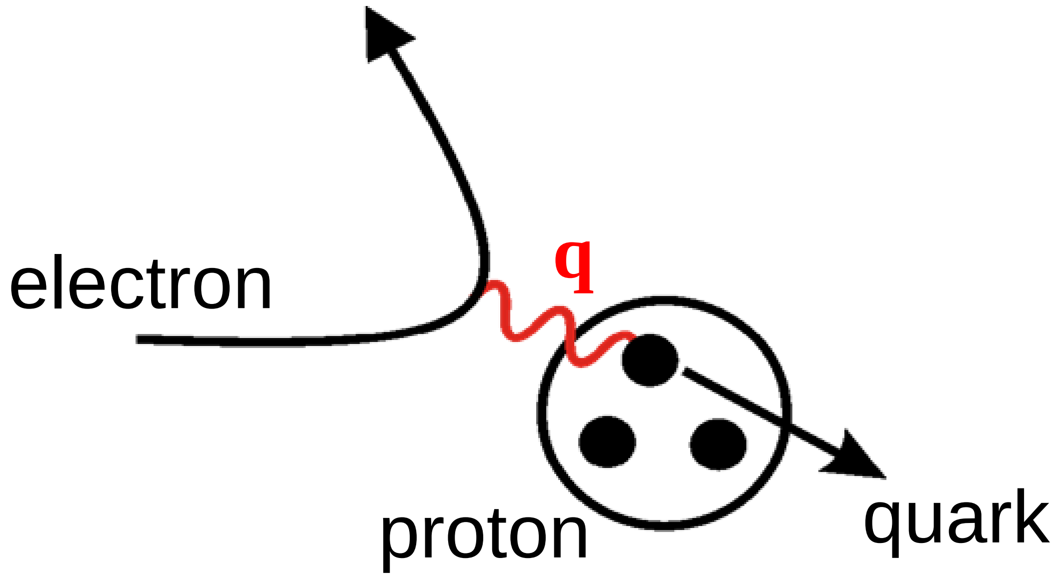
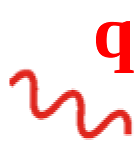
Impact of HERA on QCD and proton structure

Alan Martin (Durham)
HERA Fest
June 29, 2007

HERA: electron → ← proton

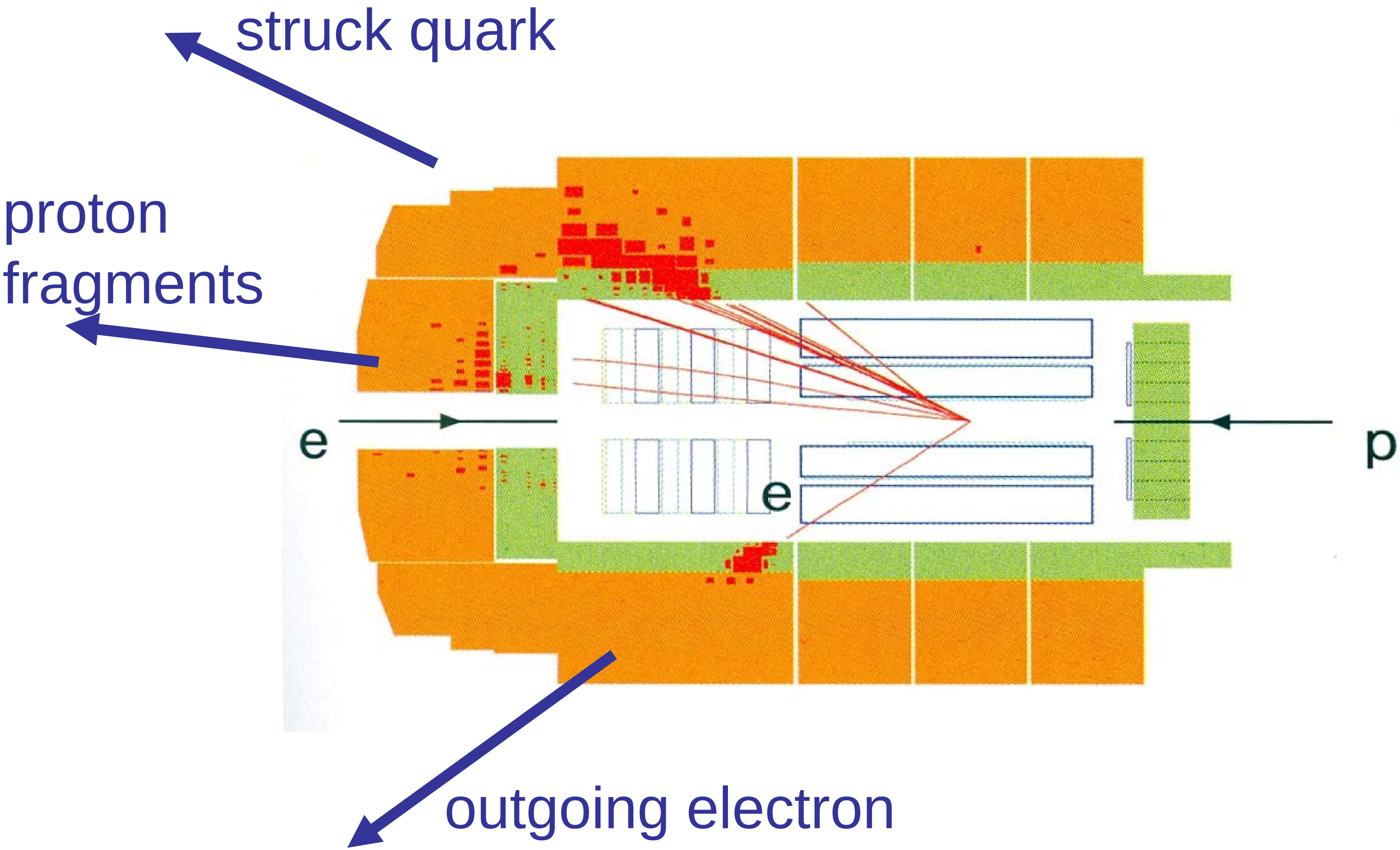


quark acts as if free,
yet never seen ?
big puzzle ~1970
→ QCD

virtual photon 

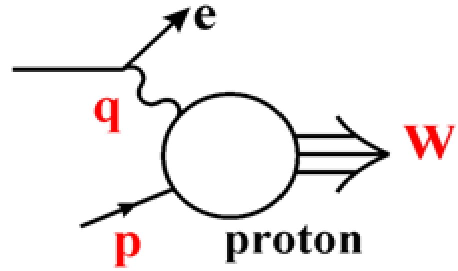
$Q^2 \equiv -q^2, \qquad \lambda = 1/Q$

(real particle: $p^2 = E^2 - \vec{p}^{\,2} = M^2$)


struck quark
proton
fragments
e
e
p
outgoing electron

$$W^2 = (p+q)^2$$
$$= M^2 + 2p.q + q^2$$

$(Q^2 \equiv -q^2)$



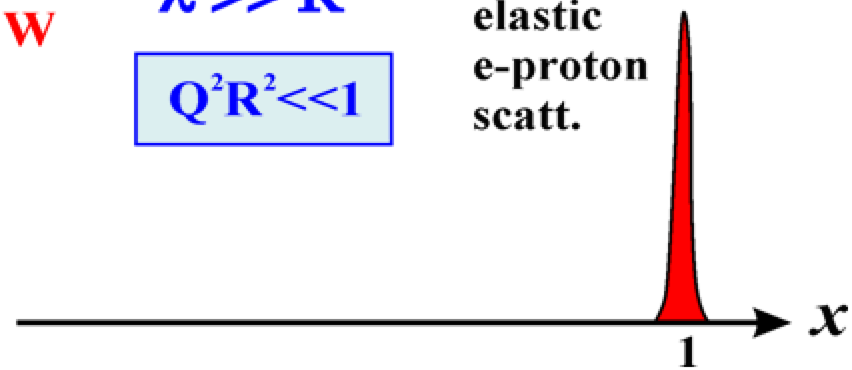
$\lambda \gg R$

$Q^2R^2 \ll 1$

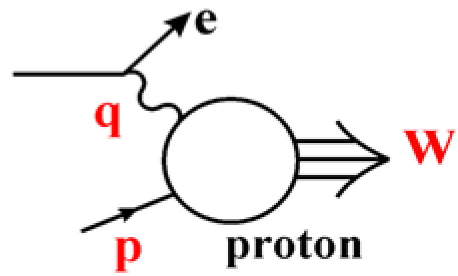
elastic
W=M

$$x \equiv \frac{Q^2}{2p.q} = 1$$

elastic
e-proton
scatt.

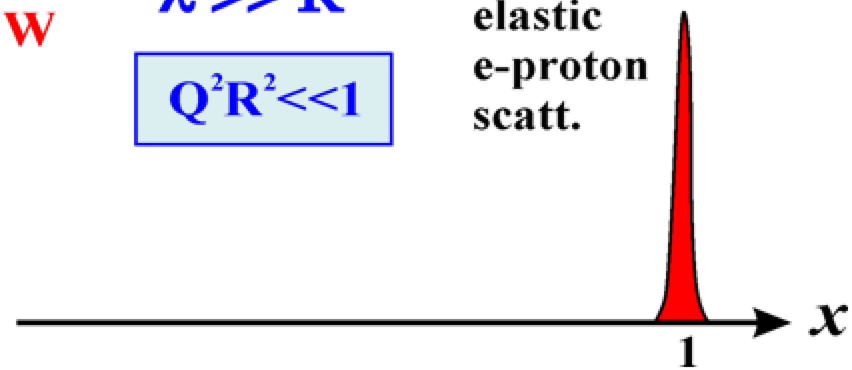


$$W^2 = (p+q)^2$$
$$= M^2 + 2p.q + q^2$$
$$(Q^2 \equiv -q^2)$$



$\lambda >> R$

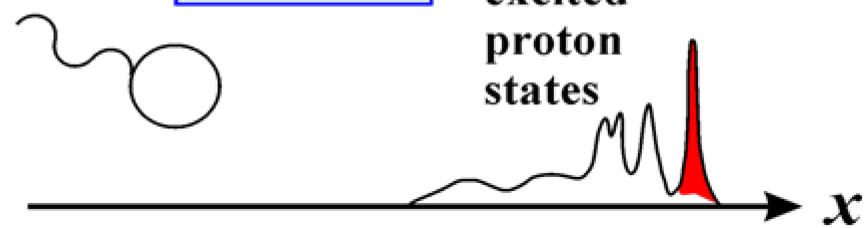
$Q^2R^2 << 1$



elastic
W=M

$$x \equiv \frac{Q^2}{2p.q} = 1$$

$Q^2R^2 \sim 1$

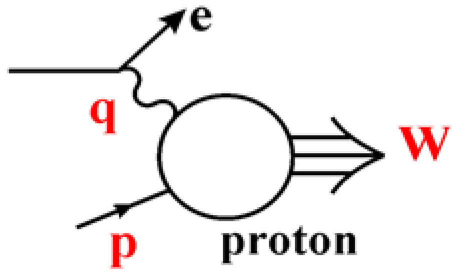


excit^{ns}
W>M

$$x < 1$$

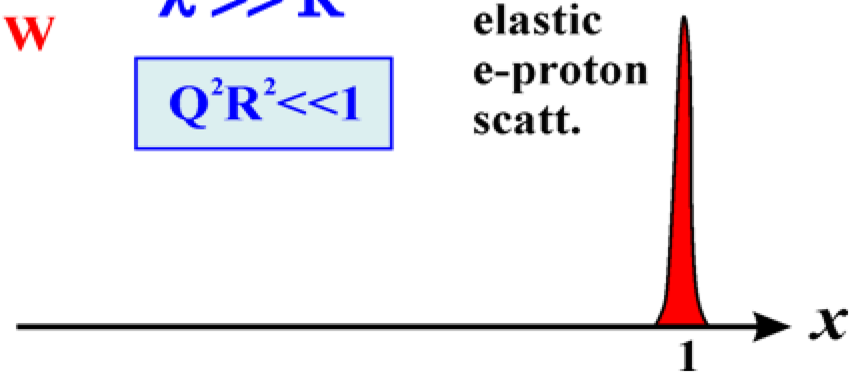
$$W^2 = (p+q)^2$$
$$= M^2 + 2p.q + q^2$$

$(Q^2 \equiv -q^2)$



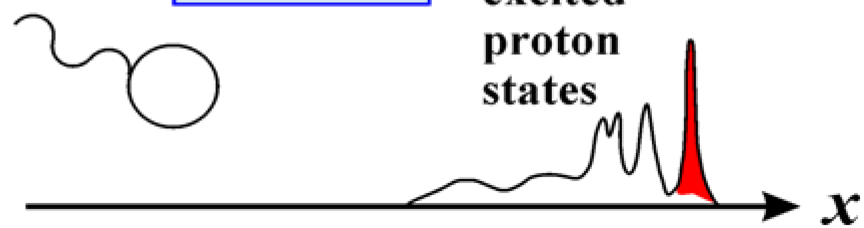
$\lambda >> R$

$Q^2R^2 << 1$



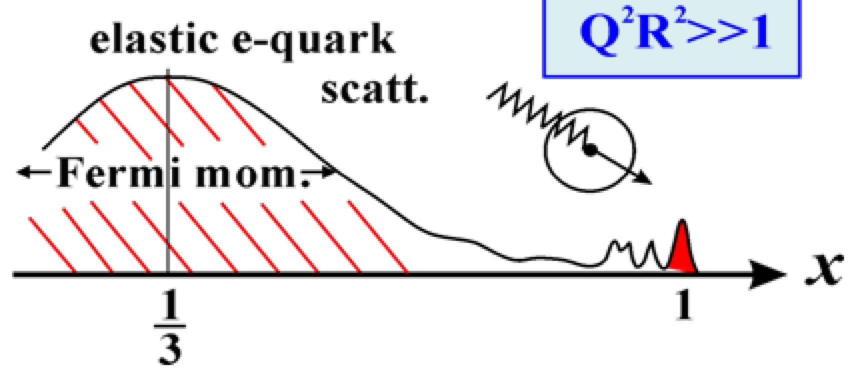
elastic W=M $\quad x \equiv \dfrac{Q^2}{2p.q} = 1$

$Q^2R^2 \sim 1$



excit^{ns} W>M $\quad x < 1$

$Q^2R^2 >> 1$

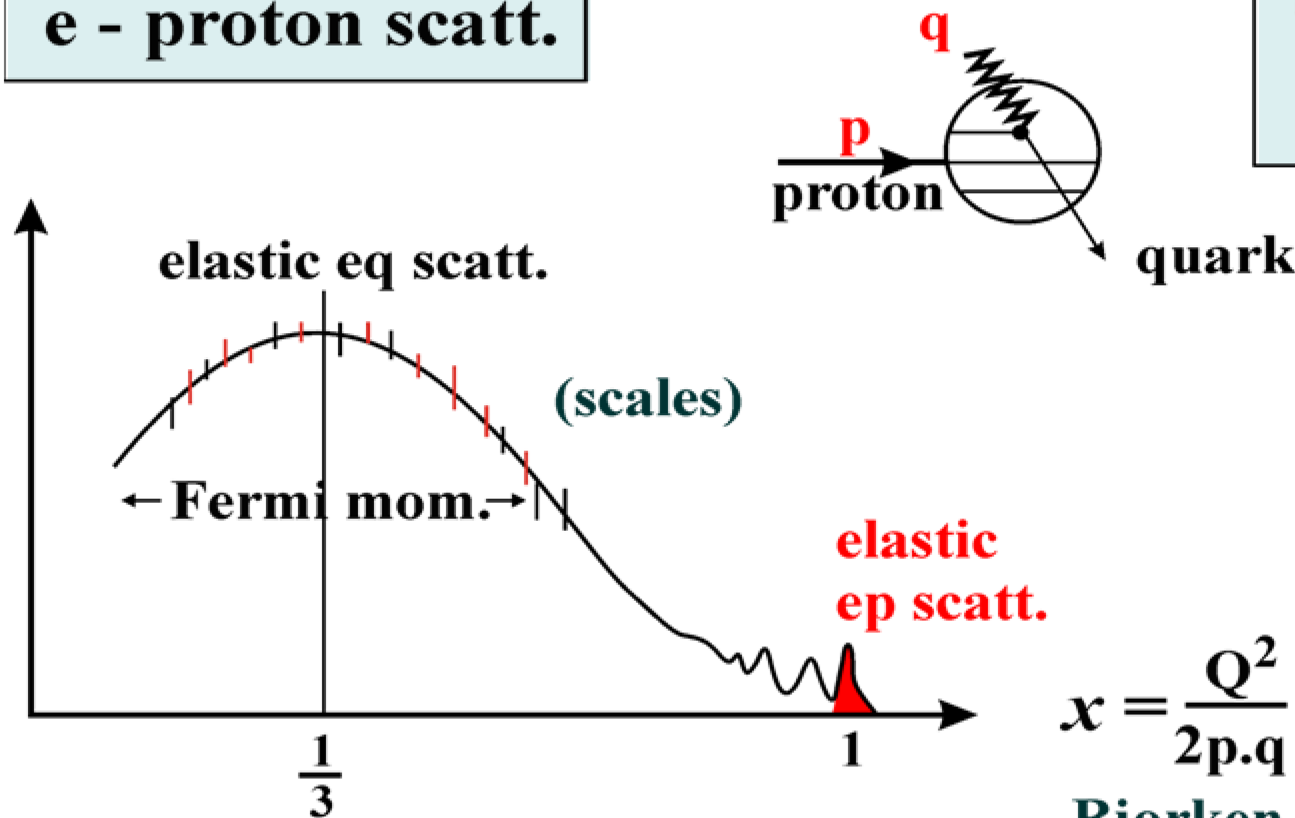


e-quark scatt: $\quad x = \dfrac{1}{3}\left(\dfrac{Q^2}{2p_q.q}\right) = \dfrac{1}{3}$

$p_q \sim \frac{1}{3}p$

e - proton scatt.

Two variables
x, Q^2

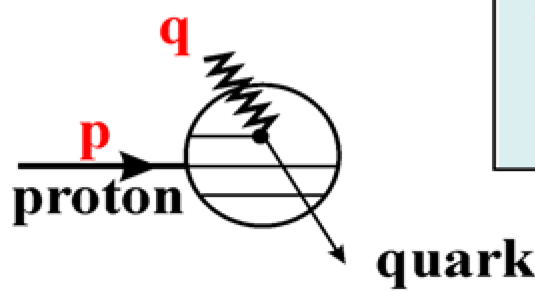


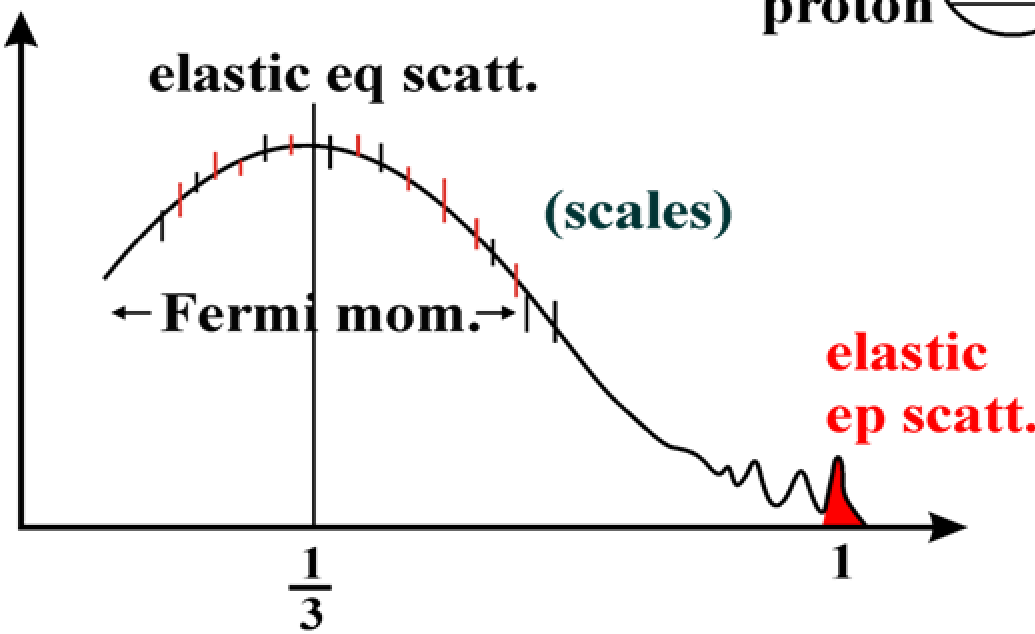
$$x = \frac{Q^2}{2p.q}$$

Bjorken scaling variable

e - proton scatt.

Two variables
x, Q^2





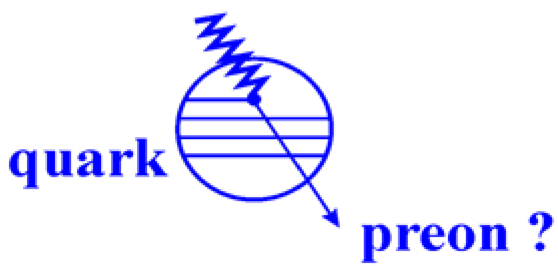
$$x = \frac{Q^2}{2p.q}$$

Bjorken scaling variable

Increase Q further

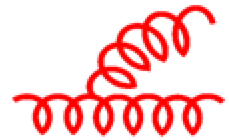
A replay ?

peak at $x = \frac{1}{12}$?

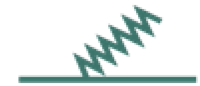


No evidence of q substructure

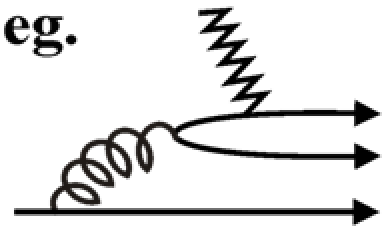
Instead of finding q substructure

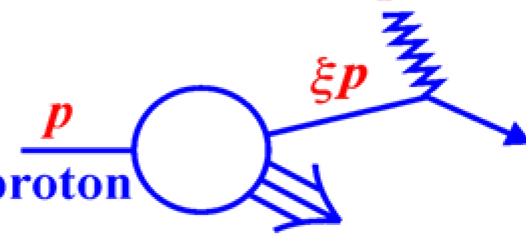


find QCD

(**compare QED** )

eg.





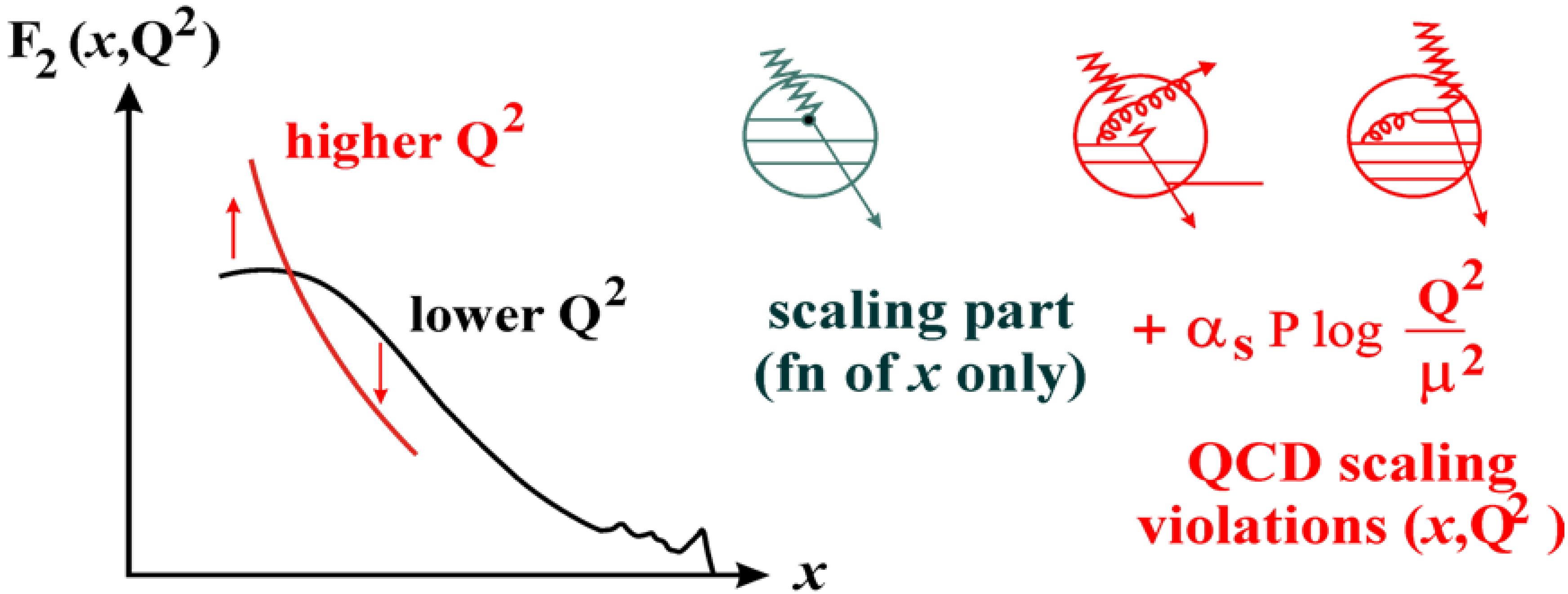
$$(\xi p + q)^2 = m_q^2 \simeq 0$$

$$2\xi p \cdot q - Q^2 \simeq 0$$

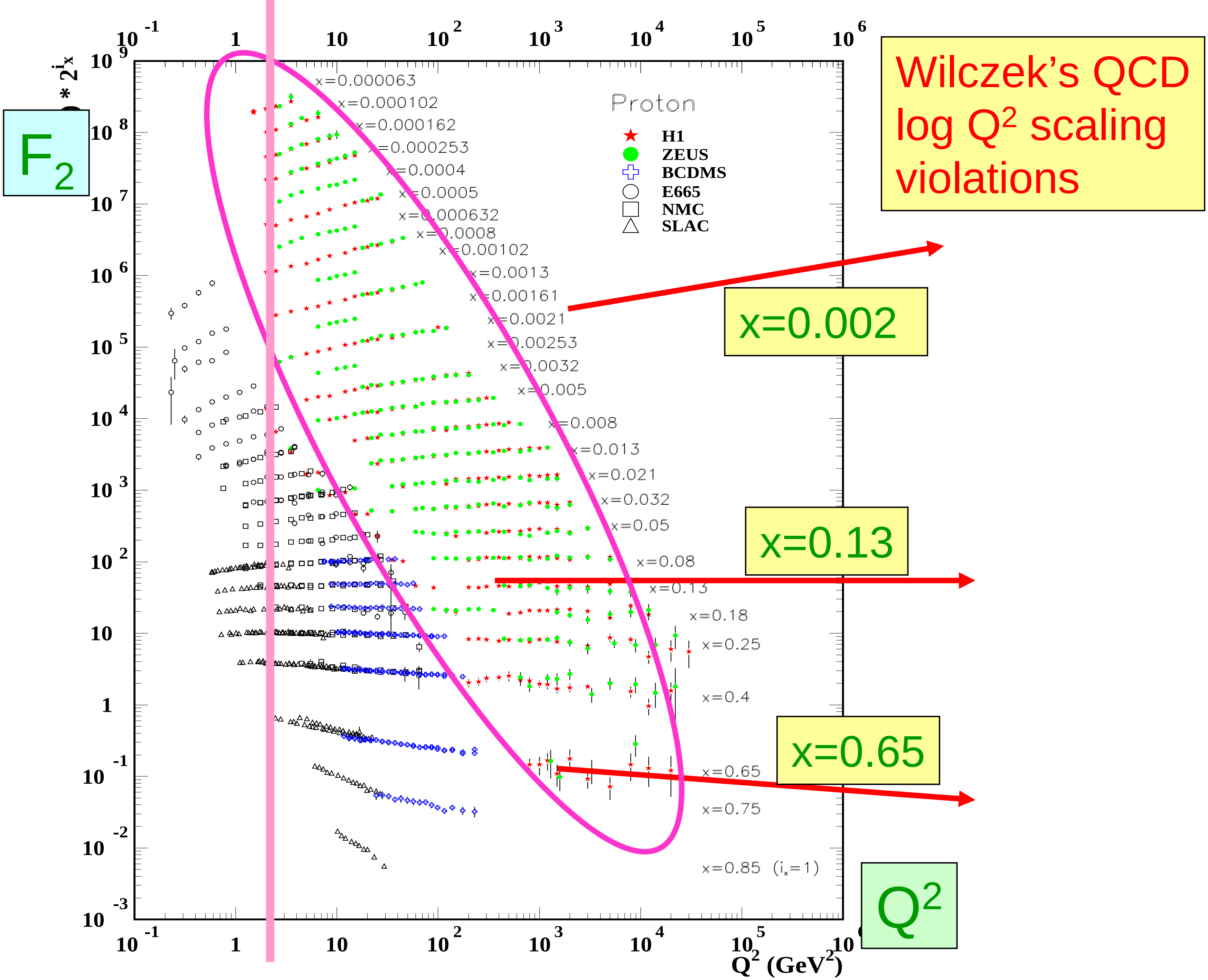
$$\xi = \frac{Q^2}{2p \cdot q} = x$$

Consequence :
as Q^2 increases, more and more partons are involved.
Each parton, on average, must have smaller *x*.

As Q^2 increases, each parton has, on average, smaller x

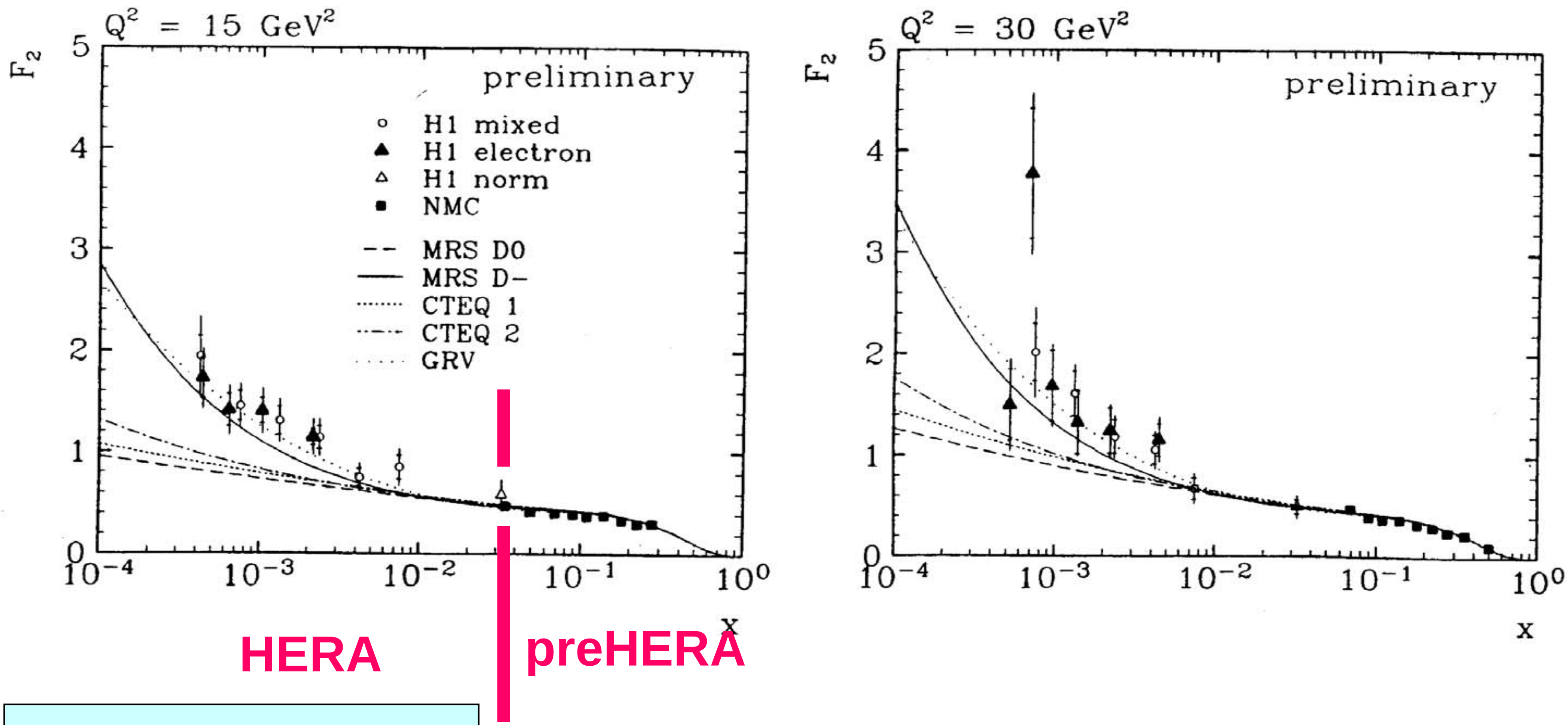


Famous experimentalist said to Wilczek :
You expect us to measure logarithms ! ?
Not in your lifetime, young man !



F2
Wilczek's QCD log Q2 scaling violations
x=0.002
x=0.13
x=0.65
Q2
Proton
H1
ZEUS
BCDMS
E665
NMC
SLAC
x=0.000063
x=0.000102
x=0.000162
x=0.000253
x=0.0004
x=0.0005
x=0.000632
x=0.0008
x=0.00102
x=0.0013
x=0.00161
x=0.0021
x=0.00253
x=0.0032
x=0.005
x=0.008
x=0.013
x=0.021
x=0.032
x=0.05
x=0.08
x=0.13
x=0.18
x=0.25
x=0.4
x=0.65
x=0.75
x=0.85 (ix=1)
Q2 (GeV2)

Workshop on HERA
Durham, March 1993



gain of 100 in reach

From the proc. of “W/S on HERA” (Durham, March 1993)

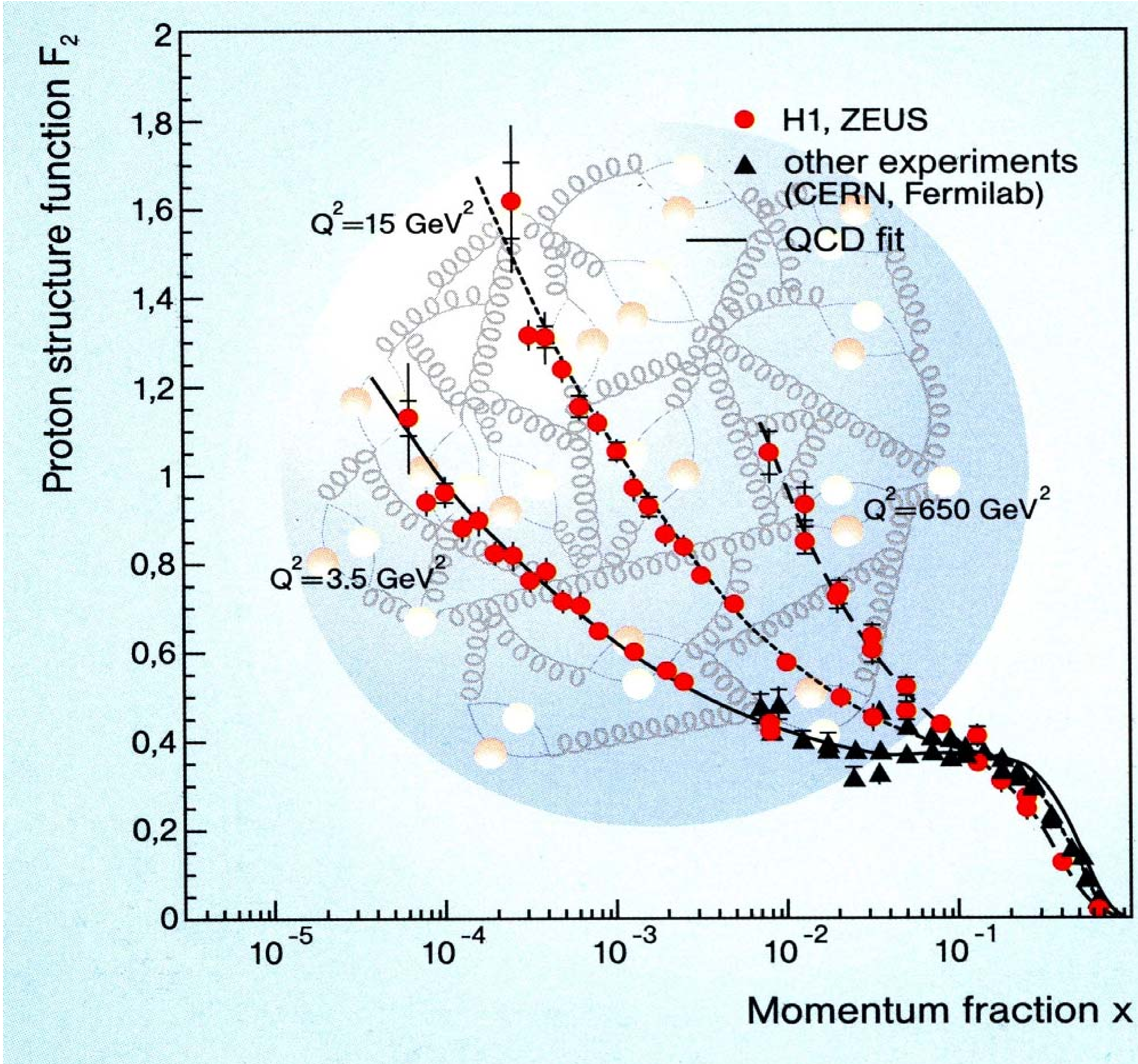
One of the moments of high drama was the presentation of the first measurement of F_2 at HERA showing that the structure function did indeed rise quite strongly at low x.

The argument over the interpretation began immediately and continued all week---was it evidence for singular BFKL-type behaviour of the gluon; was it just evidence of the need for a different parametrization; what did it imply for the Pomeron and diffractive scattering ?

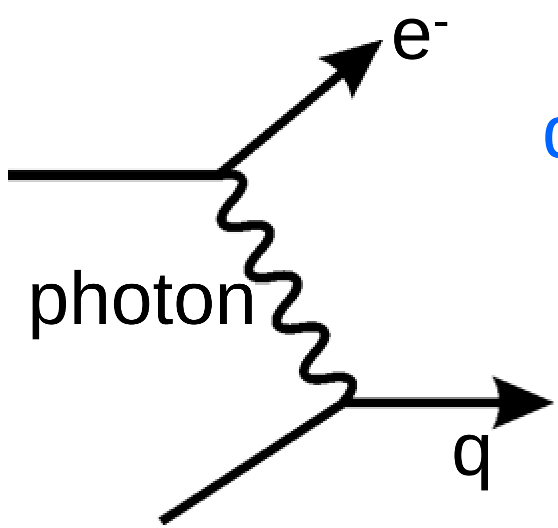
Although the protagonists tried very hard, it will take a lot more data and quite a few more Workshops to answer all these exciting questions.

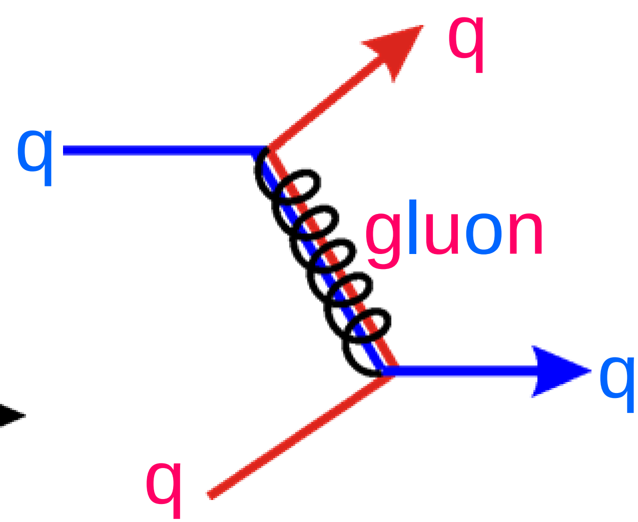
→ led directly to the DIS series of Workshops

HERA WORKSHOP
ST. JOHN'S COLLEGE, DURHAM.
MARCH 1993

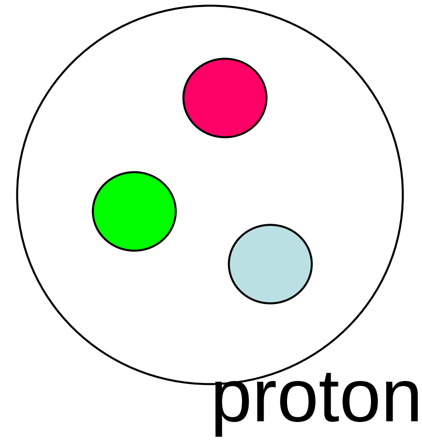


Proton structure function F_2
H1, ZEUS
other experiments (CERN, Fermilab)
QCD fit
Q^2=15 GeV^2
Q^2=650 GeV^2
Q^2=3.5 GeV^2
2
1,8
1,6
1,4
1,2
1
0,8
0,6
0,4
0,2
0
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
Momentum fraction x





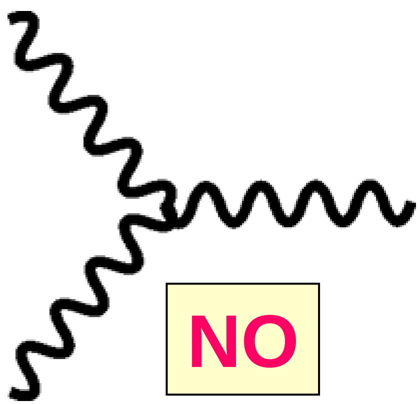
quarks have colour



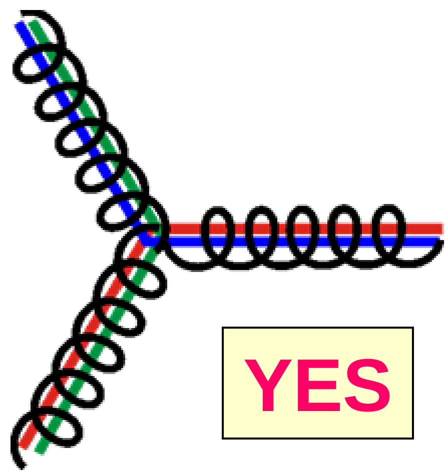
QED: photon does not carry charge

QCD: gluons do carry colour

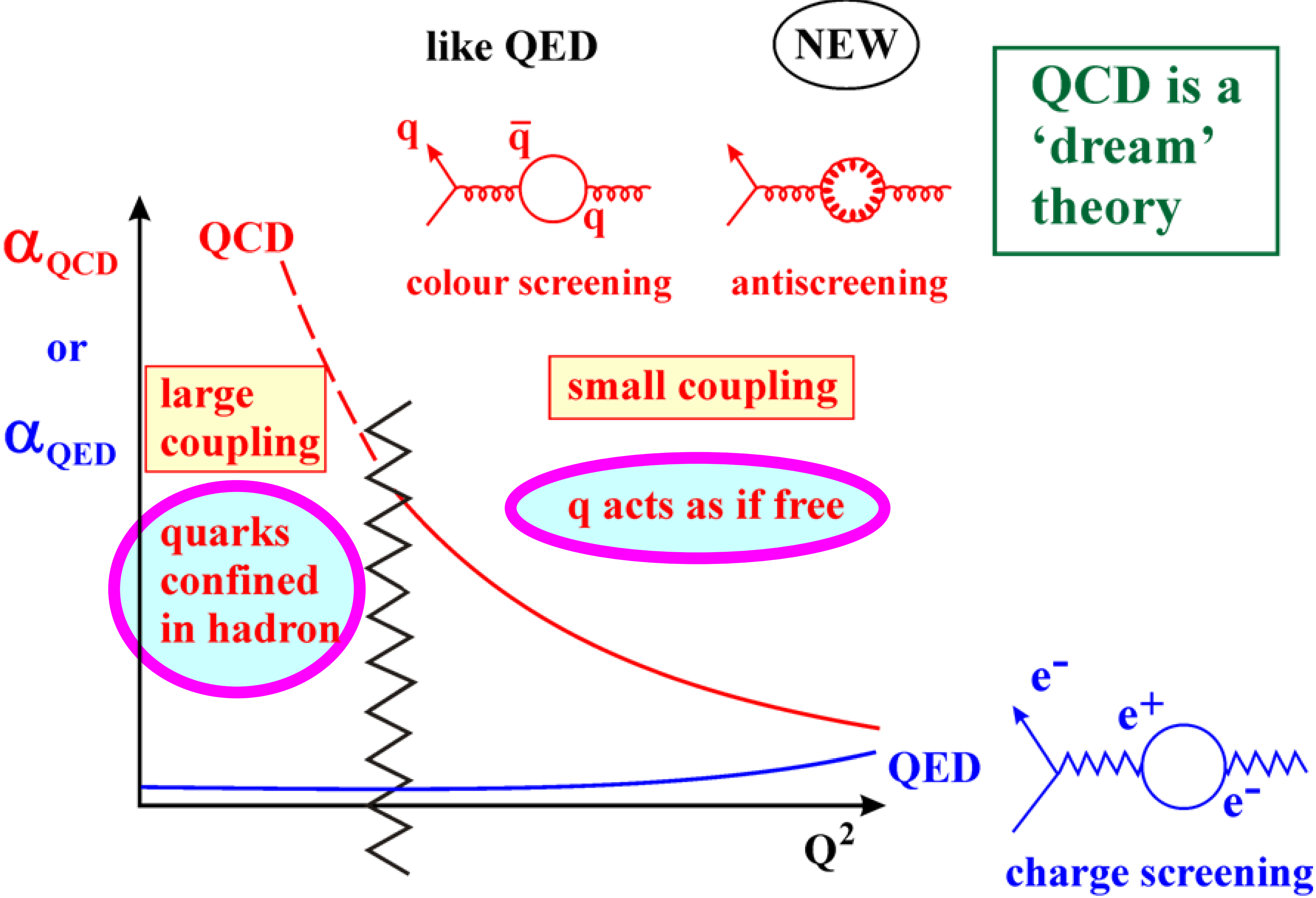
observed pts. are colourless



NO

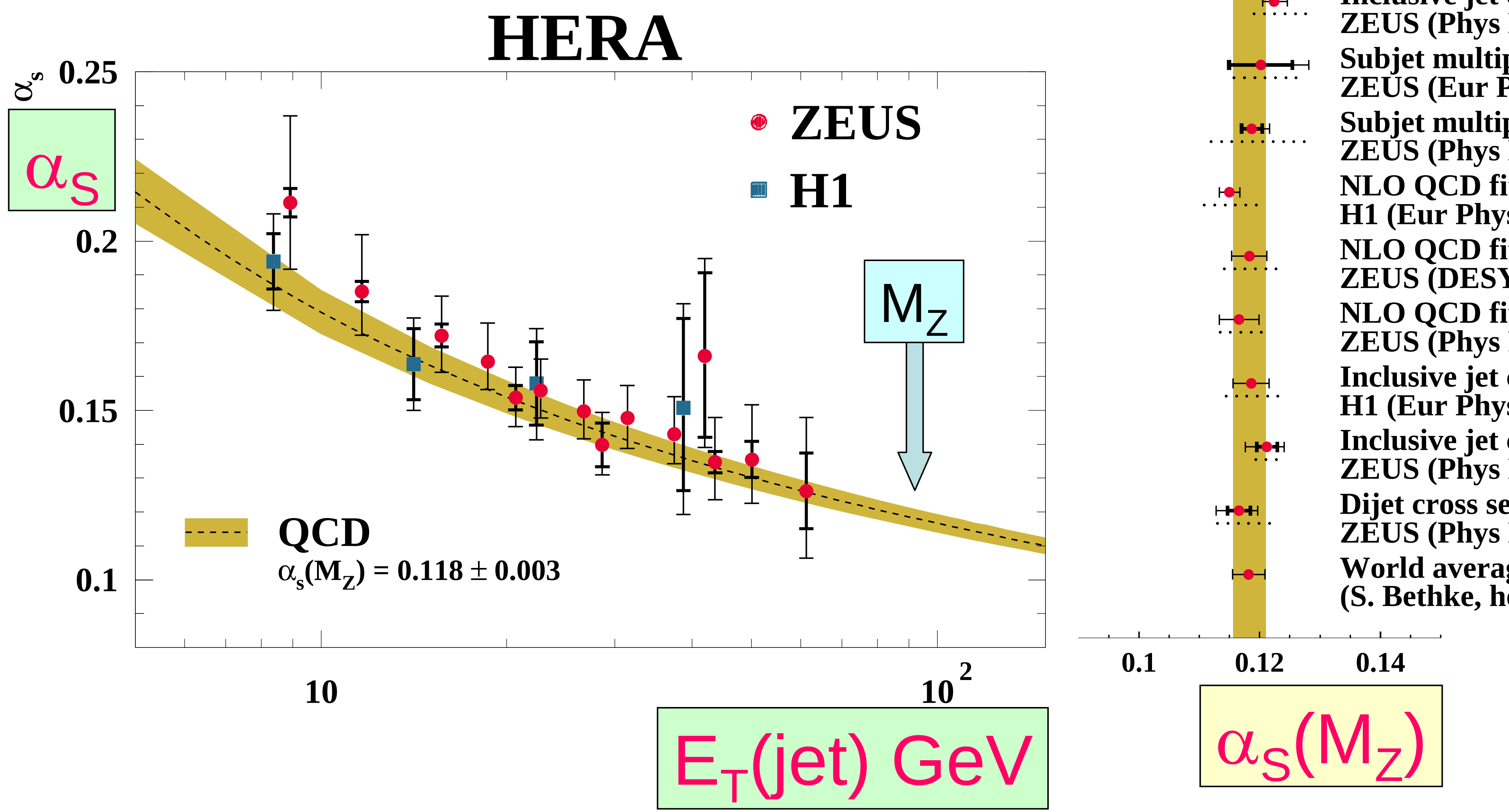


YES

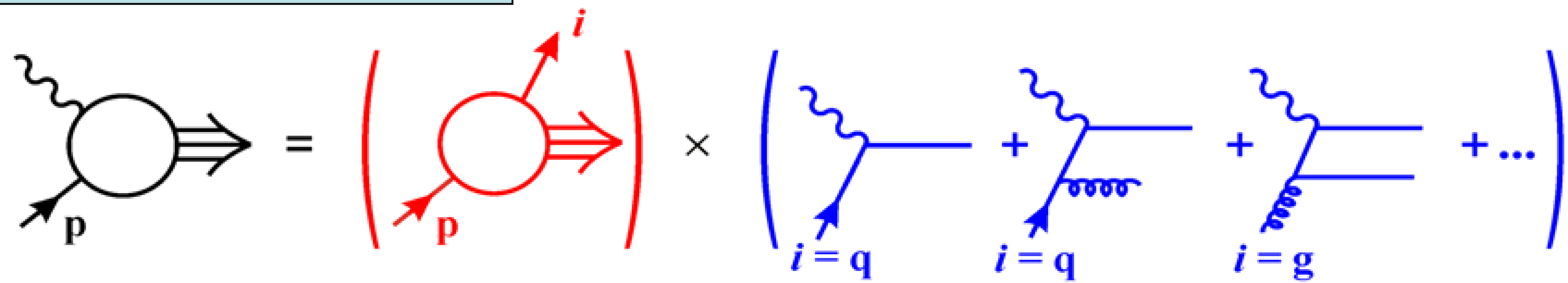


(pQCD predicts running, but not absolute value, of α_{QCD})

QCD coupling from inclusive jet data at HERA



Factorization theorem



$$F_2(x, Q^2) \quad = \quad \sum_{i=q,\bar{q},g} f_i \otimes C_{2,i}$$

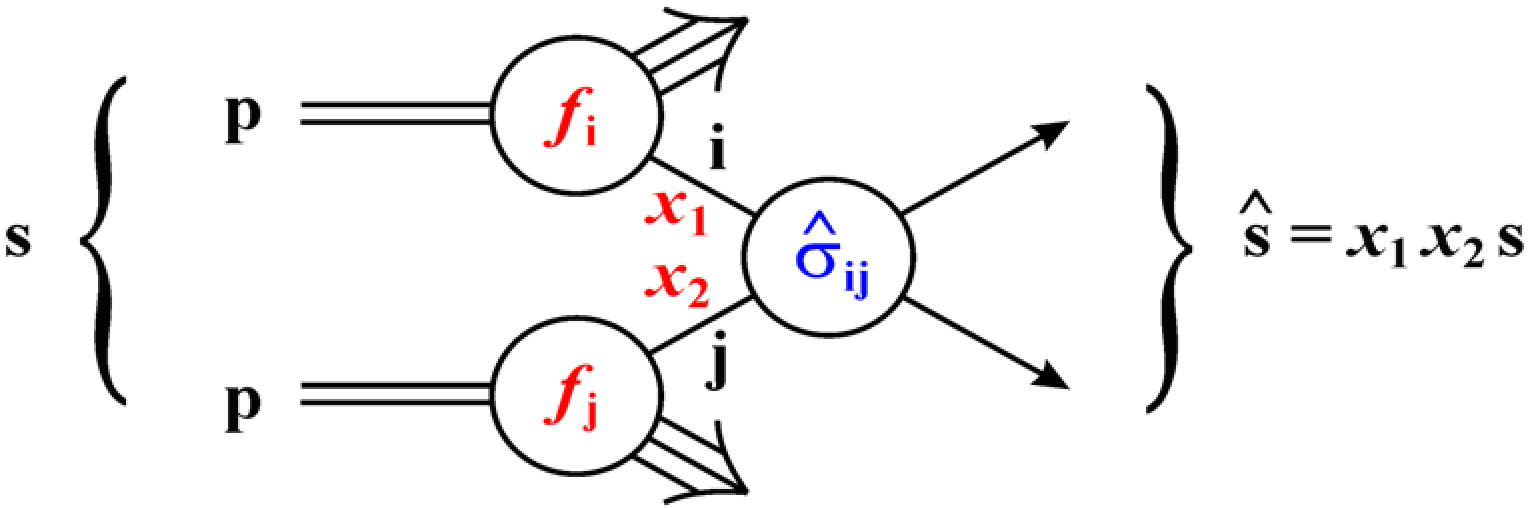
UNIVERSAL parton densities $f_i(x, Q^2)$
Q dep. given in pQCD by DGLAP eqs.

Coeff. fns, $C_{a,i}$ KNOWN from pQCD

f_i and $C_{2,i}$ are power series in α_S

LO	NLO	NNLO ....
α_S	α_S^2	α_S^3 ....

pp → X LHC (**p$\bar{p}$ → X Tevatron**)



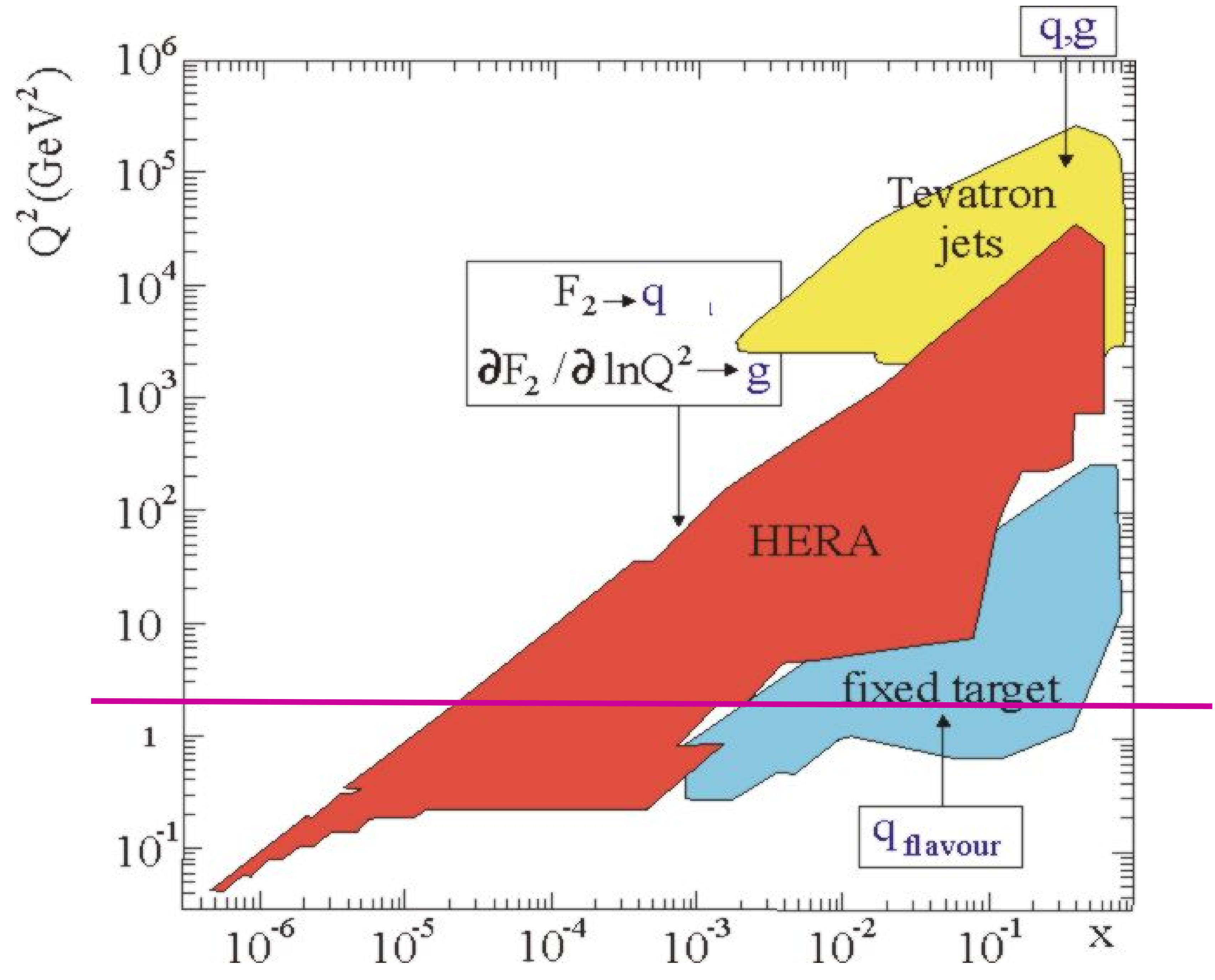
$$\sigma = \sum_{i,j} \int dx_1 dx_2 \underbrace{f_i(x_1, Q^2) f_j(x_2, Q^2)}_{\text{same universal parton densities}} \underbrace{\hat{\sigma}_{ij}(x_1 x_2 s, \alpha_S(Q^2))}_{\text{calculable}}$$

same universal parton densities

calculable

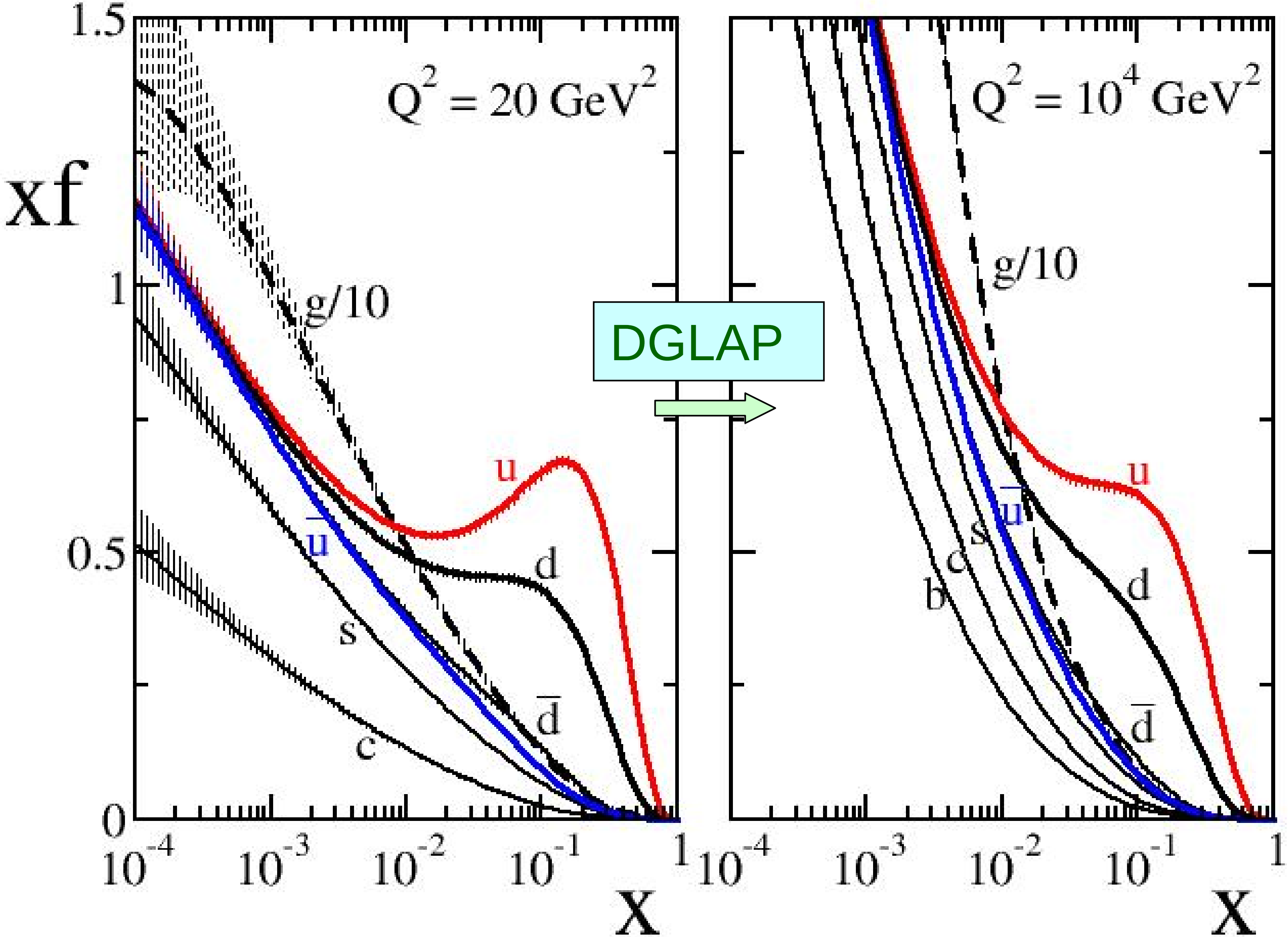
Determination of parton distributions

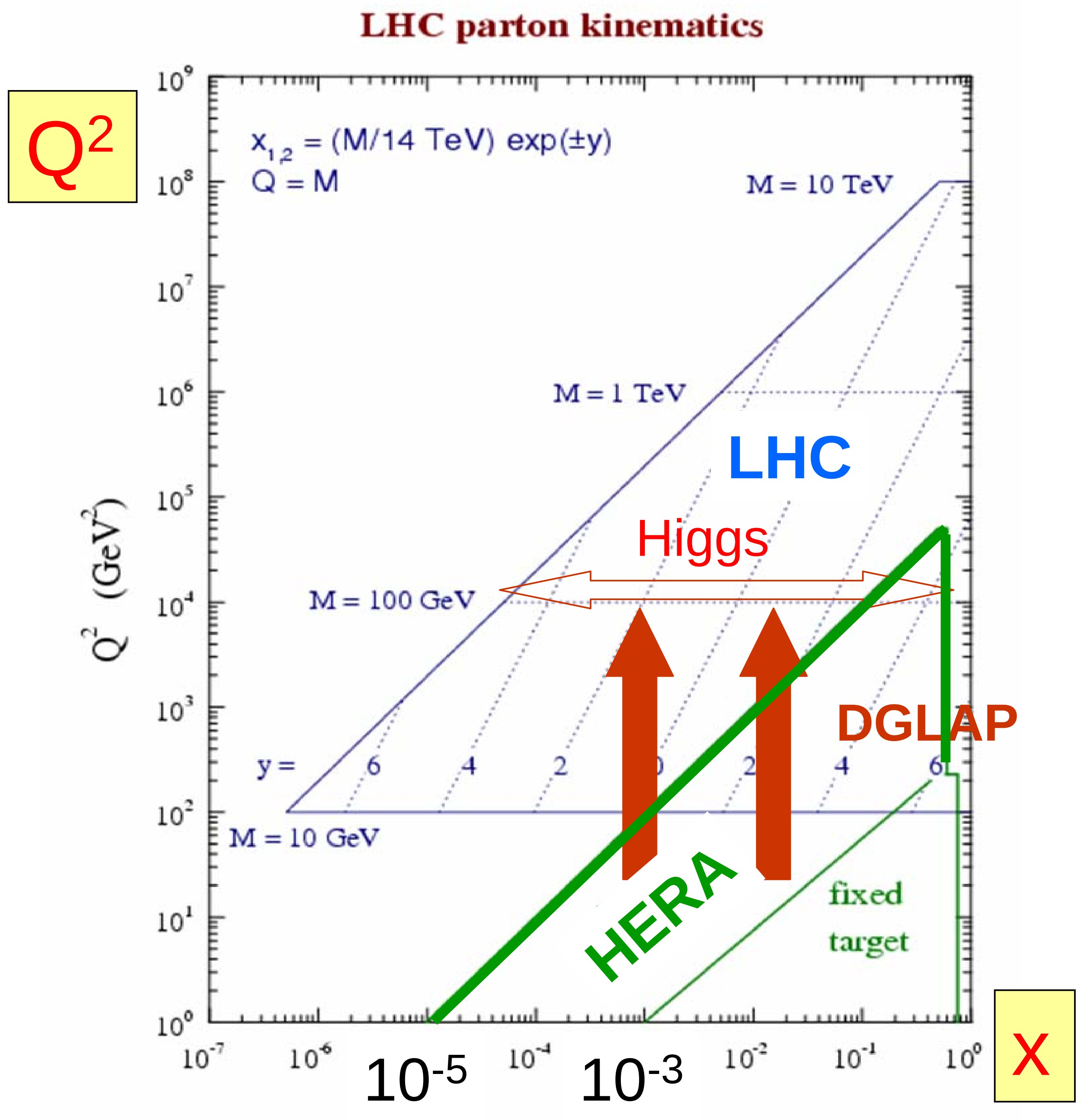
Parametrise x dep. at low pQCD scale Q_0^2	$\longrightarrow$	$f_i(x, Q_0^2)$
Evolve up in Q^2 using DGLAP eqs.	$\longrightarrow$	$f_i(x,\ Q^2 > Q_0^2)$
Global fit to HERA + all related data	$\longrightarrow$	f_i's



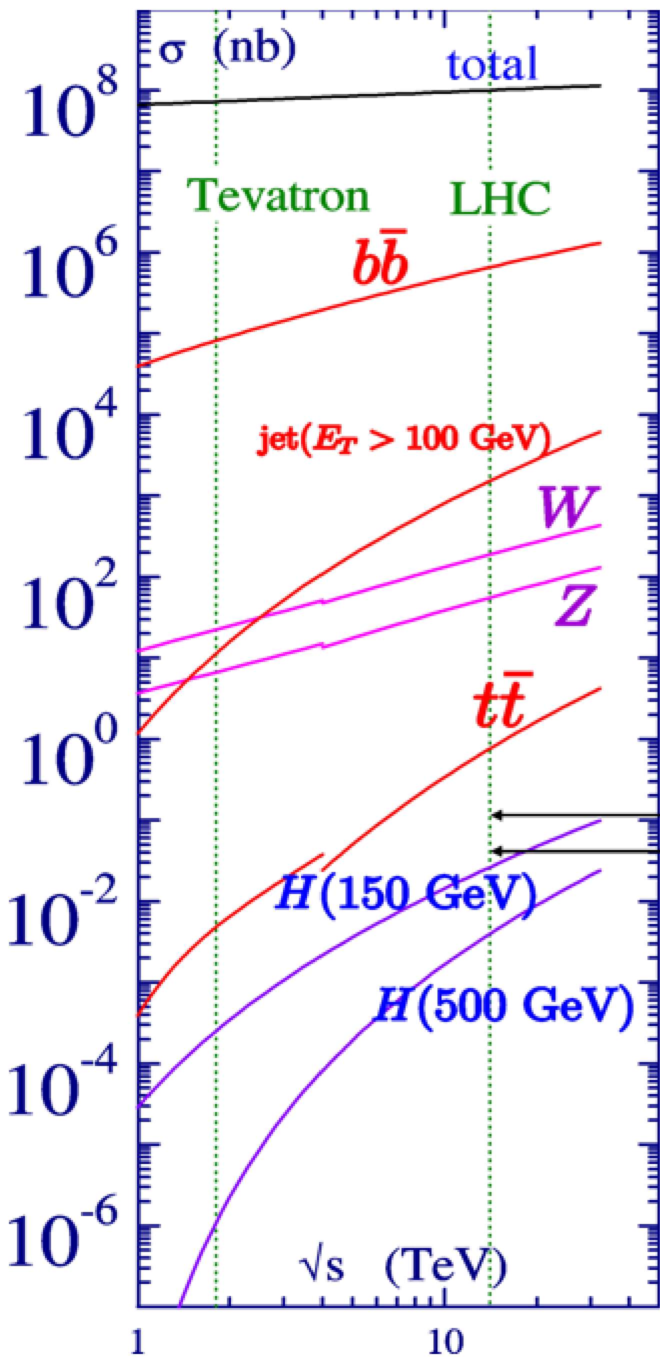
q,g
Tevatron
jets
F2 → q
∂F2 / ∂ lnQ2 → g
HERA
fixed target
q flavour
Q2 (GeV2)
x

NNLO Partons (2007)





LHC parton kinematics
Q2
x
$x_{1,2}$ = (M/14 TeV) exp(±y)
Q = M
M = 10 TeV
M = 1 TeV
M = 100 GeV
M = 10 GeV
y = 6 4 2 0 2 4 6
LHC
Higgs
DGLAP
HERA
fixed target
Q^2 (GeV^2)
10^{-5}
10^{-3}



events/sec if $\mathcal{L} = 10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

$b\bar{b} \sim 10^6/\mathrm{sec}$ CKM, CP violation

$W \rightarrow e\nu \sim 20/\mathrm{s}$ M_W, Γ_W

$Z \rightarrow ee \sim 2/\mathrm{s}$ luminosity

$t\bar{t} \sim 1/\mathrm{s}$ m_t

gluino-pair?
squark-pair?
Higgs?
(few/minute)

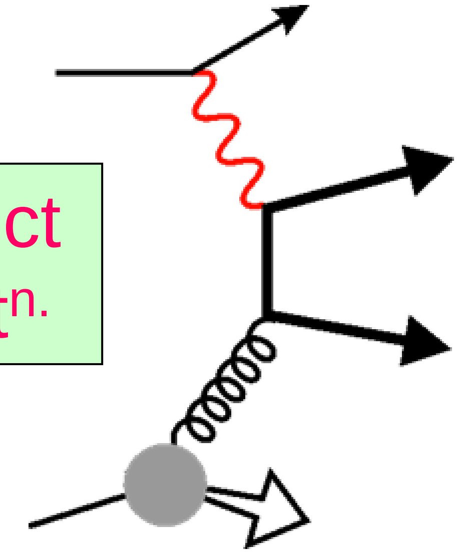
} discovery?

or, more exciting, something totally unexpected

Structure of photon (and proton) from dijet photoprod. at HERA

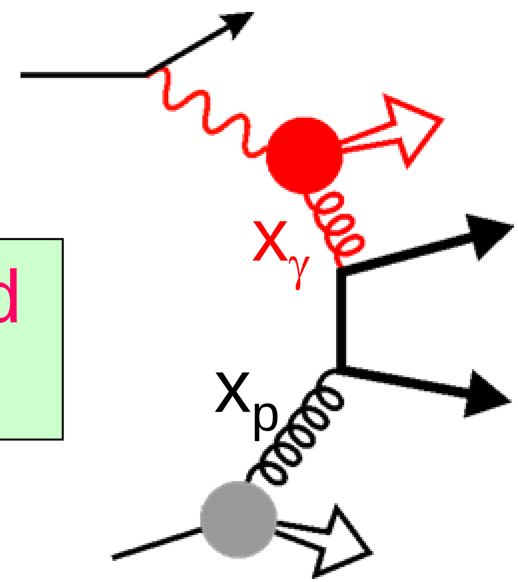
Forward dijets give info. on
1) γ parton distrib$^{ns.}$ (at low x_γ)
2) gluon distrib$^{n.}$ in proton
(from direct/high x_γ)

direct
γ int$^{n.}$



No existing set of photon distrib$^{ns.}$ gives an adequate (NLO) description of "resolved" HERA data

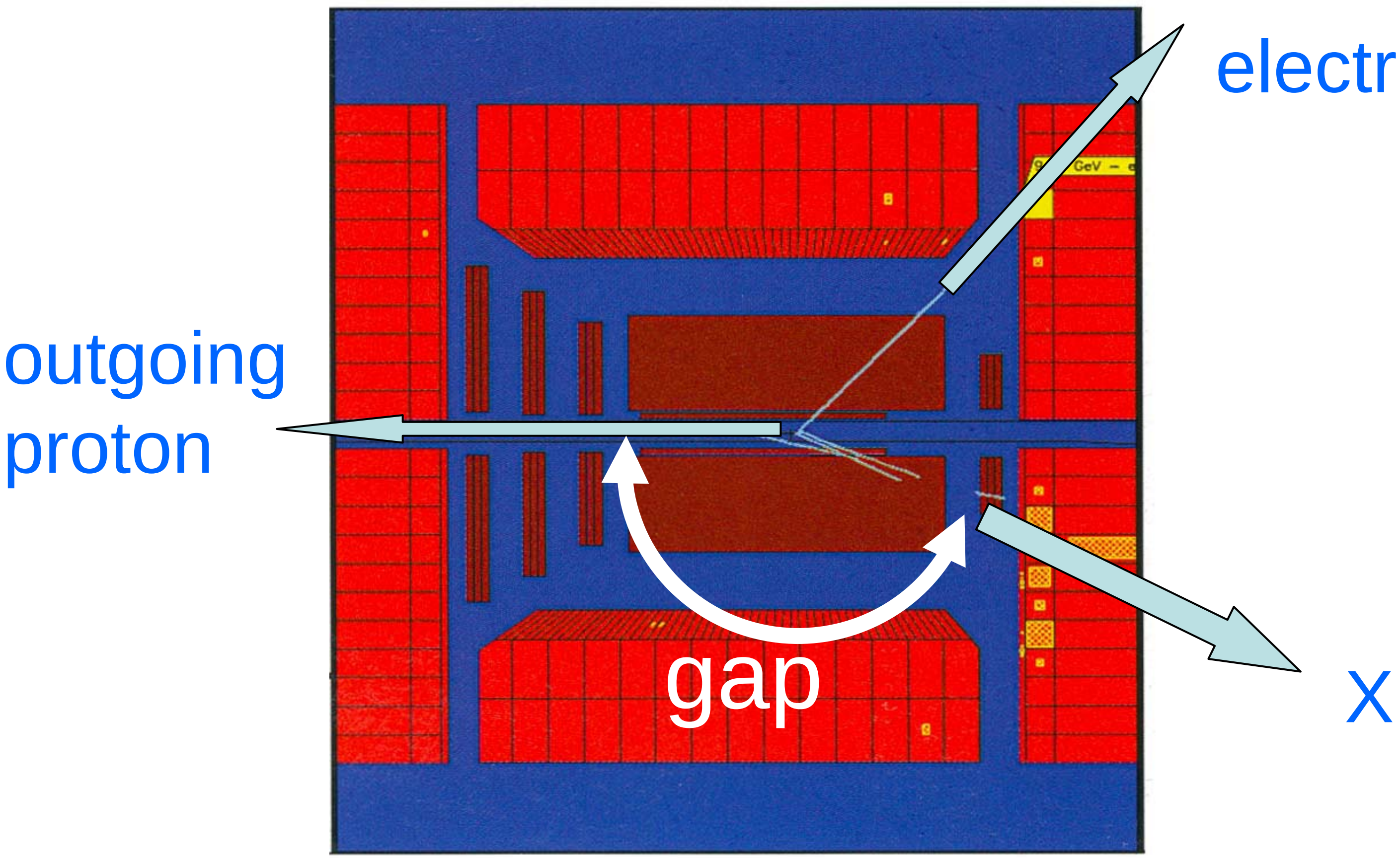
resolved
γ int$^{n.}$

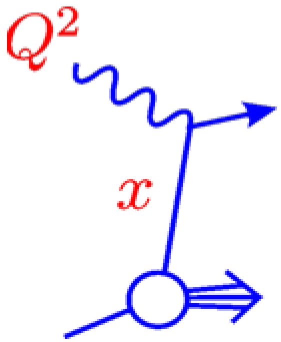


DIS: ep→eX (γ*p→X)

HERA finds that about 10% of these events are

diffractive DIS: ep→eX+p (γ*p→X+p)



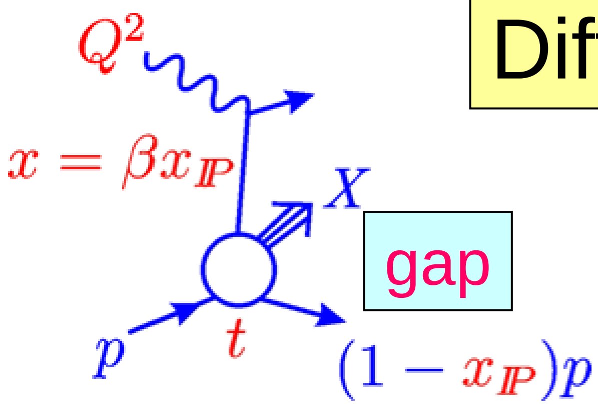


DIS

$$F_2(x, Q^2) = \sum_{i=q,\bar{q},g} f_i \otimes C_{2,i}$$

same

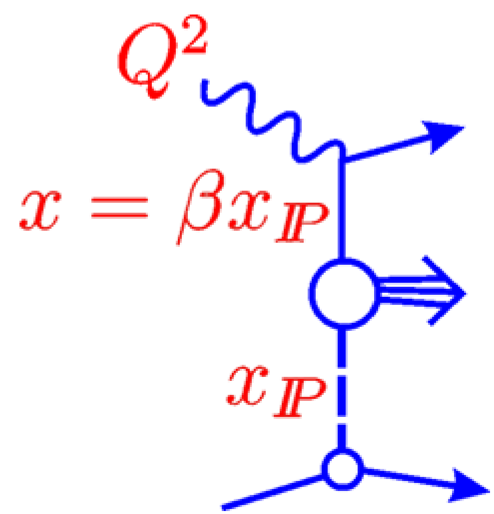
Diffractive DIS

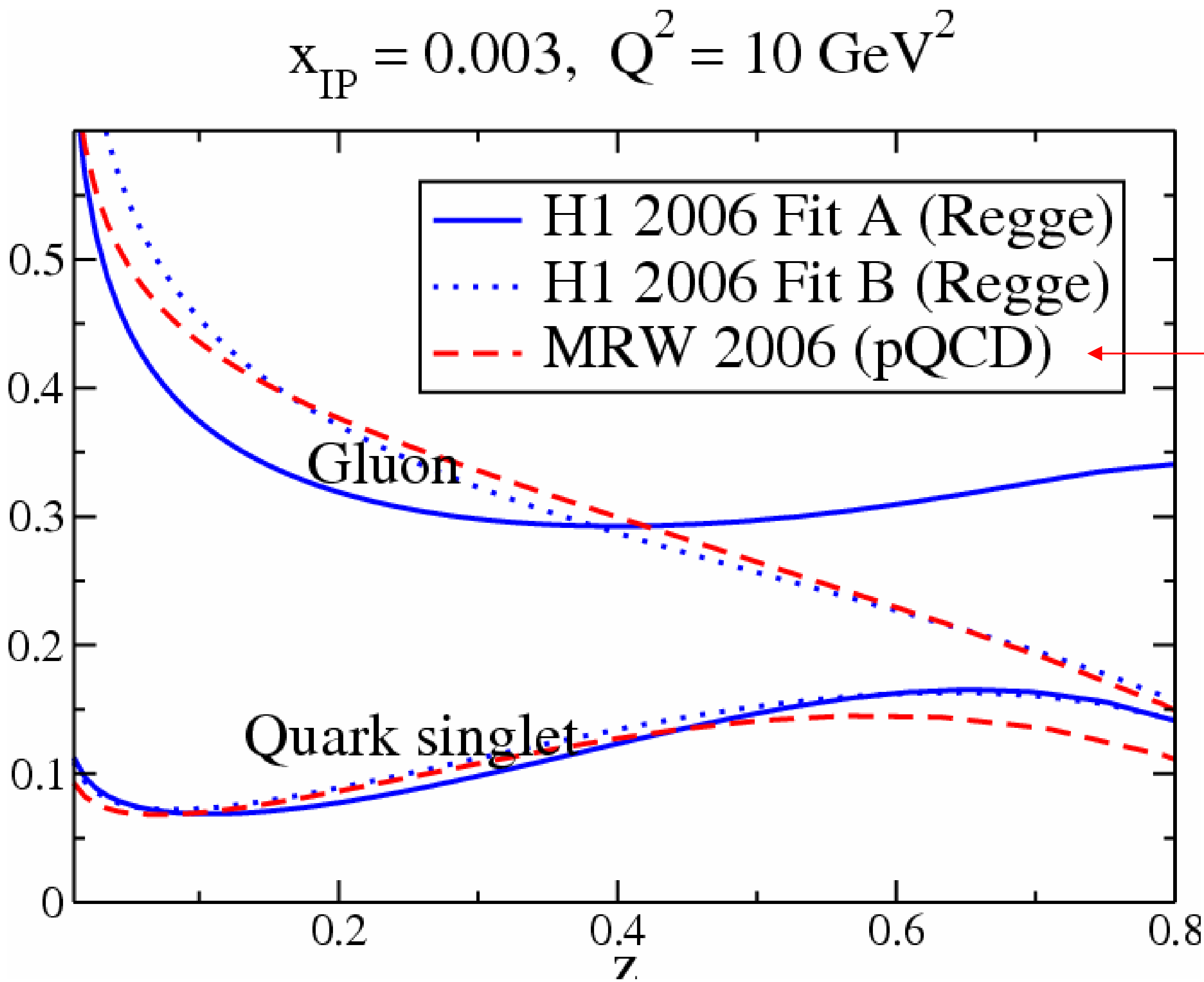


$$F_2^{D(3)}(x_{I\!P}, \beta, Q^2) = \sum_i f_i^D \otimes C_{2,i}$$

If then assume, Regge factorization:

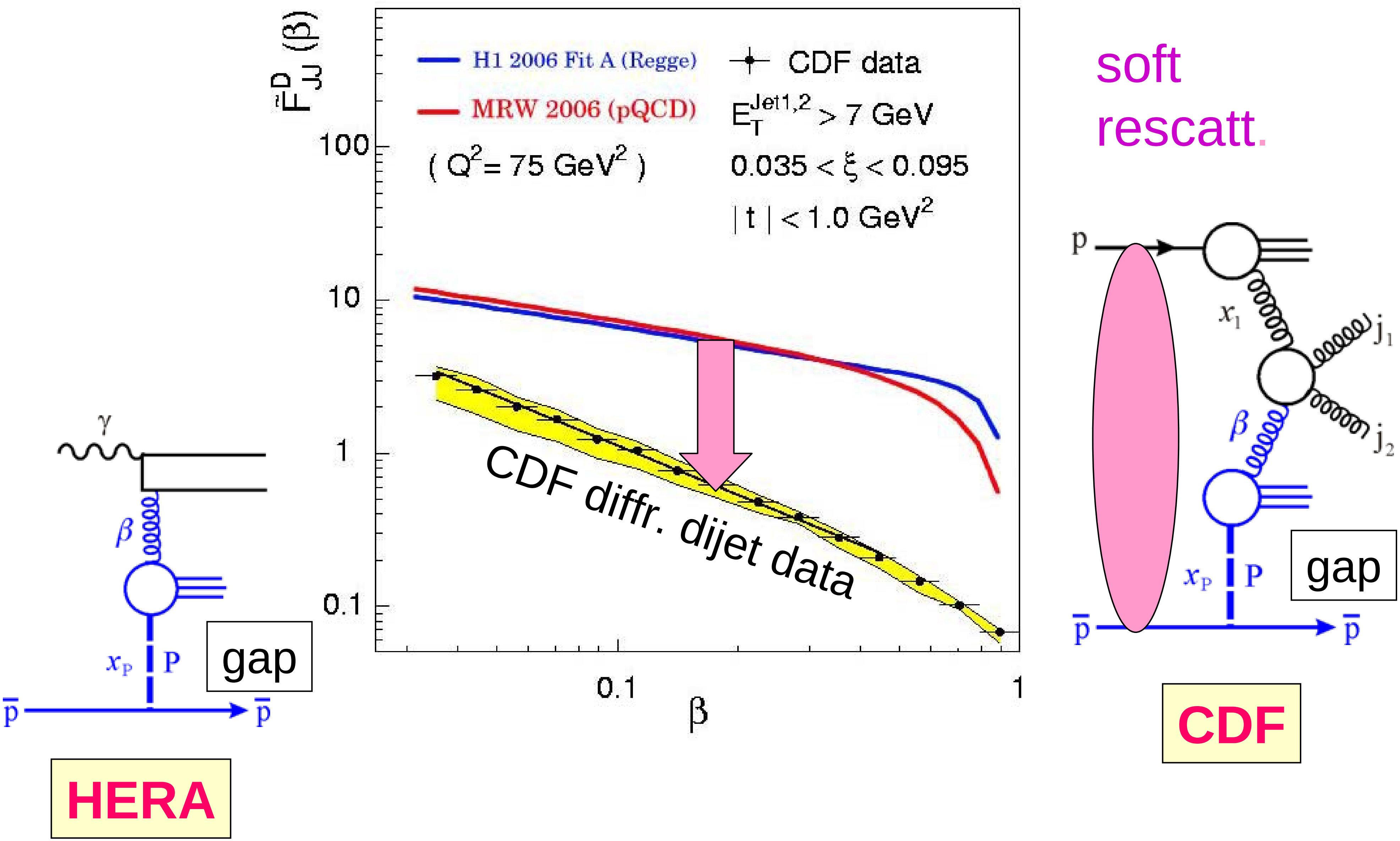
$$f_i^D(x_{I\!P}, \beta, Q^2) = \mathrm{Flux}(x_{I\!P})\; f_i^{I\!P}(\beta, Q^2)$$



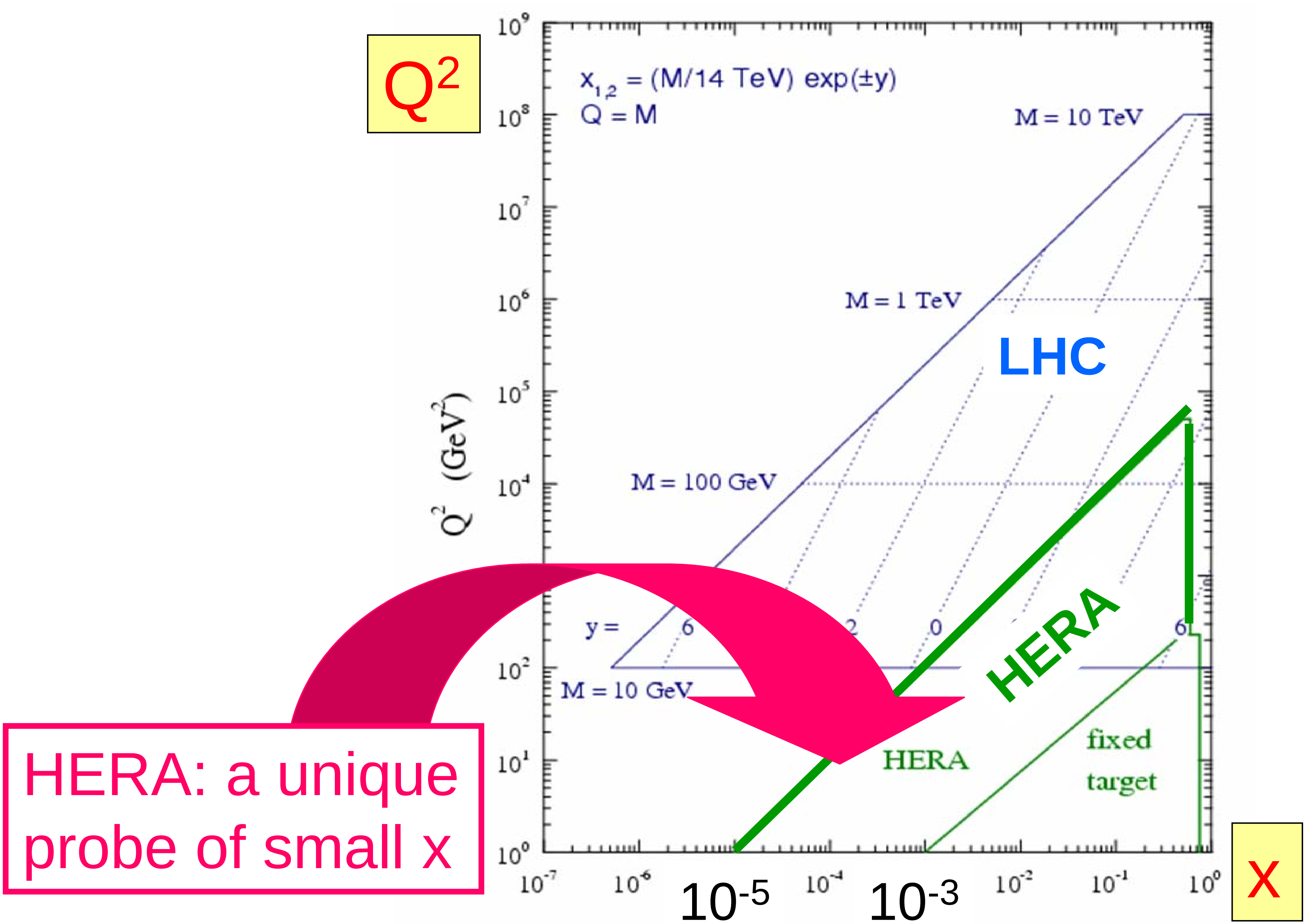


direct+resolved
Pomeron
(cf. photon)

diffractive partons g^D, q^D can be used to predict diffractive processes with hard scale? Yes, but…

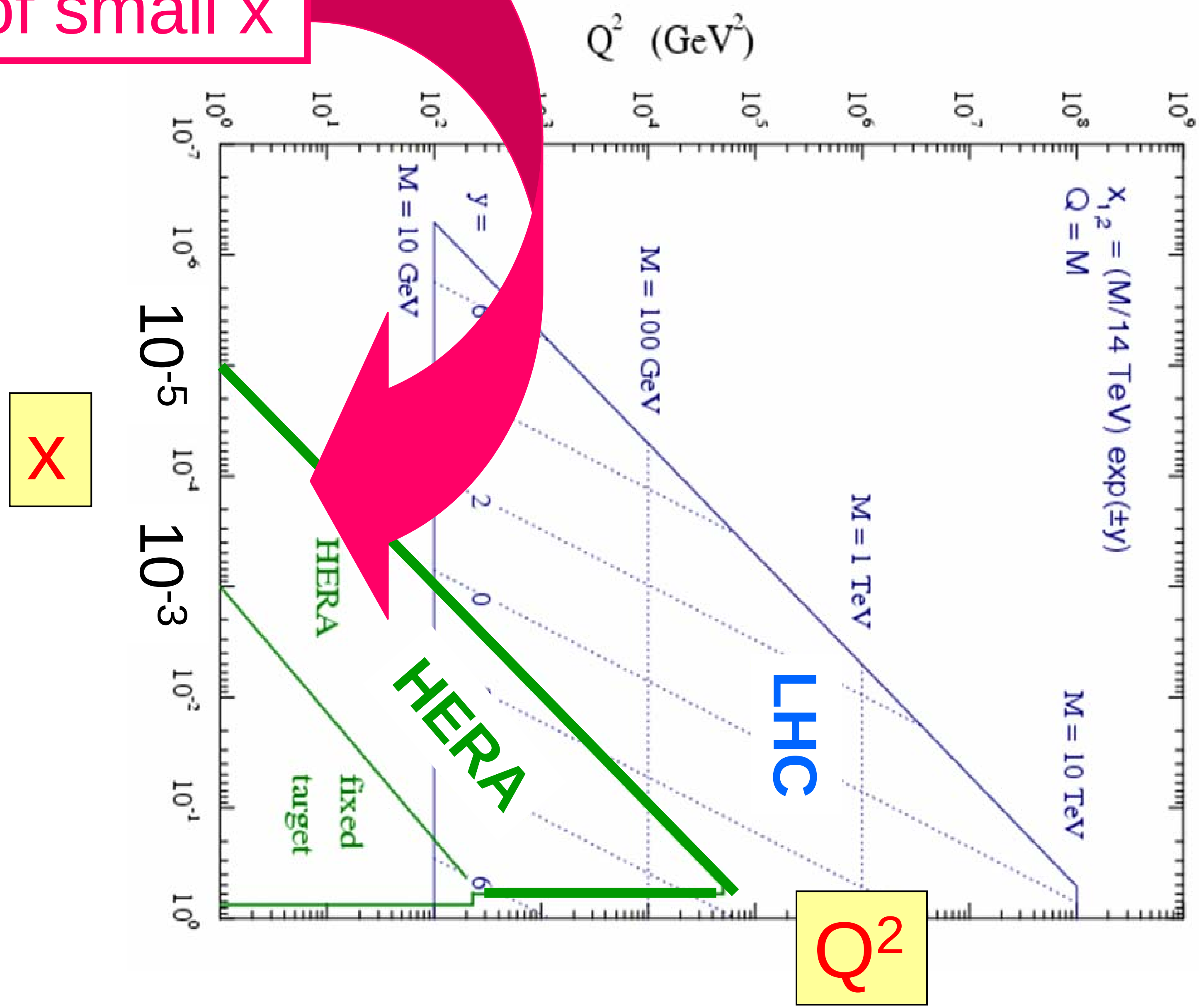


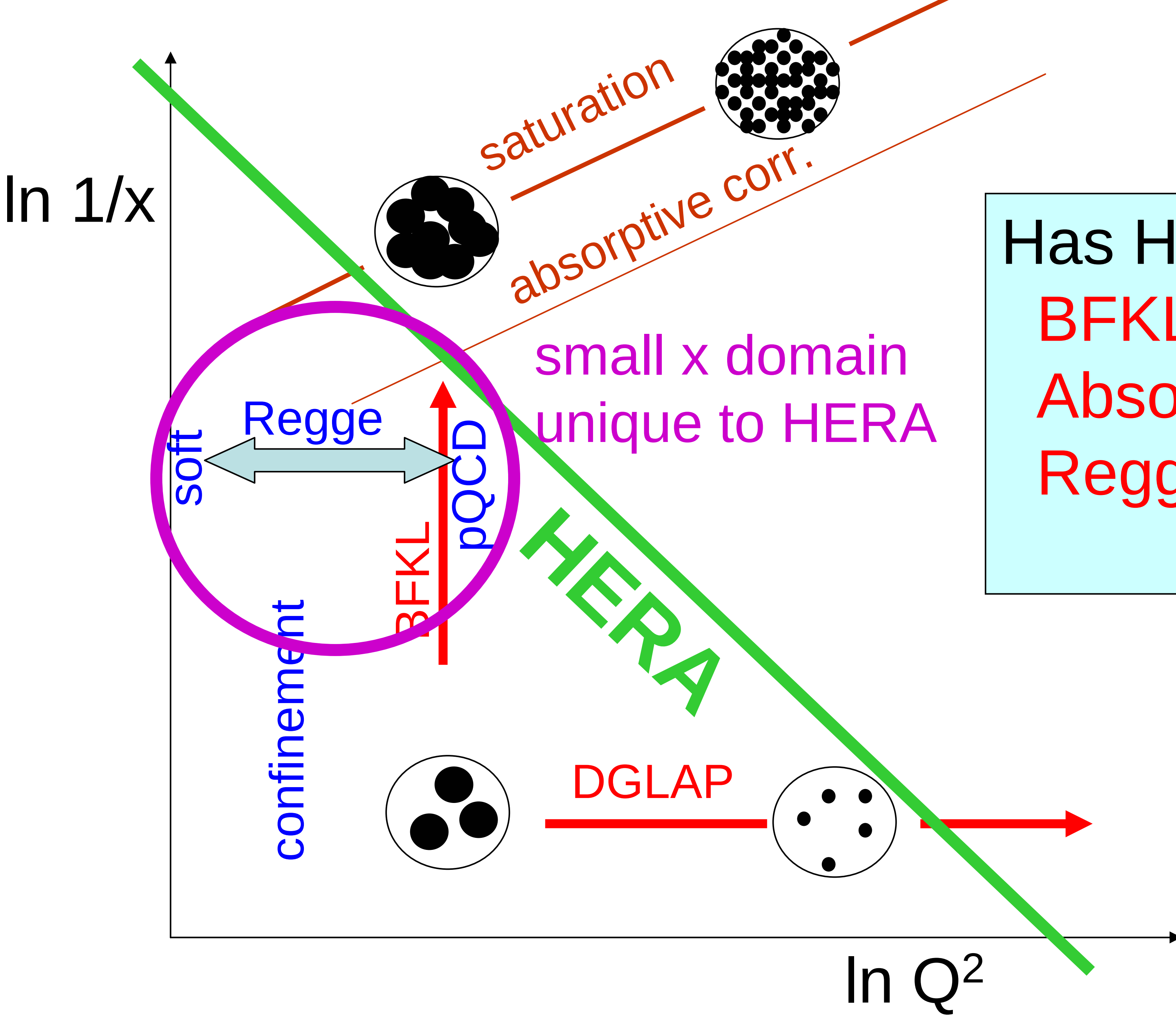
H1 2006 Fit A (Regge)
MRW 2006 (pQCD)
(Q²= 75 GeV²)
CDF data
E_T^Jet1,2 > 7 GeV
0.035 < ξ < 0.095
| t | < 1.0 GeV²
CDF diffr. dijet data
F̃_JJ^D (β)
β
100
10
1
0.1
0.1
1
soft rescatt.
p
x1
j1
j2
β
xP
P
gap
p̄
p̄
CDF
γ
β
xP
P
gap
p̄
p̄
HERA



Q2
x1,2 = (M/14 TeV) exp(±y)
Q = M
M = 10 TeV
M = 1 TeV
LHC
M = 100 GeV
y =
6
2
0
6
M = 10 GeV
HERA
HERA
fixed
target
Q2 (GeV2)
10-7
10-6
10-5
10-4
10-3
10-2
10-1
100
x
HERA: a unique
probe of small x

HERA: a unique probe of small x





Has HERA seen
BFKL?
Absorption?
Regge (soft→ pQCD)

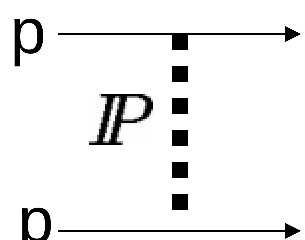
"soft" – particles go forward – no large scale – no pQCD

domain of Regge exchange: at HE Pomeron exchange

$$A(s,t) \sim f(t)\, s^{\alpha_{I\!P}(t)}$$

DL: 1.08 0.25

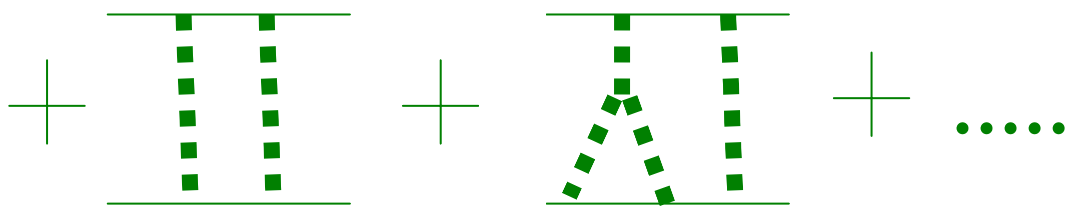
$$\alpha_{I\!P}^{\text{eff}}(t) = \alpha_{I\!P}(0) + \alpha' t$$



σ_{total}, $\dfrac{d\sigma_{\text{elastic}}}{dt}$

$s^{\alpha_{I\!P}(0)-1}$ shrinks

DL incomplete --must allow for multi-Pomeron effects

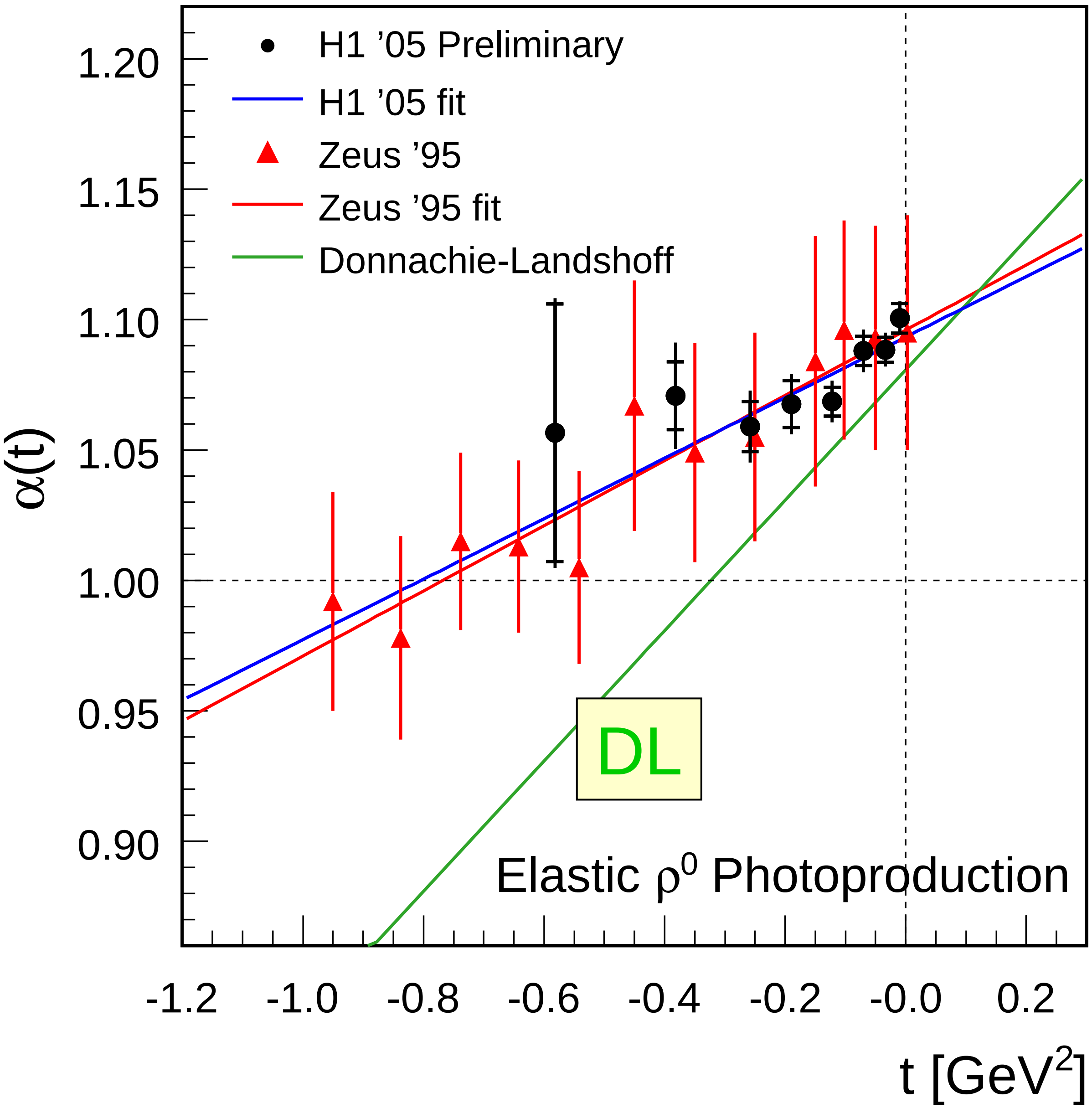


also cause shrinkage

also suppress growth of σ_{total}

so $\alpha_{I\!P}^{\text{bare}}$ has smaller α', larger $\alpha_{I\!P}(0)$ to fit same data

$$\alpha_{\mathbb{P}}(t) = \alpha_{\mathbb{P}}(0) + \alpha' t$$



HERA data for

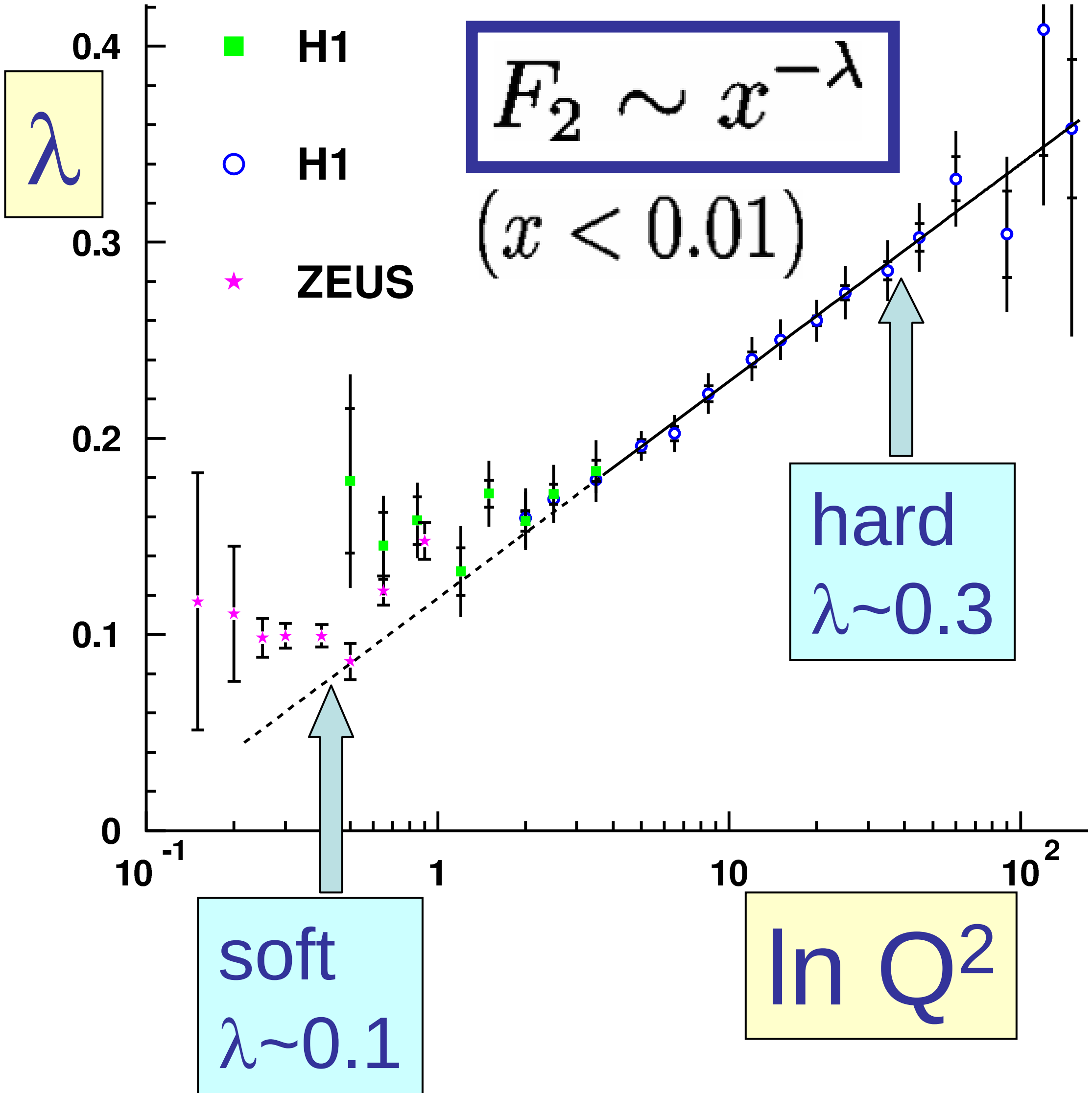
$\gamma\, p \rightarrow \rho\, p$

less rescattering than $pp \rightarrow pp$

α' smaller

$\alpha_{\mathbb{P}}(0)$ larger

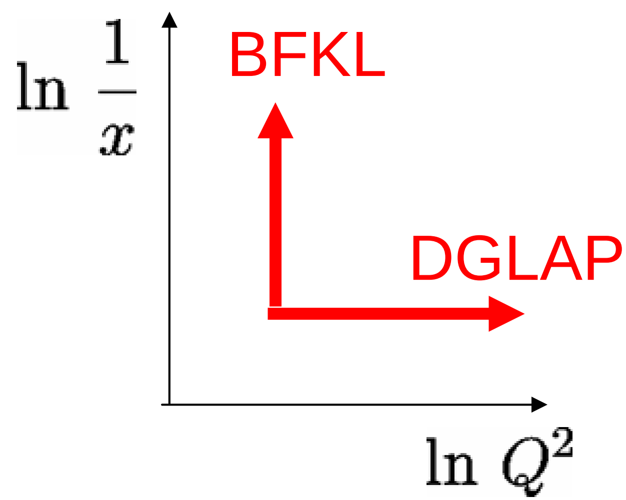
BFKL: $\frac{\partial f_g}{\partial \ln(1/x)} = K \otimes f_g = \lambda f_g$ $\quad f_g \sim e^{\lambda \ln(1/x)} \sim x^{-\lambda}$



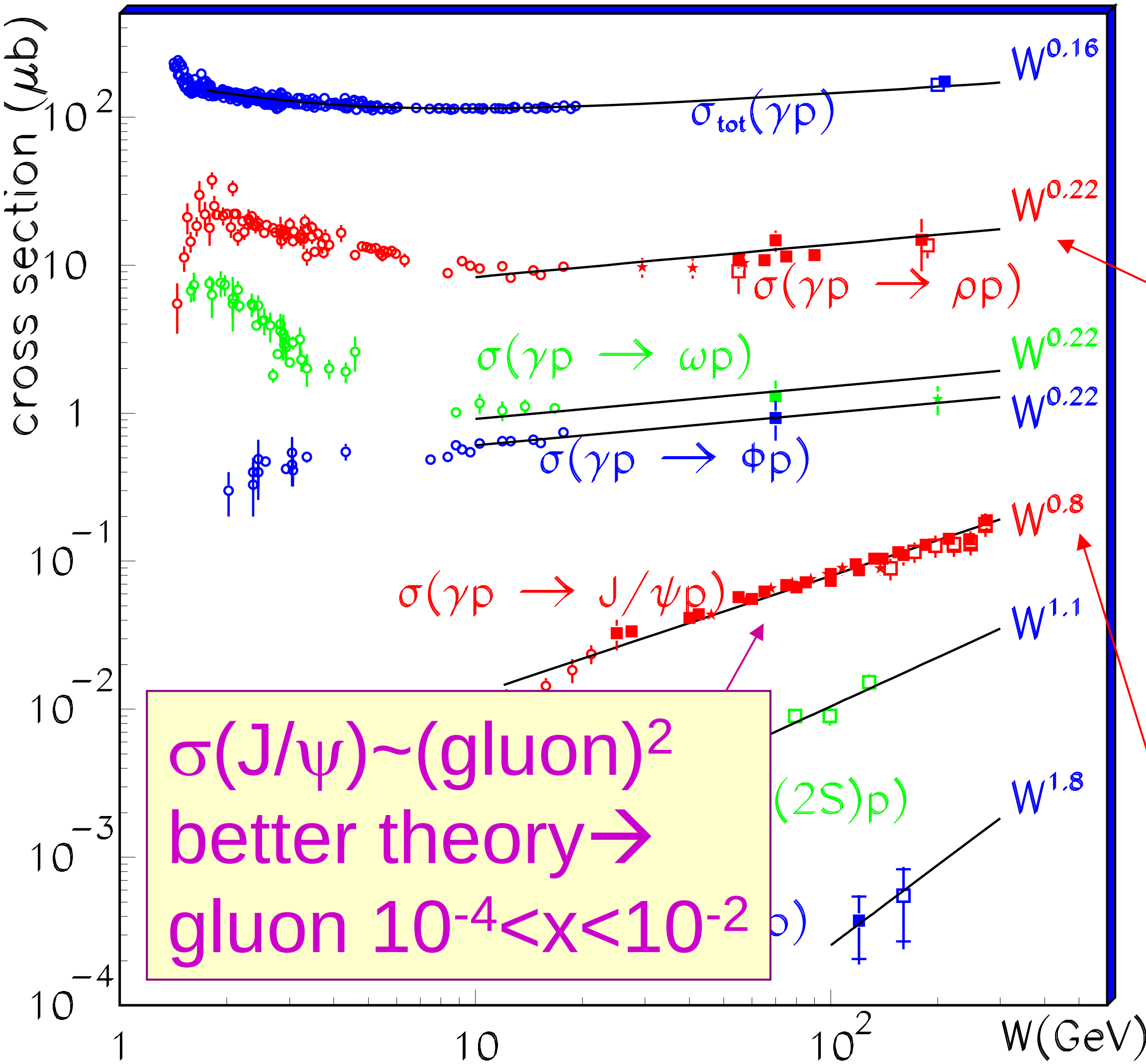
LL+NLL+partial all-order resum

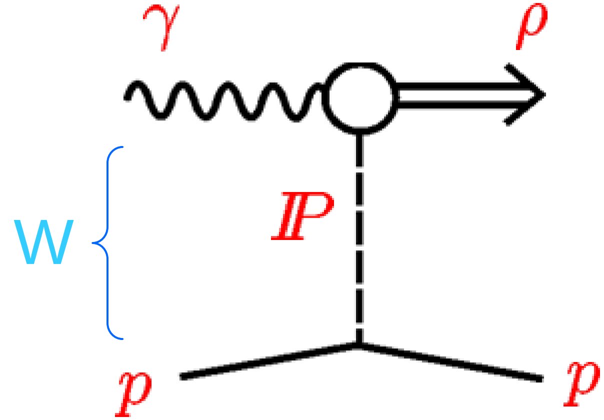
$f_g \sim x^{-0.3}$

DGLAP: $\frac{\partial g}{\partial \ln Q^2} \sim P \otimes g$



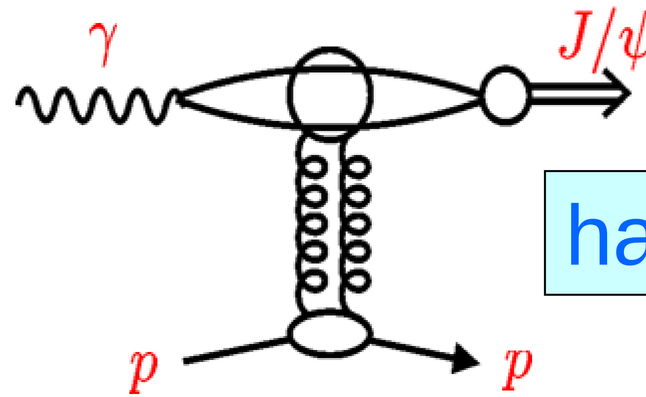
Photoprod. of vector mesons





soft

$$\sigma \sim W^{4(\alpha_{I\!P}-1)} \sim W^{0.2}$$

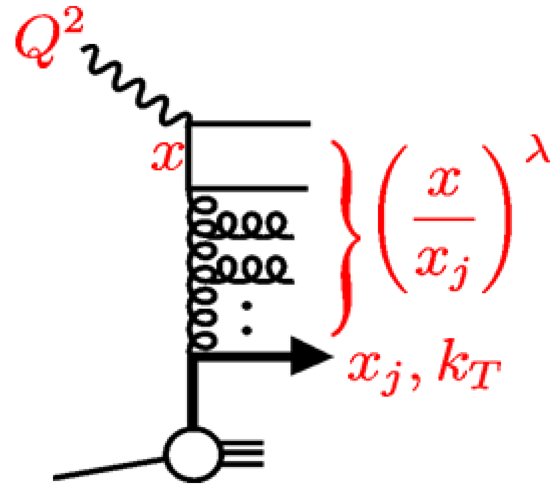


hard

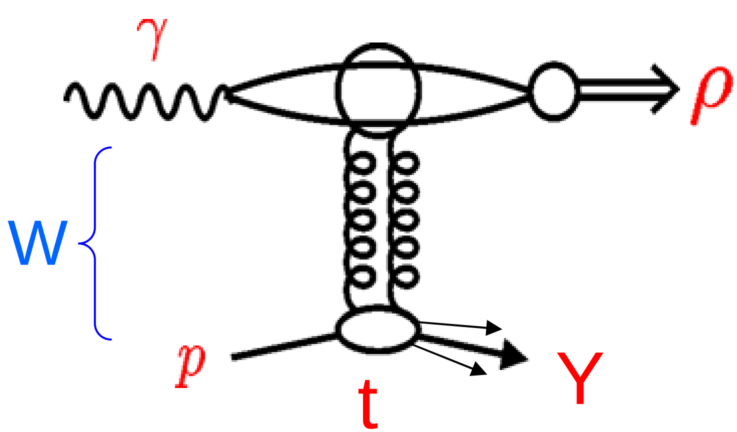
$$\sigma \sim W^{4\lambda(m_c^2)} \sim W^{0.8}$$

To identify BFKL need to "neutralize" DGLAP

Ex.1: forward jet with k_T~Q



choose x_j as large as possible,
x_j~0.1, lose small (x/x_j) "reach"

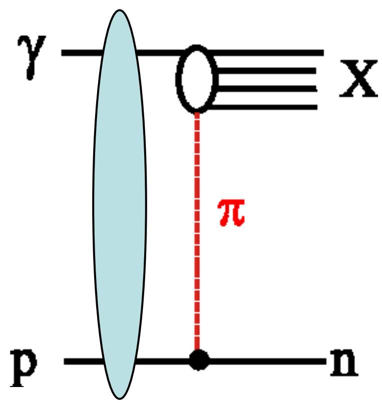


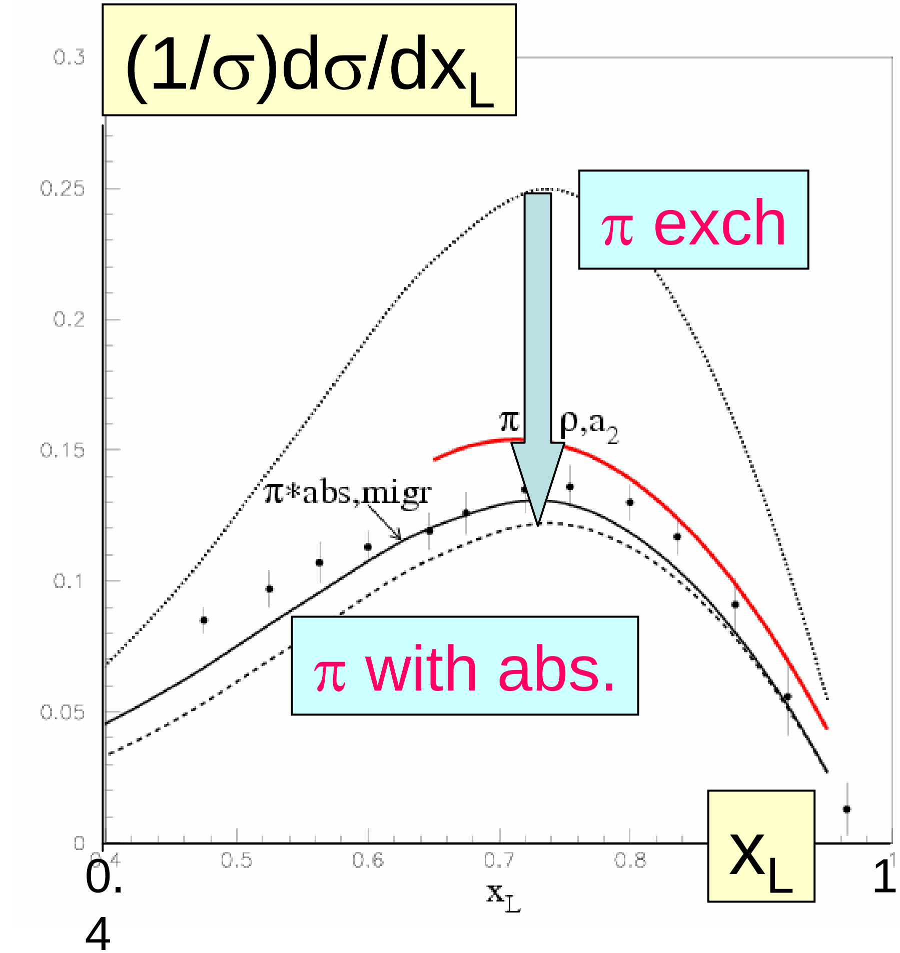
Ex. 2: γ p→ ρ Y at large t

measure W dependence in a bin at large t for M_Y<5 GeV, say

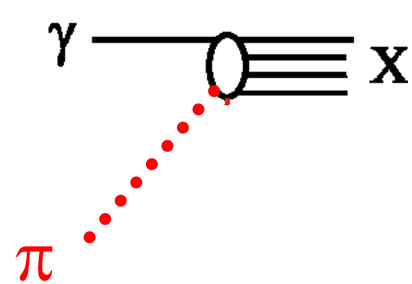
Evidence of absorptive/ rescatt. effects at HERA

1. photoproduced leading neutrons from ZEUS





DIS leading neutron data reveal information on the parton distributions of π in the unexplored small x domain.



2. Diffractive dijet production at HERA:
   Interesting rescattering effects predicted,
   but await the final experimental (H1, ZEUS) verdict.

3. HERA data for γ p → V p, with V = ρ, J/ψ.., gives an
   effective Pomeron slope, α', which decreases as
   Q^2+M^2 increases --- i.e. rescatt./absorption decreases

4. Impact parameter dep. dipole description, with DGLAP
   evolution, of vector meson production, DVCS, F_2,….
   gives evidence of a saturation scale $Q_s^2 < 1$ GeV^2
   in the HERA kinematical domain.

Apologies for omitting so much of HERA physics

particularly the spin and flavour physics coming from HERMES and HERAb

HERA: an outsider's view

The accelerator and expts have been a tremendous success
-----have delivered a wealth of new information,
-----and exceeded the expectations in precision

Greatly illuminates QCD, especially the structure of the proton, Pomeron, photon, pion

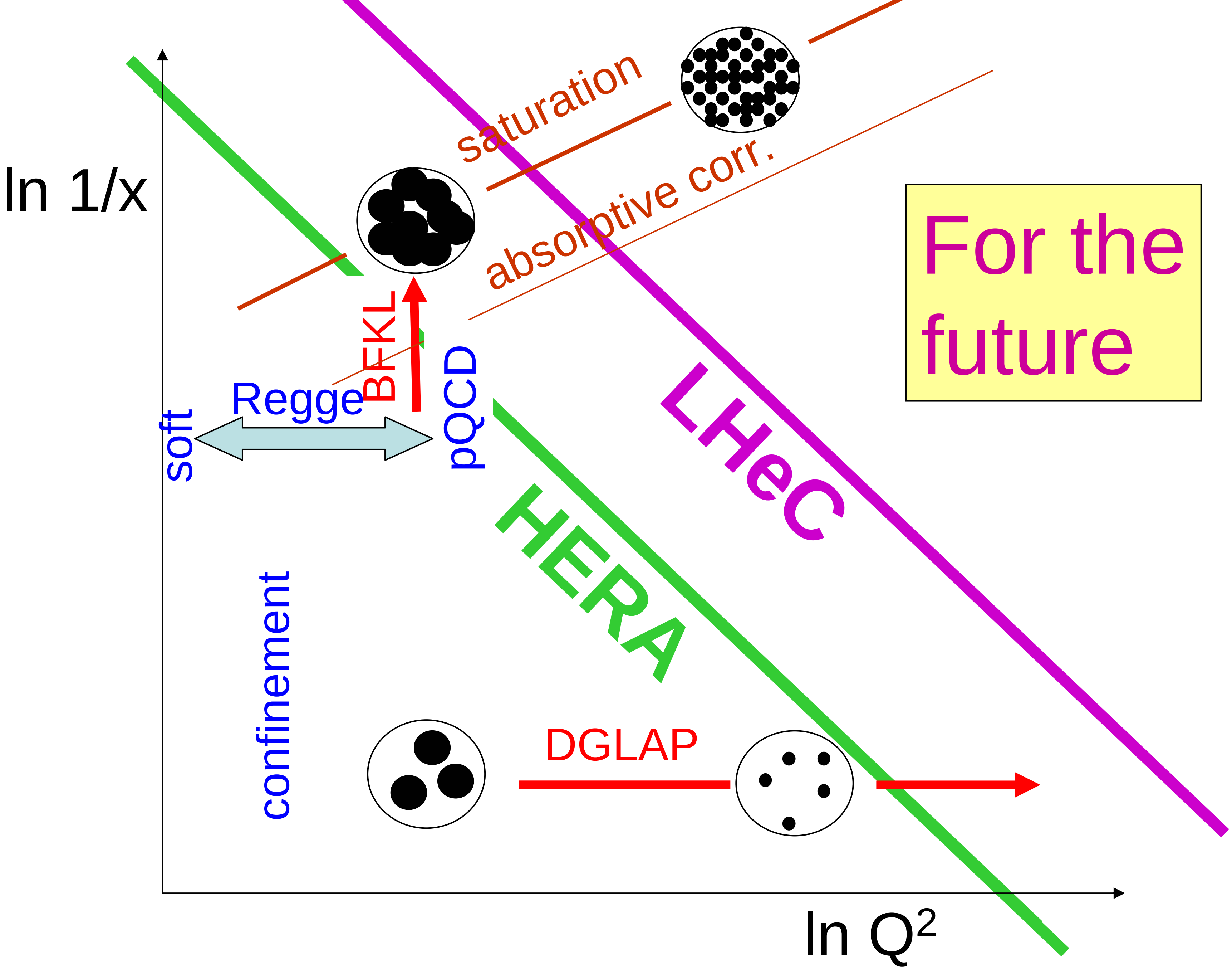
Unique probe of the important small x domain

Much of the data is well ahead of theory---much still to be learnt

Impact for LHC

1. HERA measurements, via parton distributions, essential for predictions of event rates at the LHC.
2. Studies of diffraction at HERA, particularly of the survival probabilities of rapidity gaps, allow rescattering effects to be quantified. Use this to determine these effects at the LHC.

Still lots of HERA data sought after by theorists


ln 1/x
saturation
absorptive corr.
For the future
BFKL
Regge
soft
pQCD
LHeC
HERA
confinement
DGLAP
ln Q2

Many congratulations to all who have worked at HERA

Highly

Exceptional

Research

Achievement