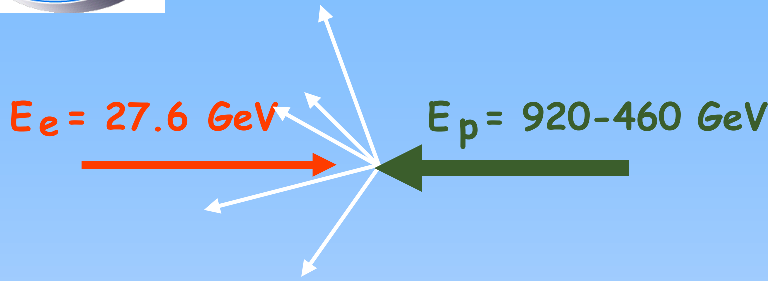
XX^th International Workshop on Deep-Inelastic Scattering and Related Subjects

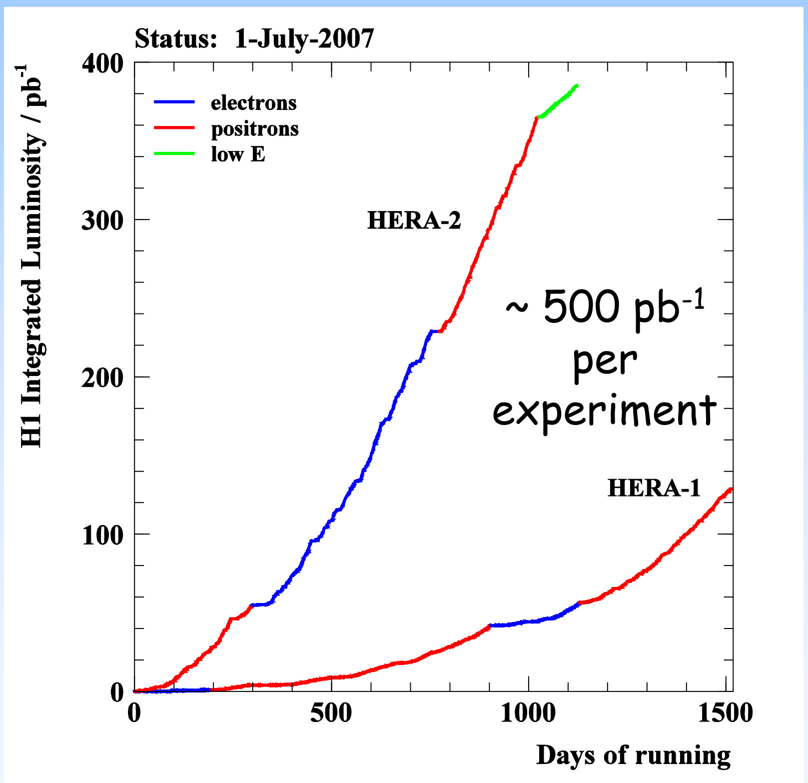
Precision QCD Measurements at HERA

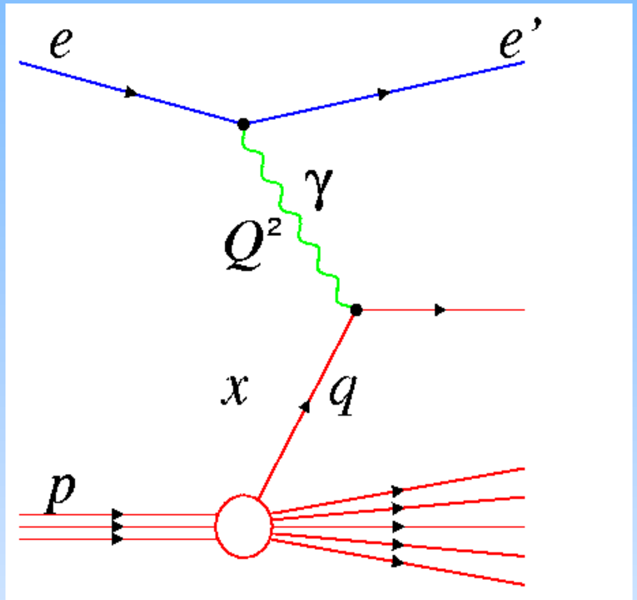
Karin Daum -Wuppertal/DESY
on behalf of the H1 and ZEUS collaborations

New Physics
Diffraction
Jets
Heavy Flavour
Hadronic Final States

ep-scattering at HERA







$Q^2=-q^2$ photon virtuality

$x=x_{BJ}$ Bjorken scaling variable

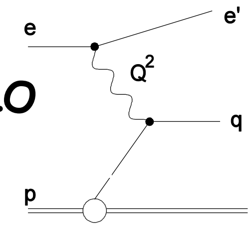
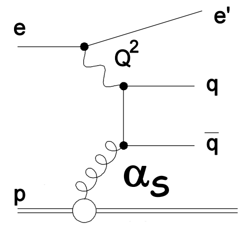
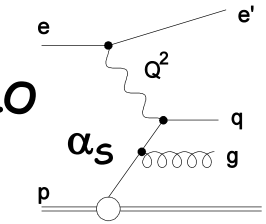
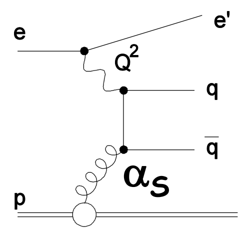
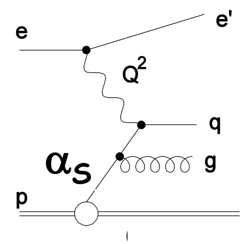
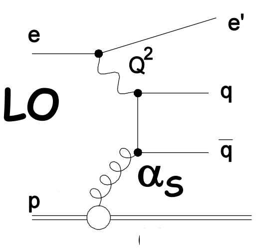
y Inelasticity in proton rest frame

2 kinematic regimes :

$Q^2 \cong 0$ GeV^2 : **Photoproduction (γp)**

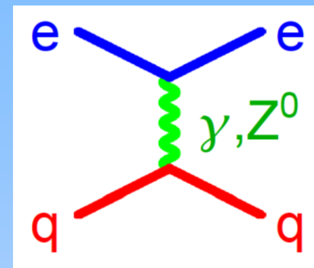
$Q^2 > 1$ GeV^2 : **DIS**

Interaction matrix @ HERA

DIS	LO 		NLO 	NNLO…
jets			LO 	NLO…
charm beauty		LO 		NLO…
	quarks	**gluon**	**quarks**	

Reduced DIS NC cross section

Neutral current

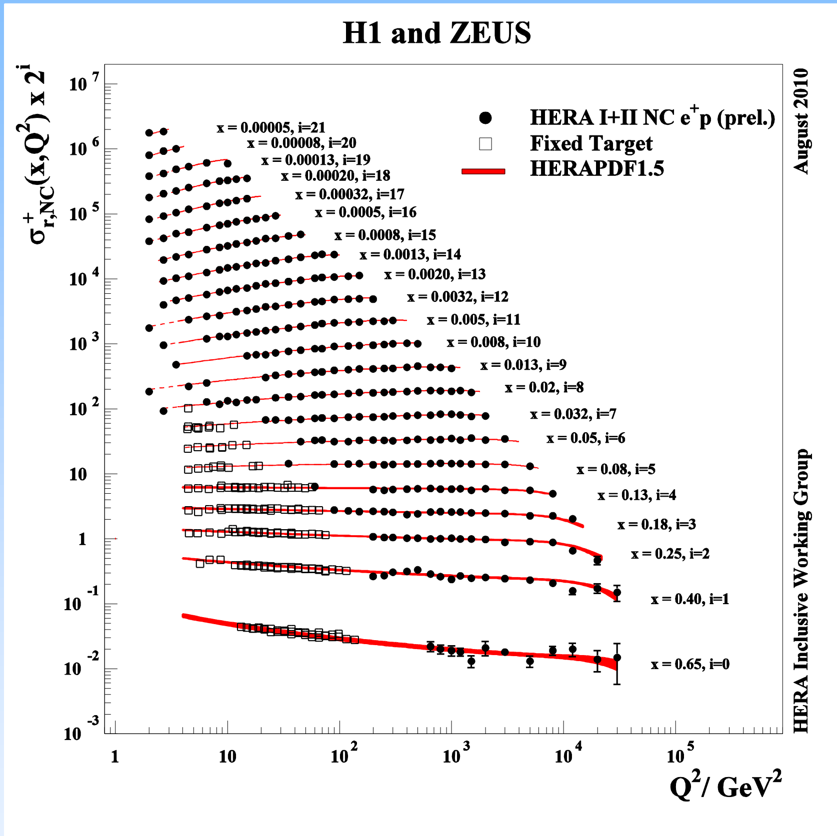


$$\sigma_{NC}^{red}(e^{\pm}p) = \frac{xQ^4}{2\pi\alpha_{em}Y_+}\frac{\mathrm{d}^2\sigma_{NC}}{\mathrm{d}x\mathrm{d}Q^2} = \tilde{F}_2 \mp \frac{Y_-}{Y_+}x\tilde{F}_3 - \frac{y^2}{Y_+}\tilde{F}_L$$

- $\tilde{F}_2$: valence + sea quarks dominant
- $x\tilde{F}_3$: valence quarks high Q^2
- $\tilde{F}_L$: gluons high y

$$Y_{\pm} = 1 \pm \left(1 - y^2\right)$$

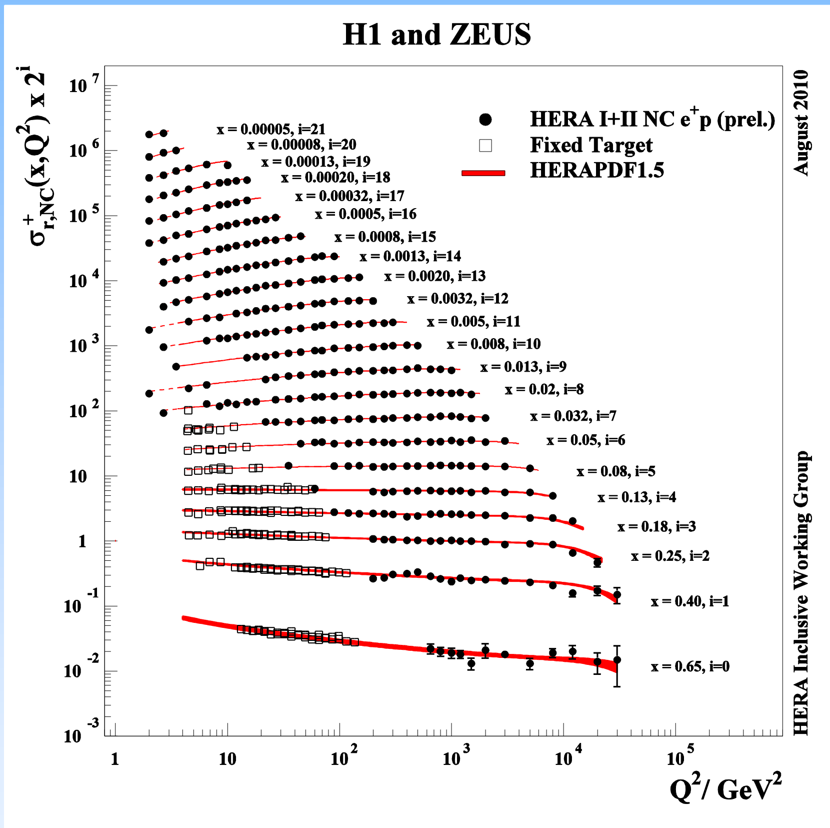
Reduced DIS NC cross section

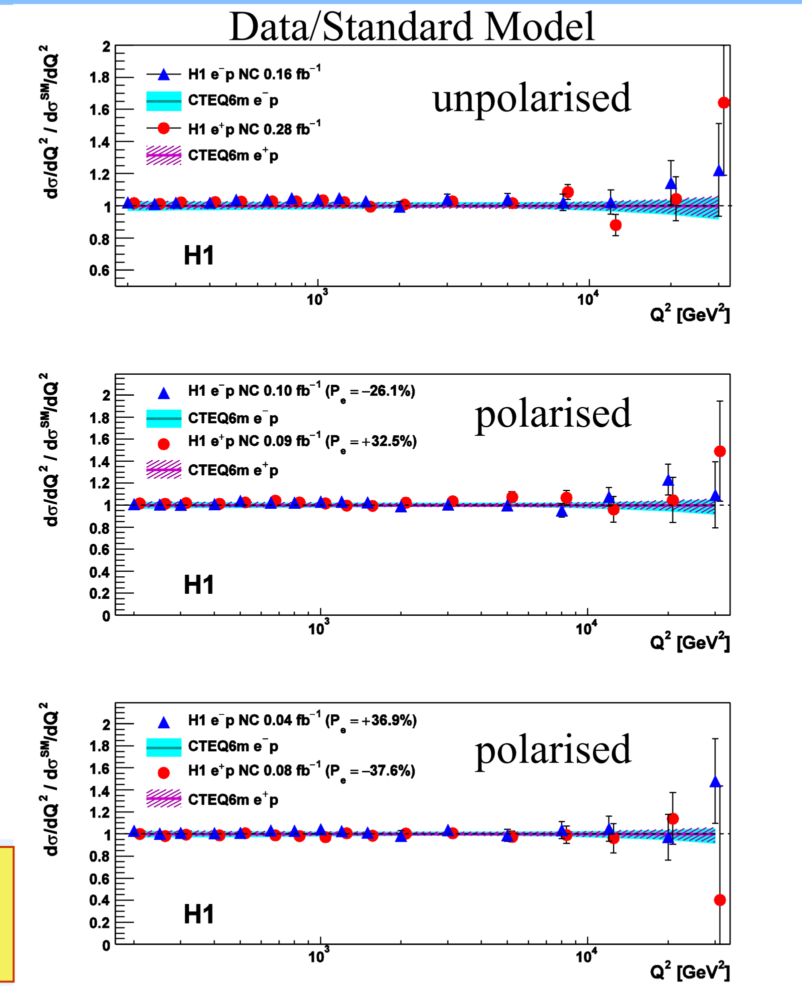


Data well described by NLO QCD over 4 orders of magnitude in x, Q^2

Search for new physics

DESY-11-114



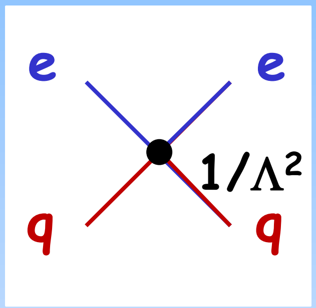


Data well described by NLO QCD at high Q^2 $\Rightarrow$ limits on new physics

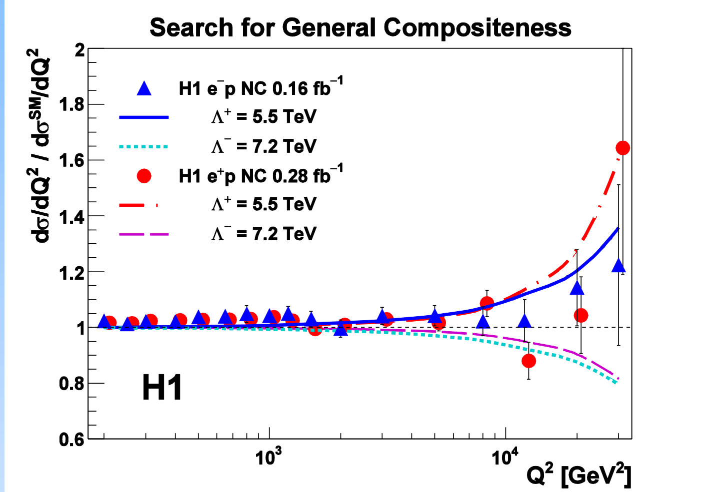
Contact interactions

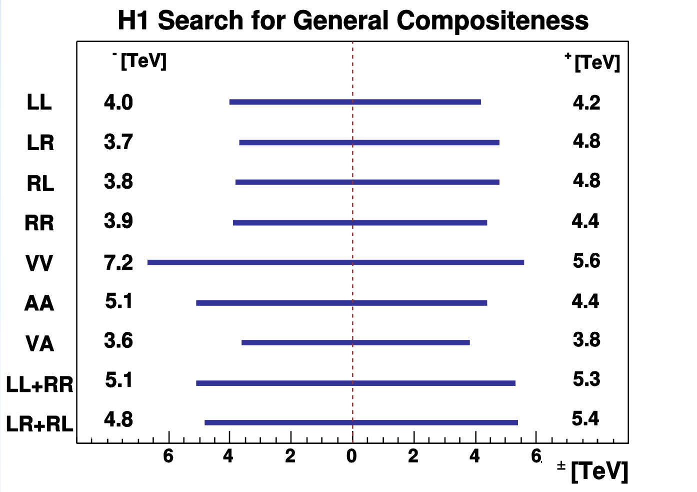
H. Pirumov DESY-11-114

New physics with scale $\Lambda >> Q^2$



- Compositeness
- Leptoquarks
- Extra dimension
- Quark radius

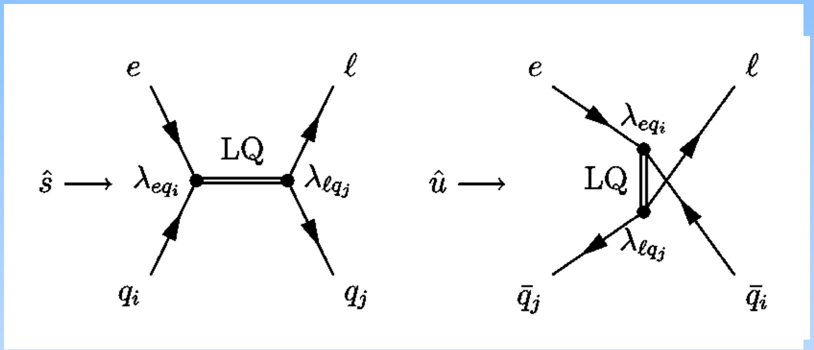


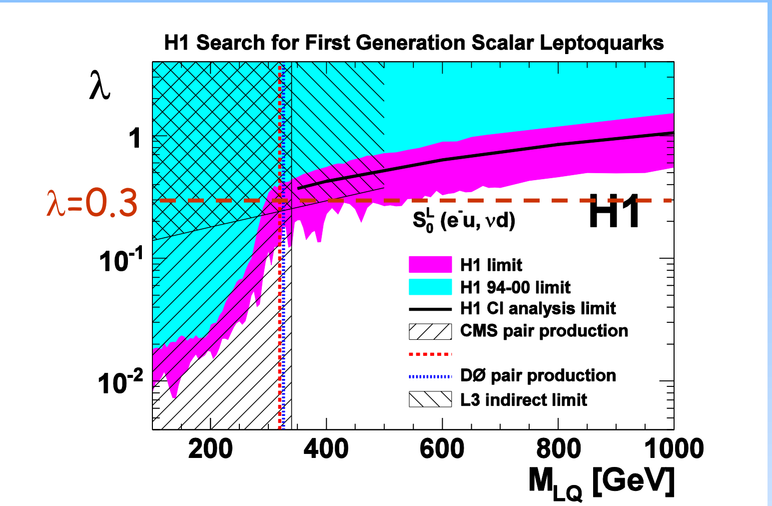


Limits on compositeness scale up to 7.2 TeV

1^{st} generation leptoquarks

DESY-11-123 H. Pirumov, S. Antonelli ZEUS-prel-11-000

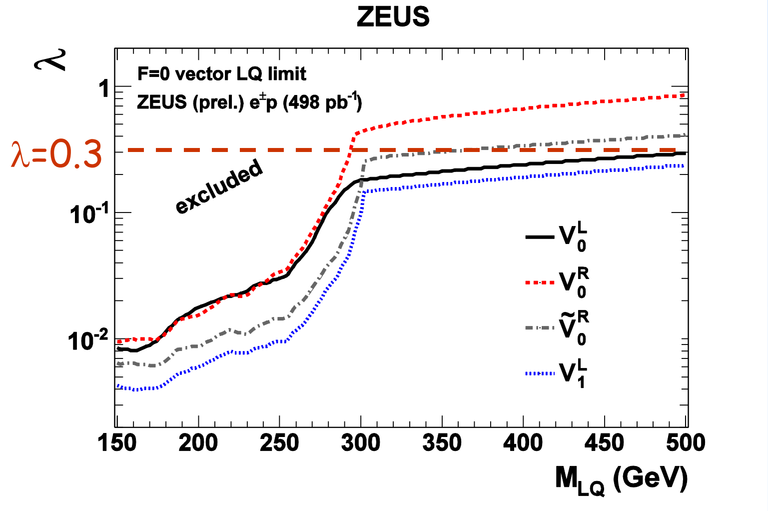




LQ-limits in the BRW model:

[GeV]	H1	ZEUS
Vector (λ=0.3)	800	629
Scalar (λ=0.3)	530	466

scalar LQ limit from ATLAS 607 GeV
No vector LQ limits from LHC so far

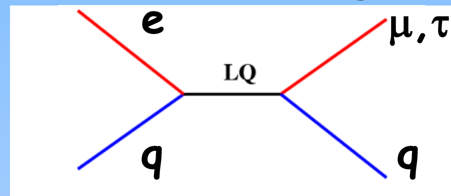


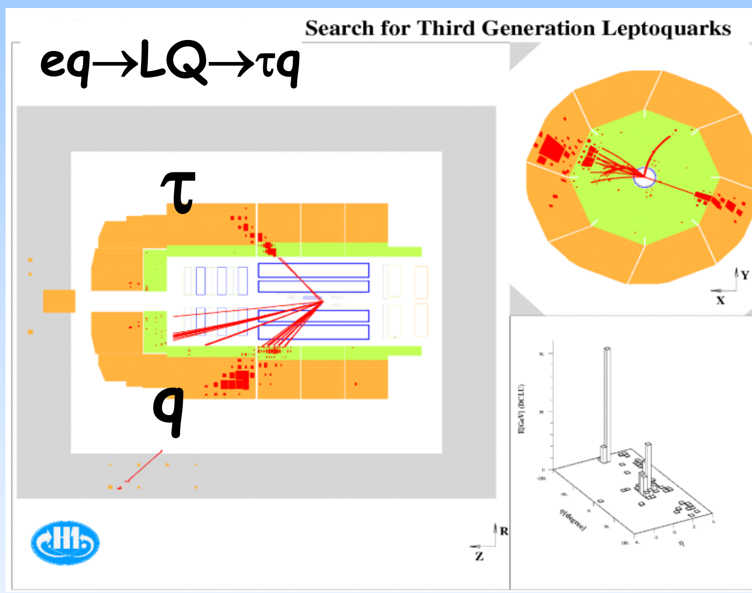
LFV leptoquarks

H. Pirumov
DESY-11-044

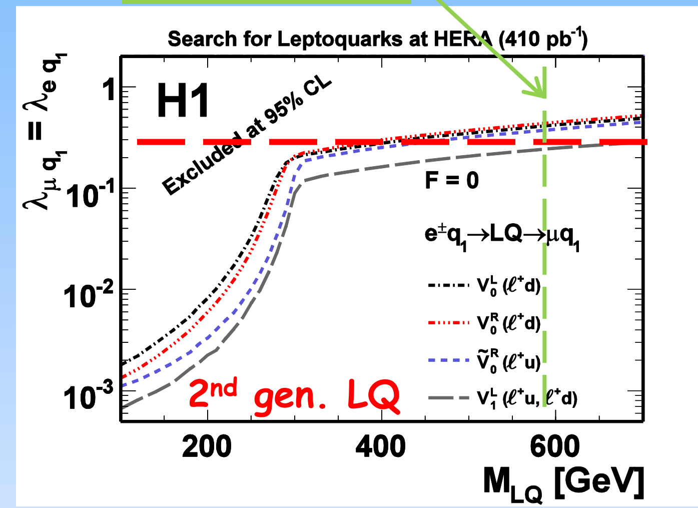
Interaction of lepton flavour violating leptoquarks:

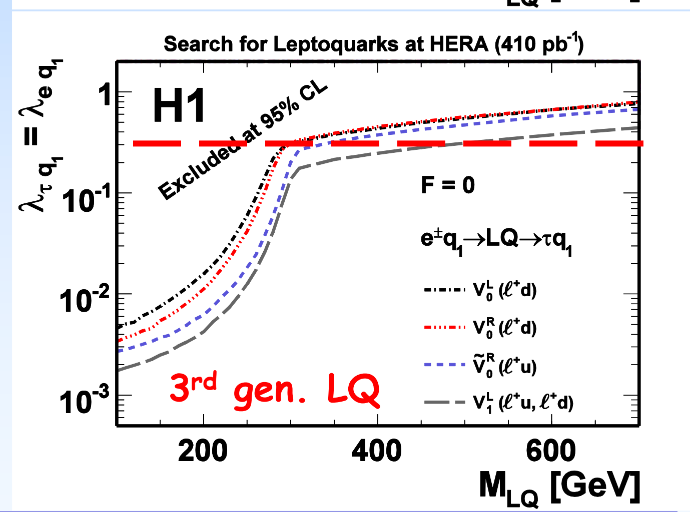
$eq \rightarrow LQ \rightarrow \mu(\tau)q$





Limit from Atlas





Mass limits (λ=0.3) ranges up to
712 GeV (2nd generation LQ)
479 GeV (3rd generation LQ)

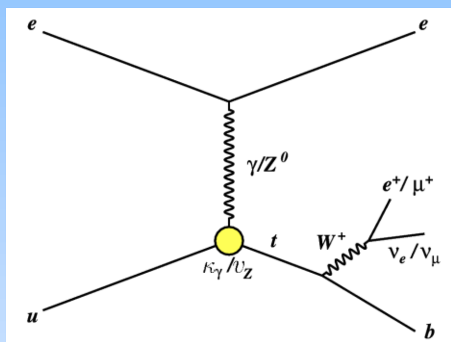
Single top production

S. Antonelli

DESY-11-114

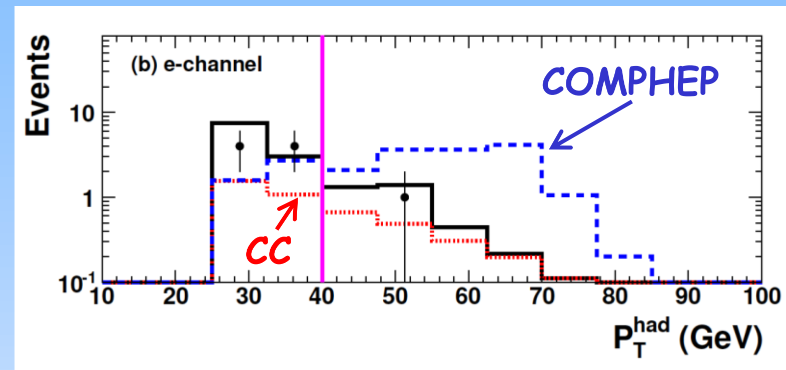
SM (CC) : ep → νtX

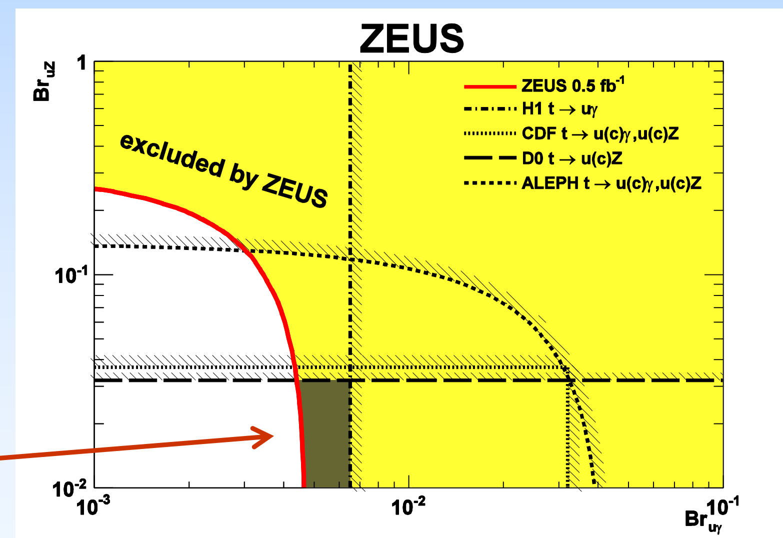
↳$\nu(\mu)\nu$b



FCNC: ep → etX

↳e(μ)νb

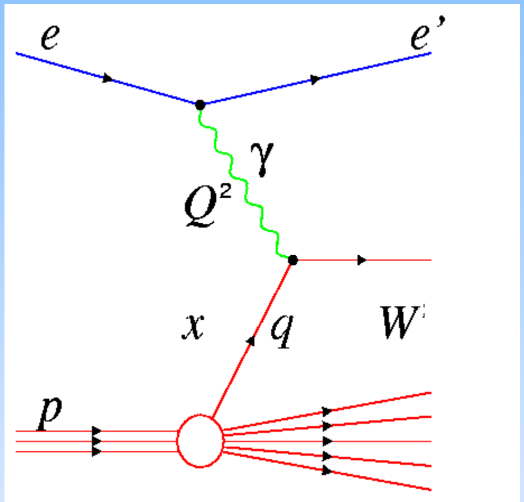




Exclusion region extended for small tuZ-couplings

Diffraction

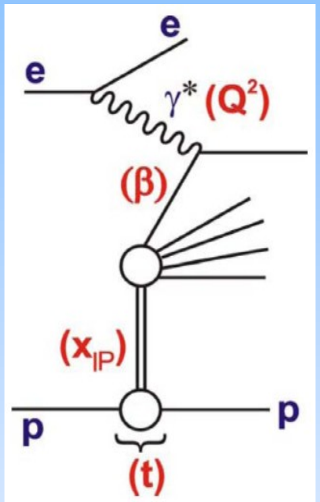
Standard ep-scattering



A surprise @ HERA start:
≈10% with no fwd-activity
⇒ diffraction

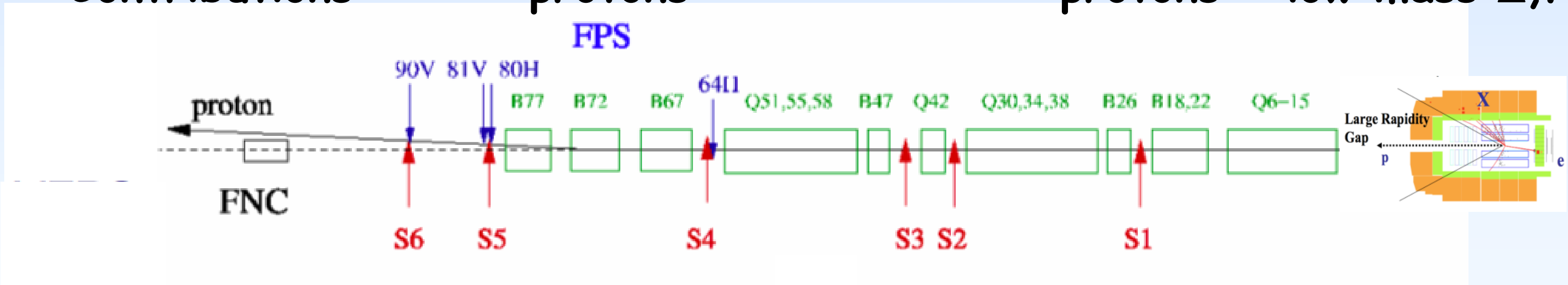
- x_{IP} p-momentum fraction carried by the colourless exchange (IP)
- β IP-momentum fraction carried by the struck quark
- t momentum transfer at the proton vertex

Diffractive ep-scattering



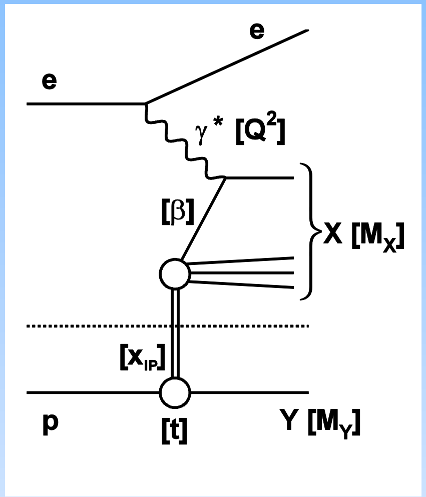
Techniques: leading proton or large rapidity gap

Contributions: protons | protons + low mass Δ,N*



Diffraction

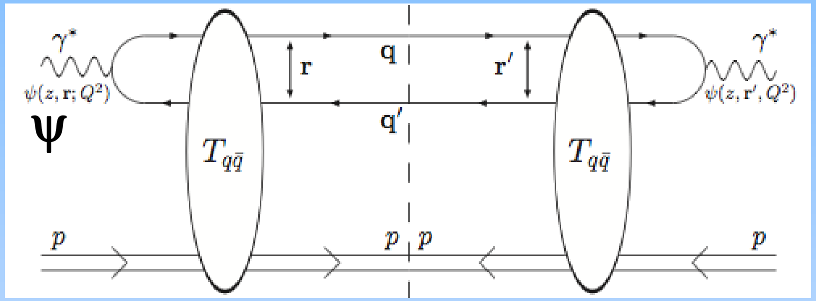
DGLAP pQCD Approach



Collinear factorisation:
- Q^2 evolution à la DGLAP
- diffractive PDFs

Proton vertex factorisation:
β, Q^2 dependence decoupled from
x_{IP}, t dependence
Pomeron PDF ⊗ Pomeron flux
Pomeron flux from Regge theory

Dipol Approach



+qqg dipol diagrams

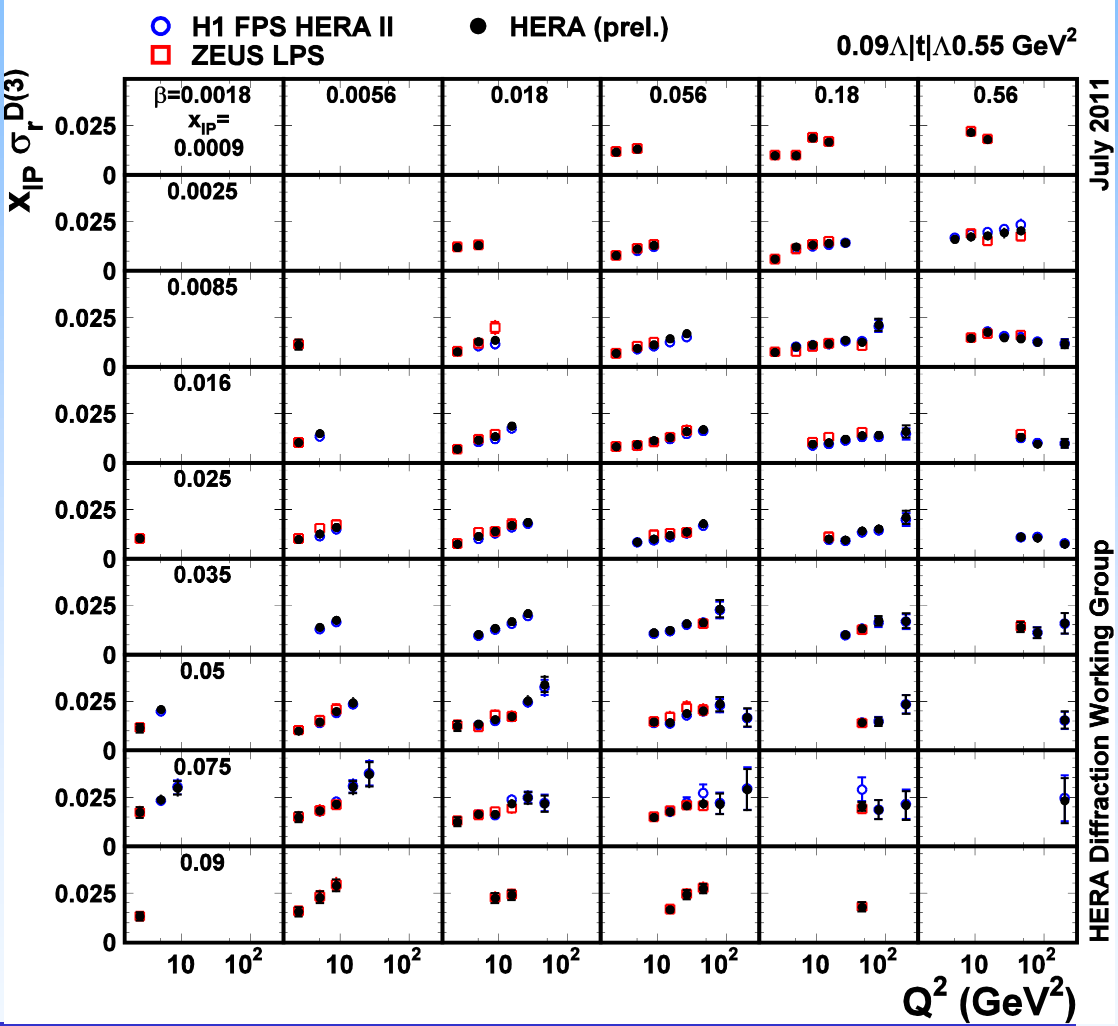
$\psi(z,r,Q^2)$: γqq wave function
T_{qq}: qq(qqg)-proton elastic scattering amplitude
T_{qq} parameterized in the saturation model

Combination of FPS/LPS data

V. Sola H1prelim-11-111, ZEUS-prel-11-011

Combination includes all correlations

profits from different detectors (systematics)



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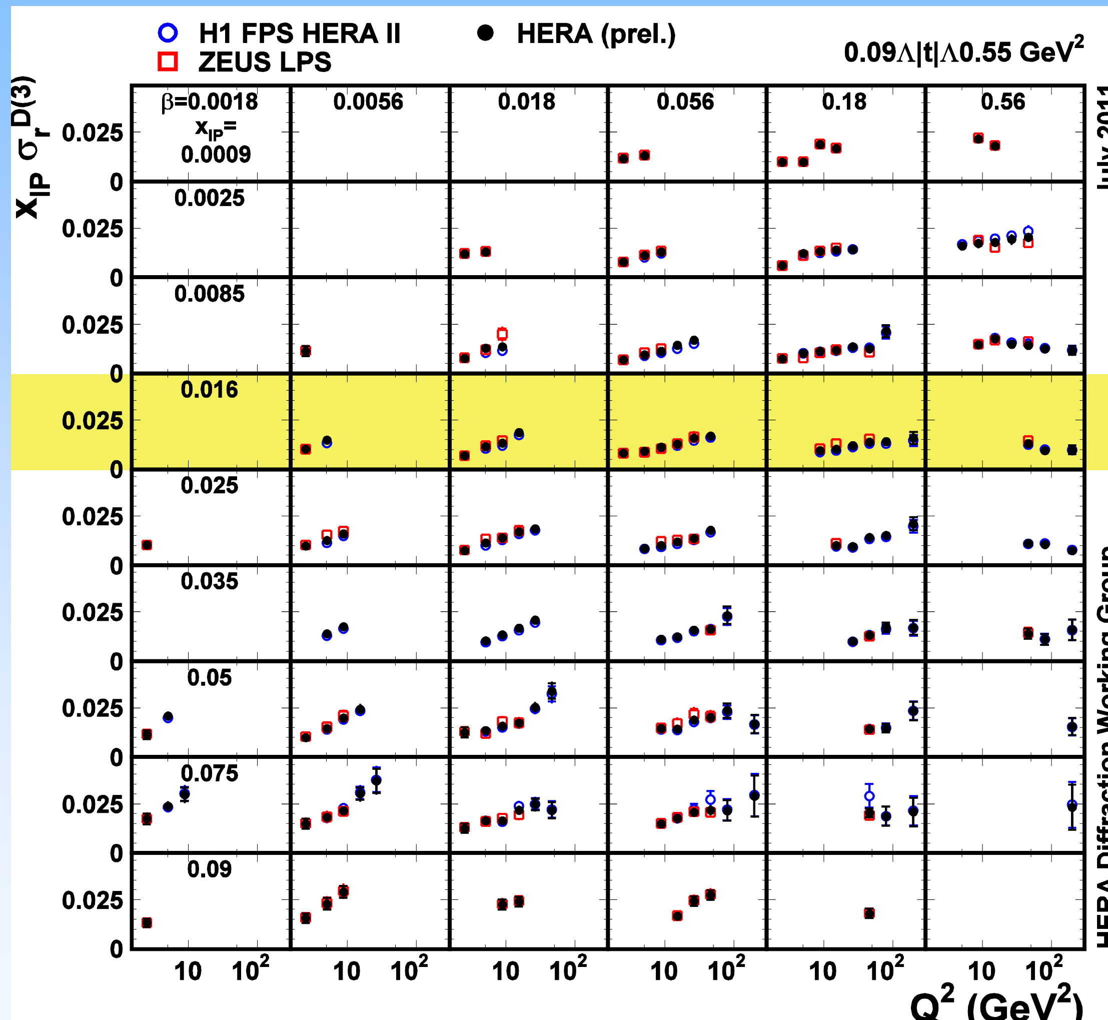


Combination of FPS/LPS data

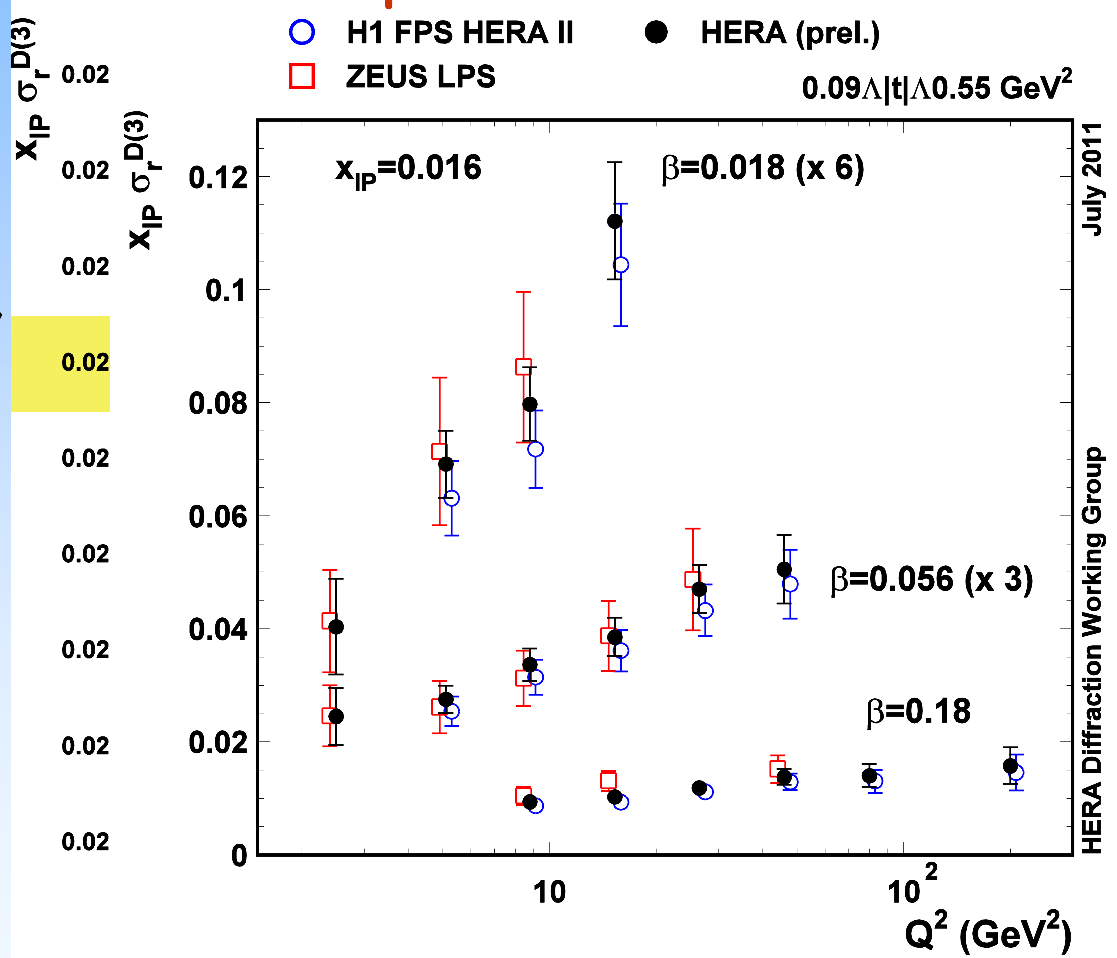
V. Sola H1prelim-11-111, ZEUS-prel-11-011

Combination includes all correlations

profits from different detectors (systematics)

cross calibration reduces uncertainties significantly

The power of combination



Scaling violation clearly visible

Most precise data as test bench for theory

Diffraction with LRG

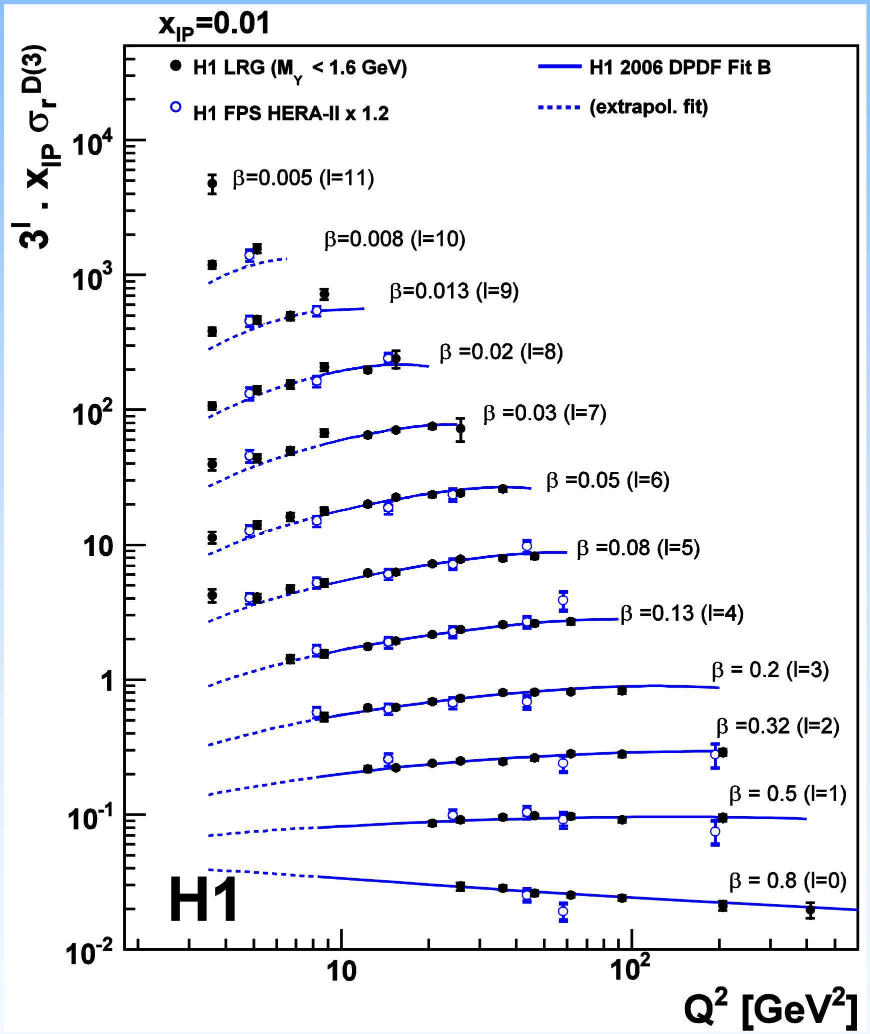
E. Sauvan DESY-12-041

New data sets combined with previously published data
35× more data @ medium Q^2

$$\frac{\text{LRG}}{\text{FPS}} = 1.203 \pm 0.019 \pm 0.087$$

(exp) (norm)

(agrees with previous meas.)



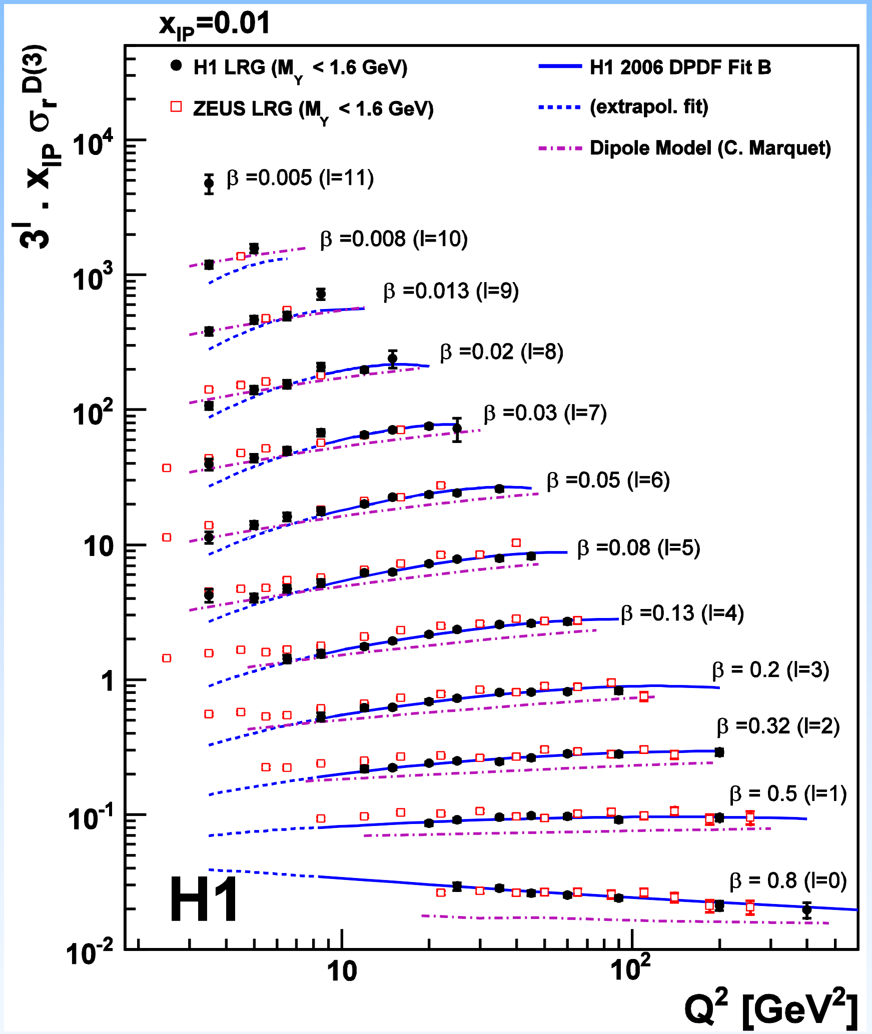
LRG and FPS data agree well
NLO QCD (DPDF) does well for Q^2>10 GeV^2

Diffraction with LRG

E. Sauvan DESY-12-041

Comparison to recent ZEUS data
(corrected to same Q^2 and $M_Y<1.6$ GeV)

ZEUS data: ≈10% higher
shape agreement



NLO QCD + DPDF:
- problems @ low Q^2
- good for Q^2>10 GeV^2

Dipol model with saturation:
- good @ low Q^2
- too low at high Q^2 and β

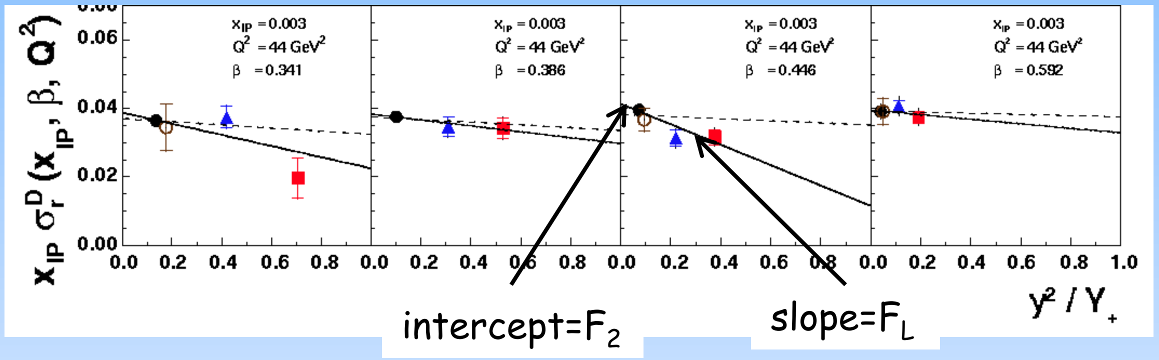
F_L in Diffraction

D. Salek DESY-11-084

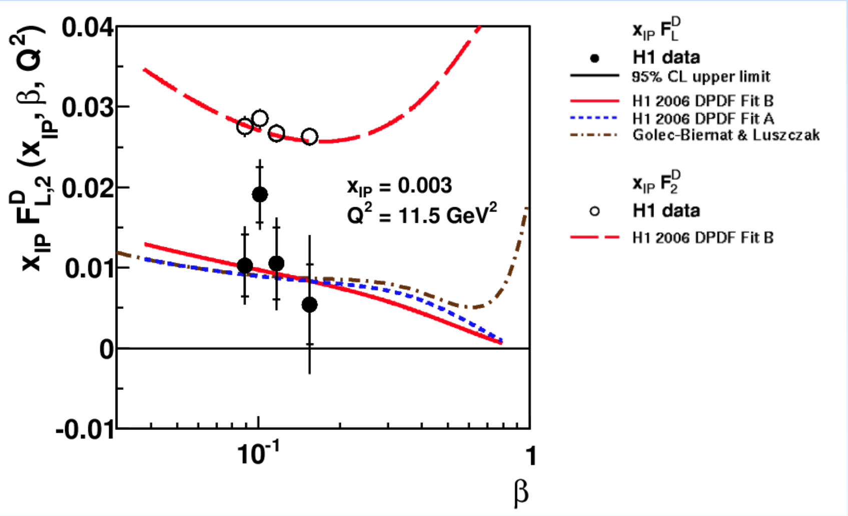
"Rosenbluth plot"

$$\sigma_r^D \propto F_2^D - \frac{y^2}{1+(1-y)^2} F_L^D$$

σ_r^D for same x, Q^2
at different E_p (s)



Direct measurement of
F_2^D and F_L^D (no assumptions)



Clearly non-zero F_L^D
Predictions agree
(no distinction possible)

F_L^D in Diffraction

D. Salek DESY-11-084

$$\sigma_r^D \propto F_2^D - \frac{y^2}{1+(1-y)^2} F_L^D$$

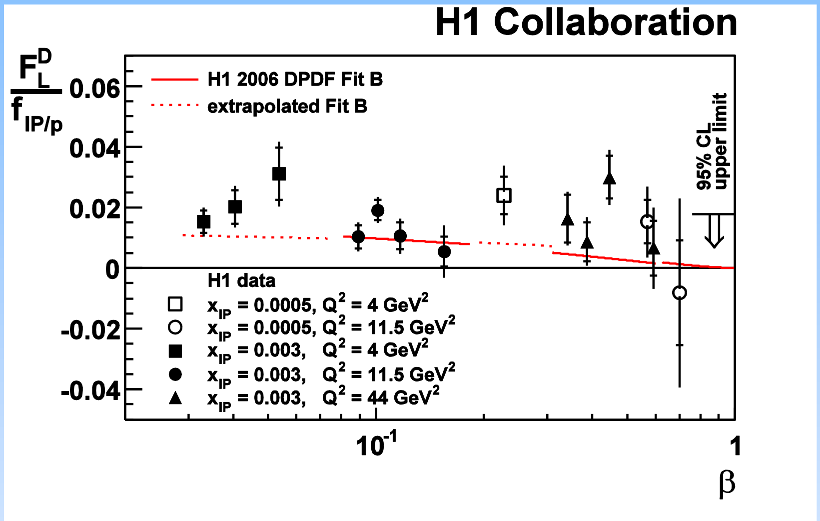
σ_r^D for same x, Q^2
at different E_p (s)

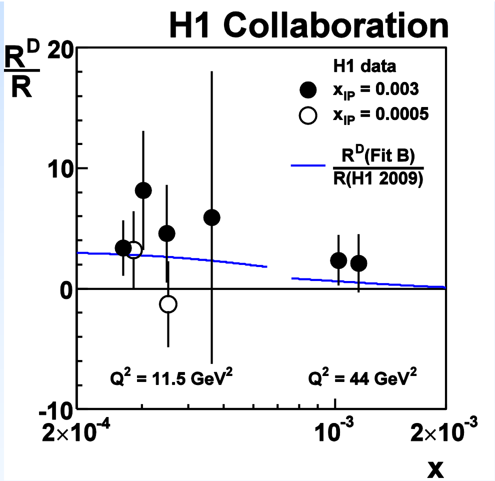
First measurement of F_L^D

$$R^D = \frac{F_L^D}{F_2^D - F_L^D}$$

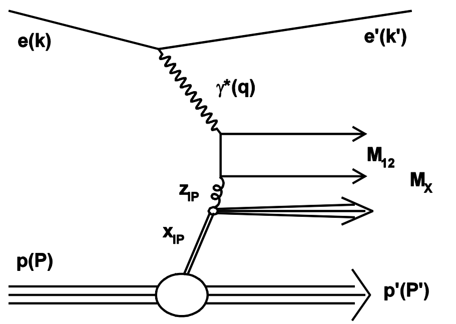
$R^D/R = 2.8 \pm 1.1$

Longitudinal photons more important in diffraction than in inclusive DIS





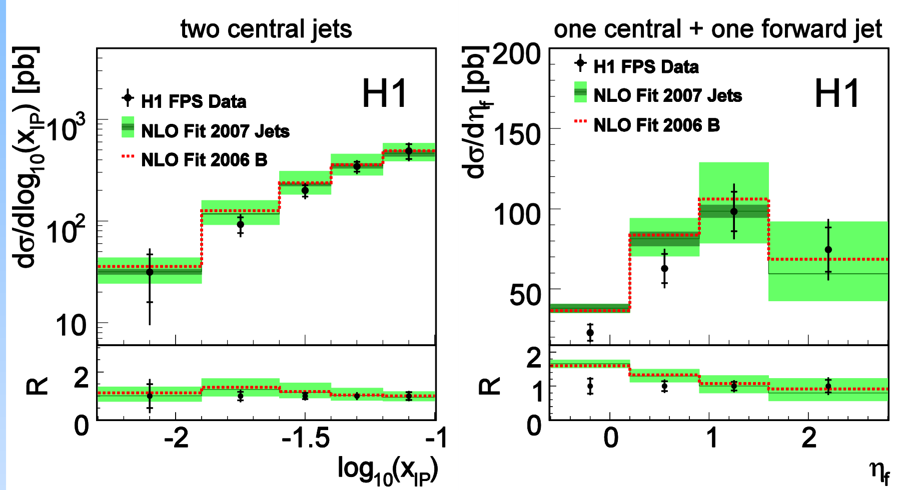
Diffractive Di-jet production (FPS)

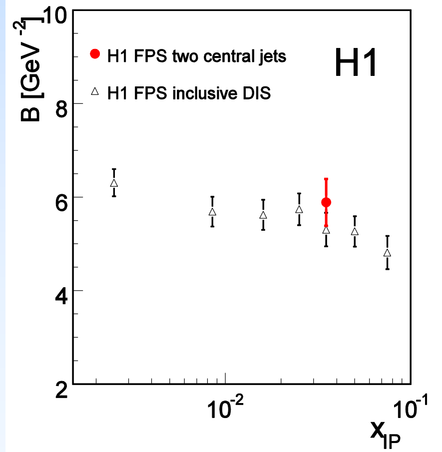


2 topologies:
2 central jets

1 cen. + 1 fwd. jets
Deviations from DGLAP ?

R. Polifka DESY-11-166



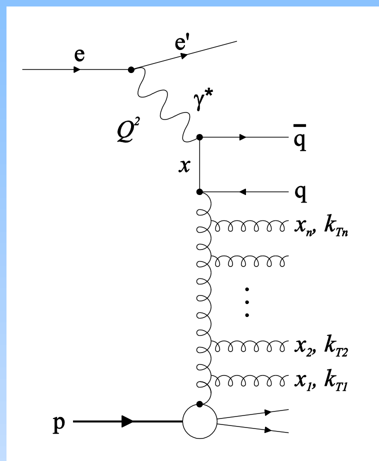


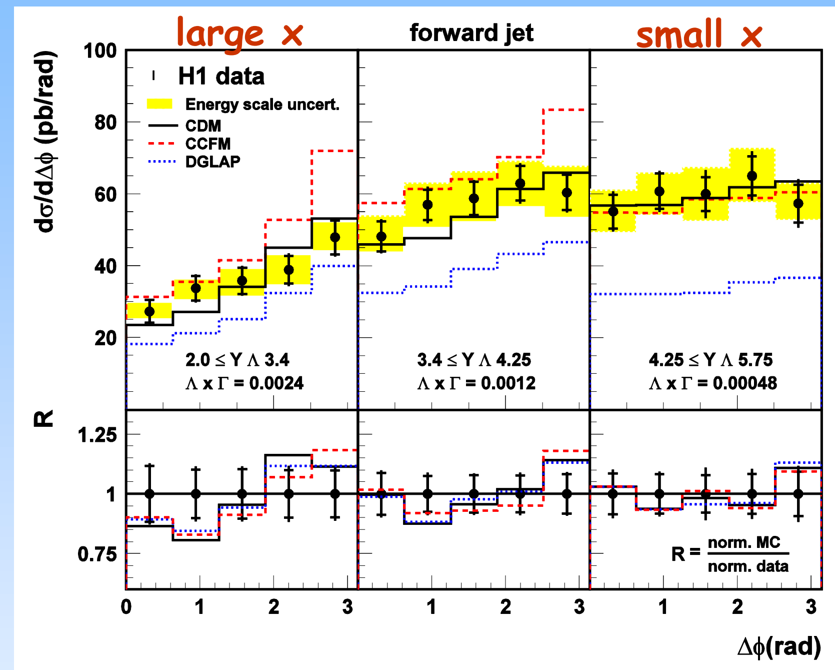
DPDF + NLO QCD works well
No sign for deviations from DGLAP

t-slope consistent with inclusive diff.
⇒ Proton vertex factorisation holds

Forward jet correlations (DIS)

L. Goerlich DESY-11-183





<u>Test of QCD dynamics @ low x:</u>

- DGLAP: strong k_T ordering
- BFKL: weak k_T ordering ⇒ more fwd jets
- CCFM: random in k_T ⇒ even more fwd jets

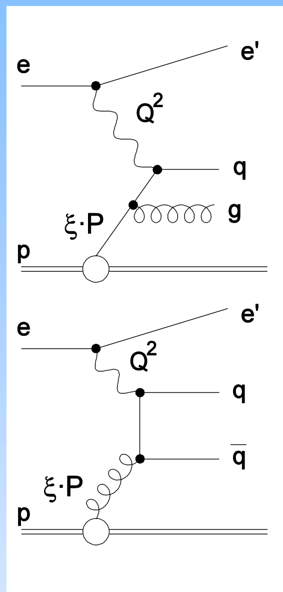
Expected de-correlation effects from $O(\alpha_s^n)$

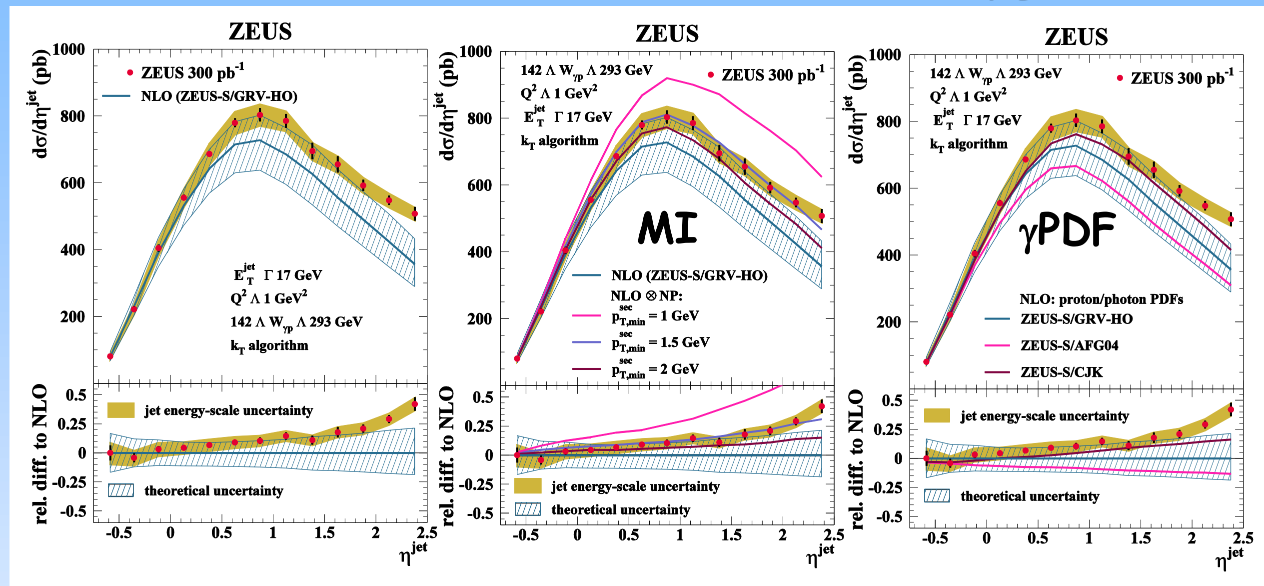
- Cross section described best by BFKL-type model (CDM)
- $\Delta\varphi$ shape: initial differences washed out by parton showers

Inclusive jets in photoproduction

E. Paul

DESY-12-045

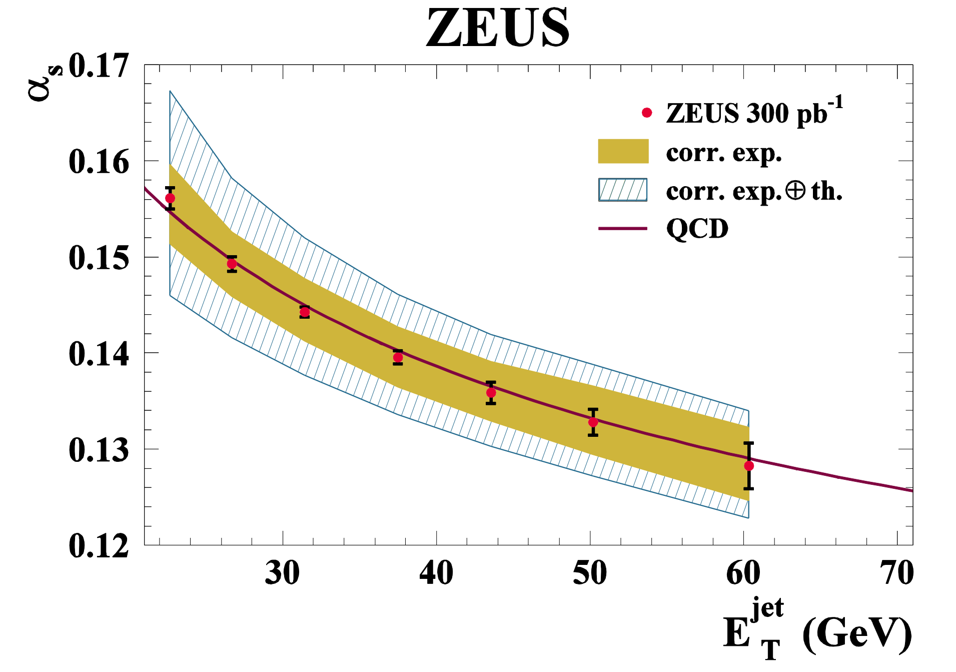




NLO QCD underestimates data @ low p_T and large η
Theory my be reconciled with data by
- -adding multiple interactions or
- -using a different photon PDF

Inclusive jets in photoproduction

E. Paul DESY-12-045



Analysis based on different jet algorithms:
kt, anti-kt, SIScone

Results are very consistent

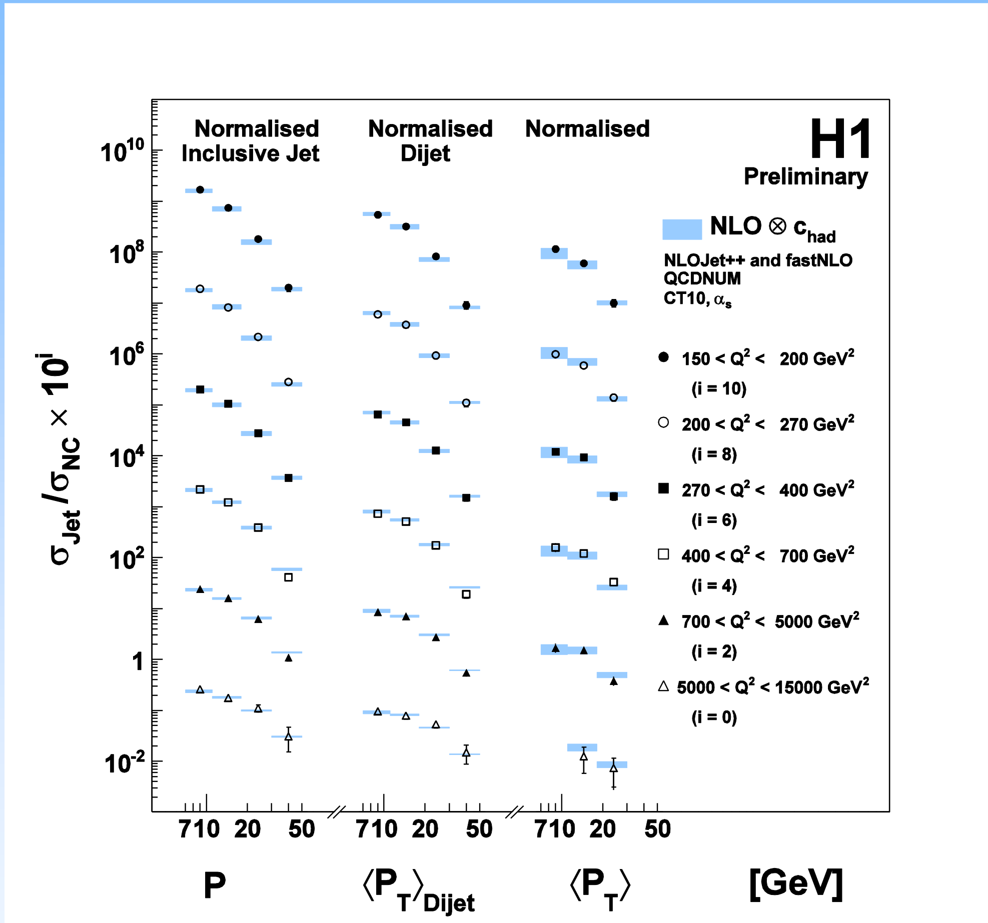
Running of α_s clearly visible in a single experiment

$$\alpha_S(MZ) = 0.1206 \,^{+0.0023}_{-0.0022}\ \text{(exp.)}\ ^{+0.0042}_{-0.0035}\ \text{(theo.)}$$

As for many other processes at HERA theory uncertainties are dominating due to missing NNLO calculations

Normalised jet cross sections in DIS

D. Britzger H1prelim-12-031



Combined NLO fit to normalised inclusive, dijet and trijet cross sections

$$\alpha_S(MZ)=0.1166\pm0.0011(exp)\pm0.0014(PDF)\pm0.0008(had)\ {}^{+0.0044}_{-0.0035}\ (theo)$$

α_s from HERAPDF 1.6/1.7

K. Nowak H1prelim-11-031, ZEUS-prel-11-001

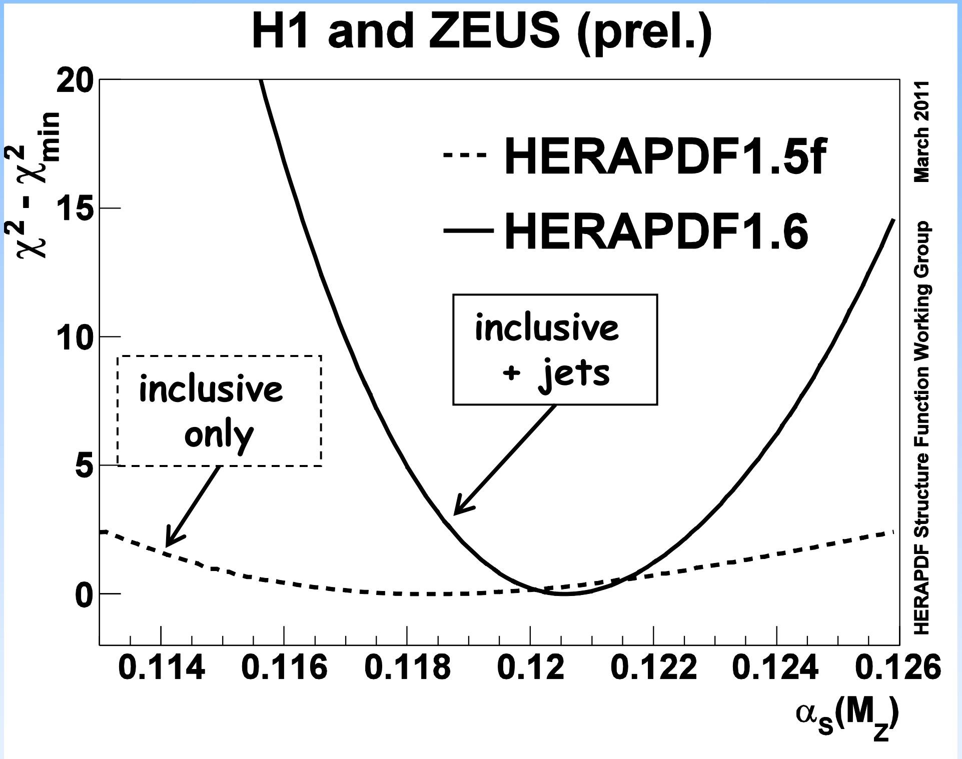
HERAPDF 1.6

Combined PDF+α_s fit to:
- combined incl. HERA-I+II data
- published DIS jet data

HERAPDF 1.7

Combined PDF+α_s fit to:
- combined incl. HERA-I+II data
- published DIS jet data
- combined F_2^{cc} data
- low proton energy data

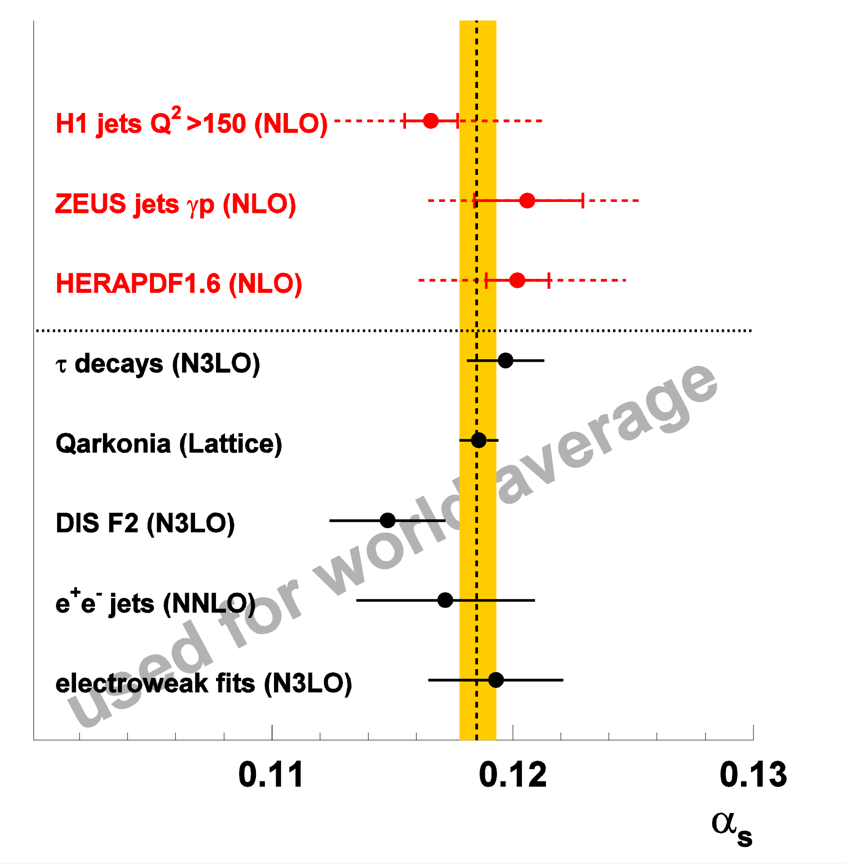
$\Rightarrow$ same results $\Rightarrow$ all processes "see" the same PDFs



$$\alpha_s(MZ)=0.1202\pm0.0013(exp)\pm0.0007(model)\pm0.0012(had)\ {}^{+0.0045}_{-0.0036}\ (theo)$$

Summary on α_s

α_s determinations at HERA with sizable uncertainties – missing NNLO



World average dominated by α_s from lattice calculations (appropriate for perturbative calculations?)

All extractions do have caveats

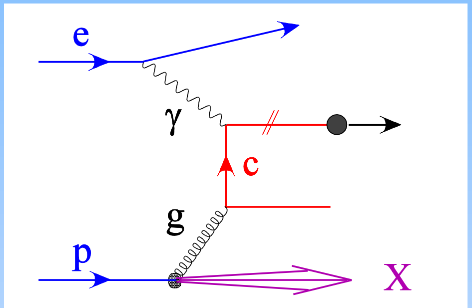
e.g. non-perturbative physics

higher order contributions…

α_s from HERA with small experimental uncertainties
Precision spoiled due to lack of NNLO calculations

Heavy flavour physics @ HERA

Heavy flavour predominantly
via photon-gluon-fusion



Charm contribution to DIS at HERA up to ~30% (Beauty: 1-2%)

Perturbative calculations are faced with a "battle of scales*)"

m_c, p_T, Q^2

*) O.Behnke

Different approaches:

"massive" = charm produced perturbetively
"massless" (ZM-VFNS) = charm constituent of the proton
- both not valid in the full phase space

GM-VFNS combines both approaches
- but how to do the transition? Just make a choice!

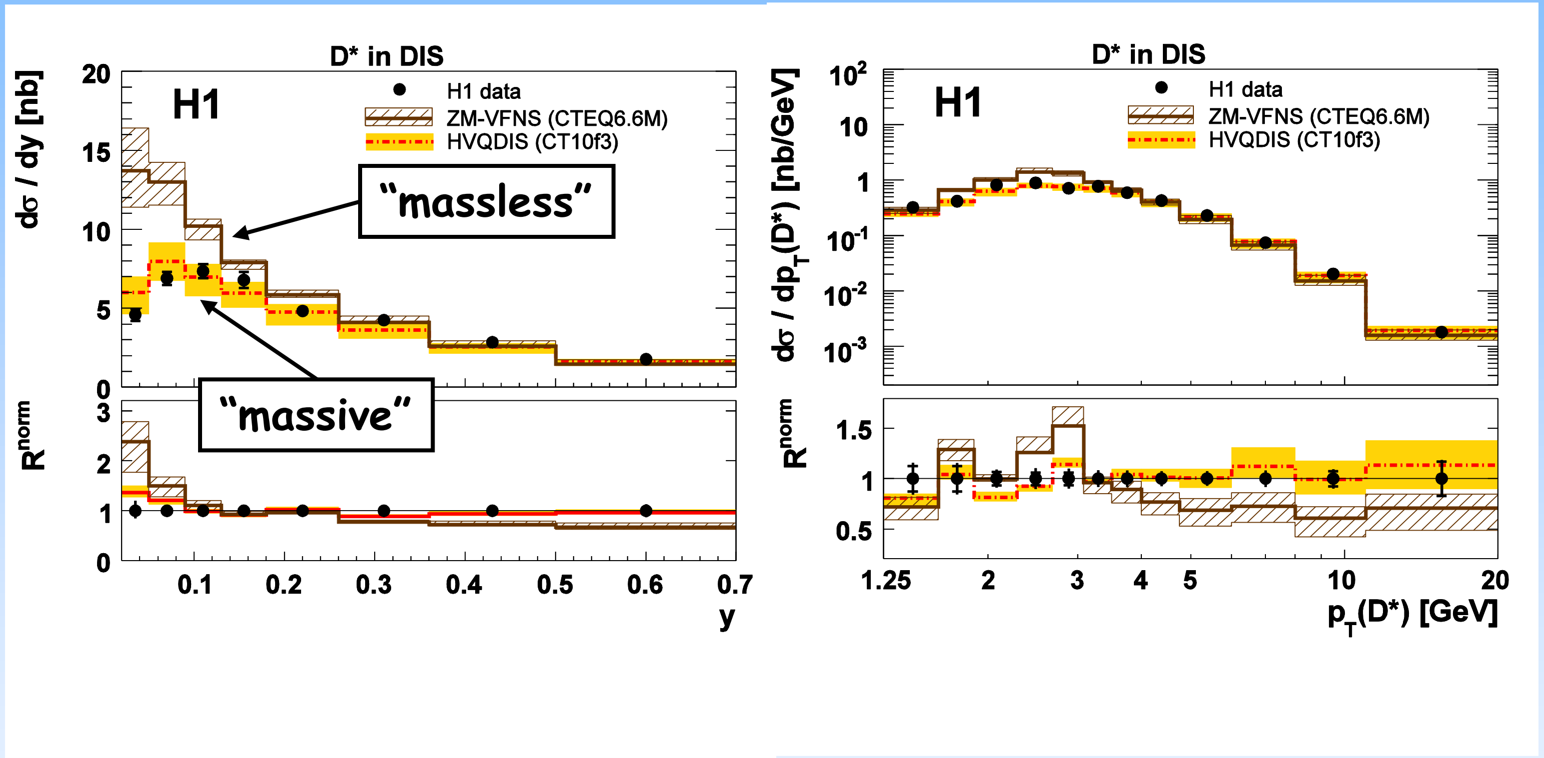
Can charm data tell and thereby remove ambiguities?

We better understand charm to get reliable PDFs

D* production in DIS

E. Hennekemper

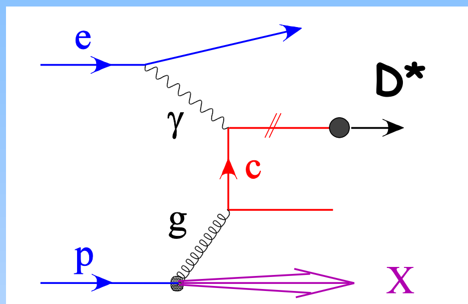
DESY-11-066

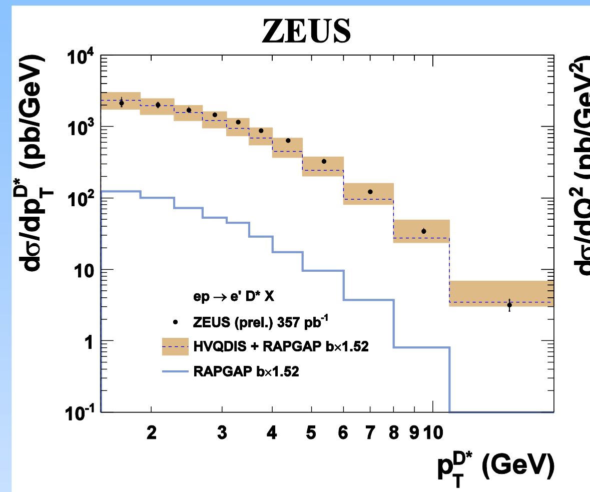


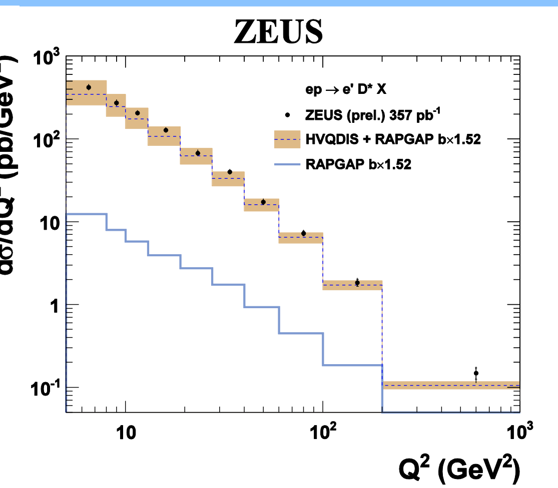
-Massive NLO QCD describes data reasonably
-Massless (ZM-VFNS) fails

D* production in DIS

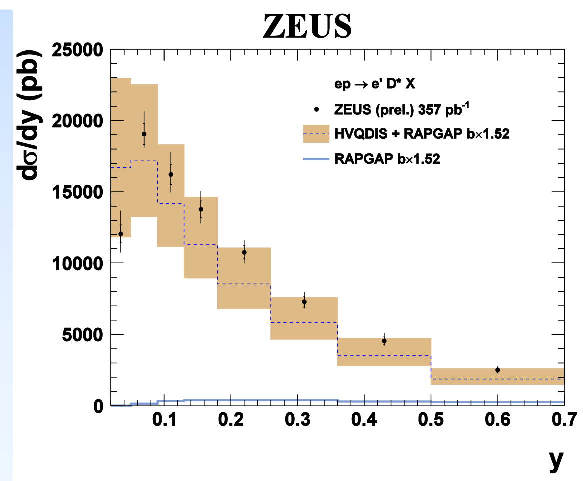
A. Gizhko ZEUS-prel-11-012







Charm tagging:
reconstruction of
D* mesons



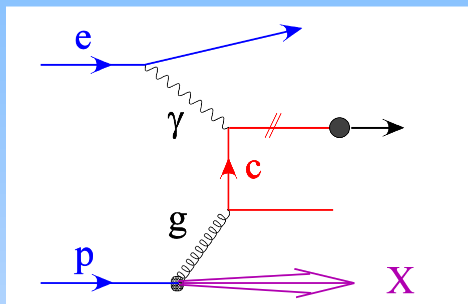
-High precision data well described by NLO QCD in the full analysis phase space

$\Rightarrow$ provide precise input for F_2^c

Charmed jets in DIS

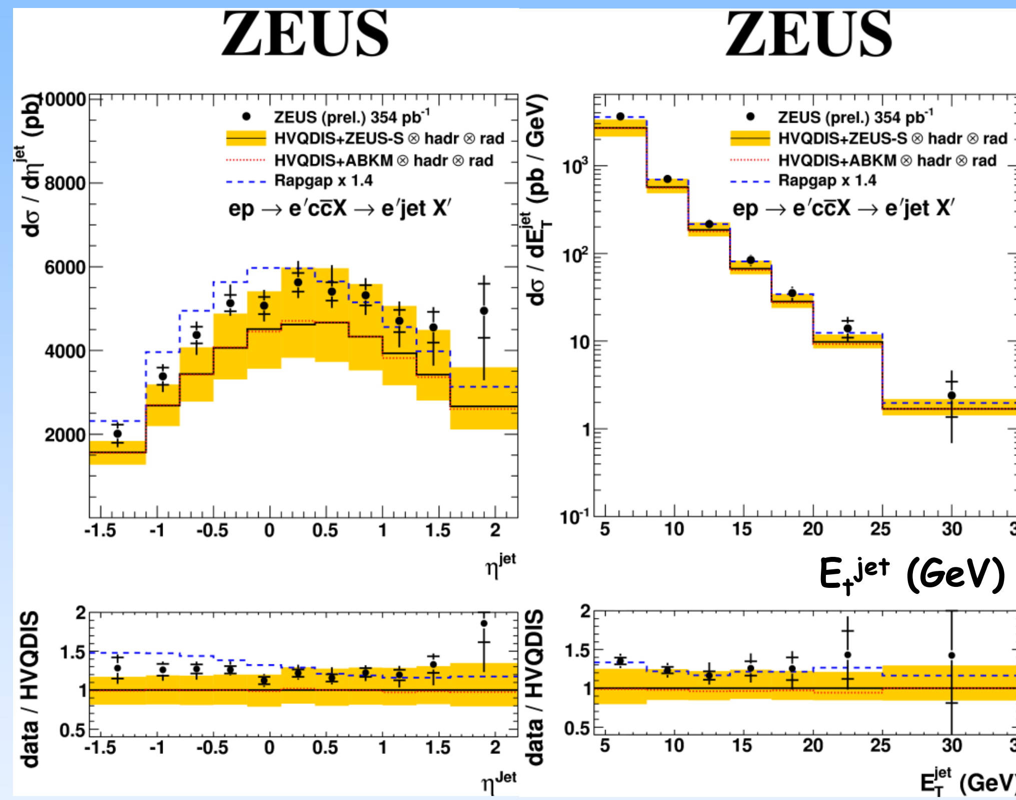
V. Libov

ZEUS-prel-12-002



Heavy flavour predominantly via photon-gluon-fusion

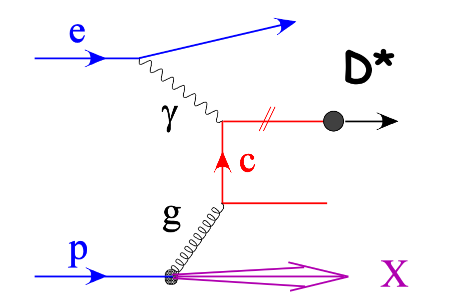
Charm tagging:
displaced tracks in jets
plus jet mass



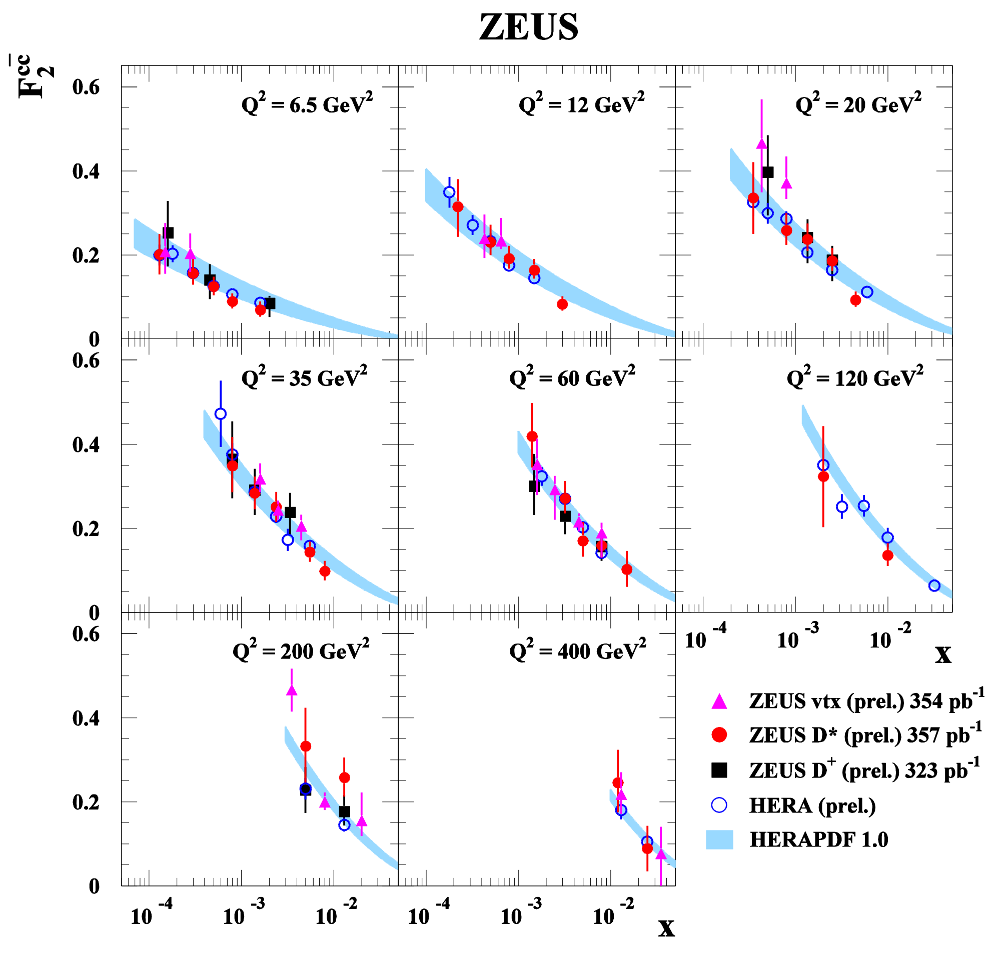
Charmed jet production described by theory within uncertainties
Data more precise than NLO QCD predictions also for charm

F_2^c from charmed jets in DIS

V. Libov ZEUS-prel-12-002



$$F_2^{cc} = \sigma_{red}^{cc} + \frac{y^2}{1+(1-y)^2} F_L^{cc}$$



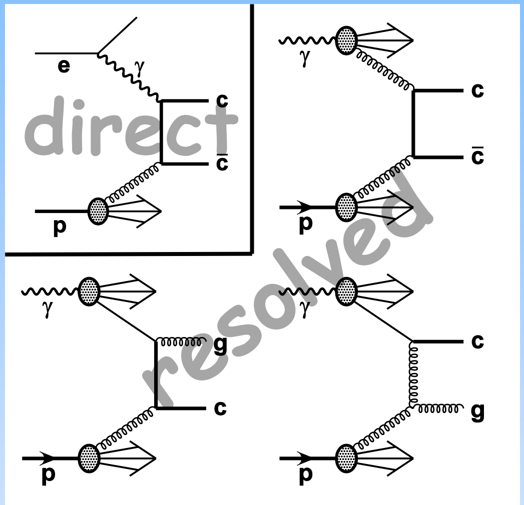
Charm tagging:
displaced tracks in jets
plus jet mass

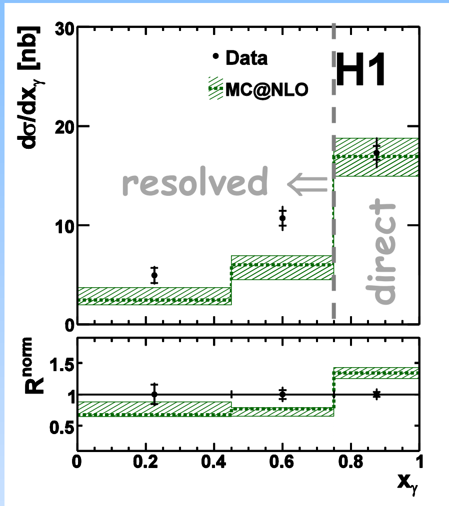
- F_2^c: good agreement among measurements
- valuable input for PDFs

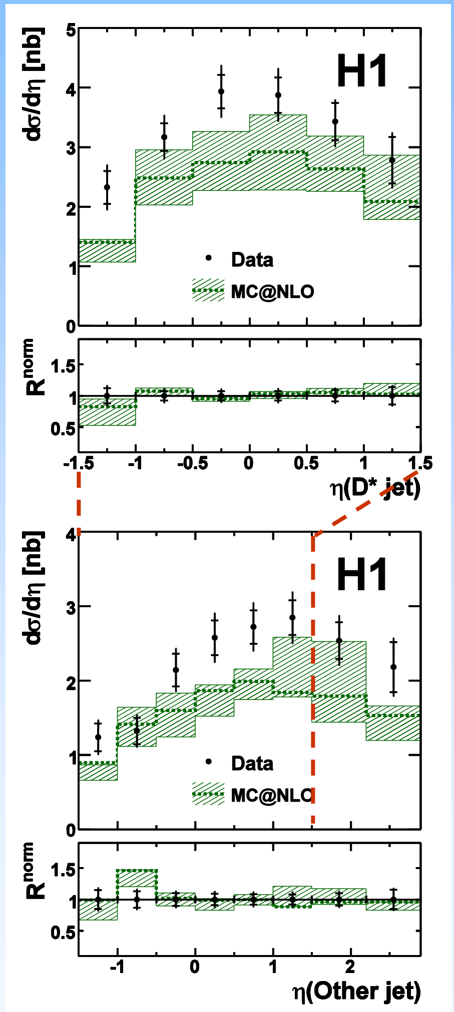
Dijet D* meson photoproduction

Z. Staykova

DESY-11-248

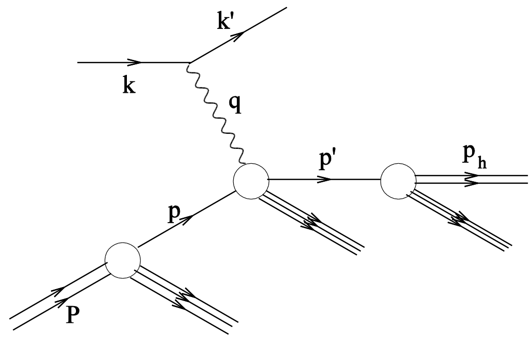






-MC@NLO underestimates resolved contribution
-non-D* jet has significant from gluons for $\eta>0$

Production of hadrons



Courtesy: AKKS hep-ph/0611029

LO MC models discussed:

Lepto (MEPS): matrix element with parton showers

CDM: color dipol model

+ Lund string model

NLO calculations discussed:

$\sigma(ep \rightarrow ehX) \propto PDF \otimes \sigma \otimes FF$

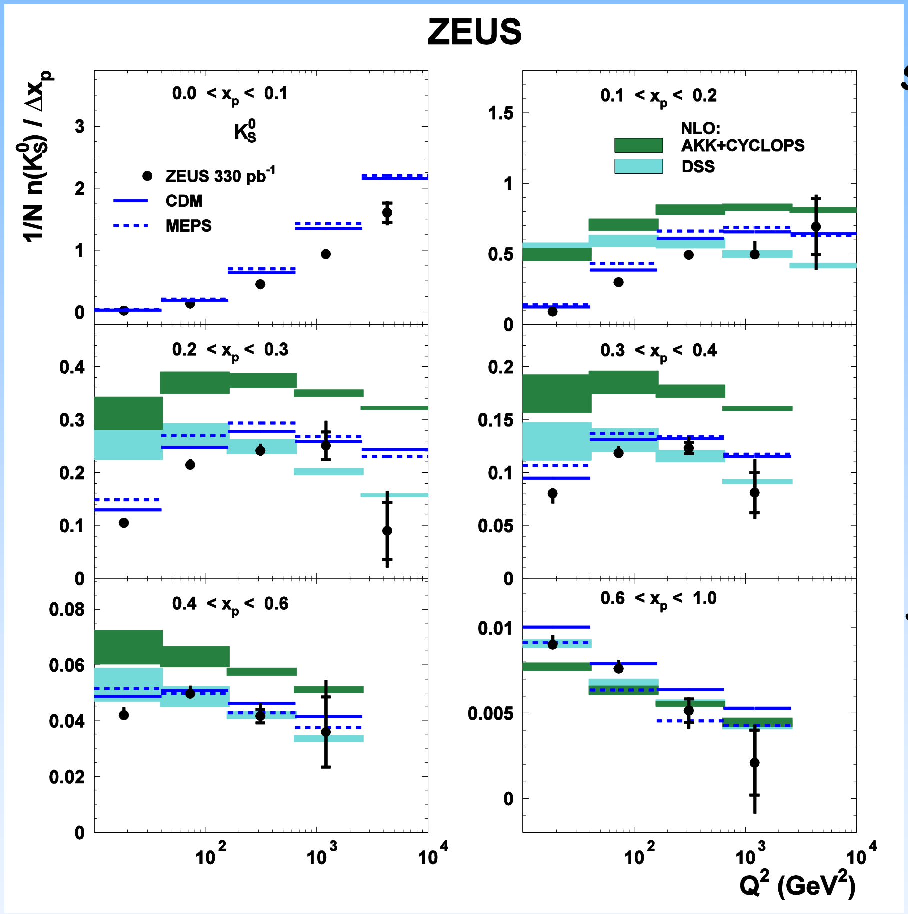
FF with contributions from quark, anti-quark and gluon (as PDFs)

AKK+CYCLOPS: parameterized from fits to e^+e^- data
DSS: parameterized by fitting to e^+e^-, pp and ep data

Understanding fragmentation as important as understanding PDFs

K_0^S and Λ^0 scaled momentum spectra

I. Abt DESY-11-205



Steep rise with Q^2 at small x_p
Population due to gluon splitting

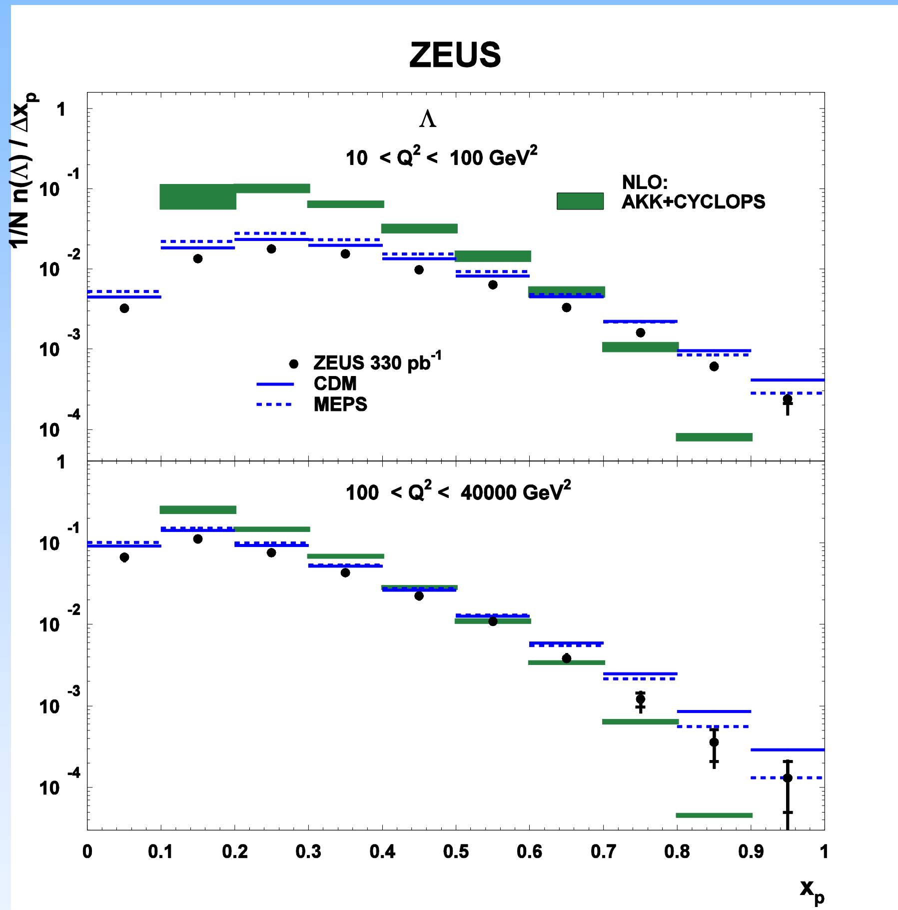
Scaling violations clearly visible

Steep fall with Q^2 at small x_p
Depletion due to gluon radiation

Monte Carlo models (CDM, MEPS) give a fair description
NLO QCD: AKK+CYCLOPS fails – DSS reasonable at larger x_p

K_0^S and Λ^0 scaled momentum spectra

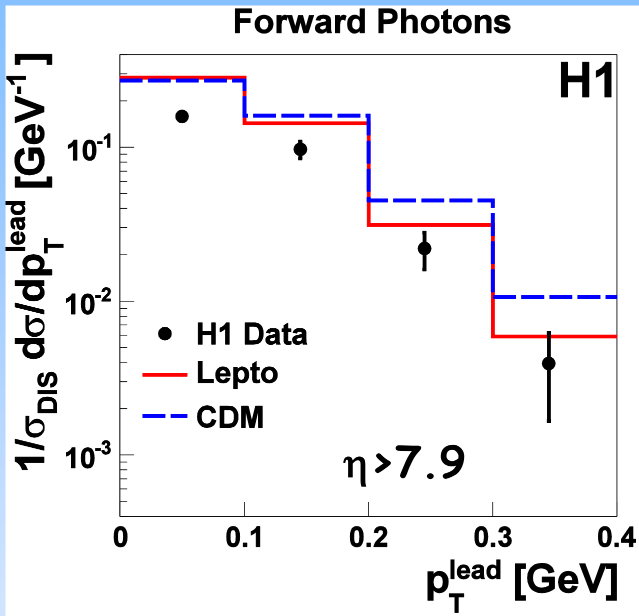
I. Abt DESY-11-205



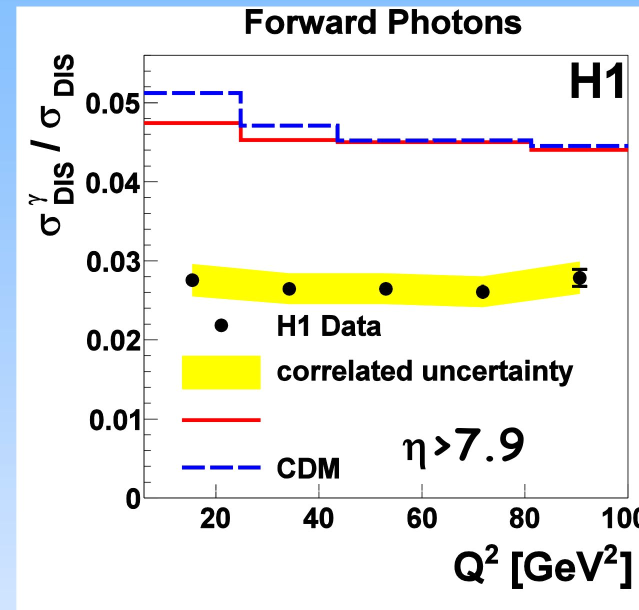
CDM, MEPS give a fair description – but 20% too high
NLO QCD: AKK+CYCLOPS much too steep in x_p

Production of very forward photons

H. Zohrabyan DESY-11-093

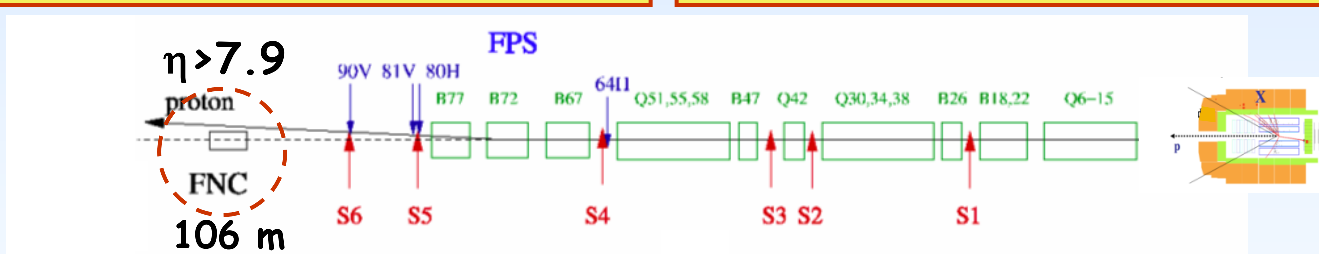


main source:
$\pi^0 \to \gamma\gamma$



At large η MCs much above data ⇒ fragmentation to π^0s in p-remnant not well modeled in MCs

γ-yield independent of Q^2,x ⇒ p-remnant does not "feel" the hard interaction



Conclusions

- The Standard Model is healthy
  - no sign for new physics at HERA
- HERA provides precision measurements in many areas of QCD
  - analyses are profiting from all the efforts made to get the best data
- There is a grain of salt:
  - almost everywhere large theory uncertainties due to missing of NNLO QCD calculations

Still some way to go to finalise the rich HERA physics programme