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New Trends in HERA Physics 2003, Ringberg Workshop

Outline

- Introduction, Theoretical framework
- Experimental tools and techniques
- Open beauty measurements in DIS and PHP
- Charm in DIS and PHP
- Charm associated dijets in DIS and PHP
- Charm fragmentation
- Summary and conclusions

Introduction

- Heavy flavour production is an essential mechanism to probe QCD in details
- Study of heavy quarks yields the opportunity of studying pQCD with an additional hard scale

  $\Rightarrow$ to understand the multiscale QCD

- Parton densities of proton and photon need to be precise

  $\Rightarrow$ future colliders pp, e^+e^- and $\gamma\gamma$ ...

- QCD production rate should be accurately understood, which can be a significant background to "new" physics − LHC.

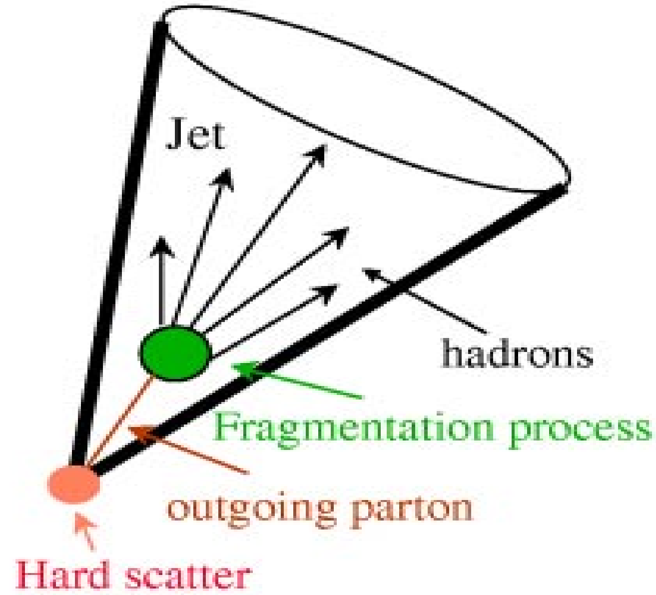
However :

i] QCD Calculations are in terms of final state partons

ii] Reliant on non−perturbative models, such as Lund, Cluster to describe the fragmentation

$\Rightarrow$ The two need to be "matched" to perform a comparison

- Production of $q\bar{q}$
- Development of Parton shower
- Transition of partons to hadrons (Hadronisation)
- Unstable hadrons decay (according to BR)



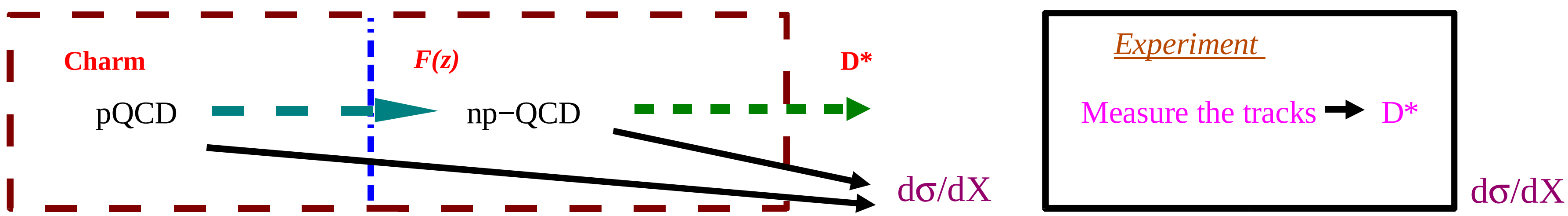
- The Perturbative part of QCD:
  1. Dynamics of the Hard scattering.
  2. Probe the photon and proton structure ...

- Study of non−pertubative part of QCD

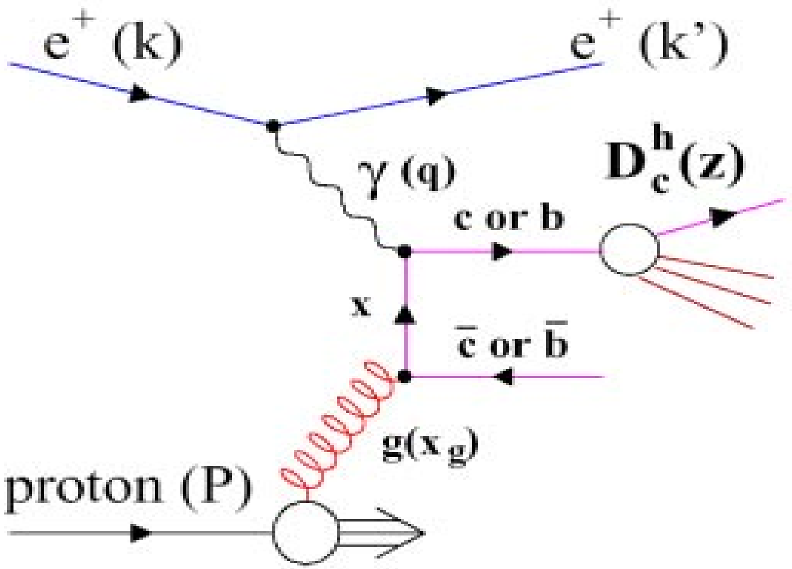
  Fragmentation, Hadronisation, "soft strong interactions" ... etc

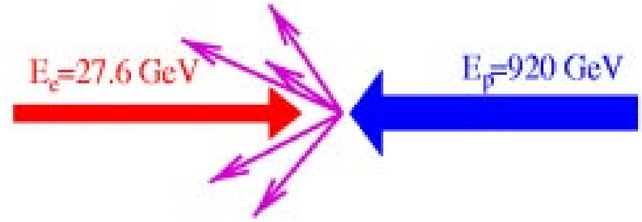
  * Fragmentation − binding the heavy quark with light quark into a hadronic state

Note: A non−perturbative part cannot be determined in absolute terms, but only relatively to how one defines the perturbative part and its parameters.



Introduction



At HERA 

ep Kinematics:

$Q^2 = -q^2 = (k - k')^2$: 4−momentum transfer squared

x : fraction of the proton momentum − Bjorken−x

y : Inelasticity of the interaction

W : Center−of−Mass of the γp system

For a generic collision to produce heavy quarks :

$$\gamma + p \rightarrow Q\bar{Q} + X$$

Kinematic regimes:

$Q^2 \leq 1\ \mathrm{GeV}^2 \rightarrow$ Photoproduction (γp)

$Q^2 >> 1\ \mathrm{GeV}^2 \rightarrow$ Deep inelastic scattering (DIS)

$$\sigma(s) = \sum_{ij} \int dx_1 \int dx_2\, f_i^{\gamma}(x_1, \mu_F)\, f_j^{P}(x_2, \mu_F)\, \hat{\sigma}_{ij}(x_1 x_2 s, m^2, \mu_R^2) \int dz\, D_Q^H(z)$$

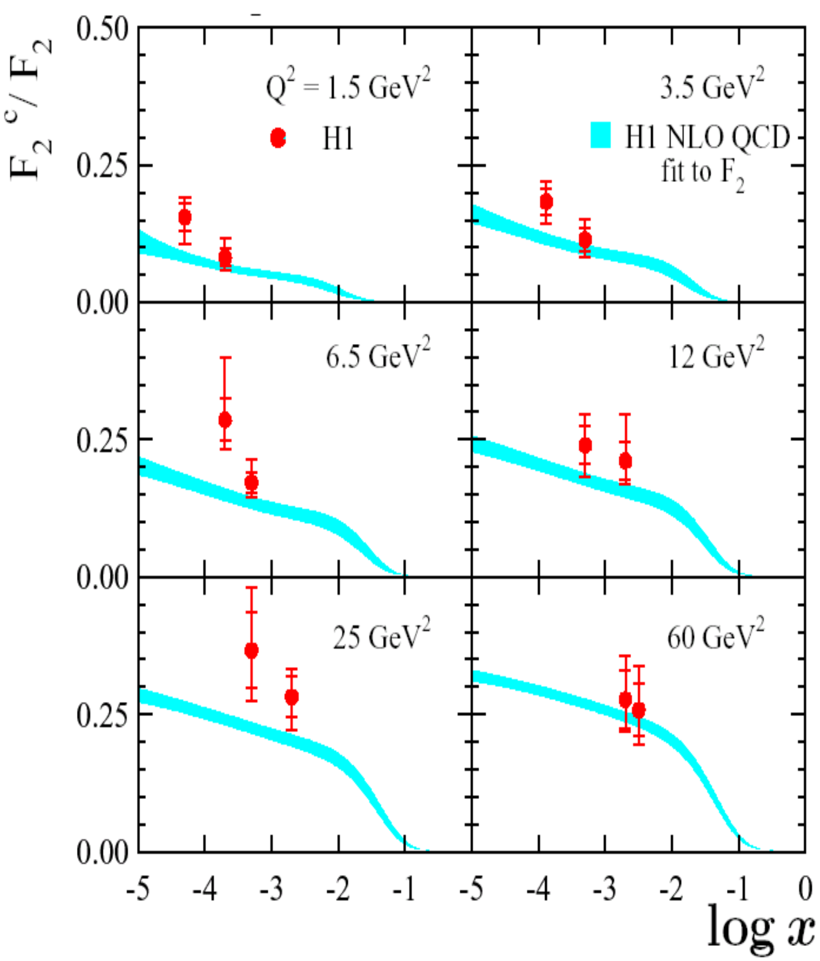
PDF ⊗ **Hard Scattering** ⊗ **Fragmentation**

PDF ⊗ Hard scatter sensitive :

- +ve scaling violation for all x_γ
  - ⇒ Fraction of direct and resolved photon processes with Q^2 ?
- For large Q^2, hadronic contribution decreases
  - ⇒ Q^2 dependence, Is Q^2 and $m_Q{}^2$ independent ?
  - ⇒ Continuum between PHP and DIS where resolved vanishes
- $[\Lambda^2 \leftrightarrow m^2_Q$ and $e^4_{qk}] \Rightarrow \sigma_{\text{light quarks}} > \sigma_{\text{charm}} > \sigma_{\text{bottom}}$

  [What about with Q^2]
- Evolution scheme for heavy quarks ?
- Do we really need explicit charm contribution in the PDF_γ ?
- Choice of renormalisation and factorisation scale
  - ⇒ Multi−scale problem due to large m_c and $m_b > \Lambda_{QCD}$

F_2^c / F_2



Large charm contribution to F_2

Theoretical framework

Fragmentation sensitive:

- How well we understand the final state partons dress themselves to final state hadrons
  - ⇒ Lund, Cluster, Peterson fragmentation ...
  - ⇒ How correct are these models and current parametrisations ?
- Are u and d quarks produced equally w.r.t to say (charm) ? $R_{u/d} = \frac{c\bar{u}}{cd}$
- What is the s−quark production suppression ? $\gamma_s = \frac{2c\bar{s}}{c\bar{d} + c\bar{u}}$
- Are vector (D*) and pseudoscalar (D) meson produced as predicted by spin counting ? $P_V = \frac{V}{V+PS} \, (= 0.75\,?)$
- What are the relative fragmentation fractions of charm hadrons ? $f(c \rightarrow D) = \frac{N(D)}{N(c)} = \frac{\sigma(D)}{\sum_{all} \sigma(D)}$

Are these ratios, fractions and functions universal

⇒ Compare HERA results with those in e^+e^- annihilations

Theoretical framework

Collinear approach :

all incoming and outgoing partons are on mass shell.

only longitudinal component of momenta considered.

partons are considered 'frozen' inside the hadrons.

i] (LO + PS) (DGLAP):

AROMA : BGF, Lund fragmentation

HERWIG : DIR+RES, Cluster hadronisation

RAPGAP : LO, Lund fragmentation

PYTHIA : DIR+RES, Lund fragmentation

ii] NLO−FO:

Fixed order, massive scheme. No explicit charm excitation component.

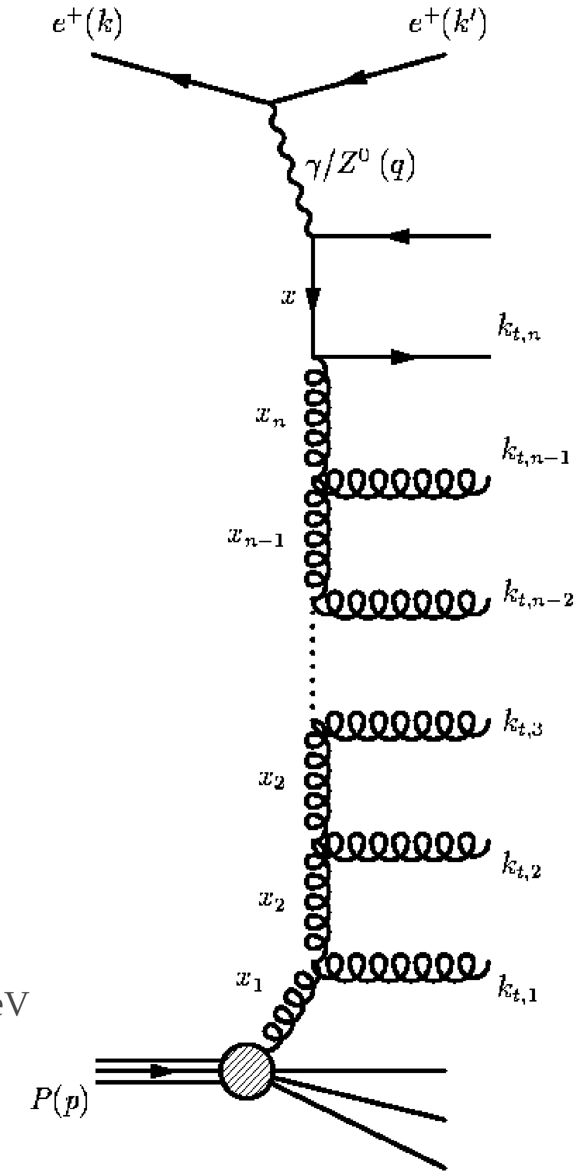
DGLAP evolution, Peterson fragmentation

Only light quarks (u,d,s) are active flavours in proton and photon.

Charm and bottom are only produced dynamically, Scheme valid for $p_{\perp}^{2} \approx m_{Q}^{2}$

γp : FMNR (Frixione et al.), Scale $\mu_0 = \mu_F = \mu_R$; $\mu_0 = \sqrt{(m_Q^2 + p_t^2)}$; $m_c = 1.5$ and $m_b = 4.75$ GeV

DIS: HVQDIS (Harris & Smith), Scale $\mu_0 = \mu_F = \mu_R$; $\mu_0 = \sqrt{(4m_Q^2 + Q^2)}$



Theoretical framework

iii] Resummed calculation in NLL (Kniehl et al.):

u,d,s,c as an active flavour in photon and proton, Scheme valid for $Q^2, p_\perp^2 >> m_Q^2$

explicit charm excitation component

iv] Matched Calculation, FONLL (Cacciari et al.)

Fixed order + NLL scheme : Incorporate mass effects upto FO−NLO

resummation of p_T logs upto NLL.

k_T −factorization approach :

valid for small $x \sim m_T/\sqrt{s}$

CCFM evolution, Additional scale provided, based on the angular ordering

Maximum allowed angle Ξ provided by the quark box.

incoming particles are off−shell with +ve transverse momenta k_t

Based on the virtuality down the ladder resolved photon processes can be simulated.

LO + PS (CCFM):

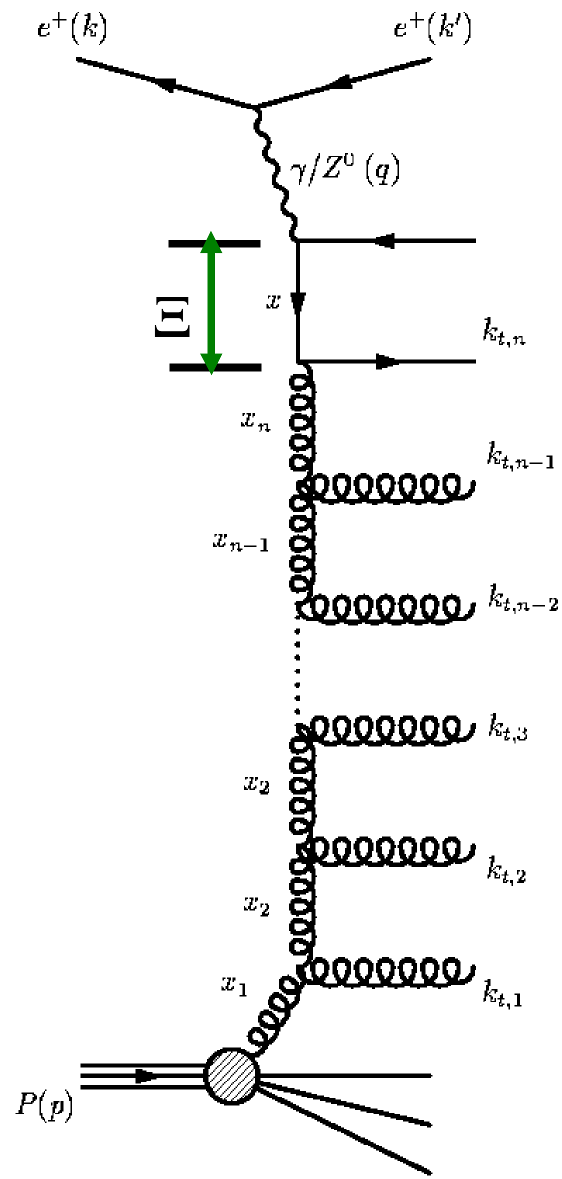
CASCADE (H. Jung et al.) : Off shell BGF Matrix element.

Initial state (CCFM)

Final state & Fragmentation (PYTHIA and Lund)

"Unintegrated" k_T dependent gluon density.

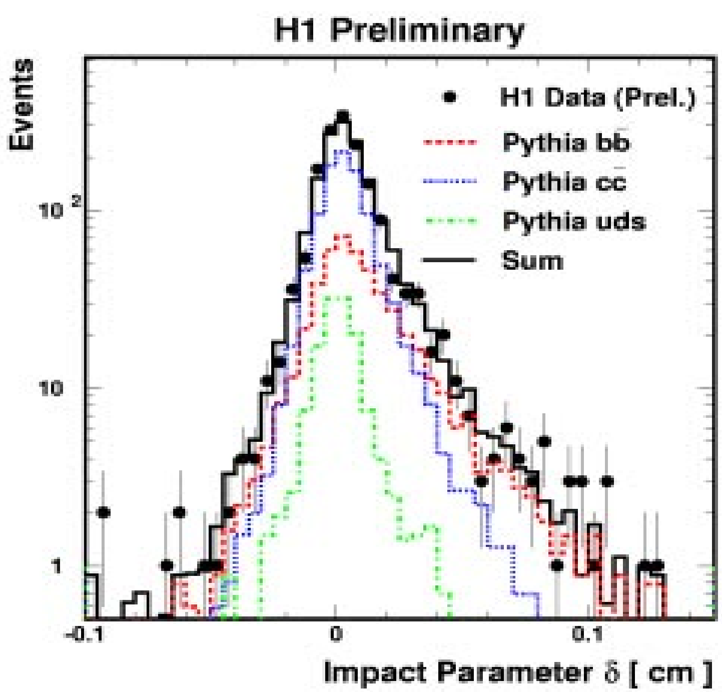
Applicable for both DIS and Photoproduction.



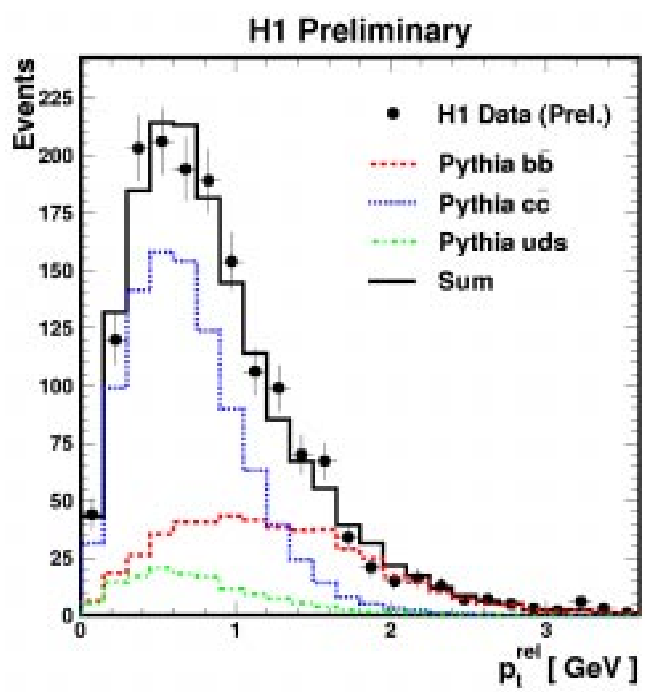
Semileptonic *B* decays in 2−jet events:

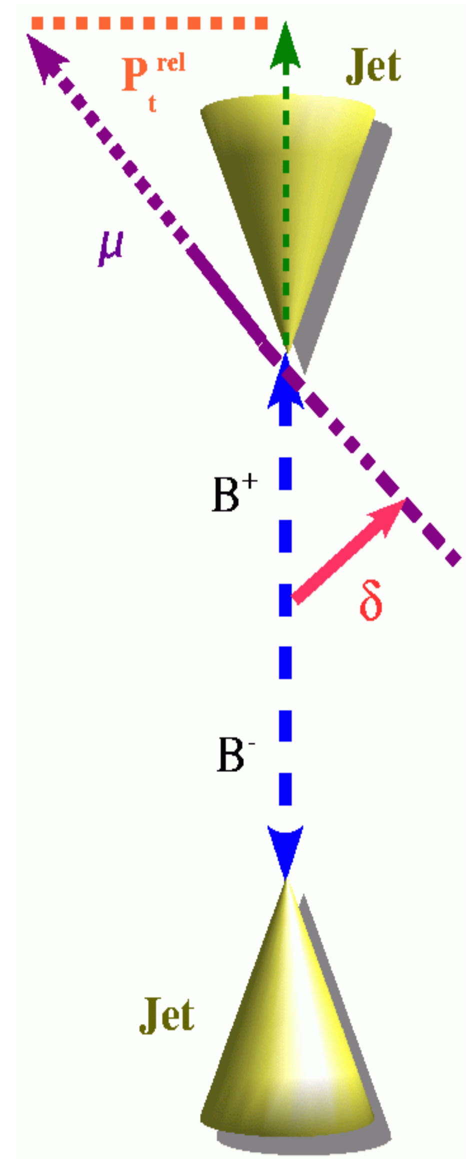
- **Large B −Mass (p_T^{rel})** → p_T of μ relative to the jet. [H1 & ZEUS]
- **Long B − Lifetime (δ)** → distance of μ to the impact parameter [H1]
- Combination of the above two.

$f_b \sim (30.7 \pm 2.5)$ %



$f_b \sim (28.8 \pm 2.8)$ %





Beauty in DIS

- $Q^2 > 2$ GeV^2, $0.05 < y < 0.7$, $\mathcal{L}$ (99−00) ~ 60 pb^{-1}
- 1 muon: $p_T^{\mu} > 2$ GeV.
- 1 jet: $E_T^{Breit} > 6$ GeV, $-2 < \eta_{jet} < 2.5$

$$\sigma_{vis} = [\ 38.7 \pm 7.7\ (\text{stat.})\ ^{+6.1}_{-5.0} (\text{sys.})\ ]\ \text{pb}$$

- NLO QCD (DGLAP) agree within errors

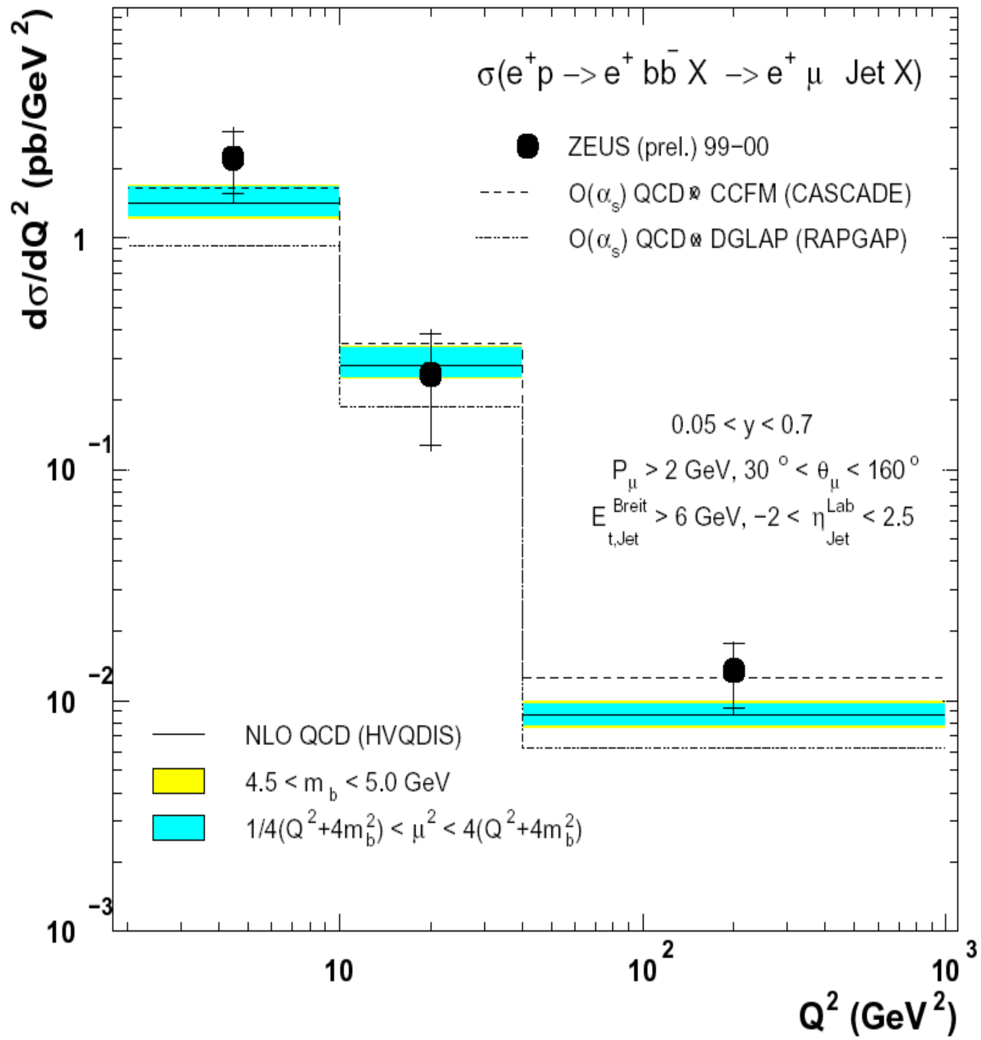
  NLO (Harris et al.): $\sigma_{vis} = 28.1^{+5.3}_{-3.5}$ pb

- RAPGAP (DGLAP, LO+PS) is lower then the data

- CASCADE (CCFM) agrees well with the data

  $\sigma_{vis} \approx 35$ pb

ZEUS (p_T^{rel} method): $ep \rightarrow e\ jet\ \mu\ X$

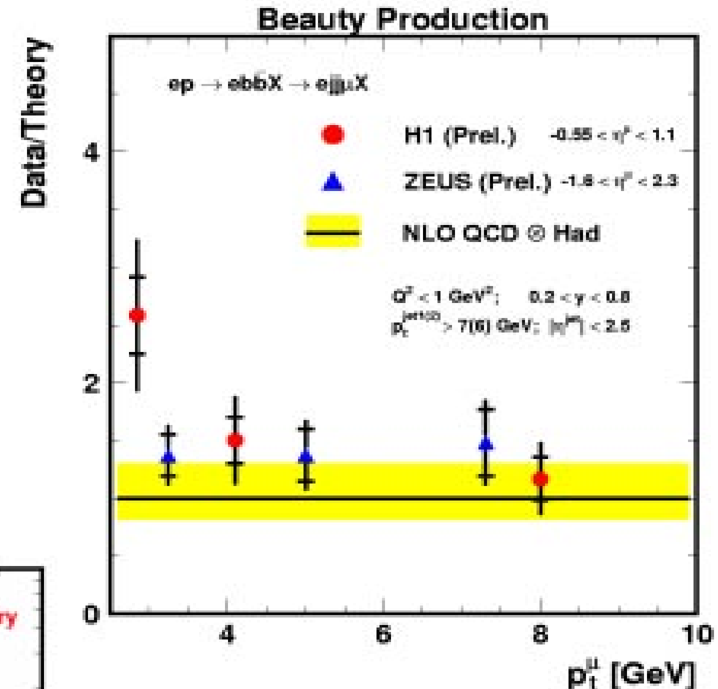


NLO is in reasonable agreement both shape and normalisation

B in γp (photoproduction)

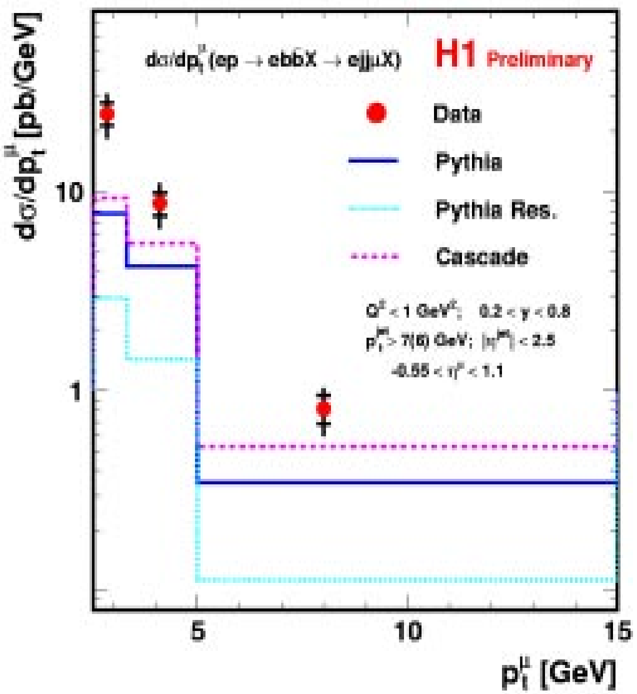
Dijet sample with low $Q^2 < 1$ GeV^2 : $0.2 < y < 0.8$, $E_t^{jet1(2)} > 7$ (6) GeV

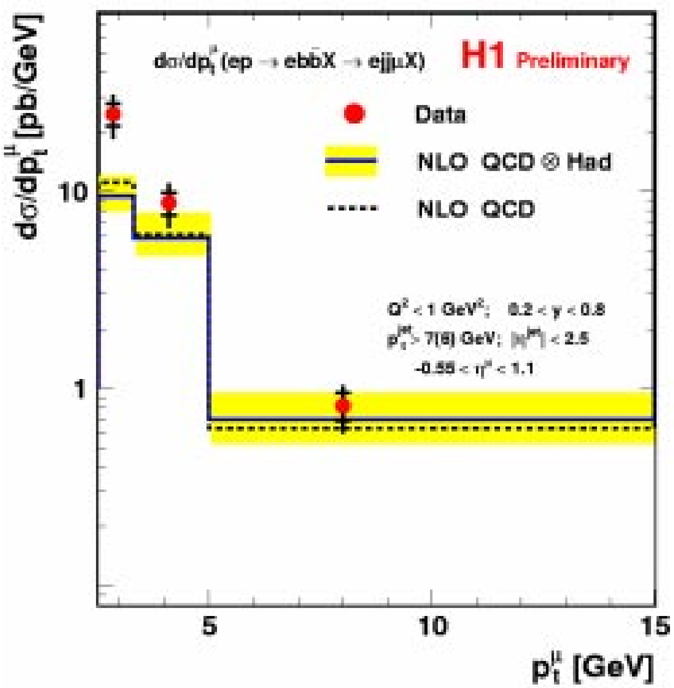
- **H1 (δ + p_T^{rel})** : $|\eta^{jet}| < 2.5$, $p_T(\mu) > 2.5$ GeV, $-0.56 < \eta(\mu) < 1.1$
- **ZEUS (p_T^{rel})** : $|\eta^{jet}| < 2.5$, $p_T(\mu) > 2.5$ GeV, $-1.6 < \eta(\mu) < 2.3$



- LO + PS (DGLAP, CCFM) MC models: Too low in normalisation.
- NLO QCD : Reasonable agreement with ZEUS & H1 within errors.

Too low at low $p_T(\mu)$ [H1] ?



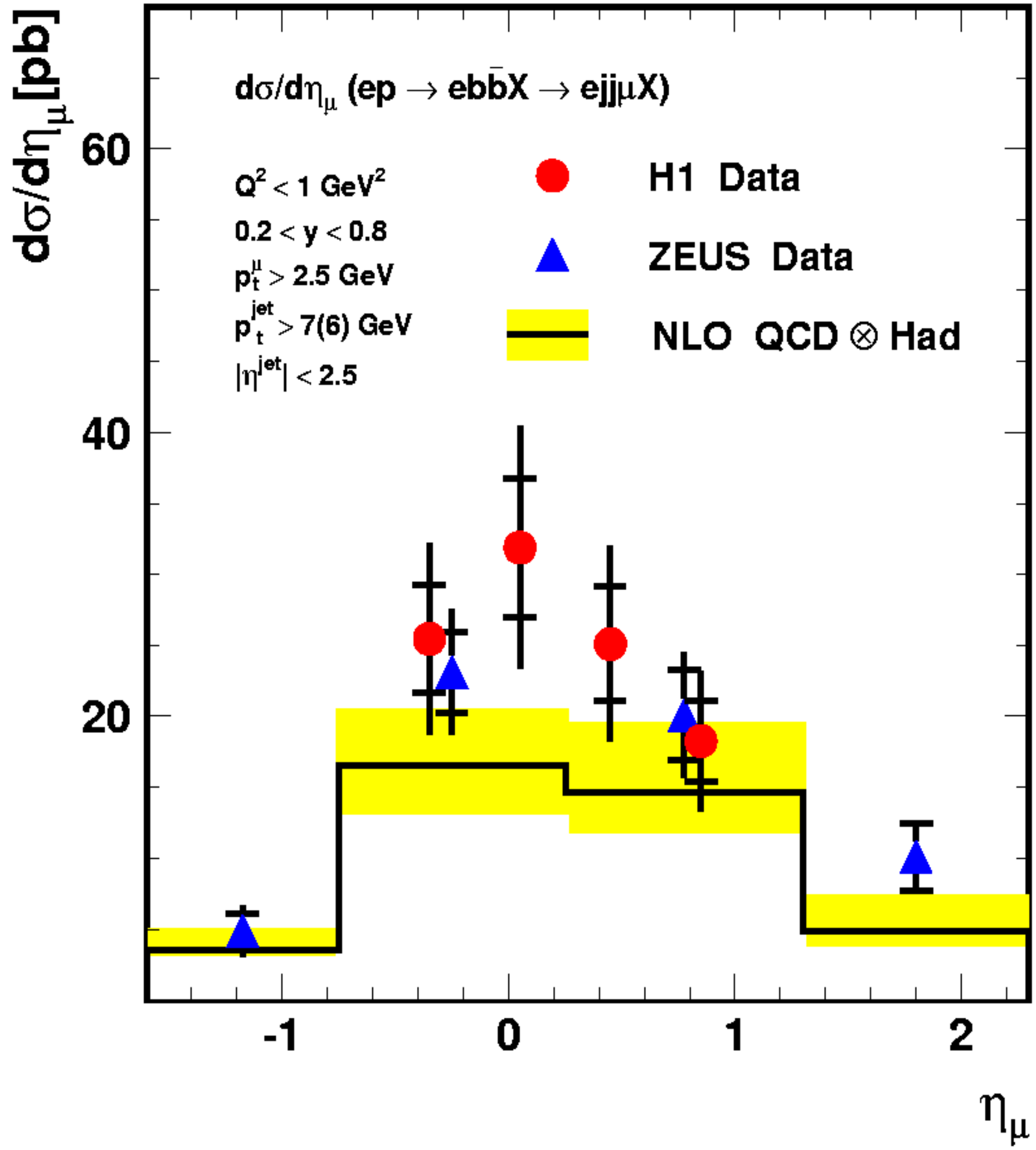


Experimental and theoretical uncertainties are of the same order

$\mathcal{B}$ in γp (photoproduction)

Close look at η (μ) distribution:

- Good agreement between H1 and ZEUS data.
- All data points are above NLO, but agreement within uncertainties.



Open B production: Conclusion

- New differential b−cross section measurements
- Two methods (p_T^{rel}, δ) methods explored
- DIS : After long efforts both from theoretical and experimental side the visible cross section is in reasonable agreement with the QCD calculations, within the experimental and theoretical uncertainties.
- γp(PHP) : H1 and ZEUS measurements agree

  Measurements are mostly above NLO QCD predictions:

  $\Rightarrow$ Discrepancies $\leq$ 1.5 sigma

- Data is still generally higher than NLO QCD, but somewhat less than others ...

More data needed and is coming ...

Experimental tools and techniques – Charm tagging

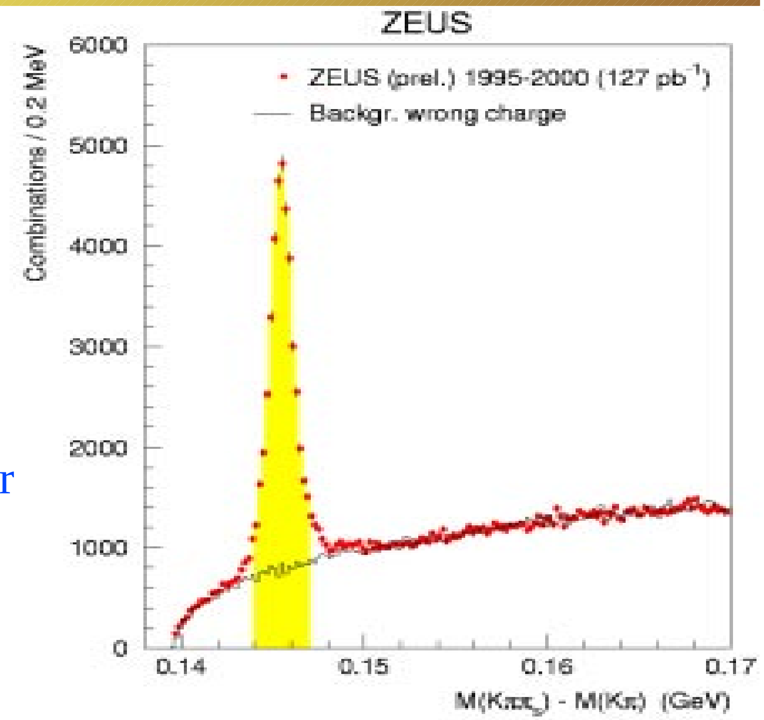
- **Δm tag :** $m_{D^*} - m_{D0} \sim 10$ MeV

$D^{*+} \to D^0 \pi_s^+ \to (K^- \pi^+)\, \pi_s^+ + c.c$

$f\,(c \to D^*) = 0.235$

$\mathcal{L} \sim 127\ pb^{-1}$ (ZEUS 95−00) N(D*) = 31350 ± 240

$p_T^{D^*} > 2$ GeV, $|\eta^{D^*}| < 1.5$ precision better than 1% stat error



- **H1 CST (Central Silicon Tracker) lifetime tag:**

$D^+ \to K^- \pi^+ \pi^+ + c.c$

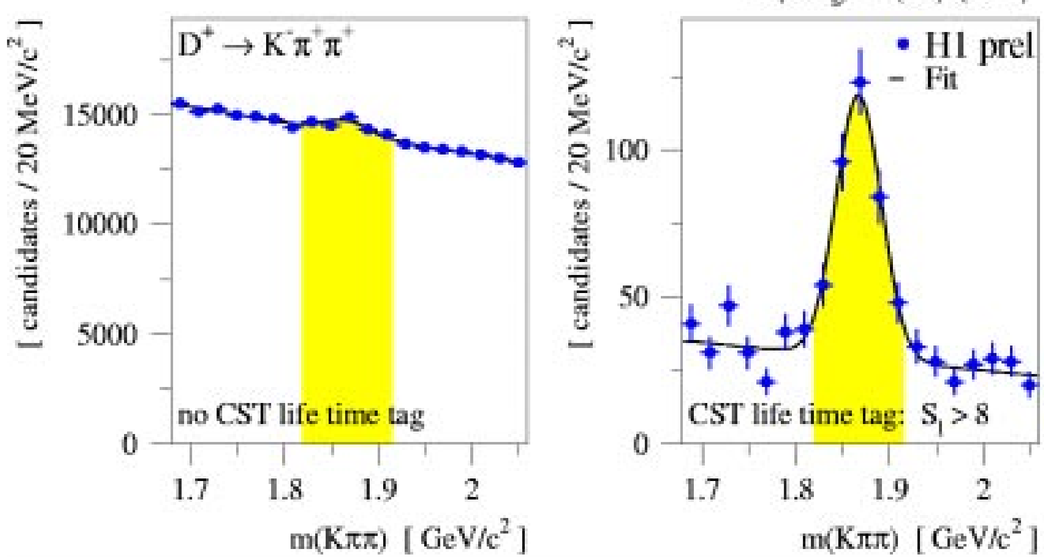
$f\,(c \to D^+) = 0.232,$

$\mathcal{L} \sim 47.8\ pb^{-1}$ (H1)

$p_T^{D+} > 2$ GeV, $|\eta^{D+}| < 1.5$

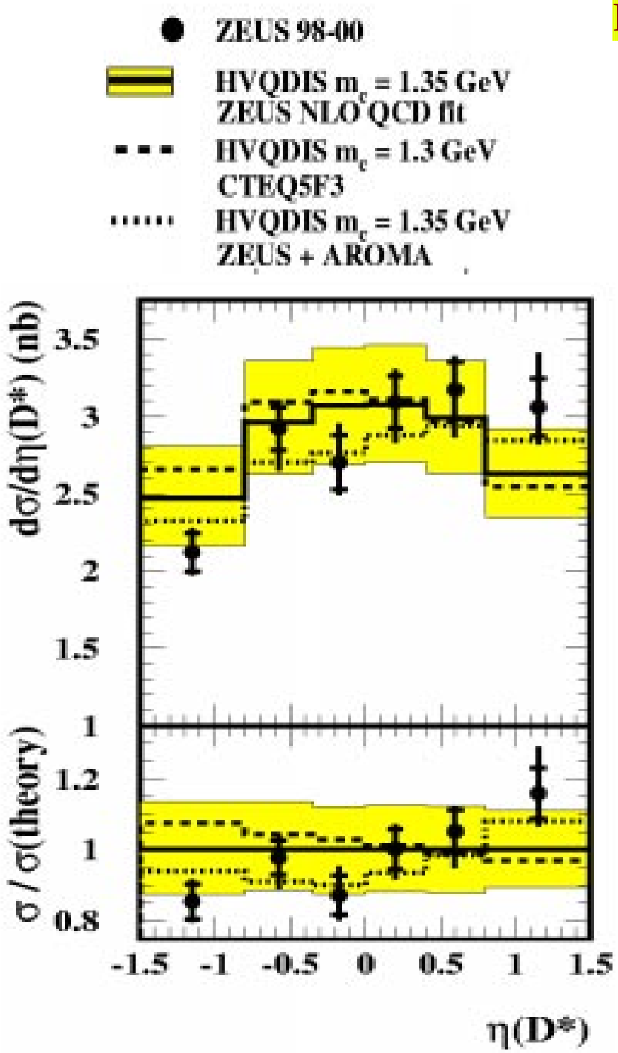
Decay significance length $S_l = l/\sigma_l > 8$

Improvement in signal/backgr. $\sim \mathcal{O}(50)$



Charm in DIS

Proton PDF sensitive measurements



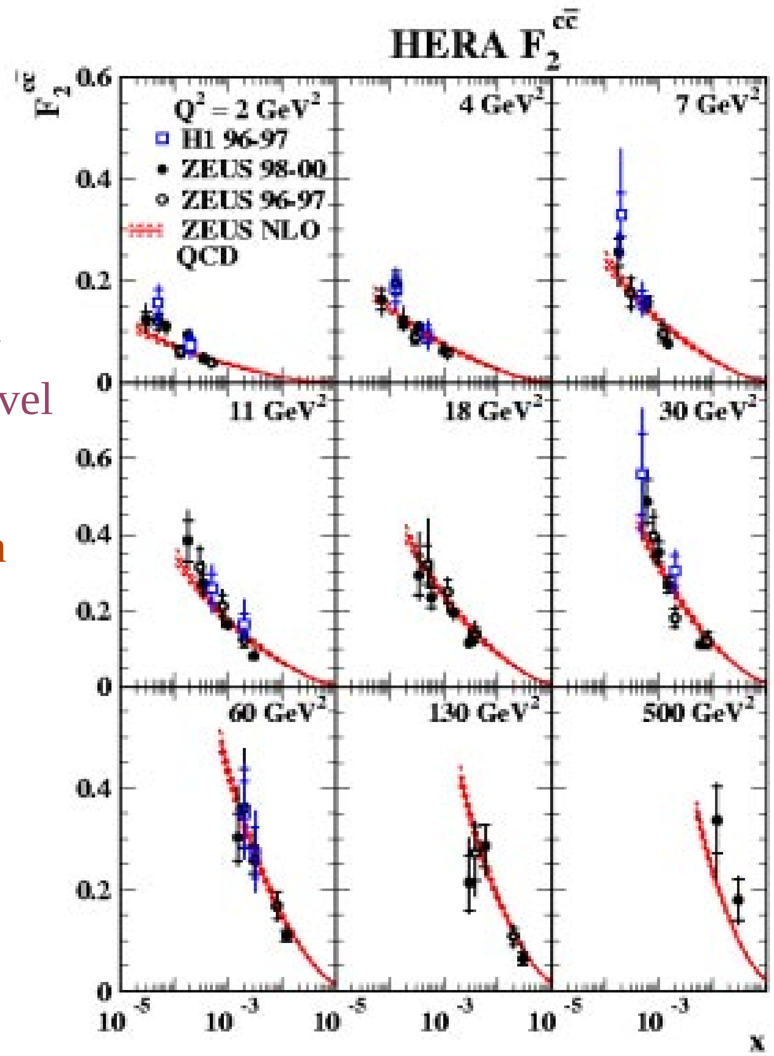
Charm from σ(D*) w.r.t

HVQDIS ⊗ *xg(x)*

Very nice confirmation of gluon from scaling violation at 10% level

Sensitive to differences between fitted gluons

Theoretical uncertainties dominate → m_c, μ_R, μ_F, and ε_c



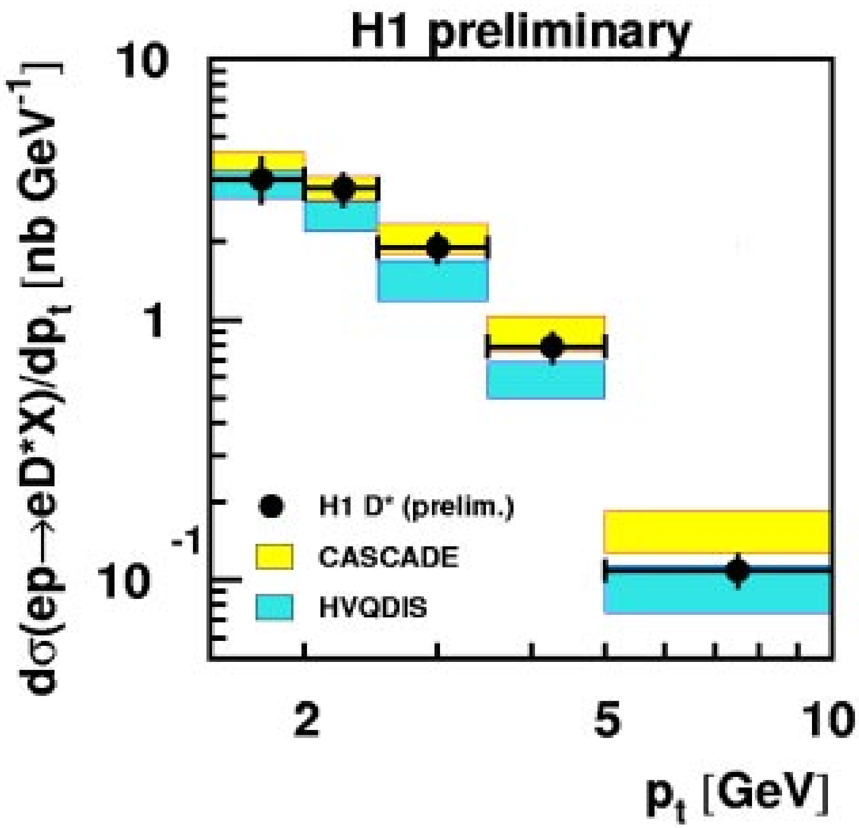
Total visible: $\sigma(e^{\pm}p \to e^{\pm}D^{*}X) = 8.44 \pm 0.20(\text{stat.})^{+0.37}_{-0.36}(\text{syst.})$

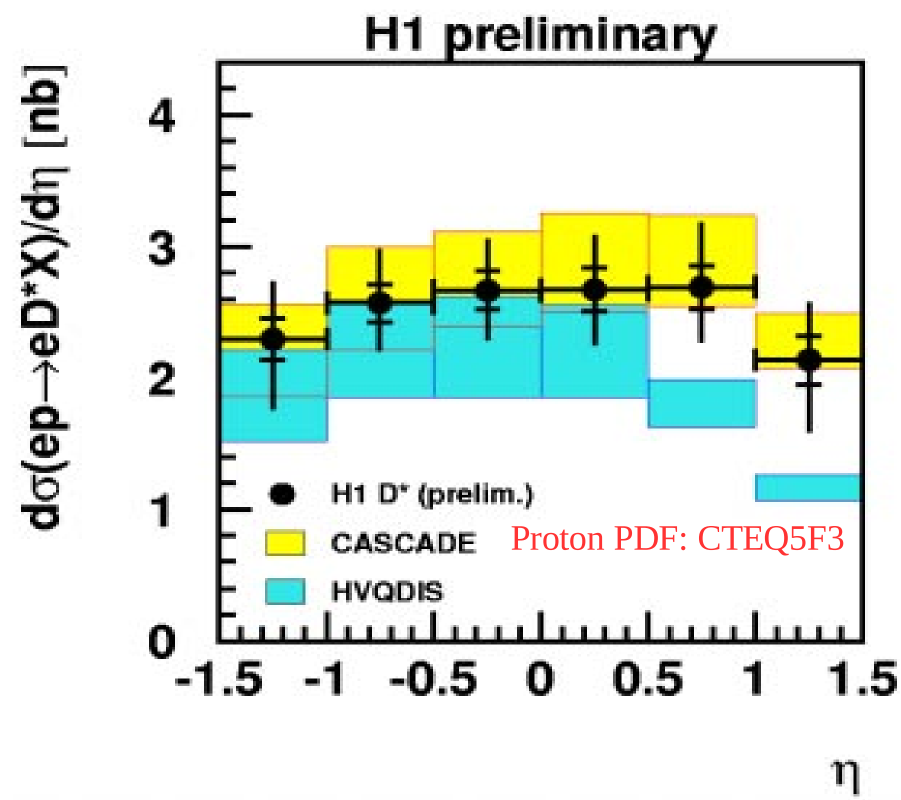
HVQDIS : $8.41\ ^{+1.09}_{-0.95}$

F_2^{cc} obtained with extrapolation in η and p_t (NLO HVQDIS)

Charm in DIS

Proton PDF sensitive measurements





Scale: $m_c = 1.3$, $\varepsilon_c = 0.035$ to $m_c = 1.5$, $\varepsilon_c = 0.10$

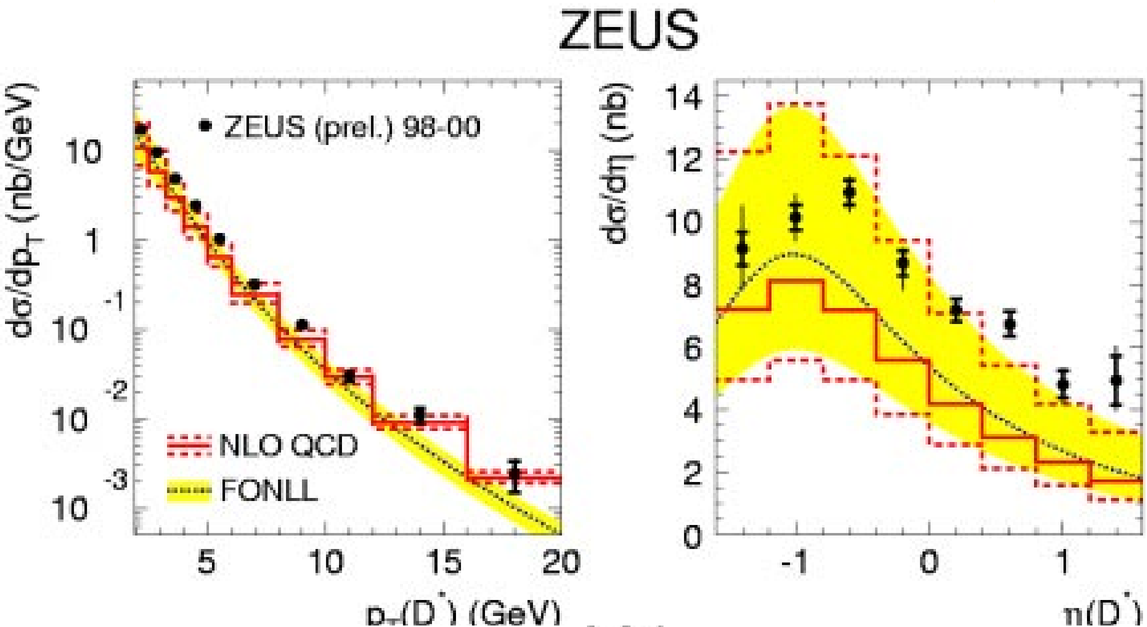
$2 < Q^2 < 100$ GeV^2, $0.05 \leq y \leq 0.7$

$1.5 < p_t(D^*)$ 15 GeV, $|\eta(D^*)| < 1.5$

- CASCADE (CCFM) agrees rather well with the data specially +ve η
- HVQDIS(NLO) : Reasonable agreement with the data

  Prediction is below in normalisation specially +ve η

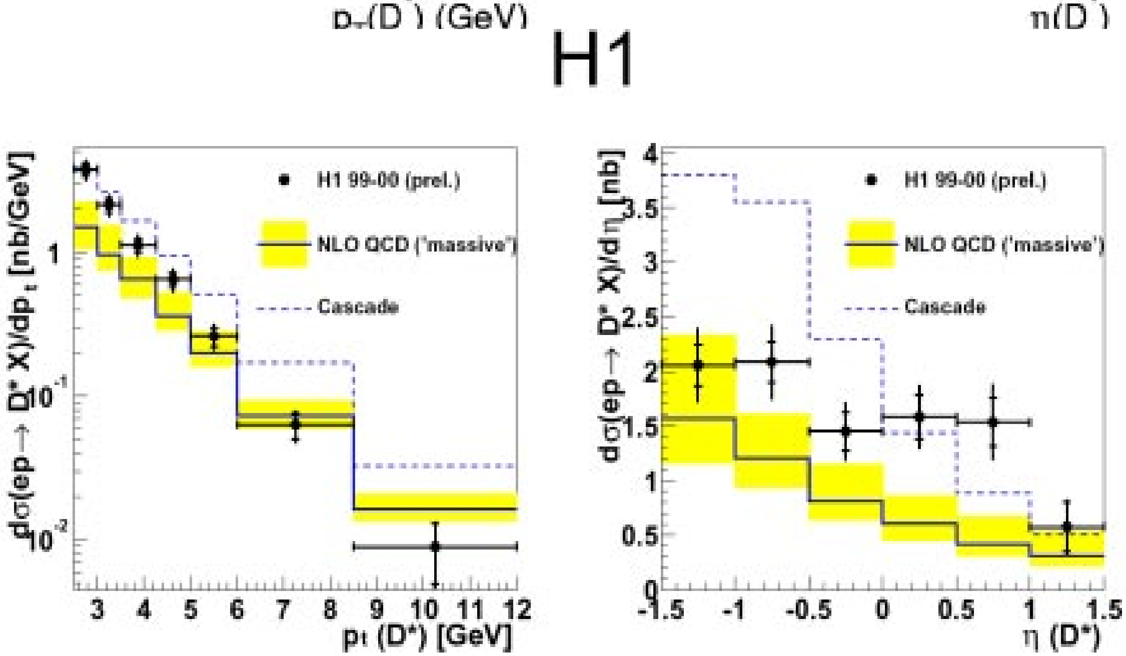
Charm in Photoproduction



$Q^2 < 1$ GeV^2; $130 < W_{\gamma p} < 280$ GeV ; 79 pb^{-1}

$p_T(D^*) > 1.9$ GeV, $|\eta(D^*)| < 1.6$

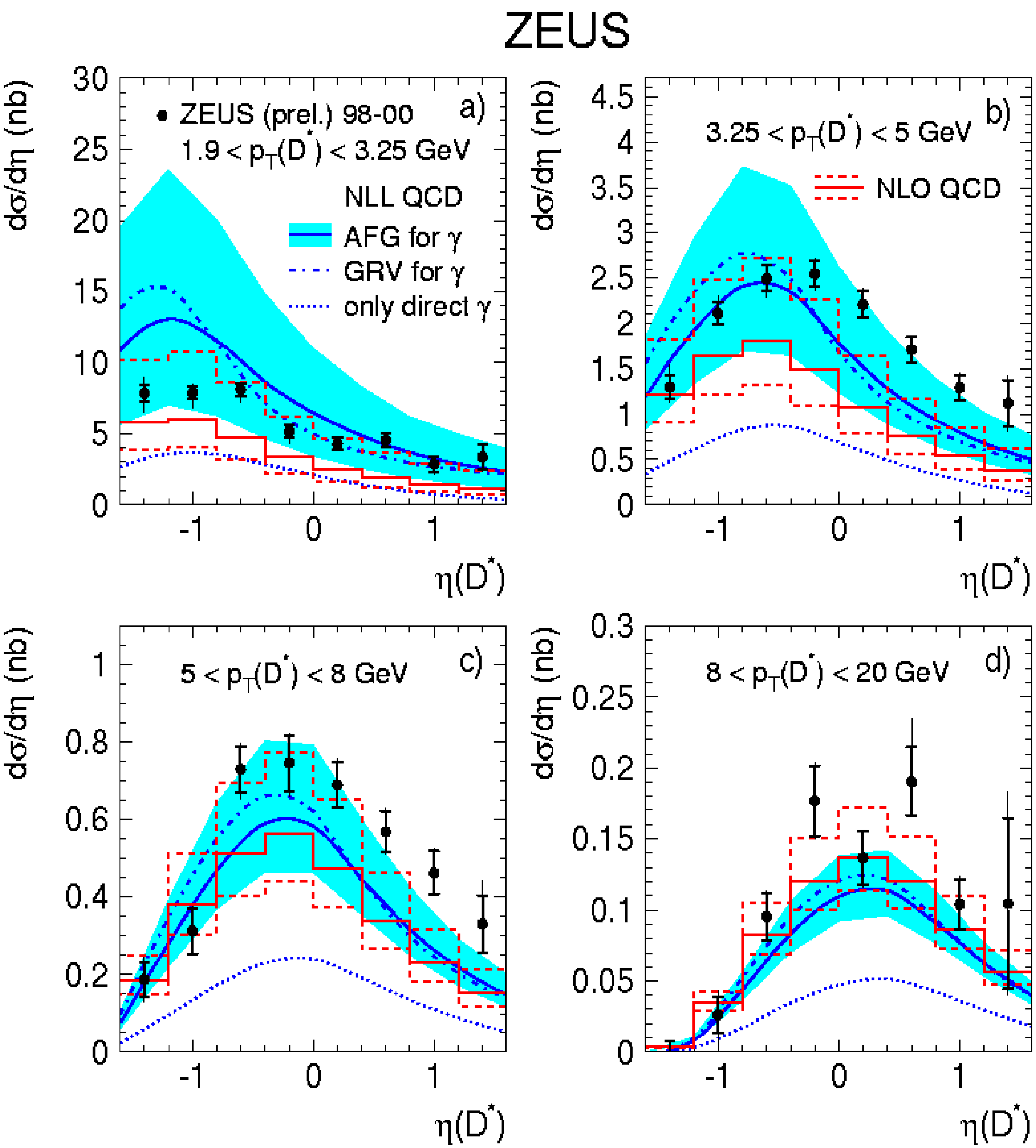
- Remarkable precise data.
- NLO below data for low p_T and forward η
- FONLL even below NLO for high p_T
- CASCADE is above DATA for all regions



$Q^2 < 0.01$ GeV^2; $171 < W_{\gamma p} < 256$ GeV ; 49 pb^{-1}

$p_T(D^*) > 2.5$ GeV, $|\eta(D^*)| < 1.5$

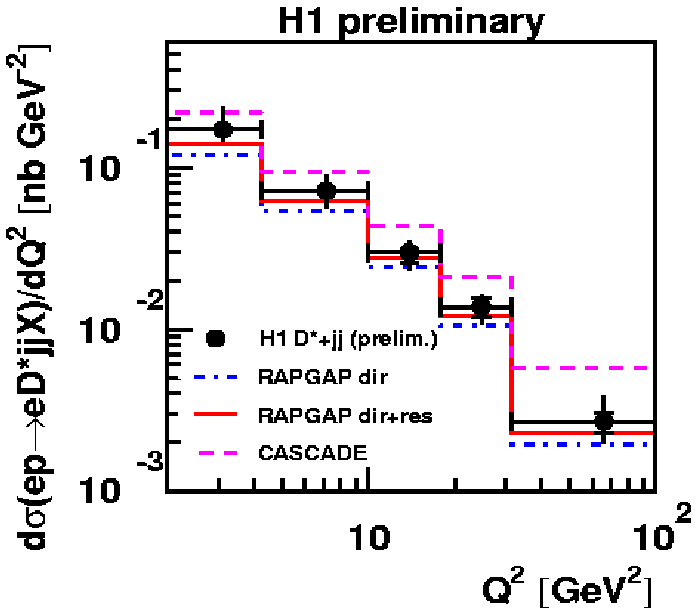
Charm in Photoproduction



Differential distributions in various p_T region:

- NLL above the data at low p_t
- NLL direct only cannot describe the data
- NLO below data at medium p_T and high η
- Description by NLO/NLL QCD is not perfect in all p_t regions

Charm associated dijet in DIS

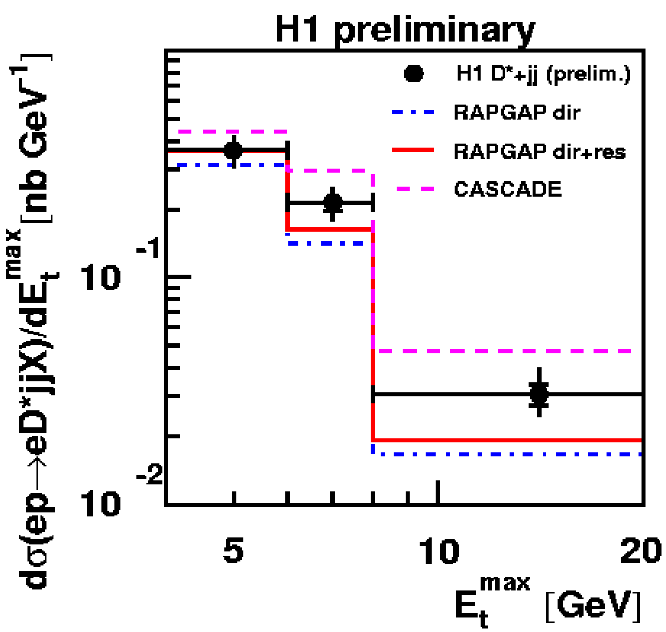


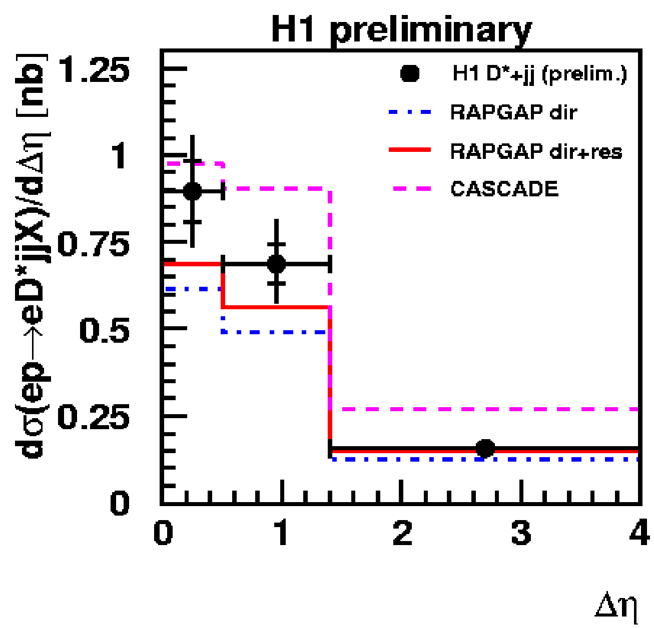
H1 (99−00) : D* + Dijets (Breit frame), $\mathcal{L}$ ~ 47.8 pb^{-1}

$E_t^{jet1,2} > 4, 3$ GeV; $-1 < \eta_{lab}^{jet1,2} < 2$

Distributions as a function of Q^2, E_t^{max} and $\Delta\eta$ studied

- CASCADE (CCFM evolution) higher than DATA
- RAPGAP (LO + PS) (Direct only) is very low
- RAPGAP (Dir+Res) still low



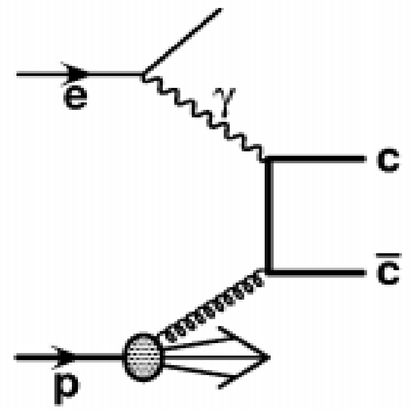


Parameters used :

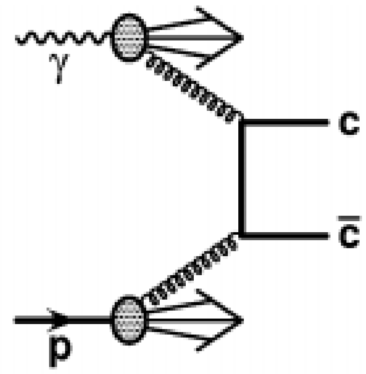
m_c = 1.4 GeV

Peterson ε_c = 0.078

Charm production and parton dynamics



Direct−γ: γ−g fusion



Resolved−γ: g g → cc

Define observable:

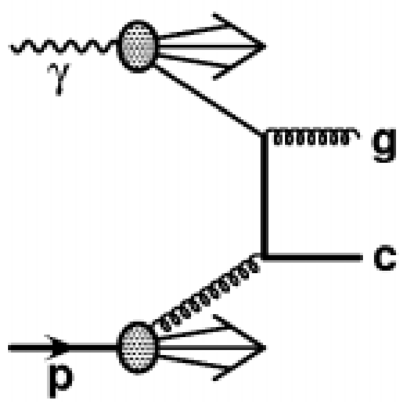
direct photon $x_\gamma^{obs} > 0.75$

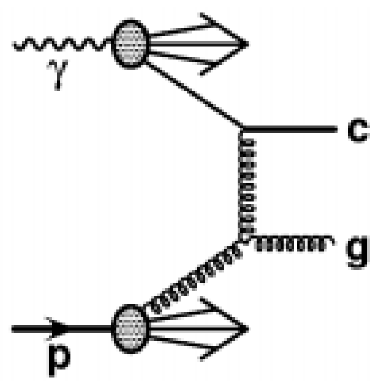
resolved photon $x_\gamma^{obs} < 0.75$

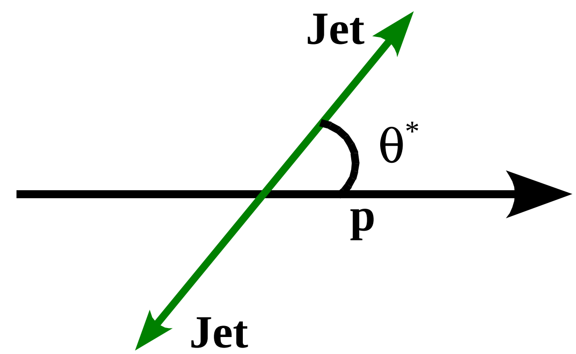
q−exchange $d\sigma/d|\cos\theta^*| \sim (1 - |\cos\theta^*|)^{-1}$

g−exchange $d\sigma/d|\cos\theta^*| \sim (1 - |\cos\theta^*|)^{-2}$

(Rutherford scattering)







θ^* = center of mass scattering angle

Resolved−γ: c excitation

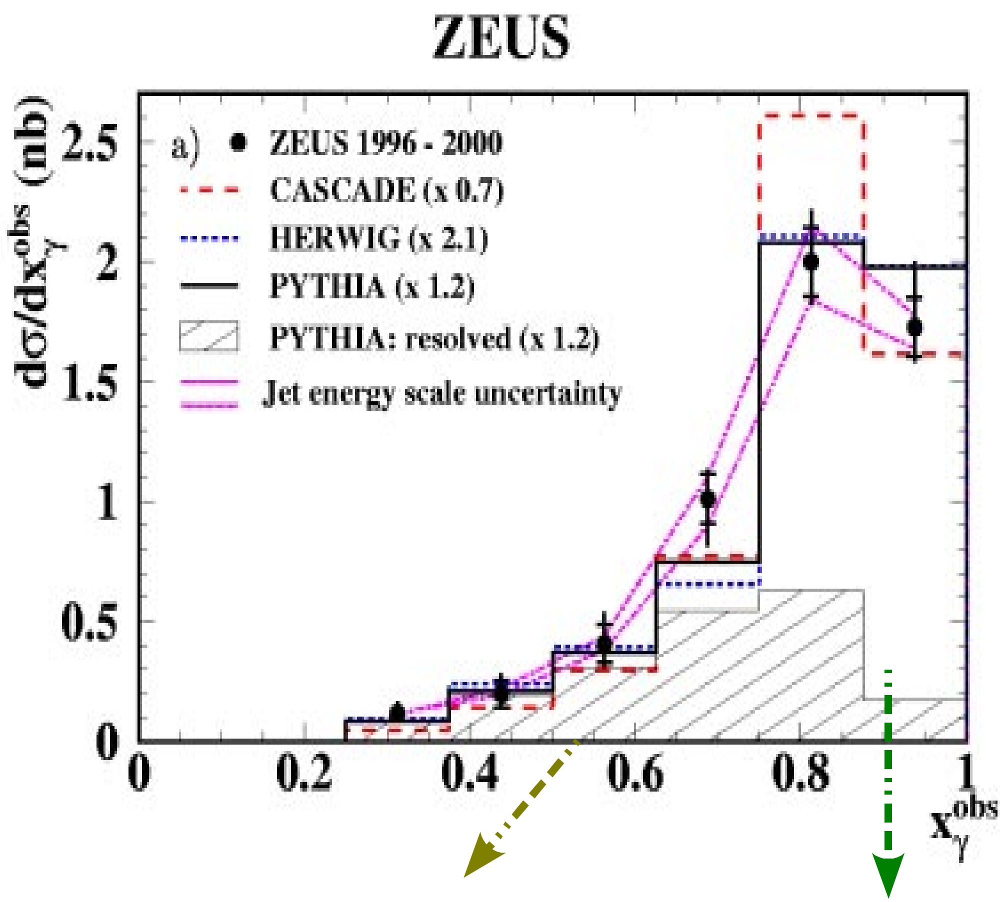
q−exchange

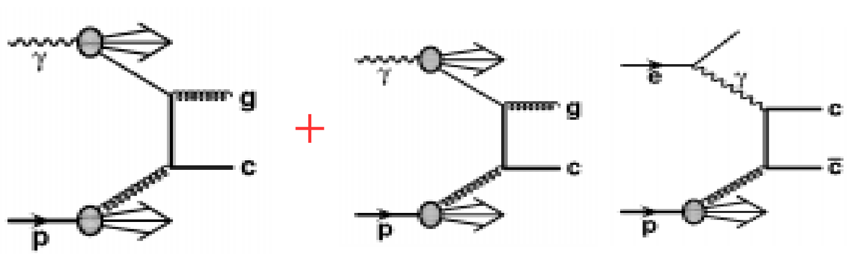
g−exchange

In NLO only sum of direct + resolved is well defined

Parton dynamics: Charm associated dijet in photoproduction

D* dijet events enable study of photon structure in particular its charm content.





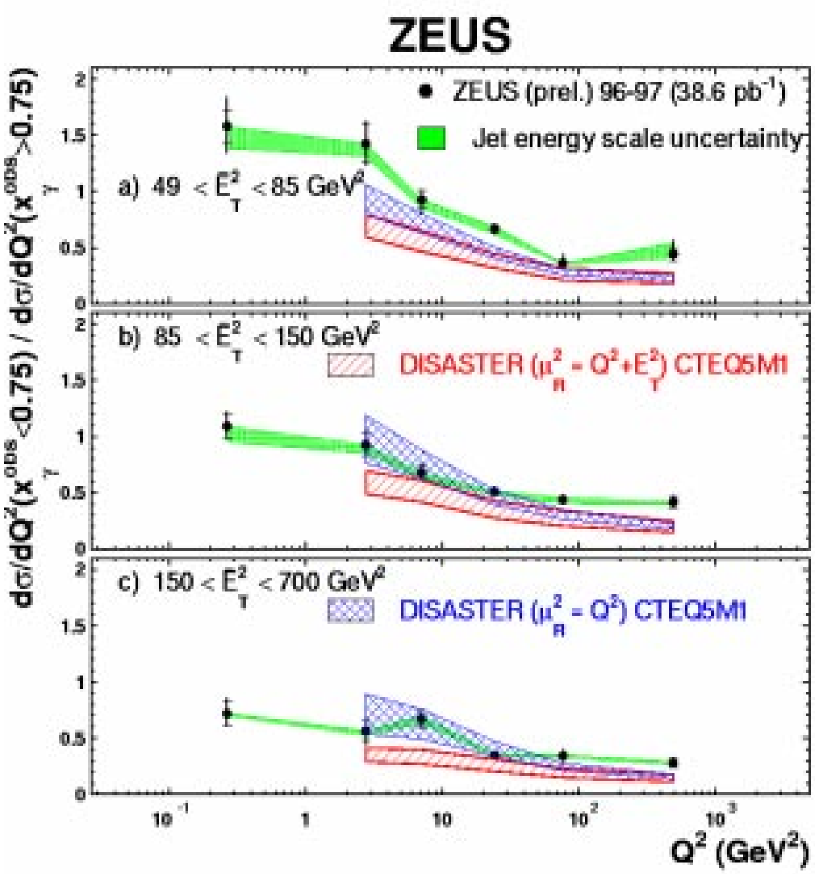
Sample Used :D* and at least 2 hadron jets [120 pb^{-1}]

- With $p_T^{D*} > 3.0$ GeV, $|\eta^{D*}| < 1.5$
  $p_t(K,\pi) > 0.5$ GeV, $p_t(\pi_s) > 0.15$ GeV.
- Dijets $E_t^{jet} > 5$ GeV, $|\eta^{jet}| < 2.4$, $M_{jj} > 18$ GeV
  $|0.5*(\eta^{jet1} + \eta^{jet2})| < 0.7$ (measure of η^{boost})

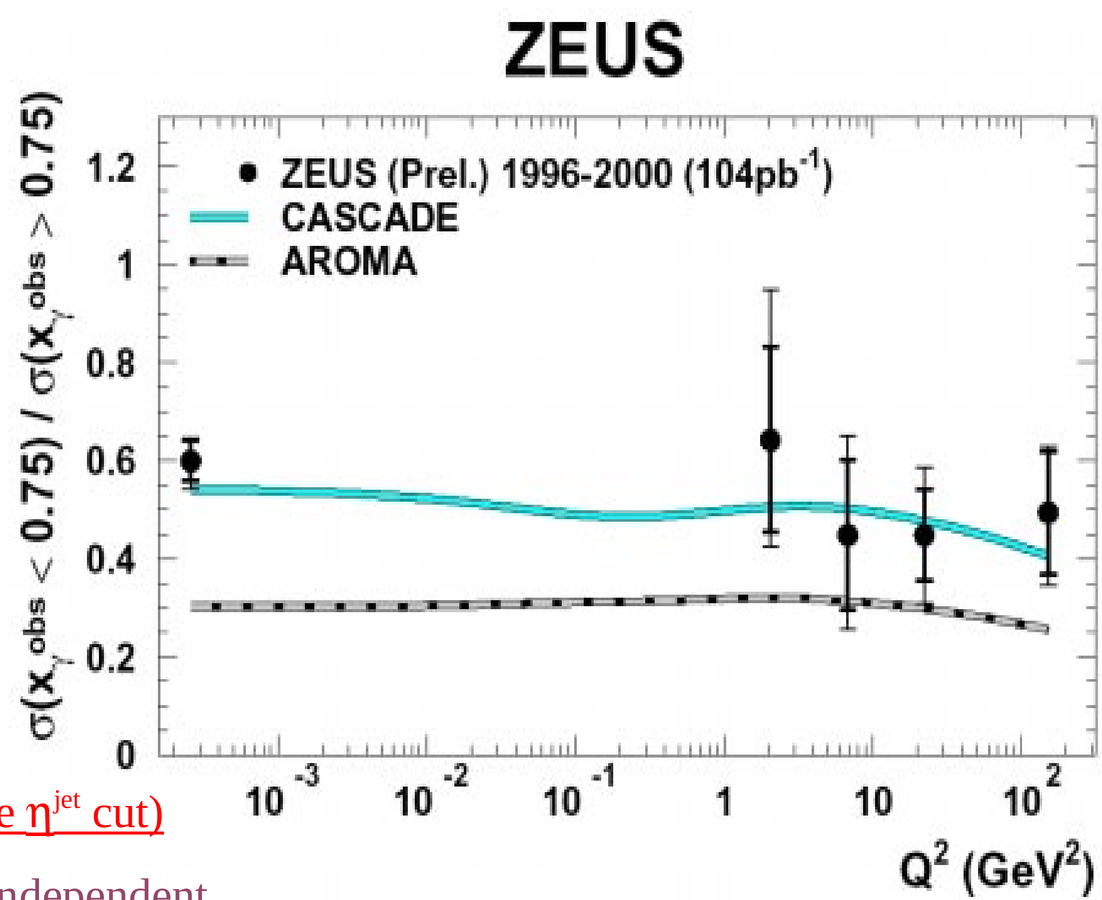
Kinematic region : $Q^2 < 1$ GeV^2, $130 < W_{\gamma p} < 280$ GeV

- Resolved fractions are significant ~ 35%
- PYTHIA, HERWIG and CASCADE in general can reproduce the shape
- CASCADE too high for high x_γ^{obs}
- NLO (Not shown) : Cannot discribe the low x_γ^{obs} region

Parton dynamics: Charm associated Dijet



$F^{\gamma}_2(x_\gamma, Q^2) = F^{\gamma}_{2,point} + F^{\gamma}_{2,hadronic} = F^{\gamma}_{2,point} + \alpha \sum_{\kappa=1,3} e^4_{qk}[a(x_\gamma) \log(Q^2/\Lambda^2) + b(x_\gamma)]$



Similar sample in DIS: (No M_{jj} and average η^{jet} cut)

Suppression due to charm and Q2 are not independent

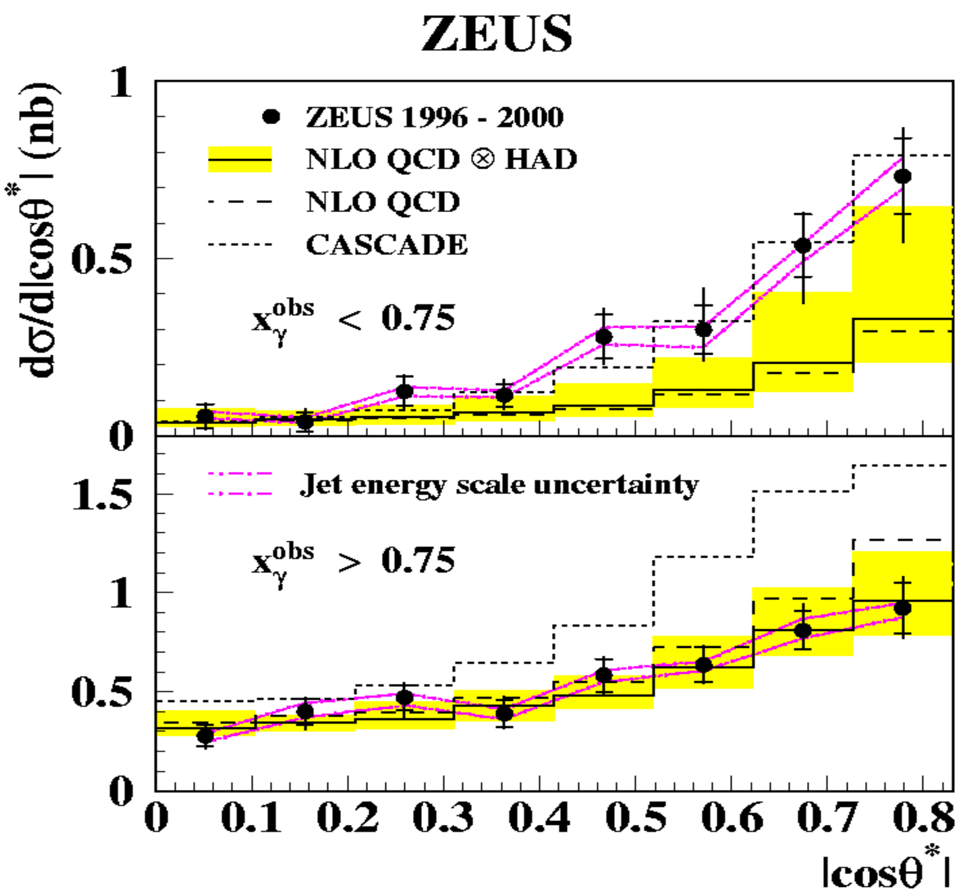
AROMA (LO, no photon structure) cannot describe the data

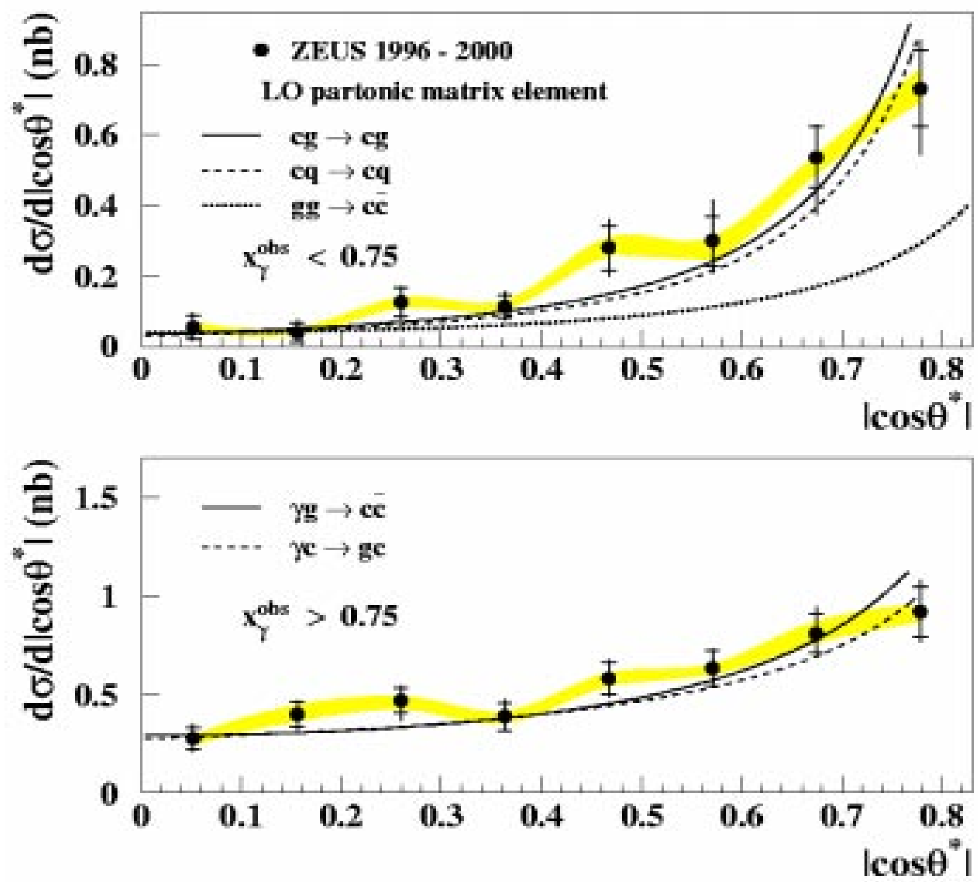
CASCADE agrees very well in the continuum from PHP to DIS

SaS1D (LO, virtual PDF) could describe the shape (Not shown)

Parton dynamics: Charm associated dijet in photoproduction

Hard scatter sensitive measurement





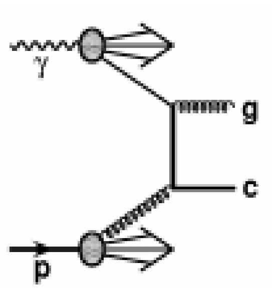
- Resolved distribution rises strongly at high $|\cos\theta^*|$, signature of g−exchange
- Direct distribution shows a shallower rise, consistent with q− exchange
- DATA lies above the NLO calculation for $x_\gamma^{obs} < 0.75$
- Large theoretical uncertainty observed for $|\cos\theta^*|$ distribution.

Fit to $(1 - |\cos\Theta^*|)^{-\kappa}$:

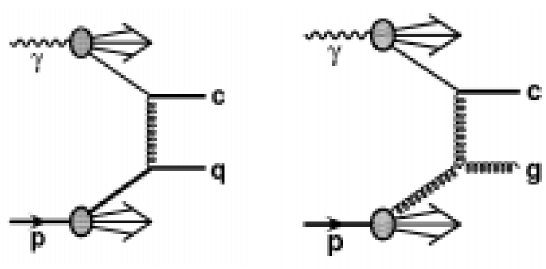
$\kappa = 1.74 \pm 0.18$ ($x_\gamma^{obs} < 0.75$) [~ 2 for g−exchange]

$\kappa = 0.74 \pm 0.11$ ($x_\gamma^{obs} > 0.75$) [~ 1 for q−exchange]

Study of various sub−processes with charm

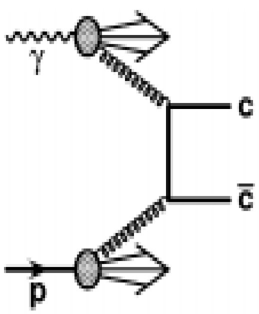


q−exchange

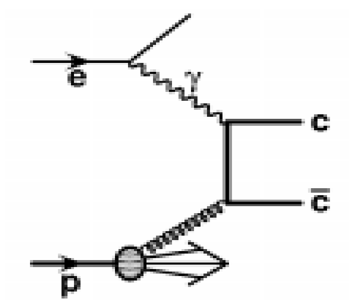


g−exchange

Resolved−γ (pythia) : c excitation ~35%

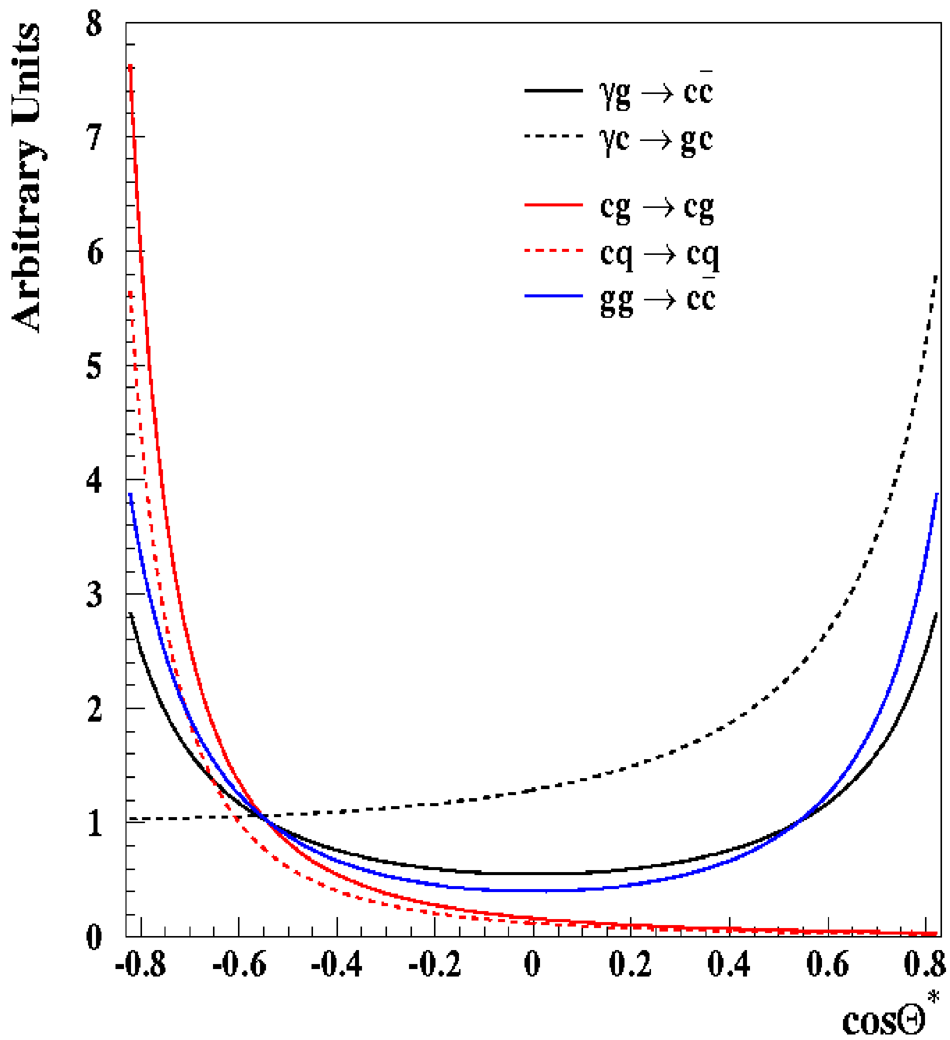


⇐ Resolved−γ: g g → c $\bar{c}$ ~ 0.46%

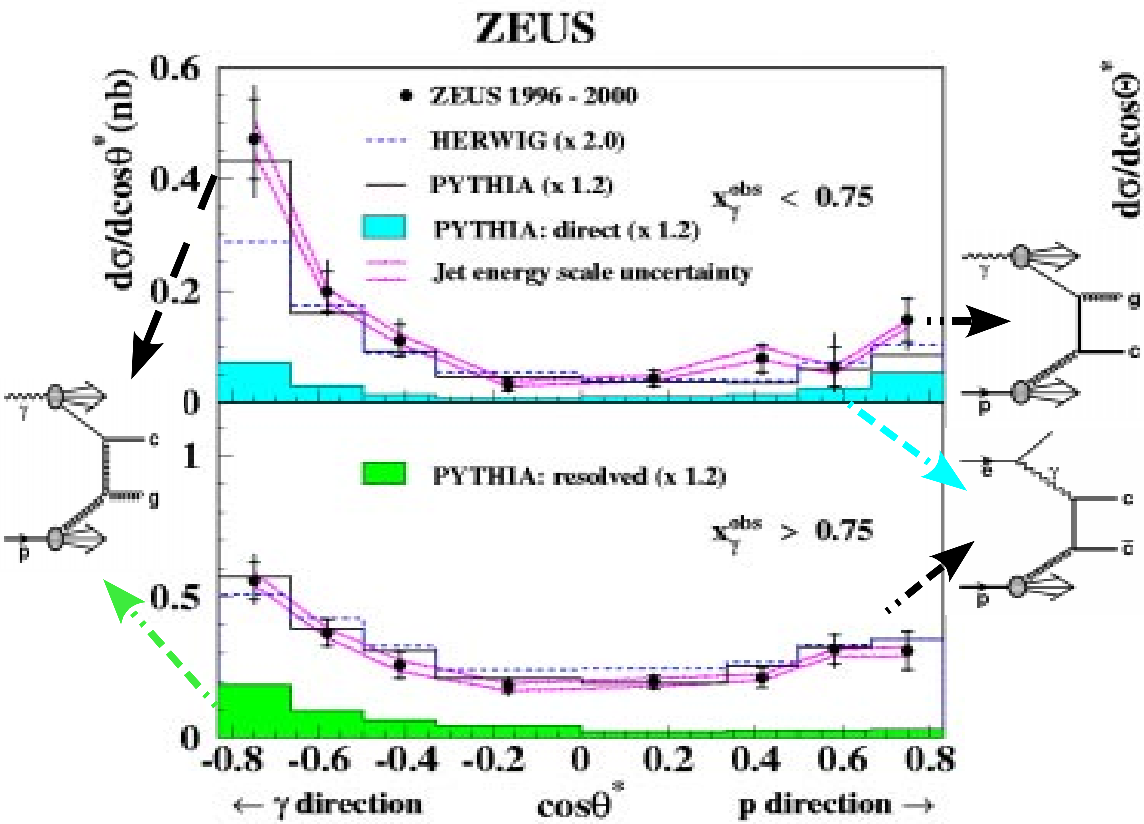


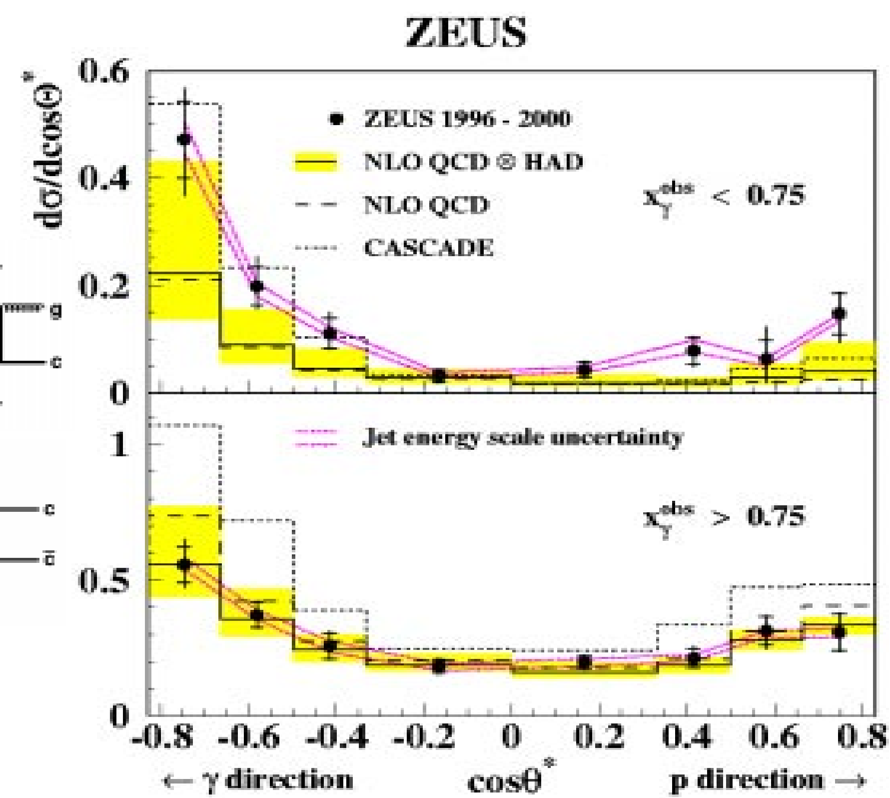
⇐ Direct−γ: γ−g fusion ~ 62%

Just from Matrix elements



Charm associated dijet in Photoproduction





Match the jet with a D* in (η−φ) space

Define: Jet (1) = D* Jet

Jet (2) = other Jet

For $x_{\gamma}^{obs} > 0.75$: NLO agrees with DATA

CASCADE too high in x−section

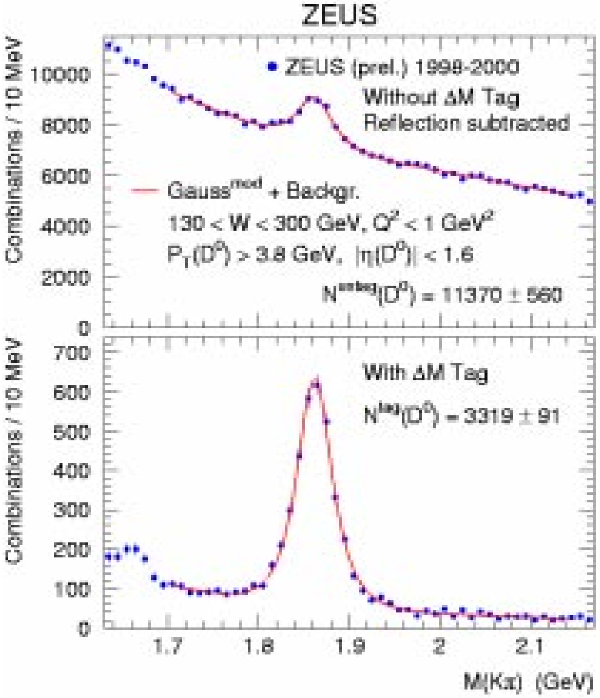
For $x_{\gamma}^{obs} < 0.75$: NLO underestimates the DATA both proton and photon direction

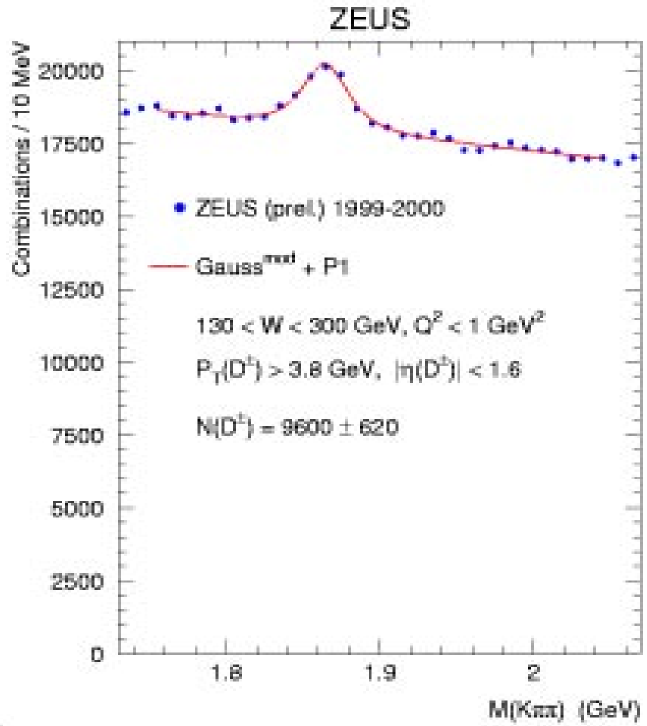
Contribution of LO resolved to $x_{\gamma}^{OBS} > 0.75$ explains the asymmetric distribution in $\cos\theta^{*}$

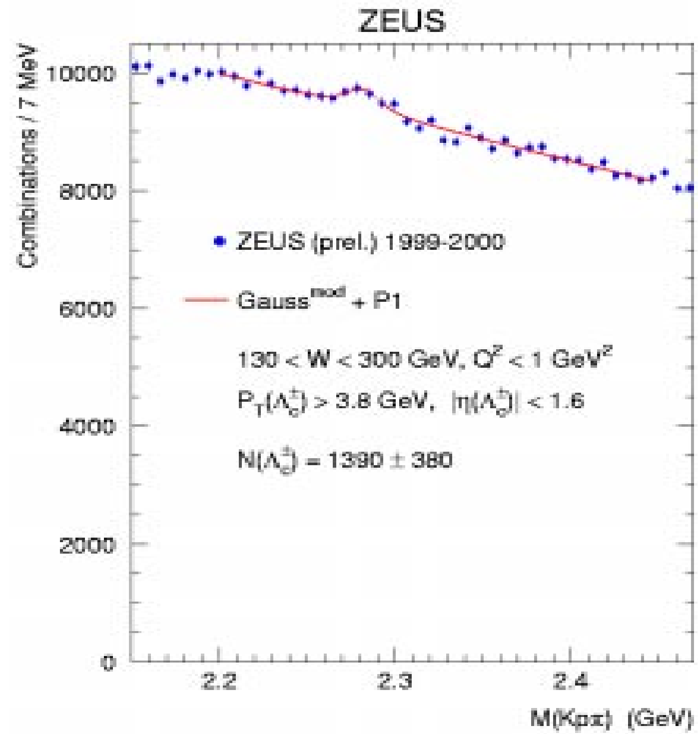
CASCADE :agrees well both shape and norm..

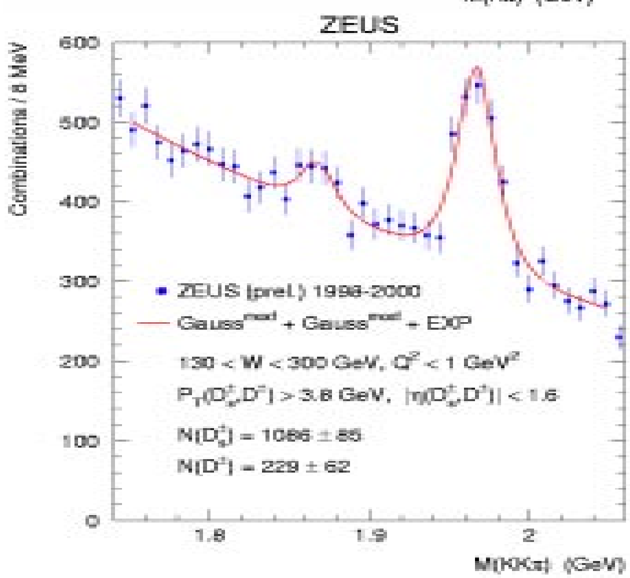
Clear evidence of charm from the photon

Charm fragmentation









HERA is a charm factory :

Various charmed meson production

130 < W < 280 GeV, $Q^2 < 1$ GeV^2

$p_T(D, \Lambda_c) > 3.8$ GeV, $|\eta(D,\Lambda_c)| < 1.6$

Cross section measured: $\sigma^{untag}(D^0)$, $\sigma^{tag}(D^0)$, $\sigma(D^{*\pm})$

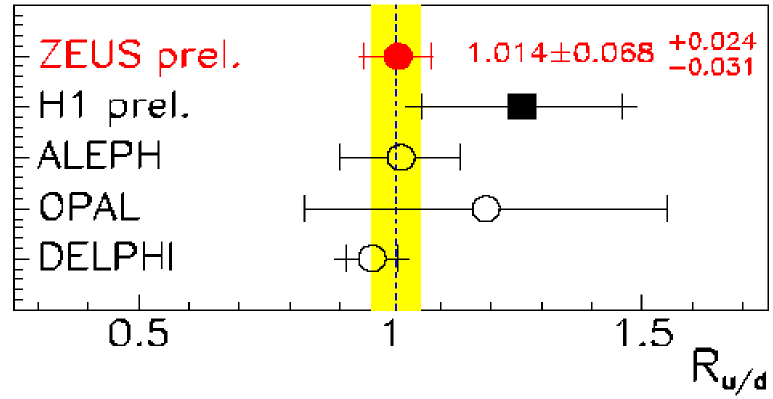
$\sigma(D^{\pm})$, $\sigma(D_s^{\pm})$, $\sigma(\Lambda_c^{\pm})$

Charm fragmentation

Charm fragmentation fractions:

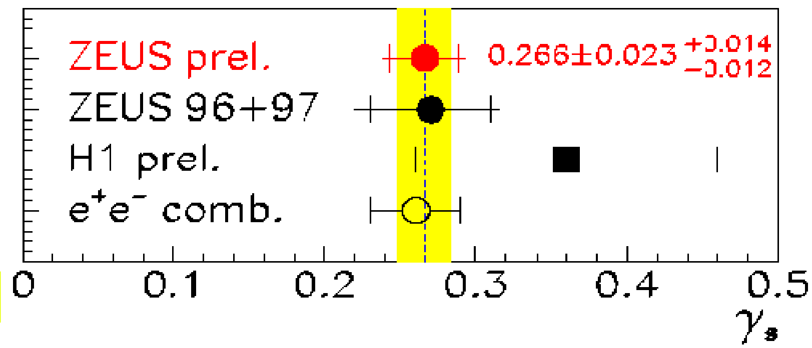
$$R_{u/d} = \frac{c\bar{u}}{c\bar{d}} = \frac{\sigma(D^{0,*0})}{\sigma(D^{\pm,*\pm})} = \frac{\sigma^{untag}(D^0)}{\sigma(D^{\pm}) + \sigma^{tag}(D^0)}$$

u and *d* quarks are produced equally in charm fragmentation



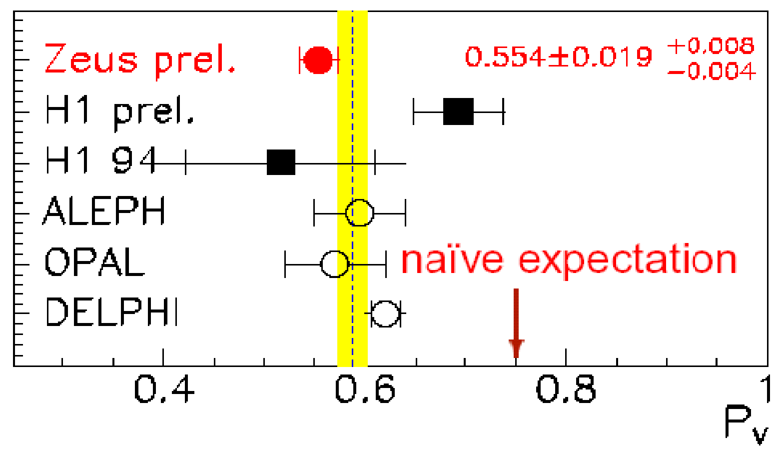
$$\gamma_s = \frac{2c\bar{s}}{c\bar{d} + c\bar{u}} = \frac{2\sigma(D_s^{\pm})}{\sigma^{dir}(D^{\pm}) + \sigma^{dir}(D^0) + 2\sigma(D^{*\pm})}$$

s−quark is suppressed by factor ~3−4 in charm fragmentation



$$P_V = \frac{V}{V+P} = \frac{\sigma(D^*)}{\sigma(D^*) + \sigma^{dir}(D)} \neq 3/4$$

"naïve" spin counting does not work for charm



Charm fragmentation

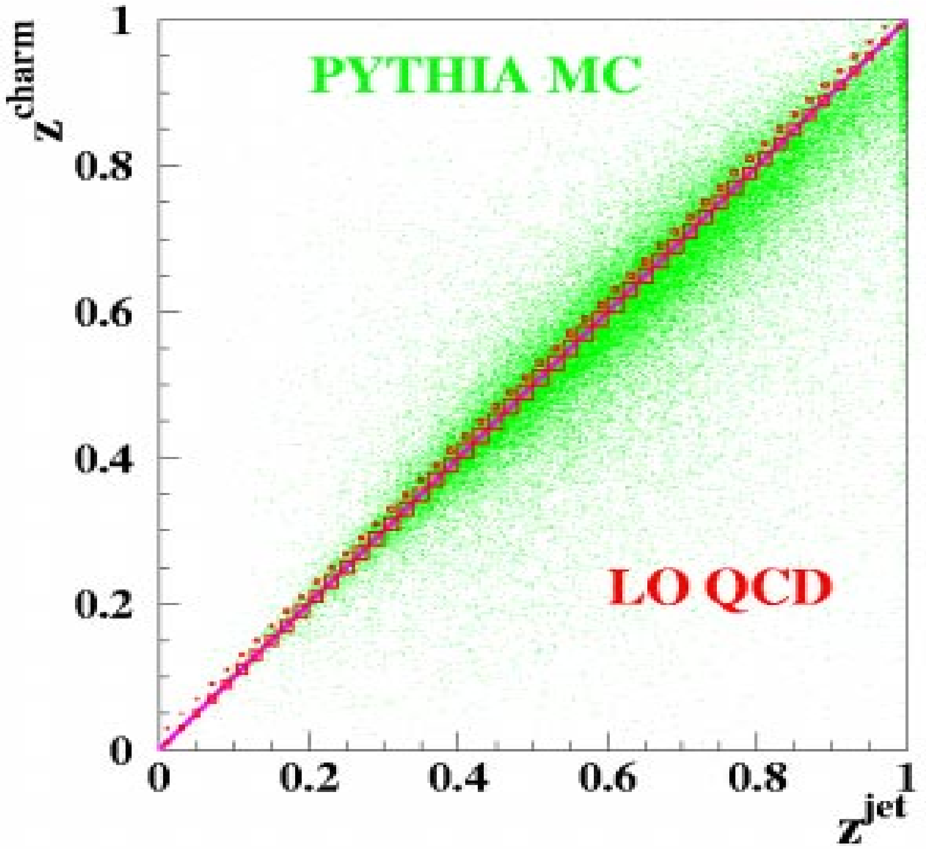
Charm fragmentation fractions

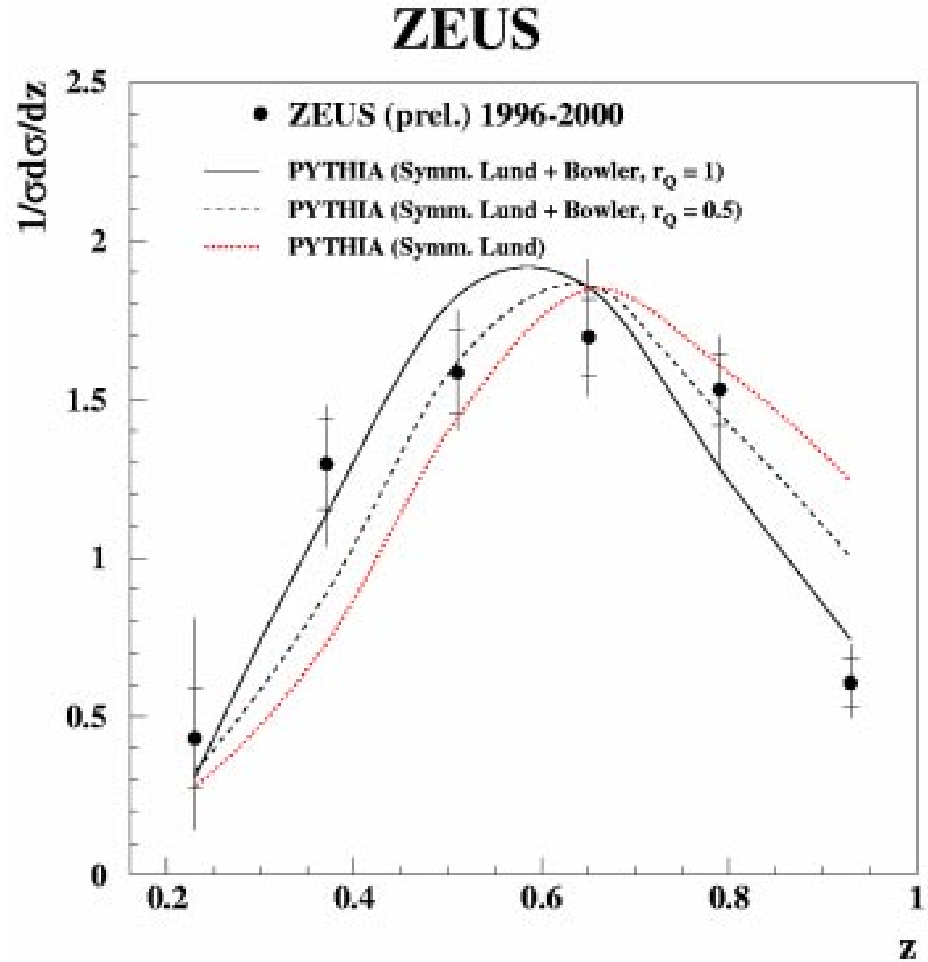
ZEUS prel. (γp) $P_T(D,\Lambda_c) > 3.8$ GeV, $\lvert\eta(D,\Lambda_c)\rvert < 1.6$	Combined e^+e^- data	H1 prel. (DIS)
$f(c \to D^+) = 0.249 \pm 0.014^{+0.004}_{-0.008}$	0.232 ± 0.010	$0.202 \pm 0.020^{+0.045}_{-0.033}{}^{+0.029}_{-0.021}$
$f(c \to D^0) = 0.557 \pm 0.019^{+0.005}_{-0.013}$	0.549 ± 0.023	$0.658 \pm 0.054^{+0.117}_{-0.142}{}^{+0.086}_{-0.048}$
$f(c \to D_s^+) = 0.107 \pm 0.009 \pm 0.005$	0.101 ± 0.009	$0.156 \pm 0.043^{+0.036}_{-0.035}{}^{+0.050}_{-0.046}$
$f(c \to \Lambda_c^+) = 0.076 \pm 0.020^{+0.017}_{-0.001}$	0.076 ± 0.007	
$f(c \to D^{*+}) = 0.223 \pm 0.009^{+0.003}_{-0.005}$	0.235 ± 0.007	$0.263 \pm 0.019^{+0.056}_{-0.042}{}^{+0.031}_{-0.022}$

charm fragmentation fractions are universal

Charm fragmentation

Assume that charm jet is good approximation to outgoing charm quark





D* relative to hadronic jet:

$z^{jet} = (E + P_{\|})_{(D^*)} / (E + P_{\|})_{jet}$

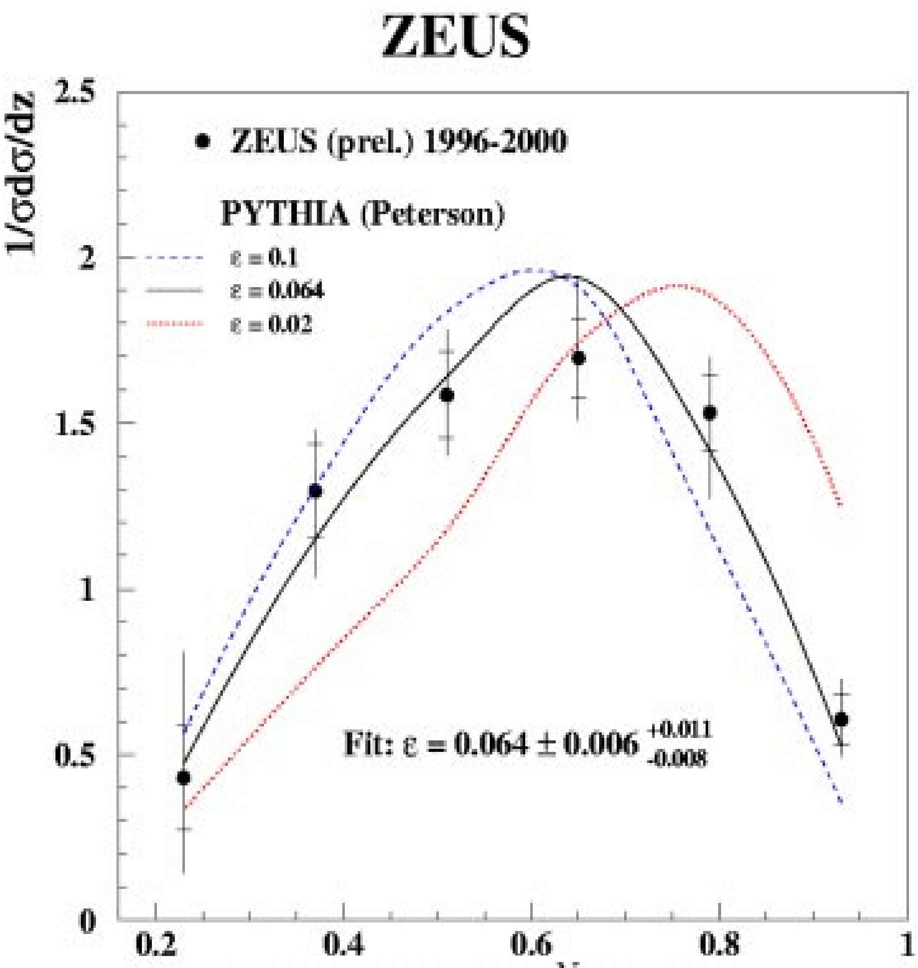
D* relative to charm from hadr scatter :

$z^{charm} = (E + P_{\|})_{(D^*)} / (E + P_{\|})_{charm}$

$$f(z) \propto \frac{1}{z^{1+r_Q \beta m_Q^2}} z^{a_\alpha} \left(\frac{1-z}{z}\right)^{a\beta} \exp\left(\frac{-\beta \cdot m_\perp^2}{z}\right)$$

r_Q = 1 (default) is preferable

Charm fragmentation

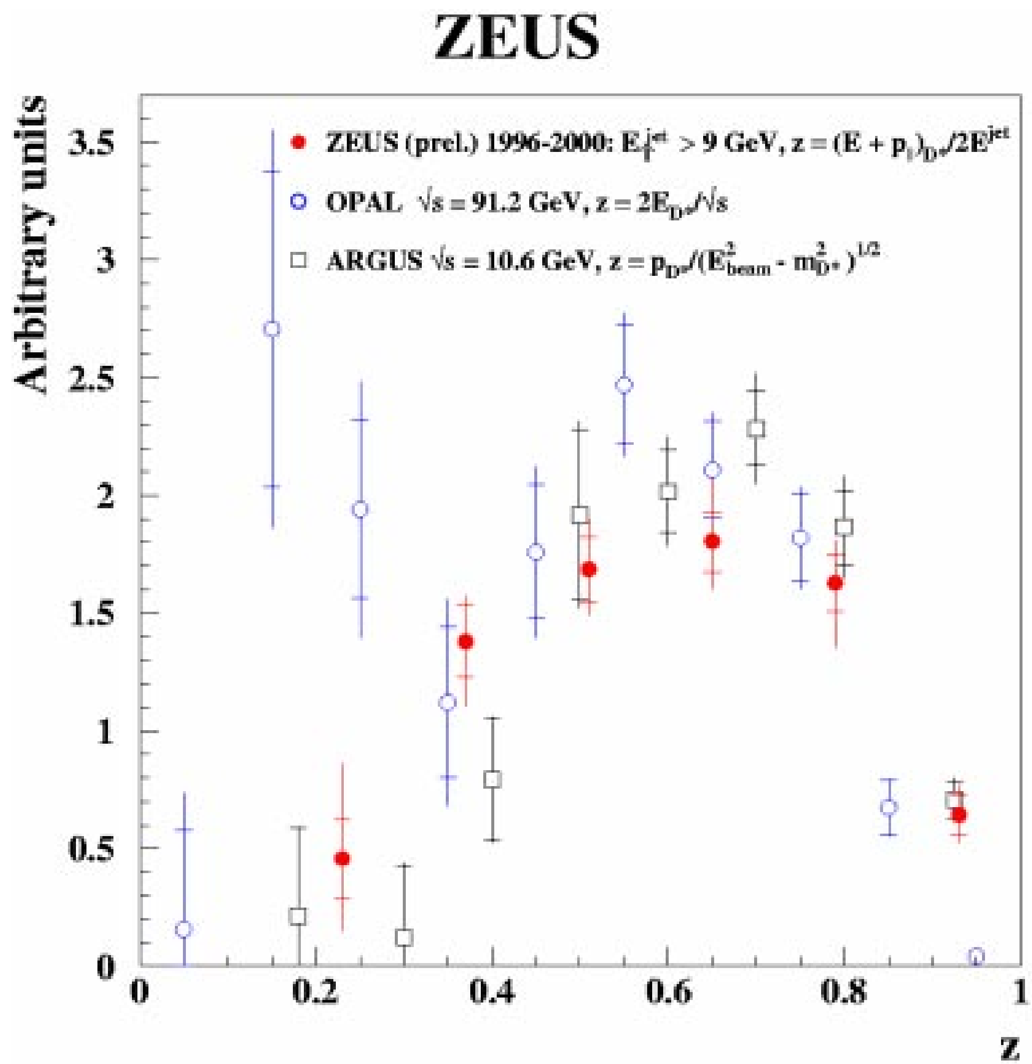


$$D_Q^H(z) = \frac{N}{z[1-(1/z)-\epsilon/(1-z)]^2}$$

ε = 0.05 (PYTHIA default)

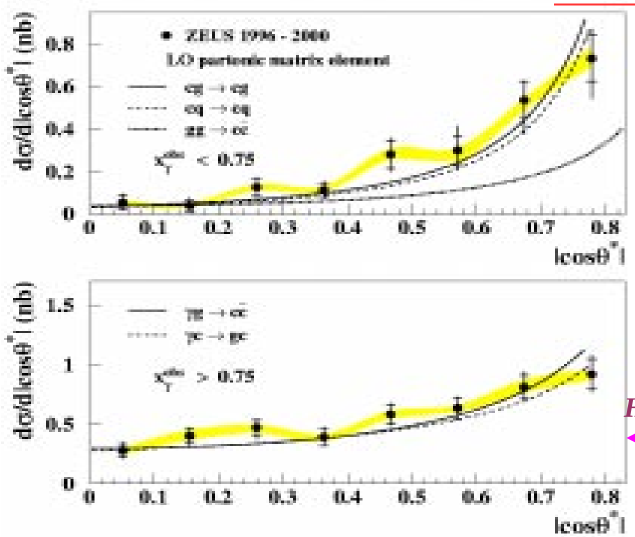
ε = 0.053 (LL fit to ARGUS data, Nason and Oleari)

Independent ways of measuring the fragmentation

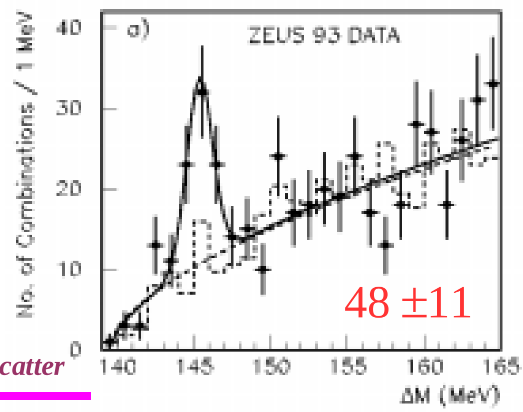


Universality of charm fragmentation function ?

Summary and Conclusions



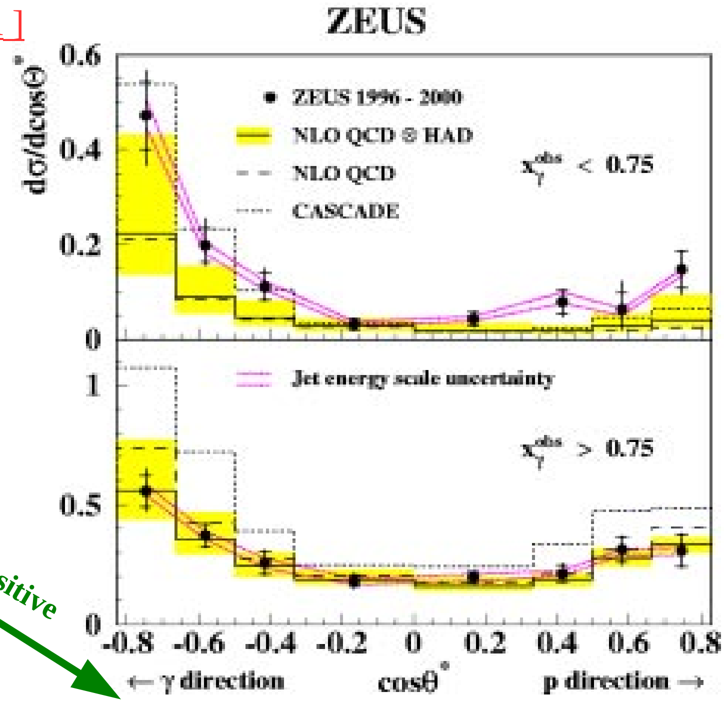
DESY 95−013 :[First heavy flavour signature at HERA]

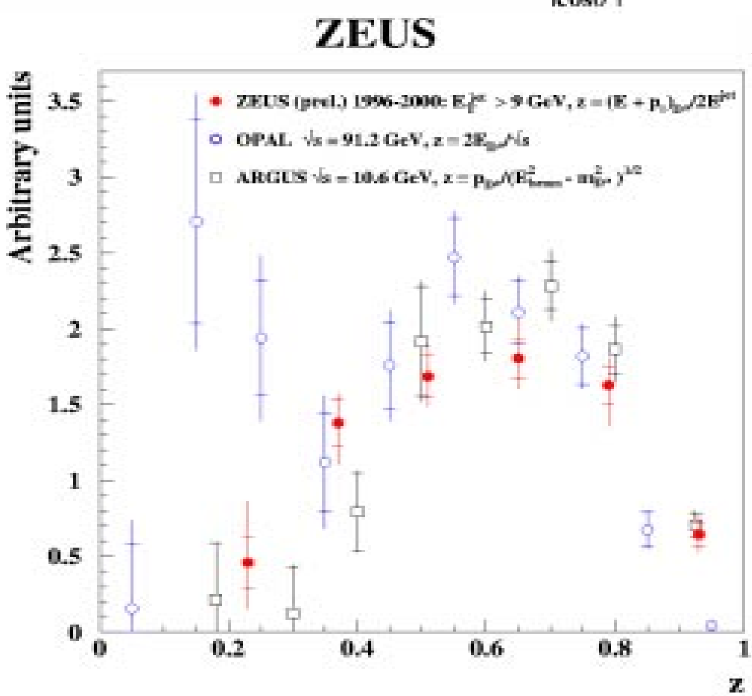


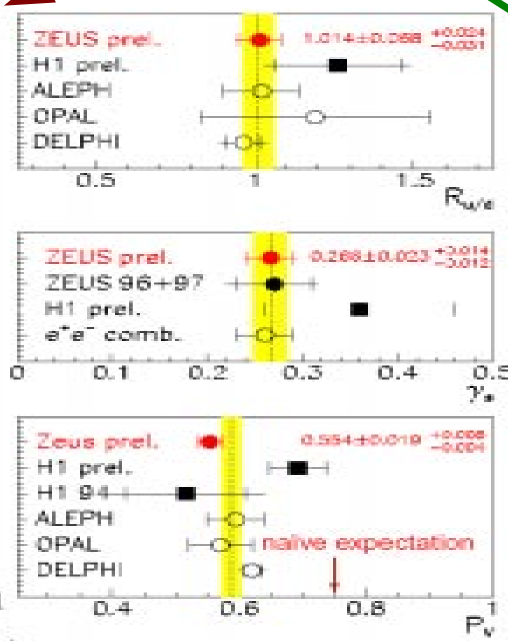
Hard Scatter

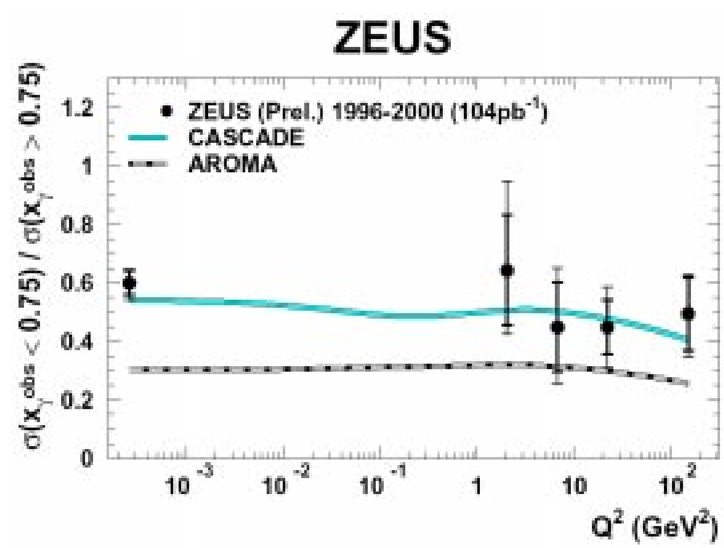
Fragmentation

PDF_γ sensitive









Summary and Conclusions

HERA−I provided quite an enormous amount of high statistics open charm and beauty measurements

Precision of data is much better than theoretical uncertainties

New trends @ HERA : New beauty measurements in the visible region of phase space

Very precise charm measurements in both DIS and PHP regime

PDF_γ sensitive measurements like angular distribution, virtual photon with charm

$\Rightarrow$ Measurements related to multiscale issues in pQCD.

New F_2^{cc} measurements can be used to constrain the gluon density in proton

Charm fragmentation function and the fractions measured for the first time.

Many issues like : Pole mass, Binding force of the hadronic component −gluon PDF etc ..

.... still needs to be addressed.

Some part of PDF $\otimes$ Hard Scatter $\otimes$ Fragmentation understood ... still a lot is left

More to come from final HERA−I data and even more with higher luminosity HERA II