Confronting fragmentation function universality with single hadron inclusive production at HERA and e^+e^- colliders

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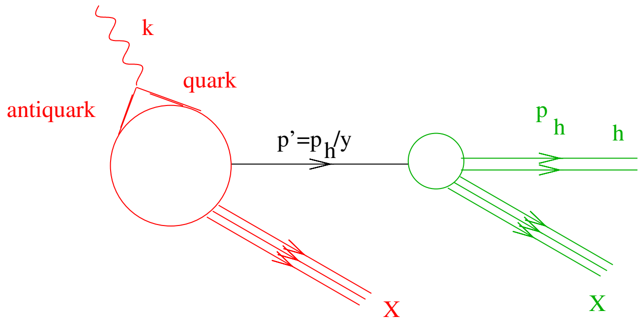
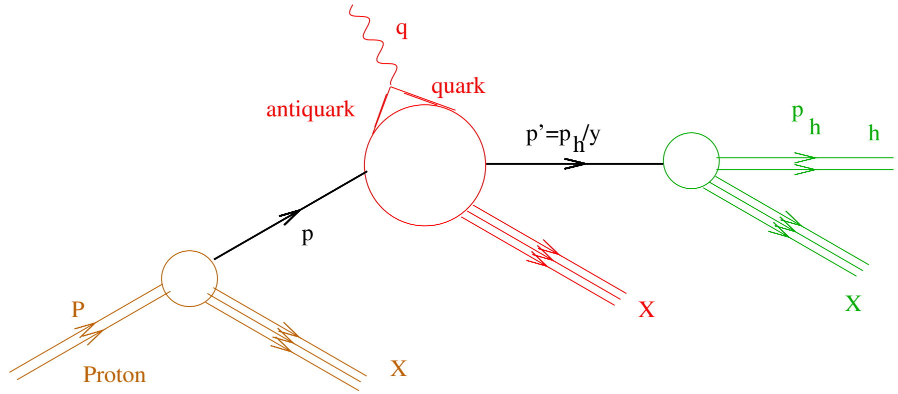
Factorization in e^+e^- / $ep \to h + X$

e^+e^-: $x_p = \frac{2p_h}{\sqrt{s}}$, $s = k^2$ $\quad$ ep: $x_p = \frac{2p_h \cdot q}{q^2} (= \frac{2p_h}{Q} \text{ Breit}), x = \frac{Q^2}{2P\cdot q}, Q^2 = -q^2$

$\frac{d\sigma^h}{dx_p}(x_p, s)$: $\quad$ $\frac{\frac{d}{dx_p}\int_{\text{cuts}} dQ^2 dx \frac{d^2\sigma^h}{dx dQ^2}}{\int_{\text{cuts}} dQ^2 dx \frac{d^2\sigma^h}{dx dQ^2}}$:





perturbative ⊗ FFs $\quad$ PDFs ⊗ perturbative ⊗ FFs

$G_I = 1$ $\quad$ G_I from Ith PDF

$$\frac{d\sigma^h}{dx_p}(x_p, s \text{ or } Q^2) = \sum_i \int_{x_p}^1 \frac{dy}{y} \frac{d\sigma^i}{d(x_p/y)} \left(\frac{x_p}{y}, s \text{ or } Q^2, \mu_f^2\right) D_i^h(y, \mu_f^2)$$

$$\text{LO}: \quad \approx \sum_I e_{q_I}^2 (Q^2) G_I(Q^2) D_I^h(x_p, Q^2)$$

$$\text{DGLAP}: \quad \frac{d}{d\ln\mu_f^2} D_i^h(x, \mu_f^2) = \int_x^1 \frac{dy}{y} \sum_j P_{ij}\left(\frac{x}{y}, a_s(\mu_f^2)\right) D_j^h(y, \mu_f^2)$$

$ep \to h + X$: Theory + Experiment

$$h = \pi^\pm + K^\pm + p/\overline{p}$$

Theory

- PDFs: CTEQ6M
  MRST2001
- NLO, $n_f = 5$, $\Lambda_{\mathrm{QCD}} = 226$ MeV (CTEQ6M)
- FFs: AKK, KKP, Kretzer $\Big\} \longrightarrow x_p > 0.1$
- Also vary: $\mu = \mu_f$
  quark tagging
  gluon FF
  hadron mass m_h (low Q)
  hadron species
- Neglect: quark mass, higher twist, small/large x_p resum $\Big\} \longrightarrow$ low Q
  ...
- Default: CTEQ6M, AKK, $m_h = 0$, $\mu_f = Q$
- Software: CYCLOPS

Experiment

- Data: H1, ZEUS (current region)
- Distributed in: x_p, Q
- Given: E, s
- Cuts on (x, Q) plane:

$$W^2 = (P+q)^2 = Q^2\left(\frac{1}{x} - 1\right)$$

$$y = \frac{P\cdot q}{P\cdot k} = \frac{Q^2}{xs}$$

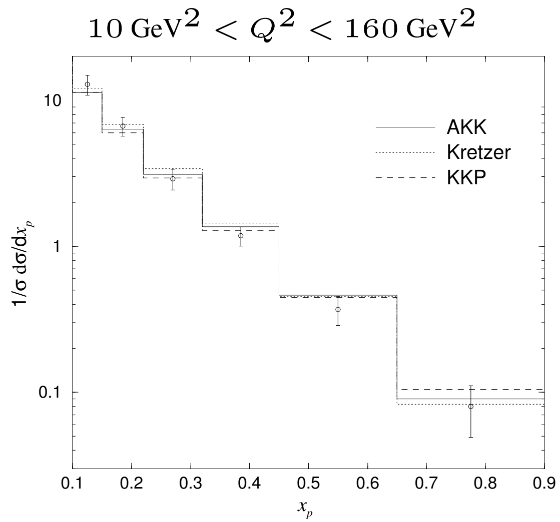
$$E' = E - Q^2\left(\frac{E}{xs} - \frac{1}{4E}\right)$$

$$\cos\theta_e = \frac{xs\left(4E^2 - Q^2\right) - 4E^2Q^2}{xs\left(4E^2 + Q^2\right) - 4E^2Q^2}$$

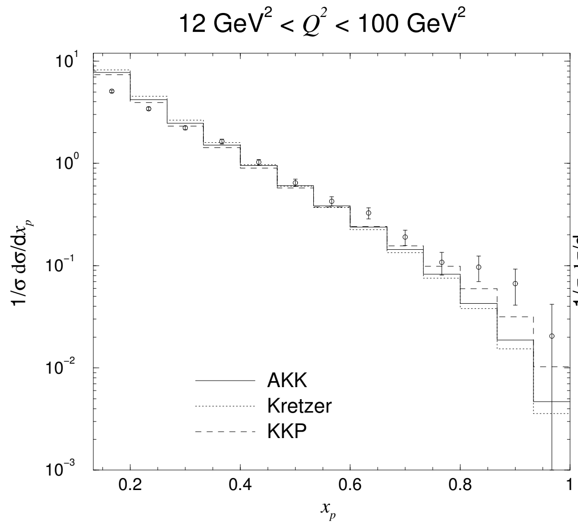
$$\cos\theta_p = \frac{xs(xs - Q^2) - 4E^2Q^2}{xs(xs - Q^2) + 4E^2Q^2}$$

x_p distributions vs. FFs

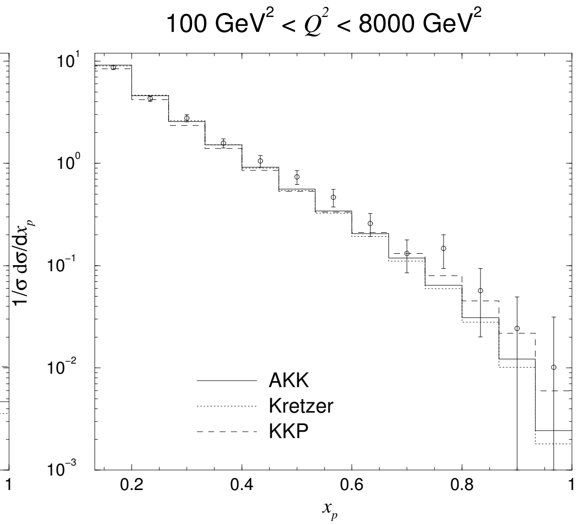
ZEUS



H1



H1



Large x_p: Inadequate e^+e^- data $\longrightarrow$ FF discrepancies

AKK $\simeq$ Kretzer

Low Q

- H1:
  small x_p bad (small exp. errors, various theory issues)
  large x_p undershoot: resummation?
- ZEUS: General agreement

High Q (H1)

General agreement

(smaller pred. errors)

Hadron mass effects at small x_p, low Q

Particles confined to 3-axis:

$$(V^+, V^-) = \frac{1}{\sqrt{2}} V^0 (+,-) V^3$$
$$\mathbf{V}_T = \mathbf{0}$$

$$p_h = \left(\frac{m_h^2}{2\xi_p q^-}, \xi_p q^- \right)$$
$$q = \left(-\frac{Q^2}{2q^-}, q^- \right)$$

Variable ξ_p:

- Like DIS Nachtmann ξ
- 3-axis boost invariant
- true "x" of factorization

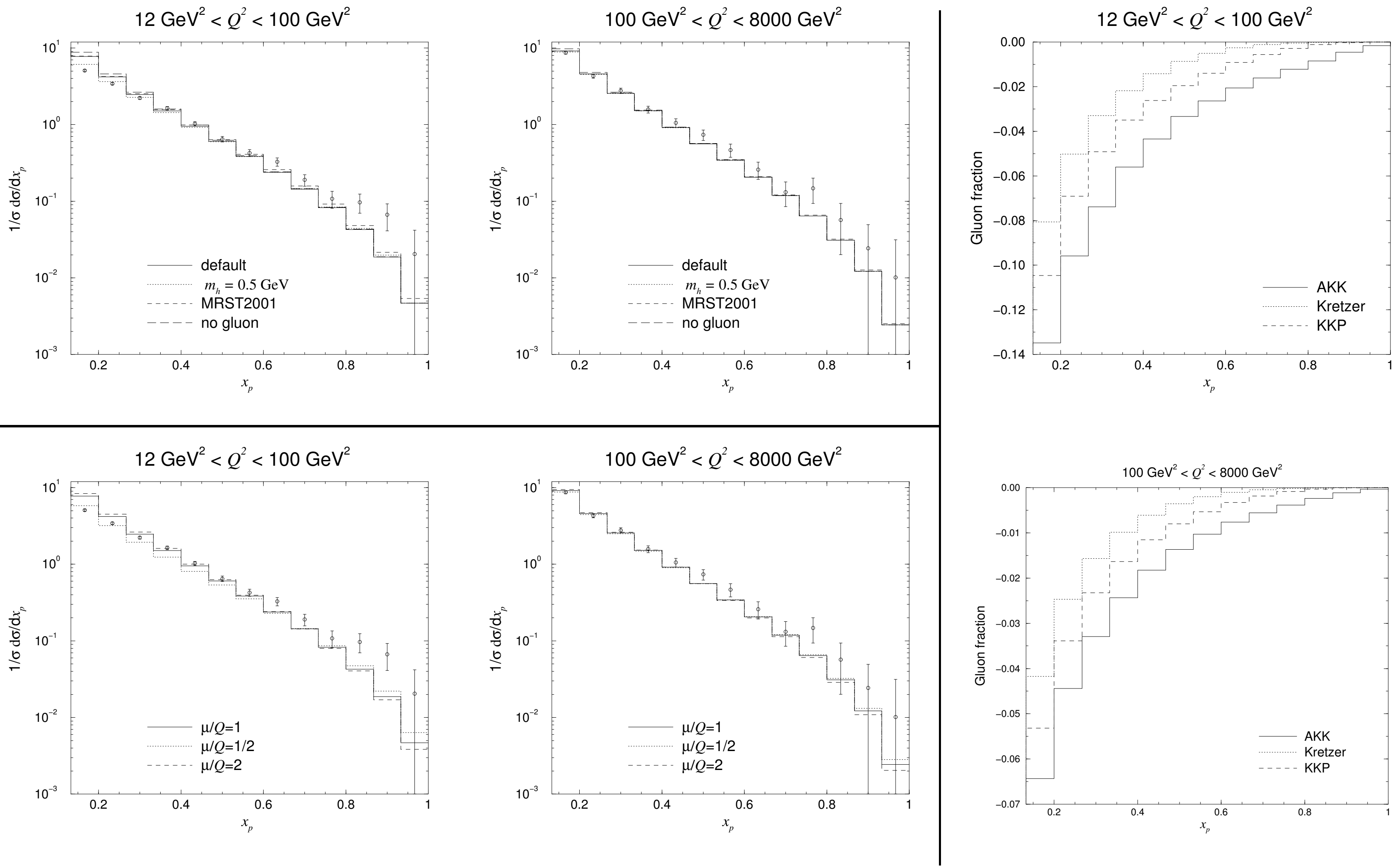
Leading twist factorization:

- $p' = \left(0, \frac{p_h^-}{y} \right)$
- $\frac{d\sigma^h}{d\xi_p}(\xi_p, Q^2) = \int_{\xi_p}^1 \frac{dy}{y} \frac{d\sigma^h}{dy} \left(y, Q^2, \mu_f^2 \right) D \left(\frac{\xi_p}{y}, \mu_f^2 \right)$

Relation to experiment:

- $x_p = \xi_p \left(1 - \frac{m_h^2}{Q^2 \xi_p^2} \right)$
- $\frac{d\sigma^h}{dx_p}(x_p, Q^2) = \frac{1}{1 + \frac{m_h^2}{Q^2 \xi_p^2}} \frac{d\sigma^h}{d\xi_p}(\xi_p, Q^2)$

$Q\uparrow$, pred. errors $\downarrow$ (H1)



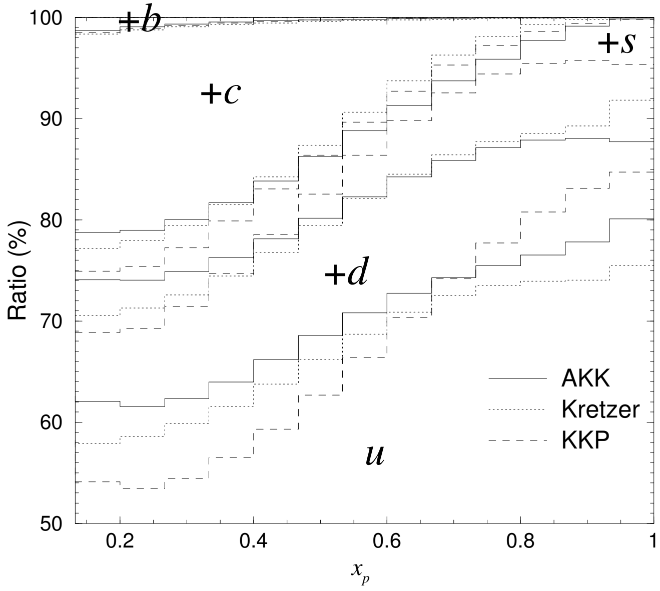
$\longrightarrow$ look at high Q data

Quark tagging (H1)

Identify quark flavour at e.w. vertex

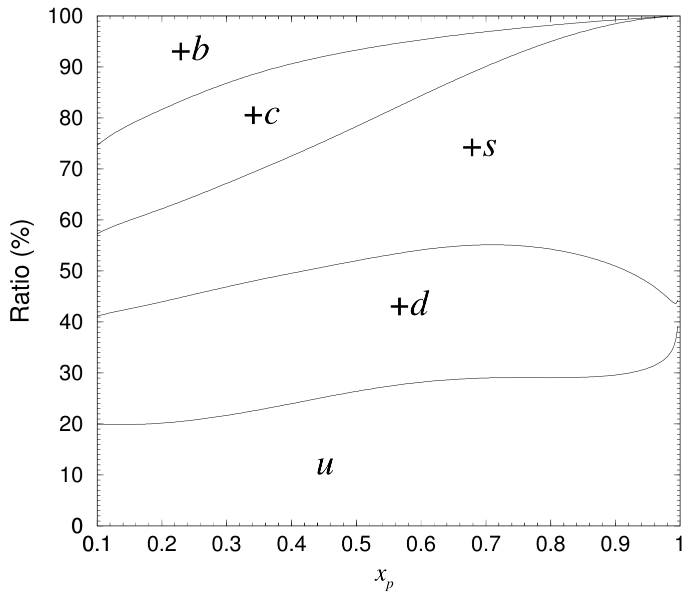
$ep \to h + X$

100 GeV^2 < Q^2 < 8000 GeV^2



$e^+e^- \to h + X$

$\sqrt{s} = 91$ GeV

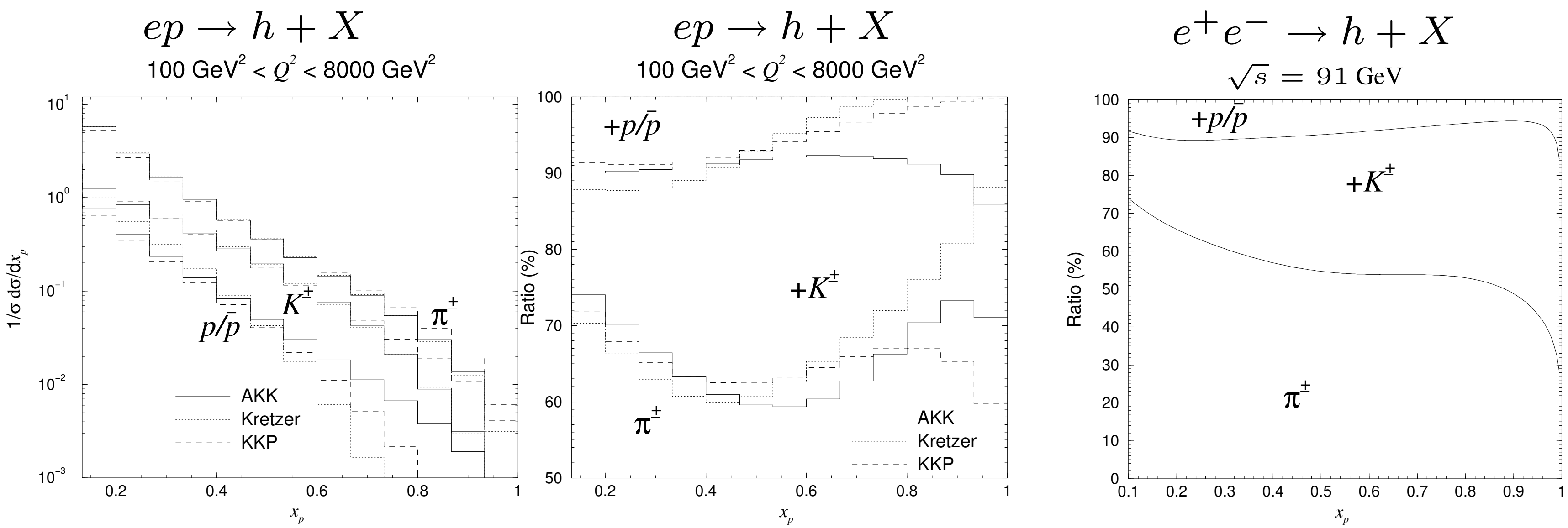


Proton is good source of u

s relatively large

In principle, ep and e^+e^- together can separate uds FFs

Hadron identification (H1)



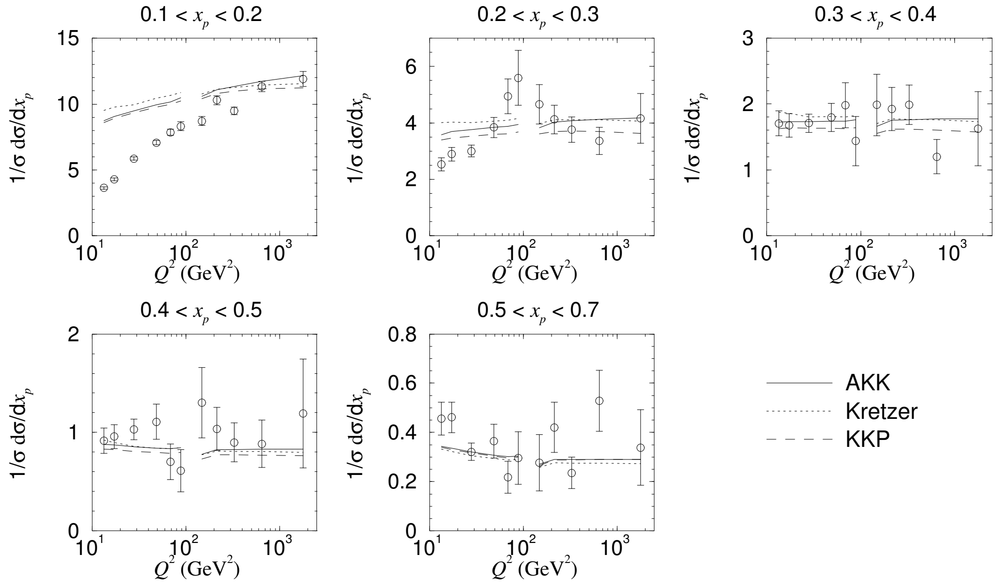
AKK $\simeq$ Kretzer

$p/\overline{p}$ badly constrained

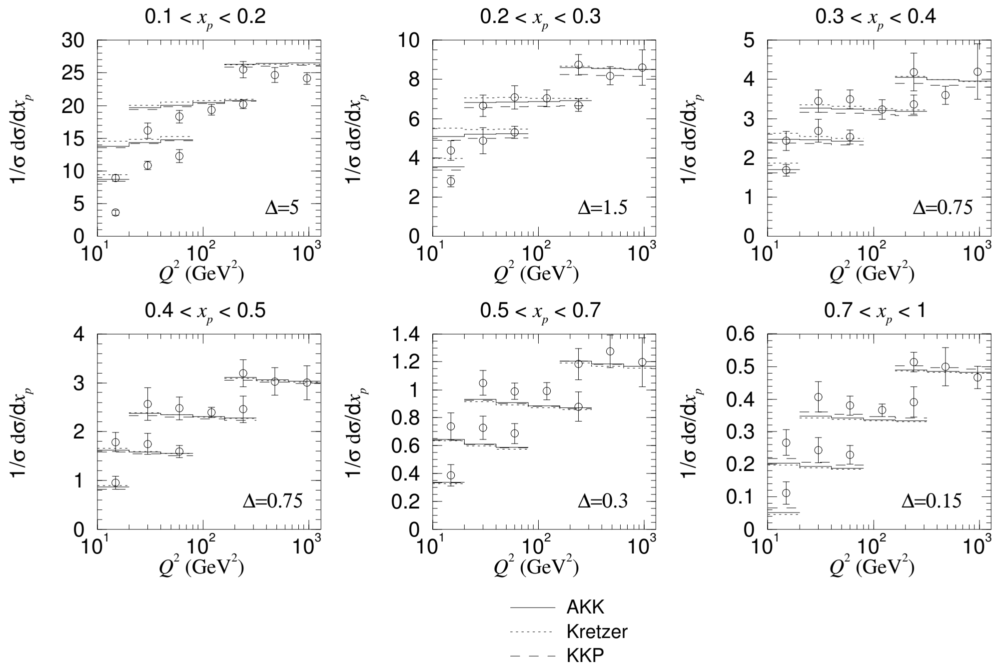
$K^{\pm}$ lower in $ep \longrightarrow$ less s fragmentation?

Q distributions vs. FFs

H1



ZEUS



Agreement if x_p intermediate

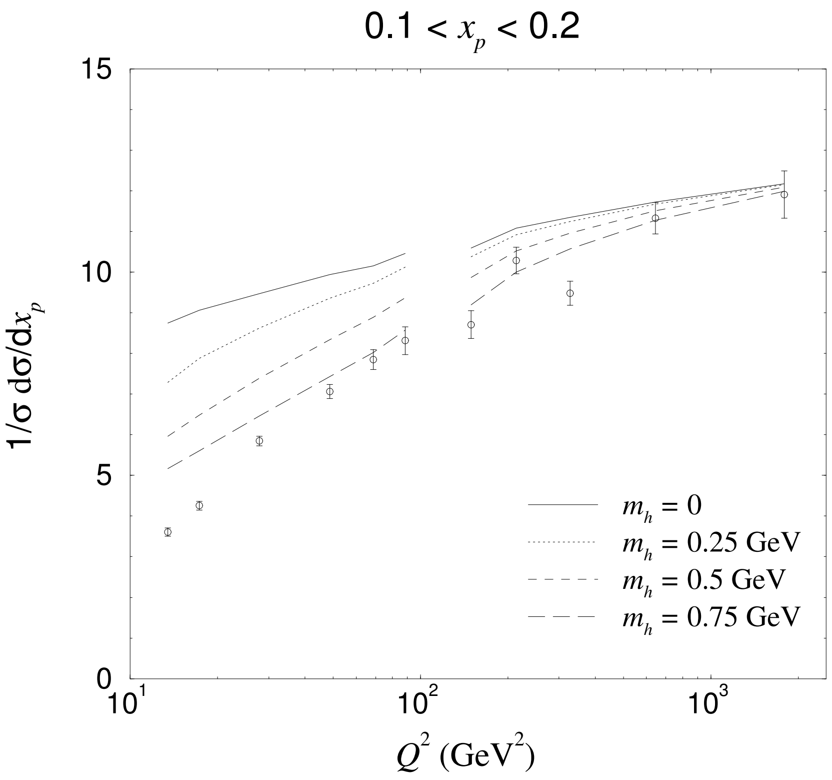
and / or Q large

Large x_p:

undershoot $\rightarrow$ resummation?

Hadron mass dependence vs. Q (H1)

Mass effects are most relevant at smaller x_p

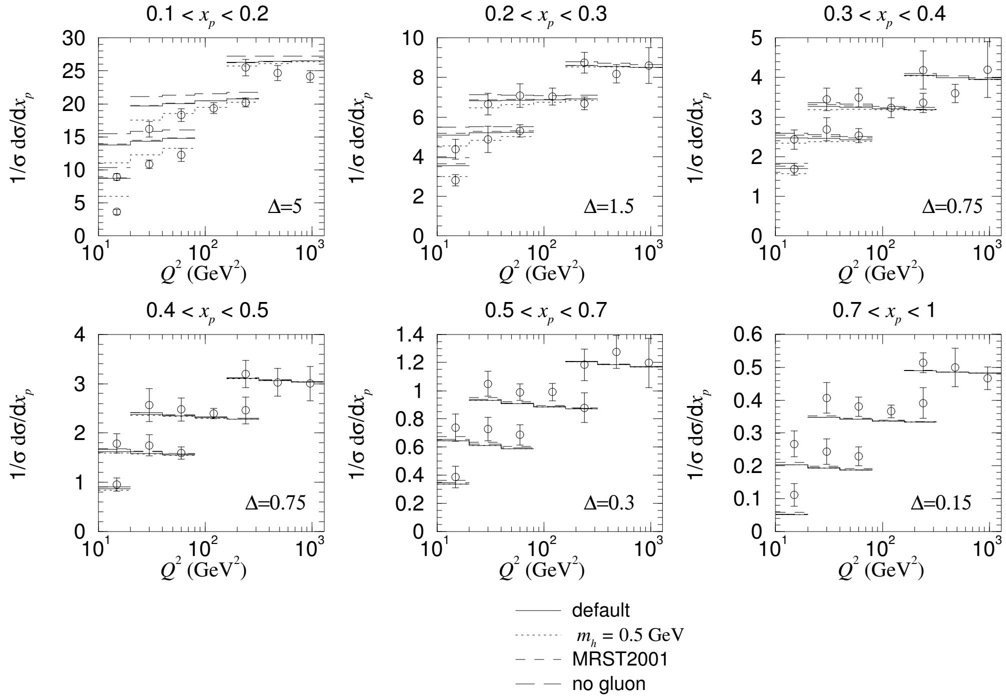


Low Q: mass effects improve comparison

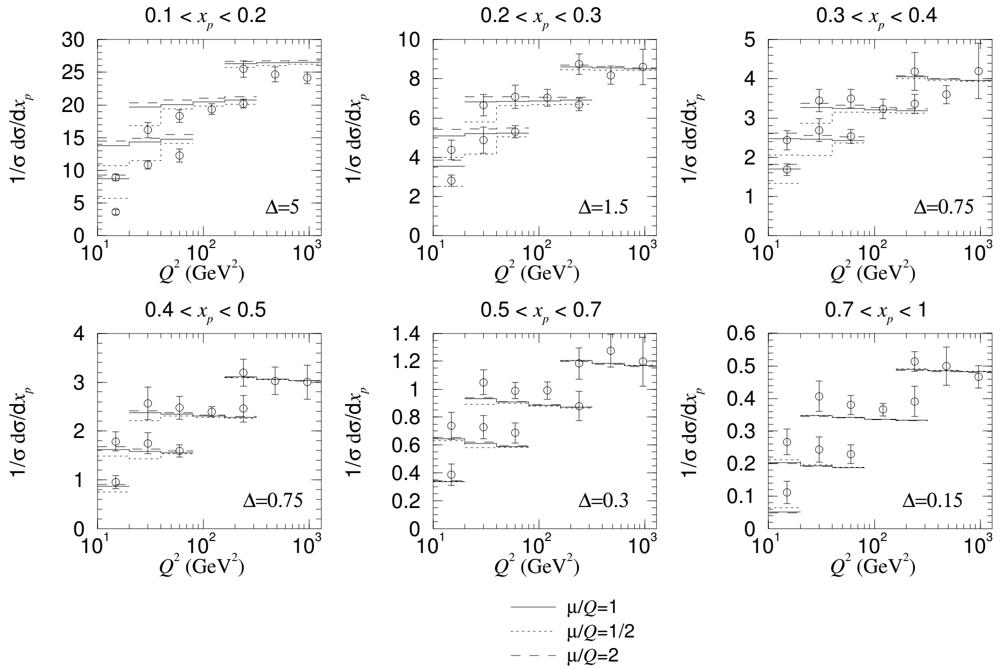
Large mass required for agreement

$\longrightarrow$ other theoretical input required

Pred. errors (ZEUS)



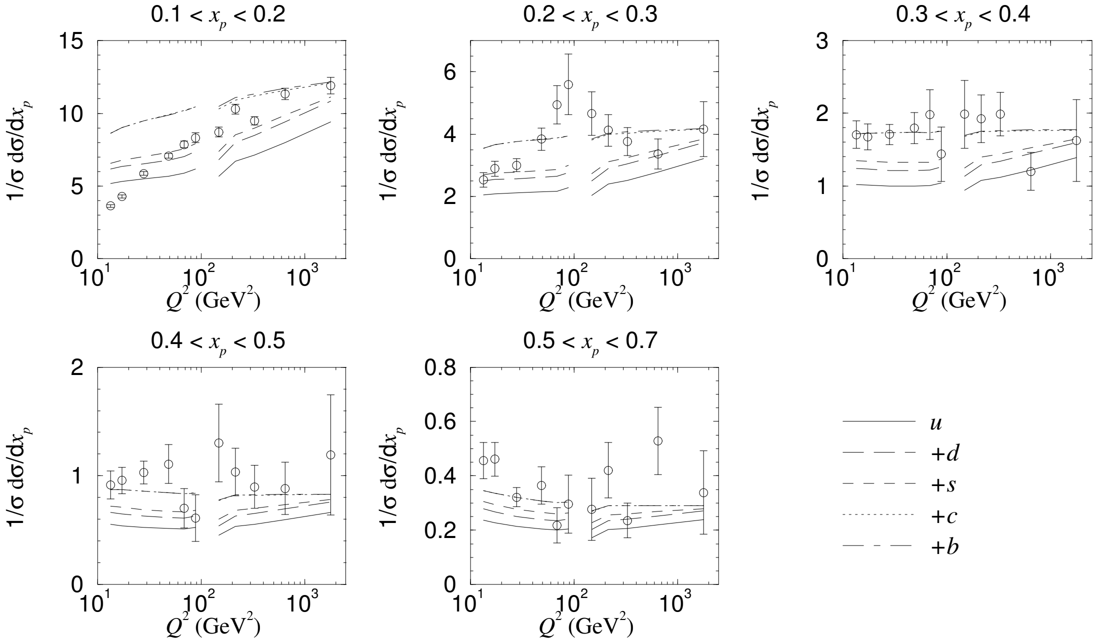
Important at small x_p, low Q



Low Q, $\mu/Q = 1/2$:

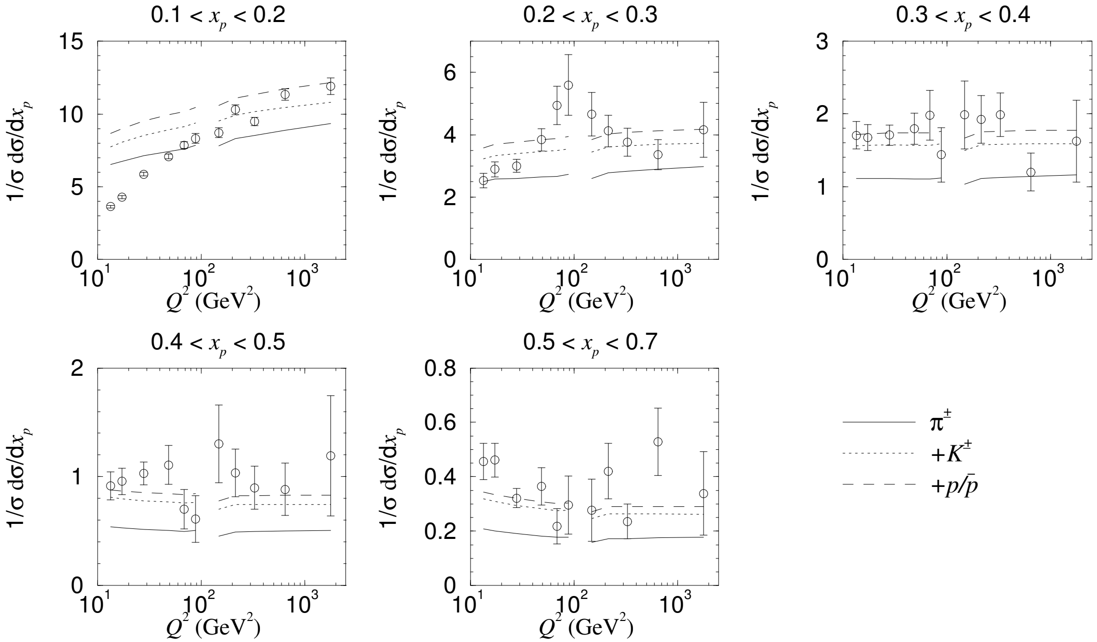
c threshold $\longrightarrow$ non-physical dip

Components (H1)



$Q\uparrow$: $u\uparrow$ $c, s\downarrow$

$b \simeq 0$



Fractions roughly constant in Q

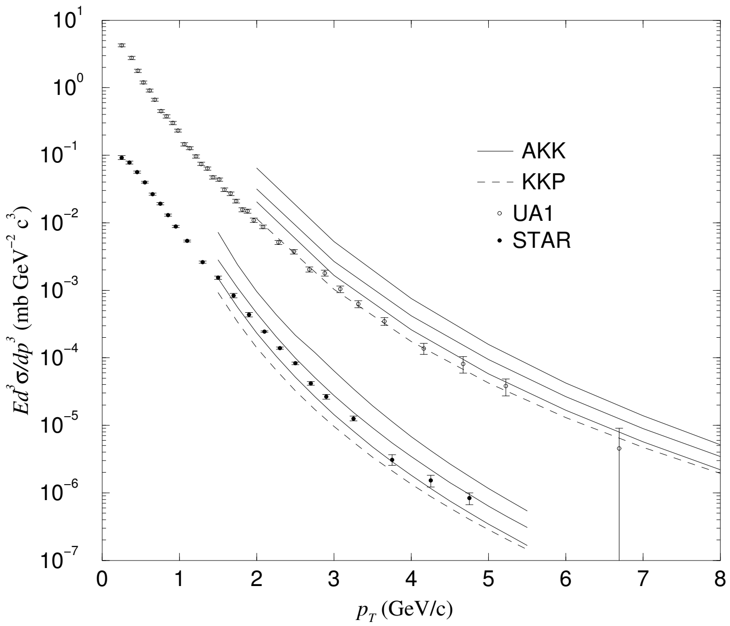
Summary

- AKK, KKP, Kretzer predictions $\simeq$ high Q and/or intermediate x_p @ HERA
- Gluon fragmentation unimportant
- AKK $\simeq$ Kretzer
- Low Q: Deviations at small x_p (various effects), large x_p (resummation?)
- Data from e^+e^- and future ep: improve uds separation
- Future high Q HERA data (hadron identified + quark tagged(?)) valuable

$pp \to h + X$

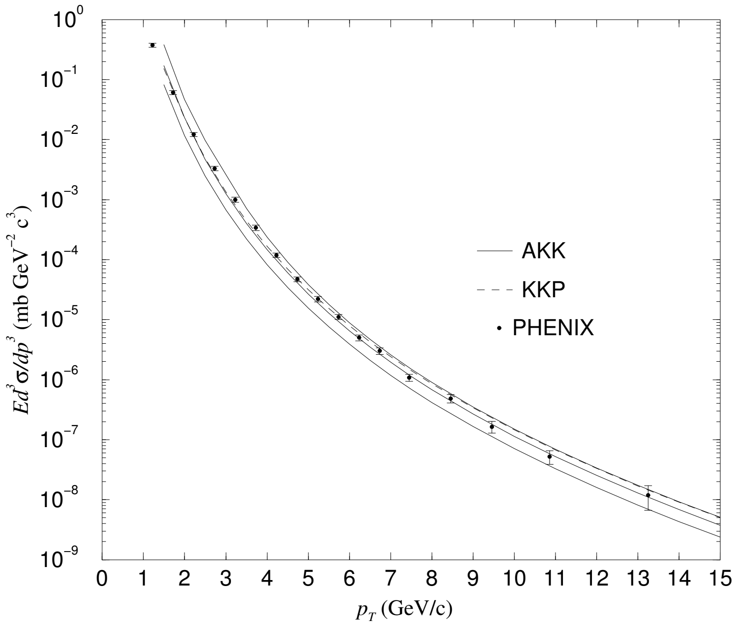
g fragmentation

- pp description: dominates
- e^+e^- fits: not well constrained
  (no $g\gamma$ coupling)
- ep description: not important



More optimistically

- pp: q fragmentation still relevant
- e^+e^- fits: $g \to \pi^\pm$ OK
  (accurate $\pi^\pm$ data)
- Future HERA data:
  better FFs for fragmentation@LHC



Global Analyses of Unpolarized FFs

- Light charged hadrons (l.c.h.) $\pi^\pm$, $K^\pm$, $p/\bar{p}$
- Σ Hadron (quark) spins and charge

Most recent are

Kniehl-Kramer-Pötter (2000)

$$D_u^{\pi^\pm}(x, M_0) = D_d^{\pi^\pm}(x, M_0)$$
$$D_u^{K^\pm}(x, M_0) = D_s^{K^\pm}(x, M_0)$$
$$D_u^{p/\overline{p}}(x, M_0) = 2D_d^{p/\overline{p}}(x, M_0)$$

Albino-Kniehl-Kramer (2005)

- Update of KKP
- $D_{u,d,s}^h$ from OPAL tagging probabilities
- Also for K_0^S, Λ

Since 2000, l.c.h. studies also from

- Kretzer ($\pi^\pm$, $K^\pm$, charged)
- Bourhis, Fontannaz, Guillet, Werlen (charged)

e^+e^- data

Rely mostly on e$^+$+e$^-$ $\to Z, \gamma \to X + h (= h^+ + h^-)$

- h identified
- ALEPH, DELPHI, SLD ($\sqrt{s} = 91$ GeV), TPC (29 GeV) (uds, c, b)
- OPAL tagging probabilities ($\sqrt{s} = 91$ GeV) (u, d, s, c, b)

OPAL probabilities rather model independent
(SU(2) isospin, quark b.r.'s from pQCD)

Excluded in AKK:

- h unidentified (contaminated with other charged particles) - use for checking
- $x_p < 0.1$ (soft gluon logarithms)

Importance of $ep \to h + X$ data

p_T and y distributions

- $p\overline{p}$ @ UA1/2+CDF

  large p_T: scale uncertainty

  small p_T: non-perturbative

- γp @ H1+ZEUS

  as above, + errors from γ PDFs

- $\gamma\gamma$ @ OPAL

  as above

ep

- Breit frame:

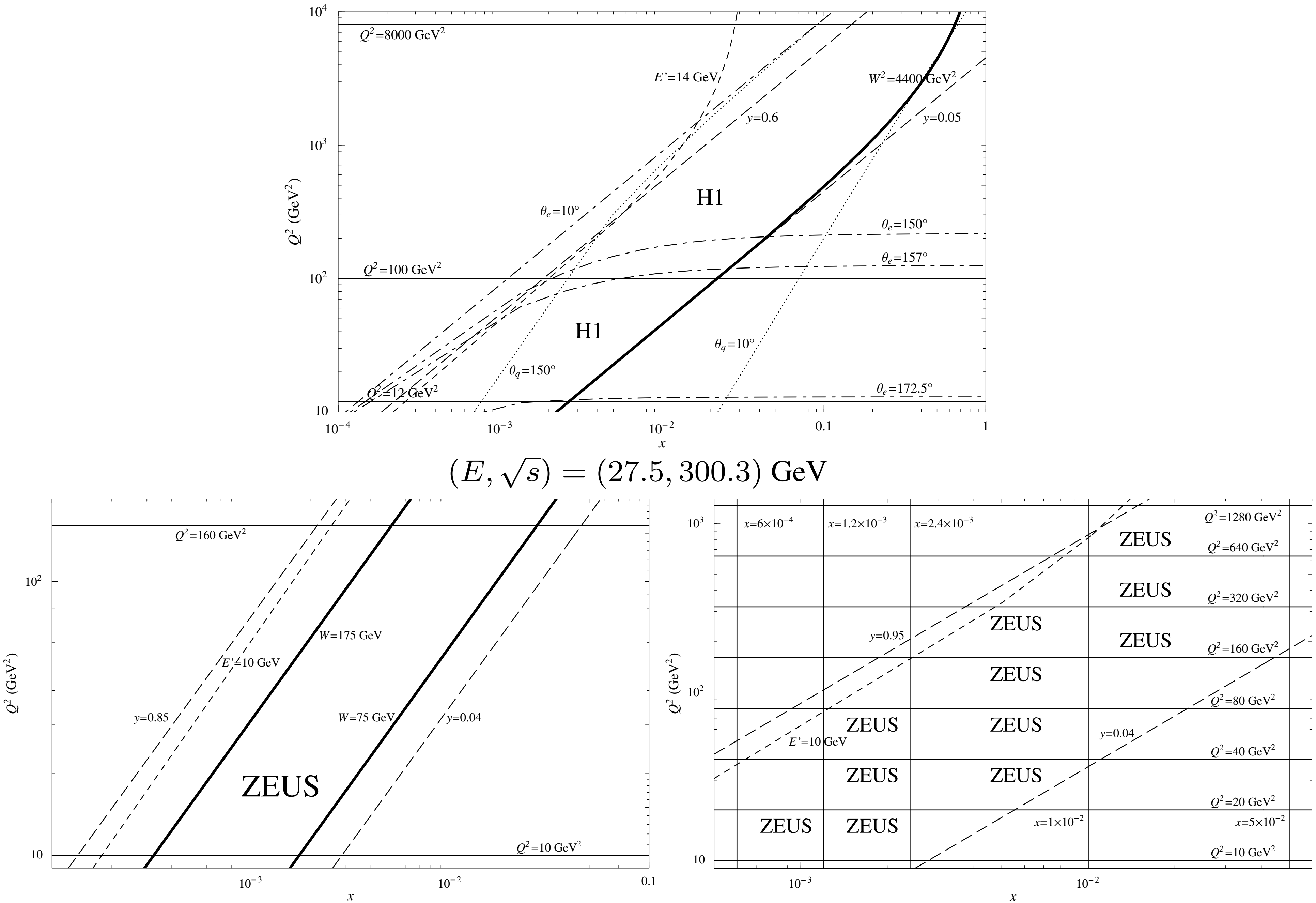
  target / current separation clean

- x_p in current region

  $\simeq x_p$ of e^+e^- event hemisphere

  $\longrightarrow$ direct test of FF universality

Cuts in (x, Q) plane



$(E, \sqrt{s}) = (27.5, 300.3)$ GeV

$(E, \sqrt{s}) = (26.7, 296)$ GeV

$(E, \sqrt{s}) = (27.5, 300.3)$ GeV