PHOTOPRODUCTION

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Summary of recent developments......

(1) Jets (single & dijet rates)

(2) Jet profiles

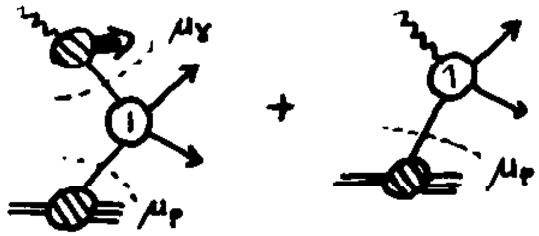
(3) Open charm (D^*'s)

(4) Inelastic J/ψ

(won't discuss diffraction...)

JET CROSS SECTIONS

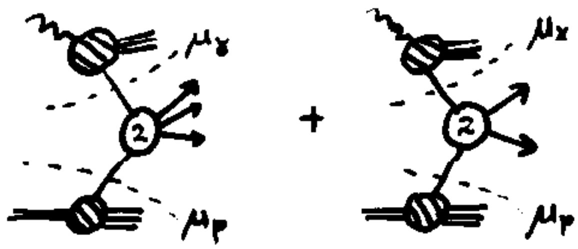
(LO)



Resolved Direct

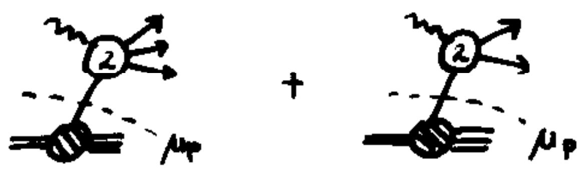
No μ_γ dependence
$\therefore$ Large ambiguity.

(NLO)



Resolved

+



Direct

 and  μ_p & μ_γ <u>dependent</u>
(collinear divergence is factorized)

Cancels against LO dependence $\Rightarrow$ Reduced ambiguity.

ie, Vary μ_γ = vary amount of NLO direct that is included in LO resolved

$\boxed{\therefore \text{ Separation of Direct \& Resolved is factorization scheme dependent beyond LO.}}$

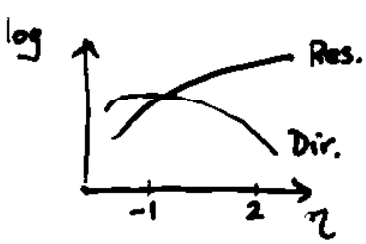
Single jet inclusive

NLO calculation in agreement except for .....

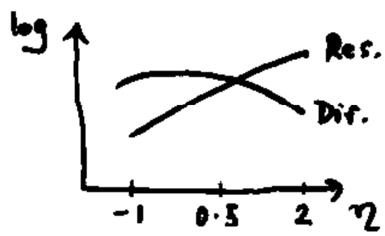
forward jets at low E_T [plots]

These are the jets which are broader than expected from Monte Carlo (without multiple interactions)

..... these are just the jets which are most sensitive to the gluon in the photon!



Low E_T



High E_T

* Precise data is ready for comparison with theory

{ But, forward jets need understanding before we can safely extract γ pdf's }

Multiple interactions receive some support from data

[plot]

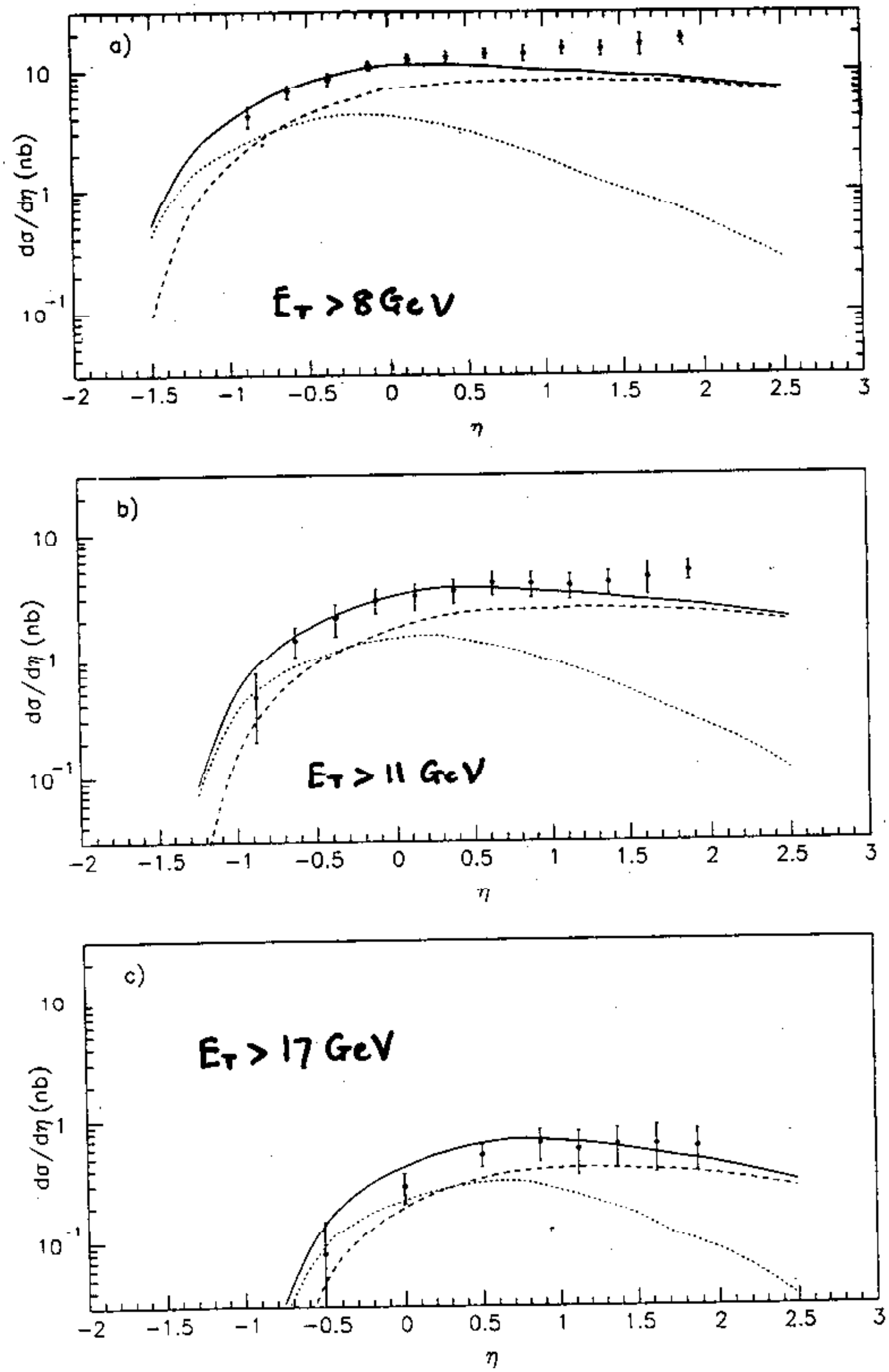


Figure 9: Inclusive single-jet cross section $d\sigma/d\eta$ integrated over E_T above $E_T^{min} = 8$ GeV (a), 11 GeV (b), and 17 GeV (c) with $R = 1$ and GS(HO) photon structure function. The ZEUS data [4] are compared with NLO calculations of the resolved part (dashed lines), the direct part (dotted lines), and the complete photoproduction (full lines) as a function of η.

[Klasen, G. Kramer, Salesch.]

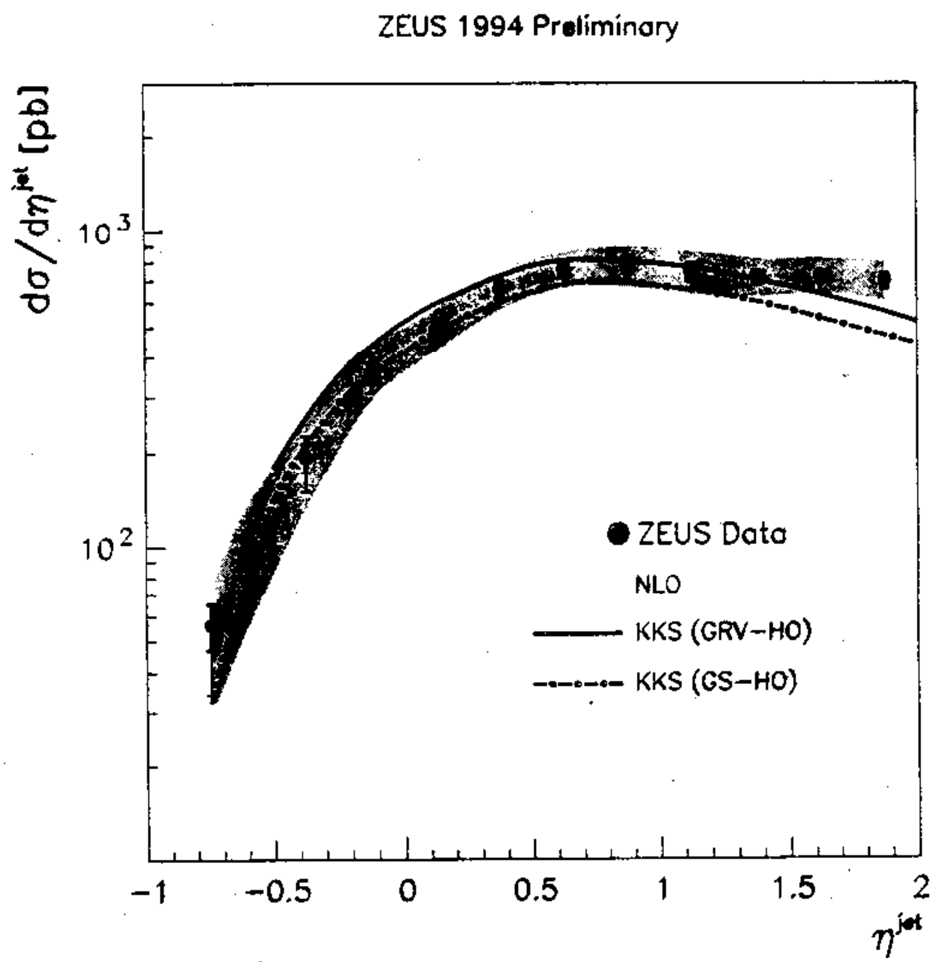


Figure 2: Measured differential ep cross section $d\sigma/d\eta^{jet}$ for inclusive jet production integrated over $E_T^{jet} > 17$ GeV in the kinematic region defined by $Q^2 \leq 4$ GeV^2 and 134 GeV $< W <$ 277 GeV. The thick error bars represent the statistical errors of the data, and the thin error bars show the statistical and systematic errors —not associated with the energy scale of the jets— added in quadrature. The shaded band indicate the uncertainty due to the energy scale of the jets. For comparison, NLO calculations from Kramer, Klasen and Salesch using the photon parton distributions of GRV-HO (solid line) or GS-HO (dash-dotted line) are shown.

Dijets

Single jets

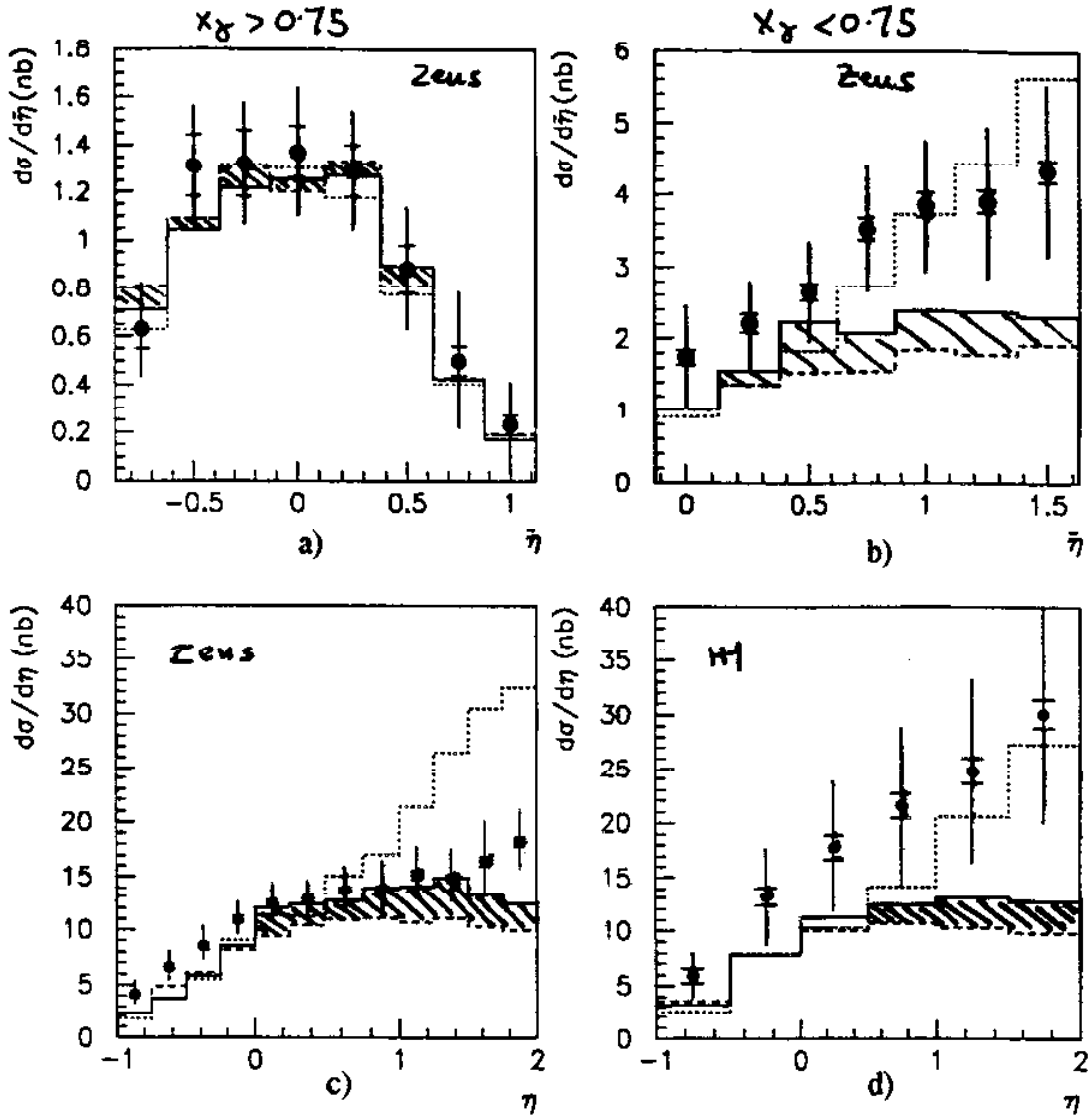


Figure 8: ZEUS data compared with HERWIG. a) and b) show the differential dijet cross sections for direct and resolved photon events respectively (where the separation is defined by a cut on x_γ^{obs}) by the ZEUS collaboration [3]. c) and d) shows the differential inclusive jet cross section as a function of η^{jet} as measured by the ZEUS [25] and H1 [26] collaborations respectively. The inner error bars indicate the statistical uncertainty, and the outer one the statistical and systematic errors added in quadrature. In all cases the solid histogram shows the calculation of the default multiple interaction model, the dotted line shows the calculation using the default but using LAC1 instead of GS2 for the parton distribution set, and the dashed line shows the result of HERWIG with no multiple interactions.

[Butterworth, Forshaw, Seymour]

Dijets

Backward dijets
⇒ gluon in proton (low x)
($x_\gamma > 0.75$)

Forward dijets
⇒ gluon in photon
($x_\gamma < 0.75$)

$$x_\gamma^{obs} = \frac{\sum_{jets} E_T^{jet} e^{-\eta^{jet}}}{2y E_e} \qquad \left\{ \begin{array}{lll} x_\gamma = 1 & \text{direct} & (2 \to 2) \\ x_\gamma < 1 & \text{resolved} & \end{array} \right\}$$

NLO calculations now available
(and data using kt-algorithm)
(H1 now has a dijet cross-section) ZEUS

Klasen + Kramer, G
Owens
Aurenche

$x_\gamma > 0.75$ still large contamination from resolved γ pdf.
To really enhance sensitivity to small-x gluon in proton cut on $x_\gamma > 0.9$
→ feasible up to large E_T
eg, $250 pb^{-1}$ ~ 4500 events with $E_T \gtrsim 30$ GeV.

$x_\gamma < 0.75$ evidence that effects beyond uncertainty in γ pdf are important at low E_T.
(these are forward jets)
⇒ same "problems" as in single jets.
Again multiple interactions can help [see earlier plot]

[see Rob Saunders' talk for latest ZEUS studies]

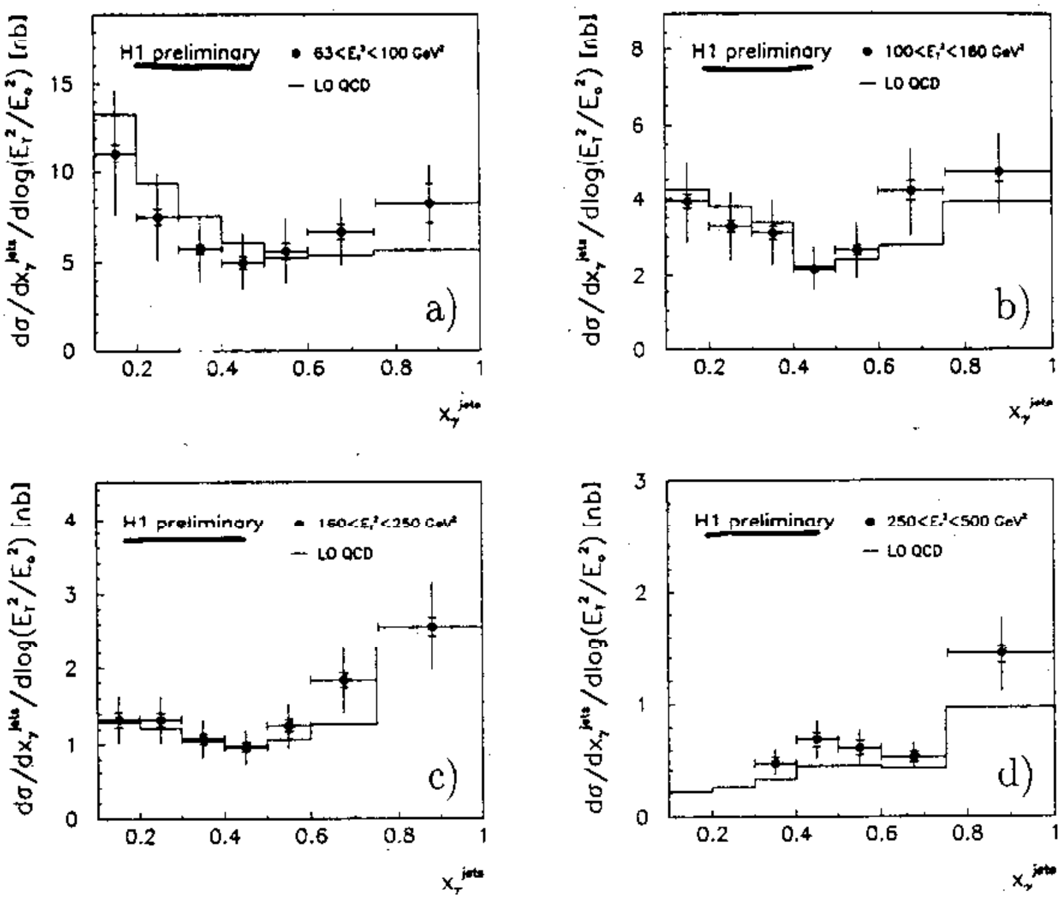


Figure 1: The measured differential di-jet ep cross section is shown as a function of the reconstructed parton fractional energy x_γ^{jets} in different bins of the jet transverse energy $63 < E_T^2 < 500\,\mathrm{GeV}^2$ (a-d, full circles, $E_o^2 = 1\,\mathrm{GeV}^2$). The cross section is integrated over the photon virtuality $Q^2 < 4\,\mathrm{GeV}^2$, the relative photon energy $0.2 < y < 0.83$ and the jet pseudo-rapidities in the HERA laboratory frame $-0.5 < \eta^{jet1,2} < 2.5$ and $\Delta\eta^{jets} < 1$. The data are compared to a LO QCD calculation of the PYTHIA generator with multiple interactions using the GRV-LO parton distribution functions for the proton and the photon (histogram).

Direct enriched

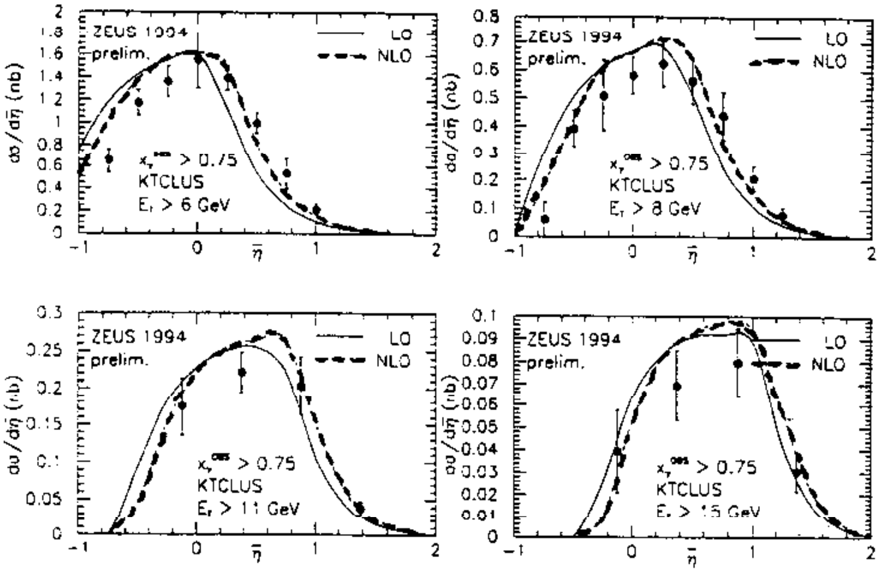


Figure 9: *Inclusive dijet cross section $d\sigma/d\bar{\eta}$ at $x_\gamma^{\rm OBS} > 0.75$ as a function of $\bar{\eta}$ and integrated over $\eta^* \in [-0.5, 0.5]$ and $E_T > 6,\ 8,\ 11,$ and 15 GeV. Our leading and next-to-leading order predictions are compared to preliminary 1994 data from ZEUS using the KTCLUS algorithm.*

Resolved enriched

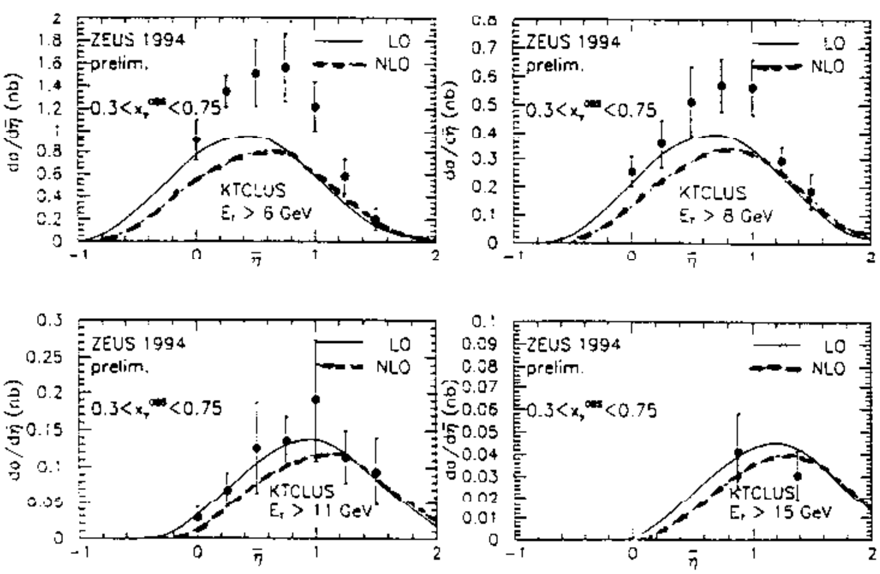
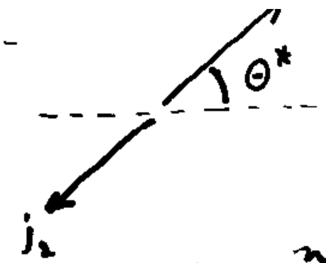
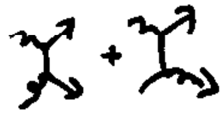
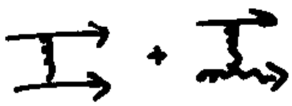


Figure 10: *Inclusive dijet cross section $d\sigma/d\bar{\eta}$ at $x_\gamma^{\rm OBS} \in [0.3, 0.75]$ as a function of $\bar{\eta}$ and integrated over $\eta^* \in [-0.5, 0.5]$ and $E_T > 6,\ 8,\ 11,$ and 15 GeV. Our leading and next-to-leading order predictions are compared to preliminary 1994 data from ZEUS using the KTCLUS algorithm.*



* Insensitive to pdfs
* Sensitive to spin & colour of hard subprocess

Direct  $\sim (1 - |\cos\theta^*|)^{-1}$

Resolved  $\sim (1 - |\cos\theta^*|)^{-2}$

ZEUS 1994

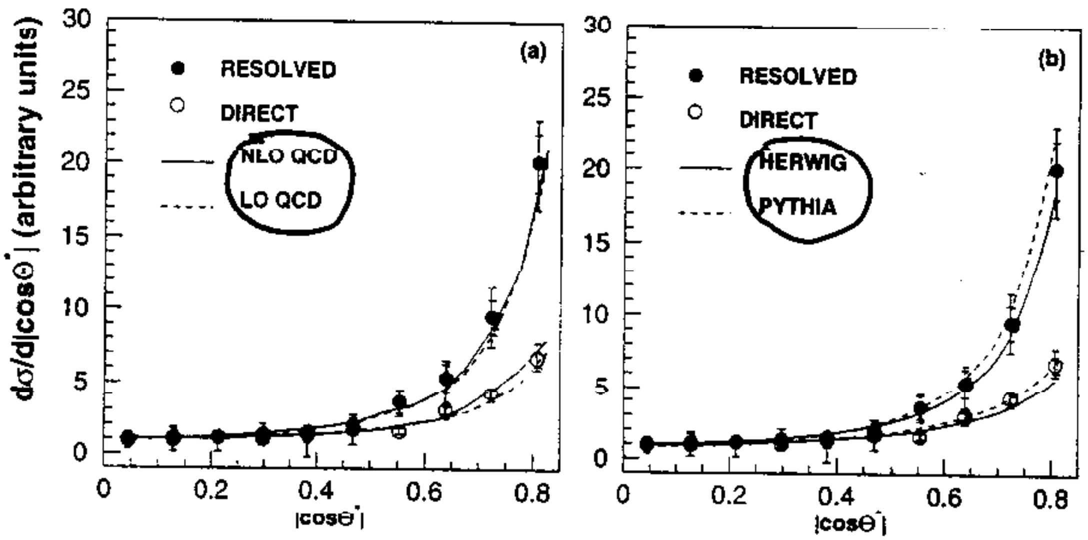
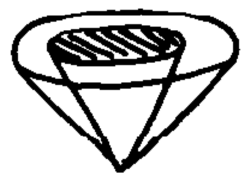


Figure 4: $d\sigma/d|\cos\theta^*|$ normalized to one at $\cos\theta^* = 0$ for resolved (black dots) and direct (open circles) photoproduction. In (a), the ZEUS data are compared to the NLO prediction (solid line) and the LO prediction (broken line). The parton distribution sets used in the calculation are CTEQ3M [26] for the proton and GRV (LO) [21] for the photon. In (b), the broken line is the PYTHIA distribution and solid line is HERWIG distribution. The inner error bars are the statistical errors, the outer error bars are the sum in quadrature of the statistical and systematic errors, excluding the energy scale and luminosity uncertainties (see Table 1).

NLO
[Owens]

JET SHAPES

"What is a jet?"



$\rho(r, R, E_T, \eta)$ = fraction of jet energy lying within a cone of radius r within a jet of radius R.

LO* Comparison with data [plots]

⇒ Can fit data with a variable R_{sep}

Iterative cone algorithm (eg PUCELL)

↳ Cells above threshold energy, E_0, define seeds; Draw cones around seeds & iterate.

Theory ⇒ no iterations needed for 3 parton final state

⇒ Combine "jets" if $R_{ij} < \text{Min}\left[\frac{(E_{T_i} + E_{T_j})R}{\max(E_{T_i}, E_{T_j})}, R_{sep}\right]$

⇒ $R_{sep} = R$ for PUCELL (3 parton final state)

(since seeds > R apart will never be combined)

[nb/ Merging prescription needed in data & for ≥ 4 parton final states - since final cones can overlap]

By treating R_{sep} as a variable, to be fitted to data, one is parameterizing higher order effects

↳ Power Corrections, Parton Shower, Hadronization } to learn more need to stud these issues directly.

$$* \; 1-\rho \sim \frac{O(\alpha_s^3)}{O(\alpha_s^2)}$$

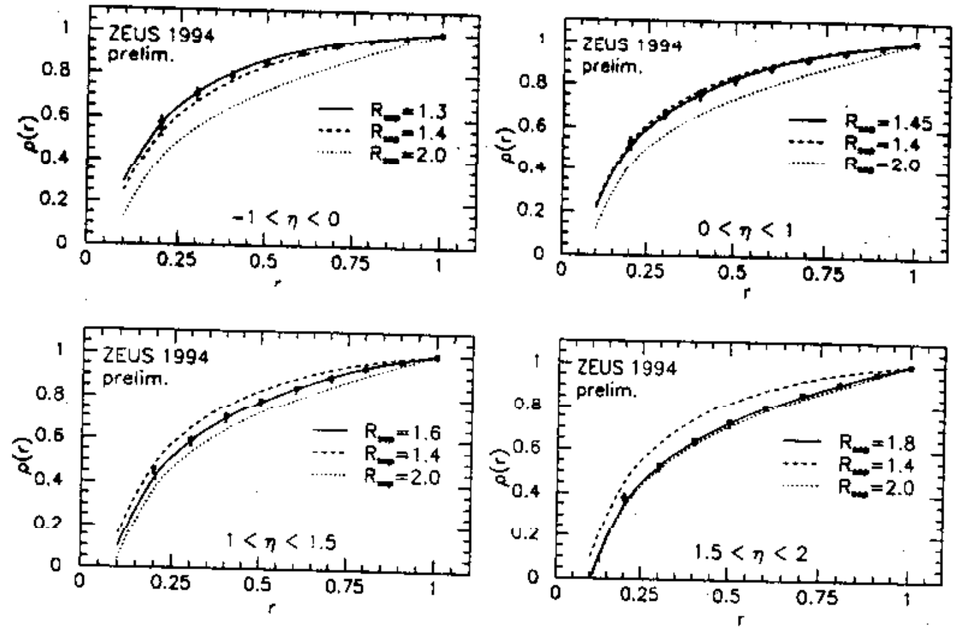
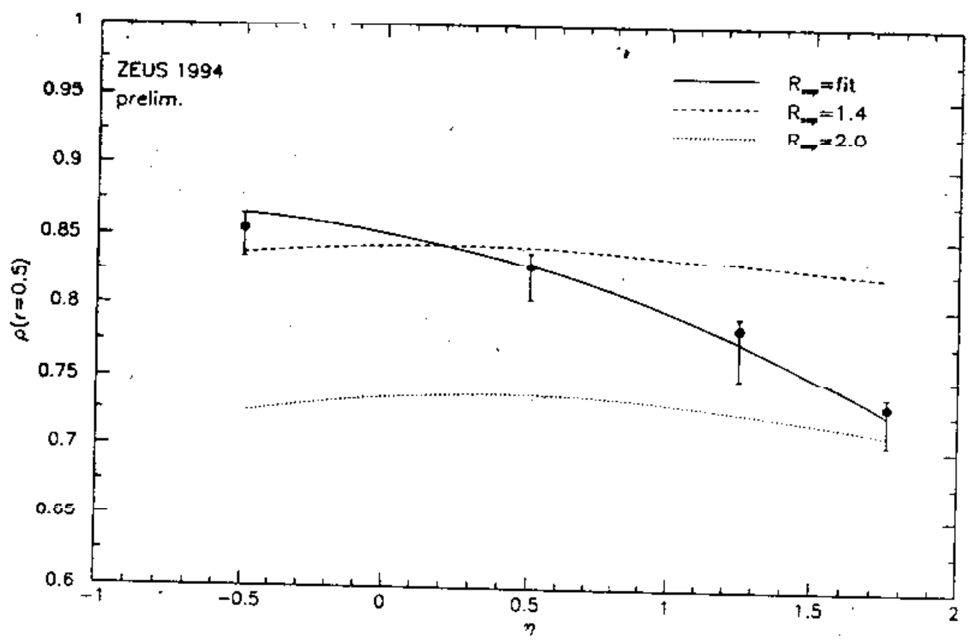


Figure 1: *Jet shape $\rho(r)$ for complete single-jet photoproduction integrated over $E_T > 14$ GeV and four different regions of η. We compare our results using the Snowmass convention with $R = 1$ and three different values of R_{sep} to preliminary 1994 data from ZEUS.*



broadening of forward jets

Figure 2: *Jet shape $\rho(\eta)$ for complete single-jet photoproduction for $r = 0.5$ and integrated over $E_T > 14$ GeV and the same regions of η as in the last figure. We compare our results with one variable and two fixed values of R_{sep} to preliminary 1994 data from ZEUS.*

[Klasen & Kramer]

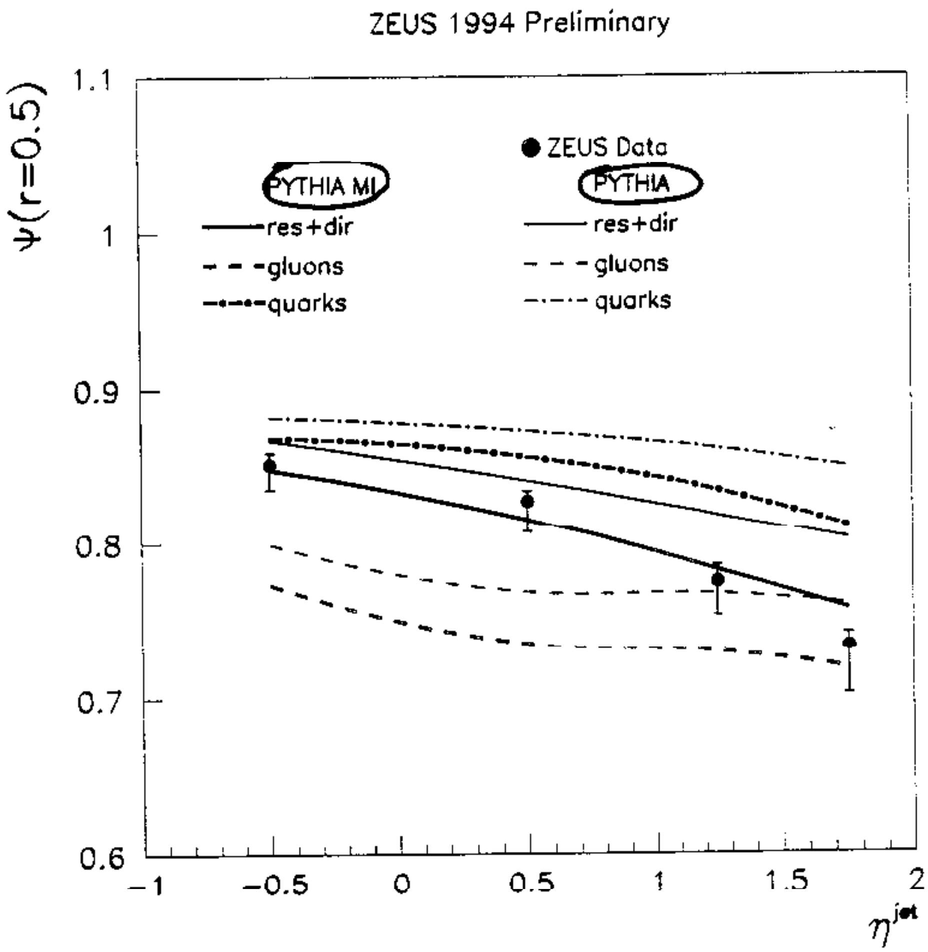
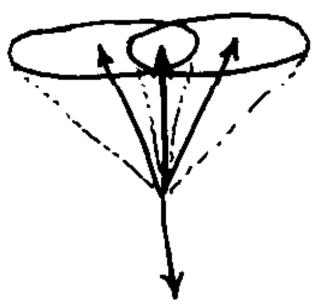


Figure 4: The measured jet shape at the fixed value of $r = 0.5$, $\psi(r = 0.5)$, as a function of η^{jet} for inclusive jet photoproduction in the kinematic region defined by $Q^2 \leq 4$ GeV^2 and $0.2 < y < 0.85$, and for jets in the E_T^{jet} range above 14 GeV. The error bars show the statistical and systematic errors added in quadrature. The statistical errors on the measurements are negligible and are *not* shown as separated error bars. For comparison, various predictions of PYTHIA including resolved plus direct processes are shown: quark jets (thin dot-dashed line), gluon jets (thin dashed line) and all jets (thin solid line). The predictions of PYTHIA MI for the same cases are displayed with thick lines.

NLO calculation needs 4 parton final state [Giele & Kilgore]

But algorithm is only IR safe at lowest order.



↑ denotes parton of threshold energy, E_0, emitted in overlap region.

⇓

Would now merge jets ie, 2 jet event

⇒ log E_0 dependence in jet shape. [Seymour]

Note - this is an acute problem in fixed order pert. theory but not after Sudakov resummation, eg, parton shower. ie, it doesn't show up in Monte Carlo.

Prob. of parton in overlap region, $P_{lo} \sim \alpha_s \log E_T/E_0$ (fixed order)

After summation, $P_{all} \sim 1 - e^{-P_{lo}}$
(as $E_0 \to 0$ a soft gluon is guaranteed to be in overlap region, $P_{all} \to 1$)

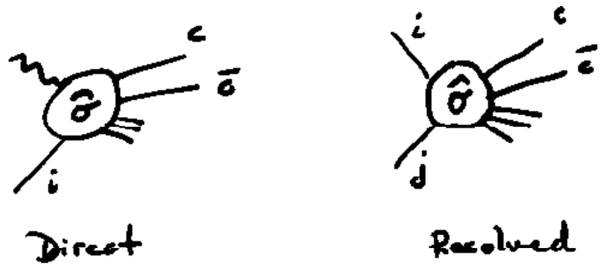
(Can fix this problem [S. Ellis] by treating mid-point between jets as a seed cell (regardless of any activity).)

$k_\perp$ algorithm avoids this problem ("subjets") [Seymour]

⇒ "Study of jet structure is only just beginning"

Open Charm

"Massive Charm"

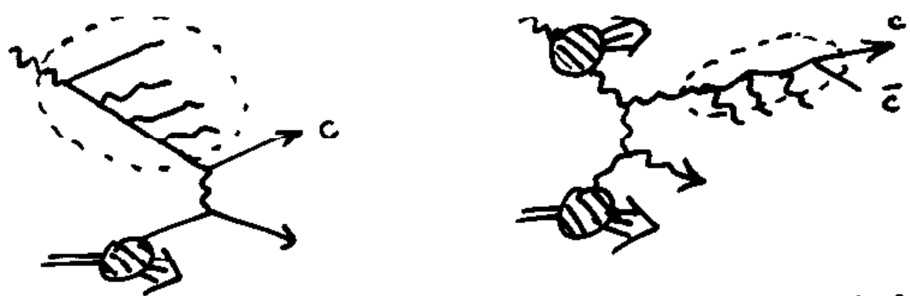


Charm only appears in $\hat{\sigma}$, $m_c^2 \gg \Lambda^2$ provides hard scale

ie, no notion of "intrinsic" charm.

But if $p_\perp^2 \gg m_c^2$ .....

eg



Not included (high order effects)

ie, large $\log p_\perp/m_c$ terms in $\hat{\sigma}$ are not summed

"Massless Charm"

$m_c = 0 \Rightarrow$ charm pdf's & frag. functions ($D_{i/c}(\mu, x)$)

$\Downarrow$

DGLAP evolution sums the $\ln p_\perp/m_c$ terms BUT misses $m_c/p_\perp$ effects.

PERTURBATIVELY calculable.

Peterson or $x^{\alpha}(1-x)^{\beta}$ fragmentation function (FF)

⇒ Well constrained by e^+e^- data

HERA data

$p_\perp \lesssim 10$ GeV (ie, relatively low $p_\perp$)

* Original suggestion that MASSIVE CHARM calculation was too low [plots]

More recently.... [Cacciari + Greco
Binnewies, Kniehl, Kramer, Spira]

* Massive charm can fit data - full NLO calculation with FF refitted to LEP data (massive ≈ massless
* Massless charm can fit data - large renorm/fact^{n} scale ambiguity ($p_\perp$ is small) [plots]

Challenge

Interplay of $\ln p_\perp^2/m_c^2$ & $m_c/p_\perp$ effects

↳ Study of "intrinsic" charm in γ from data at $p_\perp \gg m_c$

↳ Precise data needed to help unravel physics for $p_\perp \sim m_c$

⇒ Just started .... a lot to learn from increase in stat

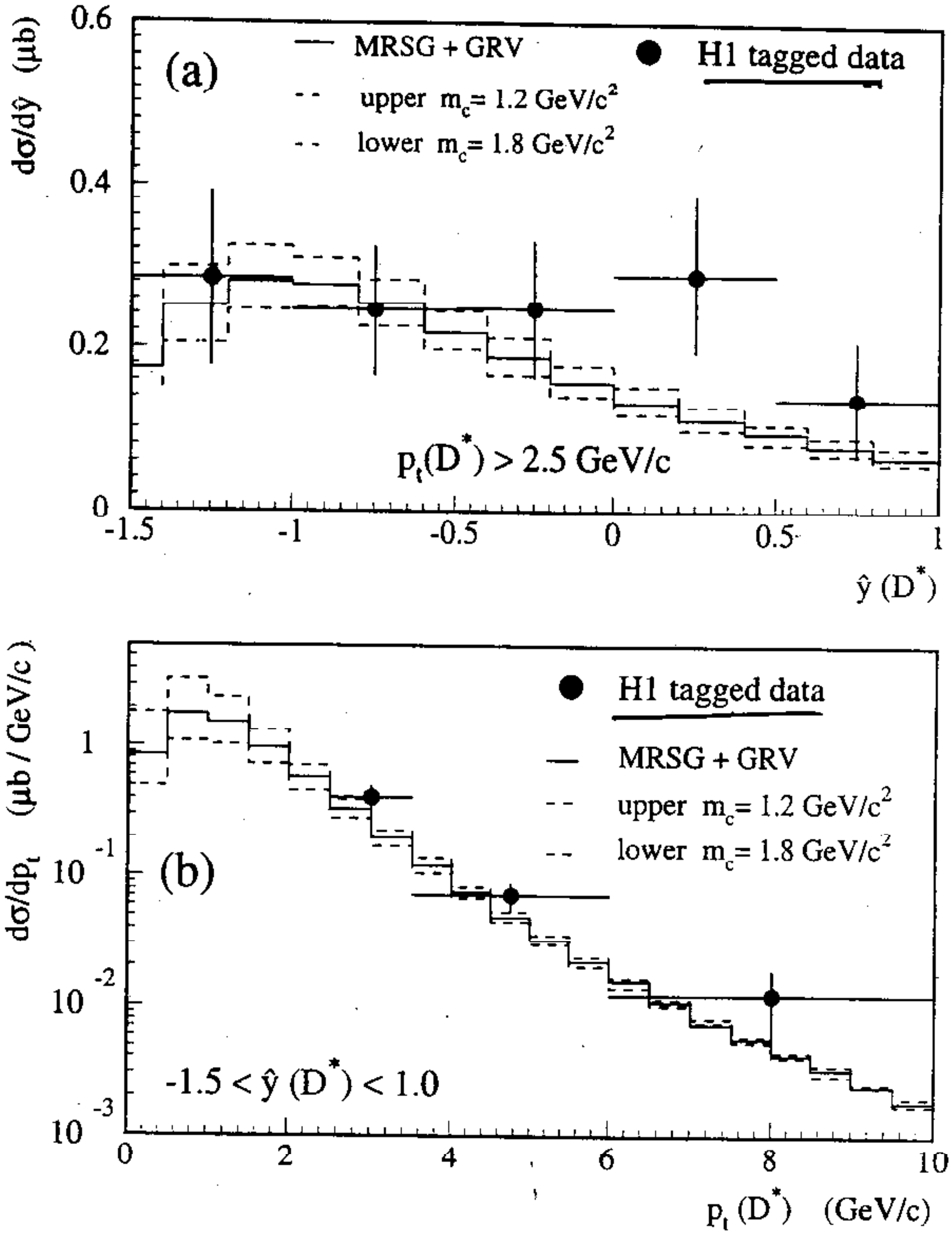
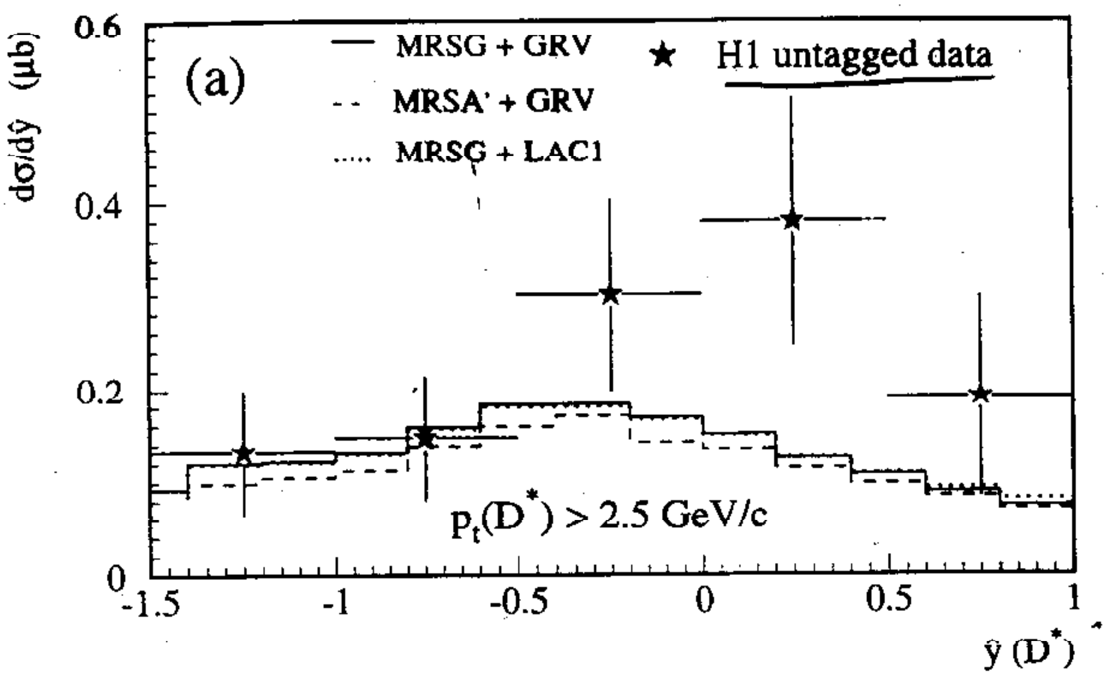


Figure 3: Differential cross sections for the tagged sample (solid dots). (a) $1/(2B_{c\to D^{*+}}) \cdot d\sigma(\gamma p \to D^{*\pm}X)/d\hat{y}$ for events with $p_t(D^*) > 2.5$ GeV/c and (b) $1/(2B_{c\to D^{*+}}) \cdot d\sigma(\gamma p \to D^{*\pm}X)/dp_t$ for events with $-1.5 < \hat{y}(D^*) < 1$. The solid histogram shows the NLO QCD prediction, using the MRSG proton parton density parametrization with a charm quark mass of 1.5 GeV/c^2. The upper (lower) dashed histogram indicates the effect of changing the charm quark mass to 1.2 (1.8) GeV/c^2. The histograms are averages of calculations done at three representative $W_{\gamma p}$ values, weighted by the photon flux integrated over the represented range. Common systematic errors of $\mathcal{O}(15\,\%)$ are not shown.



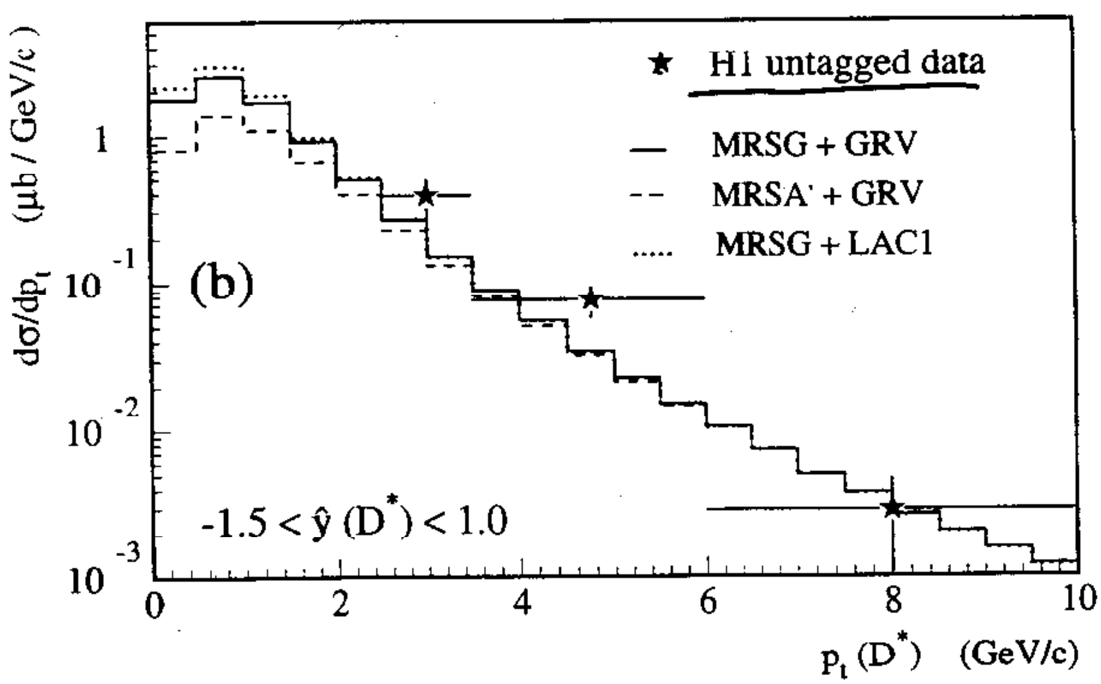


Figure 4: Differential cross sections for the untagged sample (solid stars). (a) $1/(2B_{c\to D^{*+}}) \cdot d\sigma(\gamma p \to D^{*\pm}X)/d\hat{y}$ for events with $p_t(D^*) > 2.5$ GeV/c and (b) $1/(2B_{c\to D^{*+}}) \cdot d\sigma(\gamma p \to D^{*\pm}X)/dp_t$ for events with $-1.5 < \hat{y}(D^*) < 1$. The histograms show NLO QCD predictions for various parton density parametrizations for the proton and the photon: MRSG + GRV-G HO (solid), MRSA' + GRV-G HO (dashed), and MRSG + LAC1 (dotted). A charm quark mass of 1.5 GeV/c^2 is used for the calculations. The histograms are averages of calculations done at three representative $W_{\gamma p}$ values, weighted by the photon flux integrated over the represented range. Common systematic errors of $\mathcal{O}(15\,\%)$ are not shown.

D* in Photoproduction (ZEUS 1994 Preliminary)

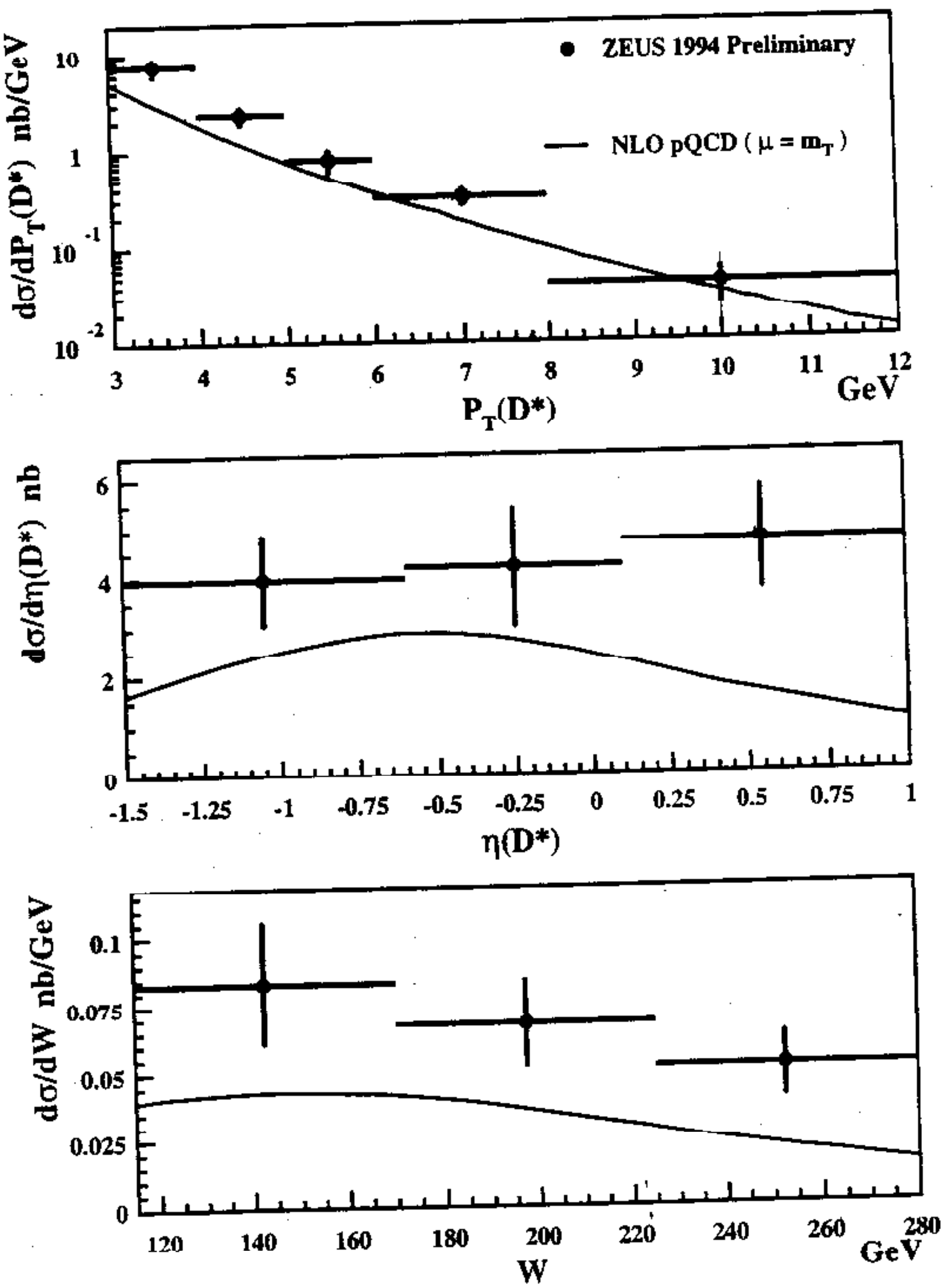


Figure 4: Differential cross sections of the reaction $ep \to D^{*\pm} + X$ as a function of $P_T(D^*)$, $\eta(D^*)$ and W in the kinematic range of this measurement. The solid curves are predictions of the NLO calculation described in the text.

MRSG (proton)
GRV-G HO (γ).
Peterson

H1 data

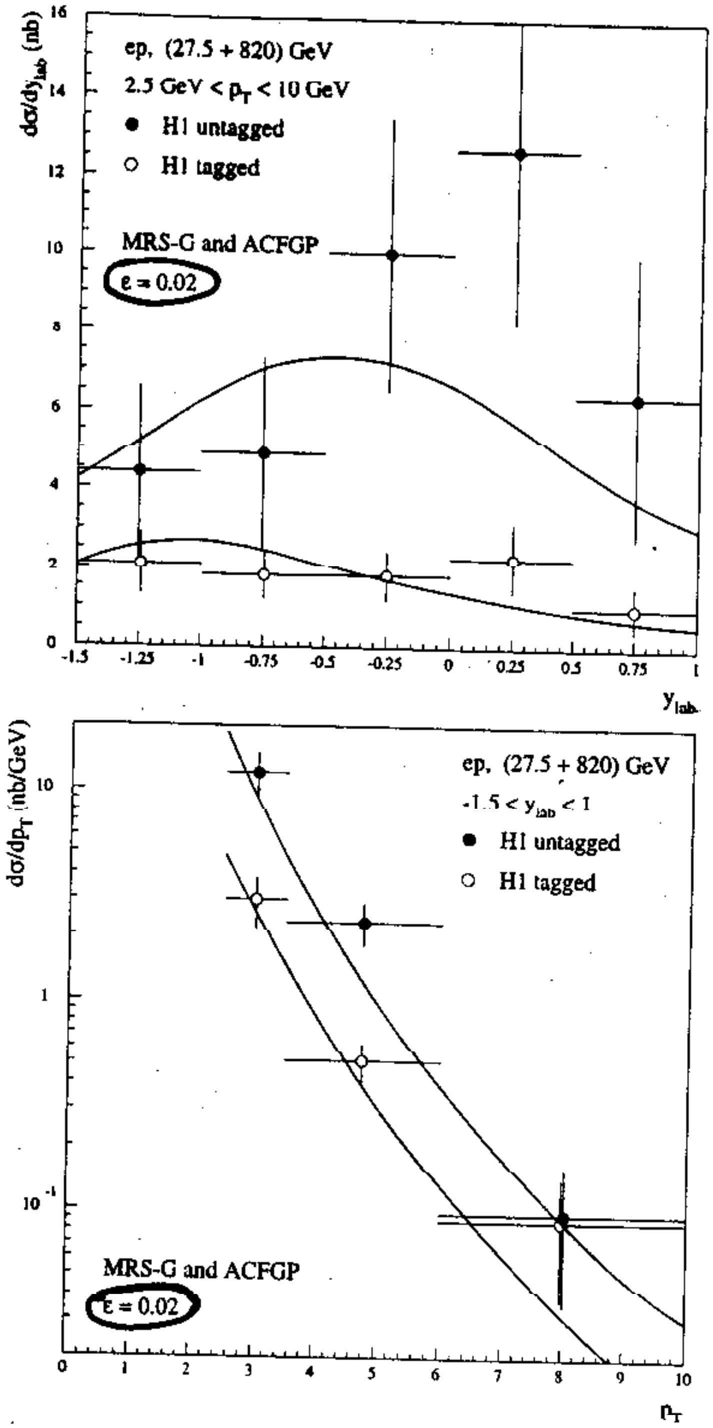


Figure 5: Comparison of our results with the experimental data from the H1 Collaboration, Ref. [27].

to-leading accuracy, and a non-perturbative one, which we fit to e^+e^- data taken by ARGUS and OPAL and subsequently use to predict photoproduction cross sections, to be compared ~~with data by H1 and ZEUS.~~

[Cacciari & Greco]

Zeus data

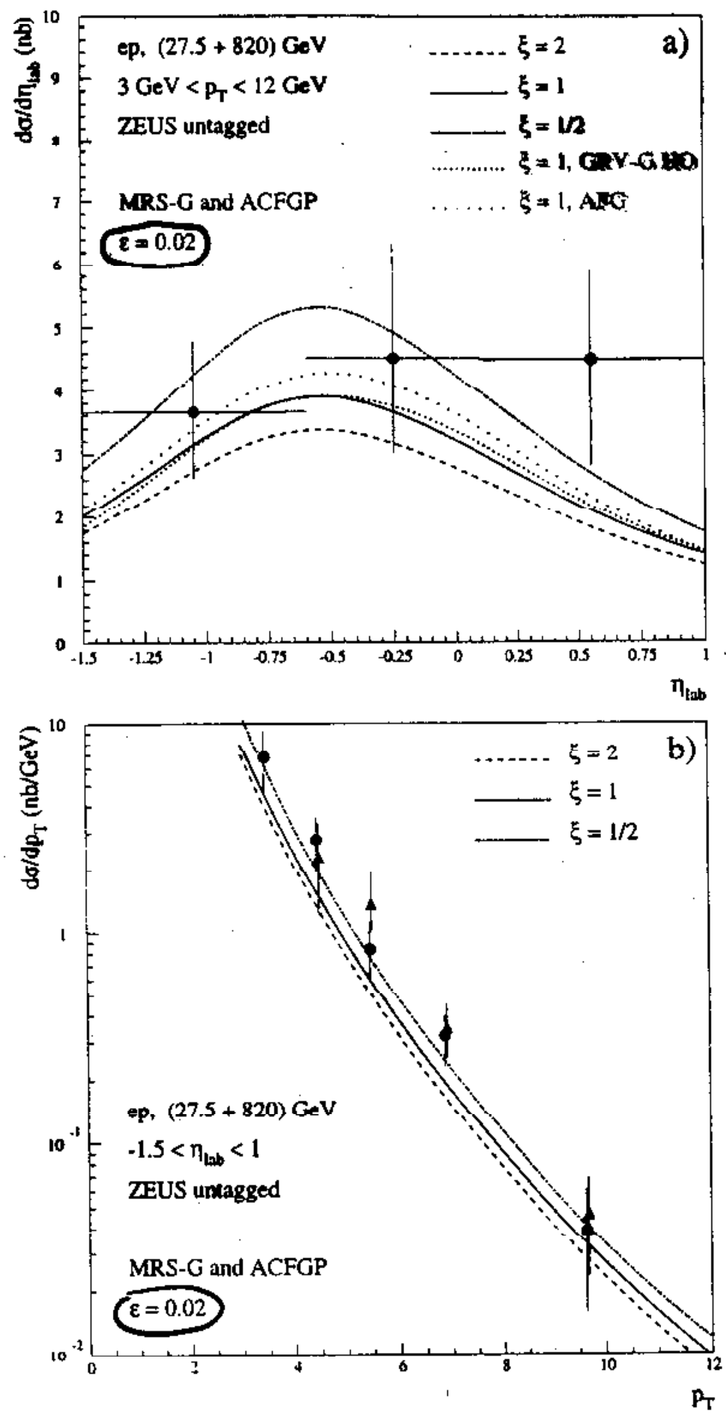


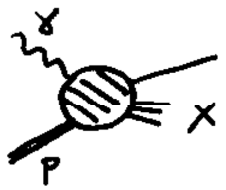
Figure 4: Comparison with pseudorapidity (a) and transverse momentum (b) experimental distributions from ZEUS [26], and effect of variation of renormalization and factorization scales, as $\mu = \xi m_T$, and of the photon pdf's sets.

[Cacciari & Greco]

Charmonium

Non Relativistic QCD (NRQCD) factorization (Bodwin, Braaten, Lepage)

$M_Q \gg \Lambda_{QCD}$



H is charmonium state.

$$d\sigma(H+X) = \sum_{n} d\hat{\sigma}(c\bar{c}[n]+X)\,\langle O_n^H \rangle$$

Inclusive cross-section

n denotes quantum #'s of H.

$d\hat{\sigma}(c\bar{c}[n]+X)$: Short distance cross-section (pQCD) ie, M_c is only relevant scale.

$\langle O_n^H \rangle$: Long distance physics (ie, $M_c v$, $M_c v^2$ $v \ll 1$)
(Prob. of a pointlike $c\bar{c}$ pair to form H inclusively)
(lattice, experiment)

$\Rightarrow$ $\boxed{\text{Systematic way of computing inclusive charmonium production (up to corrections} \sim (\Lambda/M_c)^m)}$

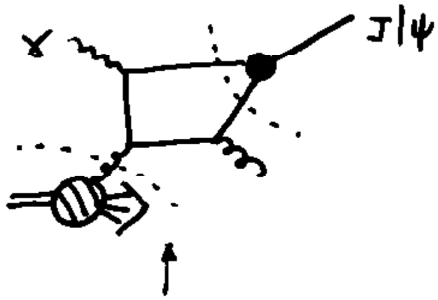
(1) Organise as an expansion in v
("velocity scaling" laws allow dominant operators to be identified)

(2) Expand $d\hat{\sigma}$ as a power series in $\alpha_s(M_c)$.

$$\left[\begin{array}{l} z = \dfrac{P_H \cdot P}{P_\gamma \cdot P} < 0.9 \quad \text{to suppress elastic / diffractive} \\ P_\perp^H > 1\ \text{GeV} \quad \text{to ensure factorization} \end{array}\right]$$

eg/ $\underline{\underline{LO(v)}}$ $\quad [n] = [\underset{\substack{\uparrow \\ \text{Colour singlet}}}{\underline{1}}, \underset{\substack{\uparrow \\ {}^{2S+1}L_J}}{{}^3S_1}]$ $\quad$ for J/ψ

ie/ $LO(v)$ = Colour Singlet Model



$$\langle O^{J/\psi}[\underline{1}, {}^3S_1] \rangle \sim |\phi(0)|^2$$

(eg/ from Γ_{ee}^{ψ})

$LO(\alpha_s)$ matrix element

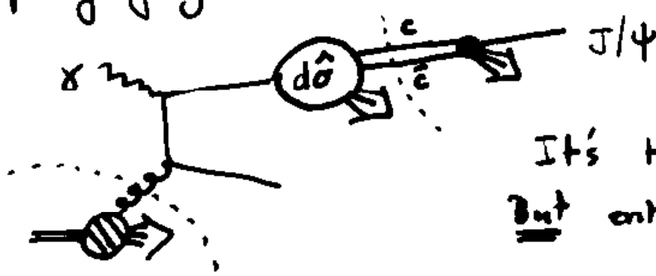
$NLO(\alpha_s)$ calculations done $\quad$ (Zunft, Steegborn, Zerwas, M. Krämer)

& are large [plot]

↳ and reduce sensitivity to gluon density of the proton

(*) A further subtlety at large $p_\perp^{\psi}$ – "Fragmentation"

An example of fragmentation :



It's Higher Order in α_s

But enhanced by $\sim p_\perp^2 / m_c^2$

(not important in total rate)

(*) Also... for small z ⇒ Resolved γ contribution must be considered.

[Godbole, Roy, Sridhar ; Kniehl, Kramer, G]

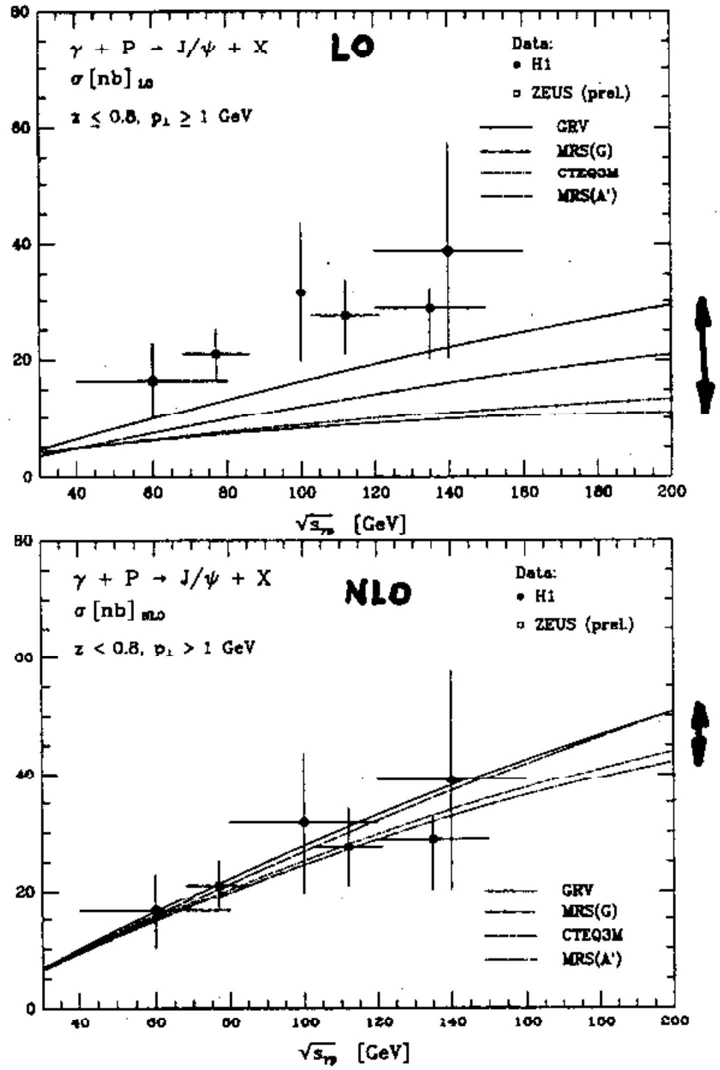
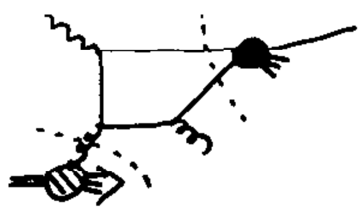


Fig. 3. LO and NLO color-singlet prediction for the total inelastic J/ψ photoproduction cross section as a function of the photon-proton energy for different parametrizations of the parton distribution in the proton compared to experimental data from H1 and Zeus.

(Cacciari + Krämer)

NLO(v) Colour Octet contributions

(for $z < 0.9$ $p_\perp > 1$ GeV)



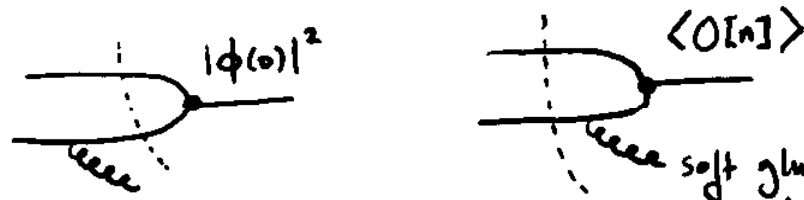
$[n] = [\underline{8}, {}^1S_0]$

$= [\underline{8}, {}^3S_1]$

$= [\underline{8}, {}^3P_{0,1,2}]$

$$\langle O^{J/\psi}[n] \rangle \sim \underline{\underline{v^4}} \cdot \langle O^{J/\psi}[\underline{1}, {}^3S_1] \rangle$$

cf



Singlet   Octet   soft gluon absorbed (factorized) into NRQCD matrix element.

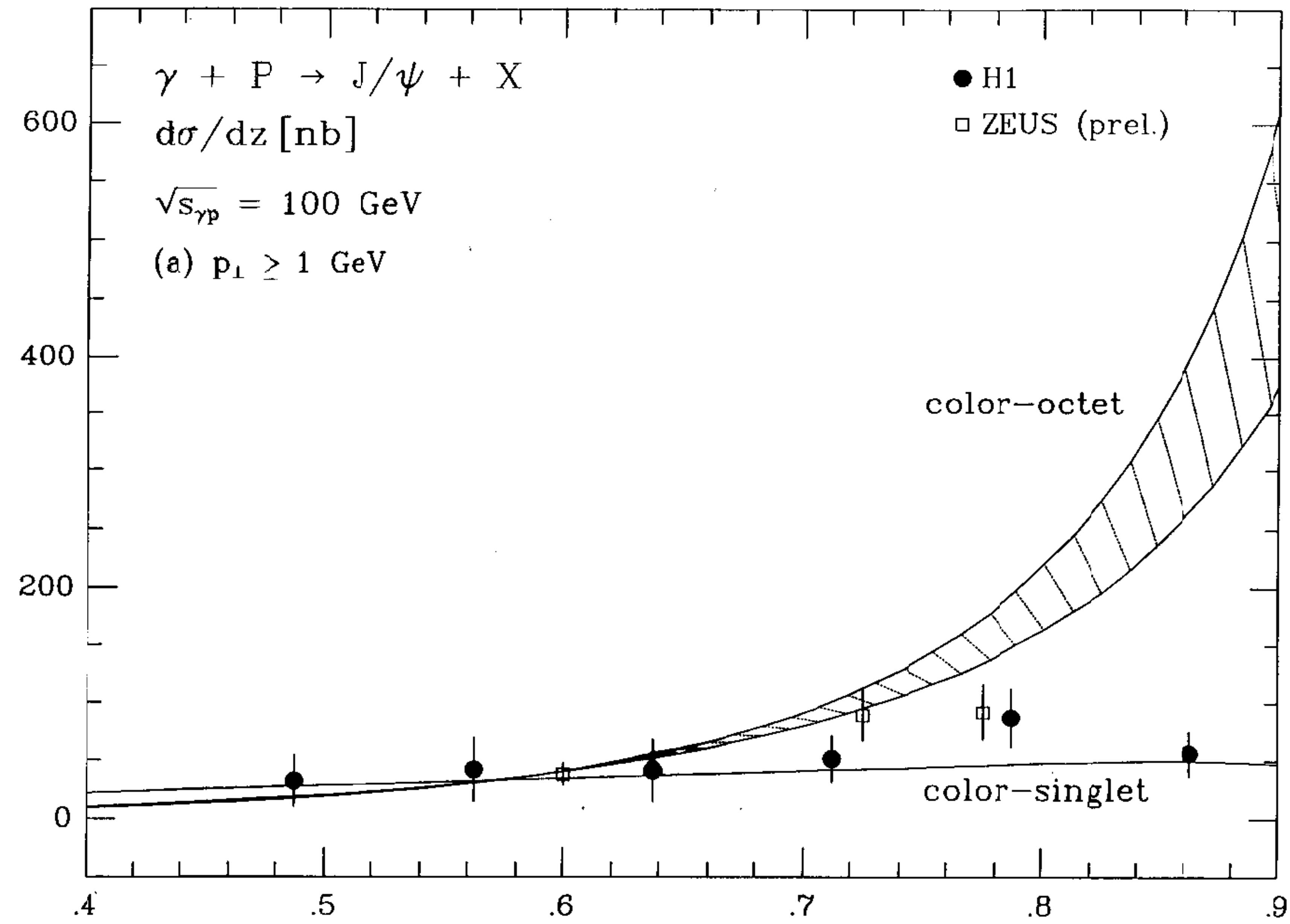
$[\underline{8}, {}^1S_0]$ and $[\underline{8}, {}^3P_{0,2}]$ channels STRONGLY ENHANCED relative to singlet channel $\Rightarrow$ Compensates $\sim v^4$ suppression.

TEVATRON data can be explained by fragmentation & colour octet extensions to CSM.

Use Tevatron to "fix" $\langle O \rangle$'s for HERA ($\approx 10^{-2}$ GeV^3)

$d\sigma/dz$ distribution is sensitive to OCTET Contributions

[plot]



$\frac{\langle O^{J/\psi}[\underline{8}, {}^3P_0] \rangle}{m_c^2}$ in range $[-0.01, 0.01]$ GeV^3 (Hatched region)

(M. Krämer)

Octet contributions not supported by HERA data

But Tevatron sensitive to $[{}^3S_1, \underline{8}]$

ie, $[{}^1S_0, \underline{8}]$ & $[{}^3P_0, \underline{8}]$ constrained weakly

HERA has the potential to test NRQCD in much more detail....

$$\left.\begin{array}{l} \circledast \text{ fragmentation} \\ \circledast \ \psi', \chi, \Upsilon, \underbrace{J/\psi + \gamma}_{[{}^3S_1, \underline{8}]}, \ldots\ldots \end{array}\right\} \text{luminosity}$$

Duality approach....

$$\sigma_{onium} = \frac{1}{9} \int_{2m_c}^{2m_D} dm \, \frac{d\sigma^{c\bar{c}}}{dm}$$

$$\sigma_\psi \propto \sigma_{onium}.$$

(Fritzsch, Halzen, ...)

$\Rightarrow$ Polarization studies.

For the Future ....

* What is going on with the forward jets ?
  Understanding needed before extraction of gluon in γ is possible.

* Jet structure studies just beginning .....

* Open charm ..... microvertex detectors $\Rightarrow$ high stats
  eg charm in dijets (x_γ cut)

* Inelastic quarkonium (heavy)
  Huge benefit from increase in statistics
  $\Rightarrow$ Possibility to really test NRQCD.

* Also .... virtual γ structure function
  Prompt γ production
  Data just accumulating.