events must be at least of order α_s

- High-E_T jet production in the Breit frame
  - $\rightarrow$ suppression of the Born contribution (struck quark has zero E_T)
  - $\rightarrow$ suppression of the beam-remnant jet (zero E_T)
  - $\rightarrow$ lowest-order non-trivial contributions from $\gamma^* g \rightarrow q\bar{q}$ and $\gamma^* q \rightarrow qg$
  - $\Rightarrow$ directly sensitive to hard QCD processes (α_s)

JETS observables in the BREIT Frame

* Small experimental uncertainties → Jets with relatively high transverse energy
* Small theoretical uncertainties → NLO QCD calculations

→ Jet algorithm: longitudinally invariant k_T cluster algorithm (Catani et al)

(small parton-to-hadron effects, infrared safe, suppression of beam-remnant jet)

... more technically

- Sources of experimental systematic uncertainties:
  - electron kinematics → Lorentz transformation
  - model dependence for data correction (detector, hadronization, parton showers, QED)
  - **absolute hadronic energy scale**

- transverse momentum in Breit frame stems mainly from QCD process
- longitudinally invariant k_T jet-algorithm in the Breit Frame
  - collinear and infrared safe
  - iterative clustering $d_{i,j} = \min(E^2_{T,i}, E^2_{T,j}) \cdot ((\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2)$
  - result: n jets with $d_{i,j} > R_0$ where $R_0 = 1$

NLO pQCD calculations

- truncated pertubation series $\Rightarrow$ explicit μ_R dependence
- choice of jet-observables, kinematic region, etc. where pQCD most predictive
  $\Rightarrow$ low k-factors (NLO/LO), low μ_R dependence
- possible choices of μ_R and μ_F : $Q, E_T, f(Q, E_T)$
  assess theoretical uncertainty due to missing higher orders through μ_R-dependence of σ_{jet} and measured α_S by varying $\mu_R \longrightarrow$ convention: $\mu_R \nearrow 2\mu_R$ and $\mu_R \searrow 0.5\mu_R$
- pQCD calculation programs $\longrightarrow$ implementation of user jet algorihm
  - ▶ DISENT: 2+1 jets NLO (α_S^2)
  - ▶ NLOJET++: 3+1 jets NLO(α_S^3)

and

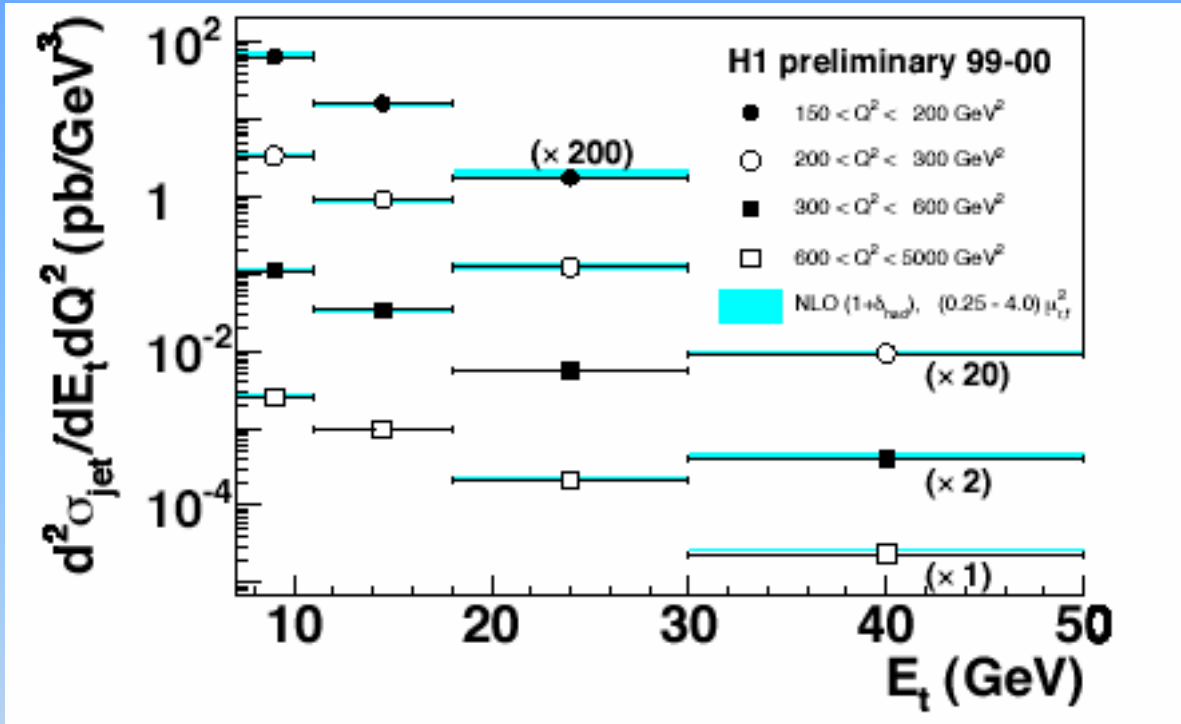
- interfaced to various PDFs (like CTEQ, MRST)
- Parton Level cross sections – need to rely on LO MC for hadronisation corrections

Here are the DATA:

H1 Inclusive Jet Production in DIS

DIS phase space
$150 < Q^2 < 5{,}000\ \mathrm{GeV}^2$
$0.2 < y < 0.6$

Inclusive jet phase space
$E_{T,Breit} > 7$ GeV
$-1 < \eta_{lab} < 2.5$



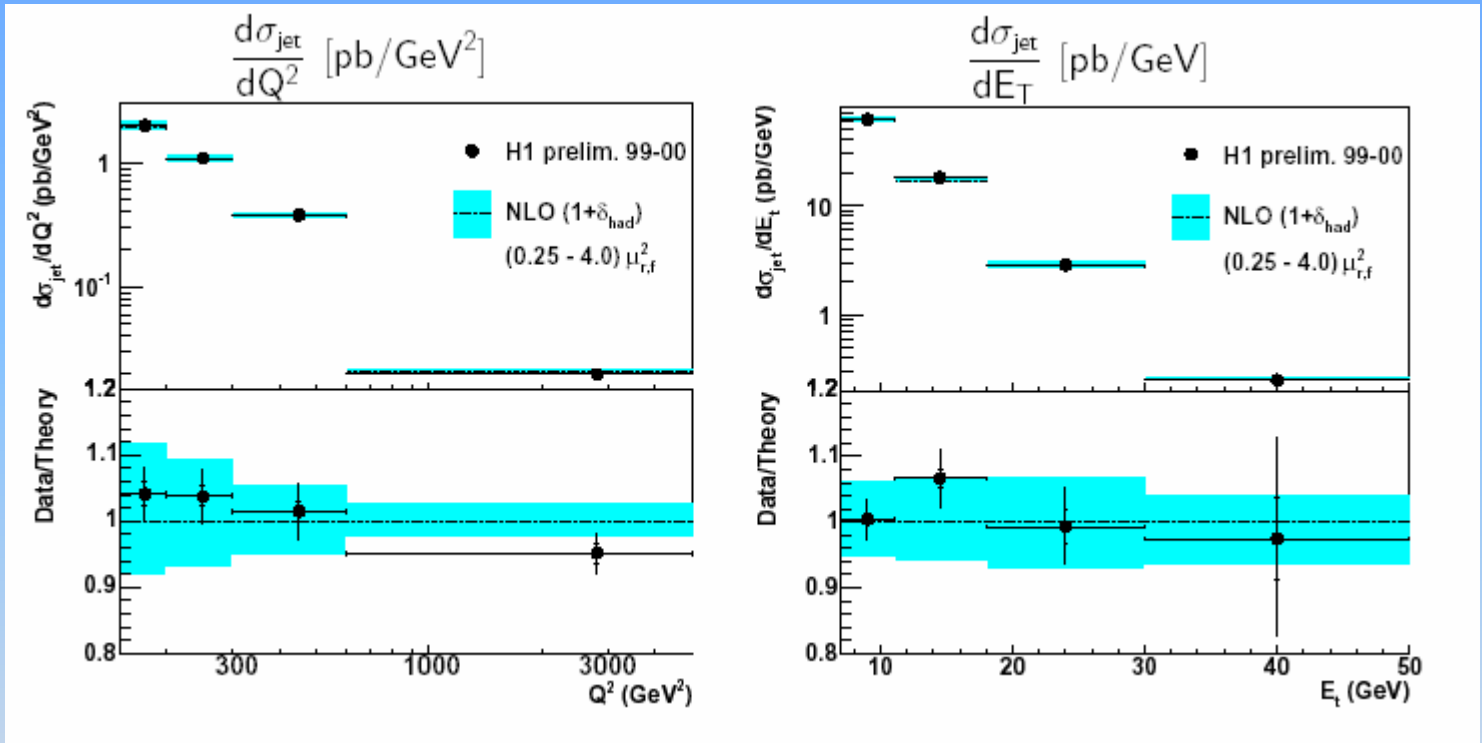
- Data correction (det.&QED):
  (CDM[DJANGO]+MEPS[RAPGAP])/2

- dominating exp. uncertainty:
  abs. hadronic energy scale
  → vary E in HCAL by $\pm 2\%$

- NLO pQCD (NLOJET):
  - scales: $\mu_R = E_T, \mu_F = Q$
  - PDFs: CTEQ5M1
  - hadronization corrections:
    (CDM[DJANGO]+MEPS[RAPGAP])/2

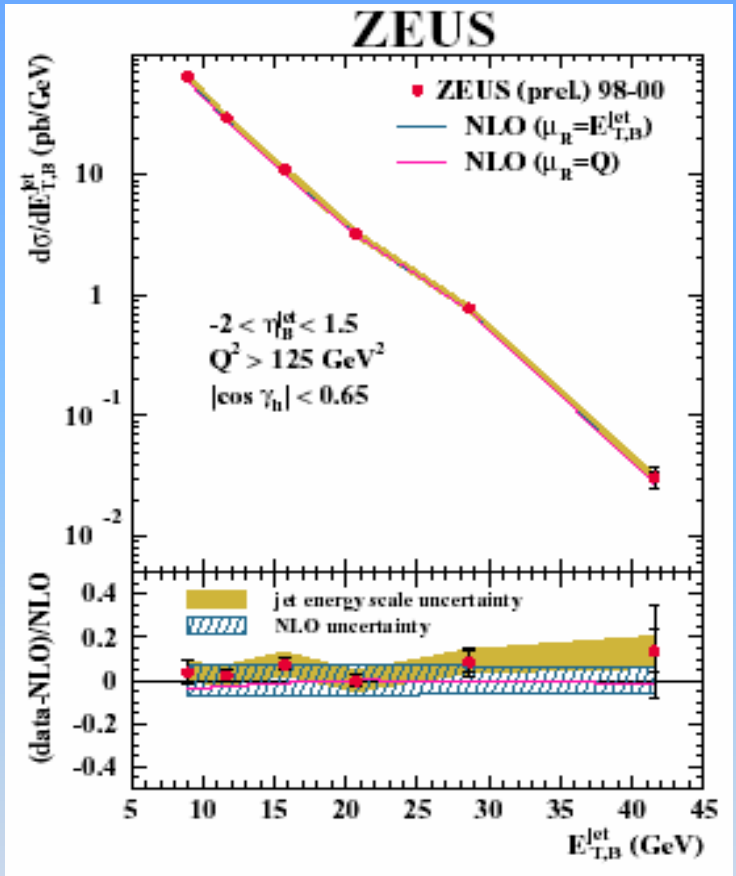
Excellent agreement between DATA and NLO over many orders of magnitude !

...and the experimental error is smaller than the theoretical one !



NLO = NLOJET
scale; $\mu_R=E_t$, $\mu_F=Q$
PDF = CTEQ5M1
δ_{had} from CDM/PS

ZEUS Inclusive Jet Production in DIS



DIS phase space
$Q^2 > 125$ GeV^2
$|\cos\gamma_h| < 0.65$

Inclusive jet phase space
$E_{T,Breit} > 8$ GeV
$-2 < \eta_{lab} < 1.5$

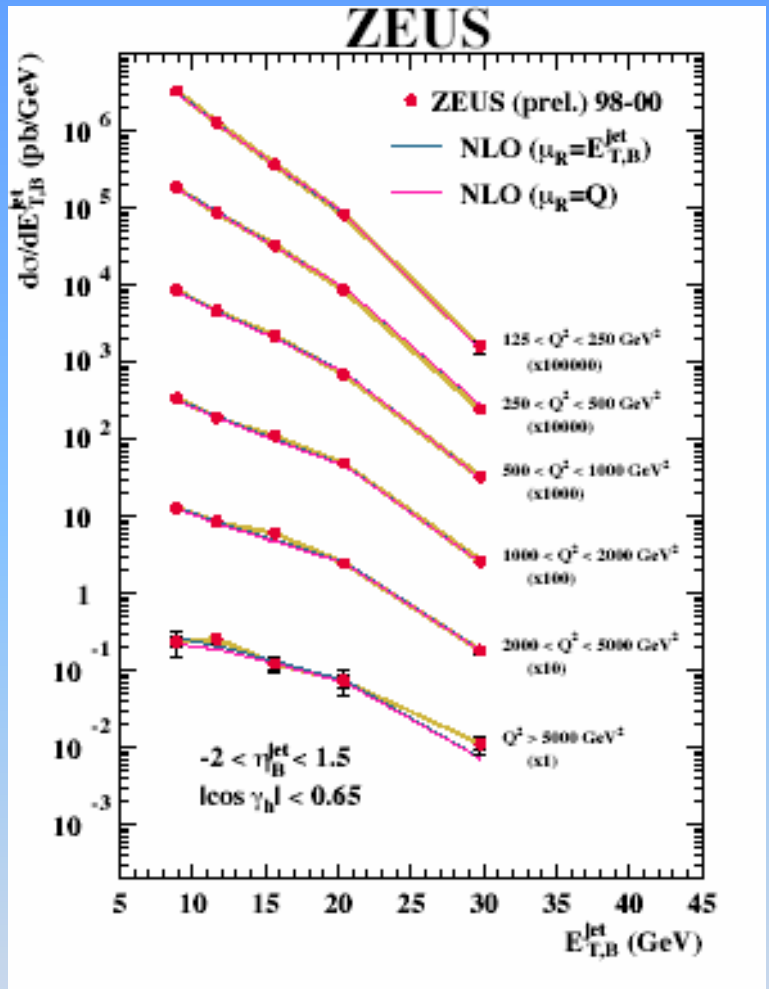
μR = μF = ET, or Q, αs(MZ)= 0.1175, MRST99 PDFs
Plus hadronisation corrections and Z0 corrections

Largest experimental systematic uncertainty from absolute energy scale of jets ⇒ 5%

higher-order terms (> NLO); varying μ_R between $\frac{1}{2} \cdot E^B_{T,jet}$ and $2 \cdot E^B_{T,jet} \Rightarrow \pm 5\%$
uncertainty on $\alpha_s(M_Z)$ (± 0.0027); $\Rightarrow \pm 4\%$
uncertainties on the proton PDFs; $\Rightarrow \pm 3\%$

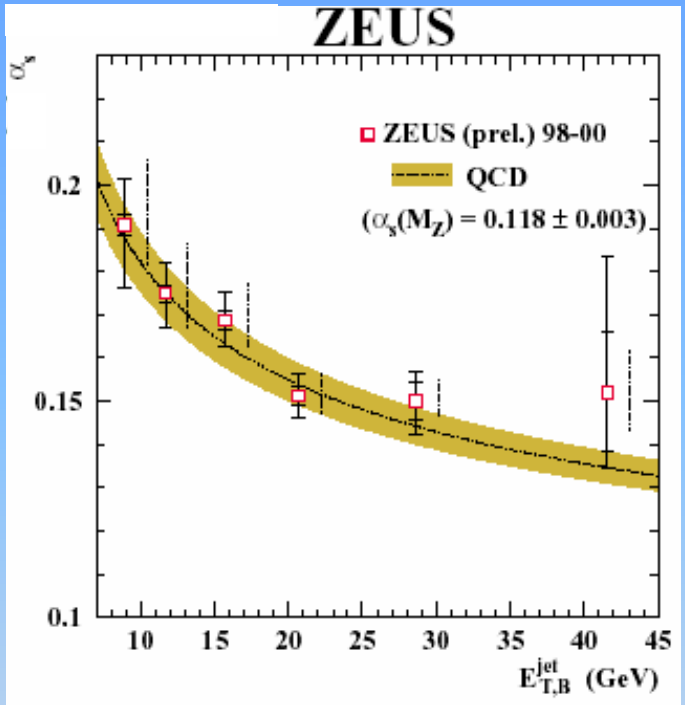
exp. and theor. errors same scale

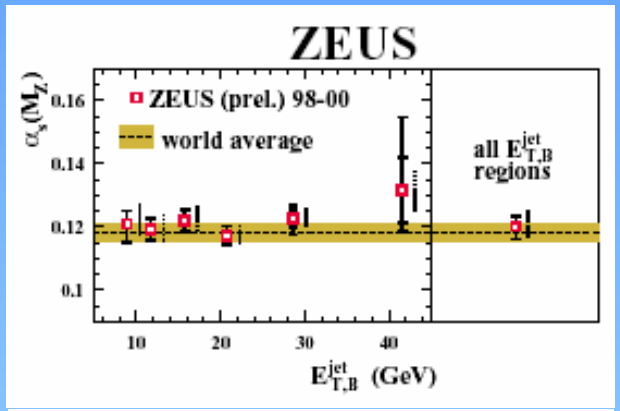
measurements at different Q^2 also for ZEUS…



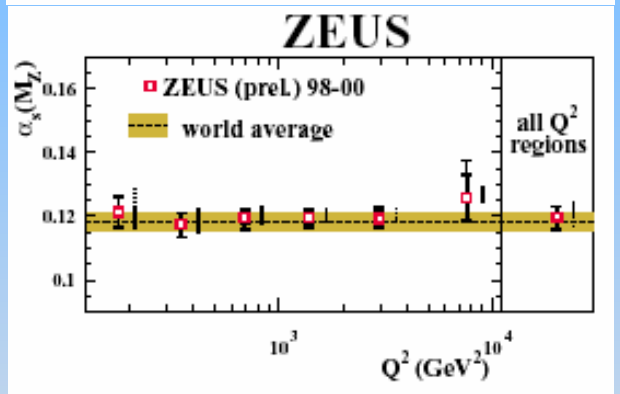
Inclusive jet cross sections in NC DIS in the Breit frame provide direct sensitivity to α_s and the gluon density in the proton with small experimental and theoretical uncertainties

Running and Extraction of α_s from Inclusive jets





α_s vs E_t



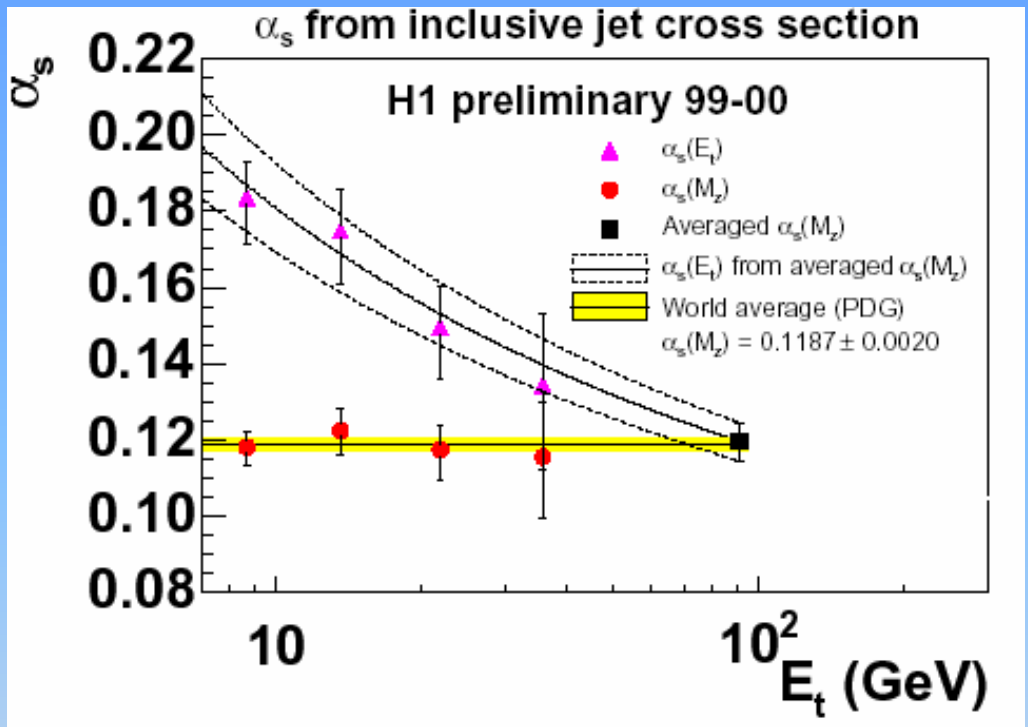
α_s vs Q^2

Best result for Q^2 bins with Q^2>500 GeV^2
$\Rightarrow$ uncertainties minimised

$Q^2 > 500$ GeV^2

$$\alpha_s = 0.1196 \pm 0.0011(stat)^{+0.0019}_{-0.0025}(sys)^{+0.0029}_{-0.0017}(th)$$

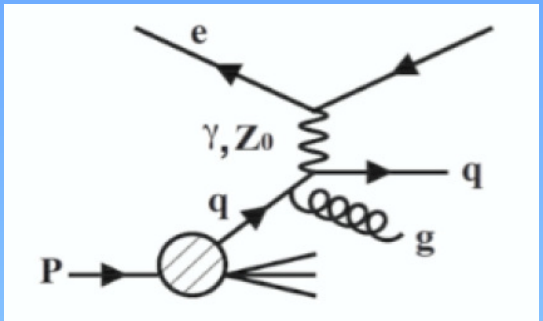
and H1

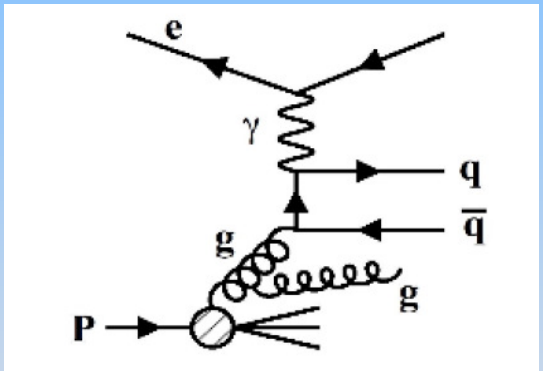


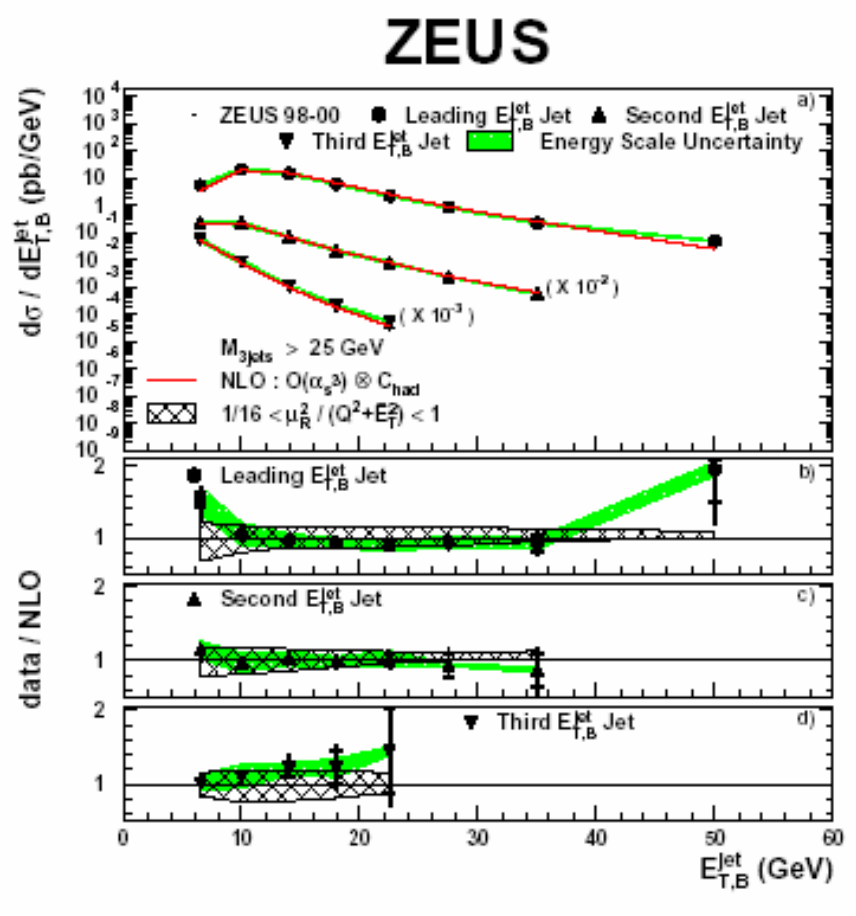
$$\alpha_S = 0.1197 \pm 0.0016(\exp)^{+0.0046}_{-0.0048}(th)$$

before showing the whole sets of α_S measurements,
look at the MULTI-JET data sets $\Rightarrow$

Di-Jet and Tri-Jet PRODUCTION in DIS



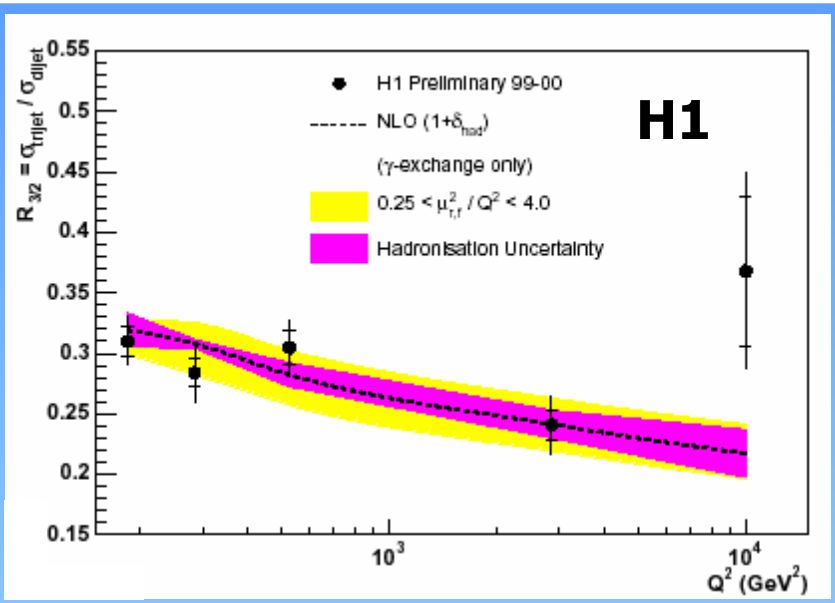


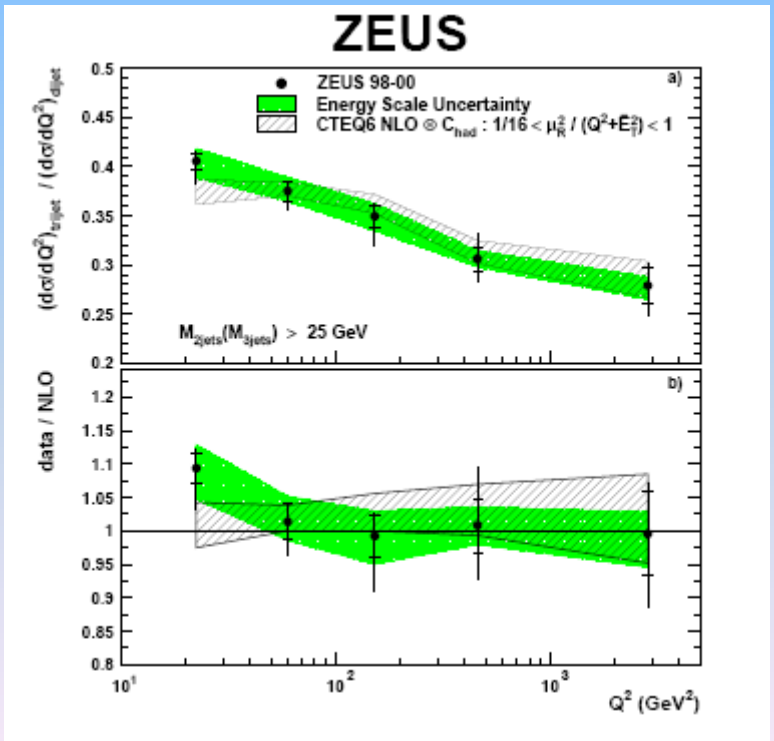


larger errors, but ...

The α_S dependency of their ratio is a sensitive test of pQCD

3-jet / 2-jet cross section ratio



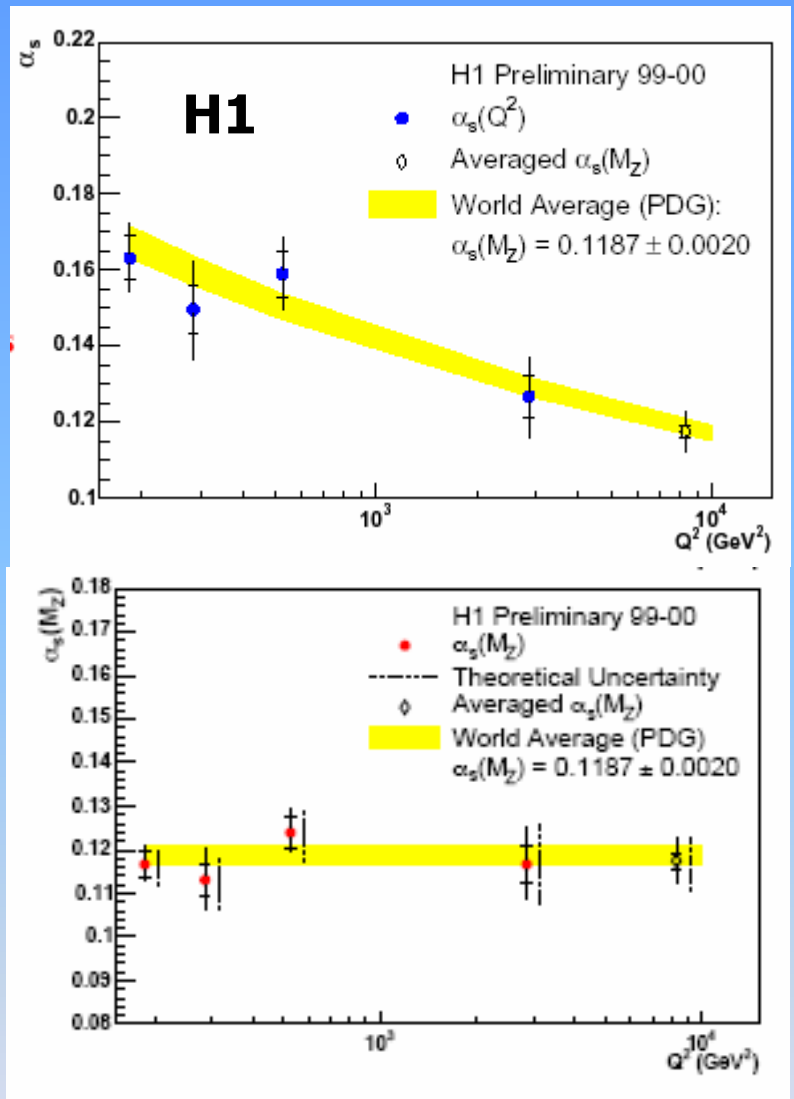


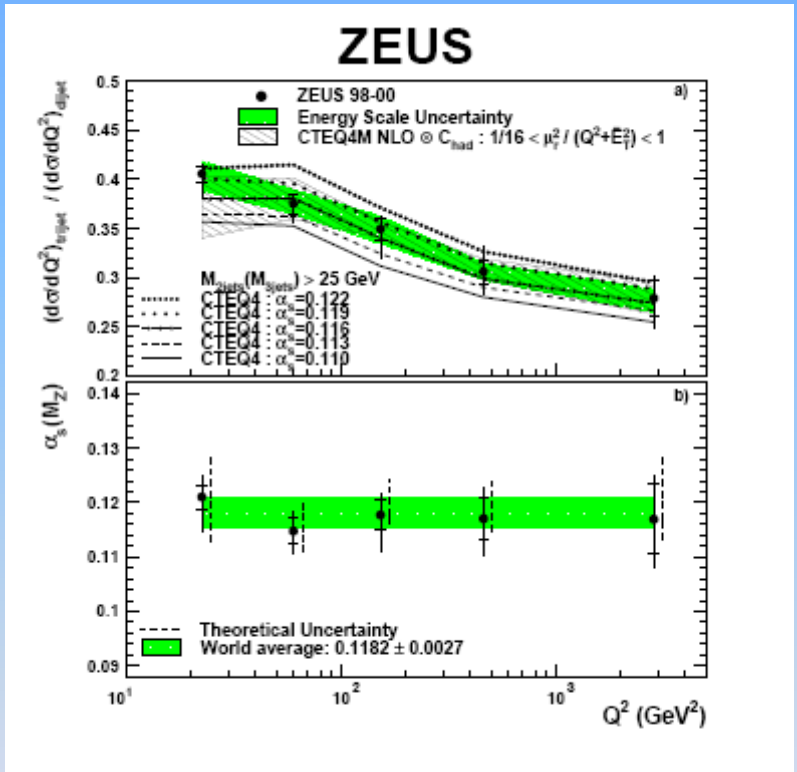
Good agreement for $Q^2 < m^2_{Z^0}$

Largest experimental uncertainty: calorimeter energy scale

Largest theoretical uncertainty: renormalization and factorization scale

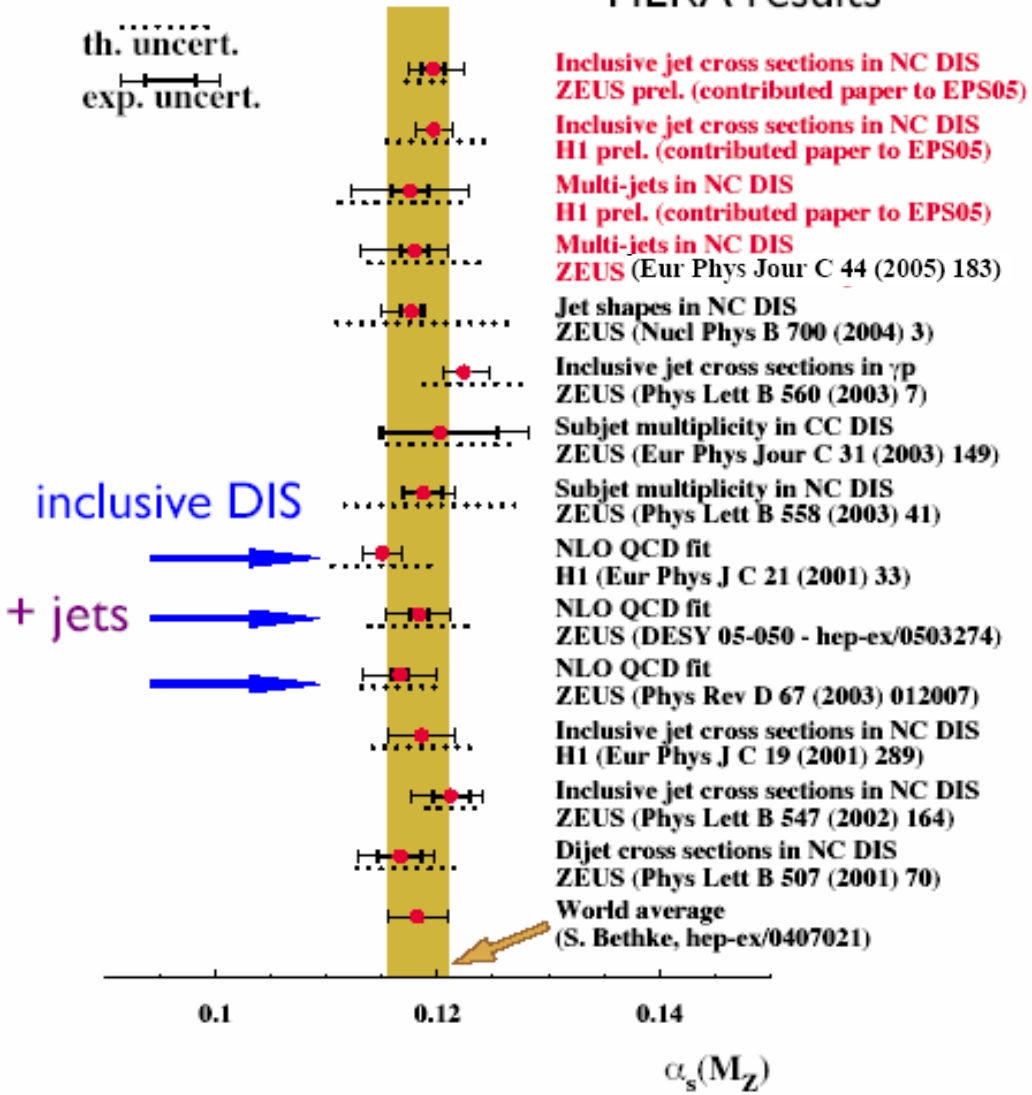
α_s measurements from 3-jet / 2-jet cross section ratio





room for improvements (HERA-II)

HERA results



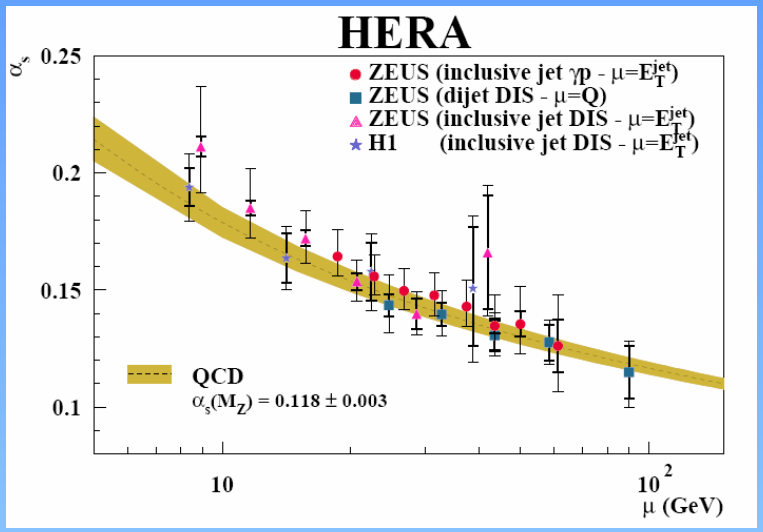
α_s

DIS inclusive jets

results of
inclusive DIS pdf fits
(with $\alpha_s(M_Z)$ as free parameter)
consistent with
final state analyses
and world average

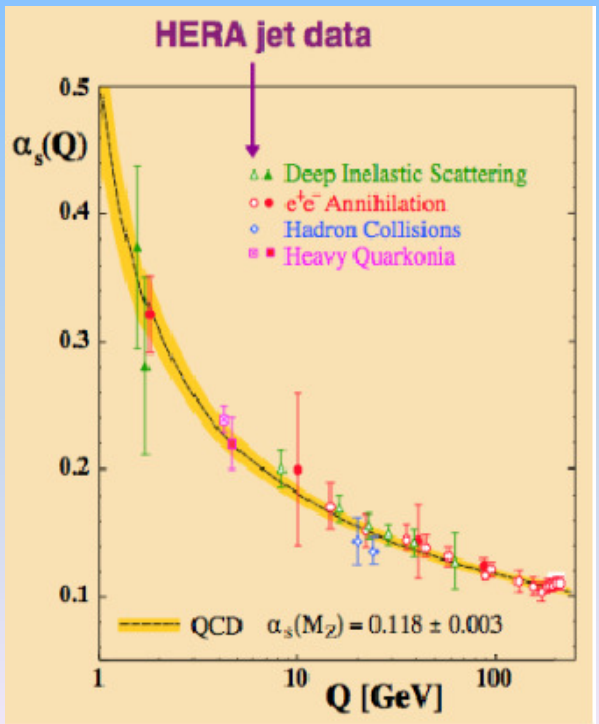
- exp. precision calls for NNLO analysis
- calculations exist for inclusive DIS (Moch, Vermaseren, Vogt)

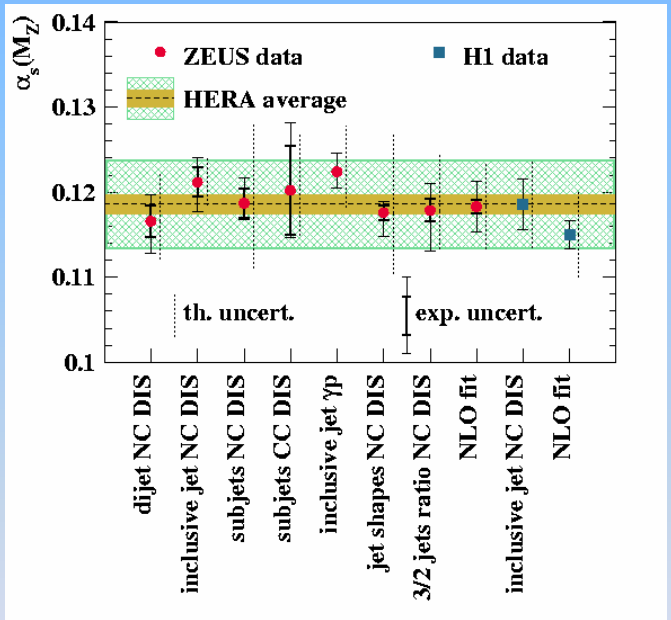
α_s running…



HERA-average:

$$\alpha_s(M_Z^2) = 0.1186 \pm 0.0011(\text{exp.}) \pm 0.0050(\text{th.})$$



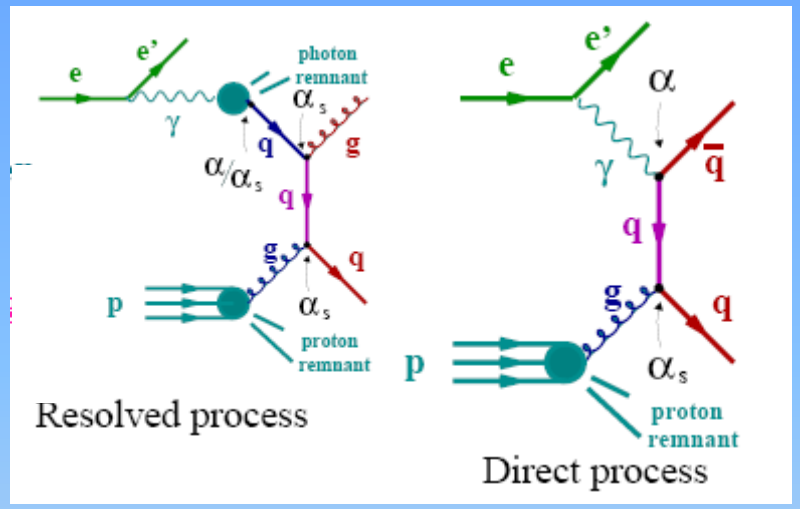


- small experimental error ~1%
- theory error dominates (NLO)
- call for NNLO

JETS in γ-production

… again, another testing ground for QCD

- The biggest contribution to the production of jets comes from photoproduction($Q^2 \sim 0$)
- At leading order, two processes contribute to the dijet photoproduction cross section:



pQCD calculations of jet cross sections

$$d\sigma_{jet} = \sum_{a,b} \int_0^1 dy\, f_{\gamma/e}(y) \int_0^1 dx_\gamma\, f_{a/\gamma}(x_\gamma, \mu^2_{F\gamma}) \int_0^1 dx_p\, f_{b/p}(x_p, \mu^2_{Fp})\; d\hat{\sigma}_{ab\to jj}$$

longitudinal momentum fraction of γ/e^+ (y), parton a/γ (x_γ), parton b/proton (x_p)

→ $f_{\gamma/e}(y)$ = flux of photons in the positron (WW approximation)

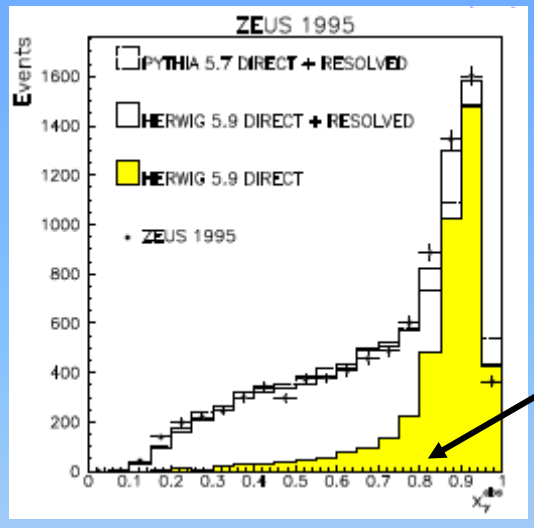
→ $f_{a/\gamma}(x_\gamma, \mu^2_{F\gamma})$ = parton densities in the photon (for direct processes $\delta(1-x_\gamma)$)

→ $f_{b/p}(x_p, \mu^2_{Fp})$ = parton densities in the proton

→ $\sigma_{ab\to jj}$ subprocess cross section; short-distance structure of the interaction

- Measurements of jet photoproduction provide
  - → Test of NLO QCD predictions based on current parametrisations of the proton and photon PDFs
  - → Dynamics of resolved and direct processes
  - → Photon structure: information on quark densities from F_2^γ in e^+e^-; gluon density poorly constrained. Jet cross sections in photoproduction are sensitive to both the quark and gluon densities in the photon at larger scales $\mu^2_{F\gamma} \sim E^2_{T,jet}$ $(200 - 10^4\ \mathrm{GeV}^2)$
  - → Proton structure: well constrained by DIS except for the gluon density at high x. Jet cross sections in γp are sensitive to parton densities at x_p up to ~ 0.6
- Observable to separate the contributions: the fraction of the photon's energy participating in the production of the dijet system $x_\gamma^{OBS} = \frac{1}{2E_\gamma}\sum_{i=1}^{2} E_T^{jet_i} e^{-\eta^{jet_i}}$

Well observed from the "first days"

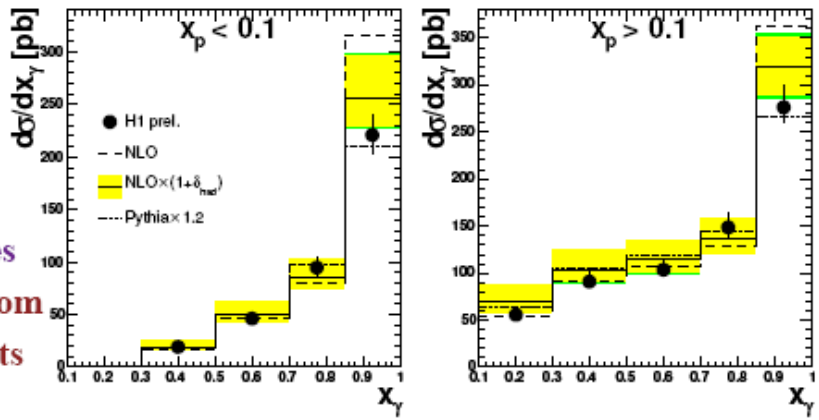


ZEUS

x_γ=0.8 cut

Photon structure

- Measurements of $d\sigma/dx_\gamma$ for $x_p < 0.1$ (g_p processes) and $x_p > 0.1$ (q_p processes)
- Comparison to NLO calculations using CTEQ6M (proton) and GRV-HO (photon) PDFs
  - → Good description of the data along the entire range of x_γ for both ranges in x_p
- Consistent with QCD-evolved photon PDFs determined from measurements in $\gamma\gamma$ at lower scales and proton PDFs as determined from HERA and fixed-target experiments



H1

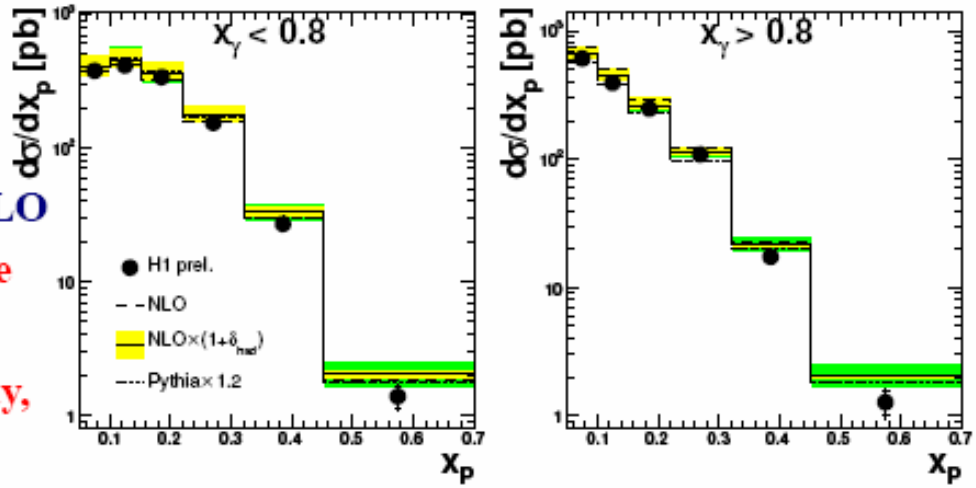
- New measurements of $d\sigma/dx_p$ for $x_\gamma < 0.8$ (resolved processes) and $x_\gamma > 0.8$ (direct processes)
- Comparison to NLO calculations using CTEQ6M (proton) and GRV-HO (photon) PDFs
- Theoretical uncertainties:

→ terms beyond NLO; estimated by varying μ_R up and down by a factor of 2
  ⇒ dominant at low x_p

→ uncertaintites of the proton PDFs; ⇒ increasingly important as x_p increases

- The NLO QCD calculations agree with the data in the low x_p range
- At high x_p ($x_p > 0.32$) there are discrepancies between data and NLO

→ Measurements at high x_γ provide further constraints on the proton PDFs, particular the gluon density, free from the photon PDFs



H1

Proton structure

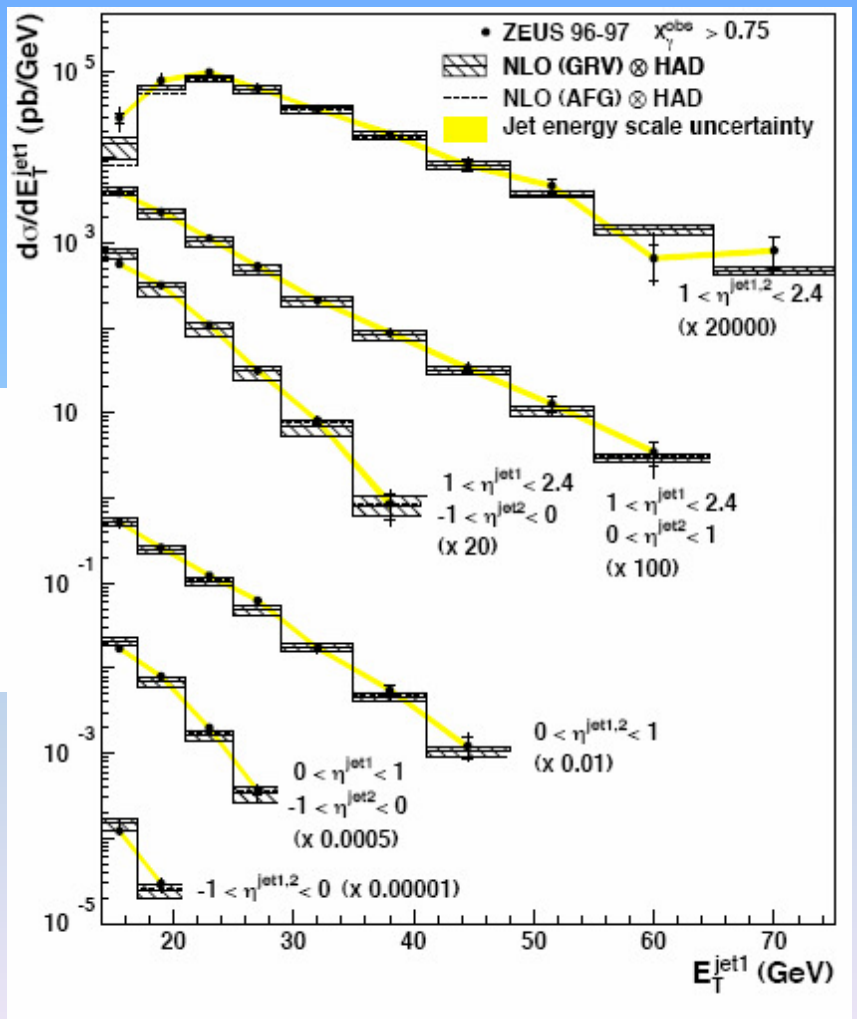
More QCD fits from H1 will come !

Similar situation for E_T distributions

- Consider the enriched sample of direct-γ
- Good agreement with NLO at high ET
- small experimental uncertainties:
  - → jet energy scale (~1%)
    - ⇒ ± 5% on the cross section
- small theoretical uncertainties

$Q^2 < 1$ GeV^2
$134 < W < 277$
$p_{t,max} > 14$ GeV
$p_{t,2} > 11$ GeV
$-1.0 < \eta_{jet} < 2.4$

ZEUS high E_t di-jets in γ-p



⇒ Perform a simultaneous QCD fit * on α_S and Gluon PDF at high x_p

** Pioneering paper of H1 in 2001*

Gluon Parton Distribution

Disadvantages of "ortodox" method (inclusive ep scattering):

- gluon distribution contributes indirectly
- Fixed-target DIS: higher twists, heavy target corrections, isospin symmetry assumption

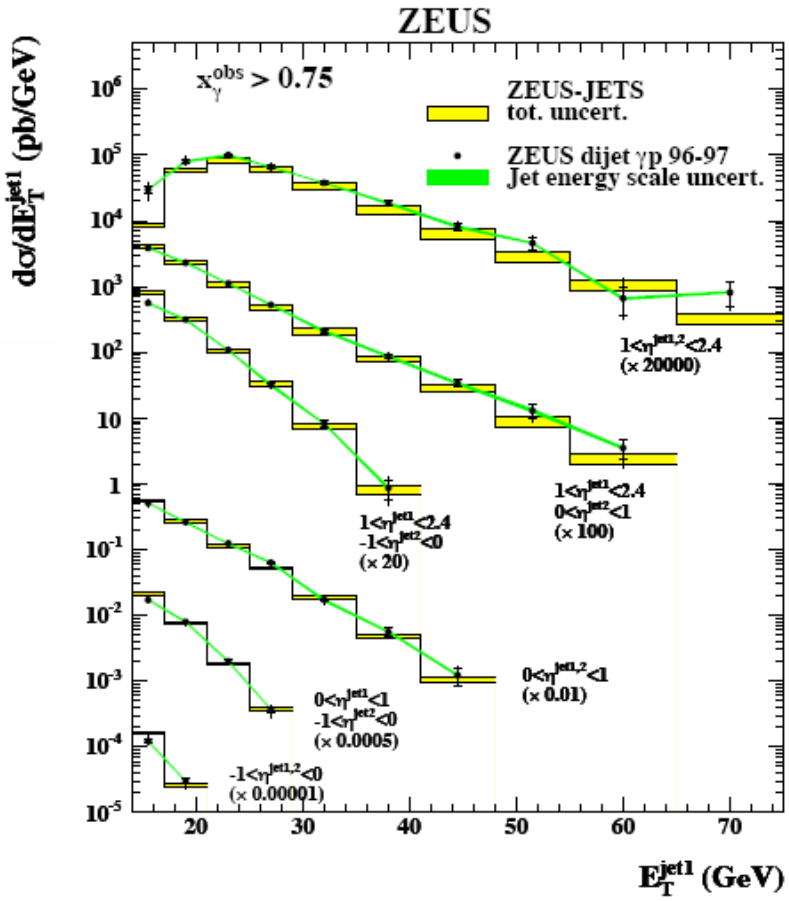
With HERA, sufficient sensitivity to determine the proton PDF within a single (ep) experiment.
Use of measurements of jet cross section
$\Rightarrow$ Directly sensitive to the gluon density with small experimental + theoretical uncertainties

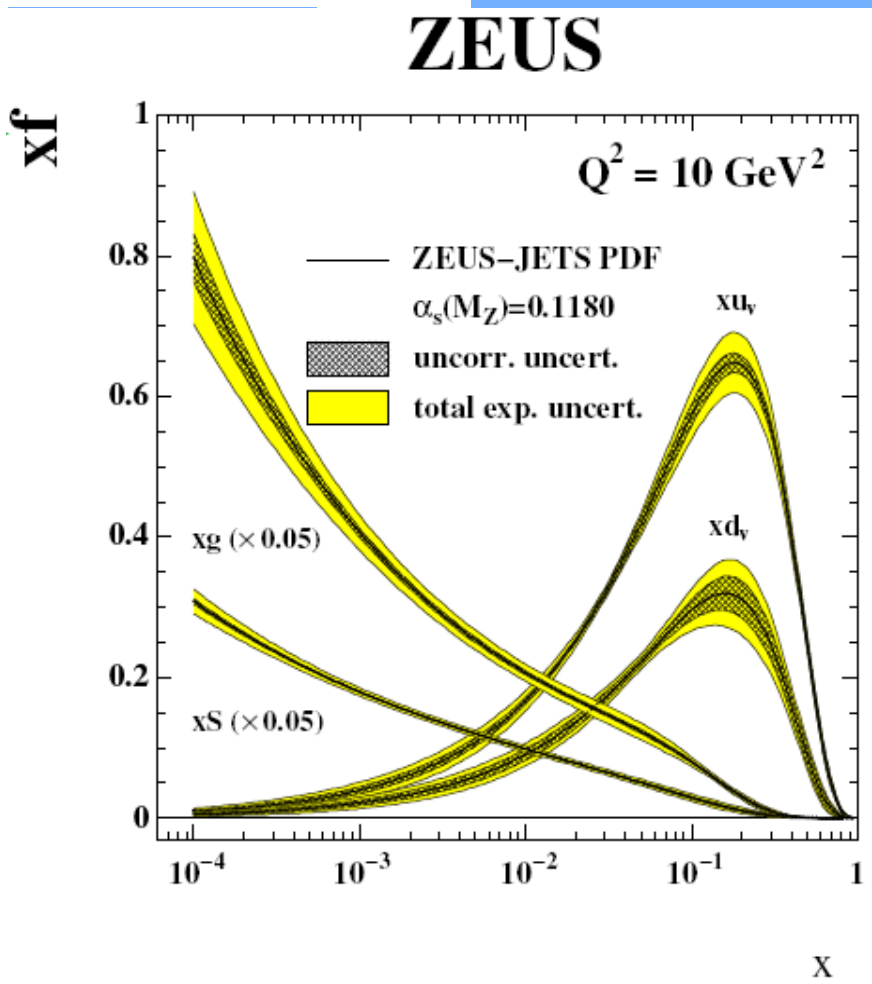
Recent results from ZEUS on "old" data are very good, improving the determination of the proton PDF

Determination of the proton PDFs using SF data and jet data in NC DIS and γp collisions from ZEUS only (!)

$$\Rightarrow \boxed{6.3 \cdot 10^{-5} < x < 0.65,\ 2.7 < Q^2 < 30000\ \mathrm{GeV}^2}$$

di-jets in photoproduction





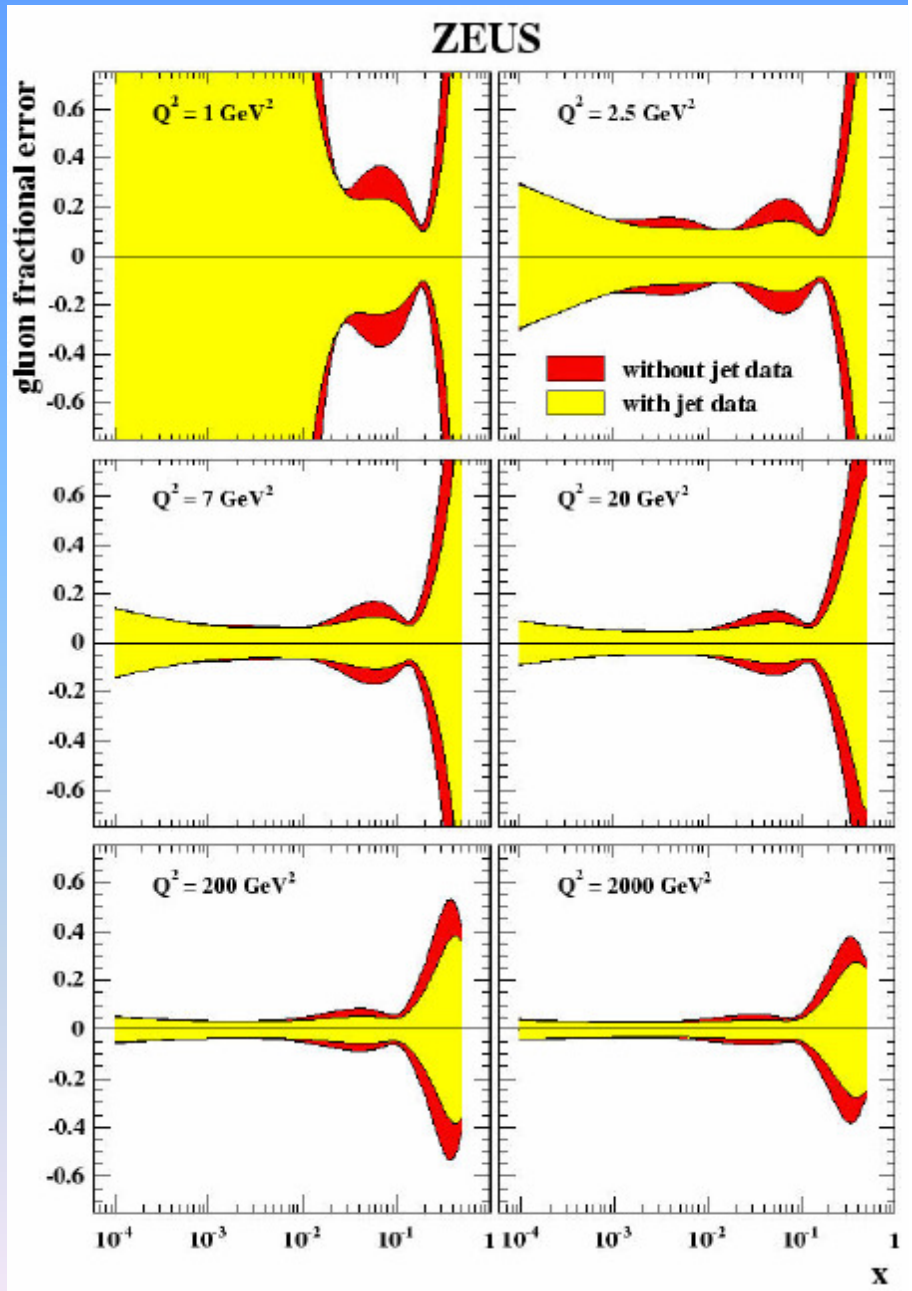
Sizeable reduction of the gluon uncertainty

Comparing the gluon distribution obtained from fits with and without jet data:

- no significant change of shape:
  no tension between incl. and jet data

- jet cross sections help in constraining the gluon density in the region:
  $0.01 < x < 0.4$

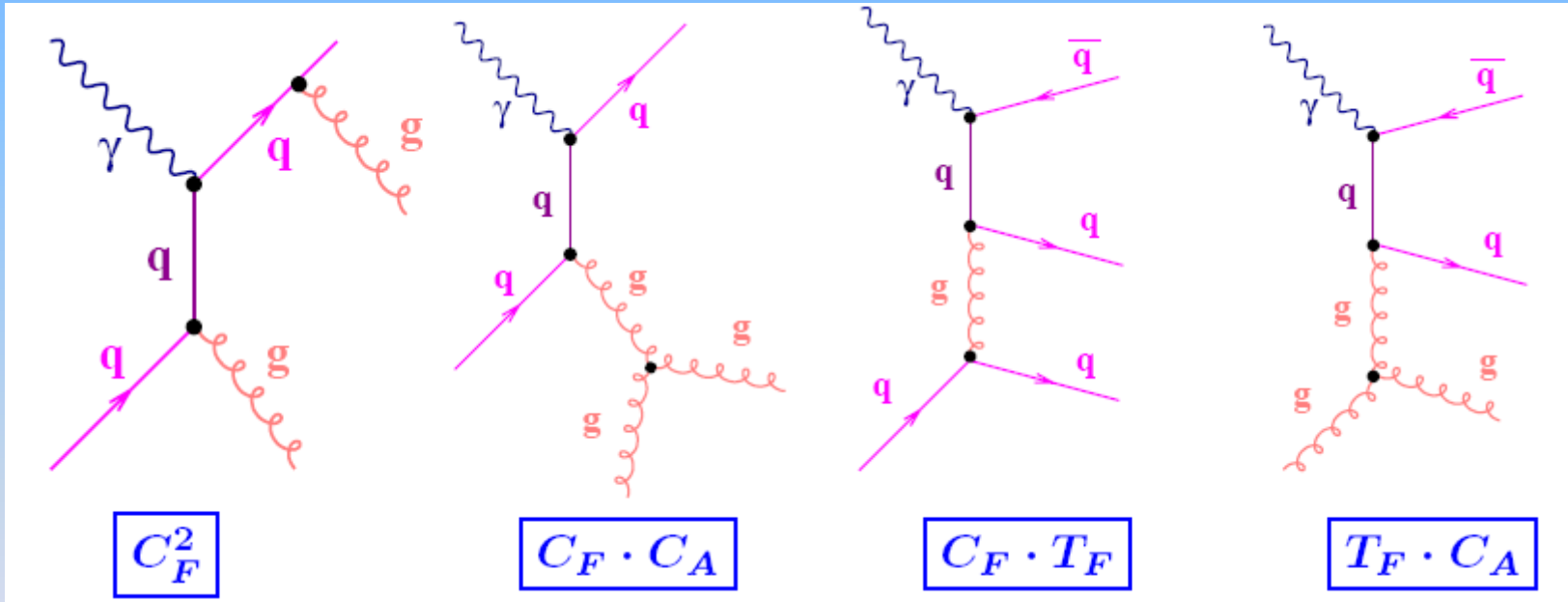
- Sizeable reduction of the gluon unc:
  e.g. from 17% to 10% at x=0.06 and Q^2=7 GeV^2
  →similar reduction by a factor two in the mid-x region over the full Q^2 region



Color and sub-jet dynamics

Photo-production of three-jet events

Direct-γ processes provide a clean way to study the effects of the different color configuration:

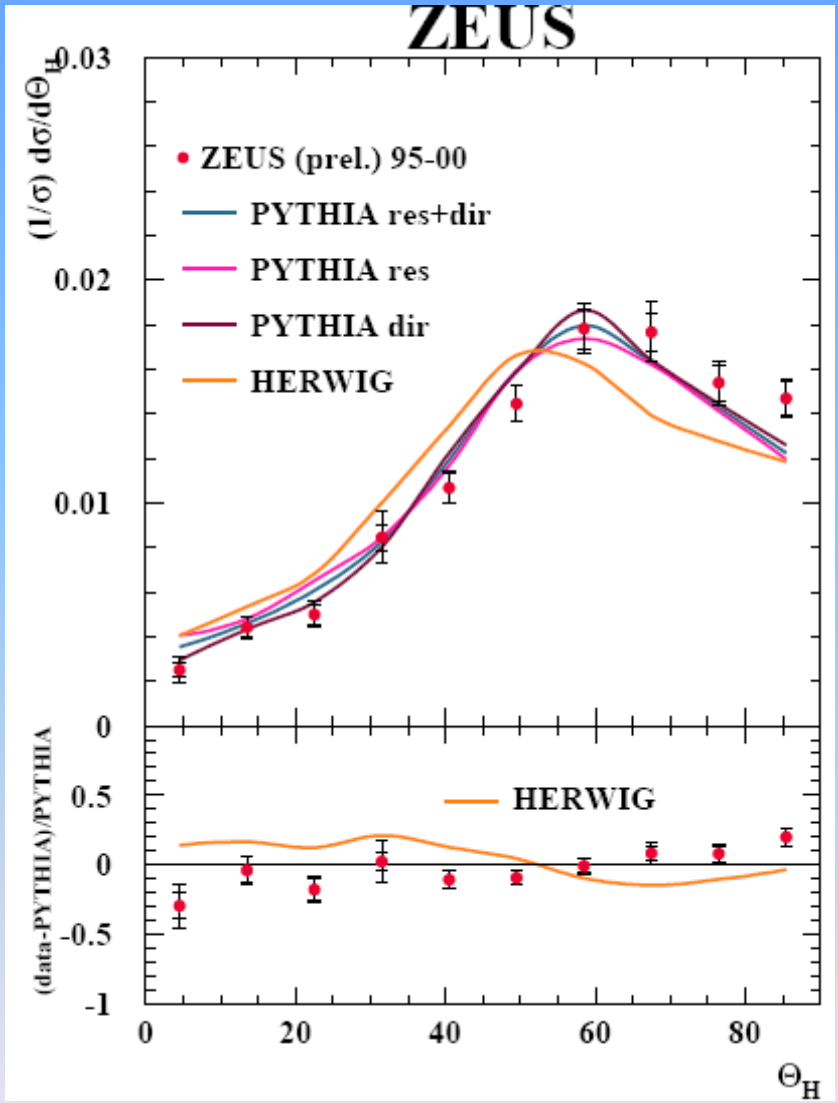


The predicted cross section at $\mathcal{O}(\alpha\alpha_s^2)$ can be written as

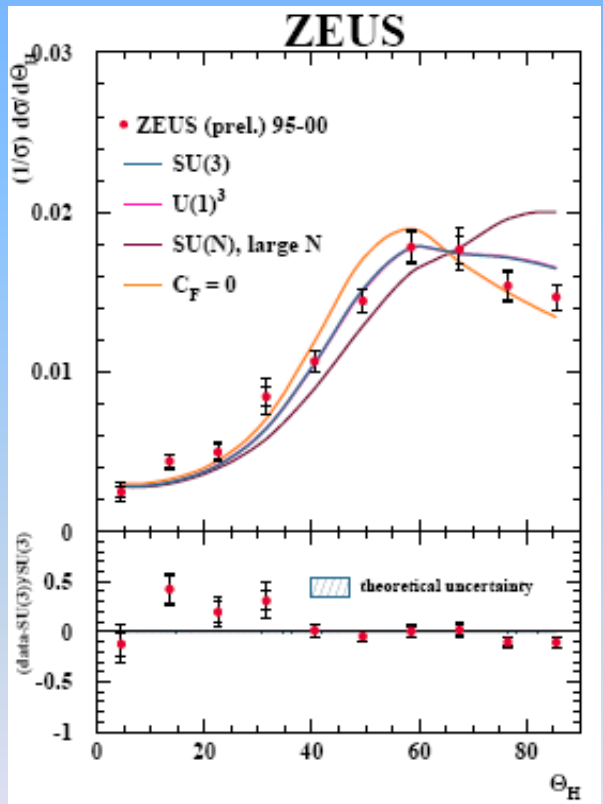
$$\sigma_{ep\to 3\text{jets}} = C_F^2 \cdot \sigma_A + C_F C_A \cdot \sigma_B + C_F T_F \cdot \sigma_C + T_F C_A \cdot \sigma_D$$

Angular observables for angular correlations…

θ_H: the angle between plane containing the beamline and highest E_T jet and the plane containing the second and third highest E_T jets.



Comparisons to fixed order calculations based on different symmetry group:



The prediction of SU(3) describes reasonably well the data

ZEUS Sub-jet distributions

DIS

Go to region where jet structure can be calculated perturbatively.

Inclusive Jets with,
$Q^2>125\ GeV^2$, $E_T>14$ GeV

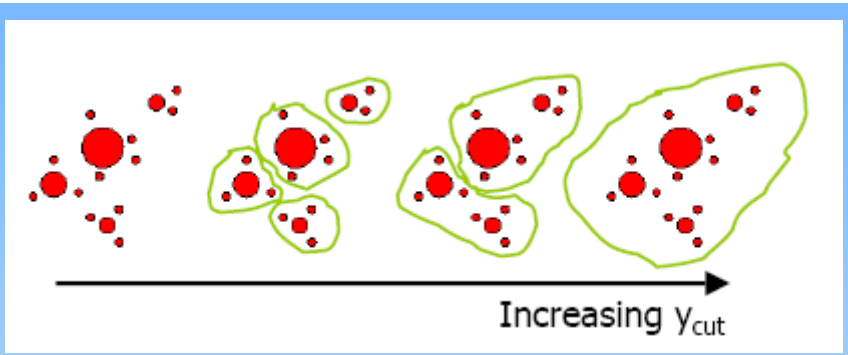
Then study QCD radiation patterns and jet structure

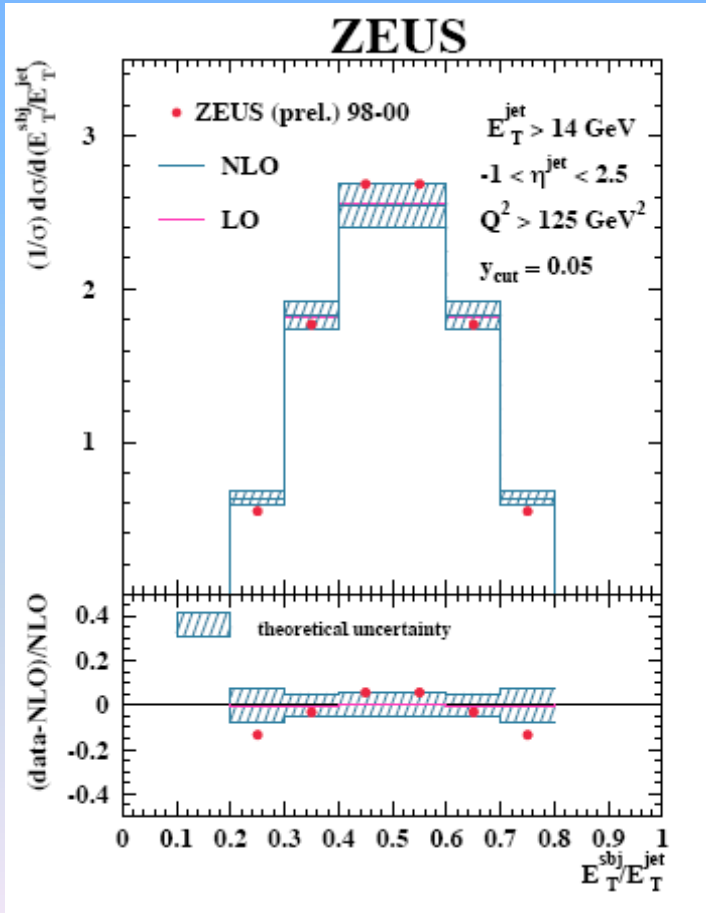
Analysis performed in lab frame where calculations can be made at NLO for jets consisting of up to 3 partons

Rerun K_T jet finder over particles of found jet using a distance measure to define subjets

$d_{cut} = y_{cut}.(E_{T,jet})^2$

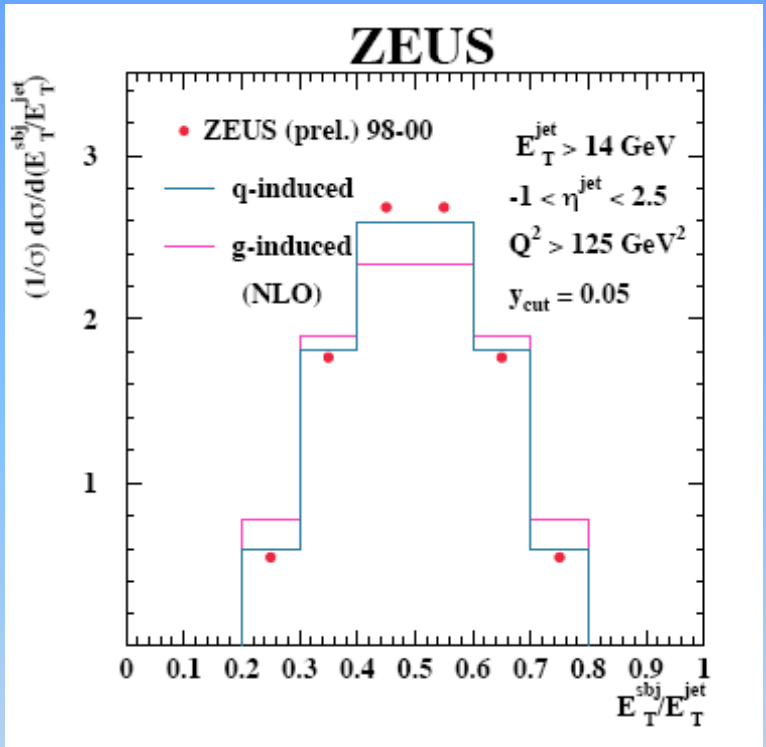
sample consists of jets that have two sublets for y_{cut}=0.05





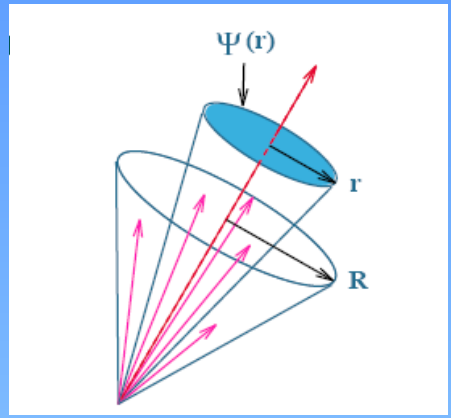
All distributions are reasonably described by NLO QCD

NLO predicts the relative contribution of quark (gluon) induced processes is 82% (18%)



data are best described by calculations for subjets coming from qg pairs

- Measurement of jet substructure allows investigations on
  - → the differences between quark- and gluon-originated jets and
  - → the dynamics of the different partonic final states,
  - → as well as determinations of α_s

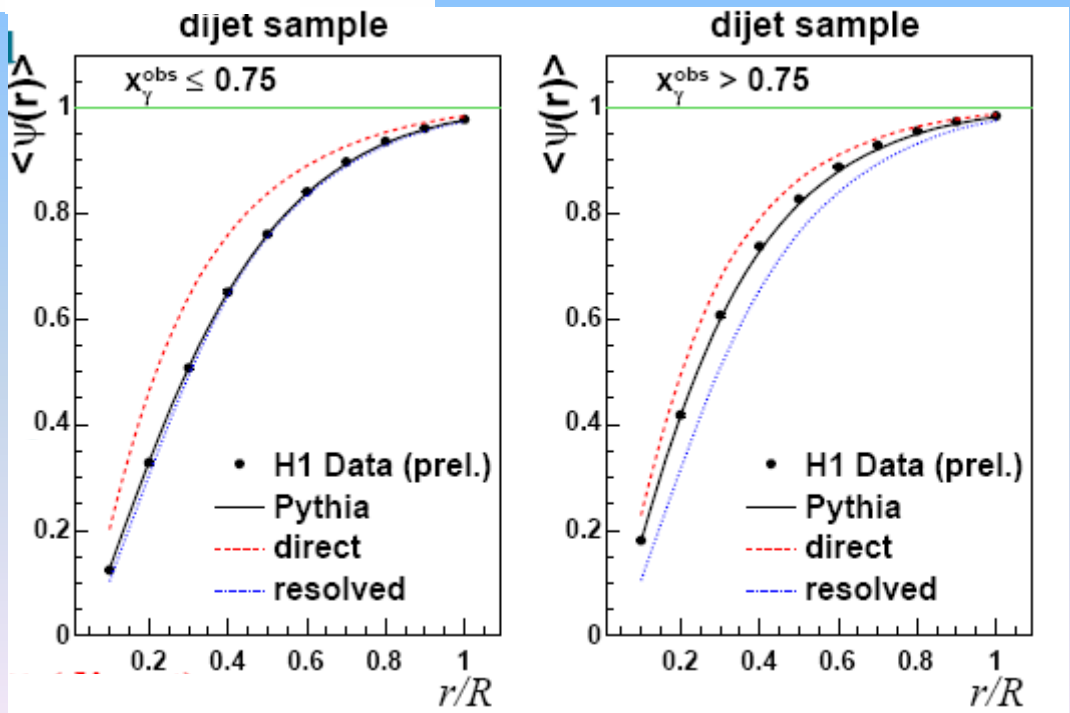


- Jet substructure in photoproduction:
  - → Resolved processes give rise to quark and gluon jets through $q_\gamma g_p \to qg$, $g_\gamma g_p \to gg$, ...
  - → Direct processes give rise mostly to quark jets through $\gamma g \to q\bar{q}$

H1 γ-p data

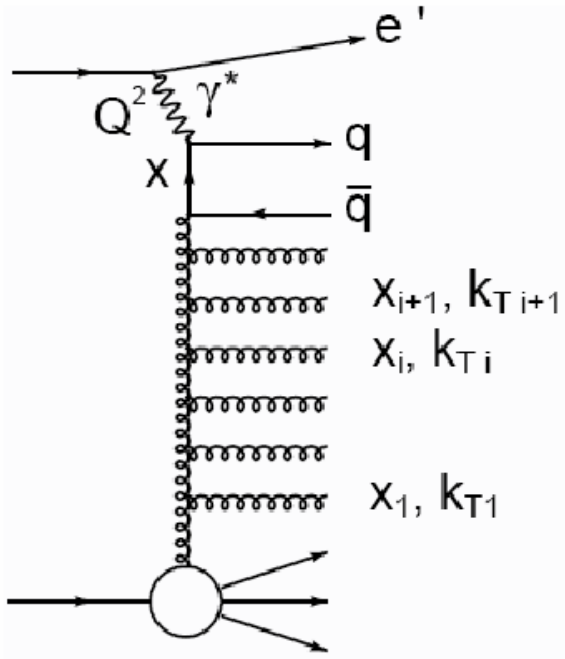
The jets in the region x_γ<0.75 are broader than in the region x_γ>0.75

Consistent with a larger fraction of gluon (broad) jets in resolved-photon events than in direct-photon events



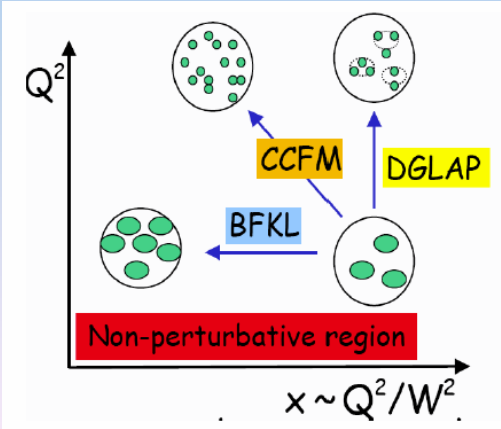
QCD dynamics

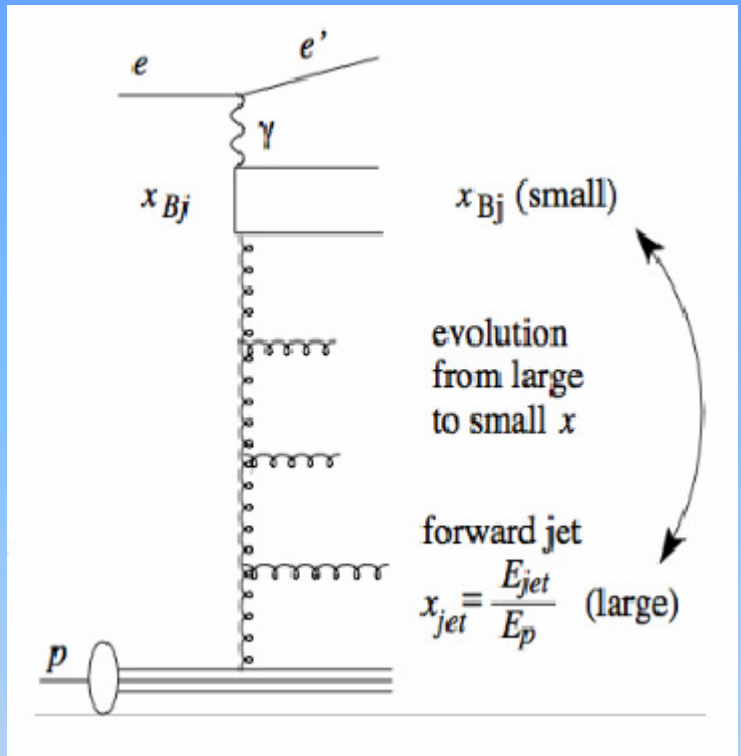
HERA: DIS at low-x_{Bj} down to 10^{-5}
$\Rightarrow$ large γ^*p center of mass energy (W)



- standard DGLAP approximation, large Q^2 :
  sums terms $\sim\alpha_s \log Q^2$
  strong ordering of parton k_T
- BFKL evolution equation, low x :
  sums terms $\sim\alpha_s \log(1/x)$
  strong ordering in x_i / no ordering in k_T
- CCFM equation applicable at all x and Q^2:
  implements angular ordering resulting from QCD interference effects

Inclusive F2 measurement not able to discriminate between different QCD approaches $\Rightarrow$ Study of Hadronic Final States (JETS)





HERA extends x_{Bj} until 10^{-5}

⇒ **FORWARD JETS**
(proton direction)

possibility to study parton dynamics,
by looking for effects beyond DGLAP

Caveat: different Monte Carlo models not clear where applicable

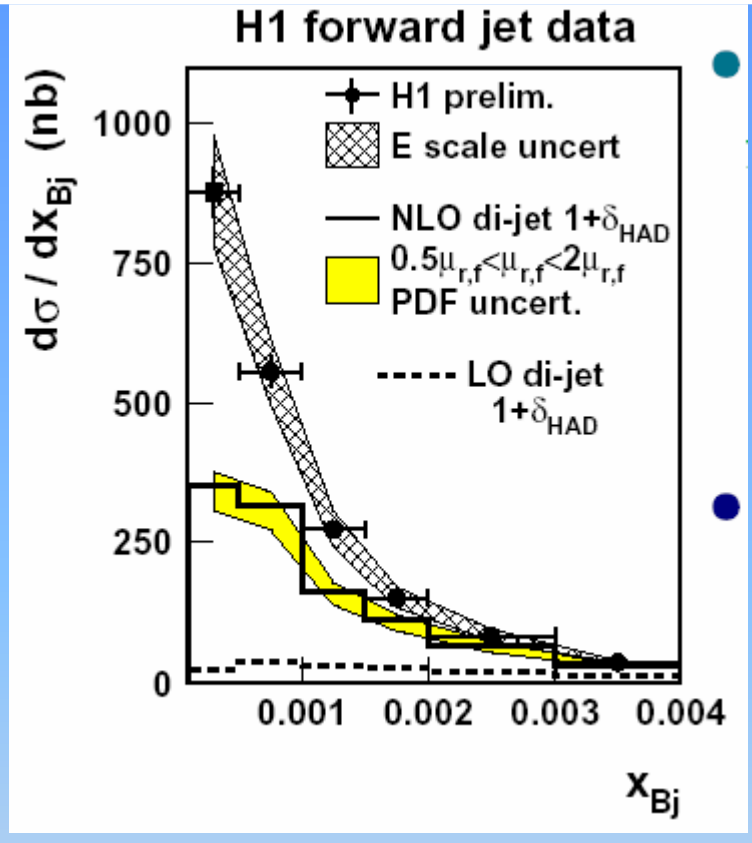
H1 data in the kinematic region:

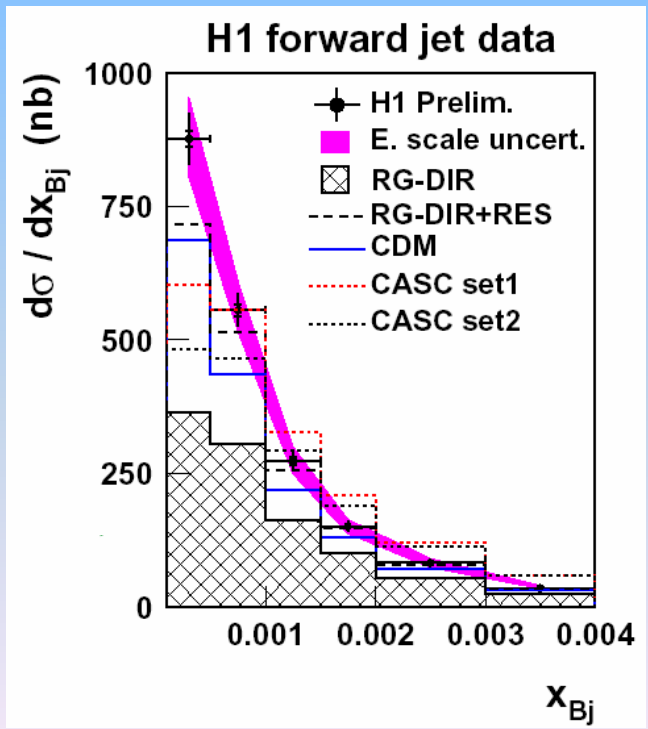
$10^{-4} < x < 4 \cdot 10^{-3}$ and $5 < Q^2 < 85$ GeV^2

$p_{t,jet} > 3.5$ GeV, $7° < \theta_{\rm jet} < 20°$

$0.5 < p^2_{t,jet}/Q^2 < 2$

$x_{jet} = E_{jet}/E_p > 0.035$



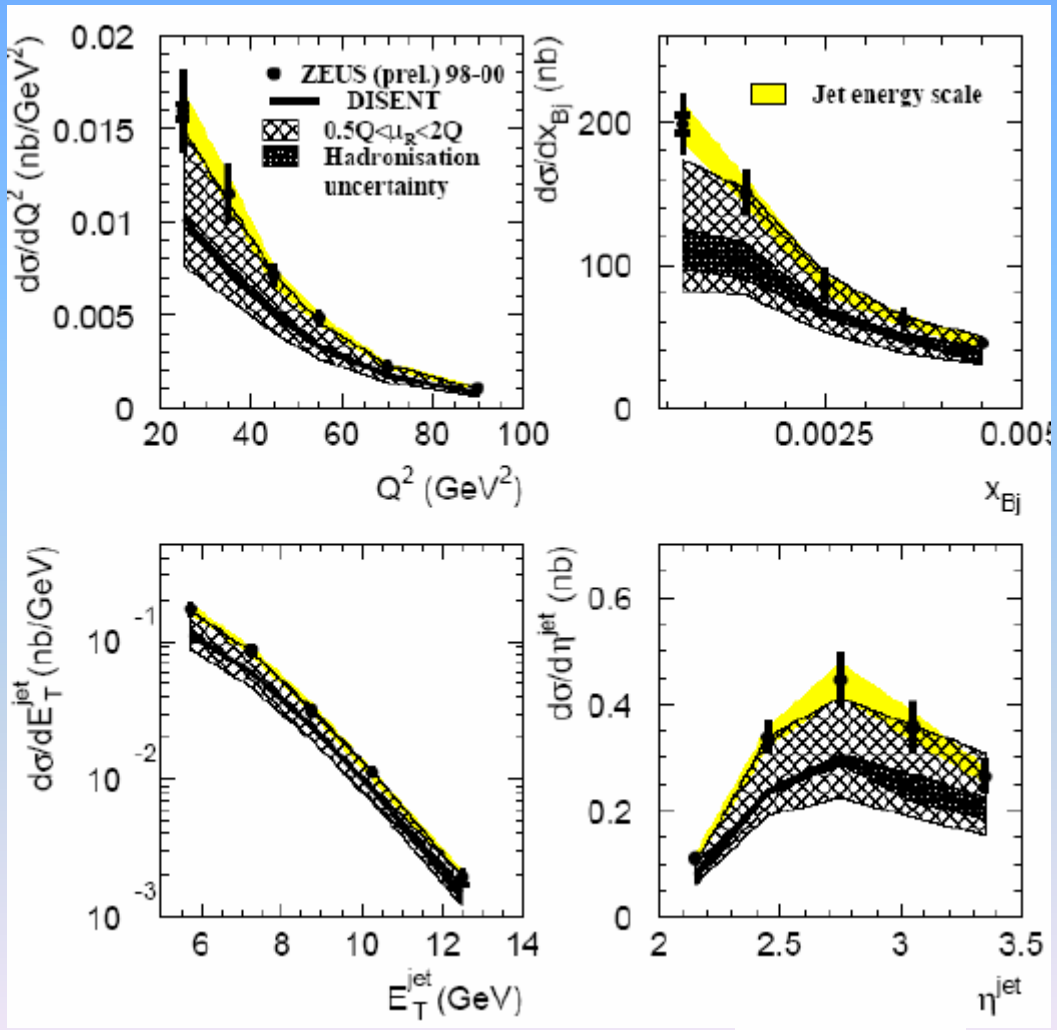


- LO-DGLAP fails completely !
- NLO-DGLAP well below data at low-x
- Monte Carlo models with extra parton radiation provide an improved description of the data
- inclusion of a resolved-photon component (RG-DI+RES)
- parton emissions not ordered in k_T (CDM)

ZEUS data less striking…

(NLO(α_S^2)-DISENT MC below the data but within theoretical errors)

⇒ needs of next NLO ?



(but ZEUS uses $\mu_R^2=Q^2$, while H1 takes $\mu_R^2=\langle p_T^2\rangle$)

Is it a HERA business ? or HERA phase space too limited to distinguish between different evolution models ?

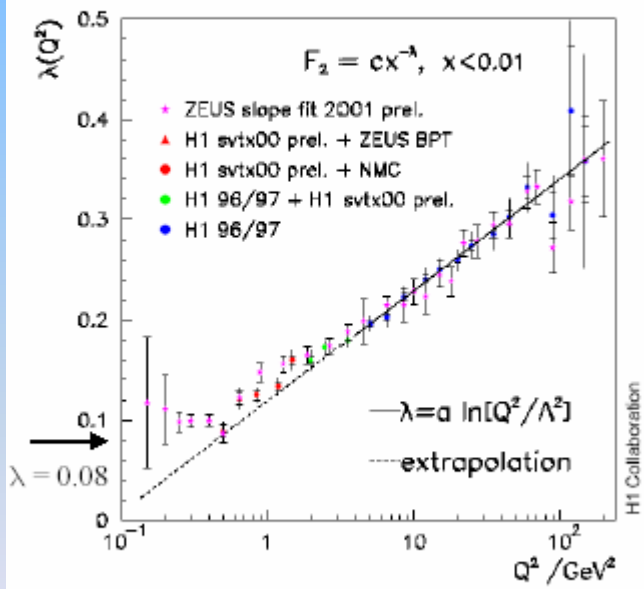
...if nobody else is going to show ...

Definitively, physics has to be clarified.

Also consider Structure Functions results at low-x

Rise of F_2 towards low x

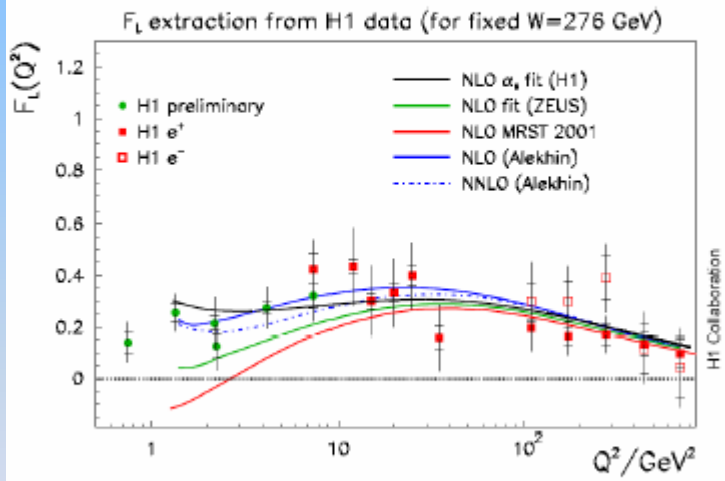
$$F_2(x,Q^2) = c(Q^2)x^{-\lambda(Q^2)}$$



- change of behavior at $Q^2 \approx 1$ GeV^2

Longitudinal SF $F_L(x,Q^2)$

$$F_L = \frac{Y_+}{y^2}(F_2^{QCDfit} - \tilde{\sigma}_{NC})$$



- direct F_L measurements not done at HERA (yet)

→ low proton beam energy running

Conclusions

- QCD is a lively field at HERA !
- Up till now studies on 1996-2000 DATA
- Statistical ≤ Theoretical errors
- HERA-II will lower systematics errors
- Need THEORY works !

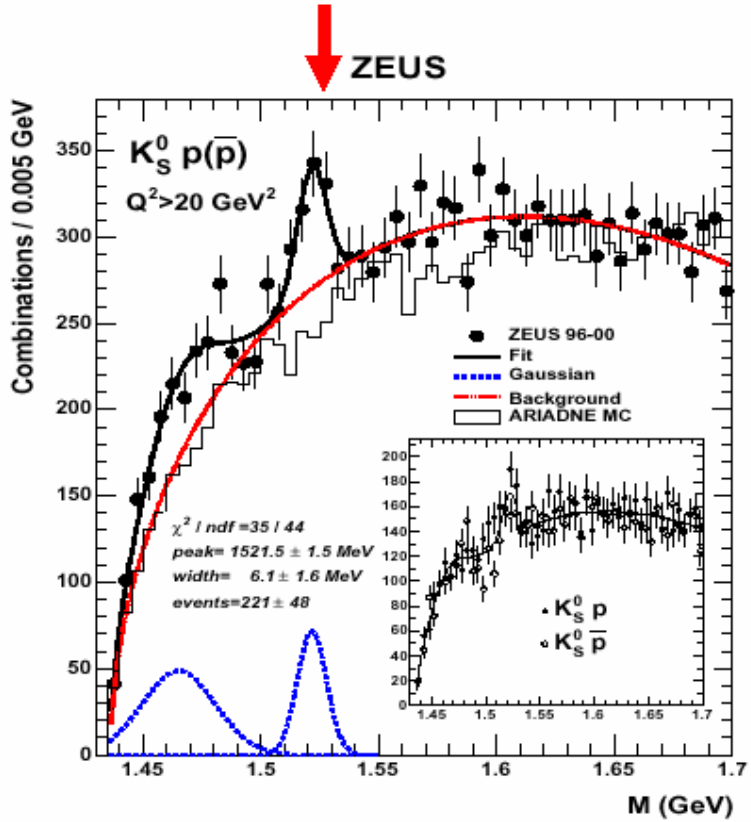
  - Most precise α_S measurement !
  - Use of Jets for PDF
  - Forward Jet discrepancy
  - pQCD evolution(s) not clear yet
  - low-x_{Bj} regime not clear yet

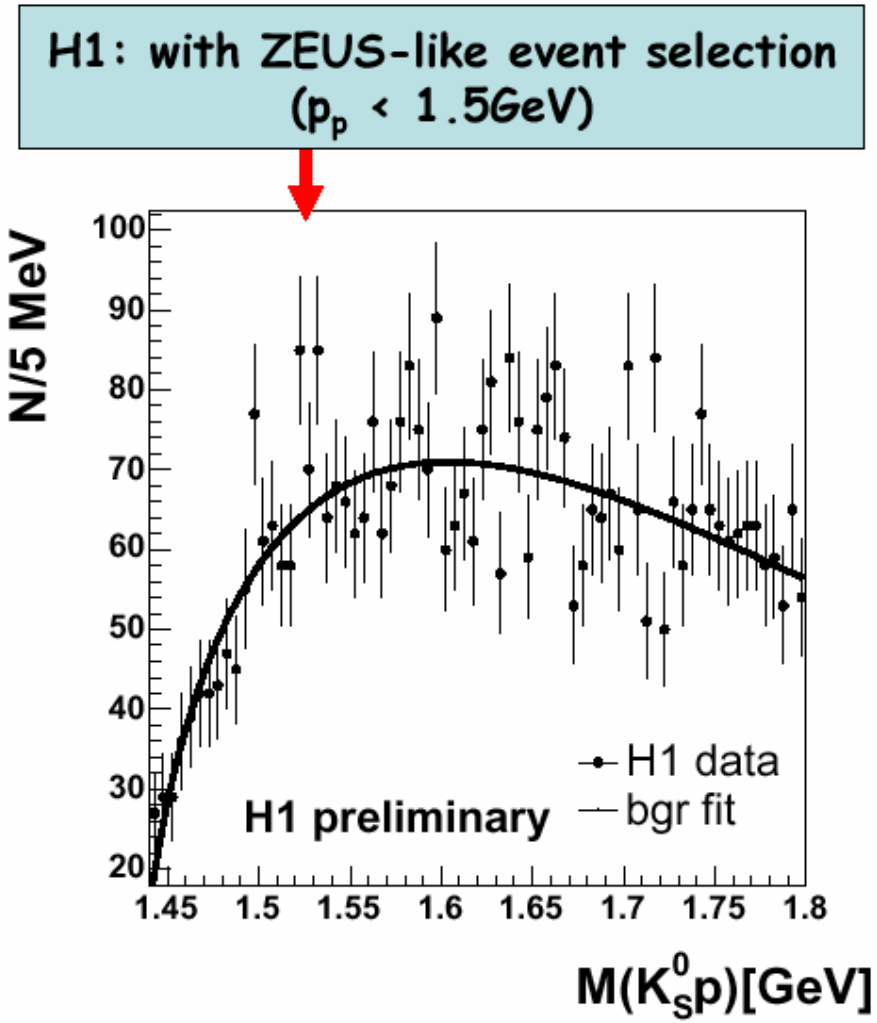
    - Need HERA-II for LHC studies

(the improvements of the precision on the gluon density at mid-to-high x has important implications for discovery physics)

Backup Slides

PENTAQUARKS at HERA



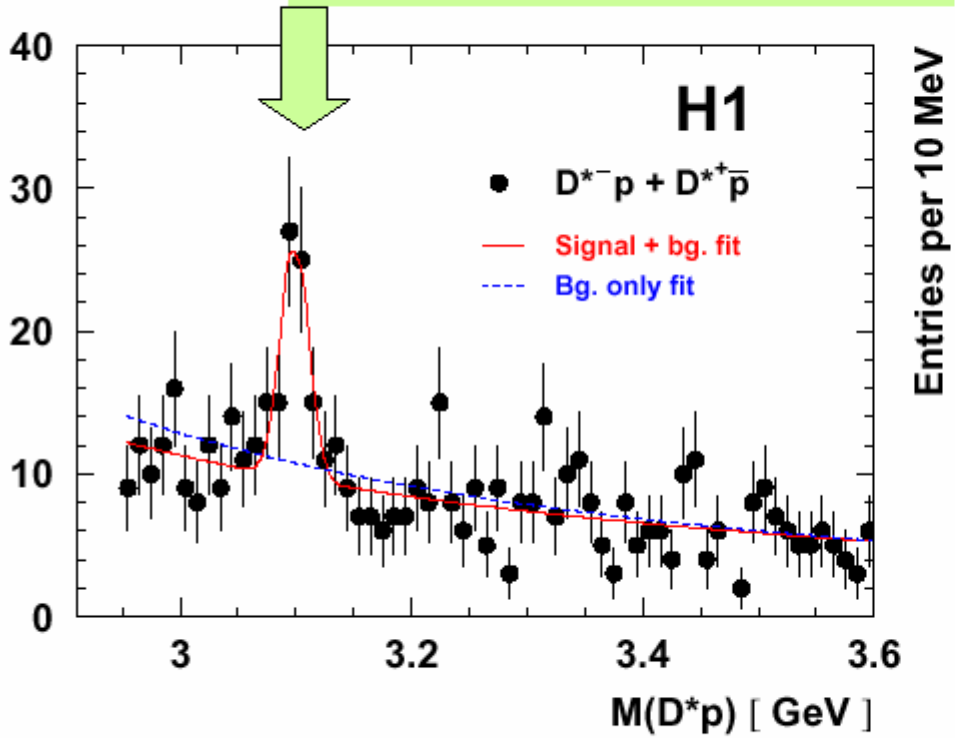


$\theta^+(1530)$: still compatibility ZEUS/H1, need HERA-II DATA

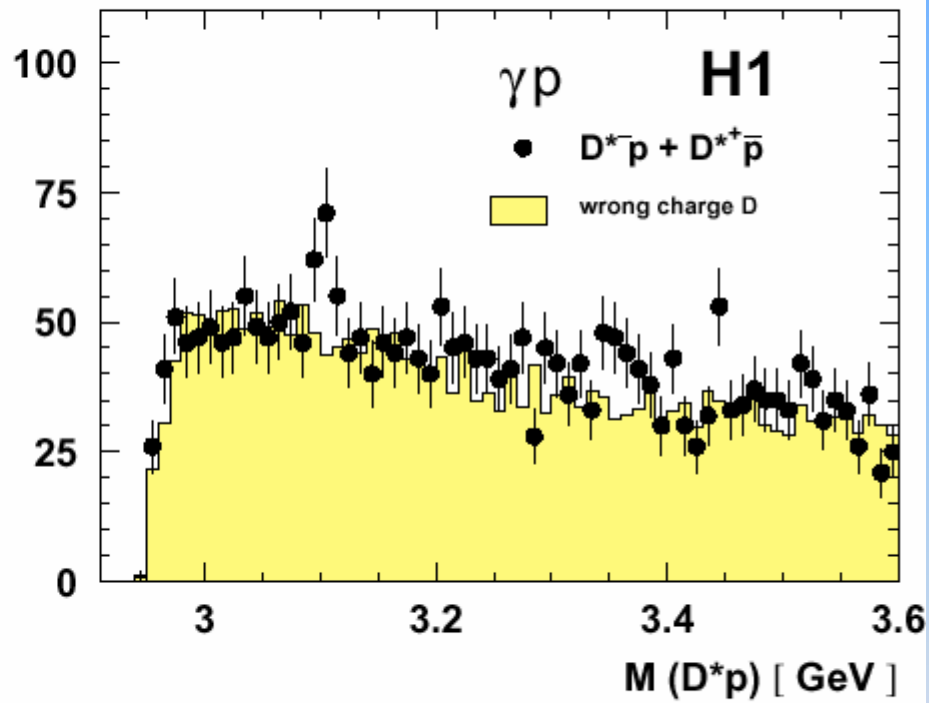
Not seen by ZEUS

DIS

Mass = 3099+-3+-5 MeV
Width = 12 +-3 MeV



Photoproduction



Very clear peak in D*p mass
both in DIS and in photoproduction

$\theta_c(3100)$: still compatibility H1/ZEUS, need HERA-II DATA

• Pentaquark results from H1 and ZEUS show incoherent views.

Θ^+ candidates are seen in ZEUS data and not in H1 data.
Θ_c candidates are seen in H1 data and not in ZEUS data.

•Properties of observed signals are studied. There are several indications that their production mechanism is different from the ordinary baryons.

- Θ^+ : Fwd/Bwd asymmetry, $\Theta/\overline{\Theta}$ asymmetry,
  (associate production with $\Lambda(1520)$: LEPS)
- Θ_c : deficit in the central region.
  Harder fragmentation function.

•We definitely need new results from HERA-II to conclude if 5-q system exists.