Measurement of $F_2^{c\bar{c}}$ and $F_2^{b\bar{b}}$ at Low and High Q^2 at H1

Tatsiana Klimkovich

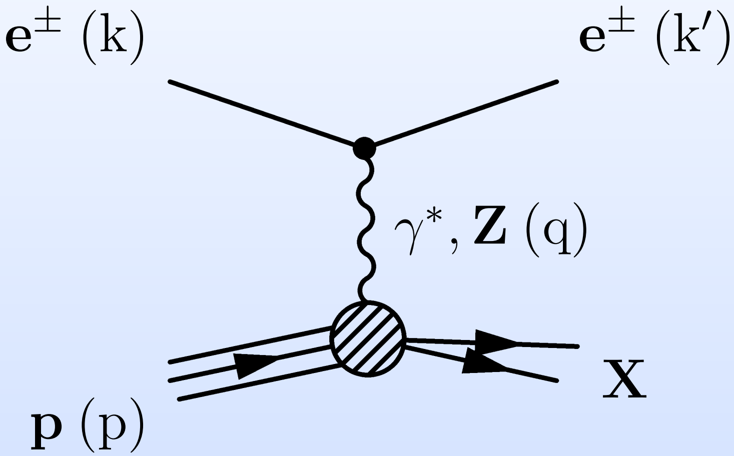
DESY, FLC, H1

Contents

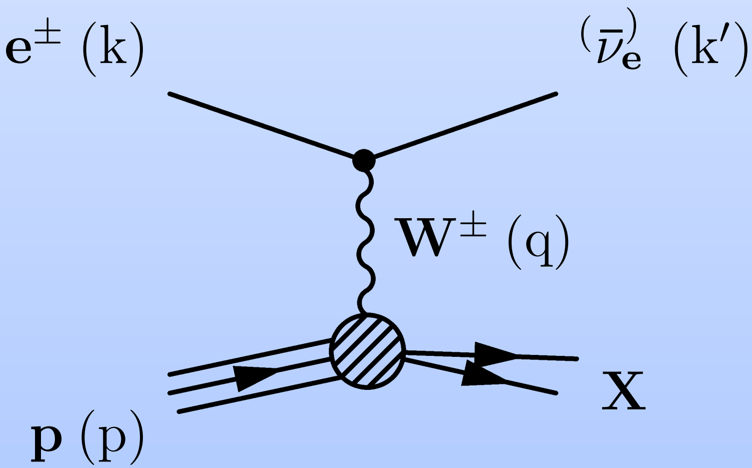
- Heavy Flavour Production in Perturbative QCD
- H1 Experiment at HERA
- Motivation for the Analysis
- Inclusive Method of Heavy Quark Measurement using simple c- and b-tagging
- Measurement of $F_2^{c\bar{c}}$ and $F_2^{b\bar{b}}$ at Low and High Q^2

Kinematics of ep Collisions

Neutral Current



Charged Current



Lorentz-Invariant Variables:

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

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

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

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

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

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

$$\mathbf{Q^2 = xys}$$

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):

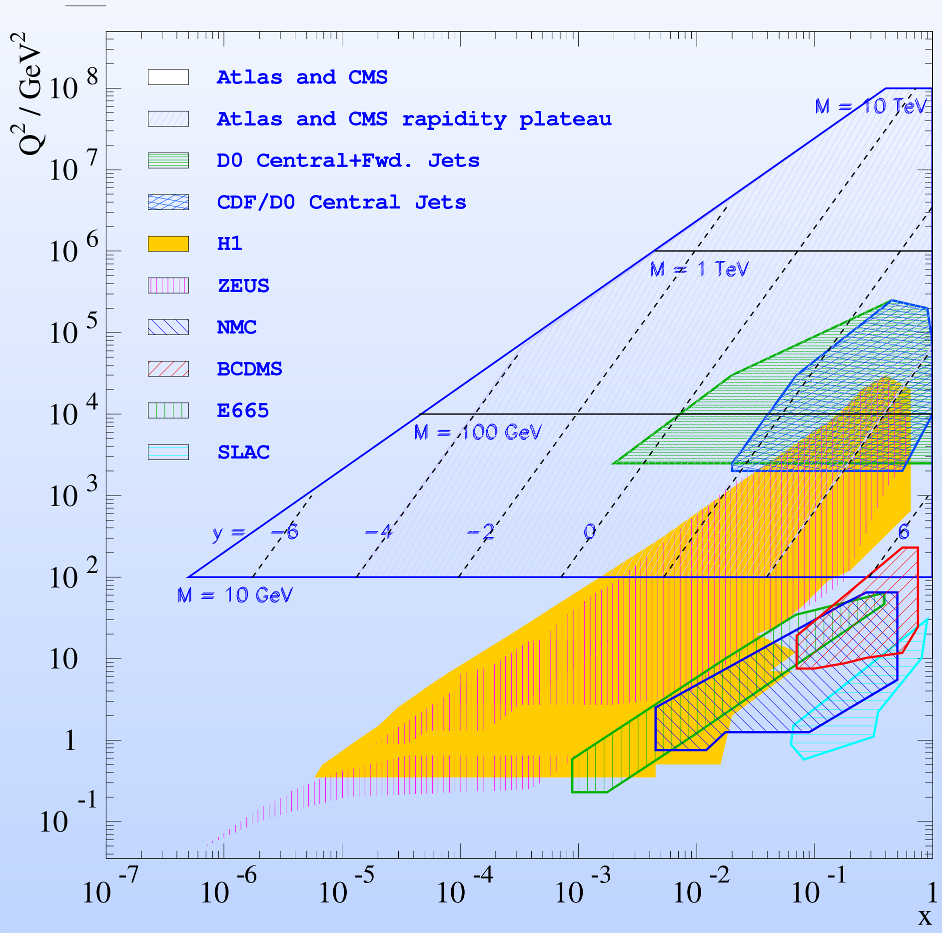
1 GeV$^2 < Q^2 < 100$ GeV^2

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



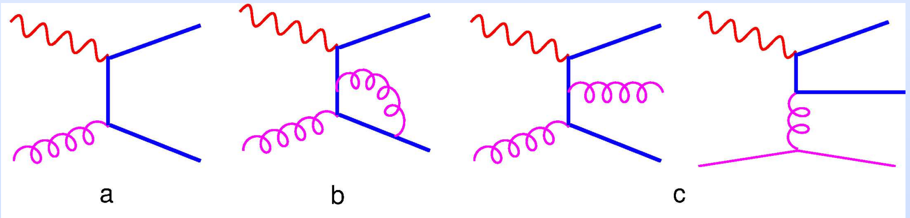
Heavy Flavour Production in Deep Inelastic Scattering

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

"Massive scheme"

Fixed Flavour Number Scheme (FFNS)

LO Process: PGF process



Quarks are treated like massive

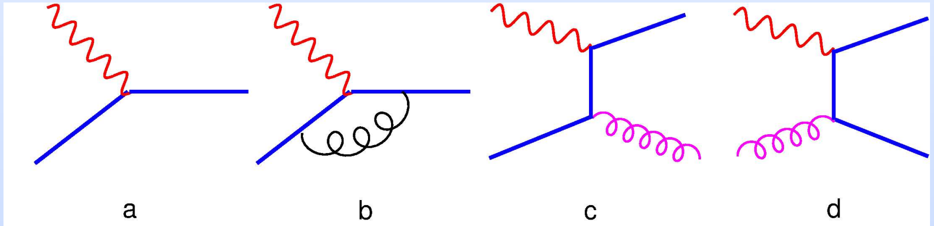
$\Longrightarrow$ **do not contribute to proton structure function**

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

"Massless scheme"

Zero Mass Variable Flavour Number Scheme (ZM-VFNS)

LO Process: QPM process (flavour excitation)



Quarks are treated like massless partons

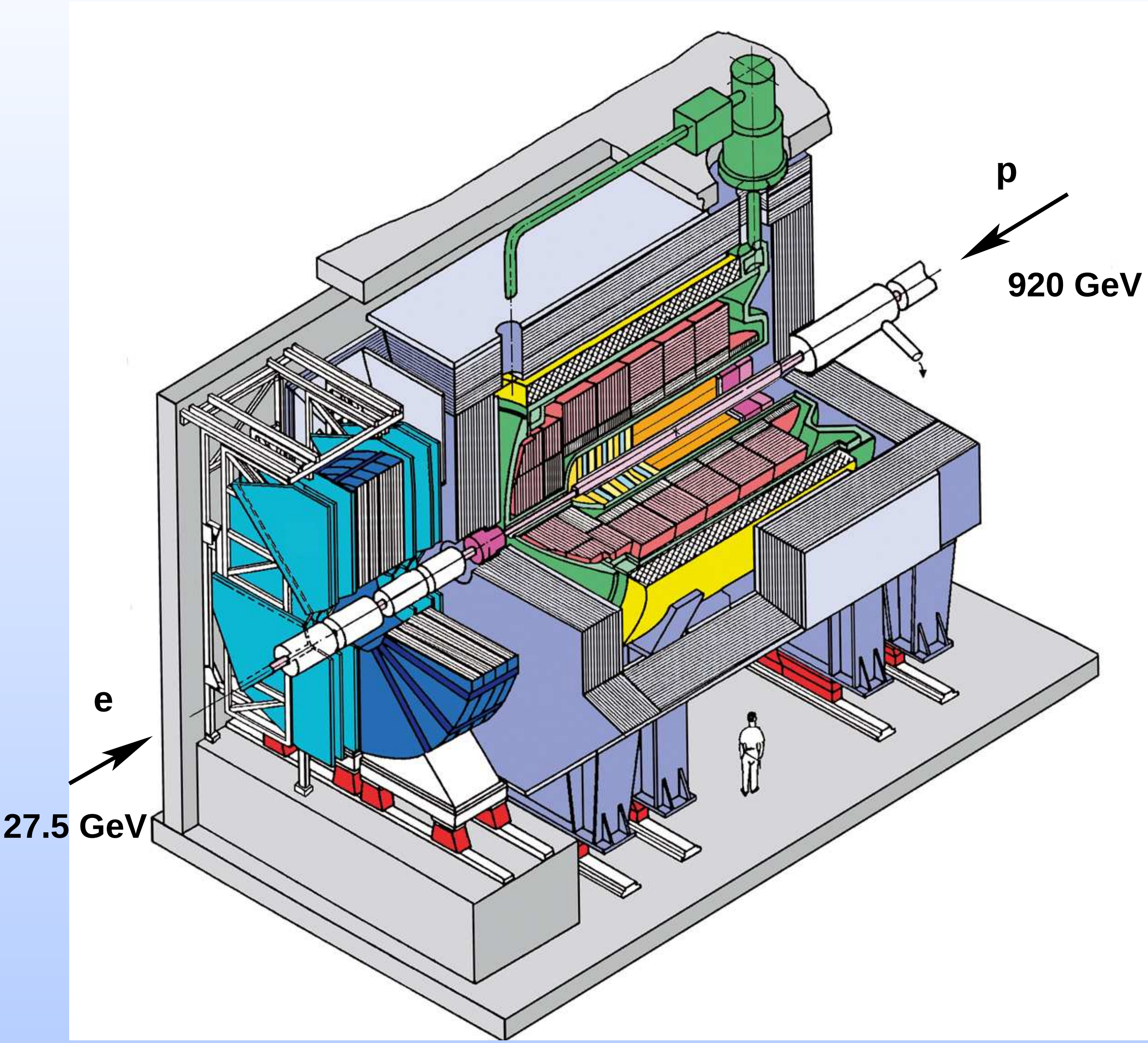
$\Longrightarrow$ **contribute to proton structure function**

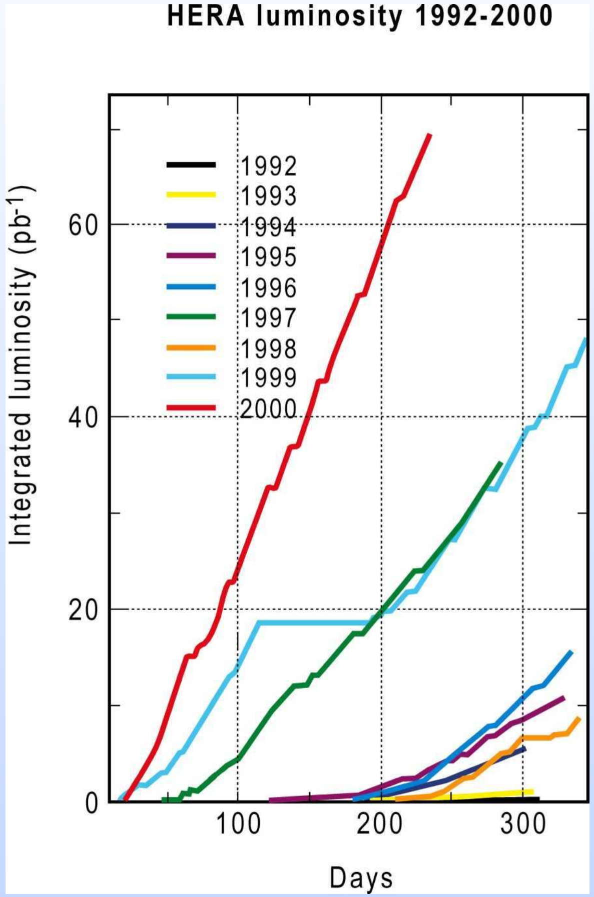
Do not give reliable description over the whole Q^2 range

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

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

H1 Detector



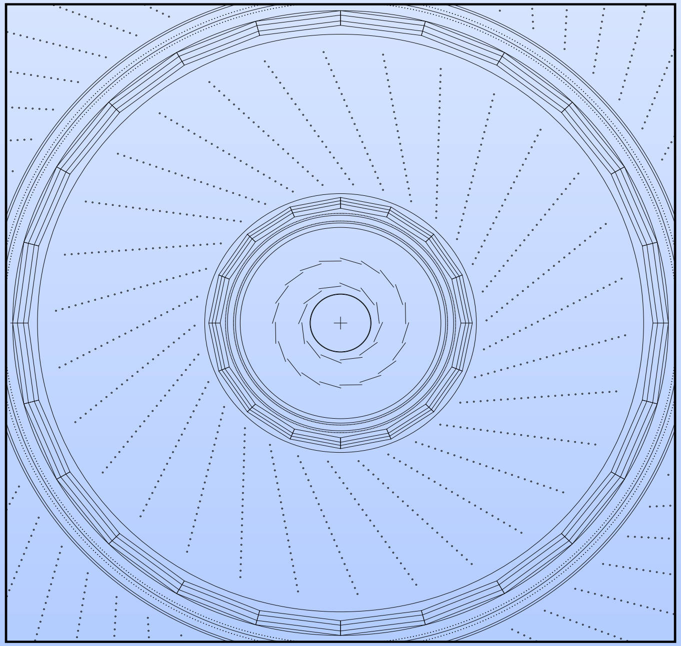


e^+p NC 99/2000 HERA-I data

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

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

H1 Central Silicon Tracker



- 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: $33\mu m \oplus \frac{90\mu m}{p_T}$ [GeV]
- The efficiency to link 2 CST hits to a CTD track: 76%

Motivation for Analysis

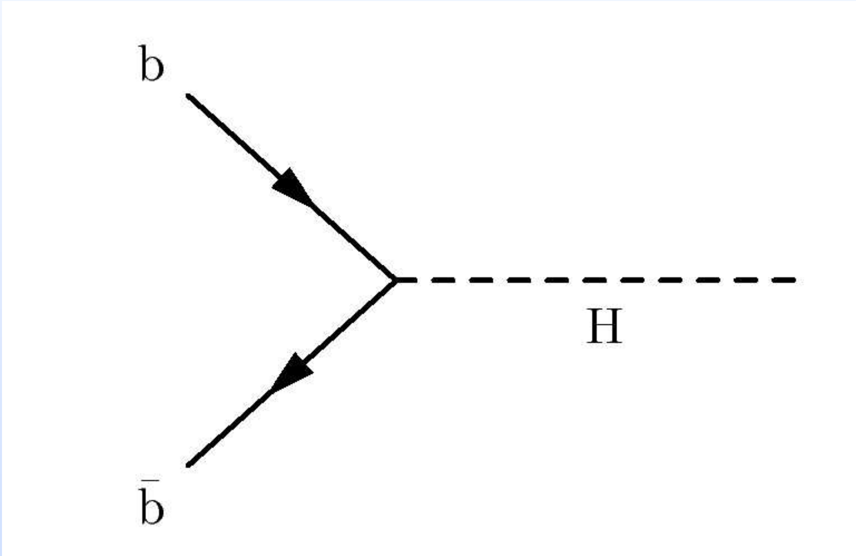
- Aim: to make a measurement of charm and beauty
  - in transition region $Q^2 \sim M^2_{HQ}$: $6.3 < Q^2 < 120$ GeV^2
  - in high Q^2 region: $Q^2 > 110$ GeV^2
- Existing Methods:
  - D^*
  - μ

  } exclusive methods
  - 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

Motivation for the Analysis

Higgs Production via Quark Fusion at the LHC



SM cross section is small due to low Yukawa coupling

Can be enhanced in MSSM (h, H, A, $H^{\pm}$)

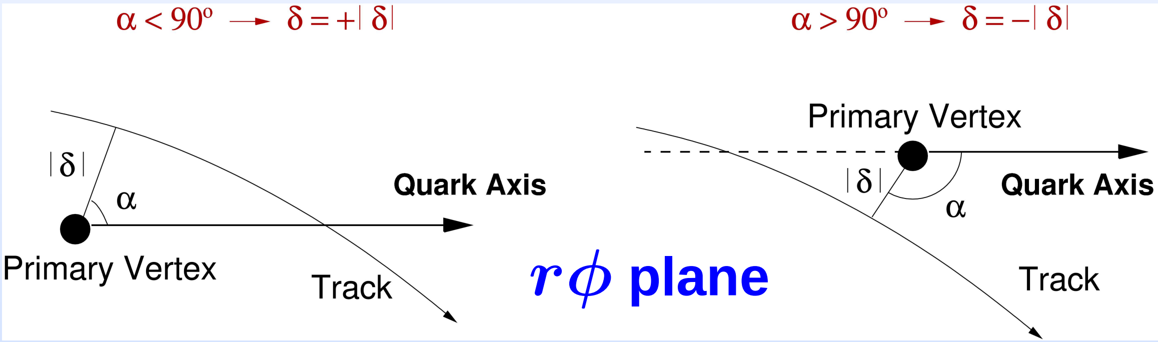
$\Longrightarrow$ **knowledge of beauty PDF at the scale $Q = m_H/2$ or $Q = m_H/4$ is important!**

This is high Q^2 region at HERA

- **Low Q^2: measurement of c and b PDFs are important to check the validity of the theoretical descriptions of heavy quark production around the threshold region $Q^2 \sim M_{HQ}^2$**

Technique

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



- **The sign is infered from a quark axis approximating the flight 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 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:

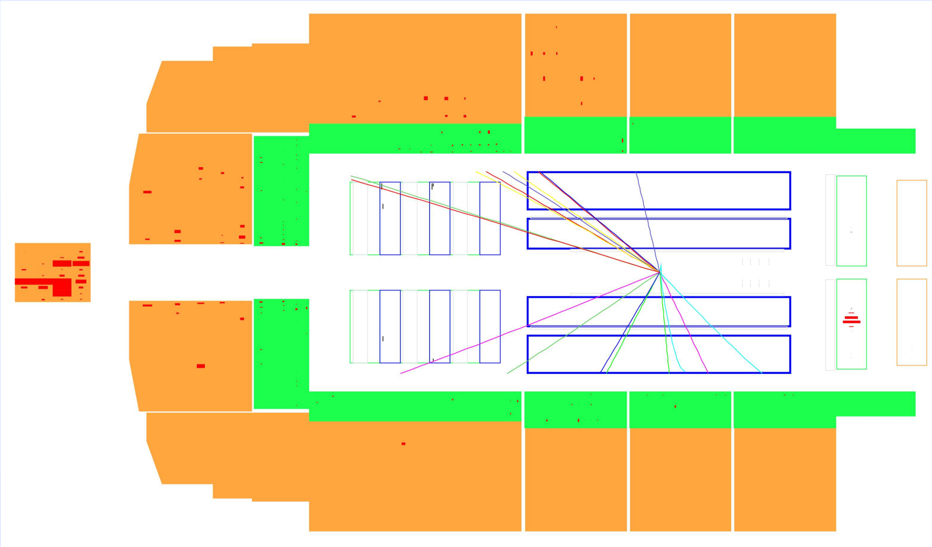
Sample	Program	Fragmentation	L [pb^{-1}]
uds	DJANGO	LUND	90
$c\bar{c}$	RAPGAP	LUND	162.9
$b\bar{b}$	RAPGAP	LUND	981.3
$c\bar{c}$	RAPGAP	Peterson	124.54
$b\bar{b}$	RAPGAP	Peterson	969.05
$c\bar{c}$	CASCADE	LUND	124.6
$b\bar{b}$	CASCADE	LUND	671.53
γp	PHOJET	LUND	2.576

Event Selection

We require:

- e^+ **in SpaCal**
- $6.3 < Q^2 < 120\ \mathrm{GeV}^2$
- $y_{e\Sigma} > 0.07$
  $y_e < 0.63$ **for** $Q^2 < 18\ \mathrm{GeV}^2$
  $y_e < 0.7$ **for** $Q^2 > 18\ \mathrm{GeV}^2$
- **-20 cm** $< z_{vertex} <$ **20 cm**
- $\sum_i (E_i - p_{z,i}) > 35\ \mathrm{GeV}$
  (against γp and ISR)
- $R_e <$ **4 cm**
- **0** $< R_{BDC-SPACAL} <$ **2.5 cm**
- **Inclusive Triggers**

Low Q^2 Event in H1 detector

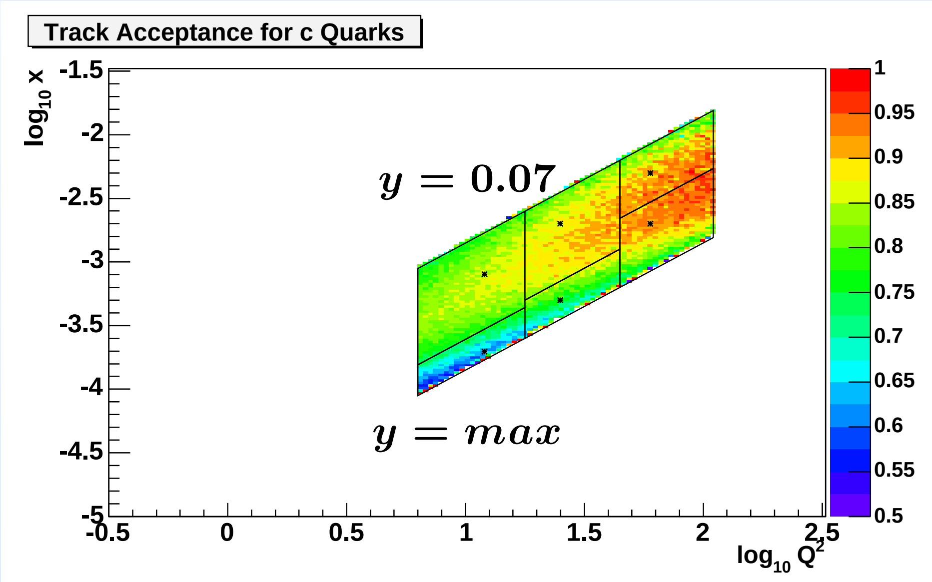


High Q^2: $Q^2 > 110$ GeV^2, e^+ in LAr

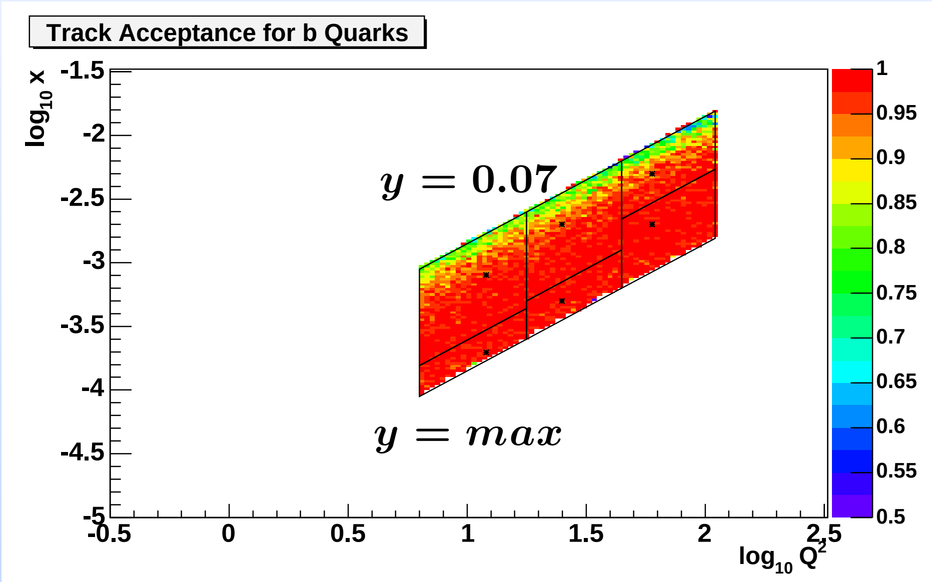
Track Acceptance (low Q^2)

Acceptance for a charged track from c, b hadrons to be in CST acceptance ($30^\circ < \theta < 150^\circ$, $p_T > 0.5$ GeV) and generated z-vertex within ± 20 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** $Q^2 < 17.78\ \mathrm{GeV}^2$
  $y_{max} = 0.7$ **for** $Q^2 > 17.78\ \mathrm{GeV}^2$

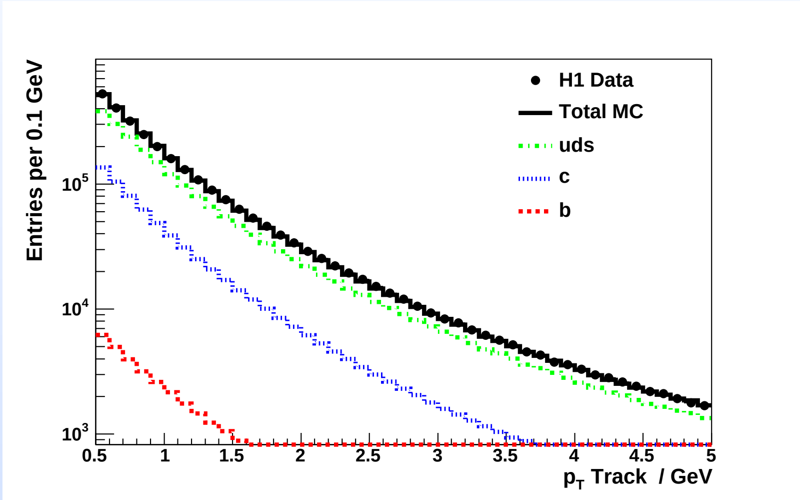
CST Track Selection

Track reconstruction imrovement:

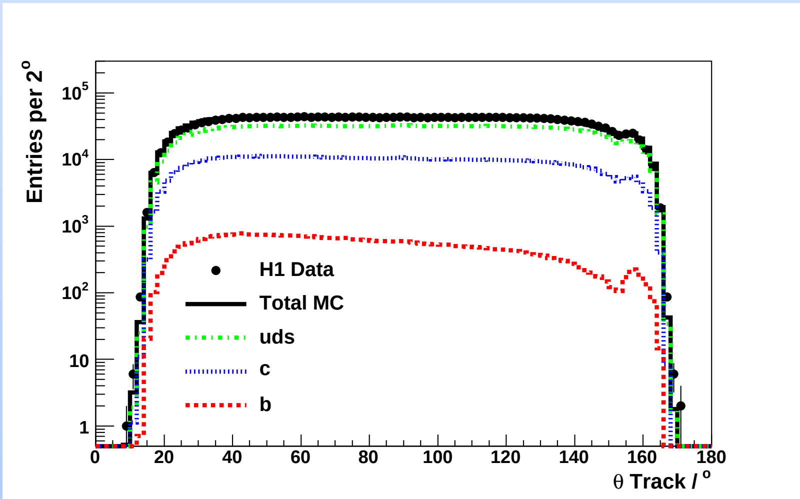
CJC tracks are linked to CST hits (CST tracks)

- $N_{CST} > 1$
- Prob$_{link} > 0.1$
- $p_T >$ 500 MeV
- $R_{start} <$ 50 cm
- $L_{track} >$ 10 cm
- -18 $< z_{CST\ hits} <$ 18 cm

p_T of Tracks



θ 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)

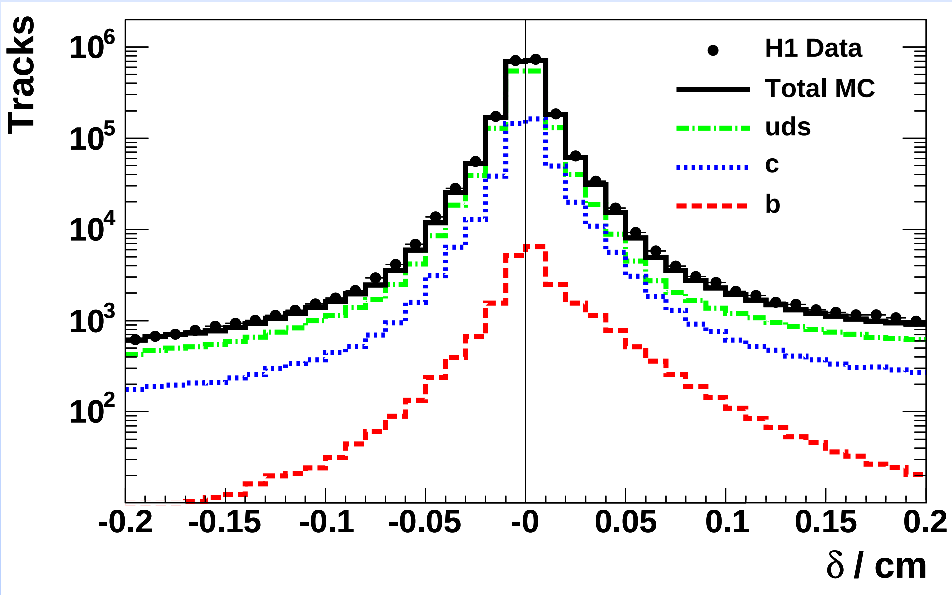
- **If we don't have jets:**

  Quark axis is approximated by $180^\circ - \phi_{\mathrm{elec}}$

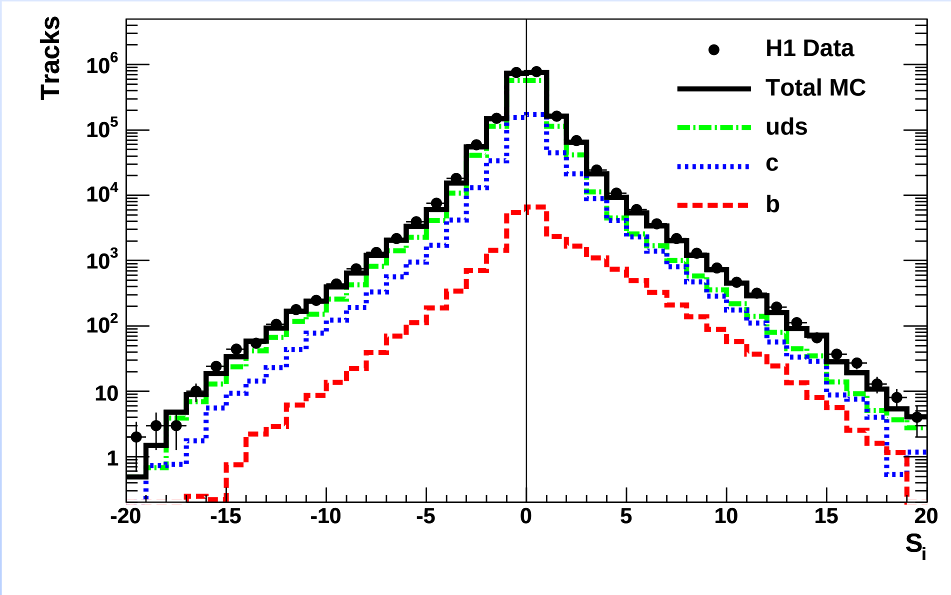
DCA and Significance

- 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

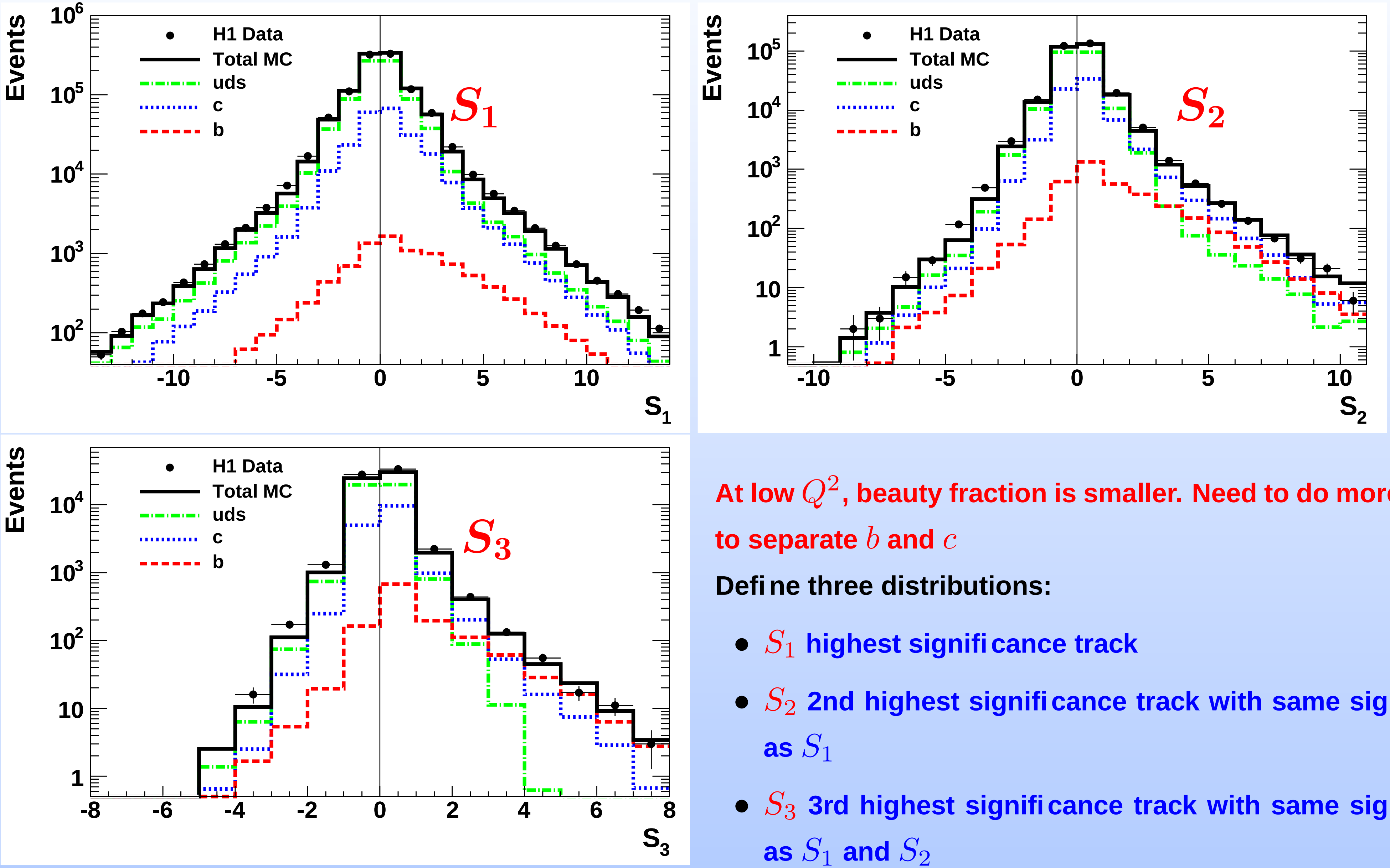


Significance



Scale factors to the MC distributions are applied

Significance (S_i) Definition



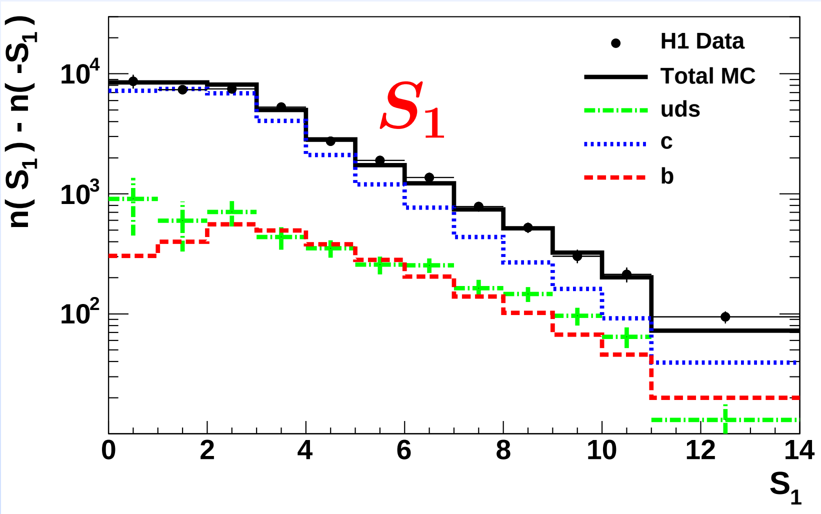
At low Q^2, beauty fraction is smaller. Need to do more to separate b and c

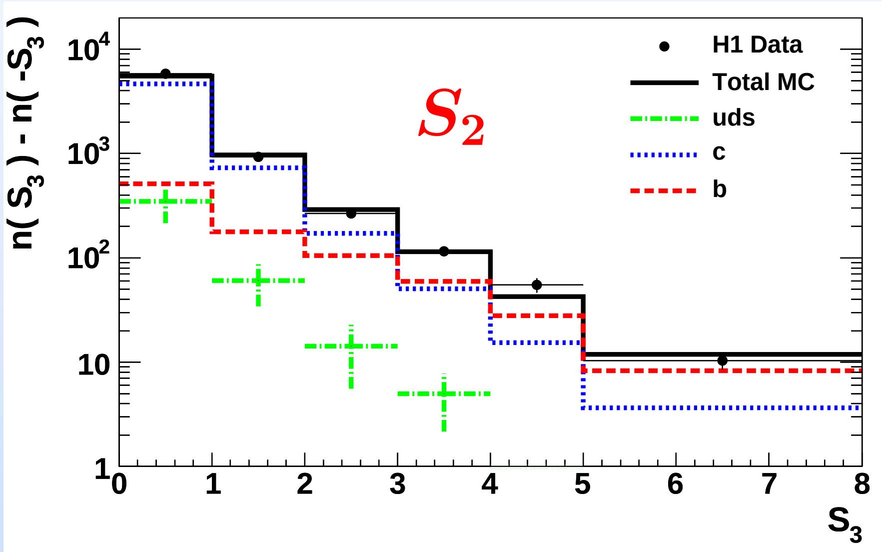
Define three distributions:

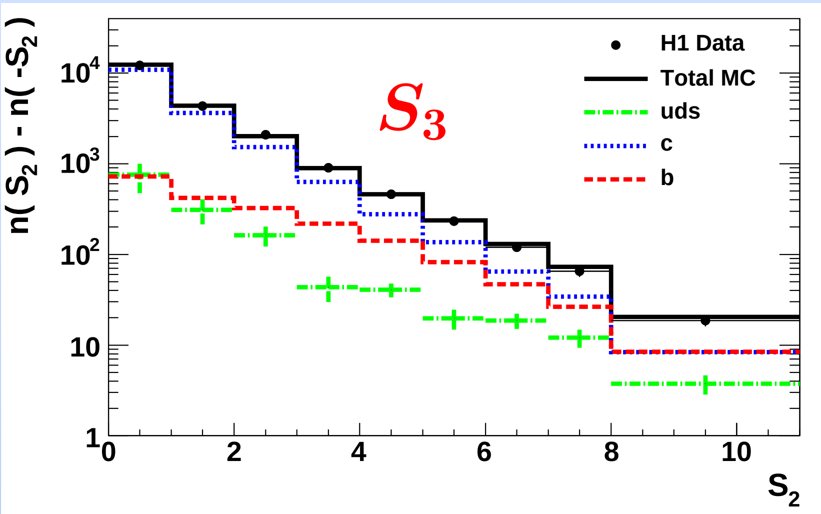
- S_1 highest significance track
- S_2 2nd highest significance track with same sign as S_1
- S_3 3rd highest significance track with same sign as S_1 and S_2

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

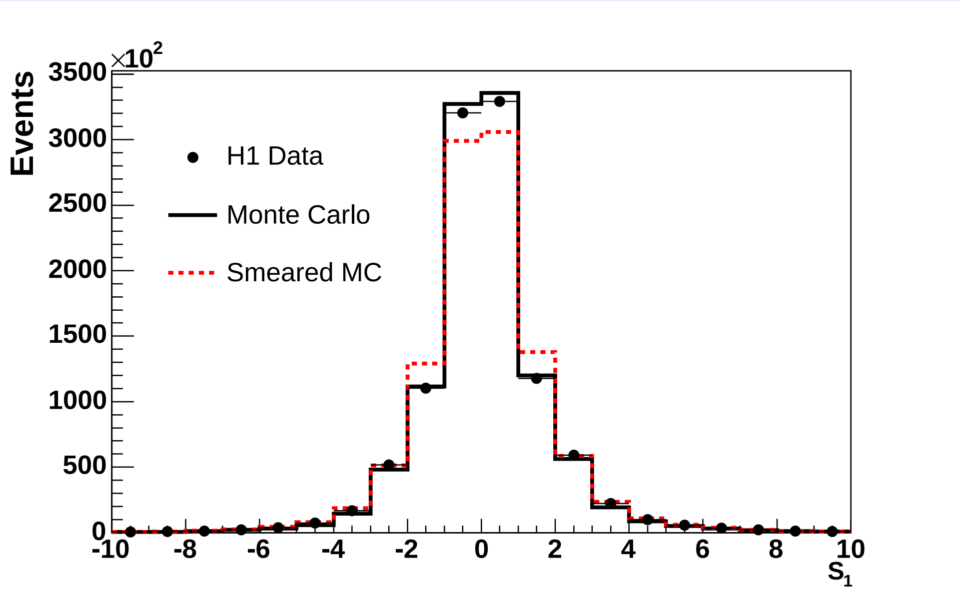
Systematic Errors (low Q^2)

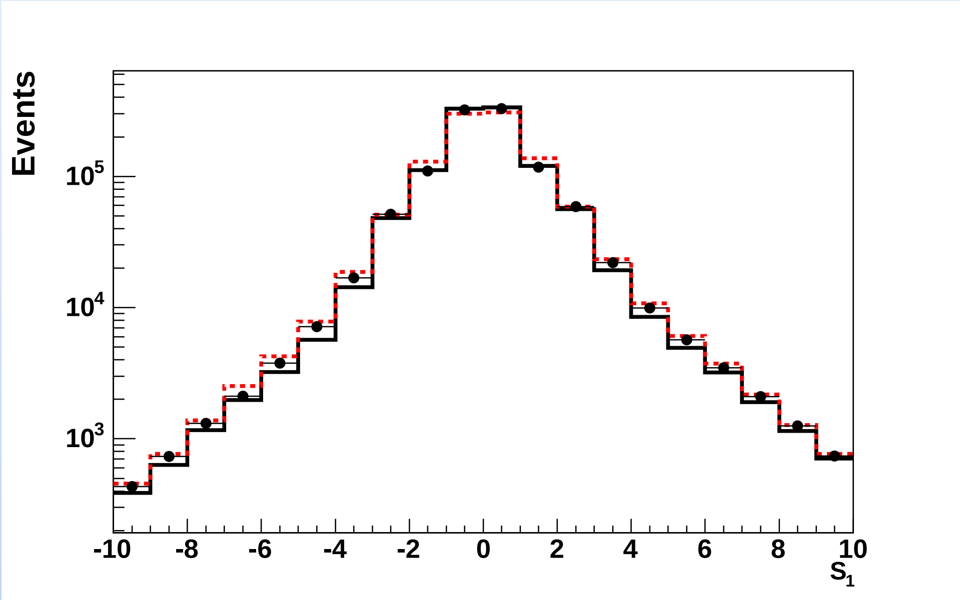
source	uncertainty	error $c\bar{c}$ / %	error $b\bar{b}$ / %
Track efficiency	± 2.23 (2% CJC, 1% CST)	1.4-1.7	8-10
DCA resolution	$\pm 25\mu m$ ($\pm 200\mu m$ tails)	2.5-3.2	13-21
s asymmetry	50% uncertainty	5.0-5.2	4.7-7.7
Fragmentation	LUND / Peterson	0.4-0.7	4.6-6.9
QCD model	Rapgap/CASCADE	1.9-2.2	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	$2^{\circ}(5^{\circ})$ 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

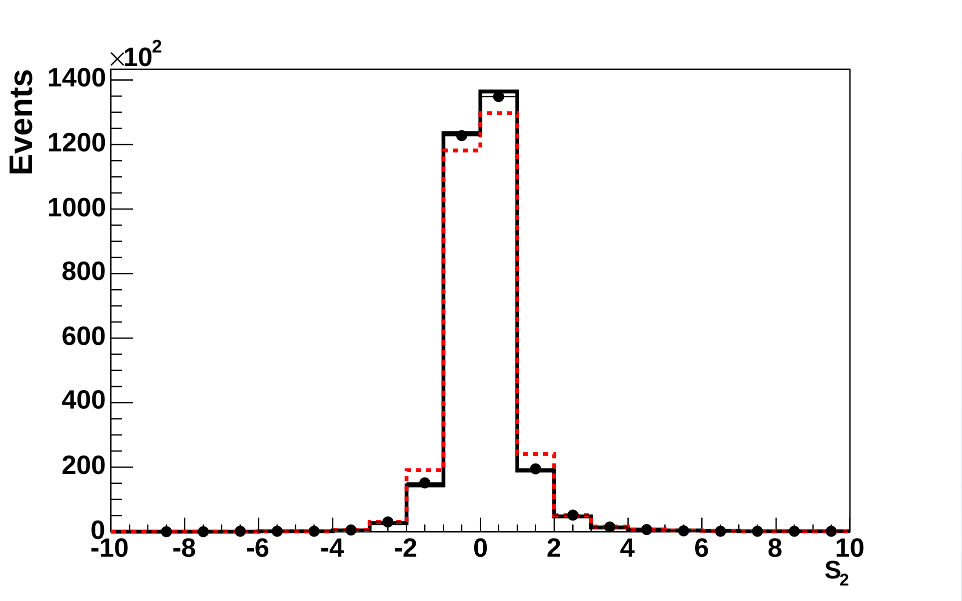
95% of events smeared by 25 μm, 5% of events smeared by 200 μm

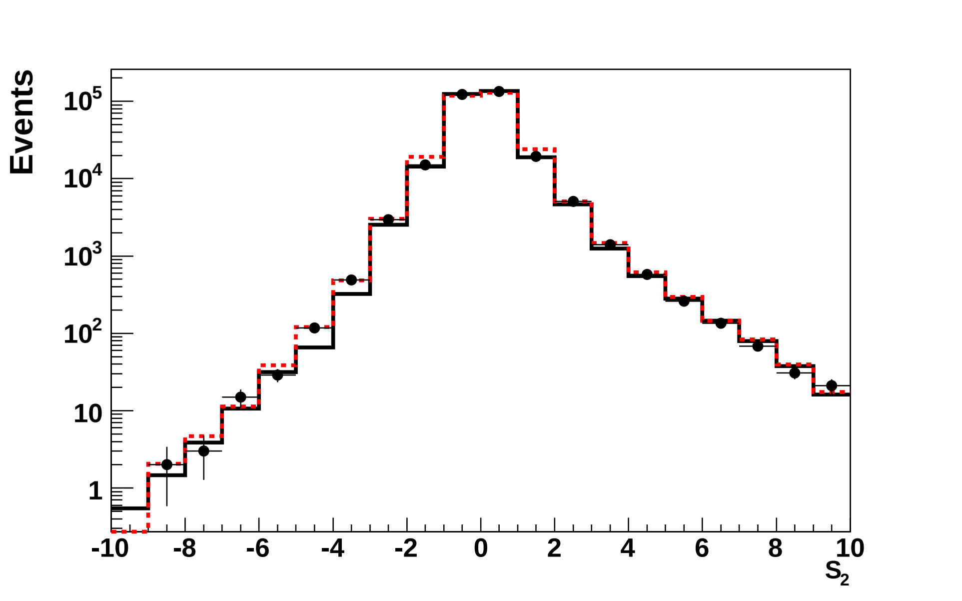




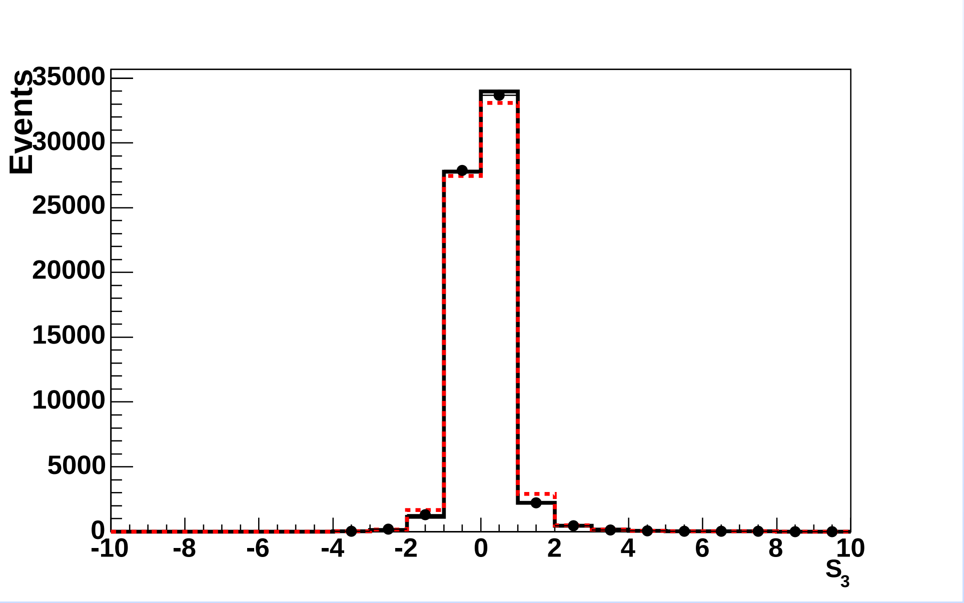
Normalised MC before (after) smearing black (red)

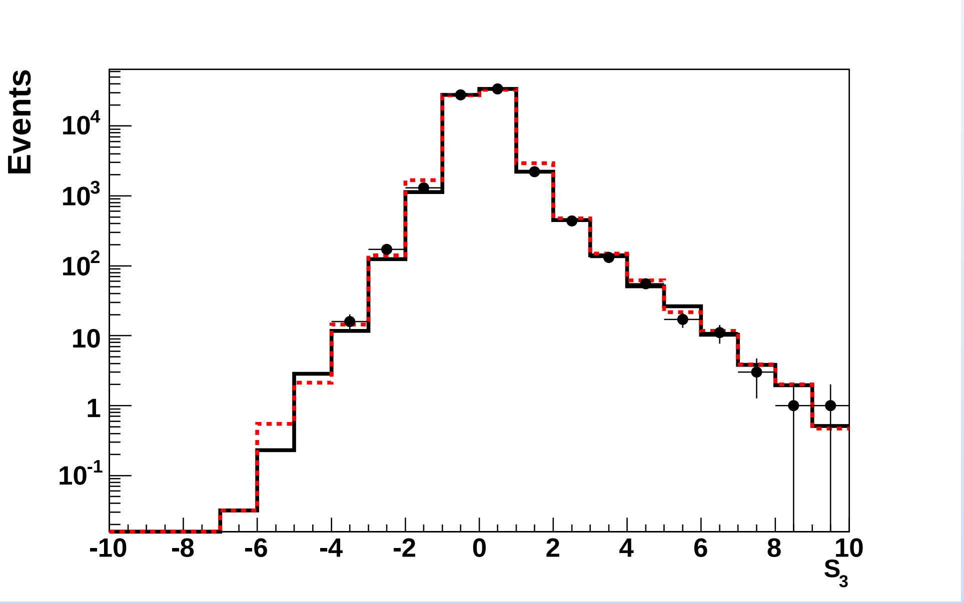
DCA resolution for S_2





DCA resolution for S_3



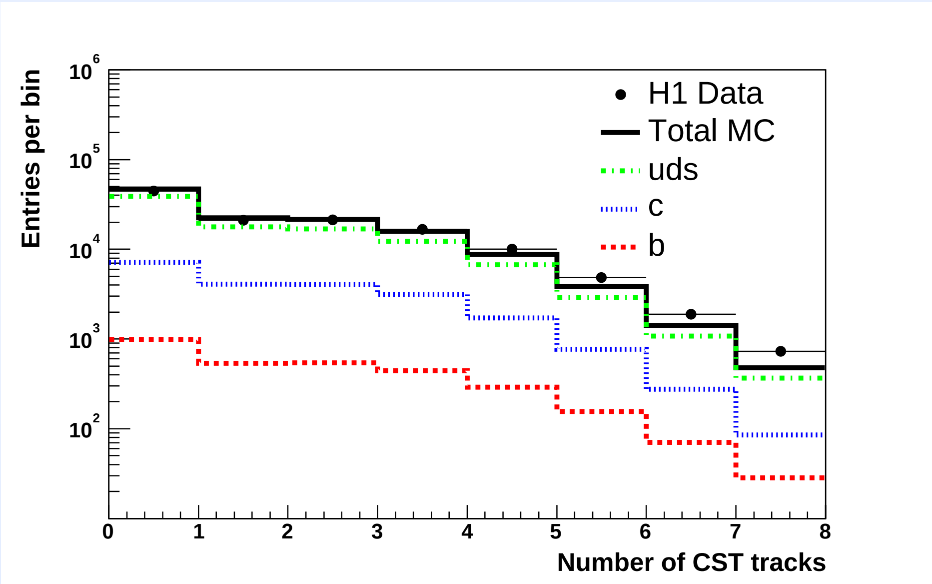


Description of Light Quark Multiplicity

Can contribute to systematic errors

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

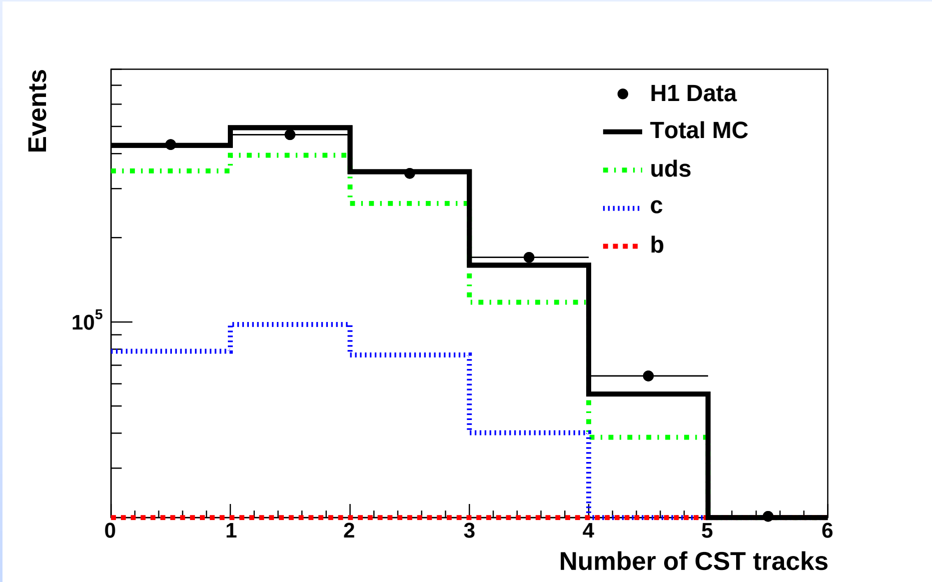
High Q^2



uds MC: Rapgap

$c\bar{c}$, $b\bar{b}$ MC: Rapgap

Low Q^2

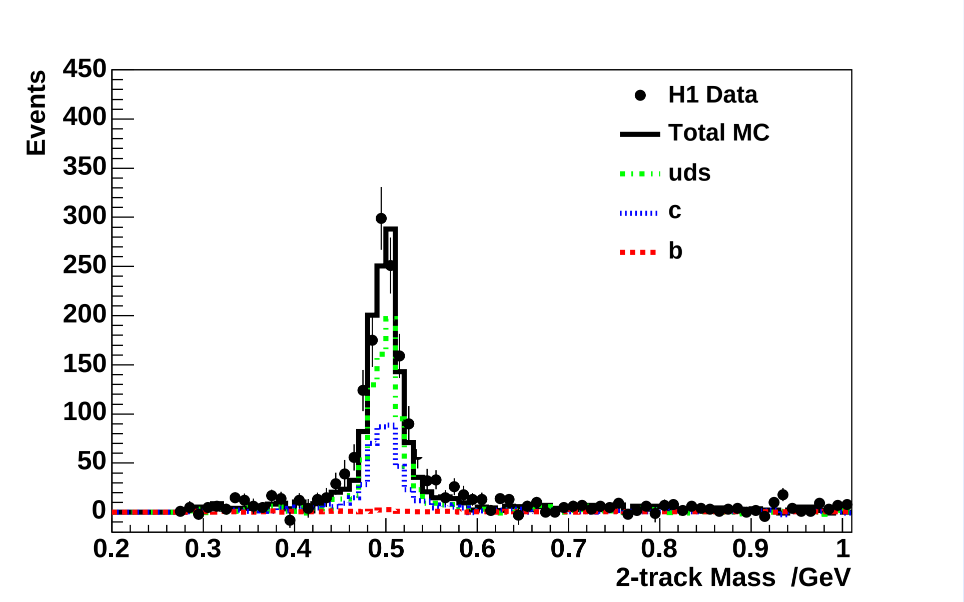


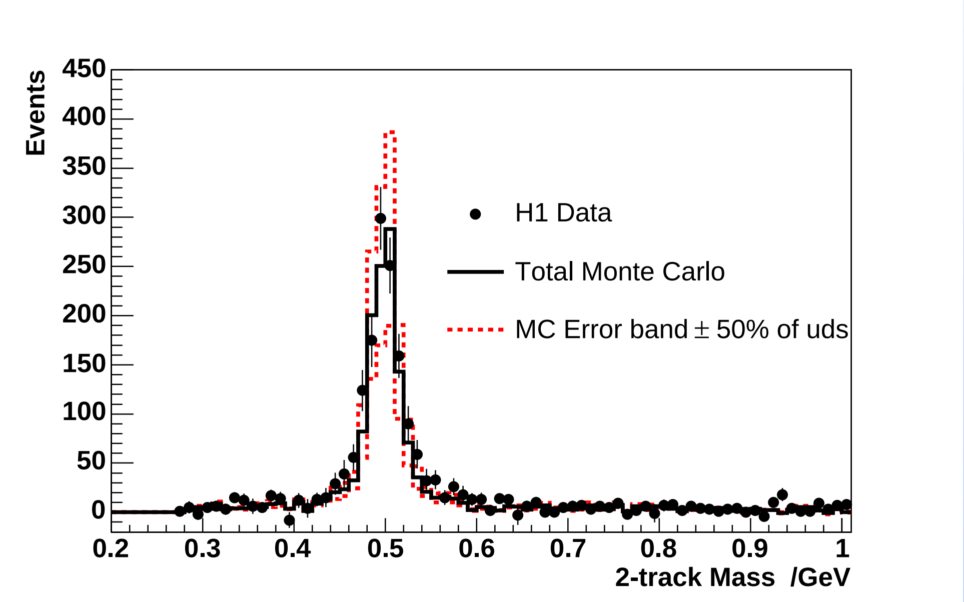
uds MC: Django

$c\bar{c}$, $b\bar{b}$ MC: 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 $\tilde{\sigma}^{c\bar{c}}$

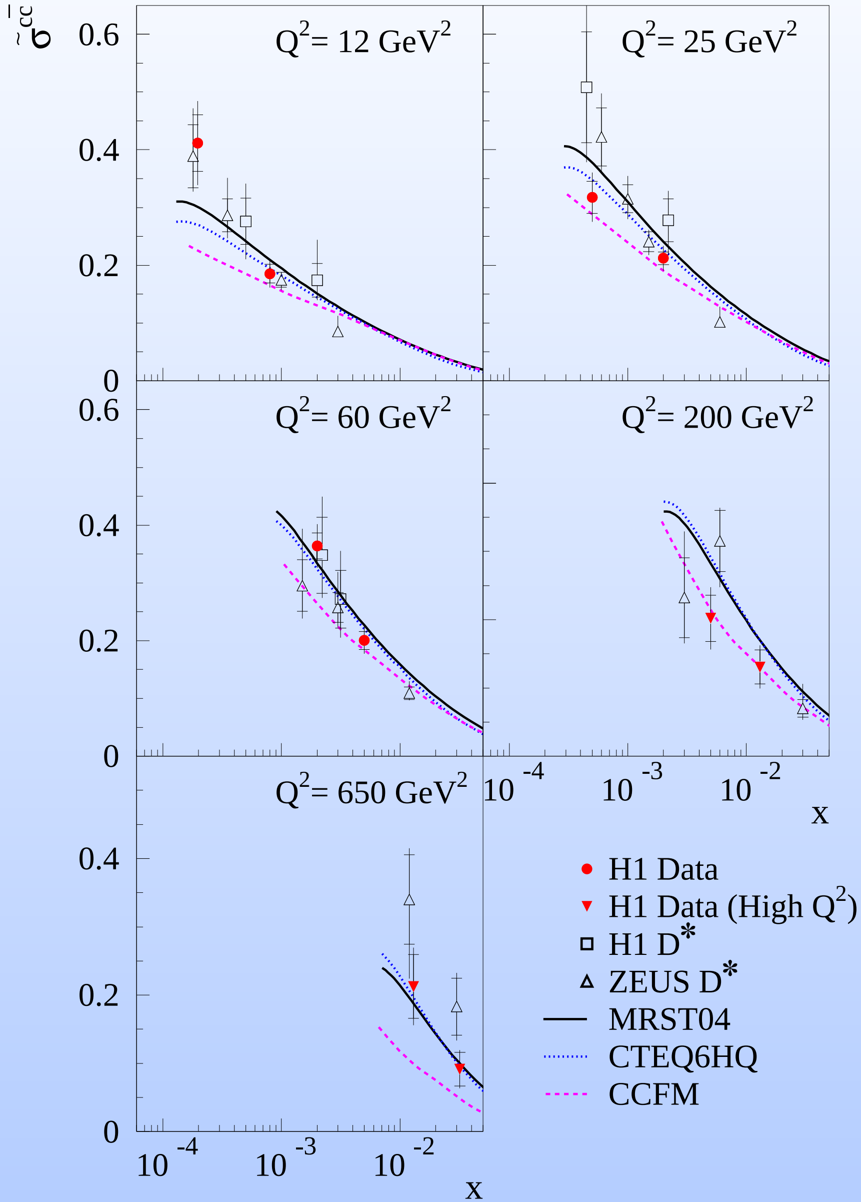
$\tilde{\sigma}^{c\bar{c}}$

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

MRST04 - Variable FNS

CTEQ6HQ - Variable FNS

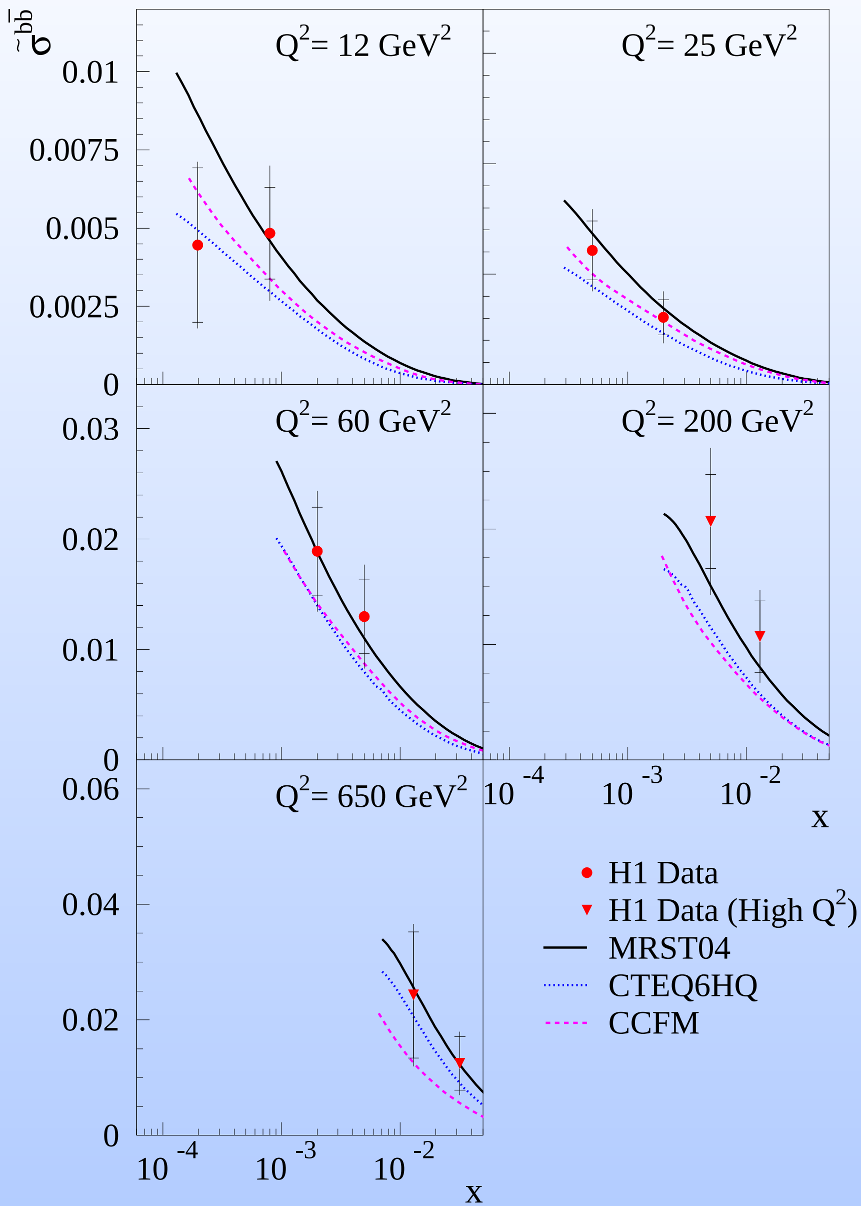
CCFM (Cascade) - Massive scheme



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**

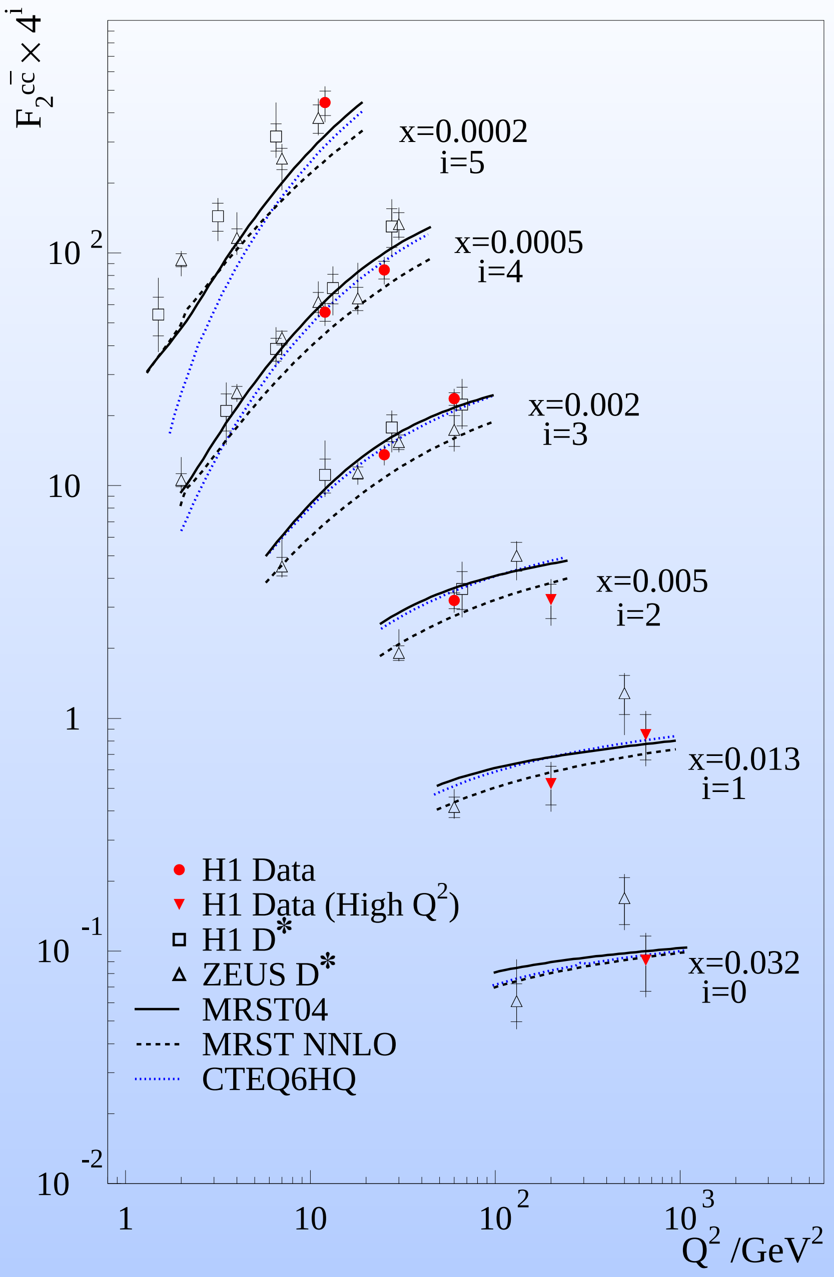


MRST04 - Variable FNS

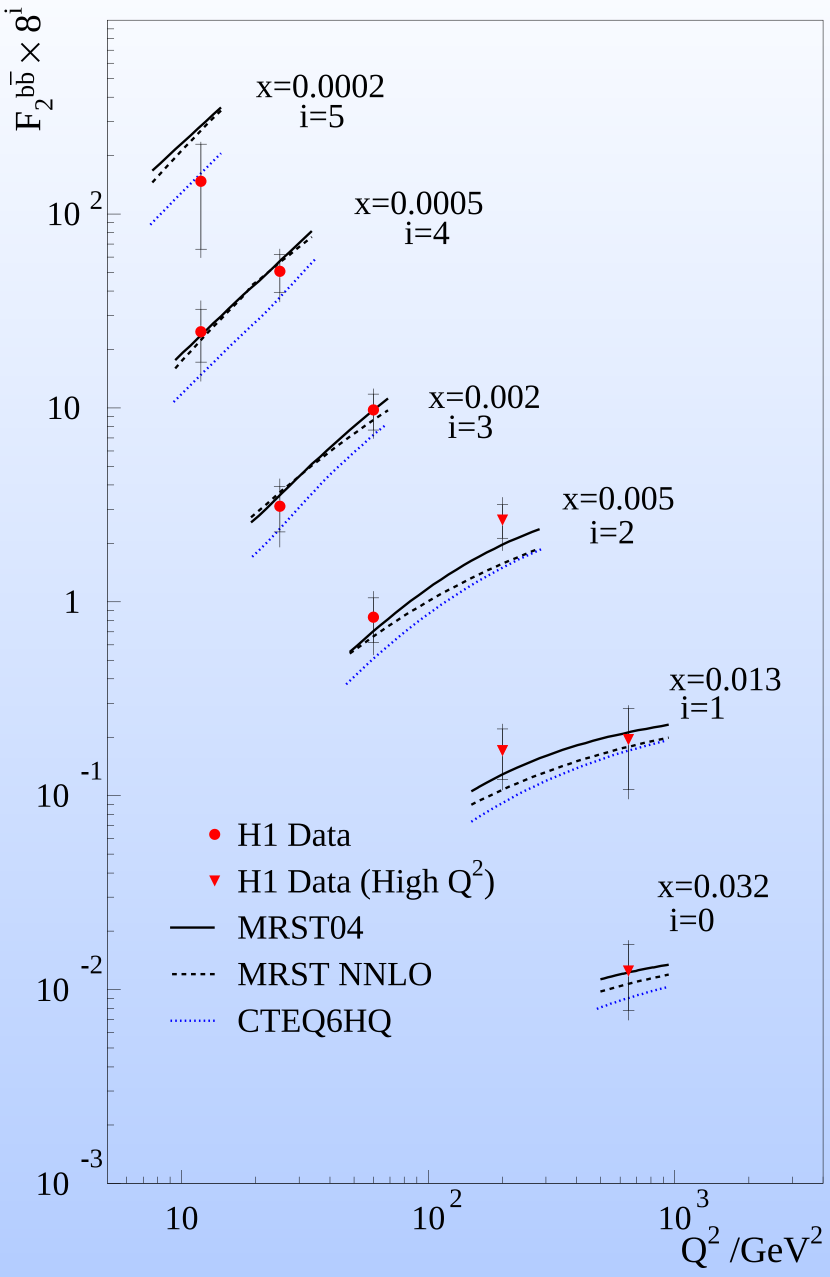
CTEQ6HQ - Variable FNS

CCFM (Cascade) - Massive scheme

$F_2^{c\bar{c}}$ vs Q^2



$F_2^{b\bar{b}}$ vs Q^2



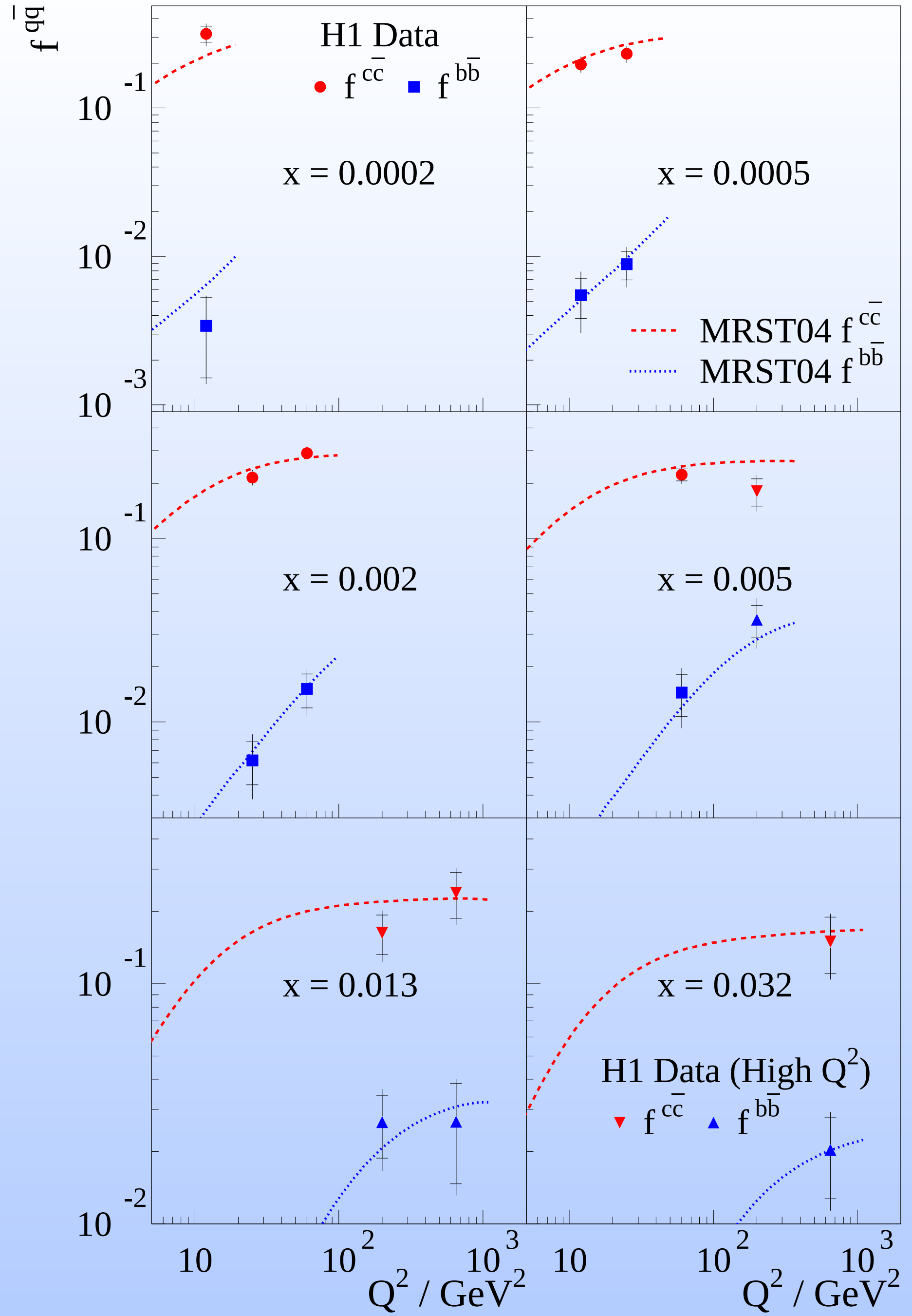
Contribution to σ:

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

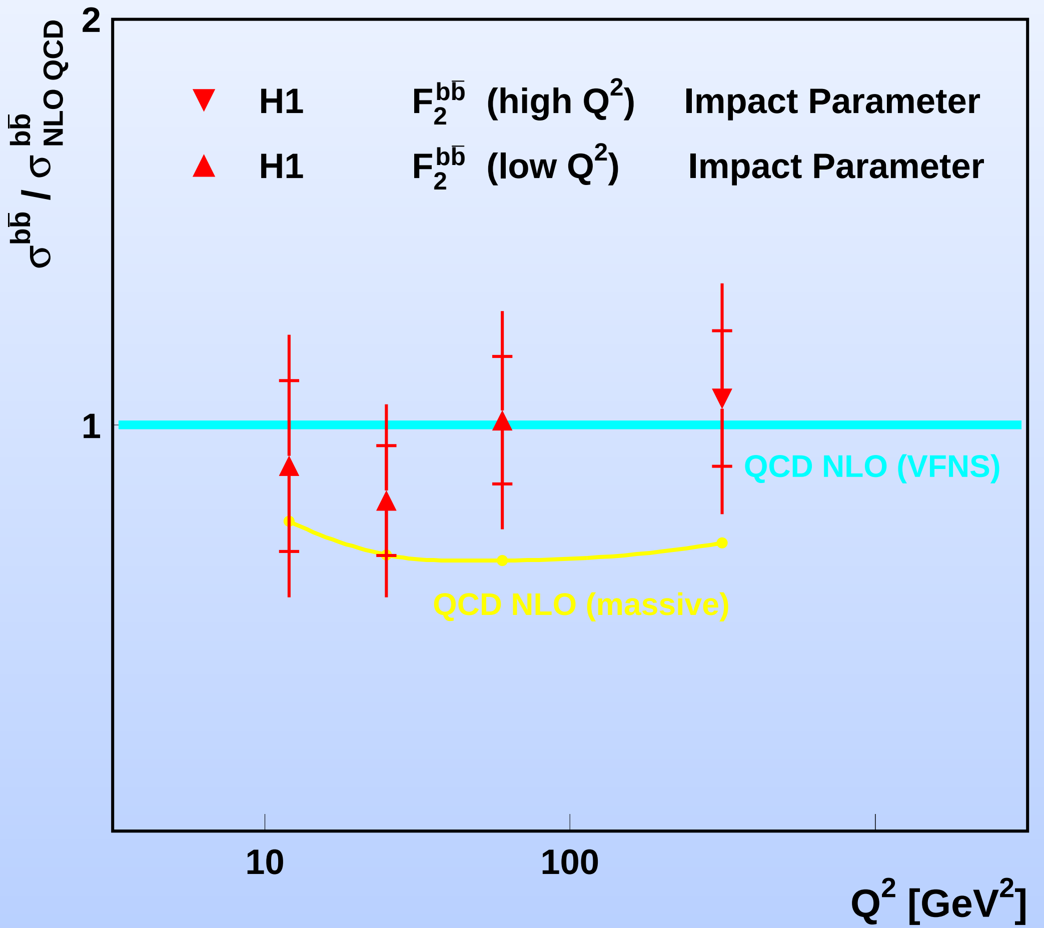
c and b fractions fall towards low Q^2

b fraction falls by a larger amount

MRST04 - Variable FNS



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



Conclusions

- The first measurement of $F_2^{b\bar{b}}$ in the low and high Q^2 kinematic regime
- Good description by predictions of perturbative QCD calculations
- First measurement of $F_2^{b\bar{b}}$
- 24% of charm and 0.8% of beauty contribution to the total ep cross section at low Q^2
- 18% of charm and 2.7% of beauty contribution to the total ep cross section at high Q^2

Outlook

- **Increased statistics using HERA II data**
- **Single and di-jet cross section measurements using b-tagged jets with increased statistics. $\Longrightarrow$ Basis to test models relevant for heavy quark jet production at the LHC**

HERA is taking lumi... till 2007

INTEGRATED LUMINOSITY (03.05.06)