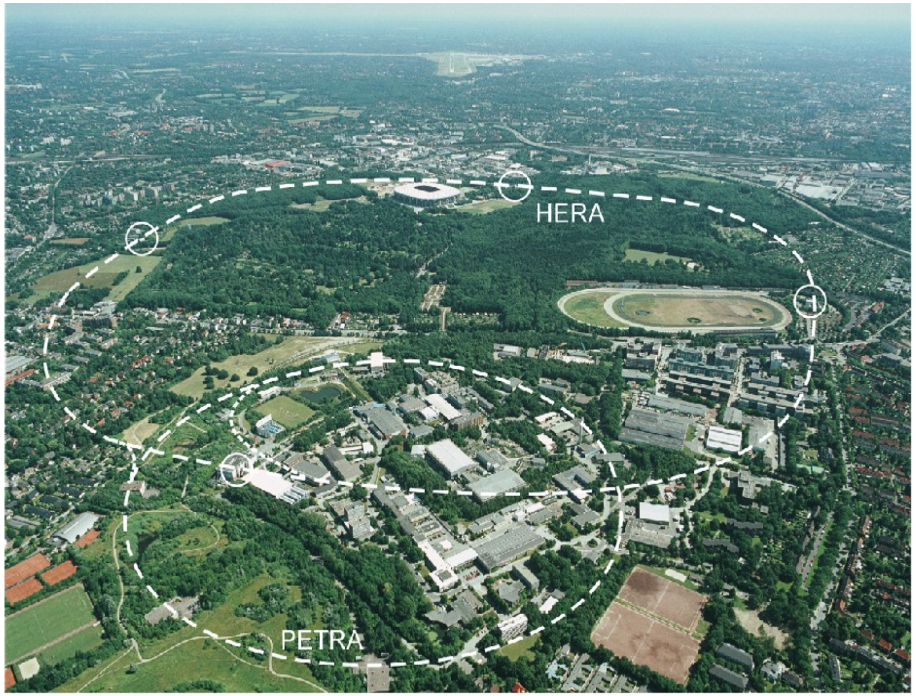
Extraction of $F_2^c(x,Q^2)$ from D* cross sections at H1



- Introduction
- D* cross sections
- Fragmentation & Extrapolation
- Extraction of $F_2^c(x,Q^2)$
- Conclusions

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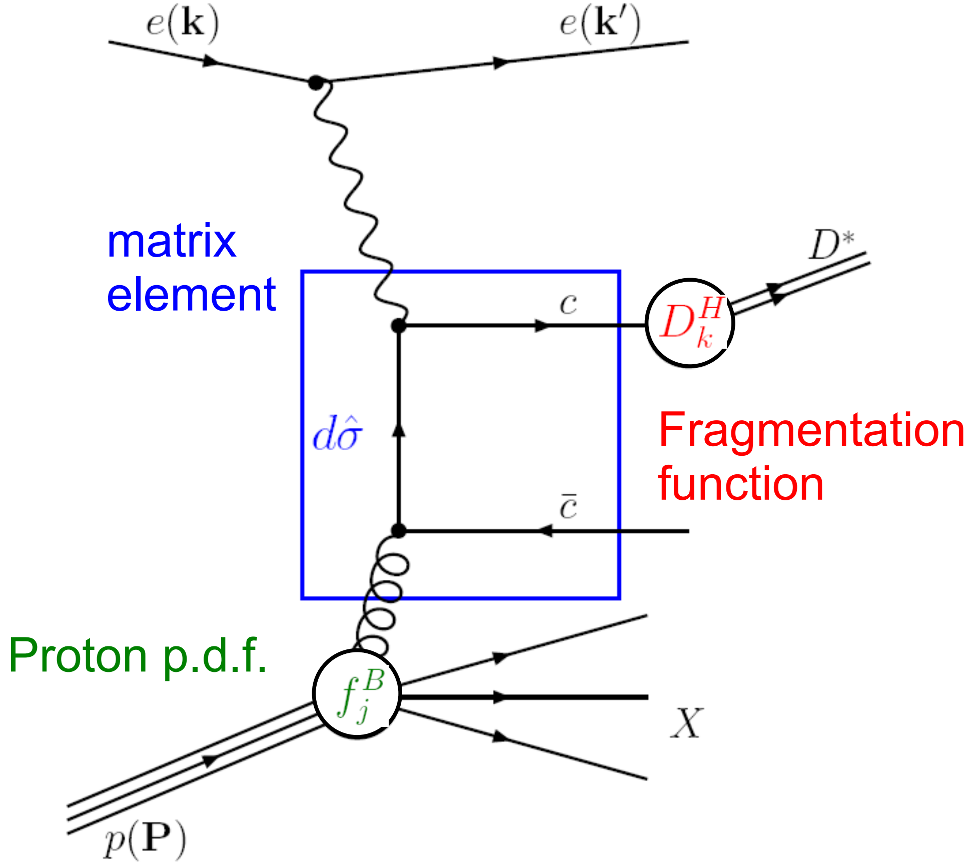
Kirchhoff Institute for Physics
University of Heidelberg

D* production: Boson gluon fusion

Dominant process: BGF process



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

- Photon virtuality Q^2
- Inelasticity y
- Bjørken x x

D* via Fragmentation:

- Pseudo-rapidity η
- Transverse momentum p_T
- (In)elasticity z

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 in different heavy flavor schemes

Fragmentation function: from data

Theoretical models

Study production mechanism:

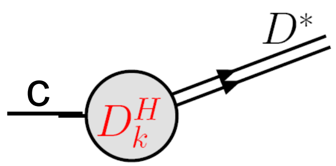
Perturbative QCD:

- Q^2, m^2_c or p^2_T provide a hard scale → **multiscale problem**
- Test of heavy flavor treatment in pQCD

Non-perturbative QCD:

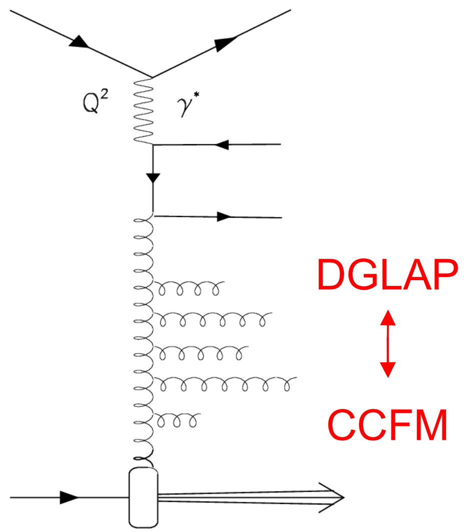
- Parton densities: *gluon structure of the proton* → **test universality**
- Fragmentation

Models discussed in the following:



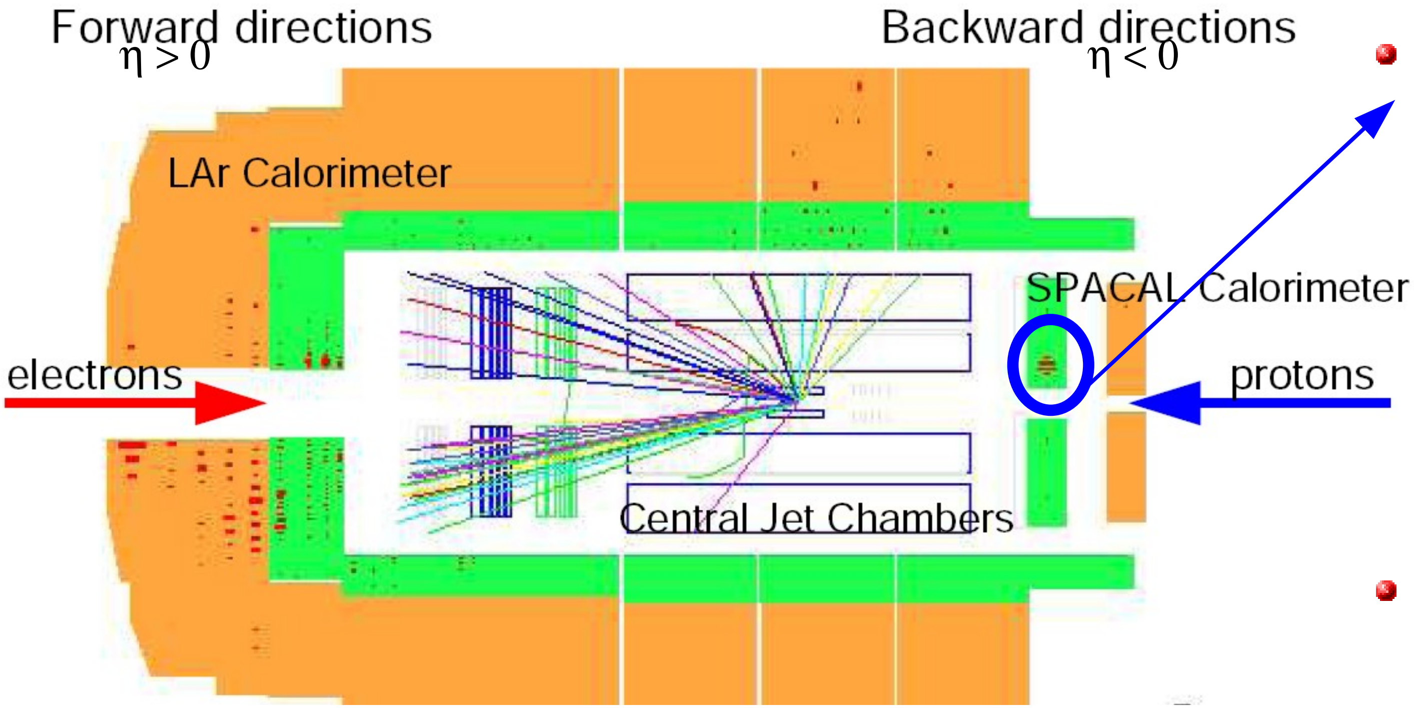
CASCADE vs. HVQDIS:

$LO(\alpha_s)$ + PS	↔	$NLO(\alpha_s^2)$
CCFM	↔	DGLAP
only gluons	↔	all partons
Lund frag.	↔	Independent frag.
massive BGF	↔	massive BGF (FFNS)



Note: RAPGAP + HERACLES used correction of data

Event selection



- Scattered electron in backward calorimeter:

  Q^2: 5 - 100 GeV^2

  ► Summary given here

- OR in main calorimeter:

  Q^2: 100 - 1000 GeV^2

  ► Talk by M. Brinkmann

- Luminosity: ~ 350pb^{-1}

Visible range for the D* cross section:

Q^2 : 5 - 100(0) GeV^2

y : 0.02 - 0.70

p_T(D*) : > 1.5 GeV

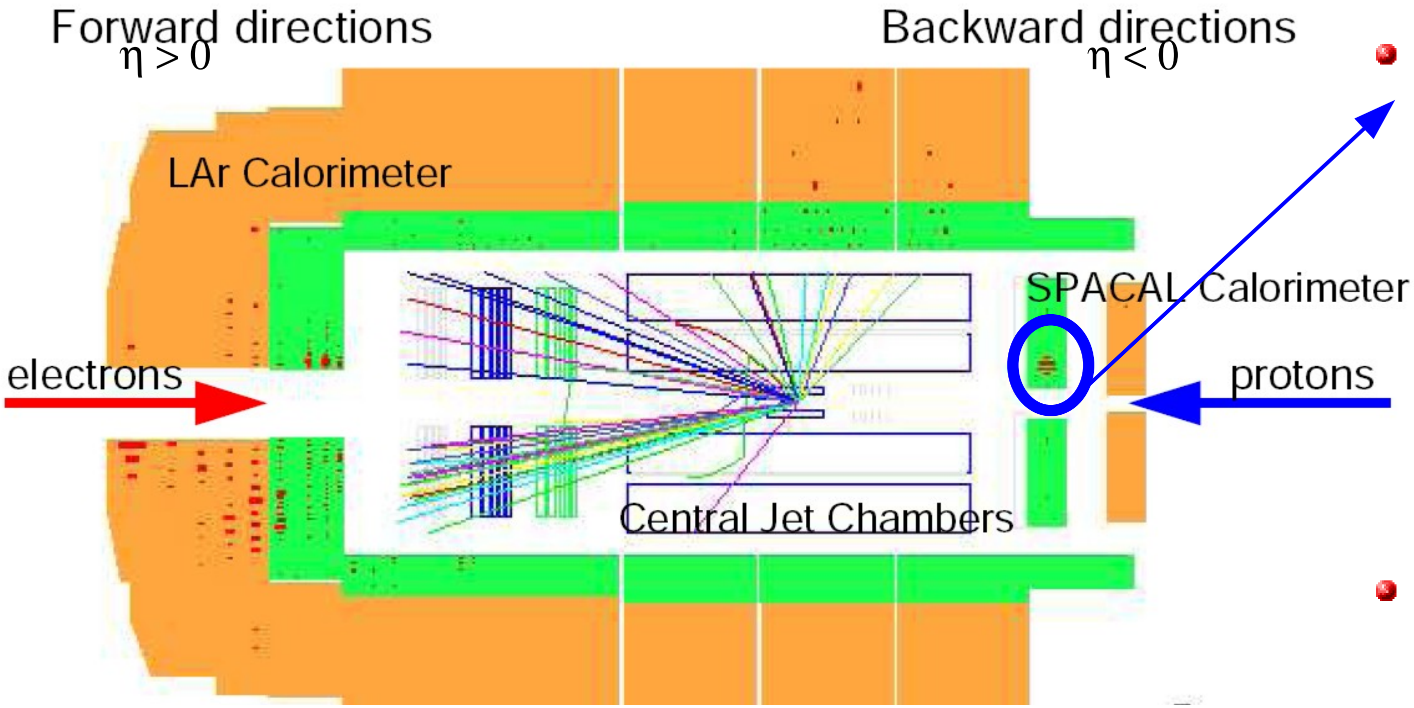
|η (D*)| : < 1.5

D* reconstructed in golden decay channel:

(with a total BR of 2.57%)

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

Event selection



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Visible range for the D* cross section:

Q^2	: 5 - 100(0) GeV^2
y	: 0.02 - 0.70
$p_T(D^*)$	: > 1.5 GeV
$\lvert\eta(D^*)\rvert$	: < 1.5

For $F_2^c(x,Q^2)$:

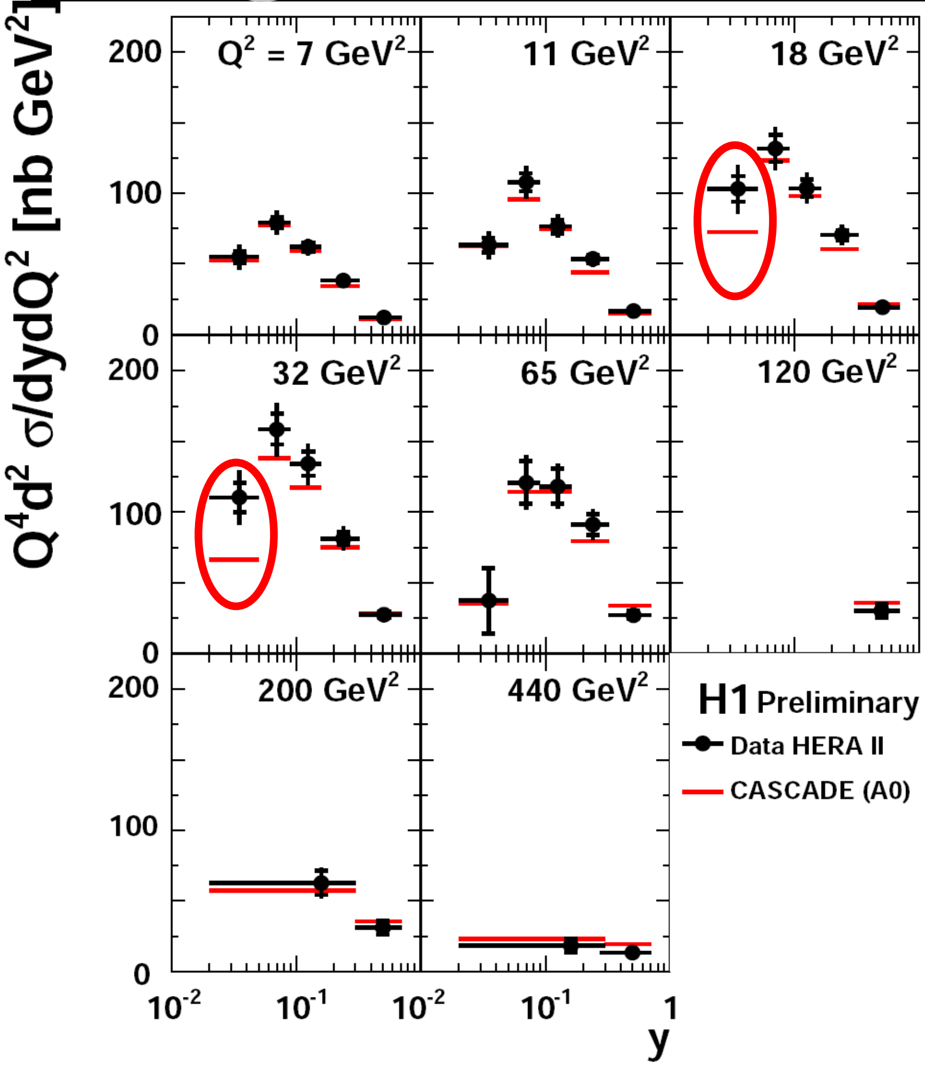
$p_T(D^*) \rightarrow 0$ GeV
$\lvert\eta(D^*)\rvert \rightarrow 10$

D* reconstructed in golden decay channel:

(with a total BR of 2.57%)

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

D* cross sections in y-Q^2



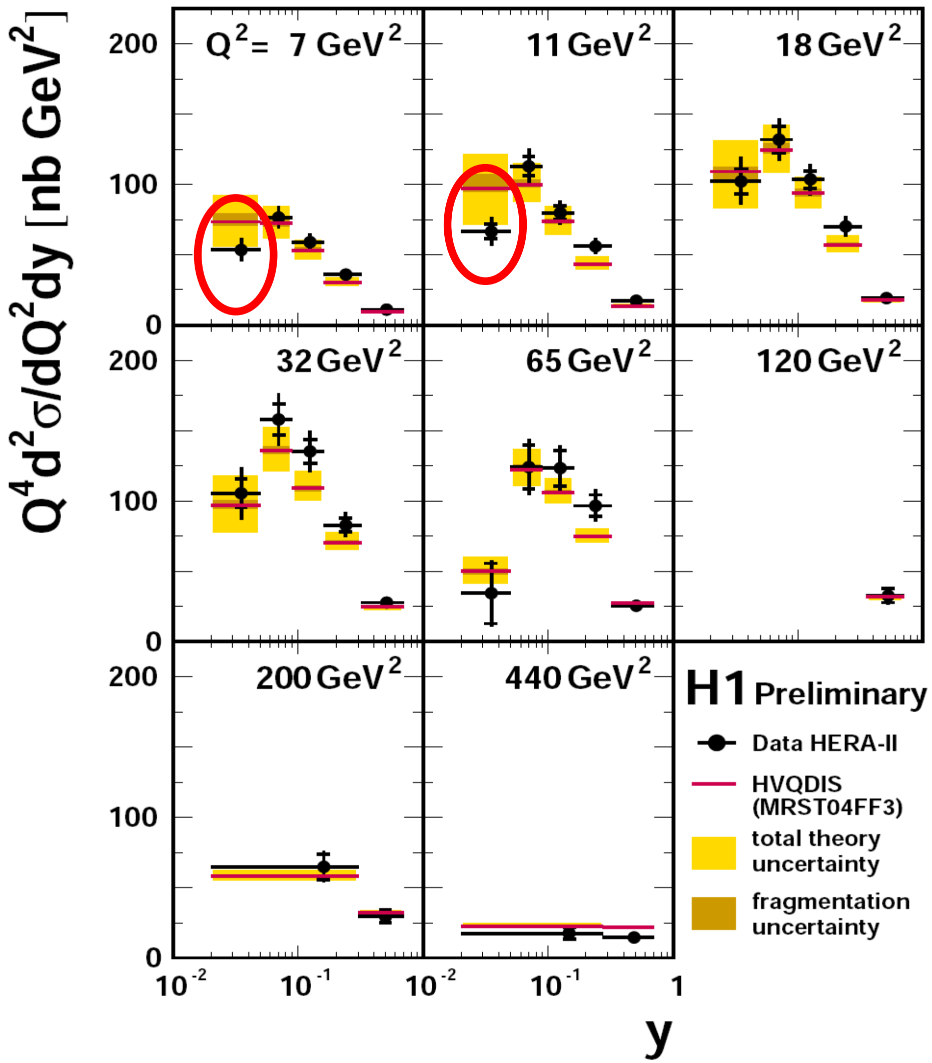
Considered in cross section:

- Data corrected with RAPGAP
  → ε ~ 60%
- Contribution due to b-quarks not subtracted → but < 2%
- Correction due to other D^0 decay channels
  → 4%
- Correction for NLO-QED effects using HERACLES → 2%

More information:
https://www-h1.desy.de/psfiles/confpap/ICHEP08/H1prelim-08-072.ps
and http://www-h1.desy.de/psfiles/theses/h1th-504.pdf

- CASCADE describes the data reasonable
- difficulties to describe the new (lowest) y-bin (→ highest x)

D* cross sections in y-Q^2



Error estimation of the NLO-calculation with parameter variation:

charm mass: $1.3 < m_c < 1.6$ GeV

renormalization & factorization scale:

$0.5 < \mu_{f,r}/\mu_0 < 2$,

with $\mu_0^2 = Q^2 + 4m_c^2$

fragmentation: comes later

More information:

https://www-h1.desy.de/psfiles/confpap/ICHEP08/H1prelim-08-072.ps and http://www-h1.desy.de/psfiles/theses/h1th-504.pdf

- Equally good described by HVQDIS (NLO, DGLAP) and CASCADE (LO+PS, CCFM)
- Both have difficulties to describe the new (lowest) y-bin (→ highest x)
- Data don't prefer a specific model – **use both for the extraction of $F_2^c(x,Q^2)$**

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

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

Only at high y: This measurement
O(2-3%) → negligible

What is done to measure $F_2^c(x,Q^2)$:

Double differential cross section measurement
in **visible phase space**

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

Double differential prediction of
cross section in **visible phase space**
(DGLAP & CCFM)

Prediction of $F_2^c(x,Q^2)$ in **full phase space (η, p_T)**
(DGLAP & CCFM)

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

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

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Double differential prediction of cross section in **visible phase space** (DGLAP & CCFM)

Prediction of $F_2^c(x,Q^2)$ in **full phase space (η,p_T)** (DGLAP & CCFM)

$p_T(D^*)$ → 0 GeV
$|\eta(D^*)|$ → 10

- Extrapolation into not measured region → Fragmentation has an influence

Determine Fragmentation Function (FF) from data !

Fragmentation functions (FF)

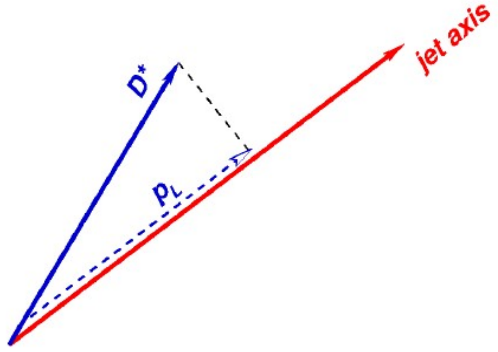
Slides taken from talk by J. Bracinik (DIS 2008):
http://indico.cern.ch/contributionDisplay.py?contribId=236&sessionId=14&confId=24657

Jet method:

- momentum of c-quark approximated by momentum of rec. D^*-jet

$$z_{\mathrm{jet}} = \frac{(E+p_{\mathrm{L}})_{D^*}}{(E+p)_{\mathrm{jet}}}$$

- $k_\perp$-clus jet algorithm applied in γp-frame ($E_t(D^* jet) > 3$ GeV)



Analyses based on:

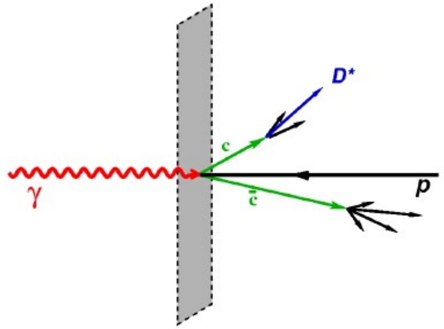
- D* reconstructed in golden decay
- HERA I data with L = 47pb^{-1}

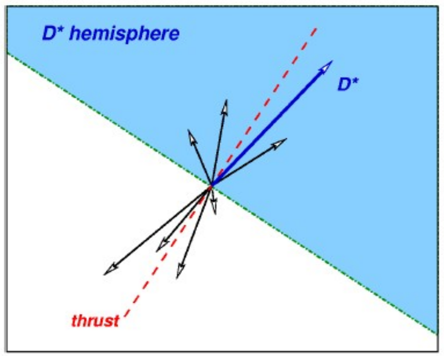
Hemisphere method:

- momentum of c-quark approximated by momentum of rec. D^*-hemisphere

$$z_{\mathrm{hem}} = \frac{(E+p_{\mathrm{L}})_{D^*}}{\sum_{\mathrm{hem}}(E+p)_i}$$

- $\eta(\mathrm{part}) > 0$ for p-remnant suppression
- thrust axis in plane perpendicular to γ used for hemisphere division





Fragmentation functions (FF)

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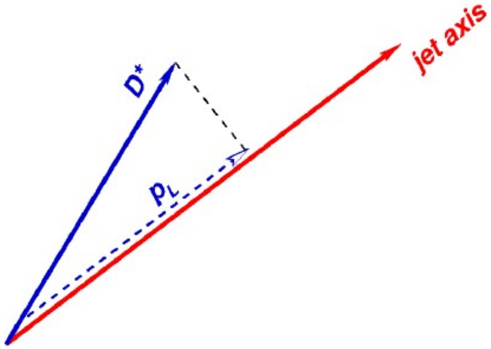

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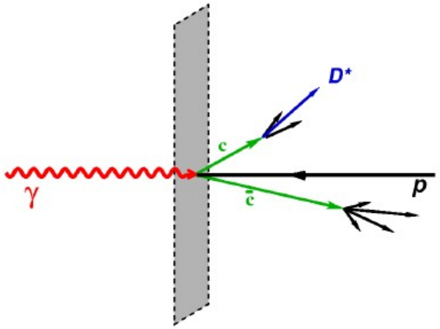
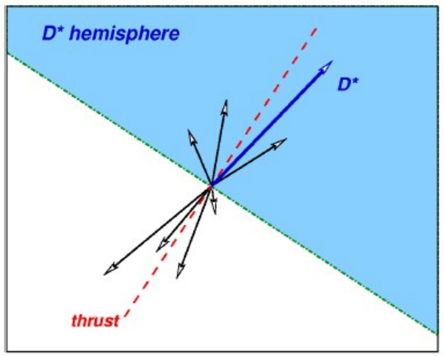


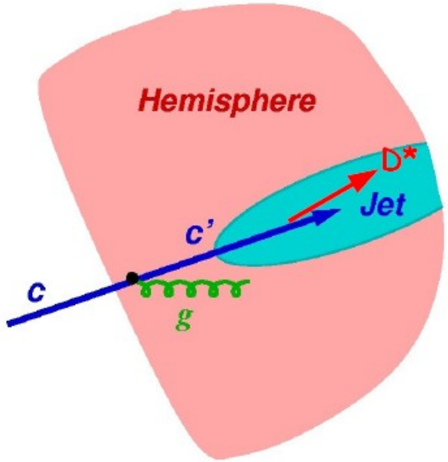


Analyses based on:

- D* reconstructed in golden decay
- HERA I data with L = 47pb^{-1}

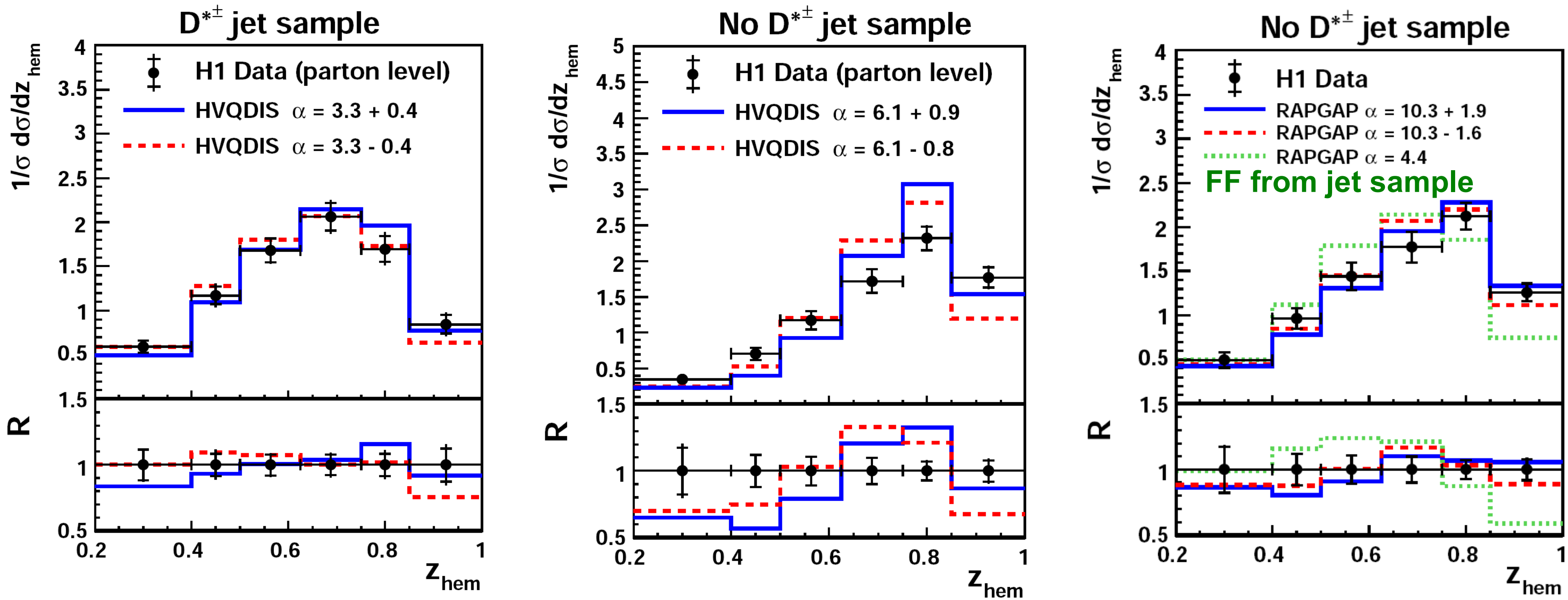
Differences of the methods:

- Jet method & hemisphere method:



- Methods are different, i.e. hemisphere method sums more gluon radiation and does not need a hard scale (jet E_T-cut)
- Hem. method is sensitive to threshold region !

Fragmentation functions (FF)



--> NLO (HVQDIS) describes D*-jet sample

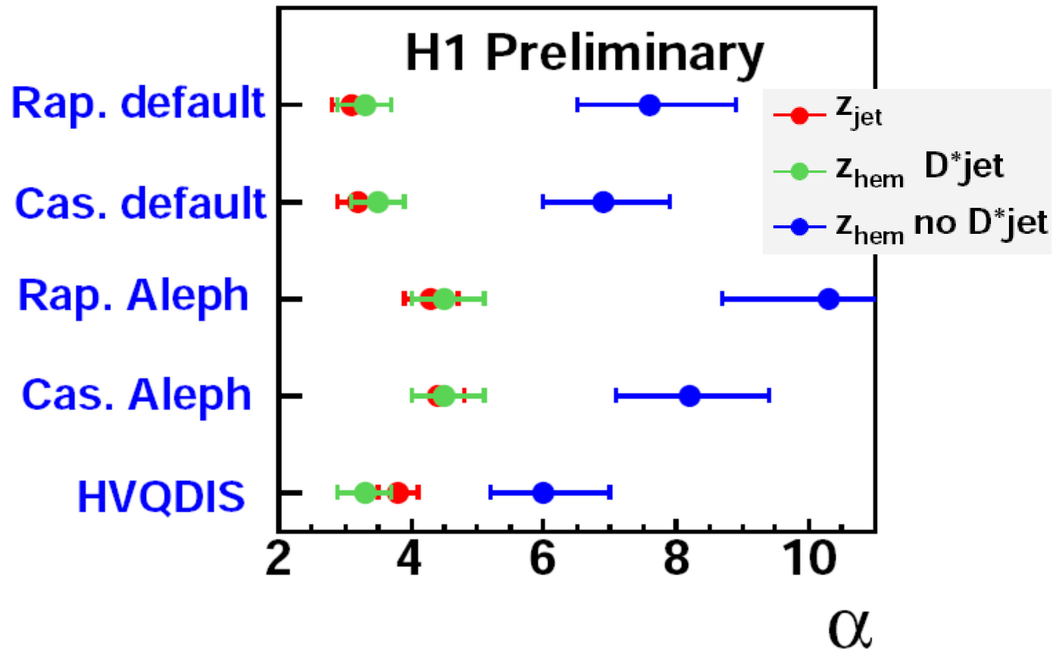
--> Extracted FF (hemisphere method) differs by 4σ from FF extracted from jet sample

--> NLO (HVQDIS) fails to describe the no-D*-jet data (χ^2_{min}/n.d.f. =40/4)

Fragmentation functions (FF)

- 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

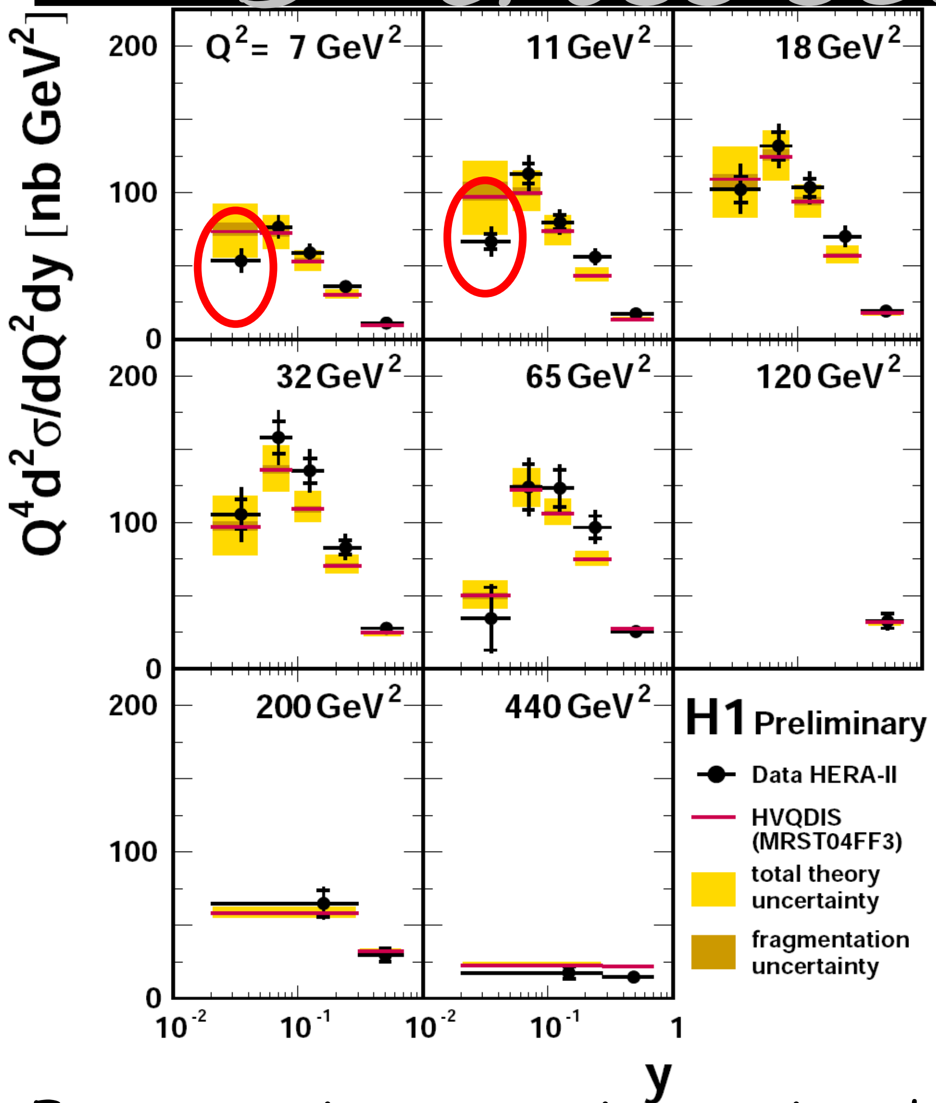


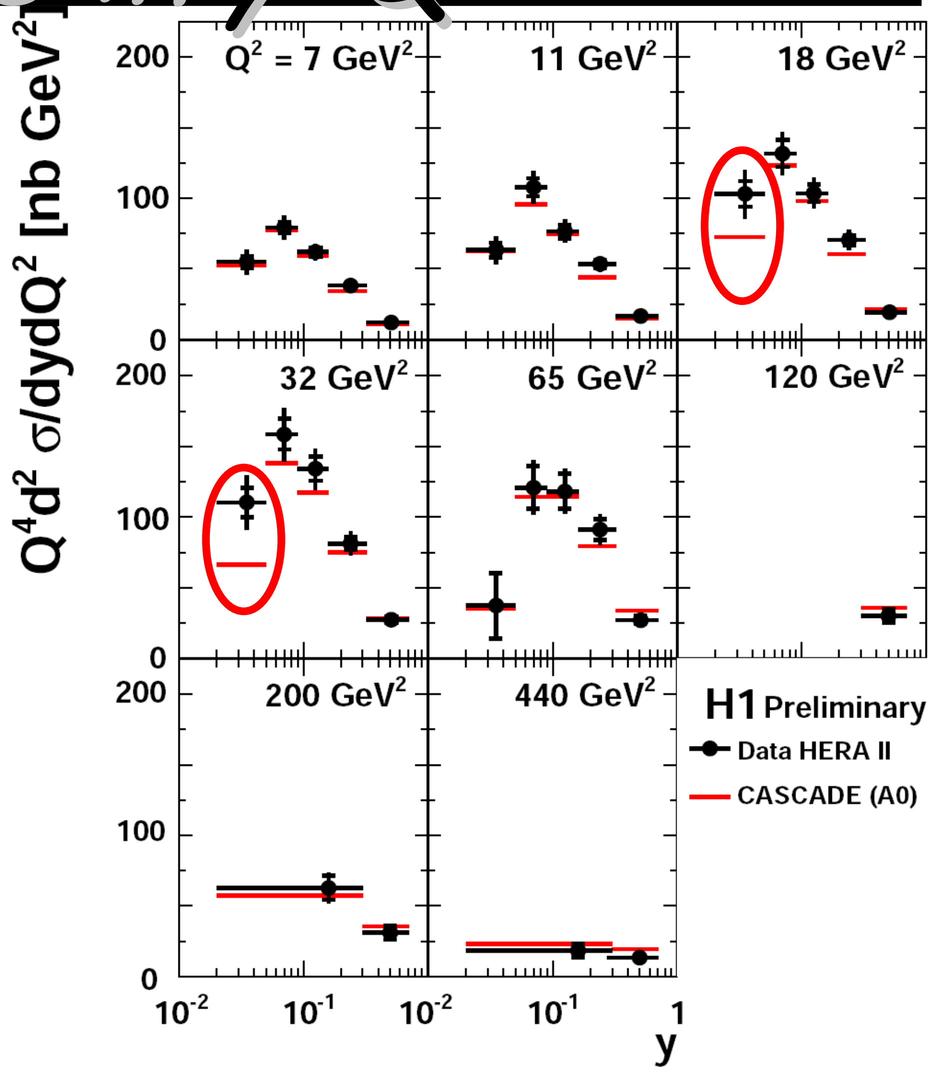
- Fragmentation uncertainty from FF values used for extrapolation:

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

- Threshold position from $\hat{s}$ (cms energy of hard subprocess): $70 \pm 20\ \mathrm{GeV}^2$ (HVQDIS), $70 \pm 20\ \mathrm{GeV}^2$ (CASCADE)

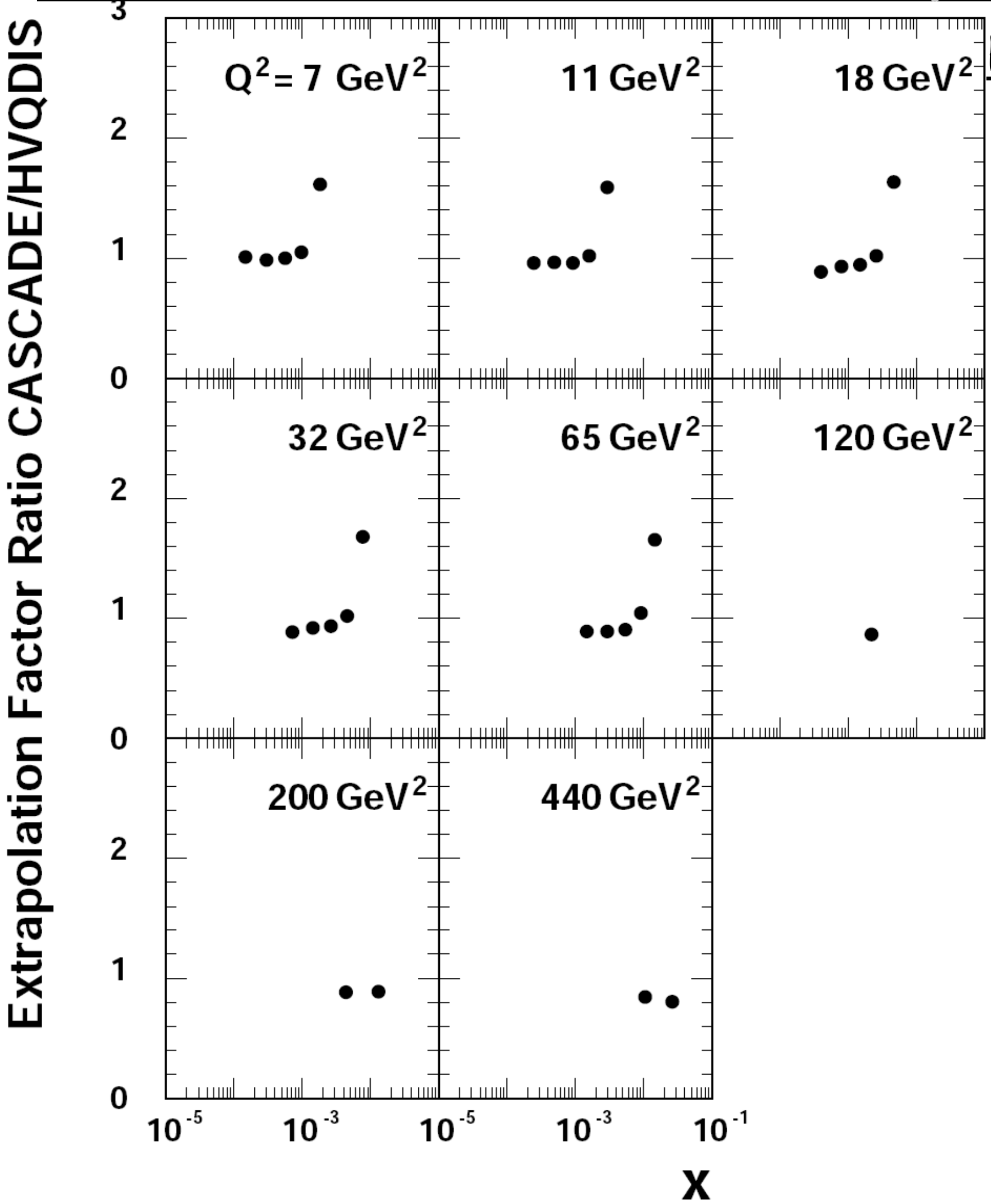
D* cross sections in y-Q^2





- Fragmentation uncertainty assigned to NLO & CASCADE reweighted
- In visible phase space small influence
- y-Q^2 cross sections are used for the extraction of $F_2^c(x,Q^2)$

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



Extrapolation to full phase space:

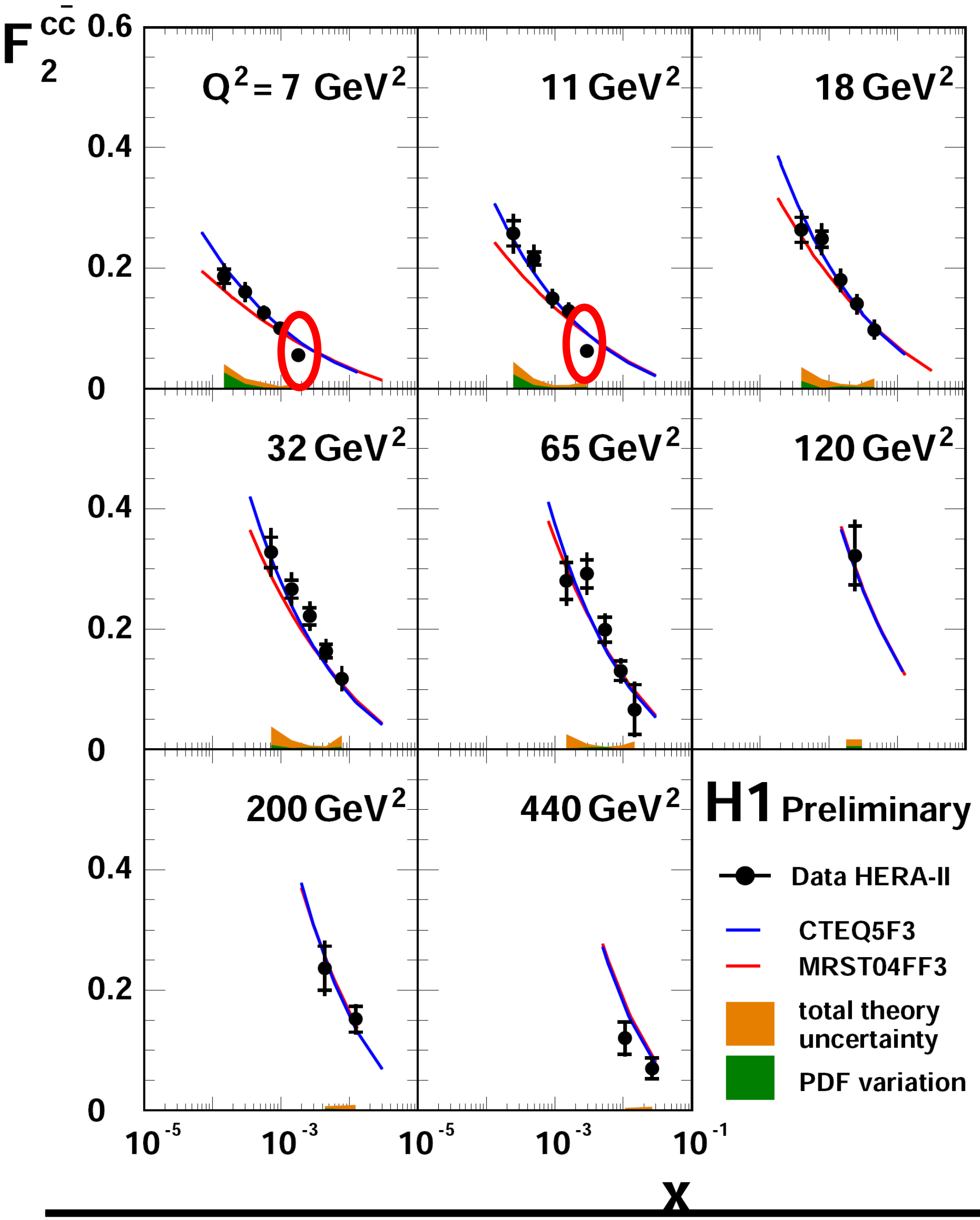
$$f^{\text{extra}} = \frac{\frac{d^2}{dydQ^2} \cdot \sigma^{\text{theo}}_{\text{full}}}{\frac{d^2}{dydQ^2} \cdot \sigma^{\text{theo}}_{\text{vis}}}$$

$p_T(D^*) \rightarrow 0$ GeV
$|\eta(D^*)| \rightarrow 10$

- CASCADE & HVQDIS used, $f_{avg} \sim 3$
- Ratio CASCADE/HVQDIS within 10%
- BUT at high x differences of up to 80%
- reason is the restricted phase space
  $\rightarrow$ larger $\eta(D^*)$ range needed !

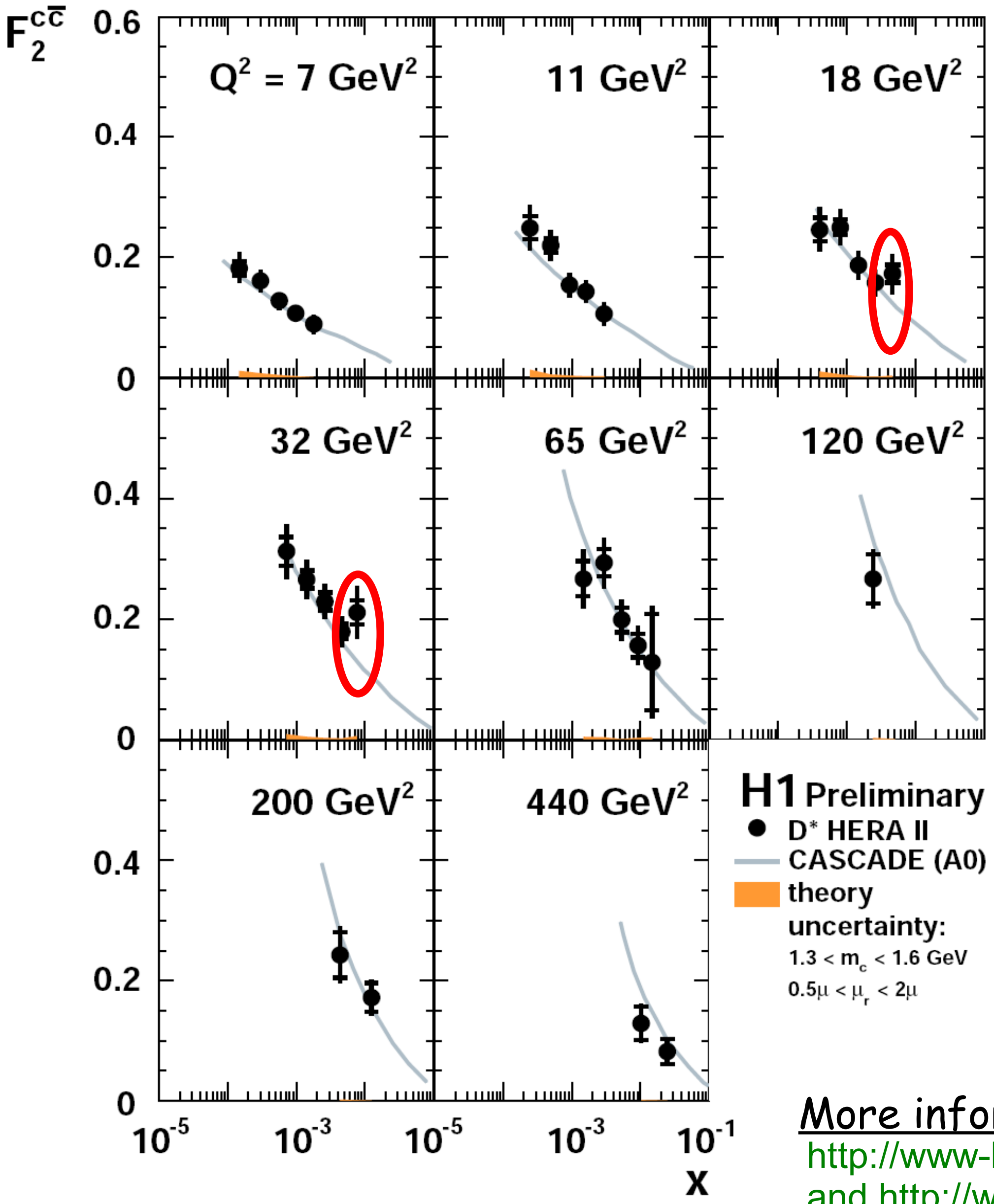
- Extrapolation uncertainty:
  charm mass: $1.3 < m_C < 1.6$ GeV
  renormalization & factorization scale:
  $0.5 < \mu_{f,r}/\mu_0 < 2$, $\mu_0^2 = Q^2 + 4m_C^2$
  PDF: MRST vs. CTEQ
  Fragmentation: as discussed...
- Partial cancellations of uncertainties

F_2^c in NLO DGLAP scheme



- **20x statistics of last Publication**
- Extrapolation error:
  typically 5 – 10%
- Fragmentation: applied to sys. Error of data typically 2 – 7%
- HVQDIS using different proton PDFs describes the F_2^c data reasonable
- Deviations at large x – originating from differences at cross section level

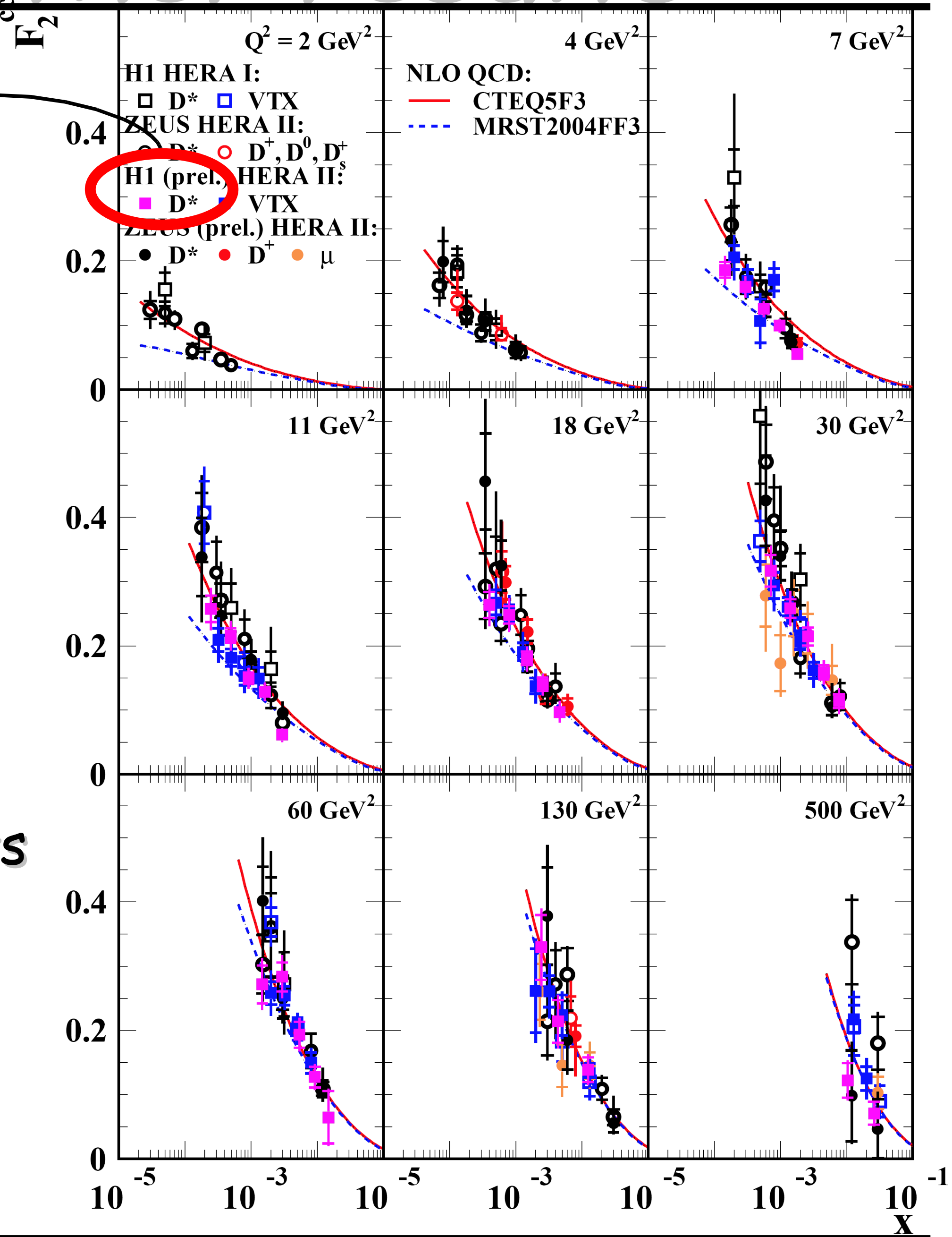
F_2^c in CCFM scheme



- **20x statistics of last Publication**
- Extrapolation error:
  typically 2 - 6%
  (no factorization scale & PDF variation)
- Fragmentation: applied to sys. Error of data typically 2 – 7%
- CASCADE describes the F_2^c data reasonable
- Deviations at large x – originates from differences at cross section level

More information:
http://www-h1.desy.de/psfiles/confpap/ICHEP08/H1prelim-08-172.ps
and http://www-h1.desy.de/psfiles/theses/h1th-504.pdf

Comparison to other results



This presentation !

- Most precise HERA measurement so far at $5 < Q^2 < 60$ GeV^2
- good agreement of different data sets (D*, D mesons, displaced tracks)

Talk by P. Thompson

Conclusions

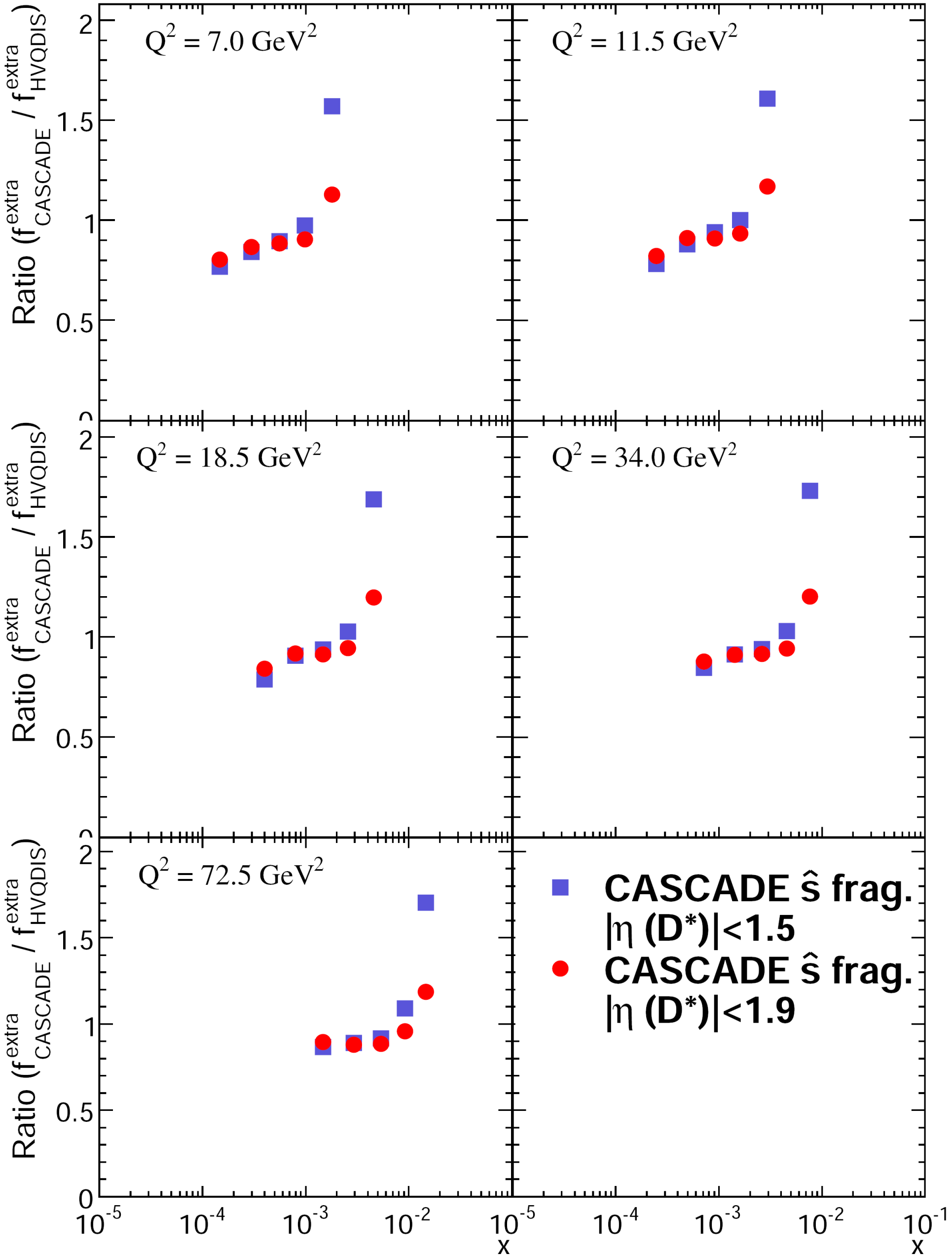
- **Full HERA II data sample for $F_2^c(x,Q^2)$ analysed L ~ 350pb^{-1}**
- **Most precise $F_2^c(x,Q^2)$ – on the way to final precision !**
- **Described by DGLAP & CCFM and consistent with other results**

- Closer look: - Fragmentation uncertainty from Results of H1 measurement of Fragmentation fcts. estimated
  - Larger differences in extrapolation at high x between models corresponds to most forward $\eta(D^*)$
  - Extend phase space for cross section measurement towards larger $\eta(D^*)$ and smaller $p_T(D^*)$
- Combination with other $F_2^c(x,Q^2)$ measurements possible

→ Talk by P. Thompson

Backup

Backup: Extrapolation



Result of Study from my Ph.D. Thesis:

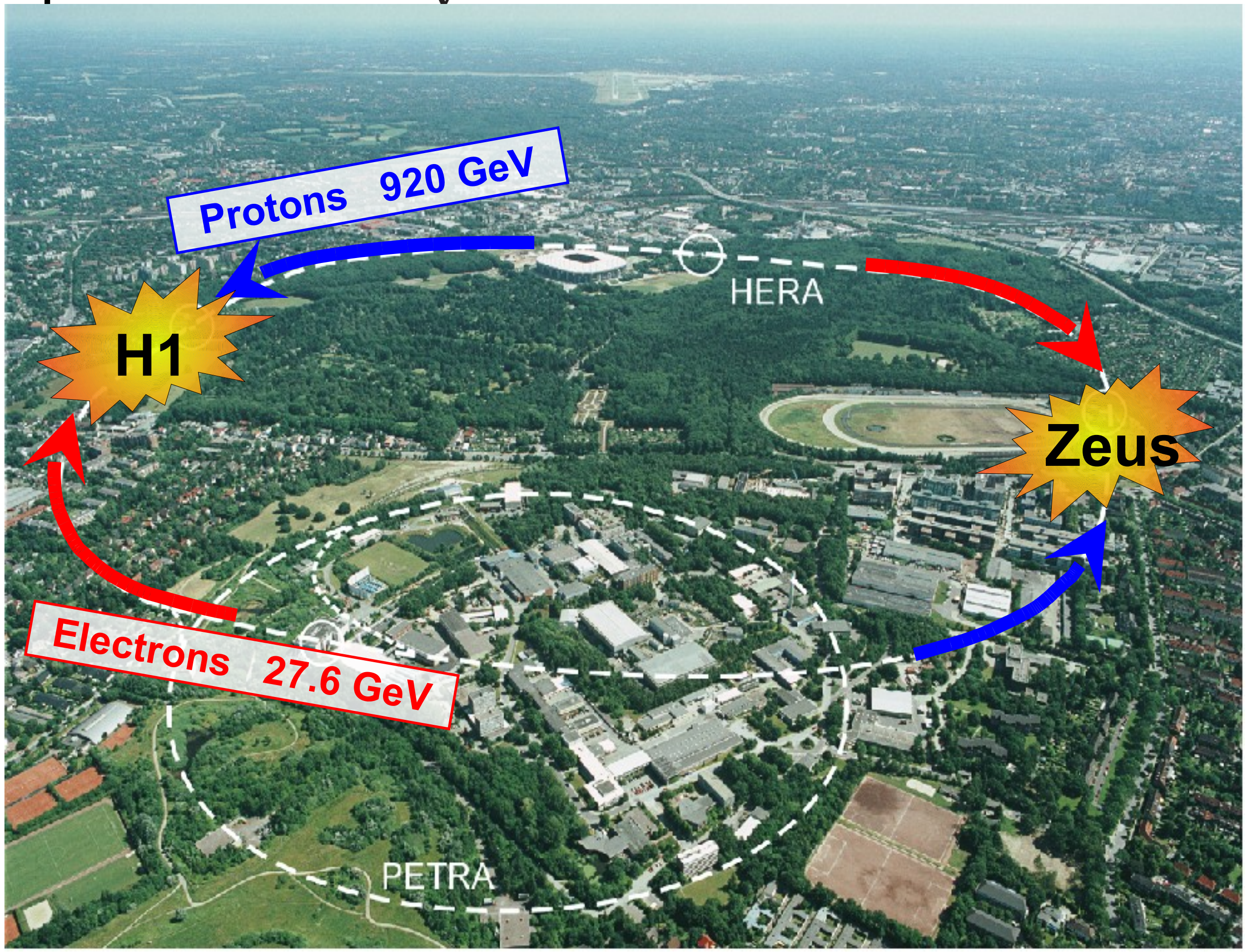
- "Fragmentation model" from H1 measurement of FF applied
- Ratio: CASCADE / HVQDIS

More information:

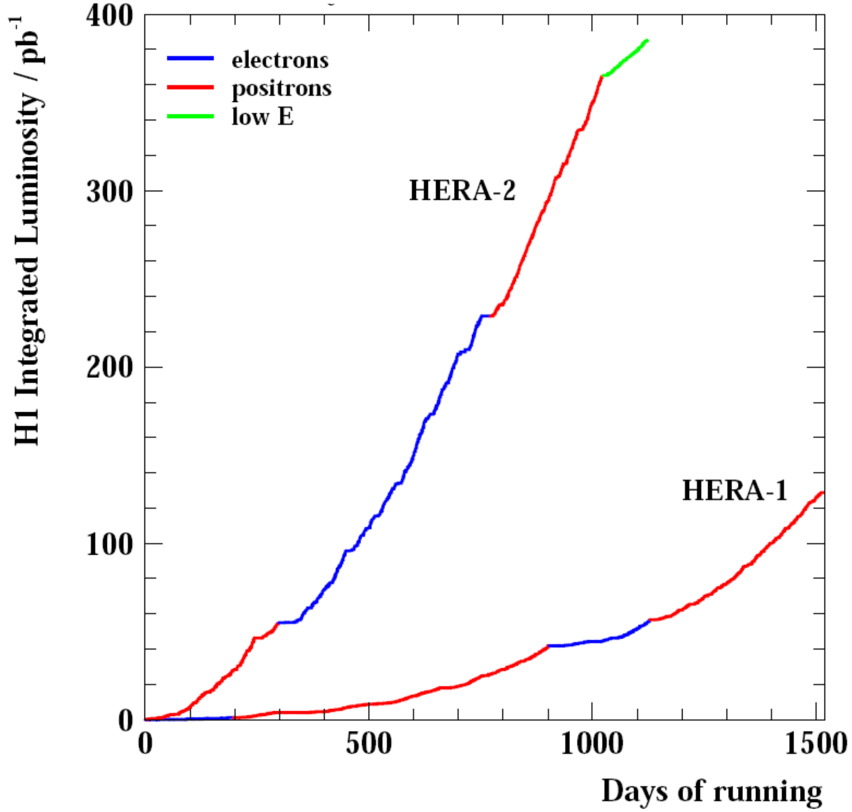
Ph.D. Thesis A. Jung:
http://www-h1.desy.de/psfiles/theses/h1th-504.pdf

Backup: The HERA collider

ep collisions at $\sqrt{s} \approx 320\ \mathrm{GeV}$:



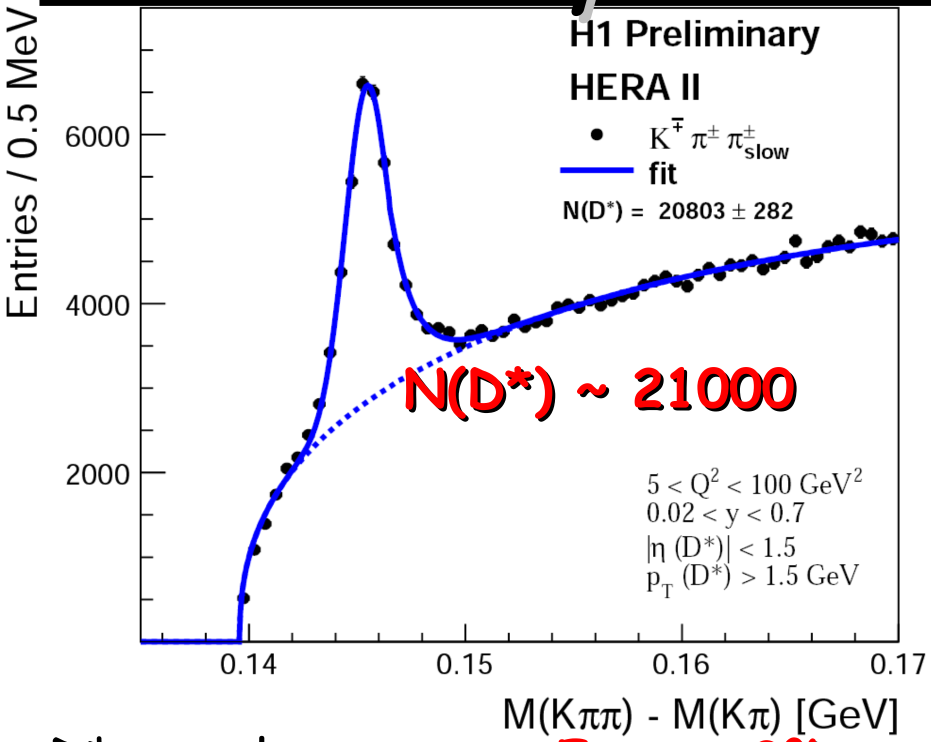
Collected Data samples:



--> Two multi-purpose detectors: H1 & Zeus

--> Collected Luminosity: HERAI + HERAII ~ 0.5 fb^{-1}

Backup: D* event selection



- decay: $D^{*\pm} \rightarrow D^0\pi^{\pm}_{slow} \rightarrow (K^{\mp}\pi^{\pm})\pi^{\pm}_{slow}$
- higher resolution in mass difference:

  ΔM = M(Kππ)-M(Kπ)
- Larger phase space with use of electron-Σ-method:

  lower y of 0.02
- Fit asymmetric shape: with ROOFIT

Crystal-Ball:

$$f(x) = \begin{cases} \dfrac{\left(\frac{n}{|\alpha|}\right)^n \exp(-\frac{1}{2}\alpha^2)}{\left(\frac{n}{|\alpha|}-|\alpha|-\frac{x-m}{\sigma}\right)^n} & \text{if } \frac{x-m}{\sigma} < -\alpha, \quad \textbf{exponential decay} \\ \exp\left(-\frac{1}{2}\left(\frac{x-m}{\sigma}\right)\right)^2 & \text{if } \frac{x-m}{\sigma} \geq -\alpha \quad \textbf{Gauss distribution} \end{cases}$$

Background (Granet Parametrisation:)

$$f(x) = p_0 \cdot (x - m_{\text{Cutoff}})^{p_1} \cdot e^{-p_2 \cdot x \, (-p_3 \cdot x^2)}$$

Determines in units of σ where: Gauss → Expo

- D* sample: **stat. Error ~2%**

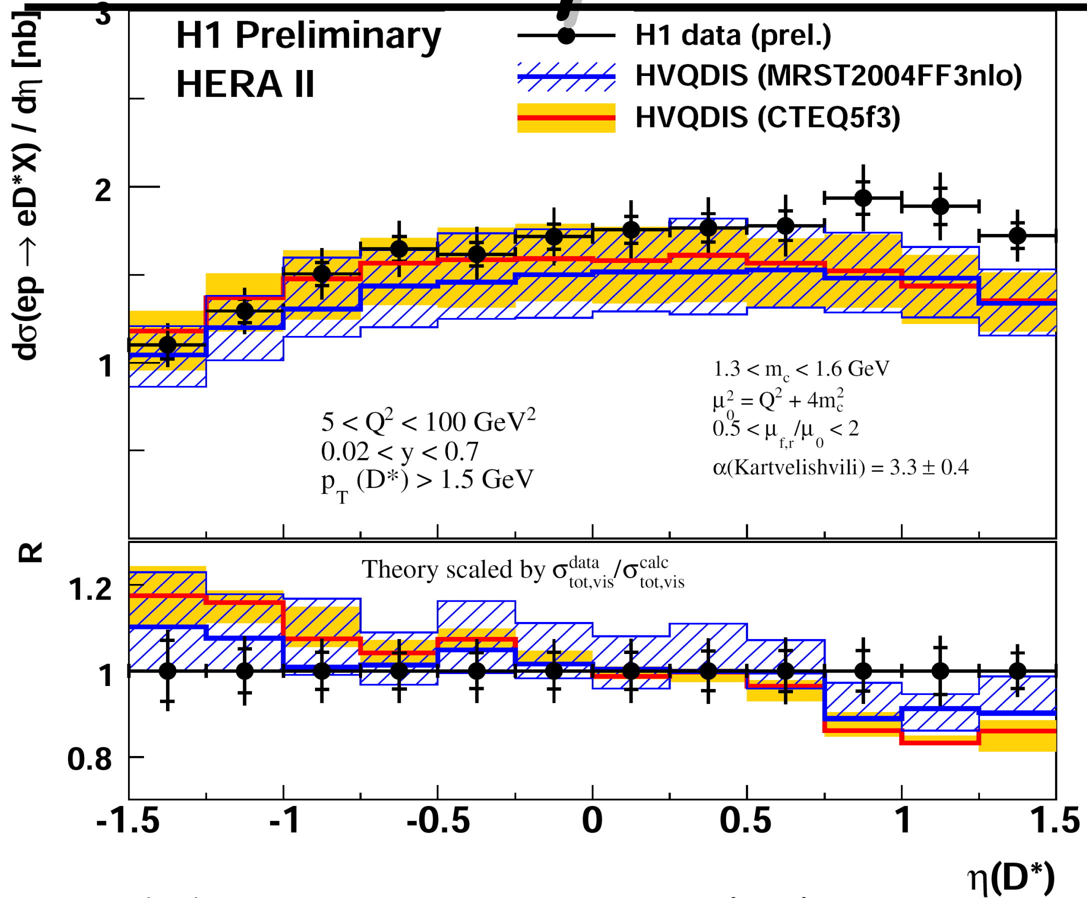
  syst. Error ~9%

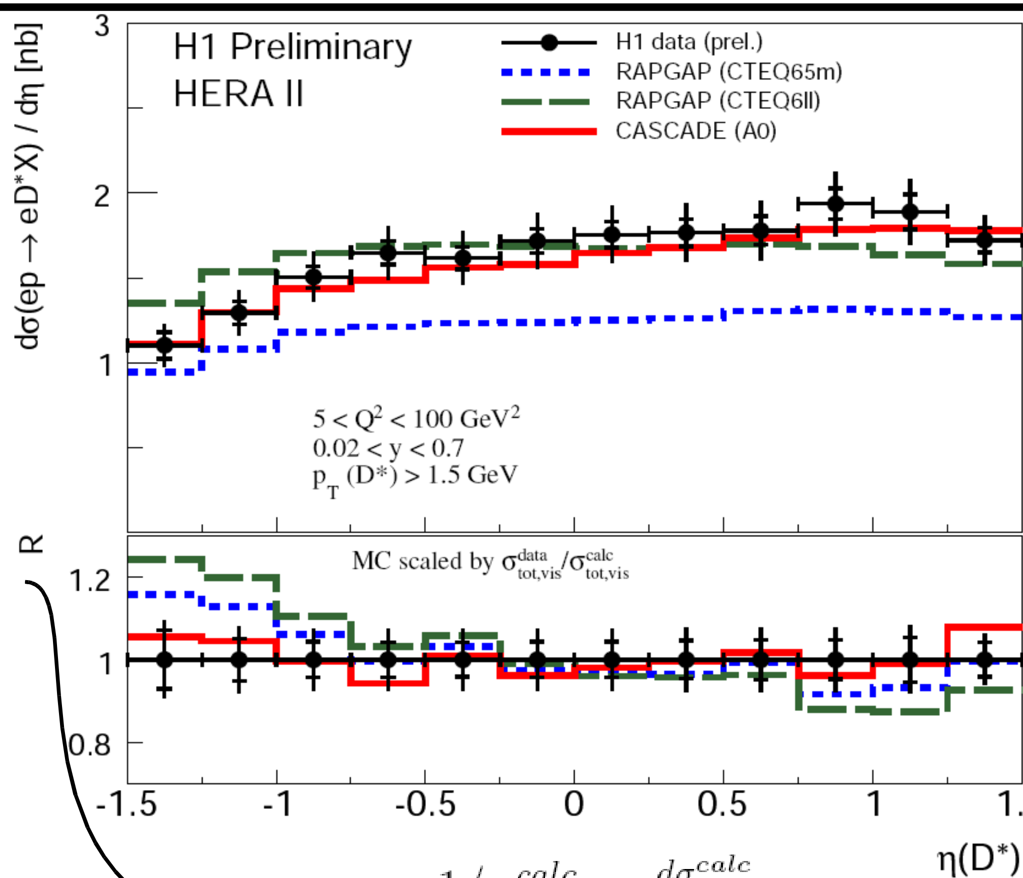
$$\sigma_{\text{tot}}^{\text{vis}} = \frac{N_{D^\star} \cdot (1-r)}{\mathcal{L} \cdot \mathcal{B}(D^\star \rightarrow K\pi\pi_{\text{slow}}) \cdot \epsilon \cdot (1-\delta_{rad})}$$

Additional D* cuts:

$p_T(K) > 0.3$ GeV
$p_T(\pi) > 0.3$ GeV
$p_T(\pi_{slow}) > 0.12$ GeV
$p_T(K) + p_T(\pi) > 2$ GeV
$|M(D^0)| < 0.080$ GeV

Backup: D* cross sections





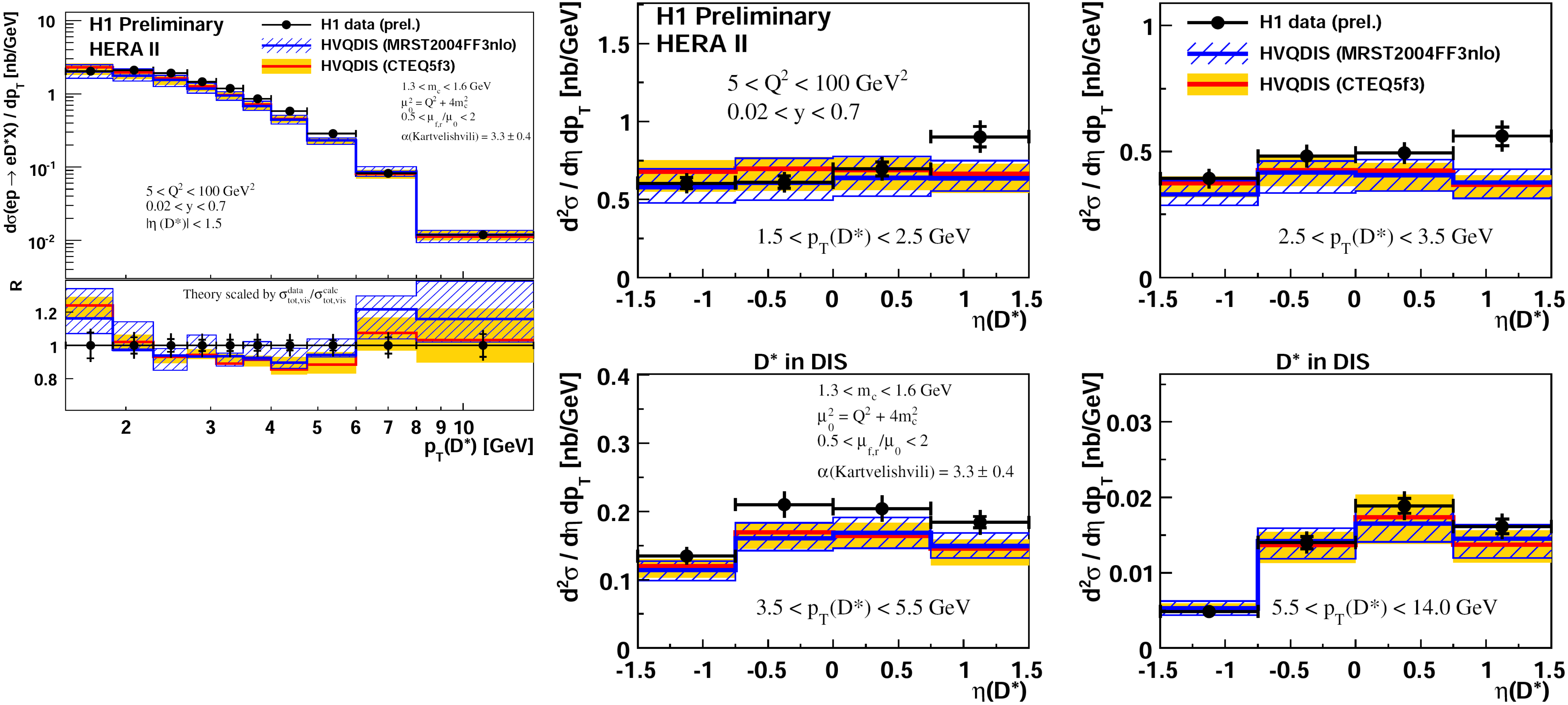
$$R = \frac{1/\sigma^{calc}_{tot,vis} \cdot \frac{d\sigma^{calc}}{dY}}{1/\sigma^{data}_{tot,vis} \cdot \frac{d\sigma^{data}}{dY}}$$

- Good description by NLO calculation
- Small deviations in forward η(D*) with full HERA2 statistics
- differences are located at low transverse momenta
- data shows sensitivity to the proton PDF
- CASCADE describes nicely the shape

$$\eta = -\ln\left(\tan\left(\frac{\theta}{2}\right)\right)$$

https://www-h1.desy.de/psfiles/confpap/ICHEP08/H1prelim-08-072.p
and http://www-h1.desy.de/psfiles/theses/h1th-504.pdf

Backup: D* cross sections

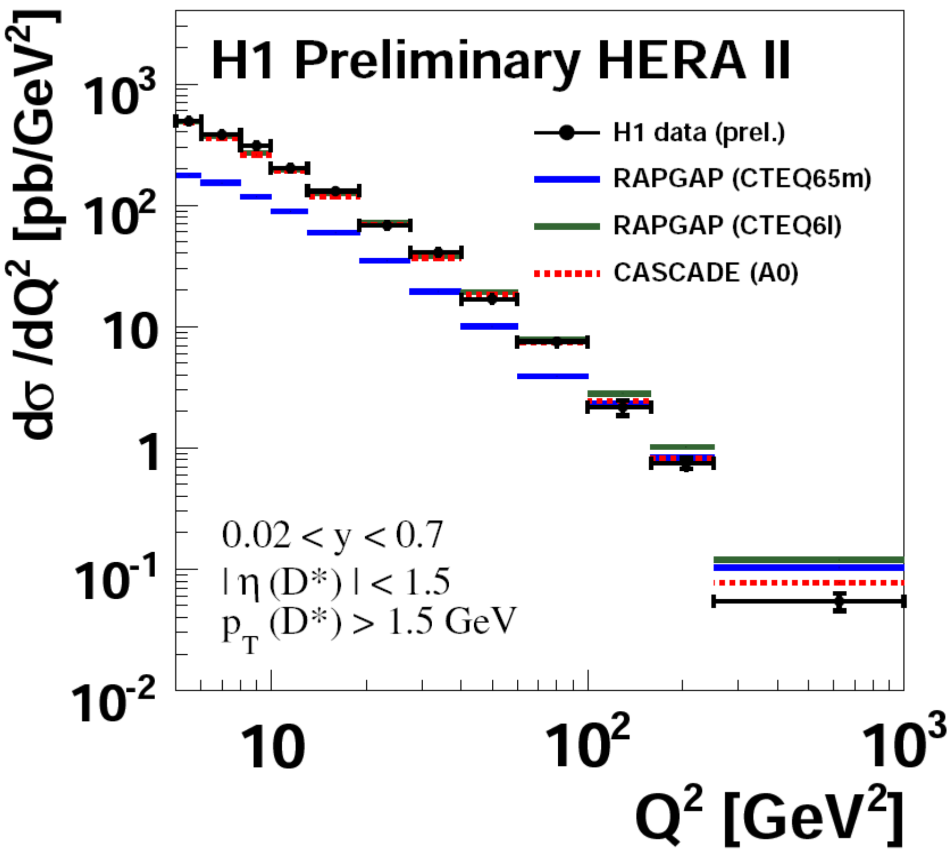


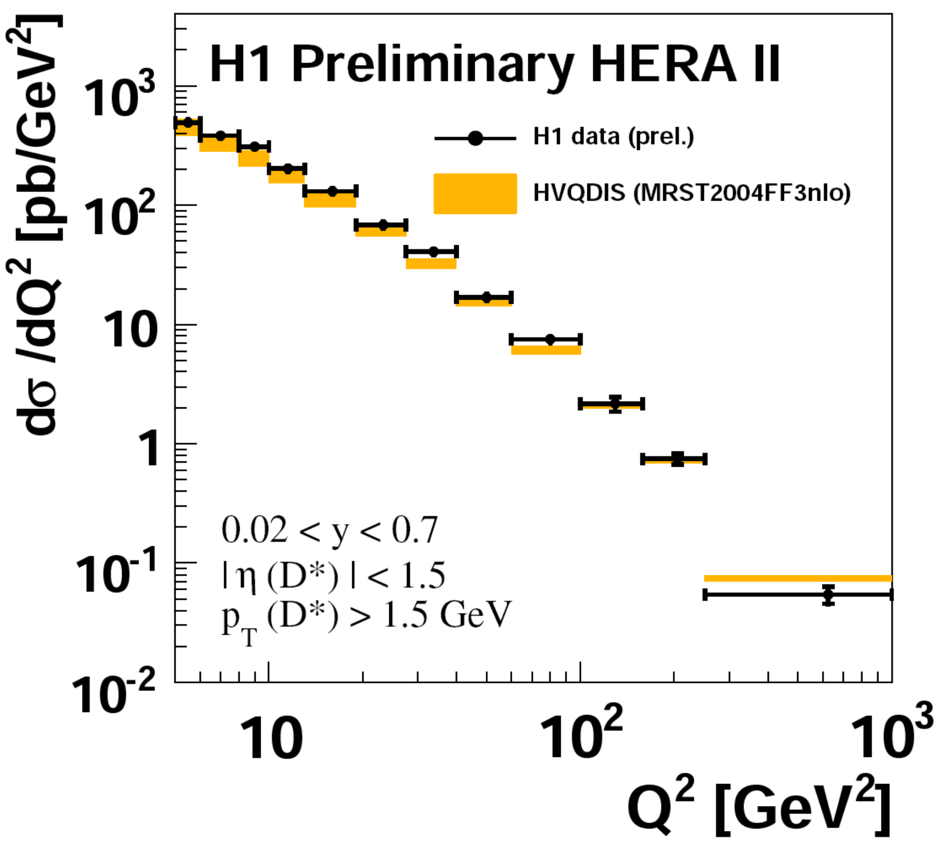
--> In general NLO gives a good description of the data of single & double differential dists

--> forward $\eta(D^*)$ at low $p_T(D^*)$: data is above the NLO-calculations

--> better precision of the data is needed – more bins in larger phase space

Backup: D* cross sections





Total integrated Cross section in Q^2: 5 - 100 GeV^2:

Data:	**(4.85 ± 0.07(stat.) ± 0.42 (sys.)) nb**
HVQDIS (CTEQ):	**(4.43 +0.69 -0.47) nb**
HVQDIS (MRST):	**(4.17 +0.59 -0.37) nb**

Total integrated Cross section in Q^2: 100 - 1000 GeV^2:

Data:	**(0.24 ± 0.02(stat.) ± 0.03 (sys.)) nb**
HVQDIS (MRST):	**(0.25 +0.02 -0.02) nb**

→ Talk by M. Brinkmann