Heavy Quark Production

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Experimental Review: open charm and beauty production
Mostly HERA, with LEP and TeVatron

Progress in technique

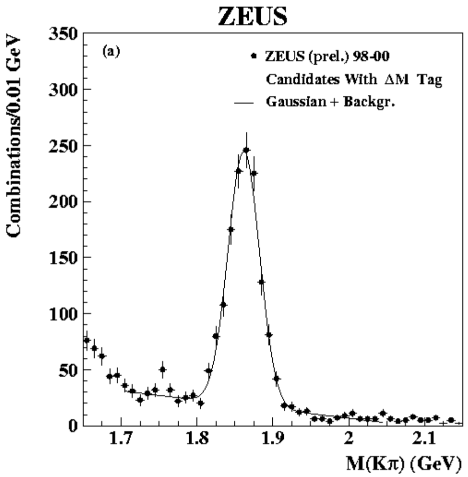
- Charm finding: decay length tag, CDF 2-track trigger
- Beauty finding: p_T^{rel}, impact parameter, $D^*\mu$ correlations
- Progress in theory; understanding corrections, CCFM

Results

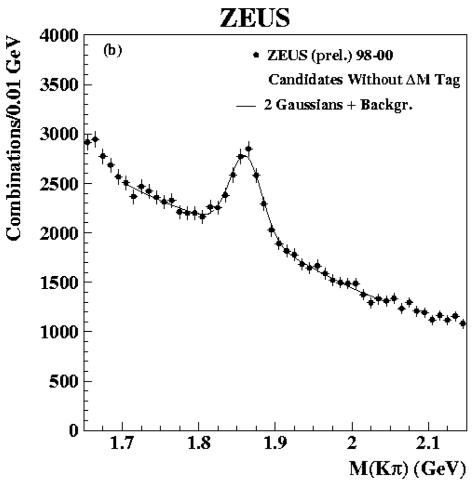
- Charm content of photon
- DIS: double differential, $F_2^{c\bar{c}}$, diffraction
- Beauty production c.f. NLO and $\gamma\gamma$ reactions

Charmed meson finding

$D^{*+} \rightarrow D^0 \pi^+, \Delta m$ cut

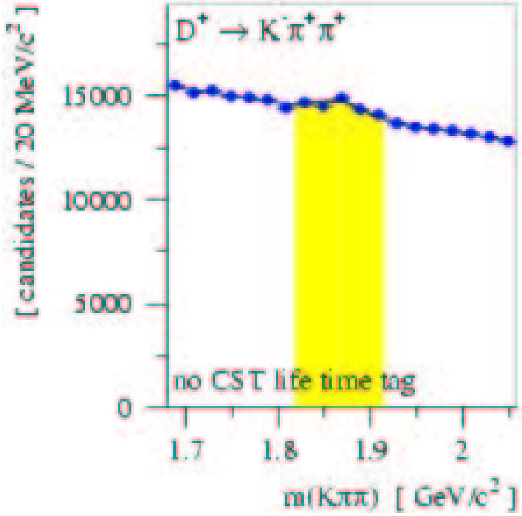


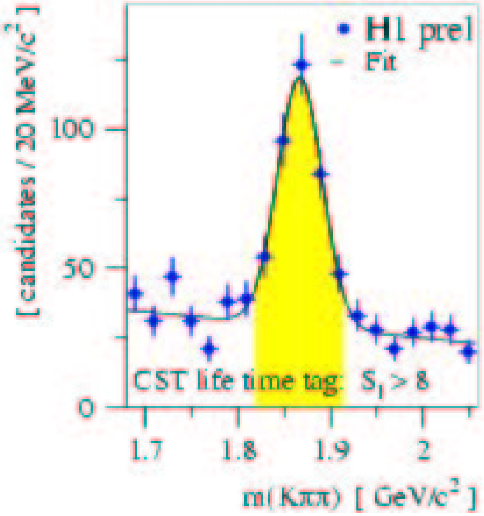
$D^0 \rightarrow K^- \pi^+$, not from D^*

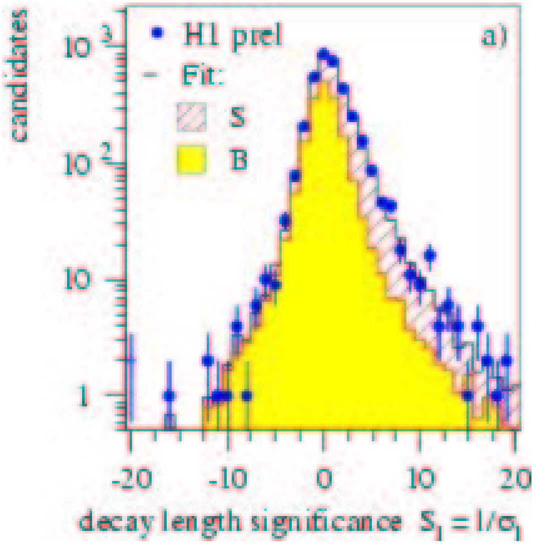


$D^+ \rightarrow K^- \pi^+ \pi^+$

H1: add decay length tag





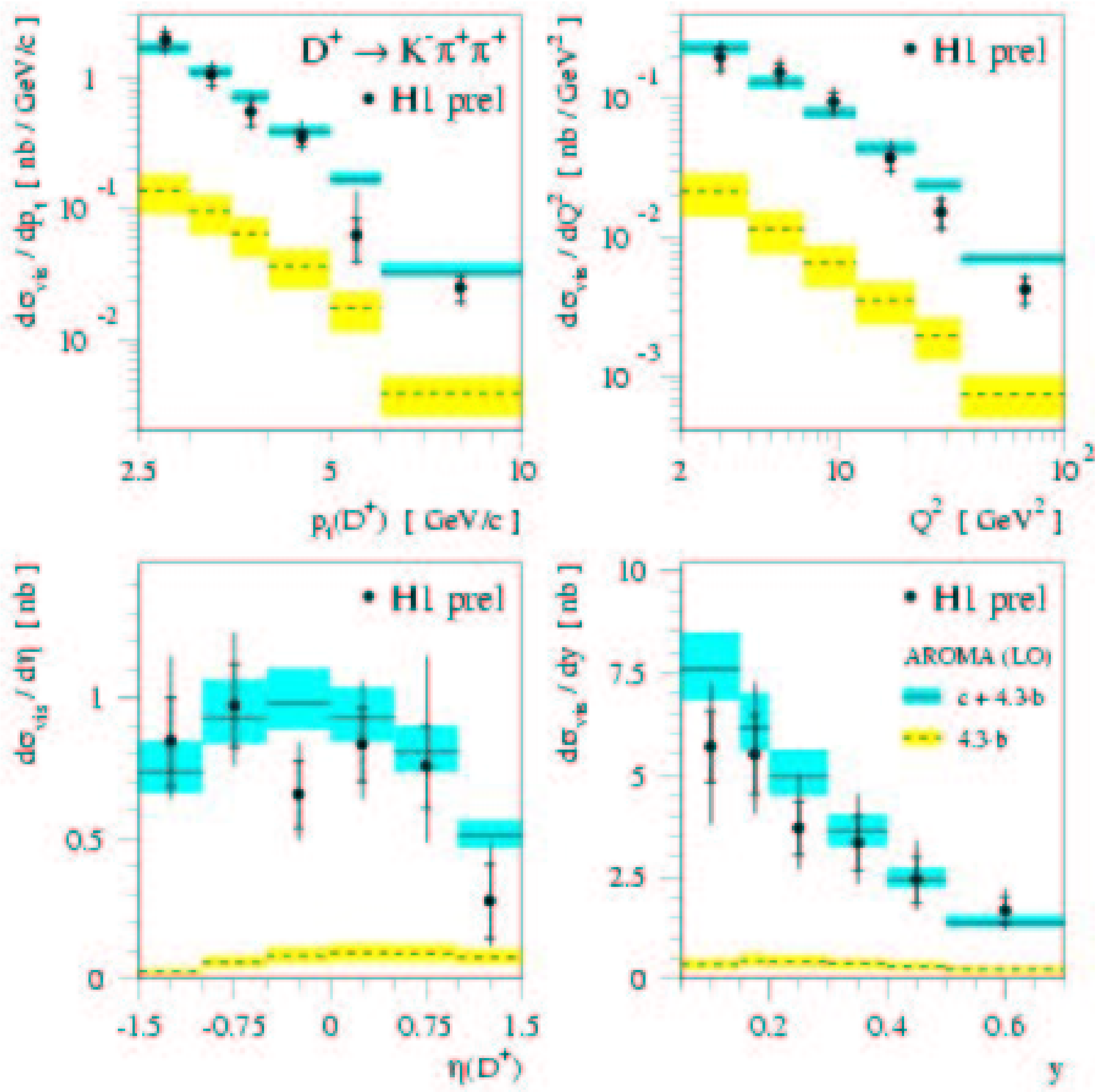


H1: see

D^+, D^0, D_s, D^{*+}

ZEUS: SVX now installed

D^+ production in DIS: H1



$$D^+ \rightarrow K^-\pi^+\pi^+$$

$2<Q^2<100$ GeV^2; $0.05<y<0.7$

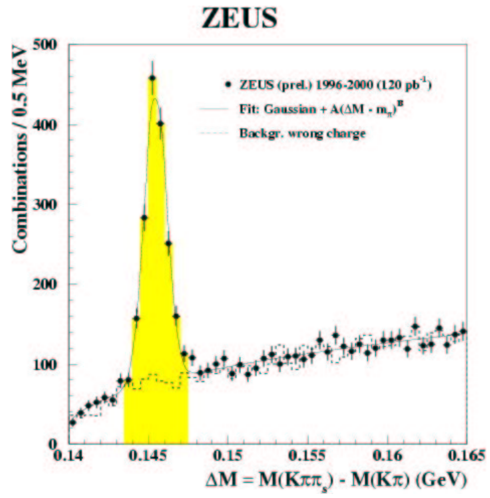
$p_t(D) > 2.5$ GeV; $|\eta(D)| < 1.5$

$$\sigma_{vis}(ep \rightarrow eDX) = (2.16 \pm 0.19^{+0.46}_{-0.35})nb$$

LO+PS good description
of shape and normalisation

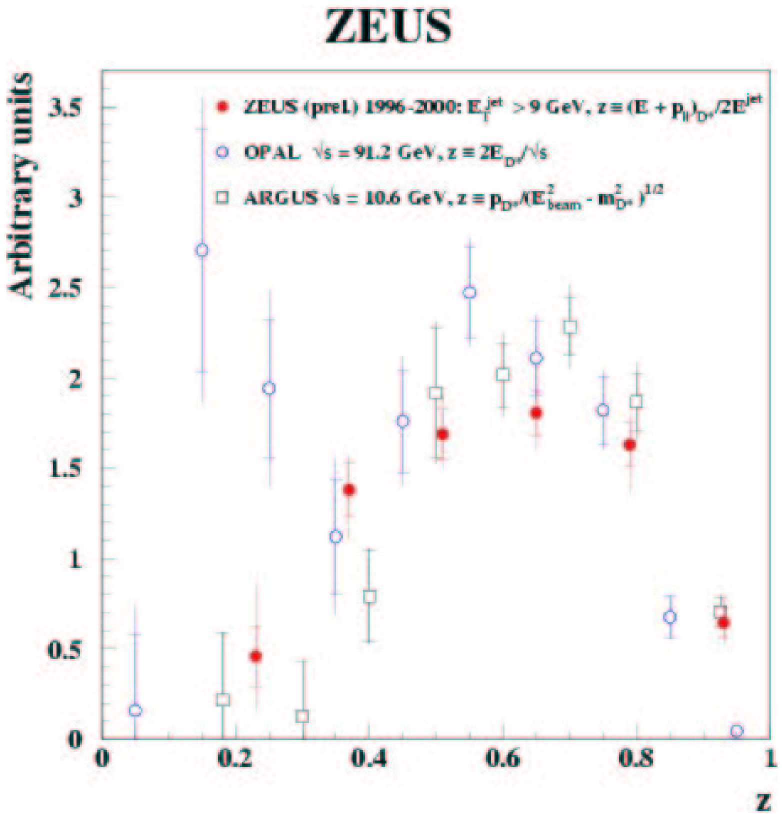
similar results for
D^*, D^0, D_s production

Charm Fragmentation



PHP : $z = (E + p_{par}) / 2E_{jet}$

$(E^T_{jet} > 9\,\text{GeV})$



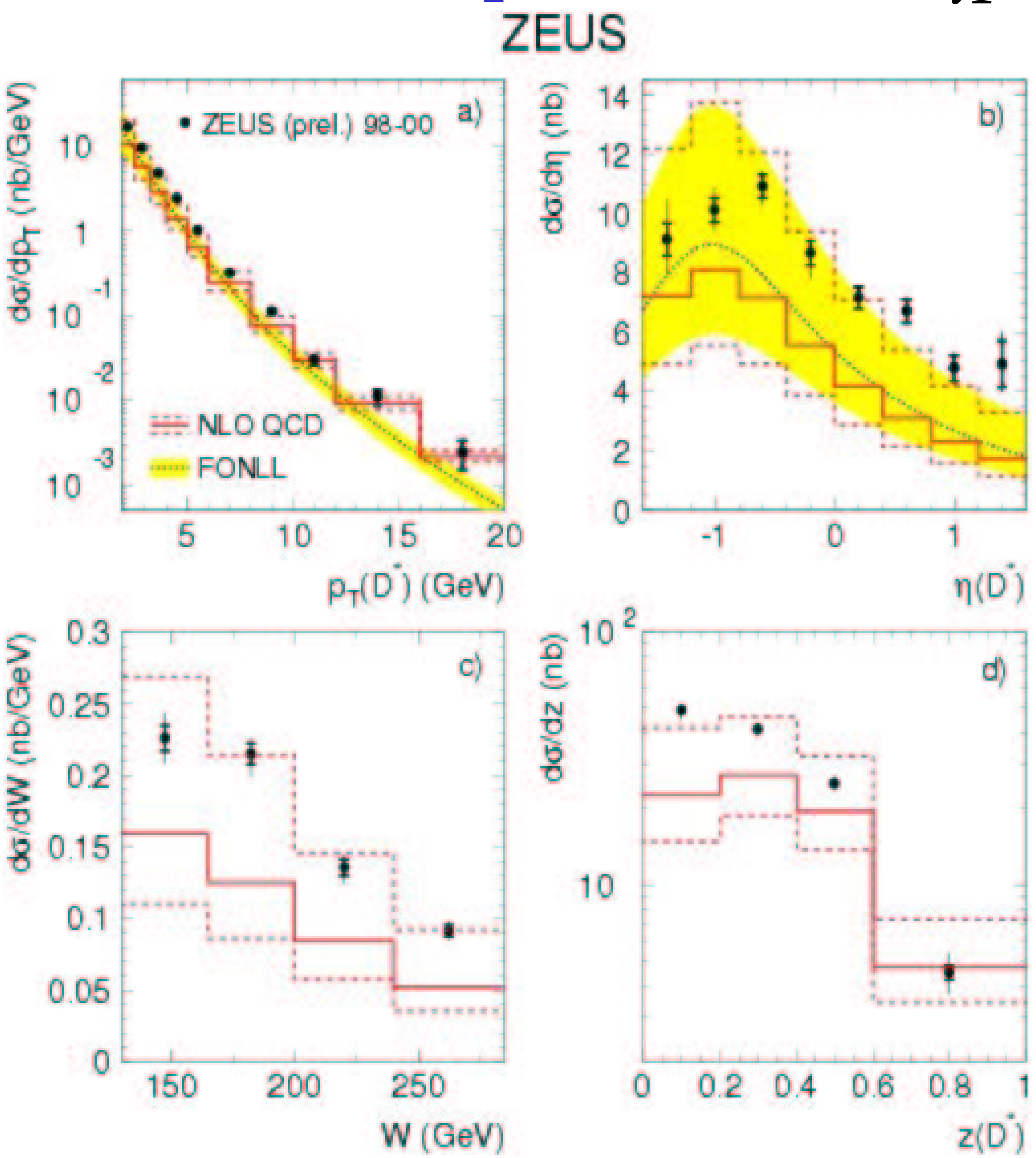
DIS flavour rates (H1)

	D^+	D^0	D_s	D^{*+}
f(c-D)	0.202	0.658	0.156	0.263
± (stat)	0.020	0.054	0.043	0.019
± (syst)	0.04	0.12	0.04	0.05
± (theo)	0.03	0.07	0.05	0.03
world	.232	0.549	0.101	0.235
ave (±)	0.018	0.026	0.027	0.010

Fragmentation:	H1	world ave
R(u/d)	1.26 ± .11 ± .04	1.00 ± .09
γ_s	0.36 ± .10 ± .04	0.26 ± .07
V/(P+V)	.693 ± .045 ± .006	0.601 ± .032
or	$.613 \pm .061^{+.033}_{-.088}$	

HERA charm frag looks like LEP charm frag

Photoproduction: $\gamma p \to D^* + ...$



$1.9 < p_T < 20$
$-1.6 < \eta < 1.6$
$130 < W < 285$

Theory: NLO+FONLL
- shape reasonable
- lie somewhat below data

$\gamma p \rightarrow c\bar{c}X$ 2 jets. D* tag

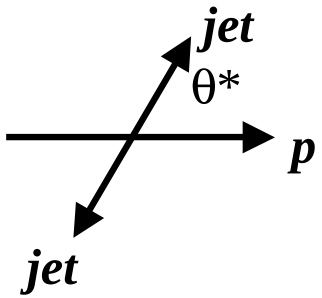
Fraction of photon energy in two highest-E_T jets:

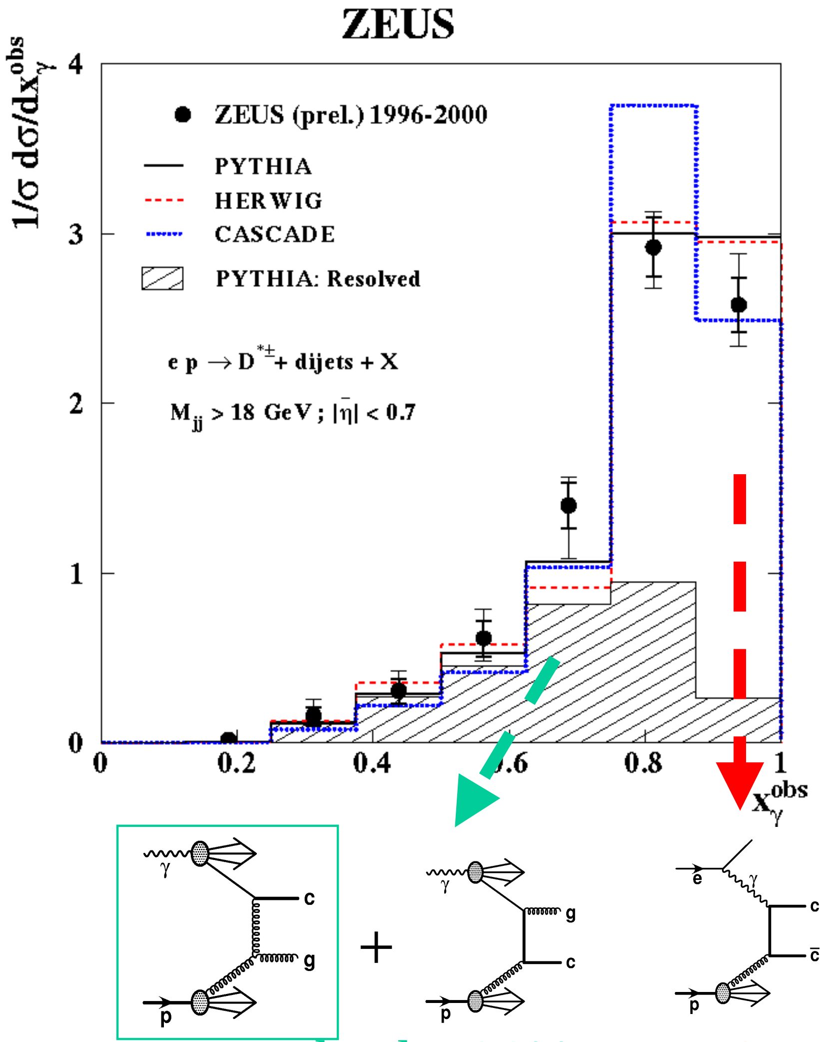
$$x_\gamma^{obs} = (\sum_{j=1}^{2} E_T e^{-\eta}) / 2yE_e$$

Direct $x_\gamma^{obs} > 0.75$ q-exchange
$d\sigma/d\cos\theta^* \sim (1 - |\cos\theta^*|)^{-1}$

Resolved $x_\gamma^{obs} < 0.75$ c in remnant
includes g-exchange
$d\sigma/d\cos\theta^* \sim (1 + \cos\theta^*)^{-2}$

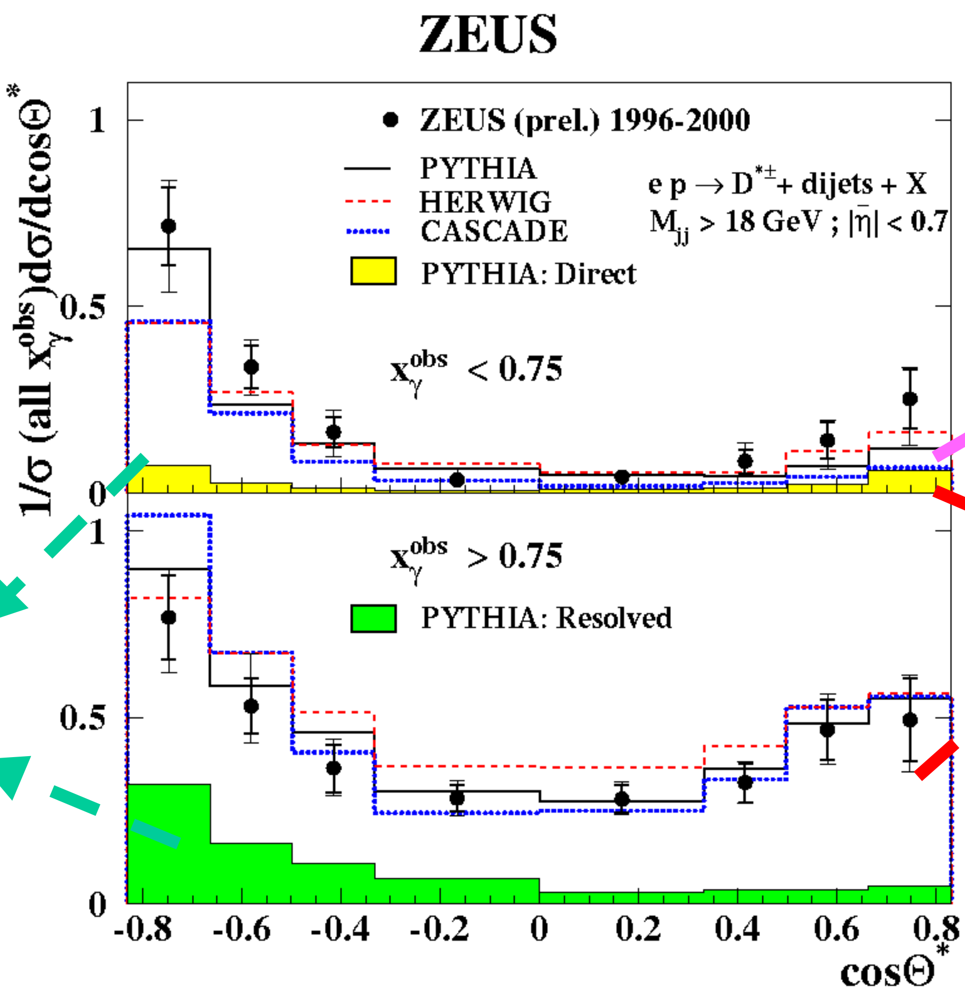
Rutherford scattering



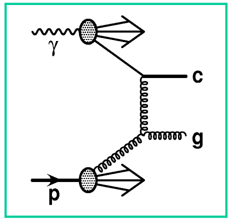


Resolved ~ 36% Direct 64%

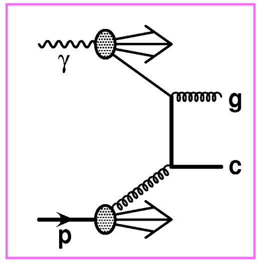
Dijet angular distributions

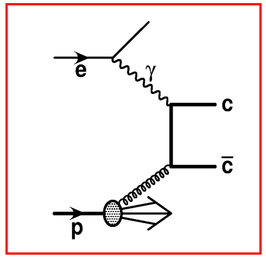


← photon direction proton direction →



Match jet to D*
in η–φ space



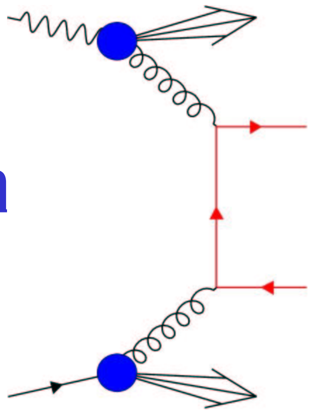


Contribution of LO resolved to $x_\gamma^{obs} > 0.75$ explains asymmetric cosθ*

Clear evidence for charm content of photon

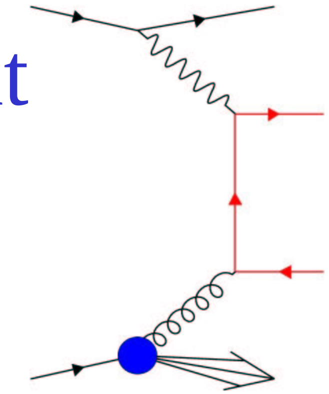
Photo-production

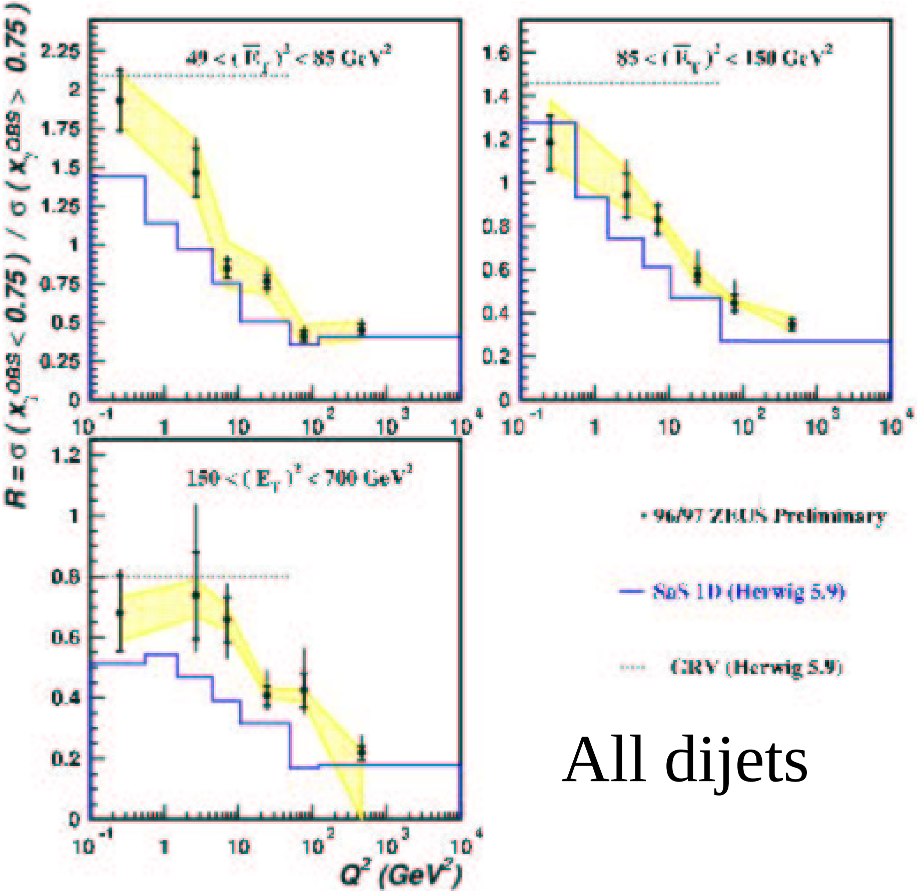
mostly resolved



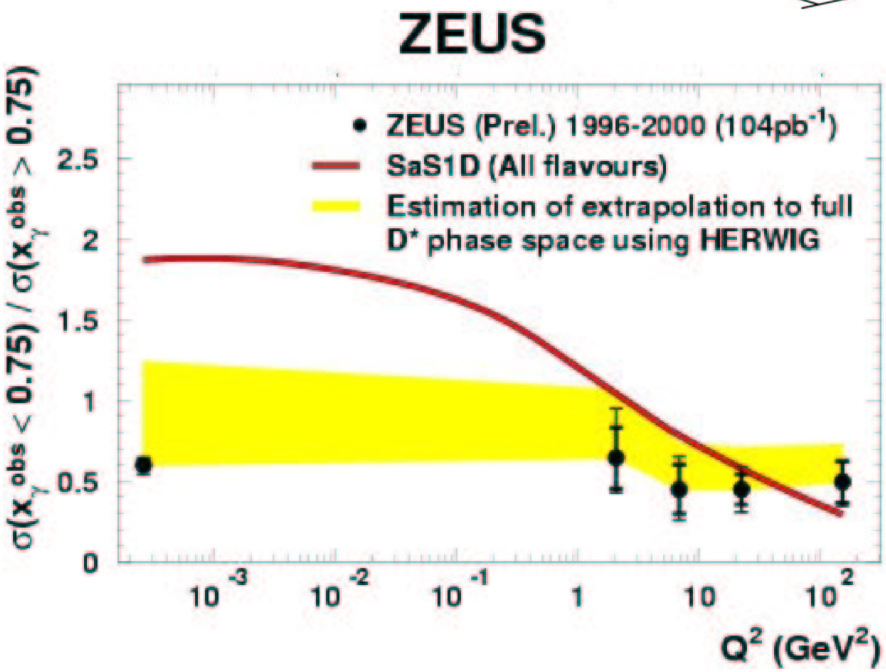
Deep.**I**nel.**S**cat

mostly direct





All dijets

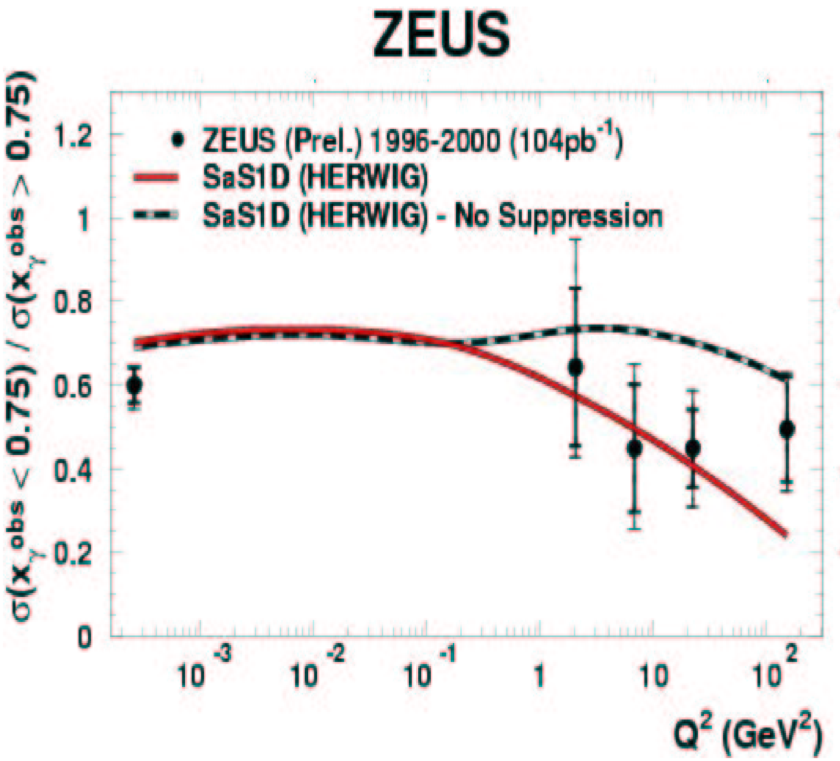


Dijets with D^*:

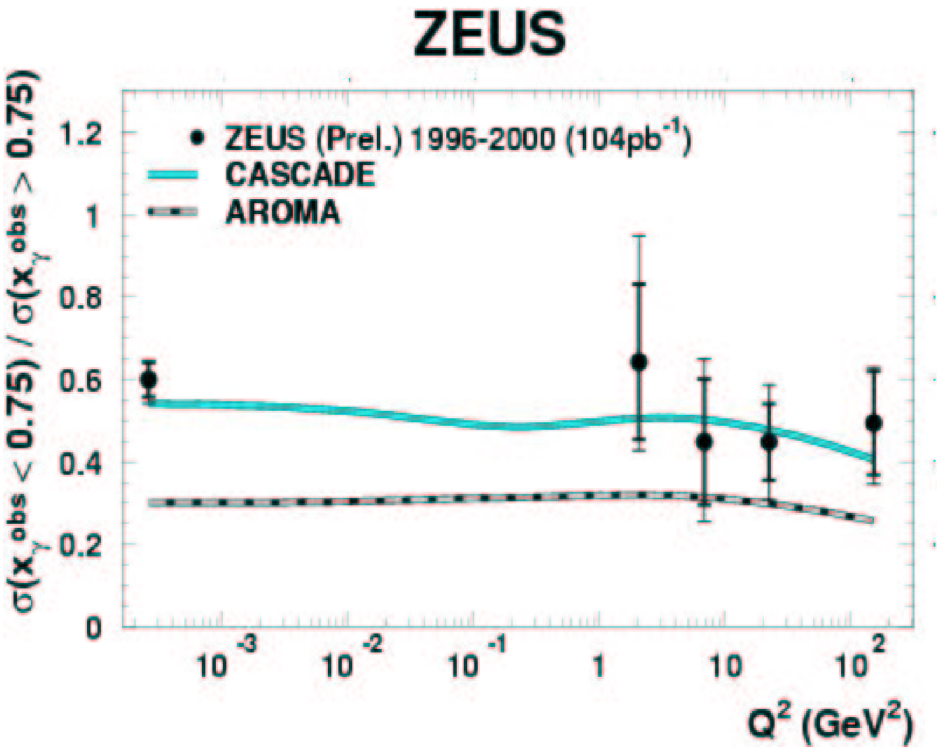
Ratio resolved/direct

indep of Q^2 for charm

D^* resolved/direct ratio



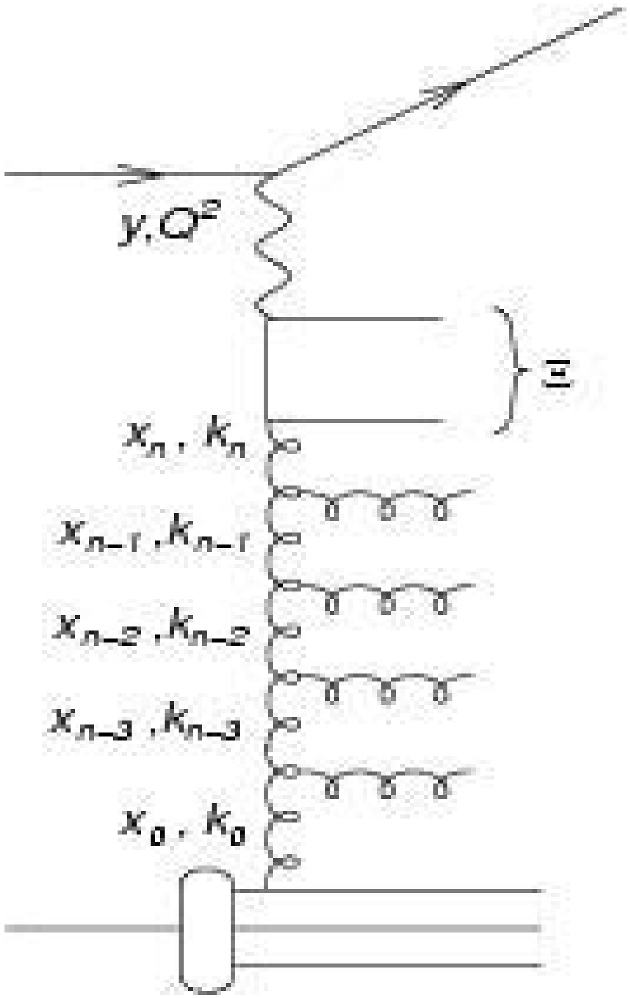
SaS1D: γ* structure



No γ* structure assumed
Low x_γ^{obs} comes from parton shower evolution
AROMA (DGLAP) below data
CASCADE (CCFM) closer

Charm production in DIS

Photon-gluon fusion dominates



2 hard scales: m_c, Q^2: use to measure *xG(x)*

Parton shower at high Q^2

DGLAP - order in k_T(HVQDIS)
? Problems at low-x

BFKL - order in x
low x OK, Q^2 evolution?

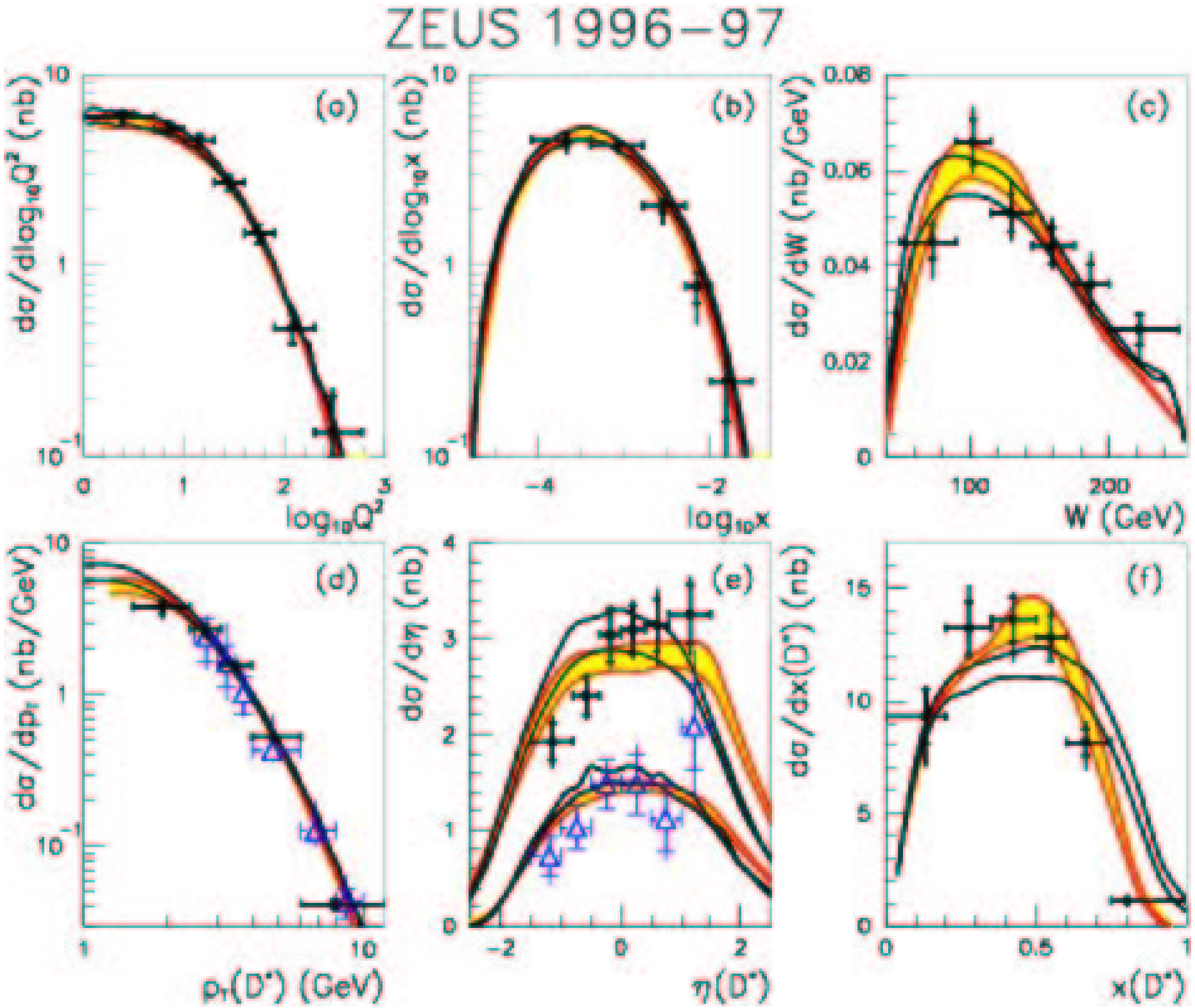
CCFM - order in η (CASCADE)
unify ?

CCFM evolution gives *xG(x)* different from DGLAP:

- *xG(x)* higher for $0.01<x<0.1$
- more b-production

*D** differential cross-sections

HVQDIS (NLO-DGLAP) describes OK

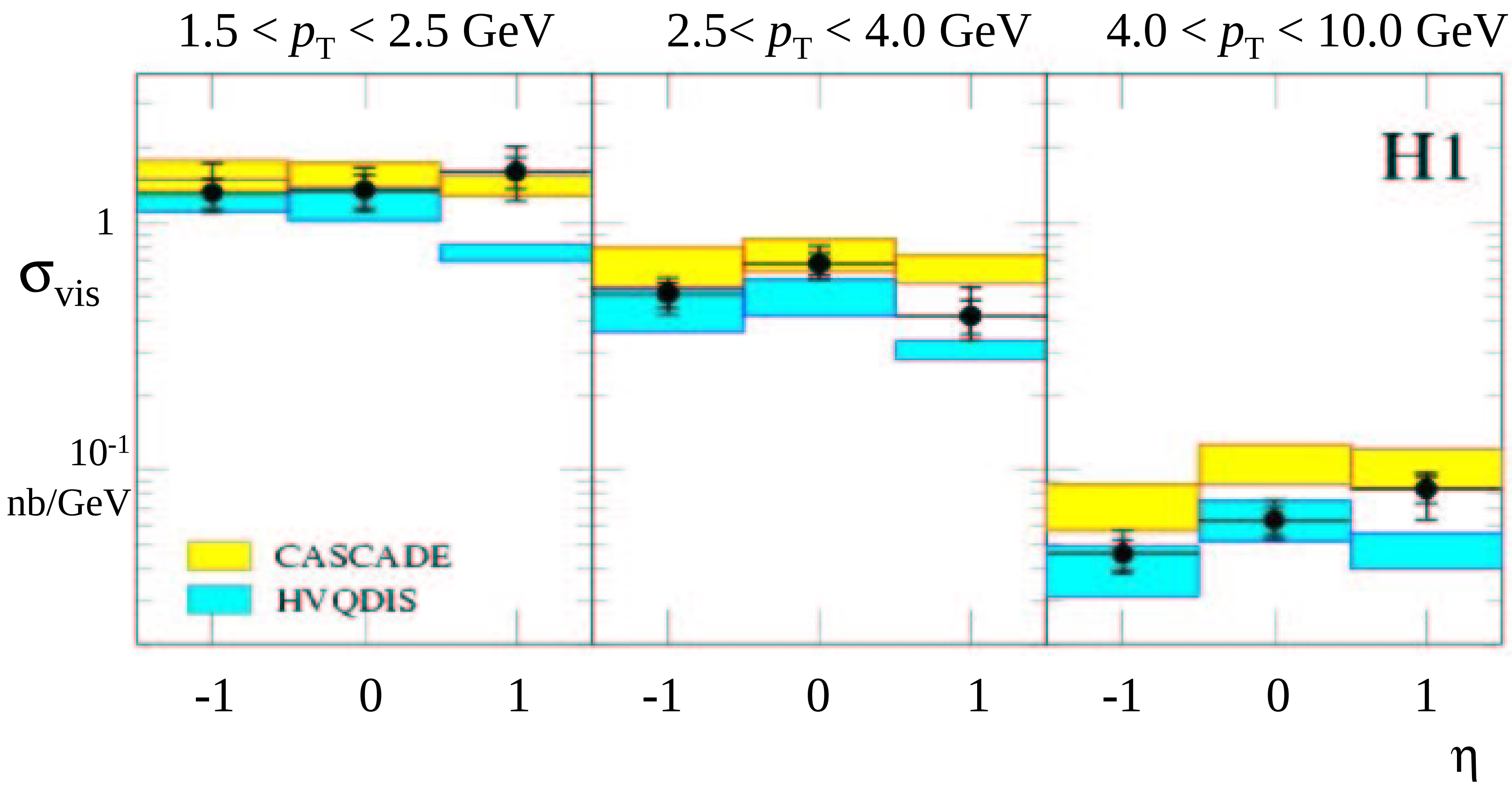


black $K2\pi$

blue $K4\pi$

bands - difft fragmentation functions

Double differential *D** $\frac{d^2\sigma}{dp_T d\eta}$

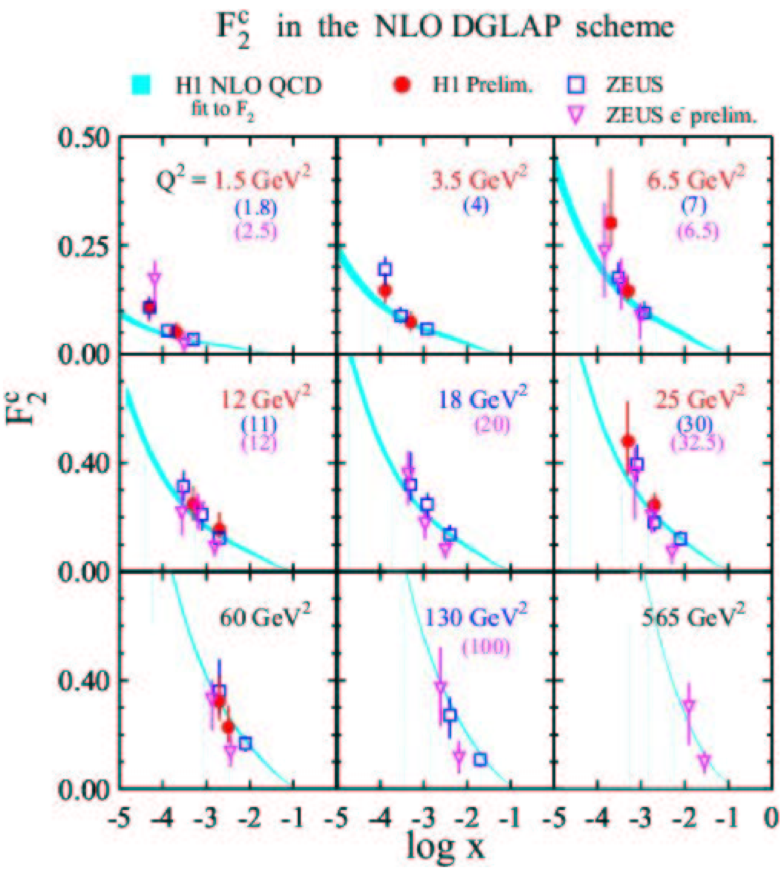


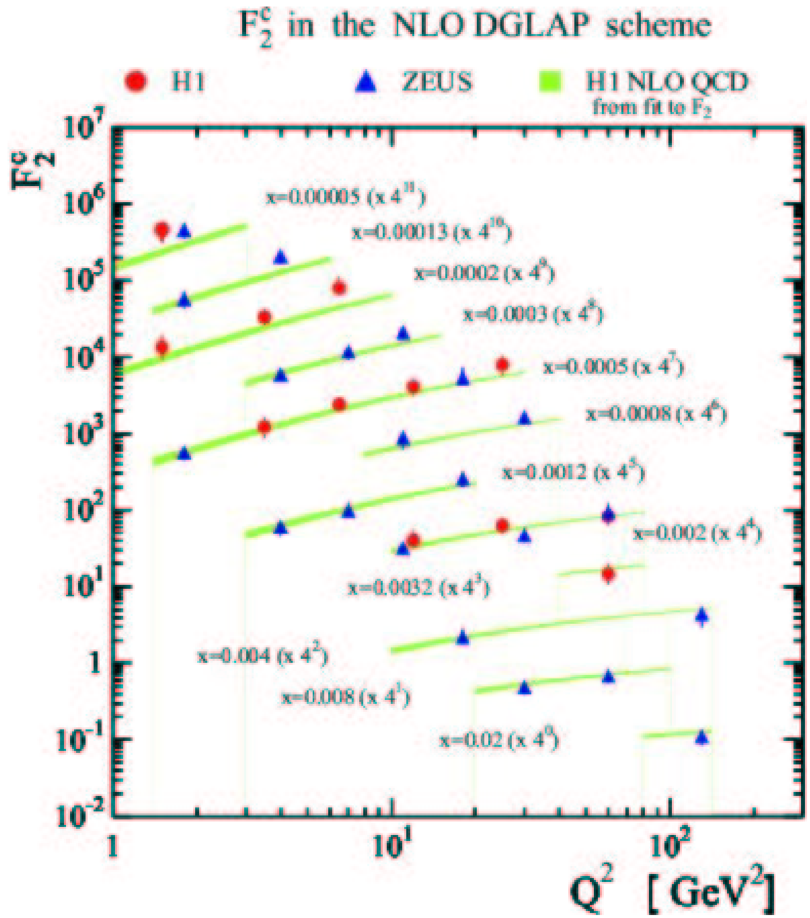
HVQDIS significantly below forward *D** data

CASCADE : η(*D**) better but above data at large p_T

$F_2^{c\bar{c}}$ Determine from D^* rate.

Large extrapolation to full acceptance



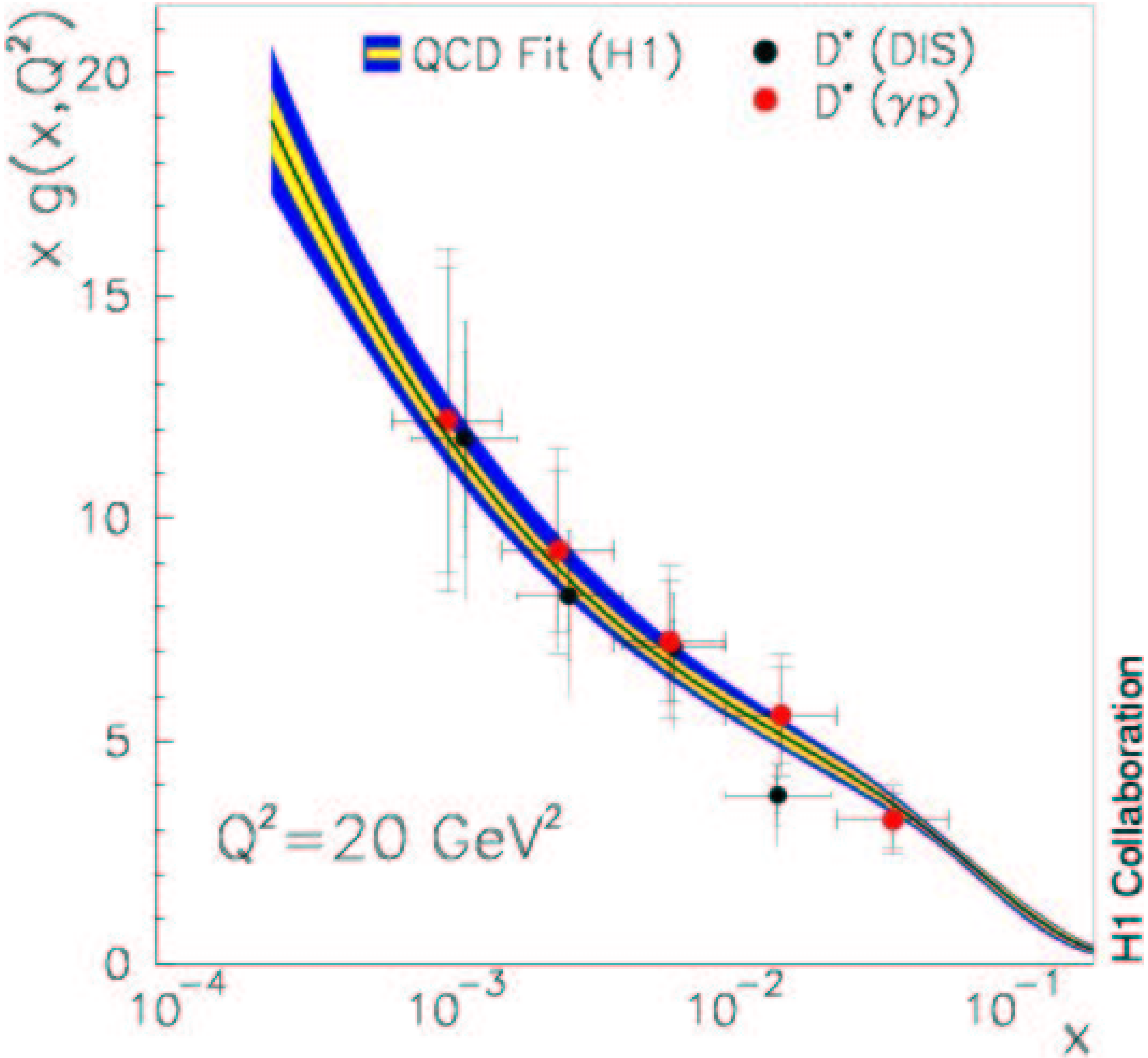


NLO calcn. with gluon from fit to F_2 reasonable

Strong rise at low x, high Q^2

Steeper Q^2 dependence than F_2 charm contributes about 50% of scaling violation in F_2

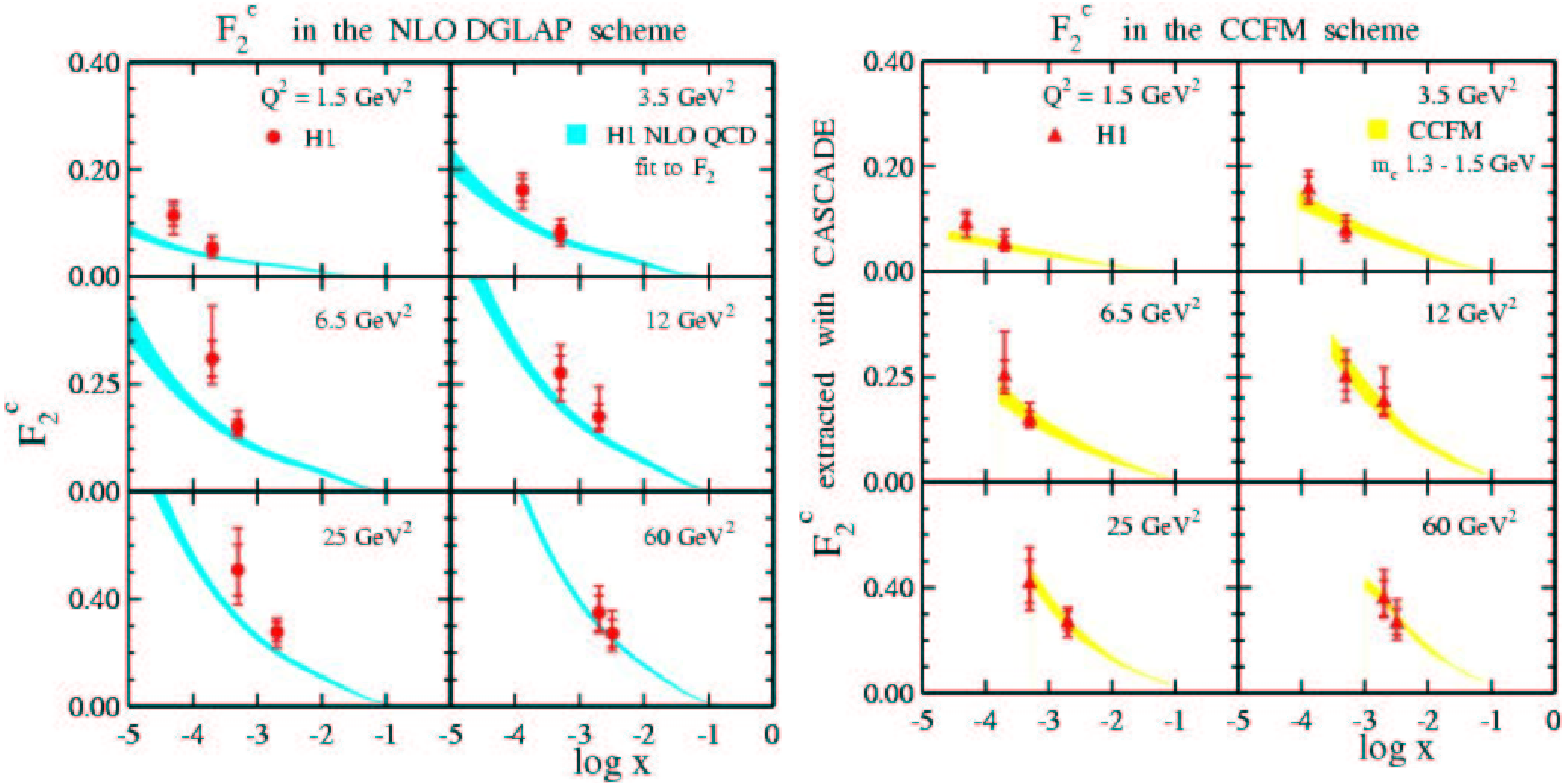
F_2^g Determine from *D** rate.



Consistent results

- DIS
- *D** in DIS
- *D** in γp

$F_2^{c\bar{c}}$ DGLAP v. CCFM

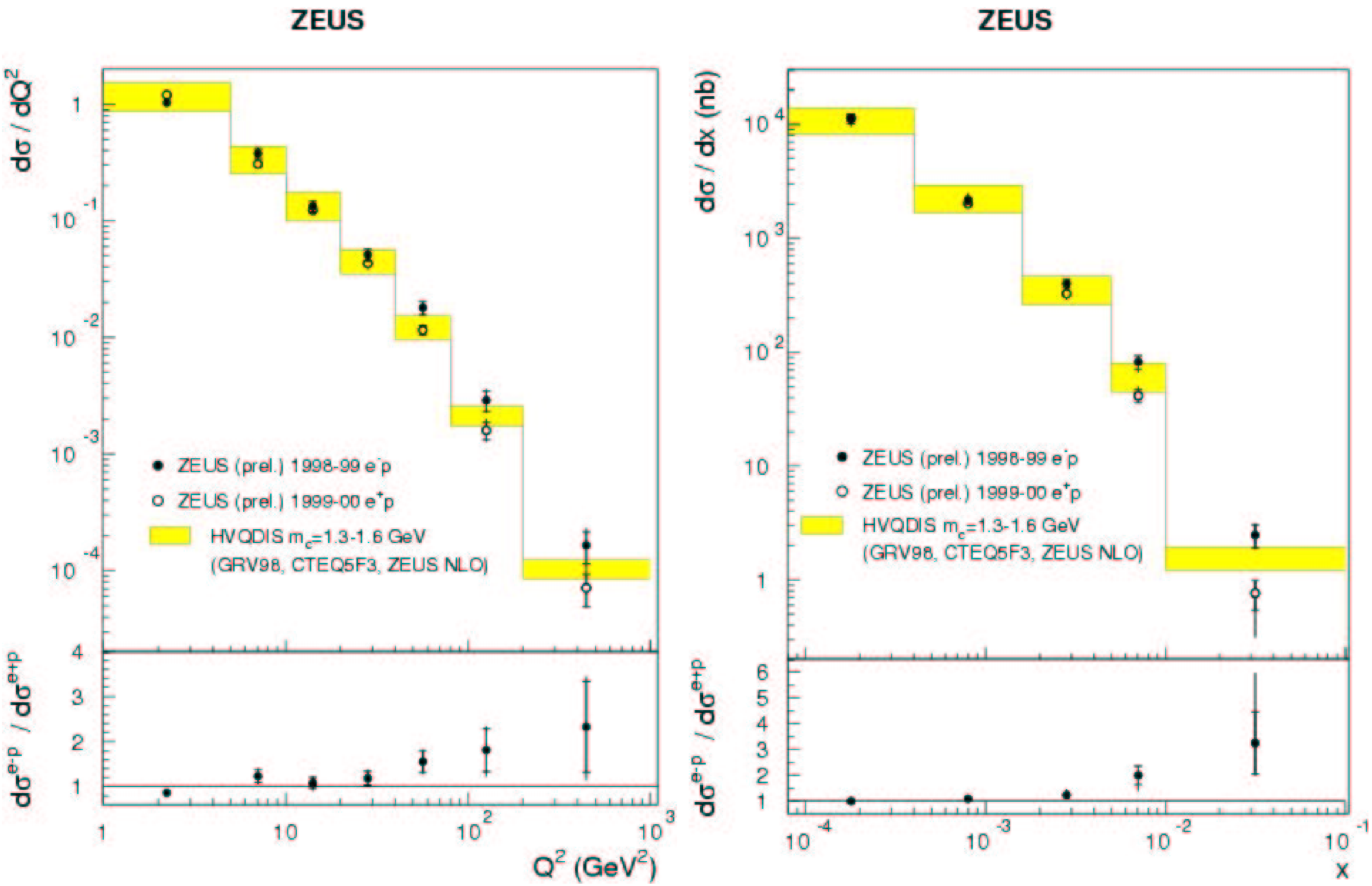


Smaller extrapolation factors using CCFM and smaller extracted F_2

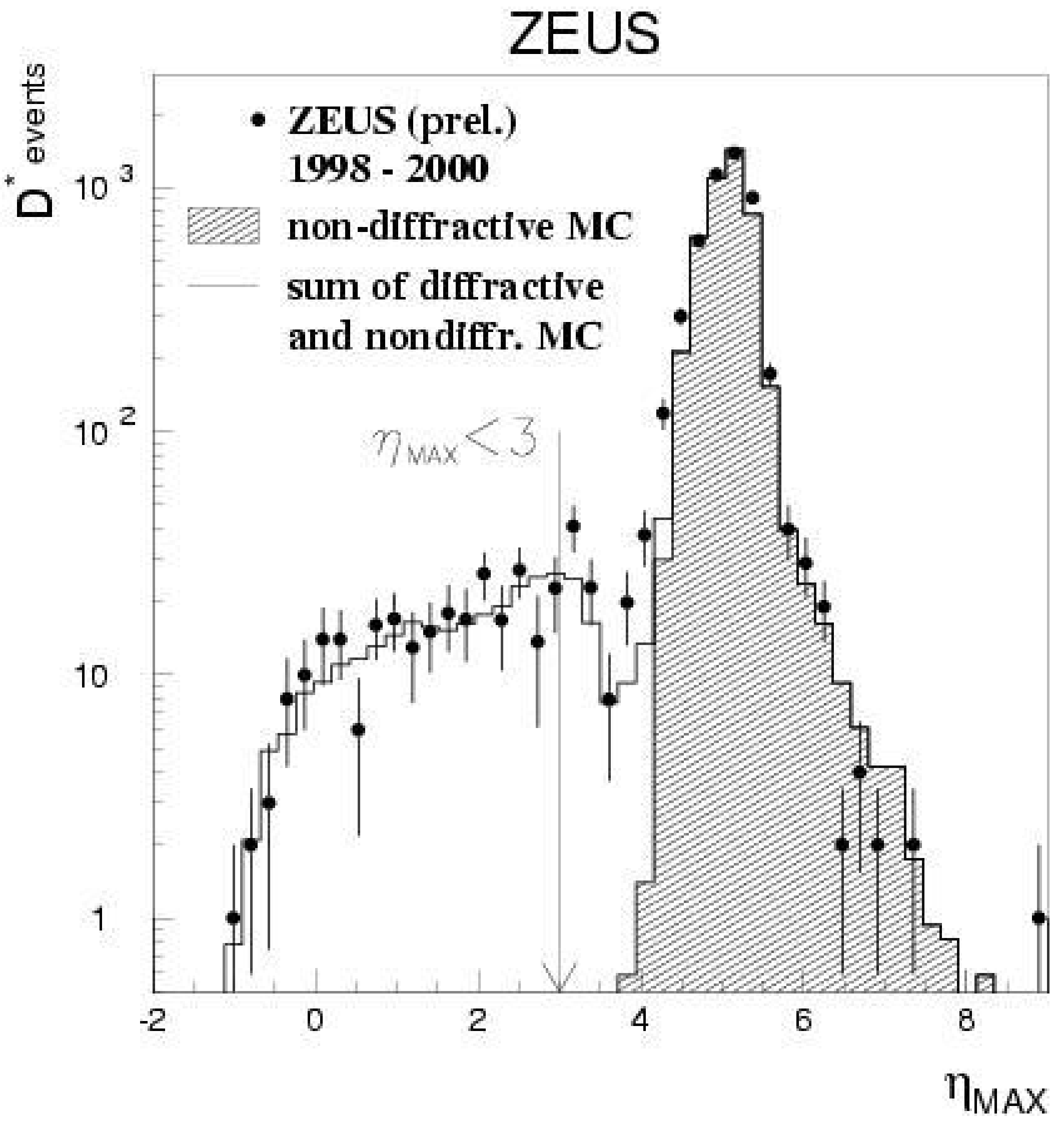
$F_2^{c\bar{c}} / F_2$ approaches 4/11 at low x and high Q^2 (large errors)

D^* production in e^+p less than in e^-p

Effect at high Q^2 and high x

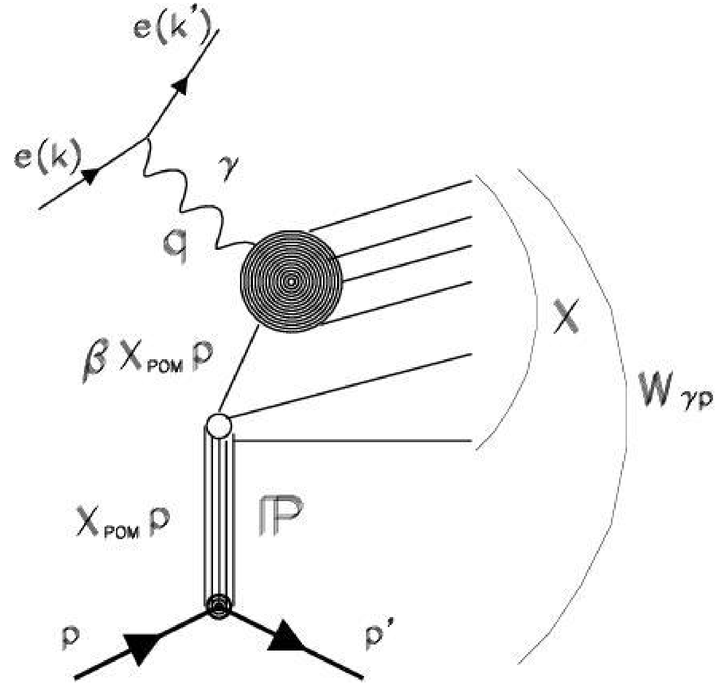


D^* in diffractive DIS



Large rapidity gap

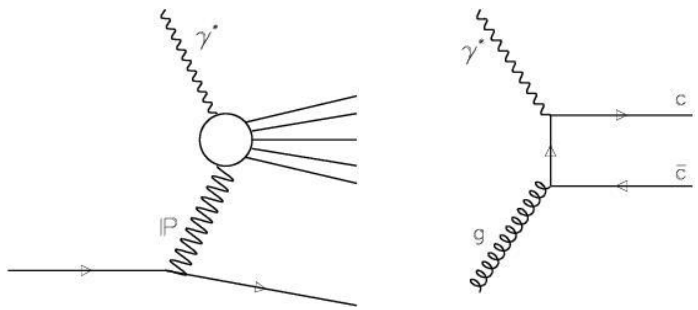
Select $\eta_{max} < 3$



See also H1: DESY-01-105

Models of diffraction

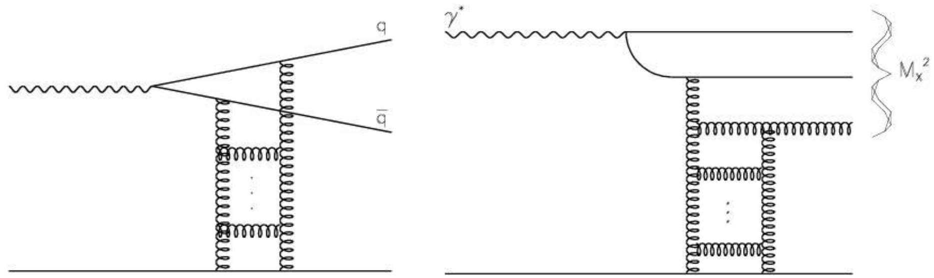
Resolved Pomeron models



Charm production probes gluon content of Pomeron

- RAPGAP
- ACTW: options quark dominated or gluon dominated

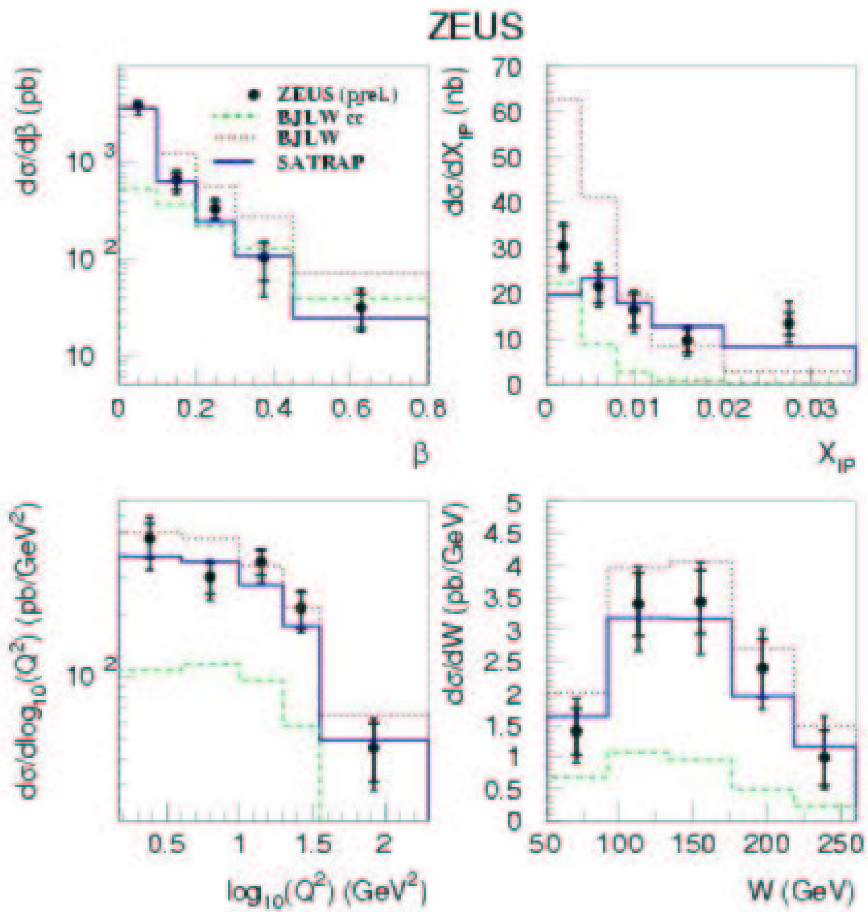
Perturbative QCD models



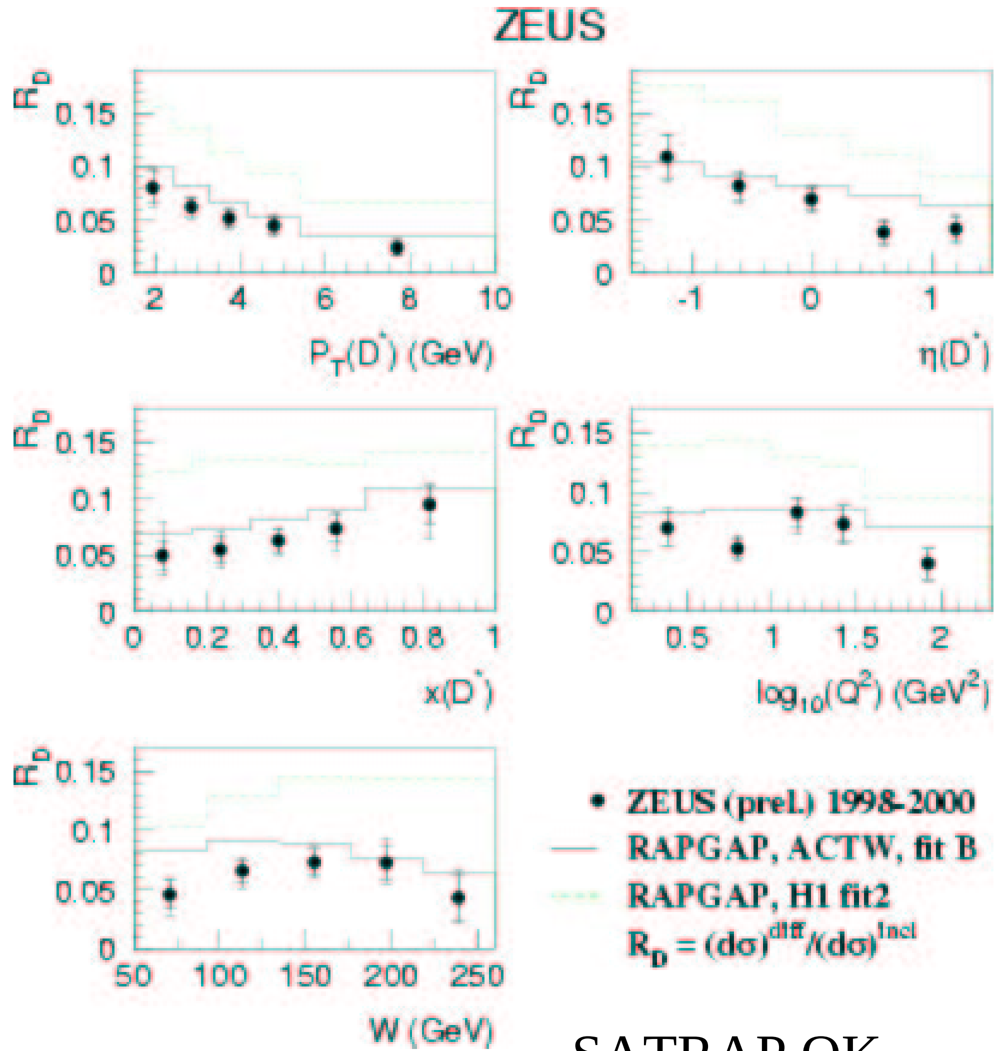
gluon ladder or higher order processes

- RIDI
- RAPGAP (BJLW) options $c\bar{c}$ or $c\bar{c}g$
- SATRAP 'saturation model'

Sample model comparisons



NLO QCD, ACTW g-dominated OK



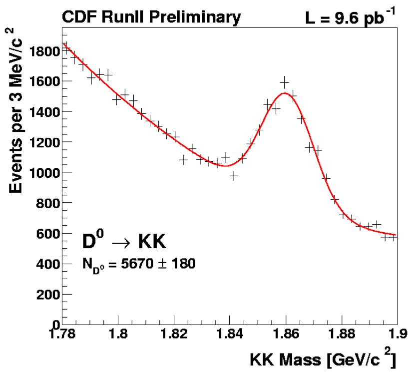
SATRAP OK
BJLW between
cc and *ccg*

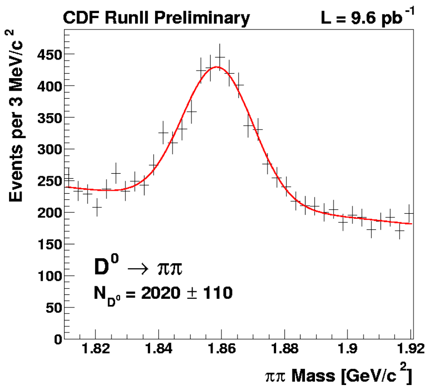
Diffr. Fraction $R(D^*) = (6.3 \pm 0.6^{+.3}_{-.7} \pm .3)\%$

Charm finding at TeVatron: CDF two-track trigger.

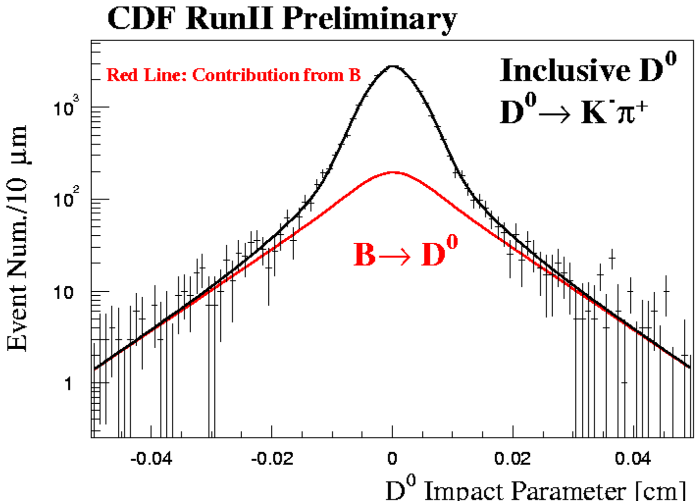
A step increase in quality

CP eigenstates: KK, $\pi\pi$





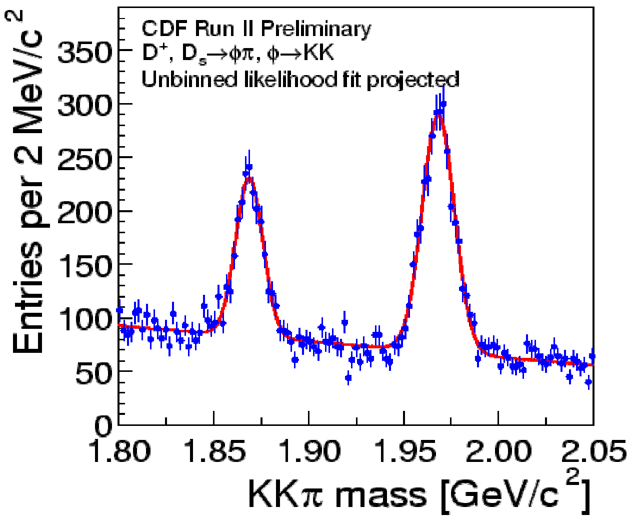
$B \to D^0 \to K^- \pi^+$ decays

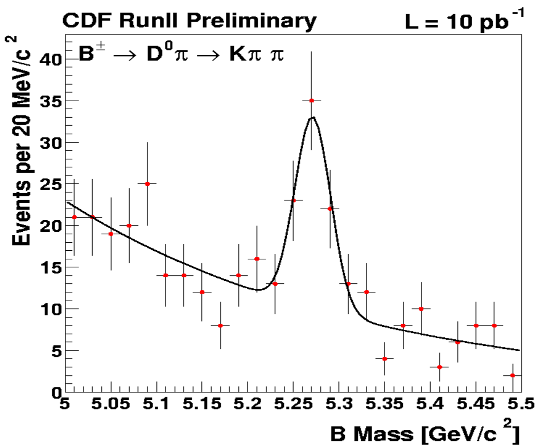


D^0 impact parameter

$D^+ \to \phi\pi^+$

$D_s \to \phi\pi^+$





$B^\pm \to D^0 \pi \to K\pi\pi$

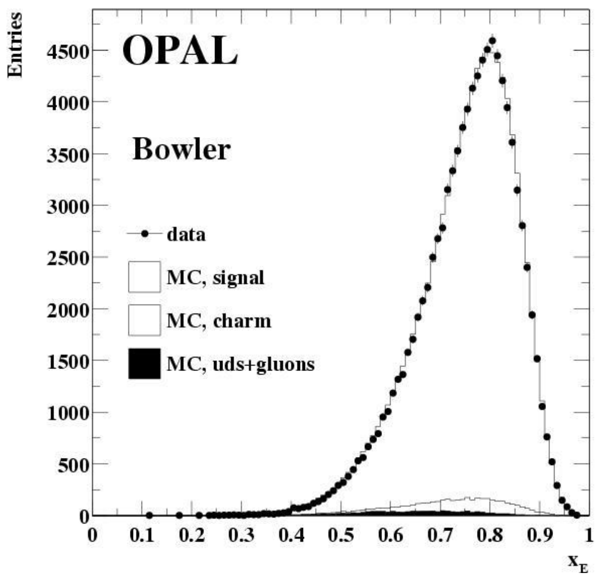
Reconstructed hadronic B-decay

b-production

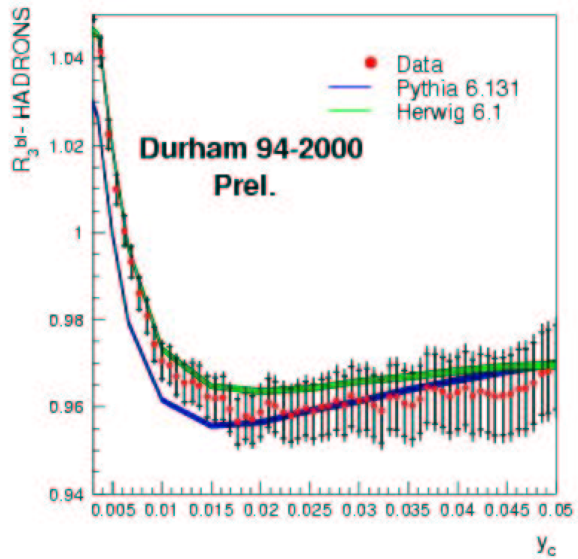
e^+e^- annihilation: precise measurements: lifetime tag, high pt lepton, jet shape

Beautifully understood production and fragmentation

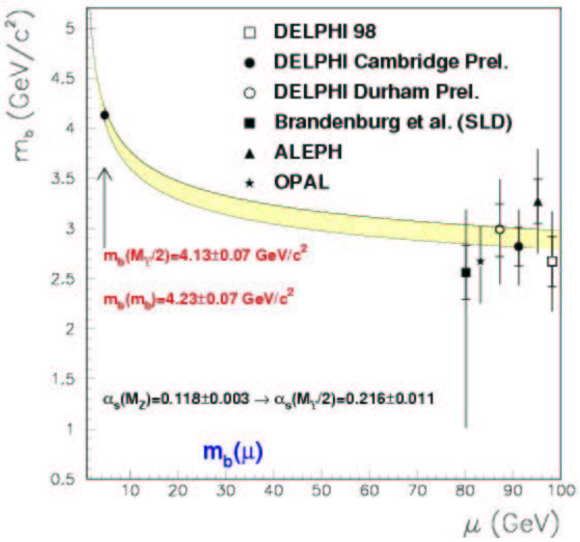
Astounding agreement with theory



Fragmentation



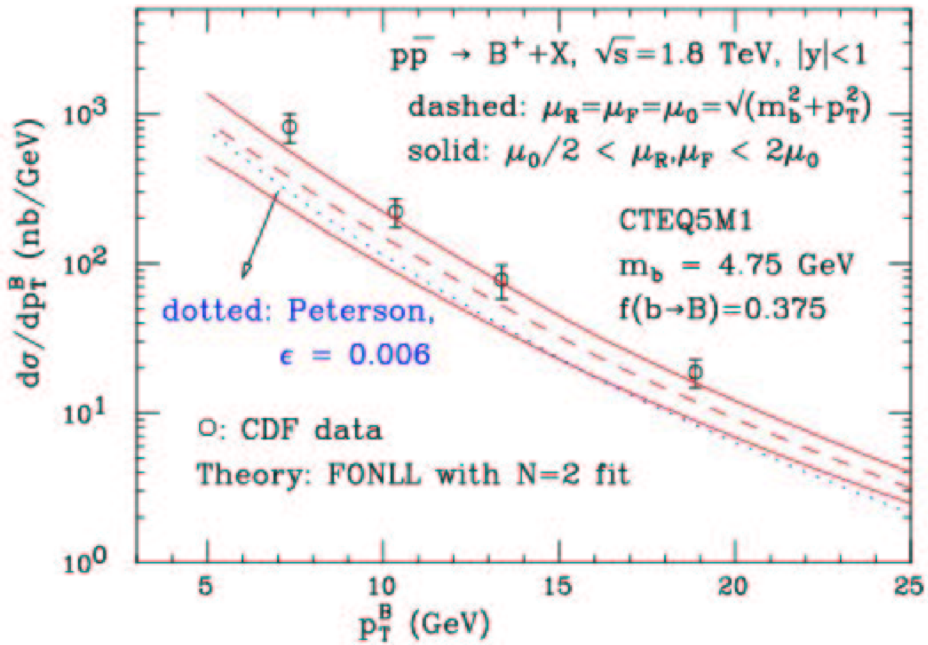
$R_{3j}(b)/R_{3j}(\text{all})$ depends on m_b



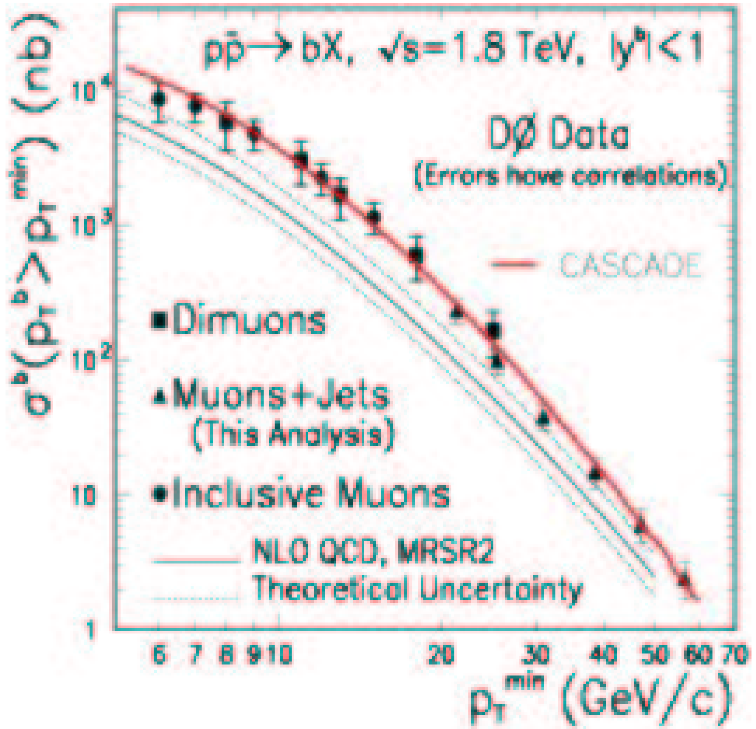
$m_b(\mu)$

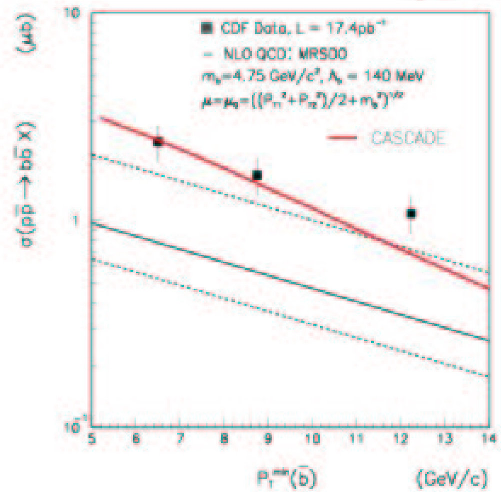
b-production in $p$bar-p collisions

CDF run I: $B^+ = J/\psi\ K^+$



D0





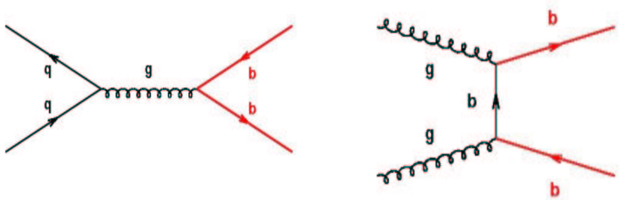
CDF

Updated theory:
Peterson frag tuned for LL
theory update FONLL
σ(data)/σ(theory) = 1.7 (was 2.9)
No contradiction.

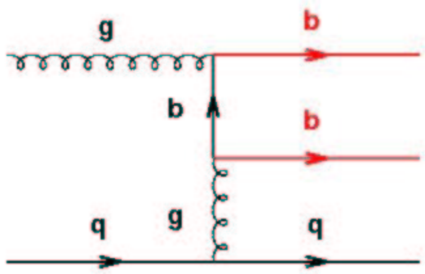
CASCADE fits D0 & CDF data

High *b*-tagging efficiency allows correlation studies of production mechanism

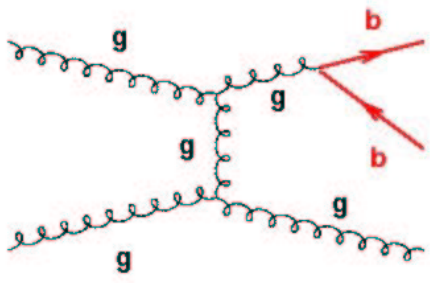
lowest order



flavour excitation

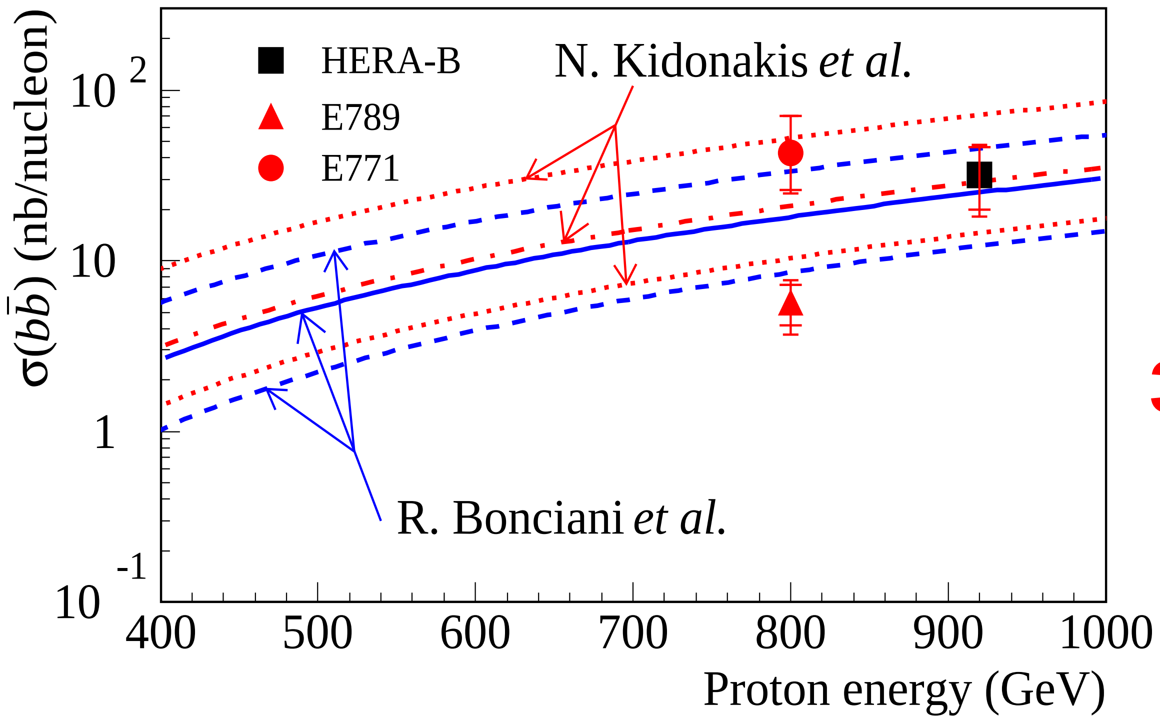


gluon splitting



CDF:
Study angular differences in events with two *b*-tags

b-production in pN collisions



Hera-B @ 920 GeV:

$\sigma_{TOT}(bb) =$

$32\ ^{+14}_{-12}\,(\text{stat})\ ^{+6}_{-7}\,(\text{syst})$ **nb/nucl**

(92% $b \to J/\psi$ in our x_F range)

The result shows good agreement with recent calculations beyond NLO

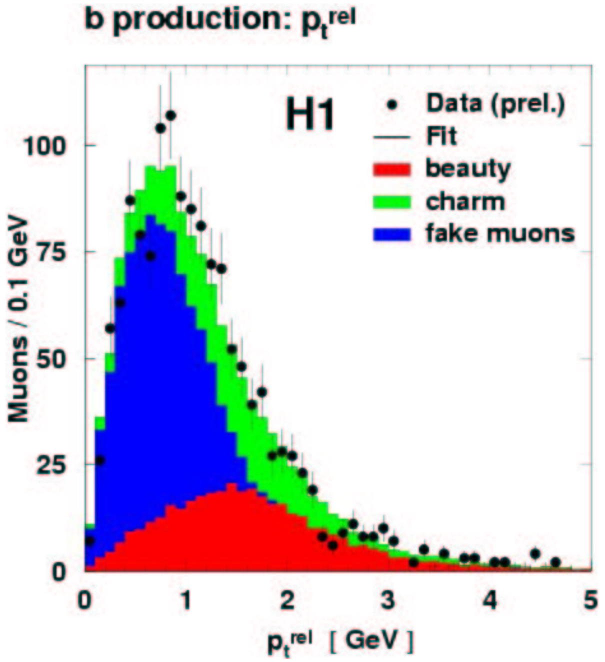
R. Bonciani *et al.* (2002),
NLO+NLL with latest MRST PDF
Nucl.Phys.B529 (1998)

N. Kidonakis *et al.* (2001),
NLO+NNLL
Phys.Rev D64 (2001) 114001-1

Open beauty production at HERA

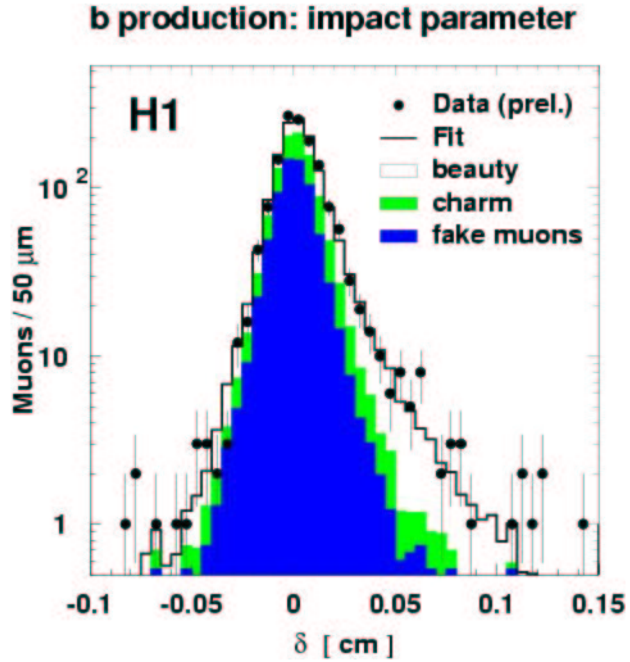
1) Lepton/jet p_T^{rel}

(H1,ZEUS) $F_b = (27 \pm 3)\%$



2) add μ impact param. δ

(H1) $F_b = (26 \pm 5)\%$



H1: Max-likelihood combining p_T^{rel} and δ

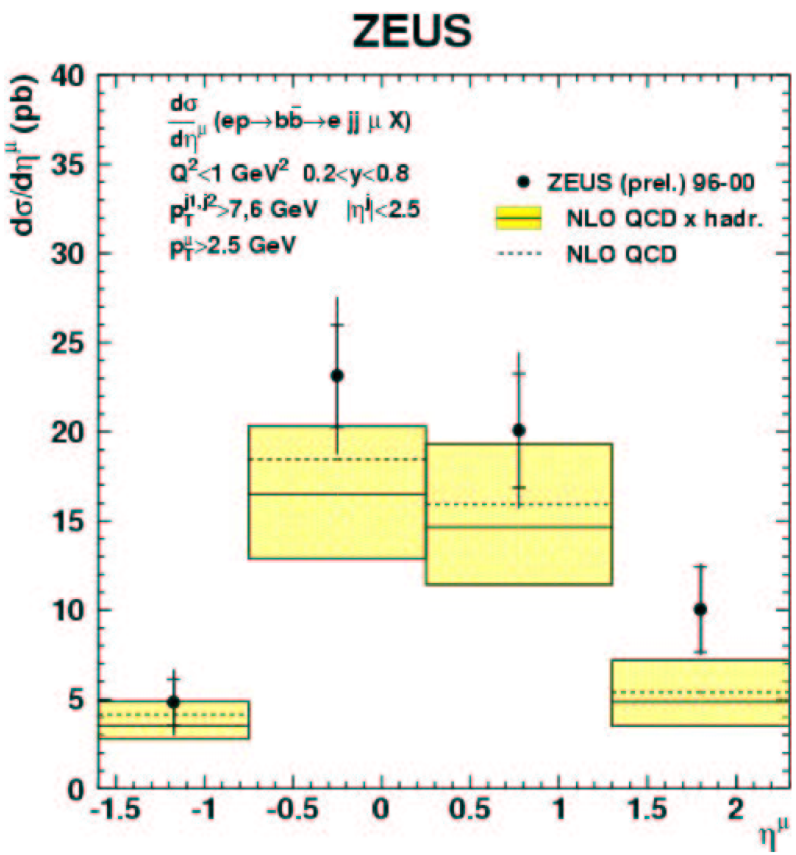
$Q^2 < 1$, $0.1<y<0.8$, $p_t^{\mu}>2$, $35^o<\theta<130^o$, k_T-jet with $E_T>5$

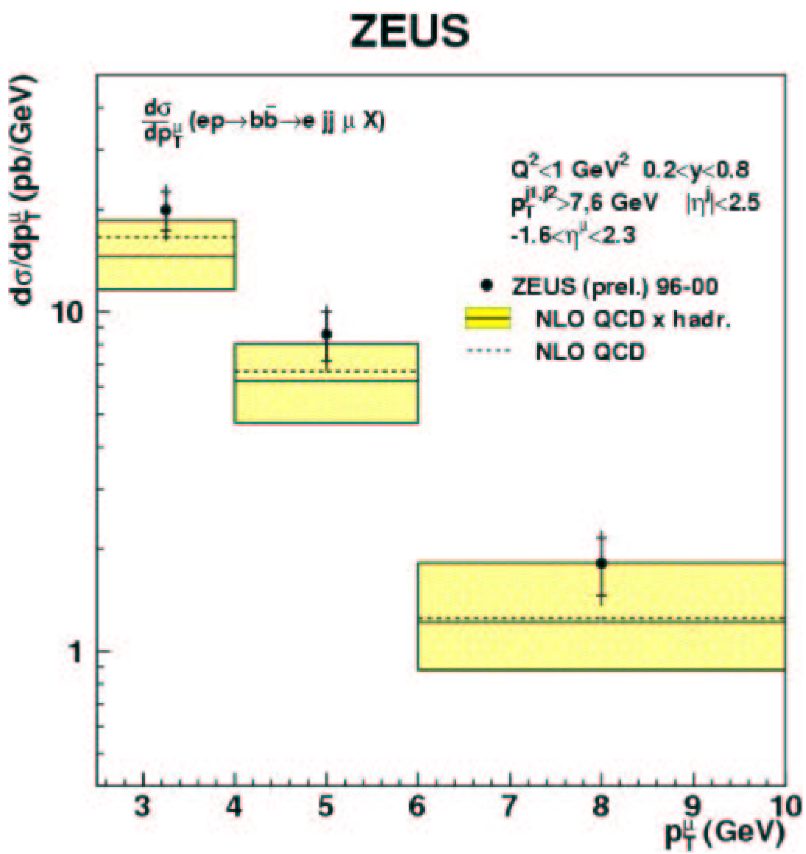
Photo-production

Result	**160 ± 16 ± 29 pb**
NLOQCD(FMNR)	54 ± 9 pb
CASCADE(CCFM)	67 pb
AROMA(DGLAP)	38 pb

Beauty in photoproduction

ZEUS: p_T^{rel} 98 pb^{-1}





$Q^2 < 1$, $0.2<y<0.8$, $p_t^{\mu}>2.5$, $-1.6<\eta_{\mu}<2.3$
2 or more jets with $p_{T,1(2)} > 7(6)$ $|\eta_j|<2.5$

Result: Total dijet cross-section

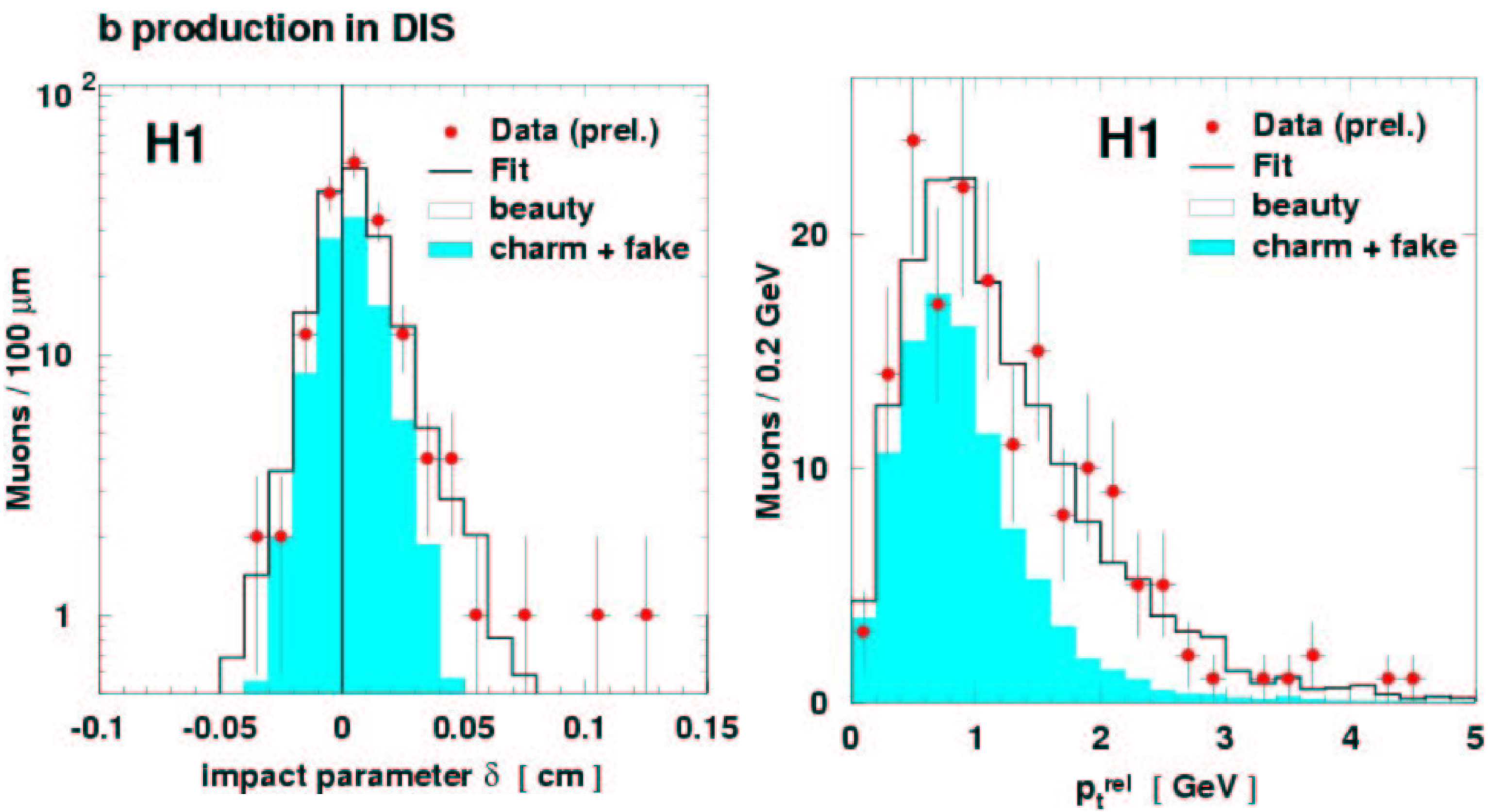
$$\sigma(ep \rightarrow bb \rightarrow \text{jet jet X}) =$$

733 ± 61 ± 104 pb

NLOQCD(FMNR) 381^{+117}_{-78} pb

Beauty in Deep Inelastic Scattering (1)

H1: Max-likelihood combining p_T^{rel} and δ 10.5 pb^{-1}



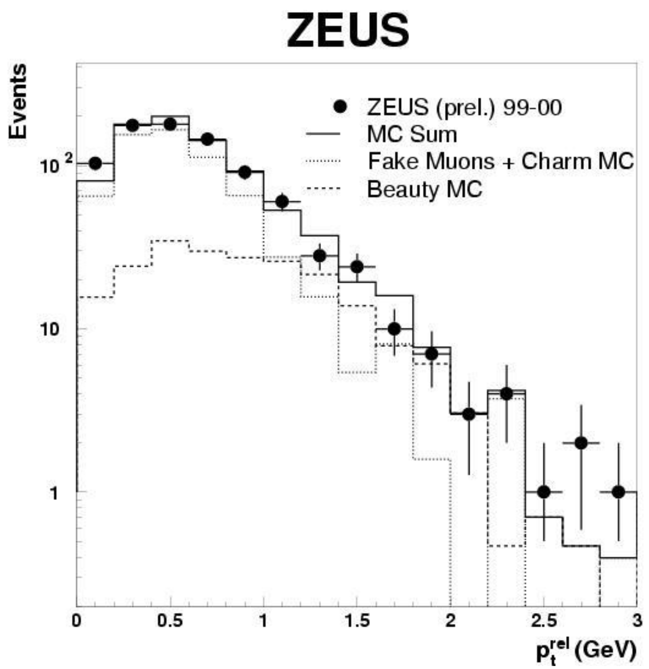
168 evts
(43+-8)%
from *b*

$2 < Q^2 < 100$, $0.05 < y < 0.7$,
$p_t^{\mu} > 2$, $35^o < \theta < 130^o$,
Jet requirement

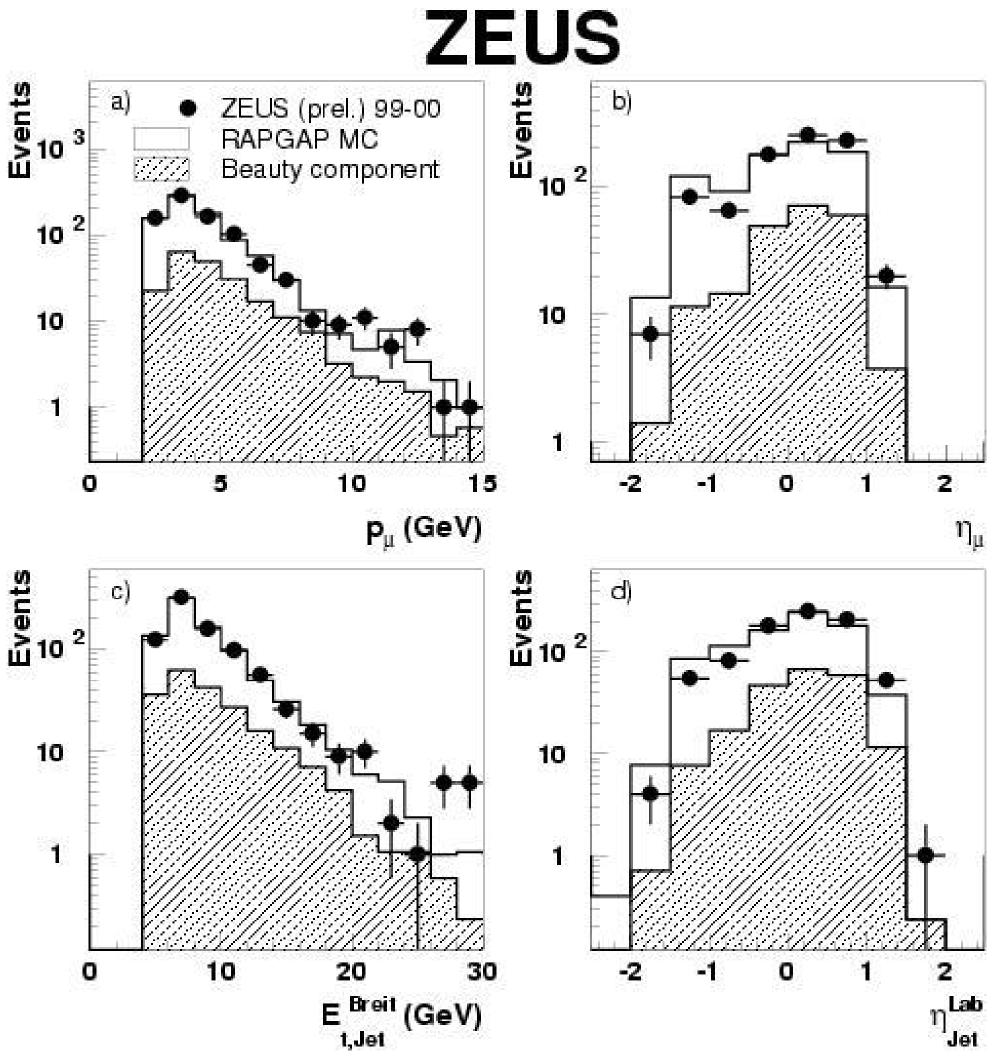
Result	**39 ± 8 ± 10 pb**
NLOQCD(HVQDIS)	11 ± 2 pb
CASCADE(CCFM)	15 pb
AROMA(DGLAP)	9 pb

Beauty in Deep Inelastic Scattering (2)

ZEUS: p_T^{rel} 60 pb^{-1}



836 evts
(25 ± 5)%
from *b*

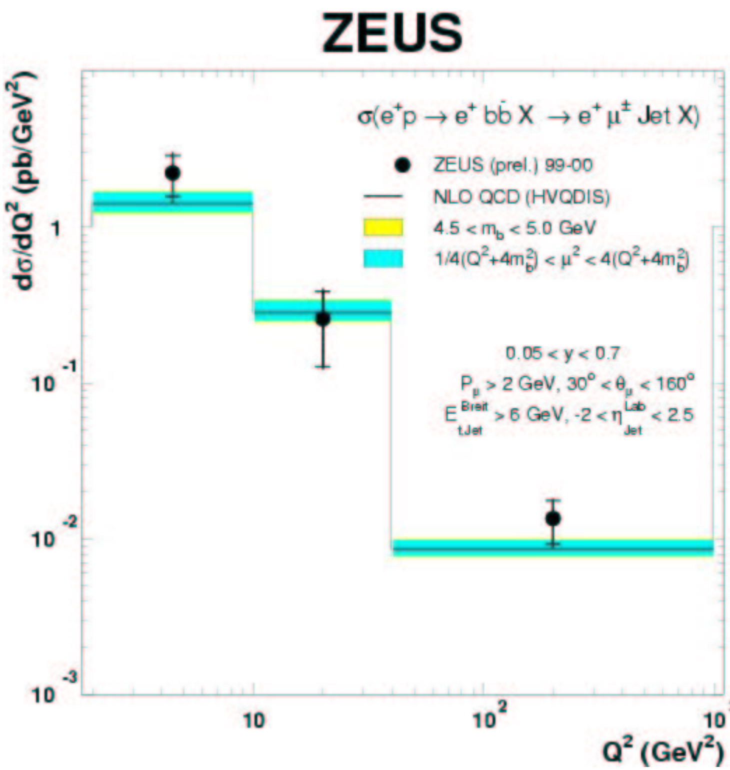


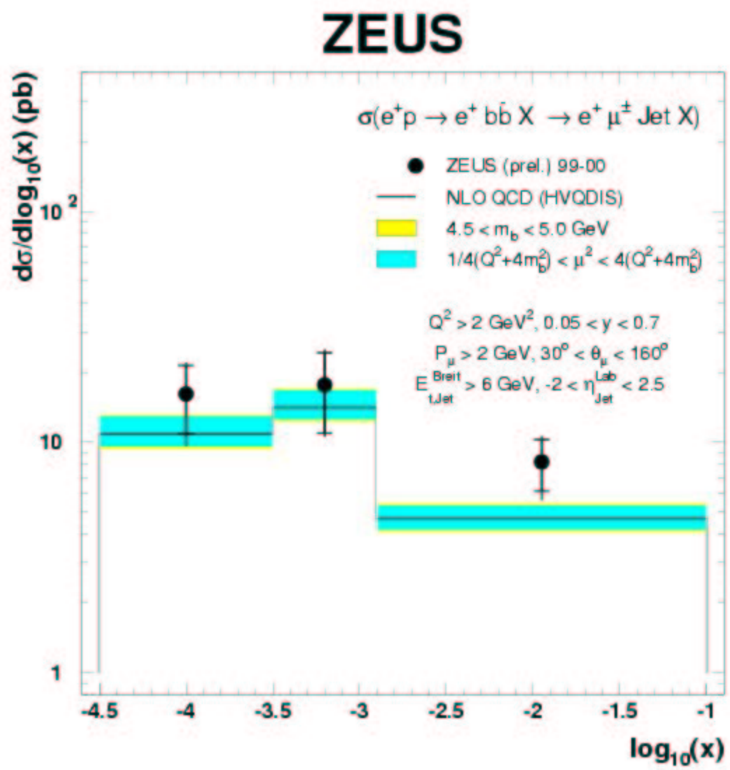
$Q^2 > 2$, $0.05 < y < 0.7$, $p^\mu > 2$, $30^o < \theta_\mu < 160^o$
jet with $E_T^{Breit} > 6$ $-2 < \eta_{LAB} < 2.5$

Shape well described by RAPGAP MC
(LO, LL higher orders, JETSET hadr.)

Beauty in Deep Inelastic Scattering (3)

First differential distributions for *b* in DIS





$Q^2 > 2$, $0.05 < y < 0.7$, $p^\mu > 2$, $30^o < \theta_\mu < 160^o$
jet with $E_T^{Breit} > 6$ $-2 < \eta_{LAB} < 2.5$

$$\sigma(ep \to ebbX \to e \text{ jet } \mu X) =$$

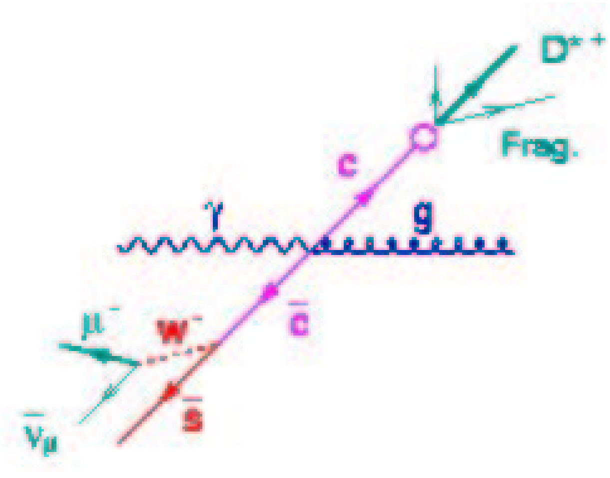
$38.7 \pm 7.7\ ^{+6.1}_{-5.0}$ pb

NLOQCD(HVQDIS) $28.1^{+5.3}_{-3.5}$ pb

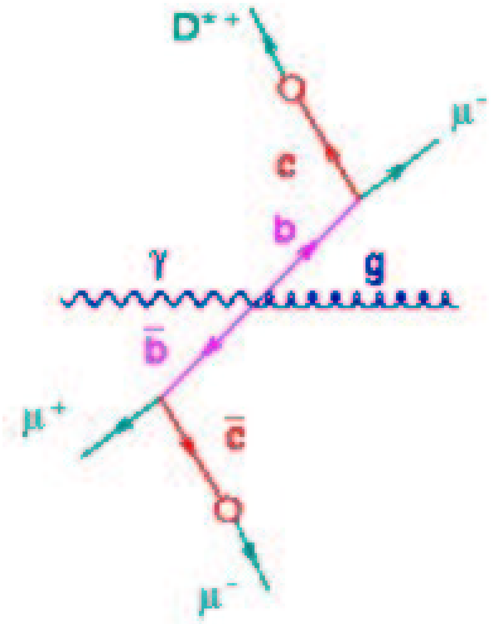
Open beauty production at HERA

3) *D**μ correlations

Charm production



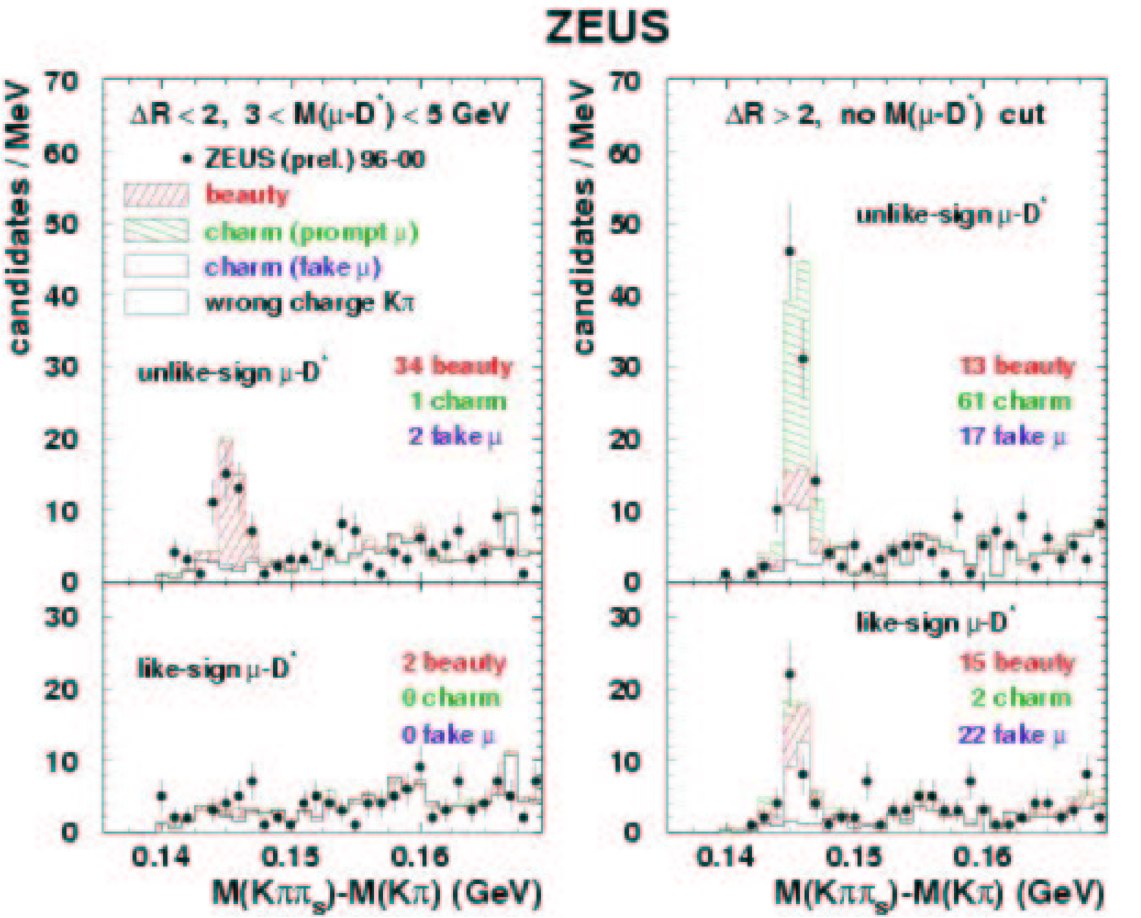
Beauty production

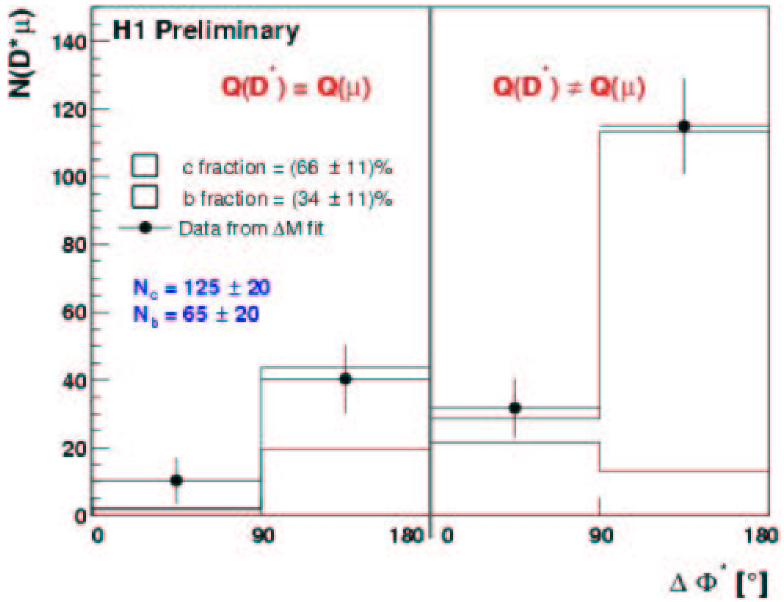


opposite hemisphere &
unlike-sign charge
(cut on $\Delta r = \sqrt{\Delta\eta^2 + \Delta\phi^2}$)

same hemisphere, unlike-sign
opposite hemisphere, like-sign
opposite hemisphere, unlike-sign

$D^*\mu$ production





ZEUS: p_T(D*)>1.9, |η|<1.5, p_T(μ)>1.4, $-1.3<\eta_\mu<1.75$

σ = **214 ± 52$^{+96}_{-84}$** pb

for PHP: y(b)<1, $Q^2<1$, $0.05<y<0.85$

$\sigma(ep \to eb(\bar{b})X) =$ **15.1 ± 3.9$^{+3.8}_{-4.7}$** pb

NLOQCD (FMNR)= $5.1^{+1.7}_{-1.1}$ pb

$$\sigma(ep \to eQ\bar{Q}X \to eD^*\mu X)$$

H1:

p_T(D*)>1.5, |η|<1.5

p_T(μ)>1, $|\eta_\mu|<1.74$

$0.05<y<0.75$

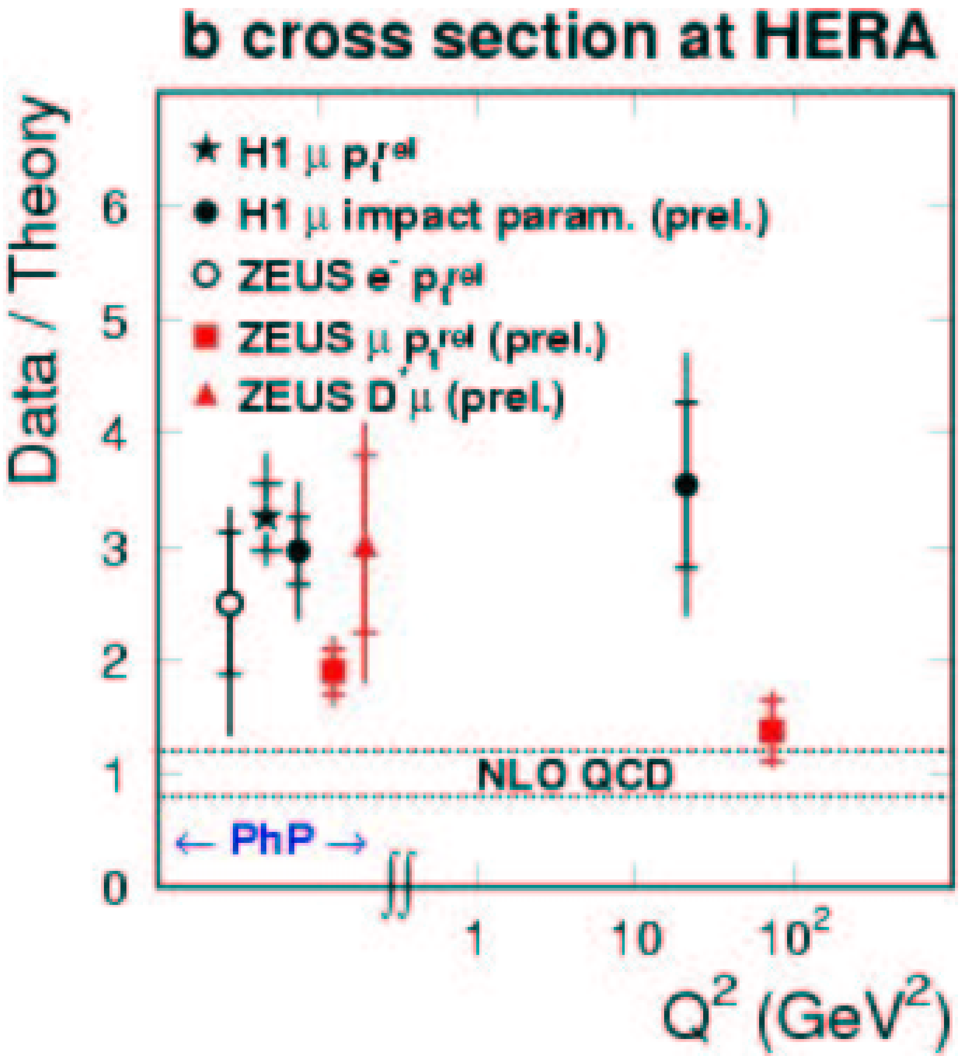
σ(charm)=**720 ± 115 ± 245** pb

σ(beauty)=**380 ± 120 ± 120** pb

charm: data/LO(AROMA) =1.8

beauty: data/LO(AROMA) =3.6

b-production at HERA. Compare to NLO QCD



New Results

New method - *D**μ

PHP - data above NLOQCD

DIS - ?

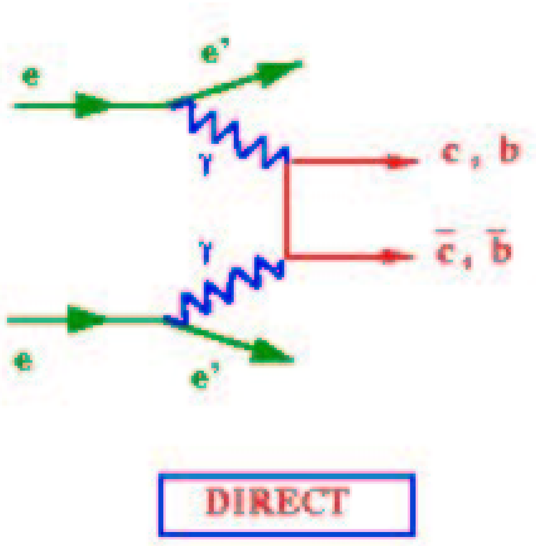
Measurements in different kinematic regions. Model assumptions needed to compare

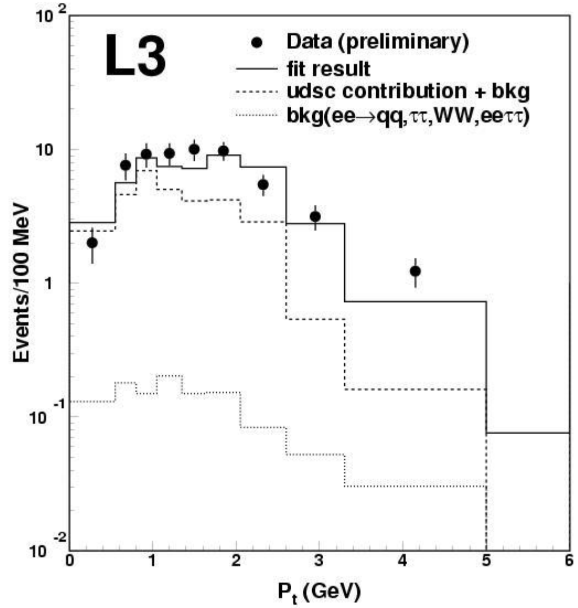
HERAII:

H1 - new fwd Si tracker + trigger

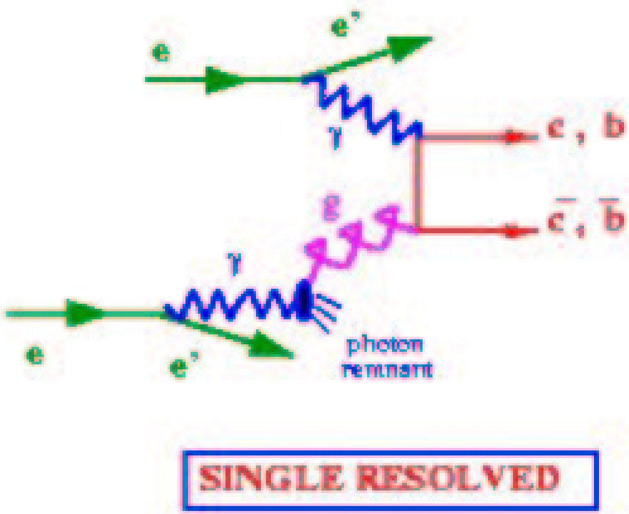
ZEUS - new SVX

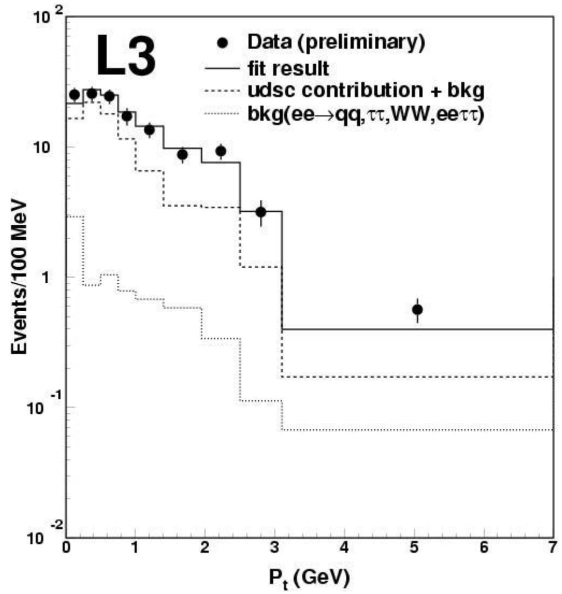
$\gamma\gamma$ collisions $(e^+e^- \rightarrow e^+e^-c\bar{c}X,\ e^+e^-b\bar{b}X)$





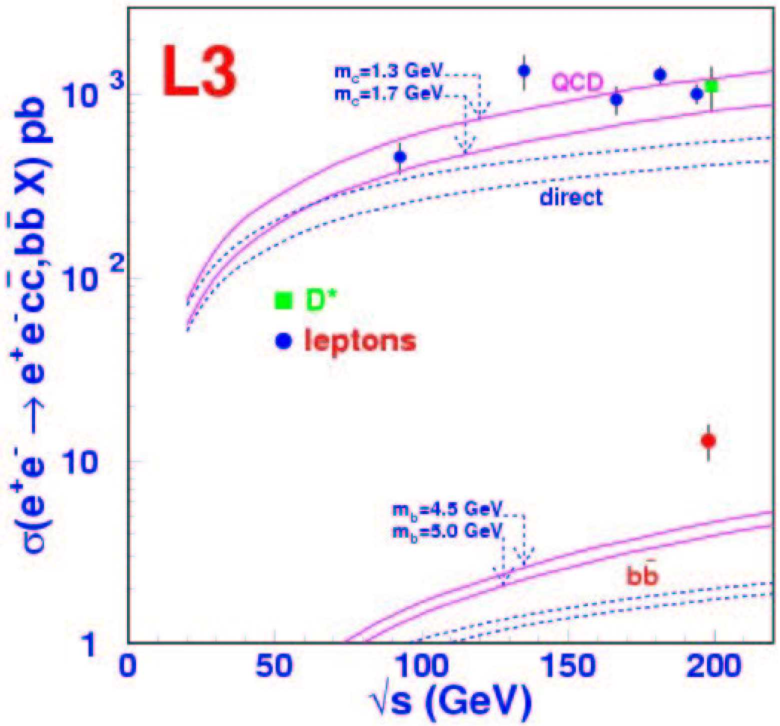
$p_T^{\mathrm{rel}}(e)$

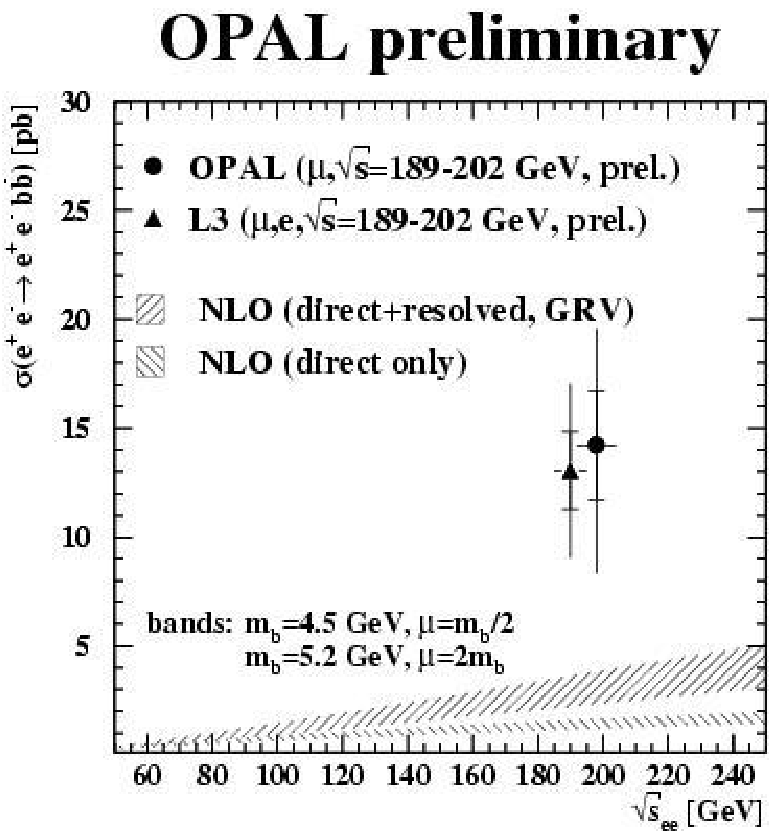




$p_T^{\mathrm{rel}}(\mu)$

$\gamma\gamma \to c\bar{c}X, b\bar{b}X$ results





$\sigma(e^+e^- \to e^+e^- c\bar{c}X)$ agrees with NLO incl. resolved γ contribution

$\sigma(e^+e^- \to e^+e^- b\bar{b}X)$ lies well above NLO

Summary

The quality of the data is improving fast -
new techniques at HERA and TeVatron.

Charm: fragmentation at HERA is like at LEP
PHP: evidence for charm in photon
DIS: goodish agreement with NLO DGLAP
exploring DGLAP v. CCFM

Beauty: LEP - precision! Theory & data agree astoundingly
TeVatron 70% discrepancies to theory regarded as progress
HERA: new techniques and better acceptance but position
vis-à-vis theory unclear. Much work needed

HERA: upgrade promises better *c* and *b* ID.
TeVatron: will greatly improve *c* and *b* production dynamics