TESTS OF THE STANDARD MODEL AT HERA

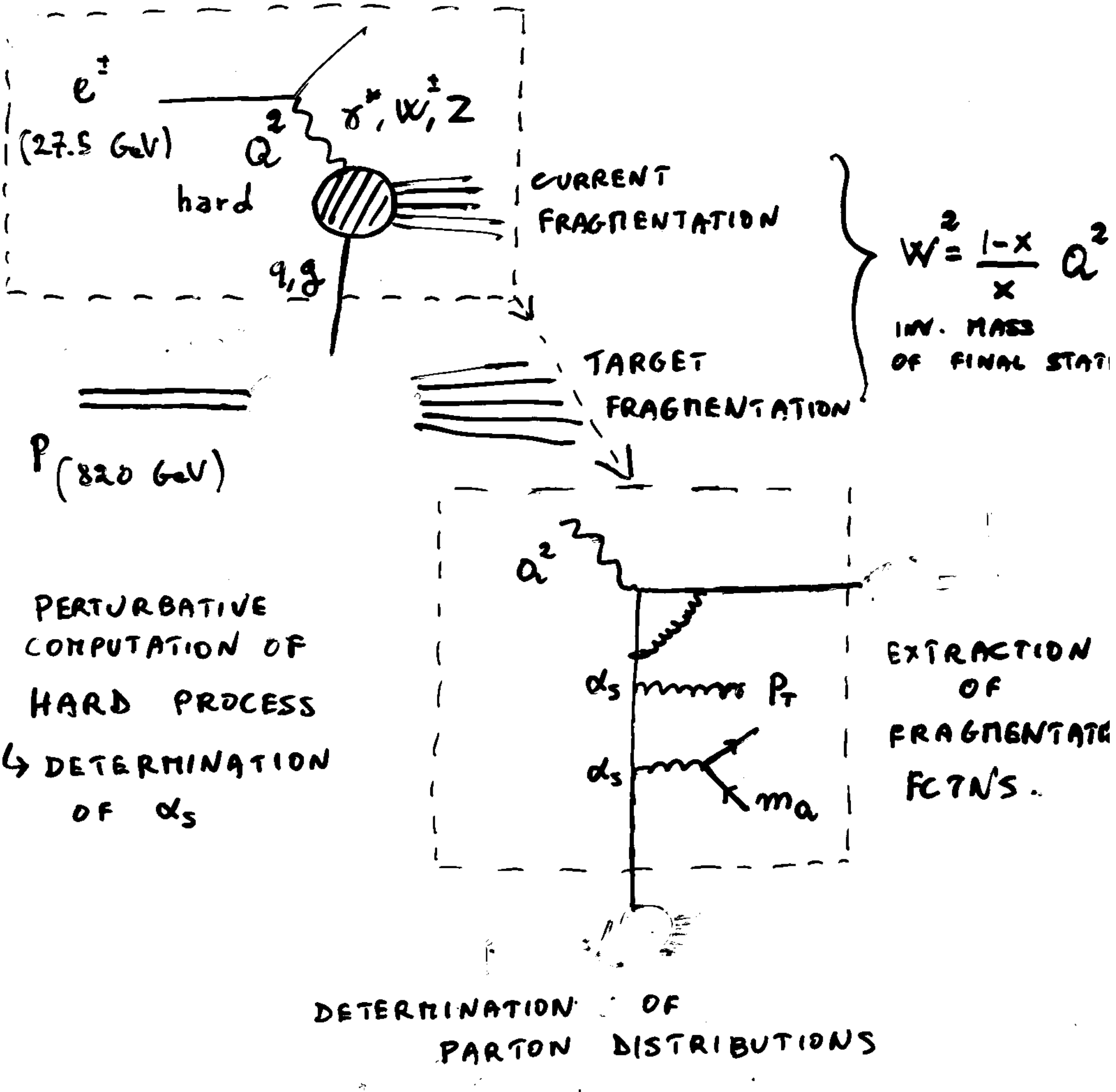
STEFANO FORTE

INFN [illegible]

EPS '99

Tampere, July '99

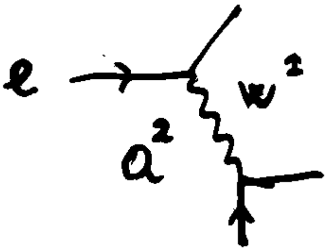
ℓN SCATTERING: FACTORIZATION



$$\frac{d\sigma}{dx\,dQ^2} \sim \int_x^1 \frac{dy}{y}\, \sigma^{hard}\left(\frac{x}{y}, \frac{Q^2}{\mu^2}; \alpha(\mu^2)\right) f(y; \mu^2)$$

THE ELECTROWEAK SUBPROCESS

CHARGED CURRENTS ⇝ W MASS



$$\longrightarrow \quad \frac{d^2\sigma}{dQ^2} \propto \frac{G_F^2}{4\pi} \frac{M_W^4}{(M_W^2 + Q^2)^4}$$

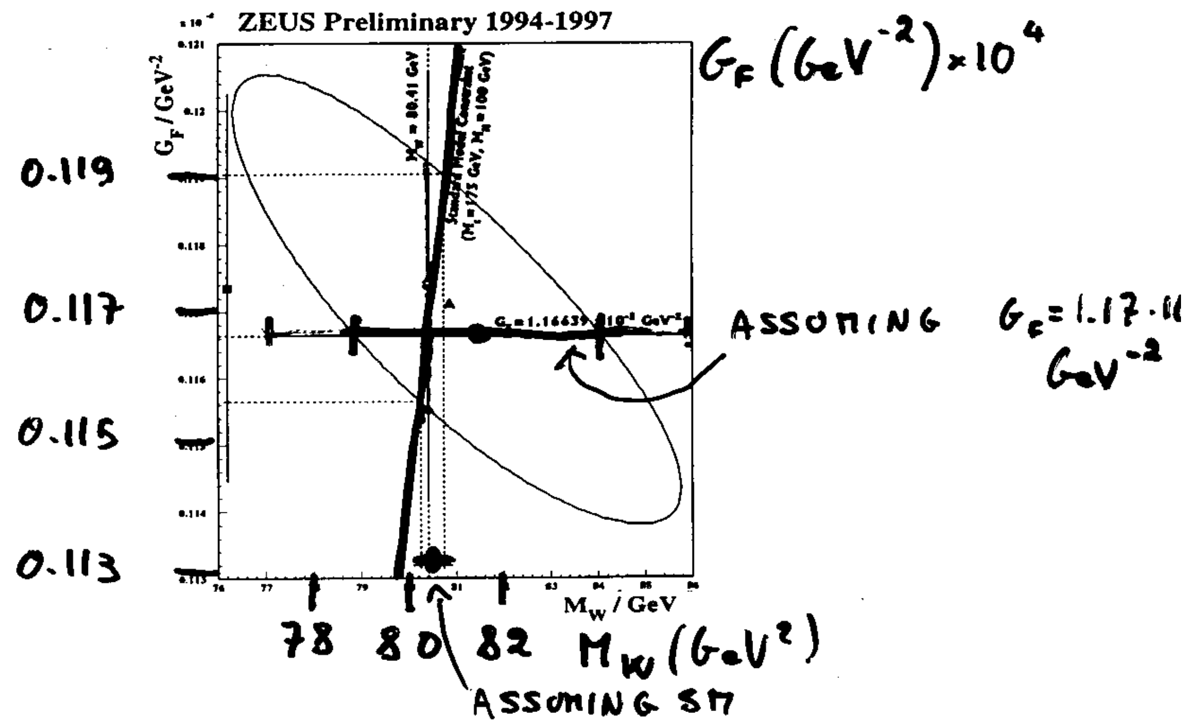
FIT OF Q^2-DEP ⇝ W MASS

ZEUS '99 $\quad M_W = 80.9^{+4.9}_{-4.6}\,(\text{stat})\,^{+5.0}_{-4.3}\,(\text{syst})\,^{+1.3}_{-1.2}\,(\text{pdf})$ GeV

NOTE ERROR DUE TO CHOICE OF PARTONS

RESULT CONSISTENT W/LEP, BUT HARDLY A STRINGENT TEST...

SM CONST.



ASSUMING SM ($M_H = 100$ GeV)

$$M_W = 80.5^{+0.24}_{-0.25}\,(\text{stat})\,^{+0.13}_{-0.15}\,(\text{syst})\,^{+0.30}_{-0.31}\,(\text{pdf}) \text{ GeV}$$

CFR PDG $M_W = 80.4 \pm 0.1$ GeV

TESTING QCD VS.
USING QCD

- FUNDAMENTAL TESTS OF THEORY EXCEEDINGLY SUCCESFUL
  ([illegible])
- NEED RELIABLE COMPUTATIONS
- α_s & PDFs NECESSARY INPUT TO ANY HADRON COLLIDER PROCESS
- QCD BACKGROUNDS TO NEW PHYSICS

→ DETERMINE PARAMETERS (PDFs, α_s)

→ STRETCH PERTURBATIVE DOMAIN

- FACTORIZATION ⇝ LESS INCLUSIVE PROCESSES
- MANY SCALES ⇝ SMALL X, HARD RESUMMATION
- BEYOND LOG ACCURACY ⇝ LARGE X, SOFT RESUMM

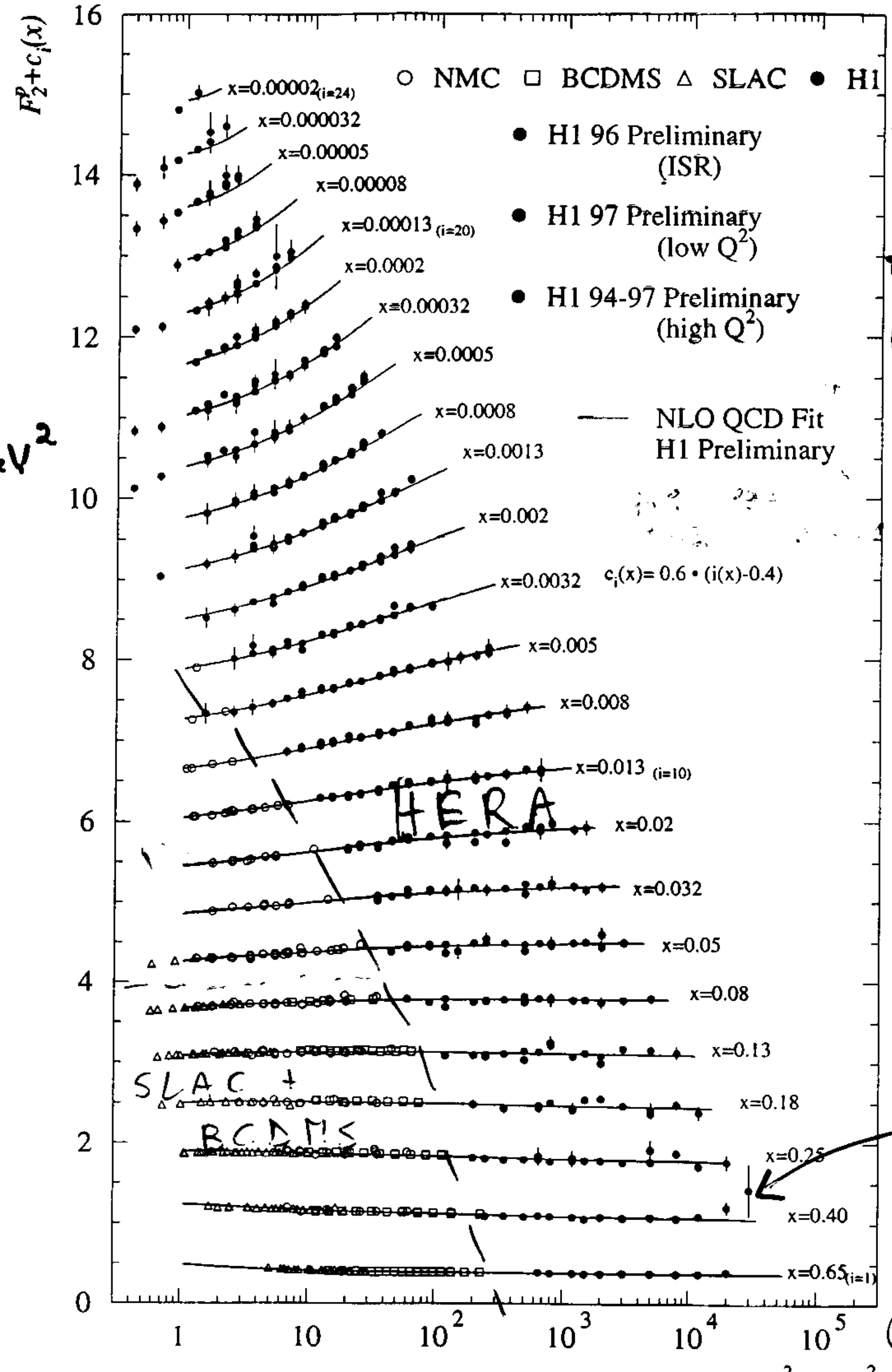
SUMMARY

- STRUCTURE FCTNS. & PARTON DISTNS.
  - THE STATE OF THE ART: F_2 @ HERA
  - ERRORS ON PDFS
  - PDFS FROM LESS INCLUSIVE PROCESSES
- QCD AT SMALL X
  - NLO EVOLUTION: TEST OF QCD & α_s DETERMINATION
  - $\ln \frac{1}{x}$ RESUMMATION IN THE A-P EQNS
  - ENERGY EVOLUTION: THEORY (F_L) + PHENOMEN. (FORW. JETS
- DIFFRACTION & LEADING HADRON: FRACTURE FUNCTIONS

NLO EVOLUTION OF F_2

- NUMERICAL RESOL. OF NLO ALTARELLI-PARISI EQN.
  ↳ FIT OF OPTIMAL PDF AT "INITIAL" SCALE
- HUGE KIN. COVERAGE → ~1500 DATA FIT → 16 PARM. (PDFS) + 7 PARMS (NORM.) + 5 PARMS (HIGHER TW...)

$W^2 > 7 GeV^2$



$Q^2 (GeV^2)$

"HIGH Q^2 ANOMALY"

PURE NLO AMAZINGLY ACCURATE (χ^2/DOF = 0.99 WITH CORR. ERRORS)

THIS [illegible] A "FIT"!

WHAT IS REMARKABLE ?

- A SMOOTH ENOUGH FCTN. CAN ALWAYS BE FITTED WITH A REASONABLE # OF PARMS

  e.g. NMC/SMC FITS OF $F_2(x, Q^2)$ (Guhadar '98

  ↳ 14 PARMS, EXCELLENT FIT

  THIS IS JUST A FIT! (NO EV. EQNS., NO DYNAMICS)

- FITS BASED ON NON-PERTURBATIVE MODELS AVAILABLE:

TWO-POMERON $F_2 = \sum_{i=0}^{2} f_i(Q^2)\, x^{-\varepsilon_i}$ Donnachie, Landshoff '98-'99

10 PARMS, $x < 0.07$, all Q^2 (HERA) → ~500 points, $\chi^2 = 1.0$

"STOCHASTIC VACUUM" 2 PARMS, $0 < Q^2 < 35\,\mathrm{GeV}^2$, $x < 0.05$

"VERY GOOD AGREEMENT" Rueter '98

"REGGE DIPOLE" 23 PARMS, ALL x, Q^2 (HERA) → ~1300 points, $\chi^2 = 1.$

Desgrolard '98

"LOG SCALING" $F_2 = a + m \ln \frac{Q^2}{Q_0^2} \ln \frac{x_0}{x}$ Buchmüller, Haidt '96

Haidt '99

4 PARMS, $x < 0.01$, $Q^2 > 5\,\mathrm{GeV}^2$ (NOW ALL Q^2)

~80 POINTS, $\chi^2 = 1.1$

IS THE POMERON MODEL AN ALTERNATIVE TO QCD AT LARGE Q^2? CFR LANDSHOFF

CAN ONE USE PQCD AS $Q^2 \to 0$? CFR HAIDT

QCD IS PREDICTIVE!

- Q^2-DEP. OF MOMENTS FIXED

$$t = \ln \frac{Q^2}{\Lambda^2} \qquad \frac{d}{dt} \int_0^1 dx\, x^{N-1} F_2(x, Q^2) = \gamma_N(\alpha(Q^2)) \int dx\, x^{N-1} F_2(x, Q^2)$$

- INFINITE SET OF PARM-FREE PREDICTIONS

  DEP ON ∞ SET OF NORMALIZATIONS

DETERMINING PDFS:
HISTORY

- PARAMETRIZE INDIVIDUAL PDFS @ $Q^2 = Q_0^2$

e.g. $f = A\, x^{-\lambda} (1-x)^{\eta} (1 + \varepsilon \sqrt{x} + \gamma x)$

$f = \{ u_v = u - \bar{u};\ d_v = d - \bar{d};\ s = u + \bar{u} + d + \bar{d} + s + \bar{s};\ g;\ HQ \}$

- EVOLVE, COMPUTE STR. FCTN., FIT TO DATA

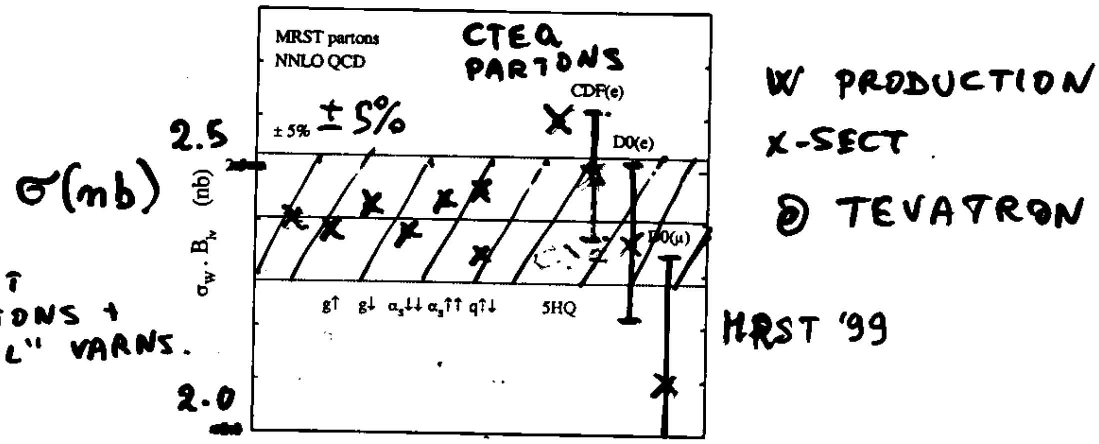
→ "GLOBAL FITS" MRS (T) '98, CTEQ '99

ERRORS ?

ERRORS ON PARTON SET ↔ CONTOURS IN PARM. SPACE

- GENERALLY NOT AVAILABLE: WOULD NEED FULL CORRELNS
- COVARIANCE MATRIX PATHOL. WHEN DEP. NONLINEAR (EXPONENTS) d'Agostini '95,'98
- THEOR. BIAS BUILT IN FUNCT. FORMS
- INFO. NON HOMOGENEOUS BETWEEN DIFFERENT EXPTS, KIN. REGI

NEGLIGIBLE ?



- DIFFERENCE BETWEEN PARTON SETS COMPARABLE TO EXPT. ERRORS

DETERMINING PDFS: THE POST-MODERN ERA

THE PROBLEM: • WHEN MEASURING A NUMBER, RESULT IS VALUE ± ERROR;

• MANY NUMBERS: RESULT + COVARIANCE MATRIX

HERE THE SOUGHT-FOR RESULT IS A SET OF FUNCTIONS, WITH ERRORS IN FUNCTION SPACE

DETERMINING A SET OF FUNCTIONS FROM A FINITE SET OF DATA POINTS IS AN ILL-POSED PROBLEM!

THE SOLUTION: BAYESIAN INFERENCE

A.K.A. FUNCTIONAL INTEGRATION

A.K.A. LATTICE MONTE-CARLO APPROACH

Giele 199[illegible], Keller 199[illegible], Kosower

$$\langle O[f] \rangle = Z^{-1} \int [Df]\, O[f]\, e^{-S[f]}$$

O ↑ observable (e.g. x-sect); f ↖ pdf; $[Df]$ ↑ integr over distribn of pdfs; $e^{-S[f]}$ ↑ measure (quality of fit)

$$S[f] = \sum_{\substack{\text{data}\\ \text{expts}}} (d - Ef)\, \Sigma^{-1} (d - Ef)$$

$S[f]$ ↑ likelihood; d ↑ data pts.; Ef ↑ theor. pred. (evolved pdfs); Σ^{-1} ← covariance matrix

$[Df] \longrightarrow \prod_i d\lambda_i$ discrete parametrization

DO INTEGRALS BY MONTECARLO!

RESULTS ARE PARAMETRIZ. INDEPENDENT

INCREASE PARMS → CONTINUUM LIMIT

• CAN ADD NEW DATA WITHOUT REDOING ANALYSIS

• $S_{tot}[f] = \sum_{\text{expts}} S_{exp}[f]$

• ALL CORRELATIONS INCLUDED (INCL. NONGAUSSIAN)

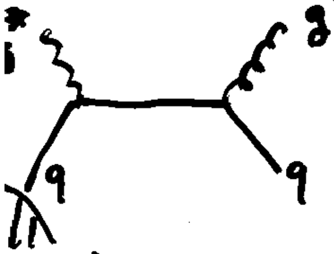
PDFS : LESS INCLUSIVE INFO

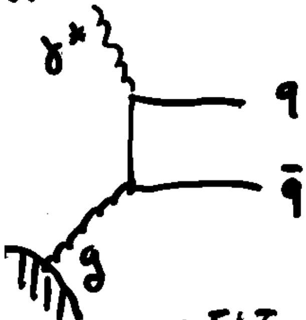
- LARGER THEOR. UNCERTAINTIES

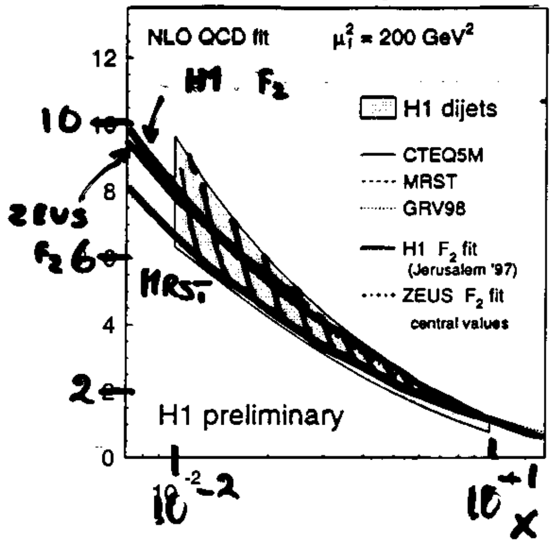
  HO CORRNS, HADRONIZATION, JET/FINAL ST. RECONSTRUCTION (MONTE CARLO

GLUON $g(x)$ $\left(F_2 \rightarrow \frac{dg(N)}{dt}\right)$, INDIVIDUAL QUARK FLAVORS $\left(F_2 \rightarrow \sum_i q_i + \bar{q}_i\right)$

GLUON & DIJETS → CDF HIGH p_T JETS!







$xG(x)$ @ $Q^2 = 200\ GeV^2$

$70 < E_T^2 < 1200\ GeV^2$

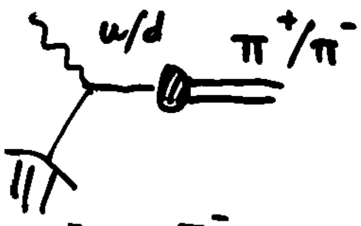
H1 '98-99

H1 DIJET FIT \\\\

- FIT INCLUDING F_2 DATA @ "FIXED" Q^2 (200-600 GeV^2)
  ↳ NO SCALING VLNS BUT FIX QUARK CONTRIB.
- α_s FIXED HERE BUT IF GLUON FIXED

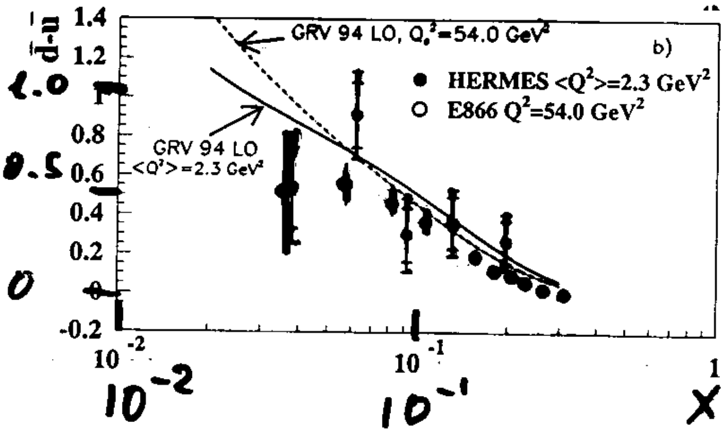
H1 '98-99 $\alpha_s(M_Z) = 0.118 \pm 0.002\,(stat.)\,^{+0.007}_{-0.008}\,(syst)\,^{+0.007}_{-0.008}\,(th)$

QUARK & SEMI-INCLUSIVE DIS → HERA HIGH Q^2 EVENT



$$\frac{N_p^{\pi^-} - N_n^{\pi^-}}{N_p^{\pi^+} - N_p^{\pi^+}}$$

$$\hookrightarrow \frac{\bar{u} + u - (d + \bar{d})}{(u - \bar{u}) - (d - \bar{d})}$$



$\bar{d} - \bar{u}(x)$ @ $Q^2 = 54\ GeV^2$

E866

HERMES '98

- FLAVOR ASYMMETRY OF QUARK SEA IN π PROD. ON p, n (FIXED TARGET) HERMES '98
- CONSISTENT W/ DRELL-YAN E866 '98

SMALL X EVOLUTION: DOUBLE SCALING

STRUCTURE FUNCTIONS GROW AT SMALL X:

RISE DRIVEN BY $\ln \frac{1}{x}$ TERMS GENERATED BY ALTARELLI-PARISI EVOLUTION

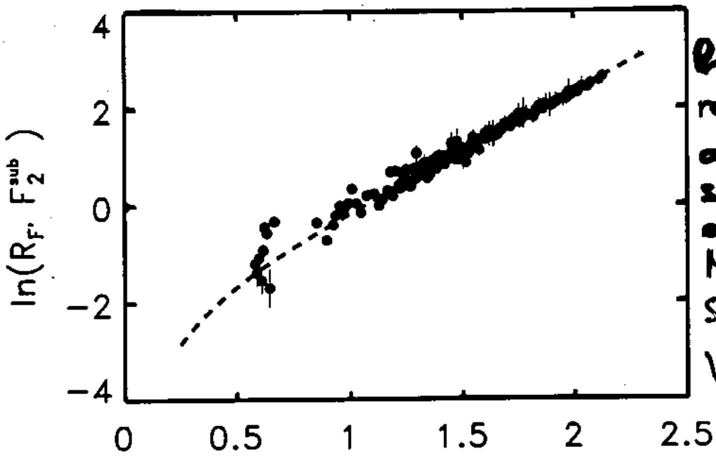
↳ WAVE EQUATION AT SMALL-X R.D. Ball, S.F. '94

UNIVERSAL ASYMPTOTIC BEHAVIOR $x \to 0,\ Q^2 \to \infty$

$$F_2 \sim \exp\left[2\gamma\sqrt{\ln\frac{x_0}{x}\ln\frac{\alpha_s(Q_0^2)}{\alpha_s(Q^2)}}\right]$$

de Rújula et al. '74

DOUBLE ASYMPT. SCALING



$$\sigma = \sqrt{\ln\frac{x_0}{x}\ln\frac{\alpha_s(Q_0^2)}{\alpha_s(Q^2)}}$$

$\ln F_2$ rescaled by computable subleading effects Mankiewicz Saalfeld Weigl '96

- LINEAR RISE OF $\ln F_2$ WITH SLOPE

$$\gamma = 2C_A/\beta_0\ ;\ C_A = N_c\ ,\ \beta_0 = \frac{1}{2}\left(11 - \frac{2}{3}N_f\right)$$

INDEP. OF PDF (DEP. ONLY THROUGH NORMALIZATION OF F_2

QCD PREDICTION IS PARAMETER-FREE

- WHOLESALE SCALING VIOLATIONS

ACCURATE DETERMINATION OF α_s BY TWO LOOP CORRNS.
VERY WEAK DEP. (SUBLEADING) ON PDF, SMALL HIGHER TWISTS

PRELIMINARY ('96) RESULT

$$\alpha_s = 0.120 \pm 0.005\,(\text{exp.}) \pm 0.009\,(\text{th.})$$

R. Ball, S.F. 96

NEED REANALISYS INCLUDING RECENT DATA!

$\ln\frac{1}{x}$ PERTURBATIVE INSTABILITY

- OBSERVED RISE OF F_2 DUE TO $\ln\frac{1}{x}$ GENERATED BY ONE- AND TWO-LOOP PERTURBATIVE EVOLUTION

  HIGHER LOOPS → HIGHER LOGS $\alpha_s^n \leftrightarrow \left(\ln\frac{1}{x}\right)^n$

- SERIES OF LEADING $\ln\frac{1}{x}$ CONVERGENT

  COEFFICIENTS KNOWN FROM "BFKL" EQN (GLUON SECTOR) Jaroszewicz '…

  ALSO KNOWN FOR QUARK = α_s × GLUON Catani, Hautmann '93

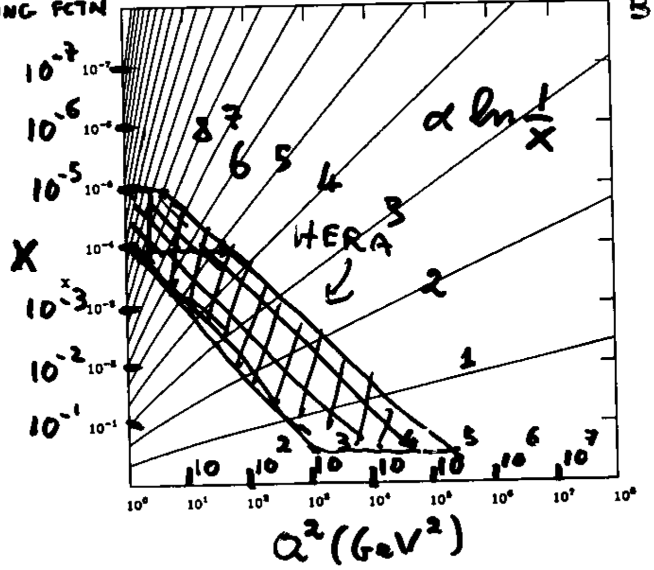
  ⇝ CAN "IMPROVE" 2LOOP EVOLUTION ⇝ WEAK EFFECT BUT DISAGREES WITH DATA! R. Ball, S.F. '96

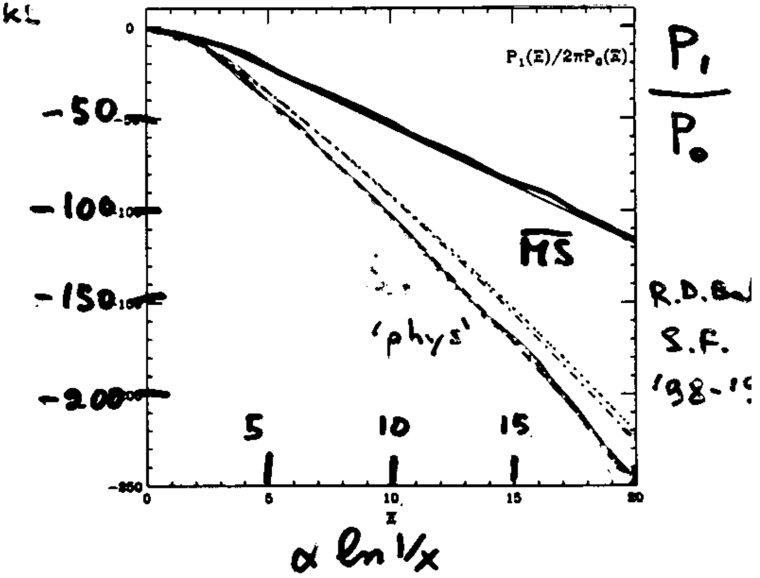
NLLX CORRECTION :

$$P^{LLX}(x, Q^2) = \frac{\alpha}{x}\left[P_0\left(\alpha \ln 1/x\right) + \alpha_s P_1\left(\alpha \ln 1/x\right)\right]$$

← Fadin, Lipatov '98

LEADING Ln1/x SPLITTING FCTN ↑ BFKL





$\frac{P_1}{P_0}$ R.D.Ball, S.F. '98-'9…

- NLLX/LLX GROWS LINEARLY WITH $\alpha \ln 1/x$ IN $\overline{MS}$
- NLLX/LLX $\sim -(10\div 80) \times \alpha_s$ IN HERA REGION!

[illegible] LLX [illegible]...

BUT WHY DOES TWO LOOP WORK? CFR. F_2 PLOT

NLLX RESULT ALMOST COMPLETELY RE-CHECKED del Duca, Schmidt '98; Camici, Ciafaloni '98

MUST REORGANIZE THE SMALL-X EXPANSION

RESUMMATION

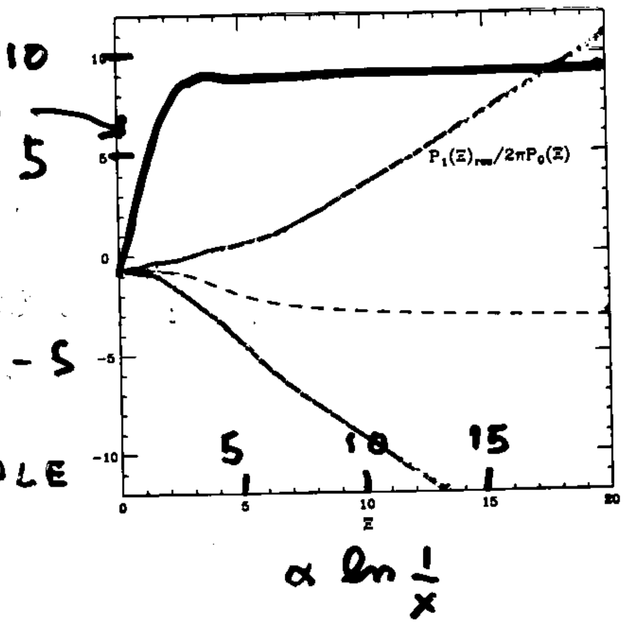
- $\frac{\text{NLLX}}{\text{LLX}}$ GROWTH DRIVEN BY (COMPUTABLE) NL CONTRIBN. TO ASYMPTOTIC BEHAVIOR OF F_2:

$x \to 0$
fixed Q^2

$$F_2 \sim x^{\alpha(\lambda_0 + \alpha\lambda_1 + \dots)}$$

GROWTH IS GENERIC: $\frac{N^k \text{LLX}}{\text{LLX}} \sim \left(\alpha \ln \frac{1}{x}\right)^{2k-1}$

→ ALL CONTRIBUTIONS TO ASYMPTOTIC BEHAVIOR MUST BE TREATED AS LEADING ORDER



P_1 / P_0

FACTOR 2, 1/2 OF FACTN. SCALE

R.D. Ball, S.F. '99

ASYMPT. BEHAVIOR RESUMMED INTO UNKNOWN PARM. λ COULD BE DONE BY FINE-TUNING FACTN. SCALE...

RESIDUAL PERTURBATIVE EXPANSION STABLE...
$P_n / P_0 \sim \alpha^n$ AFTER RESUMMATION

BUT ASYMPTOTIC REGGE BEHAVIOR CANNOT BE DETERMINED AT ANY FINITE PERTURBATIVE ORDER WITHIN A PERTURBATIVE APPROACH BASED UPON MASS FACTORIZATION

ENERGY EVOLUTION

ALTARELLI-PARISI EVOLUTION GENERATES $\ln\frac{1}{x}$ CONTRIBUTIONS BY EVOLVING IN Q^2 & INCLUDING $\ln\frac{1}{x}$ IN EVOLN. KERNELS BUT CAN EVOLVE DIRECTLY IN

$$\xi \equiv \ln\frac{s}{s_0} = \ln\frac{1}{x} \qquad s_{\gamma p} = Q^2\,\frac{1-x}{x} \approx \frac{Q^2}{x}\,,\ s_0 = Q^2$$

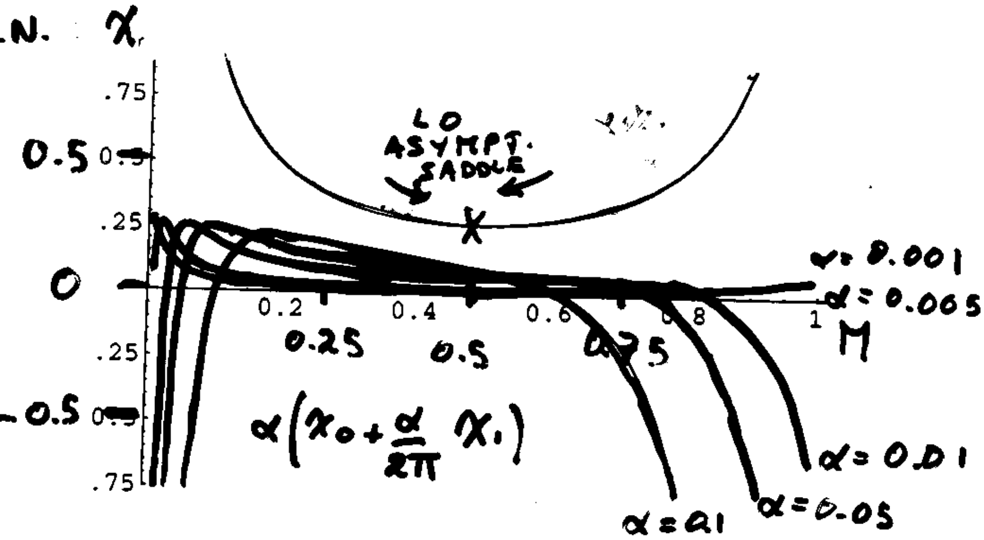
ENERGY EVOLUTION

ENERGY EVOLN. KERNEL χ

BFKL '75 ↓

$= \chi_0 + \frac{\alpha}{2\pi}\chi_1$ ↑

Fadin-Lipatov '98



$$\frac{d}{d\xi}F(\xi,M) = \alpha\,\chi(M)\,F(\xi,M)\ ;\ F(\xi,M) \equiv \int_0^\infty \frac{dQ^2}{Q^2}\left(\frac{Q^2}{\Lambda^2}\right)^{-M} F(\xi,Q^2)$$

ANALOGOUS TO USUAL QCD EVN, BUT $x \leftrightarrow Q^2$ ROLES INTERCHANGE

- SHAPE OF KERNEL QUALITATIVELY CHANGED BY NLO CORRN:

ASYMPT. BEHAVIOR (REGGE LIMIT)

EVOLUTION DRIVES TOWARDS MIN. OF χ:

L.L.X. →

$$F \sim \exp \xi\alpha\chi(M_{min}) = x^{\alpha\chi(M_{min})}$$

NLLX → NO REAL MIN → F OSCILLATES D. Ross '98

- CONFIRMED BY FULL SOLUTION Levin '98 Bartels et al. '98
- RUNNING COUPLING W/ Q^2 AT NLLX MAKES THINGS WORSE Mueller, Kovchegov '98

MORE RESUMMATION ?

MATCHING TO AP EQN.

↳ $\chi_0 \underset{M\to 0}{\sim} \frac{1}{M}$; $\chi_1 \sim -\frac{1}{M^2}$; $\chi_2 \sim \frac{1}{M^3}$ ...

COULD HAVE PREDICTED INSTABILITY !

· CURES ?

- RESUMMATION OF RUNNING COUPLING
  Mueller-Kovchegov '98
- SCALE OPTIMIZATION BFKLP
- CHOICE OF s_0, SUBLEADING $\ln Q^2$ RESUM.
  Salam
- "GEOMETRIC" RESUMM. $\chi = \frac{\alpha \chi_0}{1 + \alpha \frac{\chi_1}{\chi_0}}$ Ciafaloni Colferai
- CUTOFF OF RAPIDITY INTEGR. Lipatov, Schmidt

ALL BASED ON INCLUSION OF FORMALLY SUBLEADING TERMS

· WHAT IS THE HARD SCALE ?

ENERGY LOGS: FORWARD JETS

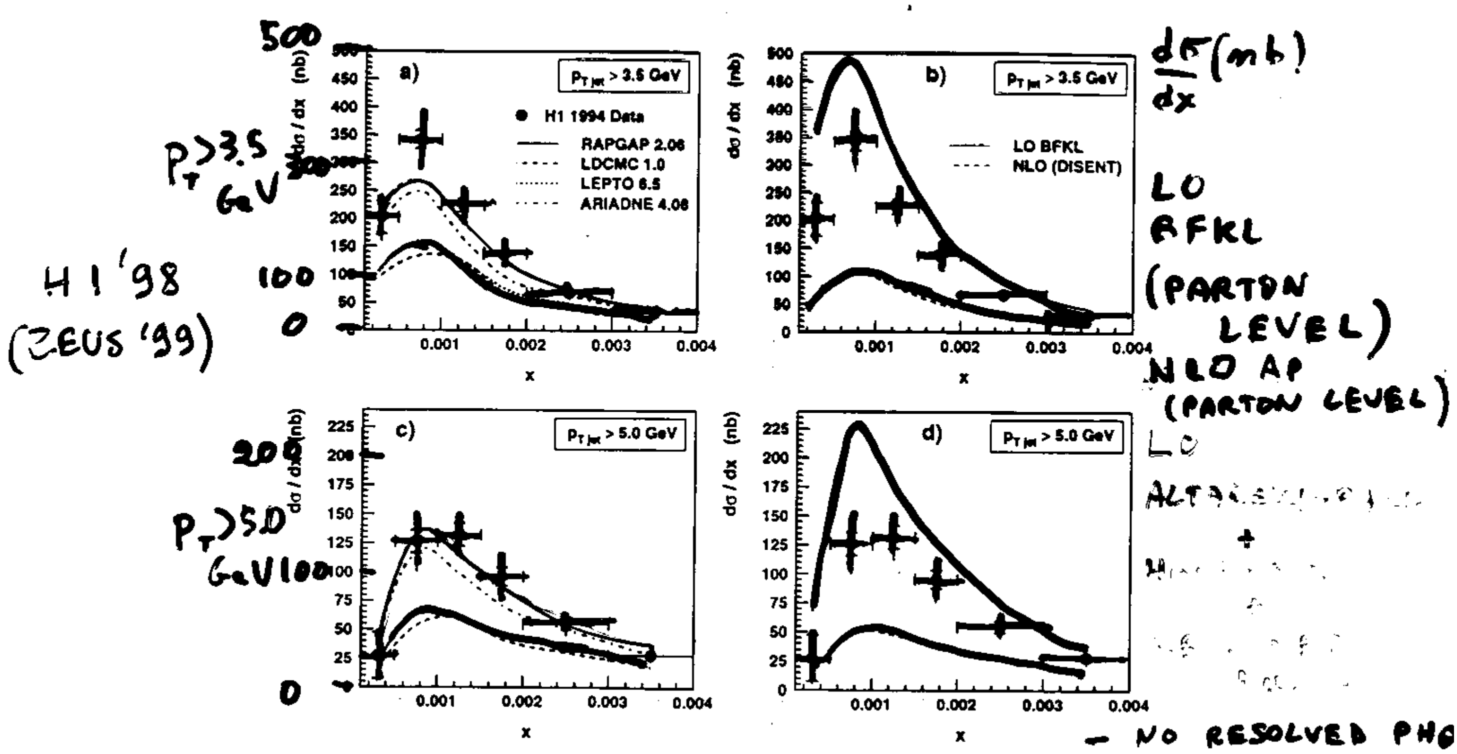
- IDEA: CHOOSE EVENTS w/ LONG x EVOLUTION LENGTH

Mueller-Navelet '87
Mueller 90-

BY SELECTION OF JET KINEMATICS

- LO PROCESS SUPPRESSED

EXPECT STRONGER GROWTH AT SMALL x THAN PREDICTED BY FIXED-ORDER CALCN...



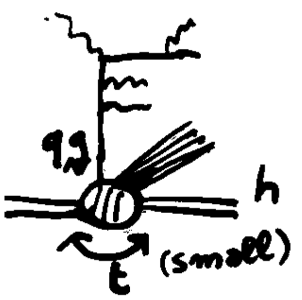
... BUT EXCELLENT AGREEMENT IS FOUND WITHIN LARGE THEOR. UNCERTAINTIES

PROVIDED RESOLVED-PHOTON IS INCLUDED

PARTON CONTENT OF γ, IMPORTANT WHEN $E_T^2 \gtrsim Q^2$

WHERE ARE THE ENERGY LOGS?

DIFFRACTION & LEADING HADRONS

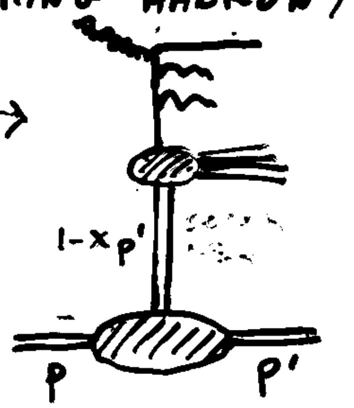


- TAG PROCESSES WHERE TARGET FRAGMENTS INTO A GIVEN HADRON (LEADING HADRON, APPROX. COLLINEAR TO INCOMING HADRON)

- DIFFRACTION ⇝

FURTHER REQUIRE HADRON TO CARRY LARGE MOMENTUM FRACTION

⇝ LARGE RAPIDITY GAP BETWEEN IT & REST OF FINAL STATE



$x_{p'} > 0.$

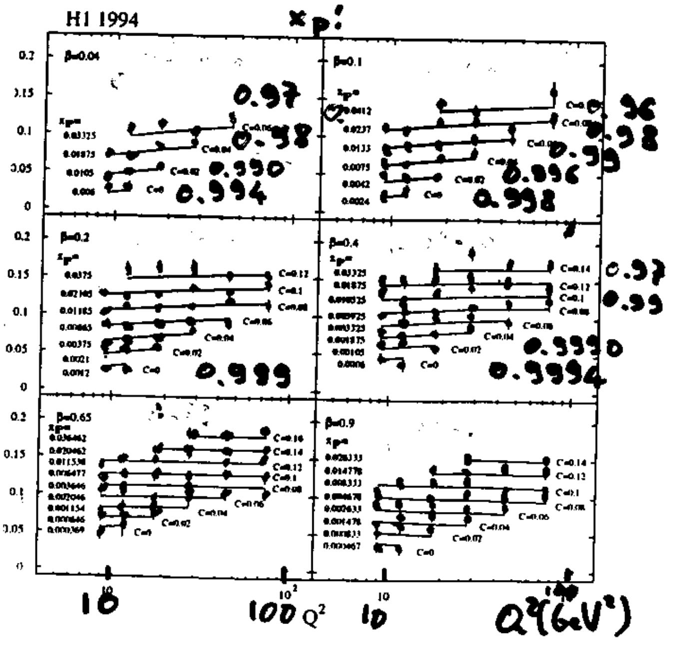
. DIFFRACTIVE COMPONENT LARGE (10% OF F_2 @ HERA)
IMPORTANT BCKGR. TO HIGGS PRODUCTION! ALSO COLORLESS..

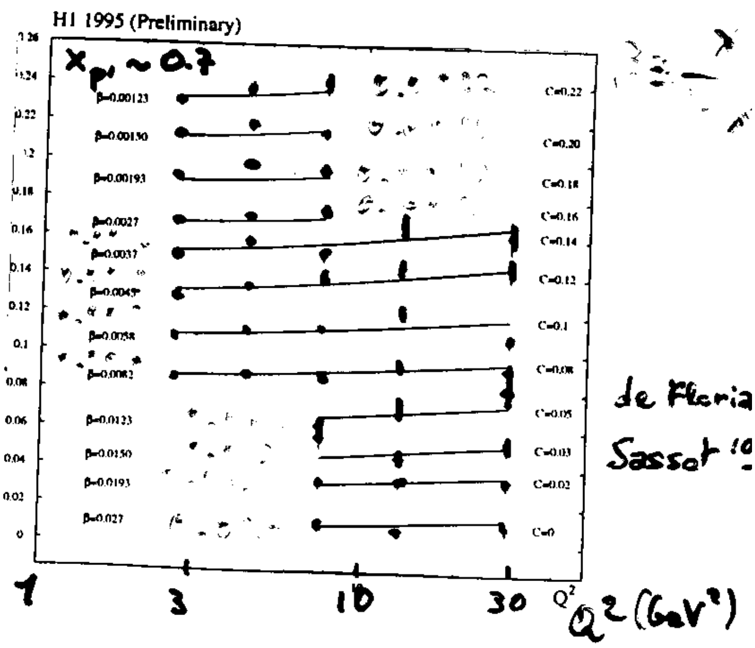
UNIFIED APPROACH: Veneziano, Trentadue '94

$$d\sigma \sim \int \frac{dy}{y}\, \sigma^{hard}\left(\frac{x}{y}, \frac{Q^2}{\mu^2}; \alpha(\mu^2)\right) M^h(y; x_h; t; \mu^2)$$

Berera, Soper '95
Collins '97
Grazzini, Trentadue, Veneziano

FACTORIZED, UNIVERSAL, DEF'D BY CUT VERTICES
EVOLVE BY ALTARELLI PARISI





de Floria, Sassot

. GOOD AGREEMENT WITH PERTURBATIVE EVOLUTION
. NON-PERTURBATIVE INFORMATION SUMMARIZED BY SINGLE OBJECT ACROSS KINEMATICAL REGIONS

CONCLUSION

QCD HAS COME OF AGE:
HERA IS THE LEP OF QCD

- RELIABLE COMPUTATIONS AVAILABLE FOR MORE INCLUSIVE PHENOMENA 3 LOOPS?
- FACTORIZATION GRADUALLY EXTENDED DIFFRACTI
- ACCURATE PHENOMENOLOGY FEASIBLE PDFS W/ ERRORS
- RESUMMATIONS EXTEND KIN. REGION POWER ACCURACY? SMALL X?!

PERTURBATIVE COMPUTATIONS LEAD TO EXCELLENT PHENOMENOLOGY EVEN WHEN THEY SHOULD MISERABLY FAIL!