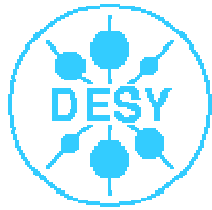


QCD at the HERAscale

and implications for the TERAscale



Achim Geiser, DESY Hamburg
for the H1 and ZEUS collaborations
+ some personal views



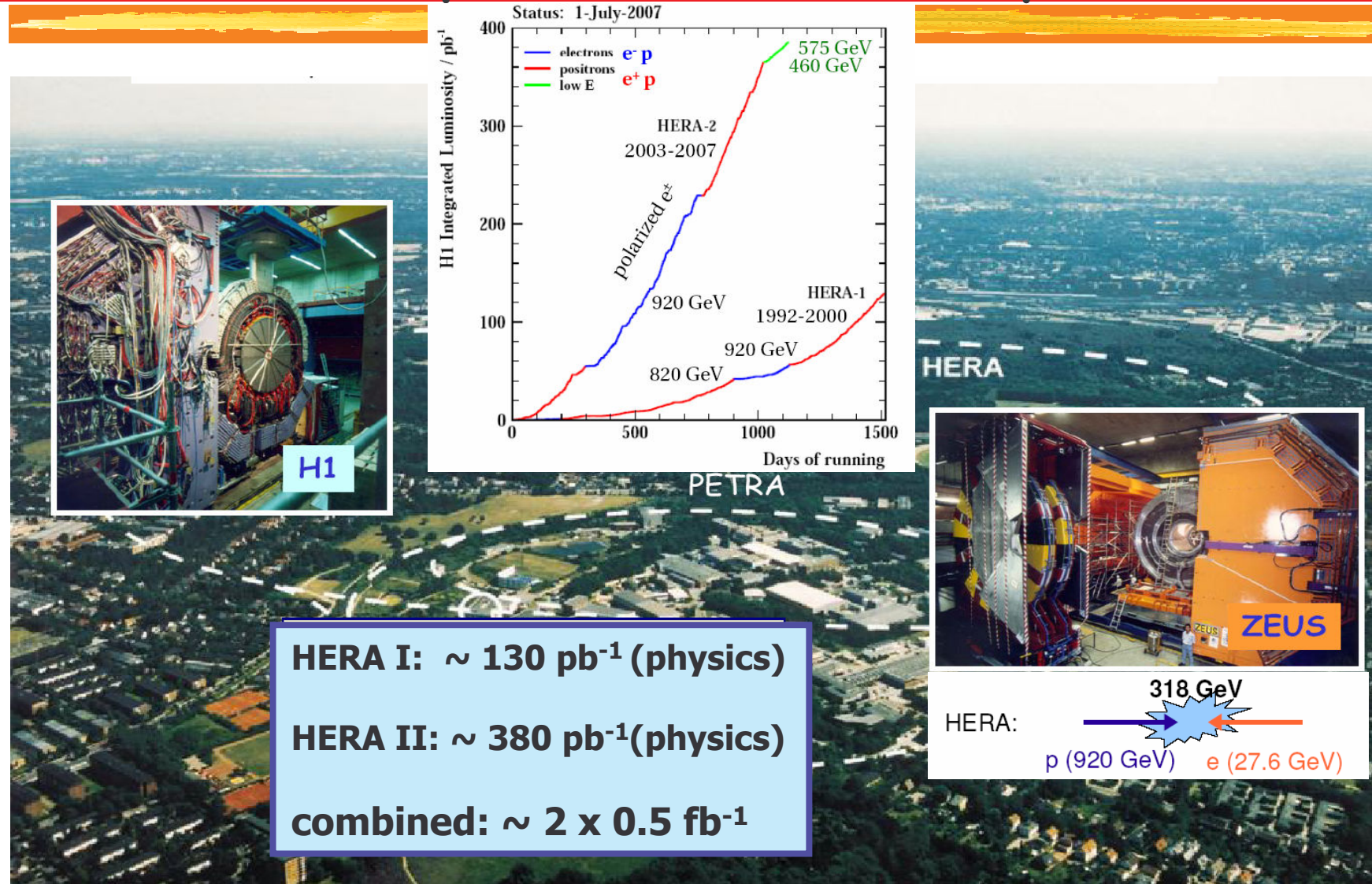
XXVIII Physics in Collision
Perugia, Italy, 28 June 2008



- introduction
- structure functions, parton densities, and α_s
- semi-inclusive final states
(heavy flavours, single photons, diffraction)
- conclusions

jet physics:
see previous
talk by
C. Royon

The HERA ep collider and experiments



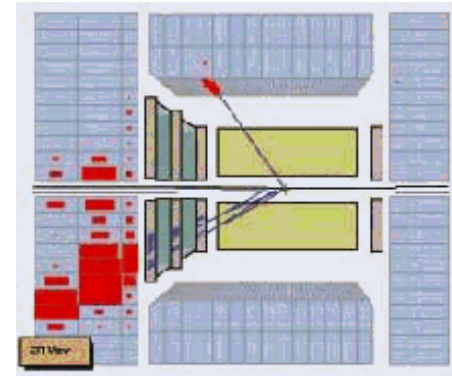
HERA = currently best (?) QCD laboratory

■ Proton structure:

- structure functions and parton density functions (PDF)
- heavy flavours

■ General QCD studies

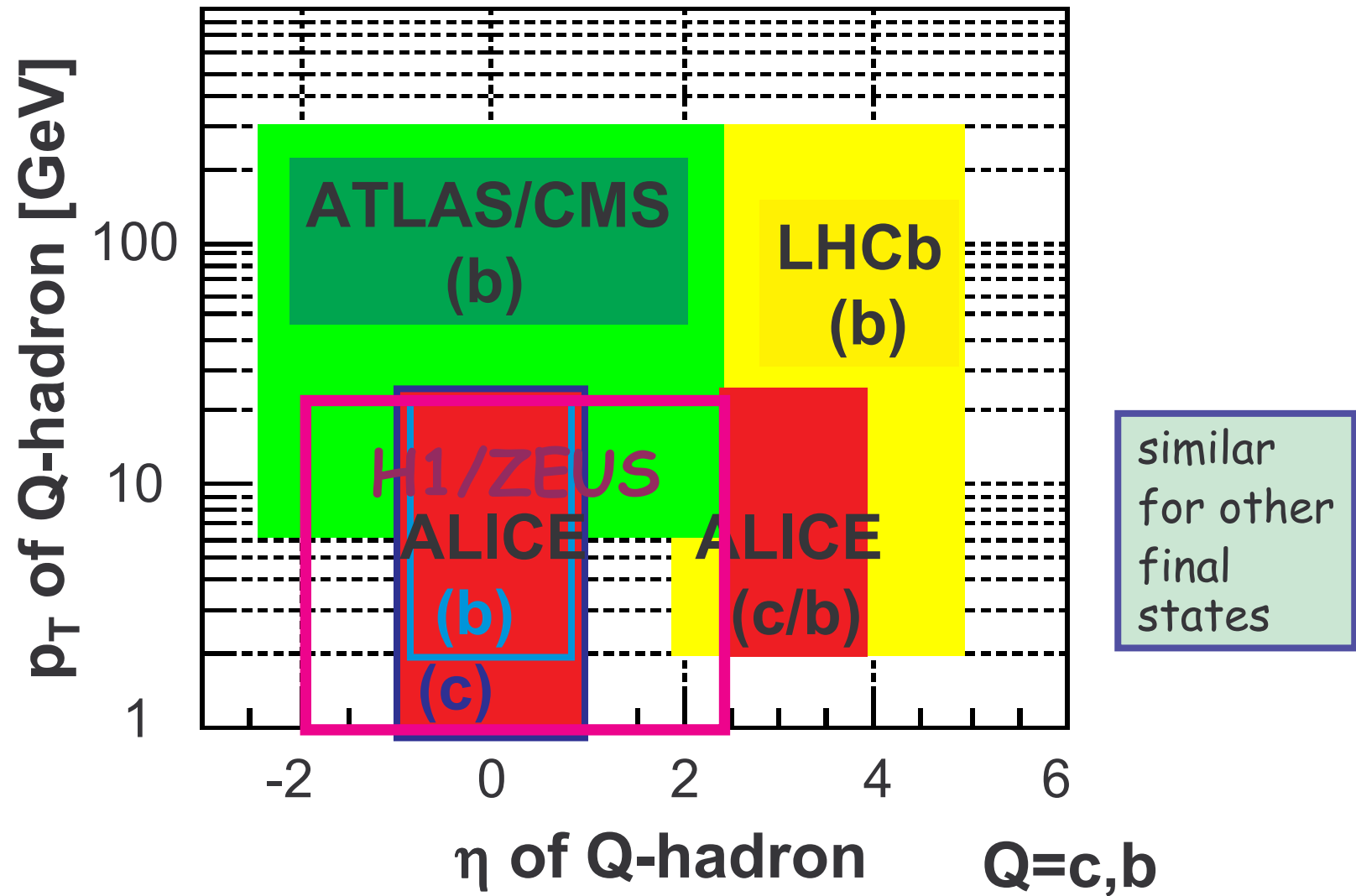
- jets and α_s
- semi-inclusive final states



apologies:
no time for
experimental
methods

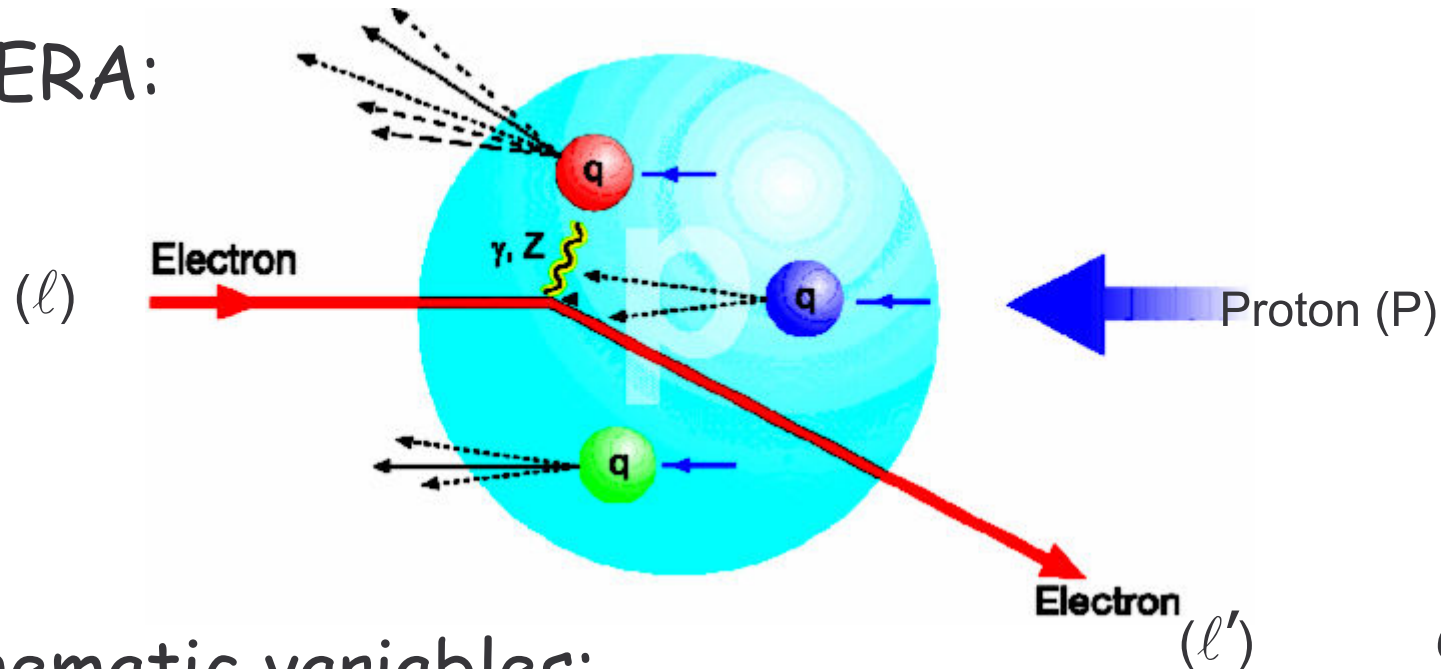
■ Both direct and indirect relations to measurements at Tevatron and LHC

example:
acceptance for open heavy flavor at LHC/HERA



Kinematics of Deep Inelastic Scattering (DIS)

HERA:



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

$$Q^2 \lesssim 1 \text{ GeV}^2:$$

photoproduction

$$Q^2 \gtrsim 1 \text{ GeV}^2:$$

DIS

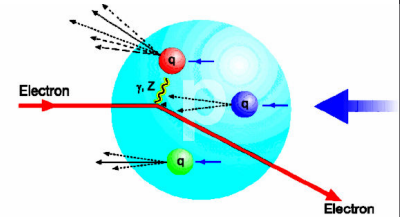
The structure of the proton

- Measure cross section

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

at high Q^2

-> talk V. Chekelian



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

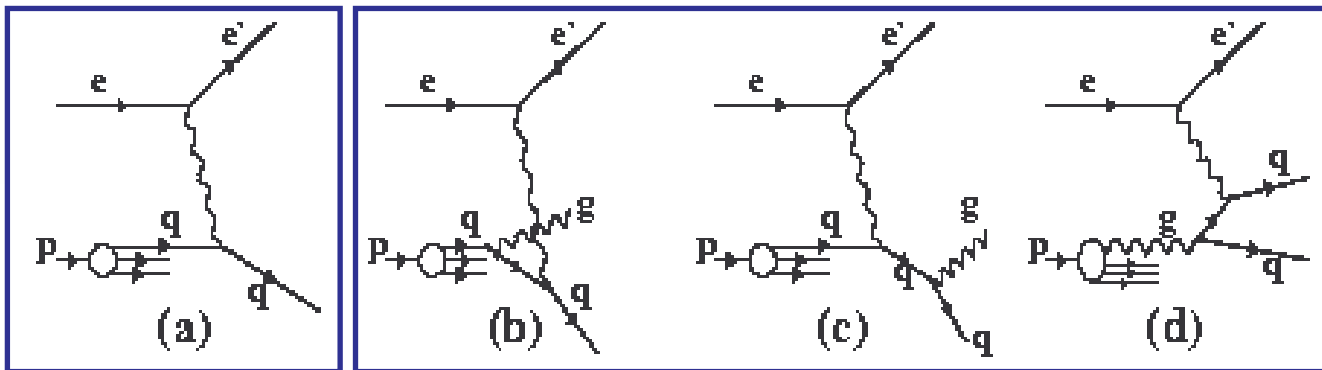
- Parton distribution functions (PDF) in pQCD

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

q_i – probability to find quark with flavour i in proton

-> talk E. Gallo

"higher"
order QCD
corrections

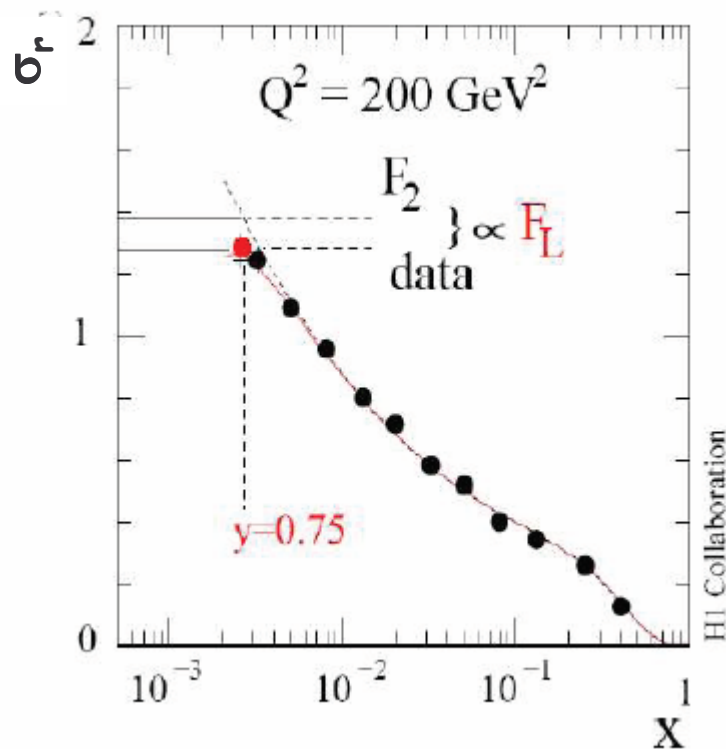


in general:
 F_2 structure
function
is **not** PDF

Reduced cross section

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

=0 for real spin $\frac{1}{2}$ partons
(Callan-Gross)



$F_2 \sim$ quark distributions

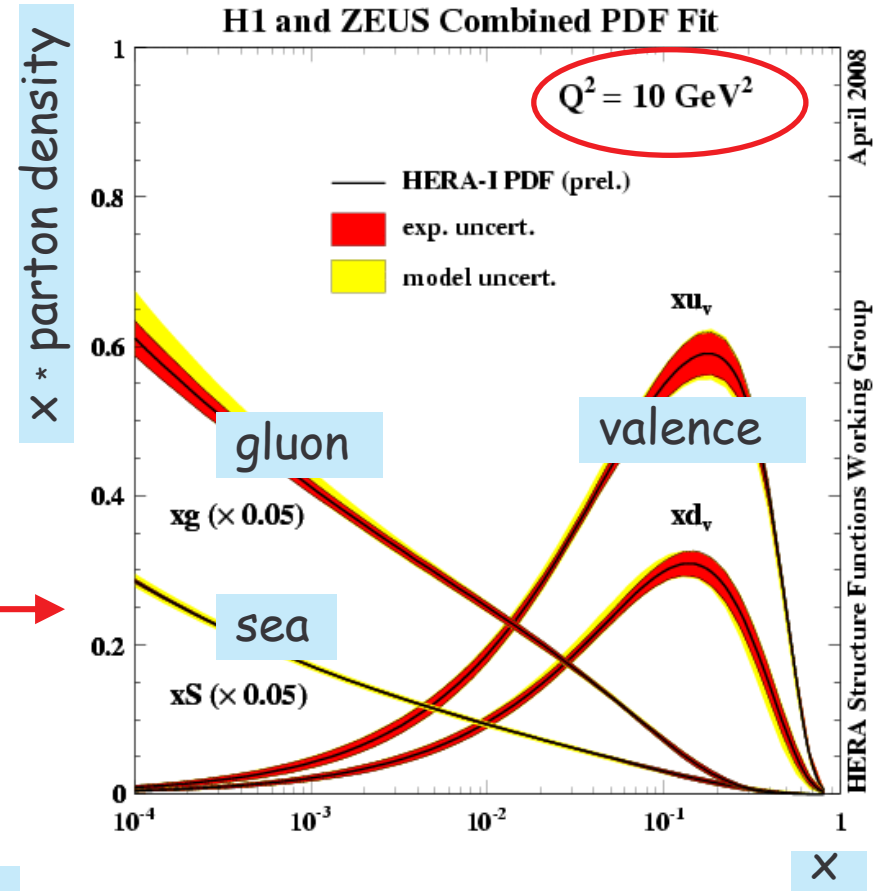
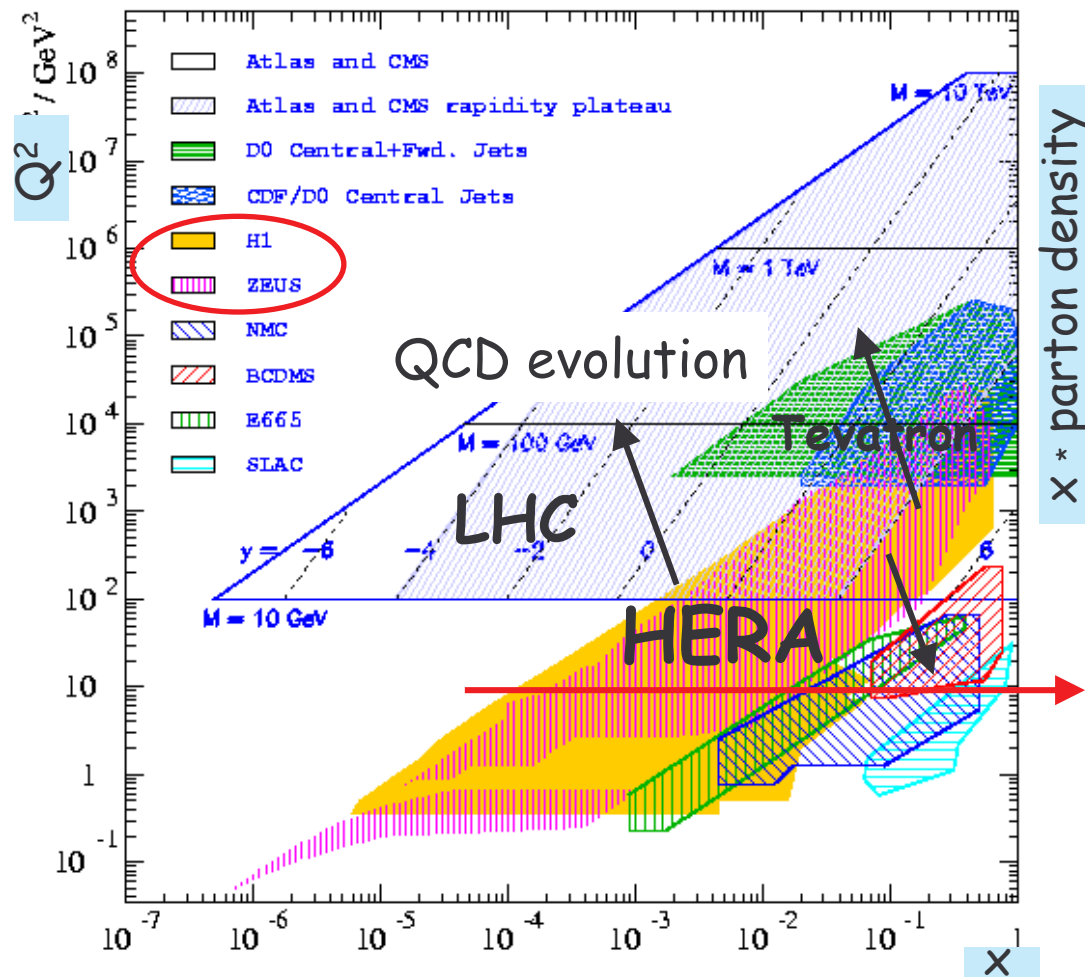
$$F_L(x, Q^2) \sim \alpha_s x g(x, Q^2)$$

-> talk V. Chekelian

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

in most of phase space:
 $\sigma_r \approx F_2$

Parton density functions

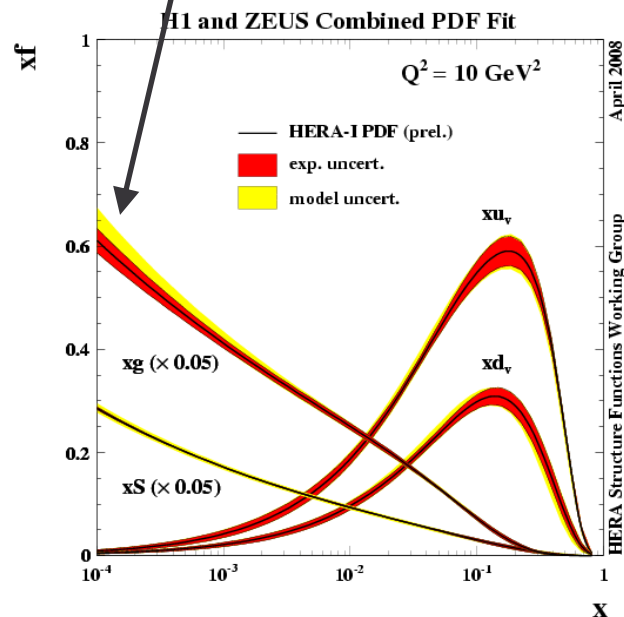


HERA PDFs essential for LHC

F_2 and gluon density

DGLAP QCD evolution:
sea quarks, $g \rightarrow q\bar{q}$
positive slope
(scaling violations)

gluon density

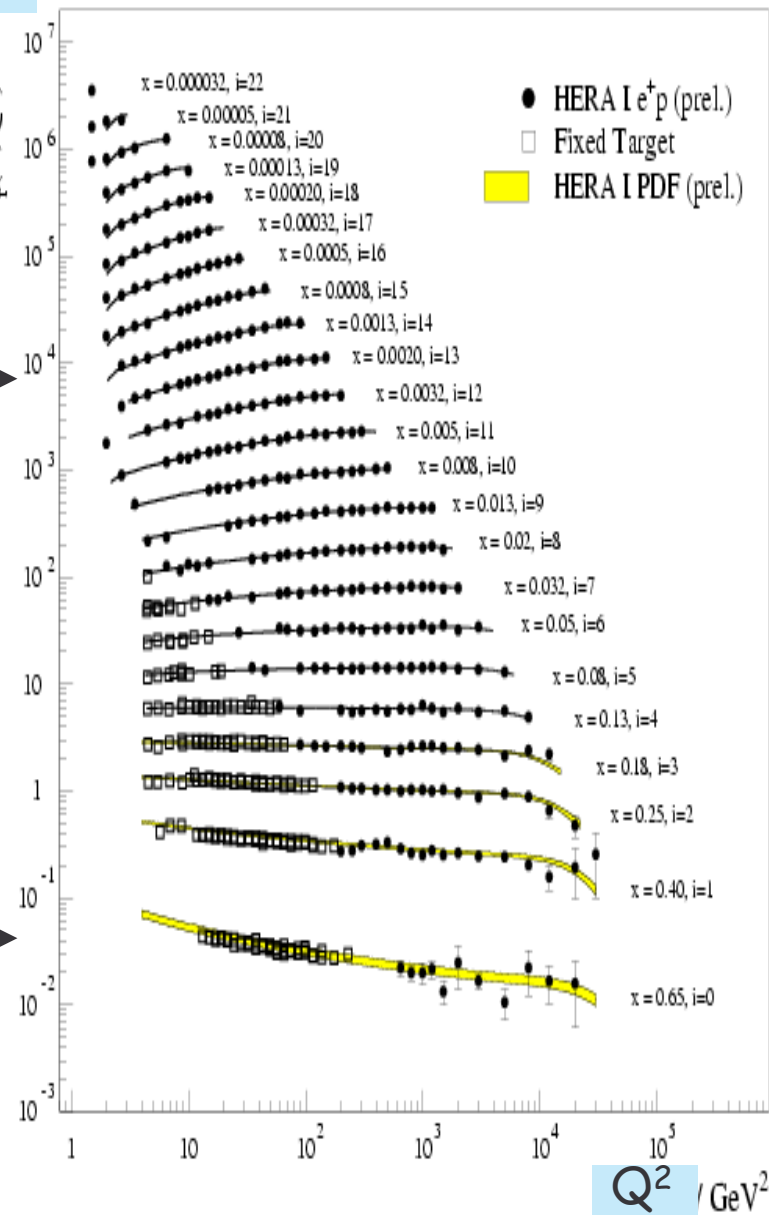


valence quarks
 $q \rightarrow qg$

negative slope

$\sigma_r(x, Q^2) \times 2^i \sim F_2$

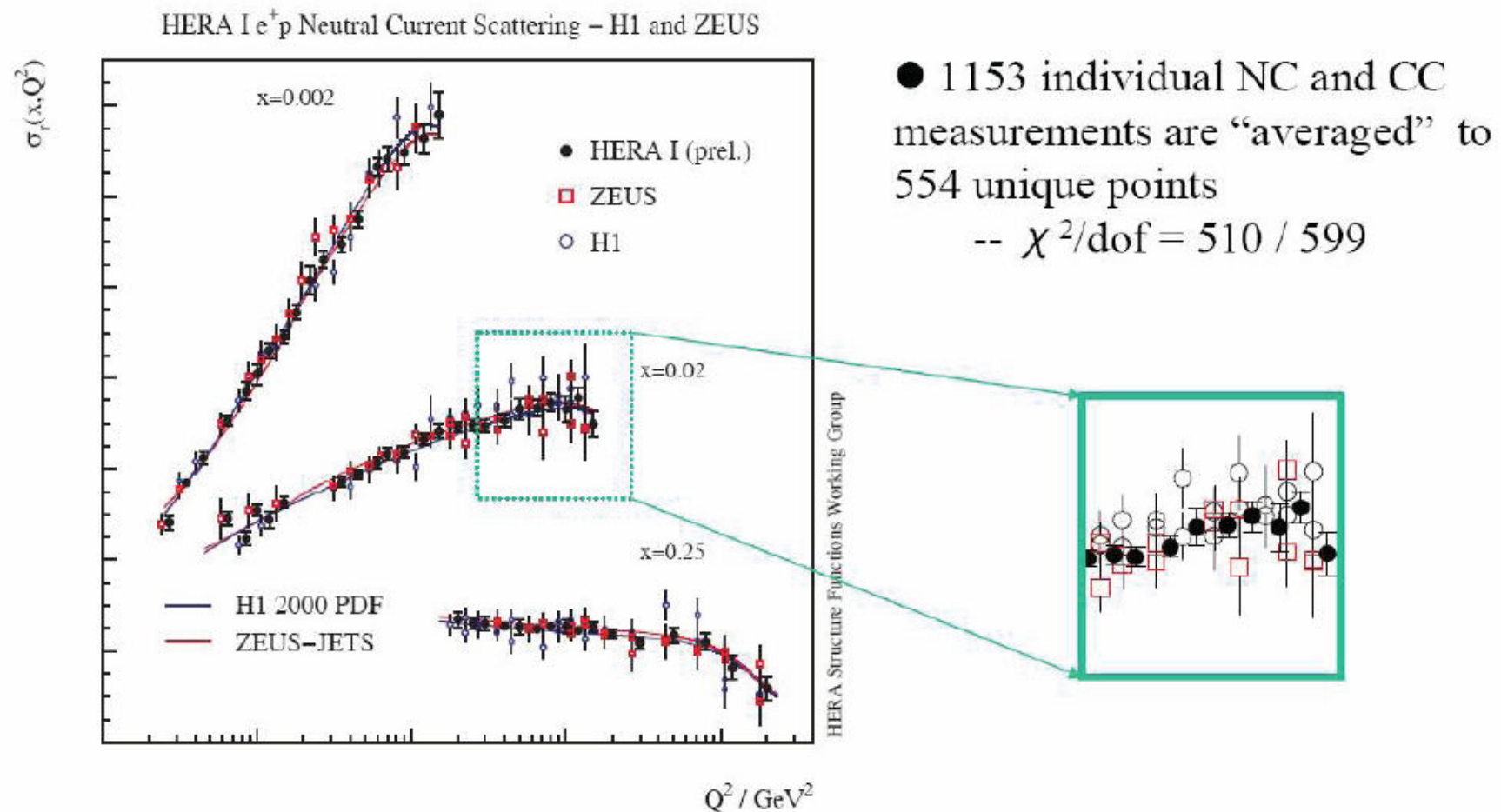
H1 and ZEUS Combined PDF Fit



Geiser, QCD at the HERAScale, PIC08

H1 and ZEUS cross section combination

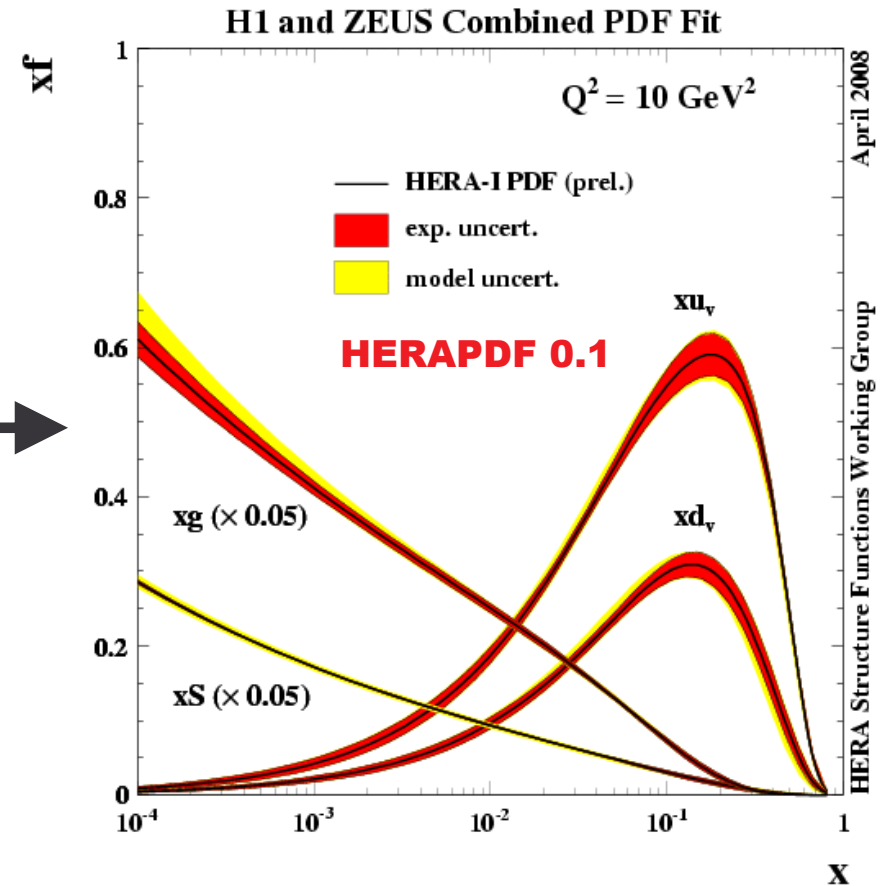
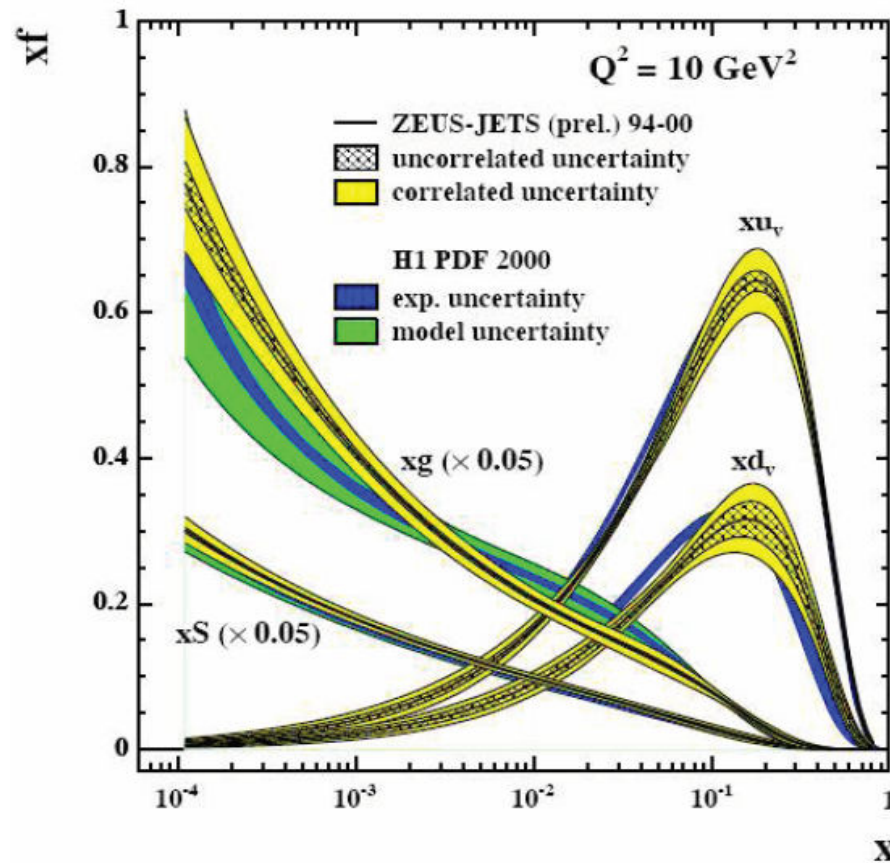
coherent treatment of experimental effects
→ **cross calibration** (improvement better than naive $\sqrt{2}$)



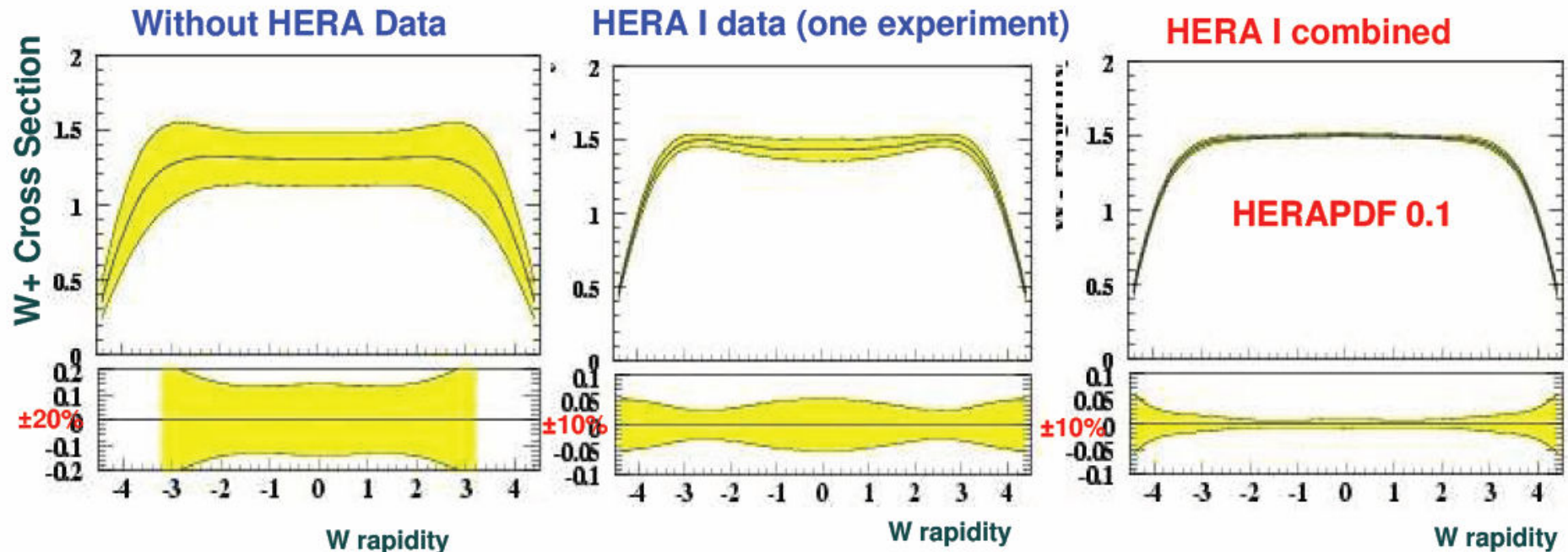
strong improvement

most notably at low x

(also at high Q^2 , LHC domain)



e.g.: predictions for W production at LHC

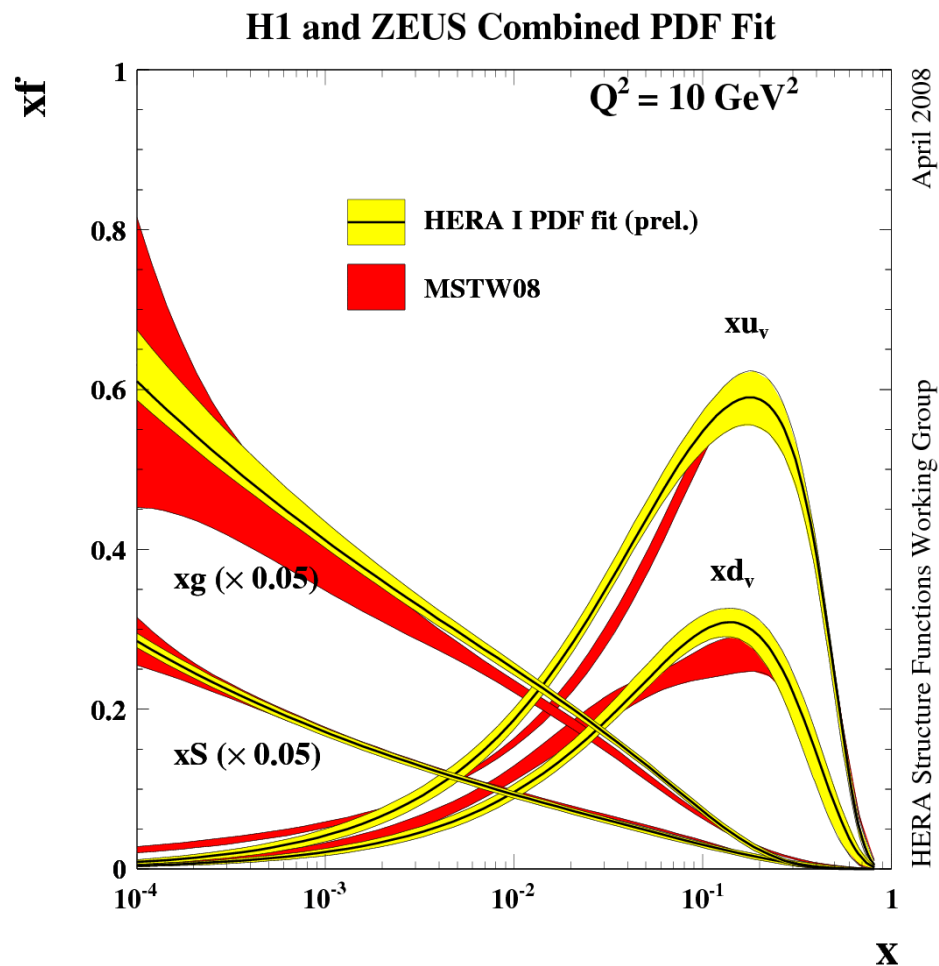
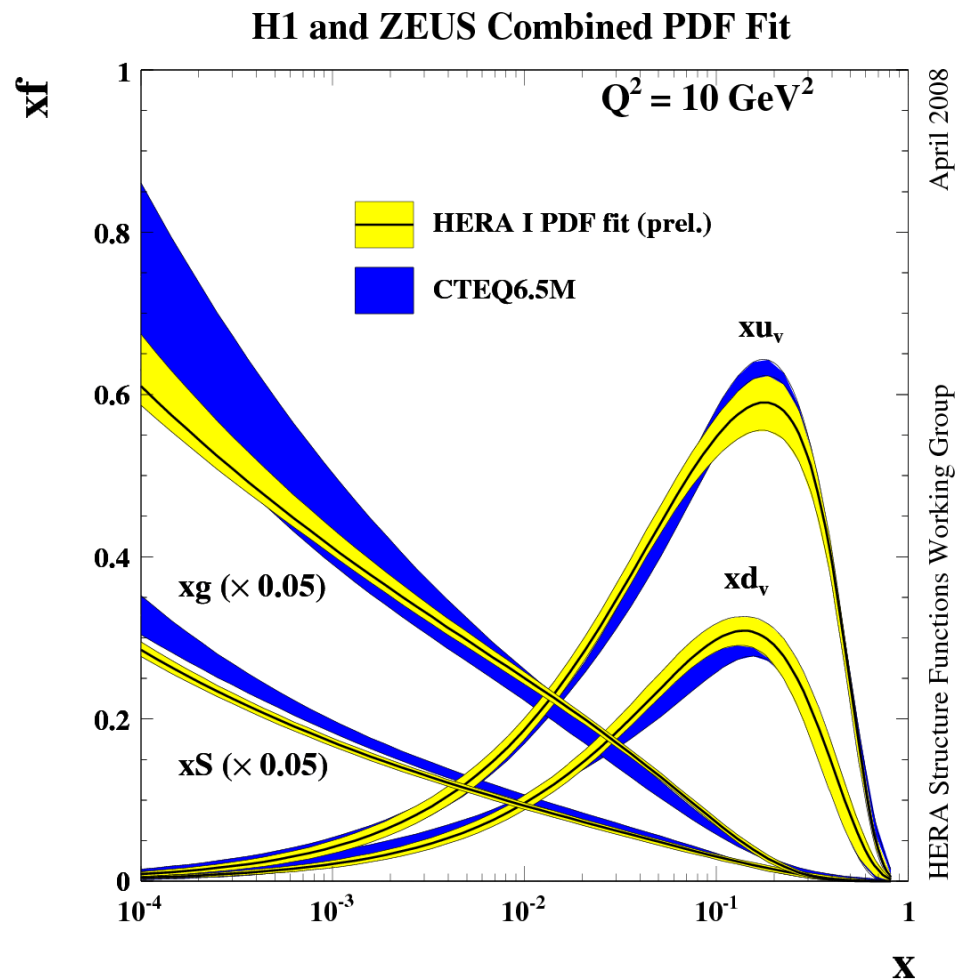


only the fit uncertainty shown here,
no model variations

strong improvement

HERAPDF available for use in generators

comparison with other PDFs



Luminosity measurements at LHC

LUMINOSITY MEASUREMENTS: A COMPARISON



Luminosity measurements at LHCb: summary

predictions:

	2008 (5pb ⁻¹)	2009 (0.5fb ⁻¹)	2010 (2fb ⁻¹)
Van Der Meer	20%	5 -10%	5 -10%
Beam-Gas	10%	< 5%	< 5%
$Z \rightarrow \mu\mu$	5%	4%	4%
pp pp + $\mu^+\mu^-$	20%	2.5%	1.5%

can also be reverted
to constrain PDFs

-> talk D. Wiedner

relies on knowledge
of PDFs

Jonathan Anderson

HERA-LHC workshop

28th May 2008

J. ANDERSON (LHCb)

Hera-LHC workshop

ATLAS/CMS: QUALITATIVELY SIMILAR CONCLUSIONS

BUT AFTER 1ST YEAR, DIRECT MEASUREMENT: TOTEM (3%), ALFA (5%)

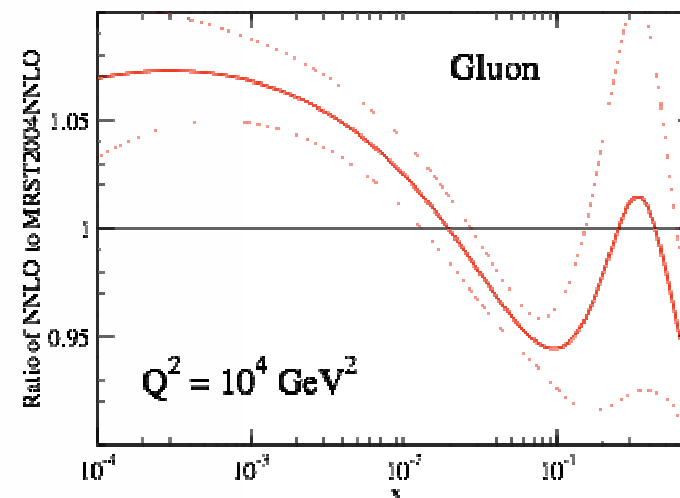
PDFs: beware of heavy flavour treatment

PREVIOUS DISCREPANCIES RESOLVED!

Predictions for **W** and **Z** cross-sections for LHC and Tevatron (in brackets) with common fixed order QCD and vector boson width effects, and common branching ratios.

	$B_{l\nu} \cdot \sigma_W$ (nb)	$B_{l+l-} \cdot \sigma_Z$ (nb)
MSTW 2008 NLO (prel.)	20.45 (2.650)	1.965 (0.2425)
MSTW 2008 NNLO (prel.)	21.44 (2.739)	2.043 (0.2512)

Ratio to MSTW 2008 (prel.)	σ_W	σ_Z
MRST 2006 NLO (unpublished)	1.002 (0.995)	1.009 (1.001)
MRST 2006 NNLO	0.995 (1.004)	1.001 (1.010)
MRST 2004 NLO	0.974 (0.990)	0.982 (1.000)
MRST 2004 NNLO	0.936 (0.991)	0.940 (1.003)
CTEQ6.6 NLO	1.019 (0.978)	1.022 (0.987)



Increases from MRST2006 compared to MRST2004 due to changes due to improved (NLO) or completed (NNLO) heavy flavour prescription.

6% increase!

correction,
not uncertainty

Virtually no change from MRST2006 → MRST2008. Not guaranteed to be true for all quantities.

Consistent with CTEQ6.6, but systematic differences mirror shape of gluon/quarks.

similar findings by CTEQ

PDF4LHC/MSTW

R. THORNE

Hera-LHC workshop

Why are heavy flavours important?

- charm contribution to F_2 up to 40%!

- kinematic effect of mass

- competing scales for perturbative expansion

e.g. $m, Q^2, p_T \rightarrow$ terms $\log Q^2/m^2$
 $\log p_T^2/m^2$ etc.



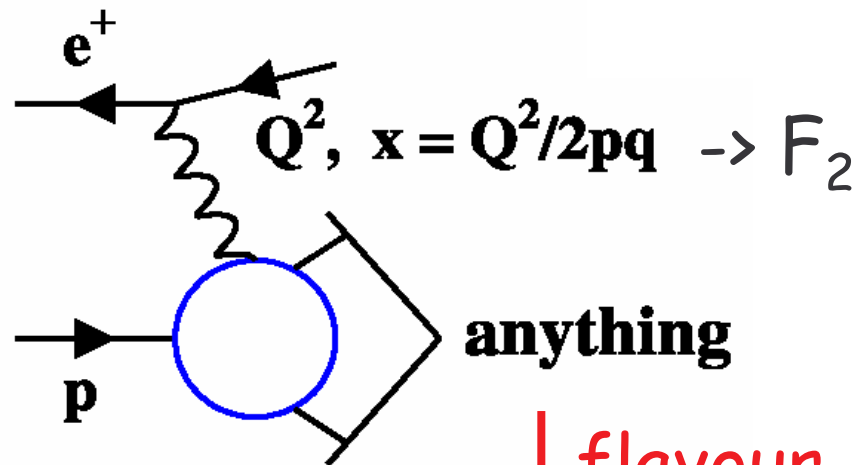
=> “massless” treatment allows resummation, but fails near
“mass threshold” -> avoid!

=> “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)

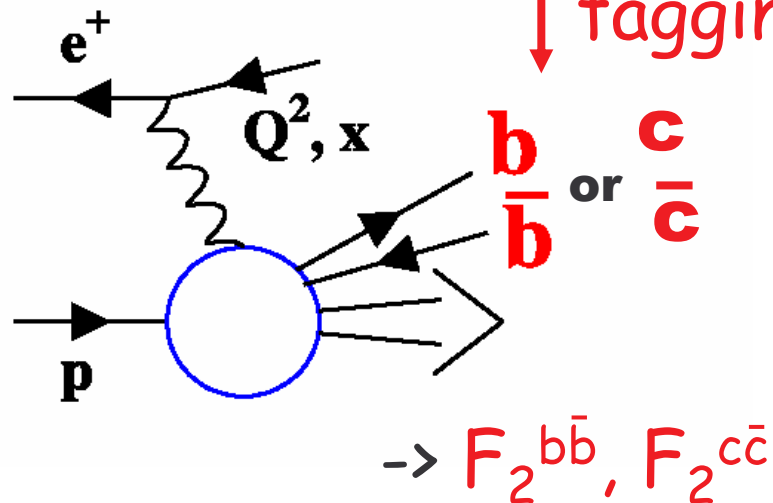
check different schemes against HERA data

Heavy flavour contributions to F_2

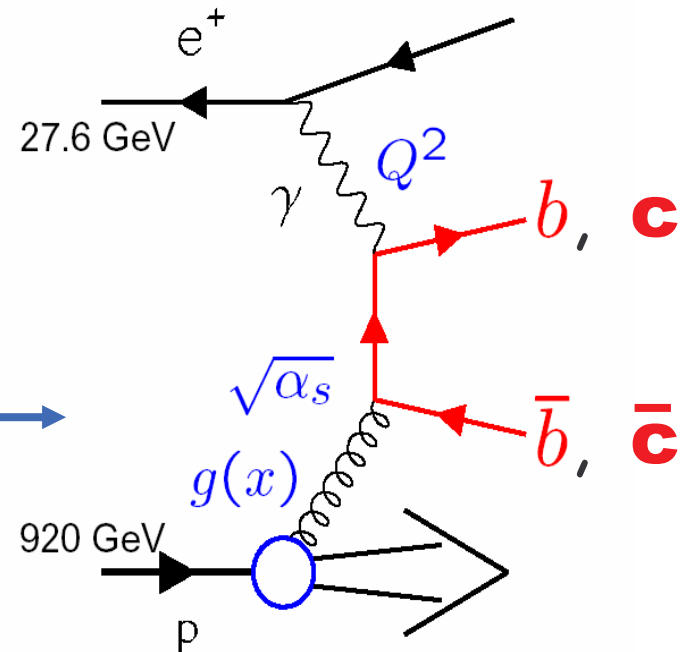
mainly
Boson Gluon Fusion,
driven by gluons
multiple hard scales:
 $Q^2, m_{b,c}, p_T$



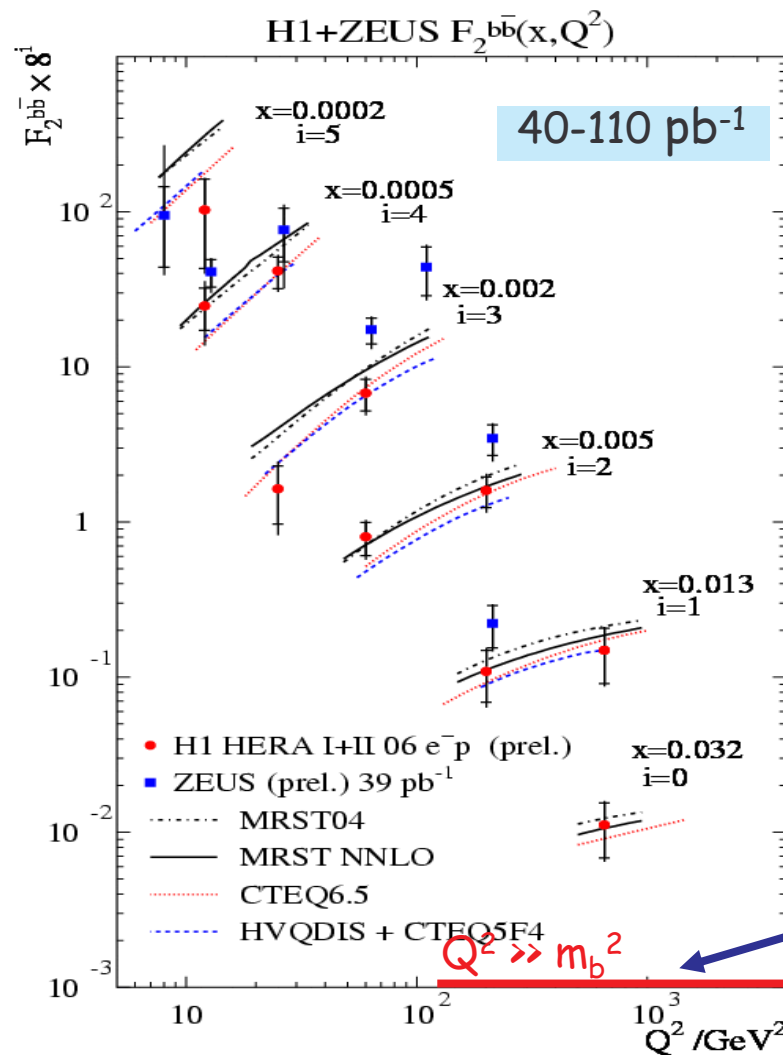
flavour
tagging



QCD



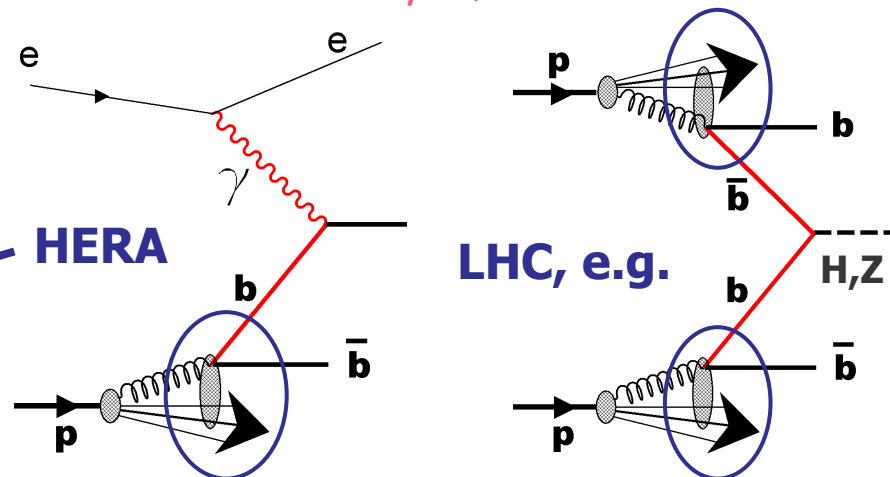
Beauty contribution to F_2



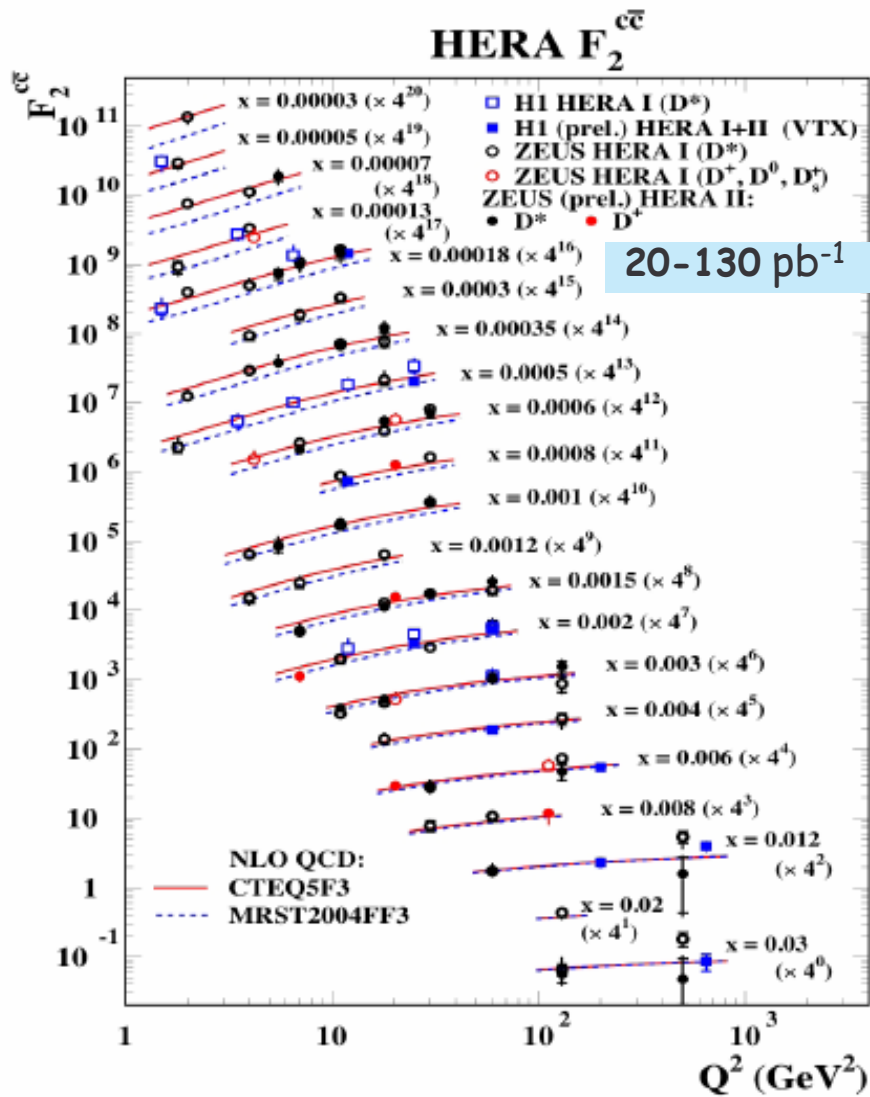
data in agreement with NLO and NNLO, but errors still large (only small fraction of data analysed)

improved measurements
→ **discriminate between different schemes**

→ **check b PDF for LHC:**
see also talk C. Royon, Z + b at Tevatron



Charm contribution to F_2



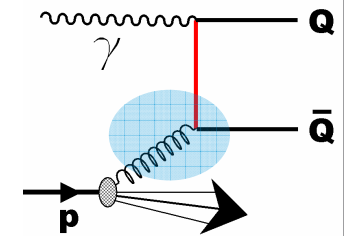
• Large amount of measurements using different methods available.

in agreement with QCD predictions
→ gluon PDF ~OK !

understand mass effects from beauty

→ improved theory

→ further test/constrain gluon PDF



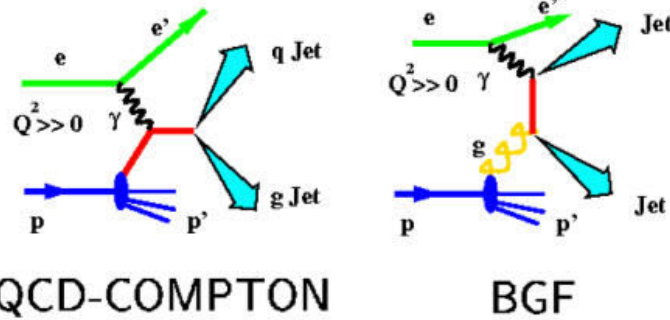
Dataset:

- $\square$ H1 HERA I (D*)
- $\blacksquare$ H1 (prel.) HERA I+II (VTX)
- $\circ$ ZEUS HERA I (D*)
- $\circ$ ZEUS HERA I (D⁺, D⁰, D_s⁺)
- $\bullet$ ZEUS (prel.) HERA II

L [pb⁻¹]:

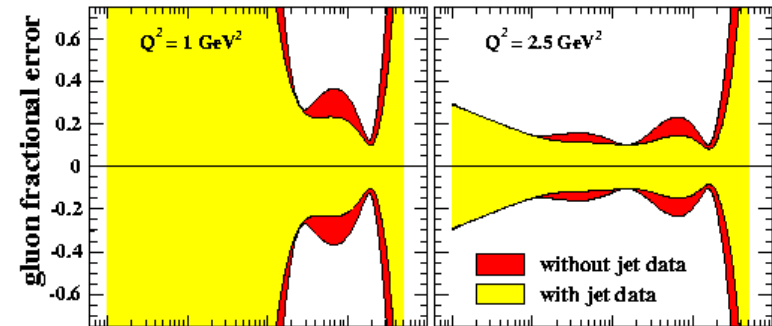
- 19
- 58 + 54
- 82
- 82
- 135

Jets at HERA constrain gluon distribution



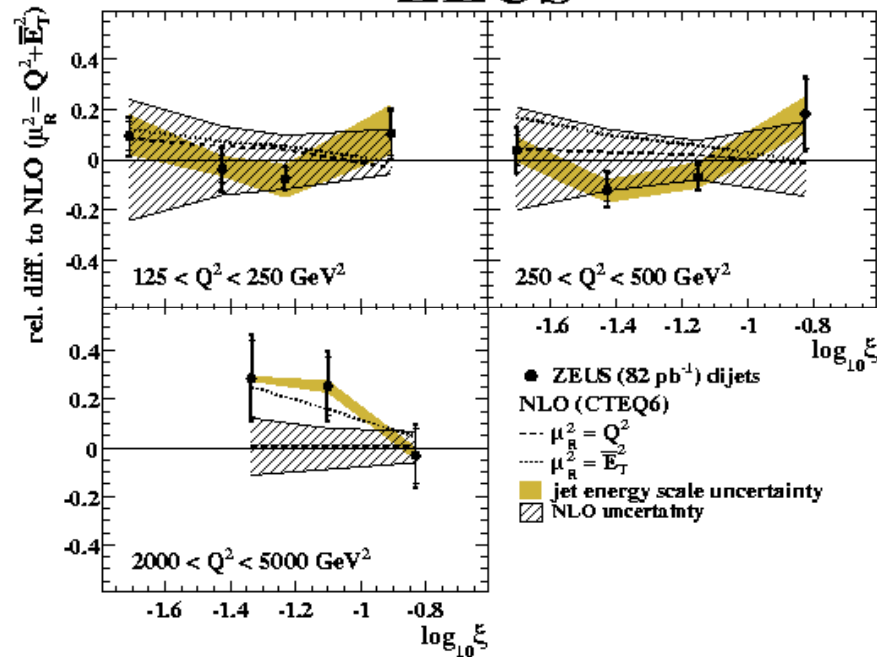
see talk C. Royon

ZEUS

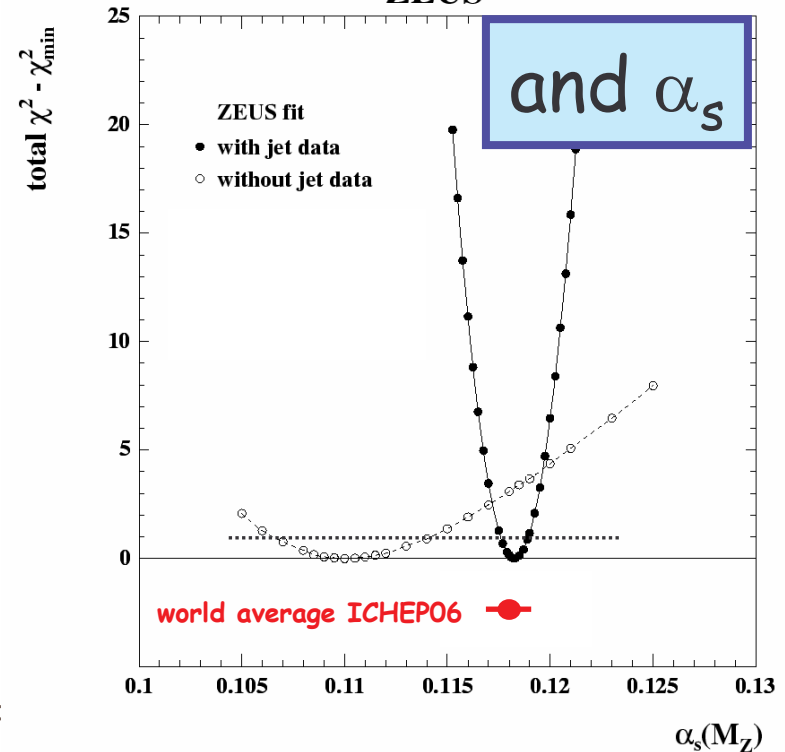


examples:

ZEUS

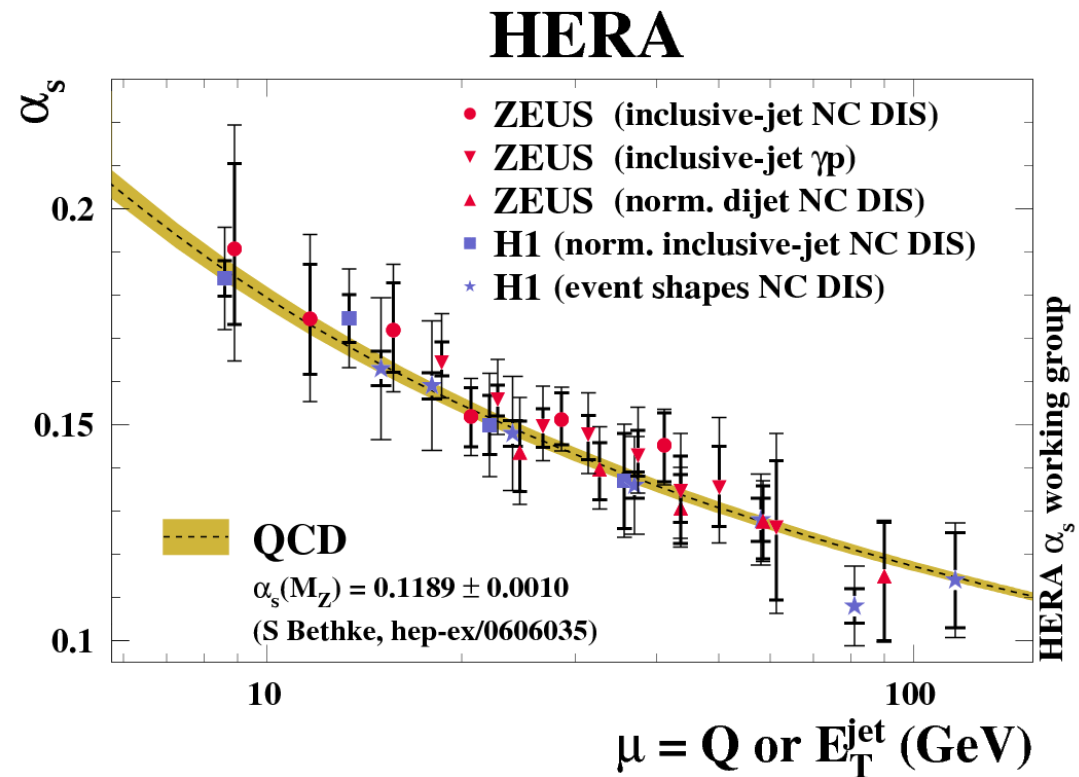
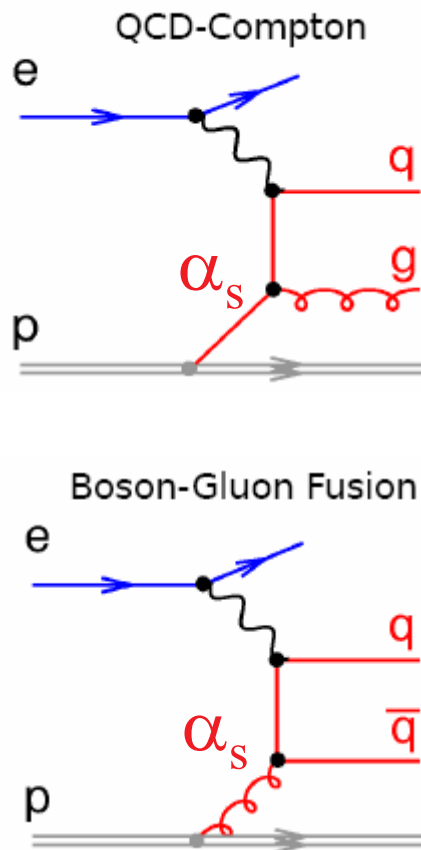


ZEUS



measurement of α_s

ep interactions directly sensitive to α_s

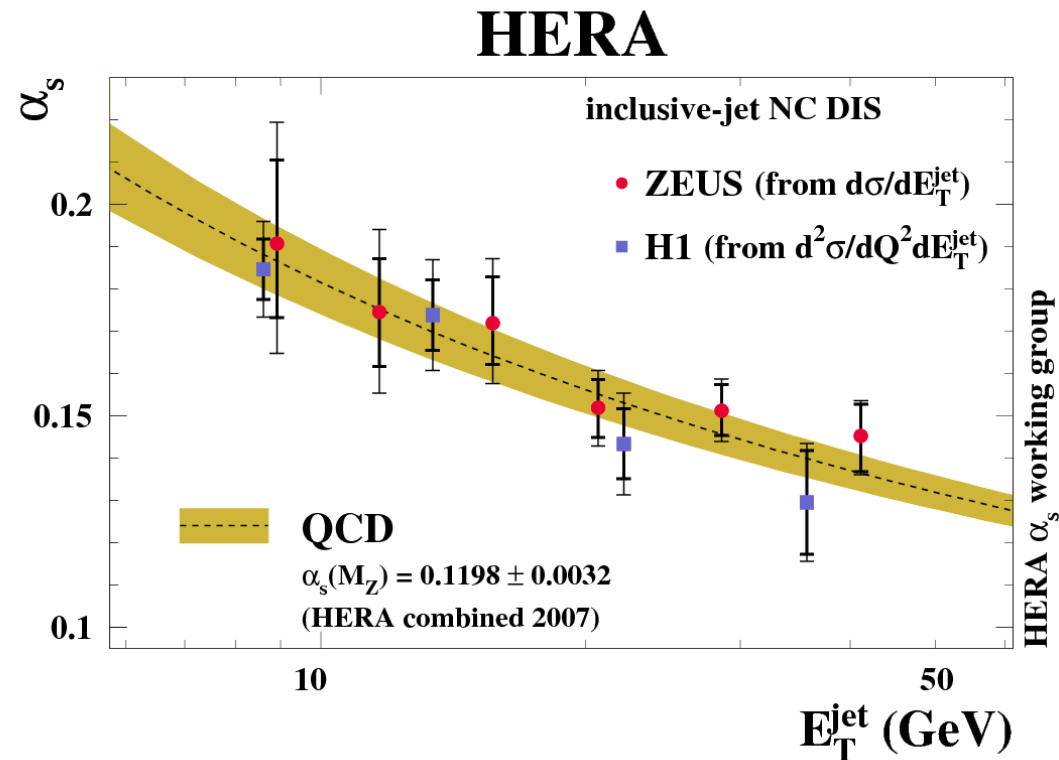


ZEUS/H1 combined α_s

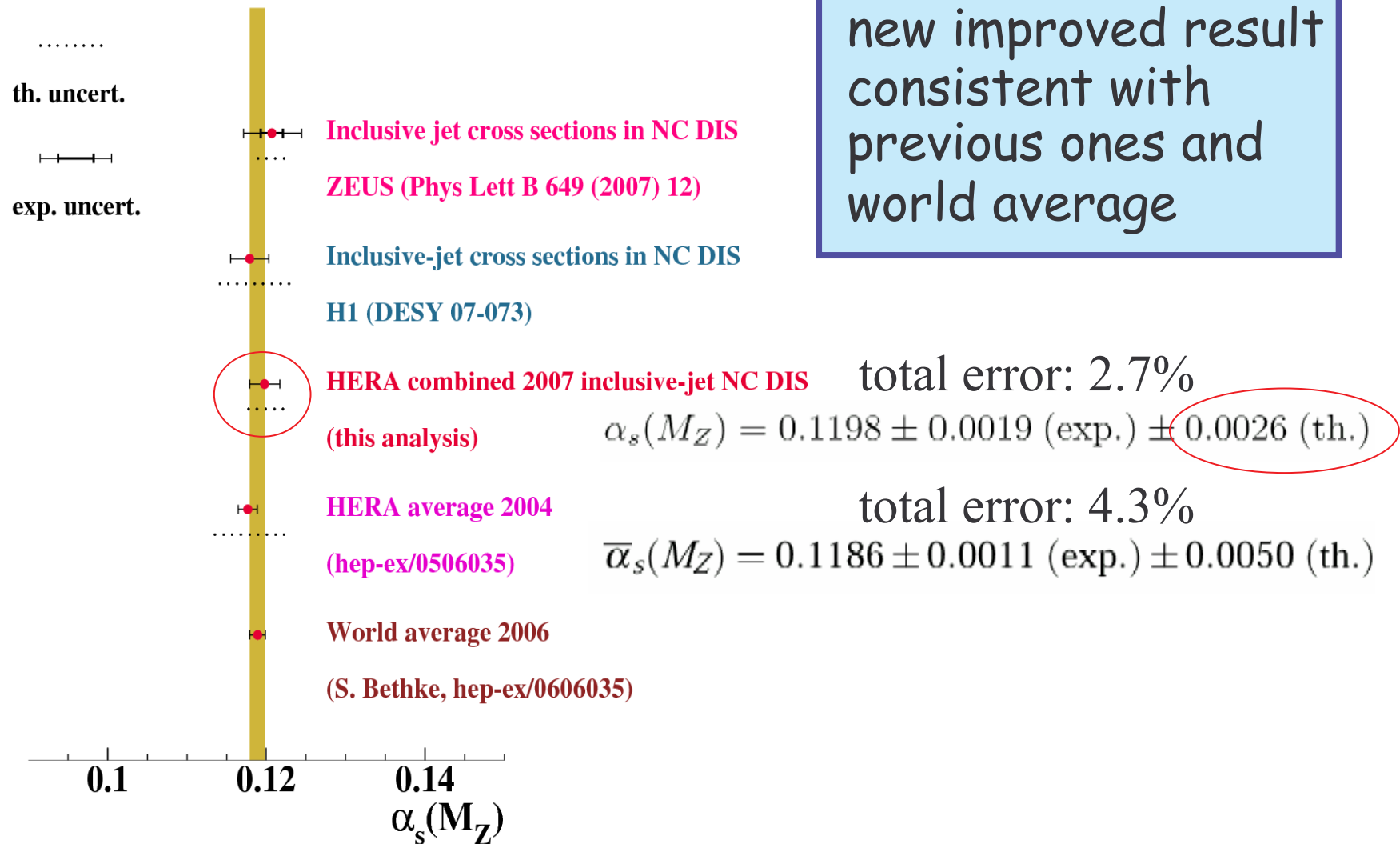
can gain in sensitivity by combining measurements with different systematics/different theory uncertainties

select suitable subset of measurements

focus on small NLO error
(NNLO not yet available)

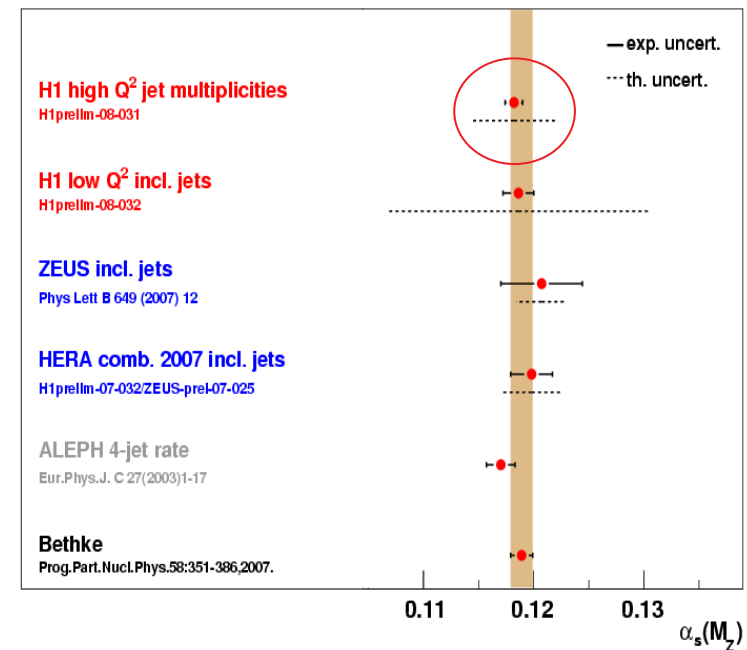
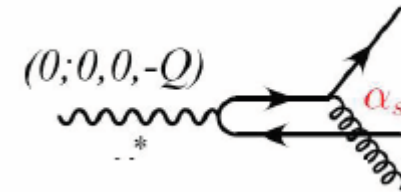
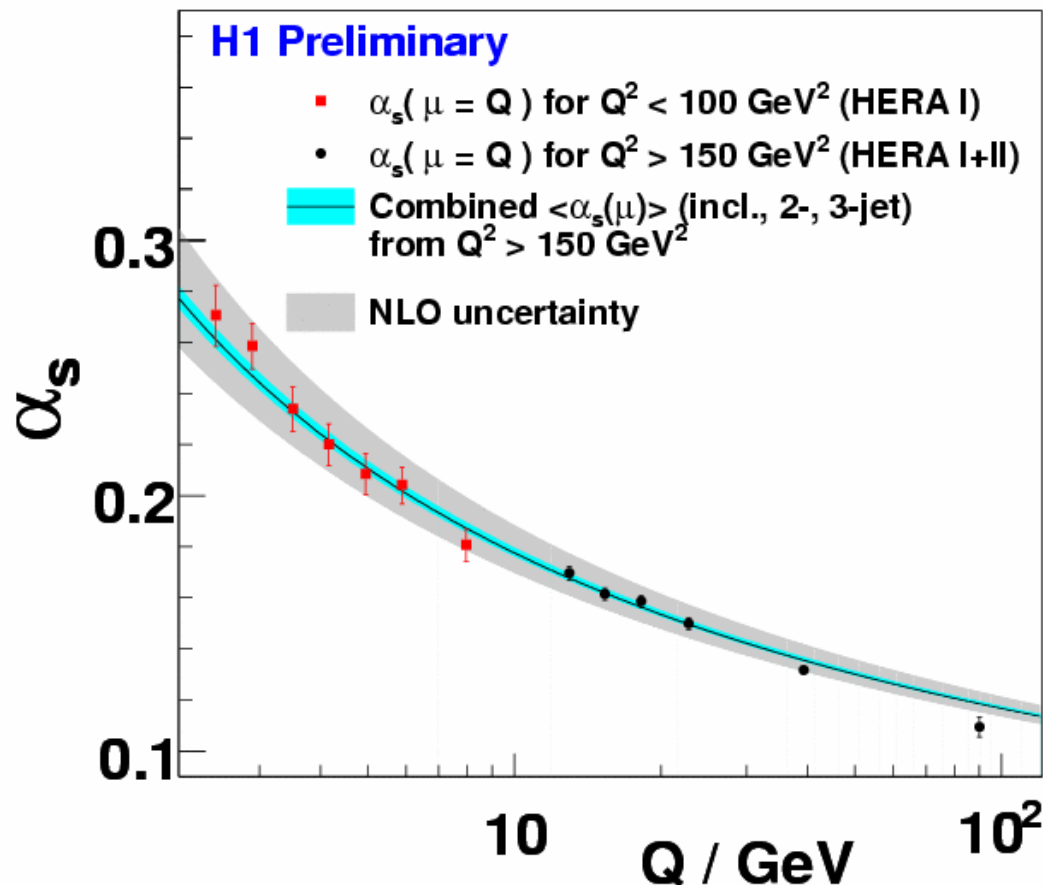


combined α_s



most recent HERA α_s measurements

α_s from Jet Cross Sections



already from single measurement/single experiment, experimental error smaller than world average $\rightarrow$ need to improve theory

HERA α_s competitive to e^+e^-

New NNLO α_s fits in e^+e^-

• $\alpha_s(M_Z)$

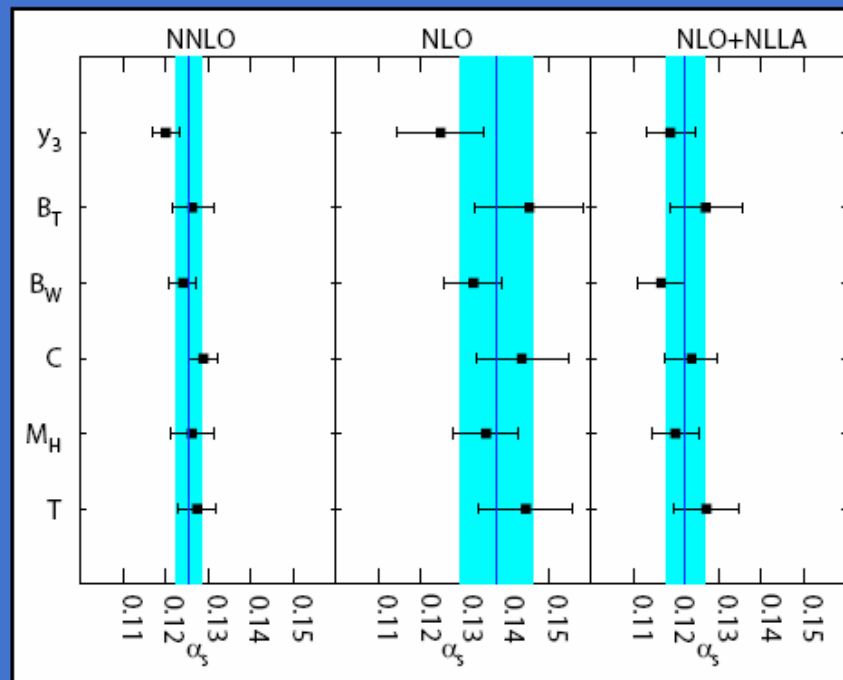
• consistent results at NNLO,

• scattering between variables much reduced.

• calculate weighted average for $\alpha_s(Q)$ from 6 variables

$$\bar{\alpha}_S = \sum_{i=1}^6 w_i \alpha_S^i, \quad w_i \propto \frac{1}{\sigma_i^2}$$

$\Rightarrow \bar{\alpha}_S(M_Z) = 0.1240 \pm 0.0033$



Luisoni,
HERA-LHC
workshop

HERA comb. 2007: 0.1198 ± 0.0032

will improve further
once NNLO available!

encouragement

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

for recent progress, see e.g. HERA-LHC workshop

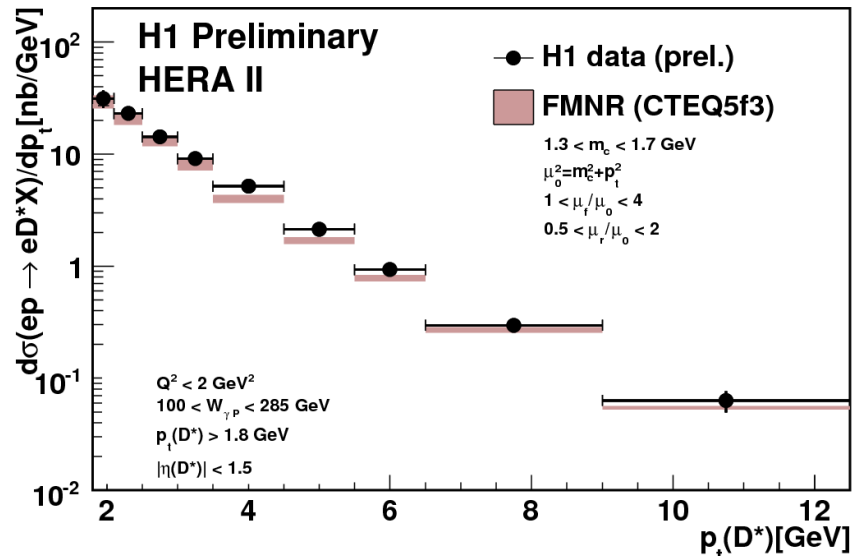
test QCD with semi-inclusive final states

- charm and beauty production
- single photon production
- jets → previous talk C. Royon
- inclusive diffraction
- exclusive VM production → talk W. Bartel
- constraints on BSM physics → talk S. Gruenendahl

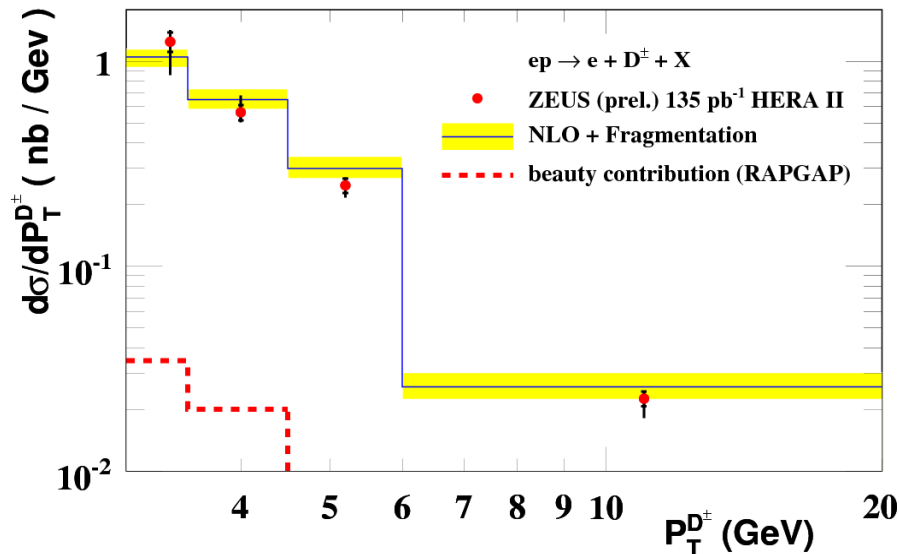
⇒ investigate validity of QCD
and validity of predictions for LHC

charm: D^*/D^+ p_T distributions

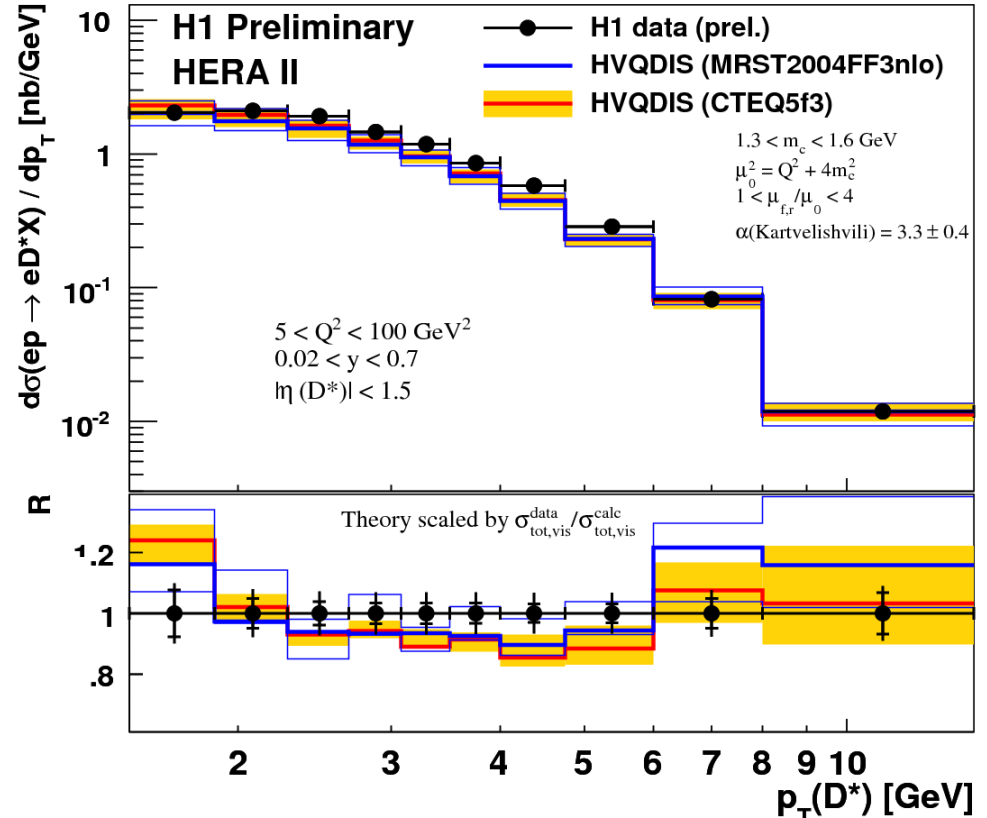
D^* in Photoproduction



ZEUS D^+ in DIS



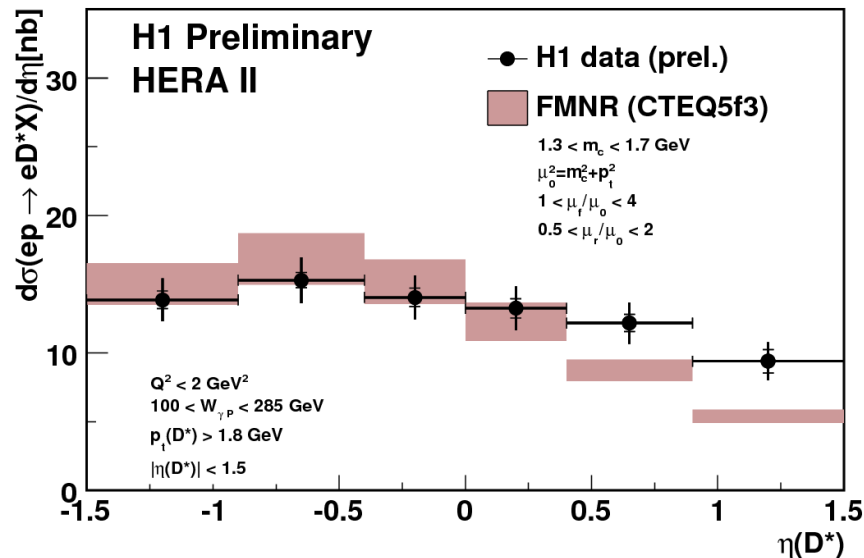
D^* in DIS



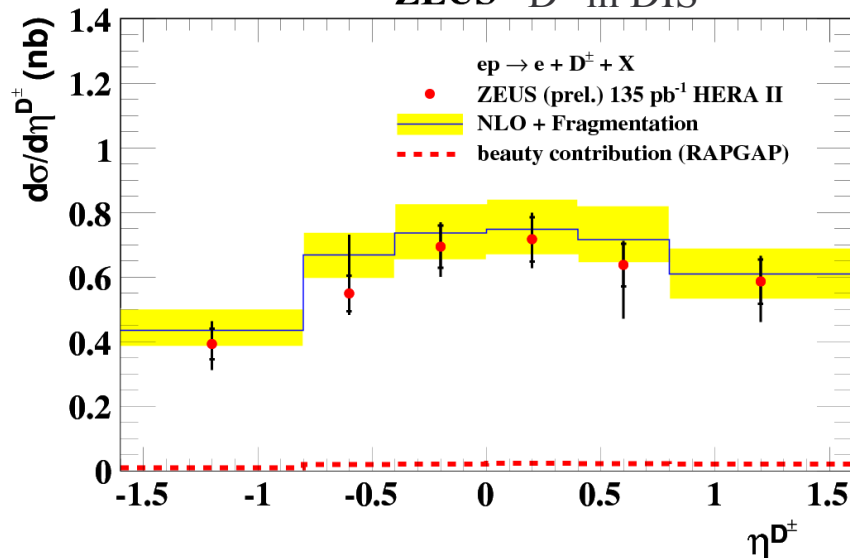
reasonably described by
NLO QCD

charm: D^*/D^+ p_T distributions

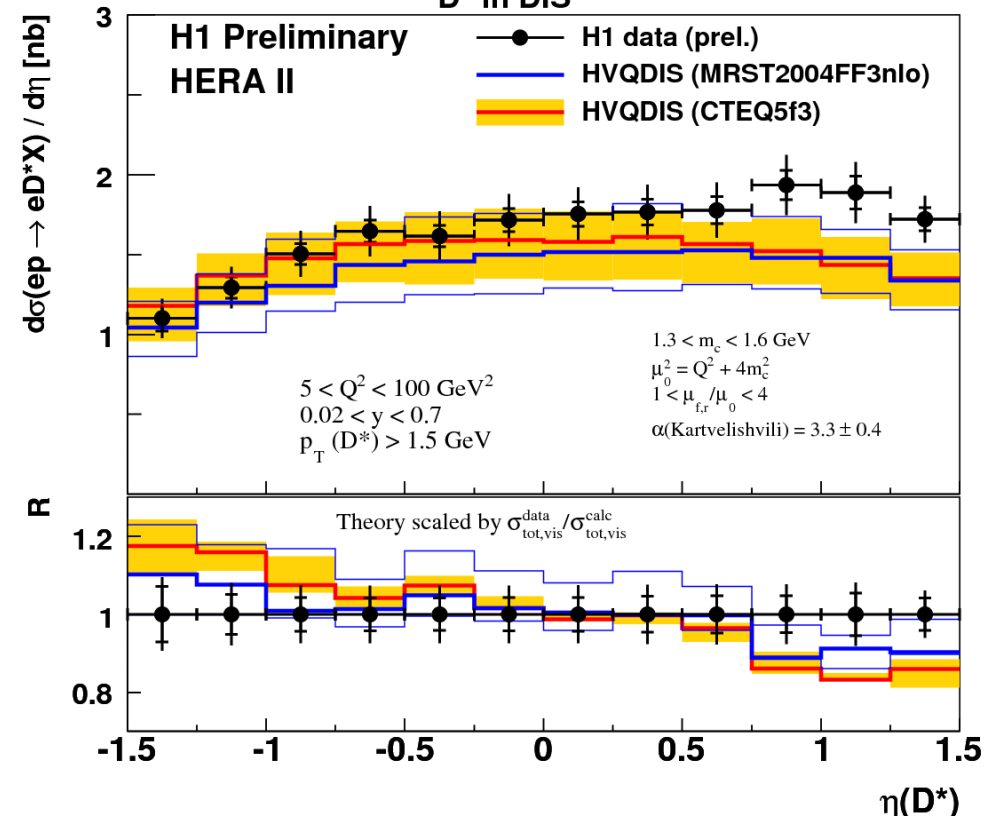
D^* in Photoproduction



ZEUS D^+ in DIS



D^* in DIS



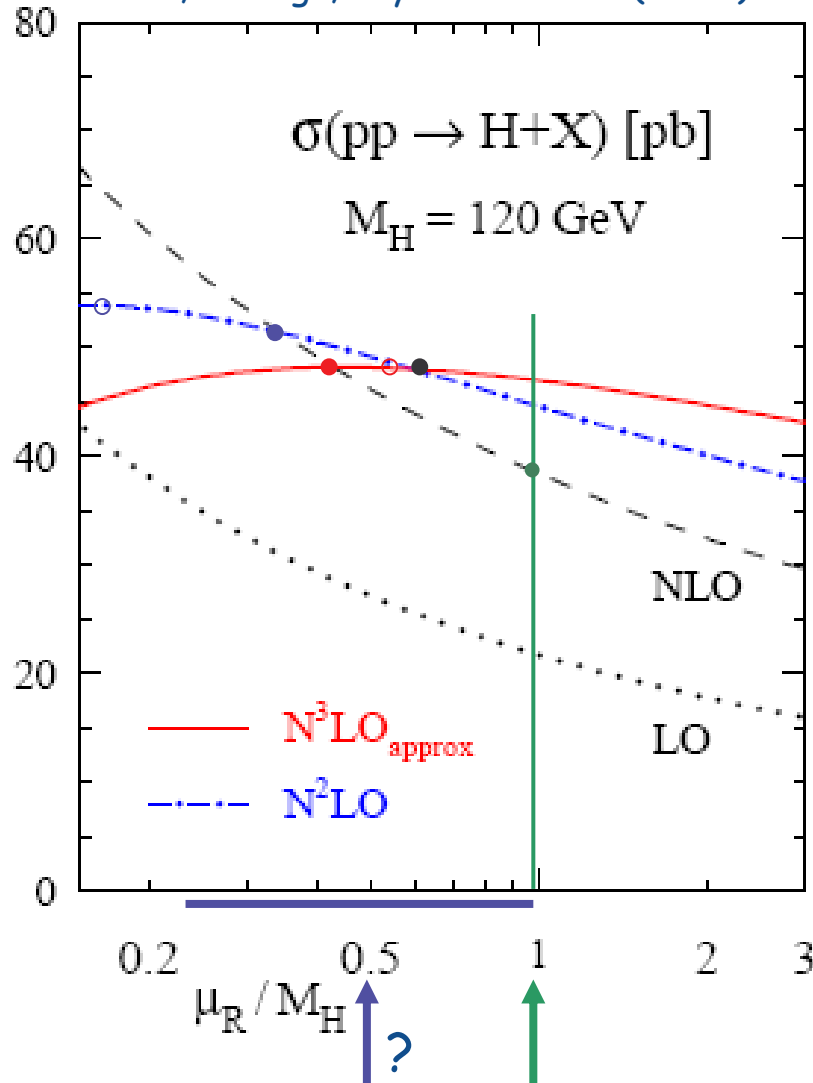
differences in forward region?
recheck: PDFs, fragmentation,
 m_c , choice of scales, ...

e HERAScale, PIC08

pick as example²⁹

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

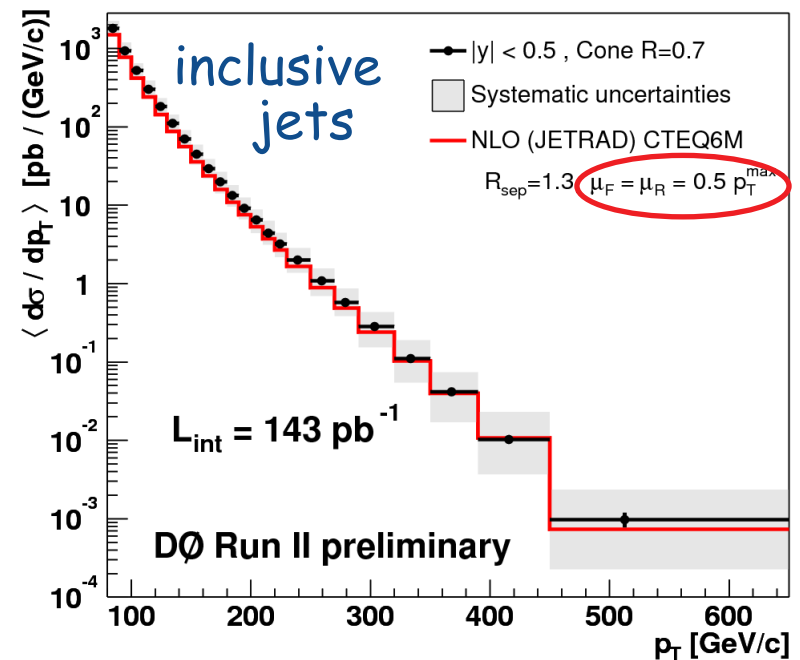
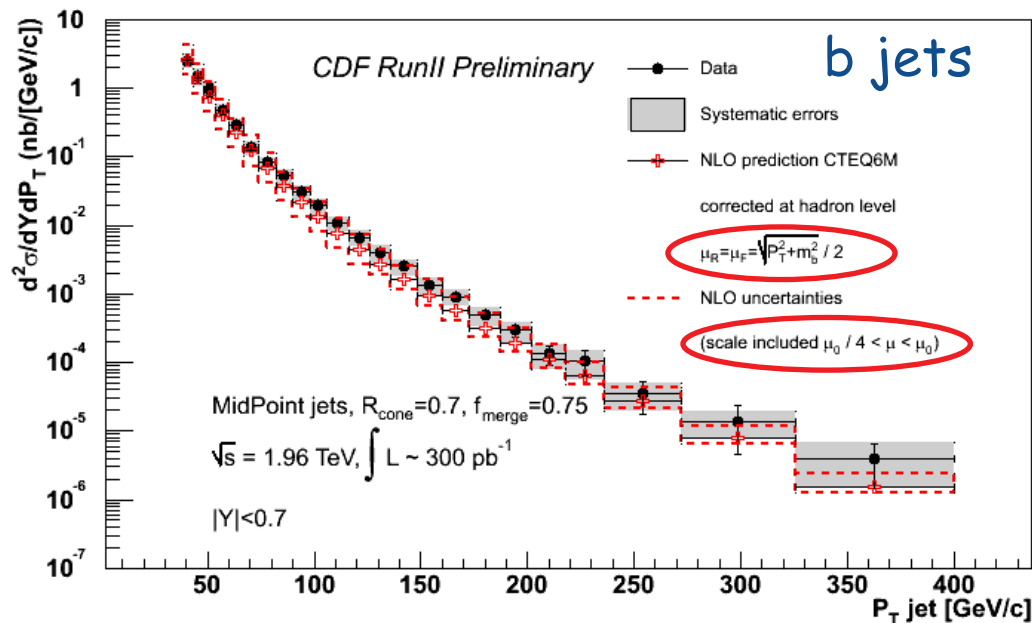
NNLO/N³LO calculations, where available, often suggest ren./fact. scale ~ half "natural" scale for NLO

personal remark: either dedicated scale study, or

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

more details: [arXiv:0711.1983](https://arxiv.org/abs/0711.1983) [hep-ex]

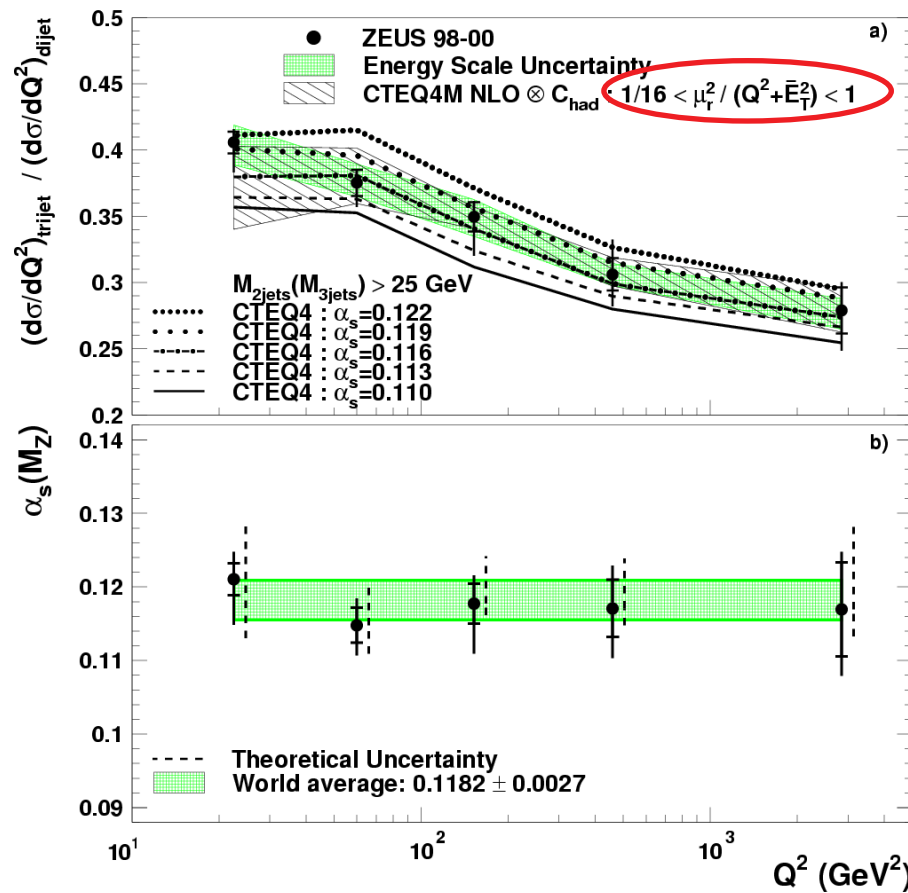
some people are doing this already:



also partially at HERA (examples)

multijet-Production in DIS

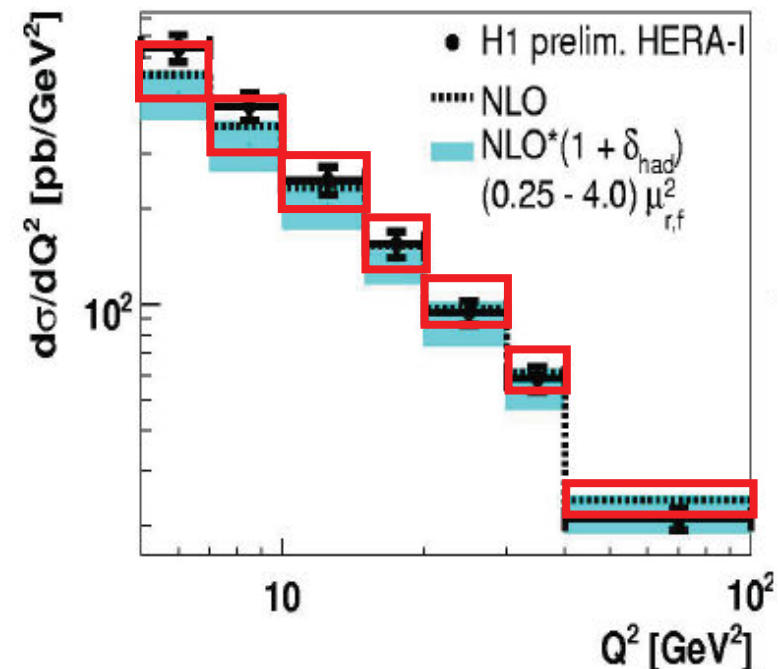
ZEUS



inclusive jets at low Q^2

new scale

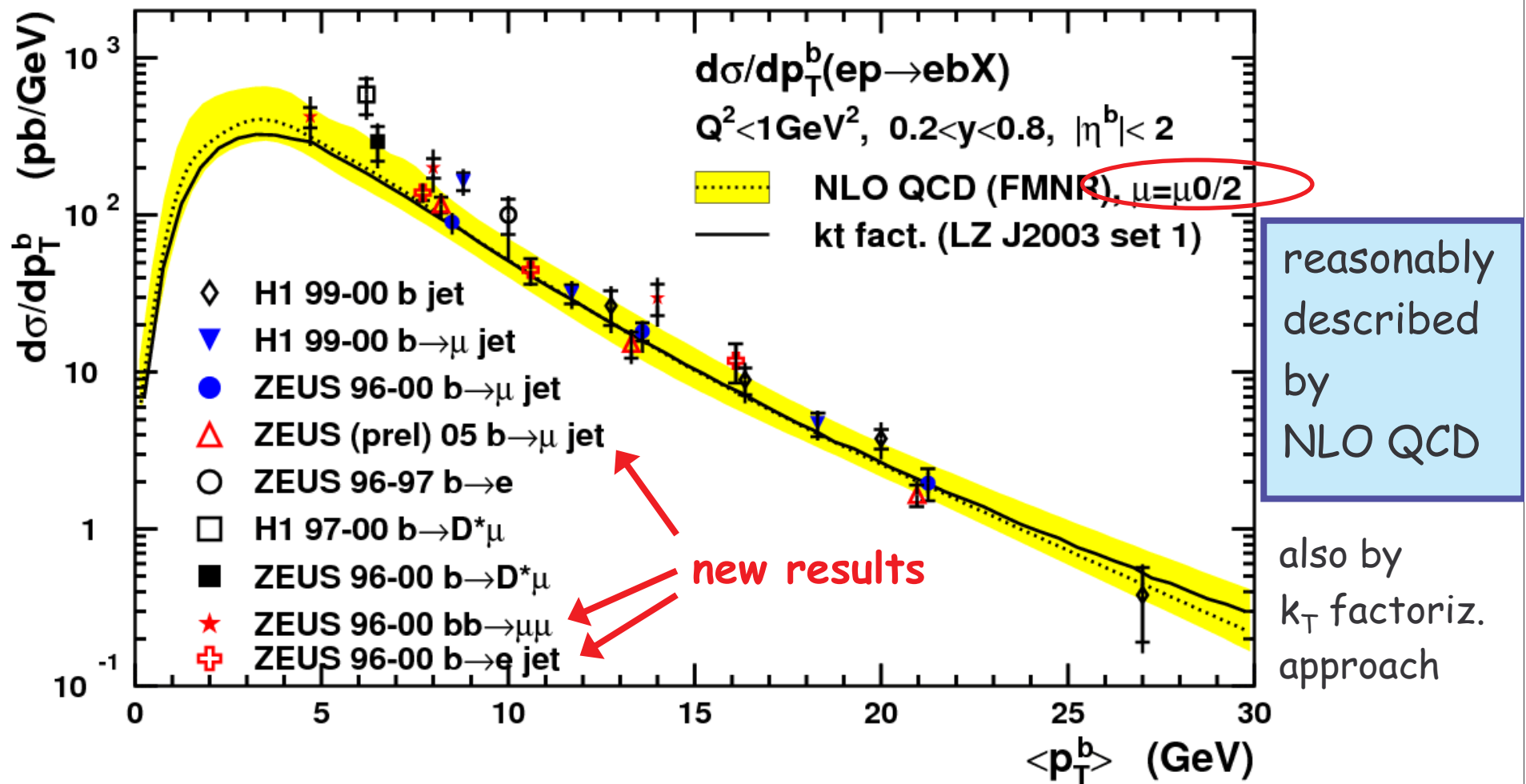
approximate estimate (A.G.), to be calculated exactly



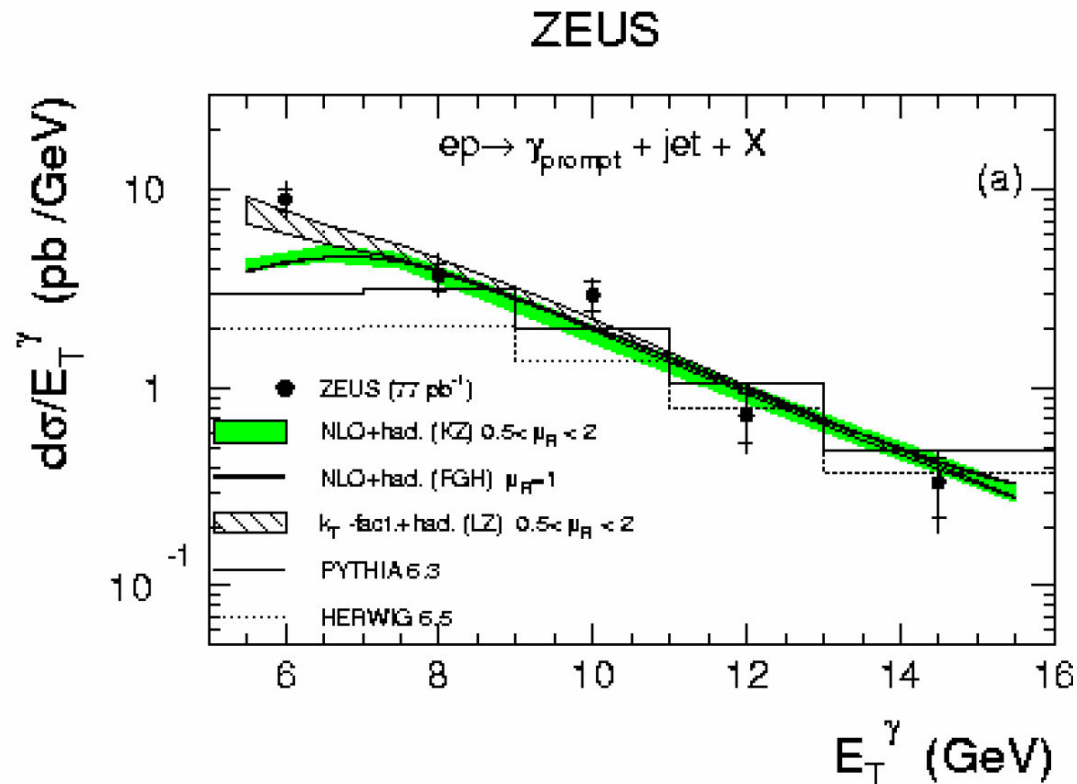
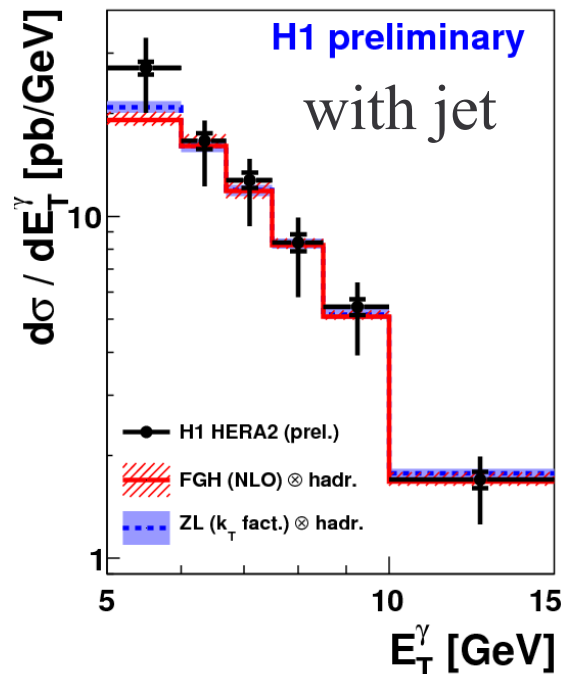
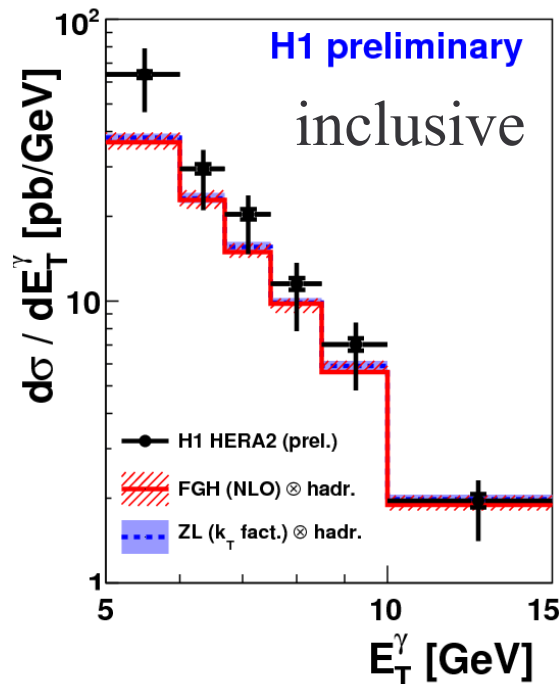
many other measurements OK with natural scale (but also with reduced scale)

beauty at HERA

HERA



single photon production



k_T factorization slightly better than
NLO at low E_T ? else both OK

can Tevatron results be used for LHC?

e.g. inclusive W/Z
production
(LHC luminosity monitor)

see also talk T. Bolton

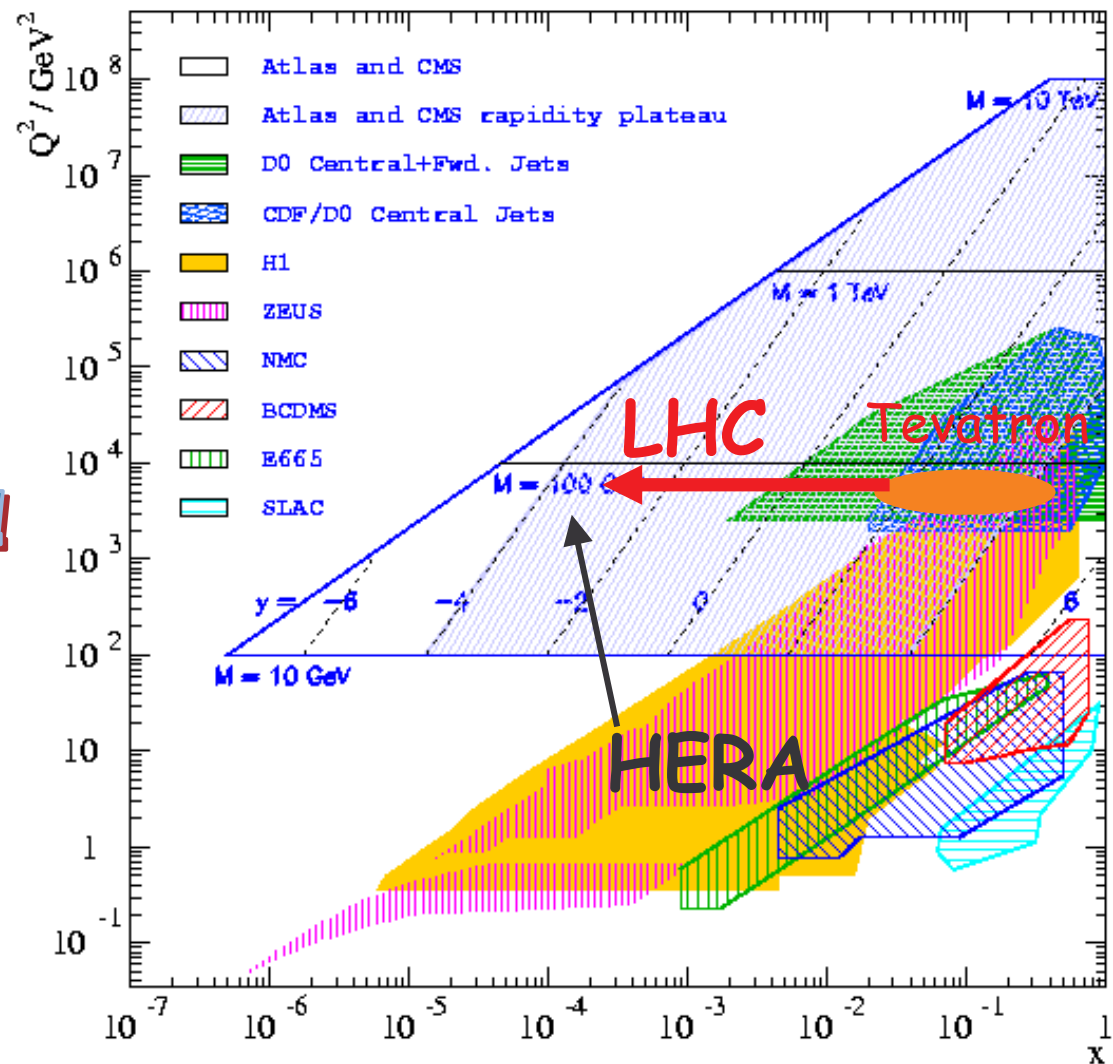
**beware of
low x effects!**

saturation
multiple interactions

BFKL vs. DGLAP

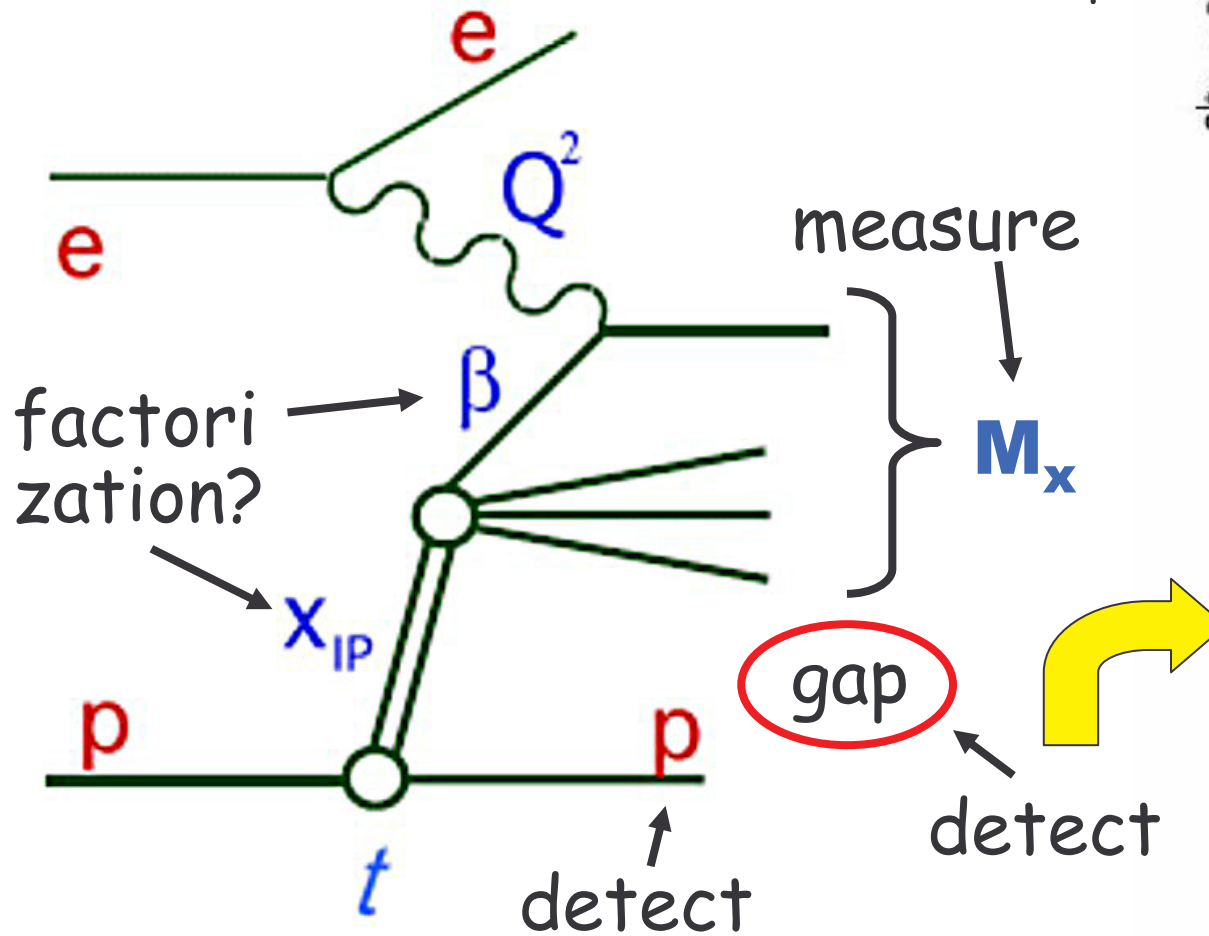
=> study at HERA

see talk C. Royon

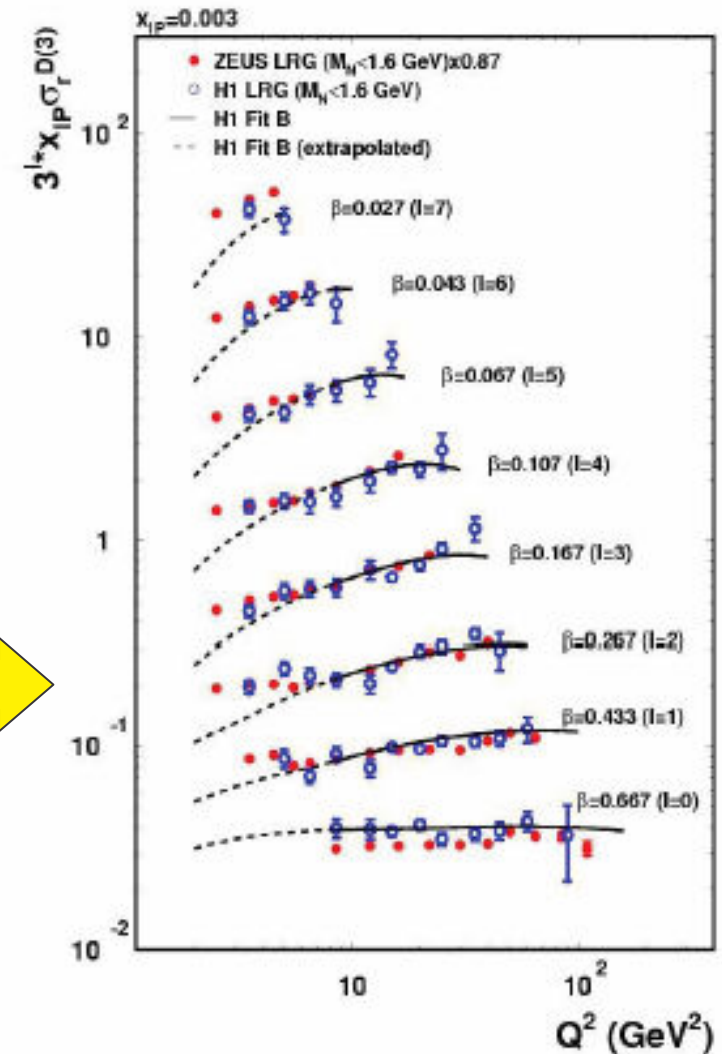


Diffractive structure functions

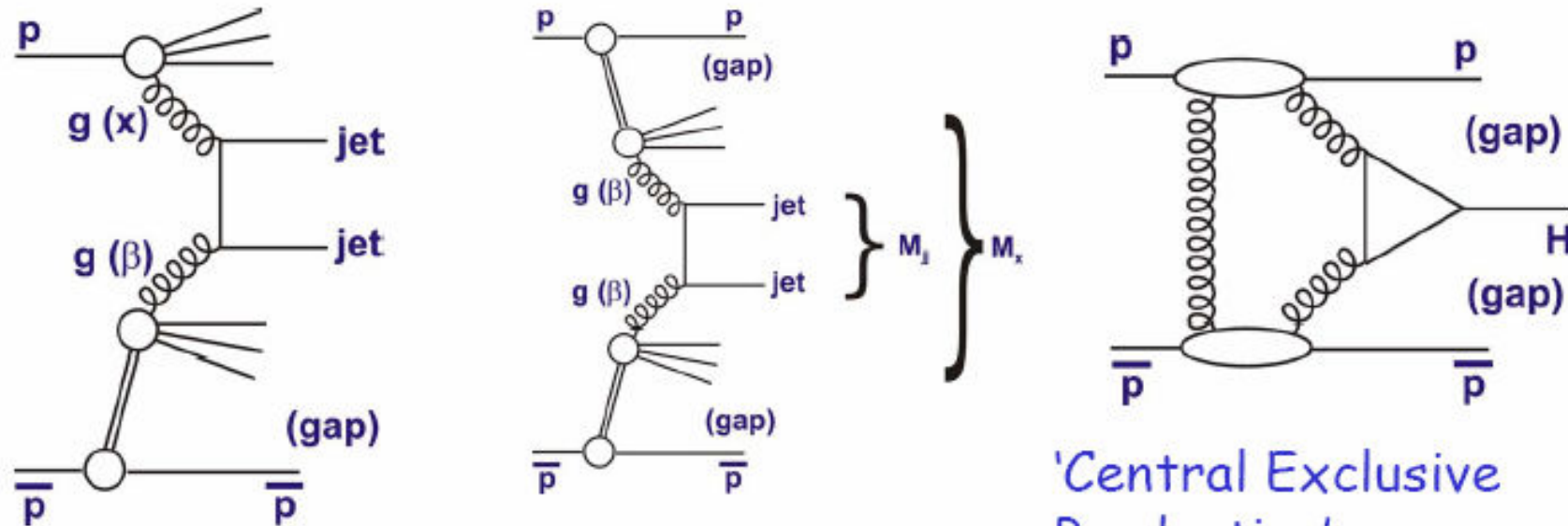
HERA:



HERA inclusive diffraction



Diffraction at the LHC



Opportunity to study Single and Double Diffraction with and without hard scales (jet, heavy flavours, W , Z).

- Depend on DPDFs from HERA
- Also on gap survival factors!

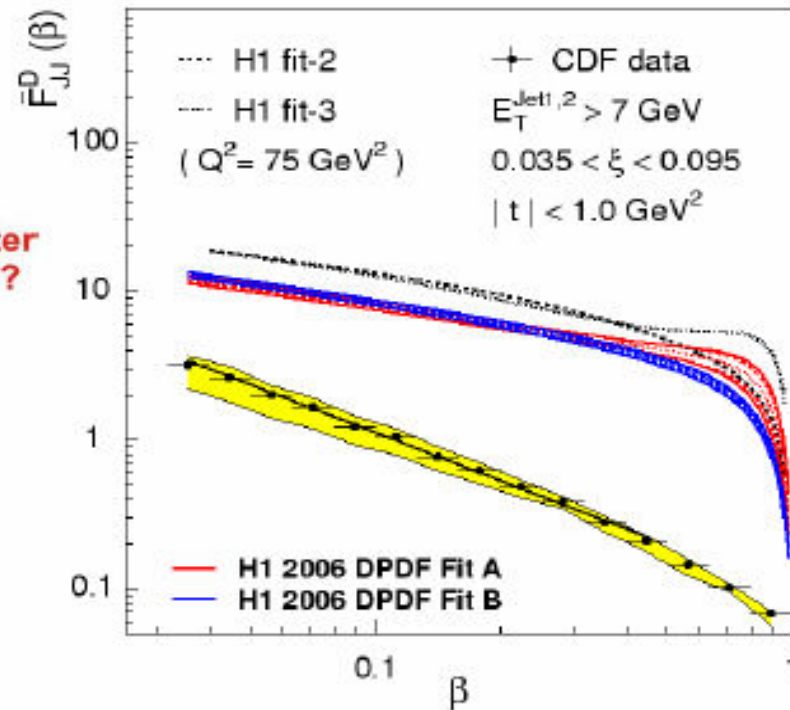
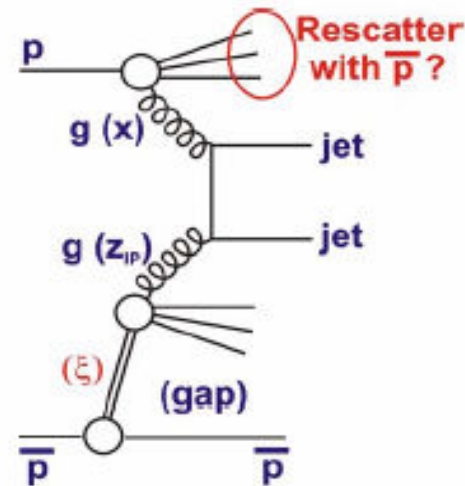
'Central Exclusive Production'

- DPDFs for backgd
- Unintegrated gluon $\rightarrow J/\Psi / \Upsilon$
- Gap survival models (KKMR, GLM ...)

... lots of possible input from HERA!

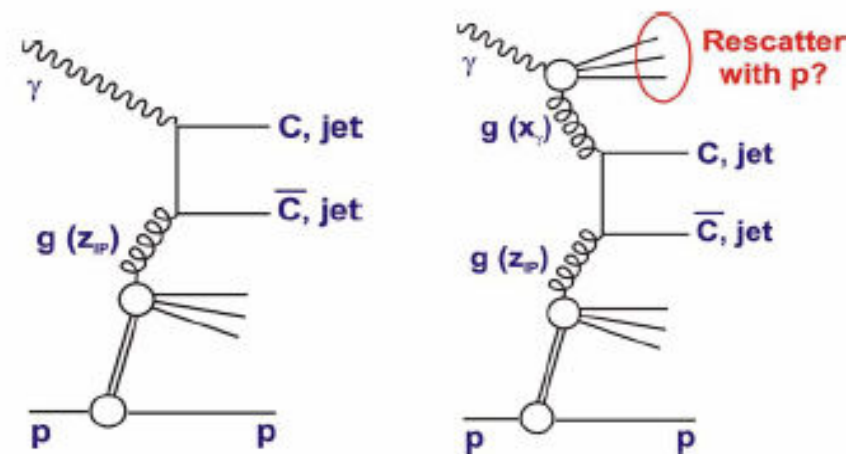
Meanwhile in pp(bar) ...

- Huge corrections when applying DPDFs: 'Gap survival' factor ~ 10

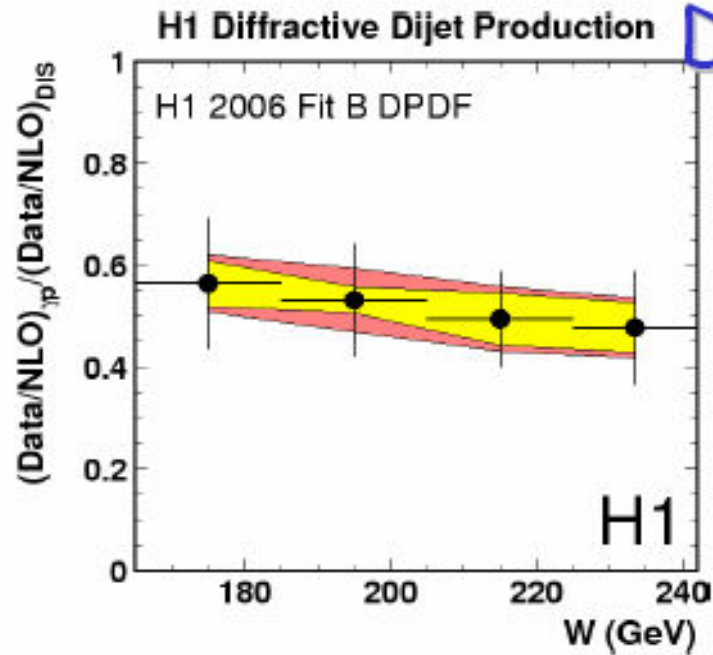


... γp as a Control Expt?

- Most models predict gap survival probability ...
- = 1 (direct)
 - < 1 (resolved ... e.g. Kaidalov, Khoze, Martin. Ryskin $\rightarrow \sim 0.34$)

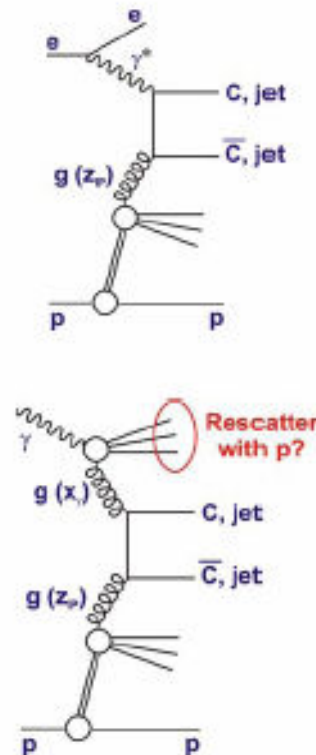


Dijet Photoproduction:

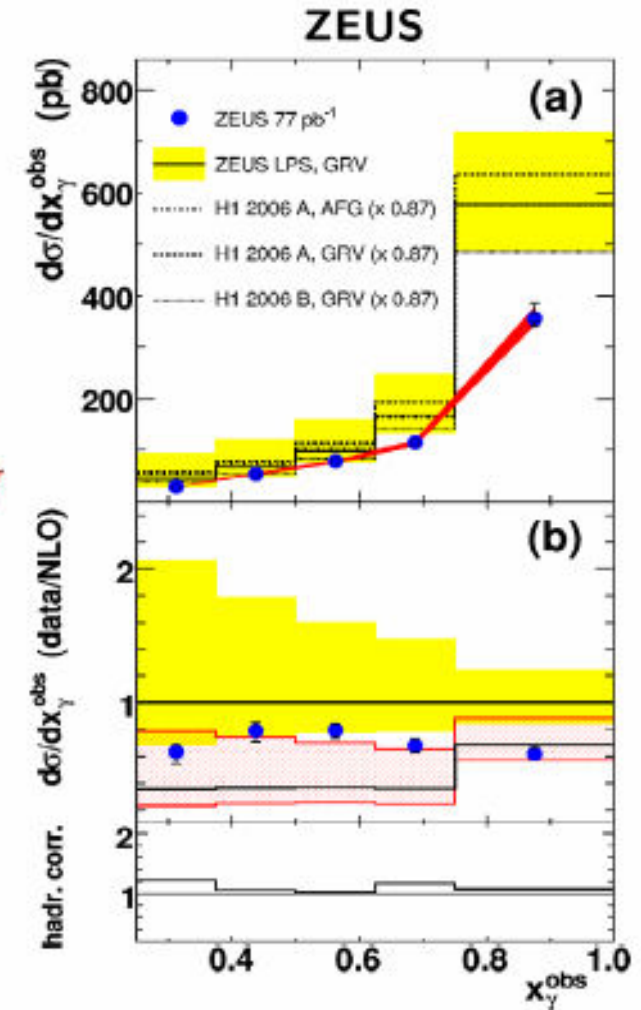


- H1 97: $E_{\text{T}}^{\text{jet1}} > 5 \text{ GeV}$
 "Suppression by factor ~2"

- ZEUS 99-00: $E_{\text{T}}^{\text{jet1}} > 7.5 \text{ GeV}$
 "Weaker suppression"
 partially due to different E_{T} cuts



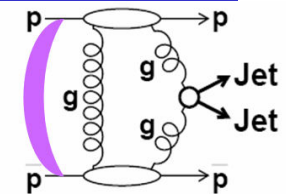
(Valkarova)



- Neither collaboration sees difference between resolved and direct regions, in contrast to theoretical expectations!

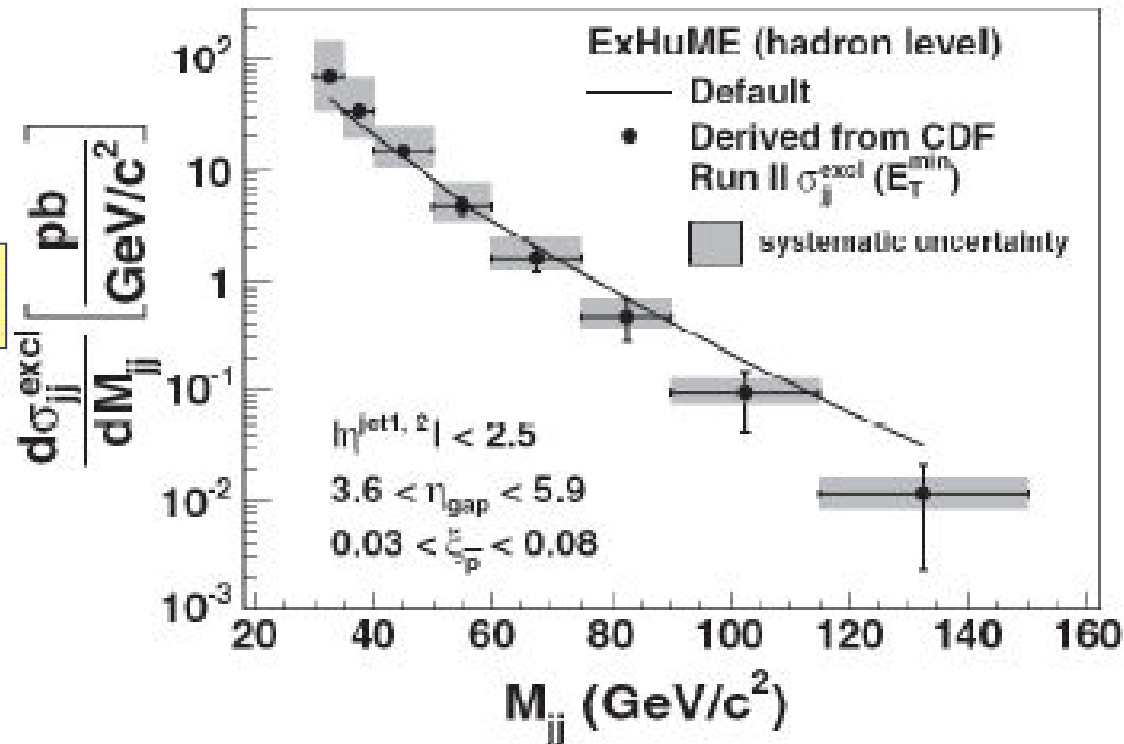


Exclusive dijet x-section vs. M_{jj}



(K. Goulianos)

arXiv:0712.0604 ,
PRD to appear soon



curve: ExHuME hadron-level exclusive dijet cross sections vs. dijet mass
points: derived from CDF excl. dijet x-sections using ExHuME

Stat. and syst. errors are propagated from measured cross section uncertainties using M_{jj} distribution shapes of ExHuME generated data.

Summary and conclusions

- HERA is currently best (?) QCD laboratory
- In general, good agreement with NLO QCD, **success of the standard model !**
 - > extract PDFs, α_s , ... with great precision also F_L -> this afternoon
 - improve understanding of how to treat specific final states
 - NNLO calculations in progress.
- Currently, only small fraction of the HERA II statistics has been analyzed in many cases. Combination of H1/ZEUS results has started
 - > **towards 1 fb⁻¹ results.**
 - > expect **significant further improvements** over next two years
- many of these improvements **relevant for physics at other colliders, in particular LHC**

