Charm and beauty of HERA
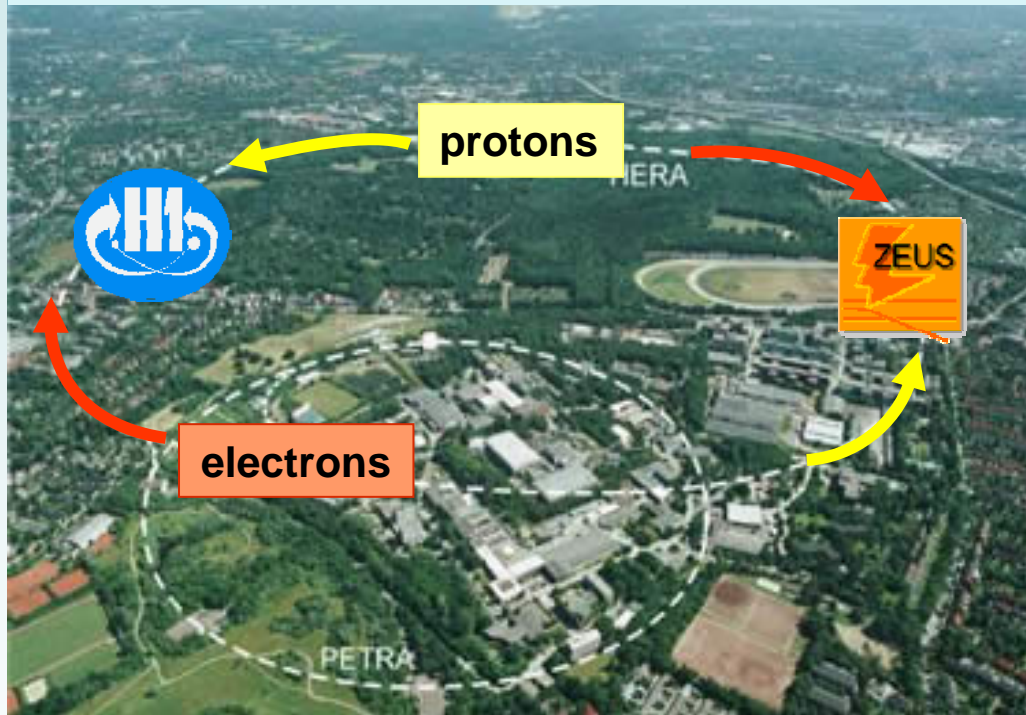
Katerina Lipka (DESY)

XXIèmes Rencontres de Blois 2009 « Windows on the Universe »
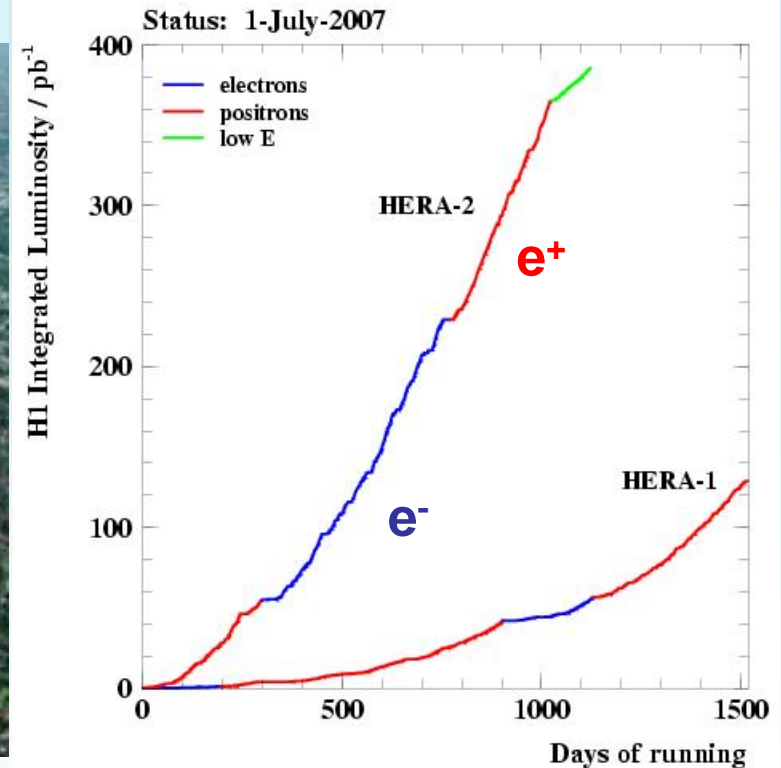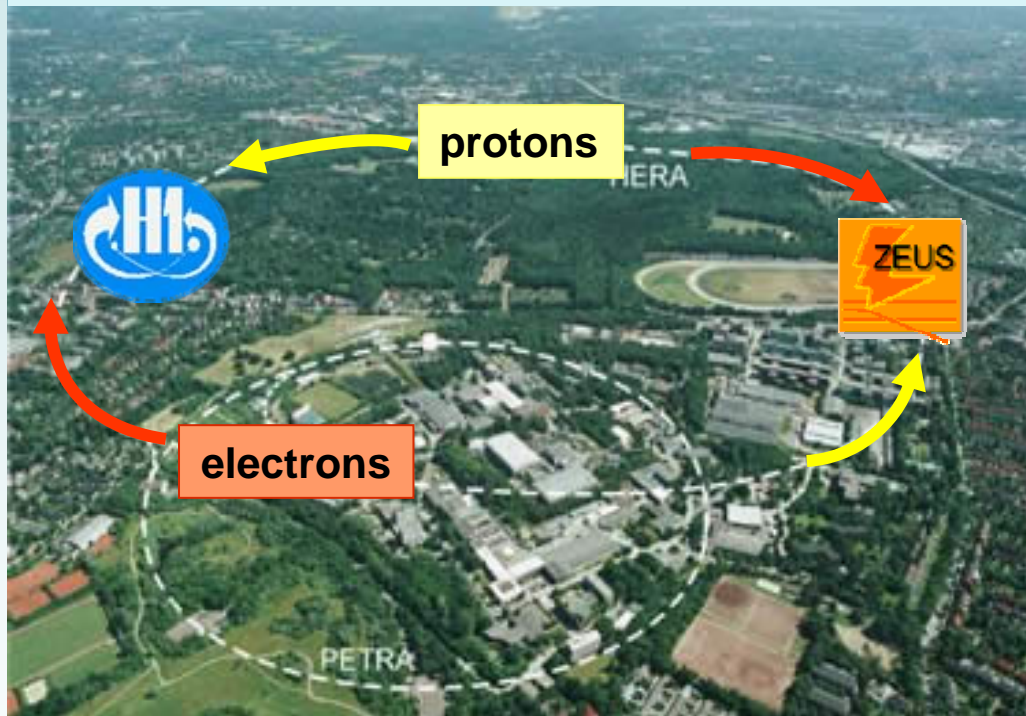
HERA Super-microscope at DESY (Hamburg)

till June 2007: electron-proton collisions at 318 GeV

HERA Super-microscope at DESY (Hamburg)

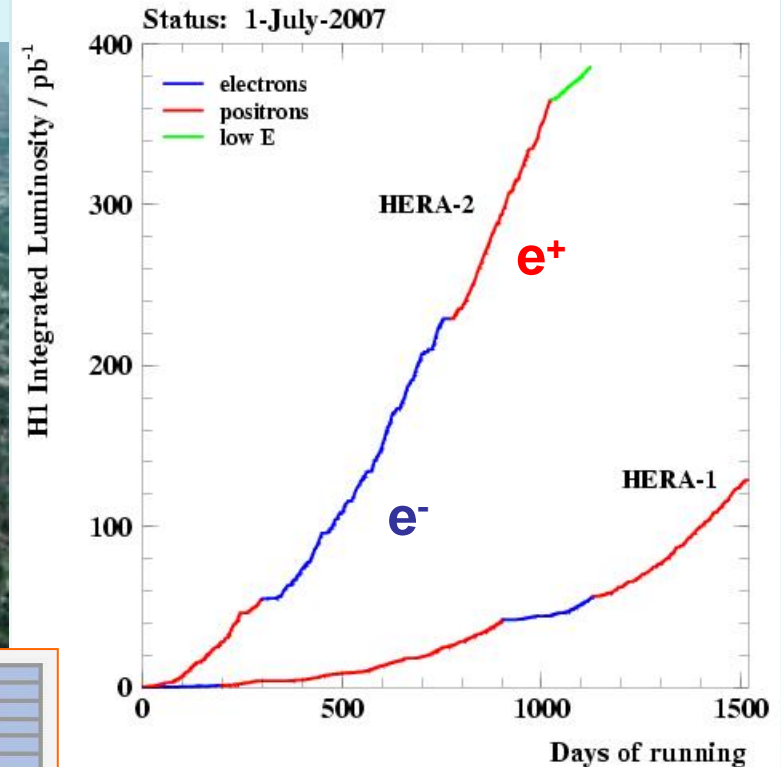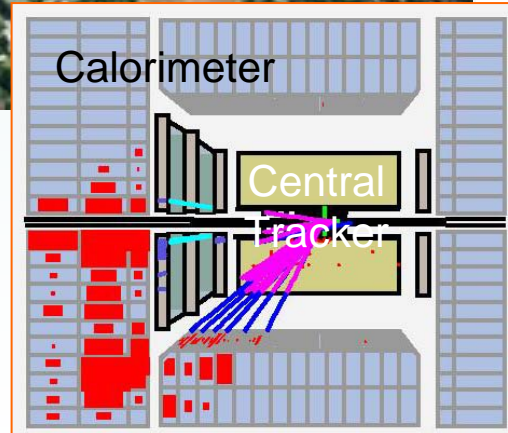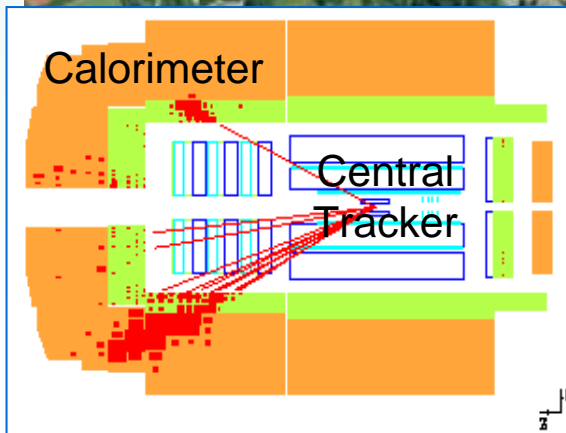till June 2007: electron-proton collisions at 318 GeV

Full HERA Luminosity

~0.5 fb^{-1} / experiment

major part HERA II

HERA Super-microscope at DESY (Hamburg)

till June 2007: electron-proton collisions at 318 GeV
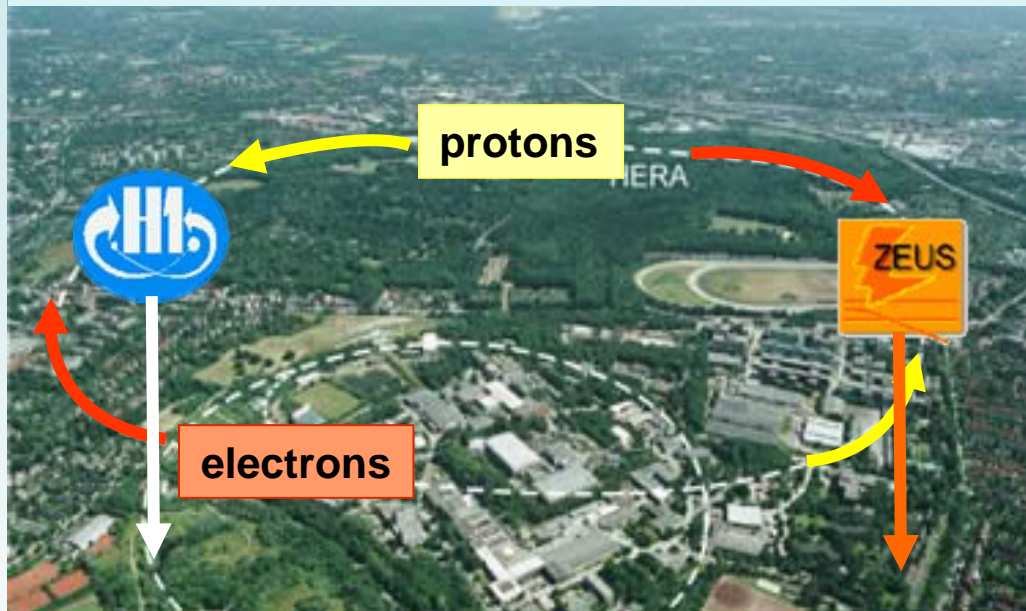
protons

electrons

Calorimeter

Central Tracker

Calorimeter

Central Tracker

Status: 1-July-2007

- electrons
- positrons
- low E

H1 Integrated Luminosity / pb^{-1}

HERA-2

e$^+$

e$^-$

HERA-1

Days of running

Full HERA Luminosity

~0.5 fb^{-1} / experiment

major part HERA II

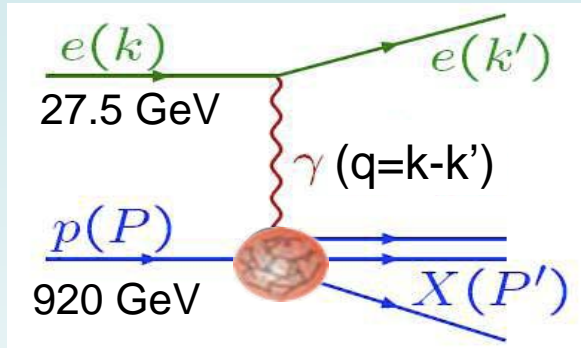# Collisions at HERA and high energy photons
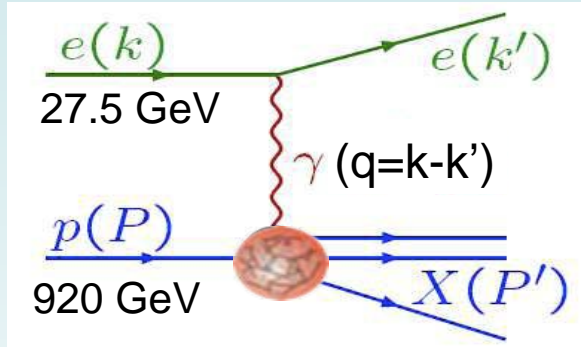
e-p scattering at HERA

$e(k)$

27.5 GeV

γ (q=k-k')

$p(P)$

920 GeV

$X(P')$

$e(k')$

Kinematics:

$s=(k+P)^2$

$Q^2=-(k-k')^2$

$x=Q^2/2P\cdot q$

$y=P\cdot q/P\cdot k$

$Q^2=s\cdot x\cdot y$

Collisions at HERA and high energy photons

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e ⟶ ⟵ **p** compatible with

50 TeV γ beam on a p target

Collisions at HERA and high energy photons

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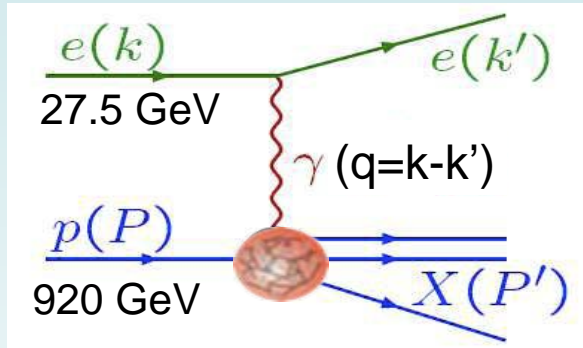
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e   **p**

compatible with

50 TeV γ beam on a p target

Cosmic rays

Energies and rates of the cosmic-ray particles

CAPRICE
AMS
BESS98
Ryan et al.
Grigorov
JACEE
Akeno
Tien Shan
MSU
KASCADE
CASA-BLANCA
DICE
HEGRA
CasaMia
Tibet
Fly Eye
Haverah
Yakutsk
AGASA
HiRes

protons only

all-particle

electrons

positrons

antiprotons

$E^2 dN/dE$ (GeV cm^{-2}sr^{-1}s^{-1})

E_{kin} (GeV / particle)

HERA measurements

3

Heavy quarks and high energy neutrinos

flux ratios

pp-reach environment with charm

AGN

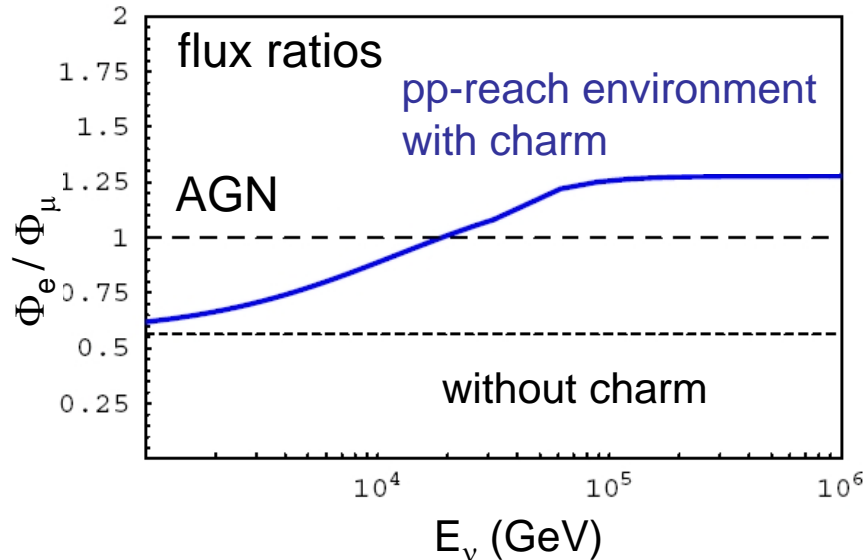**without charm**

Φ_e / Φ_μ

E_ν (GeV)

Cosmic sources: semi-leptonic decays of charmed mesons dominate at high energies *(Gandhi et al., arXiv:0905.2483)*

Background in telescope experiments: atmospheric (prompt) ν and μ, charm contributes significantly

➢ Understanding of heavy quark production and fragmentation needed

4

Heavy quarks and high energy neutrinos

flux ratios

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without charm

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➤ Understanding of heavy quark production and fragmentation needed

$\phi_{\nu_e}(E) / \phi_\mu(E)$

$0<\lambda<0.5$

$\phi_{\nu_\mu}(E) / \phi_\mu(E)$

$\log_{10}(E/\text{GeV})$

➤ Precision of the gluon density essential
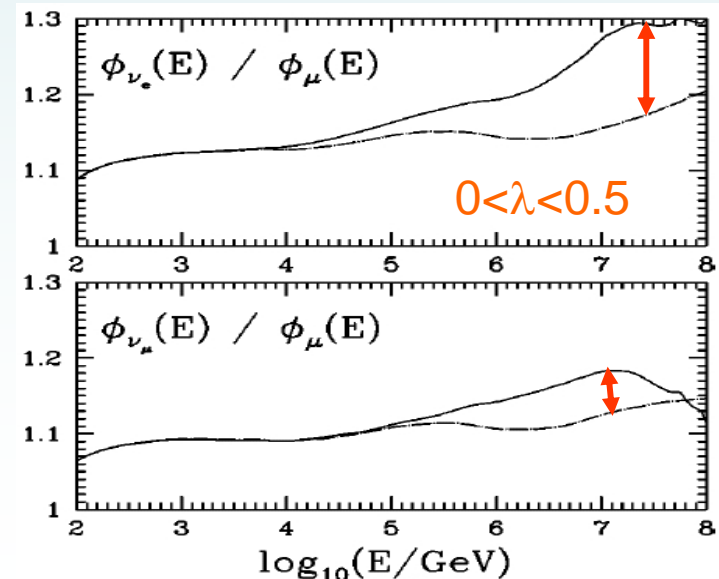
Example *(Gelmini et al., Phys. Rew D67,017301)*

momentum fraction of the struck parton in the nucleus in the atmosphere $x < 10^{-5}$
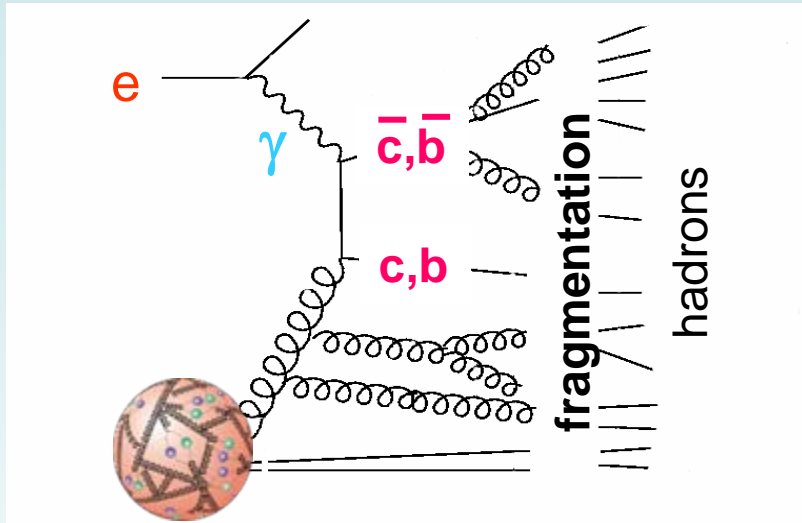
gluon density: $xg(x) \sim x^{-\lambda}$, CTEQ PDF set

4

Heavy quarks at HERA

Dominated by Boson – Gluon Fusion (BGF)

- significant fraction of total DIS

  - charm up to 30%, beauty up to 1%

- gluon directly involved

- heavy quark mass: additional hard scale

  - pQCD calculations possible

  - multiple scales: calculations complicated

Factorization: heavy flavour hadron production cross section =

Proton Structure ⊗ Photon Structure ⊗ Matrix Element ⊗ Fragmentation
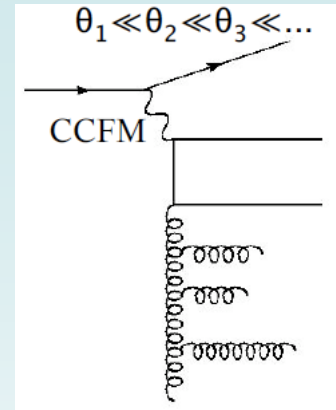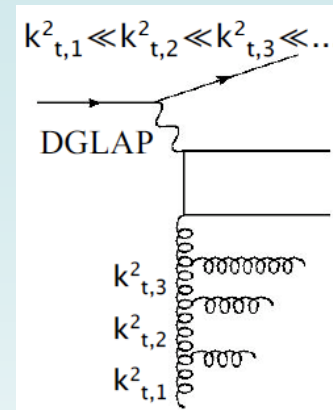
Possible with HERA data:

- measure cross sections and fragmentation functions,

- test calculations of the hard ME, learn more about gluon density

5

Models of heavy quark production at HERA

Event Generators: LO ME + Parton Showers

proton structure (parton densities):

- RAPGAP, PYTHIA: DGLAP evolution
- CASCADE: CCFM evolution

**pQCD calculations:** due to multi-scale problem (m_{HQ}, p_T, Q^2) several approaches:

- massless (ZM-VFNS) HQ exist in the proton, reliable for $Q^2 >> m^2_{HQ}$

- massive (FFNS) HQ dynamically produced in BGF, reliable for $Q^2 \sim m^2_{HQ}$
  - NLO program for DIS ($Q^2 > 2$ GeV) HVQDIS
  - NLO program for photoproduction ($Q^2 \sim 0$): FMNR

- GM-VFNS: combination of massless and massive schemes:
  - NLO program for HQ in photoproduction
  - Used in the latest PDF fits by HERA, CTEQ, MSTW

Heavy quark tagging methods at HERA

Reconstruction of charmed mesons: $D^*, D^{\pm}, D^0$ from decay particles in detector

Via "mass difference" method:

$$\Delta m = M_{inv}(K\pi\pi) - M_{inv}(K\pi)$$

$D^* \rightarrow D^0 \pi \rightarrow K\pi\pi$
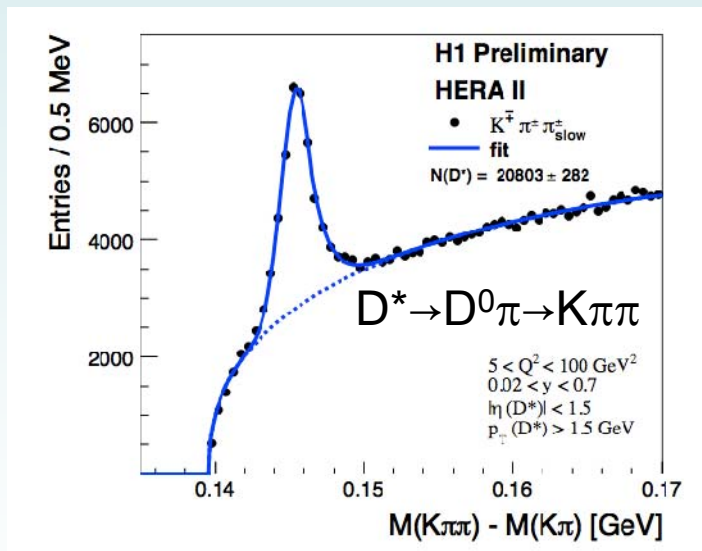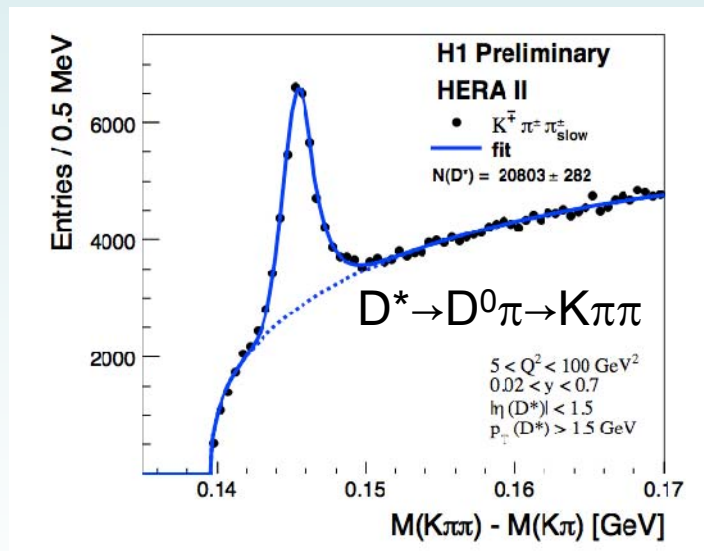
Signal obtained from the fit

Heavy quark tagging methods at HERA

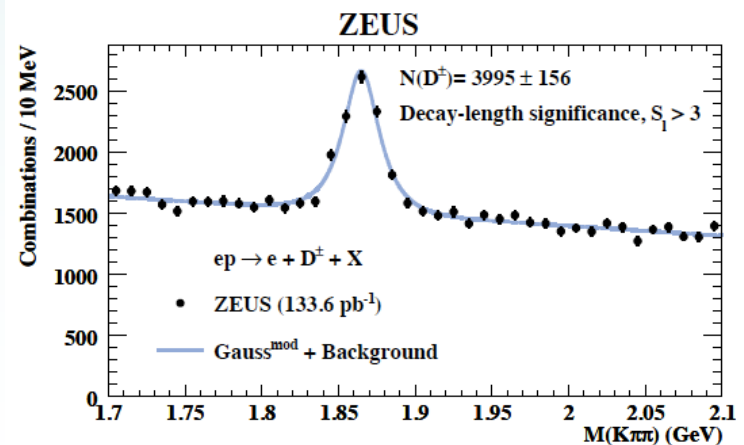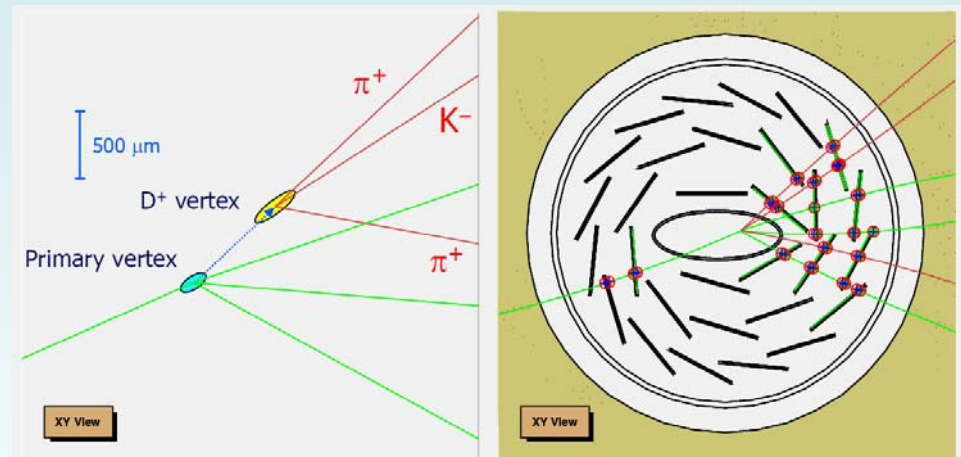Reconstruction of charmed mesons: $D^*, D^\pm, D^0$ from decay particles in detector

Via "mass difference" method:
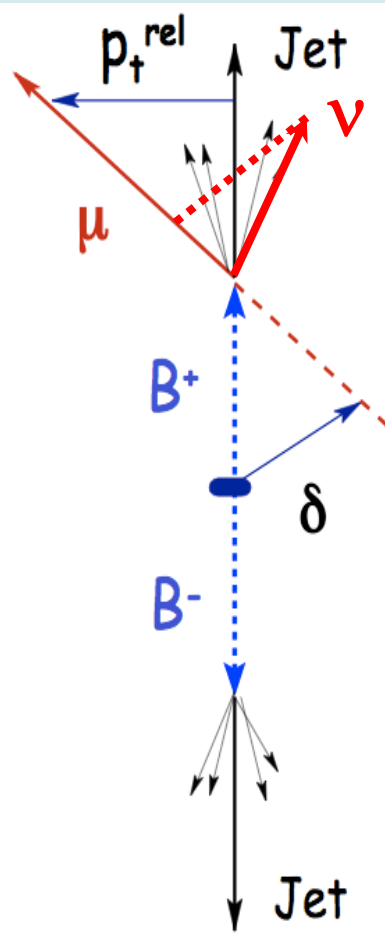
$$\Delta m = M_{inv}(K\pi\pi) - M_{inv}(K\pi)$$

Via vertex reconstruction:

$D^* \to D^0\pi \to K\pi\pi$
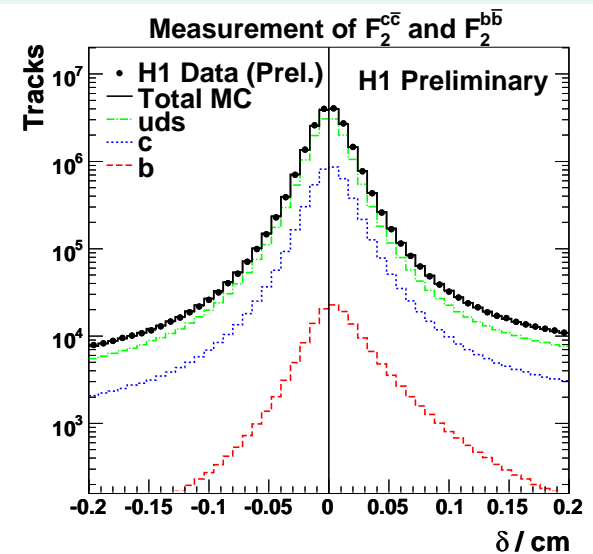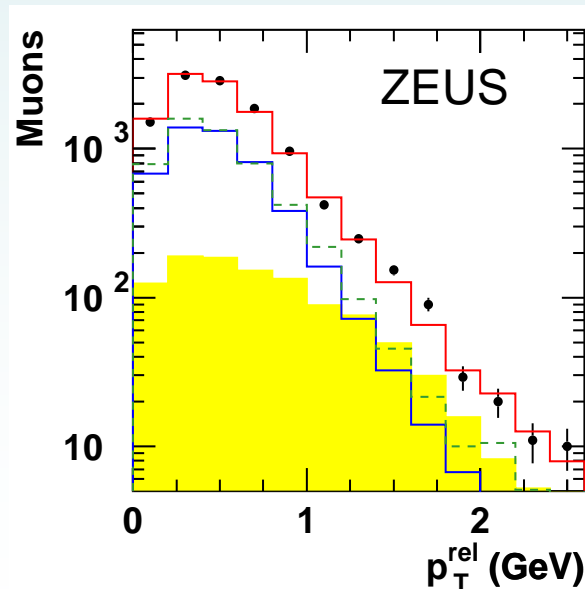
Signal obtained from the fit

Heavy quark tagging methods at HERA

Use properties of B-hadrons: large mass, long lifetime

- Charm comes alone with beauty:
- Semi-leptonic decays (e,μ)
- Large mass: transverse momentum to Jet axis: muon p_t^{rel}
- Large lifetime: impact parameter δ, Significance $S=\delta/\sigma(\delta)$
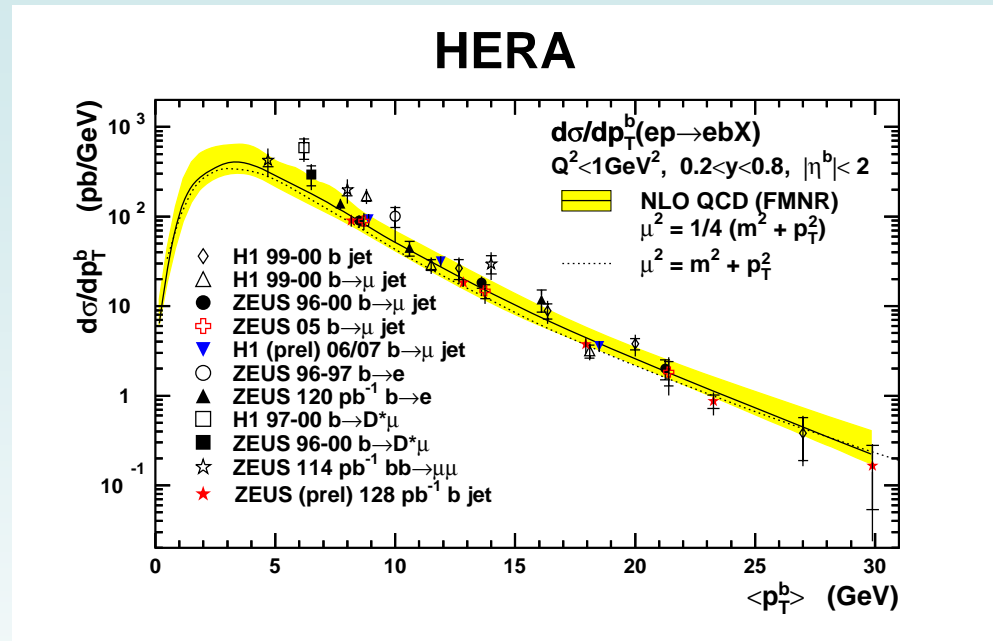- Different systematic uncertainties wrt. D-meson measurements

Heavy Quarks in Photoproduction

HERA Beauty:

- different measurements agree

- good agreement with massive NLO

  theory uncertainty : scale choice
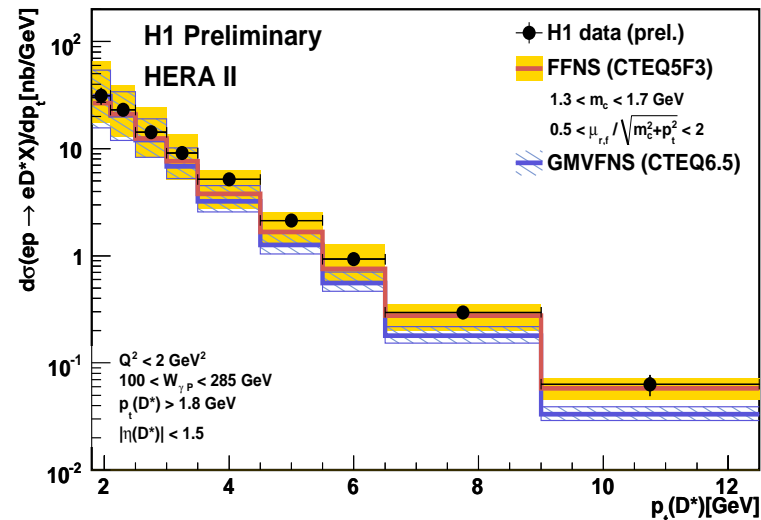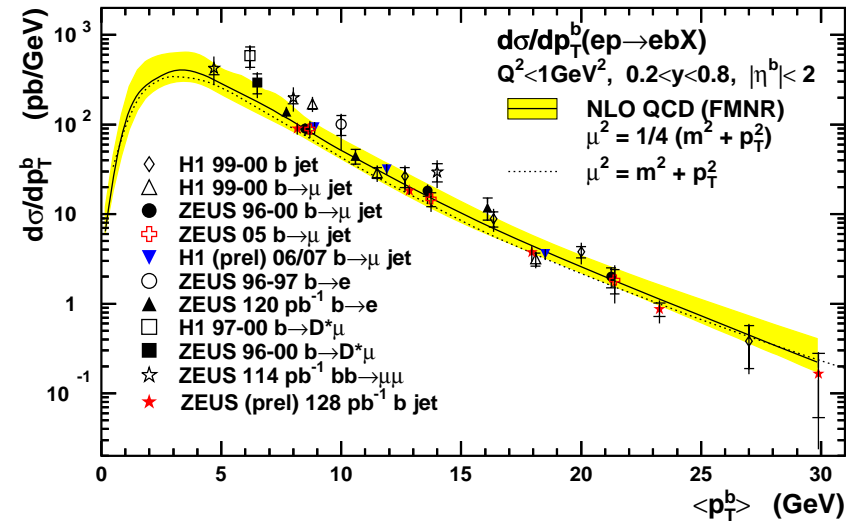
Heavy Quarks in Photoproduction

HERA Beauty:

- different measurements agree
- good agreement with massive NLO

  theory uncertainty : scale choice

Charm via D*:
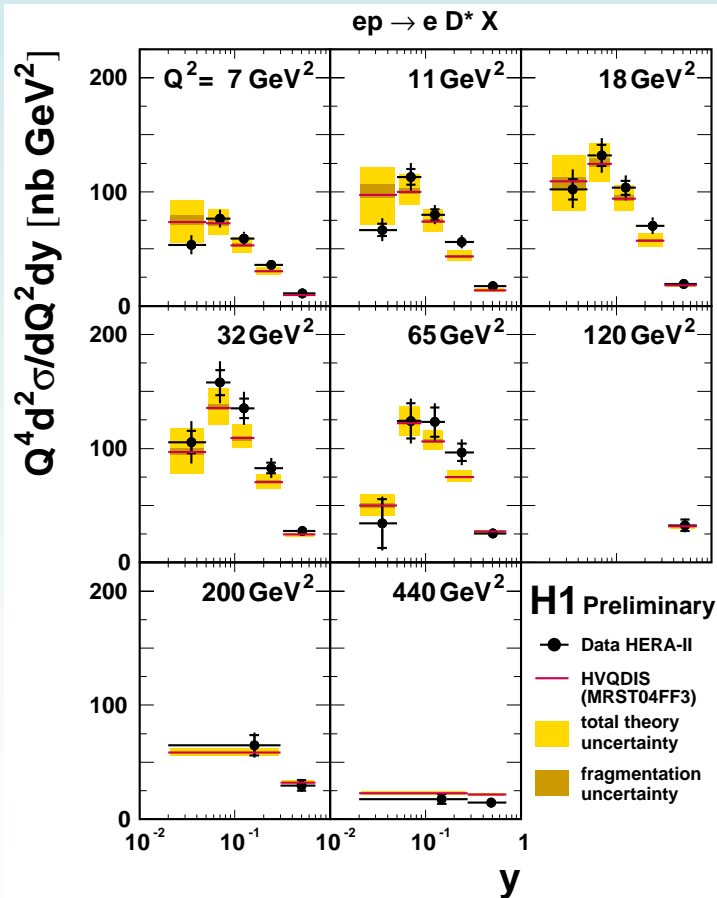
- Precise experimental measurement
- good agreement with massive NLO
- fair agreement with GM-VFNS
- large theory uncertainty (scale)

Heavy Quarks in Deep Inelastic Scattering

Charm from D*

Charm and Beauty in semi-leptonic decays

Charm: massive NLO agrees with data
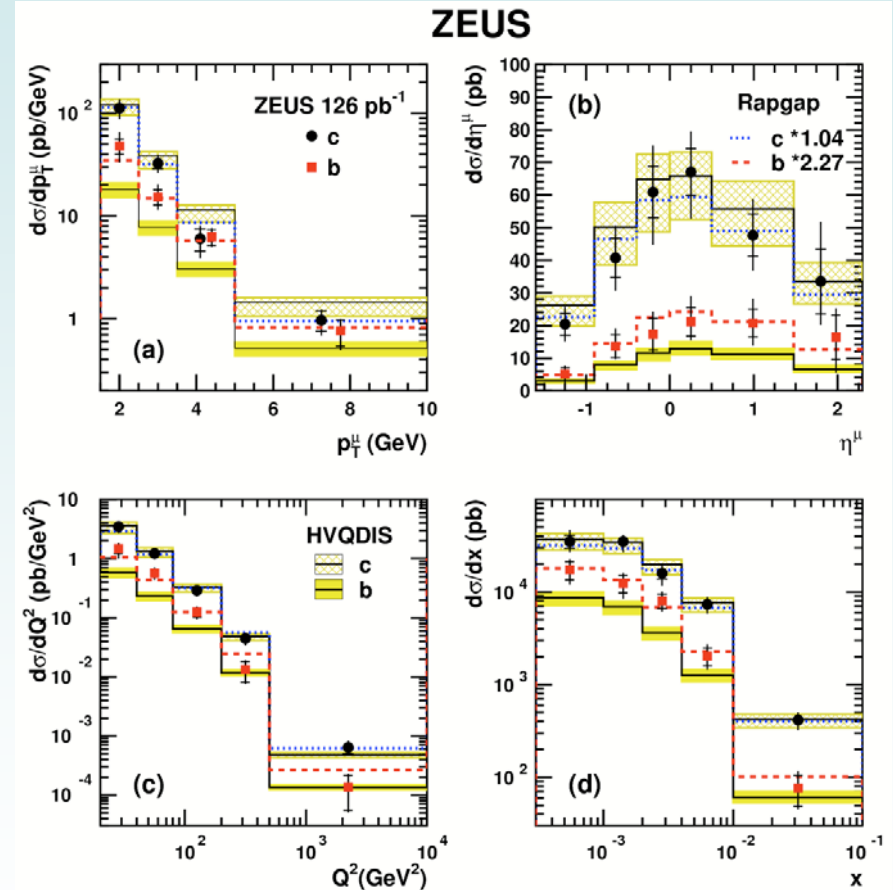
Beauty: NLO lower in normalization

Theory uncertainties: HQ mass, scales, fragmentation model

Charm Fragmentation: $c\ (E_c) \to D^*\ (z{\cdot}E_c)$

Photoproduction:

c-quark approximated by D* jet

E_T**(D*-jet)>9 GeV**

Fit with the massive NLO

fragmentation model: Kartvelishvili

$$D_c^{D^*}(z) \propto z^\alpha (1-z)$$

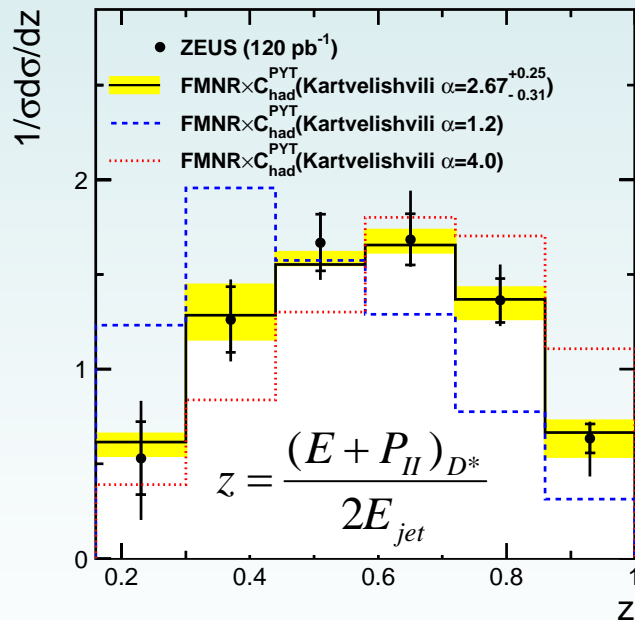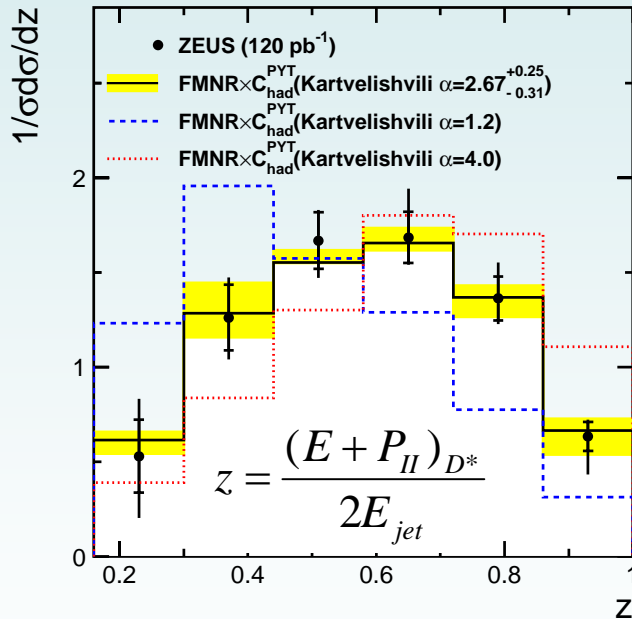# **Charm Fragmentation:** $c\ (E_c) \rightarrow D^*\ (z \cdot E_c)$

Photoproduction:

c-quark approximated by D* jet

E_T(D*-jet)>9 GeV

DIS: **c-quark approximated by D* hemisphere**

2 regions probed: above charm threshold (jet)

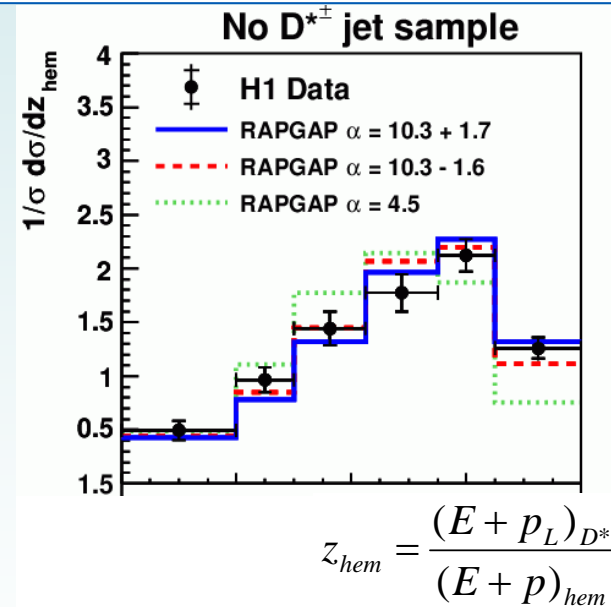**close to charm threshold (no jet)**

$$z = \frac{(E + P_{II})_{D^*}}{2E_{jet}}$$

- ZEUS (120 pb⁻¹)
- FMNR×C$_{had}^{PYT}$(Kartvelishvili α=2.67$^{+0.25}_{-0.31}$)
- FMNR×C$_{had}^{PYT}$(Kartvelishvili α=1.2)
- FMNR×C$_{had}^{PYT}$(Kartvelishvili α=4.0)

Fit with the massive NLO

fragmentation model: Kartvelishvili

$$D_c^{D^*}(z) \propto z^\alpha (1-z)$$

No D*± jet sample

- H1 Data
- RAPGAP α = 10.3 + 1.7
- RAPGAP α = 10.3 - 1.6
- RAPGAP α = 4.5

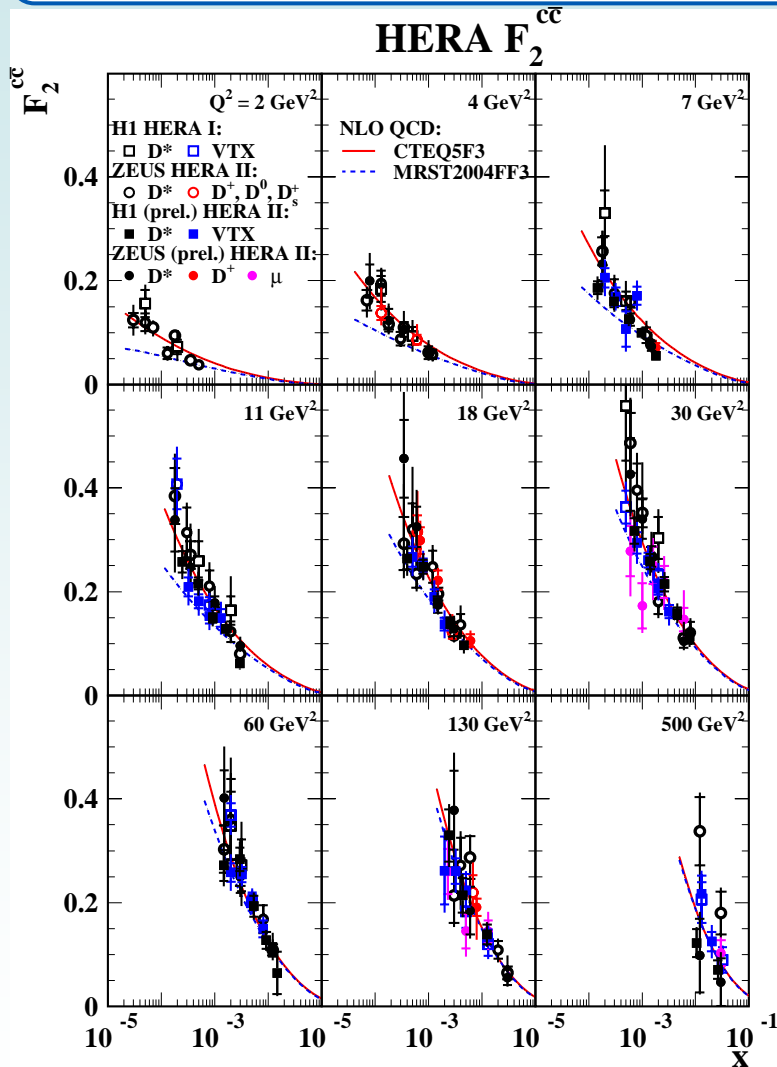$$z_{hem} = \frac{(E + p_L)_{D^*}}{(E + p)_{hem}}$$

- above charm threshold:

   fragmentation in ep consistent with e^+e^-

- close to charm threshold: much harder

11

Charm Contribution to Proton Structure


HERA $F_2^{c\bar{c}}$

- Plenty of measurements

- Nice agreement between methods

- Experimental precision of several measurements will further improve

- Different methods being combined: orthogonal errors!

- H1 and ZEUS results will be combined

- Sensitivity to the models (PDFs)

- Need proper (precise) theory

Experimental errors will further decrease – we are on the way to the final precision

Charm Contribution to Proton Structure

HERA $F_2^{c\bar{c}}$

$F_2^{c\bar{c}}$ Combined D* and Charm Lifetime Tag
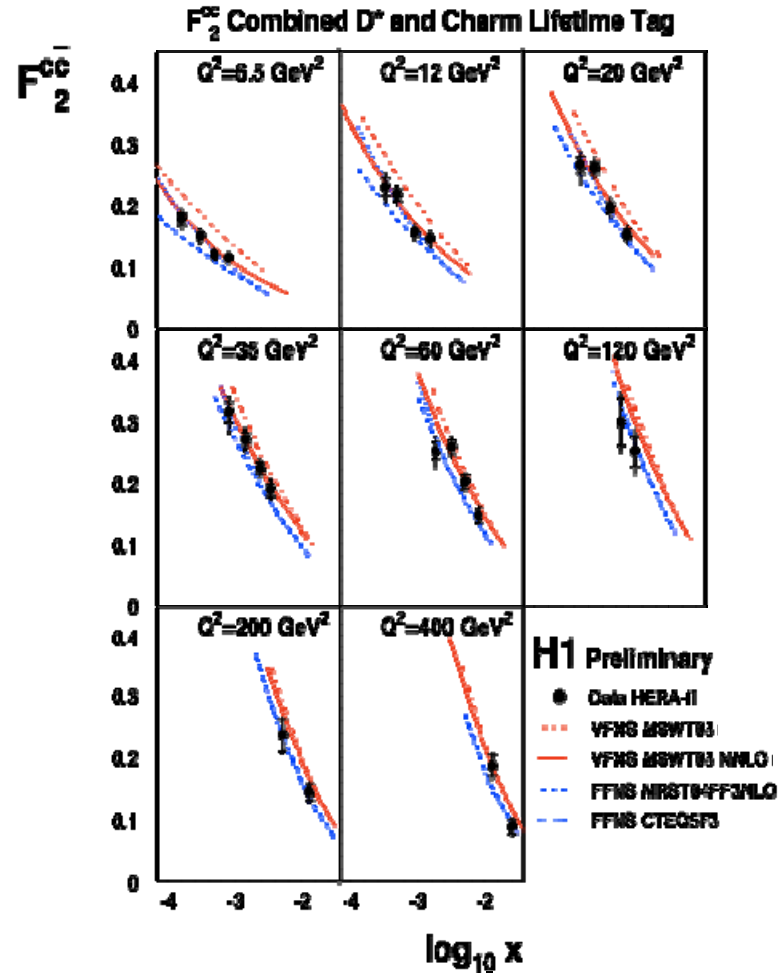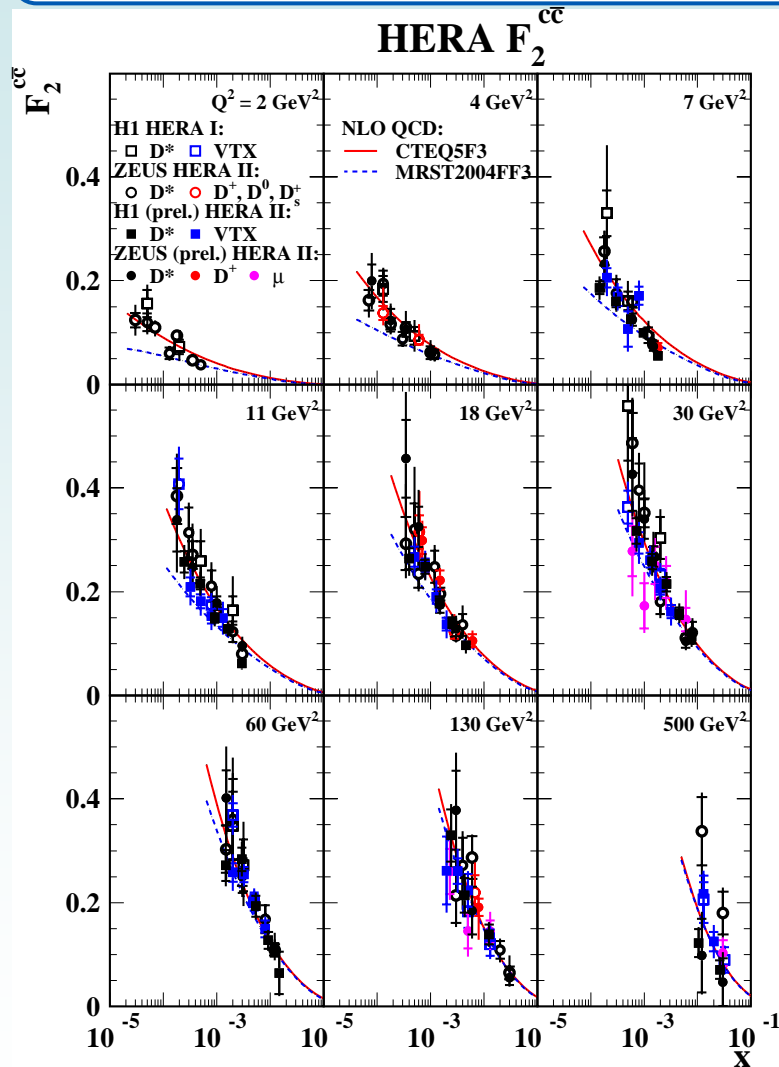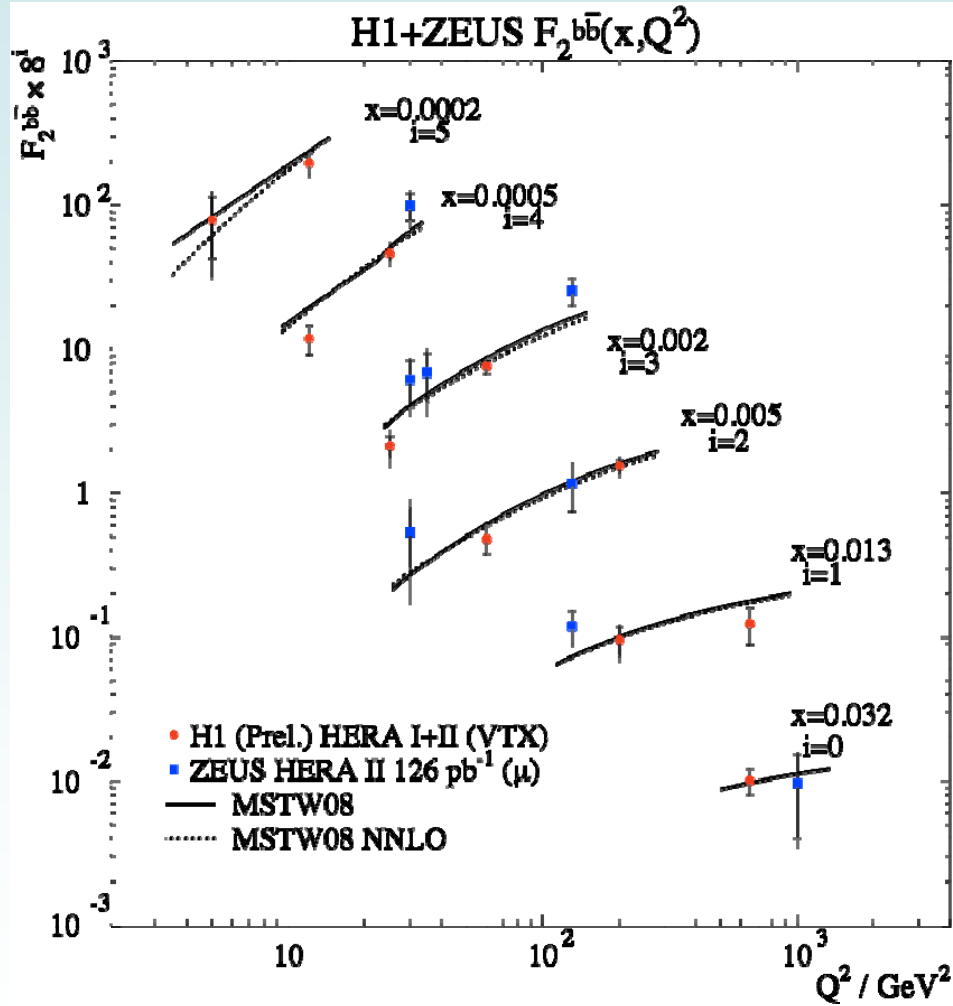
Experimental errors will further decrease – we are on the way to the final precision

Beauty Contribution to the Proton Structure

Data compared to GM-VFNS

(MSTW NLO, NNLO)

• Overall good description

• Small differences between NLO and NNLO

Summary

Charming window on the Universe:

Neutrino physics needs more insight on heavy quark production

Heavy quark production at HERA is a powerful tool to test QCD

- direct probe to gluon density in the proton

- test of the hadronisation models

Contribution to proton structure model dependent

- massive NLO pQCD describes data well in photoproduction and DIS

- model uncertainties larger than experimental errors

BACK UP

Heavy quarks in cosmic rays

High energy neutrinos: intensity, spectrum, flavour ratios give insight on source dynamics and might indicate new physics

Heavy quark (mostly charm) production plays important role:
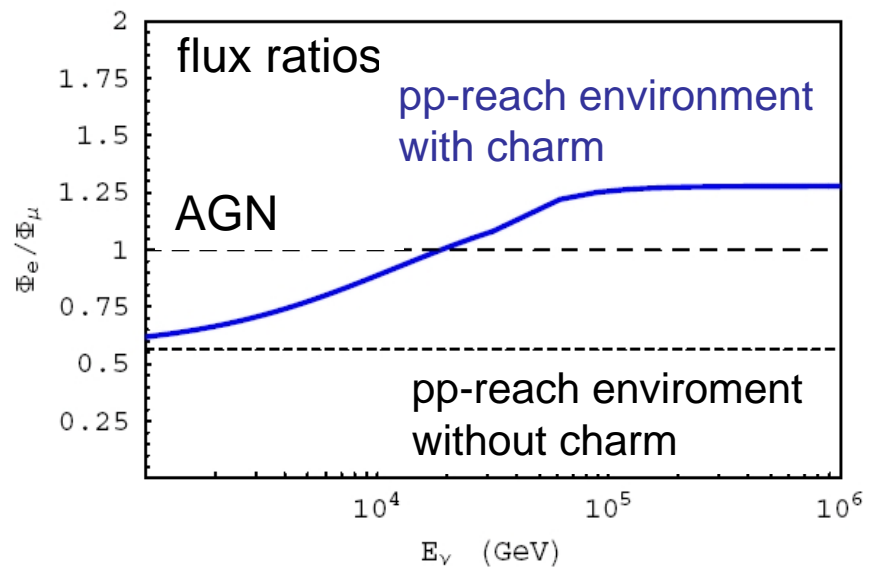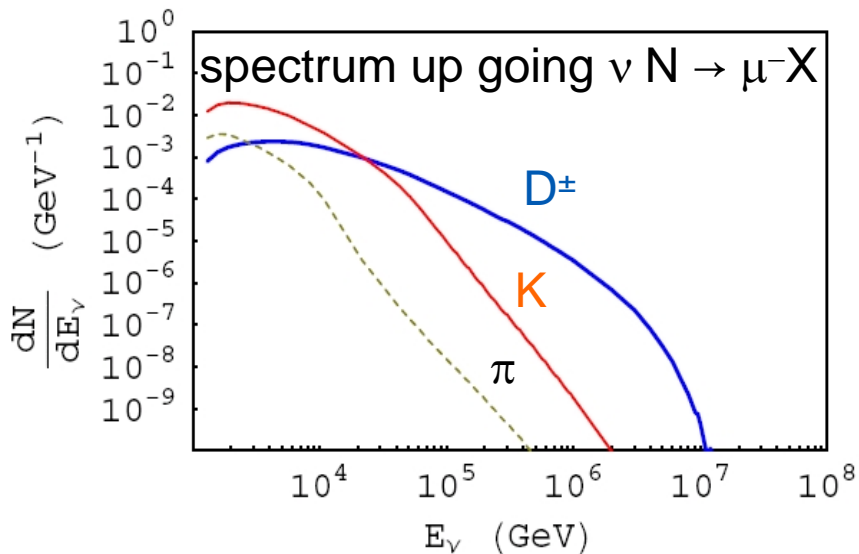
Most important (irreducible) background: atmospheric ν and μ

➢ understanding of heavy quark production and fragmentation necessary

➢ precision of the gluon density in the proton essential

Heavy quarks in cosmic rays

Neutrino astronomy with telescopes: detection principle $\nu_\mu + N \to \mu\, X$

Most important (irreducible) background: atmospheric ν and μ

- low energies (~GeV): conventional sources (π, K)

- high energies (1-100 TeV): prompt μ, ν from decays of heavy flavour hadrons

➢ understanding of heavy quark production and fragmentation necessary

➢ precision of the gluon density in the proton essential:

Example: flux ratio for prompt ν / μ

(Gelmini, Gondolo, Varieschi, Phys. Rew D67,017301)

momentum fraction of the struck parton in the nucleus in the atmosphere

$x < 10^{-5}$

gluon density: $xg(x) \sim x^{-\lambda}$

$0 < \lambda < 0.5$