HERA results and implications for LHC physics

on behalf of the H1 and ZEUS collaborations

H. Jung, DESY, FRG

LHC days in Split, Croatia, 5-9 Oct 2004

HERA is a machine to study QCD !
HERA experiments for precision measurements !!

- Parton Density Functions
  Inclusive cross section and structure function: F_2 and the gluon
- Parton radiation
  Jet production - from central to forward (proton) direction
- Diffraction
  factorization and breaking
- HERA and the LHC
- Conclusion

HERA to Split the Proton and implications for LHC physics

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  factorization and breaking - link to multiple scatterings at LHC
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The HERA collider and experiments

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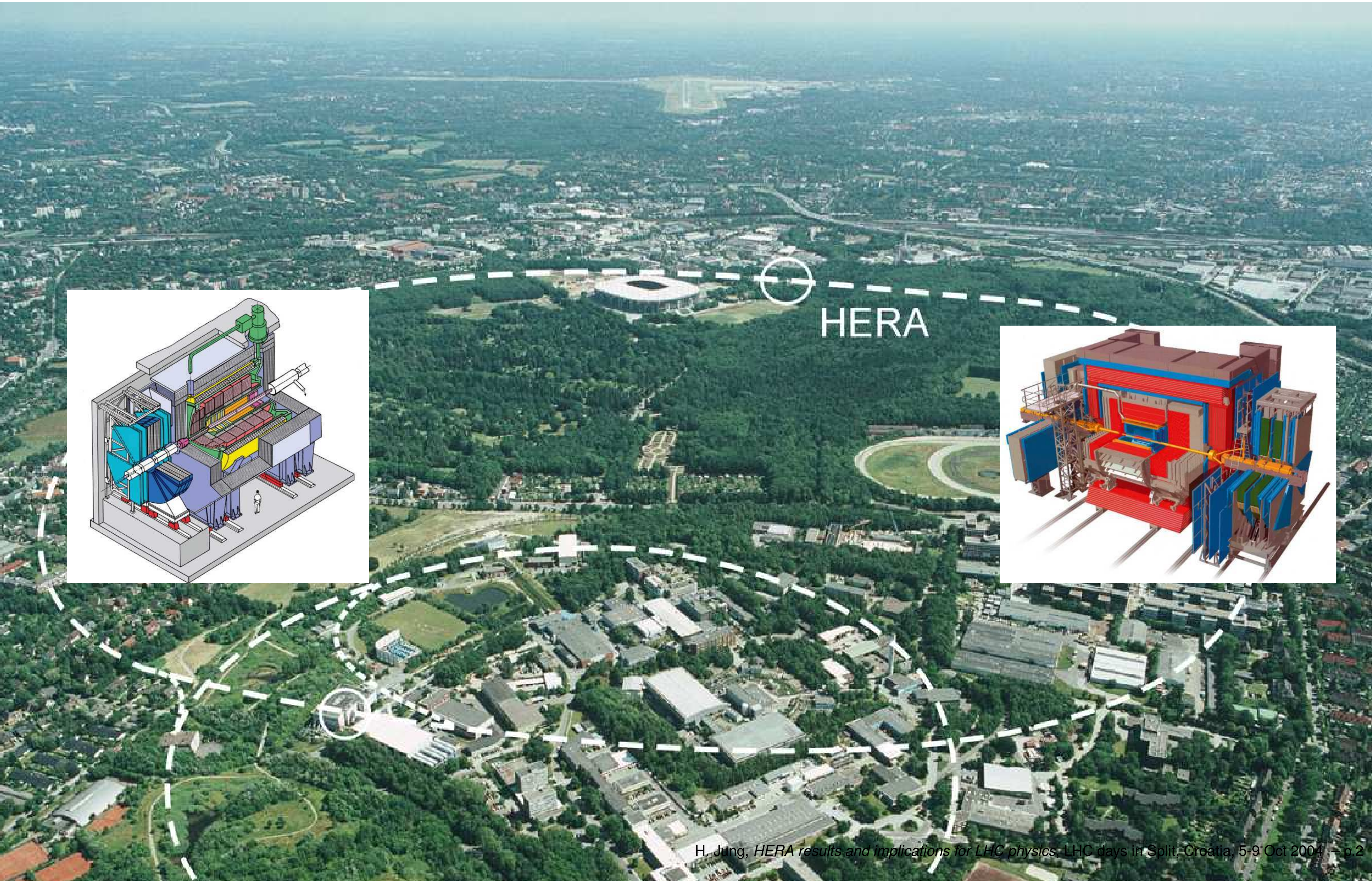
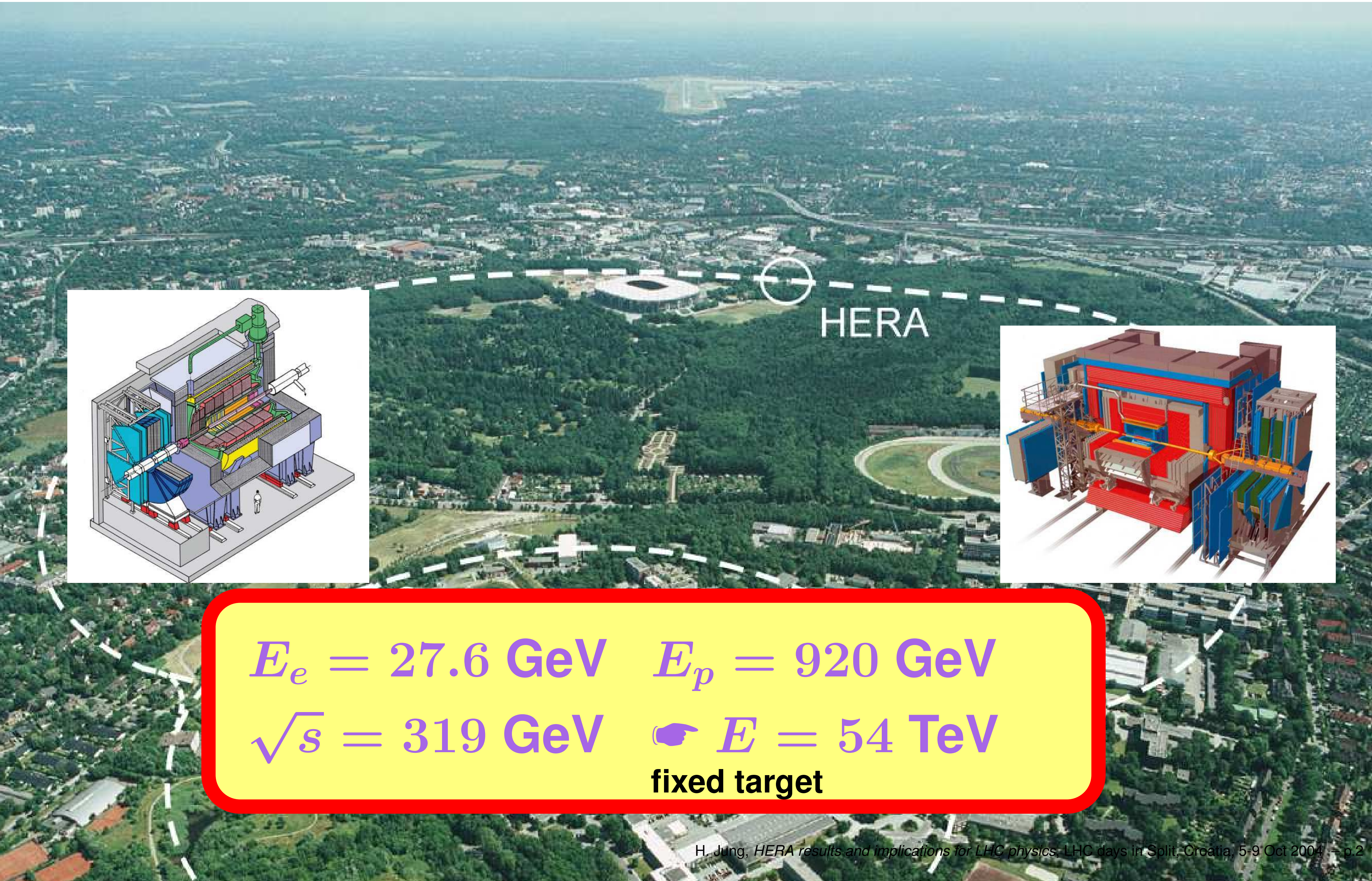


The HERA collider and experiments

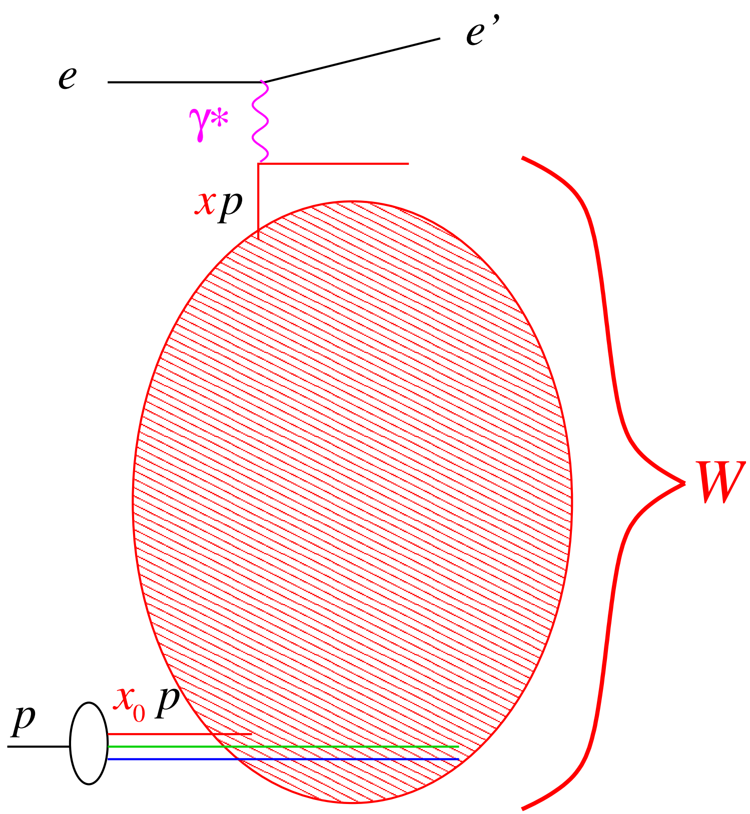


$E_e = 27.6$ **GeV** $E_p = 920$ **GeV**

$\sqrt{s} = 319$ **GeV** ☛ $E = 54$ **TeV**

fixed target

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

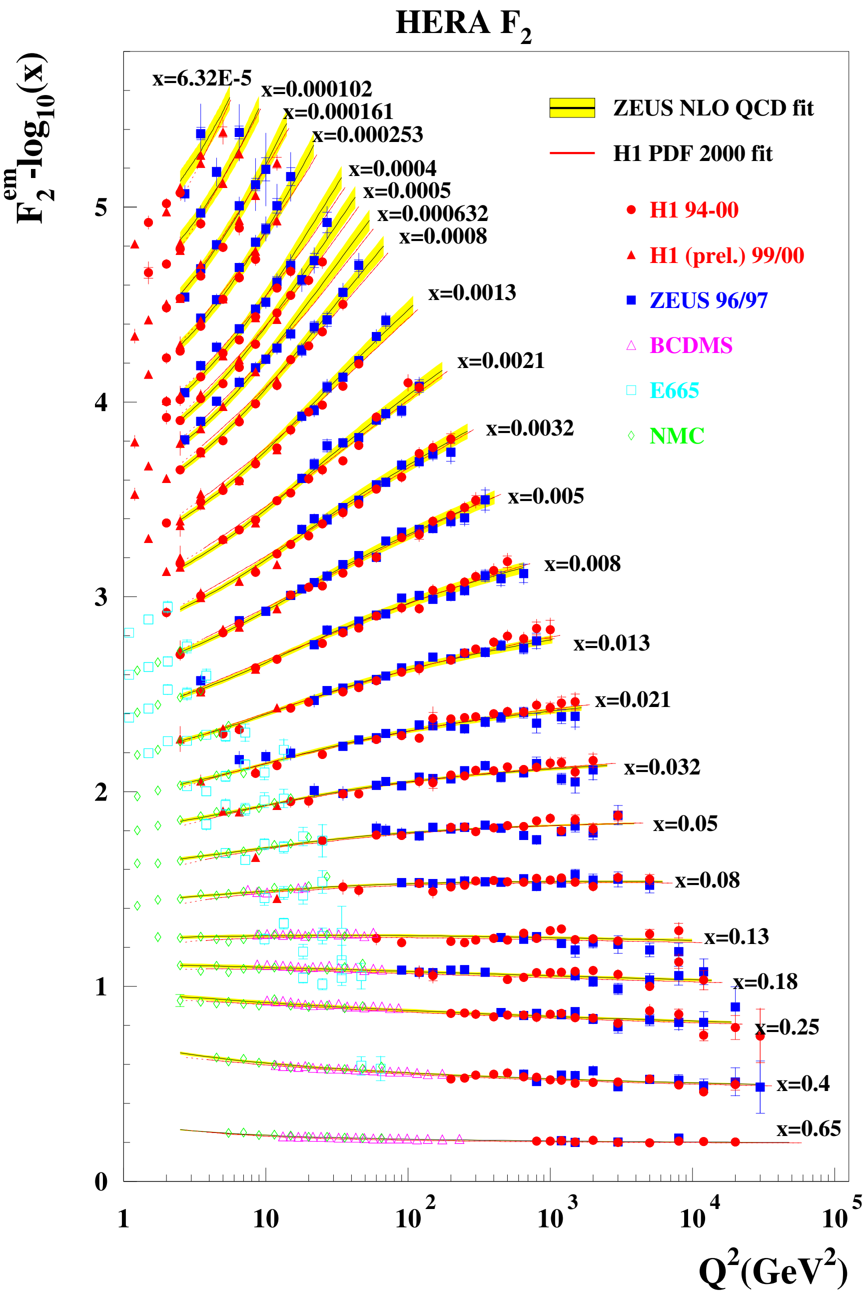
$$\sigma^{\gamma^* p}(W, Q^2) = \frac{4\pi\alpha}{Q^2} F_2(x, Q^2)$$

and

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

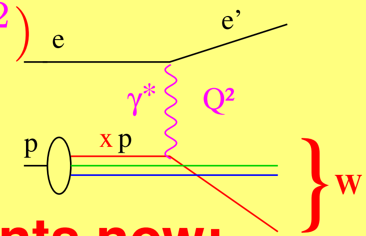
- Q^2 dependence of $F_2(x, Q^2)$ predicted by QCD
- test theory over large range in Q^2

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:

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

$1 < Q^2 < 30000$ **GeV**^{2}

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

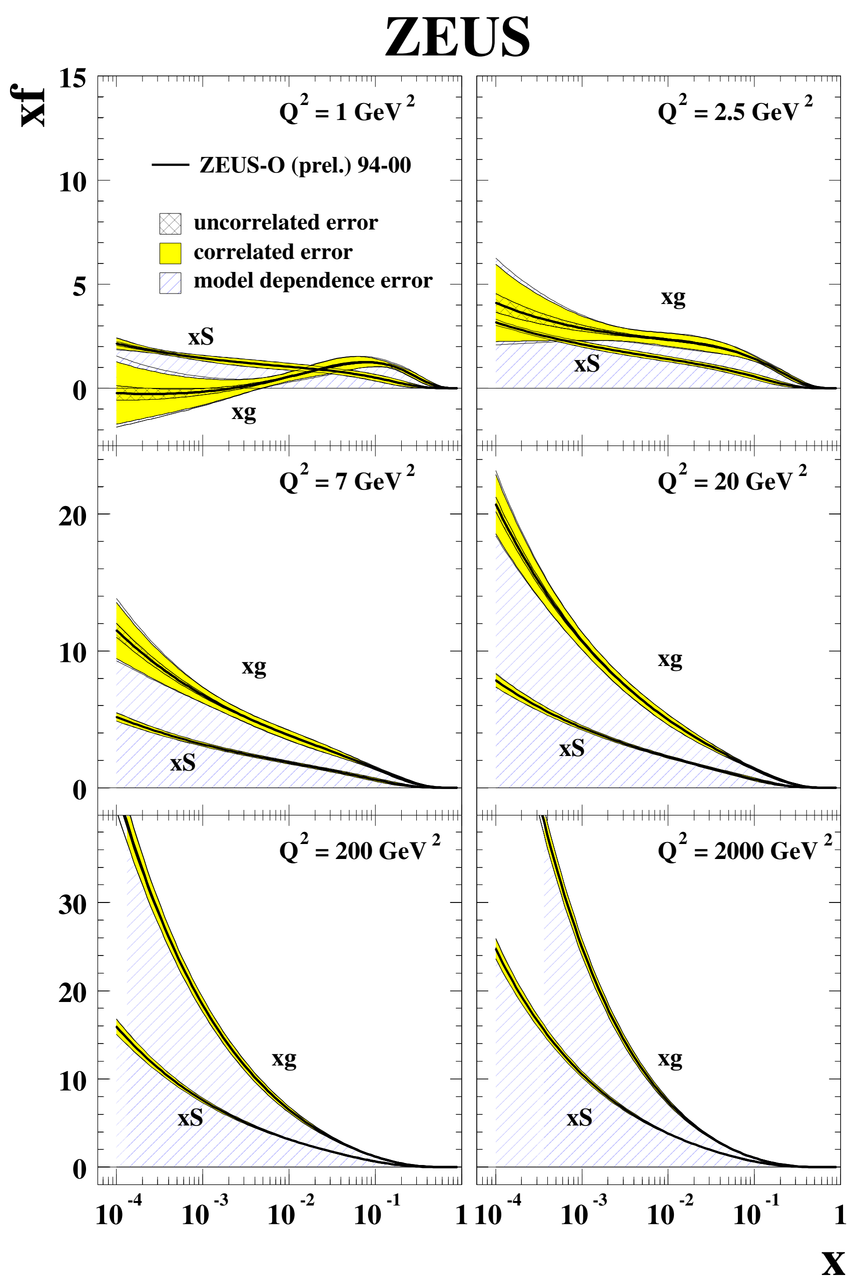
Similar pdf sets by MRST, CTEQ etc

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

BUT what about the gluon ???

direct measurement with F_L ???

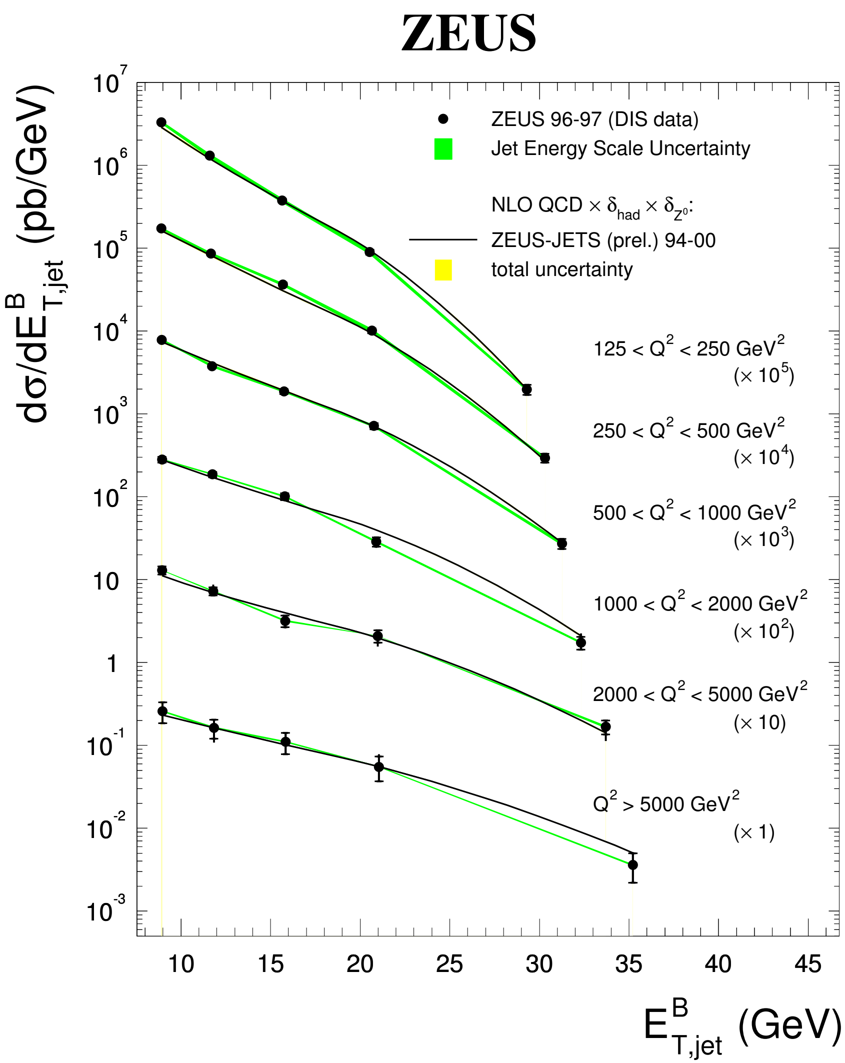
NLO analysis of F_2 (ZEUS)

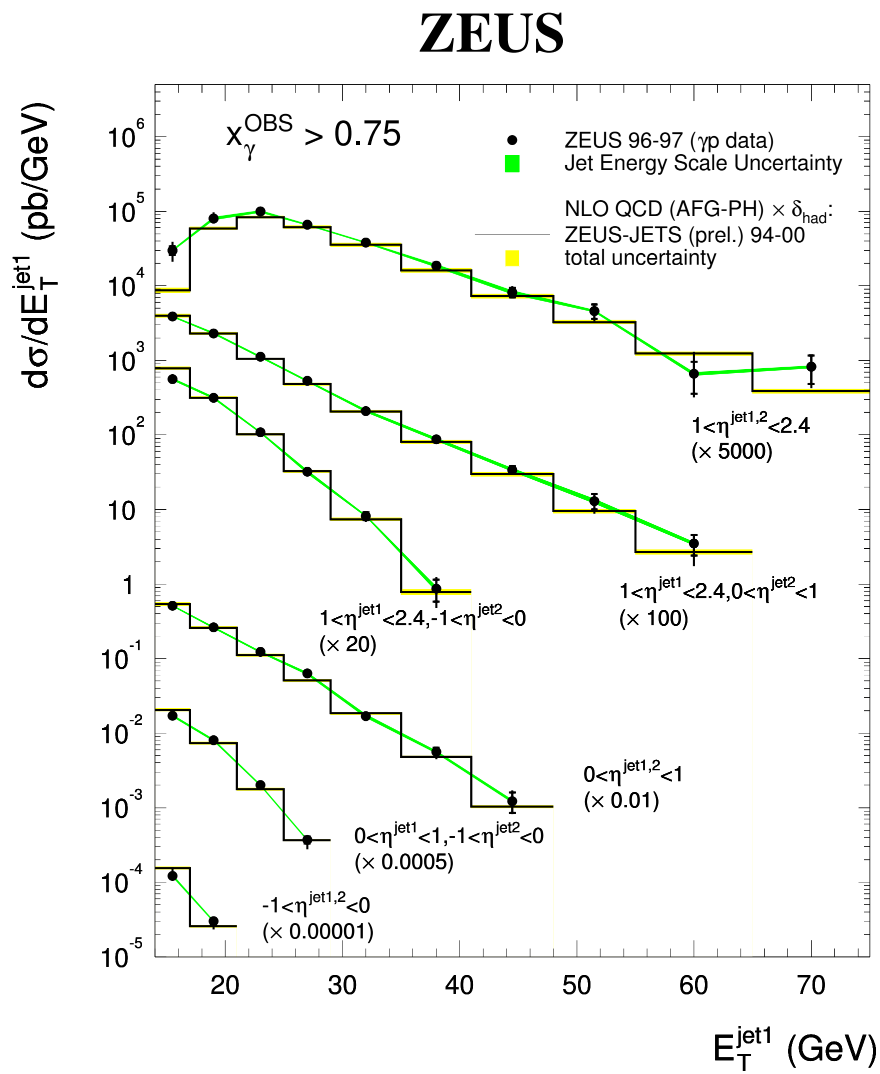


NLO DGLAP fit to F_2
$2.5 < Q^2 < 30000$ GeV^2
$6.3\,10^{-5} < x < 0.65$
pdf extracted...

- large uncertainty of gluon at $x \gtrsim 0.1$
- large uncertainty of gluon at small Q^2 and small x
- DGLAP not applicable for $Q^2 < 1 - 2$ GeV ???
- constrain gluon at large x with jet data
- what about small x ?

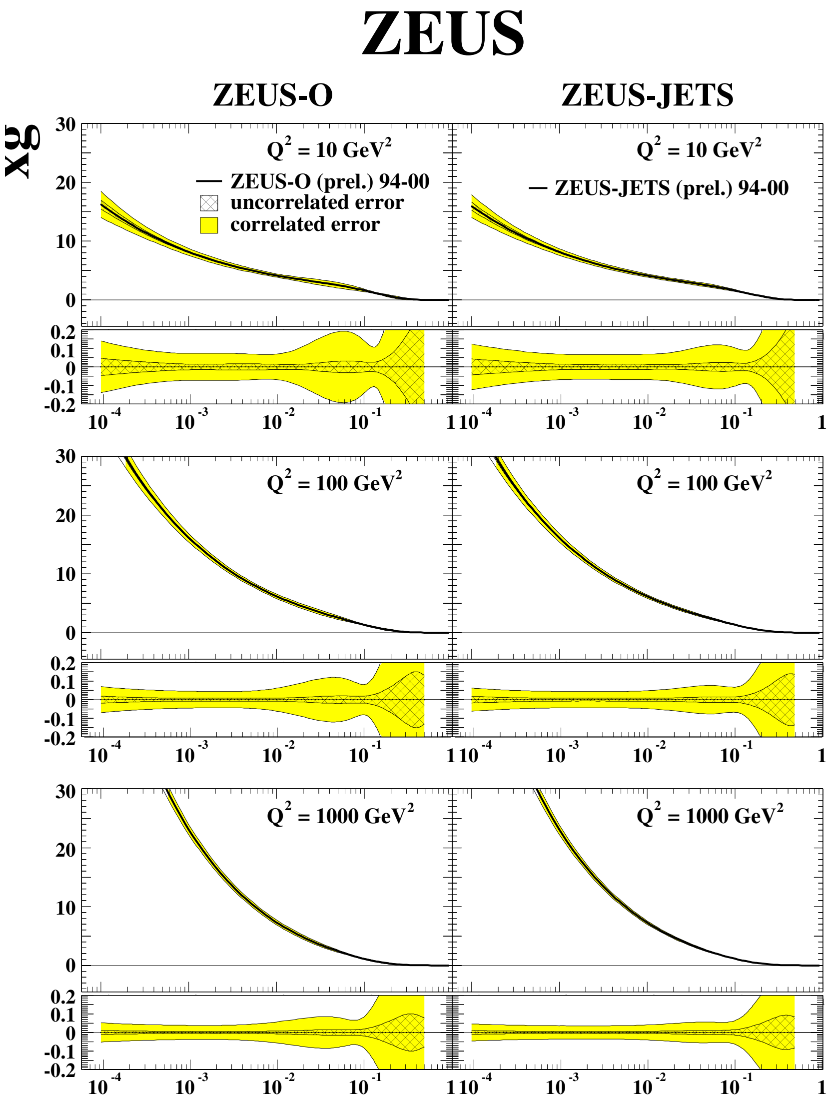
Improve F_2 fits with Jets (ZEUS)

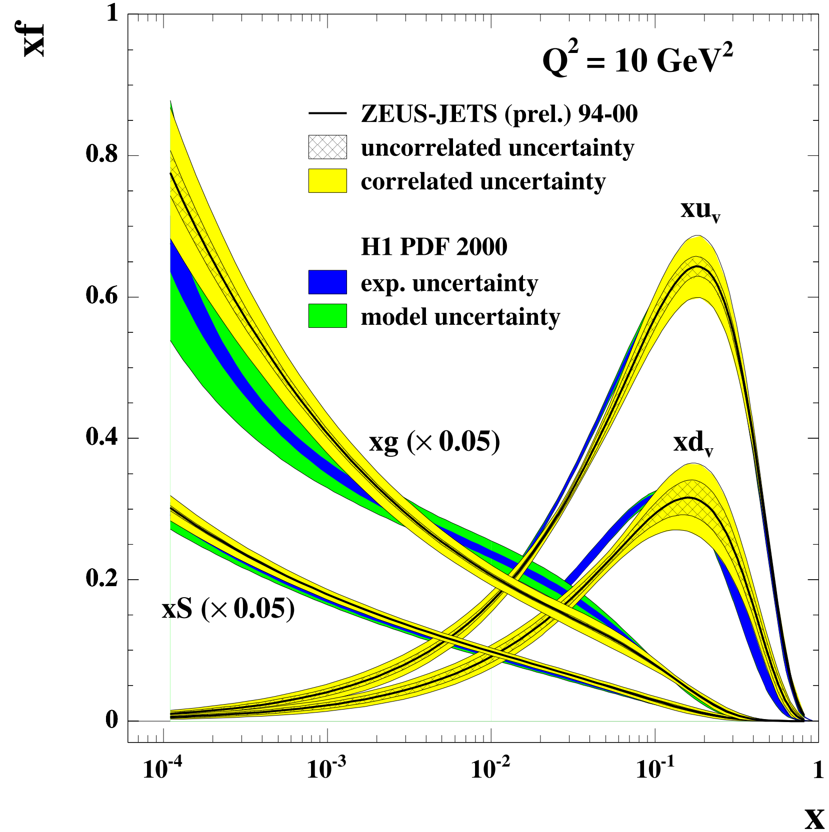




- use DIS jets to constrain fits
- use γp (only direct) jets also !!!

Parton Density Functions from F_2 and Jets

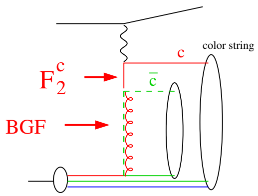




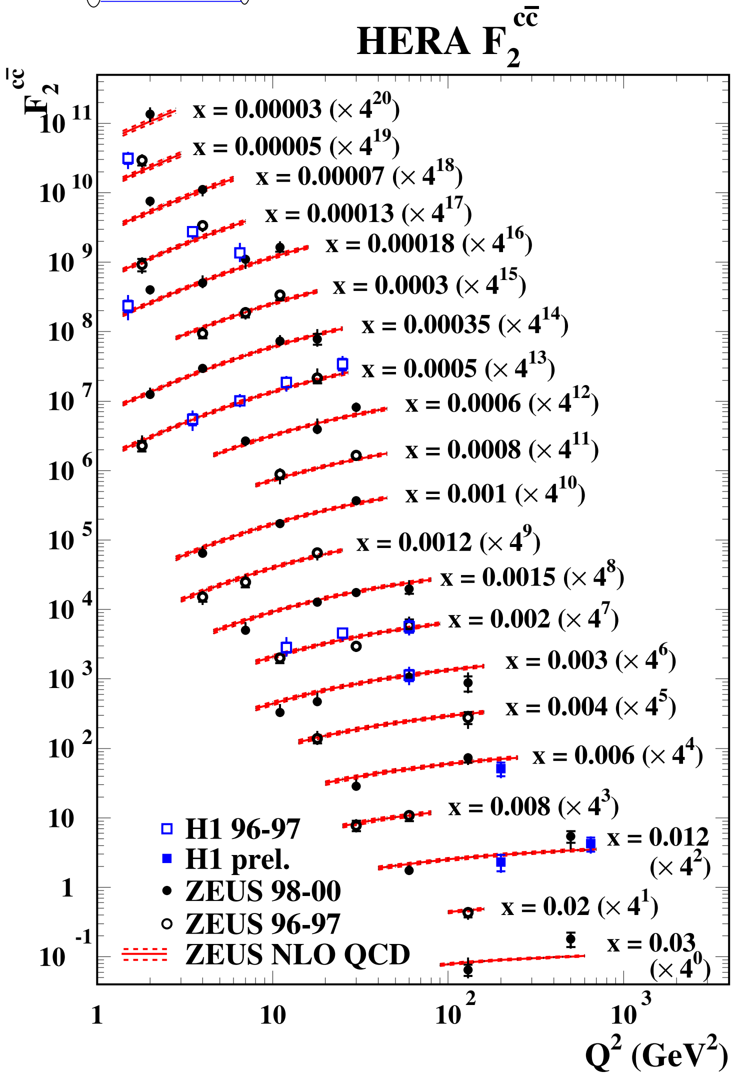
- gluon improved at large x

- NLO DGLAP fit to F_2 and Jets
- pdfs agree within uncertainty
- further improvement on gluon - F_L

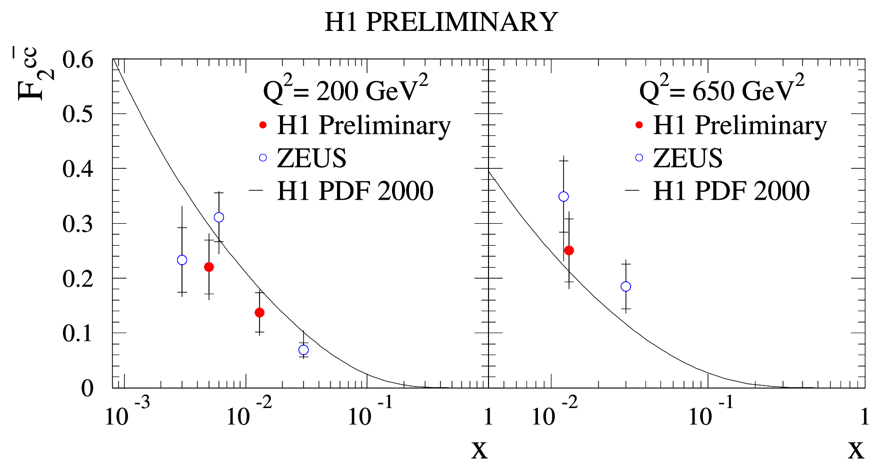
Heavy Quark Structure Functions F_2^c and F_2^b

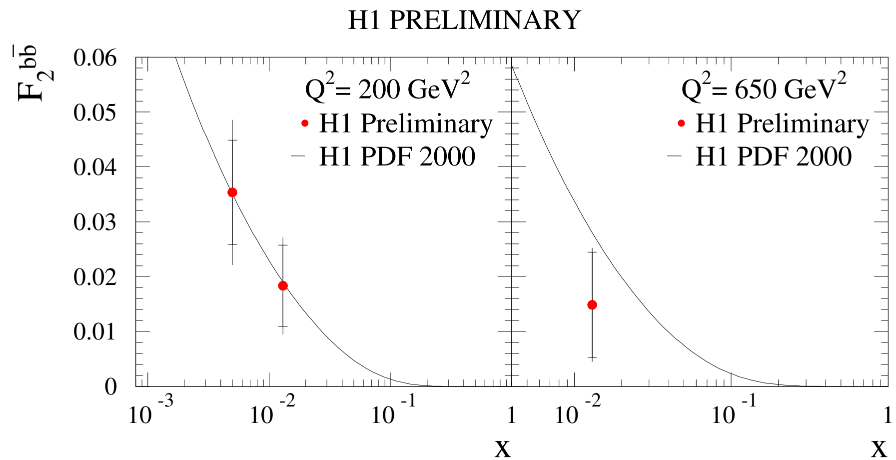


- heavy quark pdf or gluon ?



- use silicon tracker for life-time info
- large Q^2 ☛ small extrapolations





- NLO DGLAP fit to $F_2^{c,b}$

Structure Functions at HERA

are well described by

NLO - DGLAP

Structure Functions at HERA

are well described by

NLO - DGLAP

is that all we can learn ???

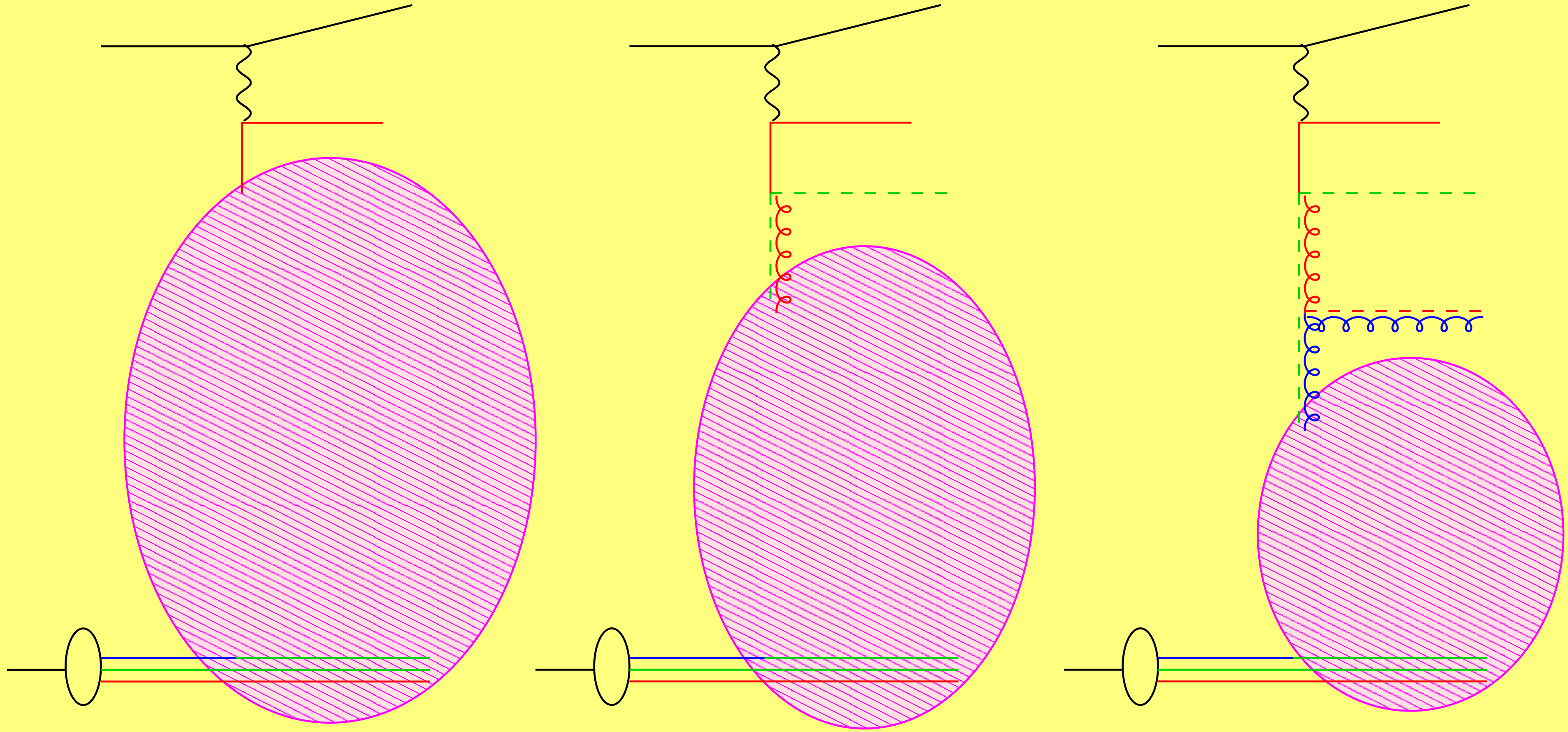
Structure Functions at HERA

are well described by

NLO - DGLAP

HERA and QCD is more !!!

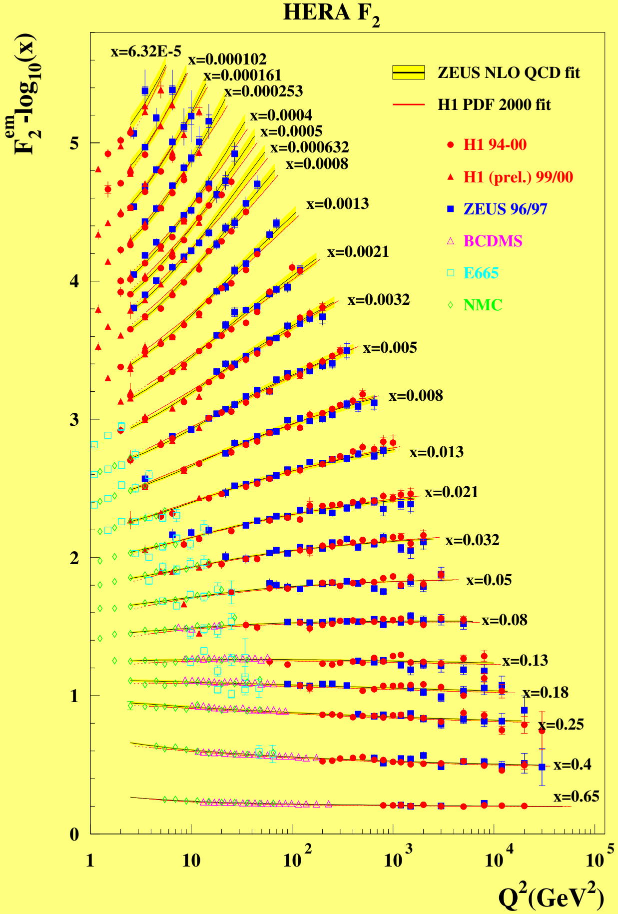
The challenge is Hadronic Final State !

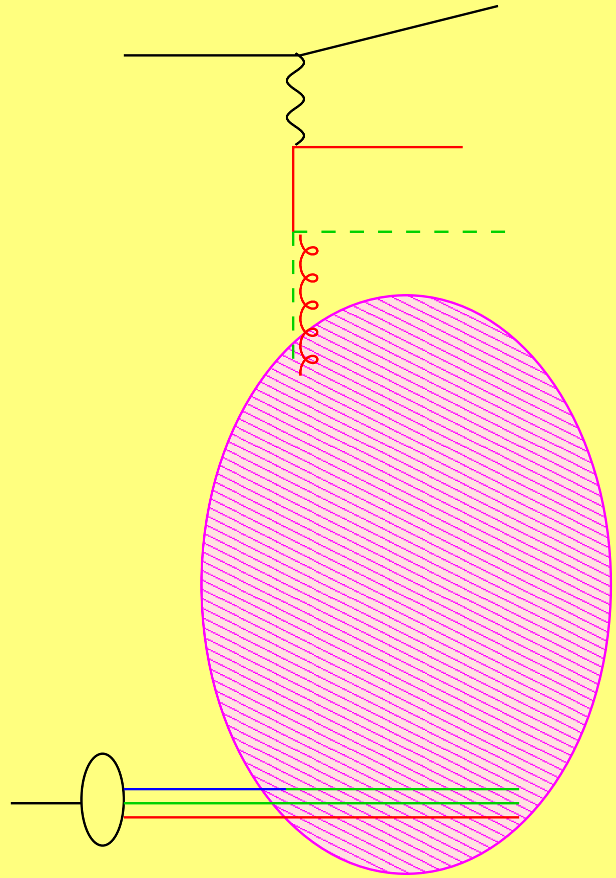


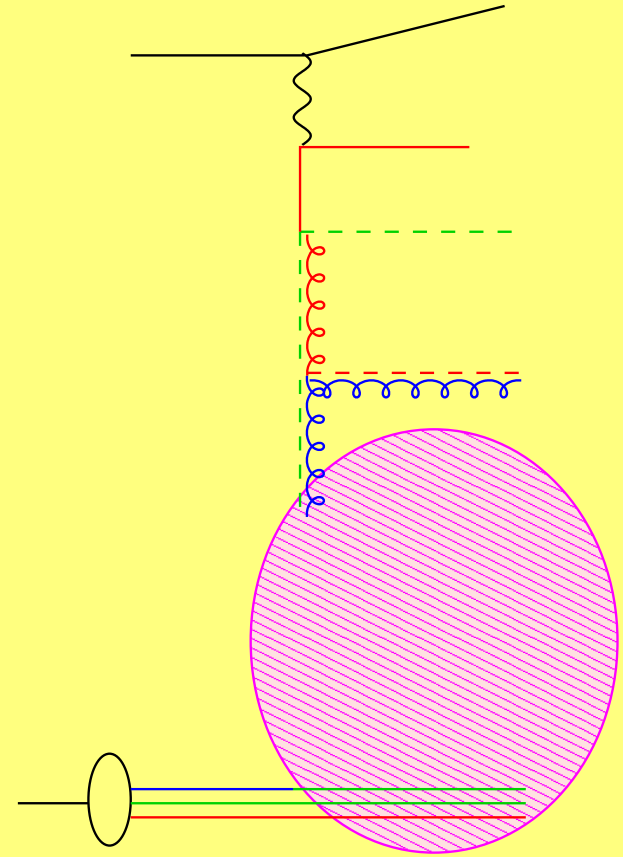
QPM process	BGF ($\mathcal{O}(\alpha_s)$) process	$\mathcal{O}(\alpha_s^2)$ process
total x-section	**heavy quarks charm & bottom**	
	2 -jet	3 -jets

The challenge is Hadronic Final State !

$F_2 \sim \sigma(\gamma^* p \to X)$







QPM process — **total x-section**

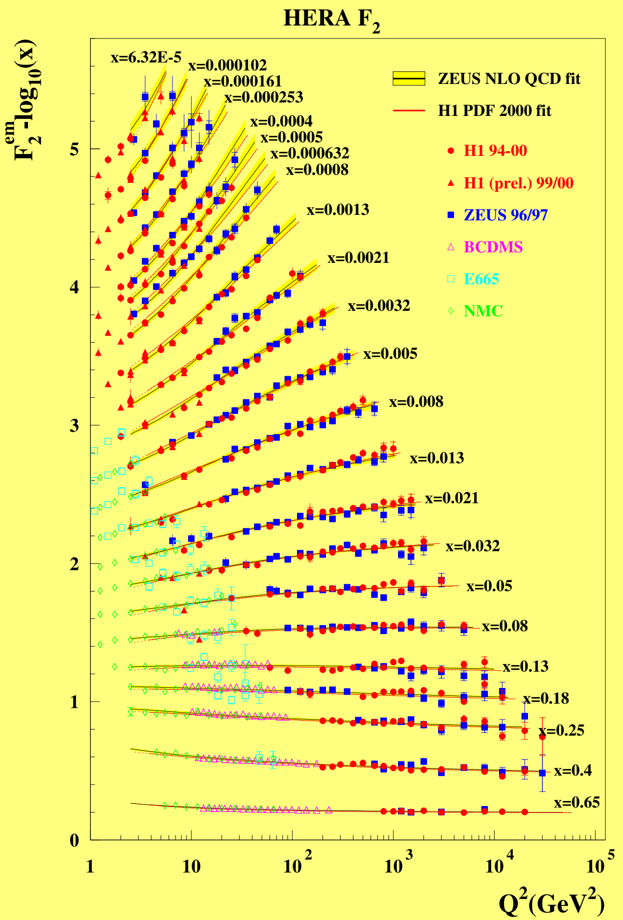
BGF ($\mathcal{O}(\alpha_s)$) process — **heavy quarks charm & bottom** — **2 -jet**

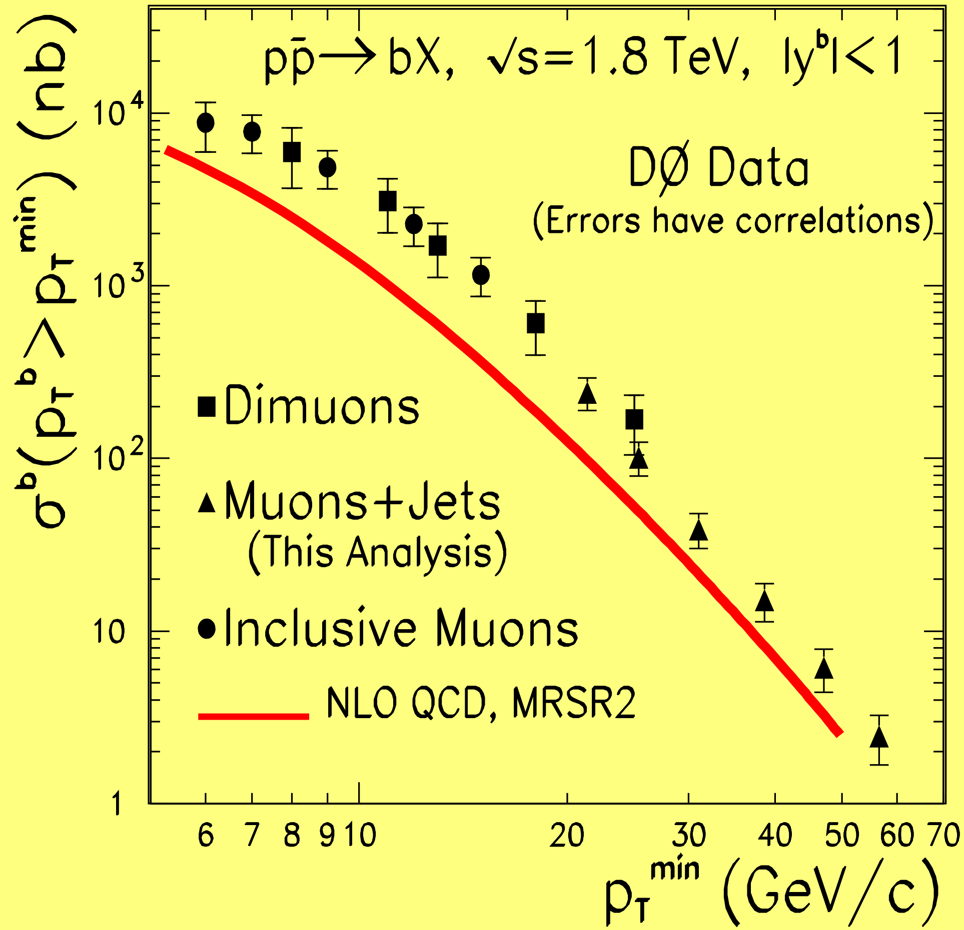
$\mathcal{O}(\alpha_s^2)$ process — **3 -jets**

The challenge is Hadronic Final State !

$F_2 \sim \sigma(\gamma^* p \to X)$

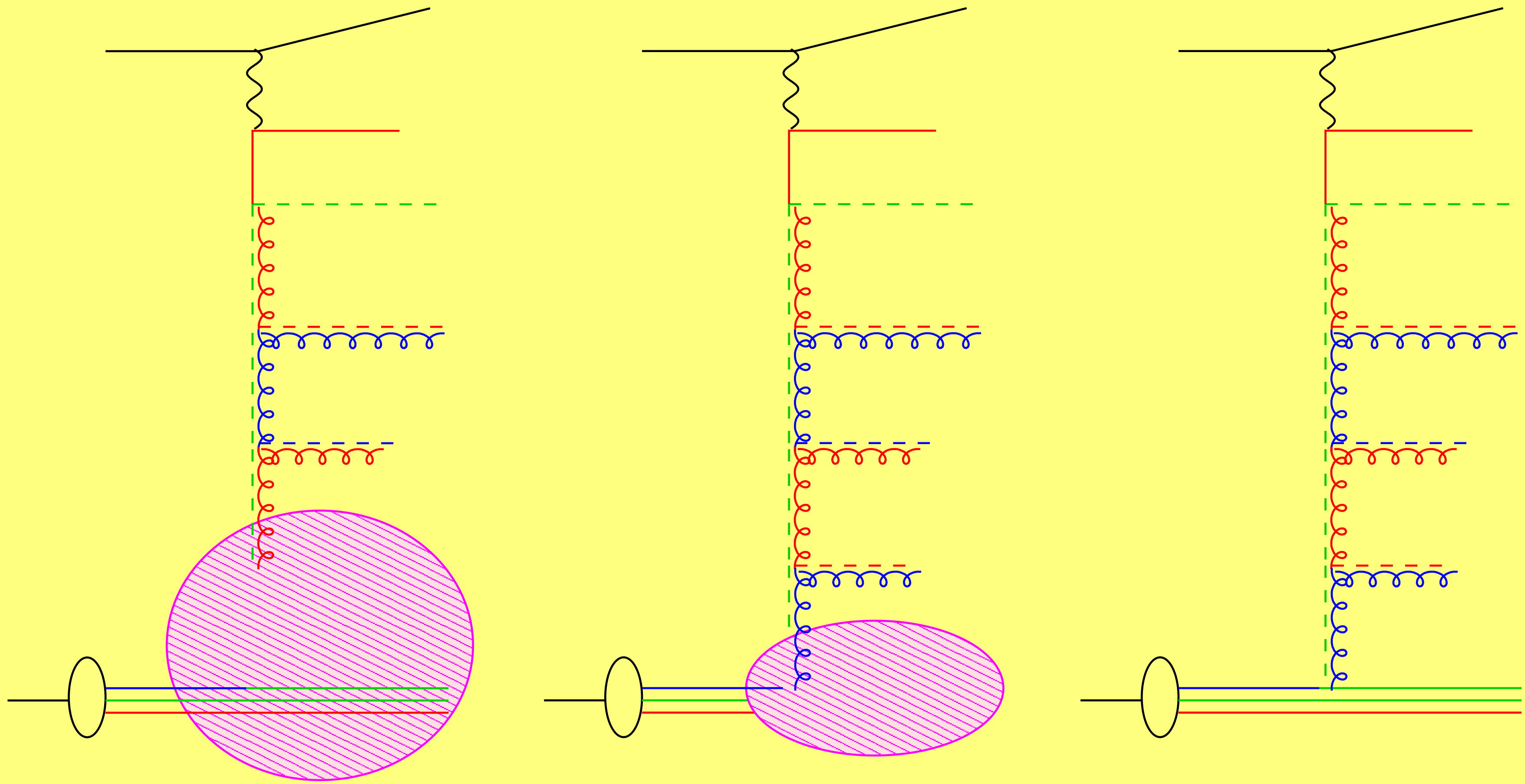
bottom $p\bar{p}$





QPM process	BGF ($\mathcal{O}(\alpha_s)$) process	$\mathcal{O}(\alpha_s^2)$ process
total x-section	**heavy quarks charm & bottom**	
	2 -jet	**3 -jets**

Where is the problem ? Hadronic Final State !



processes of $\mathcal{O} > \alpha_s^3$ have not been calculated explicitely

investigate parton radiation pattern
forward jets !!!

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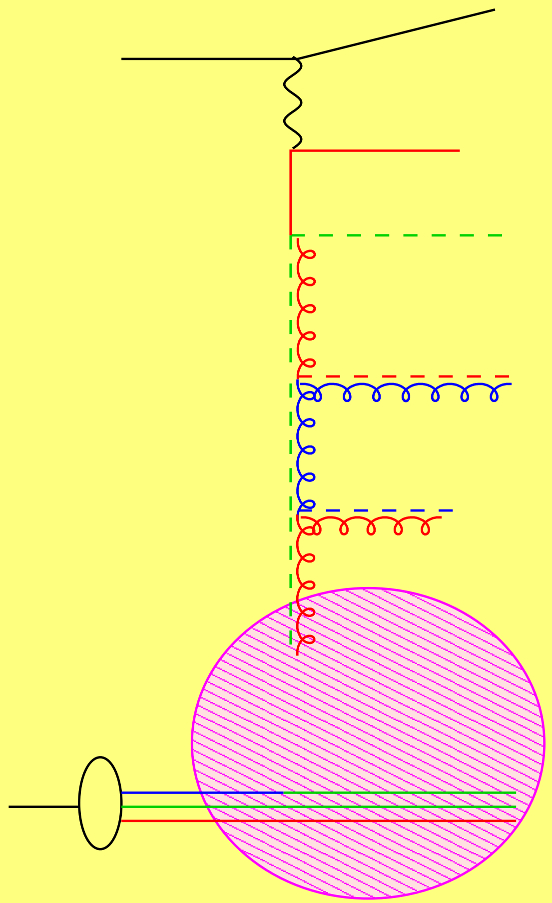
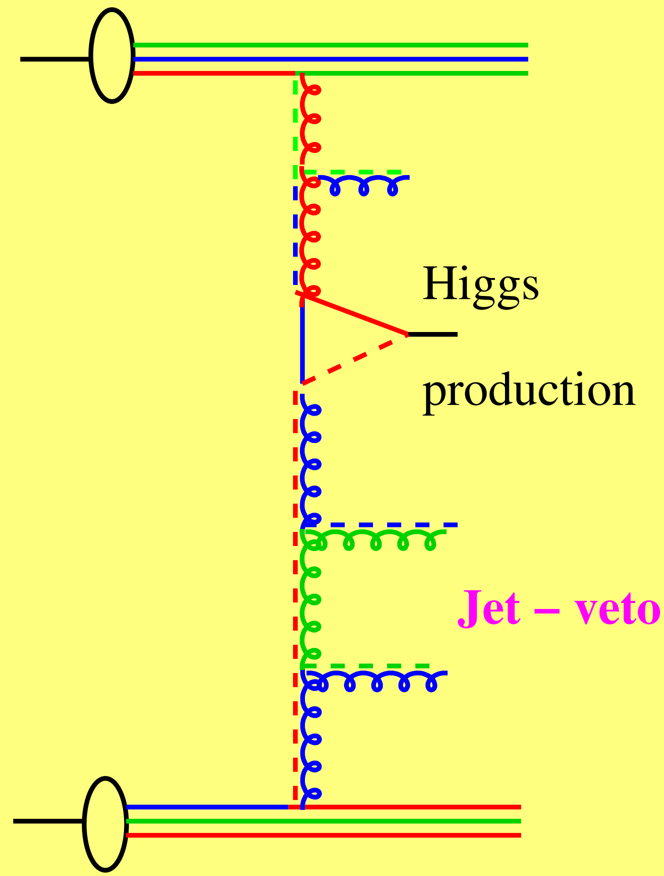




processes of $\mathcal{O} > \alpha_s^3$ have not been calculated explicitely

investigate parton radiation pattern
forward jets !!!
☛ **jet veto in Higgs production**

Di - jets at small x in DIS

DIS selection:

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

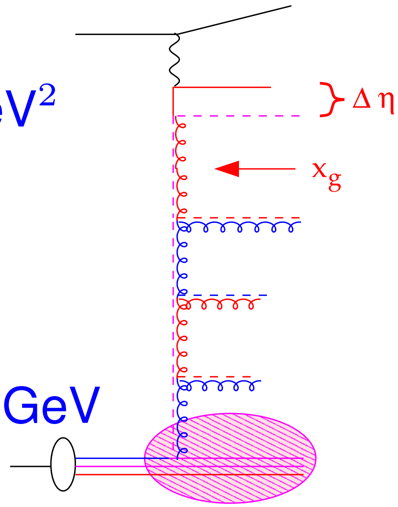
$10^{-4} < x < 10^{-2}$

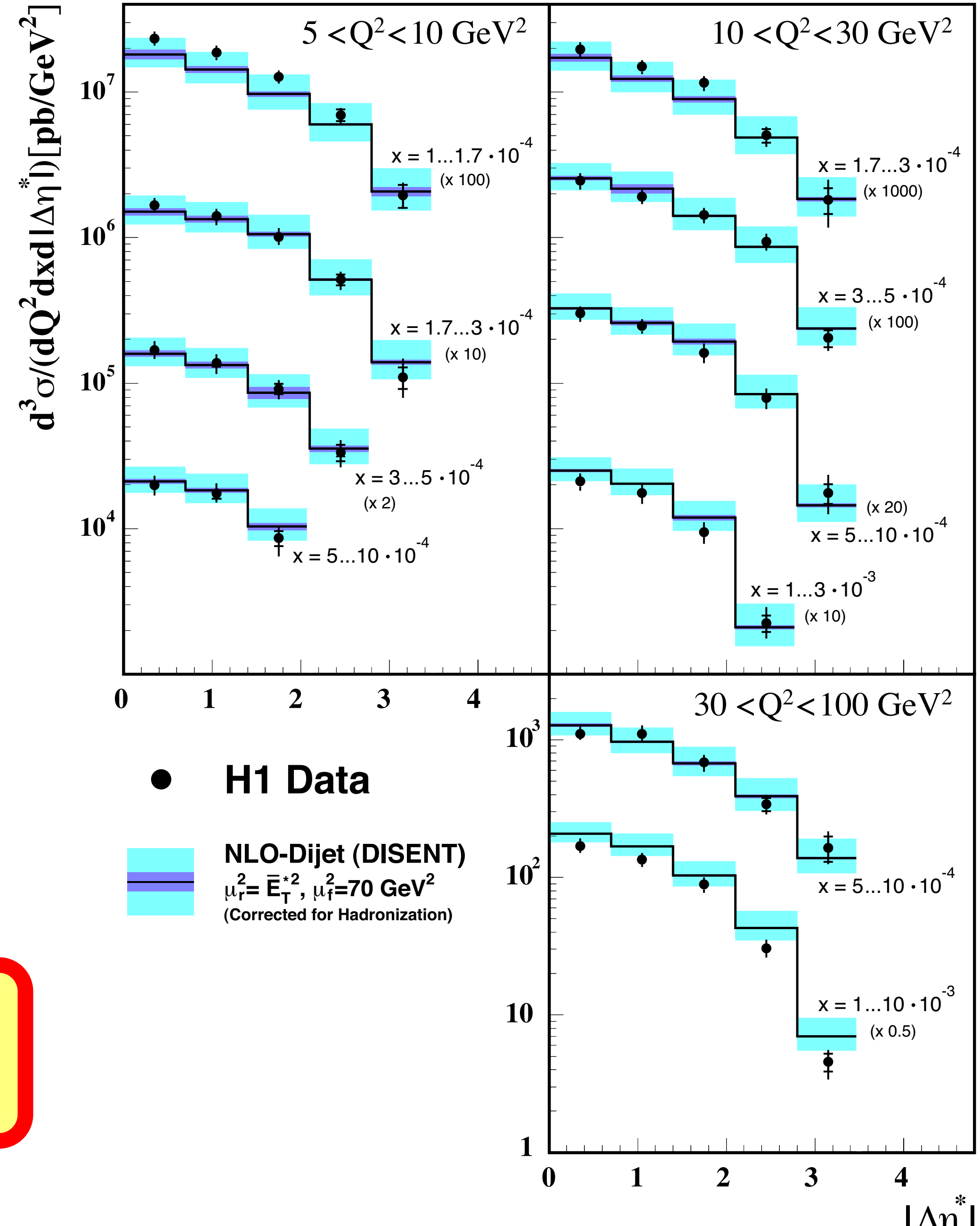
$0.1 < y < 0.7$

di-jets

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

$-1 < \eta_{jets}^{lab} < 2.5$

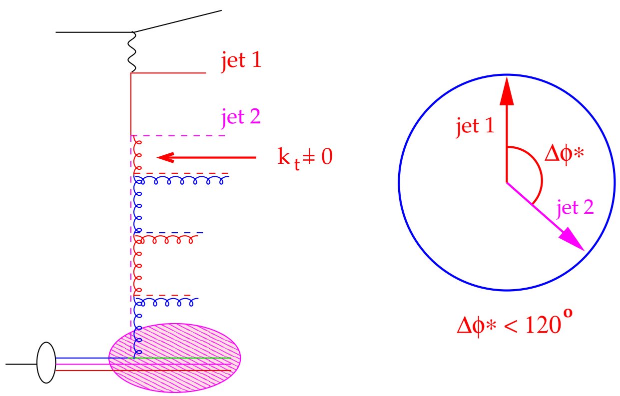




$\Delta\eta$ small	☛ small x_g
$\Delta\eta$ large	☛ large x_g

NLO ... agrees ...
within large scale uncertainty !?!

Di - jets in DIS: one of the problems !

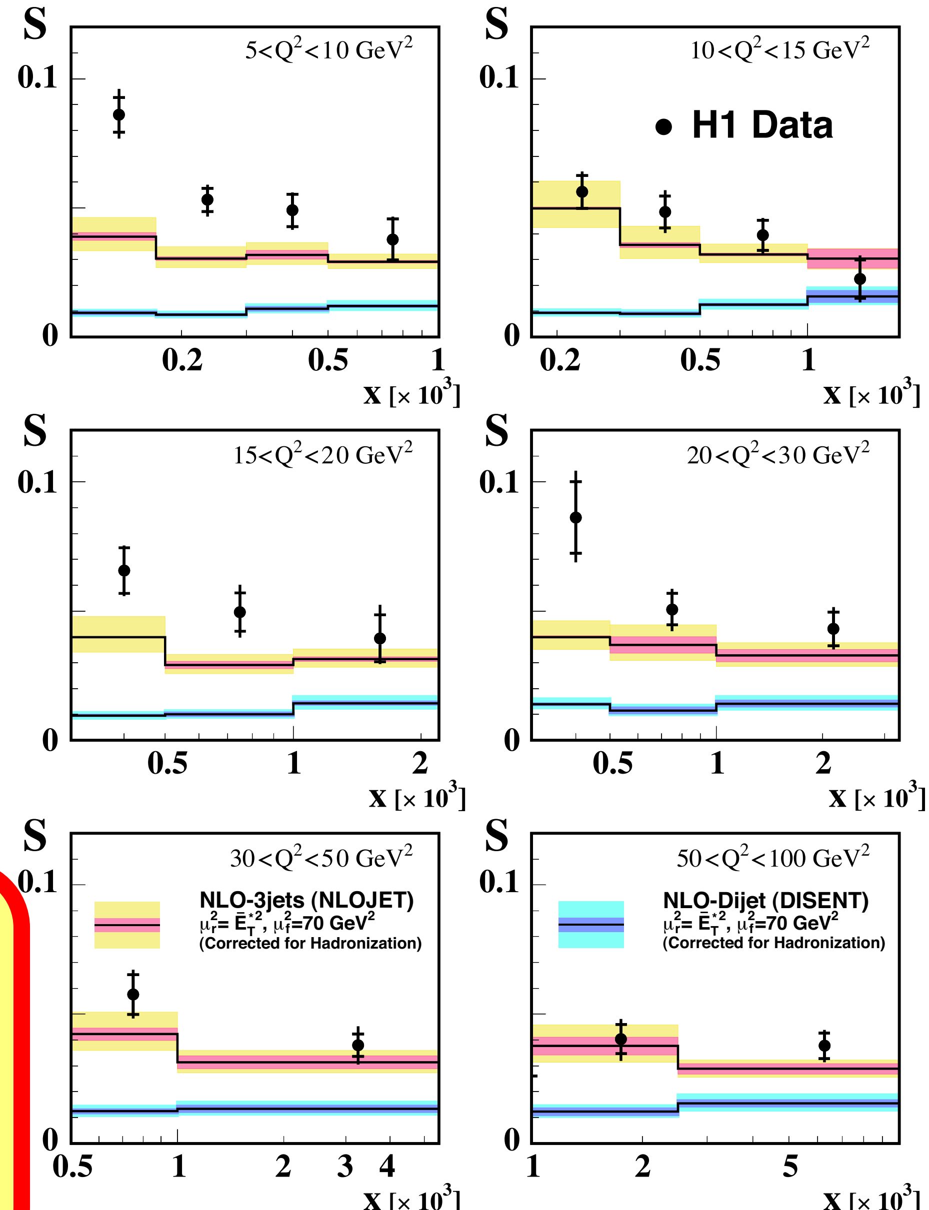


- Measurement of $\frac{d\sigma}{d\Delta\Phi}$ exp. difficult
- Measure:

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

☛ sensitive to finite k_t ...

☛ un-integrated gluon density !?!

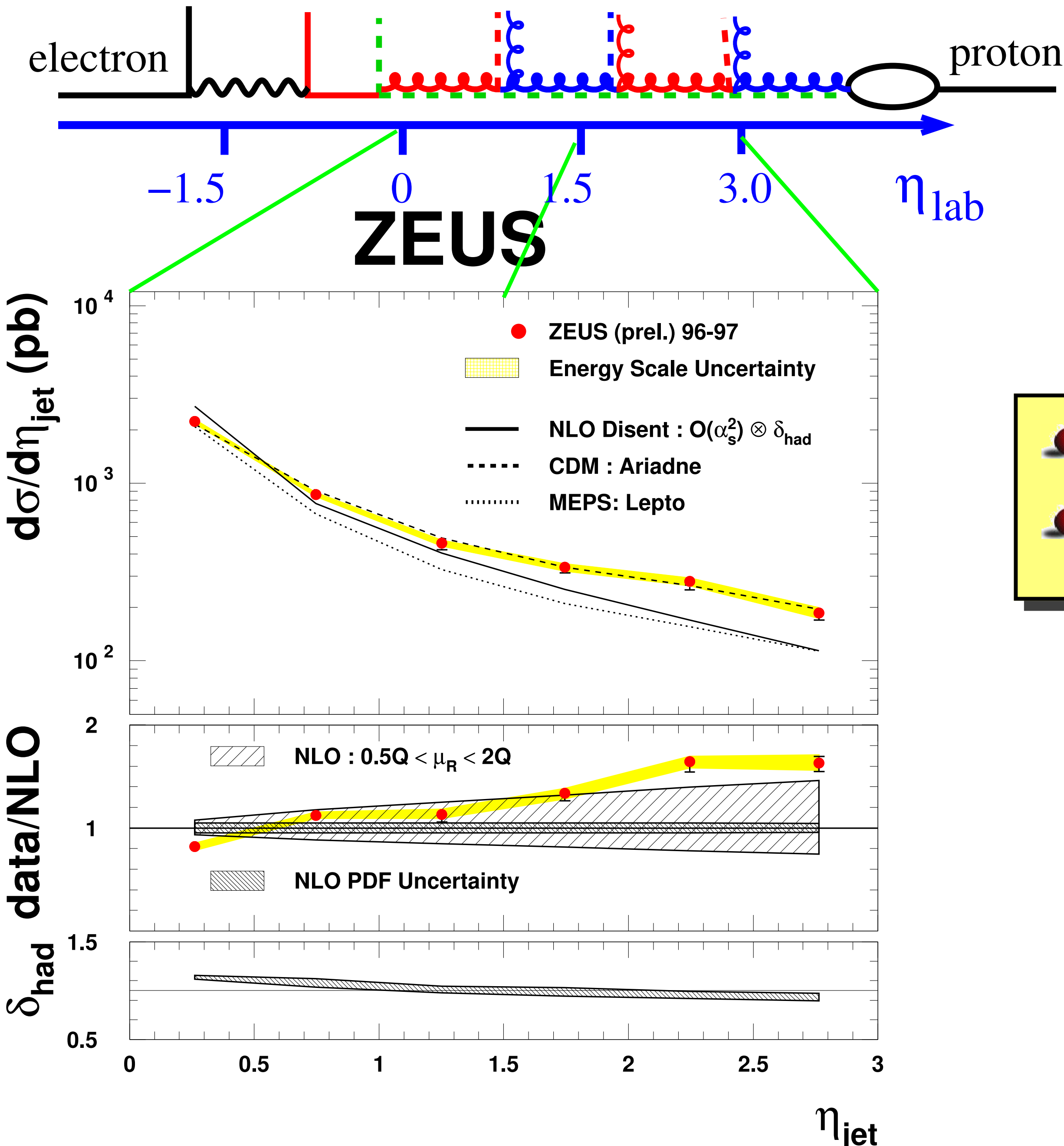


Data higher than NLO - 2jet (3jet)

new dynamics ???

beyond DGLAP ???

Inclusive Jets in Deep Inelastic Scattering



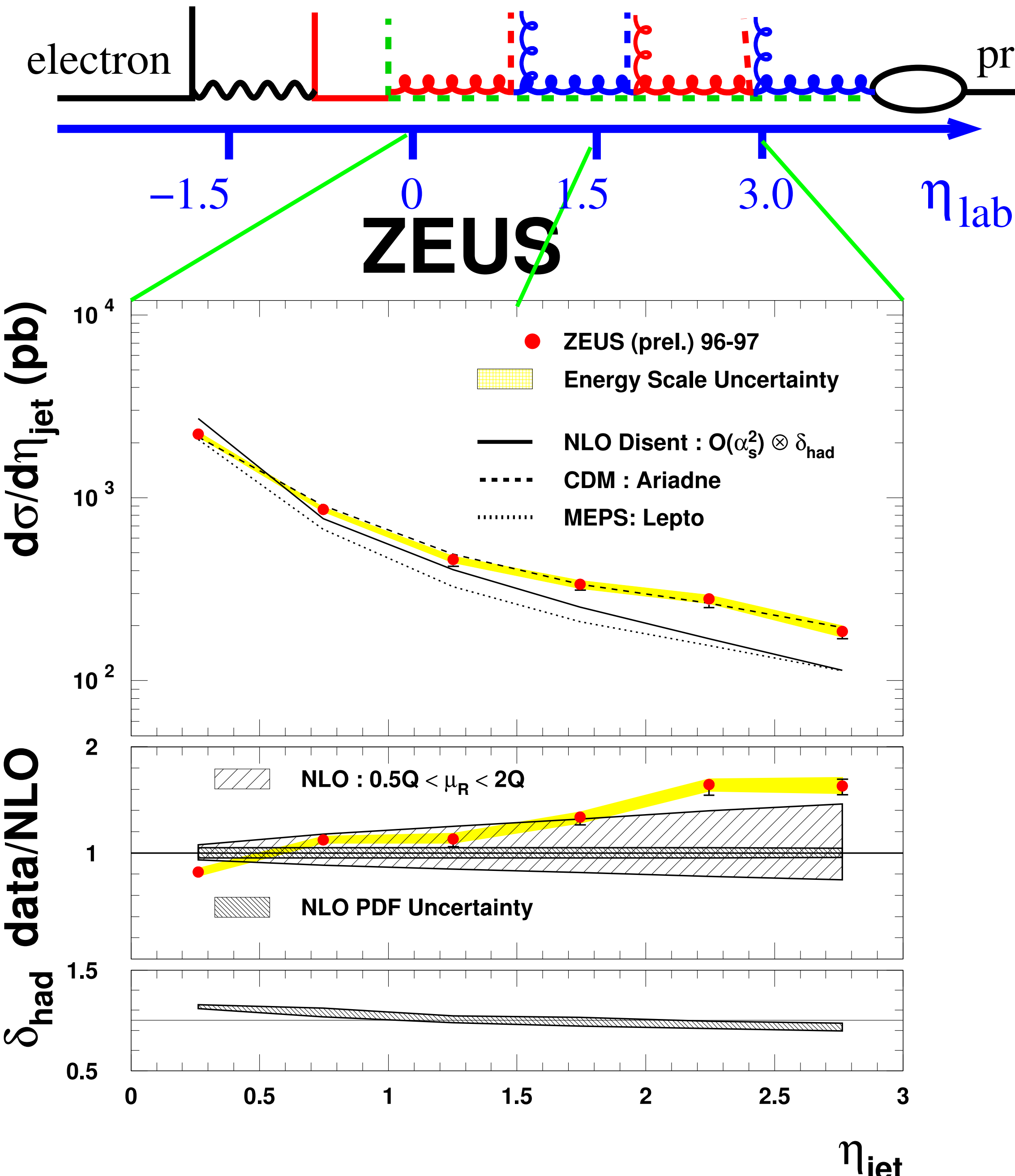
$Q^2 > 25$ GeV^2

incl. k_t jet-algo
$E_t > 6$ GeV

$0 < \eta_{lab} < 3$

- central region ok
- difference to NLO in forward region

Inclusive Jets in Deep Inelastic Scattering



$Q^2 > 25$ GeV^2

incl. k_t jet-algo
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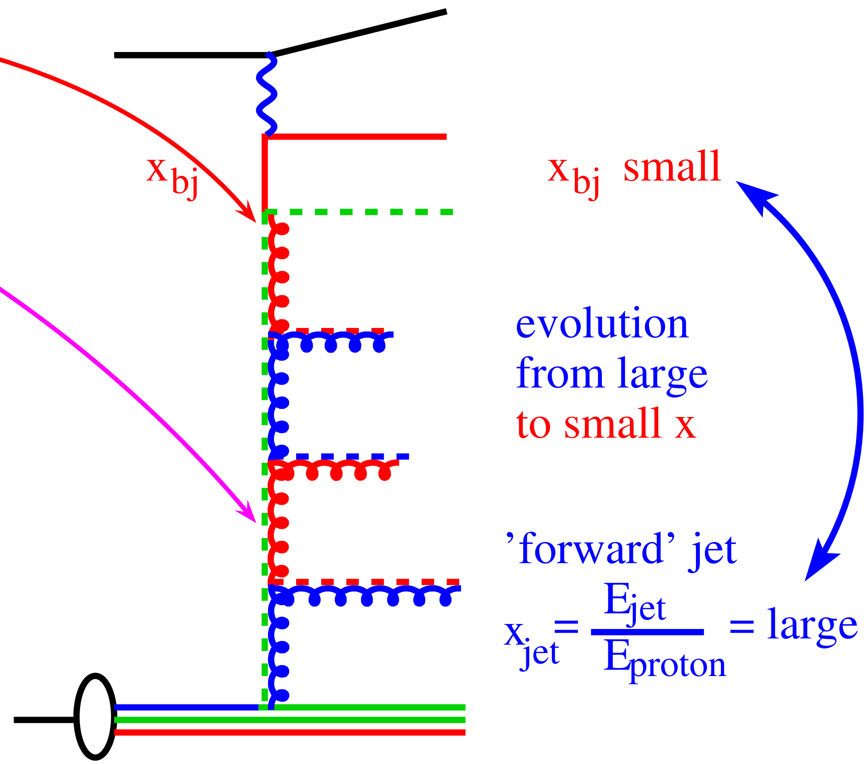
- central region ok
- difference to NLO in forward region

- watch out !!!!
  $\sim$ 20 % of jets deviate significantly from DGLAP + $\mathcal{O}(\alpha_s^2)$!!!

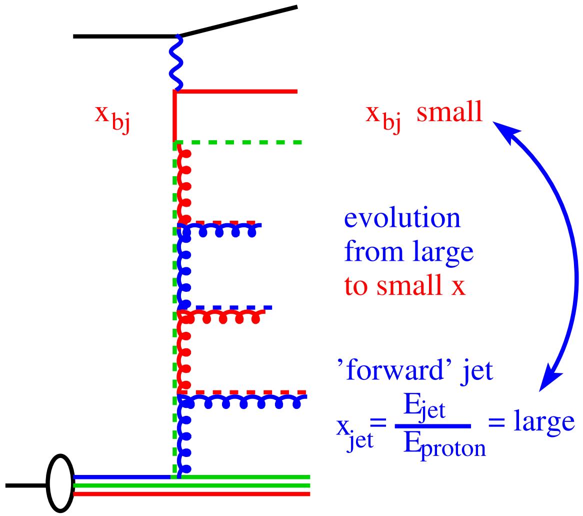
Forward jets: going beyond DGLAP ?

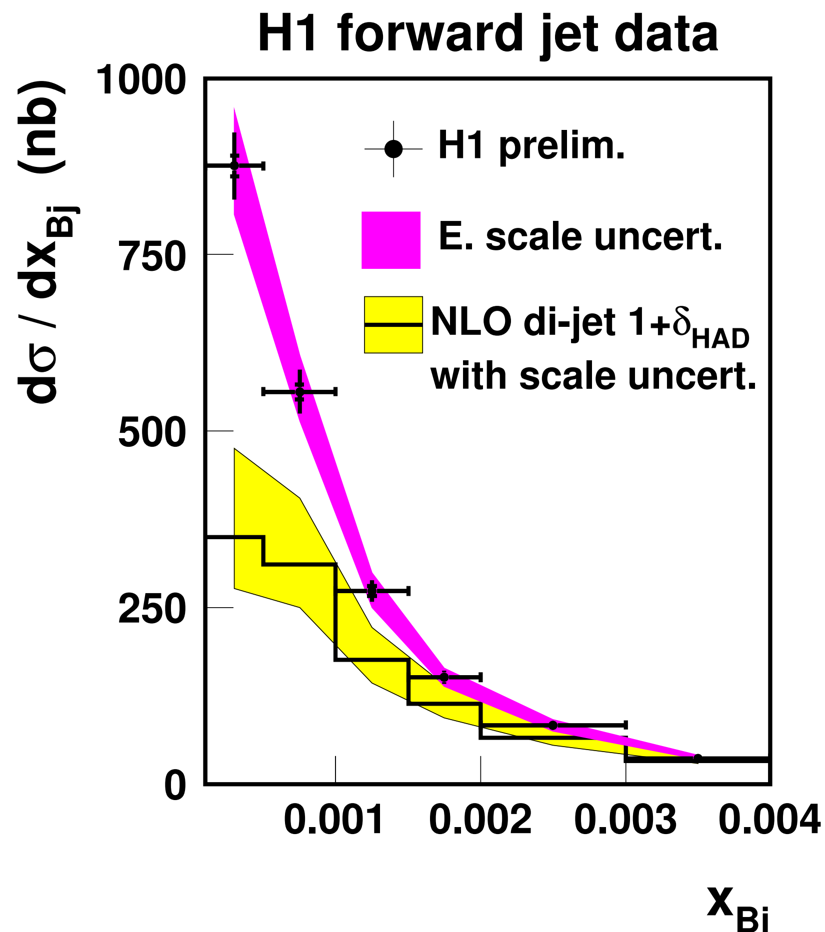
DGLAP works fine in central region !
Investigate forward region
Anything new there ?
Observe deviations from DGLAP ?
☛ evidence for BFKL ?
or
☛ CCFM ?
or
☛ no approximation is good ?



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





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

forward jet (incl. k_t algorithm)

$1.7 < \eta_{jet} < 2.8$

$x_{jet} > 0.035$

$0.5 < \frac{p_t^2\ jet}{Q^2} < 5$

- **DGLAP with NLO-dijet too small**
- **need something different ☛ different evolution ?**
- **more hard parton radiation ☛ BFKL/CCFM ???**

Parton radiation at small x

- describe multiparton emissions only in approximations
- put everything beyond $\mathcal{O}(\alpha_s^2)$ into

QCD evolution equations
approximation of higher orders

BUT which use when ?

DGLAP

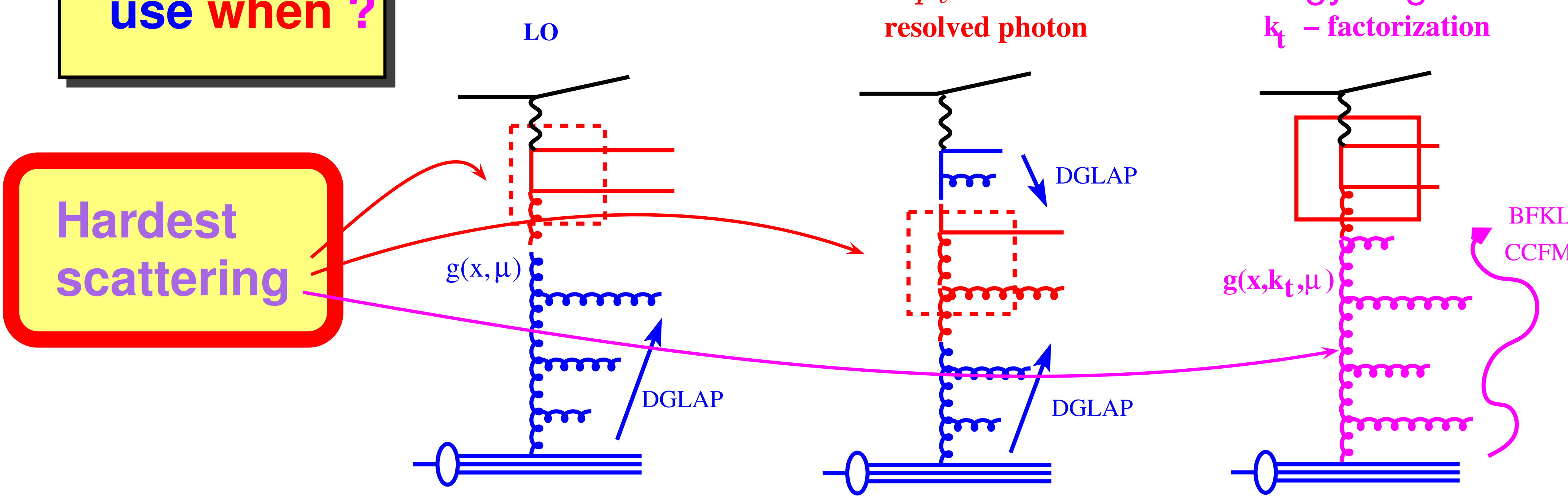
single ladder

2 ladders

each ordered in p_t

BFKL / CCFM

ordered in energy/angle



Parton radiation at small x

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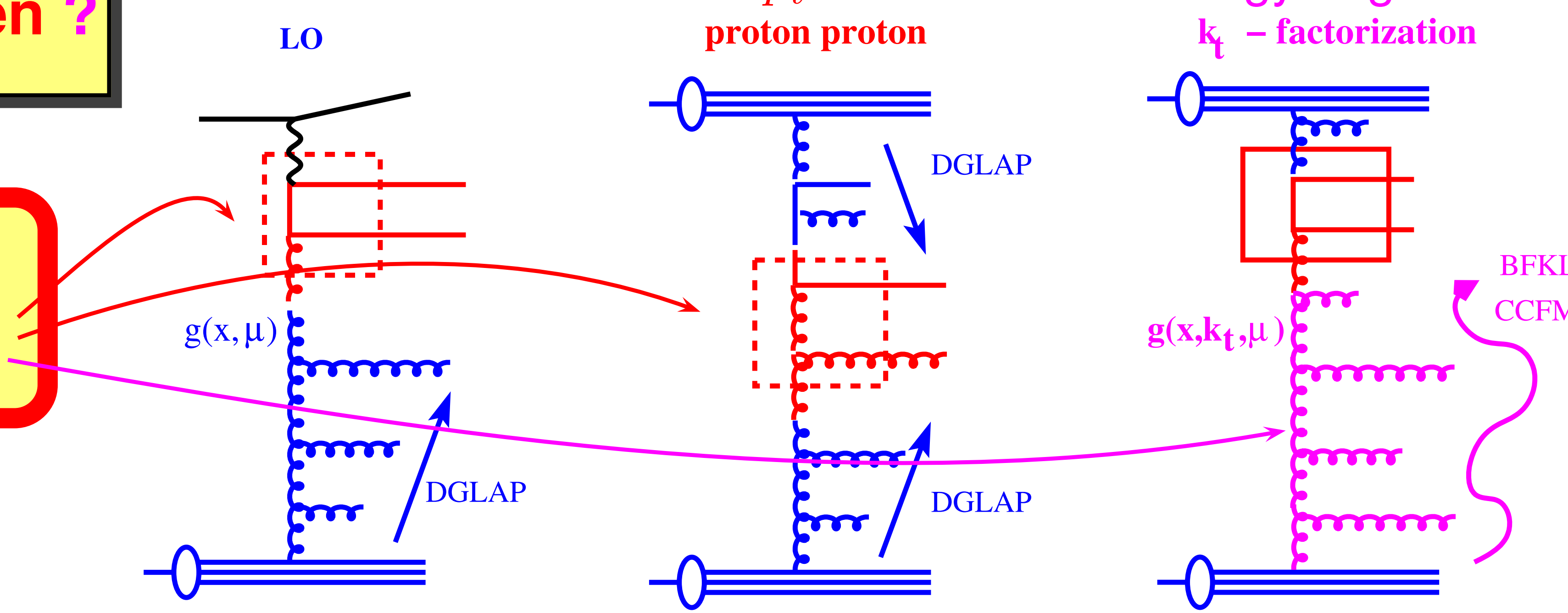
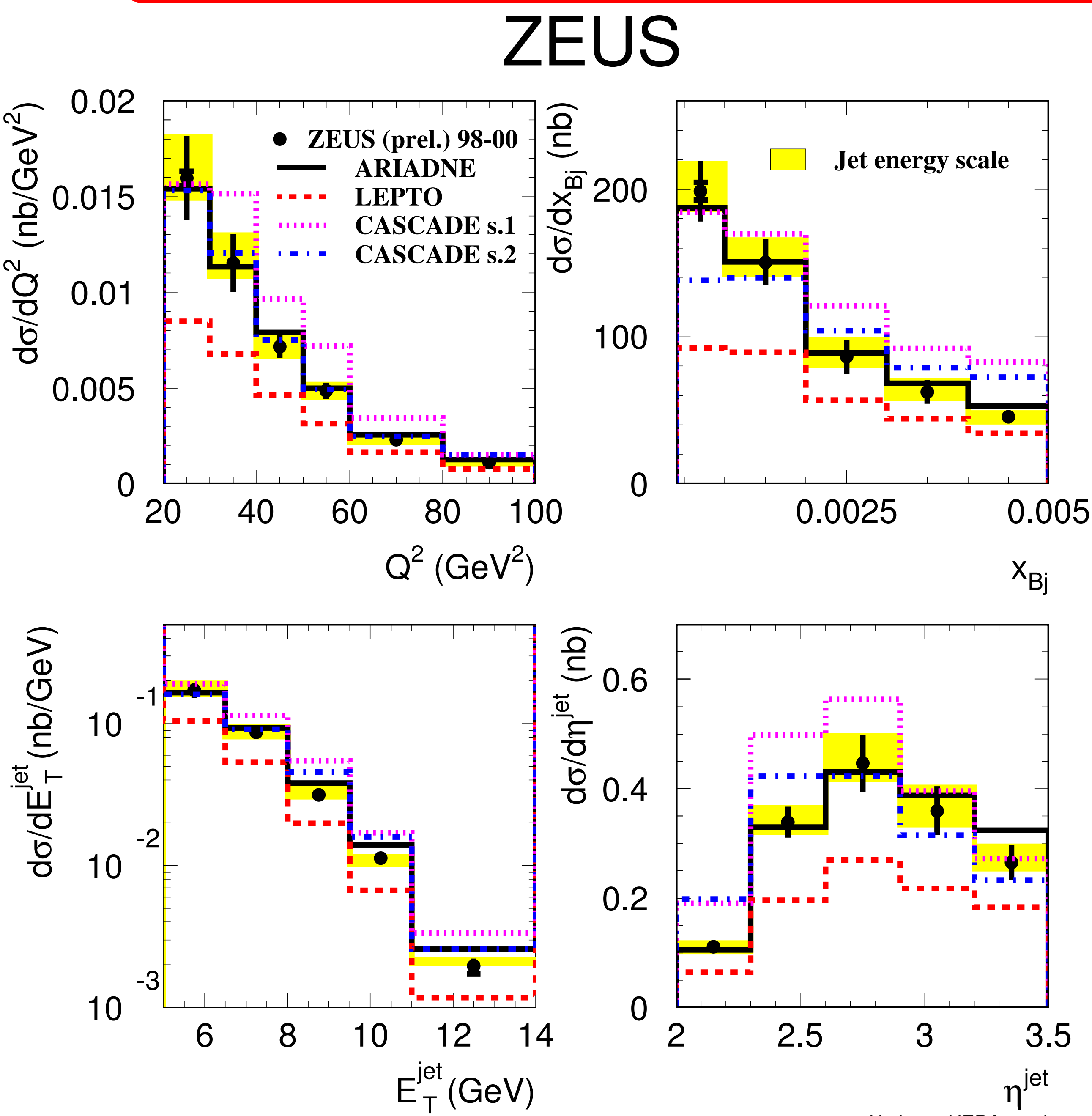
DGLAP | BFKL / CCFM
single ladder | 2 ladders | ordered in
each ordered in p_t | energy/angle

BUT which use when ?

Hardest scattering



Parton dynamics at small x: Forward Jets

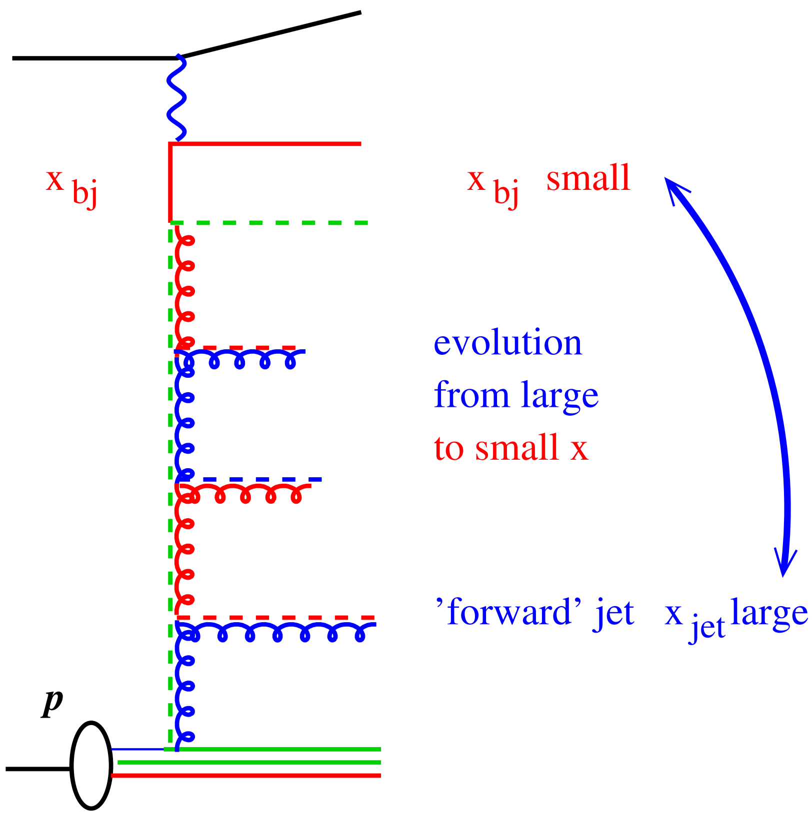


$20\ \text{GeV}^2 < Q^2 < 100\ \text{GeV}^2$
forward jet (incl. k_t algorithm)
$E_t > 5$ GeV

$2 < \eta_{jet} < 3.5$
$x_{jet} > 0.036$
$0.5 < \frac{p_{t\ jet}^2}{Q^2} < 2$

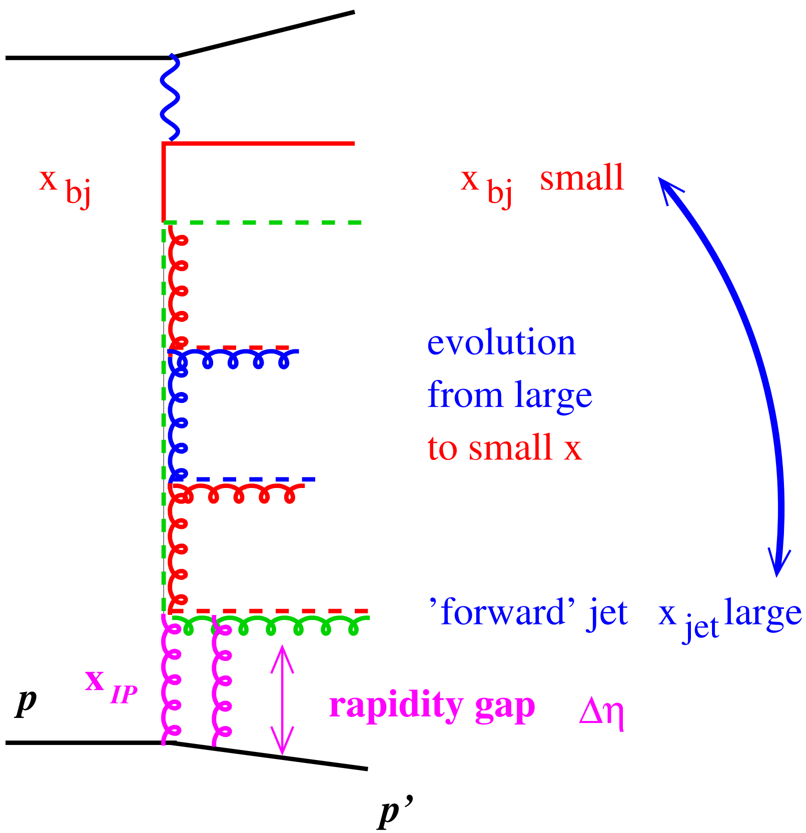
- data above DGLAP
- approaches with different radiation pattern: better !
- CCFM/BFKL close to data

Why worry about forward jets ?



- forward jets: $\sim$ 20 % of jet production
- forward jets probe QCD radiation along the parton ladder
- is there more than NLO calcs and DGLAP evolution ?
- understand QCD radiation pattern !

Why worry about forward jets ?



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- diffractive dijets: 5 - 10 % of jet production
- diffraction: suppression of QCD radiation
- diffraction: understand QCD radiation

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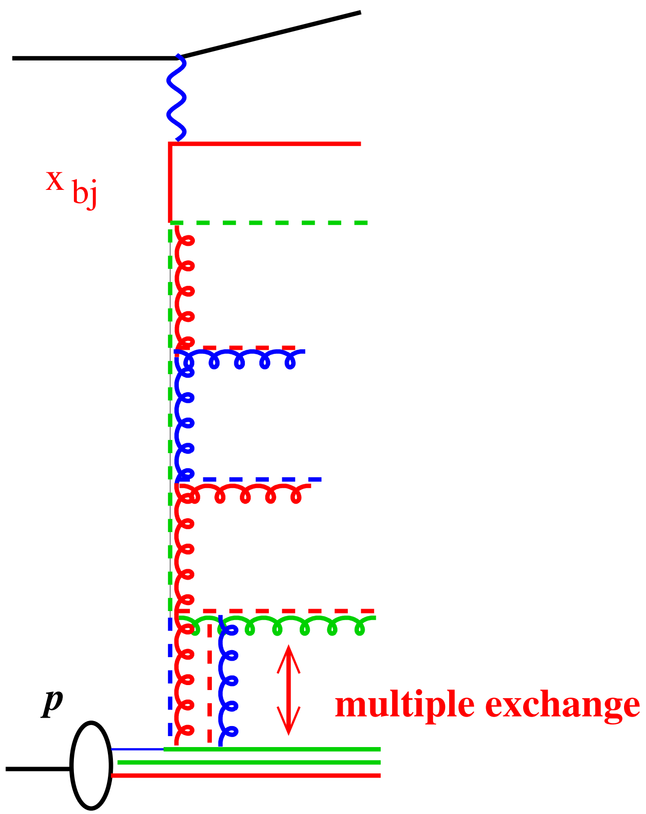

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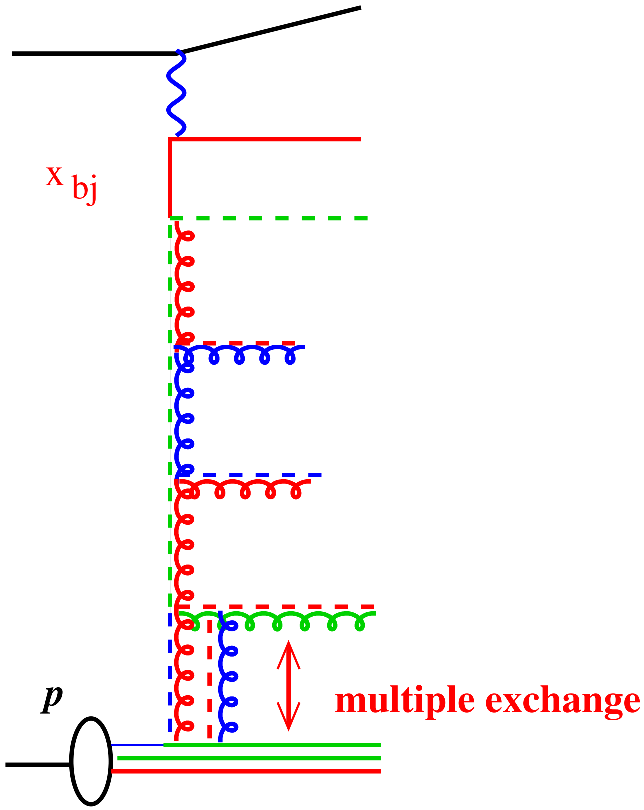

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- diffraction: suppression of QCD radiation
- diffraction: understand QCD radiation
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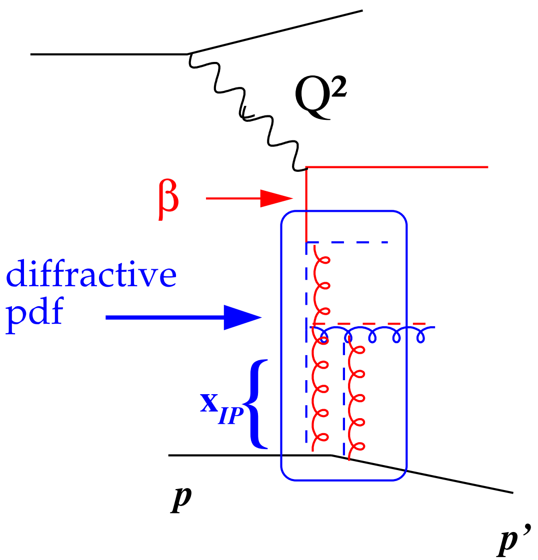
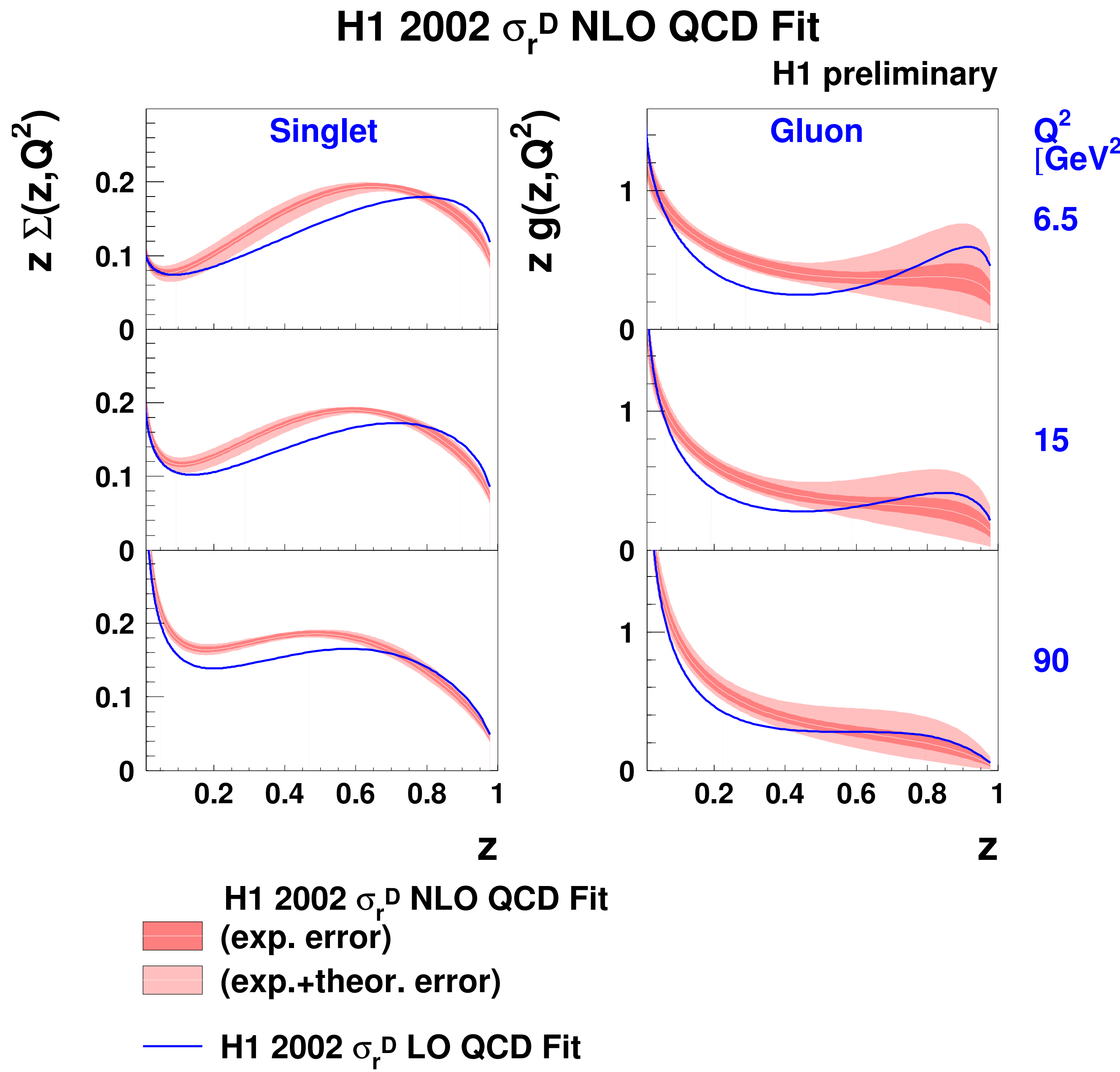
understand radiation in forward region:
suppression of radiation and multiple scatterings

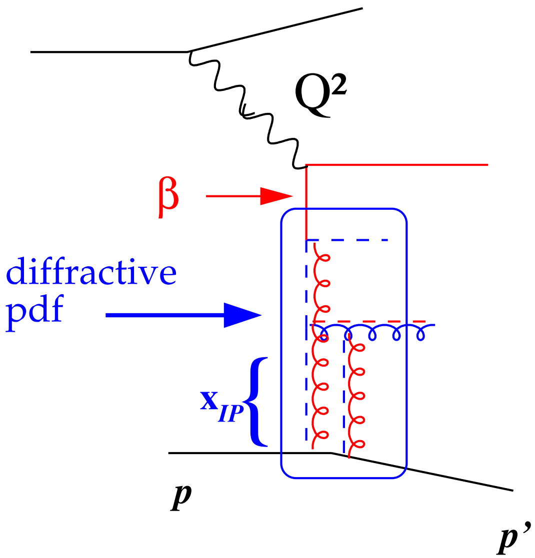
Diffractive Parton Density Functions



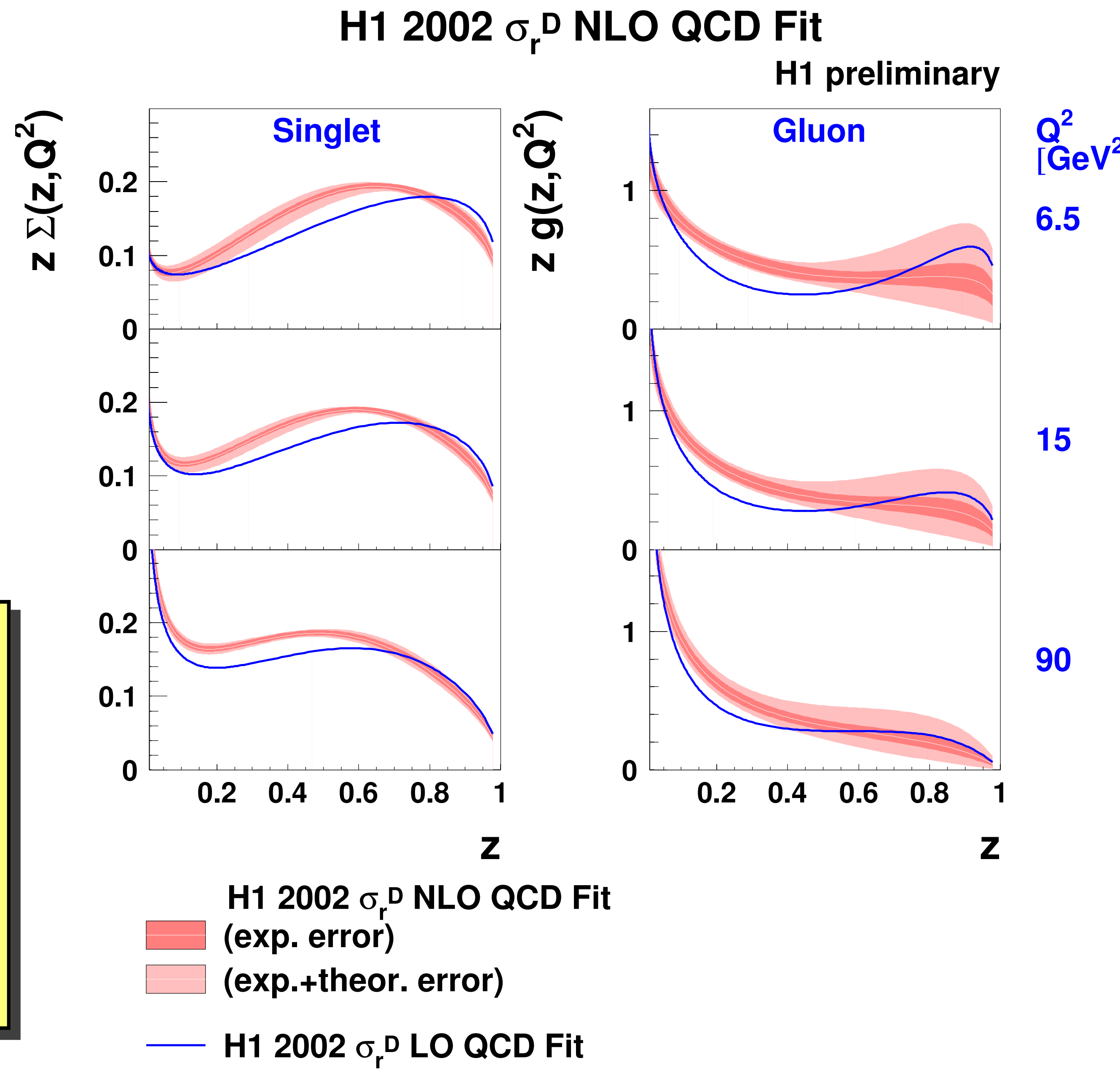


- measure diffractive cross section in
  $6.5 < Q^2 < 120$ GeV^2
  $x_{I\!P} < 0.05$
  $0.01 < \beta < 0.9$
- extract diffractive PDF using LO/NLO DGLAP

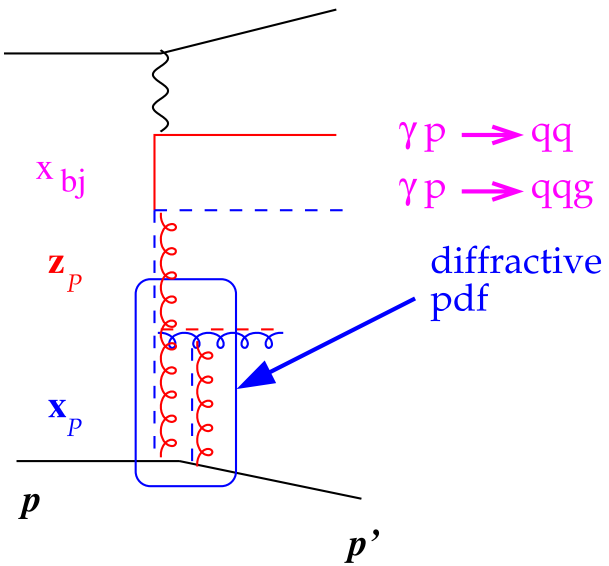
Diffractive Parton Density Functions



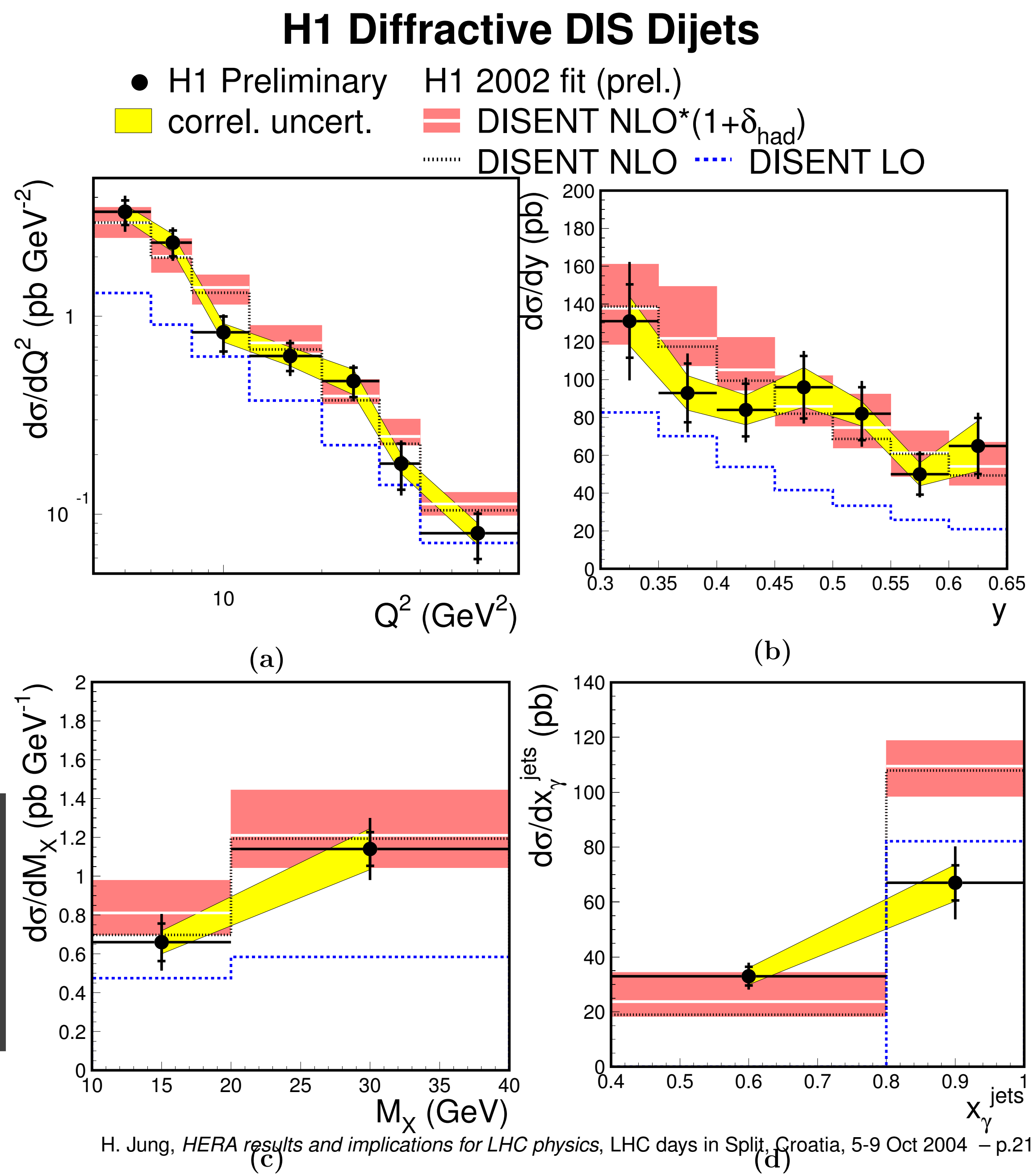
- factorization in diffraction $\sigma^D = \int f^D(\beta, x_{I\!P}, Q^2, t)\hat{\sigma}$ at large Q^2
- as in non-diffraction ...
- apply diff PDF to jet production



Diffractive Jets at large Q^2

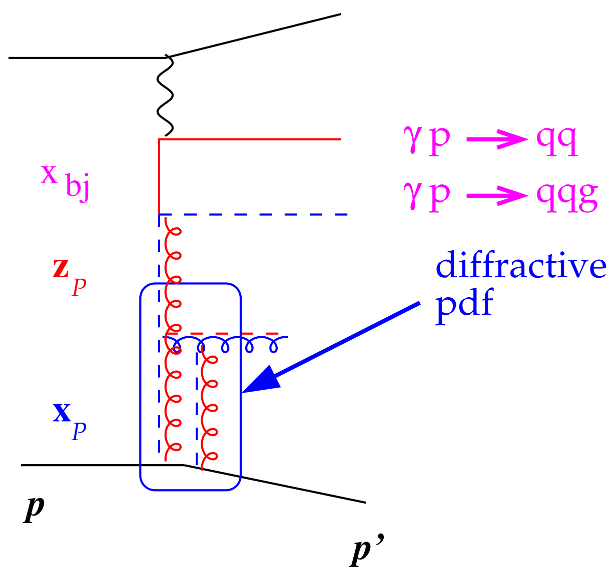


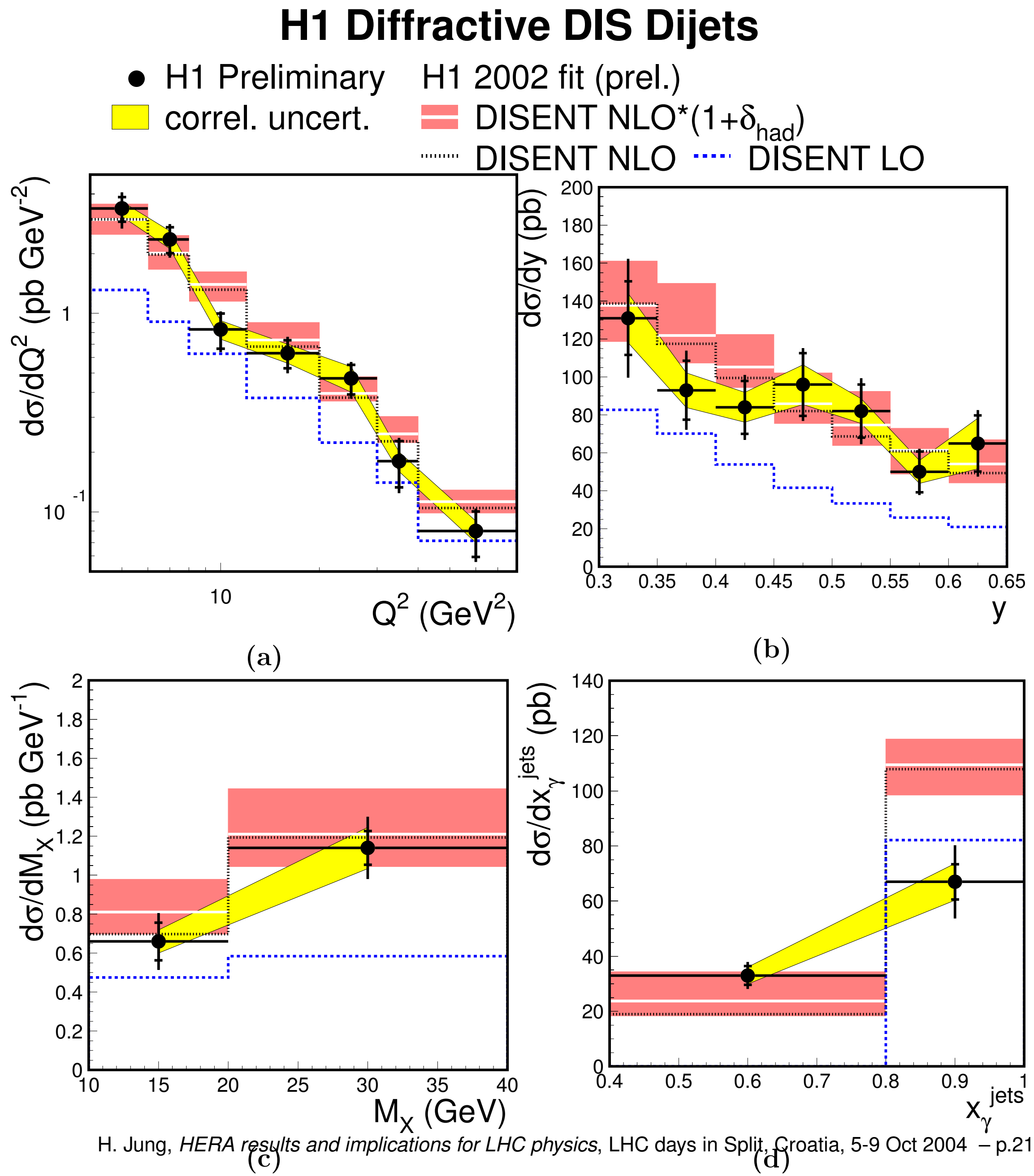
$4 < Q^2 < 80$ GeV^2, $0.1 < y < 0.7$
$x_{I\!P} < 0.05$, $M_Y < 1.6$ GeV,
$p_{T\ jet} > 4$ GeV, $-1.0 < \eta_{jet}^{lab} < 2.2$



- use diffractive pdfs from NLO fit to F_2^D !!!
- use NLO calc for dijets

Diffractive Jets at large Q^2

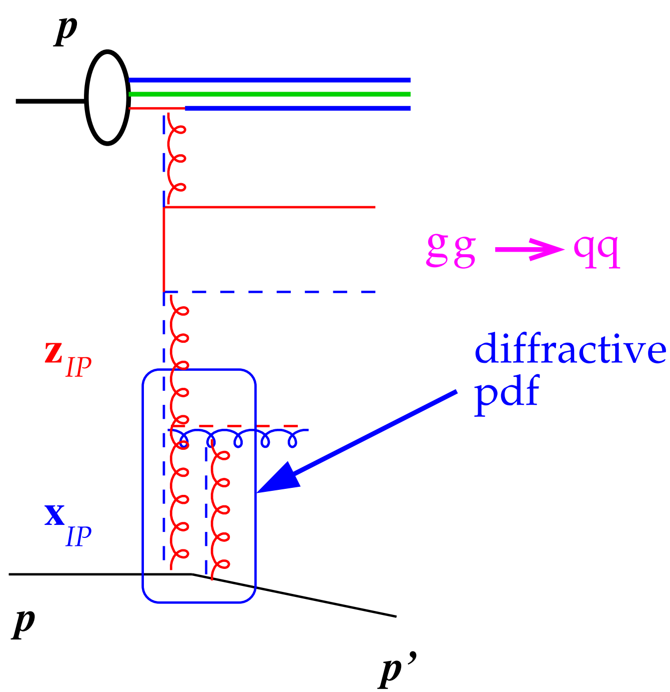


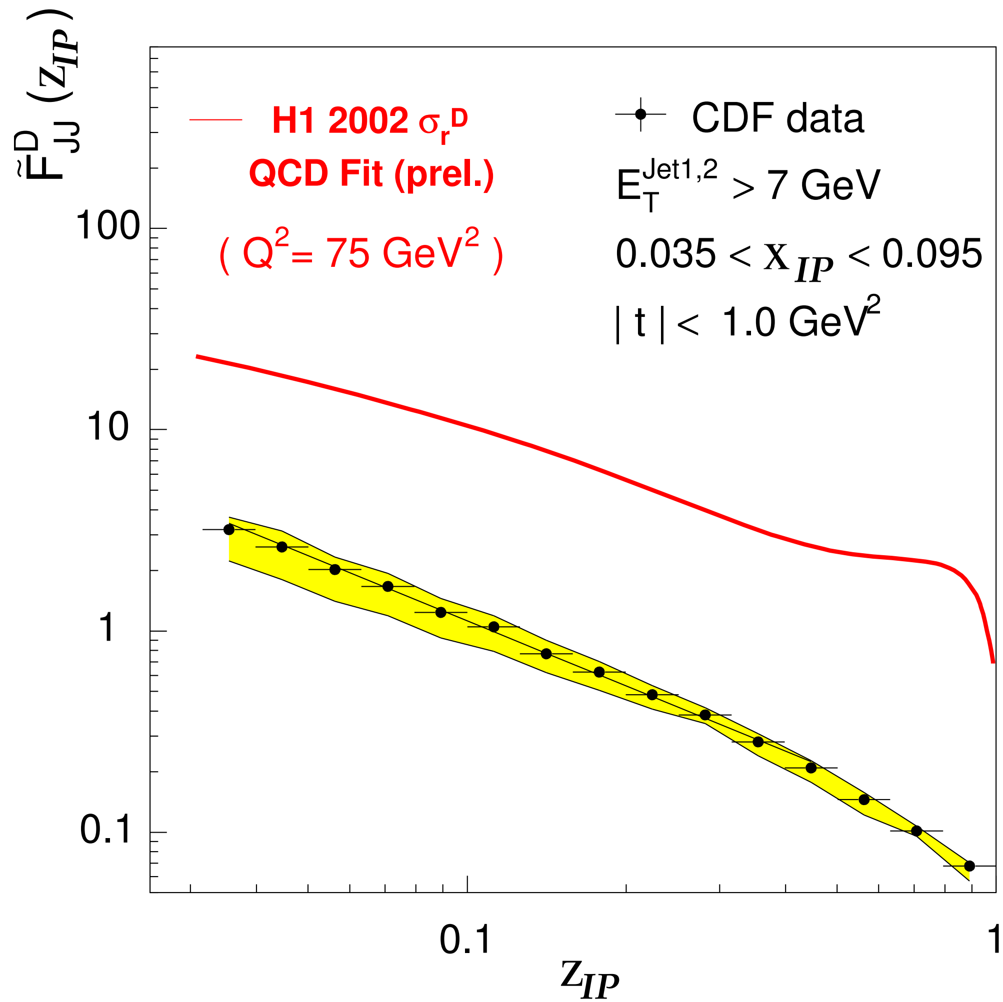


- Good description of measurement

- **factorization in diffraction at large Q^2: ✔**

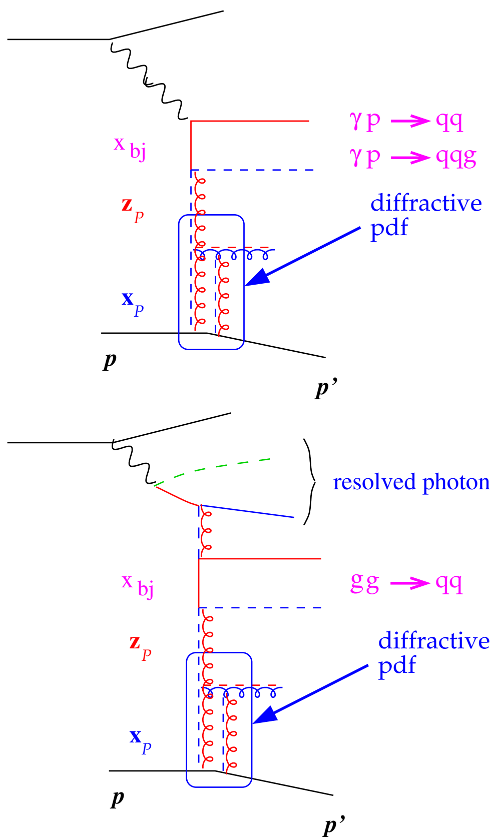
Diffractive dijets at the Tevatron

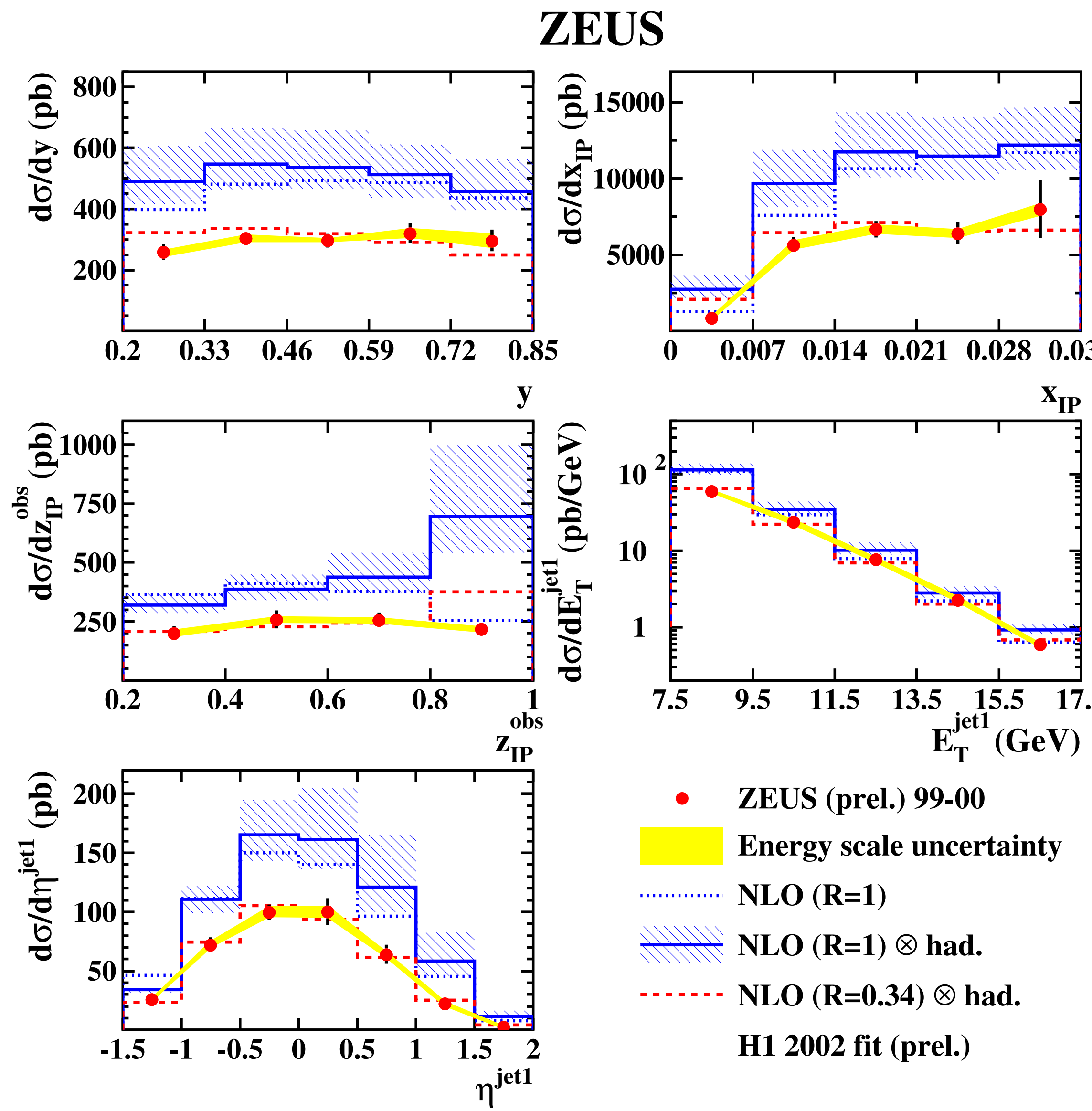




- using diffractive PDF from HERA to predict diffractive jets in $p\bar{p}$
- ☛ factor $\sim$ 10 too large
- factorization breaking in diffraction, why ?
- study dijets in γp at HERA
- suppression due to multiple scatterings ???
- different models ....

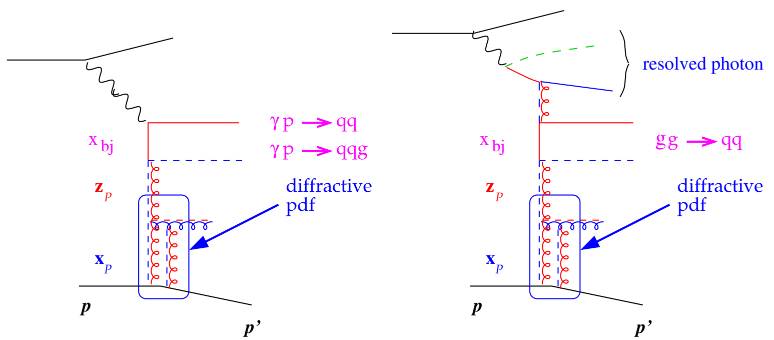
Diffractive photoproduction of dijets



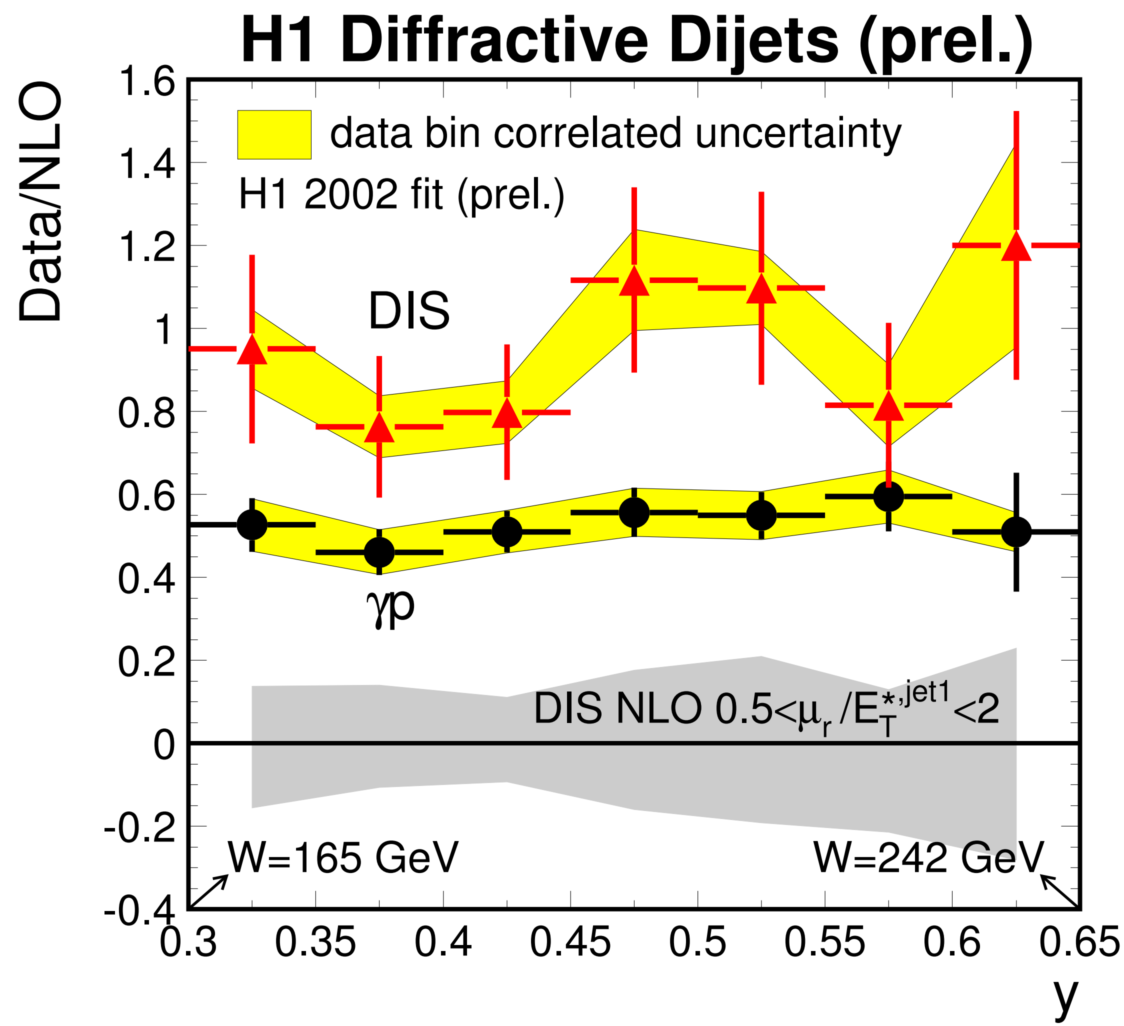


- with x_γ turn on res. photons
- resolved photon
  ☛similar to proton ...
- study suppression of diff. jet production

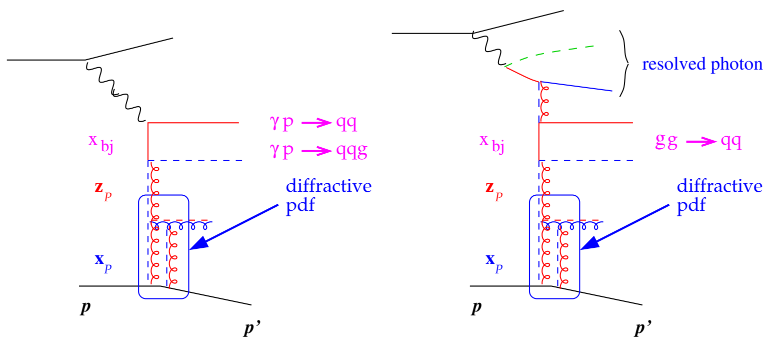
Diffractive photoproduction of dijets: bridge to diffraction in pp



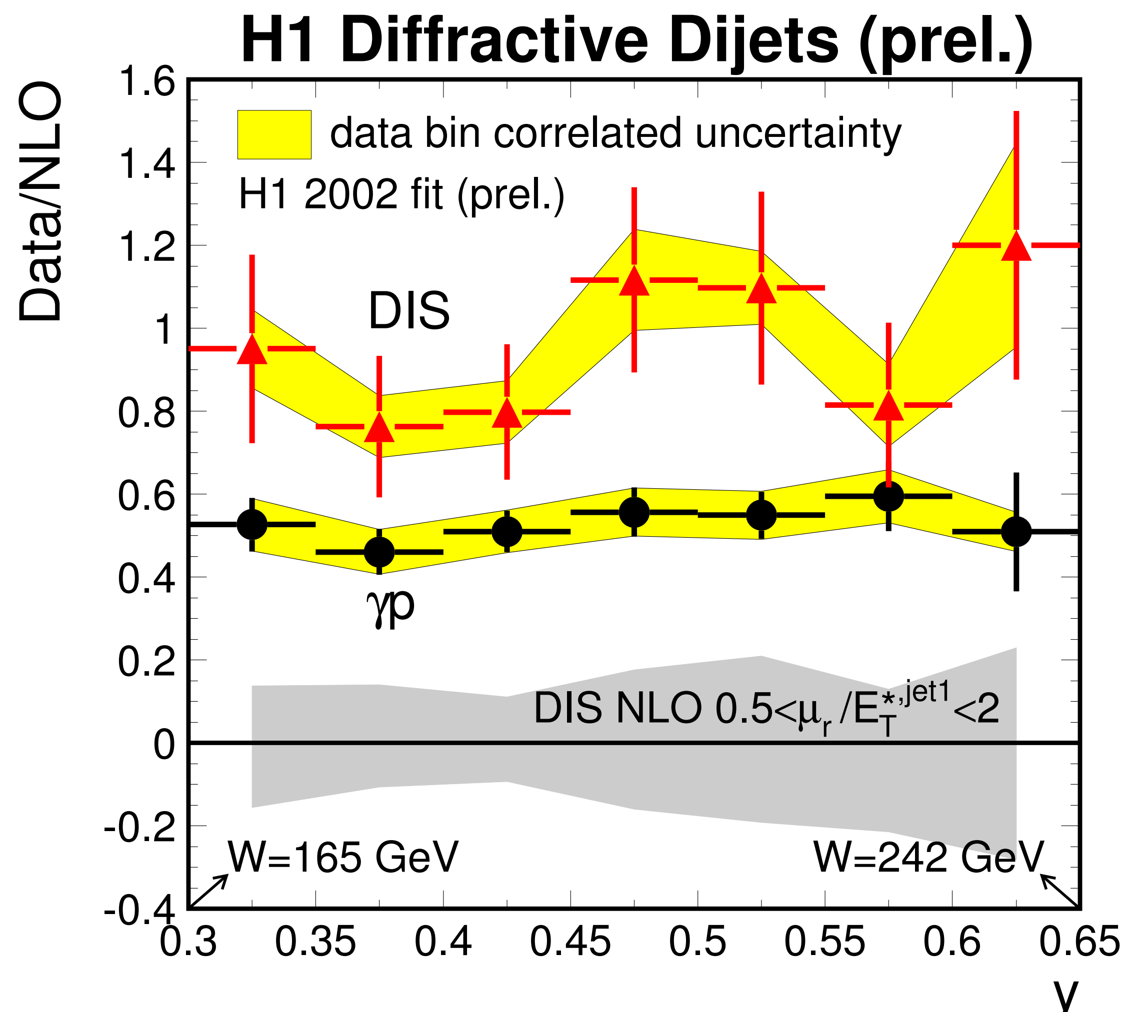
- DIS dijets agree with NLO calculation
- resolved photon $\sim$ proton !!!
- photo-production data factor $\sim$ 2 larger than NLO calc - in resolved γ and direct γ



Diffractive photoproduction of dijets: bridge to diffraction in pp



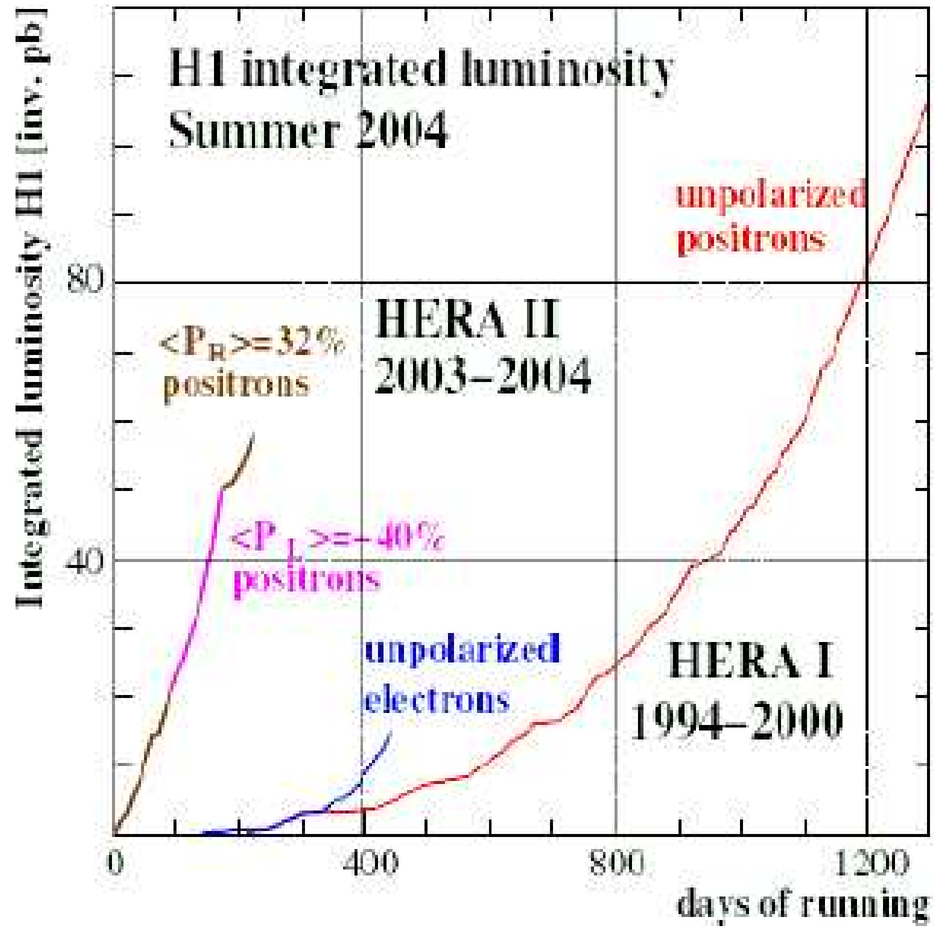
- DIS dijets agree with NLO calculation
- resolved photon ∼ proton !!!
- photo-production data factor ∼ 2 larger than NLO calc - in resolved γ and direct γ



Important also for diffractive Higgs production at LHC !!!

Performance and Program of HERA II

- detector and lumi upgrade
- efficient data taking since Oct 2003
- 1st results presented at ICHEP04
- Program:
  F_2 at high Q^2 (high stat.)
  polarized charged current,
  electroweak sector $xF_3(x, Q^2)$,
  $F_2^{c\bar{c}}(x, Q^2)$, $F_2^{b\bar{b}}(x, Q^2)$
  AND also high stat. for
  heavy quark x-sections,
  high E_T jets,
  parton dynamics in new range,
  multiple scatterings etc,
  diffraction - new proton spectrometer



New, precise measurements from HERA to come !!!

HERA - LHC workshop

Aims of the Workshop:

- To identify and prioritize those measurements to be made at HERA which have an impact on the physics reach of the LHC.
- To encourage and stimulate theory and phenomenological efforts
- To examine and improve theoretical and experimental tools
- To increase the quantitative understanding of the implication of HERA measurements on LHC physics

Midterm meeting next week !!!

Conclusions and Summary

- F_2 - total cross section, $2-3\ \%$ precision reached:

✔ 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 ???

- Diffraction ☛ understand parton radiation

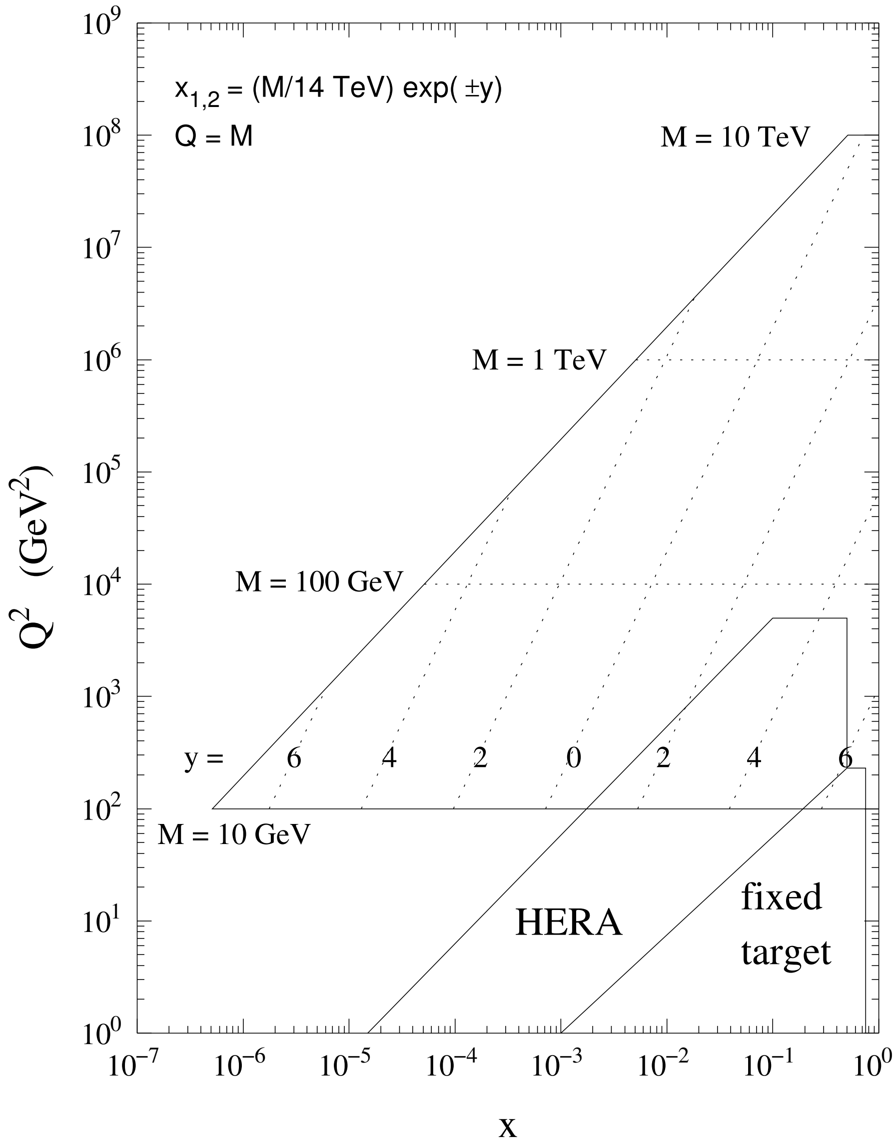
☛ bridge to multiple scatterings

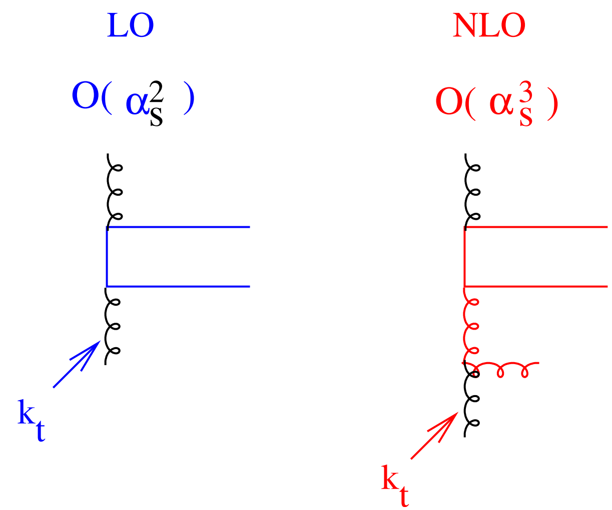
☛ measure it ...

- Future:
  - more data still to come ... HERA 2, and ?
  - fruitful collaboration between HERA and LHC

Understanding QCD at small x is the challenge !!!

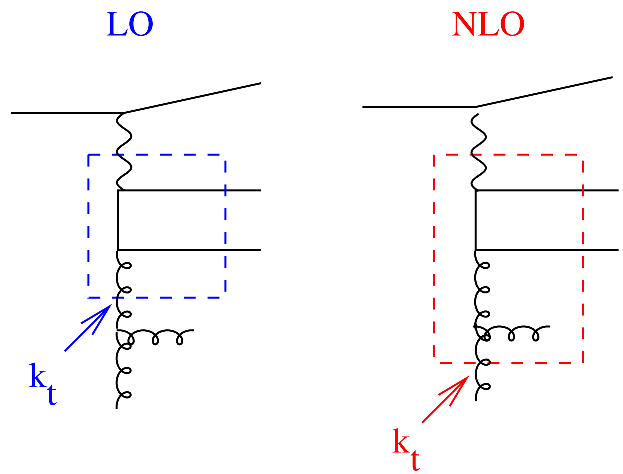
Overlap of HERA and the LHC

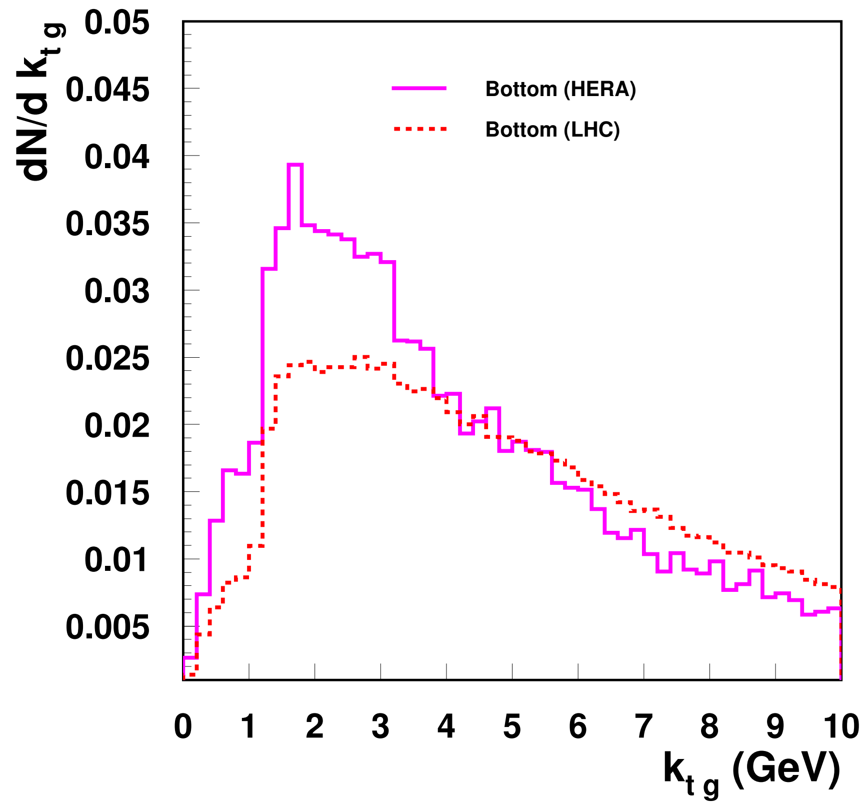




- Q^2, or p_t^2 or E_t^2 gives the maximum possible k_t
- for most applications small k_t important
- large Q^2 gives larger tail of distribution
- goto uPDFs ?

Is our picture correct ?





- is Q^2, or p_t^2 or E_t^2 the relevant scale ?
- largest x-section at small k_t
- it is the k_t that matters....

- k_t's in the same range for HERA and LHC !!!!