QCD @ LHC.cern.ch

日笠 健一 (東北大)

QCD @ Tevatron.fnal.gov

日笠健一（東北大）

NO PHYSICS

@ LHC

w/o QCD

FUNDAMENTALS

QCD

$$\mathcal{L} = -\frac{1}{4} F^2 + \sum_q \bar{q} (i \not{D} - m_q) q$$

$$D_\mu = \partial_\mu + i g T^a A_\mu^a$$

$$F_{\mu\nu}^a = \partial_\mu A_\nu^a - \partial_\nu A_\mu^a - g f^{abc} A_\mu^b A_\nu^c$$

Gauge group: SU(3)

quarks in fundamental rep. 3

Parameters

gauge coupling g or α_s or Λ

quark masses

relevant event data [59]. In particular, data from purely hadronic initial states are used as they can provide important constraints on the gluon distributions.

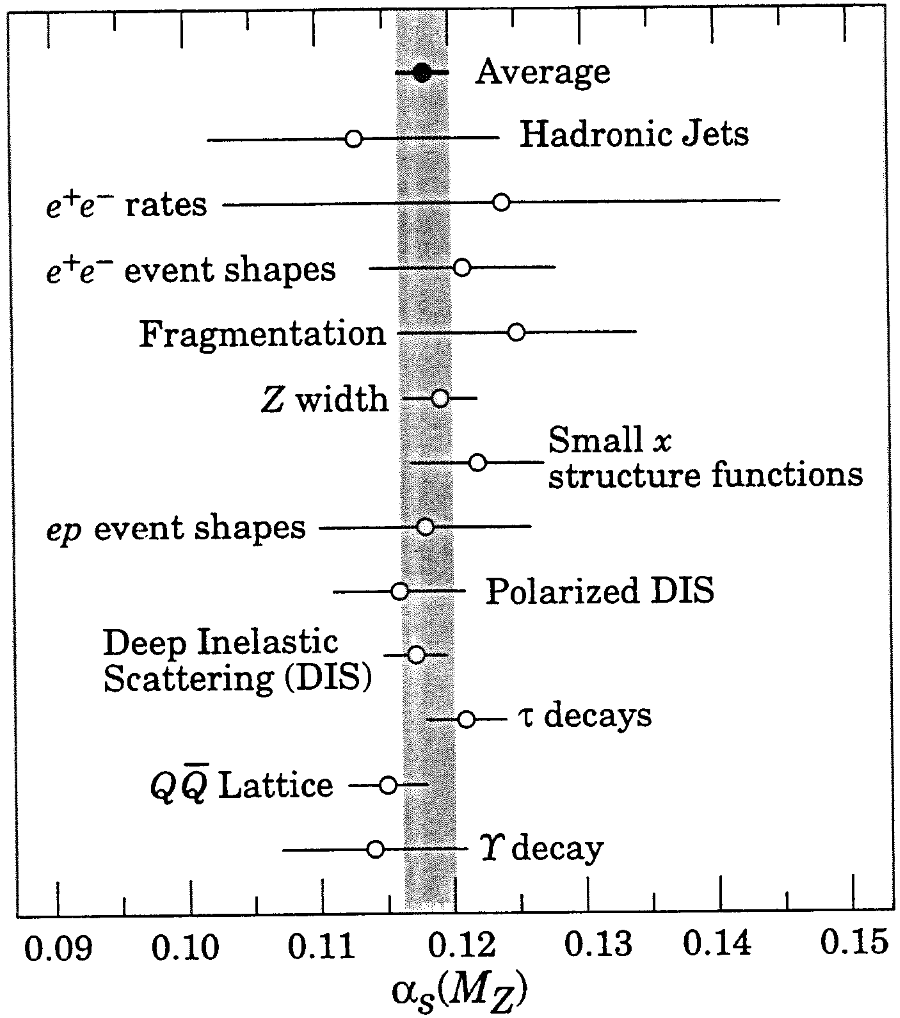
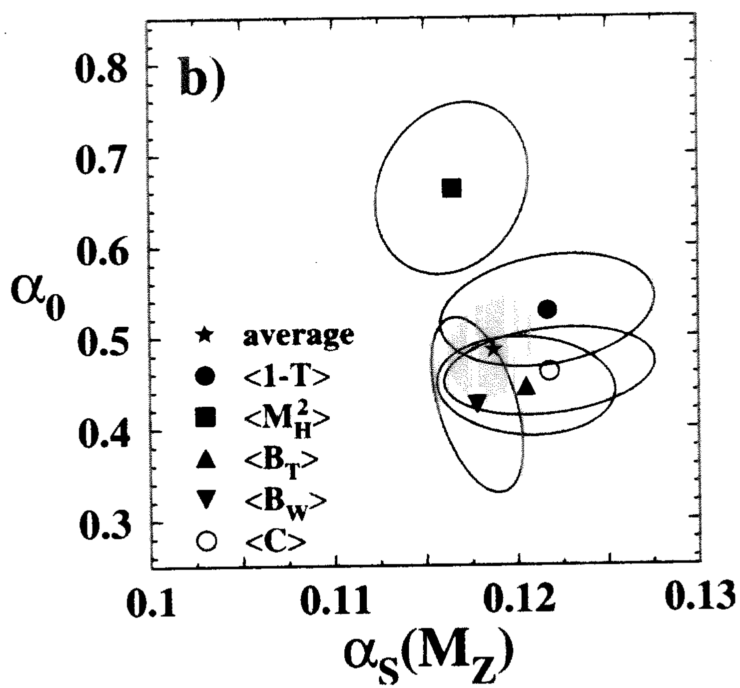


Figure 9.1: Summary of the value of $\alpha_s(M_Z)$ from various processes. The values

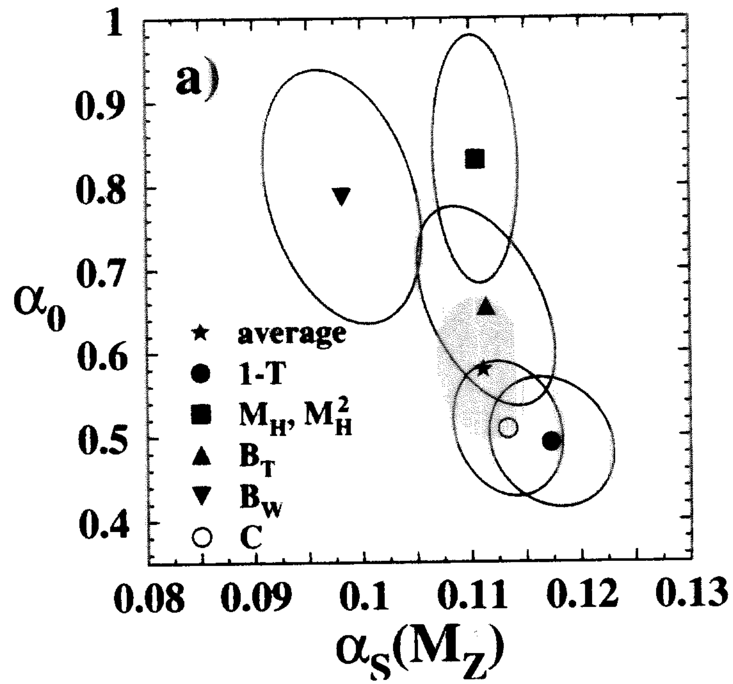
Mean Values



$$\alpha_s(M_Z) = 0.1187 \pm 0.0014 \pm 0.0001 {}^{+0.0028}_{-0.0015}$$

$$\alpha_0(2\ \mathrm{GeV}) = 0.485 \pm 0.013 \pm 0.001 {}^{+0.065}_{-0.043}$$

Distributions



$$\alpha_s(M_Z) = 0.1111 \pm 0.0004 \pm 0.0020 {}^{+0.0044}_{-0.0031}$$

$$\alpha_0(2\ \mathrm{GeV}) = 0.579 \pm 0.005 \pm 0.011 {}^{+0.099}_{-0.071}$$

$$\alpha_S(M_{Z^0}) = 0.1171 {}^{+0.0032}_{-0.0020}, \quad \alpha_0(2\ \mathrm{GeV}) = 0.513 {}^{+0.066}_{-0.045}$$

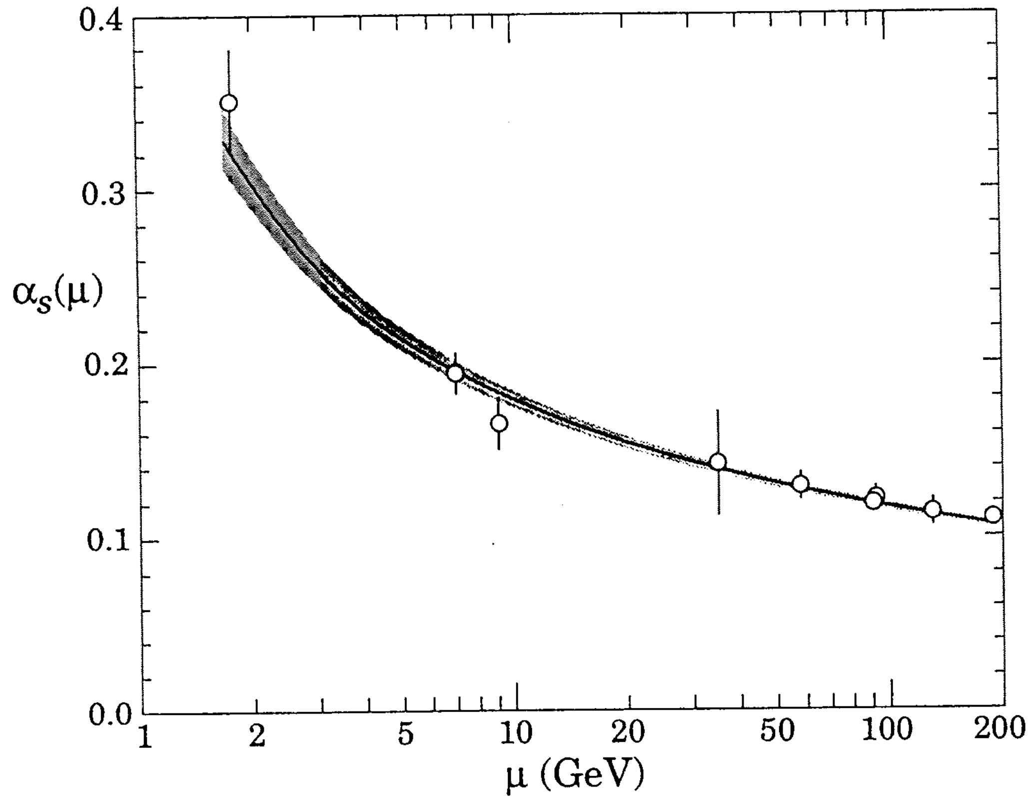
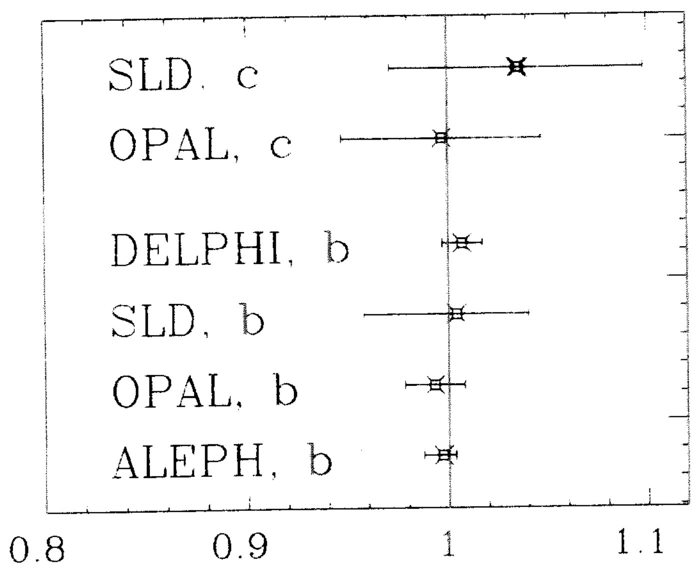


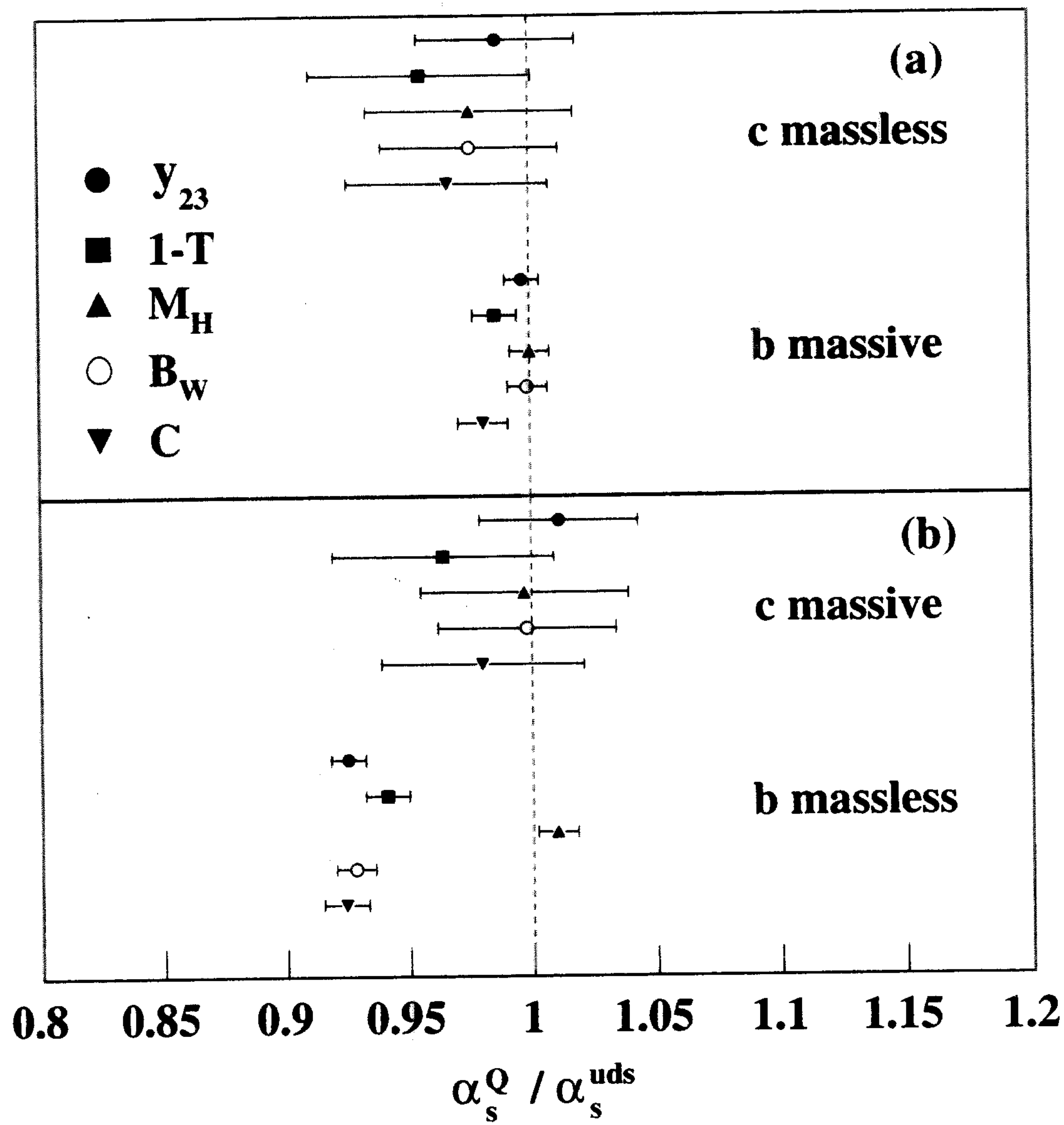
Figure 9.2: Summary of the values of $\alpha_s(\mu)$ at the values of μ where they are measured. The lines show the central values and the $\pm 1\sigma$ limits of our average. The figure clearly shows the decrease in $\alpha_s(\mu)$ with increasing μ. The data are, in increasing order of μ, τ width, deep inelastic scattering, Υ decays, e^+e^- event rate at 25 GeV, event shapes at TRISTAN, Z width, e^+e^- event shapes of M_Z, 135, and 189 GeV.

OPAL

Flavour independence of the strong coupling

$\alpha_S^{(b/c)}/\alpha_S^{(uds)}$ is much more consistent with 1 if heavy flavour mass effects are included





- Z peak data (1991/1995)
- hadronization corrections: Montecarlo models (fixed color factors)

OPAL:

$C_A = 3.02 \pm 0.25 \pm 0.49$

$C_F = 1.34 \pm 0.13 \pm 0.22$

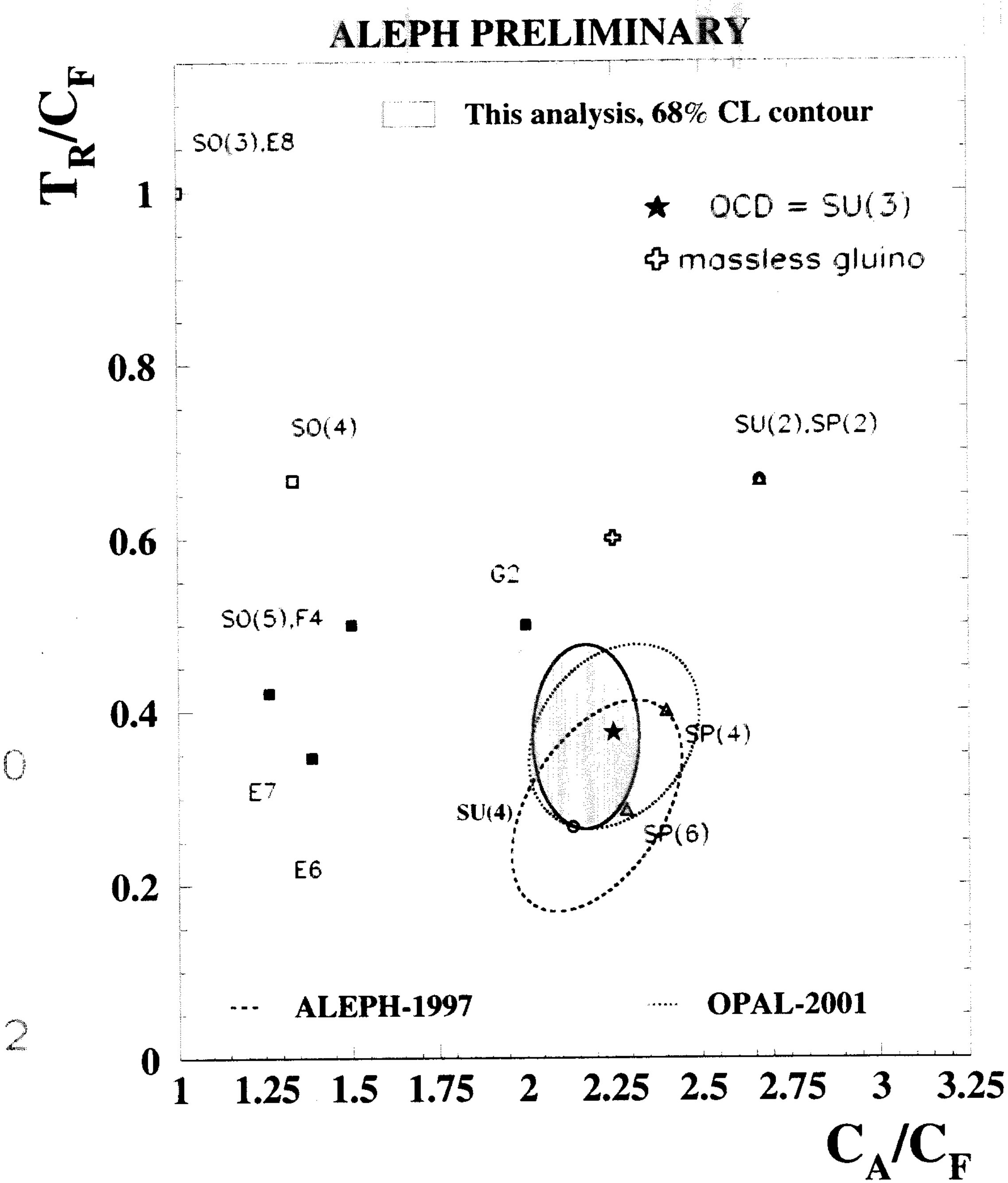
$\alpha_S(M_Z) = 0.120 \pm 0.011 \pm 0.020$

ALEPH:

$C_A = 2.93 \pm 0.14 \pm 0.49$

$C_F = 1.35 \pm 0.07 \pm 0.22$

$\alpha_S(M_Z) = 0.119 \pm 0.006 \pm 0.022$



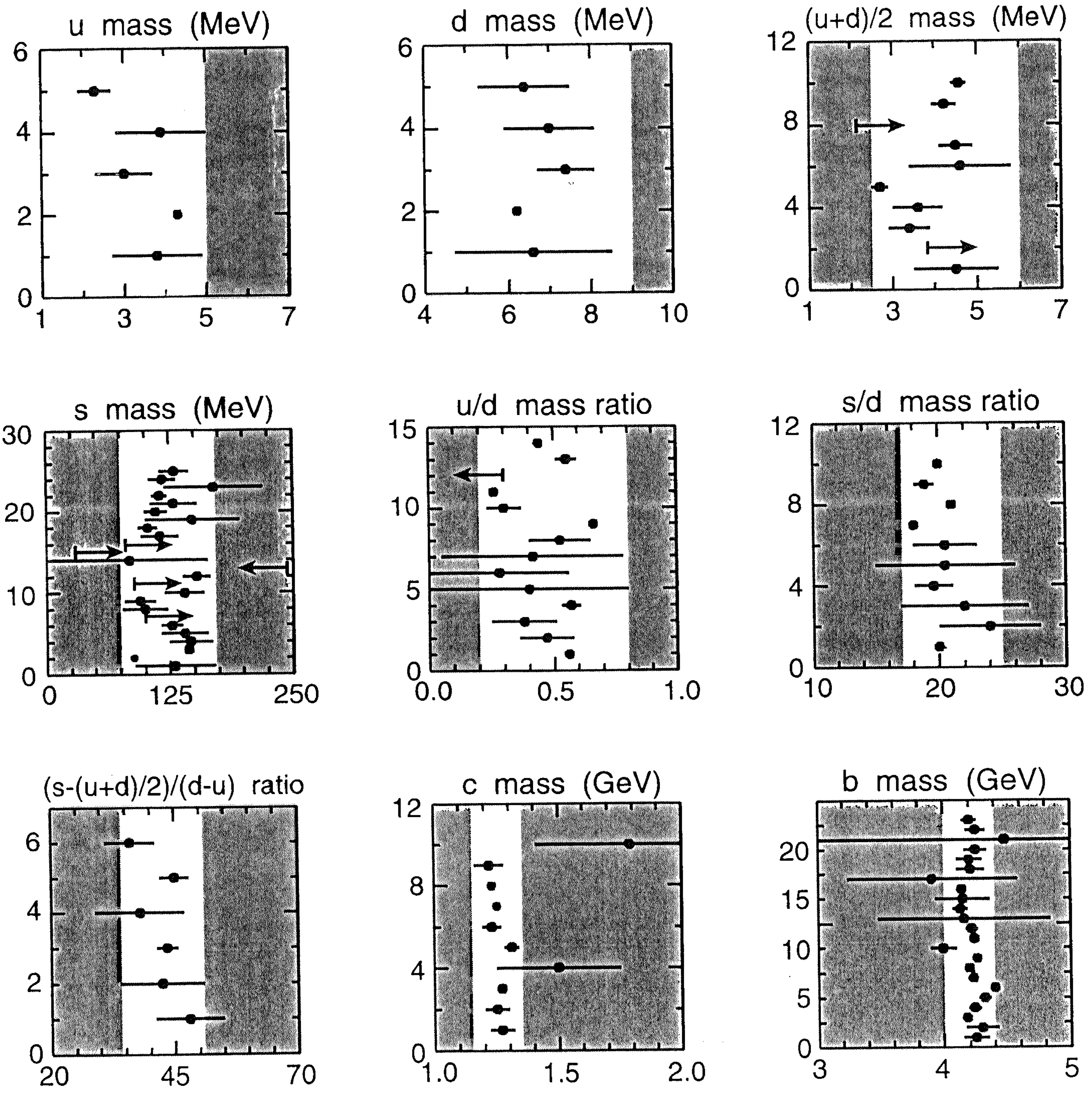


Figure 1: The values of each quark mass parameter taken from the Data Listings. Points from papers reporting no error bars are colored grey. Arrows indicate limits reported. The grey regions indicate values excluded by our evaluations; some regions were determined in part though examination of Fig. 2.

PARTON PICTURE

Proton : not elementary

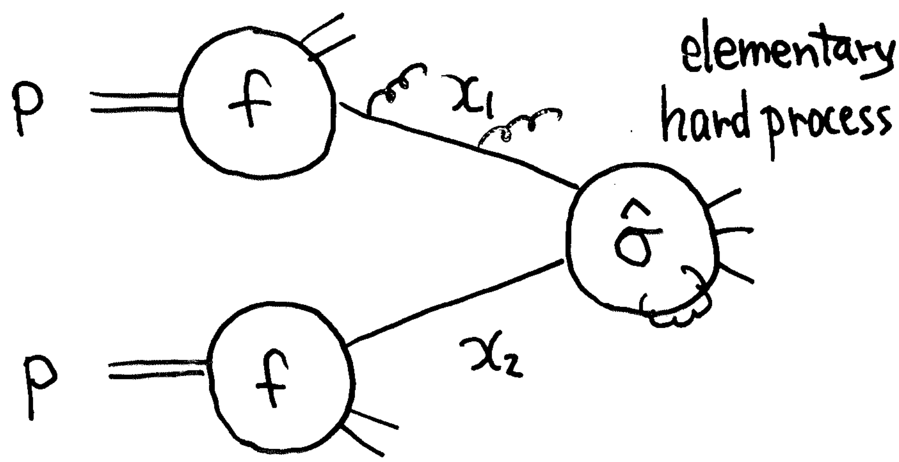
→ need "wave function"

structure functions

parton distribution functions (PDF's

calculable in principle

have to be measured in practice



$$d\sigma = \int dx_1\, dx_2\, f(x_1)\, f(x_2)\, d\hat{\sigma}(\hat{s} = s x_1 x_2)$$

PARTON PICTURE

Proton : not elementary

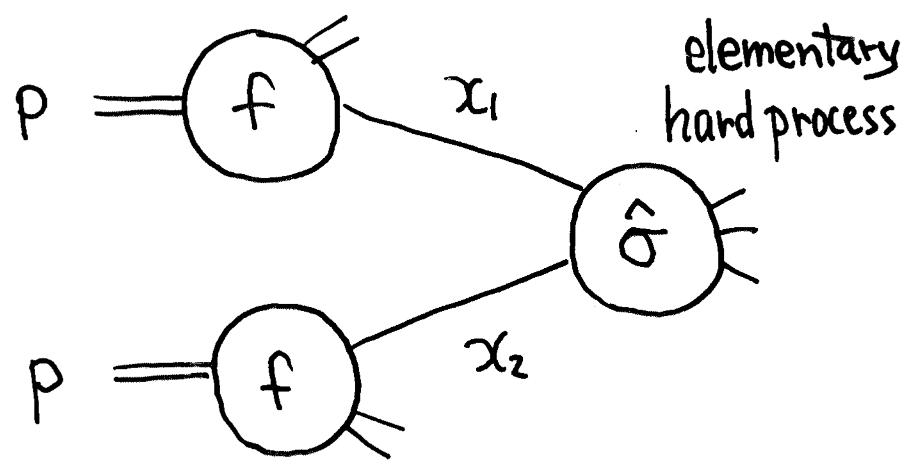
→ need "wave function"

structure functions

parton distribution functions (PDF's

calculable in principle

have to be measured in practice



$$d\sigma = \int dx_1\, dx_2\, f(x_1)\, f(x_2)\, d\hat{\sigma}(\hat{s} = s x_1 x_2)$$

$$\sigma = \int dx_1\, dx_2\, f(x_1)\, f(x_2)\, \hat{\sigma}(\hat{s} = x_1 x_2 s)$$

$$= \int d\tau\, dy\, f(\sqrt{\tau}\, e^{y})\, f(\sqrt{\tau}\, e^{-y})\, \hat{\sigma}(\hat{s} = \tau s)$$

$$\tau = x_1 x_2$$

$$y = \frac{1}{2} \log \frac{x_1}{x_2} \quad \text{rapidity}$$

$$= \int d\tau\, \hat{\sigma}(\hat{s} = \tau s)\, \frac{d\mathcal{L}}{d\tau}$$

$$\frac{d\mathcal{L}}{d\tau} = \int dy\, f(\sqrt{\tau}\, e^{y})\, f(\sqrt{\tau}\, e^{-y})$$

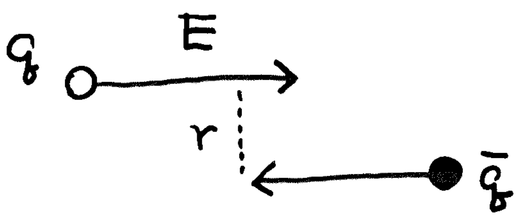
parton luminosity

1/s rule

Interesting cross sections $\lesssim \frac{1}{\hat{s}}$

These processes occur in one or a few angular momentum states

s-channel photon exch $\rightarrow$ $J = 1$

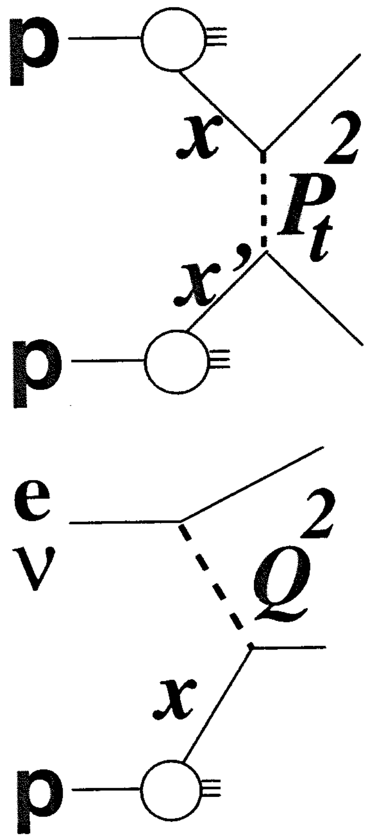


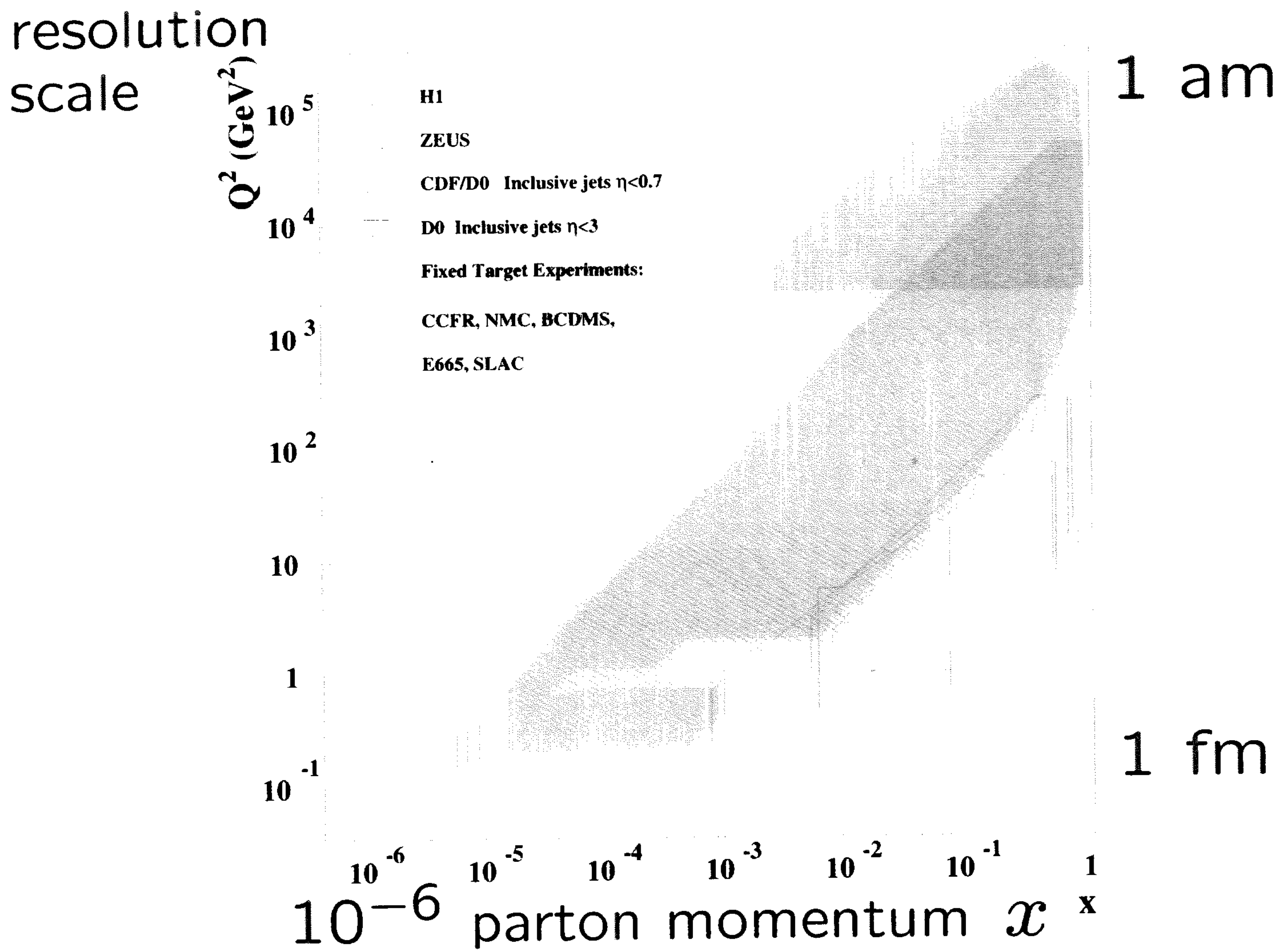
$$L \sim rE \sim 1$$

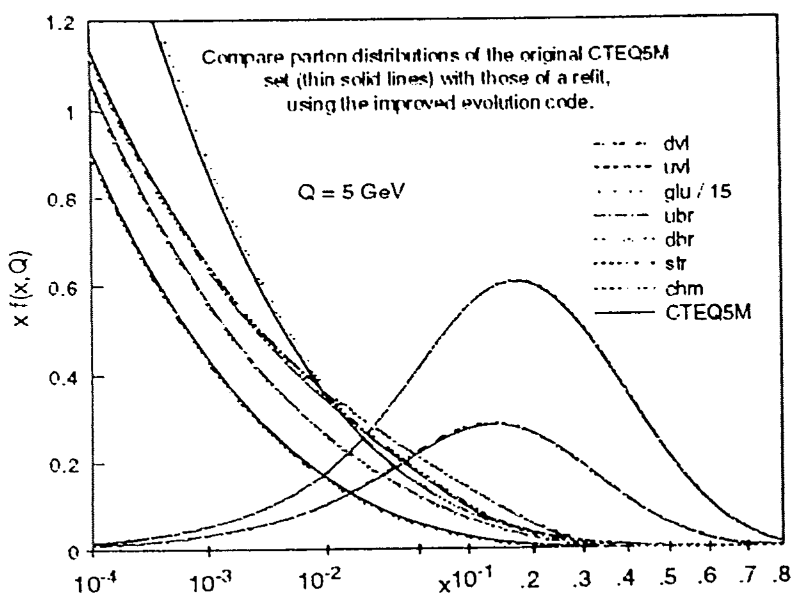
$$\sigma \lesssim 4\pi r^2 \sim \frac{4\pi}{E^2}$$

(partial wave unitarity)

Proton: observables, kinematic reach







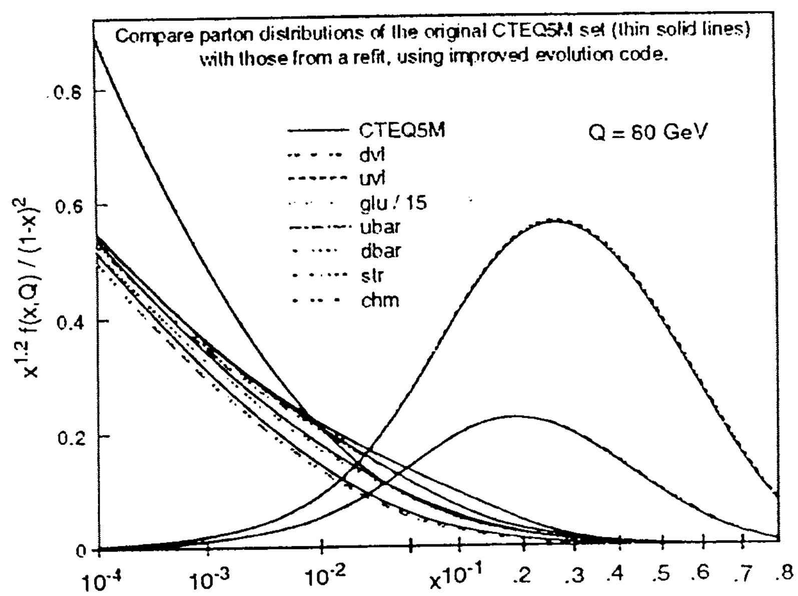
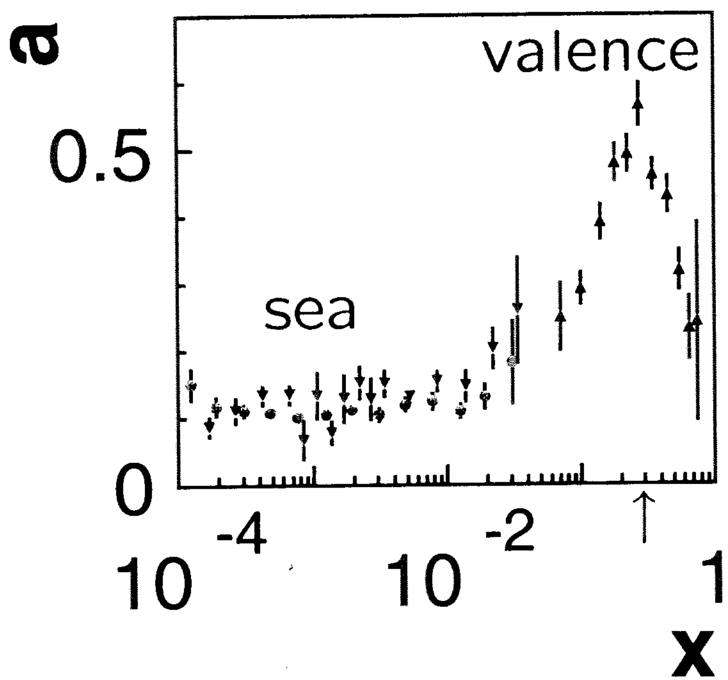


Fig. 7: Comparison of CTEQ5M (original) and CTEQ5M1 (revised) distributions at two energy scales.

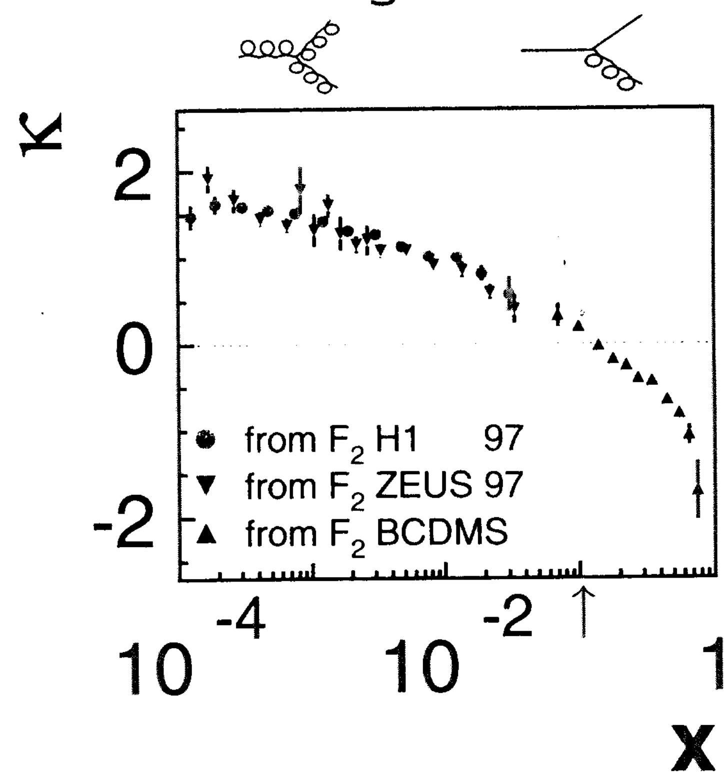
Proton structure

$$F_2(x, Q^2) = \mathbf{a}(x) \left[\ln \frac{Q^2}{\Lambda^2} \right]^{\kappa(x)} , \quad \Lambda = 350\text{MeV}$$

quark distribution
at $Q^2 = 0.3\text{GeV}^2$

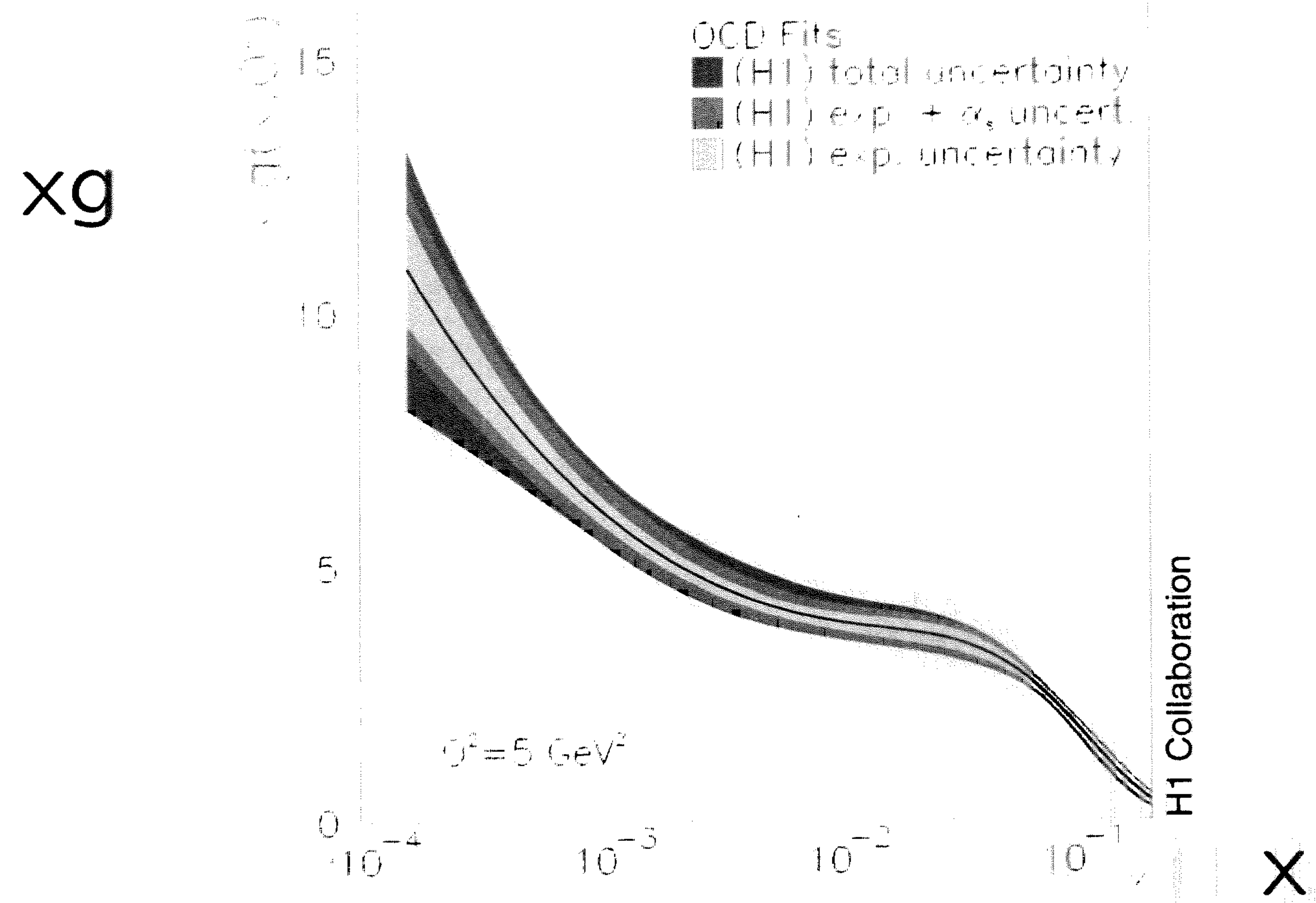


scaling violations



$\Rightarrow$ constant sea, large scaling violations

HERA: gluon in proton



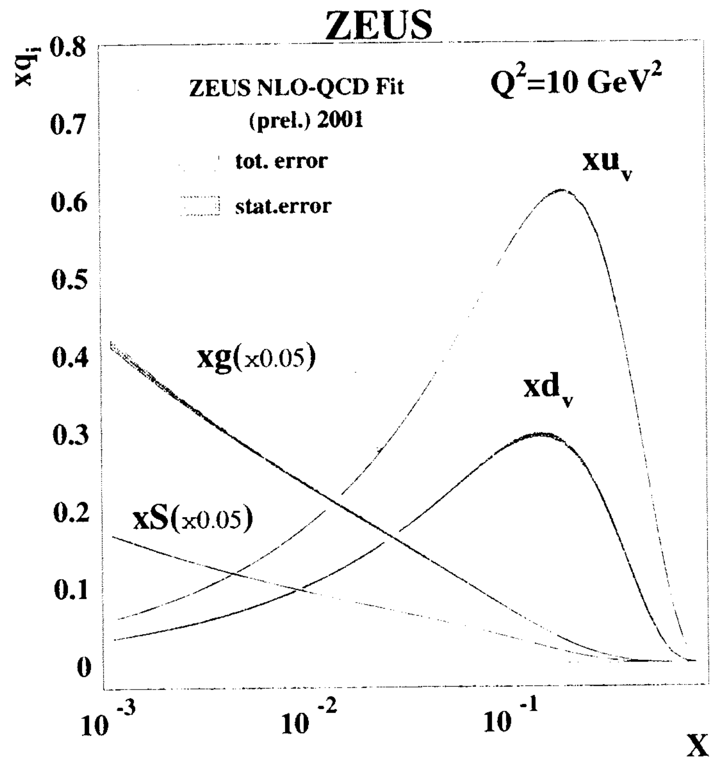
$\Rightarrow$ precision ($Q^2 = 5$GeV^2,$0.001 < x < 0.01$)$\sim$ 10%

Uncertainties in parton distributions

major progress: treatment
of correlated errors

Pascaud, Zomer
Botje
Giele, Keller, Kosower
Pumplin, Stump, Tung
H1
ZEUS
...

xq_i



x

$\Rightarrow$ essential for cross section predictions

e.g. W at LHC: $\Delta\sigma/\sigma = 2 - 4$ %

$|y| \sim 1$. The integrated ratio Eq. (14) is calculated to be

$$\sigma(Z)/\sigma(W^-) = \begin{cases} 0.556 \ \text{(BGOR)}, \\ 0.604 \ \text{(GHR)}, \\ 0.586 \ \text{(HS)}. \end{cases} \tag{18}$$

The difference among the three is less than 10%. Note that the values in Eq. (18) are 50% lower than that in Eq. (17). This comes from the steep decrease of the luminosi-

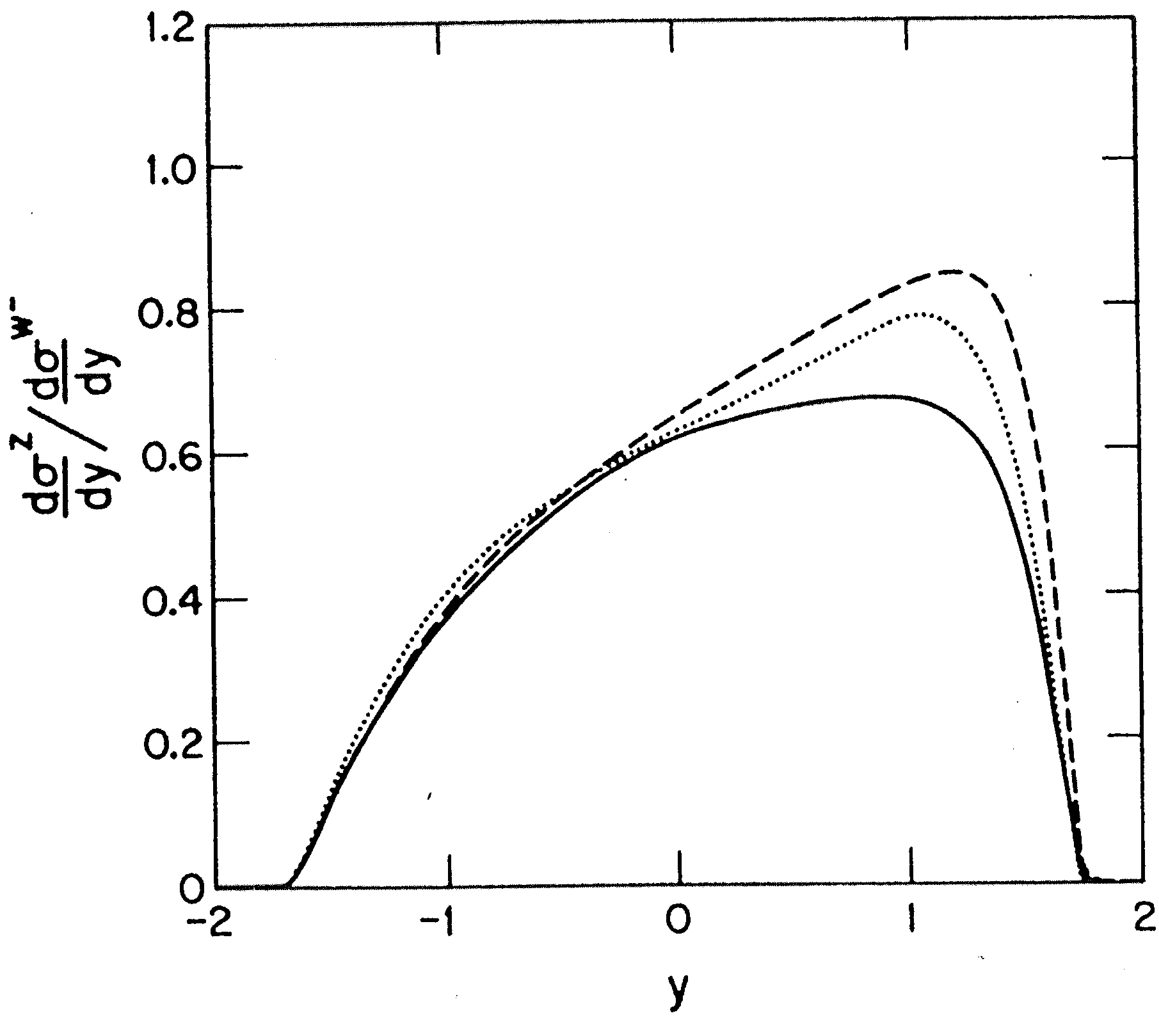


FIG. 3. The ratio of the differential cross section of W and Z at $\sqrt{s} = 540$ GeV as a function of rapidity. Solid (dashed, dotted) curve is calculated using the distribution functions of BGOR (GHR, HS).

関数列の収束

$$\lim_{n\to\infty} f_n(x) = f(x)$$

一様収束

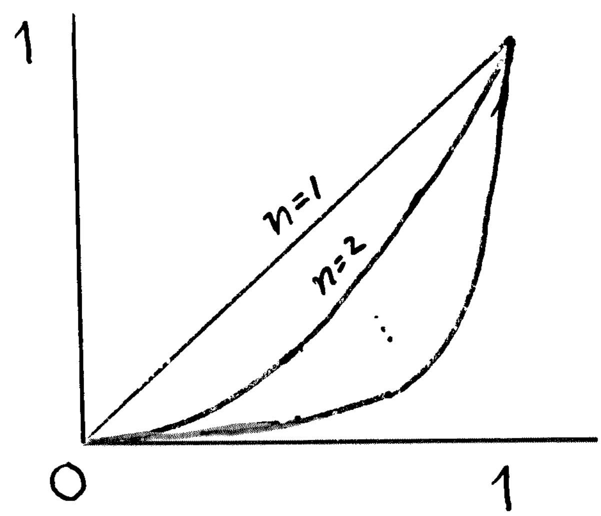
$$\forall \varepsilon > 0 \quad \exists n_0 \quad \forall n \geq n_0 \quad \| f - f_n \| \leq \varepsilon$$

$$\| f \| = \sup | f(x) |$$

$$0 < x < 1 \qquad f_n(x) = x^n$$

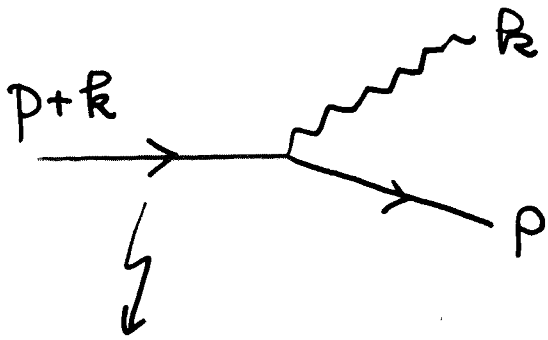
$n \to \infty$ で $x^n \to 0$ に収束するが

一様収束でない



Gauge theory is full of this sort of singular behaviors

Collinear and soft divergences



$$\frac{1}{(p+k)^2-m^2} = \frac{1}{2p\cdot k} = \frac{1}{2p_0 k(1-\beta\cos\theta)}$$

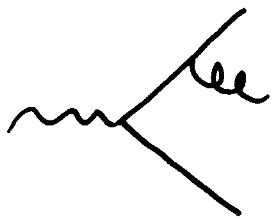
$k \to 0$ infrared singularity

If $m=0$ $\beta = 1$

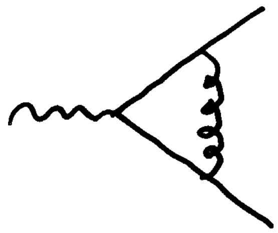
$\cos\theta \to 1$ collinear singularity

Infrared cancellation

Real emission



Virtual correction



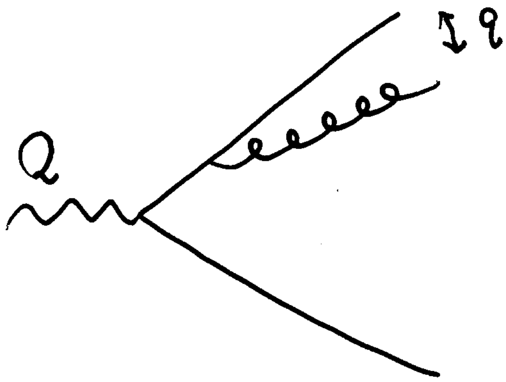
Infrared safe quantities

Perturbative QCD

breaks down at hadron scale.

but. even before getting there,

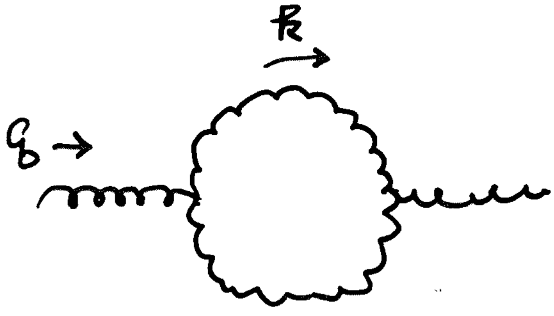
Can encounter large logarithms



$\alpha_s \log \frac{Q}{q}$

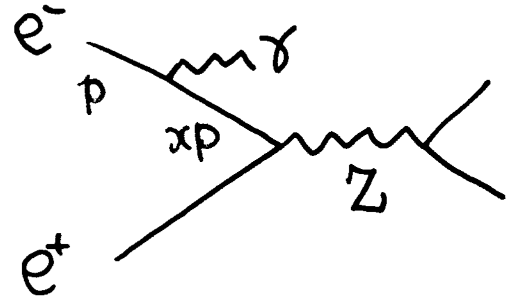
IR insensitive quantities

expect small h.o. corrections



$$\int^{\Lambda} \frac{d^4k}{(k^2+q^2)^2} \sim \log \frac{\Lambda^2}{q^2}$$

Initial radiation



$$\sigma(s) = \int dx\, F(x)\, \sigma_0(xs)$$

↑ $\alpha \log \frac{s}{m_e^2}$

QED F(x) can be calculated

QCD s dependence of F(x) can be calculated

Perturbative structure

expansion in α_s

logarithms. resummations

Power suppressed corrections

quark mass effects

$\langle G^2 \rangle$. higher twist

hadronization

Double parton scattering

Event overlap

$$\sigma = \sigma_0 \Big[1$$

$$+ \alpha_s \log + \alpha_s$$

$$+ \alpha_s^2 \log^2 + \alpha_s^2 \log + \alpha_s^2$$

$$+ \alpha_s^3 \log^3 + \alpha_s^3 \log^2 + \alpha_s^3 \log + \alpha_s^3$$

$$+ \cdots$$

↑ LL ↑ NLL

Remarkable progress in NNLO calculations

Current goal: jet production in hadronic collisions.

- Double soft limit (Berends and Giele, 1989)
- Double collinear and soft-collinear (Campbell and Glover, 1998; Catani and Grazzini, 1999; Del Duca, Frizzo and Maltoni, 2000)
- $2 \to 3$ amplitude at one loop level (Bern, Dixon and Kosower, 1993; Kunszt, Signer and Trócsányi, 1994).
- Collinear limit of one loop amplitudes (Bern, Dixon, Dunbar and Kosower, 1994; Kosower, 1999; Kosower and Uwer, 1999)
- Soft limit of one loop amplitudes (Bern, Del Duca, Schmidt, 1998; Bern, Del Duca, Kilgore and Schmidt 1999; Catani and Grazzini, 2000)
- Some analytic phase space integrals (Gehrman, Glover; Catani, de Florian, Grazzini)

The two loop $2 \to 2$ contribution recently computed (Anastasiou, Glover, Oleari, Tejeda-Yeomans; 2001).

Recursion relations among feynman integrals reduce the problem to the computation of a small number of master integrals.
The hardest of those (double box, planar and crossed) only recently solved (Smirnov, 1999; Tausk, 1999).

All ingredients needed for a full NLO computation of jet cross sections in hadronic collisions are in place now.

The implementation into a useful result is still a formidable task.
But it does not look far...

RESUMMATIONS

"Standard" resummations

UV log → running coupling

Collinear radiation → PDF scaling violation

Threshold

$\frac{\alpha_s}{\beta} \sim 1$ → resum Coulomb gluon exch.

Small p_T

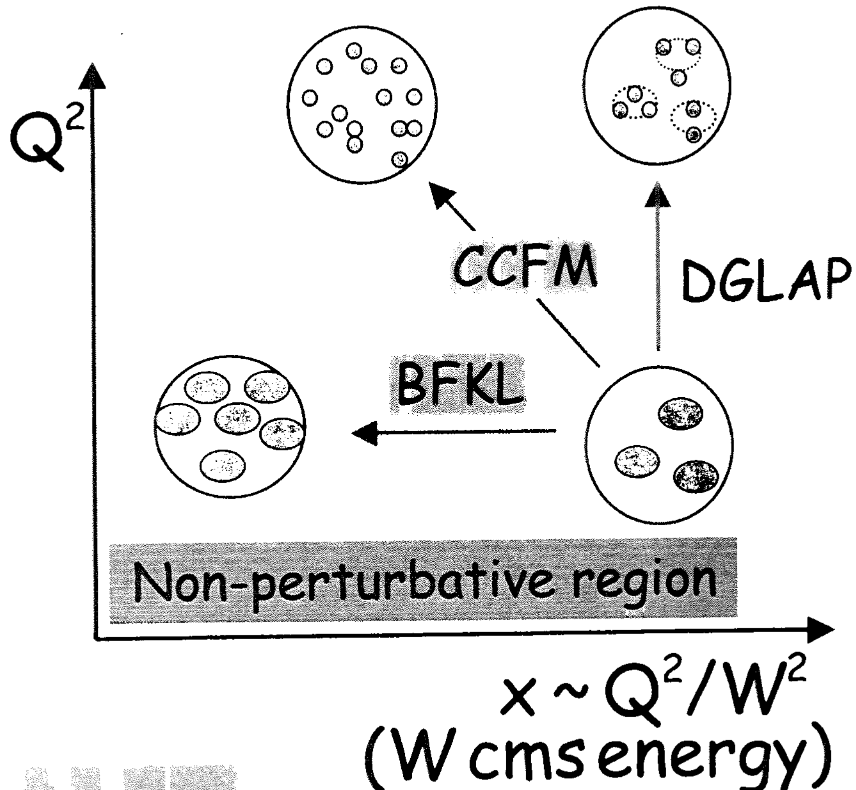
Sudakhov double log

Small x

resum $\alpha_s \log x$ BFKL

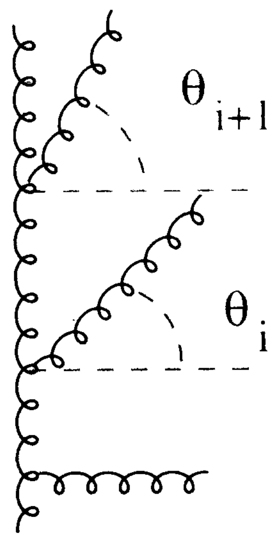
Mini-Introduction: Parton Evolution

Let's look inside the proton:



DGLAP Dokshitzer, Gribov. Lipatov, Altarelli, Parisi (72-76)

- describes change of parton densities with varying spatial resolution
- resums terms $\sim \alpha_s \log Q^2$
- assumes strong ordering of parton k_T



CCFM Catani, Ciafaloni Fiorani, Marchesini (88-90)

- Interpolates DGLAP/BFKL
- Angular ordering
- includes colour coherence for small z: random k_T walk

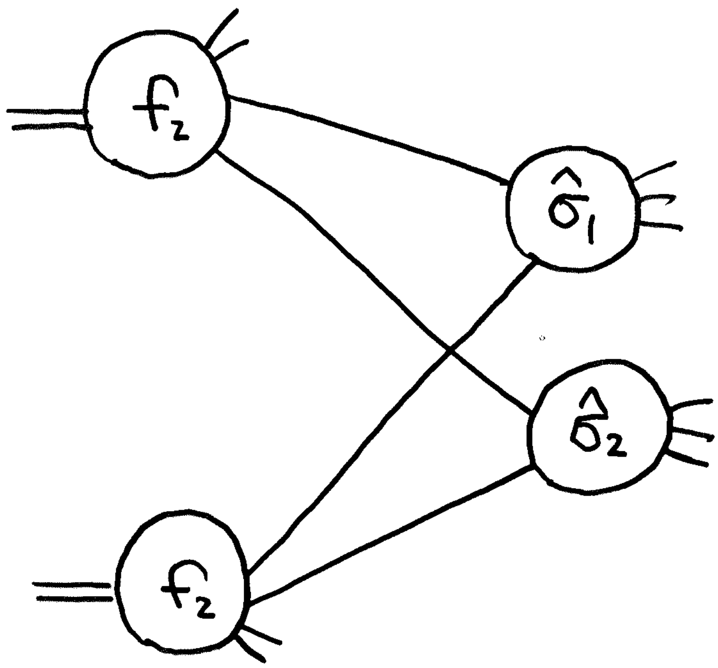
implemented in **CASCADE/LDC** MC:

Jung, Salam (2000)
Lönnblad et al. (98-01)

BFKL

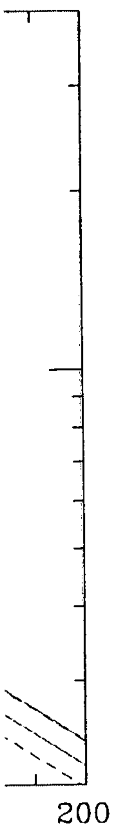
- describes how high momentum parton is dressed by a cloud of gluons localised in fixed transverse spatial region
- resums terms $\sim \alpha_s \log 1/x$ (should be large at small-x)
- diffusion pattern i.e. no k_T ordering

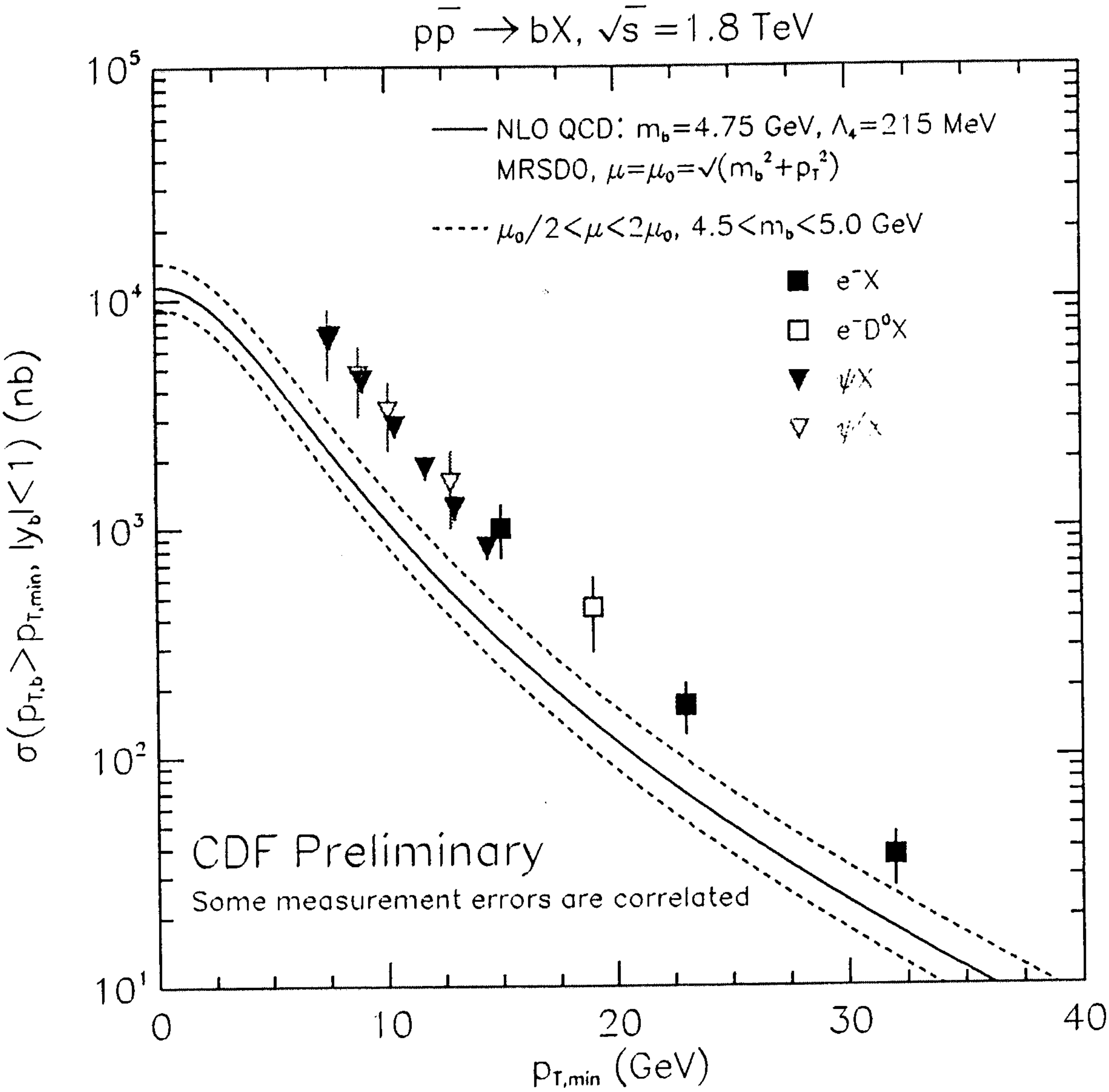
DOUBLE PARTON SCATTERING



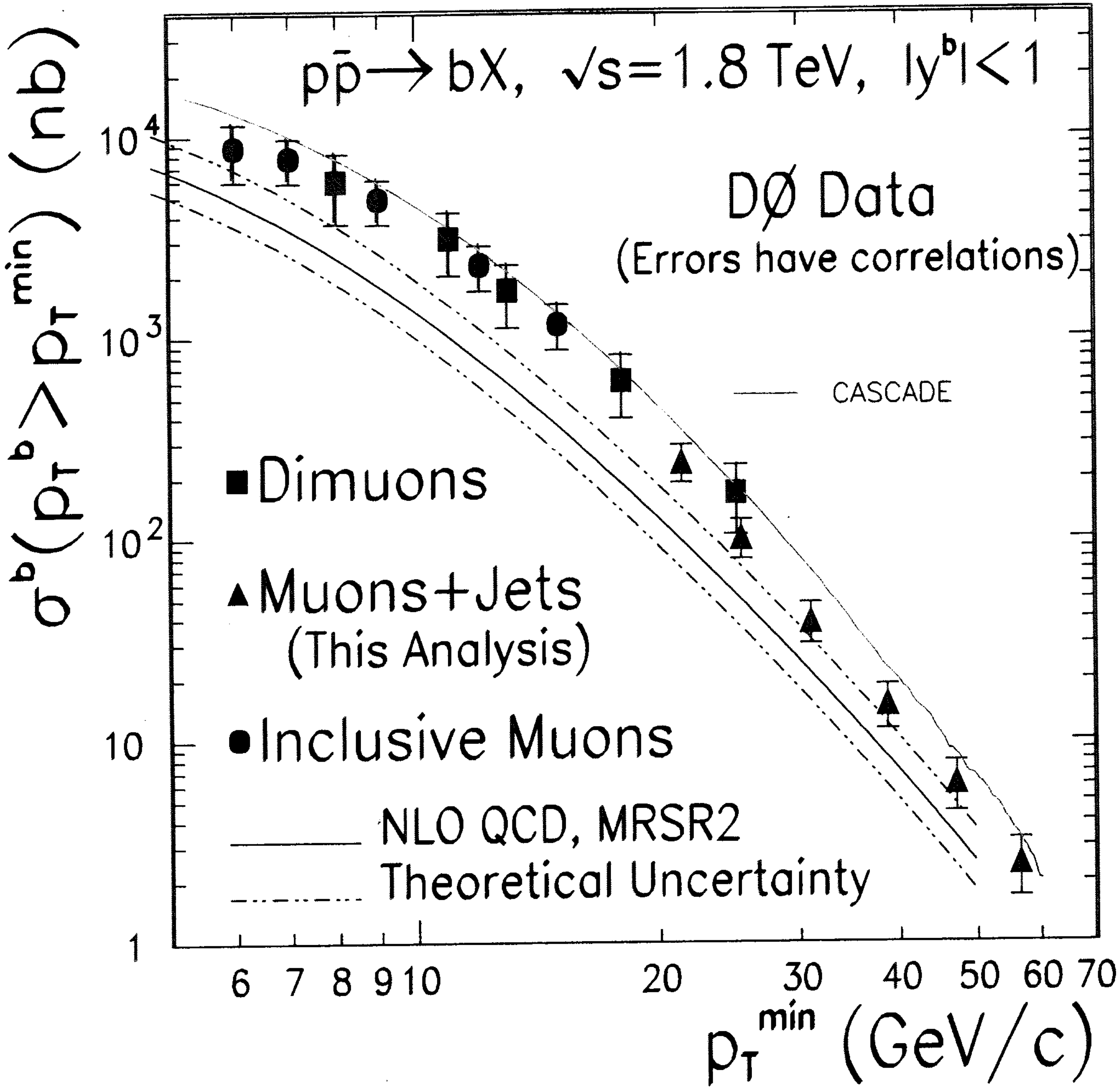
$$\sigma \sim \hat{\sigma}_1 \hat{\sigma}_2 R^2$$

$R \sim$ proton size


200


pp̄ → bX, √s = 1.8 TeV
NLO QCD: m_b=4.75 GeV, Λ_4=215 MeV
MRSD0, μ=μ_0=√(m_b^2+p_T^2)
μ_0/2<μ<2μ_0, 4.5<m_b<5.0 GeV
e⁻X
e⁻D⁰X
ψX
ψ'X
CDF Preliminary
Some measurement errors are correlated
σ(p_T,b > p_T,min, |y_b|<1) (nb)
p_T,min (GeV)
0
10
20
30
40
10^1
10^2
10^3
10^4
10^5

B-Production at the TEVATRON



NLO too low
CASCADE/CCFM better

Cascade:

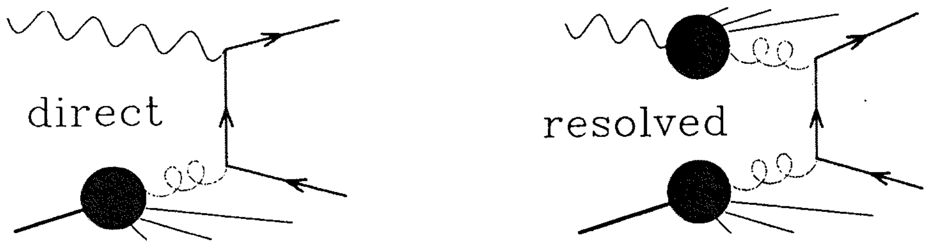
- Fit unintegrated gluon to HERA data
- Use off-shell matrix elements
- Obtain prediction for pp-cross section

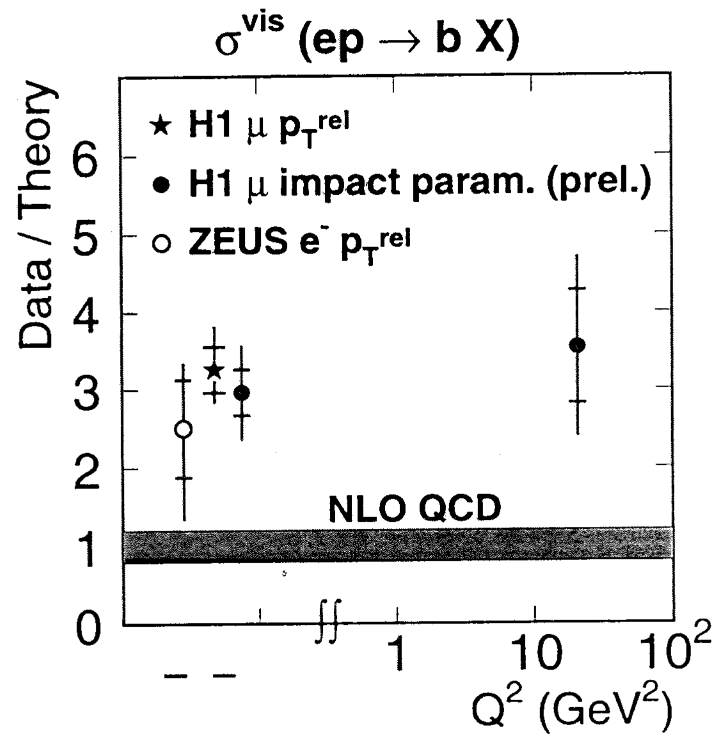
b excess at HERA

New H1 results confirm previous findings:

- $\sigma(b)$ from impact parameter fit in photoproduction
- $\sigma(b)$ in DIS

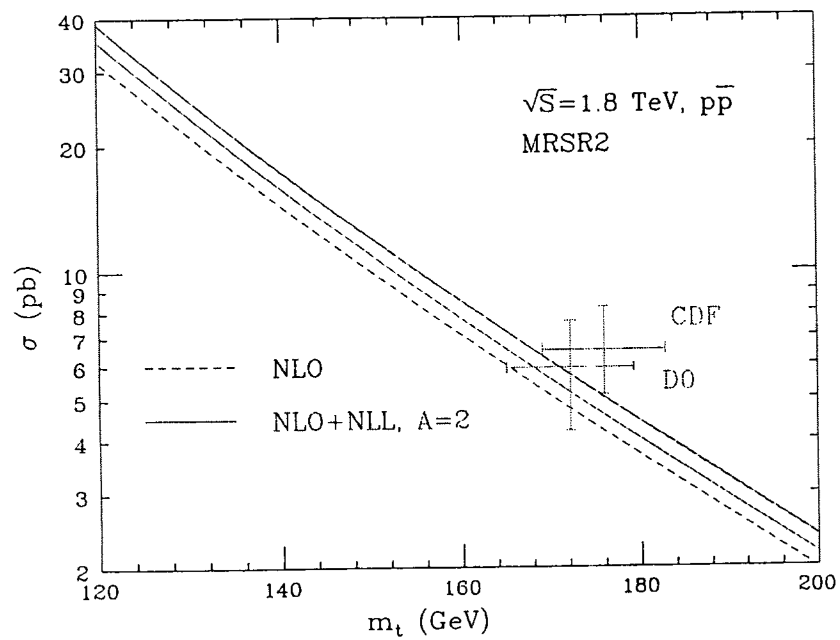
both in excess over QCD calculations.

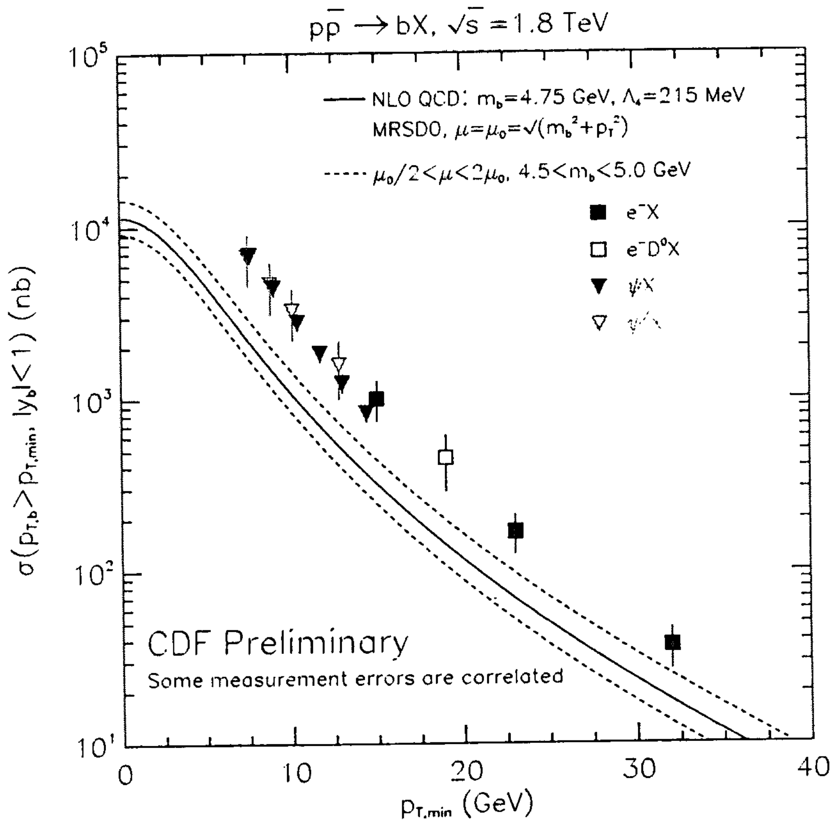




Theoretical uncertainties are small. In DIS production, no resolved contribution. Similarities with $\gamma\gamma$ result.

Very difficult to justify!


√S=1.8 TeV, pp̄
MRSR2
NLO
NLO+NLL, A=2
CDF
D0
σ (pb)
m_t (GeV)


pp̄ → bX, √s = 1.8 TeV
NLO QCD: m_b=4.75 GeV, Λ_4=215 MeV
MRSD0, μ=μ_0=√(m_b²+p_T²)
μ_0/2<μ<2μ_0, 4.5<m_b<5.0 GeV
e⁻X
e⁻D⁰X
ψX
CDF Preliminary
Some measurement errors are correlated
σ(p_T,b>p_T,min, |y_b|<1) (nb)
p_T,min (GeV)