Summary of Working Group C: Hadronic Final States

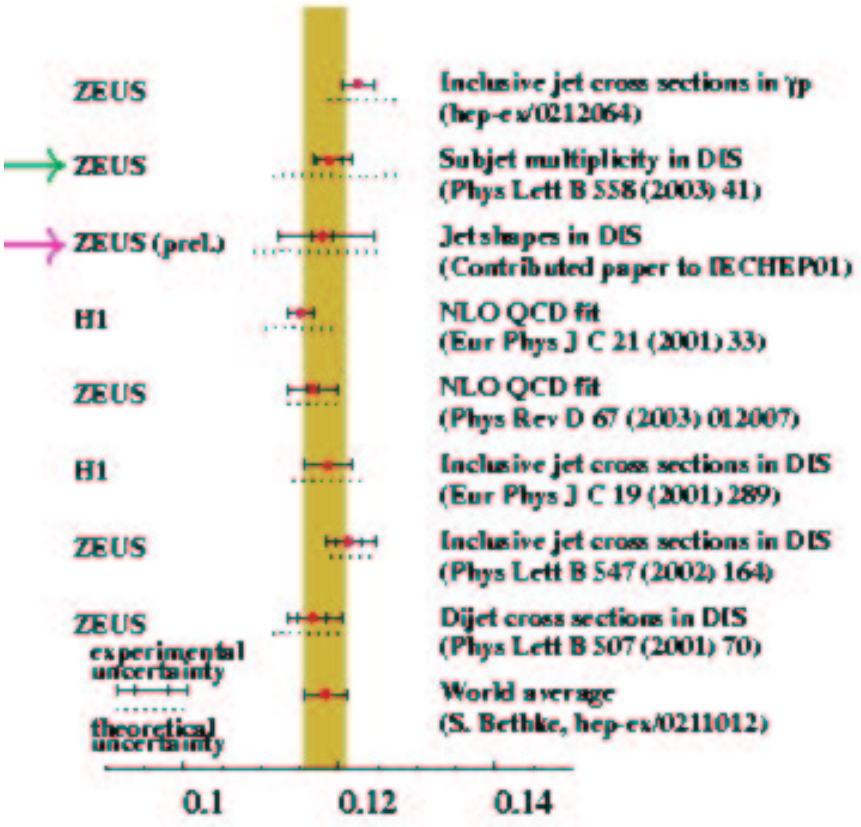
DIS03, St.Petersburg

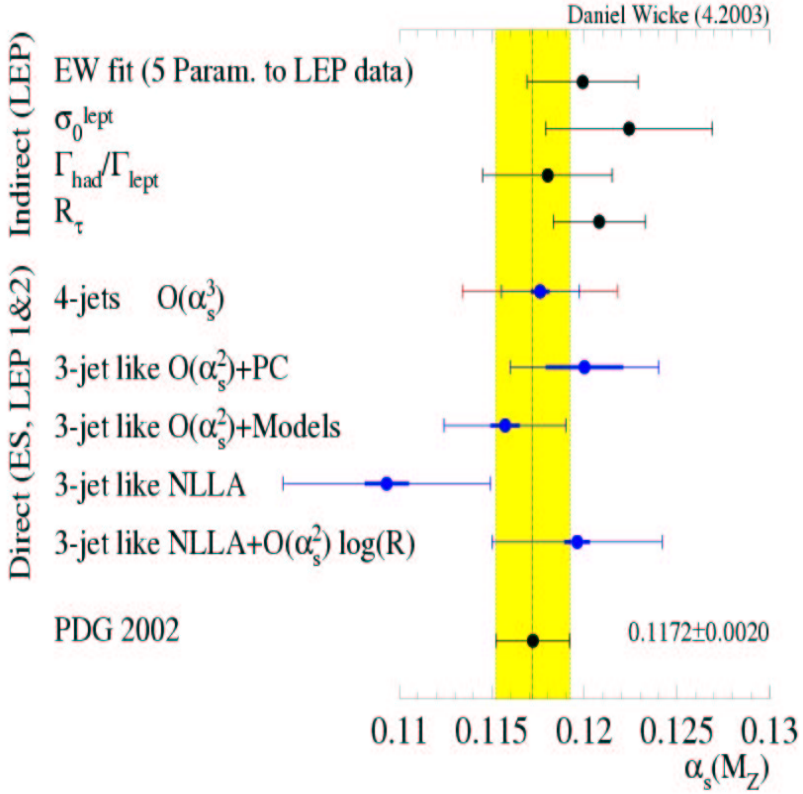
Conveners: Jon Butterworth, Yuri Dokshitzer

- Event shapes & energy flows: DIS final states vs e^+e^- .
- Jets and energy flows: proton-antiproton vs proton-photon vs photon-photon.
- Fragmentation, resonances, non-perturbative effects.
- Unintegrated parton distributions and low x.

Precision QCD studies in DIS and e^+e^-

- Combined LEP results on α_s (Krumnack,Terron, Passon, Specka)
- HERA I jet measurements (also in CC jet production)



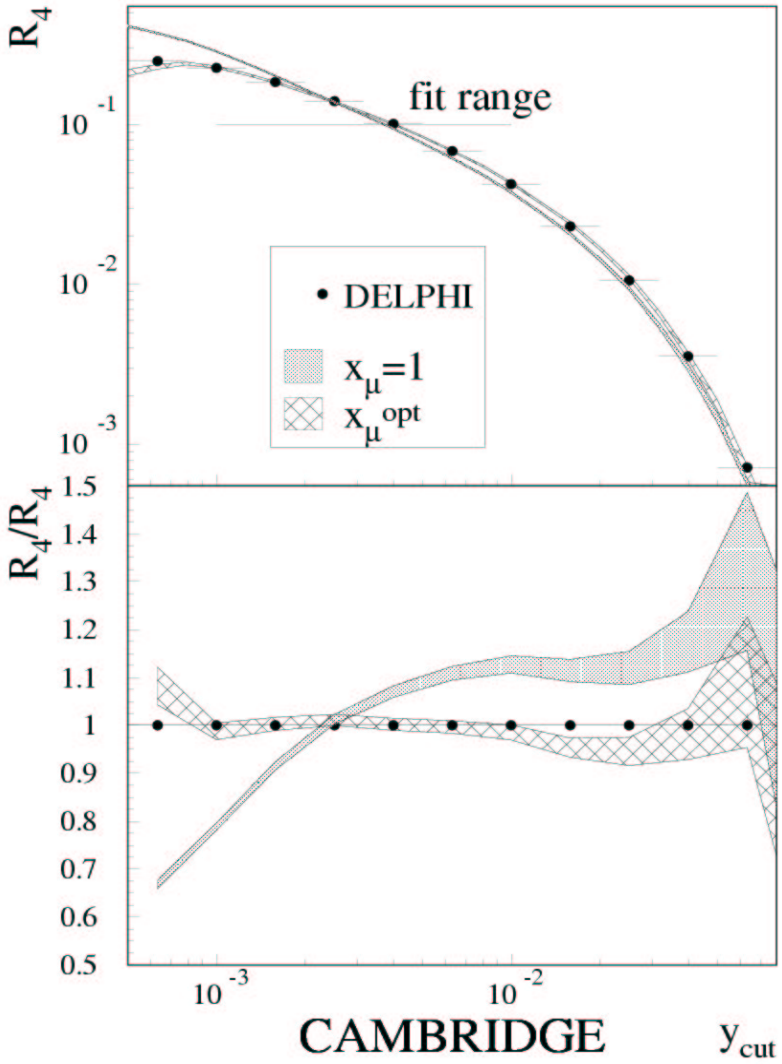


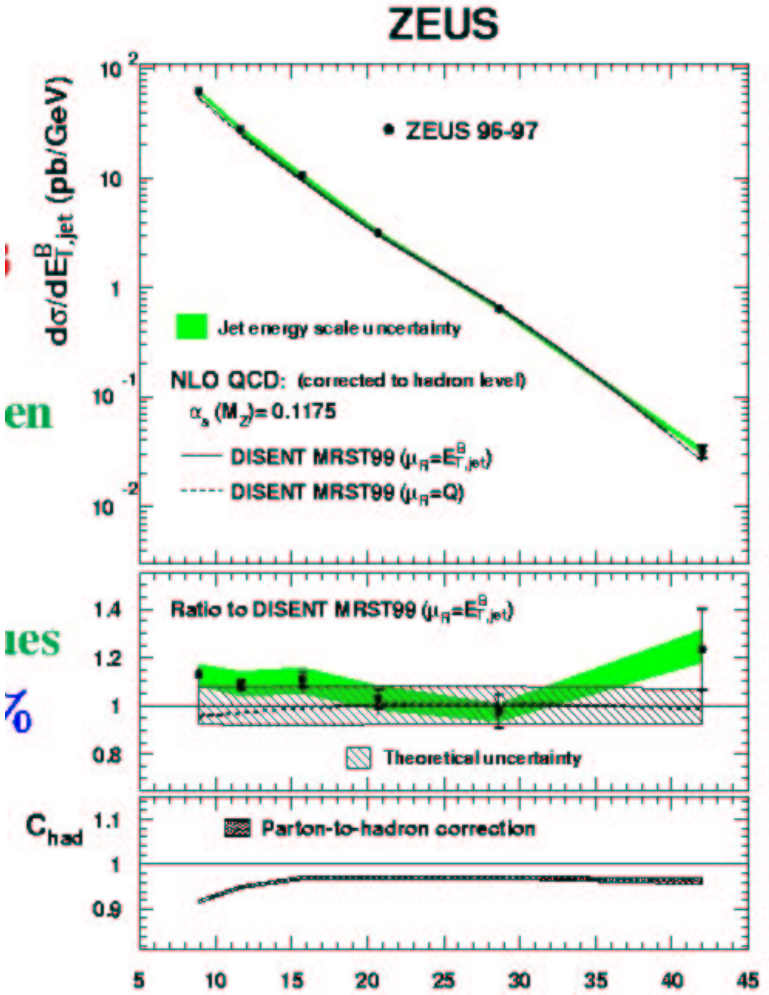
Sits on top of a multitude of advances in understanding

Precision QCD studies

- LEP Combined WG:
  - Common theory and lots of dialogue with theorists (Cambridge jet algorithm for high jet multiplicities, power corrections...)
  - Common treatment/comparison of hadronisation
  - Proper treatment of correlations.
- HERA measurements
  - From jet rates, shapes, subjets and fits to structure functions
  - No combined values as yet. Should be done.
- Remaining issues
  - Uncertainty from higher orders estimated from scale uncertainty. Can agree an approach, but it remains arbitrary... (LEP: Experimentally optimised scales?)
  - LEP and HERA precision in most methods now limited by theoretical uncertainties.

Precision QCD studies in DIS and e^+e^-





Precision QCD studies in DIS and e^+e^-

- Theoretical discovery: Non-global logarithms (Dasgupta & Salam ~ talk from Marchesini)
  - Non-global effects occur when an observable is only sensitive to a limited region of phase space...
  - ...Like a detector?
- Affects
  - Single jet profiles/substructure
  - Rapidity cuts (gap or just acceptance)
  - Energy in cone/prompt photon isolation
  - Interjet energy flows
  - ...
- New, phenomenlogical avenue in QCD, not yet thoroughly studied in phenomenology or experiment.
  - Will resumming these reduce scale uncertainties in predictions?

Precision QCD studies in DIS and e^+e^-

- Technical improvements.
  - Giulia Zanderighi, Andrea Banfi, Automated Resummation (*CAESAR*). Also applied to event shapes in hadron-hadron.
  - Nikolaos Kidonakis, A master formula for NNLO soft and virtual QCD corrections.
  - Nikolaos Kidonakis, Two-loop and n-loop eikonal vertex corrections
  - Lorenzo Magnea, Resummation of N-independent terms in DIS and DY'
- Other discussion.
  - Paul Hoyer, Rescattering effects on DIS parton distributions
  - Stephane Peigne, Universality-breaking effects in diffractive DIS and Drell-Yan production

CAESAR

Banfi, Salam, Zanderighi

- Resummation of large logarithms in event shape/jet variables is needed to make accurate predictions/describe data.
- Though the theory is 'known', each variable requires a new calculation (i.e. theorist)... on average one paper per variable.
- Systematic algorithmic approach means a computer can take over.
  - User provides routine which calculates the variable
  - CAESAR does some checks (NGL, exponentiation, ... essentially makes sure it can be resummed with current theoretical understanding)
  - Result is equivalent of an analytic calculation. Can study scale dependence, apply hadronisation corrections etc.
  - Result is free of subleading logs... can be matched to NLO ME in principle (work in progress, with Z.Nagy).

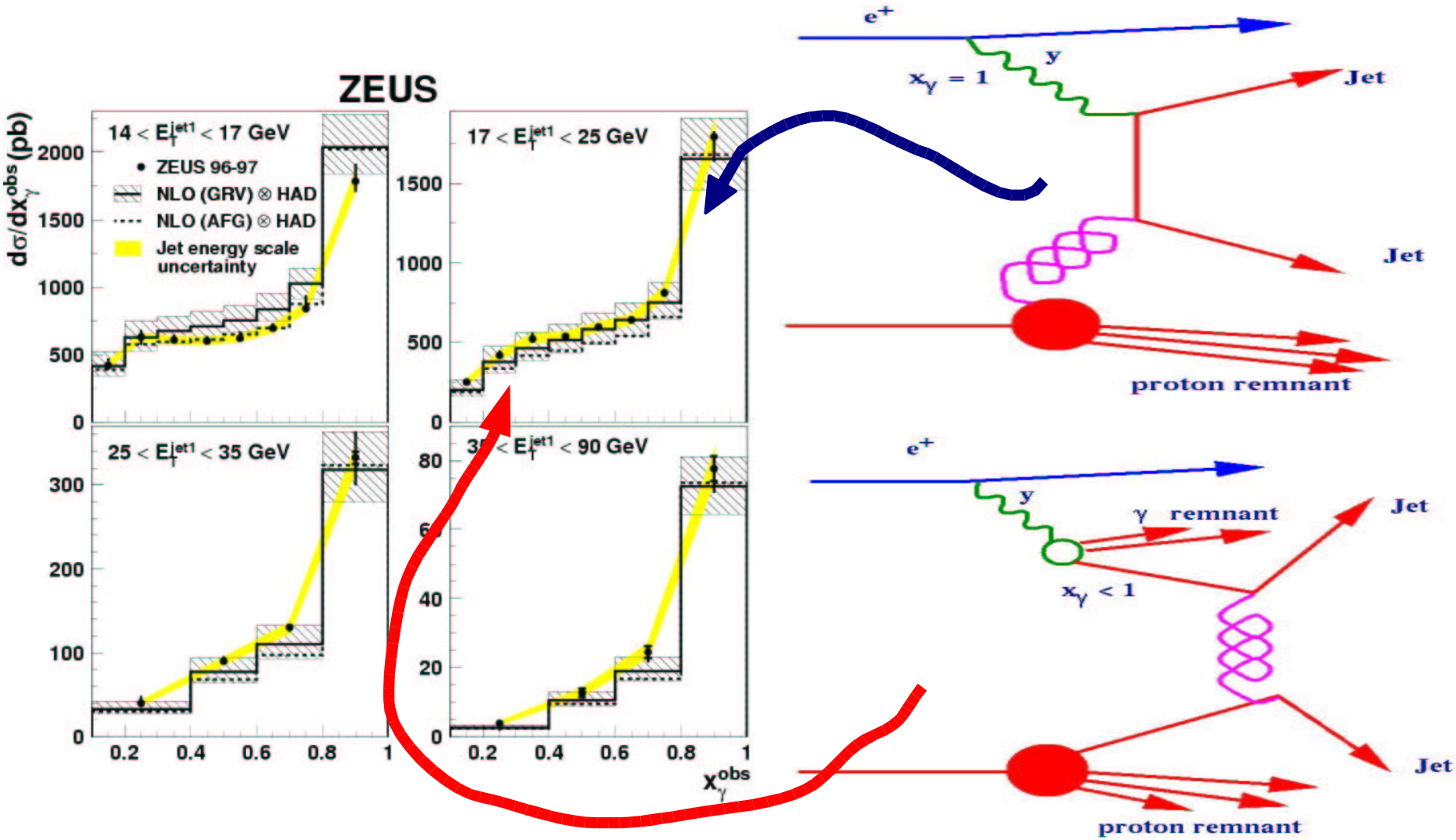
Proton anti-proton vs proton-photon vs photon-photon (Jet cross sections, Energy flows and Underlying Events)

or

HERA and LEP as 'hadron-hadron' colliders

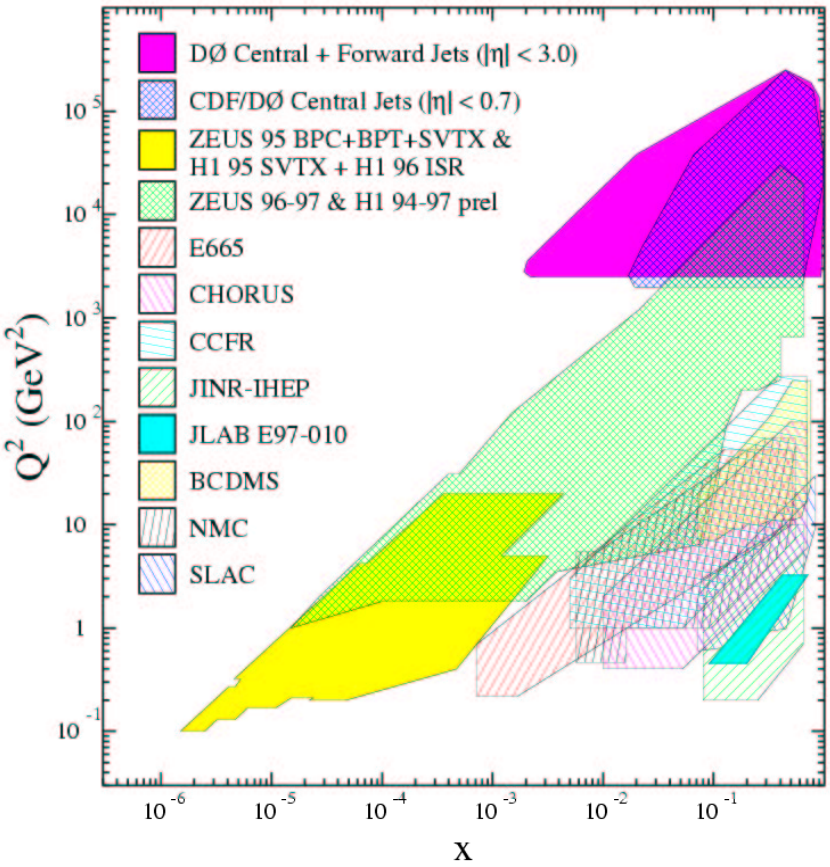
- Almost on-shell photons come along with the electron beam & collide with protons.
- These photons can fluctuate to acquire a hadron-like structure.
- LEP and HERA can look like hadron-hadron machines but can also do "simpler" measurements with a pointlike photon. (in Deep Inelastic Scattering or direct photoproduction).

HERA as a 'hadron-hadron' collider

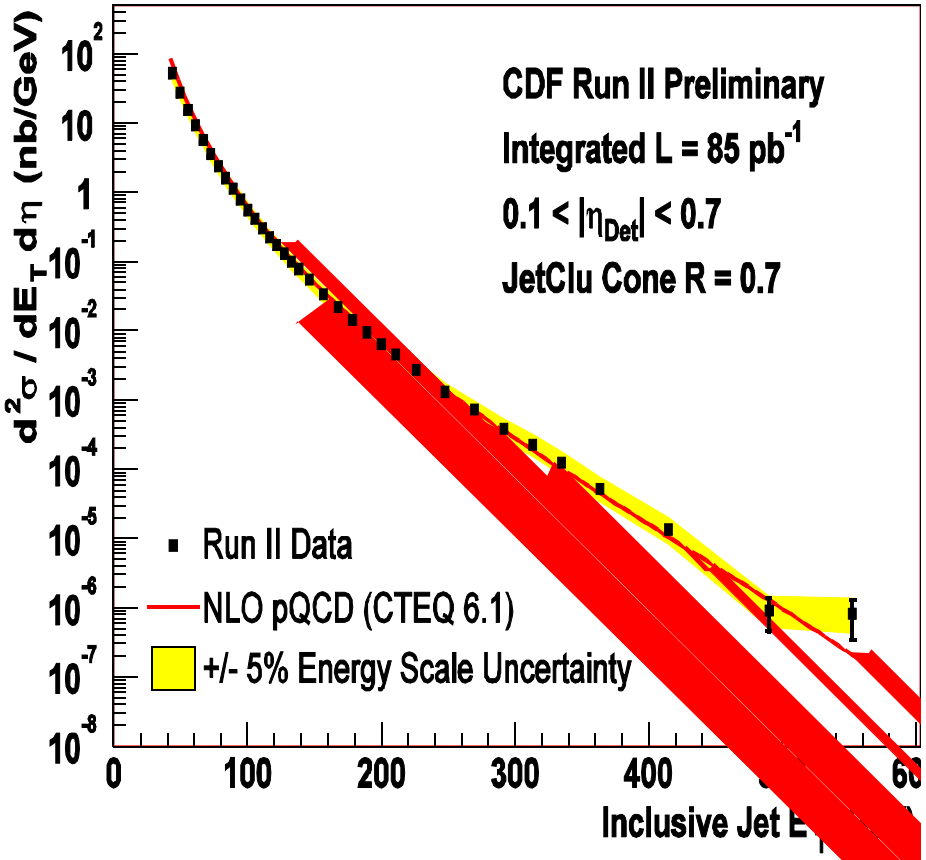


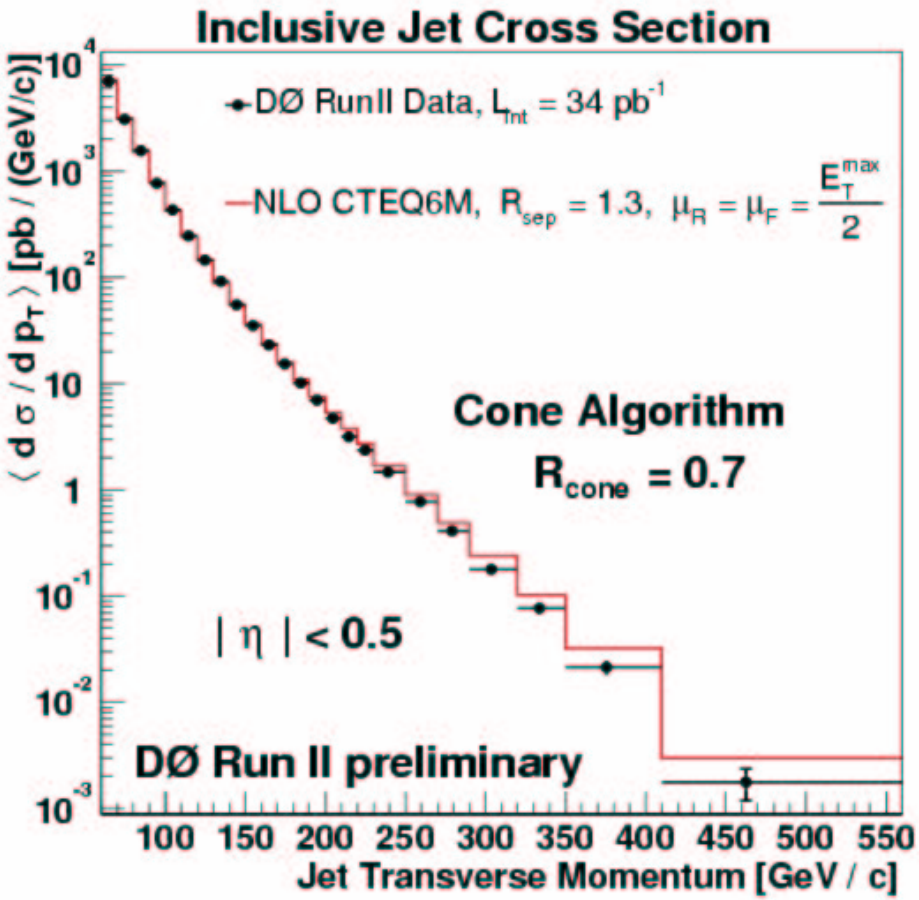
Proton anti-proton vs proton-photon vs photon-photon

- Jets, dijets and shapes from Tevatron Run II.
  - Higher energy, better triggers, better understanding of calorimeter, resolutions, energy scales in progress.
  - Calorimeter energy scale known to 5%
  - Unsmeared, full detector corrections applied.
  - *Still using cone algorithm.*
  - *Still correcting for energy outside jet/underlying event.*

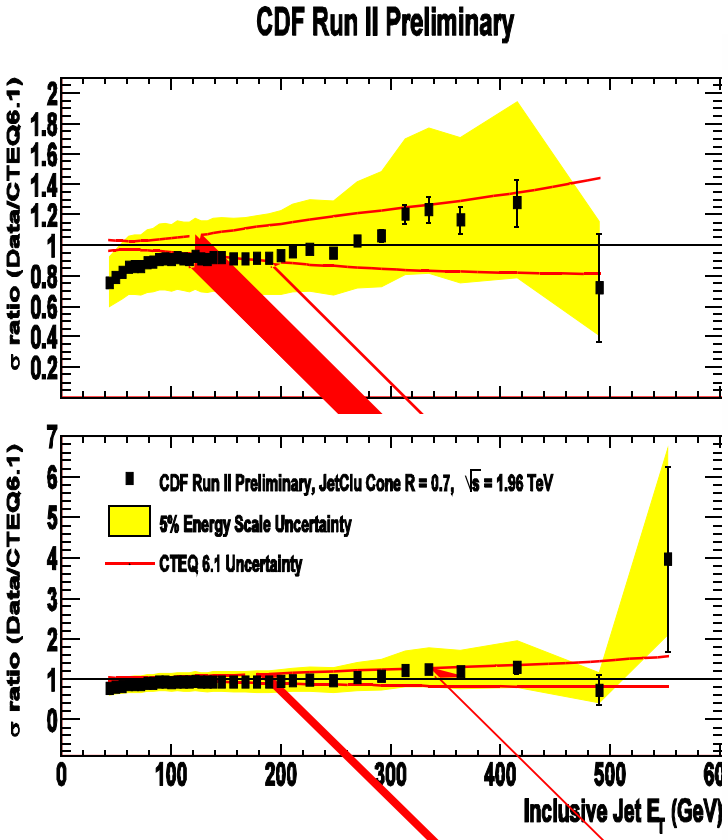


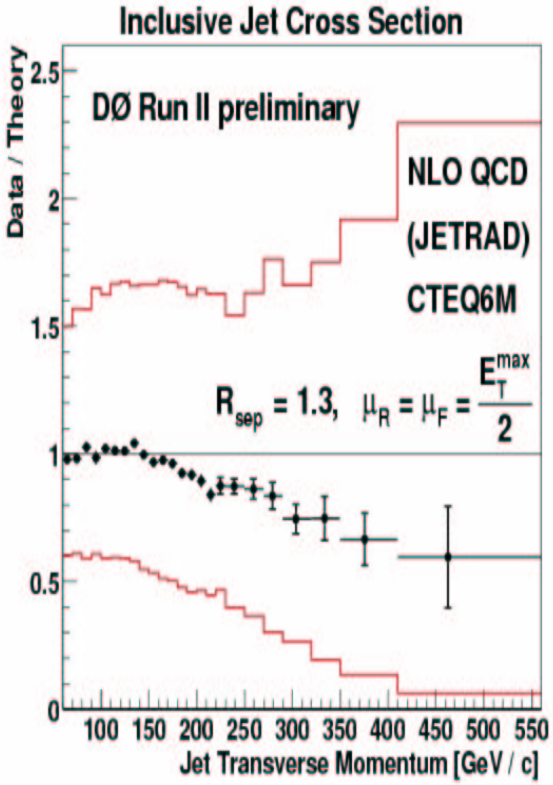
Proton anti-proton vs proton-photon vs photon-photon

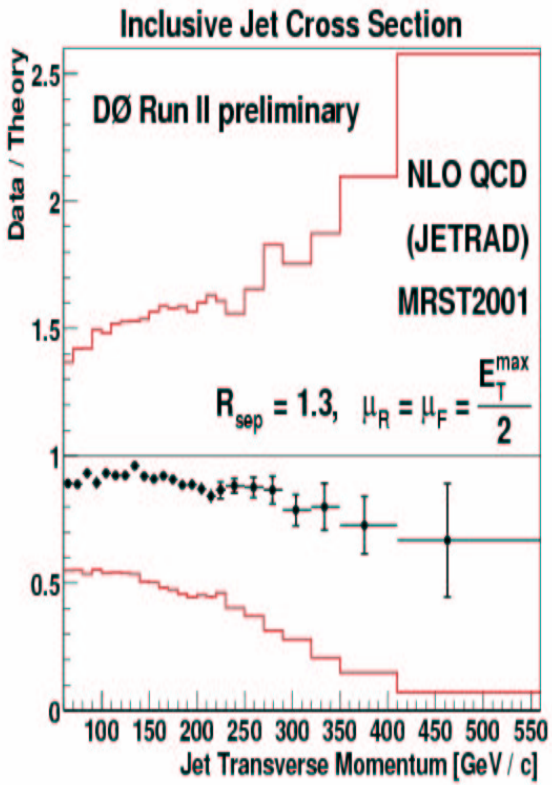




Inclusive Jet Cross Sections





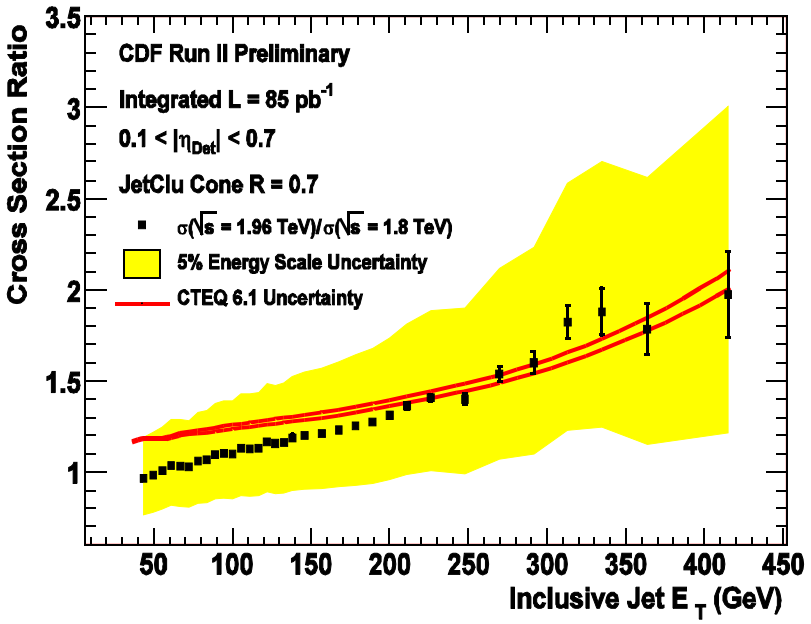


Transverse energy up to 550 GeV.

No sign of the apparent effect which caused excitement in Run I

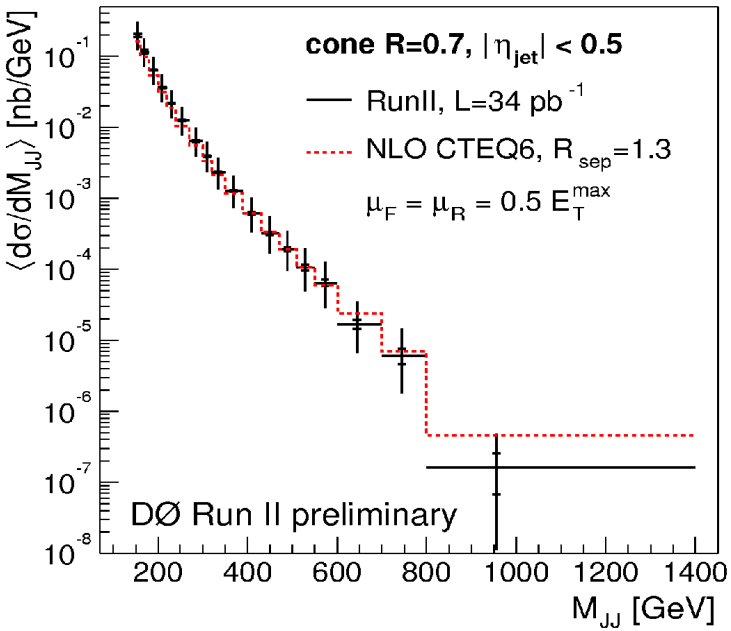
Inclusive jets

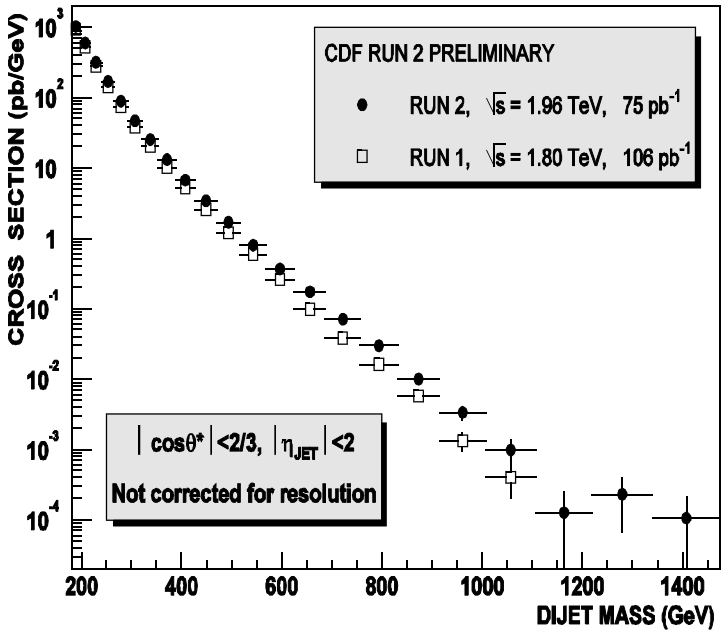
- Comparison with Run I
  - 1.8 TeV vs 1.96 TeV
  - Many errors cancel for ratio. Remaining dominated by Run II energy scale.
  - Good agreement.



Dijet Mass Distribution

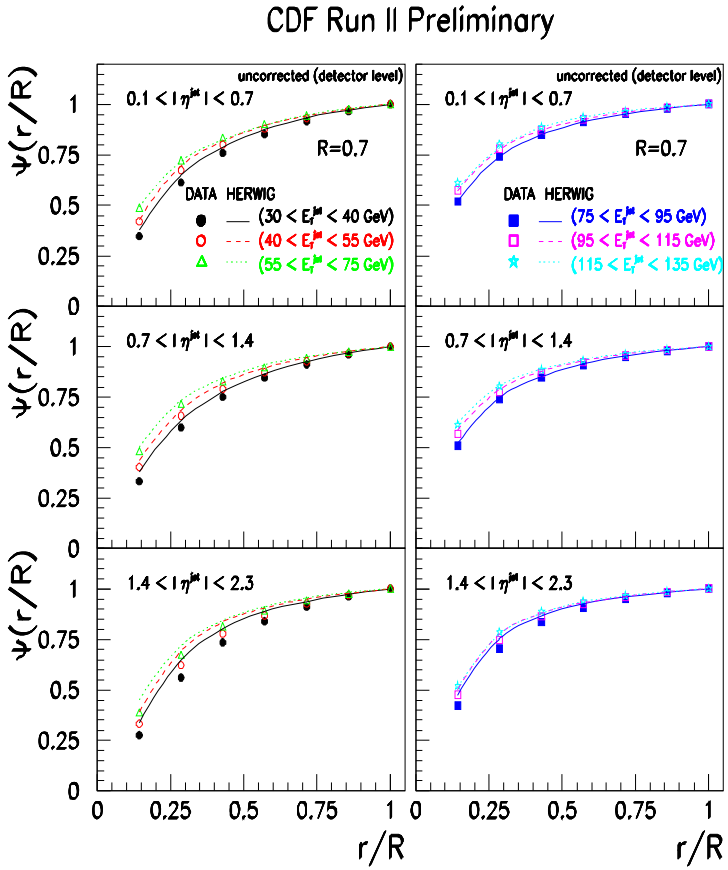
- Comparison with Run I and NLO QCD
  - 1.8 TeV vs 1.96 TeV
  - Masses up to 1634 GeV
  - Good agreement with NLO QCD

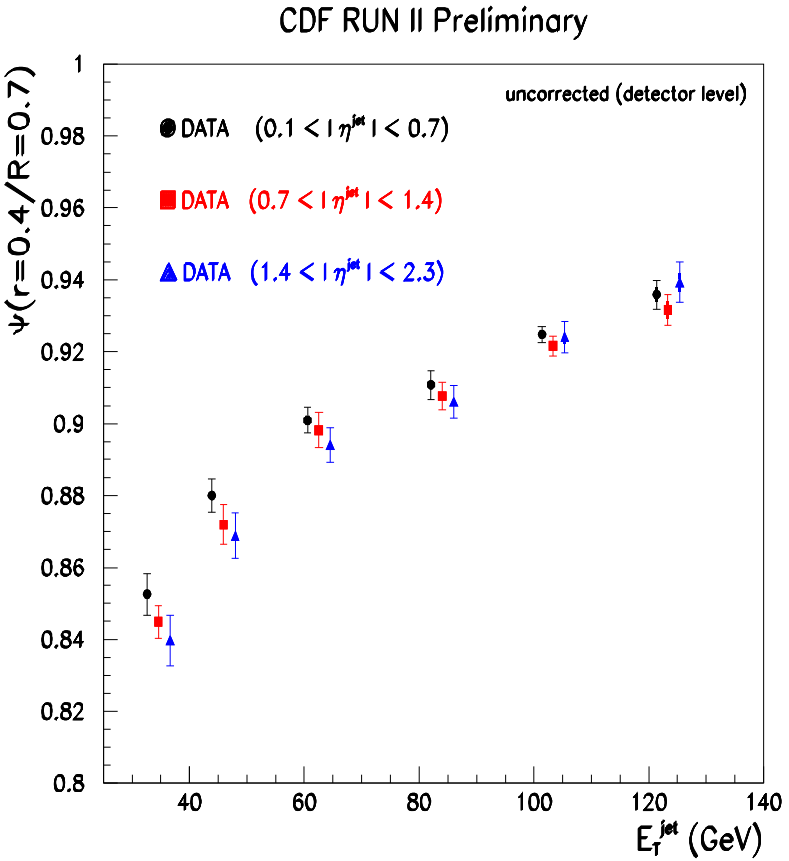




Jet shapes and energy flows between jets

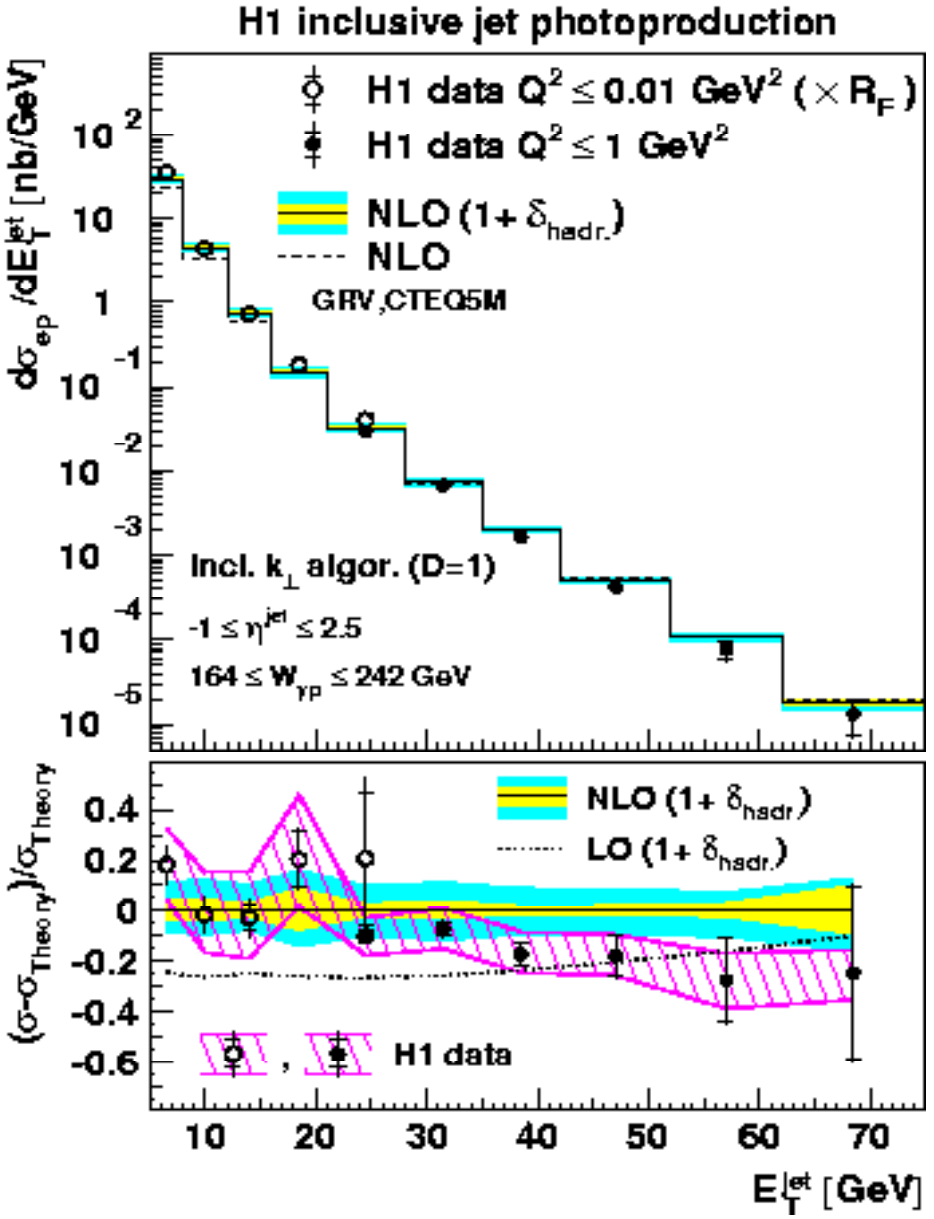
- HERWIG and PYTHIA doing ok.
- Not yet corrected to particle level.
- Forward jets are broader



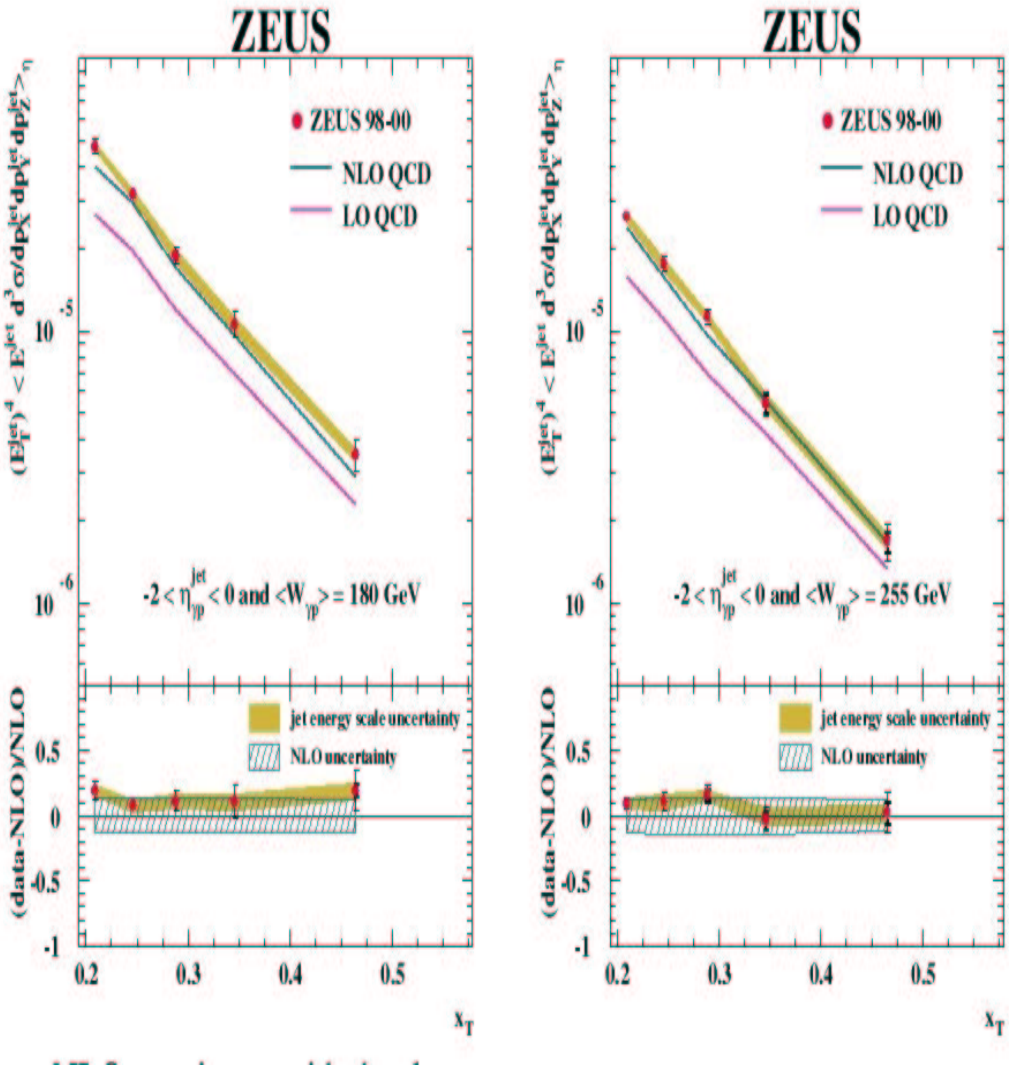


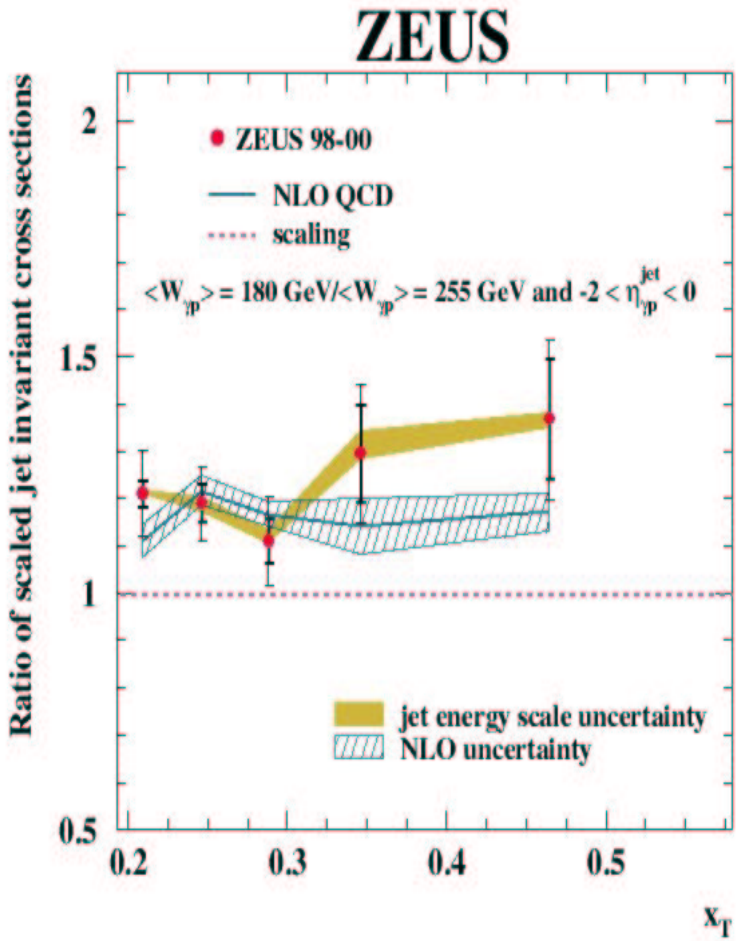
Proton-photon

- Measured up to 70 GeV
- Hadronisation/underlying event important below about 15 GeV, but not above.
- High E_T data should be included in global fits of photon PDF (resolved) and proton PDF (direct).
- Measure scaling violations at high transverse energies, different photon energies -> α_s

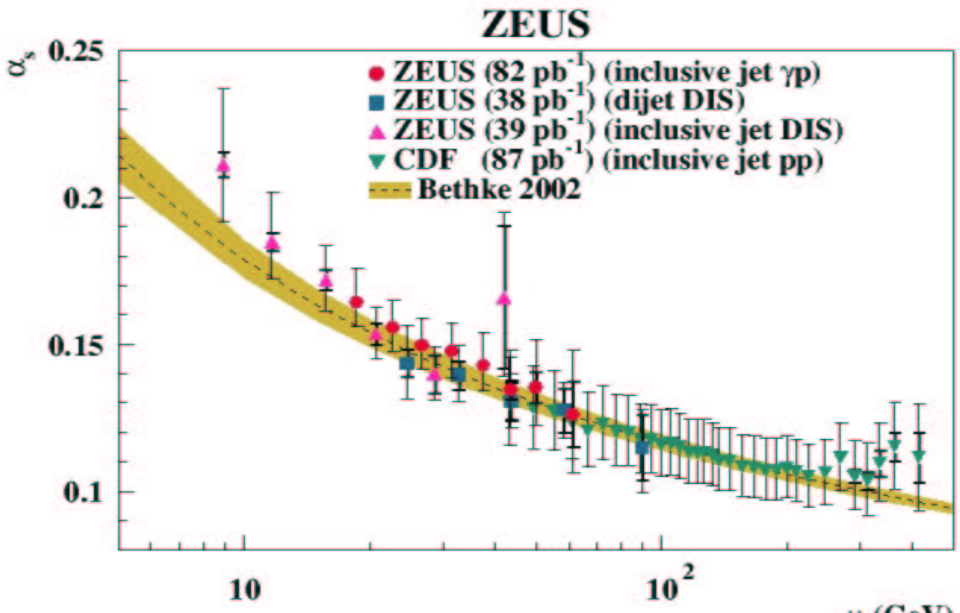


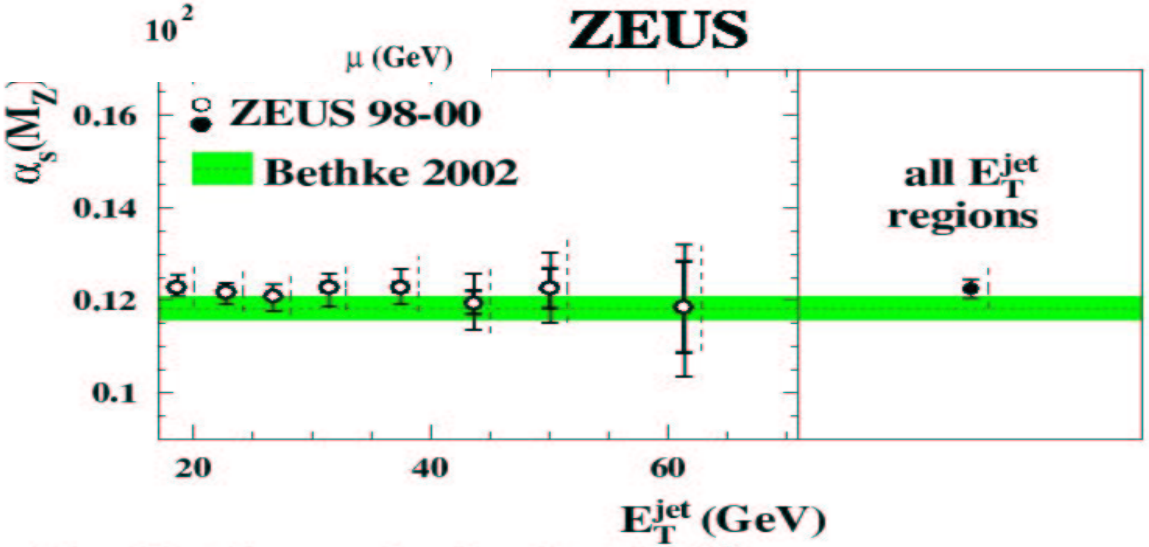
Proton-photon





Proton-photon

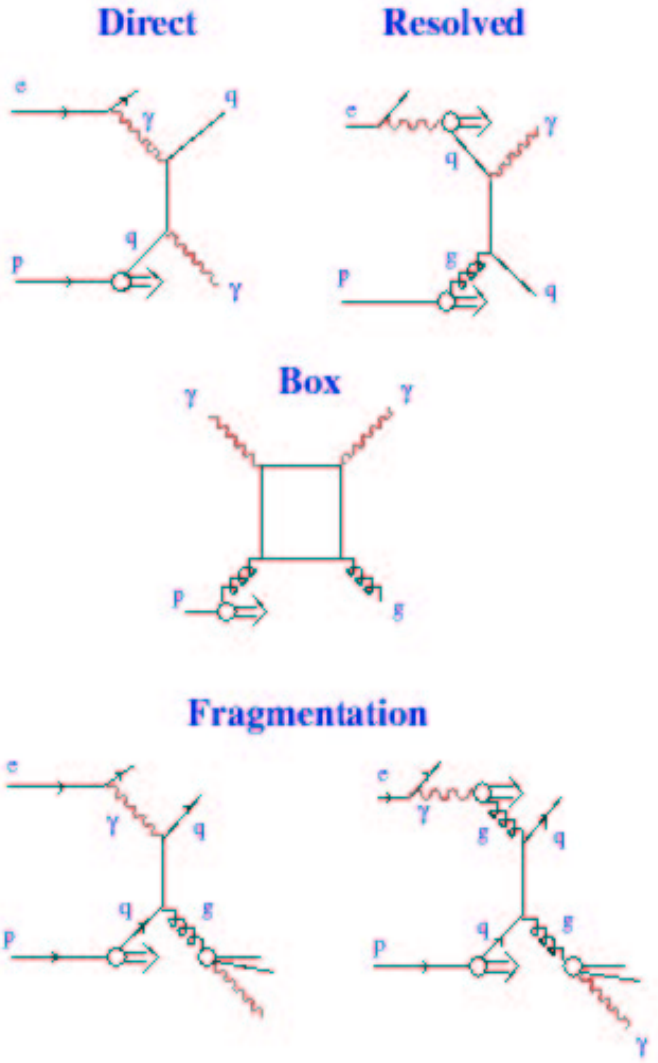




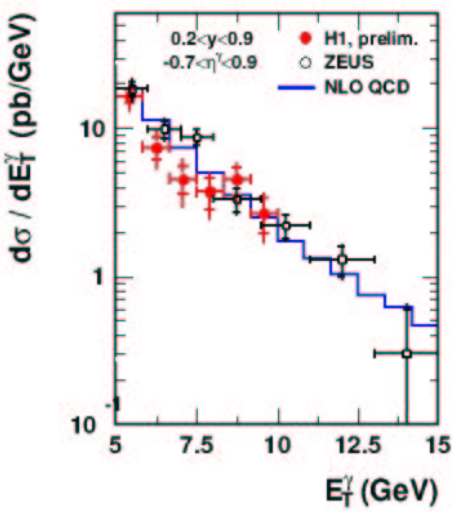
- Running the coupling back to the Z^0 mass...

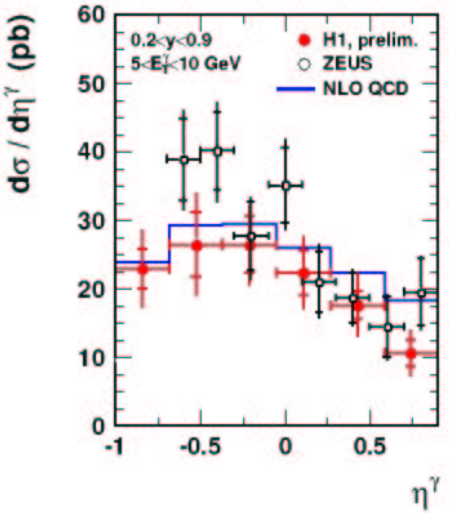
$$\alpha_s(M_Z) = 0.1224 \pm 0.0001(\text{stat.})^{+0.0022}_{-0.0019}(\text{exp.})^{+0.0054}_{-0.0042}(\text{th.})$$

Proton-Photon: Prompt Photons

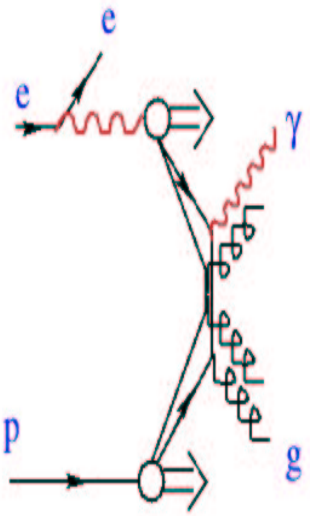


- In principle, more direct access to hard process.
- Good testing ground for QCD and for measurement of PDFs.
- Calibration tool at hadron colliders.
- Isolation requirement leads to sensitivity to QCD final state effects.



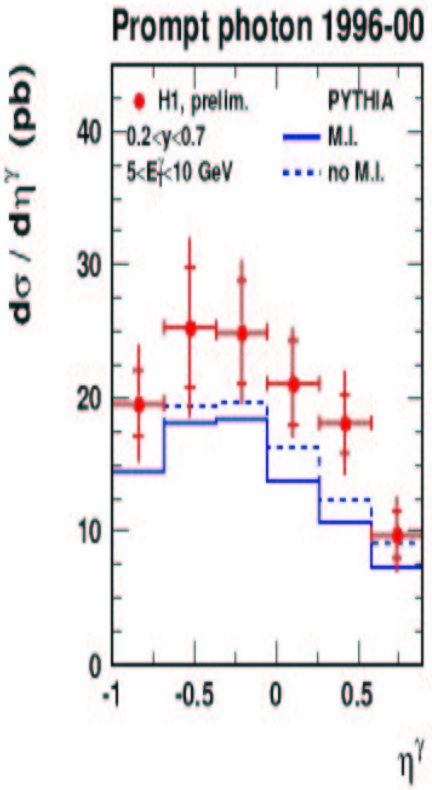


Proton-Photon: Prompt Photons



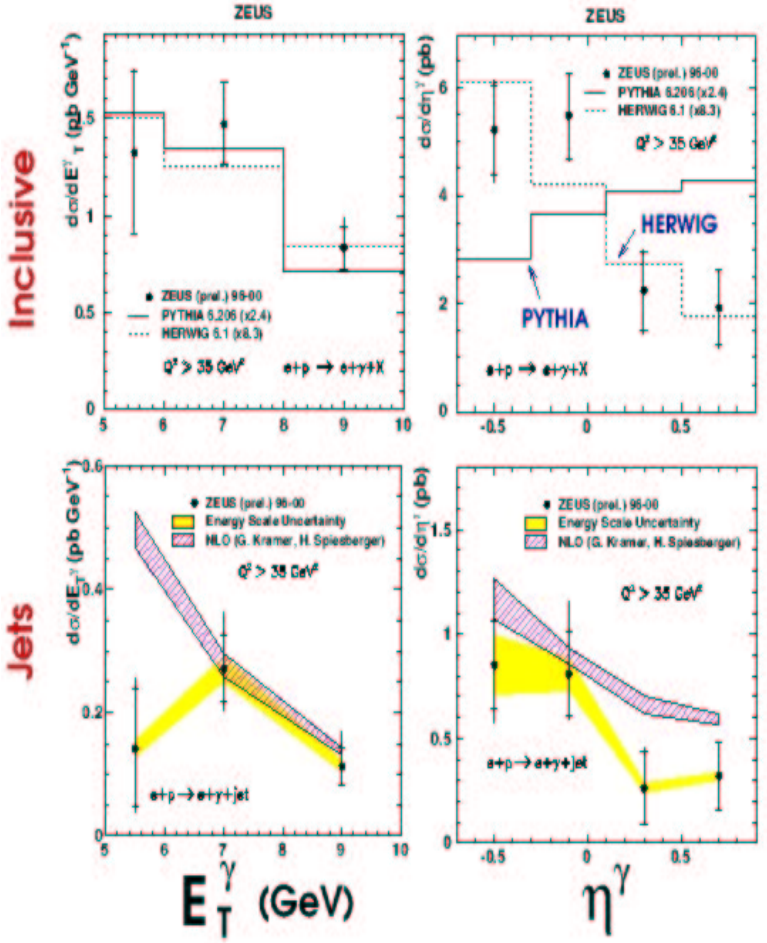
Underlying event activity

Hadronic energy in the isolation cone



Effect about 25% for positive η according to PYTHIA

First measurement in DIS

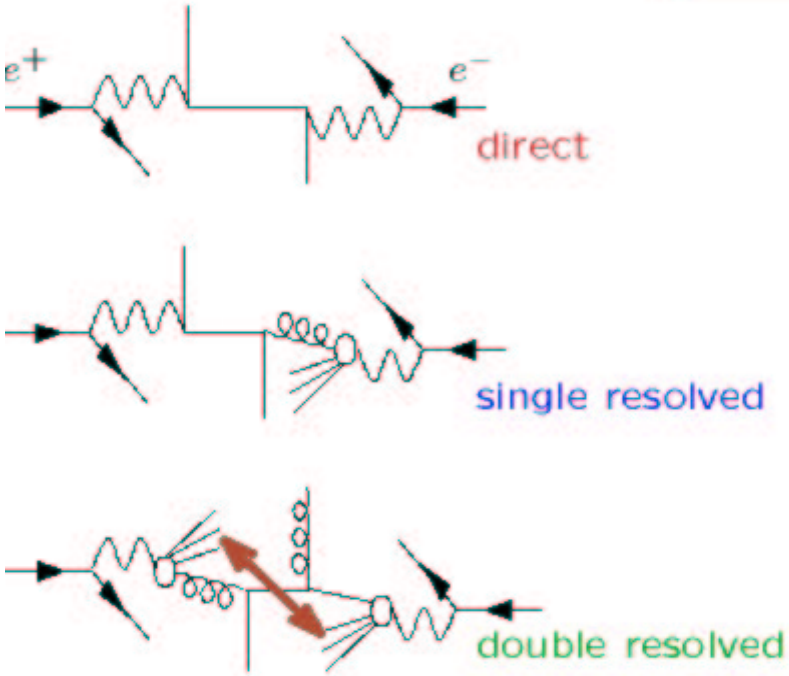


Also: NLO describes instrinsic k_T in prompt photon photoproduction (Fontannaz et al)

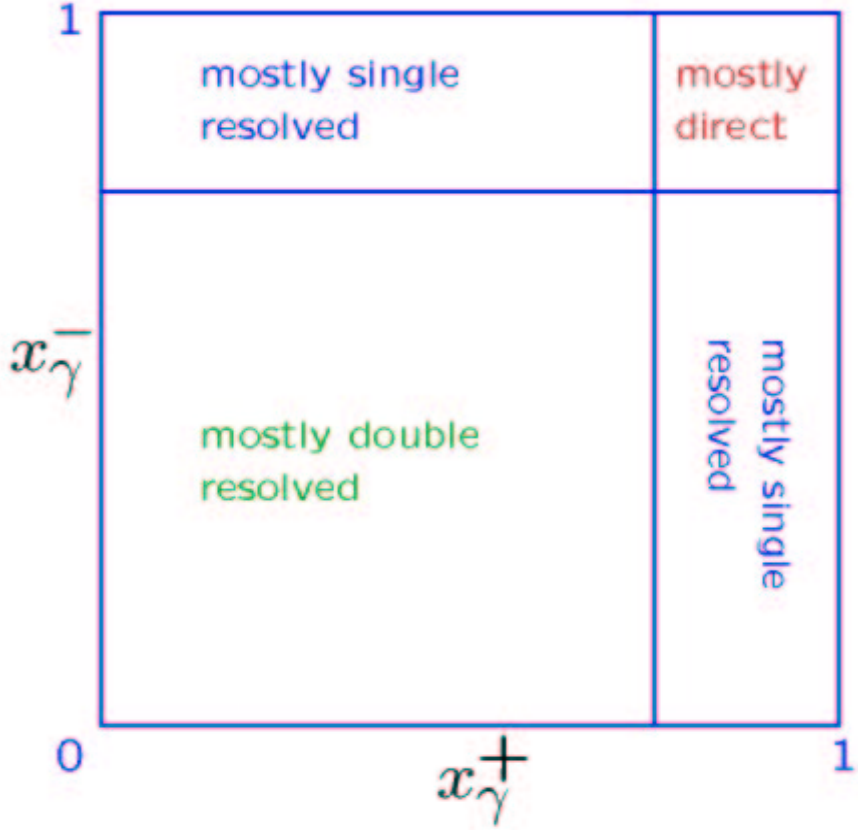
Photon-Photon

Estimate of fraction of photon momentum entering hard collision

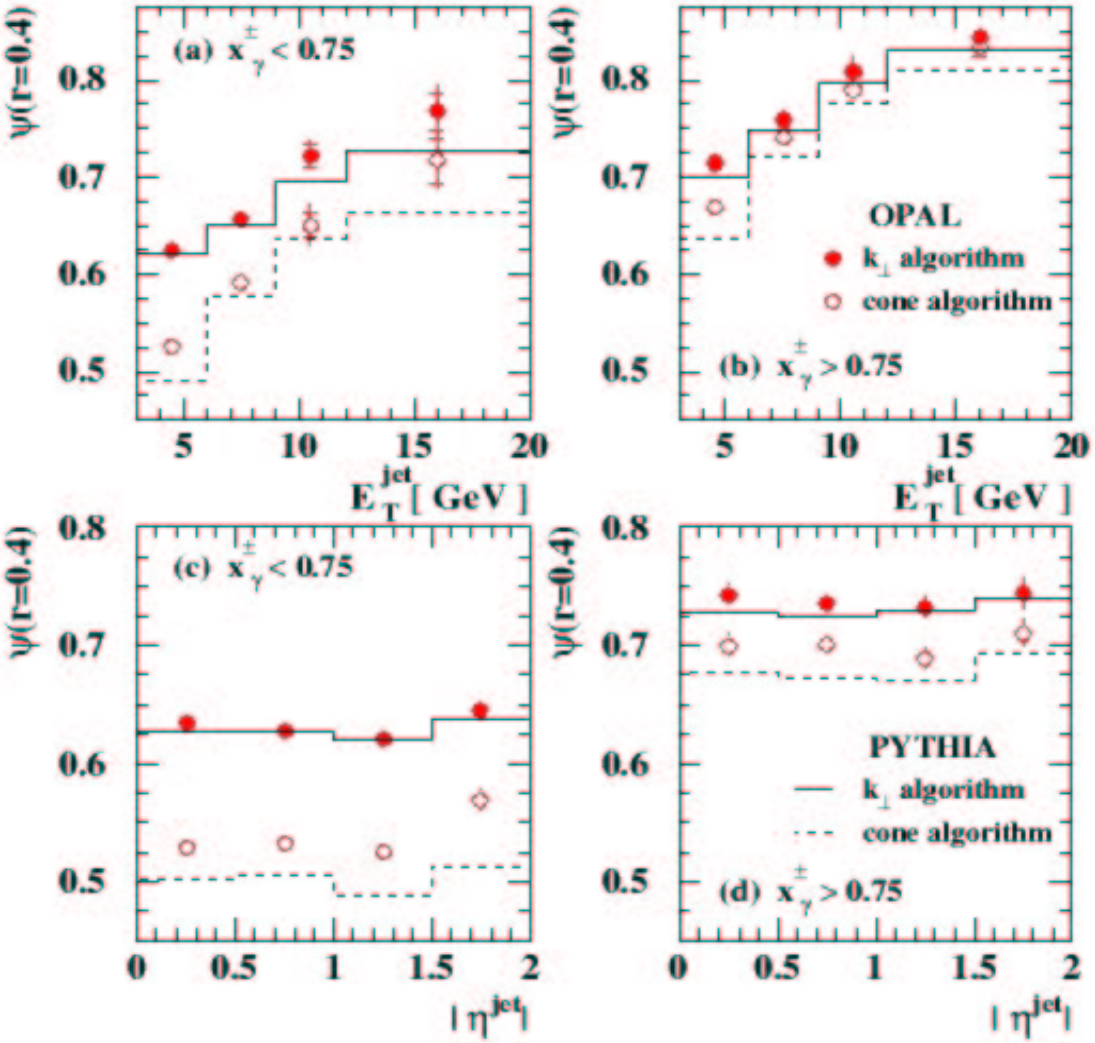
$$x_\gamma^{\pm} = \frac{\sum_{\text{jet1,2}} E \pm p_z}{\sum_{\text{hadrons}} E \pm p_z}$$



multiple parton interactions (MIA)?



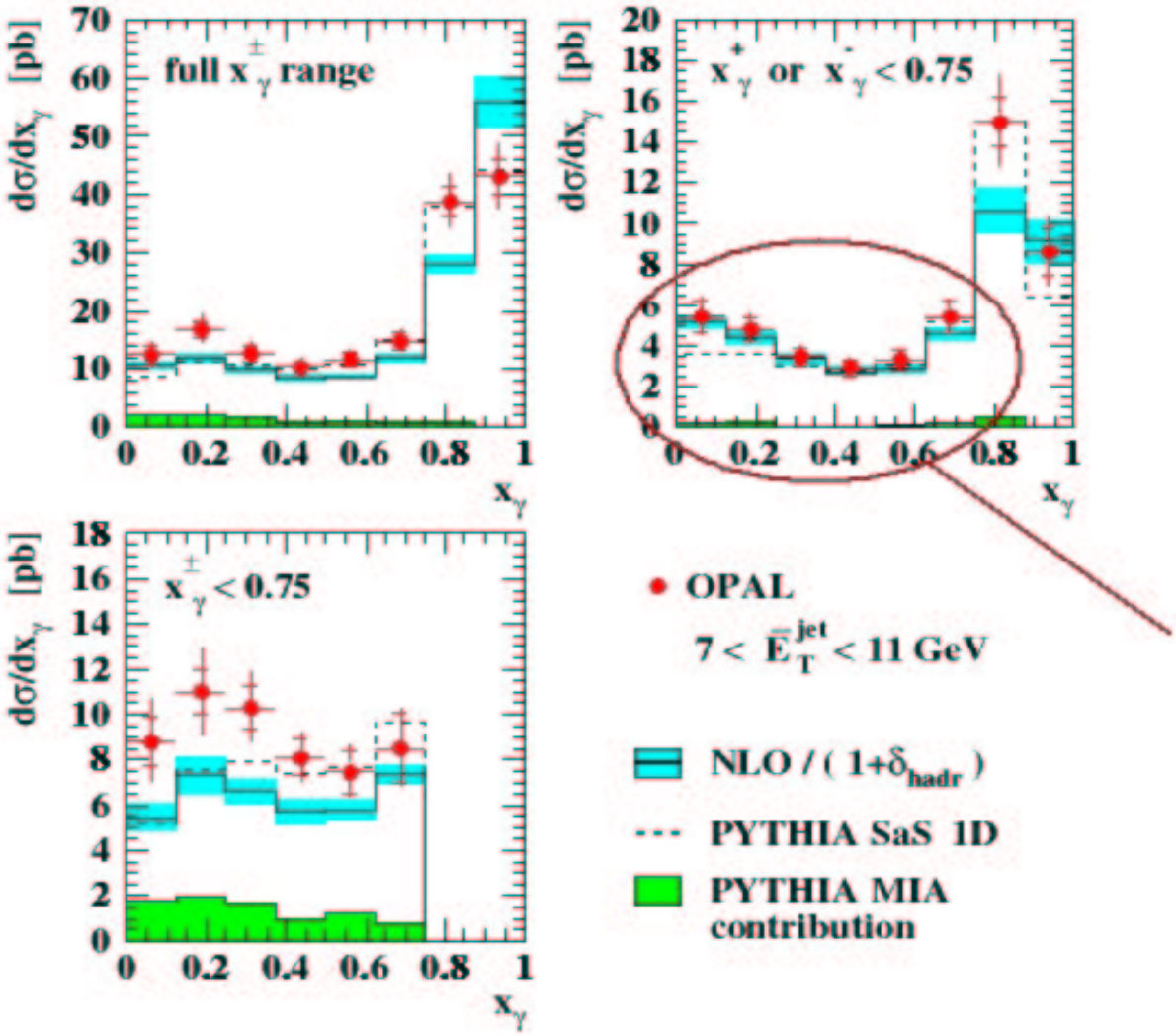
Photon-Photon



Quark jets are more collimated than gluon jets, but both show the same dependence on E_T and η

$k_\perp$ jets are more collimated than cone jets and are better described by the Monte Carlo

Photon-Photon



. . . MIA, which (PYTHIA says) are very small for single res. enhanced sample, as expected

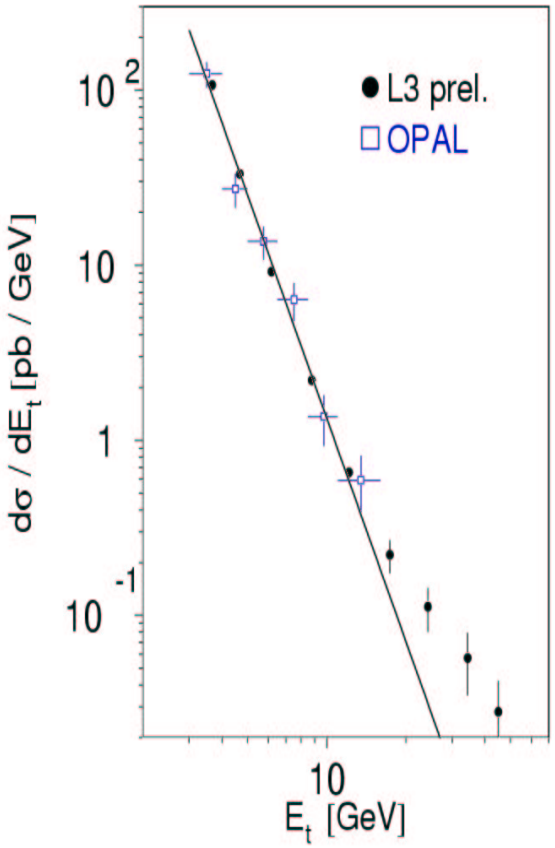
Small hadronisation corrections and no disturbance from MIA

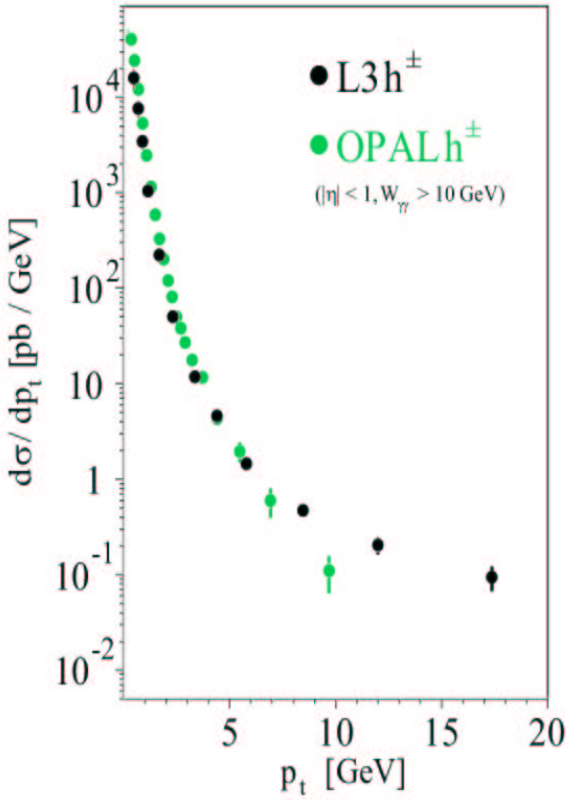
NLO should work here – and it does!

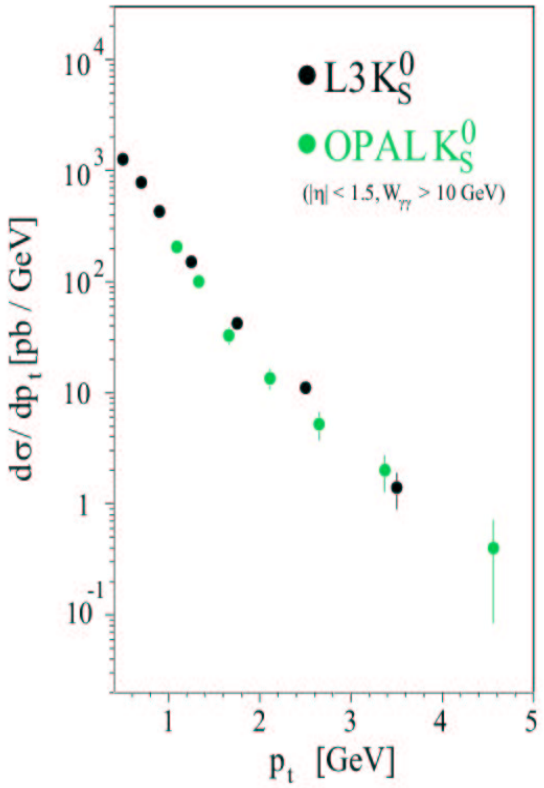
Photon-Photon

Jets

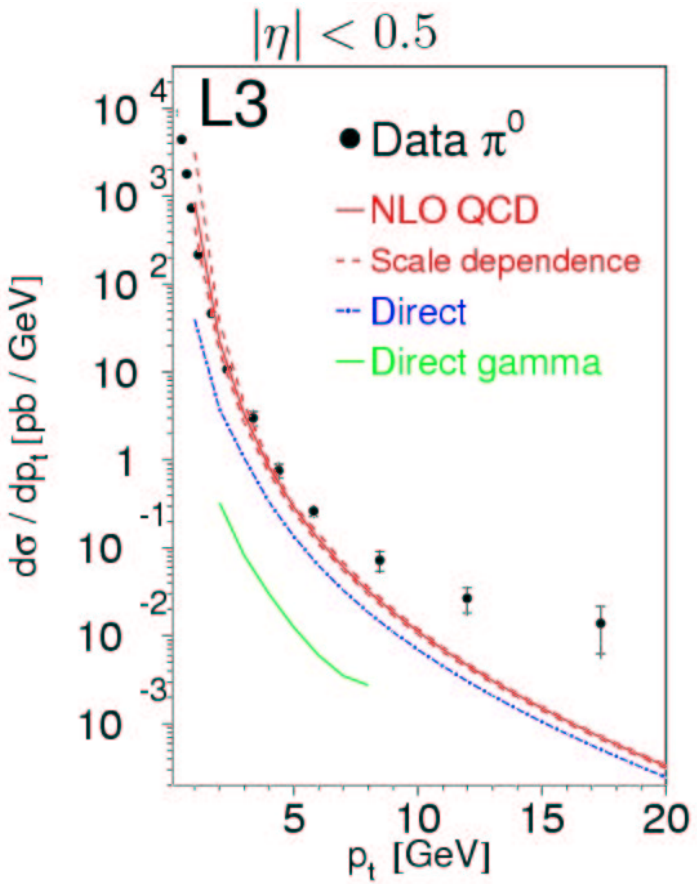
Hadrons



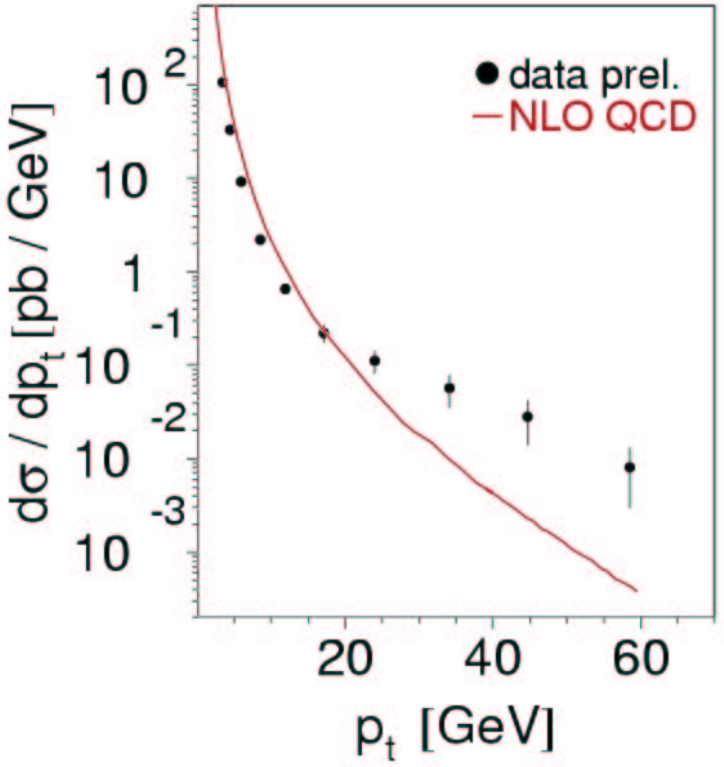




Photon-Photon

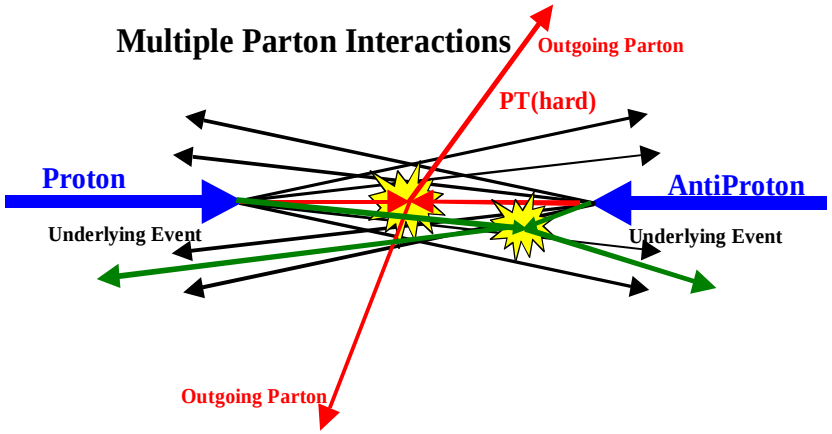


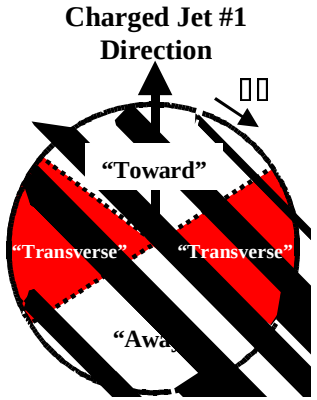
NLO QCD: S. Frixione and L. Bertora



Jet shapes and energy flows between jets (underlying events and minimum bias data)

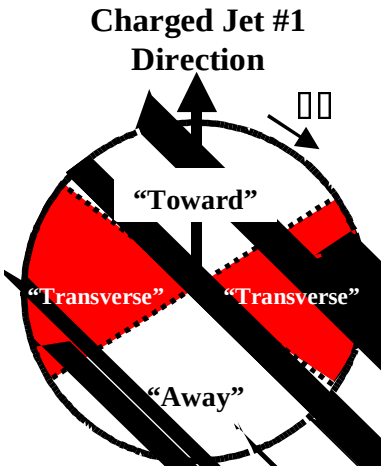
- Models based on physics (even on QCD) but need to be fairly complex to describe correlations, fluctuations, energy dependencies seen in the data.
- Have also been tested/tuned at HERA and LEP (and with older hadron-hadron data).
- Necessary input for detector development and precision measurements at current machines and LHC and FLC.
- Important to understand energy dependence.

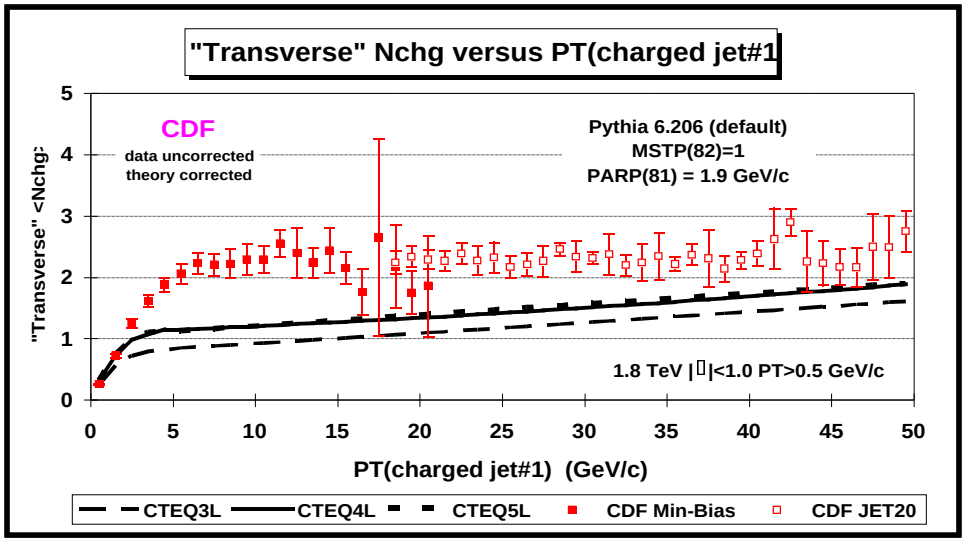


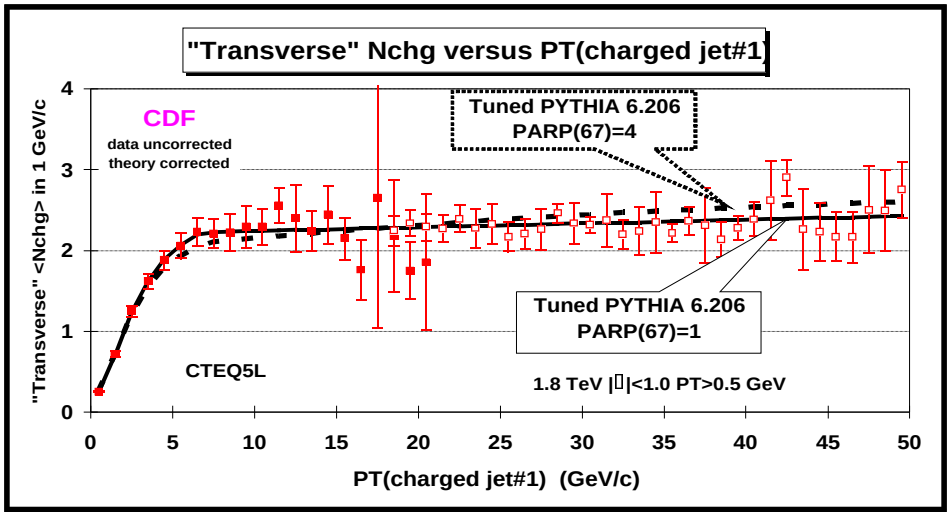


Jet shapes and energy flows between jets (underlying events and minimum bias data)

- HERWIG and PYTHIA do ok after tuning (defaults fail).







Proton anti-proton vs proton-photon vs photon-photon (Jet cross sections, Energy flows and Underlying Events)

- In most cases NLO is there and works within uncertainties.
- In many (most) cases the data are more accurate than the available NLO predictions,
  - Though not than those which could be made in principle, hence the importance of practical improvements cf CAESAR.
  - Non- and Semi-perturbative effects can be isolated but are important and interesting in several areas.
- Hadron-hadron is the future.
  - Nikolaj Skatchkov, On the possibilities of measuring of gluon distribution in gamma/Z0+jet events at Tevatron and LHC

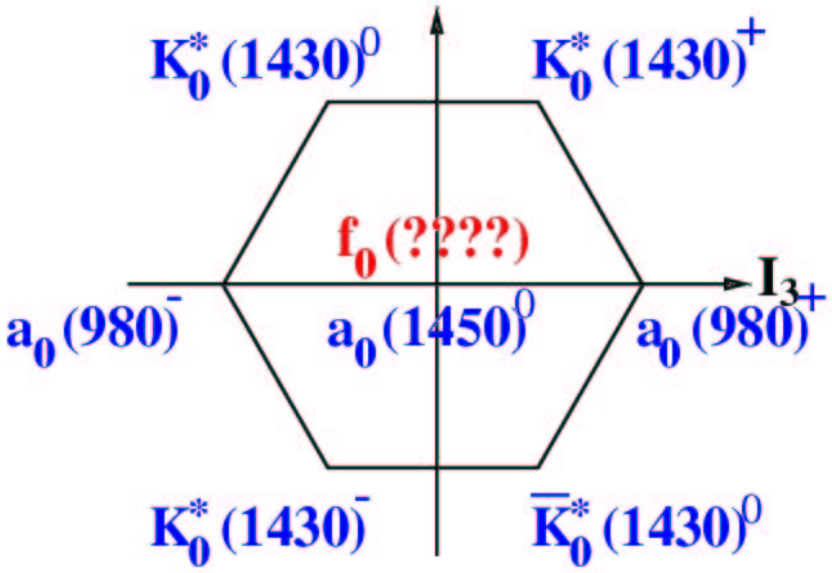
Proton anti-proton vs proton-photon vs photon-photon

A tale of three colliders

- Tevatron: (Bhatti, Lami, O'Dell, Skatchkov)
  - Not such sophisticated QCD analyses from Run I (cone, UE...)
  - Very focussed on other things at Run II : QCD an 'unfortunate necessity'?
  - Lots and lots of potential. Battle on to realise it.
- HERA (Andrieu, Sutton, Lemrani)
  - Mature analyses now being published. Precision even in photoproduction (!).
  - Standing by for more data, up to kinematic limit.
- LEP2 (Achard, Krueger)
  - Statistically limited but elegant and exciting results
  - Effort winding down. Has everything that is needed really been done?

Fragmentation, Resonances, Non-Perturbative Effects

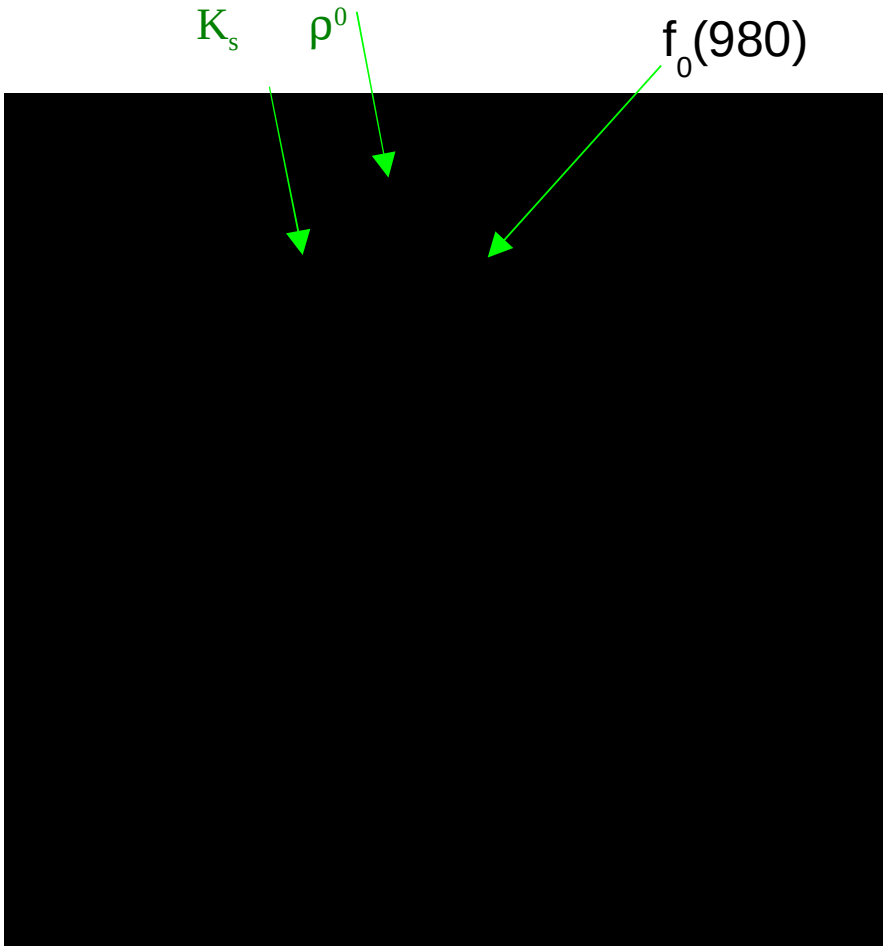
- Resonance Production
  - Erika Garutti, Electroproduction of Scalar Mesons at HERMES
  - Andy Ziegler, ZEUS Strange particle production at ZEUS
  - Anna Kropivnitskaya, Inclusive photoproduction of rho, f0, f2 and eta at H1

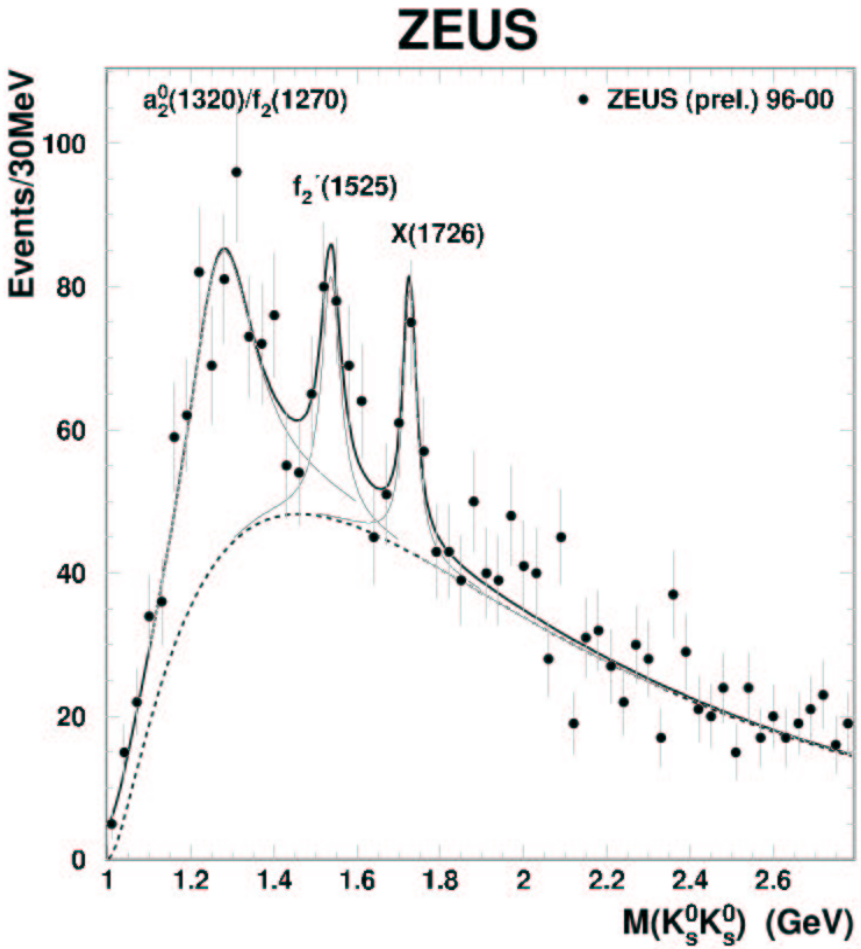


Scalar mesons can be glueball candidates.

(Are there too many of them?)

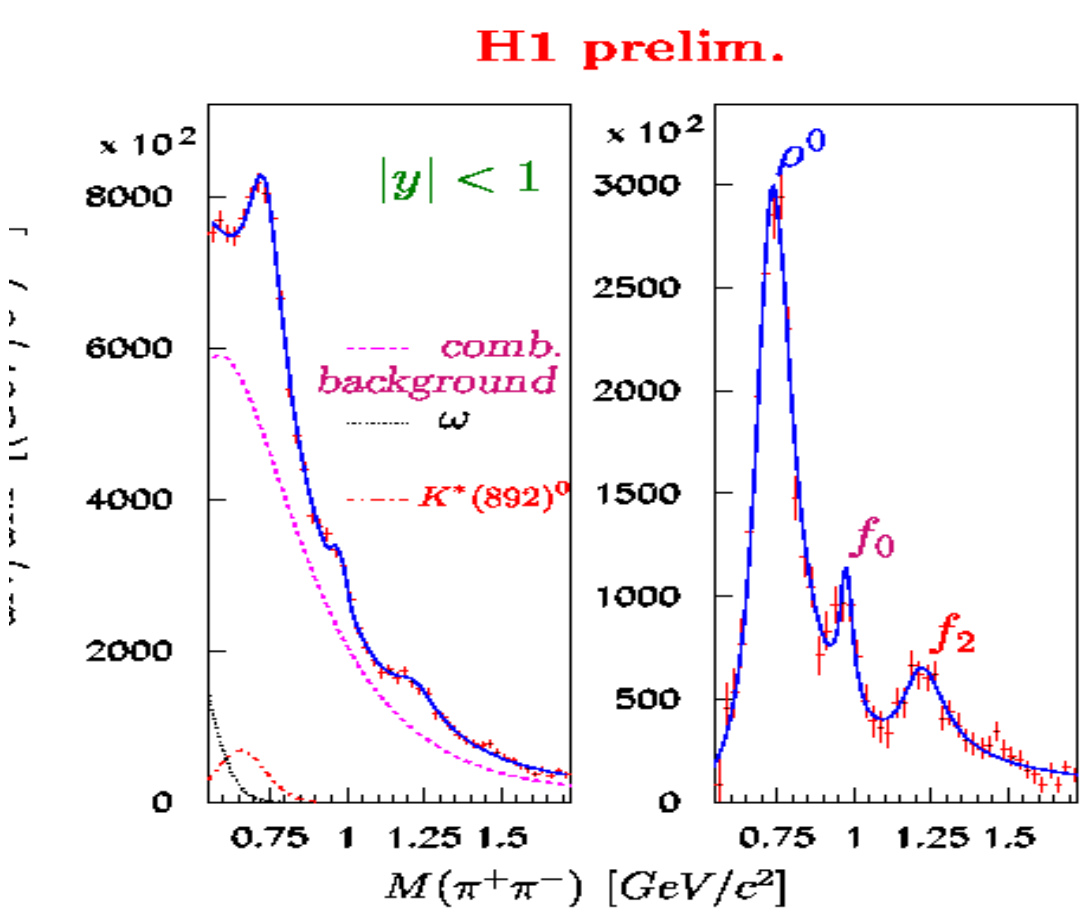
Scalar Resonances

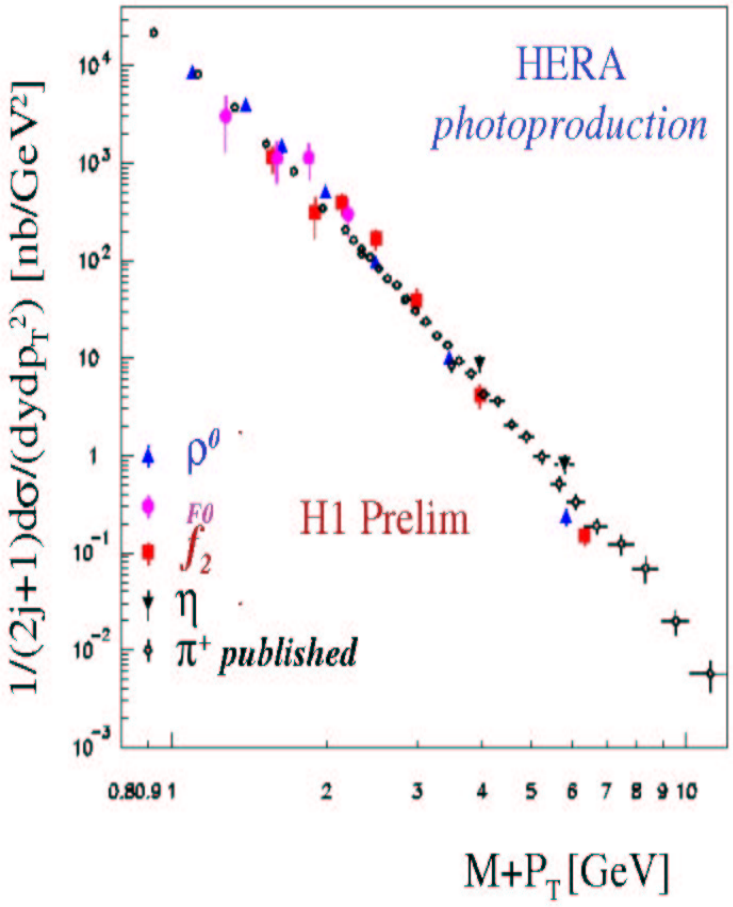




See $f_0(1710)$ for the first time in DIS

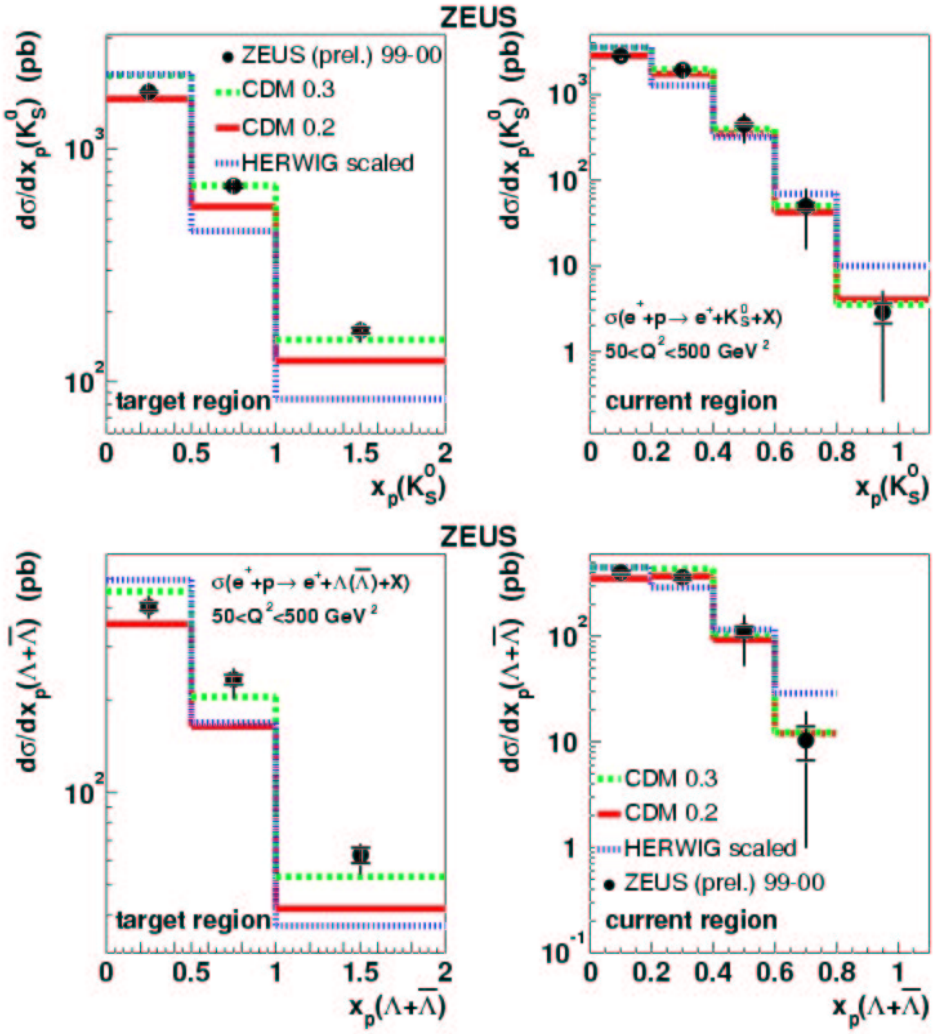
Resonances





$M(\pi^+\pi^-)$ [GeV]

Strange Particle Production



Signs that strangeness production becomes more likely in the the high x target region (gluon rich...)?

'Fuzzy QCD' in the final state

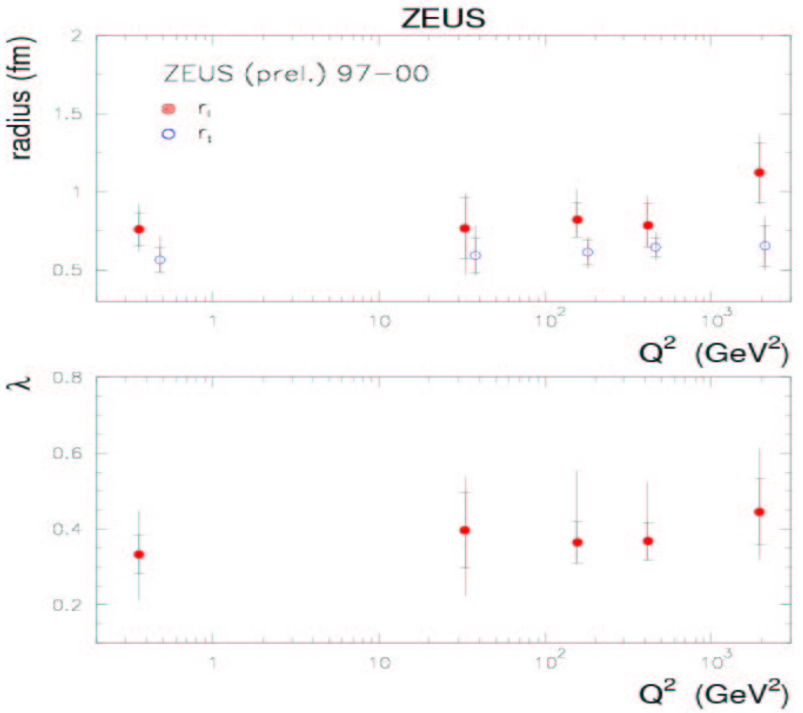
- Francois Arleo, Quenching of hadron spectra in DIS on nuclear targets
  - Alternative to usual approach: assume all quenching (rescattering in nuclei) takes place in the nucleus before hadronisation and rather than after.
  - Predicts saturation of these effects for large nuclei and equal K^+/K^- equally suppressed.
- G. Elbakian, Nuclear attenuation in Semi-Inclusive Electroproduction of Hadrons at HERMES
- Krystyna Olkiewicz, Instanton searches with ZEUS
  - Sensitivity now at levels of the predicted cross sections
  - Hampered by poor modelling of DIS final states in tails.
  - No sign of instantons seen yet.

Interplay between initial- and final-state interactions, fragmentation

- Guilliame Leibenguth, Colour reconnection studies in e+e- -> W+W- at sqrt(s)=189-208 GeV using particle flow
  - Some models ruled out.
  - No definite effect seen in Z or WW.
  - Effect on W mass is 22 +/- 43 MeV

Interplay between initial- and final-state interactions, fragmentation

- Krystyna Olkiewicz, Madjid Boutemeur: Bose-Einstein Correlations in DIS and in $\pi^0\pi^0$ Pairs From Hadronic Z Decays
  - No Q^2 or s dependence
  - Dependence on multiplicity in Z events (increased correlations at high multiplicity).
  - According to MC at LEP, correlations are between particles from different resonant decays (!)

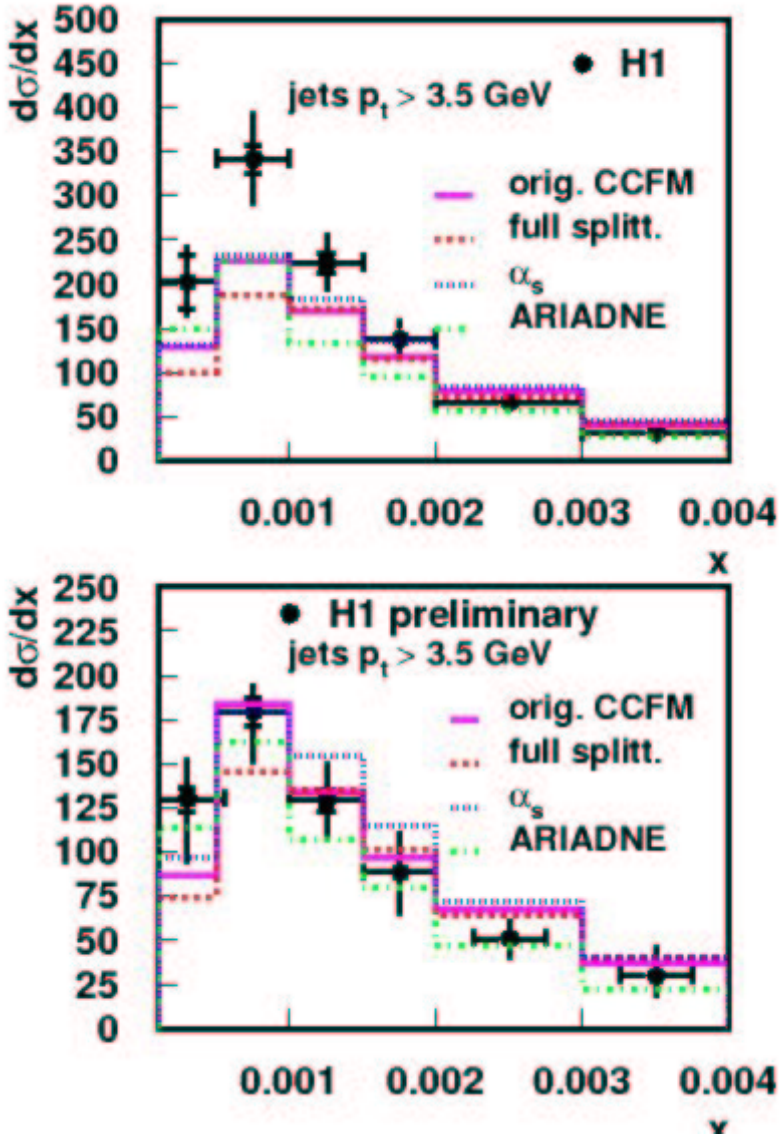


Low x resummation, unintegrated parton distributions

- Does QCD contain Regge theory?
  - Forward Jets: Lidia Goerlich, Sabine Lammers
  - Rapidity gaps and energy flows between jets in photoproduction: Mark Sutton
  - The triple-pole pomeron; from Regge theory to DGLAP evolution: Gregory Soyez
- Do we need and can we do low-x resummations?
  - From unintegrated gluon distributions to particle production in hadronic collisions at high energies: Antoni Szczurek
    - Significant effect of k_T on central particle multiplicities at SPS
  - Dijet Production at Low Bjorken-x in DIS: Roman Poeschl

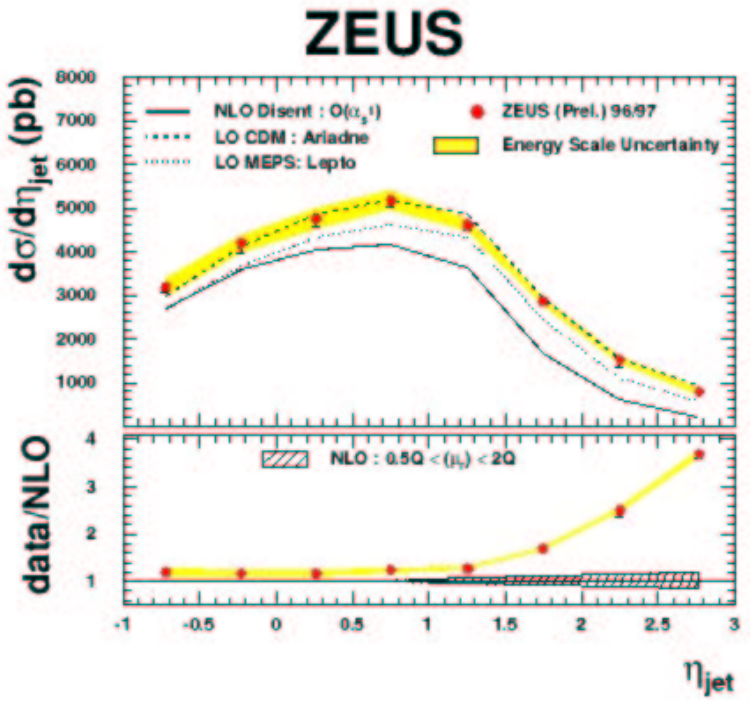
Low x resummation, unintegrated parton distributions

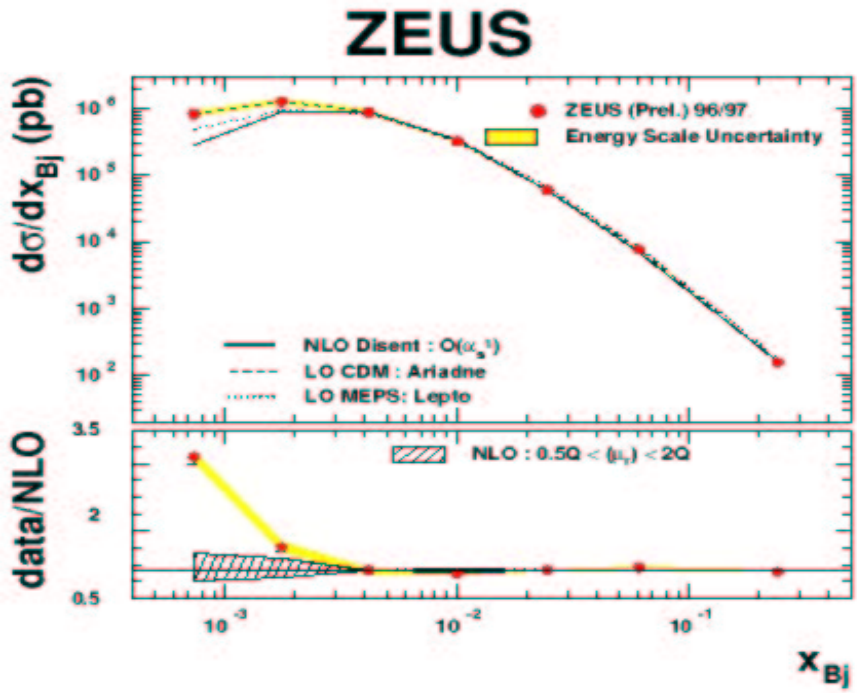
- Do we need and can we do low-x resummations?
  - The status of CCFM and unintegrated pdfs: Hannes Jung
  - New fits now available. Better treatment of soft region of Cascade (cut offs) and non-leading contributions. Better agreement with new data.



Forward Jets

- Inclusive jet cross section in forward region:





- Suggestive. But dominated by QPM-like events.
- Look at high eta jets in low x events... *(forces a 'dijet' topology)

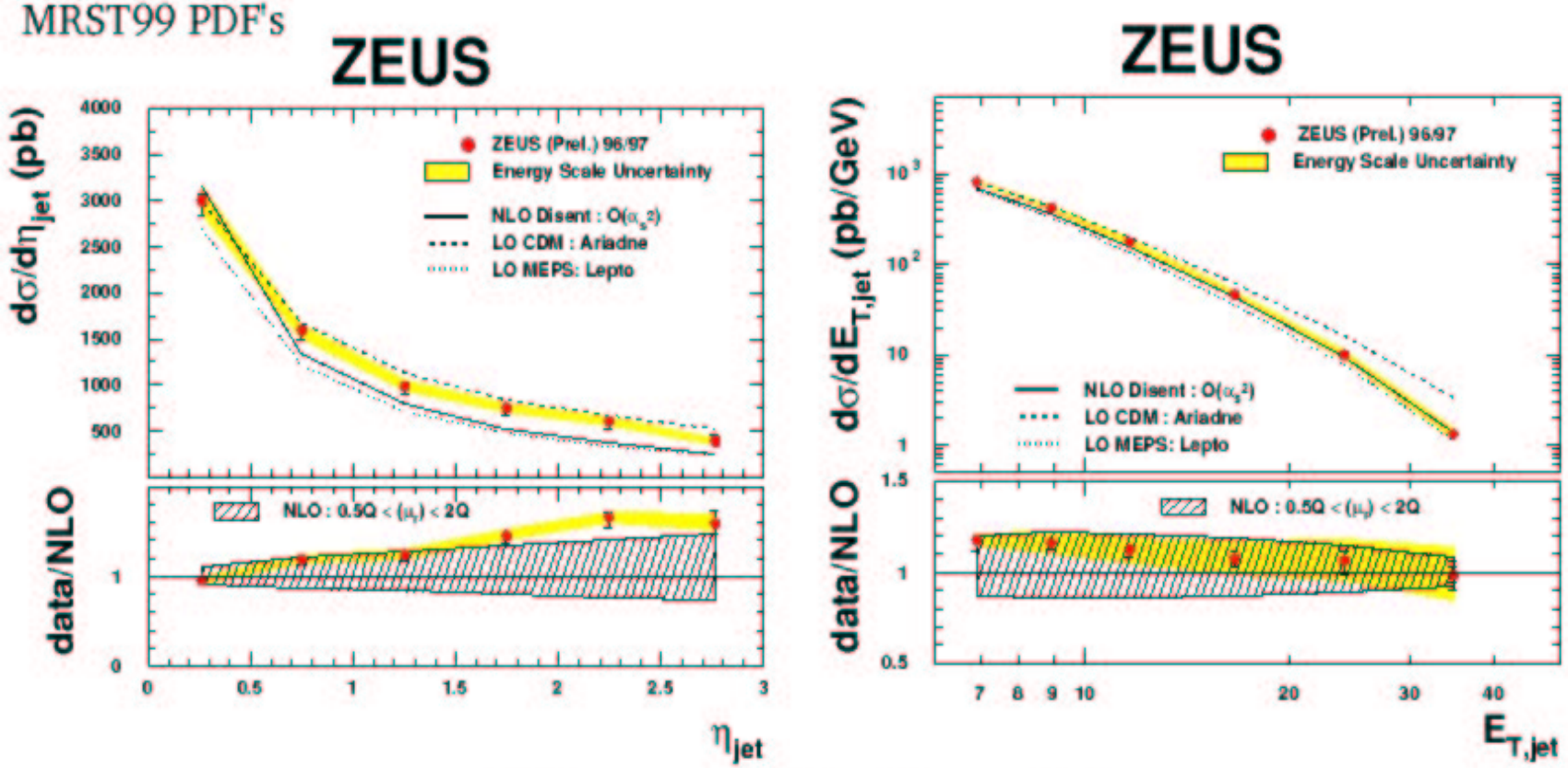
Forward Jets

DISENT implementation of NLO calculation

LO = $O(\alpha_s^1)$; NLO = $O(\alpha_s^2)$

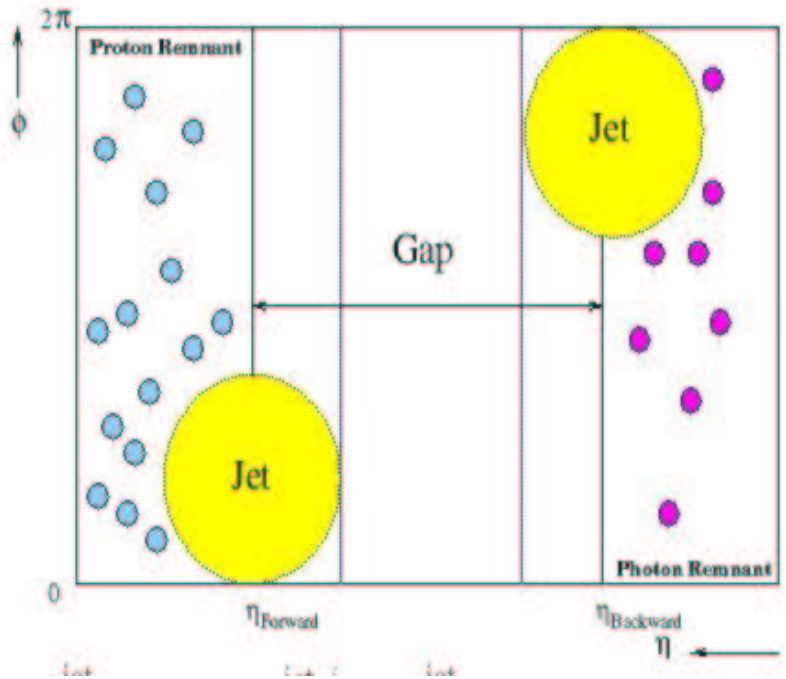
MRST99 PDF's

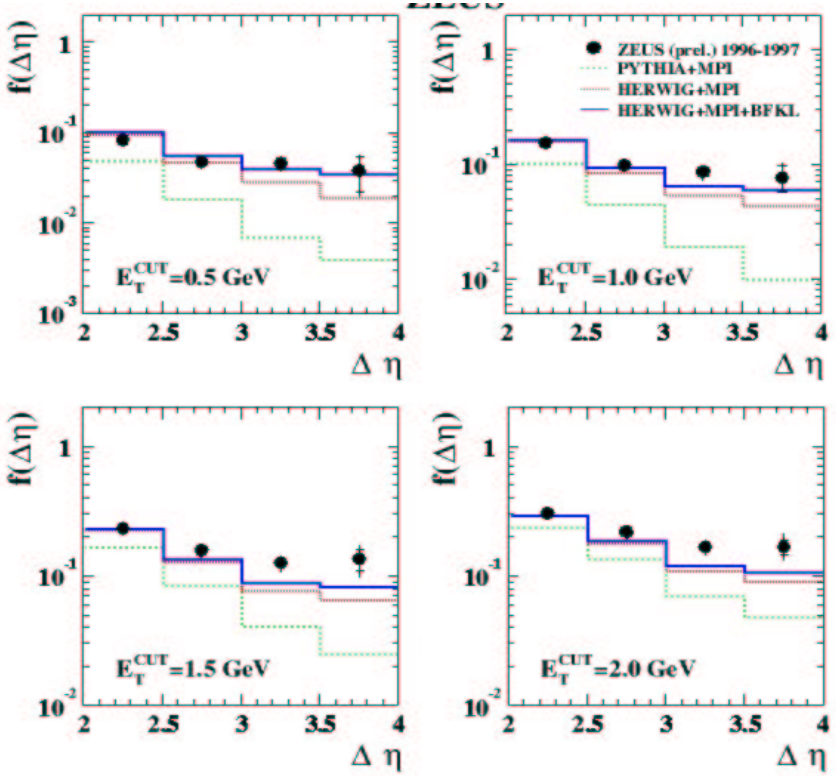
"Dijet" Phase Space



NLO agrees with data within
larger renormalization scale uncertainty

Gaps between Jets

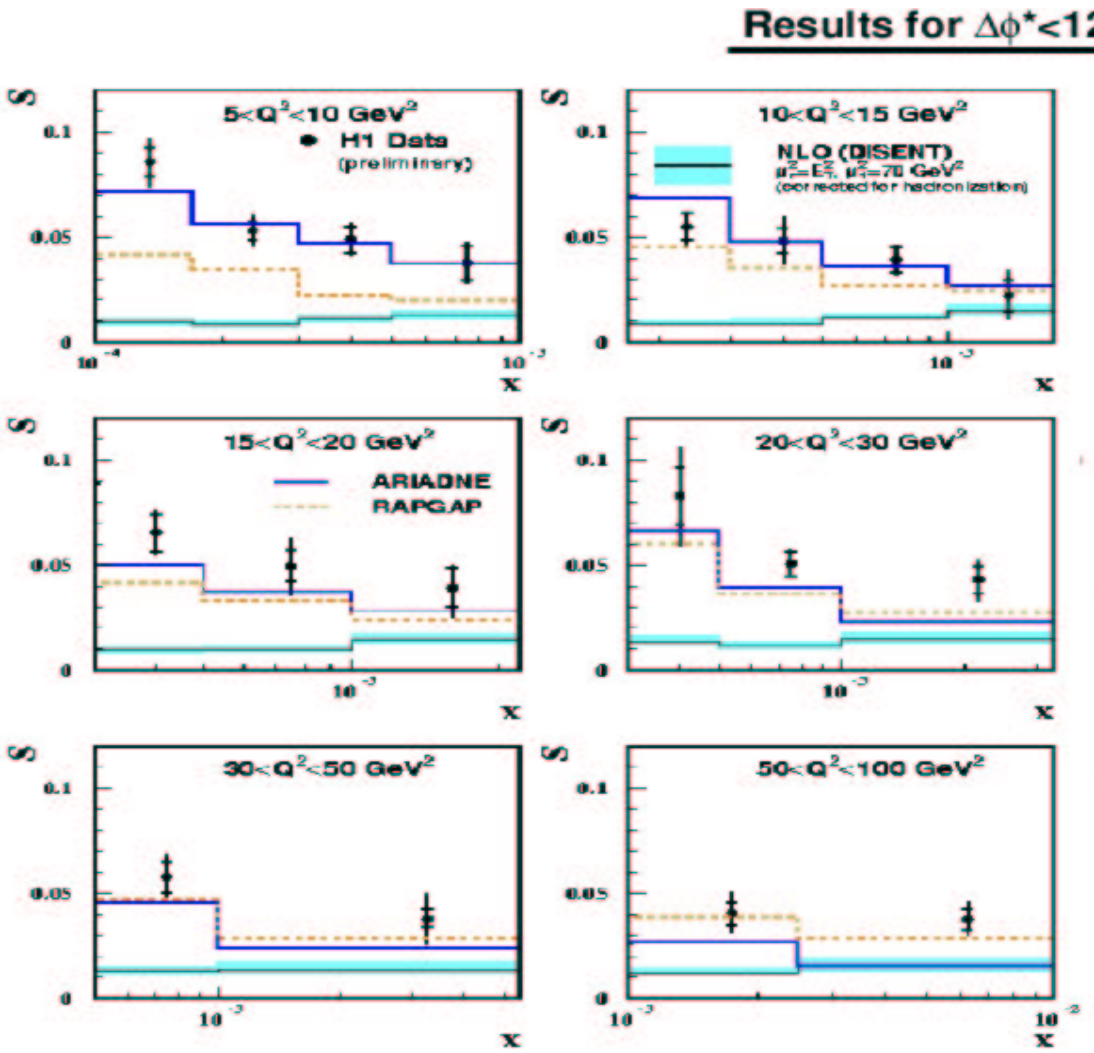




New technique (a la H1 DESY 02-023).

Confirms published H1 and ZEUS results: evidence for hard colour singlet exchange.

Dijets at Low x



- Data rises towards low x
  Increasing parton virtuality due to longer parton ladder ?
- NLO is significantly away from data
- Indication that virtuality of incoming parton *cannot* be neglected ?
- LO Models give (at least) right order of magnitude

(NB this phase space is unpopulated at LO, so 'NLO' is actually lowest order. NLO three-jet calculations do exist, however).

Summary of the Summary

- Lots of excellent new measurements, and more to come.
- Some significant advances in theory/phenomenology.
- NLO QCD generally needed, and pQCD generally doing well.
  - Within large theoretical uncertainties.
  - What is going on at high E_T in photon-photon?
  - Resummation needed. Maybe even low x resummation.
- Non- or semi-perturbative effects are being studied quantitatively and there are interesting models on the market. Need a systematic appoach which makes best use of data.
- Making quantitative QCD studies in final states is technically challenging for experiment and theory. Solving something 'in principle' is not enough.
- Progress is incremental, but real. And very important, from many points of view.