SUMMARY
DIS-97

- The Conference
  - Thanks to the Organizing Committee and to Argonne
  - Enriched by participation of hadron-hadron, e^+e^- communities

- Outline
  1. Introduction: the past year
  2. Those events
  3. Perturbative QCD in DIS & Beyond: 1996-7
  4. Other factorizations: new densities, new evolutions
  5. Openings to nonperturbative QCD
  6. Where are we now?

1. INTRODUCTION: IMPRESSIONS OF THE PAST YEAR FOR DIS (sketch)

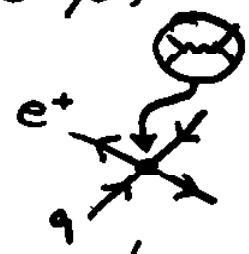
- Culminations of classic experiments: EMC, SMC, CCFR, E154...
- Increased precision for HERA's 'signature' small-x F_2
- Increases in coverage at HERA
  - large x and Q^2 (!)
  - jet(s)...
  - coming of age for diffraction, photoproduction
  - HERMES warming up
- Theory
  - Coming to grips with requirements of "precision QCD" $\Rightarrow$
  - Drive to higher order; Perturbative-nonperturbative interface
  - Reviving old ideas, inventing new directions
  - struggling to keep up!

selected illustrations follow...

2. THOSE EVENTS

- "Out of the blue" ... "about time"
  Dokshitzer

- Seem to be just consistent with other experiments (narrow window) (assumption-dependent) bounds on masses, spin, couplings, branching ratios:
  - high energy expts: Tevatron (LQ)
    LEPII (contact)
  - precision low energy:
    atomic parity, double-β, rare K

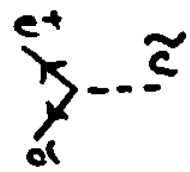


- Popular interpretations

$$\mathcal{L}_{contact} = \sum_{\substack{i,j=L,R \\ q=u,d}} \frac{\eta_{ij}}{(\Lambda_{ij})^2} \bar{e}_i \gamma_\mu e_i \, \bar{q}_j \gamma^\mu q_j$$

$$\mathcal{L}_{\not{R} SUSY} = \lambda'_{ijk} L_i Q_j D_k$$

$\hookrightarrow$ bounds $\lambda_{121} e^+ d \tilde{c}$



Blumlein
Wang
Kalinowski
Zeppenfeld
Lola
Kuhlmann

Should $\left\{ \begin{array}{c} \text{go away} \\ \text{show up elsewhere} \end{array} \right\}$ soon

Good!

Natural Questions

1. Relation to high-E_T Jets at Tevatron
2. Really a 'bump' in H1 data?
3. Evolved $\delta\alpha(x \approx 1, Q_0^2 \sim 1) \ll 1$
4. "Standard model" of evolution inadequate for $x \to 1$, $Q^2 \to \infty$?

III. PERTURBATIVE QCD: DIS AND BEYOND

3.1 The Basics: How PQCD Works

- IR Safety

$$Q^2 \hat{\sigma}(Q^2) = \sum_{n \geq 0} c_n(Q^2/\mu^2)\, \alpha_s(\mu^2)$$

$$\sigma_{tot}^{e^+e^-}, \quad \sigma_{jet}^{e^+e^-}, \quad \sigma_T^{e^+e^-}$$

- Factorization

$$Q^2 \sigma(q,p,m) = \int_x^1 d\xi\, \hat{\sigma}\left(\frac{Q^2}{p_T \xi p\cdot q}, \frac{Q^2}{\mu^2}, \alpha_s(\mu)\right) \cdot \phi_{NP}(\xi, \mu, m, \Lambda \ldots)$$

$$\equiv \hat{\sigma} \otimes \phi + \mathcal{O}\left(\frac{1}{Q^2}\right)$$

μ factorization scale

$F_{2,L}$, σ_{DY}, $\sigma_{h+h' \to 2J+\ldots}$

Levin: check the proof!

- Evolution

$$\mu \frac{d\sigma}{d\mu} = 0$$

$$\Downarrow$$

'separation of variables'

$$\left.\begin{aligned} \mu \frac{d\hat{\sigma}}{d\mu} &= -\hat{\sigma} \otimes P(\alpha_s(\mu)) \\ \mu \frac{d\phi}{d\mu} &= P(\alpha_s(\mu)) \otimes \phi \end{aligned}\right\} + \mathcal{O}\left(\frac{1}{Q^2}\right)$$

DGLAP

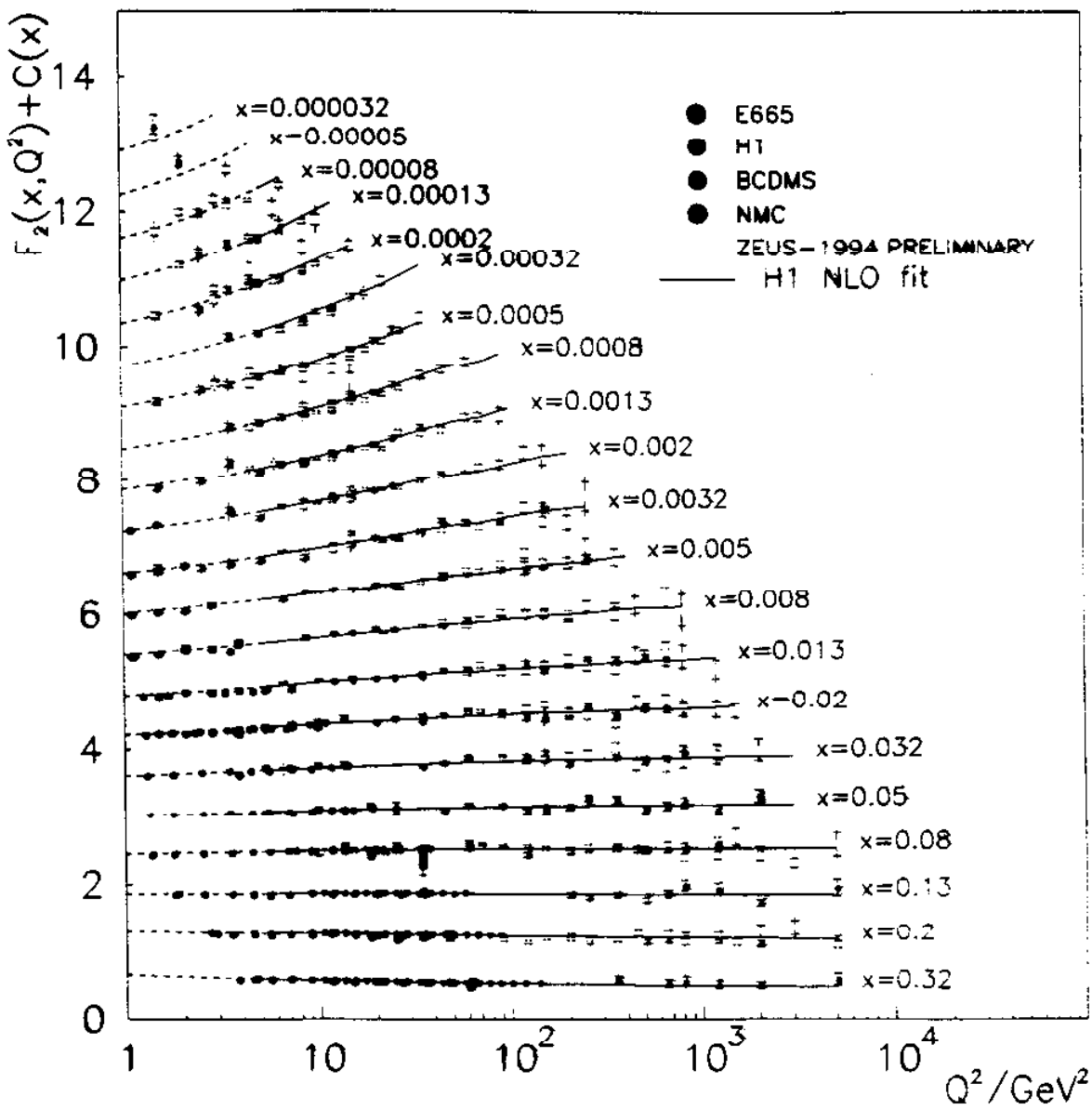
- The data

$$\frac{d\sigma}{dx\,dy} = \frac{2\pi\alpha^2(1+(1-y)^2)s}{Q^4} F_2(x, Q^2)$$

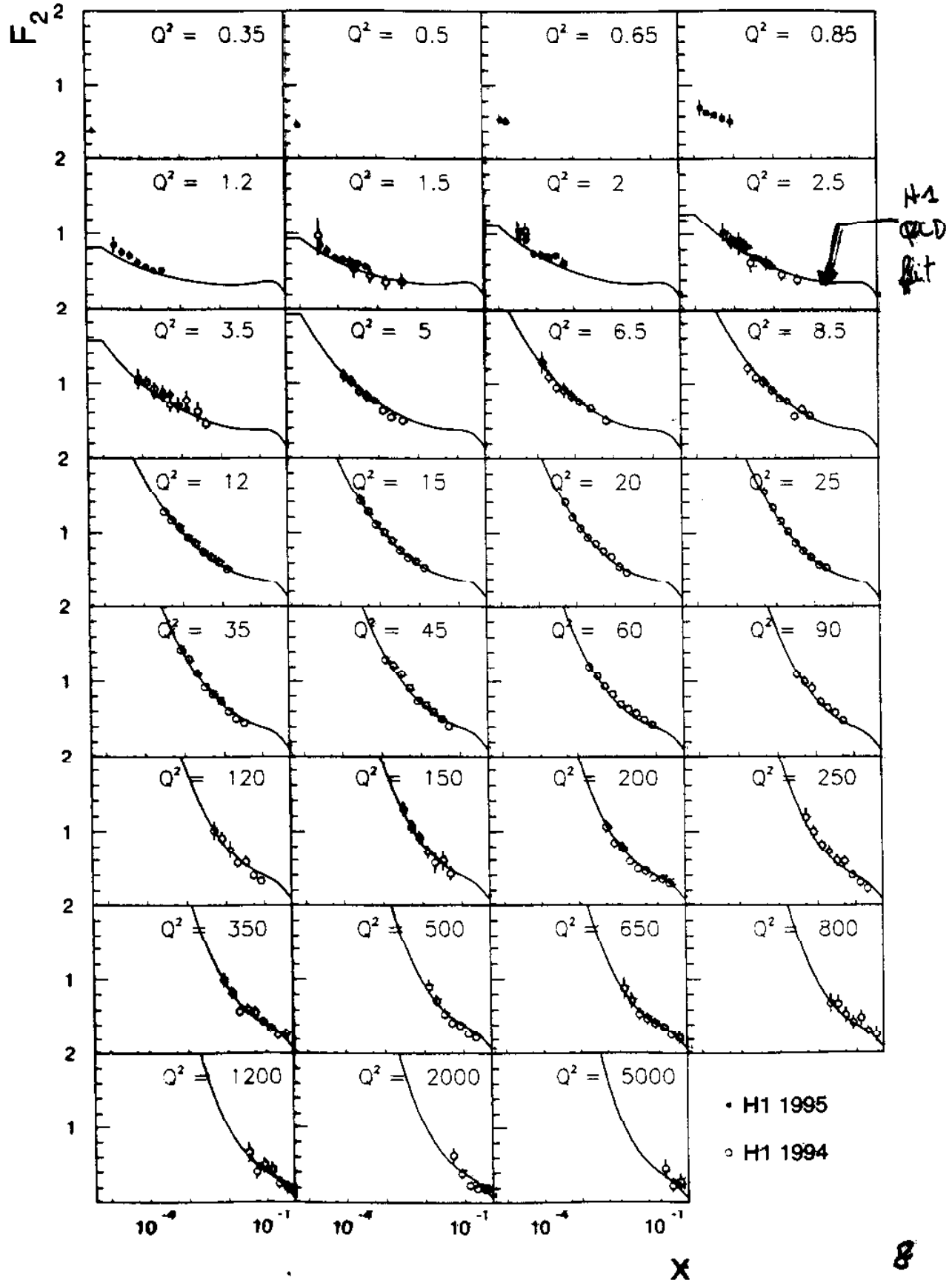
mapping out the rise as $x \to 0$ ...

- A major impact: $\alpha_s(M_Z^2)$ determinations from DIS now predominantly in agreement with e^+e^- at Z mass

Scaling Violations



H1 Results from 94 and 95 data



- **BFKL Equation for DIS**

$$F(x,Q^2) = \int_x^1 \frac{d\xi}{\xi}\, C\left(\frac{x}{\xi}, \frac{\mu^2}{Q^2}\right) G(\xi, Q^2) + \cdots + \mathcal{O}(1/Q^2)$$

$$= \int d^2k_T\, c\left(\frac{x}{\xi}, Q, k_T\right) \psi(\xi, k_T) + \cdots + \mathcal{O}(1/\ln\tfrac{1}{x})$$

$F \sim \mathrm{Im}$

ξ as "factorization scale"

$$G(\xi, Q^2) = \int^{Q^2} d^2k_T\, \psi(\xi, k_T)$$

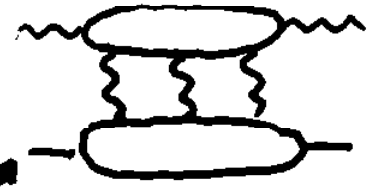
separation of variables

$\Downarrow$

$$\xi \frac{\partial}{\partial \xi} \psi(\xi, k_T) = \int d^2k_T'\, K^{(1)}(k_T, k_T')\, \psi(\xi, k') + \mathcal{O}(1/\ln\tfrac{1}{x})$$

$$\xi \psi(\xi, k_T) = \frac{c}{k_T^{1/2}}\, \xi^{-4N\ln 2\,(\alpha_s/\pi)}$$

at next $1/\ln\frac{1}{x}$:

$K^{(2)}$ and 

two k_T integrals

Fadin
Kotsky
Lipatov new!
Camici
Ciafaloni

Del Duca

$K^{(1)} \to$ all $\alpha_s^n \dfrac{\ln^{n-1} x}{x}$ in $P_{GG}(x, \alpha_s)$

$K^{(2)}$ $\alpha_s^n \dfrac{\ln^{n-2} x}{x}$ ....

- For inclusive DIS, <u>evolution</u> main prediction of QCD
- Between processes, <u>universality</u> of PDFs → predictions
- When universality fails, look for new factorization, evolution, universality "class" (polarized SFs...)

start with...

3.2 Evolution for Unpolarized Structure Functions

Catani
Thorne

- PDFs q, G

$$\mu^2 \frac{\partial}{\partial \mu^2} \begin{pmatrix} q \\ g \end{pmatrix} = \frac{\alpha_s(\mu^2)}{2\pi} \begin{pmatrix} P_{qq} & P_{qg} \\ P_{gq} & P_{gg} \end{pmatrix} \otimes \begin{pmatrix} q \\ g \end{pmatrix}$$

$$\mu^2 \frac{\partial}{\partial \mu^2} q_{ns} = \frac{\alpha_s(\mu^2)}{2\pi} P_{qq}\, q_{ns}$$

$$F_i(x, Q^2) = C_{iq} \otimes q + C_{ig} \otimes g$$

$$C(z) = \delta(1-z) + \frac{\alpha_s(Q^2)}{\pi} C^{(1)}(z) + \cdots$$

- Evolution for structure fns.

simplet to see for NS.

- replace:

$$\begin{cases} F_2^{NS}(Q) = C(\alpha_s(Q^2)) \otimes q_{ns}(Q) \\ \frac{\partial}{\partial \ln \mu^2} q_{ns}(\mu) = \gamma_{ns} \otimes q_{ns}(\mu) \end{cases}$$

by

$$\frac{\partial}{\partial \ln Q^2} F^{NS}(Q) = \left(\frac{\partial \ln C}{\partial \ln Q^2} + \gamma_{ns}\right) \otimes F^{NS}(Q)$$

$$\equiv \hat{\Gamma}_{ns} \otimes F^{NS}$$

- generalization to singlet...

- makes "consistent" treatment
  - retains accuracy at input level for $\ln 1/x$ and $\alpha_s(Q)$ Thorne
  (avoids scheme-dependent complications due to interplay of $C_{q,g}$ and q, g)

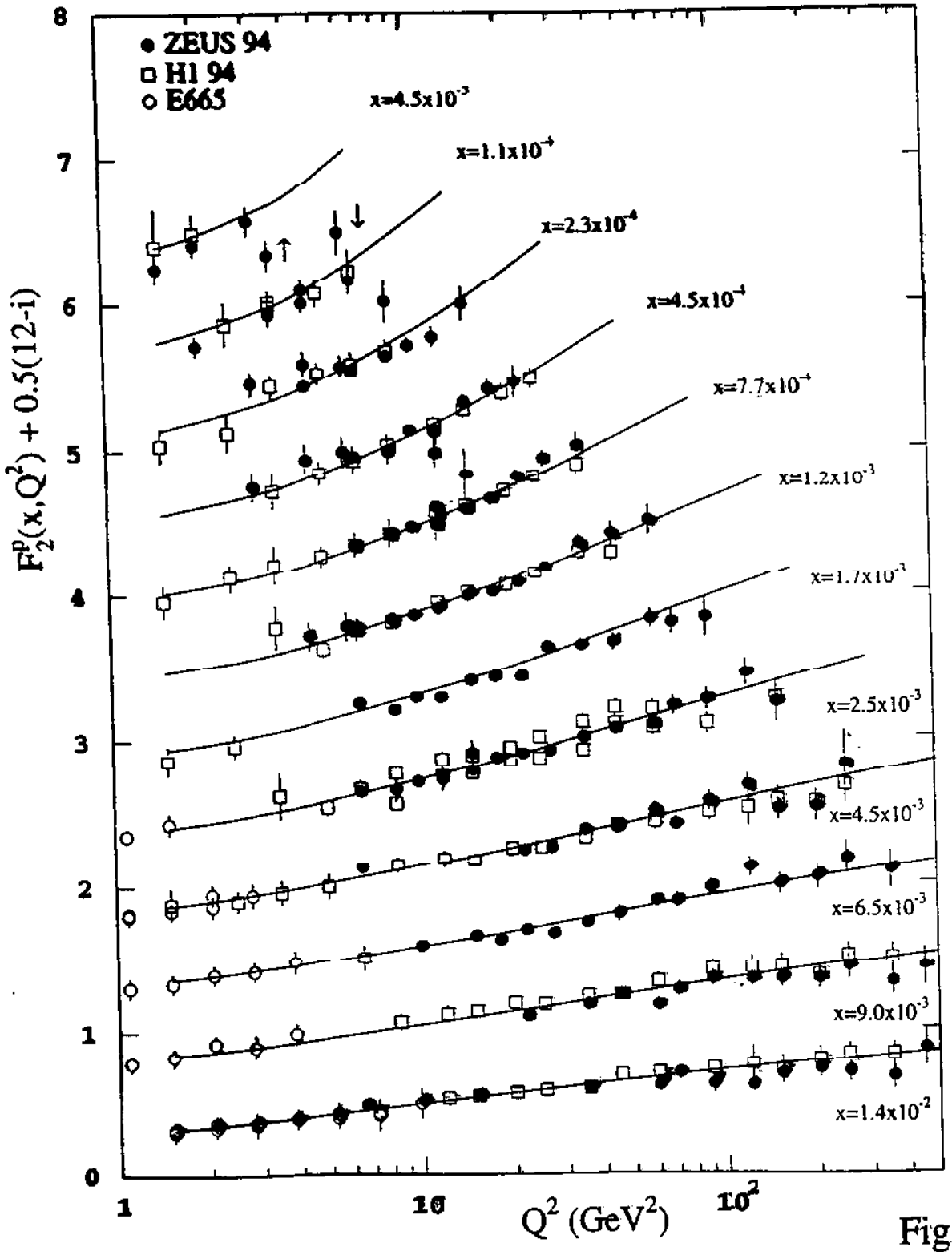


Fig. 2

R. Thorne Rutherford Preprint

- An application to large x, high Q

Laenen
Oderela
G.S.

For $x \to 1$ $\quad F_2 \simeq F_2^{NS}$

relation to $q_{ns}^{\overline{MS}}$:

$$F_2^{NS}(x,Q^2) = \int_x^1 \frac{dy}{y} C\left(\frac{x}{y}, \alpha_s(Q^2)\right) \cdot q_{ns}^{\overline{MS}}(y,Q^2)$$

in moments

$$\tilde{F}_2^{NS}(N,Q^2) = \int_0^1 dx\, x^{N-1} F(x,Q^2)$$

$$= \tilde{C}(N,\alpha_s(Q^2))\, \tilde{q}_{ns}^{\overline{MS}}(N,Q^2)$$

resummation $\left(\frac{\ln^n(1-x)}{1-x} \hookrightarrow \ln^{n+1} N\right)$

$$\tilde{C}(N,\alpha_s(Q^2)) = \exp\left[-C_F \int_0^1 dx\, \frac{x^{N-1}-1}{1-x} \int_{(1-x)}^1 \frac{dy}{y} \frac{\alpha_s(yQ^2)}{\pi} + \dots\right]$$

$$\sim \exp\left[C_F \frac{\alpha_s(Q^2)}{2\pi} \ln^2 N + \dots\right]$$

→ enhaces F_2^{NS} relative to $\phi^{\overline{MS}}$

→ slows down evolution for F_2^{NS}

$$\frac{\partial}{\partial \ln Q^2} F^{NS} = \left(\frac{\partial \ln C}{\partial \ln Q^2} + \gamma_{ns}\right) \otimes F^{NS}$$

in moments

„part of Std Model"

$$\frac{\partial}{\partial \ln Q^2} \tilde{F}^{NS}(N) = \left(\frac{C_F}{2\pi} \underbrace{\frac{\partial \alpha_s(Q^2)}{\partial \ln Q^2}}_{\sim 0} \ln^2 N + \gamma(N)\right) \tilde{F}^{N}(N) + \dots$$

3.3 PDFs & Global fits

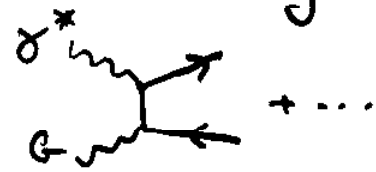
(1997 – the year of the quark mass)

MRRS (Roberts), ACOT, Lai, Oldness, Tung

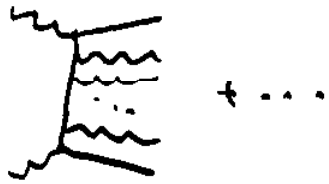
- Evolution for F_i good for specialized cases. Universality → want PDFs

- Special problem: evolution through $\mu \sim m_c$ (m_b)

- Ascetic approach: $m_c \gg \Lambda_{QCD}$ so <u>always</u> treat c as perturbatively generated:



only <u>need</u> $u(x)$, $d(x)$, $s(x)$ ...
but for $\mu \gg m_c$ either compute



or lose lots of $\alpha_s^m(Q) \ln^m \frac{Q}{m_c}$

- Intermediate (short cut) approach: ignore c for $\mu < m_c$, take $m_c = 0$ $m_c < \mu$.

- Consistent approach(es): absorb $\ln Q/m$ into evolution of $c(x, Q^2)$.

$$\text{ACOT}: \frac{d}{d\ln\mu^2} f_c(x,\mu^2) = P^{\overline{MS}} \otimes f_c$$

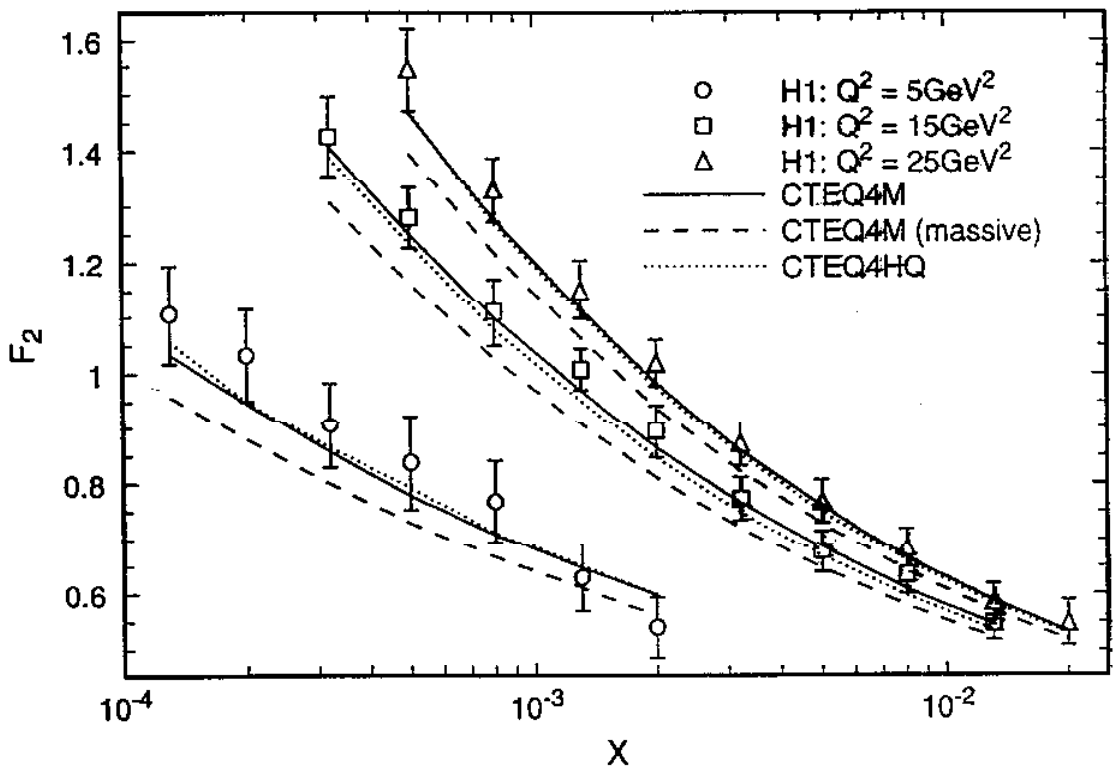
why is this choice consistent? because we can <u>choose</u> the factorization scale dependence of $\hat{\sigma}$ in

$$\sigma(Q) = \hat{\sigma}\left(\frac{Q}{\mu}\right) \otimes f_c(\mu)$$

so that order-by-order

$$\frac{\partial}{\partial \ln\mu^2} \hat{\sigma} = -\hat{\sigma} \otimes P^{\overline{MS}}$$

(requires proof of corresponding fact = theorem in presence of mass m_c) Collins


H1: Q^2 = 5GeV^2
H1: Q^2 = 15GeV^2
H1: Q^2 = 25GeV^2
CTEQ4M
CTEQ4M (massive)
CTEQ4HQ
F_2
X
1.6
1.4
1.2
1
0.8
0.6
10^{-4}
10^{-3}
10^{-2}

3.4 Using Factorization/Universality (How much can we expect?)

- QCD predictions based on factorization & PDFs run the gamut from spectacular success to spectacular failure.
  (Tevatron Jet E_T 50-200 ... W+1jet)
- Generally work best when all scales comparable.
  (DIS Dijet)
- Steeply falling distributions sensitive to NP k_T ↔ k_T from high perturbative orders.
  (E706 $\sigma_\gamma(p_T)$)

- Any edge of phase space - even p_T^{max} is dangerous

  default power suppression is $\frac{1}{(1-z)^a Q^b}$

  if $z \to 1$ is at edge of phase space.

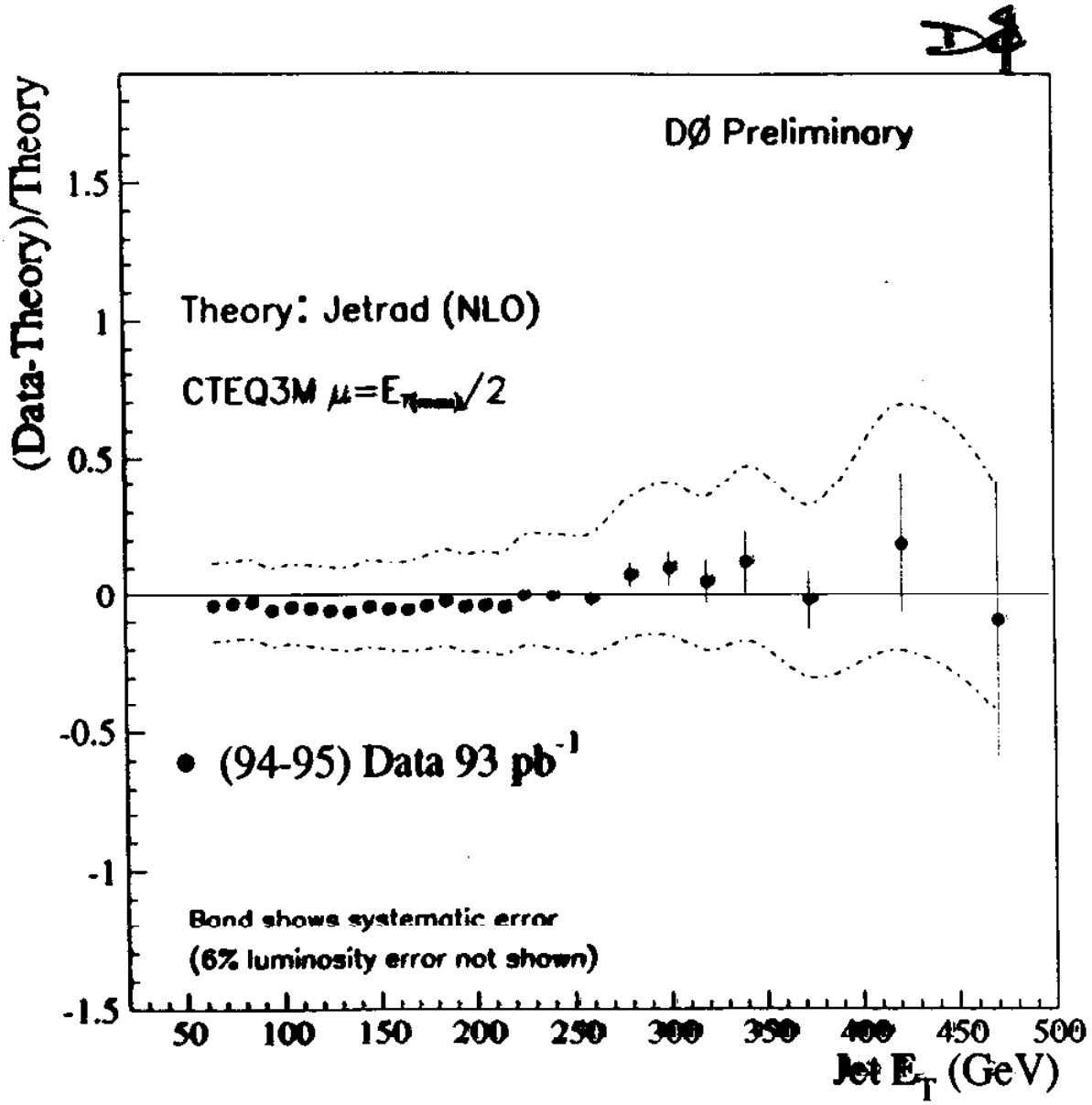
  (rise in octet contribution to ψ production $z \to 1$)

  · Beneke

- Prospects for improved partonic calculations
  - van Ritbergen (4 loops!) - β, $\tilde{g}_1(1)$
  - scattering amplitudes
    - Kosower
    - Bern - systematics of 2 gluon loops
    - Del Duca
    - Magnea - all loop QCD from strings!?

Jet Production at the Tevatron

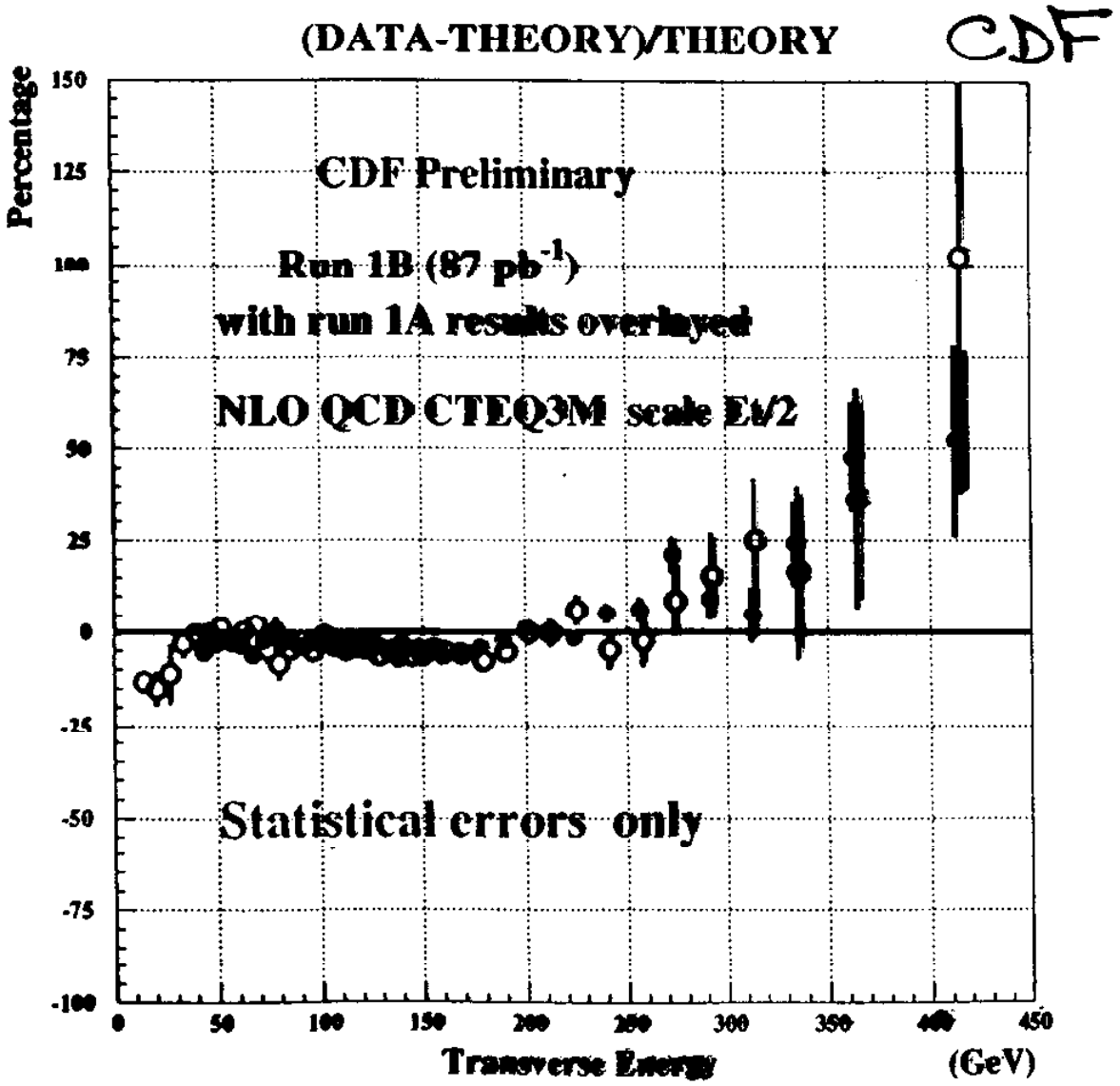
$$0.0 \leq |\eta| \leq 0.5$$



Jet Production at the Tevatron

$0.1 \leq |\eta| \leq 0.7$

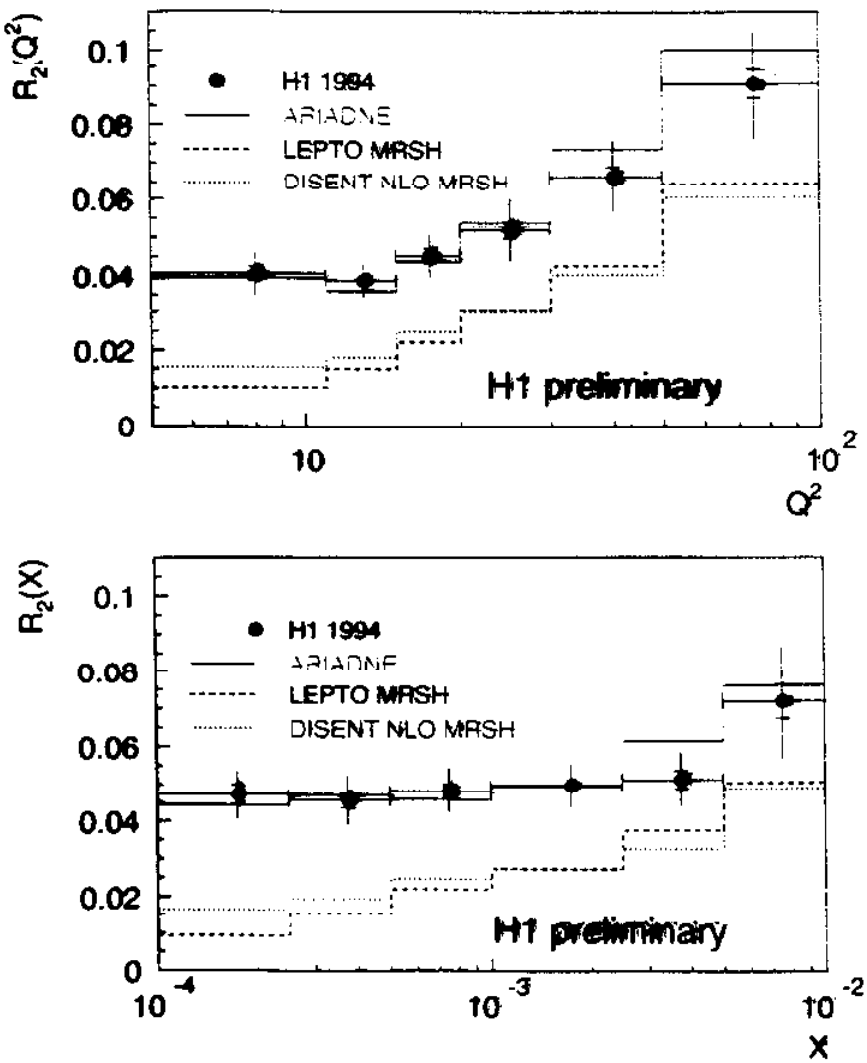
IB luminosity uncertainty ≈ 10%



Dijet Rates

- DIS selection, cone algorithm in hadronic centre of mass $R_{cone} = 1$. $p_t > 5$ GeV
- Data corrected to the hadron level

$$R_{2\text{-jet}} = \frac{N_{2\text{-jet}}}{N_{all}}$$

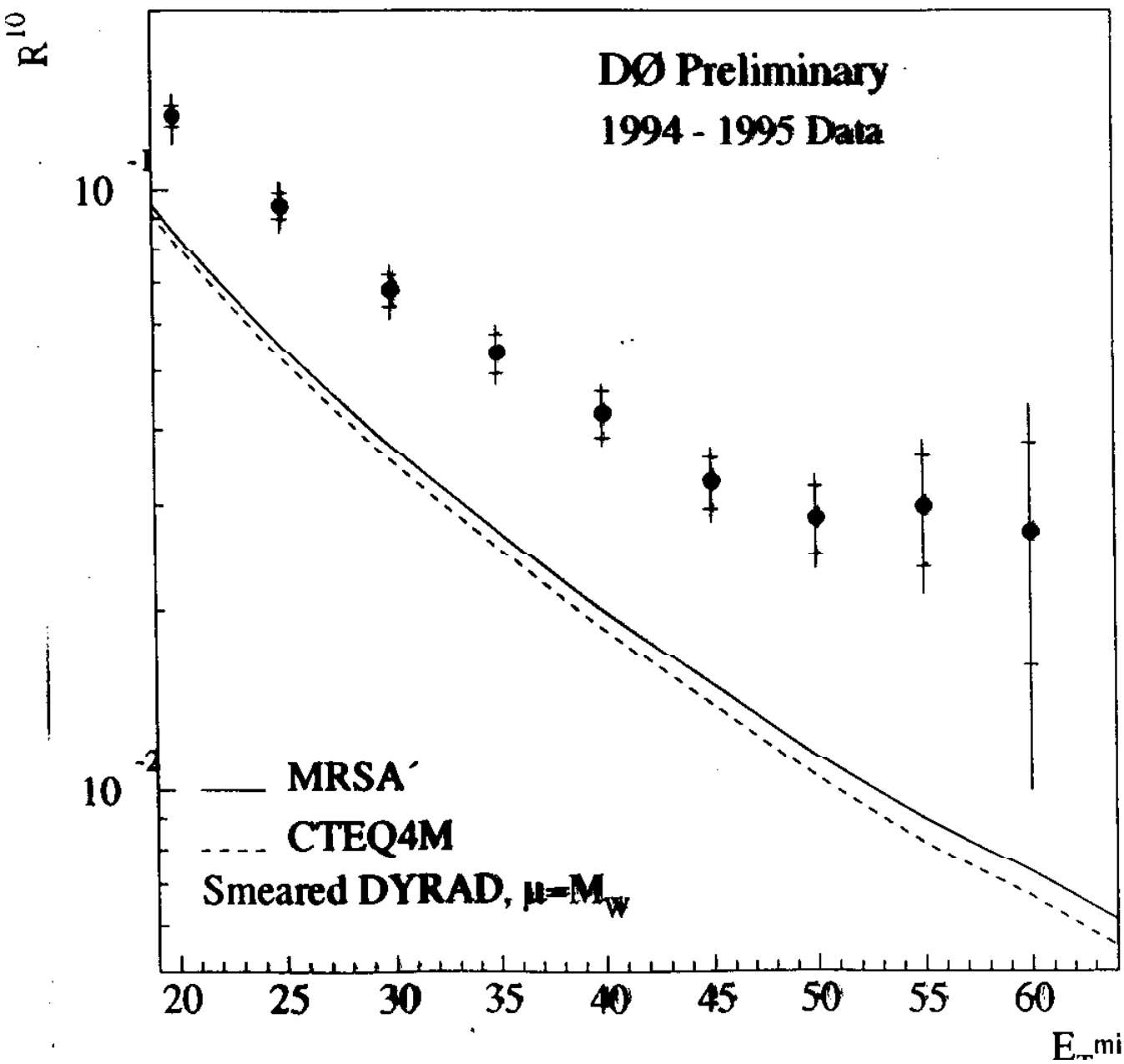


20

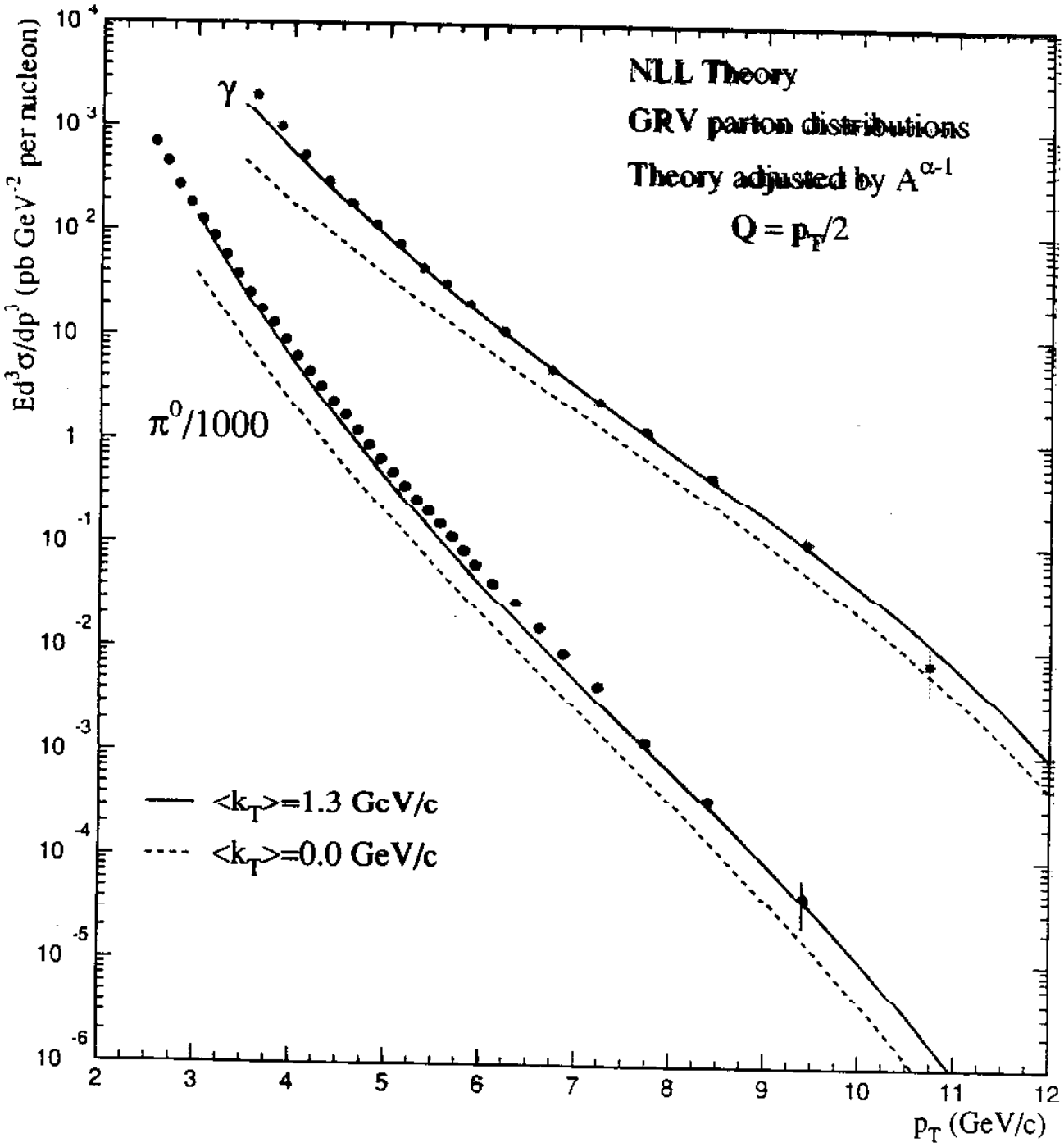
- MEPS model and NLO calculation are not able to describe data

$$\frac{W + 1 \text{ jet}}{W + 0 \text{ jet}}$$

DYRAD NLO



E706 $\pi^- Be$ at 515 GeV



M. Zielinski

4. OTHER FACTORIZATIONS: NEW DENSITIES, NEW EVOLUTIONS

(Too much of a good thing?)

4.1 Sibling distributions: inclusive polarized DIS

$$\frac{d^2\sigma}{d\Omega\, dE} = \frac{\alpha_{EM}^2}{2mQ^4}\frac{E_e}{E_e'} L_{\mu\nu} W^{\mu\nu}$$

$$W_{\mu\nu} = -\left(g_{\mu\nu} - \frac{q_\mu q_\nu}{q^2}\right)\underline{F_1} + \left(P_\mu - \frac{q_\mu}{2x}\right)\left(P_\nu - \frac{q_\nu}{2x}\right)\underline{F_2}$$
$$+ \frac{i}{E_e - E_e'}\epsilon_{\mu\nu\lambda\sigma} q^\lambda s^\sigma \underline{g_1}$$
$$+ \frac{i}{(E_e - E_e')^2}\epsilon_{\mu\nu\lambda\sigma} q^\lambda [p\cdot q\, s^\sigma - s\cdot q\, p^\sigma]\underline{g}$$

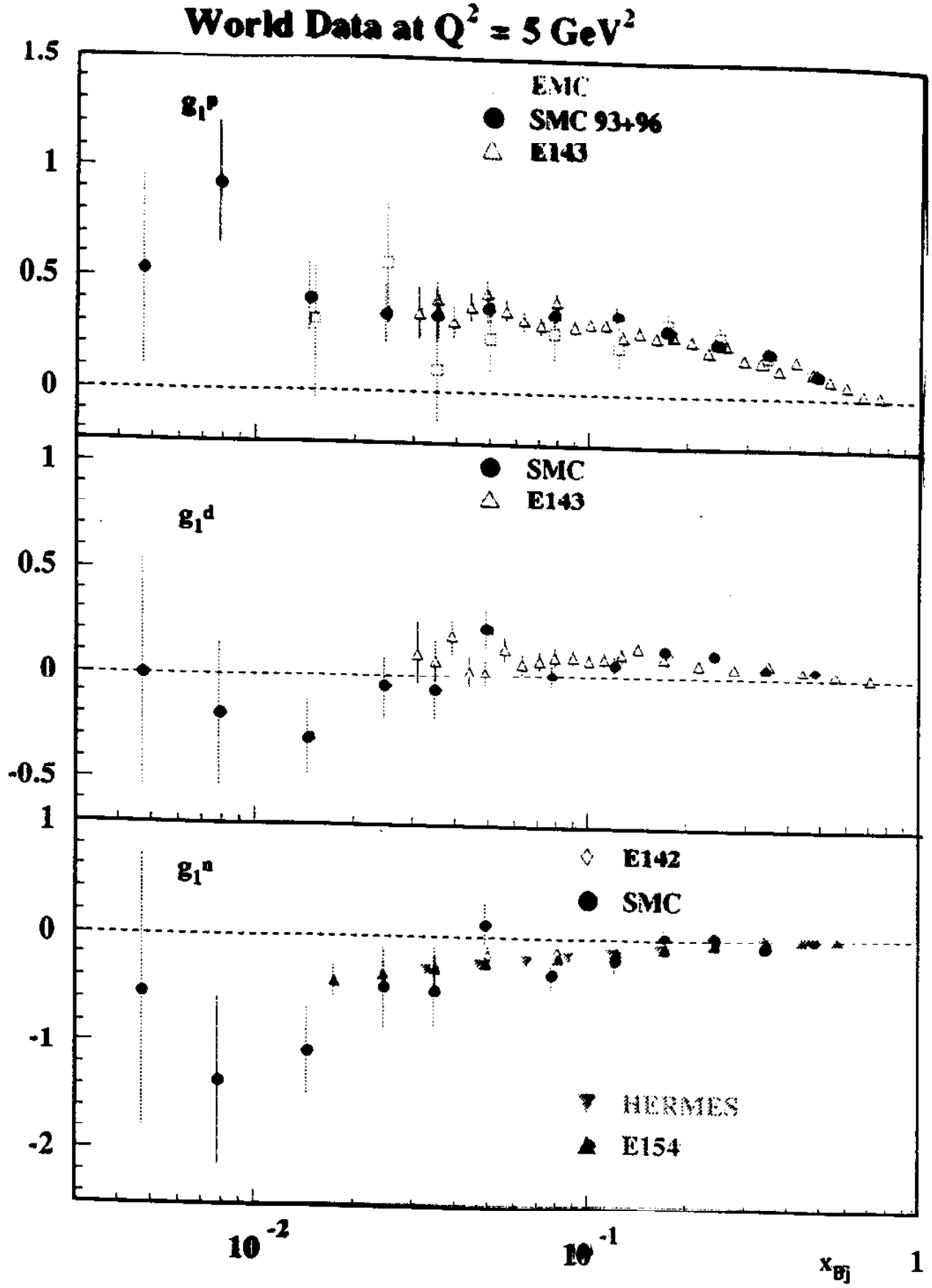
SF $\longrightarrow$ PDF

$$g_1(x) = \frac{1}{2}\sum_f e_f^2 \Delta q_f(x) + \mathcal{O}(\alpha_s)$$

$$q_f^+ + \bar{q}_f^+ - q_f^- - \bar{q}_f^-$$

also Δg

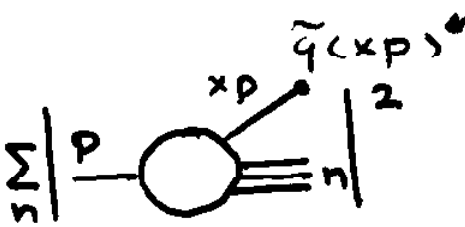
- Same factorization, evolution analysis
- Small-x behavior especially interesting
- Universality $\rightarrow$ extension to 1PI
- Overall status sharpened 96-97
- HERMES


World Data at $Q^2 = 5\ GeV^2$
g_1^p
EMC
SMC 93+96
E143
g_1^d
SMC
E143
g_1^n
E142
SMC
HERMES
E154
1.5
1
0.5
0
-0.5
-1
-2
10^{-2}
10^{-1}
1
x_{Bj}

4.2 Generalized Spin Analysis & Asymmetric Densities

Ji, Radyushkin, Freund, Guichon

"Normal PDF"

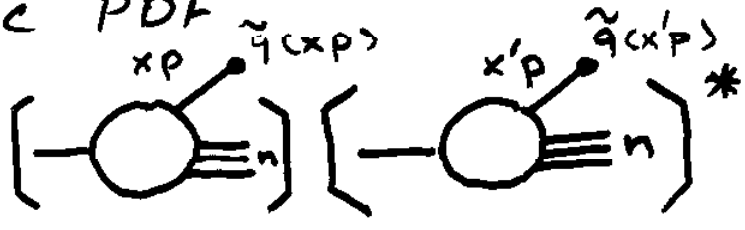
$q(x) = \sum_n$ 

Fourier transform

expectation of operator $\tilde{q}$ in $|p\rangle$

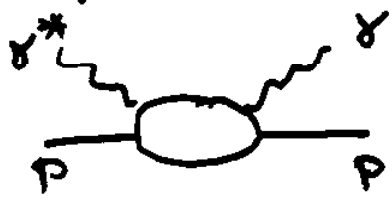
$p_0 \int dx\, x\, q(x) \rightarrow$ momentum carried by q

"Asymmetric PDF"

$Q(x,x') = \sum_n$ 

$\int dx\, x\, Q(x,x') \rightarrow$ angular momentum

Accessible in "Deeply Virtual" Compton Scattering



$p' = (1-\xi)p$

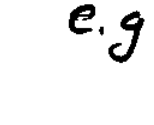
p "slows down"

something new: its direct observability is under study ... factorization/evolution

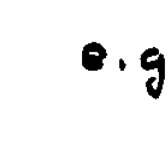
brings us to...

4.3 Diffraction; leading and nonleading "twist"

- twist: number of <u>physical</u> particles that initiate a hard scattering (amplitude <u>and</u> complex conjugate)

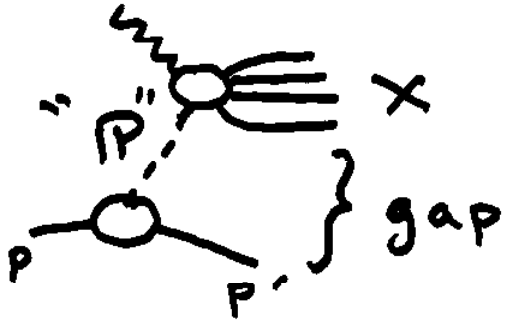
e.g. $|$ $|^2 = ($ $)($  $)^*$

twist = 2 → leading power

e.g. $|$  $|^2$ → twist 4 (leading) $\frac{1}{Q^2}$

$\epsilon_T(k)$

- diffraction



$$x_{\mathbb{P}} \cong \frac{M_X^2 + Q^2}{W^2 + Q^2} \quad (t \sim 0$$

$$\beta = \frac{Q^2}{M_X^2 + Q^2}$$

$$\beta x_{\mathbb{P}} = x_{Bj}$$

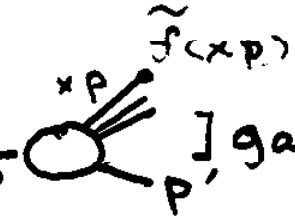
$$\frac{d^4\sigma}{dQ^2\, d\beta\, dx_{\mathbb{P}}\, dt} = \frac{2\pi\alpha^2}{\beta Q^4}\left(1 + (1-y)^2\right) F_2^{D(4)}$$

Cases:

(I) M_X^2 inclusive $\rightarrow$ hard scattering need only one parton; soft partons carry color into the final state $\rightarrow$ leading twist

single parton suggests <u>new</u> <u>factorization</u>

$$f^{Diff}(x) \sim \sum_{p+n'(gap)} \Big|$$



$$\Big|^2$$

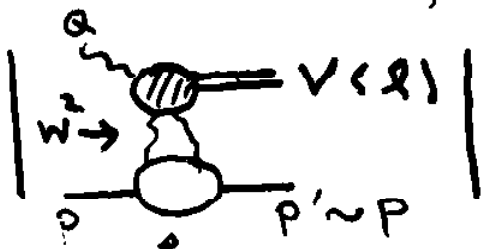
Berera

can evolve – but universality not so obvious whitmore

(II) M_X^2 exclusive $\rightarrow \geq 2$ partons to make final state color singlet $\rightarrow$ higher twist ($1/M_X^2$)

but no soft partons in final state

$$\Big|$$



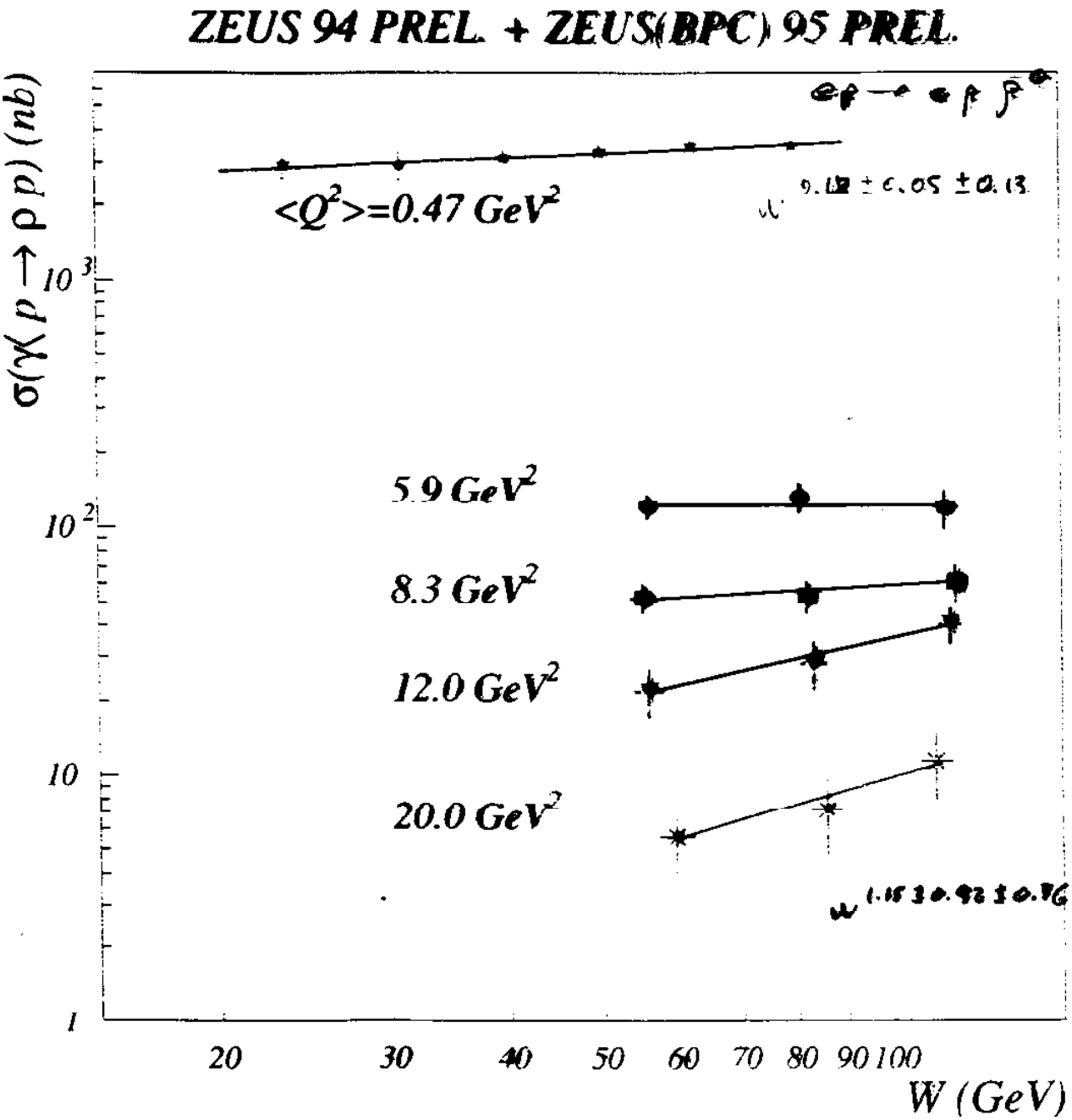
$$\Big|^2 \sim \frac{1}{Q_X^4} W^{4\lambda(Q^2)}$$

fixed!

grows with energy!

Asym. density!

Approx $\sim G(x) \sim \frac{1}{x^{\lambda(Q^2)}} \sim W^{2\lambda(Q^2)}$

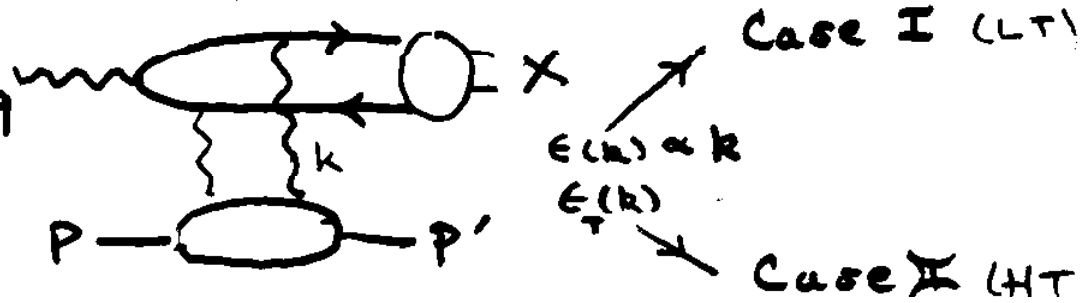

ZEUS 94 PREL. + ZEUS(BPC) 95 PREL.
σ(γ* p → ρ p) (nb)
<Q²>=0.47 GeV²
5.9 GeV²
8.3 GeV²
12.0 GeV²
20.0 GeV²
10³
10²
10
1
20
30
40
50
60
70
80
90
100
W (GeV)

- Models (McDermott)
  - IS $f^{Diff}_{a/p} = f_{\mathbb{P}/p} \otimes f_{a/\mathbb{P}}$

    Schlein

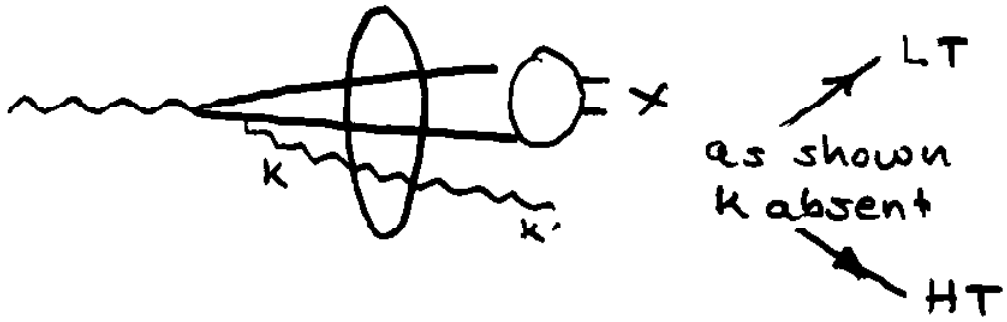
    (original motivation!)
  - Color Dipole

Nikolaev
Bartels
Wüstoff



  - Semiclassical

Hebecker
McDermott
Buchmüller

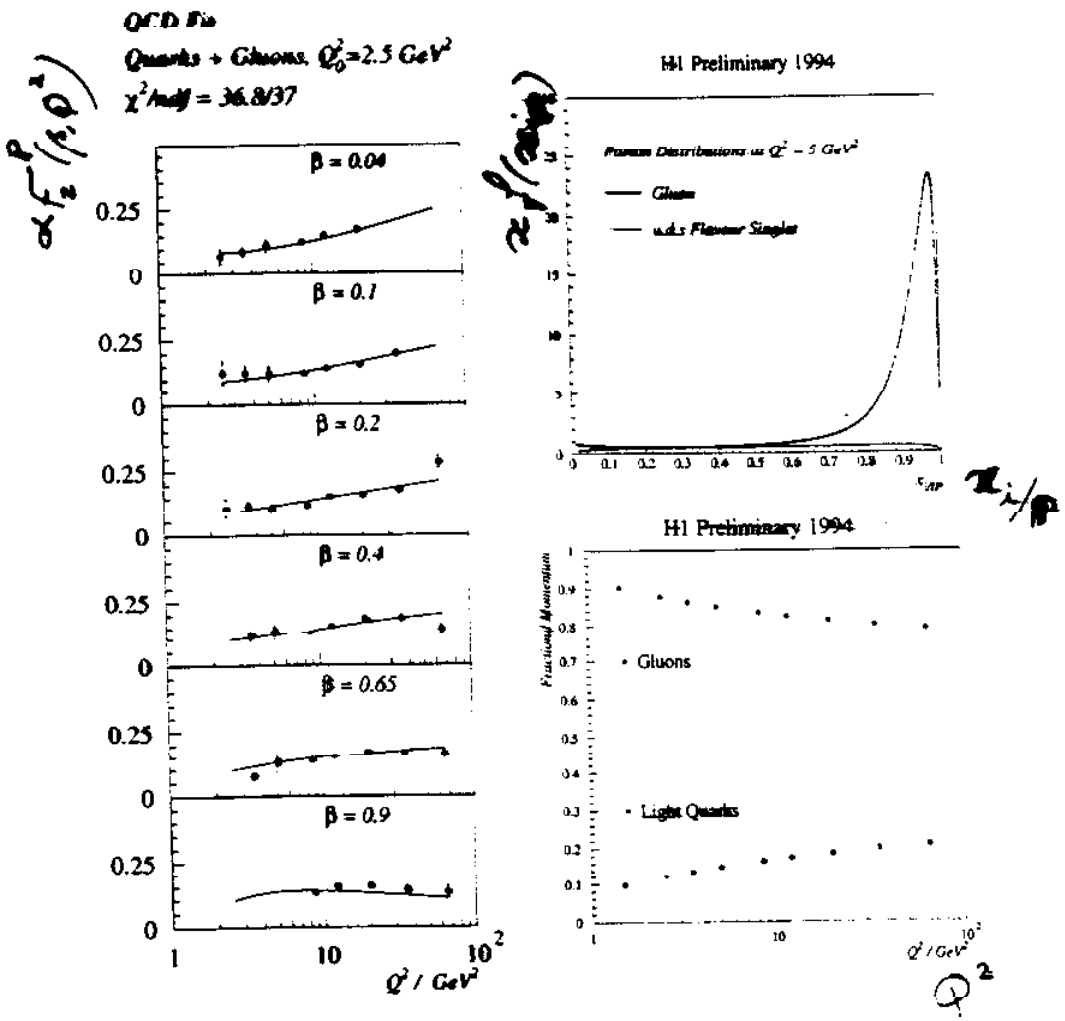


  - Fits to $f_{a/\mathbb{P}}(\beta)$

    ↳ need $\mathbb{R}$ and $\mathbb{P}$
    hard g distr. in $\mathbb{P}$ ($\beta \to 1$)
  - Dipole: at $\beta \to 1$ higher twist may dominate! $\begin{cases} HT \sim (1-\beta)^0 \\ LT \sim (1-\beta) \end{cases}$

Partonic Structure of Diffractive Exchange

$$F_2^{D(3)}(\beta, Q^2, x_{I\!P}) = f_{I\!P/p}(x_{I\!P}, t) \cdot \tilde{F}_2^{I\!P}(\beta, Q^2)$$



- $\tilde{F}_2^D$ Shows no evidence of a fall in Q^2 with increasing β
- Strong Q^2 scaling violations $\rightarrow$ very hard gluon density?
- DGLAP QCD fit including Quarks and Gluons at the starting scale gives best fit, Quark only gives a poor fit
- "Leading Gluon" gluon behaviour seen $x_{g/I\!P} \rightarrow 1$ as $Q^2 \sim Q_0^2$
- Significant fraction of the Pomeron's momentum is carried by gluons

5. OPENINGS TO NONPERTURBATIVE QCD

5.1 $Q^2 \to 0$ in diffraction

- $\sigma_{\gamma^* p}(Q^2) \to Vp \sim W^{2\lambda(Q^2)}$

  $Q^2 \frac{d\lambda(Q^2)}{dQ^2} < 0$

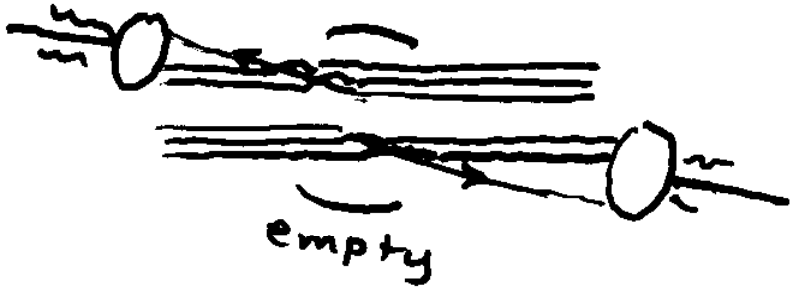
- see approach to total $\sigma_{\gamma p \to \gamma p}$

- theory? – start with 2-loop BFKL at finite Q^2, <u>then</u> we'll see what happens...

5.2 Hard rapidity gaps at the Tevatron

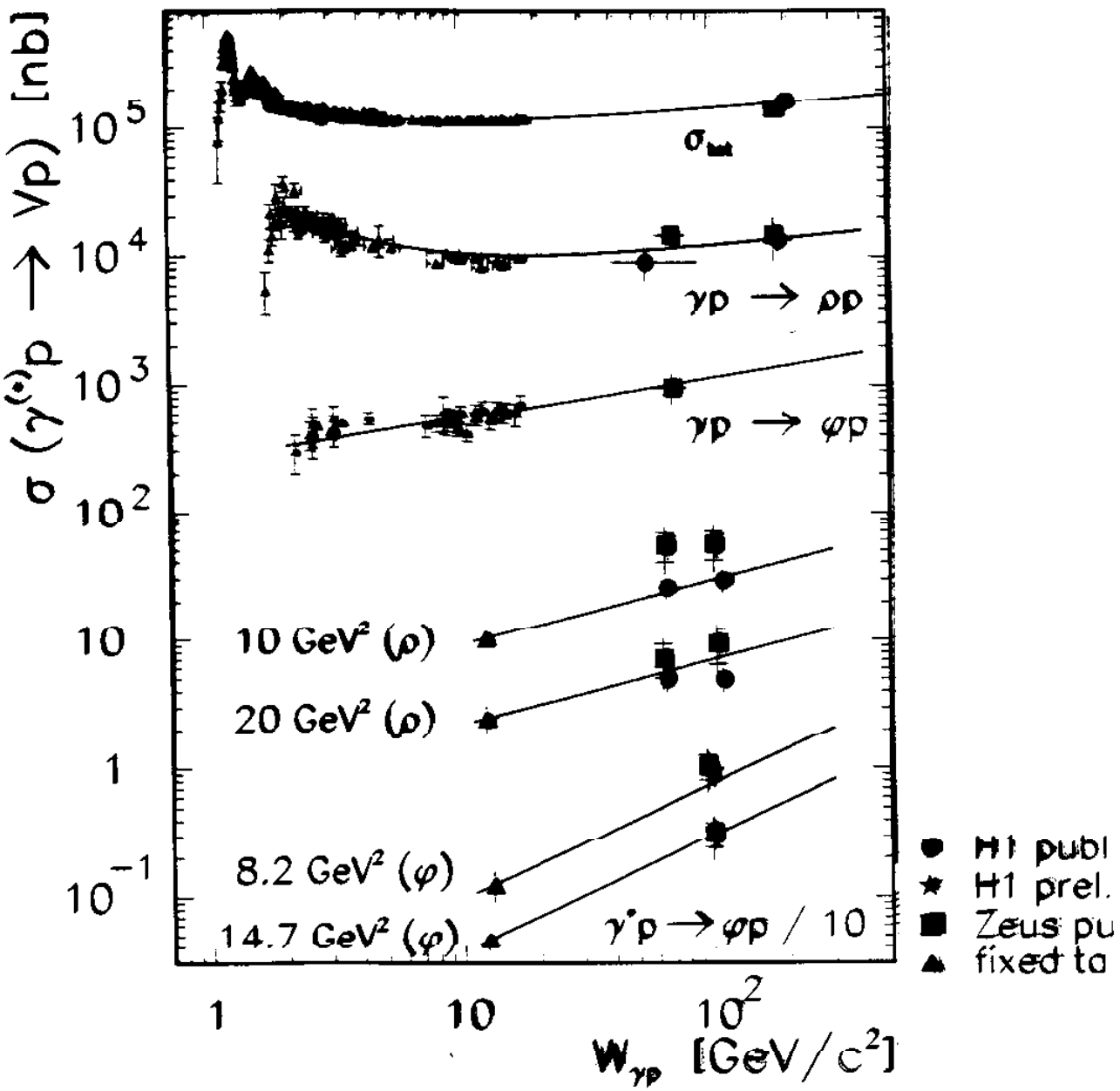
Brandt

- wisdom: singlet exchange → less radiation; local color neutralization



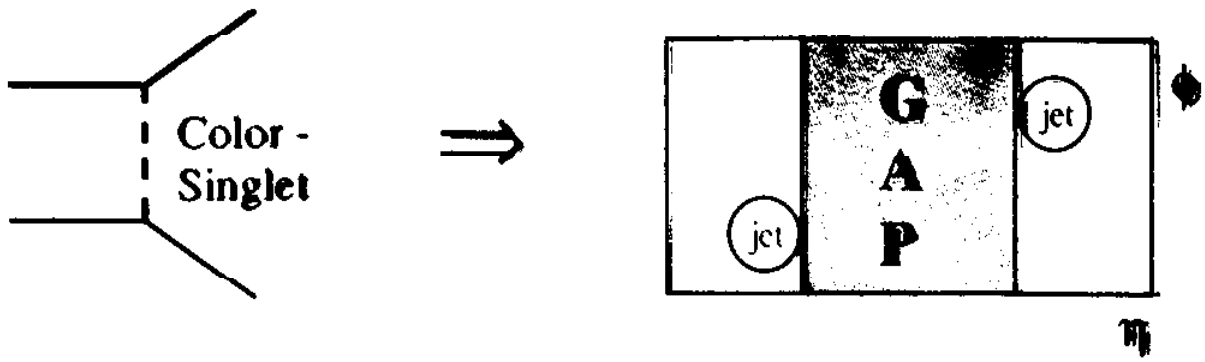
- theory requires QCD exponentiation with color exchange

$W_{\gamma p}$ dependence: ρ^0 vs Φ



- Φ : steeper rise with $W_{\gamma p}$ than in photoproduction
- increase larger for Φ than for ρ^0
  harder scale due to larger mass

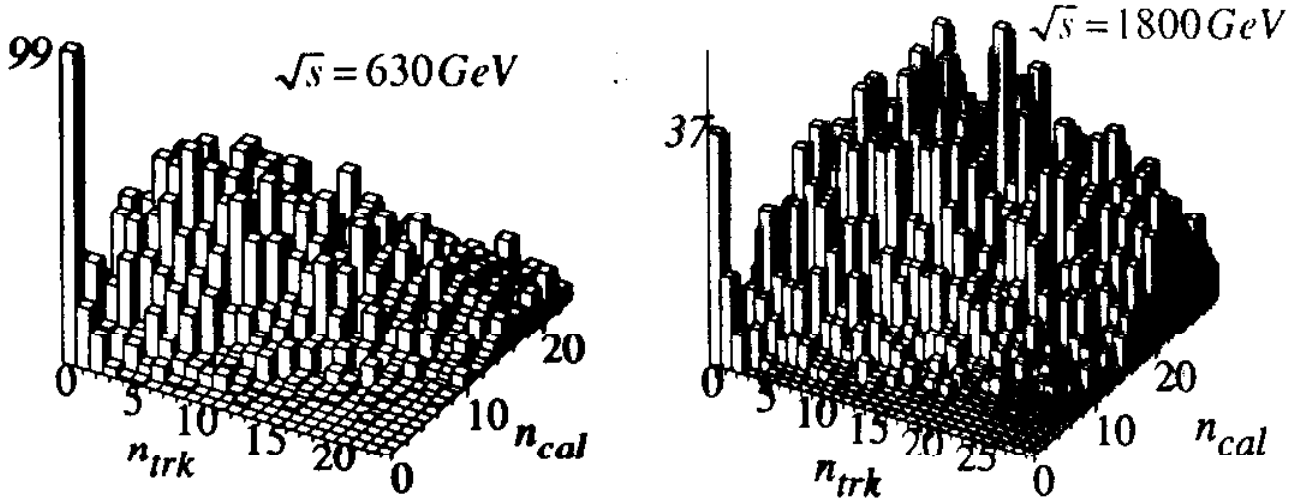
Hard Color-Singlet Exchange



- Changing $\sqrt{s}$ probes different parton x values

Predictions:

2 Gluon Model: R – f_{630} / f_{1800} ~ 0.8
Soft Color-Rearrangement Model: R ~ 1 - 2.5



$R^{data} \cong 2.6$ **D0 Preliminary**

- Fraction as function of E_T , $\Delta\eta$ at $\sqrt{s}$ = 1800 GeV also probes different parton x values
  - ★ Results are consistent with $R_{630/1800}$

5.3 Leading Power Corrections

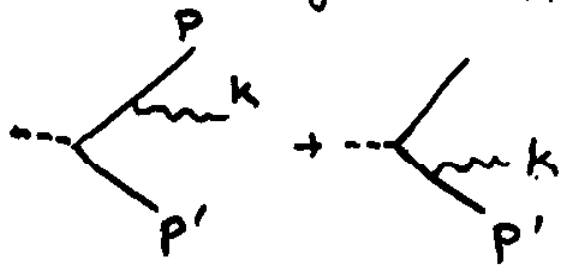
Beneke, Akhoury, Marchesini

- DIS "ideal" because Q varies in same experiment
- look for $1/Q$ corrections to event shapes
- another example: $e^{-k_T^2/\sigma^2}$ in

$$\frac{d\sigma_Z}{d^2Q_T} \quad \text{for } Q_T \ll M_Z^2$$

- most analyses like:

$$\sigma_{IRS} \sim \int_k \Bigg|$$



$$\Bigg|^2 \; w(k) + \cdots$$

vanishes at $k=0$ for IRS

$$\sim \int_0^{p\cdot p' \equiv Q^2} \frac{dk^2}{k^2}\, w(k) \ln Q^2 \, \alpha_s(k^2)$$

$$\underbrace{\int_{Q_0^2}^{Q^2}}_{\text{UV OK}} + \underbrace{\int_0^{Q_0^2} \frac{dk^2}{k^2} \overbrace{w(k)}^{\frac{a_i}{Q^i}k^i + \cdots} \alpha_s(k^2) \ln Q^2}_{\text{replace by NP parameter } \alpha_0} \sim \frac{a_i}{Q^i} \ln Q \; \alpha_0$$

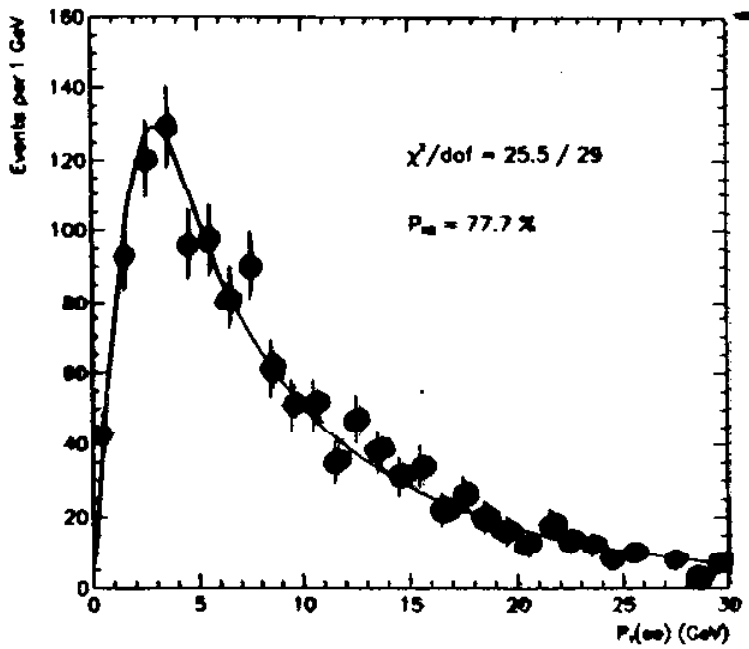
W Production Model

Landsberg - Yuan

- fit g_2 using DØ $Z \to ee$ data g_1, g_2, g_3

MRSA′	0.59	$\pm 0.10(stat)$
MRSD−′	0.61	$\pm 0.05(syst)$ GeV^2
CTEQ3M	0.54	
CTEQ2M	0.61	

DØ



Z

P_T

- deviations of fitted W mass for different pdf's

	g_2	m_T fit	$p_T(e)$ fit
MRSA′	0.59	$\equiv 0$	$\equiv 0$
MRSD−′	0.61	+20 MeV	+19 MeV
CTEQ3M	0.54	+5 MeV	+48 MeV
CTEQ2M	0.61	−21 MeV	−17 MeV

5.4 I wish I could discuss

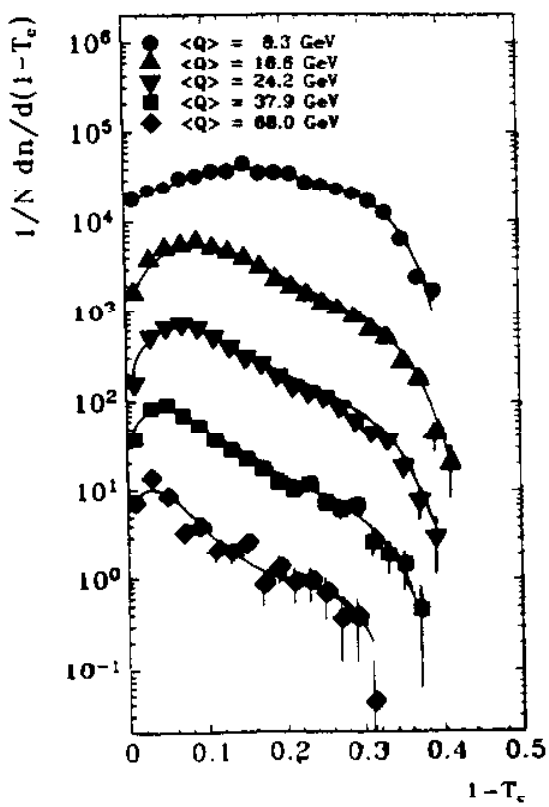
lattice Schierholz

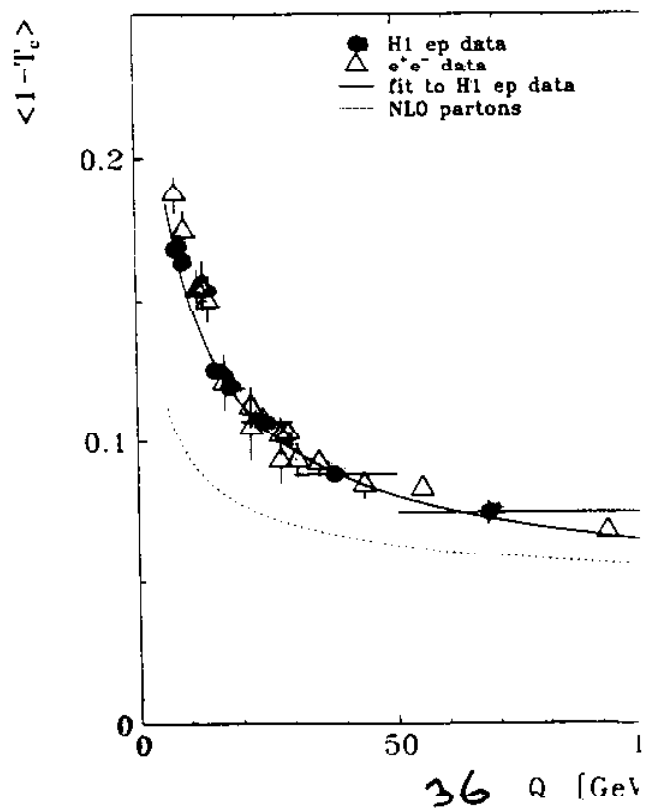
instantons Rungwald
Schrempp

and much more...

Results of QCD fits and Conclusions

Observable	$\bar{\alpha}_0(\mu_I = 2\ \mathrm{GeV})$	$\alpha_s(M_Z)$	$\chi^2/$
H1 ep data			
$\langle 1 - T_c \rangle$	$0.497 \pm 0.005\ ^{+0.070}_{-0.036}$	$0.123 \pm 0.002\ ^{+0.007}_{-0.005}$	5.0
$\langle 1 - T_z \rangle / 2$	$0.507 \pm 0.008\ ^{+0.109}_{-0.051}$	$0.115 \pm 0.002\ ^{+0.007}_{-0.005}$	8.5
$\langle B_c \rangle$	$0.408 \pm 0.006\ ^{+0.036}_{-0.022}$	$0.119 \pm 0.003\ ^{+0.007}_{-0.004}$	5.3
$\langle \rho_c \rangle$	$0.519 \pm 0.009\ ^{+0.025}_{-0.020}$	$0.130 \pm 0.003\ ^{+0.007}_{-0.005}$	3.1
common fit			
$T_c + T_z + \rho_c$	$0.491 \pm 0.003\ ^{-0.079}_{-0.042}$	$0.118 \pm 0.001\ ^{-0.007}_{-0.006}$	39/
e^+e^- data			
$\langle 1 - T_{ee} \rangle$	$0.519 \pm 0.009\ ^{+0.093}_{0.039}$	$0.123 \pm 0.001\ ^{+0.007}_{0.004}$	10.9
$\langle M_H^2/s \rangle$	$0.580 \pm 0.015\ ^{+0.130}_{-0.053}$	$0.119 \pm 0.001\ ^{+0.004}_{-0.003}$	10.9





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6. WHERE ARE WE NOW

- A very exciting time - we're sure to know much more by DIS 98! Perhaps we'll be studying the quark in the leptoquark.

- In QCD, willingness to study power deviations from purely partonic calculations is very constructive.

- Our guide in studying new, nonperturbative functions ought to be physical relevance - but of course this is hard to predict!

- DIS data of the past year has already had an important impact on theory and how we think of QCD at soft and hard scales. The coming year promises even more.