HADRONIC FINAL STATES AT HERA

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for the H1 and ZEUS Collaborations

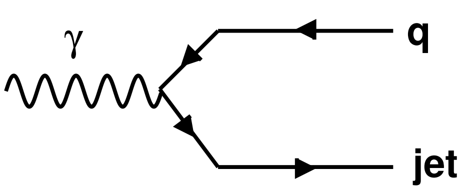
- **Charged multiplicities**
- **Inclusive jets**
- **Multijets**
- **Forward jets**
- **Strange particles**
- **Bose-Einstein correlations**

(1) CHARGED MULTIPLICITIES IN DIS (ZEUS)

HERA: 920 GeV p on 27.5 GeV $e^{\pm}$. Q^2 = virtuality of exchanged γ.

Aims:

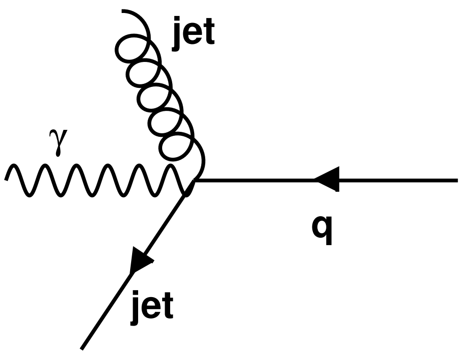
DIS **Breit Frame** at lowest order
looks like 1/2 an e^+e^- scattering event.
Study fragmentation in terms of charged particle multiplicity $<n_{\rm ch}>$.
Current (jet) region mostly within ZEUS CTD.



(LO)

Main selections:

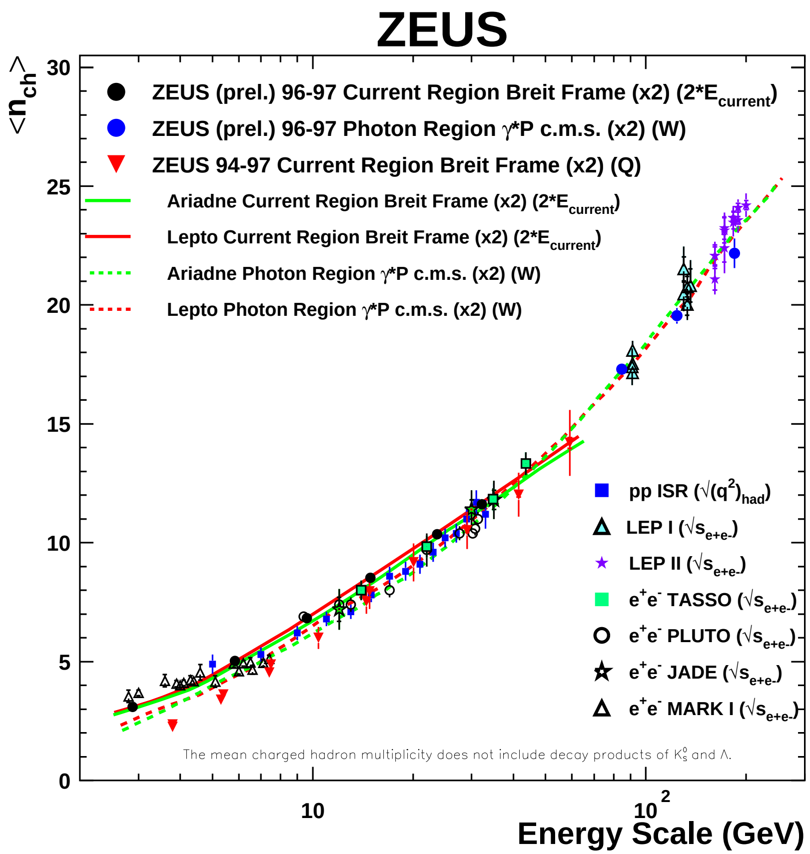
- $E_{e'} > 12$ GeV for scattered $e^{\pm}$
- cuts to reject remaining photoproduction
- reject diffractive events
- p_T of tracks > 150 MeV
- $\eta_{\rm lab} < 1.75$ for good tracks

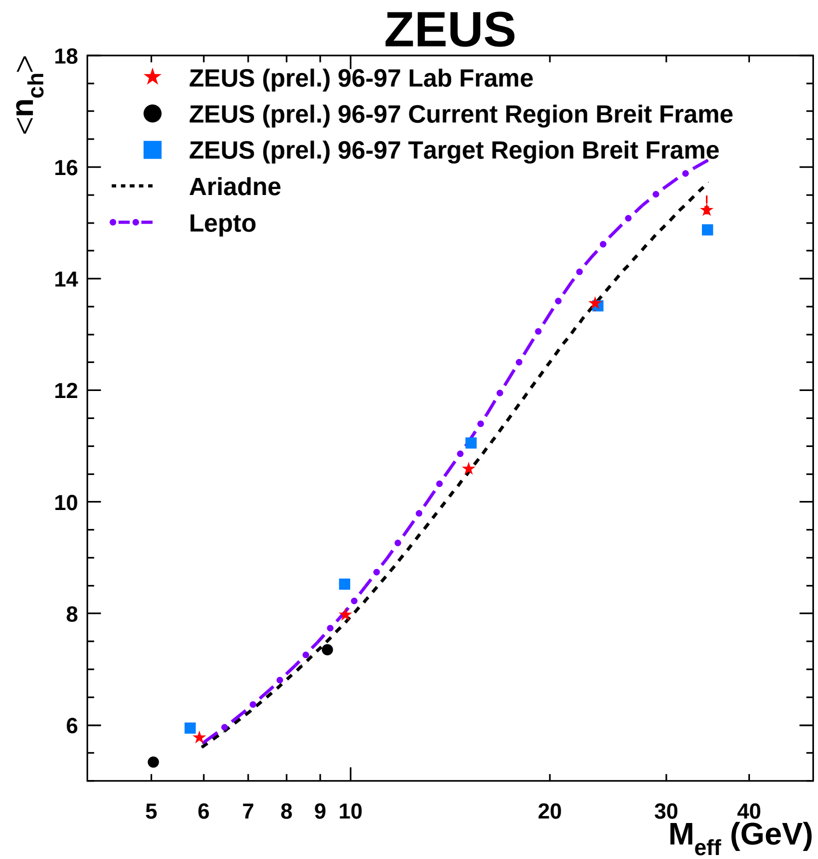


(HO)

Compare with **ARIADNE 4.08** (Colour dipole model)
and with **LEPTO 6.5**, both using Lund strings.

CHARGED MULTIPLICITIES IN DIS: RESULTS



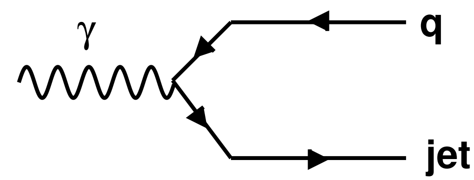


- The HERA measurements agree with others over wide range of energy scale, provided E_{current} or W is used.
- **ARIADNE** gives a better description than **LEPTO**

(2) INCLUSIVE JETS IN DIS (ZEUS)

Aims:

Improved jet measurements in Breit Frame,
$\rightarrow$ better comparison with models,
$\rightarrow$ α_S determination.

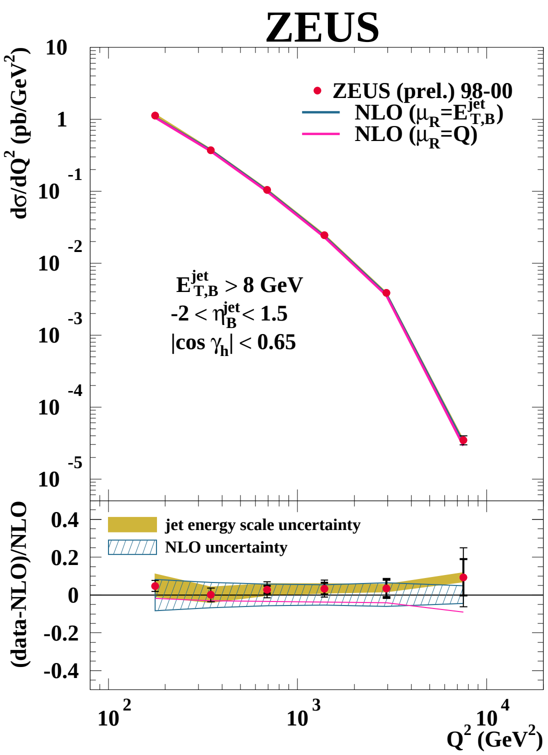


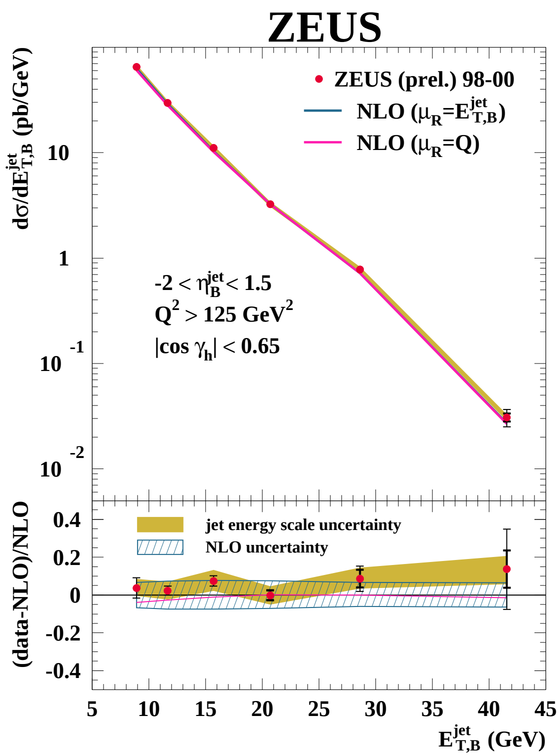
Main selections:

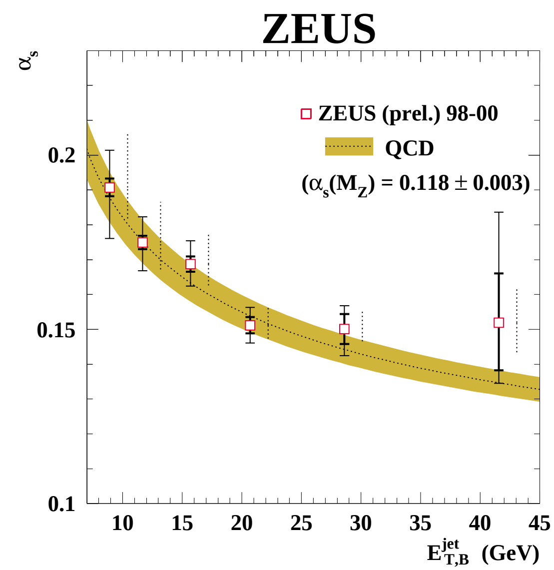
– $Q^2 > 125$ GeV^2
– cuts to reject remaining photoproduction
– Good jet acceptance: $-0.7 < \cos\gamma < 0.5$
where $\gamma =$ angle of LO emerging parton.

Reconstruct jets from calorimeter signals, with longitudinally invariant k_T cluster algorithm.
Select $-2 < \eta^B < 1.8$ and $E_T^B > 8$ GeV for jet in Breit Frame.

Compare with **DISENT** (LO + NLO) ($\alpha_S = 0.1175$)
Theory uncertainty: vary PDFs and vary renorm. scale by factor 2, 0.5.







Good agreement with earlier results and with NLO QCD (DISENT)

Evaluate α_S from $d\sigma/dE_{T,B}^{jet}$ for $E_{T,B}^{jet} > 8$ GeV:

$$\alpha_S(M_Z) = 0.1201 \pm 0.0006(\text{stat.})\ ^{+0.0033}_{-0.0038}(\text{exp.})\ ^{+0.0049}_{-0.0032}(\text{th.})$$

from $d\sigma/dQ^2$ for $Q^2 > 500$ GeV^2:

$$\alpha_S(M_Z) = 0.1196 \pm 0.0011(\text{stat.})\ ^{+0.0019}_{-0.0025}(\text{exp.})\ ^{+0.0029}_{-0.0017}(\text{th.})$$

(3) MULTIJETS IN DIS (H1, ZEUS)

Aims:

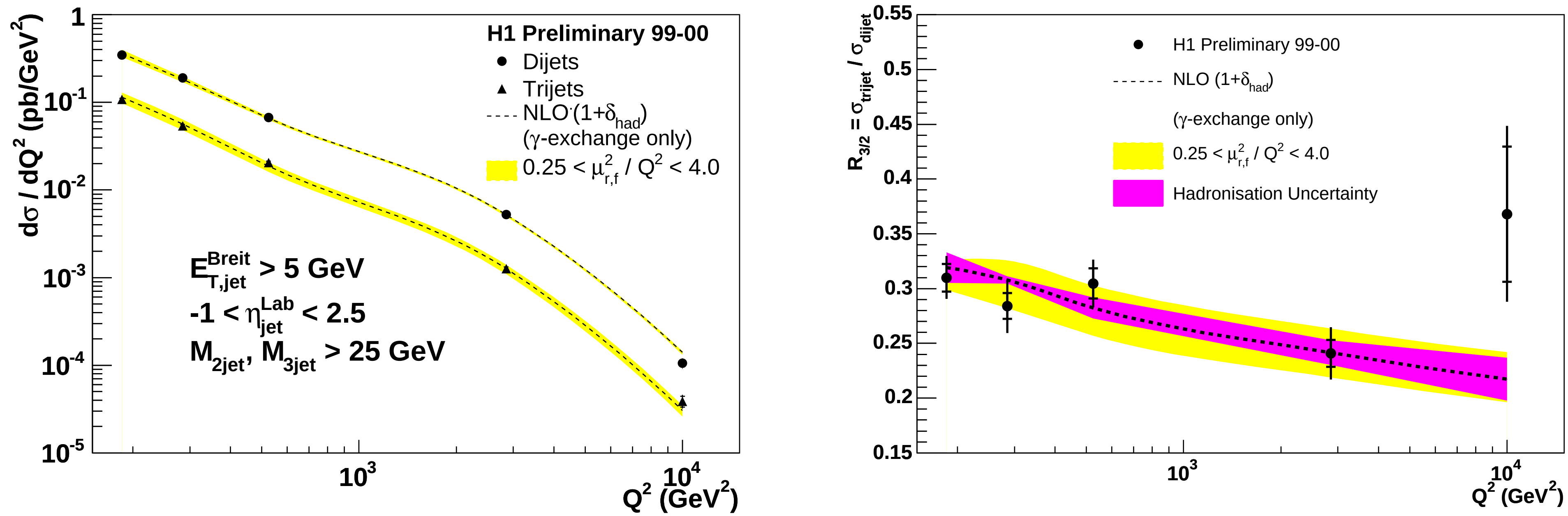
2- and 3-jet measurements in Breit Frame,
$\rightarrow$ compare with NLO calculation, α_S determination.

Main selections:

– $150 < Q^2 < 15000$ GeV^2
– $0.2 < y < 0.6$
– reject photoproduction

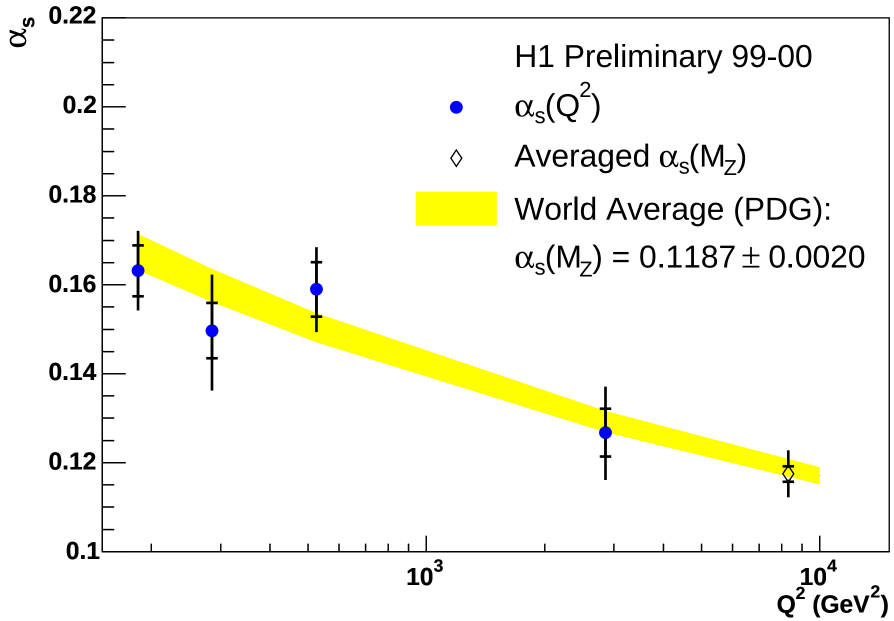
Reconstruct jets from tracks and calorimeter signals, with longitudinally invariant k_T cluster algorithm.
Require $-1 < \eta^B < 2.5$ and $E_T^B > 5$ GeV for jet in Breit Frame.

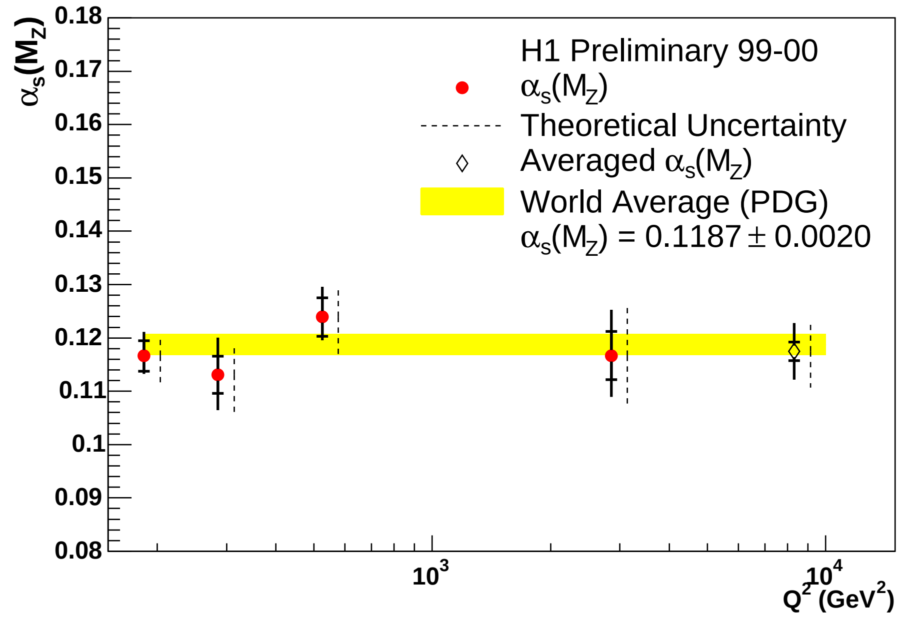
Correct measured and parton Xsecs to hadron level using ARIADNE, RAPGAP.
Compare with **NLO++**.
(DISENT and DISASTER do 2-jet but not 3-jet states in ep collisions.)
Theory uncertainty: vary PDFs, vary renorm. scale by factor 2, 0.5.



Good agreement between 2-, 3-jet cross sections and NLO QCD (NLO++)
Ratio $R_{3/2}$ agrees well except at highest Q^2 point.

(nb. e/w contribution not included in highest point.)

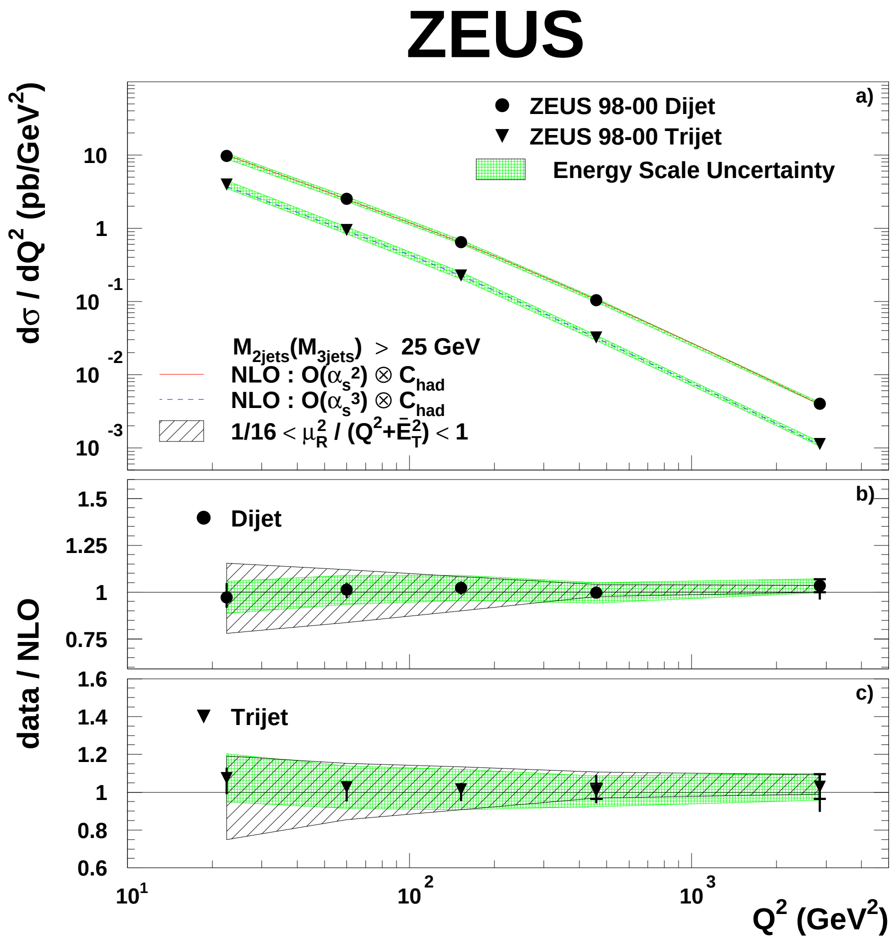


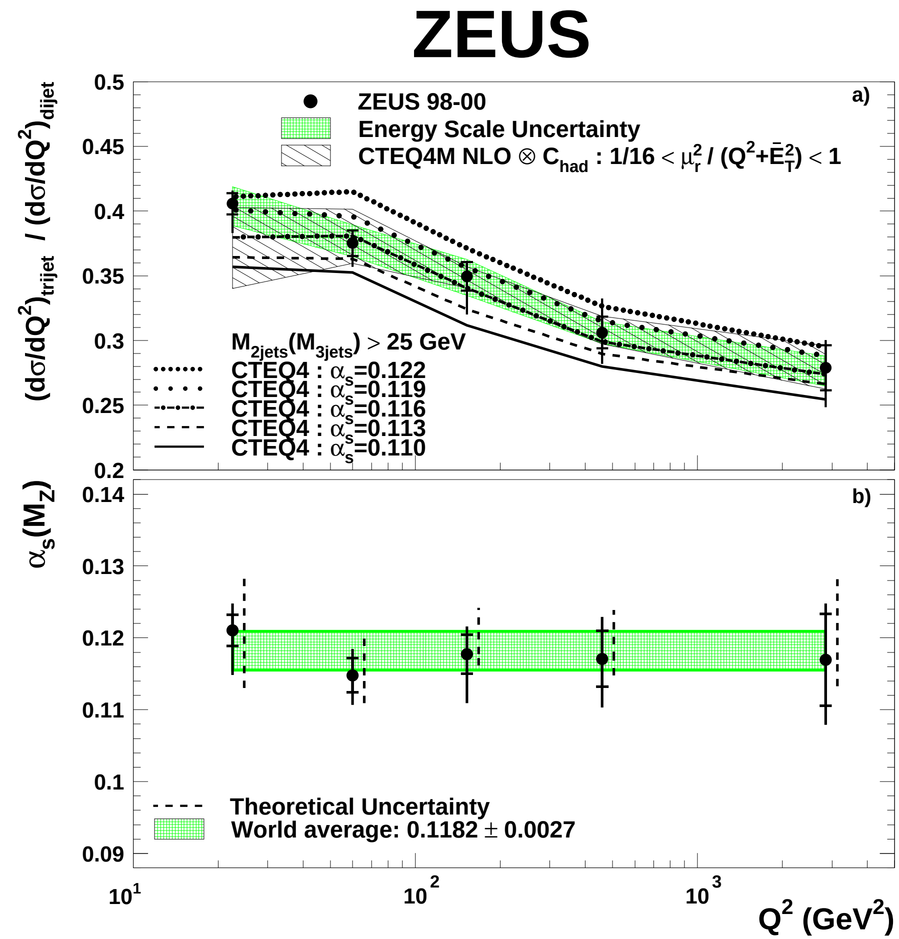


RESULTS (continued):

Use $R_{3/2}$ to evaluate α_S and $\alpha_S(M_Z)$ as functions of Q^2.
Agreement with world average, running is apparent.
Fitted value from this analysis:

$$\alpha_S(M_Z) = 0.1175 \pm 0.0017(\mathrm{stat}) \pm 0.0050(\mathrm{sys})^{+0.0054}_{-0.0068}(\mathrm{theory})$$





Similar analysis from ZEUS using NLOJET (checked against DISENT):

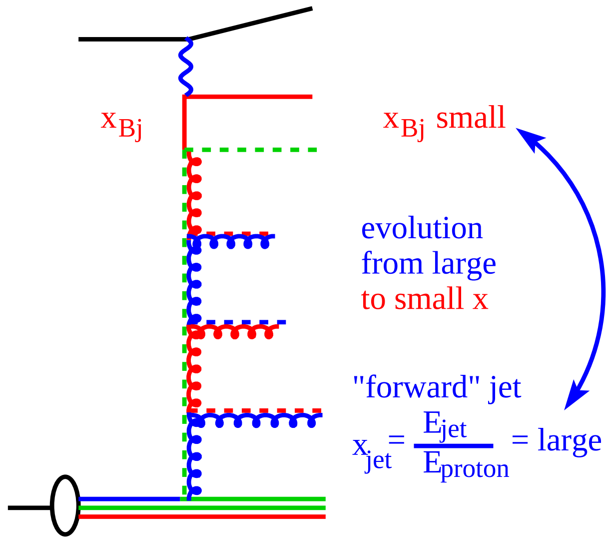
Fitted value of α_s:

$$\alpha_S(M_Z) = 0.1179 \pm 0.0013(\text{stat})^{+0.0028}_{-0.0046}(\text{exp.})^{+0.0064}_{-0.0046}(\text{theory})$$

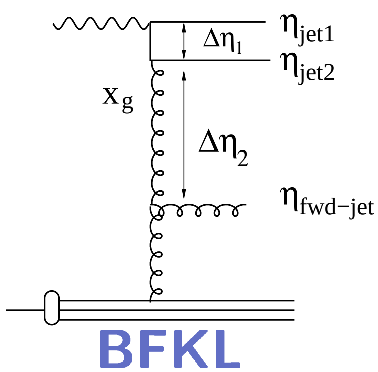
Aims:

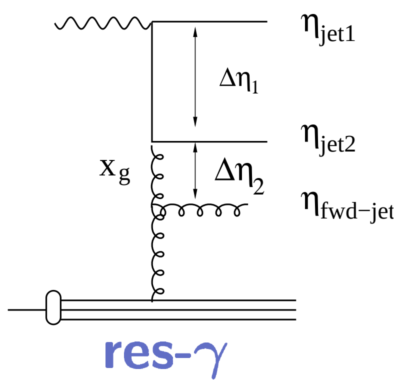
Try to reveal BFKL dynamics by studying forward jets with

$$x_{\rm jet} = \frac{E_{\rm jet}}{E_p} \gg x_{Bj} \quad \text{and} \quad p_T^2 \approx Q^2$$



In addition, properties of a central dijet system can correlate with a transition between resolved-photon-like and BFKL processes.





FORWARD JETS IN DIS

H1 cuts: (all quantities in lab.):
- $E_{e'} > 10$ GeV, $156^\circ < \theta_e < 175^\circ$; $5 < Q^2 < 85$ GeV^2
- $0.1 < y < 0.7$
- $0.0001 < x_{Bj} < 0.004$

ZEUS:
- $E_{e'} > 10$ GeV,+min. ang. cut; $20 < Q^2 < 100$ GeV^2
- $0.04 < y < 0.7$
- $0.0004 < x_{Bj} < 0.005$

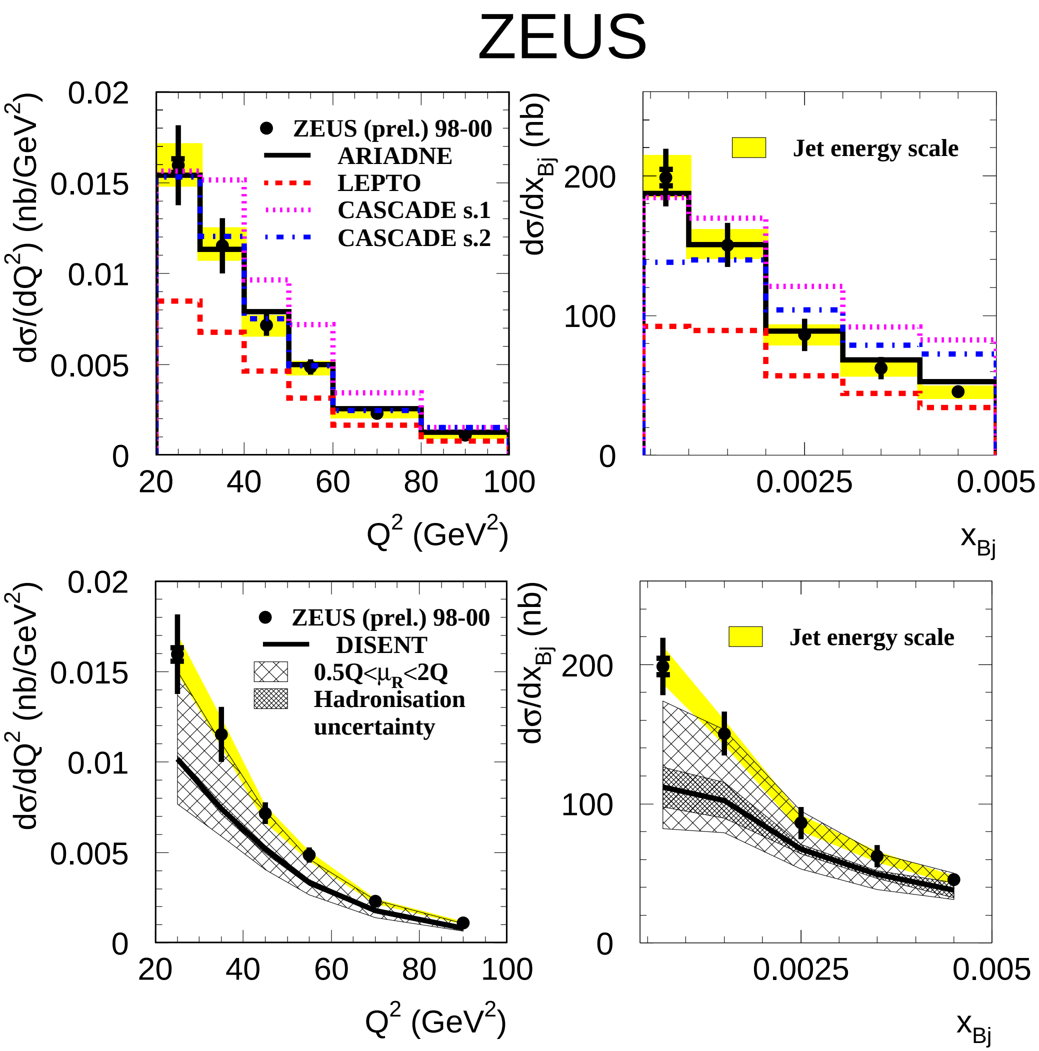
Use k_T-defined jets with:

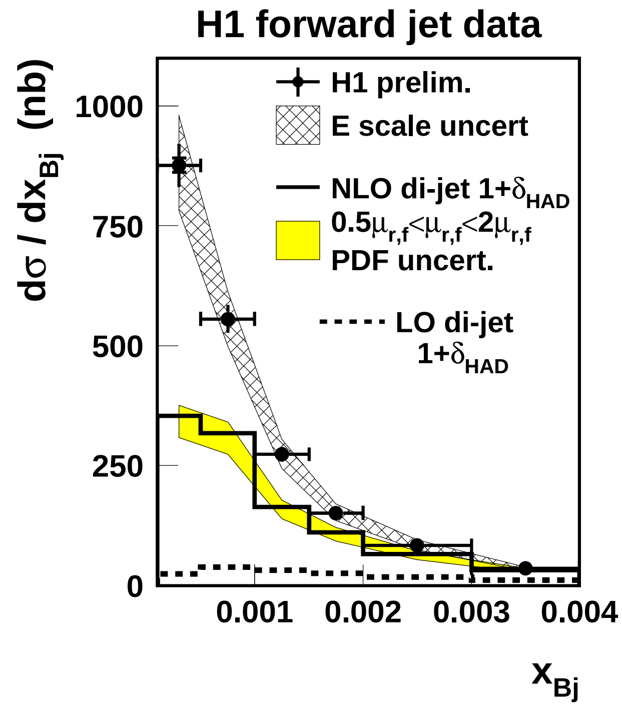
H1: $p_{T,\mathrm{jet}} > 3.5$ GeV; $x_{\mathrm{jet}} > 0.035$; $7^\circ < \theta_{\mathrm{jet}} < 20^\circ$.

ZEUS: $p_{T,\mathrm{jet}} > 5$ GeV; $x_{\mathrm{jet}} > 0.036$ or $E_{\mathrm{jet}} > 33$ GeV;
$0.5 < Q^2/E^2_{T,\mathrm{jet}} < 2.0$; $2.0 < \eta_{\mathrm{jet}} < 3.5$.

Compare to models:
- DGLAP: LEPTO, NLOJET++, DISENT
- Colour dipole model in ARIADNE
- CCFM model in CASCADE

FORWARD JETS IN DIS: RESULTS





ARIADNE ≈OK.

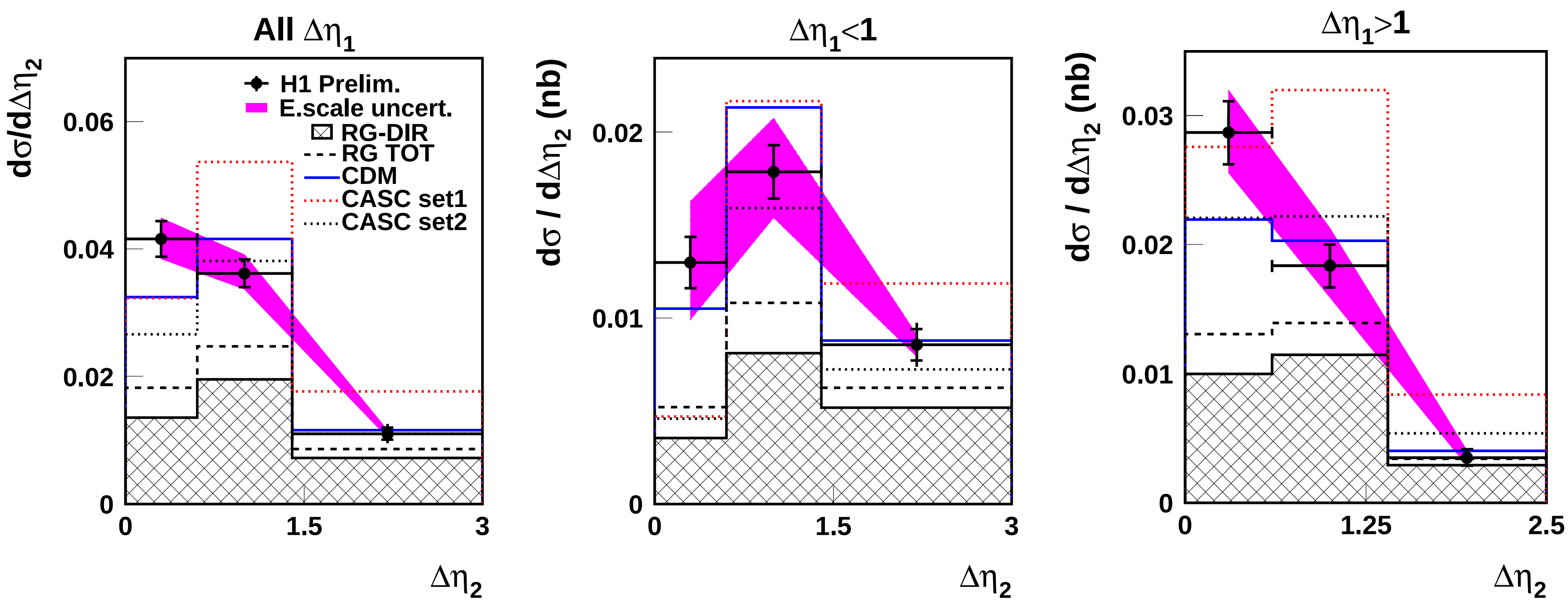
LEPTO fails.

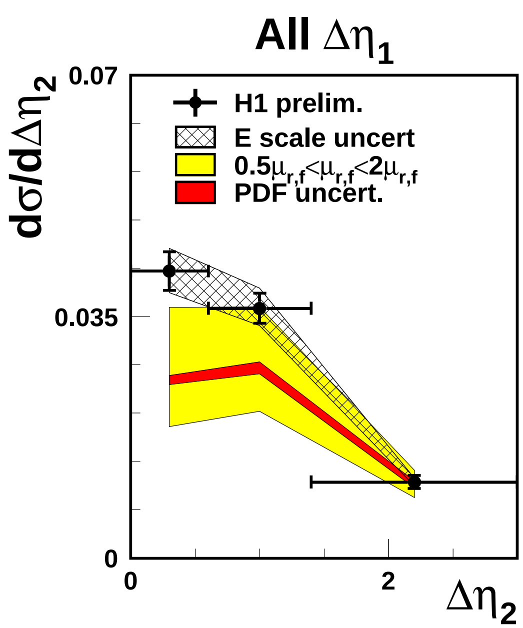
CASCADE 1, 2 poor

H1: DISENT fails.

ZEUS: DISENT is OK! – within large theory uncertainties for $x_{Bj} > 0.001$

FORWARD JETS IN DIS: RESULTS





H1 Xsecs for different separations $\Delta\eta$ between forward jet and jets of dijet pair.

All models poor in lowest $\Delta\eta 2$ bin.
DGLAP OK in highest $\Delta\eta 2$ bin.

ARIADNE, CASCADE 2, NLOJET++ ≈OK,

Aims:

- Xsecs for K^0 and Λ production;
- $\Lambda/\bar{\Lambda}$ asymmetry;
- Λ/K^0 production ratio;
- Λ polarisation = $P_\perp^\Lambda$, $P_{||}^\Lambda$;

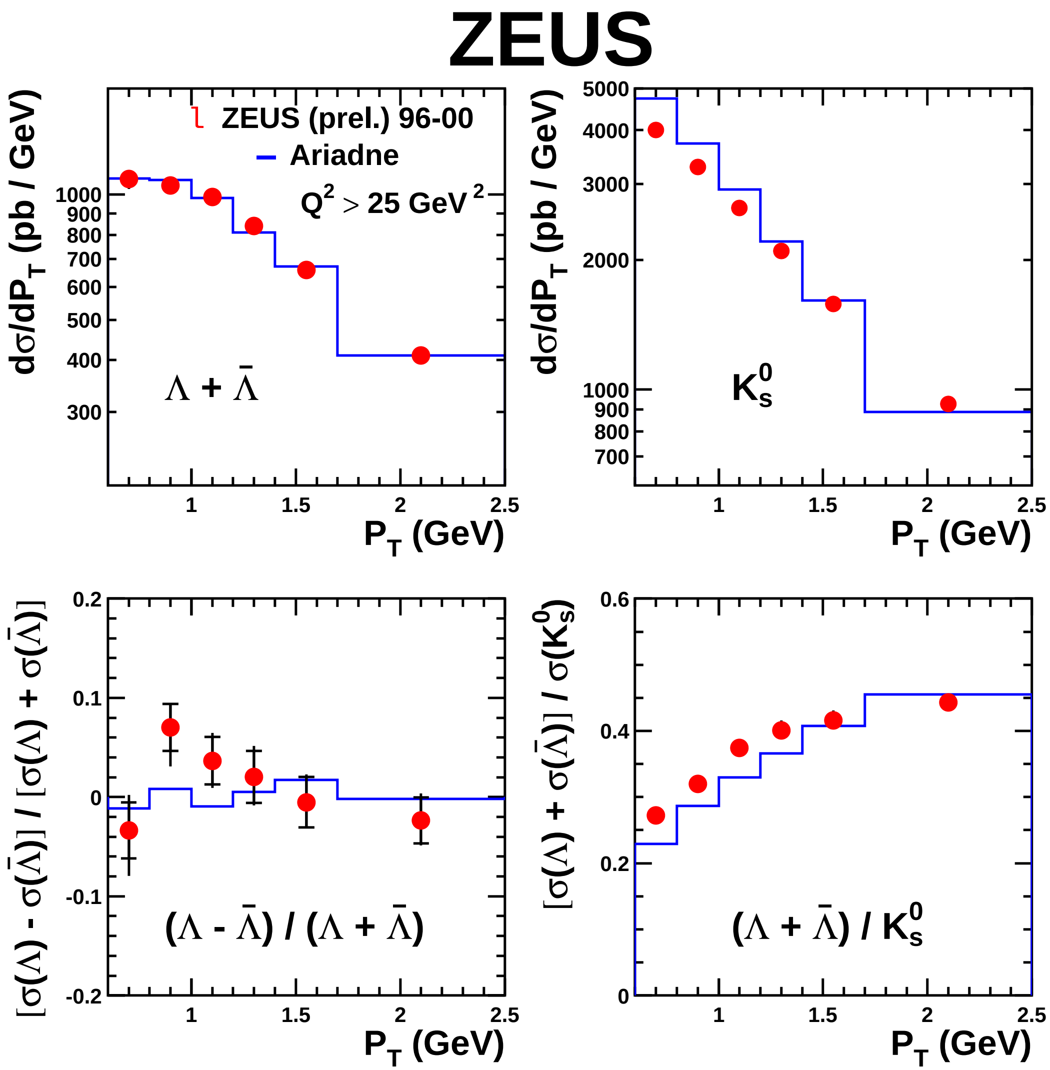
  $\frac{dN}{d\Omega} = \frac{1}{4\pi}(1 \pm \alpha P \cos\theta)$ in Λ rest frame. $\alpha = 0.642 \pm 0.013$

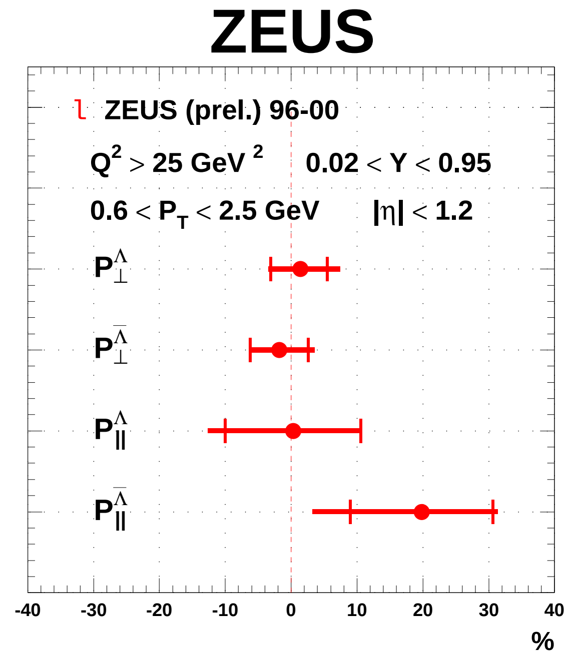
Longitudinal $P_{||}^\Lambda$ has θ between proton and Λ;
Transverse $P_\perp^\Lambda$ has θ between proton and plane of electron and Λ;

Laboratory frame: detect as $K^0 \to \pi^+\pi^-$ and $\Lambda \to p\pi^+$ and c.c.

– $Q^2 > 25$ GeV^2
– $0.02 < y < 0.95$
– $0.6 < p_T < 2.5$ GeV for each species
– $|\eta| < 1.2$ for each species

Compare with ARIADNE 4.08 predictions





← Typical set of results.

ARIADNE mostly OK.

Polarisation consistent with zero apart perhaps from $P_{||}^{\bar{\Lambda}}$

Breit Frame analysis to come.

(6) BOSE-EINSTEIN CORRELATIONS IN DIS (ZEUS)

Aim:

Measure Bose-Einstein Correlations in DIS for K^0 and $K^\pm$

Summary of formalism:

Define 2-particle correlation function as

$$R(Q^2) = \frac{P(Q_{12})^{\mathrm{Data}}}{P_{\mathrm{mix}}(Q_{12})^{\mathrm{Data}}} \Bigg/ \frac{P(Q_{12})^{\mathrm{MC,noBEC}}}{P_{\mathrm{mix}}(Q_{12})^{\mathrm{MC,noBEC}}}$$

Density P in terms of Q_{12} = 4-momentum difference, calculated for:

– particle pairs in Data events;

– particle pairs in different events (mix);

– Ditto for MC samples with no B.E.C.

Fit results using Goldhaber expression :

$$R(Q^2) = \alpha \left(1 + \lambda e^{-Q_{12}^2 r^2}\right)(1 + \delta Q_{12})$$

α = normalisation factor; r = radius of source;

λ = strength term;

(second term describes long-range effects here found to be ignorable).

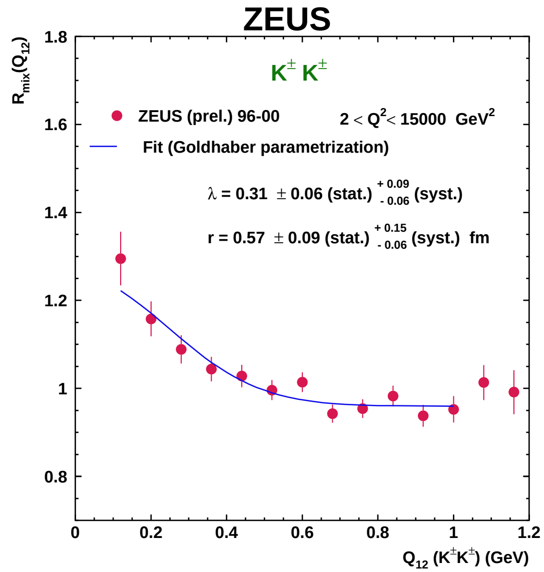
Select:

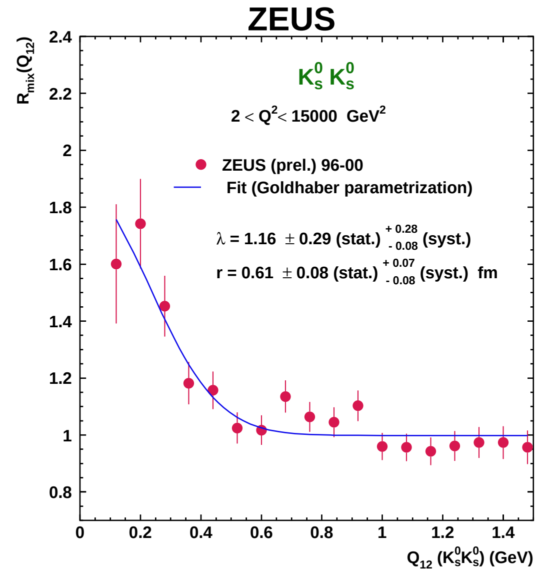
ZEUS tracks,

– $p_T > 0.15$ GeV

– $|\eta| < 1.75$.

Particle ID uses dE/dx measurement.





Results: $\rightarrow$

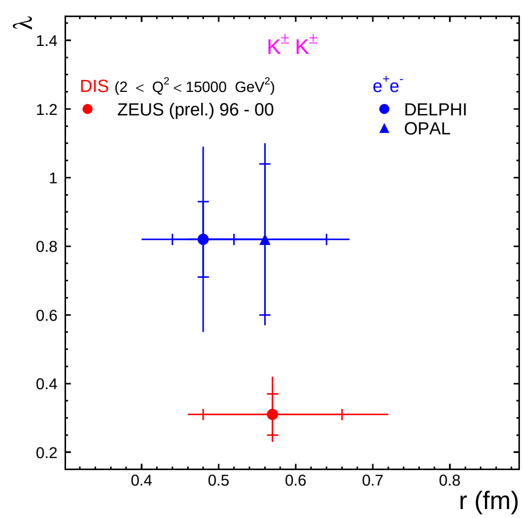
c.f. ZEUS $\pi^{\pm}$:-

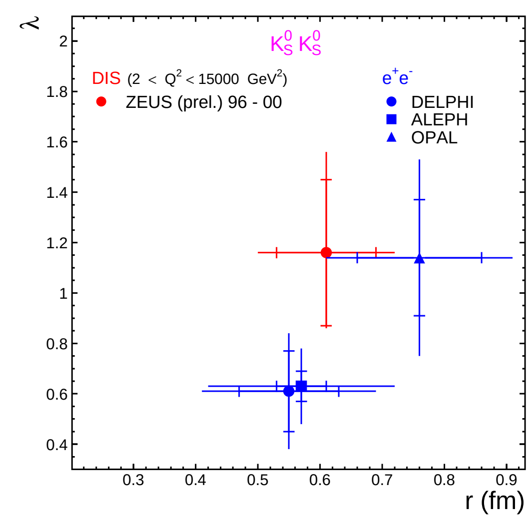
$(r = 0.666 \pm 0.009^{+0.022}_{-0.036}$

$\lambda = 0.475 \pm 0.007^{+0.011}_{-0.003}$)

λ smaller for $K^{\pm}$ than K^0.

Maybe due to resonances?





CONCLUSIONS

- **ARIADNE and NLO QCD in general are successful in describing most aspects of hadronic states in DIS.**
- **One high H1 bin at very low x (that ZEUS don't reach)**
  $\rightarrow$ signs of BFKL??
- **Charged multiplicities form a consistent picture.**
- **Strange particles present no surprises.**
- **B.E.C. measured with kaons now.**
- **More opportunities to measure α_s.**
- **HERA is still a very lively area to study QCD!**