From HERA to LHC: Measurements of heavy flavour contribution to proton structure functions

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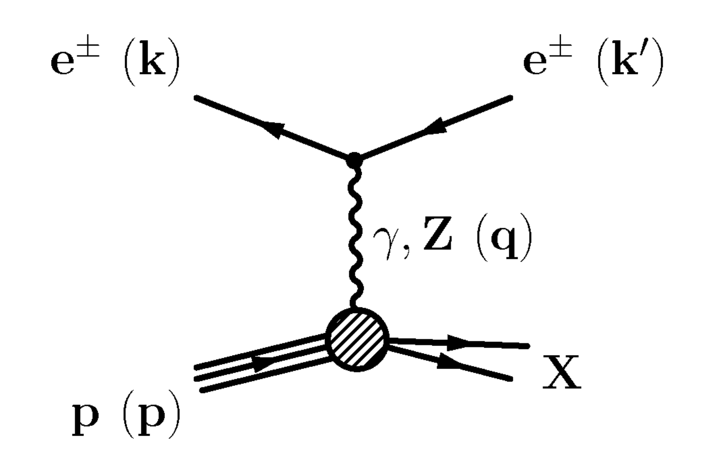
Introduction:

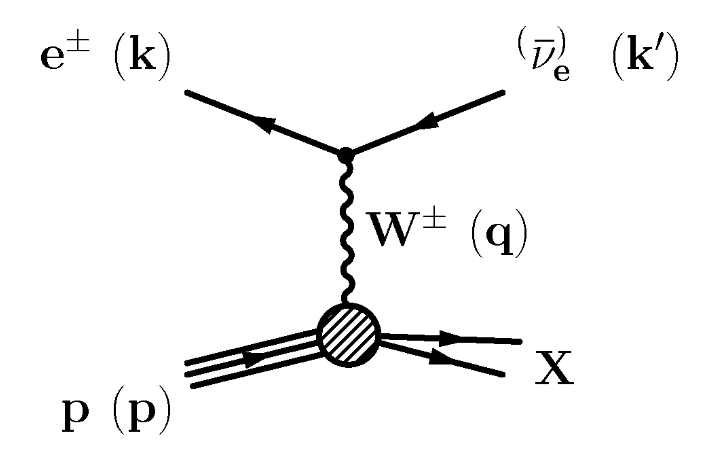
Structure Functions and Parton Density Functions (PDF)

Kinematics of ep Collisions

Neutral Current



Charged Current



Lorentz-Invariant Variables:

- Gauge Boson's Virtuality:
  transfered momontum from e to p

$$Q^2 := -q^2 = -(k - k')^2, \quad Q^2 \geqslant 0$$

- Bjørken Scaling Variable:
  fraction of proton's momentum
  carried by the interacting parton

$$x := \frac{Q^2}{2P \cdot q} \qquad 0 \leqslant x \leqslant 1$$

- Relative energy transfer at the
  positron-boson vertex in the proton
  rest frame:

$$y := \frac{P \cdot q}{P \cdot k} \qquad 0 \leqslant y \leqslant 1$$

$$Q^2 = xys$$

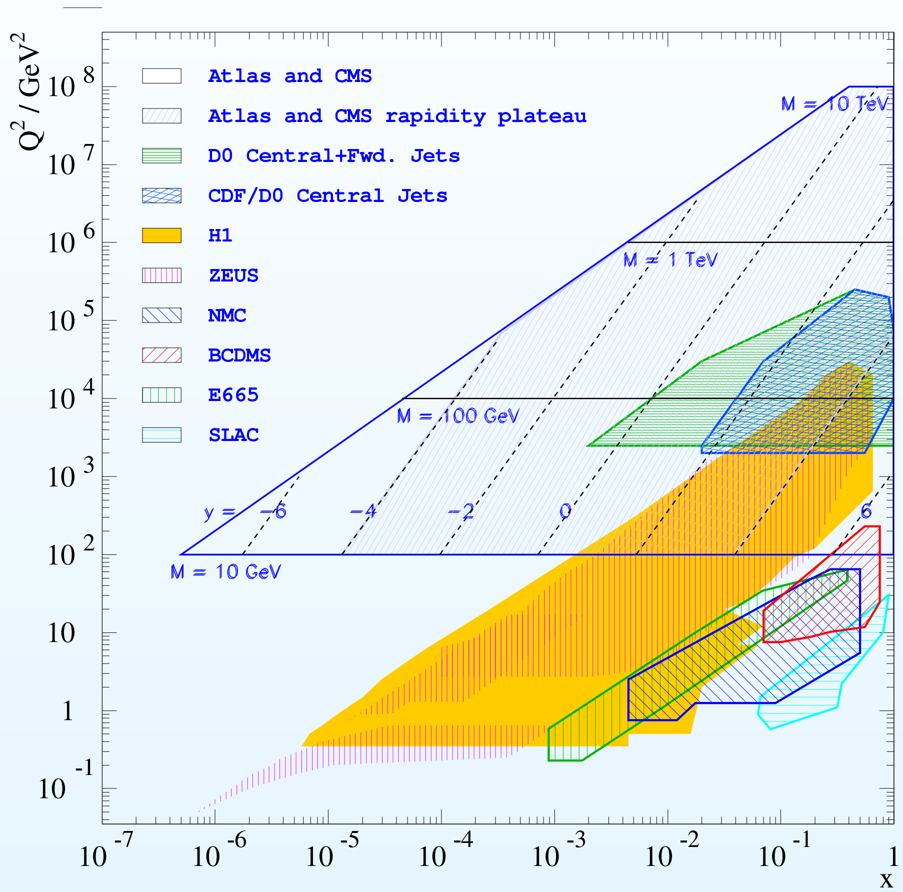
Kinematics of ep Collisions

Kinematic Regions

1. **Photoproduction (γp): $Q^2 < 1$ GeV^2**
   Dominant process - exchange of quasi-real photons

2. **Low Q^2 Deep Inelastic Scattering (DIS):**
   1 GeV$^2 < Q^2 <$ 100 GeV^2
   Main kinematic regime at HERA for the investigation of the structure of the proton. Dominant process - photon exchange

3. **High Q^2 DIS: $Q^2 >$100 GeV^2**
   Contribution of Z and $W^{\pm}$ exchange
   Important measurements of proton structure functions for the LHC



Inclusive DIS Cross Sections

Neutral current DIS reaction $ep \longrightarrow eX$

Inclusive cross section depends on two independent kinematic variables, chosen to be x and Q^2

In one-photon exchange (Born approximation):

$$\frac{d^2\sigma^{NC}}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[(1+(1-y)^2)F_2(x,Q^2) - y^2 \underbrace{F_L(x,Q^2)}_{\text{small}}\right]$$

Longitudinal structure function $F_L = F_2 - 2xF_1$

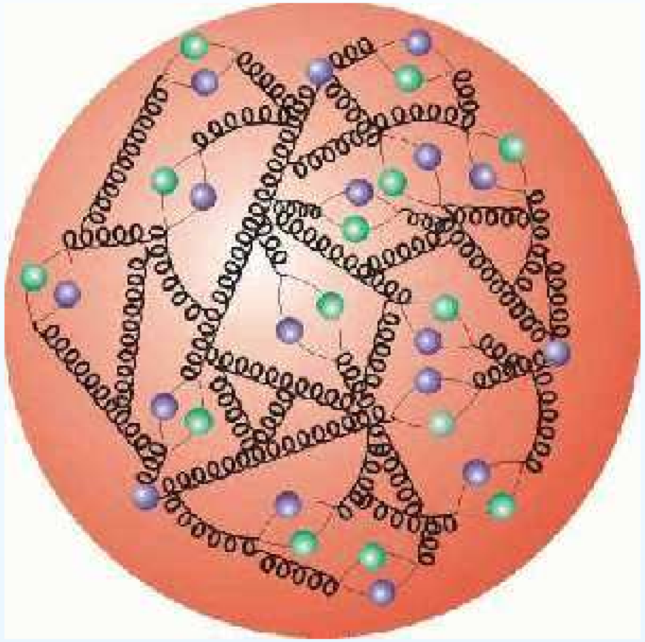
In order to reduce the strong Q^2 dependence originating from the photon propagator NC reduced cross section is used:

$$\tilde{\sigma}^{NC}(x,Q^2) = \frac{xQ^4}{2\pi\alpha^2}\frac{1}{1+(1-y)^2}\frac{d^2\sigma^{NC}}{dxdQ^2}$$

Quantum Chronodynamics (QCD)

- QCD is a non-Abelian gauge theory of strong interactions
- Based on SU(3) colour symmetry group
- Each quark exist in 3 colours (red, green, blue)
- The interaction between quarks proceeds via exchange by gluons
- Gluons can strongly interact with each other

Proton Structure



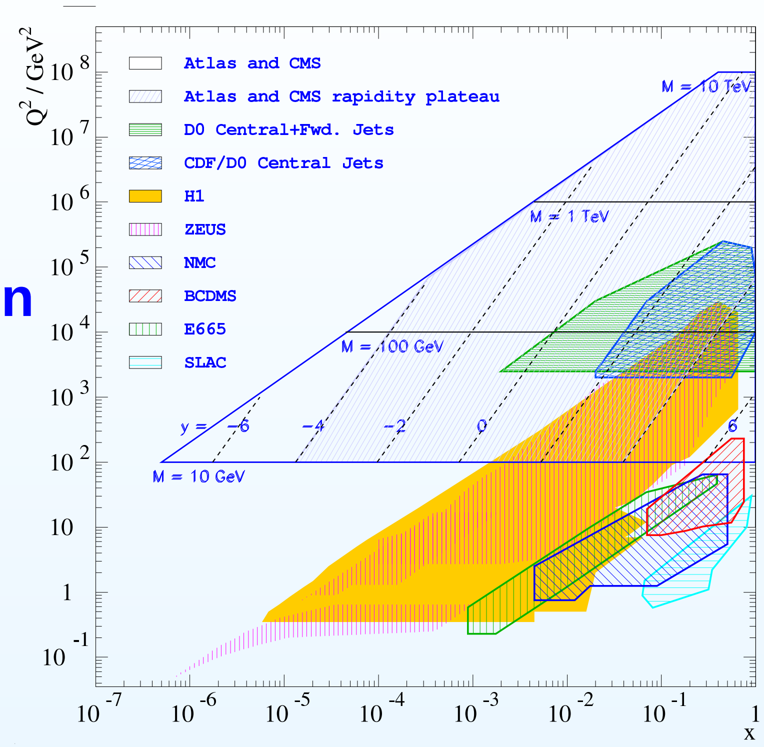
Proton constituents:

- Valence quarks (uud for proton)
- gluons
- Sea quarks ($q\bar{q}$ pairs created by gluons)

Factorization Theorem

The ep cross section can be represented as:

$$d\sigma(ep \to e' X) = \sum_i \underbrace{f_i^p(\xi, \mu_F)}_{\text{PDF}} \otimes \underbrace{d\hat{\sigma}_i(\mu_R, \mu_F)}_{\text{coeff. function}}$$



where $f_i^p(\xi, \mu_F)$ is

- parton density function (PDF), probability to find parton i with a proton momentum fraction ξ
- non-perturbative

$d\hat{\sigma}_i(\mu_R, \mu_F)$ is

- partonic cross section or coefficient function
- describes the scattering of the positron on a parton i inside the proton
- perturbatively calculable

Parton evolution equations describe the dependence of PDFs on μ_F or Q

e.g. DGLAP, BFKL, CCFM evolution equations

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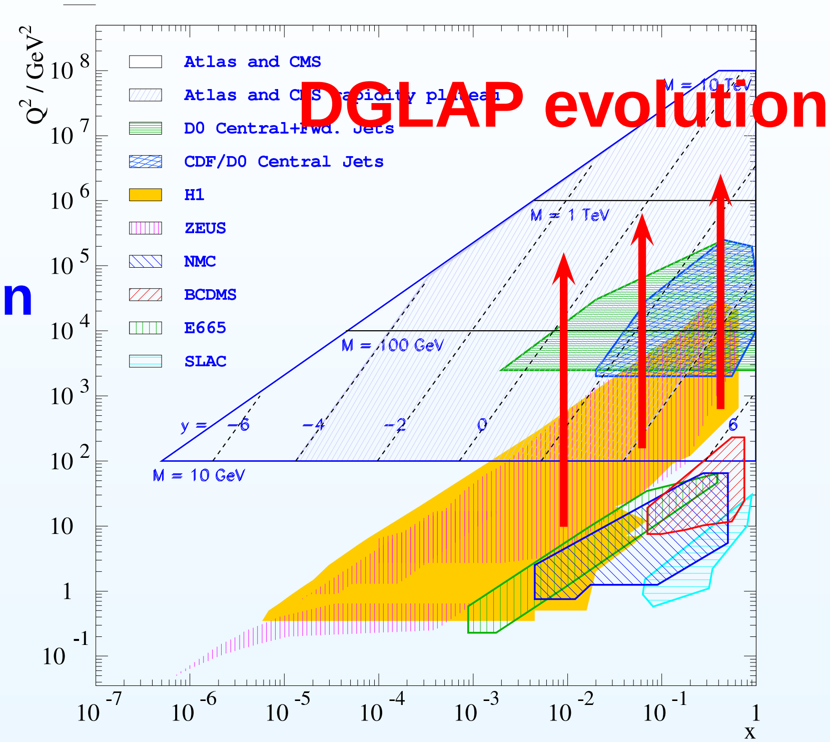

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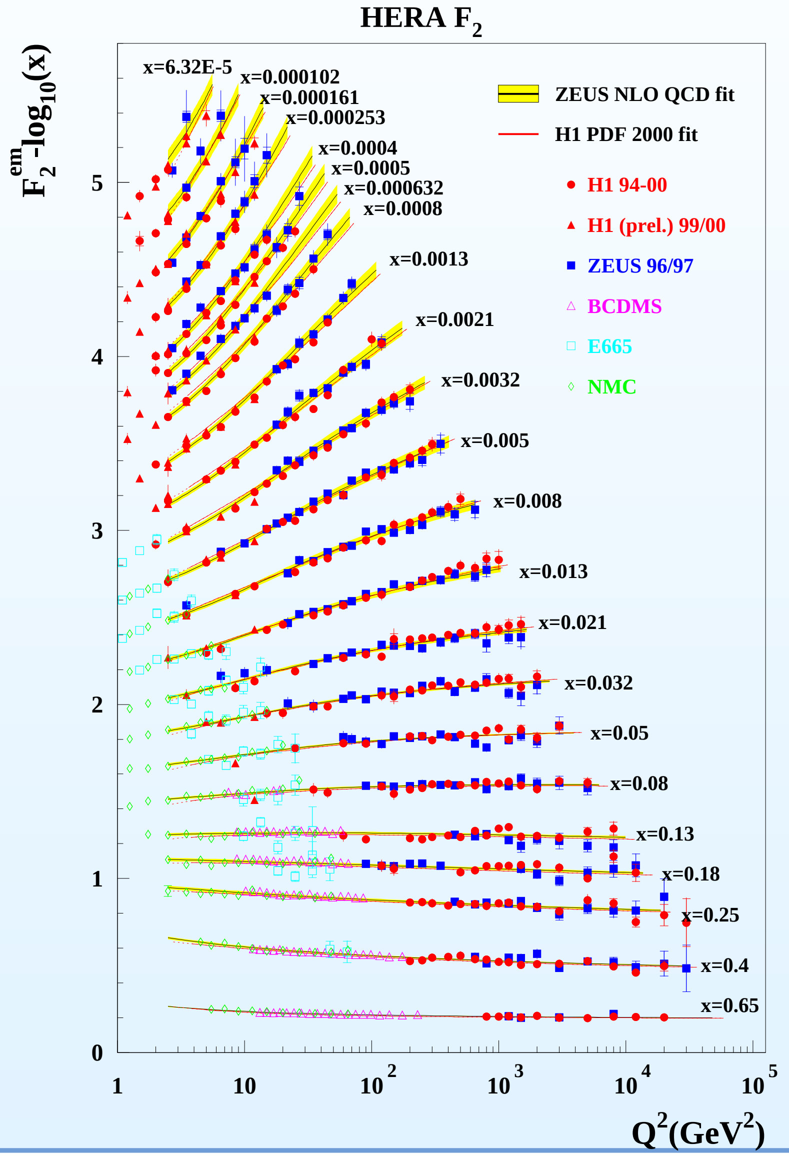
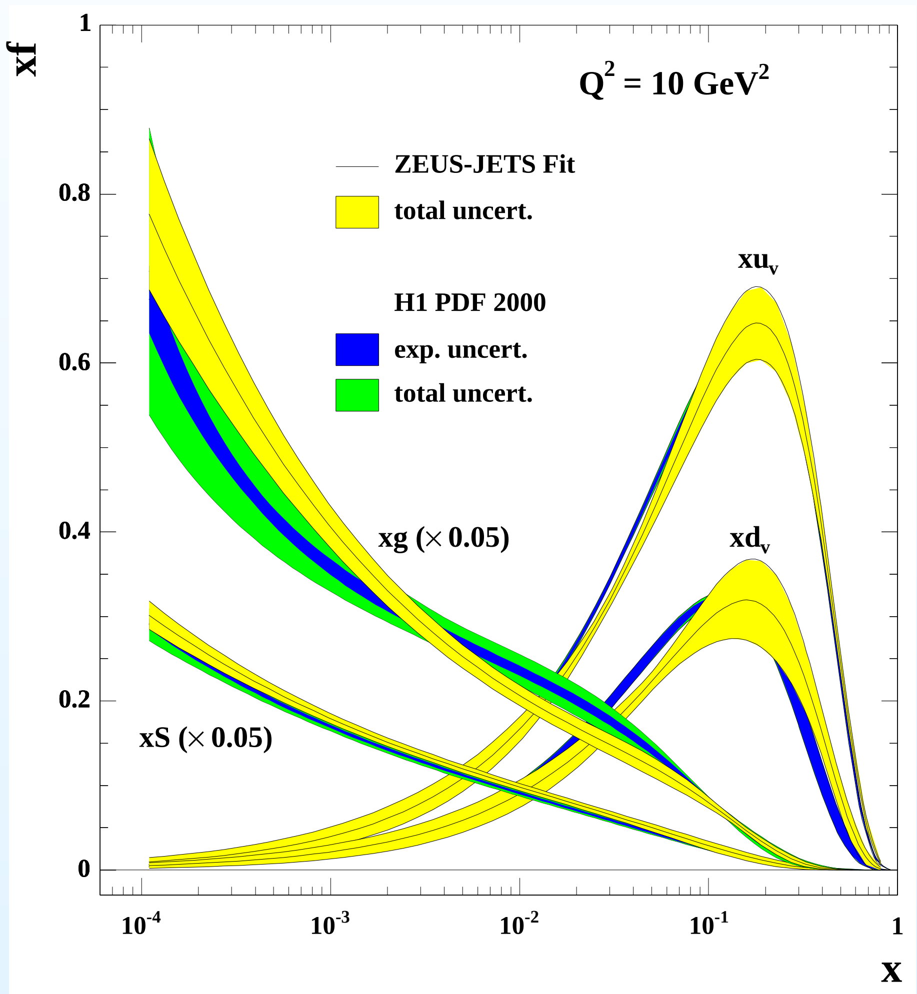
Structure Functions and PDF

Structure function F_2



Parton Density Functions



Measurements of $F_2^{c\bar{c}}$ and $F_2^{b\bar{b}}$ at HERA

- Heavy flavour production in Deep Inelastic Scattering (DIS)
- Inclusive Method of Heavy Quark Measurement using simple c- and b-tagging
- Measurement of $F_2^{c\bar{c}}$ and $F_2^{b\bar{b}}$ at Low and High Q^2

Heavy Flavour Production in Deep Inelastic Scattering I

If heavy quarks are treated as partons:

LO process:

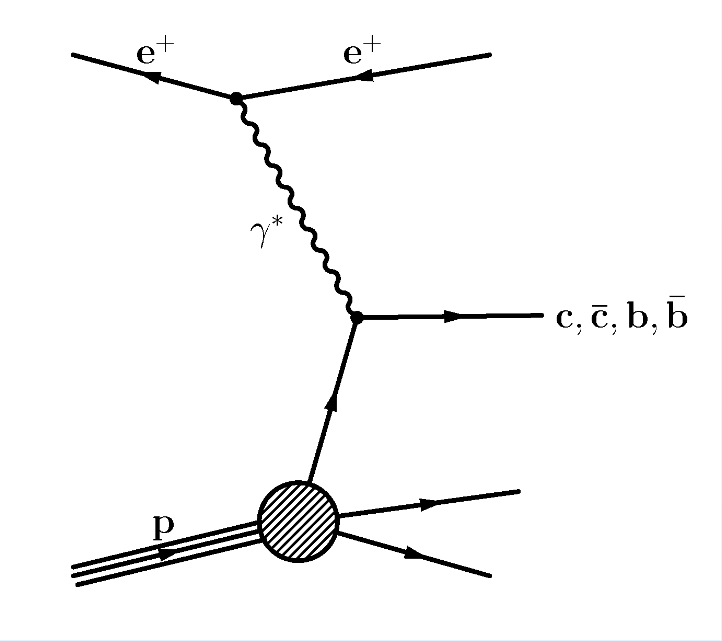
Flavour Excitation Process

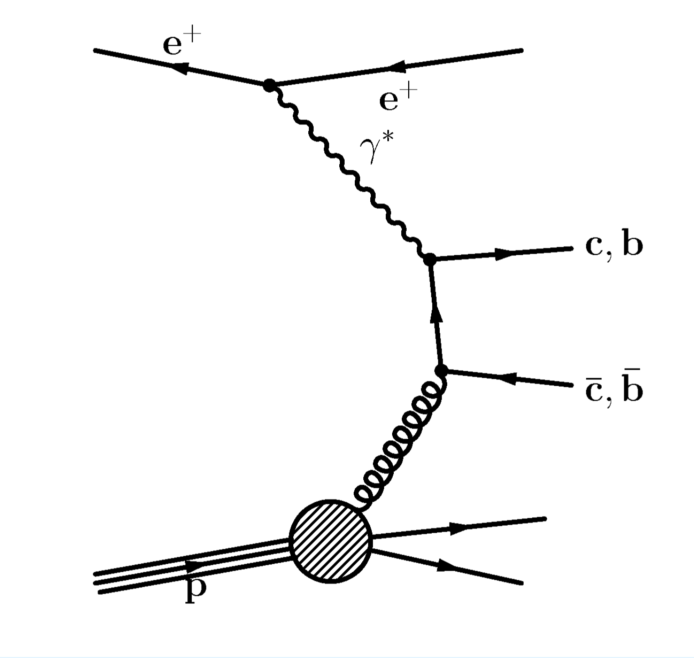
$$\gamma^* q \longrightarrow q$$

NLO process:

Photon Gluon Fusion (PGF)

$$\gamma^* g \longrightarrow q\bar{q}$$

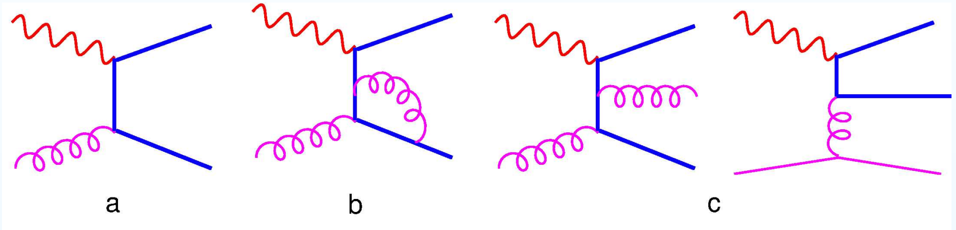




Heavy Flavour Production in Deep Inelastic Scattering II

$$Q^2 \ll M_{HQ}^2$$

“Massive scheme” or Fixed Flavour Number Scheme (FFNS)

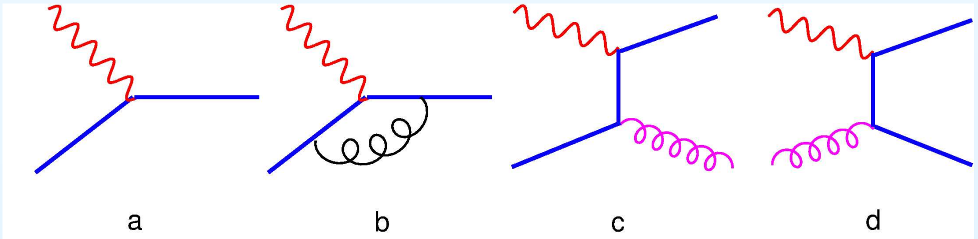


LO Process: PGF process

Quarks are treated like massive $\Longrightarrow$ do not contribute to proton structure function

$$Q^2 \gg M_{HQ}^2$$

“Massless scheme” or Zero Mass Variable Flavour Number Scheme (ZM-VFNS)



LO Process: QPM process (flavour excitation)

Quarks are treated like massless partons $\Longrightarrow$ contribute to proton structure function

Heavy Flavour Production in Deep Inelastic Scattering III

$Q^2 \ll M^2_{HQ}$ $\qquad$ $Q^2 \sim M^2_{HQ}$ $\qquad$ $Q^2 \gg M^2_{HQ}$

low Q^2 $\qquad$ high Q^2

Q^2

Heavy Flavour Production in Deep Inelastic Scattering III

$Q^2 \ll M_{HQ}^2$ $Q^2 \sim M_{HQ}^2$ $Q^2 \gg M_{HQ}^2$

low Q^2 high Q^2

→ Q^2

massive scheme

FFNS

?

massless scheme

ZM-VFNS

Heavy Flavour Production in Deep Inelastic Scattering III

$Q^2 \ll M_{HQ}^2$ $Q^2 \sim M_{HQ}^2$ $Q^2 \gg M_{HQ}^2$

low Q^2 high Q^2

Q^2

massive scheme

FFNS

?

massless scheme

ZM-VFNS

Do not give reliable description over the whole Q^2 range

Heavy Flavour Production in Deep Inelastic Scattering III

$Q^2 \ll M^2_{HQ}$ $\qquad$ $Q^2 \sim M^2_{HQ}$ $\qquad$ $Q^2 \gg M^2_{HQ}$

low Q^2 $\qquad$ high Q^2

$\longrightarrow Q^2$

massive scheme
FFNS

?

massless scheme
ZM-VFNS

Do not give reliable description over the whole Q^2 range

$\Longrightarrow$ **Variable FNS (VFNS):** Interpolate between massive and massless schemes avoiding double counting etc. ACOT(CTEQ), MRST

Treat properly threshold effects $Q^2 \sim M^2_{HQ}$

Aim of the Analysis

- Aim: to make a measurement of charm and beauty
  - in transition region $Q^2 \sim M_{HQ}^2$: $6.3 < Q^2 < 120$ GeV^2
  - in high Q^2 region: $Q^2 > 110$ GeV^2

Low Q^2: important to check the validity of the theoretical descriptions of heavy quark production around the threshold region $Q^2 \sim M_{HQ}^2$

High Q^2: important input for LHC

Motivation for the Analysis I

Processes at the LHC which entail the use of bottom in the initial state:

Name	LO process	Interest	Accuracy
single-top t-channel	$qb \longrightarrow q't$	top EW couplings	NLO
single-top tW-associated	$gb \longrightarrow tW^-$	Higgs bckg, top EW couplings	NLO
Vector boson + 1 b-jet	$gb \longrightarrow (\gamma, Z)b$	b-PDF, SUSY Higgs benchmark	NLO
Vector boson + 1 b-jet + 1 jet	$qb \longrightarrow (\gamma, Z, W)bq$	single-top and Higgs bckgs	NLO
Higgs inclusive	$b\bar{b} \longrightarrow (h, H, A)$	SUSY Higgs discovery at large $\tan\beta$	NNLO
Higgs + 1 b-jet	$gb \longrightarrow (h, H, A)b$	SUSY Higgs discovery at large $\tan\beta$	NLO
Charged Higgs	$gb \longrightarrow tH^-$	SUSY Higgs discovery	NLO

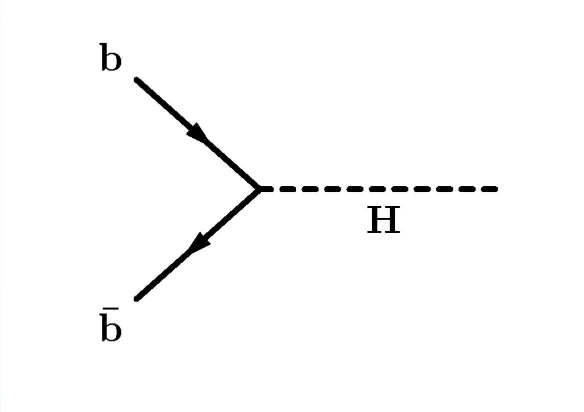
Now b PDF is derived perturbatively from the gluon distribution function

Need direct measurement of $F_2^{b\bar{b}} \Longrightarrow b$ PDF determination

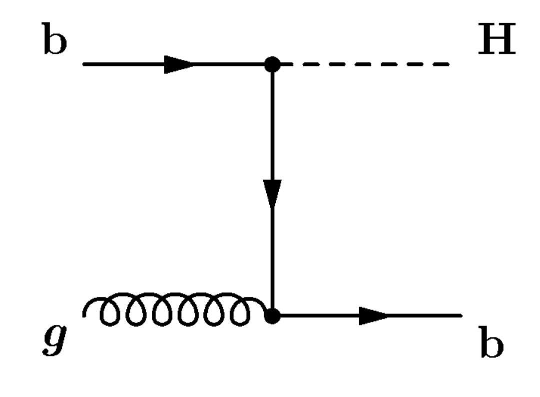
Motivation for the Analysis II

Higg Boson Production at the LHC

Inclusive Higgs production: b-quark fusion



First-order correction: Higgs + b-jet



SM cross section is small due to low Yukawa coupling ($\sim m_b/v$)

Can be enhanced in MSSM for large $\tan\beta \Longrightarrow$ Important channel for Higgs production (h, H, A) at the LHC

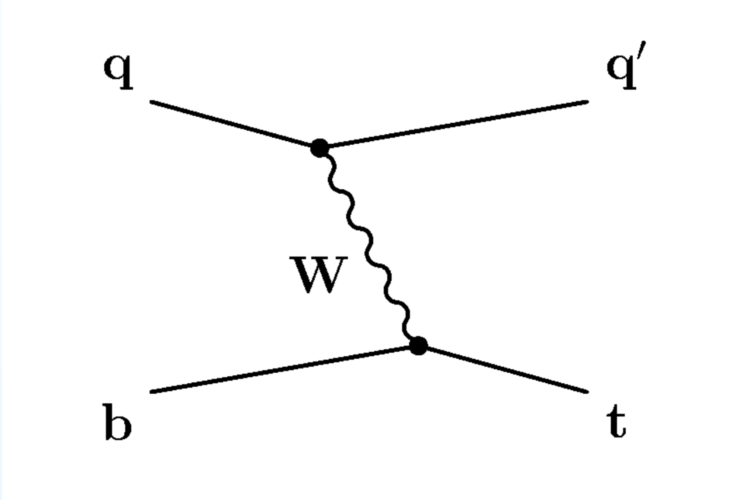
Higgs can be detected via decay to $\tau^+\tau^-$, $\mu^+\mu^-$

Knowledge of beauty PDF at the scale $Q = m_H/2$ or $Q = m_H/4$ is important!

This is high Q^2 region at HERA

Motivation for the Analysis III

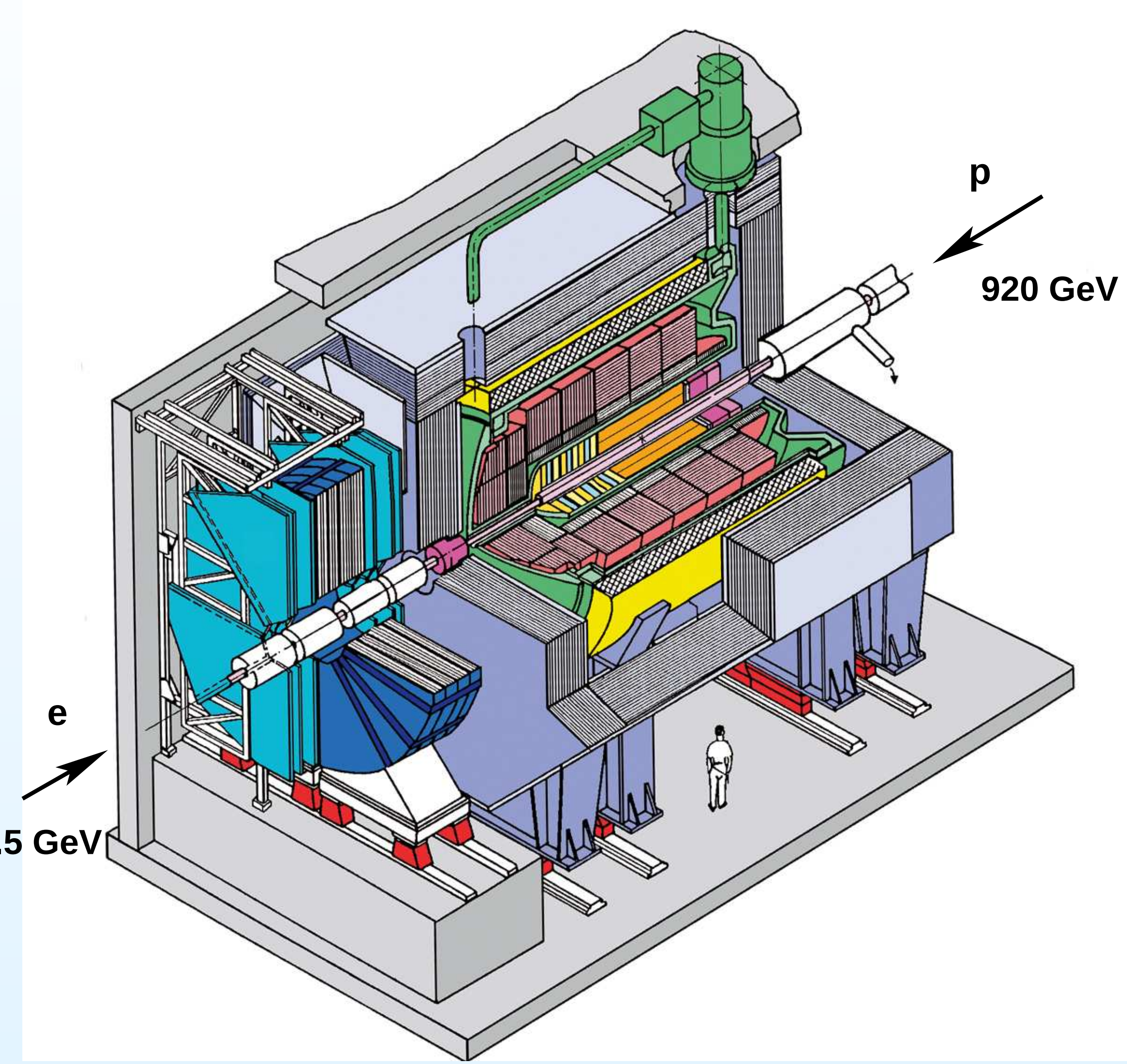
Single top-quark production

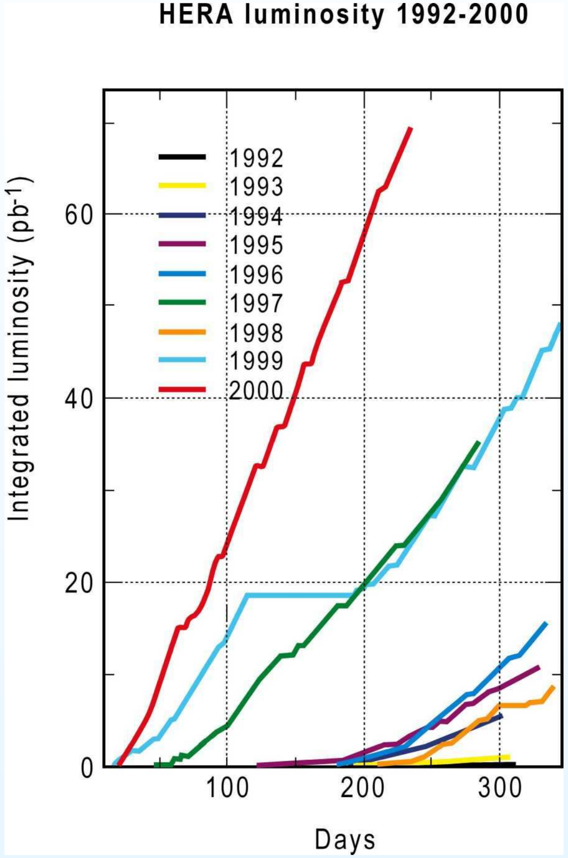


Standard Model: Direct measurement of CKM matrix element V_{tb}

Beyond the Standard Model: Sensitive to new physics associated with the charged-current weak interaction of the top quark

H1 Detector



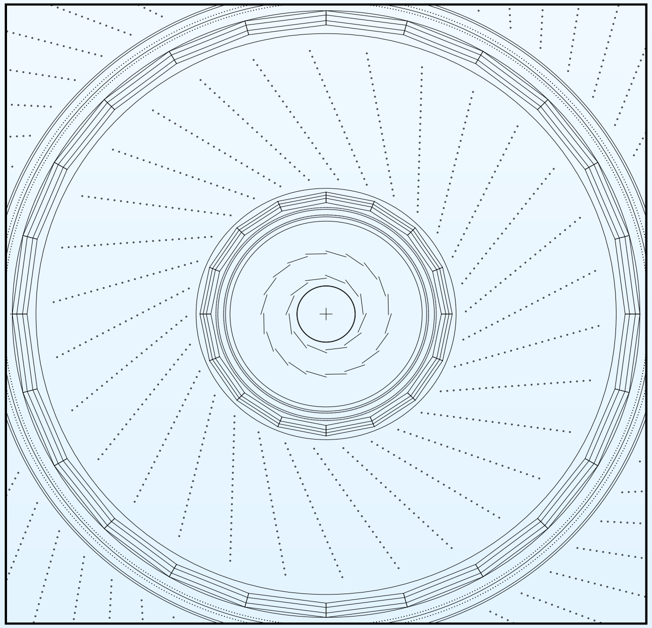


$\mathrm{e^+p}$ **NC 99/2000 HERA-I data**

$$L \simeq 57.4\,\mathrm{pb}^{-1}$$

$\sqrt{s}$ = $\sqrt{4E_eE_p}$ = 318 GeV

H1 Central Silicon Tracker (CST)



- Consists of two cylindrical layers of double-sided silicon strip detectors surrounding the beam pipe at radii of 5.7 cm and 9.7 cm
- Covers angular range $30^\circ < \theta < 150^\circ$
- Hit resolution: 12 μm in $r\phi$
  25 μm in z
- For CJC tracks with CST hist in both layers DCA resolution in xy plane: $33\ \mu\text{m} \oplus \frac{90\ \mu\text{m}}{p_\text{T}}$ [GeV]
- The efficiency to link 2 CST hits to a CTD track: 76%

Methods for c- and b-tagging at HERA

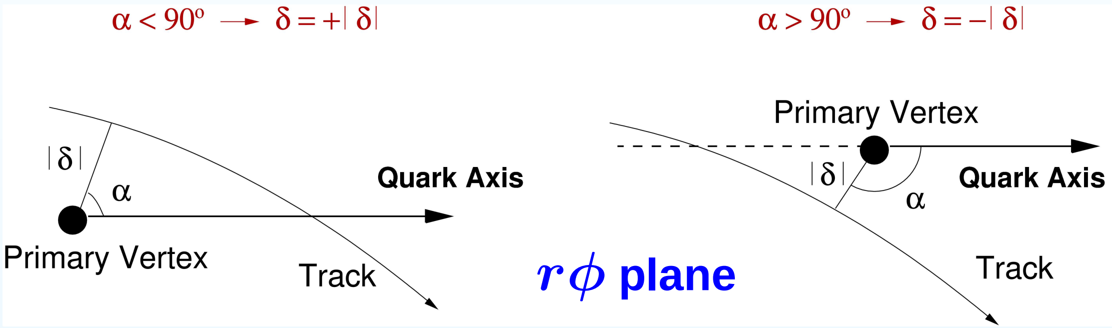
- Existing Methods:
  - D^* } exclusive methods
  - μ
  - explicit reconstruction of secondary vertex

  } Statistically limited!
- Model dependent extrapolations of exclusive methods: in D^* analysis extrapolation factors vary from 4.7 to 1.5 in p_{T} and η decreasing with increasing Q^2

- $\Longrightarrow$ **Inclusive method:** use CST-improved impact parameter for **all** tracks
- Method is based on lifetime information of heavy hadrons
- Aim to be as inclusive as possible and keep size of extrapolations in p_{T}, η to minimum
- Fraction of b falls at low Q^2 $\Longrightarrow$ experimentally challenging

Technique

Look at signed DCA (Distance of Closest Approach $\equiv$ Impact Parameter δ) for all tracks with precise measurement from Central Silicon Tracker (CST)



$r\phi$ plane

- The sign is infered from a quark axis approximating the flght direction of the decaying hadron
- Events with secondary vertex decays from heavy flavour particles will have large positive impact parameter w.r.t. primary vertex
- Light flavour primary decays will have small negative and positive impact parameter due to resolution effects

Data and Monte Carlo Samples (low Q^2)

We work with $\mathrm{e^+p}$ neutral current events, 99/2000 HERA-I Data,
$\mathcal{L} \simeq 57.4\,\mathrm{pb}^{-1}$, 1.5M events after selection, factor 10 larger than High Q^2!

Monte Carlo:

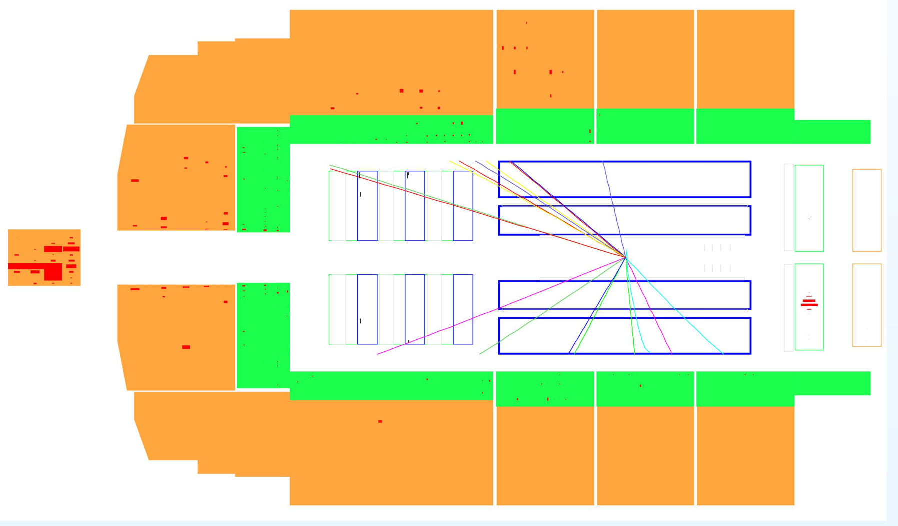
Sample	Program	Fragmentation	L $[\mathrm{pb}^{-1}]$
uds	DJANGO	LUND	90
$c\bar{c}$	RAPGAP	LUND	162.9
$b\bar{b}$	RAPGAP	LUND	981.3
$c\bar{c}$	RAPGAP	Peterson	124.54
$b\bar{b}$	RAPGAP	Peterson	969.05
$c\bar{c}$	CASCADE	LUND	124.6
$b\bar{b}$	CASCADE	LUND	671.53
γp	PHOJET	LUND	2.576

Event Selection

We require:

- Low Q^2
  - $6.3 < Q^2 < 120$ GeV^2
  - e^+ in SpaCal
- High Q^2
  - $Q^2 > 110$ GeV^2
  - e^+ in LAr

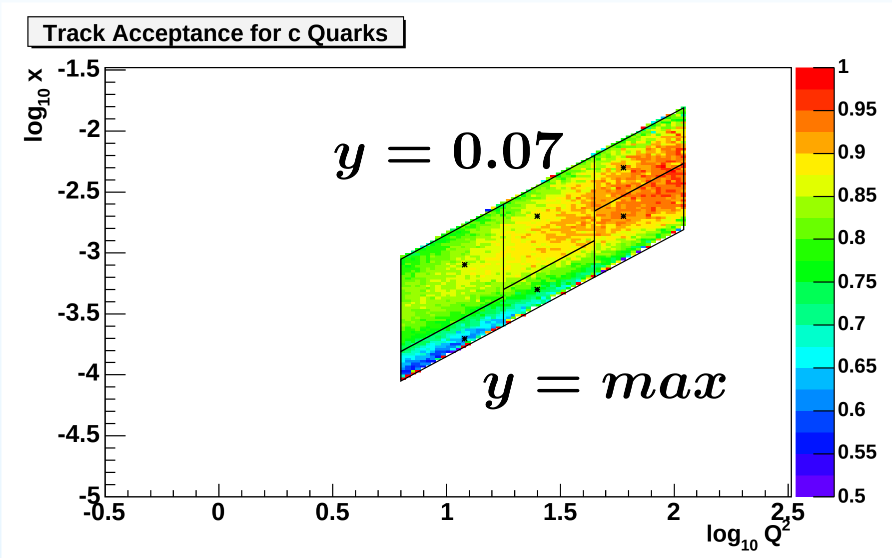
Low Q^2 Event in H1 detector



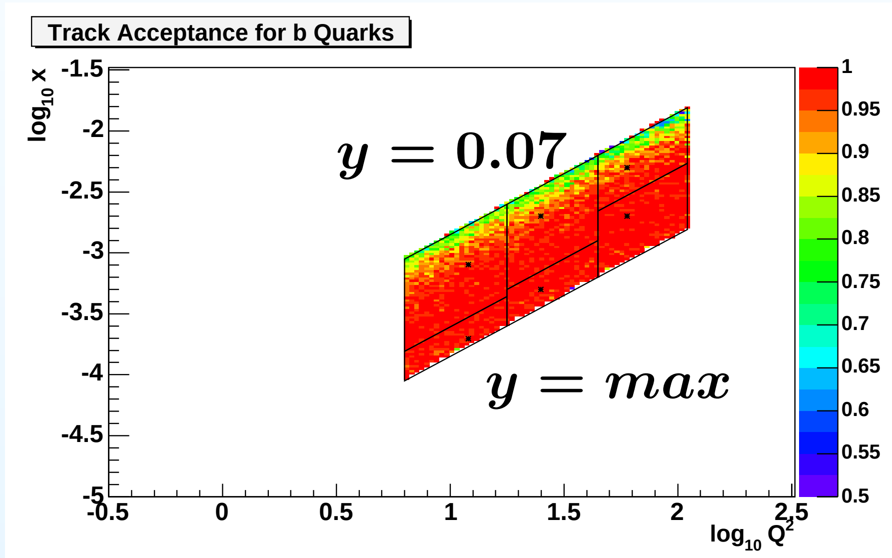
Track Acceptance (low Q^2 analysis further)

Acceptance for a charged track from c, b hadrons to be in CST acceptance $(30^\circ < \theta < 150^\circ, p_T > 0.5\ \mathrm{GeV})$ and generated z-vertex within $\pm 20\ \mathrm{cm}$

c quarks



b quarks



- Acceptance for c is $68\% - 89\%$
- Bin centres from measured F_2

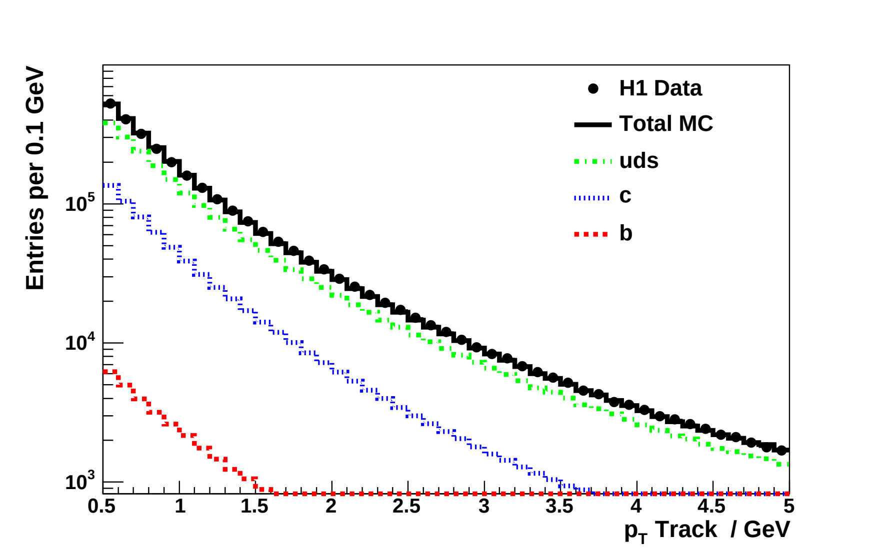
- Acceptance for b is $93\% - 99\%$
- $y_{\max}$ = 0.625 for $Q^2 < 17.78$ GeV^2
  $y_{\max}$ = 0.7 for $Q^2 >$ 17.78 GeV^2

CST Track Selection

Track reconstruction imrovement:
CJC tracks are linked to CST hits (CST tracks)

- $N_{\mathrm{CST}} > 1$
- $Prob_{\mathrm{link}} > 0.1$
- $p_{\mathrm{T}} > 500$ MeV
- $R_{\mathrm{start}} < 50$ cm
- $L_{\mathrm{track}} > 10$ cm
- $-18 < z_{\mathrm{CST\ hits}} < 18$ cm

p_{T} of tracks



Quark Axis Description

Quark axis is given by:

- **Highest p_T jet axis**
  - inclusive k_T algorithm in the lab. frame
  - $p_T >$ 2.5 GeV
  - 15$^\circ < \theta <$ 155°

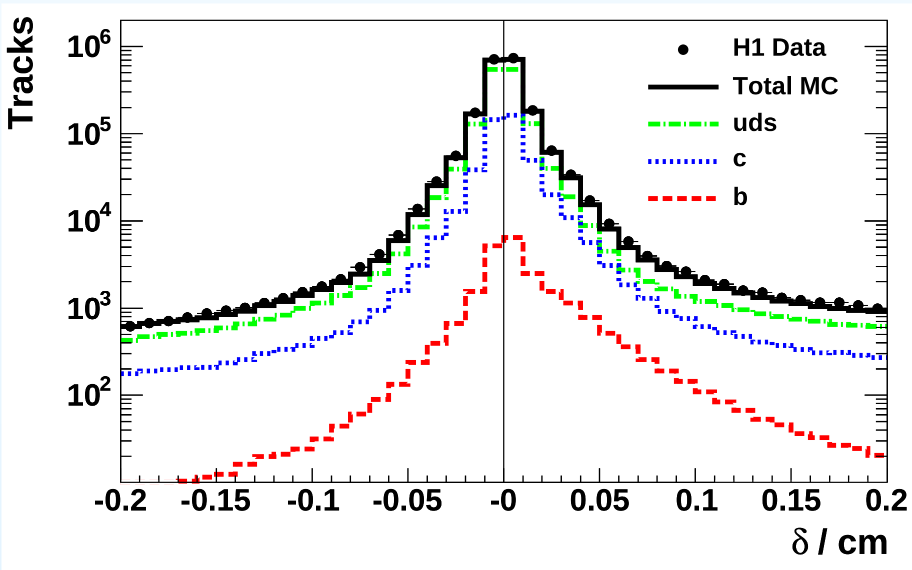
  81% of matched track-jet events for c
  95% of matched track-jet events for b
  ($>$ 97% at high Q^2)

- **If we don't have jets:**
  Quark axis is approximated by $180^\circ - \phi_{\mathbf{elec}}$

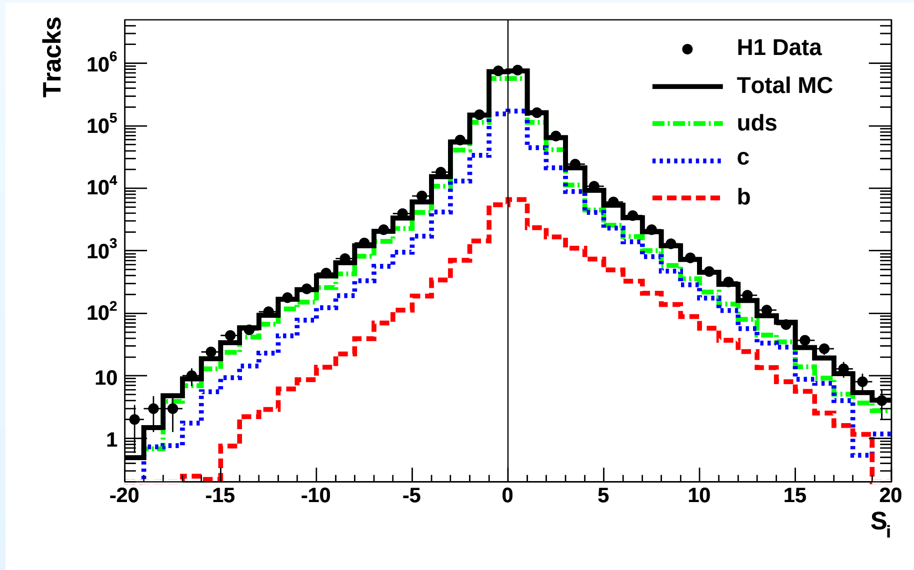
DCA and Significance

- Tracks matched to quark axis within $|\Delta\phi| < \pi/2$
- For matched tracks, plot **DCA** to primary vertex in $r\phi$ plane (δ)
  Tracks required to have $|\delta| < 1\,\mathrm{mm}$ (remove e.g. K^0 contribution)
- Significance of each track given by $S_i = \frac{\delta}{\sigma(\delta)}$

DCA

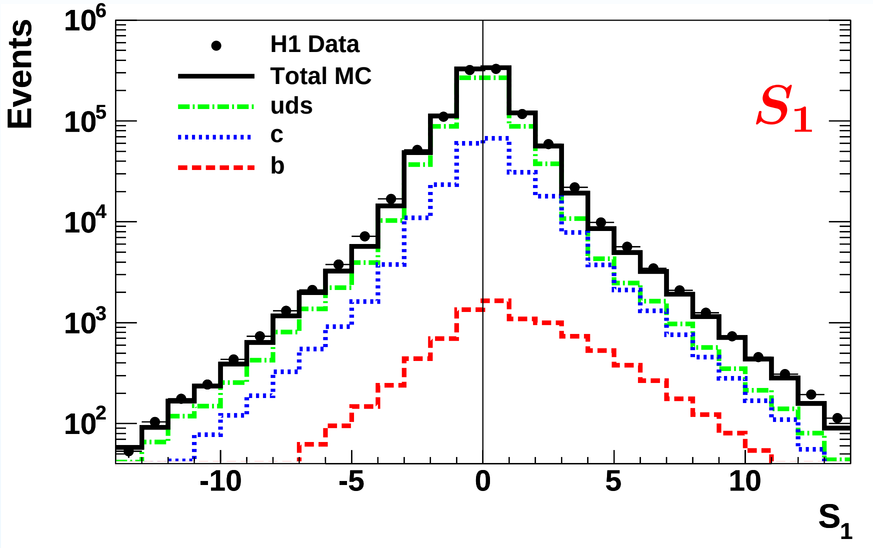


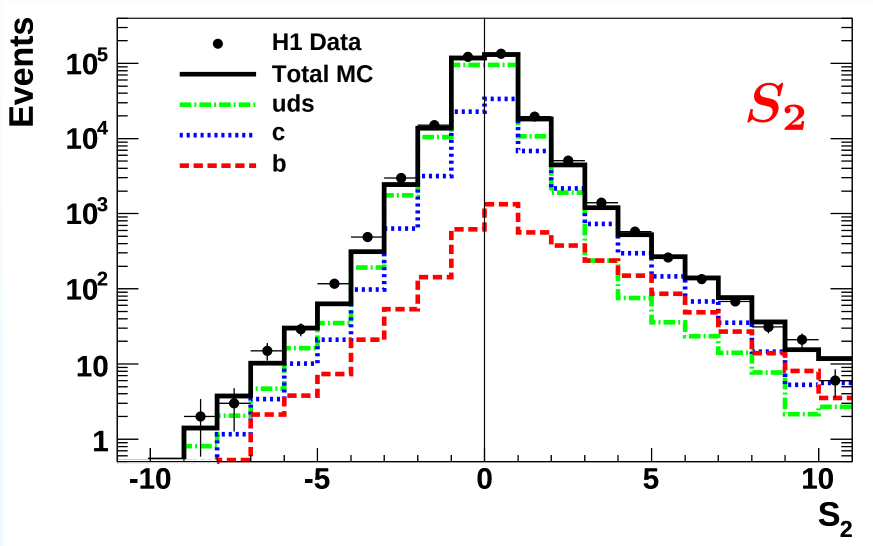
Significance

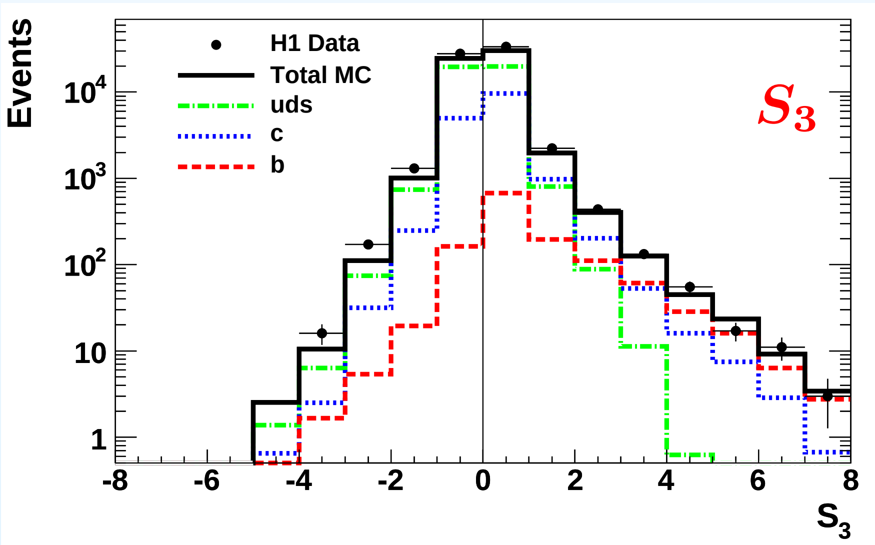


Scale factors to the MC distributions are applied

Significance (S_i) Definition







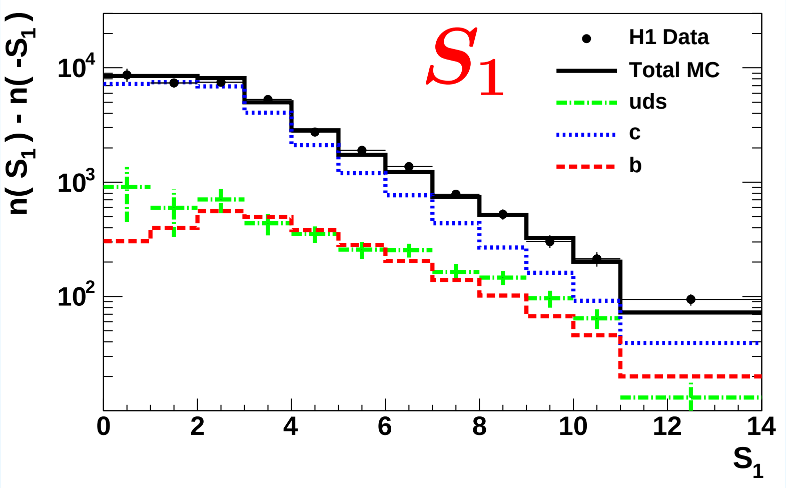
At low Q^2, beauty fraction is smaller. Need to do more to separate b and c

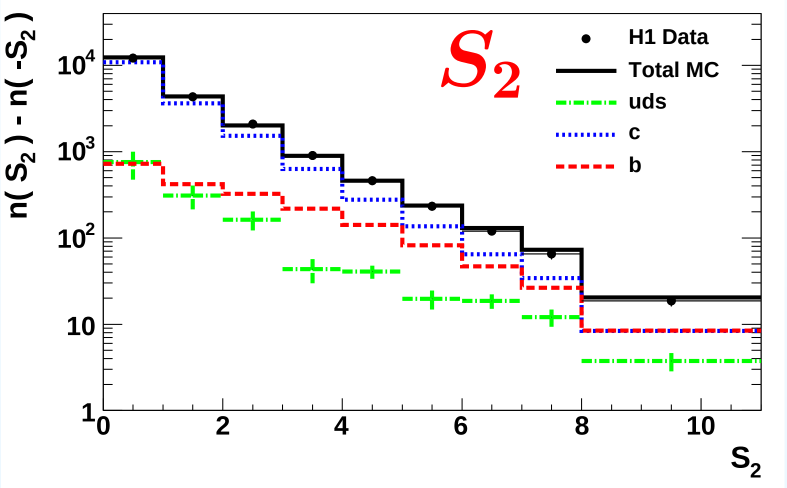
Define three distributions:

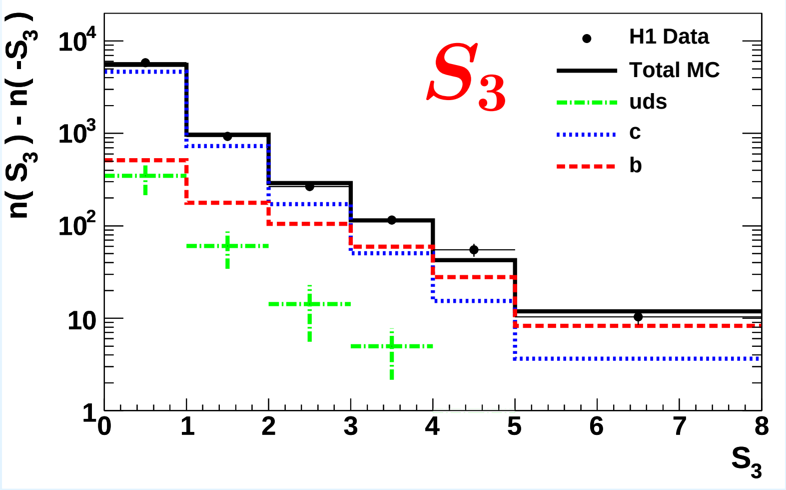
- S_1 **highest significance track**
- S_2 **2nd highest significance track with same sign as** S_1
- S_3 **3rd highest significance track with same sign as** S_1 **and** S_2

Subtracted Significance (S_i)

Subtract the negative S_i bins from the positive for both data and MC to reduce sensitivity to resolution of light quarks







For each $x - Q^2$ bin make a simultaneous fit to S_i and total number of inclusive events before CST track selection with 3 parameters:

- MC scale factor c - P_c
- MC scale factor b - P_b
- MC scale factor uds - P_l

Structure Function Extraction

Fit results: P_c = 1.28 $\pm$ 0.04, P_b = 1.55 $\pm$ 0.16, P_l = 0.95 $\pm$ 0.01

Reduced cross section:

$$\tilde{\sigma}^{c\bar{c}}(x, Q^2) = \tilde{\sigma}(x, Q^2) \frac{P_c N_c^{\mathrm{MCgen}}}{P_c N_c^{\mathrm{MCgen}} + P_b N_b^{\mathrm{MCgen}} + P_l N_l^{\mathrm{MCgen}}}$$

The differential c cross section is calculated from $\tilde{\sigma}^{c\bar{c}}(x, Q^2)$ as

$$\frac{\mathrm{d}^2\sigma^{c\bar{c}}}{\mathrm{d}x\,\mathrm{d}Q^2} = \tilde{\sigma}^{c\bar{c}}(x, Q^2)\frac{2\pi\alpha^2(1+(1-y)^2)}{xQ^4} \Longrightarrow f^{c\bar{c}} = \frac{\mathrm{d}\sigma^{c\bar{c}}/\mathrm{d}x\mathrm{d}Q^2}{\mathrm{d}\sigma/\mathrm{d}x\mathrm{d}Q^2}$$

The structure function $F_2^{c\bar{c}}$ is then evaluated from the expression

$$\frac{\mathrm{d}^2\sigma^{c\bar{c}}}{\mathrm{d}x\,\mathrm{d}Q^2} = \frac{2\pi\alpha^2}{xQ^4}[(1+(1-y)^2)F_2^{c\bar{c}} - y^2 F_L^{c\bar{c}}]$$

$F_L^{c\bar{c}}$ is estimated from the **NLO QCD expectation**

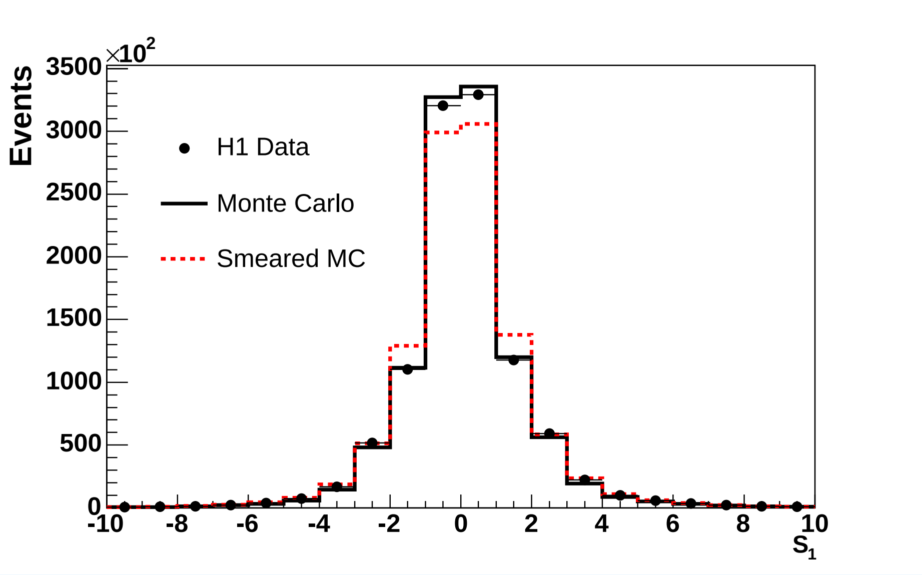
Systematic Errors (low Q^2)

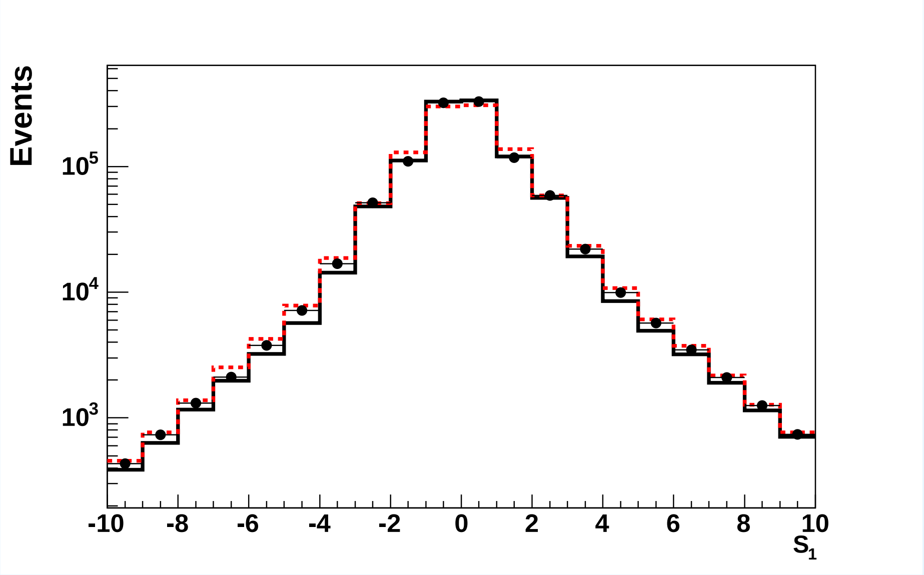
source	uncertainty	error $\mathrm{c\bar{c}}$ / %	error $\mathrm{b\bar{b}}$ / %
Track efficiency	± 2.23 (2% CJC, 1% CST)	1.4-1.7	8-10
DCA resolution	$\pm 25\mu m$ ($\pm 200\mu m$ tails)	2.5-3.2	13-21
s asymmetry	50% uncertainty	5.0-5.2	4.7-7.7
Fragmentation	LUND / Peterson	0.4-0.7	4.6-6.9
QCD model	Rapgap/CASCADE	1.9-2.2	8.8-15
Structure function	Reweight	0.3-0.8	0.6-4.6
B Multiplicity	LEP / SLD	0.2-0.3	3.0-3.1
D Multiplicity	MARKIII	3.1-3.2	2.9-5.4
Hadronic Energy Scale	4%	1.1-1.8	1.1-1.9
Quark Axis	$2^o (5^o)$ shift	2.0	1.3-1.7
Total		**8-13**	**20-33**

DCA resolution for S_1

Most effects in DCA come from the description of the MC of the internal alignment/resolution of the CST

95% of events smeared by 25 μm, 5% of events smeared by 200 μm





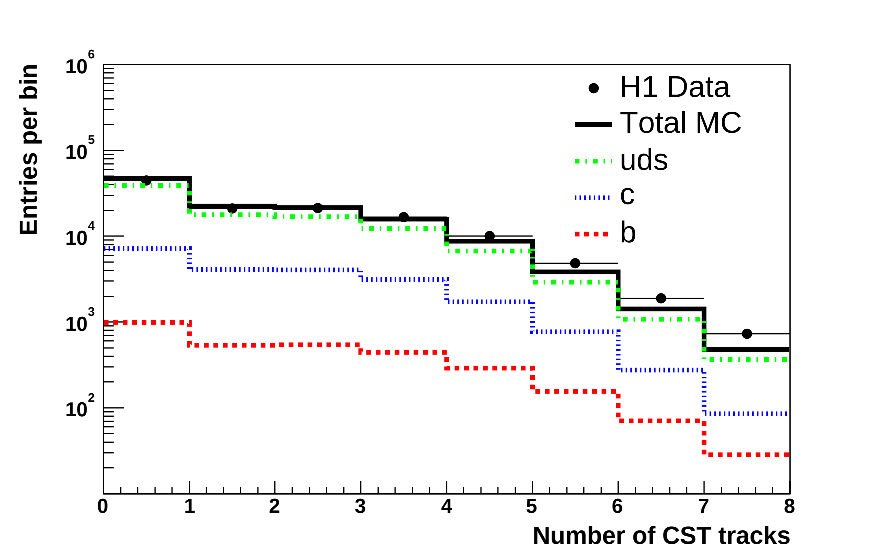
Normalised MC before (after) smearing black (red)

Description of Light Quark Multiplicity

Can contribute to systematic errors

CST Tracks per Event (events after track-jet association)

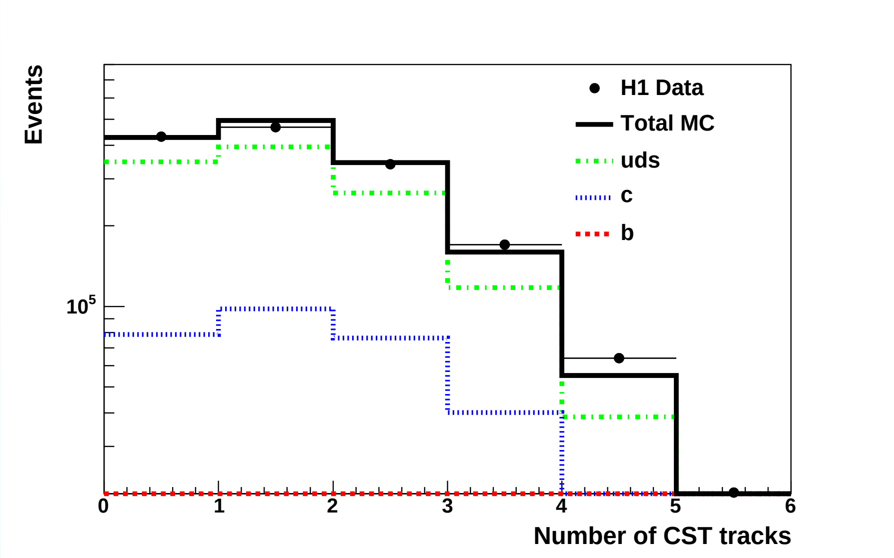
High Q^2



uds Monte Carlo: Rapgap

$c\bar{c}$, $b\bar{b}$ Monte Carlo: Rapgap

Low Q^2



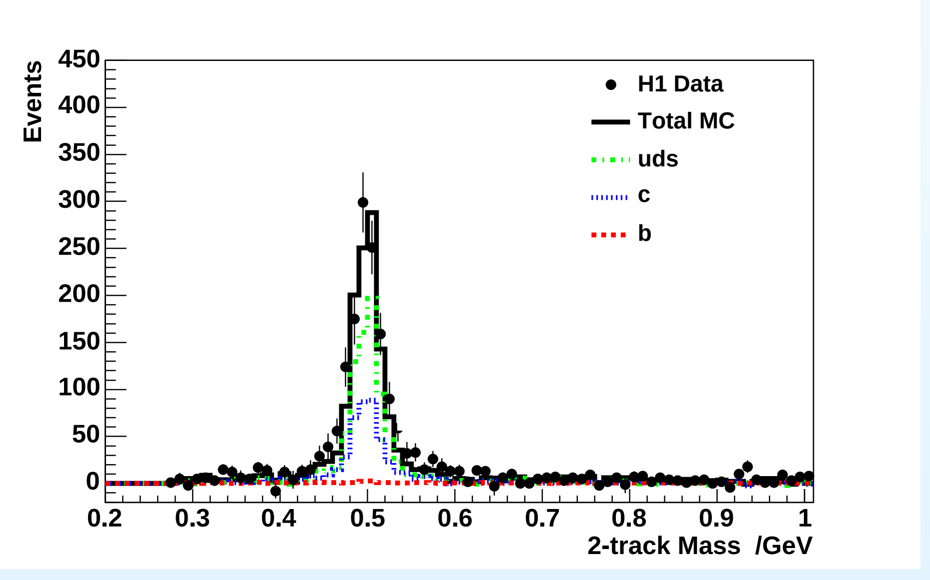
uds Monte Carlo: Django

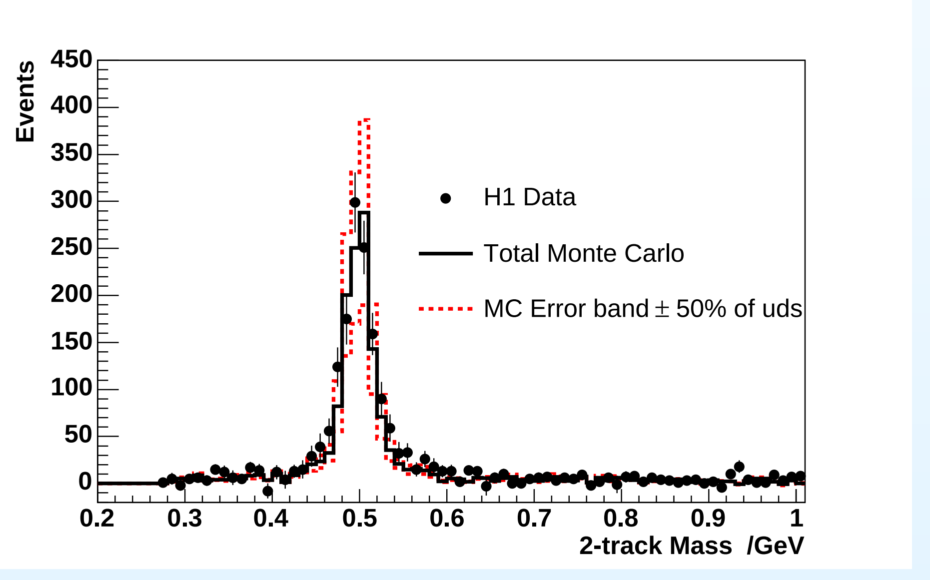
$c\bar{c}$, $b\bar{b}$ Monte Carlo: Rapgap

Light quark asymmetry

- Enhance strangeness by looking at events with 2 tracks both with $0.1 < |DCA| < 0.5$ cm
- Clear K_0 peak. Reasonable agreement after background subtraction

Uncertainty of $\pm 50\%$

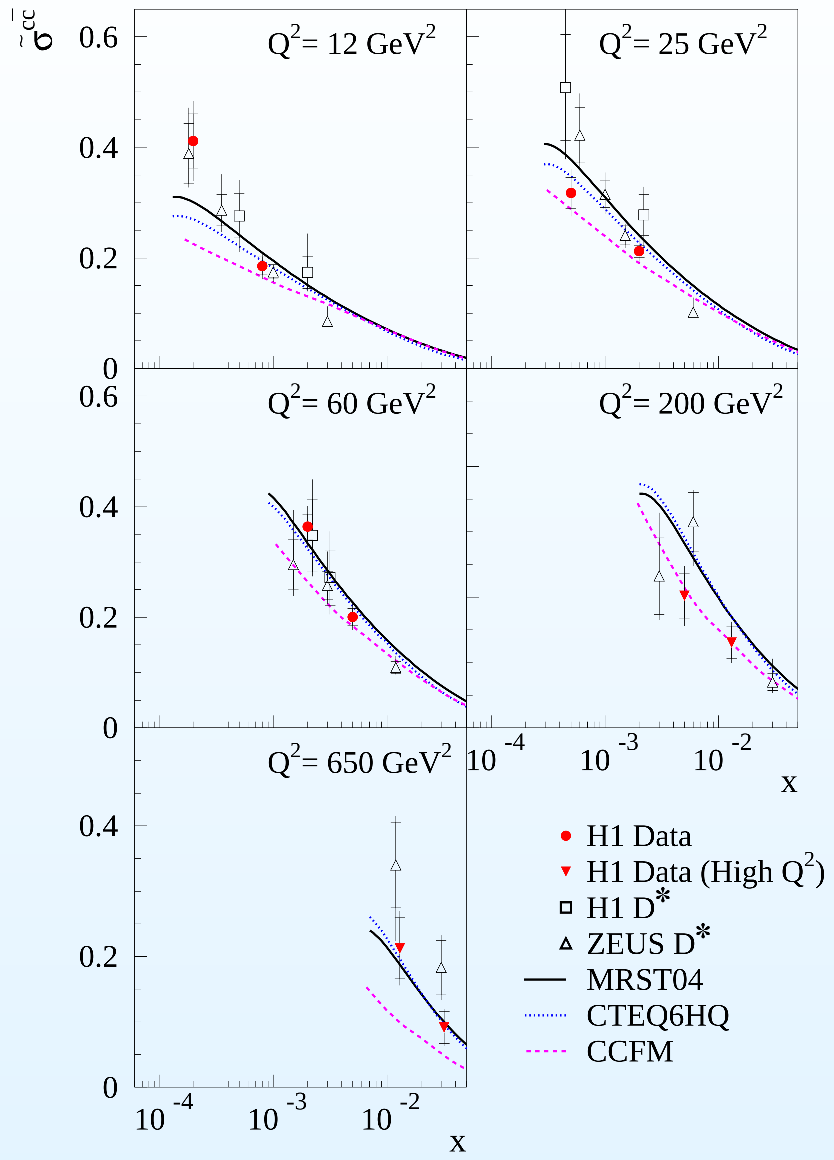




Reduced Cross Section $\tilde{\sigma}^{c\bar{c}}$

$$\tilde{\sigma}^{c\bar{c}}$$

- **Consistent results with H1 and ZEUS D^* measurements**
- **Consistent with pQCD predictions**



MRST04 - Variable FNS

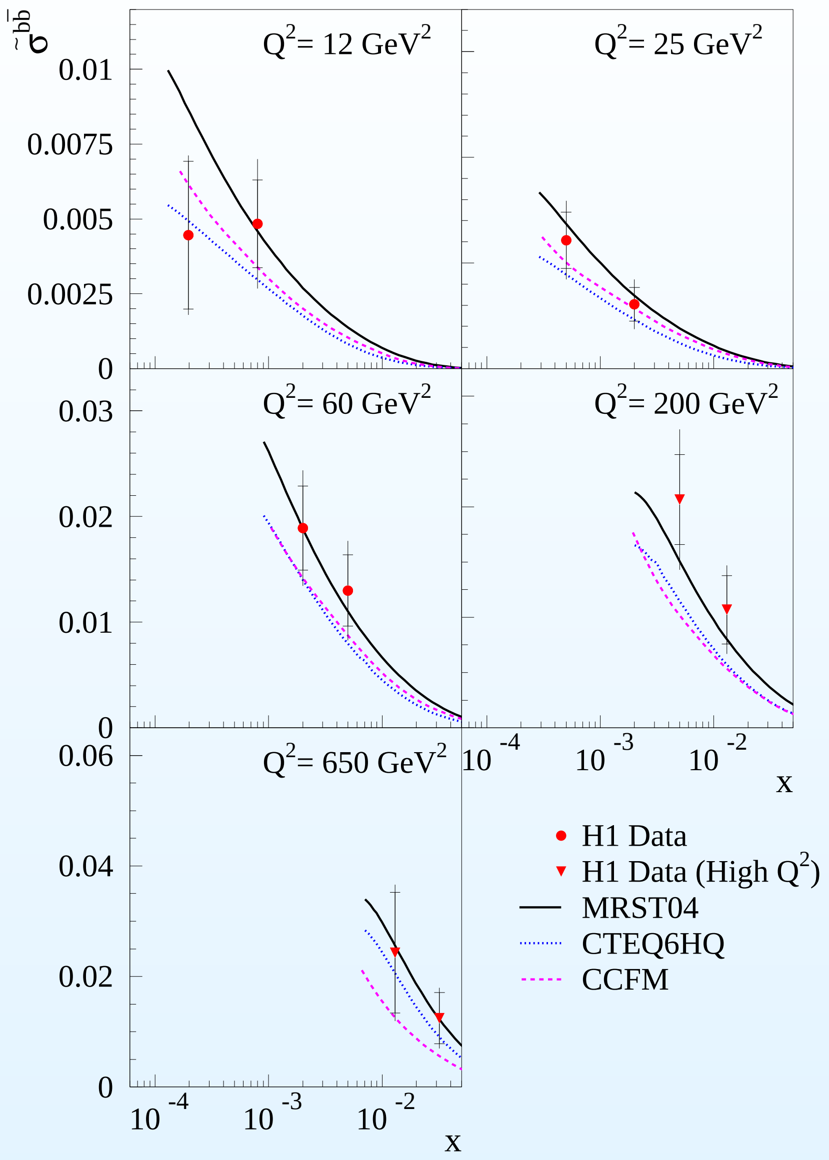
CTEQ6HQ - Variable FNS

CCFM (Cascade) - Massive scheme

Reduced Cross Section $\tilde{\sigma}^{b\bar{b}}$

$$\tilde{\sigma}^{b\bar{b}}$$

- First measurement of $\tilde{\sigma}^{b\bar{b}}$
- Consistent with pQCD predictions
- MRST04 describes the data best

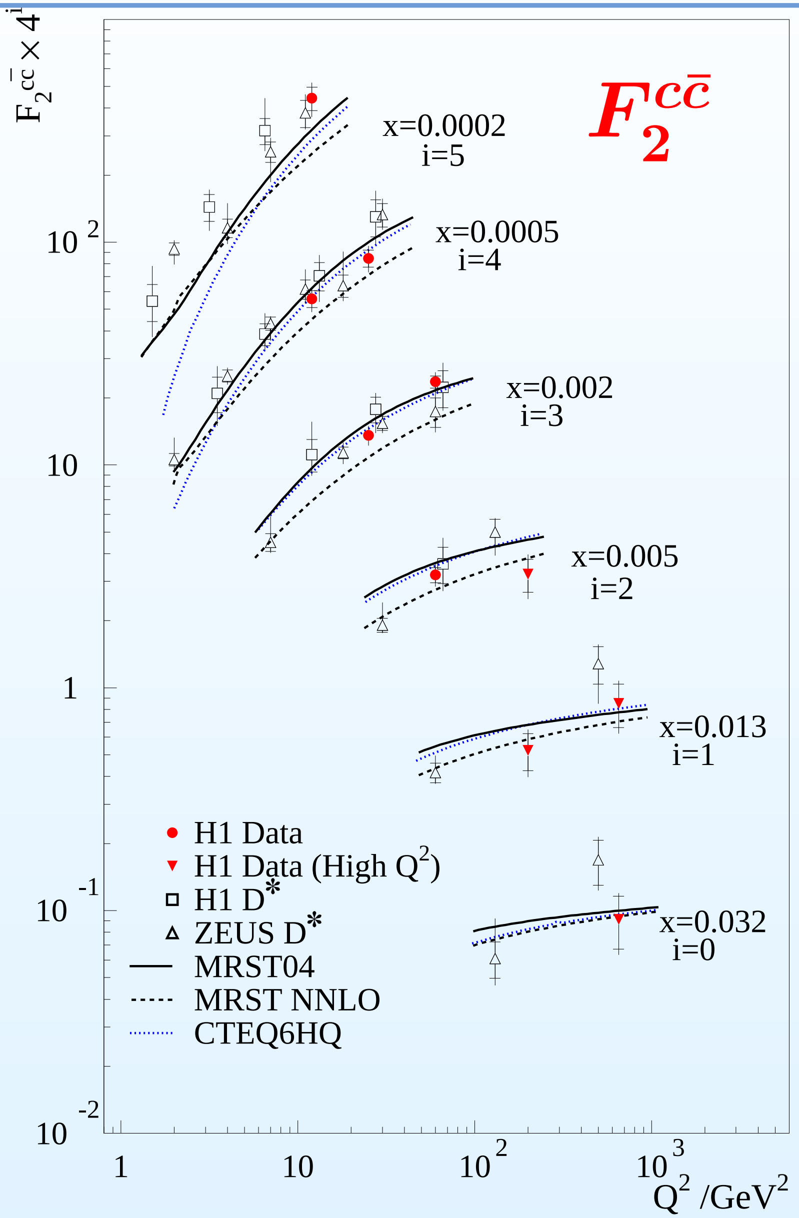


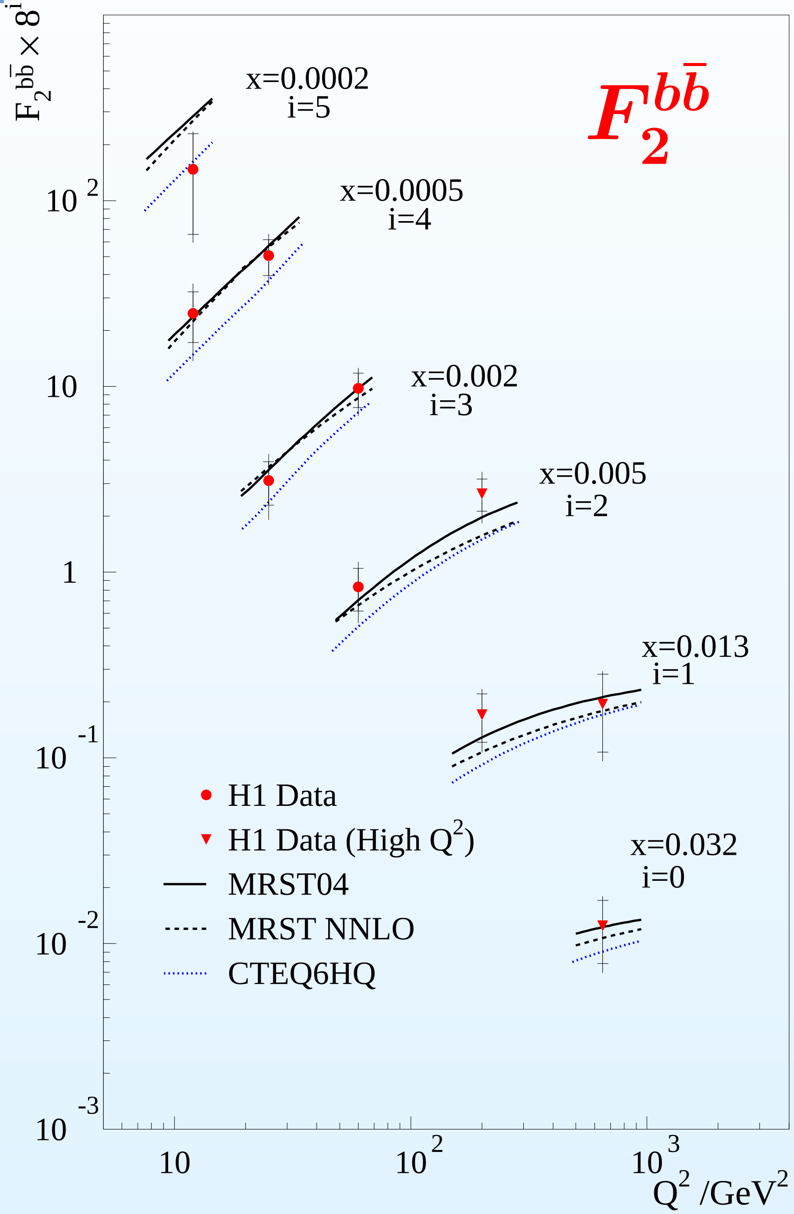
MRST04 - Variable FNS

CTEQ6HQ - Variable FNS

CCFM (Cascade) - Massive scheme

Scaling violation plots: $F_2^{q\bar{q}}$ vs Q^2



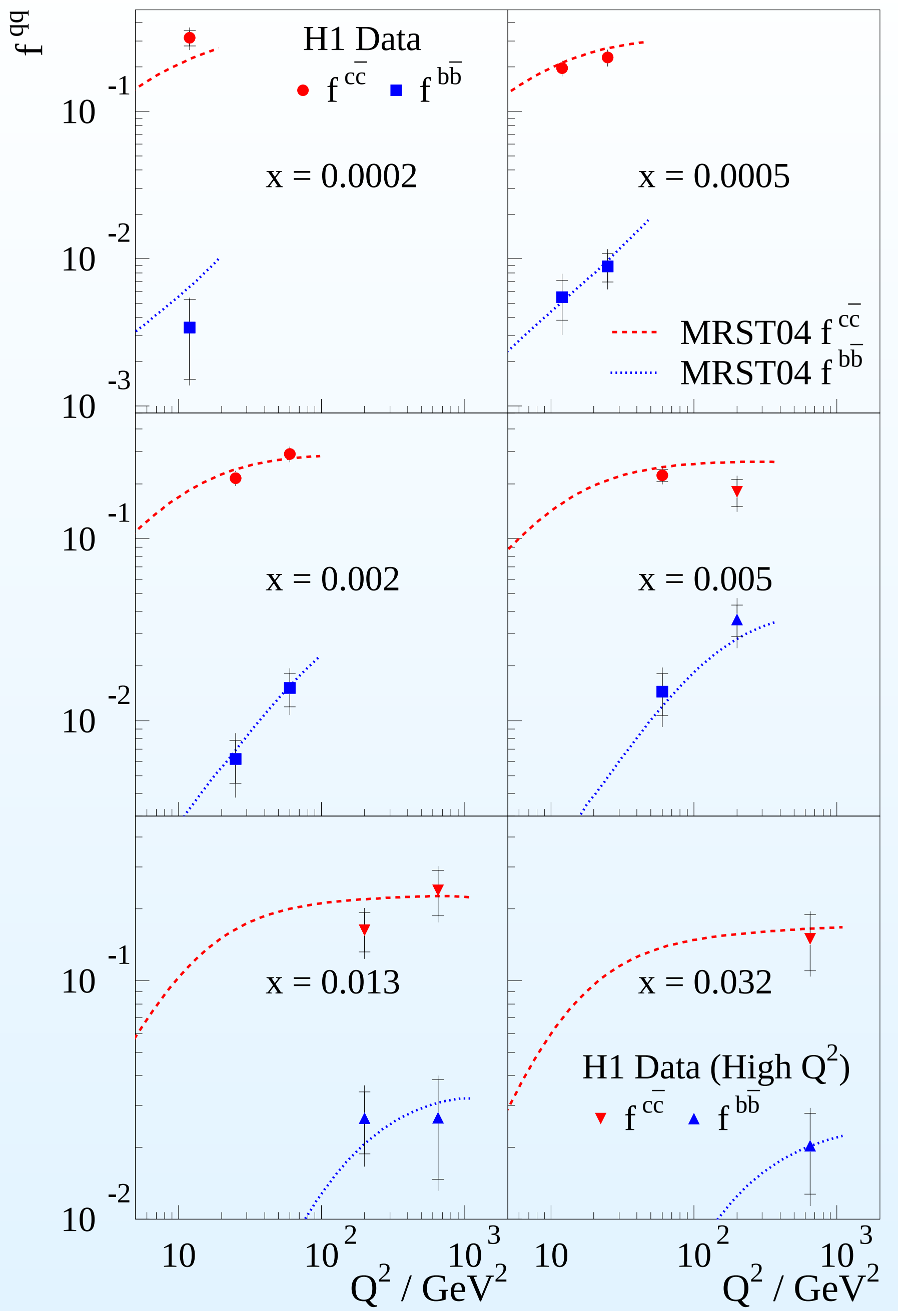


Contribution to inclusive σ

$$f^{q\bar{q}} = \frac{d\sigma^{q\bar{q}}/dx dQ^2}{d\sigma/dx dQ^2}$$

c and b fractions fall towards low Q^2
b fraction falls by a larger amount

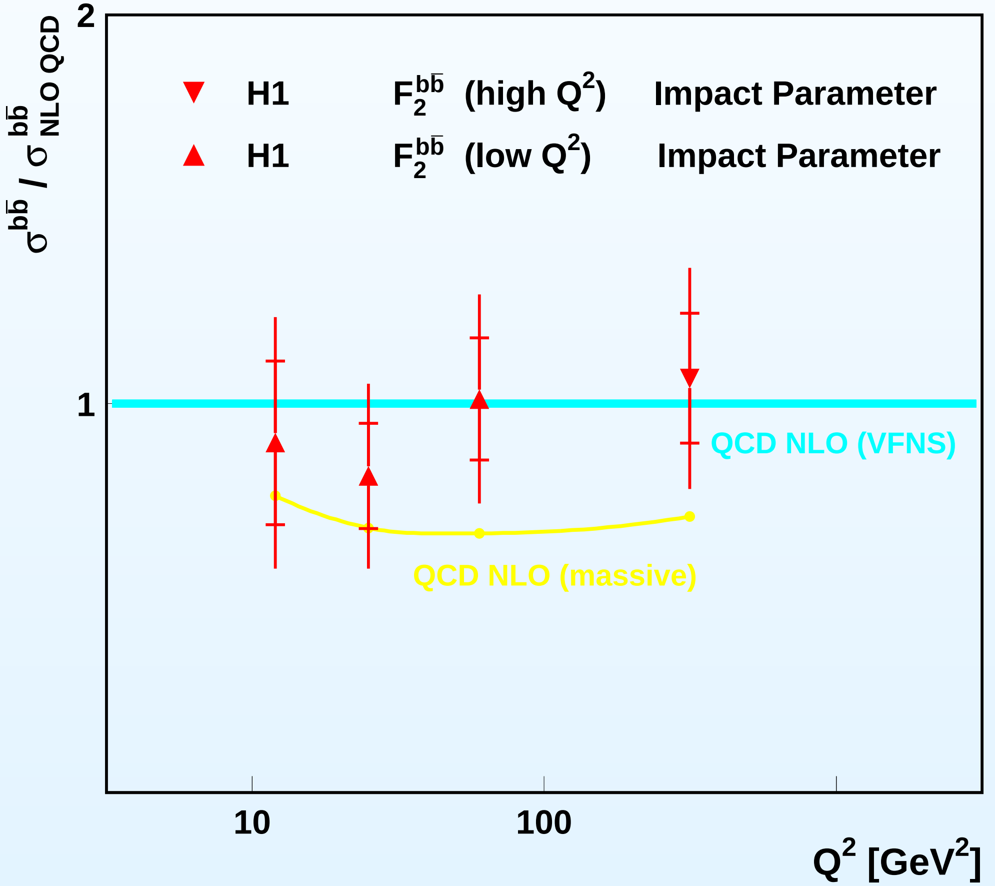
MRST04 - Variable FNS



Data vs Theory for $\sigma^{b\bar{b}}$

QCD NLO (VFNS): MRST

QCD NLO (massive): HVQDIS

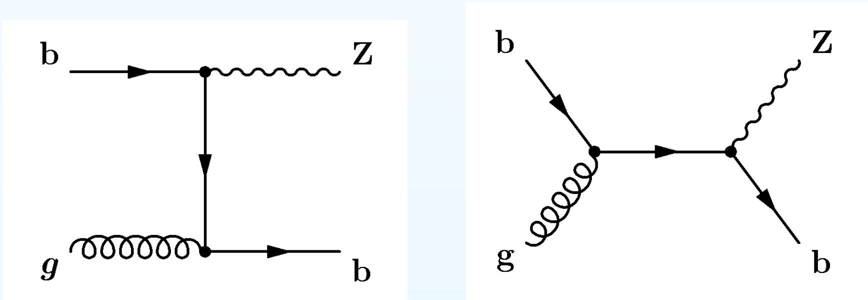


Measurements at Tevatron and LHC

Measurements at Tevatron

Tevatron: $p\bar{p}$ collisions; $\sqrt{s}$ = 1.96 TeV

Z + b-jet production



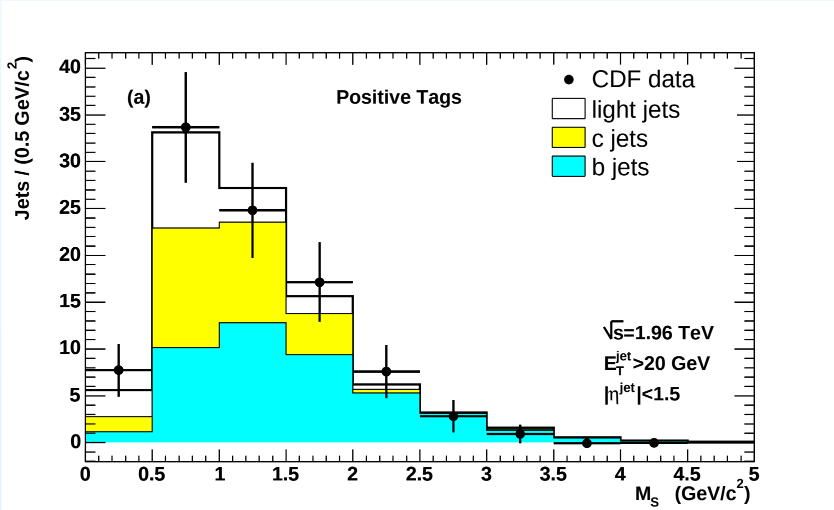
Cross section is sensitive to b PDF

Analysis is performed by D0 and CDF: hep-ex/0410078; hep-ex/0605099

Method (CDF):

- Select events with $Z \rightarrow e^+e^-$, $\mu^+\mu^-$
- Separate b-jets from others: based on template fit of the secondary vertex mass distributions
- E_T^{jet} $>$20 GeV, $|\eta^{jet}|$ $<$1.5

Mass at the secondary vertex



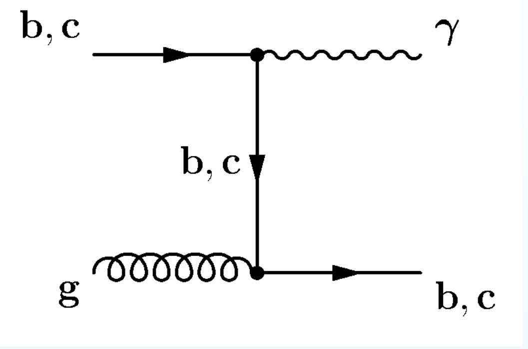
Measurements at Tevatron

CDF results (ICHEP 2006, K.Hatakeyama):

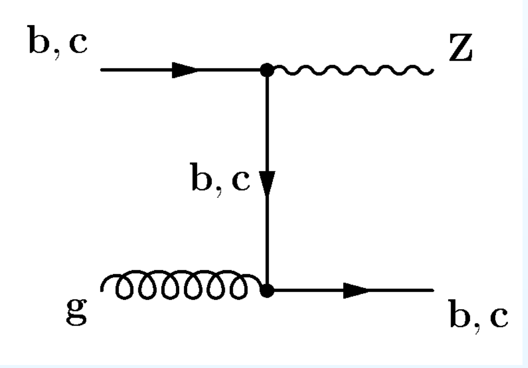
E_T^{jet}>20 GeV, $\lvert\eta^{jet}\rvert$<1.5 R_{jet}=0.7	CDF measurement	PYTHIA	NLO (MCFM, CTEQ6)
σ(Z+*b*-jet)	0.93 ± 0.29 ± 0.21 (pb)		0.45 ± 0.07 (pb)
σ(Z+*b*-jet)/ σ(Z)	0. 37 ± 0.11 ± 0.08 %	0.35 %	0.19 ± 0.03 %
σ(Z+*b*-jet)/ σ(Z+jet)	2.36 ± 0.74 ± 0.53 %	2.18 %	1.81 ± 0.27 %

Consistent with NLO within errors, however statistically limited.

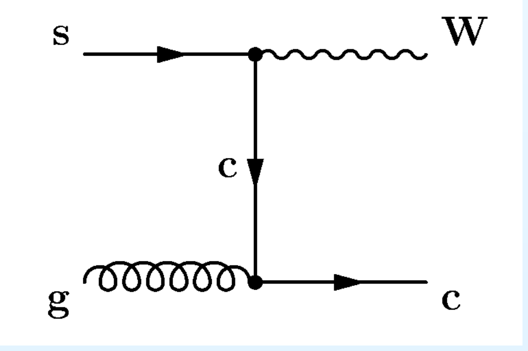
Future measurements at LHC



sensitive to c, b PDFs



sensitive to c, b PDFs



can constrain strange PDF

Conclusions

- HERA provides important input for LHC analyses
- The first measurement of $F_2^{b\bar{b}}$ in the low and high Q^2 kinematic regime
- $F_2^{c\bar{c}}$ and $F_2^{b\bar{b}}$ are well described by predictions of perturbative QCD calculations
- Average contribution to the inclusive ep cross section:

	Low Q^2	High Q^2
Charm	24%	18%
Beauty	0.8%	2.7%

Outlook

- Increased statistics using HERA II data
- ZEUS has vertex detector MVD since HERA II
- HERA is taking lumi till middle 2007

INTEGRATED LUMINOSITY (29.11.06)