Hard Processes in ep-Scattering

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Inclusive DIS

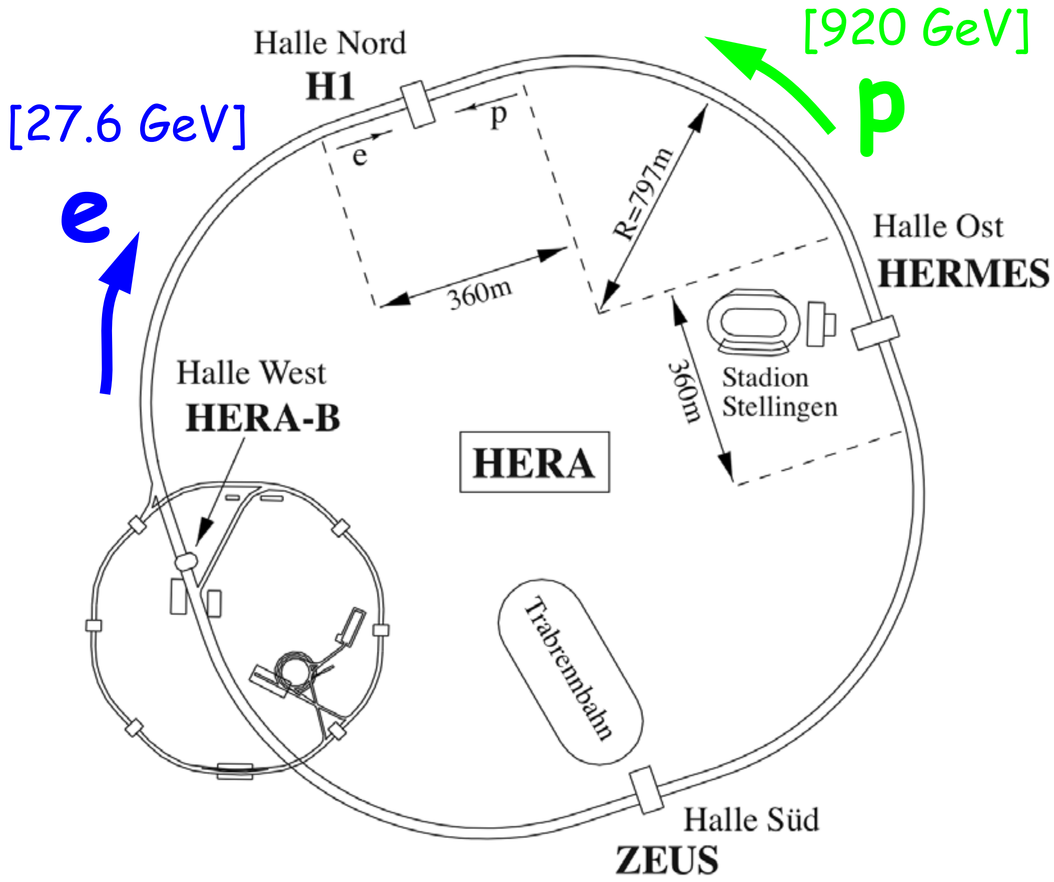
Jet Physics

Searches at HERA

The HERA ep-Collider

@ DESY/Hamburg

$\sqrt{s}$ = 320 GeV



HERA I [1994 -2000]

e^+p Scattering: L ~ 100 pb^{-1}

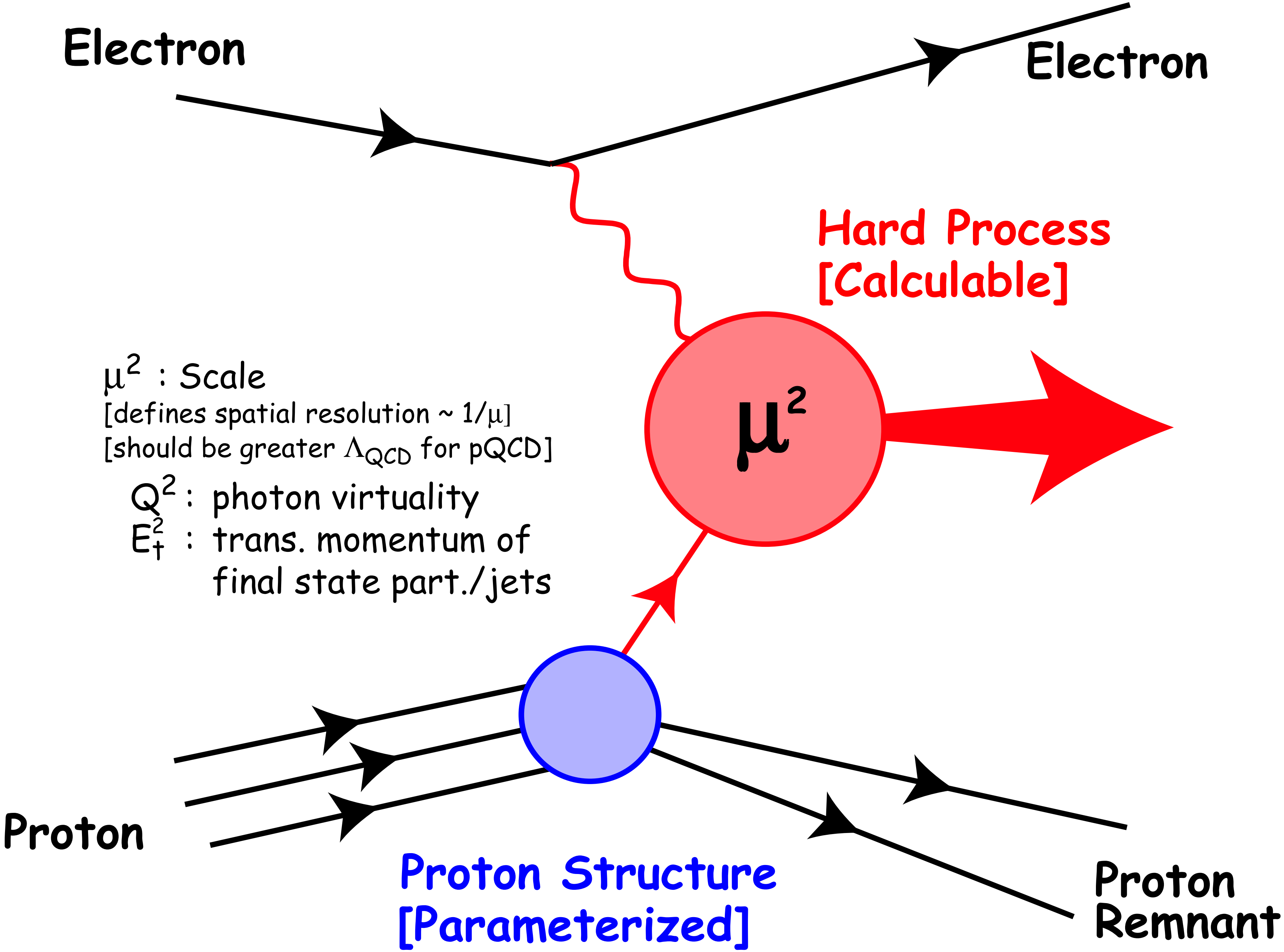
e^-p Scattering: L ~ 15 pb^{-1}

HERA II [2003++]

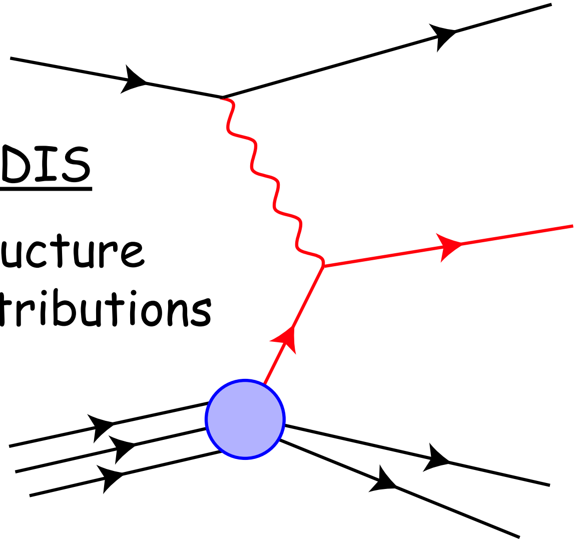
Int. Luminosity: 1000 pb^{-1}

$e^{\pm}$-Polarisation ~50%

[+ low energy ep-data]

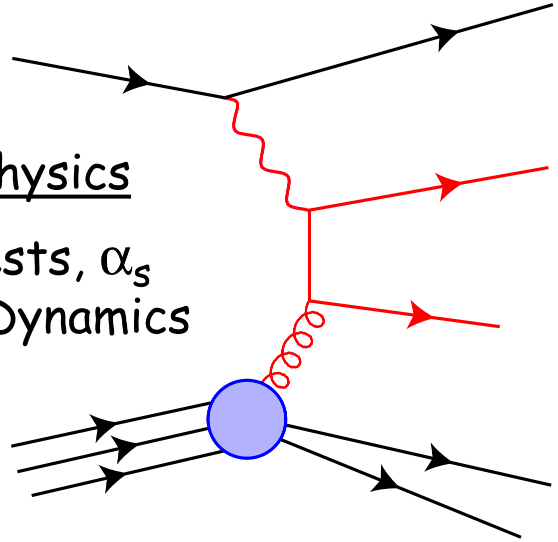

Electron
Electron
Hard Process
[Calculable]
μ^2
μ^2 : Scale
[defines spatial resolution ~ $1/\mu$]
[should be greater Λ_{QCD} for pQCD]
Q^2 : photon virtuality
E_t^2 : trans. momentum of final state part./jets
Proton
Proton Structure
[Parameterized]
Proton Remnant

Selected Topics



I. Inclusive DIS

Proton Structure
Parton Distributions

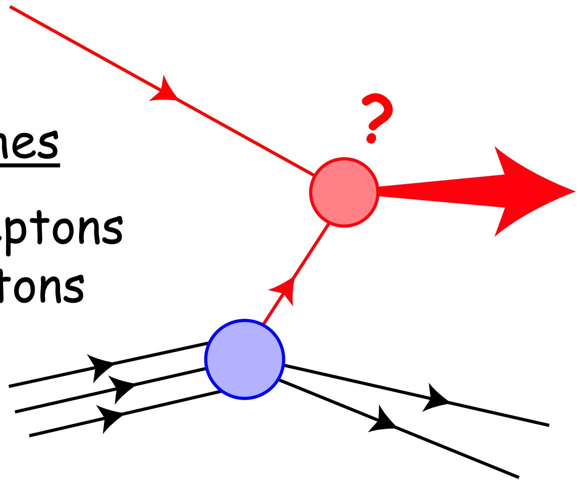


II. Jet Physics

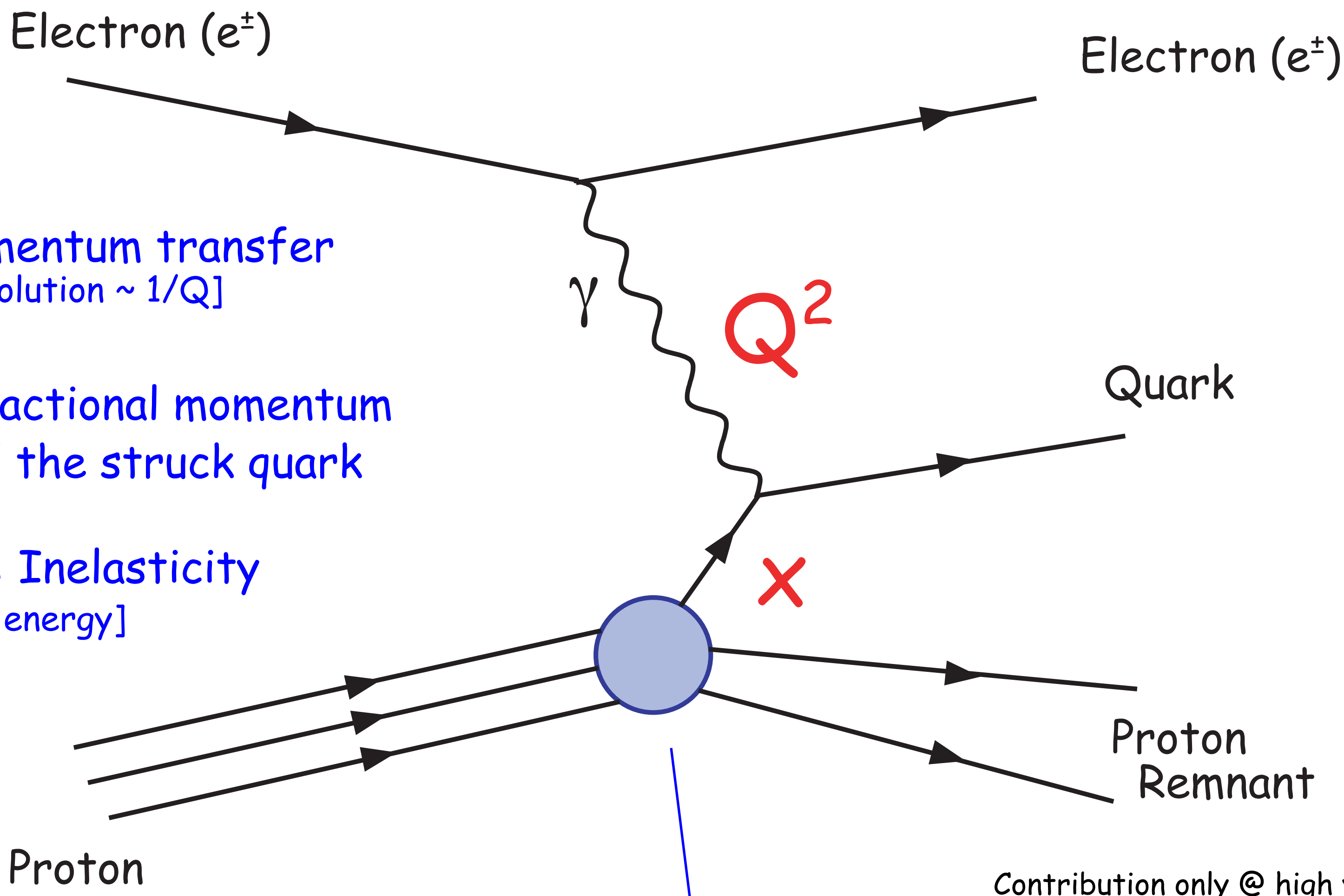
QCD Tests, α_s
Parton Dynamics

III. Searches

High P_t Leptons
Multi-Leptons



Inclusive Deep-Inelastic Scattering



Q^2: four-momentum transfer
[spatial resolution ~ 1/Q]

x: fractional momentum of the struck quark

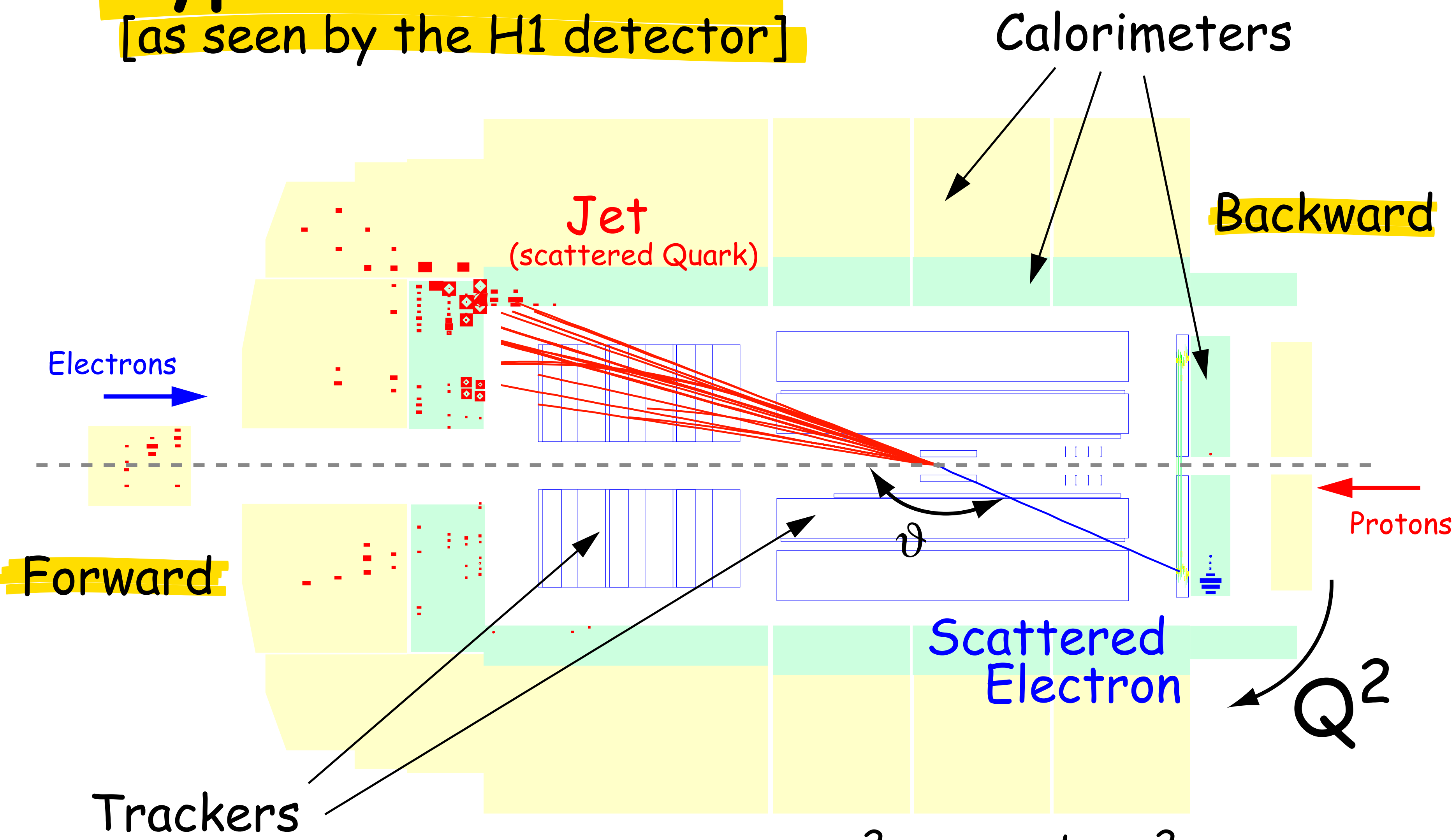
$y = Q^2/sx$: Inelasticity
[$\sqrt{s}$: cms energy]

$$\frac{d^2\sigma}{dx\,dQ^2} = \frac{2\pi\alpha^2}{xQ^4}\{[1-(1-y)^2]\,F_2(x,Q^2) - y^2 F_L(x,Q^2)\}$$

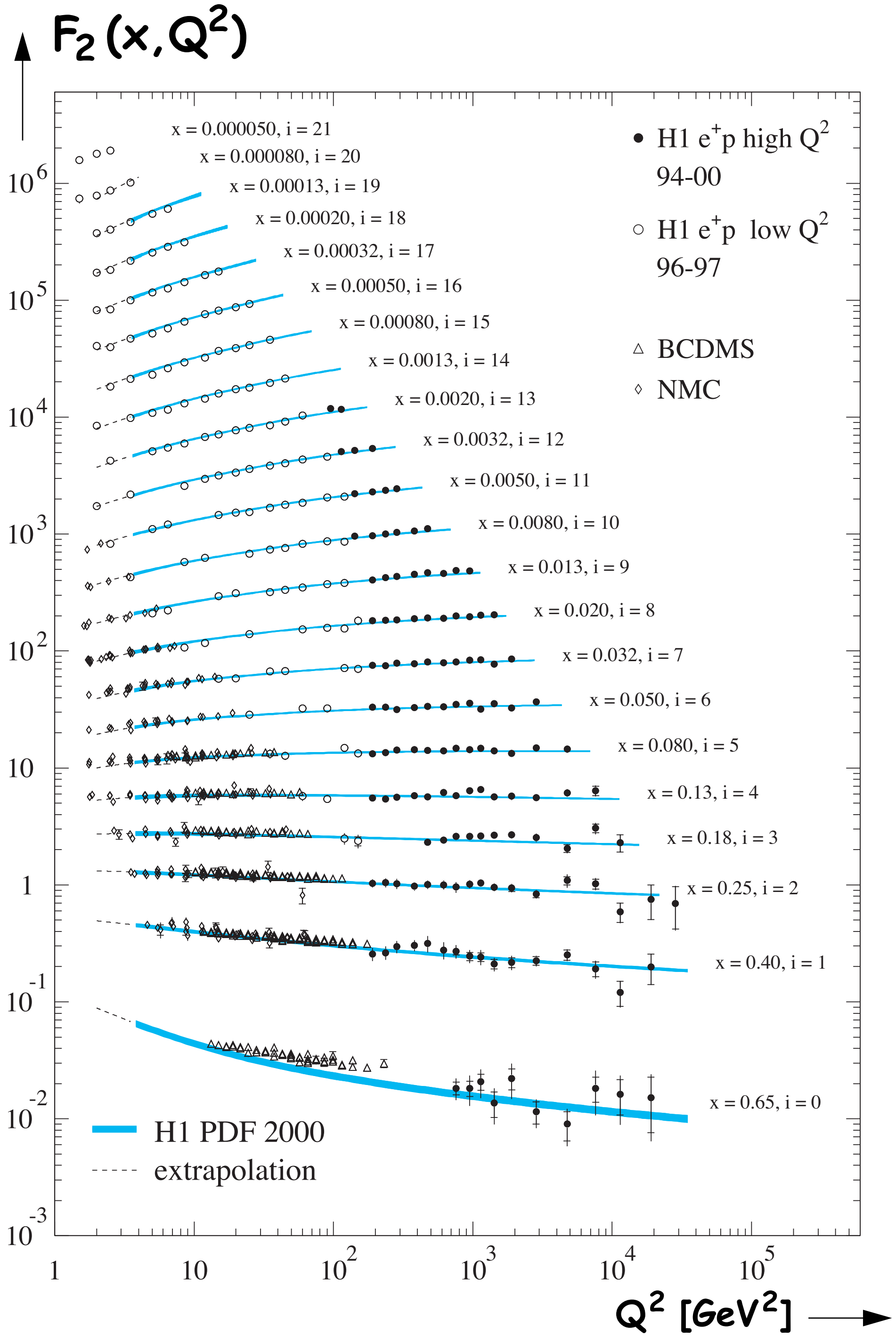
Contribution only @ high y
Related to gluon density
[LO: F_L=0]

Typical DIS-Event

[as seen by the H1 detector]



$$Q^2 = 4E_eE_e'\cos^2(\vartheta/2)$$



HERA [& Fixed Target] F_2-Measurements

$$F_2(x,Q^2) = \sum e_q^2 x q(x,Q^2)$$

Precision: 2-3% (bulk region)

Scaling violations at low $x < 10^{-2}$

$dF_2/d\log Q^2 \sim g(x,Q^2)\cdot\alpha_s(Q^2)$

From NLO QCD Fits:

Quark densities
Gluon density
Strong coupling constant

Determination of PDFs

fitting DIS data from HERA and Fixed Target Experiments

Procedure:

- Assume parametric form of parton distribution functions at starting scale $Q_0^2 \sim O(5\ GeV^2)$.
  [H1: 4 GeV^2; ZEUS: 7 GeV^2].
  [# Parameters: O(10)]
- Fit all data by evolving the PDFs to higher Q^2

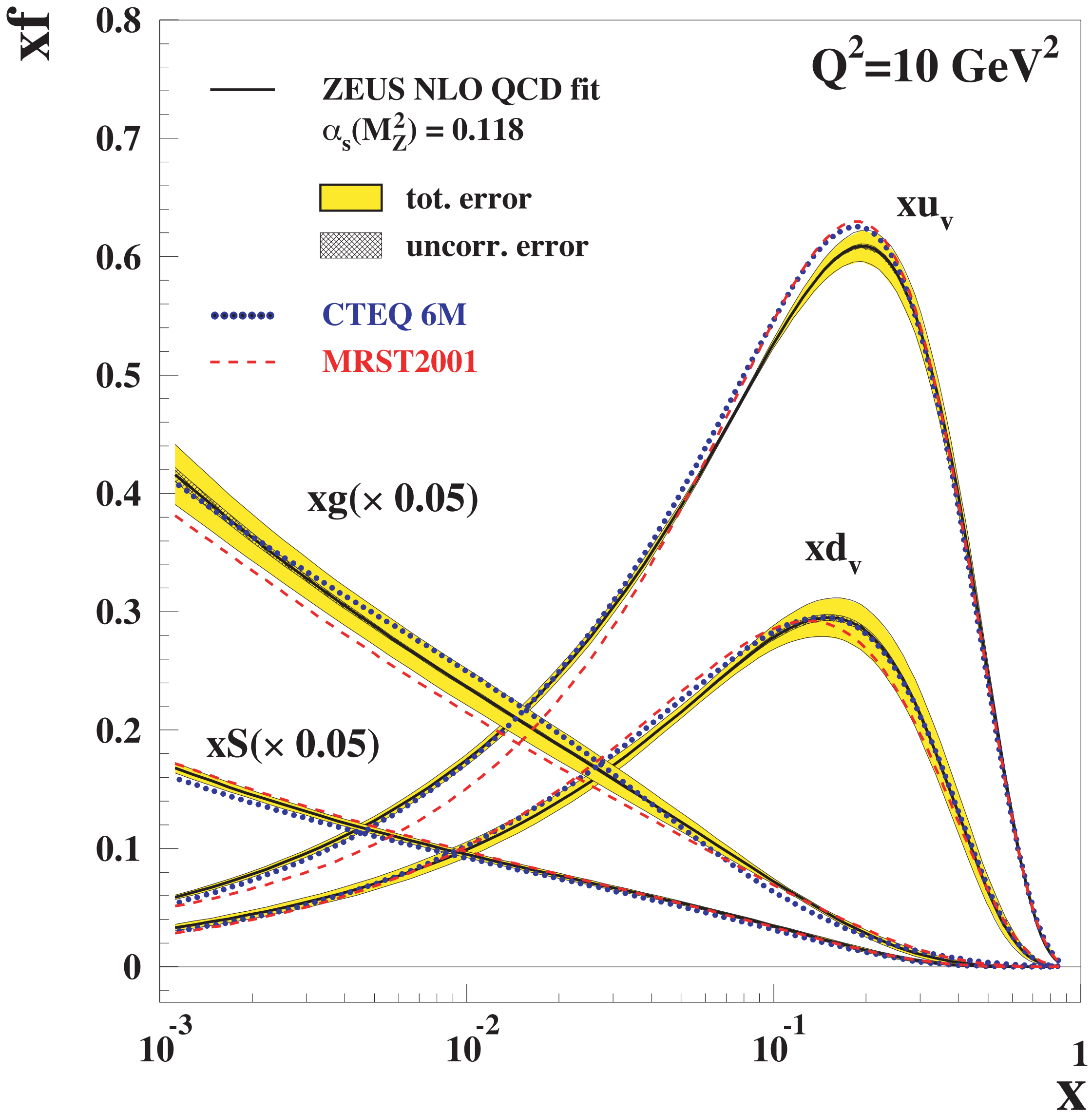
Parametric Forms:

- $xg(x) = ax^b(1-x)^c\ \zeta(x)$
- $xu(x) = a'x^{b'}(1-x)^{c'}\ \xi(x)$

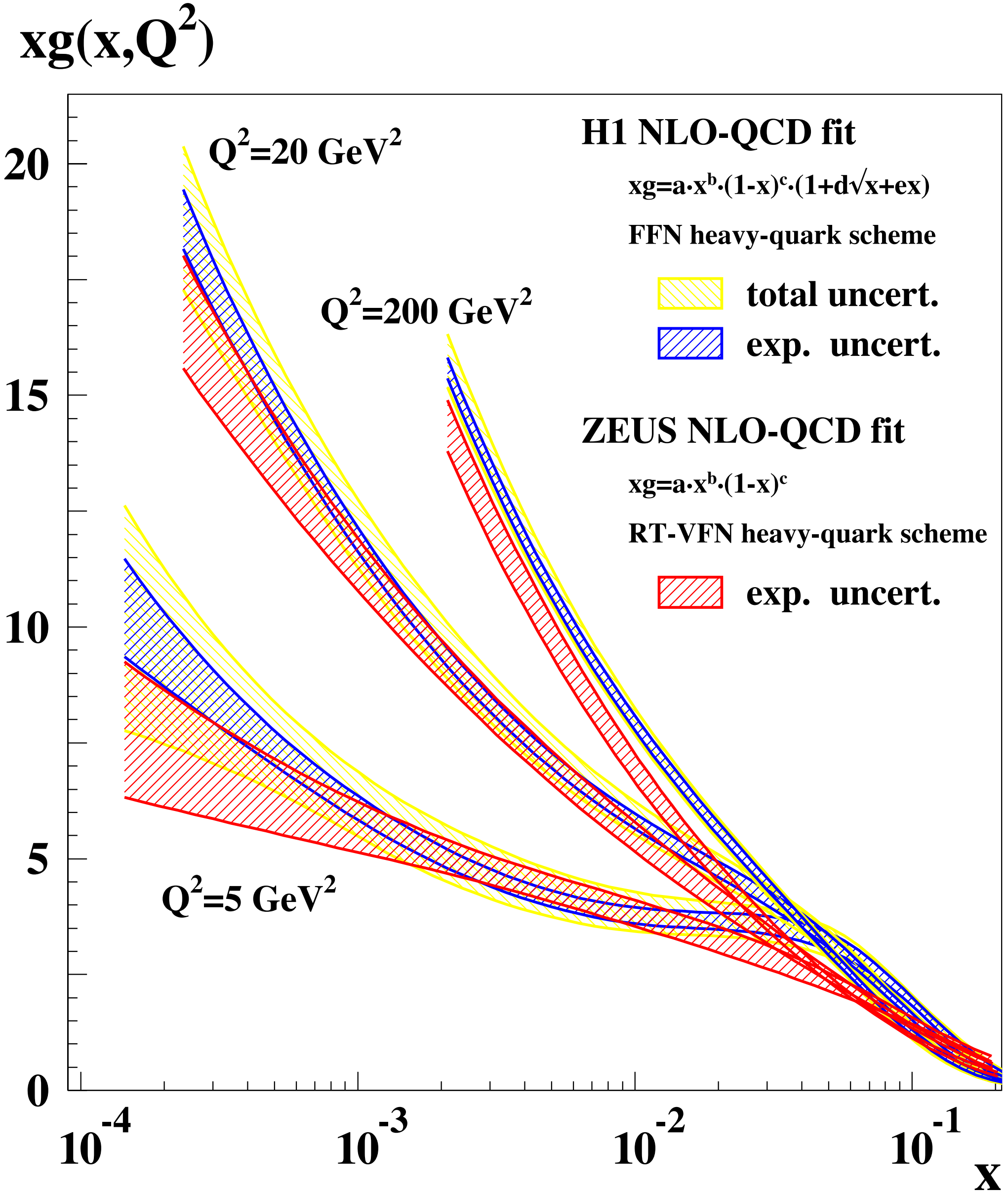
...

e.g.: H1 $\rightarrow \zeta(x) = 1+d\sqrt{x} + ex$

ZEUS $\rightarrow \zeta(x) = 1$



$xg(x,Q^2)$ — Comparison of Results

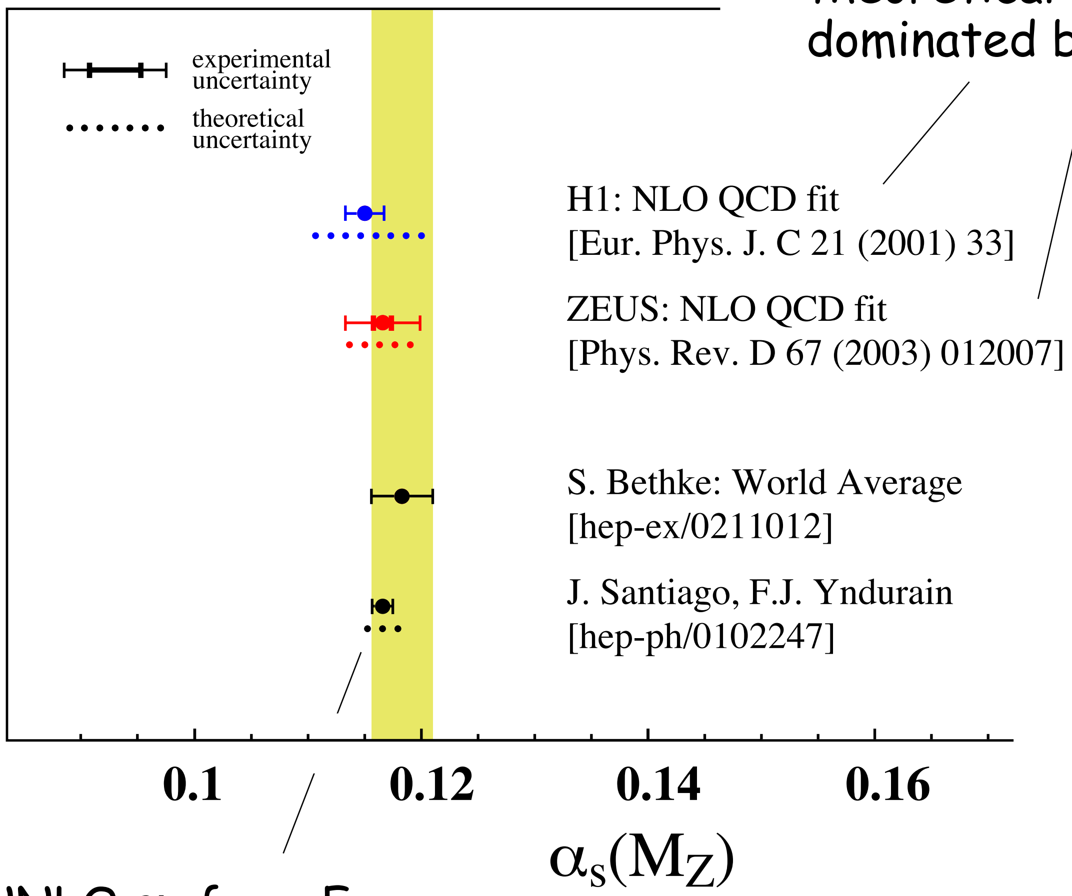


Independent fits
Experimental errors only

Different approaches
Different goals
[H1: $g(x)$ & α_s, Zeus: PDFs]

Parametric forms:
Influence of choice
to be investigated

theoretical error
dominated by scale uncertainty



renorm. scale uncertainty

exp. & model uncertainty

ZEUS:

$\alpha_s = 0.1166 \, ^{+0.0052}_{-0.0052} \pm 0.004$

H1:

$\alpha_s = 0.1150 \, ^{+0.0019}_{-0.0018} \pm 0.005$

[World average: 0.1183 ± 0.0027]
S. Bethke: hep-ph/0211012

NNLO α_s from F_2

moment analysis based on Bernstein polynomials

systematic error includes:

- NNNLO correction estimate
- higher twist effects

NNLO (and still improved precision) promises world beating α_s from HERA

Determination of F_L

DIS cross section:

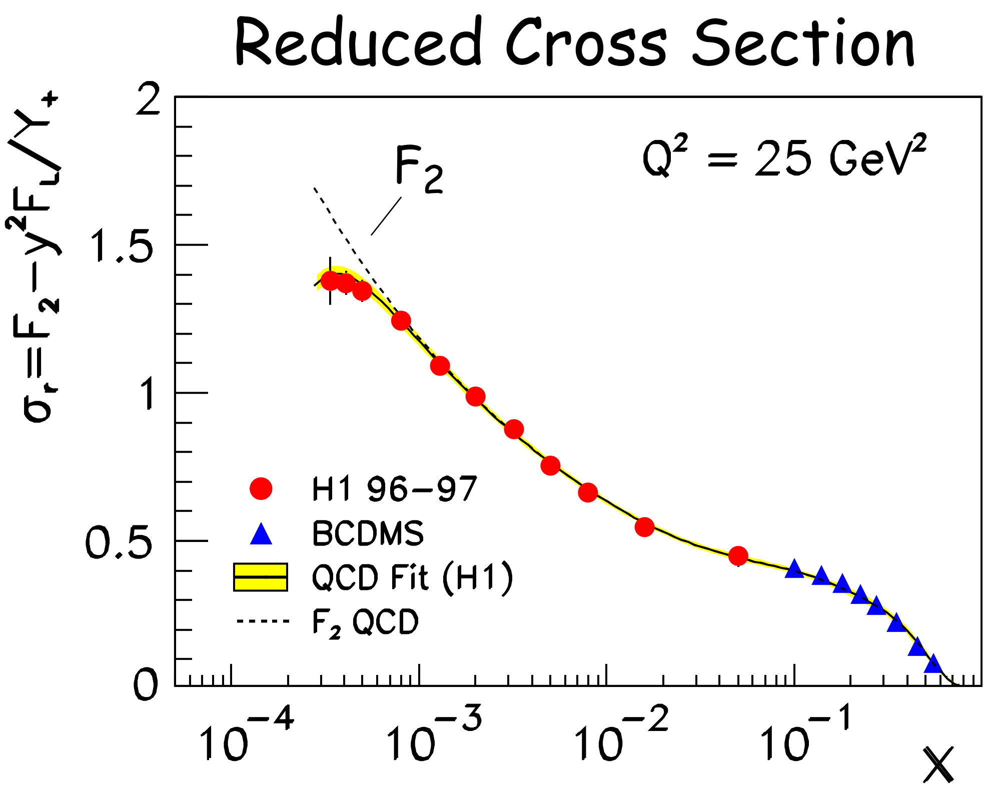
Contributes only @ high y

$$\frac{d^2\sigma}{dx\,dQ^2} = \frac{2\pi\alpha^2}{xQ^4}\{[1-(1-y)^2]\,F_2(x,Q^2) - y^2F_L(x,Q^2)\}$$

$F_L \sim \alpha_s g(x) \rightarrow$ constrains $xg(x)$
Provides important QCD test

Direct measurement requires data at different cms-energies

Indirect determination possible assuming F_2 to be known



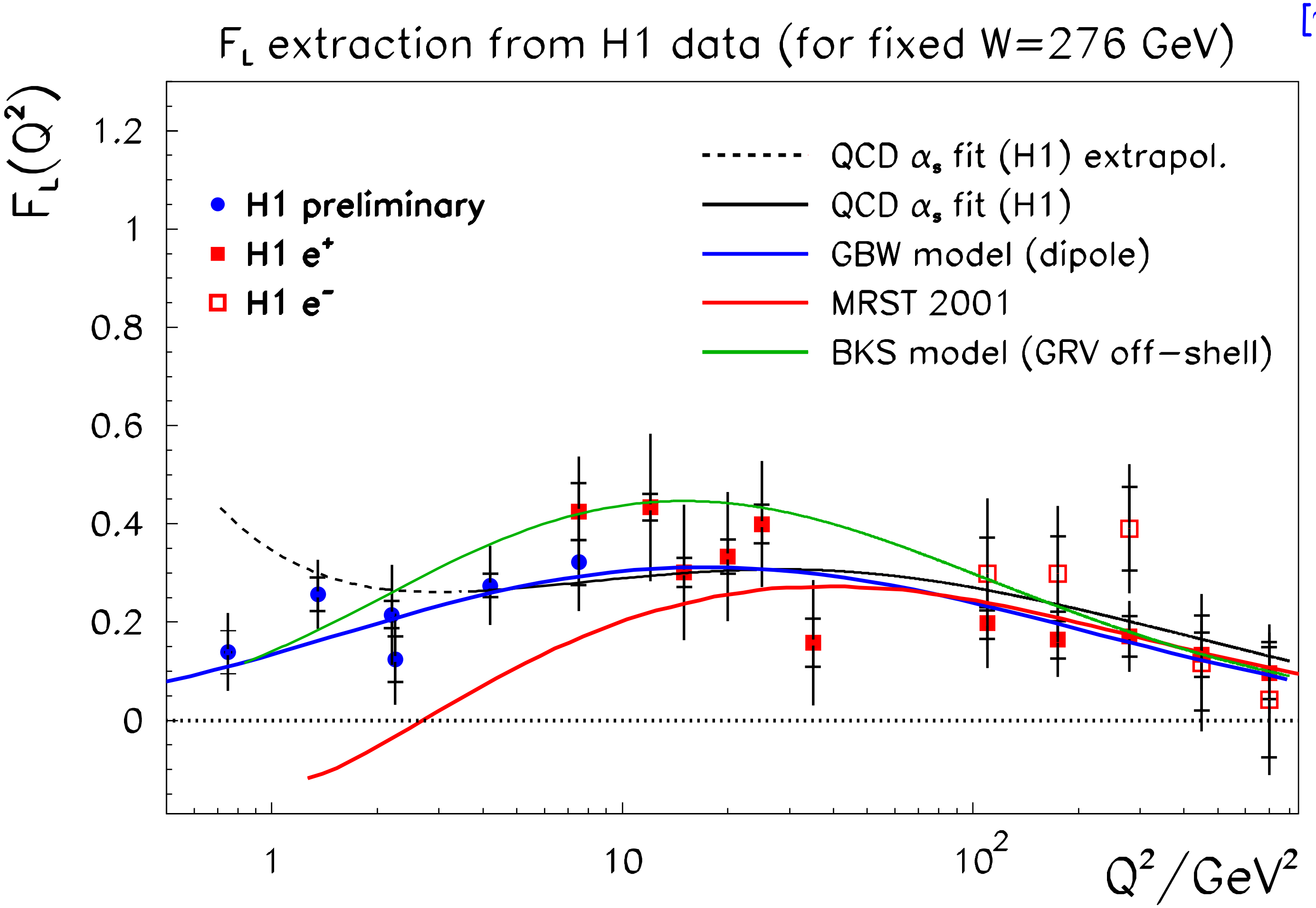
$$F_L \sim F_2 - \sigma_r$$

extrapolation method

also: derivative method
shape method

F_L at fixed y=0.75

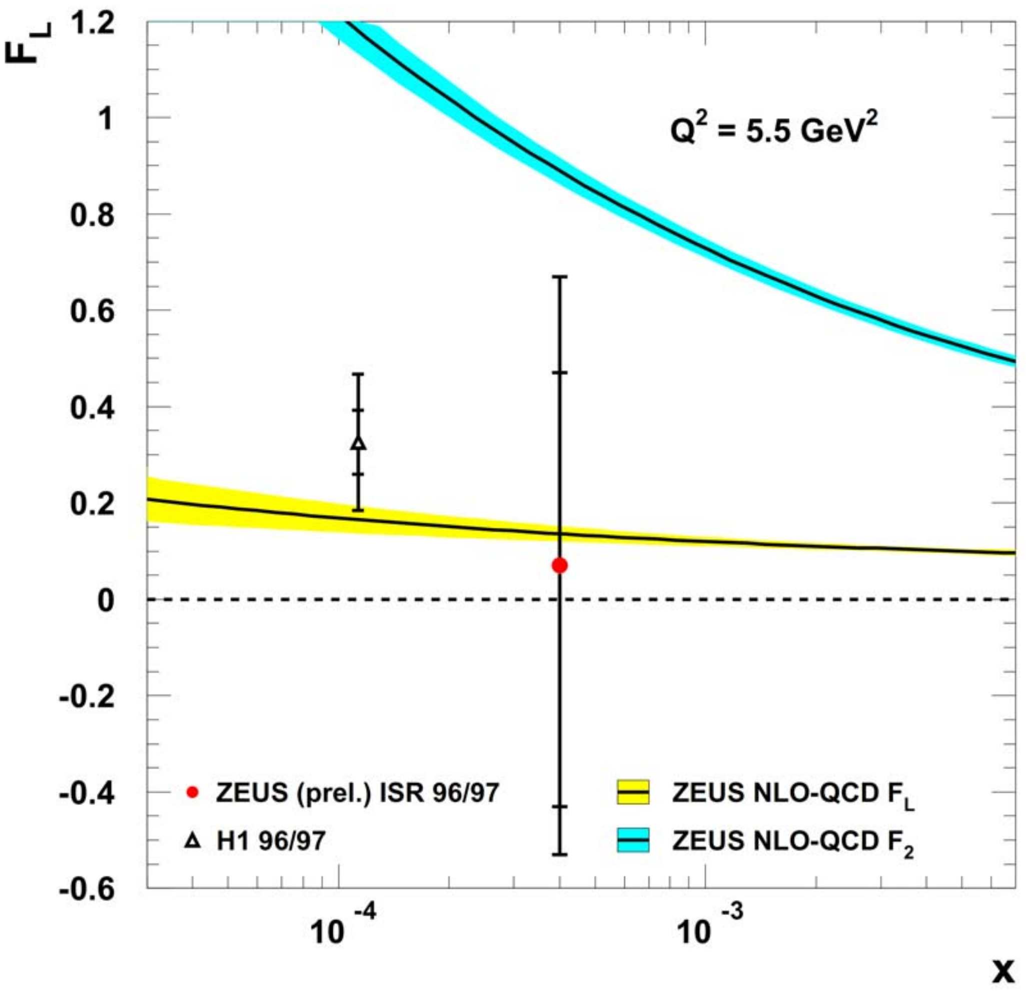
$W^2 \approx ys$
[γp cms-energy]



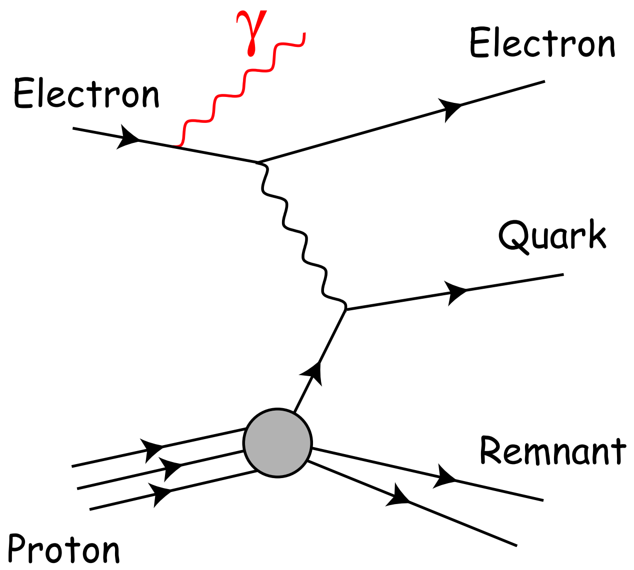
Data in basic agreement with NLO QCD Fit to F_2 data.
New low Q^2 results provide additional constraints.

Direct F_L-Measurement

using radiative deep-inelastic scattering data



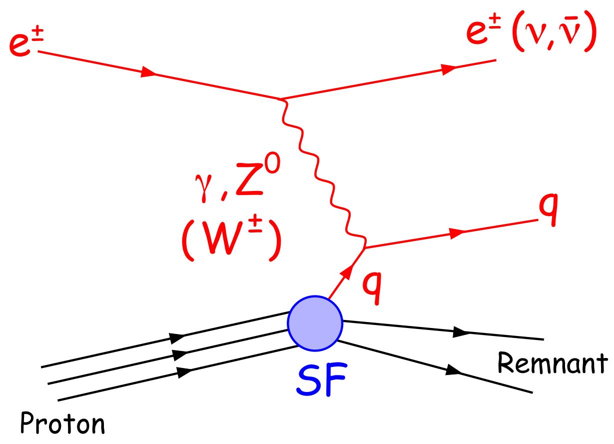
ISR reduces
ep cms-energy



Errors large

Data prefer small F_L

DIS Cross Section @ High Q^2



Influence only @ high y

$$\frac{d^2\sigma(e^\pm)}{dx\,dQ^2} \sim \xi F_2 \mp \zeta x F_3 - \eta y^2 F_L$$

different contribution from xF_3 for different lepton charge

Neutral Current:

$$F_2 \sim x\sum_i [q_i + \bar{q}_i]$$

$$xF_3 \sim x\sum_i [q_i - \bar{q}_i]$$

Use e^+p/e^-p data to extract xF_3
Sensitivity to valence quark density

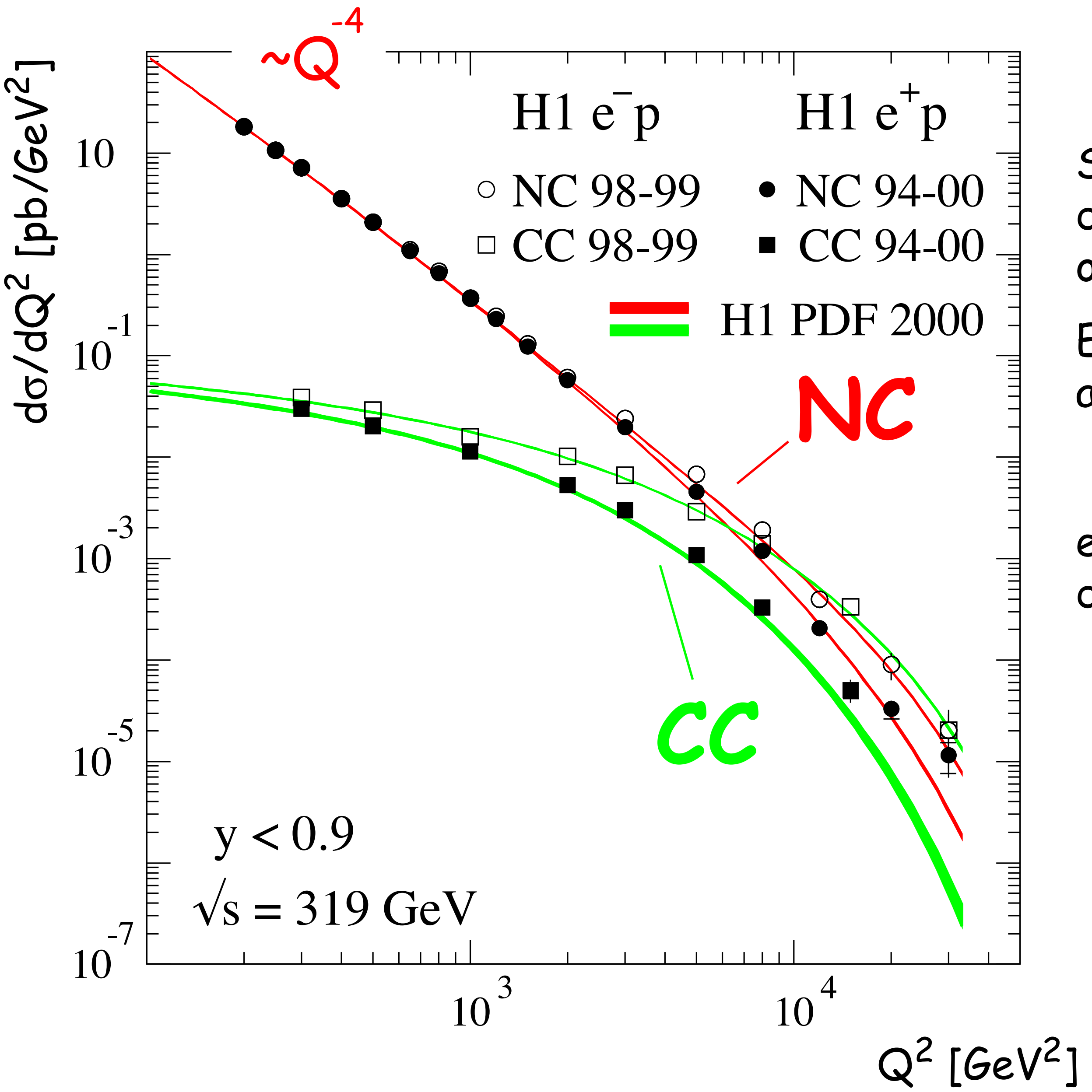
Charged Current:

$$d^2\sigma(e^+) \sim x\,[d + \bar{u}]$$

$$d^2\sigma(e^-) \sim x\,[u + \bar{d}]$$

Use e^+p/e^-p data to disentangle up-/down-quark content at high x

NC and CC Cross Sections



Standard Model describes cross sections over large range of Q^2

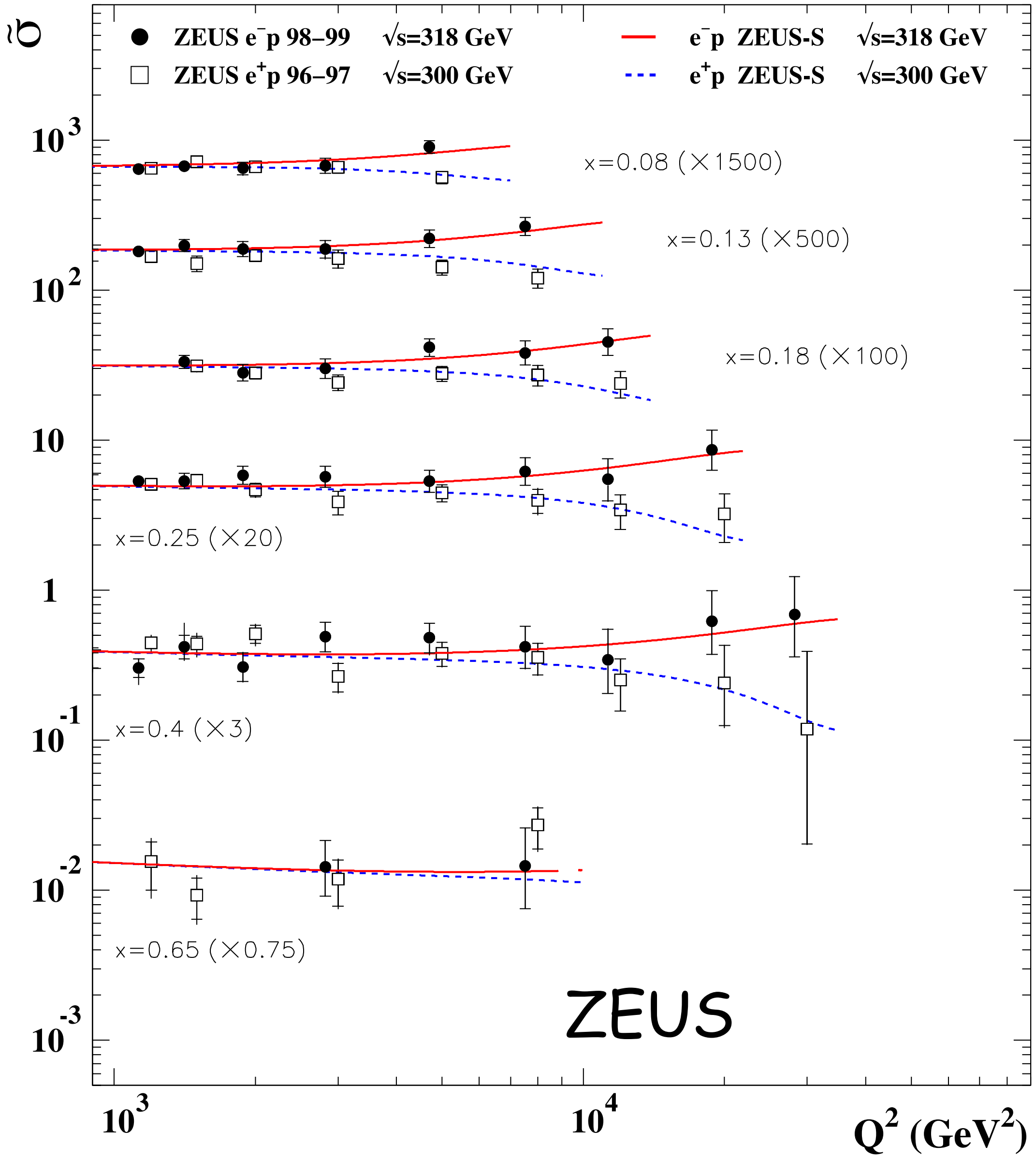
Electroweak 'unification' at large $Q^2 \sim M_Z^2$

e^+p/e^-p cross sections differ due to different

quark contributions

helicity structure of EW interactions

NC Reduced Cross Section



$1/(xQ^4)$-dependence removed

xF_3 Extraction:

$$\tilde{\sigma}^{NC}(e^-) = \xi F_2 + \zeta x F_3$$

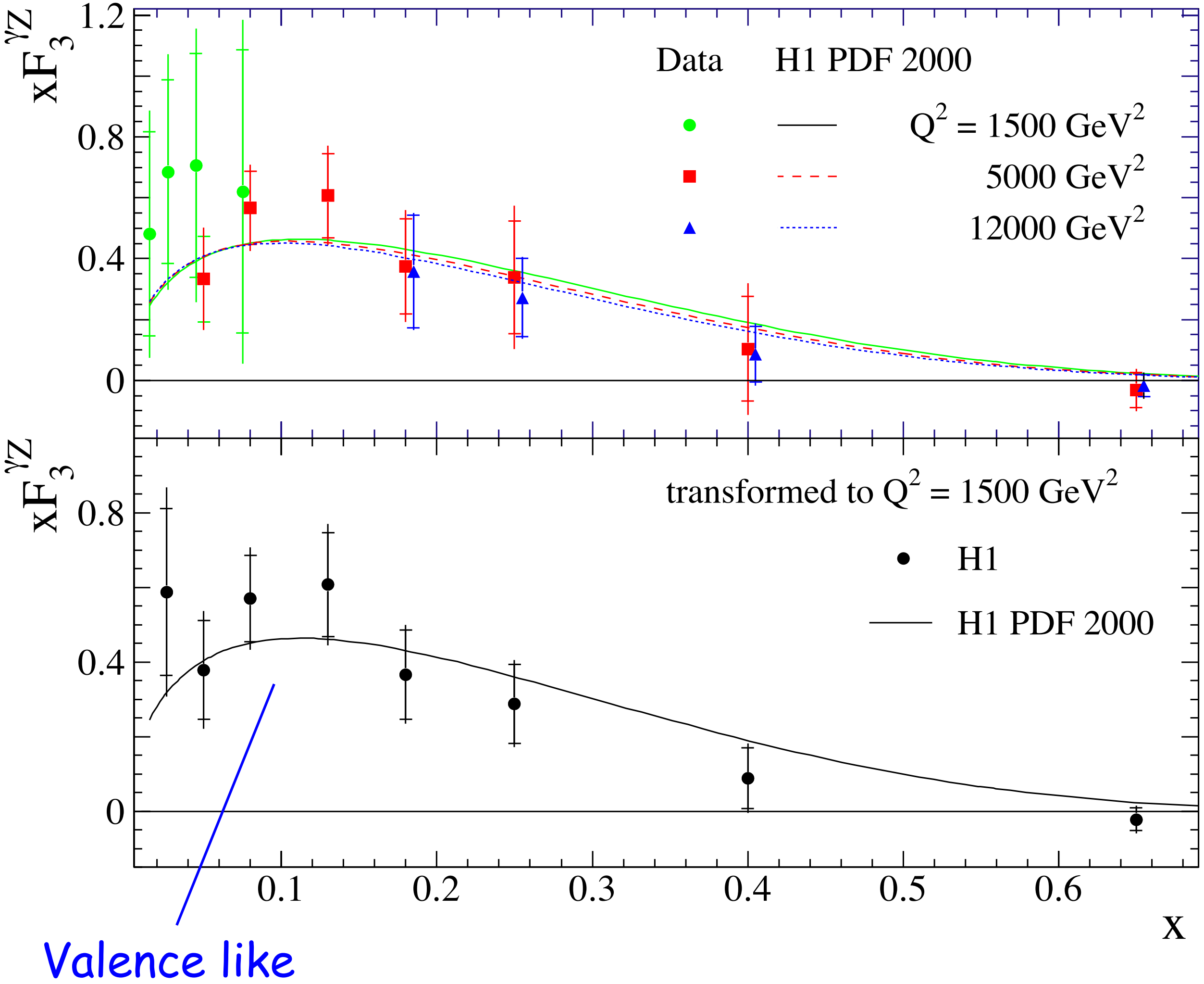
$$\tilde{\sigma}^{NC}(e^+) = \xi F_2 - \zeta x F_3$$

$$xF_3 = \frac{1}{2}\zeta^{-1}\left[\tilde{\sigma}^{NC}(e^-) - \tilde{\sigma}^{NC}(e^+)\right]$$

$$\sim \sum [q(x, Q^2) - \bar{q}(x, Q^2)]$$

At high Q^2: sensitivity to valence quark densities down to $x \sim 10^{-2}$

$xF_3^{\gamma Z}$

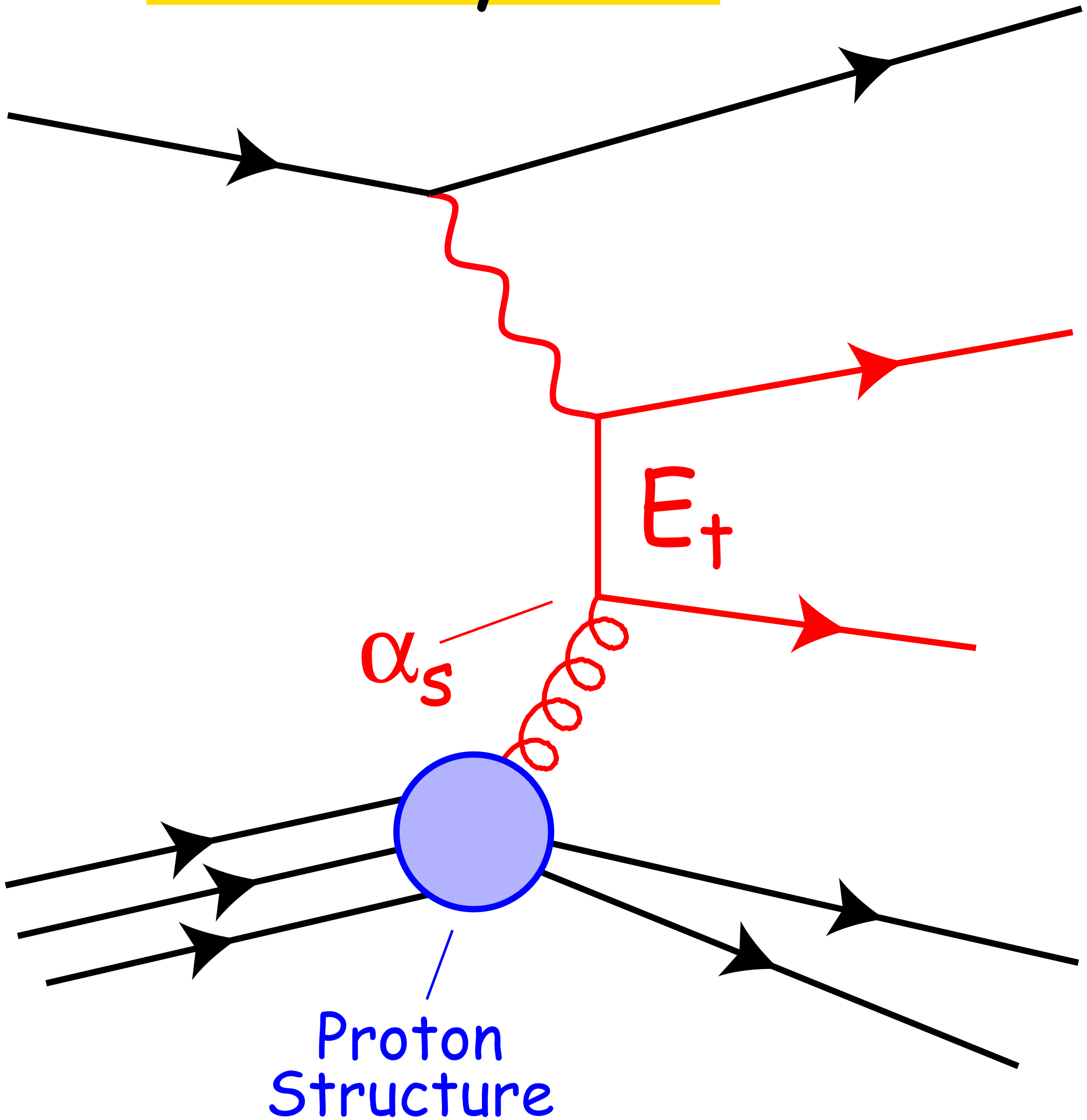


Q^2 dependence calculated to be small

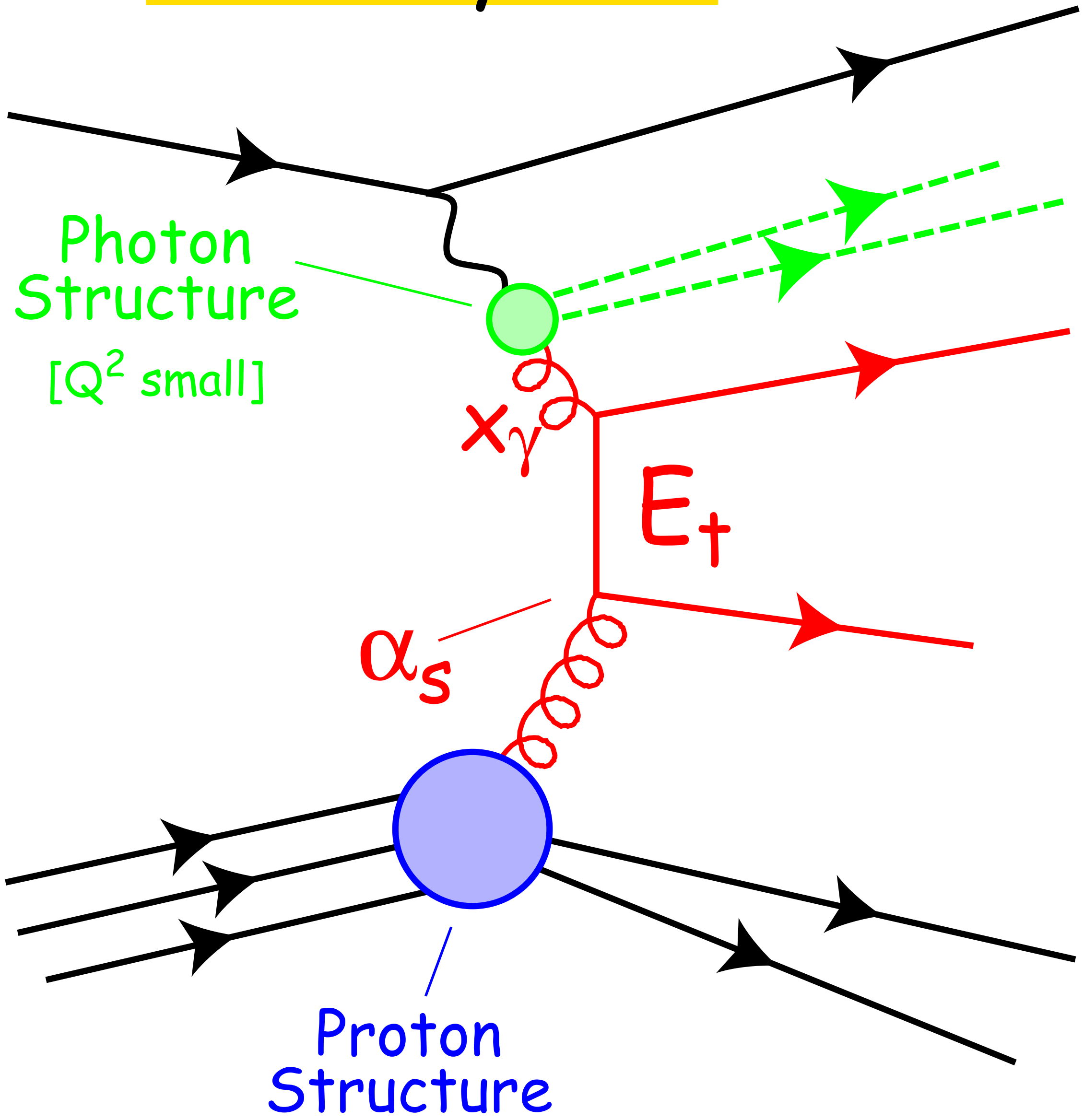
Average over different Q^2-ranges

Uncertainty dominated by statistical errors
Needs more luminosity from HERA II

Jet Physics



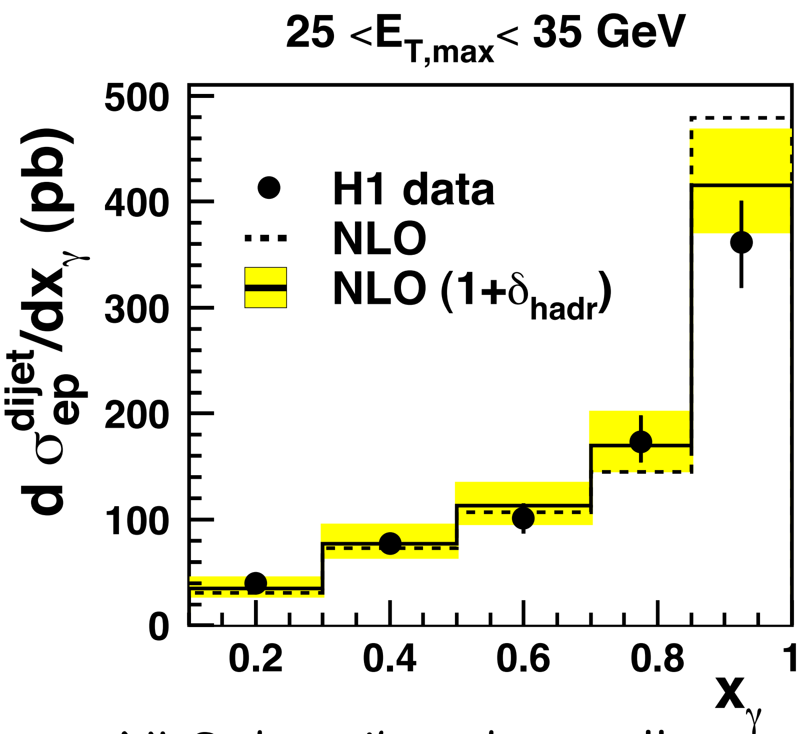
Jet Physics

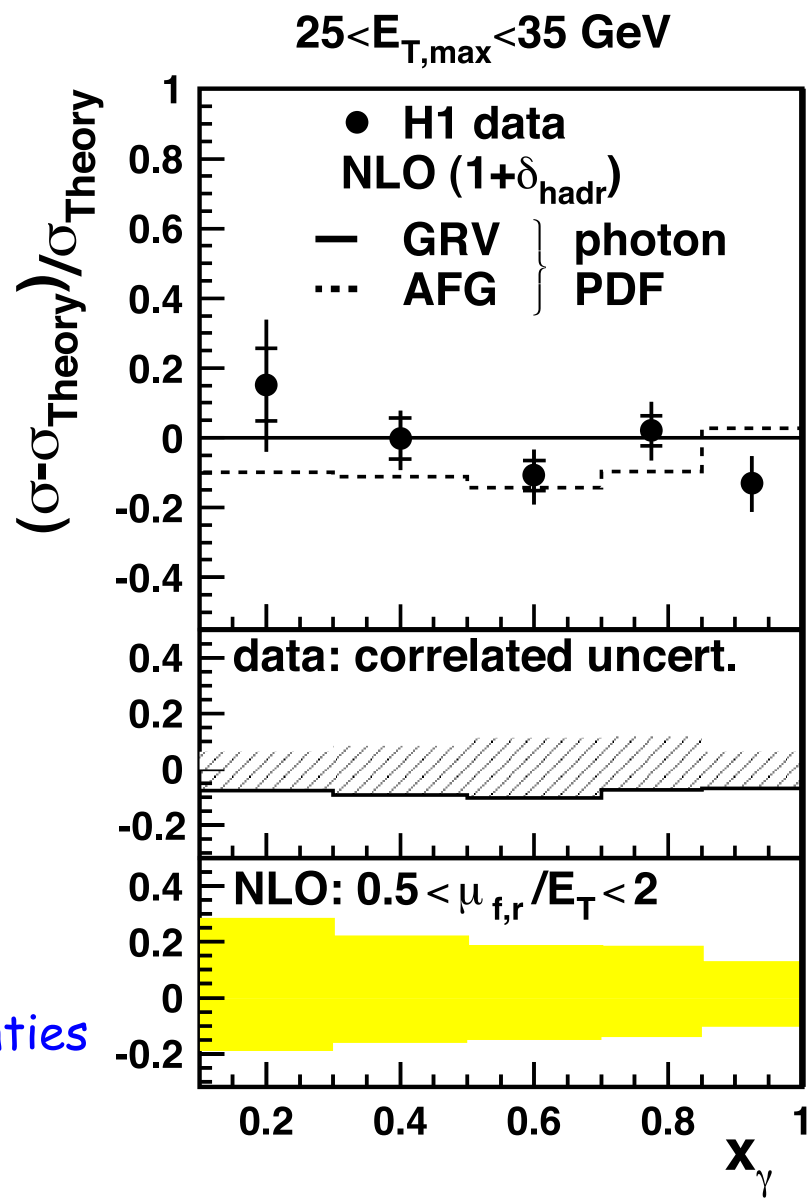


Photon Structure
[Q^2 small]
x_γ
E_t
α_s
Proton Structure

Dijets in Photoproduction

The Structure of Real Photons ($Q^2 \approx 0$)

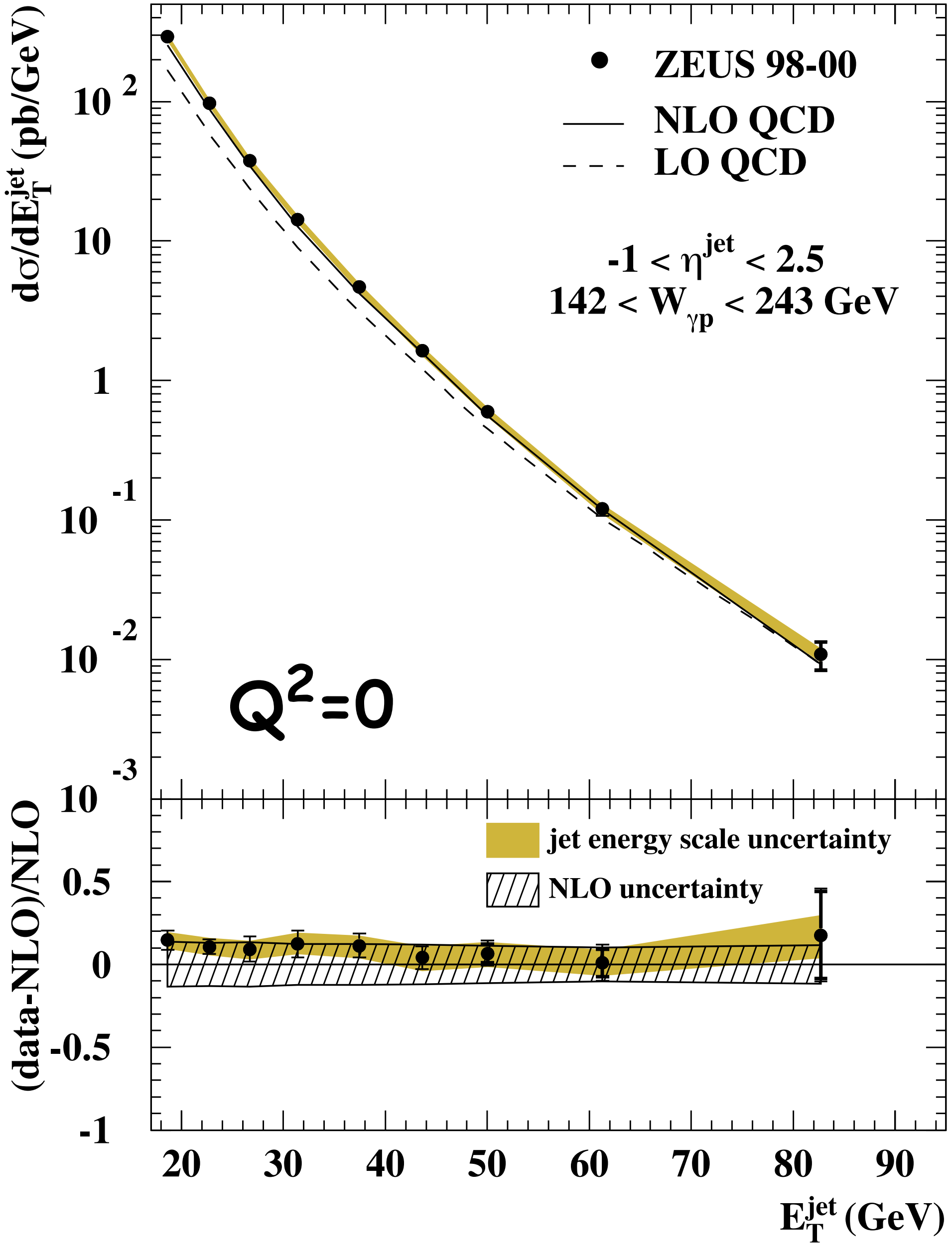




- NLO describes data well
- Variation due to γ-PDF small
- Large scale uncertainty

Further progress with reduction of experimental and theoretical uncertainties

Inclusive γp Jet Cross Section



Sensitivity to α_s

Sensitivity to p- and γ-structure

$$\sigma_{jet}^{pert} = \sum_n \alpha_s^n \left(\sum_{i=g,q} C_{i,n} \otimes pdf_i \right)$$

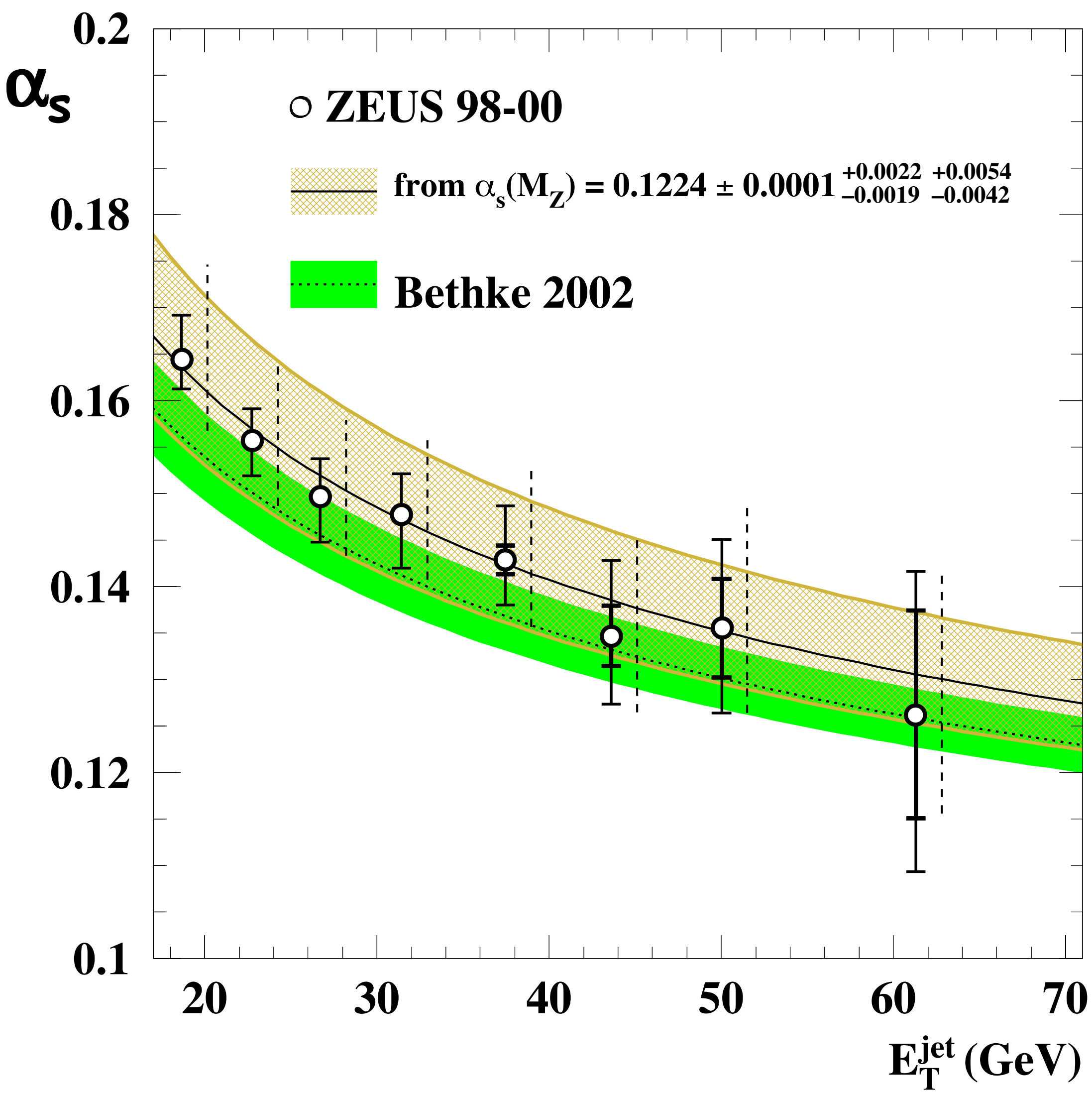
Coefficient functions

Coefficient functions:
NLO calculation available

PDFs from global fits

Allows α_s extraction
by fitting cross section data

α_s Result from Jets



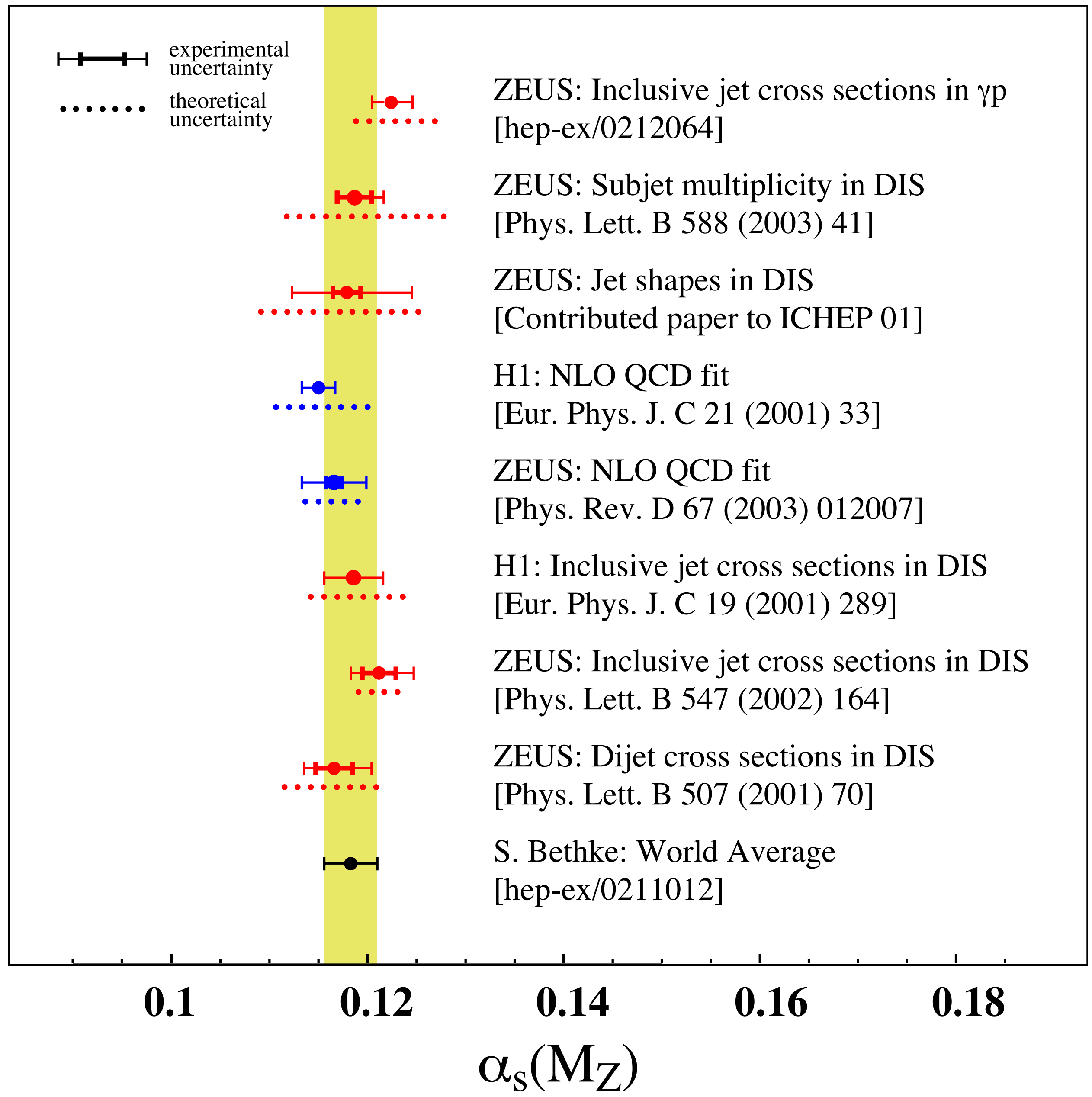
stat.

$$\alpha_s(M_Z) = 0.1224 \begin{array}{l} +0.0001 \\ -0.0001 \end{array} \begin{array}{l} +0.0022 \\ -0.0019 \end{array} \begin{array}{l} +0.0054 \\ -0.0042 \end{array}$$

exp.

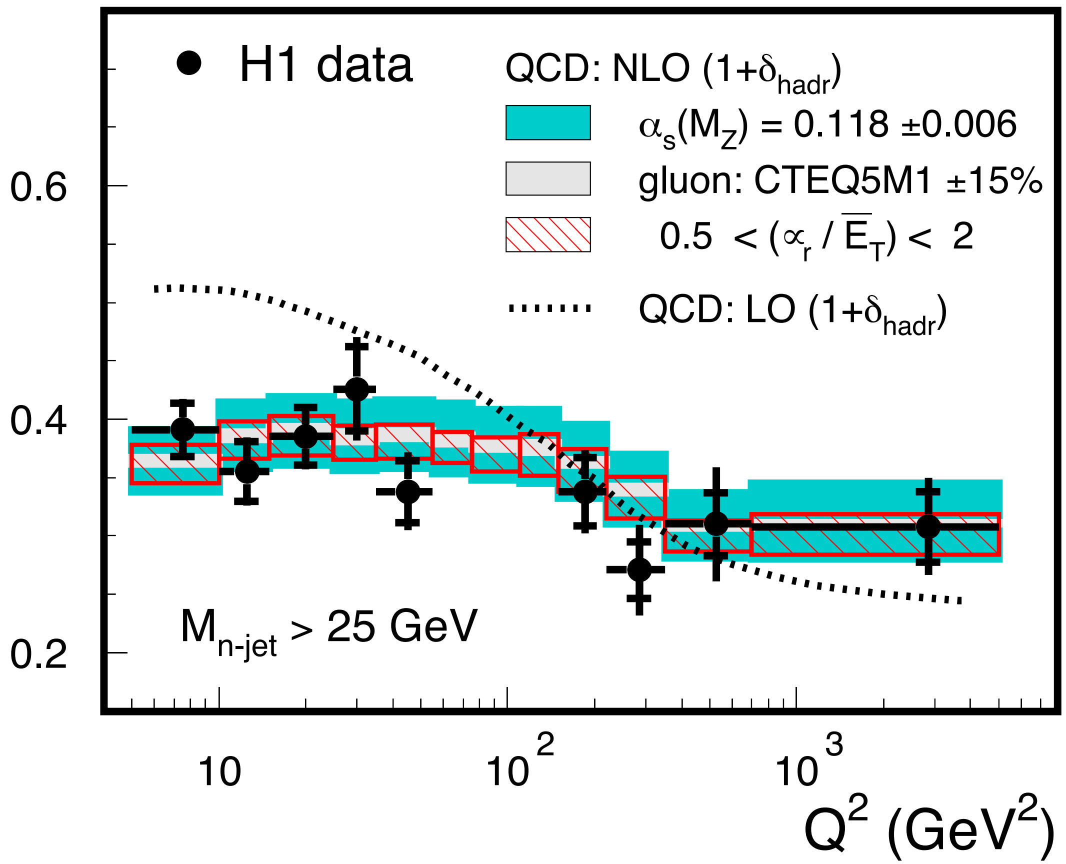
theo.

Best value of α_s from jets @ HERA


experimental uncertainty
theoretical uncertainty
ZEUS: Inclusive jet cross sections in γp
[hep-ex/0212064]
ZEUS: Subjet multiplicity in DIS
[Phys. Lett. B 588 (2003) 41]
ZEUS: Jet shapes in DIS
[Contributed paper to ICHEP 01]
H1: NLO QCD fit
[Eur. Phys. J. C 21 (2001) 33]
ZEUS: NLO QCD fit
[Phys. Rev. D 67 (2003) 012007]
H1: Inclusive jet cross sections in DIS
[Eur. Phys. J. C 19 (2001) 289]
ZEUS: Inclusive jet cross sections in DIS
[Phys. Lett. B 547 (2002) 164]
ZEUS: Dijet cross sections in DIS
[Phys. Lett. B 507 (2001) 70]
S. Bethke: World Average
[hep-ex/0211012]
0.1
0.12
0.14
0.16
0.18
$\alpha_s(M_Z)$

3-Jet/2-Jet Ratio in DIS

$R_{3/2} = \sigma_{3jet} / \sigma_{2jet}$



Small scale uncertainty
Small influence of gluon PDF

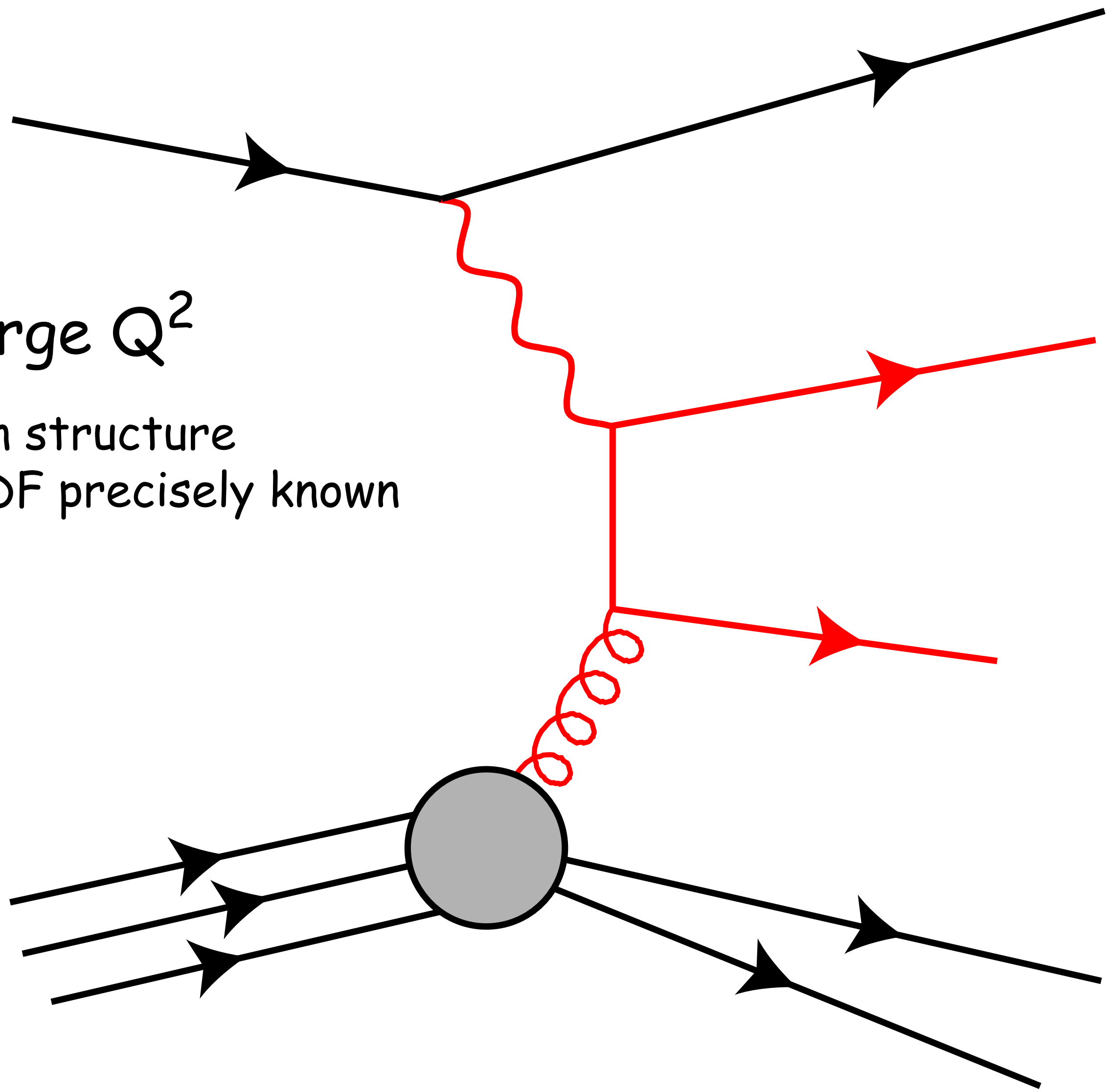
Promises
precision measurement of α_s

Jet Physics

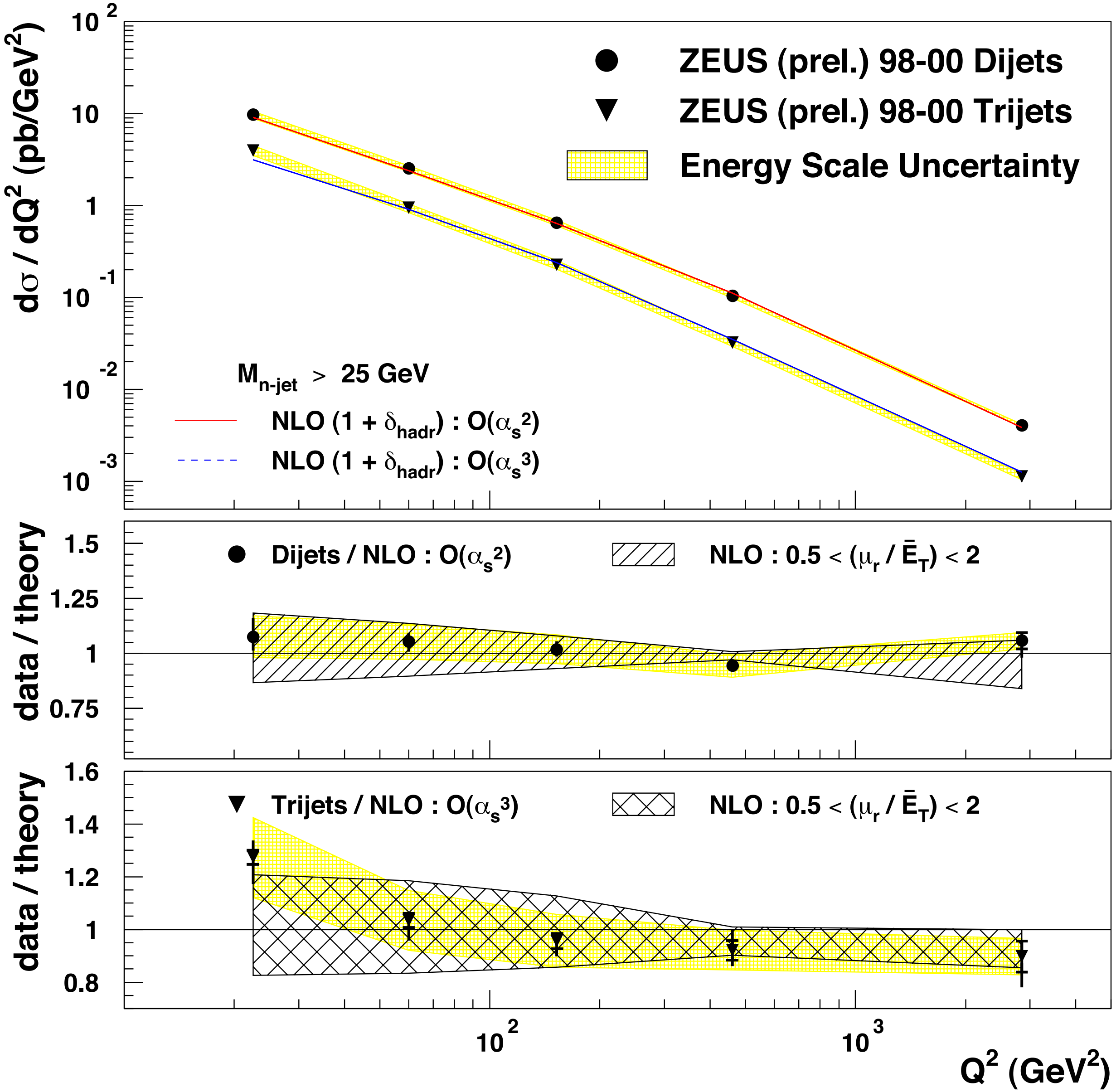
Testing perturbative QCD ...

... at large Q^2

no photon structure
proton PDF precisely known



Dijet and Trijet DIS Cross Section



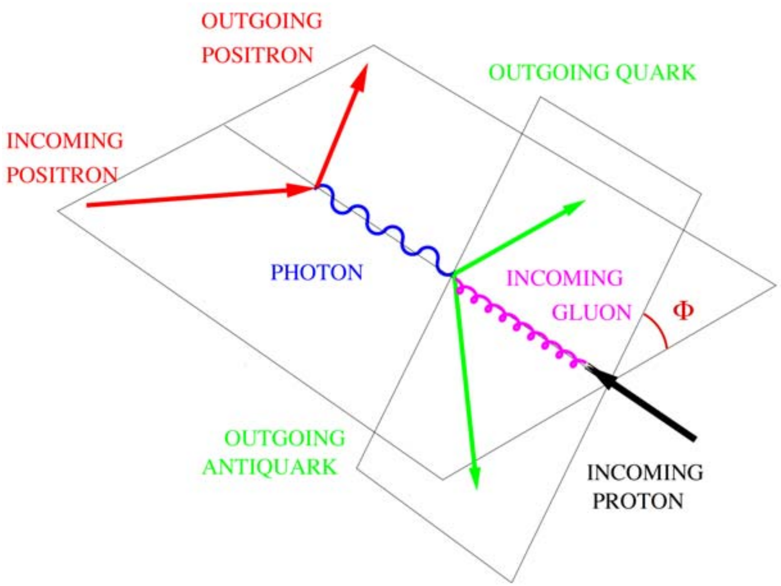
$E_t^{Breit} > 5$ GeV

$M^{Jets} > 25$ GeV

Cross section well described by NLO

Azimuthal Asymmetry of Jets

[A clean test of perturbative QCD]

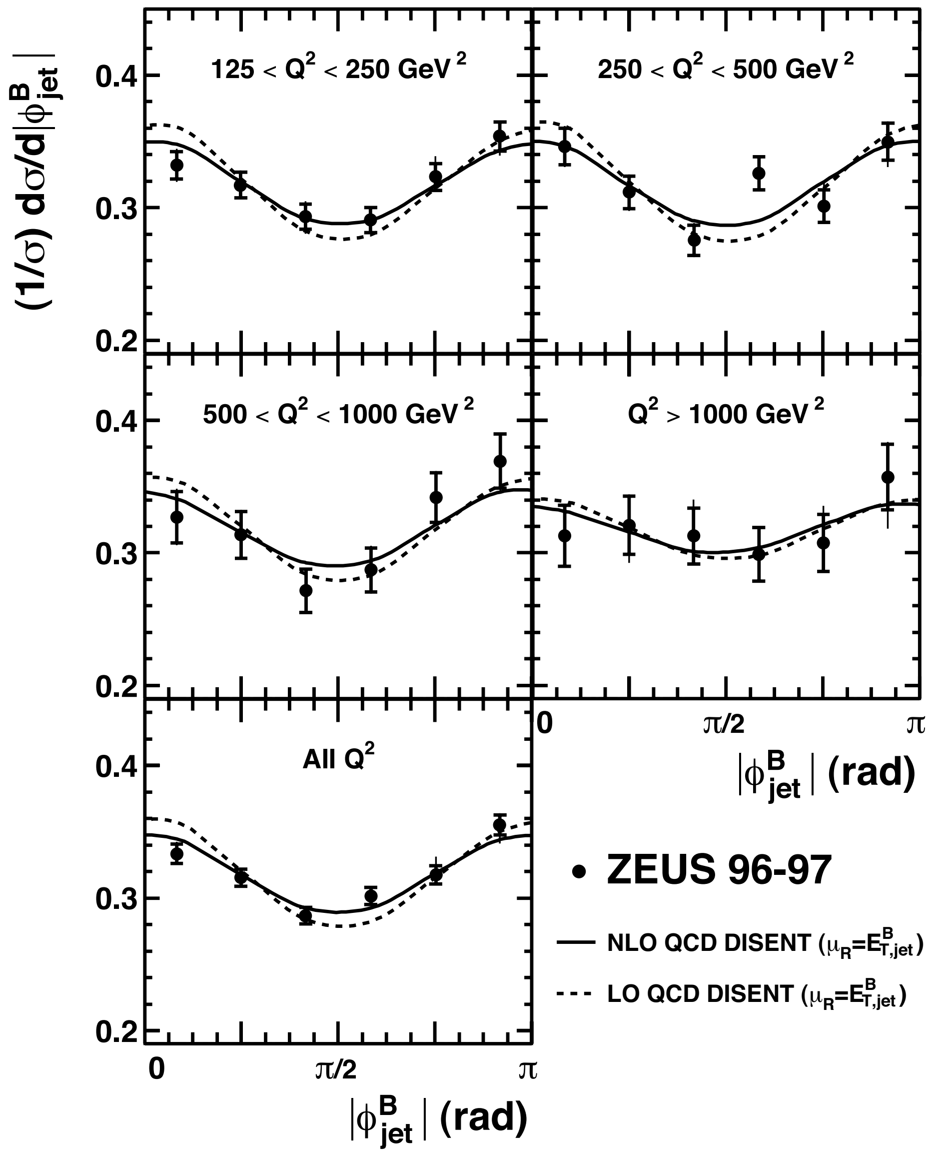


Inclusive jets:

$$\frac{d\sigma}{d\phi^B_{jet}} = A + C \cdot \cos(2\phi^B_{jet})$$

extra cosϕ term only if
q/g-jets are distinguished

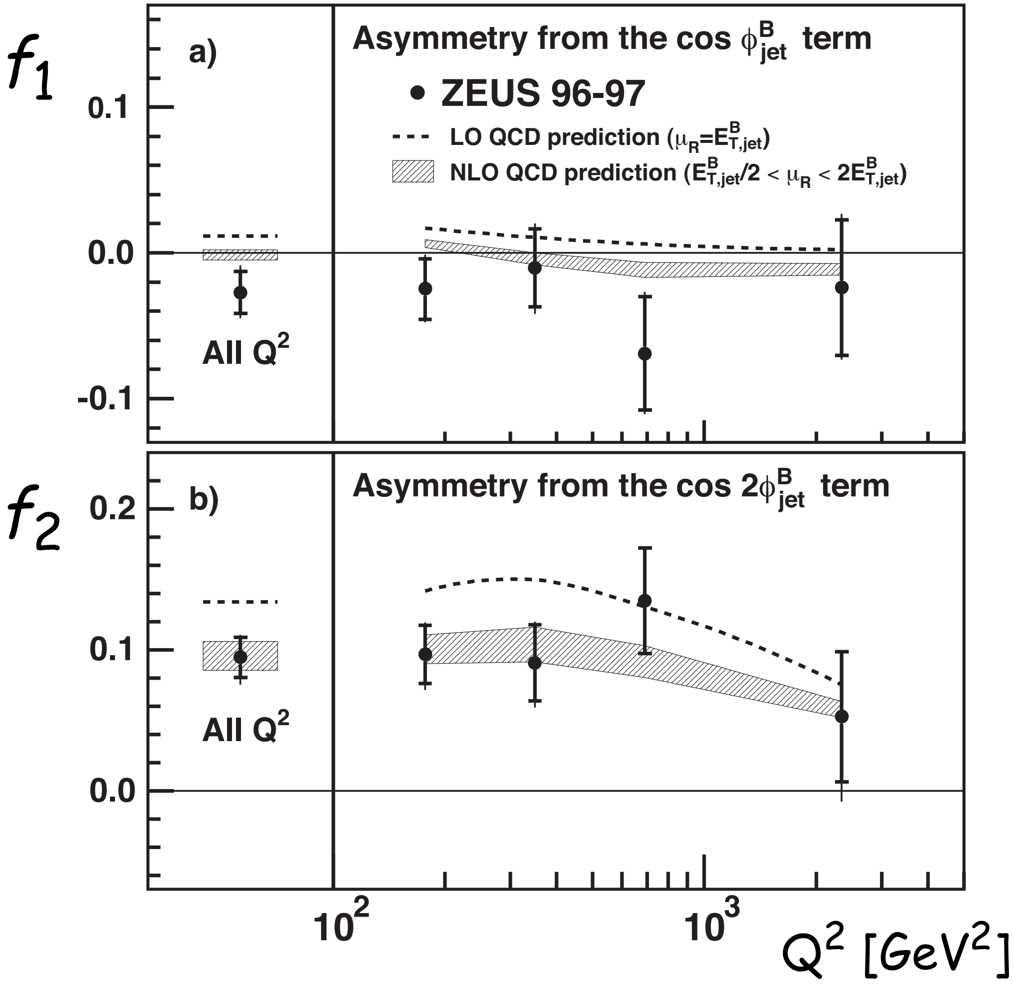
Asymmetry predicted
to decrease with rising Q^2



Q^2 Dependence

of azimuthal asymmetry of jets

$$\frac{1}{\sigma}\cdot\left[\frac{d\sigma}{d|\phi^B_{jet}|}\right] = \frac{1}{\pi}\left[1 + f_1\cos(\phi^B_{jet}) + f_2\cos(2\phi^B_{jet})\right]$$



$f_1 = -0.0273\,^{+0.0188}_{-0.0175}$ [Data]

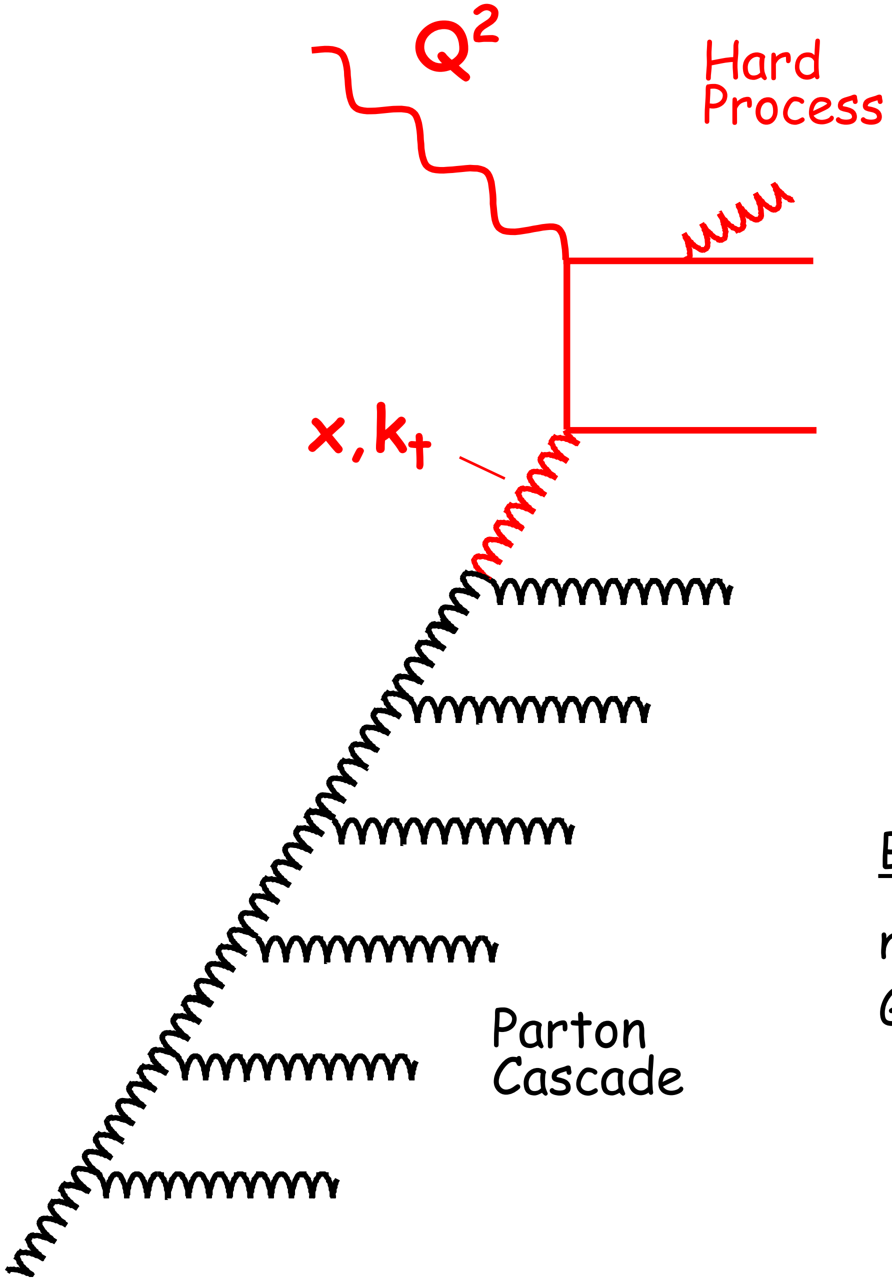
$f_1 = -0.0003\,^{+0.0025}_{-0.0044}$ [NLO]

$f_2 = +0.0947\,^{+0.0158}_{-0.0195}$ [Data]

$f_2 = +0.0984\,^{+0.0074}_{-0.0131}$ [NLO]

NLO pQCD calculation
in agreement with measurement

QCD Dynamics
at low x



DGLAP evolution:

k_t-ordering: $k_{t,1}^2 \ll \ldots \ll k_{t,n}^2 \ll Q^2$
Gluon density: $g(x,Q^2)$

$k_t \approx 0$

Correct?

BFKL, CCFM evolution:

non-k_t-ordering
Gluon density: $g(x,Q^2,k_t^2)$

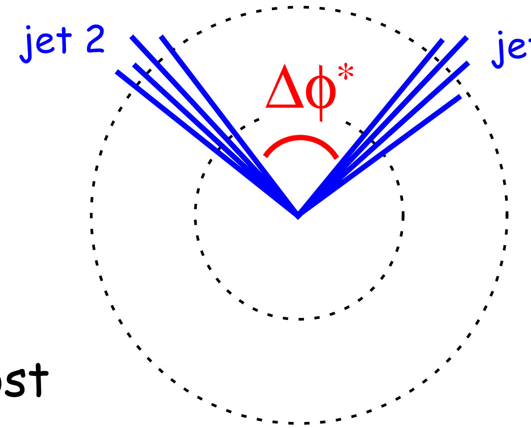
$k_t > 0$
possible.

Azimuthal Correlations

in inclusive dijet production

Inclusive
Dijet selection

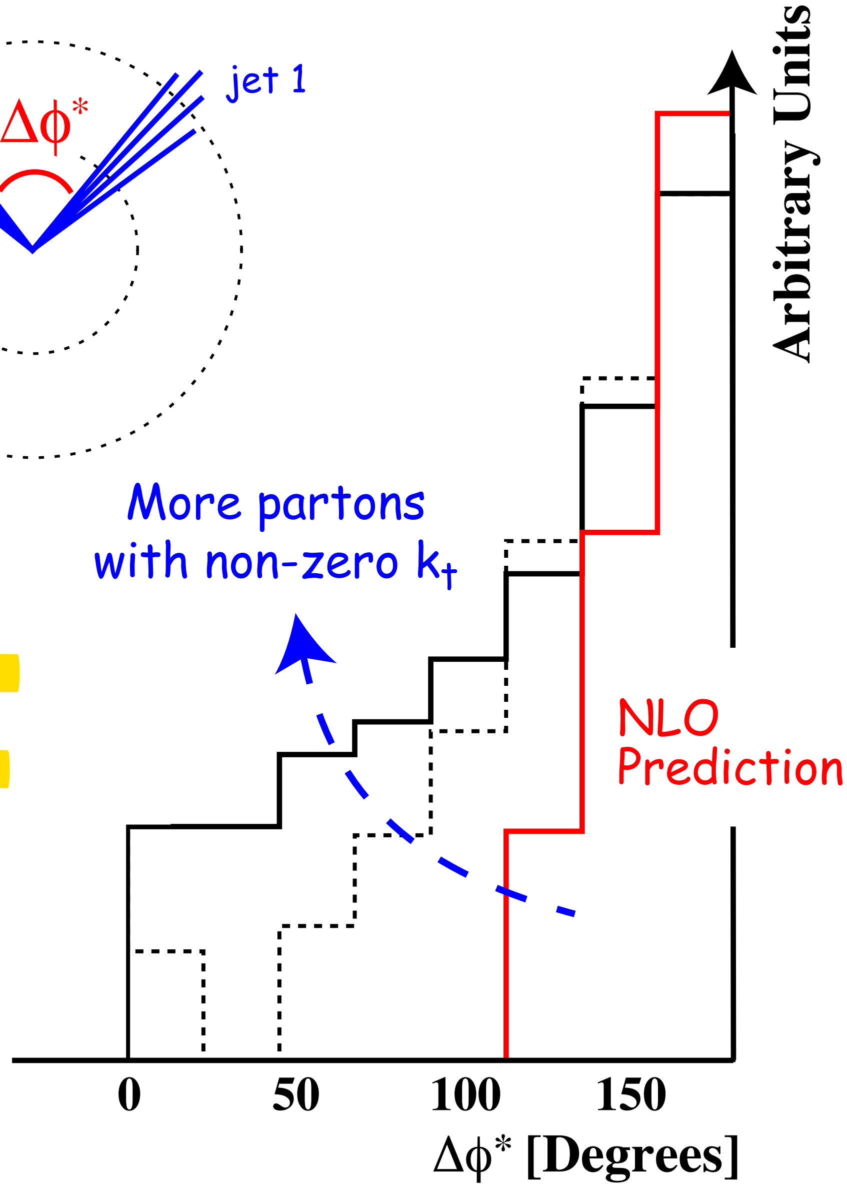
$\Delta\phi^* = \left\{ \begin{array}{l} \text{azimuthal angle} \\ \text{between two most} \\ \text{energetic jets} \end{array} \right.$



Study:

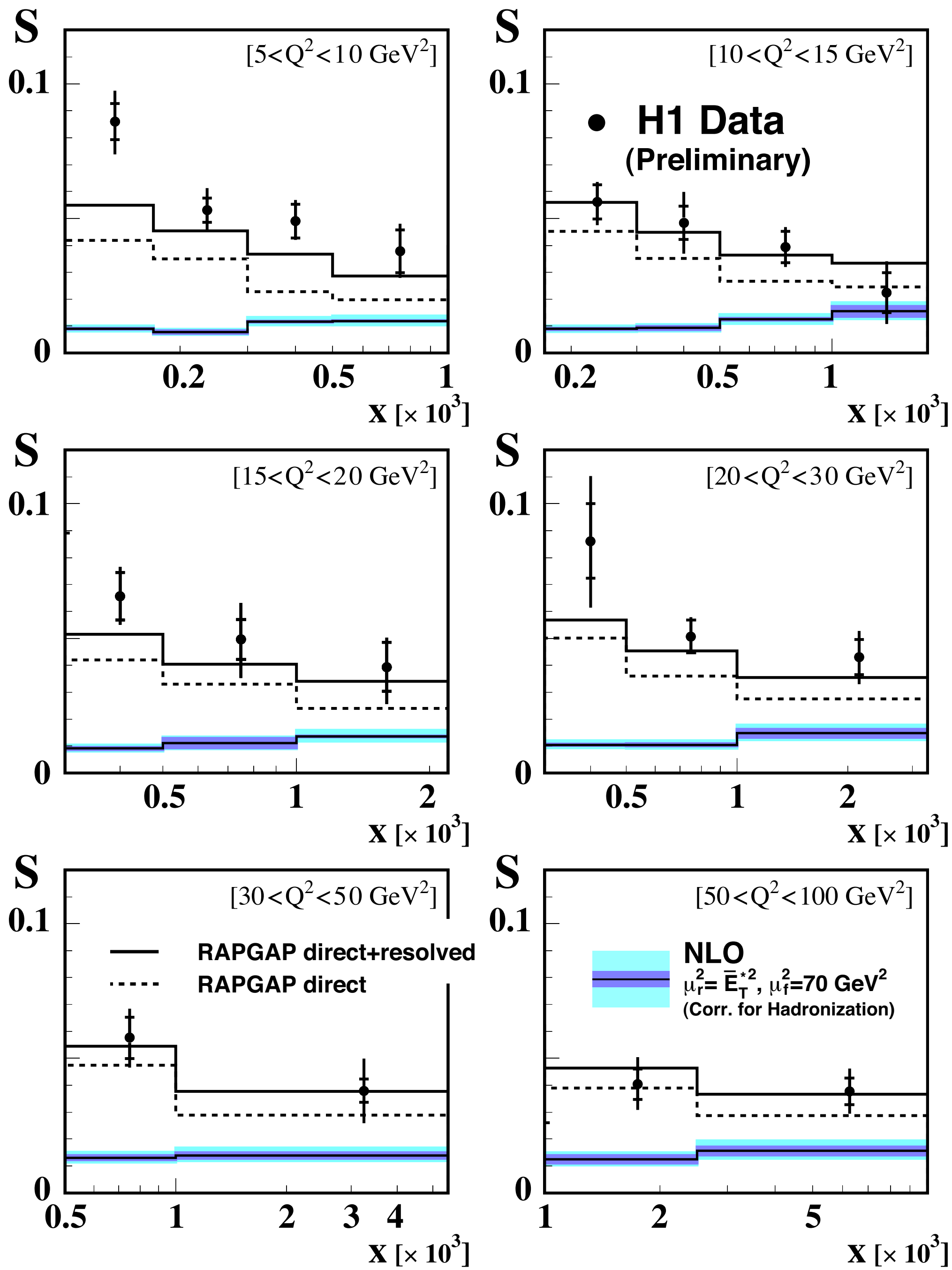
$$S = \frac{\text{dijet events with } \Delta\phi^* < 120^\circ}{\text{all dijet events}}$$

NLO: max. 3 jets
i.e. $\Delta\phi^* > 120^o \rightarrow S = 0.$

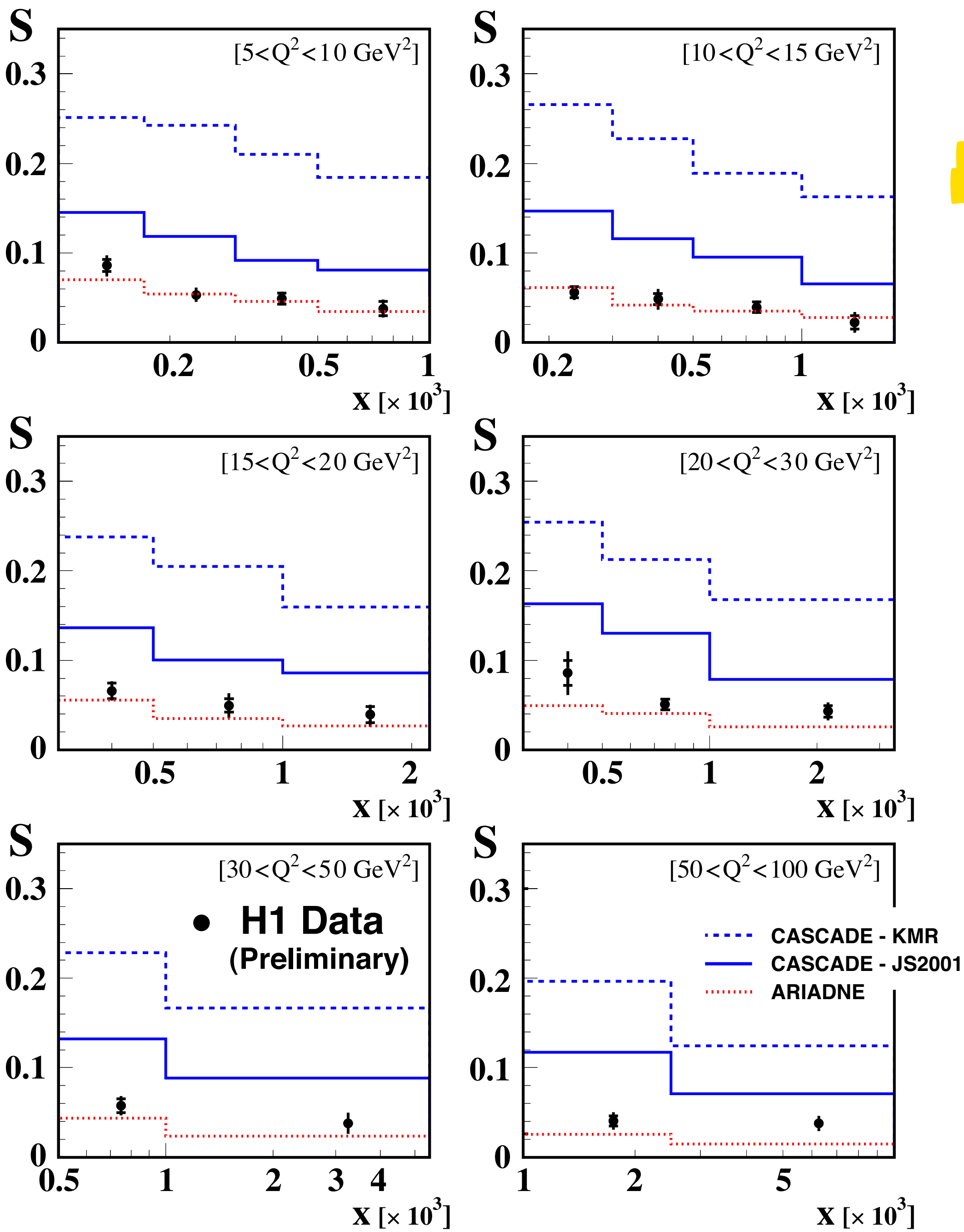


S-Distribution

[Comparison with NLO and RAPGAP]



- NLO fails to describe the S-distribution
  [as expected due to $\Delta\phi > 120°$]
- LO Monte Carlo [RAPGAP]
  [with k_t-ordered parton emission]
  - direct only: fails
  - dir. + res.: fails at small x
- Substantial contribution from partons/gluons with non-zero k_t



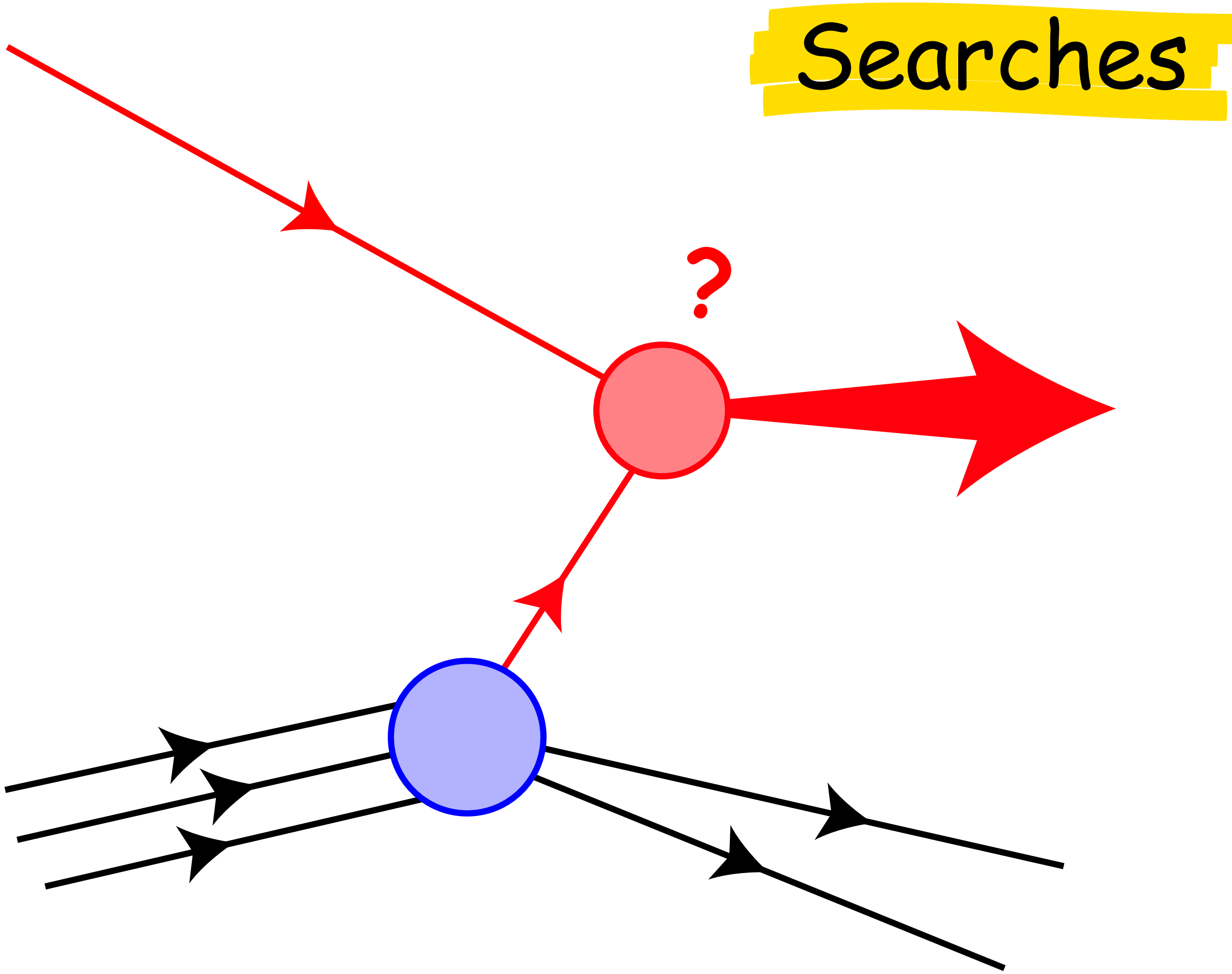
S-Distribution

[Comparison with ARIADNE and CCFM]

- Best description of S-distribution by ARIADNE
  [non-k_t-order parton emission (CDM)]
- CASCADE Monte Carlo
  [incorporates CCFM evolution equations]

  Fails for both avail. sets of unintegr. gluon distributions
  [difference: hardness of k_t-spectrum]

  Measurement provides
- Constraints on unintegrated gluon density


Searches
?

Searches at HERA

Contact Interactions

Large Extra Dimensions

Compositeness

Excited Fermions

R_p-violating SUSY

Magnetic Monopoles

Odderons

Instantons

Leptoquarks

Lepton Flavour Violation

Isolated High P_t Leptons

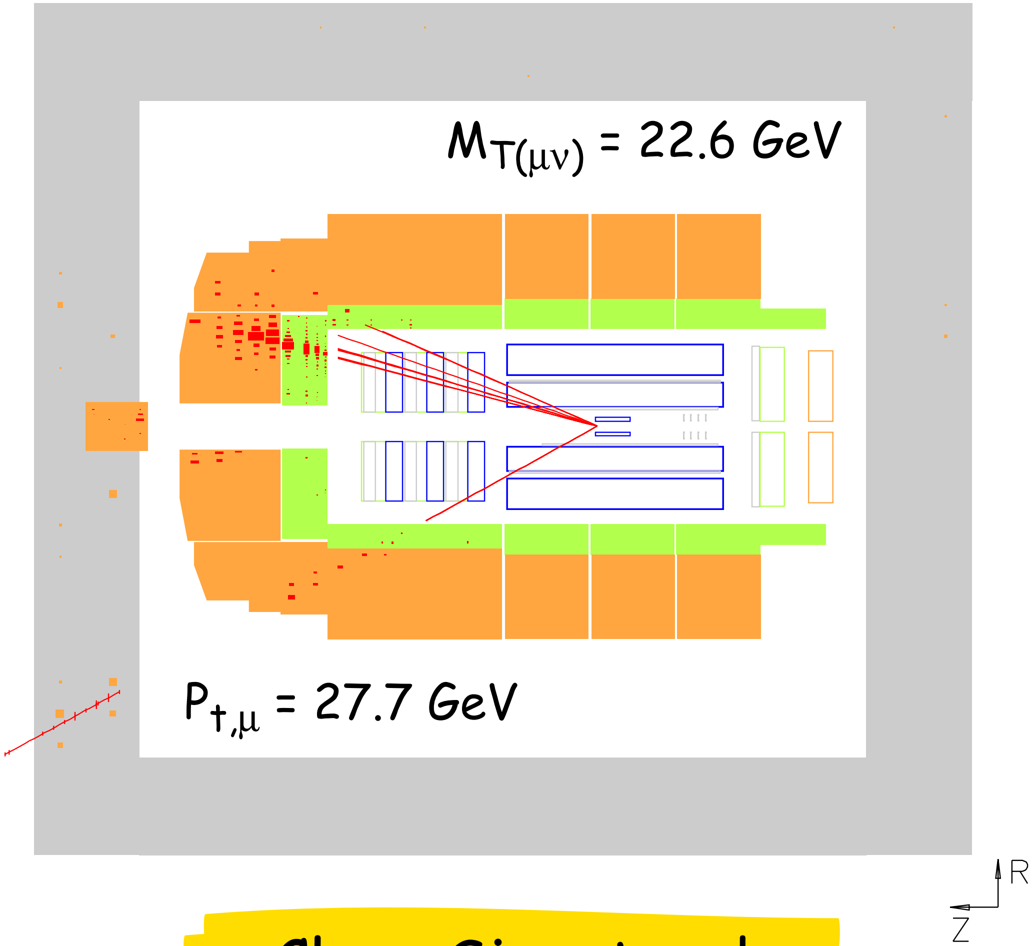
Multi-Lepton Events

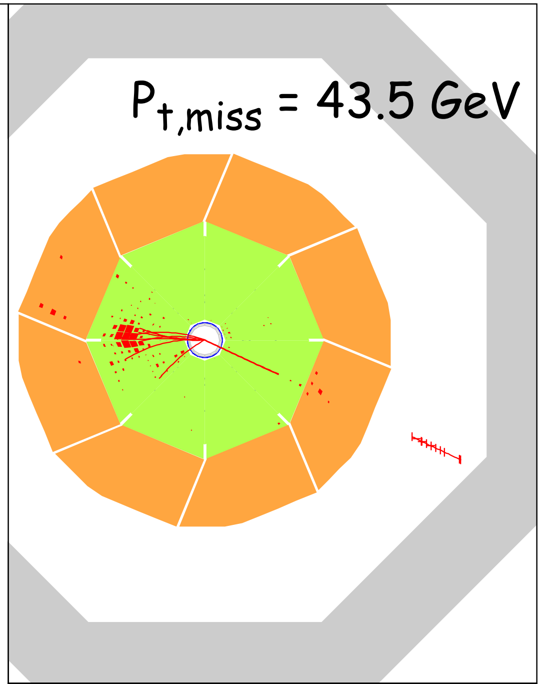
Single Top Production

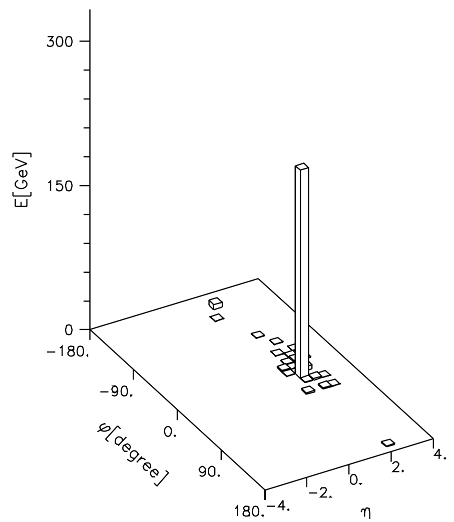
Flavour Changing NC

Many limits — Excess seen in two areas

High P_t Leptons
with missing Transverse Momentum

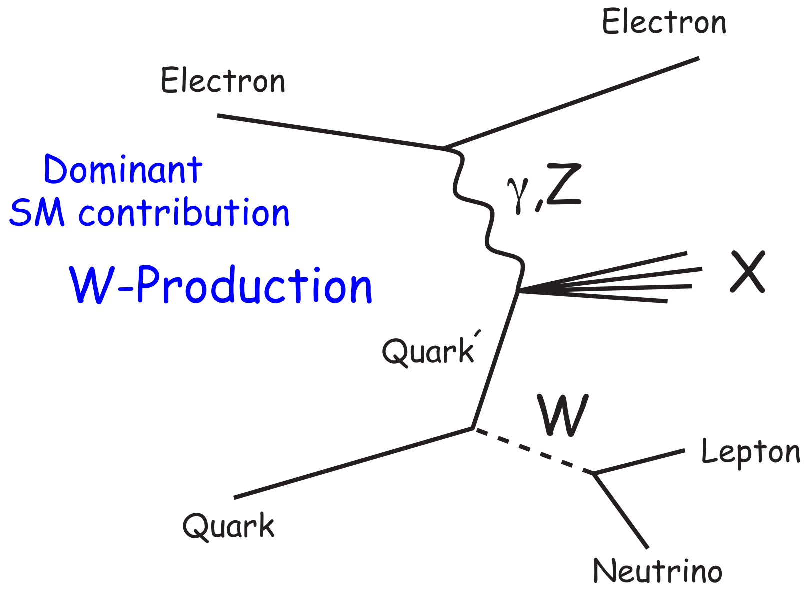




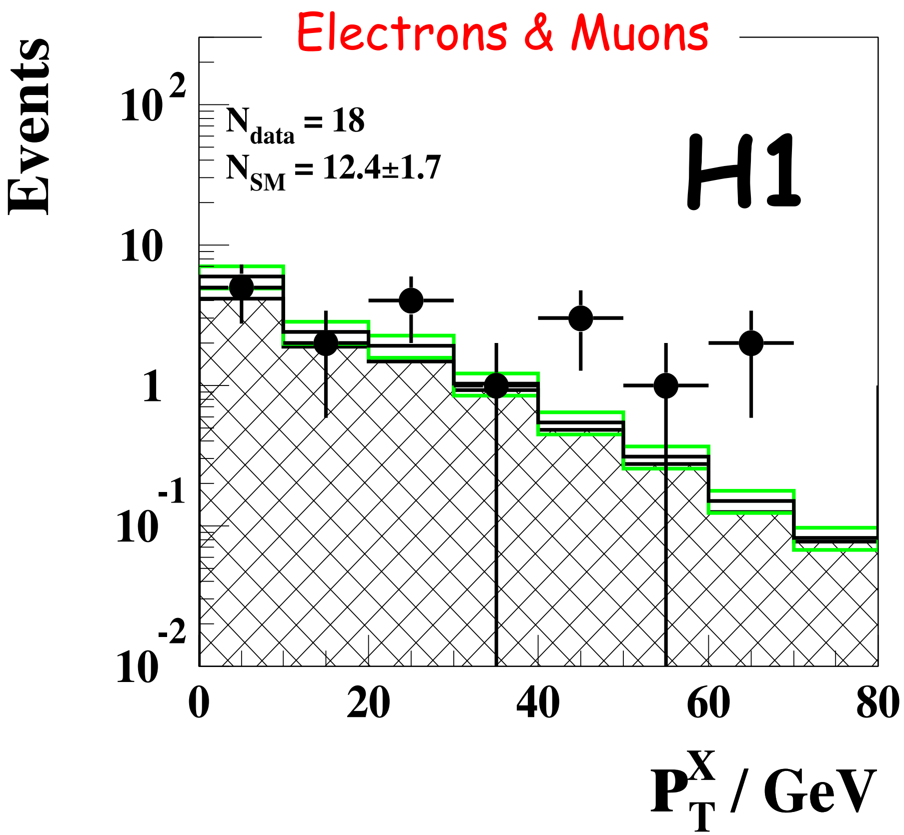


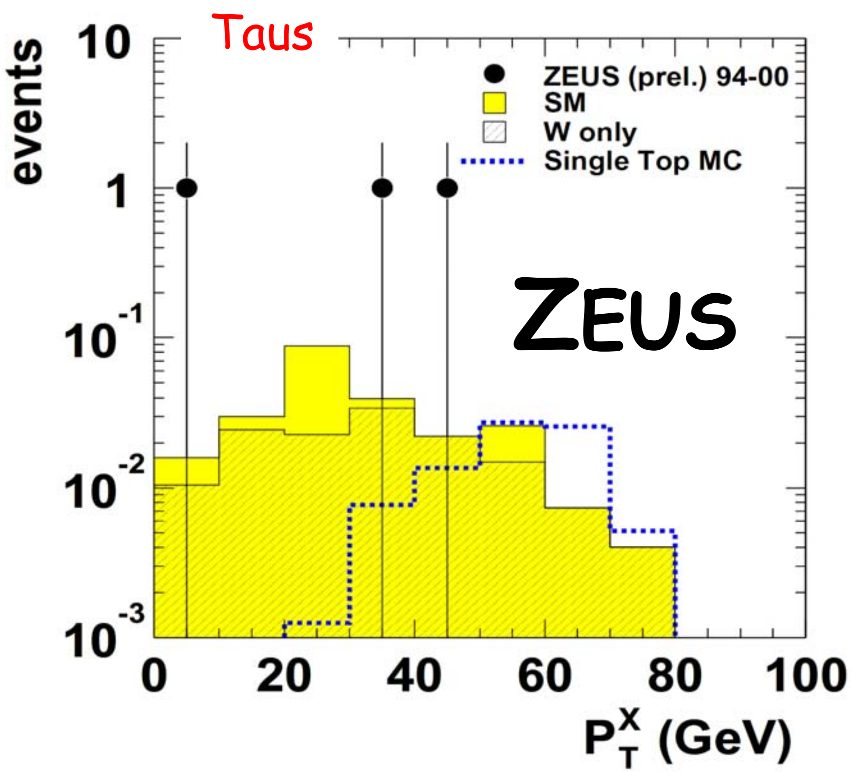
Clear Signature!

P_t^X Distributions of high P_t Lepton



H1: Excess in e/μ-channel
ZEUS: Excess in τ-channel





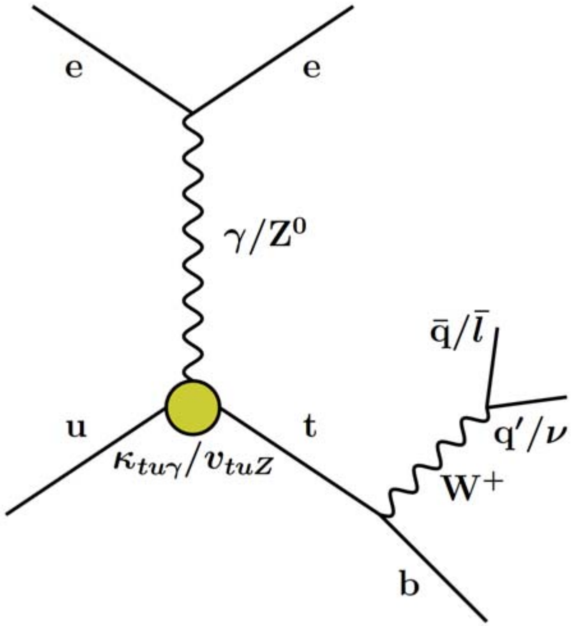
High P_t Leptons at High P_t^X

Data/Expectation comparison

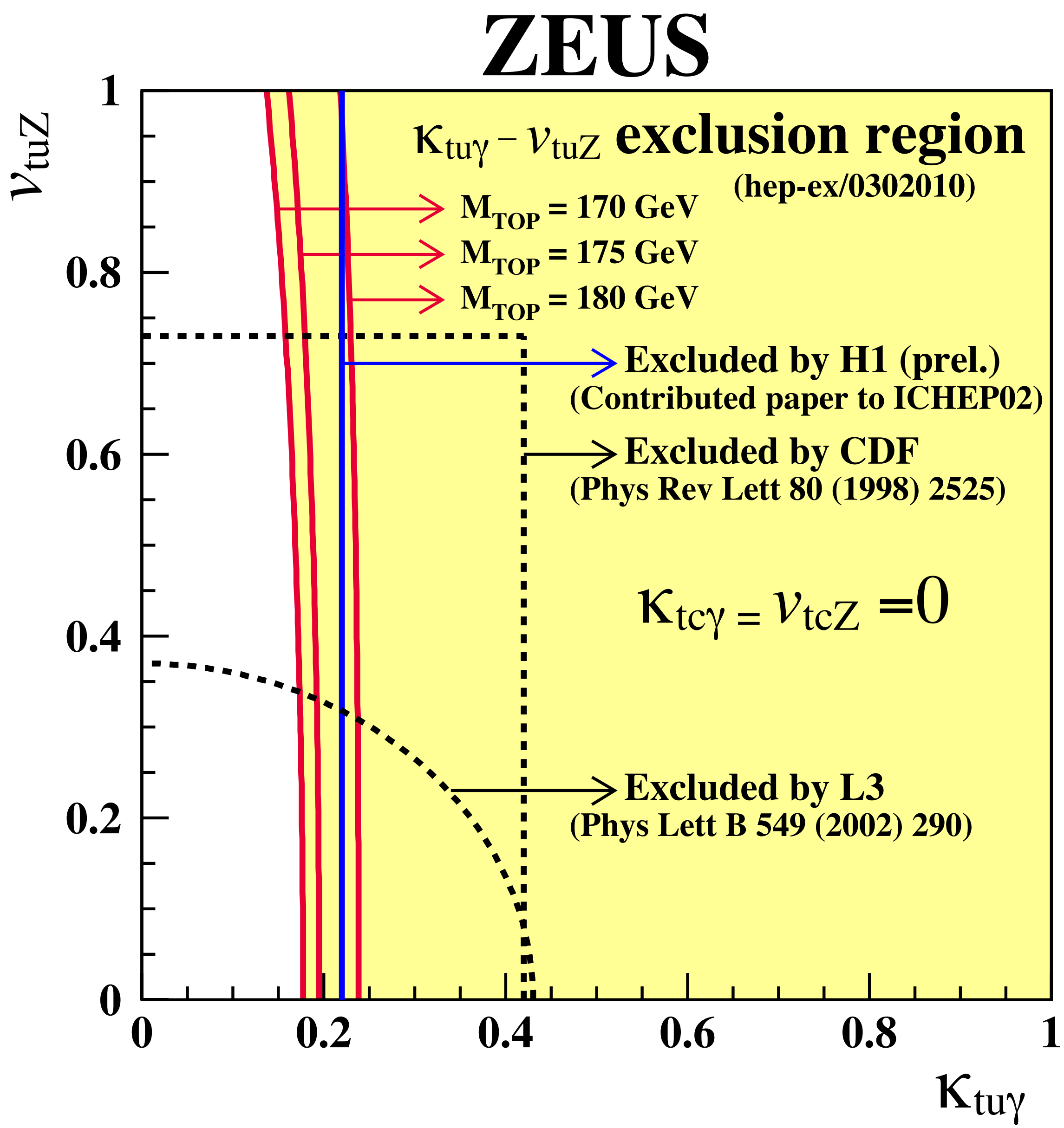
H1 94-00 e^+p (104.7 pb^{-1})	Electrons obs/exp. (W)	Muons obs/exp. (W)	Taus obs/exp. (W)
$25 < P_T^X < 40$ GeV	1 / 0.94 ± 0.14 (0.82)	3 / 0.89 ± 0.14 (0.77)	—
$P_T^X > 40$ GeV	3 / 0.54 ± 0.11 (0.45)	3 / 0.55 ± 0.12 (0.51)	—

ZEUS 94-00 $e^{\pm}p$ (130.1 pb^{-1})	Electrons obs/exp. (W)	Muons obs/exp. (W)	Taus obs/exp. (W)
$P_T^X > 25$ GeV	$2 / 2.90^{+0.59}_{-0.32}$ (45%)	$5 / 2.75^{+0.21}_{-0.21}$ (50%)	$2 / 0.12^{+0.02}_{-0.02}$ (83%)
$P_T^X > 40$ GeV	$0 / 0.94^{+0.11}_{-0.10}$ (61%)	$0 / 0.95^{+0.14}_{-0.10}$ (61%)	$1 / 0.06^{+0.01}_{-0.01}$ (83%)

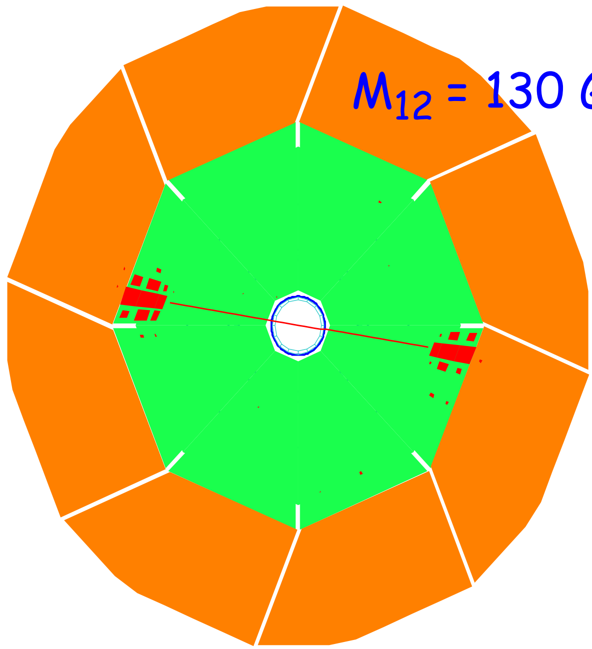
Anomalous Top Production in FCNC



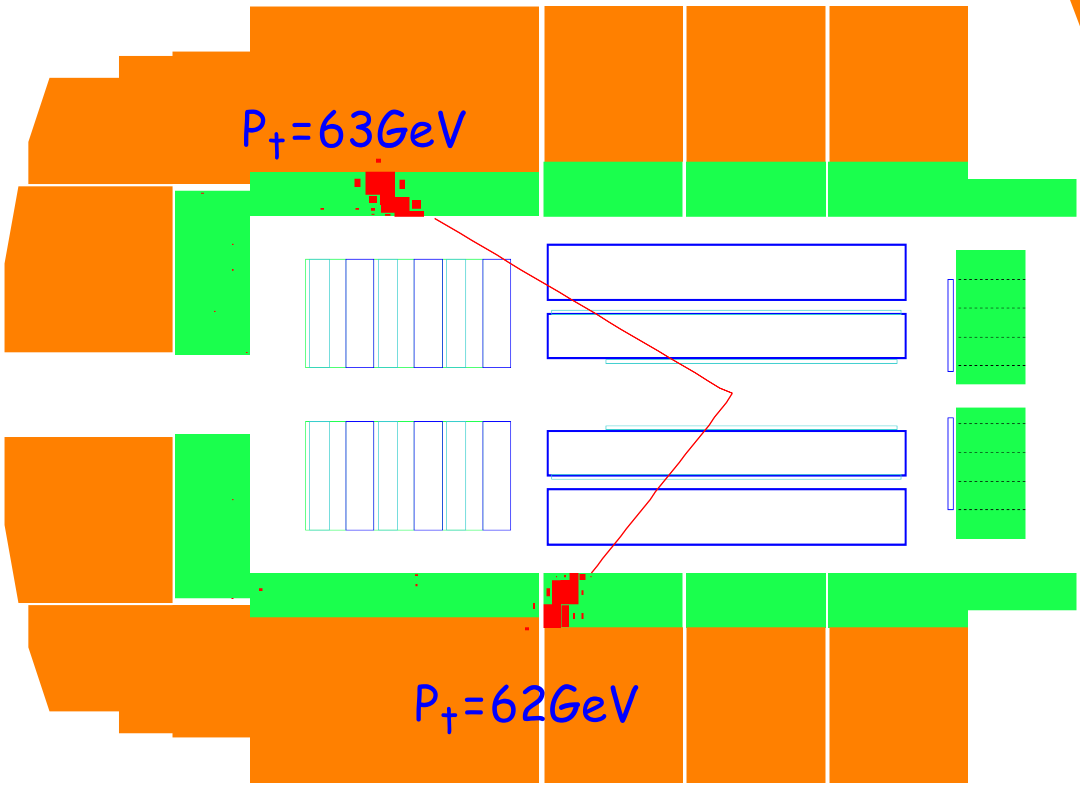
- HERA
  $e^+p \longrightarrow etX$
  [very sensitive to $\kappa_{tu\gamma}$]
- LEP
  $e^+e^- \longrightarrow tu$
- TEVATRON
  top decay $\longrightarrow \gamma q, Zq$



Multi-Electron Production



Multi-Electron Event

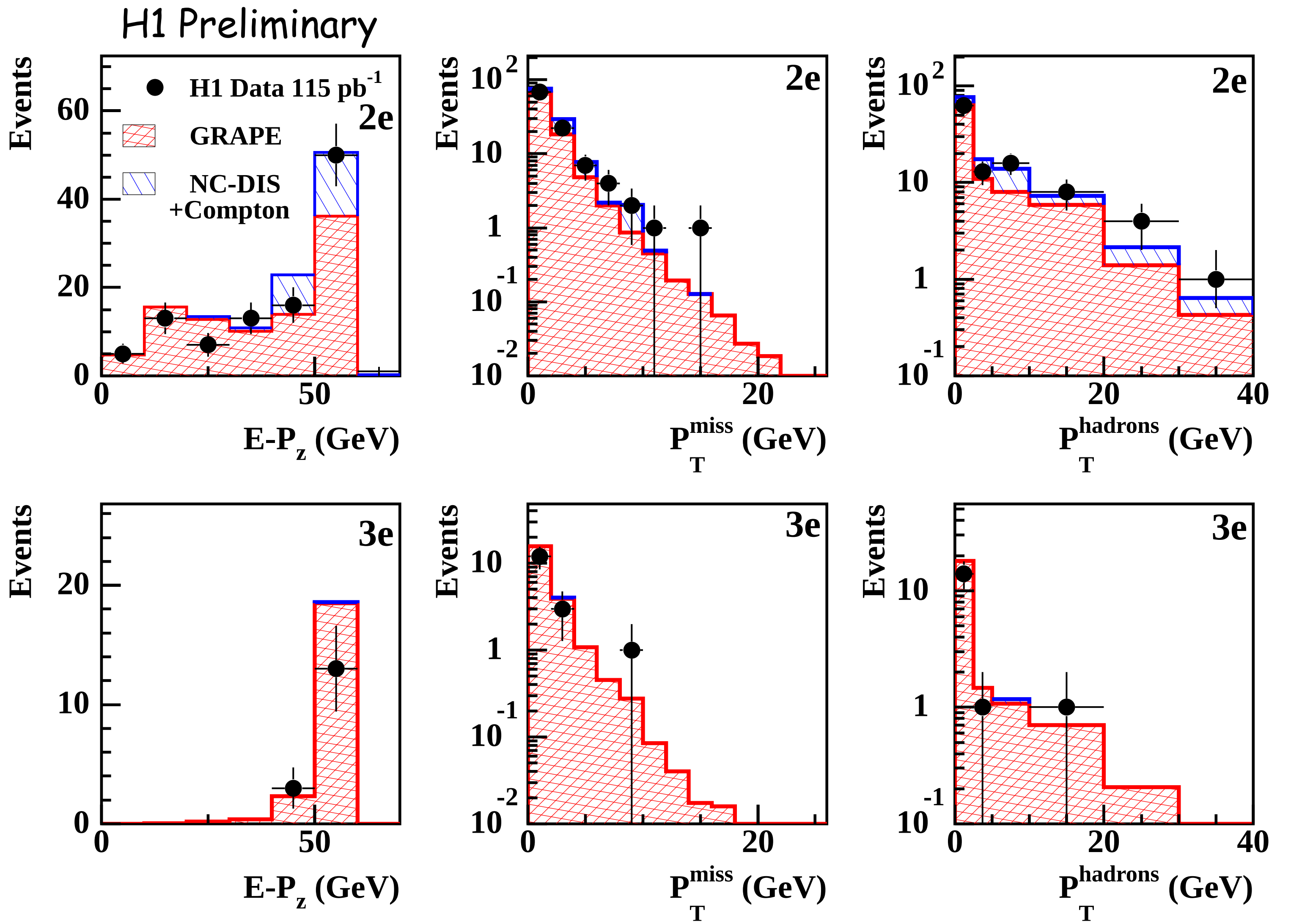


Selection:

- 2 electrons with $P_t^{1(2)} > 10$ GeV (5 GeV)
  [with $20^o < \theta < 150^o$]
- 3rd electron (if any) with $E_3 > 5$ GeV (10 GeV)
  [with $5^o < \theta < 175^o$]

Observation of 6 events with $M_{12} > 100$ GeV

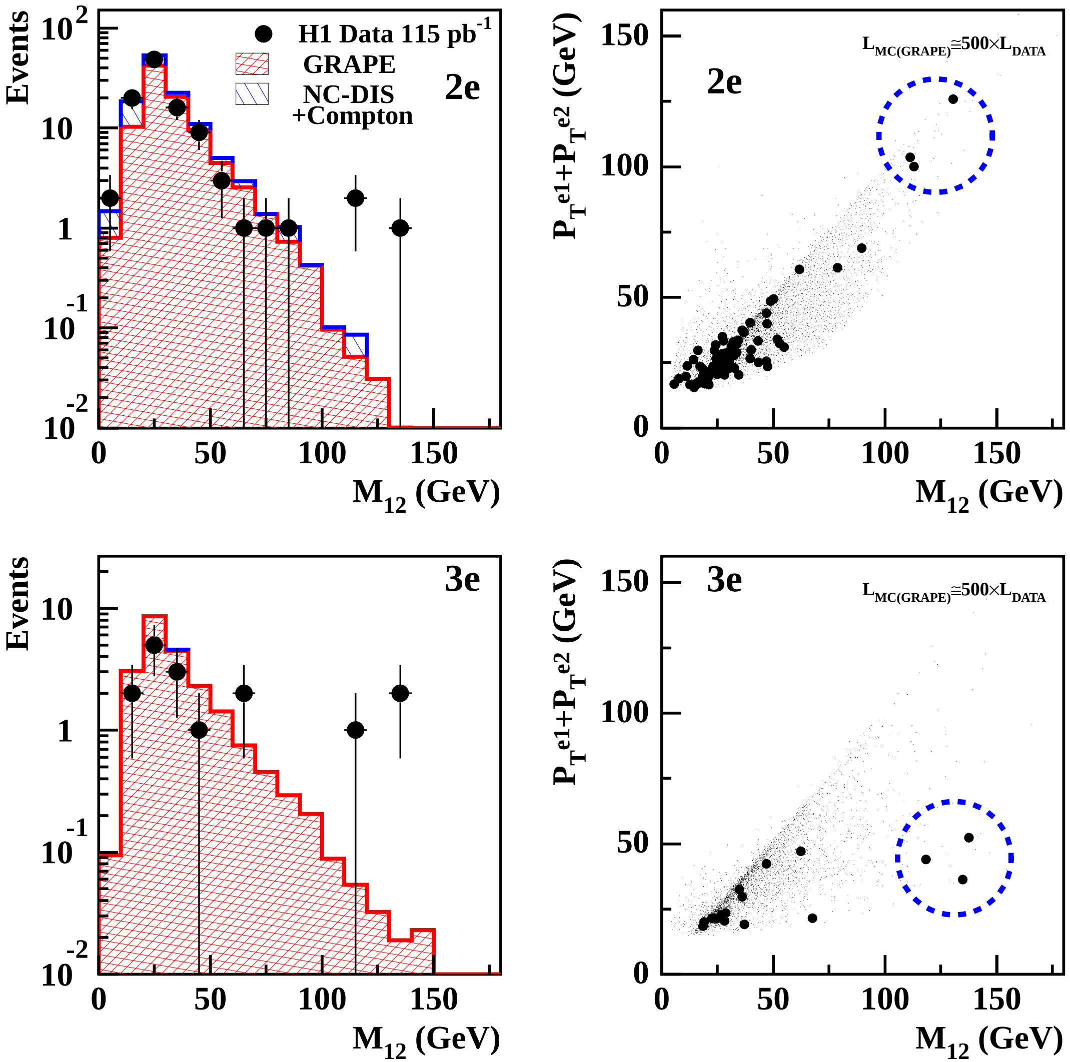
Multi-Electron Analysis



Good overall description of data by MC prediction

Multi-Electron Analysis

H1 Preliminary



$M_{12} > 100$ GeV H1 Prel.

	Data	SM
2e	3	0.25±0.05
3e	3	0.23±0.04

Excess @ high M_{ee}>100 GeV

$M_{12} > 100$ GeV ZEUS Prel.

	Data	SM
2e	2	0.77±0.08
3e	0	0.37±0.04

Needs confirmation with HERA II data

Summary

Proton Structure

Improved precision — F_2 error ~2-3% (bulk)
PDF extraction — extraction of xF_3
F_L measurements provide important QCD test.

QCD Tests and α_s-Measurements

α_s results competative — NNLO DIS promises world beating α_s
pQCD tests using azimuthal jet asymmetries

QCD Dynamics

Study of azimuthal jet separation
provides constraint on unintegrated gluon distributions

Searches at HERA

Excess seen for: Isolated leptons, multi-leptons