A Review of HERA Low x Results on Forward Jets and Particles, F_2 and F_L Measurements at Low Q^2

on behalf of the H1 and ZEUS collaborations

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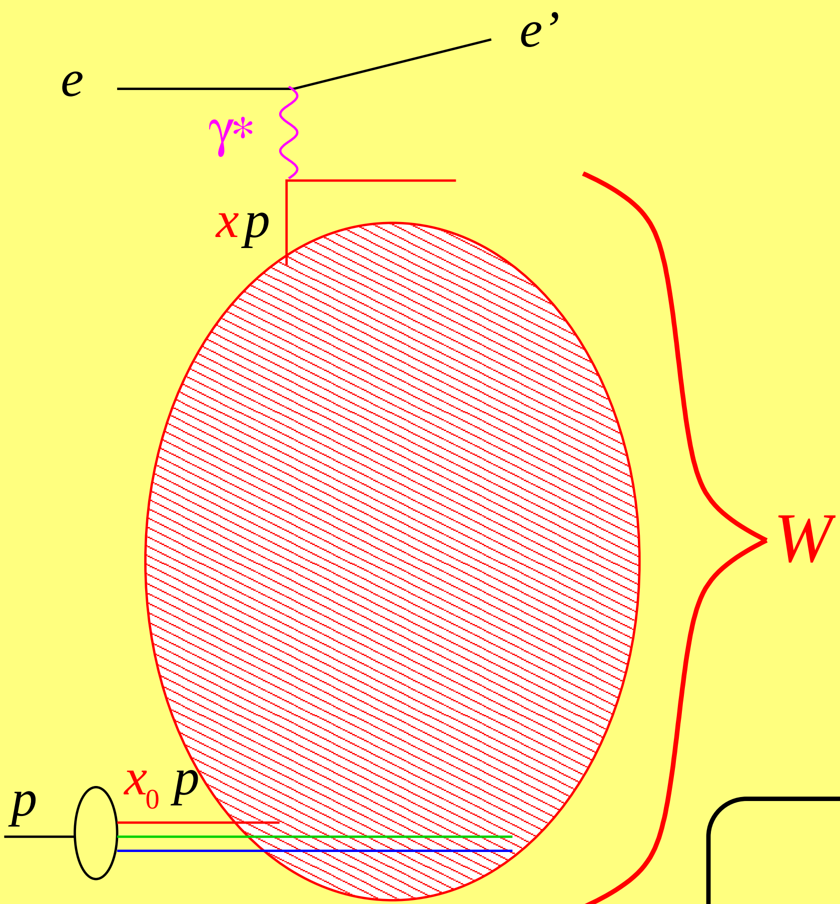
Xth Blois Workshop on Elastic and Diffractive Scattering, Helsinki, 23 - 28 June 2003

- Inclusive cross section and structure function: F_2, the gluon and F_L
- Parton dynamics at high energies
- From central to forward (proton) direction:
  - inclusive jet production
  - forward jet production
  - forward π^0 production
- Conclusion

The general hard process in ep



$s = (p_e + p_p)^2$

$Q^2 = -(p_e - p_{e'})^2$

$y =$ **scaled γ energy**

$W^2 = (p_\gamma + p_p)^2 = Q^2 + ys$

$x = \frac{Q^2}{ys} = \frac{Q^2}{W^2+Q^2}$

$\frac{d\sigma^{ep}}{dy\,dQ^2} = \Gamma(y, Q^2)\sigma^{\gamma^* p}(W, Q^2)$

with

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

and

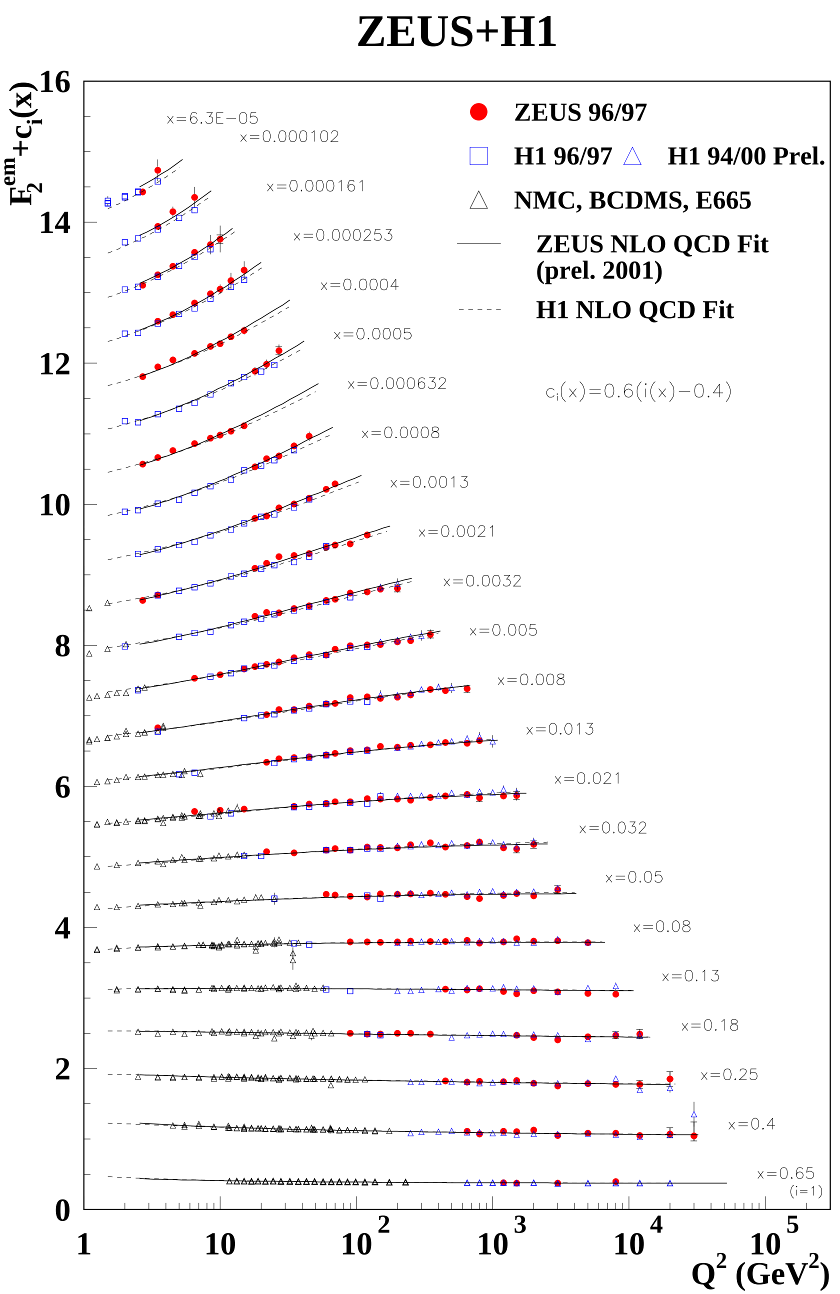
$F_2(x, Q^2) = \sum_i e_i^2 x q_i(x, Q^2)$

Q^2 dependence of $F_2(x, Q^2)$

predicted by QCD

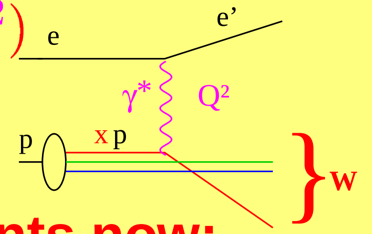
test theory over large range in Q^2

The structure function $F_2(x, Q^2)$



$F_2(x, Q^2) = \sum_i e_i^2 x q_i(x, Q^2)$

$x = \frac{Q^2}{W^2+Q^2}$



- **Precision measurements now:** $\sim 1-2$ **% stat,** ~ 2 **% sys.**

Scaling violations perfectly described with NLO DGLAP:

$0.63 \cdot 10^{-5} < x < 0.65$

$1 < Q^2 < 25000$ GeV^2

- **adjust input pdf to fit F_2 data**
- **extract pdf's from F_2 fit**

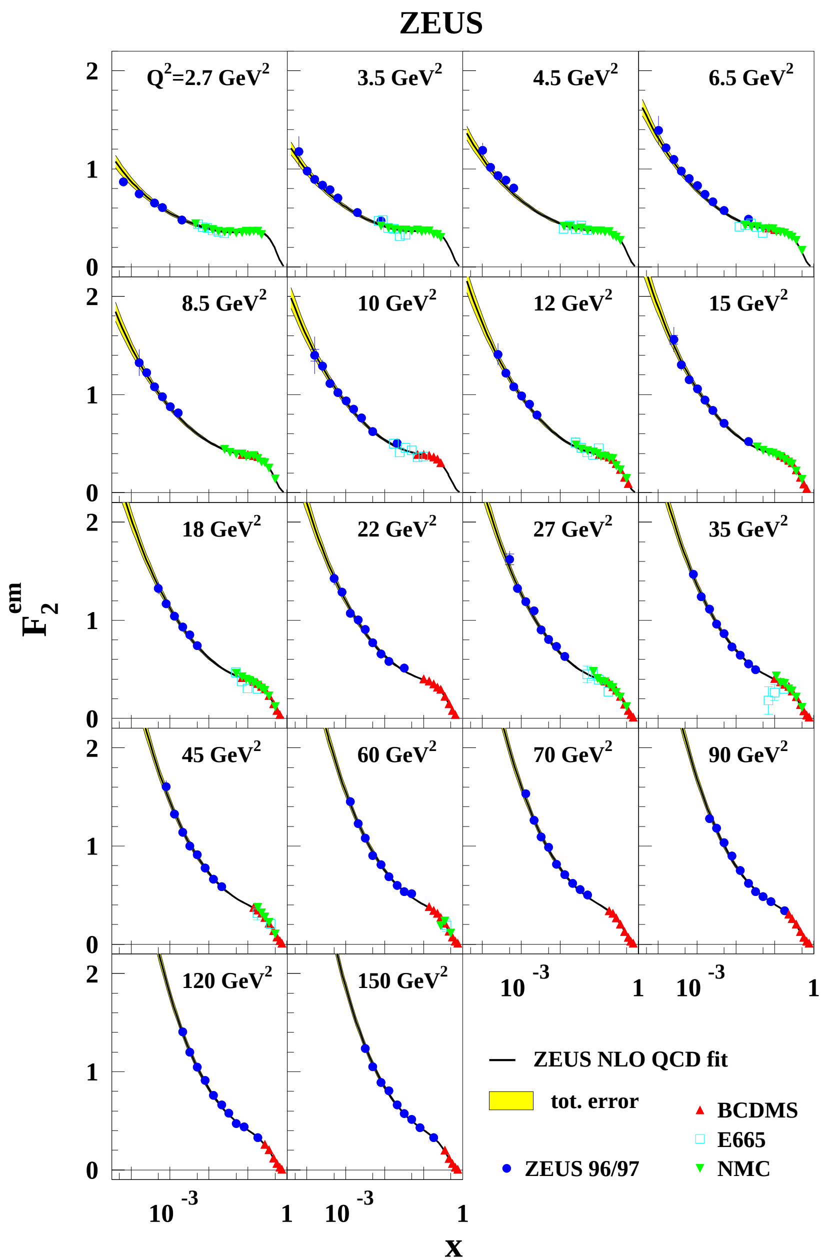
Similar **pdf sets by MRST, CTEQ etc**

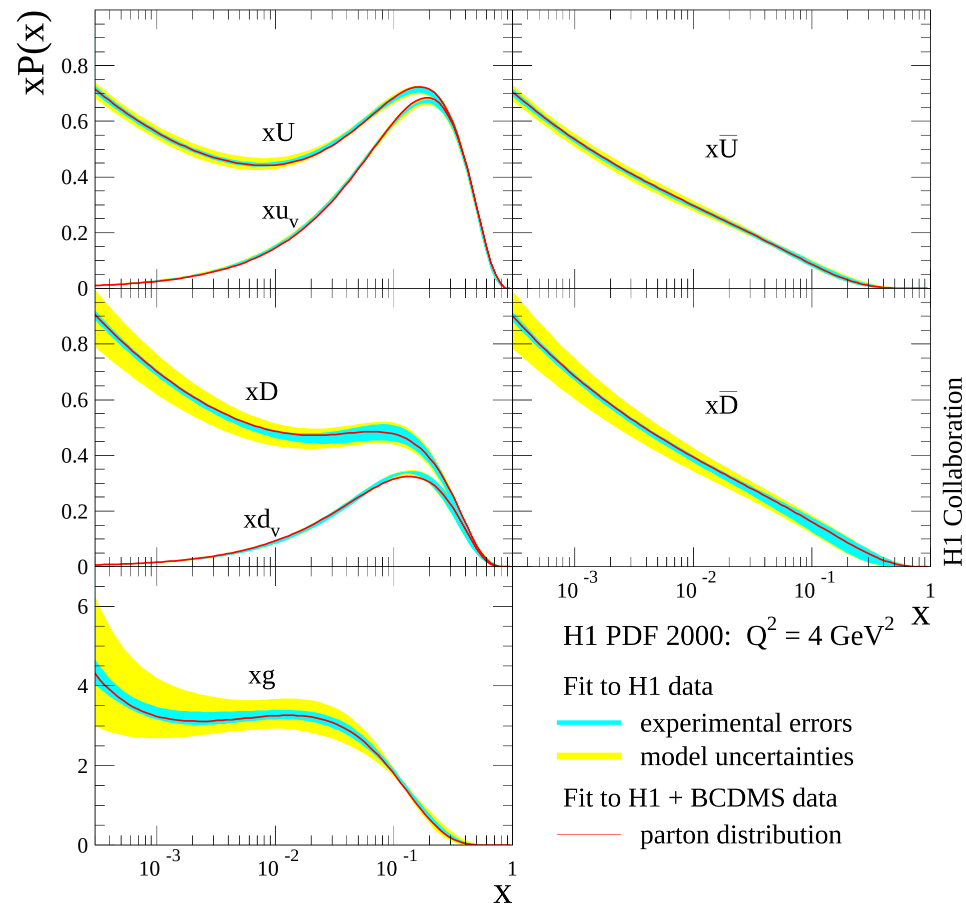
- **use pdfs to predict xsect. even at $p\bar{p}$**

BUT **what at small x and Q^2 ???**

predictions for F_L ???

NLO analysis of F_2 (ZEUS, H1)





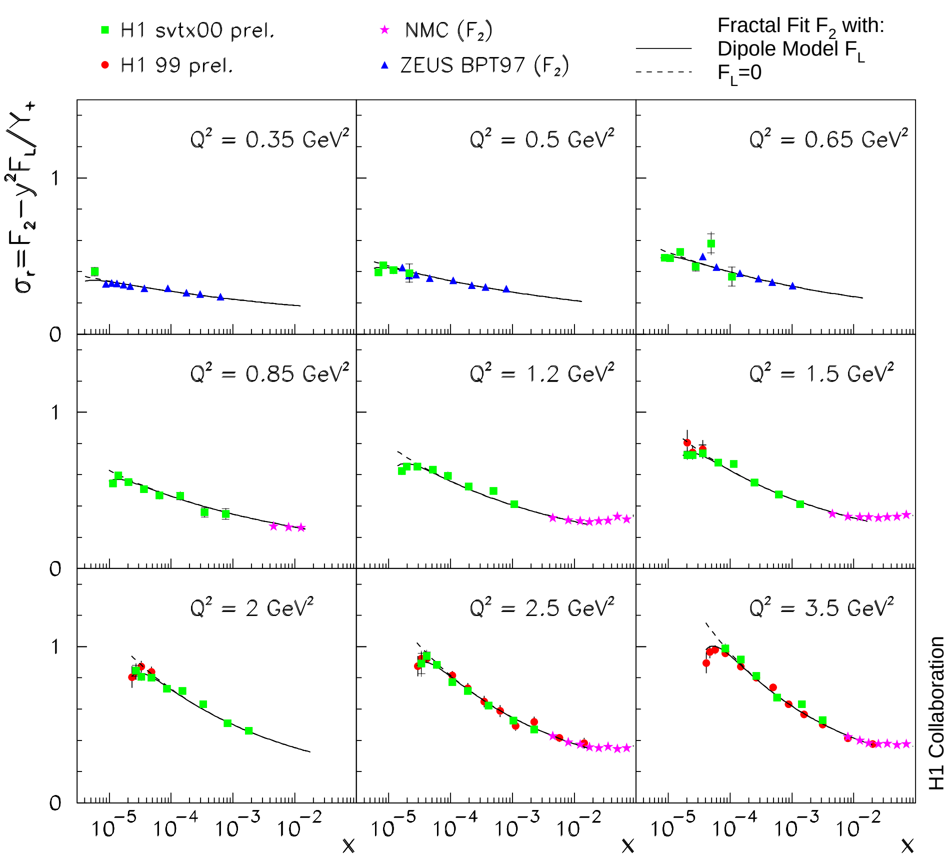
NLO DGLAP fit to $F2$
covering $2.5 < Q^2 < 30000\text{GeV}^2$
covering $6.3\,10^{-5} < x < 0.65$
pdf extracted...

σ_{tot} at small Q^2: measured and extrapolated

- precision measurement at low Q^2:

  $\sigma_r = F_2 - y^2 \frac{F_L}{Y_+}, \quad Y_+ = 1 + (1-y)^2$

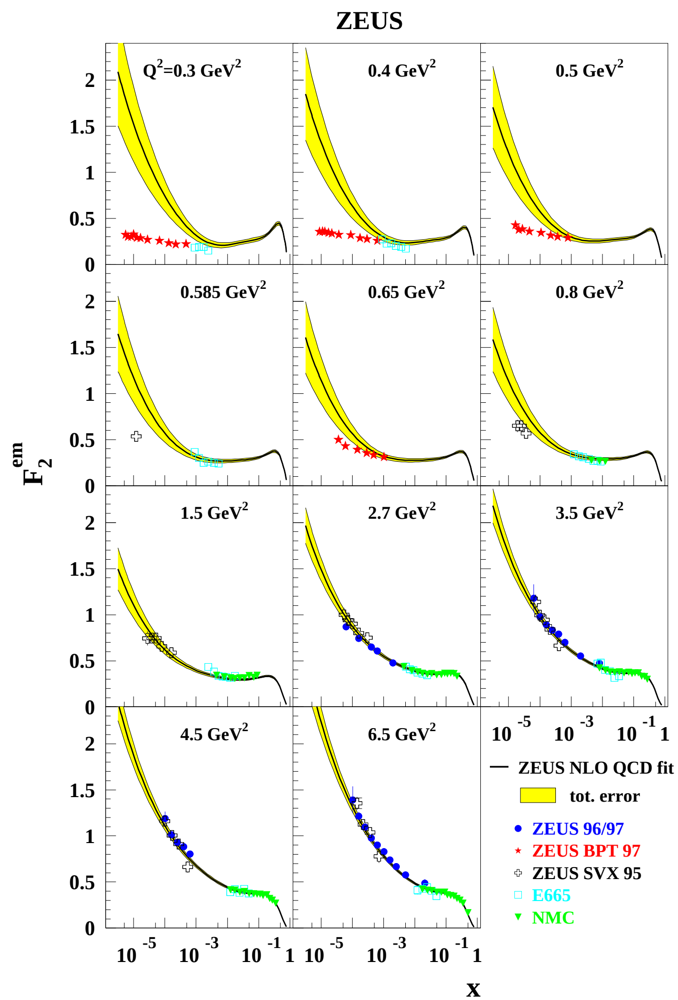
  tot error $\sim 4\%$



- observe turnover of σ_r ☞ F_L effect

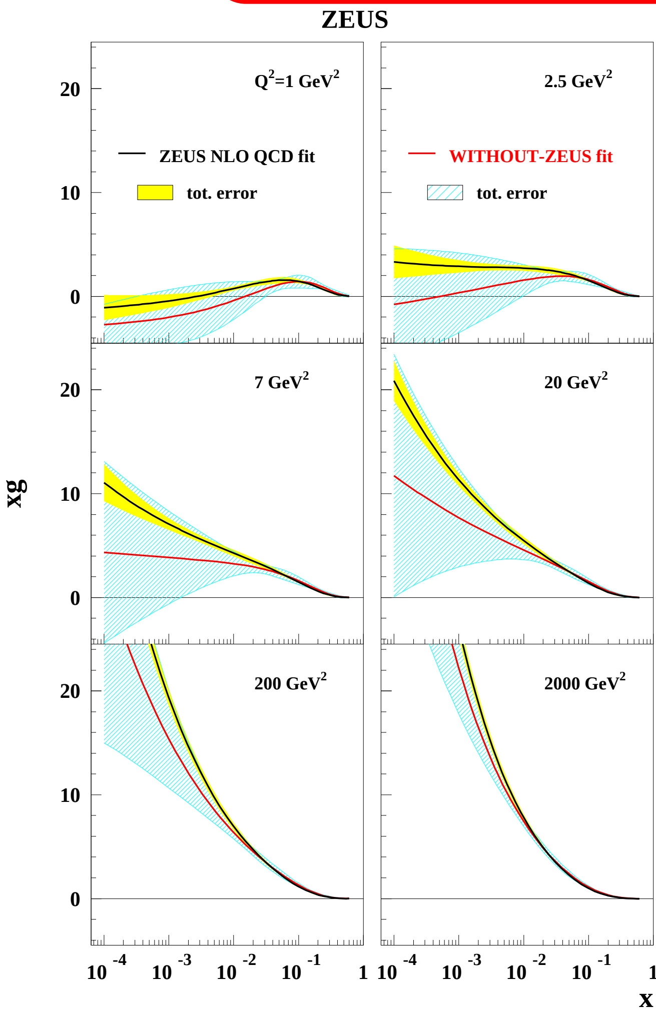
- backward evolution with DGLAP from $Q^2 > 4$ to $Q^2 < 1$ GeV^2

☞ reliable ???

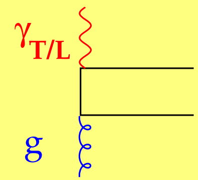


☞ fails for $Q^2 < 1$ GeV^2

From F_2 to gluon density and F_L



$\sigma_L(\gamma g \rightarrow q\bar{q}) \longrightarrow F_L$

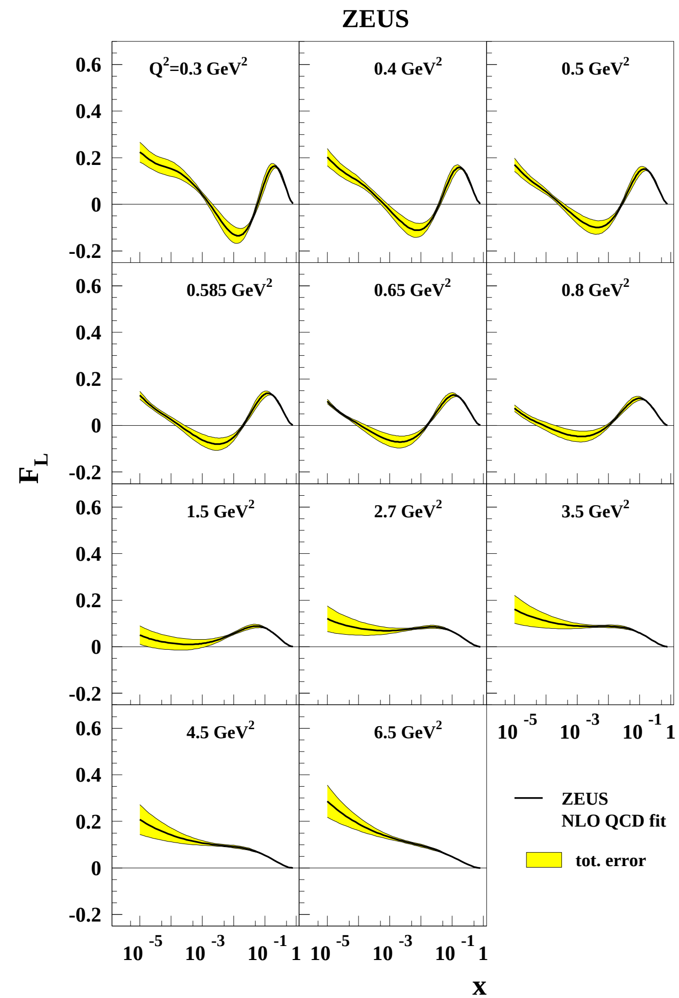


longitudinal γ

$F_L \propto \alpha_s\, xG(x,Q^2)$

predict F_L

from gluon



gluon becomes negative at small Q^2

end of DGLAP ????

BUT gluon is not observable !!!

Measurement of F_L at small x and Q^2

$\frac{d\sigma}{dx\,dQ^2} \sim$

$\left(F_2(x,Q^2) - y^2 F_L(x,Q^2)\right)$

$0 \leq F_L \leq F_2$

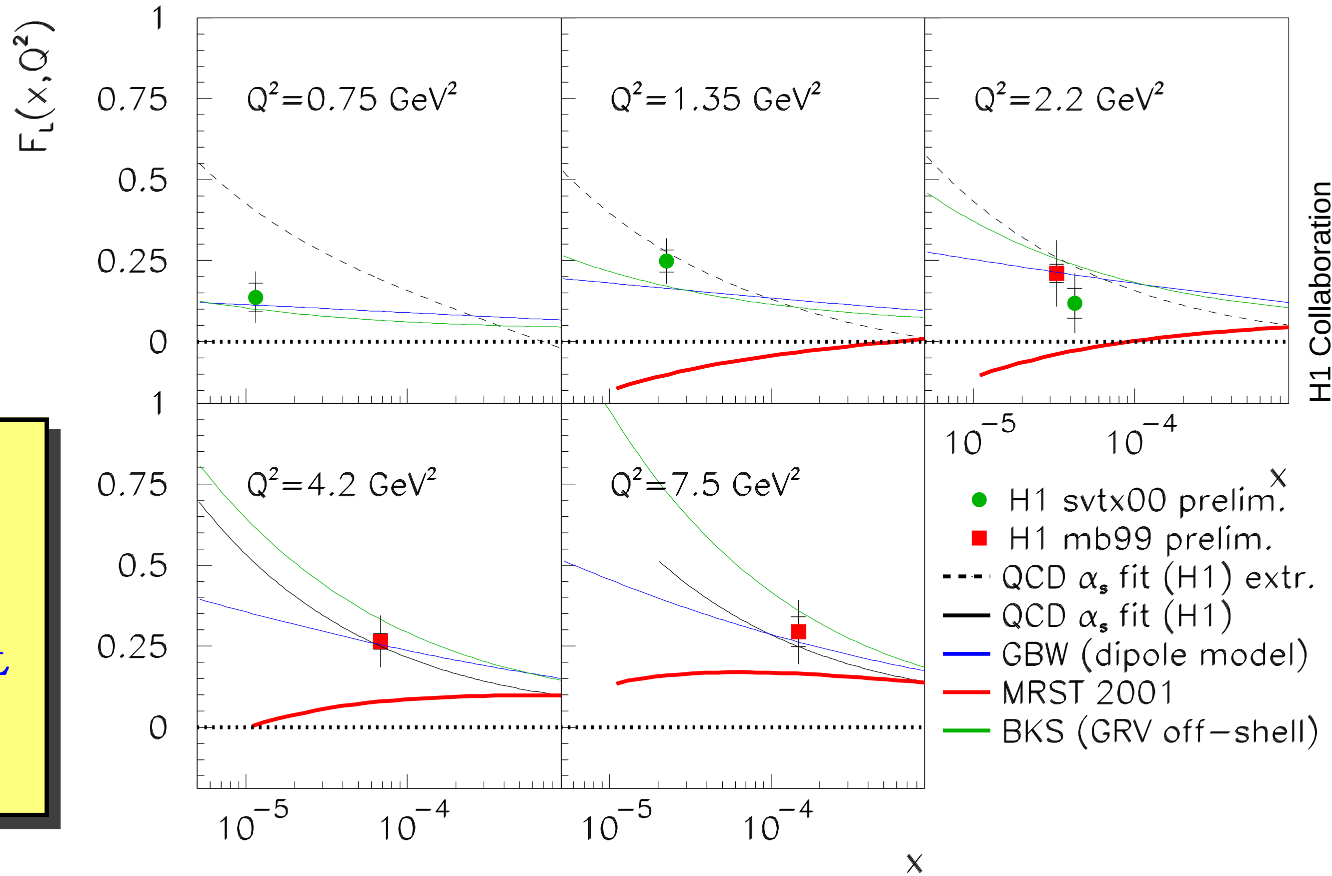
F_L effect at large y

different methods to extract $\boldsymbol{F_L}$

use ansatz for $F_2 = x^{-\lambda}$

$\boldsymbol{\sigma_{FIT} = c\,x^{-\lambda} - \frac{y^2}{1+(1-y)^2} F_L}$

fit in $\boldsymbol{Q^2}$ bins

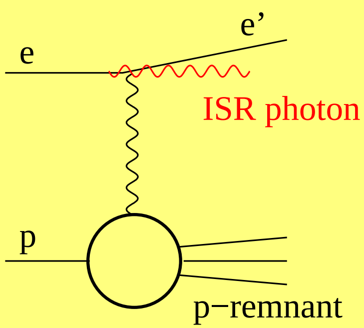


F_L from un-integrated pdf (BKS) ☞ works pretty well !!!! , also dipole (GBW)

H1 fits only for $Q^2 > 1$ ... MRST fails !!!!

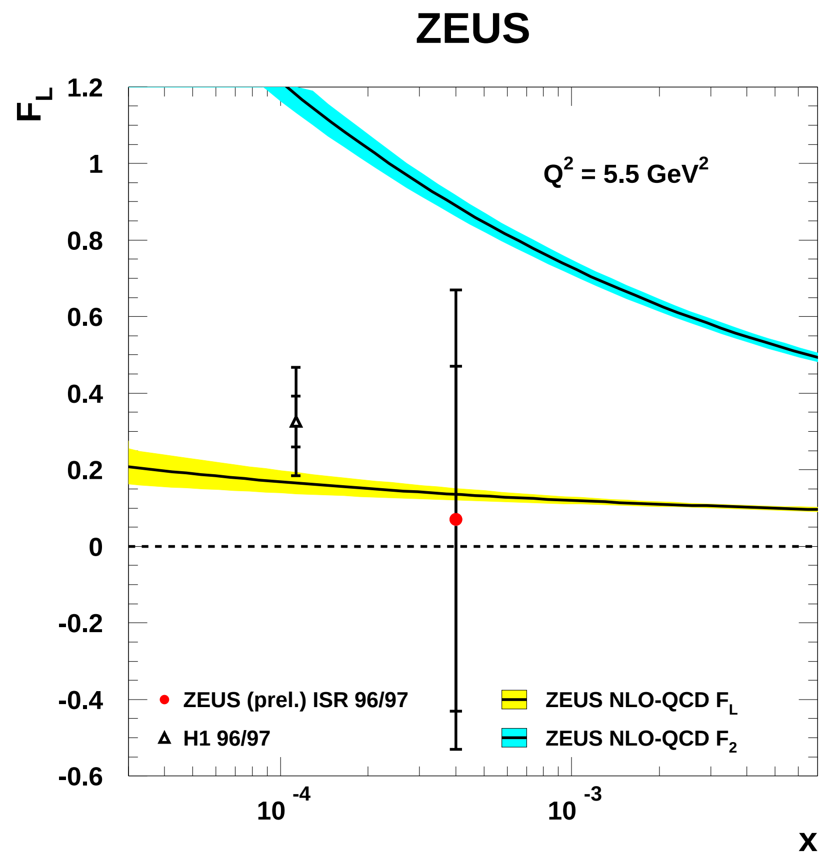
Measurement of F_L

extract F_L from Initial State QED radiation



Emission of ISR γ ☛ reduction of E_e

Emission of ISR γ ☛ reduction of $\sqrt{s_{\gamma p}}$



F_L small, agrees with NLO DGLAP prediction at $Q^2 > 1$ GeV^2 !!!

Energy dependence of $\sigma^{\gamma^* p}$

energy dependence of $\boldsymbol{\sigma_{tot}}$

$p\bar{p}$: $\boldsymbol{\sigma_{tot} \sim s^{0.1}}$

γp: $\boldsymbol{\sigma_{tot} \sim (W^2_{\gamma p})^{0.1}}$???

$\gamma^* p$: $\boldsymbol{\sigma_{tot} \sim (W^2_{\gamma^* p})^{\lambda(Q^2)}}$

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

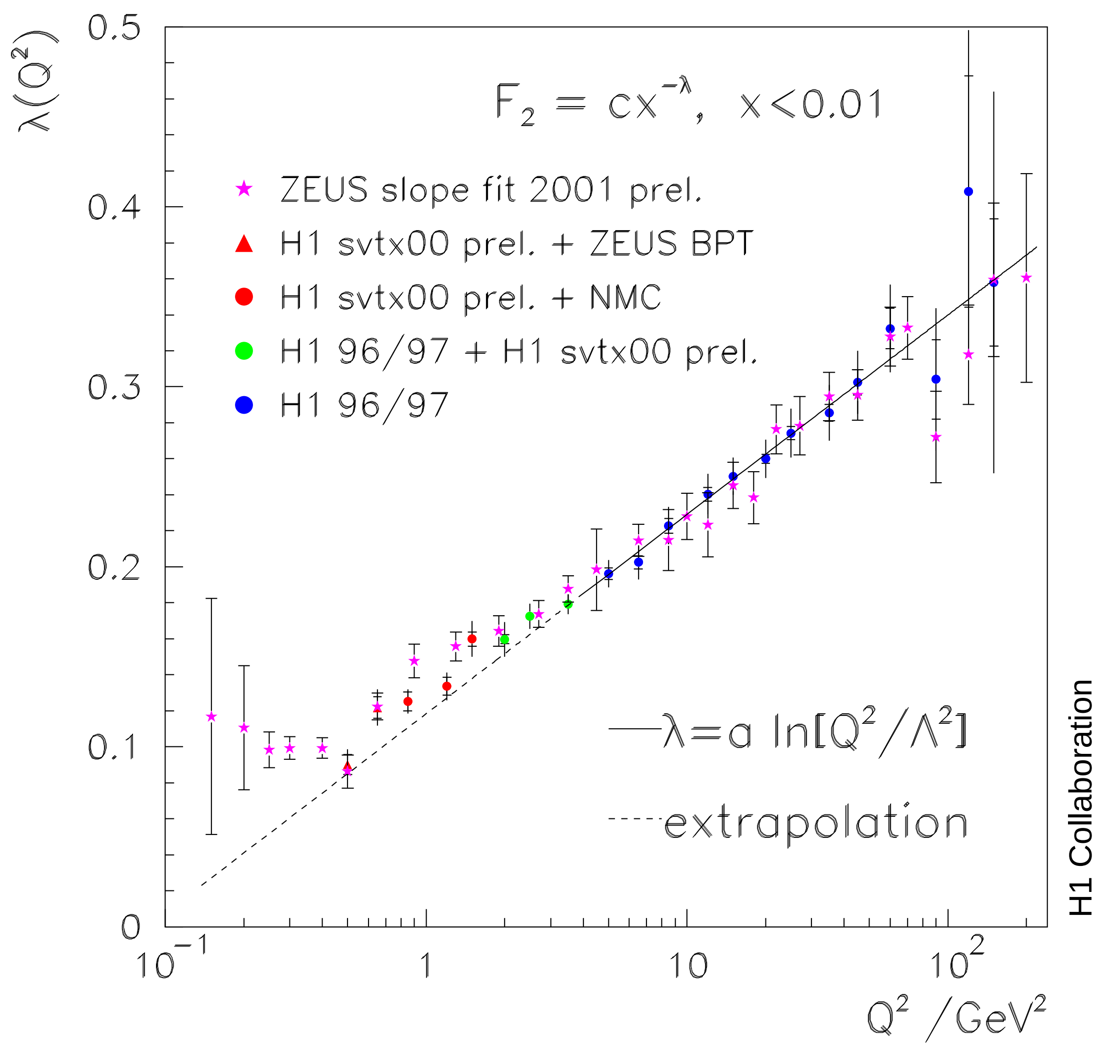
$x = \frac{Q^2}{ys} = \frac{Q^2}{W^2+Q^2}$

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

$\sigma^{\gamma^* p}(W, Q^2) \propto (W^2)^\lambda$

transition from hard to soft ....

at $\boldsymbol{Q^2 \sim 0.5}$ GeV^2 ???



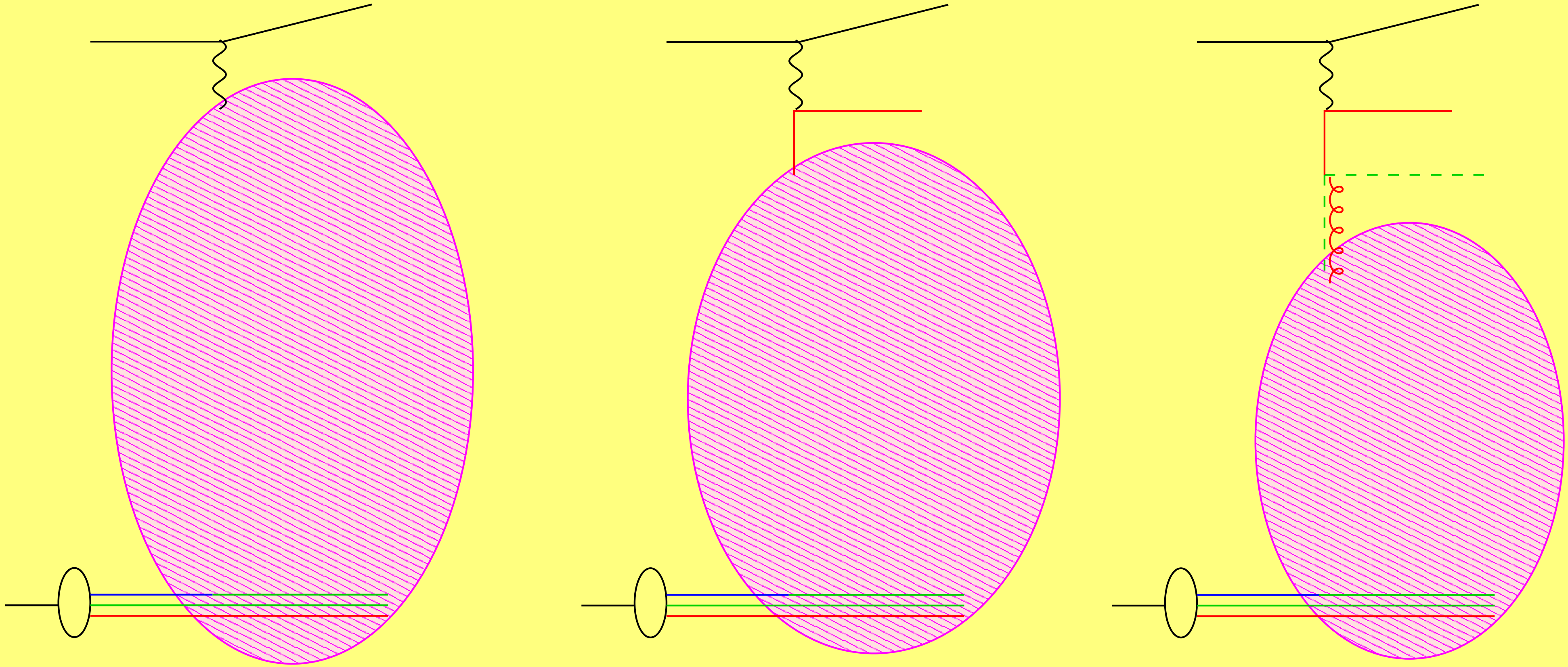
What did we learn from inclusive measurements ????

- F_2 measurements now at $\sim 2-3\%$ level
- (first) F_L measurements obtained (different methods ☛ agree !!!)
- DGLAP works, for $Q^2 > 1-2$ GeV^2
- collinear pdf extracted and successful at large Q^2
- DGLAP not applicable at $Q^2 < 1-2$ GeV^2:
  - pdf and F_L become negative ☛ unphysical....
- Success from k_t-factorisation !!!

  un-integrated pdf's work even for F_L !!!

To understand in detail parton cascade evolution look into hadronic final state .... !!!

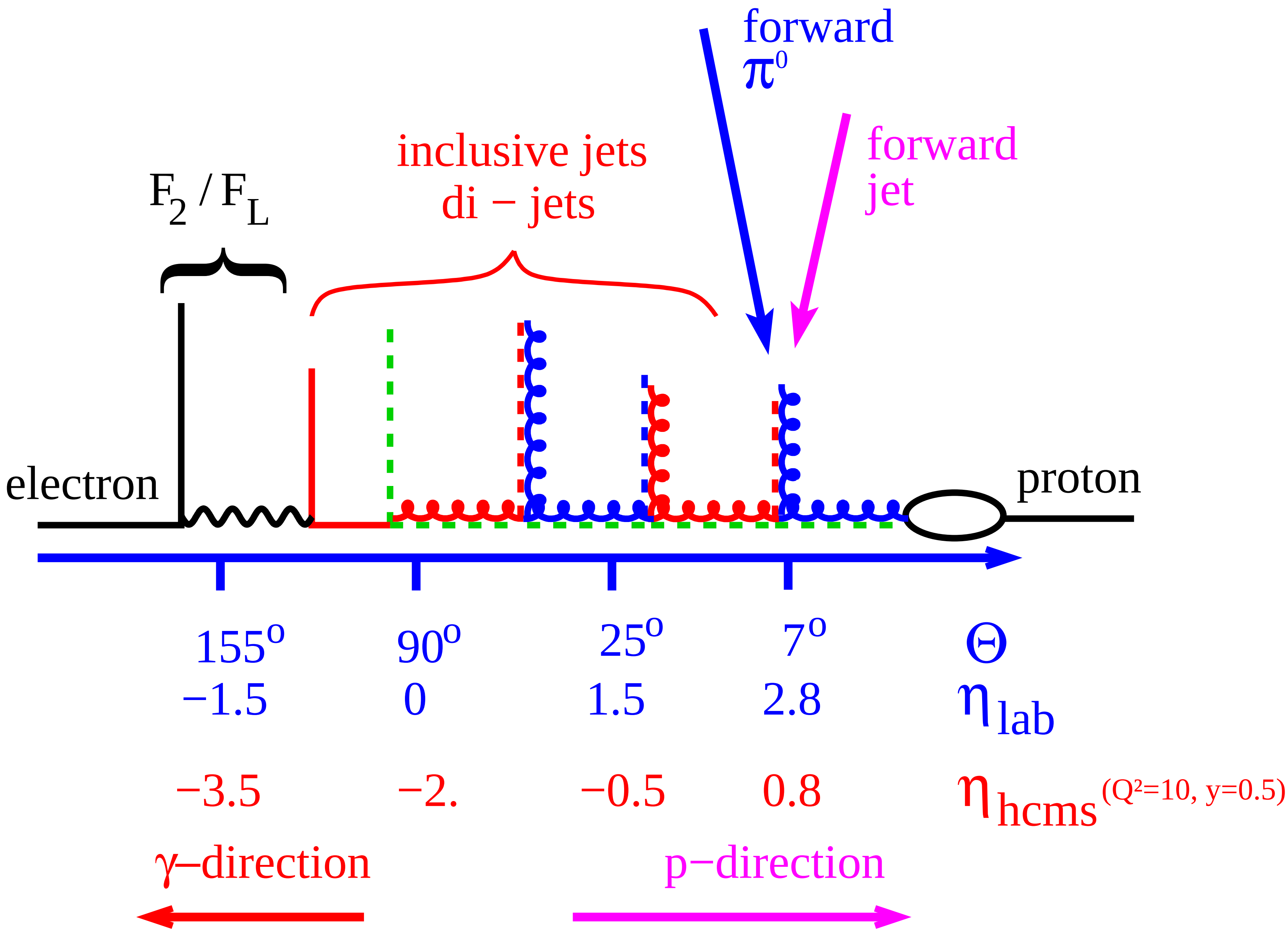
From total cross section (F_2) to Jets !



Total cross section F_2 **single inclusive jet**

LO - (QPM) process ($\mathcal{O}(\alpha_s^0)$) NLO (BGF) ($\mathcal{O}(\alpha_s)$)

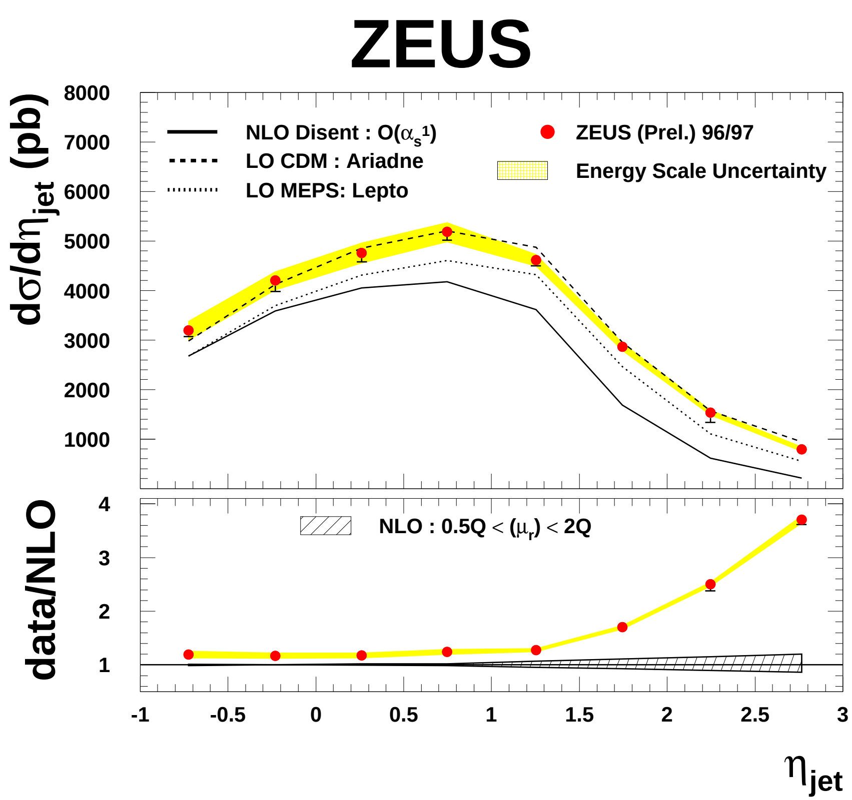
Angular coverage of experiments at HERA

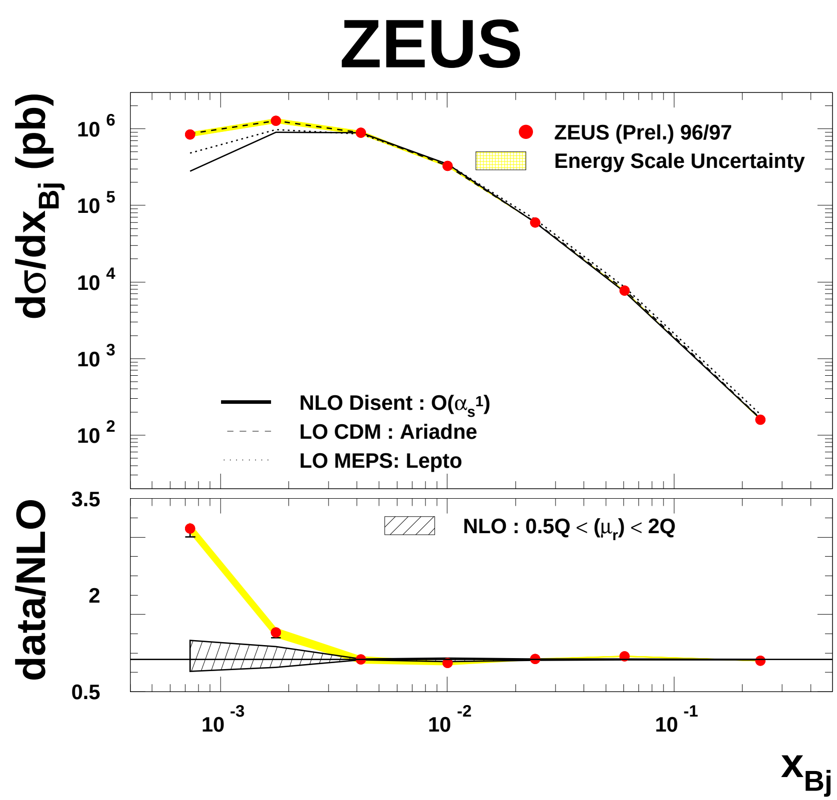


Single inclusive jets

DIS selection: $Q^2 > 25$ GeV^2 $\quad y > 0.04$

jets (long. k_t algo applied in lab): $E_{T,jets}^{lab} > 6$ GeV $\quad -1 < \eta_{jet}^{lab} < 3$

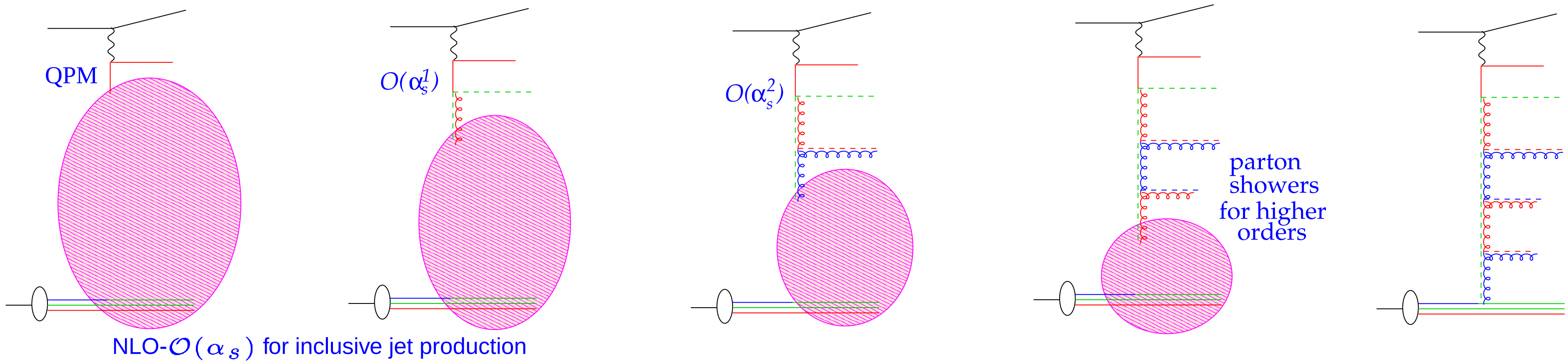


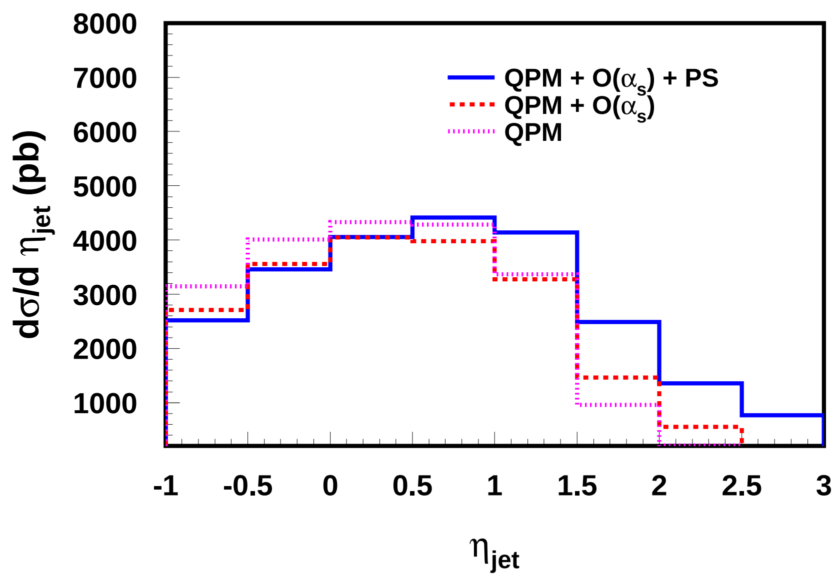


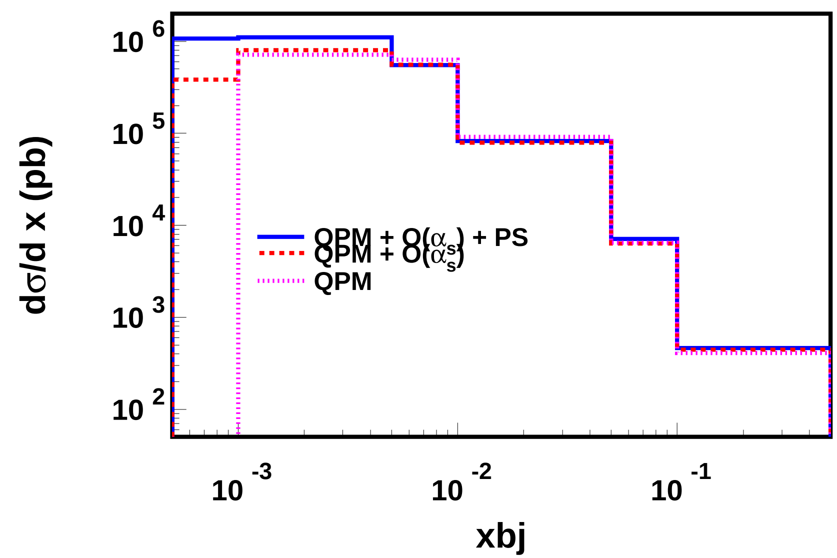
Oopps: NLO-$\mathcal{O}(\alpha_s)$ fails at small x ... PS Monte Carlos much better !!!

The failure of NLO in single inclusive jets

contributions to inclusive jet production





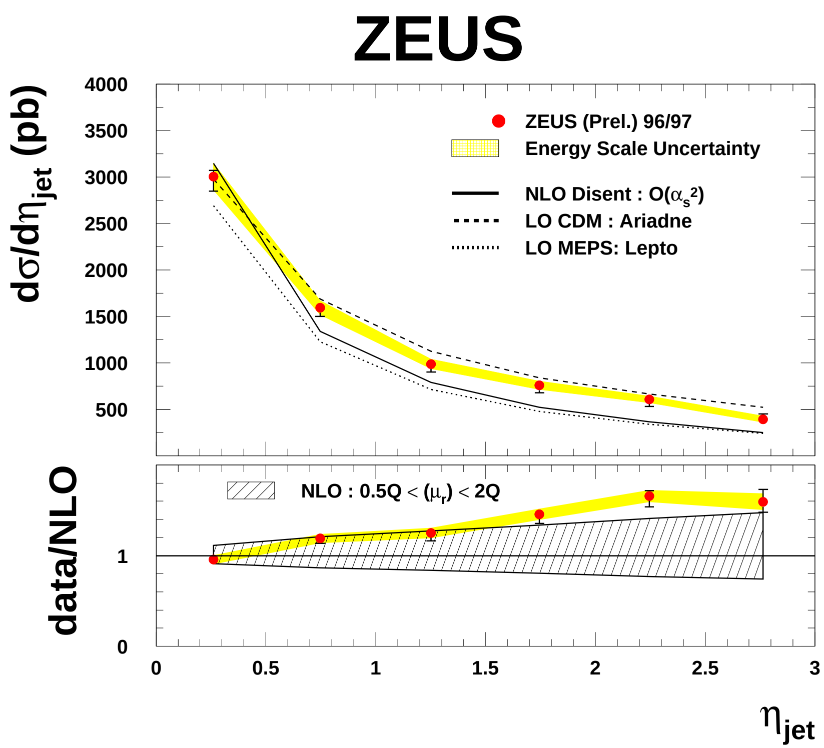


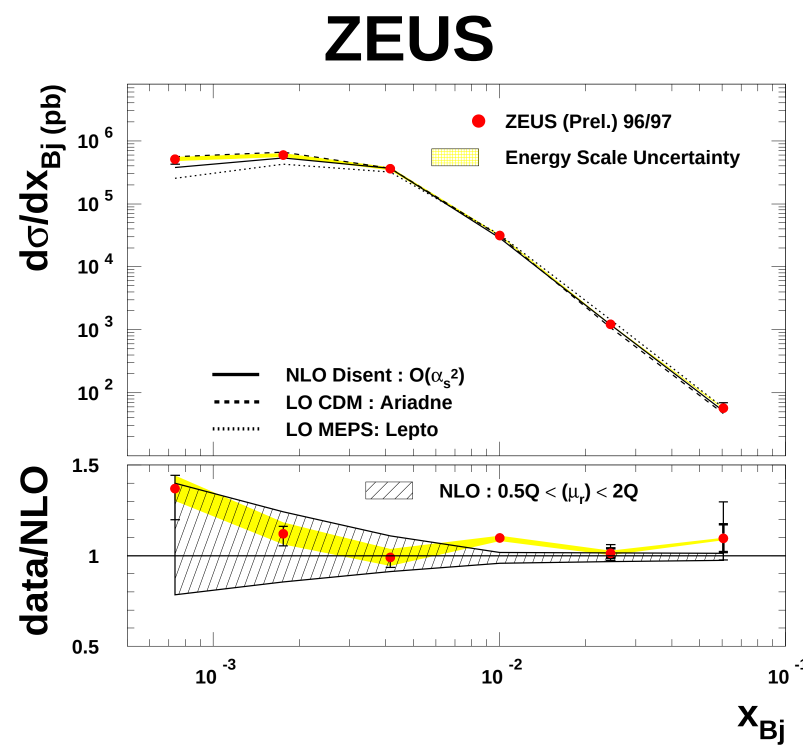
there is more DGLAP than $QPM + \mathcal{O}(\alpha_s)$ at small x ... !!!

Inclusive (di-) jets

DIS selection: $Q^2 > 25$ GeV^2 $\quad y > 0.04$

di-jets (long. k_t algo applied in lab): $E_{T,jets}^{lab} > 6$ GeV $\quad 0 < \eta_{jet}^{lab} < 3 \quad cos(\gamma_{had}) < 0$ (for di-jet topology)

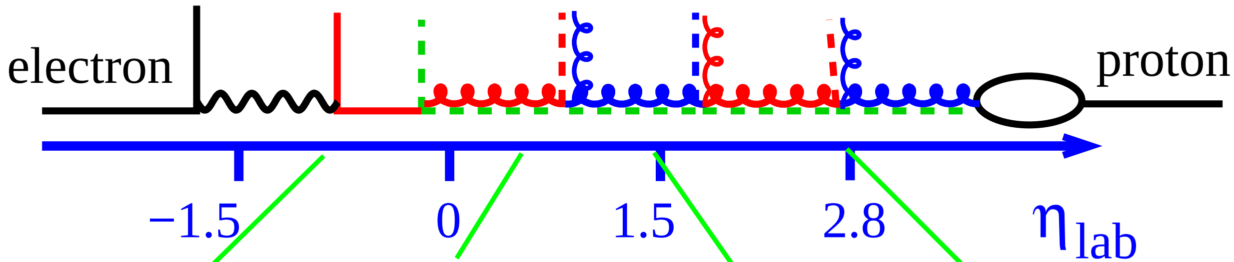




for di-jets: NLO-$\mathcal{O}(\alpha_s^2)$ ... agrees ...

within large scale uncertainty ... higher order corrections needed ...

Inclusive di-jets in Breit Frame



event selection:

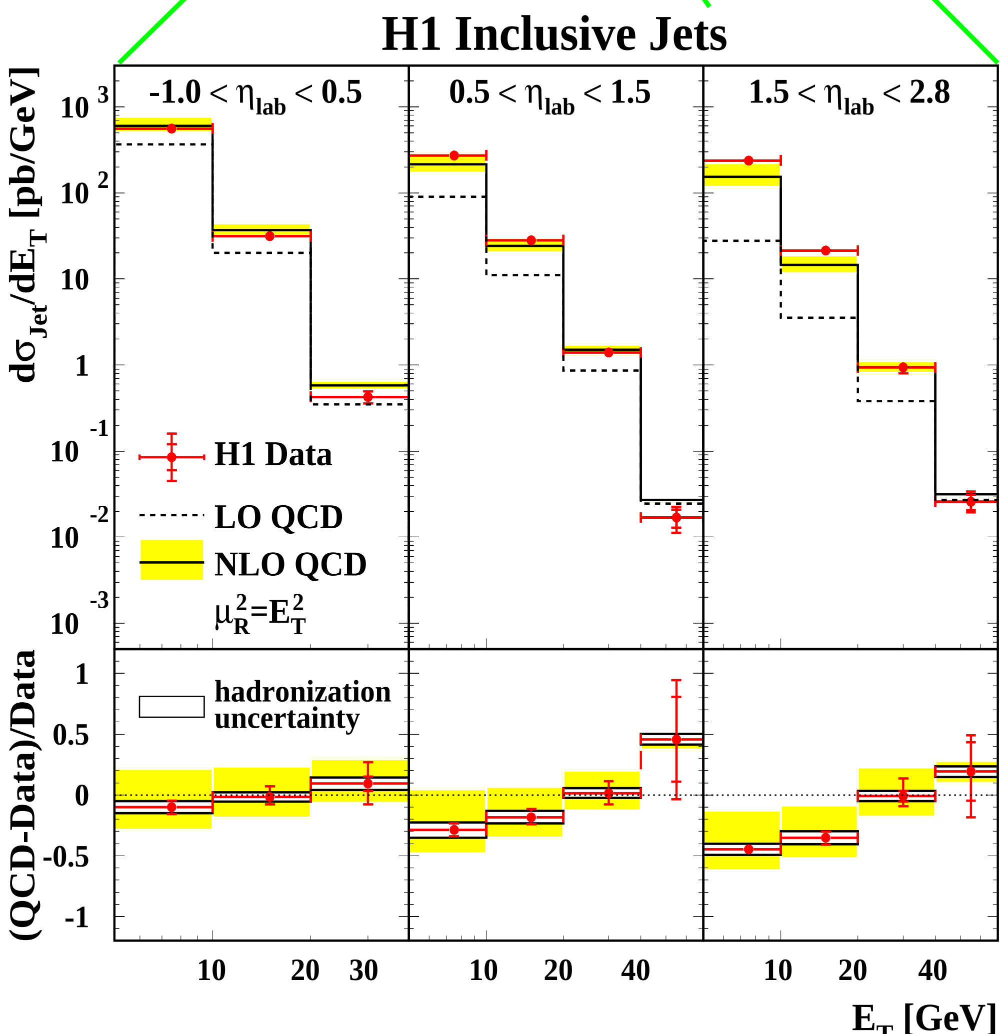
$5 < Q^2 < 100$ GeV^2

$0.2 < y < 0.6$

incl. k_t jet-algo in Breit-frame

$E_t > 5$ GeV

$-1 < \eta_{lab} < 2.8$



- central region ok
- difference to NLO in forward region at small E_t

☛ small x region

- need more parton emissions than given by $\mathcal{O}(\alpha_s^2)$ (NLO)

!!!

Multi parton dynamics at small x

- describe multi-parton emissions **only** in approximations
- put everything beyond $\mathcal{O}(\alpha_s^2)$ into **Evolution Equations**

BUT which use when ?

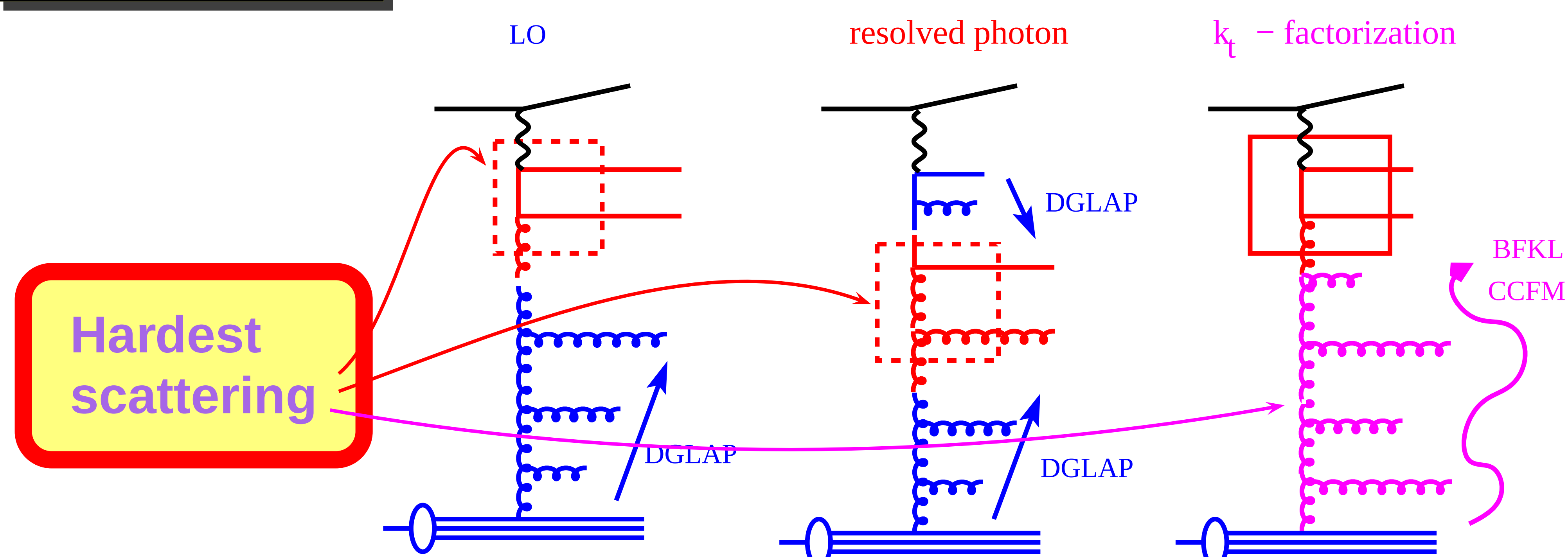
DGLAP

single ladder ordered in p_t

2 ladders each ordered in p_t

BFKL CCFM

ordered in energy/angle



Parton dynamics at small x: forward jets and forward π^0

DGLAP works fine in central region !

Investigate forward region

Anything new there ?

Observe deviations from DGLAP ?

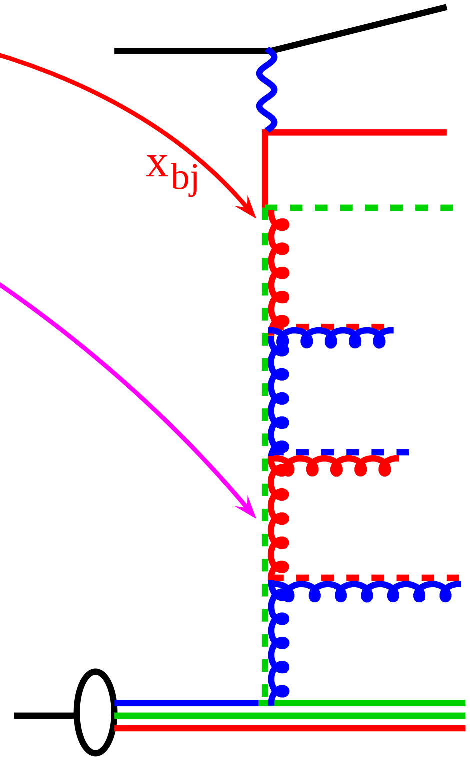
☛ evidence for BFKL ?

or

☛ CCFM ?

or

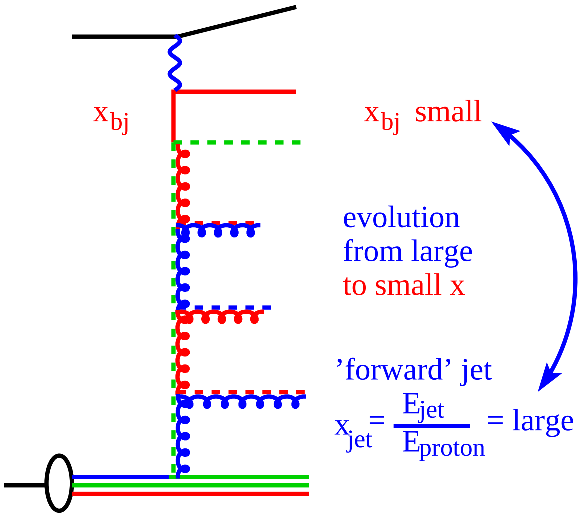
☛ no approximation is good ?

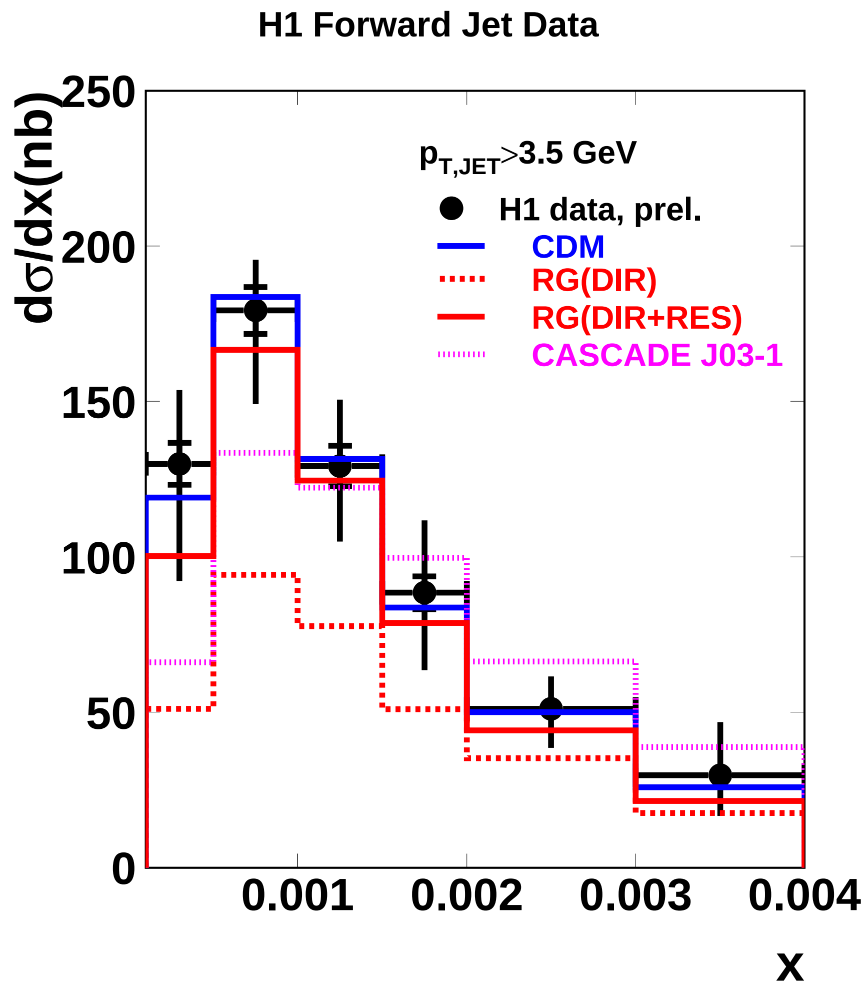


Mueller - Navelet jets in DIS: Jet (π^0) in p - direction with $p_t^2 \sim Q^2$, x_{jet} large, BUT small x_{bj}

☛ suppress DGLAP (Q^2) evolution, allow evolution in x (BFKL)

Parton dynamics at small x: Forward Jets





DIS : $5\ \text{GeV}^2 < Q^2 < 75\ \text{GeV}^2$

forward jet (incl. k_t algorithm)

$7^o < \theta_{jet} < 20^o$

$x_{jet} > 0.035$

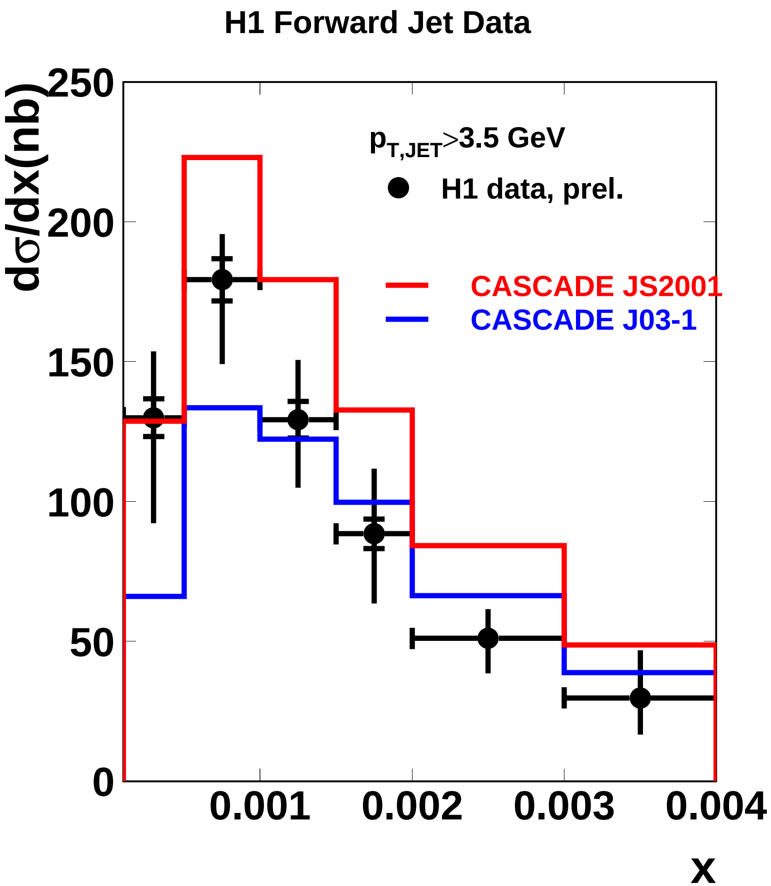
$0.5 < \frac{p_t^2\ _{jet}}{Q^2} < 2$

DGLAP too small, need **resolved virtual photons (DIR+RES)**

or **Color Dipole Model (CDM)**

or **k_t factorisation with CCFM (CASCADE)**

Forward Jets
sensitive to un-integrated gluon density ?



$\sigma(ep \to e'q\bar{q}) =$

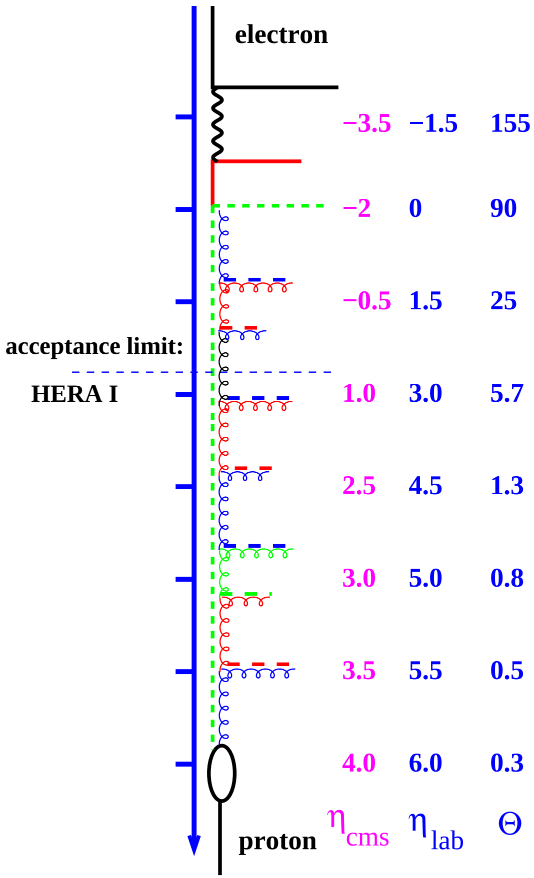
$\int \frac{dy}{y} d^2Q \frac{dx_g}{x_g} \int d^2k_t \hat{\sigma}(\hat{s}, k_t, Q) x_g \mathcal{A}(x_g, k_t, \bar{q})$

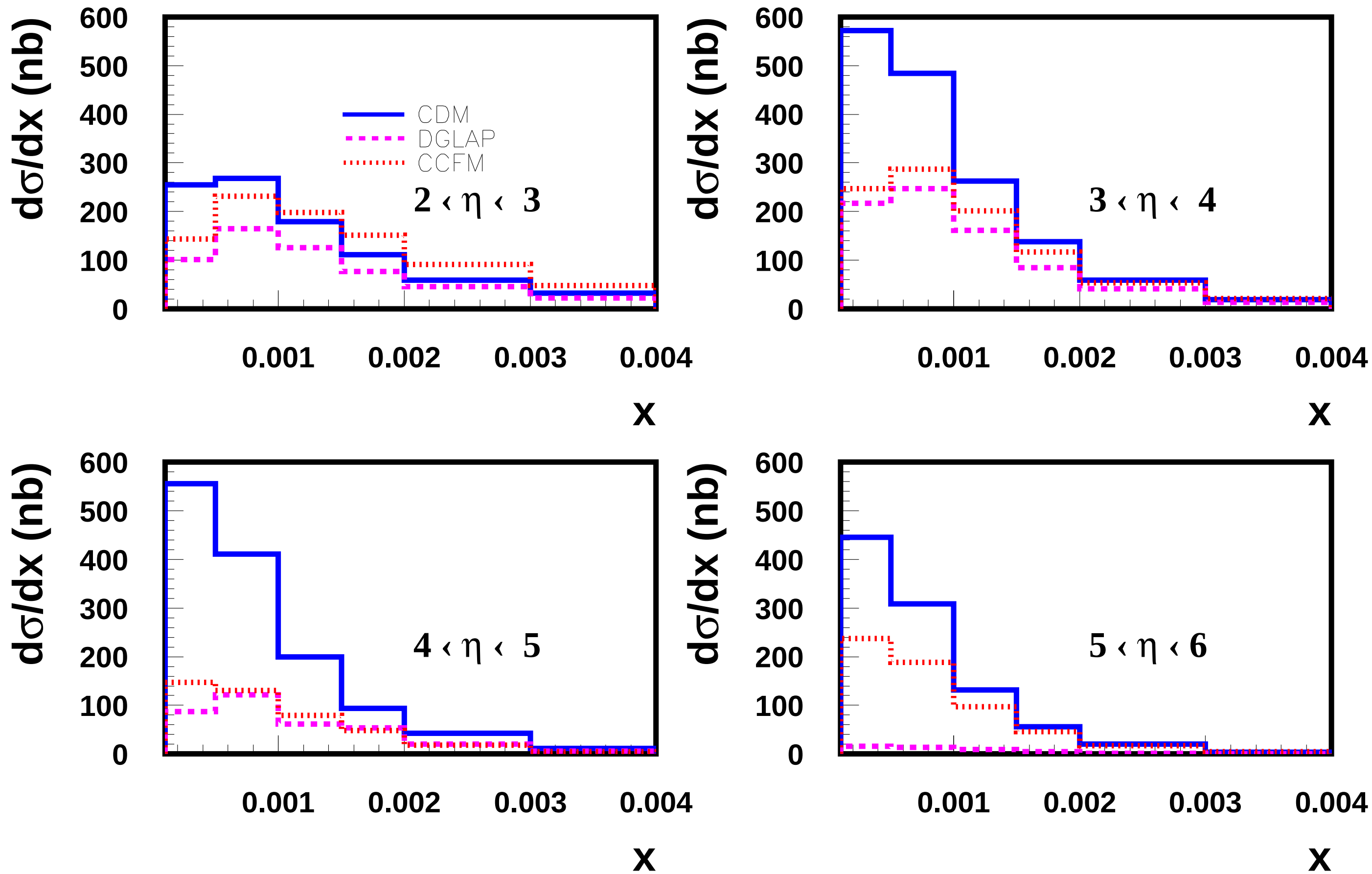
with $\int d^2k_t x_g \mathcal{A}(x_g, k_t, \bar{q}) \simeq x_g G(x_g, Q^2)$

- CCFM un-integrated gluon fitted to H1/ZEUS F_2 data
- JS2001 CCFM
  allow soft gluons $k_t > 0.2$ GeV
- J03-1 CCFM
  only hard gluons $k_t > 1.4$ GeV
  full P_{gg} splitting function
  (including non - singular terms)

forward jets important for constraining un-integrated gluon densities !!!

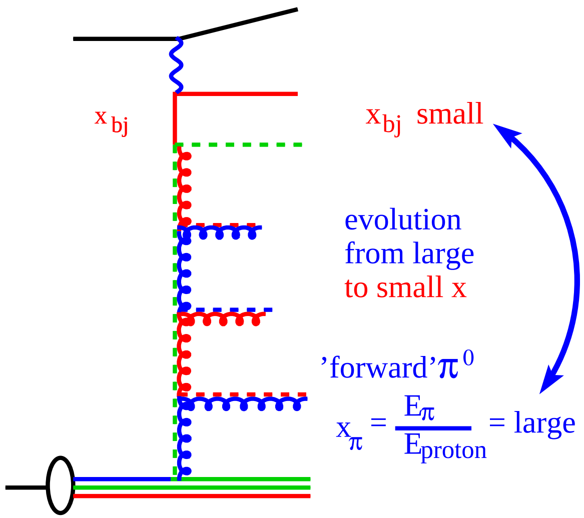
Forward Jets - at smaller angles





forward jets important for understanding parton radiation pattern in QCD !!!

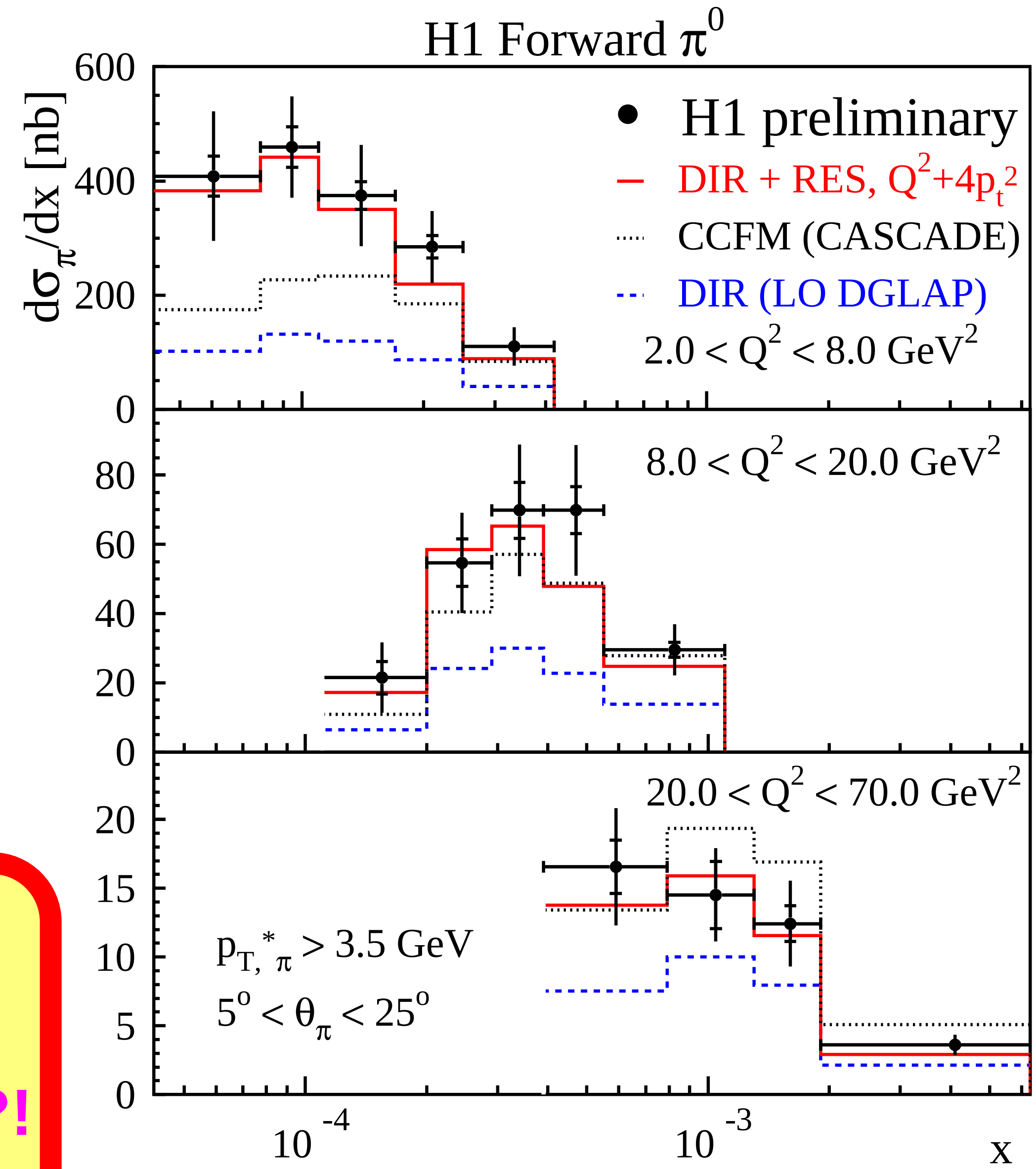
Parton dynamics at small x: Forward π^0



DIS : forward π^0 (instead of jet)

$5^o < \theta_\pi < 25^o$

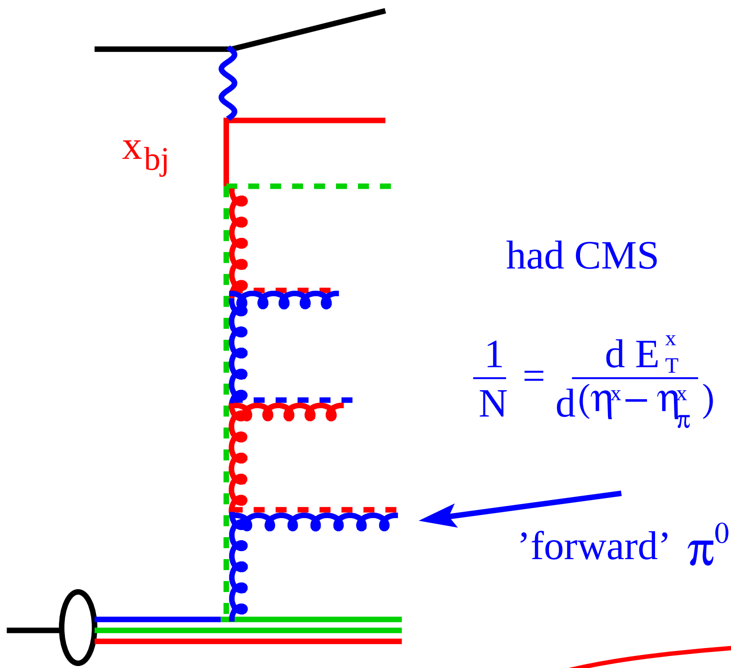
$x_\pi > 0.01$

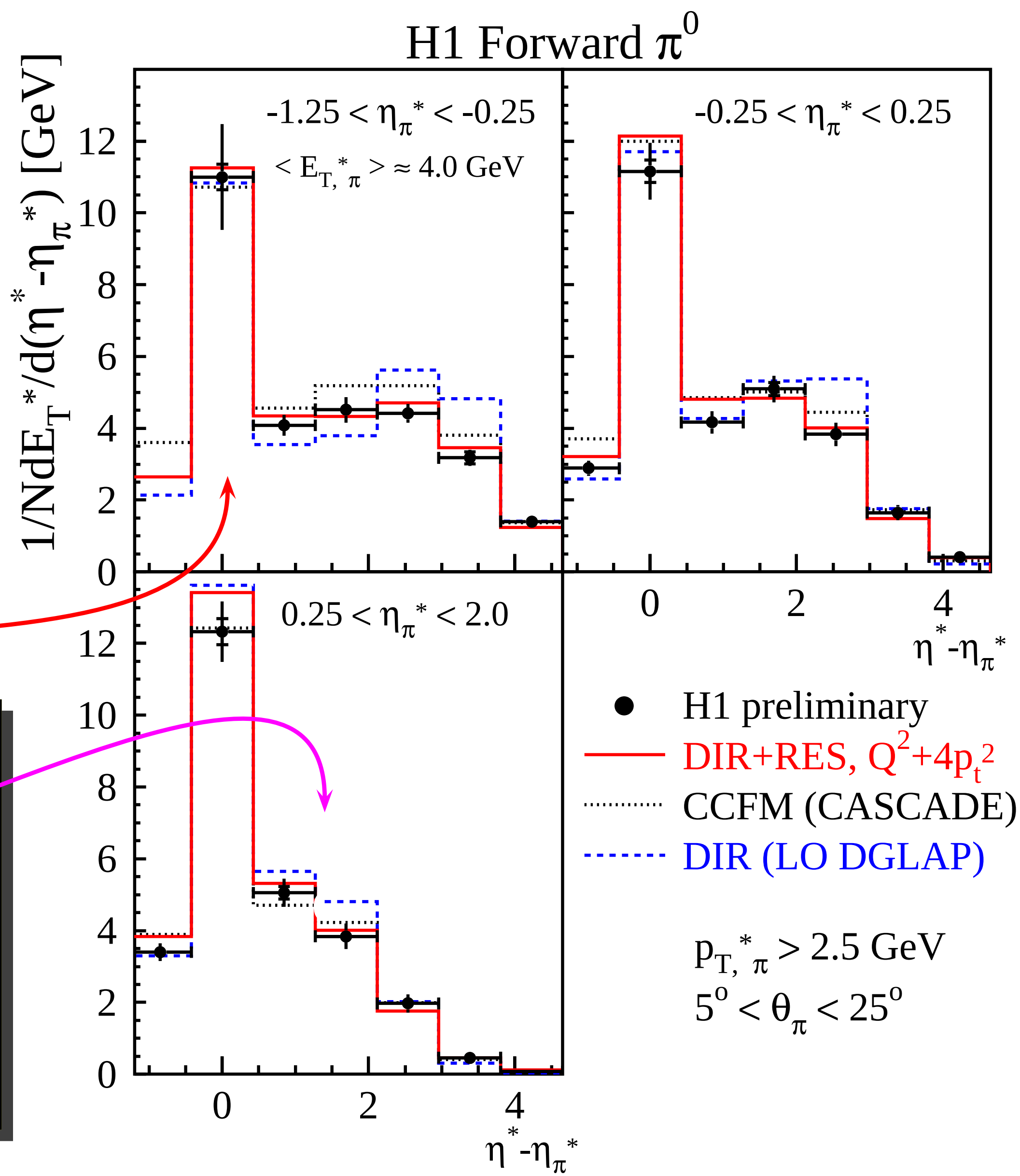


DGLAP too small, need:

- **resolved virtual photons ?!?**
- **CCFM too small at small x !?!**
- **WHY ?!?**

Parton dynamics at small x: Forward π^0 II





in hadronic CMS

- π^0 close to proton
- π^0 towards photon
- E_T-flow around π: transverse momentum compensation along ladder

HERA 2

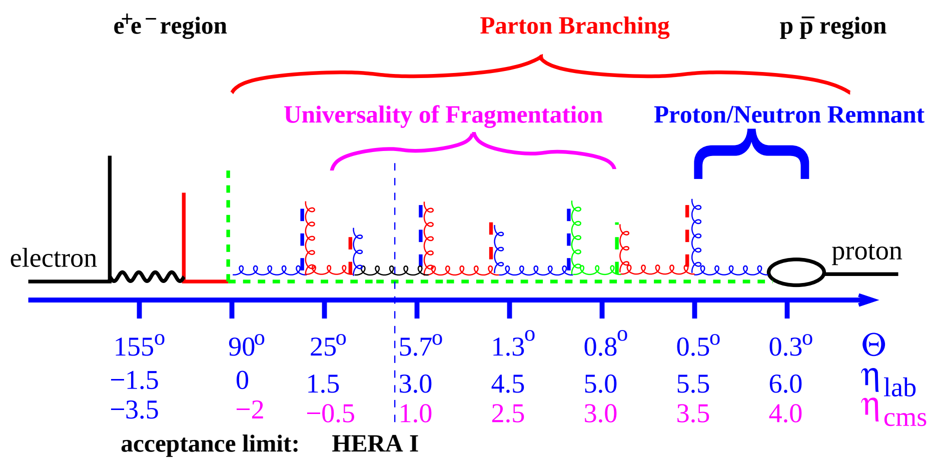
- collect 1fm^{-1} until 2006/2007
- measure high Q^2 region precisely (high statistics program)
  polarised charged current
  electroweak sector $xF_3(x, Q^2)$
  heavy quarks $F_2^{c\bar{c}}(x, Q^2)$, $F_2^{b\bar{b}}(x, Q^2)$ with extended x range
  heavy quarks cross sections
- measure high E_T jets precisely
- diffraction - new proton spectrometer in H1 (talk by X. Janssen)
  $F_2^{D(4)}$, diffractive jets, diffractive charm
  vector-mesons
- machine plans
  restart July, Lumi runs end Sept.
  goal: 20 pb^{-1} till end 2003

New interesting, precise measurements from HERA to come !!!

HERA 3

- Interest to continue running of HERA after 2006/2007
- HERA program with protons/deuterons, measure $\bar{d} - \bar{u}$ & large x pdf's precisely
- two groups expressed interest: H1 and a new experiment
- 70 institutes, 200 individuals, and large theory support
- Special emphasis on small x, small Q^2 measurements
- extend angular coverage down to small angles for electron and proton region

- transition region
- F_2, F_L



- Collective phenomena:
- Parton evolution BFKL/CCFM/DGLAP (dressed gluons)
- Gluon - Trunks, Multi-Gluon
- Diffraction, Saturation

THE challenge is QCD !!!

Conclusions and Summary

- F_2 - total cross section, $2-3\,\%$ precision reached:
  - longitudinal cross section measured, 1st time in transition region !
- ✔ standard DGLAP plus fixed NLO matrix elements at $Q^2 > 1$ GeV^2 ok

  BUT more than DGLAP at small Q^2 needed
- high precision measurements of jets from central to forward region performed

  either NLO predictions have very large scale uncertainties ???

  or measurements much larger than standard DGLAP + NLO
  - need to go beyond DGLAP, BFKL ... CCFM ???
- Forward jets/particles ☞ sensitive to un-integrated gluons

  ☞ measure it ...
- Future:
  - more data still to come ... HERA 2, HERA 3 !!!!
  - data more precise than theory error (scale uncertainty)
  - higher order calcs needed ...

Understanding QCD at small x is the challenge !!!

Di - jets in $\gamma^* p$-CMS

DIS selection:

$5 < Q^2 < 100$ GeV^2

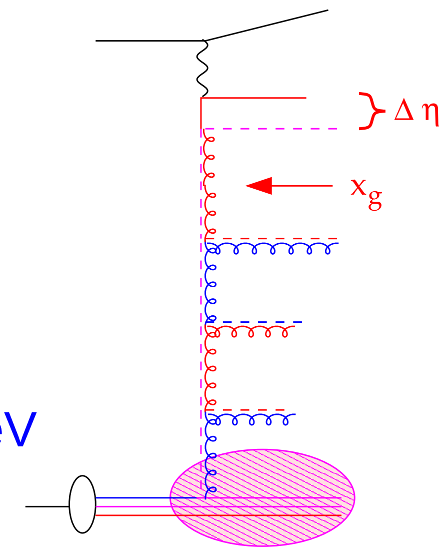
$10^{-4} < x < 10^{-2}$

$0.1 < y < 0.7$

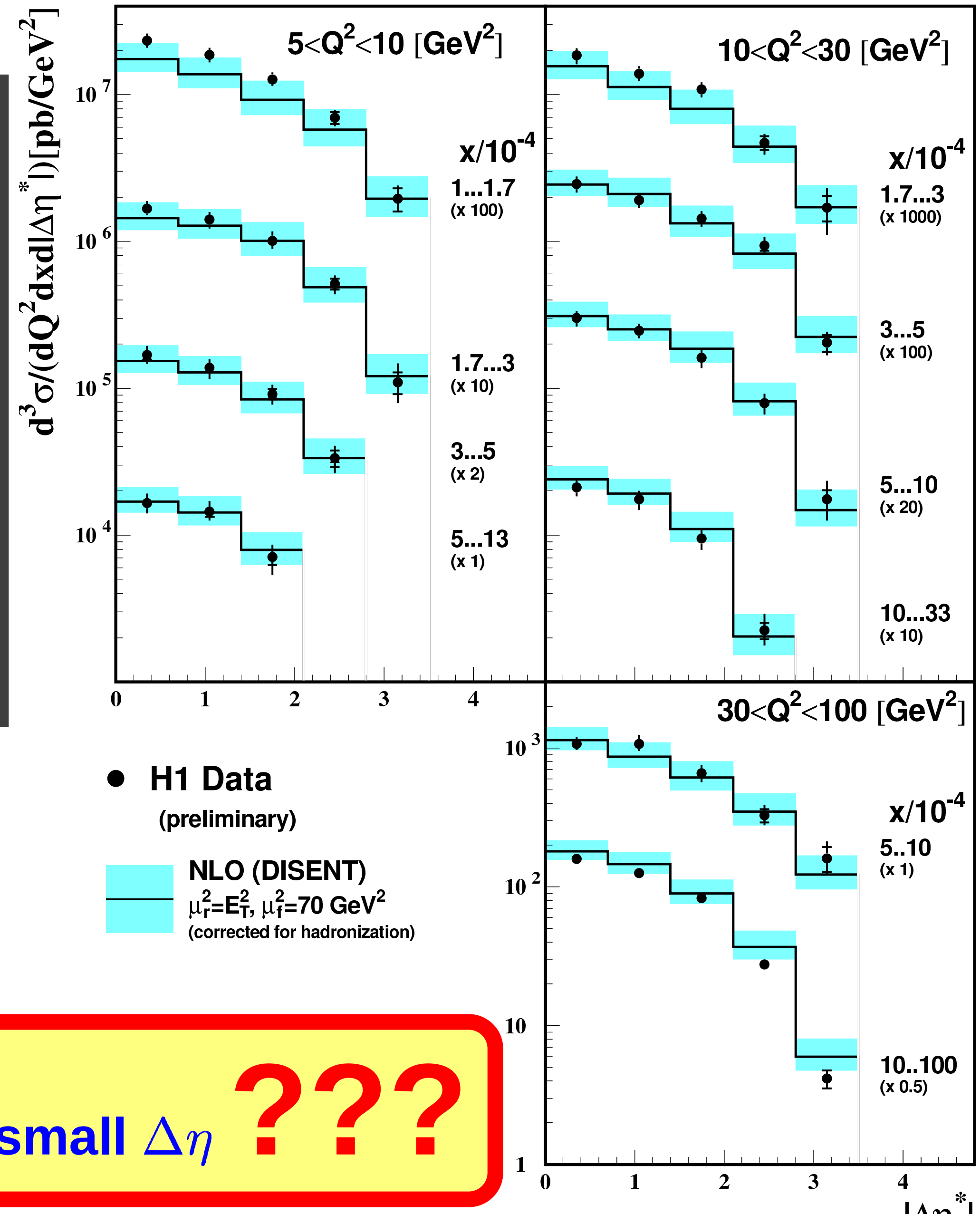
di-jets

$E^{cms}_{T,jets1,2} > 5(7)$ GeV

$-1 < \eta^{lab}_{jets} < 2.5$

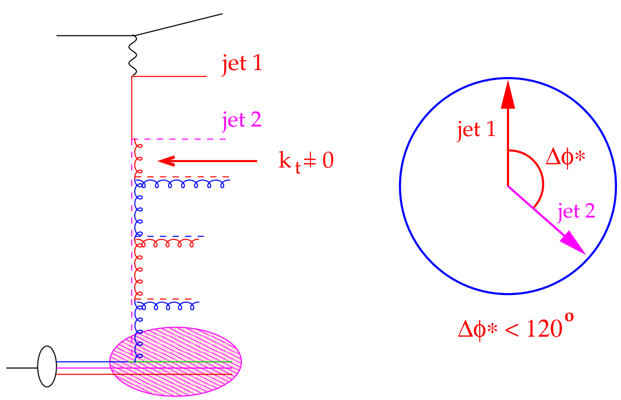


$\Delta\eta$ small ☛ small x_g
$\Delta\eta$ large ☛ large x_g



NLO ... agrees ...
within large scale uncertainty, also at small $\Delta\eta$???

Di - jets in DIS: more about parton cascade !

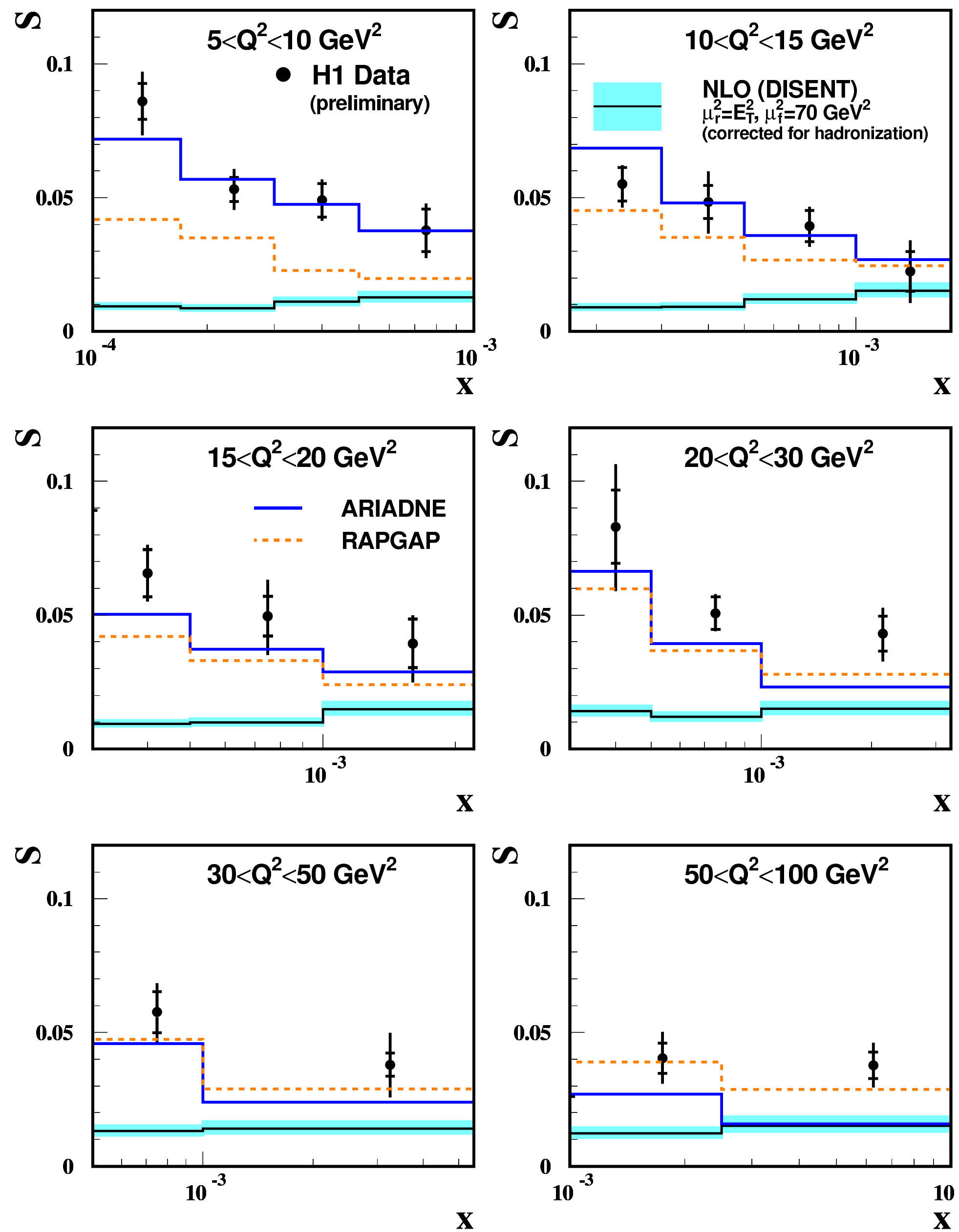


- Measurement of $\frac{d\sigma}{d\Delta\Phi}$ exp. difficult
- Measure:

$$S(x, Q^2, \Delta\Phi) = \frac{\int_0^{120^o} d\sigma d\Phi}{\int_0^{180^o} d\sigma d\Phi}$$

☛ sensitive to finite k_t ...

☛ un-integrated gluon density ...



Data higher than NLO-$\mathcal{O}(\alpha_s^2)$

parton shower + $\mathcal{O}(\alpha_s)$ better

CDM (non-ordered) perfect

new dynamics ???