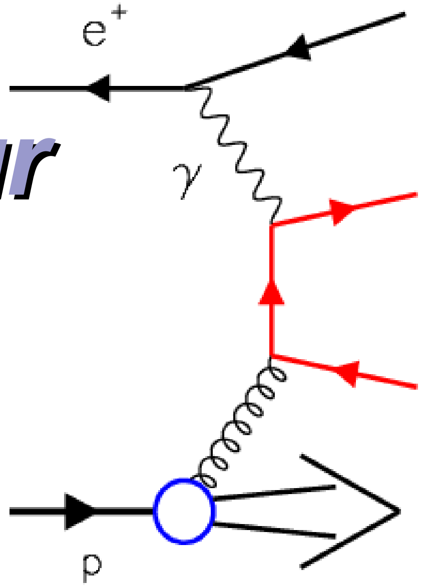
Heavy flavour production at HERA



Incontri di Fisica delle Alte Energie

Torino 14 - 16 Aprile 2004

Andrea Longhin

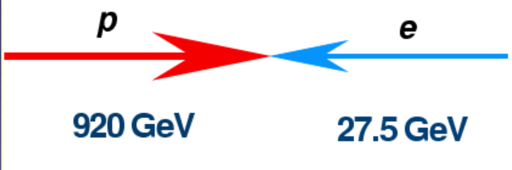
INFN Padova

Outline

- **Introduction**
- **Charm: D* in photoproduction (PHP) and Deep Inelastic Scattering (DIS), fragmentation,angular distributions.**
- **Open Beauty: production in PHP and DIS**
- **Conclusions and Outlook**

- Not covered... heavy vector mesons, c-diffractive production, c+jets etc...

HERA

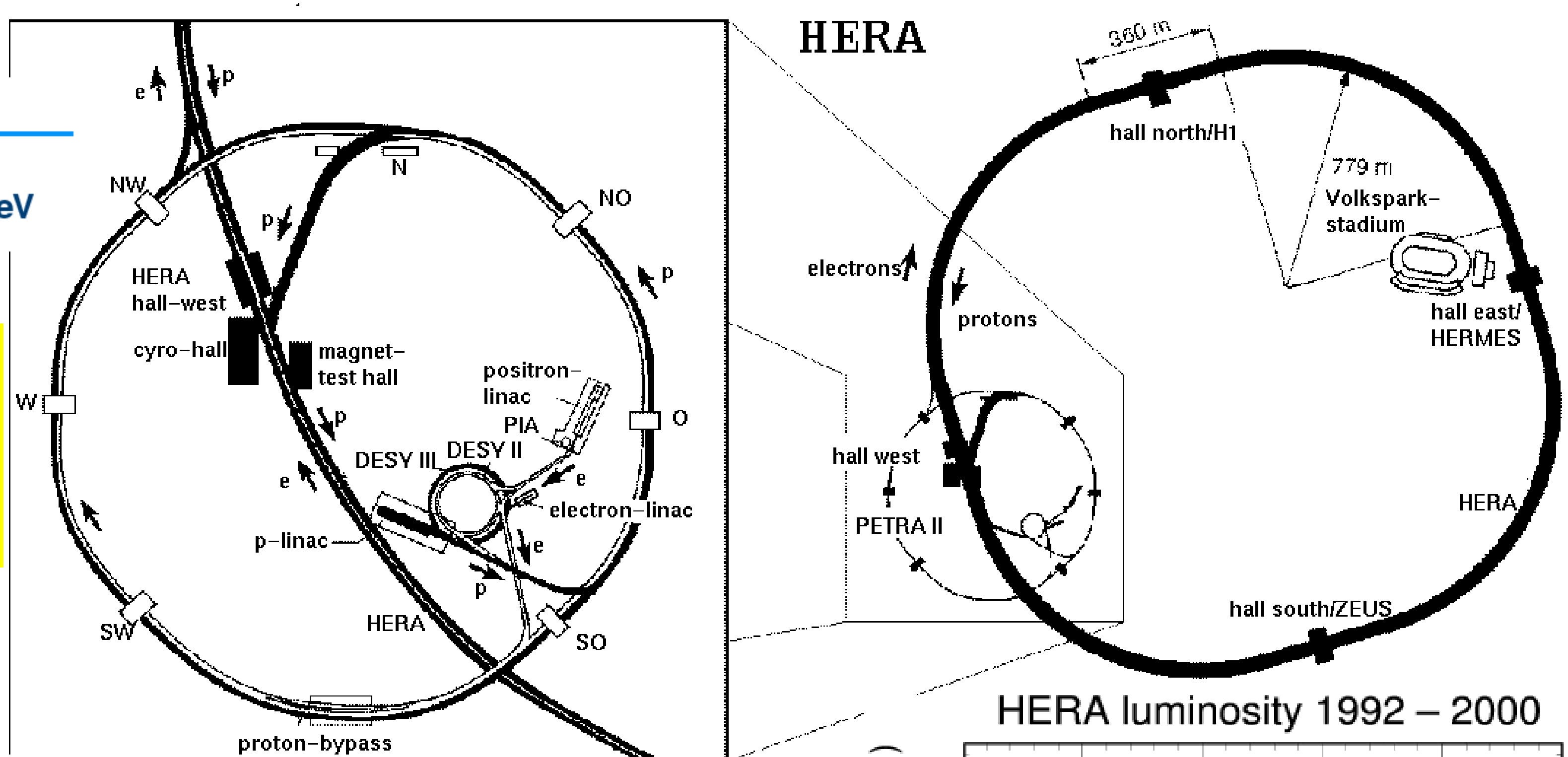


1992-97 E_p = 820 GeV

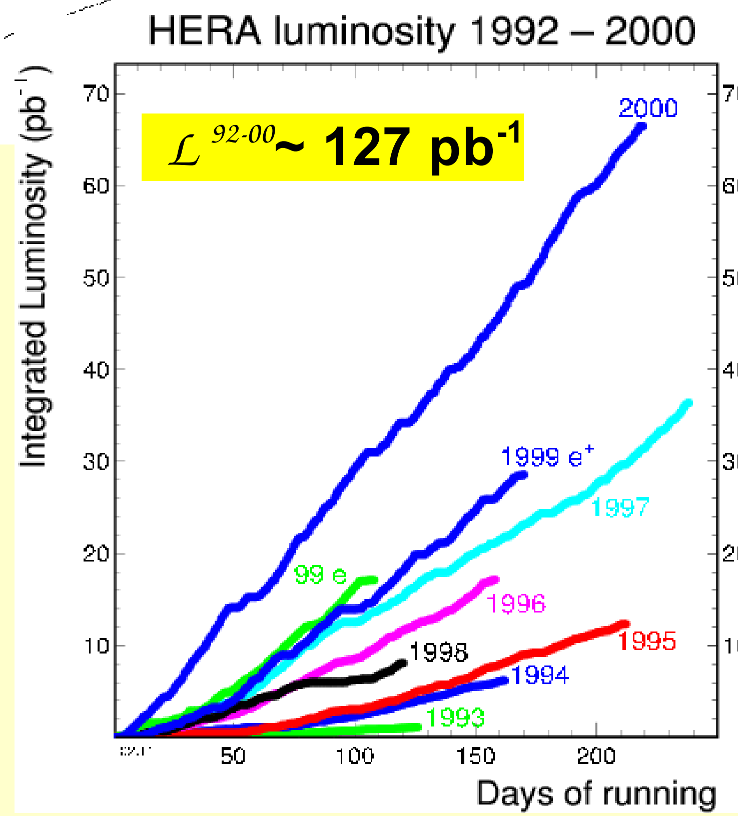
E_{CM} ~ 300 GeV

1998-00 E_p = 920 GeV

E_{CM} ~ 318 GeV



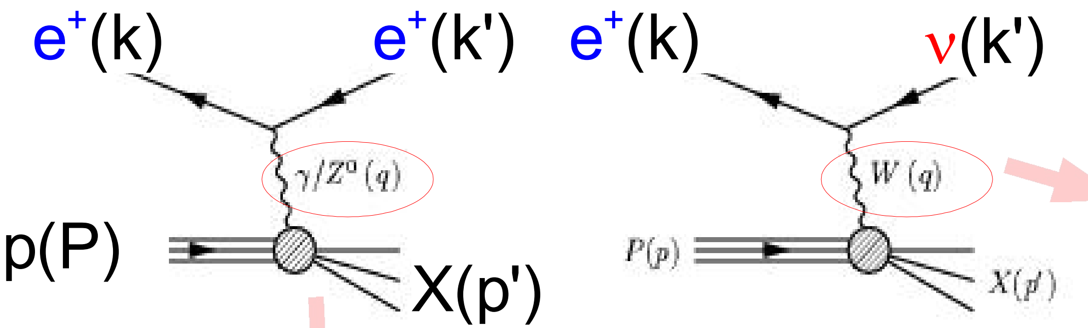
World's only *ep* collider



$e \longrightarrow\!\!\longleftarrow p$

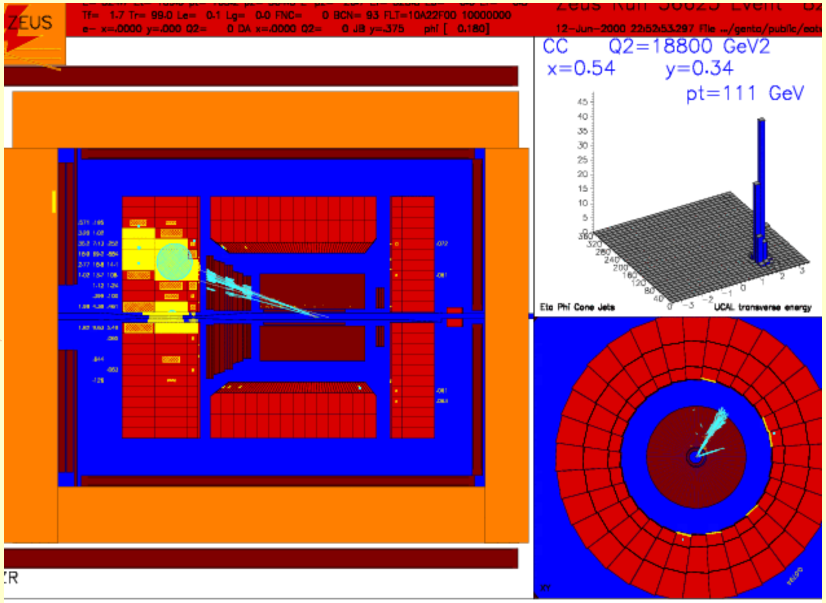
Processes ...

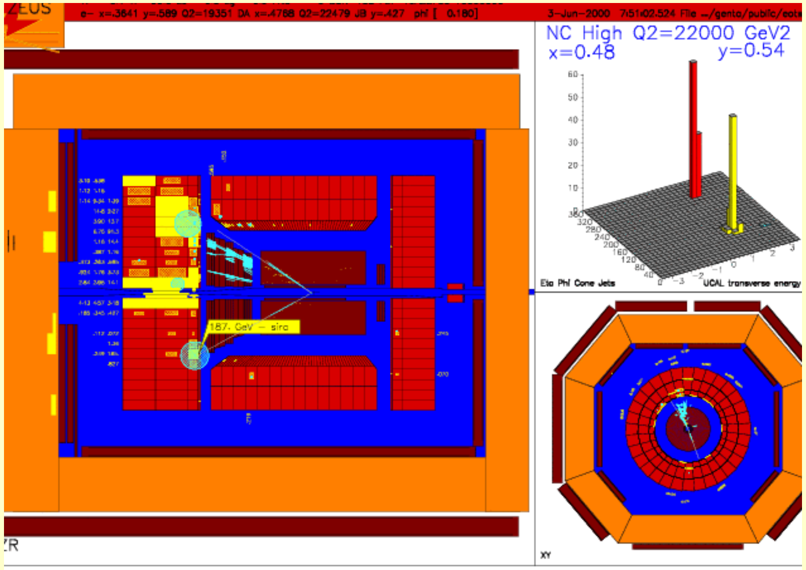
Neutral current (NC) | **Charged current (CC)**



NC dominant

CC relevant at high $Q^2 \sim M^2_{W/Z}$





HQ production studied so-far only in NC processes

Kinematic variables

- Square of e 4-mom. transfer $\quad Q^2 = -(k-k')^2$
- Bjorken-x scaling variable $\quad x = \dfrac{Q^2}{2P\cdot Q}$
- Fractional E-transfer for e $\quad y = \dfrac{P\cdot Q}{P\cdot k}$
- γp CMS energy $\quad W = (P+q) \cong \sqrt{4E_eE_py}$

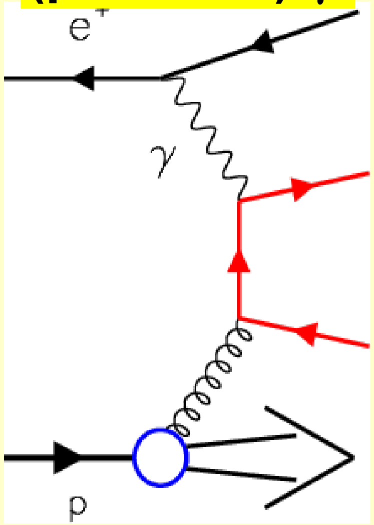
Two Q^2 regimes ...

- **Deep Inelastic Scattering (D I S):** $Q^2 > 1\ GeV^2$ — e **scattered in the main CAL "highly virtual"** γ
- **Photoproduction (P H P):** $Q^2 < 1\ GeV^2,\ \langle Q^2\rangle \sim 10^{-3}\ GeV^2$ — e **scatterd in the beam pipe "quasi - real"** γ

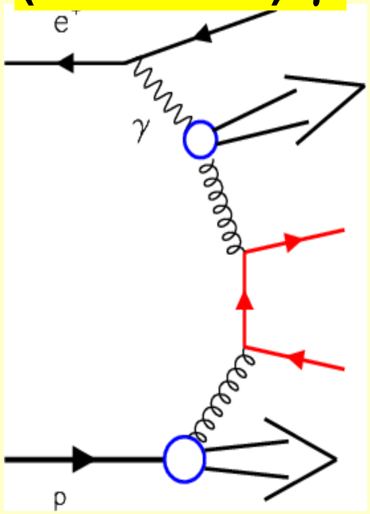
Why study Heavy Flavour production at HERA ?

- Heavy quark mass (m_c, $m_b >> \Lambda_{QCD}$) → ***hard scale***
  - Stringent test of pQCD in a "**clean**" environment
    - ***Still … deviations observed in the past in*** ep ***experiments (as well as*** $p\bar{p}$, e^+e^- ***)***
  - Charm: is m_c **large enough** for pQCD ?
- Sizeable Q^2 (*scattered* e) and p_T (jets) involved:
  - possibility to study **multi-scale** processes
- Study non perturbative effects (*e.g.* c-*fragmentation universality*)
- Direct handle on
  - g-**density** in the p $xg(x)$ (direct "BosonGluonFusion")
  - γ partonic **structure** (resolved photon)
- A full set of cross section **predictions at NLO** level available at HERA
- Possibility of **independent** experimental methods

Direct (pointlike) γ



Resolved (hadronic) γ



Perturbative QCD heavy flavour calculations at HERA

- **Fixed order NLO calculations** (massive-HQ produced dinamically)
  - c/b : FMNR (Frixione et al.) HVQDIS (Harris & Smith)
  - 3-4 active flavours in p and γ (no explicit flavour excitation)
  - Not valid for $p_T >> m_Q$, $Q >> m_Q$

- **Resummed NLL calculations** (massless HQ c as an active flavour)
  - c: Kniehl et al.
  - 4 active flavours in p and γ (HQ structure function, flavour excitation)
  - Valid for $p_T >> m_Q$, $Q >> m_Q$

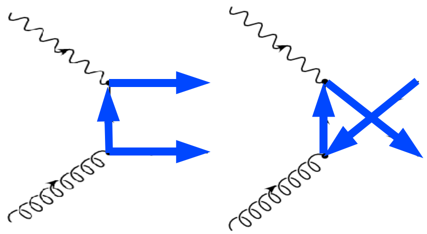
- **Matched calculations** (FONLL Cacciari et al.)
  - NLO mass effects + NLL p_T resummation

- **Leading Order Monte Carlo**
  - PYTHIA ,HERWIG, AROMA , RAPGAP (DGLAP evolution, dir & res)
  - CASCADE (CCFM-like evolution dir only but res effectively produced. k_T dependent g-density)

Example: b at NLO

[20] J. Smith, W.L. van Neerven, Stony Book Report, ITP-SB-91-40 (1991)

- **Leading order $\alpha_s \alpha_{em}$**



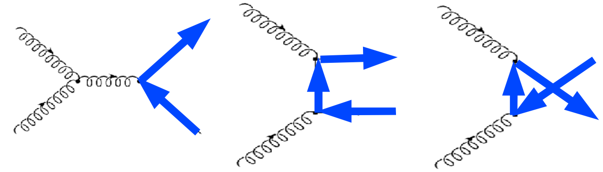
Direct γ

63 %

Boson gluon fusion (BGF)

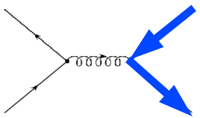
$\gamma g \rightarrow b \bar{b}$

Gluon-gluon fusion



9 %

$gg \rightarrow b\bar{b}$



Resolved γ

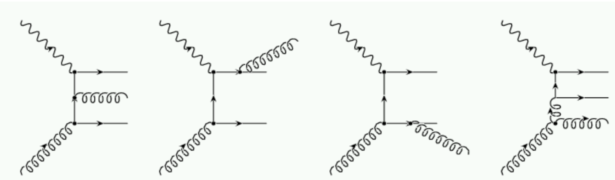
2 %

$q\bar{q} \rightarrow b\bar{b}$

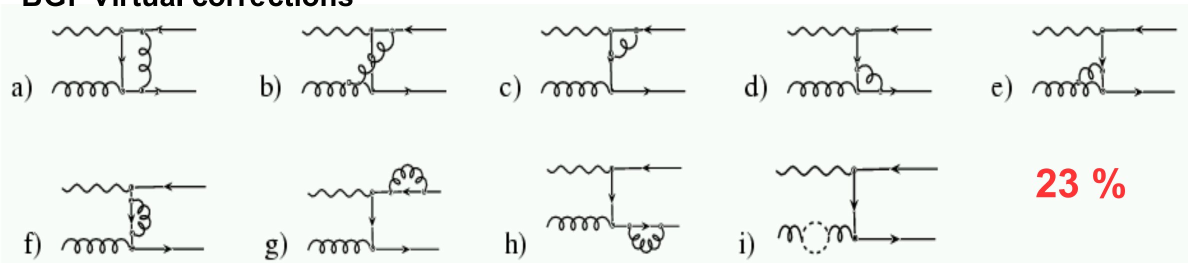
Quark-quark fusion

- **Next to leading order $\alpha_s^2 \alpha_{em}$**

BGF corrections from g-emission

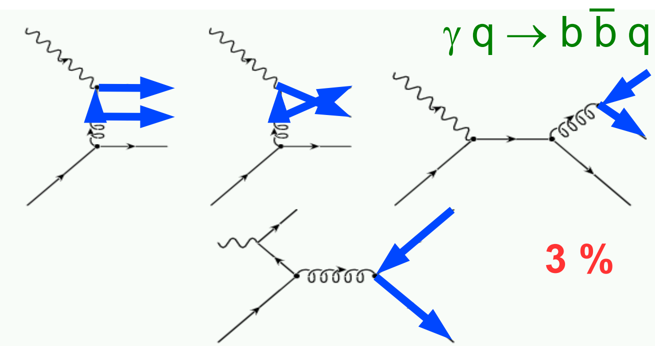


BGF virtual corrections



23 %

light quark in the initial state



3 %

$\sigma_{\gamma g} O(\alpha_s)$	4.16	nb
$\sigma_{\gamma g} O(\alpha_s^2)$	1.54	
$\sigma_{\gamma q} O(\alpha_s^2)$	0.20	
$\sigma_{q\bar{q}} O(\alpha_s^2)$	0.12	
$\sigma_{gg} O(\alpha_s^2)$	0.57	
	6.59 nb	σ_{tot}

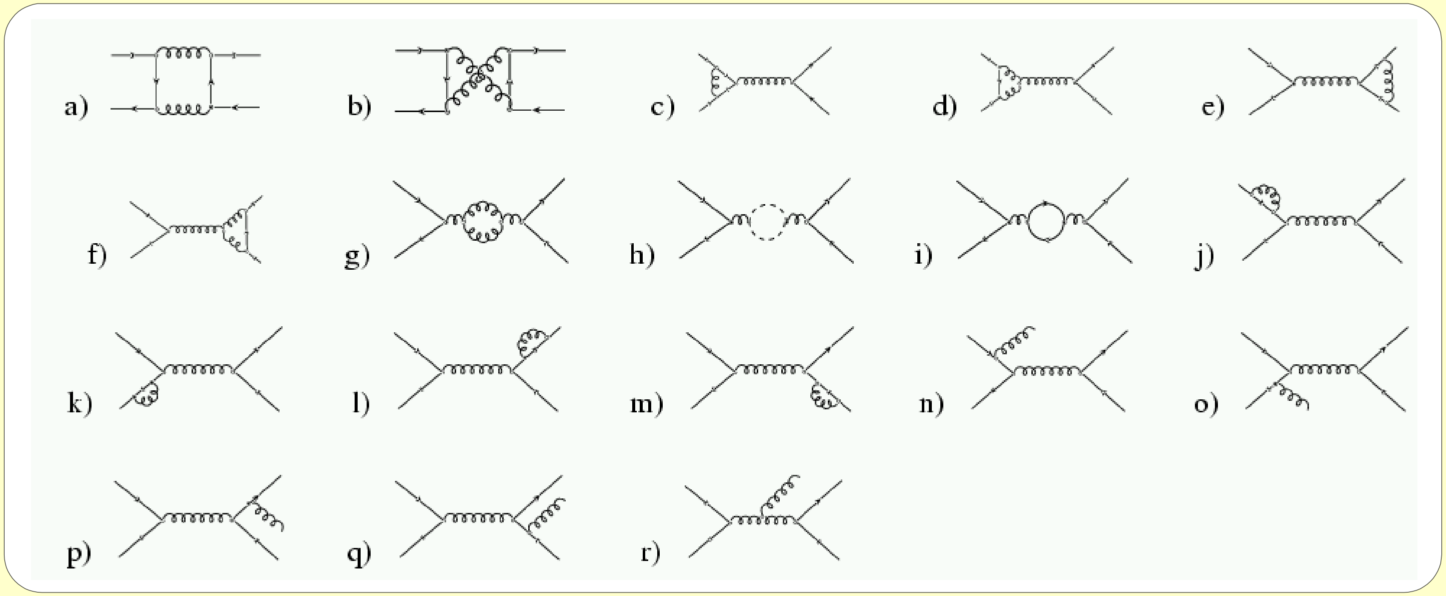
$\overline{\text{MS}}$ scheme
hard scale $m = m_b = 4.75$ GeV

Virtual corrections for hadronic diagrams are also calculated:

*P.Nason, S. Dawson, R.K. Ellis, Nucl. Phys. **B303**, 607 (1988)*
*P.Nason, S. Dawson, R.K. Ellis, Nucl. Phys. **B327**, 049 (1989)*

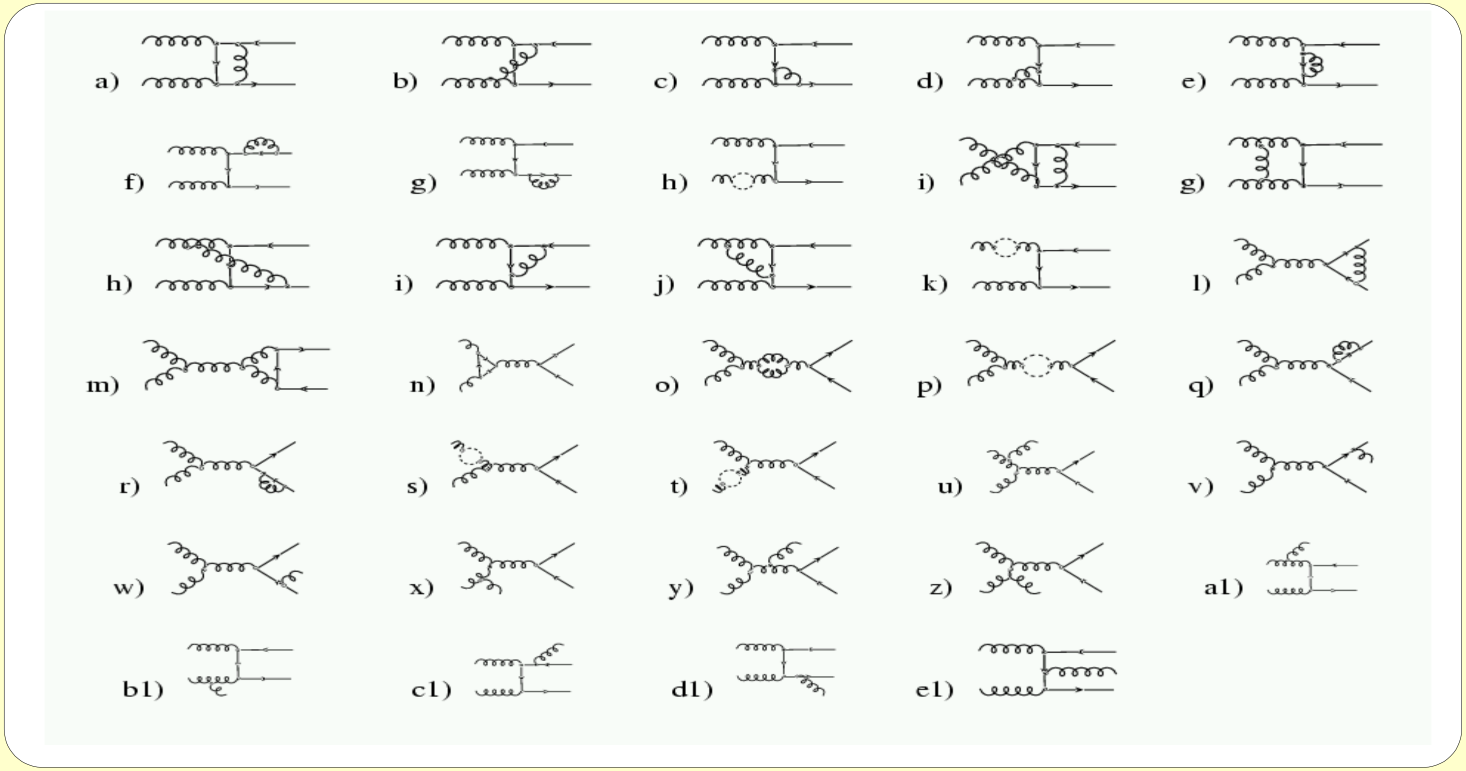
Quark quark fusion virtual corrections

$q\bar{q} \to b\bar{b}$



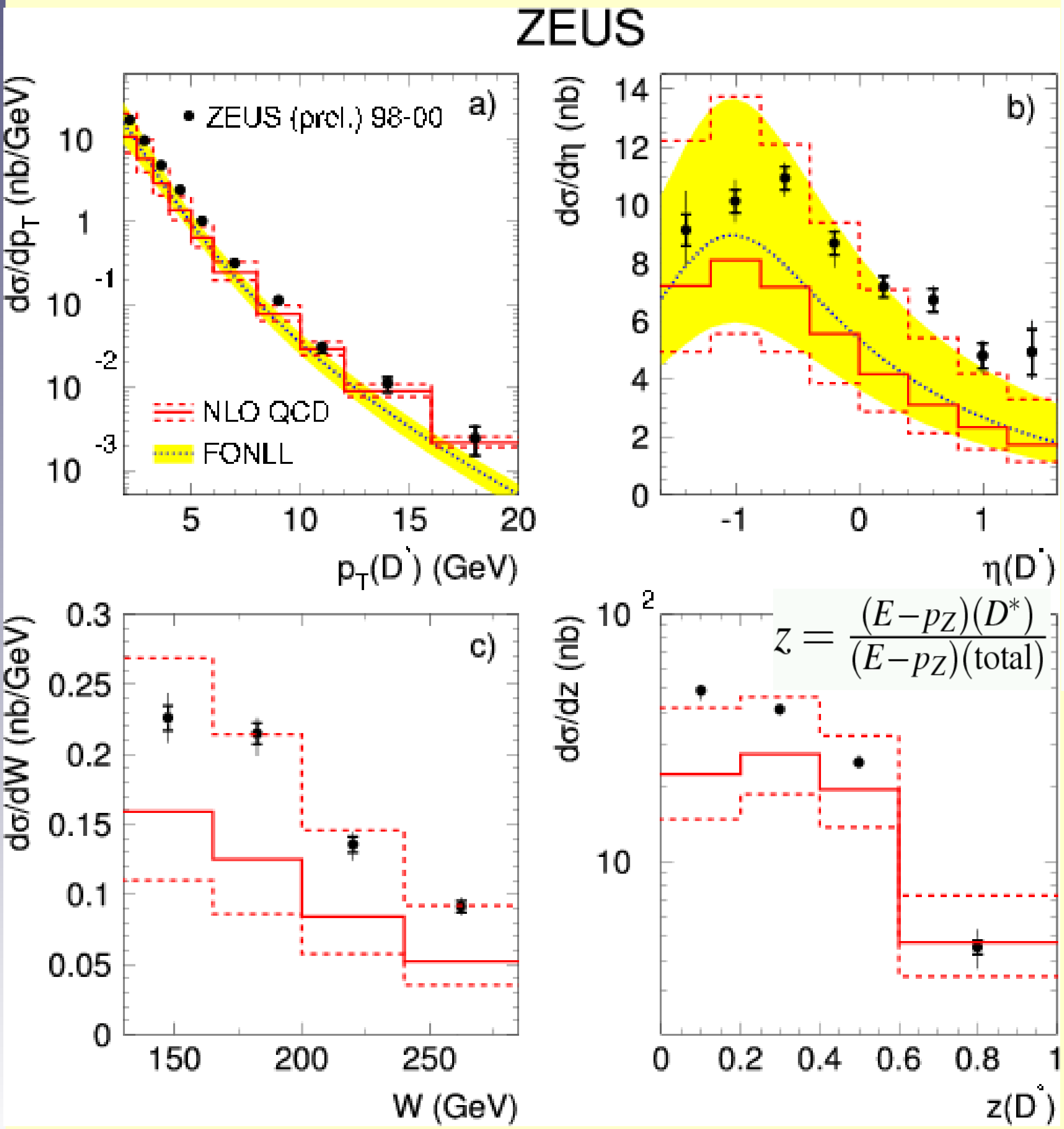
g-g fusion virtual corrections

$gg \to b\bar{b}$

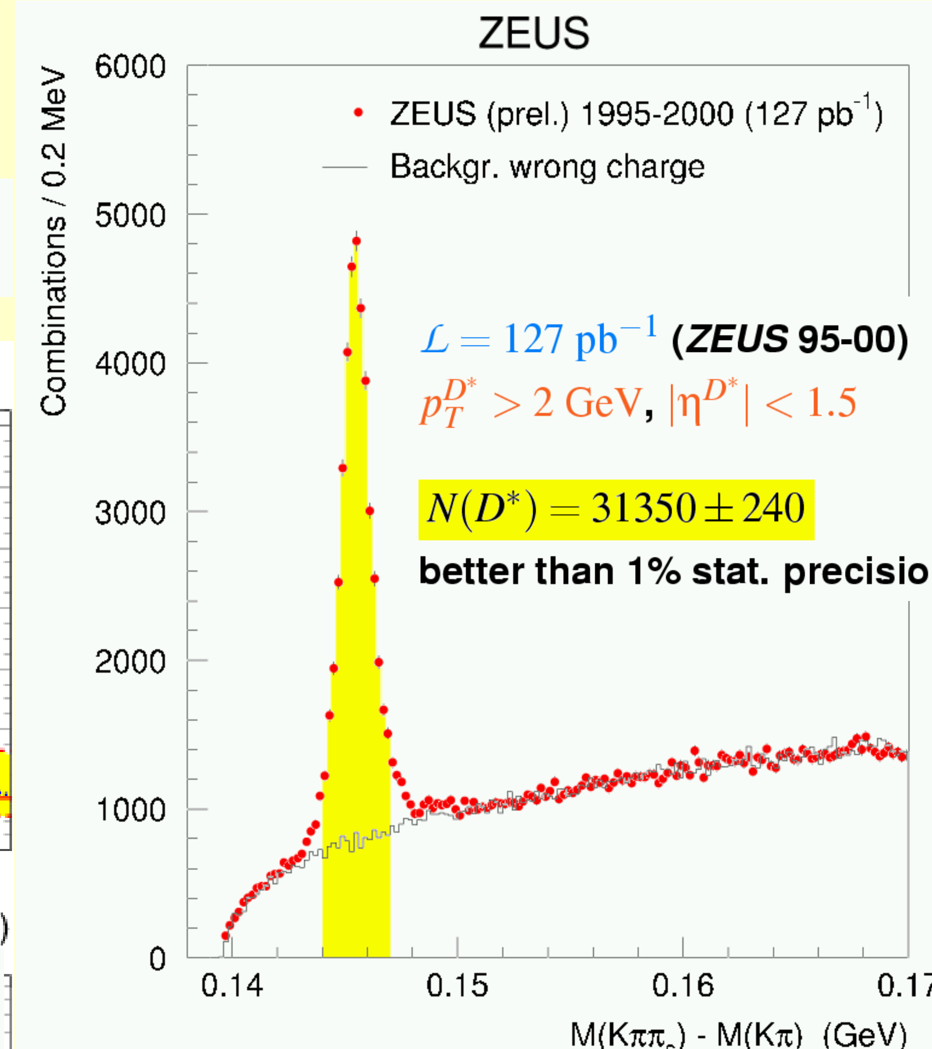


D* photoproduction

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



$$z = \frac{(E-p_Z)(D^*)}{(E-p_Z)(\text{total})}$$



$\mathcal{L} = 127\ \mathrm{pb}^{-1}$ **(*ZEUS* 95-00)**

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

$N(D^*) = 31350 \pm 240$

better than 1% stat. precision

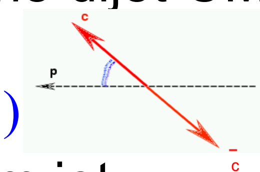
- FO NLO, reasonable agreement, some deviations at forward η, low z
- Matched FONLL. Similar to FO, slightly worse at large p_T

D* photoproduction: dijet angular distributions

D*+ at least 2 jets with E_T>5 GeV and M_{jj}>18 GeV

- Jet angle wrt beam in the dijet CM system:

  $\cos\theta^* = \tanh((\eta^{jet1}-\eta^{jet2})/2)$

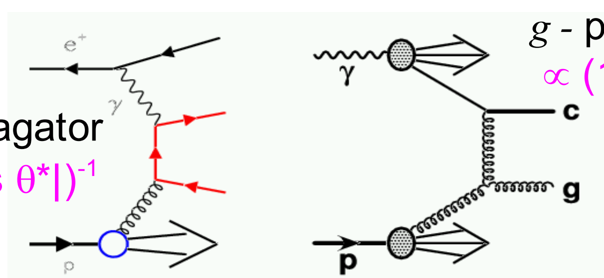


- Associate D* with charm jet → sign of cos θ*
- Split sample into
  - Resolved enriched (x_γ^{OBS}< 0.75)
  - Direct enriched (x_γ^{OBS}>0.75)

Strong asymmetric rise of cross section in γ direction for resolved

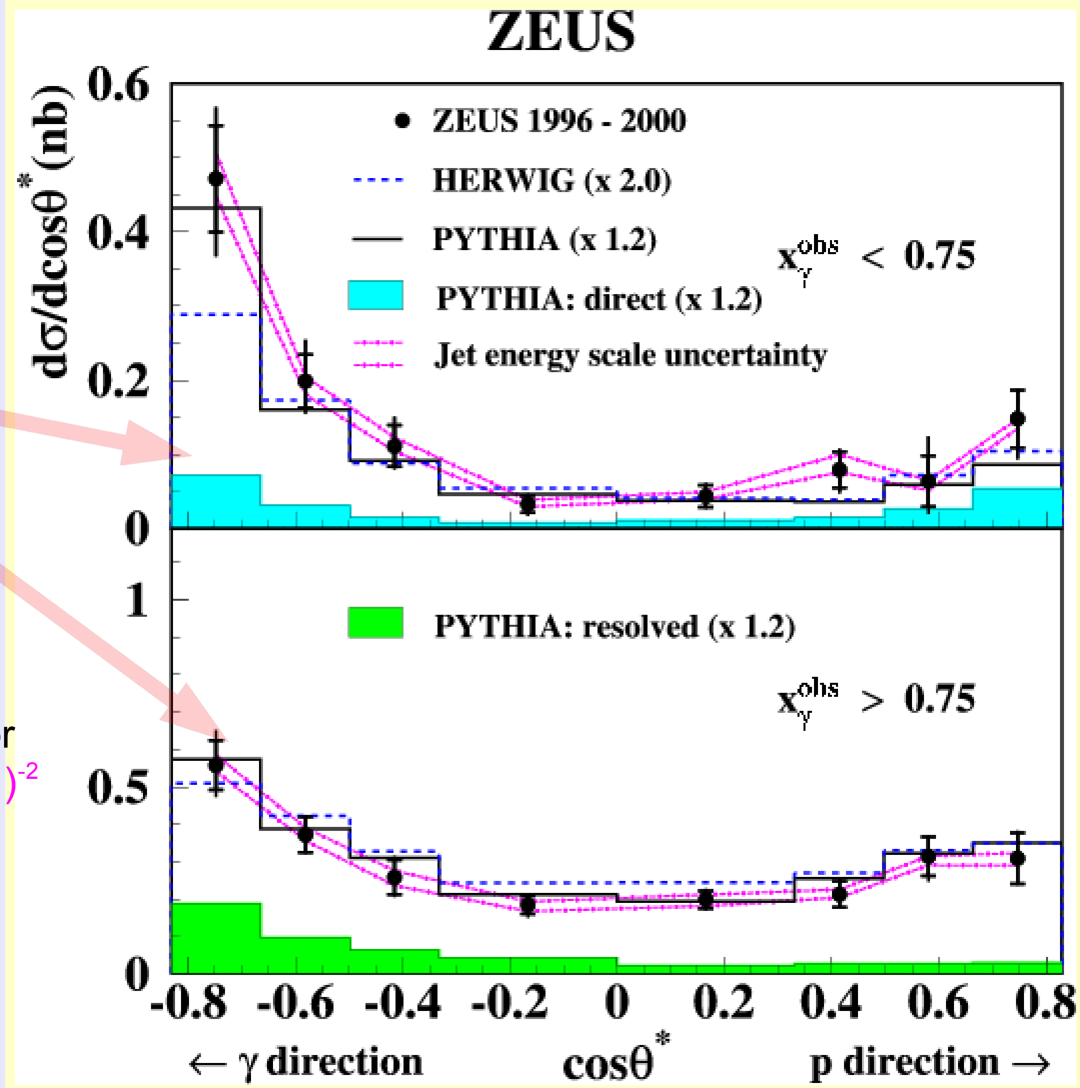
q - propagator $\propto (1-|\cos\theta^*|)^{-1}$

g - propagator $\propto (1-|\cos\theta^*|)^{-2}$



- Clear indication for g-propagator
- Charm in the γ

$$x_\gamma^{OBS} = \frac{\sum_{jets} E^T e^{-\eta}}{2yE_e}$$ ~ fraction of γ energy in the hard interaction

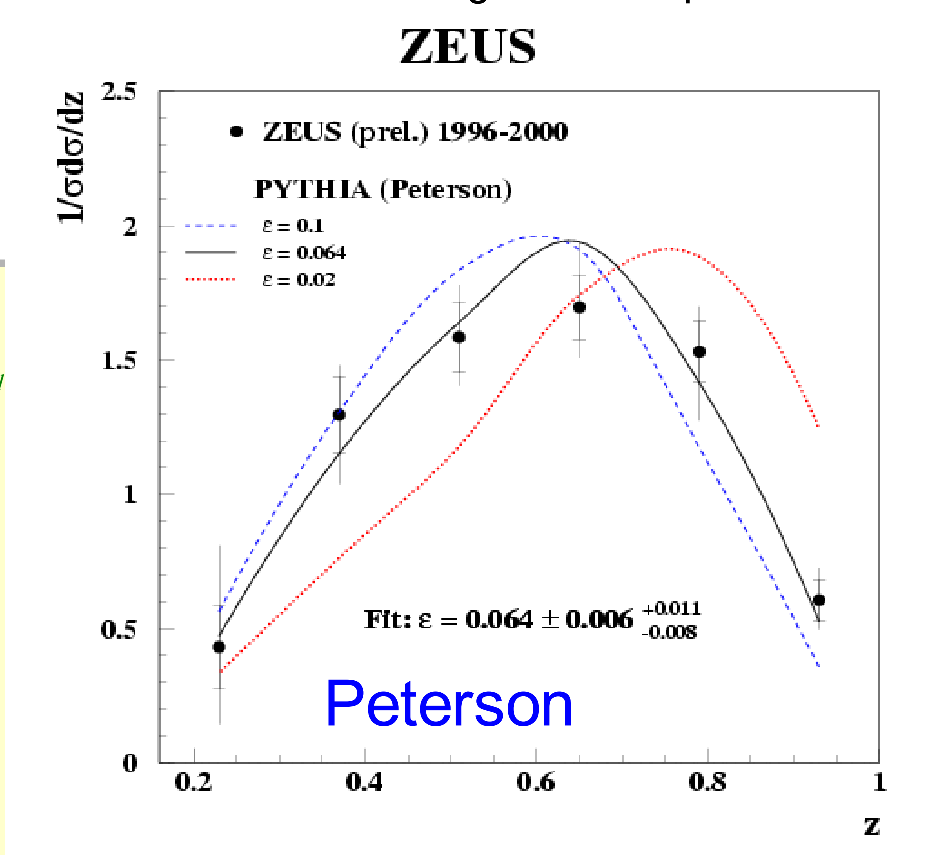


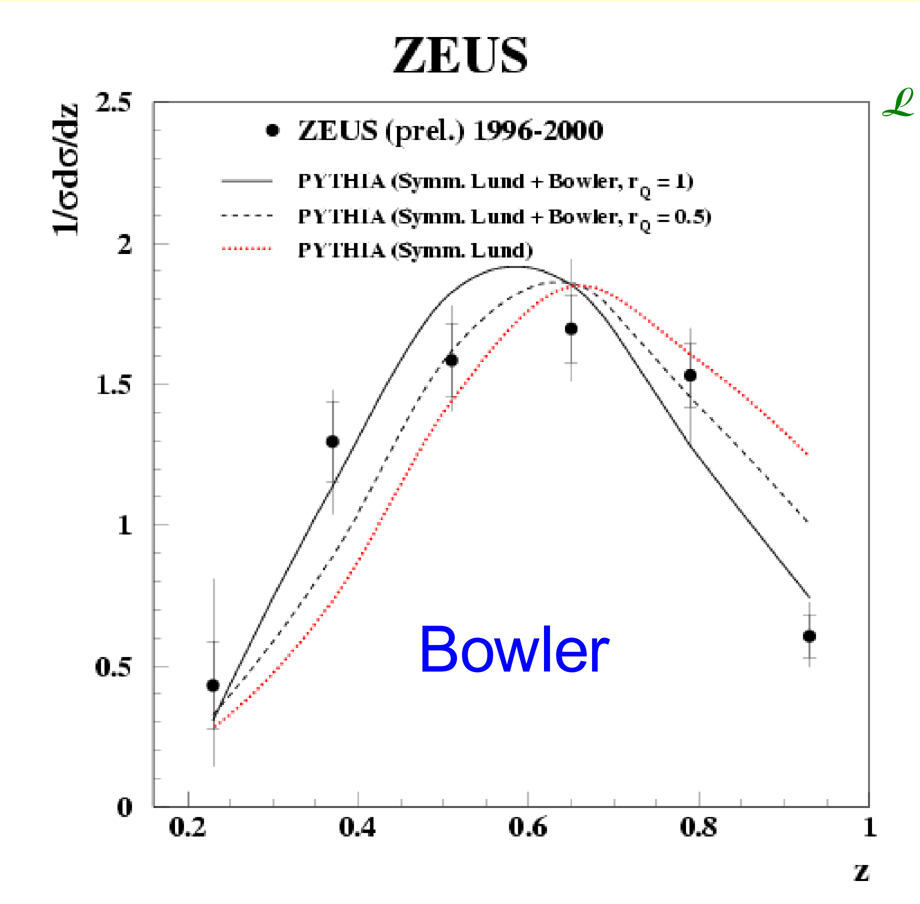
Charm fragmentation studies

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

- k_T- clustering jets: $E_T^{jet} > 9$ GeV, $|\eta^{jet}| < 2.4$
- $D^* \rightarrow K\pi\pi_s$: $p_T^{D^*} > 2$ GeV $|\eta^{D^*}| < 1.5$
- D^* *jet* association: distance in $\eta-\phi < 0.6$

Sensitive to fragmentation parameters





$\mathcal{L} = 120\ pb^{-1}$

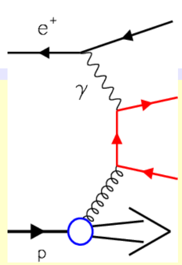
- *Peterson best fit:* $\varepsilon = 0.064 \pm 0.006^{+0.011}_{-0.008}$

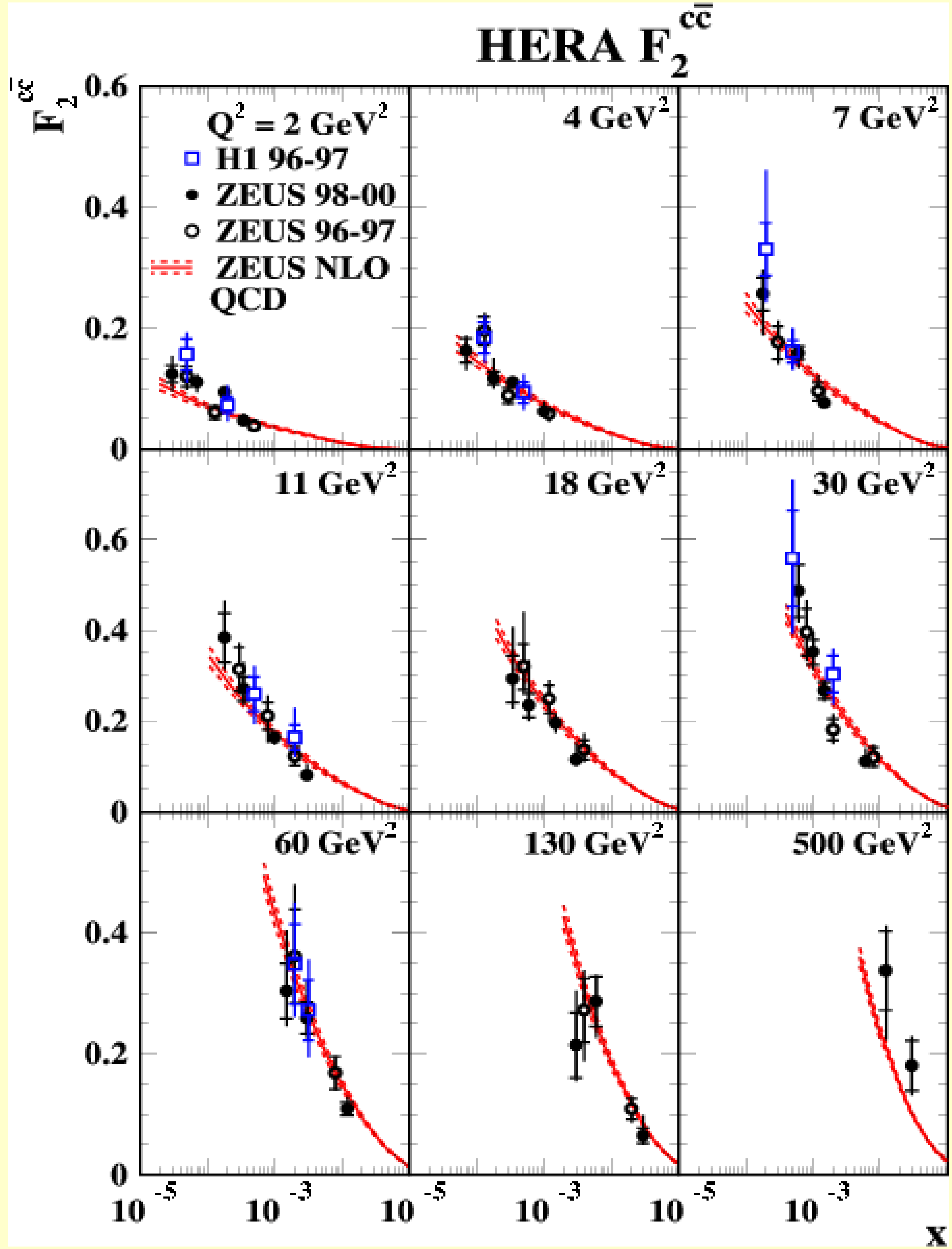
  (Pythia def. = 0.05, e^+e^- = 0.053)
- *Bowler best fit:* r_Q*=1 (def.)*

  (for a=0.3, b=0.58 GeV $^{-2}$ fixed)

Charm in DIS

- Charm production accounts for up to 40 % of $F_2(x,Q^2)$ (*at high* Q^2 *and low* $-x$)
- Important to understand it properly
- Extract F_2^c from differential cross sections
  - Model dependent extraction
  - Good agreement between ZEUS and H1
- F_2^c rises sharply with decreasing x *(gluon PDF...)*
- Use differential cross sections to contrain gluon density in future NLO QCD fits





Charm fragmentation in PHP

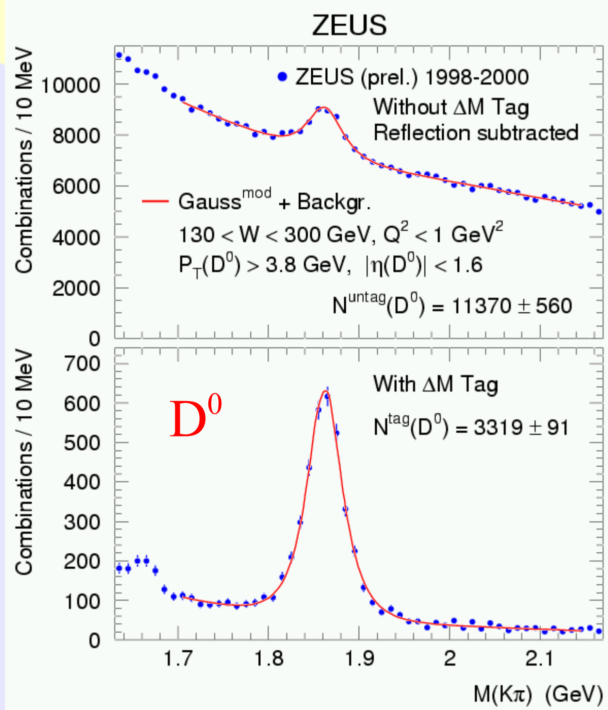
Identify $D^{*\pm}$, D^0, $D^\pm$, $D_s^\pm$, $\Lambda_c^\pm$

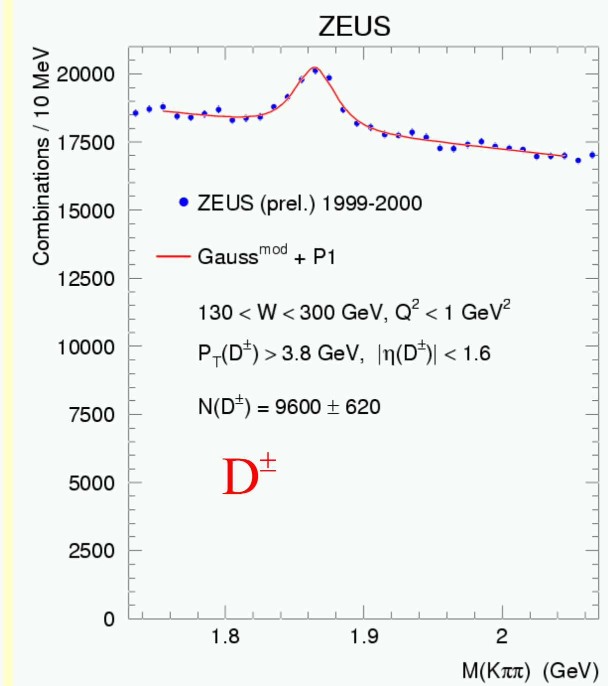
($p_T > 3.8$ GeV $|\eta|<1.6$

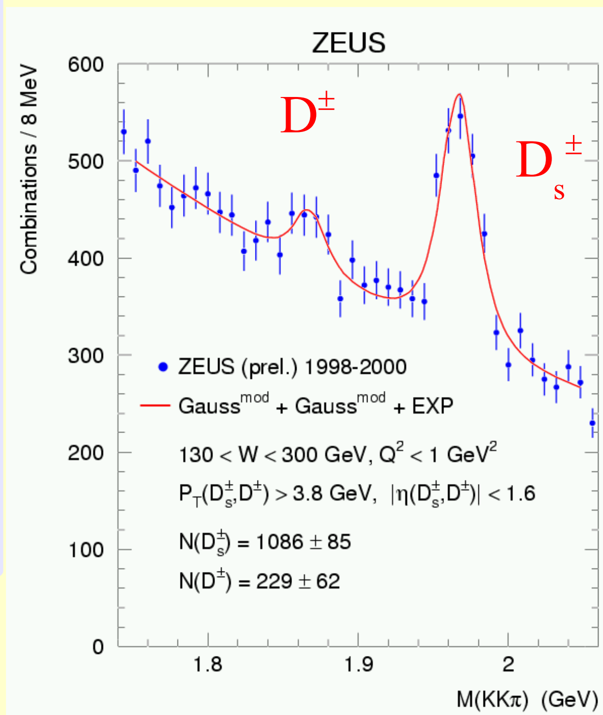
$130 < W < 300$ GeV, $Q^2 < 1$ GeV^2)

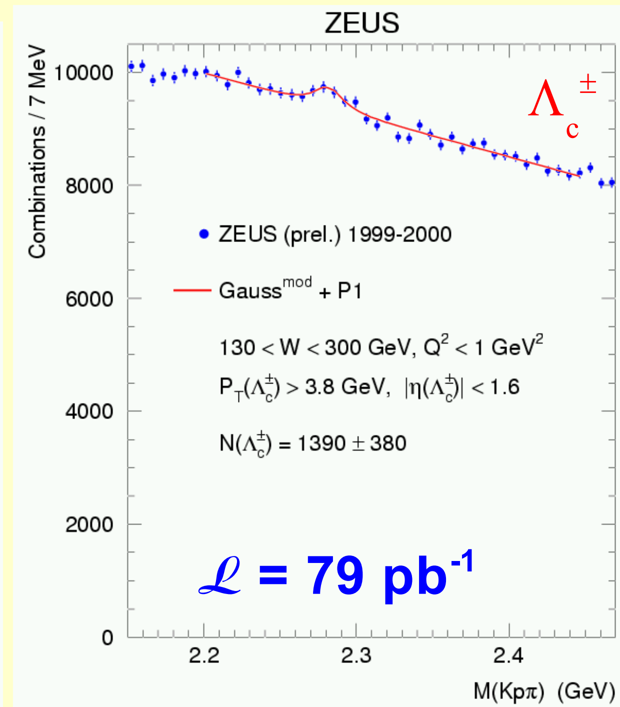
and measure:

- $R_{u/d}$
  ratio of neutral & charged D rates
- γ_s
  strangeness suppression factor
- P_V
  fraction of D mesons in a vector state
- P_V^d
  fraction of charged D mesons in a vector state
- $f(c \rightarrow D, \Lambda_c)$
  fragmentation fractions









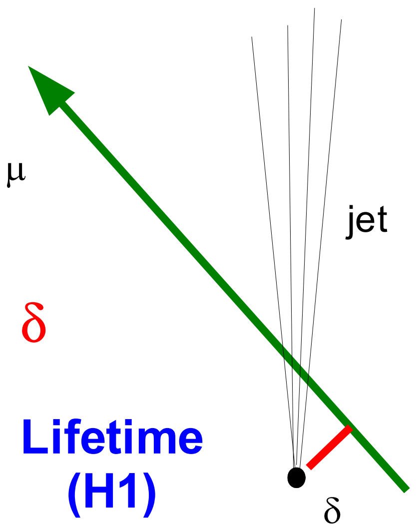
Charm fragmentation (contd)

	ZEUS prel. (γp) results	H1 prel. (DIS) results	e^+e^- results
$R_{u/d}$	$1.014 \pm 0.068^{+0.024}_{-0.031}$	$1.26 \pm 0.20 \pm 0.11 \pm 0.04$	$0.963 \pm 0.051 \pm 0.054$ 1.02 ± 0.12 1.19 ± 0.36
γ_s	$0.266 \pm 0.023^{+0.014}_{-0.012}$	$0.36 \pm 0.10 \pm 0.01 \pm 0.08$	0.26 ± 0.03
P_v^d	$0.557 \pm 0.023^{+0.009}_{-0.006}$	$0.693 \pm 0.045 \pm 0.004 \pm 0.009$	0.595 ± 0.045
P_v	$0.554 \pm 0.019^{+0.008}_{-0.004}$	$0.613 \pm 0.061 \pm 0.033 \pm 0.008$	$0.620 \pm 0.014 \pm 0.014$ 0.57 ± 0.05
$f(c \to D^+)$	$0.249 \pm 0.014^{+0.004}_{-0.008}$	$0.202 \pm 0.020^{+0.045+0.029}_{-0.033-0.021}$	0.232 ± 0.010
$f(c \to D^0)$	$0.557 \pm 0.019^{+0.005}_{-0.013}$	$0.658 \pm 0.054^{+0.117+0.086}_{-0.142-0.048}$	0.549 ± 0.023
$f(c \to D_s^+)$	$0.107 \pm 0.009 \pm 0.005$	$0.156 \pm 0.043^{+0.036+0.050}_{-0.035-0.046}$	0.101 ± 0.009
$f(c \to \Lambda_c^+)$	$0.076 \pm 0.020^{+0.017}_{-0.001}$		0.076 ± 0.007
$f(c \to D^{*+})$	$0.223 \pm 0.009^{+0.003}_{-0.005}$	$0.263 \pm 0.019^{+0.056+0.031}_{-0.042-0.022}$	0.235 ± 0.007

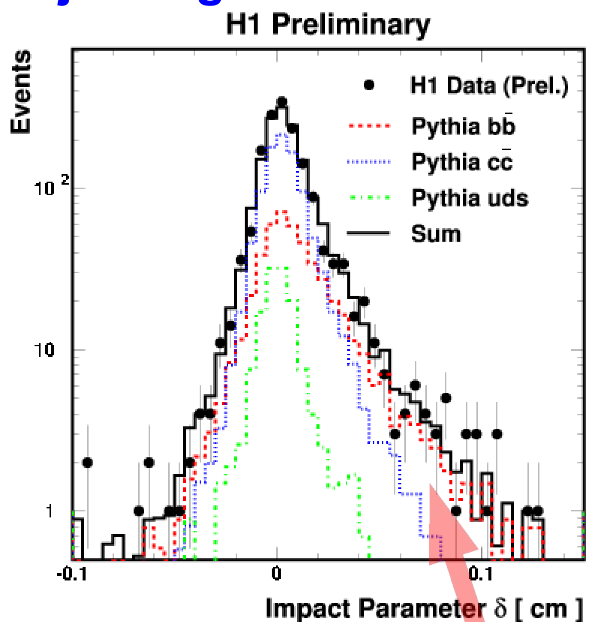
- Results from e^+e^- and ep in good agreement (c-fragmentation universality)
- HERA results competitive with e^+e^-

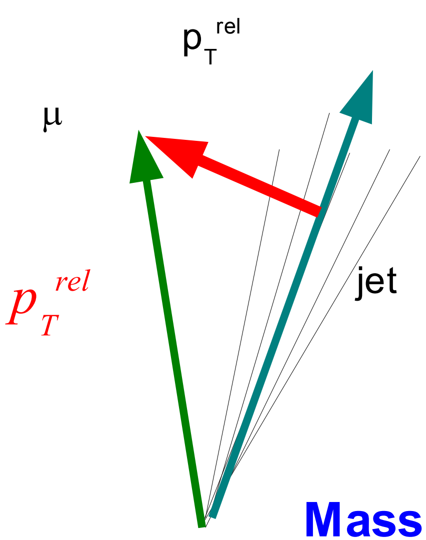
Beauty: signal tagging

Inclusive semi-leptonic b-decays: lepton + jets signature

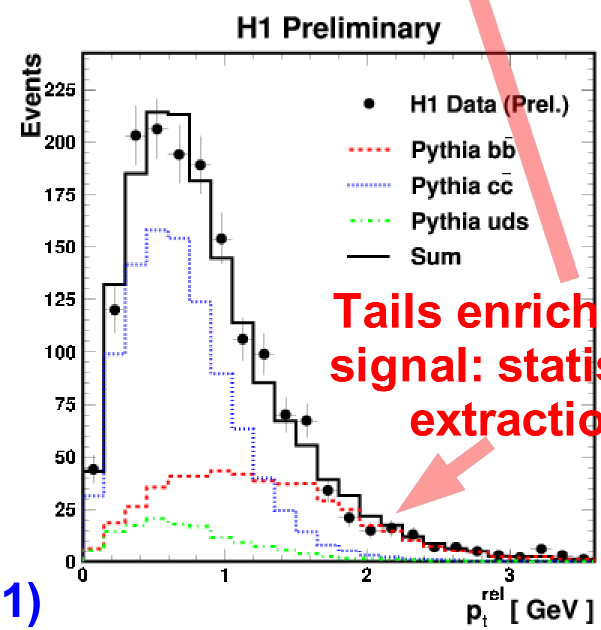


Lifetime (H1)



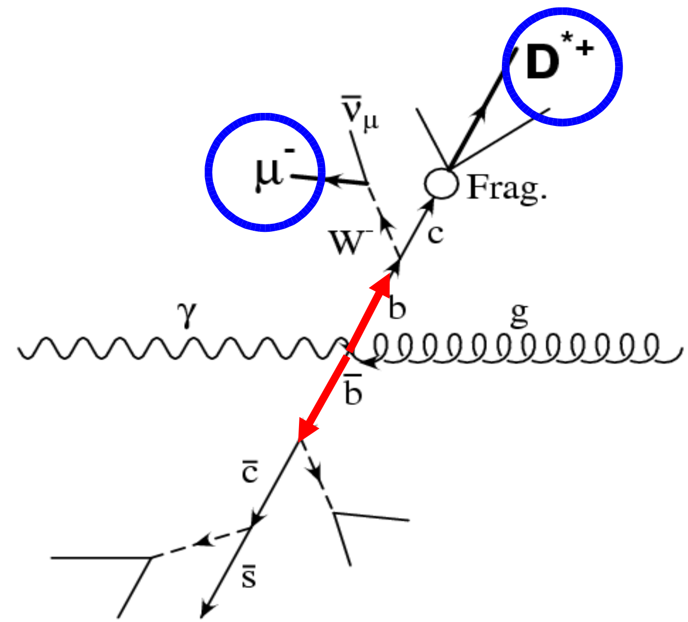


Mass (ZEUS+H1)



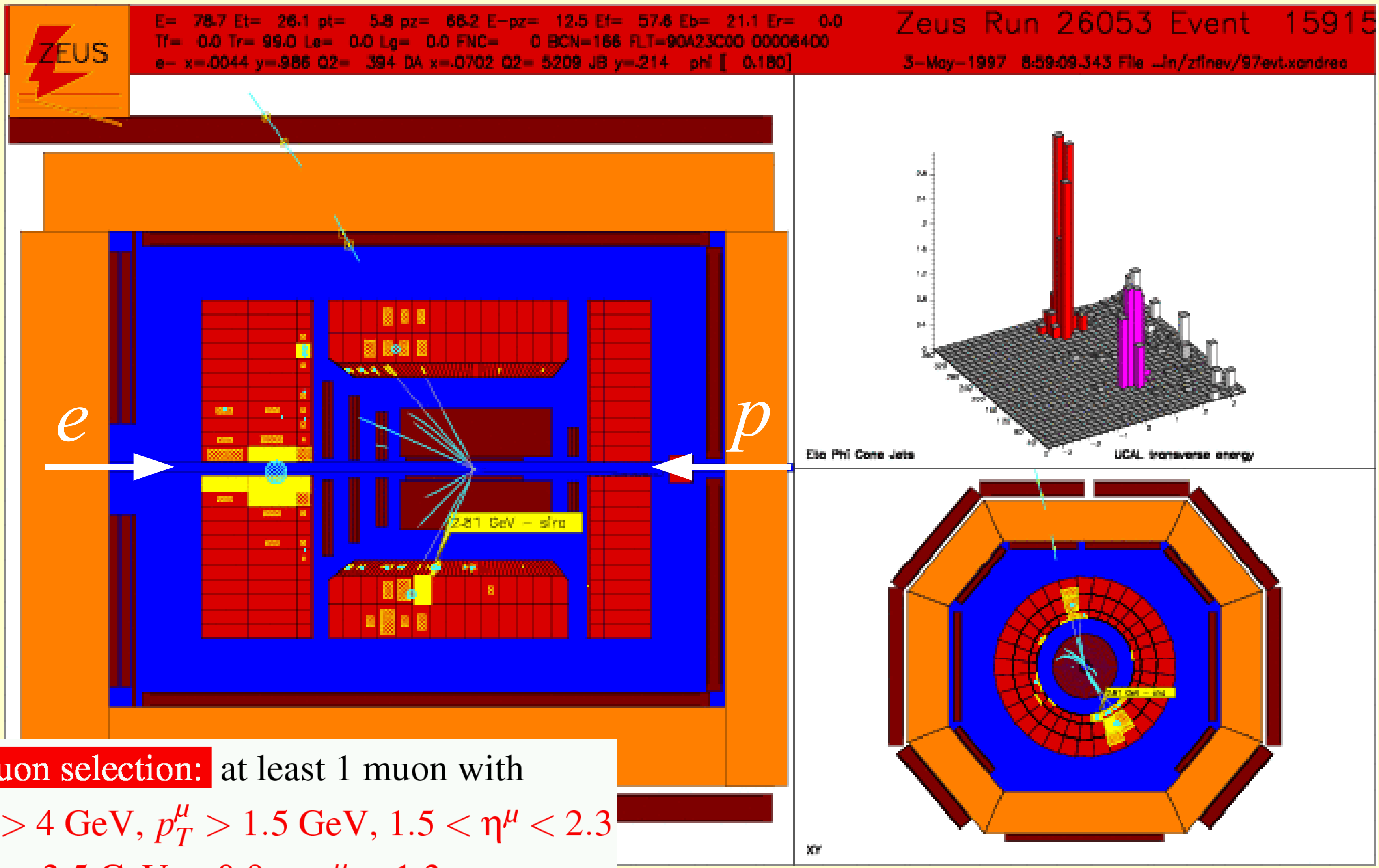
Tails enriched in signal: statistical extraction

Double tag: μ–D* signature



- In the unlike sign μ-D* "collinear" sample high b purity (cc events are back to back!)
- LOW statistics BUT Access to low $p_T(b)$ region !

b with μ +dijet in PHP: selection



Muon selection: at least 1 muon with

$p^{\mu} > 4$ GeV, $p_T^{\mu} > 1.5$ GeV, $1.5 < \eta^{\mu} < 2.3$

$p_T^{\mu} > 2.5$ GeV, $-0.9 < \eta^{\mu} < 1.3$

$p^{\mu} > 2.5$ GeV, $-1.6 < \eta^{\mu} < -0.9$

Jet selection

$p_T^{\mathrm{jet}1,2} > 7,6$ GeV, $|\eta^{\mathrm{jet}1,2}| < 2.5$

$\mathcal{L} = 110\ \mathrm{pb}^{-1}$

$\eta = -\log(\tan\theta/2)$

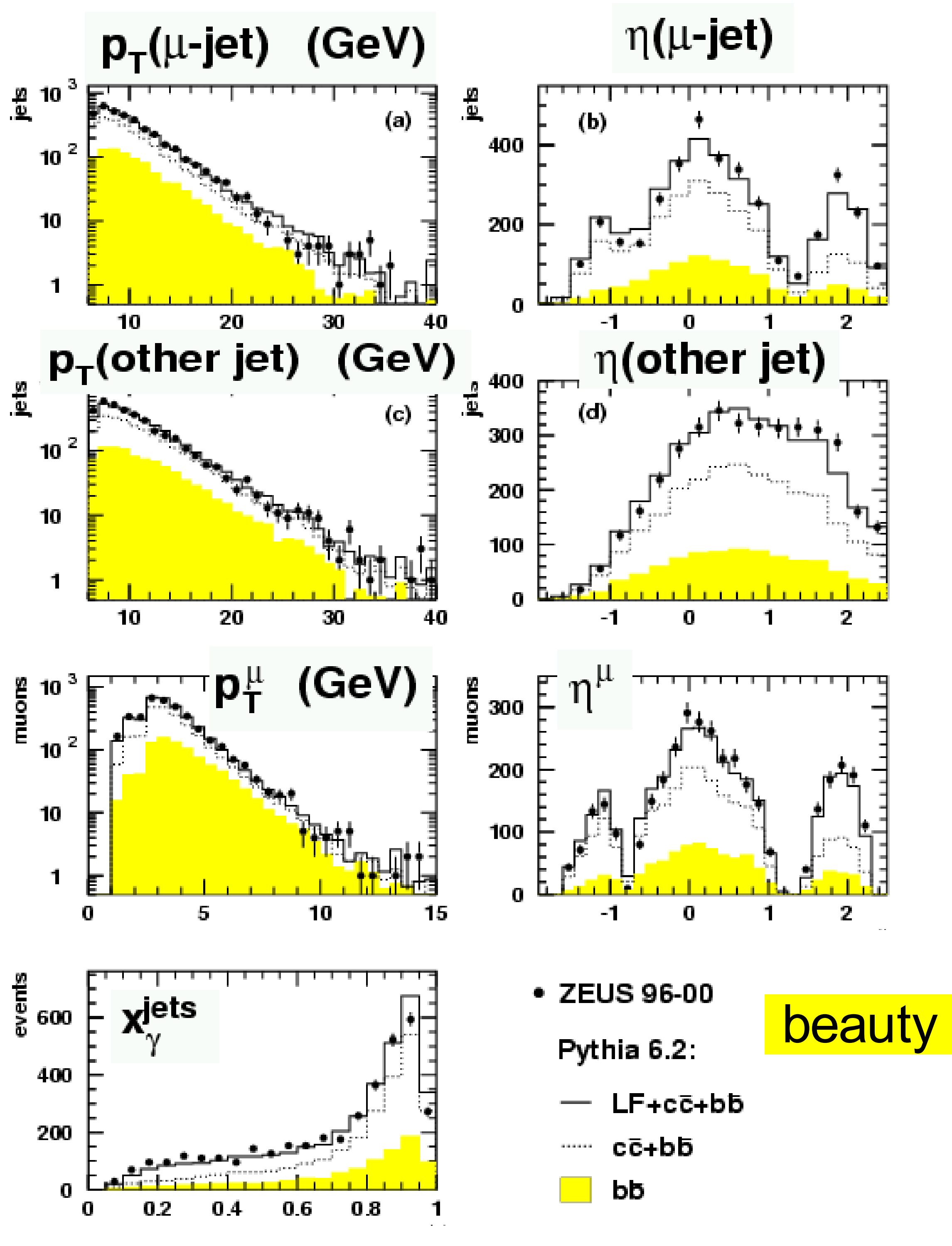
$\eta > 0$ ~ *p direction*

Control plots

- Data compared to the Pythia MC distributions from b c and LF mixed accordingly to PYTHIA cross sections and normalised to the data

- Good agreement between data and Monte Carlo

$$x_\gamma^{\text{jets}} = \frac{\sum_{i=1}^{2}(E-p_z)^{\text{jet}_i}}{E-p_z}$$

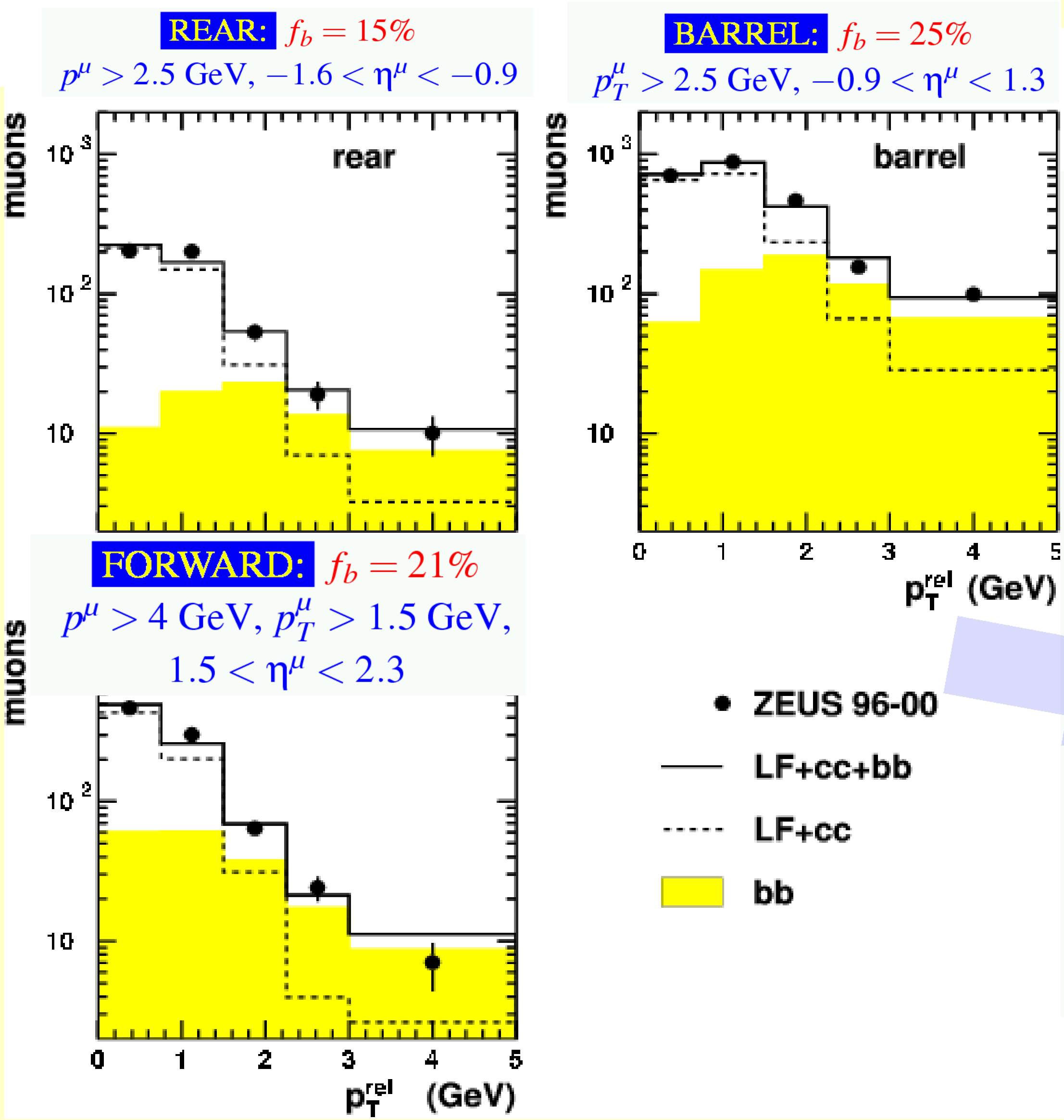


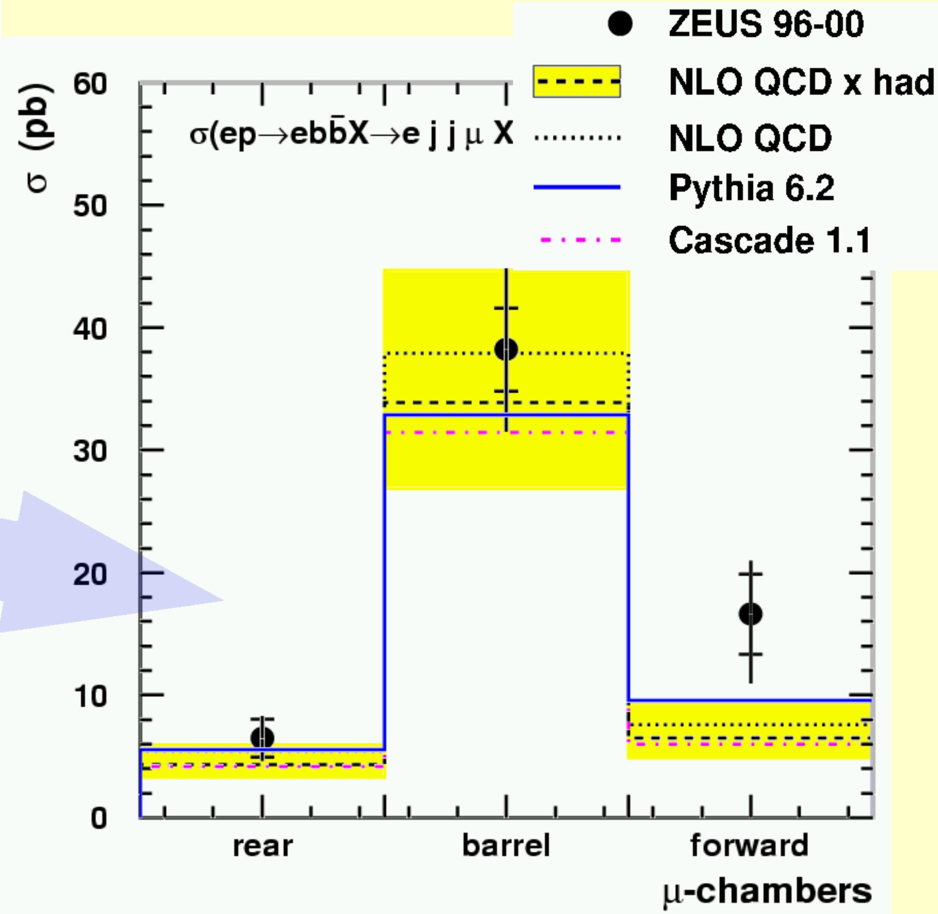
b with μ +dijet in PHP: signal extraction and σ_{vis}

$ep \rightarrow e\, bb\, X \rightarrow e \text{ dijet } X$

$Q^2 < 1$ GeV^2
$0.2 < y < 0.8$
$p_T^{jet1(2)} > 7(6)$ GeV
$|\eta^{jet1(2)}| < 2.5$

b-fraction determined in the region of good acceptance for the muon





Good agreement with NLO and Pythia

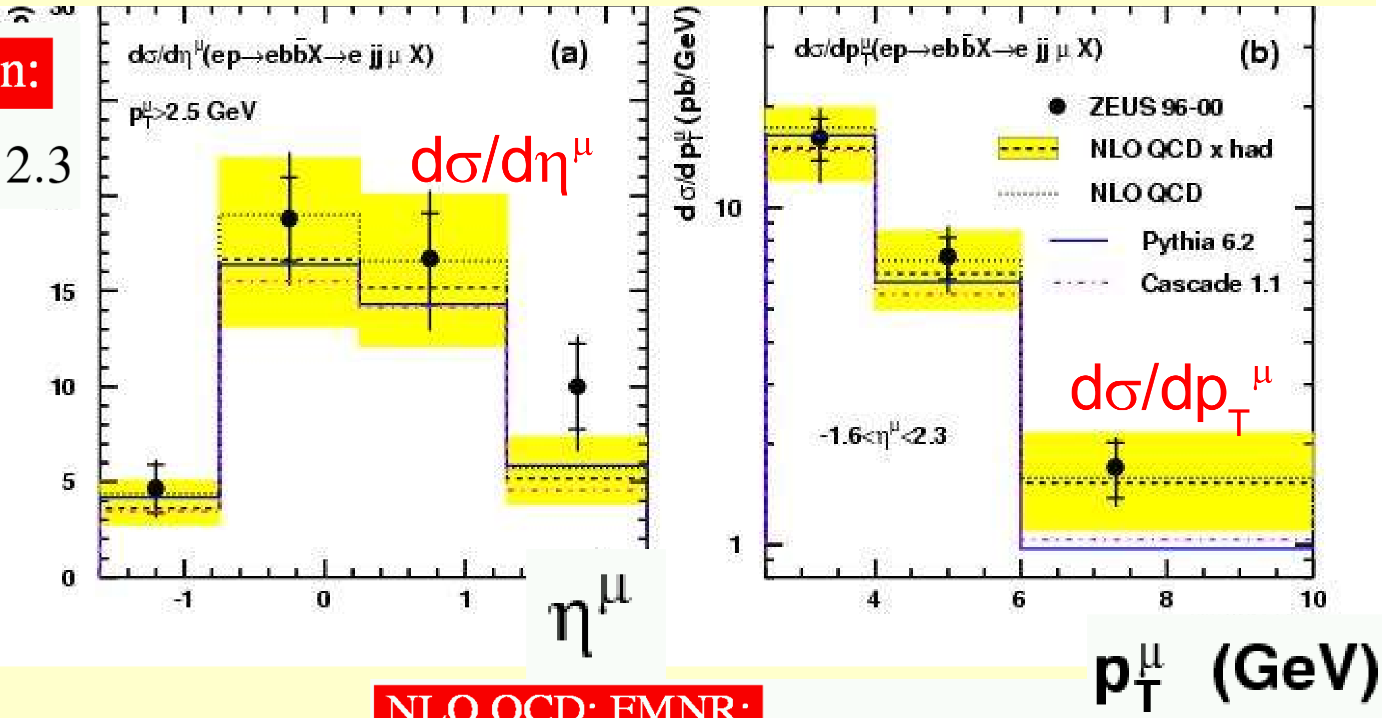
b in μ +dijet in PHP: differential muon σ

- p_T^{rel} fit in each bin

μ kinematic region:

$$p_T^{\mu} > 2.5\ \mathrm{GeV},\ -1.6 < \eta^{\mu} < 2.3$$

Good agreement with NLO and Pythia



Main systematics:

- μ-chambers efficiencies
- shape of the bck p_T^{rel} distribution

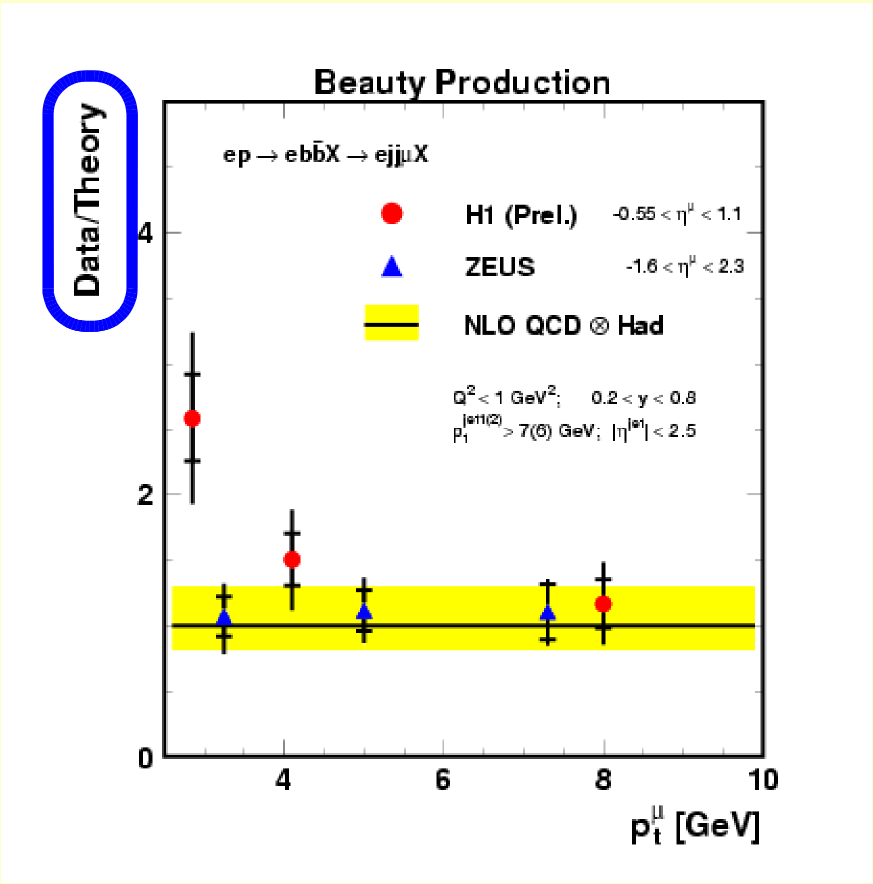
(Pythia 6.2 p_T^{rel} distribution reweighted to a dijet control sample of real data)

NLO QCD: FMNR:

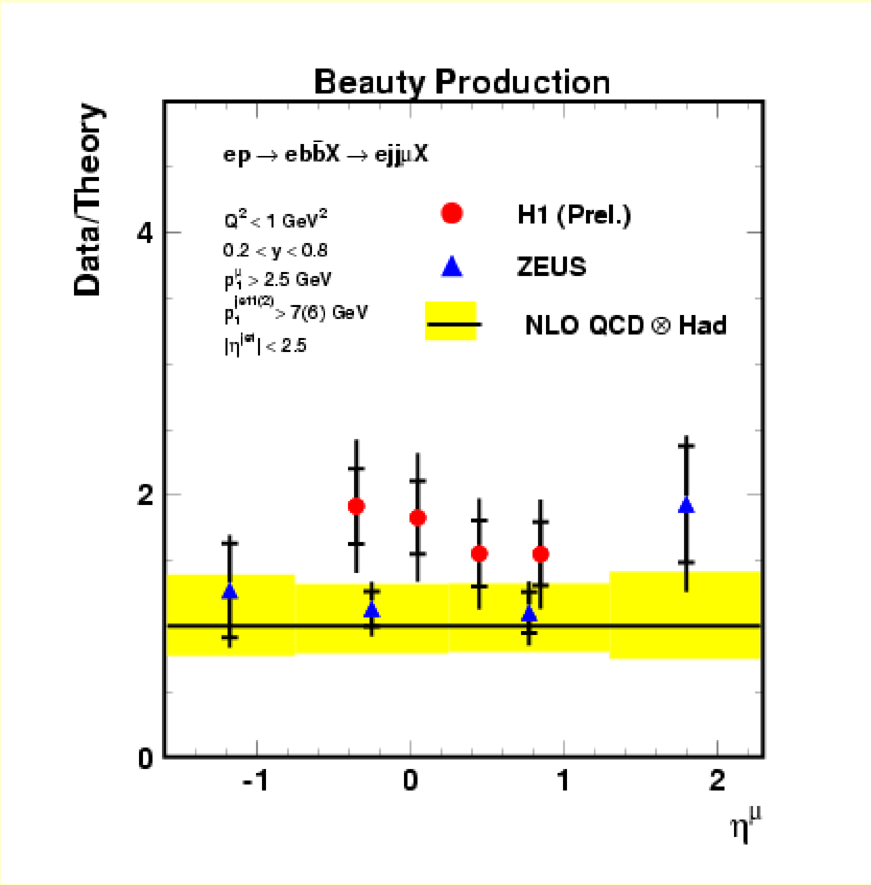
- GRVG-HO for γ, CTEQ5M for p;
- $m_b = 4.75\ \mathrm{GeV},\ \mu = m_T = \sqrt{< p_T^b >^2 + m_b^2}$;
- jets done running k_T on partons;
- parton level jets corrected to hadron level using PYTHIA and HERWIG: from 20% (rear region) to 3% (large p_T^{μ})
- $b \to B$ fragmentation with Peterson, $\varepsilon = 0.0035$;
- $B \to \mu$ according to PYTHIA.

b in μ + dijet for PHP: differential muon σ ZEUS-H1

H1 $p_T^{rel} + \delta$



ZEUS p_T^{rel}

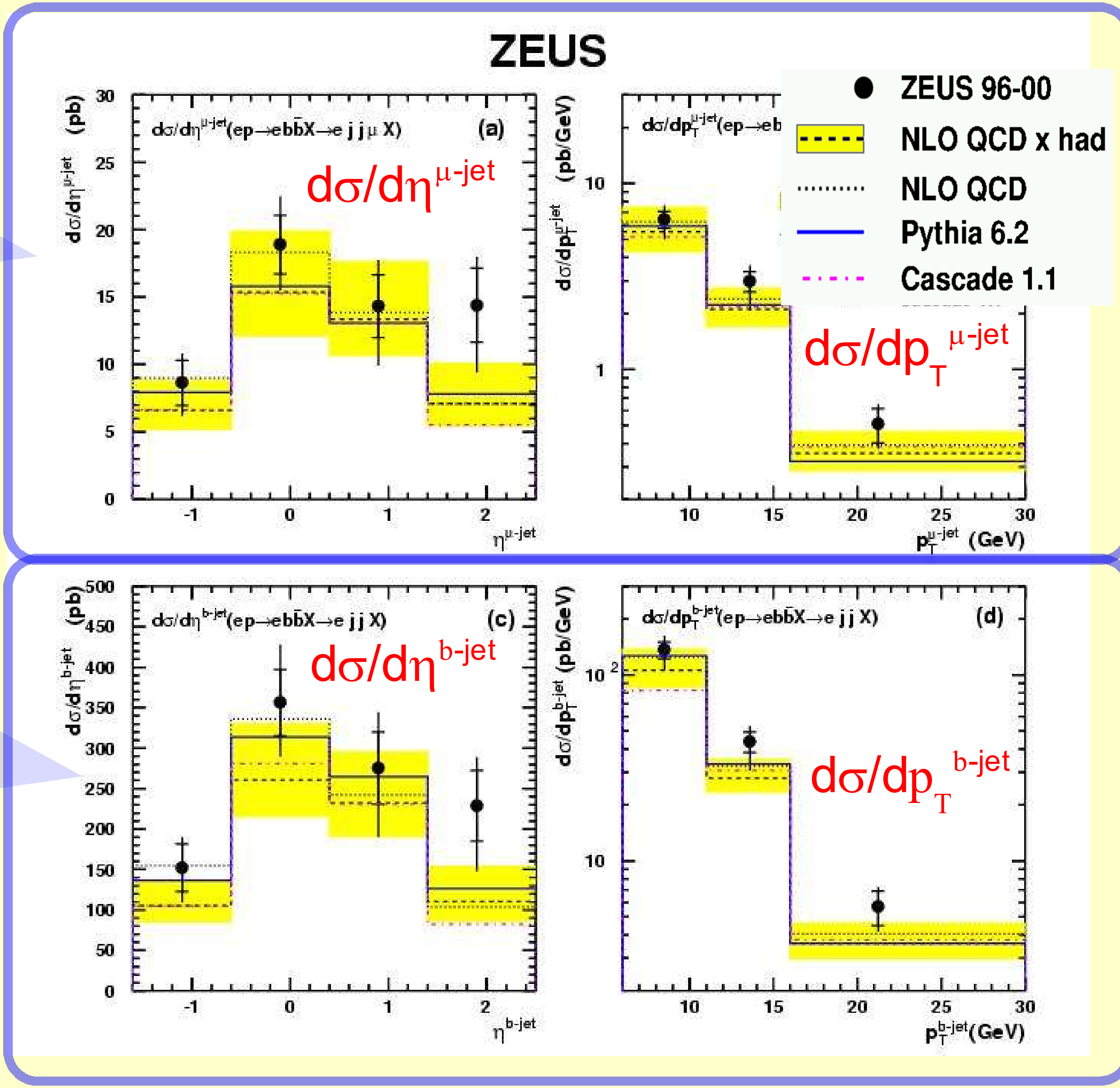


H1 in a more central region gets a poorer agreement with NLO (especially at low p_T^μ)
to be investigated ...

b in μ +dijet in PHP: differential jet σ

- p_T^{rel} fit in each bin

μ-jet

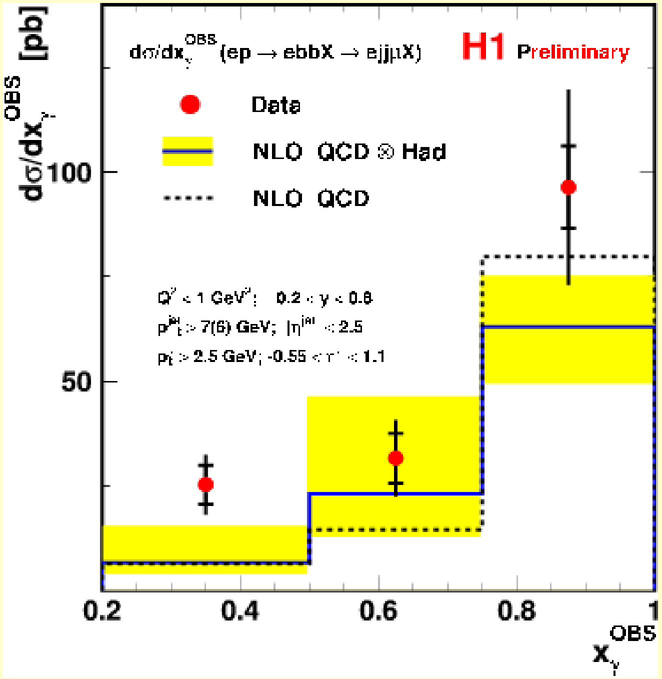


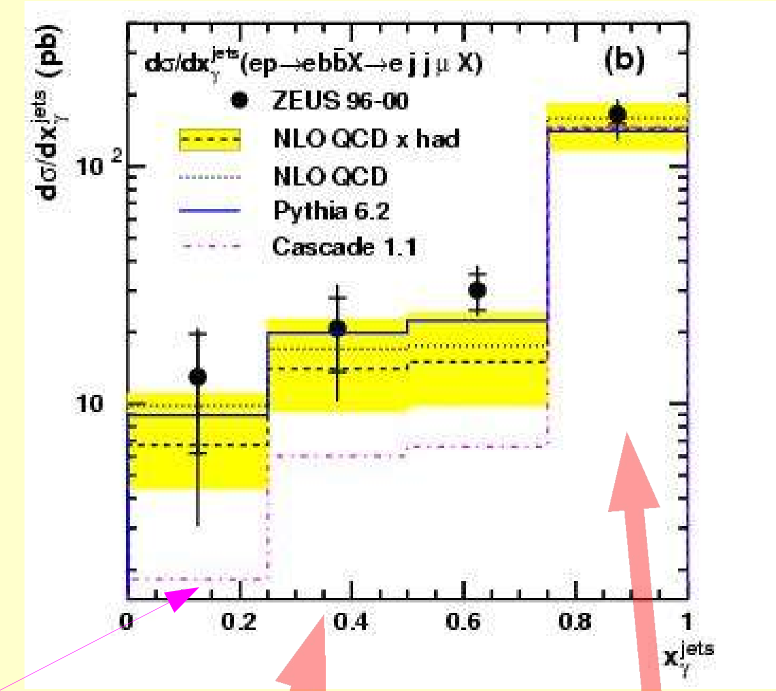
- μ-jet cross sections extrapolated for μ decay and *BR* using Pythia

B-jet

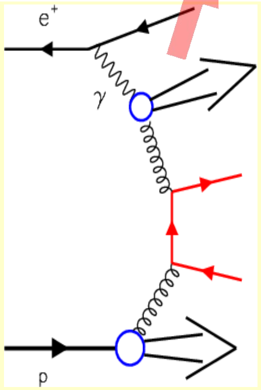
Good agreement with NLO and MC

b in μ + dijet in PHP: direct-resolved production

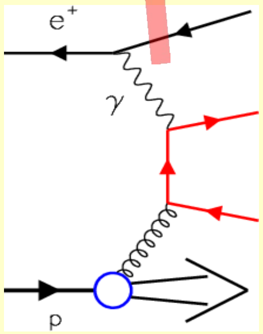




CASCADE tends to underestimates the hadronic component



Resolved (hadronic) γ

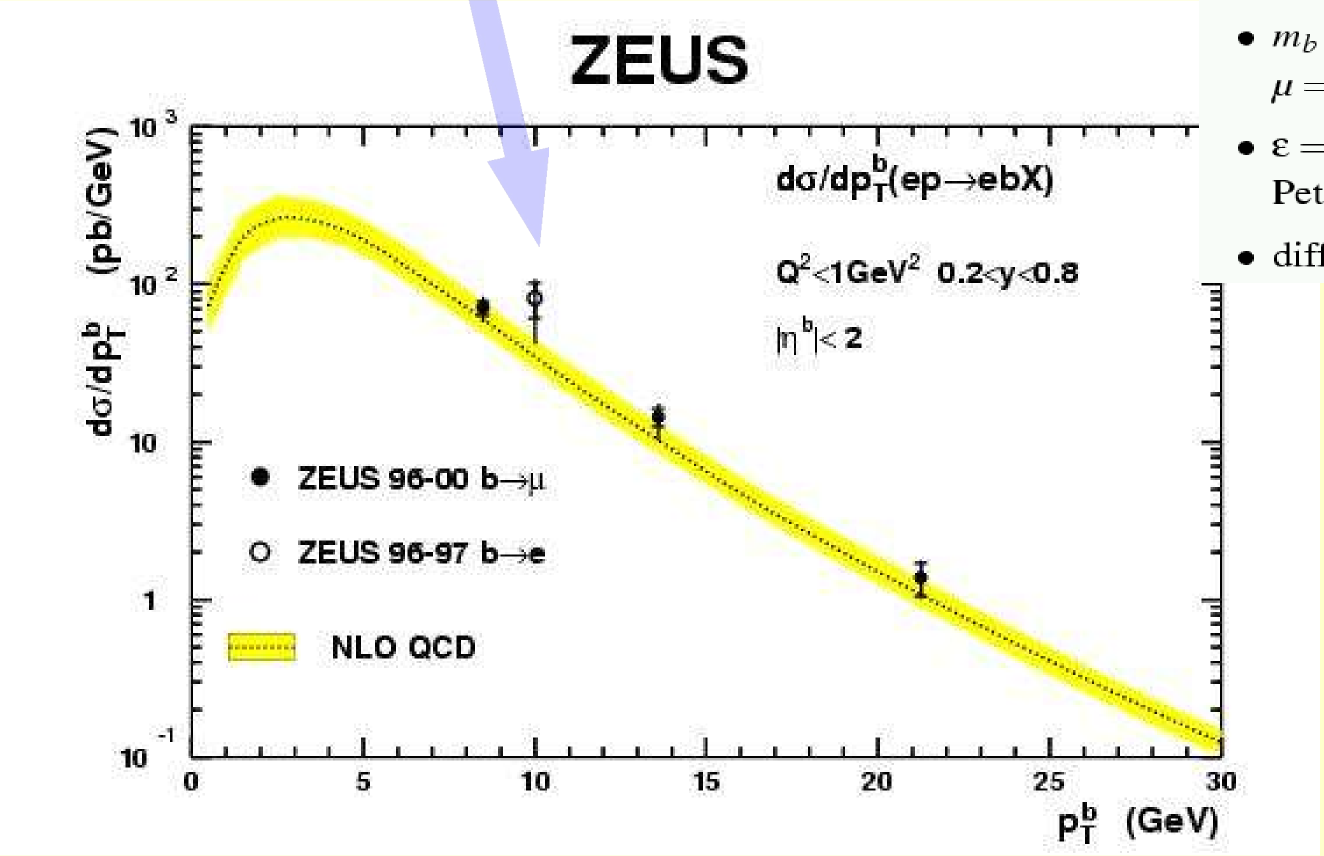


Direct (pointlike) γ

Summary of the ZEUS b- in PHP measurements

To be extended soon with more statistics

Cross section for b-quark extrapolated using NLO calculations



Uncertainty on NLO calculations:

- $m_b = 4.5$ GeV, $\mu = m_T/2 \rightarrow m_b = 5.0$ GeV, $\mu = 2m_T$: variations from +34% to -22%;
- $\varepsilon = 0.0020 \rightarrow \varepsilon = 0.0055$, Peterson to Kartvelishvili: $\pm 3\%$;
- different parton densities and $\Lambda^{(5)}_{QCD}$: $\pm 4\%$.

Good agreement with NLO and previous measurements

... low $p_T^{\ b}$ region to be covered with the $\mu + D^*$ analysis (see next)

Beauty in Deep Inelastic Scattering

Production believed to be dominated by direct photon processes

- p_T^{rel} fit in each bin

ZEUS p_T^{rel}

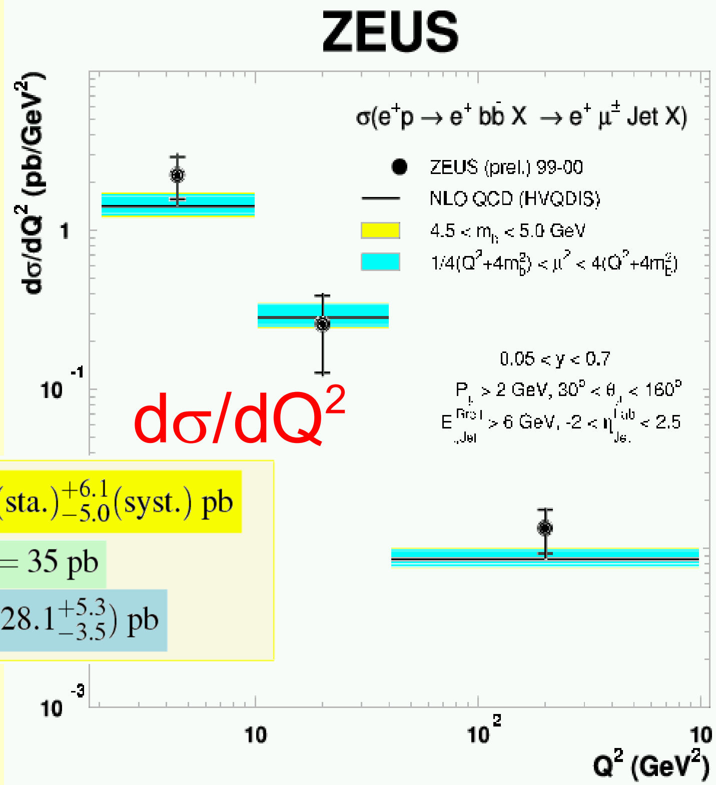
$\mathcal{L}$ = 60 pb^{-1}

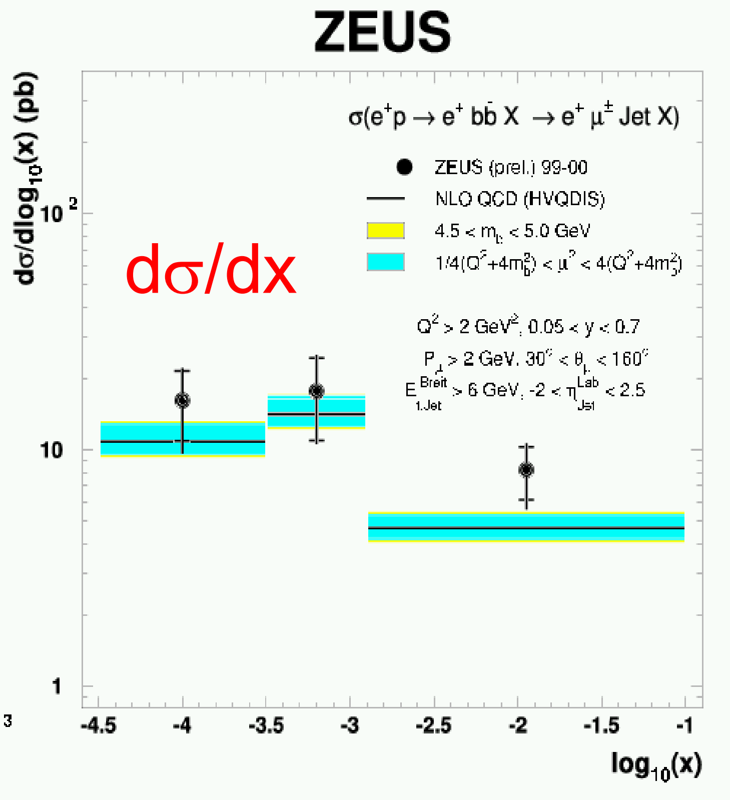
Q^2 > 2 GeV^2
0.05 < y < 0.7
p^{μ}>2 GeV 30° < θ^{μ} < 160°
$E_t^{jet,BREIT}$> 6 GeV
-2< η^{jet} < 2.5

$\sigma_{vis}(ep \to eb\bar{b}X \to e\mu jetX) = 38.7 \pm 7.7(\text{sta.})^{+6.1}_{-5.0}(\text{syst.})$ pb

CASCADE MC (CCFM)	$\sigma_{vis} = 35$ pb
NLO-DGLAP (HVQDIS)	$\sigma^{NLO}_{vis} = (28.1^{+5.3}_{-3.5})$ pb

Good agreement with NLO





H1

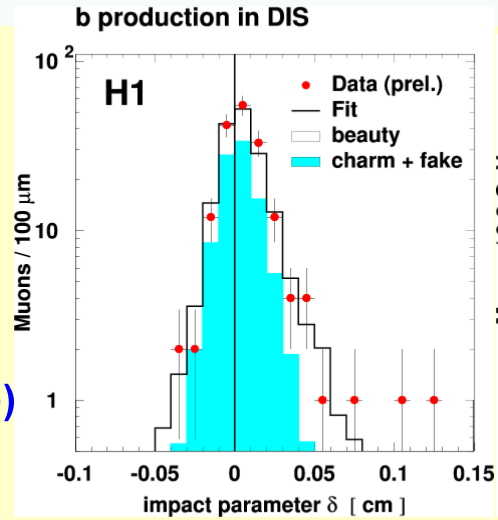
p_T^{rel}+ δ

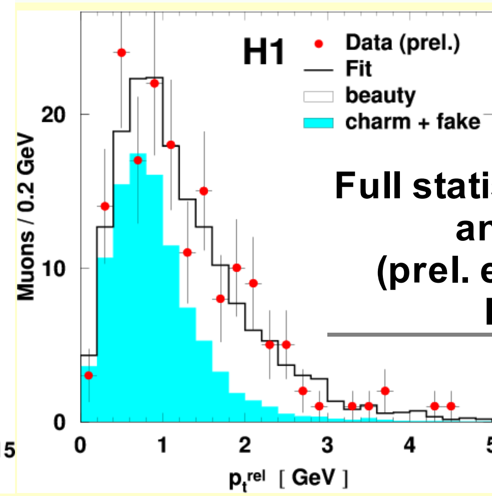
$\mathcal{L}$ = 10.5 pb^{-1}

Q^2 > 2 GeV^2
0.05 < y < 0.7
p_T^{μ}>2 GeV 35° < θ^{μ} < 130°

σ_{vis} = (39 $\pm$ 8 (stat.) $\pm$ 10(sys.))

σ_{vis}^{NLO} = (11 $\pm$ 2) pb

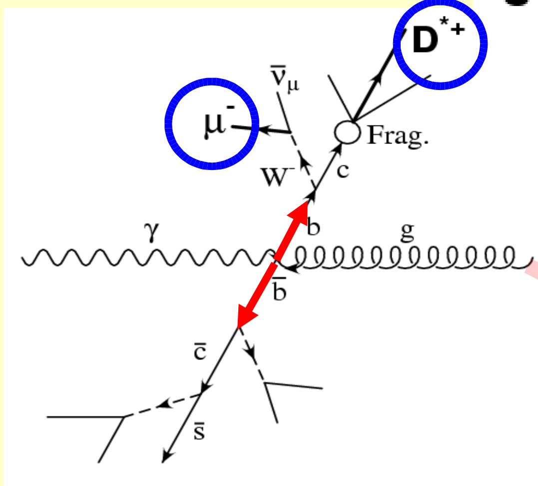


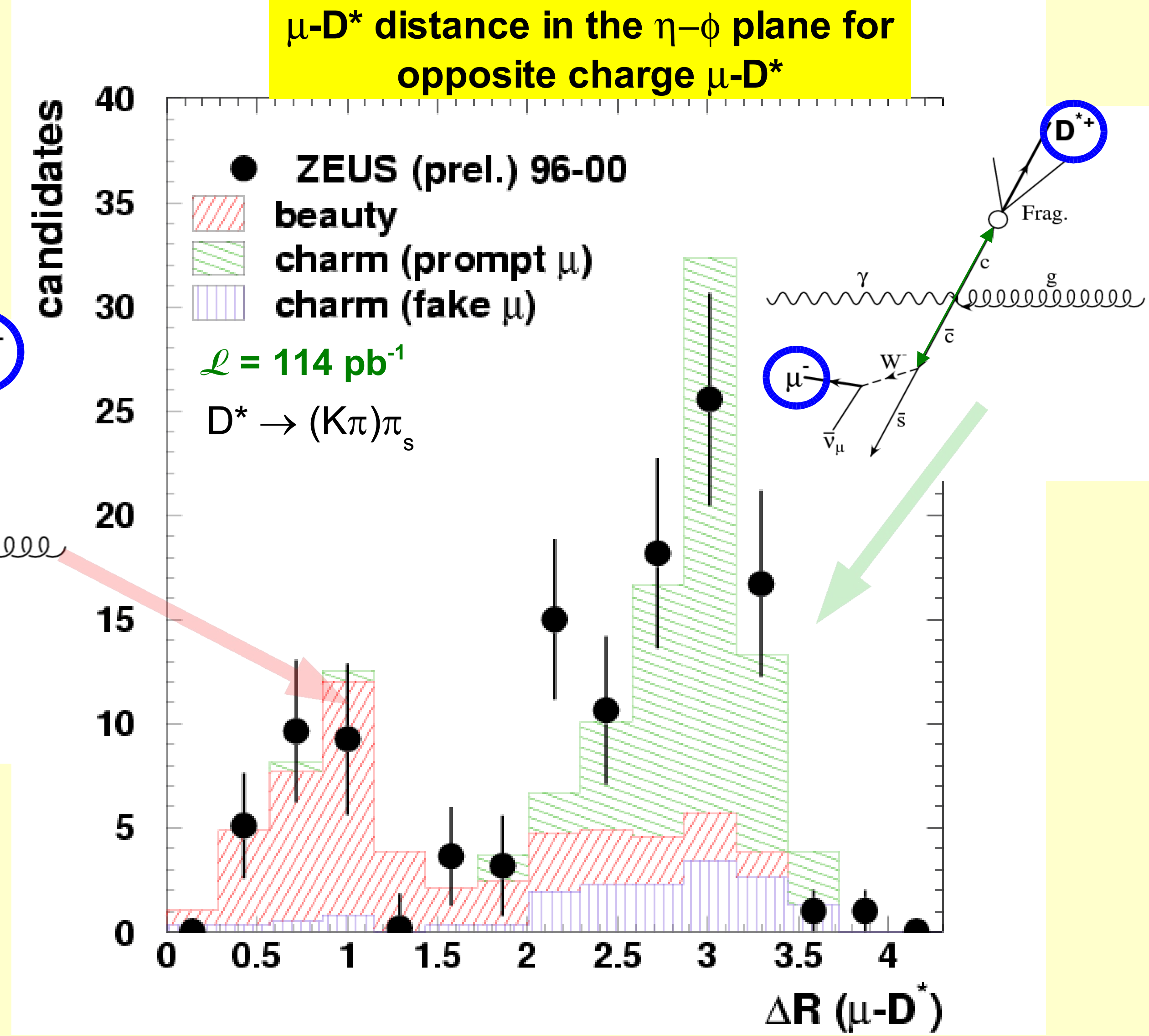


Full statistics still to be analysed (prel. expected for DIS04)

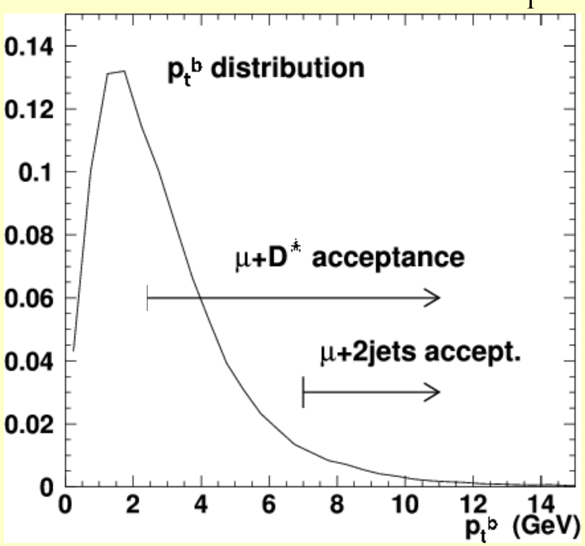
Beauty with a μ + D* tag

Exploits signal extraction by studying μ-D* correlations in angle and charge





Method sensitive to low $p_T^{\,b}$ values where the bulk of the cross section sits (no jets involved, lower p_T cuts)



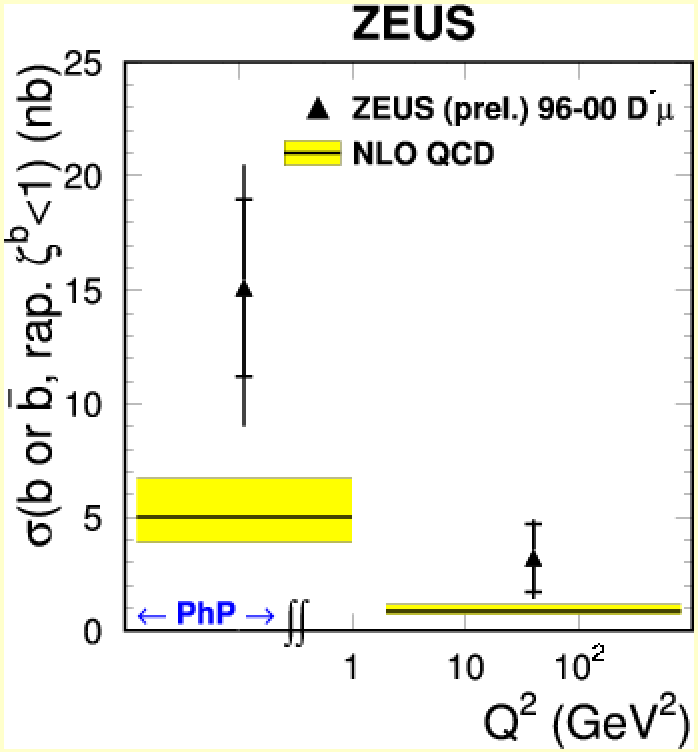
- Like sign sample used as control sample (beauty+fake muons)
- μ-D* systems provides info on the originating b-quark
- differential cross section in $p_T^{\,b}$ and $y_{rap}^{\,b}$ being worked out
- Increase in statistics by adding the $D^* \to (K\pi\pi\pi)\pi_s$ channel

μ + D* : comparison with NLO

- PHP and DIS σ_{vis} converted at **b-quark level** with Monte Carlo hadronisation models to compare with NLO calculations (FMNR for PHP and HVQDIS for DIS)

  $y_{rap}^{b} < 1$
  no p_T^{b} cut
  $Q^2 < 1$ GeV^2 + $0.05 < y < 0.85$ in PHP
  $Q^2 > 2$ GeV^2 + $0.05 < y < 0.7$ in DIS

- The μ–spectrum in the B^0 CMS as implemented in the PYTHIA MC has been checked to reproduce the measured one (at the B-factories with e).



Data tends to be above NLO

$$\sigma_{PHP}(ep \to b\bar{b}X) = 15.1 \pm 3.9\ (\text{stat.})\ {}^{+3.8}_{-4.7}\ (\text{sys.})\ \text{nb}$$

$$\sigma_{DIS}(ep \to b\bar{b}X) = 3.2 \pm 1.5\ (\text{stat.})\ {}^{+0.9}_{-1.0}\ (\text{sys.})\ \text{nb}$$

NLO (FMNR, HVQDIS)

$$\sigma^{NLO}_{PHP}(\gamma^* p \to bb\,X) = 5.0^{+1.7}_{-1.1}\ \text{nb}$$

$$\sigma^{NLO}_{DIS}(ep \to bb\,X) = 0.87^{+0.28}_{-0.16}\ \text{nb}$$

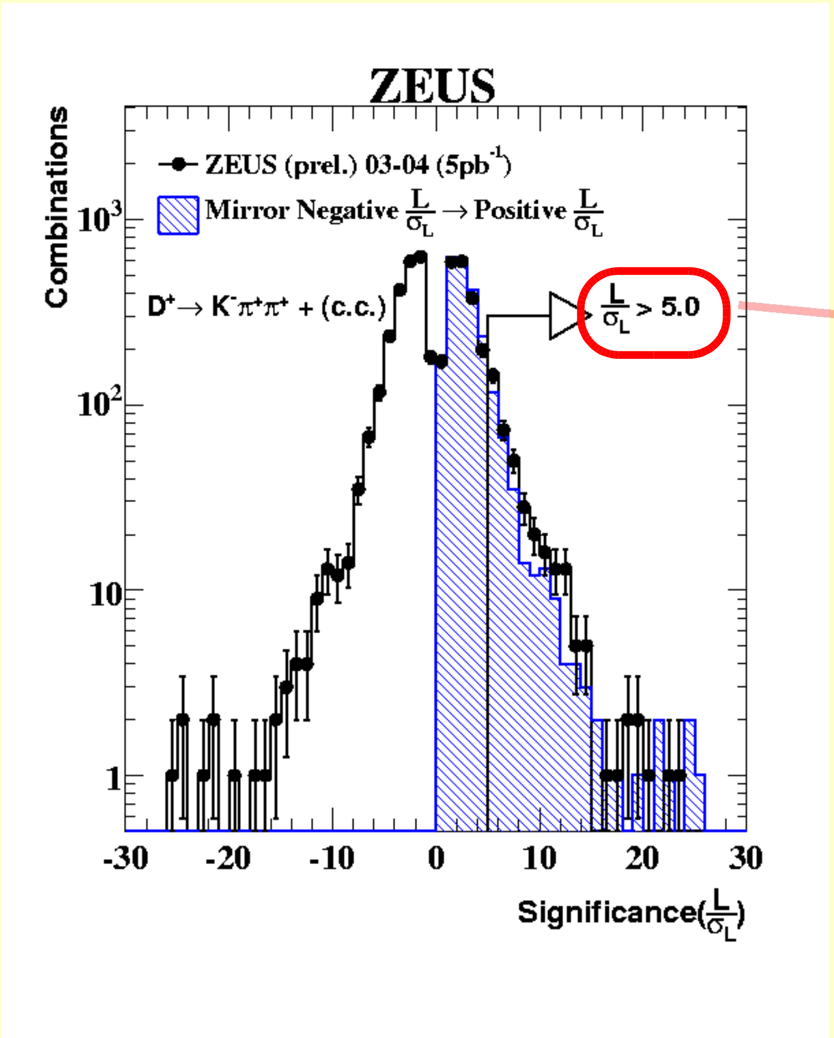
- H1 results compared to LO: **Charm** : Data / LO (Aroma) = 1.8
  Beauty : Data / LO (Aroma) = 3.6

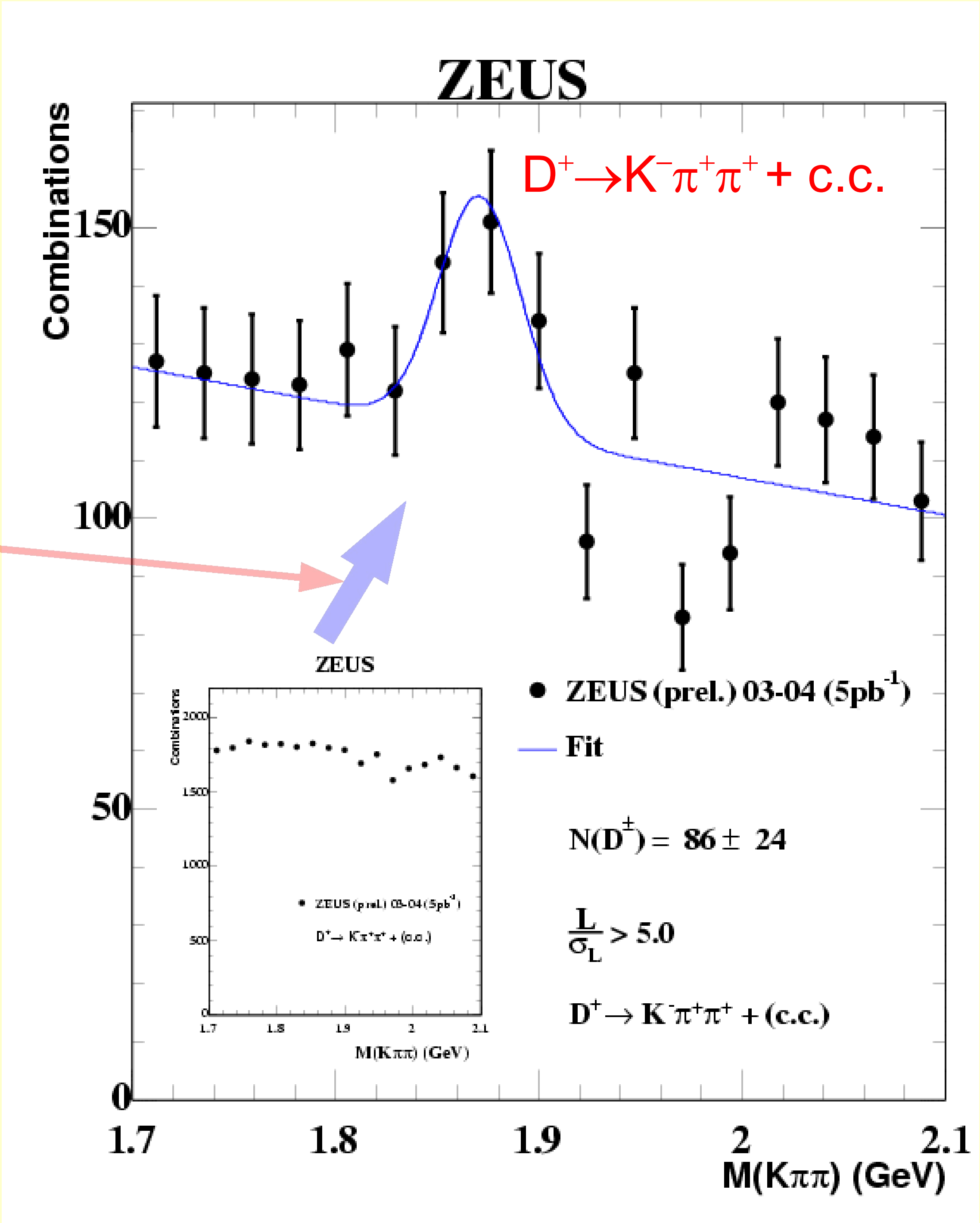
Conclusions and Outlook

- Heavy flavour production in *ep* collisions is a good testing ground for pQCD
- Charm production:
  - Precise studies possible in perturbative and non perturbative sector!
  - Reasonable agreement with expectations, some aspects need further clarification (deviation in certain phase space regions ... i.e. high η)
- Beauty production
  - Measured with μ+dijet (high statistics) and μ+D* (complementary: low p_T^b) in both PHP and DIS.
  - Good agreement with NLO (ZEUS). Slight excess (H1)
  - Excess in μ+D* (to be confirmed with more stats !)
- HERA II higher luminosity and new detectors in both H1 and ZEUS (better tracking, displaced vertices, better coverage of forward region) will contribute to resolve the remaining issues

$D^{\pm}$ reconstruction with new data

The newly commissioned ZEUS MicroVertexDetector is working properly



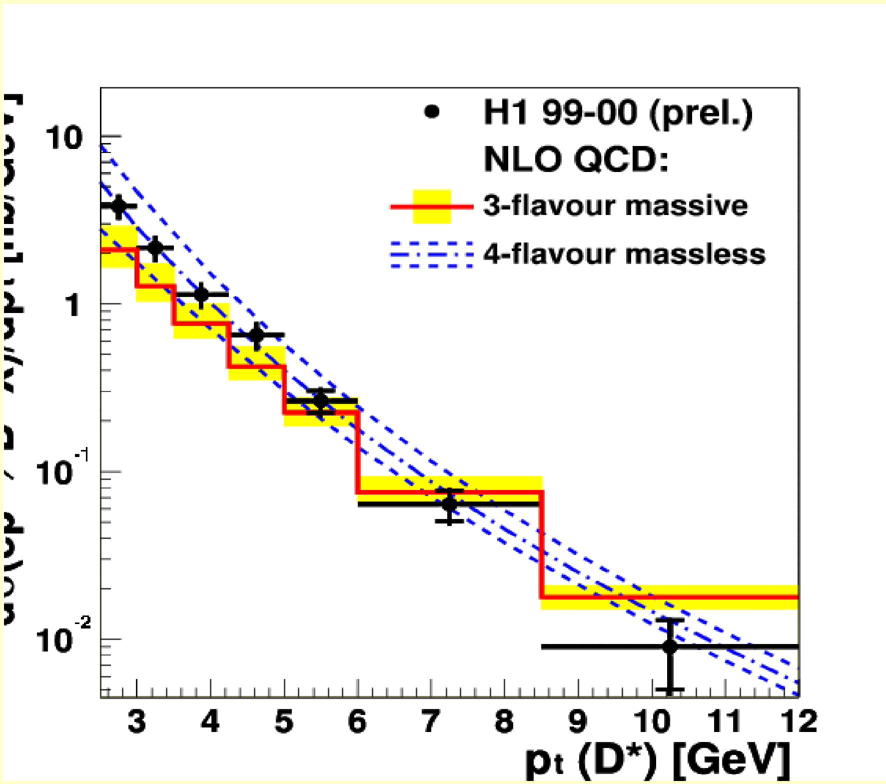


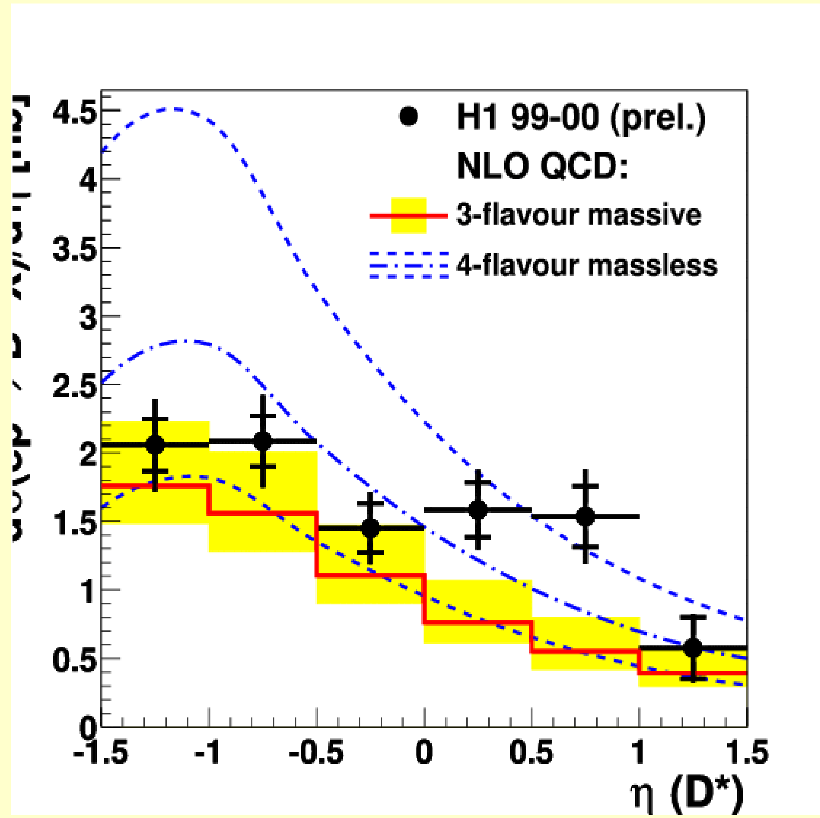
PYTHIA 6.2:

- includes direct, resolved and flavour excitation (27%) processes;
- b–quark string fragmentation with Peterson, $\varepsilon = 0.0041$;
- branching–ratios for b decay, $b \to \mu X$ and via cascade, taken from the PDG;
- $B \to \mu$ momentum spectrum checked with measurements from Belle and BaBar;

CASCADE 1.1:

- k_T factorisation;
- CCFM evolution for the proton parton densities;
- Peterson fragmentation, $\varepsilon = 0.0041$.





CTEQ5M1 + AGF structure functions

$m_c = 1.5 \pm 0.2$ GeV $\mu_0 = \sqrt{m_c^2 + p_T^2}$

$\mu_R = \mu_F = \mu$

$\mu_0/2 < \mu < \mu_0$

$f(c \rightarrow D^*) = 0.235$ $\varepsilon = 0.035$ *(FO NLO)* ,
0.02 (FONLL)