From the HERAscale to the Terascale:
QCD results from HERA and implications for LHC

Achim Geiser, DESY Hamburg

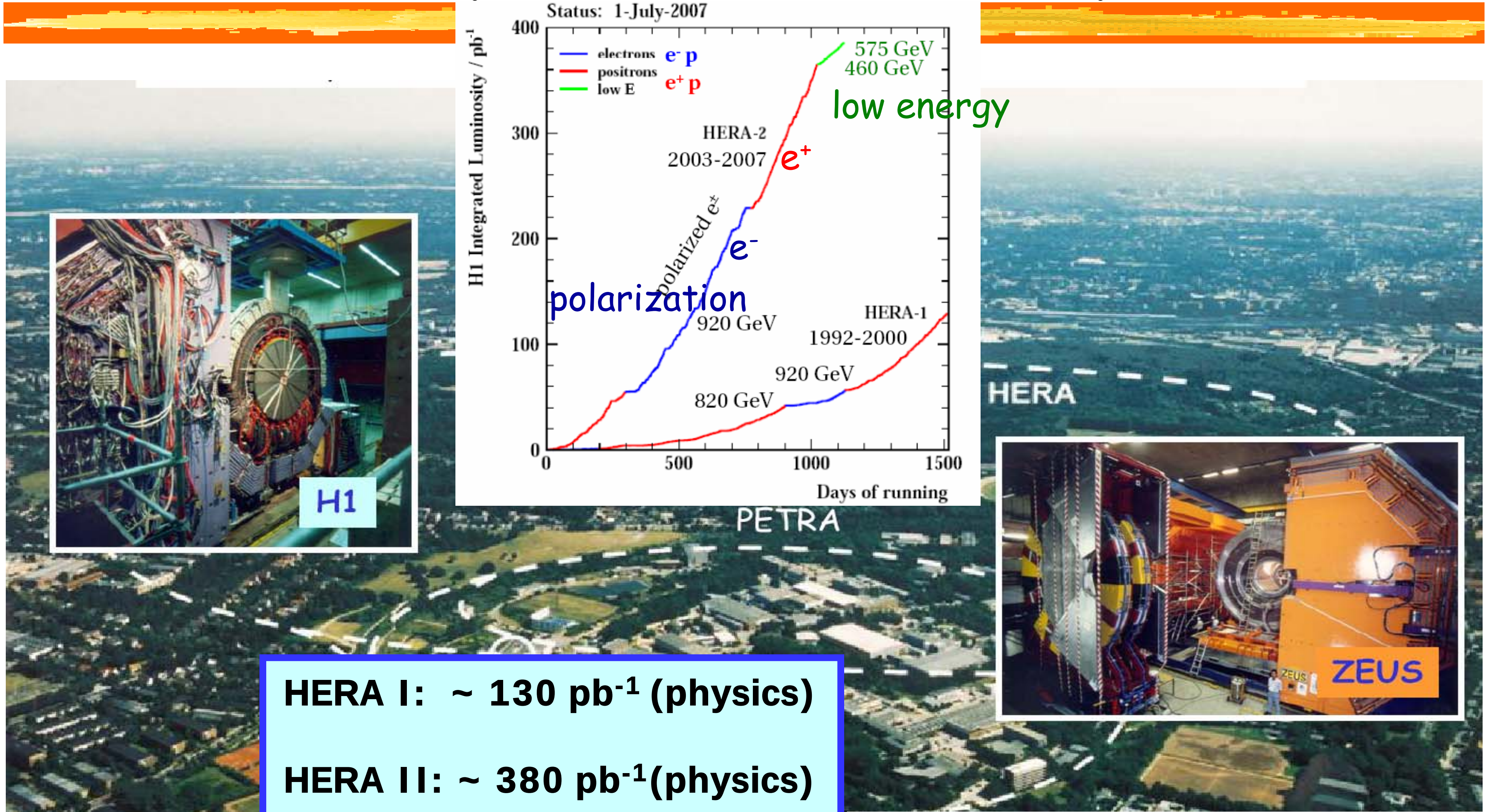
workshop on QCD at the LHC
ECT, Trento, Italy, September 28, 2010

- **HERA as a proton imaging device** (proton structure and PDFs)
- **HERA as a QCD machine**
  (jets, α_s, heavy flavours, colour strings)
- **Conclusions**

sorry for omitting diffraction

disclaimer: not all of the material necessarily reflects the views of the ZEUS and H1 collaborations

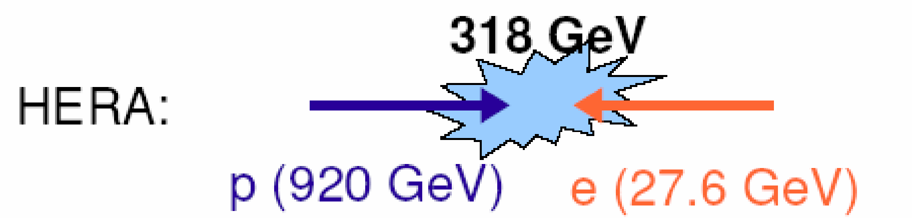
The HERA ep collider and experiments



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

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

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



Some aspects of comparison HERA-LHC

HERA

ep: soft QCD effects
larger than e^+e^-, smaller than pp
mostly well measured and parametrized

very well suited to measure
proton structure and precise
Standard Model (SM) effects
at scales up to ~100 GeV ("HERAscale")

small window of opportunity for
new physics particularly
sensitive to ep initial state

not discussed here

LHC

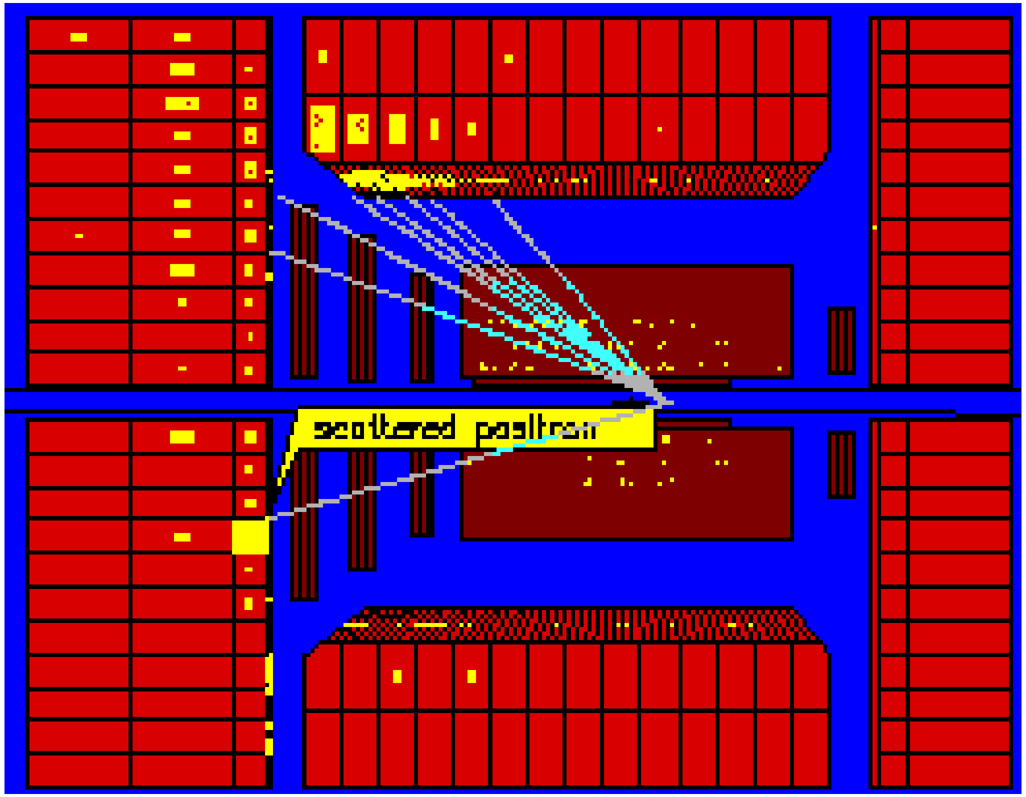
pp: large soft QCD effects
mostly still to be measured

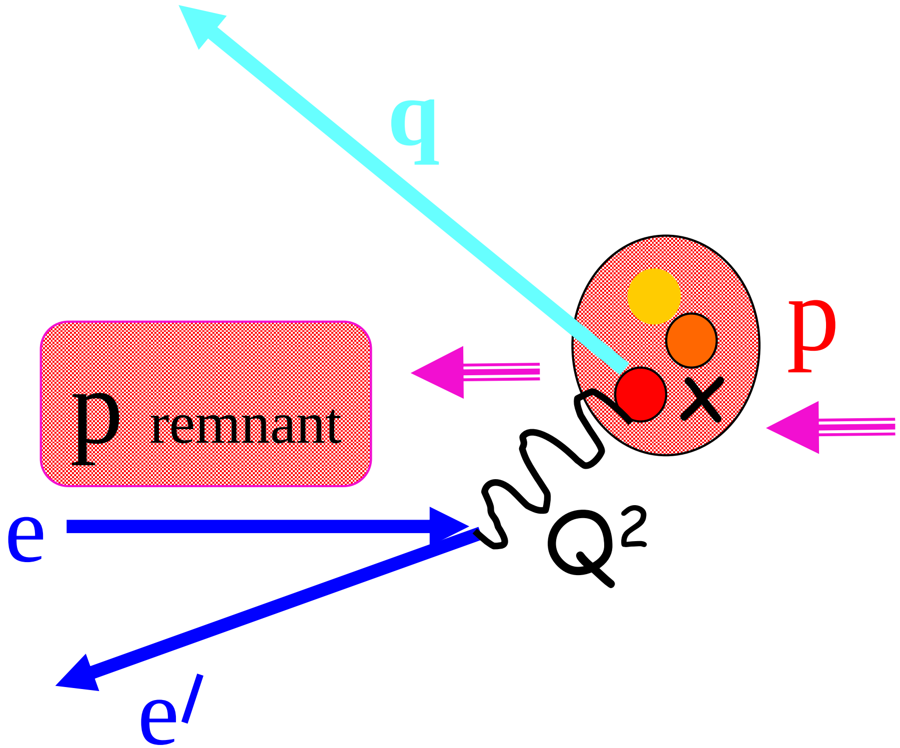
proton structure needs
external input (e.g. HERA).
SM measurements at higher
energy but often less precise

large sensitivity to
new physics up to scale of
several TeV (Terascale)

complementary!

Deep Inelastic ep Scattering at HERA

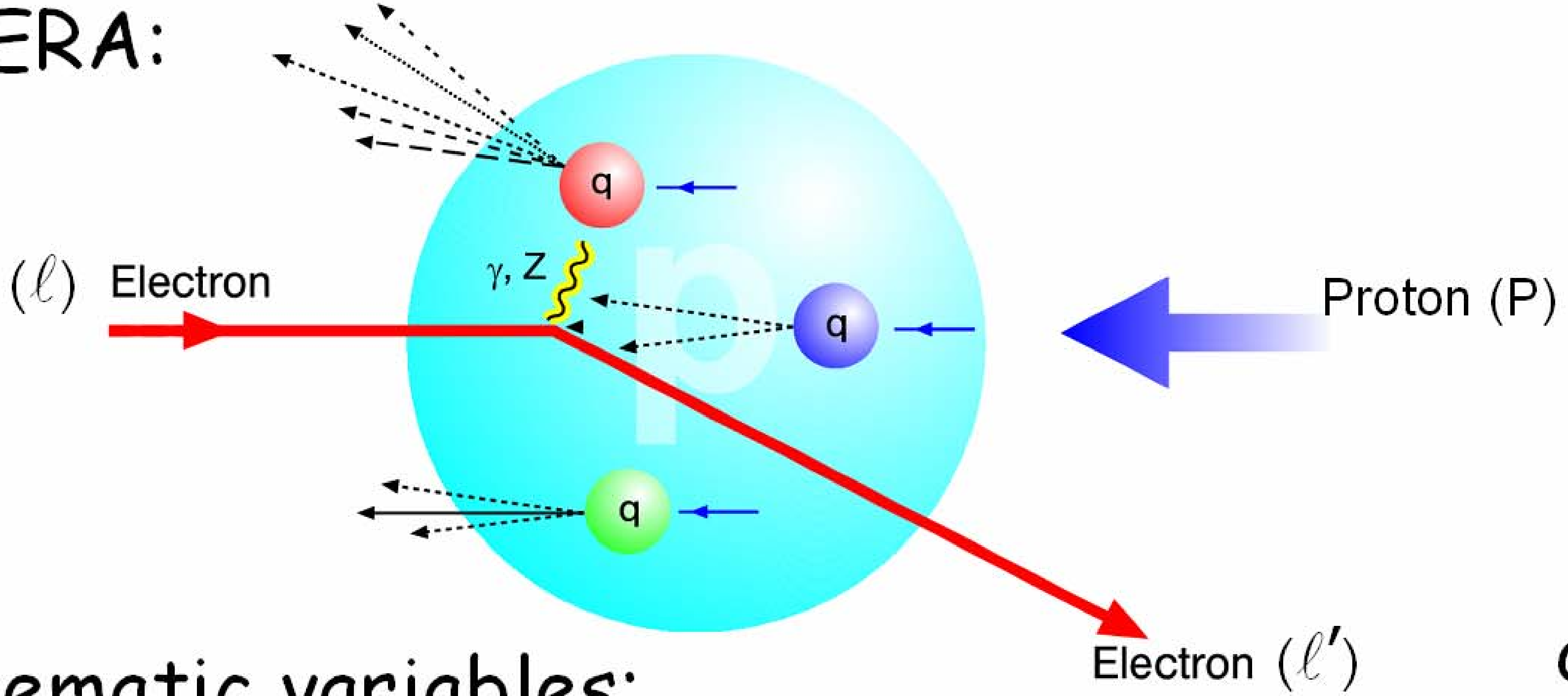




Measure parton density functions (PDF)
= density of quarks and gluons in proton

Kinematics of Deep Inelastic Scattering (DIS)

HERA:



$q = \ell - \ell'$

kinematic variables:

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

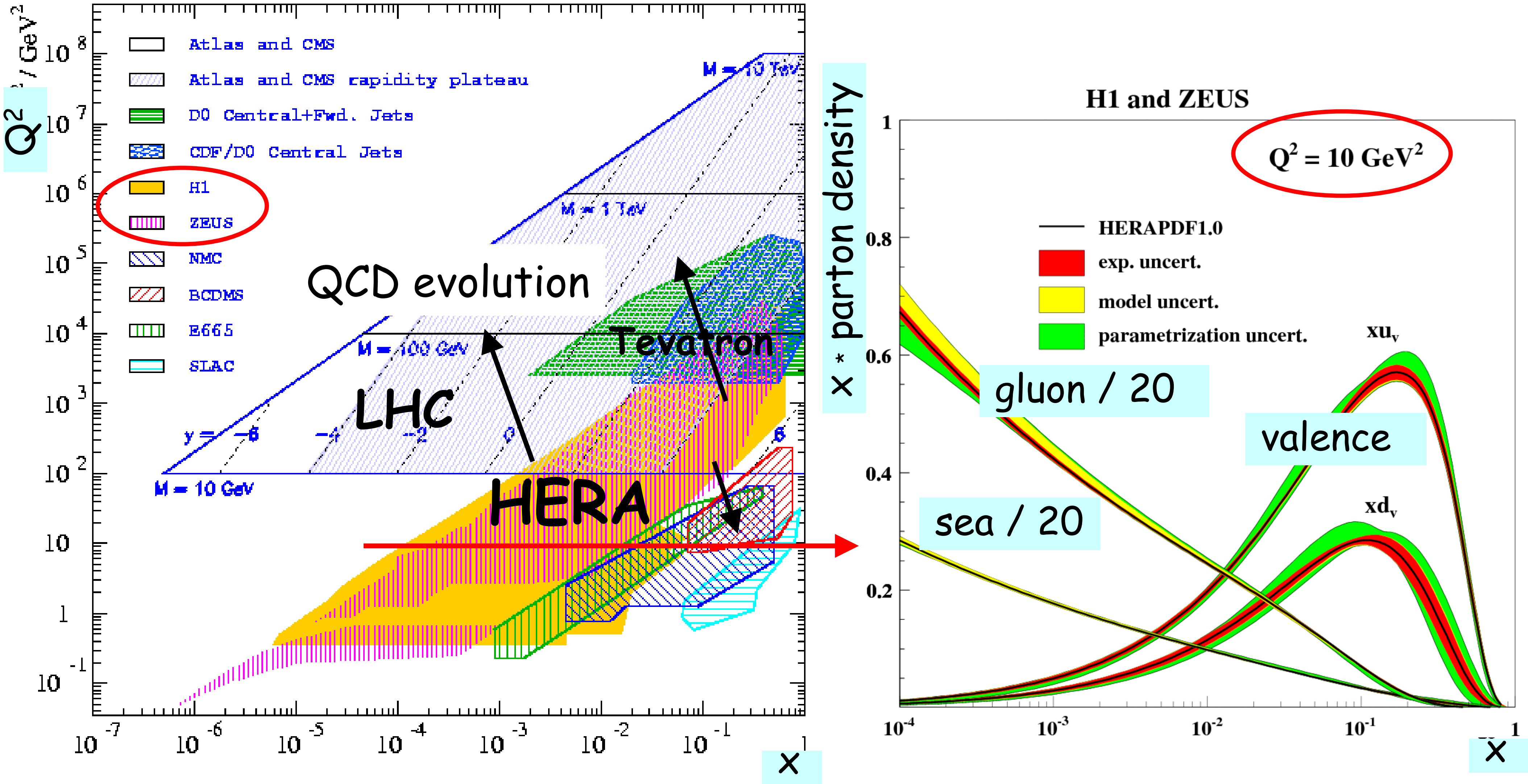
$x = \frac{Q^2}{2Pq}$ Bjorken scaling variable,
for $Q^2 \gg (2m_q)^2$: momentum fraction of p constituent

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

$Q^2 \lesssim 1\ GeV^2$: photoproduction

$Q^2 \gtrsim 1\ GeV^2$: DIS

Parton density funcions



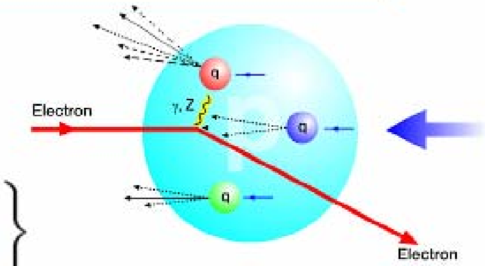
HERA PDFs essential for LHC

The structure of the proton

- Measure cross section

special HERA run in 2007

small



$$\frac{d^2\sigma}{dx\,dQ^2} = \frac{2\pi\alpha^2}{Q^4 x}\left\{\left[1+(1-y)^2\right] F_2(x,Q^2) - y^2 F_L(x,Q^2) \;\; +\text{-}Y_{-}\; xF_3\right\}$$

at high Q^2

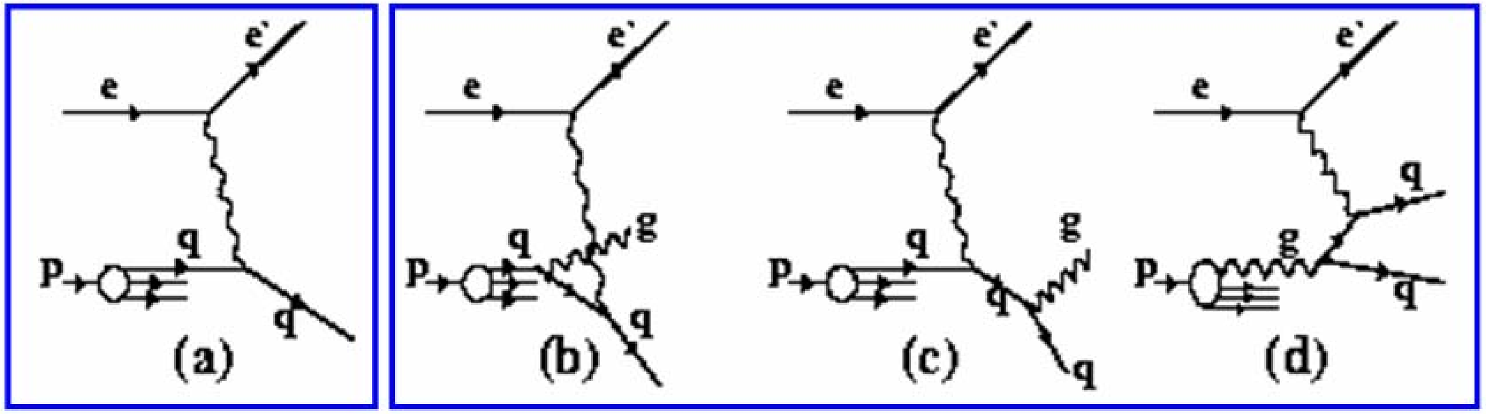
to 0th order QCD (Quark Parton Model, $Q^2 \gg m_q^2$):

- Parton distribution functions (PDF) in pQCD

$$F_2^{em}(x,Q^2) = x\sum_i e_i^2 [q_i(x,Q^2) + \bar{q}_i(x,Q^2)]$$

q_i – probability to find quark with flavour i in proton

"higher" order QCD corrections

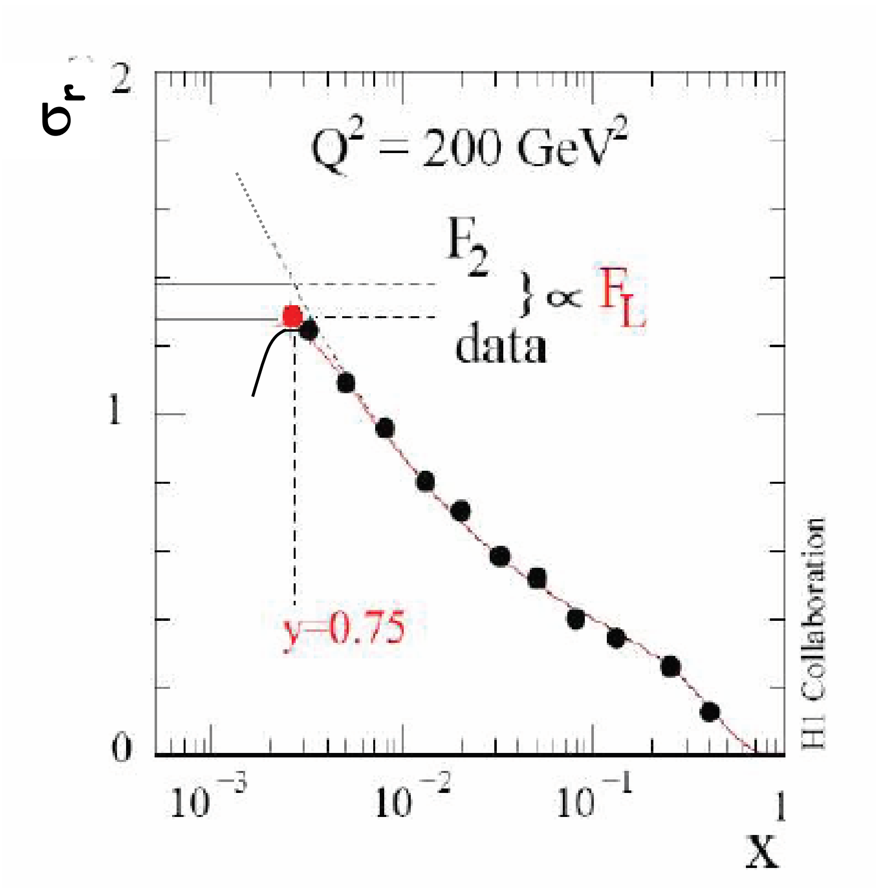


in general: F_2 structure function is **not** PDF

Reduced cross section

$$\sigma_r = F_2(x, Q^2) - \frac{y^2}{Y_+} \cdot F_L(x, Q^2)$$ = **measured quantity**

$=0$ for real spin ½ partons (Callan-Gross)



F_2 ~ quark distributions

$$F_L(x, Q^2) \sim \alpha_s x g(x, Q^2)$$

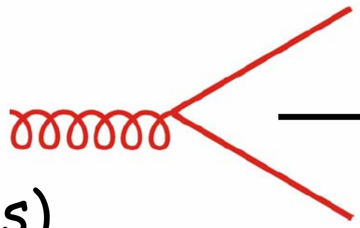
~ virtual quarks from transverse virtual gluons, regularizes reduced cross section at low x/high y!

in most of phase space:
$\sigma_r \sim= F_2$

F_2 and gluon density

DGLAP QCD evolution:

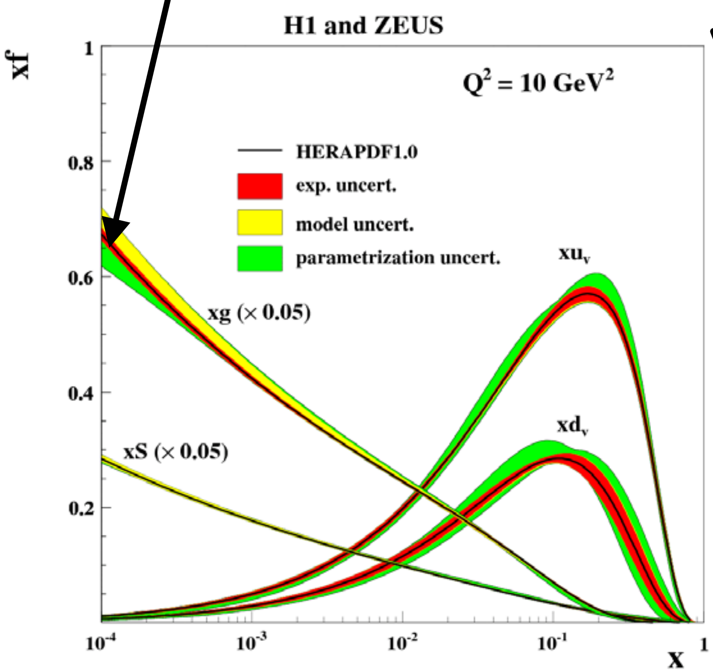
sea quarks, $g \to q\bar{q}$



positive slope

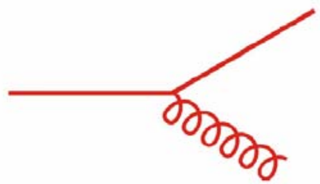
(scaling violations)

gluon density

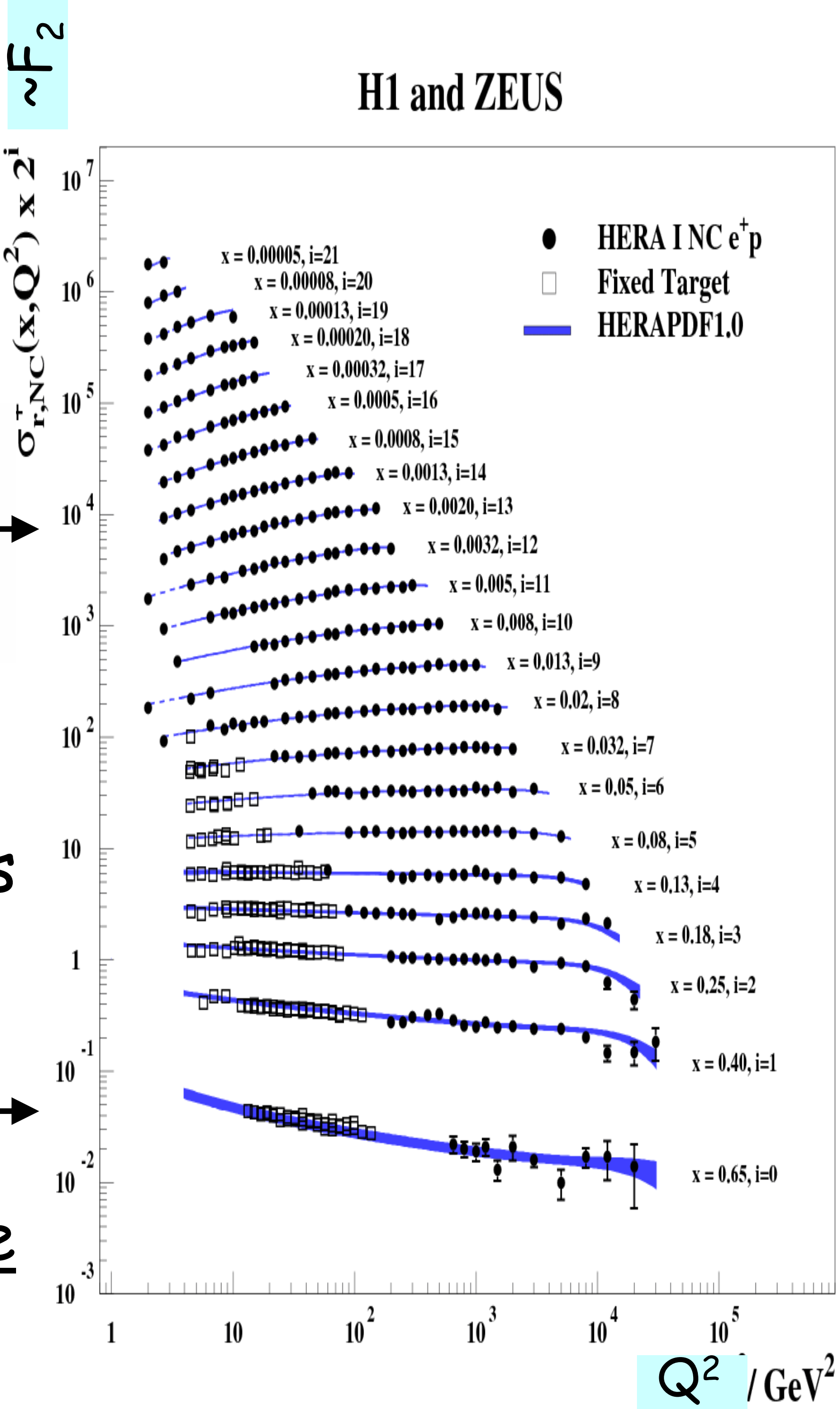


valence quarks

$q \to qg$



negative slope



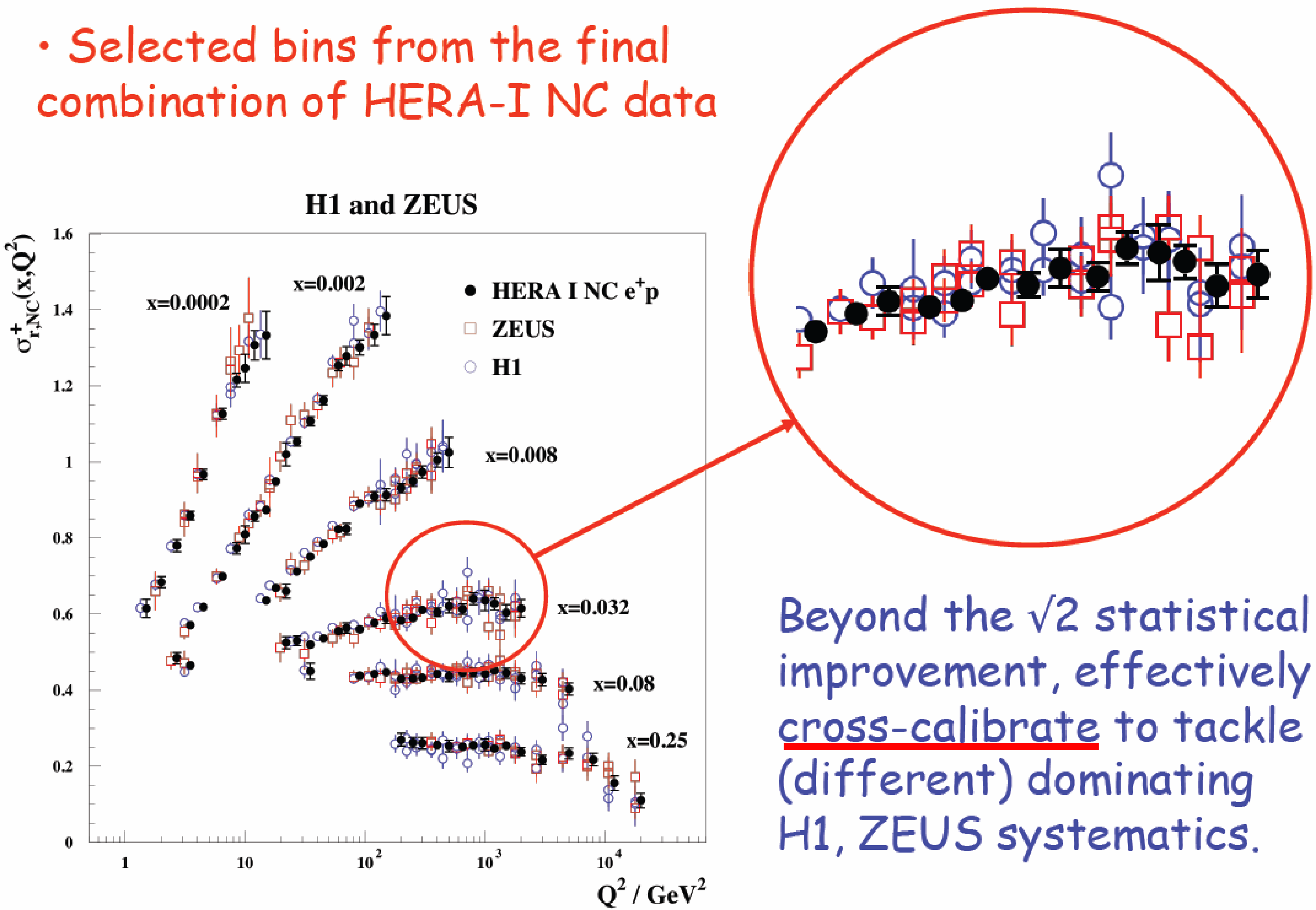
H1 and ZEUS cross section combination

JHEP 1001:109 (2010)

coherent treatment of experimental effects

see talk S. Glazov

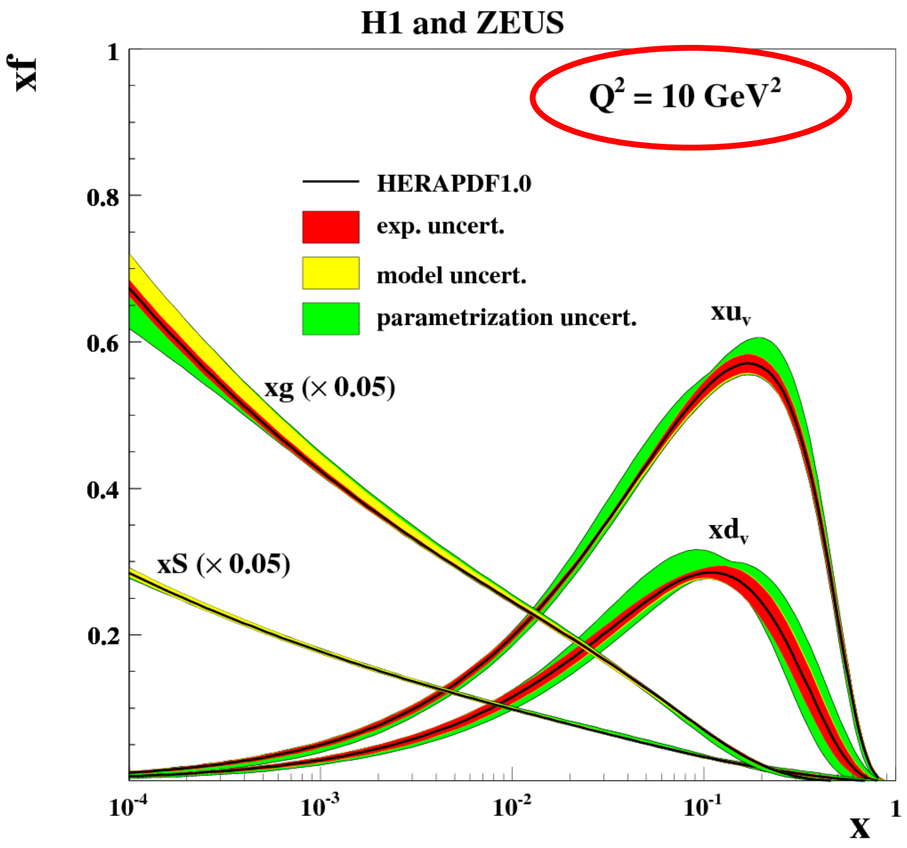
• Selected bins from the final combination of HERA-I NC data

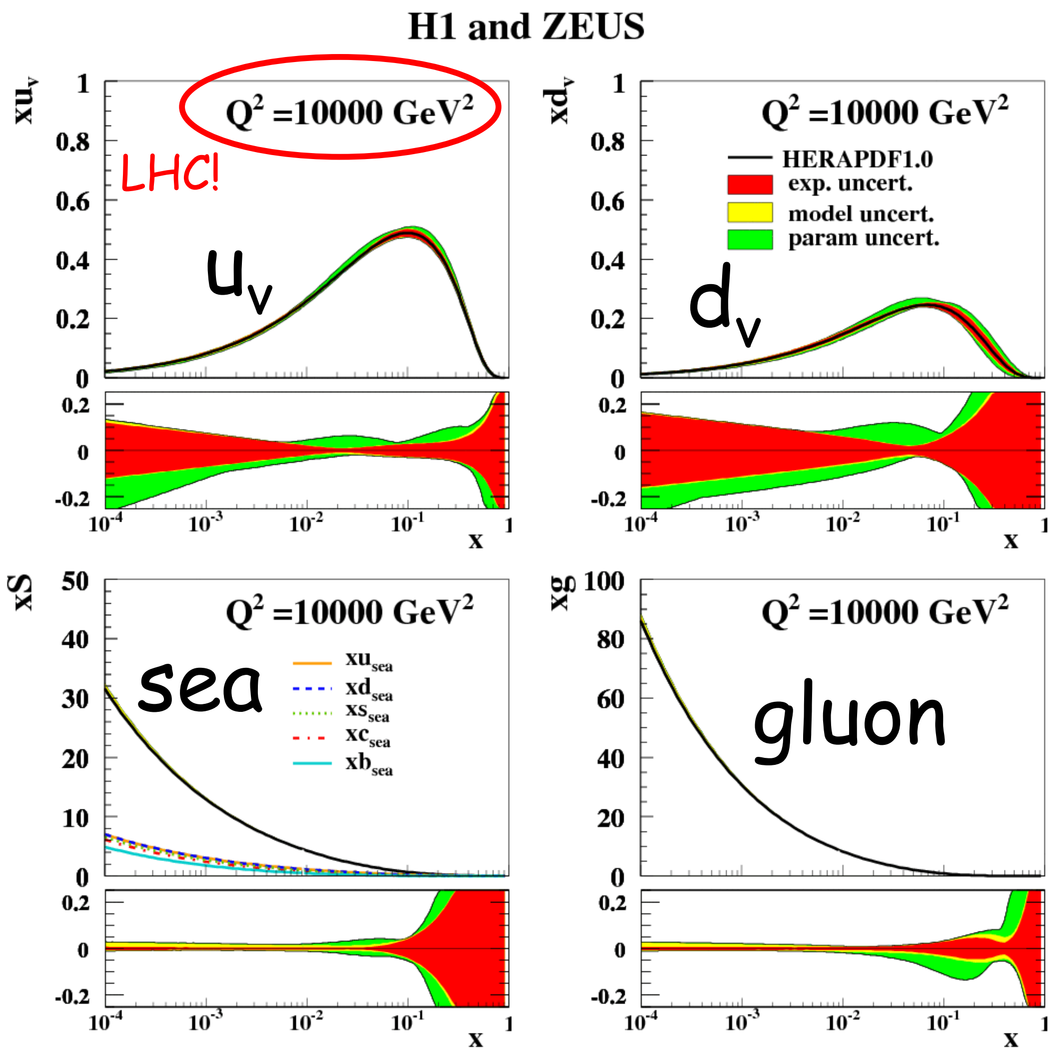


Beyond the √2 statistical improvement, effectively cross-calibrate to tackle (different) dominating H1, ZEUS systematics.

NLO QCD fit to combined HERA I data

HERAPDF1.0

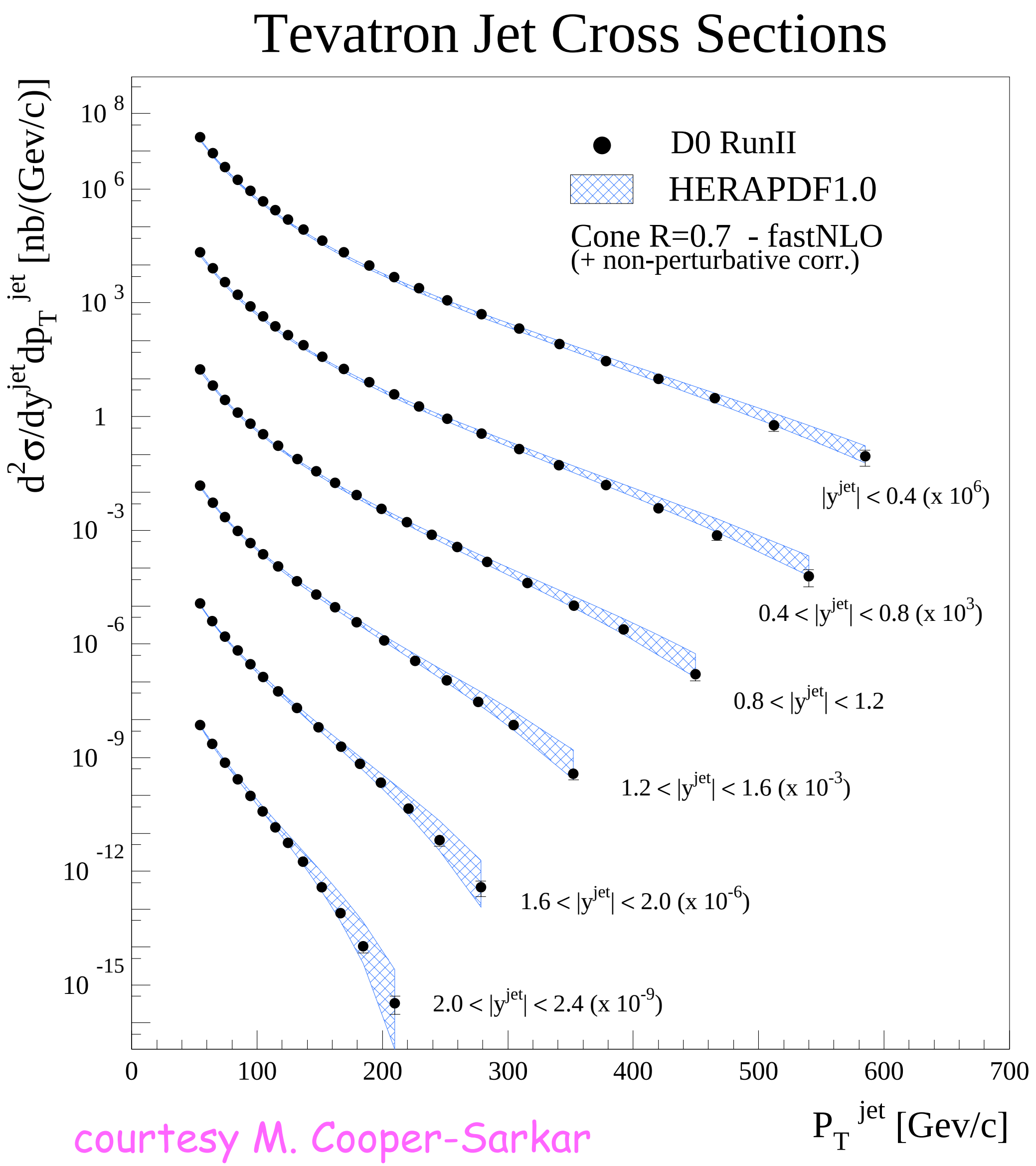




High precision, massive treatment for heavy flavours (TR-VFNS), detailed study of PDF unc.

available in LHAPDF

Comparison to Tevatron jet data



courtesy M. Cooper-Sarkar

frequent criticism of HERAPDF:
fit does not contain Tevatron Jet data

... but nevertheless describes them very well !

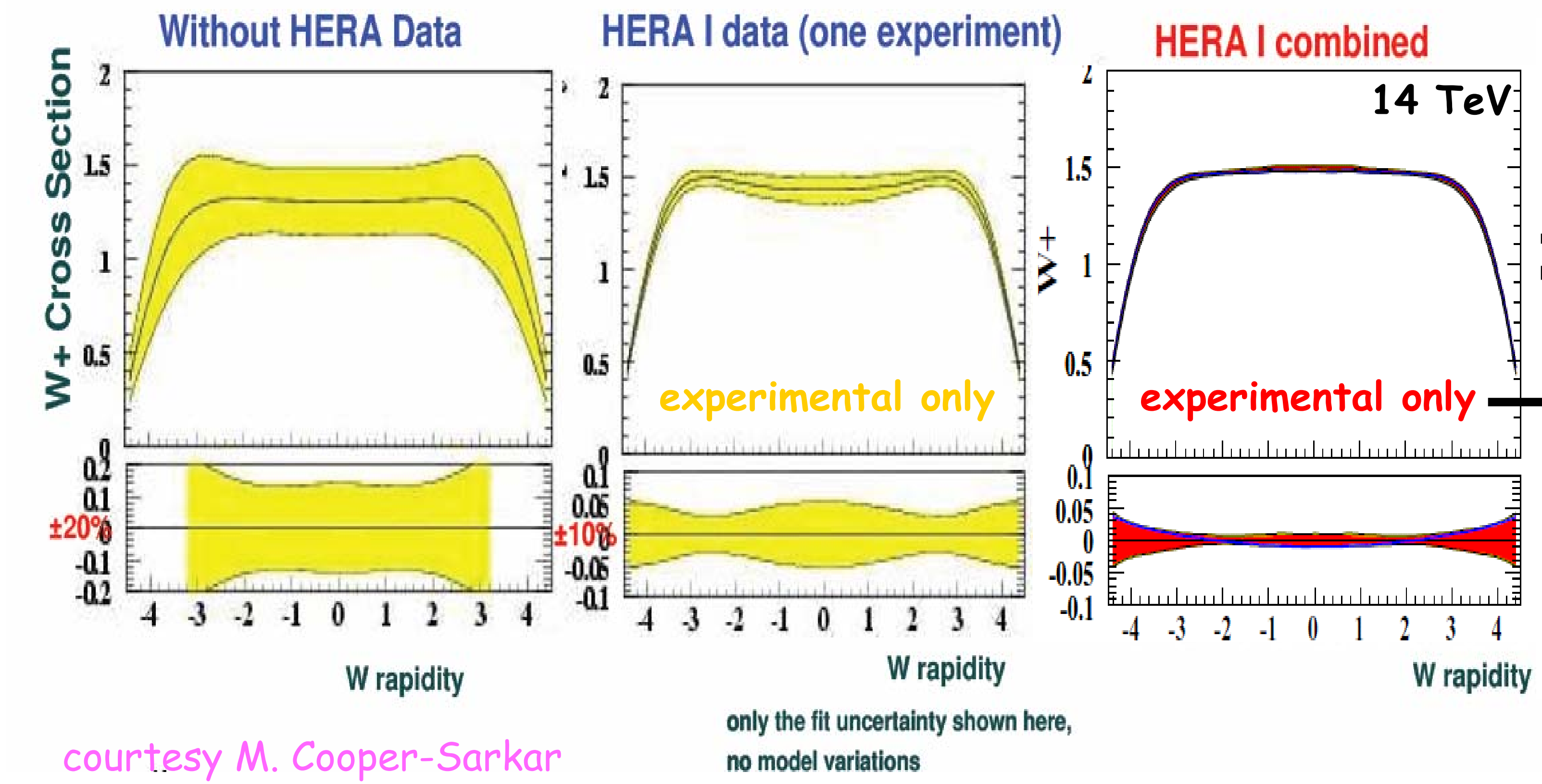
(also W)

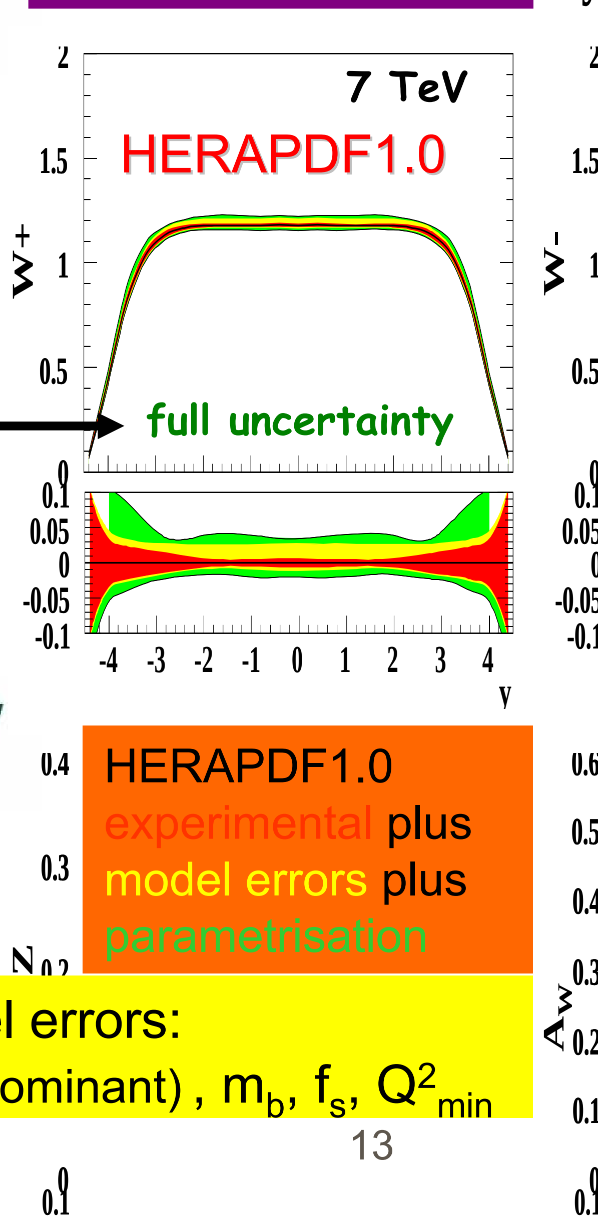
see talk
M. Cooper-Sarkar

strong improvement

see talk
M. Cooper-Sarkar

e.g.: predictions for W production at LHC





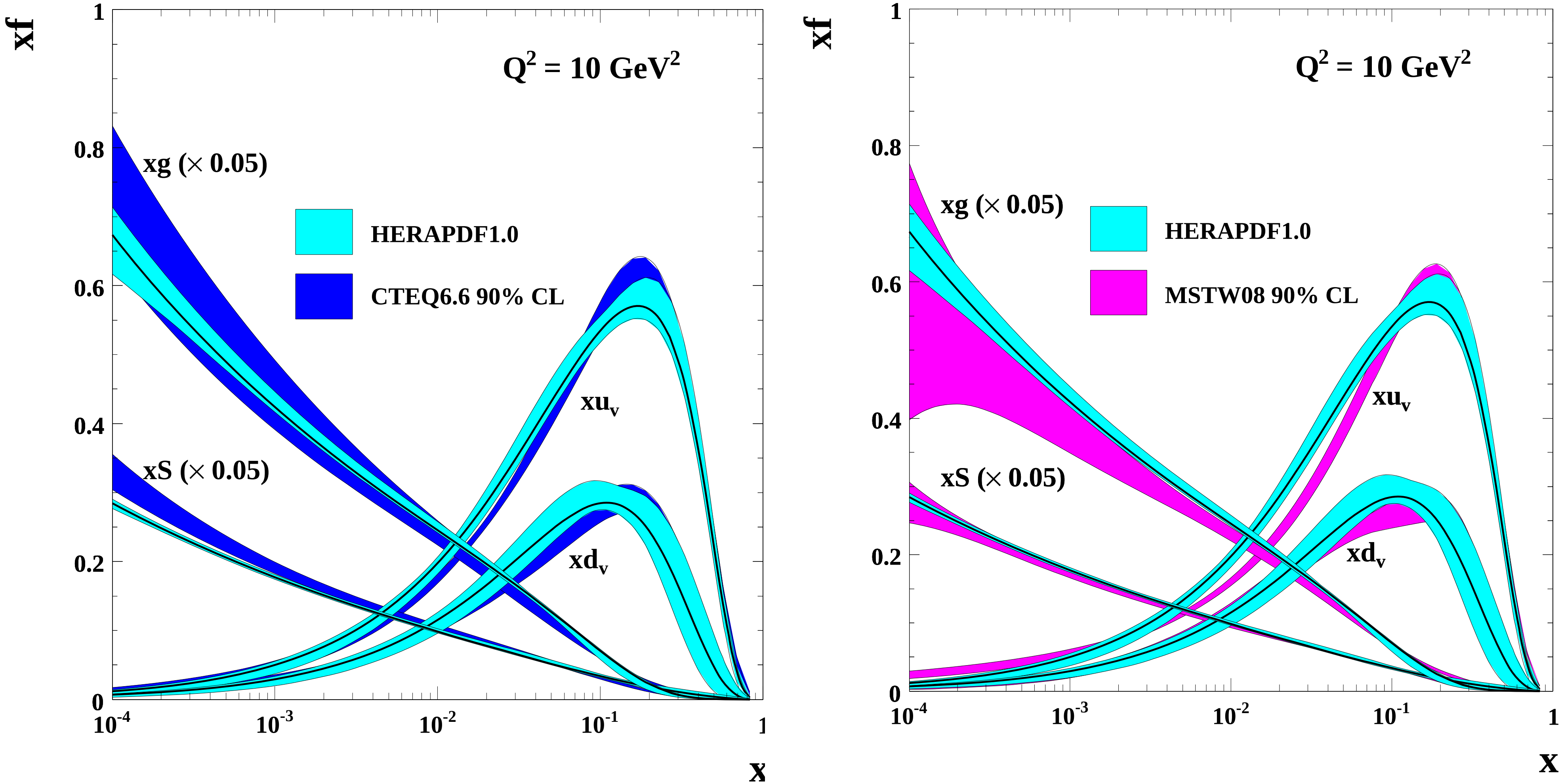
HERAPDF1.0
experimental plus
model errors plus
parametrisation

Model errors:
m_c (dominant) , m_b, f_s, Q^2_{min}

improvement driven by low x sea and gluon
(W mainly produced via sea-sea partons)

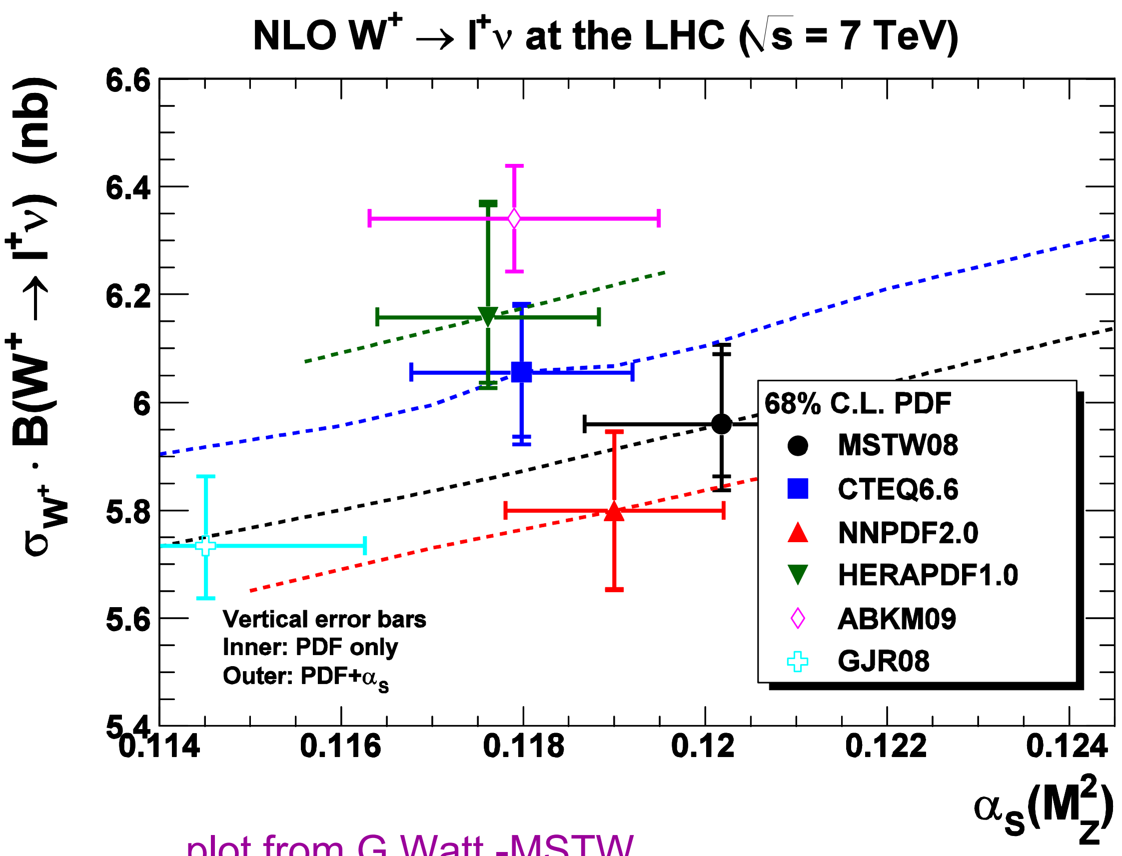
comparison to other PDFs

HERAPDF1.0 vs. CTEQ6.6 and MSTW08



predictions for W cross section at LHC

see talks
J. Stirling
M. Cooper-Sarkar



plot from G.Watt -MSTW

Comparisons of W+ cross-section as a function of $\alpha_S(M_Z)$

MSTW08
CTEQ66
HERAPDF1.0
NNPDF2.0
ABKM09
GJR08

similar for Z, W^-

relevant for luminosity measurement at LHC (standard candles)

see talk
M. Grazzini

significant contribution to uncertainty from heavy quark treatment

Why are heavy flavours important?

- charm contribution to F_2 up to 40%!
- **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.

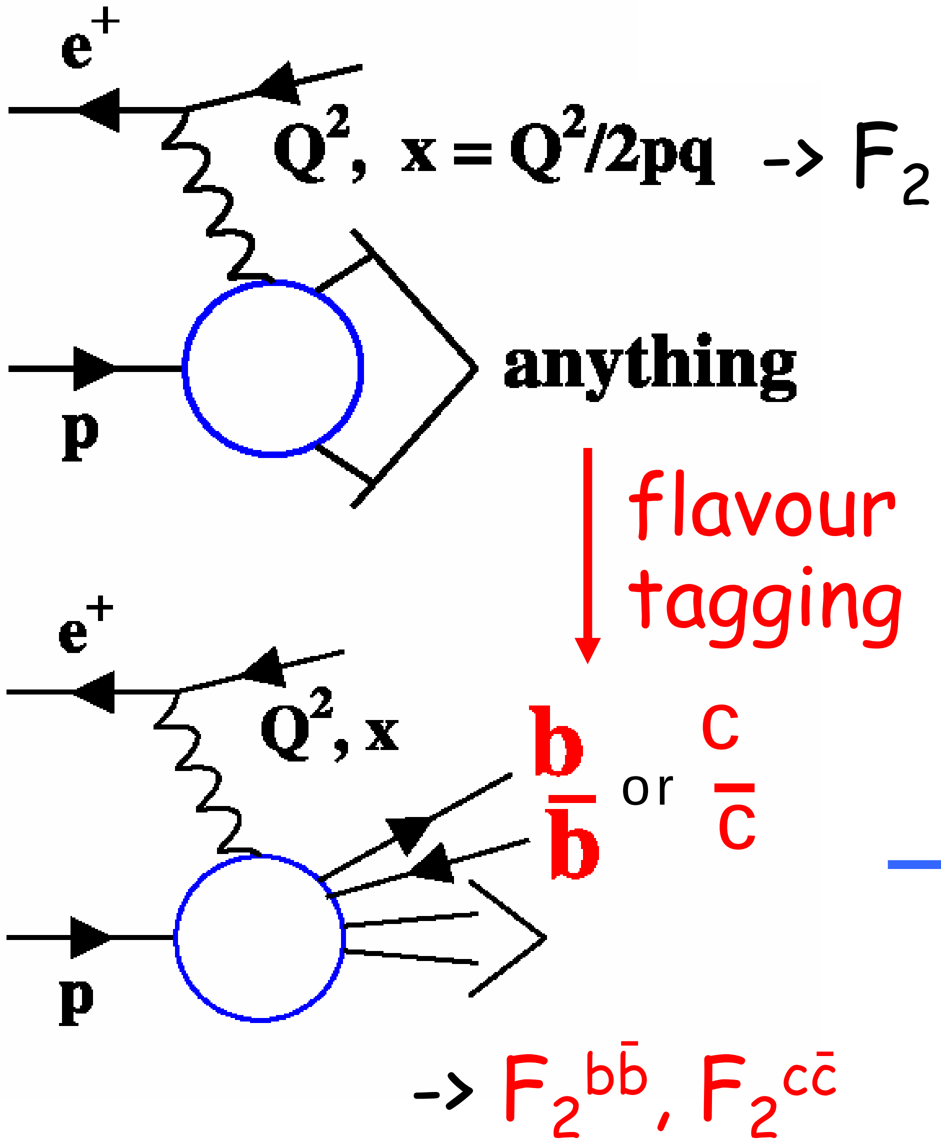
see talks
P. Jimenez-Delgado,
P. Nason,
J. Blümlein,
M. Ubiali,
et al. ...

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

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

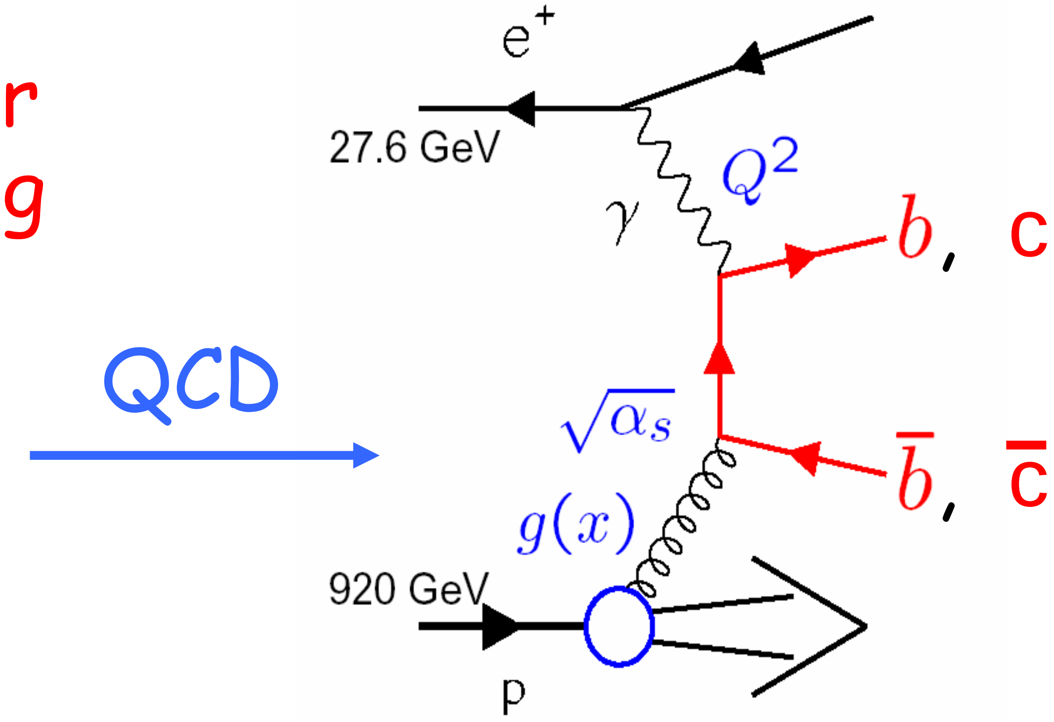
check different schemes against HERA data

Heavy flavour contributions to F_2

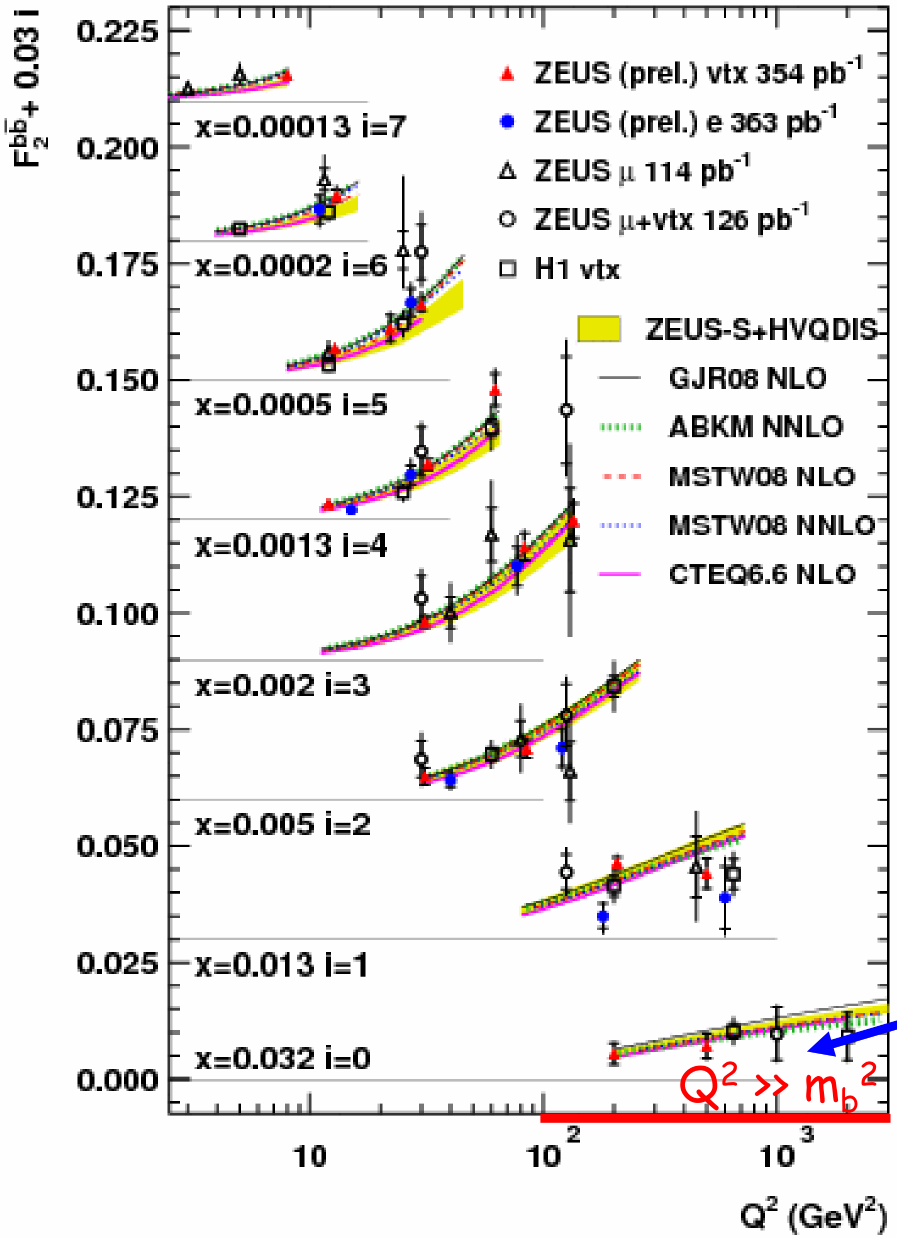


mainly
Boson Gluon Fusion,
driven by gluons

multiple hard scales:
Q^2, $m_{b,c}$, p_T



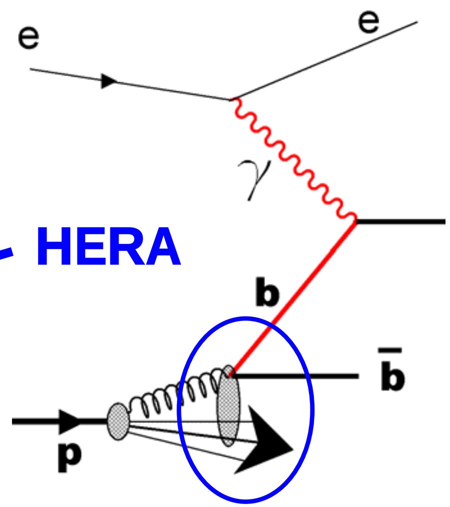
beauty contribution to F_2

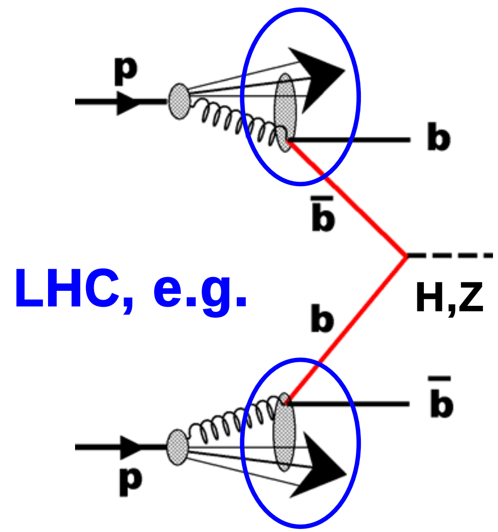


data in agreement with NLO and NNLO, but

start to
discriminate between different schemes

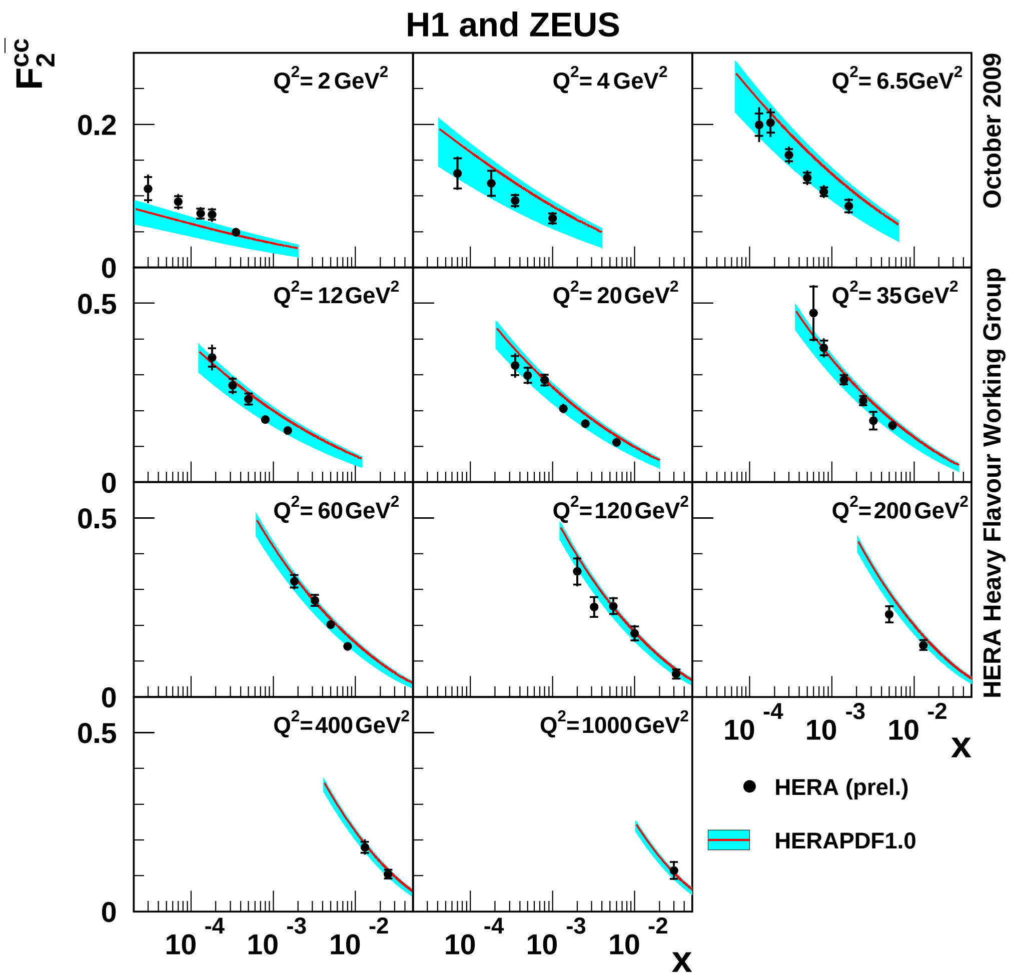
check b PDF for LHC:

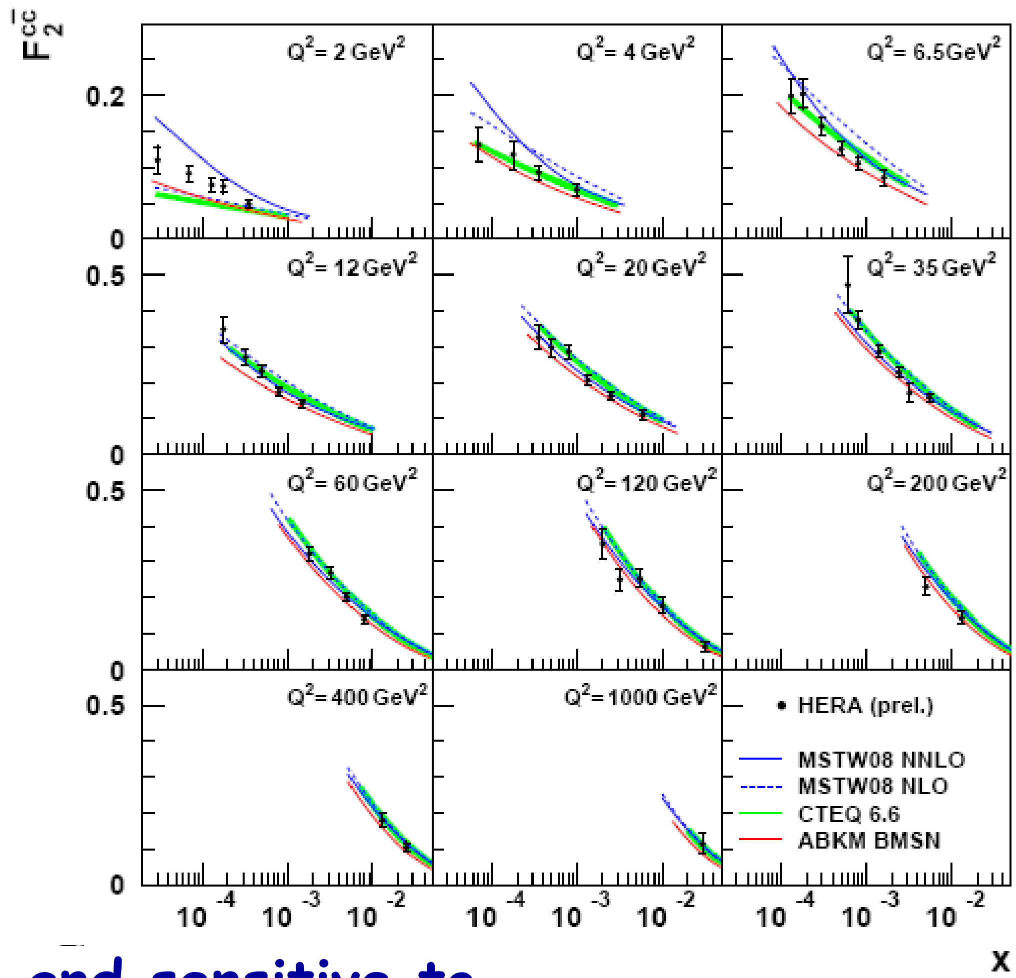




charm contribution to F_2

combined HERA (H1 and ZEUS) data: reasonable agreement with QCD





but sensitive to m_c:
uncertainty band 1.35-1.65 GeV

and sensitive to
heavy flavour schemes

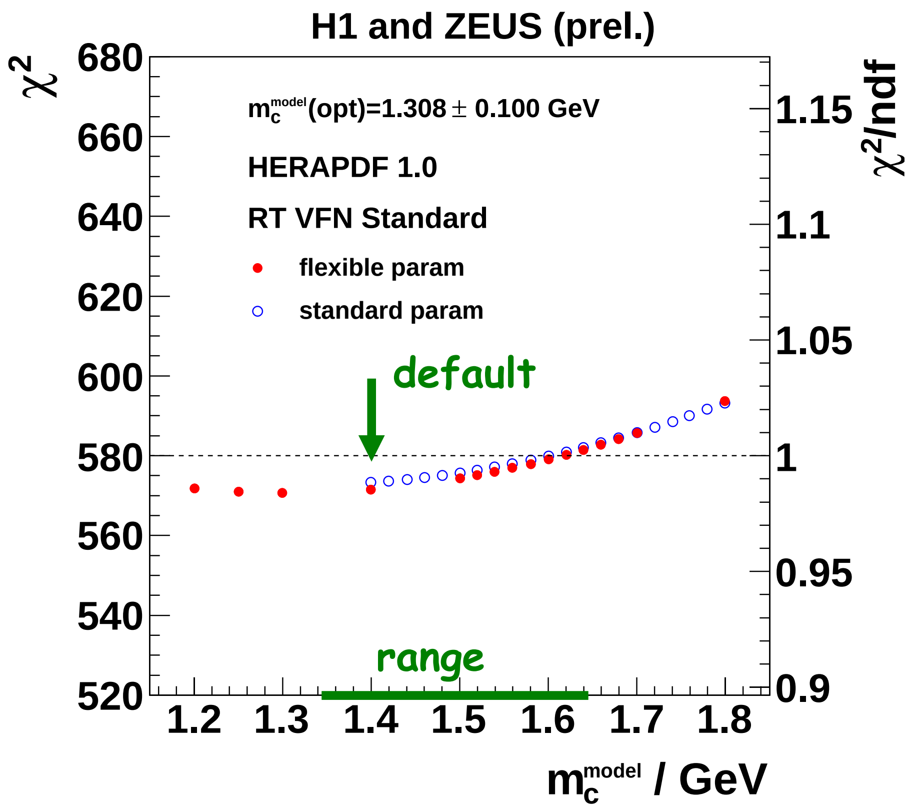
here: massive
VFNS schemes

include charm data in HERAPDF fit

see talk
R. Placakyte

does not change the PDFs significantly (for fixed m_c), but affects χ^2:

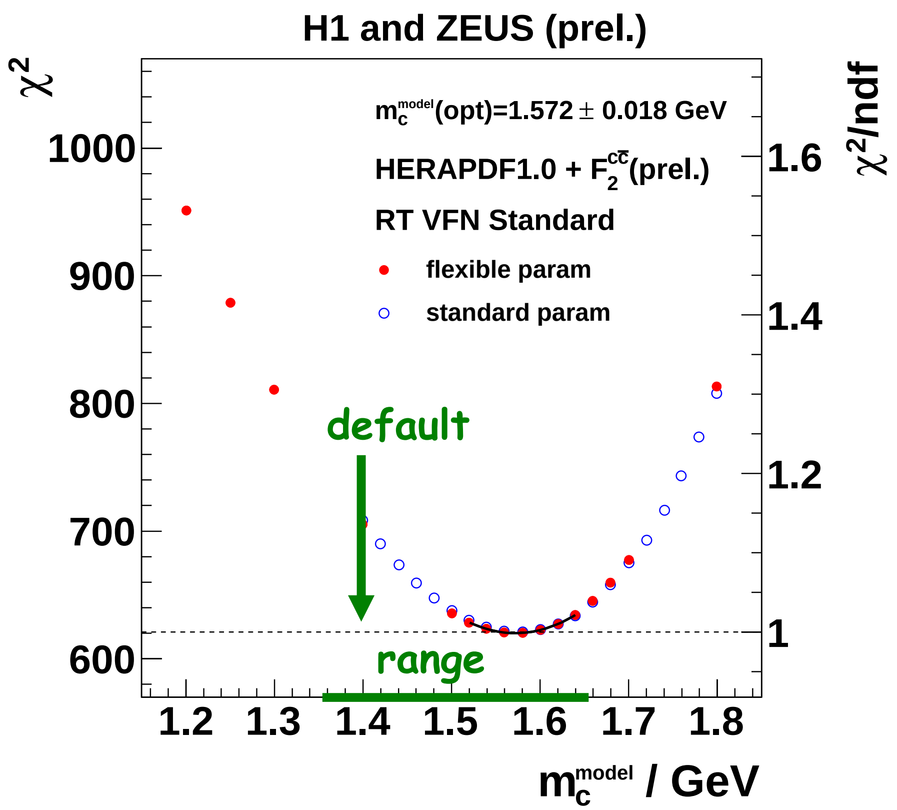
without charm data



shallow mass dependence .

(pole mass + modifications from VFNS scheme -> effective model parameter)

with charm data

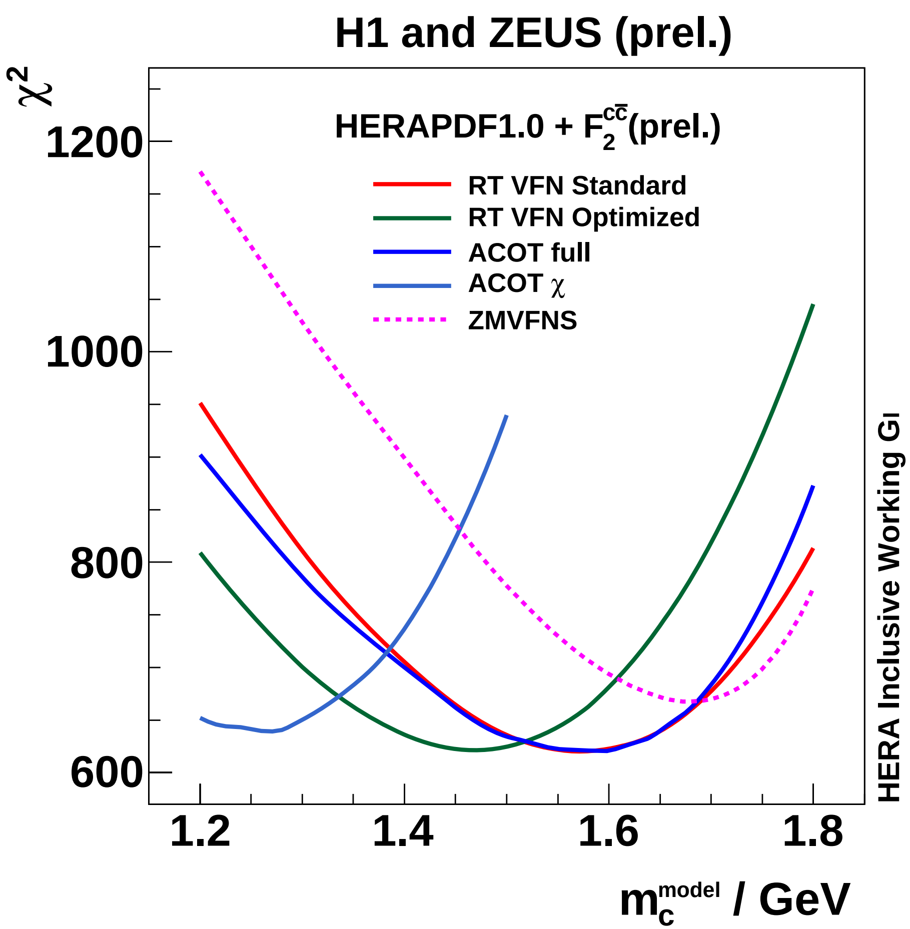


strong mass dependence

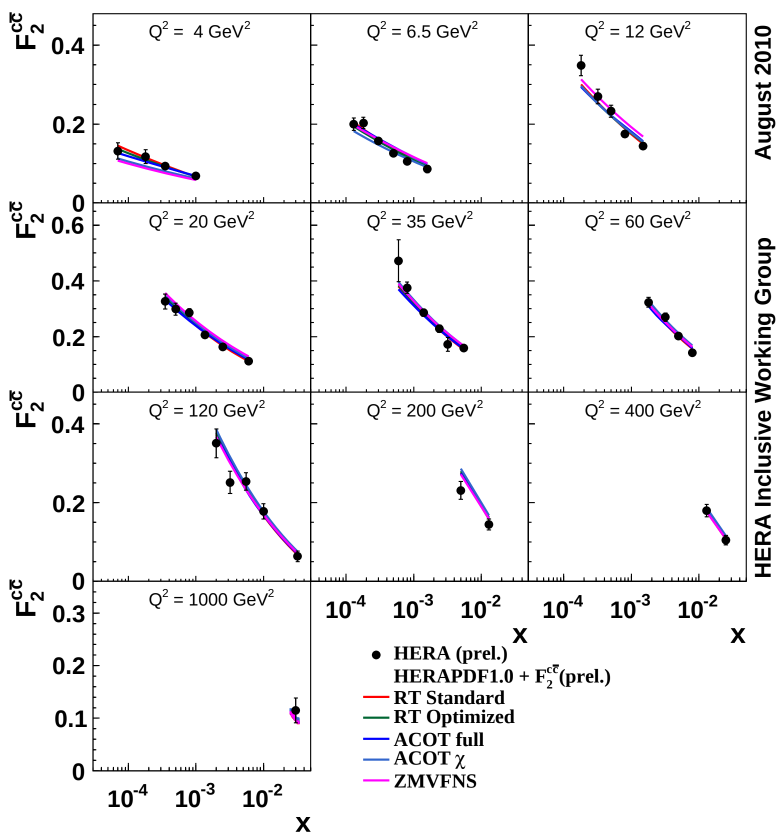
m_c^{model} = 1.57 ± 0.02 GeV

reanalyse HERAPDF+F_2^c using different VFNS schemes

other par., α_s

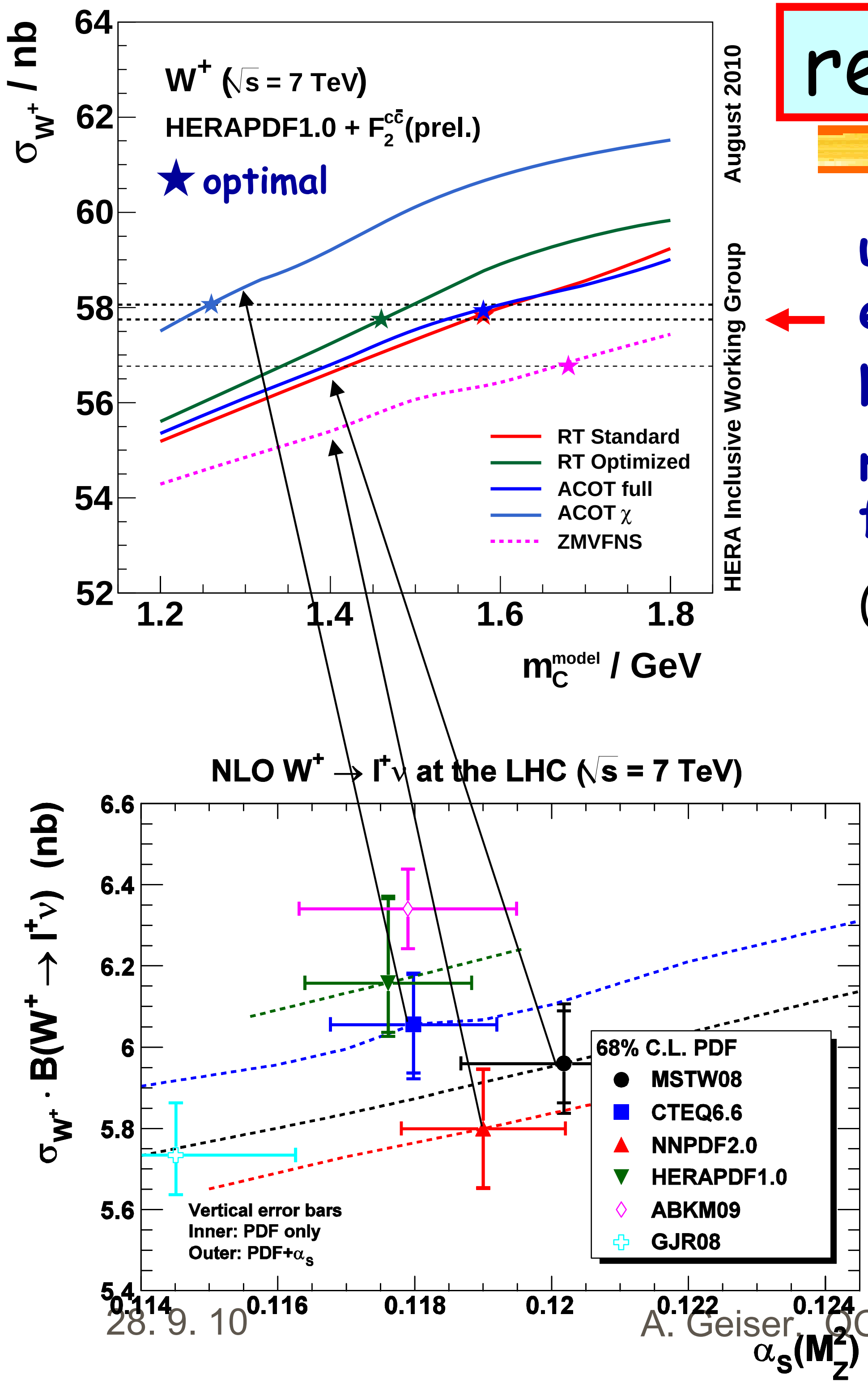


	m_c^{model}(opt) / GeV	stat	syst	
RT stand (default)	1.57	±0.02	+0.01	-0.03
RT optim	1.47	±0.02	+0.01	-0.03
ACOT full	1.58	±0.02	+0.02	-0.04
ACOT χ	1.25	±0.02	+0.02	-0.04
ZMVFNS	1.67	±0.02	+0.06	-0.06



different "optimal" effective masses for different VFNS schemes yield very similar fit

recheck W/Z predictions
for LHC



using "optimal" mass parameter for each scheme reduces spread between predictions to <1% ! (except ZMVFNS: ~2%)

reason: charm data constrain sea quark flavour composition in relevant x range

(differences for gluon remain)

scheme	m_c^{model}(opt)	χ^2/dof	χ^2/ndp	σ_Z(nb)	σ_{W^+}(nb)	σ_{W^-}(nb)
RT Standard	$1.58^{+0.02}_{-0.03}$	620.3/621	42.0/41	$29.27^{+0.07}_{-0.11}$	$57.82^{+0.14}_{-0.22}$	$40.22^{+0.10}_{-0.15}$
RT Optimized	$1.46^{+0.02}_{-0.04}$	621.6/621	46.5/41	$29.17^{+0.07}_{-0.13}$	$57.75^{+0.14}_{-0.26}$	$40.15^{+0.10}_{-0.18}$
ACOT full	$1.58^{+0.03}_{-0.04}$	621.2/621	59.9/41	$29.28^{+0.10}_{-0.13}$	$57.93^{+0.18}_{-0.24}$	$40.16^{+0.12}_{-0.16}$
S-ACOT-χ	$1.26^{+0.02}_{-0.04}$	639.7/621	68.5/41	$29.37^{+0.08}_{-0.15}$	$58.06^{+0.16}_{-0.30}$	$40.23^{+0.11}_{-0.21}$
ZMVFNS	$1.68^{+0.06}_{-0.07}$	667.4/621	88.1/41	$28.71^{+0.19}_{-0.20}$	$56.77^{+0.33}_{-0.34}$	$39.46^{+0.24}_{-0.25}$
			differences	0.7% 2.3%	0.5% 2.3%	0.2% 2.0%

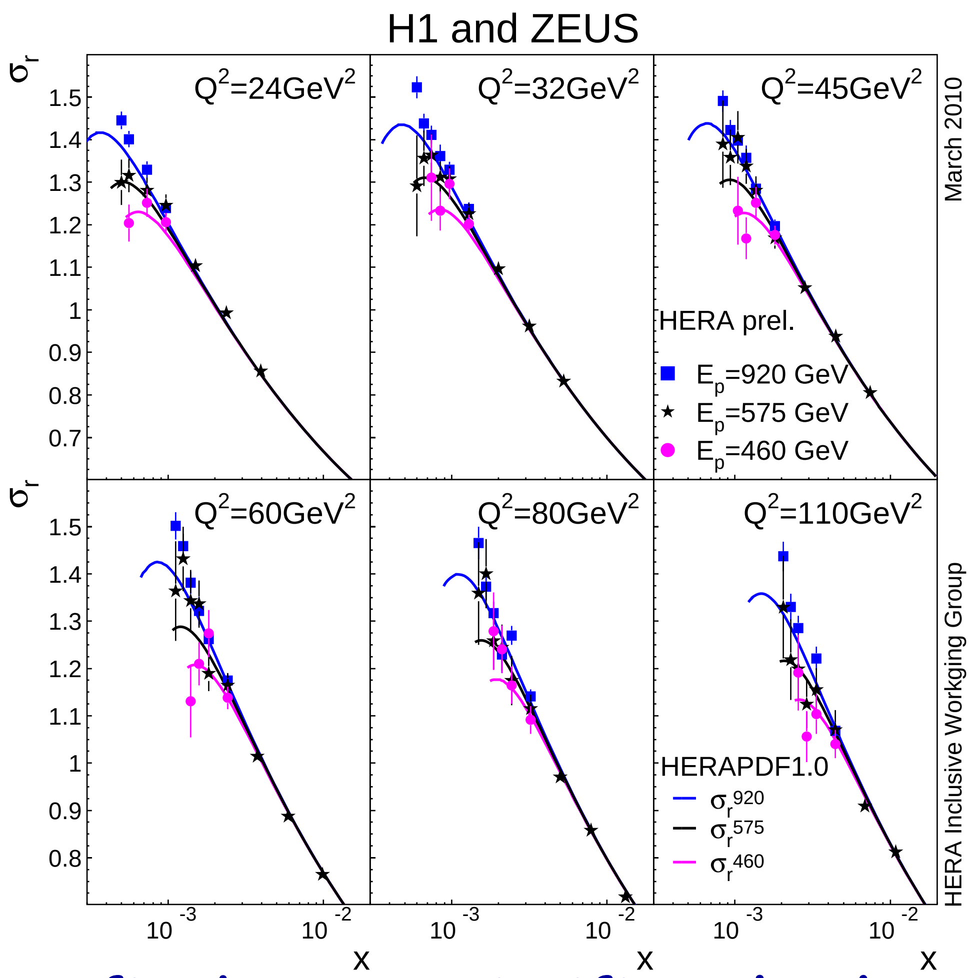
MSTW08, CTEQ6.6, NNPDF2.0 use different schemes and do not all use charm mass parameters at the optimal values

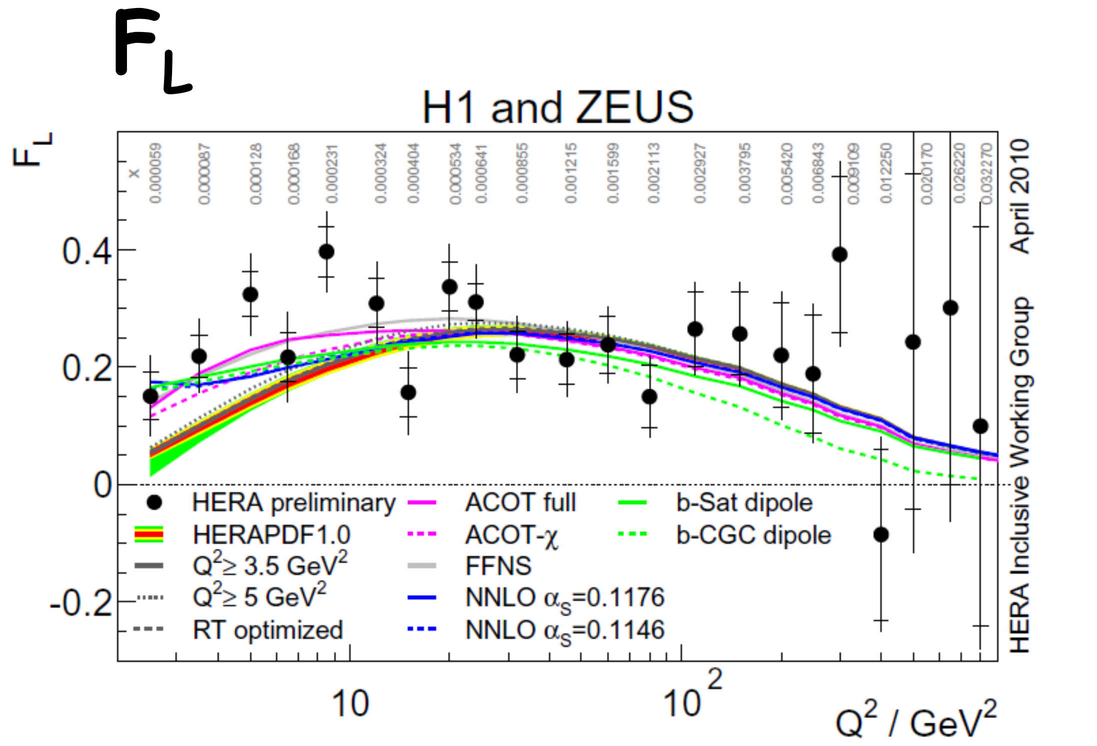
-> may partially explain differing predictions

add low energy data (F_L region)

combined HERA data, Ep= 920, 575, 460 GeV

see talk
V. Radescu





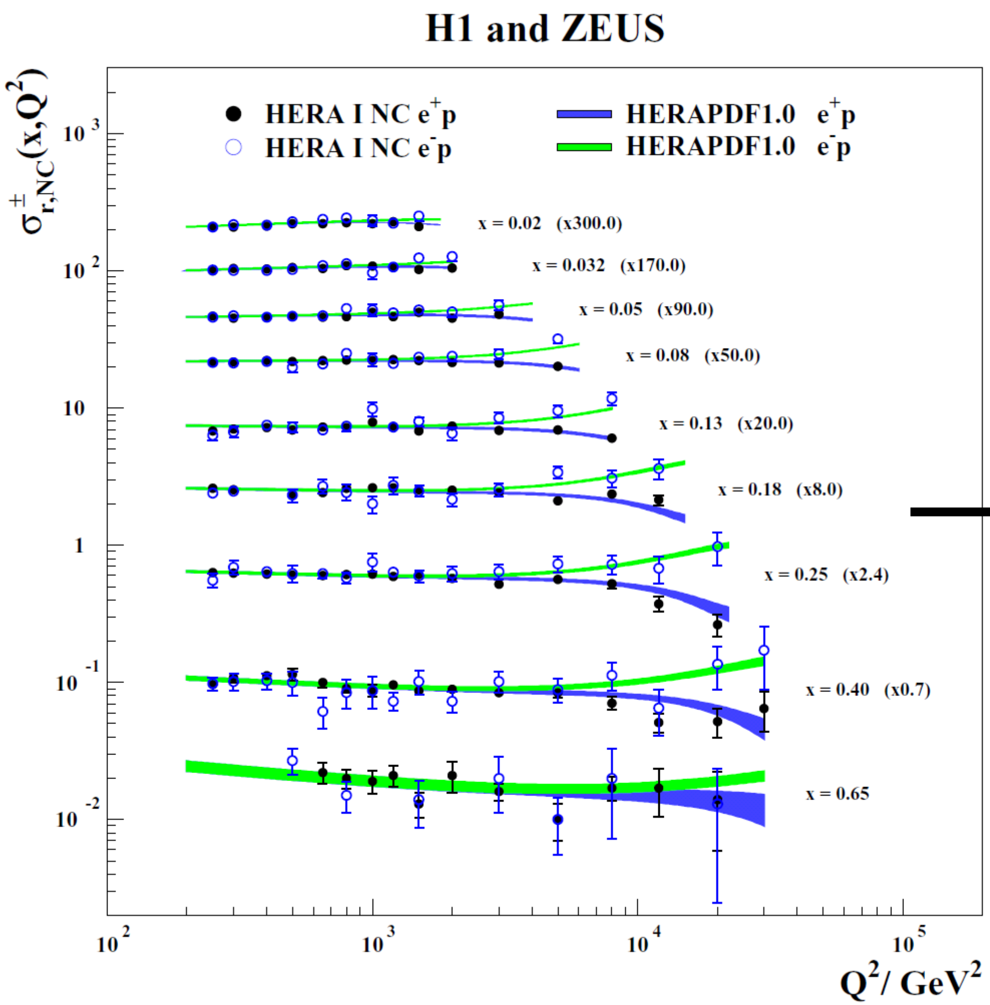
fit does not significantly change PDFs, but bad χ^2 at low x and Q^2

using NNLO or using different heavy flavour scheme (e.g. FFNS) can help for F_L

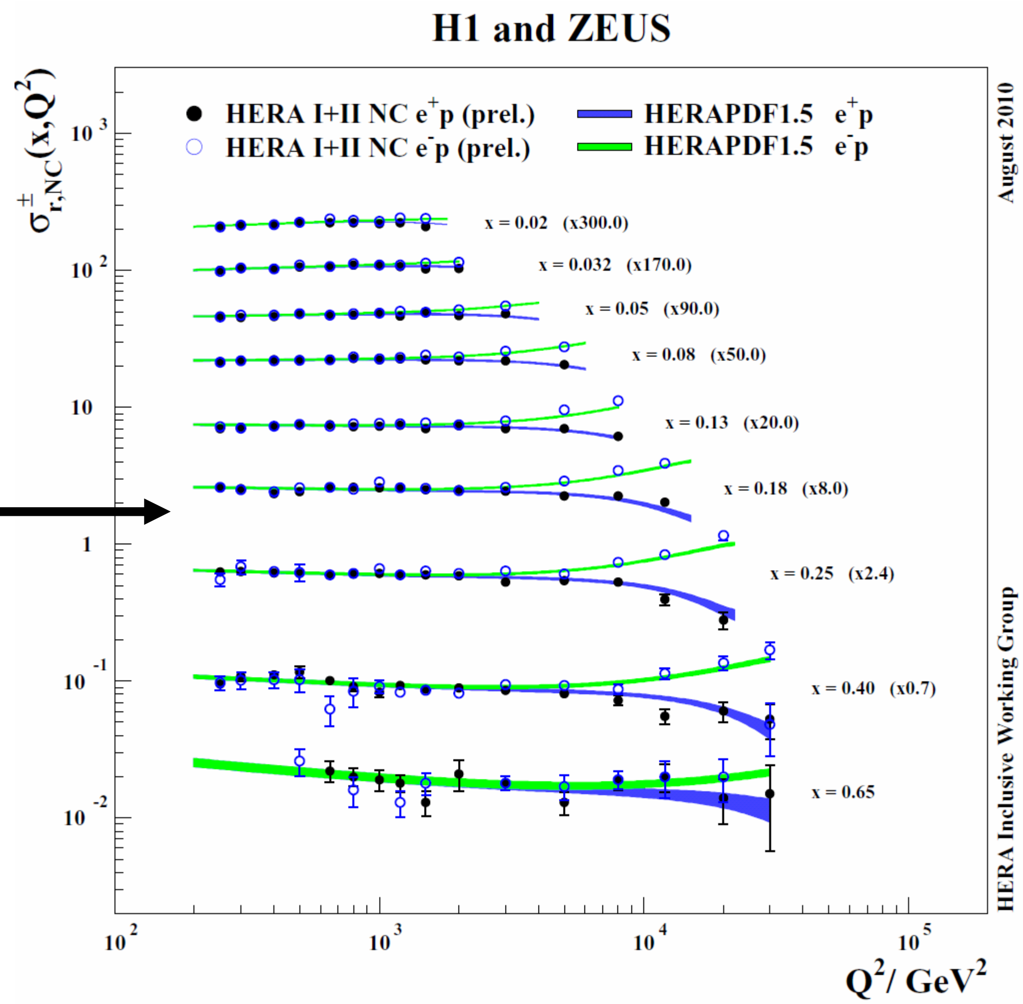
add high Q^2 HERA II data to combination

ongoing effort: NC

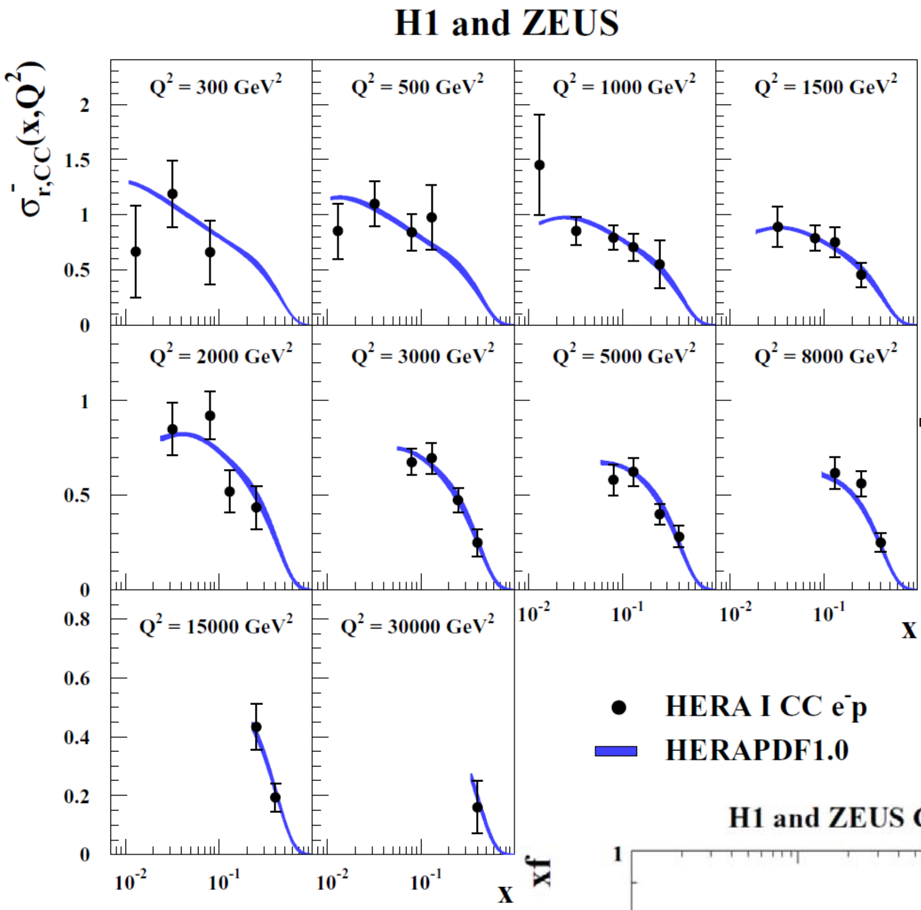
see talk A. Glazov



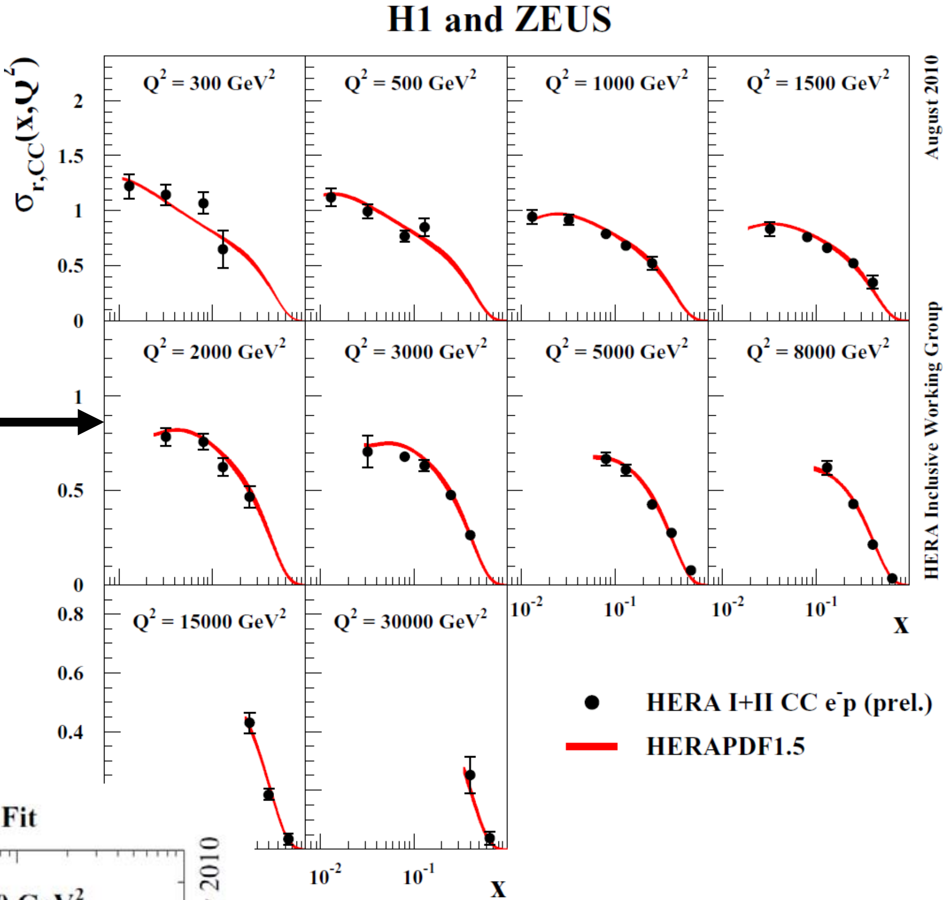
HERAPDF1.0



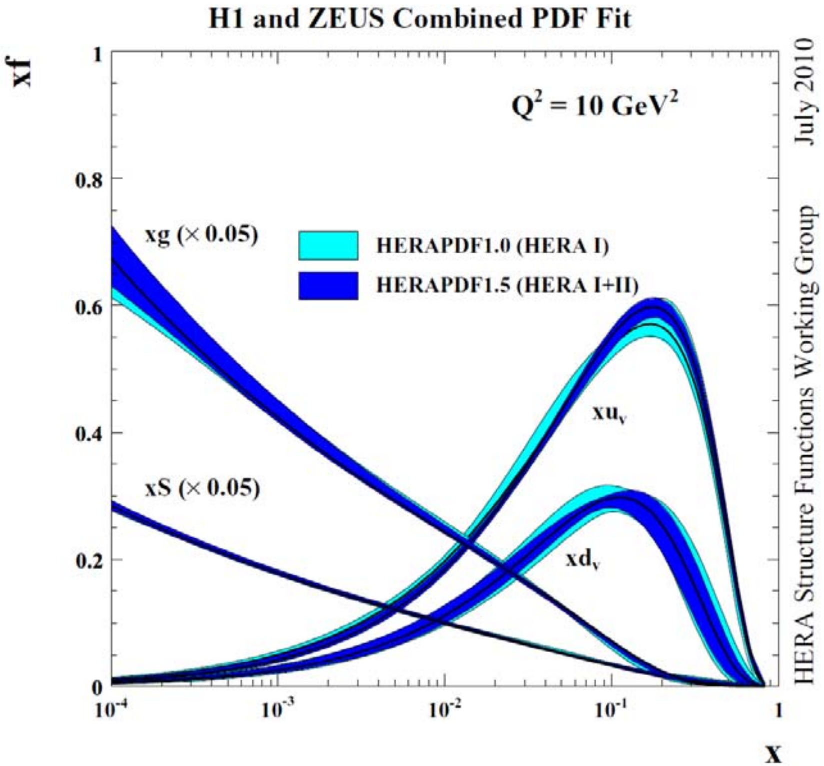
HERAPDF1.5



CC: e.g. e⁻



refit:

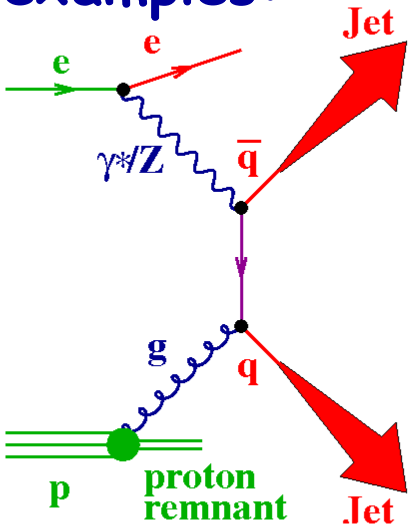


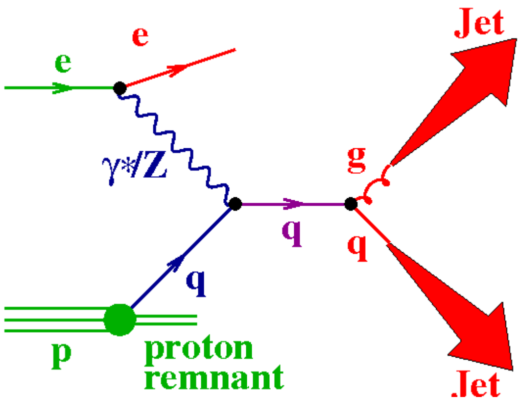
HERAPDF1.5 :

significantly improved uncertainties at high x

Jets in ep interactions (HERA)

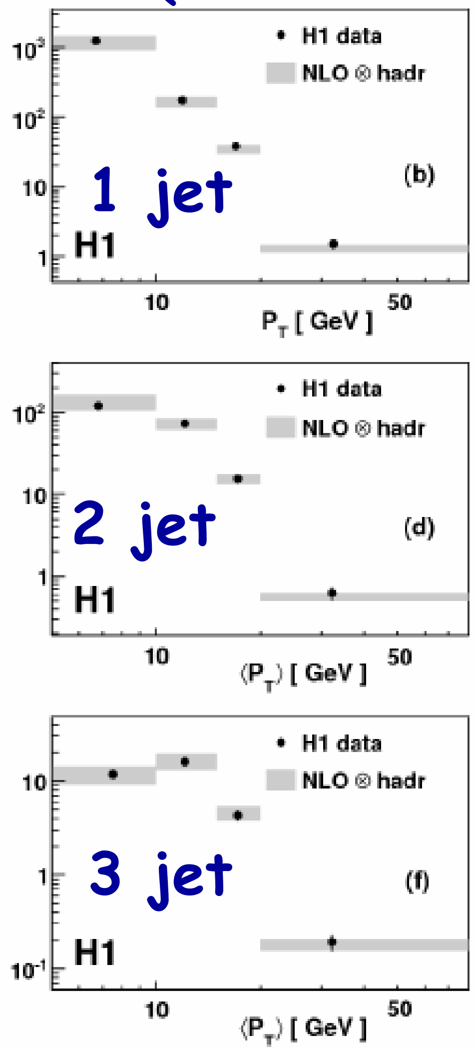
examples:



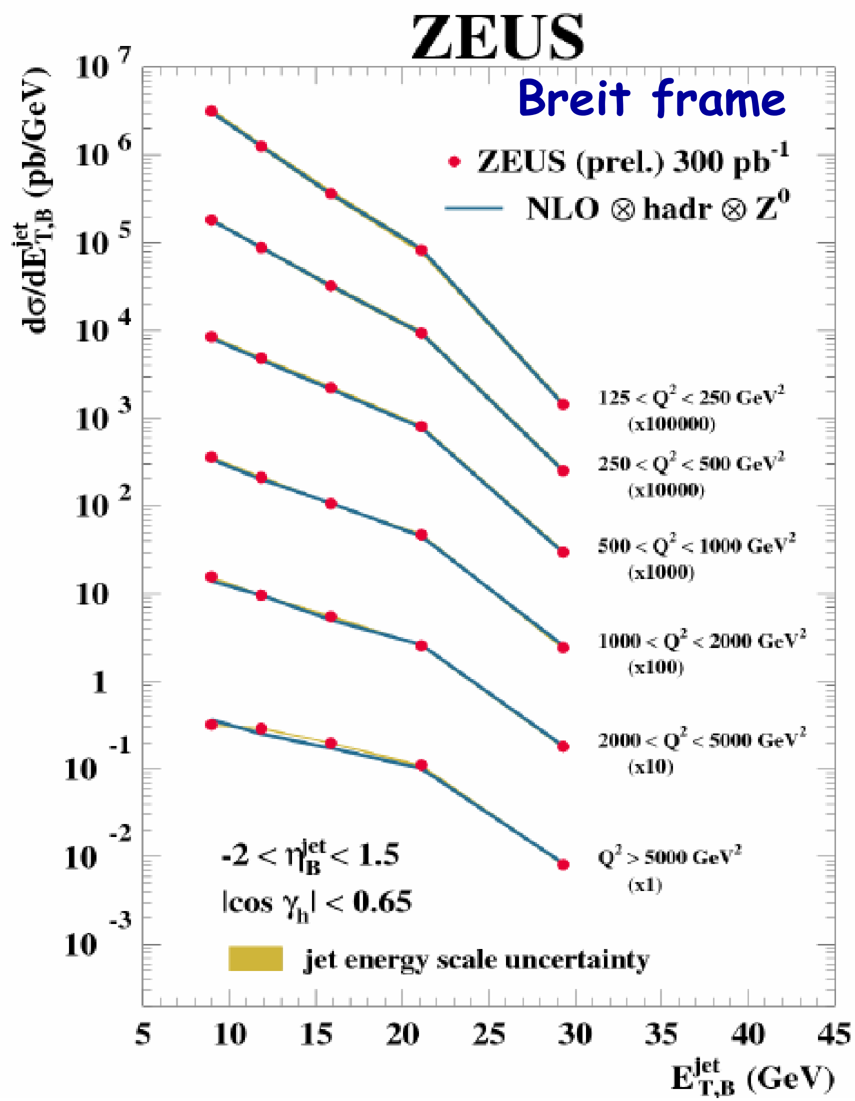


Eur. Phys. J. C67 (2010) 1

$5 < Q^2 < 100\ GeV^2$



ZEUS-prel-10-002



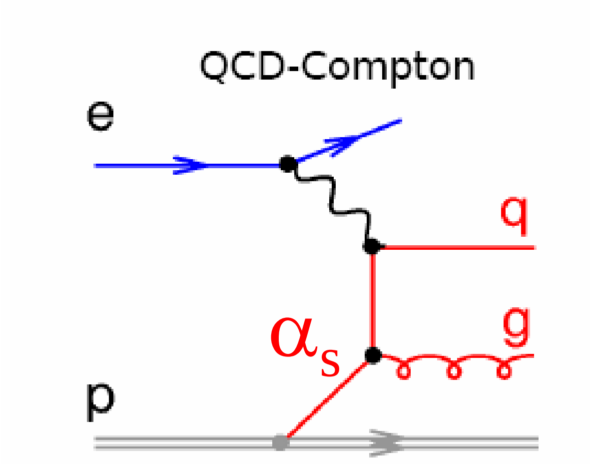
QCD works!

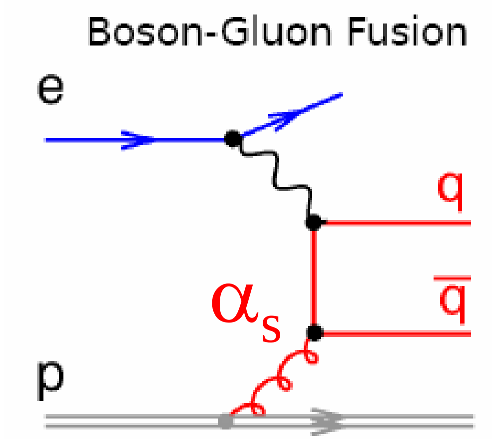
=> Measurements of α_s

Input to PDFs

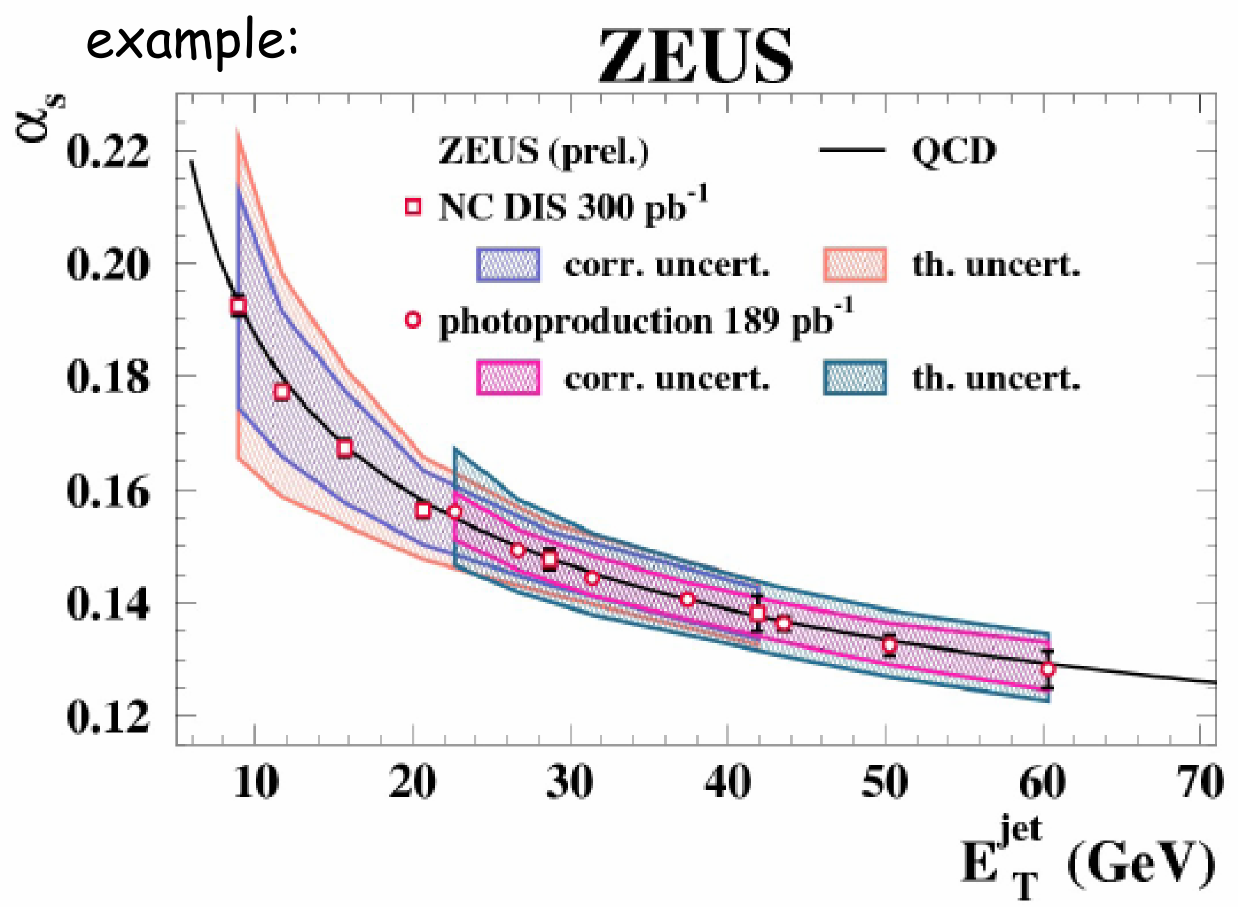
Running of α_s

ep interactions directly sensitive to α_s





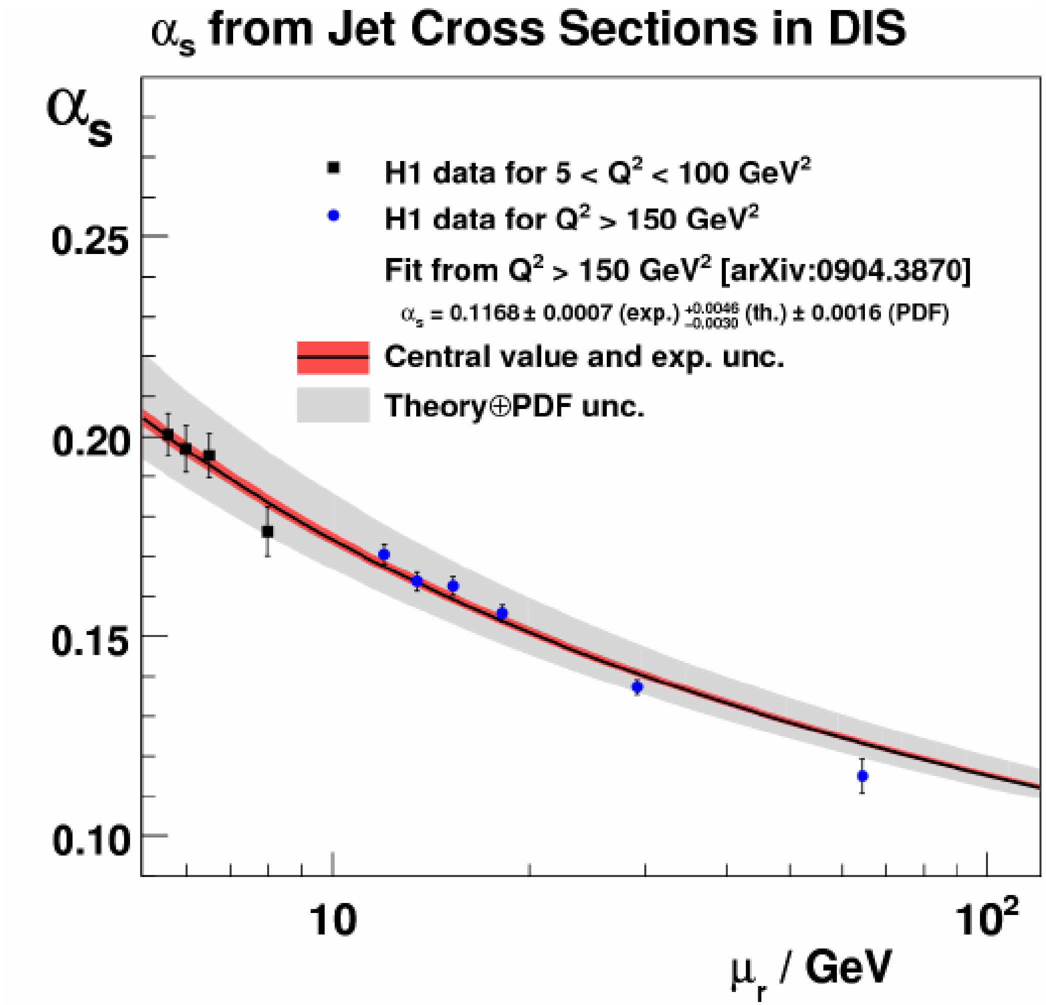
example:

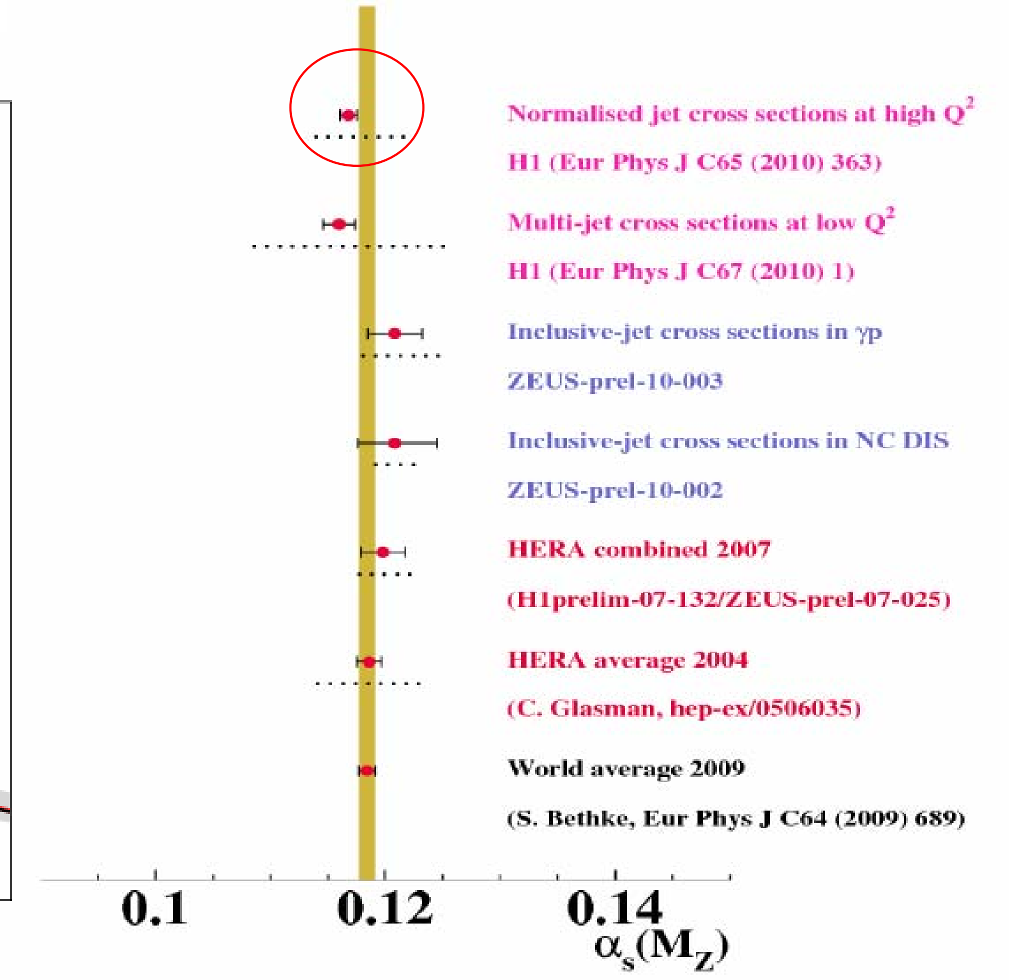


running of α_s from single experiment

recent HERA α_s measurements

example:





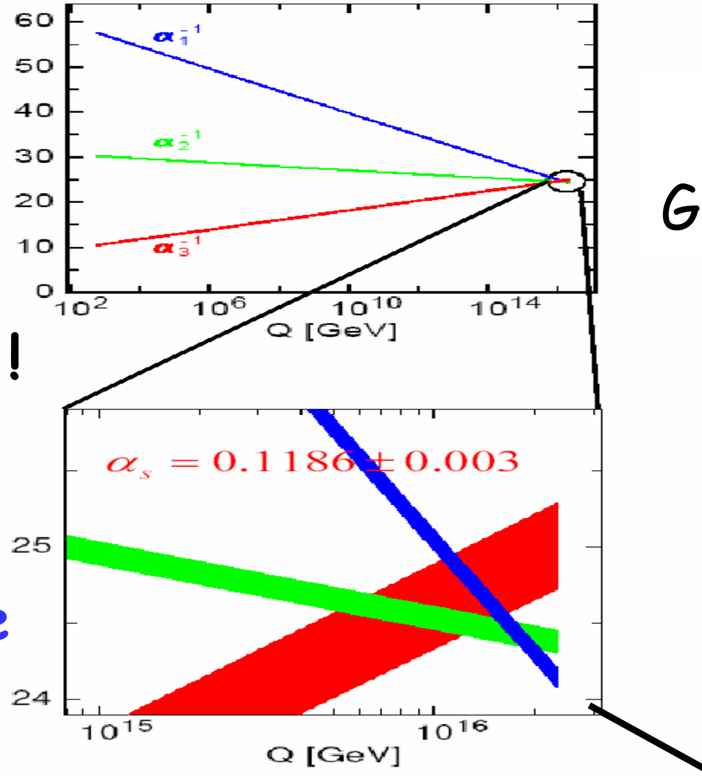
already from single measurement/single experiment, experimental error similar to world average -> need to improve theory !

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%))

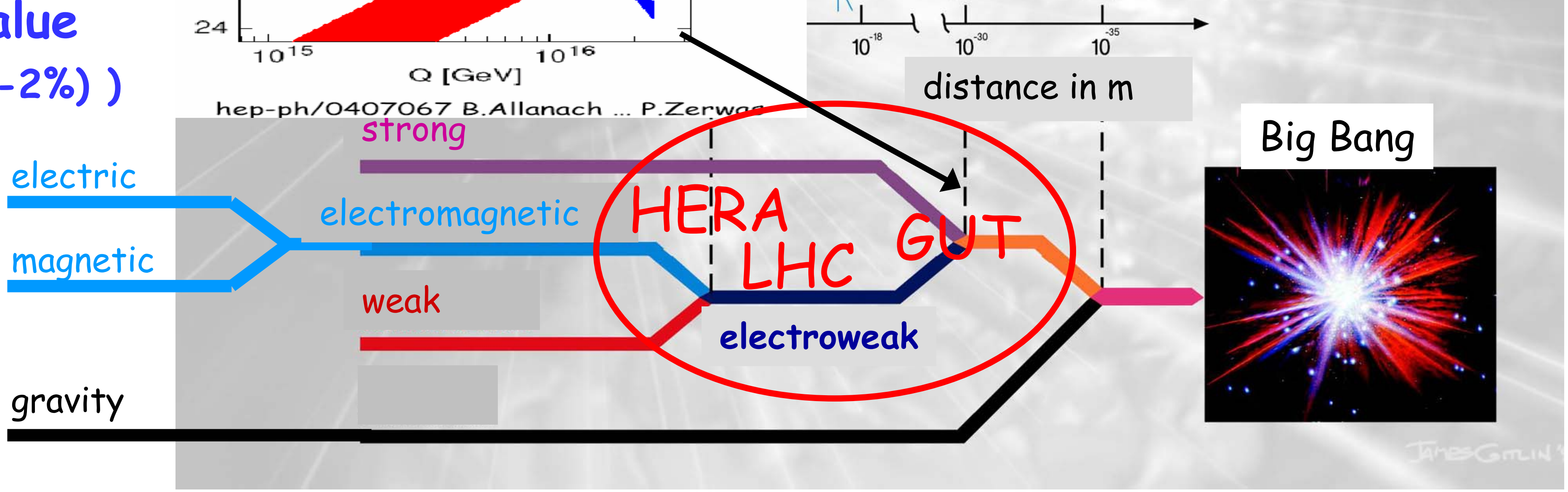


hep-ph/0407067 B.Allanach ... P.Zerwas

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

infrared and collinear safe jet algorithms

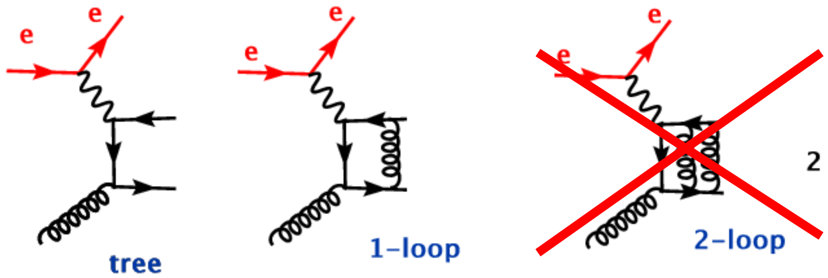
DESY-10-034, march 2010

see talk
M. Cacciari

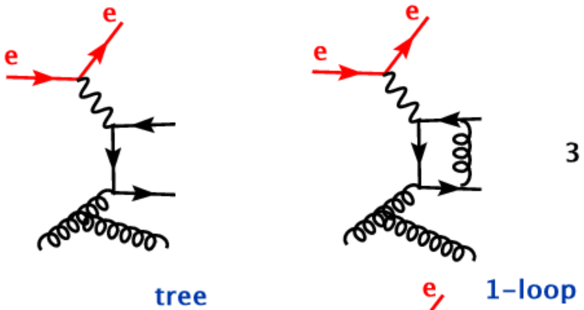
- **kt** used for HERA data since decades
- LHC mainly uses **anti-kt**
- study of **anti-kt** and **Siscone** at HERA added recently

  (before first LHC results)

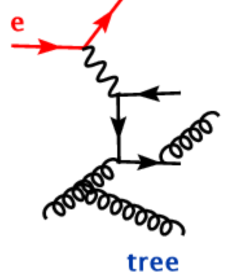
- high Q^2 jet data



2 FINAL STATE PARTONS



3 FINAL STATE PARTONS

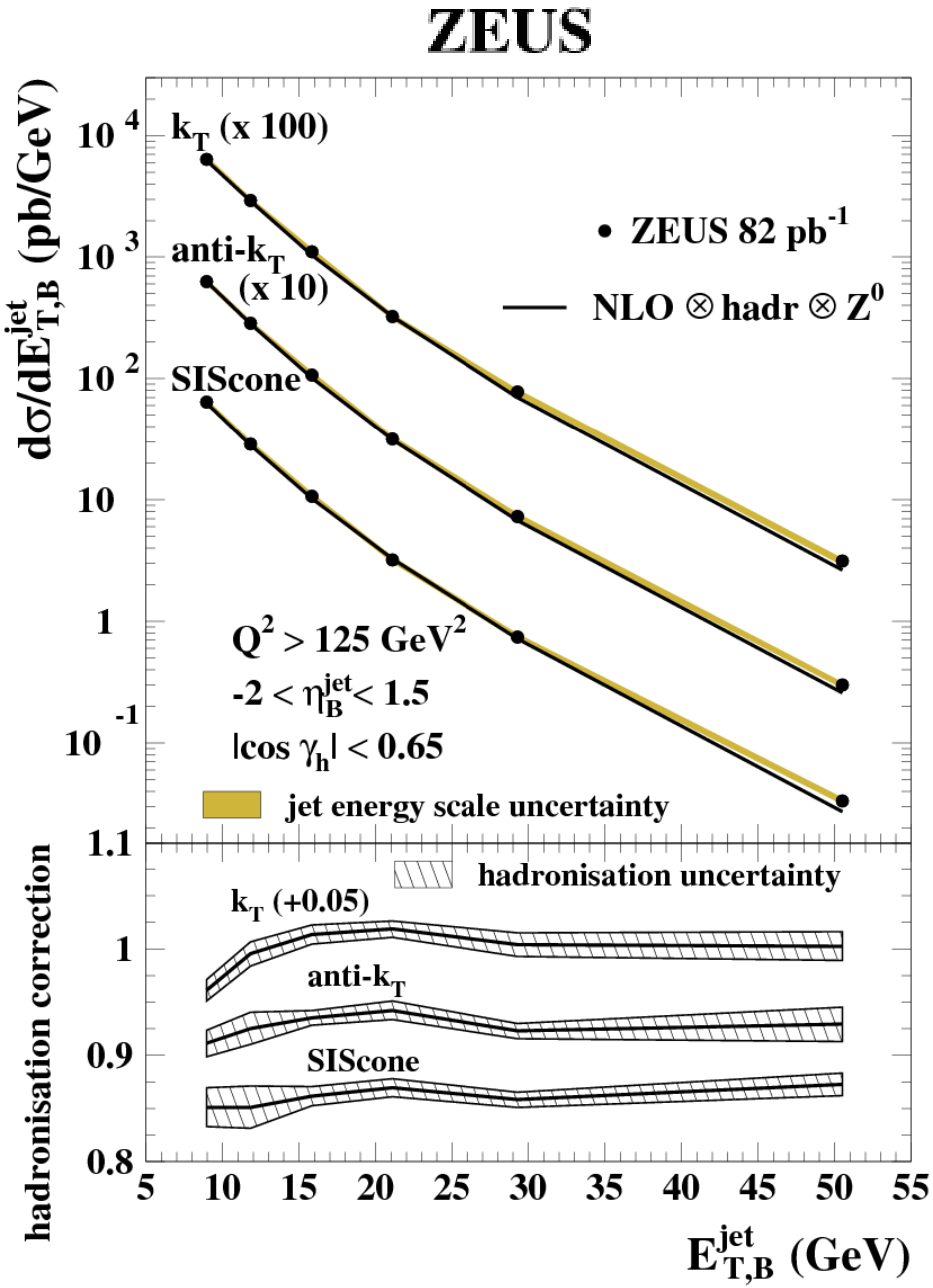


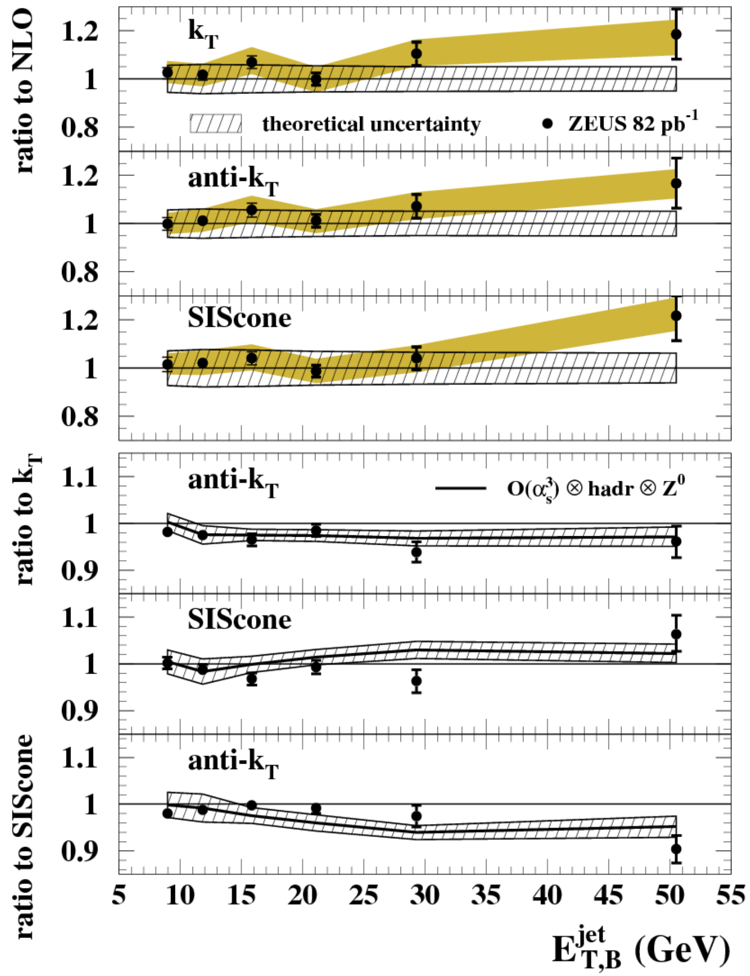
4 FINAL STATE PARTONS

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

- similar measurements also for
  photoproduction at HERA II

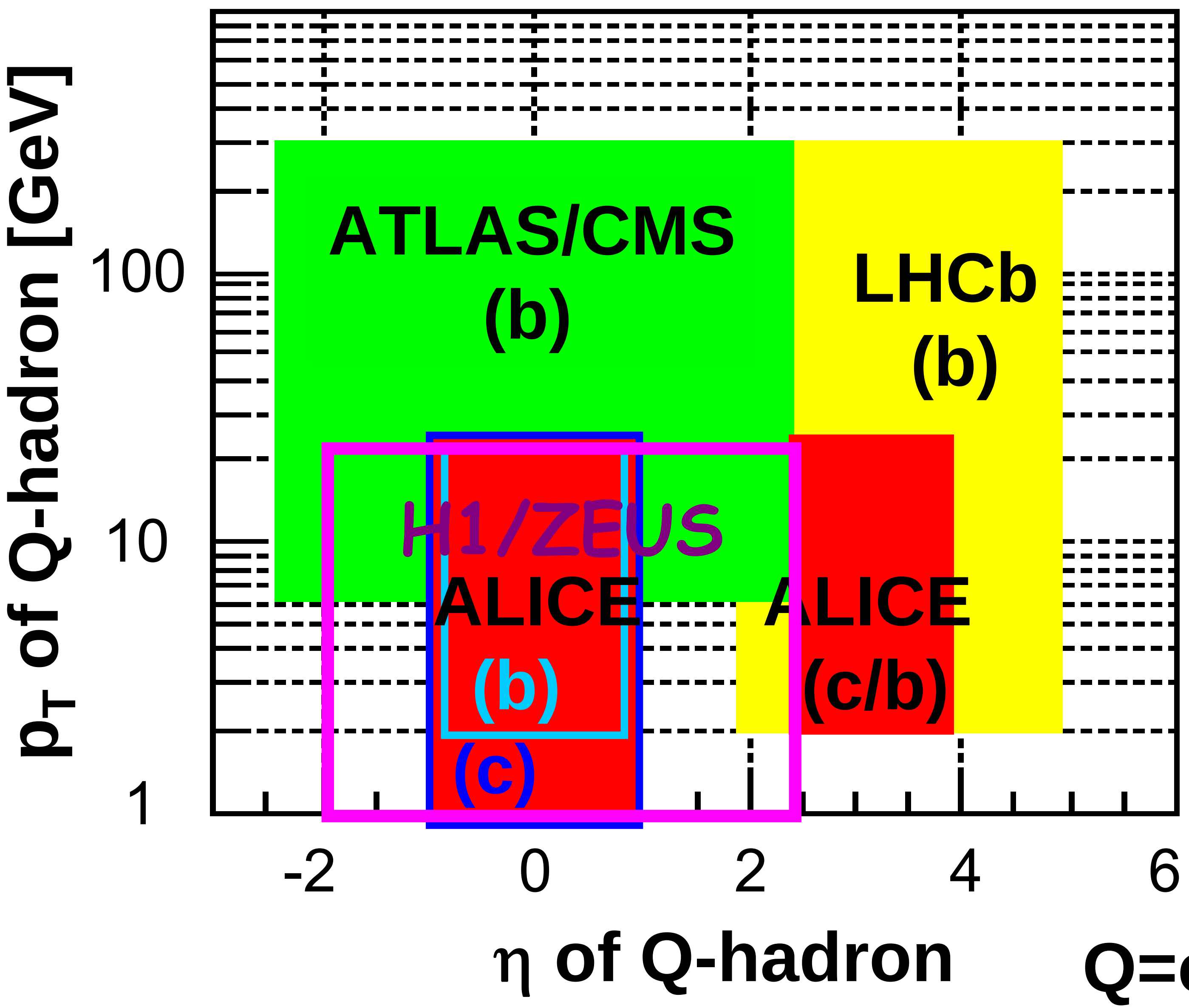
kt-, anti-kt and SisCone Jet production at high Q^2





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

example:
acceptance for open heavy flavor at LHC/HERA

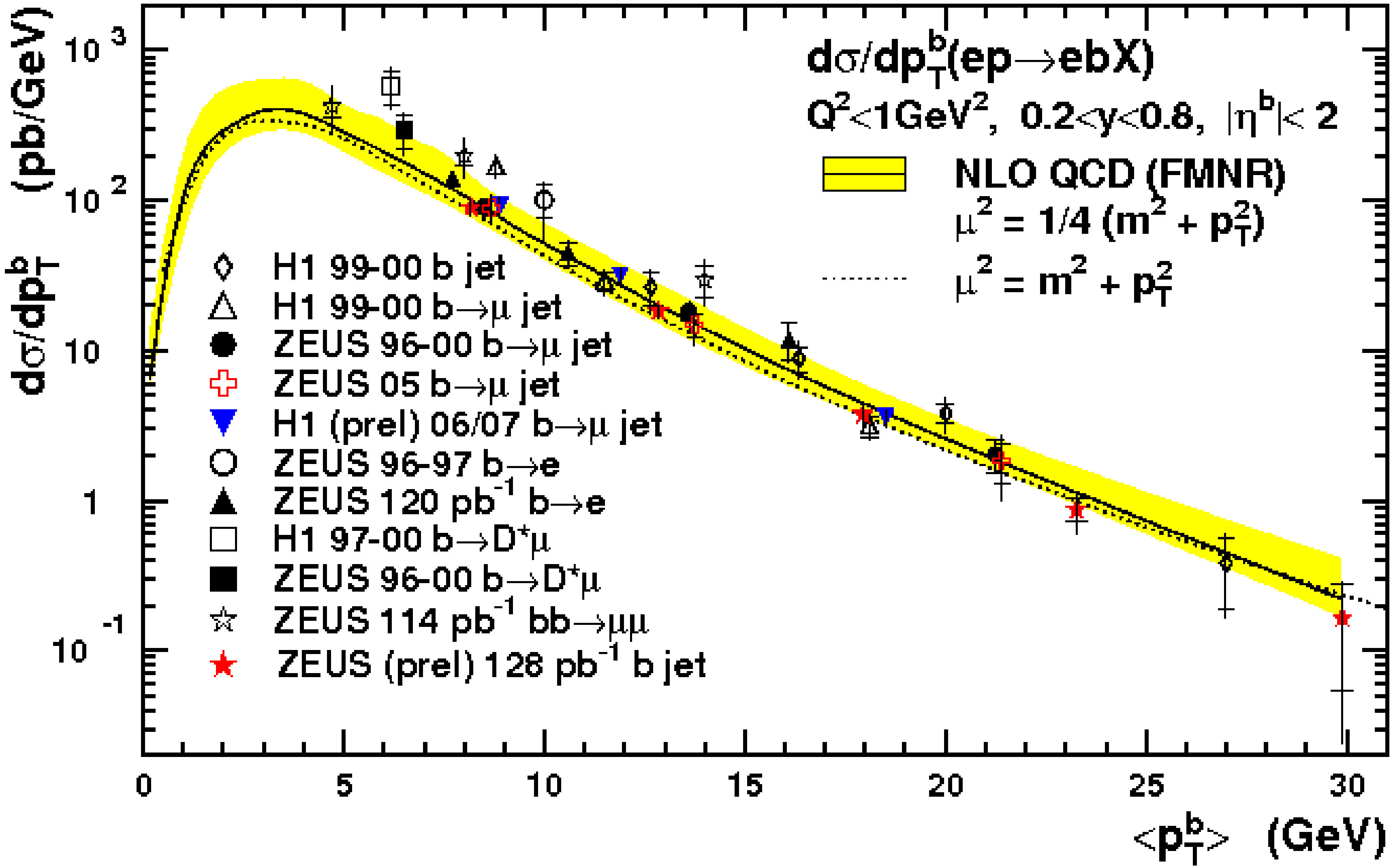


Q=c,b

similar for other final states

beauty in photoproduction

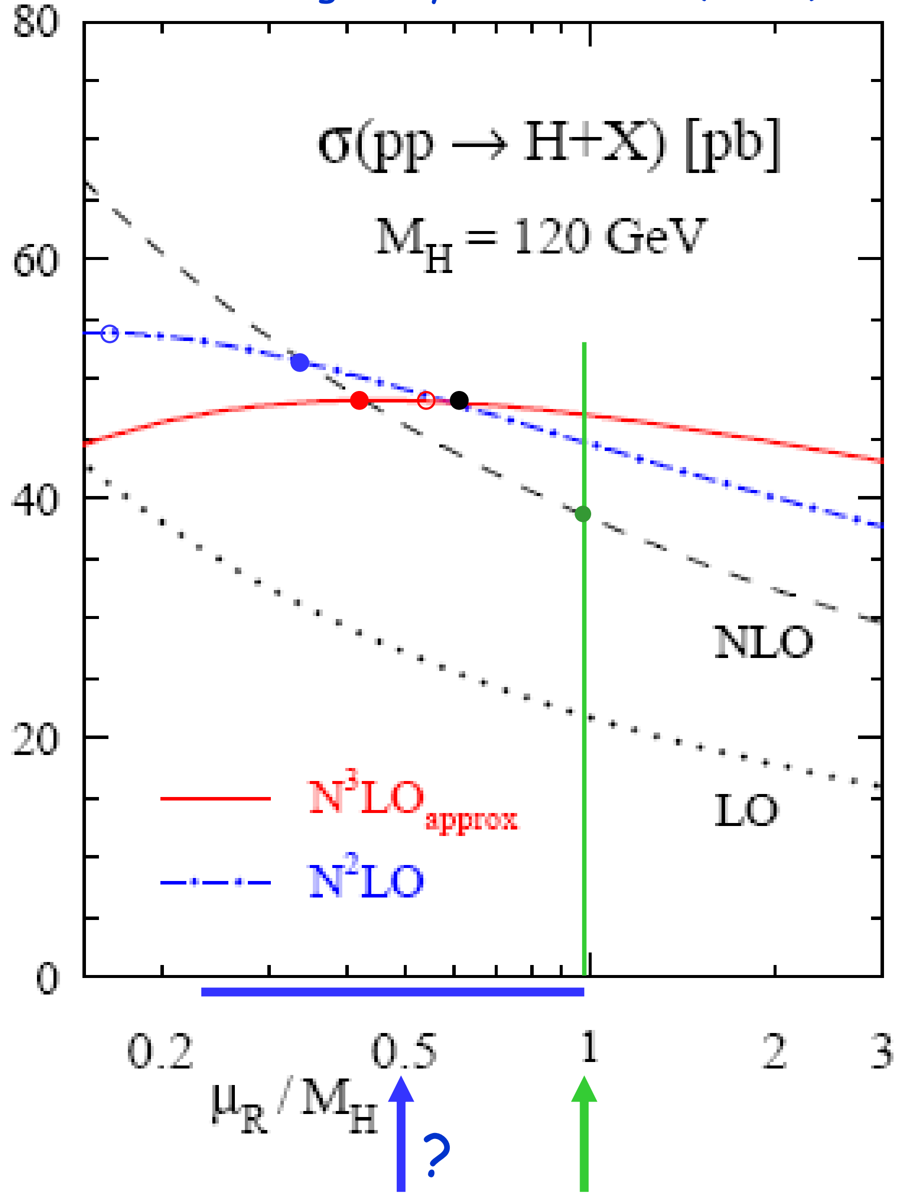
HERA



reasonably described by NLO QCD

NLO scale choice? example: Higgs at LHC

S. Moch, A. Vogt, Phys.Lett. B631 (2005) 48



in principle arbitrary, but

NNLO stability:

- ● NNLO = NLO
- ○ $d\sigma_{NNLO}/d\mu = 0$

N³LO stability:

- ● N^3LO = NLO
- ● N^3LO = NNLO
- ○ $d\sigma_{NLO+NLL}/d\mu = 0$

— "natural" scale

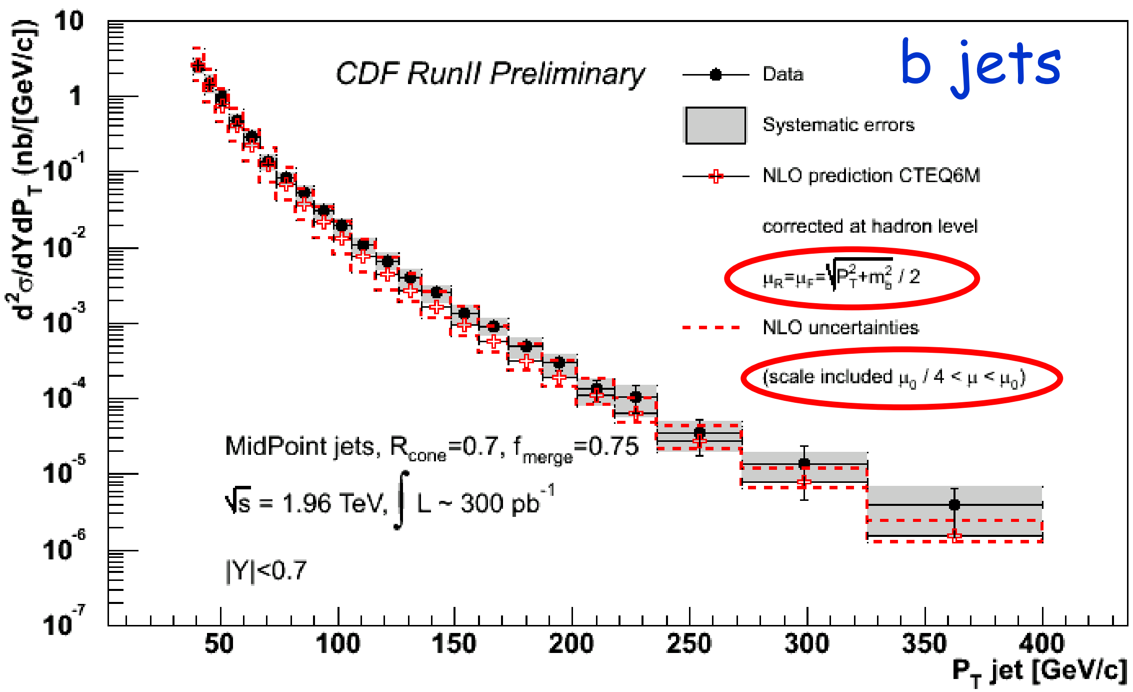
NNLO/N3LO calculations, where available, often suggest ren./fact. scale ~ half "natural" scale for NLO

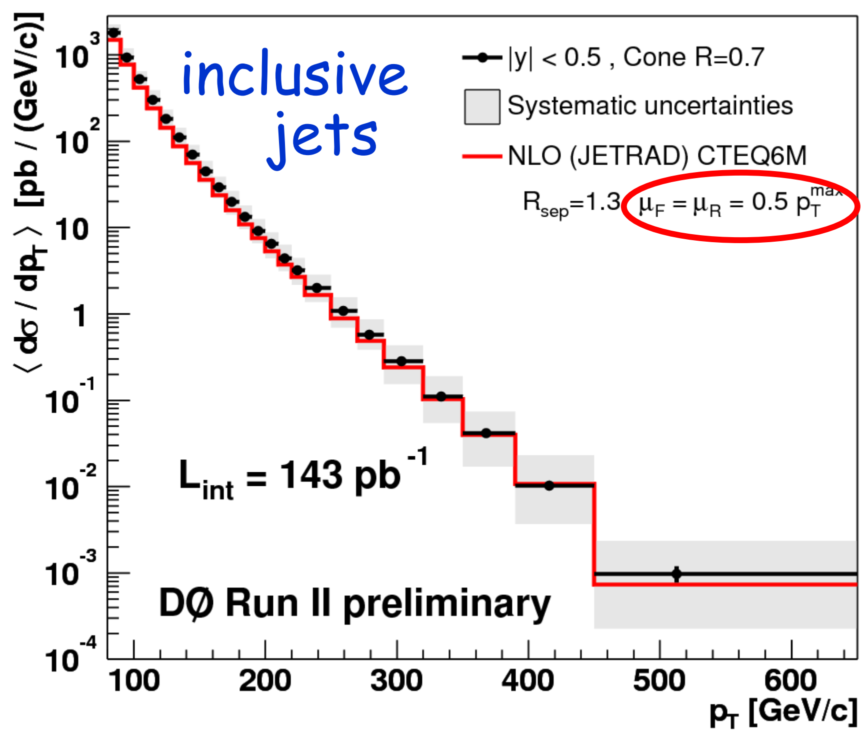
personal remark: either dedicated scale study, or

- consider to use default QCD scale $\mu_0/2$ for your favourite NLO cross section predictions, <u>including LHC,</u> in particular before claiming discrepancies

more details: **arXiv:0711.1983** [hep-ex]

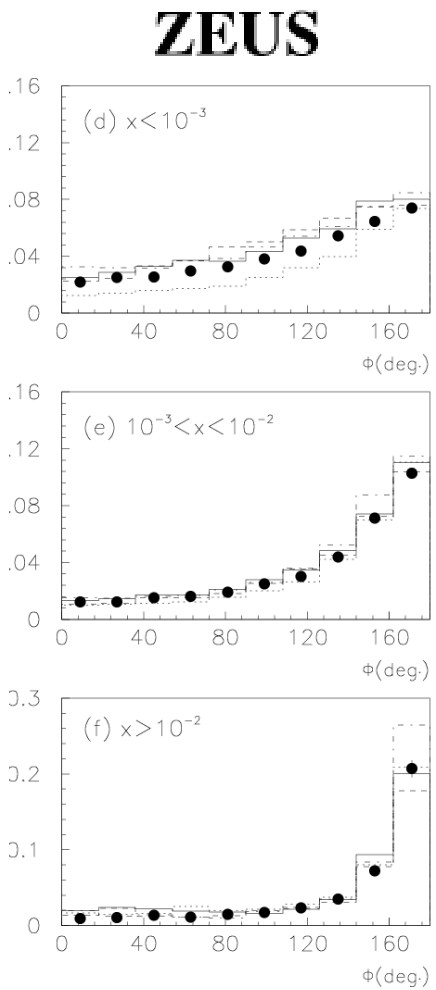
some people are doing this already:



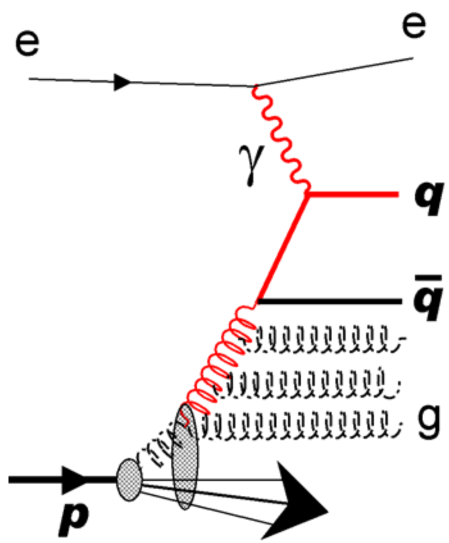


Observation of colour strings/dipoles

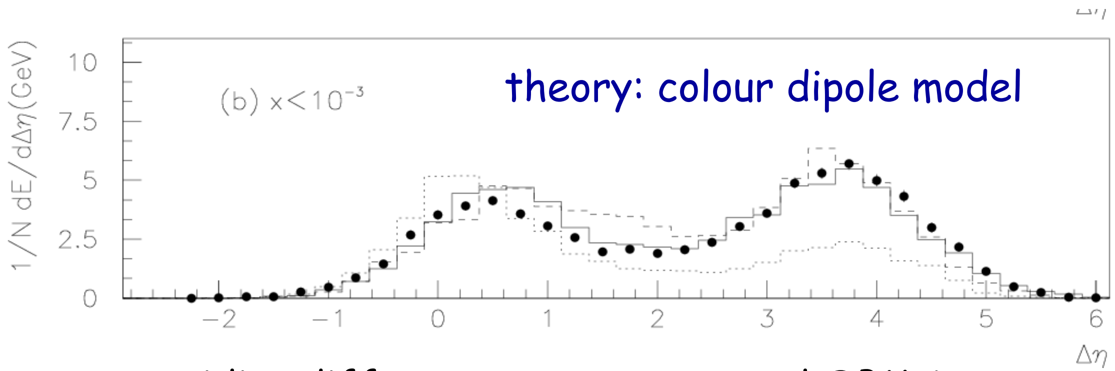
in hadronic energy flow in DIS at HERA: Z. Phys. C59 (1993) 231



angle w.r.t. electron



"In the low x region, the peak in the hadronic energy flow in the direction of the current jet is shifted [...] towards the proton remnant with most of the energy appearing between the position of the expected jet peak and that of the proton remnant."



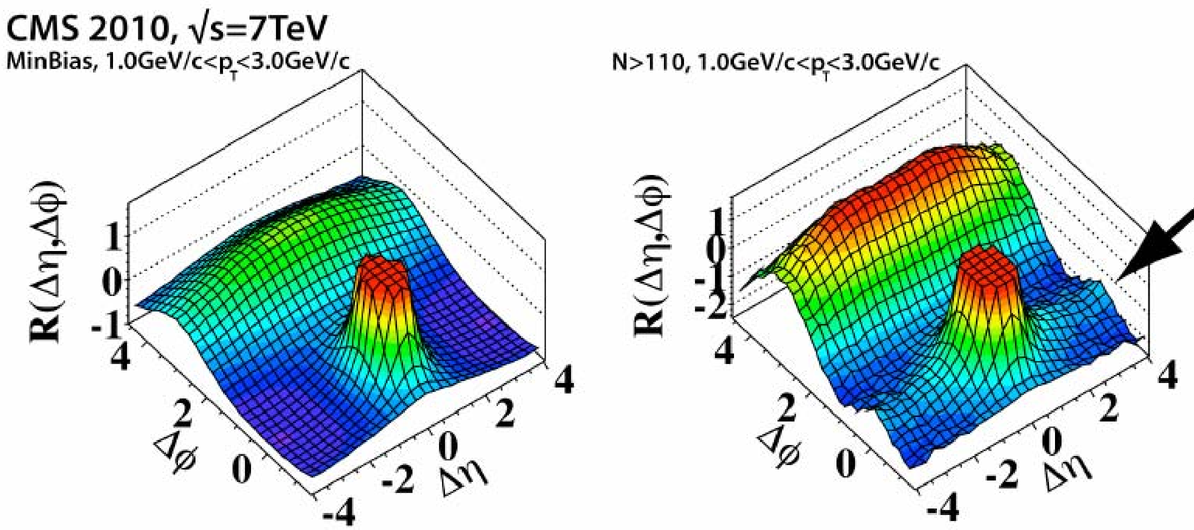
rapidity difference w.r.t. expected QPM jet

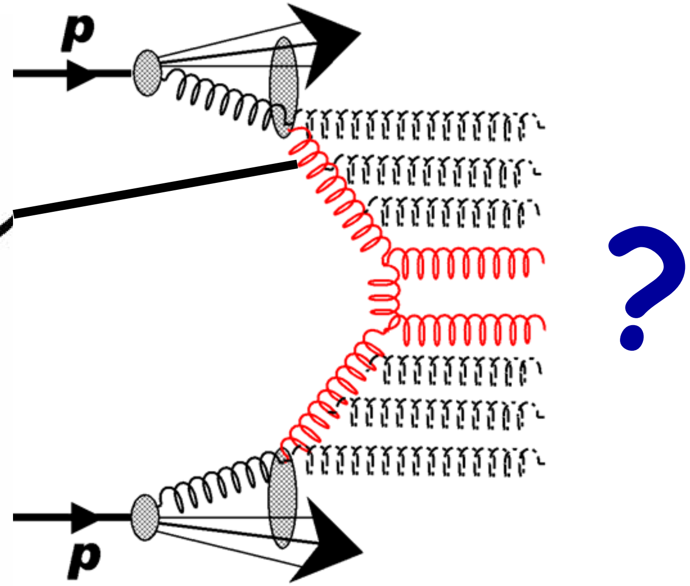
see also H1, DESY-94-033

Long range two-particle correlations in CMS

see talk
G. Dissertori

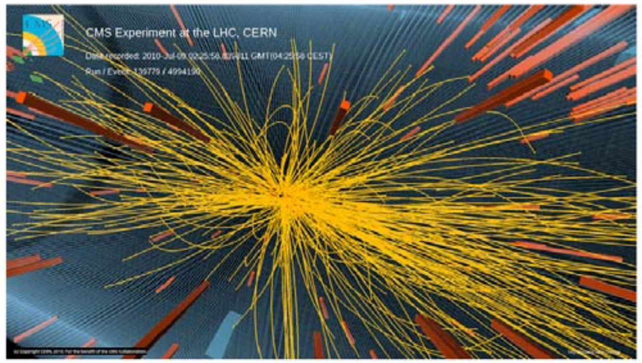
arXiv:1009.4122 [hep-ex]





could it simply be a rediscovery of
colour strings/dipoles
between (semi-)hard partons
and proton remnant ?

see talk
G. Veres



Summary and conclusions

- **HERA is currently one of the best QCD laboratories**

  in general, **agreement** with NLO QCD, **success of the Standard Model !**

  HERA contribution to PDFs will remain THE reference for decades

  Many data sets being added. Currently special attention on F_2^c.

  HERA has potential to yield world best measurements of α_s
  (need NNLO calculations ! partially in progress).

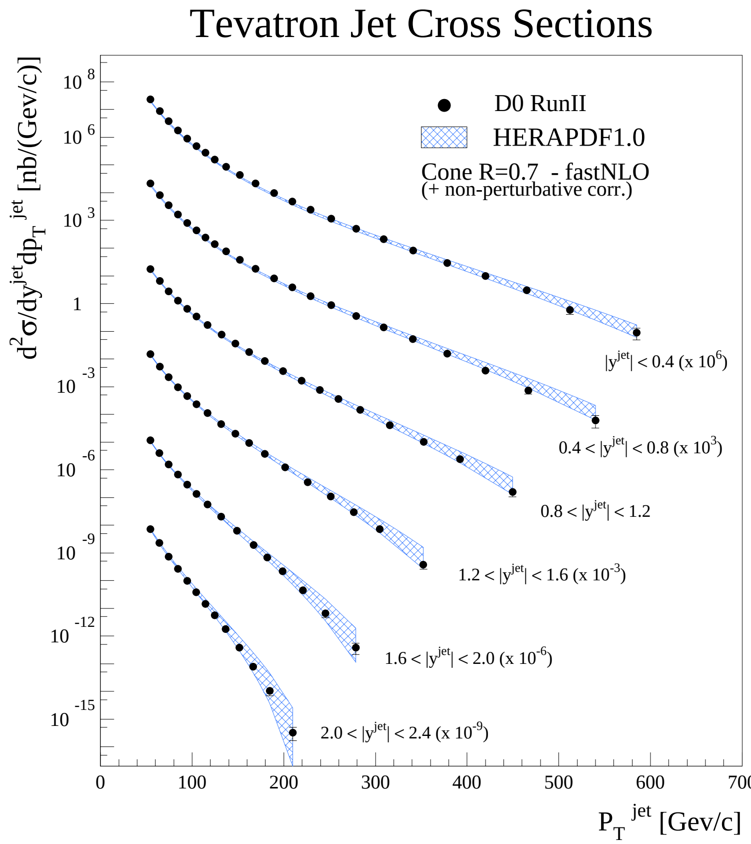
  have colour strings/dipoles, seen at HERA since 1993, been rediscovered at LHC?

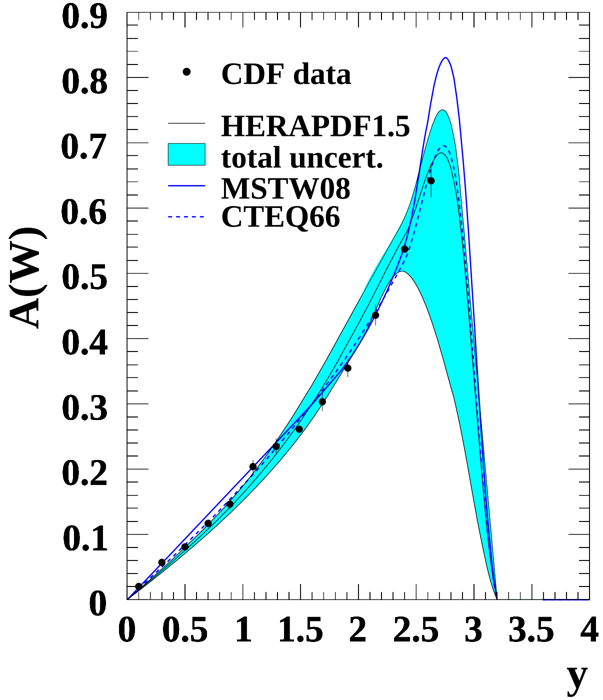
- for QCD only fraction of statistics has been analyzed so far in many cases.
  combination of H1/ZEUS results ongoing (first results published)
  -> **towards full 1 fb^{-1} results (H1+ZEUS, HERA1+2)**.
  -> expect **significant further improvements** over next few years

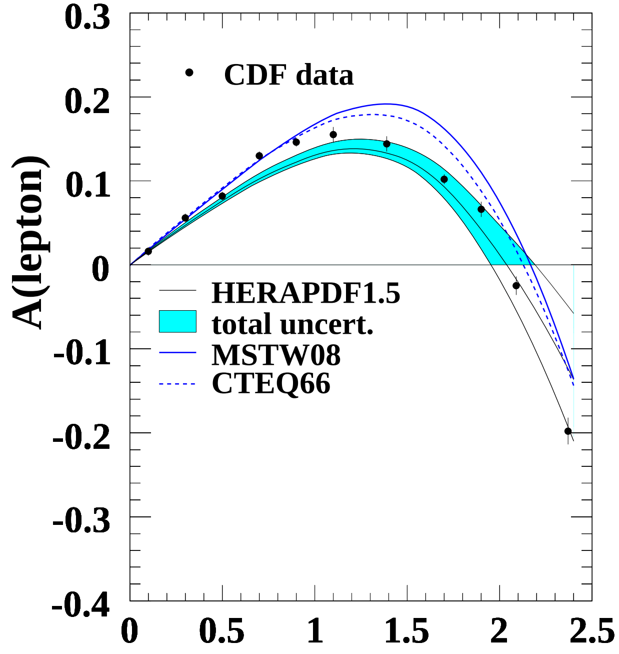
- many of these improvements **relevant for physics at LHC**

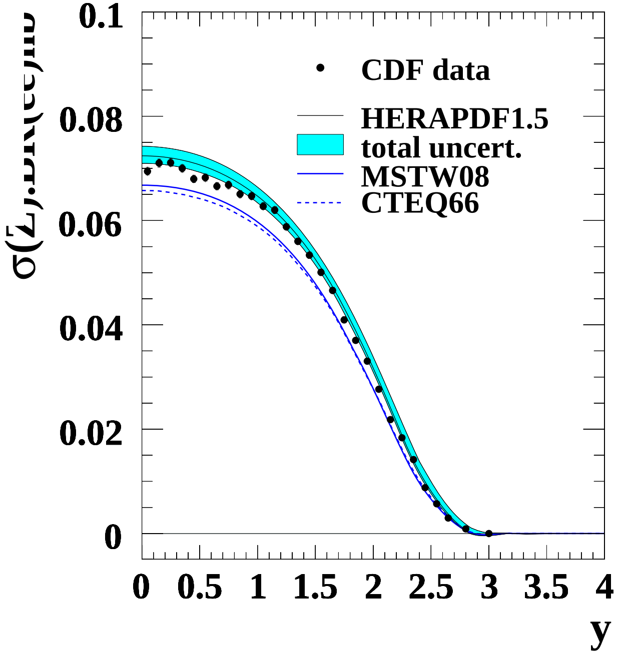
Unused + Backup slides

Comparison to Tevatron



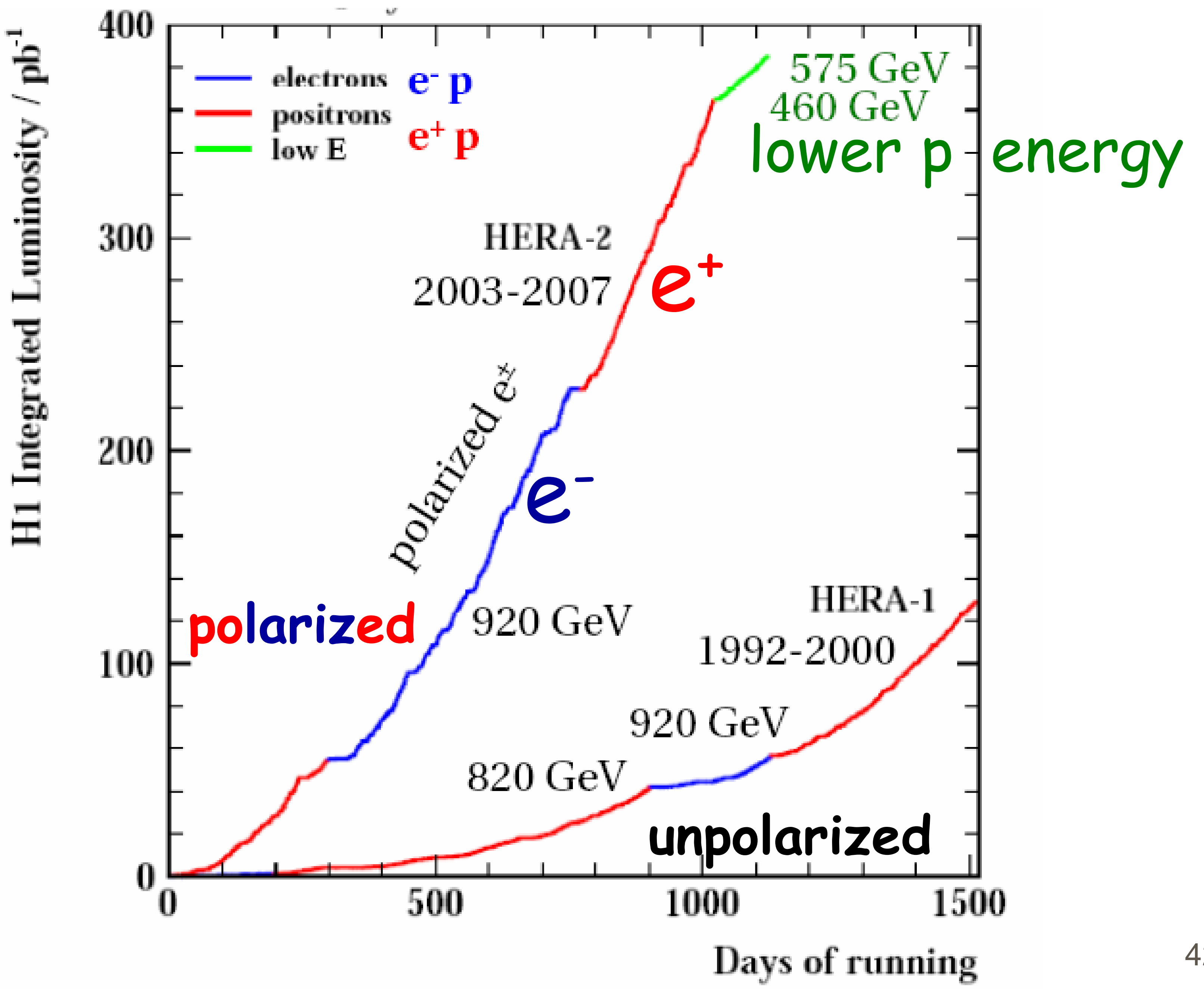




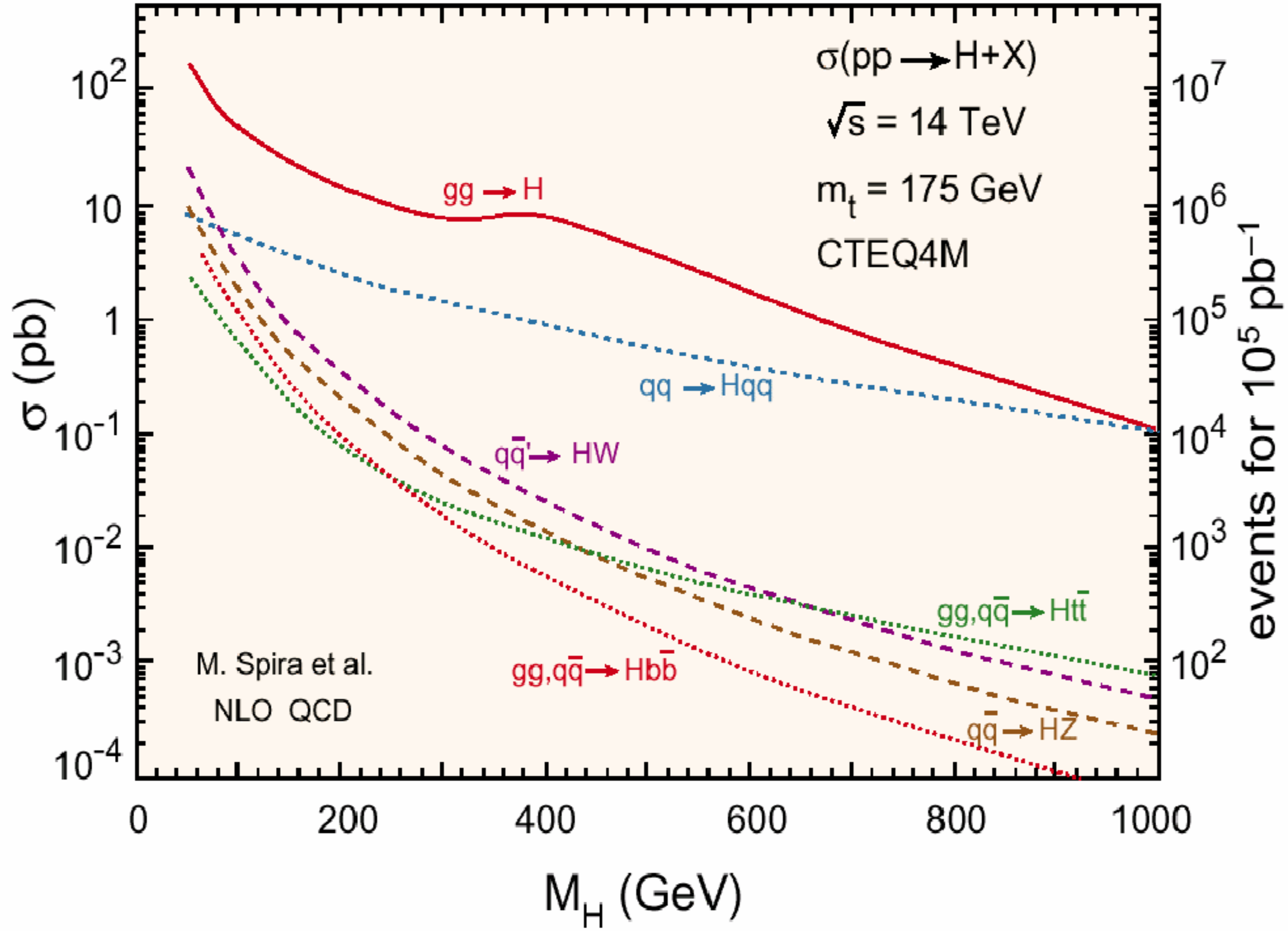


see talk
PDF discussion group

HERA physics luminosity vs. time



Example: Higgs cross section at LHC

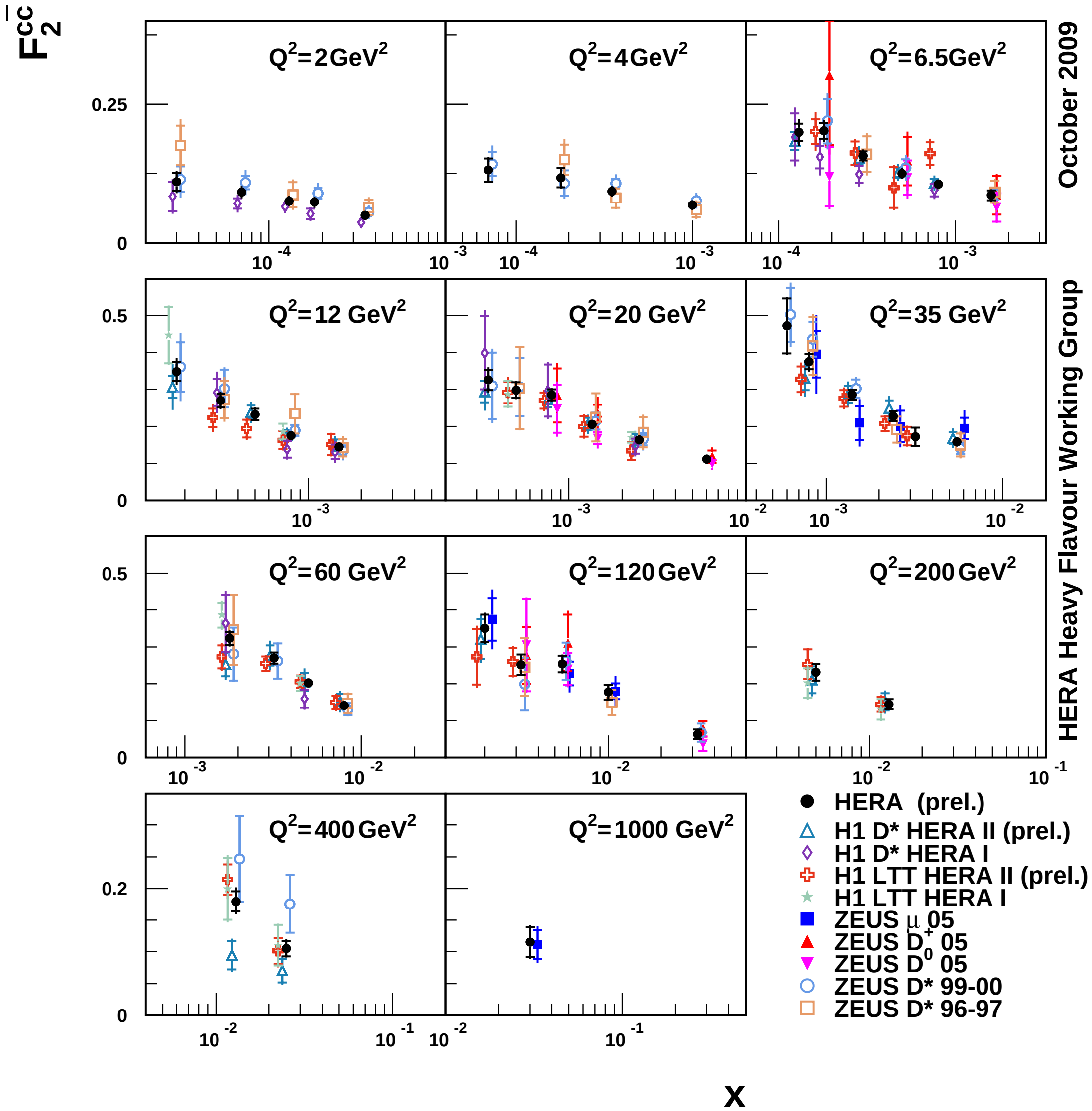


Knowledge of gluon and quark distributions needed

Charm contribution to F_2

see talk R. Placakyte

H1 and ZEUS have also combined charm data recently



can Tevatron results be used for LHC?

e.g. inclusive W/Z production

(LHC luminosity monitor)

beware of low x effects!

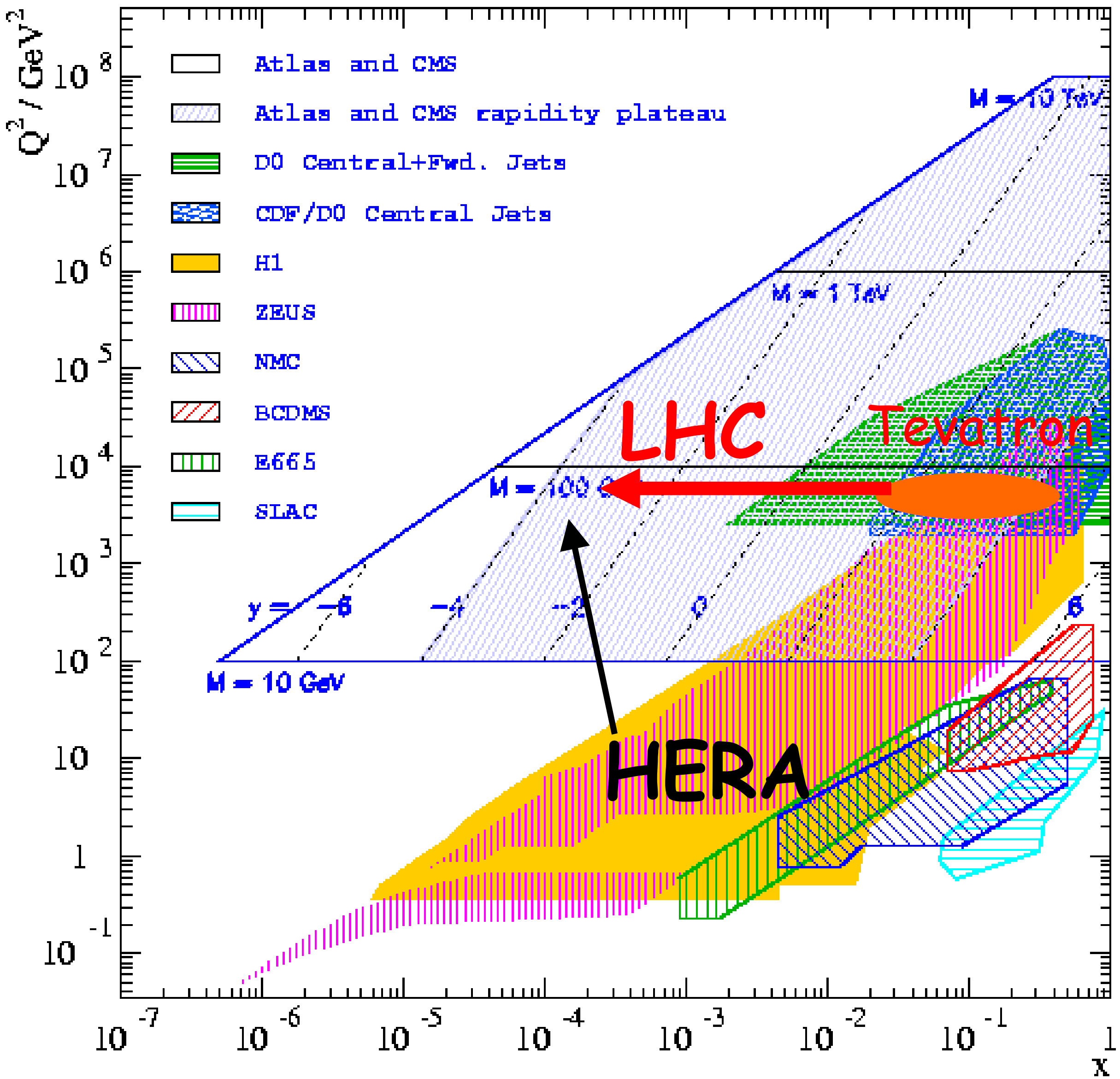
saturation

multiple interactions

BFKL vs. DGLAP

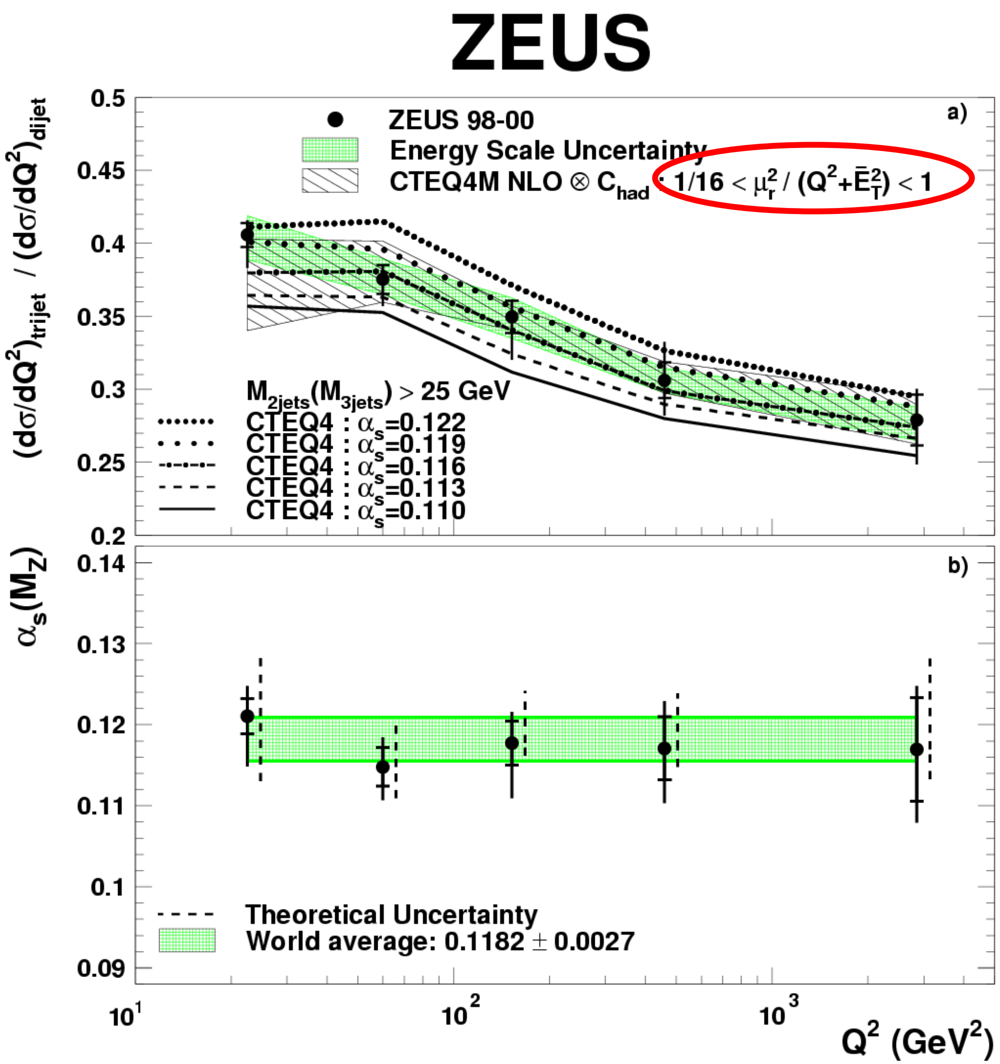
=> study at HERA

(sorry, not today)



Use of $\mu_0/2$ at HERA (examples)

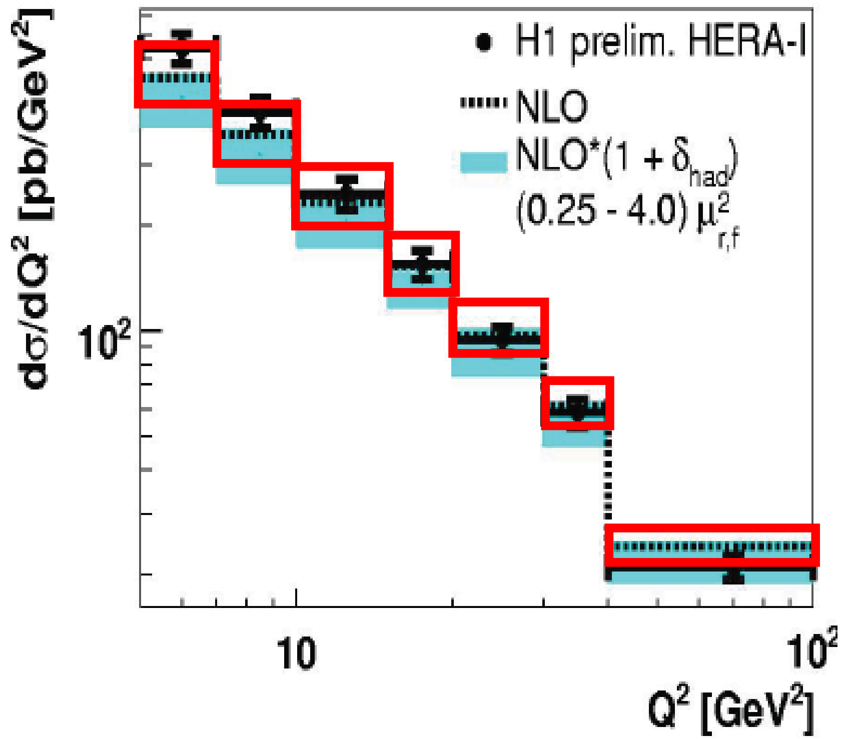
multijet-Production in DIS



new scale

inclusive jets at low Q^2

approximate estimate (A.G.), to be calculated exactly



many other measurements OK with natural scale (but also with reduced scale)