Jets and the Hadronic Final State at HERA

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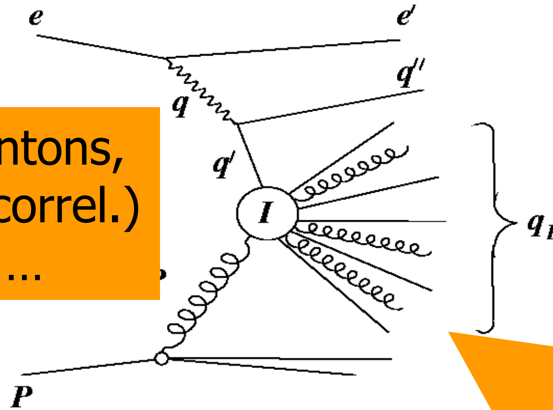
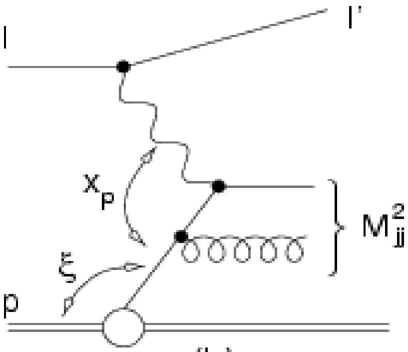
Outline

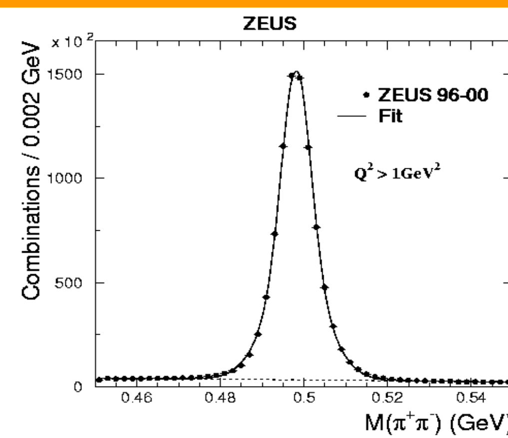


Exotics (Instantons, Bose-Einstein correl.) and more …

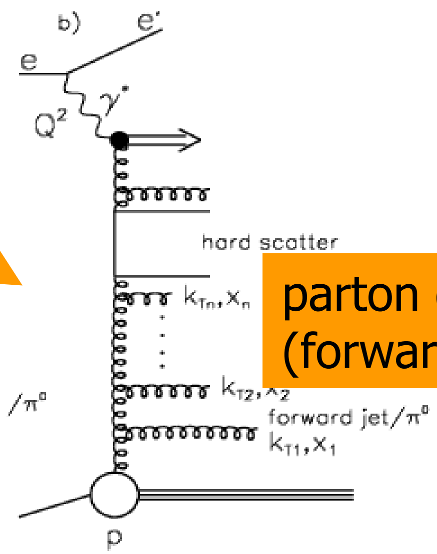


Basically only new results since EPS03.

Particle resonances/production (strange pentaquarks, anti-d)



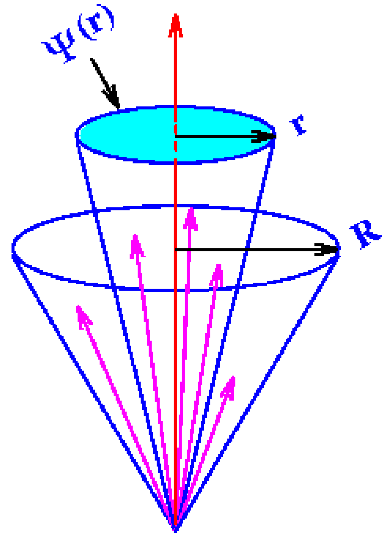
Jets (QCD tests, α_s, fits, resolved γ)



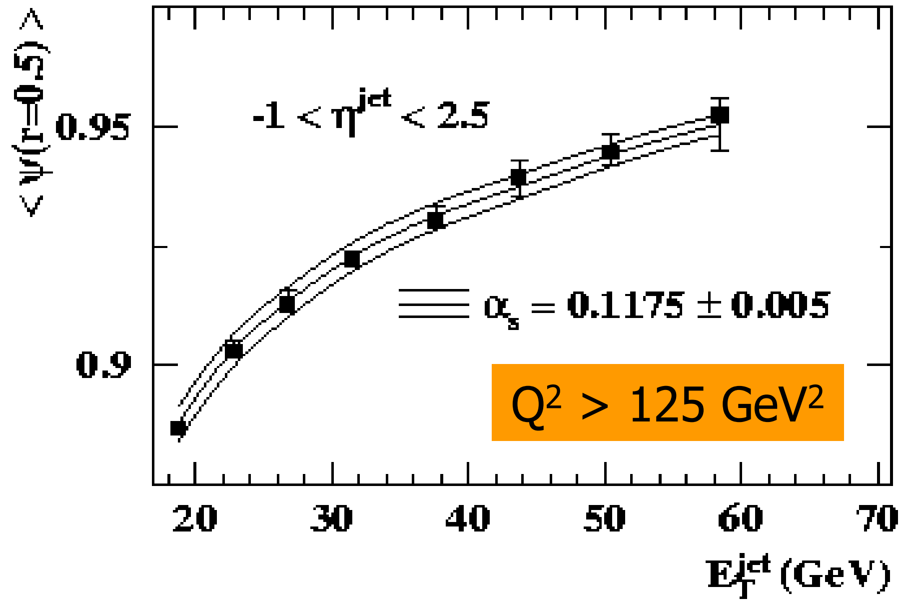
parton dynamics (forward jets, π^0)

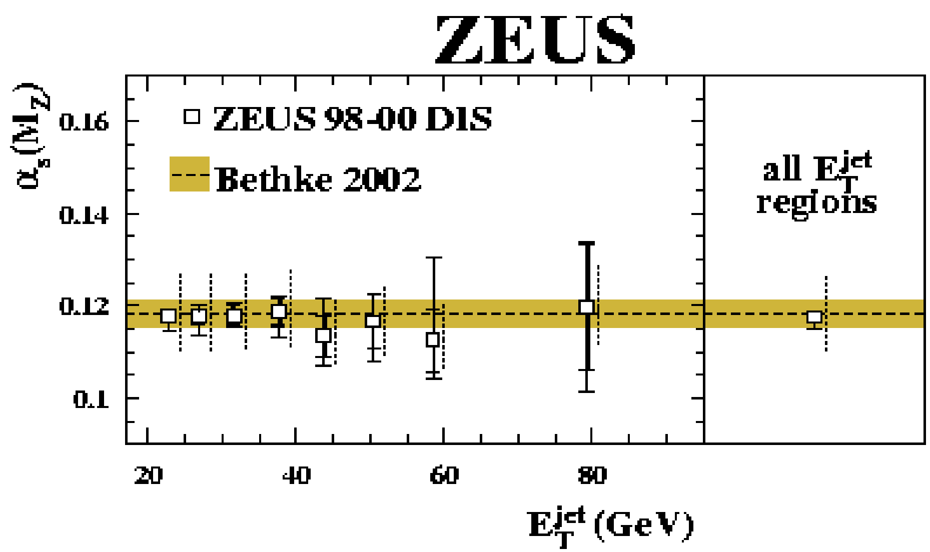
More Measurements of α_s

From jet structure in DIS and γp



- Measurement of jet shape ψ and subjet multiplicity $n_{sub}(y_{cut})$.
- DIS: $Q^2 > 125$ GeV^2
- $E^L_T > 13$ GeV





- Data well described by QCD MC models and NLO QCD calculations.

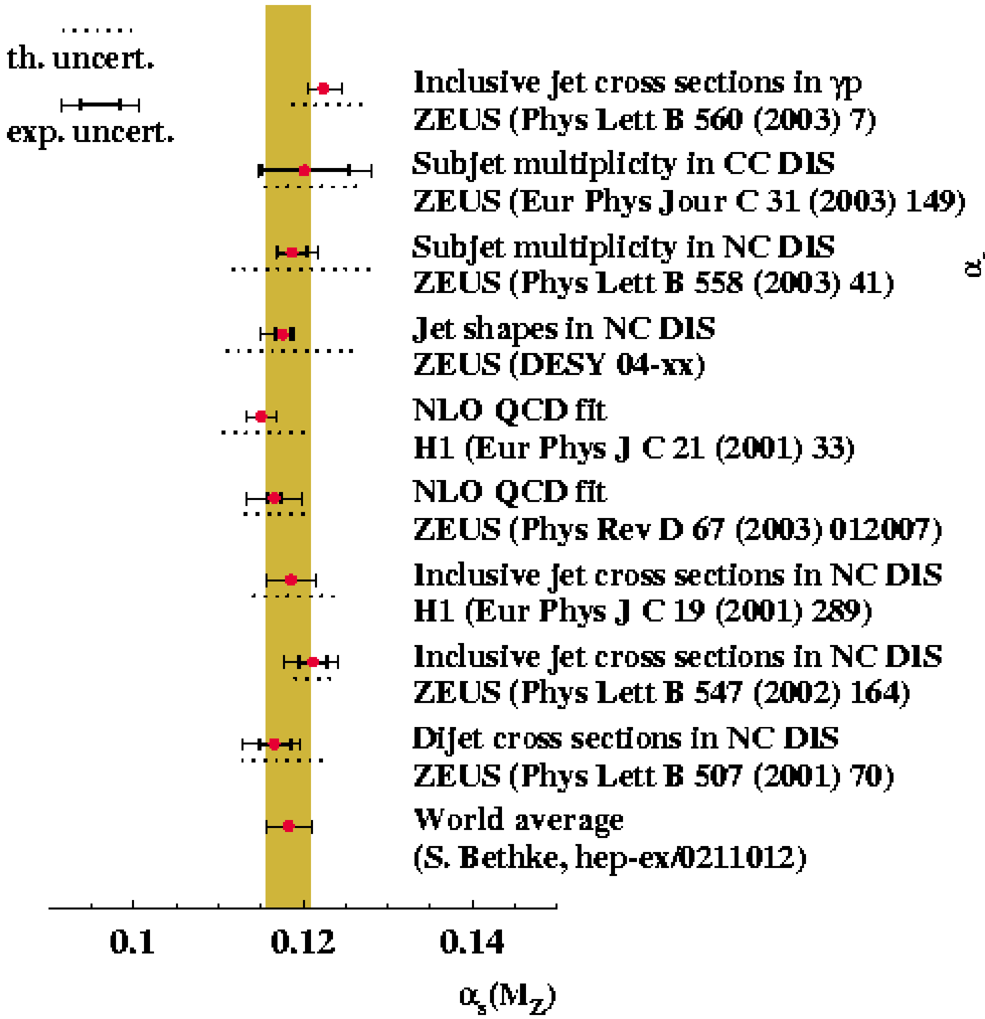
  Behaviour consistent with expectation from gluon contribution.

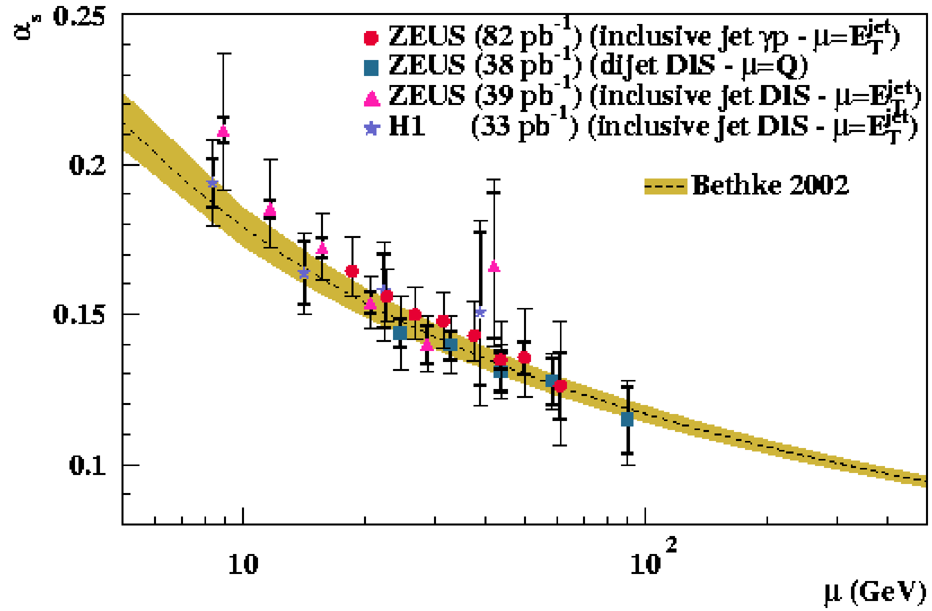
- Use of DIS $<\psi(r=0.5)>$ averaged over all jets for α_s extraction:

$\alpha_s(M_Z) = 0.1176 \pm 0.0016 \pm 0.008$

α_s from Jets at HERA

Huge number of precise data

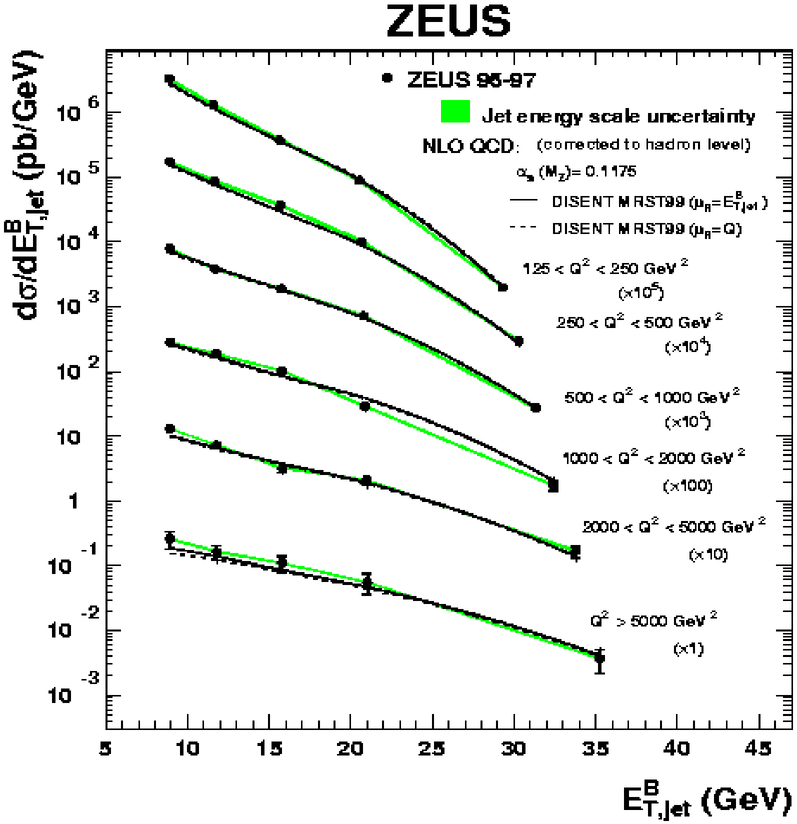




Jets in Global QCD Fits

ZEUS: First use of F2 **AND** jet data in fits

- Aim: Improve on high-x gluon.
- inclusive DIS jets (Q^2 > 125 GeV^2) and γp dijets for direct photons (x_γ>0.75).
- Problem: Need NLO calculation; very time-consuming convolution needed many 1000 times:



$$\sigma_{jet} = \sum_{a=q,\bar{q},g} \int dx\ f_a(x,\mu_f)\ \hat{\sigma}_a(x,\alpha_s(\mu_r),\mu_f)$$

- Solution: Grid in (x,μ_f) for each cross-section bin and parton flavour; assume $f_a(x,\mu_f)$ flat in (x,μ_f) bin

$$\sigma_{jet}(x,\mu_f) \approx \tilde{f}_a(x,\mu_f) \times \sum_{a=q,\bar{q},g} \int dx\ \hat{\sigma}_a(x,\alpha_s(\mu_r),\mu_f)$$

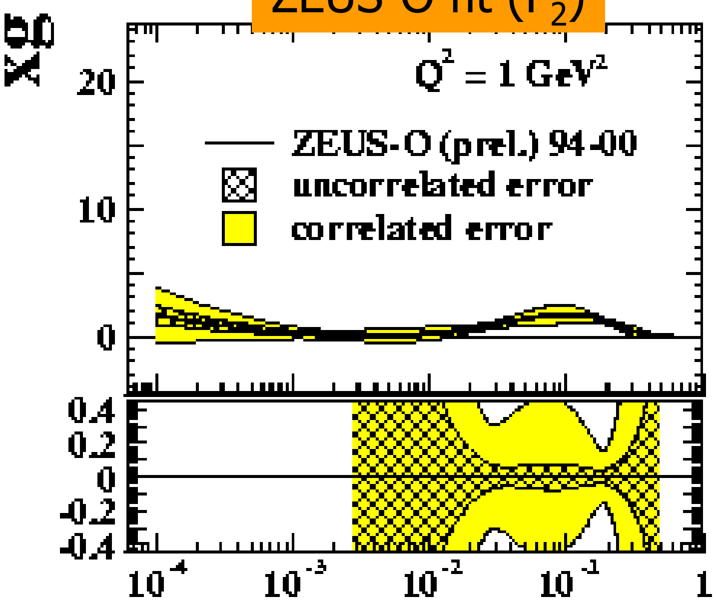
No convolution needed!
CPU time: 36000s → 0.5s

Jets in Fits ctd'

Improvement in gluon density **xg** at hig x

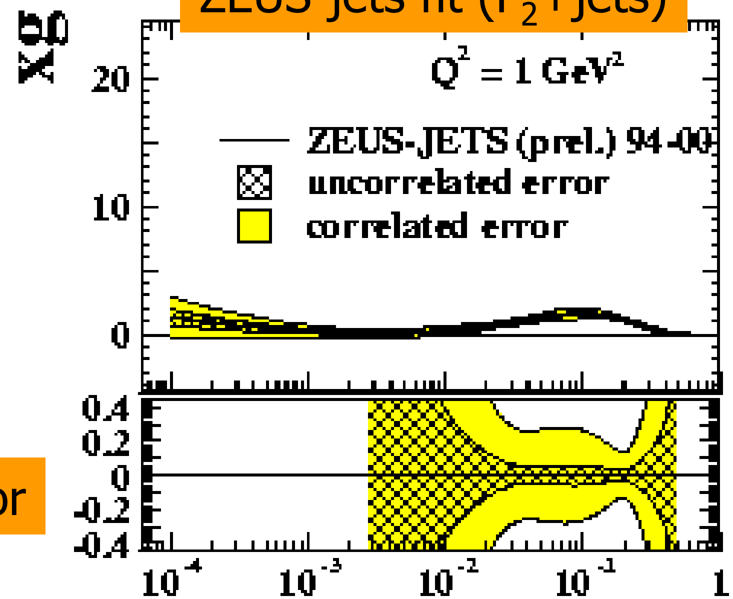
- Striking difference between ZEUS-O and ZEUS-jets fits.
- Sum rules port improvement to values higher than 'jet-x'.
- Further improvements (besides larger data samples):
  - Charm data to supplement F_2^c.
  - Tevatron jet data for even higher x.

ZEUS-O fit (F_2)



Normalised error

ZEUS-jets fit (F_2+jets)



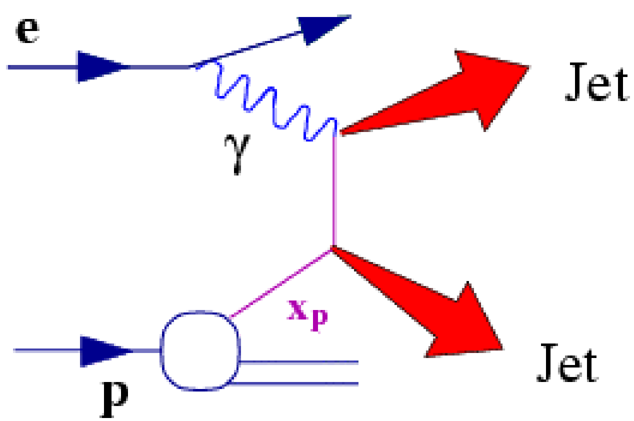
Classification of Jet Events

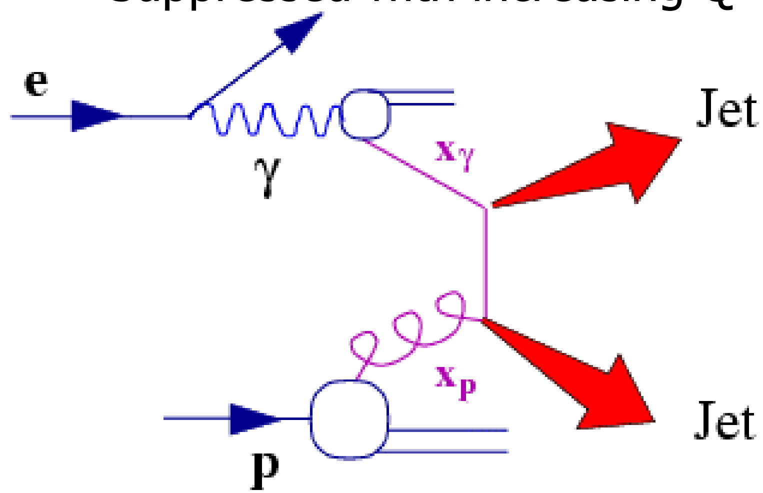
DIS, Photoproduction, direct, resolved

DIS: Q^2 >> 0 GeV^2
Photoproduction: Q^2~0 GEV^2

Resolved:
hadronic constituent of photon couples to scattering. Large influence on event. Suppressed with increasing Q^2

Direct:
Photon couples to hard scattering as a whole

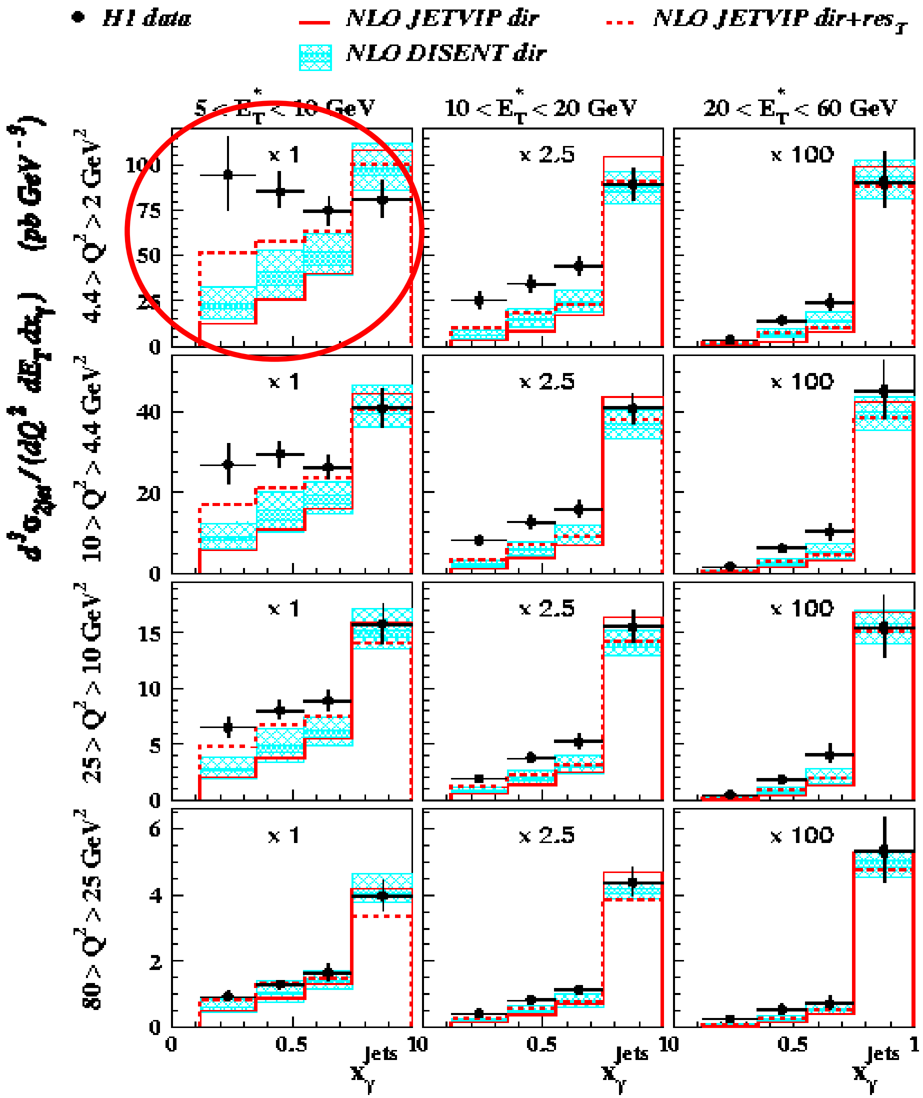




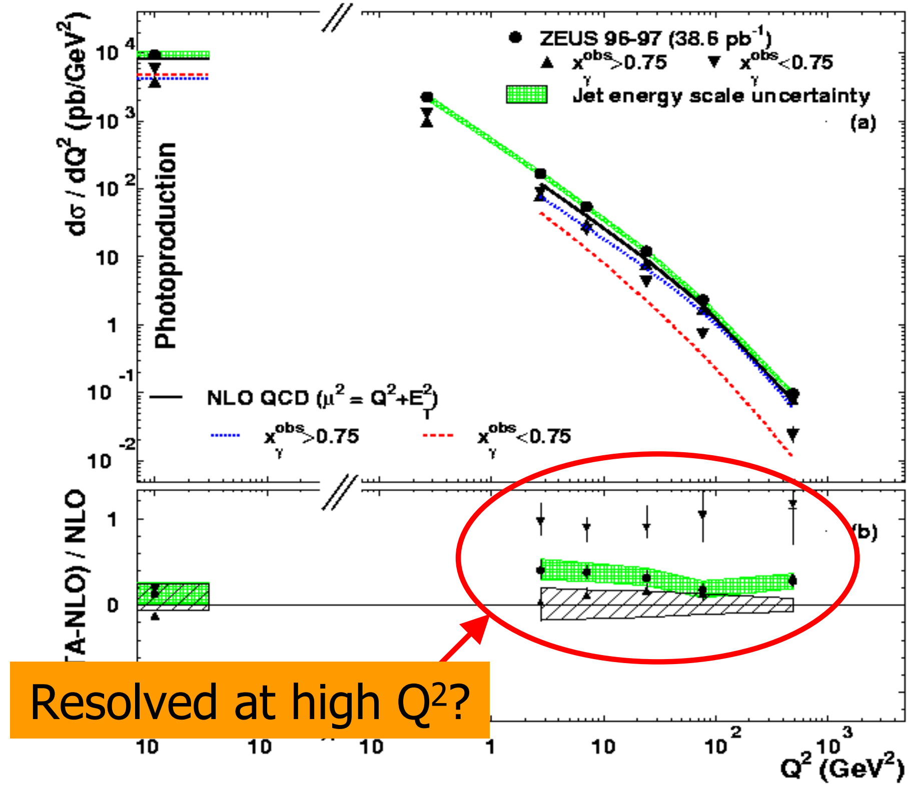
Note: Resolved photon contribution may mimic higher orders.

Jets: Problematic regions

Transition from γp to DIS



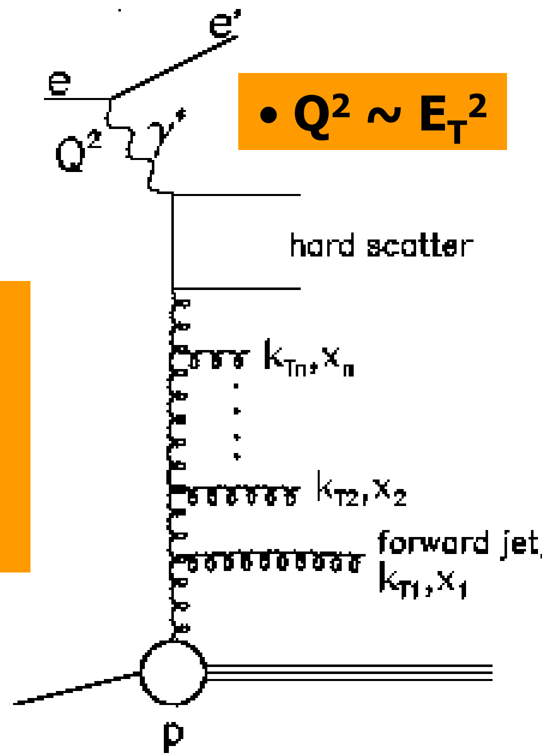
- H1 $5<Q^2<100\,\mathrm{GeV}^2$: **inclusive** dijets described by NLO QCD. $|\Delta\phi|$?
- ZEUS 0-$2000\,\mathrm{GeV}^2$: MC with resolved γ okay, DIS NLO bad at low x^{obs}_{γ}.
- H1 $2<Q^2<80\,\mathrm{GeV}^2$: Triple-diff. Cross-sections. NLO problems at low x_{γ}, Q^2.



Forward Jets and π^0

Probing parton dynamics (evolution schemes of proton PDF)

- Remember: Forward (Muller-Navalet) jets used to hunt for signs of breakdown of standard DGLAP and onset of BFKL dynamics expected at low x.



• $Q^2 \sim E_T^2$

Due to assumptions: large (transverse) energy jets/particles in forward direction suppressed in DGLAP.

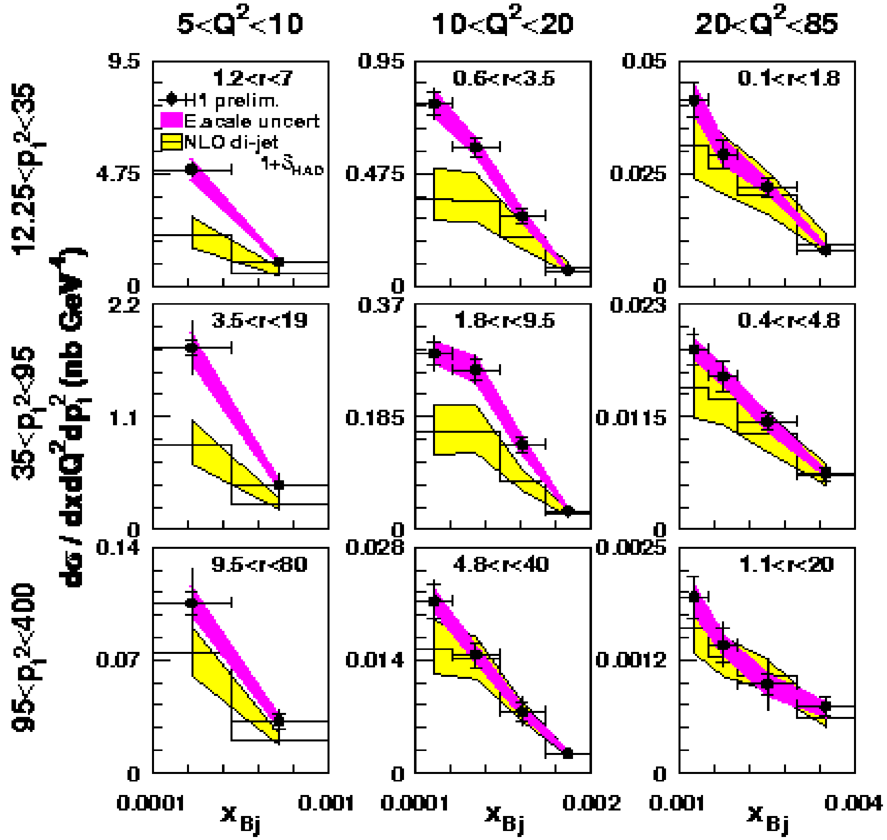
• $x_{jet} > x_{bj}$
• $7^o < \eta_{jet} < 20^o$

Status: Unclear!
→ Direct DGLAP fails.
→ but: No existing BFKL program
→ resolved seems to help

Forward Jets, π^0

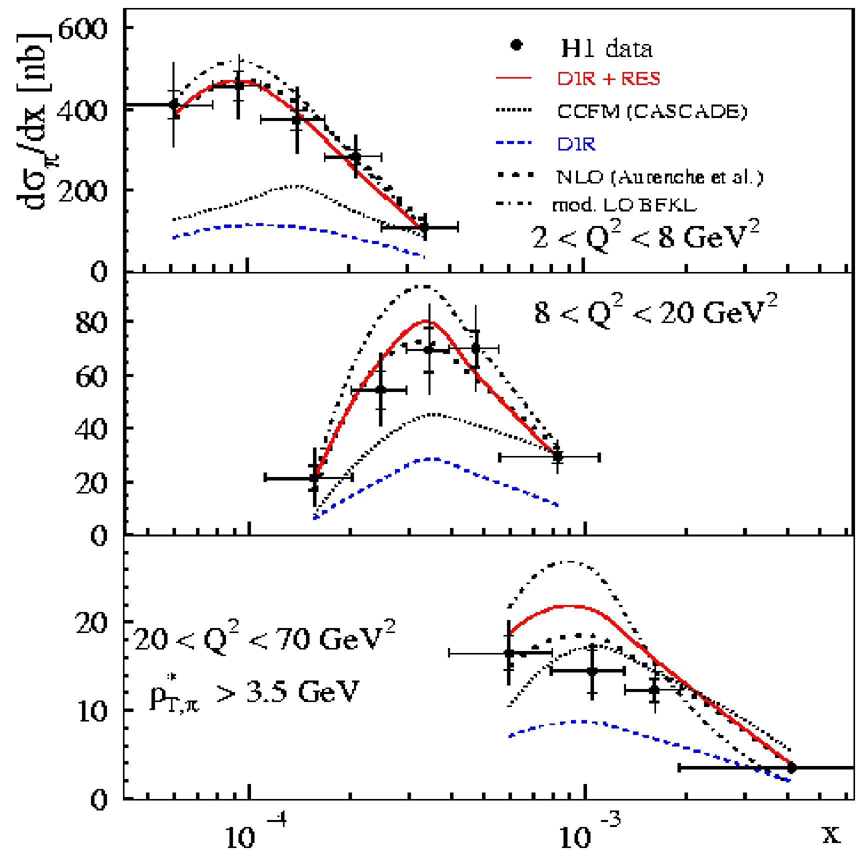
Only at high x, Q^2 NLO works for jets. For pions NLO good.

H1 jets: $d^3\sigma/dp_t^2dQ^2dx_{bj}$, $7^o<\eta_{jet}<20^o$



DISENT NLO for jets. Problems at low Q^2
Resolved photon MC okay.

H1 π^0: $d\sigma/dx_{bj}$, $5<\eta_{jet}<25^o$

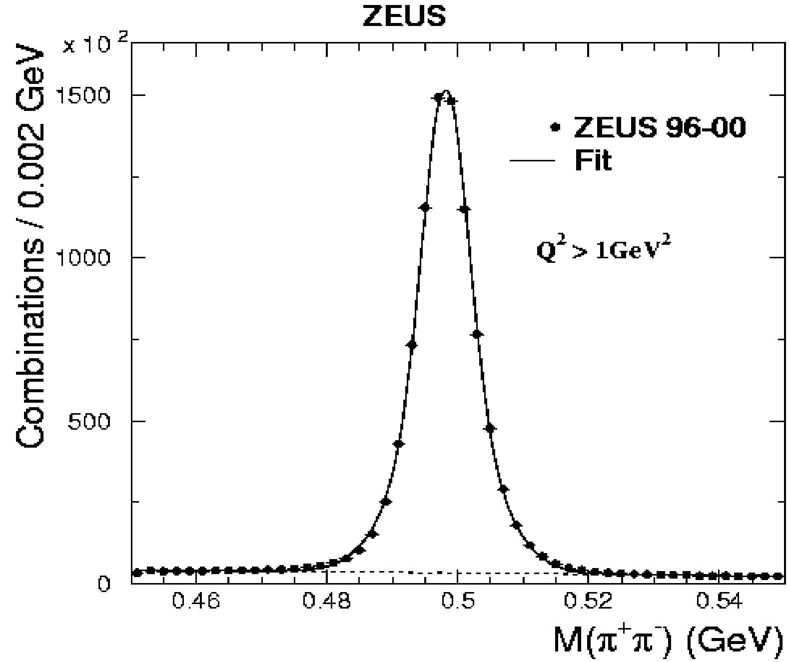


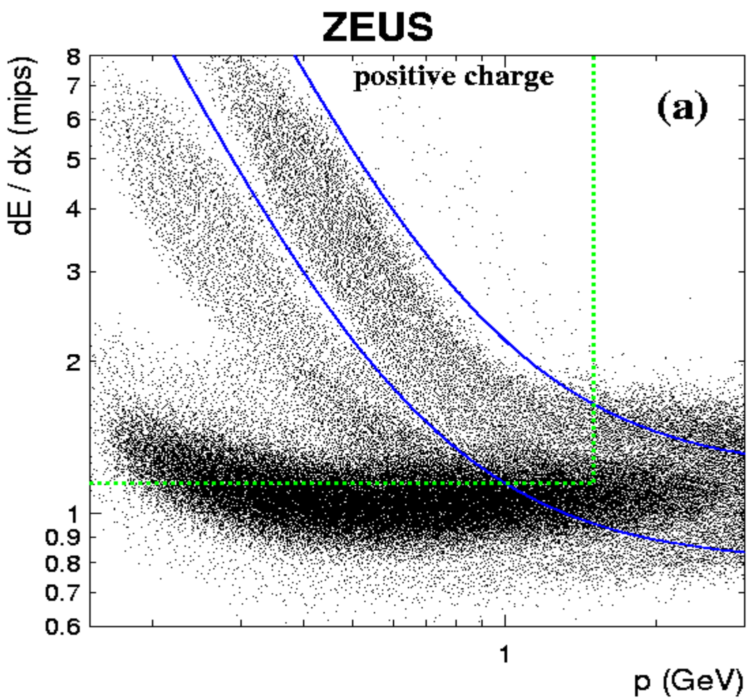
NLO ME+frag. funcs. (Aurenche et al.)
Also LO MC + resolved γ works (scale?).

Pentaquarks

K_s^0p and $\Xi\pi$ channels

- Recent observation of K^+n or K^0p resonances with positive strangeness at 1530 MeV consistent with pentaquark prediction uudd$\bar{s}$.
- Also $\Xi\pi$ with ddssu possible candidate (Na49, 1862 MeV).
- Complication to search: PDG 'bumps' in the same channel (but never confirmed by any HEP experiment).
- Selection:
  - $K^0 \rightarrow \pi^+\pi^-$.
  - p / pbar from dE/dx
  - Fit invariant mass distribution with 2 gaussians + BG function

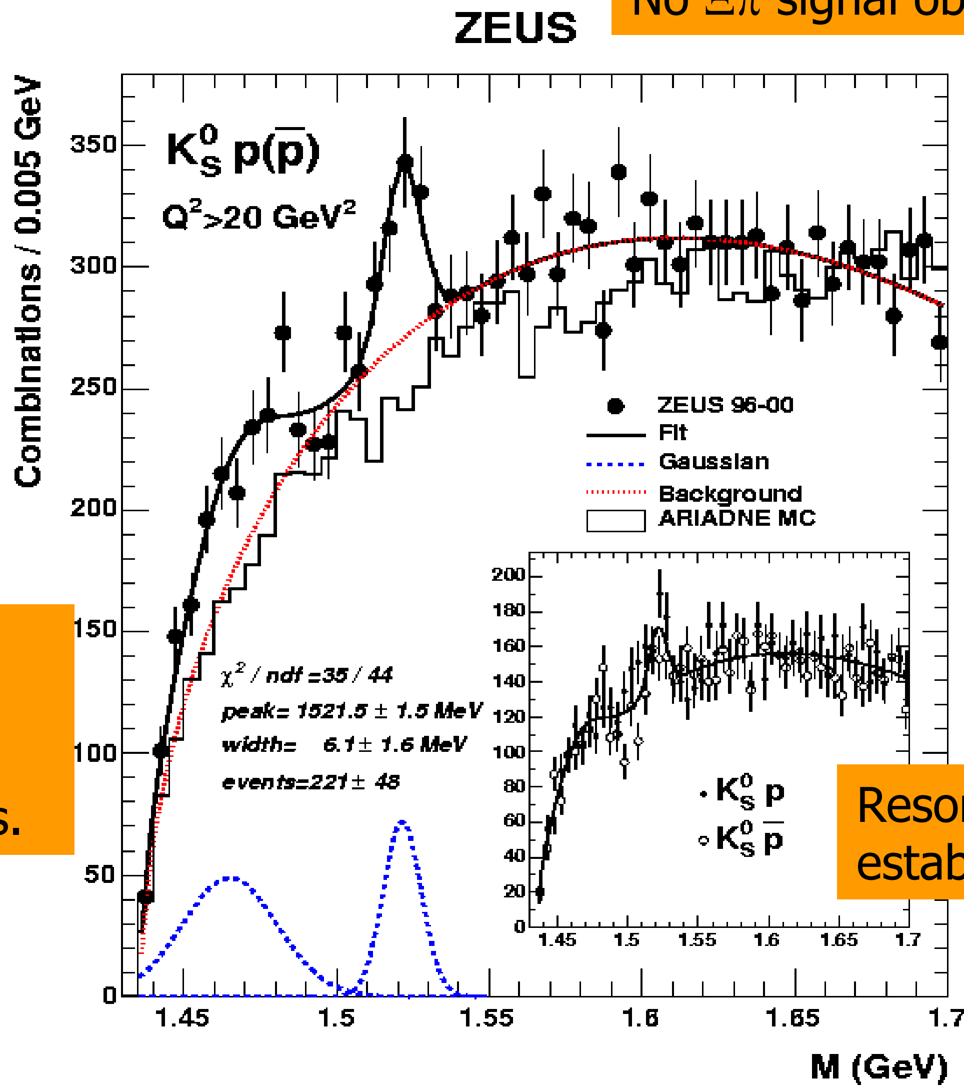




Pentaquarks ctd'

K_s^0p and $\Xi\pi$ channels

No K^+p (Θ^{++}) PQ observed.
No $\Xi\pi$ signal observed (NA49).



M_{PQ} = 1521±2.5 MeV)
Width: 6.1 MeV
221±48 events
96±34 antipentaquarks.

Resonance in K^0pbar → establish antipentaquark!

Summary

QCD at HERA is a rich field

- HERA I data analysis in full glory
  - Many beautiful measurements; precise determinations of α_s.
  - Now turning towards more and more exclusive signatures (multi-differential measurements, exotics, jets+heavy flavours, etc.)
  - Statements in many cases not limited by experimental errors but by precision or even non-existence of theory (or tools).
    ➔ parton dynamics, orders in α_s, resolved contributions etc.

- Working towards aim of having jet data in QCD fits. High HERA II statistics will allow even better measurements.
  ➔ Aim: Constrain gluon at high x.
  ➔HERA can contribute to the LHC program.

- HERA II: Looking forward to more beautiful measurements.

Many things cannot be shown here – no time → see next slide!

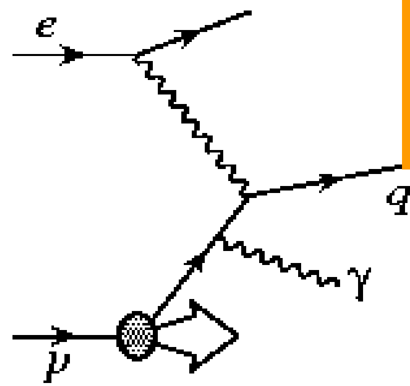
Extras

→ prompt photons in DIS and Photoproduction
→ QCD Instantons
→ Bose-Einstein correlations
→ Event shapes in DIS
→ Azimuthal asymmetries
→ anti-deuteron production

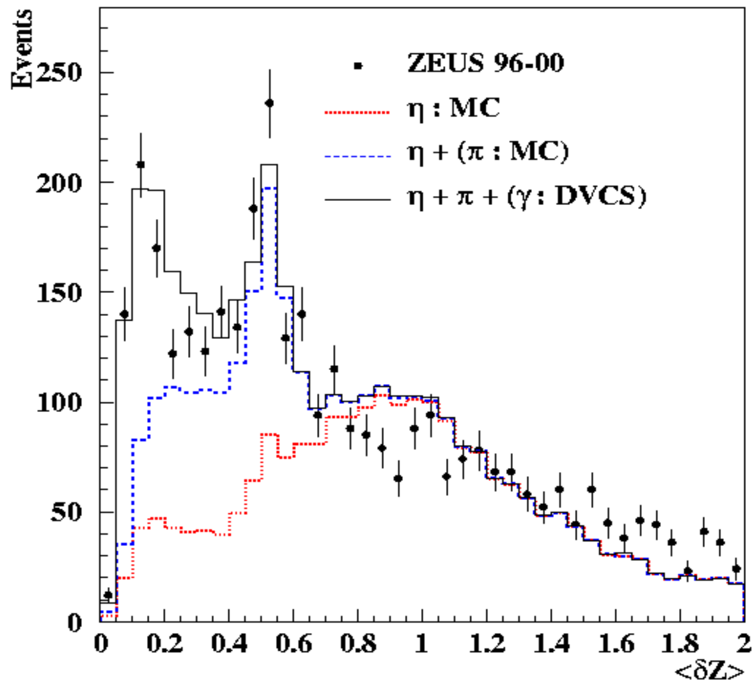
Prompt Photons in DIS and γp

Direct tests of hard dynamics

- Prompt photons largely insensitive to hadronisation
- Studied by many experiments; at HERA in photoproduction and DIS (ZEUS).
- Comparison of results to NLO pQCD calculations and PYTHIA/HERWIG MCs usually reasonable.
- ZEUS in DIS (Q^2 > 35 GeV^2): clusters in barrel calorimeter
  $5 < E_T^\gamma < 10$ GeV, $-0.7 < \eta^\gamma < 0.9$
  $E_t^{jet} > 6$ GeV, $-1.5 < \eta^{jet} < 1.8$
- Problem: π^0 and η background. Perform statistical subtraction using cluster shapes in the calorimeter



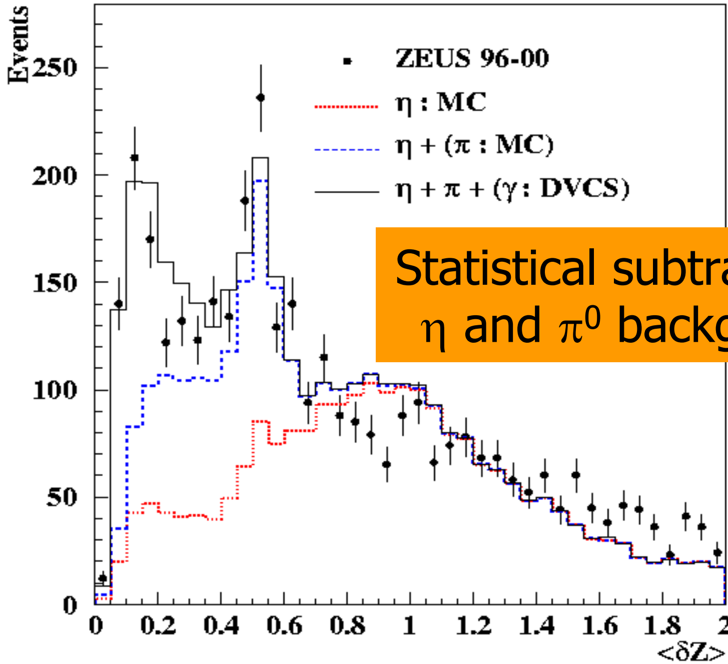
Signatures:
ep → eγ+X
ep → eγ+jet+Y



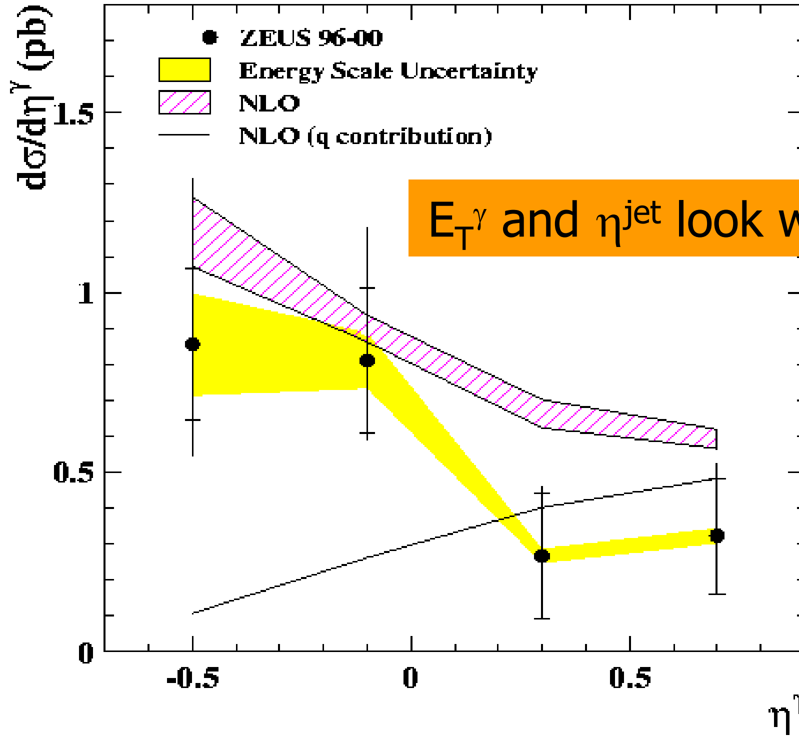
Prompt Photons in DIS

Good probe of hard dynamics; ~no hadronisation.

Signatures:
ep → eγ+X
ep → eγ+jet+Y



Statistical subtraction of η and π^0 background.



E_T^γ and η^{jet} look worse!

Isolated photon sample:

σ = 5.64±0.58(stat)±0.6(syst) pb

PYTHIA (HERWIG) factor 2 (8) off.

E_T shape well described by PYTHIA and HERWIG; problems with η shape.

Photon+jet sample:

σ = 0.86±0.14(stat)±0.4(syst) pb

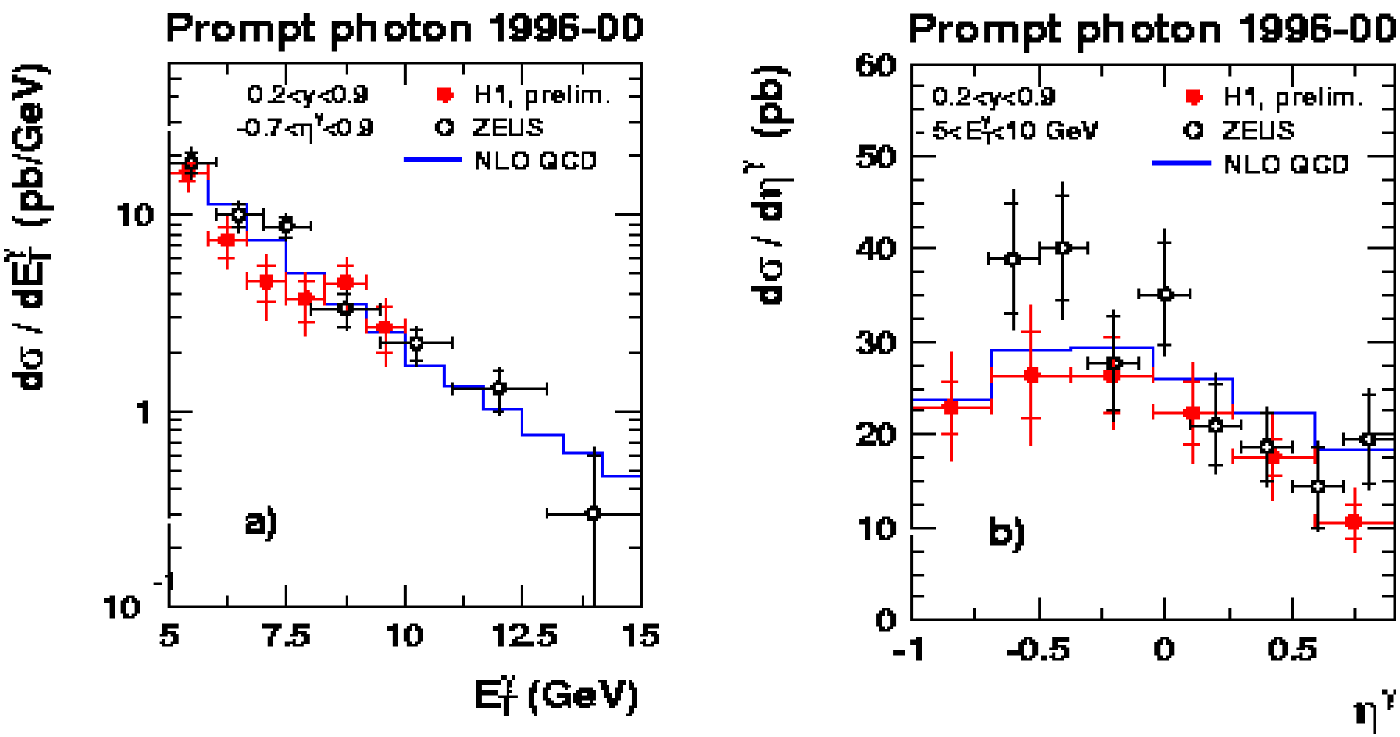
$O(\alpha^3\alpha_s)$: σ = 1.33±0.07 pb, (-30%).

MC: describes $E_T^{\gamma,jet}$ well, but rapidities?

Prompt Photons in γp: Results

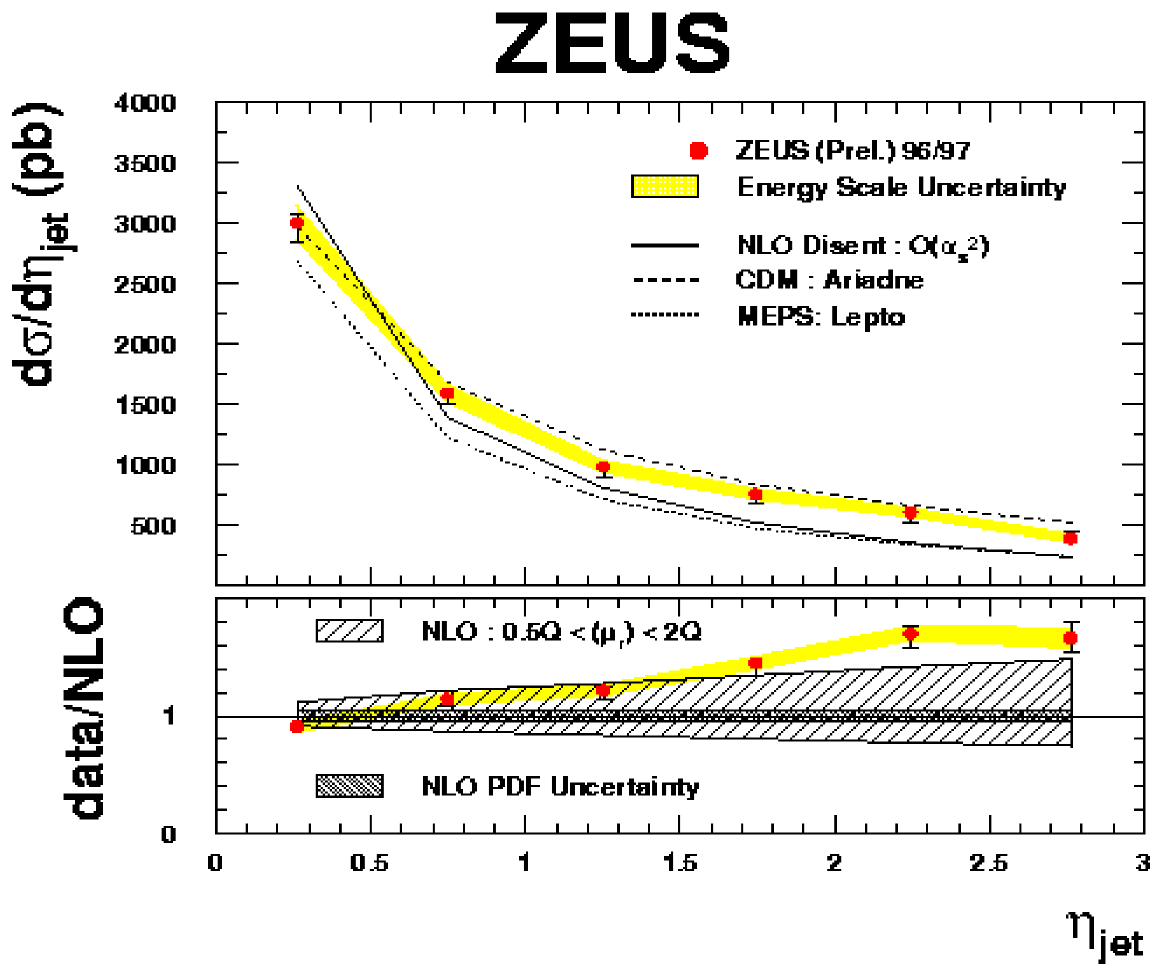
Agreement H1-ZEUS (for inclusive prompt photons)

- NLO QCD describes H1 data reasonably well, except the forward direction (underlying event activity?)
- PYTHIA describes shapes well, but is 30% low.



Forward Jets ctd'

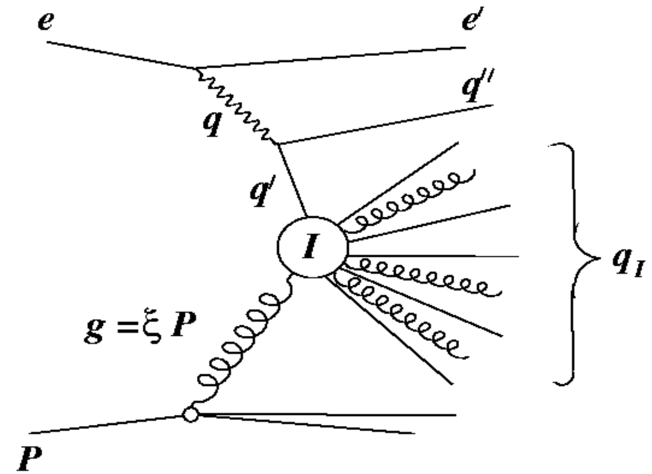
ZEUS

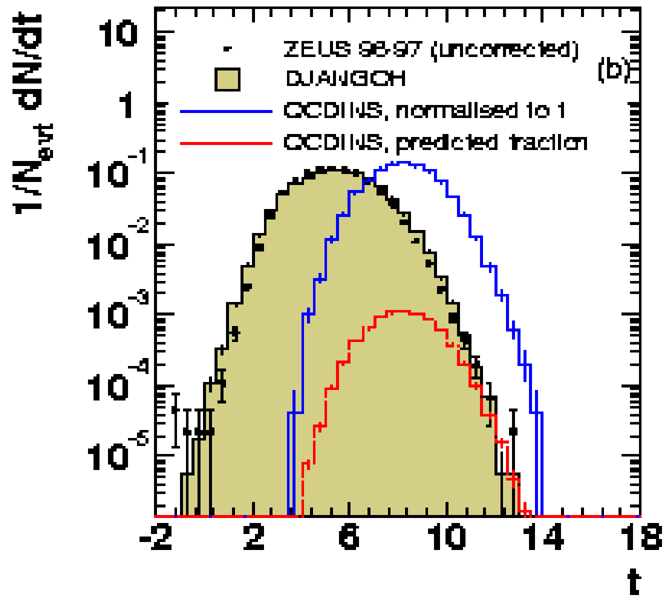


QCD Instantons

Tunneling processes between different QCD vacua

- Characteristics:
  - Isotropic high-multiplicity final state
  - High transverse energy in HCM frame
- Procedure:
  - Standard DIS selection, $Q^2 > 120\ GeV^2$
  - Instanton enhancement
  - Discriminant variable to select instantons



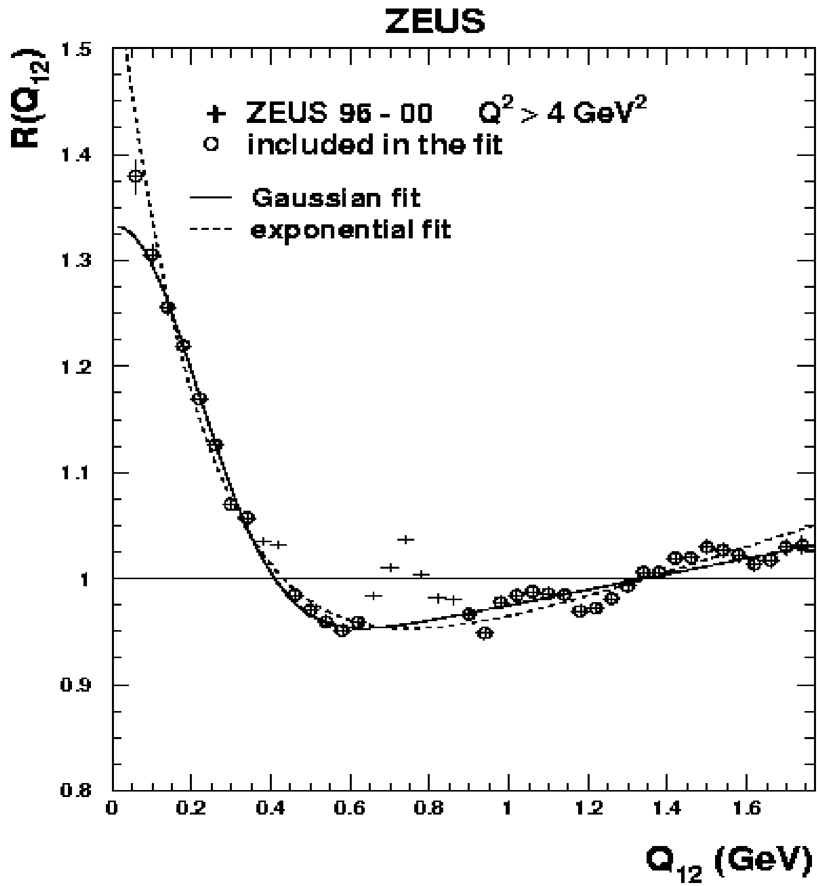


Assuming conservatively that all data events are signal, a background-Independent upper limit of 26 pb at 95% CL has been found, compared To a prediction of 8.9 pb.

Bose-Einstein Correlations

in 1,2 dimensions in DIS. Dependence on Q^2?

- Correlation: $R(Q_{12}) = \alpha(1+\beta Q_{12})[1+\lambda\exp(-r^2 Q_{12}^2)]$
- Calculate $R(Q_{12}) = \xi^{data} / \xi^{MC,noBE}$ to remove non-BE correlations (resonance decays etc.). $\xi=\rho(++,--)/\rho(+-)$



Within the experimental precision, no dependence on Q^2 can be observed ($4 < Q^2 < 8000$ GeV^2)

$\lambda = 0.475$, $r = 0.666$fm

The 2D fit suggests an elongated source shape, as predicted by the Lund model.

BE correlations are similar in DIS current and target regions.

Good agreement with other experiments is observed.

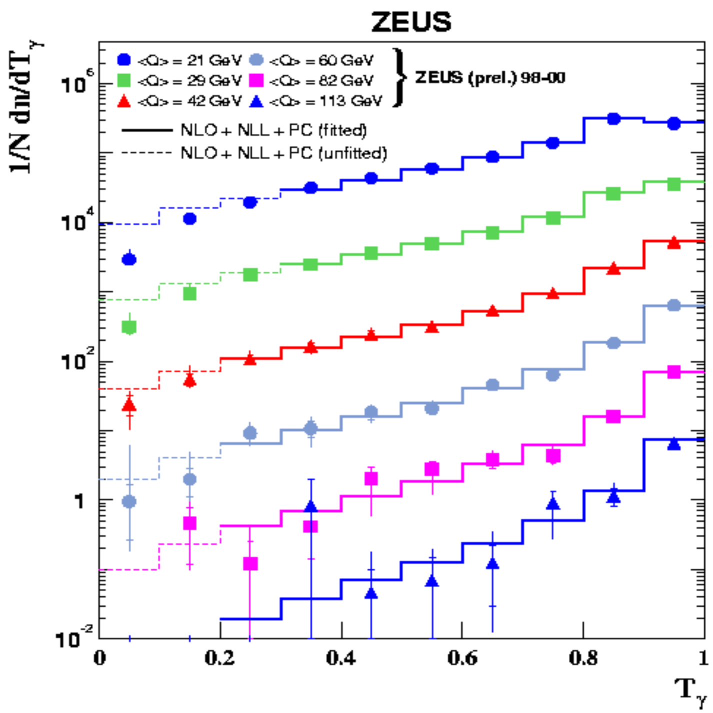
Event Shapes in DIS

in the Breit frame → topology of HFS

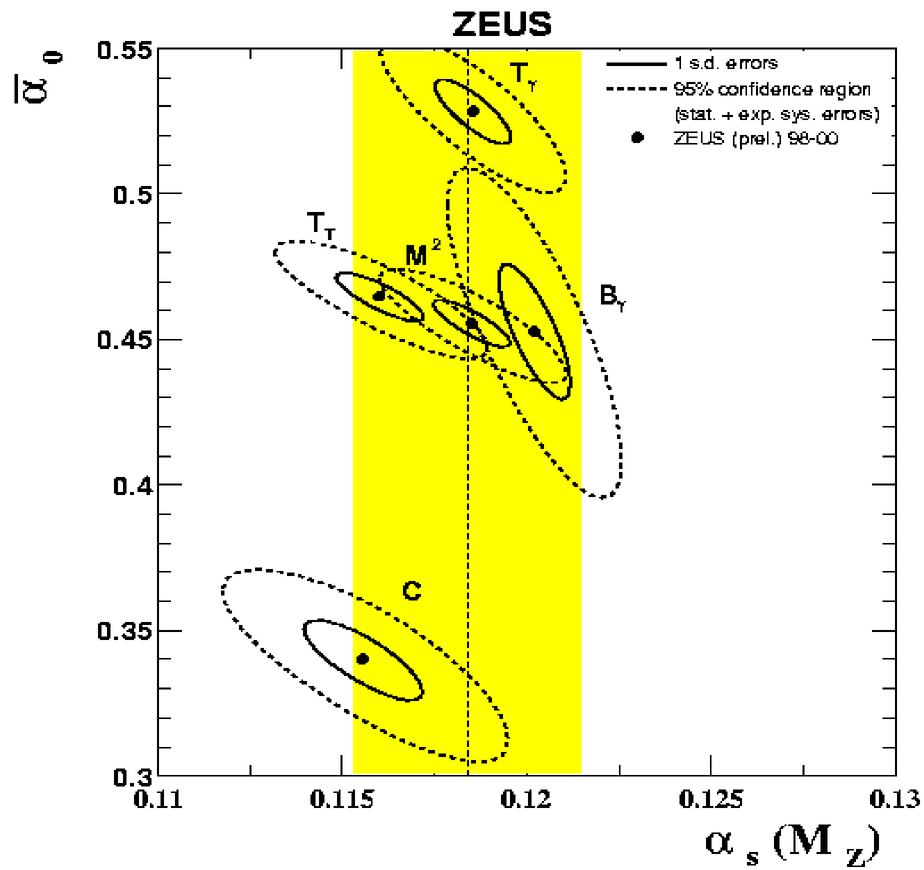
Thrust T, Broadening B, jet mass M^2 and C parameter allow test of QCD over wide energy range

but: hadronisation corrections → power corrections → fit α_s, α_0!

$$\langle F \rangle = \langle F \rangle_{NLO} + \langle F \rangle_{pow}(\alpha_s, \overline{\alpha}_0)$$



Poor convergence of event shape vars in the 1+1 jet limit → NLL resummation and various matching schemes with NLO.



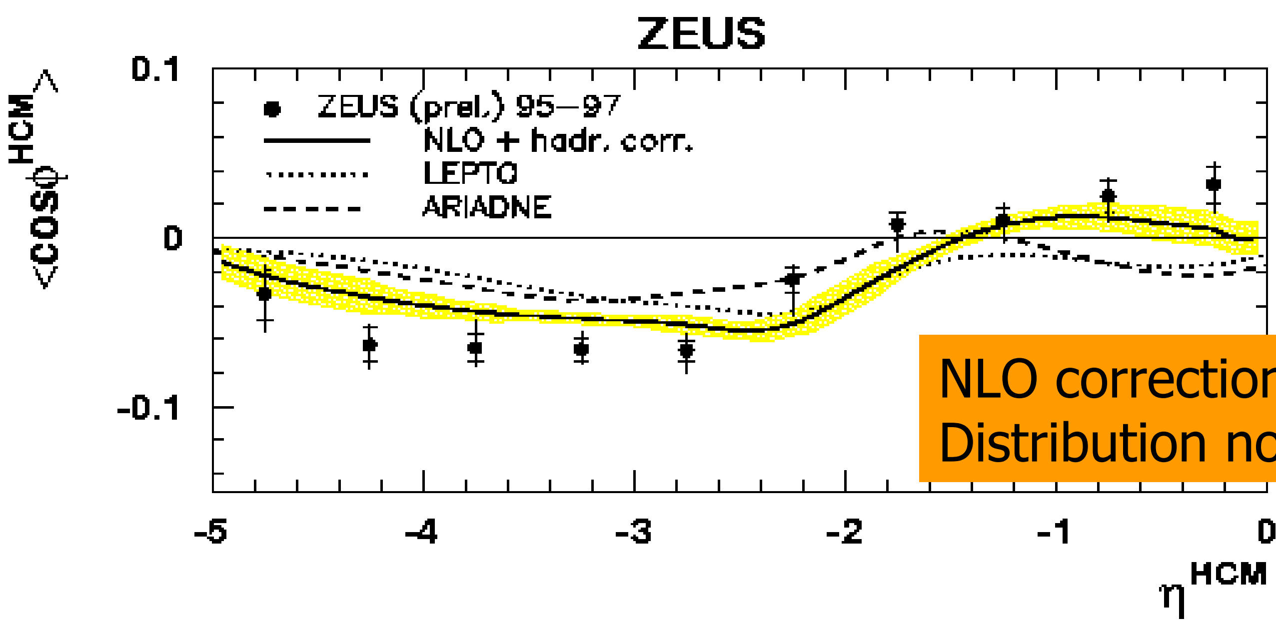
Azimuthal Asymmetries

using an energy flow method

$$d\sigma^{ep\to ehX} \Big/ d\phi = 2A(0.5 + B\cos\phi + C\cos 2\phi + D\sin\phi + E\sin 2\phi)$$

Asymmetry receives contributions frm BGF and QCD events, polarization, parity violating weak interactions, intrinsic parton k_T.

Idea: Measure <cosϕ> for various bins of pseudorapidity and compare distribution with models and NLO QCD calculations.



NLO corrections are not negligible!
Distribution not fully understood.

Anti-Deuteron Production

Comparison to pp and heavy ion rections

- Clear dE/dx signal for deuterons; good charge separation
  → 45 anti-d's, σ=2.7±0.5±0.2nb.
- Number of antideuterons ~ centra pp ISR collisions, but much lower than in Au-Au at RHIC. No heavier negative particles observed.
- Coalescence parameter B_2 much higher than in heavy ions at high energies → much smaller source volume in ep,pp?

B2=0.010±0.002±0.001±0.002