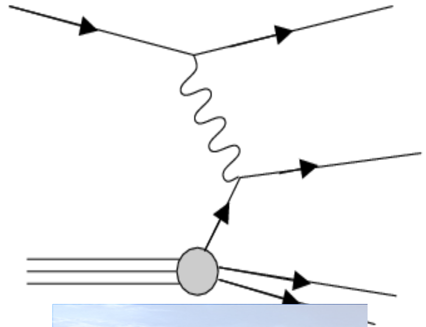
THE STRONG COUPLING AT HERA (+ a word on HERA-PDF 1.6)

Thomas Schörner-Sadenius

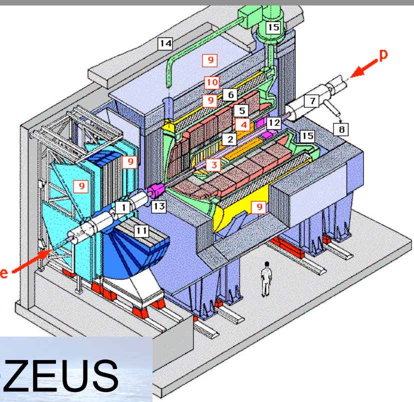
PIC 2011, Vancouver, August 2011

OUTLINE

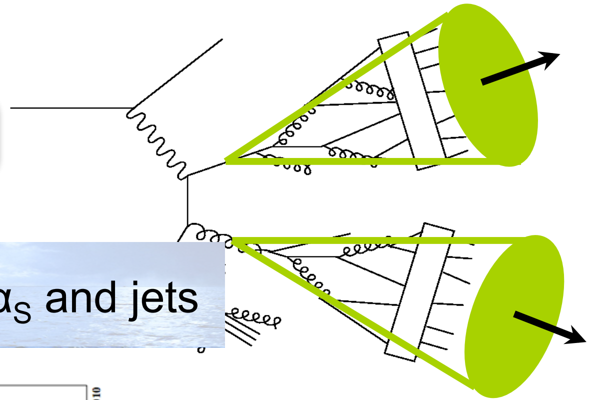
HERA



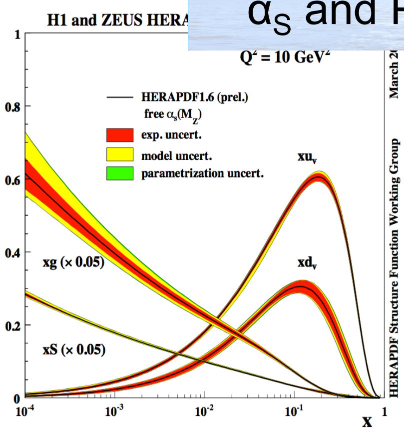
ep physics

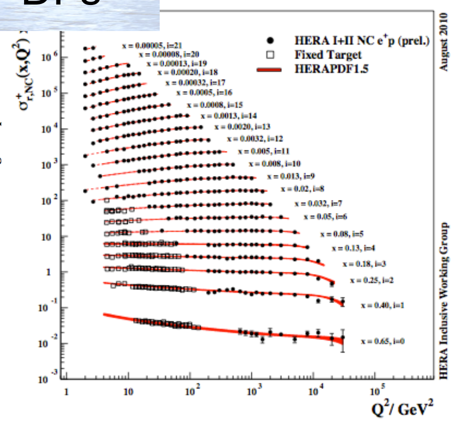


H1+ZEUS

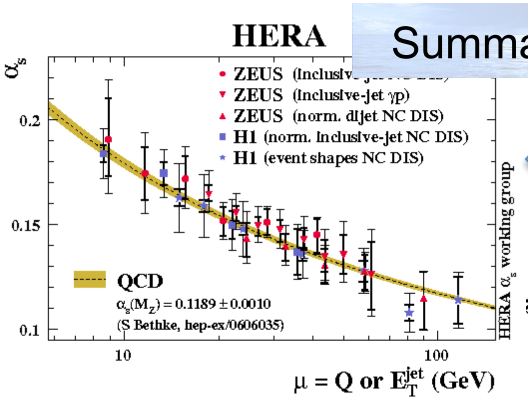


α_S and jets





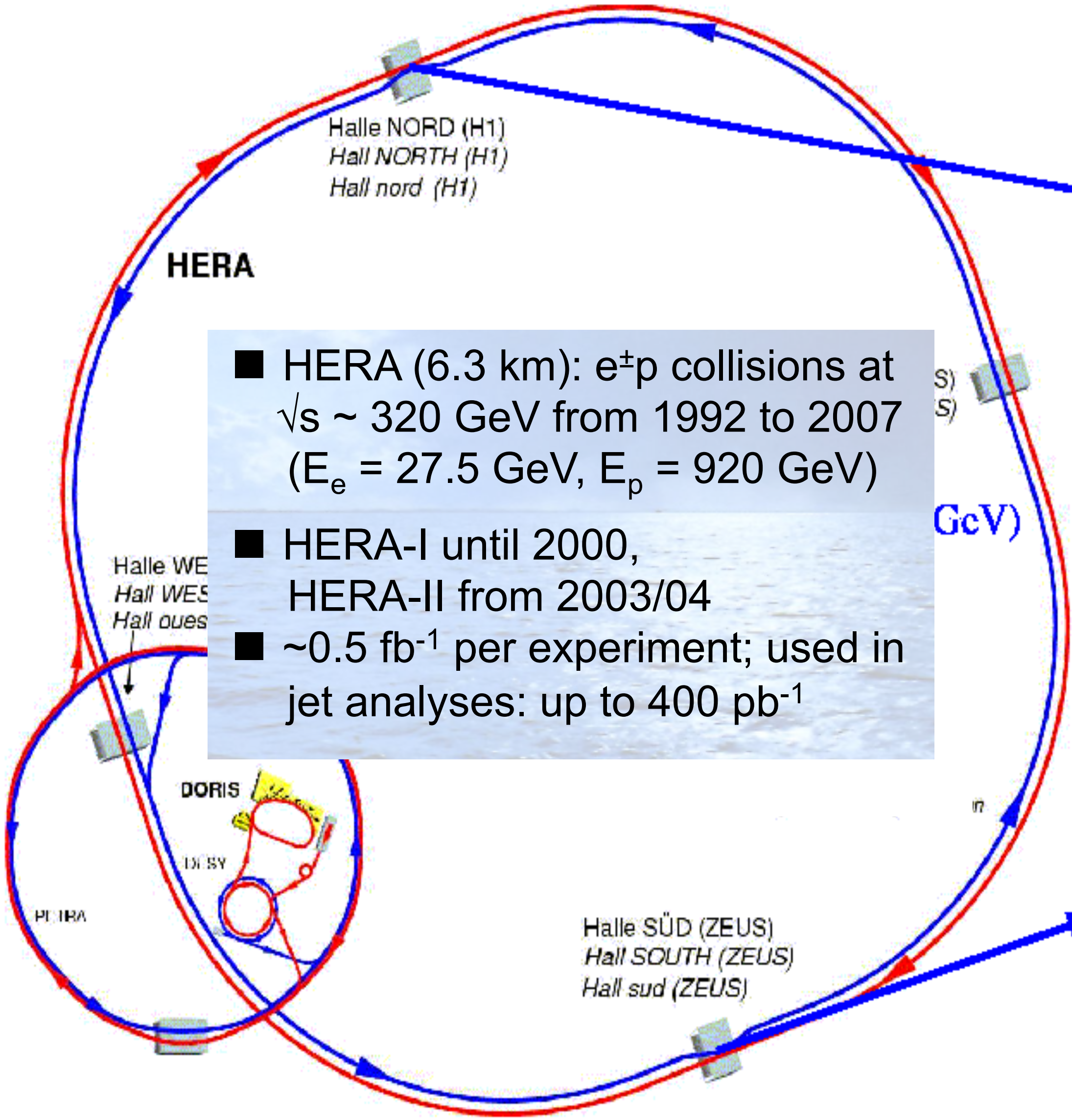
α_S and PDFs



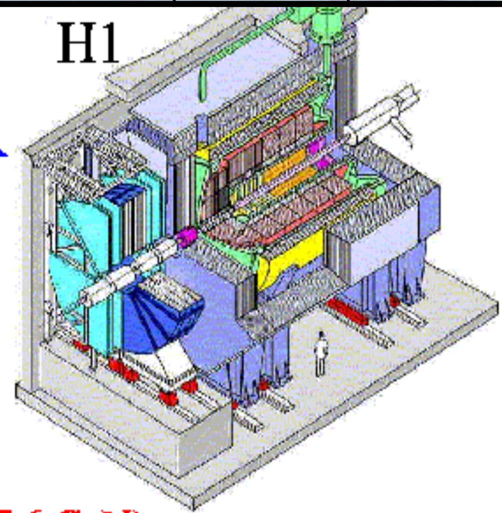
Summary

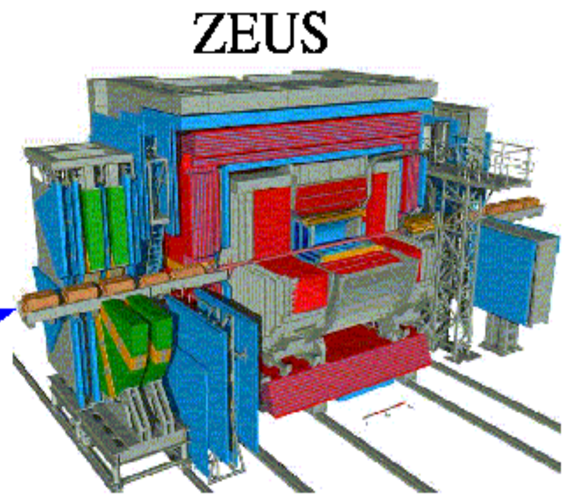
HERA AT DESY

	E_p (GeV)	HERA (pb^{-1})	ZEUS (pb^{-1})
HERA-I	820 / 920	193	143
HERA-II	920	562	407
LER/MER	460 / 575	16 / 9	13 / 8



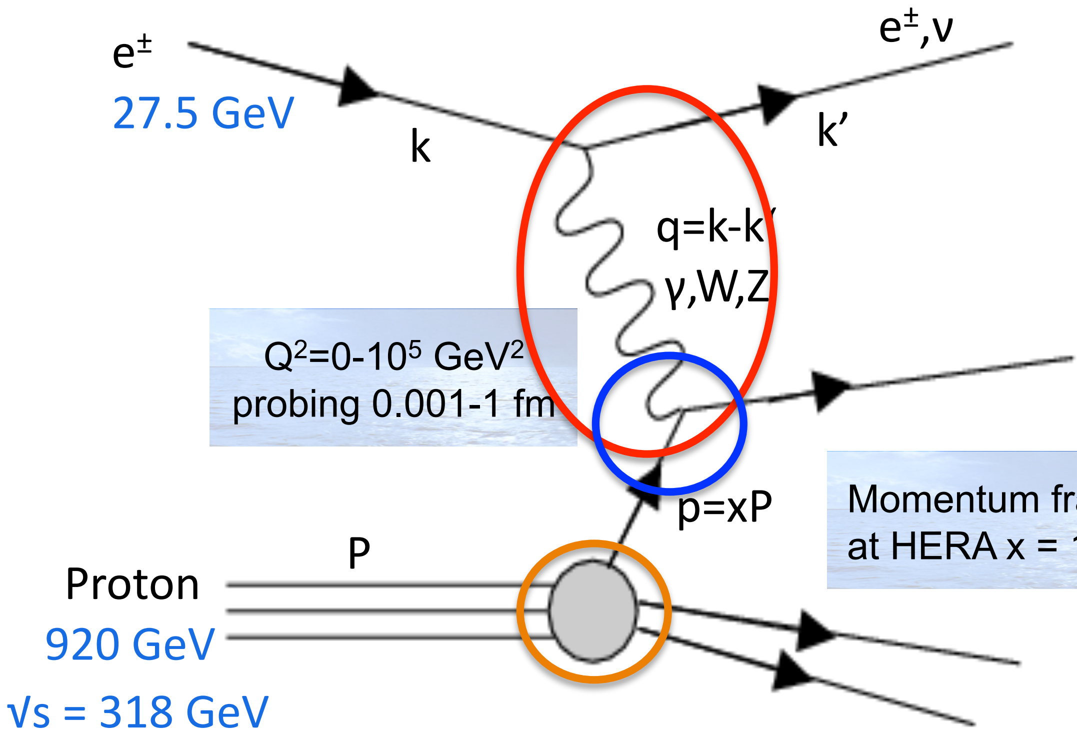
- HERA (6.3 km): e±p collisions at $\sqrt{s}$ ~ 320 GeV from 1992 to 2007 (E_e = 27.5 GeV, E_p = 920 GeV)
- HERA-I until 2000, HERA-II from 2003/04
- ~0.5 fb^{-1} per experiment; used in jet analyses: up to 400 pb^{-1}





ep PHYSICS AT HERA

The electron as probe for the proton structure



Momentum fraction x at HERA x = 10^{-6} – 1.

- Resolution Q^2:

$$Q^2 = -q^2 = -(k-k')^2 \propto 1/\lambda^2$$

- Inelasticity in p rest frame y:

$$y = qp/kp = 1 - E'_{el}/E_{el}$$

- momentum fraction x:

$$x = Q^2/(2pq)$$

$$Q^2 = xys$$

Cross section contains **electroweak** and QCD elements (**hard scattering at higher orders**, **PDFs $f_i(x,Q^2)$**).

Kinematics from electron, HFS or electron/HFS angles (`DA').

Distinguish neutral- and charged current (γ/Z vs W exchange).

Distinguish PHP (Q^2 ~ 0) and DIS.

ep PHYSICS AT HERA

- NC e±p DIS cross section:

$$\frac{d^2\sigma^{\pm}_{NC}}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[Y_+F_2 \mp Y_-xF_3 - y^2F_L\right]$$

- Extraction: reduced Xsection:

$$\sigma_r(x,Q^2) = \frac{1}{Y_+}\frac{d^2\sigma^{\pm}_{NC}}{dxdQ^2}\frac{xQ^4}{2\pi\alpha^2}$$
$$= F_2(x,Q^2)(1+\Delta)$$

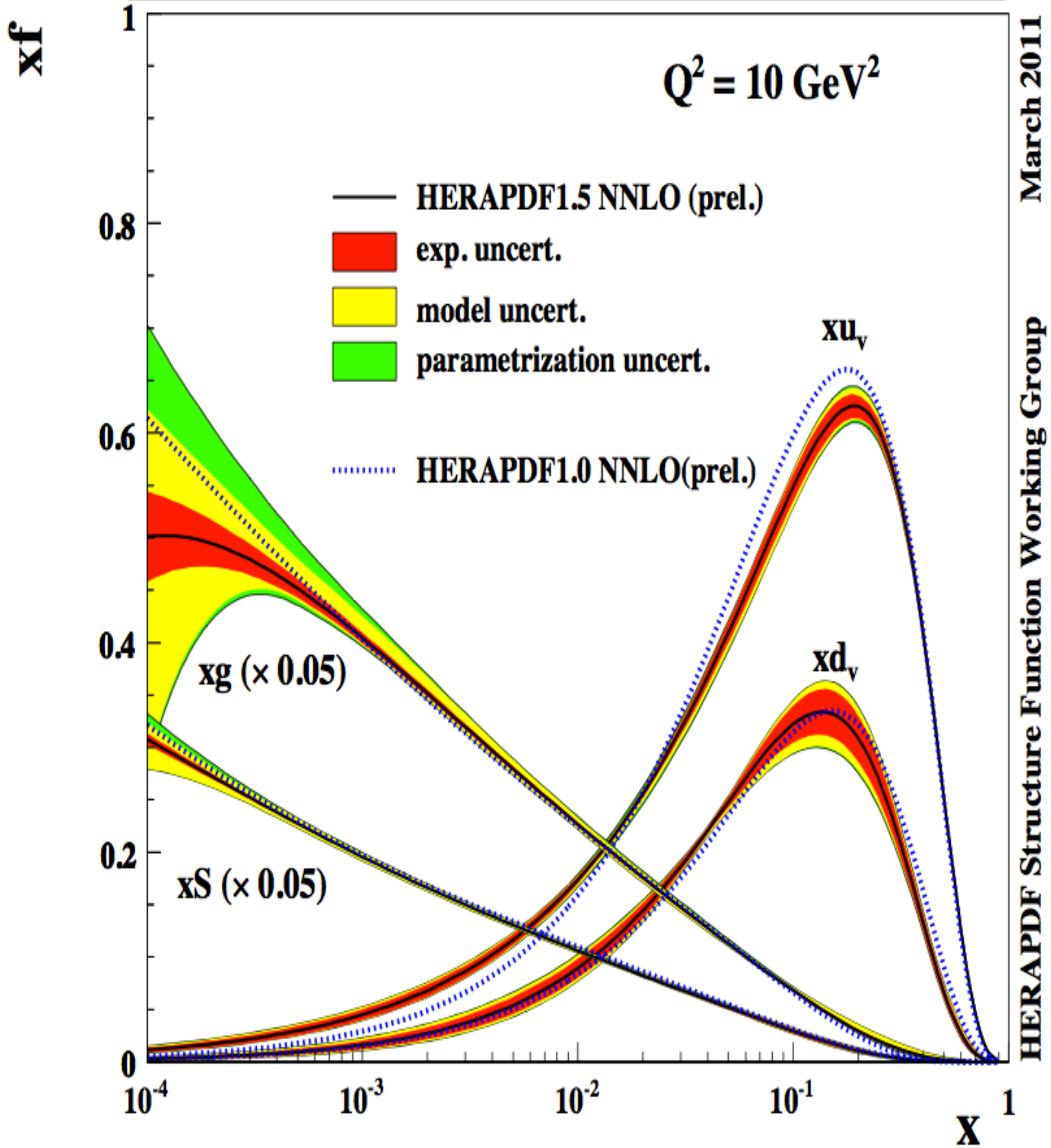
- Next: use structure function F_2:

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

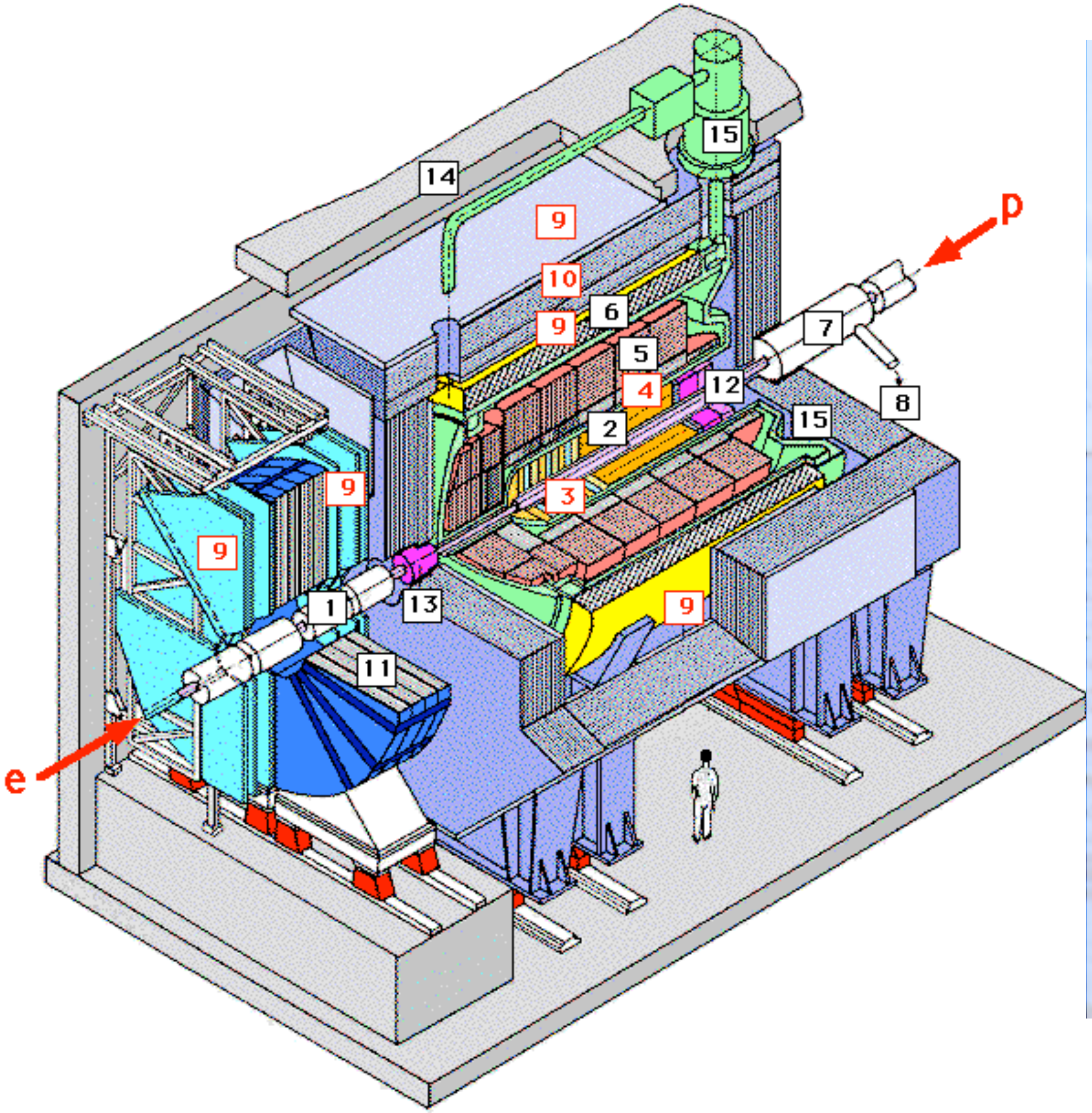
- … to extract PDFs q,g using DGLAP evolution equations!

$$\frac{dq(x,Q^2)}{d\ln Q^2} \propto \alpha_S \cdot g(x,Q^2) - \alpha_S \cdot q(x,Q^2)$$

- NLO and NNLO HERA analyses!



THE EXPERIMENTS: H1



- Asymmetric structure !
- Tracking system (silicon detectors, two large drift chambers (|η|<1.5):

$$\sigma(p_T)/p_T = 0.006 \cdot p_T/GeV \oplus 0.02$$

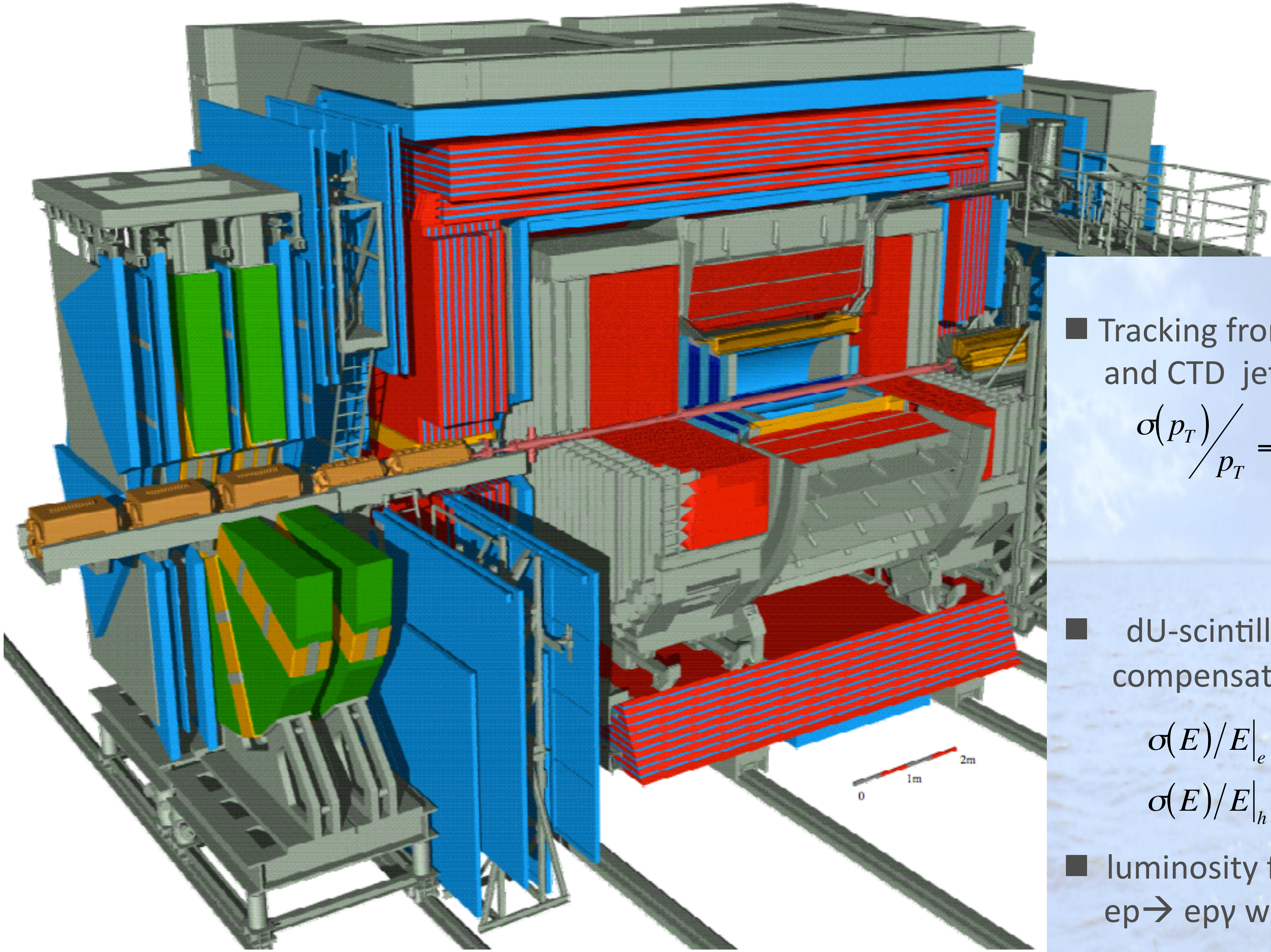
- LAr calorimeter with 45000 cells (sampling, lead / steel)

$$\sigma(E)/E|_h = 0.50/\sqrt{E[GeV]} \oplus 0.02$$

$$\sigma(E)/E|_{e^\pm} = 0.11/\sqrt{E[GeV]} \oplus 0.01$$

- Large SC coil (1.16 T)
- Backward SpaCal calorimeter (low-Q^2 electrons!)
- Hadr energy scale known to 1%

THE EXPERIMENTS: ZEUS



- Tracking from silicon (MVD) and CTD jet drift chamber:

$$\sigma(p_T)/p_T = 0.058 \cdot p_T/GeV \oplus 0.0065 \oplus 0.0014\, GeV/p_T$$

- dU-scintillator calorimeter, compensating, 12k cells:

$$\sigma(E)/E\big|_e = 0.18/\sqrt{E[GeV]}$$

$$\sigma(E)/E\big|_h = 0.35/\sqrt{E[GeV]}$$

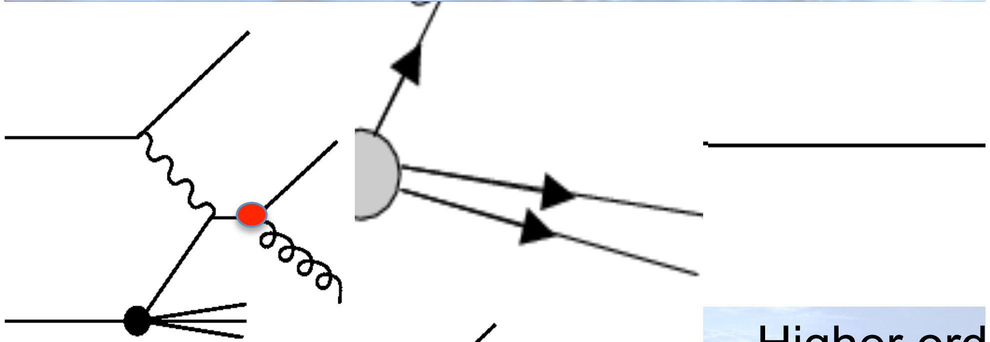
- luminosity from Bethe-Heitler: ep→ epγ with 2.3% precision.

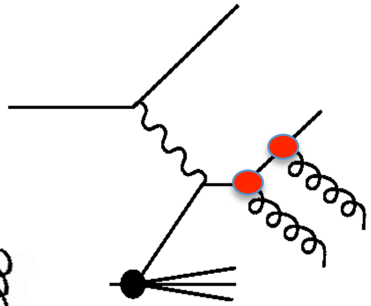
QCD INTERACTIONS AND JETS

Factorisation and series expansion in powers of strong coupling ➔ PDFs, pQCD – and α_S !

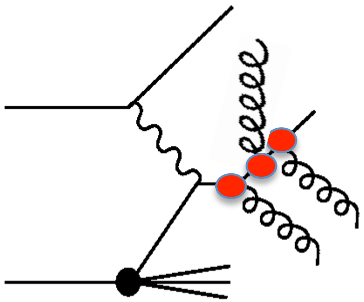
$$\sigma = f_{i/p} \otimes \hat{\sigma}_i$$
$$= \sum_n \alpha_S^n(\mu_R) \cdot \sum_{i=q,\bar{q},g} \int dx\, f_{i/p}(x,\mu_F) \cdot C_i^n(x,\mu$$

Ratio of n+1-jet to n-jet xsection ~α_S (modulo phase space, selection …)

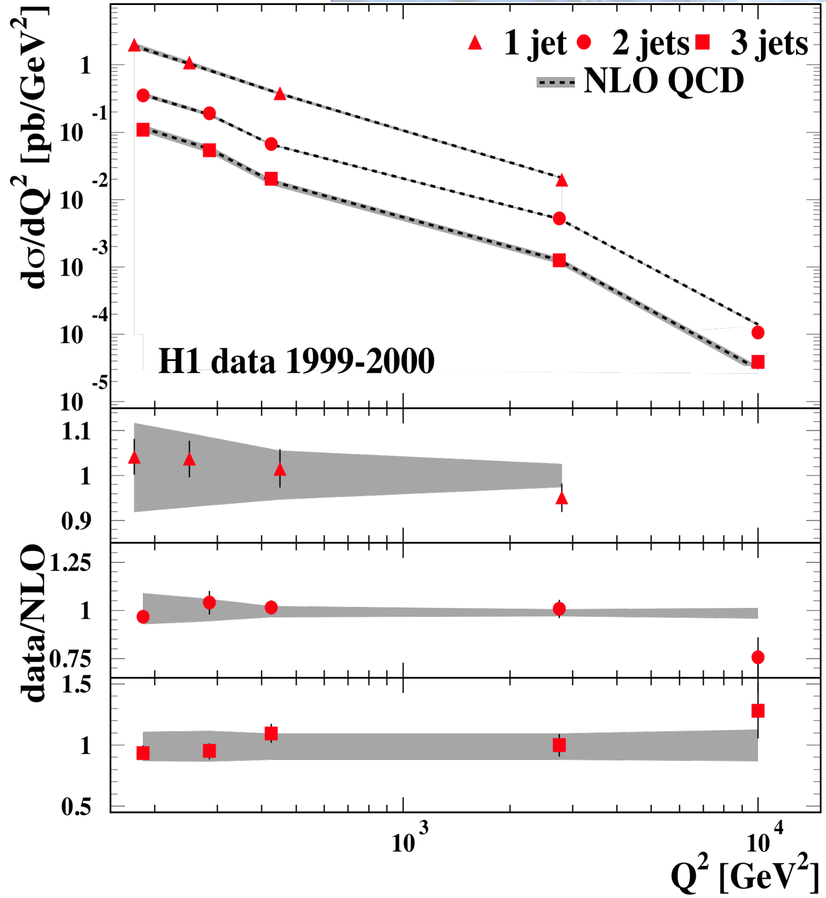




Higher ord
→ α_S !



Jets at HERA: restricted to NLO for 1,2,3-jet case!



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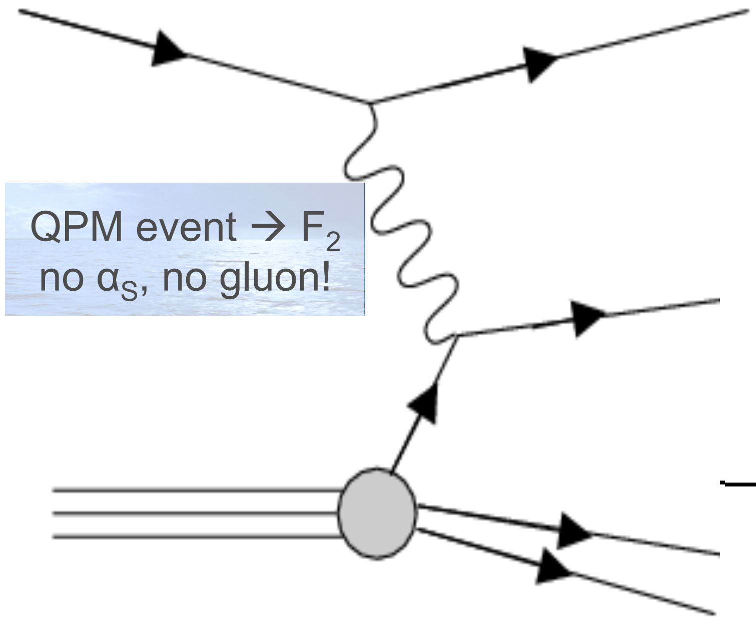

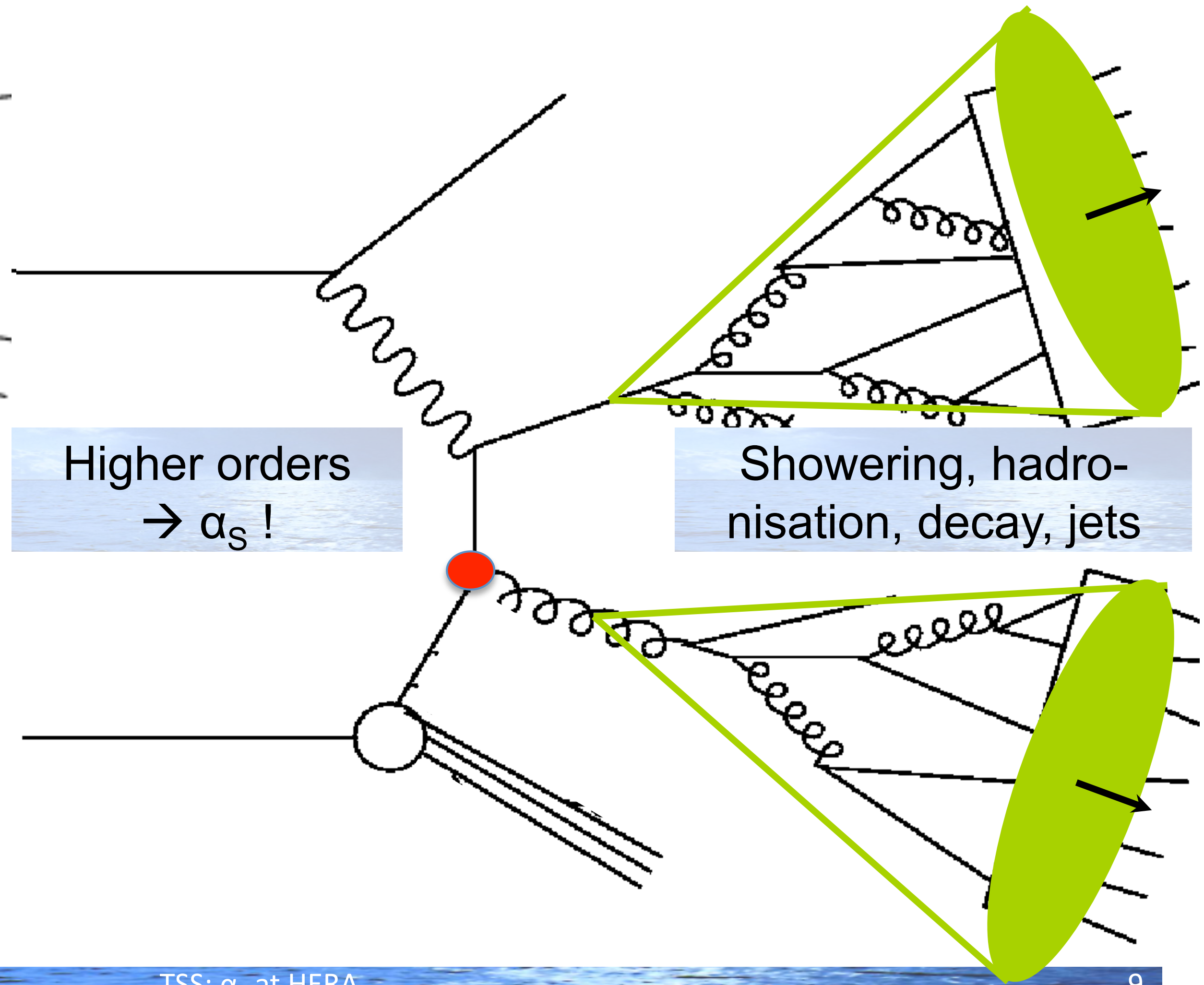

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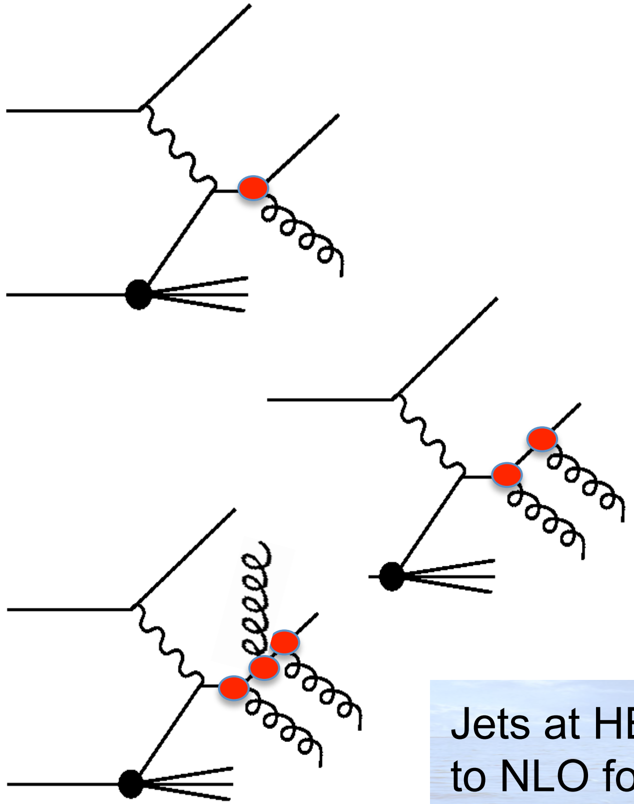

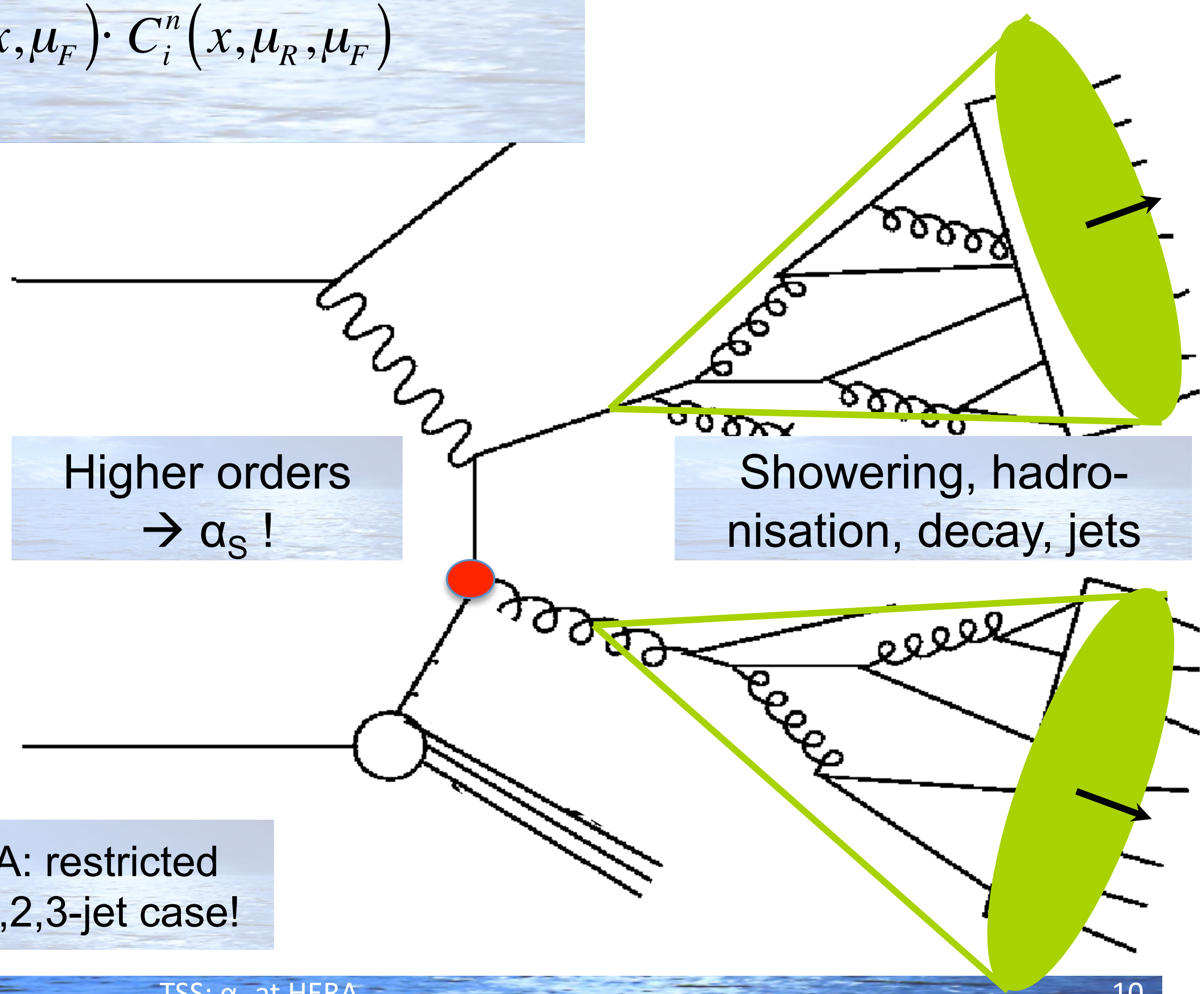

Higher orders
→ α_S !

Showering, hadro-
nisation, decay, jets

Jets at HERA: restricted
to NLO for 1,2,3-jet case!

QCD INTERACTIONS AND JETS

Factorisation and series expansion in powers of strong coupling ➔ PDFs, pQCD – and α_S !

$$\sigma = f_{i/p} \otimes \hat{\sigma}_i$$

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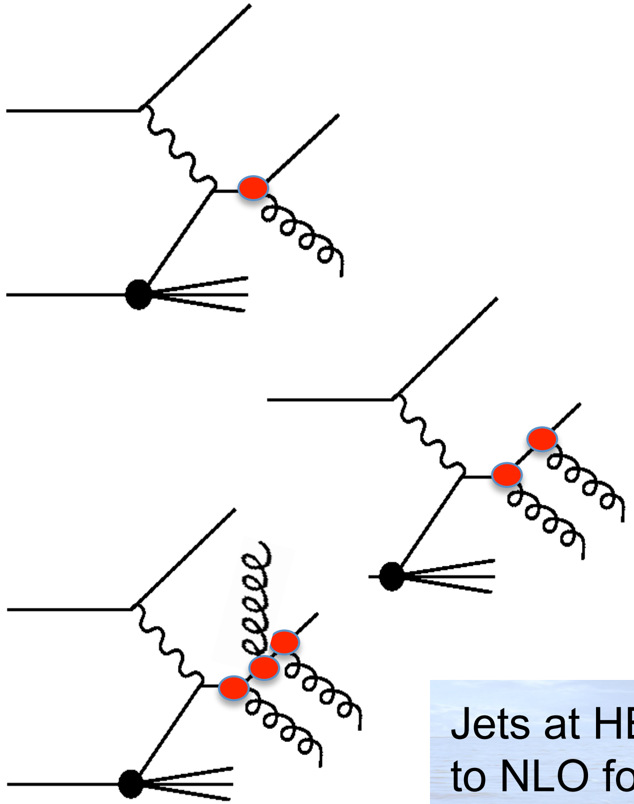
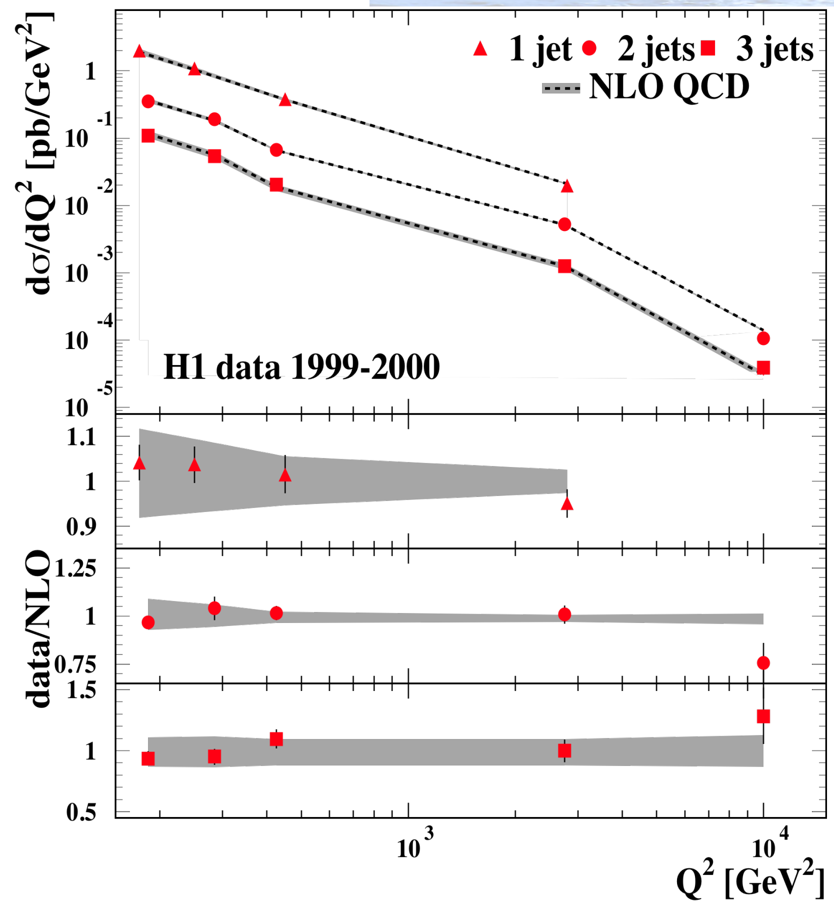




Jets at HERA: restricted to NLO for 1,2,3-jet case!

α_S: THEORY BACKGROUND

Coupling follows renormalisation group equation:

$$Q^2 \frac{\partial \alpha_s(Q^2)}{\partial Q^2} = \beta(\alpha_s(Q^2)).$$

$$\beta_0 = \frac{33 - 2N_f}{12\pi},$$
$$\beta_1 = \frac{153 - 19N_f}{24\pi^2},$$
$$\beta_2 = \frac{77139 - 15099N_f + 325N_f^2}{3456\pi^3},$$
$$\beta_3 \approx \frac{29243 - 6946.3N_f + 405.089N_f^2 + 1.49931N_f^3}{256\pi^4}$$

Pert. expansion up to 4-loop level of β function:

$$\beta(\alpha_s(Q^2)) = -\beta_0\alpha_s^2(Q^2) - \beta_1\alpha_s^3(Q^2) - \beta_2\alpha_s^4(Q^2) - \beta_3\alpha_s^5(Q^2) + \mathcal{O}(\alpha_s^6),$$

Coupling at 4-loops / at 1-loop:

$$\alpha_s(Q^2) = \frac{\alpha_s(\mu^2)}{1 + \alpha_s(\mu^2)\beta_0 \ln \frac{Q^2}{\mu^2}},$$

$$\alpha_s(Q^2) = \frac{1}{\beta_0 L} - \frac{1}{\beta_0^3 L^2}\beta_1 \ln L + \frac{1}{\beta_0^3 L^3}\left(\frac{\beta_1^2}{\beta_0^2}(\ln^2 L - \ln L - 1) + \frac{\beta_2}{\beta_0}\right) + \frac{1}{\beta_0^4 L^4}\left(\frac{\beta_1^3}{\beta_0^3}\left(-\ln^3 L + \frac{5}{2}\ln^2 L + 2\ln L - \frac{1}{2}\right)\right) - \frac{1}{\beta_0^4 L^4}\left(3\frac{\beta_1\beta_2}{\beta_0^2}\ln L + \frac{\beta_3}{2\beta_0}\right), \qquad L = \ln(Q^2/\Lambda_{\overline{MS}}^2).$$

For pQCD NLO calculations for jet physics at HERA: 2-loop calculation of α_S ! `Missing higher orders' mostly dominating uncertainty !!!

JET PHYSICS AT HERA

- Default algorithm: k_T algorithm (longitudinally invariant incl. mode) on CAL objects or CAL+track info (→ improved resolution)
- lately also use of anti-k_T and SISCone (default at LHC)
- DIS: mostly in Breit frame → photon and parton collinear → requirement of (high) E_T selects QCD events and ensures applicability of pQCD.
- Theory comparison: NLO pQCD predictions
- Analysis of 1,2,3-jet distributions (Q^2, p_T, η, …), jet shapes, jet substructure …

PHP:

- $Q^2 \sim 0$ (no electron!)
- Cuts on y, hadronic CMS energy $W_{\gamma p}$
- $E_{Tjet} > 14$ GeV

low Q^2:

- $5/10 < Q^2 < 100$ GeV^2
- $0.2 < y < 0.6$
- $E_{Tjet} > 5/8$ GeV
- High statistics, but large theory errors

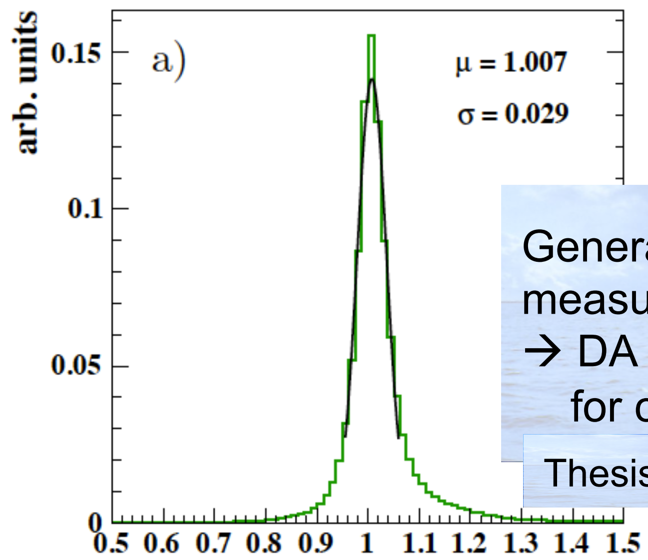
high Q^2:

- $Q^2 > 125$ GeV^2
- $0.2 < y < 0.6$ or $|\cos\gamma_{had}| < 0.65$
- $E_{Tjet} > 8$ GeV
- Small theo. errors.

CALIBRATION, ENERGY SCALES

EM calibration `simple':

- Energy scale from test beam data
- Monitoring over time (ZEUS: constant Uranium noise signal! → deviations from new dead material, LAr purity, noise/pedestal fluctuations
- Calibration derived from ratio of double-angle energy to scattered electron measurement
- absolute scale to 1%, data-MC agreement to 0.5% or so.



Generated over DA-measured electron E
→ DA energy suited for calibration!

Thesis R. Kogler 2011

Hadronic calibration:

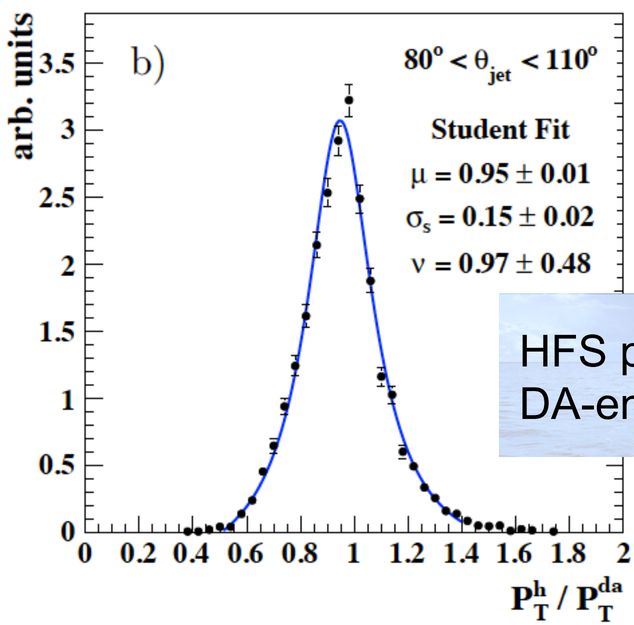
H1: Software reweighting → compensation.

ZEUS: Compensating calorimeter.

Absolute energy scale from balance of electron to hadronic final state or isolated jets (and ensuing jet energy corrections)

Result: 2% precision of absolute jet energy scale; 1% scale uncertainty! Typical effects on Xsections 2-5(10)% (dominating exp. error!)

Jet energy resolution ~75%/sqrt(E) (H1).



HFS p_T over DA-energy

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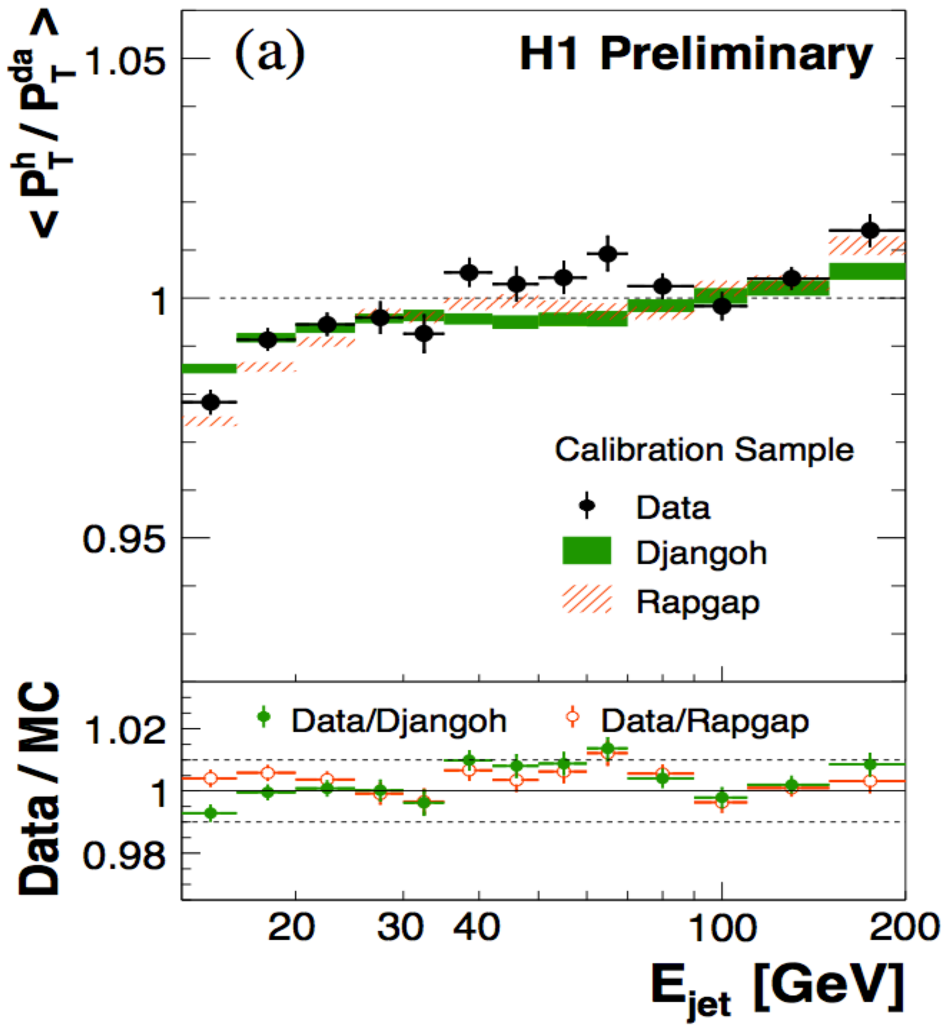
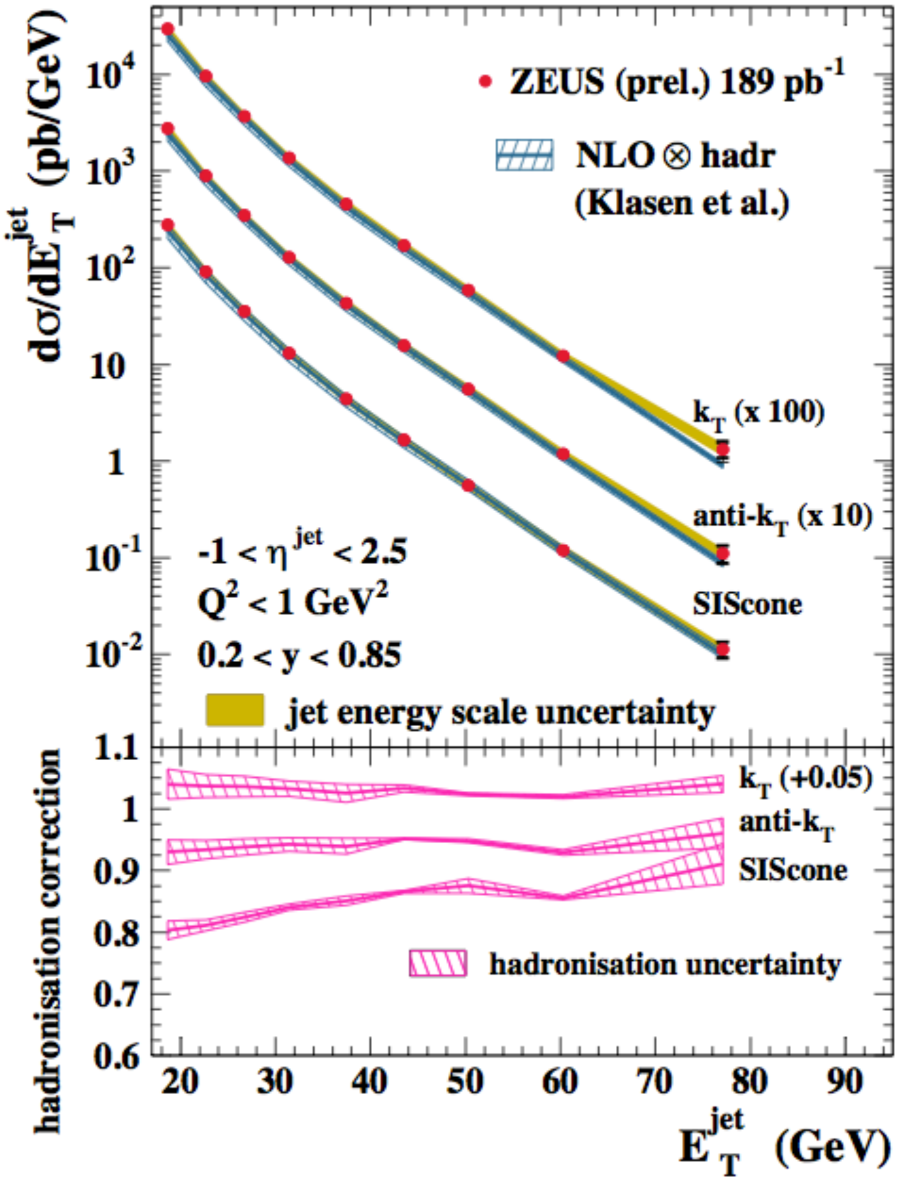


α_S FROM JETS: CROSS SECTIONS PHP



PHP inclusive jet cross sections from 21 to 71 GeV in 189 pb^{-1} of data.

First PHP jet analysis to use anti-k_T and SISCone (and k_T) jet algorithms!

Extraction of strong coupling from E_T spectra of jets (technicalities next slide):

$$\alpha_S(M_Z)\Big|_{k_T} = 0.1208^{+0.0024}_{-0.0023}(\exp)^{+0.0044}_{-0.0033}(\text{theo})$$

$$\alpha_S(M_Z)\Big|_{anti-k_T} = 0.1200^{+0.0024}_{-0.0023}(\exp)^{+0.0043}_{-0.0032}(\text{theo})$$

$$\alpha_S(M_Z)\Big|_{SISCone} = 0.1199^{+0.0022}_{-0.0022}(\exp)^{+0.0047}_{-0.0042}(\text{theo})$$

Exp. uncertainties dominated by jet energy scale (±1.7% on coupling); theory limited by missing higher orders (2.5%).

Note: Newer prel. measurement with full HERA I+II statistics available for k_T !

α_S FROM JETS: FITTING METHODS 1

pQCD cross sections depend on α_S via partonic cross sections and PDFs:

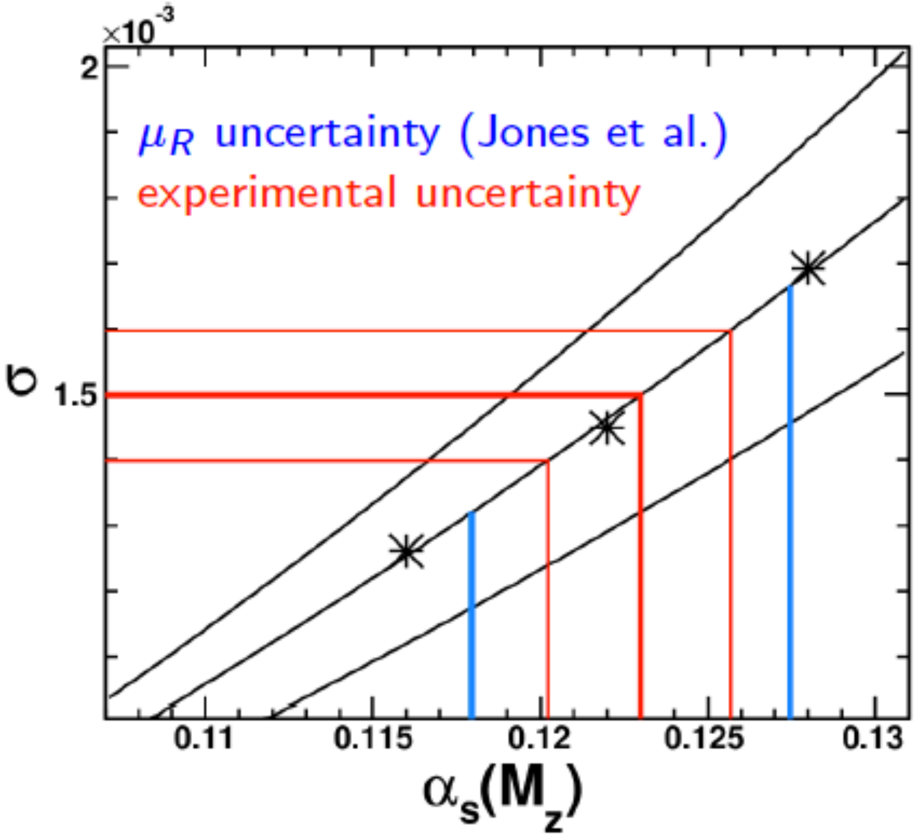
$$\sigma = \sum_{i=q,\bar{q},g} f_{i/p} \otimes \hat{\sigma}_i$$

Perform NLO calculations with different PDFs assuming different α_S values (e.g. CTEQ6AB).

Parametrise α_S dependence of Xsection dσ/dA in bin i by:

$$d\sigma/dA\Big|_i = C_1 \cdot \alpha_S^1(M_Z) + C_2 \cdot \alpha_S^2(M_Z)$$

Map measured dσ/dA to parametrisation.



Complete coupling dependence of PDFs and partonic Xsection preserved.

Estimation of scale uncertainties a la Jones et al.

Applicable to single data points or combination of several points.

Derivation of running by evolution to $\alpha_S(\mu)$ for scale μ.

α_S FROM JETS: FITTING METHODS

Hessian method as employed by H1: systematics as penalty terms:

correlated version of $\sum$(difference/error)²

$$\chi^2 = \vec{V}^T \cdot M^{-1} \cdot \vec{V} + \sum_k \varepsilon_k^2$$

penalty term for fitted systematics
"Hessian" method

$$M = M^{\mathrm{stat.}} + M^{\mathrm{uncor.}}$$

correlated for some bins

uncorrelated systematics

Thanks to A. Baghdasaryan!

$$V_i = \sigma_i^{\mathrm{exp.}} - \sigma_i^{\mathrm{theo.}}(1 - \sum_k \Delta_{ik}\varepsilon_k)$$

bin #

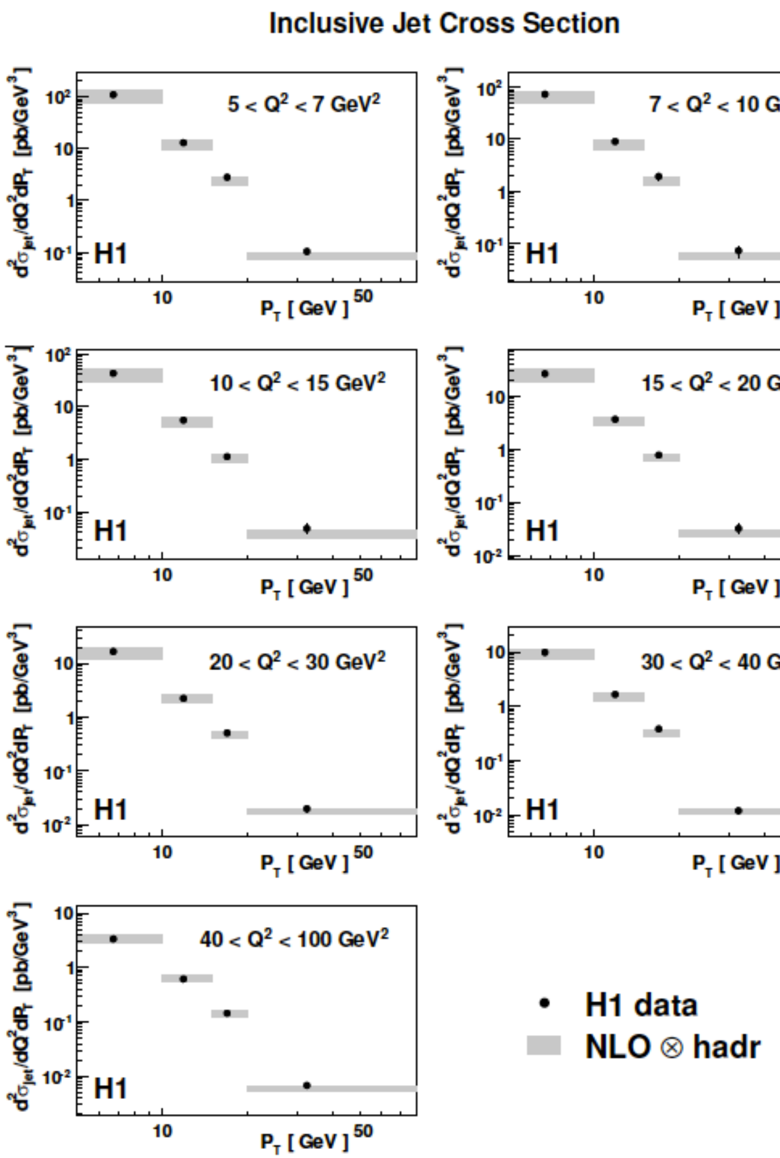
correlated systematical error #k

parameter in fit, pull
"Hessian" method

Usable for single or many observables / bins.

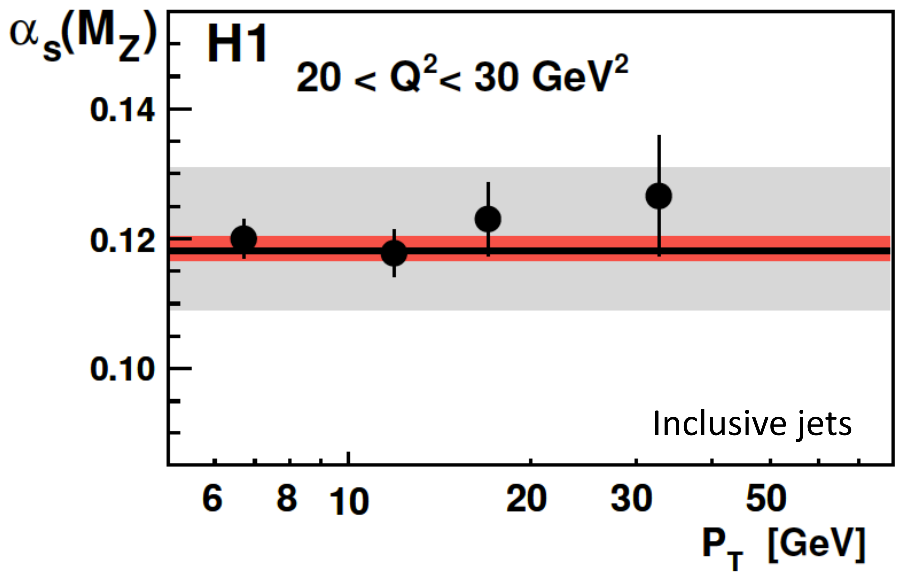
Experimental uncertainty derived at $\chi^2 = \chi_{min}^2 + 1$.

α_S FROM JETS: CROSS SECTIONS DIS



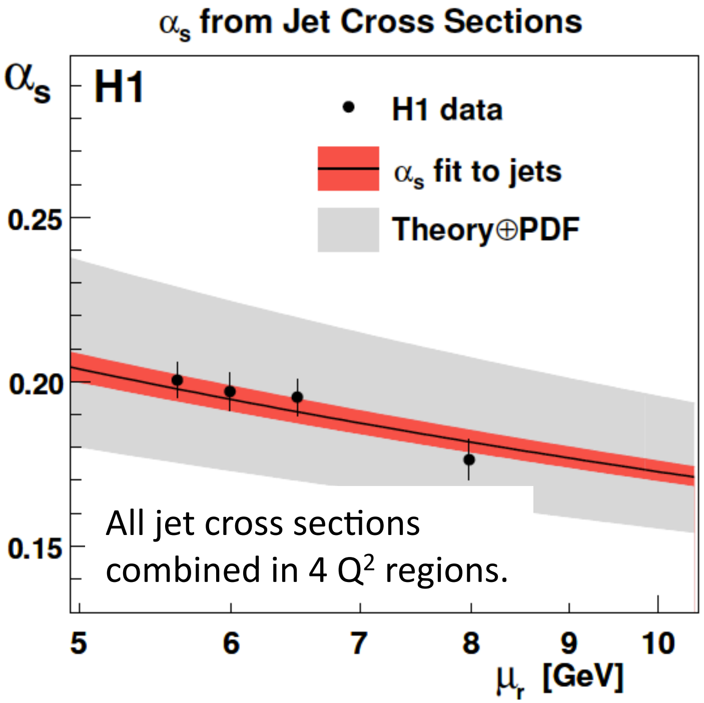
Low-Q^2 domain (DESY-09-162):

- 5-100 $GeV^{2,}$ $0.2 < y < 0.7$
- 44 pb^{-1} (1999/2000)
- 1/2/3 jets measured as fct of Q^2, p_T, ξ
- also 3/2-jet ratio → later



- Individual fits to all 61 data points.
- Combined fit to all data points from 1/2/3 jet events in one Q^2 region.
- Evolve $\alpha_S(M_Z)$ values to scale μ_R.

α_S FROM JETS: CROSS SECTIONS DIS



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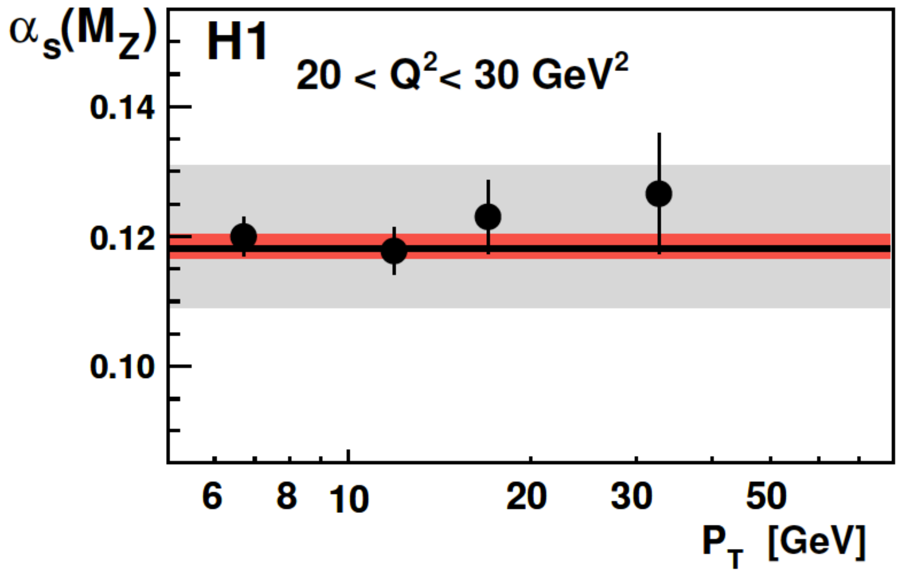

- Combined fit to all 61 data points:

$$\alpha_S(M_Z) = 0.1160$$
$$\pm 0.0014(\text{exp}) \,^{+0.0093}_{-0.0077}(\text{theo})$$
$$\pm 0.0016(\text{PDF})$$

- Dominated by μ_R error (low Q^2!)

- Individual fits to all 61 data points.
- Combined fit to all data points from 1+2+3 jet events in one Q^2 region.
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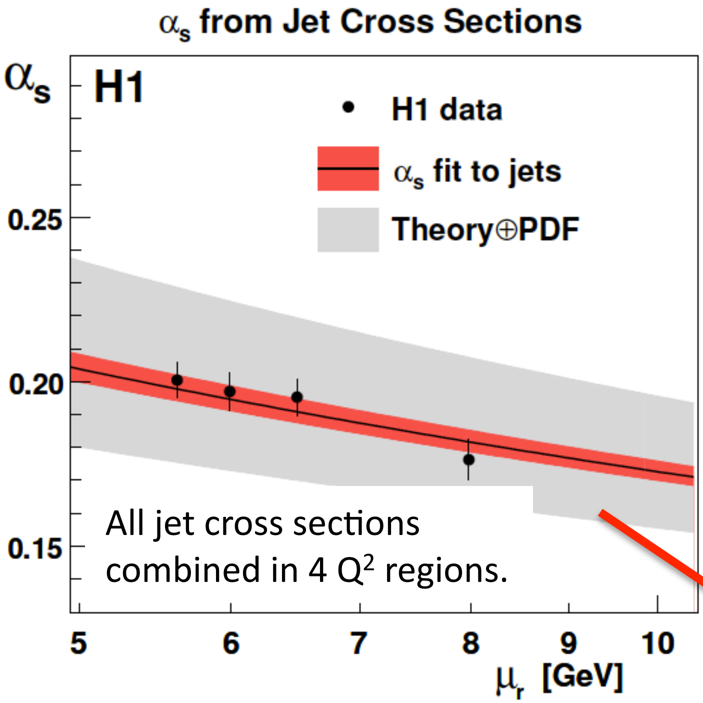
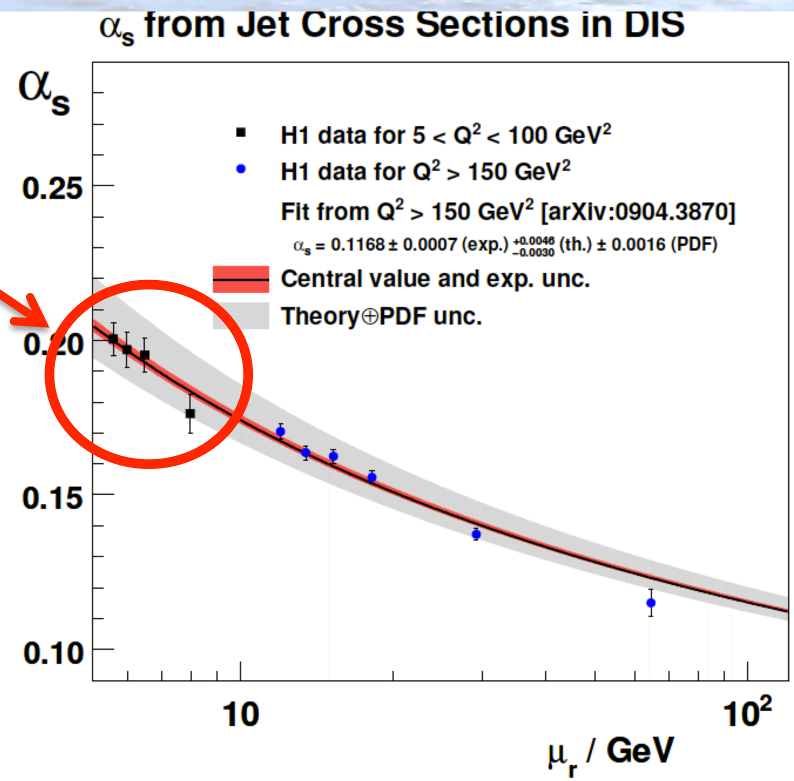
α_S FROM JETS: CROSS SECTIONS DIS



Similar measurement at high Q^2:

(1/2/3 jets and combination of all data points in 6 Q^2 regions) (DESY-09-032):

- Demonstration of running of coupling over wide range from one experiment:
- Extrapolation of high-Q^2 α_S value to low Q^2 region → excellent agreement!



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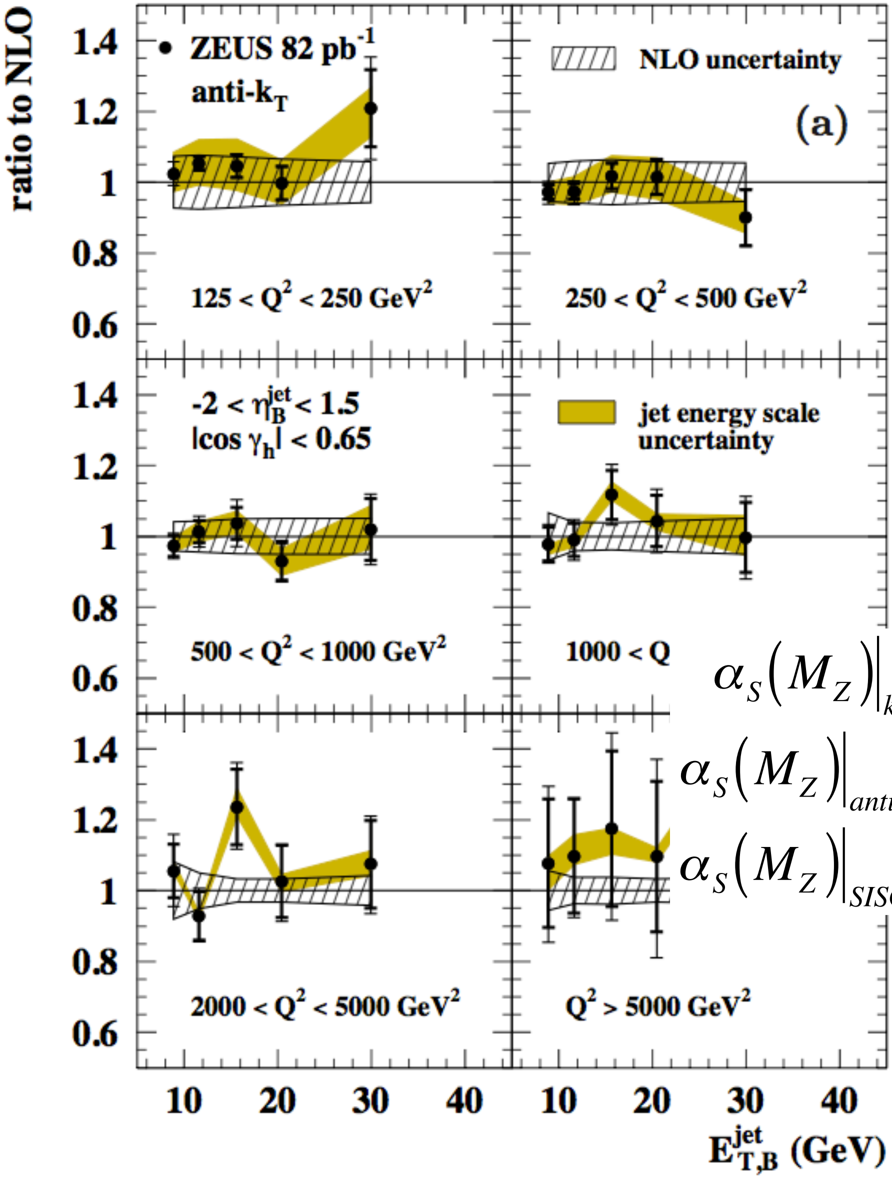


High Q^2 values: (DESY-10-034 and DESY-06-241):

- 82 pb^{-1} from 1998-2000
- k_T, anti-k_T, SISCone jet algos
- shown here: anti-k_T and description by NLO

Fit a la ZEUS to $d\sigma/dQ^2$ distribution for Q^2 > 500 GeV^2 (smallest errors).

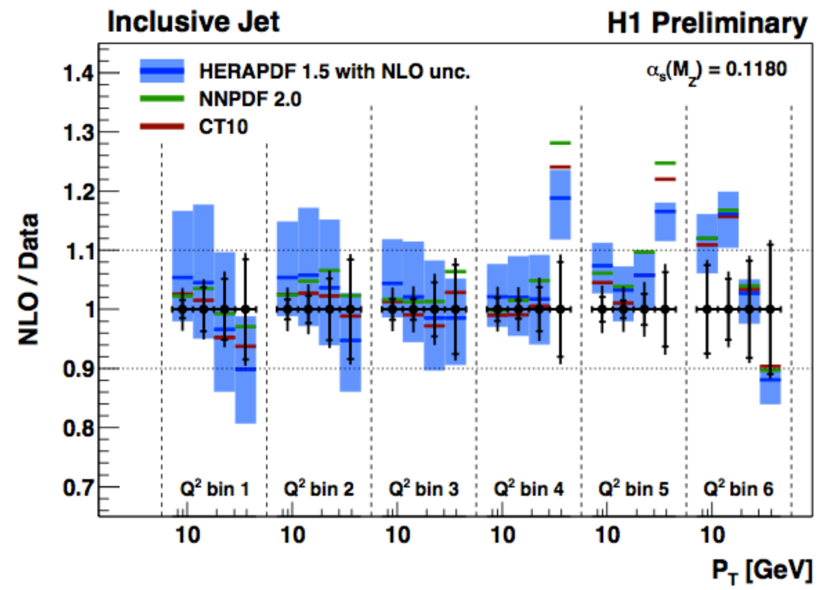
$$\alpha_S(M_Z)\big|_{k_T} = 0.1207 \pm 0.0014(\text{stat})^{+0.0035}_{-0.0033}(\text{exp})^{+0.0022}_{-0.0023}(\text{theo})$$

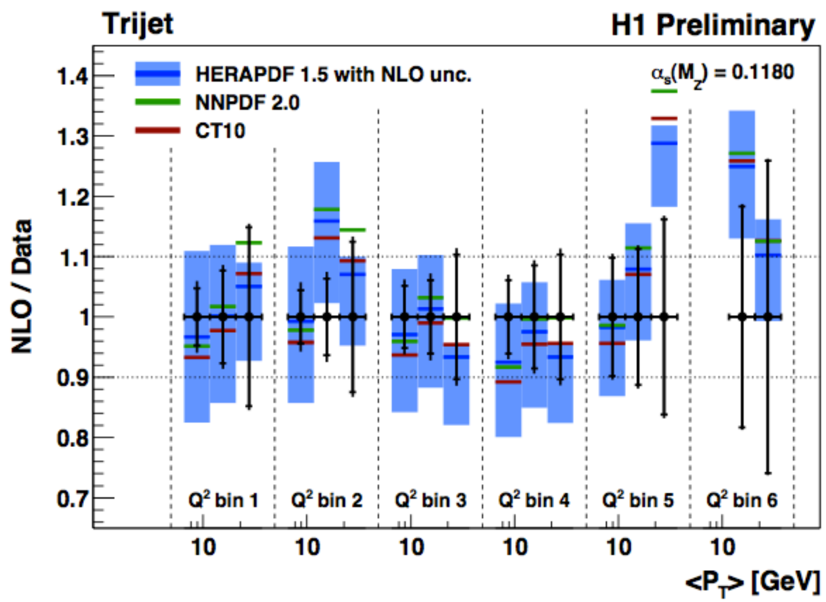
$$\alpha_S(M_Z)\big|_{anti-k_T} = 0.1188 \pm 0.0014(\text{stat})^{+0.0033}_{-0.0032}(\text{exp})^{+0.0022}_{-0.0022}(\text{theo})$$

$$\alpha_S(M_Z)\big|_{SISCone} = 0.1186 \pm 0.0013(\text{stat})^{+0.0034}_{-0.0032}(\text{exp})^{+0.0025}_{-0.0025}(\text{theo})$$

k_T measurement updated with HERA-II data of 300 pb^{-1} → similar α_S.

α_S FROM JETS: CROSS SECTIONS DIS





Also high Q^2: H1prelim-11-032:

- Again 1/2/3-jet cross sections, 351 pb^{-1}! (first time trijets double-differentially!)
- Improved calibration – scale error 1%, larger η range (-1 – 2.5) than before!
- Good NLO description of all measurements, consistent α_S values from all points.

α_S FROM JETS: CROSS SECTIONS DIS

- Fit to double-diff 1/2/3-jet p_T distributions
- Scale / theory uncertainties typically factor 2 larger than exp+PDF.
- 3-jet extraction of coupling has smallest exp. uncertainty – NLO $C_2\alpha_S^2+C_3\alpha_S^3$!!! → sensitive to slope (not normalisation).
- Note: experimental uncertainties slightly increased wrt to previous high-Q^2 analysis (DESY-09-132): There normalised Xsections were used → cancellation of uncertainties.

$$\alpha_S(M_Z)\big|_{1j} = 0.1190 \pm 0.0021(\text{exp}) \pm 0.0020(\text{pdf})^{+0.0050}_{-0.0056}(\text{th})$$
$$\alpha_S(M_Z)\big|_{2j} = 0.1146 \pm 0.0022(\text{exp}) \pm 0.0021(\text{pdf})^{+0.0044}_{-0.0045}(\text{th})$$
$$\alpha_S(M_Z)\big|_{3j} = 0.1196 \pm 0.0016(\text{exp}) \pm 0.0010(\text{pdf})^{+0.0055}_{-0.0039}(\text{th})$$

Also high Q^2: H1prelim-11-032:

- Again 1/2/3-jet cross sections, 351 pb^{-1}! (first time trijets double-differentially!)
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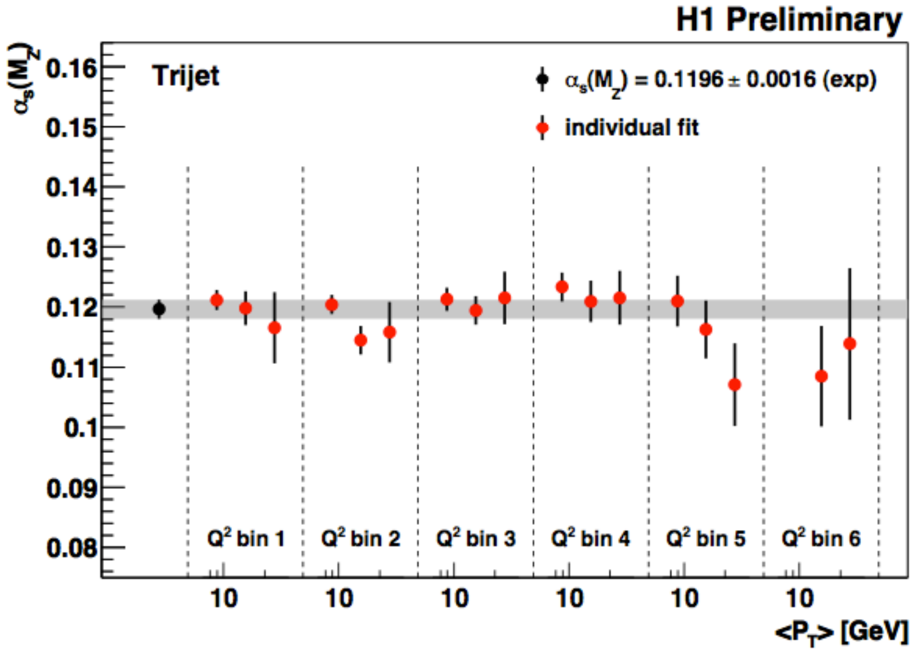
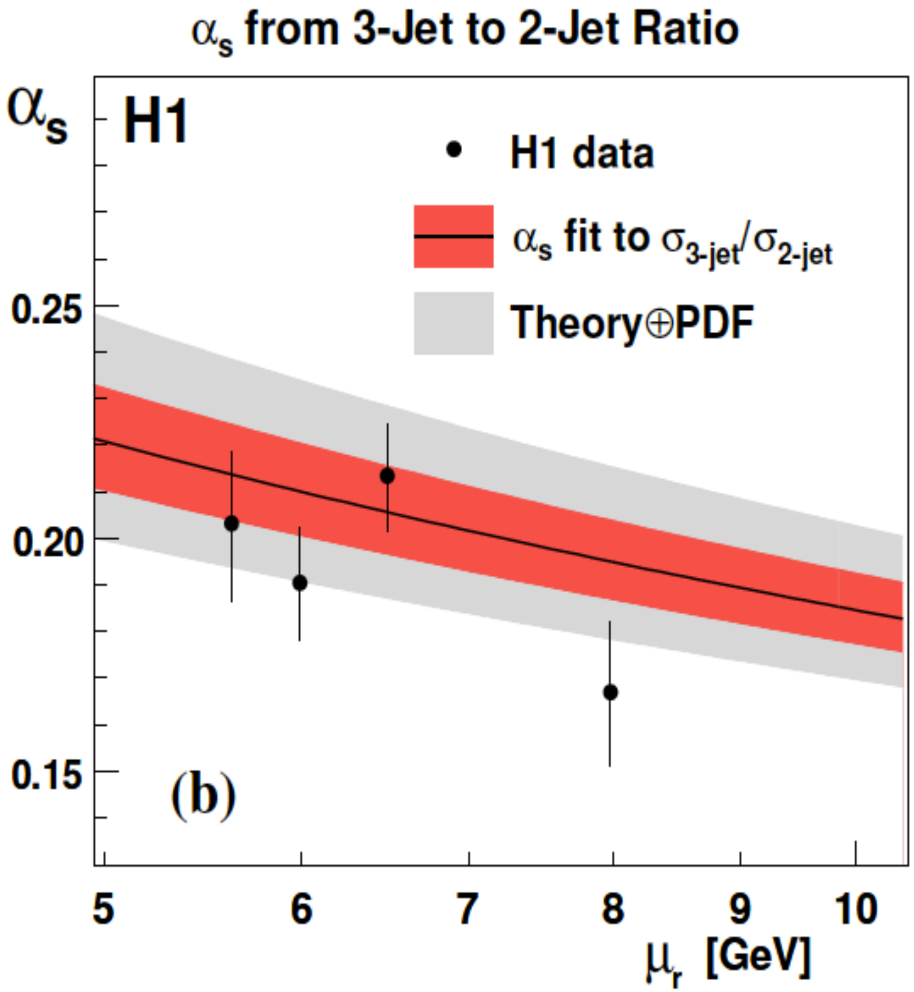


α_S FROM 3/2 JETS RATIO $R_{3/2}$



$$\alpha_S(M_Z) = 0.1215 \pm 0.0032(\text{exp})\ ^{+0.0066}_{-0.0058}(\text{theo}) \pm 0.0013(\text{PDF})$$

Features of Xsection ratio:

– Smaller sensitivity to coupling than in 3jet Xsection (only $O(\alpha_S)$)!
– Cancellation of some uncertainties (lumi, scales, PDFs …)
– Early try: ZEUS $10 < Q^2 < 5000$ GeV^2 in 82 pb^{-1} (DESY-05-019)

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

More recent: DESY-09-162:

– muti-jet measurement at low Q^2 already mentioned (less stats – 44pb^{-1}).
– Exp. error increased 3% wrt to combined fit to data points, theo down by 5%.

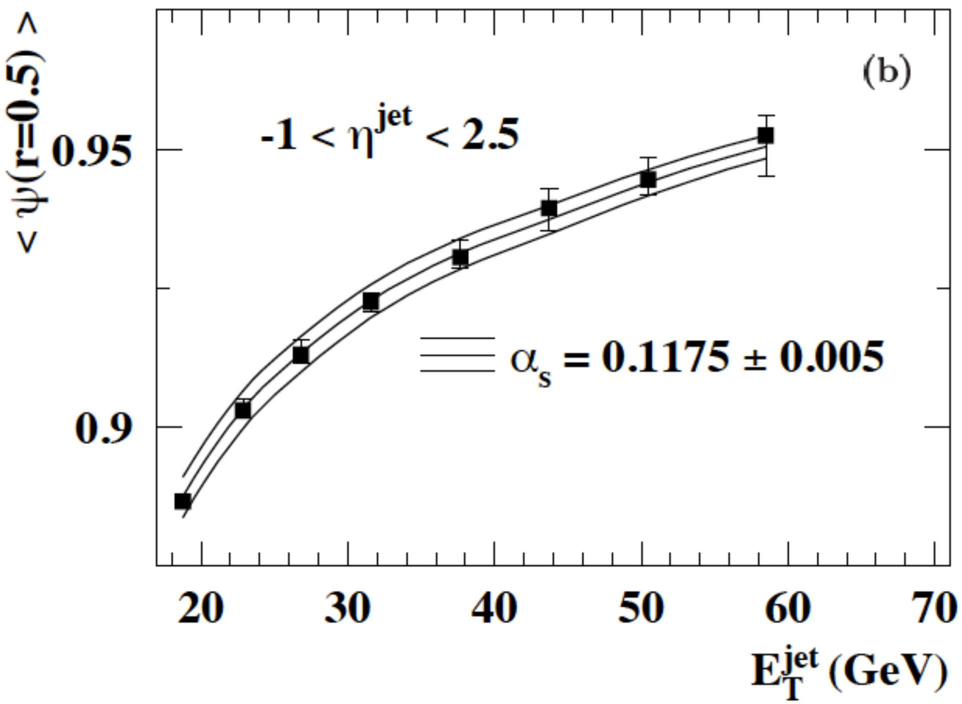
α_S FROM INTEGRATED JET SHAPE ψ

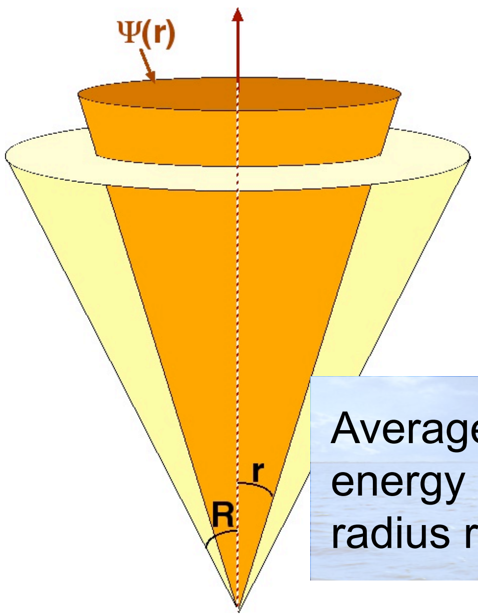
– Often used to study parton dynamics, fragmentation, q-g jet differences etc.

$$\langle\psi(r)\rangle = \frac{1}{N_{\text{jets}}}\sum_{\text{jets}}\frac{E_T(r)}{E_T^{\text{jet}}},$$

– Analysis: performed in PHP and DIS. Used for α_S: DIS with $Q^2 > 125\ \text{GeV}^2$ and k_T algorithm with $E_T > 13$ GeV.

$$[\langle\psi(r=0.5)\rangle(\alpha_s(M_Z))]_i = C_1^i + C_2^i\alpha_s(M_Z),$$





Average fractional jet energy inside cone of radius r

α_S FROM INTEGRATED JET SHAPE ψ

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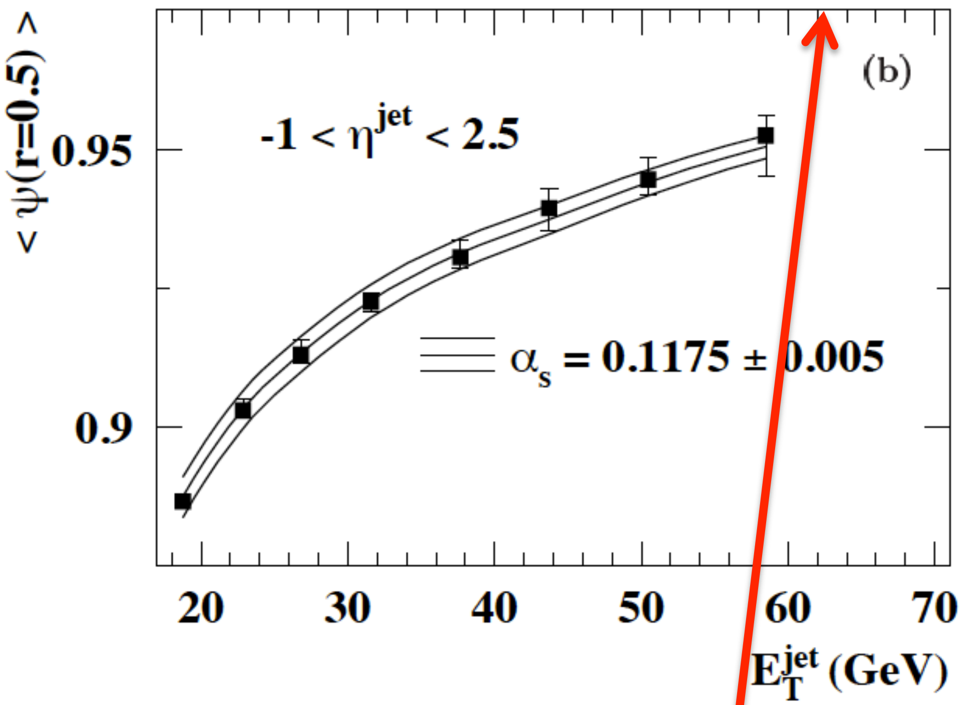
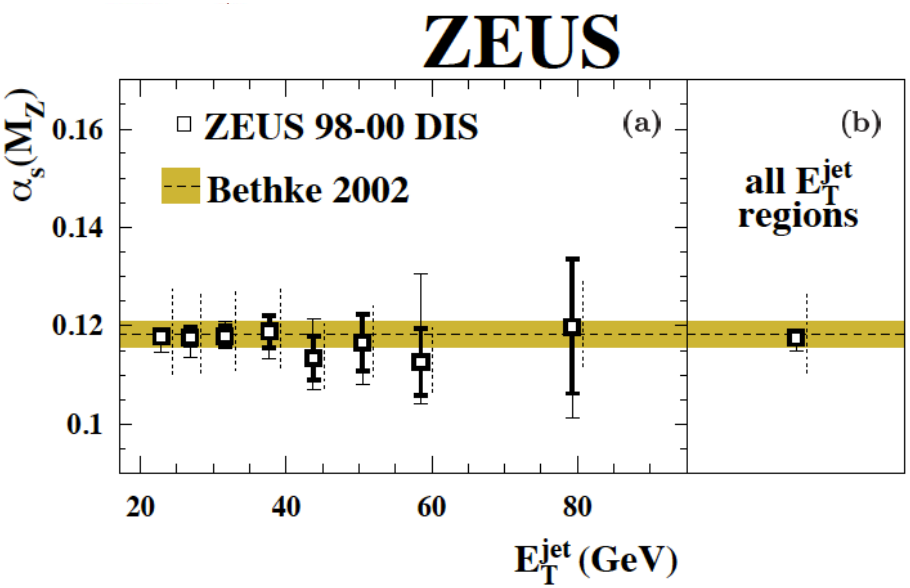
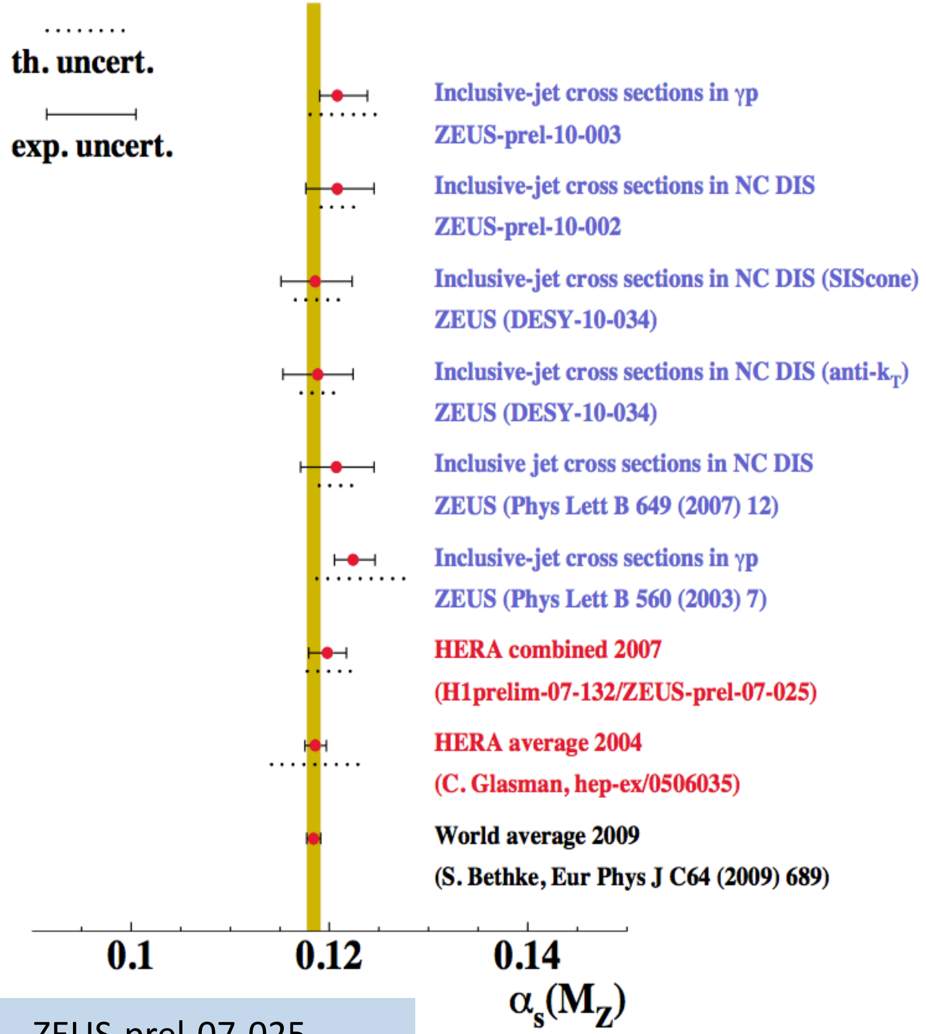




$$\alpha_S(M_Z) = 0.1176 \pm 0.0009(\text{stat})\ {}^{+0.0009}_{-0.0026}(\text{exp})\ {}^{+0.0091}_{-0.0072}(\text{th})$$

α_S FROM H1+ZEUS JETS COMBINED



ZEUS-prel-07-025
H1prelim-07-132
ZEUS-prel-10-003
C. Glasman hep-ex/0506035

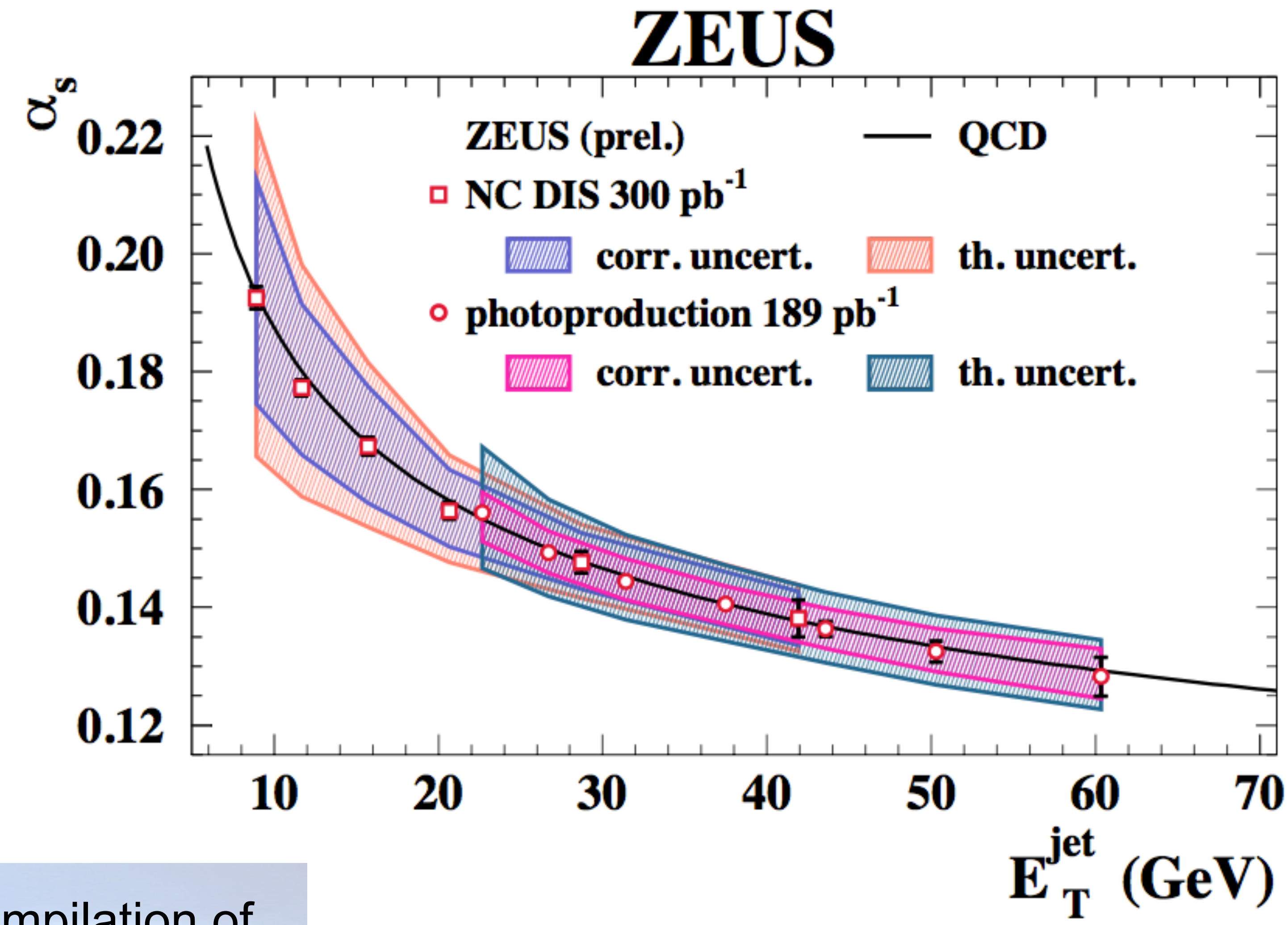
Towards a more complete picture: combined fits of H1+ZEUS jets!

- Since 2004 → combination of α_S values. Since 2007: combined fit using Hessian method.
- high-Q^2 inclusive jet cross sections (ZEUS $d\sigma/dQ^2$, H1 $d^2\sigma/dE_T dQ^2$)

$$\alpha_S(M_Z) = 0.1198 \pm 0.0019(\text{exp}) \pm 0.0026(\text{theo})$$

Result dominated by theory uncertainty → need for higher orders (NNLO pQCD preditions).

α_s FROM H1+ZEUS JETS COMBINED



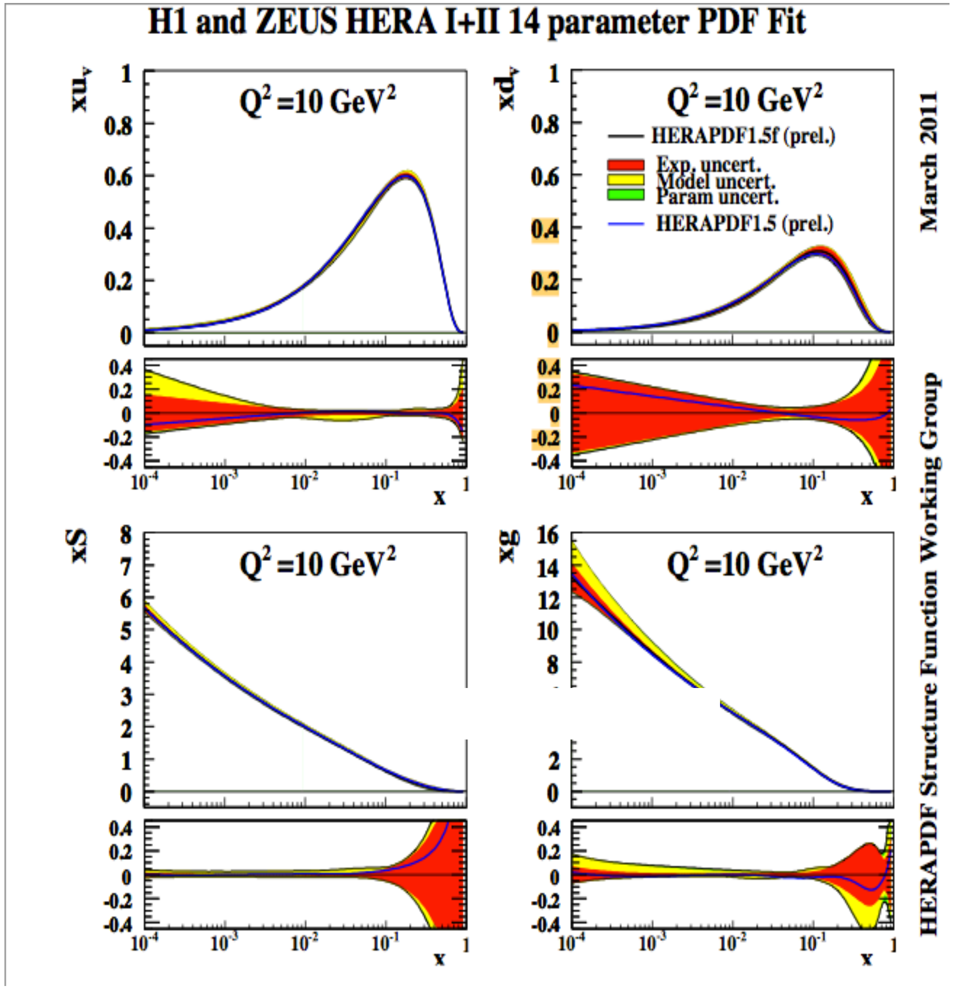
Latest ZEUS compilation of high-lumi PHP/DIS results.

α_S FROM GLOBAL QCD ANALYSES

Ringaile's talk: HERA-PDFs 1.5 and 1.5f with 10 / 14 free parameters (similar results).

14 parameters: more flexibility, reduced par. uncertainty, larger exp. errors.

Useful for inclusion of more final state data like jet cross sections:



$$
\begin{aligned}
xg(x) &= A_g x^{B_g} \cdot (1-x)^{C_g} - A'_g x^{B'_g} (1-x)^{C'_g} \\
xu_v(x) &= A_{u_v} x^{B_{u_v}} \cdot (1-x)^{C_{u_v}} \cdot (1 + D_{u_v} x + E_{u_v} x^2) \\
xd_v(x) &= A_{d_v} x^{B_{d_v}} \cdot (1-x)^{C_{d_v}} \\
x\bar{U}(x) &= A_{\bar{U}} x^{B_{\bar{U}}} \cdot (1-x)^{C_{\bar{U}}} \\
x\bar{D}(x) &= A_{\bar{D}} x^{B_{\bar{D}}} \cdot (1-x)^{C_{\bar{D}}}
\end{aligned}
$$

α_S FROM GLOBAL QCD ANALYSES

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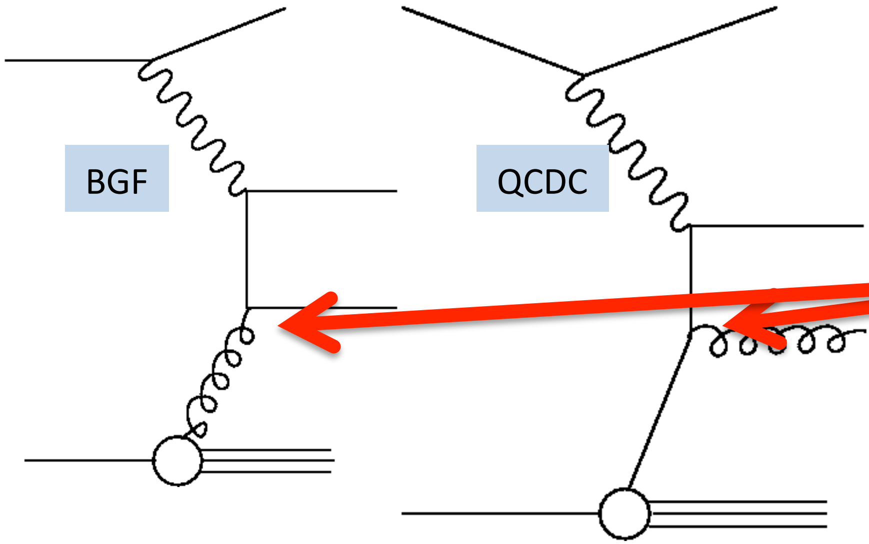
Useful for inclusion of more final state data like jet cross sections:

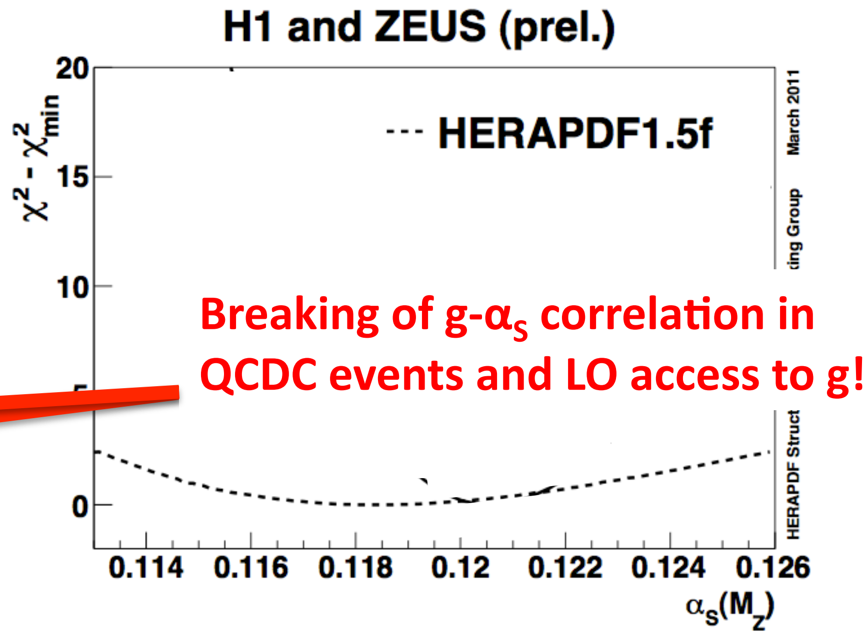
α_S and inclusive measurements:

– strong correlation of gluon density and coupling via evolution equation

$$\frac{dq_i(x,Q^2)}{d\ln Q^2} = \frac{\alpha_S}{2\pi}\int_x^1 \frac{dy}{y}\left[\sum_j q_j(y,Q^2)P_{q_iq_j}\left(\frac{x}{y}\right) + g(y,Q^2)P_{q_ig}\left(\frac{x}{y}\right)\right]$$

→ no meaningful determination of both!





Breaking of g-α_S correlation in QCDC events and LO access to g!

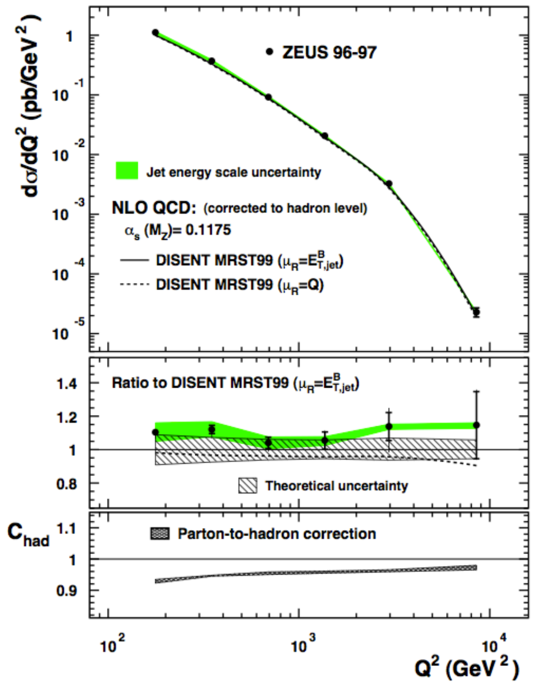
α_S FROM GLOBAL QCD ANALYSES

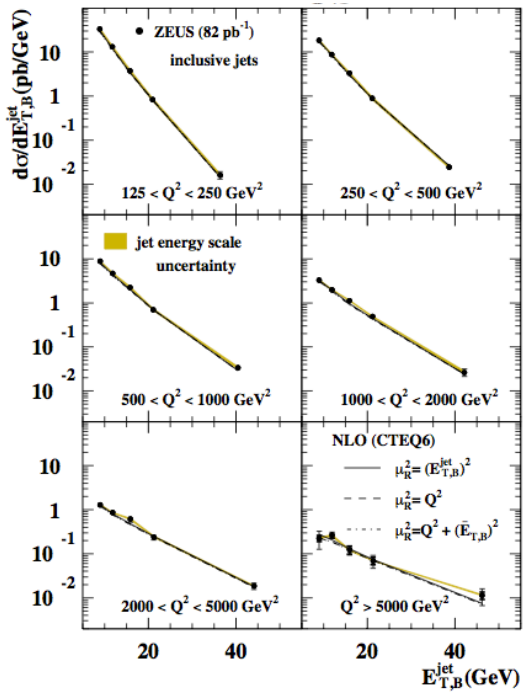
→ Inclusion of jet data provides complementary information on gluon at medium/high x and α_S constraints (unbiased by gluon shape)

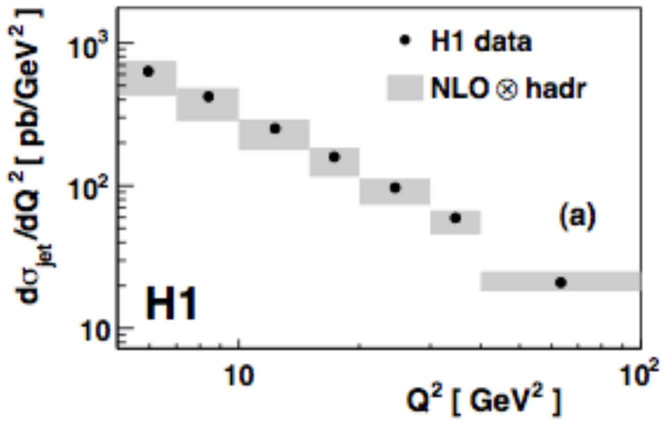
→ go for combined fits of inclusive and jet data (based on HERA-PDF 1.5f (DESY -06/128,-02/112,-09/032,-09/162)

➔ HERA-PDF 1.6 with 14 parameters!

Note: In DESY-05-050 ZEUS already combined inclusive and jet data in theoretically consistent way at NLO → ZEUS-Jets fit!

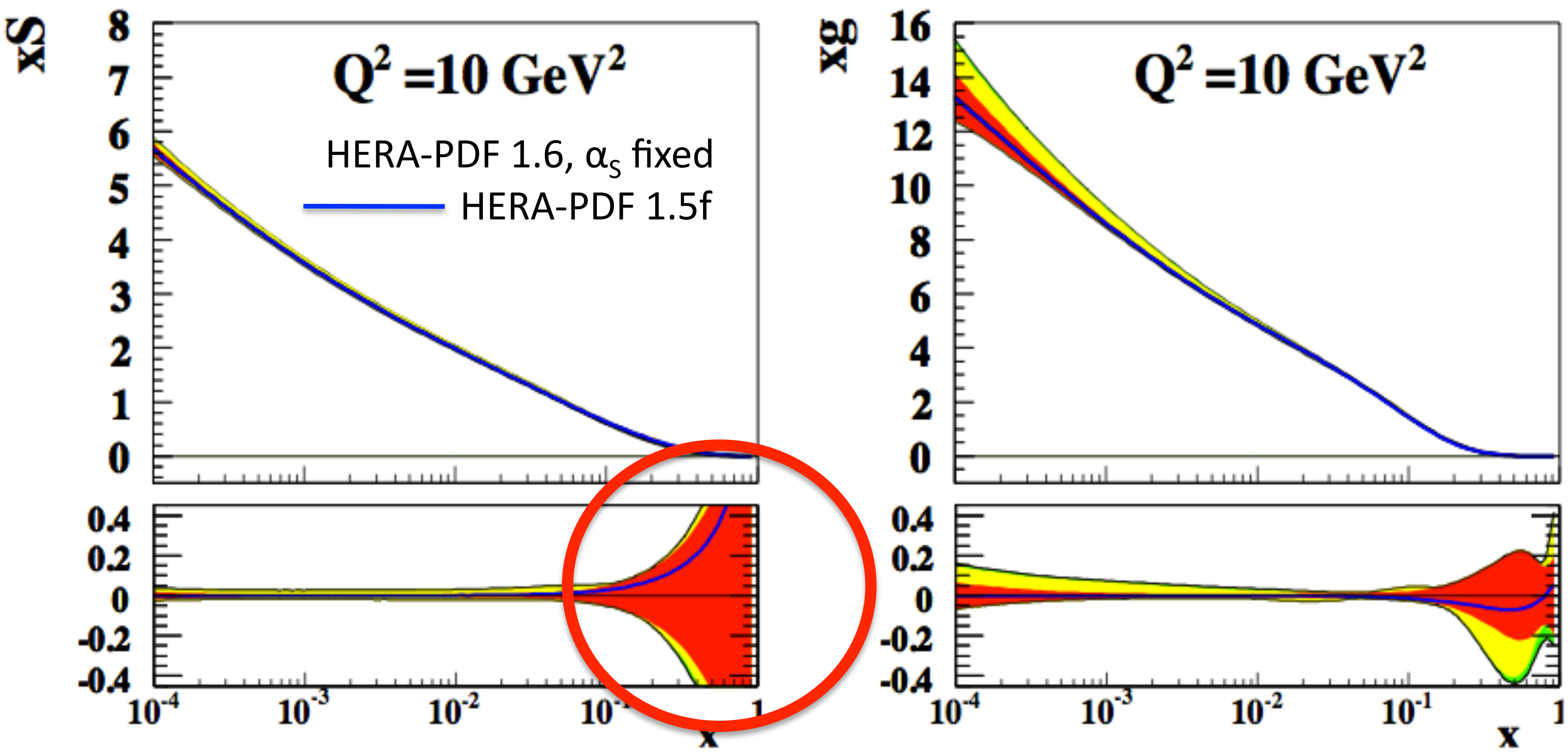






α_S FROM HERA-PDF 1.6

α_S fixed to 0.1176 → PDF similar to HERA-PDF 1.5f, but softer sea at high x.



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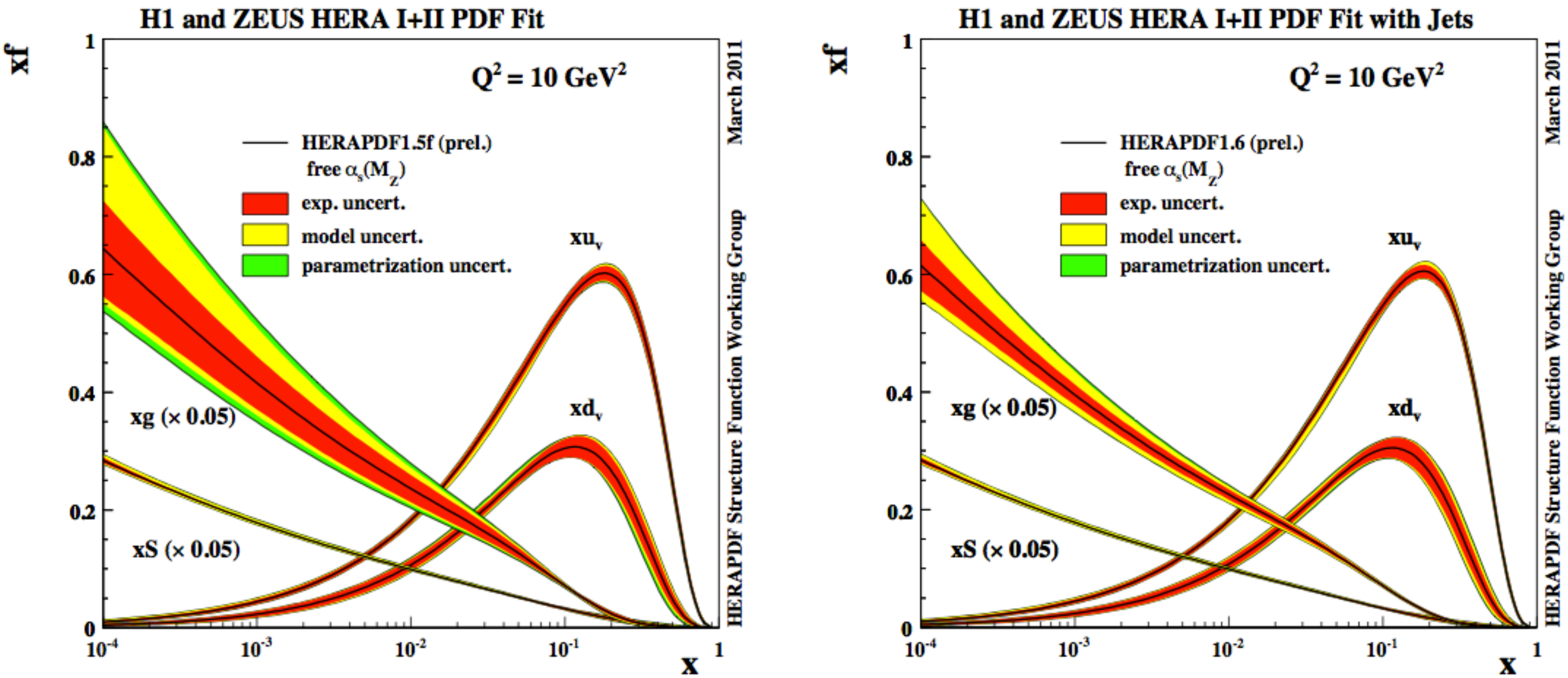
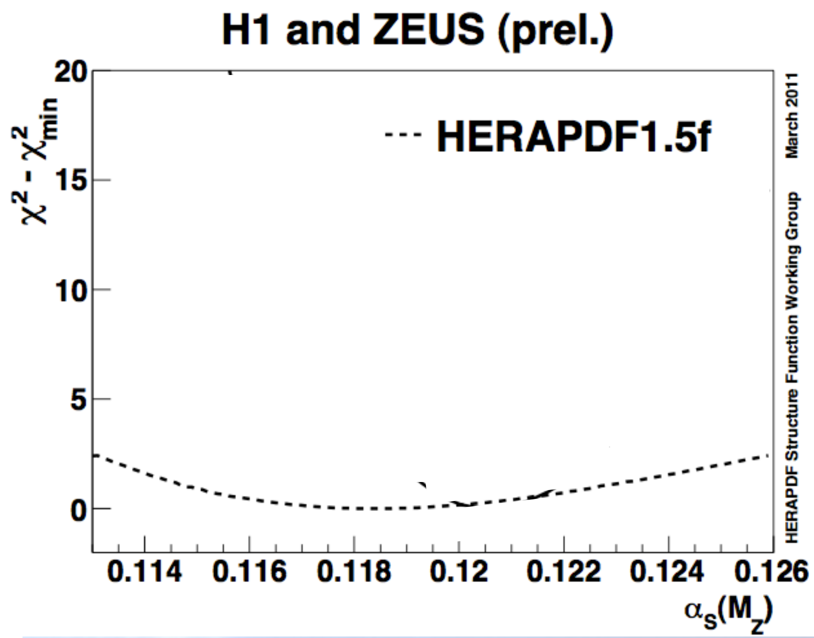


HERA-PDF 1.5f: freedom in α_S leads to large gluon uncertainty !

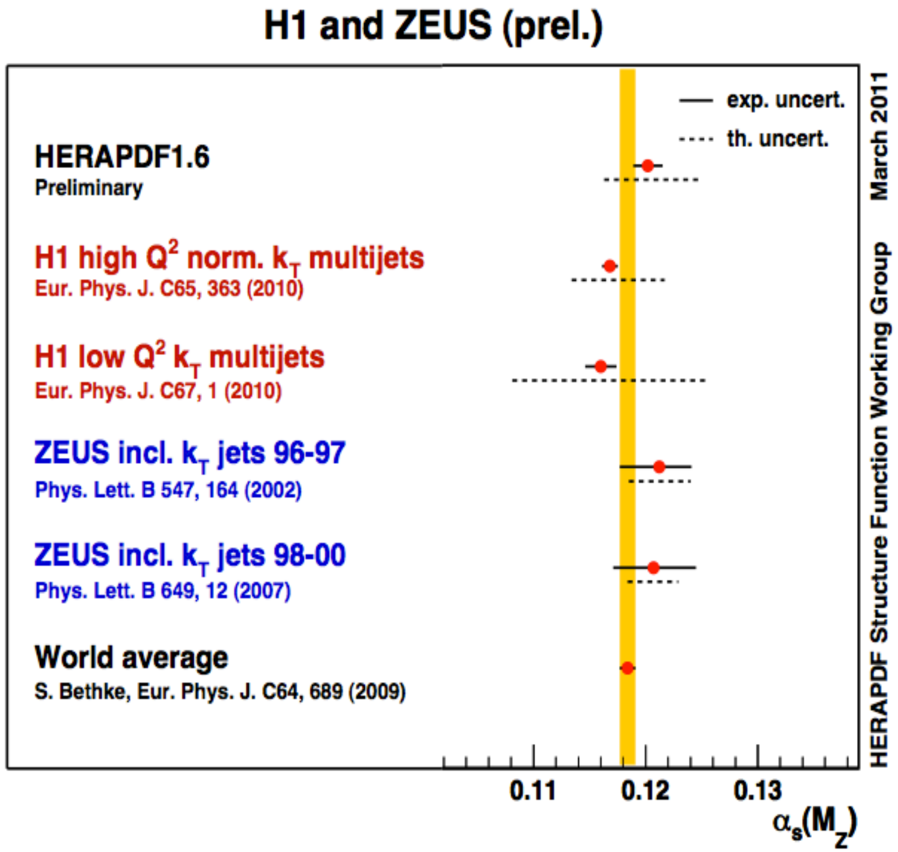
HERA-PDF 1.6: inclusion of jet data decouples coupling and gluon!

α_S FROM GLOBAL QCD ANALYSES

Similarly: coupling not constrained by HERA-PDF 1.5f! But if you turn to 1.6 and give the parametric freedom to use power of BGF and QCDC processes:



$$\alpha_S(M_Z) = 0.1202 \pm 0.0013(\text{exp})$$
$$\pm 0.0007(\text{model/param})$$
$$\pm 0.0012(\text{hadr})^{+0.0045}_{-0.0036}(\text{scale})$$

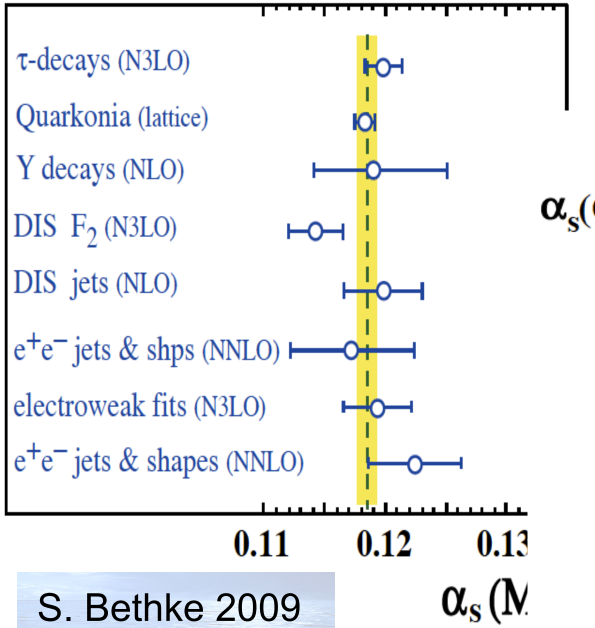


Comparison of HERA-PDF 1.6 to input jet measurements and world avg.

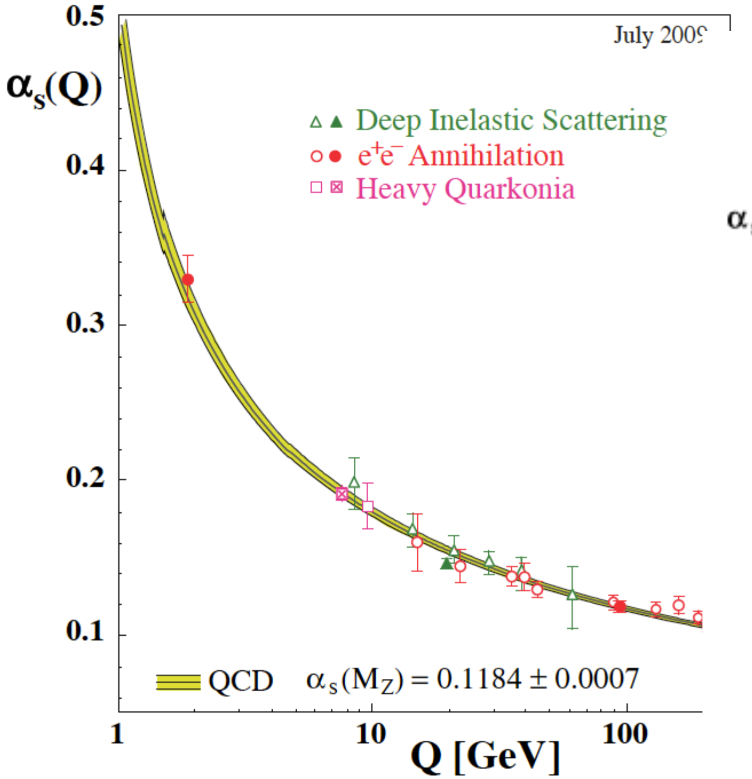
Note 1: For jet extractions PDF uncertainty part of theory error; for HERA-1.6 part of experimental error

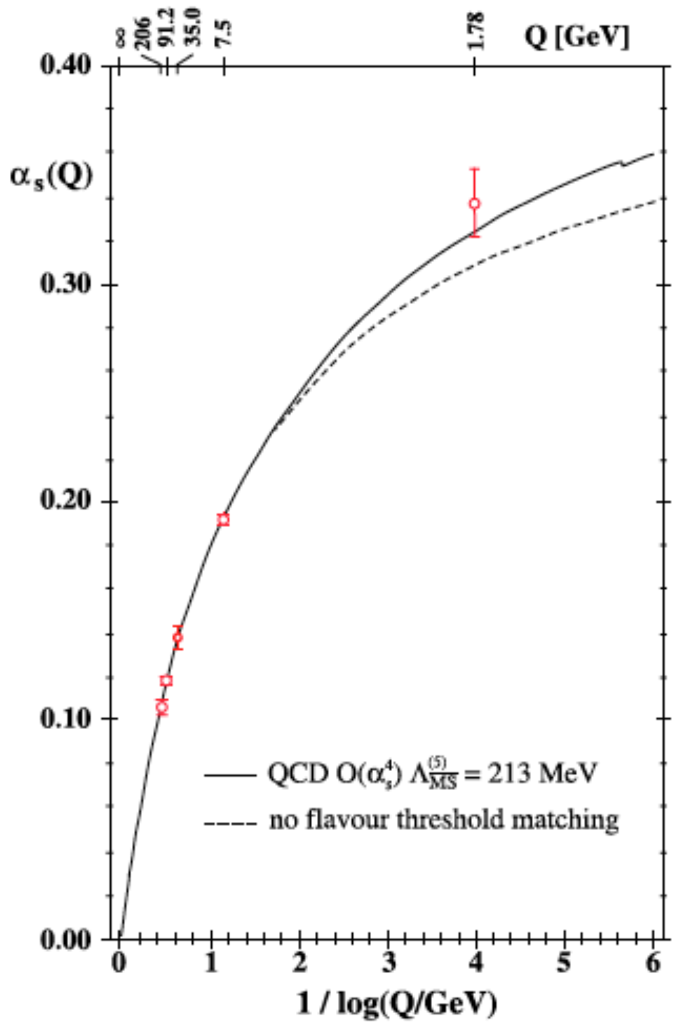
Note 2: error driven by restriction to NLO QCD!

SUMMARIES OF α_S AND WORLD DATA



S. Bethke 2009





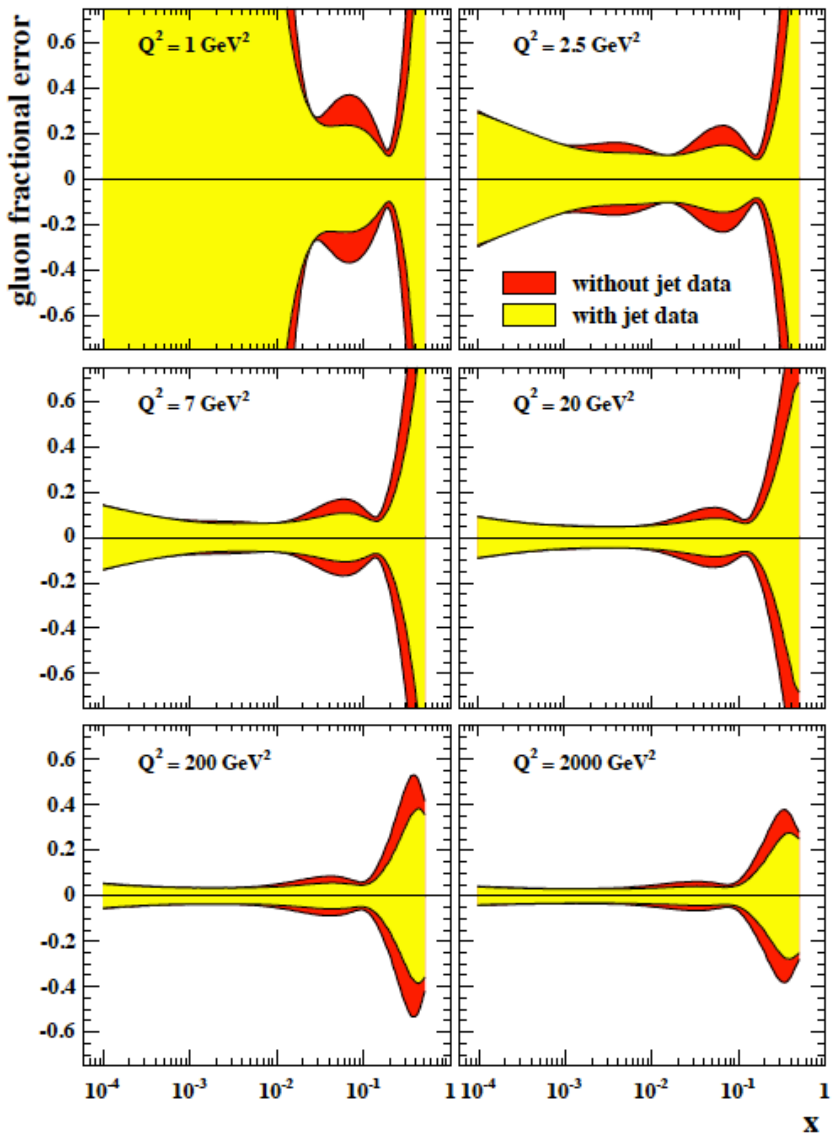
DIS / HERA results important contribution to world knowledge of α_S, similar to LEP impact. All data demonstrate asymptotic freedom!

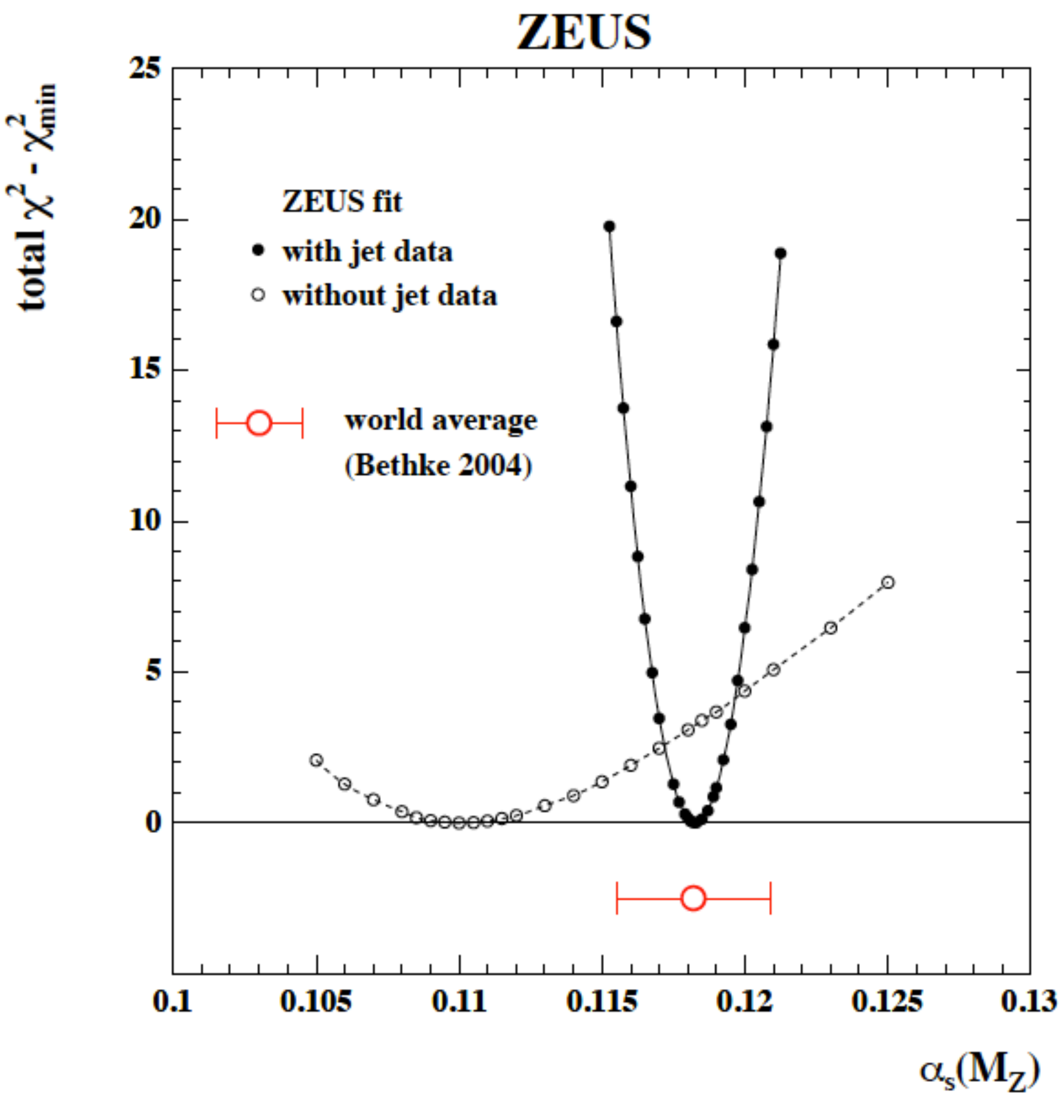
CONCLUSIONS

- HERA contributed substantially to measurements of the strong coupling constant
  - many consistent and competitive measurements
  - from jets in PHP, in DIS, from jet substructure
  - from inclusive data in combined PDF fits
  - Demonstration of running from single experiment
- Jet determinations of α_S mostly limited by theory:
  - Unknown effect of terms beyond NLO
    ➔ desperately waiting for NNLO !
- Some prospects for determinations of the coupling (not covered):
  - LHC?
  - LHeC: DIS at E_p = 7 TeV, E_e = 100 GeV
    ➔ strong coupling up to μ_R = 400 GeV or so!

BACKUP

ZEUS-JETS FIT AND α_S





$$\alpha_S(M_Z) = 0.1183 \pm 0.0028(\text{exp}) \pm 0.0008(\text{model})$$

ep PHYSICS AT HERA

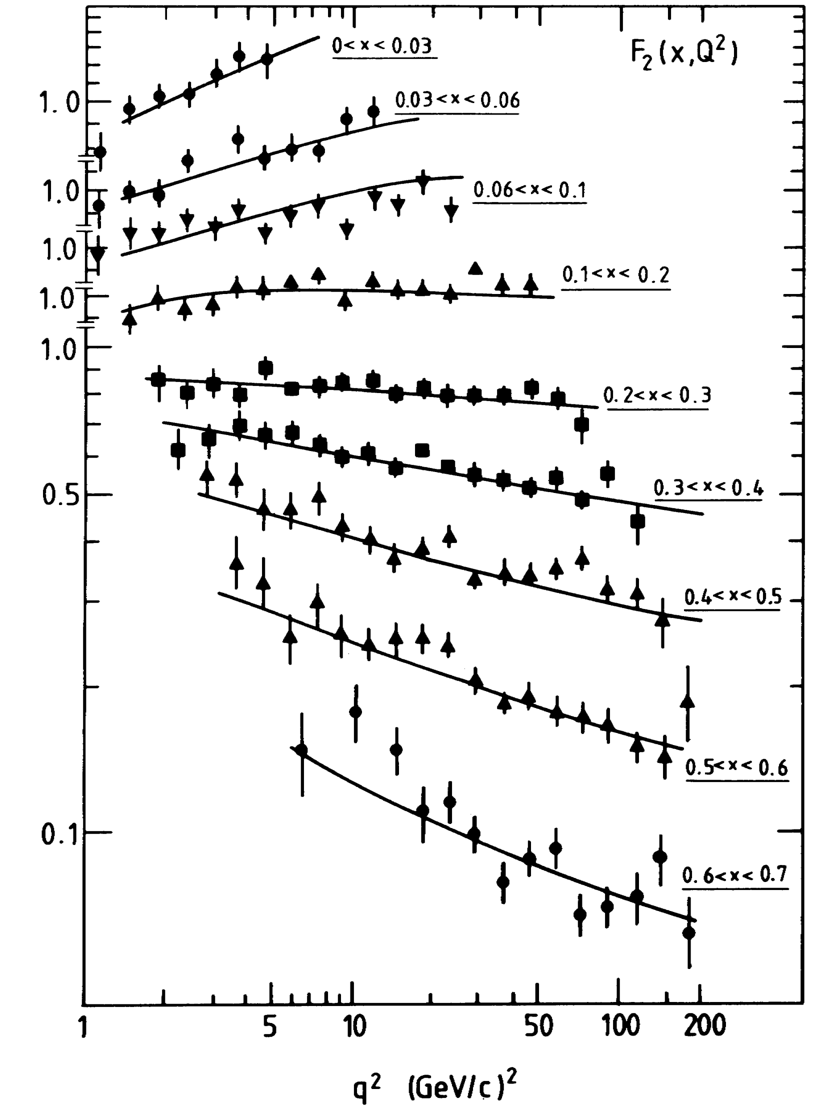
- NC e±p DIS cross section:

$$\frac{d^2\sigma_{NC}^{\pm}}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[Y_+F_2 \mp Y_-xF_3 - y^2F_L\right]$$

- Extraction: reduced Xsection:

$$\sigma_r\left(x,Q^2\right) = \frac{1}{Y_+}\frac{d^2\sigma_{NC}^{\pm}}{dxdQ^2}\frac{xQ^4}{2\pi\alpha^2}$$

$$= F_2\left(x,Q^2\right)\left(1+\Delta\right)$$



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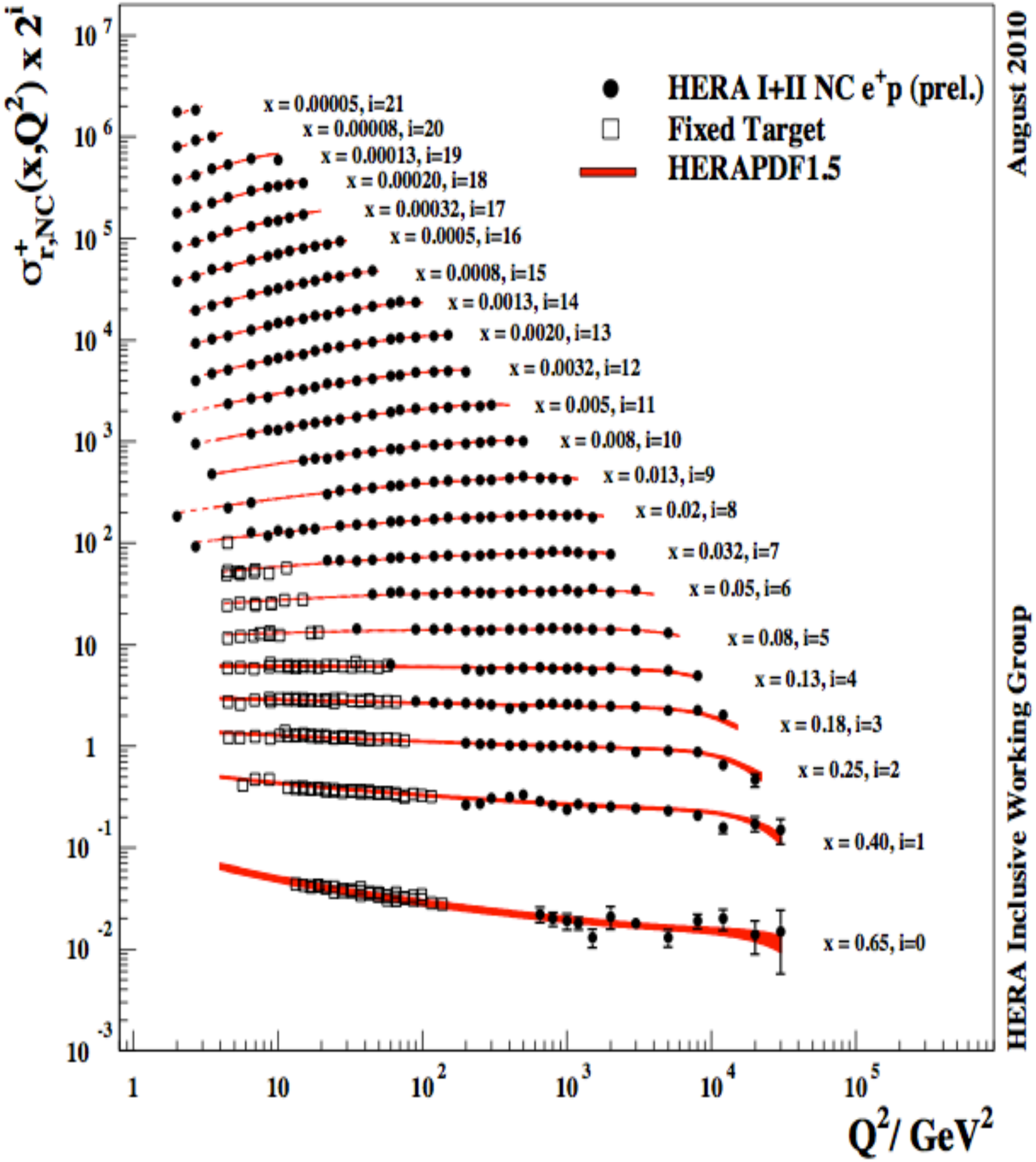

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$$= F_2(x,Q^2)(1+\Delta)$$

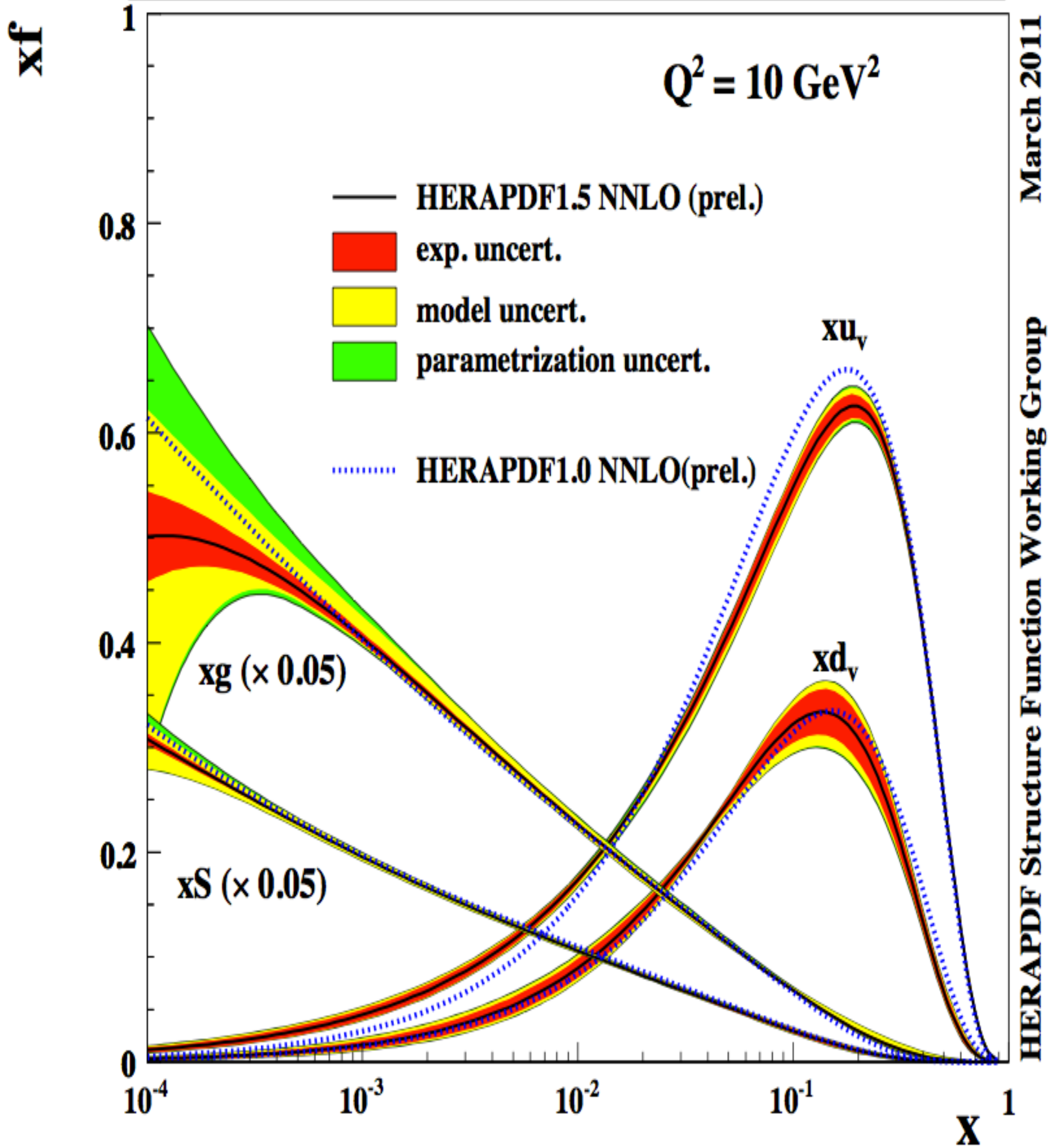
- Next: use structure function F_2:

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

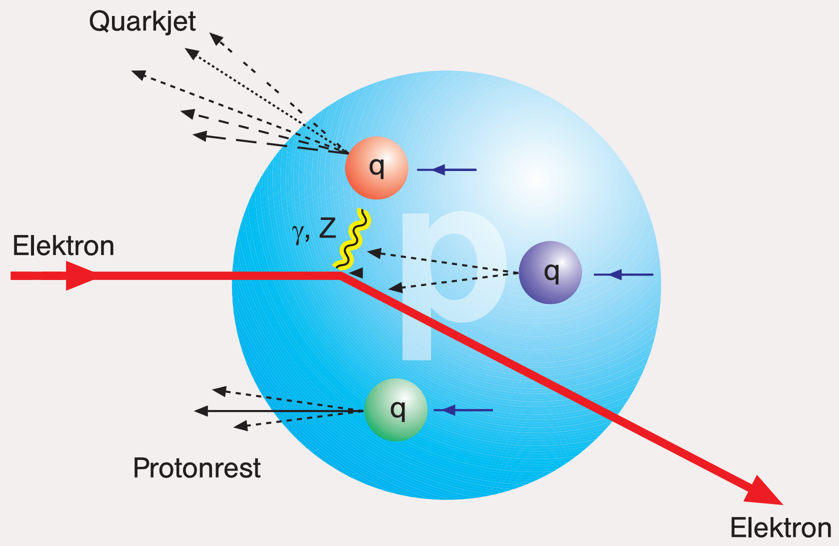
- … to extract PDFs q,g using DGLAP evolution equations!

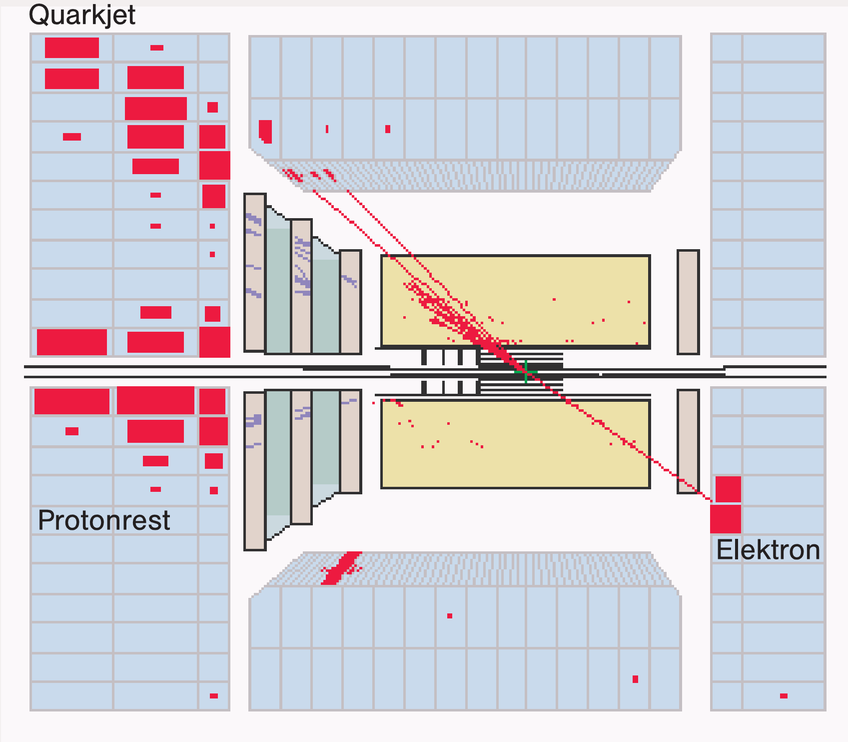
$$\frac{dq(x,Q^2)}{d\ln Q^2} \propto \alpha_S \cdot g(x,Q^2) - \alpha_S \cdot q(x,Q^2)$$

- NLO and NNLO HERA analyses!



THE EXPERIMENTS H1 AND ZEUS





HERA AT DESY

- HERA (6.3km): e±p collisions at √s ~ 320 GeV from 1992 to 2007 (E_e = 27.5 GeV, E_p = 920 GeV)
- HERA-I until 2000, HERA-II from 2003/04
- ~0.5 fb^{-1} per experiment; used in jet analyses: up to 400 pb^{-1}

JET PHYSICS AT HERA

Selection – high Q^2:
- $Q^2 > 125$ GeV^2
- $0.2 < y < 0.6$ or $|\cos\gamma_{had}| < 0.65$
- $E_{Tjet} > 8$ GeV
- Small theo. errors.

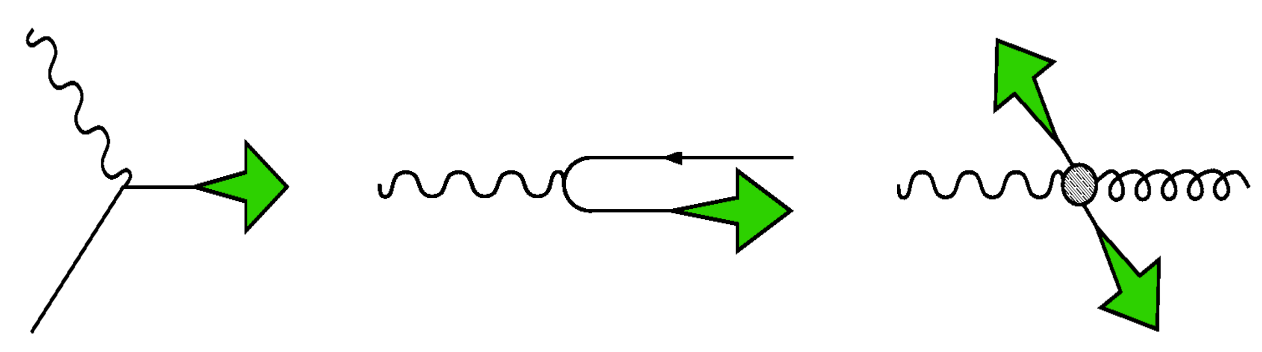
Selection – low Q^2:
- $5/10 < Q^2 < 100$ GeV^2
- $0.2 < y < 0.6$
- $E_{Tjet} > 5/8$ GeV
- High statistics, but larger theo. errors

Selection – PHP:
- $Q^2 \sim 0$ (no electron!)
- Cuts on y or $W_{\gamma p}$
- $E_{Tjet} > 14$ GeV

Analysis of 1/2/3-jet events, jet shapes etc.

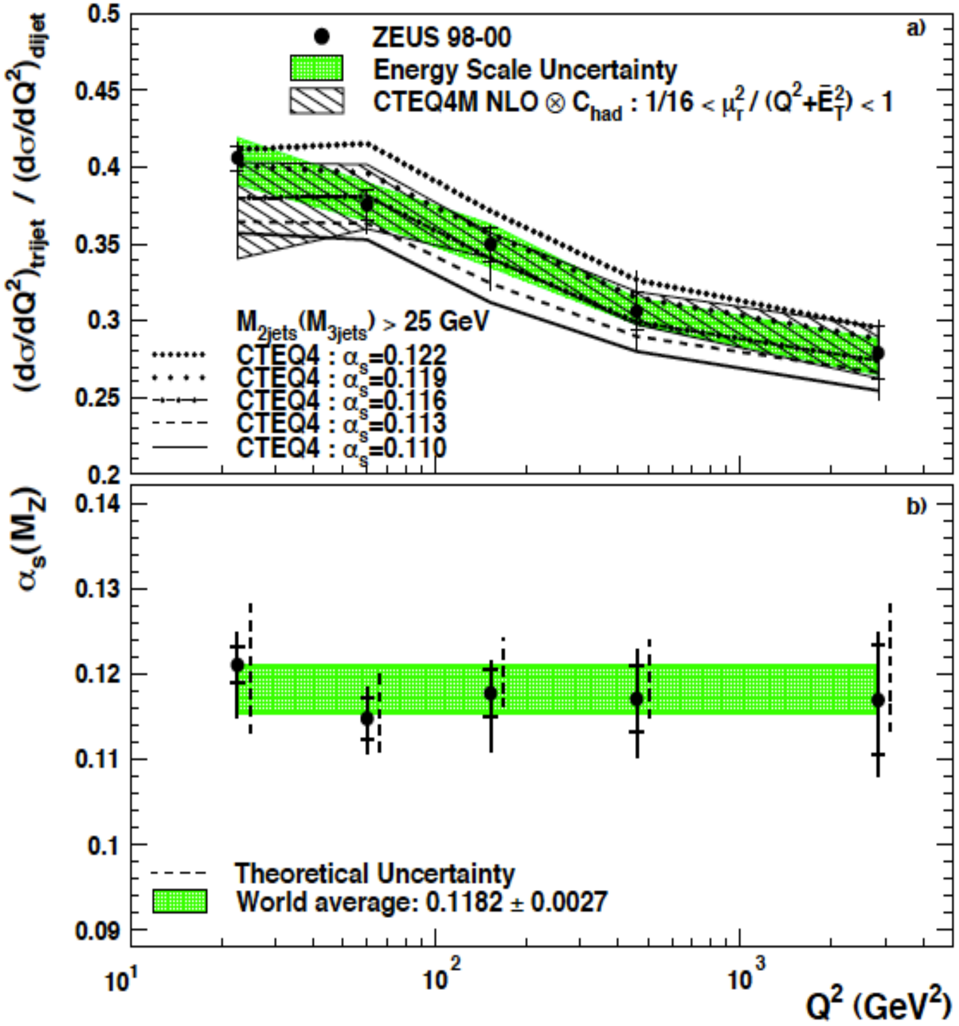
Jet finding on HFS objects (CAL only / tracks+calo info):
- default: k_T algorithm (longitudinally invariant incl. mode)
- distance criterion: $d_{iB} = E_{T,i}^2 \quad d_{ij} = \min\left(E_{T,i}^2, E_{T,j}^2\right) \cdot R_{ij}^2$
- lately also use of anti-k_T and SISCone (default at LHC)

DIS: mostly in Breit frame → photon and parton collinear



Requirement of (high) E_T → selection of QCD events AND ensuring applicability of perturbative QCD (hard scale!)

α_S FROM 3/2 JETS RATIO $R_{3/2}$



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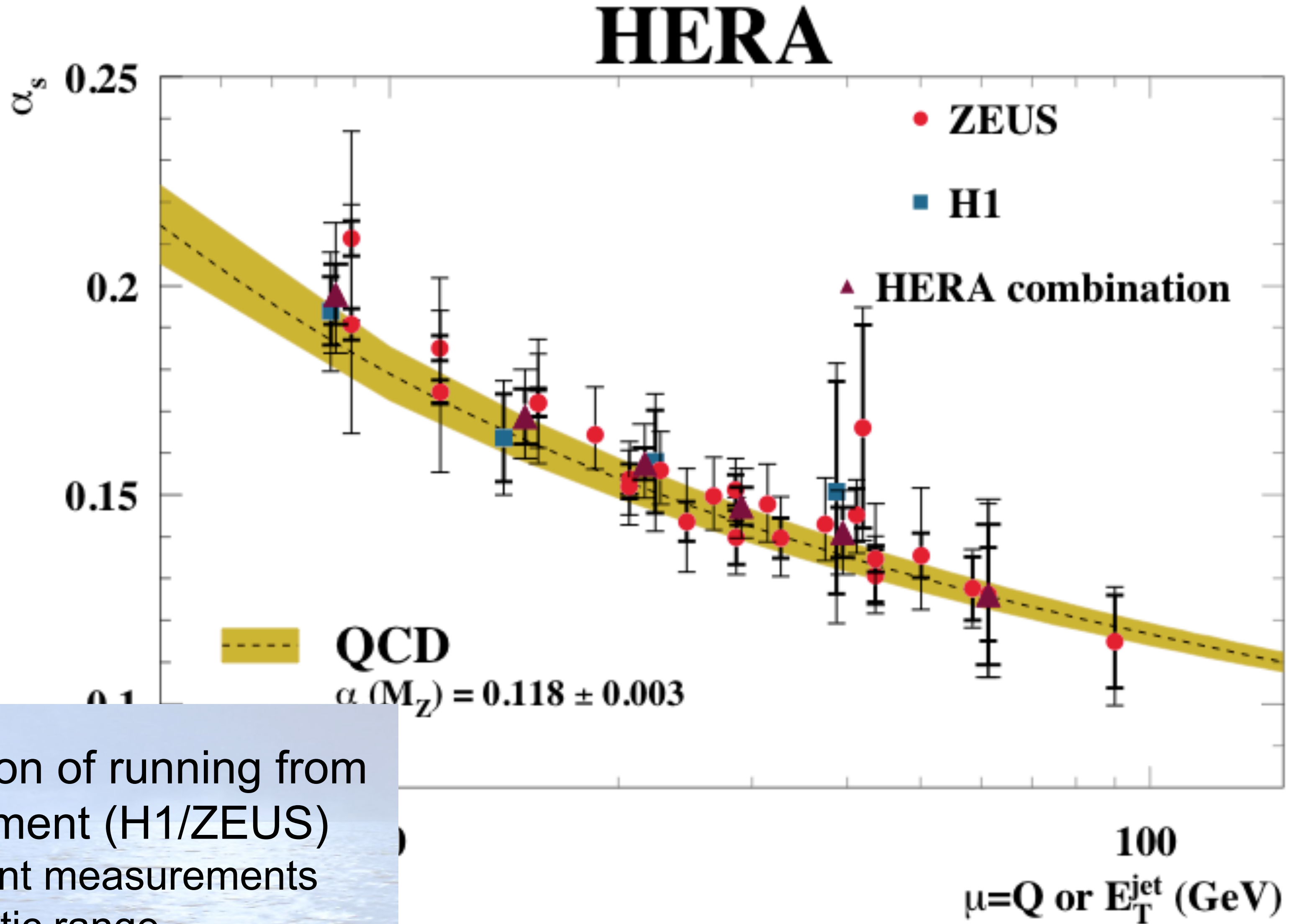
α_S FROM H1+ZEUS JETS COMBINED



Demonstration of running from
- one experiment (H1/ZEUS)
- many different measurements
- wide kinematic range