Recent Highlights on Heavy Flavour Physics at HERA

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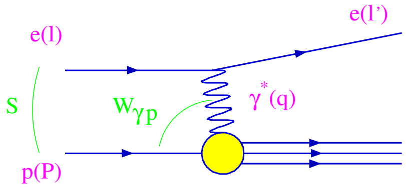
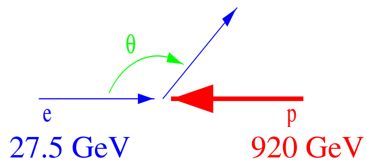
for the H1 and ZEUS collaborations

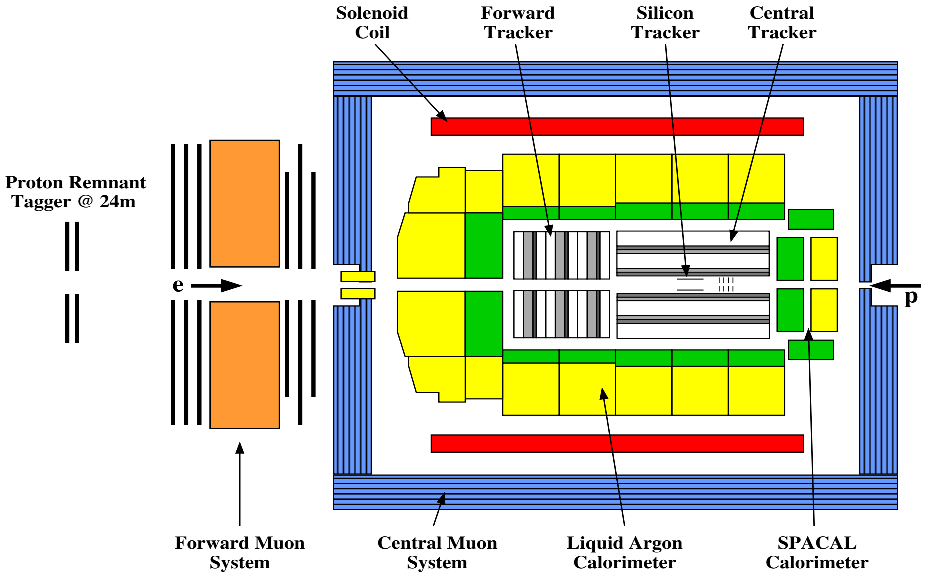
Outline of the Presentation

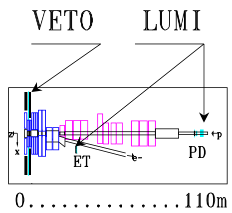
- Introduction
- Parton distributions in the proton
- Photon structure
- Comparisons with pQCD
- Summary

Kinematics of Deep Inelastic Scattering









Electron taggers at 33m and 44m →

Electron beam ⇒source of quasi-real photons
HERA ⇒ electron-proton and photon-proton collider !

$$Q^2 = -q^2 = -(\ell - \ell')^2 = 4E_e E'_e \cos\frac{\theta}{2}$$

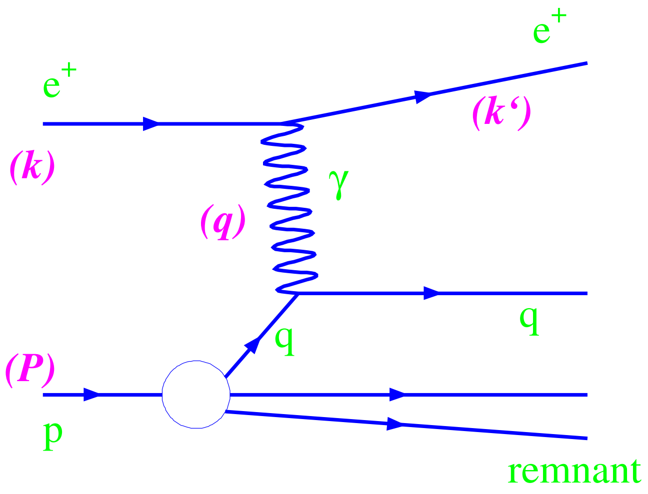
$$y = \frac{q \cdot P}{\ell \cdot P} \qquad x = \frac{Q^2}{2P \cdot q}$$

$$W^2 = (q+P)^2 \approx ys - Q^2 \qquad \eta = -ln(tan\frac{\theta}{2})$$

$$Q^2 = sxy$$

Structure functions and parton distributions

Deep inelastic scattering



$Q^2 = -q^2$ virtuality ("size" of probe)

x momentum fraction of struck parton

factorization: $\sigma \sim f_p(x) \otimes \hat{\sigma}$

$f_p(x)$ parton densities — includes soft parts

$\hat{\sigma}$ pQCD cross sections — process dependent

$$F_2(x, Q^2) = x \Sigma_q e_q^2 (q(x, Q^2) + \bar{q}(x, Q^2))$$

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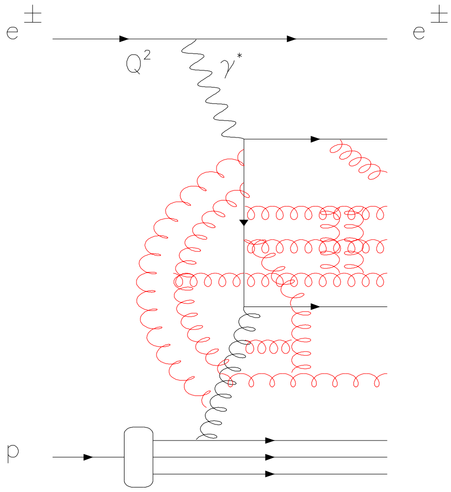
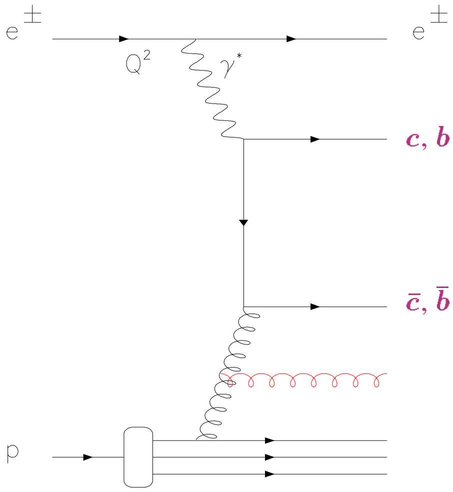
Heavy Flavour Physics

factorization applies only in presence of a hard scale

In many processes no hard scale available



need jets or high Q^2 or
heavy quark mass provide hard scale



excellent testing ground for pQCD

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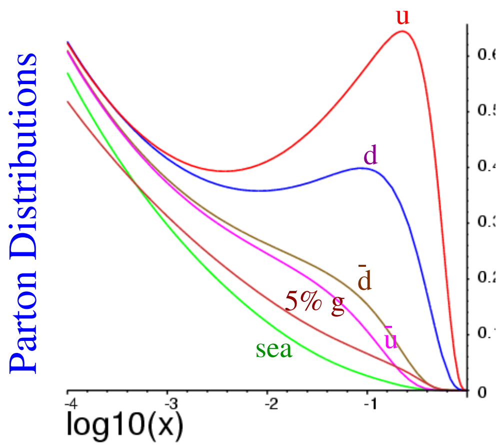
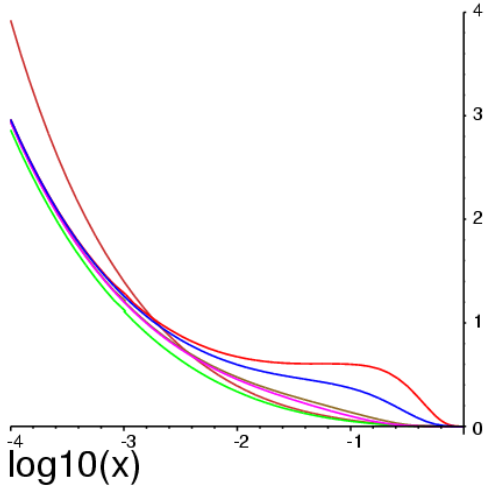


At low values of x 'steeply rising sea' $\rightarrow$ gluons

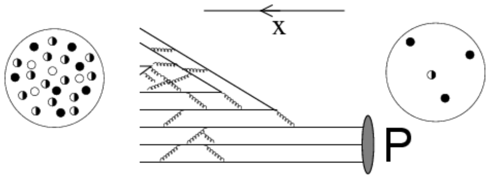
- Measure at fixed scale Q_0^2
- QCD evolution as a function of Q^2



QPM: xq_i don't depend on Q^2 $\rightarrow$ 'scaling'

increasing Q^2 $\Longrightarrow$

more $\bar{q}q$ pairs



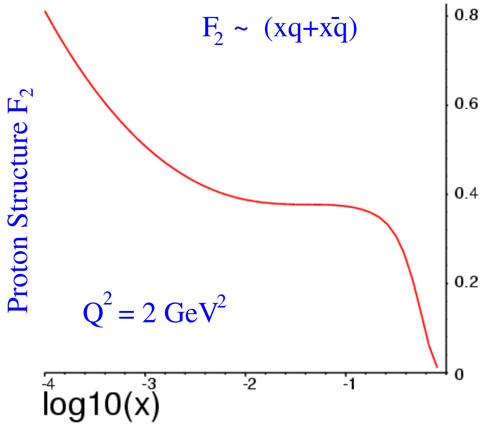
QCD $\rightarrow$ Production of $q\bar{q}$

$\rightarrow$ Dependence of the structure function from Q^2

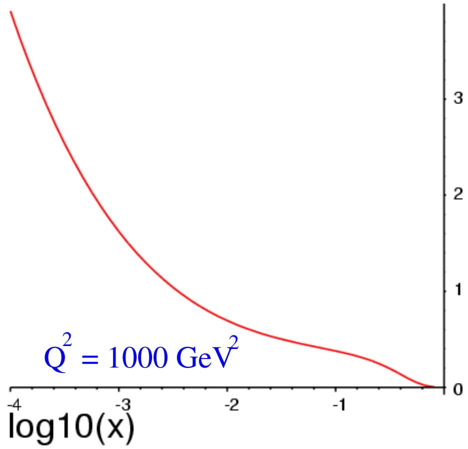
$\rightarrow$ Scaling violation

low x
increasing

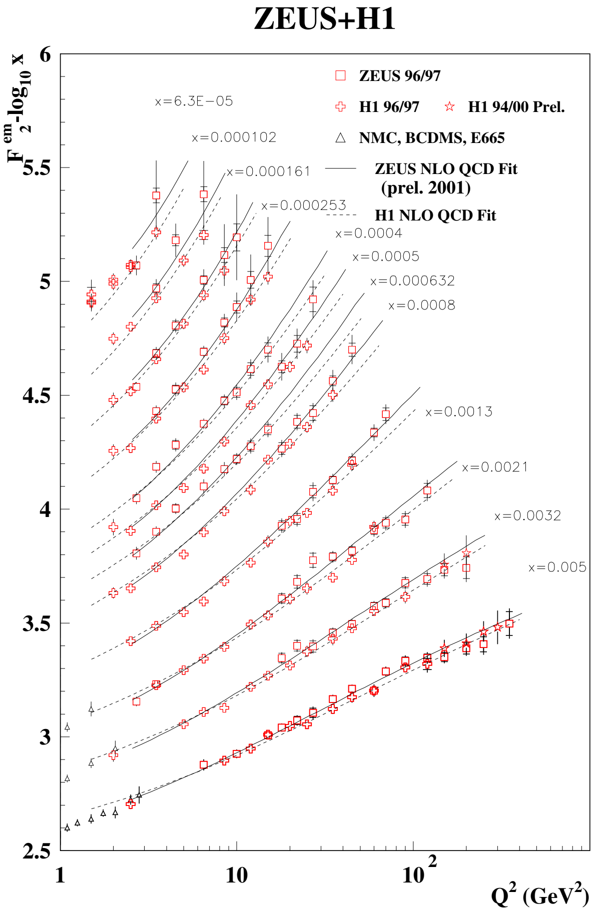
high x
decreasing

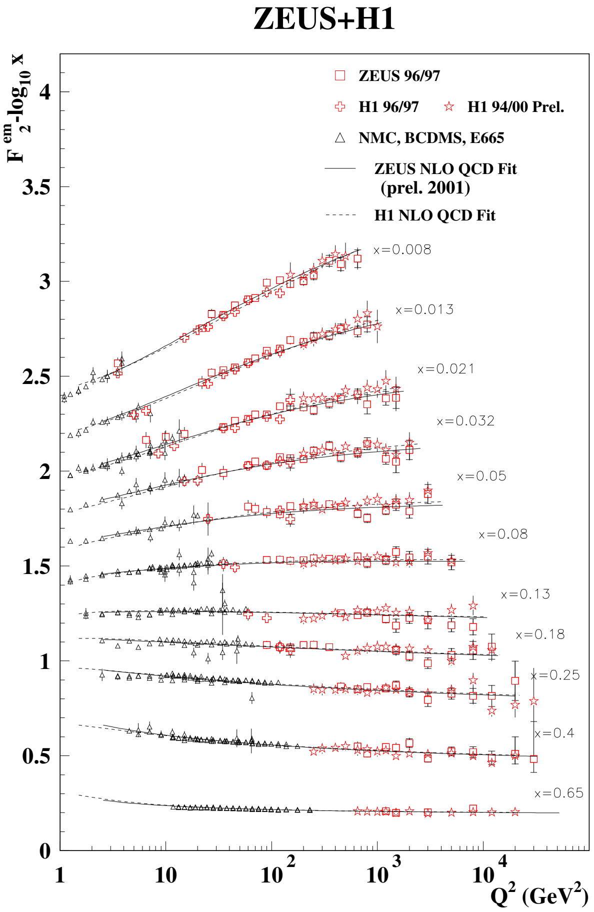


$xq(x, Q^2)$ evolves with Q^2 and
is described by QCD
pQCD $\longrightarrow$ evolution equation DGLAP

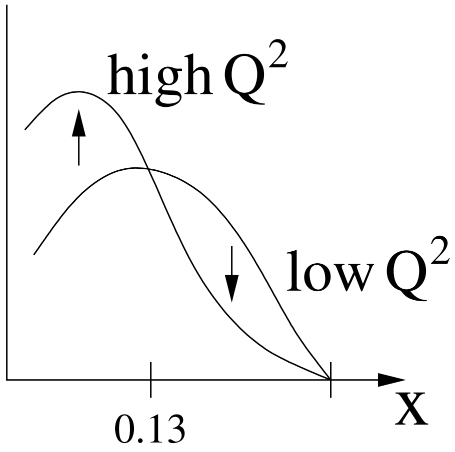


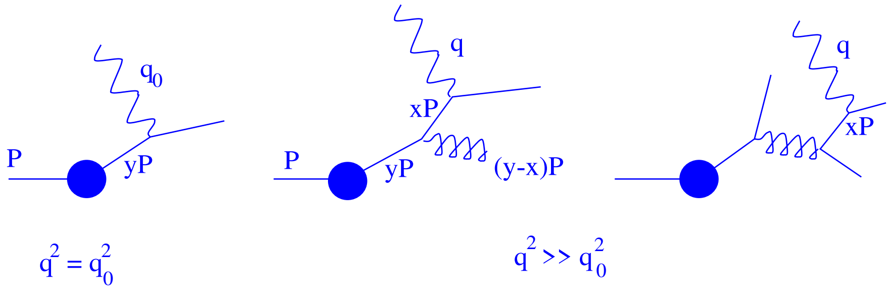
Scaling Violations of the Proton Structure Function





Testing pQCD between $Q^2 \sim 1$ and $Q^2 \sim 30000 GeV^2$
At low values of x 'steeply rising sea' $\longrightarrow$ gluons





The scaling violation is described by pQCD

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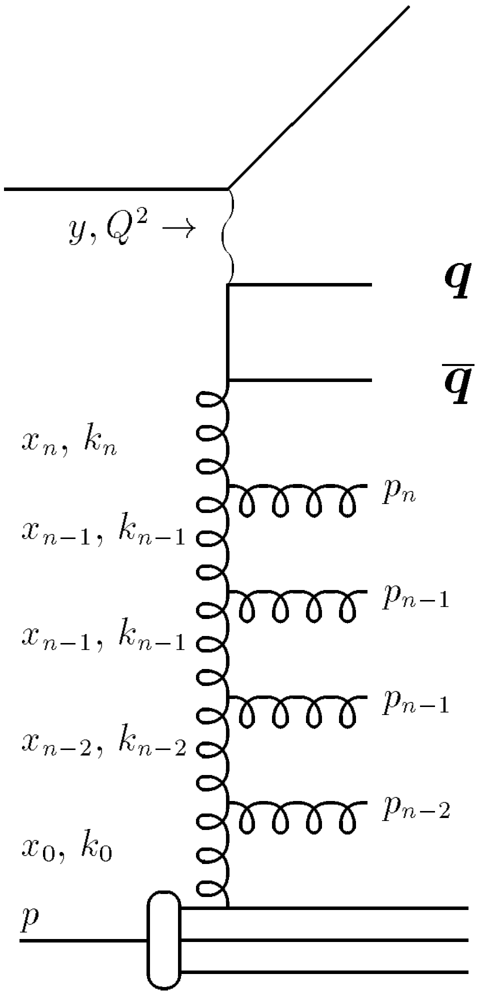
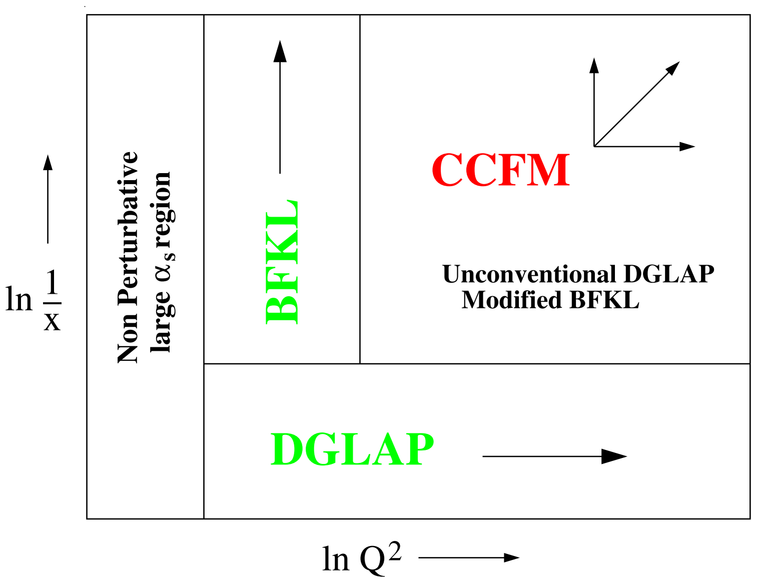
QCD Evolution





Ordered in

k_T	η	x
DGLAP	CCFM	BFKL

$$\text{BFKL} \quad \xleftarrow{x \to 0} \quad \text{CCFM} \quad \xrightarrow{x \to 1} \quad \text{DGLAP}$$

DGLAP: NLO pQCD of $c\bar{c}$, $b\bar{b}$: FMNR, HVQDIS

CCFM: new MC generator CASCADE available

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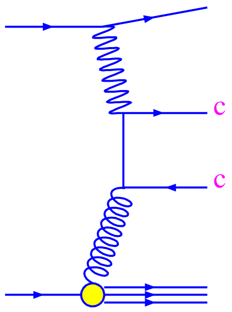
Heavy Quark Production at HERA

- $Q^2 \sim 0$ **Photoproduction(γp)**

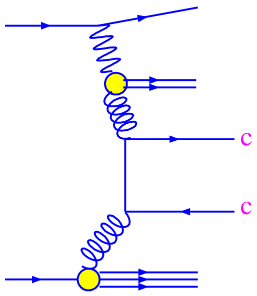
  – dominated by the exchange of almost real photons

  – The incident e is scattered at very small angles

Direct (BGF)



Resolved



  – real photons have partonic structure

- $Q^2 \geq 1GeV^2$ **Deep Inelastic Scattering** (DIS)

  ○ Exchange of virtual photons

  ○ The incident electron is scattered at large angles and therefore can be detected/measured by the calorimeter.

  ○ how important is partonic structure for virtual photon?

Heavy Flavour Physics

Tests of perturbative QCD in ep interactions

- Understanding of heavy flavour production mechanism
- Understanding of QCD evolution scheme
- Measurement of parton densities
  - sensitive to the gluon density in the proton
  - sensitive to the "photon structure"

$\Downarrow$

Testing universality of PDFs

- Charm production cross section quite large
  BUT intrinsic scale (m_c) close to pQCD limit
- Beauty production: Intrinsic scale (m_b) quite far from pQCD limit BUT cross section small

- understand QCD dynamics with c and b quarks
- test fragmentation for HQ

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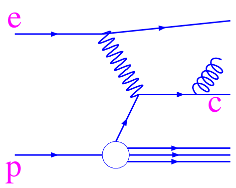
Open charm Production

Next-to-Leading order (NLO) calculations exist for c and b production

In NLO: sum of direct and resolved contributions

Various calculation schemes based on

- the DGLAP evolution:
  - "Massive" approach $m_c \neq 0$ (Frixione et al., Harris et al.)
    number of active flavours in the proton $N_f = 3$
  - "Massless" approach $m_c = 0$ (Kniehl, Kramer, Cacciari, Greco...)
    number of active flavours $N_f = 4$
    for $p_T \gg m_c$,


  - Variable Flavour Number Scheme
    (Aivazis, Olness, Collins, Tung) (Cacciari, Frixione, Nason)
    adjust number of partons N_f according to relevant scale taking mass effects into account
- the CCFM evolution
  (Ciafaloni, Catani, Fiorani and Marchesini)

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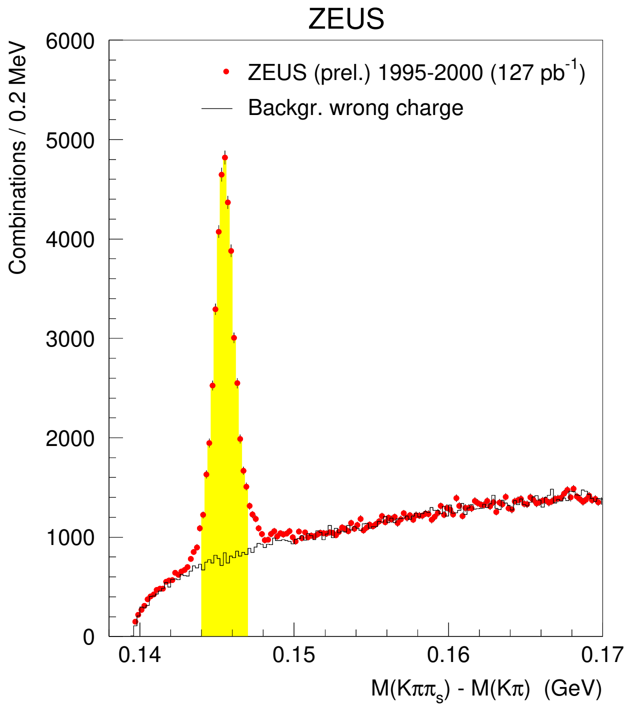
Charm Tagging

- D^{*+} mesons $\quad f(c \to D^{*\pm}) : 23.5\%$

$D^{*+} \to D^0\pi^+$ $\quad$ H1 and ZEUS

$\quad\quad \hookrightarrow K^-\pi^+$

$\quad\quad \hookrightarrow K^-\pi^+\pi^+\pi^-$ $\quad$ ZEUS



- semileptonic decays of charm into electrons $\quad$ ZEUS
  $f(c \to e^+X) : 9.8\%$

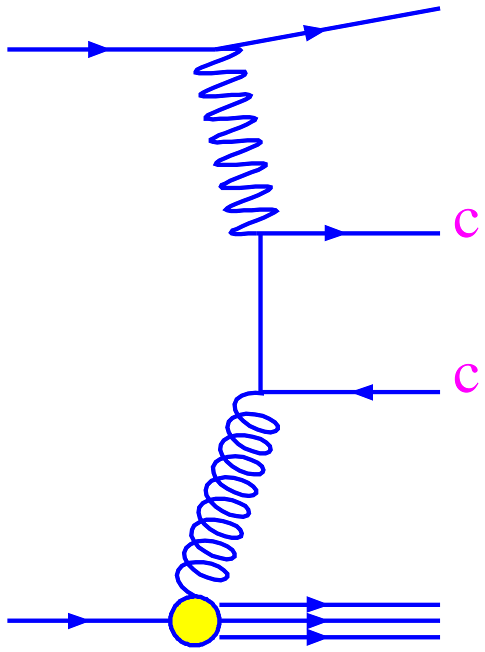
definition of "visible" range in terms of

$p_t(D^{*+}, e)$ and $\eta(D^{*+}, e)$

Deep Inelastic Scattering

DIS: high γ^* virtuality Q^2

study of open charm production in DIS



- sensitive to the gluon density in the proton
- DGLAP vs CCFM evolution

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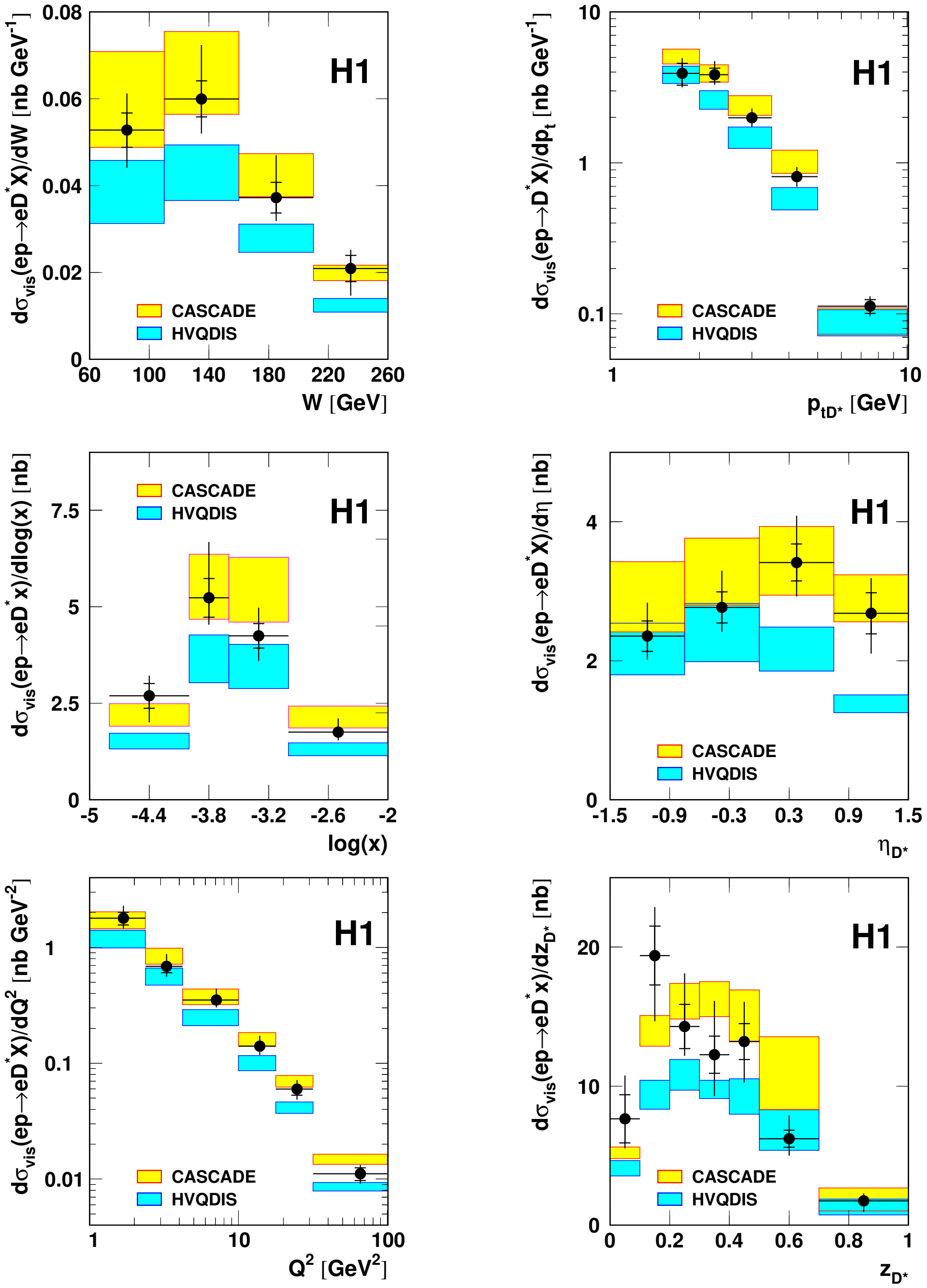
Differential Cross Sections



HVQDIS and CASCADE

GRV98HO, $m_c 1.3 - 1.5$GeV

$p_t(c \to D^*)$, ϵ_c $0.035 - 0.1$

gluon from F_2 fit, $m_c 1.3 - 1.5$GeV

ϵ_c $0.035 - 0.1$

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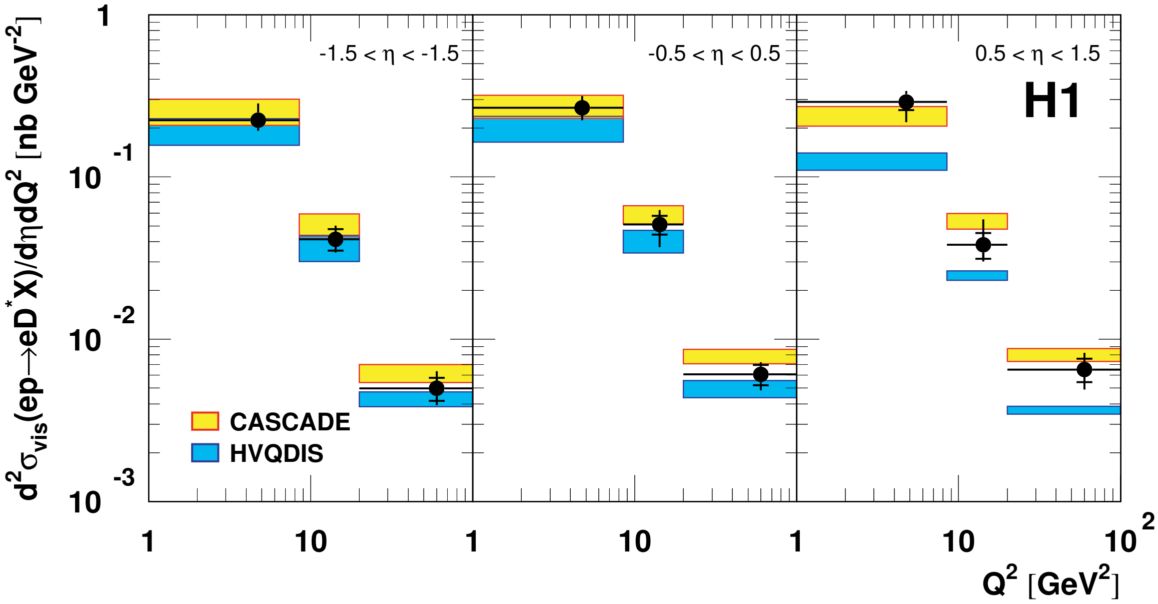
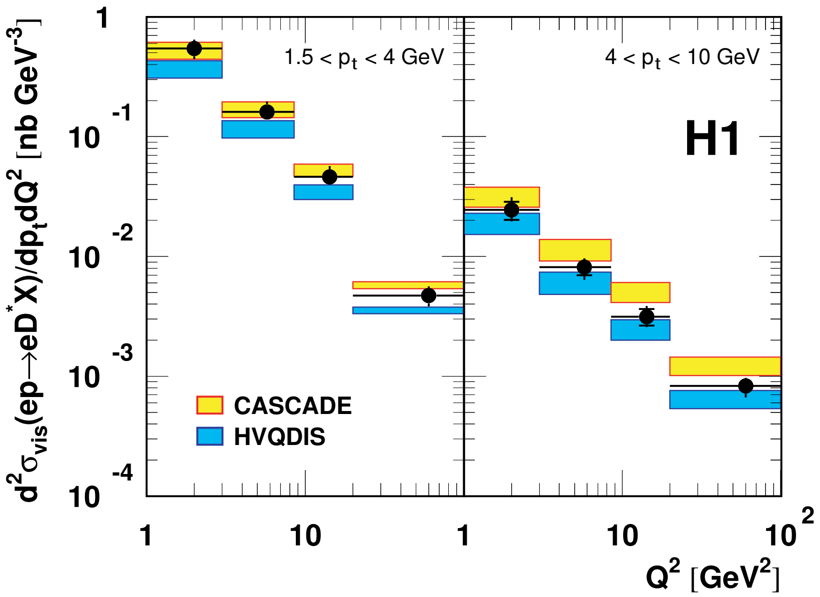
Double Differential Cross Sections





forward region : excess does not depend on Q^2
(large η) CCFM gives a better description of the data

CCFM better at low p_{TD*} NLO DGLAP better at high p_{TD*}

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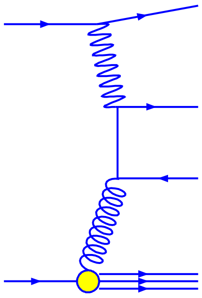
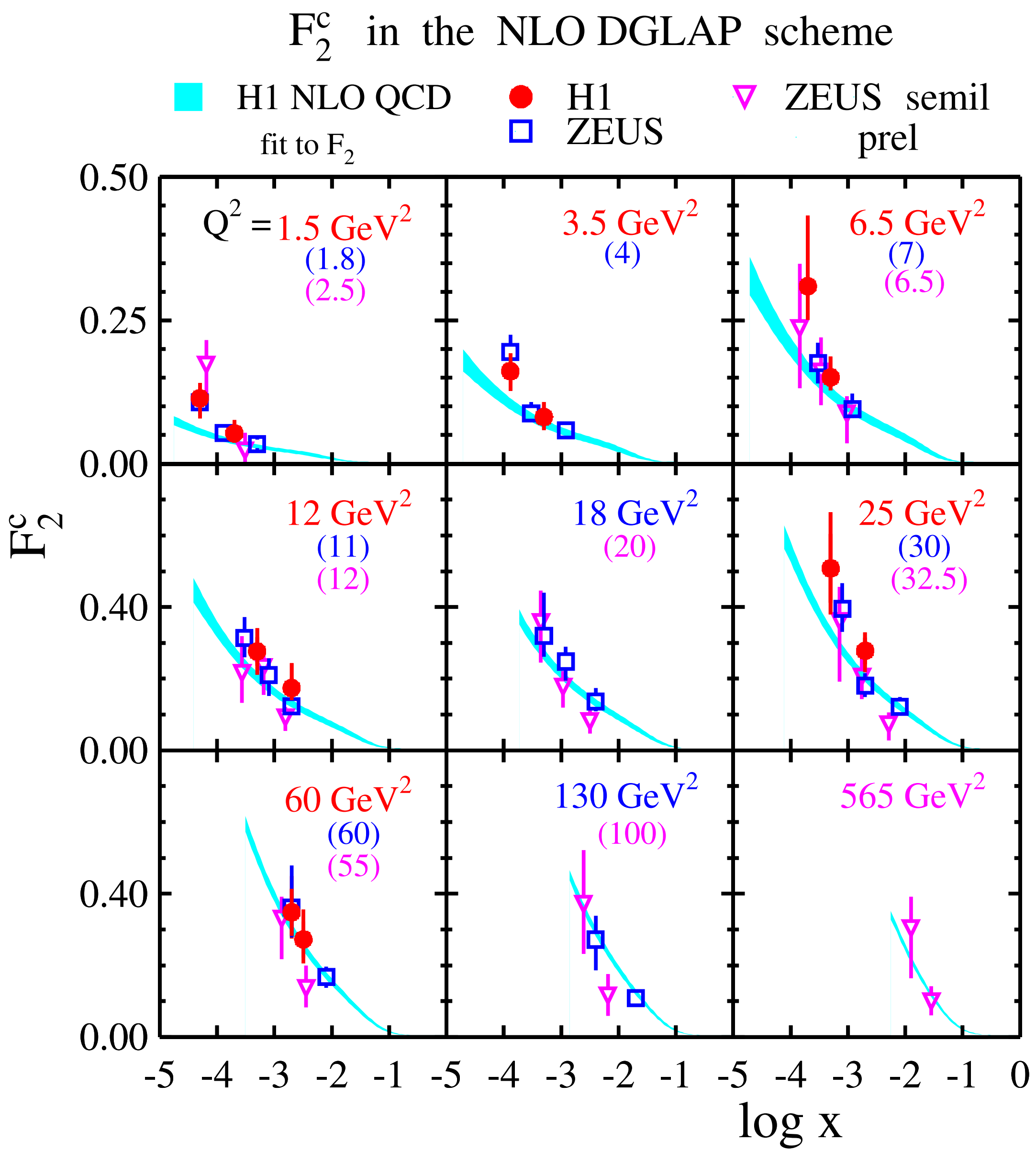
Extraction of $F_2^c(x,Q^2)$

$$\frac{d^2\sigma^{c\bar{c}}}{dx\,dQ^2} = \frac{2\pi\alpha^2}{xQ^4}(1+(1-y)^2)\cdot F_2^{c\bar{c}}(x,Q^2)$$

extrapolate outside the “visible” region in p_T and η

$$F_2^{c\ \ meas}(x,Q^2) = \sigma_{vis}^{meas}(x,Q^2)\cdot\frac{F_2^{c\ \ theo}(x,Q^2)}{\sigma_{vis}^{theo}(x,Q^2)}$$





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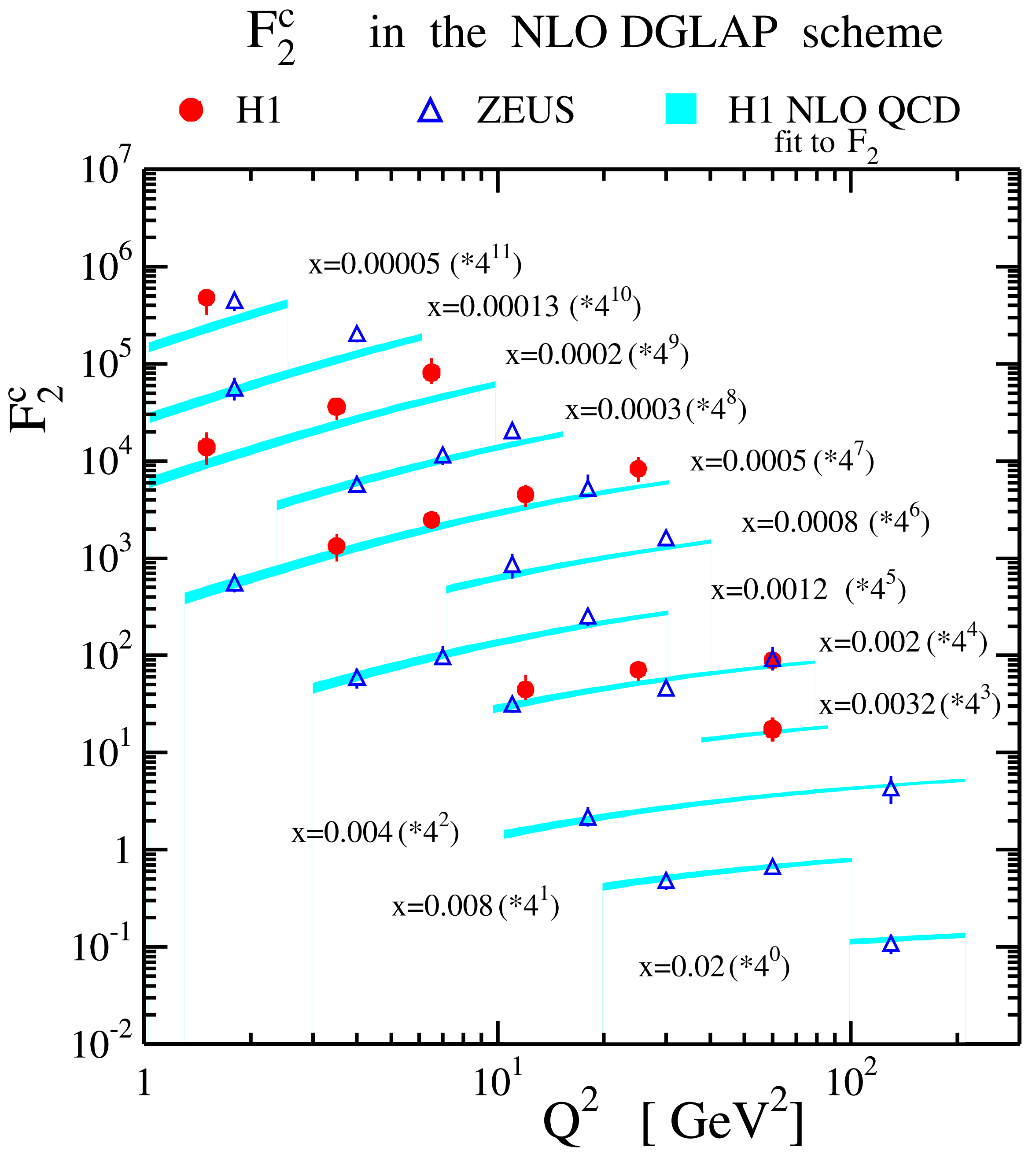
$F_2^c(x, Q^2)$



- Strong Scaling violations
- agreement with the NLO QCD fit to the inclusive F_2

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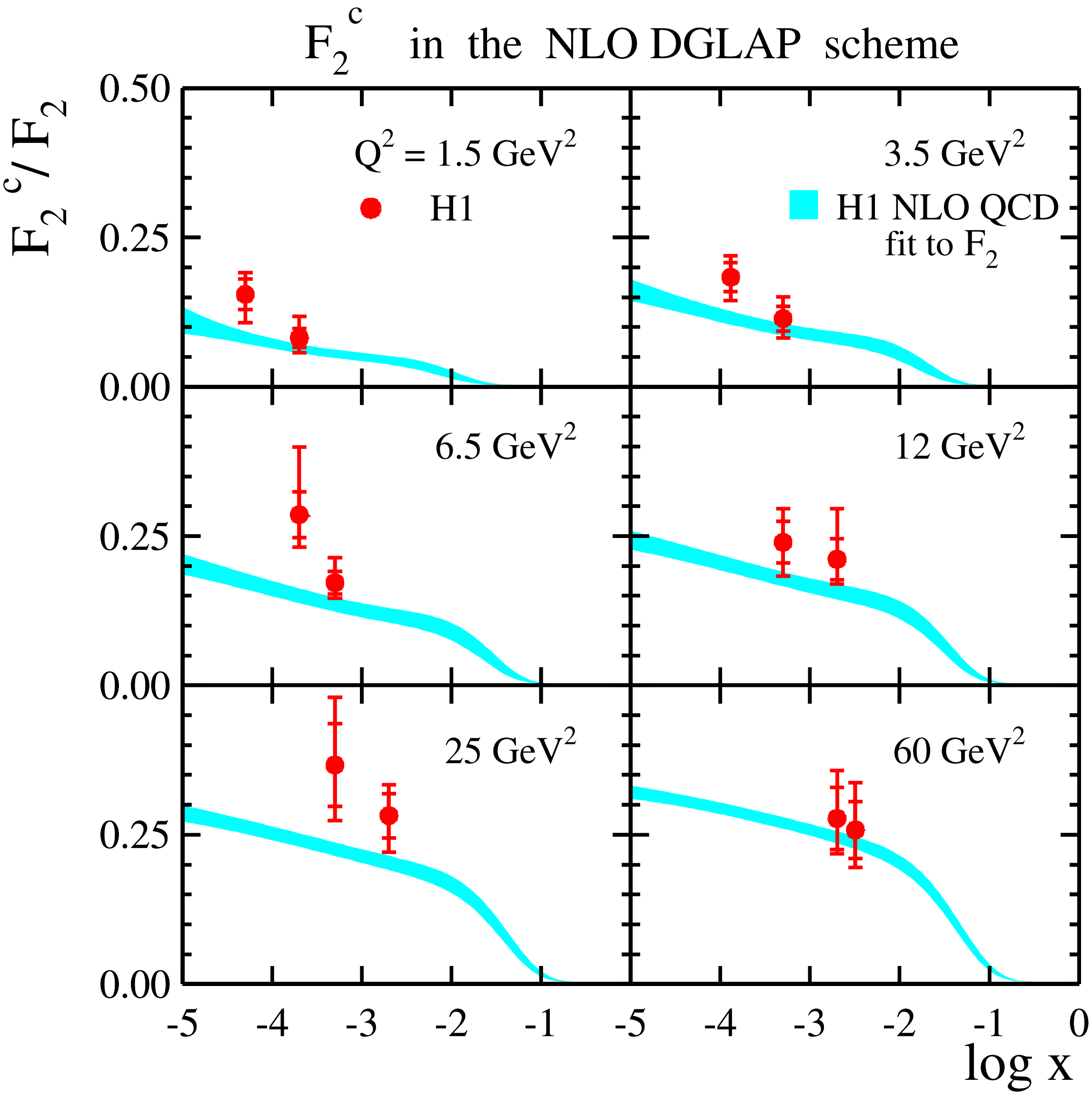
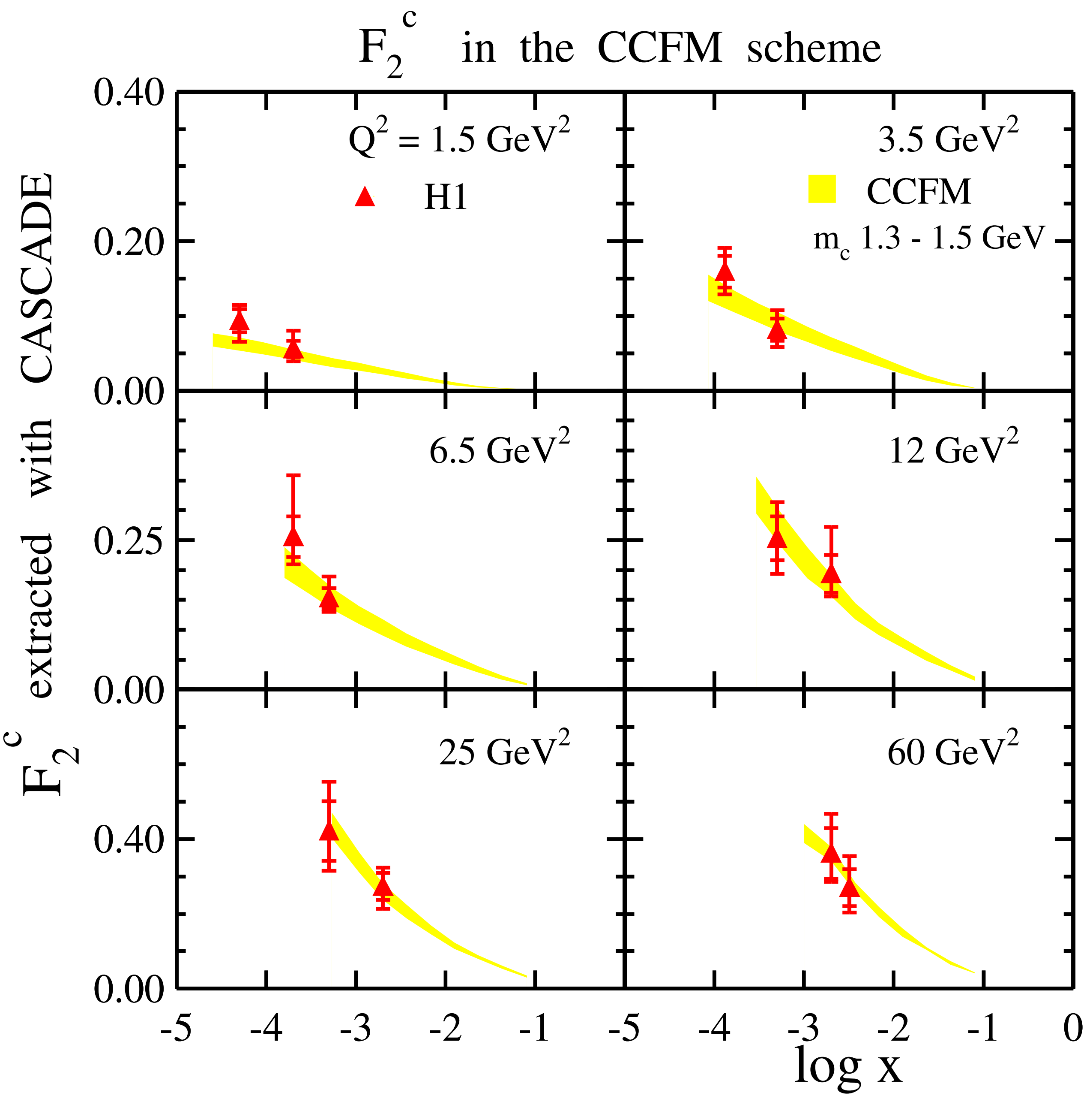
$F_2^c(x, Q^2)/F_2(x, Q^2)$



- Ratio $F_2^{c\bar{c}}/F_2$ is large $\sim 25 - 30\%$ at high Q^2 and low x

$F_2^c(x, Q^2)$



- CCFM provides a grood description of the data

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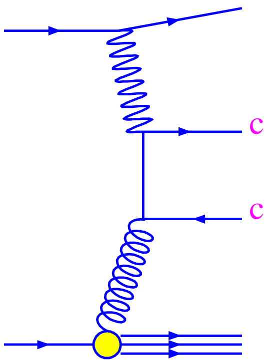
Structure of Real and Virtual Photon

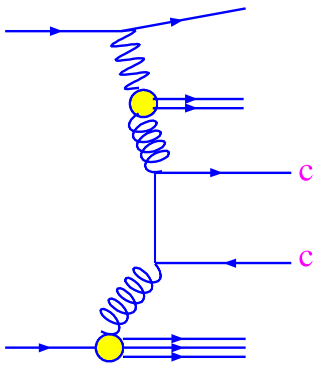
studied in the production of events with two jets

events contributing to dijet production at LO:

Direct (BGF)

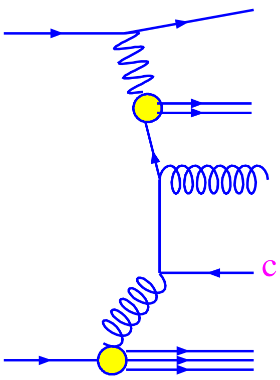


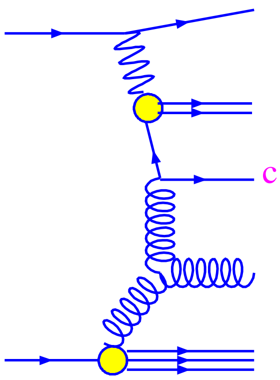
Resolved



gluon induced

charm excitation





direct and resolved separated by x_γ

x_γ: momentum fraction of the parton from photon

$$x_\gamma^{\text{obs}} = \frac{\Sigma_{\text{jets}}\, E_T e^{-\eta}}{2yE_e}$$

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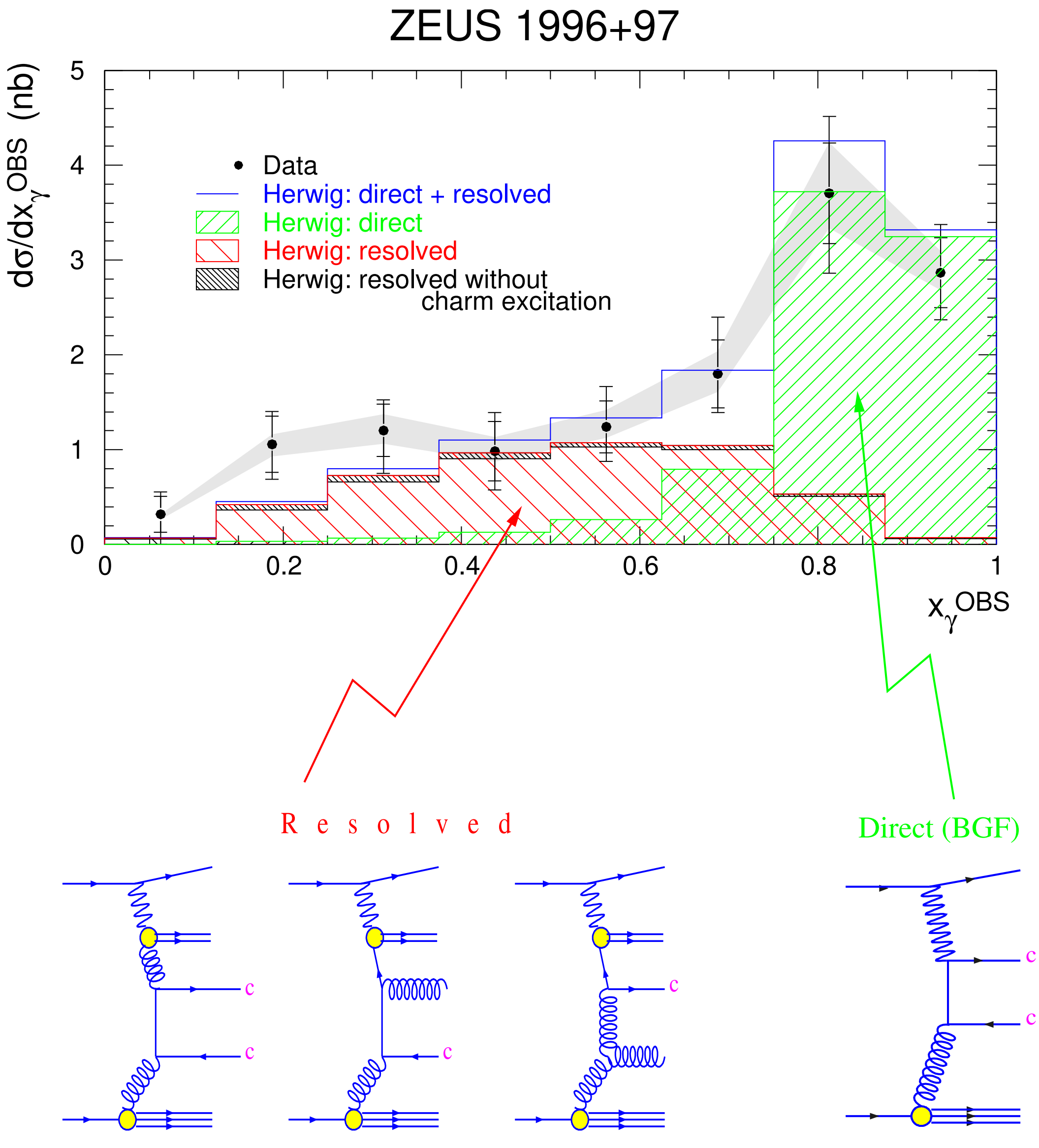
D^* in dijet photoproduction

suppression of resolved photon processes due to charm



significant contribution $\sim$ 40% of resolved photon component for dijet events with a D^*; still much below the $\sim$ 90% resolved contribution without the D^* requirement

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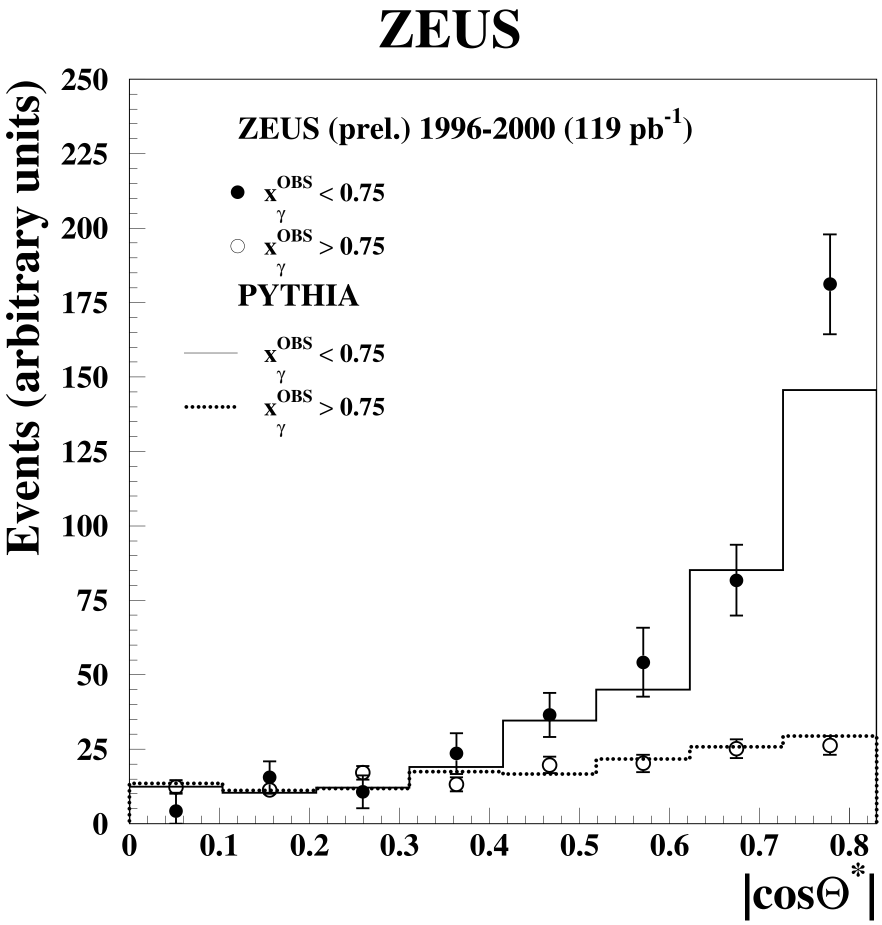
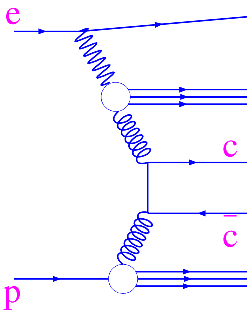
D^* in dijet photoproduction

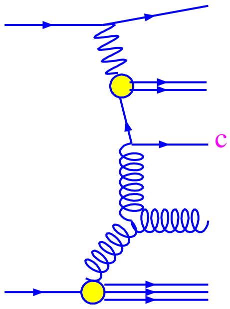
apply cut: $x_\gamma^{\rm obs} > 0.75$ to enrich in direct

and $x_\gamma^{\rm obs} < 0.75$ to enrich in resolved events





q-exchange:
$\sim (1 - |cos\theta^*|)^{-1}$



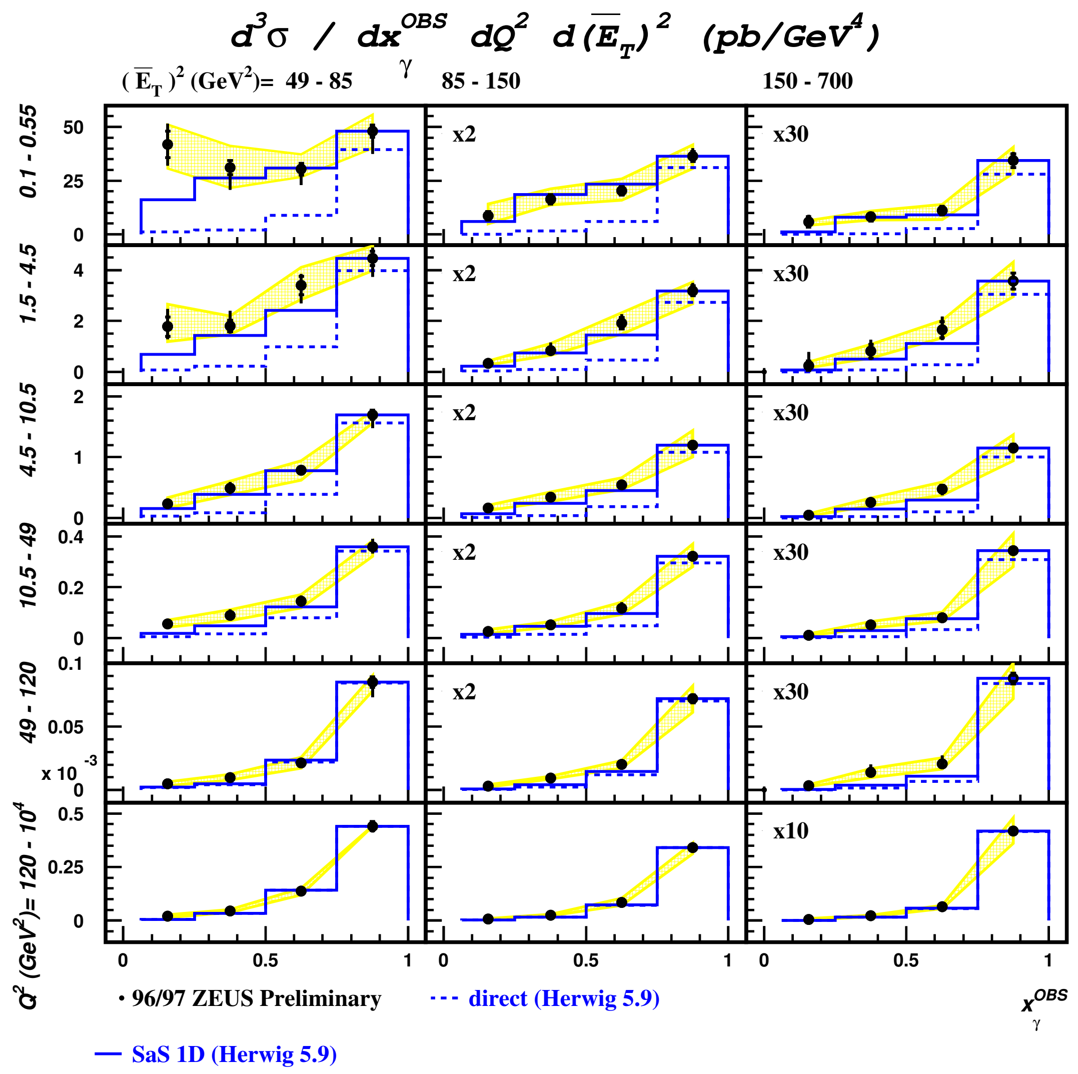
g-exchange:
$\sim (1 - |cos\theta^*|)^{-2}$

θ^*: angle between jet-jet axis and beam axis in dijet rest frame

resolved smaple $x_\gamma^{\rm obs} < 0.75$:

evidence for significant contribution from charm excitation

Differential dijet cross sections: all flavours



dijet cross section measured as a function of Q^2, $\bar{E}_T^2$ and $x_\gamma^{\rm obs}$

- low $x_\gamma^{\rm obs}$ cross section falls faster than high $x_\gamma^{\rm obs}$ with increasing Q^2 $\Rightarrow$ $\boxed{\text{suppression of resolved with } Q^2}$
- for $Q^2 > \bar{E}_T^2$ data described by LO direct

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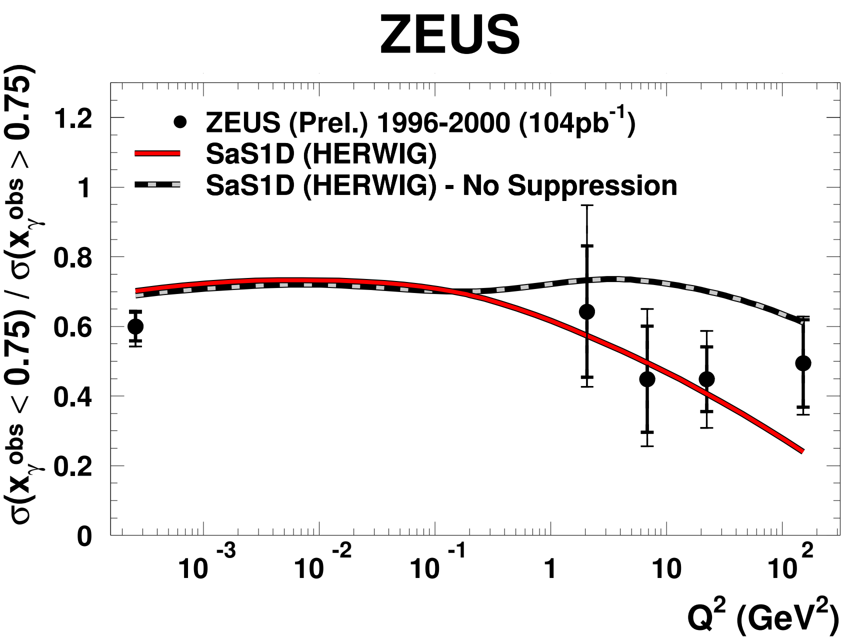
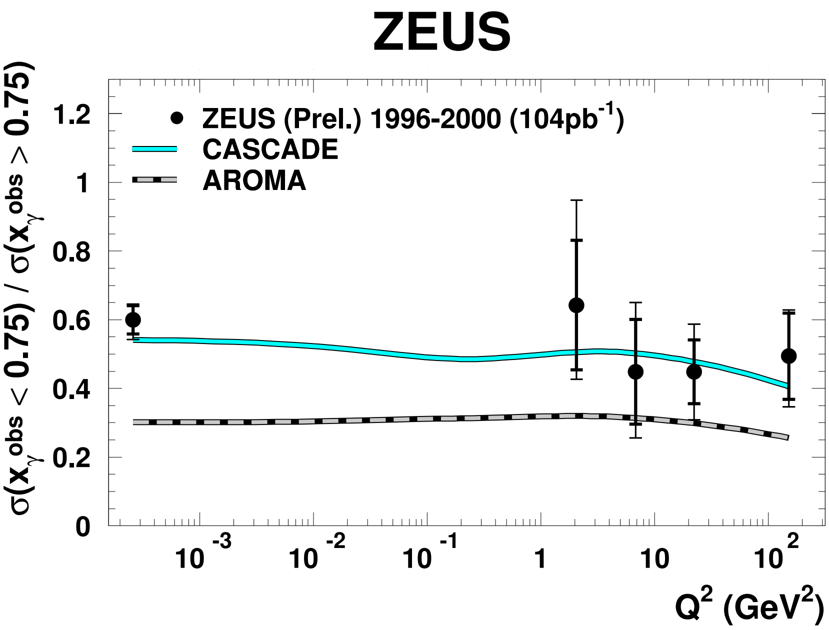
Q^2 dependence of resolved/direct contribution

Leading-Order Predictions with SAS1D-γ PDF



charm

Ratio shows little or no change with Q^2



no photon PDF

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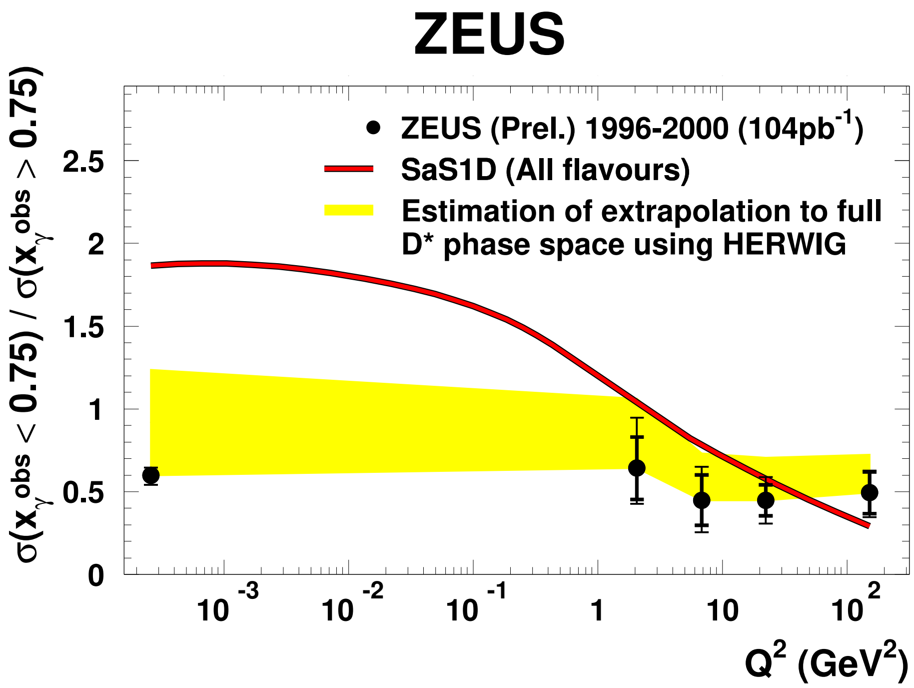
Q^2 dependence of resolved to direct contribution

charm requirment results in flatter ratio of resolved to direct contribution with increasing Q^2

suppression due to charm and Q^2 not independent?

part of the suppression due to D^* kinematical cuts



resolved contribution ($x_\gamma^{\mathrm{obs}} < 0.75$) falls much less rapidly in the presence of charm

suppressions due to Q^2 and due to charm are not independent

Conclusions: charm

- D^* production cross sections
  - measured with improved precision
  - also double differentially
  - differences seen in low x region
    CCFM and DGLAP different
    Evidence for non k_T ordered effects ?
    requires still more precise measurements

- F_2^{charm}
  - strong rise to lower x for increasing Q^2
  - large scaling violations

- D^* in dijet events
  - significant contribution of resolved photoproduction mostly due to charm excitation in the photon
  - Q^2 and charm suppression of resolved component not independent

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Open Beauty Production

$b \to \ell\,\bar{\nu}_\ell X$ with $\ell : e, \mu$

expectation

$\sigma_{uds} : \sigma_c : \sigma_b \sim 2000 : 200 : 1$

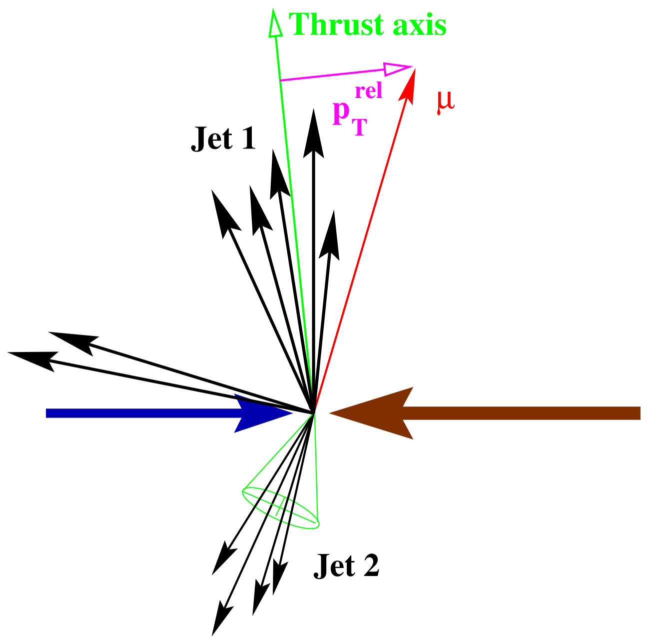
exploit large b-mass

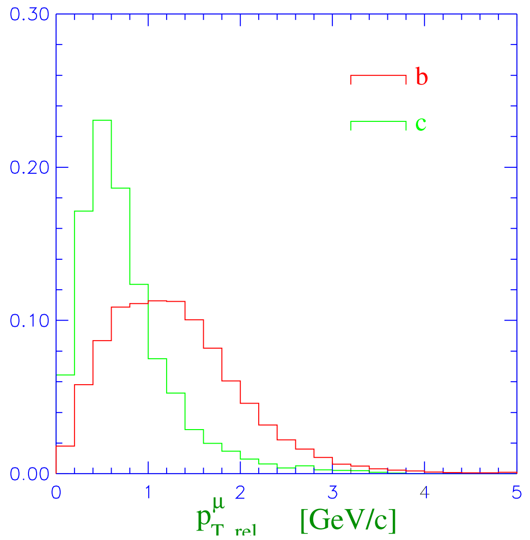
2Jets $E_T > 6$ GeV

$|\eta| < 2.5$

1μ $p^{\mu}_{T,lab} > 2\,GeV/c$ X

$35^o < \theta^\mu < 130^o$





Thrust T = max $\frac{\sum |p_i^L|}{\sum |p_i|}$

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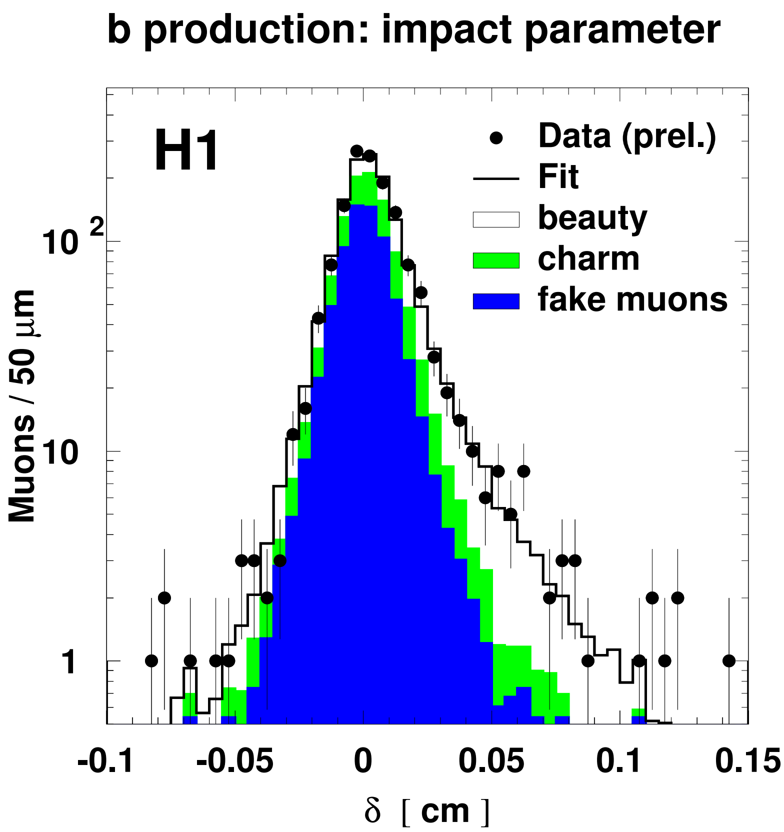
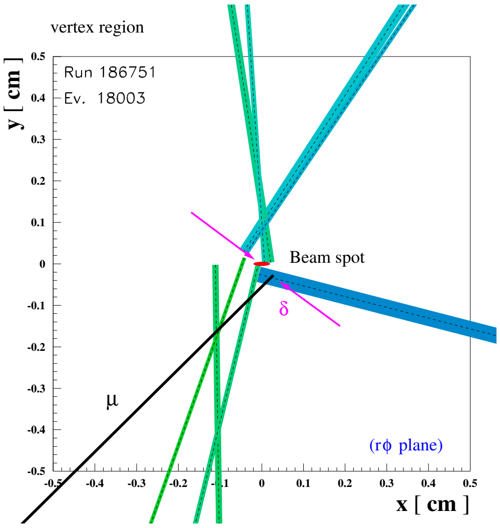
Impact Parameter

exploit longer b lifetime

2-Jet events **+ 1 muon**

$|\eta^{jet}| < 2.5 \quad E_{\perp}^{jet} > 5$ GeV $\quad p^{\mu}_{\perp,lab} > 2.0$ GeV $\quad 35^{\circ} < \Theta^{\mu} < 130^{\circ}$





$$\sigma_{vis}(ep \to eb\bar{b}X \to \mu X) = 159 \pm 30(stat.) \pm 29(syst.)\text{pb}$$

Confirms previous H1 publication

NLO QCD prediction: (*massive scheme*, BGF): 54 ± 9 pb

CASCADE: $67pb$

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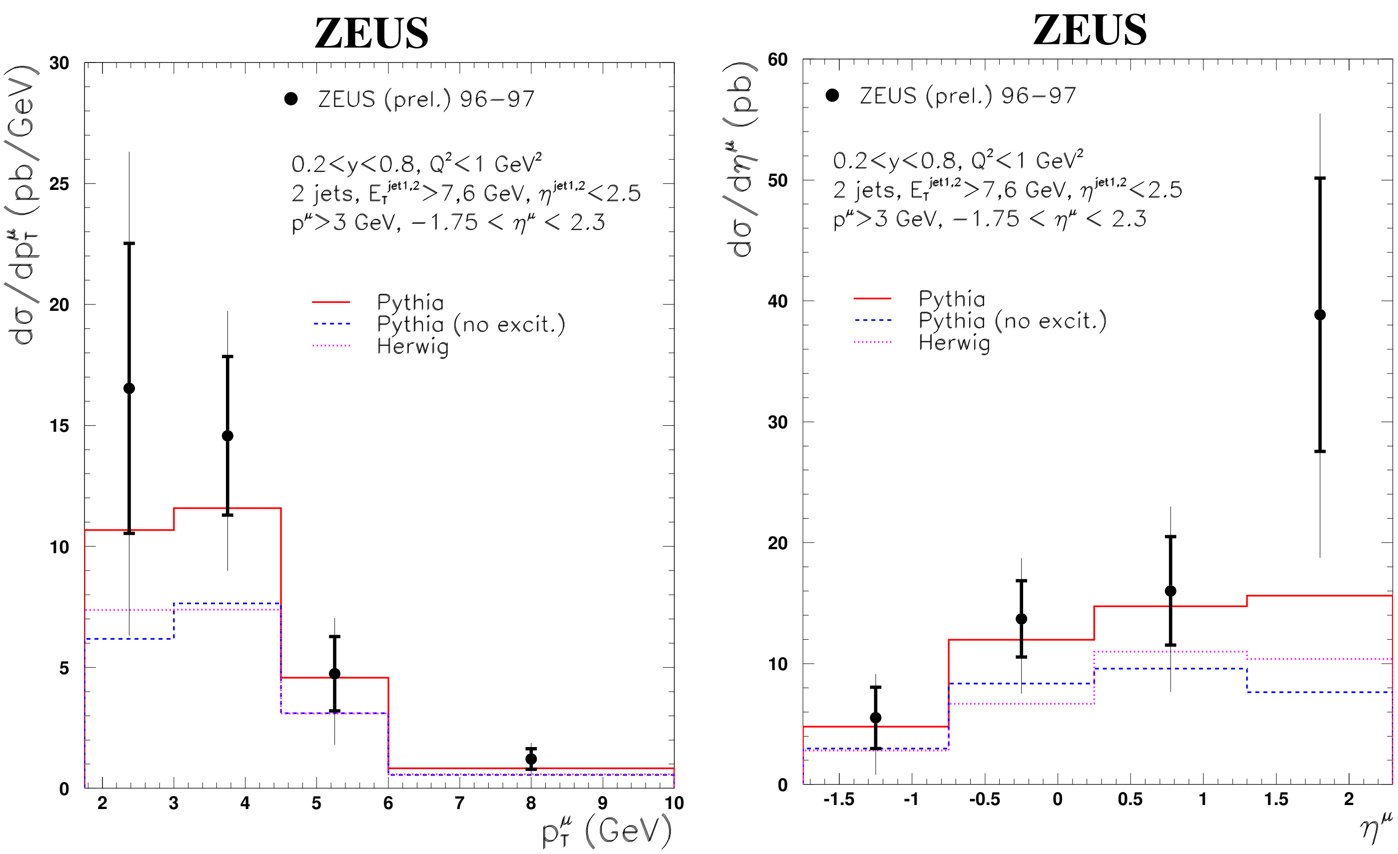
Beauty in γp: Differential cross sections

2-Jet events

$$\left|\eta^{jet}\right| < 2.5 \qquad E_{\perp}^{jet} > 7,6\ \mathrm{GeV}$$

+ 1 muon



reasonable description with LO massless MC with *b*-excitation component

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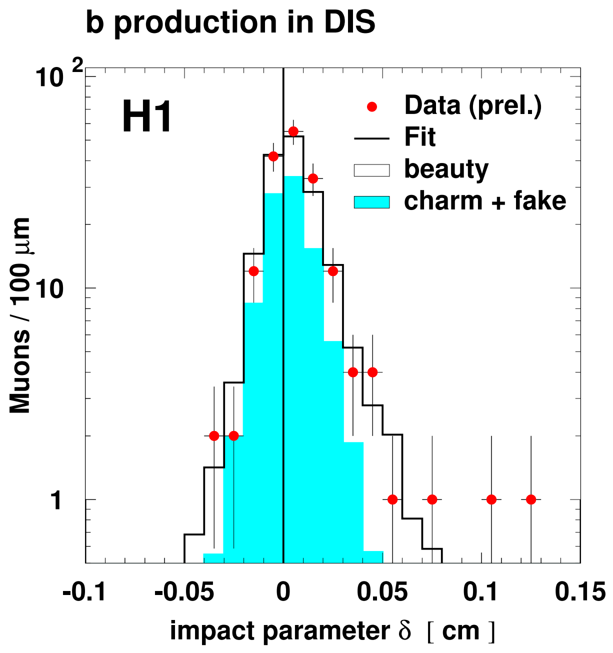
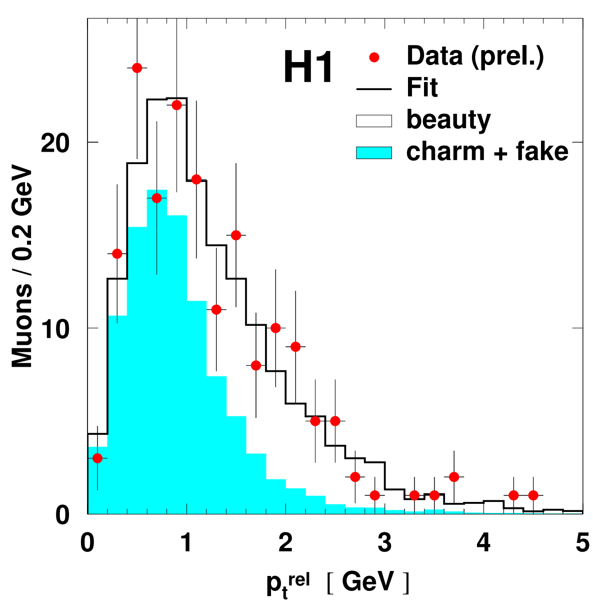
Beauty in DIS

2-Jet events $E_{\perp}^{jet} > 5$ GeV
+ 1 muon in Si tracker

Kinematic range: $2 < Q^2 < 100$ GeV^2, $0.05 < y < 0.7$
$p_T^{\mu} > 2.0$ GeV, $35^{\circ} < \theta^{\mu} < 130^{\circ}$





$$\sigma_{vis}(e^+p \rightarrow b\bar{b}X \rightarrow \mu^{\pm}X)$$

H1 prel: $39 \pm 8 \pm 10$pb	HVQDIS: 11 ± 2 pb CASCADE: 15 pb

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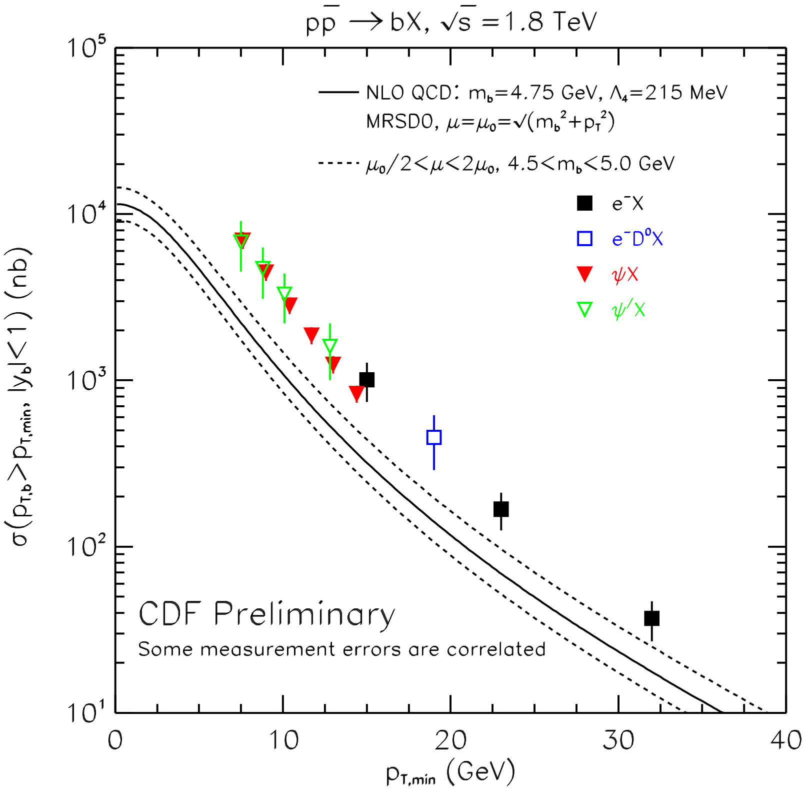
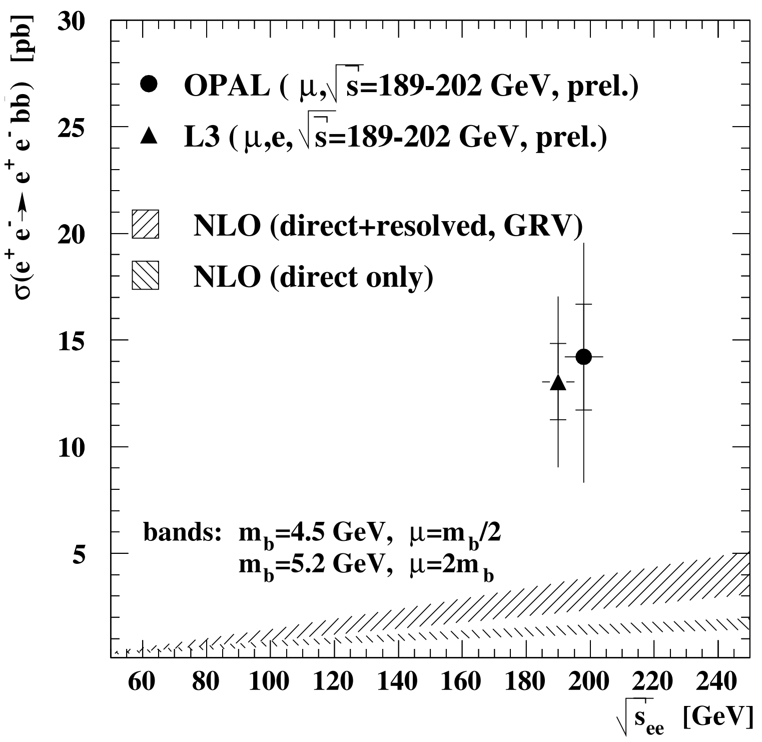
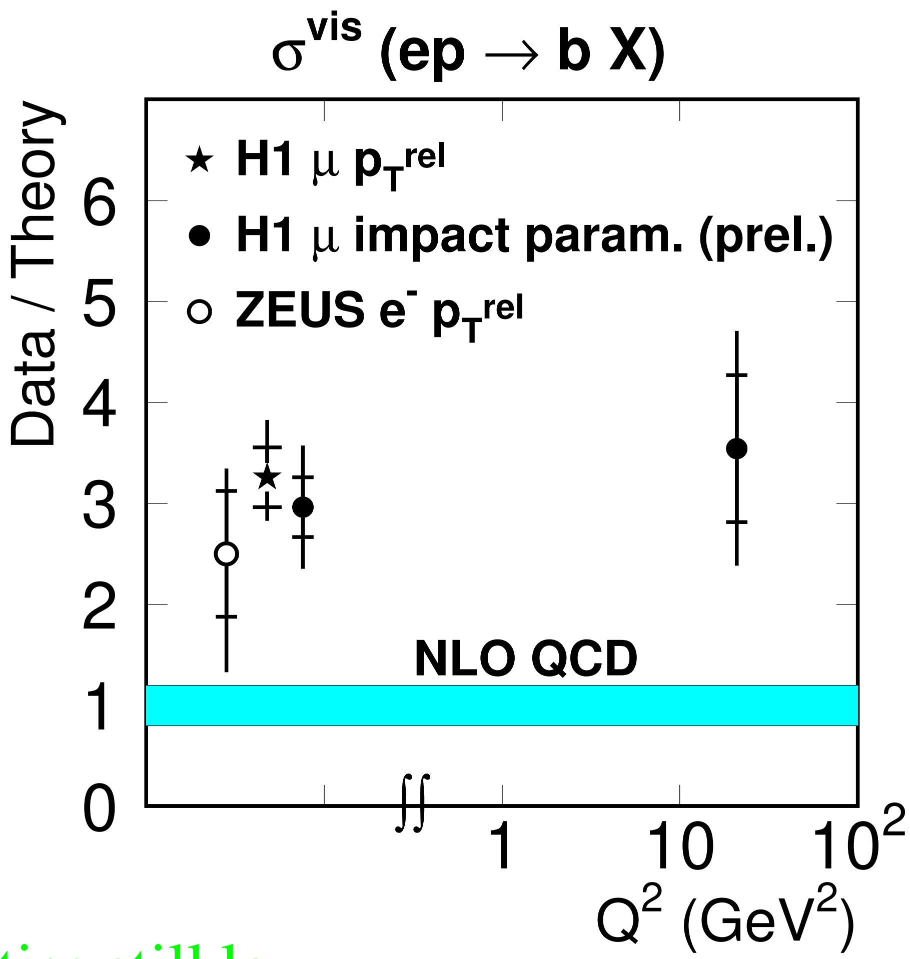
Tevatron and γγ Results on b Production





Conclusions: beauty



- statistics still low
- large fraction of resolved photon contribution?
- both in γp and in DIS

beauty cross section significantly larger than expected from NLO QCD predictions

as also seen in $p\bar{p}$ and $\gamma\gamma$ collisions

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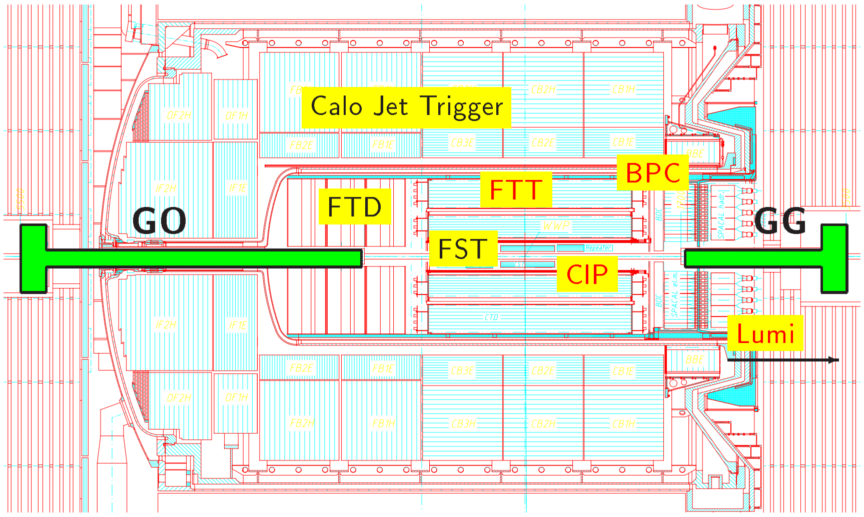
Outlook

Progress Of H1 Upgrade Projects



modifications

- backward ToF
- SpaCal
- beam pipe
- backward Si Tracker
- central Si Tracker
- LAr G0 Support
- Plug
- forward ToF
- FPS/FNC
- Polarimeter

upgrades

- Fast Track Trigger (FTT)
- Lumi Monitors
- Inner Prop. Chamber (CIP)
- Backward Prop. Chamber (BPC)

- Forward Tracker (FTD)
- Calo Jet Trigger
- Forward Si Tracker (FST)

both H1 and ZEUS have upgraded the forward region (forward tracker, silicon); ZEUS μ-vertex

HERA starts again with luminosity at the end of the year
$1fb^{-1}$ expected until 2005/2006
presently $\sim 100pb^{-1}$ accumulated

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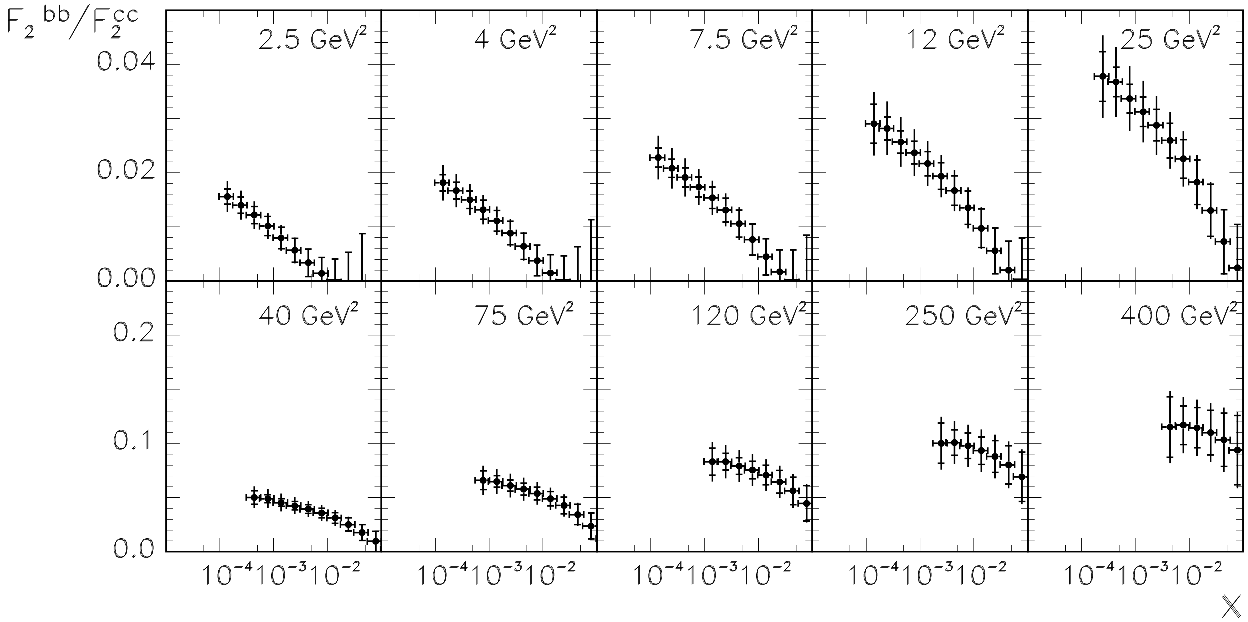
Outlook



– increase sensitivity to parton dynamics

– use more exclusive processes for detailed tests of QCD

Bright future for heavy flavour physics at HERA

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