QCD at the HERAscale

and implications for the TERAscale

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for the H1 and ZEUS collaborations

+ some personal views

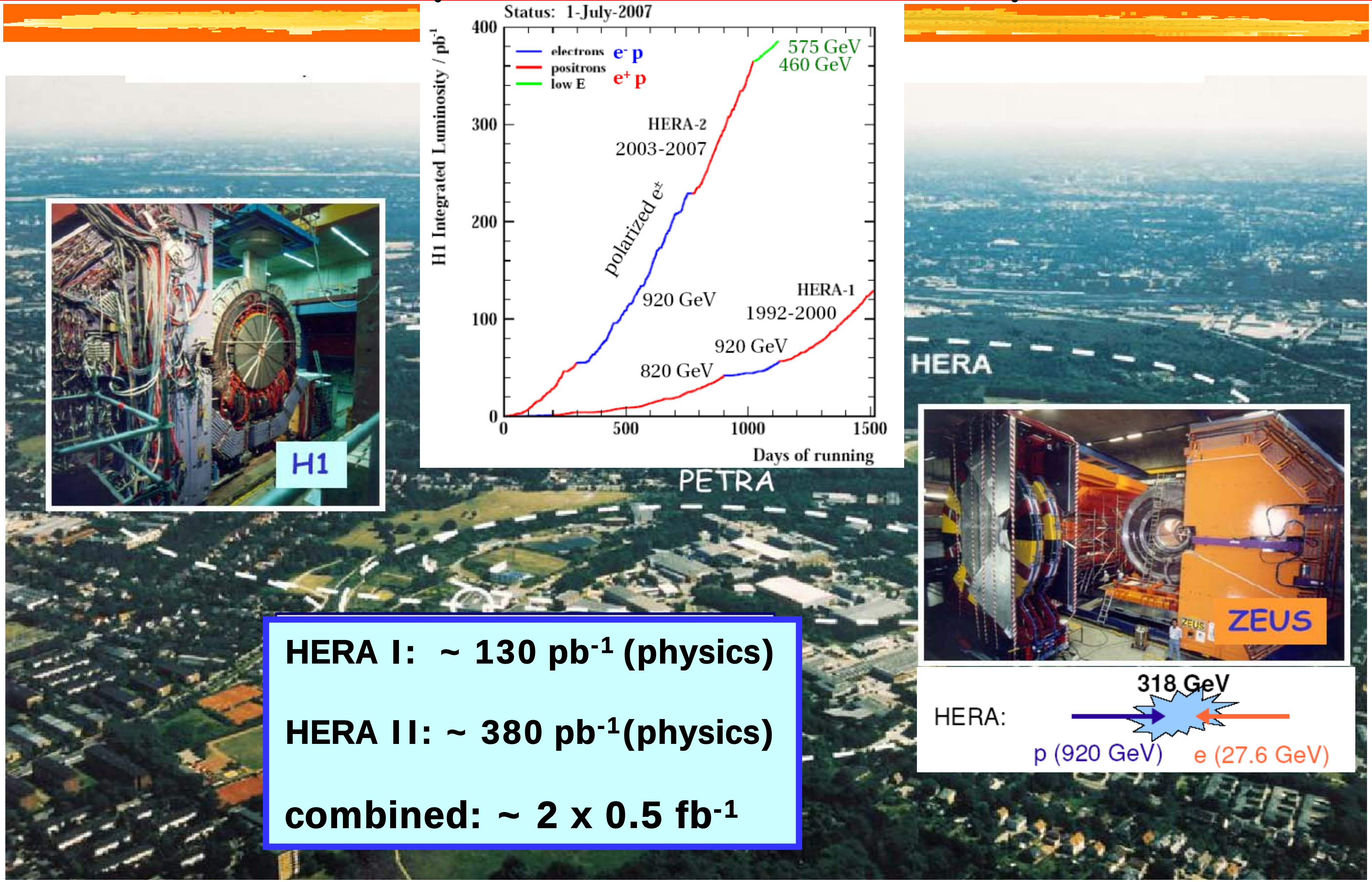
XXVIII Physics in Collision

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

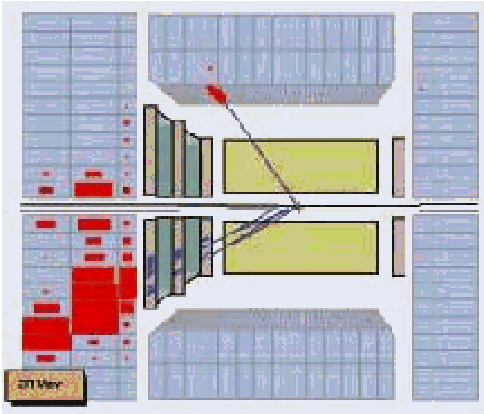


HERA I: ~ 130 pb^{-1} (physics)

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

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

HERA = currently best (?) QCD laboratory

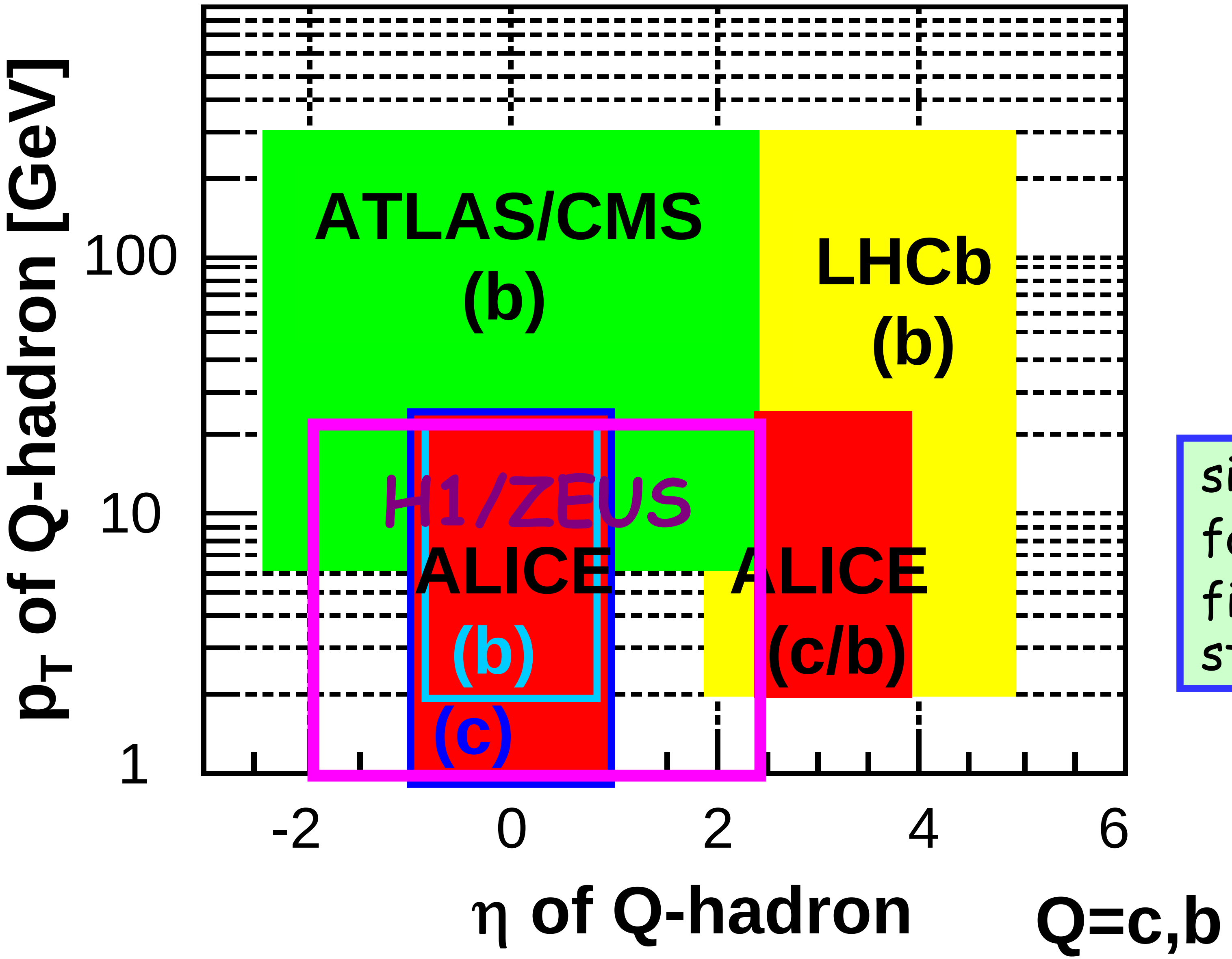


- **Proton structure:**
  - structure functions and parton density functions (PDF)
  - heavy flavours
- **General QCD studies**
  - jets and α_s
  - semi-inclusive final states

apologies:
no time for experimental methods

- **Both direct and indirect relations to measurements at Tevatron and LHC**

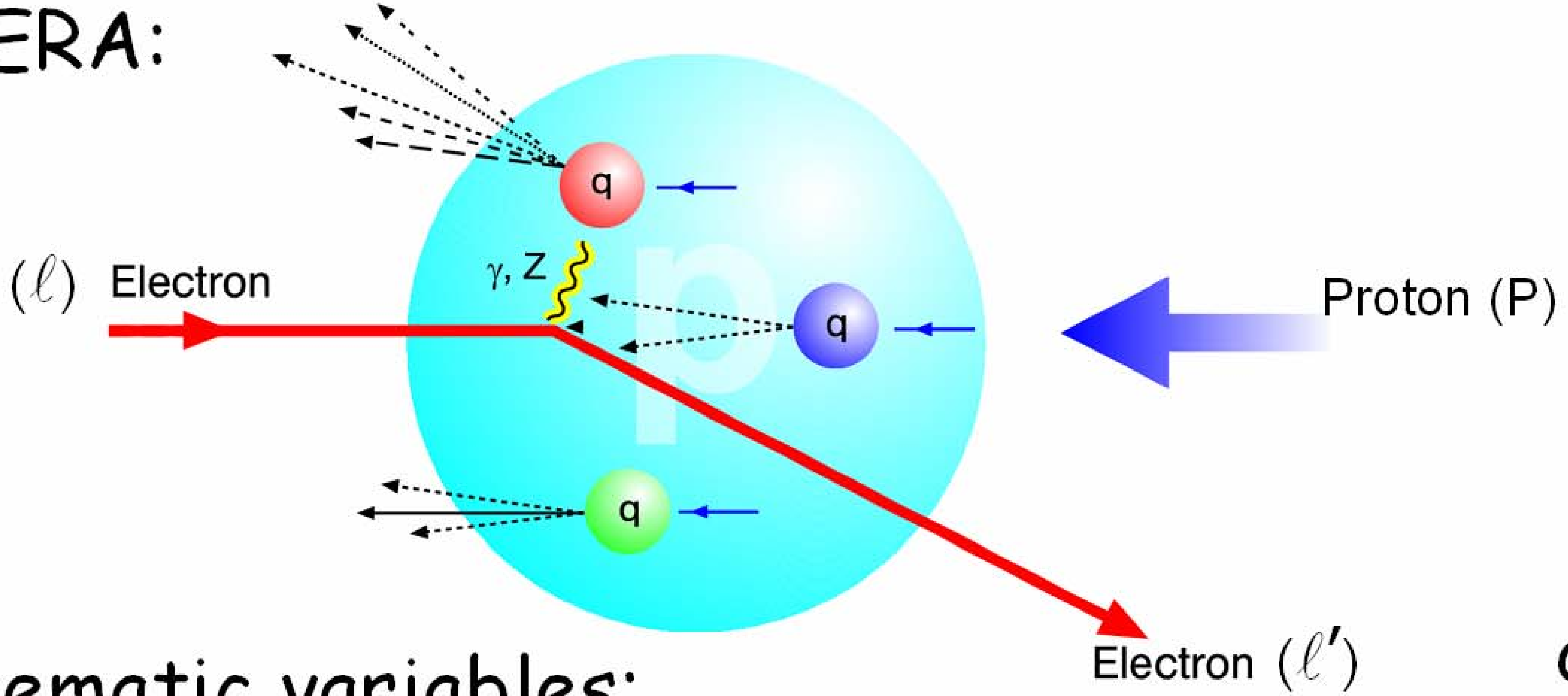
example:
acceptance for open heavy flavor at LHC/HERA



similar for other final states

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)

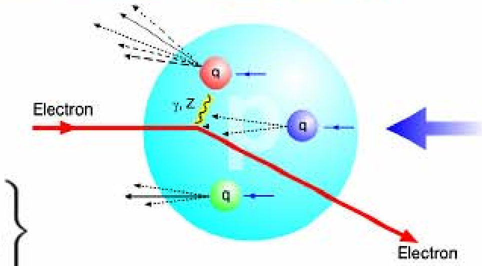
$Q^2 \lesssim 1\ GeV^2$: photoproduction

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

The structure of the proton

- Measure cross section

-> talk V. Chekelian



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

small ($y^2 F_L$); at highQ^2 (xF_3)

-> talk E. Gallo

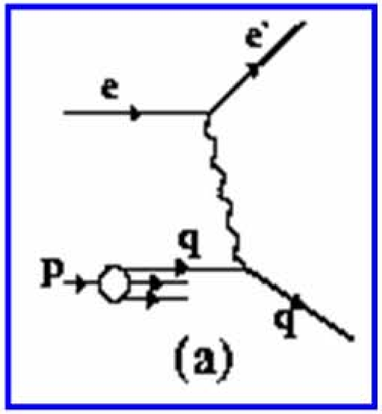
to 0th order QCD (Quark Parton Model, $Q^2 \gg m_q^2$):

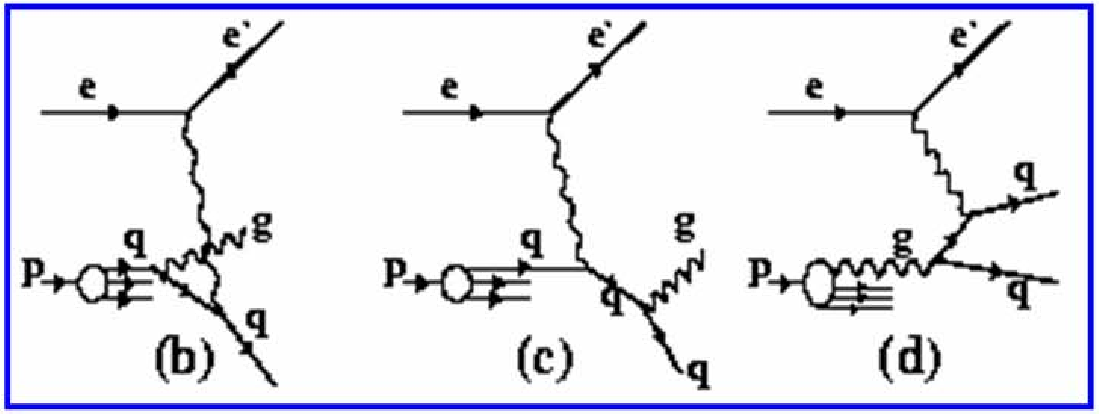
- Parton distribution functions (PDF) in pQCD

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

q_i – probability to find quark with flavour i in proton

"higher" order QCD corrections



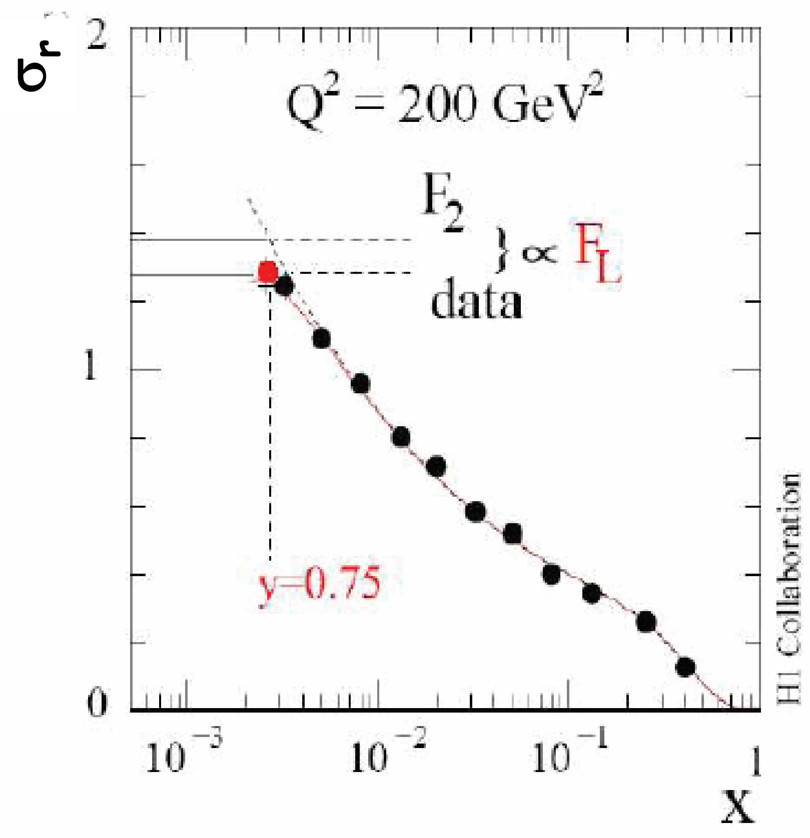


in general: F_2 structure function is **not** PDF

Reduced cross section

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

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



F_2 ~ quark distributions

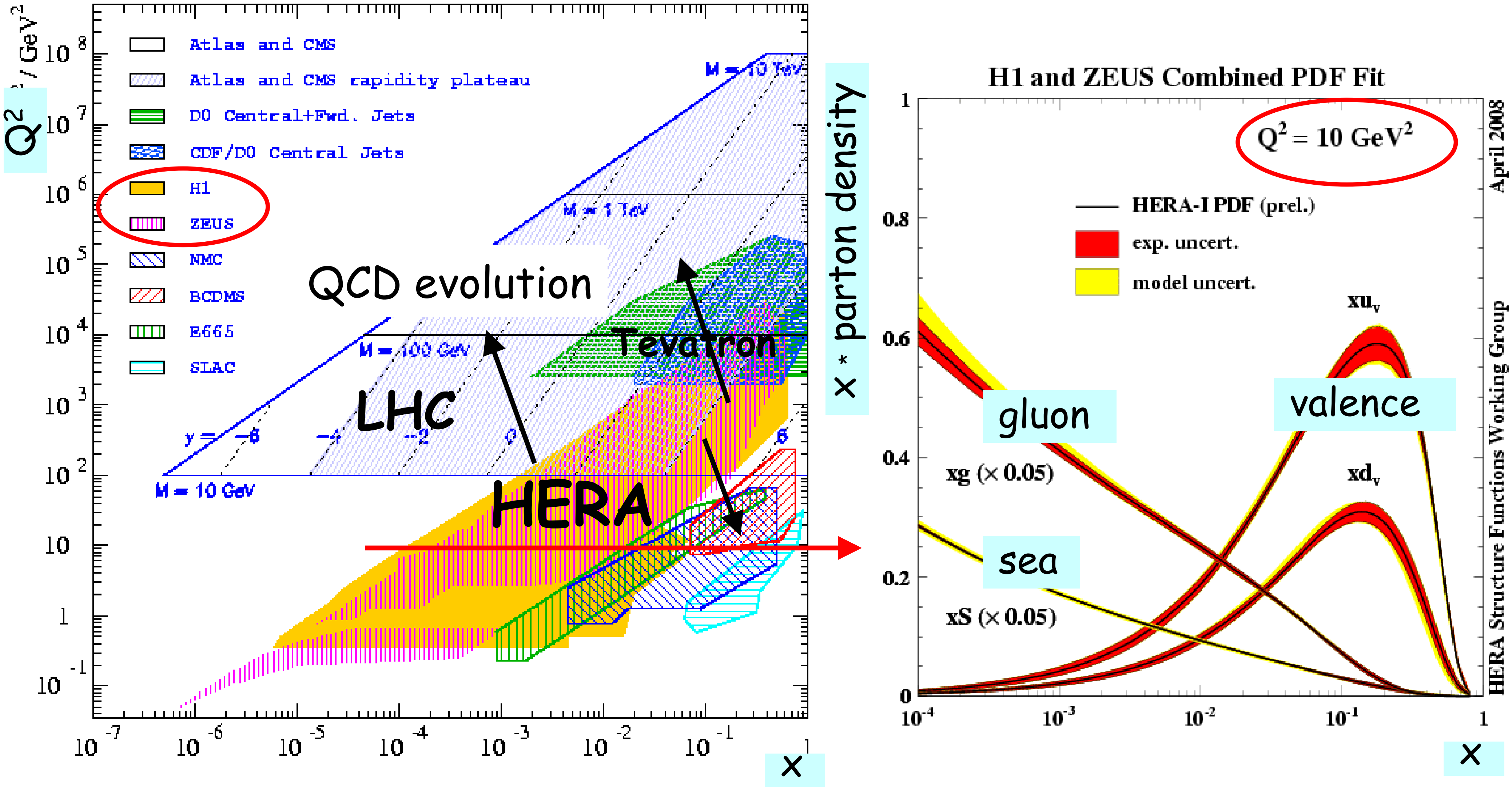
$$F_L(x, Q^2) \sim \alpha_s x g(x, Q^2)$$

-> talk V. Chekelian

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

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

Parton density funcions



HERA PDFs essential for LHC

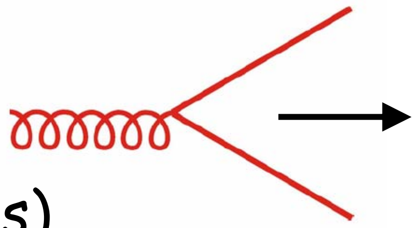
F_2 and gluon density

DGLAP QCD evolution:

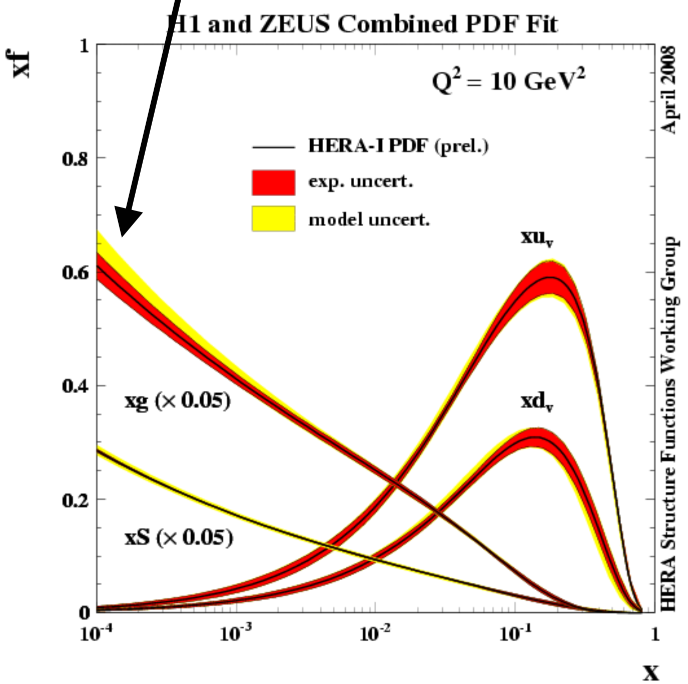
sea quarks, $g \to q\bar{q}$

positive slope

(scaling violations)

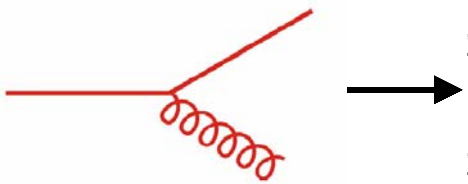


gluon density

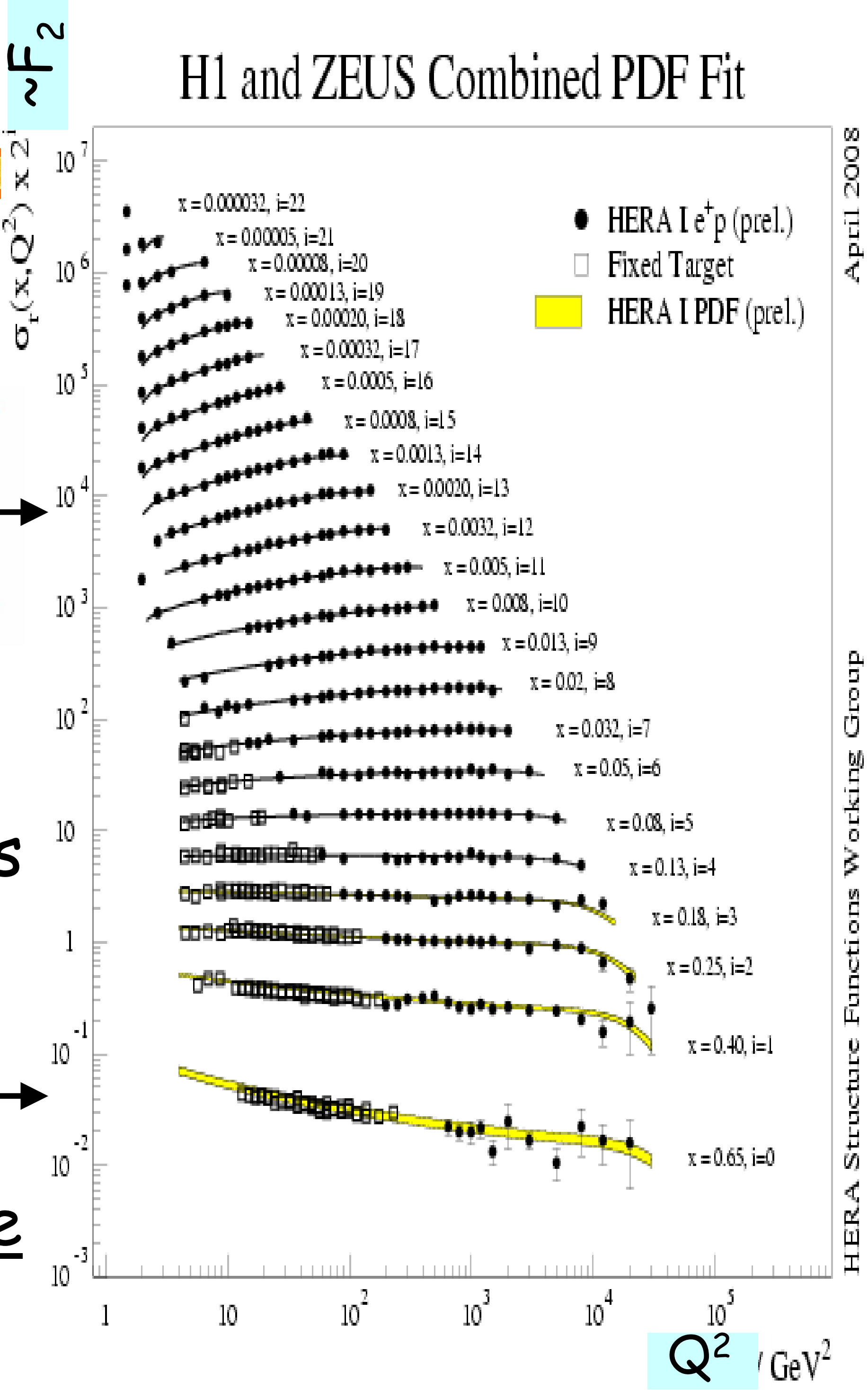


valence quarks

$q \to qg$

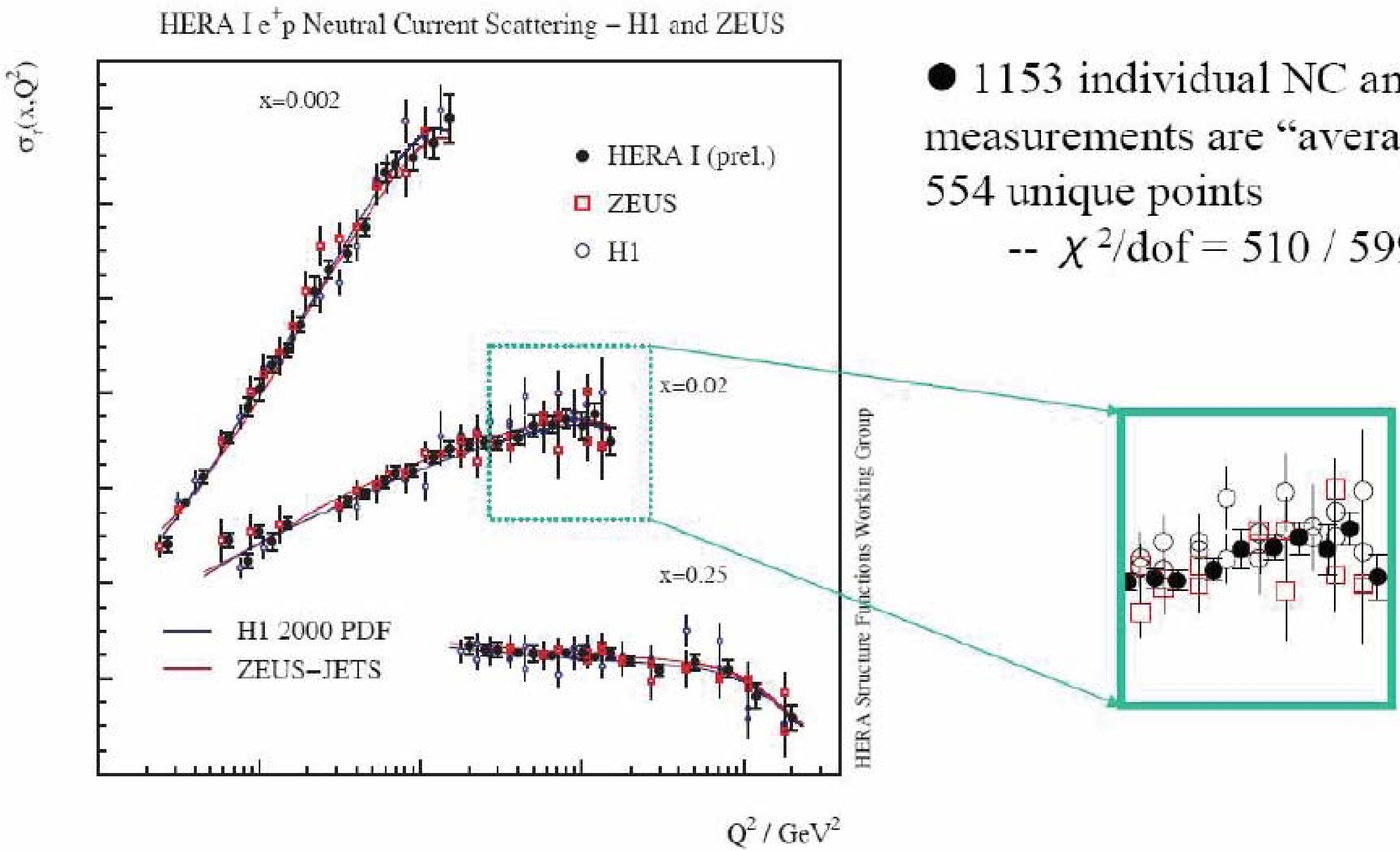


negative slope



H1 and ZEUS cross section combination

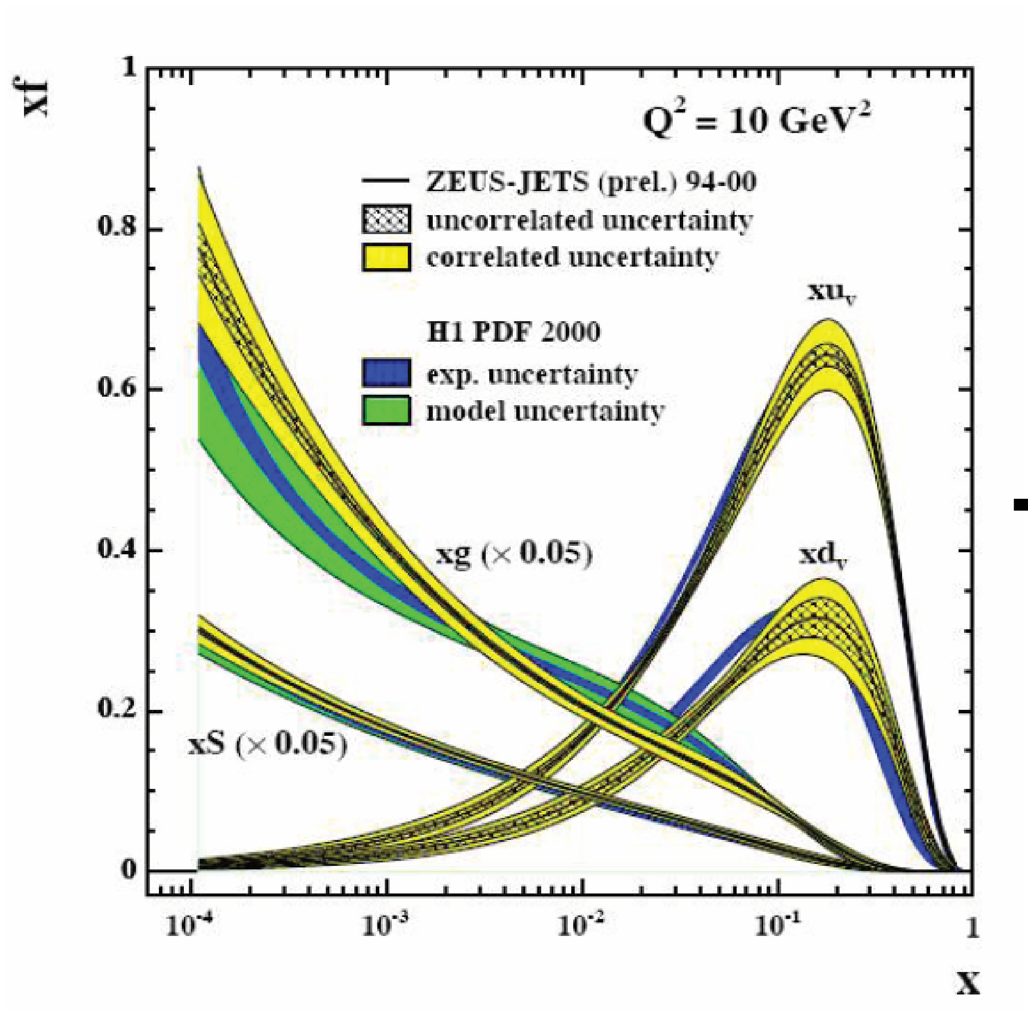
coherent treatment of experimental effects
-> cross calibration (improvement better than naive √2)

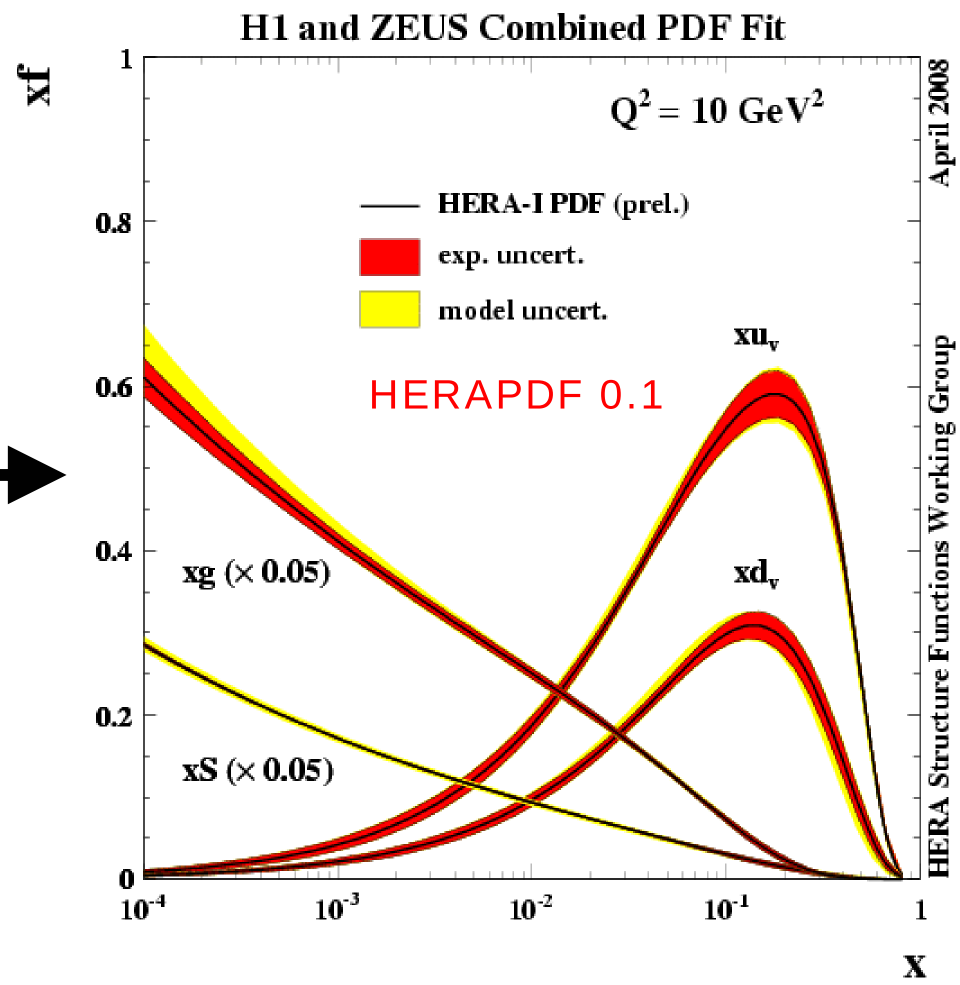


- 1153 individual NC and CC measurements are "averaged" to 554 unique points
  -- χ^2/dof = 510 / 599

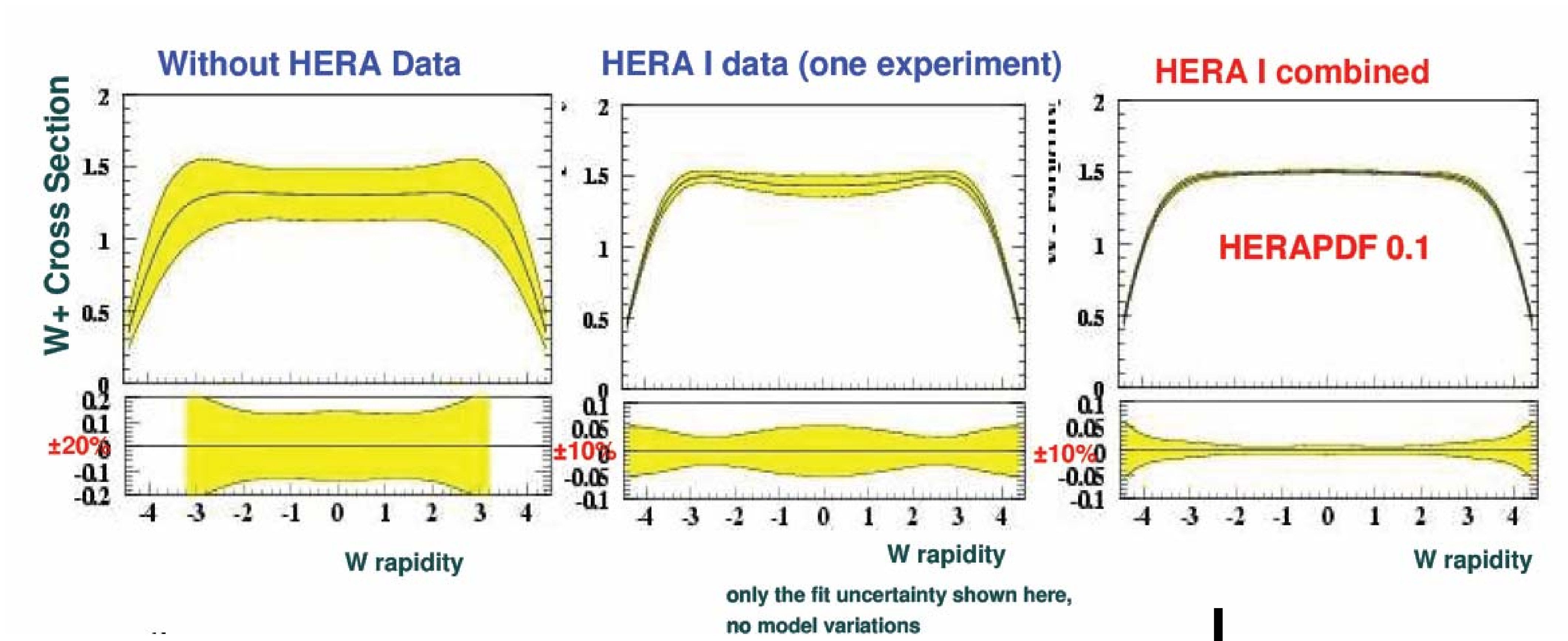
strong improvement

most notably at low x (also at high Q^2, LHC domain)





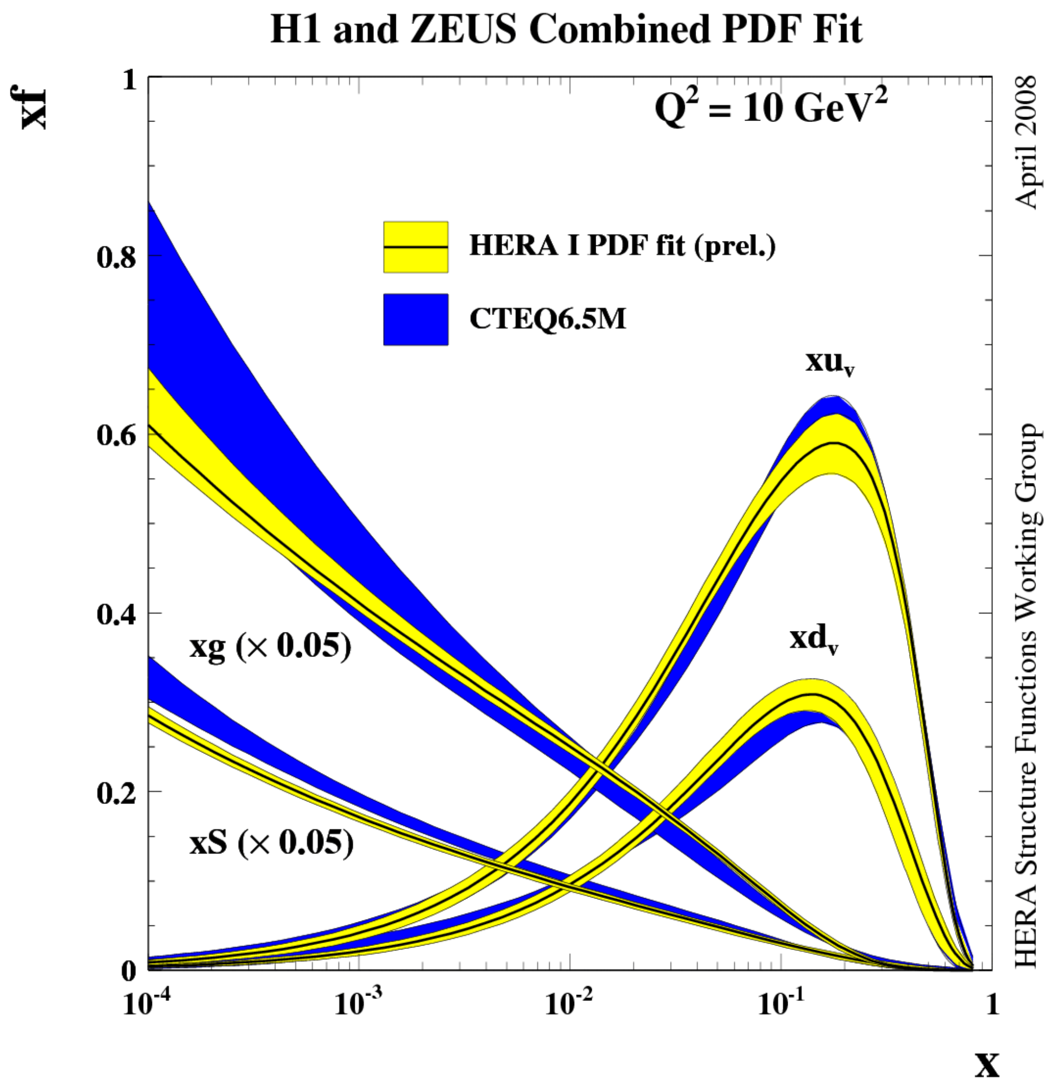
e.g.: predictions for W production at LHC

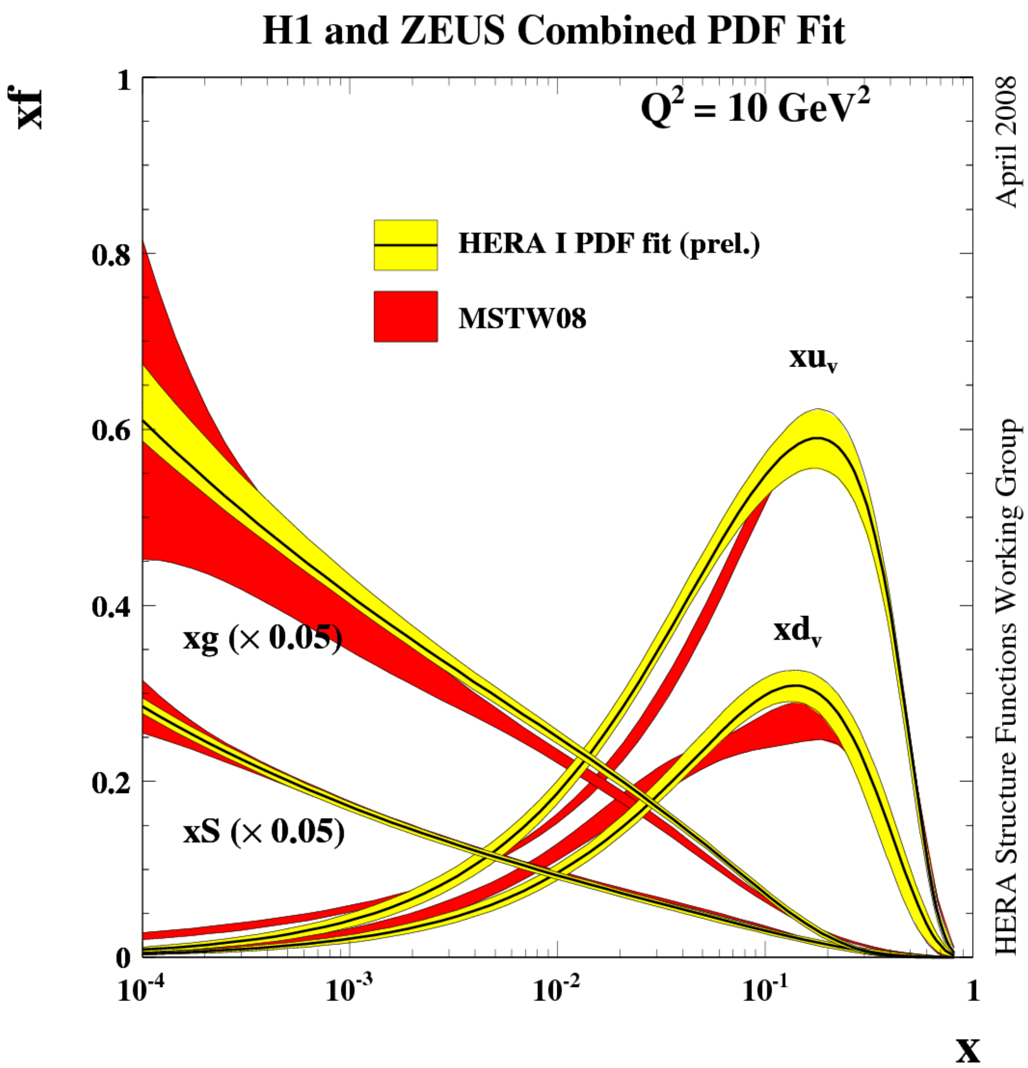


strong improvement

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%
$Z \longrightarrow \mu\mu$	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 20

J. ANDERSON (LHCB)
Hera-LHC workshop

ATLAS/CMS: QUALITATIVELY SIMILAR CONCLUSIONS

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

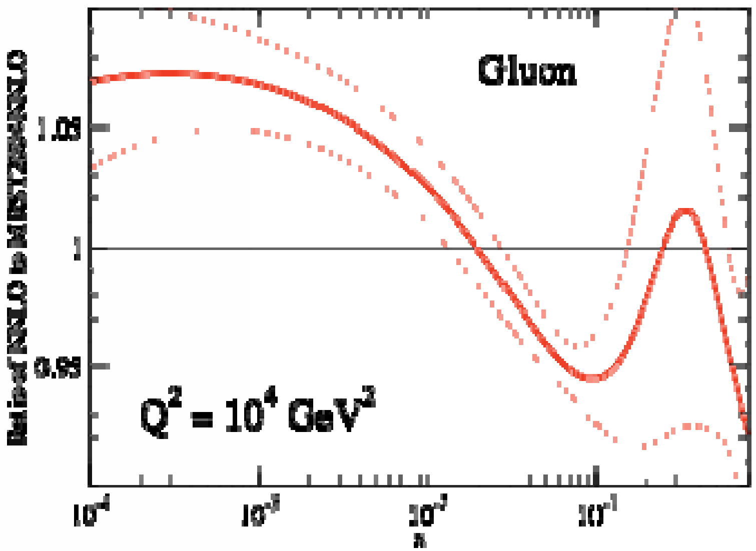
PDFs: beware of heavy flavour treatment

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

PDF4LHCMSTW

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 -> terms log Q^2/m^2

  log p_T^2/m^2 etc.

  ↑

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

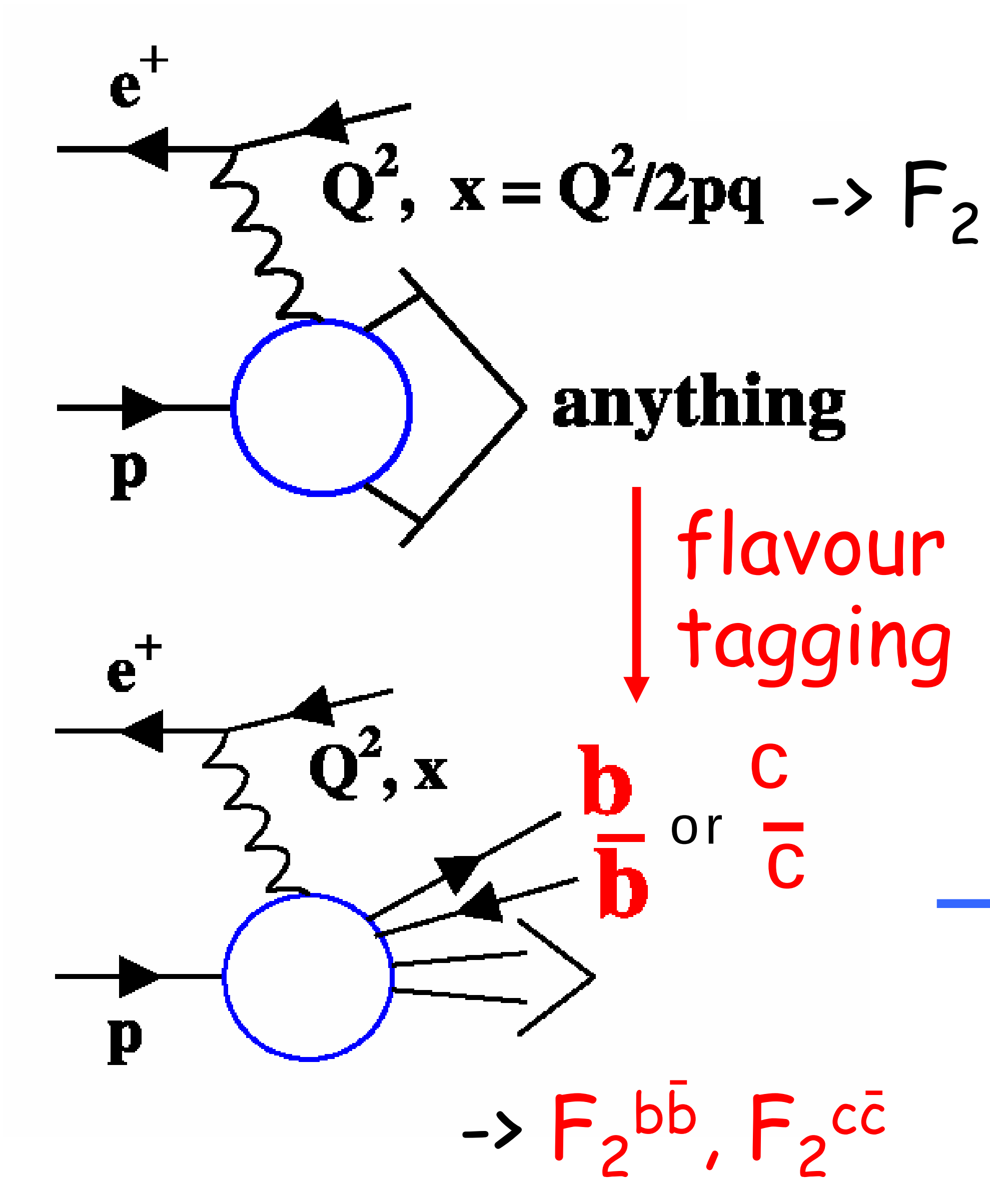
=> "**massive**" treatment gets kinematics right, but does not allow resummation (fixed flavour number schemes) or induces ambiguities in QCD corrections near flavour threshold (variable flavour number schemes)

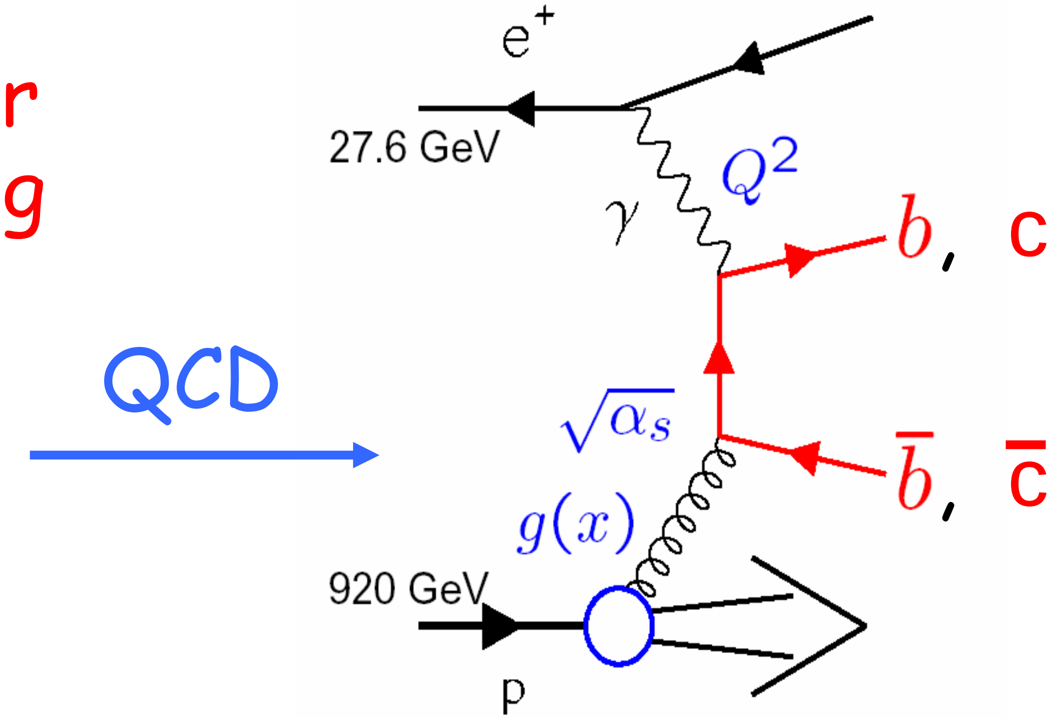
check different schemes against HERA data

Heavy flavour contributions to F_2

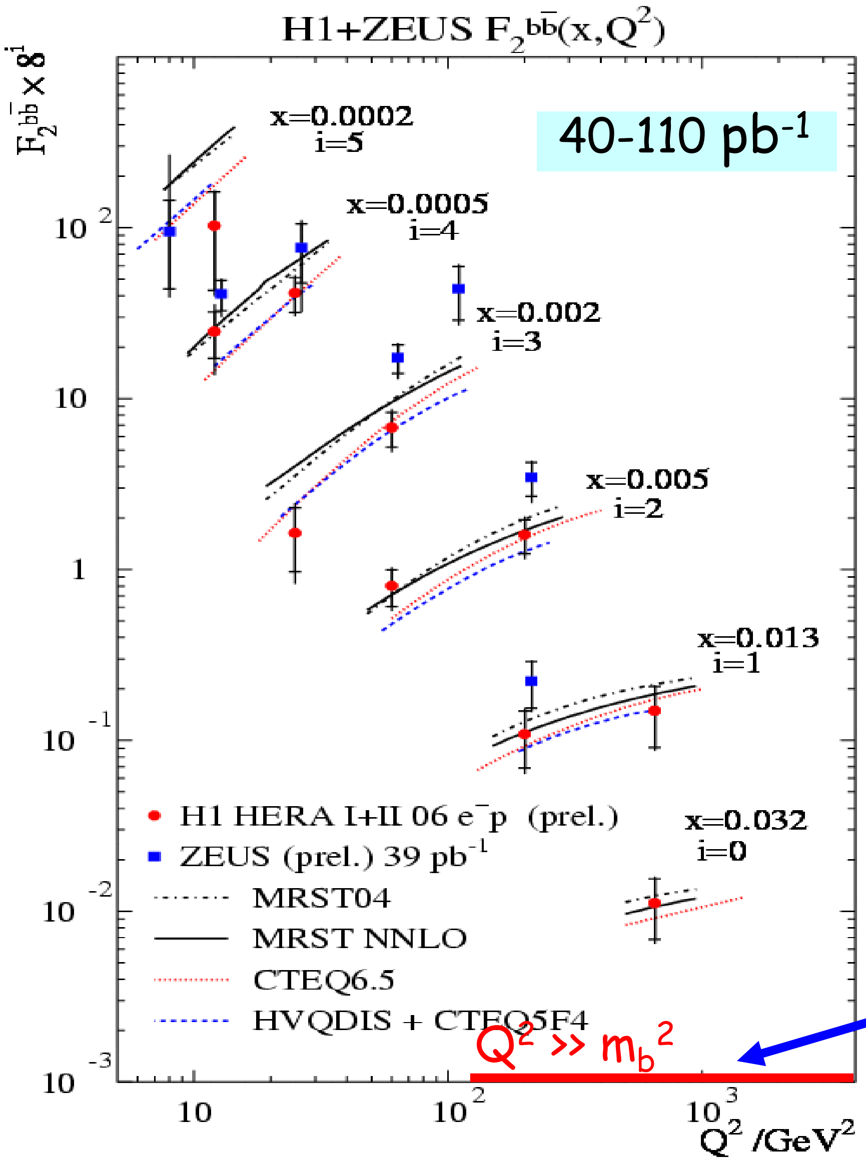
mainly
Boson Gluon Fusion,
driven by gluons

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





Beauty contribution to F_2

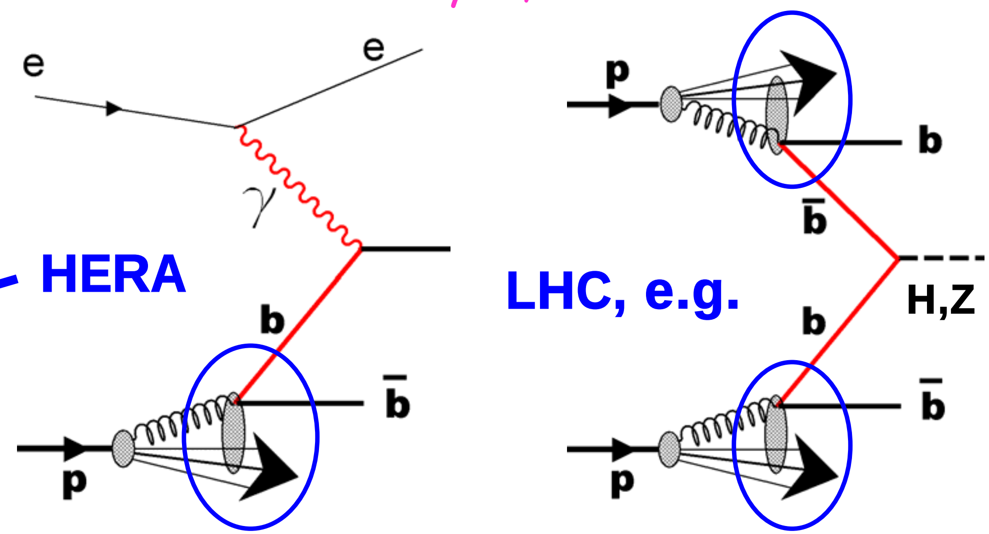


data in agreement with NLO and NNLO, but errors still large
(only small fraction of data analysed)

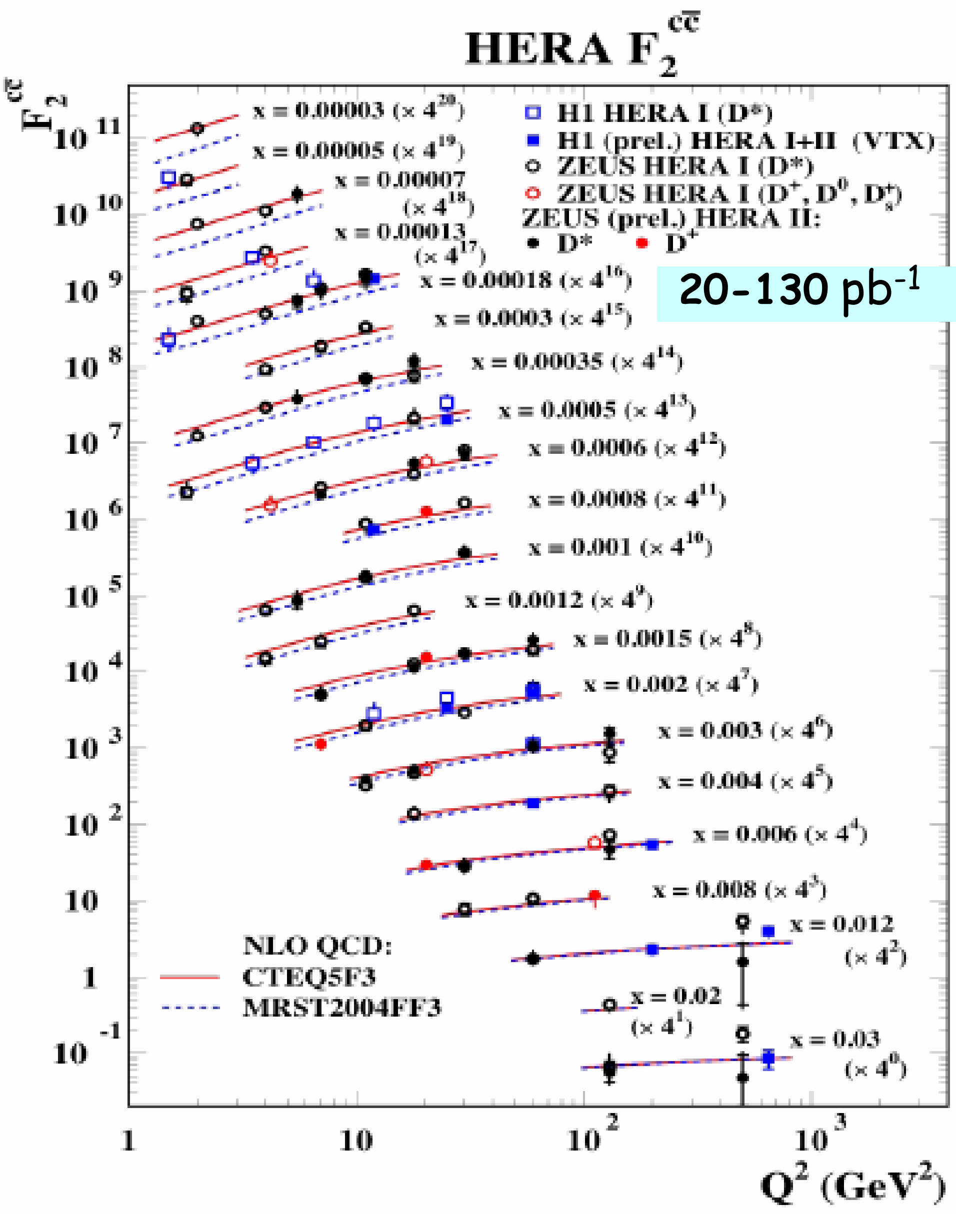
improved measurements
-> **discriminate between different schemes**

-> **check b PDF for LHC:**

see also talk C. Royon, Z + b at Tevatron



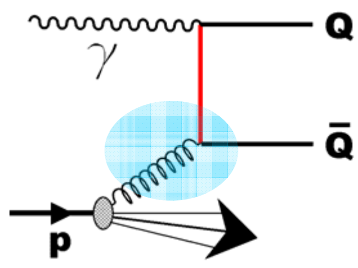
Charm contribution to F_2



- Large amount of measurements using different methods available.

in agreement with QCD predictions
-> gluon PDF ~OK !

understand mass effects from beauty



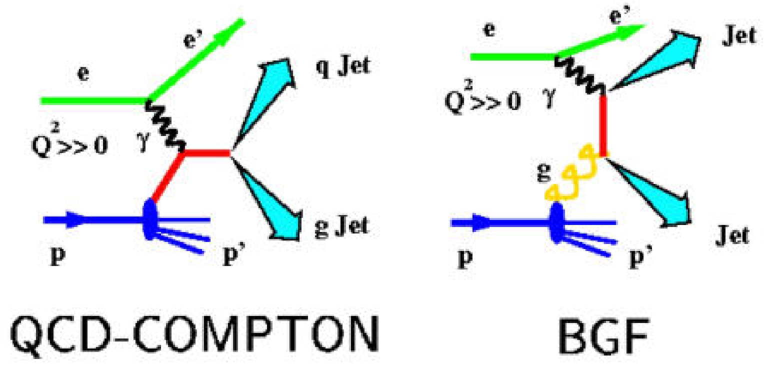
-> **improved theory**

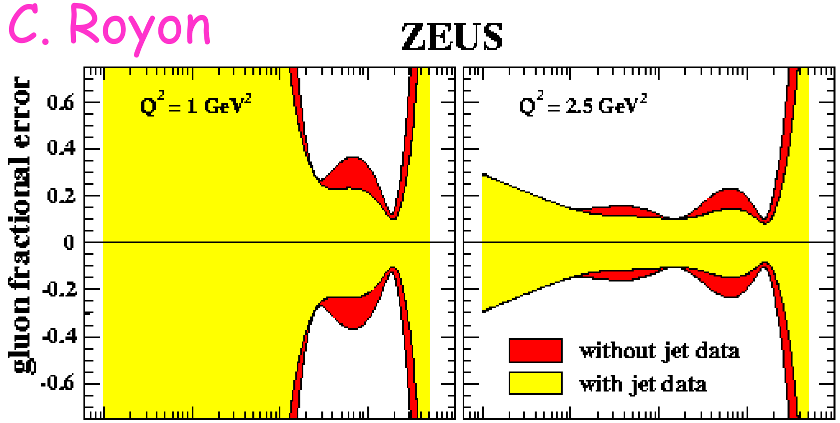
-> **further test/constrain gluon PDF**

Dataset:	L [pb^{-1}]:
H1 HERA I (D*)	19
H1 (prel.) HERA I+II (VTX)	58 + 54
ZEUS HERA I (D*)	82
ZEUS HERA I (D^+, D^0, D_s^+)	82
ZEUS (prel.) HERA II	135

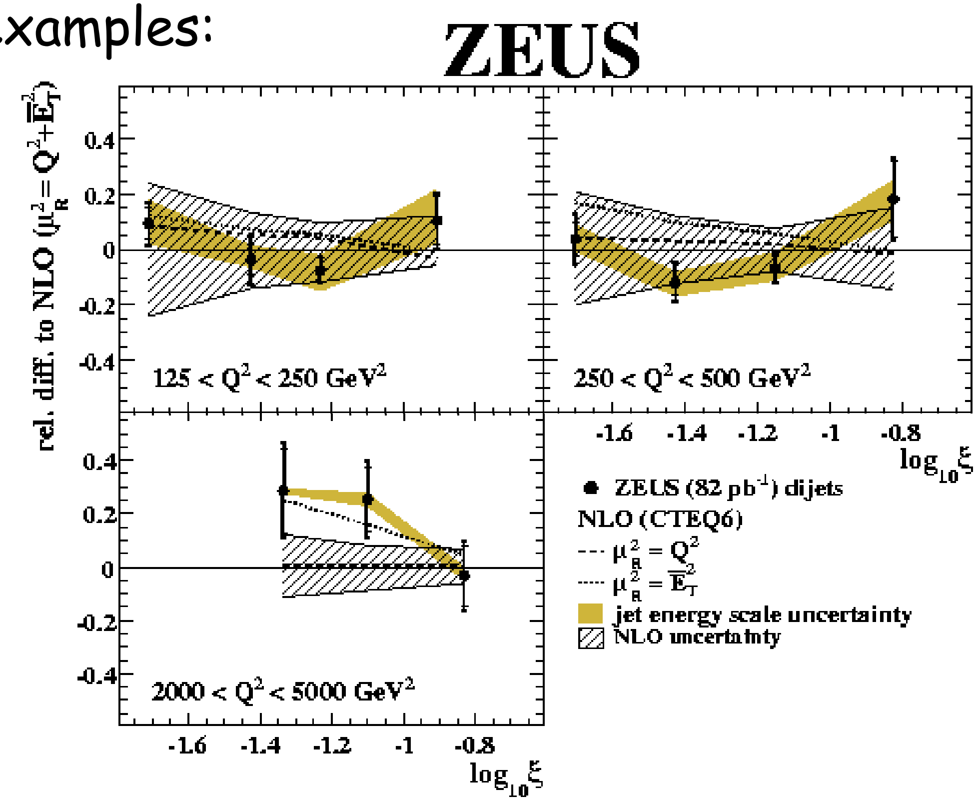
Jets at HERA constrain gluon distribution

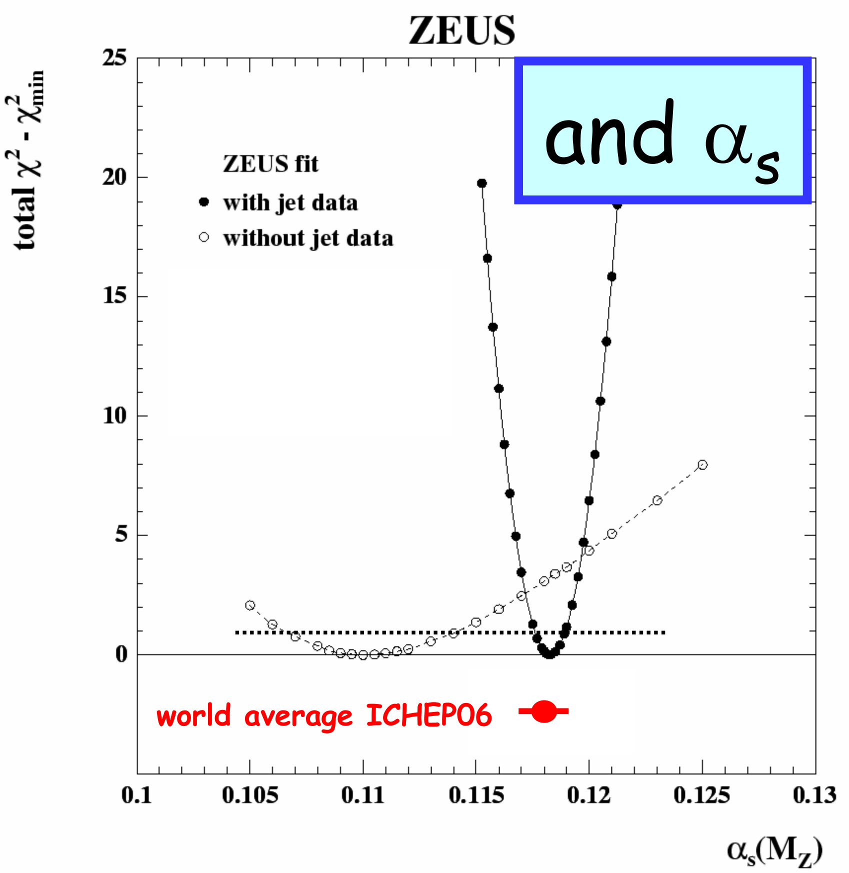
see talk C. Royon





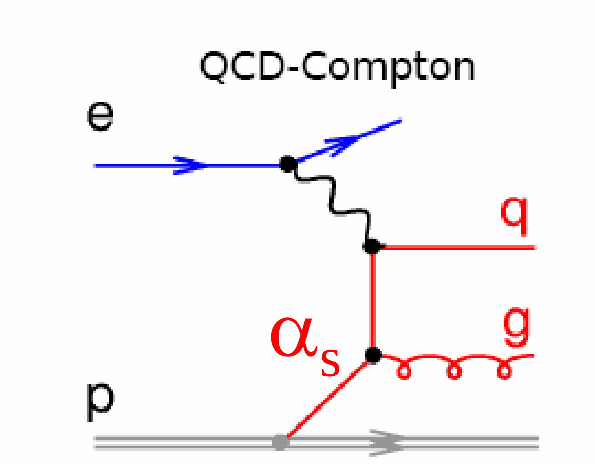
examples:

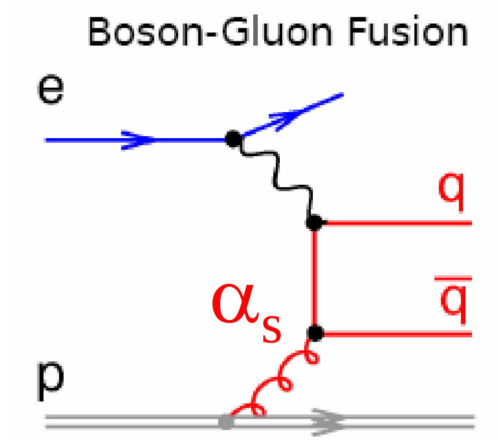


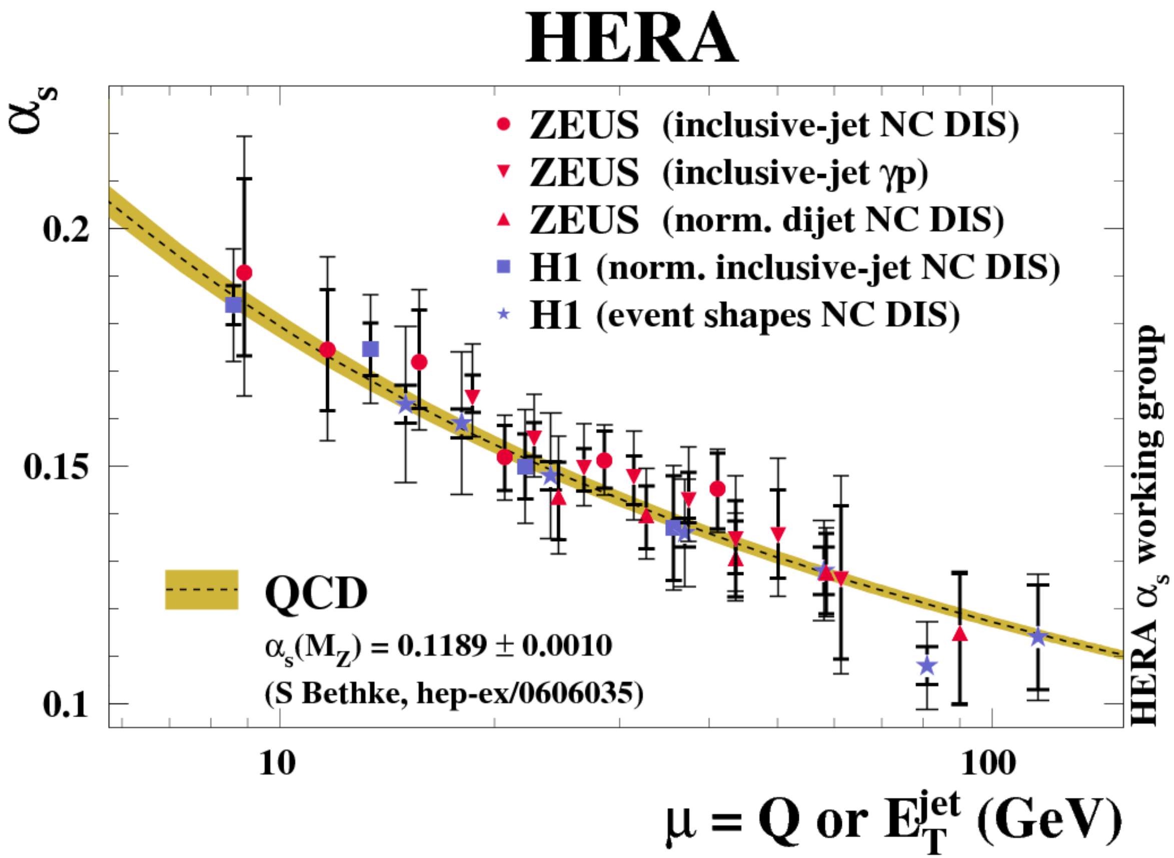


measurement of α_s

ep interactions directly sensitive to α_s





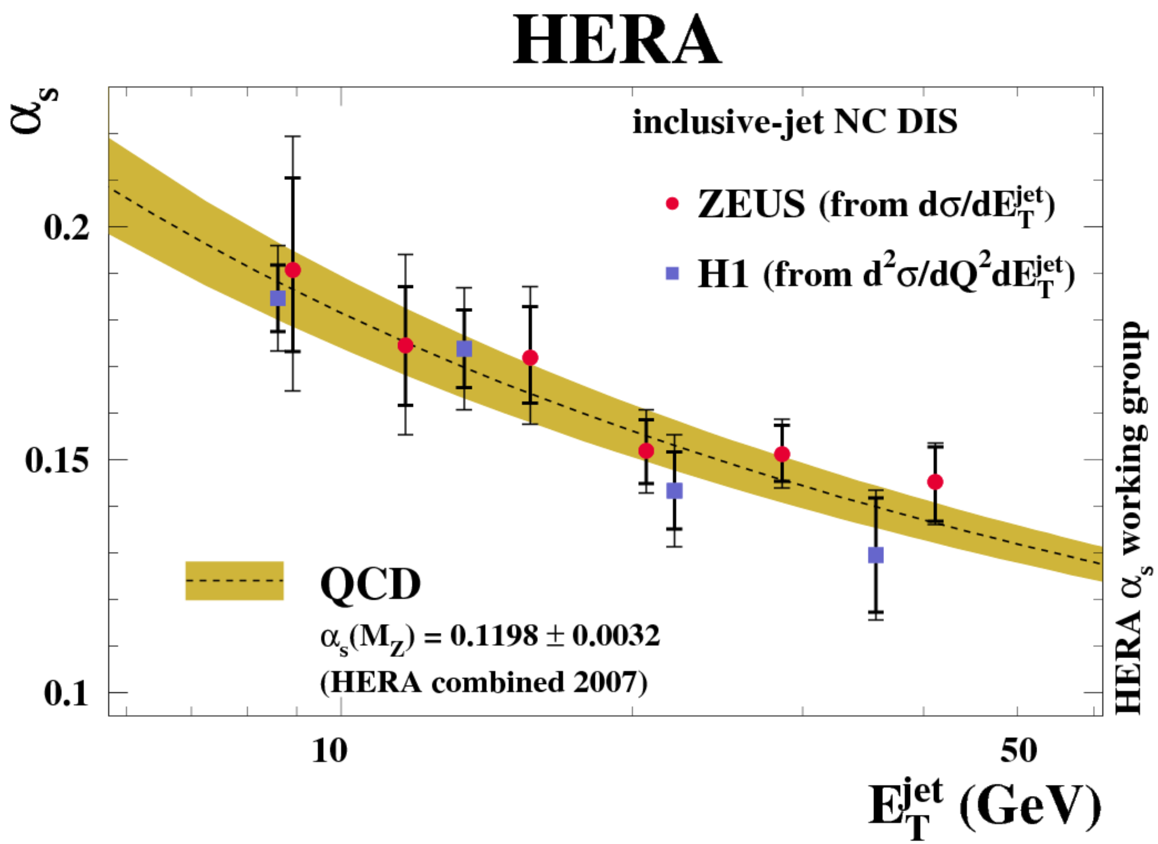


ZEUS/H1 combined α_s

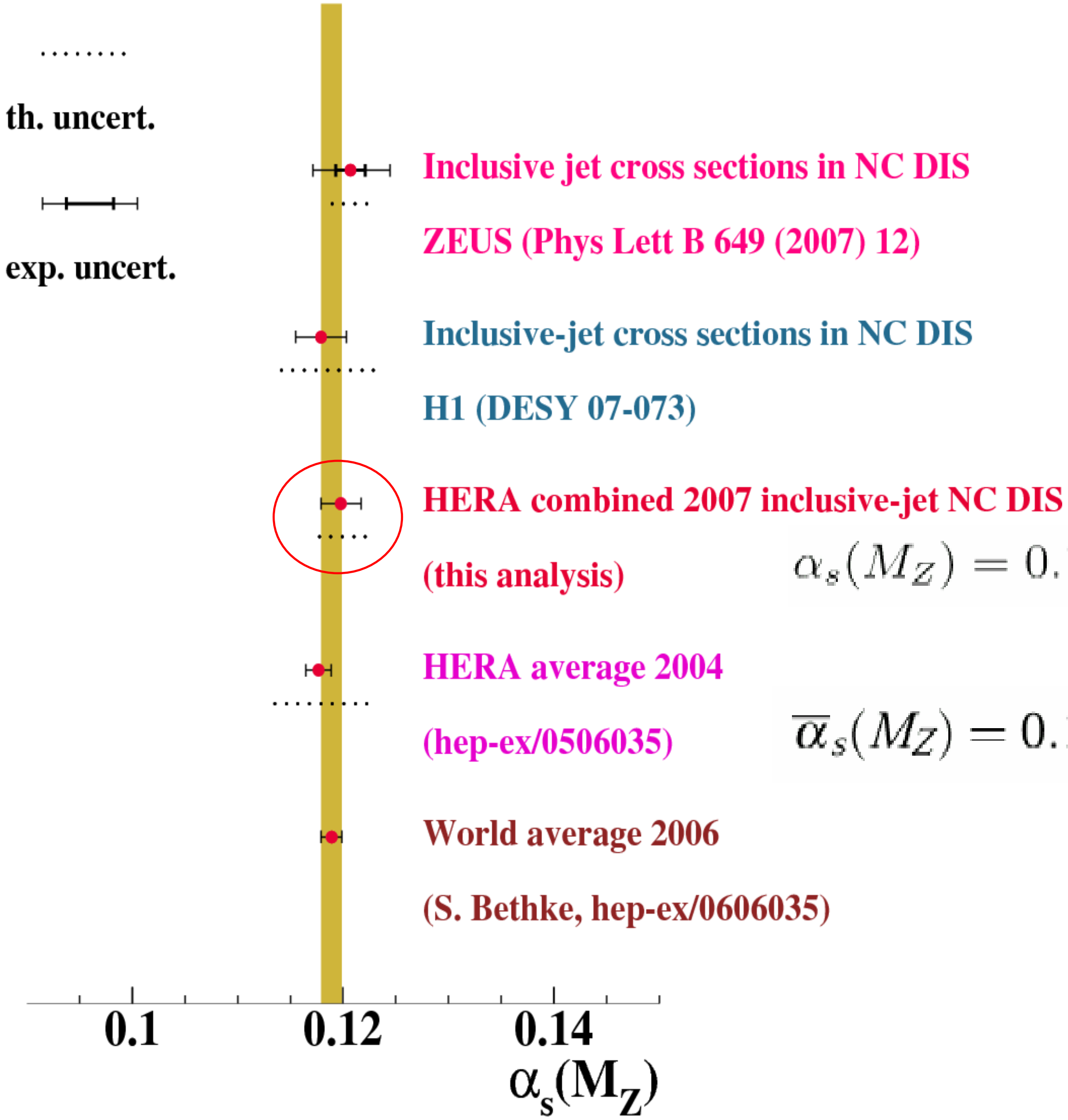
can gain in sensitivity by combining measurements with different systematics/different theory uncertainties

select suitable subset of measurements

focus on small NLO error
(NNLO not yet available)



combined α_s



new improved result consistent with previous ones and world average

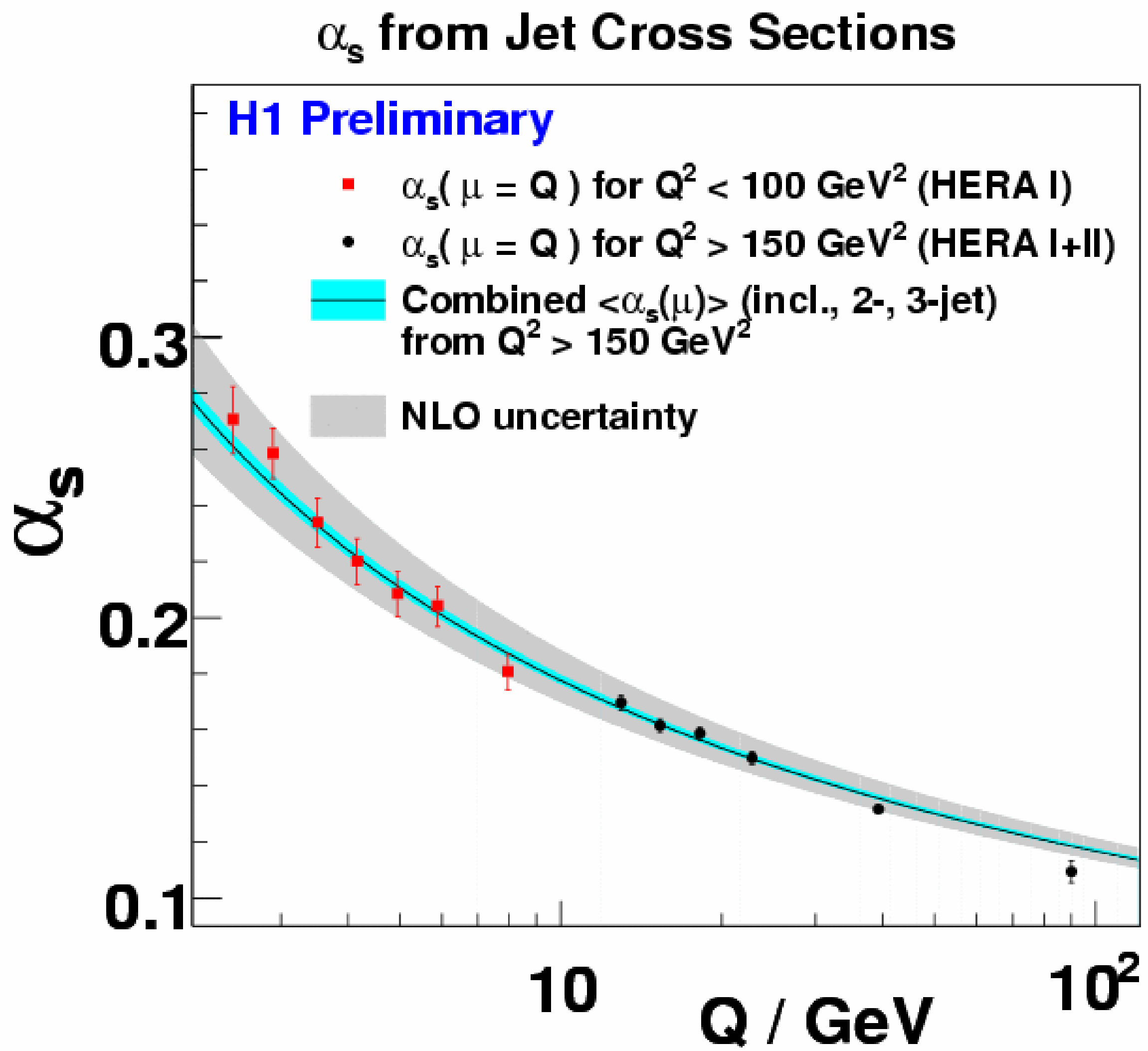
total error: 2.7%

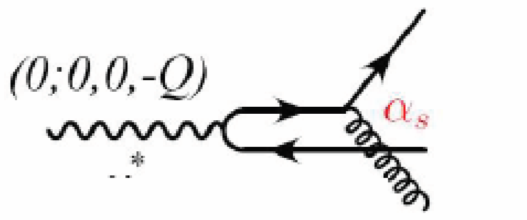
$$\alpha_s(M_Z) = 0.1198 \pm 0.0019\ (\text{exp.}) \pm 0.0026\ (\text{th.})$$

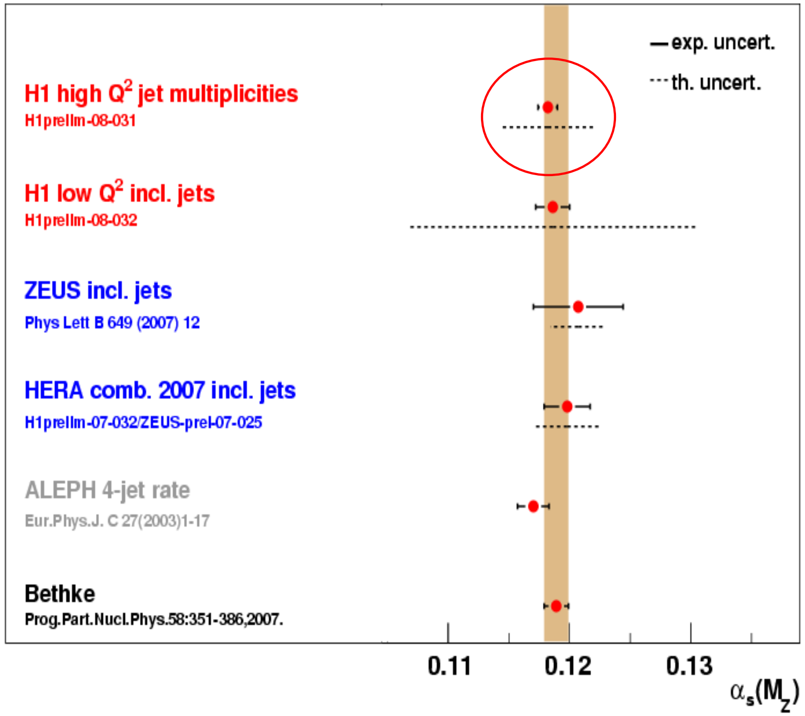
total error: 4.3%

$$\overline{\alpha}_s(M_Z) = 0.1186 \pm 0.0011\ (\text{exp.}) \pm 0.0050\ (\text{th.})$$

most recent HERA α_s measurements







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

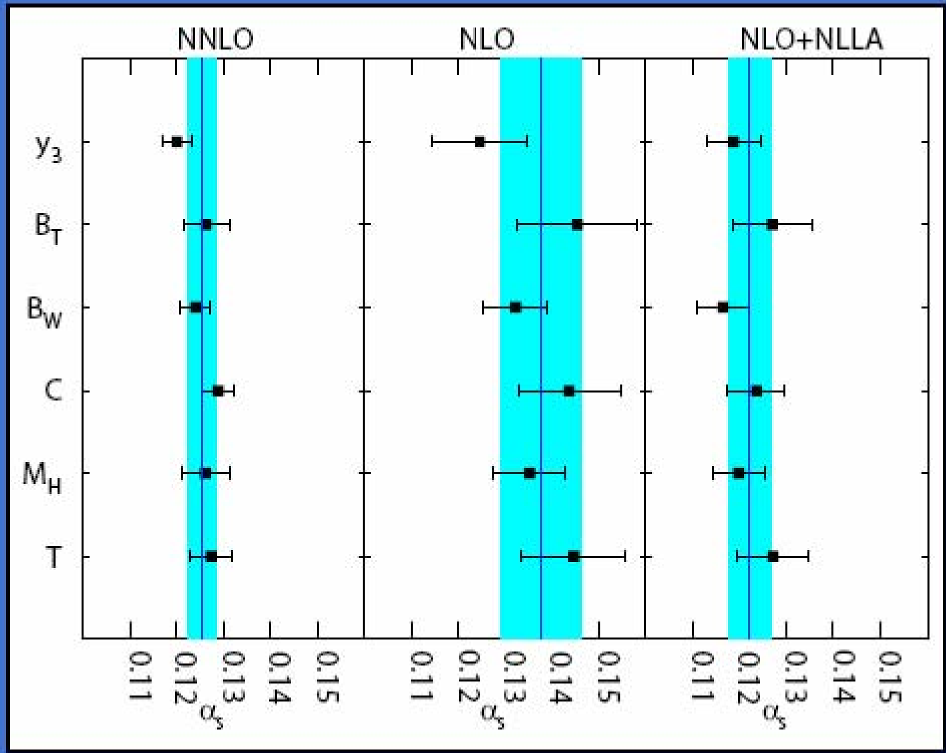
HERA α_s competitive to e+e-

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

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



Luisoni, HERA-LHC workshop

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

HERA comb. 2007: 0.1198 ± 0.0032

will improve further once NNLO available!

encouragement

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

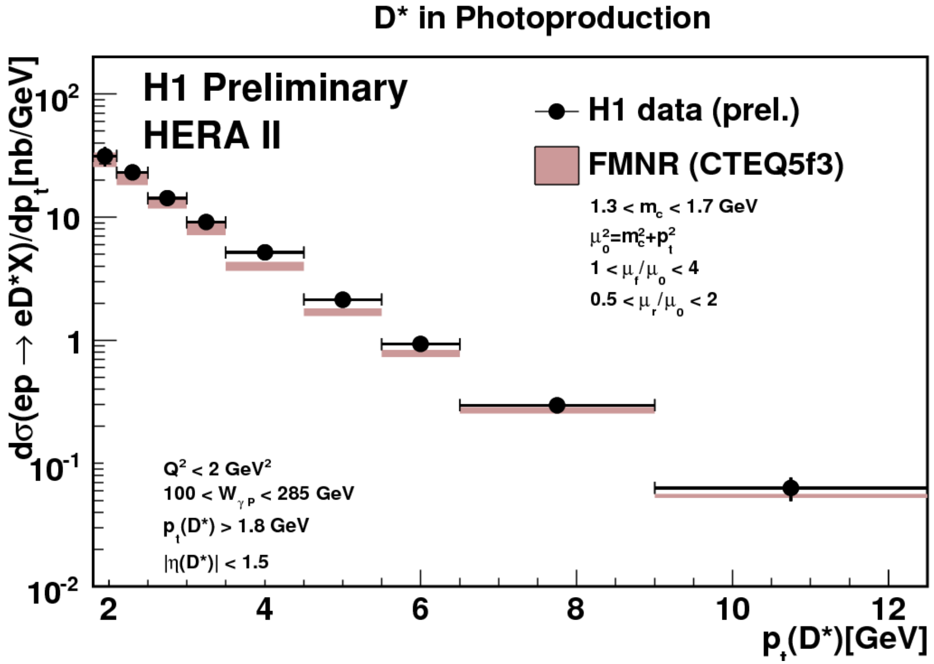
for recent progress, see e.g. HERA-LHC workshop

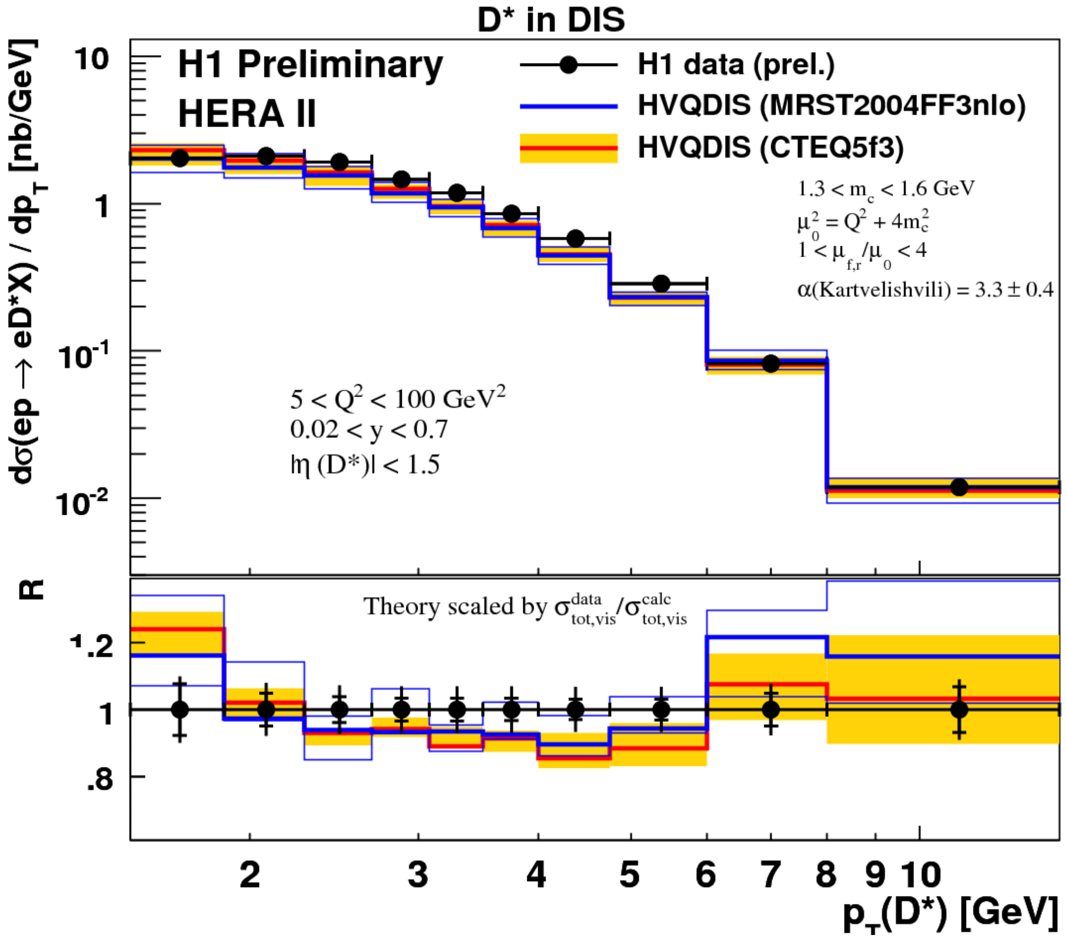
test QCD with semi-inclusive final states

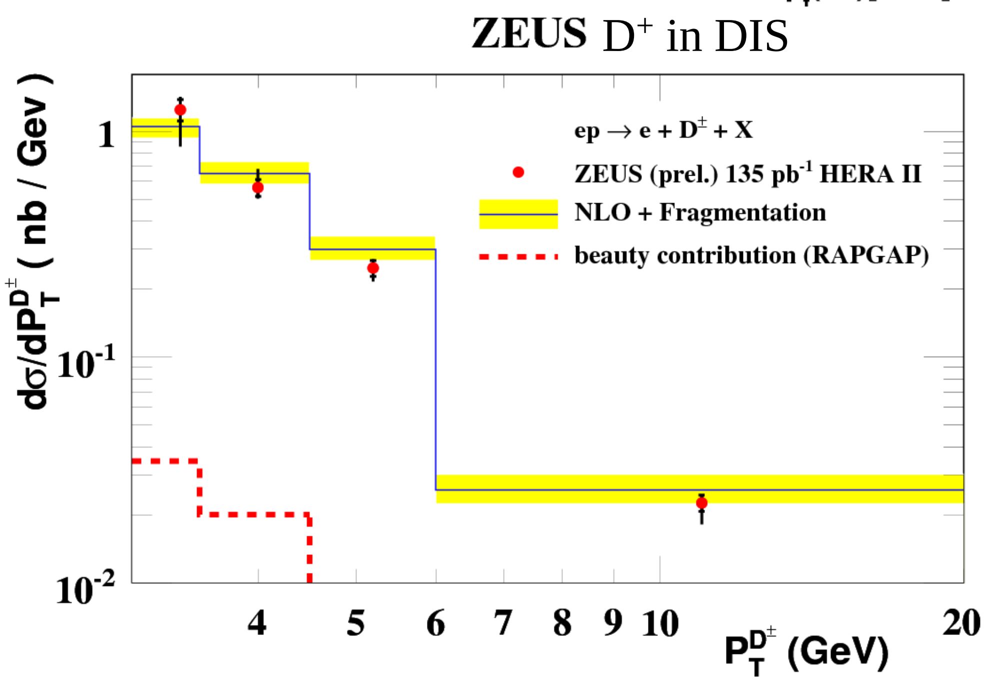
- charm and beauty production
- single photon production
- jets -> previous talk C. Royon
- inclusive diffraction
- exclusive VM production -> talk W. Bartel
- constraints on BSM physics -> talk S. Gruenendahl

=> investigate validity of QCD
and validity of predictions for LHC

charm: D*/D+ p_T distributions

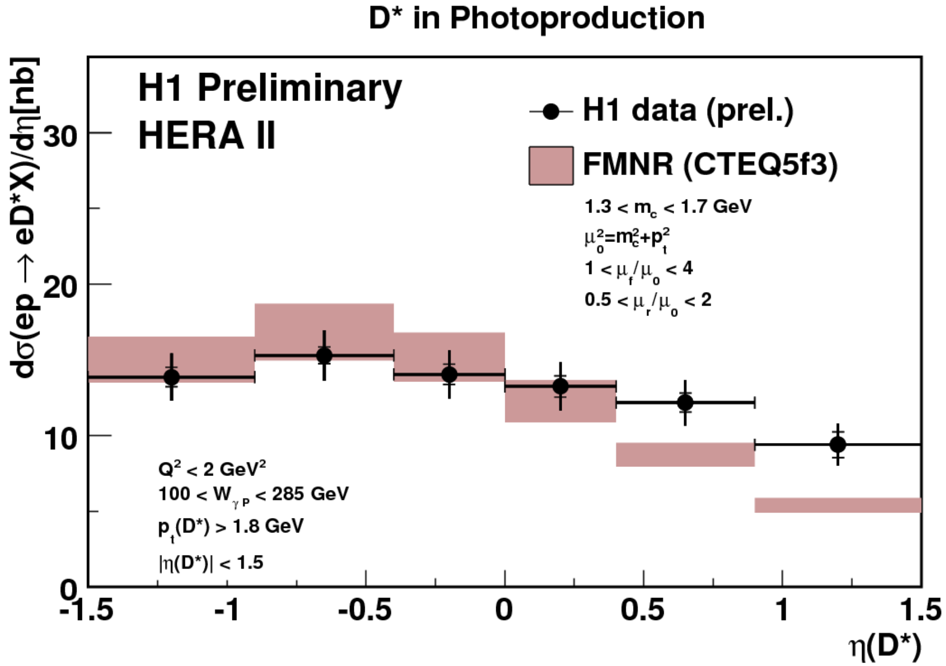


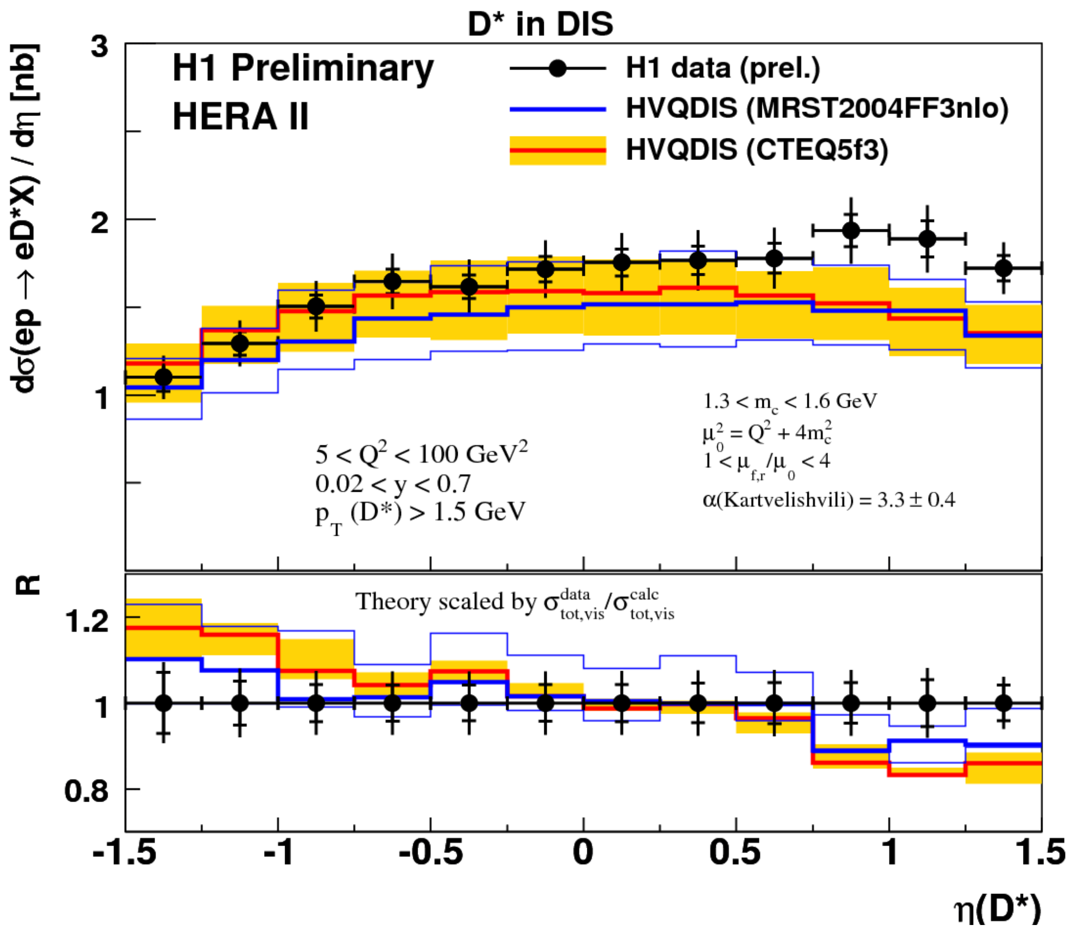


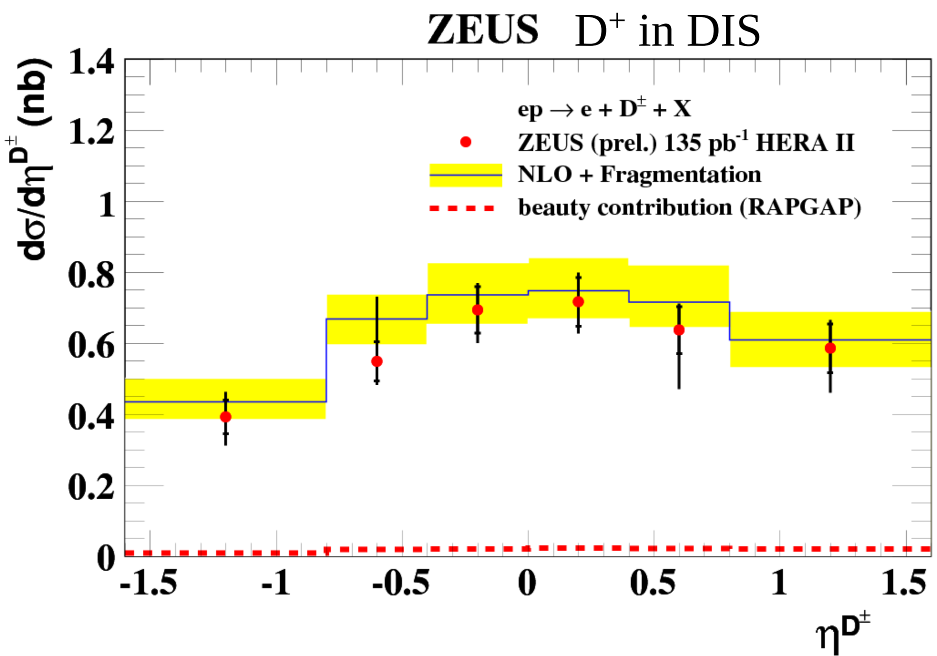


reasonably described by NLO QCD

charm: D*/D+ p_T distributions





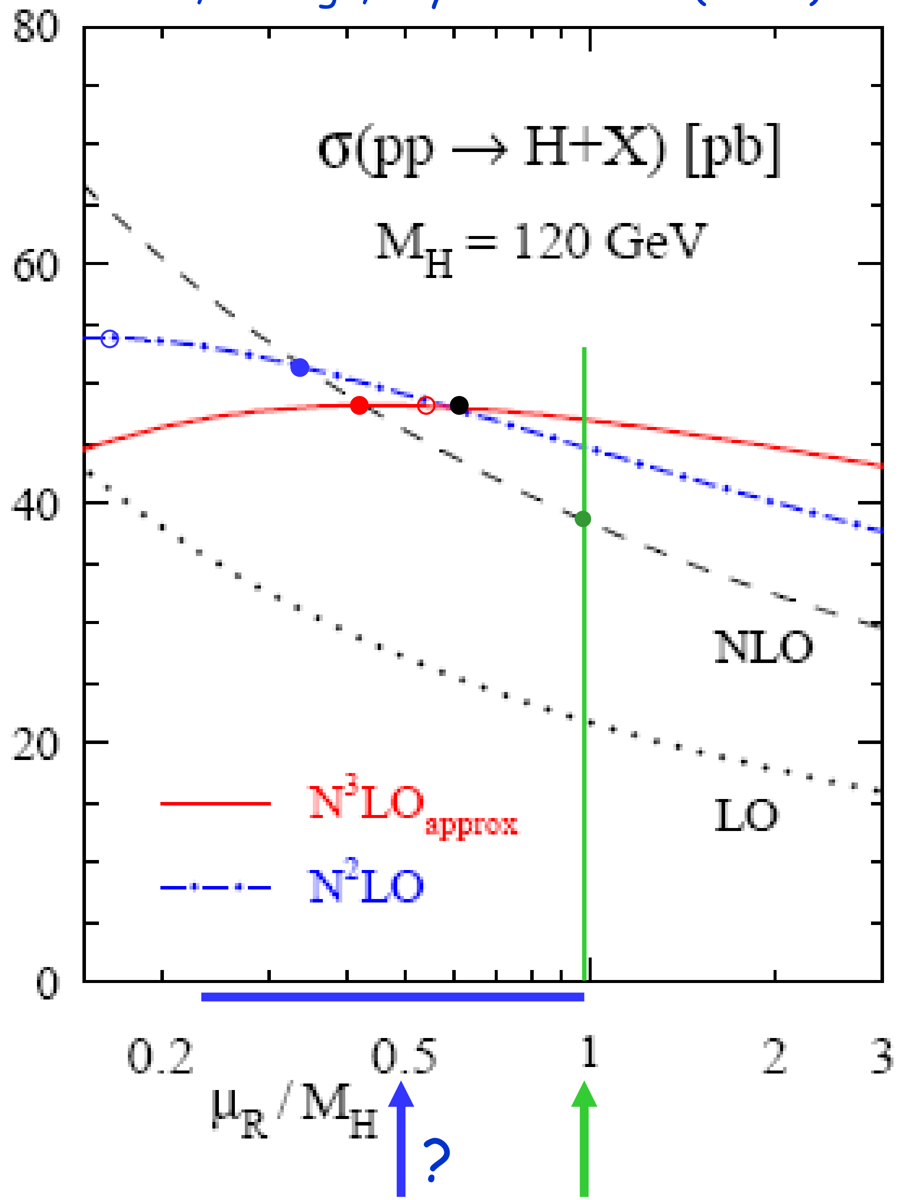


differences in forward region?
recheck: PDFs, fragmentation,
m_c, choice of scales, ...

pick as example

NLO scale choice? example: Higgs at LHC

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



in principle arbitrary, but

NNLO stability:

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

N^3LO stability:

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

— "natural" scale

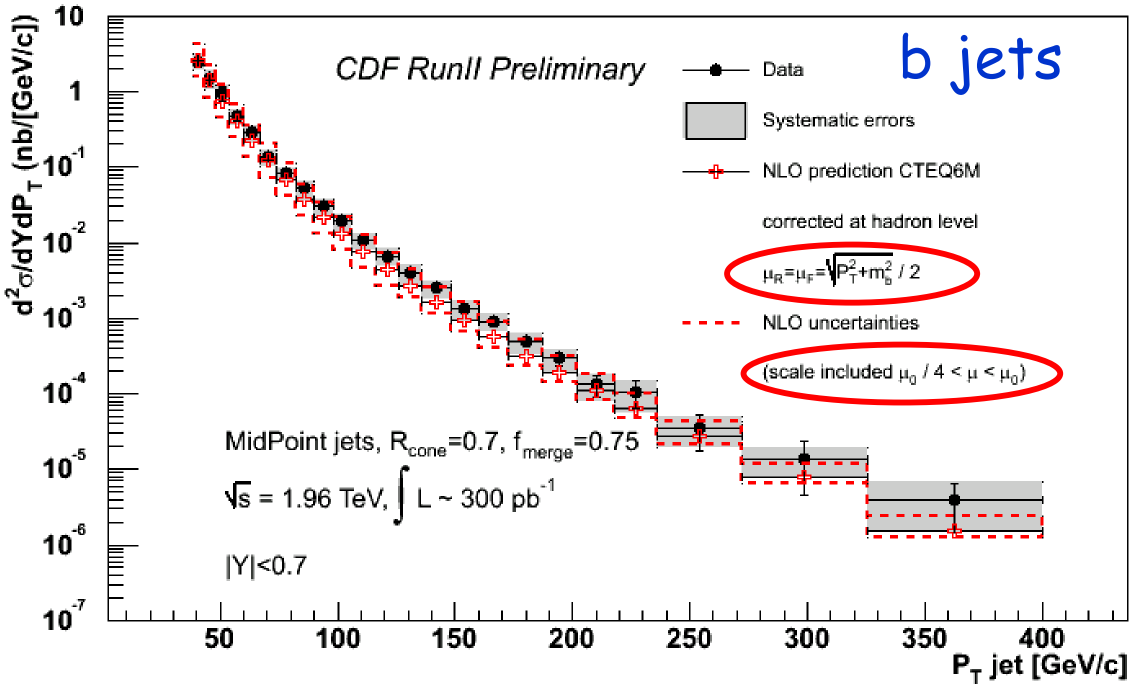
NNLO/N3LO calculations, where available, often suggest ren./fact. scale ~ half "natural" scale for NLO

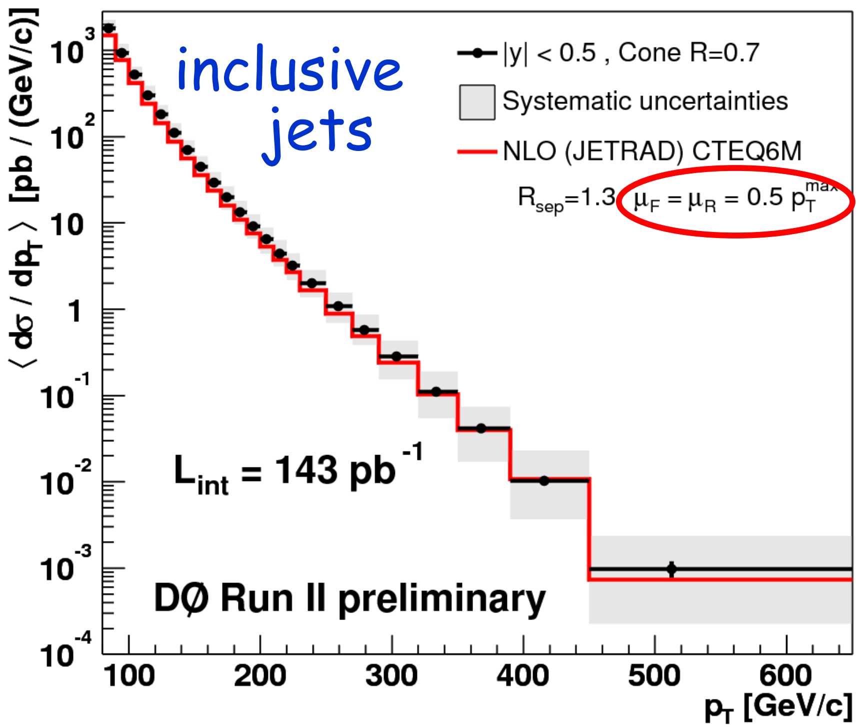
personal remark: either dedicated scale study, or

- 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:

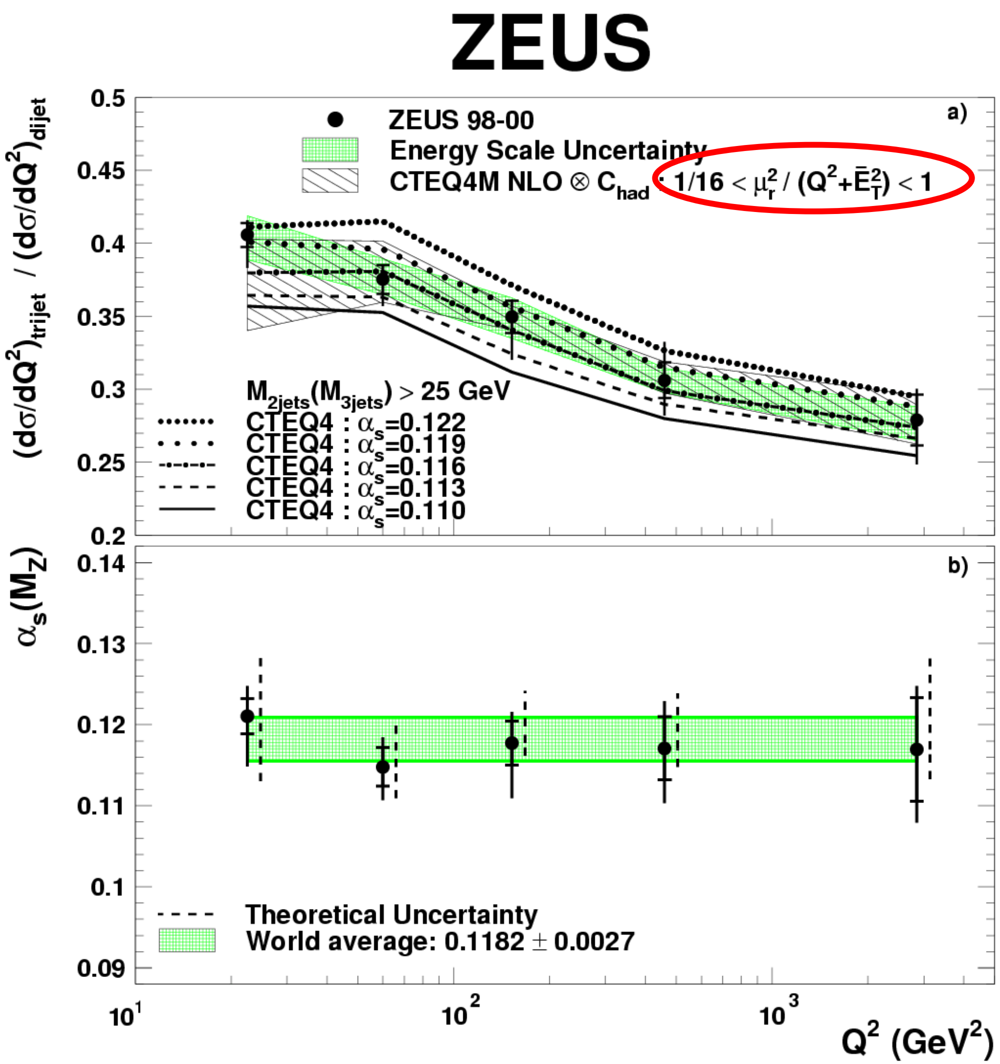




also partially at HERA (examples)

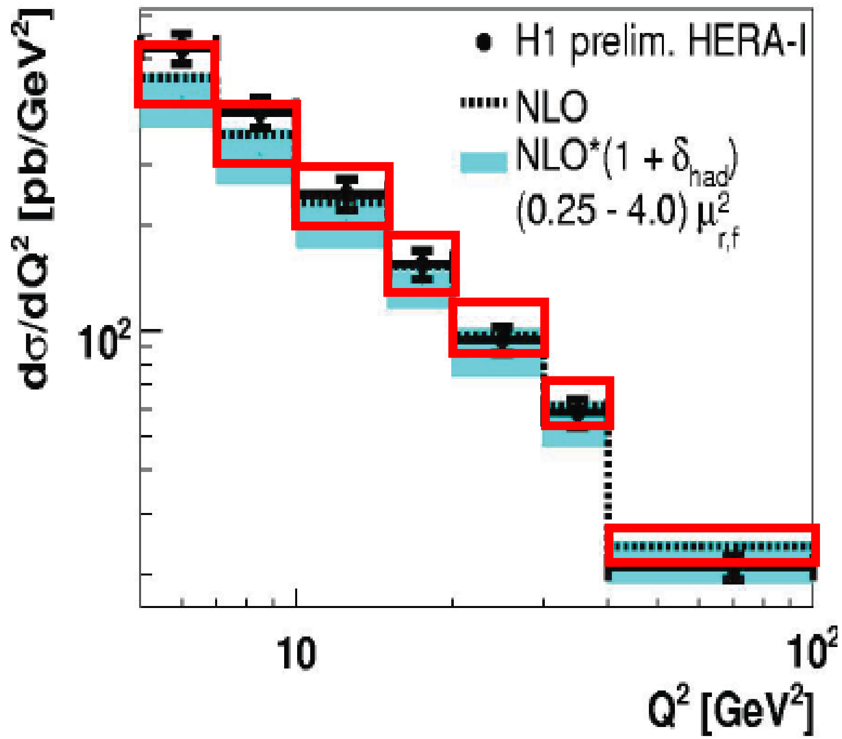
multijet-Production in DIS

new scale



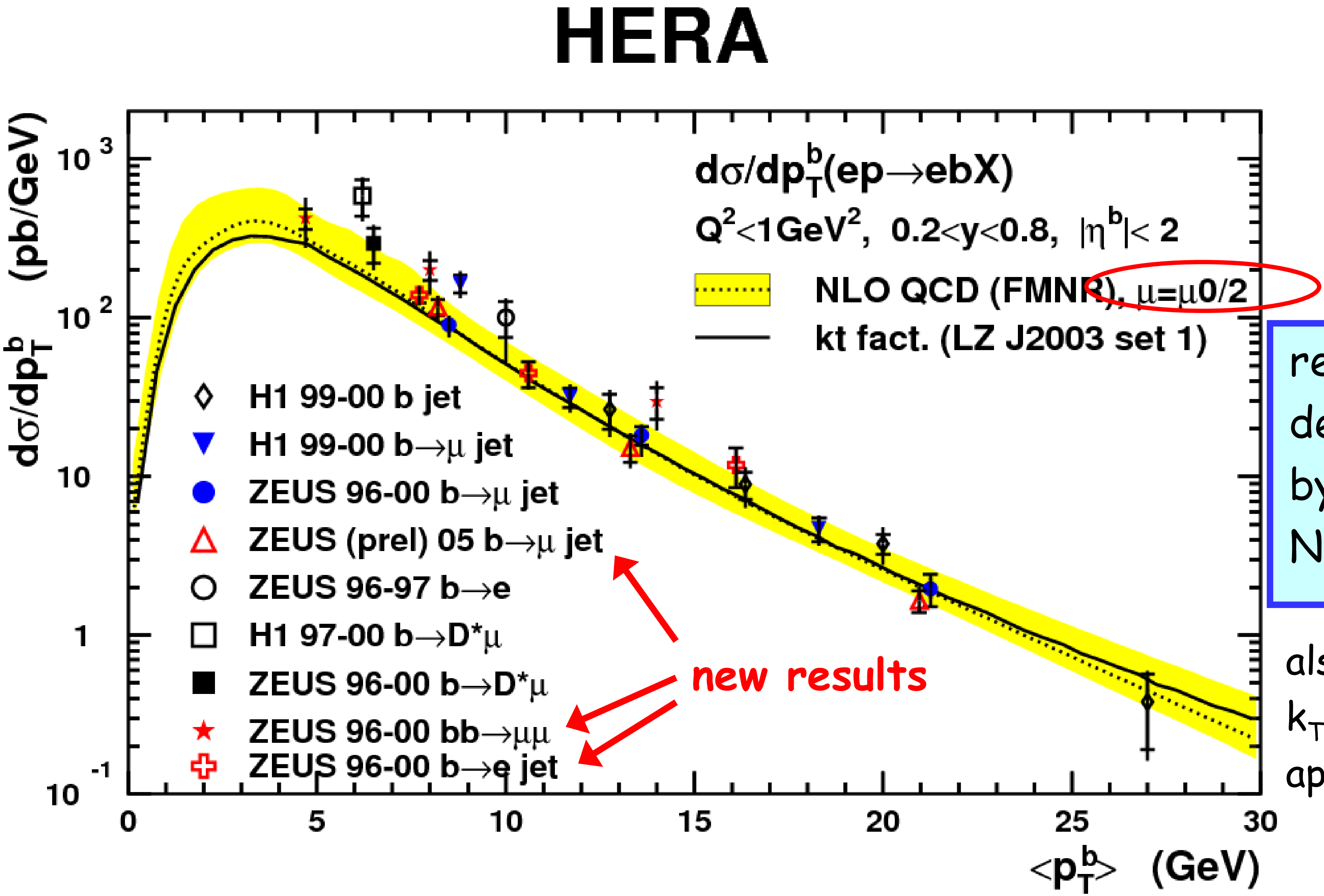
inclusive jets at low Q^2

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



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

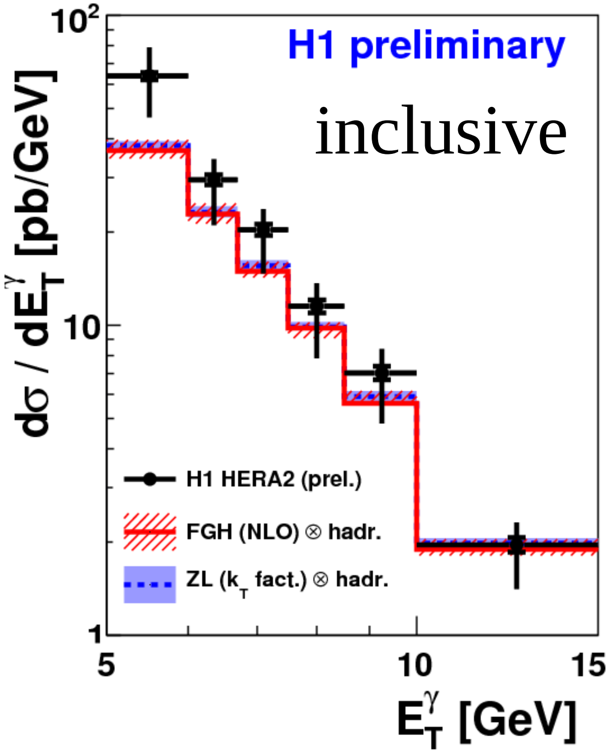
beauty at HERA

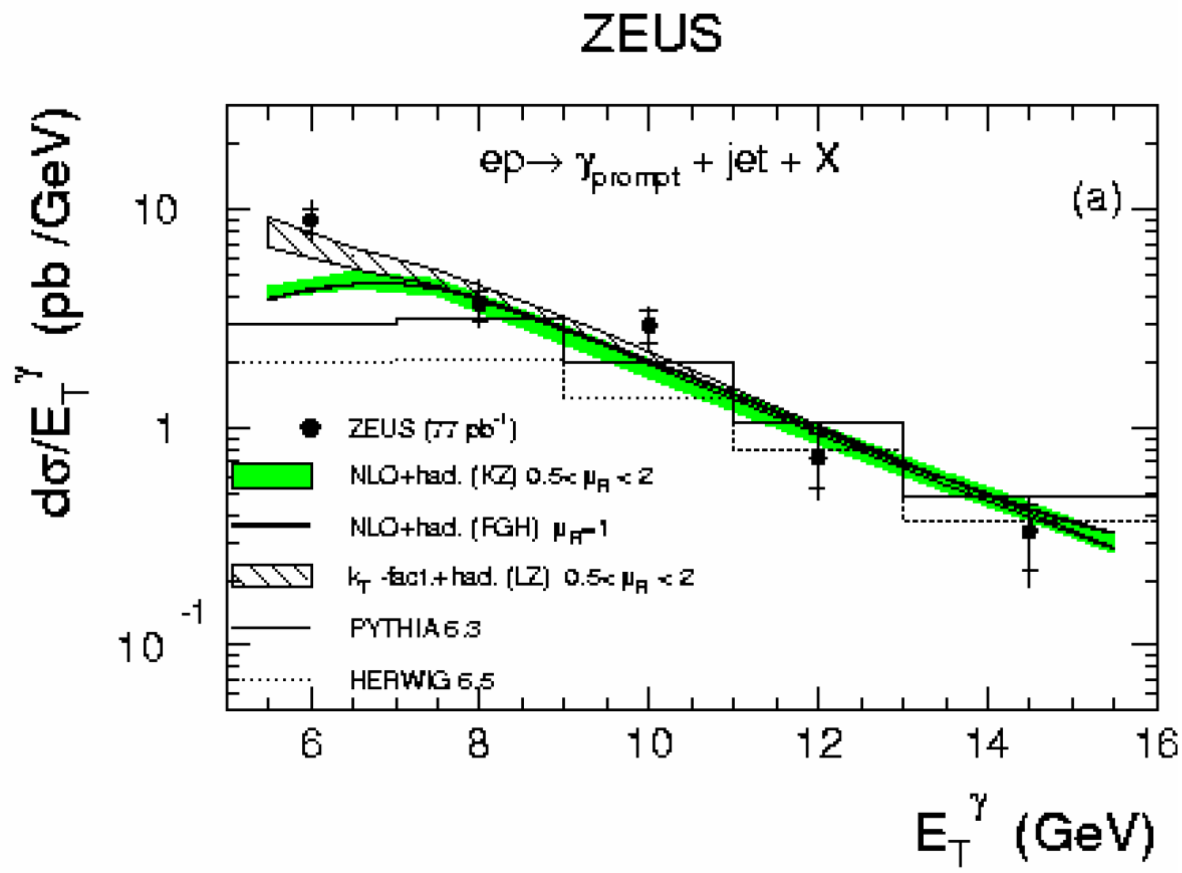


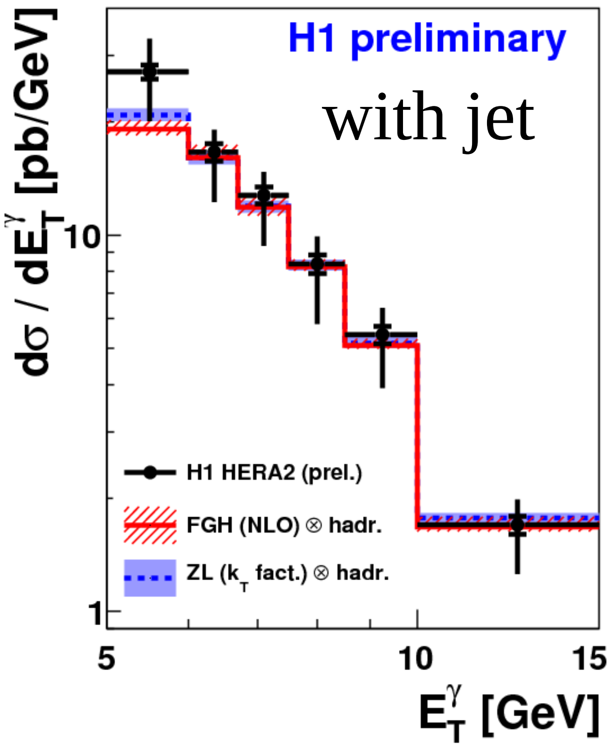
reasonably described by NLO QCD

also by k_T factoriz. approach

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!

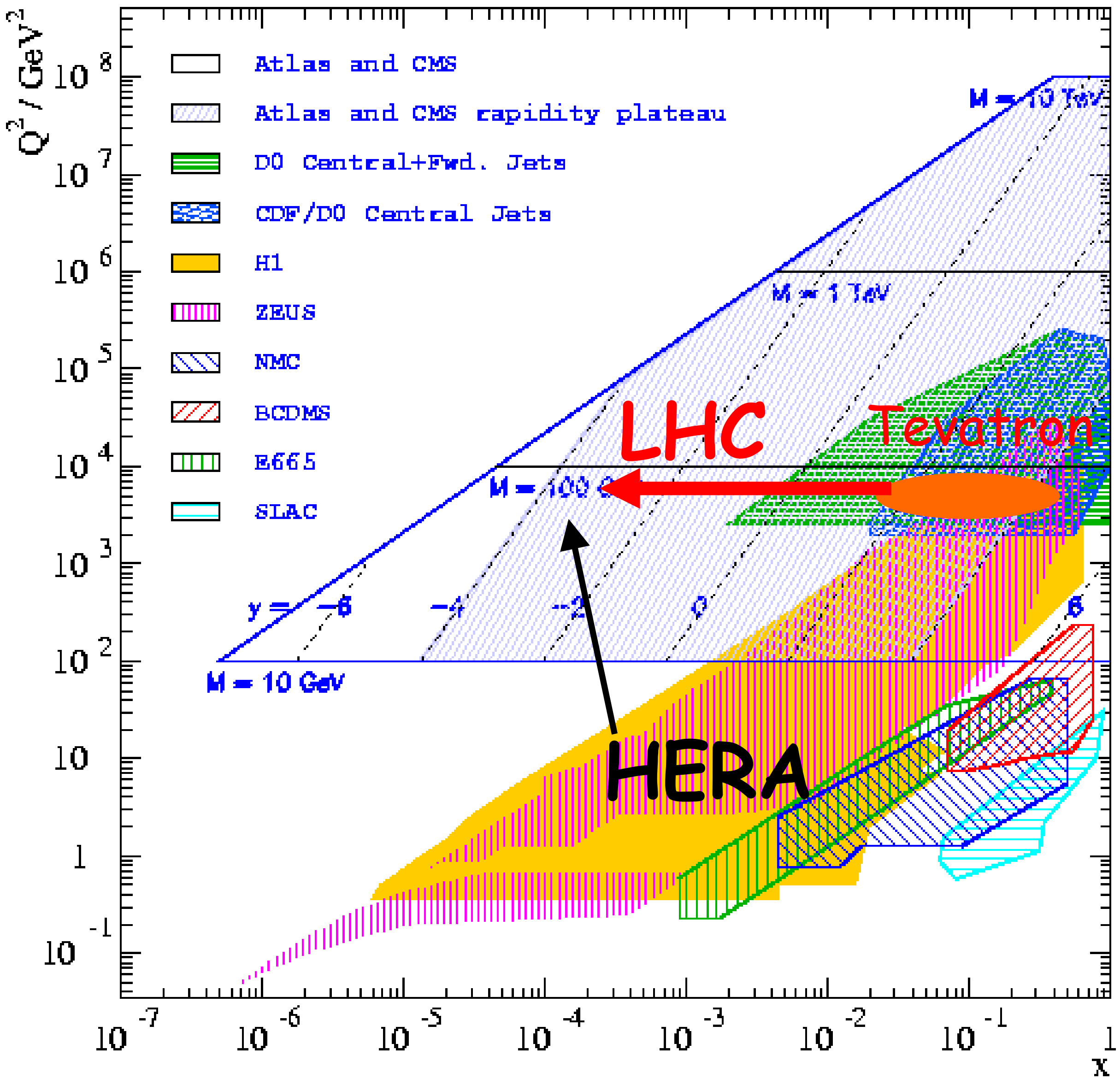
saturation

multiple interactions

BFKL vs. DGLAP

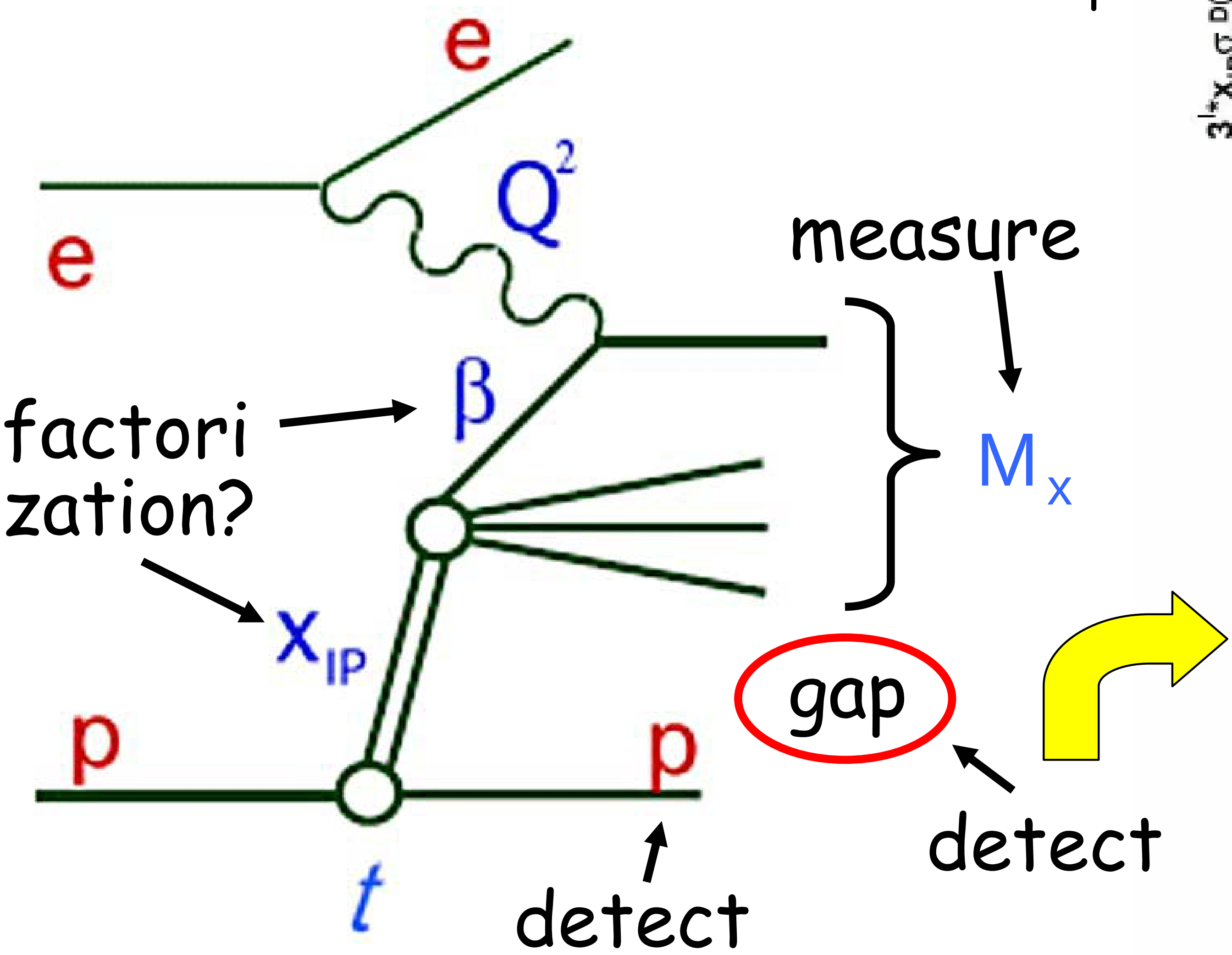
=> study at HERA

see talk C. Royon

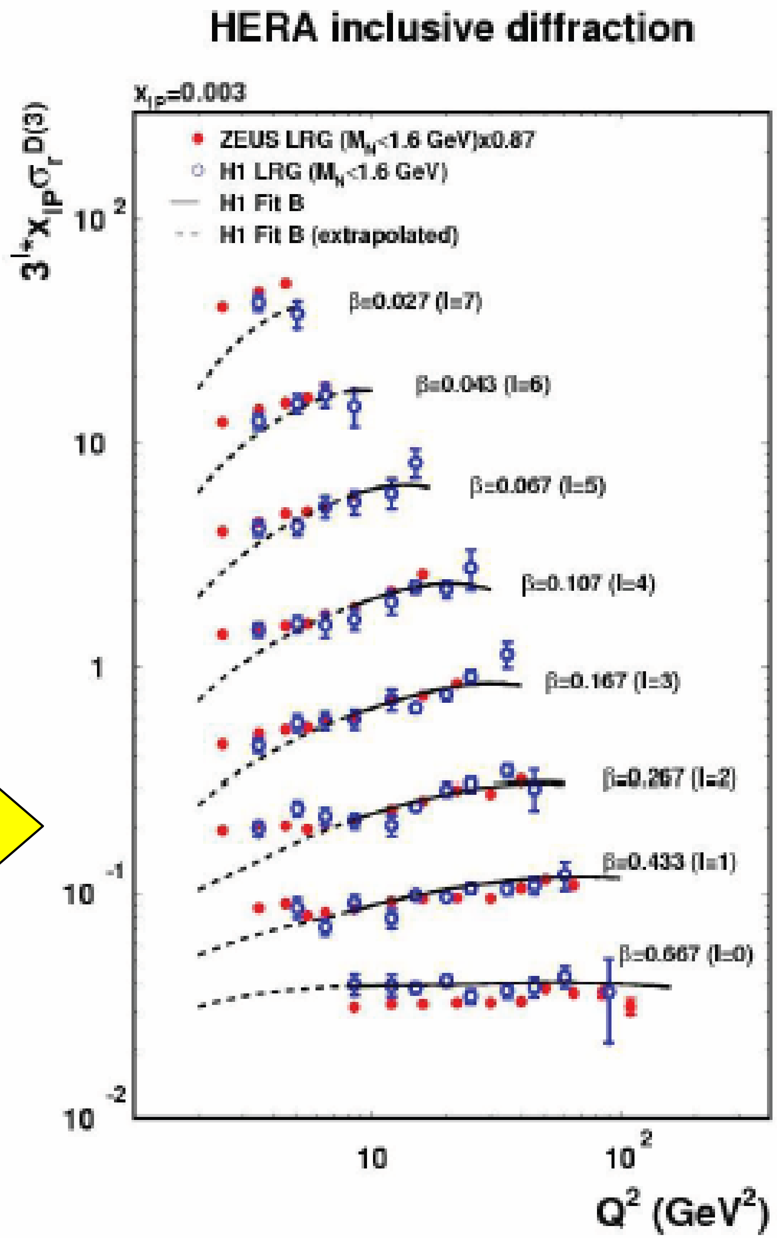


Diffractive structure functions

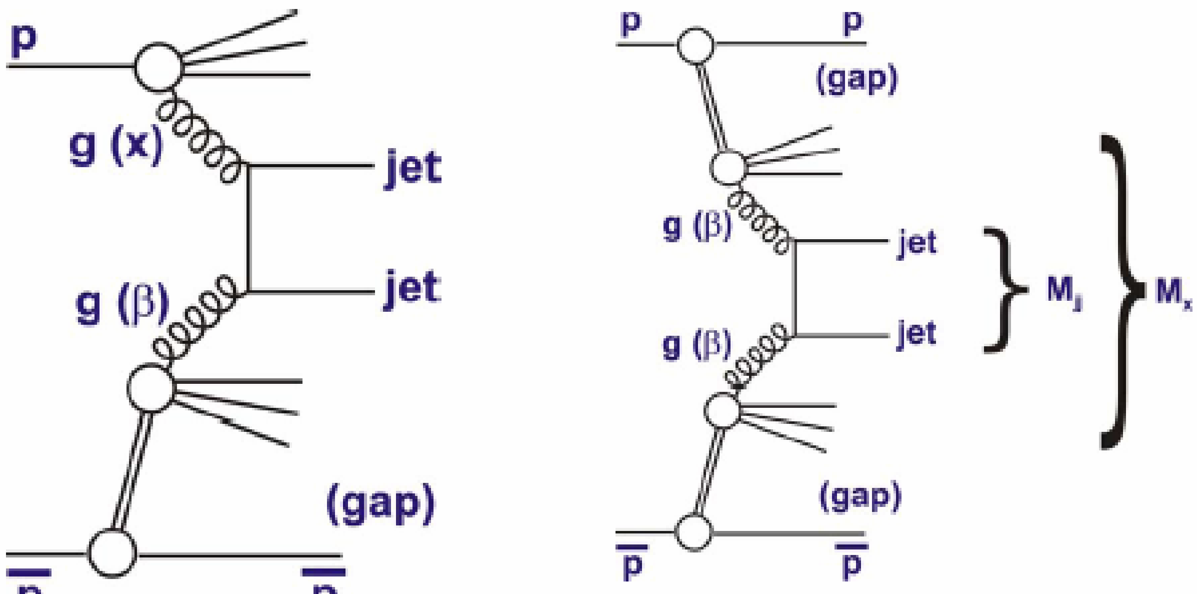
HERA:

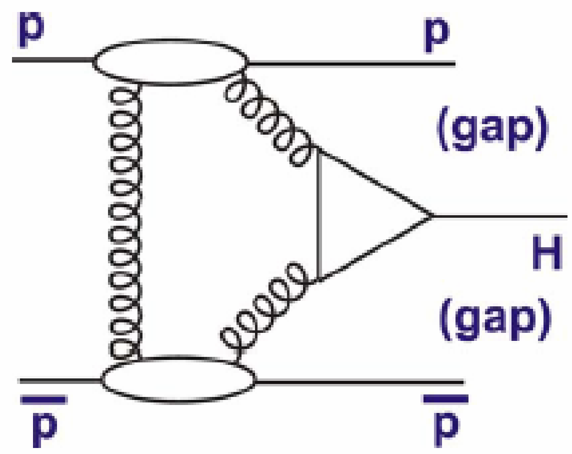


example



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!

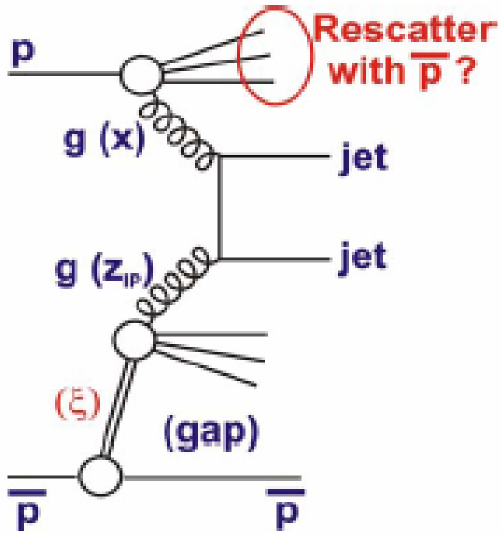
'Central Exclusive Production'

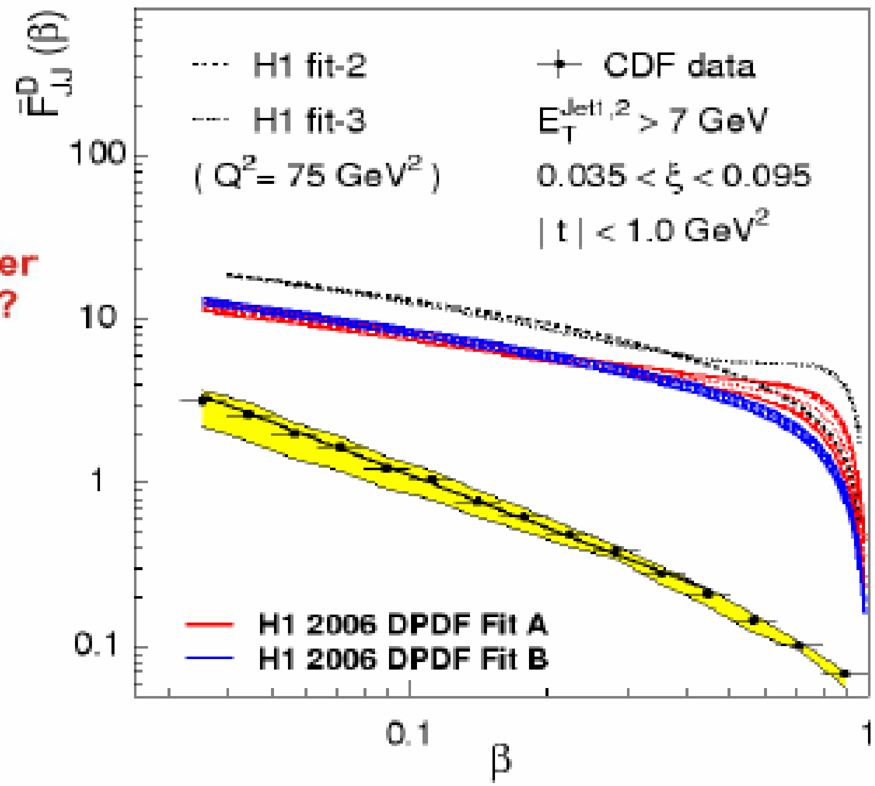
- DPDFs for backgd
- Unintegrated gluon → J/Ψ / Υ
- Gap survival models (KKMR, GLM ...)

… lots of possible input from HERA!

Meanwhile in pp(bar) ...

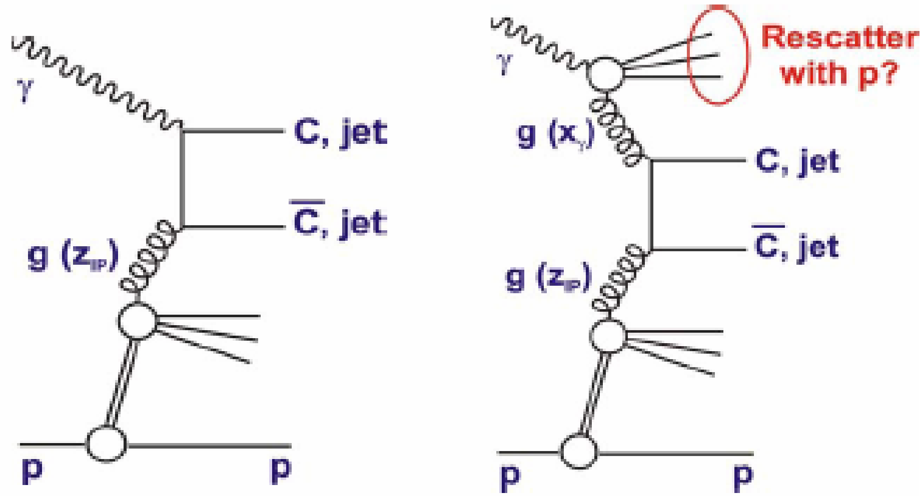
- Huge corrections when applying DPDFs: `Gap survival' factor~10



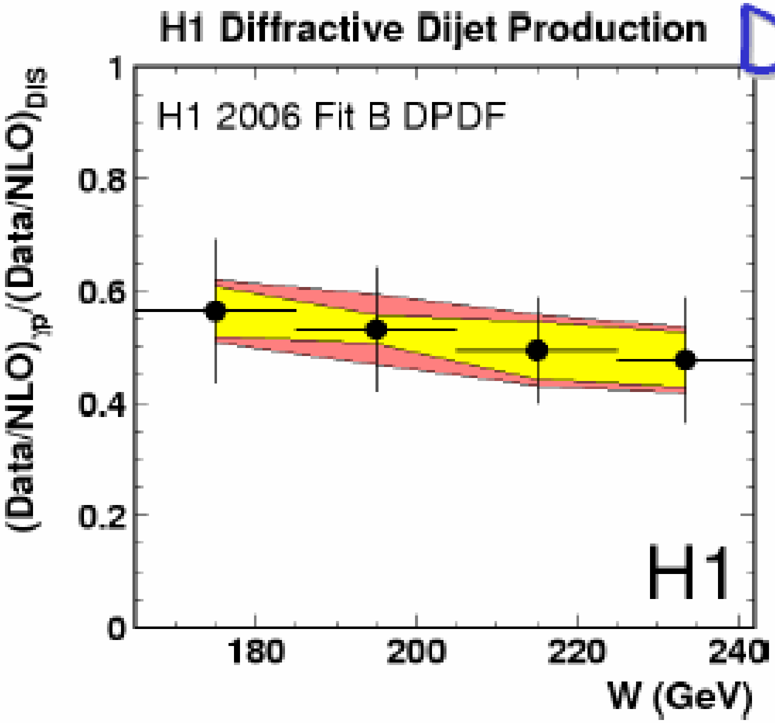


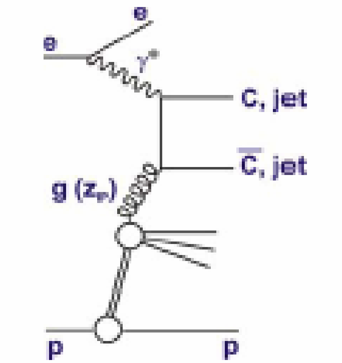
... γp as a Control Expt?

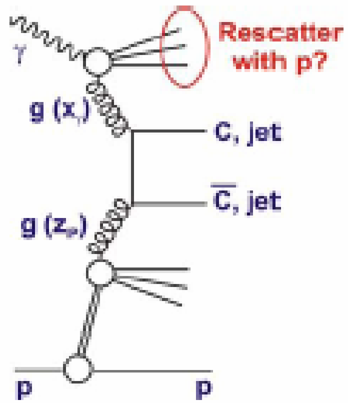
Most models predict gap survival probability ...
= 1 (direct)
< 1 (resolved ... e.g. Kaidalov, Khoze, Martin. Ryskin → ~0.34)

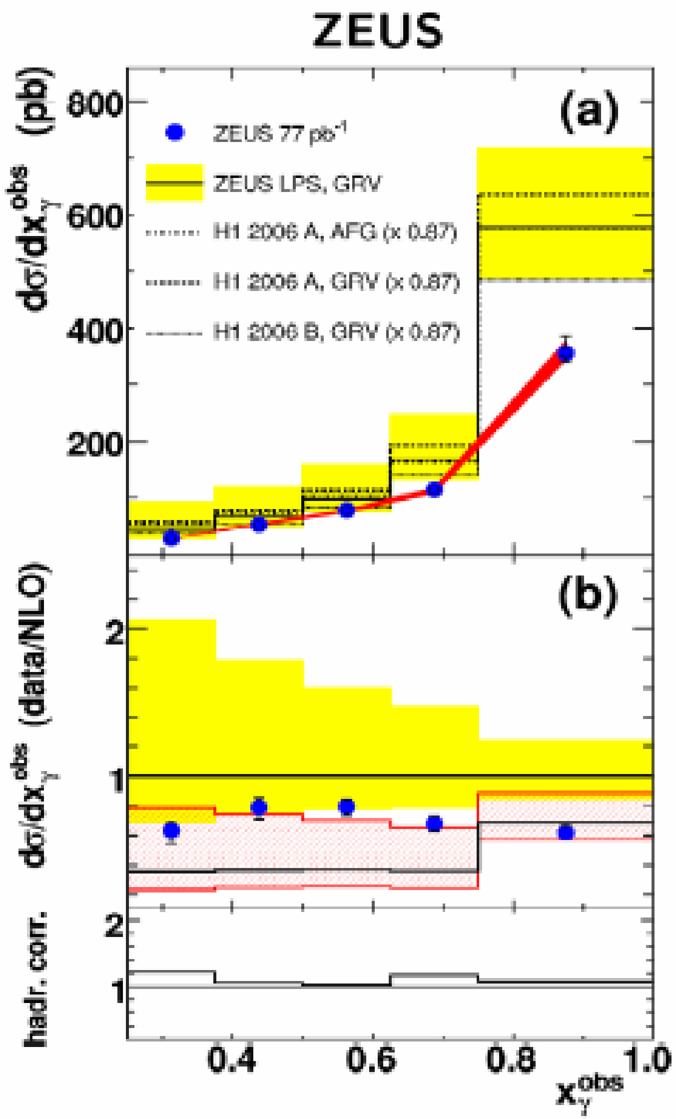


Dijet Photoprodcution:









- H1 97: $E_t^{jet1} > 5$ GeV

"Suppression by factor ~2"

- ZEUS 99-00: $E_t^{jet1} > 7.5$ GeV

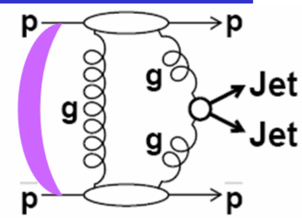
"Weaker suppression"

partially due to different E_T cuts

(Valkarova)

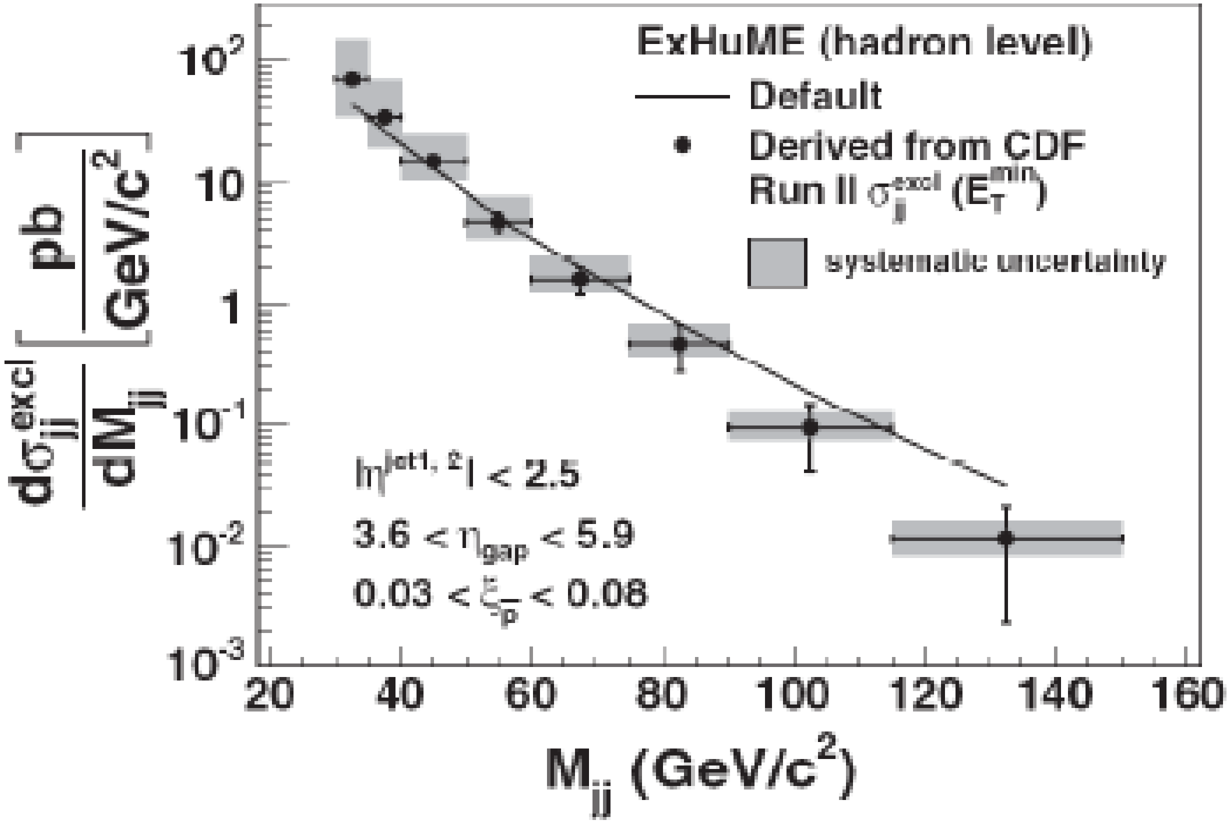
- Neither collaboration sees difference between resolved and direct regions, in contrast to theoretical expectations!

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