# Forward Jets and Forward $\pi^0$ Production at HERA


on behalf of the

H1 and Zeus collaborations

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M. Karlsson, University of Lund


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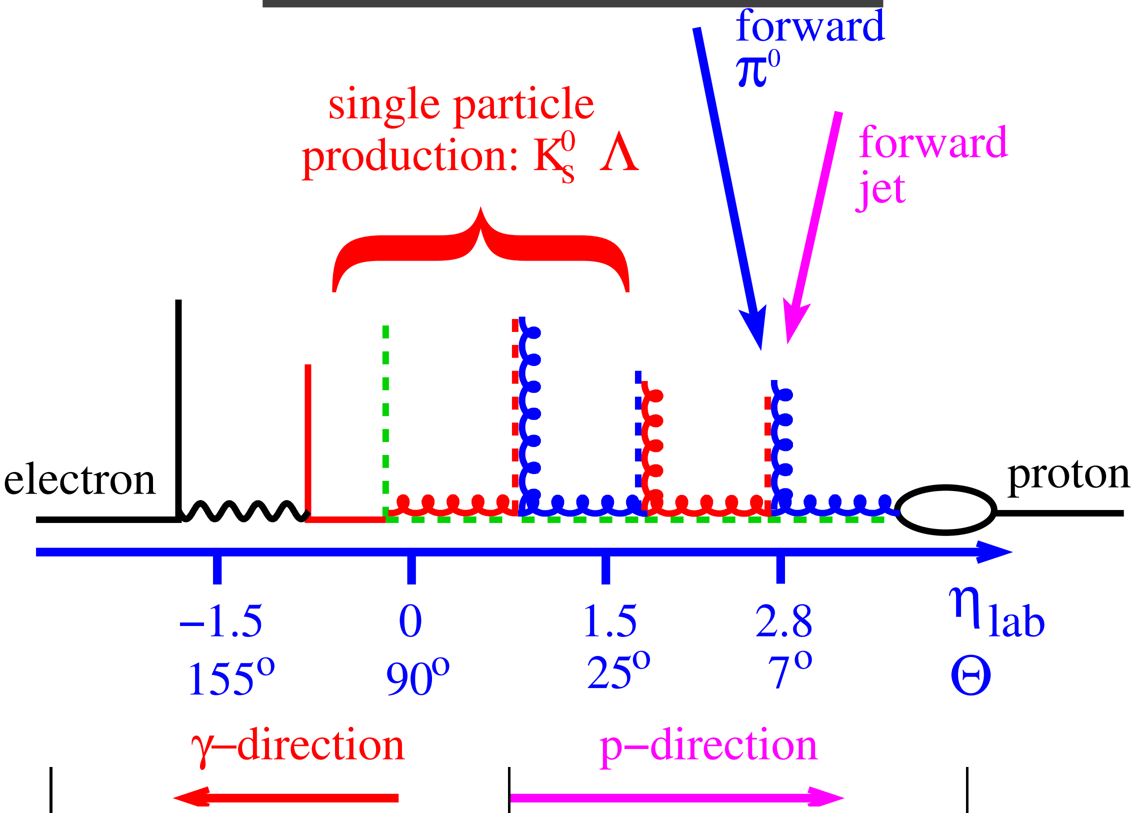
# Why Forward?




*$F_2$* - very inclusive - very well described by DGLAP.

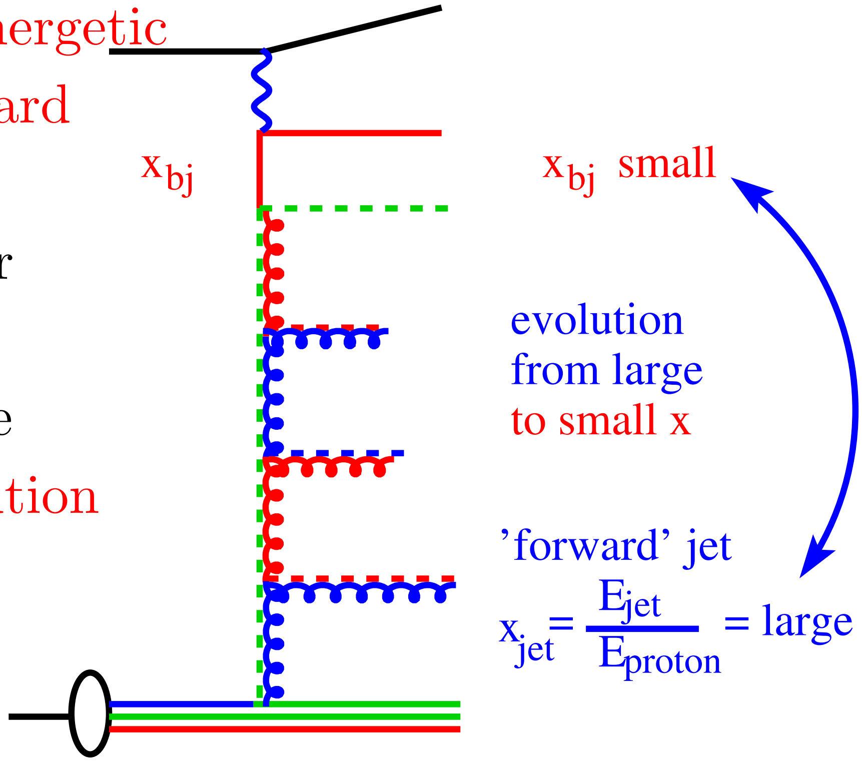
Dijet cross-section, Jet Rates - measure hard subsystem - ladder "indirectly".

Single particle production - ladder emissions included - multi-parton scenario.

Energetic jet/particle in forward region - restriction imposed on all emissions - information on full evolution ladder.

# Forward Jets

**Forward Jet Analysis** -
Events with energetic jet in the forward region. Target phase space for evolution in $x$. Suppress phase space for evolution in $Q^2$.




**Forward jet selection:**

$$p_T > 3.5\ \mathrm{GeV}\ (p_T > 5\ \mathrm{GeV})\ \text{(Energetic forward jet)}$$

$$7^o < \theta_{jet} < 20^o\ \text{(Forward jet)}$$

$$x_{JET} = \frac{E_{JET}}{E_p} > 0.035\ \text{(Energetic jet, target BFKL)}$$

$$0.5 < \frac{p_T^2}{Q^2} < 2\ \text{(Suppress DGLAP)}$$

# Forward $\pi_0$:s

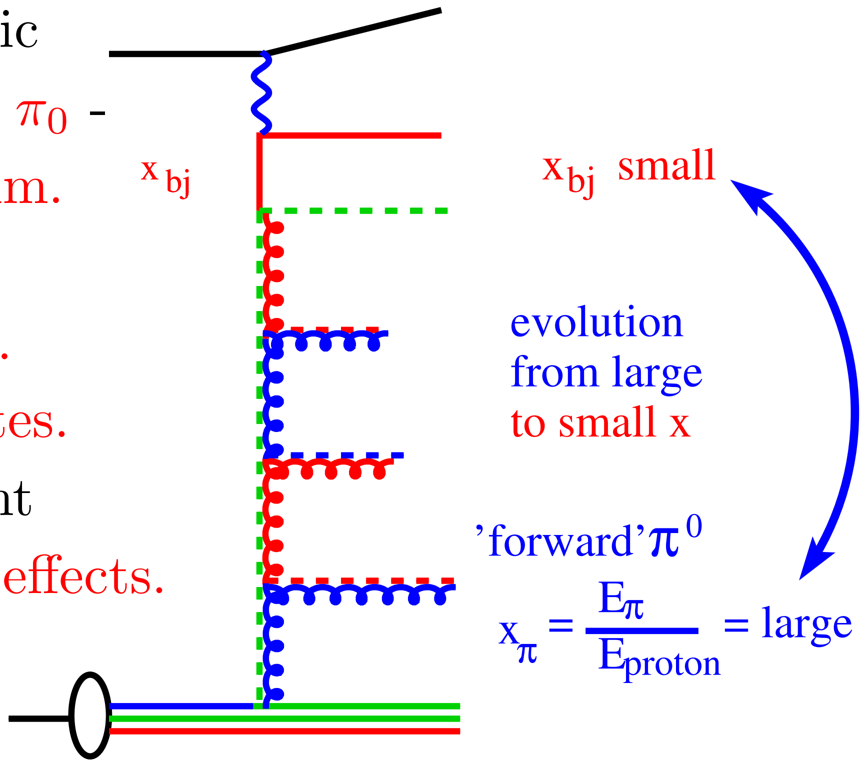
**Forward $\pi_0$ Analysis** -

Detect energetic single particle, $\pi_0$ - No jet algorithm.

Access to very forward region.

- But lower rates.

More significant fragmentation effects.




**Forward $\pi_0$ selection:**

$p_T > 2.5$ GeV ($p_T > 3.5$ GeV) (Energetic forward $\pi_0$)

$5^o < \theta_\pi < 25^o$ (Forward $\pi_0$)

$x_\pi = \frac{E_\pi}{E_p} > 0.01$ (Energetic $\pi_0$, target BFKL)

# Previous Results - Zeus and H1

H1 93 ($320nb^{-1}$) - Transverse Energy and Forward Jet Production in the Low x Regime at HERA (DESY-95-108, hep-ex/9506012)

ZEUS 95 ($6.36\ pb^{-1}$) - Forward Jet Production in Deep Inelastic Scattering at HERA (DESY 98-050, The European Physical Journal C6 (1999) 239-252)

H1 94 (2.8, 2.0 and 1.2 $pb^{-1}$) - Forward Jet and Particle Production at HERA (DESY-98-143, hep-ex/9809028)

ZEUS 95 ($6.36\ pb^{-1}$) - Measurement of the $E^2_{T,JET}/Q^2$ dependence of forward jet production at HERA (DESY 99-162, Physics Letters B 474 (2000) 1-2, 223-233)

H1 96 ($5.8\ pb^{-1}$) - Forward Pi0-Meson Production at HERA (DESY-99-094, hep-ex/9907030)

General Conclusions:

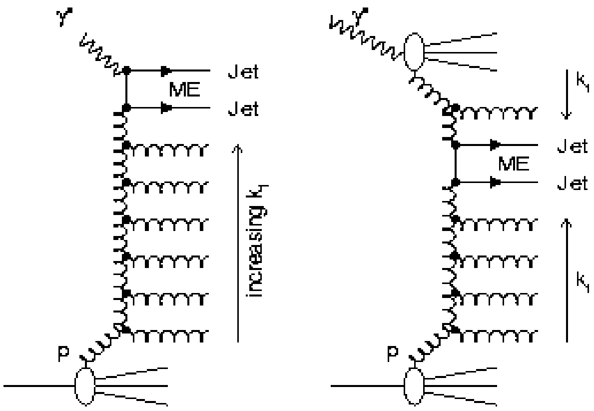
DGLAP (LEPTO, RAPGAP, HERWIG) fails.

CDM (ARIADNE) and resolved $\gamma$ (RAPGAP) OK.

# Generators

(http://www.desy.de/~heramc)

## RAPGAP

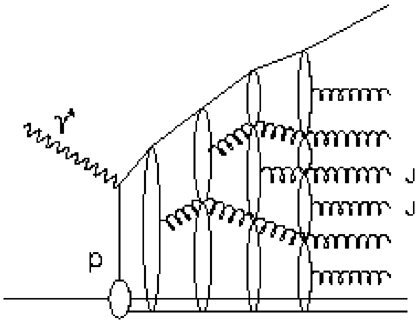


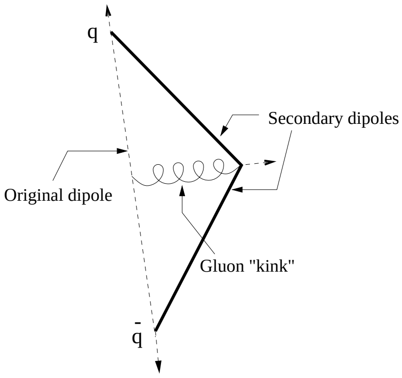

**0th and 1st order processes** - calculated from **Matrix Elements**

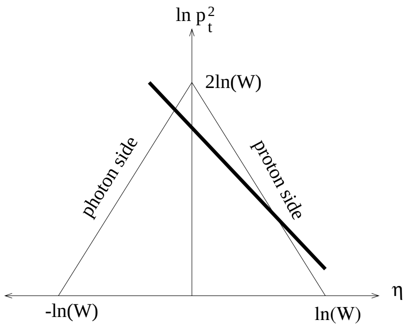
**Higher orders** - approximated via **initial and final state parton showers** - according to **backward DGLAP evolution** (from hard subsystem to proton) where the parton ladder is **strongly ordered in $Q^2$ and ${k_T}^2$**

**Resolved $\gamma$** added using **backward DGLAP evolution** (from hard subsystem to photon) where the parton ladder is **strongly ordered in $Q^2$ and ${k_T}^2$**.

# ARIADNE



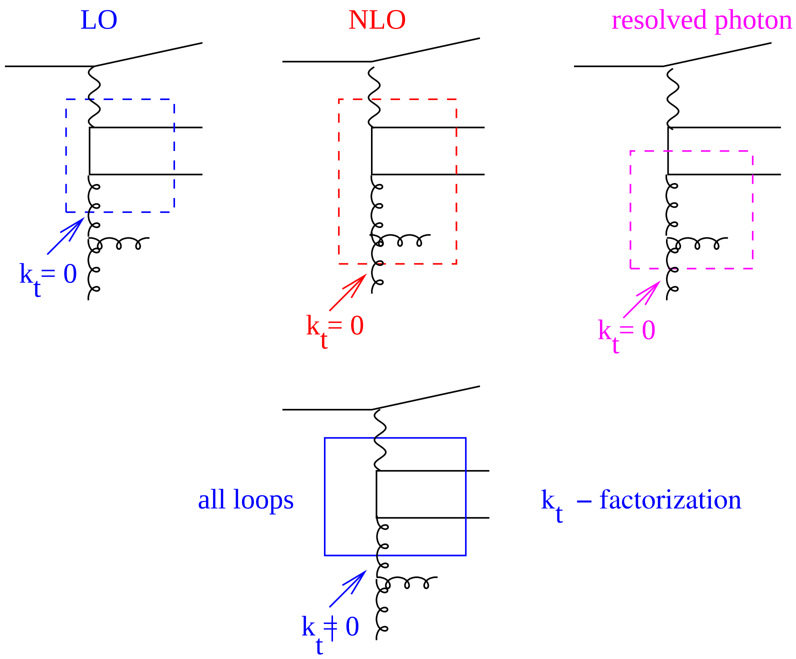




**QPM and BGF** - calculated from **Matrix Elements**

**QCDC and Higher Orders** - approximated using the **Colour Dipole Model (CDM)** - pairs of gluons span colour dipoles that radiate gluons - phase space limited by proton and set by the dipole energy, $W$ - **random walk in $k_T$** - BFKL-like.

**Extended Photon** - limits full phase space together with proton.

# CASCADE




**1st order processes** (only) - calculated with off-mass-shell **Matrix Elements**

**Higher orders** - approximated via **initial state parton showers** - according to **backward CCFM evolution** where the parton ladder follows **angular ordering**. And through **final state DGLAP parton showers**.

**Expansion of the photon -** resolved $\gamma$-like configuration possible as part of **kt factorisation** scheme.

# Forward Jet Measurement

H1 data taken 1997.

Lumi - 13.72 $pb^{-1}$

Measure forward jet cross-section as a function of:

Bjorken-$x$

$p_{T,JET}$

$x_{JET}$

For two different cuts on forward jet $p_T$:

$p_T > 3.5\ GeV$ and $p_T > 5\ GeV$

Correction to non-radiative hadron level using DJANGO/ARIADNE. (Gives clearly the best detector level description.)

Main systematic errors - model dependence (8%) and hadronic (LAR) energy scale (6%)

**Kinematic Selection:**

Electron Method

$0.1 < y < 0.7$

$5\ GeV^2 < Q^2 < 75\ GeV^2$

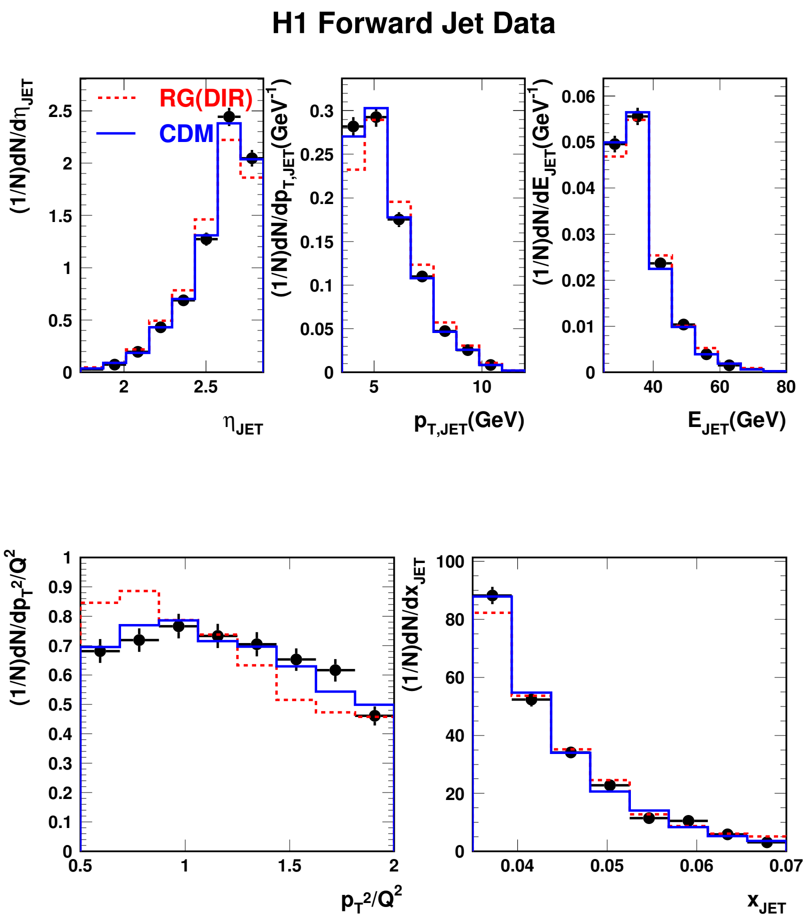
$0.0001 < x < 0.004$

# Jet Selection

Jets selected using the *Inclusive* $k_\perp$ algorithm.

Previous measurements - CONE. ($k_\perp$ - NLO calculation possible. Better resolution)

Objects - forward region - clusters.




$$1.735 < \eta_{jet} < 2.79$$

$$p_T > 3.5 \text{ GeV } (p_T > 5 \text{ GeV})$$

$$0.5 < \frac{p_T^2}{Q^2} < 2$$

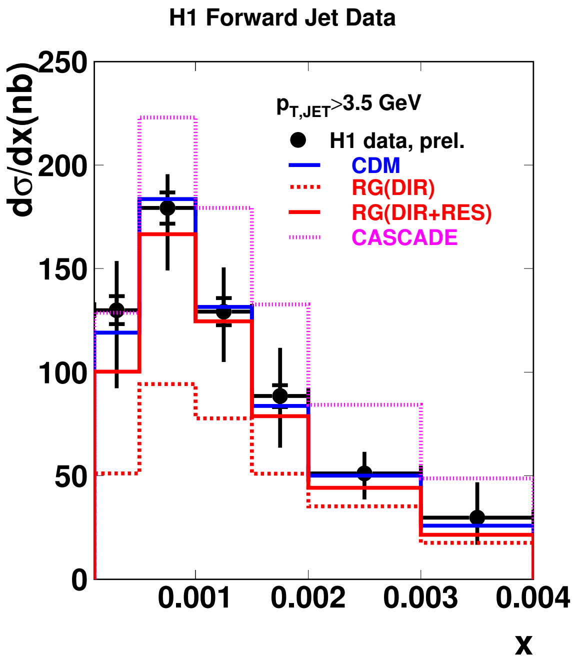
$$x_{JET} = \frac{E_{JET}}{E_p} > 0.035$$

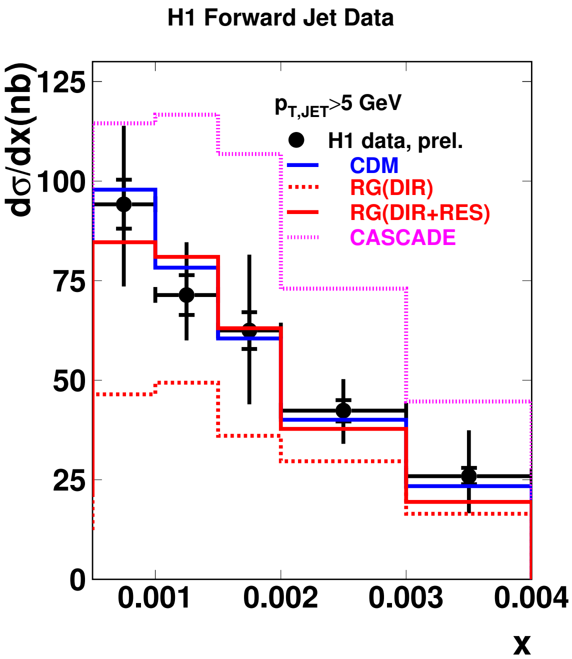
## Forward Jet Cross-section

Bjorken-$x$ cross-section

**97 Data**, RAPGAP (DIR) and (DIR+RES),
ARIADNE and CASCADE

$p_T > 3.5$ GeV $\qquad\qquad p_T > 5$ GeV



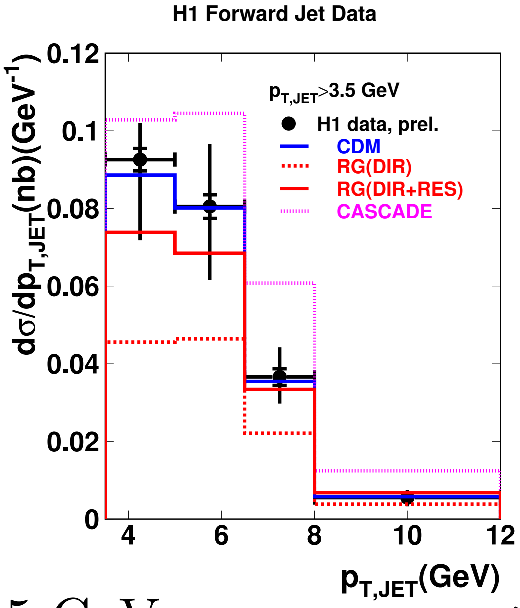

DGLAP fails. CDM often describes data within statistical errors. Resolved $\gamma$ describes data within systematical errors. CCFM overshoots data.

# Forward Jet Cross-section

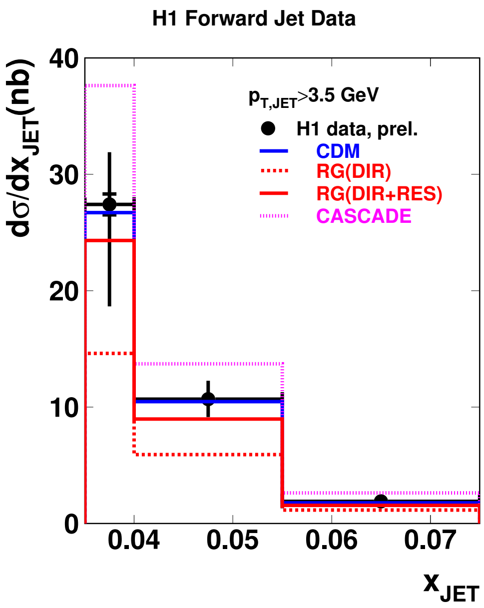
Forward Jet $p_T$ and $x_{JET}$ cross-sections

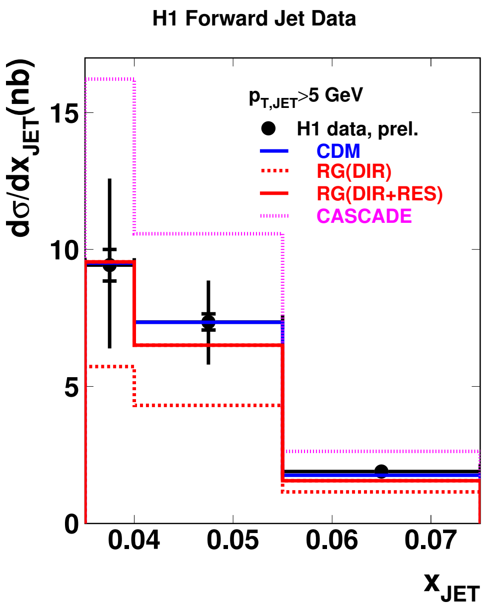
**97 Data**, RAPGAP (DIR) and (DIR+RES),

ARIADNE and CASCADE




$p_T > 3.5$ GeV $\qquad$ $p_T > 5$ GeV



# Forward $\pi^0$ Measurement

H1 data taken 1996-97.

Lumi - 21 $pb^{-1}$

Measure forward $\pi^0$:

Bjorken-$x$ and $p_T$ cross-sections

Transverse energy flow around $\pi^0$

Mean transverse energy as function of Bjorken-$x$

For $p_T > 2.5\ GeV$ and $p_T > 3.5\ GeV$.

In different region of $Q^2$.

Correction to non-radiative hadron level using LEPTO and DJANGO/ARIADNE

Main systematic errors - model dependence (10-15%), hadronic (LAR) energy scale (5-10%) and $\pi^0$ identification (5-10%)

**Kinematic Selection:**

Electron Method

$0.1 < y < 0.6$

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

$x$ down to $10^{-5}$

## $\pi^0$ **Selection**

$\pi^0$ selected from $\pi^0 \rightarrow 2\gamma$ signature.

Reconstructed as a one electromagnetic cluster with $E_{CLUS} > 8\ GeV$ in the H1 LAr calorimeter.

LAr - fine granularity forward region : 3.5 cm cells- different shapes distinguishable. Identification through analysis of transverse and longitudinal spread of shower.

Other Photon Production:
Prompt photons - negligble.
$\eta$-meson production - corrected for using MC.

**Forward $\pi^0$ selection:**

$$x_\pi = \frac{E_\pi}{E_p} > 0.01$$
$$p_T > 2.5 \text{ GeV } (p_T > 3.5 \text{ GeV})$$
$$5^o < \theta_\pi < 25^o$$

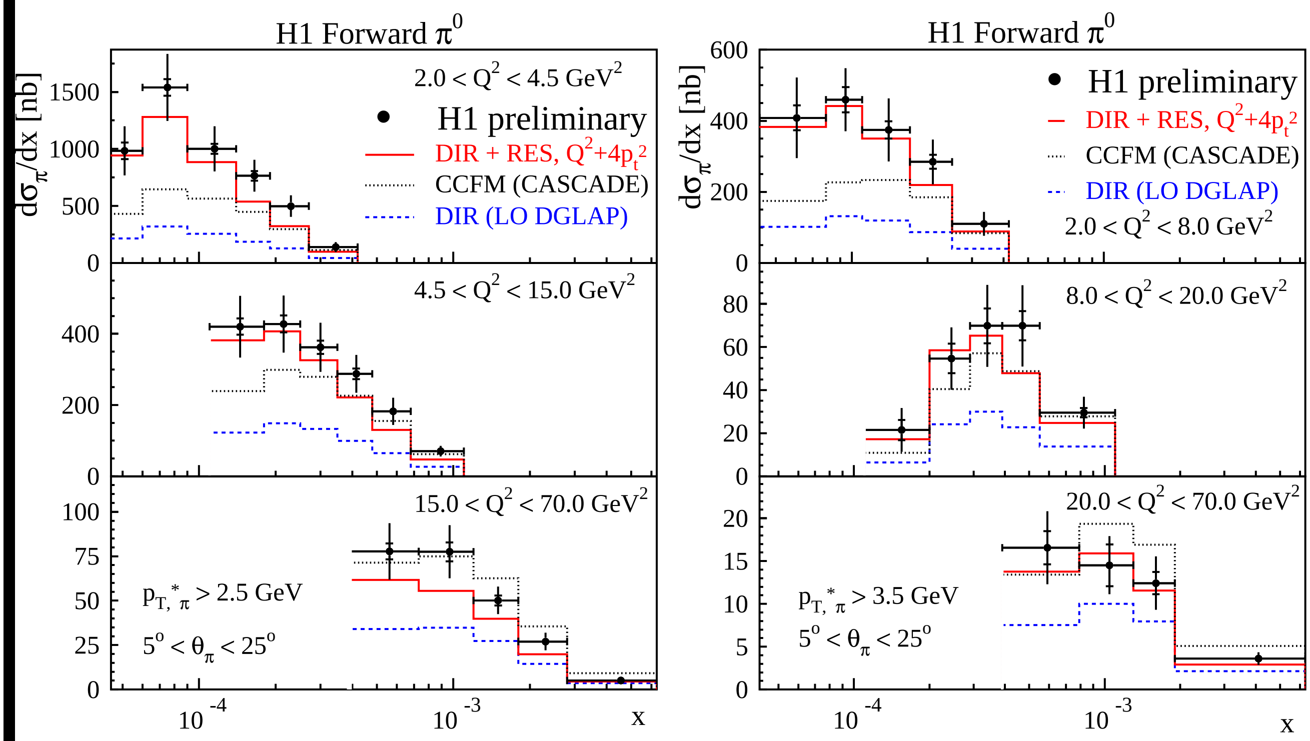
# Forward $\pi^0$ Cross-section

Bjorken-$x$ cross-section

**96-97 Data**, RAPGAP (DIR) and (DIR+RES)

$(Q^2 + 4p_T^2)$ and CASCADE

$p_T > 2.5$ GeV $\qquad$ $p_T > 3.5$ GeV

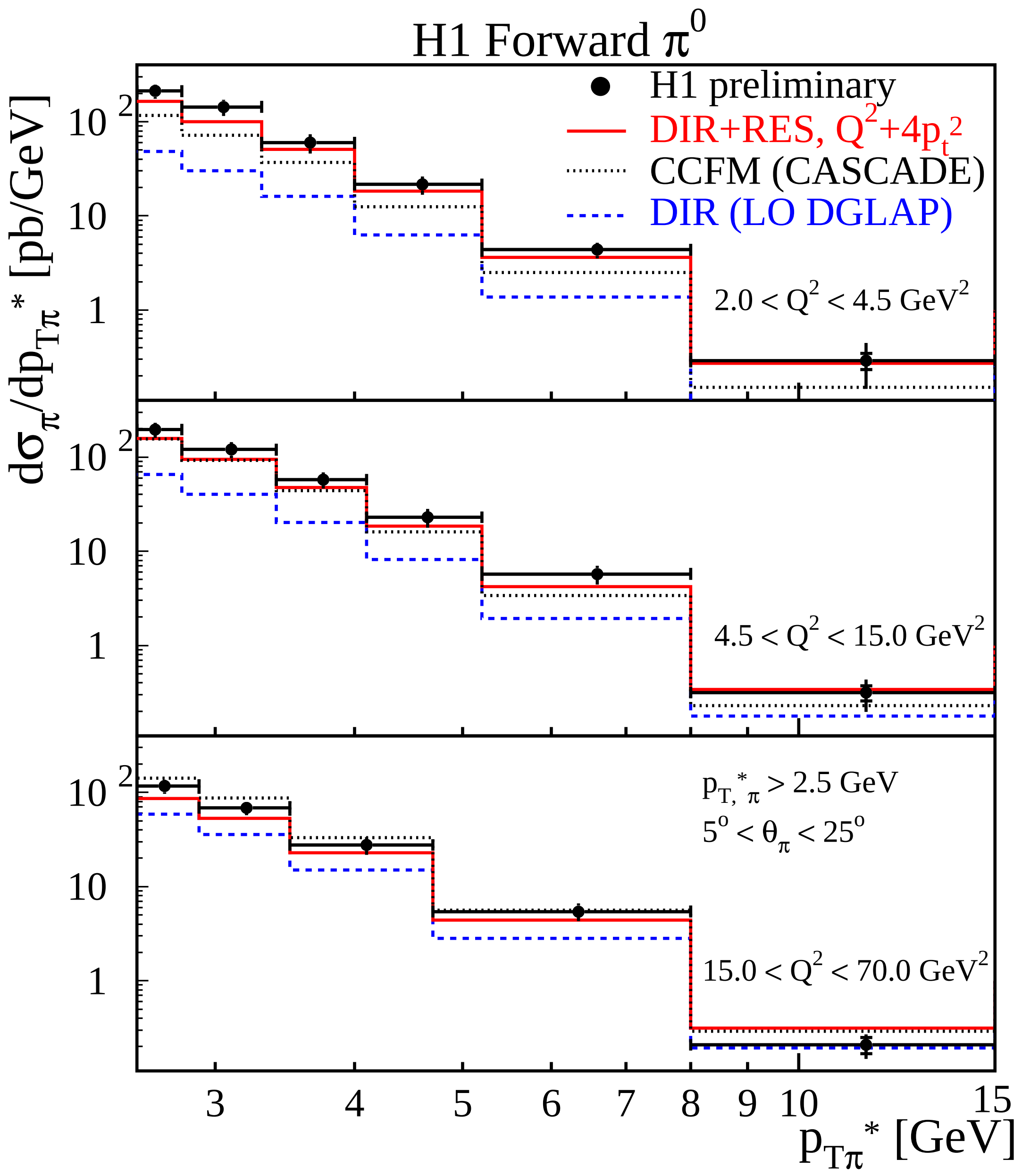



DGLAP fails. Resolved $\gamma$ provides reasonable description. CCFM below data for small $x$, above data for larger $x$.

## Forward $\pi^0$ Cross-section

$p_T$ cross-section

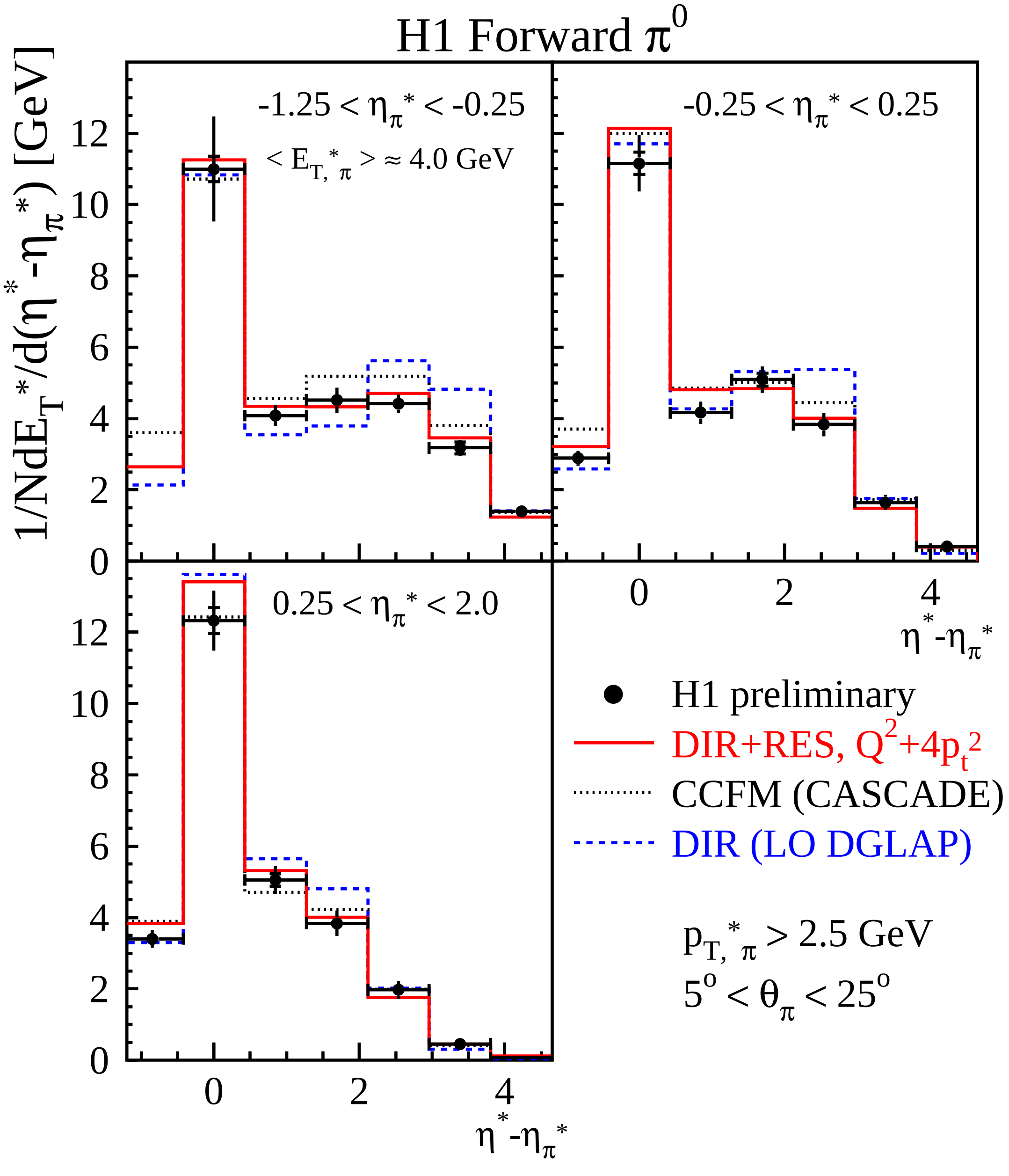
**96-97 Data**, RAPGAP (DIR) and (DIR+RES) - ($Q^2 + 4p_T^2$) and CASCADE



## Forward $\pi^0$ $E_T$ Flow

$E_T$ flow as function of distance, $\eta - \eta_\pi$, to $\pi^0$ in different regions of $\eta_\pi$ ($p_{T,\pi} > 2.5 GeV$)

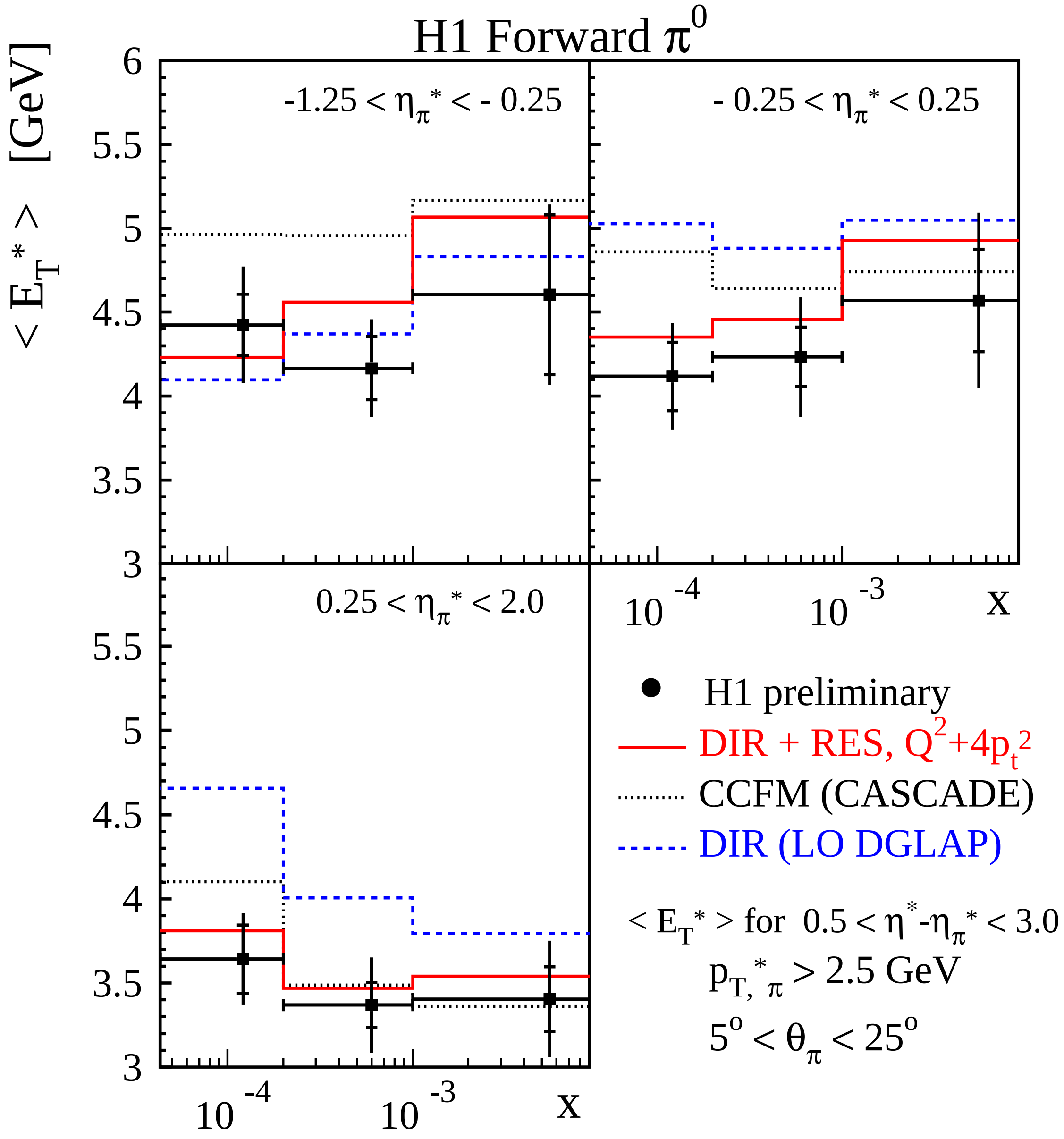
**96-97 Data**, RAPGAP (DIR) and (DIR+RES) - ($Q^2 + 4p_T^2$) and CASCADE



## Forward $\pi^0$ Mean $E_T$ Flow

Mean $E_T$ flow as function of Bjorken-$x$, in different regions of $\eta_\pi$ $(p_{T,\pi} > 2.5GeV)$

**96-97 Data**, RAPGAP (DIR) and (DIR+RES) - $(Q^2 + 4p_T^2)$ and CASCADE



# Summary

Measurements:

- New high statistics forward measurements ($13.7/21\ pb^{-1}$) using H1 96 and 97 data.
- H1 forward jet cross-section measurement including $p_{T,JET}$ and $x_{JET}$ distributions presented.
- H1 forward $\pi_0$ cross-section measurement including differential distributions in bins of $Q^2$ and $\pi_0$ energy-flow measurement presented.

Results:

- DGLAP fails...
- Forward jets described within statistical errors by CDM and within systematics by resolved $\gamma$ model.
- Forward $\pi_0$ reasonably well described by resolved $\gamma$ model.
- CCFM/CASCADE too low at low $x$, too high at high $x$.