Heavy Flavour Production at HERA

Benno List

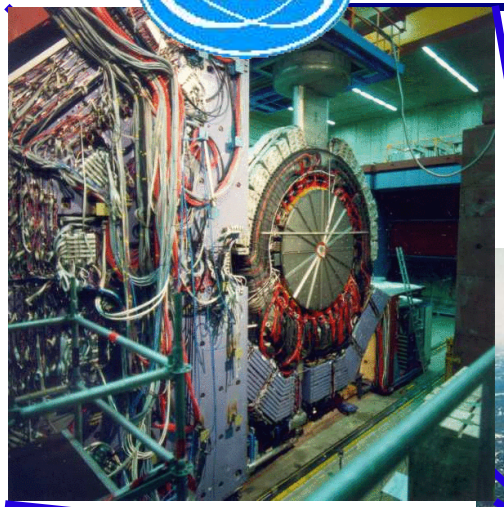
ETH Institute for Particle Physics

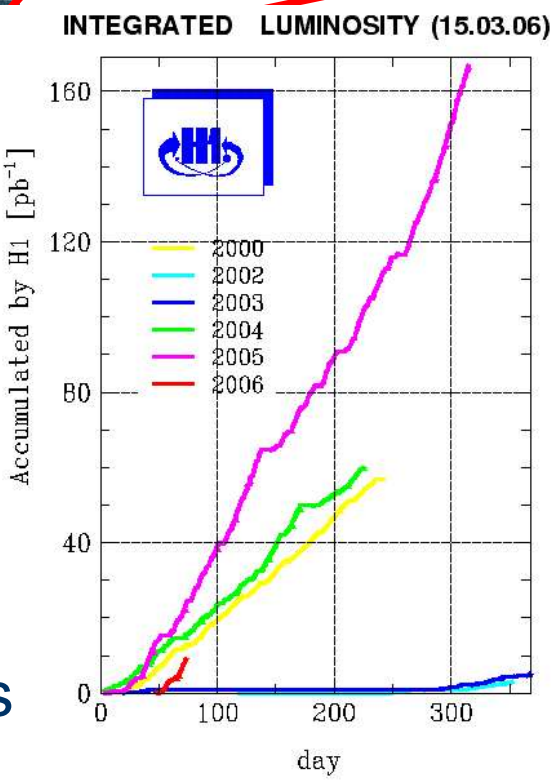
XLI[st] Rencontres de Moriond on QCD 2006

La Thuile, March 20, 2006

- Introduction
- Charm Production
- Beauty Production

HERA, H1, and ZEUS



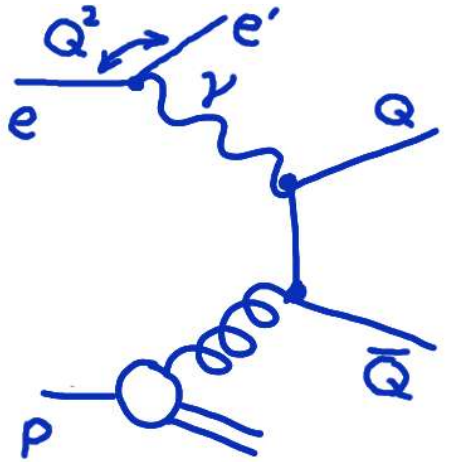


- 27.5GeV e± on 920GeV p => √s=320GeV
- HERA-I: 1992-2000: => publications
- HERA-II: 2003-2007: => 1st preliminary results

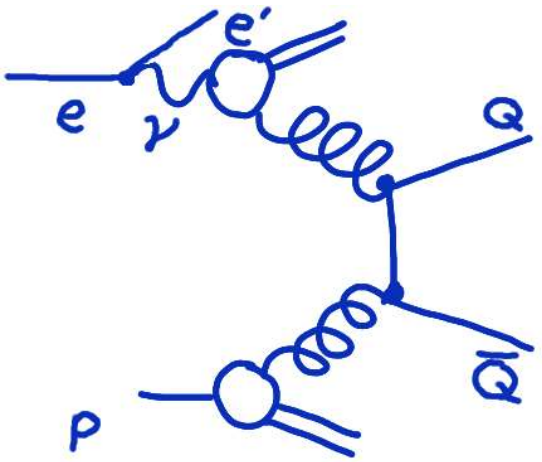
Heavy Flavour Production in ep Scattering

- Mechanism: Boson gluon fusion
- Expect 2 charm/beauty jets back to back
- Different scales to make α_s small:
  - Quark mass (fully inclusive photoproduction)
  - Jet p_t (photoproduction with jets)
  - Photon virtuality (deep inelastic scattering DIS)
- Theoretical challenges:
  - Massive vs. massless treatment of heavy quarks
  - Intrinsic gluon k_t
  - Direct vs. resolved production
- x_γ^{obs}: Fraction of photon momentum carried by jet pair: Distinguishes between direct ($x_\gamma \sim 1$) and resolved ($x_\gamma << 1$) production

„Direct“



„Resolved“



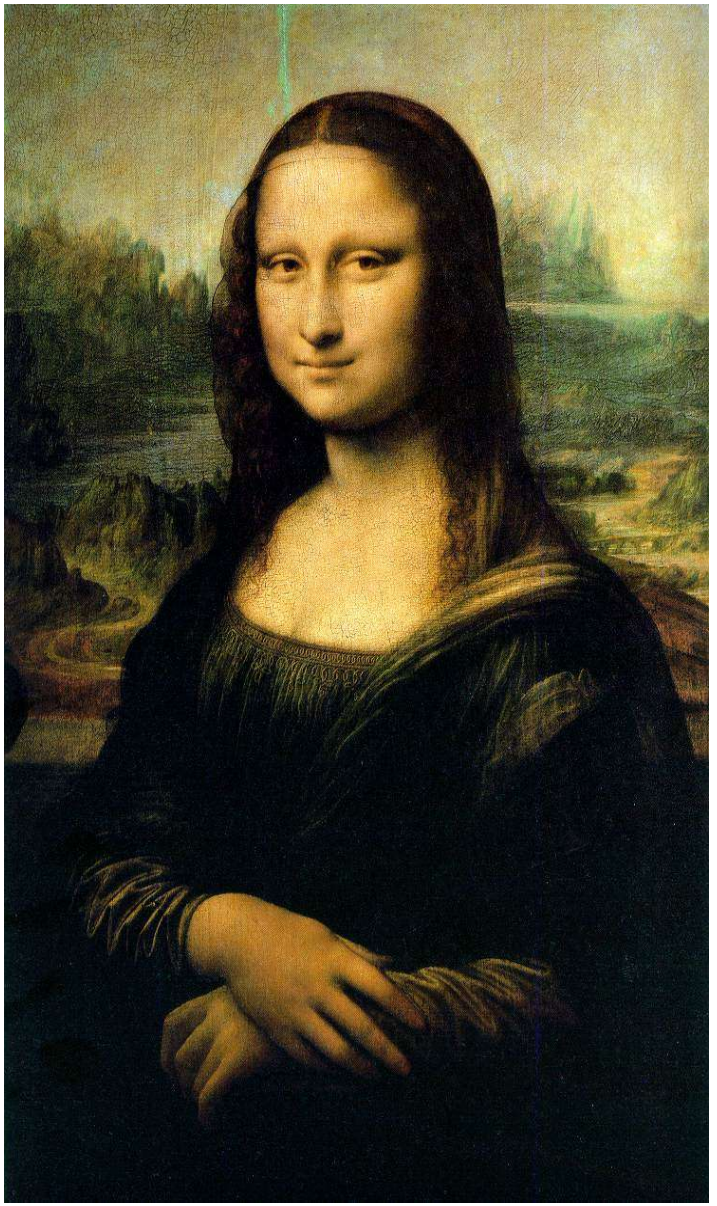
Charm

Techniques:

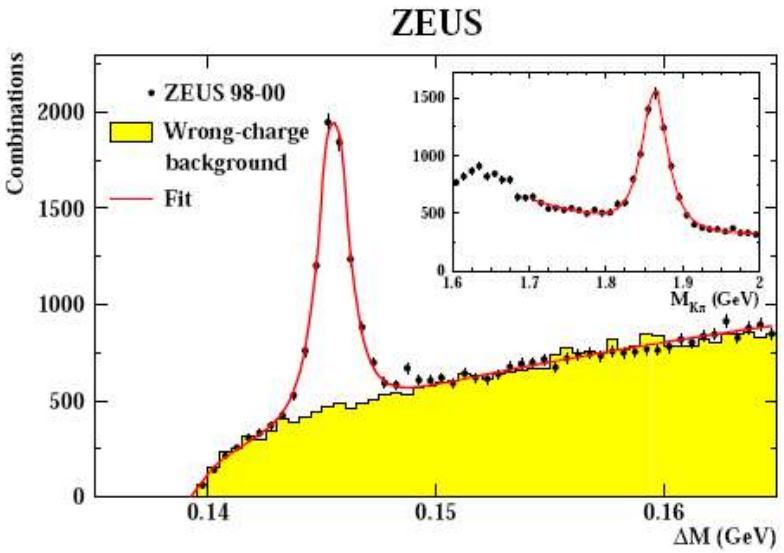
- D* tagging
- Lifetime tagging

Results:

- Charm + jets cross sections
- Inclusive cross sections in DIS

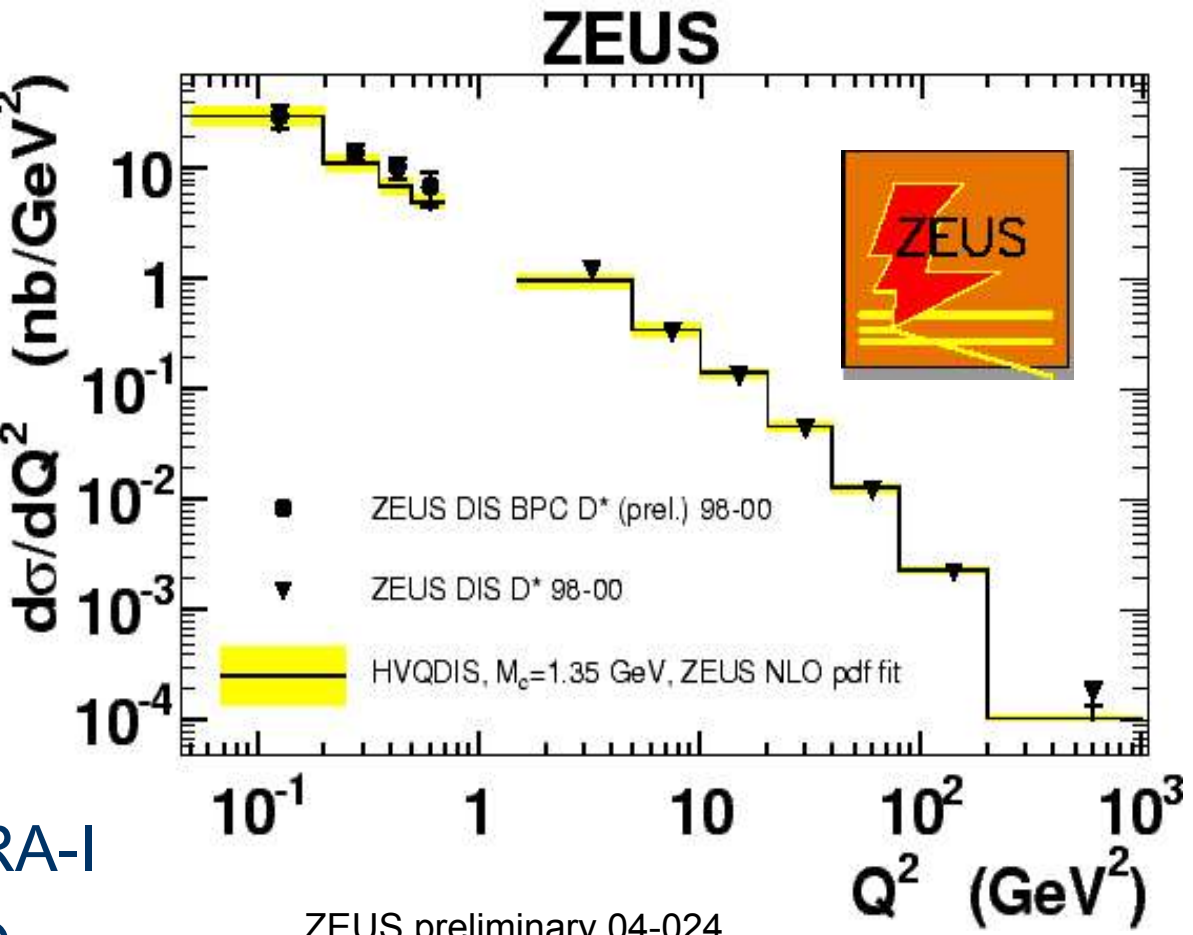


Charm Tagging via D* Production



ZEUS, PR **D69** (2004) 012004.

$$D^* \rightarrow (K\pi)\,\pi_s$$

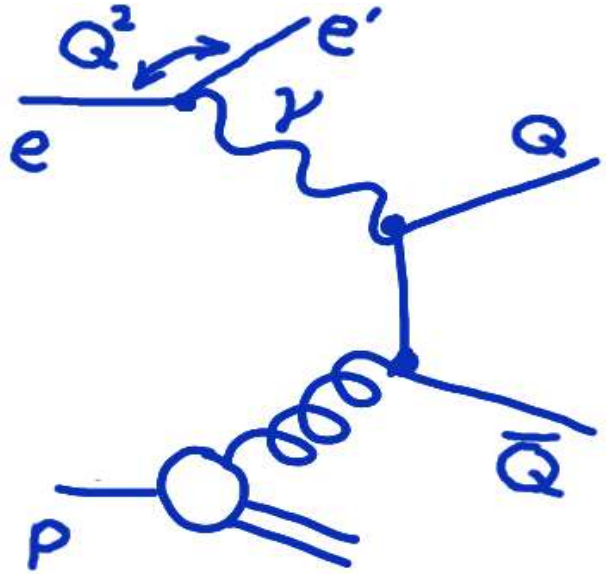


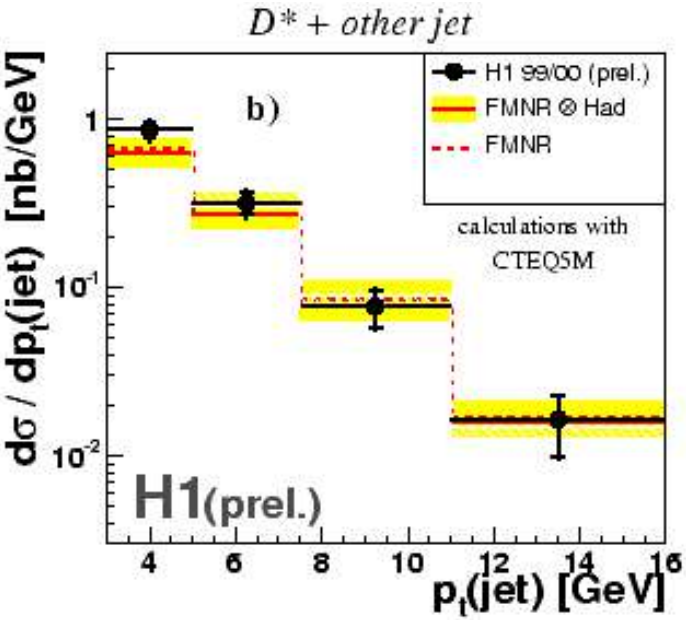
ZEUS preliminary 04-024.
ZEUS, PR **D69** (2004) 012004.

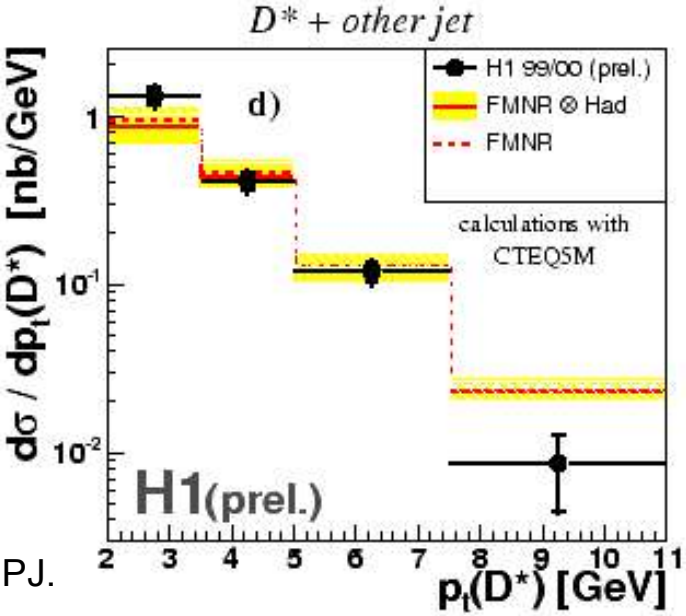
- Large D* Samples from HERA-I
- Well described by NLO QCD
- Q^2 evolution measured over 4 orders of magnitude

Charm with Jets in Photoproduction

- H1 measurement:
  - Events with a reconstructed D* + 2nd jet in photoproduction
- p_t spectra of D* and jet well described by NLO QCD (FMNR Frixione *at al.* PL B348(1995) 63)



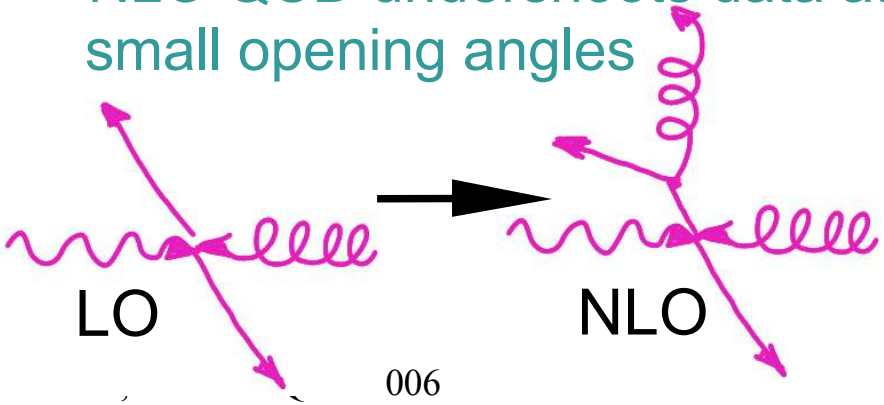




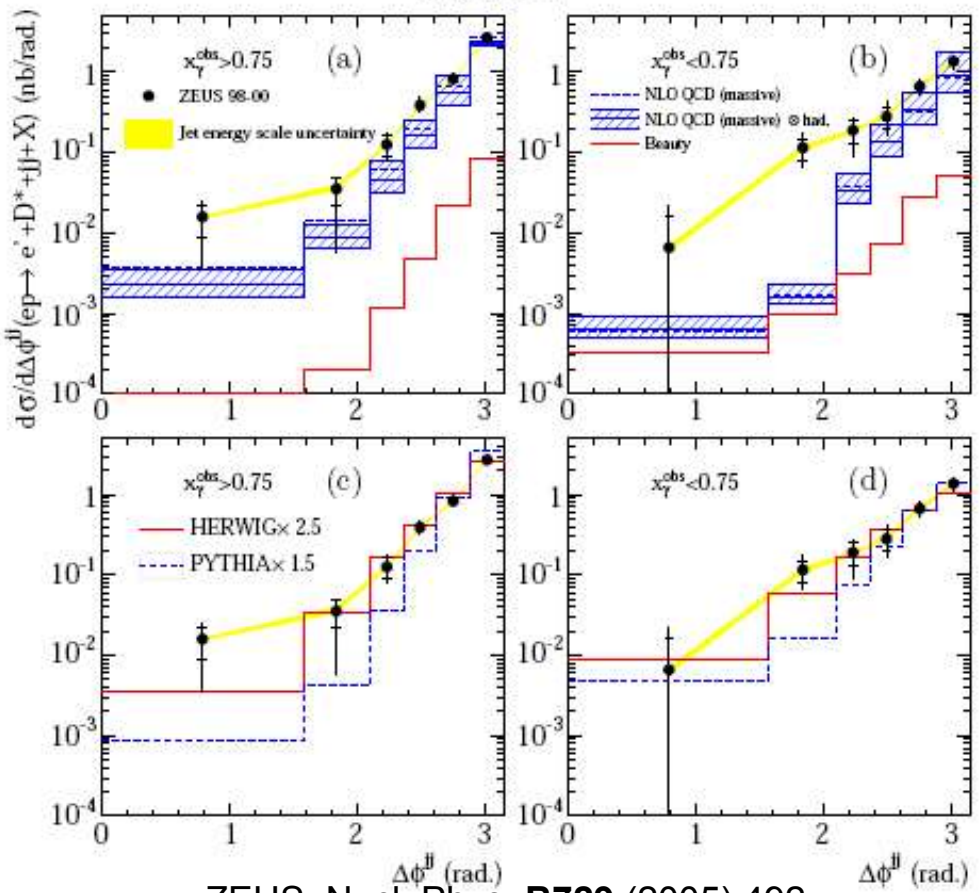
H1prelim-05-073, to be published in EPJ.

Dijets with Charm: Testing NLO QCD

- Leading order: Quarks are back-to-back
- Additional gluons: Angle between jets smaller than π
- ZEUS measurement:
  - Dijet event in photoproduction
  - D* tagged
- Direct part ($x_\gamma^{obs}>0.75$):
  - Reasonably described by massive NLO QCD (FMNR)
- Resolved part ($x_\gamma^{obs}<0.75$):
  - NLO QCD undershoots data at small opening angles

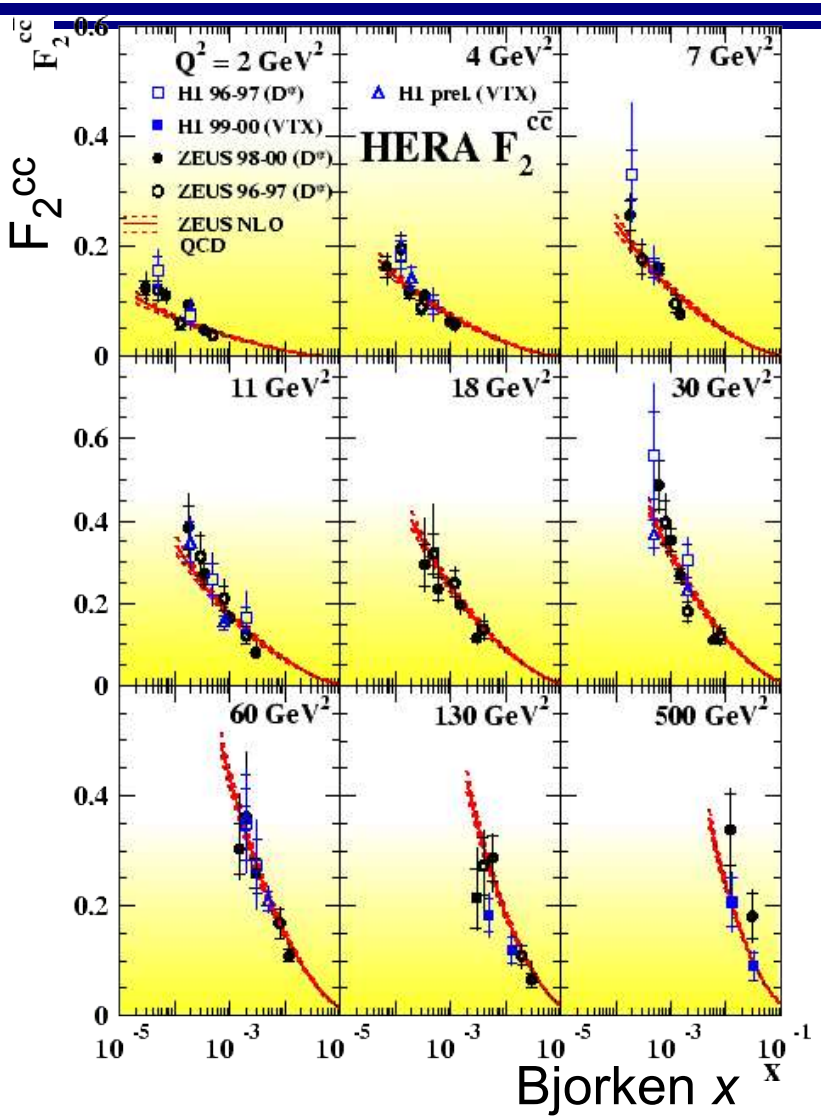


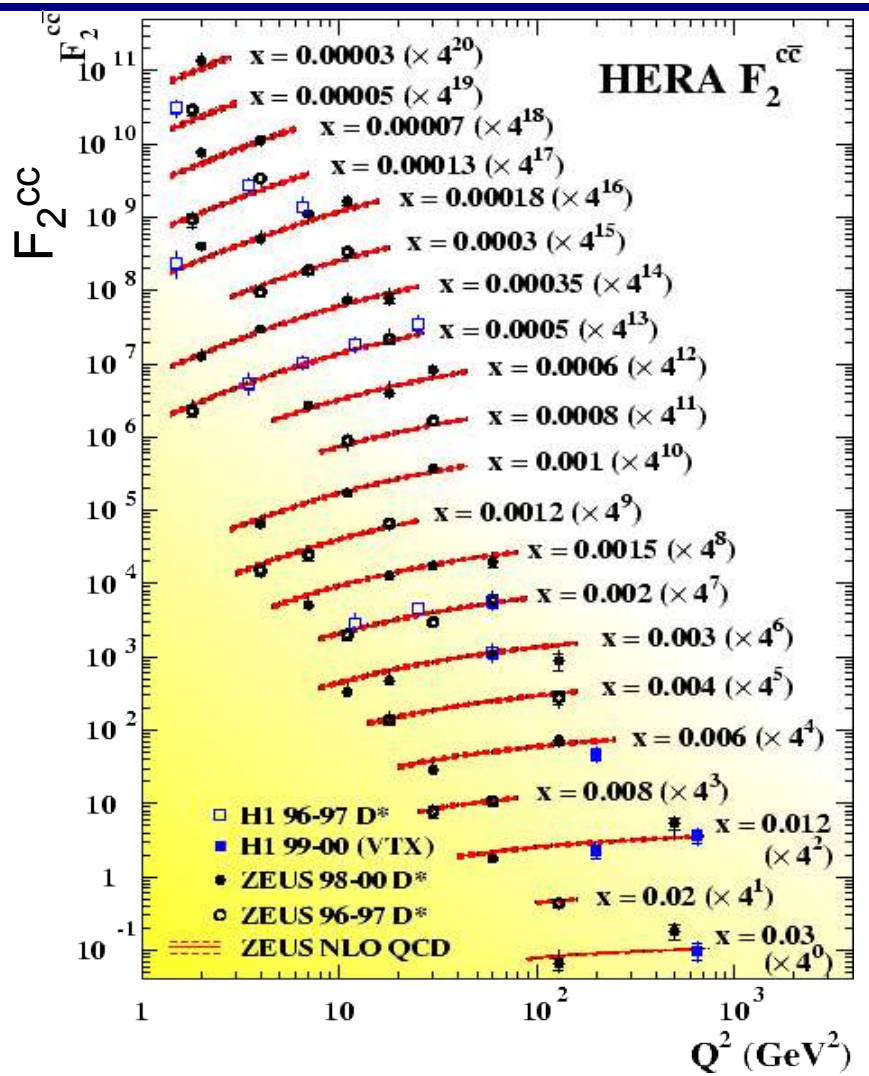
„Direct“ ($x_\gamma^{obs}>0.75$) **„Resolved“ ($x_\gamma^{obs}<0.75$)**



ZEUS, Nucl. Phys. **B729** (2005) 492.

Charm in DIS ($F_2^{c\bar{c}}$): The Harvest from HERA-I





- NLO QCD fit with gluon from inclusive DIS fits well
- At low Q^2: Slight deviations; Charm constrains gluon better than F_2

ZEUS, PR **D69**(2000)012004.
H1, EPJ **C40** (2005) 349.
H1, EPJ **C45** (2006) 23.

Beauty

Techniques

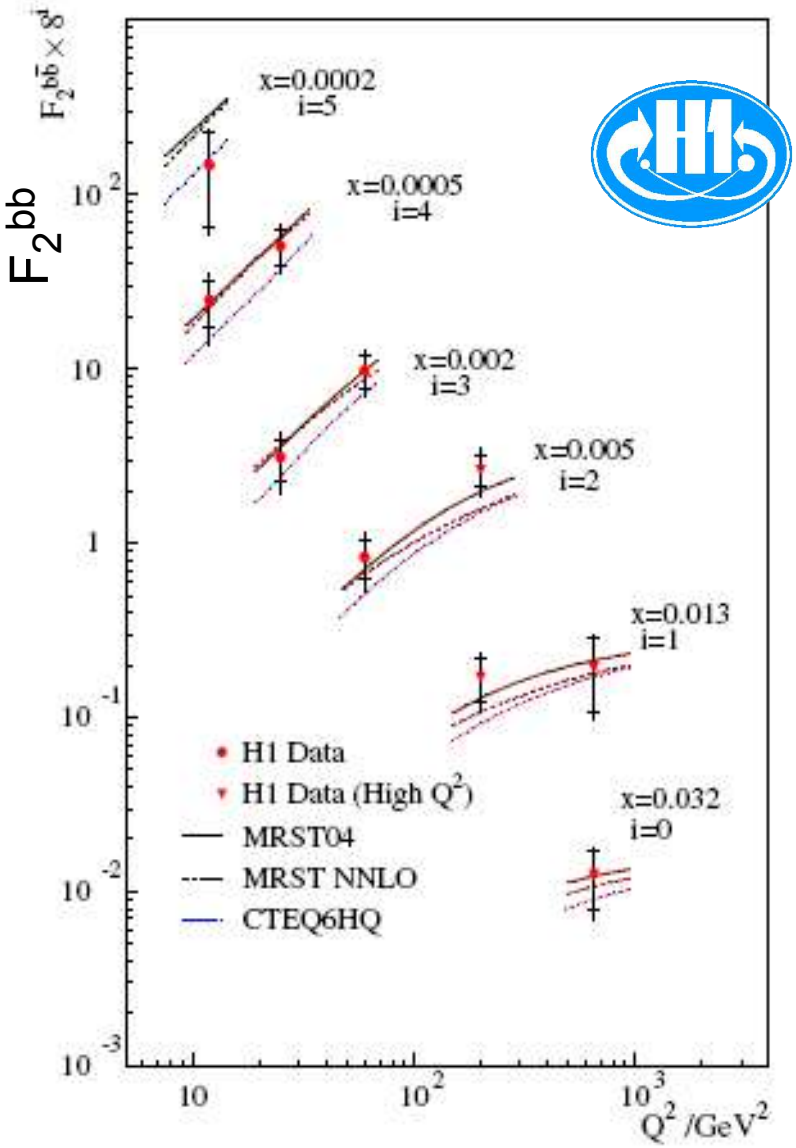
- Lifetime tagging
- Semileptonic decays: Jets+Muons
  - Relative p_t
  - Additonal lifetime information

Results:

- Inclusive cross sections (F_2^{bb})
- Visible cross sections

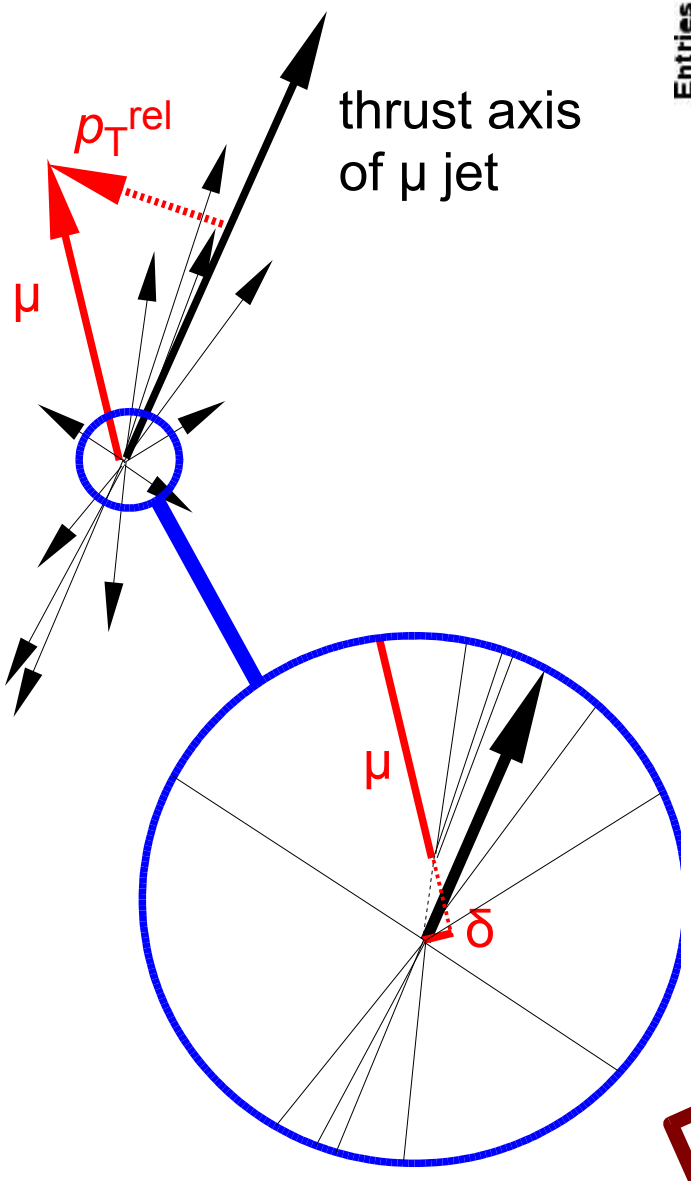
Inclusive Beauty Cross Section: F_2^{bb}

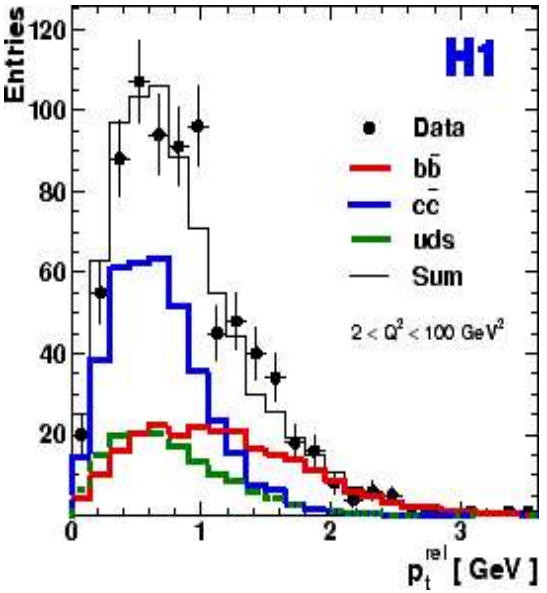
- H1: Uses lifetime tagging to extract charm and beauty together
  - First measurement of inclusive b production at HERA
  - Reasonably well described by NLO QCD
- First NNLO calculation available! (Thorne hep-ph/0506251)

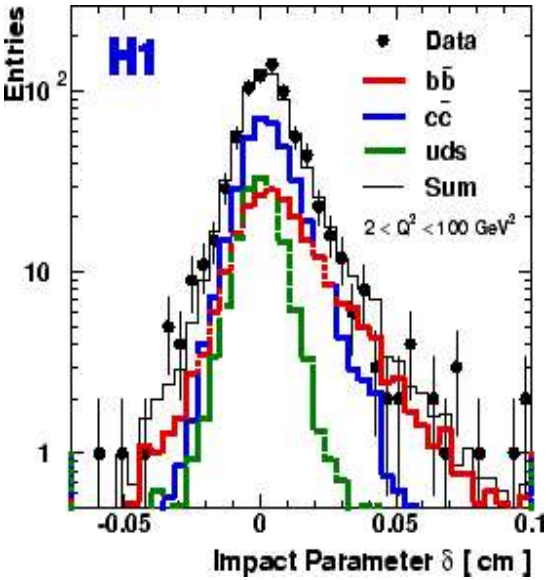


H1, EPJ **C40** (2005) 349.
H1, EPJ **C45** (2006) 23.

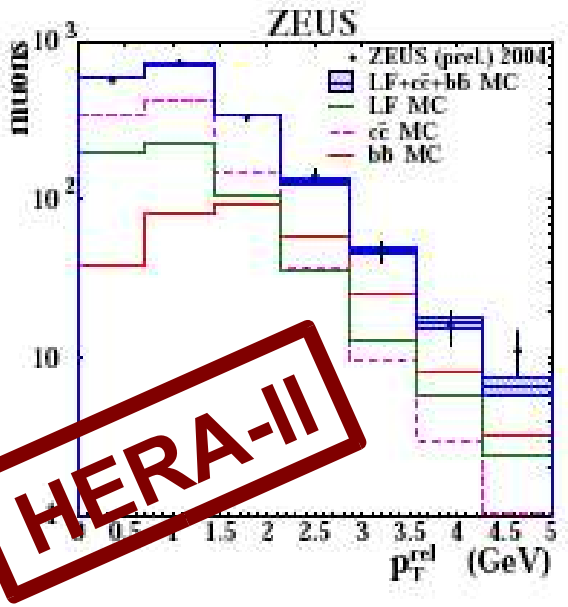
Measuring Beauty Production with μ+jets



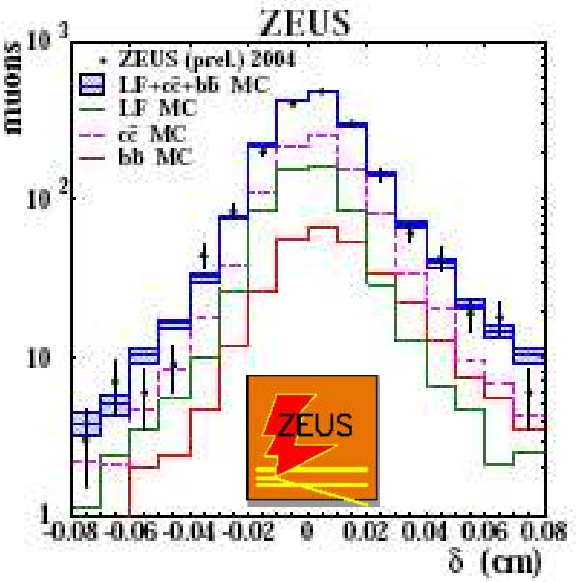




H1, EPJ **C41**(2005)453.



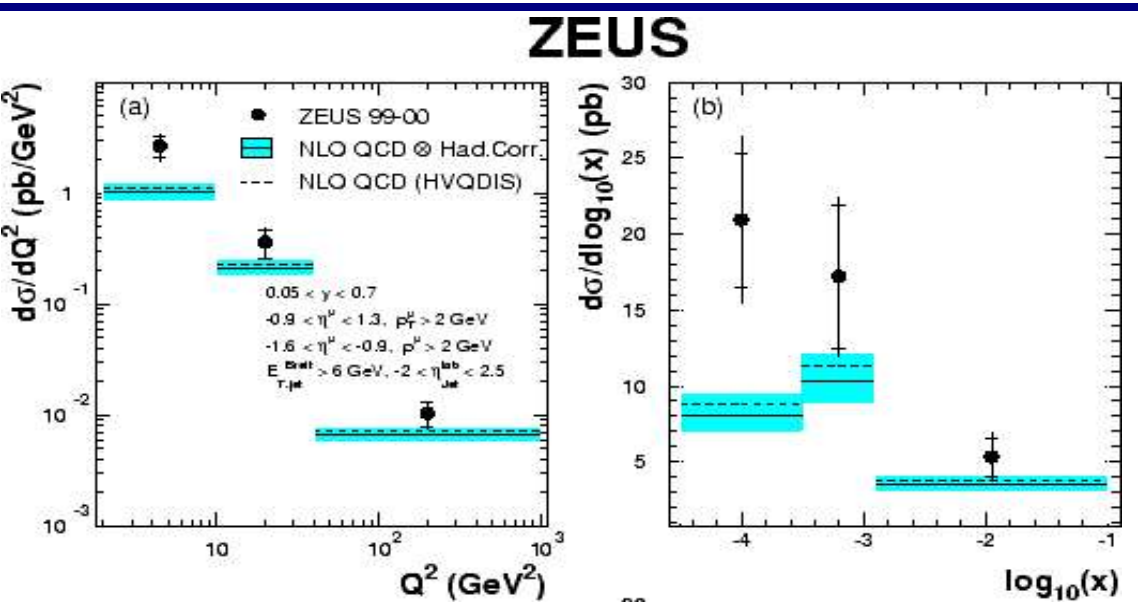
H1, hep-ex/0502107

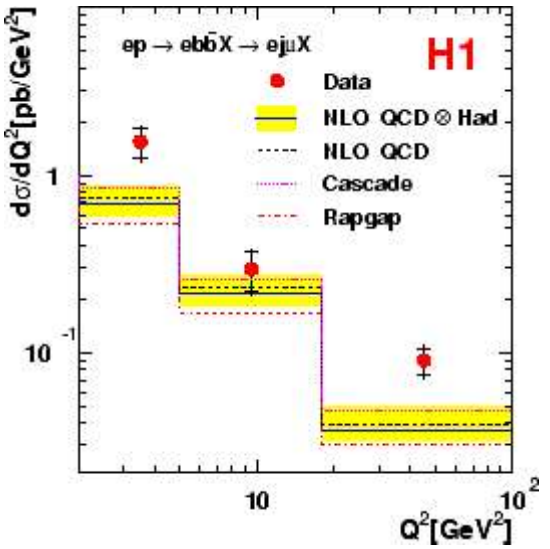


ZEUS preliminary 04-029

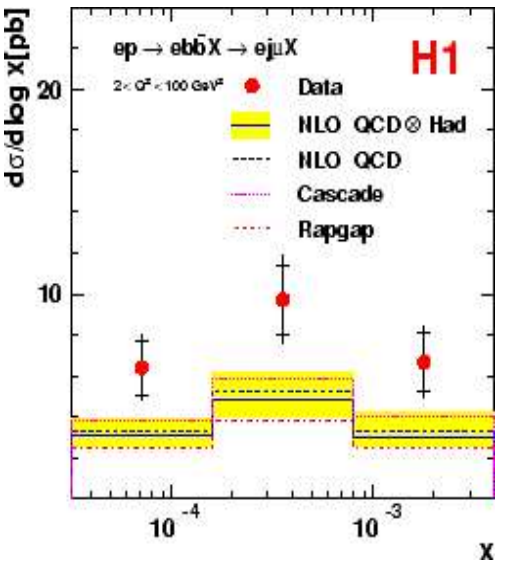
Visible Beauty Cross Sections

- At low Q^2<10GeV^2: Significant excess
- Excess at low x more pronounced
- A surprise: Would naively expect even better description than in charm case due to higher b mass
- Interplay between scales Q^2, p_t^2, and m_b^2?





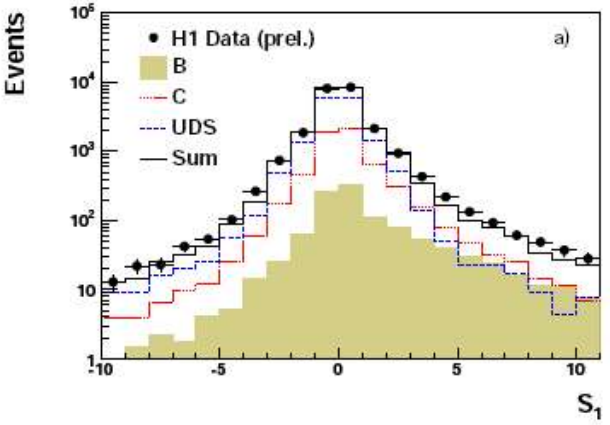
ZEUS, PL **B599** (2004) 173.

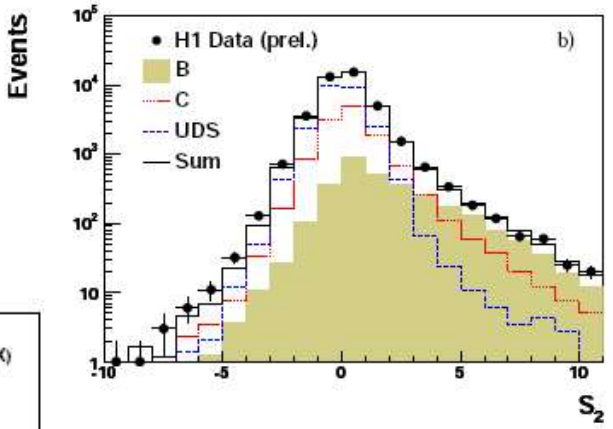


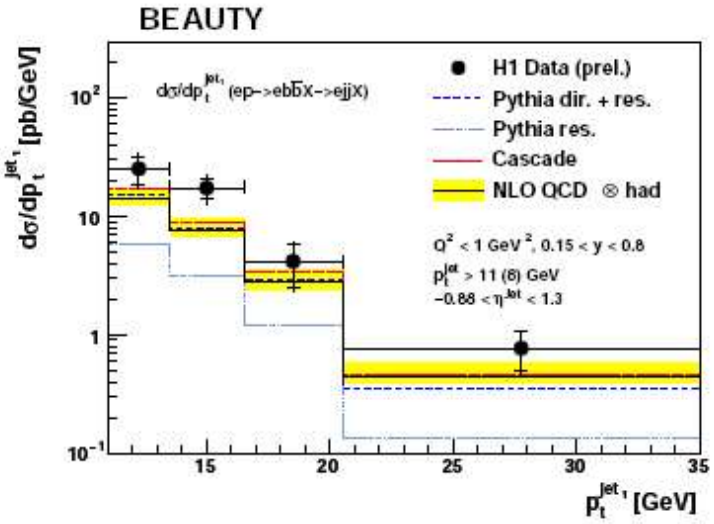
H1, EPJ **C41** (2005) 453.

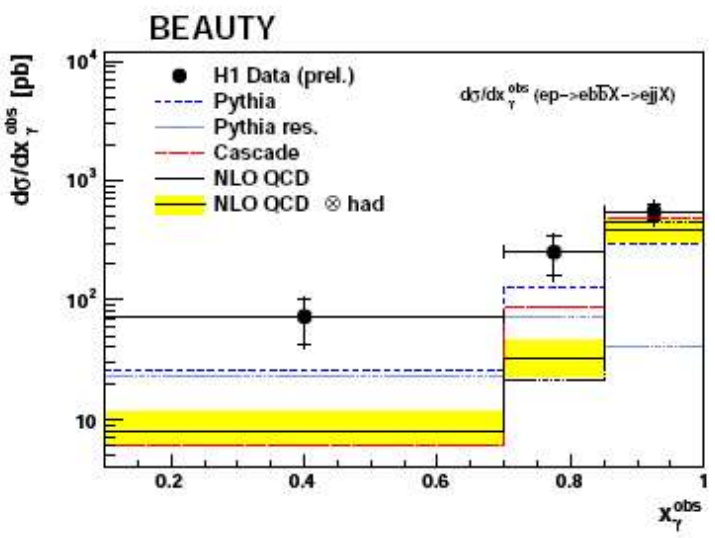
Beauty with Dijets in Photoproduction

- H1 analysis:
  - Photoproducion data
  - 2 jets with p_t>11 (8) GeV
  - Fit impact parameter distribution from silicon vertex detector for c&b fractions
- Jet p_t larger than c, b quark mass
- Excess over NLO QCD, mainly at low x_g^{obs} (resolved region)





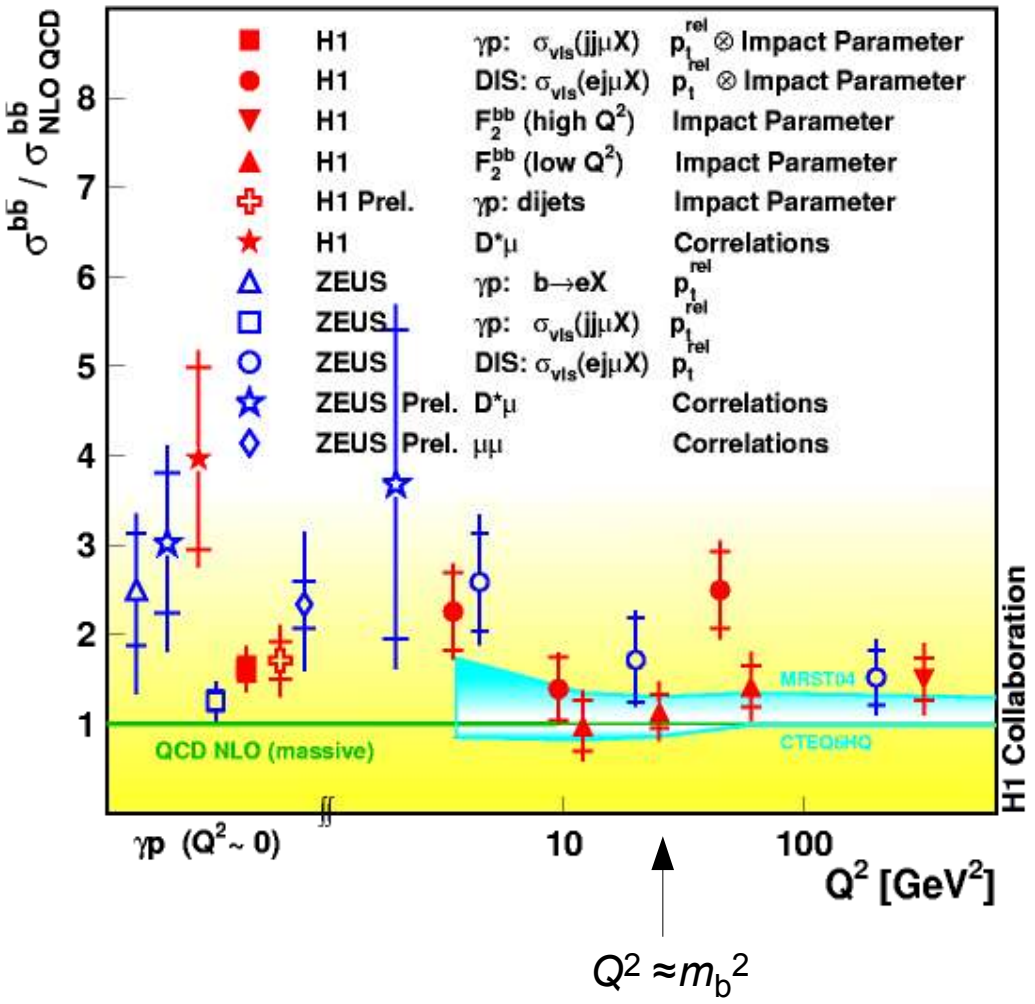




H1prelim-04-173,
publication in EPJ in progress

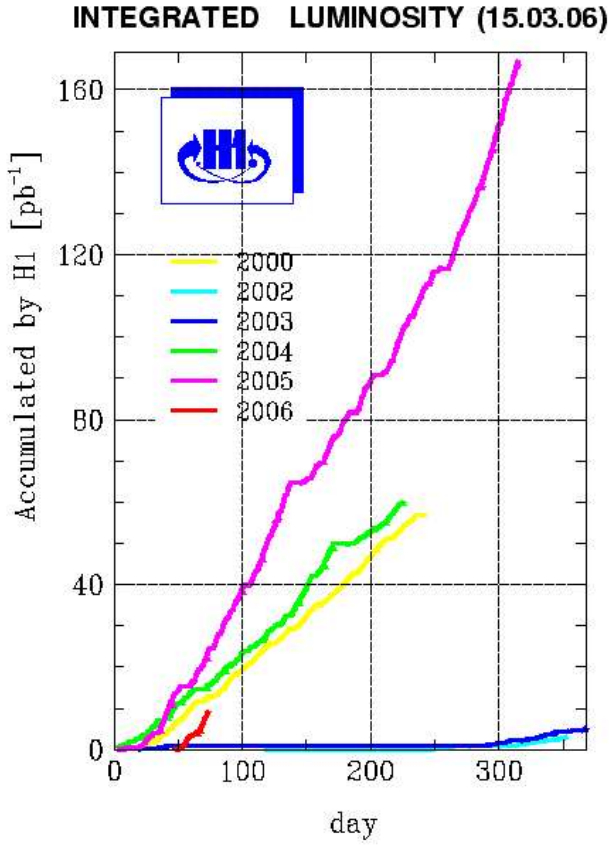
More Beauty than Expected

- All measurements consistent with a ratio data/NLO of 1.5
- Theory error (not shown) typically ~10%
- Improved theoretical understanding needed
- ... and underway:
  - NNLO calculations coming
  - Calculations taking gluon k_t into account



Conclusions and Outlook

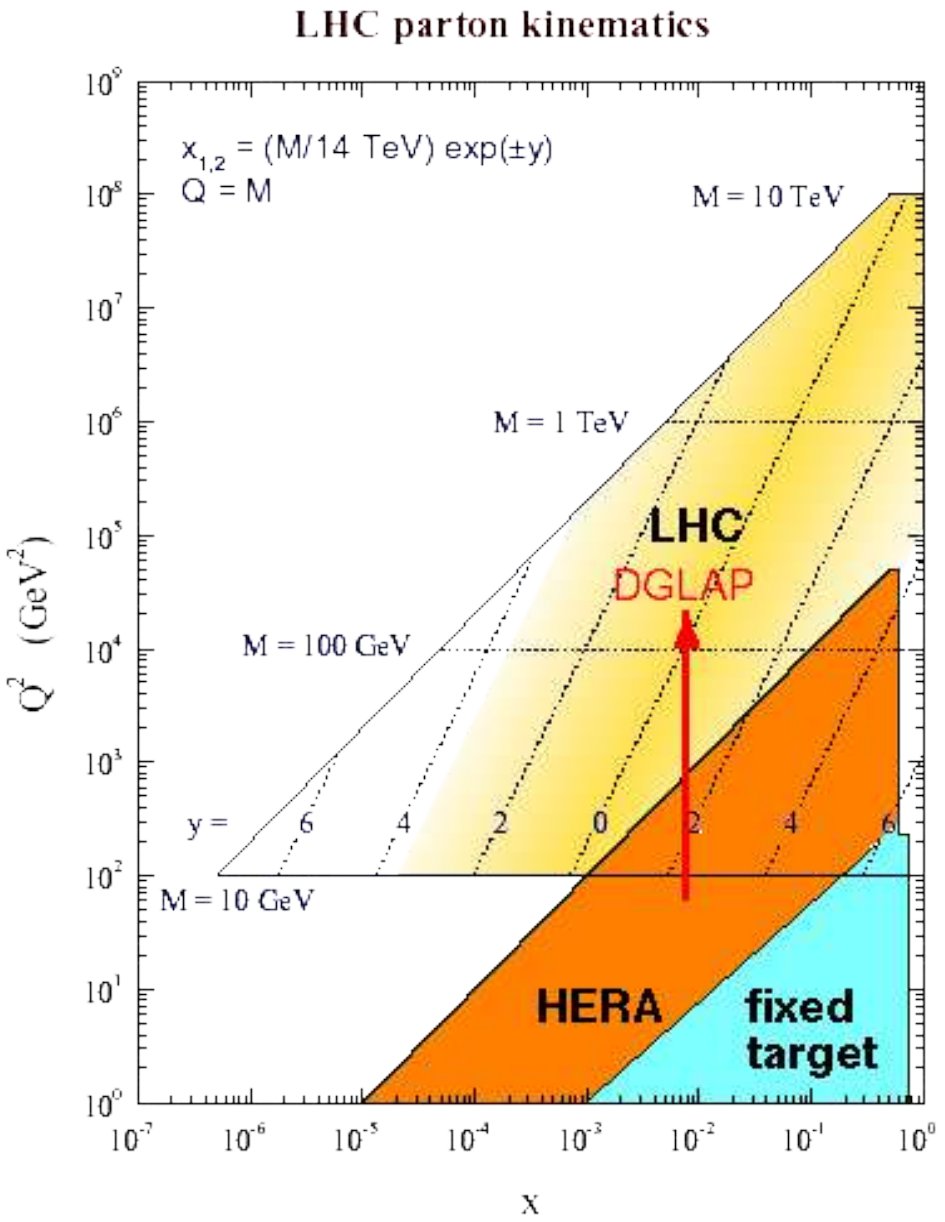
- Charm production well described by NLO QCD
- Charm data precise enough to constrain the gluon at low Q^2
- Beauty production: headed for precision
  - Data above NLO predicition
- More and more HERA-II data coming in: the future is bright!



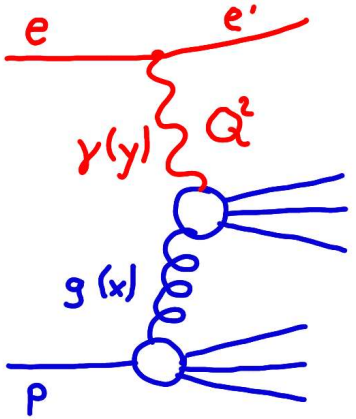
Backup

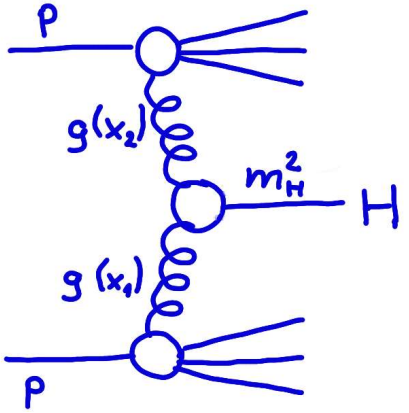
Backup slides

From HERA to LHC



- HERA provides precise parton densities needed by LHC for background and signal calculation
- HERA data pushes theory:
  - NNLO calculations
  - Evolution equations (at s_{hat}>350GeV, top is „light“!)
  - Unintegrated gluon densities



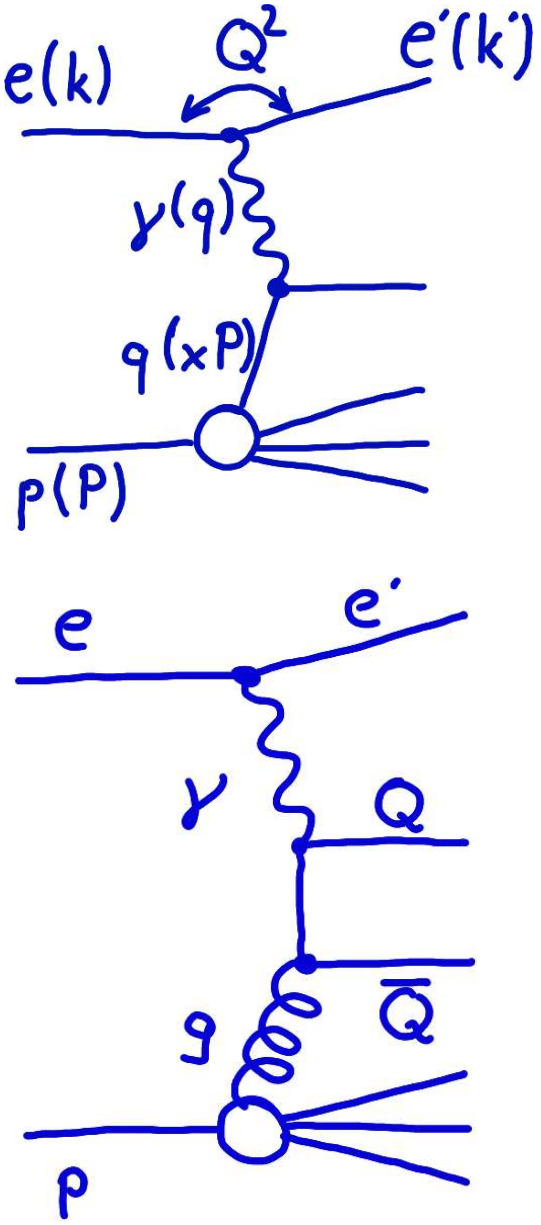


Recent Results Not Covered in this Talk

- J/psi Production:
  - H1: *Elastic J/psi production at HERA*, arXiv:hep-ex/0510016.
  - ZEUS: *Measurement of inelastic J/psi production in deep inelastic scattering at HERA,* EPJ **C44** (2005) 351 [hep-ex/0508019].
- Fragmentation:
  - ZEUS: *Measurement of charm fragmentation ratios and fractions in photoproduction at HERA,* EPJ **C44** (2005) 351 [hep-ex/0508019].
  - H1: *Inclusive production of D^+, D^0, D_s^+ and D^{*+} mesons in deep inelastic scattering at HERA*, EPJ C38 (2005) 447 [hep-ex/0408149].
  - H1: *The Charm Fragmentation Function in DIS*, H1prelim-05-074.
- Charm in Diffraction
  - H1: *Diffractive D^* Meson Production in DIS at HERA*, H1prelim-04-111.

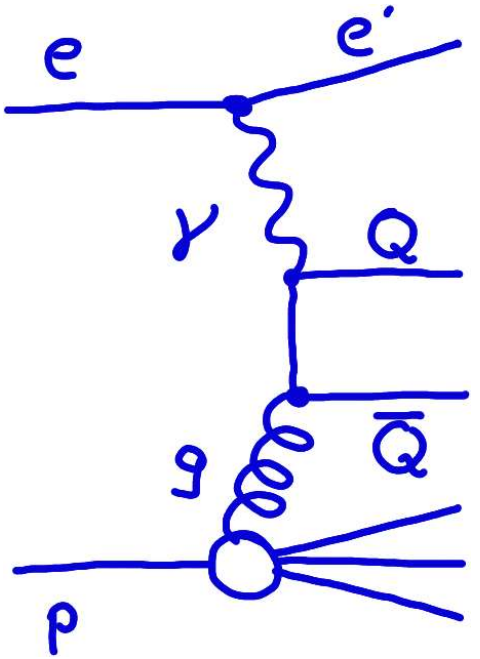
Deep-Inelastic ep Scattering

- Virtual photon of virtuality $Q^2=-q^2$ acts as pointlike probe
- Bjorken-x is momentum fraction of parton out of the proton
- „Light“ quark scattering ($m_q^2 << Q^2$) is described by a parton density within the proton
- Heavy quarks are produced dynamically by Boson-Gluon-Fusion
- Structure function F_2: Inclusive cross section, kinematic factors divided out



Theoretical Challenges

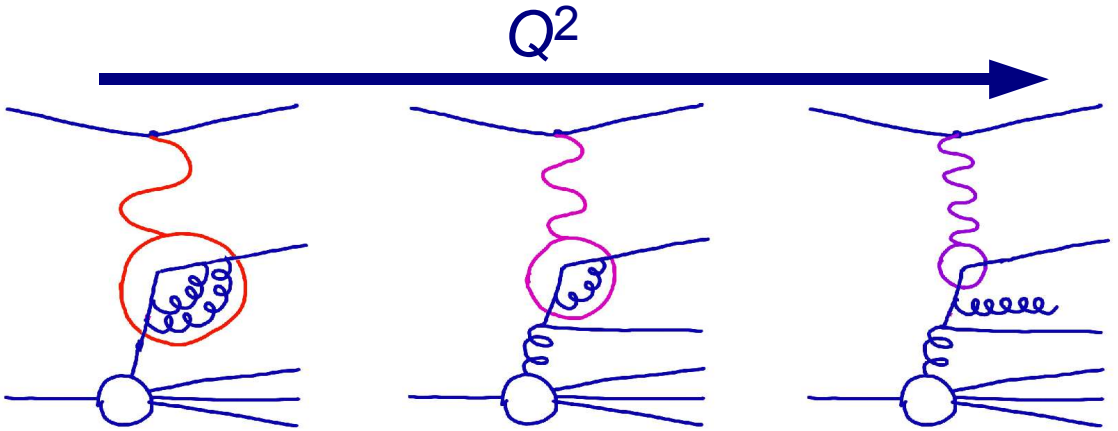
- Multi-Scale Problem: Hard scales Q^2, m_Q^2, p_T^2
- Treatment of Quarks:
  - „Massless“ quarks for $m_Q^2 < Q^2$
  - Massive quarks for $m_Q^2 > Q^2$
  - Transition region $Q^2 \approx m_Q^2$ difficult
  - Adressed by
    Variable Flavour Number Scheme VFNS
    (Lai, Tung; Chuvakin, Smith, Harris; Thorne, Roberts)



- Monte Carlo
  - LO Monte Carlo available (Pythia, Rapgap, Cascade)
  - NLO Calculations (HVQDIS), no full MCs with hadronization
  - => use LO MC for detector and hadronization effects,
    compare x-sections to NLO results

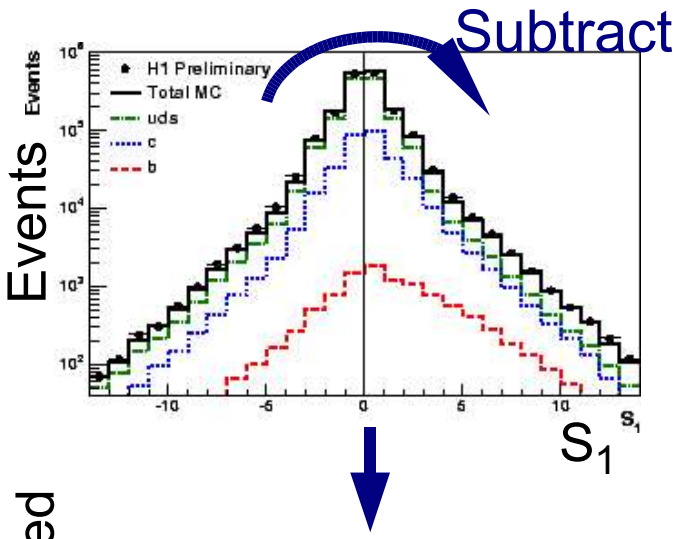
Heavy Flavours and the Gluon

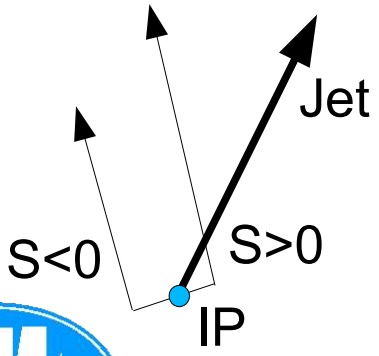
- The gluon in the proton:
  - Drives the QCD evolution of the structure functions
    (at higher Q^2 = higher resolution, more quarks at low x are visible)
  - Generates heavy quarks via boson-gluon-fusion
- Gluon extracted from inclusive structure function measurements should lead to a correct prediction of charm production
- Heavy flavour (especially charm) production measurements can improve knowledge of gluon density in the proton
- Note: Charm contributes up to 35% to proton structure at high Q^2

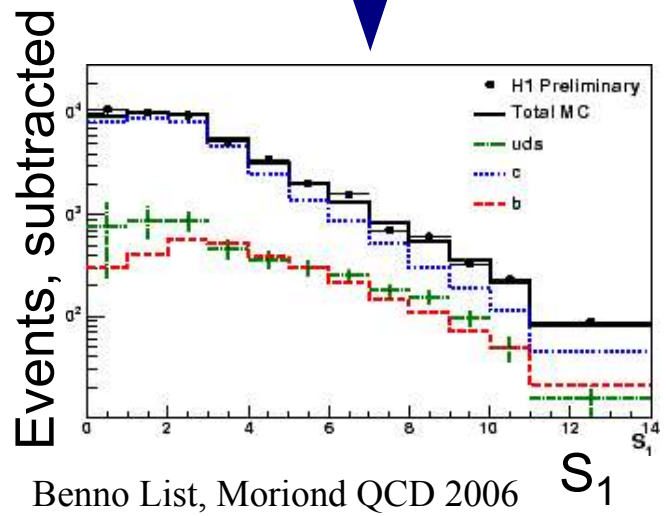


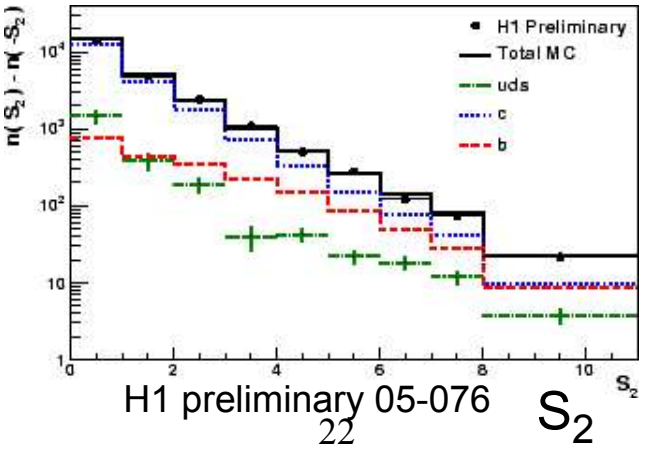
Charm from an Inclusive Lifetime Tag

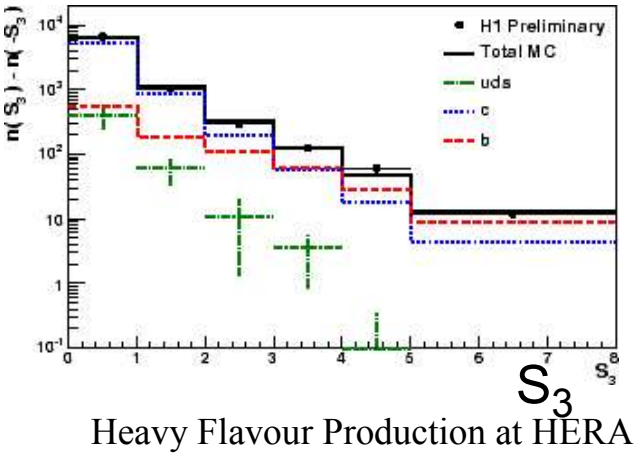
- Central Silicon Tracker resolves track impact parameters
- Measure Significances $S_i = \delta_i/\sigma\delta_i$, order them: $S_1 > S_2 > S_3$
- Use subtracted spectra to extract uds, c, and b



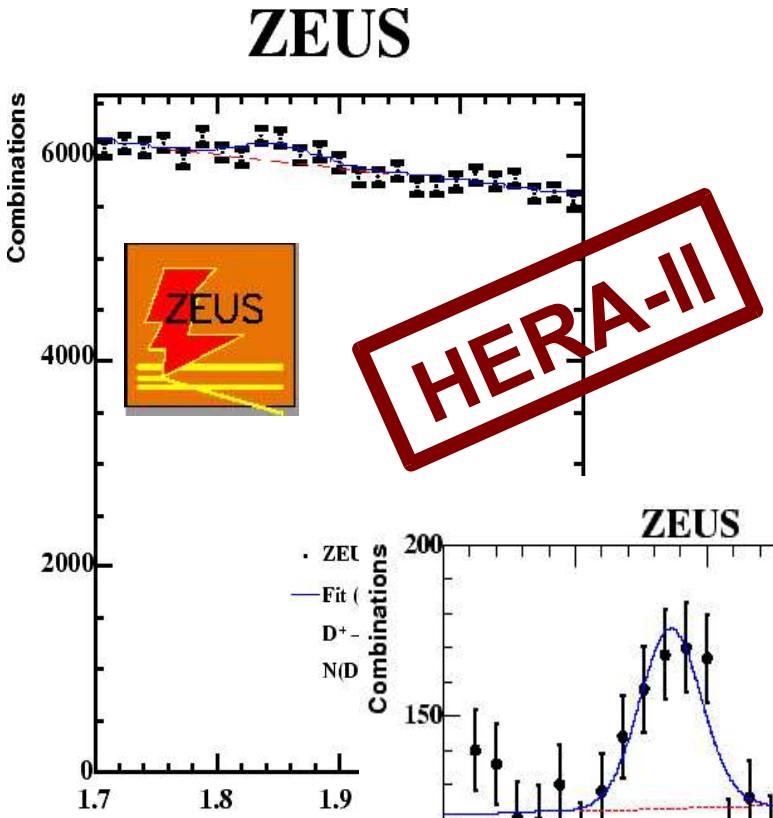


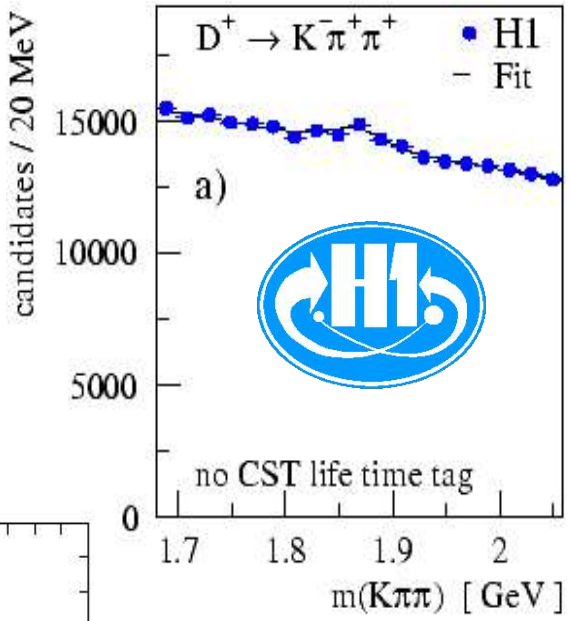


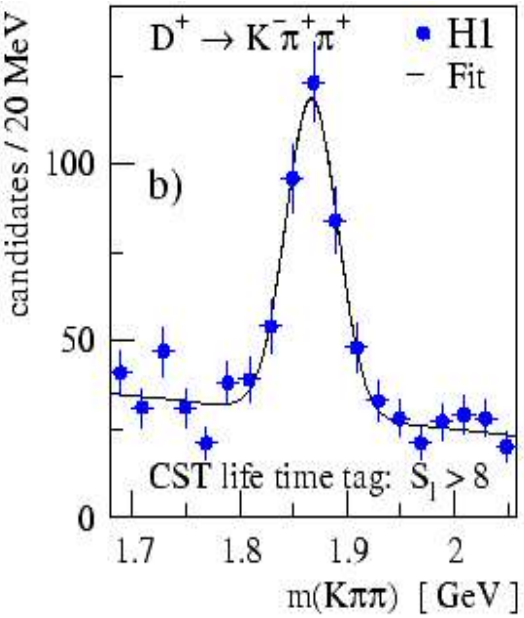




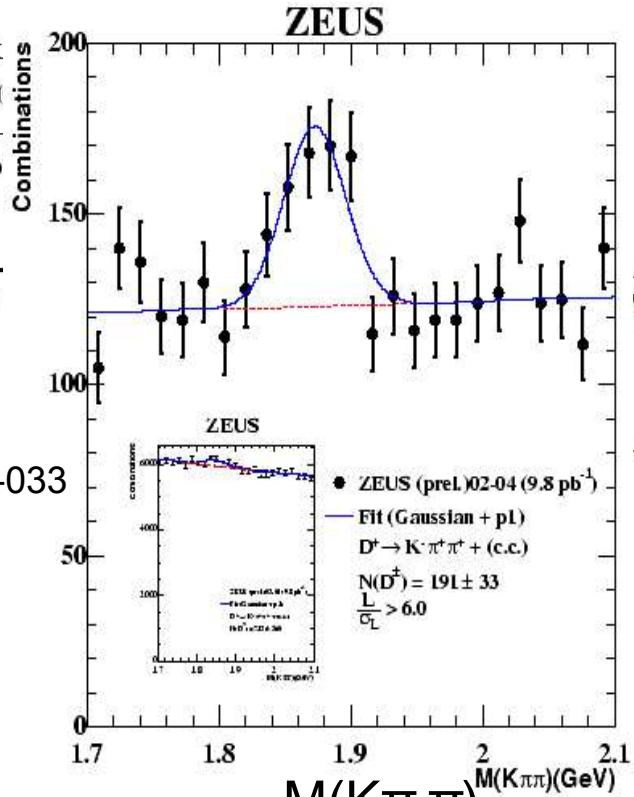
Lifetime Tagging: D^+ Signal



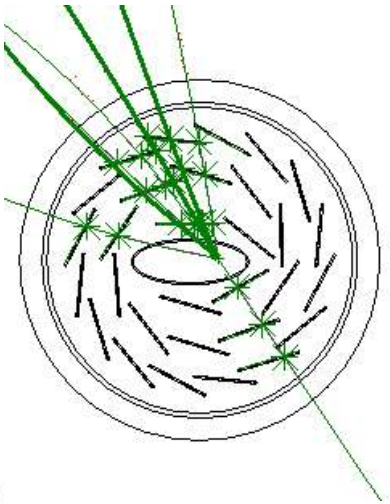


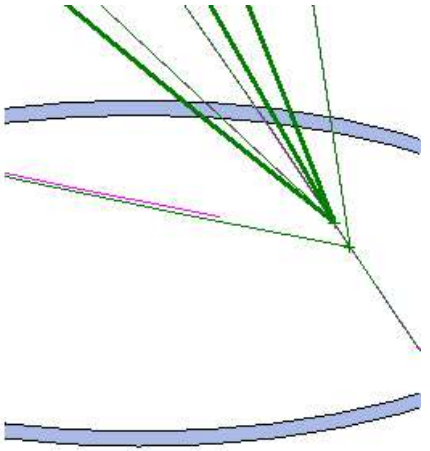


H1, EPJ **C38** (2005) 447.



ZEUS preliminary 04-033





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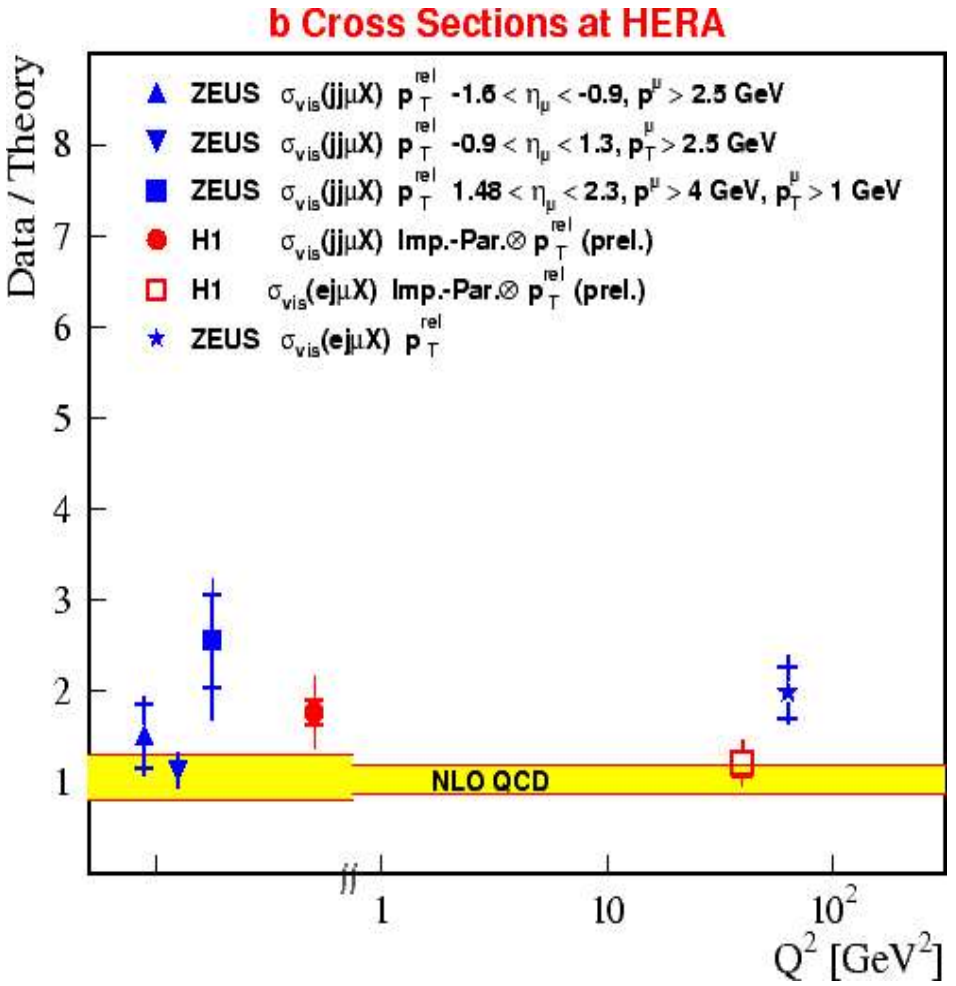
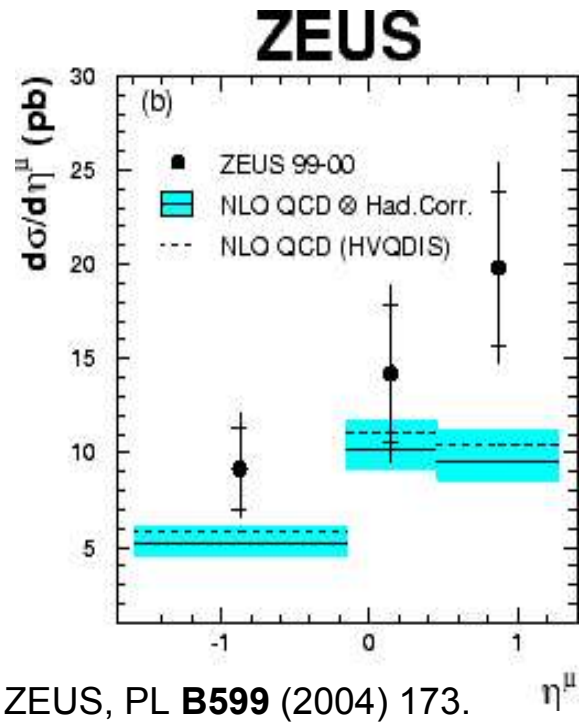


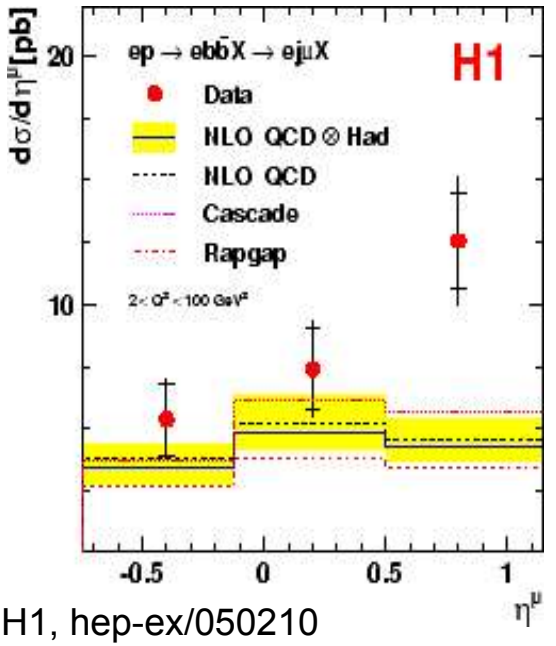
ZEUS, PL **B599** (2004) 173.

Rapity Distributions

- Both experiments observe excess in forward direction, i.e. in direction of the proton remnant



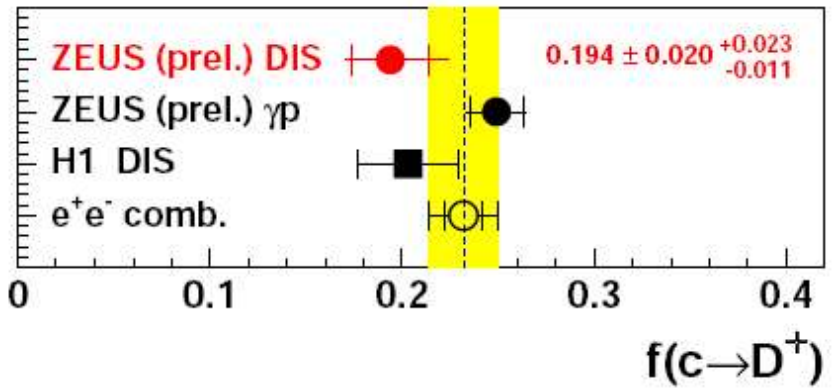
ZEUS, PL **B599** (2004) 173.

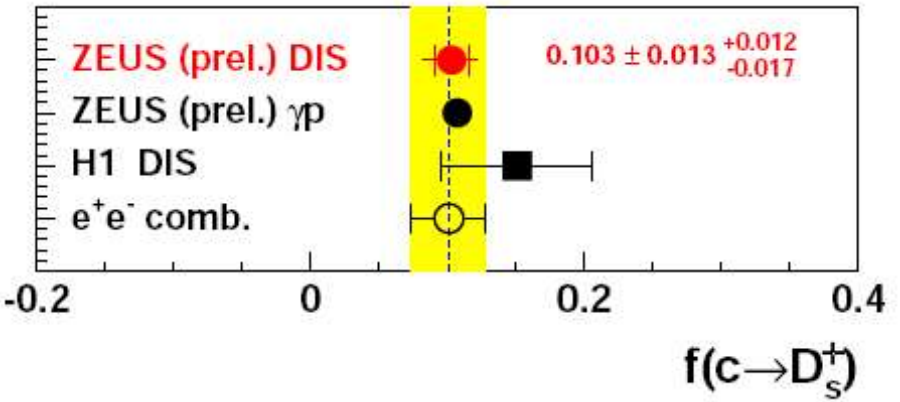


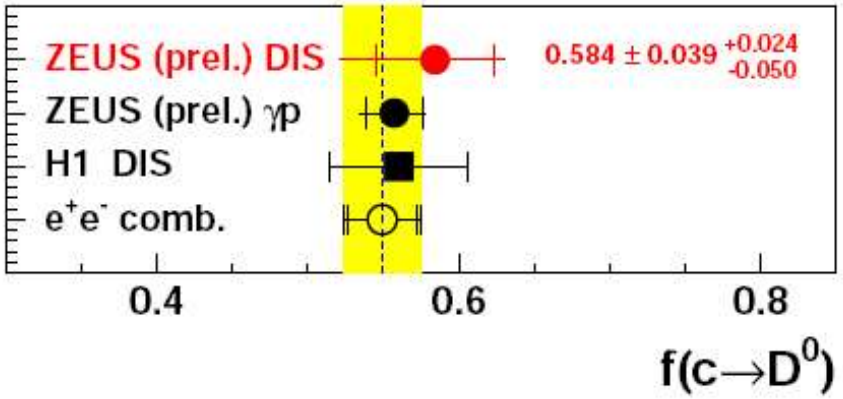
H1, hep-ex/050210

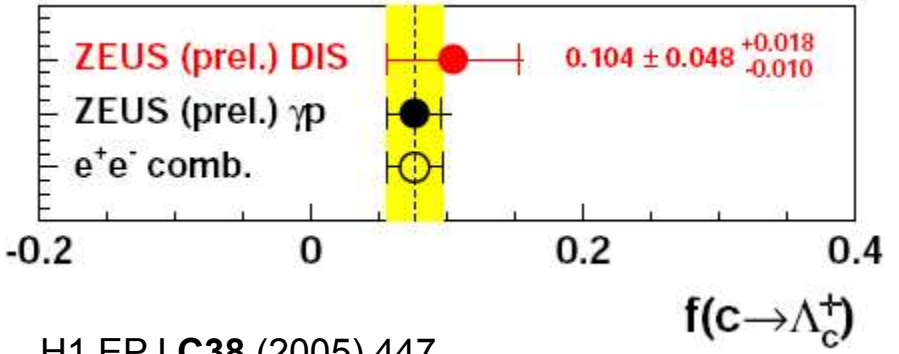
Fragmentation Ratios

- Measured by H1 and ZEUS
- Results consistent with e^+e^- data and of comparable precision



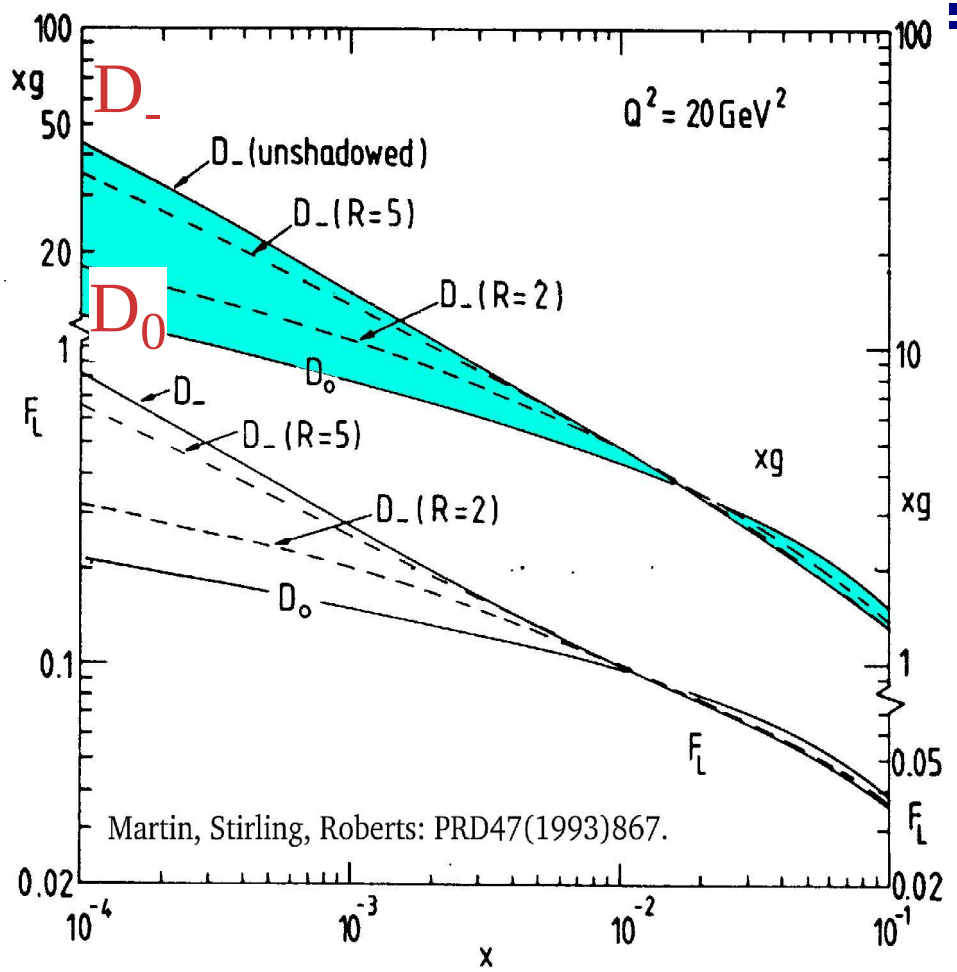






H1 EPJ **C38** (2005) 447.
ZEUS preliminary DIS2005.

The Gluon at HERA



Pre-HERA status:
gluon **guess** uncertain by a factor 3 at Q^2=20GeV^2 and x=3·10^{-4} .

Today: gluon **known** to better than 10% at Q^2=20GeV^2 and x=3·10^{-4} from F_2 measurements