Low x Physics at HERA

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for
H1 and ZEUS

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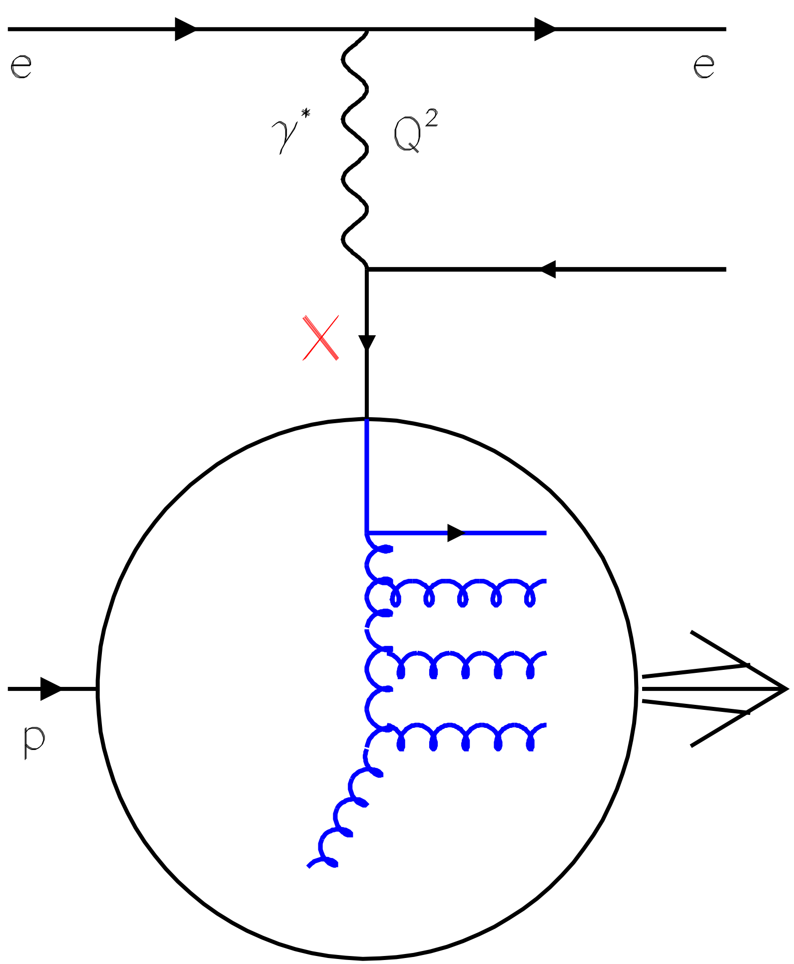
Low X at HERA



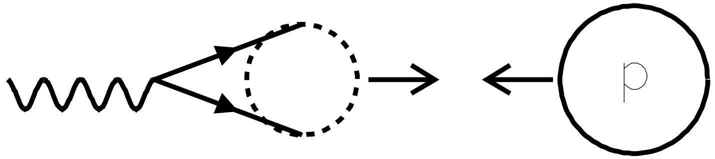
X = proton momentum fraction of parton interacting with γ^*

Low X: Scattered parton usually descends from long cascade of parton branchings! $\Rightarrow$ Interesting prehistory!

$\Rightarrow$ Description by pQCD?

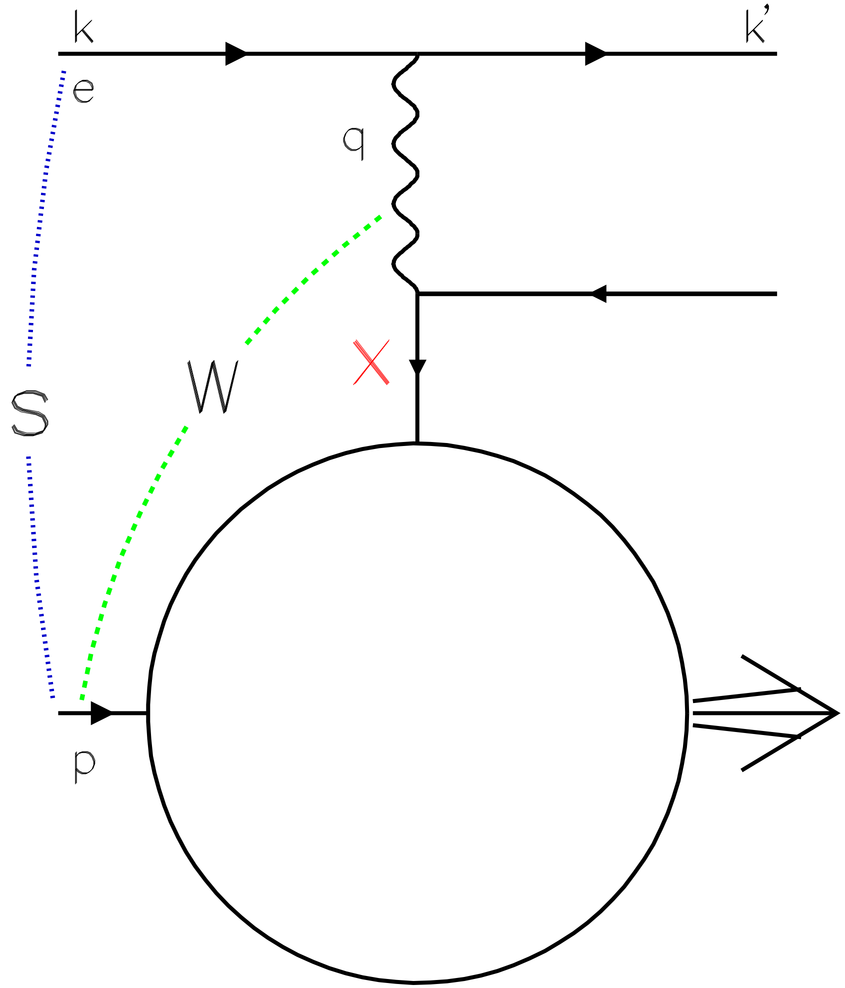
$\Rightarrow$ Rise of parton densitities towards low x - where does it stop?

$\Rightarrow$ Do we understand the transition to $Q^2 = 0$? $\gamma^* \rightarrow$ Hadron $r \sim 1/Q$



Today: Inclusive and exclusive measurements @low x vs theory

Inelastic Scattering Formalism



Kinematics:

$$s = (k+p)^2 \quad \leftrightarrow \quad \text{cms energy}$$

$$Q^2 = -(k-k')^2 \quad \leftrightarrow \quad \text{Virtuality}$$

$$y = \frac{P \cdot q}{P \cdot k} \quad \leftrightarrow \quad \text{Inelasticity}$$

$$x = \frac{Q^2}{sy} \qquad W^2 = (q+p)^2 \approx \frac{Q^2}{x}$$

Cross-sections:

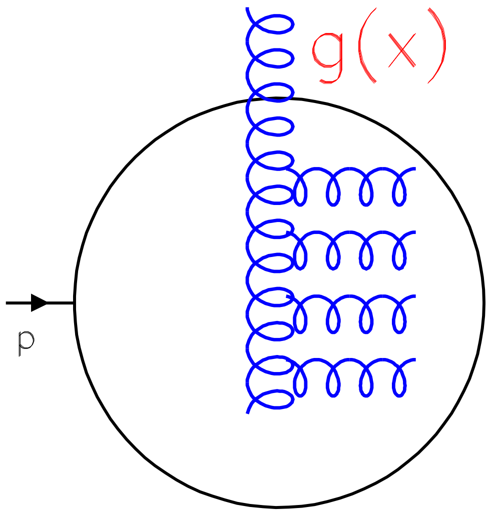
$$\frac{d^2\sigma}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[y_+ F_2(x,Q^2) - y^2 F_l(x,Q^2)\right]$$

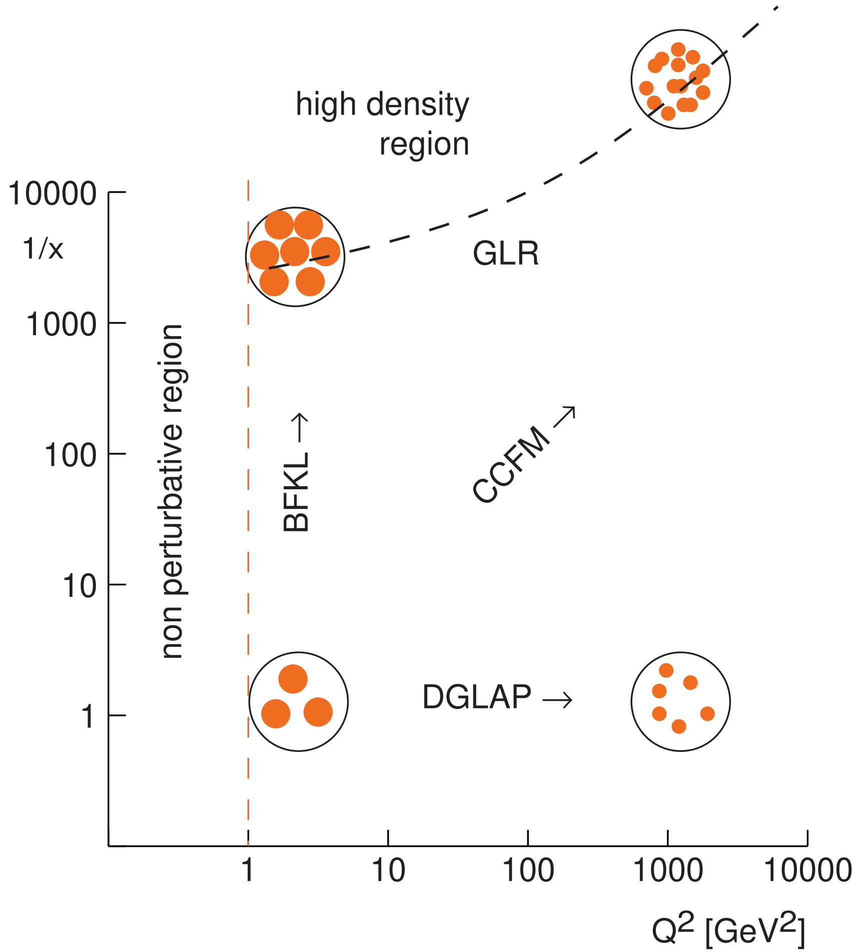
$y_+ = 1 + (1-y)^2;$ $\quad y^2 F_L$ is small

QPM: $F_2 = \sum_i e_i^2 (q_i + \bar{q}_i)$

pQCD Parton evolution schemes

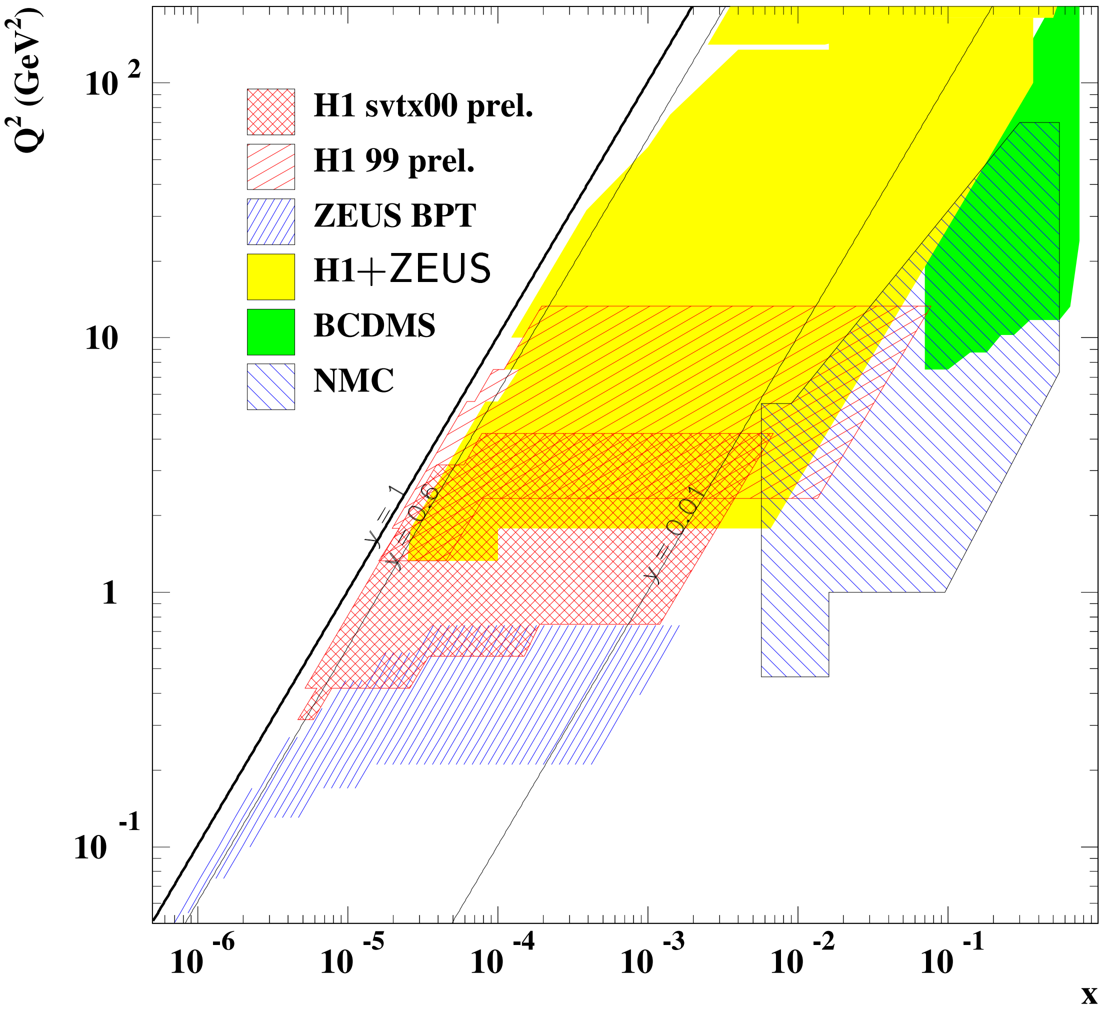
- Predict change of parton densities with varying "scales", e.g. $\ln(Q^2)$
- Resum dominant class of higher order gluon radiation diagrams





Ansatz	varying "scale"	ordering	resum terms	$\rightarrow g(x, Q^2)$
DGLAP	$\ln\ (Q^2)$	k_T	$\alpha_s \ln(Q^2)$	$\sim \exp\sqrt{\frac{12\alpha_s}{\pi} ln\frac{1}{x} ln\frac{Q^2}{Q_0^2}}$ (DLLA)
BFKL	$\ln(1/x)$	energies	$\alpha_s \ln(1/x)$	$\sim x^{-\lambda}$, $\lambda \leq 0.5$
CCFM	$\ln(Q^2)$, $\ln(1/x)$	angles	mixed	

HERA low x accessible phase space

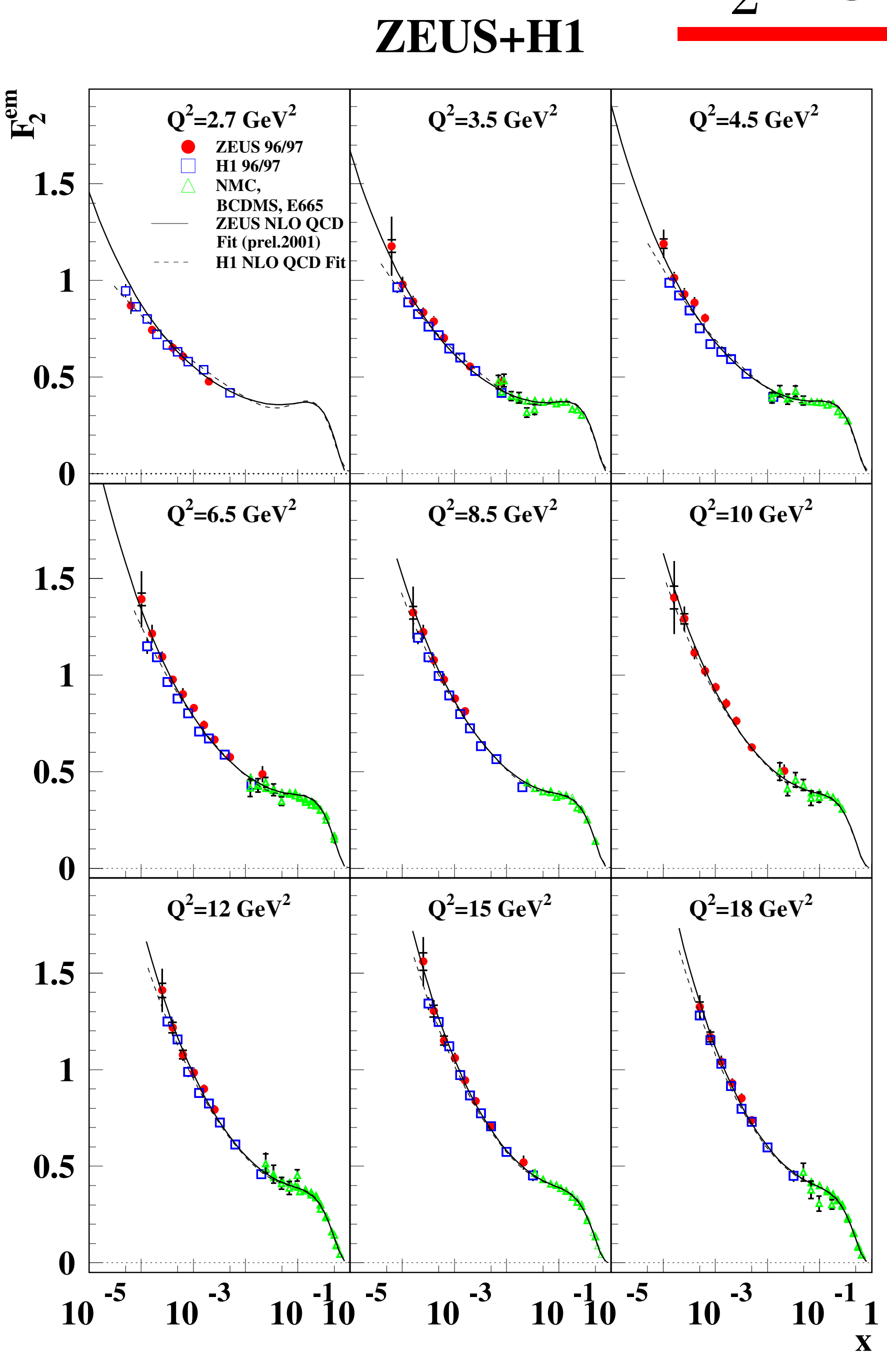


920 GeV p on 27.5 GeV $e^{\pm}$

$\Rightarrow \sqrt{s} = 318$ GeV

- Lowest reached x $\approx 10^{-6}$
- Watch the correlations between Q^2 and x!
  $x \leq 10^{-5} \rightarrow Q^2 \leq 1$ GeV^2
  $\hookrightarrow$ Entering the non per-tubative regime!

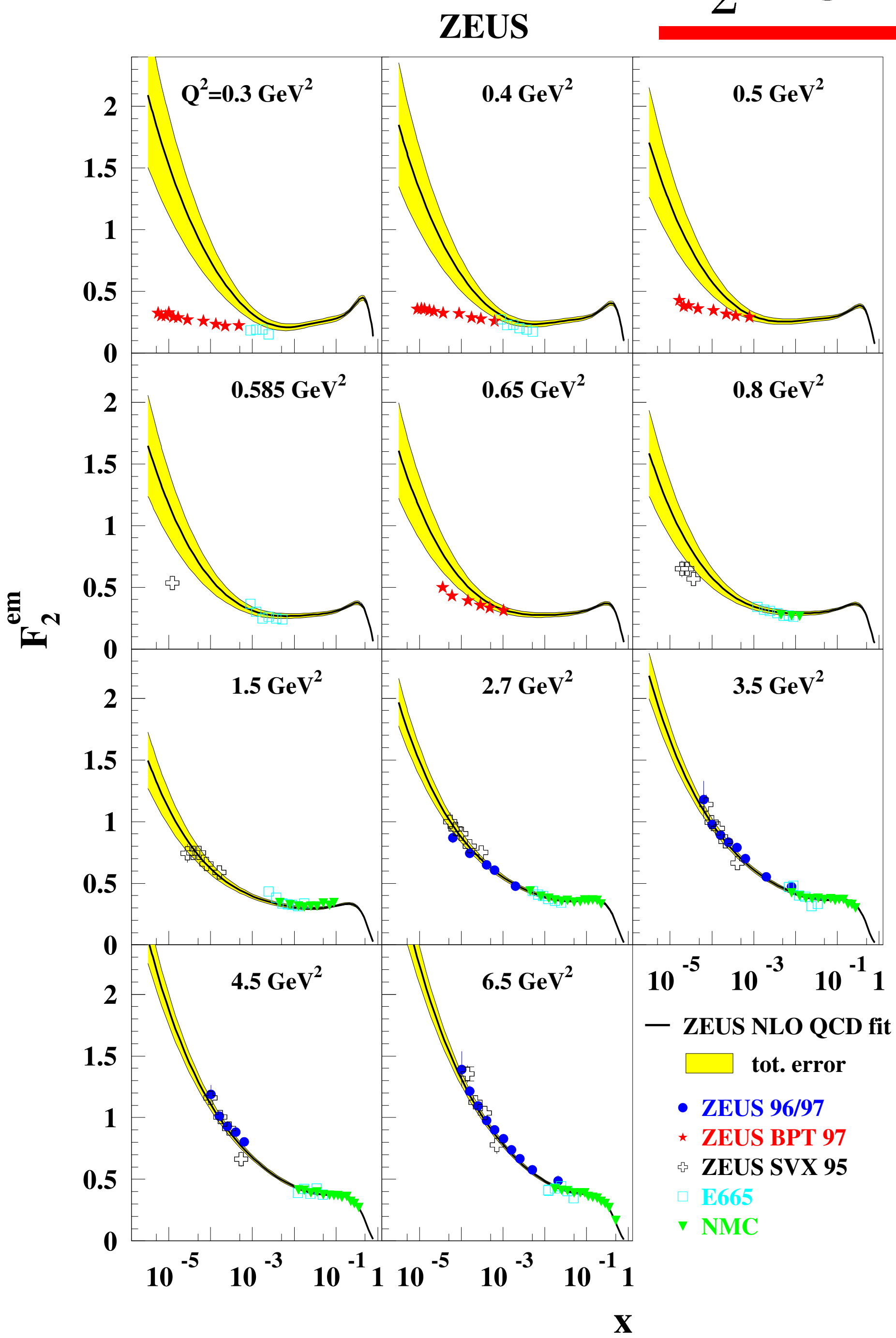
F_2 vs x at medium Q^2



- Rise towards lower x and higher $Q^2 \rightarrow$ driven by proton gluon density $g(x, Q^2)$

- Excellent description by DGLAP based NLO QCD fit! ... Down to the starting scale $Q_0^2 \approx 3$ GeV^2 of the applied evolution

F_2 vs x at very low Q^2

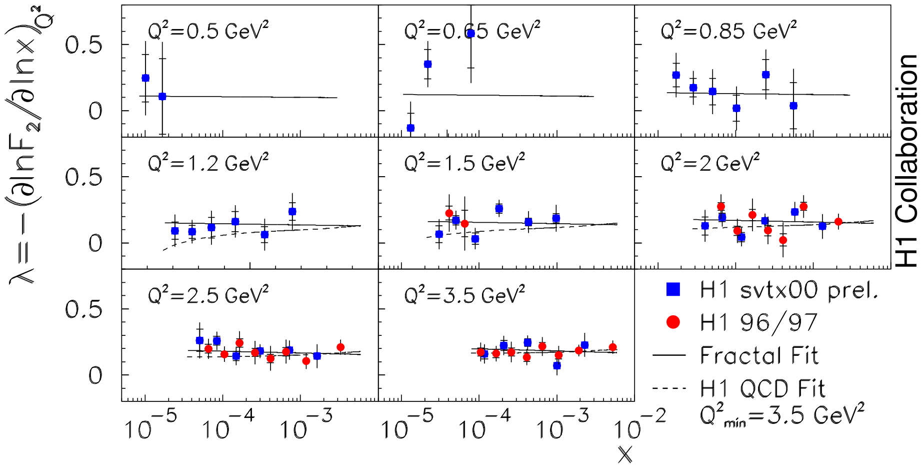


- Rise towards lowest x
  - continues down to lowest Q^2
  - dramatically slows down as $Q^2 \to 0$ GeV^2
- DGLAP NLO QCD fit fails for $Q^2 \leq 1$ GeV^2...
  - nobody expected it to work in this territory!
  - Note: Data below $Q^2 \leq 3$ GeV^2 were also not used in the fit

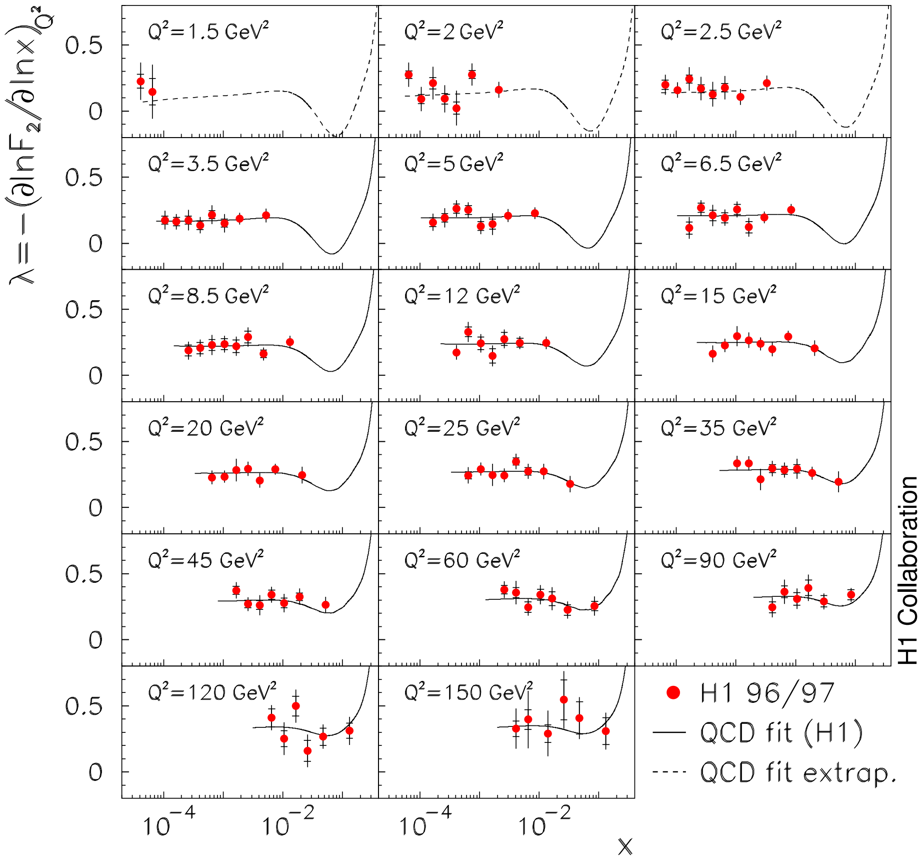
QCD Model independent F_2 analysis

Test x depend. of F_2 rise $\Rightarrow$ Measure $\lambda(Q^2) = -\frac{\partial ln F_2}{\partial ln x}|_{Q^2}$

H1 shifted vertex (preliminary)



H1 nominal vertex

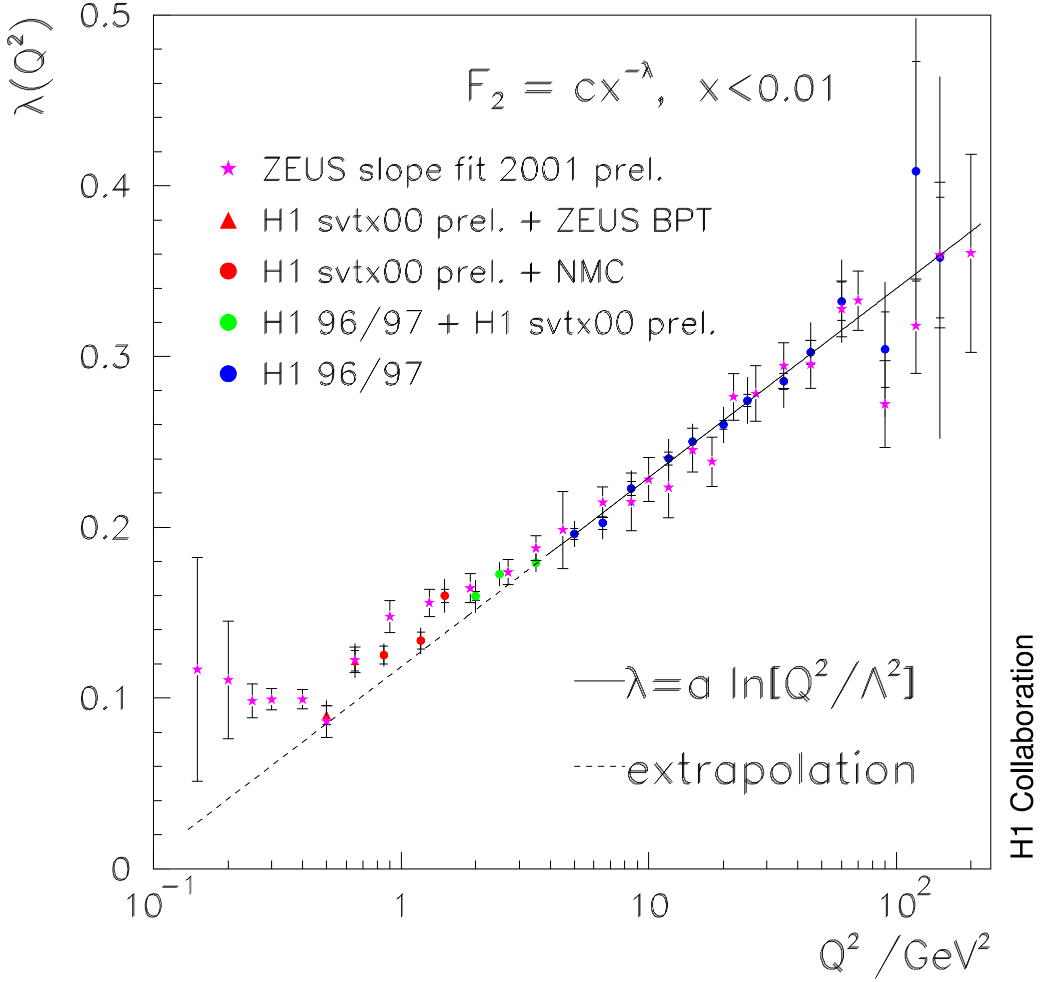


$\Rightarrow$ for fixed Q^2 and $x < 0.01$, λ roughly constant

$\Rightarrow F_2(x, Q^2) \propto x^{-\lambda(Q^2)}$

$F_2 = c \cdot x^{-\lambda(Q^2)} \rightarrow$ fit λ for $x < 0.01$, fixed Q^2

Fitted λ values for each Q^2 bin:



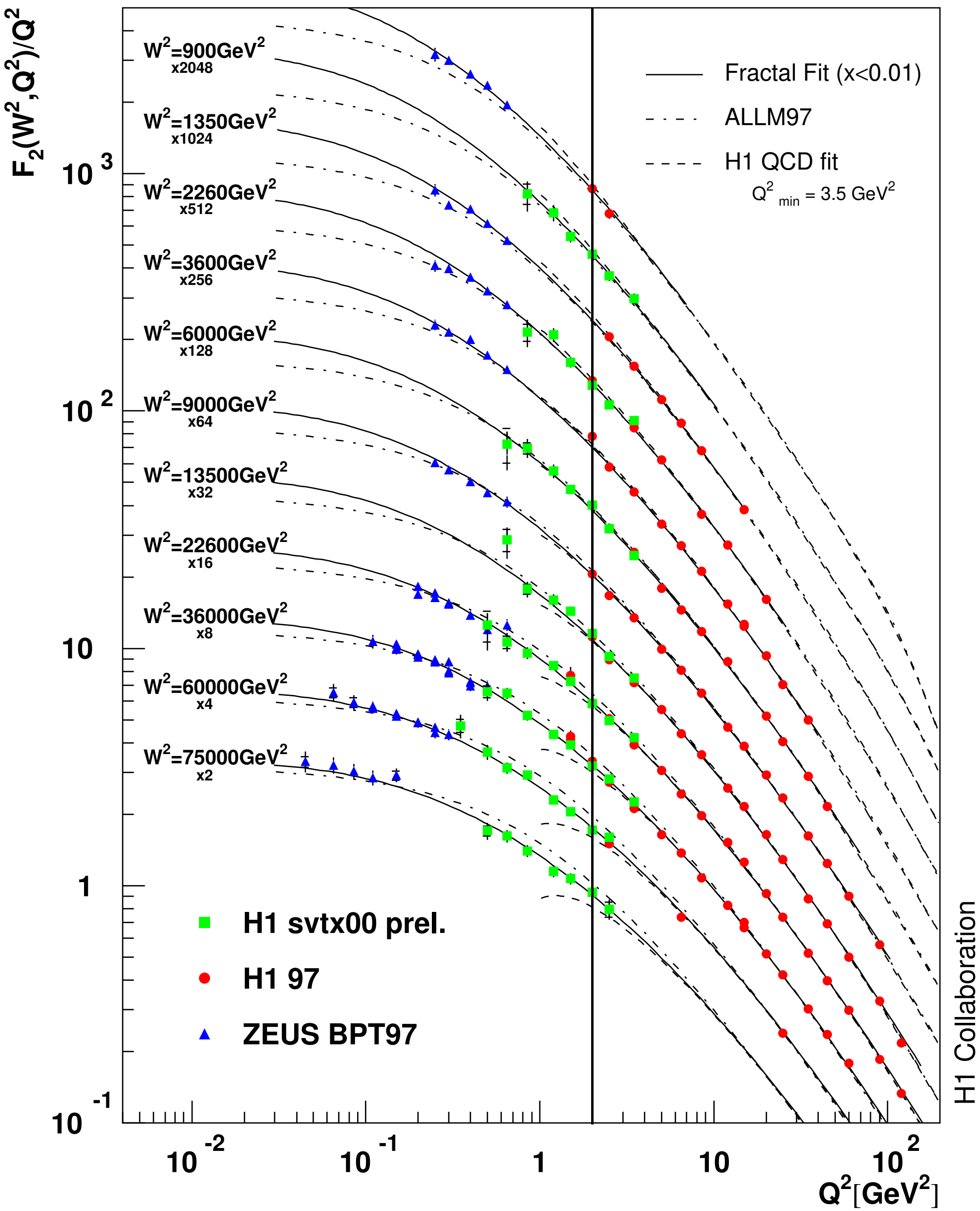
$Q^2 \geq 3.5$ GeV^2:

- $\lambda(Q^2) \sim a \cdot \ln[Q^2/\Lambda^2]$
- $\Rightarrow$ very simple parametrisation!

$Q^2 \leq 1$ GeV^2:

- λ flattens
- approaching the value expected from high energy hadron-hadron scattering $\lambda \approx 0.08$

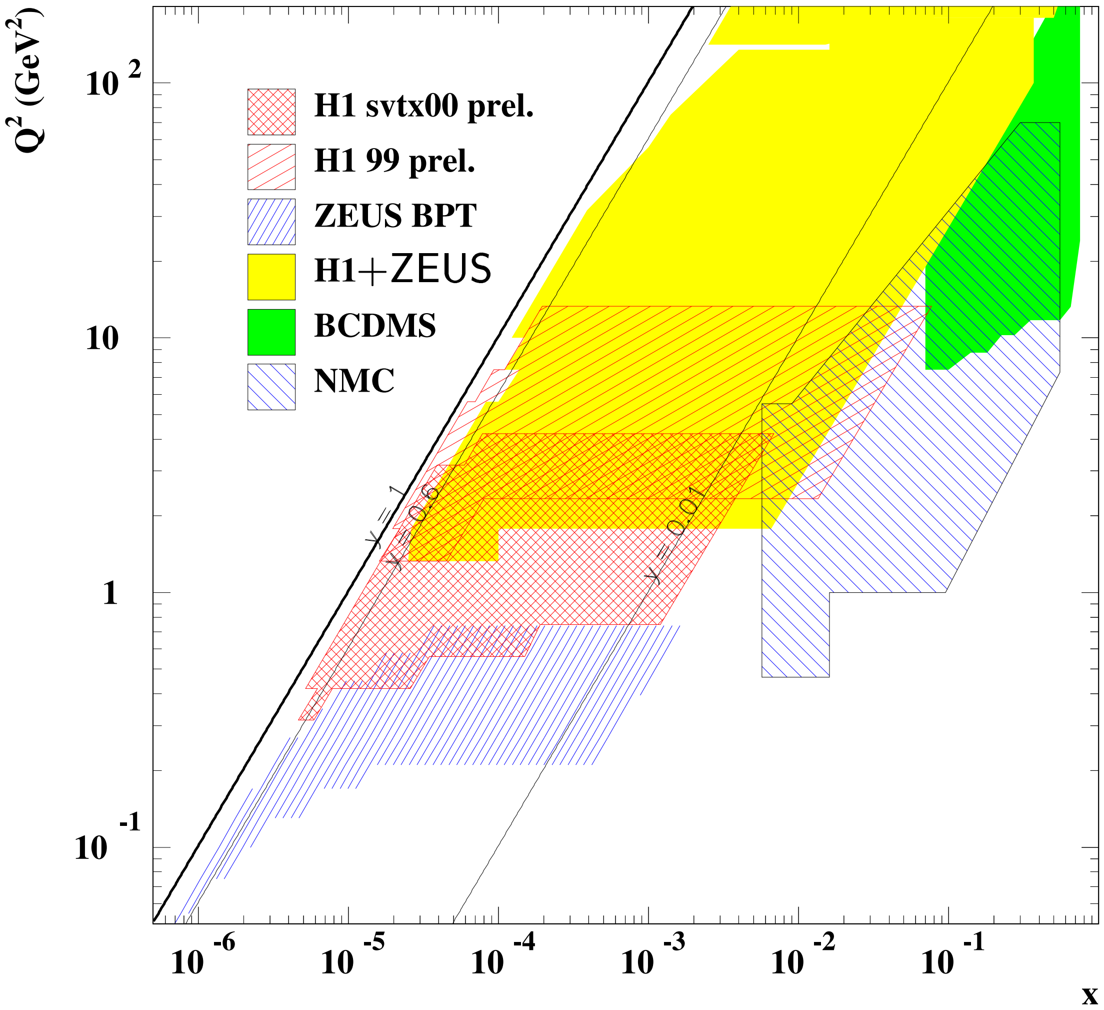
$\sigma^{\gamma^* p}$ as Q^2 tends to zero



$$\sigma^{\gamma^* p}(W^2 \approx \frac{Q^2}{x}, Q^2) = 4\pi\alpha^2 \frac{F_2(x, Q^2)}{Q^2}$$

- Smooth turnover flat $\leftrightarrow$ steep at $Q^2 \approx 1$ GeV^2
- F$_2 \to 0$ for $Q^2 \to 0$
- DGLAP NLO fit describes data $Q^2 \geq 2$ GeV^2
- *Many* non pQCD models describing the transition $Q^2 \to 0$:
  - Regge based approaches
  - Colour dipole models
  - Fractal models

Summary of *inclusive* ep scattering results



$Q^2 \geq 2$ GeV^2:

Accessible low x territory is well described by NLO DGLAP

$Q^2 \leq 2$ GeV^2:

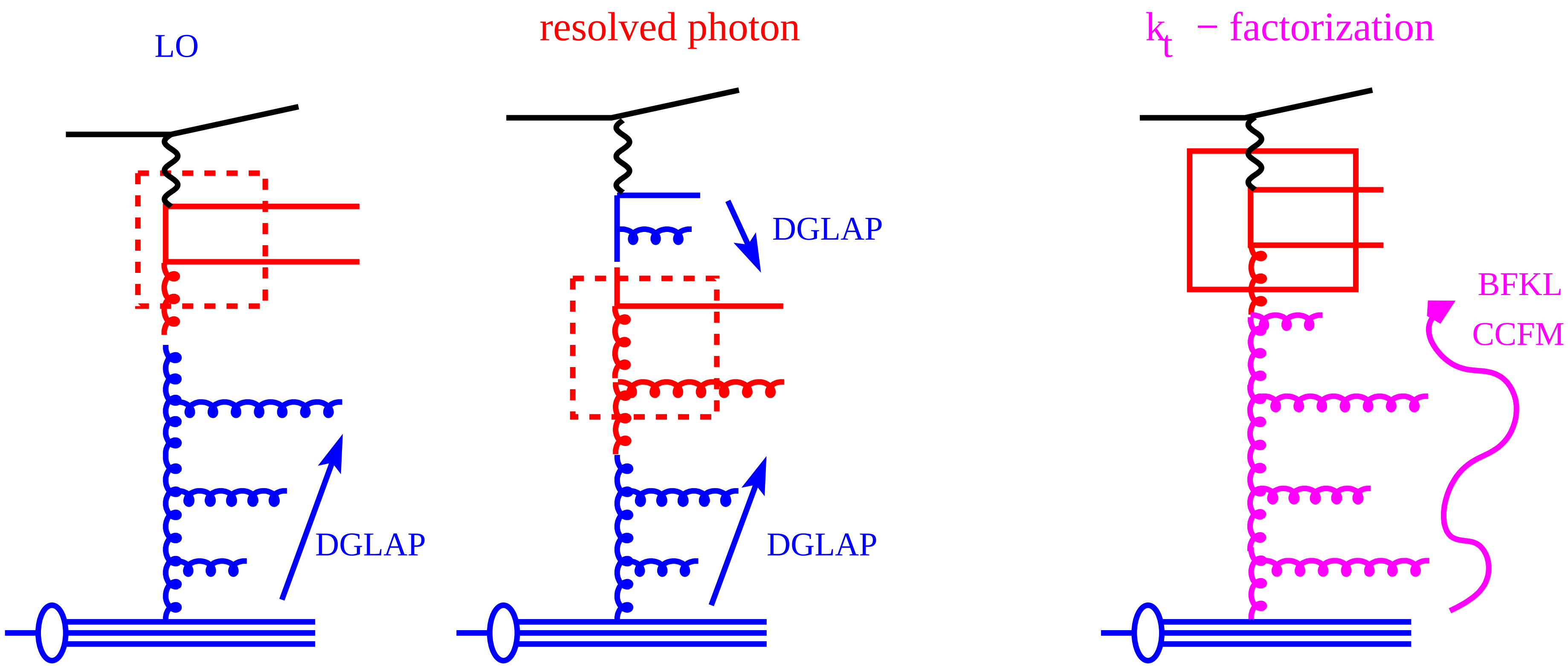
Transition to photoproduction $\rightarrow$ non pQCD models needed! (e.g. Regge theory, Colour dipole model,...)

Where do we need **BFKL???**

$\Rightarrow$ Lets look now into exclusive channels!

pQCD parton evolutions $\rightarrow$ final states

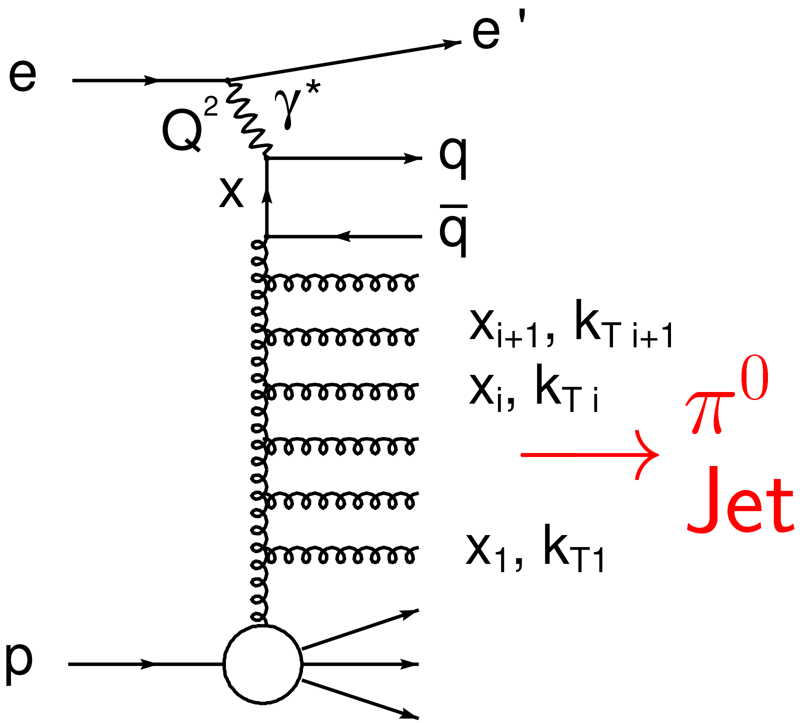
DGLAP BFKL CCFM



ordered in p_T ordered in energy in angle

$\Rightarrow$ Final states close to proton direction could tell the difference!

"BFKL enhanced" final states selection (jets, π^0)



Require:

- small x
- $p^2_{t_{jet,\pi^0}} \approx Q^2$
- large $x_{jet,\pi^0} = \dfrac{E_{jet,\pi^0}}{E_p}$

$\Rightarrow$ DGLAP (Q^2) evolution strongly suppressed

Today: H1 π^0-analysis with selection cuts $\longrightarrow$

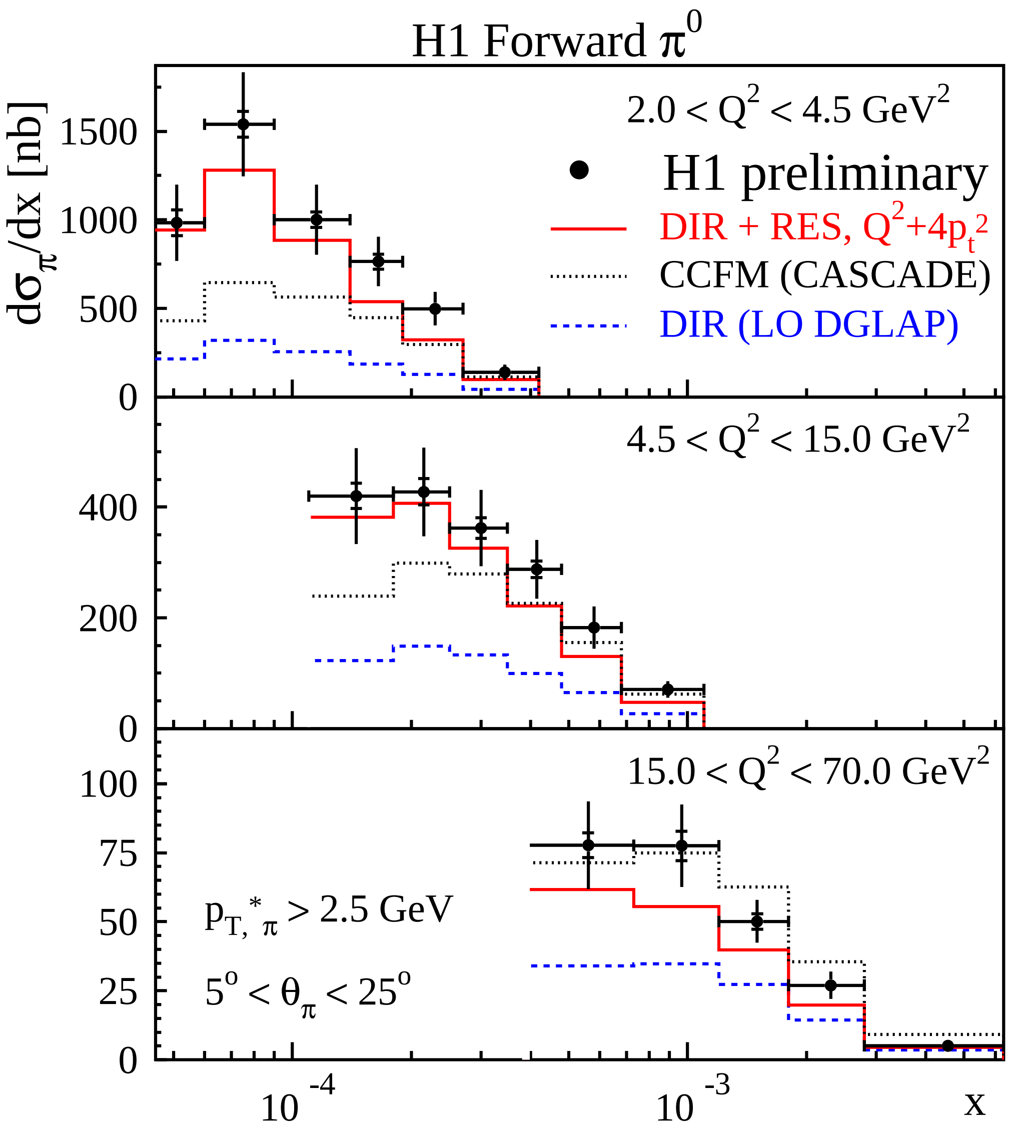
$2 < Q^2 < 70$ GeV^2

$5 < \theta_{\pi^0} < 25^0$

$p^*_{t\pi^0} > 2.5$ GeV (hcms)

$x_{\pi^0} = E_{\pi^0}/E_p > 0.01 \rightarrow E_{\pi^0} > 8$ GeV

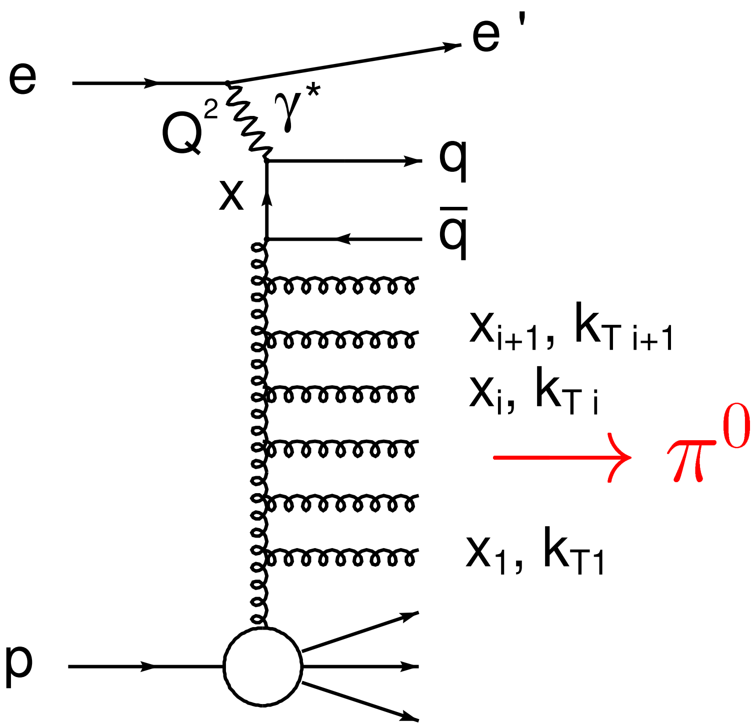
Forward $\pi^0 \to d\sigma/dx$

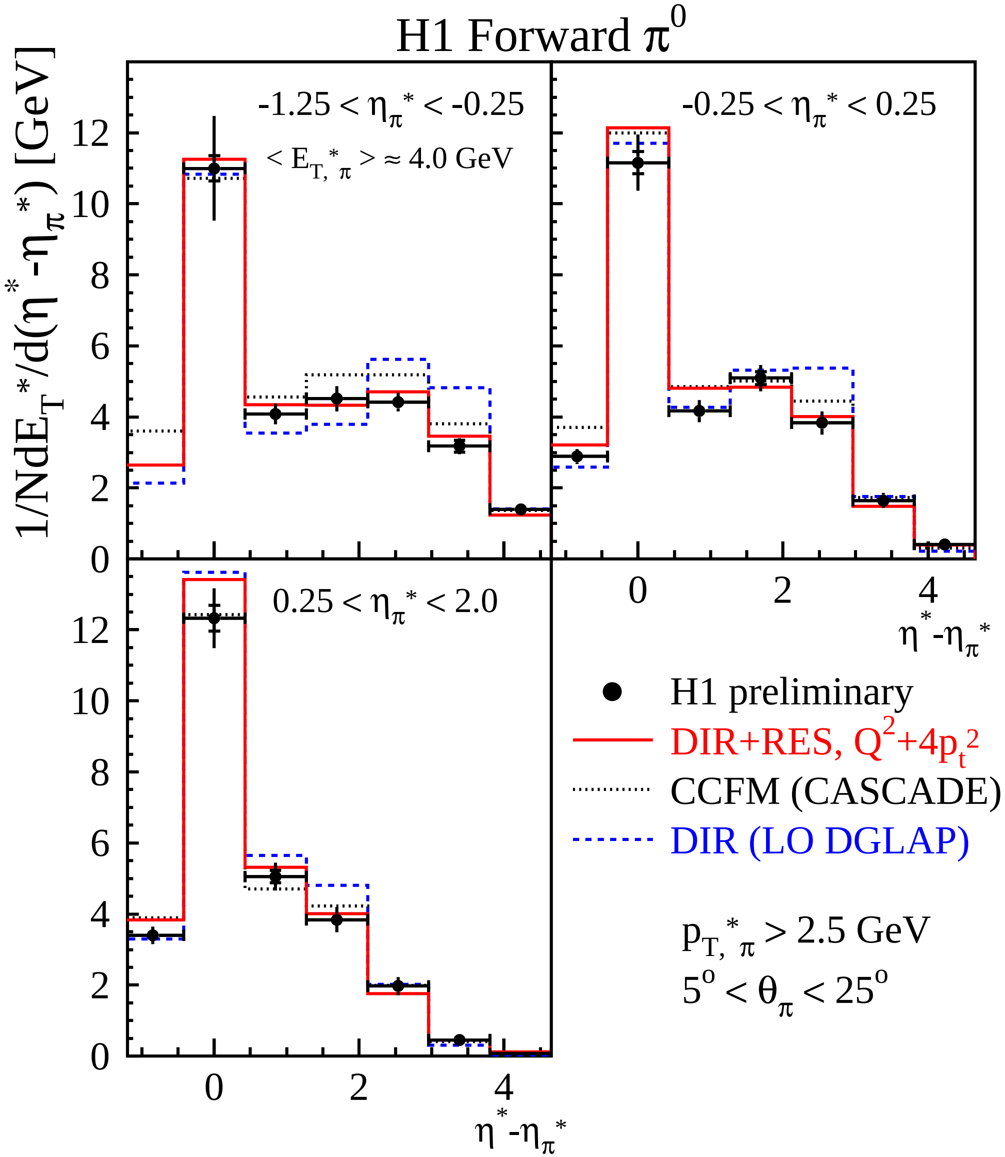


- RAPGAP (DIR + RES): (DGLAP, direct+resolved γ^*) $\Rightarrow$ reasonable description of data
- RAPGAP (DIR): $\Rightarrow$ below the data
- CASCADE (CCFM): $\Rightarrow$ below the data for $x < 0.001$ $\Rightarrow$ above the data for $x > 0.001$

Transverse energy flow around π^0 in 3 ranges of η^*_π

$\eta^*_{\pi^0}$ = rapidity in hadronic cms





Summary

- Inclusive ep scattering:
  - NLO DGLAP calculations describe inclusive data successfully down to $Q^2 \approx 2$ GeV^2 and $x \approx 10^{-5}$
  - No clear signs of BFKL or Saturation effects have been found
- Exclusive analyses $\rightarrow$ forward π^0's:
  - LO DGLAP calculations:
    * Direct photon contribution alone is insufficient!
    * Reasonable description obtained by adding resolved γ^* contributions
  - CASCADE (CCFM) gives inconsistent description