Determination of the Strong Coupling Constant with Jet Data

Junwu Huang

Peking University, China
Supervisors: Dr. G. Grindhammer, D. Britzger, Dr. R. Kogler
H1 Group, DESY

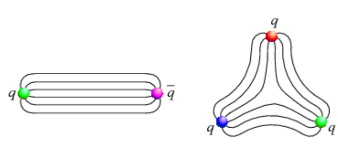
8 September 2011

QCD framework

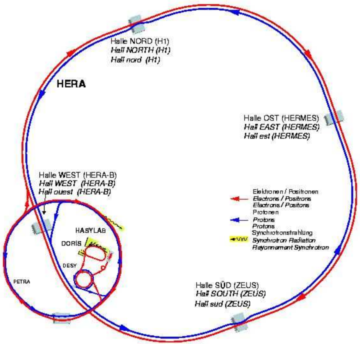
Quantum Chromodynamics (QCD) is the theoretical framework of strong interaction, i.e. the interaction between partons(quarks and gluons). The basic feature of QCD is asymptotic freedom and color confinement. α_S is the **only** free parameter of QCD.

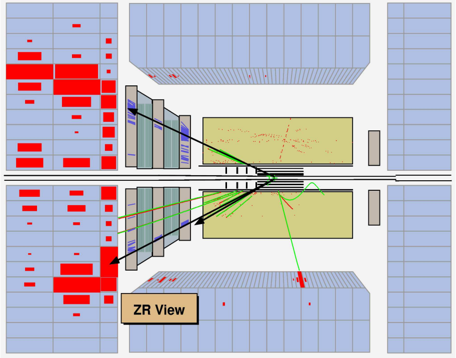
Main properties of QCD

- Asymptotic freedom(High Energy): Particles can be regarded free when hit by a high energy particle.
- Color confinement(Low Energy): No bare color particles can be observed.



HERA, ZEUS Detector and the used data

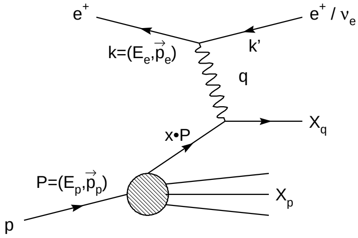




HERA is a electron proton collider with centre of mass energy $\sqrt{s} = 380\text{GeV}$. The proton energy is 920GeV and the electron energy is 27.6GeV.

ZEUS detector is asymmetric because the proton energy is much higher than the electron energy.

Deep Inelastic Scattering

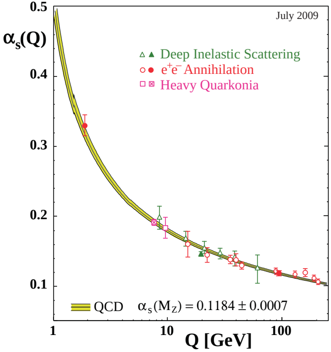


- DIS Kinematics
  - $s = (k + P)^2$ is the squared centre-of-mass energy
  - $Q^2 = -q^2$ is a measure of the strength of the interaction
  - Bjorken scaling $x = \frac{Q^2}{2P \cdot q}$ is the momentum fraction taken by the interacting parton.
- X_q is always composed by a great number of hadrons and mesons (Sometimes Jets).
- The Neutral Current DIS process is processes with a outcoming positrons.

Renormalisation and the running coupling

Renormalisation is basically the process of introducing a new mass scale to get rid of the ultra-violet divergences.

- Renormalisation scale μ_R
  - Any finite order calculation depends on the scale μ_R.
  - If calculation goes to infinite order, the result should not depend on scale



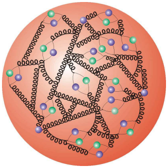
- Renormalisation Group Equation (RGE) and running coupling
  - μ_R: $\frac{d}{d\mu_R}(\text{Physical Quantity}) = 0$
  - $\alpha_s(\mu_R) = \frac{\alpha_s(M_Z)}{1+\frac{\beta_0}{4\pi}\alpha_s(M_Z)\ln\left(\mu_R^2/M_Z^2\right)}$
  - β_0 is positive gives rise to **Asymptotic Freedom**.

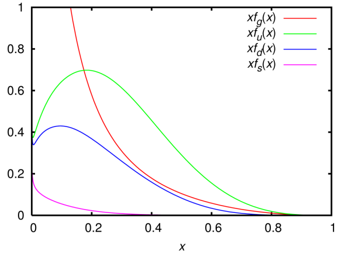
PDF and μ_F

parton distribution function and factorisation scale

PDF: The current description of a proton

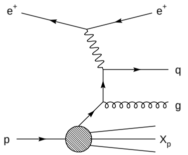
- In quark-parton model, the proton is composed of point like partons(quarks and gluns).
- The PDF is defined to be the possibility density for finding a parton with certain longitudinal momentum.
- PDF is determined by experiments since perturbative method is not valid.



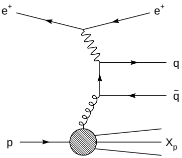


- μ_F: Facorisation scale introduced to separate perturbative and non-perturbative region.

Jet Production



Dijet production: QCD compton



Dijet production: Boson Gluon Fusion

$$\sigma = \sum_{a,n} \int_0^1 \mathrm{d}x c_{a,n} \left(\frac{x_{B_j}}{x}, \mu_R, \mu_F \right) \cdot$$
$$[\alpha_s^n(\mu_R) \cdot f_{a/h}(x, \mu_F)]$$

- Jet
  - Jet is a shower of particles in a certain angular position.
  - Dijet and multijet production allows a direct measurement of α_S.
- Breit Frame
  - In Breit Frame, the virtual Boson interacts head-on with the proton.
  - $2x_{B_j}\vec{P} + \vec{q} = 0$
  - Only interactions with strong vertex have transverse momentum (P_T) in Breit Frame.

FastNLO and Fitting

- FastNLO Calculate Feynman Diagrams to NLO with efficiency.
  - $\sigma = \sum_{a,n,l,k,m} \tilde{\sigma}_{n,a,k,l,m} \alpha_s^n(\mu_R^{(l)}) f_{a/h}(x^{(k)}, \mu_F^{(l)})$
- Fitting Find the best α_s value with **TMinuit**
  - $\chi^2(\alpha_s, \vec{\epsilon}) = \sum_i \frac{(\sigma_i^{exp} - \sigma_i^{the}(\alpha_s)[1 - \sum_k \delta_{i,k}(\epsilon_k)])^2}{\delta_{i,uncorr}^2} + \sum_k \epsilon_k^2$
  - We fit with four type of uncertainties
    - Uncorrelated Statistic Error
    - Correlated Energy Scale Uncertainty
    - Correlated Detector Systematic Uncertainty
    - Correlated Luminosity Uncertainty

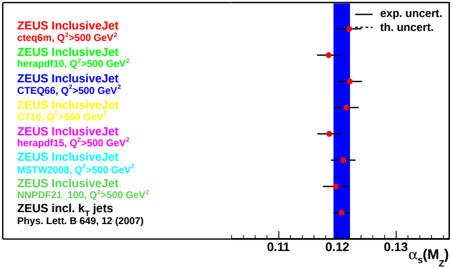
Strategy

- Firstly, we tried to analyze the ZEUS Inclusive-Jet data and reproduce the published α_s by ZEUS Collaboration to **test our framework**.
- Secondly, we analyzed the ZEUS **Dijet** data and extract α_s from the data.
- We study the errors and determines the largest value for each of them.
- We study the PDF, μ_R and μ_F dependence of the fitting result.

α_s fit with Inclusive-Jet data

Test of Framework

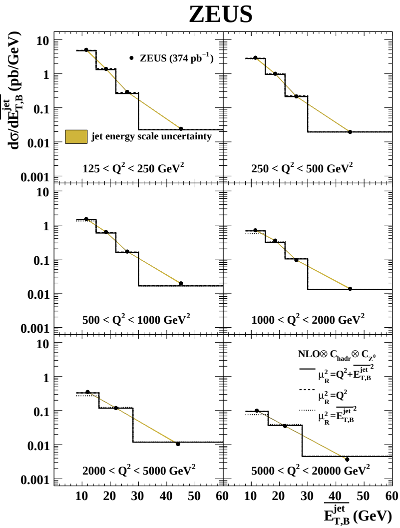
We managed to **reproduce** the α_s fit result published by ZEUS Collaboration. $\alpha_s(M_Z) = 0.1207 \pm 0.0014(stat.)^{+0.0035}_{-0.0033}(exp.)^{+0.0022}_{-0.0023}(th.)$



α_s fit for ZEUS Inclusive-Jet data taken from 2003-2007 during the HERA-II run with different PDFs

- The fitting result with the same choice of scales and binmaps using CTEQ6.6 and CTEQ6m is consistant within 1% with the published result
- The fitting result with NNPDF2.1 and HERAPDF1.5 is much smaller.
- A strong dependence on the choice of μ_R and μ_F is observed.

ZEUS Dijet Data 2003 ~ 2007

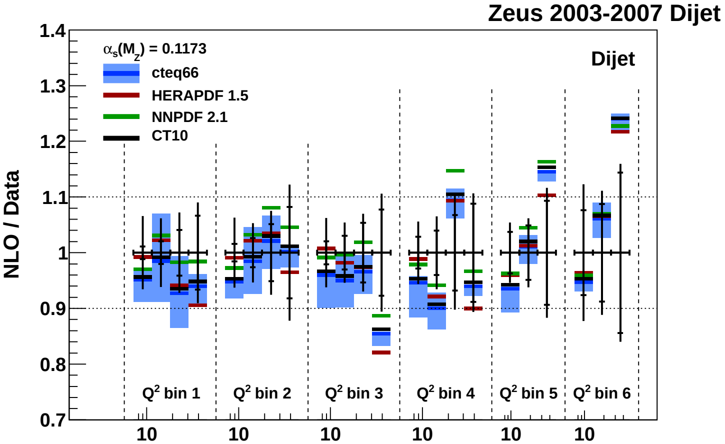


DESY-10-170

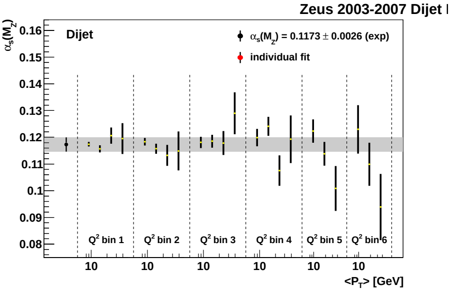
- The data used is taken by ZEUS Detector from 2003 to 2007 during the HERA II run.
- ZEUS Dijet Data are measured for 6 Q^2 bins, 4 P_T bins for $125 < Q^2 < 2000\mathrm{GeV}^2$ and 3 P_T bins for $2000 < Q^2 < 20000\mathrm{GeV}^2$
- Statistic Error, Energy Scale Uncertainty, Detector Systematic Uncertainty and Luminosity Uncertainty are published together with the Cross Section.

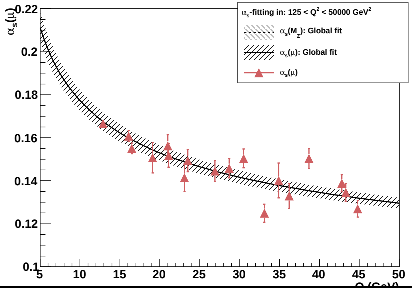
α_S fit for ZEUS Dijet data

- α_s fit with CTEQ6.6 and $\mu_R^2 = (Q^2 + P_T^2)/2$
  $\alpha_s = 0.1173 \pm 0.0026(stat.)^{+0.0009}_{-0.0002}(PDF)^{+0.0103}_{-0.0097}(Theo)$
- $\chi^2/ndf = 1.288$
- The result of α_s dijet fit also depends on PDF, μ_F and μ_R



α_s fit for each bin





- The fit for each bin is generally well.
- The high P_T and high Q^2 bins have a larger experimental error due to lack of statistics.
- The running of α_s is well preserved.

PDF dependence of α_s and the determination of PDF error

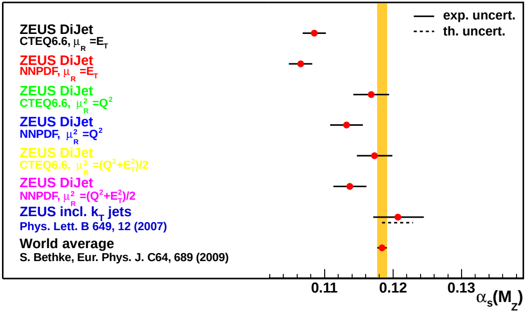
- PDF dependence of α_s Since PDFs are determined from experiments with many ways of fitting, α_s results could also depend on the choice of PDFs.

μ_F	μ_R	PDFs	α_s	err(stat)	χ^2
Q^2	$(Q^2+E_T^2)/2$	CTEQ66	0.1173	0.0026	1.288
Q^2	$(Q^2+E_T^2)/2$	CT10	0.1168	0.0026	1.257
Q^2	$(Q^2+E_T^2)/2$	HERAPDF1.5	0.1162	0.0028	1.212
Q^2	$(Q^2+E_T^2)/2$	NNPDF2.1_100	0.1137	0.0024	1.309

- The results for CTEQ6.6, CT10, HERAPDF are consistent within 1% while the result for NNPDF2.1 is quite far below as the case of inclusive-jet fit.

- PDF error PDF error are determined for CTEQ6.6. The error is ${}^{+0.0009}_{-0.0002}$.

- μ_R The selected result showed the α_s dependence on choice of the renormalisation scale μ_R. The result with 3 commen choices $(Q^2+E_T^2)/2$, Q^2, E_T^2 is displayed.

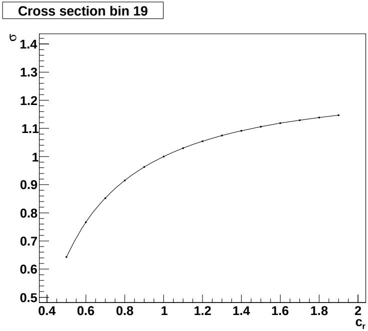


The scale E_T^2 is not prefered in the dijet production fitting. The theoretical uncertainty due to μ_R is $^{+0.01018}_{-0.00966}$.

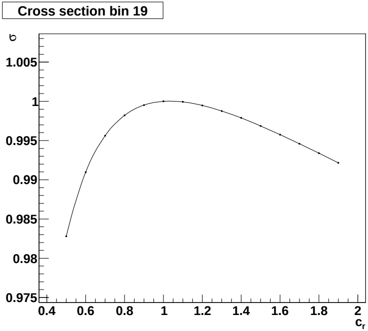
- μ_F No strong dependence on μ_F is observed. The theoretical uncertainty due to μ_F is $^{+0.00212}_{-0.00185}$.

μ_R and μ_F dependence

The reason for the invalidity of $\mu_R^2 = E_T^2$



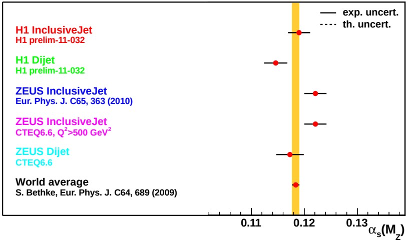
$\mu_R^2 = E_T^2$



$\mu_R^2 = (Q^2 + E_T^2)/2$

It is clear from the comarison between left and right plot that for low P_T bins, pQCD breaks down if we choose $\mu_R^2 = P_T^2$. The calculation based on the pQCD is no longer valid, which will give rise to a large theory error.

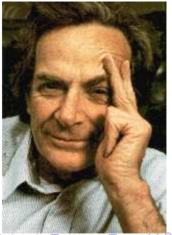
Conclusion



- α_s is reproduced from ZEUS Inclusive-Jet Data to be consistant with the ZEUS Collaboration.
- α_s is extracted from ZEUS Dijet Data and the errors of the fit is determined
- $\alpha_s = 0.1173 \pm 0.0026(Stat)^{+0.0009}_{-0.0002}(PDF)^{+0.0103}_{-0.0097}(Theo)$

- μ_R, μ_F and PDFs dependence of the result is studied.
  - $\mu_R^2 = P_T^2$ is less favored for the breakdown of pQCD in low P_T region.
  - No strong dependence on the μ_F is observed.
  - NNPDF2.1 tend to give a different result from CTEQ6.6 and others.

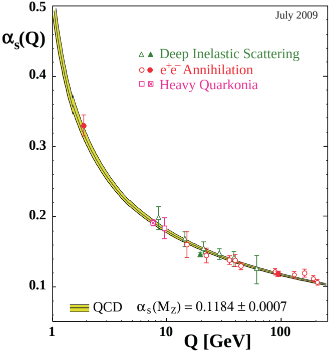
Many Thanks



Back Slide

Renormalisation and the running coupling

- Renormalisation Group Equation (RGE) and running coupling
  - General form: $\left(\mu_R \frac{\partial}{\partial \mu_R} + \beta(\alpha_s) \frac{\partial}{\partial \alpha_s}\right) \Gamma(p_i, \alpha_s) = 0$, while $\beta(\alpha_s) = \mu_R \frac{\partial \alpha_s}{\partial \mu_R}$
  - Running coupling of QCD: $\alpha_s(\mu_R) = \frac{\alpha_s(M_Z)}{1 + \frac{\beta_0}{4\pi} \alpha_s(M_Z) \ln\left(\mu_R^2 / M_Z^2\right)}$ to first order.
  - The fact that β_0 is positive gives rise to **Asymptotic Freedom**.



PDF and μ_F

parton distribution function and factorisation scale

PDF: The current description of a proton

- In quark-parton model, the proton is composed of point like partons(quarks and gluns).
- The PDF is defined to be the possibility density for finding a parton with certain longitudinal momentum.
- PDF is determined by experiments since perturbative method is not valid.

μ_F :The scale dividing the perturbative and non-perturbative region

- Initial and final state radiation are treated with MC method in non-perturbative region.
- The parton lepton interaction can be calculated with pQCD to higher order.

Back Slide

μ_F	μ_R	PDFs	α_s	err(stat)	χ^2
Q^2	$(Q^2 + E_T^2)/2$	CTEQ6.6	0.1173	0.0026	1.288
Q^2	$(Q^2 + E_T^2)/2$	NNPDF2.1_100	0.1137	0.0024	1.309
Q^2	Q^2	CTEQ6.6	0.1168	0.0026	1.326
Q^2	Q^2	NNPDF2.1	0.1132	0.0024	1.389
Q^2	E_T^2	CTEQ6.6	0.1085	0.0017	4.075
Q^2	E_T^2	NNPDF2.1_100	0.1065	0.0017	3.744