Particle Production at ZEUS

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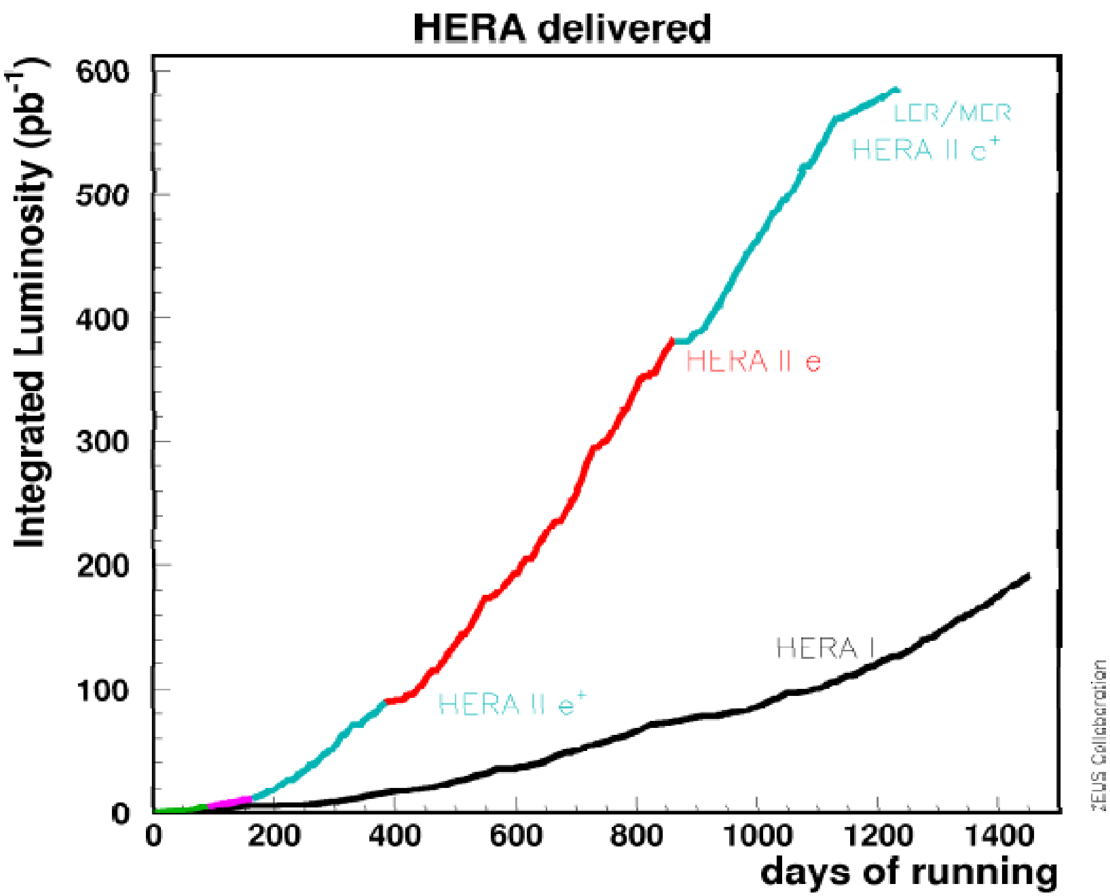
Charged Multiplicities and scaled momenta in Breit frame
Strange Particle production: K^0_s, Λ, Λ-bar
Antideuteron and antiproton production
Charm fragmentation and F_2^{cc}
Excited charm and charm-strange mesons
Baryons decaying to strange particles
KK Bose Einstein correlations, $f^0(980)$

HERA: $e^{\pm}_{L,R}p$ collisions at 300-320 GeV



ZEUS 0.50 fb^{-1}

HERAI:

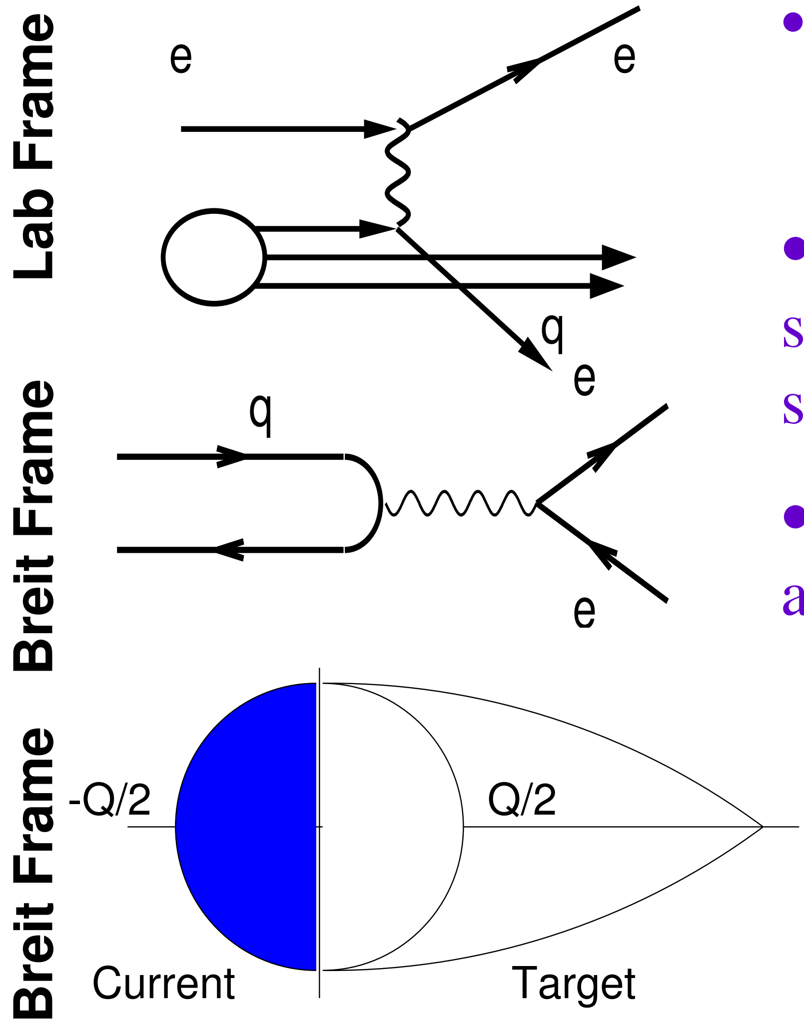
e^+p	115 pb^{-1}
e^-p	17 pb-1

HERAII (polarised $e^{\pm}$):

e^+p	182 pb^{-1}
e^-p	190 pb^{-1}

DIS particle multiplicities: use of Breit frame

DIS event



- Breit Frame definition:

- “Brick wall frame” incoming quark scatters off photon and returns along same axis.

- Current region of Breit Frame is analogous to e^+e^-.

Breit frame current jet multiplicity v Q^2

- Consistent with e^+e^- for high Q^2
- Disagreement at low Q^2 may be attributed to gluon radiation
- Idea of current analysis: Understand current and target multiplicity and compare to e^+e^-

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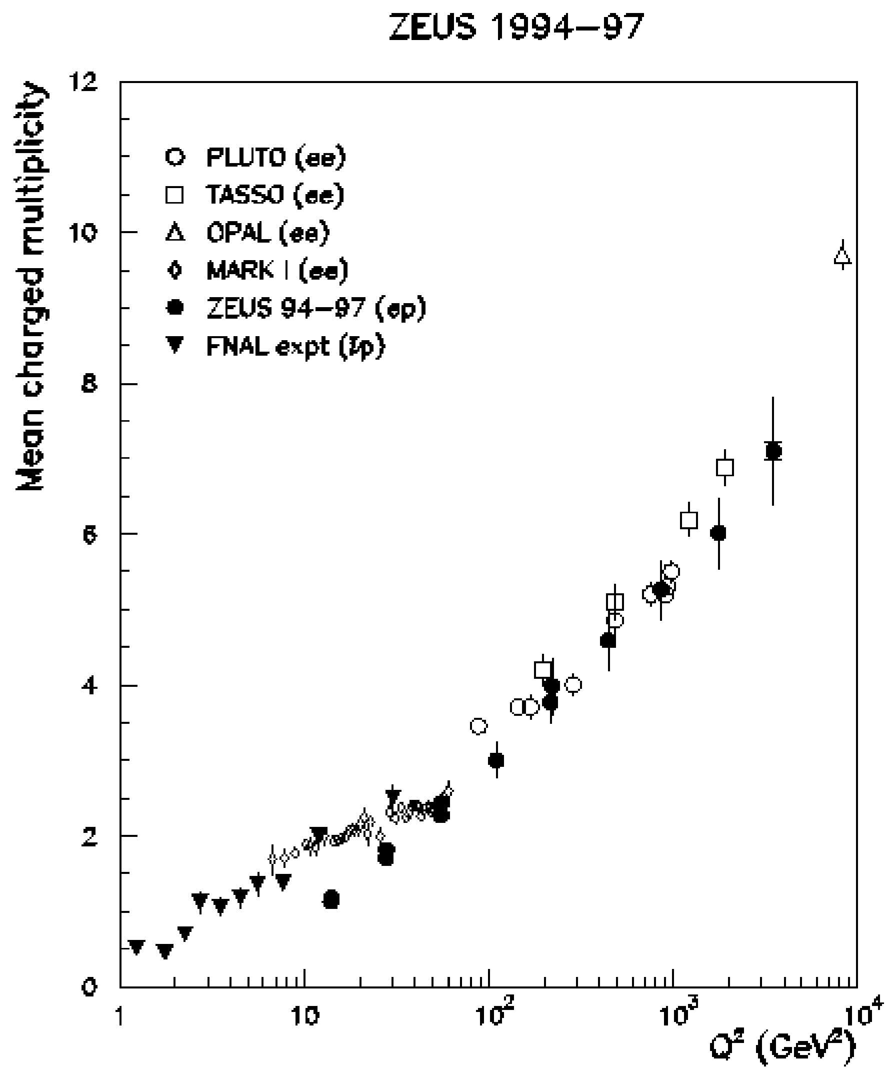
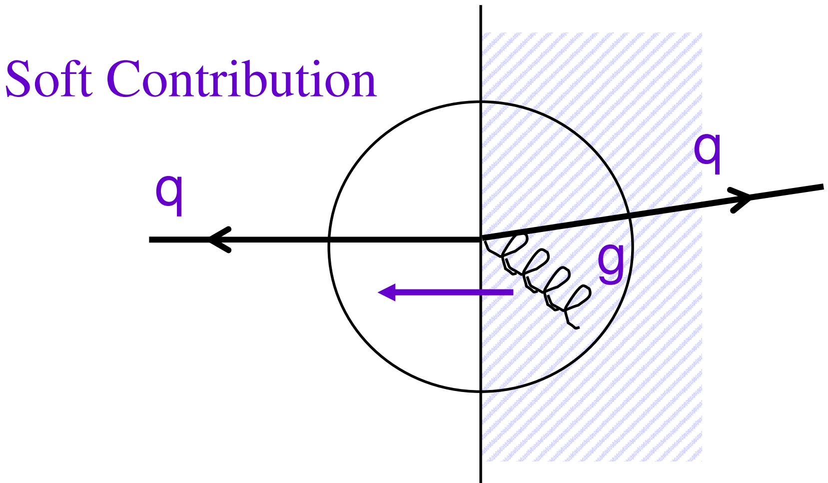
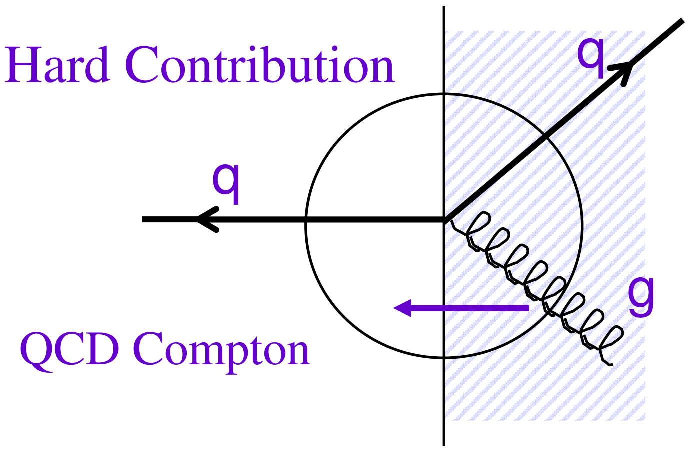


Gluon radiation, Q and E_{Breit}





- In hard and soft processes gluon radiation occurs
- These gluons can migrate to target region
- Total energy in the current region of Breit frame and multiplicity are decreased due to these migrations (Q^2 is not)
- Effect is more pronounced for low Q^2 : more low energy gluons
- Must use $2{*}E_{\mathrm{Breit}}$ and $2{*}N_{\mathrm{ch}}$ for comparing with e^+e^-

No migrations: $E_{Breit} = \frac{\sqrt{Q^2}}{2}$

With migrations: $N < N_{expected}$

$E_{Breit} < \frac{\sqrt{Q^2}}{2}$

$<n_{ch}>$ vs. $2^*E_{current}$

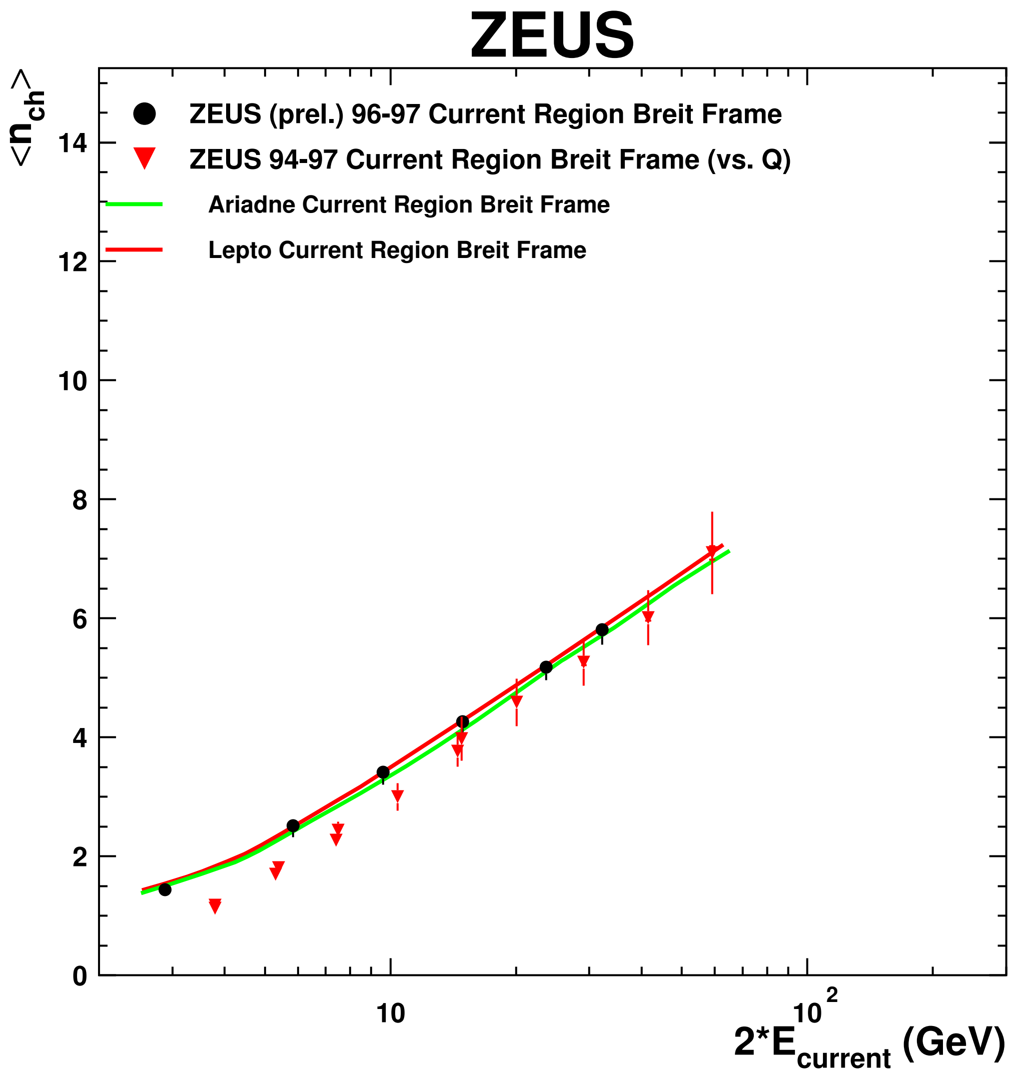
- Measurement of multiplicity dependence on $2^*E_{current}$ compared to previous ZEUS measurement vs. Q

- 2^*E gives better description of multiplicity at lower energy

- This approximation of invariant mass partially takes into account the real distribution of the particles.

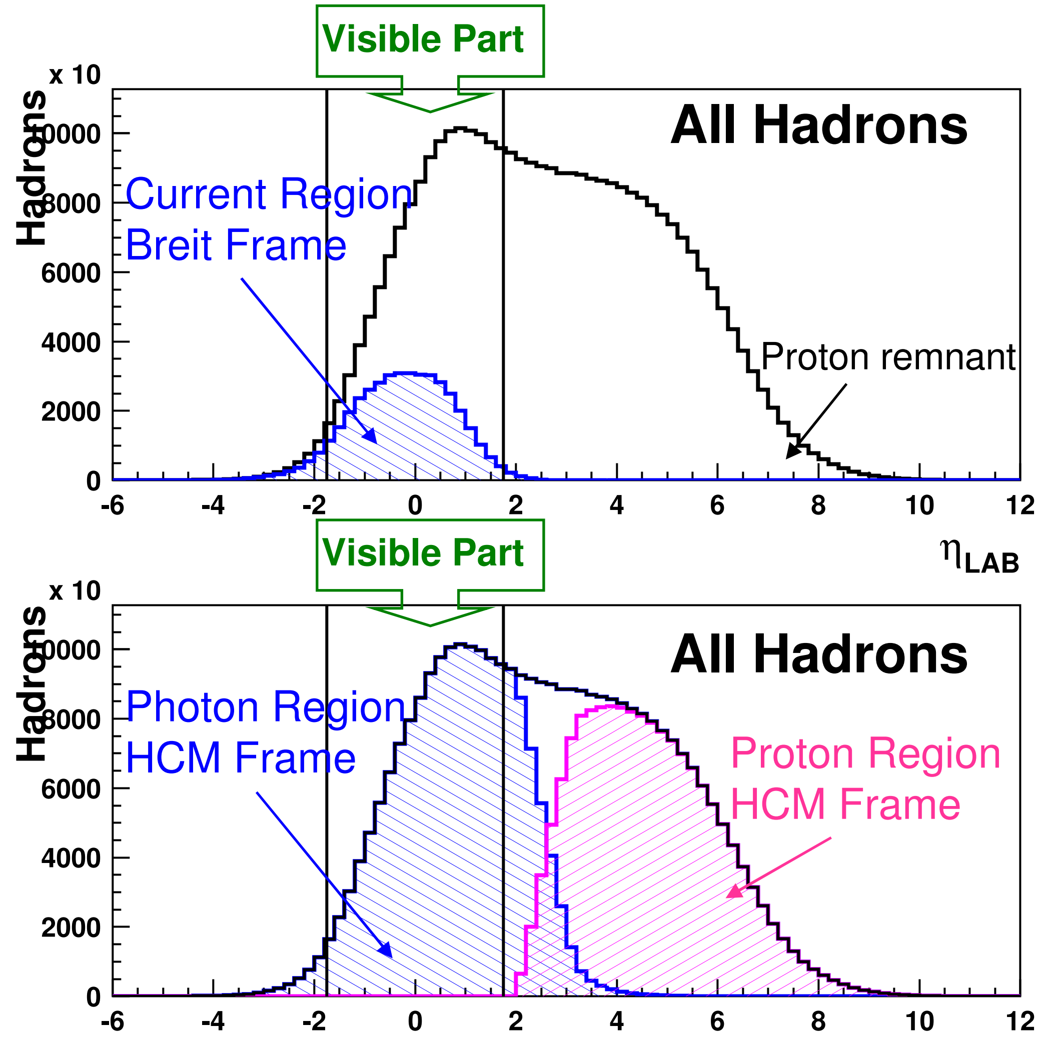
- Lepto prediction slightly above Ariadne

- Current region understood, would like to use some energy scale to compare target region for *ep* to e^+e^- ..



Visible multiplicity in Breit and hadronic centre of mass (HCM) frames

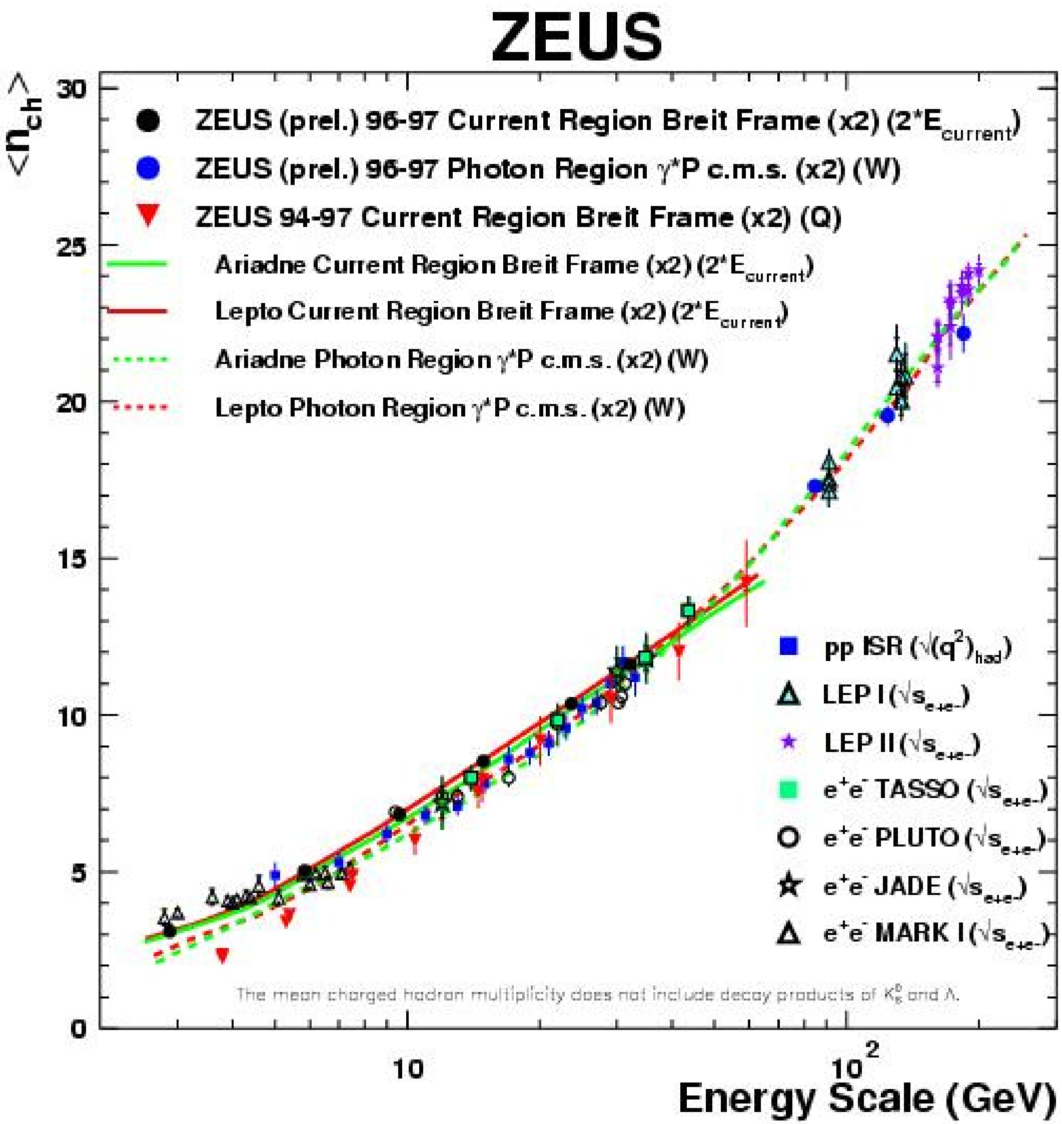
- **HCM Frame:** We see a bigger number of particle in the detector than in the current region of the Breit frame
- Photon region dominated by contribution from target region of Breit frame (~80% of visible hadrons)
- Proton region unseen in detector



$\langle n_{ch} \rangle$: *ep* (Breit, $\gamma^* p$ c.m.s.) v e^+e^-

excludes K^0, Λ decay products

2*$\langle n_{ch} \rangle$ for *ep*



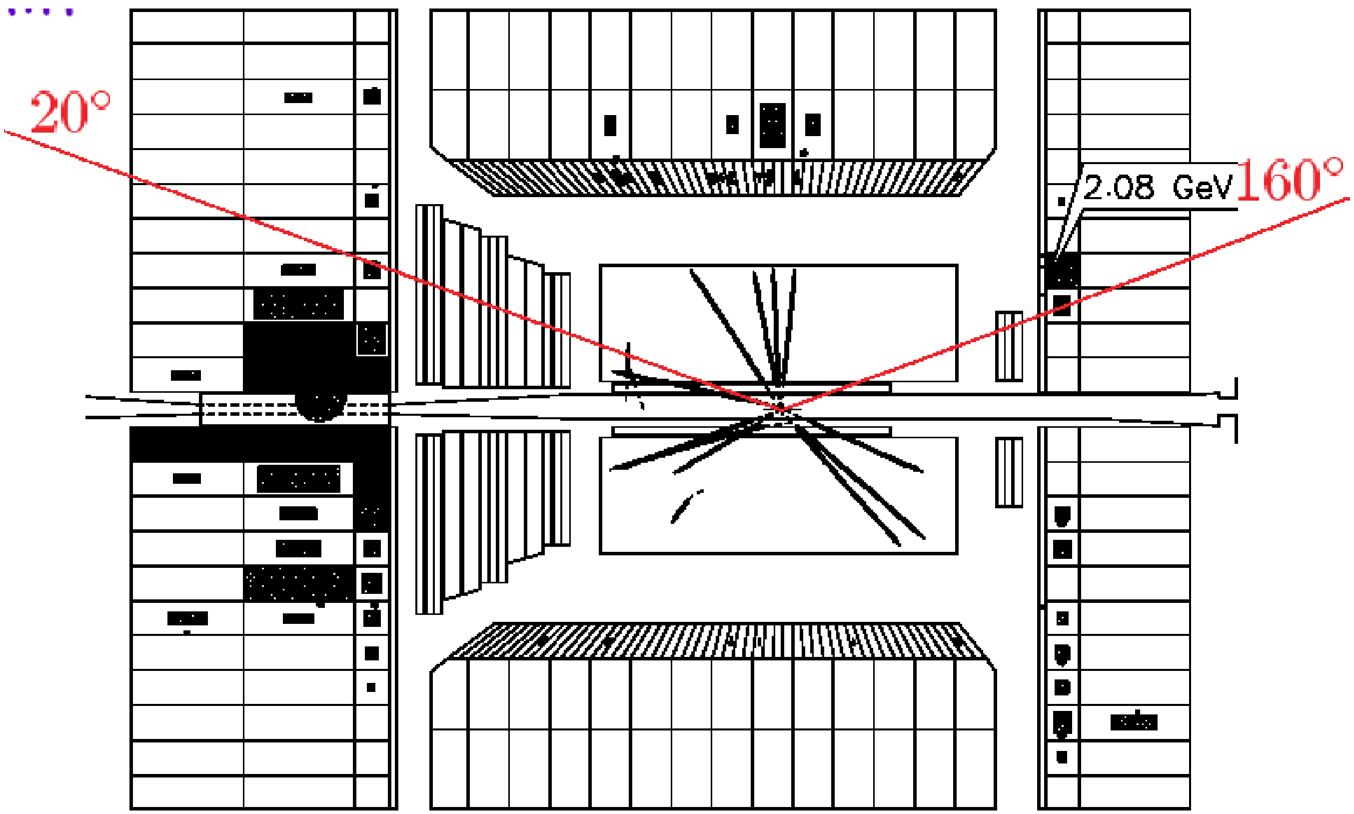
Breit frame:

Closer to e^+e^- if 2*E_{current} used as scale – black dots

$\gamma^* p$ c.m.s. current region:

close to e^+e^- over wide range using *W* as scale – blue dots

ZEUS: M_{eff} using best part of central tracker



Exclude scattered electron

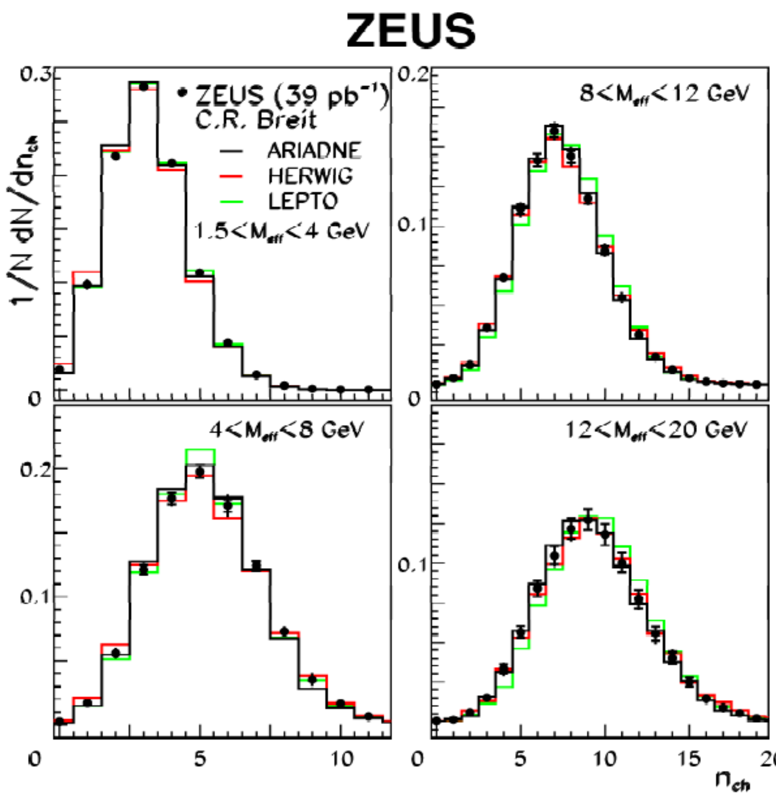
Use best angular range for counting tracks

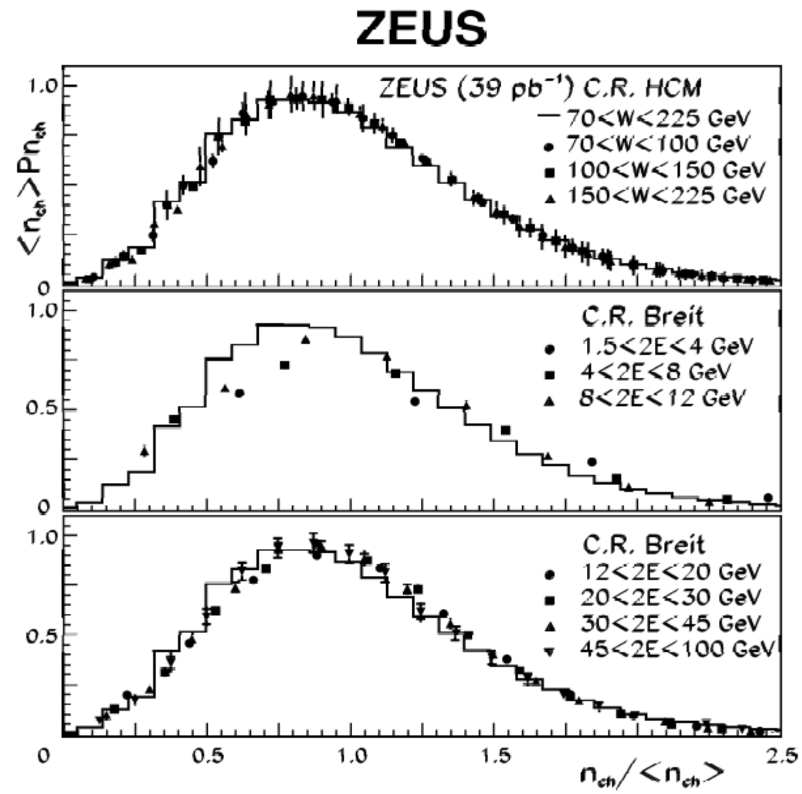
Use same angular range in calorimeter for

$M^2_{eff} = (\Sigma E)^2 - (\Sigma \boldsymbol{p})^2$

↑ vector

Current region Multiplicity Distributions





Breit frame in bins of M_{eff}

KNO scaling: HCM in W bins,

Breit in $E_{current}$ bins

Scaled momentum spectra in the current region of the Breit frame

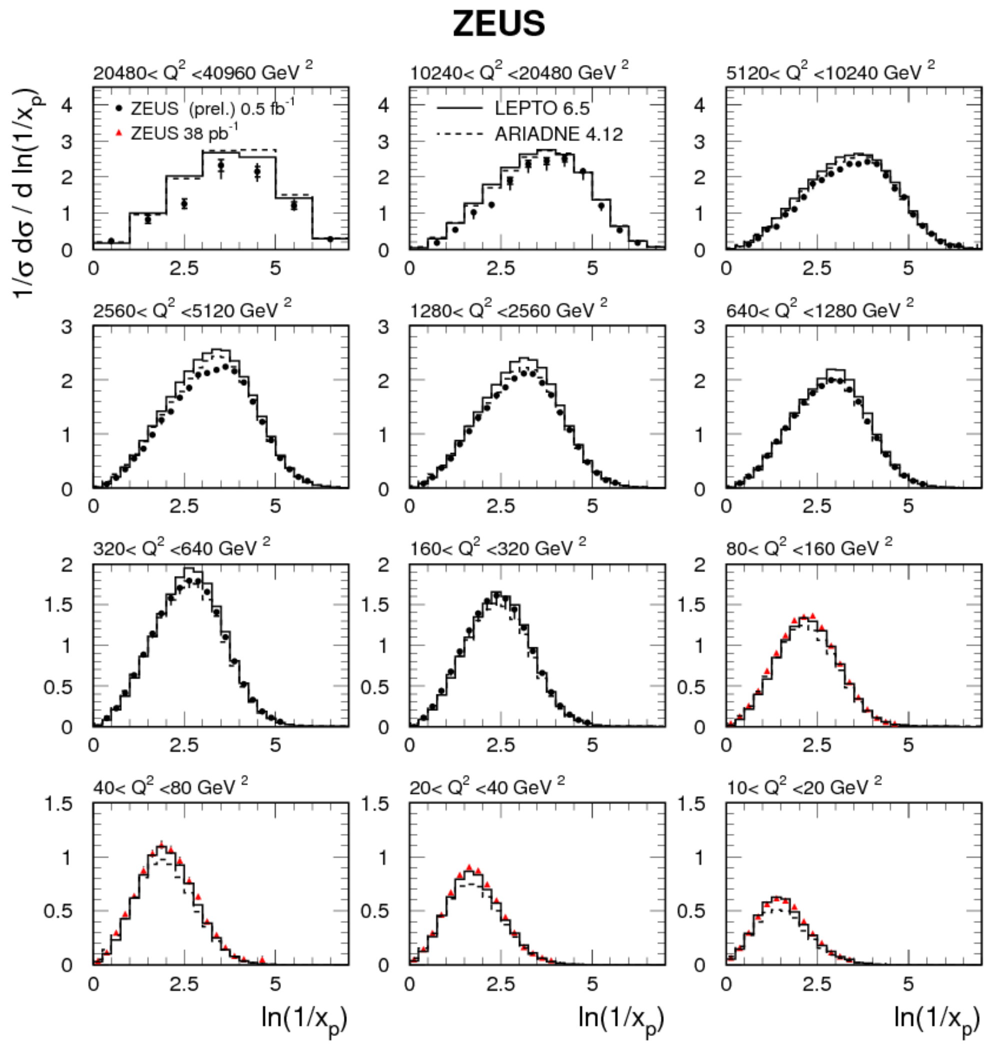
Complete Hera data 0.5fb^{-1}
160 < Q^2 <41000, 0.002<x<0.75
+ earlier data 10<Q^2<160 GeV^2

Tracks: p_T **> 150 MeV/c |η|<1.75**
Histogram $x_p = 2p(\text{Breit})/Q$
Current region only

excludes K^0, Λ decay products

Monte Carlos: reasonable fit.
Fail normalisation at highest Q^2

Depletion at low x_p (high ln(1/x_p))
due to destructive interference of
soft gluons



Comparison to MLLA predictions

MLLA+LPHD (Khoze&Ochs, Dokshitzer, Khoze, Mueller&Troyan) tuned to LEP data (different *b*-fraction):

$Q_0 = \Lambda_{\mathrm{eff}} = 270$ MeV, K_h=1.31

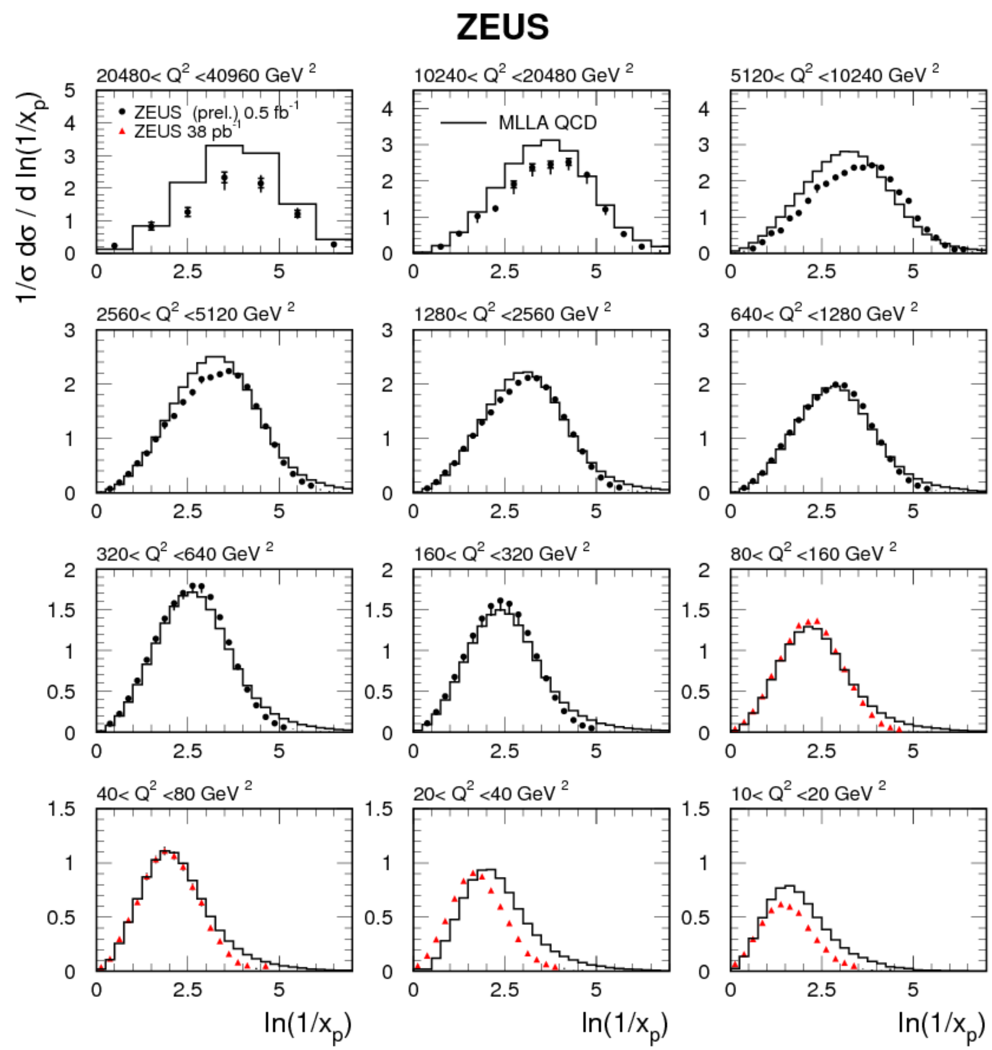
$m_{\mathrm{eff}}(\mathrm{hadron}) = Q_0$

K_h = LPHD factor

Predictions reasonable except for:

1) too-long tail at high $\ln(1/x_p)$ and low Q^2

2) At high Q^2 peak, shifted too much to left in $\ln(1/x_p)$



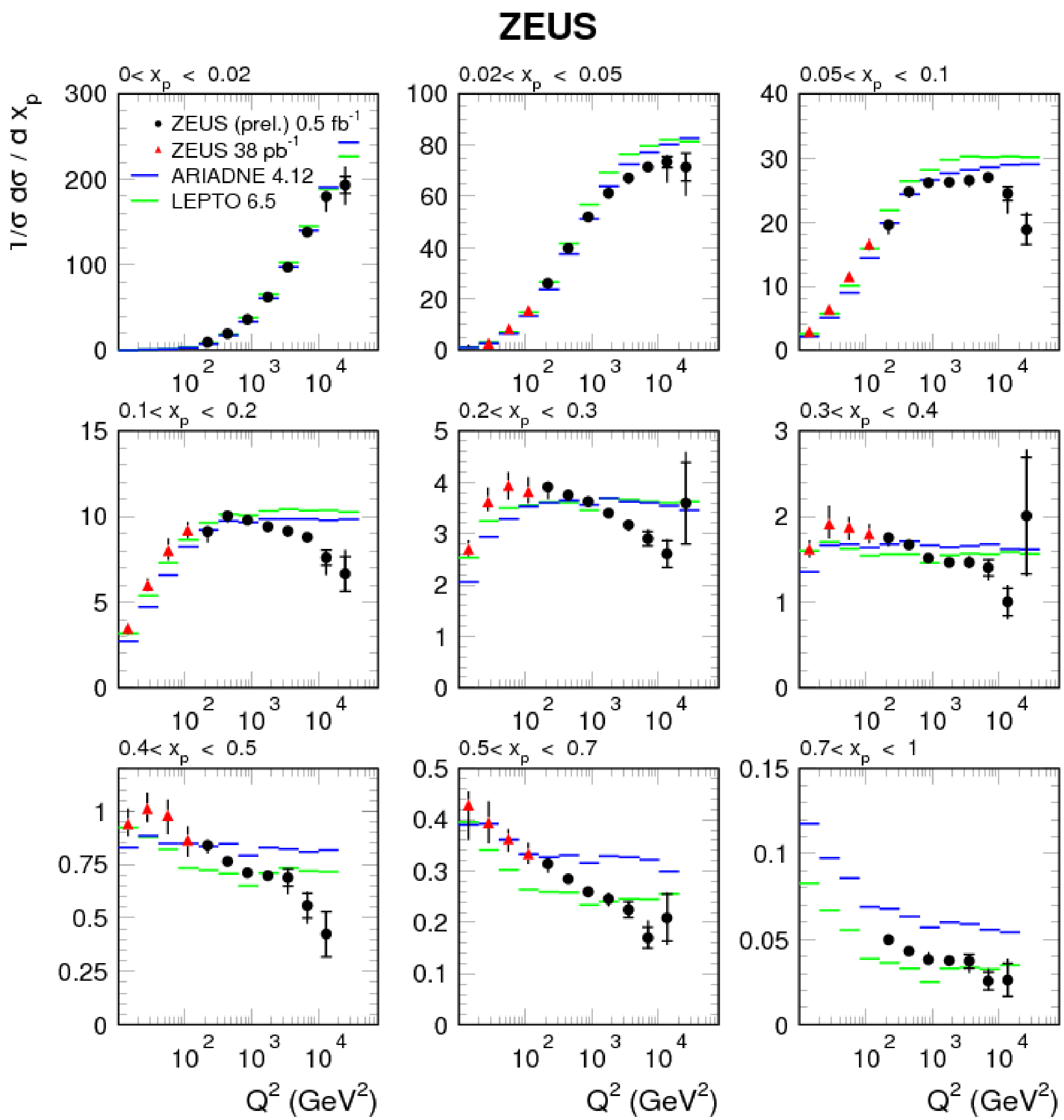
Scaling violation in fragmentation

$x_p = 2p(\text{Breit})/Q$

As expected, $1/\sigma\, d\sigma/dx_p$ rises with Q^2 at low x_p & falls with Q^2 at high x_p

Low x_p behaviour well-described by MC

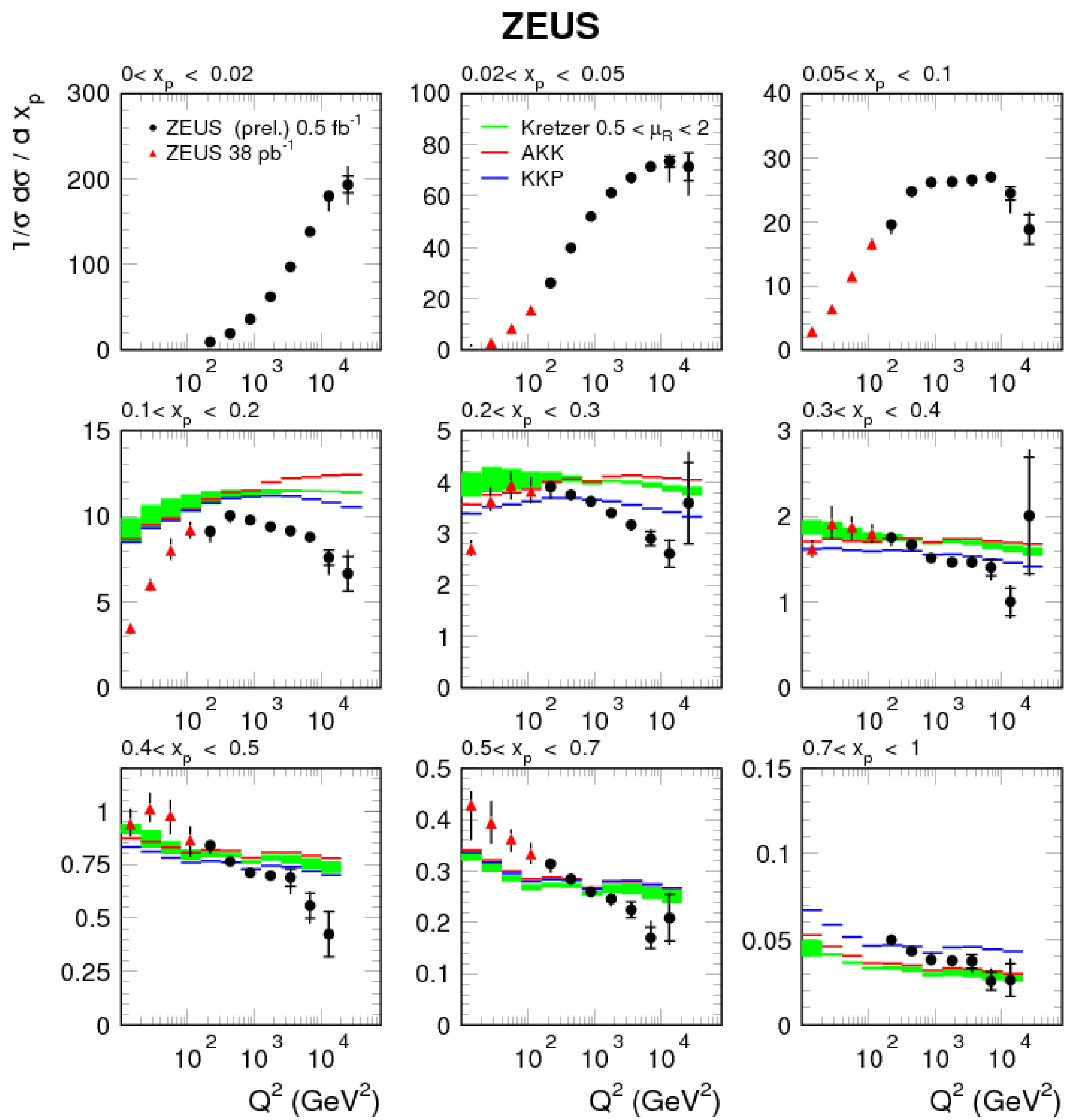
High x_p data have more variation than predicted by MC



Scaling violation compared to NLO+FF predictions based on e^+e^- data.

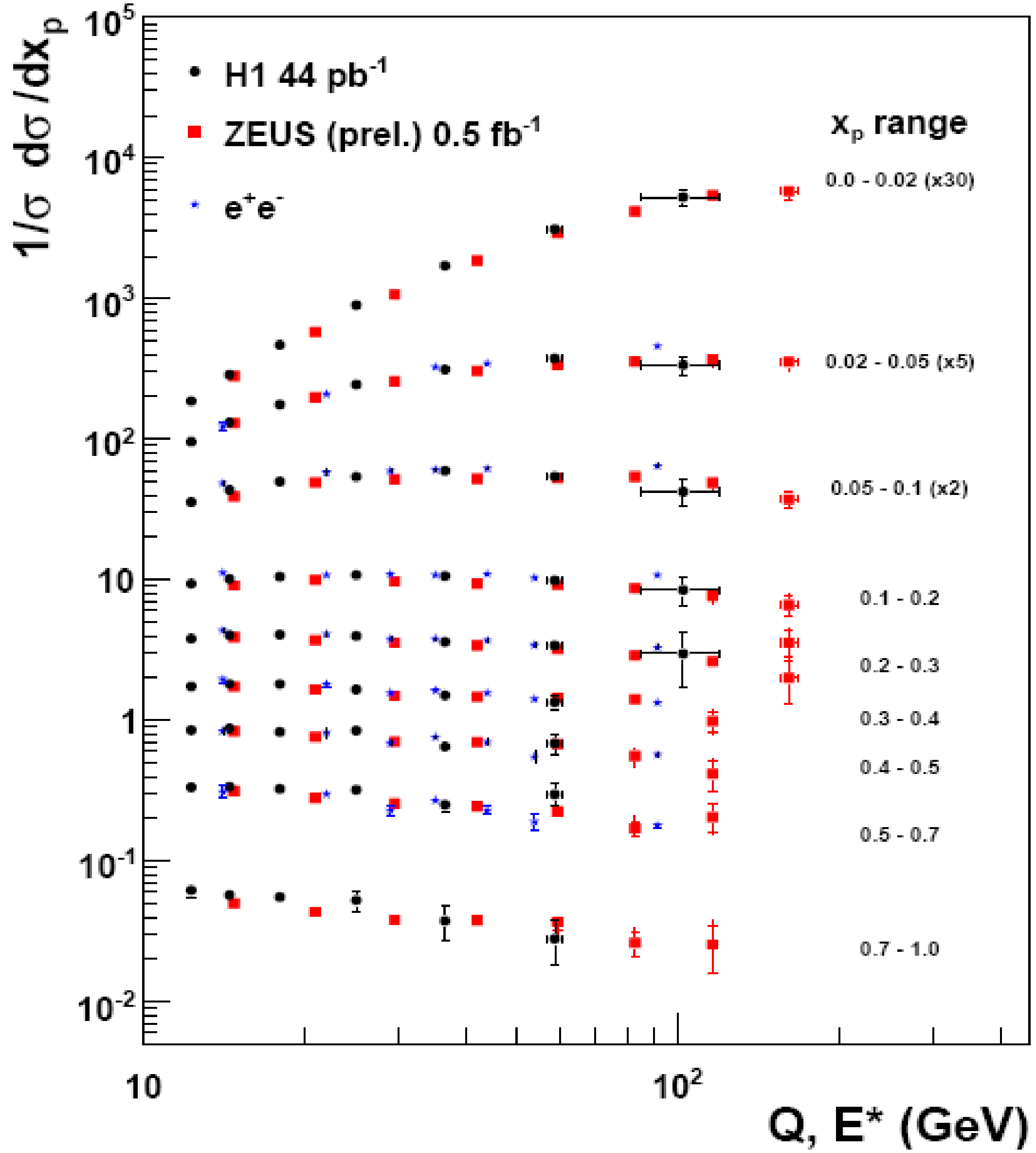
Data log-slope steeper than theories at all x_p

? Is difference due to different *b*-fraction?



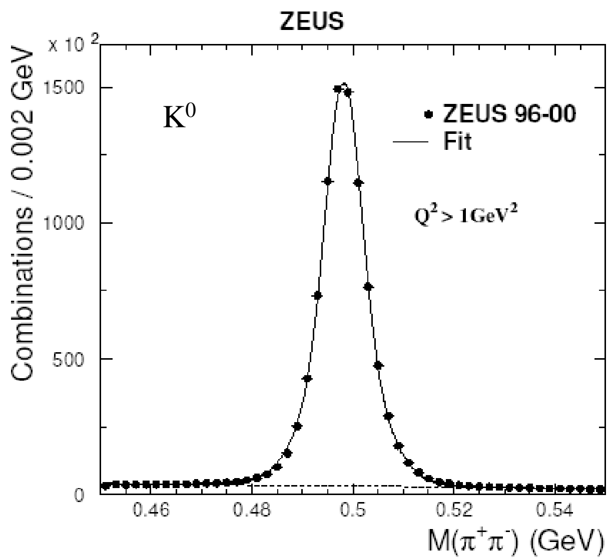
Scaling violation in fragmentation

ZEUS, H1, e^+e^- all in good agreement

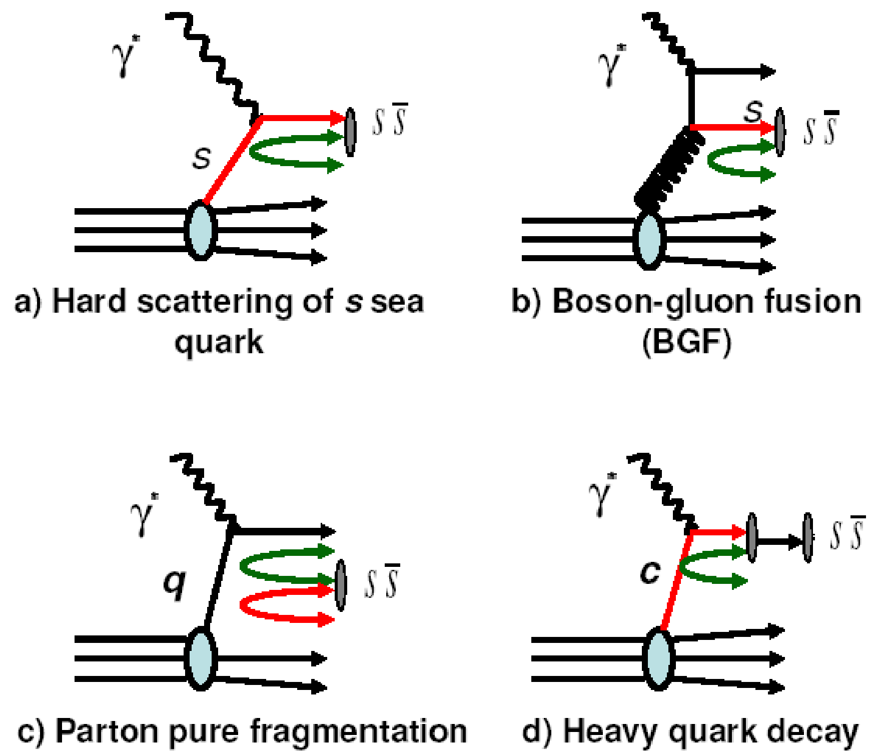


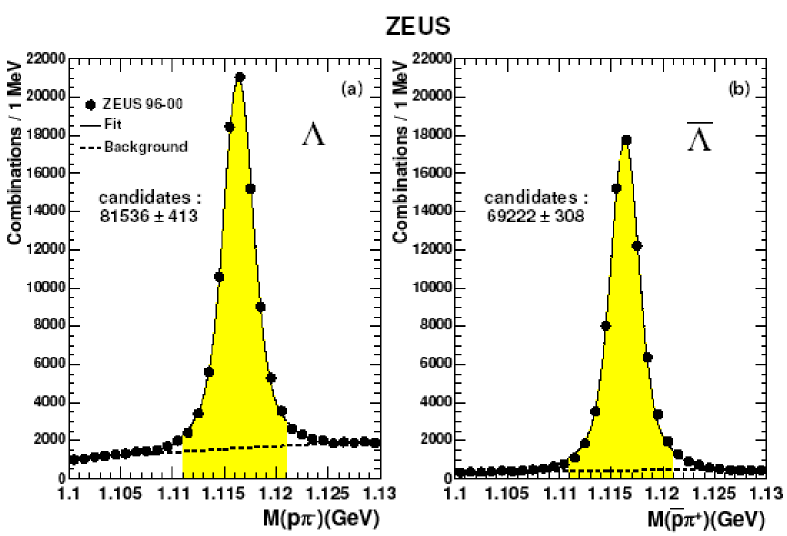
$K^0, \Lambda^0, \bar{\Lambda}^0$ production

DIS and photoproduction



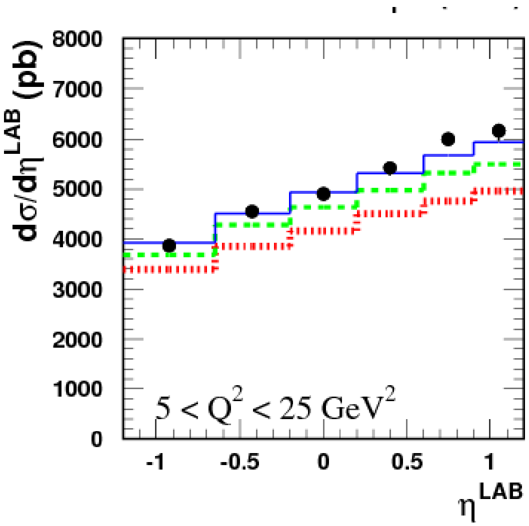
Reconstruct using central tracking detector

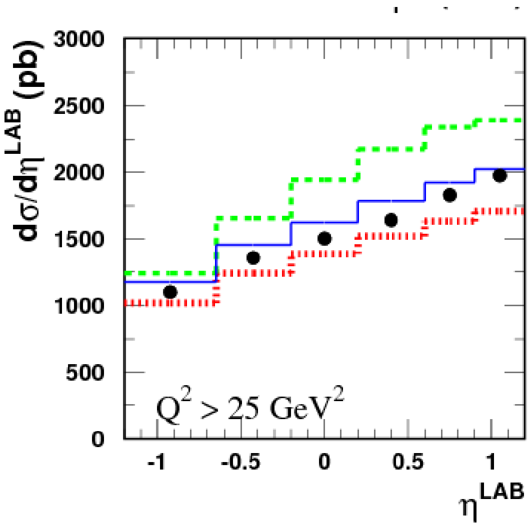


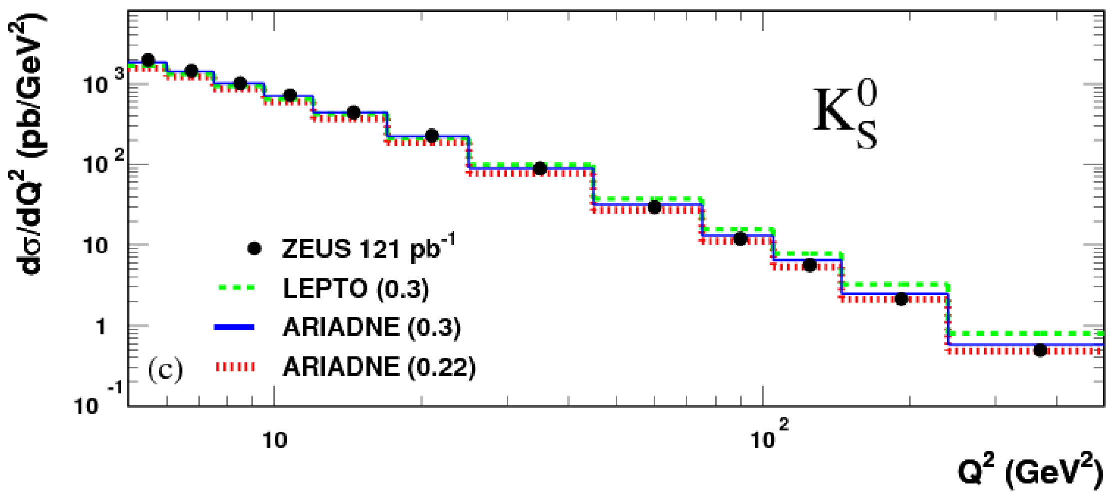


(C Liu)

K^0_s production in DIS







$0.6 < p_t^{LAB} < 2.5$ GeV
$|\eta^{LAB}| < 1.2$

Two Q^2 ranges, $0.02 < y < 0.95$

p_t^{LAB}, η^{LAB}, x_{Bj}, Q^2 distributions

General agreement with MC

No glitch at $Q^2 = 25$ GeV^2 – data sets fit smoothly together

Not possible to tune *(s/u)* ratio in either Ariadne of Lepto.

K^0_s in photoproduction

$0.6 < p_t^{LAB}$, 2.5 $|\eta^{LAB}| < 1.2$
$Q^2 < 1$ GeV^2, $0.2 < y < 0.85$

2 or more jets with
$E_T^{jet} > 5$ GeV and $|\eta^{jet}| < 2.4$

Excellent agreement with MC

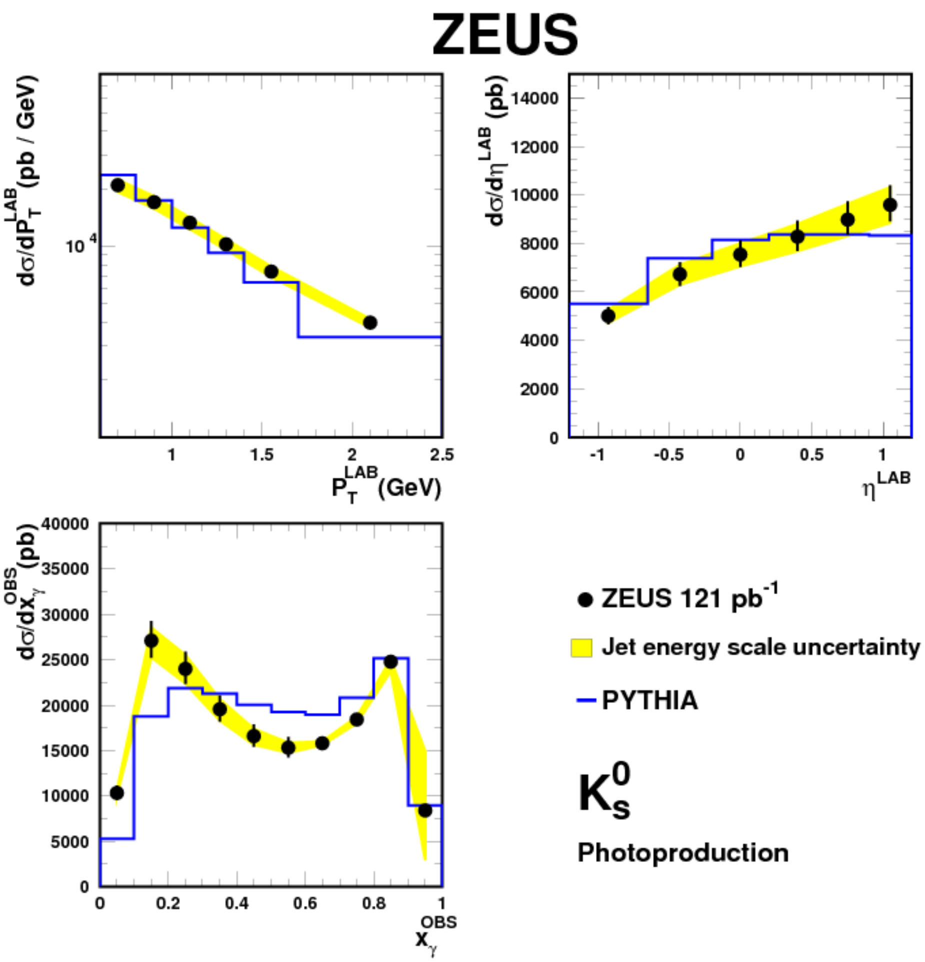
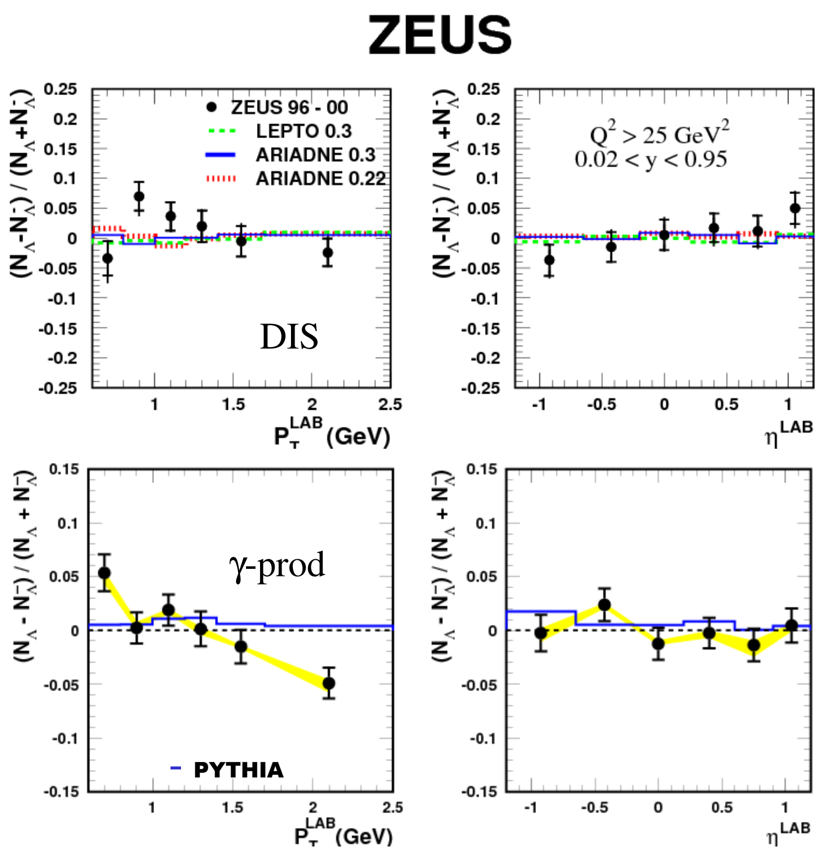
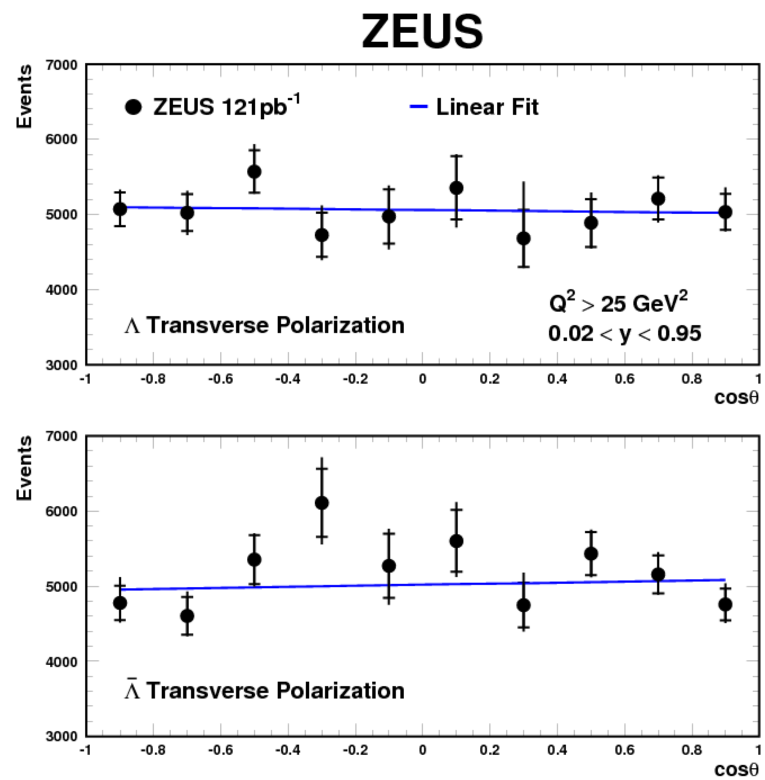


Figure 7: *Differential K^0_S cross sections as a function of $P_T^{\rm LAB}$, $\eta^{\rm LAB}$ and $x_\gamma^{\rm OBS}$, in the range $0.6 < P_T^{\rm LAB} < 2.5$ GeV and $|\eta^{\rm LAB}| < 1.2$ for events with $Q^2 < 1$ GeV^2, $0.2 < y < 0.85$ and at least two jets both satisfying $E_T^{\rm jet} > 5$ GeV and $|\eta^{\rm jet}| < 2.4$. Statistical errors are shown, unless smaller than the point size, together with the systematic uncertainty arising from the trigger efficiency added in quadrature. The uncertainty arising from the jet energy scale is also shown (shaded band). The solid histogram shows the prediction from* PYTHIA *(with multiple interactions), normalised to the data.*

$(\Lambda-\bar{\Lambda})/(\Lambda+\bar{\Lambda})$ polarisation?

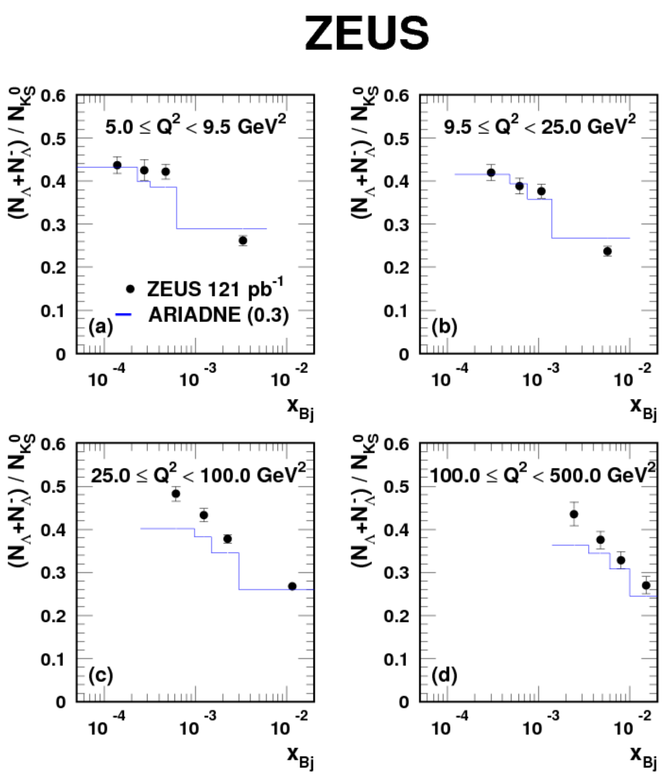


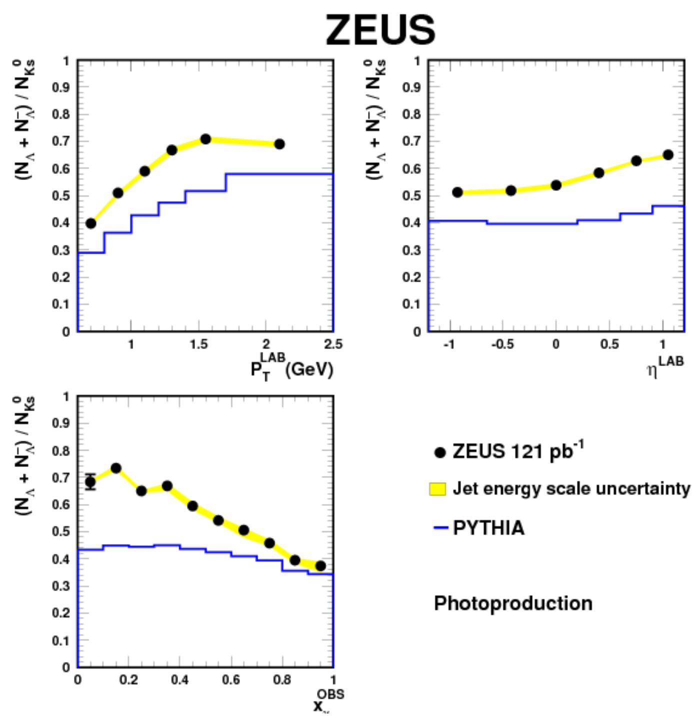
$N(\Lambda) = N(\bar{\Lambda})$



No evidence for polarisation

$(\Lambda + \bar{\Lambda})/K^0_s$

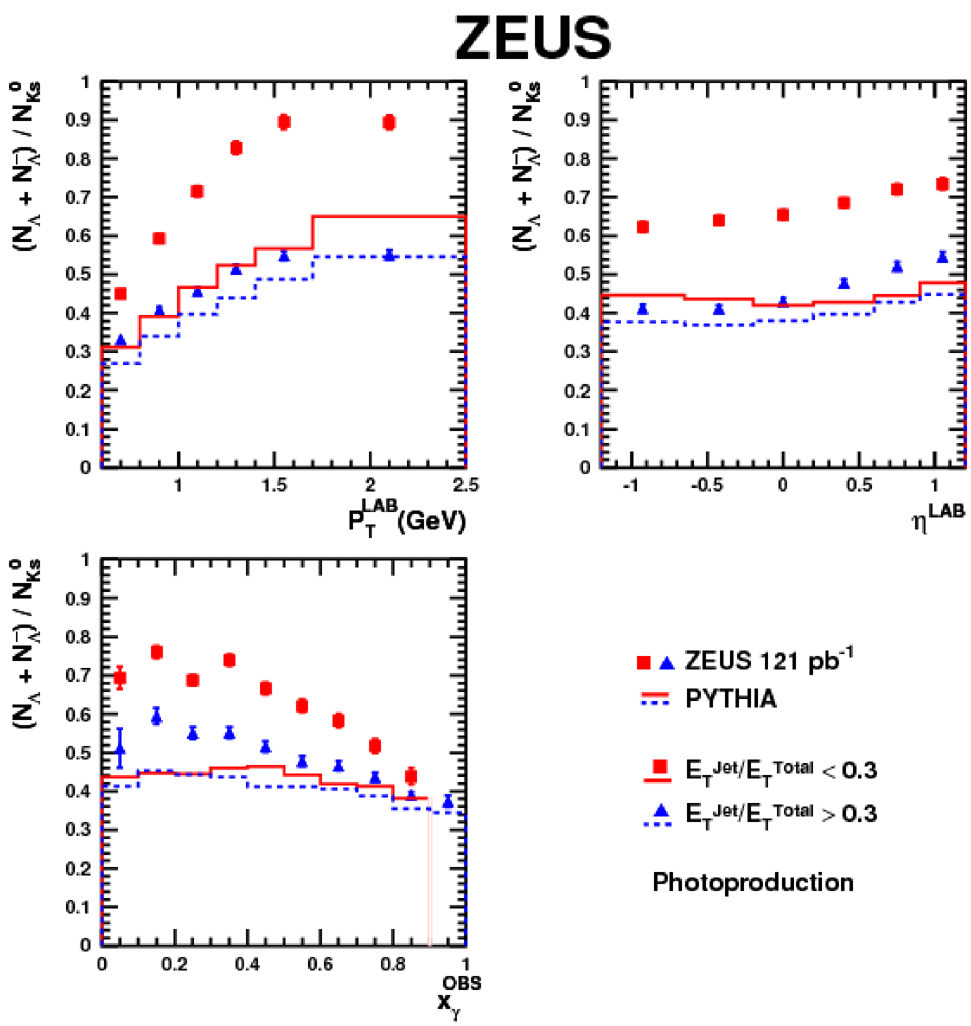




DIS – MC close to data

Photoproduction – data above MC. Why?

$(\Lambda+\bar{\Lambda})/K^0_s$: photoproduction



$0.6 < p_T^{LAB} < 2.5$ GeV/c. $|\eta^{LAB}|<1.2$
$Q^2 < 1$ GeV^2. $0.2 < y < 0.85$.
≥ 2 jets: each with
$E_T^{jet} > 5$ GeV and $|\eta^{jet}| < 2.4$

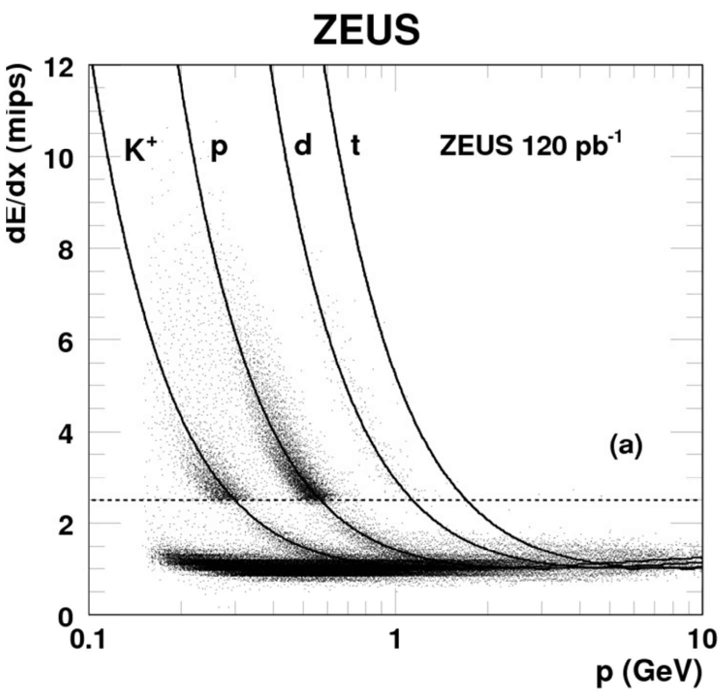
Define 2 event classes:

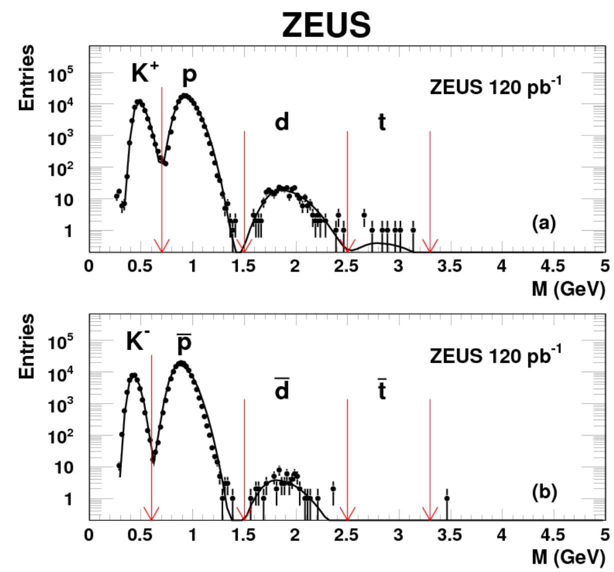
Fireball depleted. For jet of highest E_T , $E_T^{jet}/E_T^{Total} > 0.3$: baryon/meson ratio agrees with PYTHIA

Fireball enriched. For jet of highest E_T, $E_T^{jet}/E_T^{Total} < 0.3$: baryon/meson ratio well above PYTHIA

Suggests new production mechanism. Excess also seen in Λ_c

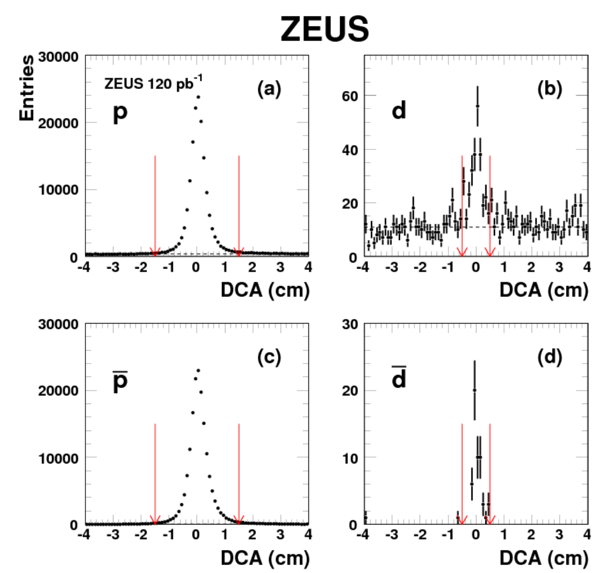
DIS: $p,\bar{p},d,\bar{d},t$ production





Results for $0.3<p_T/M<0.7$

40 CTD hits – limits $|\eta|$



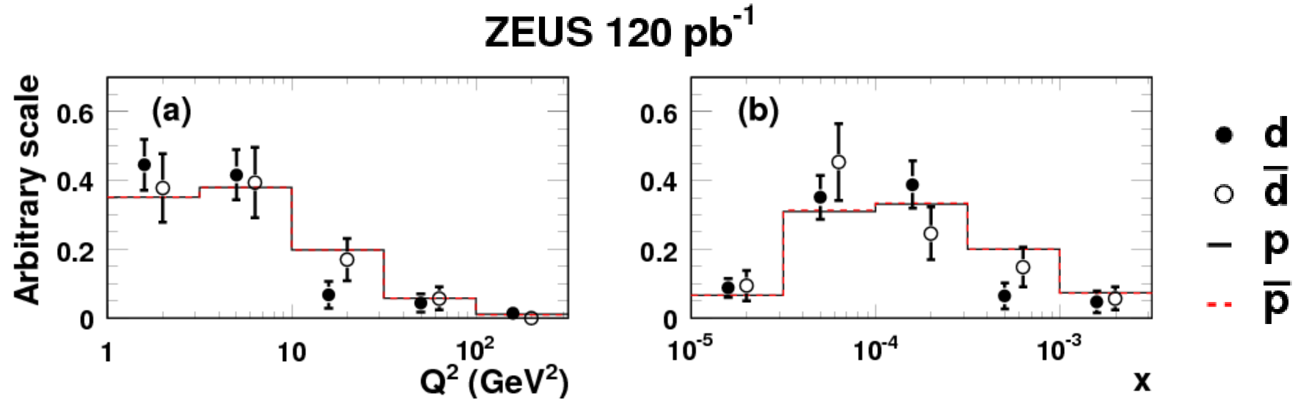
xy-dist of closest approach after cut $|\Delta Z| < 1$ cm

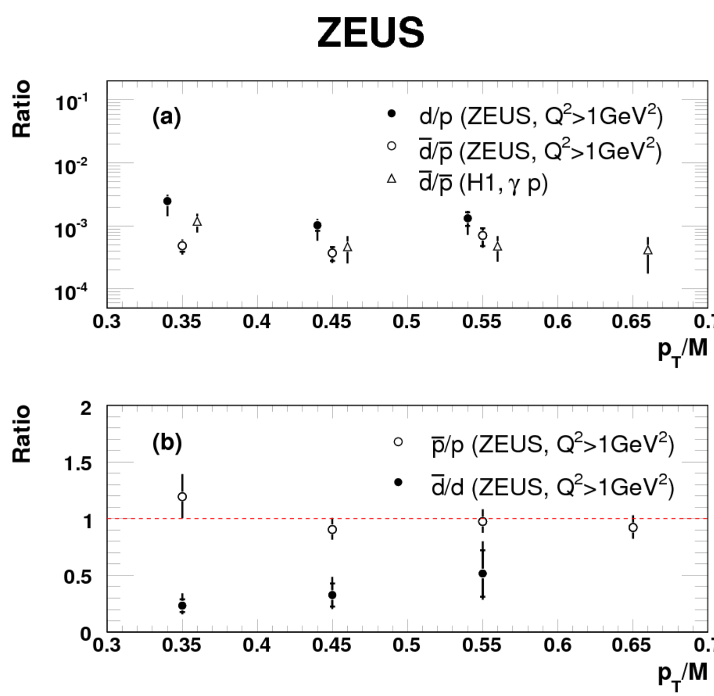
Identify low-momentum charged particles by *dE/dx* in CTD.
Eliminate background by demand tracks come from production vertex
anti-*d*: physics beyond standard fragmentation
Nothing heavier than *t* seen.

DIS: $p, \bar{p}, d, \bar{d}, t$ production

$$\bar{p}/p = 1.05 \pm 0.01^{+0.15}_{-0.14}$$

$$\bar{d}/d = 0.31 \pm 0.05^{+0.11}_{-0.06}$$





Coalescence model:

$$\frac{1}{\sigma}\frac{d^3\sigma(d)}{d^3p} = B_2\left(\frac{1}{\sigma}\frac{d^3\sigma(p)}{d^3p}\right)\left(\frac{1}{\sigma}\frac{d^3\sigma(n)}{d^3p}\right)$$

Expect $B_2(\bar{d}) = B_2(d)$

Find

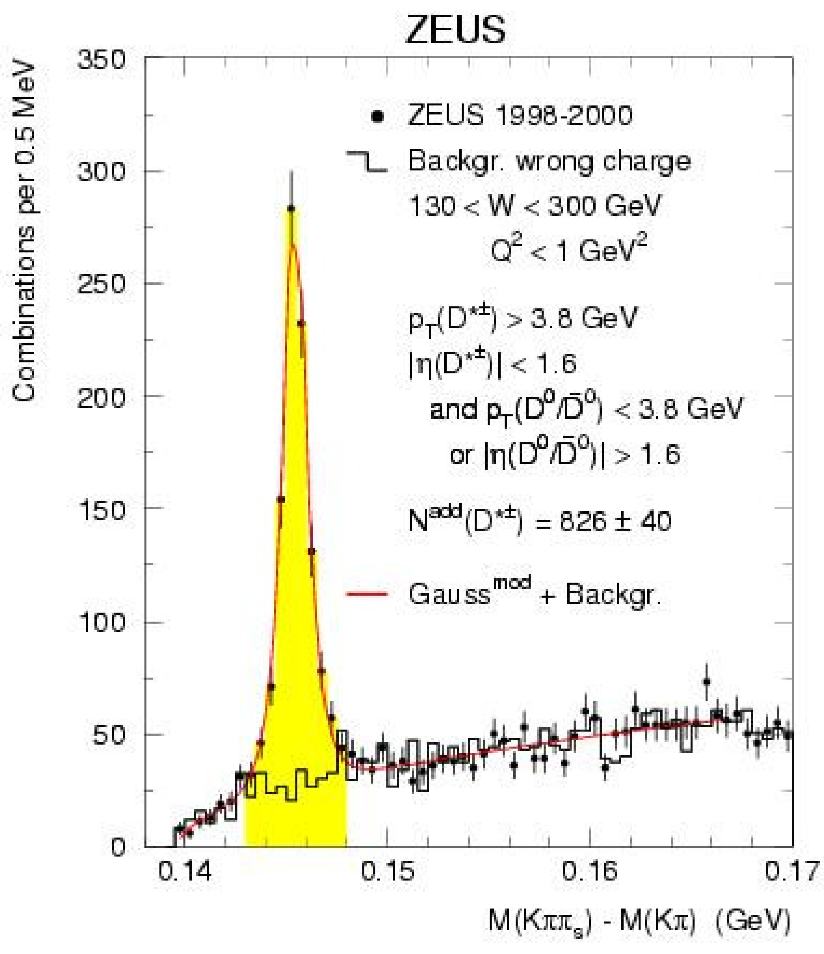
$$B_2(d) = 3.32 \pm 0.34^{+1.13}_{-1.55}$$

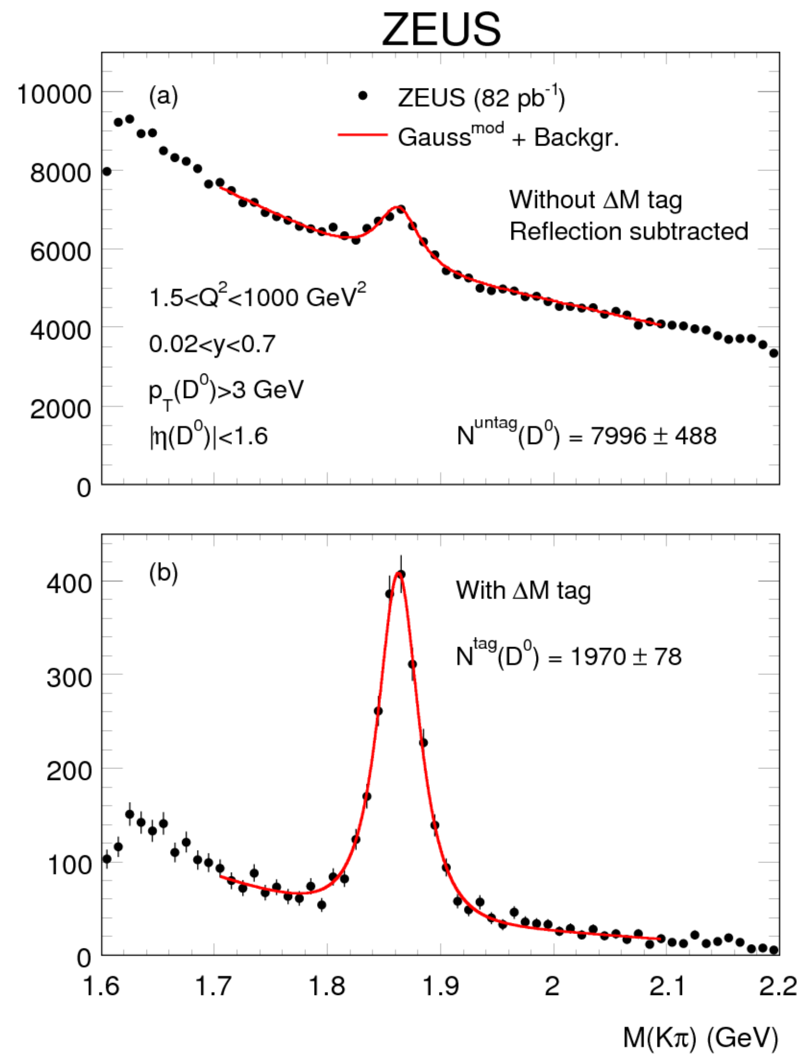
$$B_2(\bar{d}) = 0.89 \pm 0.14^{+0.19}_{-0.20}$$

Charm production

D^{*+}, D^{+}, D^{0}, D_s^{+}, Λ^{+}_{c} observed

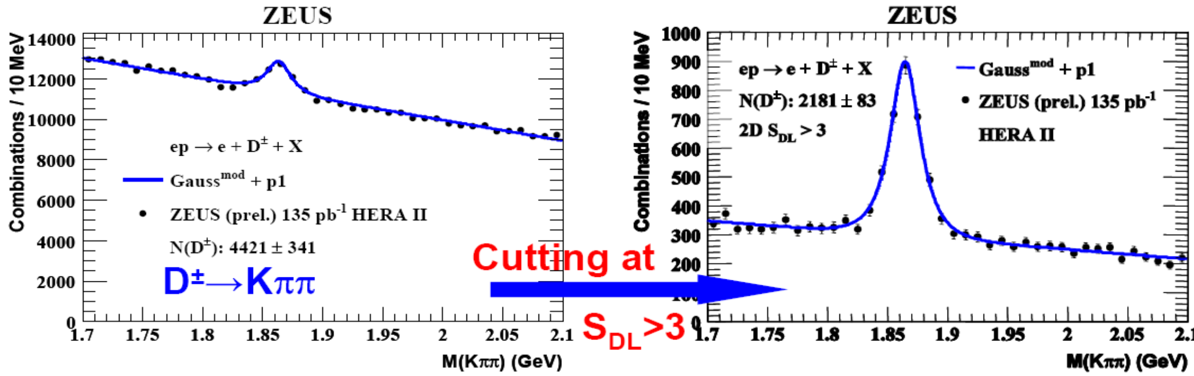
$D^0 \rightarrow K^-\pi^+$ with and without $D^{*+} \rightarrow D^0\pi^+$ tag





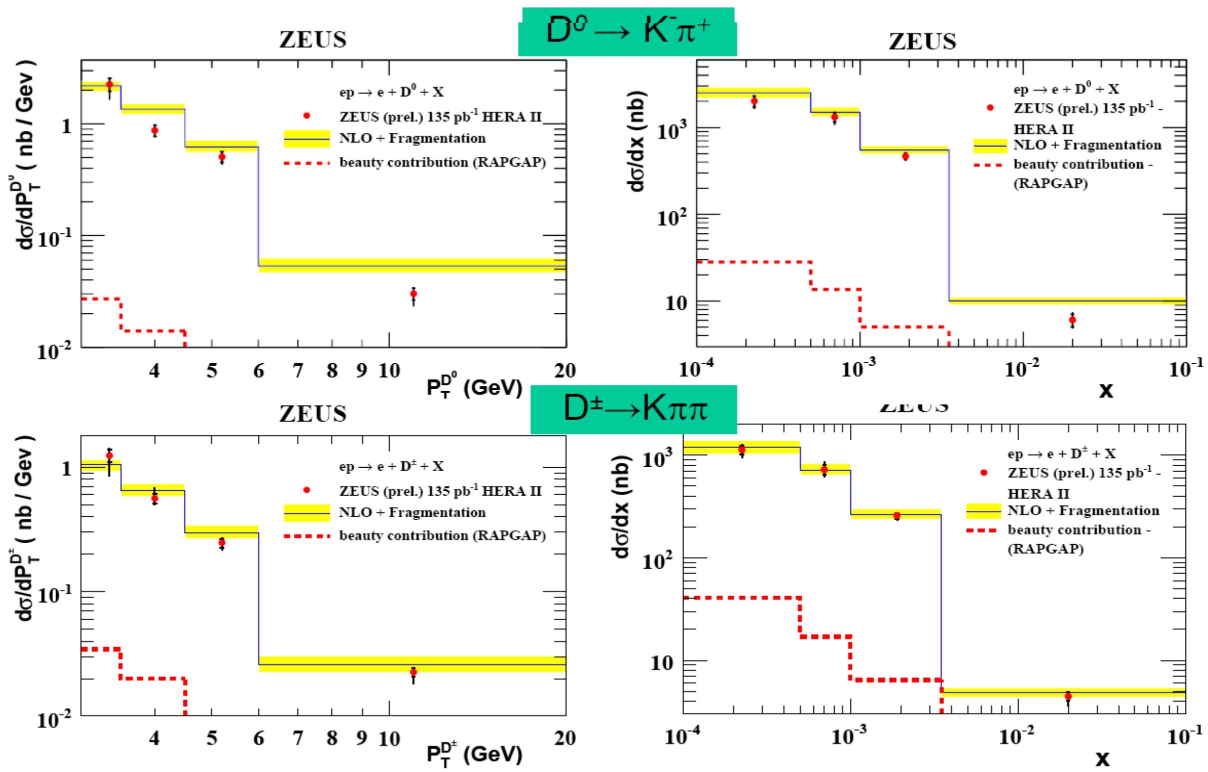
$D^{\pm}\rightarrow K^{-}\pi^{+}\pi^{+}$

No vertex cut



Using decay length significance cut

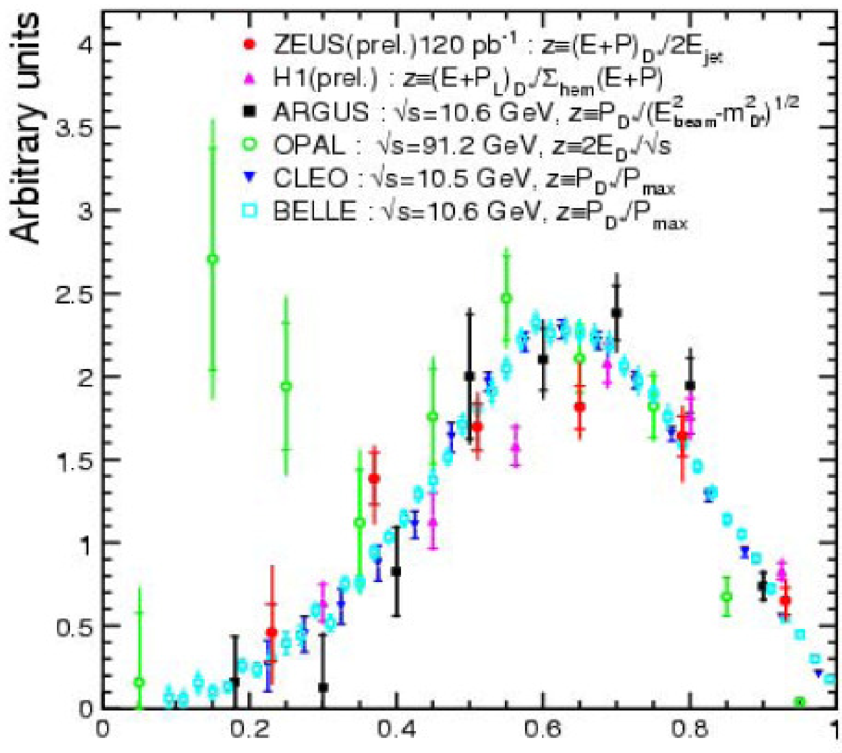
$p_T(D)$ and x distributions for D^0 and D^+



Fair agreement with (NLO + fragmentation.)

Can extract F_2^{cc}

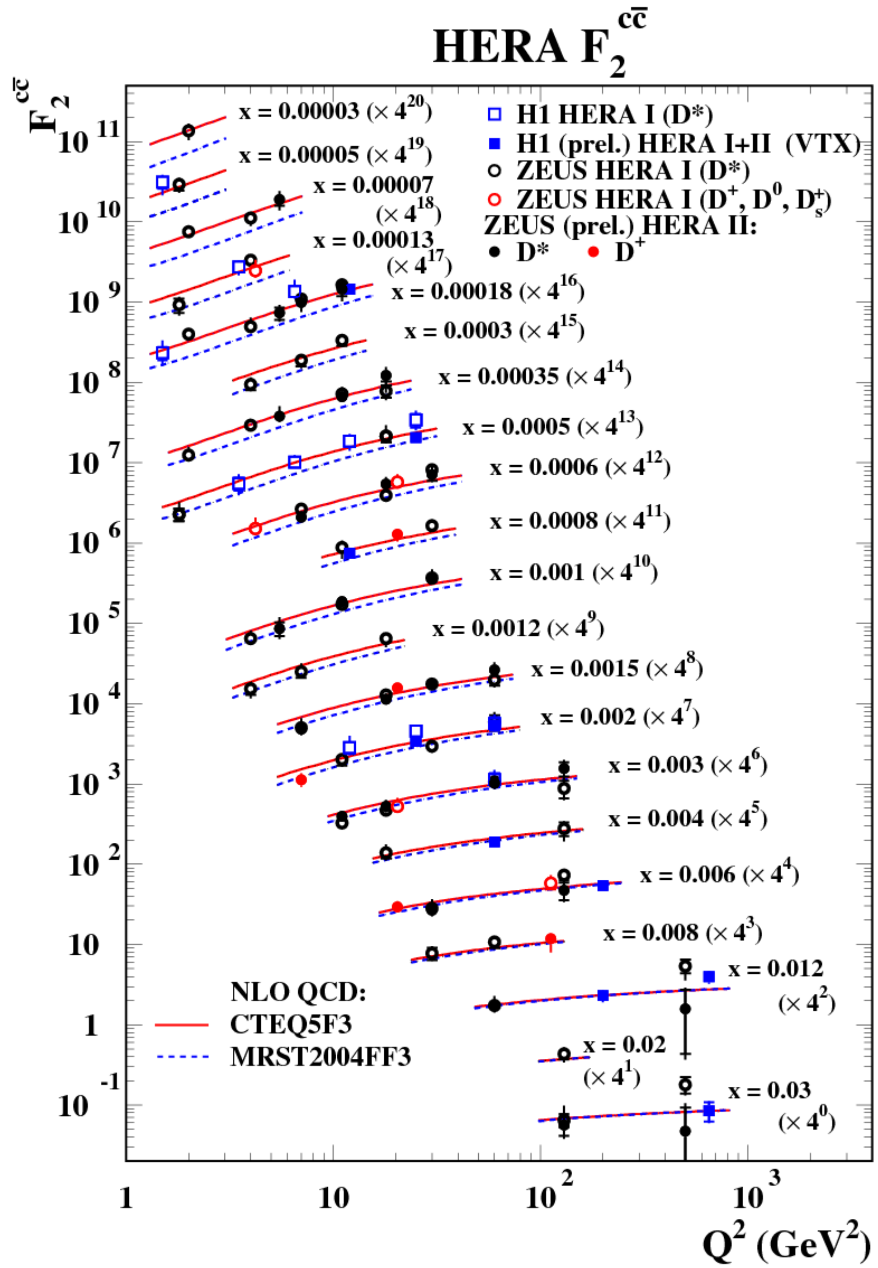
Fragmentation & $F_2^{cc}(x)$



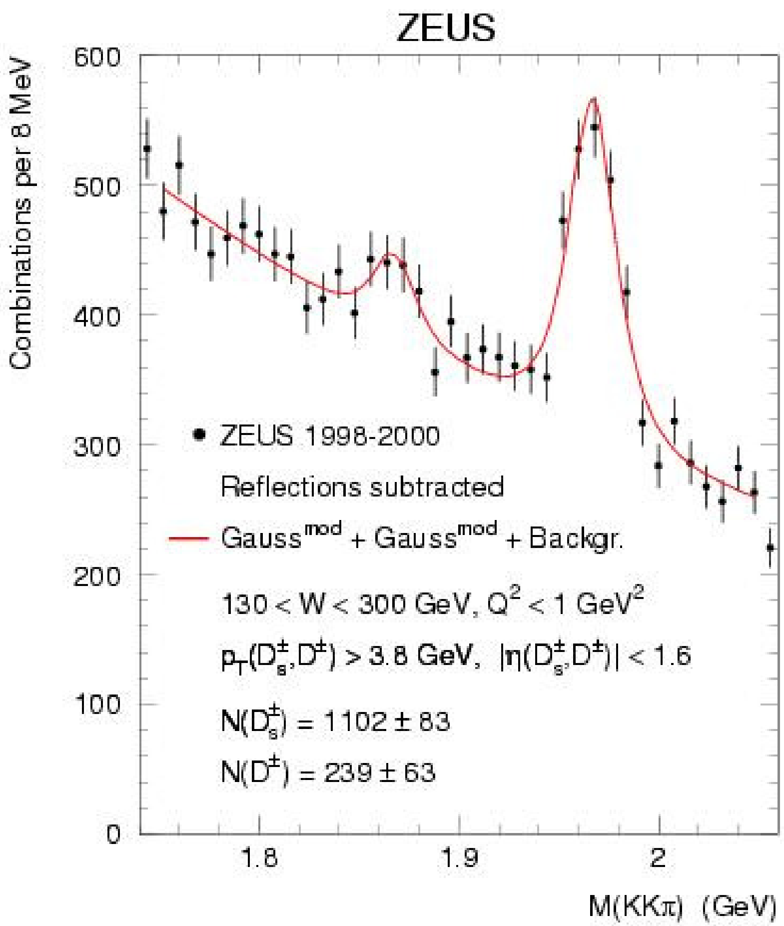
$z = \{E+P\}(D^{*\pm})/2E(\text{jet})$

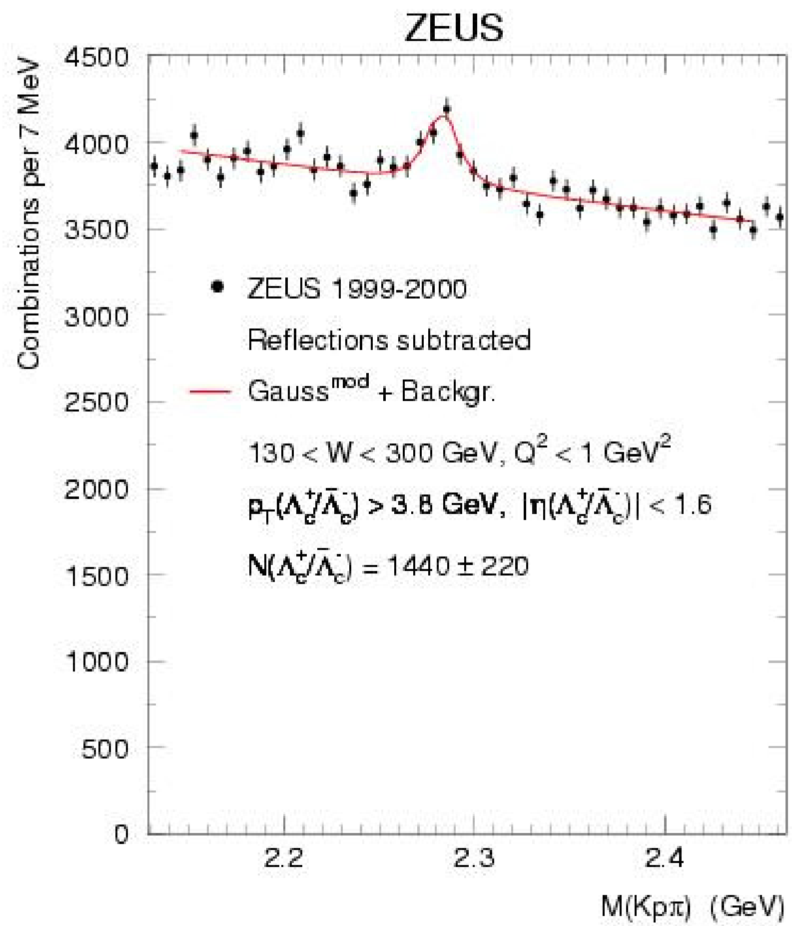
OPAL includes

g → *ccbar*. Subtract *b* → *c*



$D_s^{\pm} \rightarrow \phi\pi^{\pm}, \phi \rightarrow K^+K^-$ $\Lambda_c^+ \rightarrow pK^-\pi^+$ signals

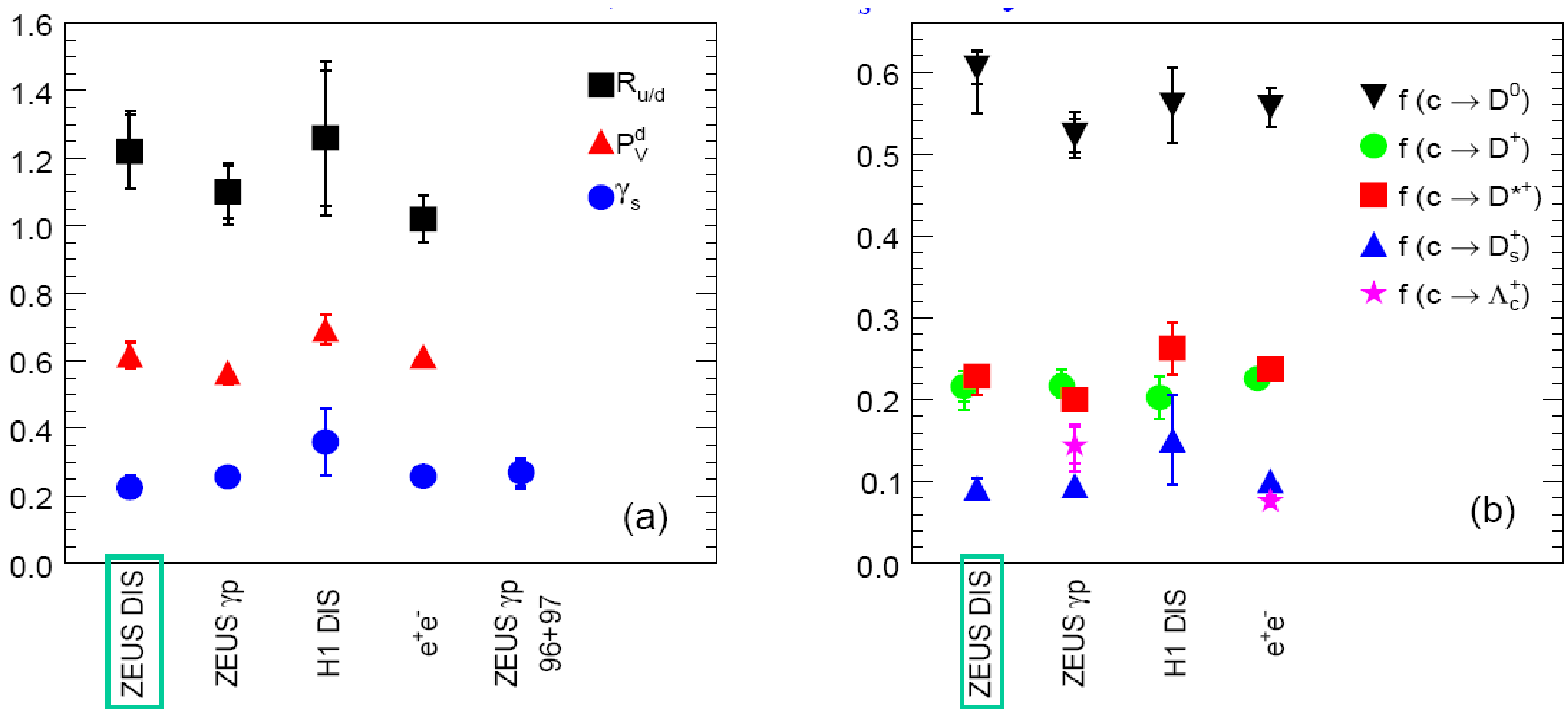




M(KK) within 8 MeV of ϕ mass

dE/dx info used for particle ID

Charm fragmentation parameters



$R_{u/d}$: ratio of neutral/charged *D* production (not via *D**)

P^d_V: fraction of D^+ produced in vector state (naively 0.75)

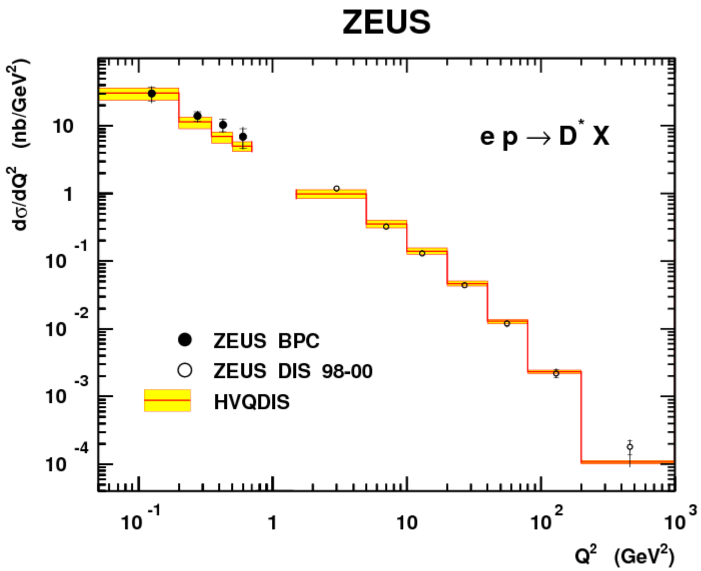
γ_s: strangeness suppression factor

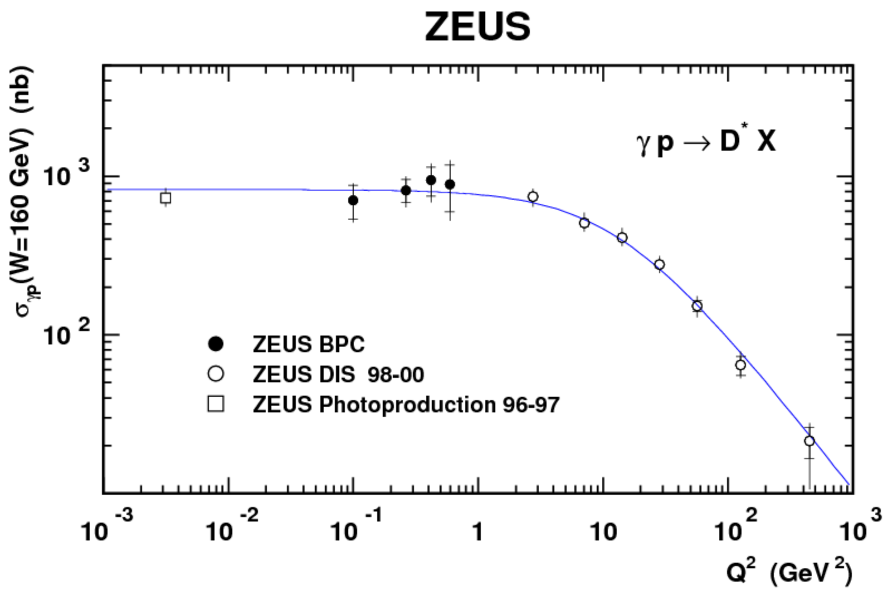
Λ_c enhanced relative to e^+e^-

cf Λ in resolved photoproduction

$D^{*\pm}$ production: $0.05 < Q^2 < 0.7$ GeV^2

Measure recoil electron in Beam-Pipe Calorimeter:
covers transition photoproduction to DIS





$\gamma p \rightarrow D^*X$: fit to

$\sigma(Q^2) = SM^2/(Q^2+M^2)$

Fit $M^2 = 13 \pm 2$ GeV^2 ~ $4m^2_c$

cf inclusive $M^2 = 0.52 \pm 0.05$ GeV^2

Excited charm and charm-strange mesons

ZEUS:

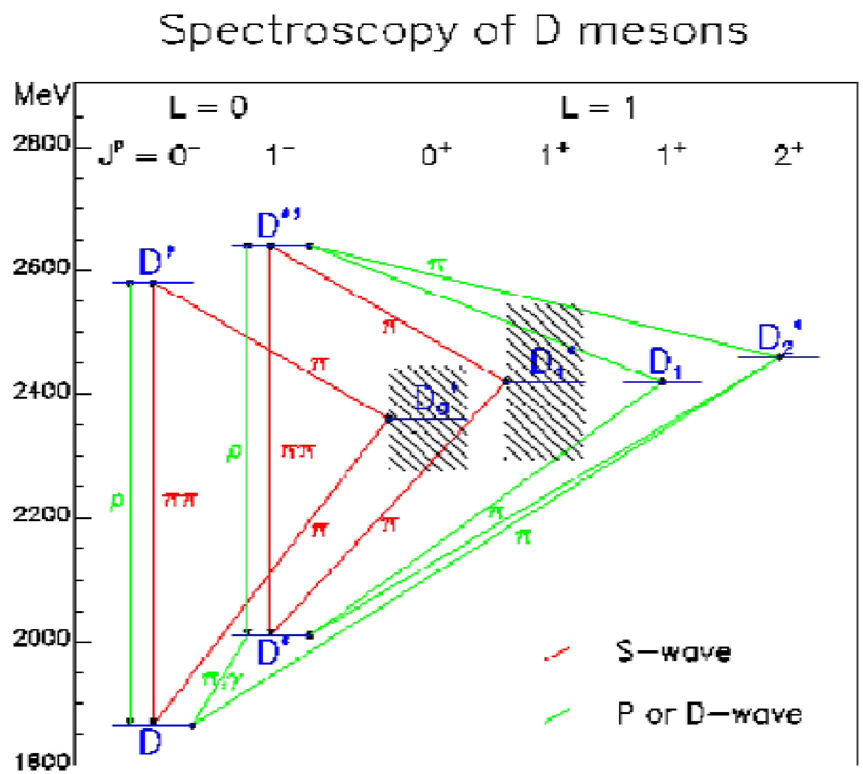
$D_1(2420)^0$, $D_2(2460)^0 \rightarrow D^{*+}\pi_a^-$

$D_2(2460) \rightarrow D^+\pi_a^-$

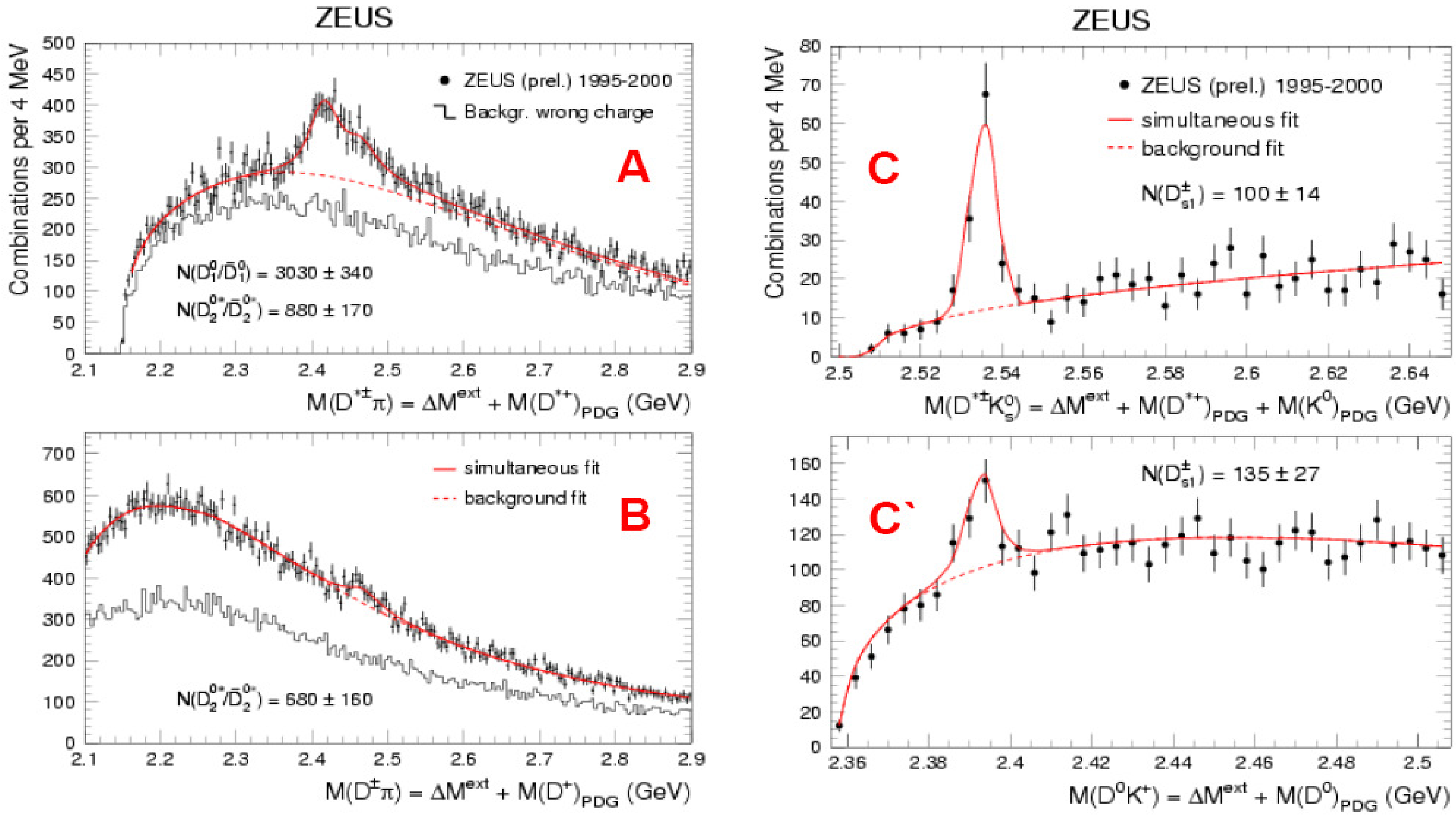
$D_{s1}^+(2536) \rightarrow D^{*+}K^0_s$

$D_{s1}^+(2536) \rightarrow D^0K^+$

Aim to measure masses, widths, fragmentation functions, helicity dependence



Excited charm and charm-strange mesons



A: $D^{*+}\pi^-$ see $D_1(2420)^0$ & $D_2(2460)^0$

B: $D^+\pi^-$ see $D_2(2460)^0$

C: $D^{*\pm}K^0{}_s$ see $D_{s1}(2536)^{\pm}$

C': D^0K^+ see Ds1+(2536)

Branching ratios & helicity measurements

$f(c \to D^0_1)$ = 3.5 ±0.4+0.4-0.6 ±0.2%

$f(c \to D_2^{*0})$ = 3.8 ±0.7±0.6 ±0.2%

$f(c \to D_{s1}^+)$ = 1.1 ±0.2 ±0.1±0.1%

Consistent with e^+e^- results

α = angle between π and π_s momenta in the D^* rest frame

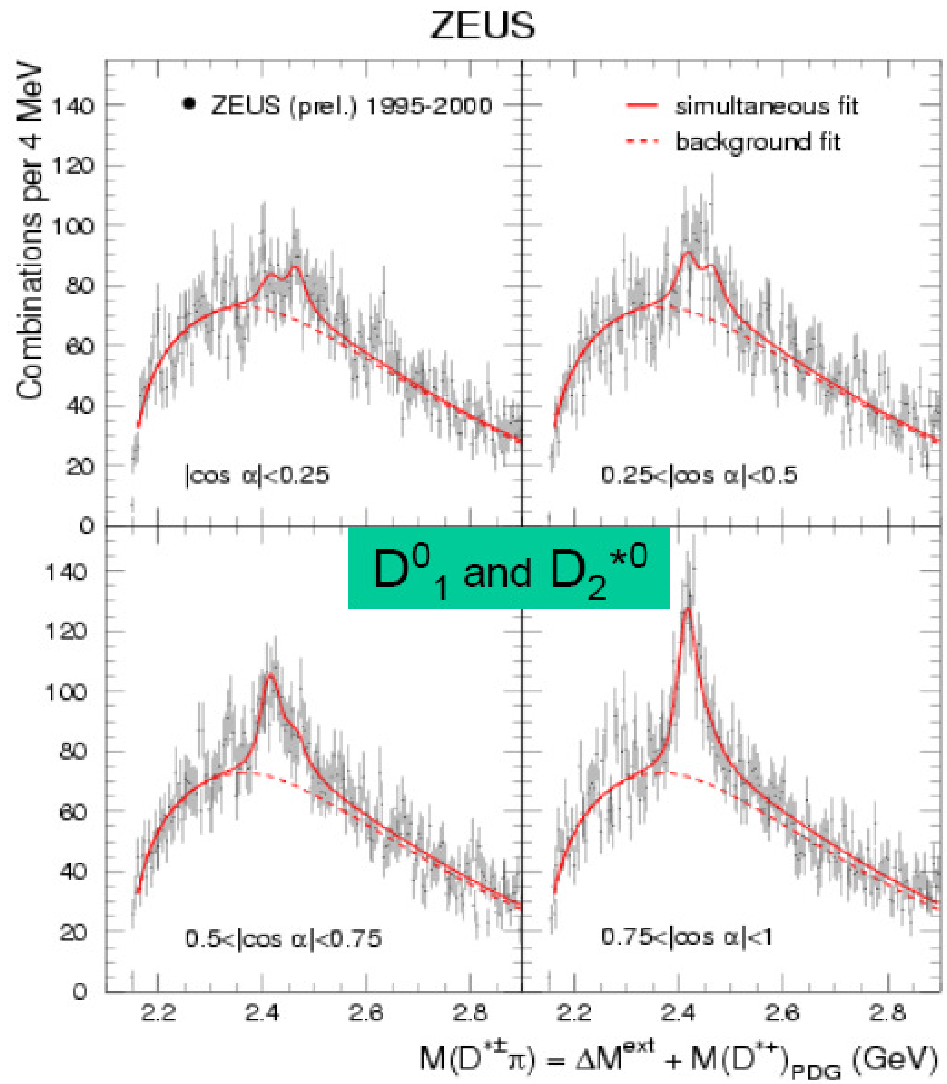
$dN/d\cos\alpha \sim (1 + R\cos^2\alpha)$

$R(D^0_1) = 6.1 \pm 2.3^{+2.0}_{-0.8}$ HQET: +3

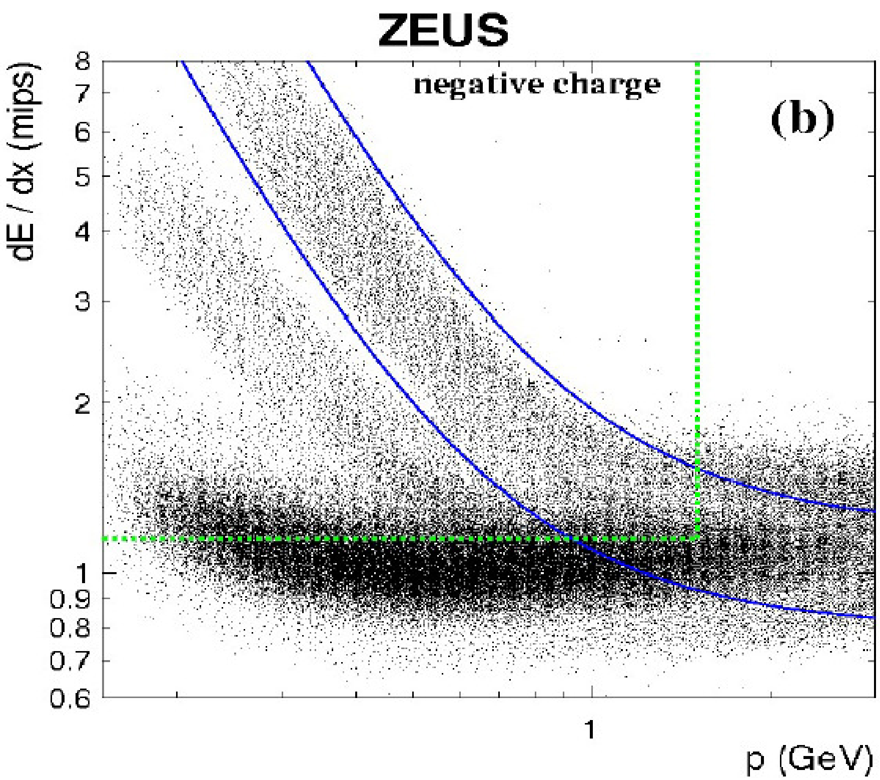
$R(Ds1+) = -0.74^{+0.23}_{-0.17} \pm 0.06$
HQET:0 – hardly consistent

Search for $D^{*\prime+}(2640) \to D^{*+}\pi^+\pi^-$

$f(c \to D^{*\prime+}) BR(D^{*\prime+} \to D^{*+}\pi^-\pi^+) <$ 0.45% (0.9% lower than OPAL limit, 5σ at DELPHI)



Baryons decaying to strange particles



$p, \bar{p}, K^+, K^-$ reconstruction:

tracks from primary vertex

dE/dx identification:

ZEUS – region method in blue band and $dE/dx > 1.5$ mips and $p < 1.5$ GeV

$K^0_s \rightarrow \pi^+\pi^-$: secondary vertex.

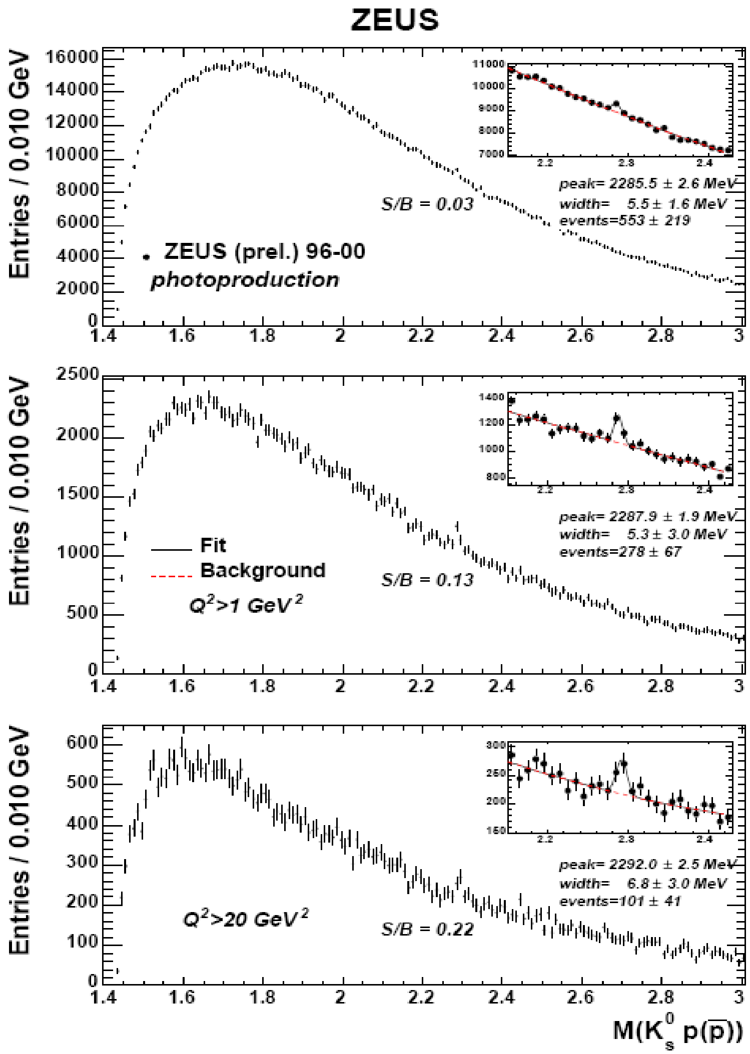
$p_T(K^0_s) > 0.3$ GeV, $|\eta\ (K^0_s)| < 1.5$

exclude Dalitz pairs, γ-conversions

exclude Λ candidates

$K^0_s p$ mass resolution 2.4 MeV

$K^0_s p$ mass spectra (Λ^*,Σ^*,Λ_c, pentaquark)



Combinatorial backgrounds higher in γp ($\langle n_{ch} \rangle$ higher) & low Q^2

Mass peaks:

Θ^+(1520) candidate in DIS

Λ_c(2286) in PHP and DIS

seen equally in *Kp, Kpbar*

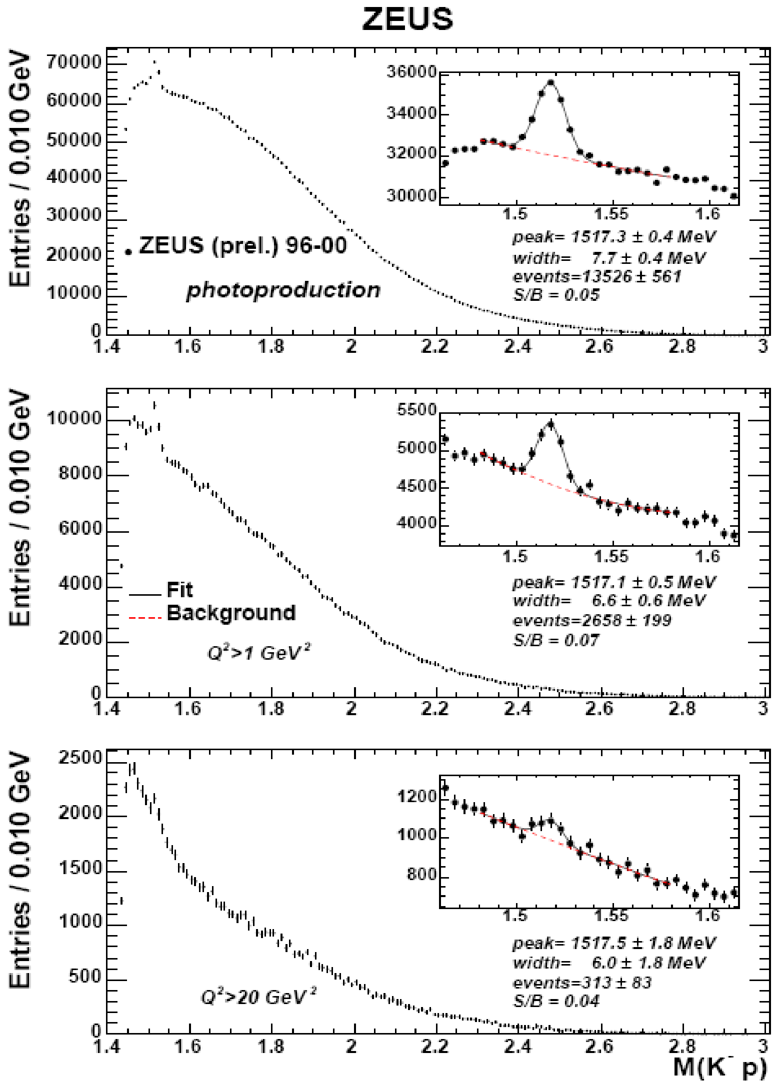
(162±36, 116±38 ev)

seen equally η >0, η <0

(131±40, 145±34 ev)

Consistent with $\gamma^* g \rightarrow c\bar{c}$

$K^{-}p$, $K^{+}\bar{p}$ mass spectra (Λ(1520))



Mass peak:

Λ(1520) in PHP and DIS

seen equally in *Kp, Kpbar*

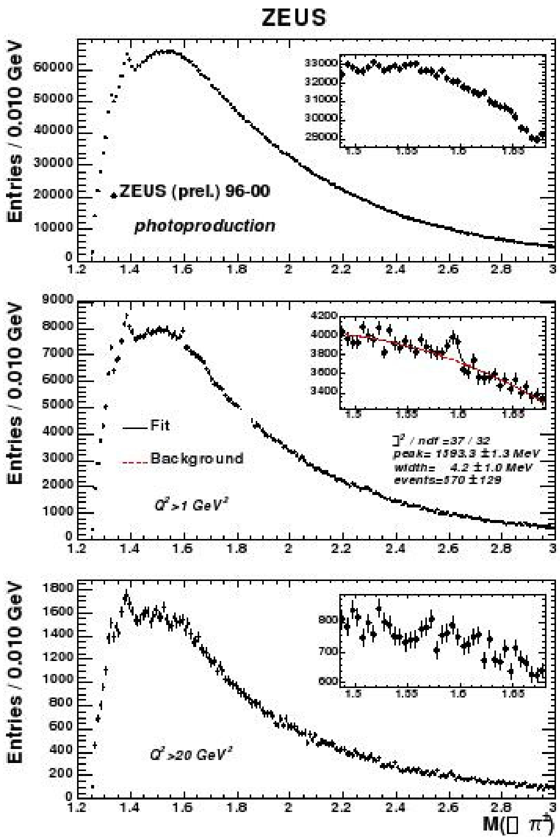
(1207±143, 1402±142 ev)

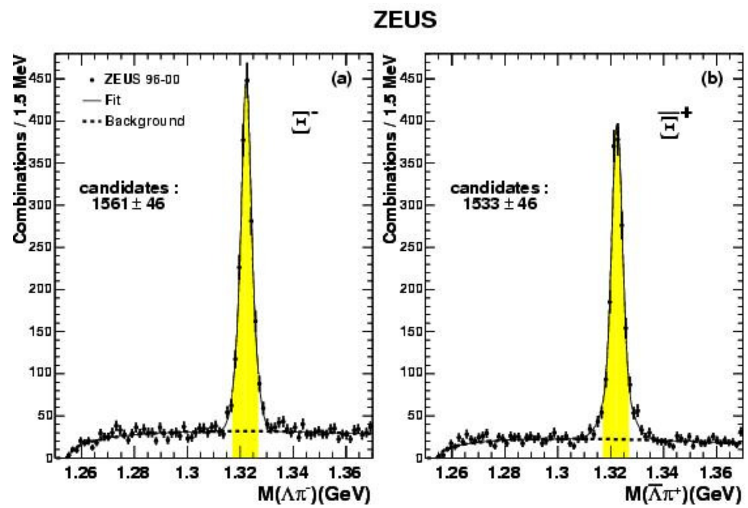
seen equally η>0, η<0

(1337±151, 1246±127 ev)

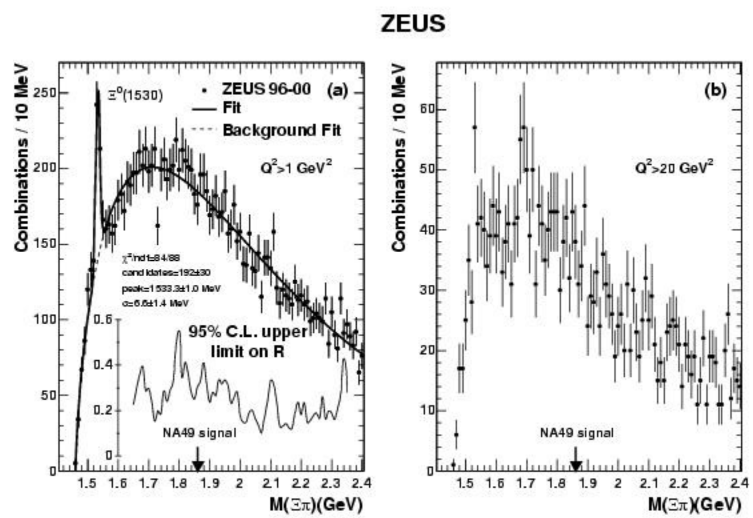
Consistent with γ*g→ $q\bar{q}$

$\Lambda^0\pi^\pm$ mass spectra (Ξ,Σ^*)





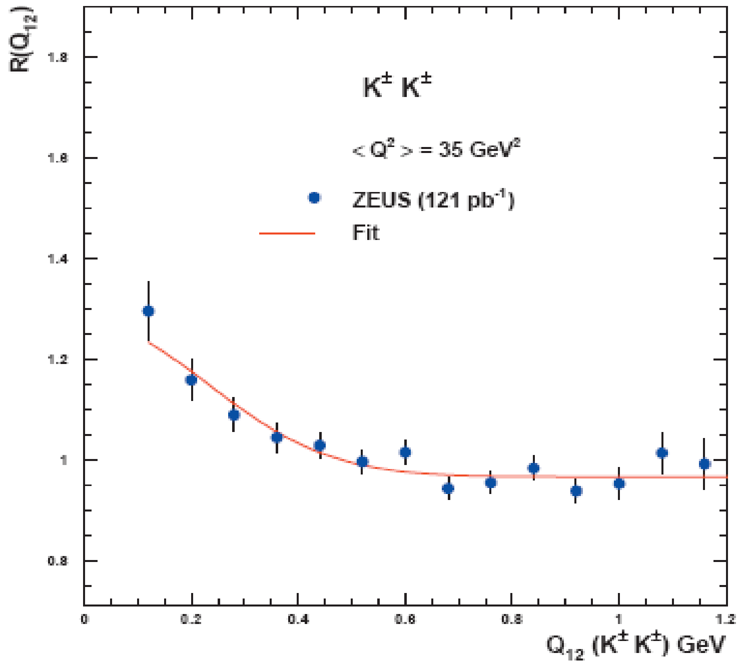
Demand decay vtx: see $\Xi^-\to\Lambda\pi^-$, also $\Xi^*\to\Xi\pi$

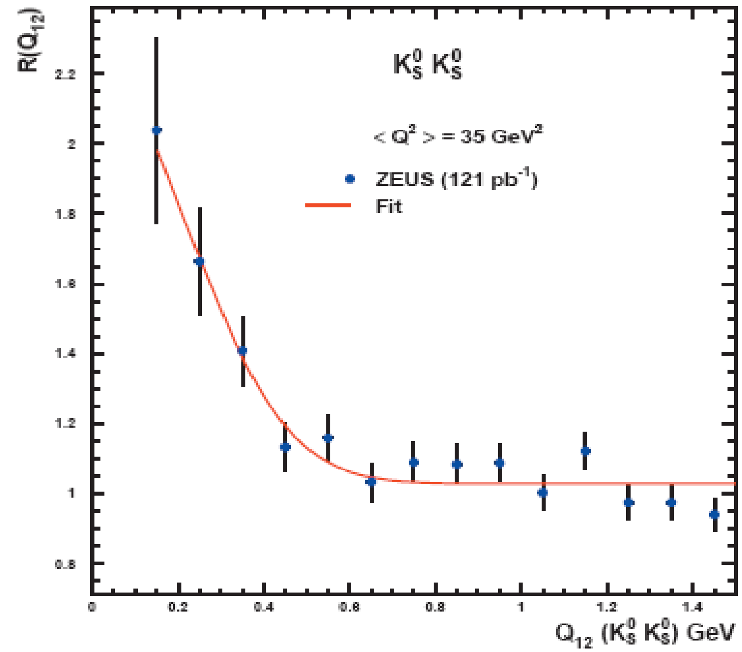


Observe: $\Xi(1320)$ $\Sigma^*(1385)$
No peak in $\Theta^+(1520)$ region

4.4σ peak near 1600 MeV for $Q^2 > 1$ DIS: $\Sigma(1580)$? $\Sigma(1620)$?

Bose-Einstein correlations: $K^0_s K^0_s$ and $K^{\pm}K^{\pm}$





$K^{\pm}$ identified by *dE/dx* in CTD

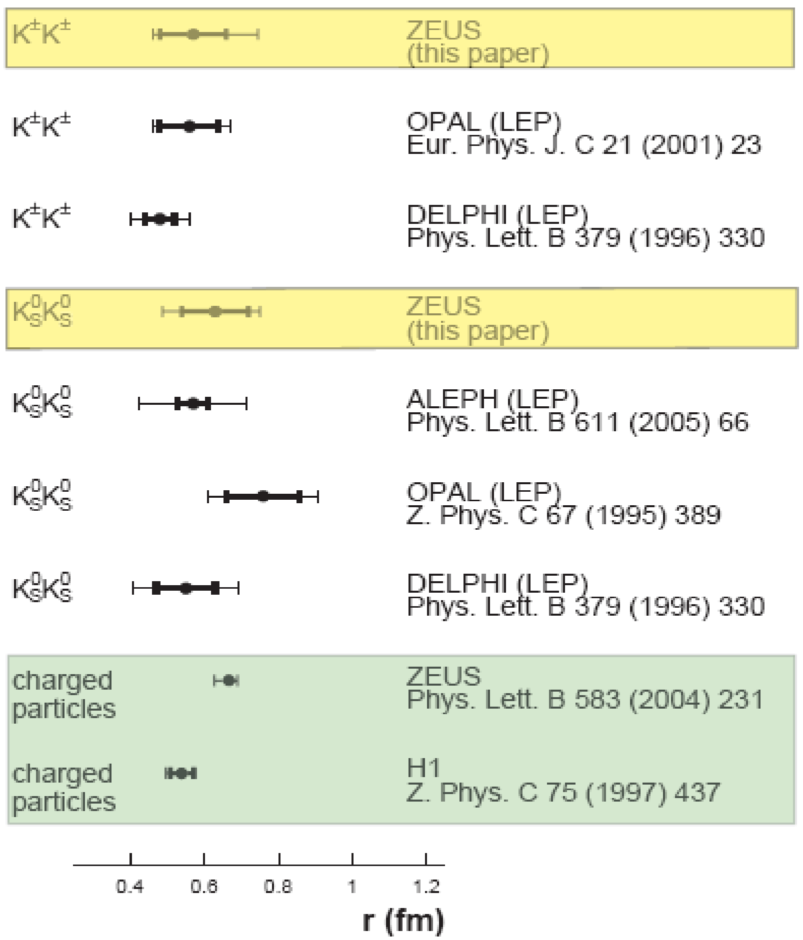
$R(Q_{12}) = P(Q_{12})/P_0(Q_{12})$ where $Q_{12}{}^2 = -(p_1-p_2)^2 = (M_{KK}{}^2 - 4M_K{}^2)$

Fit: $R(Q_{12}) = \alpha(1+\delta Q_{12})(1+\lambda \exp[-r^2 Q_{12}{}^2])$ where r = source radius, $0 < \lambda < 1$

Measure $R(Q_{12})$ *by event-mixing double ratio*

$R = \{P(\text{data})/P_{mix}(\text{data})\}/\{P(\text{MC})/P_{mix}(\text{MC})\}$

Bose-Einstein correlations: source size & strength



$K^{\pm}K^{\pm}$

$\lambda = 0.37 \pm 0.07 \,^{+0.09}_{-0.08}$

$r = 0.57 \pm 0.09 \,^{+0.15}_{-0.08}$ fm

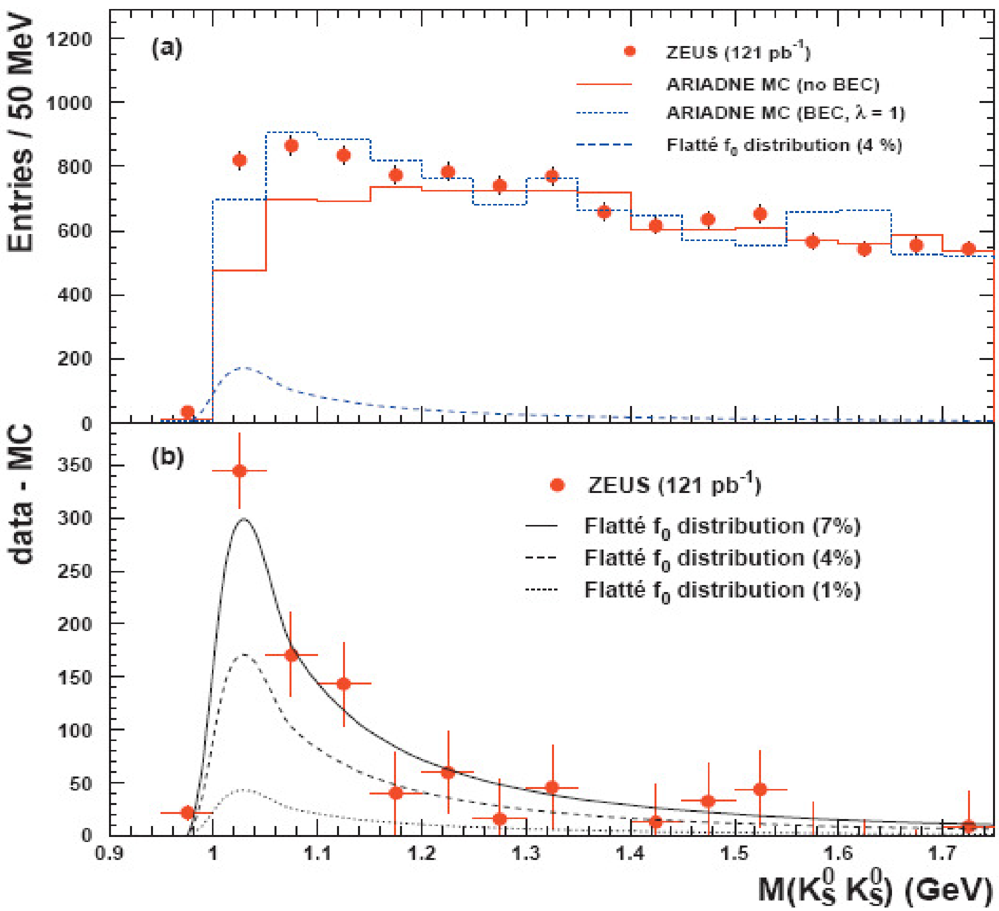
$K_s^0 K_s^0$

$\lambda = 0.70 \pm 0.19 \,^{+0.28+0.38}_{-0.08-0.52}$

$r = 0.63 \pm 0.09 \,^{+0.07+0.09}_{-0.08-0.02}$ fm

the second contribution to the systematic error comes from $f_0(980)$ resonance.

Bose-Einstein correlations: $K^0{}_s K^0{}_s$



$f_0(980) \rightarrow K^0{}_s K^0{}_s$

M=(980 ± 10), Γ = 40 to 100

Mimics B-E correlations

Best fit – 4%

Big errors:

$\lambda = 0.70 \pm 0.19\ ^{+0.28+0.38}_{-0.08-0.52}$

r not affected by f_0

Summary

Charged Multiplicities and scaled momenta in Breit frame

Scaling violations compared to LPHD and NLO

Strange Particle production

p_T,η,Q^2,x, Λ polarisation

Antideuteron and antiproton production

dE/dx. Coalescence model

Charm fragmentation and F_2^{cc}

universality: DIS, photoproduction, e^+e^-

Excited charm and charm strange mesons

Production and properties

Baryons decaying to strange particles

dE/dx for $K^\pm$,p: resonances seen

KK Bose-Einstein correlations

compare LEP, $f_0(980)$ issues