



UNIVERSITY
of
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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.

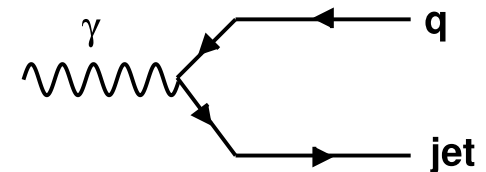
Study fragmentation in terms of charged particle multiplicity $\langle n_{\text{ch}} \rangle$.

Current (jet) region mostly within ZEUS CTD.

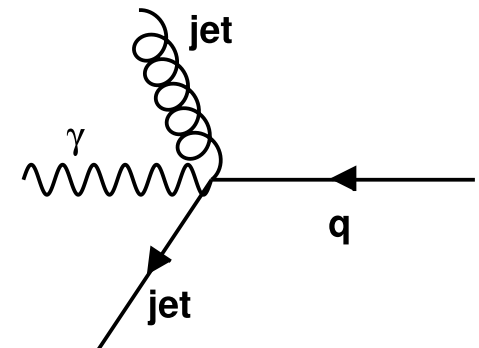
Main selections:

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

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

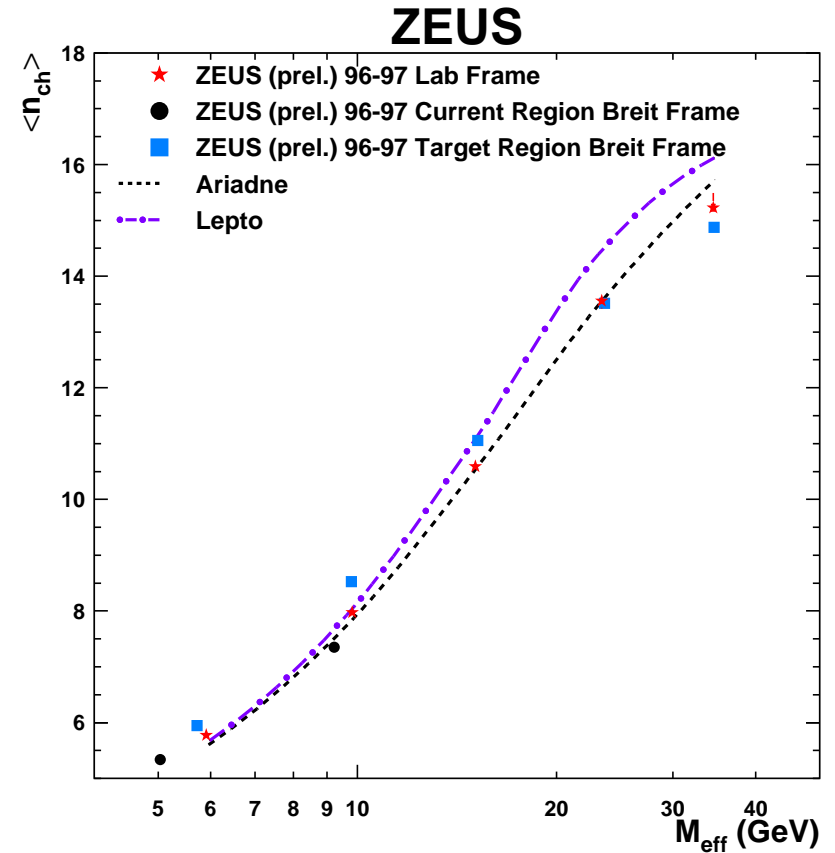
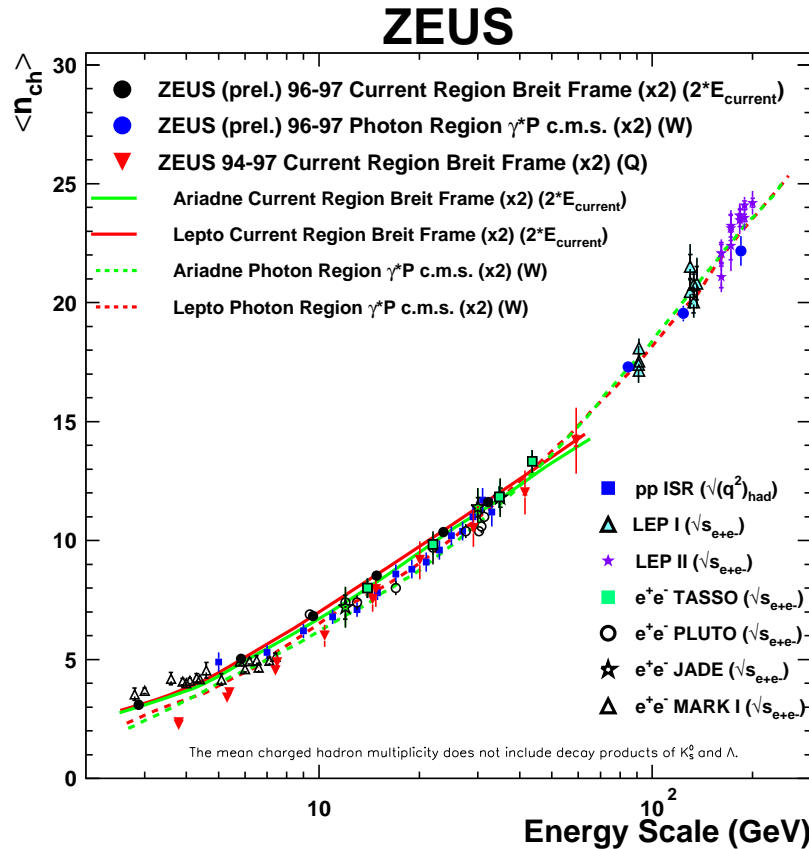


(LO)



(HO)

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

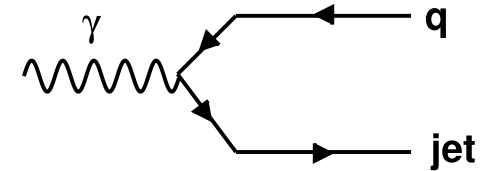
(2) INCLUSIVE JETS IN DIS (ZEUS)

Aims:

Improved jet measurements in Breit Frame,

→ better comparison with models,

→ α_S determination.



Main selections:

– $Q^2 > 125 \text{ GeV}^2$

– cuts to reject remaining photoproduction

– Good jet acceptance: $-0.7 < \cos \gamma < 0.5$

where γ = angle of LO emerging parton.

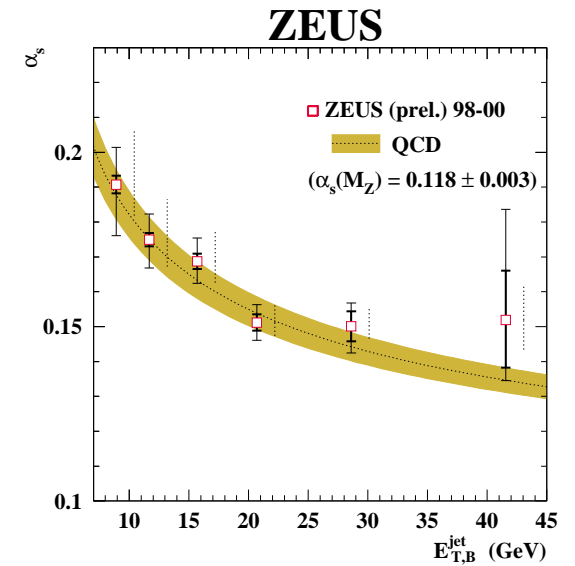
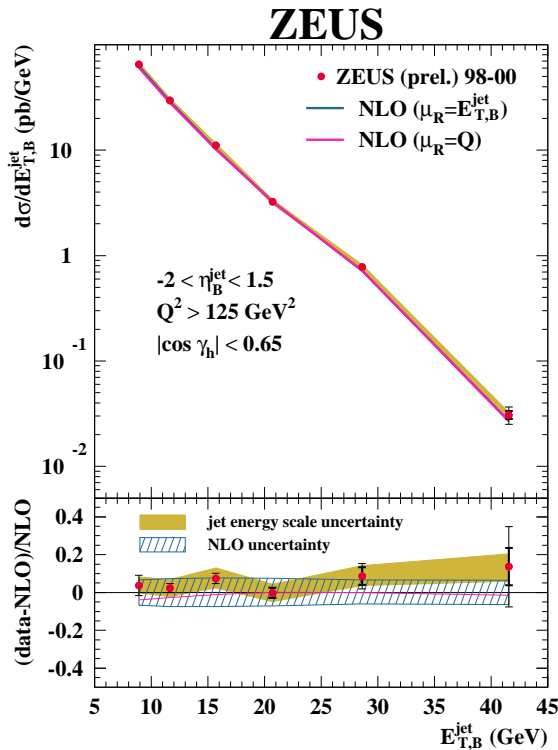
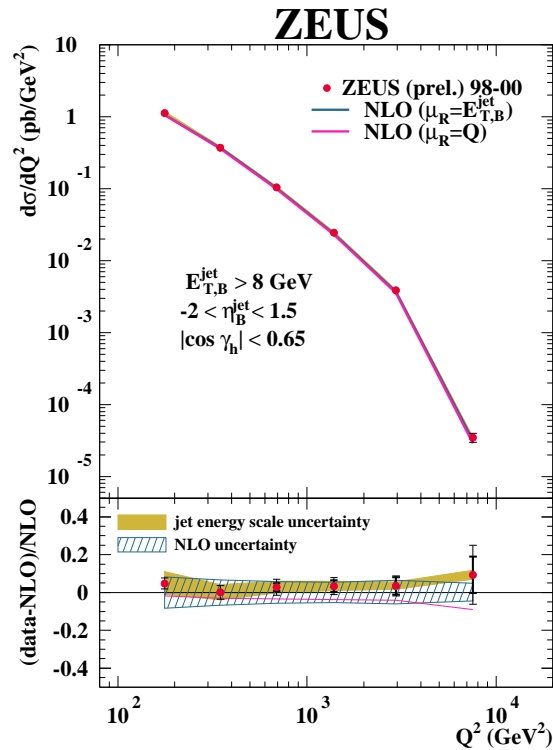
Reconstruct jets from calorimeter signals, with longitudinally invariant k_T cluster algorithm.

Select $-2 < \eta^B < 1.8$ and $E_T^B > 8 \text{ GeV}$ 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.

INCLUSIVE JETS IN DIS: RESULTS



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

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

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

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

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

(3) MULTIJETTS IN DIS (H1, ZEUS)

Aims:

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

Main selections:

- $150 < Q^2 < 15000 \text{ GeV}^2$
- $0.2 < y < 0.6$
- reject photoproduction

Reconstruct jets from tracks and calorimeter signals, with longitudinally invariant k_T cluster algorithm.

Require $-1 < \eta^B < 2.5$ and $E_T^B > 5 \text{ GeV}$ for jet in Breit Frame.

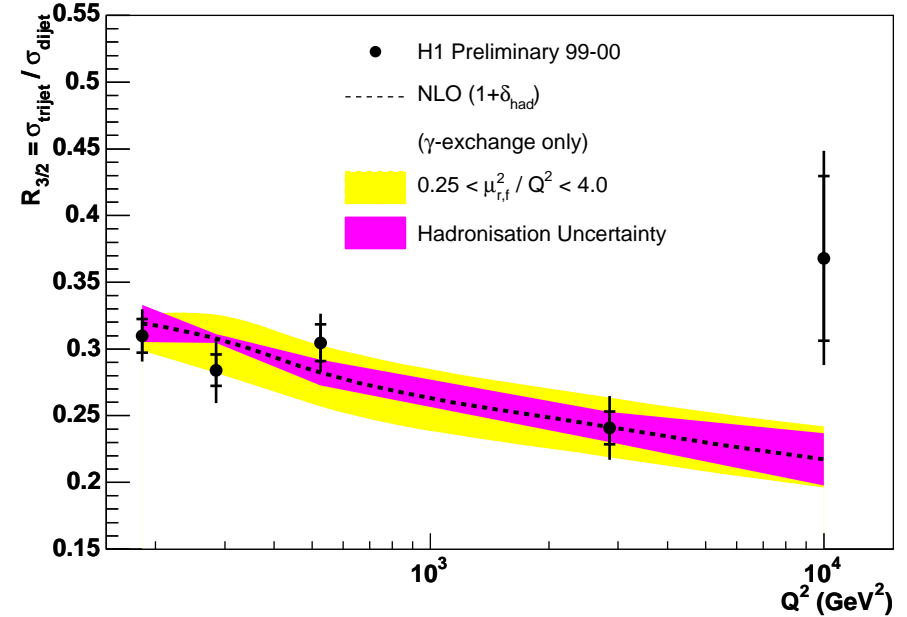
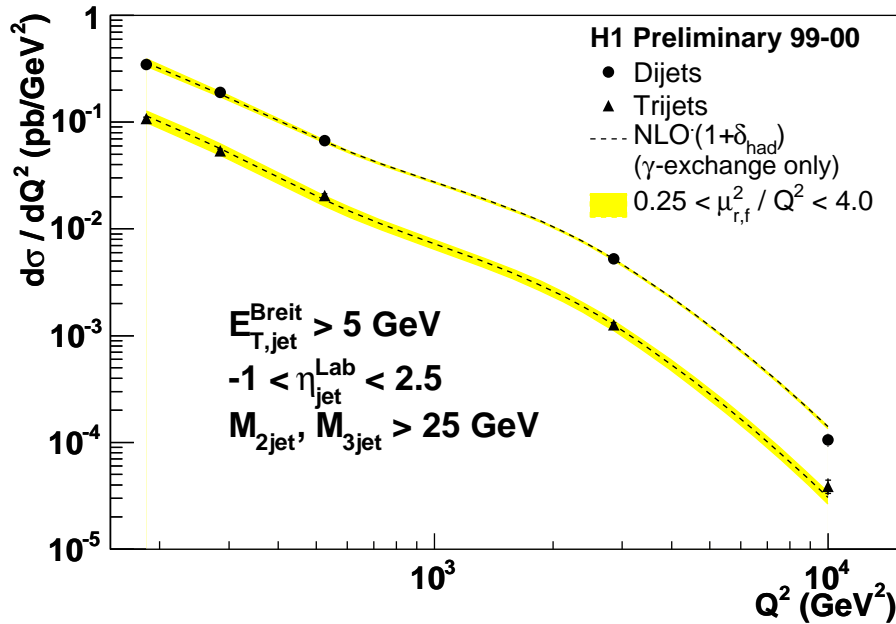
Correct measured and parton Xsecs to hadron level using ARIADNE, RAPGAP.

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.

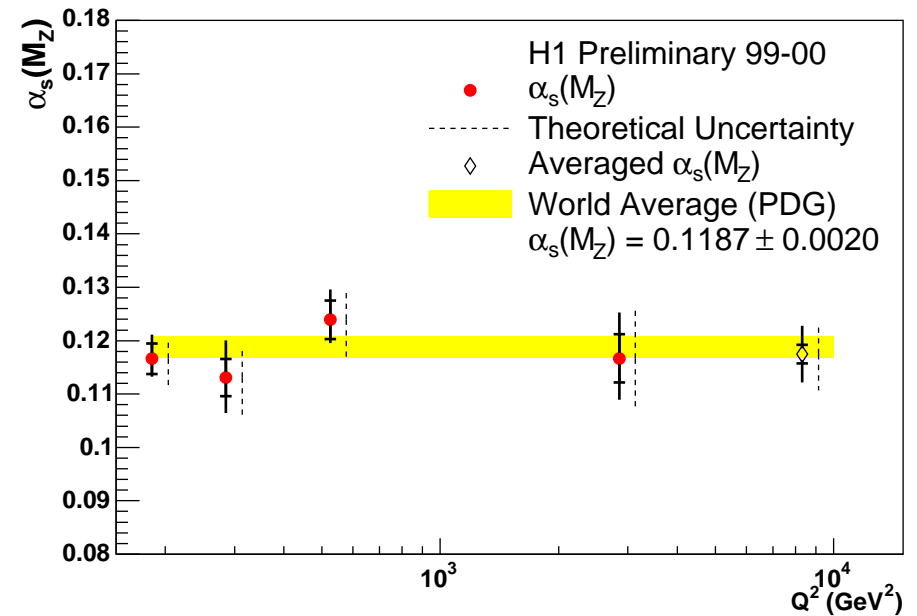
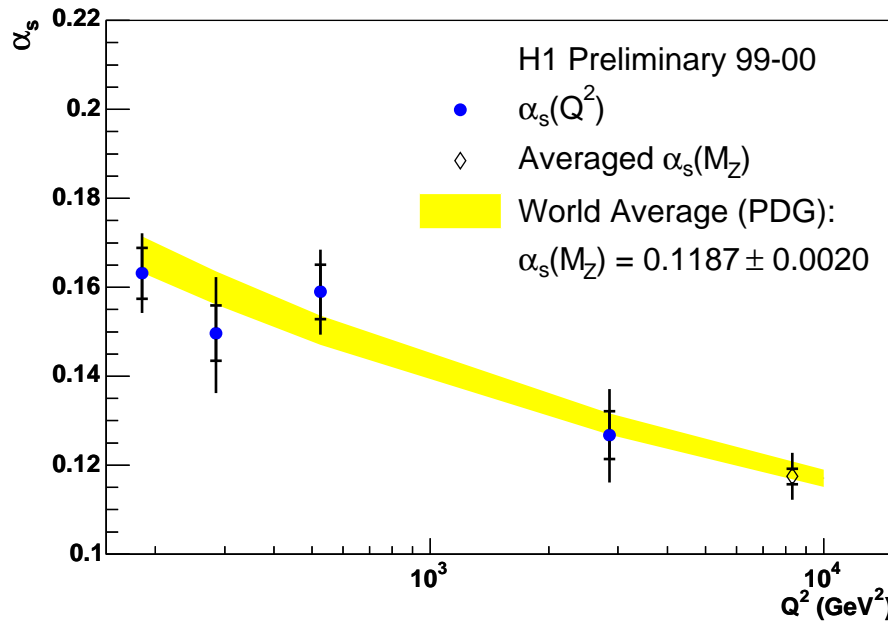
MULTIJETS IN DIS: RESULTS



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.)

MULTIJETS IN DIS



RESULTS (continued):

Use $R_{3/2}$ to evaluate α_S and $\alpha_S(M_Z)$ as functions of Q^2 .

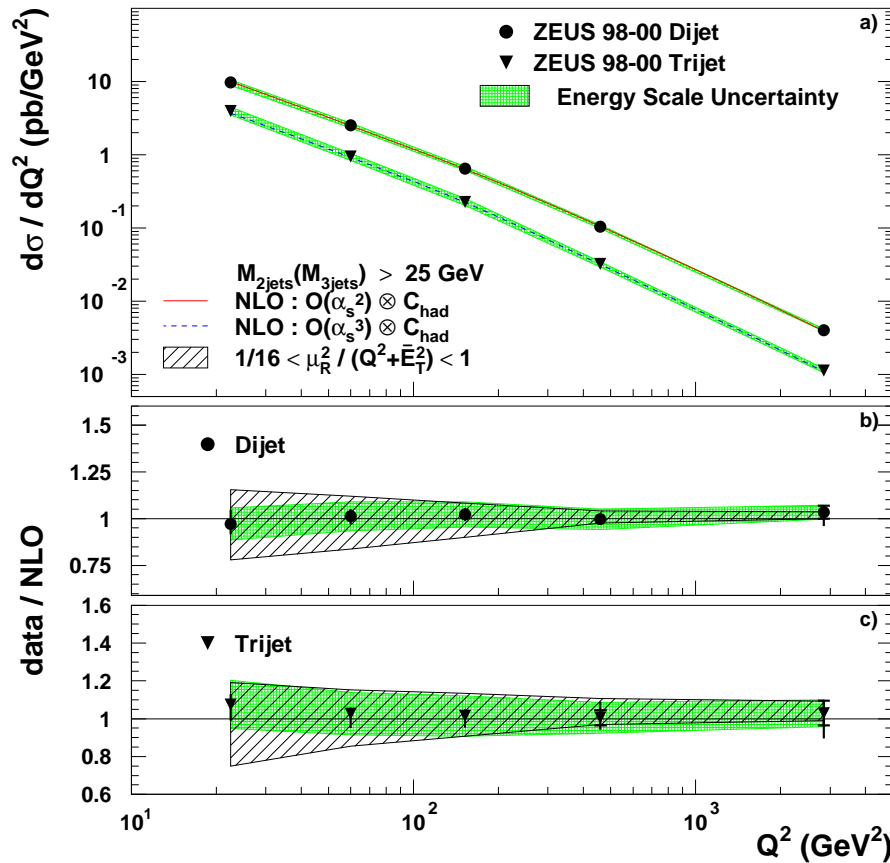
Agreement with world average, running is apparent.

Fitted value from this analysis:

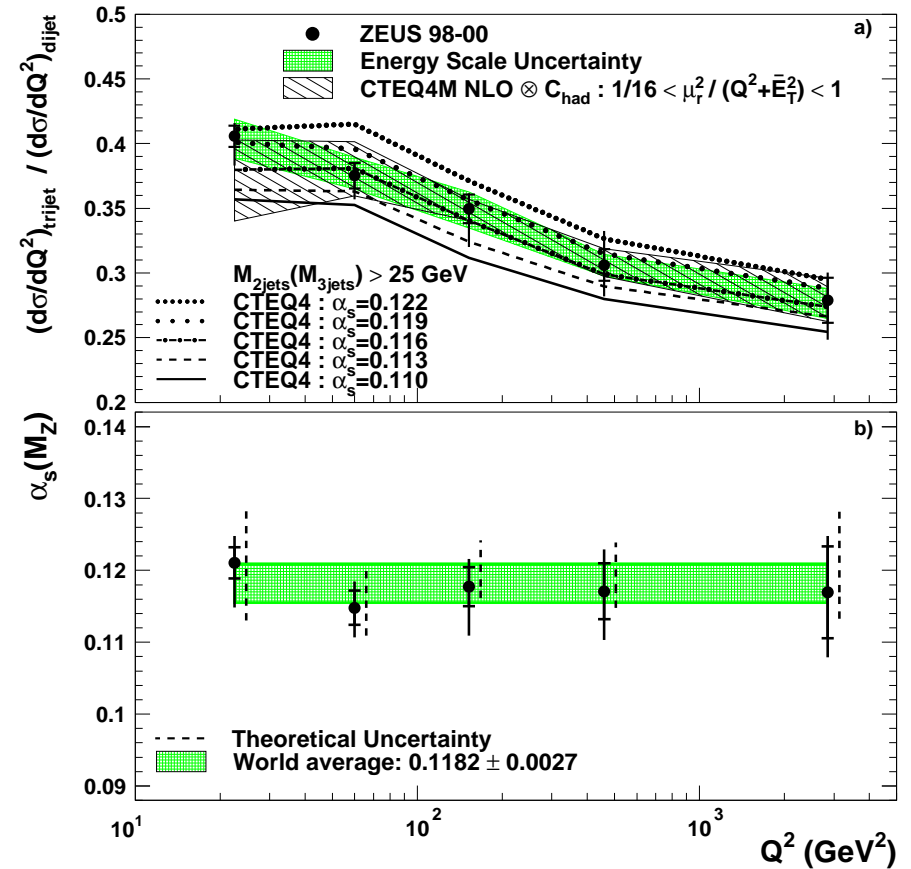
$$\alpha_S(M_Z) = 0.1175 \pm 0.0017(\text{stat}) \pm 0.0050(\text{sys})^{+0.0054}_{-0.0068}(\text{theory})$$

MULTIJETS IN DIS

ZEUS



ZEUS



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

Fitted value of α_s :

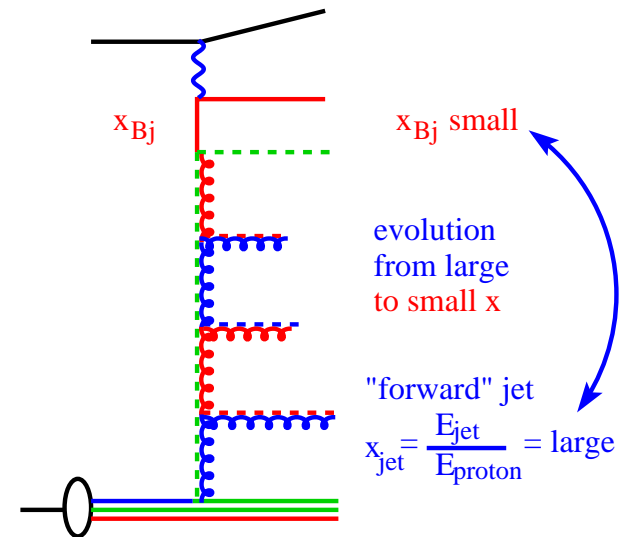
$$\alpha_s(M_Z) = 0.1179 \pm 0.0013(\text{stat})_{-0.0046}^{+0.0028}(\text{exp.})_{-0.0046}^{+0.0064}(\text{theory})$$

(4) FORWARD JETS IN DIS (H1, ZEUS)

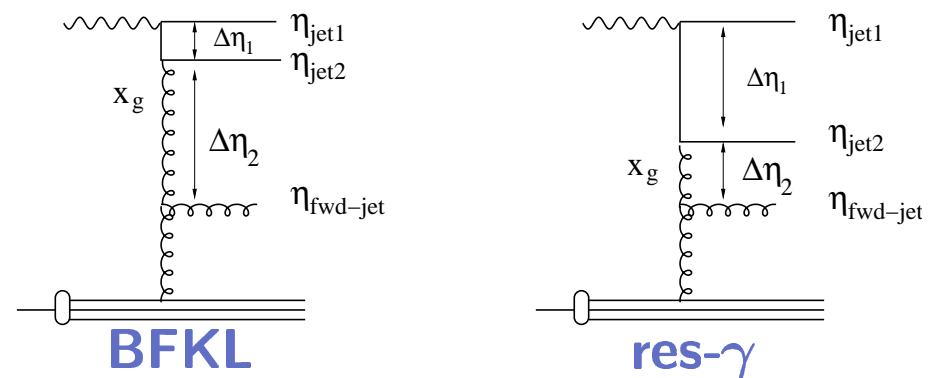
Aims:

Try to reveal BFKL dynamics by studying forward jets with

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



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.):

- $E_{e'} > 10 \text{ GeV}$, $156^\circ < \theta_e < 175^\circ$; $5 < Q^2 < 85 \text{ GeV}^2$
- $0.1 < y < 0.7$
- $0.0001 < x_{Bj} < 0.004$

ZEUS:

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

Use k_T -defined jets with:

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

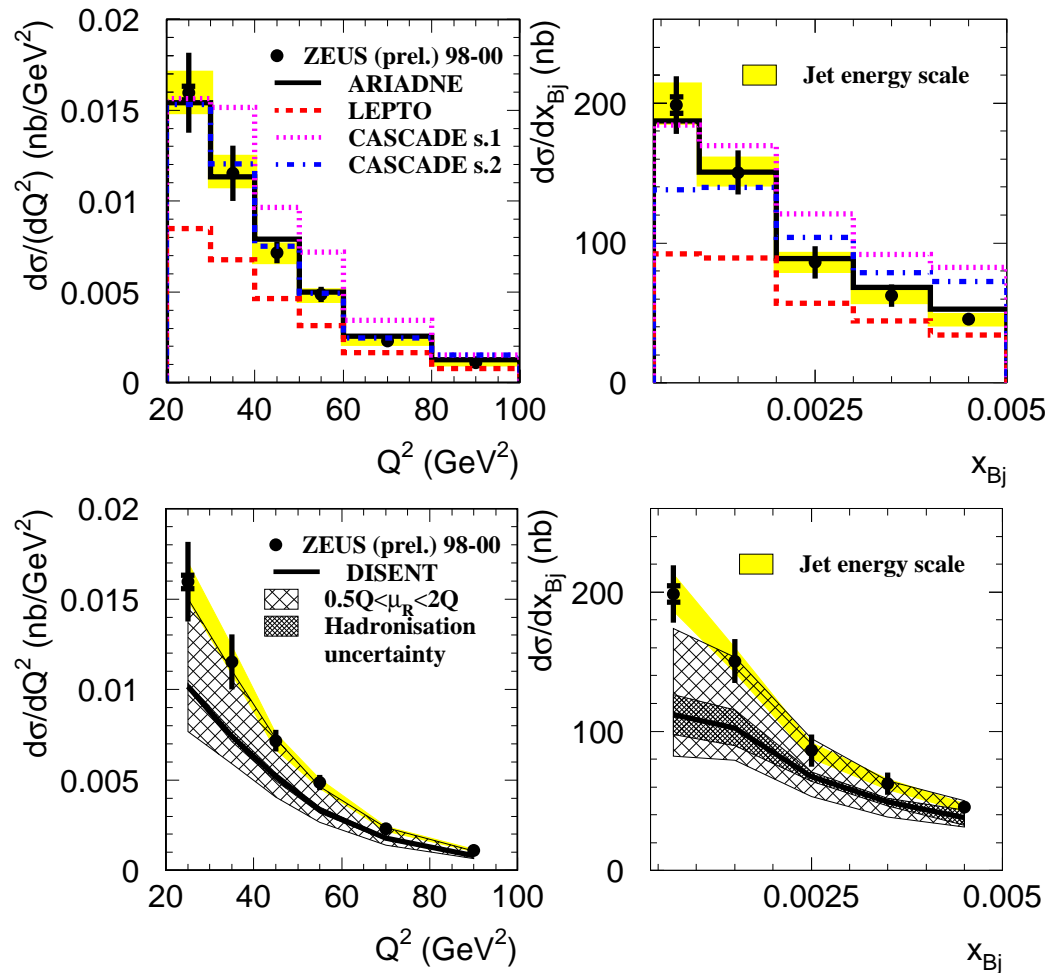
ZEUS: $p_{T,\text{jet}} > 5 \text{ GeV}$; $x_{\text{jet}} > 0.036$ or $E_{\text{jet}} > 33 \text{ GeV}$;
 $0.5 < Q^2/E_{T,\text{jet}}^2 < 2.0$; $2.0 < \eta_{\text{jet}} < 3.5$.

Compare to models:

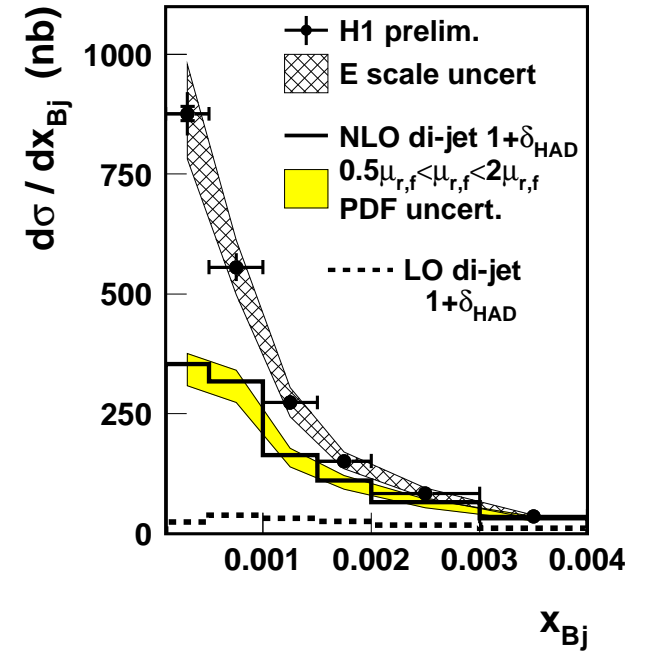
- DGLAP: LEPTO, NLOJET++, DISENT
- Colour dipole model in ARIADNE
- CCFM model in CASCADE

FORWARD JETS IN DIS: RESULTS

ZEUS



H1 forward jet data



ARIADNE \approx OK.

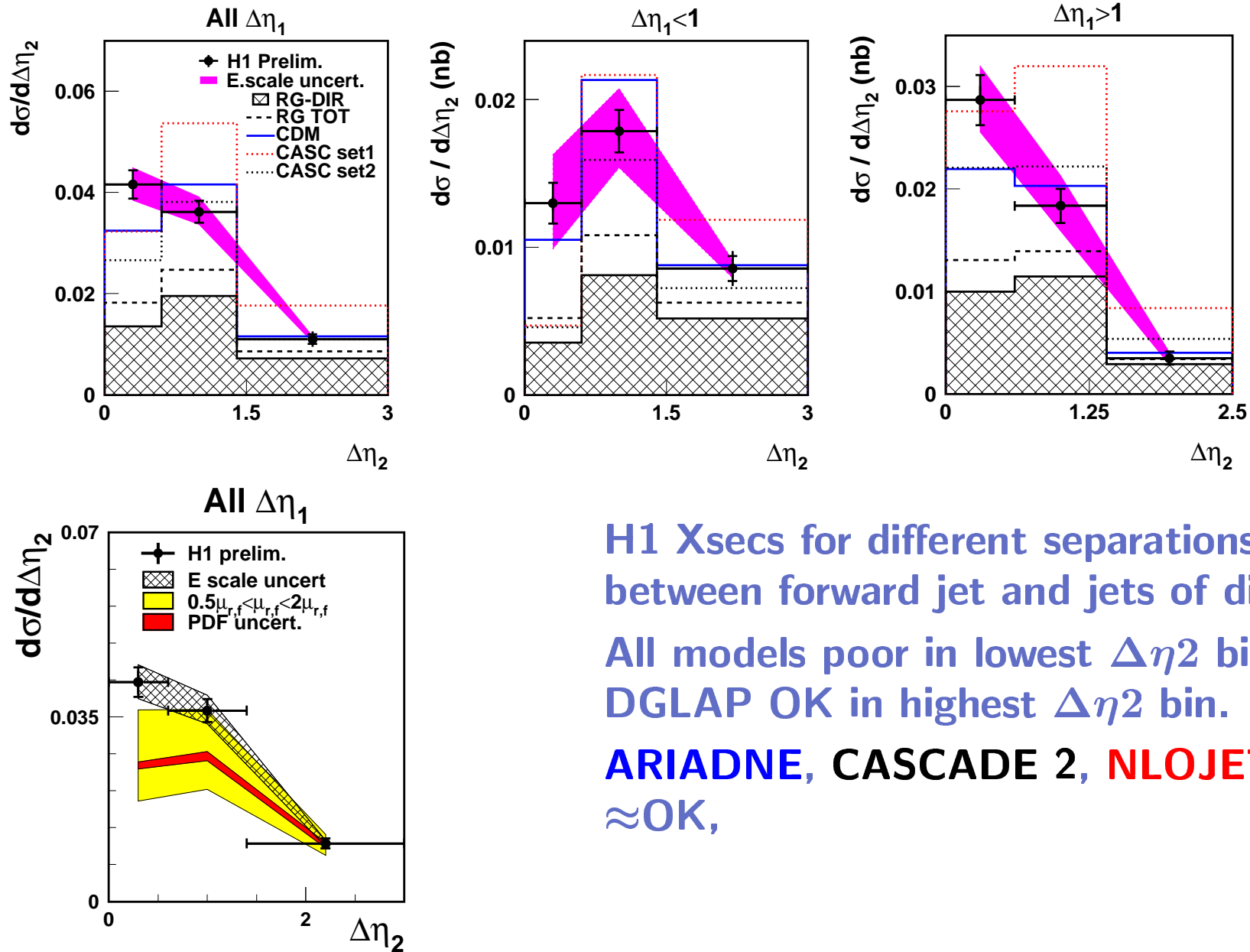
LEPTO fails.

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++
 \approx OK,

(5) NEUTRAL STRANGE PARTICLES IN DIS (ZEUS)

Aims:

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

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

Longitudinal $P_{||}^{\Lambda}$ has θ between proton and Λ ;

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

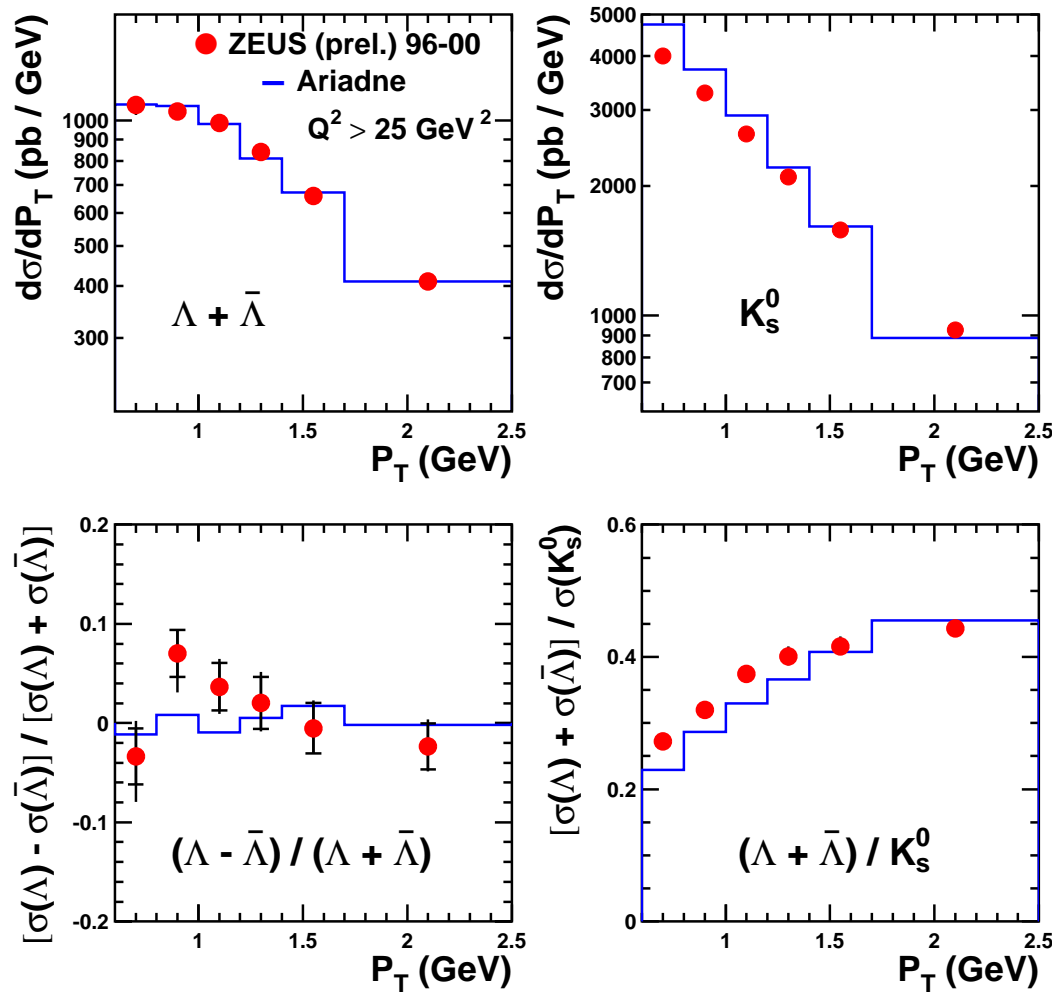
Laboratory frame: detect as $K^0 \rightarrow \pi^+\pi^-$ and $\Lambda \rightarrow p\pi^+$ and c.c.

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

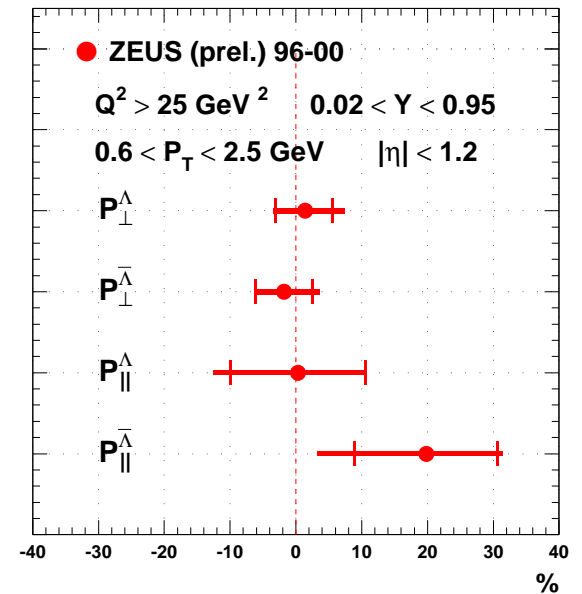
Compare with ARIADNE 4.08 predictions

NEUTRAL STRANGE PARTICLES IN DIS

ZEUS



ZEUS



← Typical set of results.
ARIADNE mostly OK.
 Polarisation consistent with zero apart perhaps from $P_{\parallel}^{\bar{\Lambda}}$
 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

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

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).

BOSE-EINSTEIN CORRELATIONS IN DIS

Select:

ZEUS tracks,

– $p_T > 0.15$ GeV

– $|\eta| < 1.75$.

Particle ID uses

dE/dx measurement.

Results: →

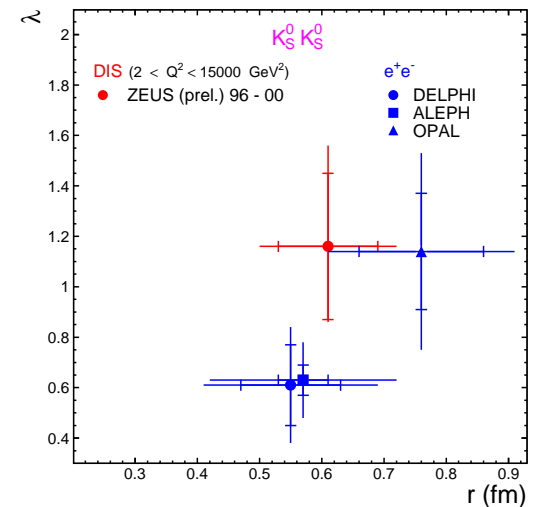
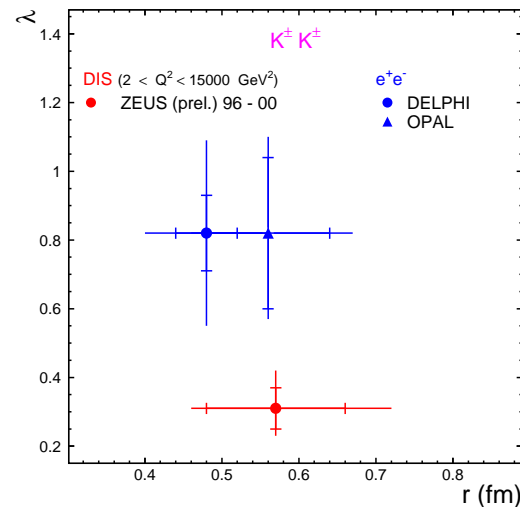
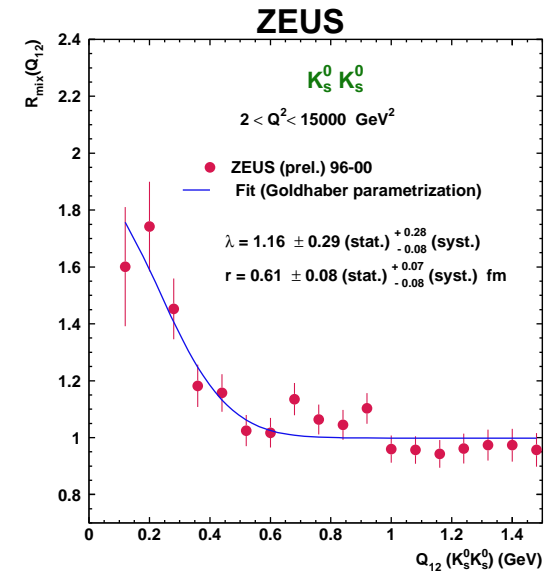
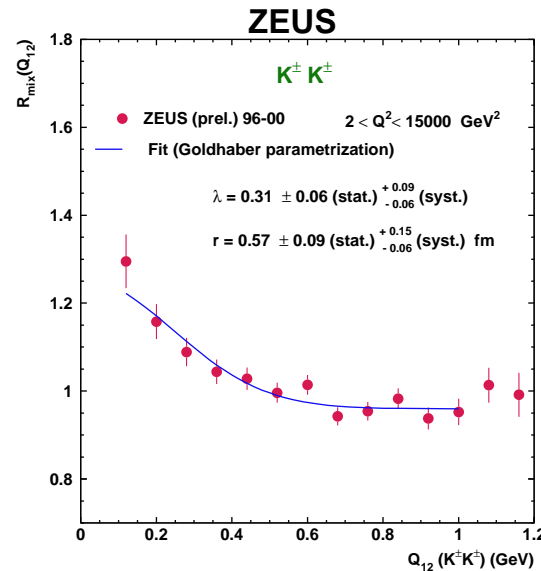
c.f. ZEUS π^\pm :-

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

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

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)
→ 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!