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# Experimental Approaches to low $x$ at HERA

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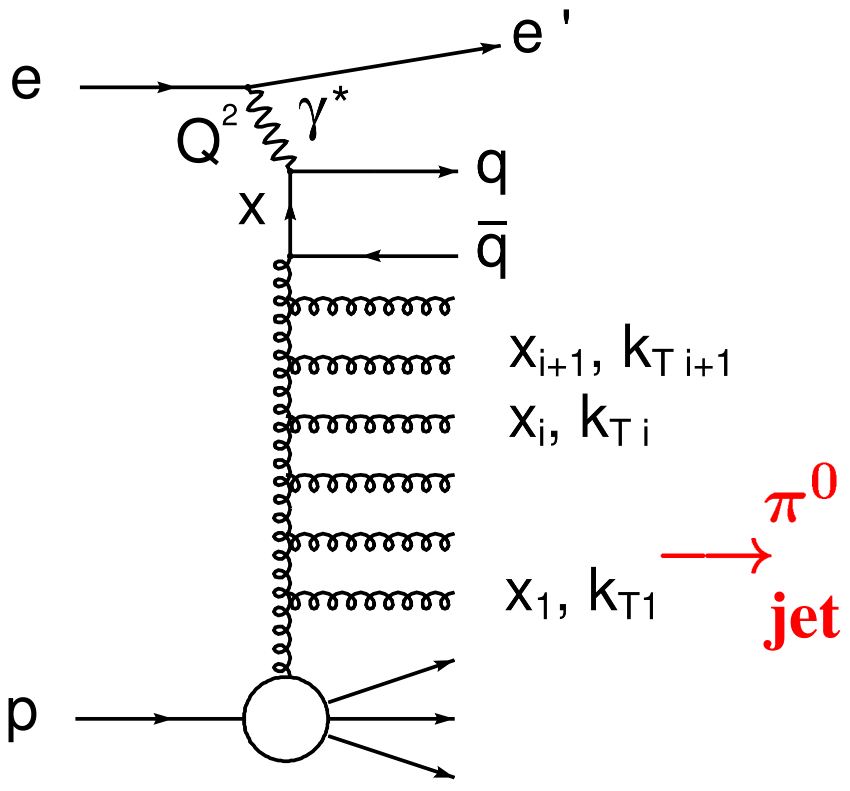
**main approaches to test low $x$ QCD dynamics**

- $F_2(x, Q^2)$
- **Heavy quark production in DIS**
- **Forward jets/particles**

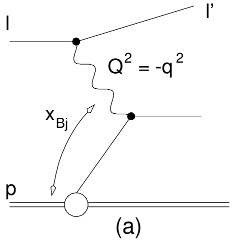
**this talk :**

- **Introduction**
- **forward jet production in DIS**
- **forward $\pi^0$ production in DIS**
- **Conclusion**

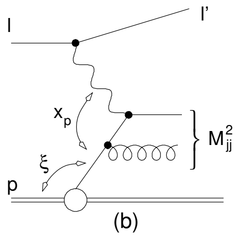


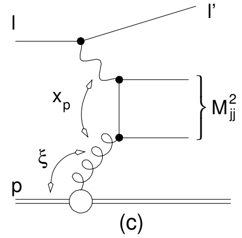

$$W^2 = Q^2(1/x - 1)$$

# Forward jets in NLO QCD $O(\alpha_s^2)$



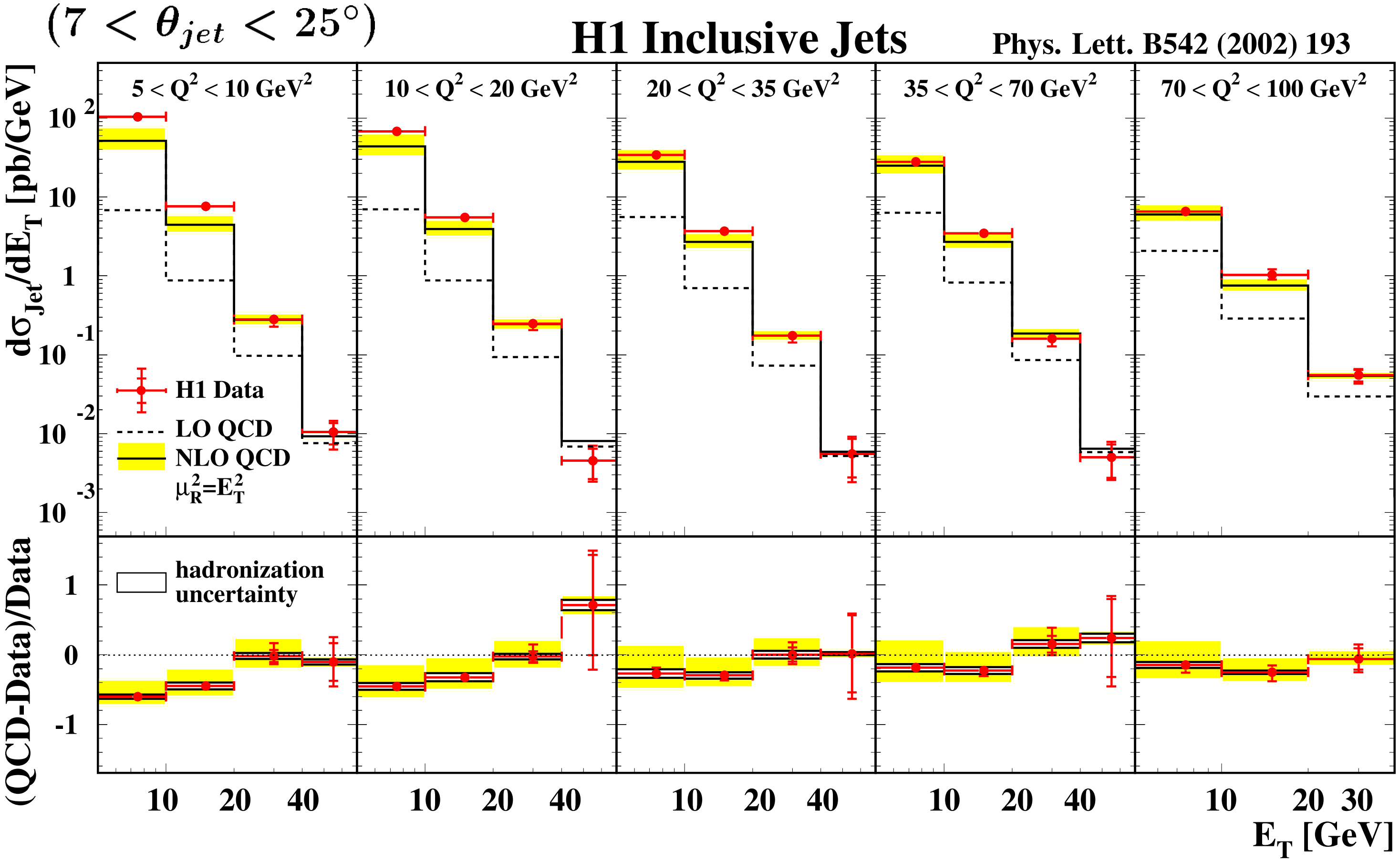

**LO**




$1.5 < \eta_{lab} < 2.8$

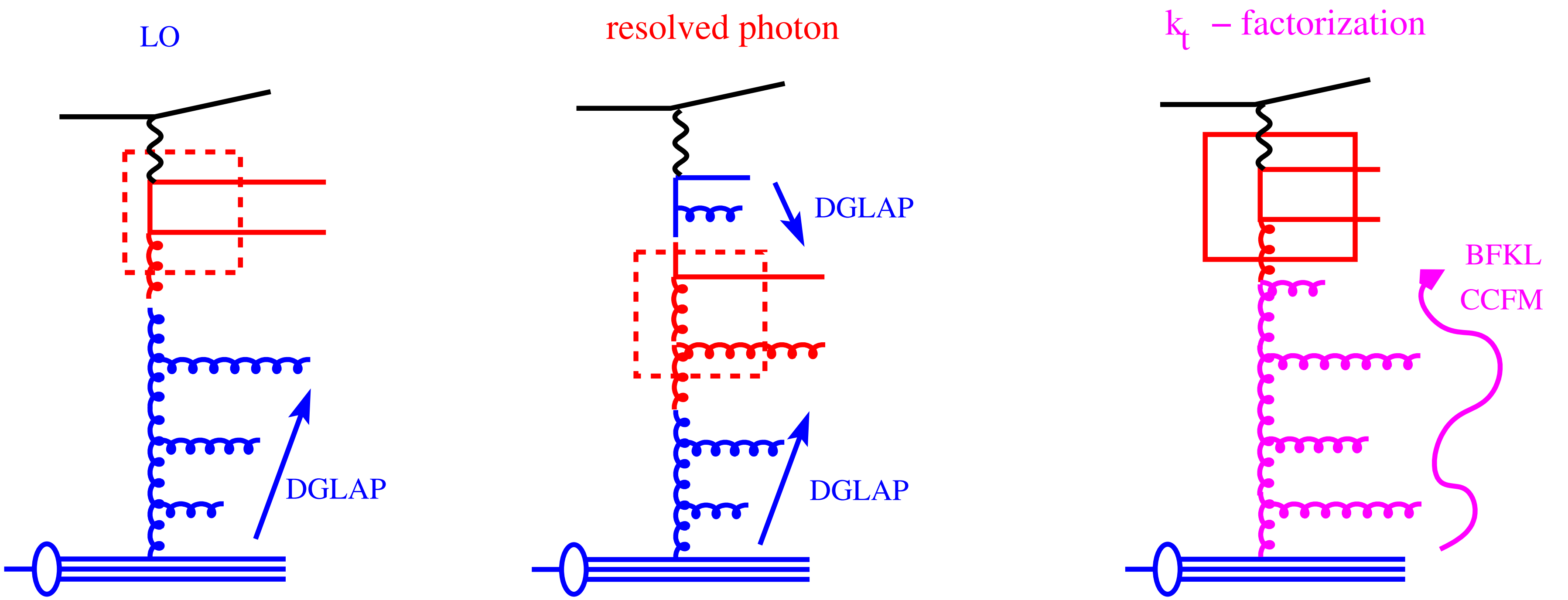
$(7 < \theta_{jet} < 25°)$




- huge NLO corrections
- problems at small $Q^2$

# Approaches to the dynamics at small $x$

**DGLAP** **BFKL** **CCFM**



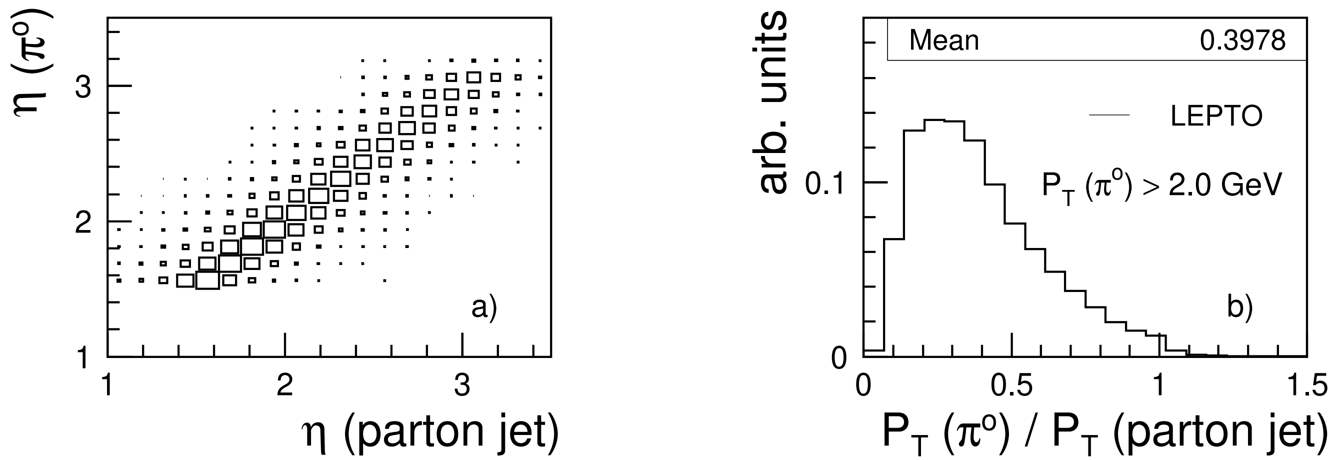

**ordered in $p_t$** **ordered in energy** **in angle**

**suppression of DGLAP ($Q^2$) evolution , but not BFKL ($x$) evolution, selecting jets/particles close to $p$ direction with**

**small $x_{bj}$, $p_t^2 \approx Q^2$, large $x_{jet} \equiv E_{jet}/E_{proton}$ (Mueller - Navelet jets)**

# Forward jet or particle production in DIS

**high $p_t$ forward jets and forward particles are sensitive to underlying partons dynamics**




## Jet measurements

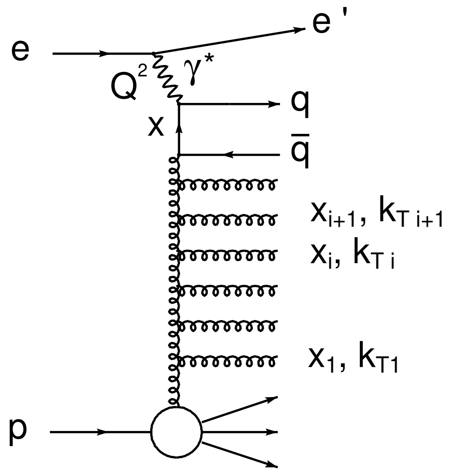
+ better parton correlation
+ higher rates
– ambiguities of jet algoriths
– exp. difficult in very forward ($p$) region

## forward particle detection $\pi^0$

– fragmetation effects more significant
– smaller rate

+ identification possible
  in more forward region

# Selection of DIS forward jets and $\pi^0$




$\longrightarrow$ $\pi^0$ / jet

similar event selections for forward jets and $\pi^0$

**forward jets**

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

$7 < \theta_{jet} < 20°$

$0.5 < p^2_{t\,jet}/Q^2 < 2$

$x_{jet} = E_{jet}/E_p > 0.035$

inclusive $k_t$ algorithm

**forward $\pi^0$ detection**

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

$5 < \theta_{\pi^0} < 25°$

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

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

$\pi^0 \rightarrow 2\gamma$ reconstructed as one narrow cluster in H1 LAr calorimeter

# Forward jets vs. $x$

**CDM Colour Dipole Model in ARIADNE**

(parton emissions random in transverse momentum, BFKL like?)

excellent description of data

**RG RAPGAP (DIR)**

(LO matrix elements with DGLAP parton showers)

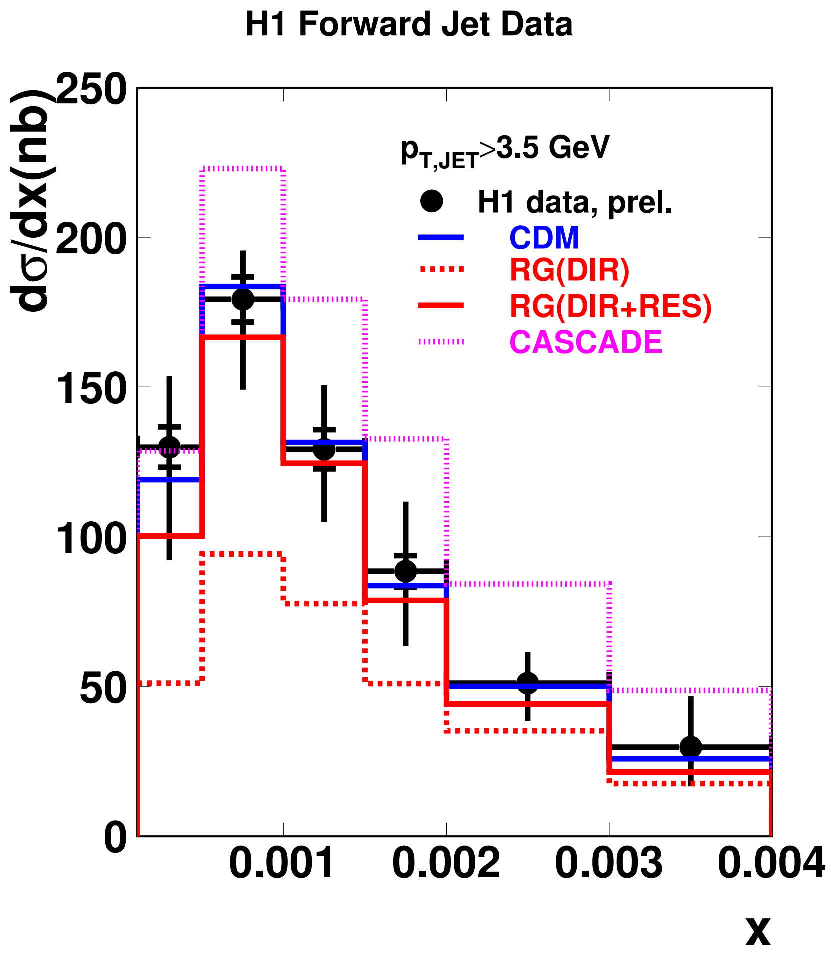
well below the data

**RAPGAP (DIR + RES)** (addition of resolved $\gamma^*$)

o.k. with inclusion of resolved $\gamma^*$

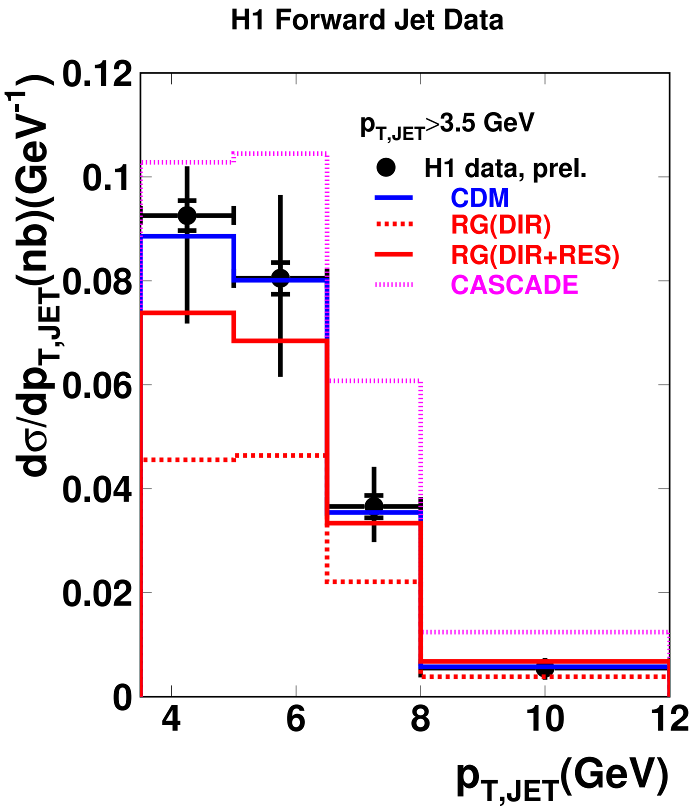
**CASCADE** (based on CCFM evolution equation)

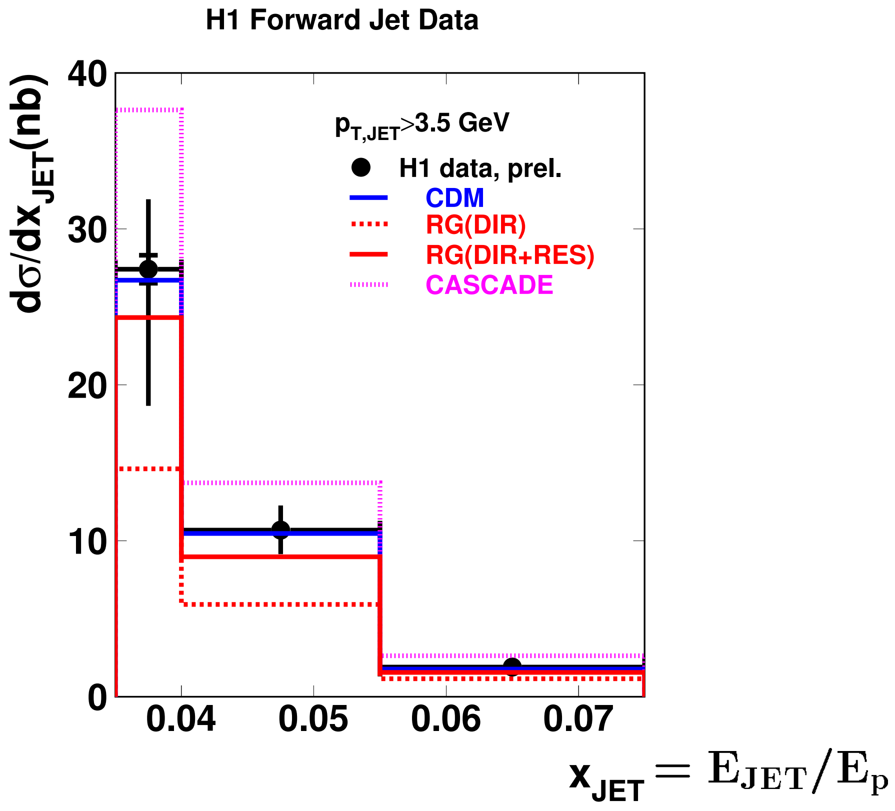
above the data




**DGLAP too small, but what needed ? $x$ ordering or resolved $\gamma$ ?**

# Forward jets $d\sigma/dp_t$ and $d\sigma/dx_{jet}$



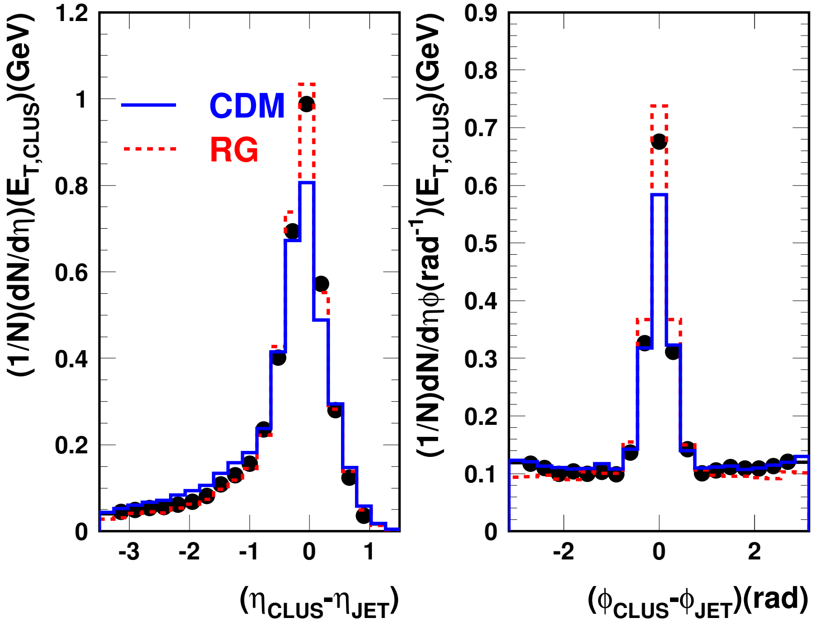




**patterns of (dis)agreement same as for $d\sigma/dx$**

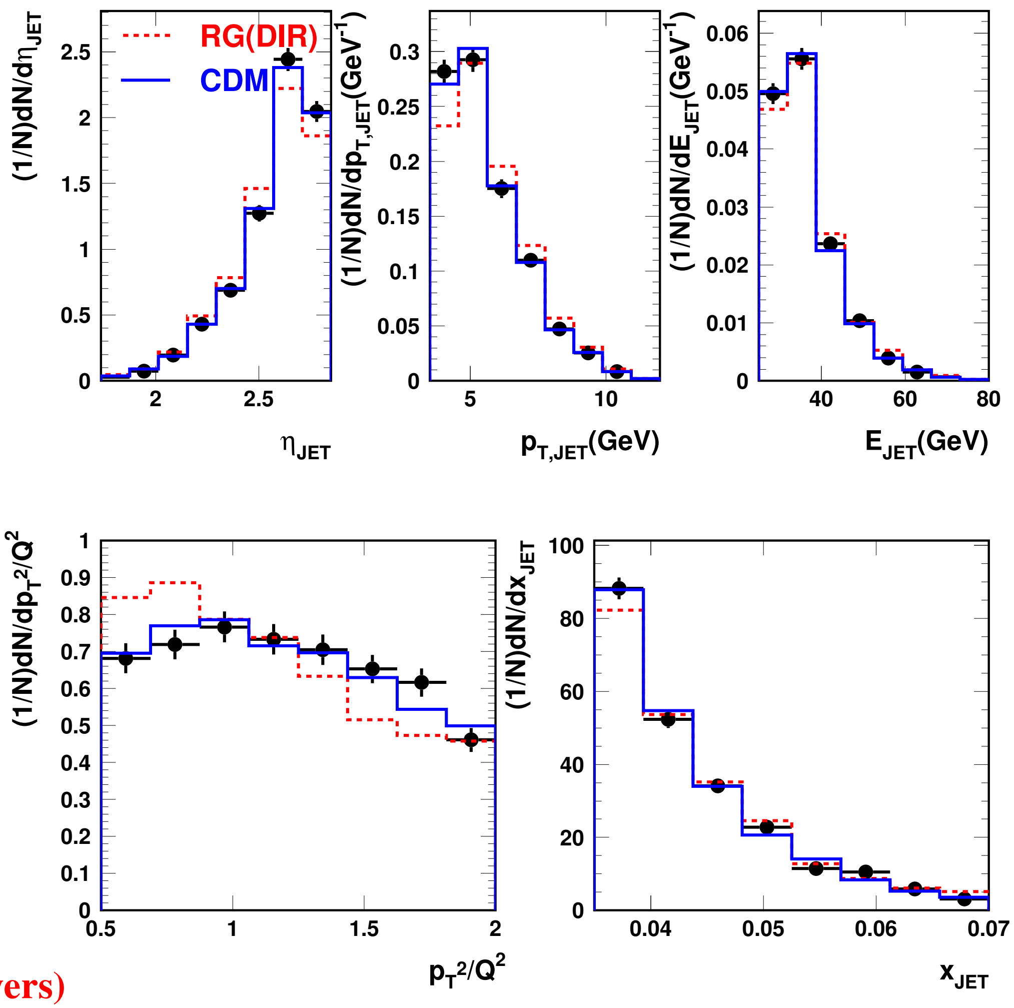
- **CDM** **o.k.**
- **DGLAP (RG dir)** **low**
- **DGLAP + resolved $\gamma^*$** **o.k.**
- **CASCADE** **high**

# normalised Jet distributions (forward jet selection)

**H1 Forward Jet Data**




**H1 Forward Jet Data**




basic distributions reasonably described

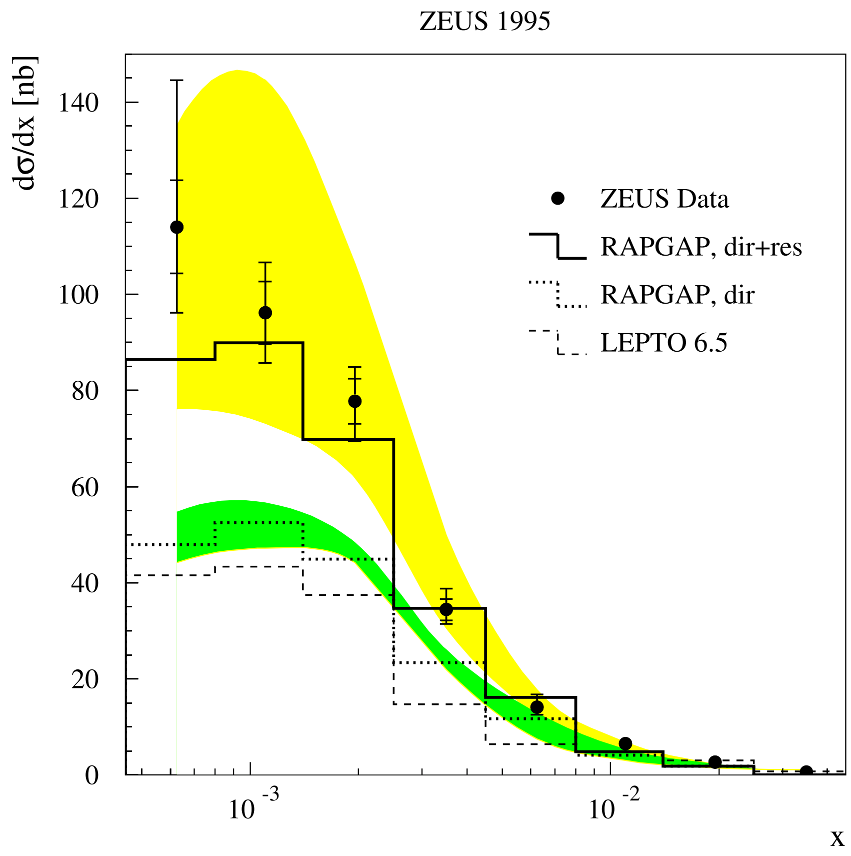
jets have more $p_t^2/Q^2$
than predicted in RG (LO + DGLAP parton showers)

# Former HERA results in present context

**forward $\pi^0$ :** H1, Phys. Lett. B 462 (1999) 440 improved by present analysis

**forward jets:** H1, Nucl. Phys. B 538 (1999) 3 improved by present analysis

**Forward jets** $0.5 < E_T^2/Q^2 < 2$ Phys. Lett. B474 (2000) 223




- DGLAP direct $\gamma$ below the data
- + resolved $\gamma$ o.k.

# Forward $\pi^0$ $\quad d\sigma/dx \quad p^*_{T,\pi} > 2.5$ GeV

**RAPGAP (DIR+RES)**

**(DGLAP, direct + resolved $\gamma*$)**

**reasonable description of data**

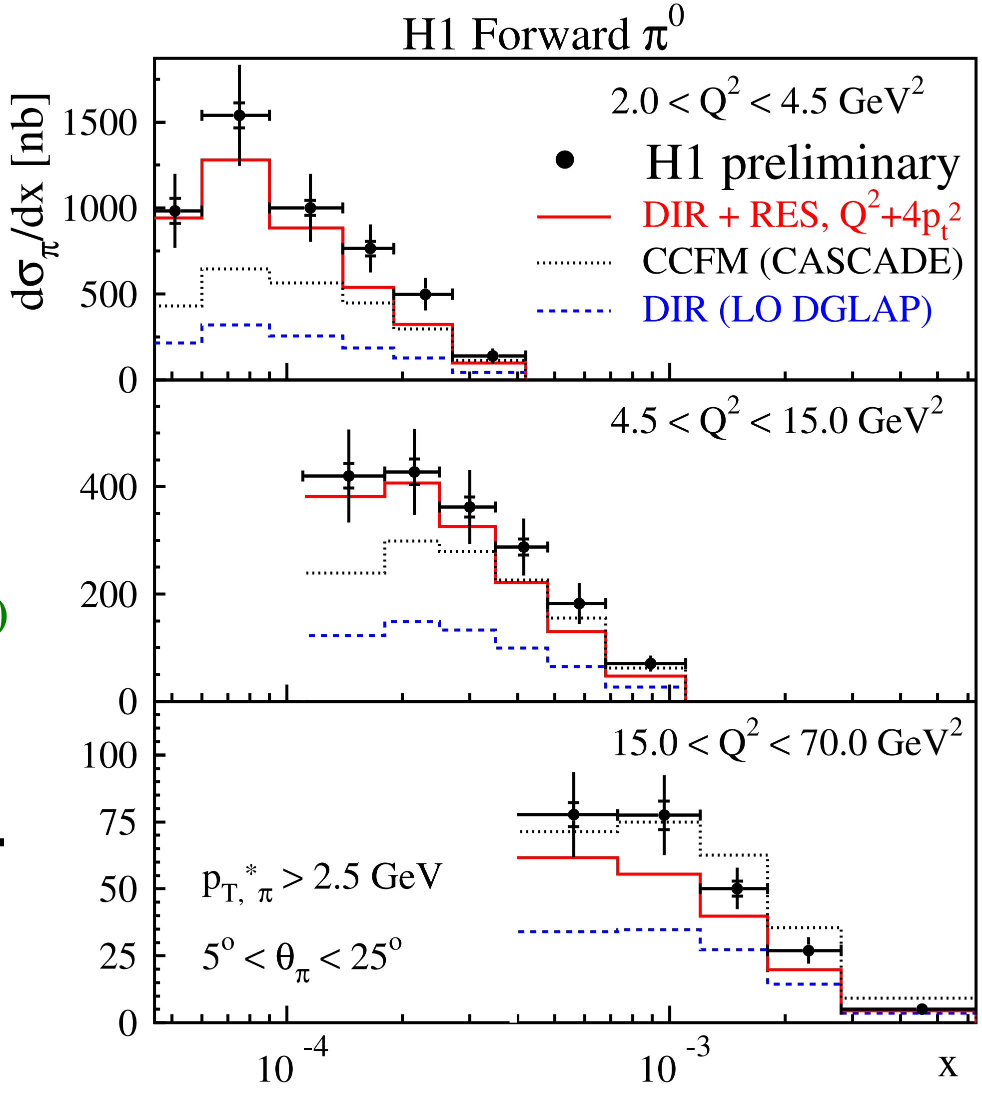
**RAPGAP (DIR)**

**below the data**

**CASCADE (CCFM)**

**below the data at small $x$, $Q^2$**

**(was high for forward jets for $x \gtrsim 0.001$ only)**

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**as in jets, DGLAP + direct $\gamma$ interaction**

**not sufficient**

# Forward $\pi^0$ $\quad d\sigma/dx \quad p^*_{T,\pi} > 3.5$ GeV

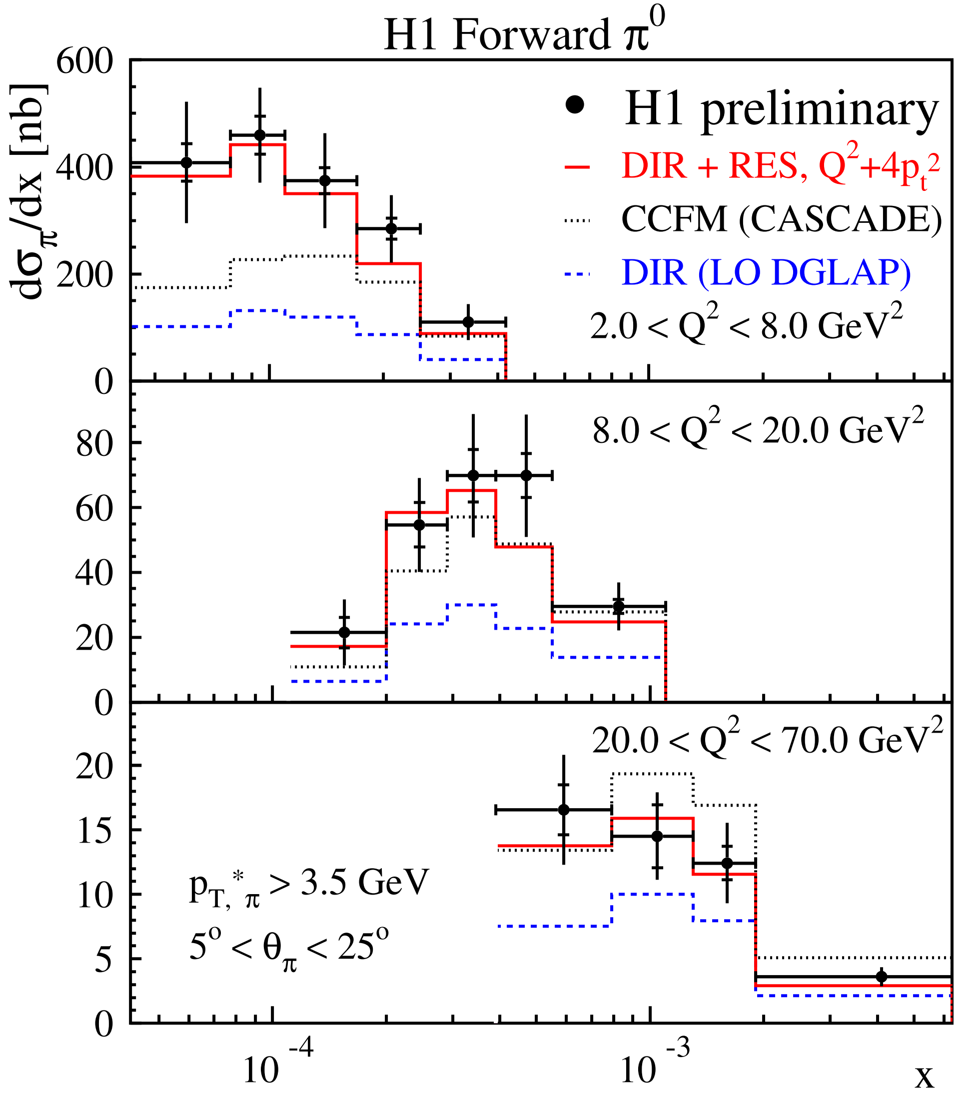
**as for $p^*_{T,\pi} > 2.5$**

**DGLAP + direct $\gamma$ interaction**

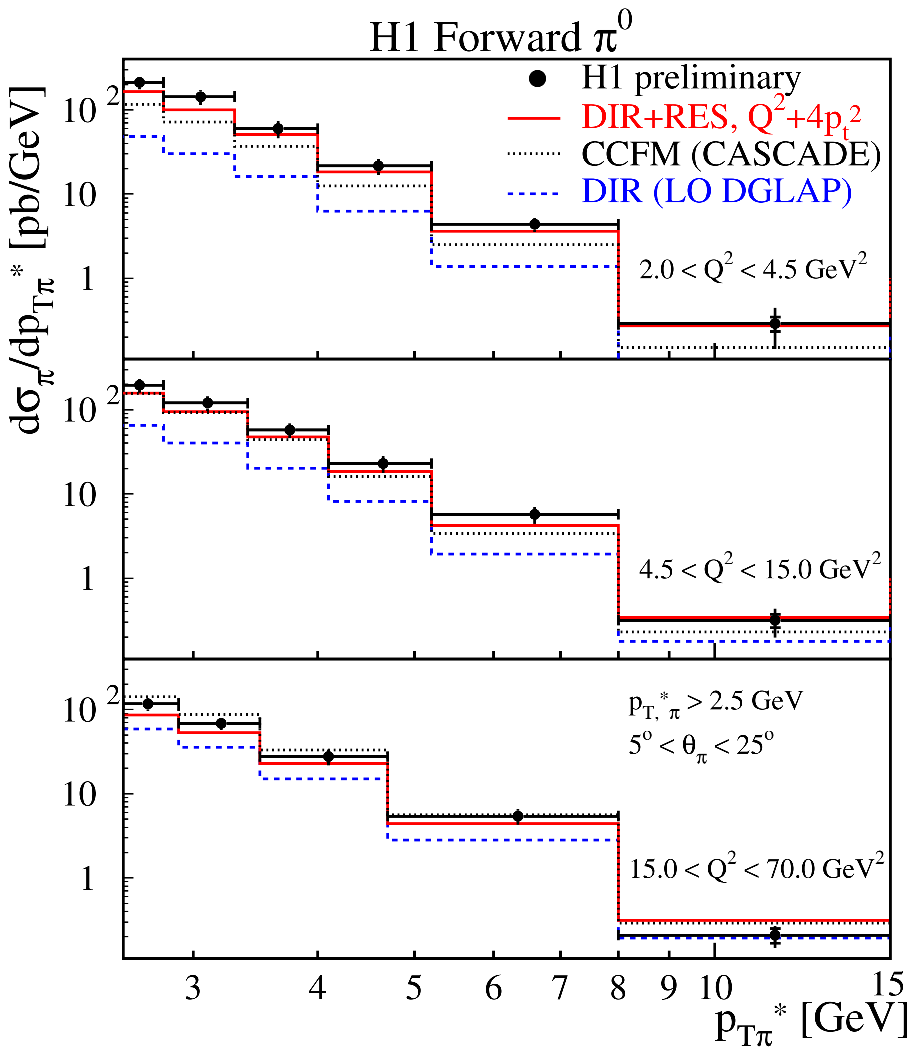
**too low everywhere**

**+ resolved $\gamma$ o.k.**

**CASCADE low at small $x$, $Q^2$**



# Comparisons of $p_t$ dependence at different $Q^2$

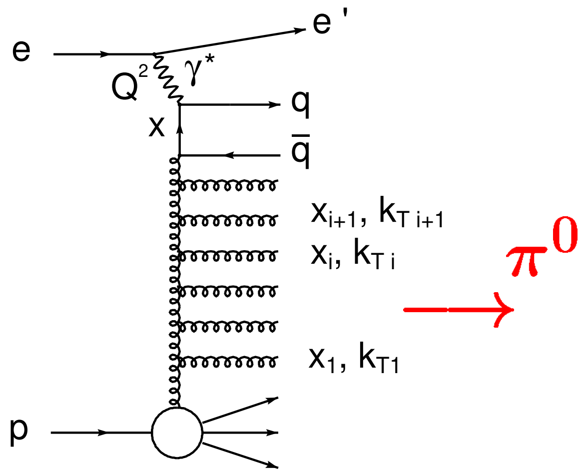


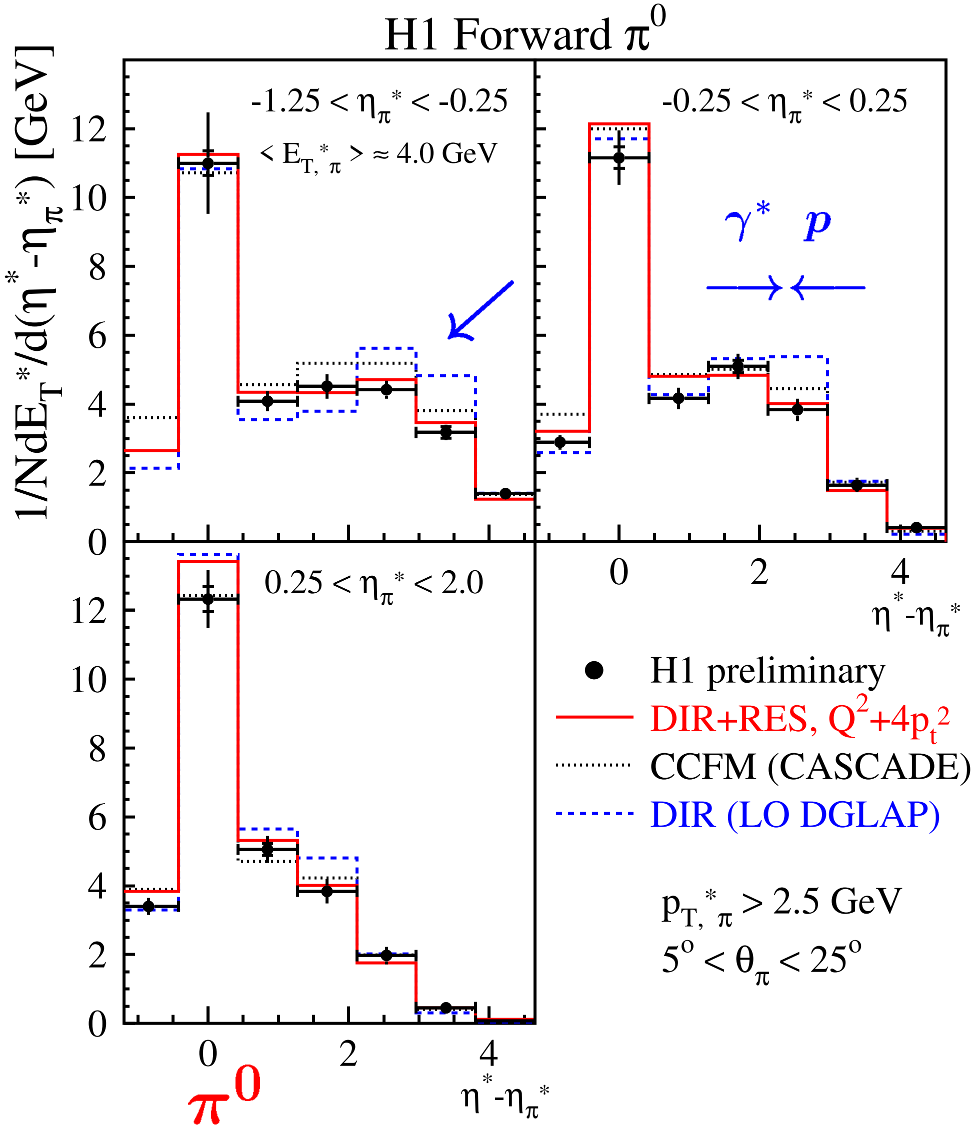

$p^*_{T\pi}$ : $p_t$ in hadronic CMS

**$p_t$ dependence well described everywhere by all calculations**

# Transverse energy flow around $\pi^0$ in 3 ranges of $\eta^*_\pi$

$\eta^*_\pi$ **rapidity in had CMS**




**at large $\eta^* - \eta^*_\pi$ less $E_t$ in data than expected in RAPGAP DIR.**

**Indication that in DGLAP approach too much $p_t$ compensation close to $\gamma^*$ ?**

# Conclusions

- data on forward (close to $p$ remnant) jets and $\pi^0$ s in DIS shown
- NLO ($O(\alpha_s^2)$ calculations problematic in this region
  where phase space for DGLAP evolution small
- DGLAP MC models with direct $\gamma^*$ interactions : too small cross sections
- with resolved $\gamma^*$ interactions good description of of the data
- Coulour Dipole Model (CDM) describes the jet data very well
  (resembling the BFKL approach in the non ordered $p_t$ production)
- CASCADE MC, based on the CCFM equation,
  predicts too small cross sections at $x \lesssim 0.001$.
- possible progress :
  - ▽ further experimental studies of ladder
  - ▽ more complete CCFM calculations
  - ▽ NLO ($O(\alpha_s^2)$) for presented data
  - ▽ NLO ($O(\alpha_s^2)$) MC with hadrons