QCD Physics - Lecture 5

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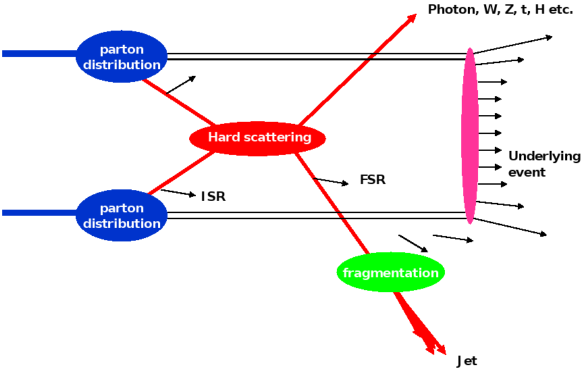
Outline


Photon, W, Z, t, H etc.
parton distribution
Hard scattering
FSR
ISR
parton distribution
Underlying event
fragmentation
Jet

High-Energy hadron-hadron interactions are described by the improved QPM

The incoming hadrons provide 'broad-band' beams of partons with varying fractions of momentum

The cross section for a hard scattering process initiated by two hadrons with four-momentum P_1 and P_2 can be written as:

$$\sigma(P_1, P_2) = \sum_{i,j} \int dx_1 dx_2 f_i(x_1, \mu^2) f_j(x_2, \mu^2) \hat{\sigma}_{ij}(p_1, p_2, \alpha_S(\mu^2), Q^2/\mu^2)$$

momenta of partons participating in the hard interactions are $p_1 = x_1 P_1$ and $p_2 = x_2 P_2$. Scale is called Q, could be mass of a weak boson, heavy quark or transverse jet energy. σ_{ij} is called the short-distance cross section

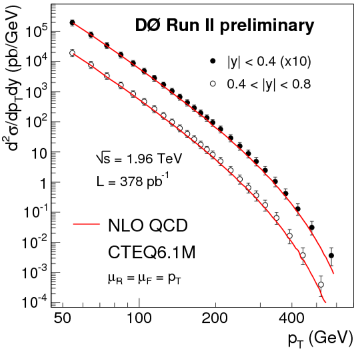
The short distance cross section ($\hat{\sigma}$) can be calculated (at high energy) as a perturbation series in α_S.
Therefore $(n+k)^{\text{th}}$-order approximation to the short distance cross section is given by:

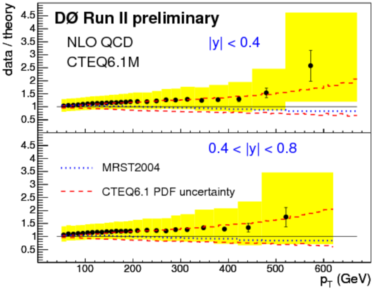
$$\hat{\sigma} = \alpha_S^k \sum_{m=0}^{n} c^{(m)} \alpha_S^m$$

$c^{(m)}$ are functions of the kinematic variables and factorisation scale

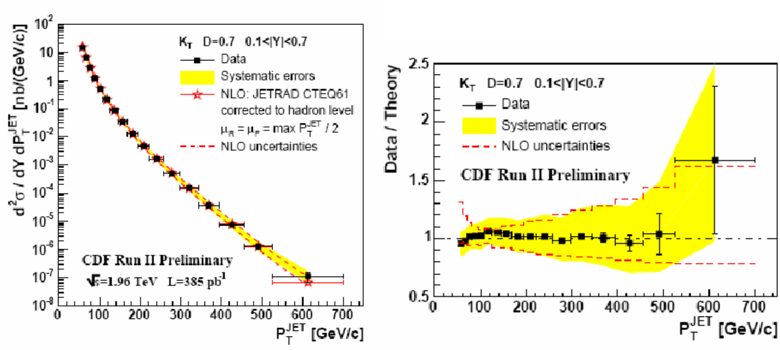
Different hard processes contribute with different leading powers k

In the leading (n=0) approximation, $\hat{\sigma}$ is identical to the normal parton scattering cross section calculated as one would for QED.





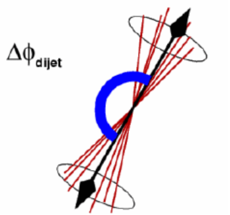
Results reasonably described, variation from theory within PDF uncertainties



reasonable description of data, largest theoretical uncertainty comes from gluon at high x

Test of higher order QCD effects in two jet events without explicitly requiring other jets

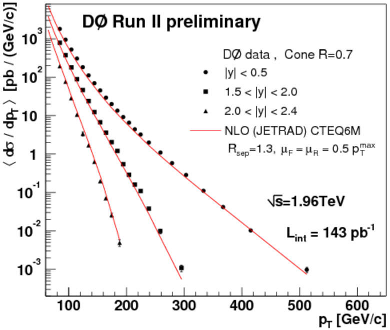
- additional radiation causes deviation of $\Delta\phi$ from π
- Phys. Rev. Lett 94 221801 (2005)



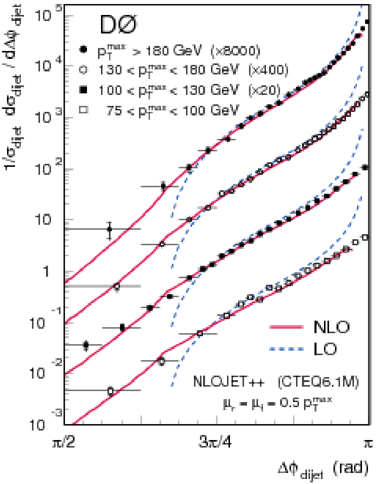
Data Sample:

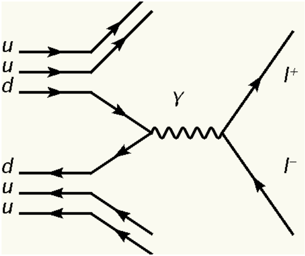
- $150\ \mathrm{pb}^{-1}$
- 2 jets $P_T > 40$ GeV, $|y| < 0.5$

Inclusive Dijets



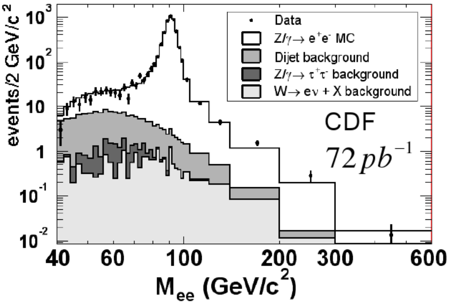
Dijet Correlations





Drell-Yan cross sections were the first hadron-hadron processes to be calculated from first principles.

$$\sigma_{AB} = \sum_q \int dx_1 dx_2 f_q(x_1) f_{\bar{q}(x_2)} \hat{\sigma}_{q\bar{q}\to l^+l^-}$$

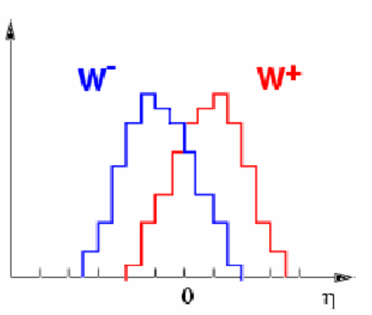


Data well predicted by MC, which uses pPDFs to predict cross section

Invariant mass distribution clearly shows Z pole

The Drell-Yan mechanism can also produce $W^{\pm}$ e;g; $u\bar{d} \rightarrow W^{+}$
The nature of this process is such that it is sensitive to the quark PDFs

Since the $u(\bar{u})$ quark tends to contain a higher fraction of the $p(\bar{p})$ momentum W^+ (W^-) tends to move in $p(\bar{p})$ beam direction

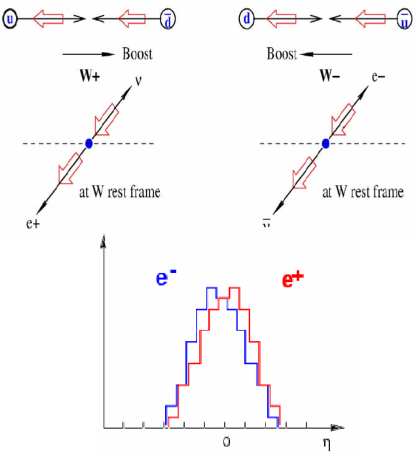


$W^{\pm}$ asymmetry and the PDFs

$$A(y_W) = \frac{d\sigma_+/dy_w - d\sigma_-/dy_w}{d\sigma_+/dy_w + d\sigma_-/dy_w}$$
$$\approx \frac{u(x_1)d(x_2) - d(x_1)u(x_2)}{u(x_1)d(x_2) + d(x_1)u(x_2))}$$

W momentum determination is vulnerable to ambiguity from neutrino

Lepton Charge asymmetry

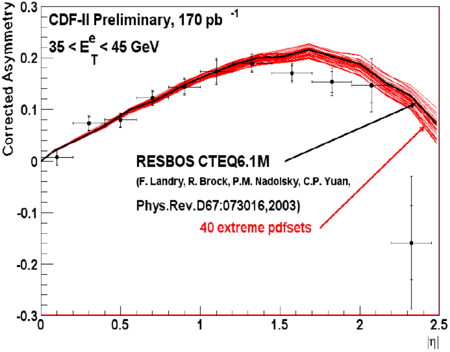


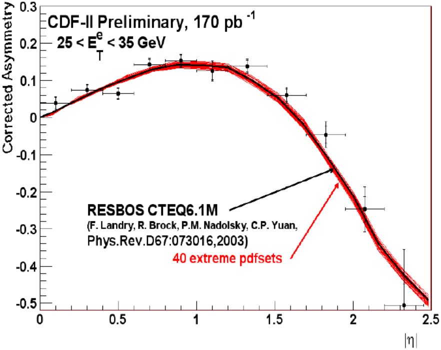
- No ambiguity from ν
- V-A decay asymmetry tends to cancel W production asymmetry

Sensitivy to $u(x)/d(x)$

$$A(\eta_1) = \frac{d\sigma_+/d\eta_l - d\sigma_-/d\eta_l}{d\sigma_+/d\eta_l + d\sigma_-/d\eta_l} \sim \frac{d(x)}{u(x)}$$

One can Divide the E_T region to increase sensitivity





Higher E_T (35-45 GeV):

- Production assymmetry enhanced
- Should be good input to a PDF

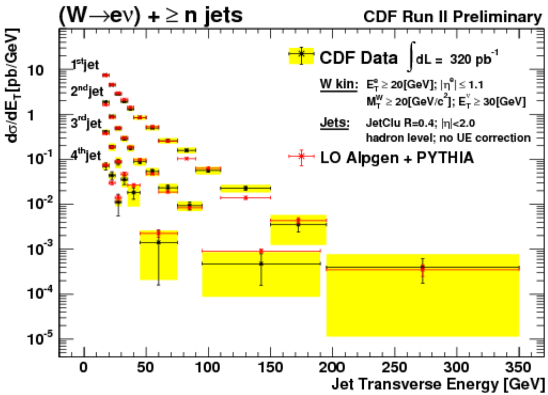
Lower E_T (25-35 GeV):

- V-A decay assymmetry enhanced

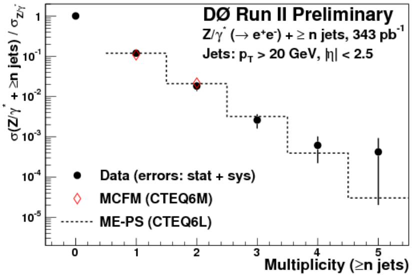
One of the most important SM processes in high energy hadron-hadron collisons is W/Z production with accompanying hadronic jets

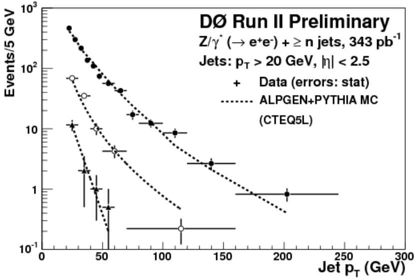
Most new physics (inc. Higgs) can be mimicked by the production of vector bosons in association with jets - understanding of this process will allow us to estimate the background correctly.

W + jets


(W→eν) + ≥ n jets
CDF Run II Preliminary
CDF Data ∫dL = 320 pb^-1
W kin: E_T^e ≥ 20[GeV]; |η^e| ≤ 1.1
M_T^W ≥ 20[GeV/c^2]; E_T^ν ≥ 30[GeV]
Jets: JetClu R=0.4; |η|<2.0
hadron level; no UE correction
LO Alpgen + PYTHIA
1st jet
2nd jet
3rd jet
4th jet
dσ/dE_T [pb/GeV]
Jet Transverse Energy [GeV]

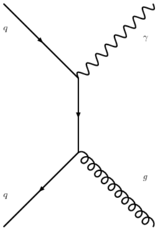
Z + jets

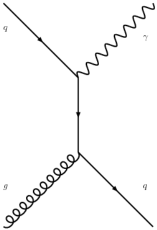




Reasonable agreement with the QCD calculations

Direct or prompt photon production is closely related to high E_T jet production





Different from ISR where photon goes down beamline
Different from FSR where photon is close to jet
Process is sensitive to gluon in proton

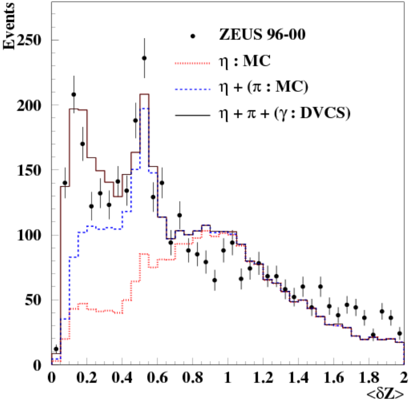
Advantages of γs over jets:

- Energy resolution of electromagnetic calorimeters is generally better than the resolution of hadronic calorimeters
- System uncertainties in the γ energy scale are smaller than jet energy scales
- Photon direction & movement simpler to reconstruct than running jet algorithms

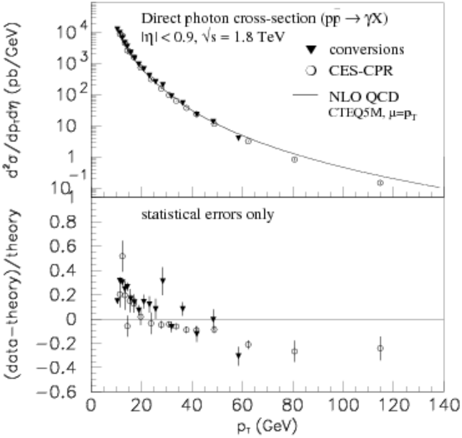
Disadvantages:

- Relatively low rate ($\mathcal{O}(\alpha\alpha_S)$ compared to ($\mathcal{O}(\alpha_s^2)$) for jets)
- large $\pi^0 \rightarrow \gamma\gamma$ and $\eta \rightarrow \pi^0\pi^0\pi^0$

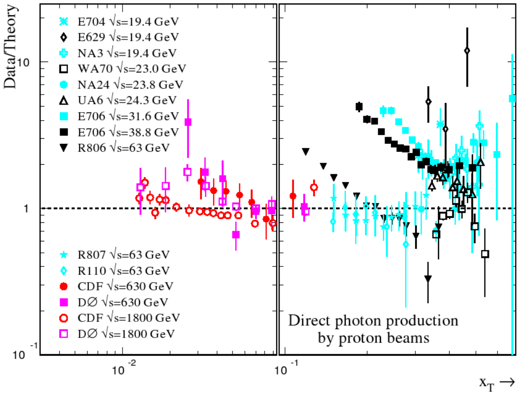
There are several handles to assess/remove η,π background



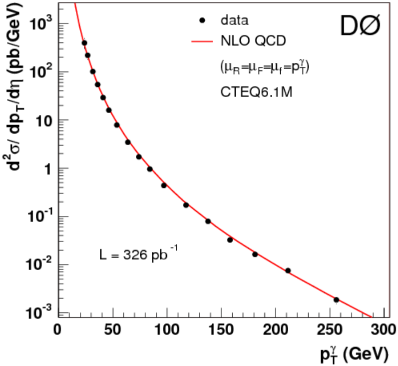
- One method is to use lateral shower width or similar cluster information in order to fit η,π,γs
- A recent method at CDF used converted photons (with e^+e^- tracks in front of the calorimeter) in order to reduce η, π

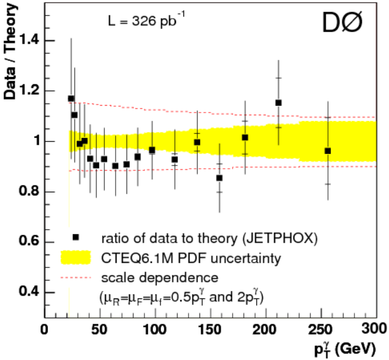


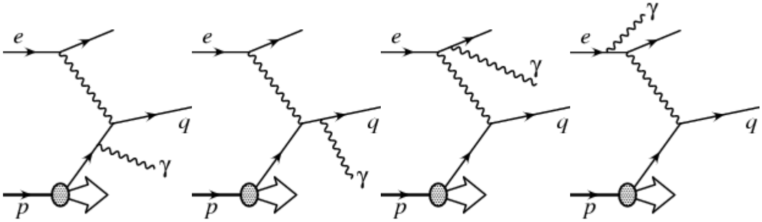
NLO QCD calculations describe data poorly



Comparison of measurements to theory against $x_T = 2p_T/\sqrt{s}$

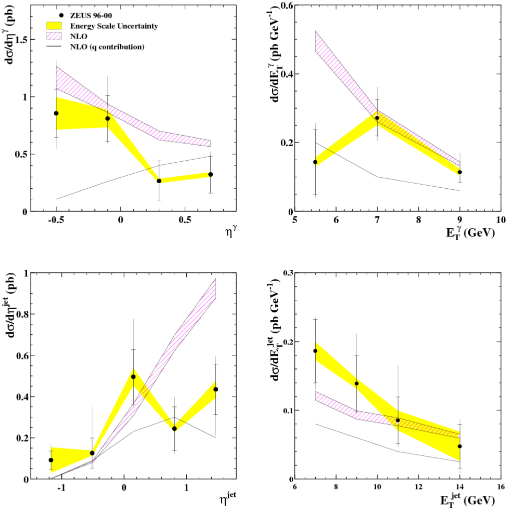

DØ
data
NLO QCD
$(\mu_R=\mu_F=\mu_f=p_T^\gamma)$
CTEQ6.1M
L = 326 pb^{-1}
$d^2\sigma/dp_T/d\eta$ (pb/GeV)
p_T^γ (GeV)


L = 326 pb^{-1}
DØ
Data / Theory
ratio of data to theory (JETPHOX)
CTEQ6.1M PDF uncertainty
scale dependence
$(\mu_R=\mu_F=\mu_f=0.5p_T^\gamma$ and $2p_T^\gamma)$
p_T^γ (GeV)



LO contributions to prompt photon production in *ep* collsions

Prompt γs in DIS

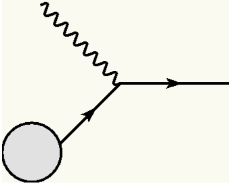


Description of data by NLO ranges from satisfactory to fair

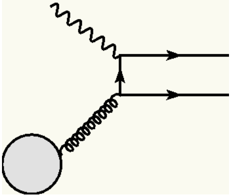
"Heavy" quark means charm, bottom, top

How do we produce Heavy Quarks in hadron collisions?

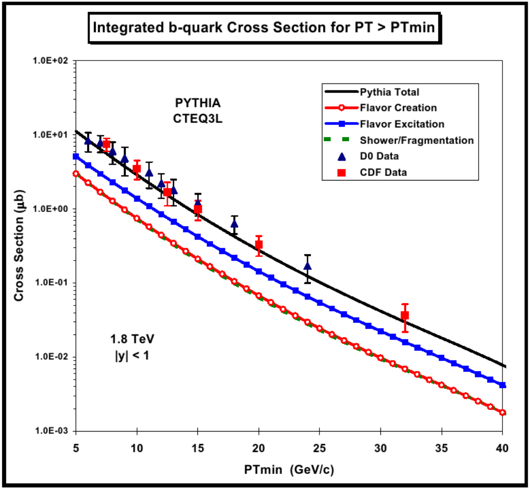
Heavy Excitation



Heavy Creation(BGF)



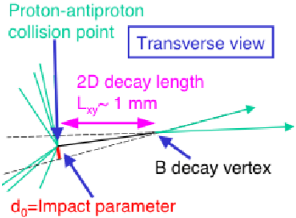
Have to be careful not to double count in calculation


Integrated b-quark Cross Section for PT > PTmin
PYTHIA
CTEQ3L
1.8 TeV
|y| < 1
Pythia Total
Flavor Creation
Flavor Excitation
Shower/Fragmentation
D0 Data
CDF Data
Cross Section (µb)
PTmin (GeV/c)
1.0E+02
1.0E+01
1.0E+00
1.0E-01
1.0E-02
1.0E-03
5
10
15
20
25
30
35
40

Heavy quarks can be measured using colour singlet states i;e; B mesons

There are different approaches to measuring a particle

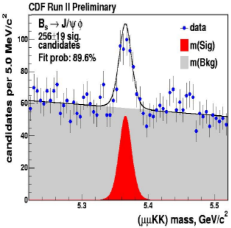
- Reconstruct a meson mass peak using tracks
- Use impact parameter and tag with knowledge of particle lifetime

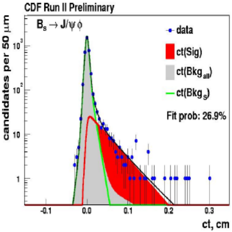


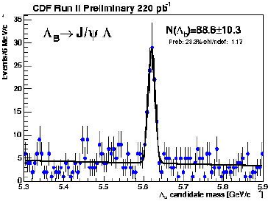
Total heavy quark production can be extracted from meson cross section using fragmentation fractions

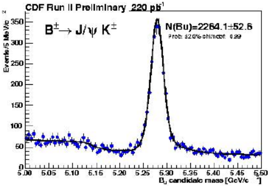
Ways to Measure Q Production

Masses and lifetimes...







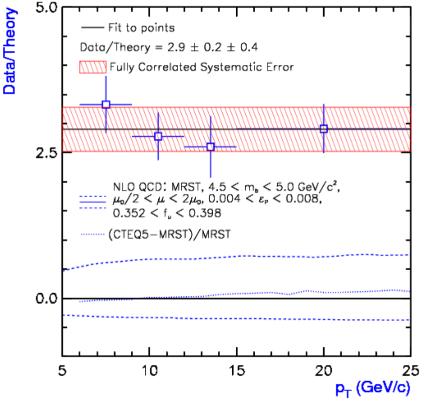


$m(B_s)$=5366.01±0.73(stat)±0.0.33 (sys)MeV/c^2

$\tau(B_s)$=1.347±0.099±0.013 ps

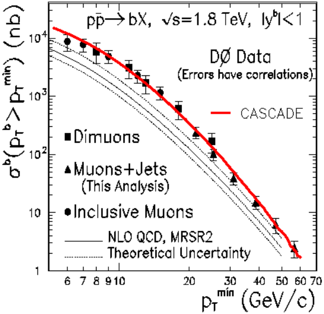
$\tau(B_s)/\tau(B_d)$= 0.89±0.072

Backgrounds

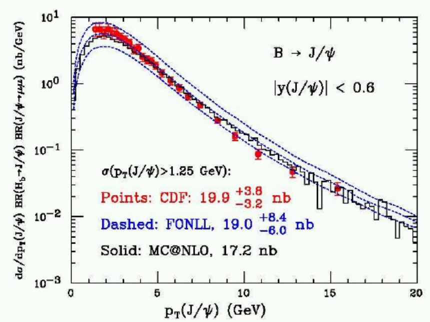


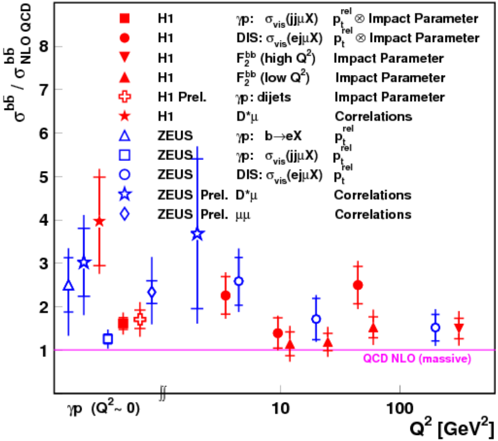
Signal extracted from fit to mass peak
Data a factor 2 over theory! Since this measurement theory has significantly improved.

$p\bar{p}$ Tevatron Run-I



Run-II

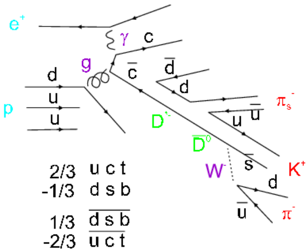



σ^bb / σ^bb NLO QCD
H1 γp: σvis(jjμX) pt rel ⊗ Impact Parameter
H1 DIS: σvis(ejμX) pt rel ⊗ Impact Parameter
H1 F2bb (high Q2) Impact Parameter
H1 F2bb (low Q2) Impact Parameter
H1 Prel. γp: dijets Impact Parameter
H1 D*μ Correlations
ZEUS γp: b→eX pt rel
ZEUS γp: σvis(jjμX) pt rel
ZEUS DIS: σvis(ejμX) pt rel
ZEUS Prel. D*μ Correlations
ZEUS Prel. μμ Correlations
QCD NLO (massive)
γp (Q2~ 0)
10
100
Q2 [GeV2]

In DIS charm and beauty production comes mainly form BGF. One can measure the structure functions $F_2^{c\bar{c}}$ and $F_2^{b\bar{b}}$
Presented here

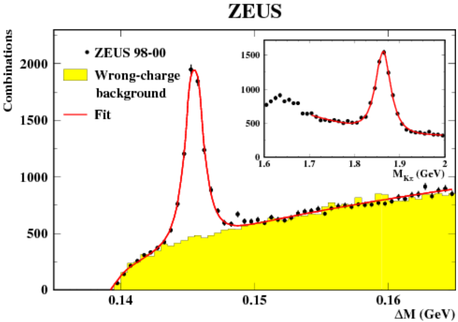
- ZEUS $F_2^{c\bar{c}}$ result using fully reconstructed D^* mesons
- H1 $F_2^{c\bar{c}}$ and $F_2^{b\bar{b}}$ using inclusive impact parameters

D^*s are chosen because they have an especially clean so called 'golden' decay channel $D^* \rightarrow K\pi\pi_s$

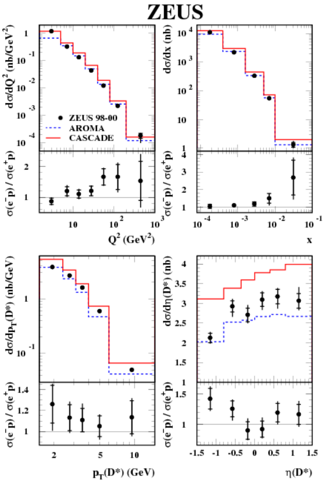


A normal DIS selection is used to select events, followed by a mass window cut on reconstructed D^0. The signal mass peak uses the difference between the D_0 and the $D^0 + \pi_s$

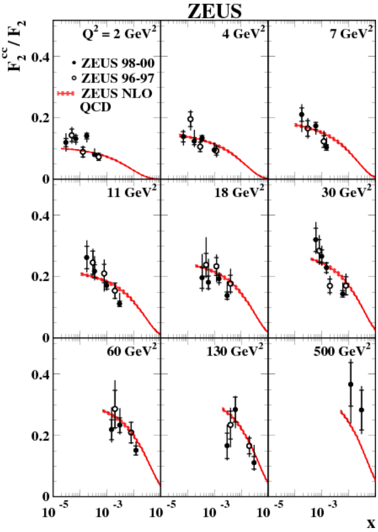
Signal:



background can be evaluated from so called wrong charge combinations, such as $K^+\pi^+\pi_s^+$ and $K^+\pi^-\pi_S^+$



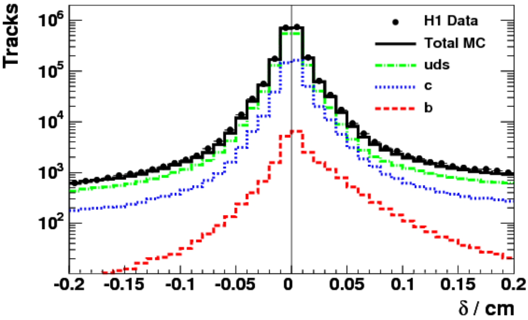
$\sigma(D^*)$ is extrapolated to the full charm cross section using fragmentation fraction to get to D^* and branching ration for $D^* \longrightarrow k\pi\pi_s$ $F_2^{c\bar{c}}$ can be extracted from this cross section in the usual way



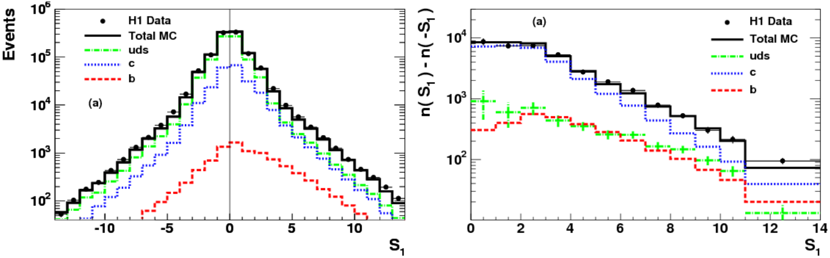
Charm contribution to F_2 can be as high as 30%

The H1 collaboration recently published a very elegant measurement of $F_2^{c\bar{c}}$ using their vertex detector

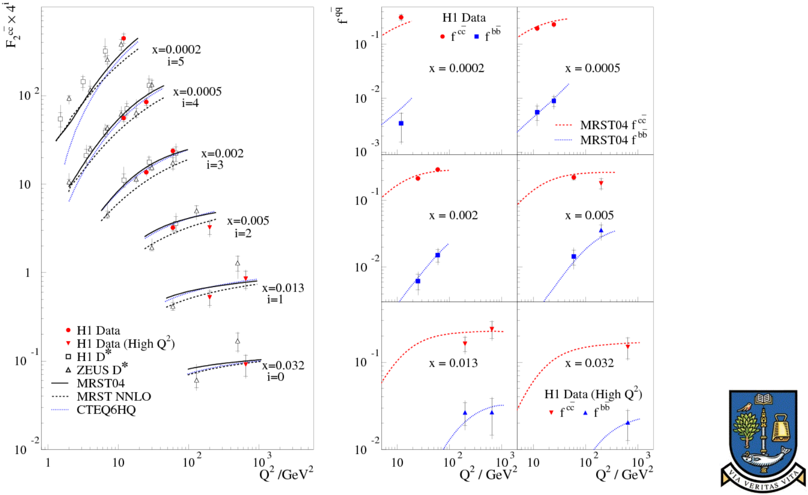
- Start with standard DIS selection
- The signed impact parameter (δ) distribution of tracks with respect to the hadronic system (reconstructed for jets in the final state) is constructed



Construct significance ($S = \delta/\sigma\delta]$) distribution



Fit to obtain fraction of c and b and use to extract $F_2^{c\bar{c}}$ and $F_2^{b\bar{b}}$


$F_2^{c\bar{c}} \times 4^i$
x=0.0002 i=5
x=0.0005 i=4
x=0.002 i=3
x=0.005 i=2
x=0.013 i=1
x=0.032 i=0
H1 Data
H1 Data (High Q^2)
H1 D*
ZEUS D*
MRST04
MRST NNLO
CTEQ6HQ
Q^2 /GeV^2
$f^{q\bar{q}}$
H1 Data
$f^{c\bar{c}}$ $f^{b\bar{b}}$
x = 0.0002
x = 0.0005
MRST04 $f^{c\bar{c}}$
MRST04 $f^{b\bar{b}}$
x = 0.002
x = 0.005
x = 0.013
x = 0.032
H1 Data (High Q^2)
Q^2 / GeV^2
VIA VERITAS VITA

$p\bar{p}$ offers a variety of QCD physics, often very different to $e^{-}e^{+}$ and ep scattering.
Of course all measurements of QCD at TeVatron will help us understand better future physics at the LHC