D* + jets in DIS and photoproduction
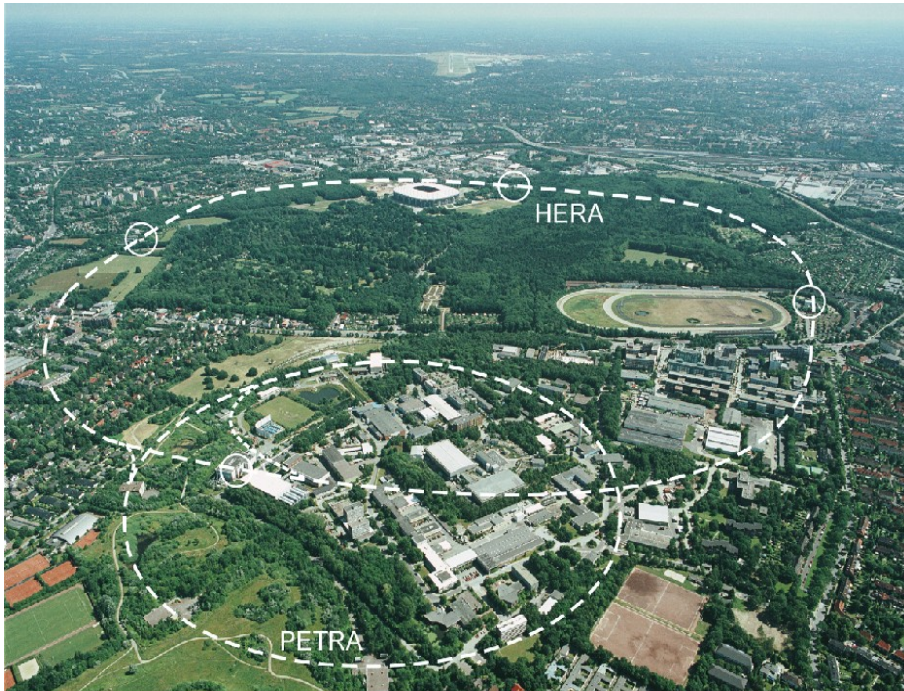
Andreas W. Jung (Fermilab)
for the H1 collaboration

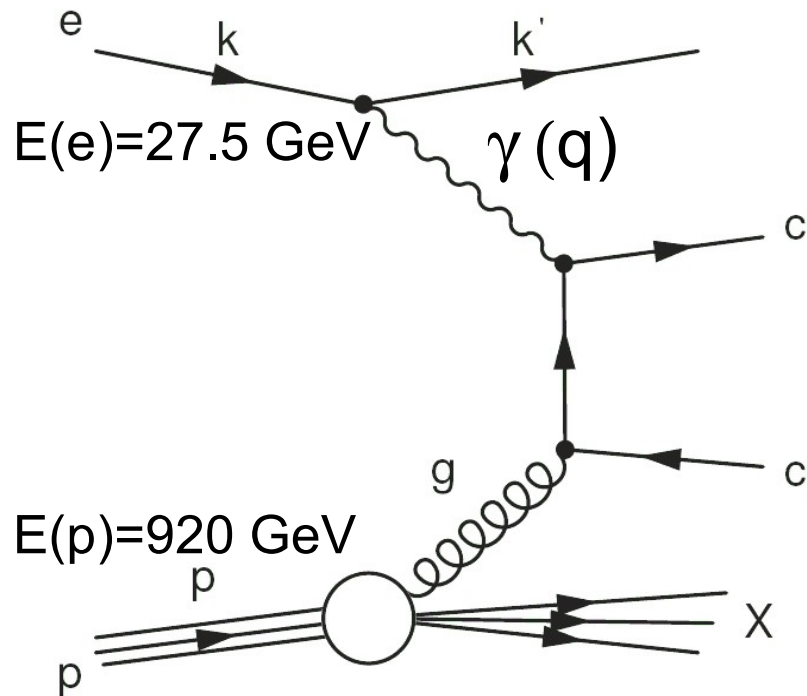- Introduction
- D* (+jet) cross sections
- Extraction of $F_2^c(x,Q^2)$
- Combination of $F_2^c(x,Q^2)$
- Conclusions

Dominant process for charm-production in *ep* -scattering:

e — k

k' — k'

E(e)=27.5 GeV γ (q)

c

c

g

E(p)=920 GeV

p

p

X

Kinematic at $\sqrt{s} \approx 320$ **GeV:**

- Photon Virtuality:

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

$Q^2 \sim 0$ GeV^2: Photoproduction
$Q^2 > 2$ GeV^2: Deep Inelastic Scattering

- Inelasticity: Bjorken x:

$$y = \frac{qp}{kp} \qquad x := \frac{Q^2}{2(\mathbf{p} \cdot \mathbf{q})}$$

D* via Fragmentation:

- Pseudorapidity: $\eta = \ln \tan\left(\frac{\theta}{2}\right)$
- Transverse momentum: p_t
- Elasticity:

$$z = \frac{E(D^*) - p_z(D^*)}{2 \cdot y E_e}$$

Study production mechanism:

- Q^2, m^2_c or p^2_T provides a hard scale for pQCD   → multiscale problem
- Test of heavy flavor treatment in pQCD
- Parton densities ("gluon structure") in the proton   → test universality

Theoretical models

Factorisation ansatz:

$$d\sigma = \sum_{i,j,k} f_j^B(x_2, \mu_f) \otimes d\hat{\sigma}_{ij \to kX}(\mu_f) \otimes D_k^H(z, \mu_f)$$

Parton density functions (PDFs) from global fits to data

Matrix element: calculable to different oders of a_s

Fragmentation function: from data

Many approaches on the market:

- **LO(a_s) + PS:**
  - collinear factorization — PYTHIA (DGLAP, massive/massless)
  - collinear factorization — RAPGAP (DGLAP, massive)
  - k_T factorization — CASCADE (CCFM, massive)

  (all MCs use Lund fragmentation (uds) and Bowler (c)

- **NLO(a_s^2):**
  - Collinear factorization — HVQDIS (DGLAP, FFNS, massive, independent Fragmentation)

  ZMVFNS (DGLAP, ZM-VFNS, massless, KKKS08)

- **NLO(a_s^2) +PS:**
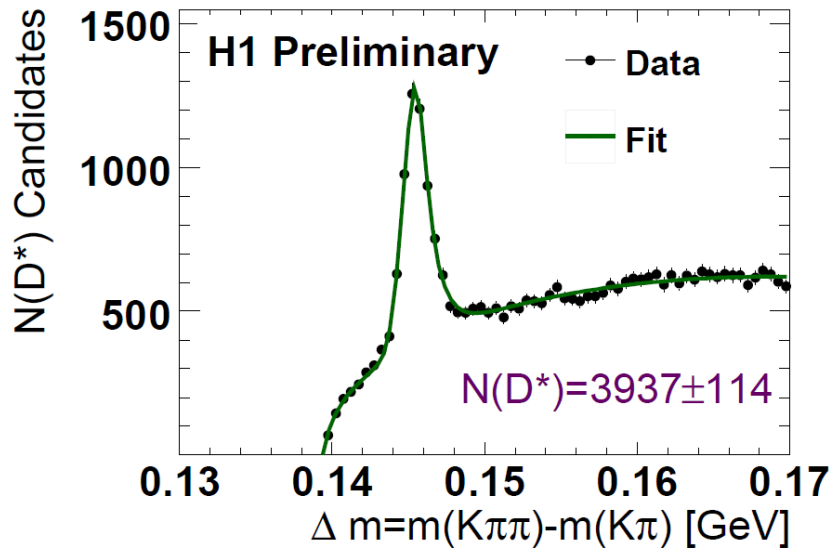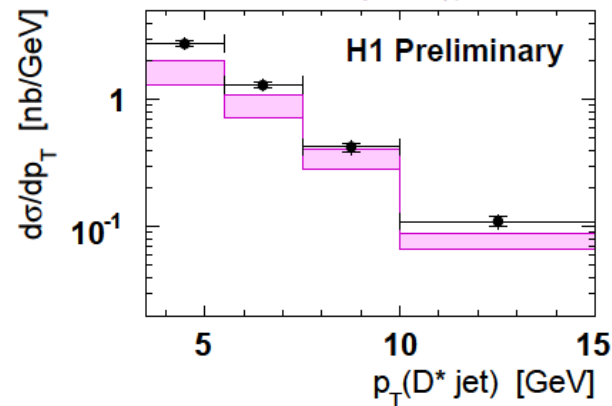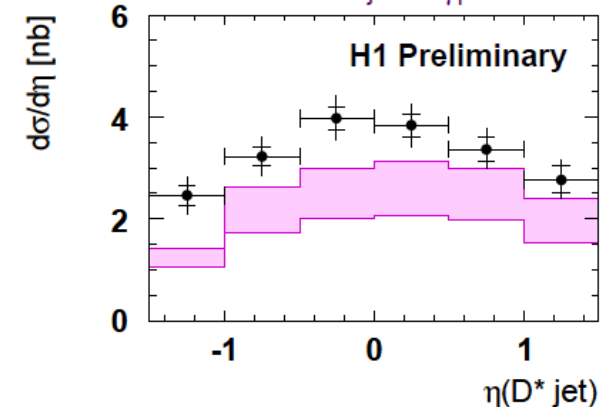 - collinear factorization — MC@NLO (DGLAP, massive, cluster fragmentation)

D*+2 jets in γp

H1 Preliminary

- Data
- Fit

$N(D^*) = 3937 \pm 114$

$\Delta m = m(K\pi\pi) - m(K\pi)$ [GeV]

D*+2 jets in γp

H1 Preliminary

$d\sigma/dp_T$ [nb/GeV]

$p_T(D^* \text{ jet})$ [GeV]

D*+2 jets in γp

H1 Preliminary

$d\sigma/d\eta$ [nb]

$\eta(D^* \text{ jet})$

D*+2 jets in γp

H1 Preliminary

$d\sigma/dp_T$ [nb/GeV]

- Data (H1 Prel.)
- MC@NLO

$p_T(\text{Other jet})$ [GeV]

D*+2 jets in γp

H1 Preliminary

$d\sigma/d\eta$ [nb]

$\eta(\text{Other jet})$

- Full HERAII sample (L = 93 pb^{-1})
- Total systematic error: ~ 9%
- Phase Space cuts:

   $p_T(D^*) > 2.1$ GeV & $|\eta(D^*)| < 1.5$

   $p_T(\text{jet}) > 3.5$ GeV & $|\eta(\text{jet})| < 1.5$

   $|\eta(D^*\text{-jet})| < 1.5$

   $-1.5 < \eta(\text{other-jet}) < 2.9$
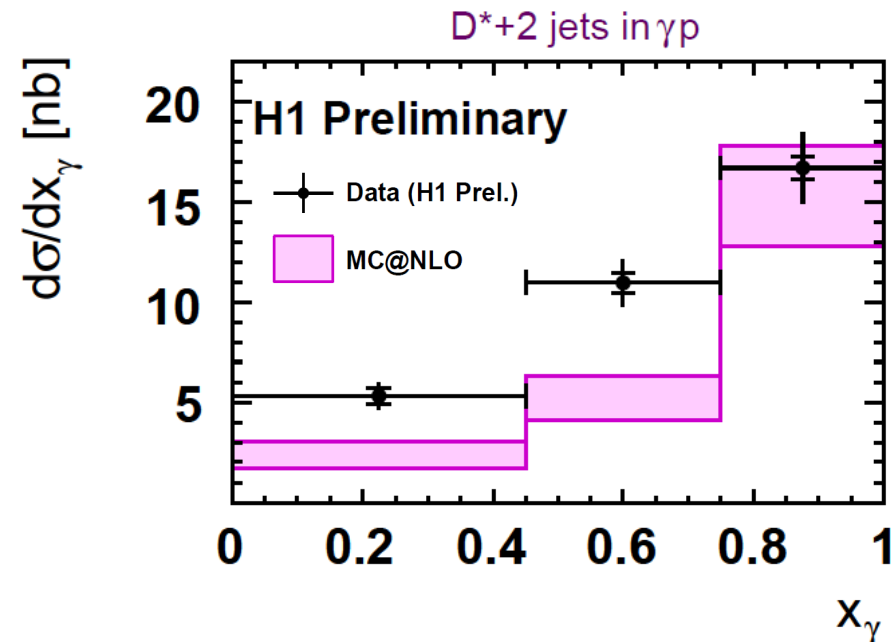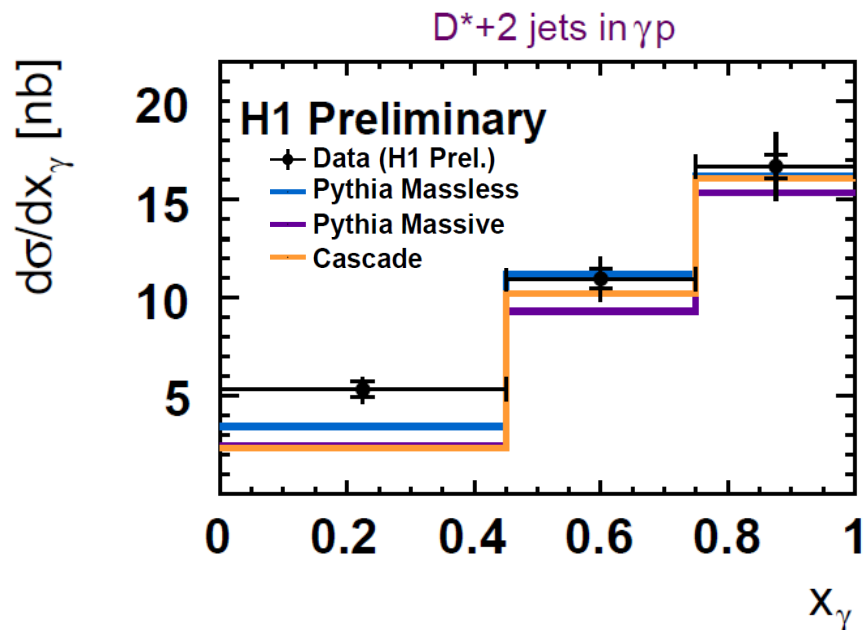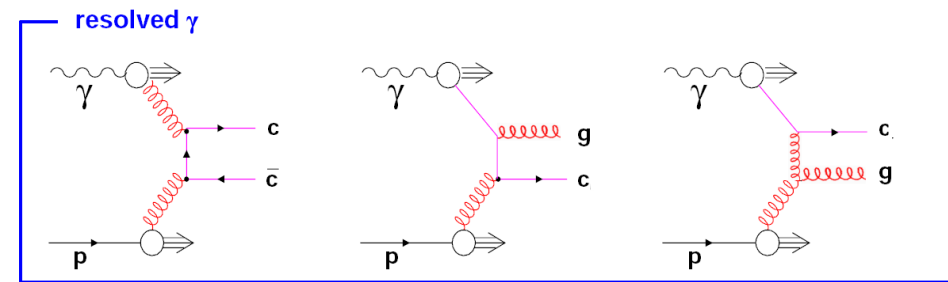
   (other-jet is jet with highest $p_T(\text{jet})$

other than D*-jet

- Comparison to MC@NLO (CTEQ66)
- Uncertainty band from scale variations
- MC@NLO too low in normalization
- Shape fits quite well

D+jets photoproduction*

- Longitudinal momentum fraction of the photon carried by the jets:
- At low x_γ significant contribution from resolved (quasi-real) photons:
  $\rightarrow$ Low x_γ sensitiv to the photon PDF

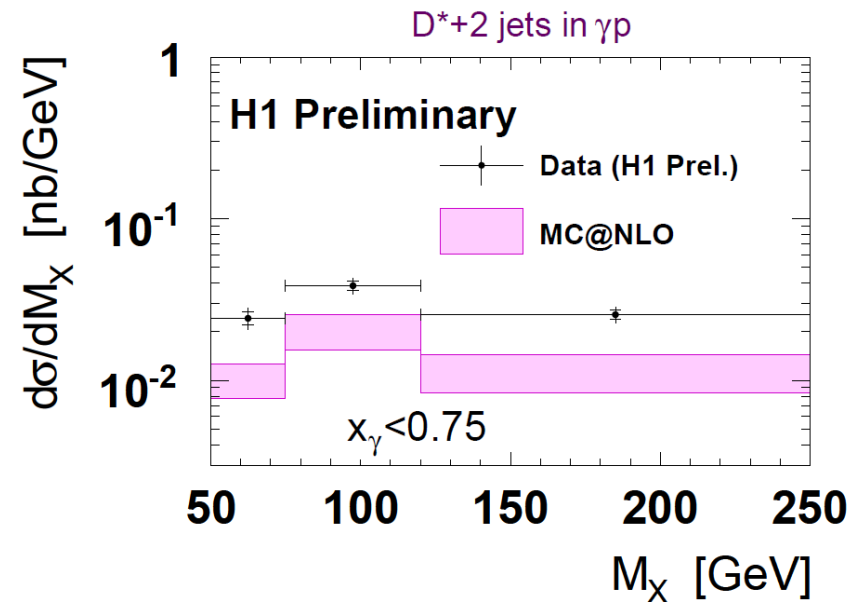$$x_\gamma = \frac{\sum_j (E - p_z)_j + \sum_k (E - p_z)_k}{2yE_e}$$

resolved γ

D*+2 jets in γp

H1 Preliminary

Data (H1 Prel.)
Pythia Massless
Pythia Massive
Cascade

D*+2 jets in γp
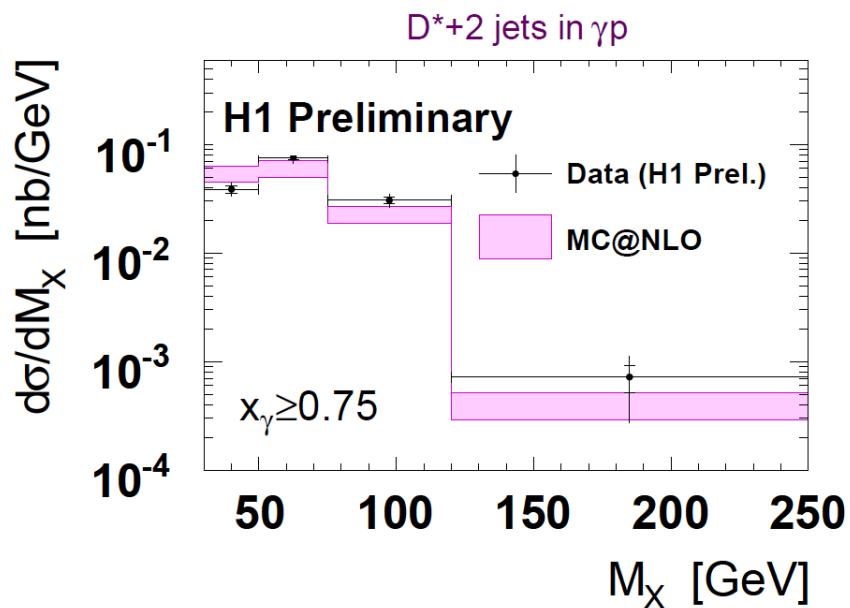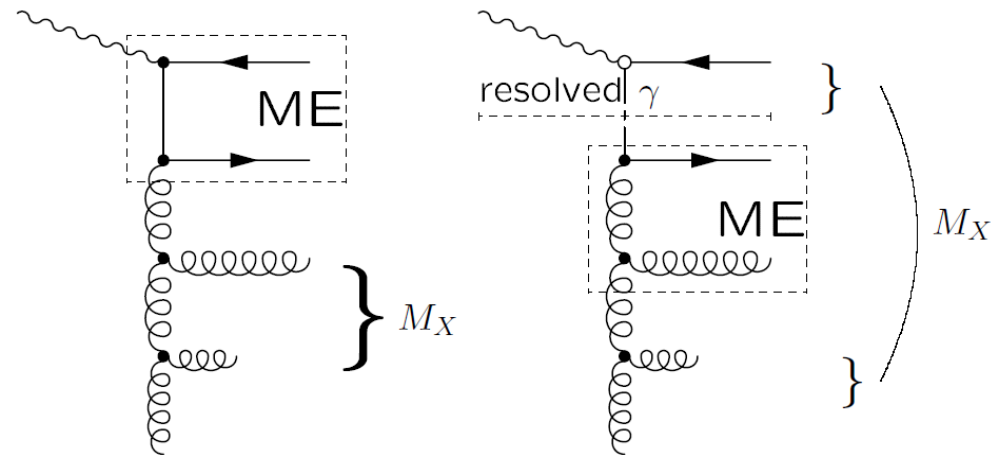
H1 Preliminary

Data (H1 Prel.)
MC@NLO

- High x_γ: direct processes well described by either MCs & MC@NLO
- Low x_γ: resolved processes not described by any model, but better by MCs

D*+jets photoproduction

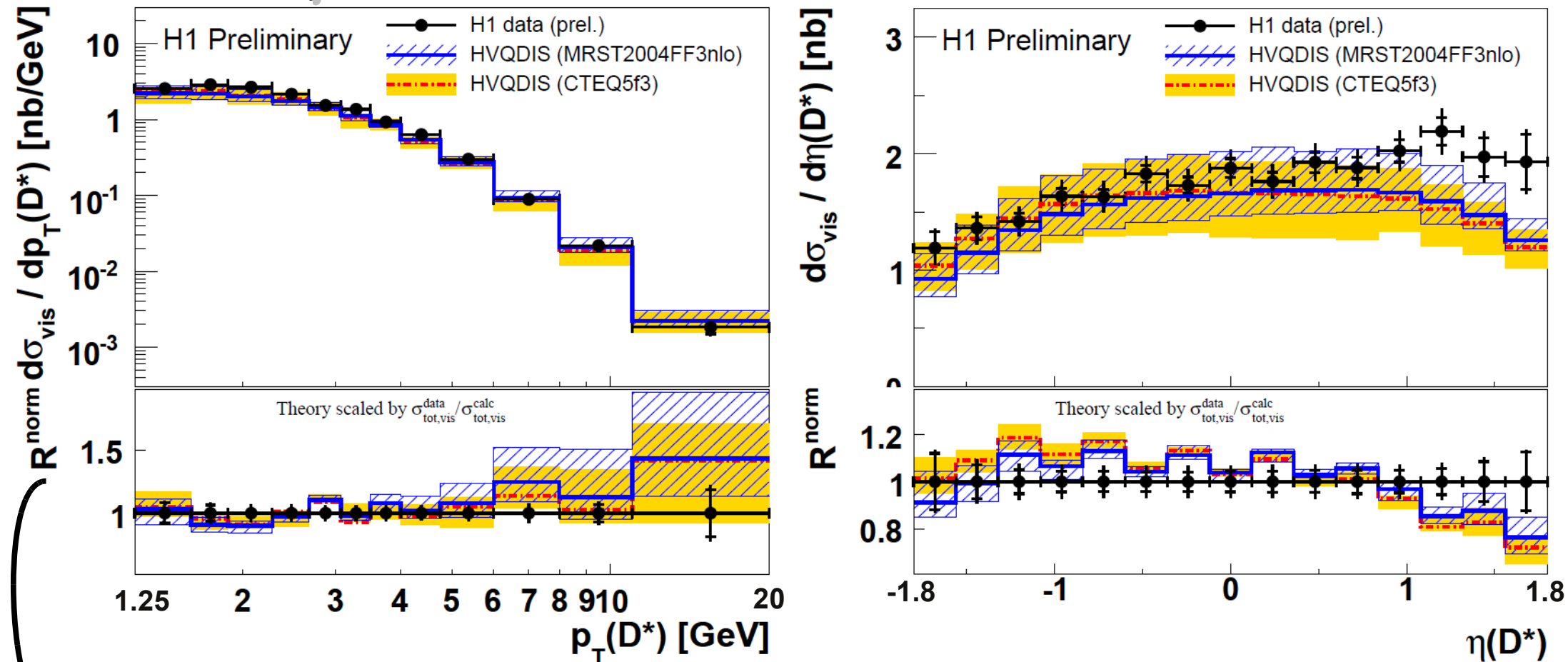- M_X invariant mass of the remnant from
  photon & proton side

- M_X not very well described: At high x_γ shape reasonably well described but at low x_γ the normalization is too low

D* production: medium Q²

Shape comparison via normalized ratio:

$$R = \frac{1/\sigma_{tot,vis}^{calc} \cdot \frac{d\sigma^{calc}}{dY}}{1/\sigma_{tot,vis}^{data} \cdot \frac{d\sigma^{data}}{dY}}$$

- Full HERAII statistics: L = 347 pb⁻¹ yields N(D*)~24705
- Total systematic error is 7.6% !
- Well understood detector allows increased Phase Space:
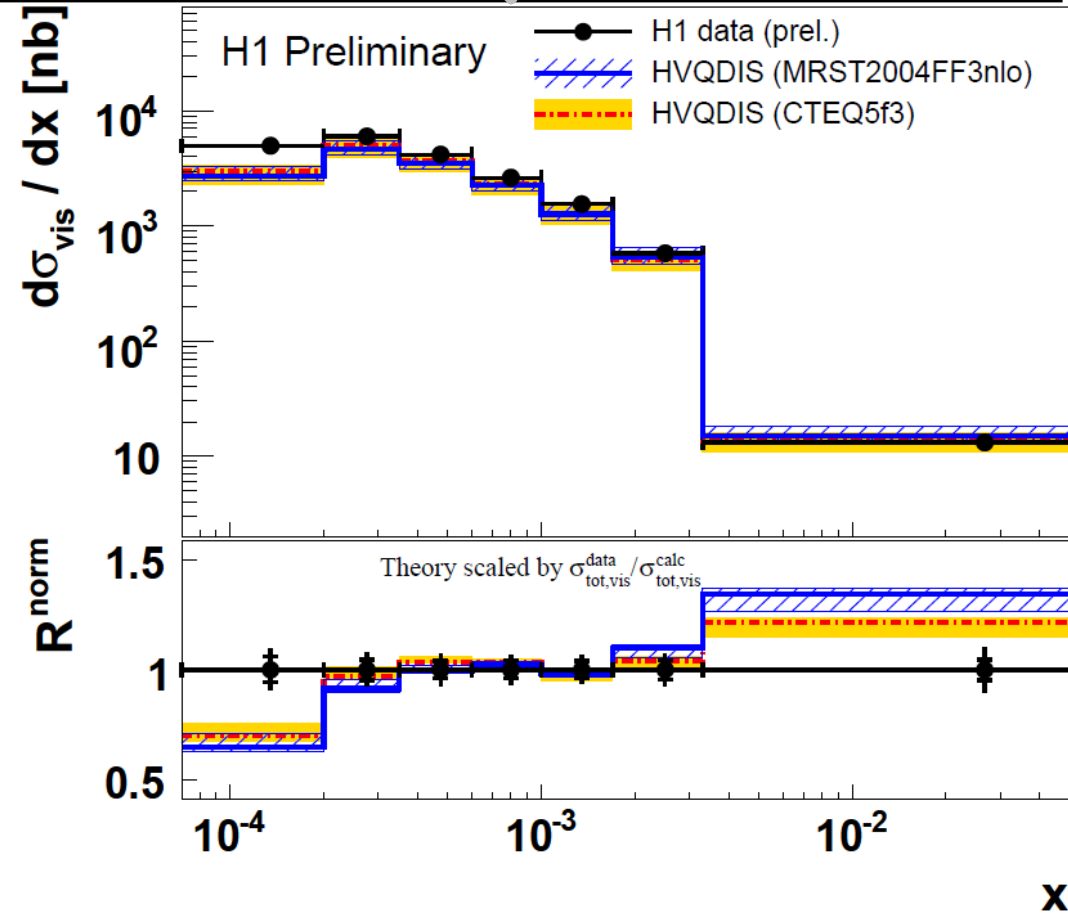
p_T(D*): > 1.25 GeV and |η (D*)| : < 1.8
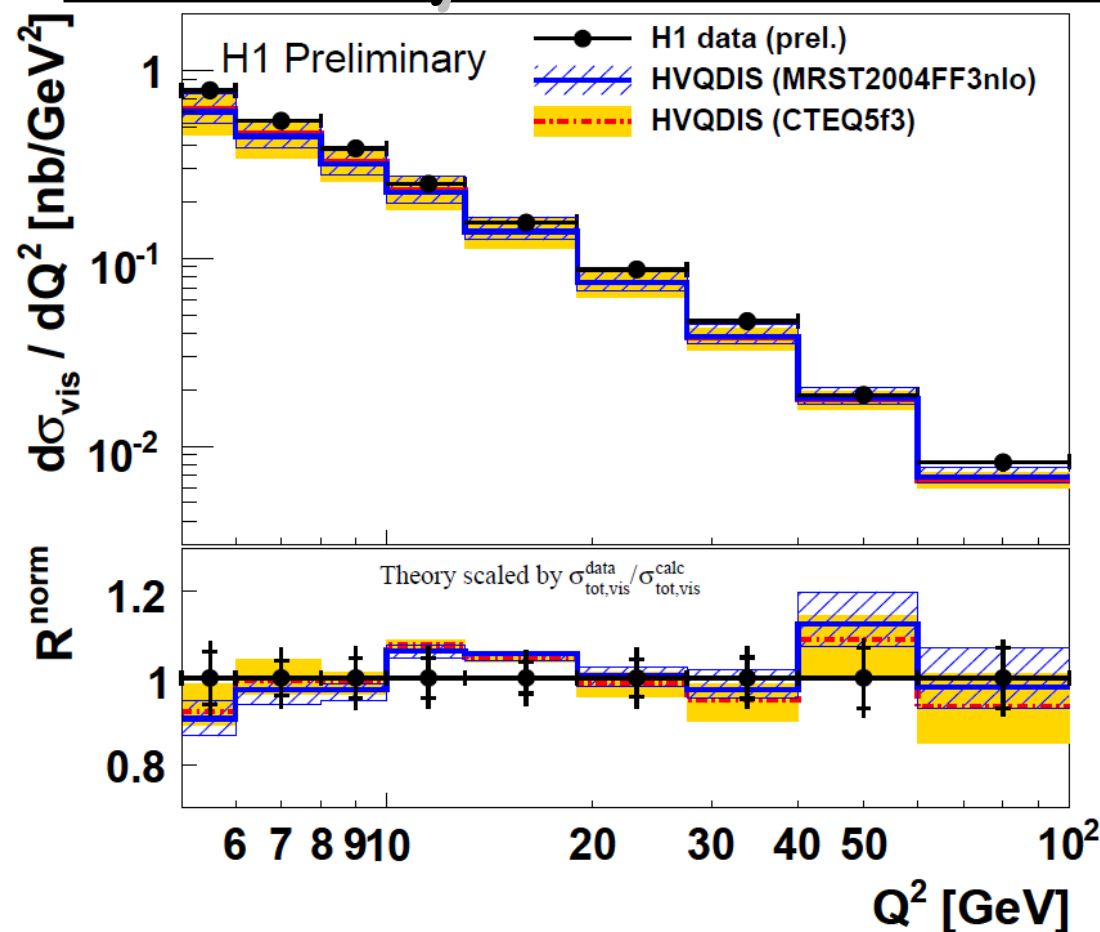
- Data are reasonable described by HVQDIS

D* production: medium Q²

- Theory uncertainty includes scale, mass & fragmentation uncertainty
- HVQDIS describes nicely the Q^2 dependency
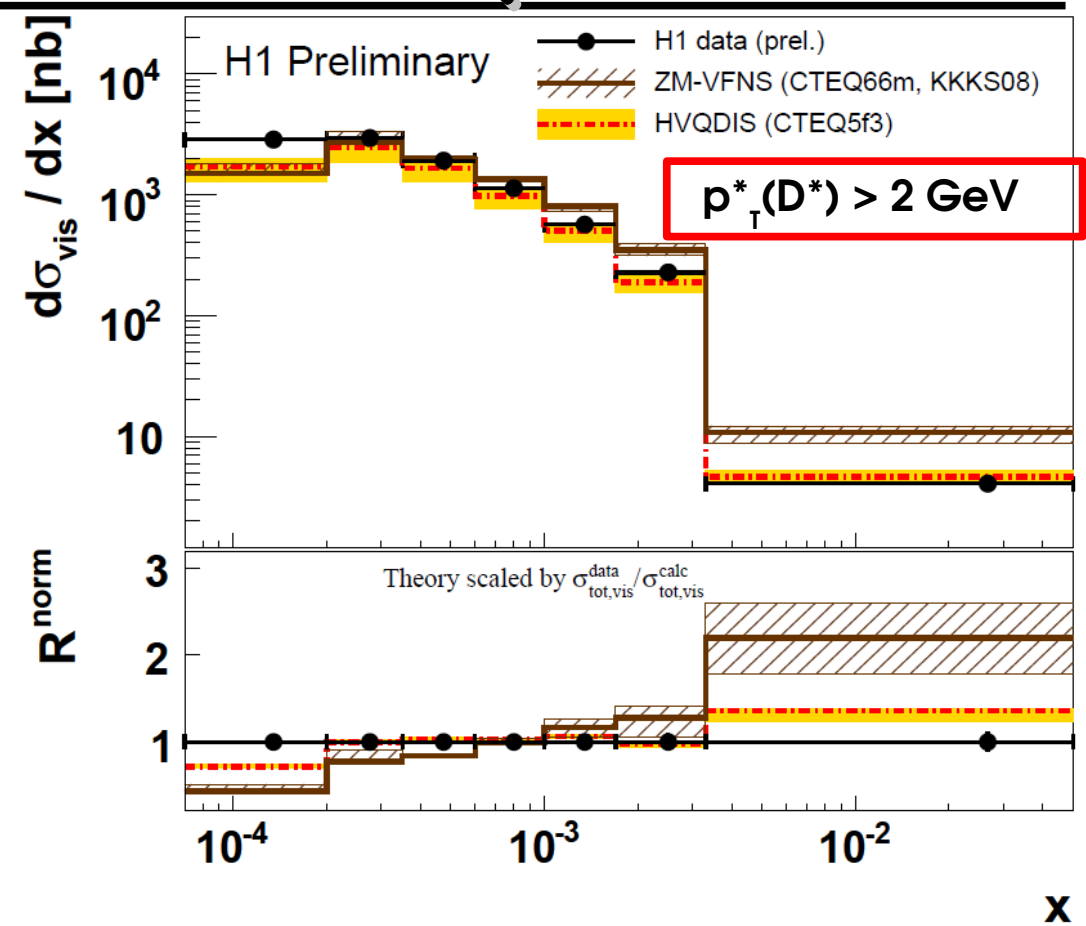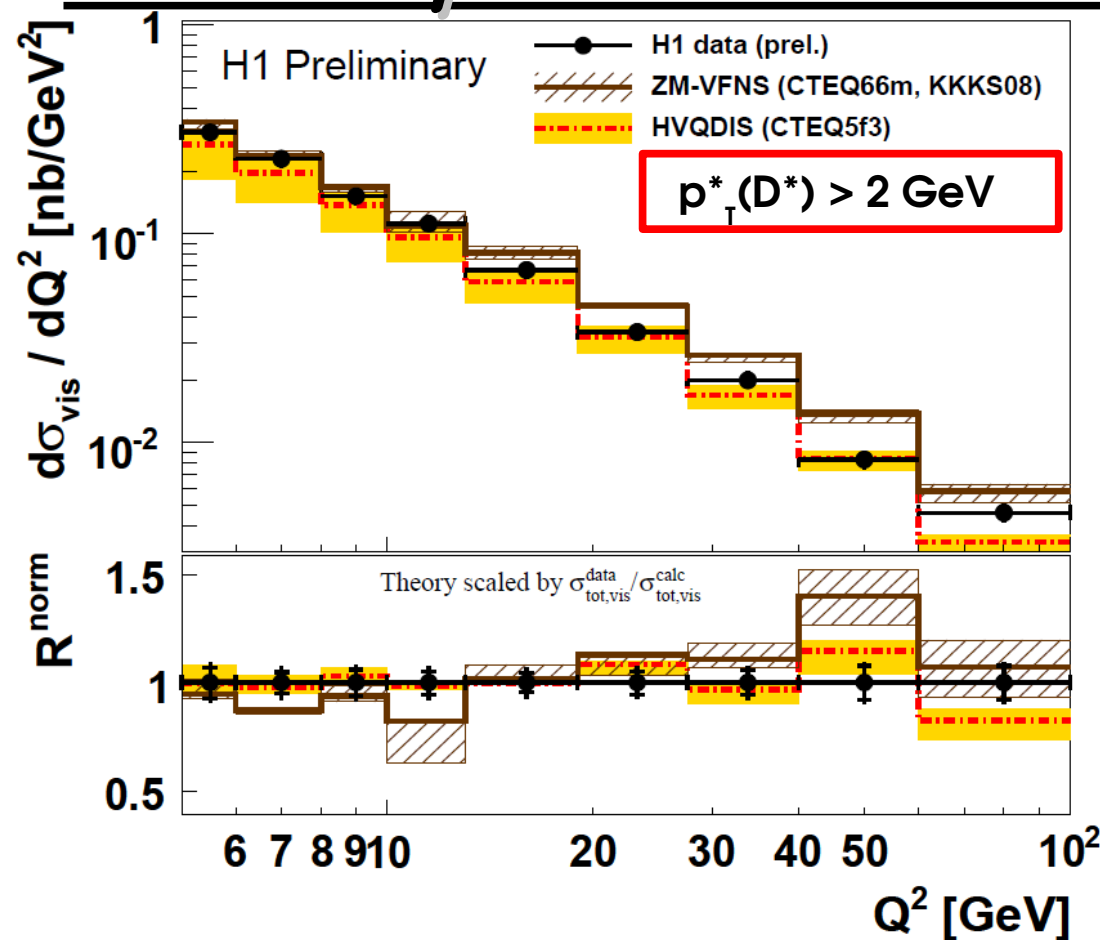- Slope in x not very well reproduced!
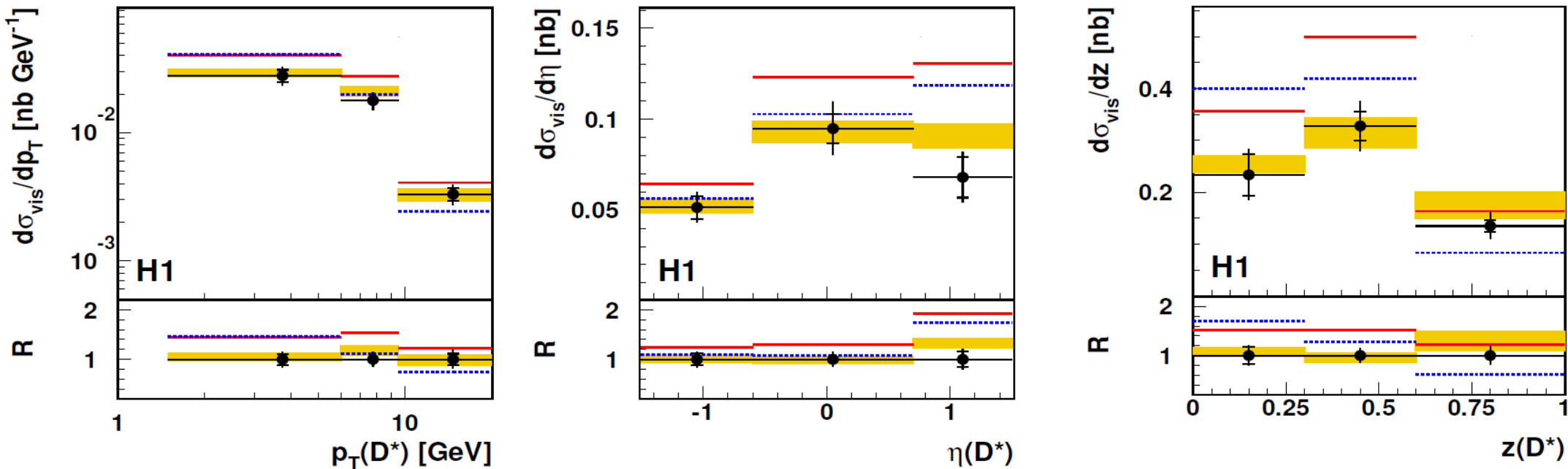- Double differential y-Q^2 has also been measured, can be used to extract $F_2^c(x,Q^2)$

- For comparison with ZM-VFNS: Cut in photon-proton rest frame: $p_T^*(D^*) > 2$ GeV

- ZM-VFNS: Theoretical uncertainty taken from scale variations

- Reasonable description of Q^2 by both NLO calculations, HVQDIS is better in shape

- For x ZM-VFNS predicts completely different slope & fails especially at large x

Remark: Only the most recent PDF sets consider mass effects!

D* production: high Q²

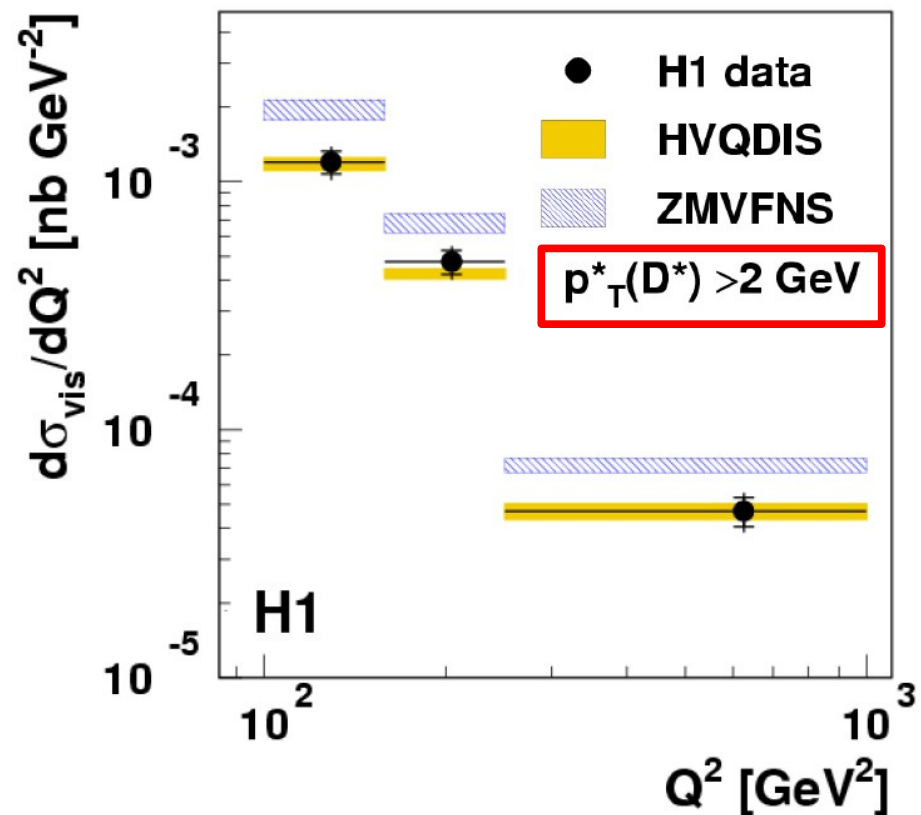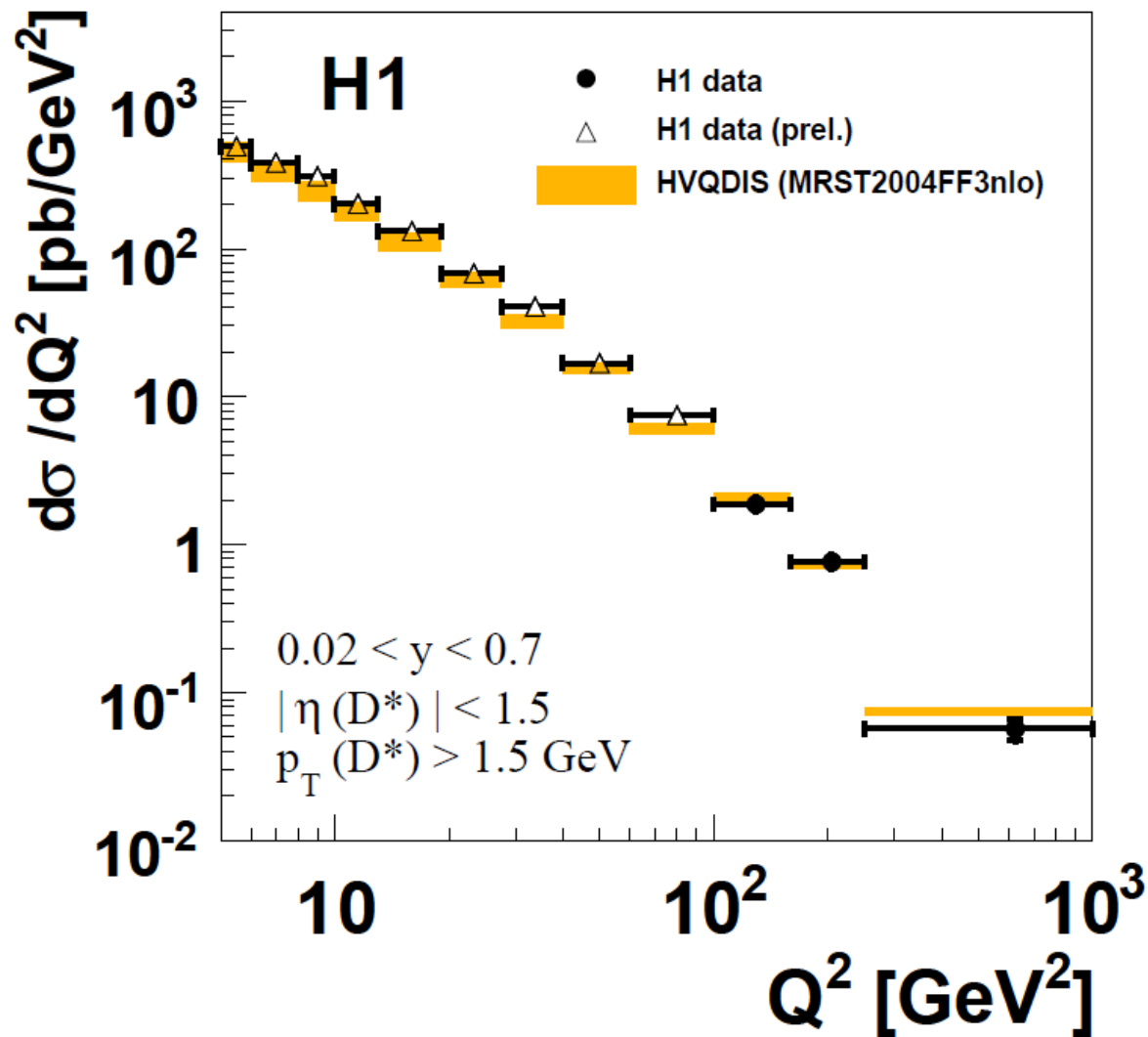- Full HERAII statistics (L = 351 pb⁻¹)
- Total systematic error: 12%

- Phase Space: $p_T(D^*)$: > 1.5 GeV and $|\eta(D^*)|$: < 1.5

- MCs fail to describe differential D* cross sections
- HVQDIS describes the data quite reasonably

- **H1 data**
- **HVQDIS**
- **RAPGAP**
- **CASCADE**

D* production: high Q^2

D* production in DIS

- Massive FFNS describes cross section over three orders of magnitude!
- Massless ZM-VFNS fails to describe high Q^2 region

Extraction of $F_2^c(x,Q^2)$

$$\frac{d^2\sigma^{c\bar{c}}(x,Q^2)}{dx\,dQ^2} = \frac{2\pi\alpha_{em}^2}{xQ^4} \cdot \left(\left[1 + (1-y)^2\right] \cdot F_2^{c\bar{c}}(x,Q^2) - y^2 \cdot F_L^{c\bar{c}}(x,Q^2) \right)$$

Only at high y: 2-3% for this measurement negligible

Experimental method to measure $F_2^c(x,Q^2)$:

Measured cross sections

$$F_2^{c\,\mathrm{exp}}(x,Q^2) = \frac{\sigma_{\mathrm{vis}}^{\mathrm{exp}}(y,Q^2)}{\sigma_{\mathrm{vis}}^{\mathrm{theo}}(y,Q^2)} \cdot F_{2\,\mathrm{full}}^{c\,\mathrm{theo}}(x,Q^2)$$
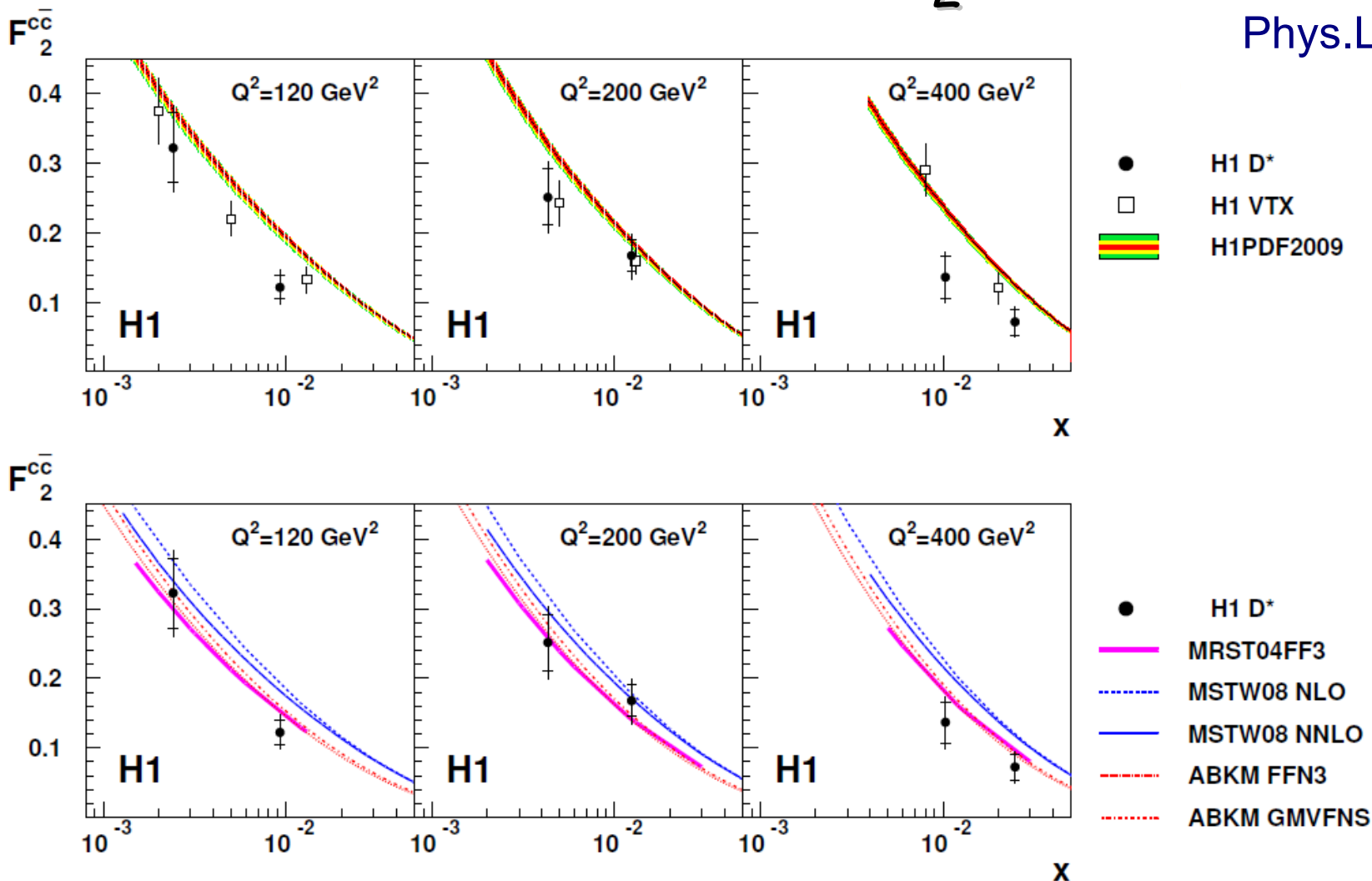
Using NLO (FFNS)

- Extrapolation uncertainty from variations of scale, mass, fragmentation
- At medium Q^2 measured D* cross section covers only 30%
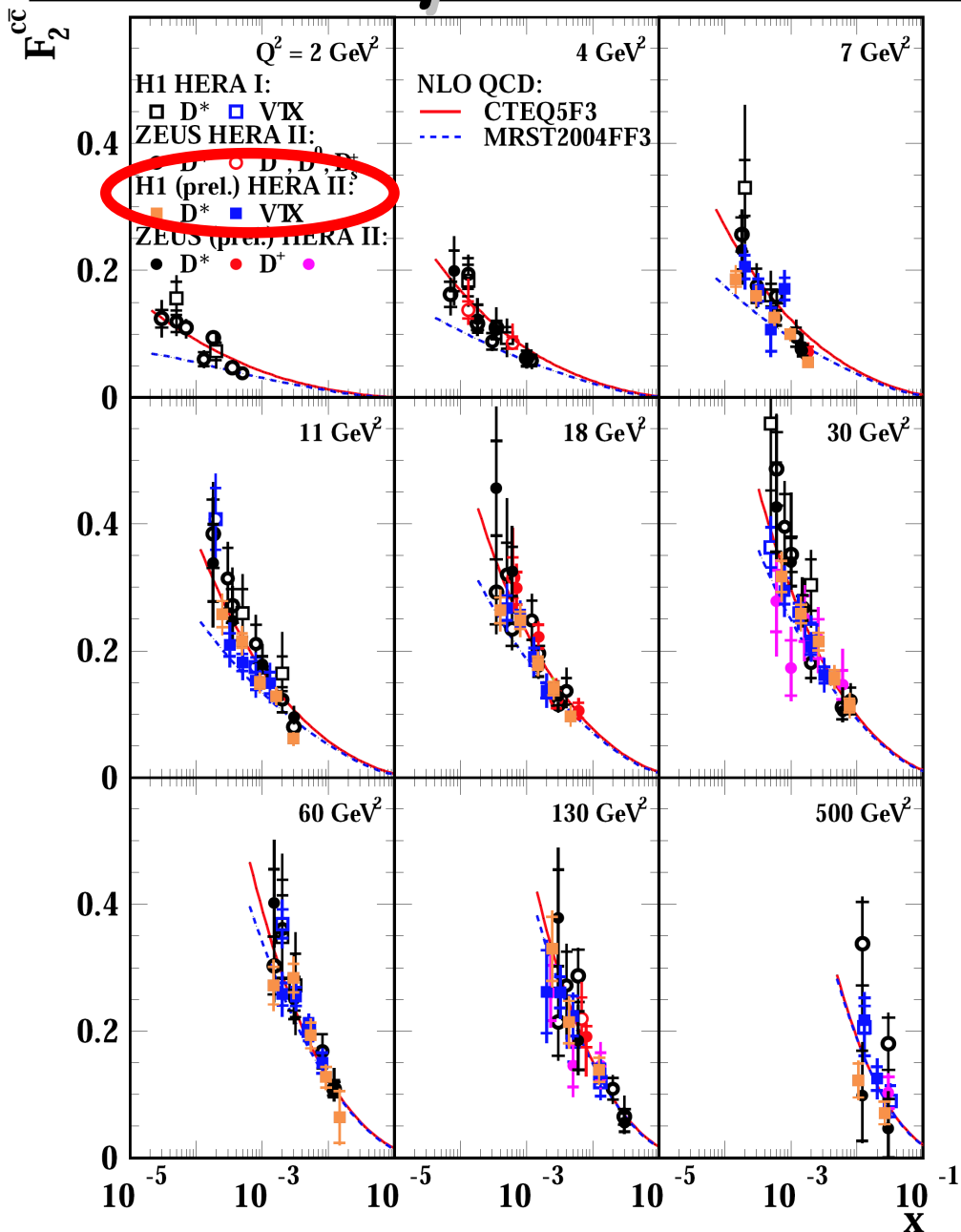   if $p_T(D^*) > 1.5$ GeV & $|\eta(D^*)| : < 1.5$

- Reasonable agreement between two experimental methods
- H1PDF2009 overall slightly above data
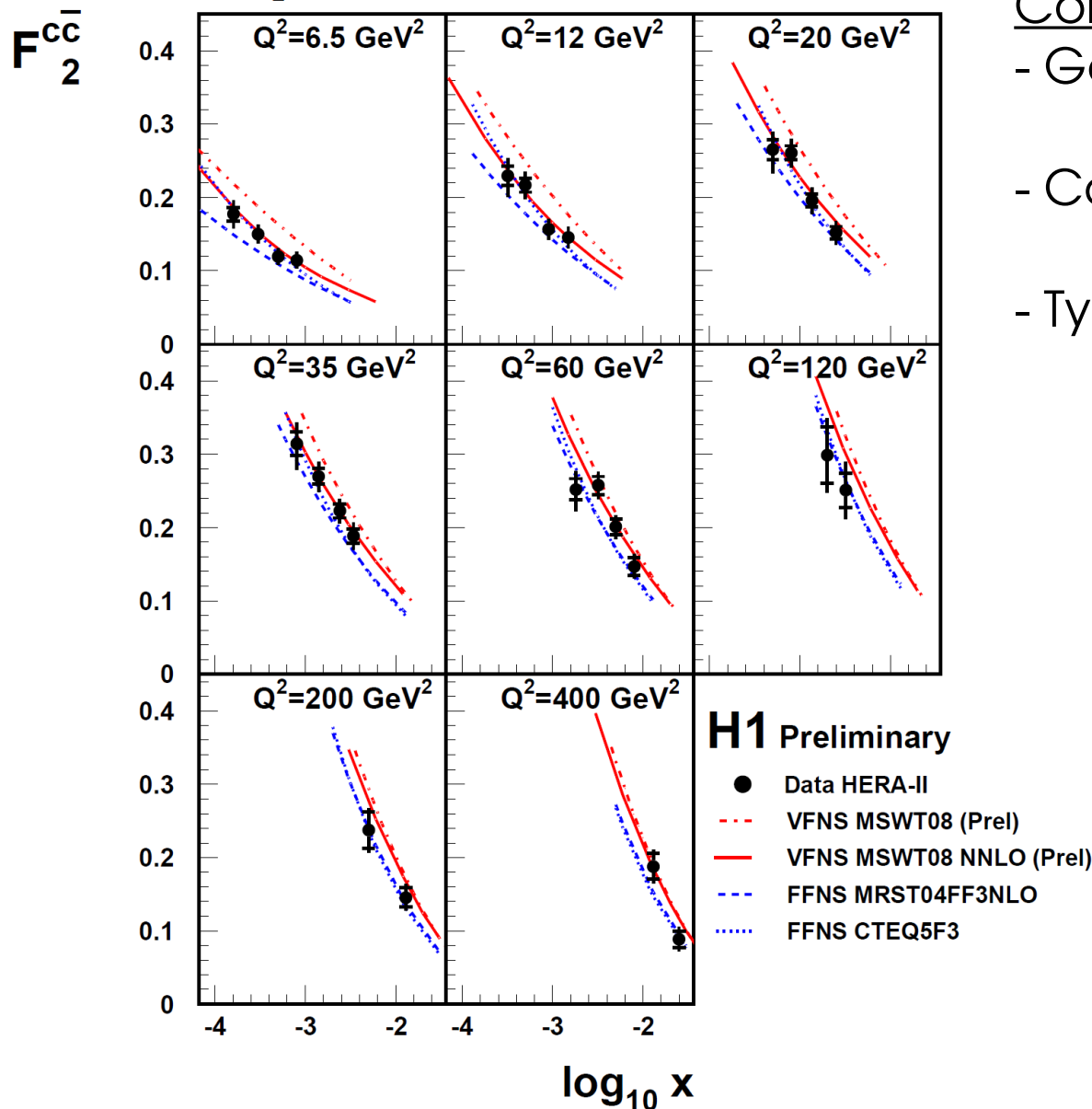- Within uncertainty data described by MSTW, ABKM

- HVQDIS using different proton PDFs describes the F_2^c data reasonable
- Nice agreement between different experimental methods & experiments
- Details on H1 VTX → (1169, P. Thompson)
- Gain in precision by combining data within one experiment and by combining with ZEUS
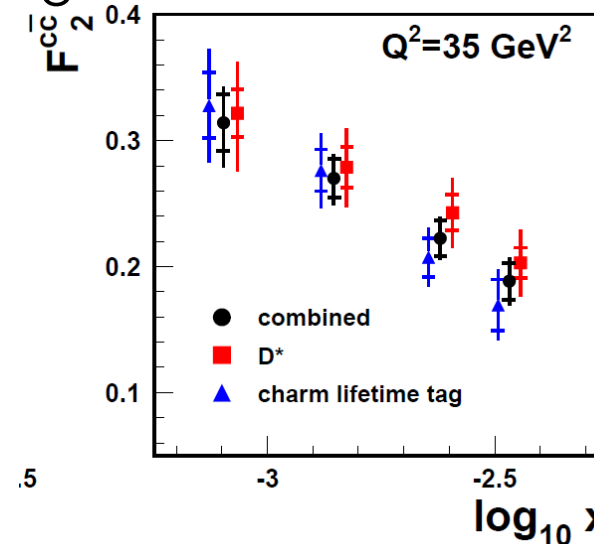
Combination of $F_2^c(x,Q^2)$

$F_2^{c\bar{c}}$ Combined D* and Charm Lifetime Tag

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

H1 **Preliminary**

- ● Data HERA-II
- ─·─ VFNS MSWT08 (Prel)
- ── VFNS MSWT08 NNLO (Prel)
- ─── FFNS MRST04FF3NLO
- ······ FFNS CTEQ5F3

Combine D* and lifetime results:
- Gain in precision because of different systematic uncertainties
- Correlation of Systematic uncertainties taken into account
- Typical gain ~25%:

- combined
- ■ D*
- ▲ charm lifetime tag

Q^2=35 GeV^2

- ● Data are reasonable described
- ● At low Q^2 data can discriminate between models
- ● For HERA combined results:
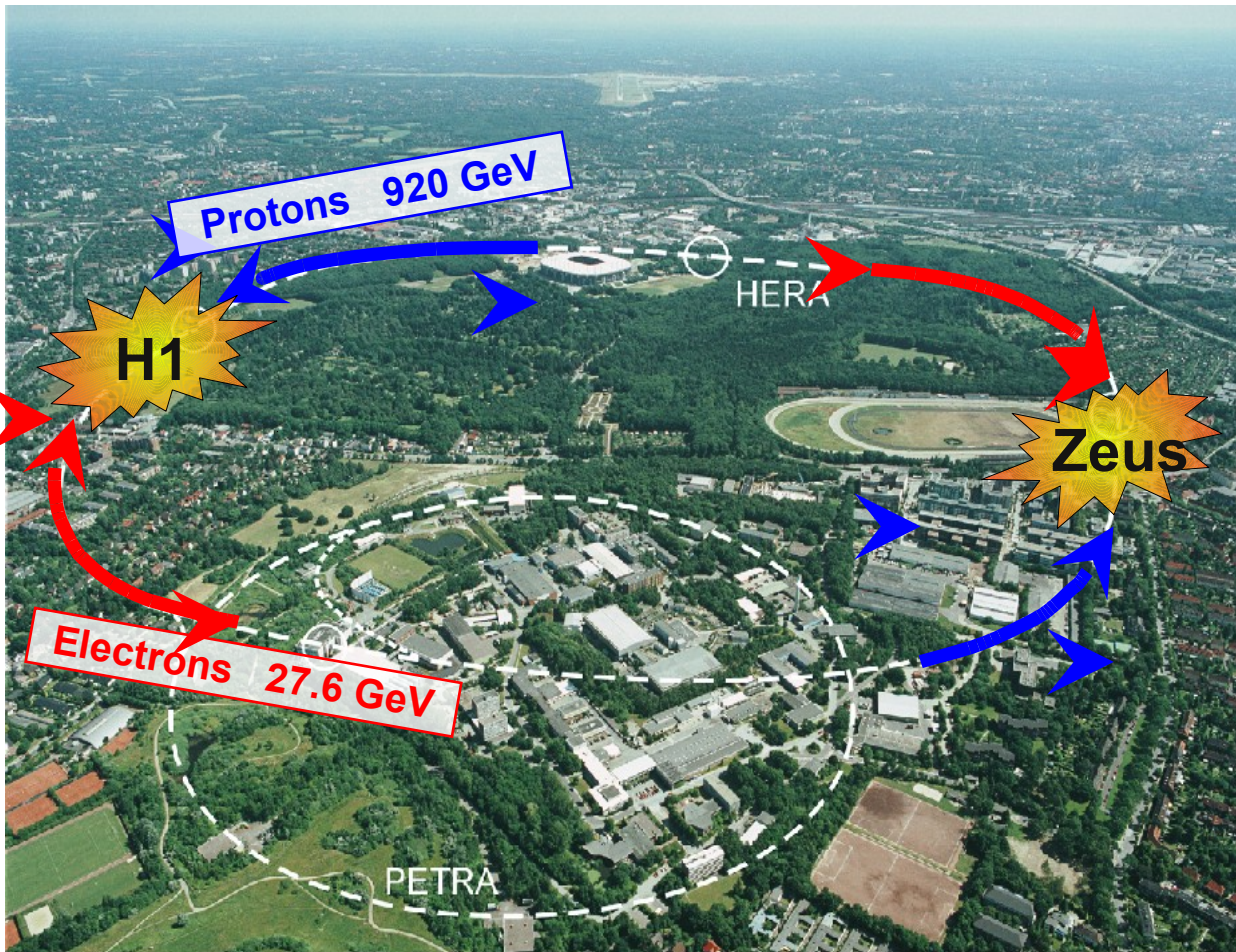 → see Talk by M. Corradi (1159)

Conclusions

- Full H1 HERA II data sample analyzed for photoproduction, medium & high Q^2 D* production:

  - Photoproduction: MCs & MC@NLO dont describe resolved photon domain

  - DIS: - HVQDIS describes Data reasonably well
    - ZM-VFNS not able to describe the D* data

- Extracted $F_2^c(x, Q^2)$ from D* data & combined with life-time data:

  - Gain in precision via combination of data
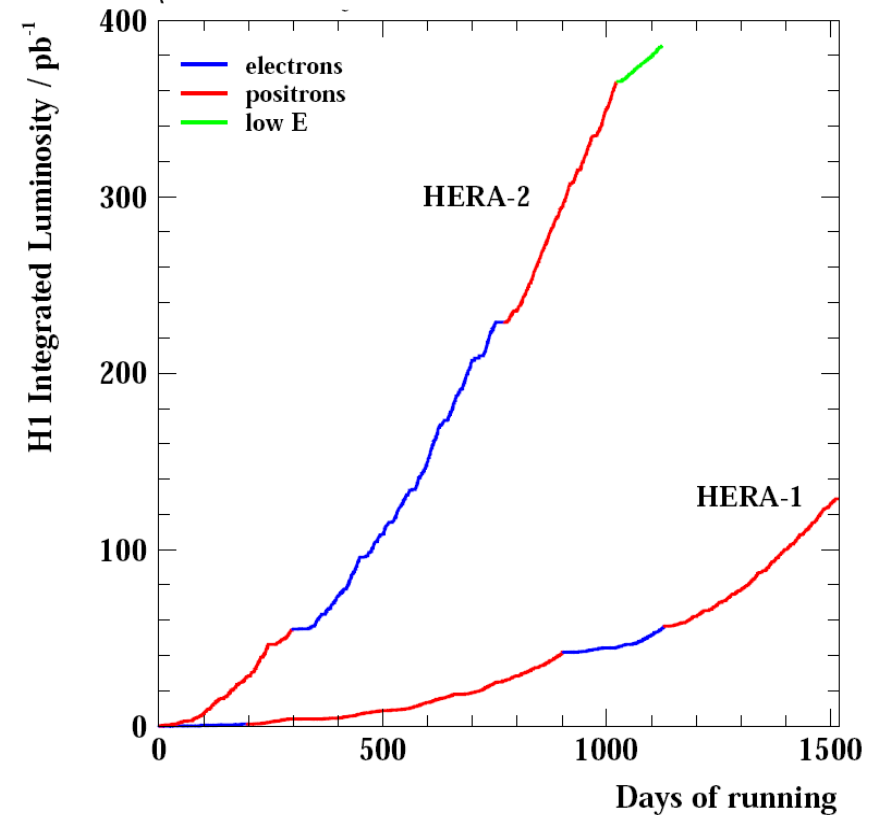
  - Reasonably described by different calculations

Backup

Collected Data samples:

--> Two multi-purpose detectors: H1 & Zeus
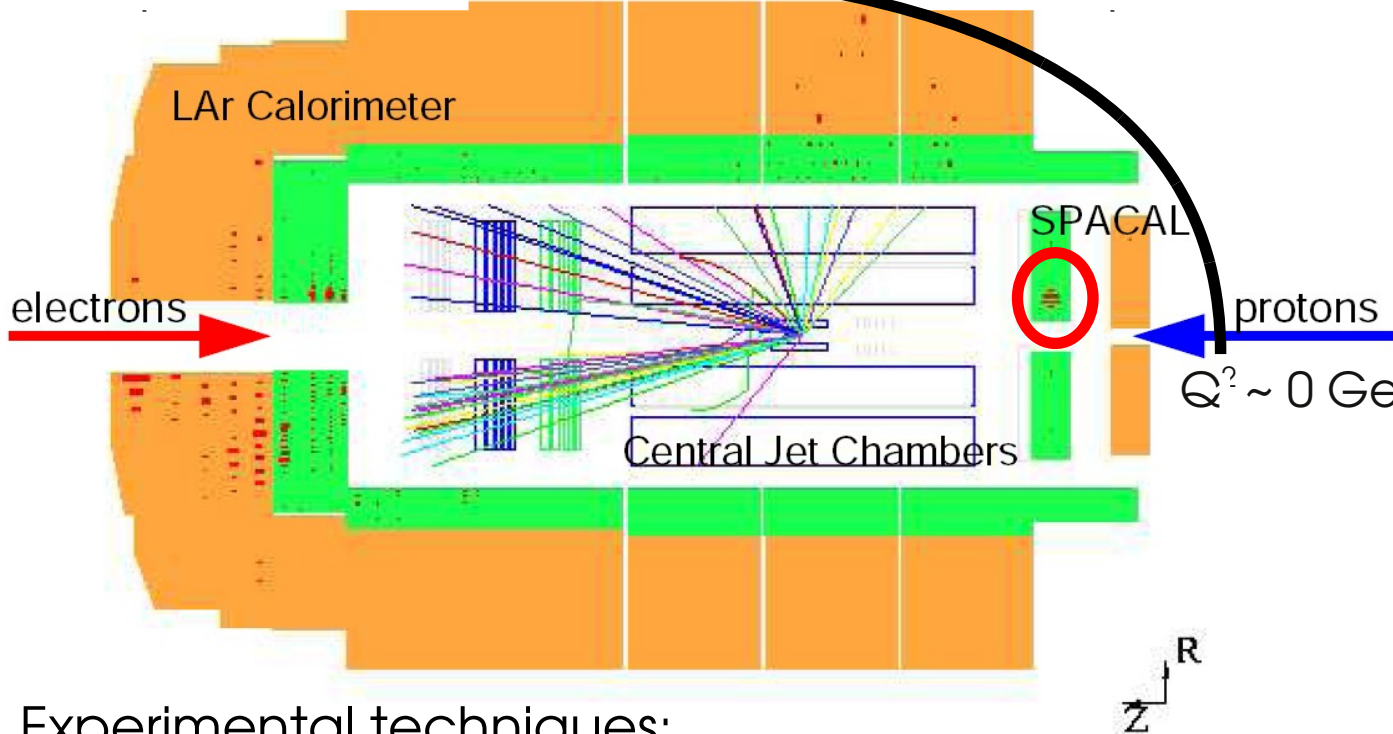
--> Collected Luminosity: HERAI + HERAII ~ 0.5 fb^{-1}

$Q^2 \sim 1000\ \text{GeV}^2$

$\sigma_{\gamma p} \sim 1/Q^4$

LAr Calorimeter

SPACAL

electrons

protons

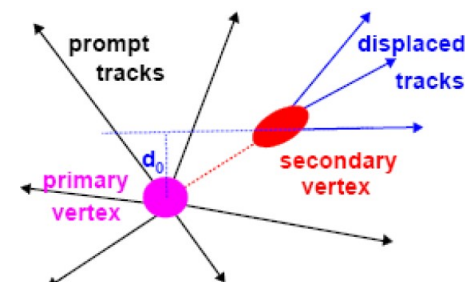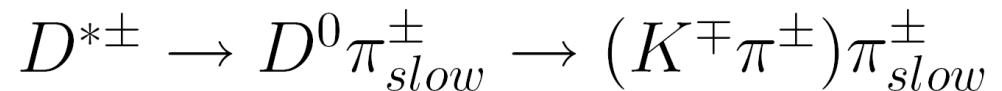$Q^? \sim 0\ \text{GeV}^2$

Central Jet Chambers

R

Z

- Untagged electron:
  $Q^2 \sim 0\ \text{GeV}^2$

  Track based final states:
  H1 Fast Track Trigger!

- Scattered electron in backward calorimeter:
  $5 < Q^2 < 100\ \text{GeV}^2$

- OR in main calorimeter:
  $100 < Q^2 < 1000\ \text{GeV}^2$

Experimental techniques:
- Fully reconstructed D*:
  total BR of 2.57%

$$D^{*\pm} \to D^0 \pi^{\pm}_{slow} \to (K^{\mp}\pi^{\pm})\pi^{\pm}_{slow}$$

- Inclusive method using lifetime of charmed mesons

  → More details: Talk by P.Thompson

prompt tracks

displaced tracks

d_0

primary vertex

secondary vertex

Theoretical models

Factorisation ansatz:

$$d\sigma = \sum_{i,j,k} f_j^B(x_2, \mu_f) \otimes d\hat{\sigma}_{ij \to kX}(\mu_f) \otimes D_k^H(z, \mu_f)$$

Parton density functions (PDFs) from global fits to data

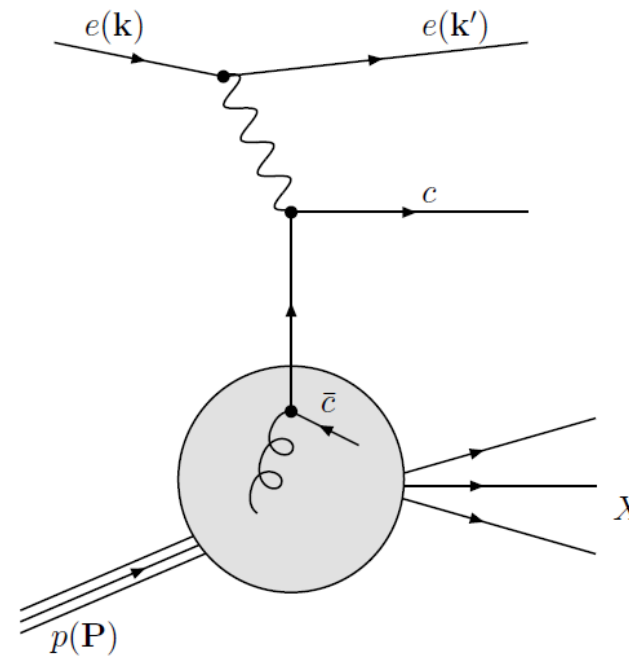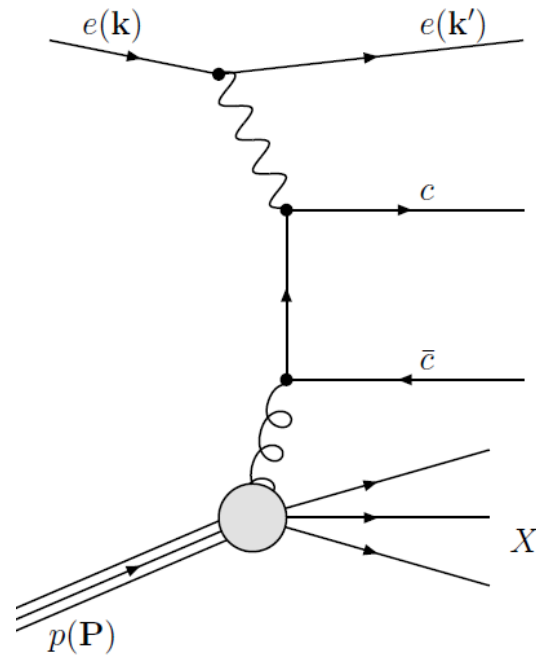Matrix element: calculable to different oders of a_s

Fragmentation function: from data

Many approaches on the market:

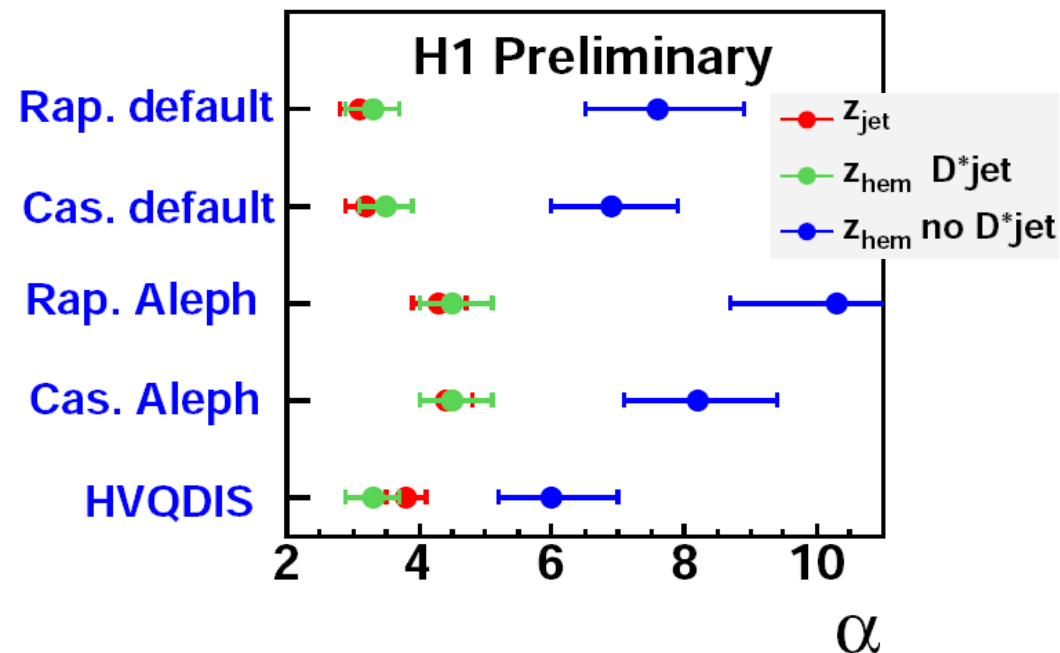- **NLO(a_s^2):**   HVQDIS (FFNS, massive)   vs.   ZMVFNS (ZM-VFNS, massless)

Fragmentation function

- If **a hard scale** is involved:
  - jet- & hemisphere method agree well
  - FF also agrees with ZEUS and LEP data
- If **no hard scale** is involved:
  - discrepancy at charm production threshold in QCD models
  - much harder fragmentation

More information:
http://arxiv.org/abs/0808.1003v2

- Fragmentation uncertainty from FF values for charm production:

	HVQDIS:	CASCADE:	RAPGAP:
at-threshold:	$\alpha = 6.0^{+1.0}_{-0.8}$	$\alpha = 8.2 \pm 1.1$	$8.7 < \alpha < 12.2$
above-threshold:	$\alpha = 3.3 \pm 0.4$	$\alpha = 4.6 \pm 0.6$	$3.9 < \alpha < 5.0$

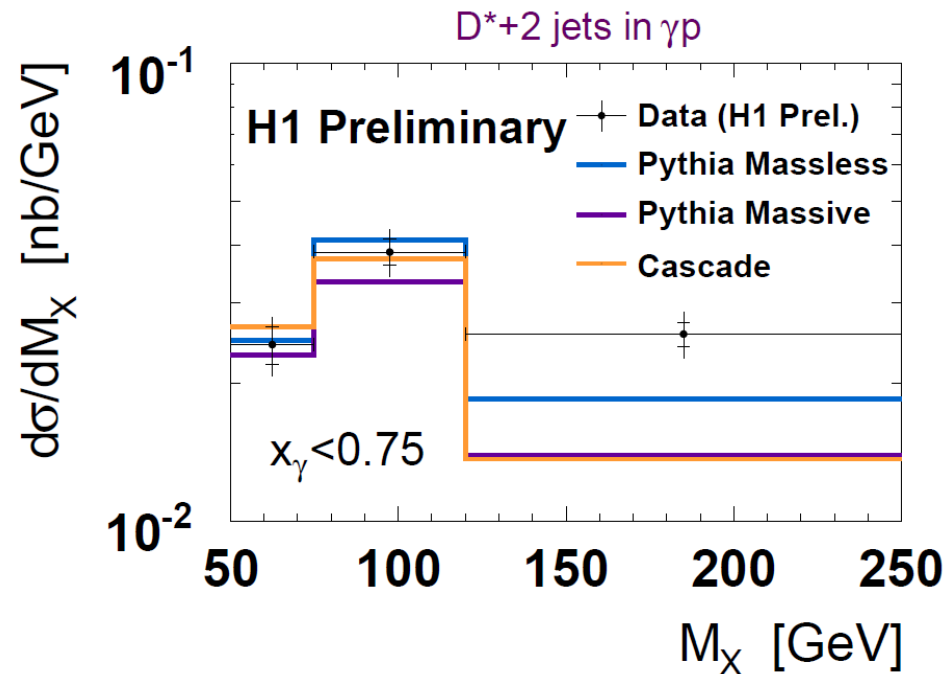- Threshold position from $\hat{s}$ (cms energy of hard subprocess):

	$70 \pm 20 \ \mathrm{GeV}^2$	$70 \pm 20 \ \mathrm{GeV}^2$	$70 \pm 20 \ \mathrm{GeV}^2$

D*+jets photoproduction

D*+2 jets in γp

D*+2 jets in γp

H1 Preliminary

Data (H1 Prel.)
Pythia Massless
Pythia Massive
Cascade

$x_\gamma \geq 0.75$

$d\sigma/dM_X$ [nb/GeV]

M_X [GeV]

H1 Preliminary

Data (H1 Prel.)
Pythia Massless
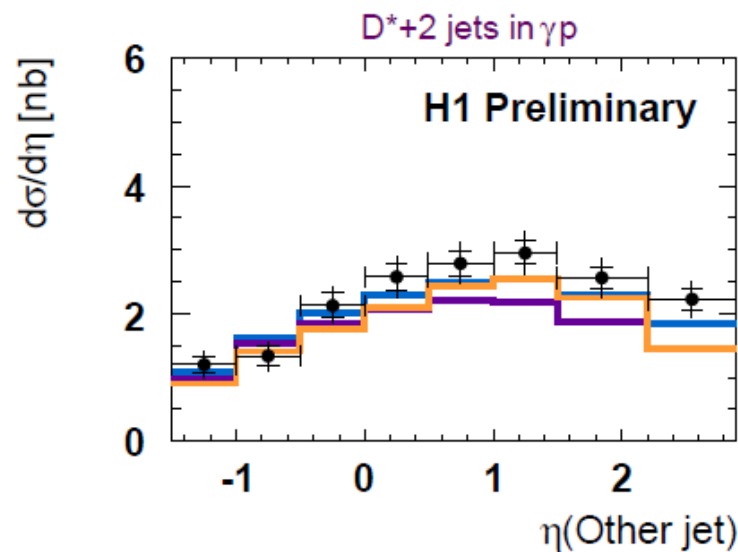Pythia Massive
Cascade

$x_\gamma < 0.75$

$d\sigma/dM_X$ [nb/GeV]

M_X [GeV]

- Parameters of the MCs & MC@NLO:

generator	proton (u)pdfs	photon pdfs
Pythia massive	CTEQ 6M NLO	SAS 2D LO
Pythia massless	CTEQ 6L LO	GRV-G LO
Cascade	Set A0	—
MC@NLO	CTEQ 6.6	GRV

• High x_γ: direct processes well described by MCs

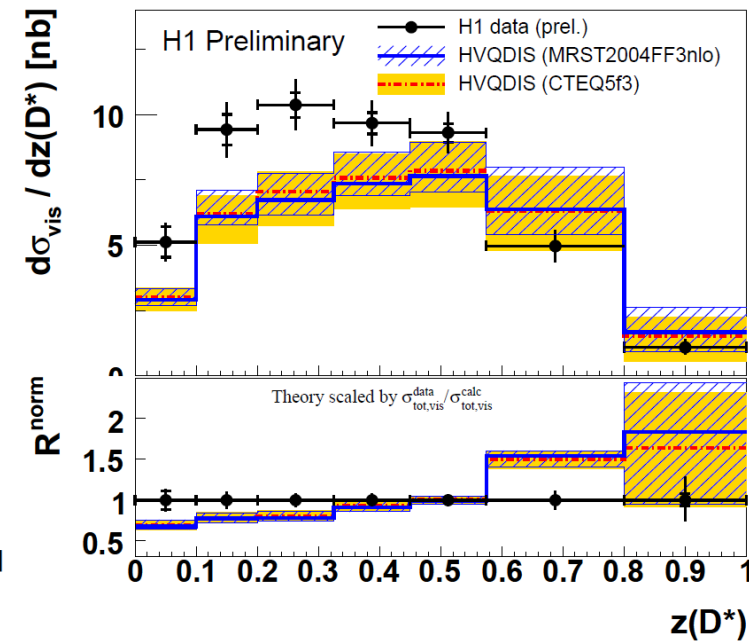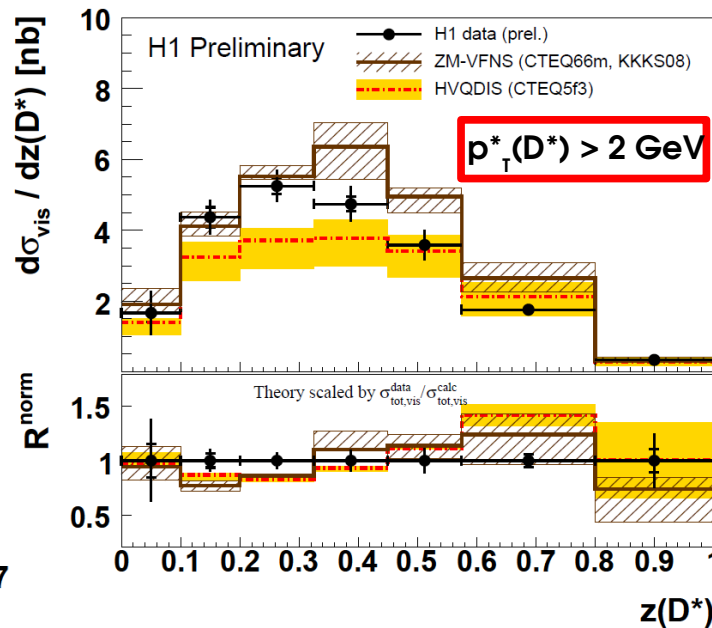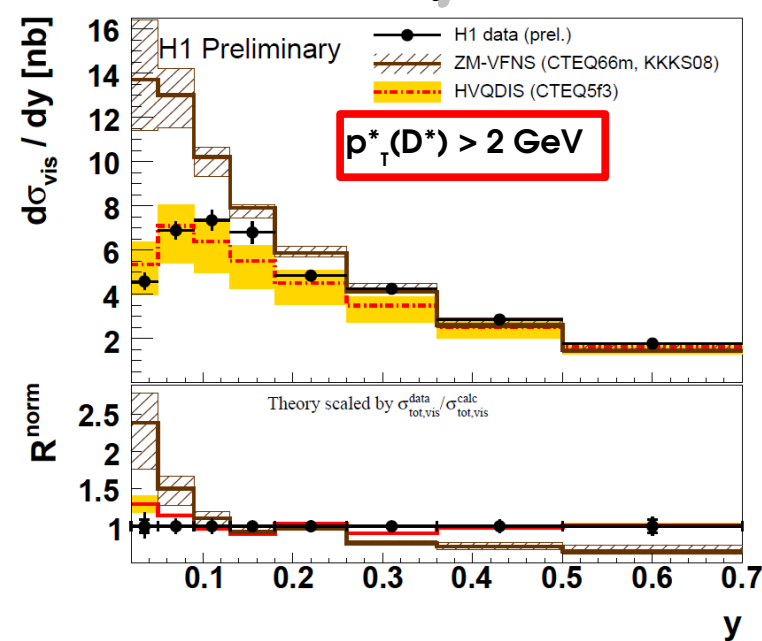• Low x_γ: resolved processes not described by any model, especially at high M_X

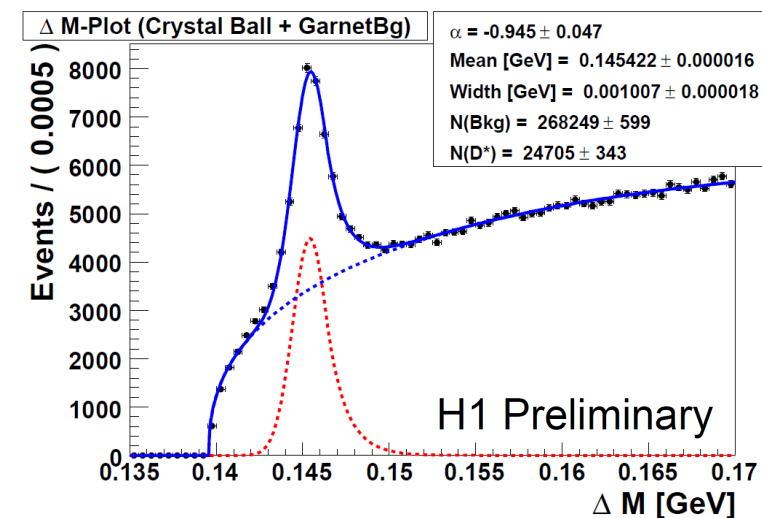# *D*+jets photoproduction*
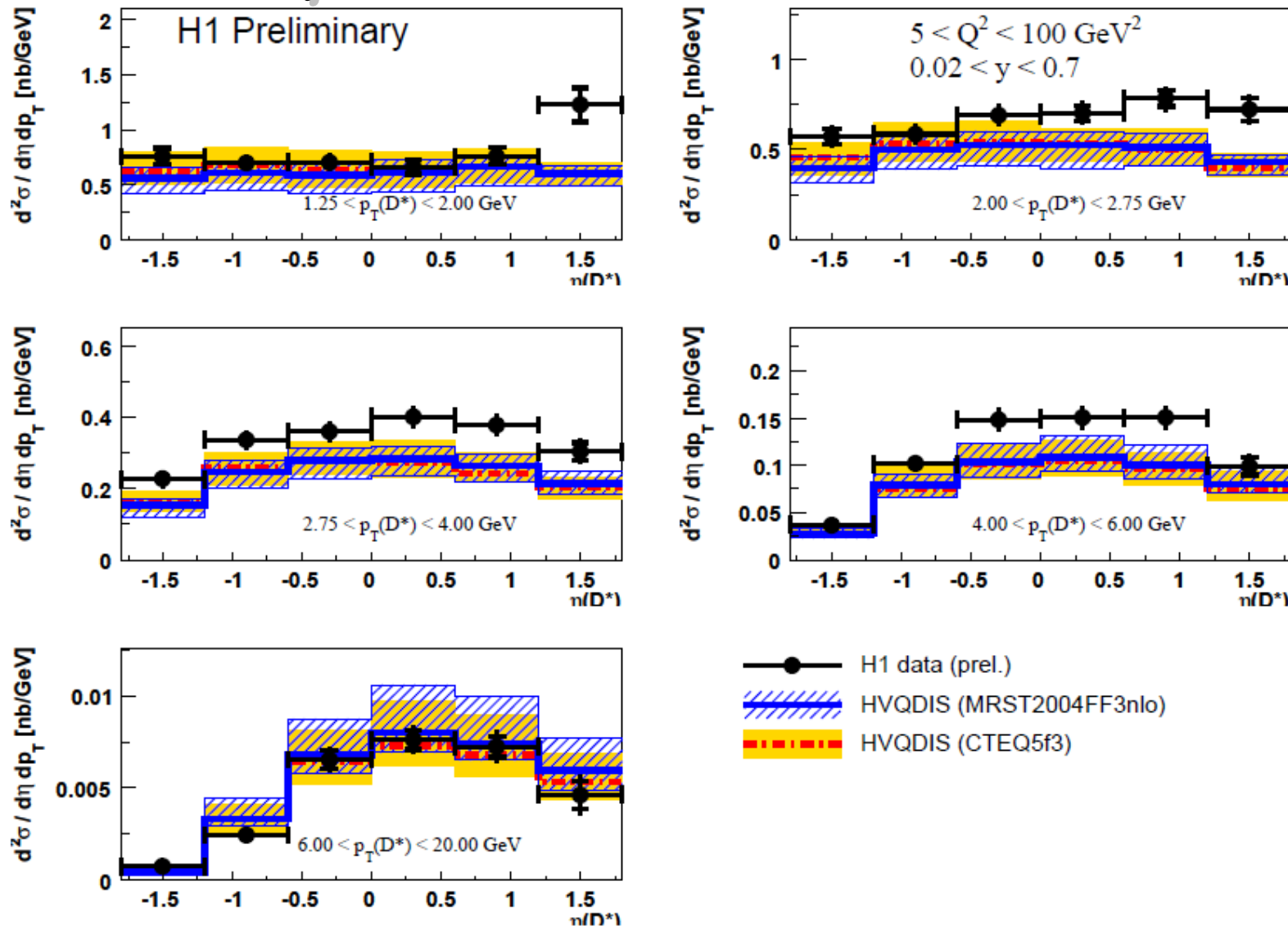

In general described by PYTHIA (CTEQ6) and CASCADE (A0)

- As seen in x also in y ZM-VFNS fails completely!
- HVQDIS overshoots at low y
- z(D*) reasonable described by ZM-VFNS & HVQDIS
- Without the additional $p_T^*(D^*)$ cut HVQDIS fails to describe z(D*)

α = -0.945 ± 0.047
Mean [GeV] = 0.145422 ± 0.000016
Width [GeV] = 0.001007 ± 0.000018
N(Bkg) = 268249 ± 599
N(D*) = 24705 ± 343

H1 Preliminary

D* production: medium Q²
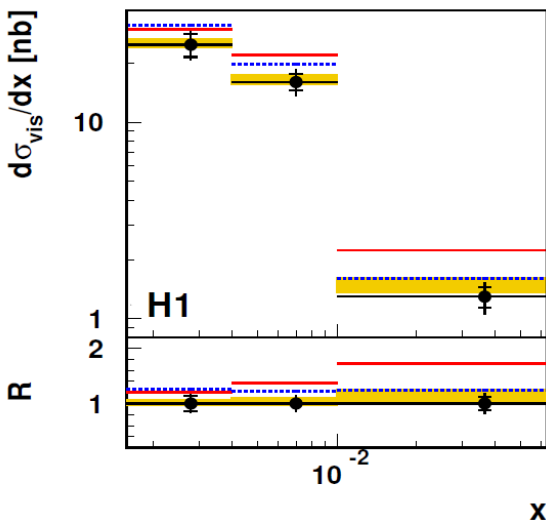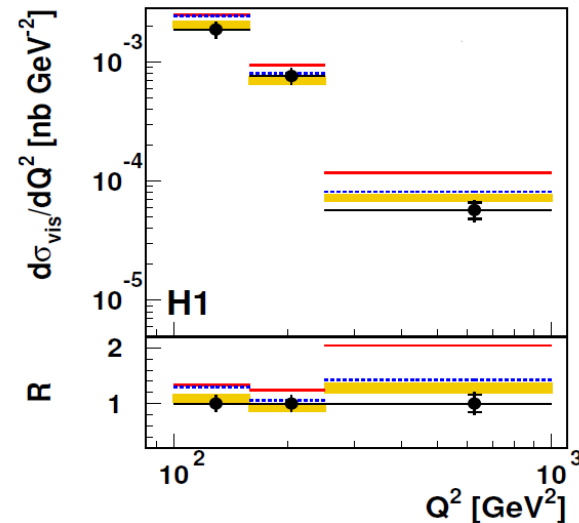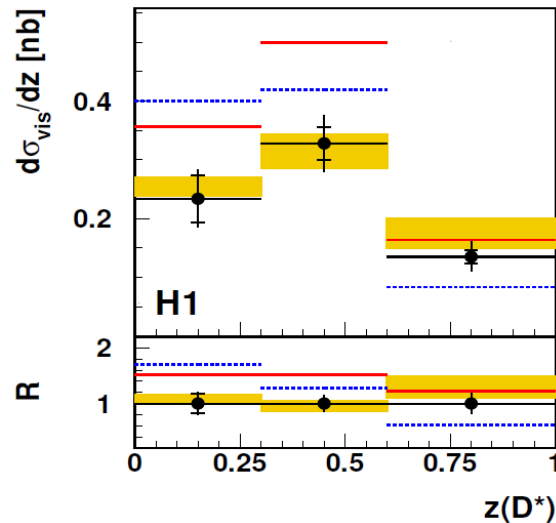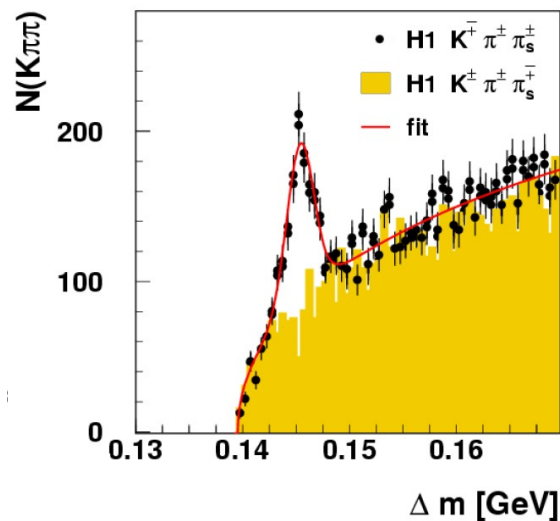

- In general η(D*)-p$_T$(D*) cross section reasonable described by HVQDIS
- Forward direction: HVQDIS undershoots data located at low p$_T$(D*)

D* production: high Q^2

- **H1 data**
- **HVQDIS**
- **RAPGAP**
- **CASCADE**

- Massive FFNS describes cross sections reasonably well
- MCs predict different slopes and fail completely to predict the Q^2 slope