QCD in High p_T Hadronic Final States in ep Interactions by H1 and ZEUS

Achim Geiser, DESY Hamburg

XIX Int. Workshop on Deep-Inelastic scattering and related subjects

Newport News, USA, April 11, 2011

- **Jets and α_s**
- **Heavy Flavours**
- **Jets in Diffraction**

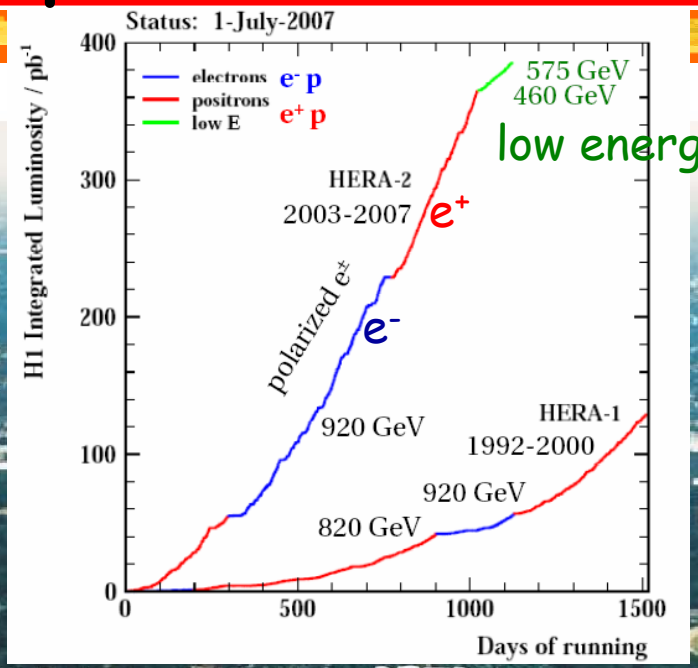
selection of new results reported at this conference

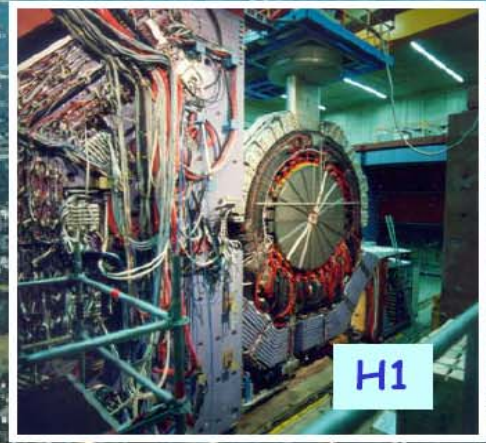
Proton Structure:

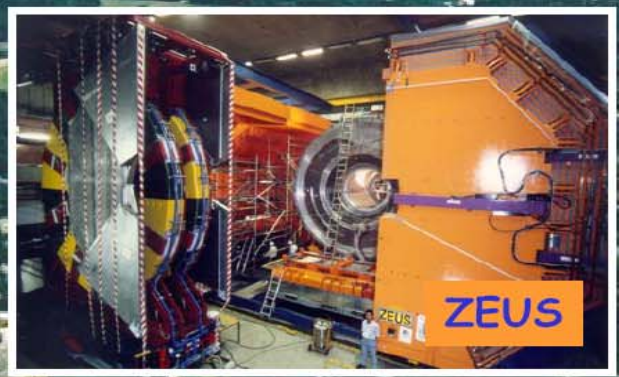
see next talk
A. Glazov

apologies: skipped vector mesons, single photons, …

The HERA ep collider and experiments







PETRA

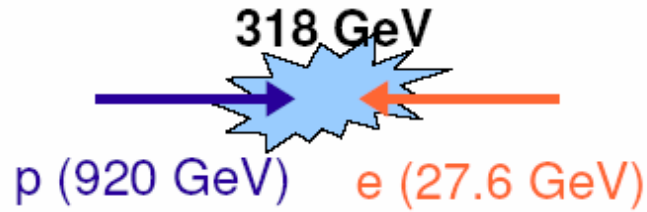
HERA

HERA I: ~ 130 pb^{-1} (physics)

HERA II: ~ 380 pb^{-1}(physics)

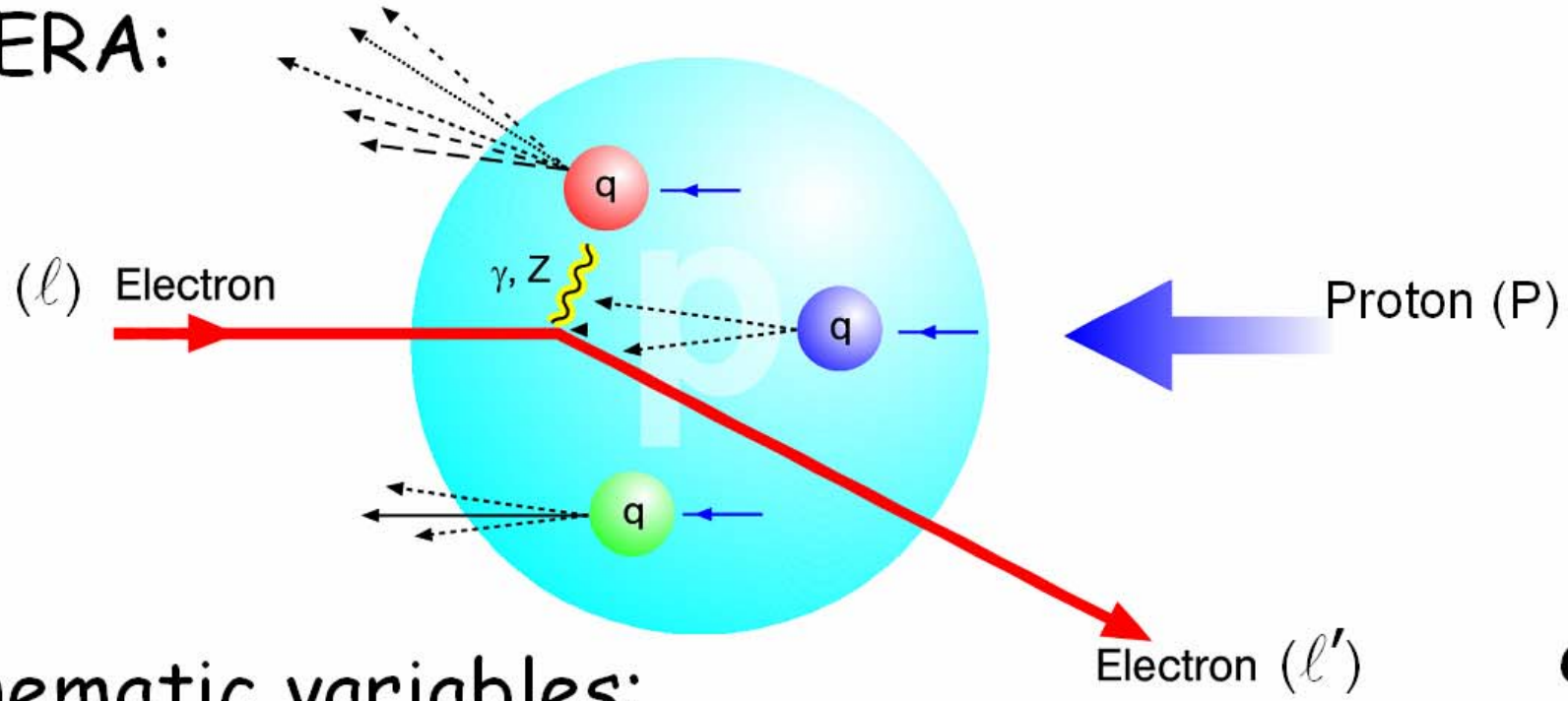
combined: ~ 2 x 0.5 fb^{-1}

HERA:



Deep Inelastic ep Scattering at HERA

HERA:



$q = \ell - \ell'$

kinematic variables:

$Q^2 = -q^2$ photon (or Z) virtuality, squared momentum transfer

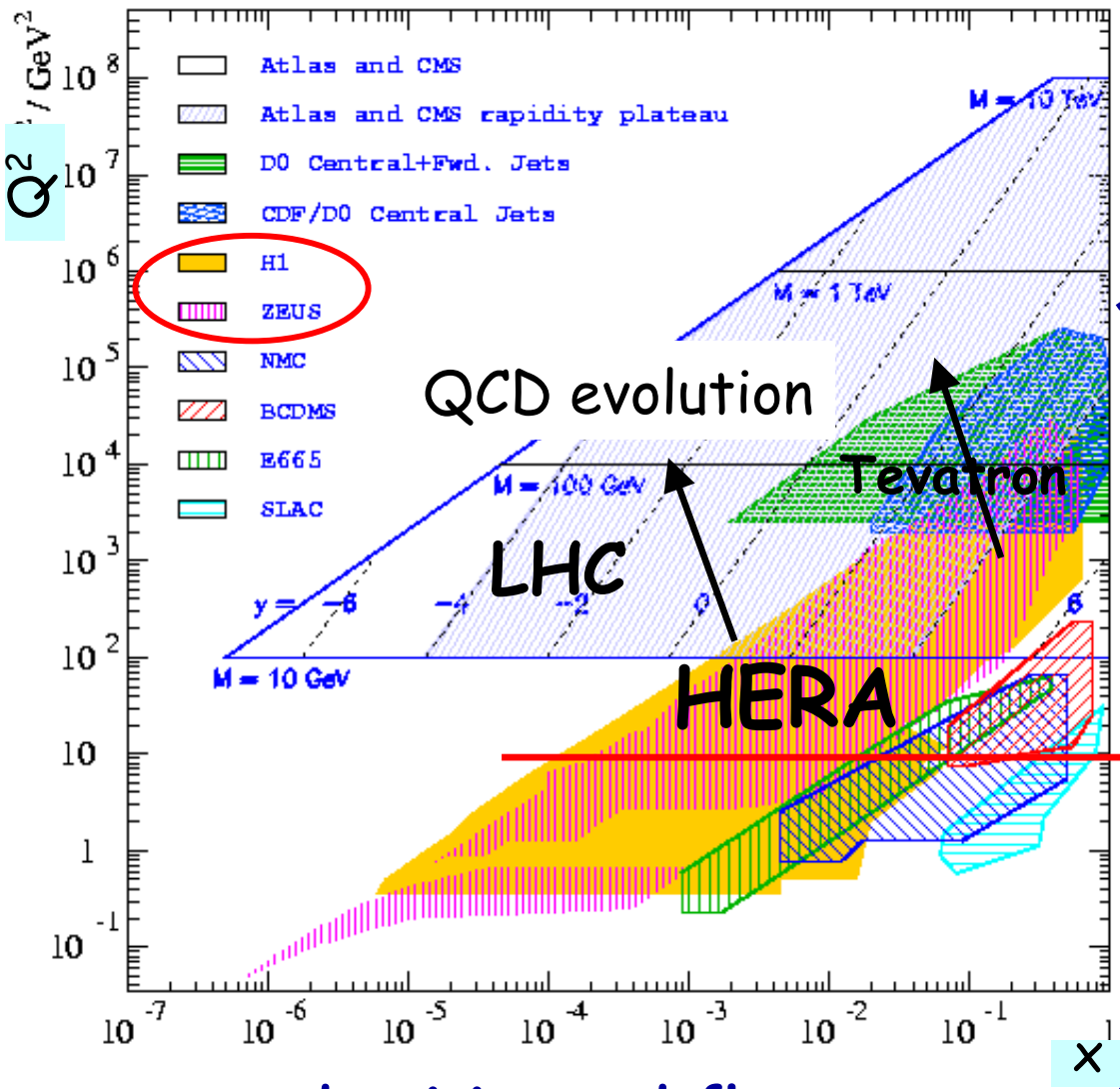
$x = \frac{Q^2}{2Pq}$ Bjorken scaling variable, for $Q^2 \gg (2m_q)^2$: momentum fraction of p constituent

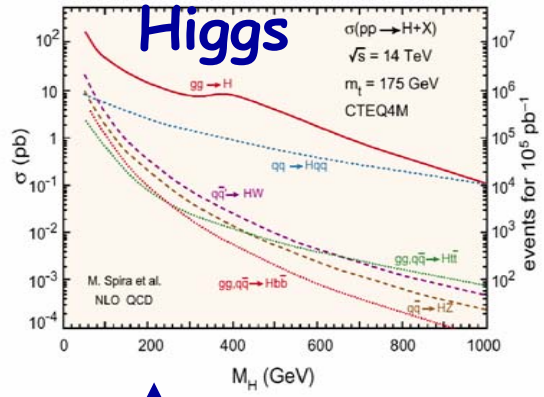
$y = \frac{qP}{\ell P}$ inelasticity, γ momentum fraction (of e)

$Q^2 \lesssim 1\ \mathrm{GeV}^2$: photoproduction

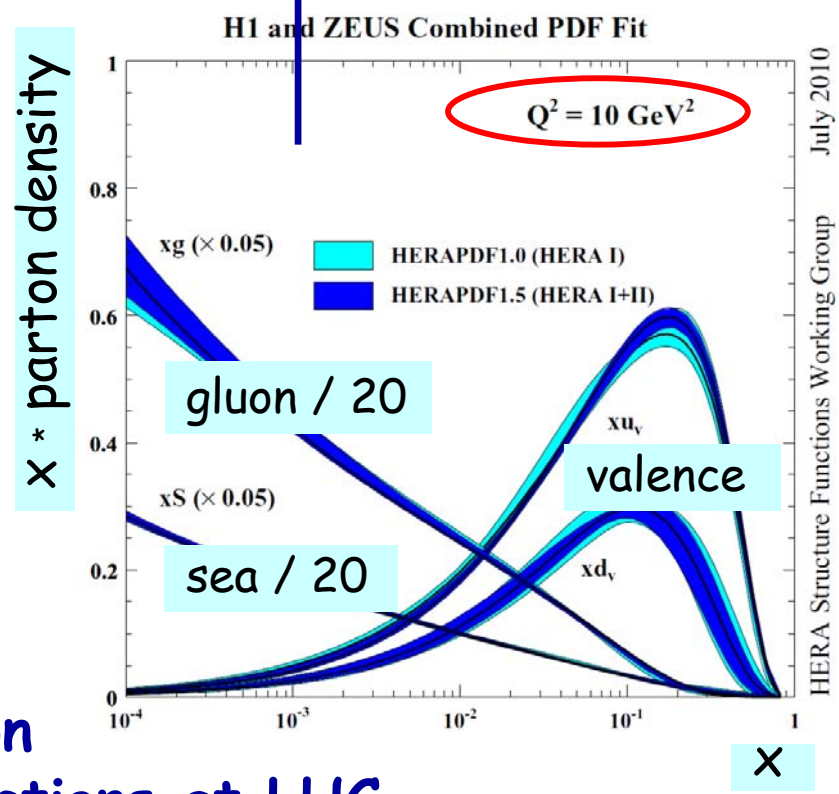
$Q^2 \gtrsim 1\ \mathrm{GeV}^2$: DIS

Parton density functions (PDF)





W,Z, top, jets, ...

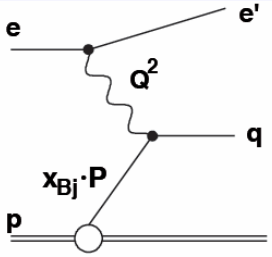


parton densities and flavour composition measured at HERA determine cross sections at LHC

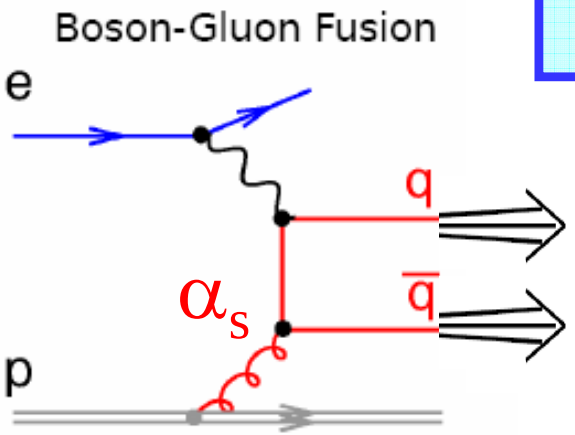
Jets and α_s

Jets in ep interactions (HERA)

QPM:



single (or no) jets in DIS: no QCD, measure quark densities (next talk)

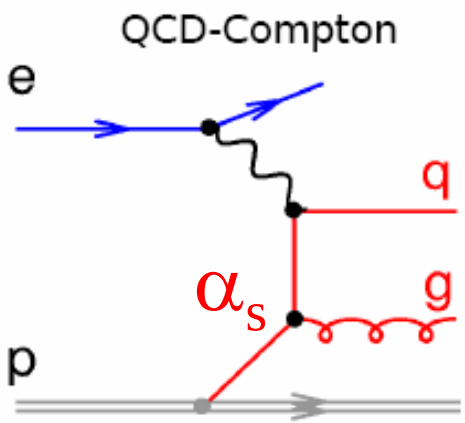


dijets in DIS or photoproduction:

measure both (**dijets**) or

integrate over 2nd jet (**inclusive jets**)

require high E_T w.r.t. photon axis

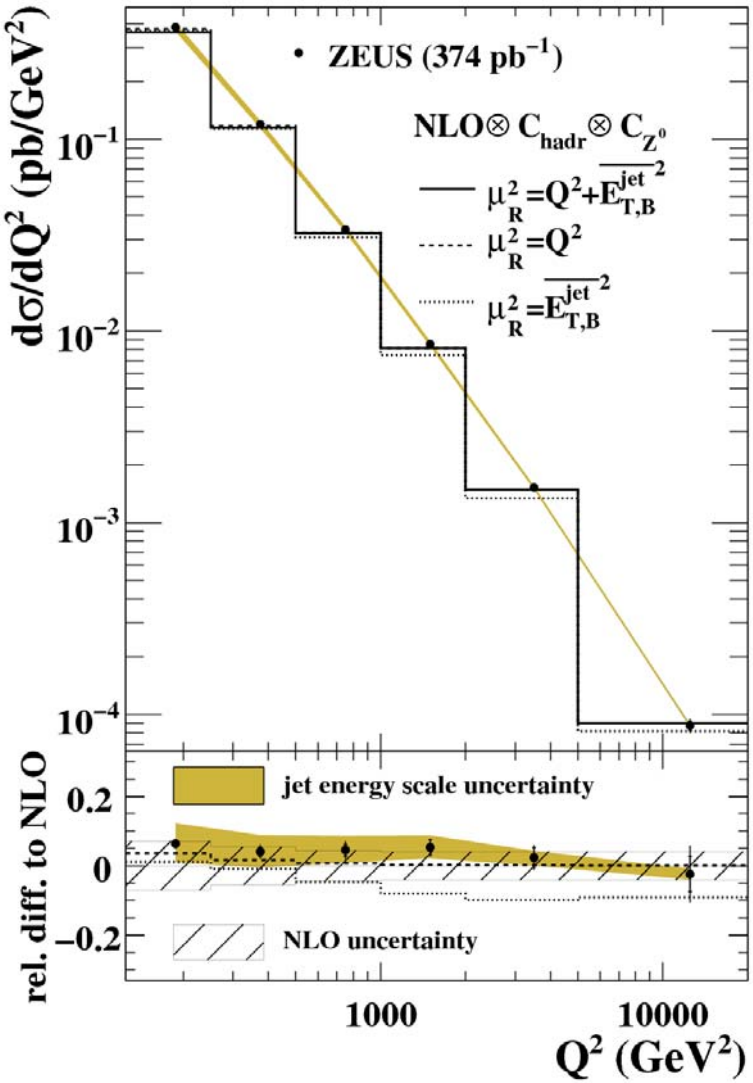


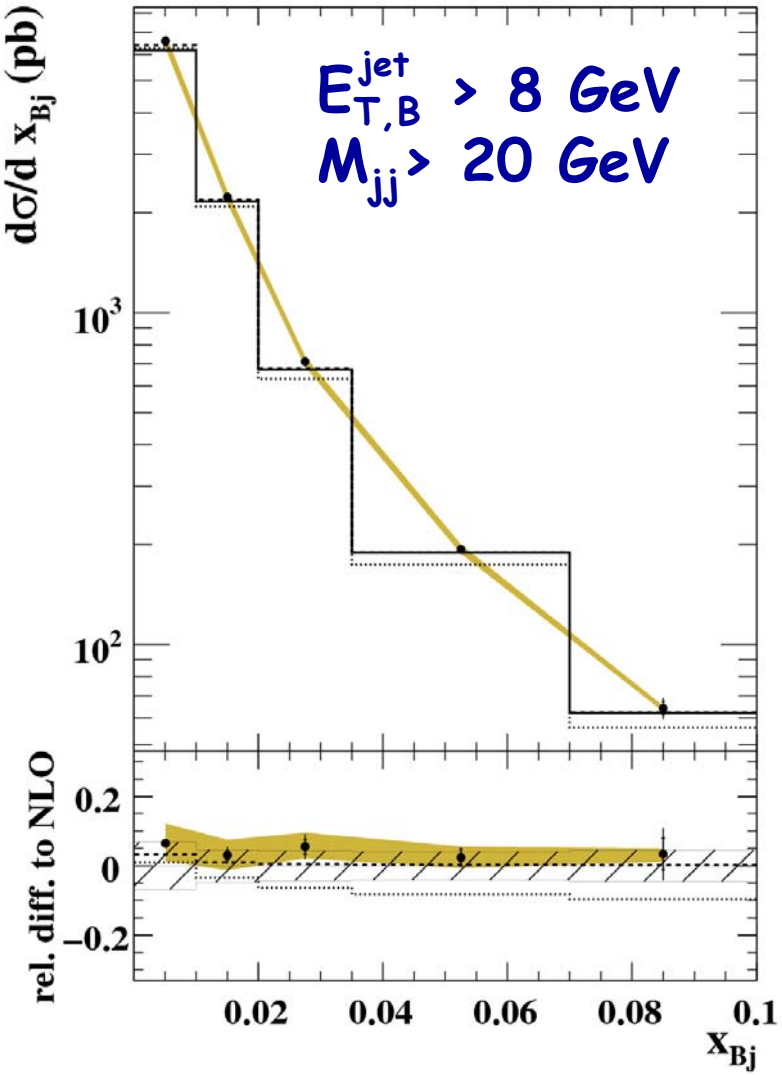
- check QCD
- study performance of jet algorithms
- measure α_s and its running
- measure gluon density (next talk)

Dijets in DIS

see talk
O. Kuprash

DESY-10-170, Eur. Phys. J. C70 (2010) 965





QCD works!

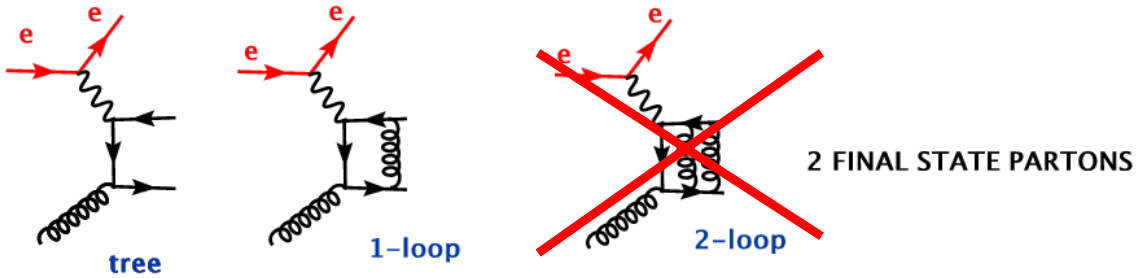
infrared and collinear safe jet algorithms

DESY-10-034, Phys. Lett. B 691 (2010) 127

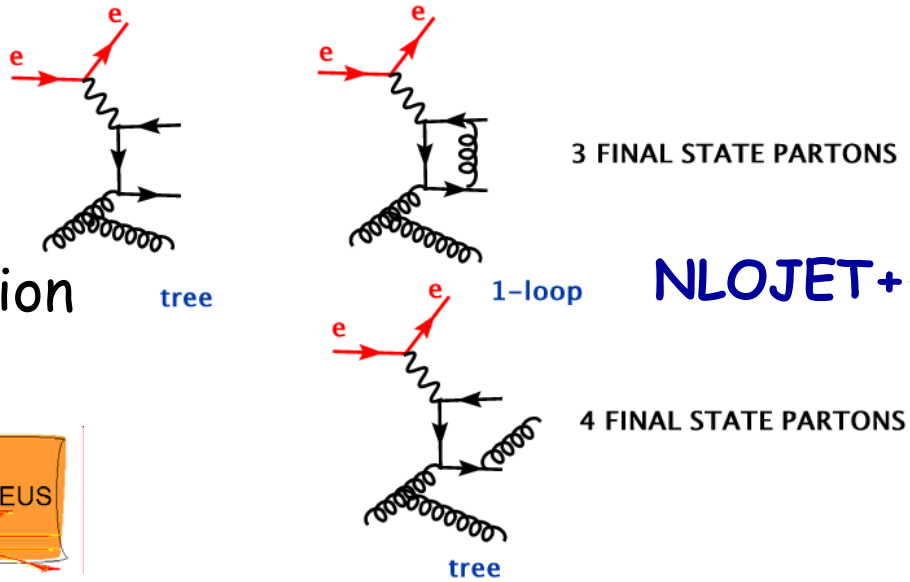
see talk
D. Lontkovskyi

- **k_T** used for HERA data since decades
- LHC mainly uses **anti-k_T**
- study of **anti-k_T** and **Siscone** at HERA added recently
  (**before** first LHC results)

- **high Q^2 jet data**



- k_T and anti-k_T start
  to differ only from
  4 partons/particles onwards
  -> need partial $O(\alpha_s^3)$ QCD calculation

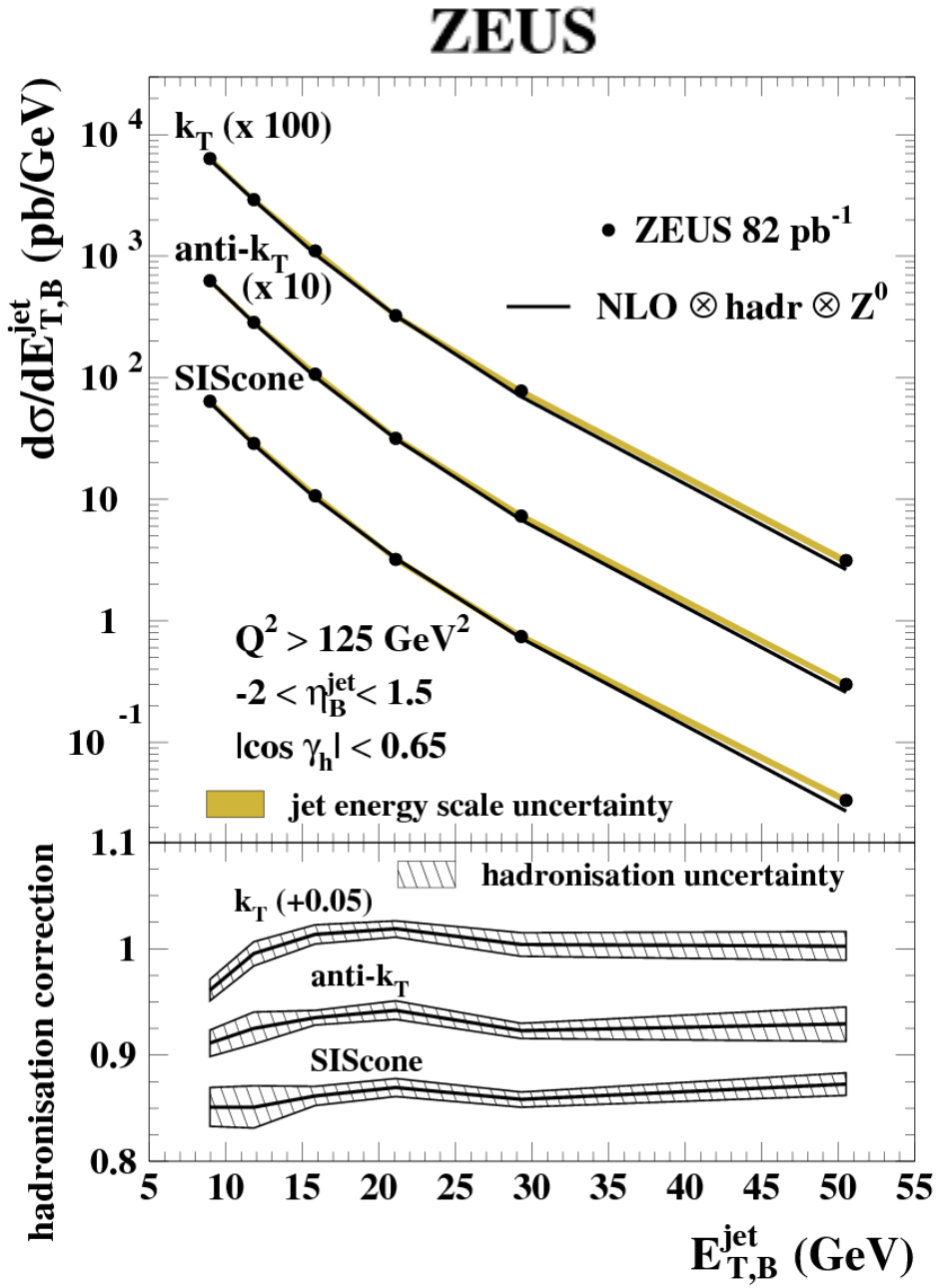


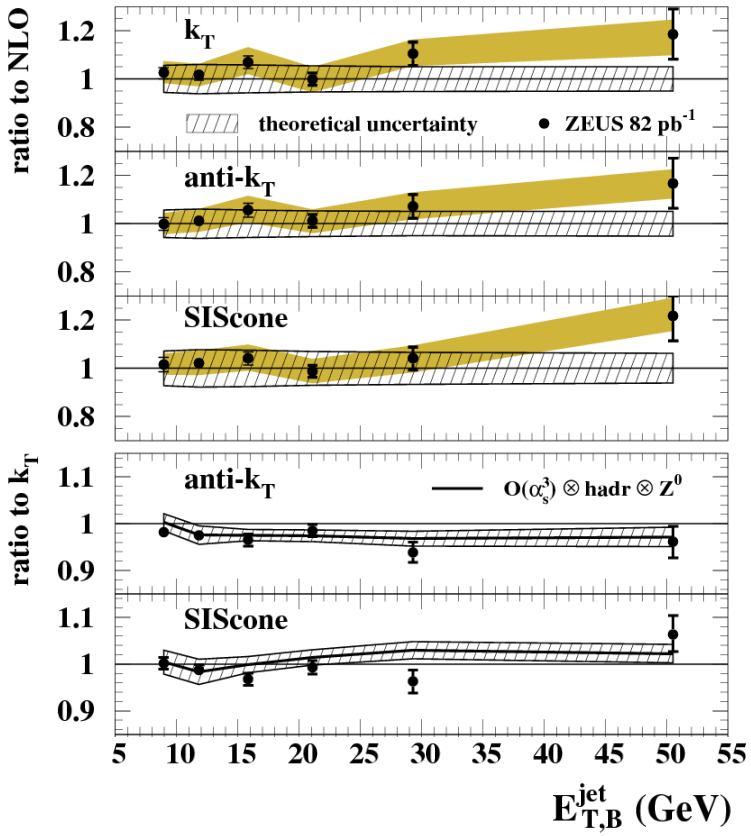
NLOJET++

- similar measurements also for
  photoproduction at HERA II

see talk
I. Makarenko

kt-, anti-kt and SisCone Jet production at high Q^2





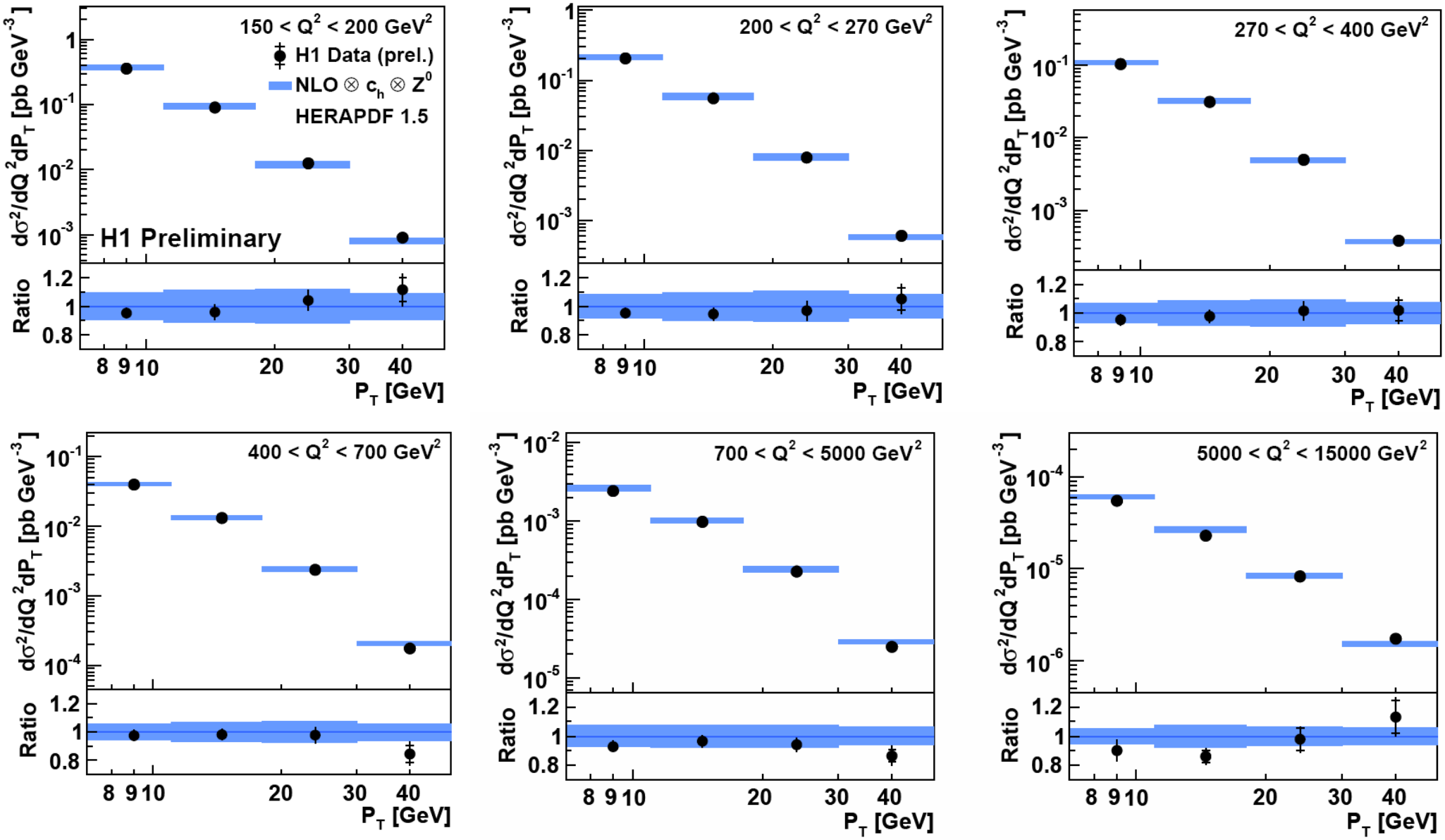
performance of all three jet algorithms very similar, well described by $O(\alpha_s^3)$ QCD

-> can safely be used at LHC

Inclusive jets in DIS

see talk
R. Kogler

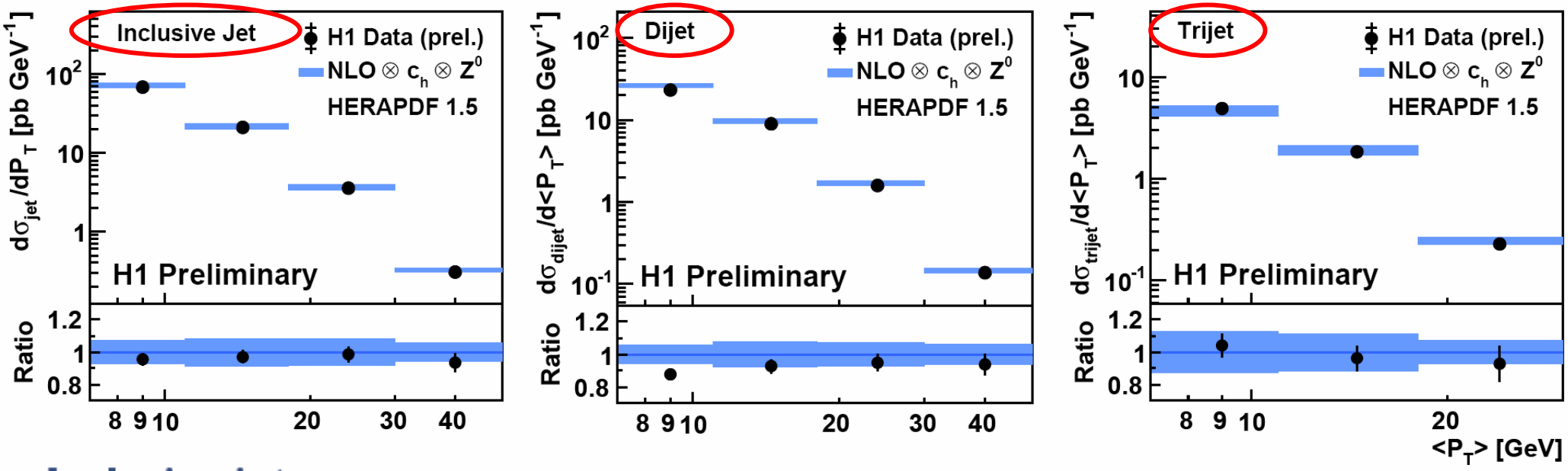
double differential in Q^2 and p_T



well described by NLO QCD + HERAPDF

Multijet production + α_s

see talk
R. Kogler



Inclusive jet:

$$\alpha_s(M_Z) = 0.1190 \pm 0.0021\ (\text{exp.}) \pm 0.0020\ (\text{pdf})\ ^{+0.0050}_{-0.0056}\ (\text{th.})$$

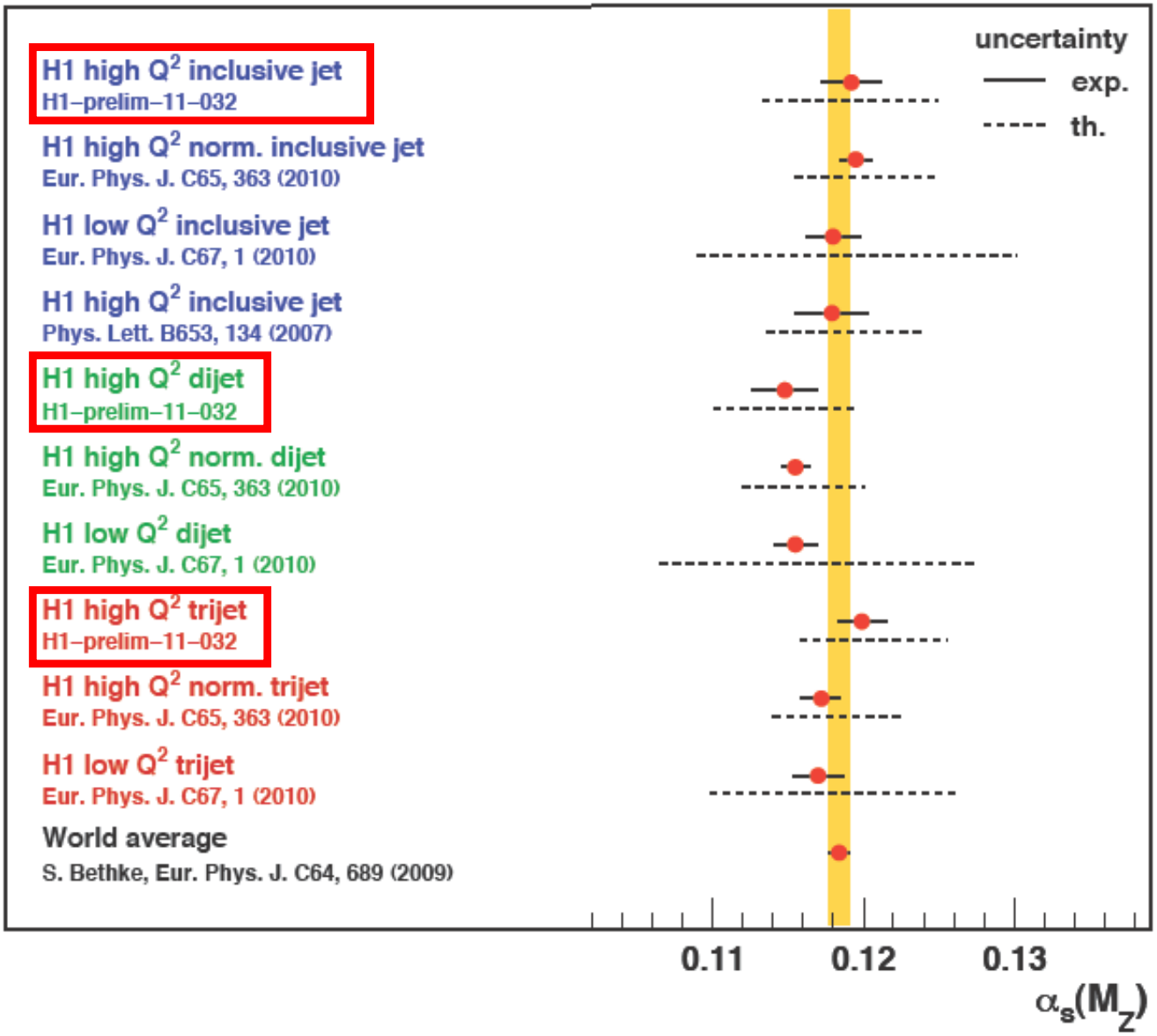
Dijet:

$$\alpha_s(M_Z) = 0.1146 \pm 0.0022\ (\text{exp.}) \pm 0.0021\ (\text{pdf})\ ^{+0.0044}_{-0.0045}\ (\text{th.})$$

Trijet: most precise ($\sim\alpha_s^2$)

$$\alpha_s(M_Z) = 0.1196 \pm 0.0016\ (\text{exp.}) \pm 0.0010\ (\text{pdf})\ ^{+0.0055}_{-0.0039}\ (\text{th.})$$

H1 summary of α_s measurements



see talk
R. Kogler

optimised for minimization of experimental uncertainties

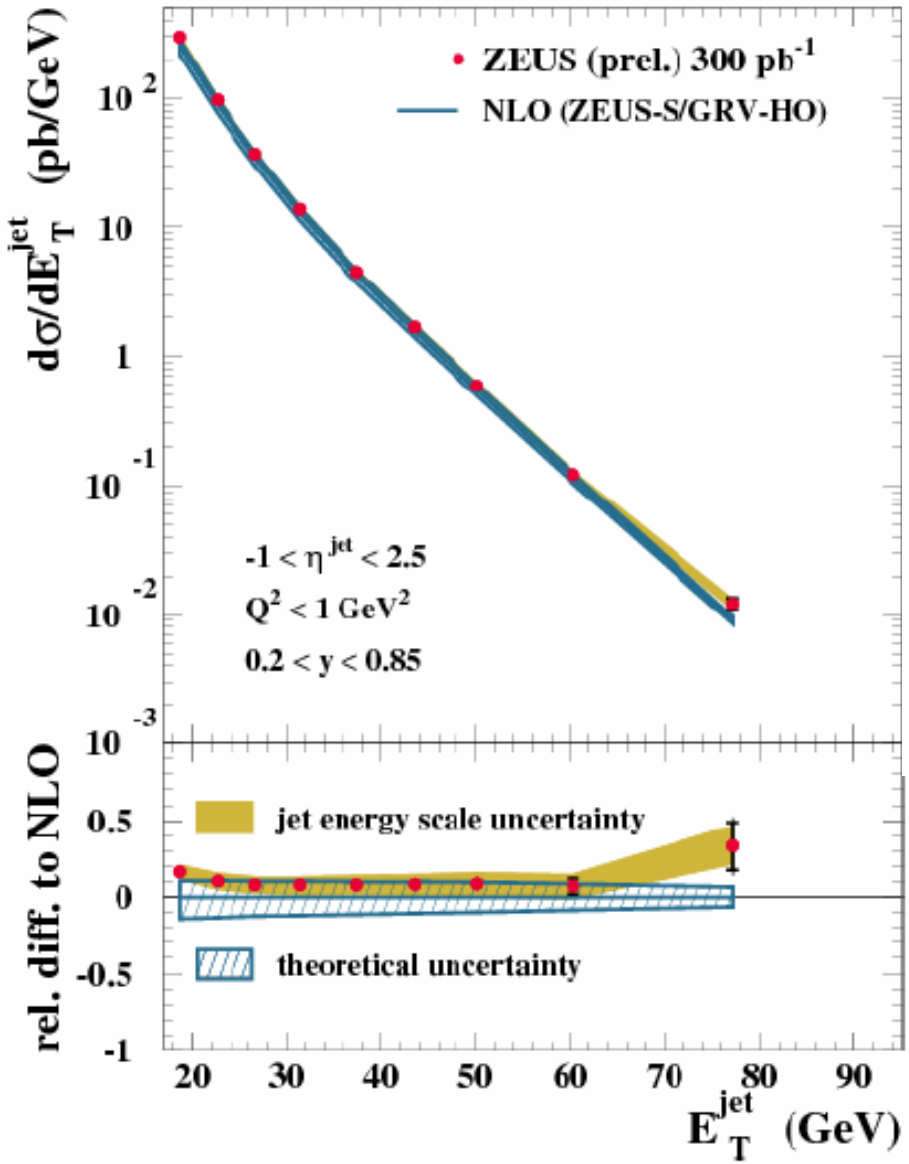
good agreement with previous measurements and world average

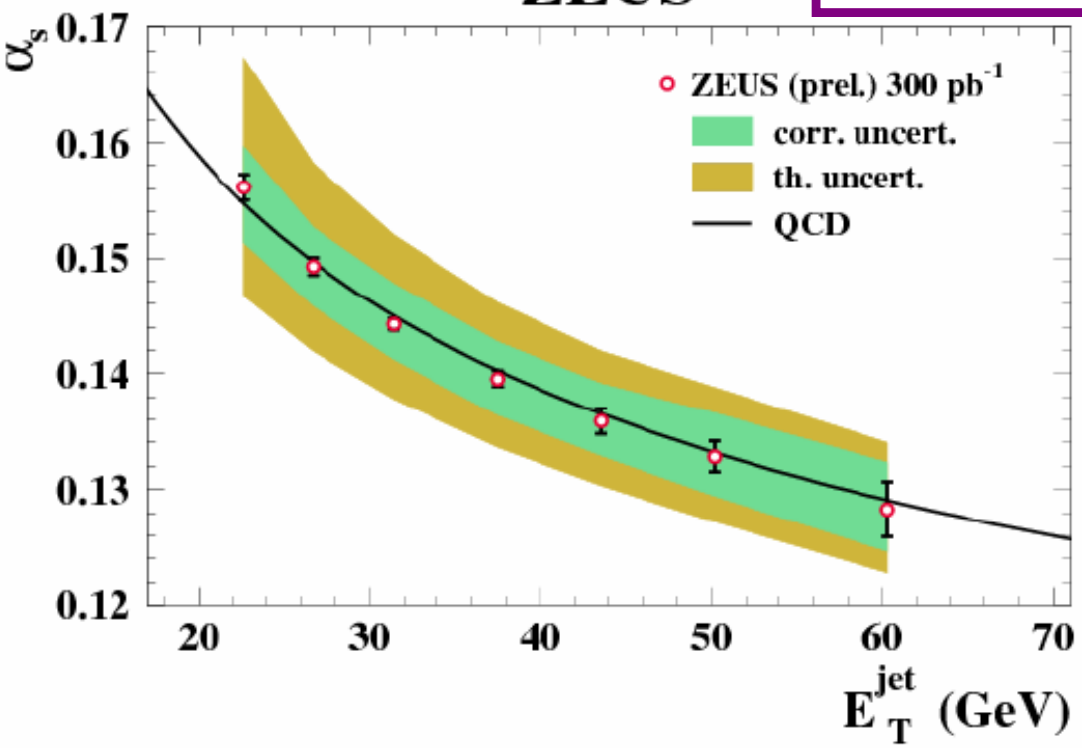
uncertainties dominated by NLO theory

Inclusive jets in photoproduction

see talk
I. Makarenko

full HERA II statistics





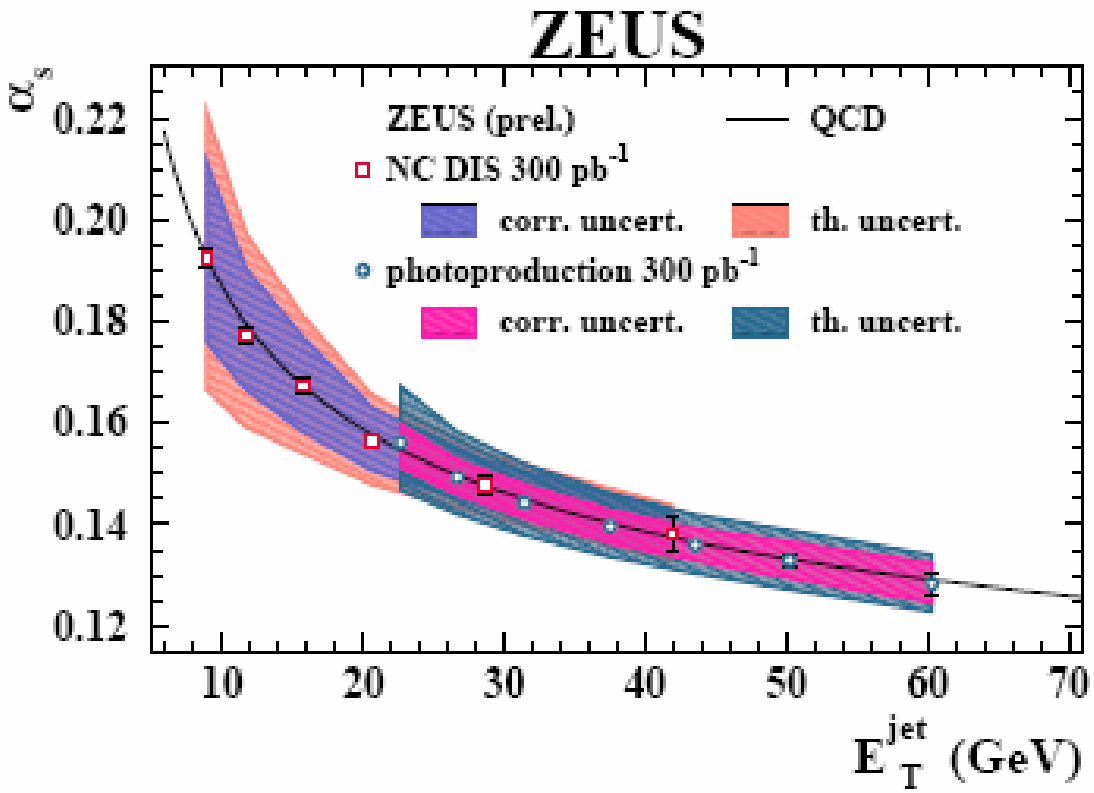
$$\alpha_S(M_Z) = 0.1206 \; ^{+0.0023}_{-0.0022}(exp.) \; ^{+0.0042}_{-0.0033}(theo.)$$

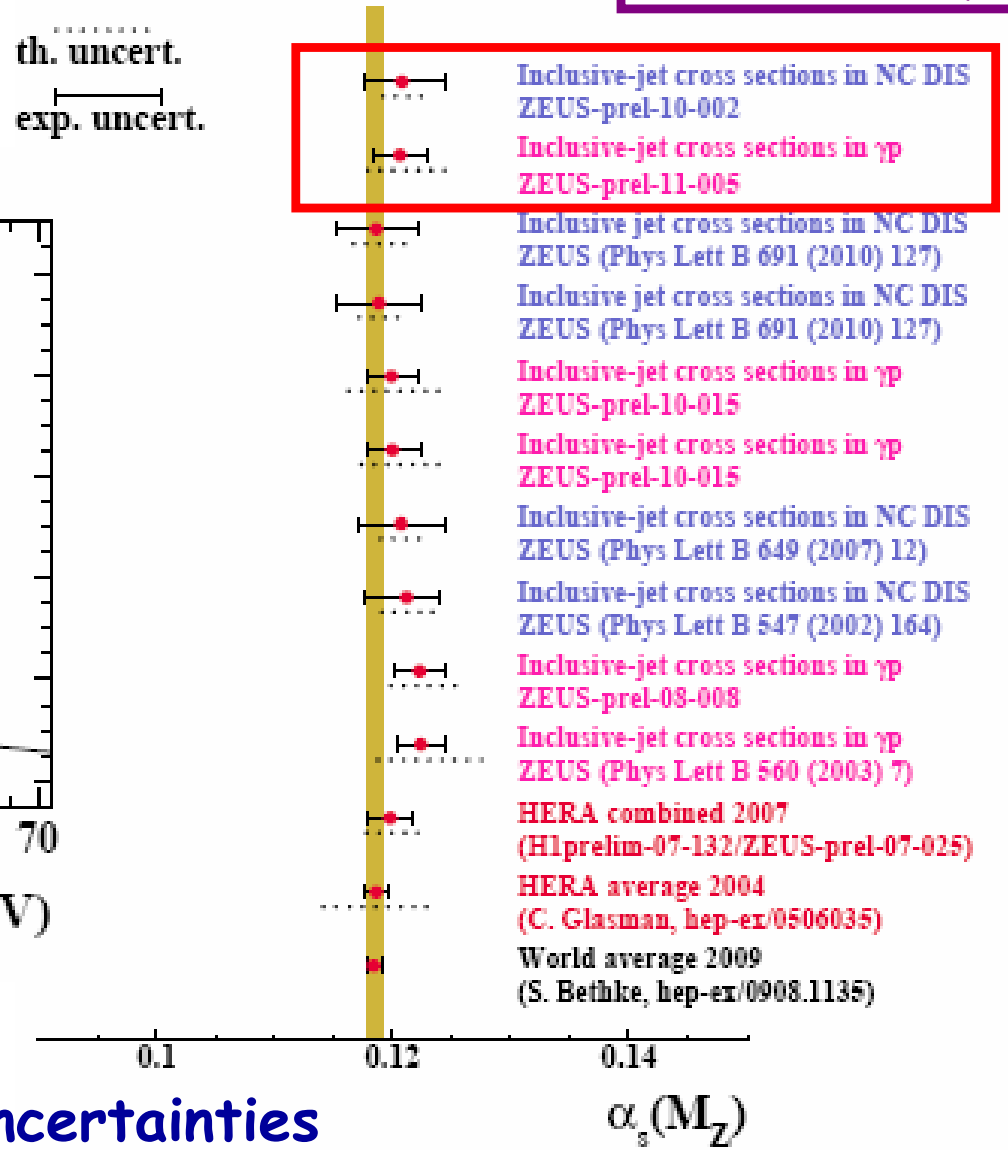
running of α_s consistent with QCD expectations

Summary of ZEUS α_s measurements

see talk
D. Lontkovskyi

α_s running



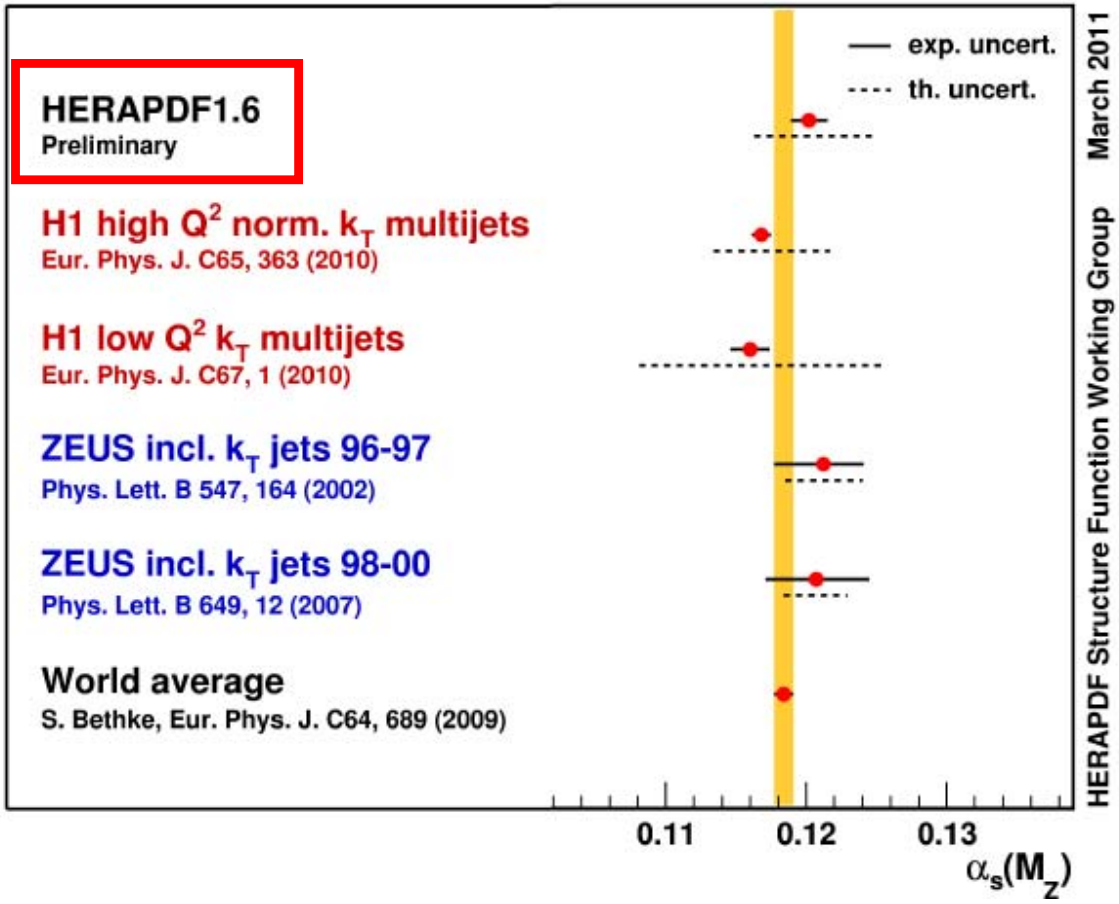


analyses optimized for minimization of theoretical uncertainties

Combined fit of HERAPDF + α_s

see talks
A. Glazov,
K. Nowak

$$\alpha_s = 0.1202 \pm 0.0013\,(\exp) \pm 0.0007\,(mod/par) \pm 0.0012\,(hadr) \; {}^{+0.045}_{-0.036}\,(scale)$$



good agreement with world average

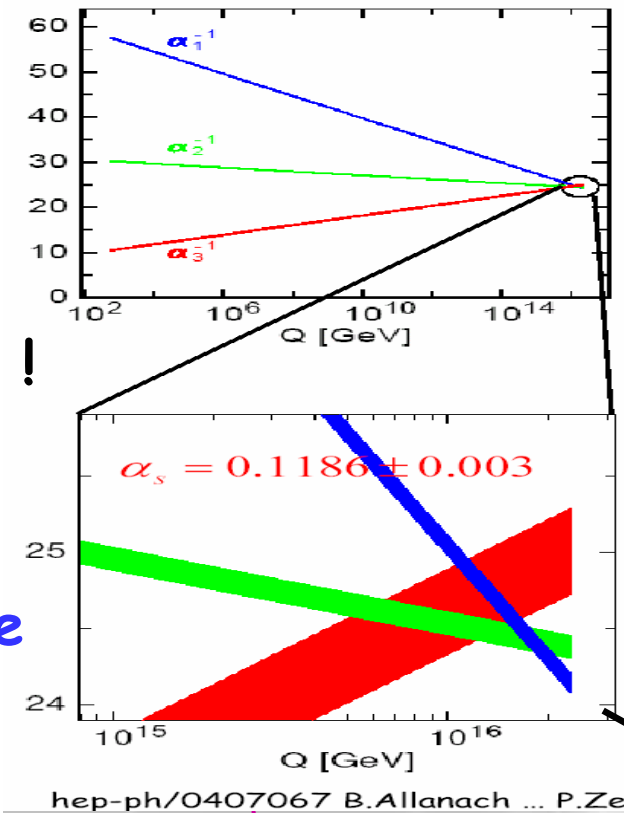
uncertainty dominated by NLO theory

reminder: α_s and grand unification

error on α_s dominates (theory!)

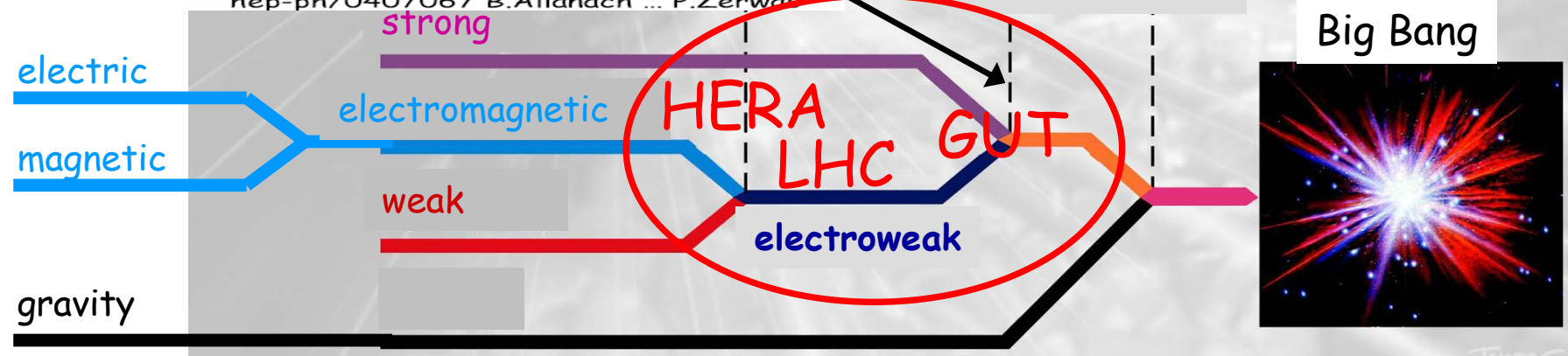
=> need NNLO QCD !

=> HERA would yield most precise α_s value (O(1-2%))



SUSY
Grand Unification

If SUSY found at LHC, HERA will help to test GUT models



encouragement

would like to express strong encouragement to the brave theory collegues who are engaged in such difficult NNLO calculations for HERA

for (some) recent progress, see e.g. HERA-LHC and PDF4LHC workshops, and theory talks at this meeting

Heavy Flavours

Why are heavy flavours important?

- charm contribution to HERA data up to 30%! (beauty ~1-3%)
- **kinematic effect of mass**
- **competing scales for perturbative expansion**

  e.g. m, Q^2, p_T -> terms $\log Q^2/m^2$

  $\log p_T^2/m^2$ etc.

=> "**massless**" treatment (ZM-VFNS) allows resummation, but fails near "mass threshold" -> avoid !

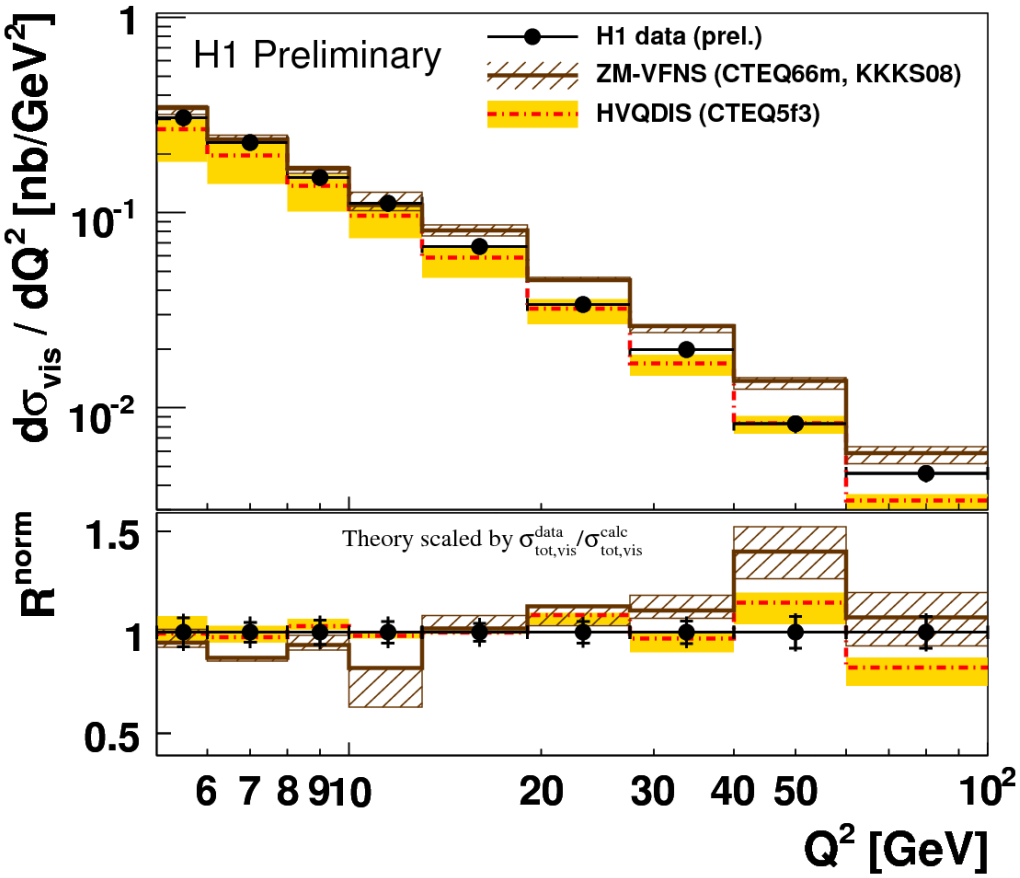
=> "**massive**" treatment gets kinematics right,
but does not allow resummation (fixed flavour number schemes, FFNS)
or induces ambiguities in QCD corrections near flavour threshold
(variable flavour number schemes, GM-VFNS)

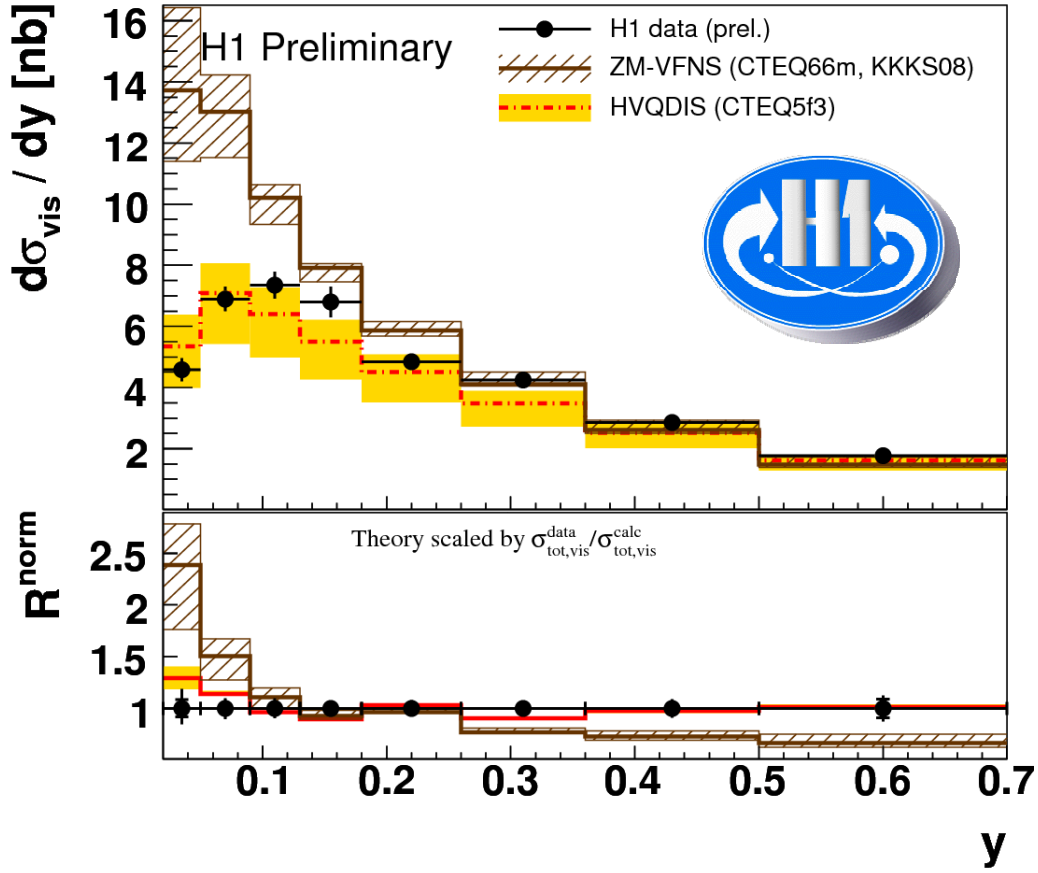
check different schemes against HERA data

Charm in DIS from D* production

see talk A. Jung

large phase space coverage: $p_T(D^*) > 1.25$ GeV, $|\eta(D^*)|<1.8$





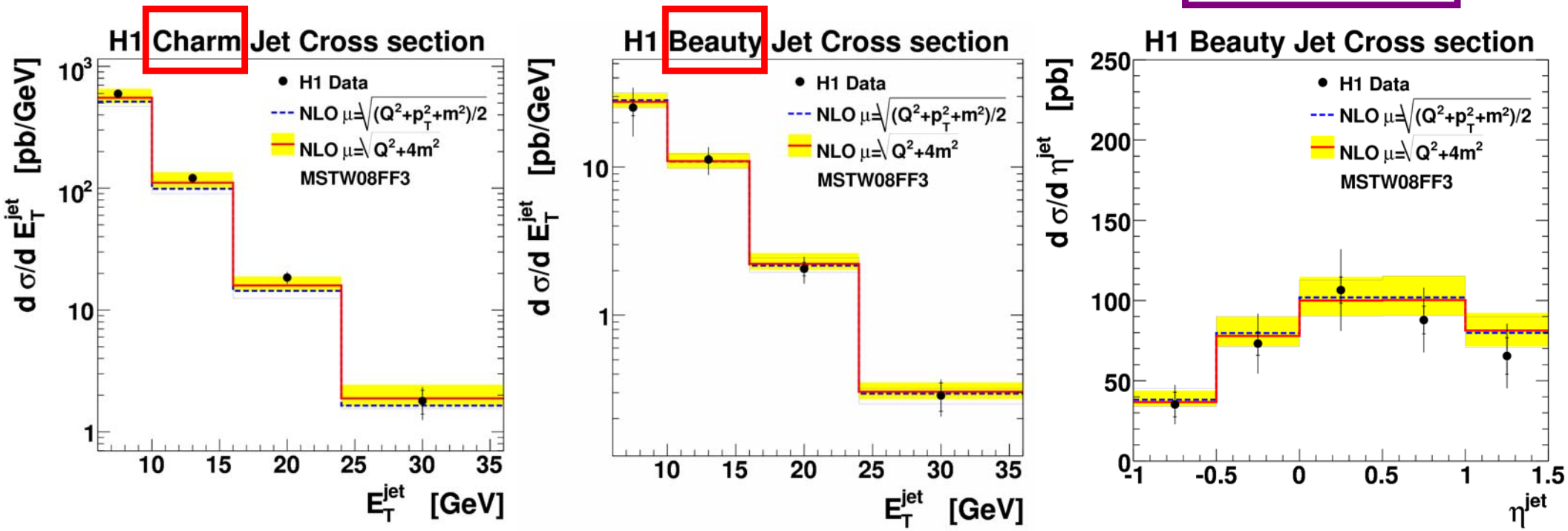
NLO: massive FFNS (HVQDIS) OK, massless ZM-VFNS fails

Beauty and Charm jets in DIS

from secondary vertices

DESY-10-083, Eur.Phys.J. C71 (2011) 150

see talk
P. Thompson



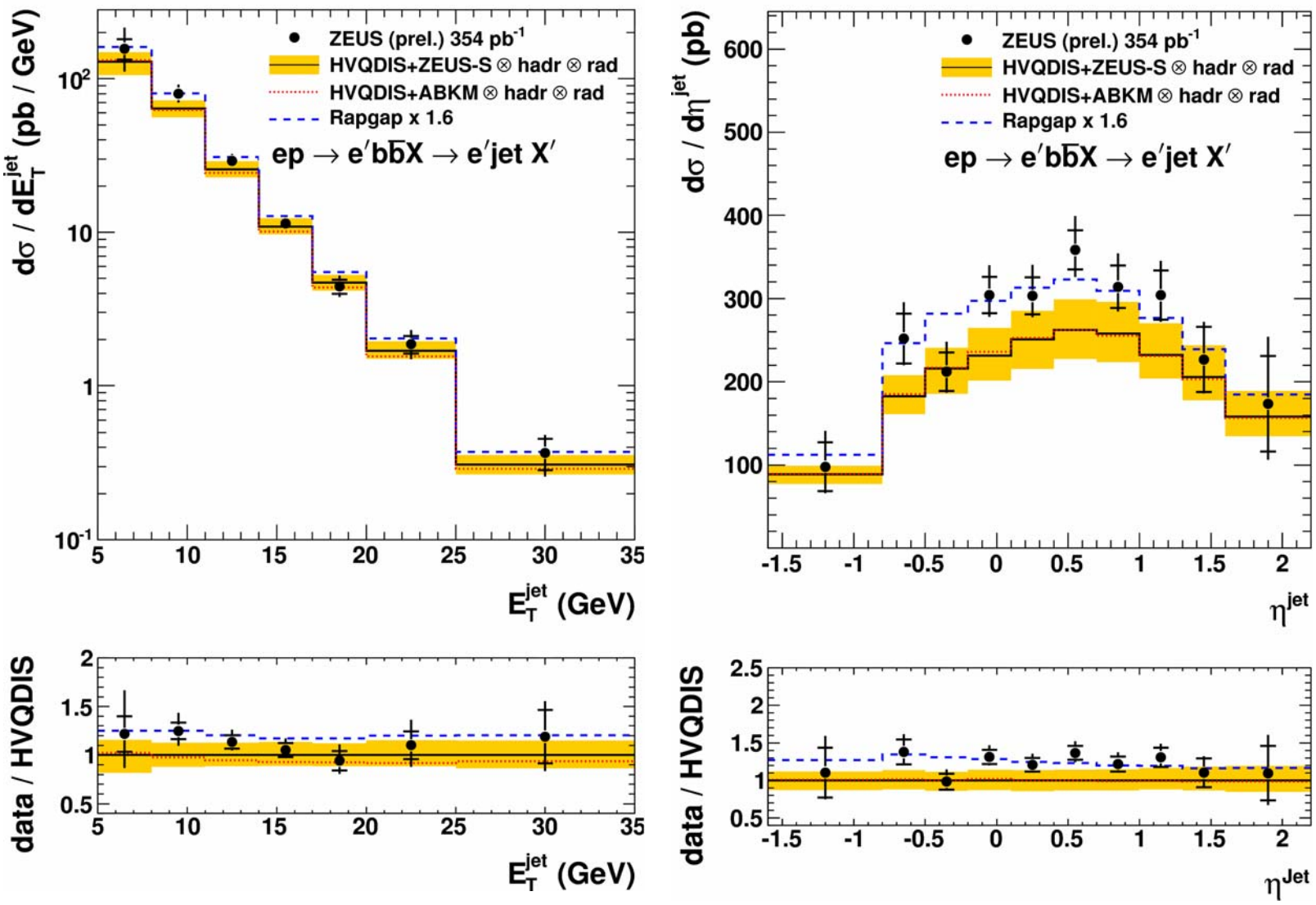
data well described by FFNS NLO QCD prediction

Beauty jets in DIS

from secondary vertices

ZEUS

ZEUS $Q^2 > 4\ GeV^2$ ZEUS



see talk V. Libov

most precise measurement so far

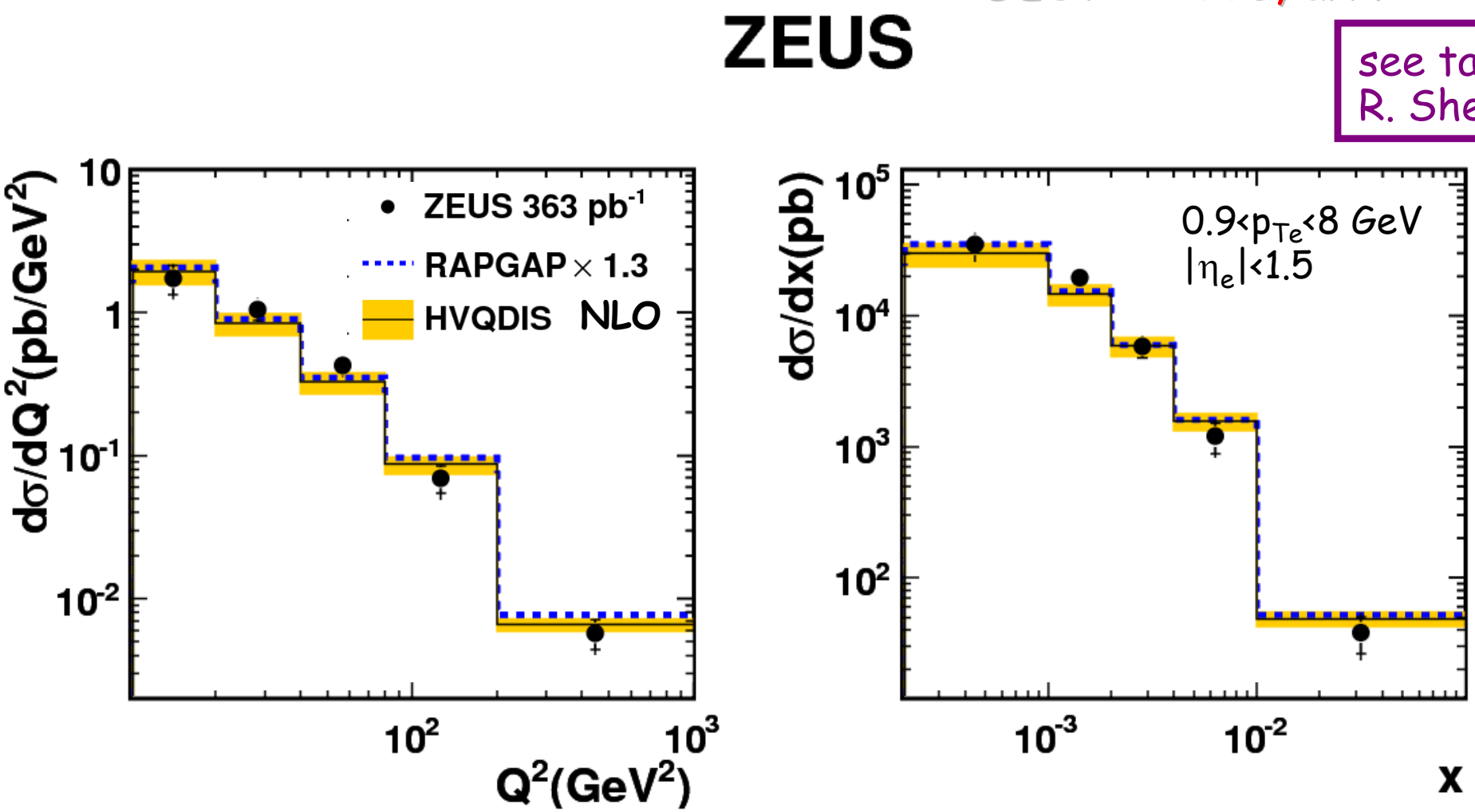
almost full phase space coverage

NLO QCD: massive FFNS (HVQDIS) a bit low but OK

Beauty in DIS from b->e decays

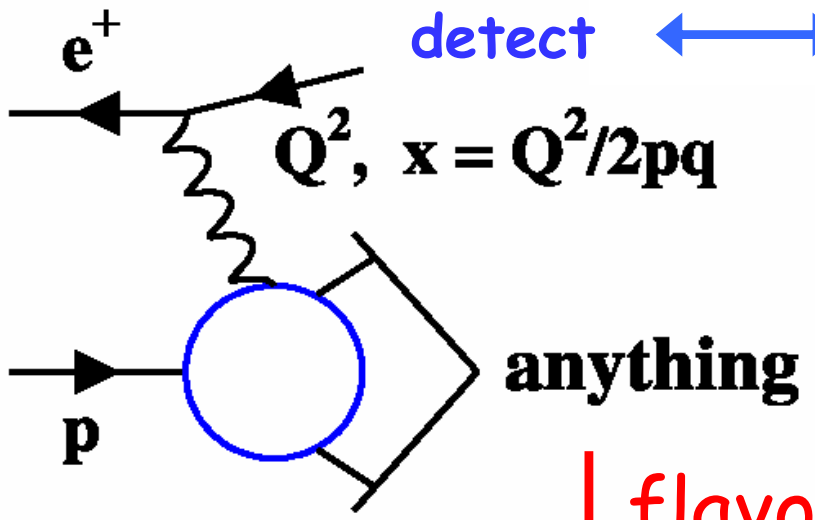
DESY-11-005, arXiv:1101.3692

see talk
R. Shehzadi



also double differential in Q^2 and x

Heavy flavour contributions to F_2

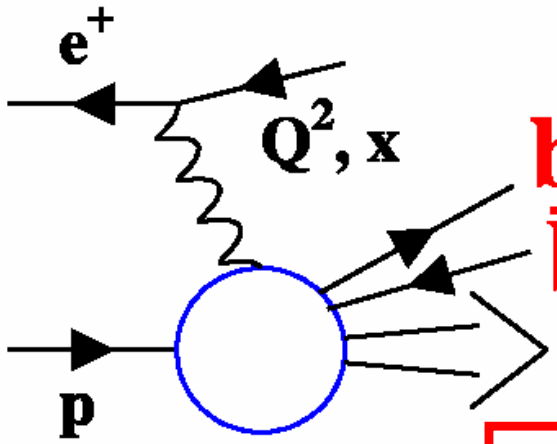


detect

Measure cross section

$$\frac{d^2\sigma}{dx\,dQ^2} \cong \frac{2\pi\alpha^2}{Q^4 x}\left\{\left[1+(1-y)^2\right] F_2(x,Q^2)\right.$$

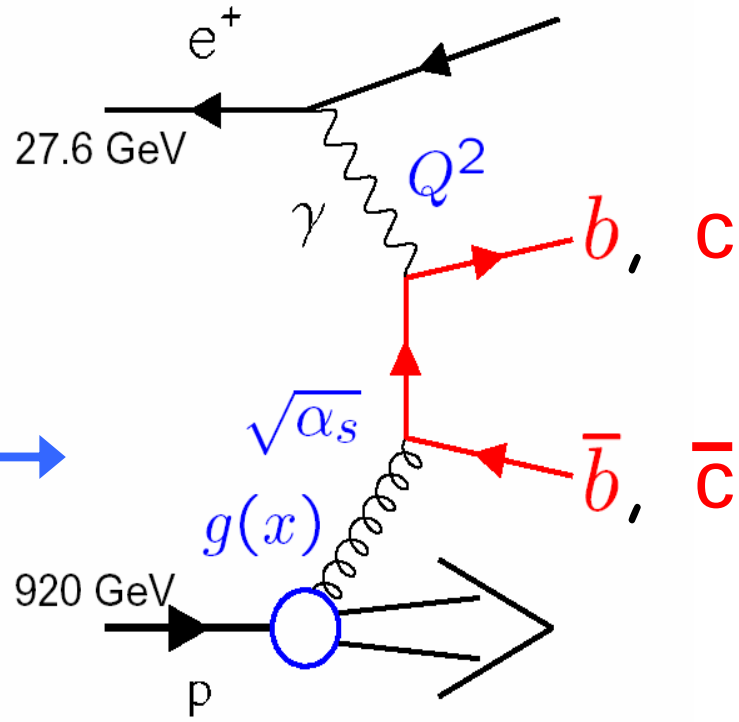
flavour tagging



$b\bar{b}$ or $c\bar{c}$

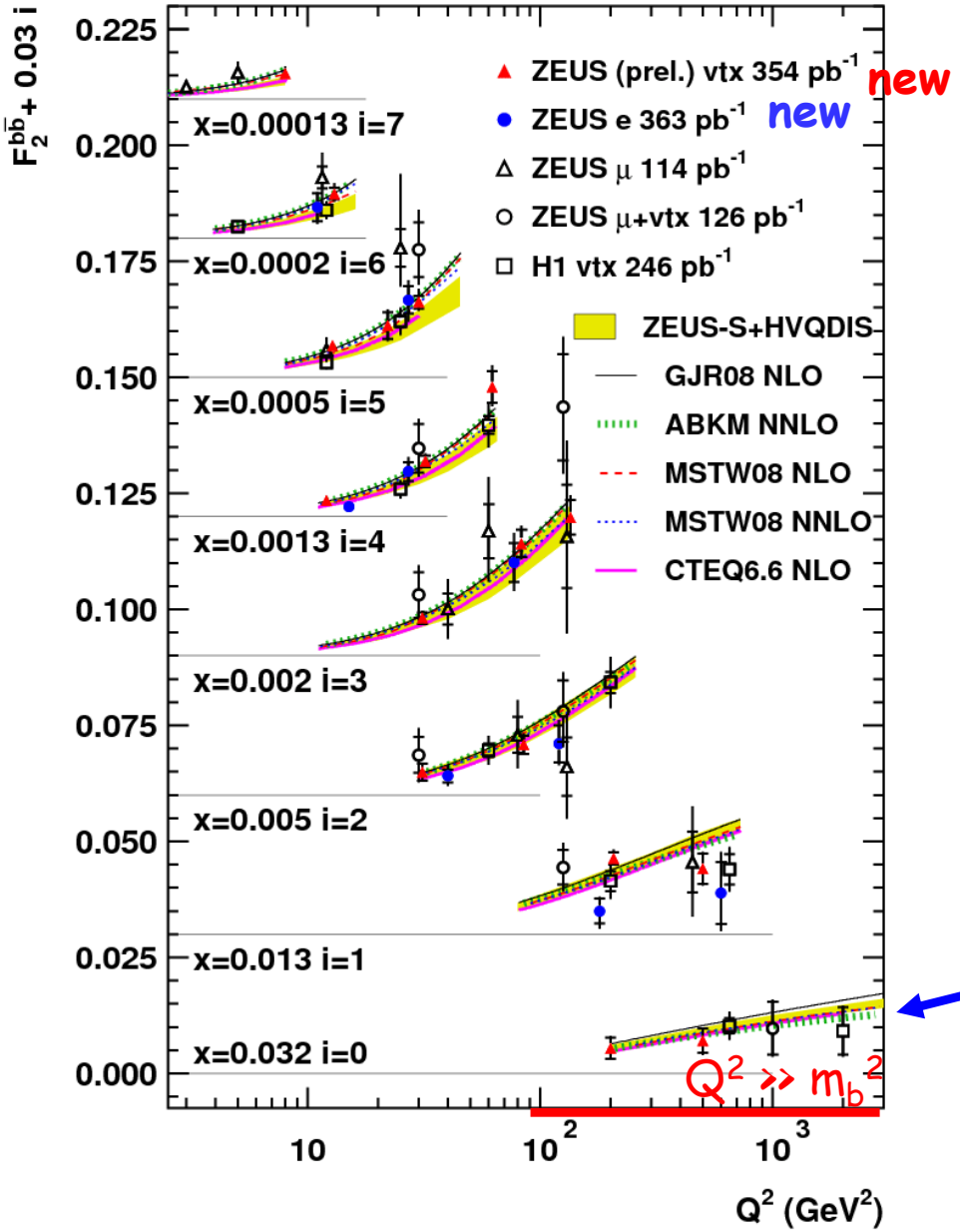
-> $F_2^{b\bar{b}}$, $F_2^{c\bar{c}}$

QCD



beauty contribution to F_2

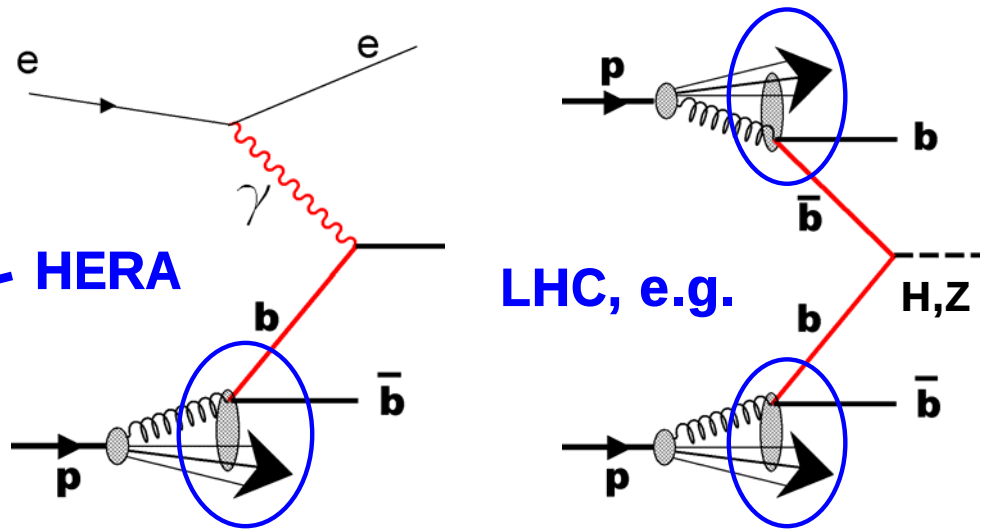
see talk
V. Libov



NLO and partial NNLO QCD in agreement with data,

NNLO slightly better

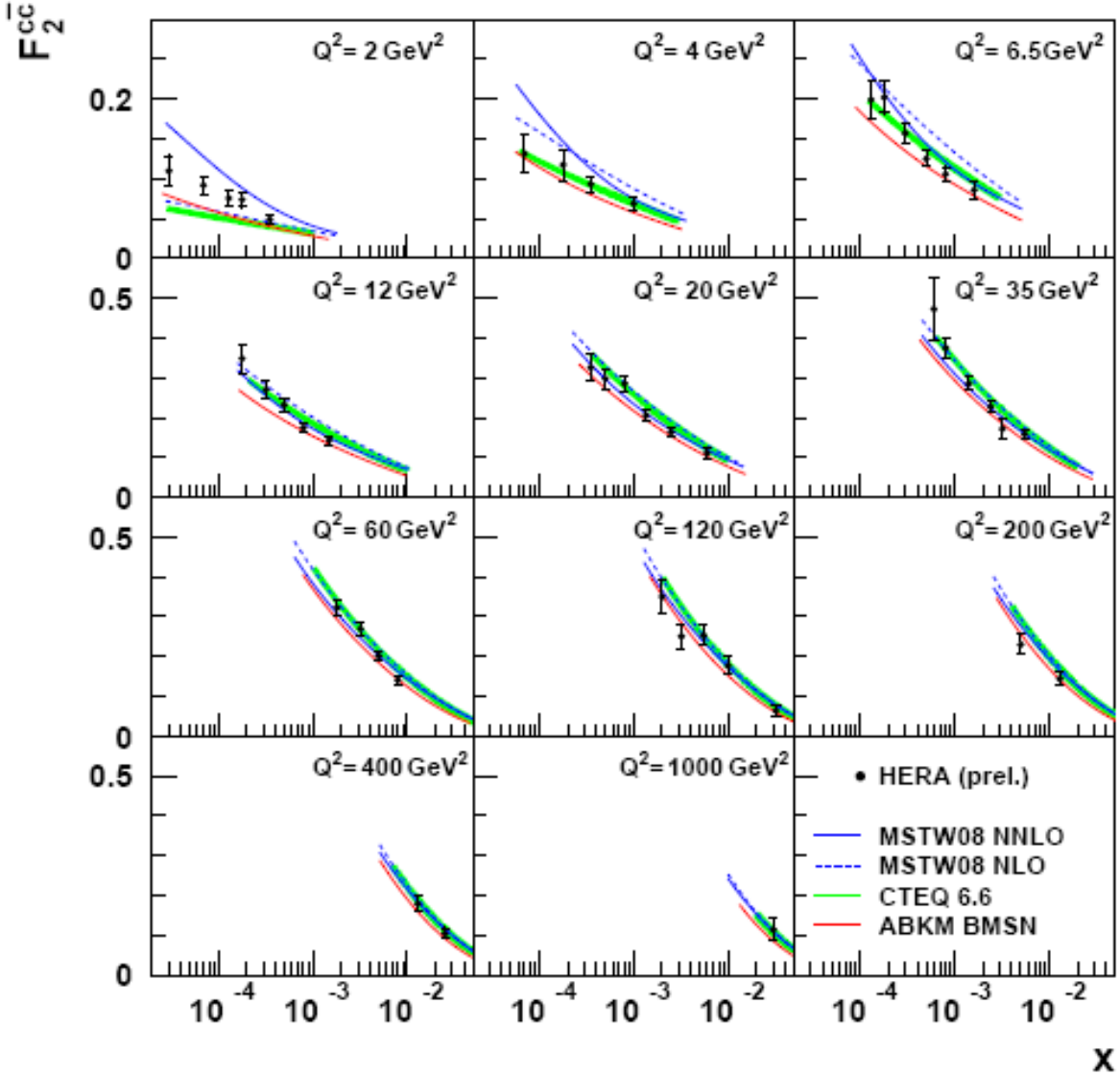
check b PDF for LHC:



charm contribution to F_2

combined HERA (H1 and ZEUS) charm data:

see talks
A. Glazov,
R. Placakyte



sensitive to m_c and to differences in Heavy Flavour schemes

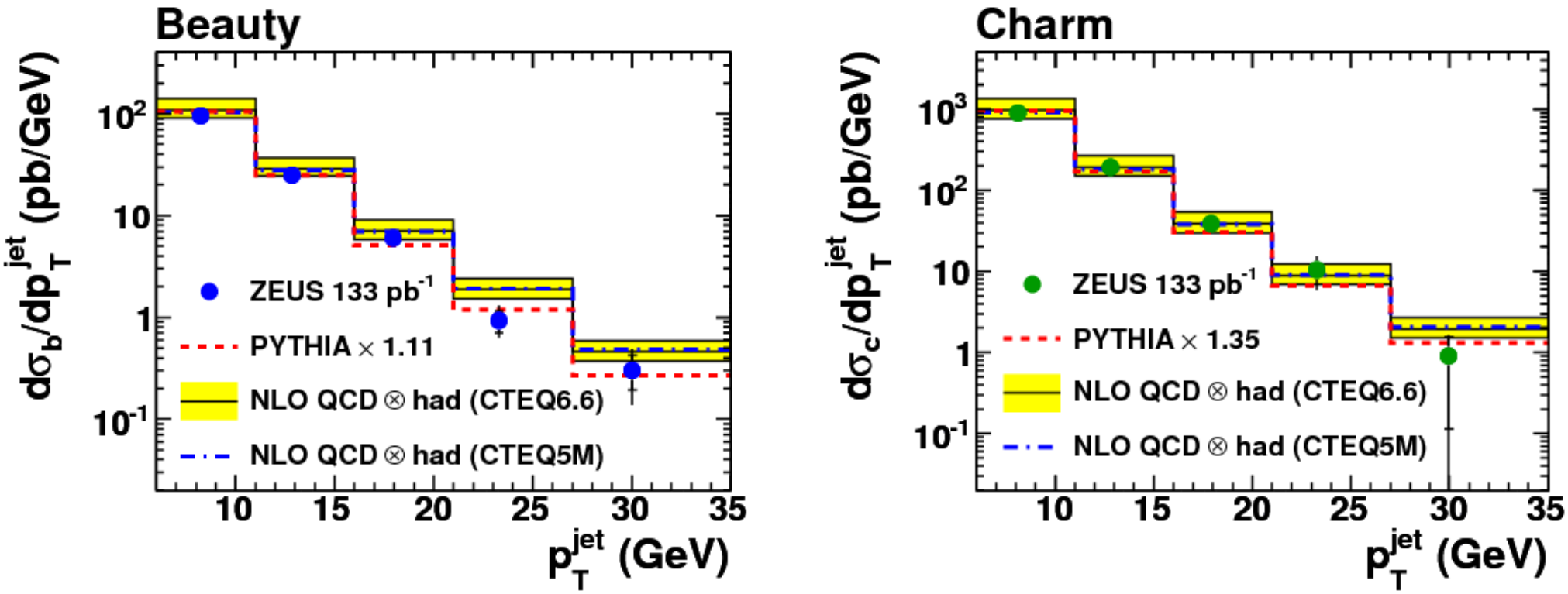
here: massive VFNS schemes

fit to these data reduces uncertainties on W/Z cross sections at LHC (next talk)

beauty and charm jets in photoprod.

from secondary vertices

see talk
I. Brock

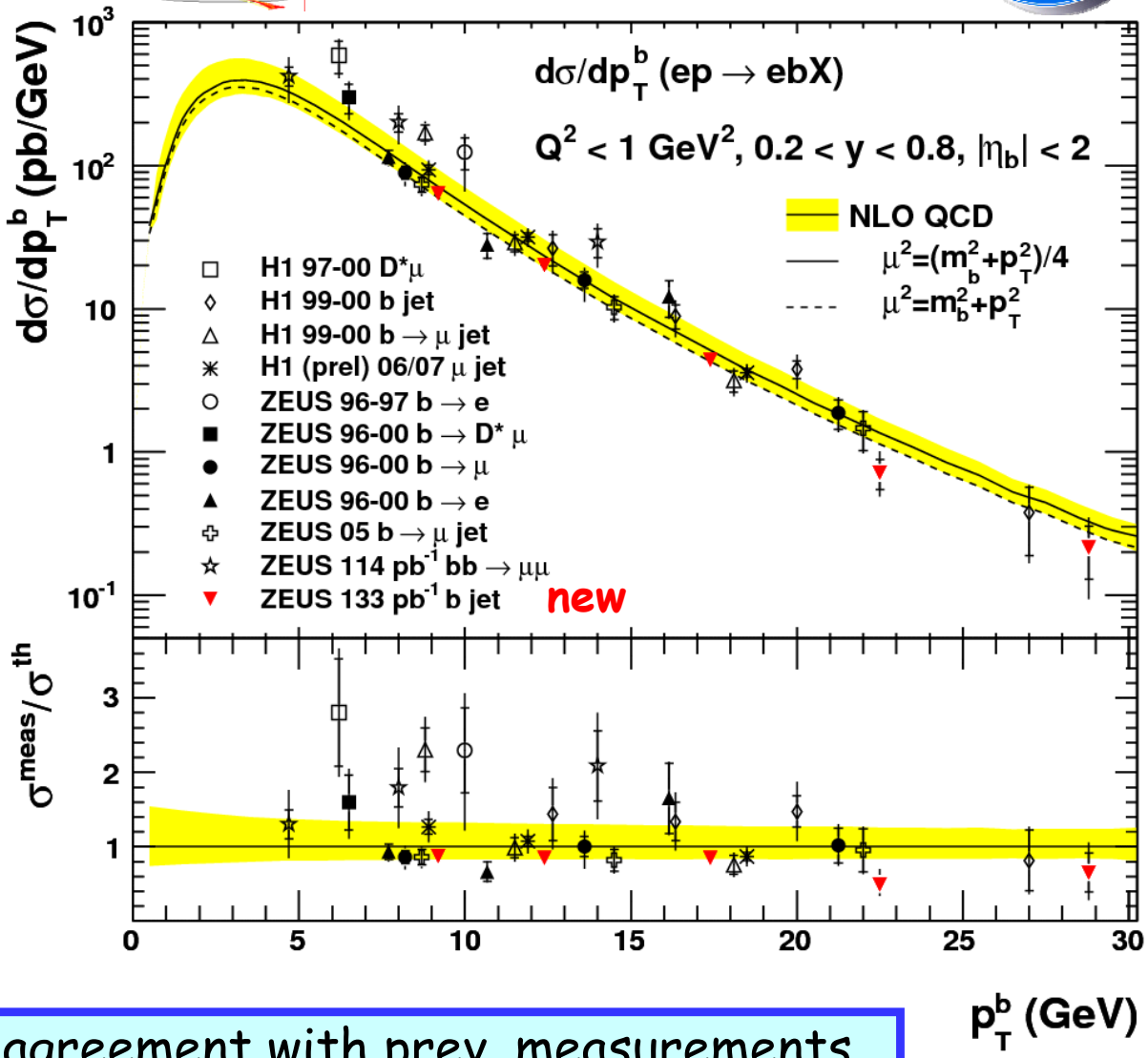


reasonably described by
NLO QCD up to high p_T

beauty in photoproduction

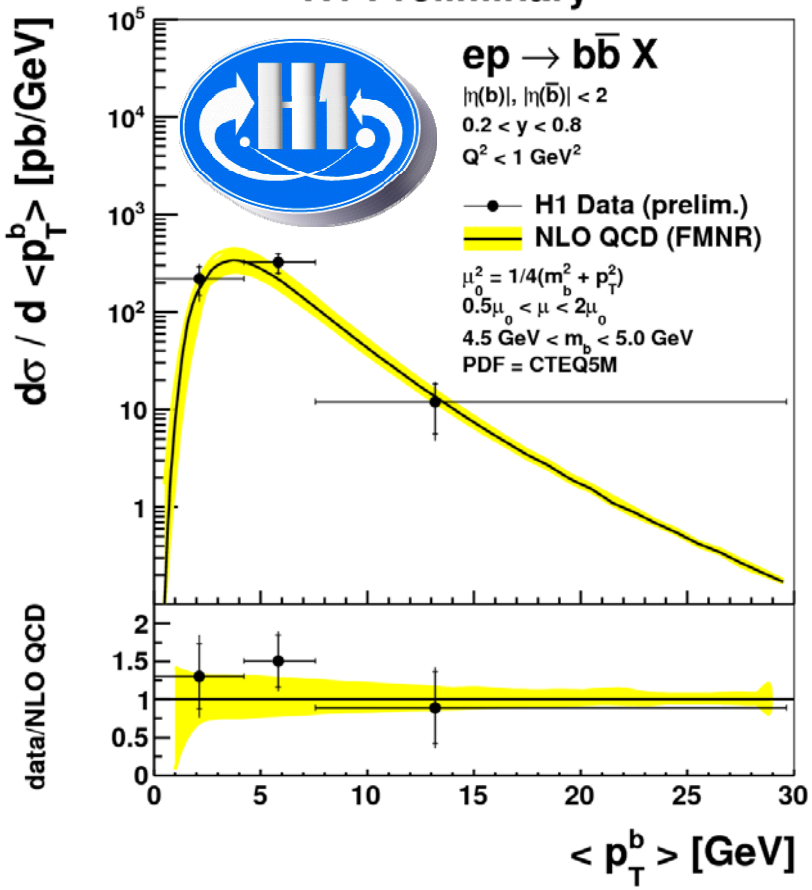
see talk
M. Sauter

HERA



from $b\bar{b}$ -> ee

new H1 Preliminary



agreement with prev. measurements

reasonably described by NLO QCD down to threshold

Jets in Diffraction

Forward Jets in Diffraction

see talk
R. Polifka

proton tagged by forward proton spectrometer

$4 < Q^2 < 110\ \mathrm{GeV}^2$

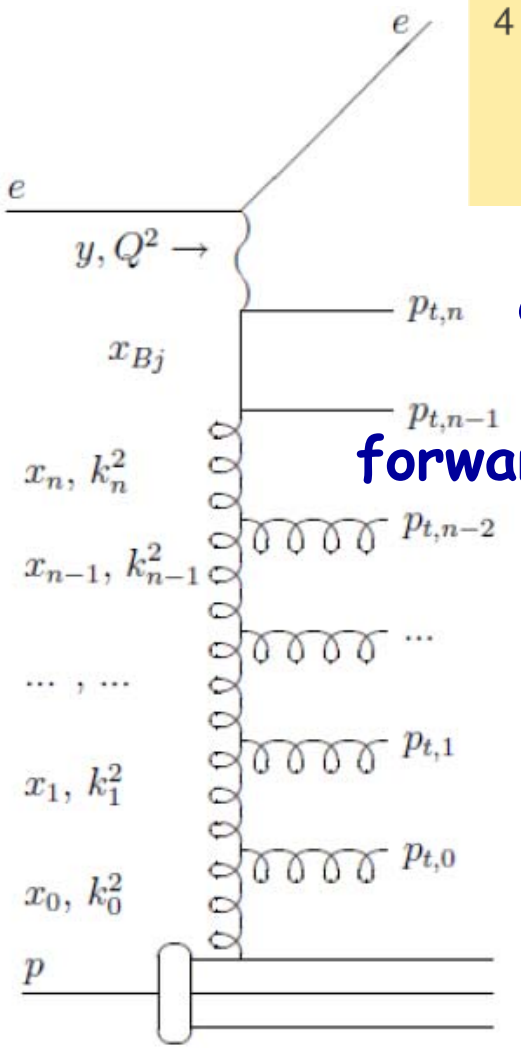
$0.05 < y < 0.7$

$X_{IP} < 0.1$

$p^*_{T,forward} > 4.5$ GeV, $p^*_{T,central} > 3.5$ GeV

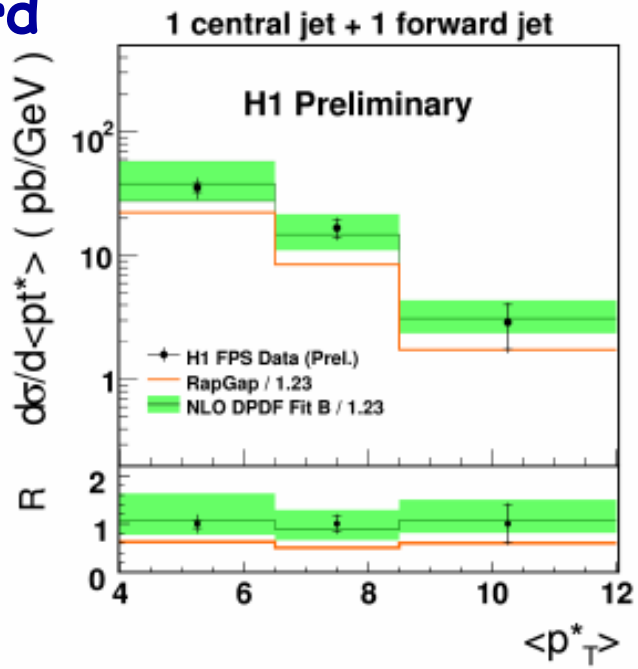
$1 < \eta_{forward} < 2.8$, $-1 < \eta_{central} < 2.5$

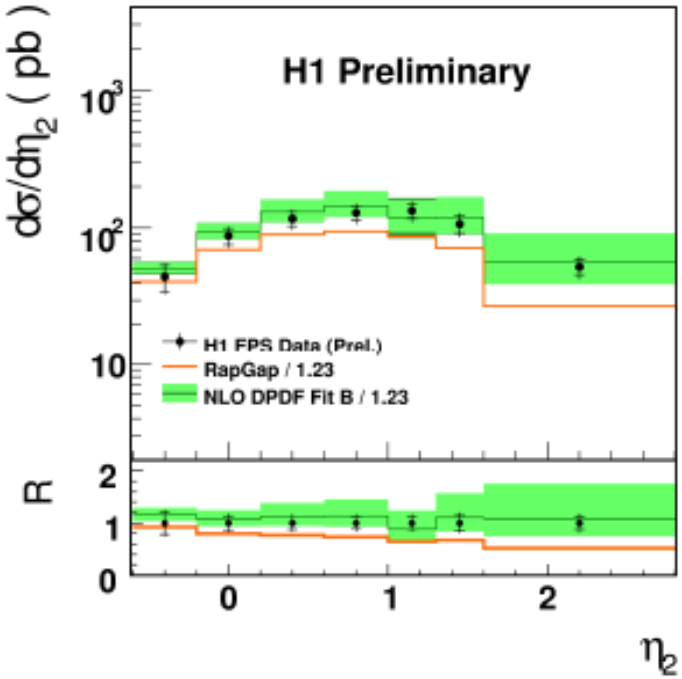
$\eta_{central} < \eta_{forward}$



central

forward



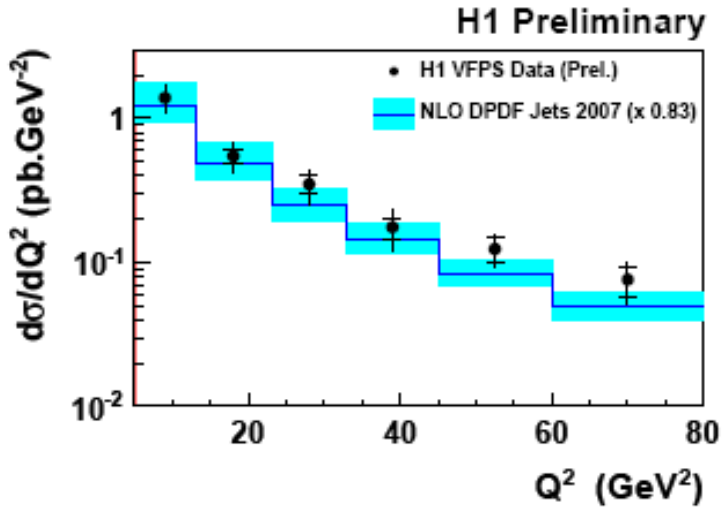


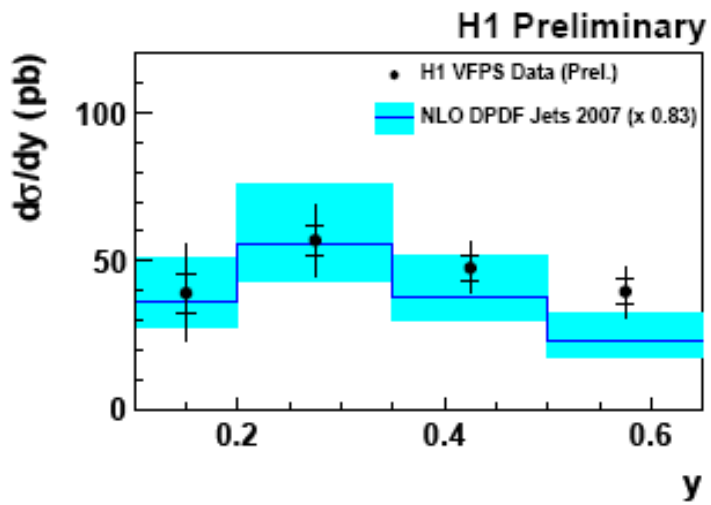
good agreement with DGLAP NLO prediction

Diffractive dijets in DIS

proton tagged by very forward proton spectrometer

see talk
J. Delvax





Jets in $\gamma^* - p$ frame

$P^*_{t,jet1} > 5.5 GeV$

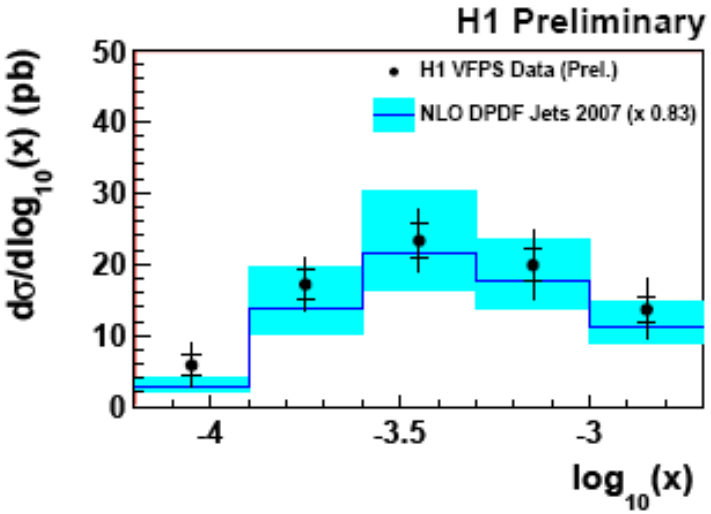
$P^*_{t,jet2} > 4 GeV$

$0.009 < x_{\mathbb{P}} < 0.024$

$5 < Q^2 < 80\ GeV^2$

$0.1 < y < 0.65$

$-3 < \eta^*_{j1,j2} < 0$



agreement between
NLO predictions using Fit Jets
2007 and Data
in shape and normalisation

Summary and conclusions

- **HERA still one of the best QCD laboratories**
  in general, **agreement with NLO QCD, success of the Standard Model !**
  (-> limits on new physics, see talks G. Brandt, E. Gallo, H. Pirumov, D. South)

- **HERA jet measurements successfully test and constrain QCD parameters**
  -> potential to yield world best measurements of α_s
  (need NNLO calculations ! partially in progress).

- **Heavy Flavour measurements at HERA successfully described by QCD, contribute to improve cross section predictions for LHC**

- new results on **diffractive jet production with tagged forward protons in agreement with DGLAP QCD expectations**

- for QCD only fraction of statistics has been analyzed so far in many cases.
  combination of H1/ZEUS results ongoing
  -> **towards full 1 fb^{-1} results (H1+ZEUS, HERA1+2)**.
  -> expect **significant further improvements** over next few years