Jet Production at HERA

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Conclusion

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- Reasonable agreement between pQCD prediction and data at high Q^2 and/or high jet E_t.

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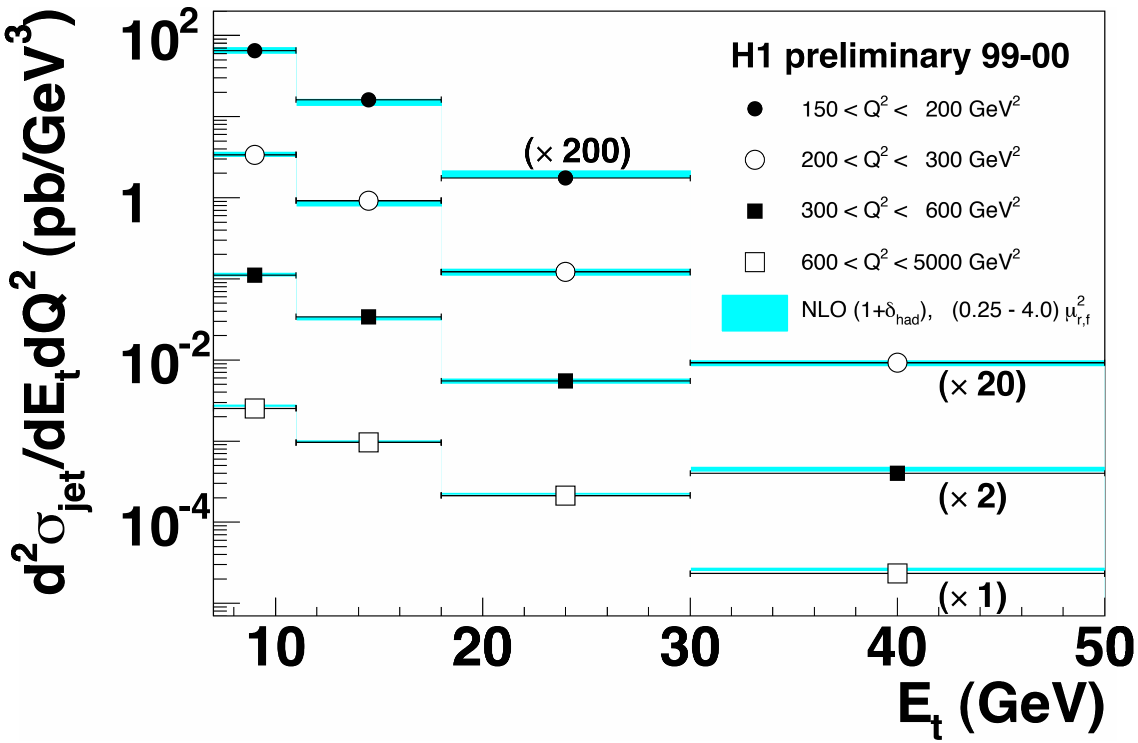
- Great success for QCD!
  - Get new job (banking pays well), or
  - Think about the errors!
  - Look for new types of measurements!

Overview

- Which errors dominate.
- Uncertainty on theory predictions.
- Uncertainty on experimental results.
- Different types of jet analyses.

H1 inclusive Jets in DIS



DIS phase space

$150 < Q^2 < 5{,}000$ GeV^2

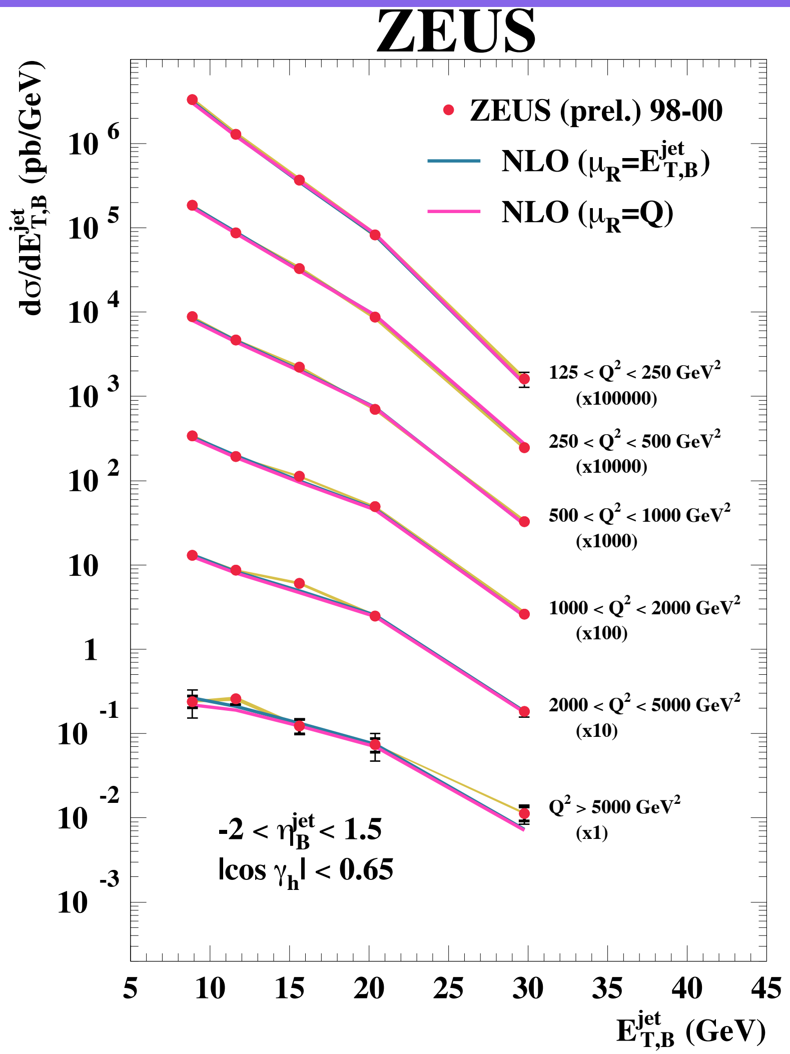
$0.2 < y < 0.6$

Inclusive jet phase space

$E_{T,\mathrm{Breit}} > 7$ GeV

$-1 < \eta_{\mathrm{lab}} < 2.5$

ZEUS inclusive Jets in DIS



DIS phase space

$Q^2 > 125$ GeV^2

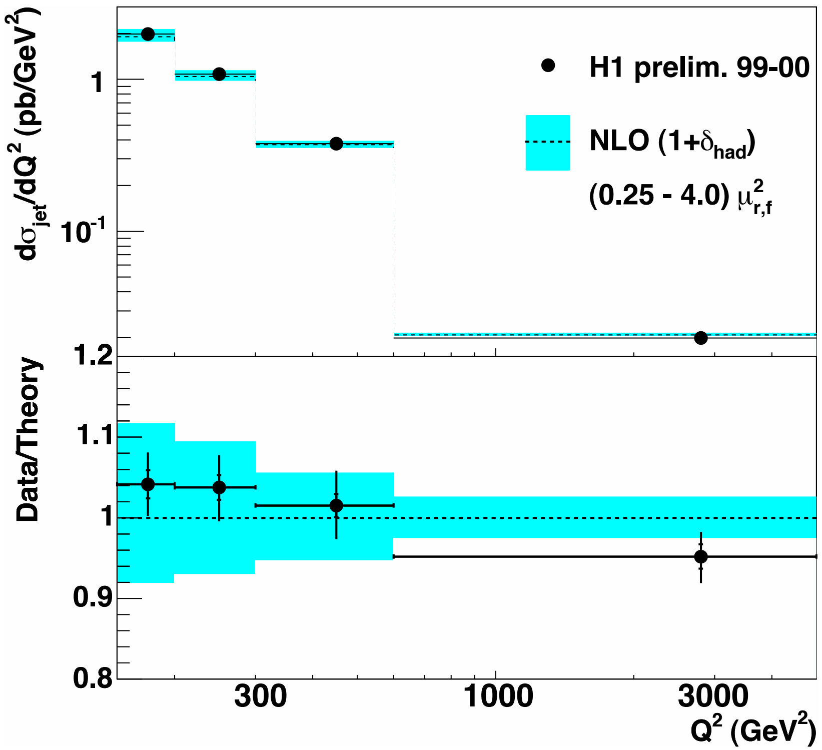
$|\cos\gamma_h| < 0.65$

Inclusive jet phase space

$E_{T,Breit} > 8$ GeV

$-2 < \eta_{lab} < 1.5$

Inclusive Jets in DIS



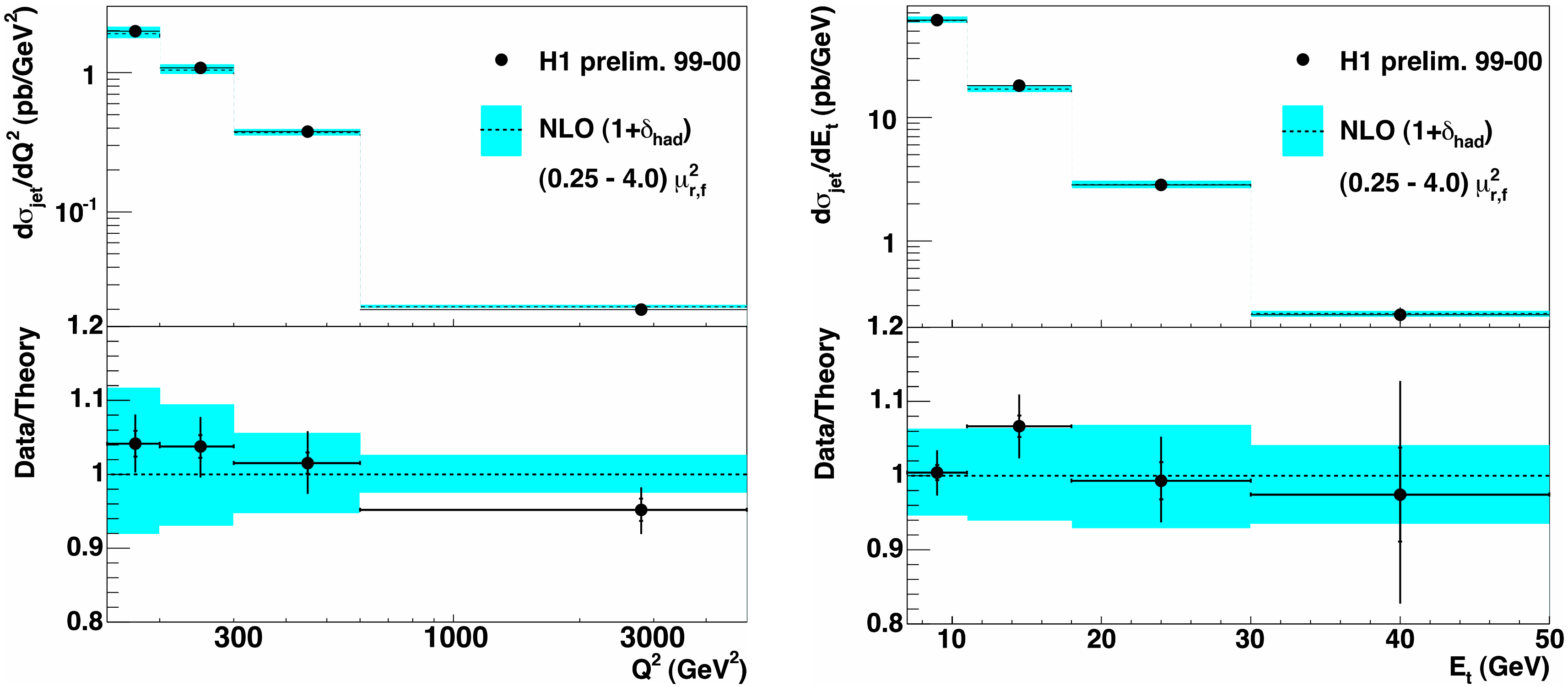
NLO = NLOJET

scale; $\mu_R = E_t$, $\mu_F = Q$

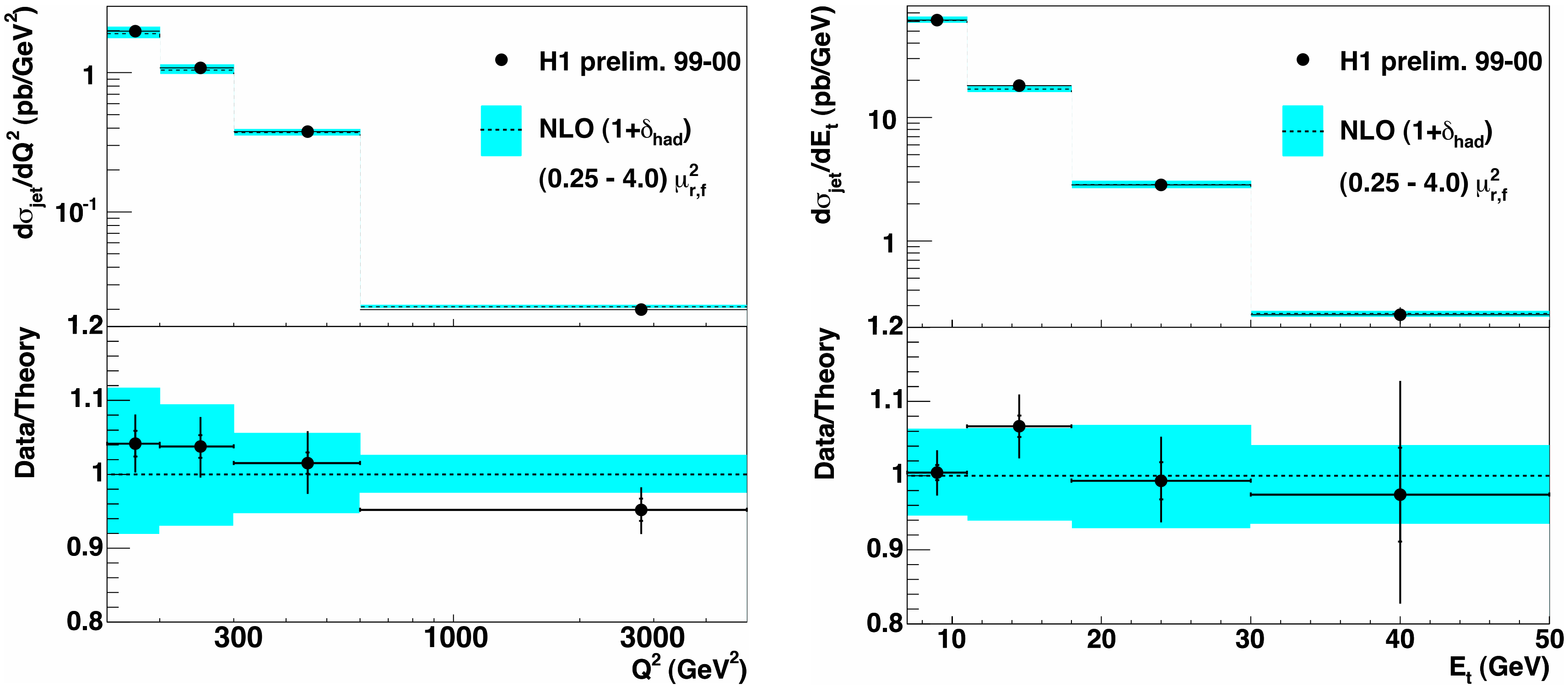
PDF = CTEQ5M1

δ_{had} from CDM/PS

Inclusive Jets in DIS

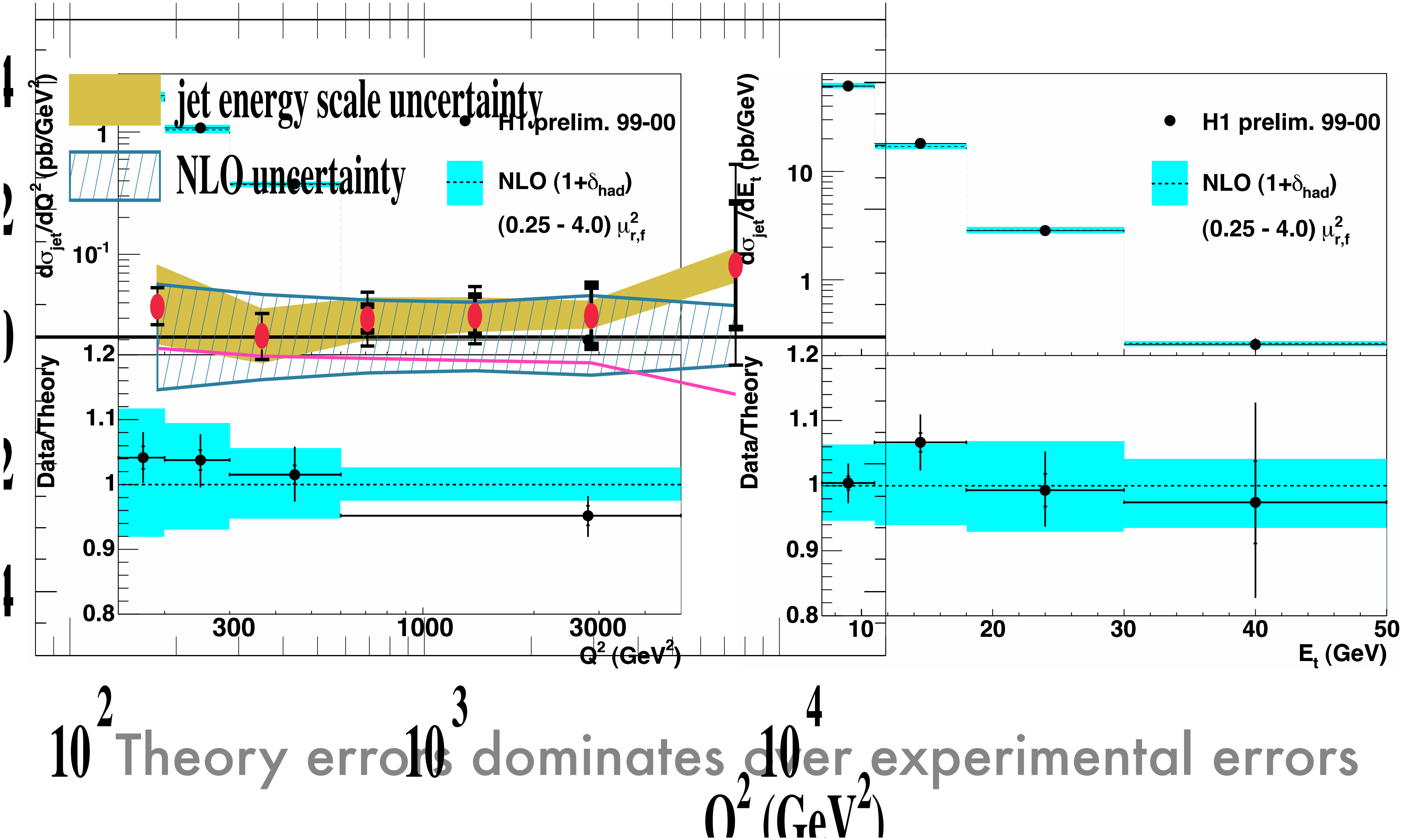


Inclusive Jets in DIS



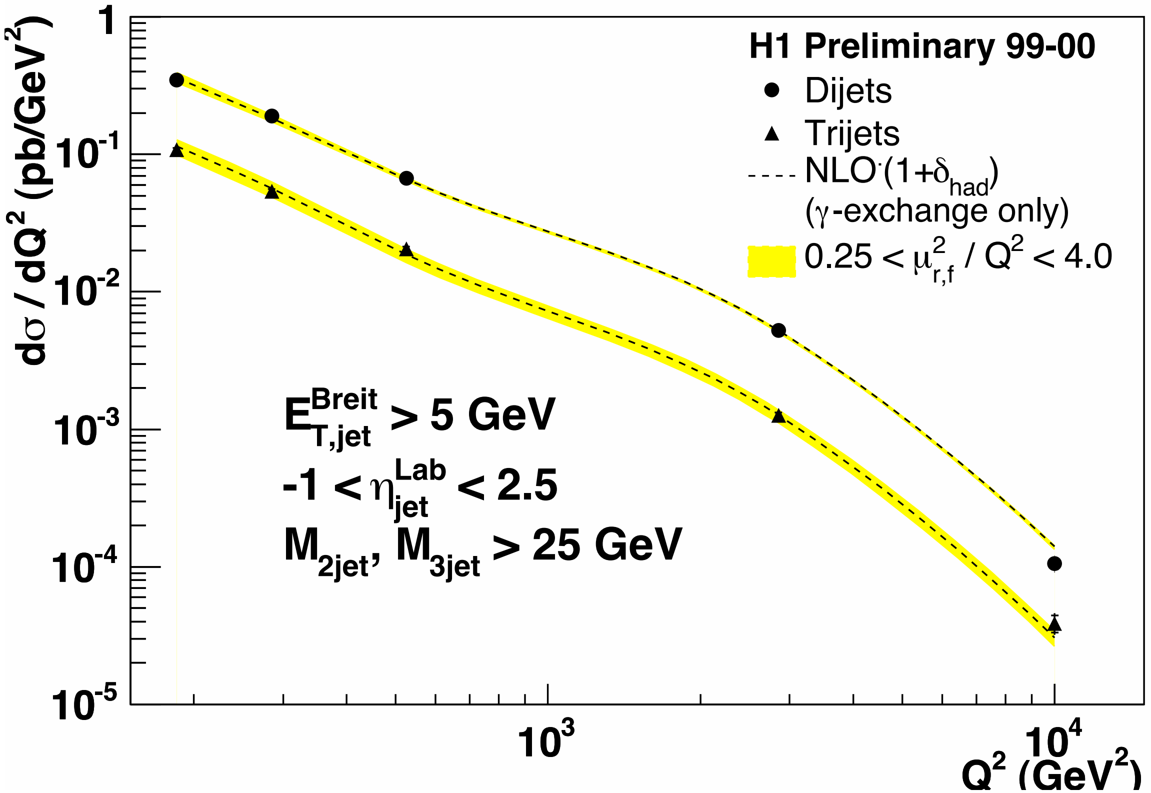
Theory errors dominates over experimental errors

Inclusive Jets in DIS



Theory errors dominates over experimental errors

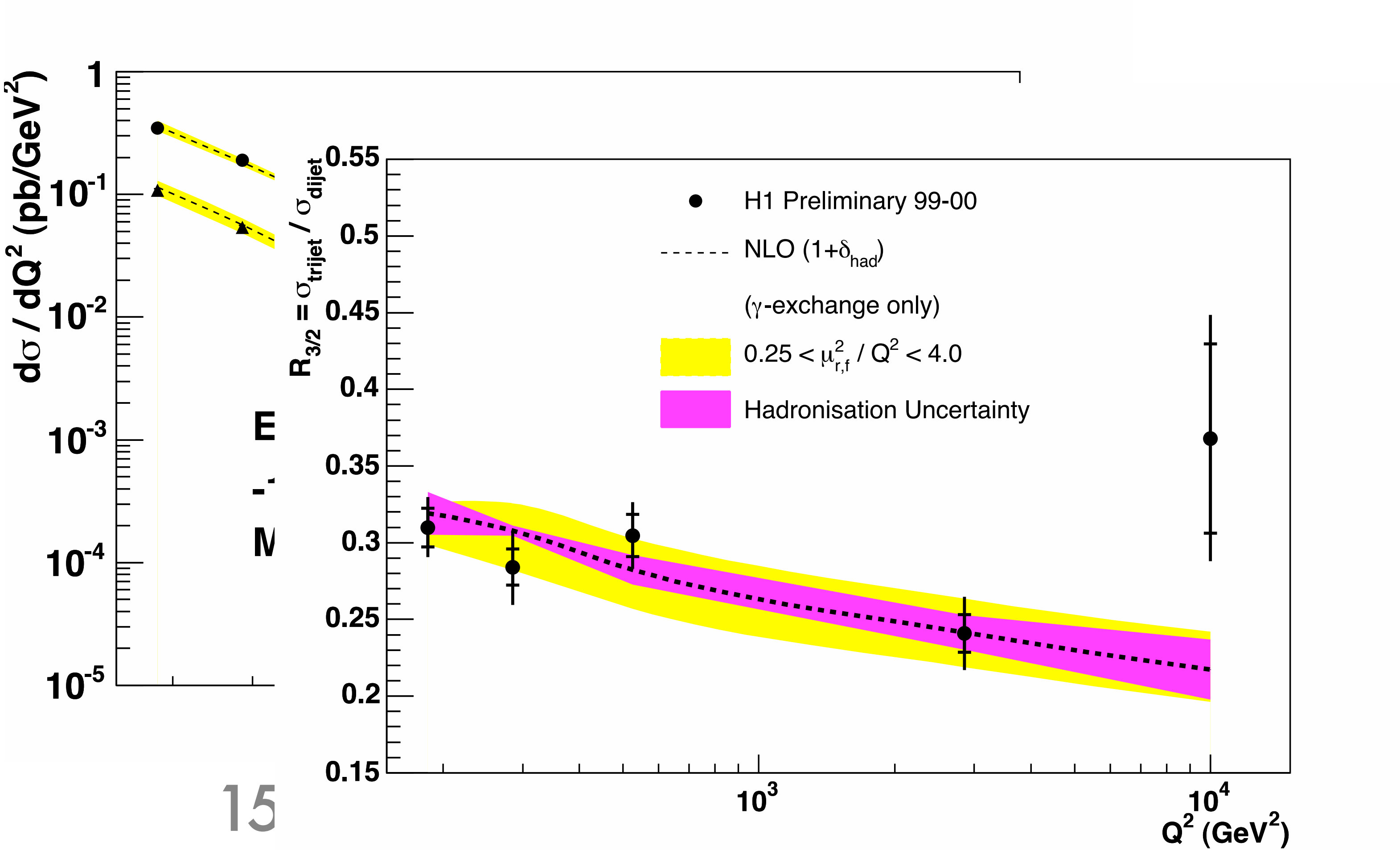
H1 Multi Jet



$150 < Q^2 < 15{,}000$ GeV^2

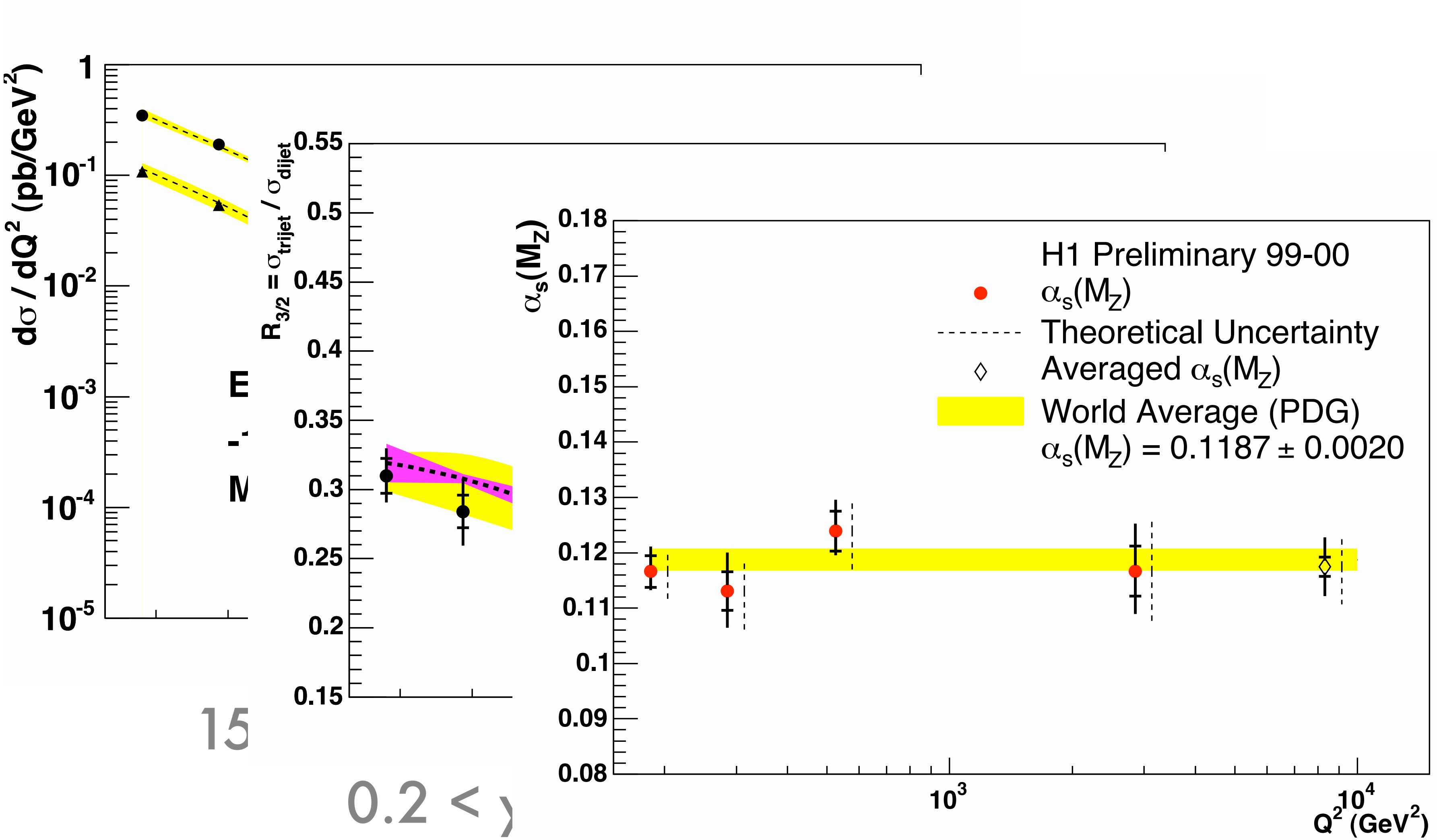
$0.2 < y < 0.6$

H1 Multi Jet



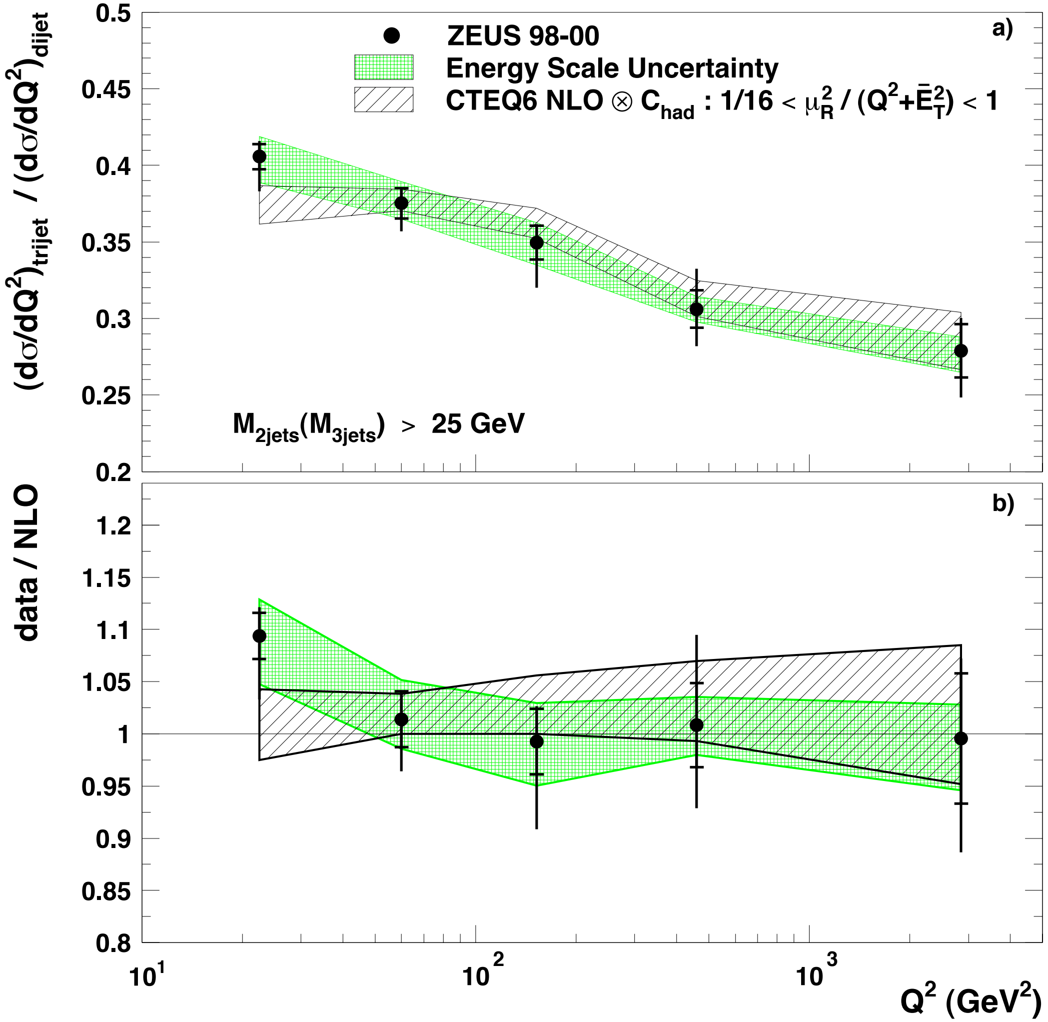
0.2 < y < 0.6

H1 Multi Jet



dσ / dQ² (pb/GeV²)
1
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
15
R3/2 = σtrijet / σdijet
0.55
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.2 <
αs(MZ)
0.18
0.17
0.16
0.15
0.14
0.13
0.12
0.11
0.1
0.09
0.08
10³
10⁴
Q² (GeV²)
H1 Preliminary 99-00
αs(MZ)
Theoretical Uncertainty
Averaged αs(MZ)
World Average (PDG)
αs(MZ) = 0.1187 ± 0.0020

ZEUS Multi Jet



DIS phase space

$10 < Q^2 < 5000\ \mathrm{GeV}^2$

$0.04 < y < 0.6$

Jet phase space

$E_{T,\mathrm{Breit}} > 5$ GeV

$-2 < \eta_{lab} < 1.5$

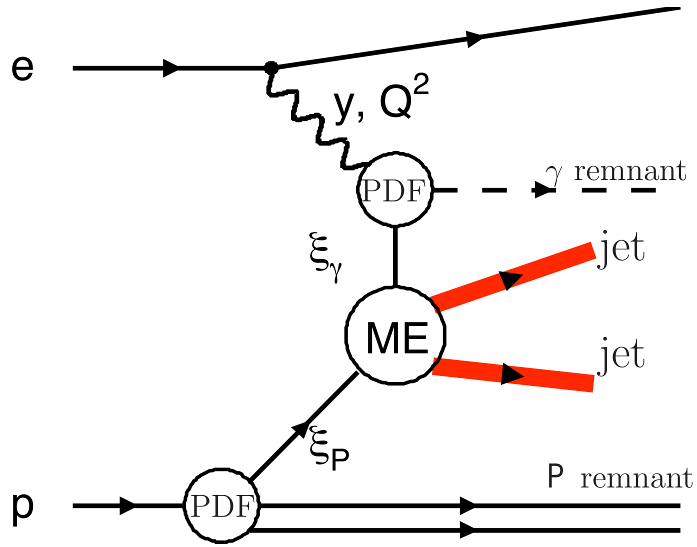
$M_{jj,jjj} > 25$ GeV

H1 High Et Dijets in γp

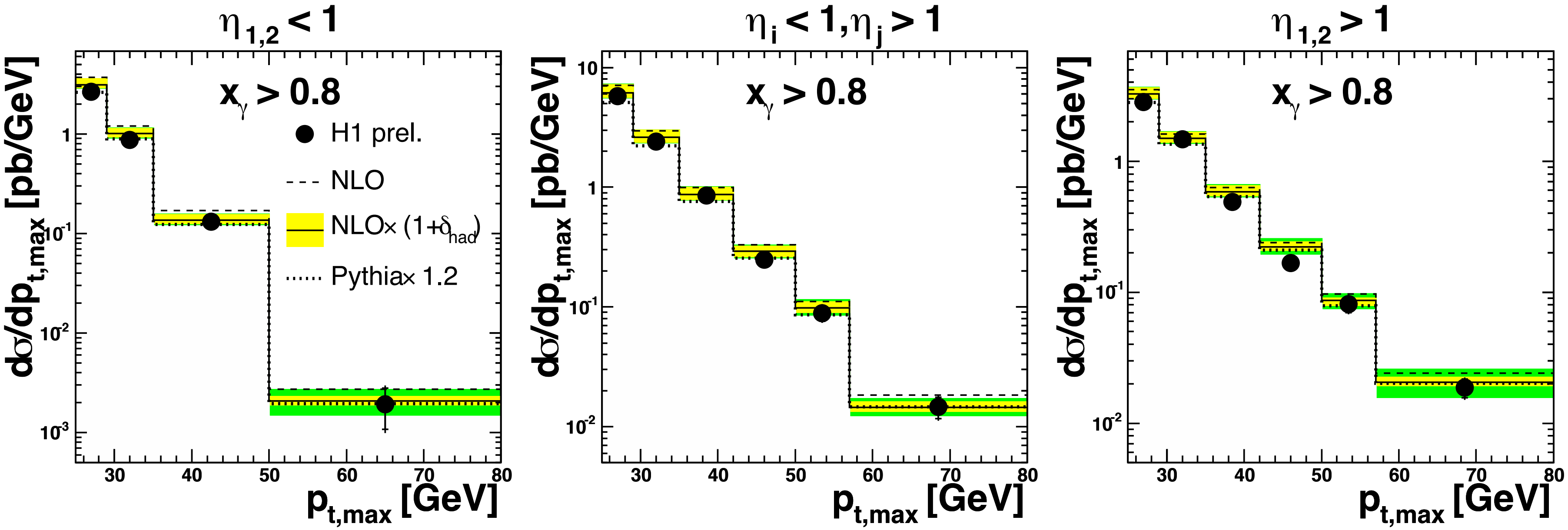
$Q^2 < 1$ GeV^2
$0.1 < y < 0.9$
$p_{t,max} > 25$ GeV
$p_{t,2} > 15$ GeV
$-0.5 < \eta jet < 2.75$

$$x_p = \frac{1}{2E_p} \cdot \sum_i^2 p_{t,i} \cdot e^{+\eta_i}$$

$$x_\gamma = \frac{1}{2yE_e} \cdot \sum_i^2 p_{t,i} \cdot e^{-\eta_i}$$

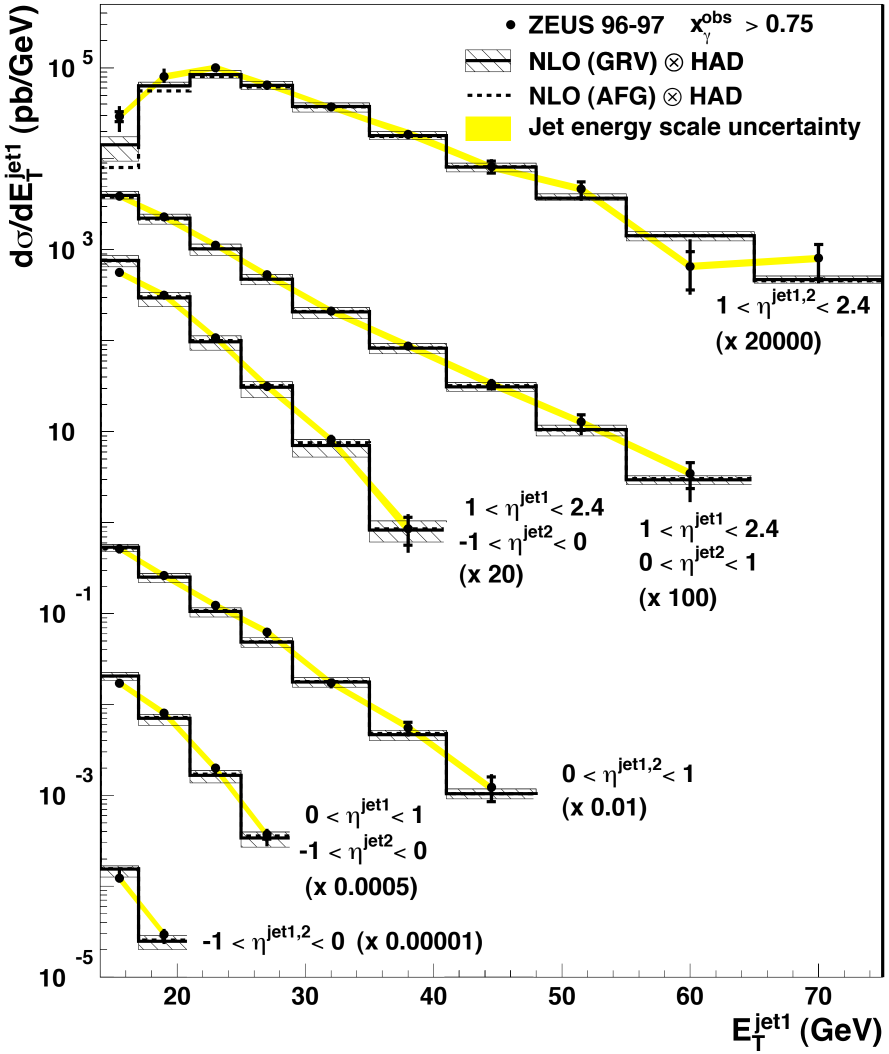


H1 High Et Dijets in γp

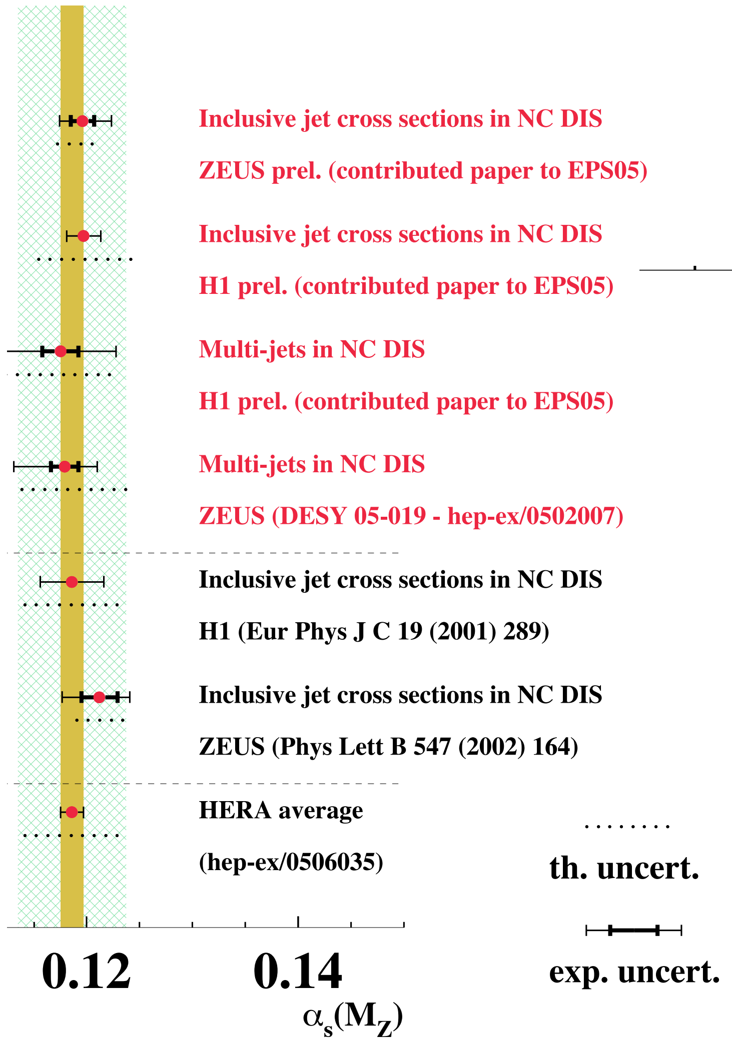


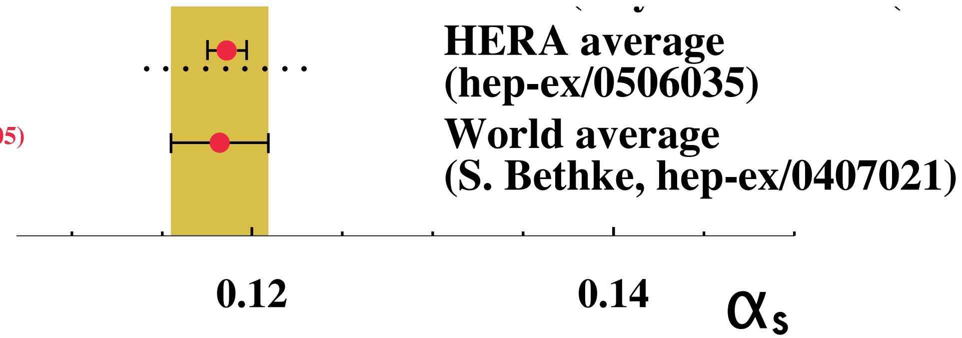
ZEUS High Et Dijets in γp

$Q^2 < 1$ GeV^2
$134 < W < 277$
$p_{t,max} > 14$ GeV
$p_{t,2} > 11$ GeV
$-1.0 < \eta_{jet} < 2.4$



Dominating Errors





If we can reduce by factor 3 our theoretical error on α_s we get most accurate measurement

MISSED POTENTIAL!

Ingredients to Theory Error

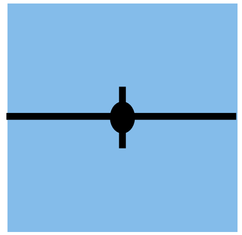
$$\sigma_{\mathrm{jet}} = \sum_{i=q,\bar{q},g} \int dx\, f_i(x, \mu_F, \alpha_S)\, \hat{\sigma}_{QCD}(x, \mu_F, \mu_R, \alpha_S(\mu_R)) \cdot (1 + \delta_{\mathrm{had}})$$

1. PDF uncertainty.
2. Scale uncertainty.
3. Uncertainty on the hadronistaion correction.

Scale Uncertainty

μ_R = Renormalisation scale

μ_F = Factorisation scale



Possible choices of μ_R and μ_F : Q, E_T, f (Q, E_T)
assess theoretical uncertainty due to missing higher orders through μ_R dependence of σ_{jet} and measured α_s by varying μ_R (and μ_F together)
convention : $\mu_R \uparrow 2\mu_R$ and $\mu_R \downarrow 0.5\mu_R$

Scale Uncertainty

μ_R = Renormalisation scale

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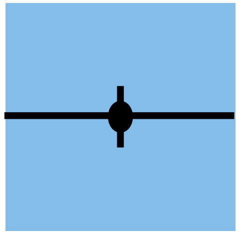

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convention : $\mu_R \uparrow 2\mu_R$ and $\mu_R \downarrow 0.5\mu_R$

whose ?

Scale Uncertainty

analysis	ZEUS	H1
inclusive jets	± 5%	± 5%
multijets (σ_{dijet})	± 10%	± 2 -10%
γp dijets	±10 - 20%	± 3 - 30%

Scale Uncertainty

Reduce Scale uncertainty by going where pQCD is most predictive; High Q and high E_T

Scale Uncertainty

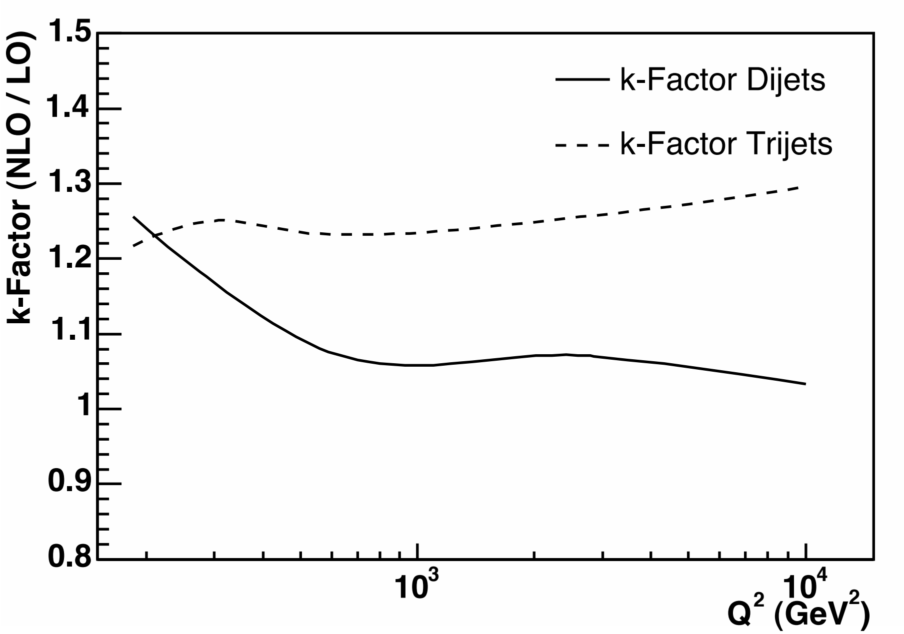
Reduce Scale uncertainty by going where pQCD is most predictive; High Q and high E_T

Chose values of μ_R and μ_F which gives best description + smallest scale uncertainty (Q and or E_T).

analysis	ZEUS	H1
inclusive jets	$\mu_R=E_T, \mu_F=Q$	$\mu_R=E_T, \mu_F=Q$
multijets	$\mu_R=\mu_F=(\langle E_T^2\rangle+Q^2)/4$	$\mu_R=\mu_F=Q$
γp dijets	$\mu_R=\mu_F=E_T/2$	$\mu_R=\mu_F=E_T/2$

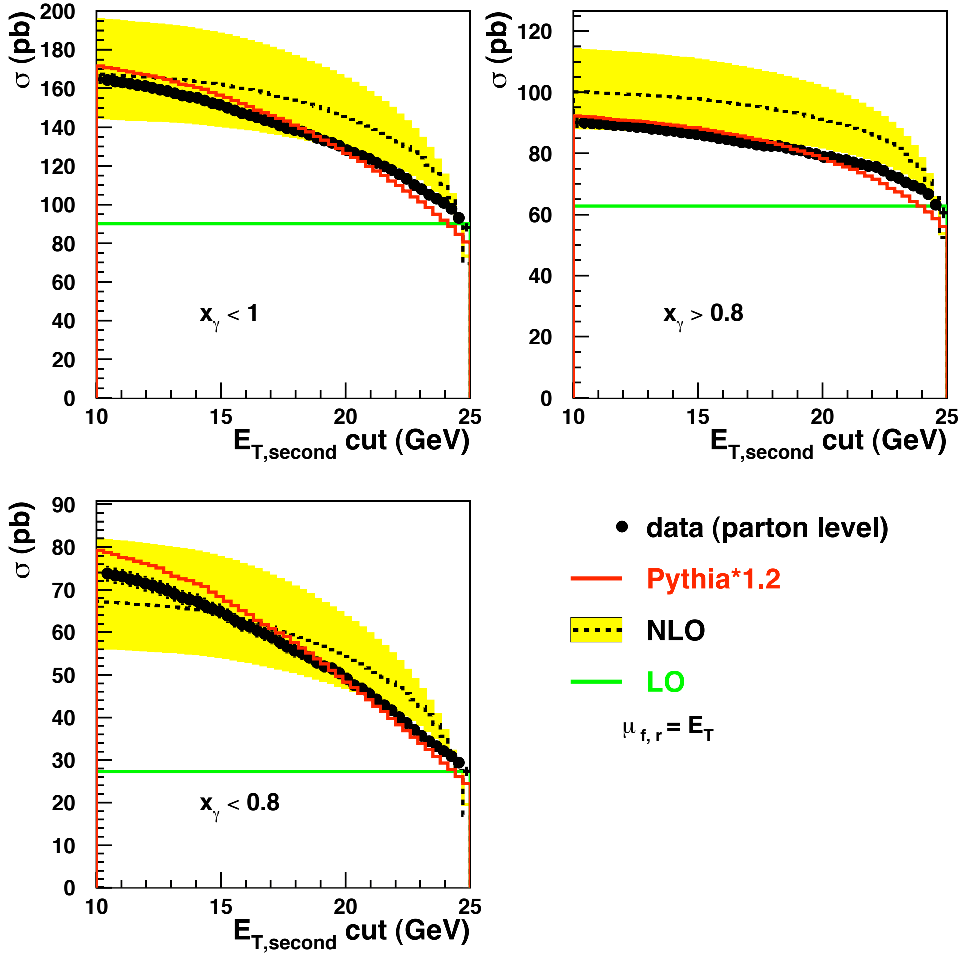
Scale Uncertainty

k-factors represent the size of the NLO correction to the born level



low k-factors (NLO/LO), low μ_R dependence

Scale Uncertainty



The smaller space between jet 1 and 2 the smaller the scale uncertainty

The smaller the space between jets 1 and 2 the less sensitivity to NLO

S.Caron

Scale Uncertainty

If the scale uncertainty is there as an estimate of how higher orders will affect the predicted cross section, why not calculate higher orders?

NNLO for jet cross sections?

(they exist for inclusive measurements)

Scale Uncertainties

S. Brodsky's: no ambiguity for the renormalisation scale !
(ambiguity due to the choice of the factorisation scale remains)

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On the elimination of scale ambiguities in perturbative quantum chromodynamics

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G. Peter Lepage
Institute for Advanced Study, Princeton, New Jersey 08540
*and Laboratory of Nuclear Studies, Cornell University, Ithaca, New York 14853**

Paul B. Mackenzie
Fermilab, Batavia, Illinois 60510
(Received 23 November 1982)

We present a new method for resolving the scheme-scale ambiguity that has plagued perturbative analyses in quantum chromodynamics (QCD) and other gauge theories. For Abelian theories the method reduces to the standard criterion that only vacuum-polarization insertions contribute to the effective coupling constant. Given a scheme, our procedure automatically determines the coupling-constant scale appropriate to a particular process. This leads to a new criterion for the convergence of perturbative expansions in QCD. We examine a number of well known reactions in QCD, and find that perturbation theory converges well for all processes other than the gluonic width of the Υ. Our analysis calls into question recent determinations of the QCD coupling constant based upon Υ decay.

Also results is renormalisation scheme independence

C.f. Brodksy at PHOTON'05: the n_f dependence sets the renormalisation scale at NLO !

Hadronisation Uncertainty

Apply hadronisation correction (δ_{had}) to parton level predictions to be able to compare with data (which is at the hadron level)

Only have hadronisation for Leading Order Matrix Element Monte Carlos

Assumption
LO ME + Parton cascade = NLO

Effect of hdronisation on MC taken as δ_{had}

Hadronisation Uncertainty

ME + Parton cascade + hadronisation

RAPGAP + PS + Lund string

Django + CDM

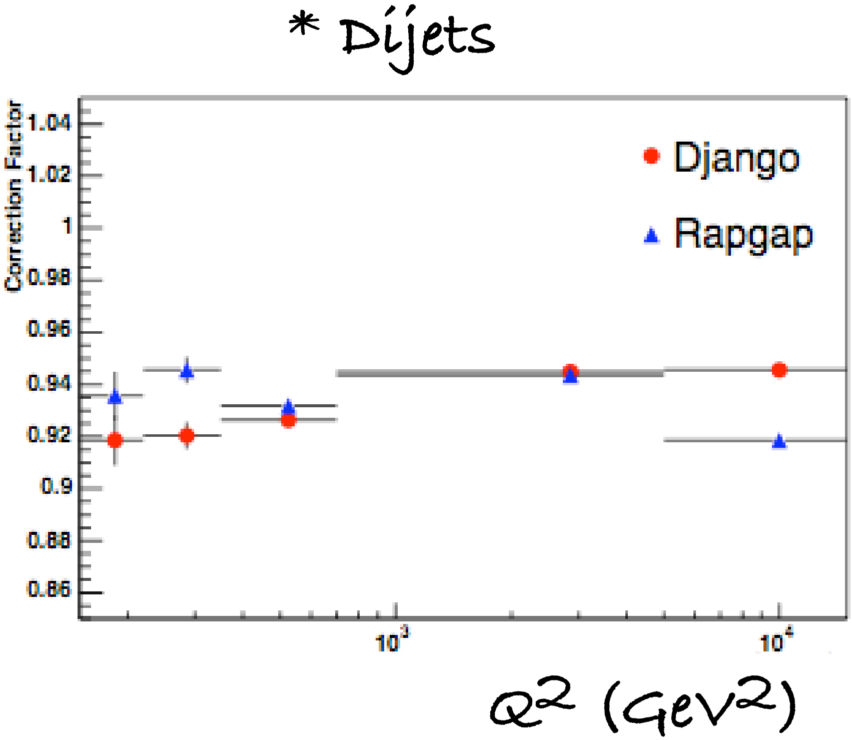
Cluster

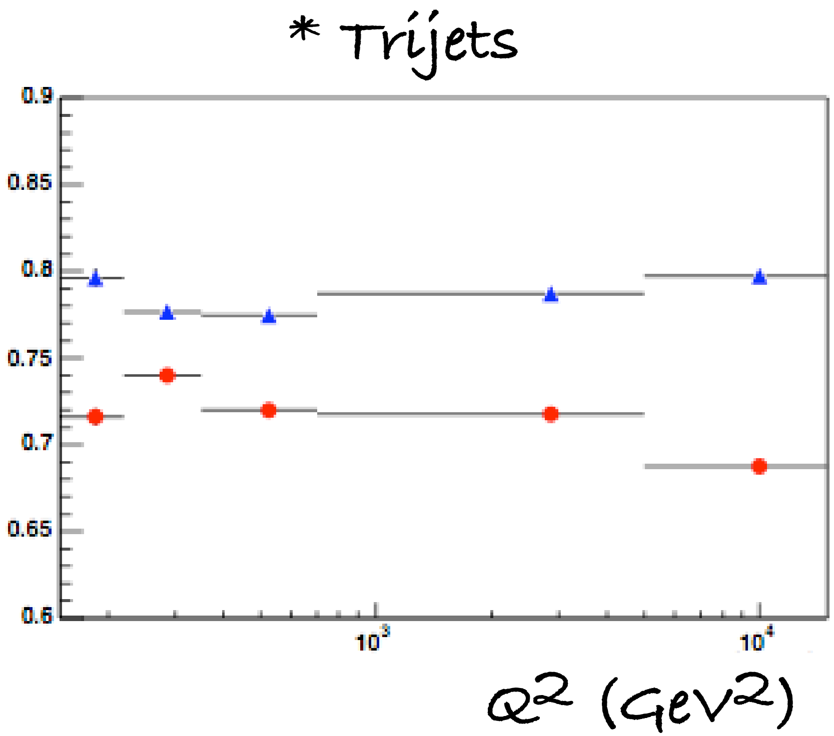
HERWIG or PYTHIA for γp

difficult to use

Typically take mean of two models as δ_{had}
and 1/2 difference as uncertainty

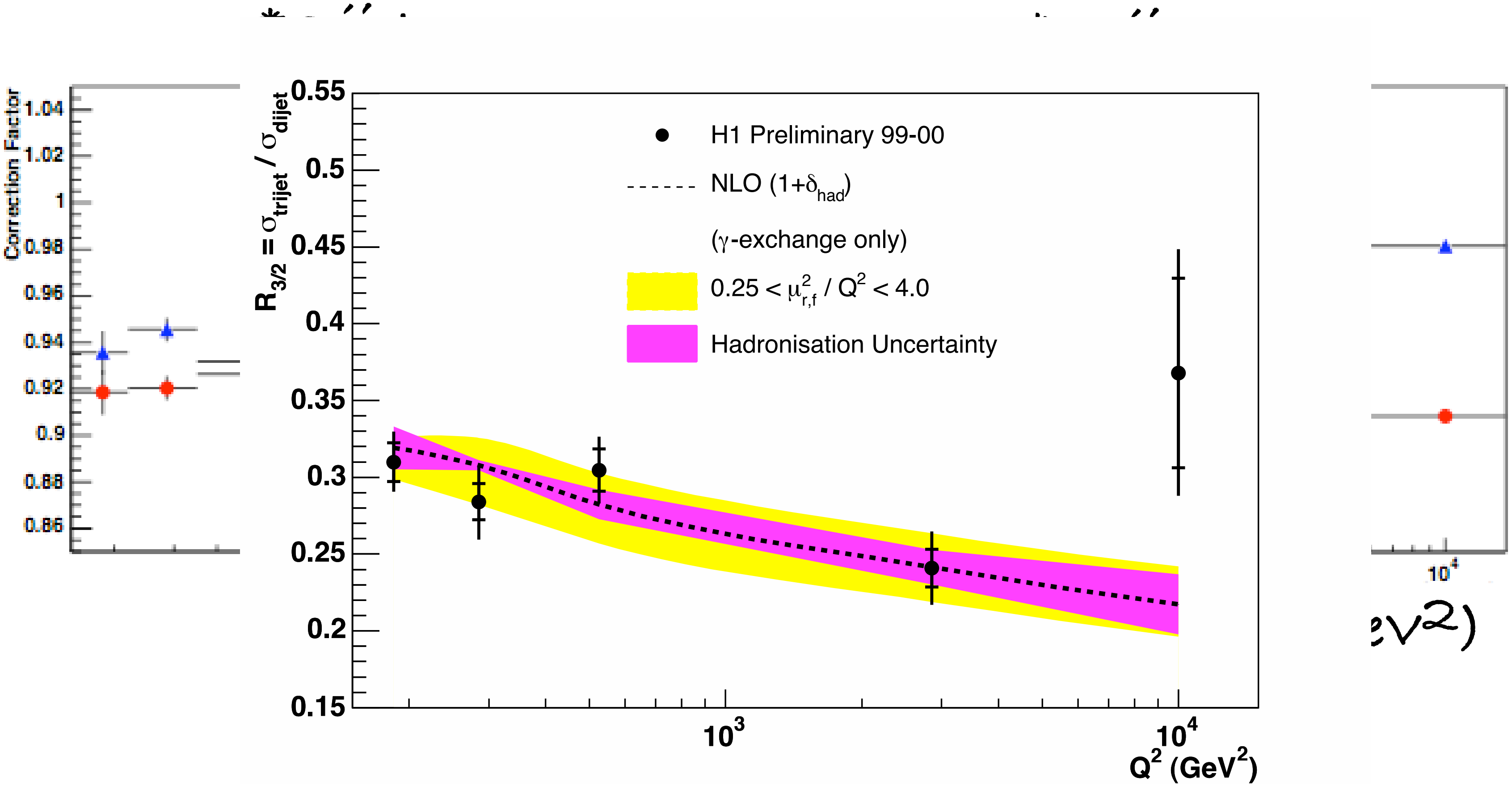
Hadronisation Uncertainty





P.Prideaux

Hadronisation Uncertainty



P.Prideaux

Hadronisation Uncertainty

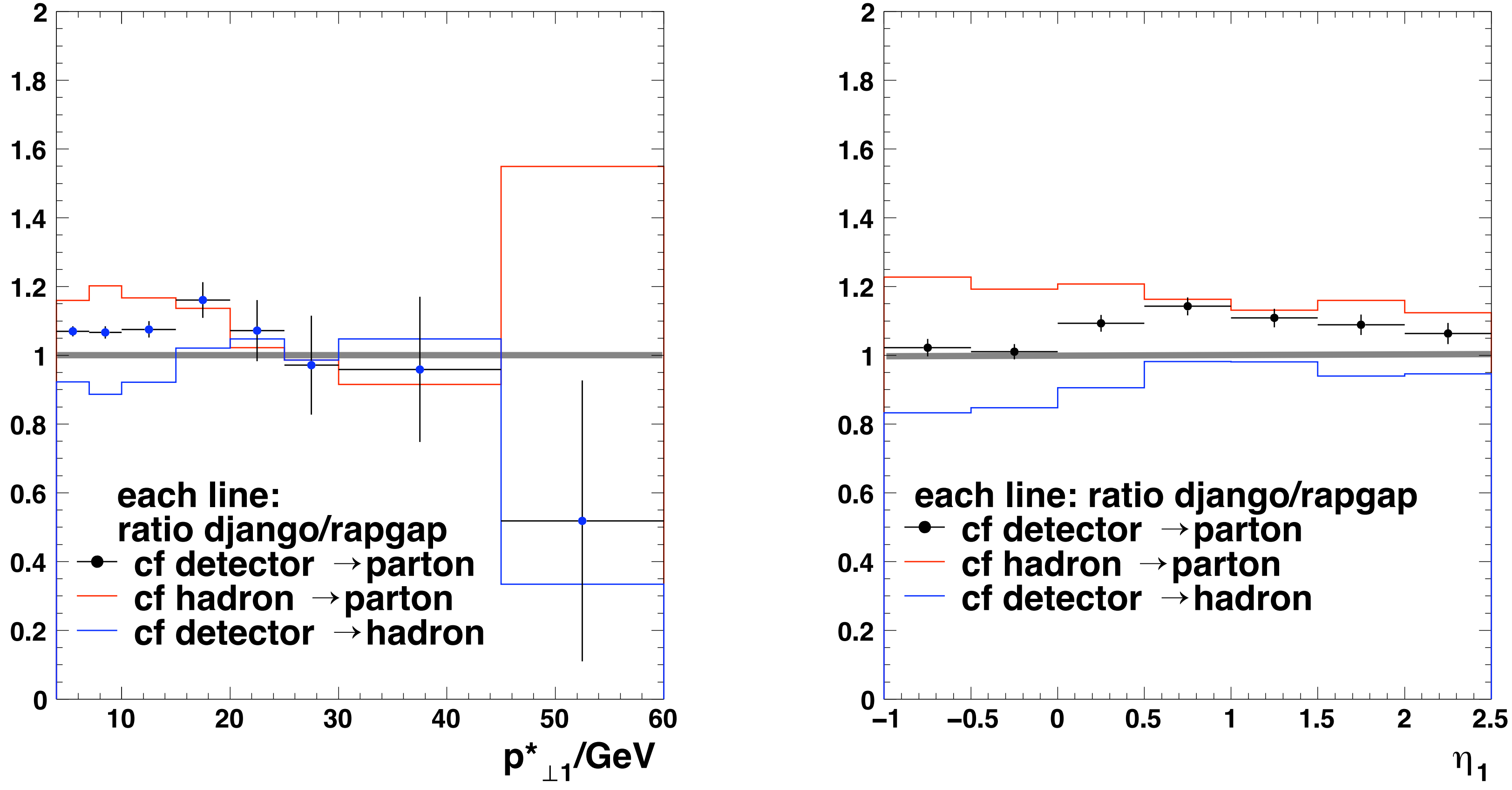
analysis	ZEUS	H1
inclusive jets	±3%	
multijets (σ_{dijet})	± 6%	±2%
γp dijets	± 2 - 3%	

Hadronisation Uncertainty

- Take more combinations to estimate error (cluster model in RAPGAP!)
- MC@NLO provides “TRUE” NLO parton level + hadronisation
- Correct data to parton level ?
  - No need to provide δ_{had} to theorists.
  - Uncertainty counted only once, but
  - Model dependence in data?

Hadronisation Uncertainty

Ratio Django / Rapgap



MC study of 3 jet events

C.Werner

PDF Uncertainty

PDF Uncertainty

Test NLO pQCD

PDF Uncertainty

Test NLO pQCD

↓

Small PDF uncertainty

PDF Uncertainty

Test NLO pQCD

↓

Small PDF uncertainty

"Improve" PDF's

PDF Uncertainty

Test NLO pQCD → Small PDF uncertainty

"Improve" PDF's → Maximise PDF uncertainty

PDF Uncertainty

Test NLO pQCD

↓

Small PDF uncertainty

"Improve" PDF's

↓

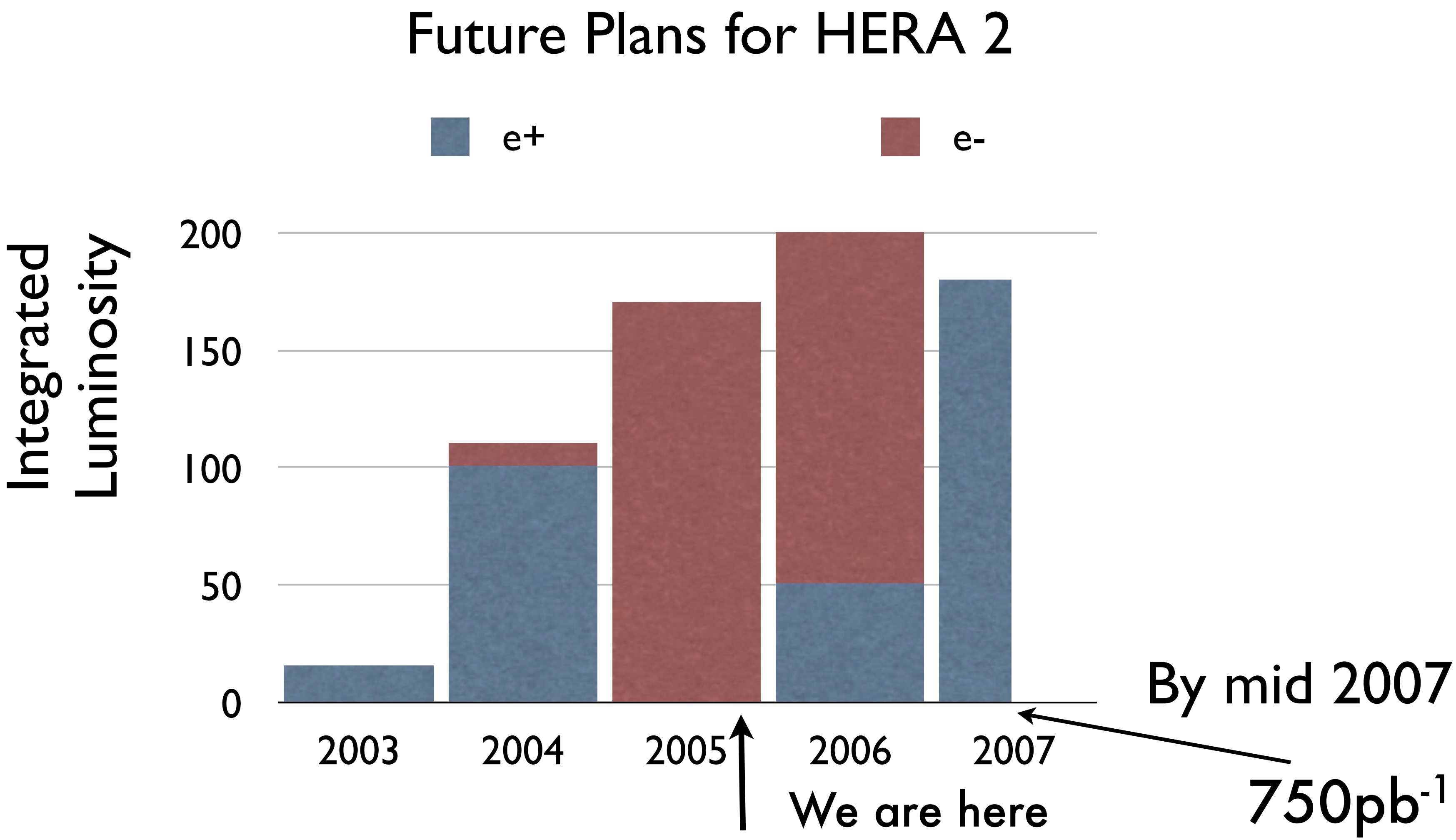
Maximise PDF uncertainty

Incompatible aims?

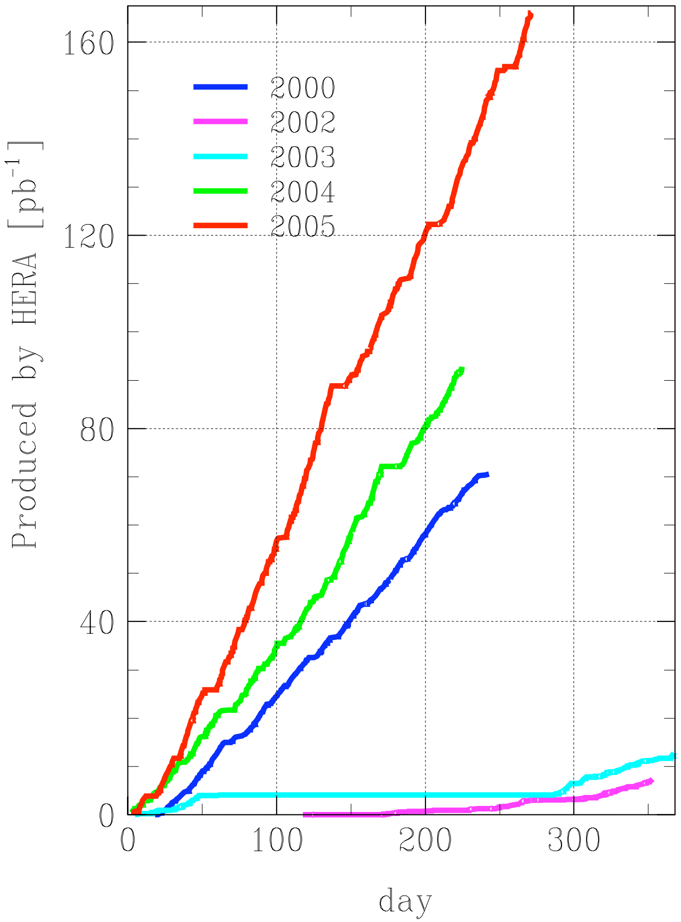
Experimental Errors

- Statistical errors.
- Measurement error of scattered electron (if you do a boost).
- Hadronic energy scale uncertainty.
- Model uncertainty.
- + Luminosity, trigger (small)

Statistical Errors



Statistical Errors

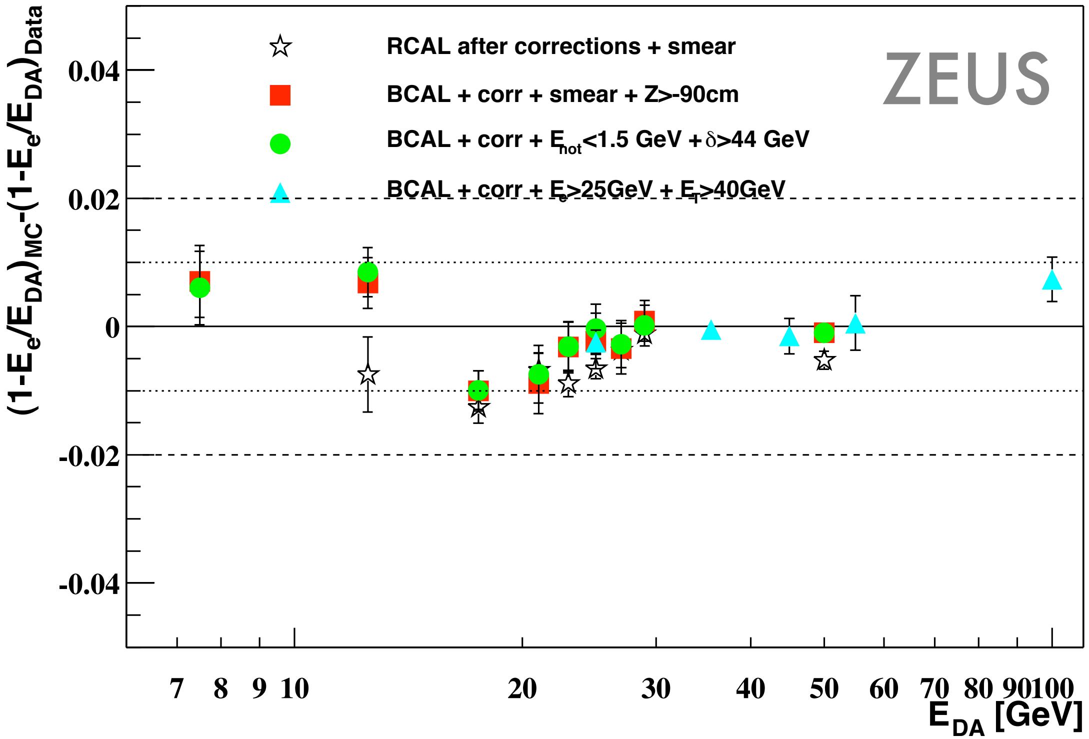


HERAII has delivered promised Luminosity

Expect to have x10 Lumi available for analysis compared to 2000!

statistical errors will be ~1/3 of previous analysis

Electron Reconstruction



ZEUS 1%

H1 0.7-3%

Difference between data and MC of the energy scale of scattered electron as function of E_{DA}

hep-ex/0206036

Electron Reconstruction

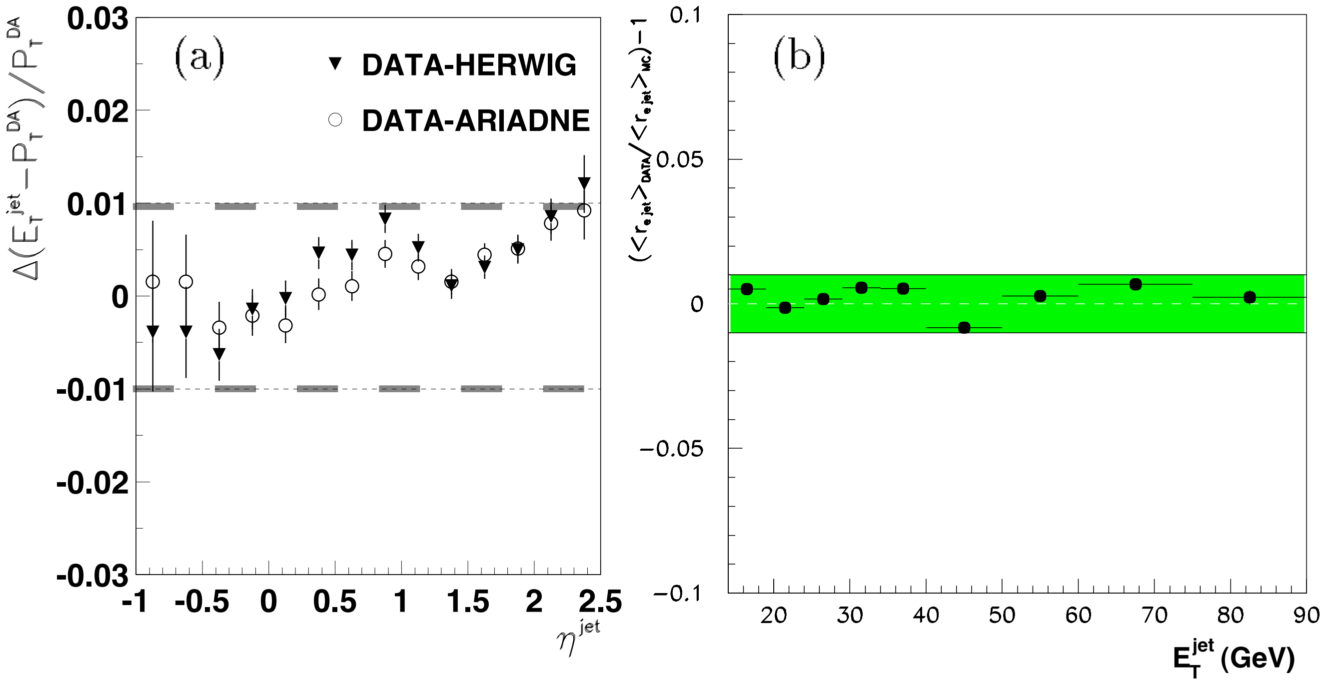
analysis	ZEUS $\delta\sigma_{jet}$	H1 $\delta\sigma_{jet}$
inclusive jets	1.0% → < 1%	0.7-3.0% →
multijets	1.0% →	0.7-3.0% → 1.5%
γp dijets	0	0

Electron Reconstruction

analysis	ZEUS $\delta\sigma_{jet}$	H1 $\delta\sigma_{jet}$
inclusive jets	1.0% → < 1%	0.7-3.0% →
multijets	1.0% →	0.7-3.0% → 1.5%
γp dijets	0	0

Not a major source of error

Hadronic Energy Scale



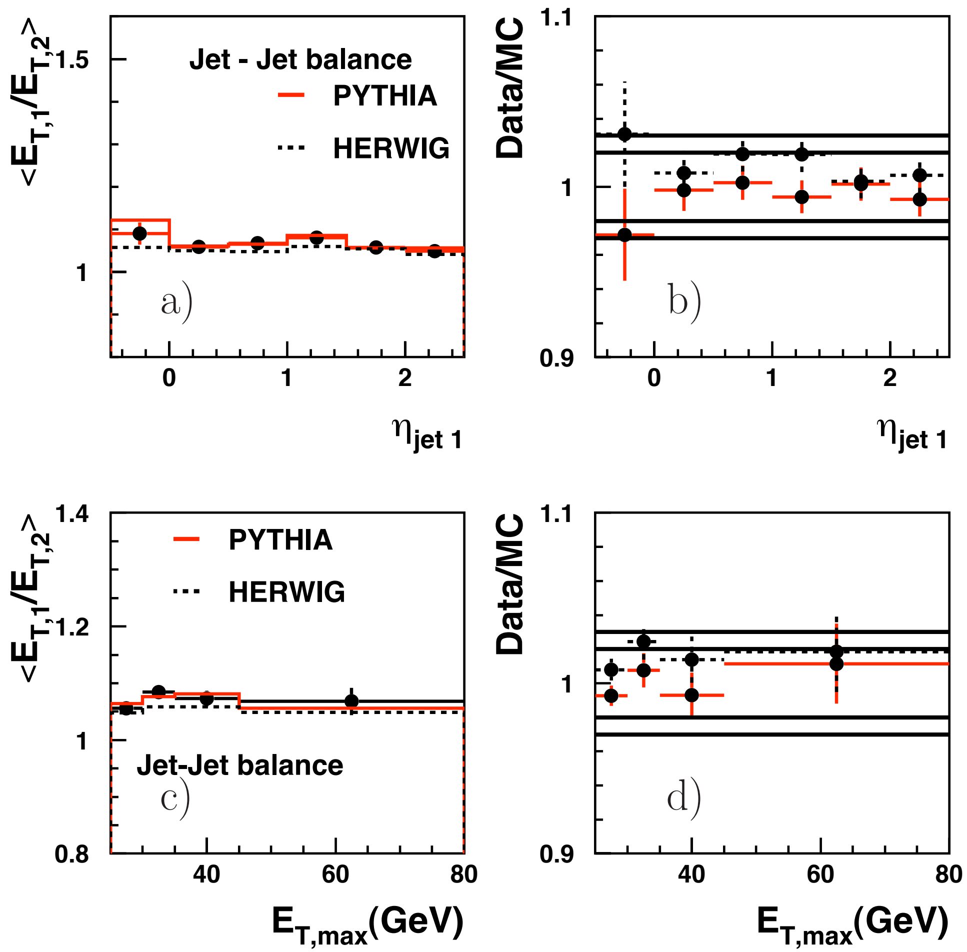
Pt balance between jet and scattered electron

ZEUS

$E_{T,jet}$ > 10 GeV → ± 1%,

$E_{T,jet}$ < 10 GeV → ± 3%

Hadronic Energy Scale



jet - jet balance in dijet photoproduction

Cross check of Hadronic calibration made with DIS events

H1

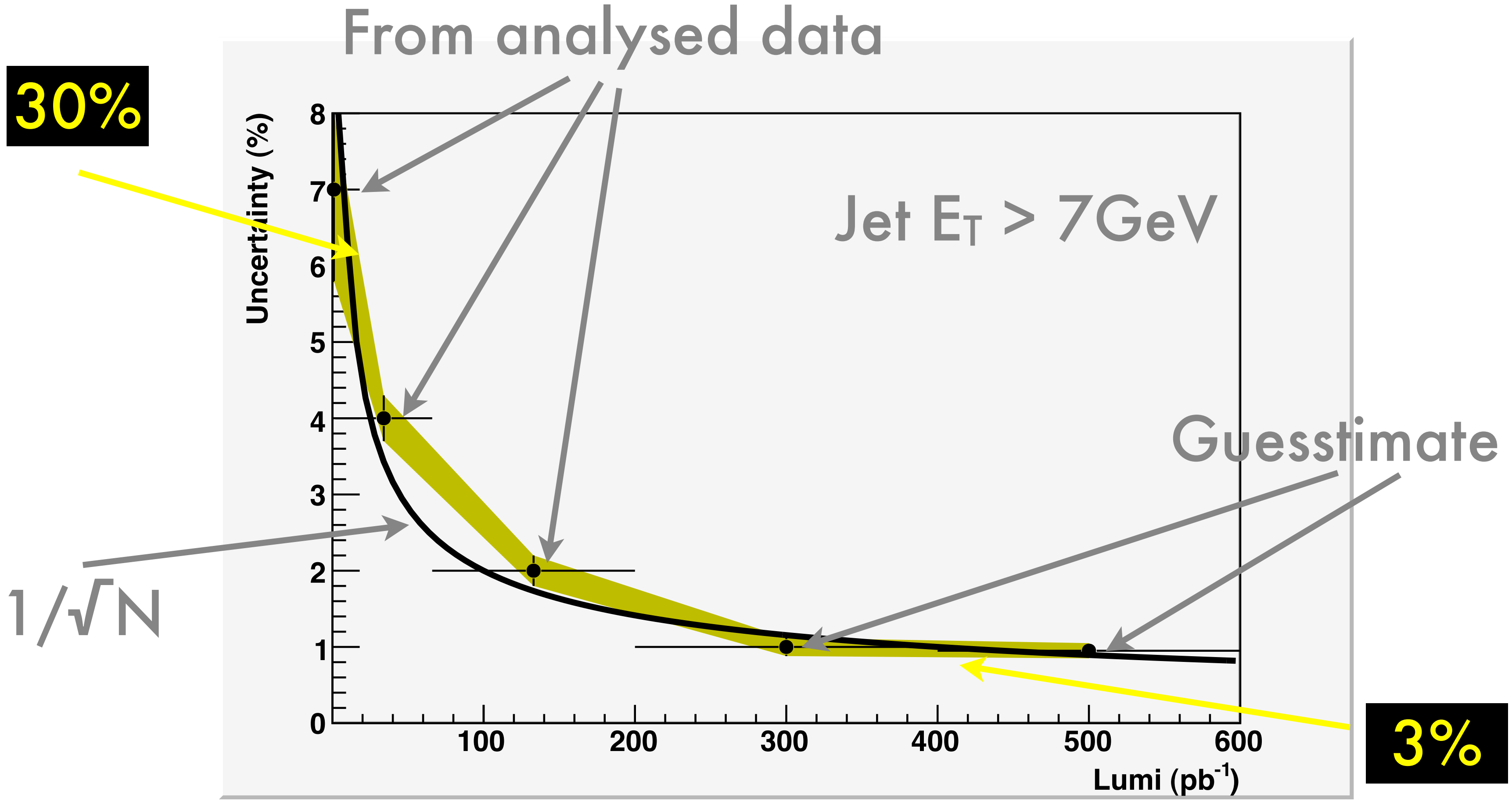
$E_{T,jet}$ > 5 GeV → 2%

Thesis S.Caron

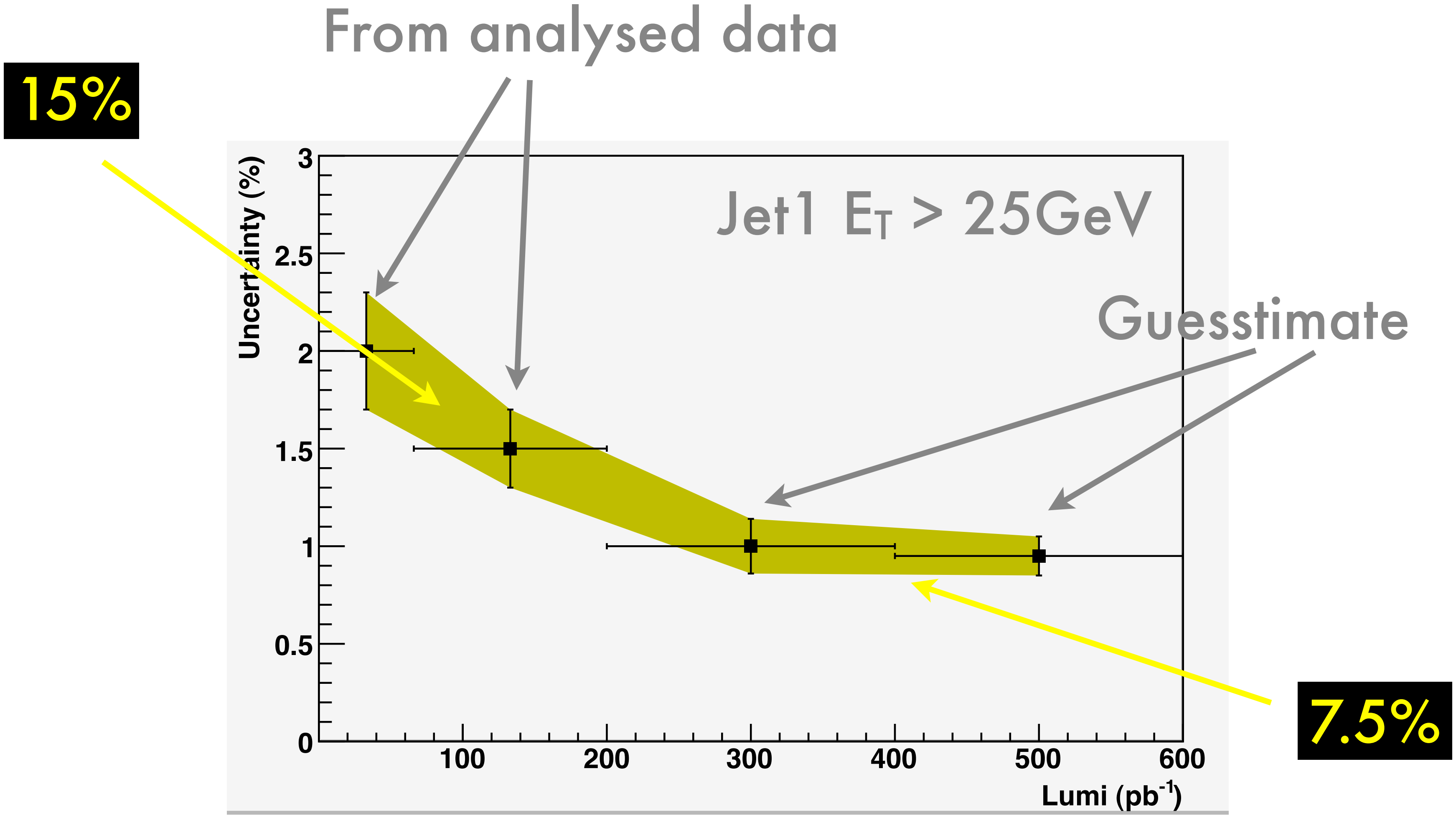
Hadronic Energy Scale

analysis	ZEUS $\delta\sigma_{jet}$	H1 $\delta\sigma_{jet}$
inclusive jets	1.0% (3% E_t<10) →5%	2%→5%
multijets	1.0% (3% E_t<10) →6%	2%→5%
γp dijets	1%→ 5%	1.5%→10%

Hadronic Energy Scale



Hadronic Energy Scale



Model Uncertainty

See discussion on Hadronisation Correction

Model Uncertainty

analysis	ZEUS	H1
inclusive jets	±7%	
multijets (σ_{dijet})	± 2%	± 1% after reweighting
γp dijets	±4%	± 2 - 5%

Difference between using PS vs CDM

or HERWIG and PYTHIA

Alternative analyses

ZEUS analyses

Sub jet distributions in inclusive-jet production in deep inelastic scattering at HERA (EPS 384)

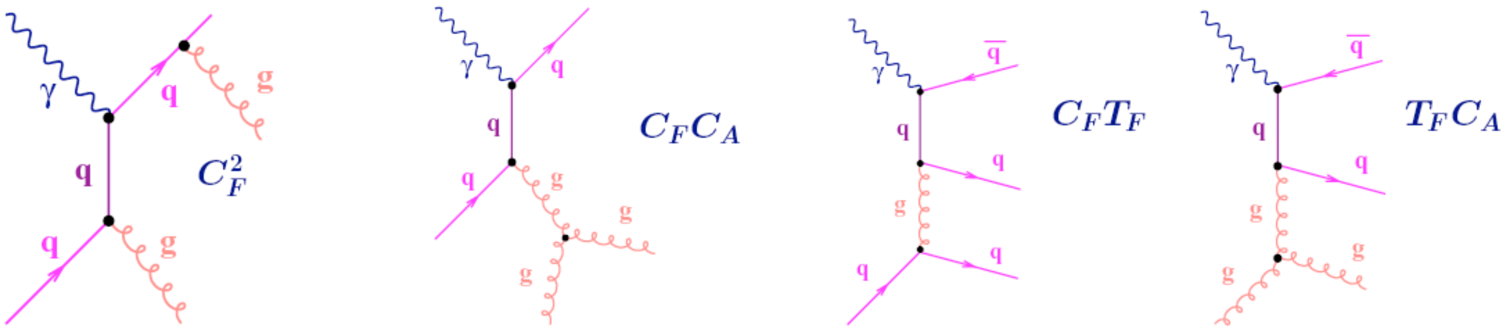
Angular correlation's in three-jet production in deep inelastic scattering at HERA (EPS 383)

Study of interjet energy flow at HERA (EPS 380)

Substructure dependence of jet cross sections at HERA and determination of α_s (DESY-04-072)

ZEUS 3Jet Correlations

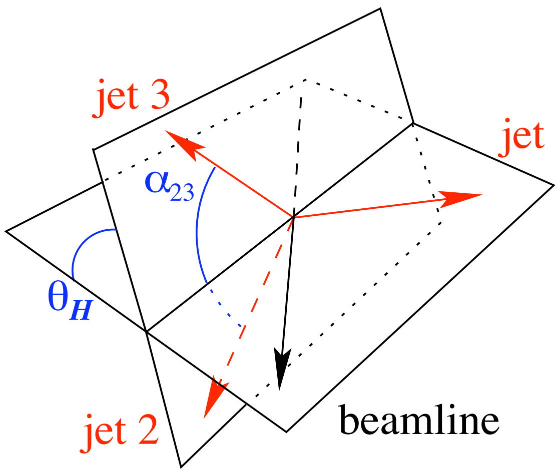
$\sigma_{ep\to 3jets} = C^2_F\sigma_A + C_FC_A\sigma_B + C_FT_F\sigma_C + T_FC_A\sigma_D$ (LO)



SU(N): $C_F=(N^2-1)/2N$, $C_A=N$, $T_F=1/2$ (NA)

The qqg and ggg couplings have different spin structures
Angular correlations in three jet production sensitive to the underlying gauge structure of QCD matrix elements.

ZEUS 3Jet Correlations



θ_H: the angle between plane containing the beamline and highest E_T jet and the plane containing the second and third highest E_T jets.

η_{max}:Pseudo-rapidity in the Breit frame of the most forward of the three highest E_T jets.

α_{23}: the angle between the second and third highest E_T jets.

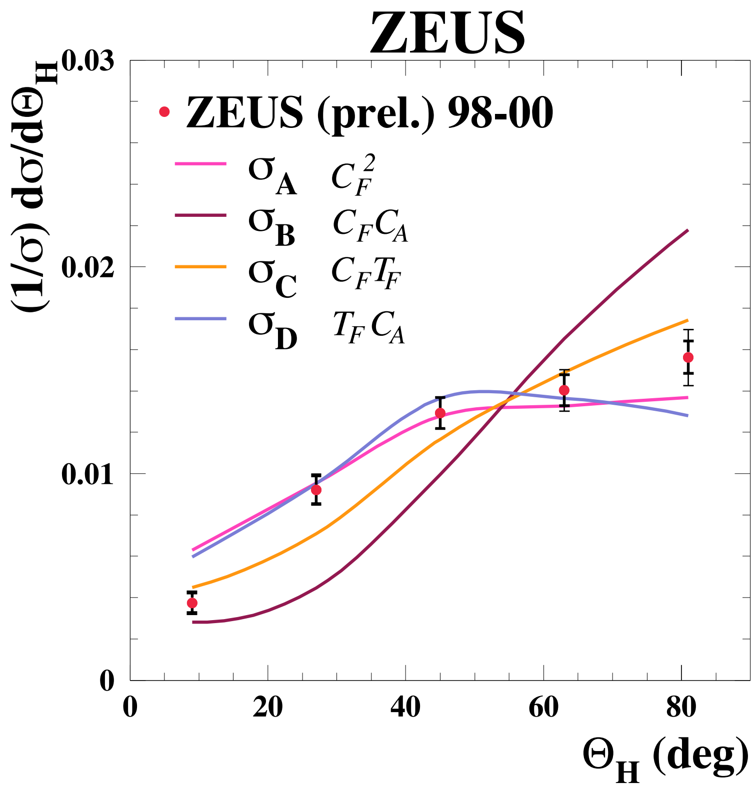
$$\cos(\beta_{\mathrm{KSW}}) := \cos(\tfrac{1}{2}[\angle[(\vec{p_1} \times \vec{p_3}), (\vec{p_2} \times \vec{p_B})] + \angle[(\vec{p_1} \times \vec{p_B}), (\vec{p_2} \times \vec{p_3})]])$$

ZEUS 3Jet Correlations

Q^2>125 GeV,
$E_{T,jet1}$ > 8GeV, $E_{T,jet\ 2,3}$ > 5 GeV,
-2 < η_{jet} < 1.5

~82 pb^{-1} = 1,015 events!

SU(3) contribution
σ_A=23%,
σ_B=13%,
σ_C=39%,
σ_D=25%

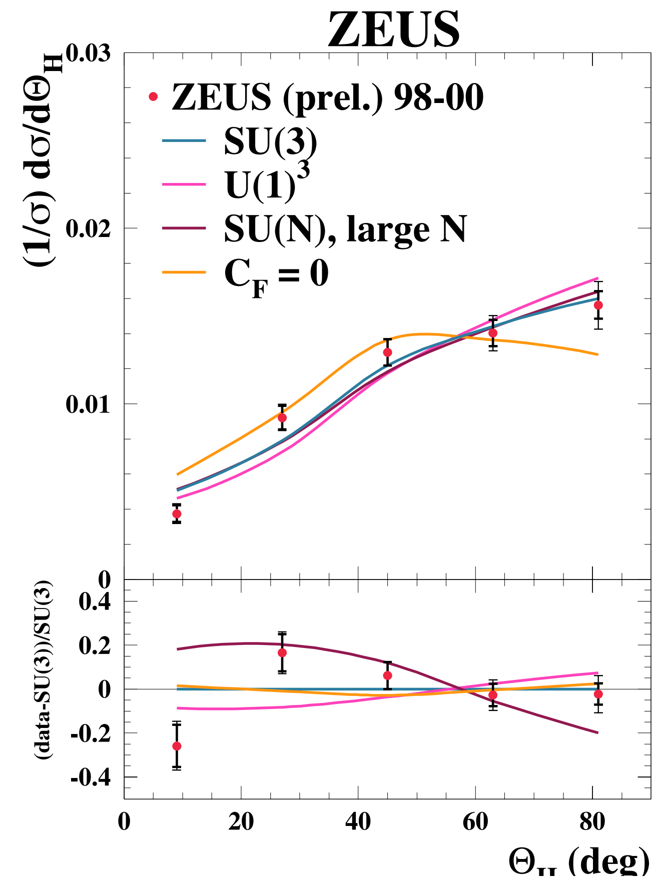


ZEUS 3Jet Correlations

Data disfavour SU(N) in the limit large N and $C_F = 0$

Some differences between SU (3) and U(1) - discrimination statistically limited

All data consistent with SU(3)



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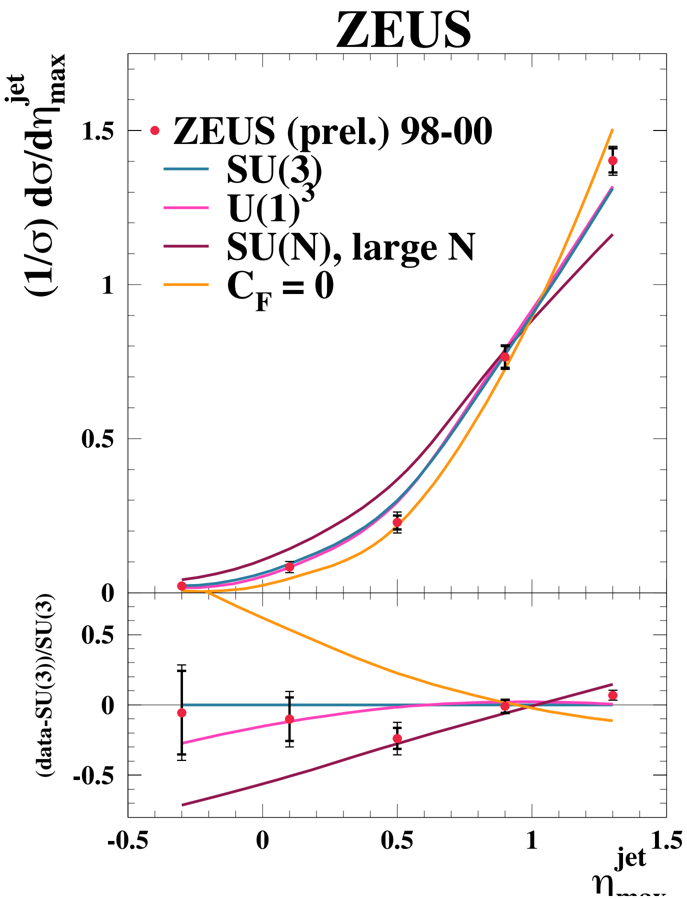


ZEUS Subjet Distributions

Go to region where jet structure
can be calculated perturbatively.

Inclusive Jets with,
$Q^2 > 125\ GeV^2$, $E_T > 14$ GeV

Then study QCD radiation
patterns and jet structure

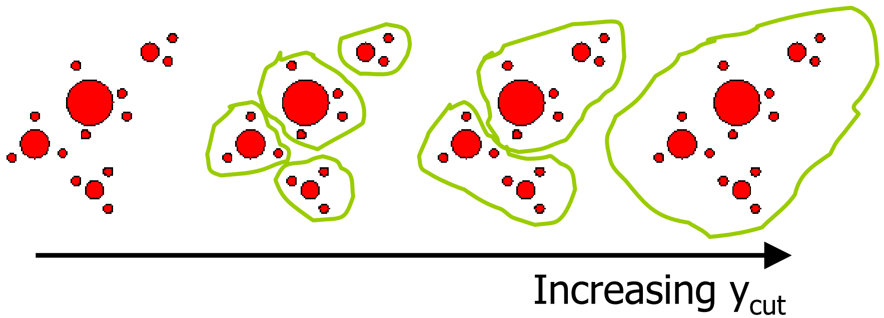
Analysis performed in lab frame where
calculations can be made at NLO for
jets consisting of up to 3 partons

ZEUS Subjet Distributions

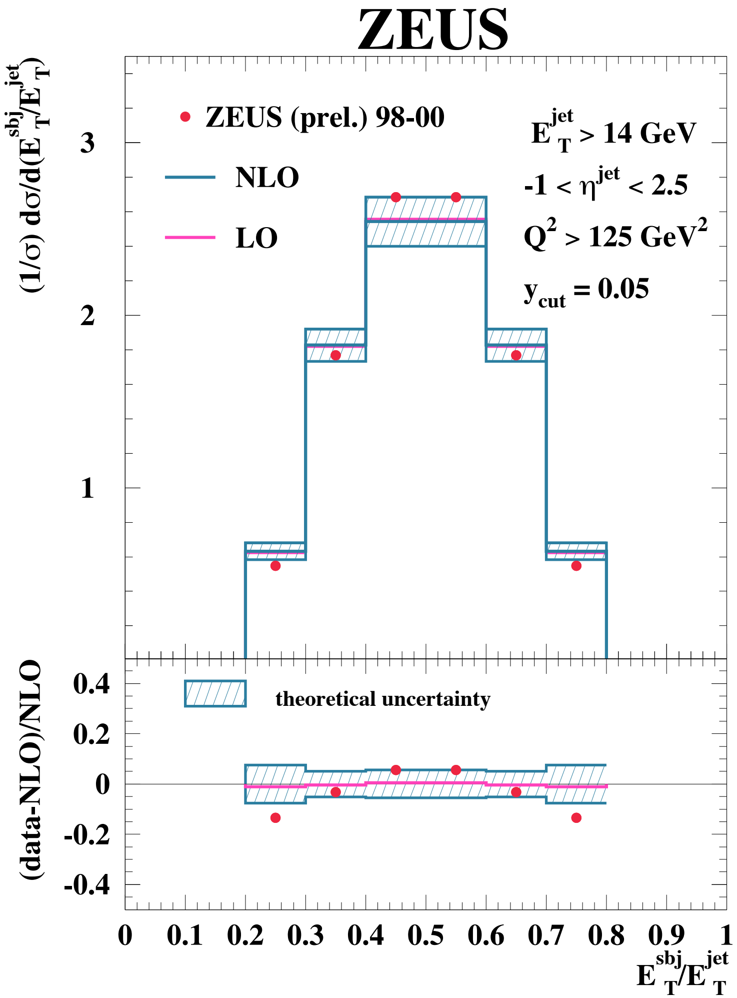
Rerun K_T jet finder over particles of found jet using a distance measure to define subjets

$d_{cut} = y_{cut}.(E_{T,jet})^2$

sample consists of jets that have two sublets for y_{cut}=0.05



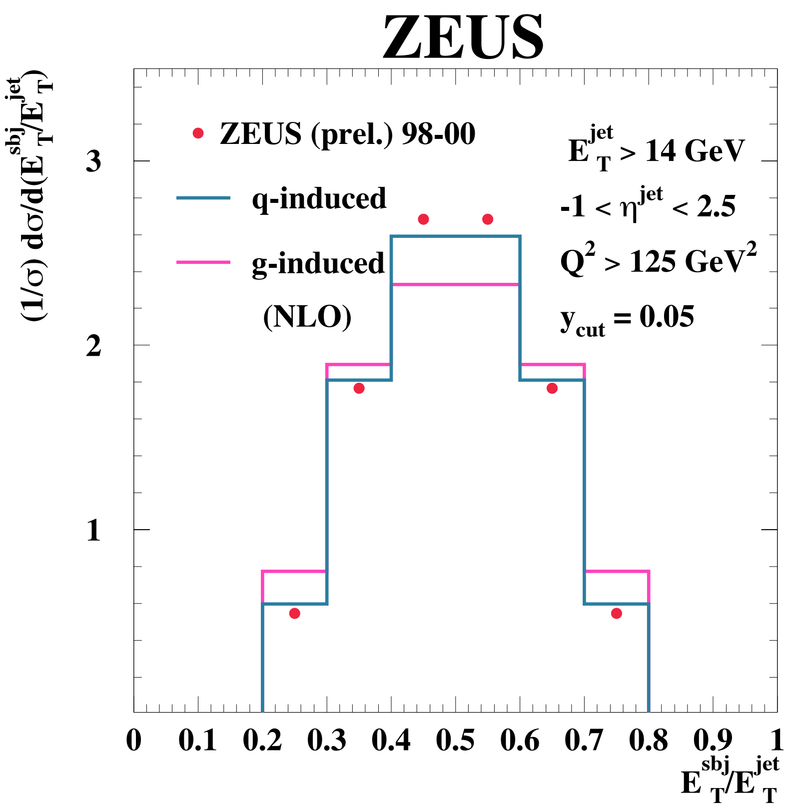
ZEUS Subjet Distributions



Basically tested variables E_{Tsub}/E_{Tjet}, η_{sub}-η_{jet}, $|\Phi_{sub}$-$\Phi_{jet}|$ orientation of subjets in η-Φ space with respect to proton beam.

All distributions are reasonably described by NLO QCD

ZEUS Subjet Distributions



NLO predicts the relative contribution of quark (gluon) induced processes is 82% (18%)

data are best described by calculations for subjets coming from qg pairs

Conclusion

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- Plenty of room for improvement in Experimental results.
- This has to be done for HERAII