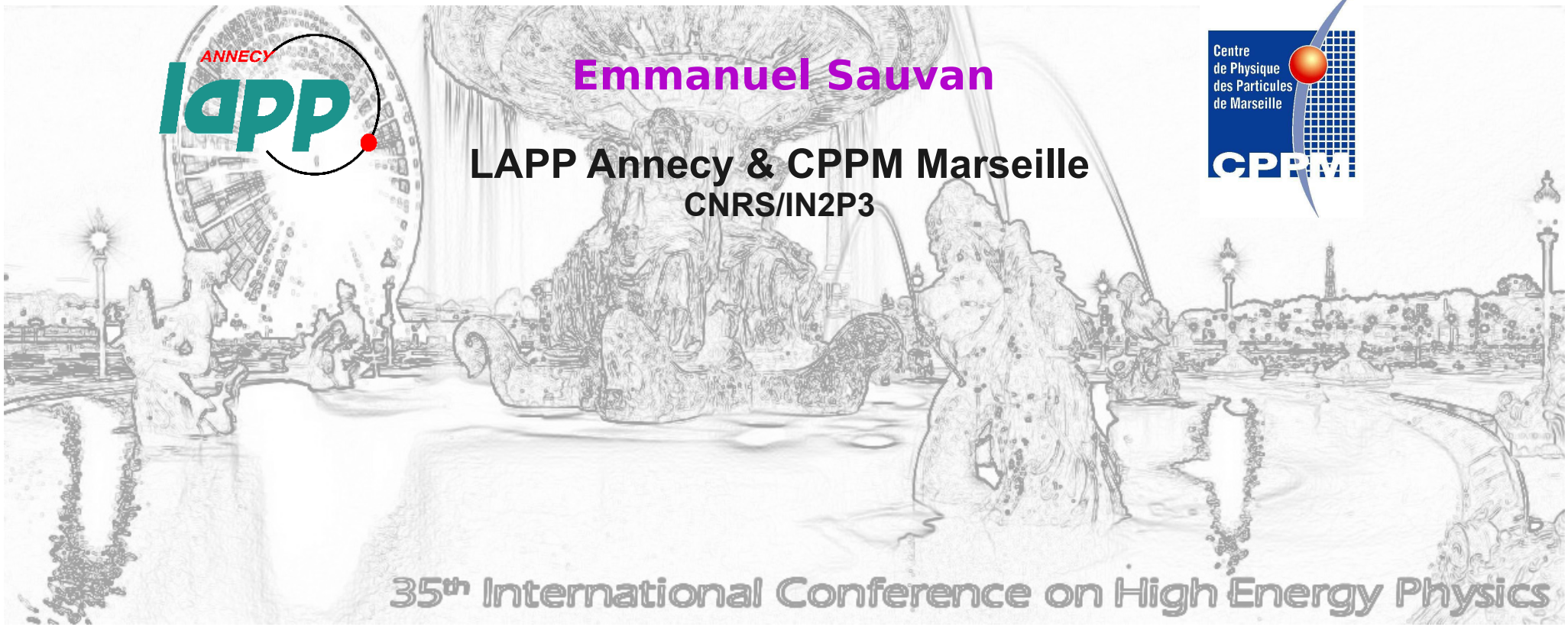
Experimental QCD Results and Impact on LHC Physics



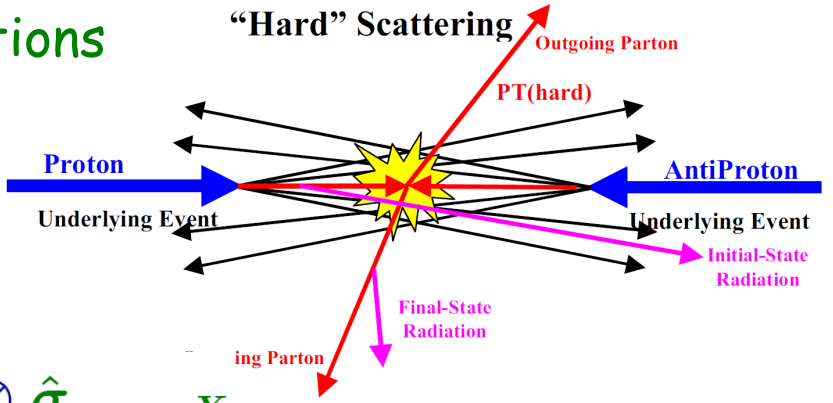
Emmanuel Sauvan

LAPP Annecy & CPPM Marseille
CNRS/IN2P3

QCD at proton Colliders

Hard process + soft (underlying) interactions

(the majority in fact …)

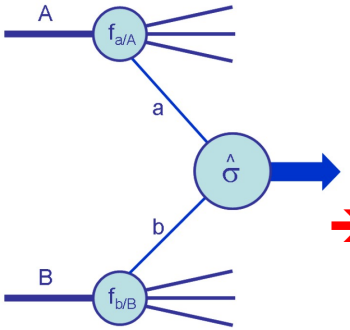


- Rely on the factorisation theorem:

$$\sigma_{pp\to X} \sim \sum_{q_i}\sum_{q_j} f_{q_i}(x,Q^2)\, f_{q_j}(x,Q^2) \otimes \hat{\sigma}_{q_i q_j \to X}$$

Soft QCD, non-perturbative (PDFs)

Hard cross section, perturbative

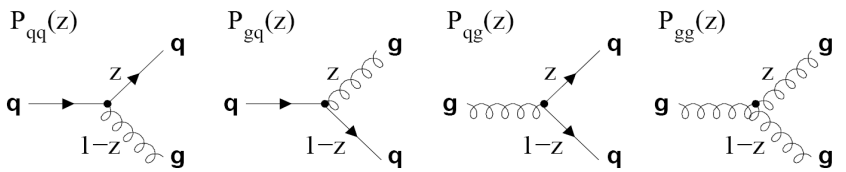


➔ Proton structure described by Parton Density Functions

↘ Need to be measured

↘ Validity and precision of existing pQCD calculations ?

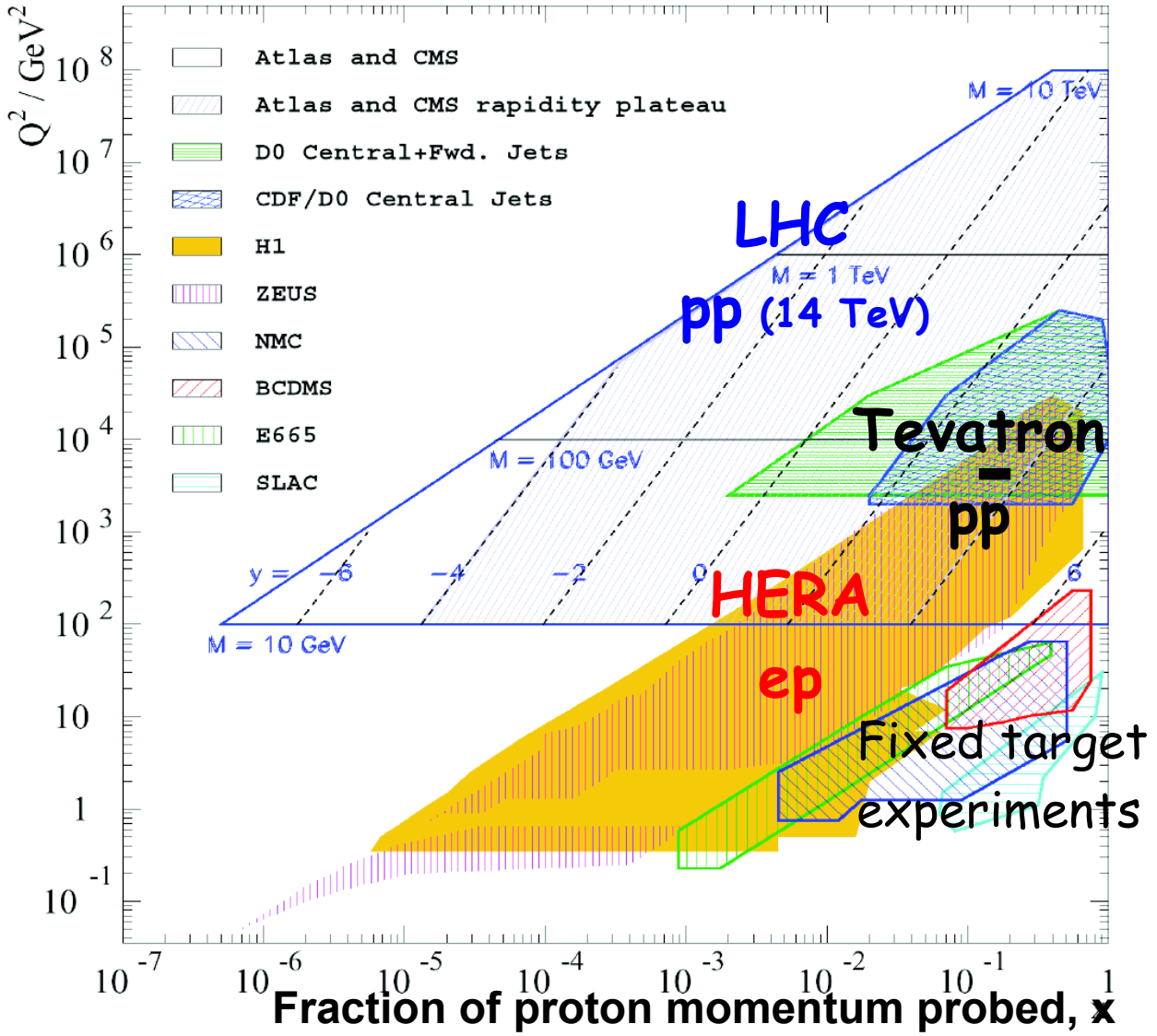
➔ But the evolution of f(x) with Q^2 is described by perturbative QCD: DGLAP equations

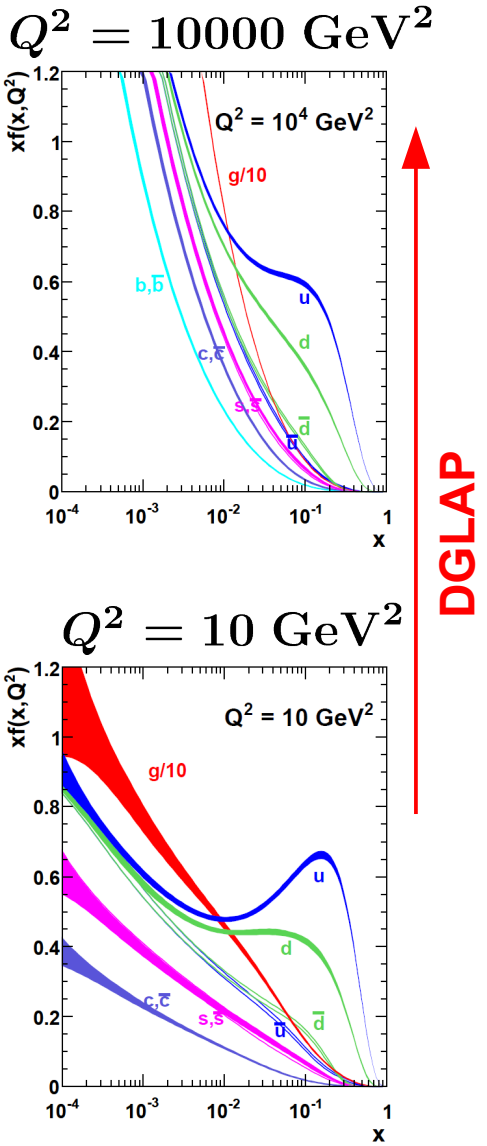


↘ Is DGLAP always valid ? (BFKL at lower x ?)

Probing the proton

Scale of the probe, Q^2

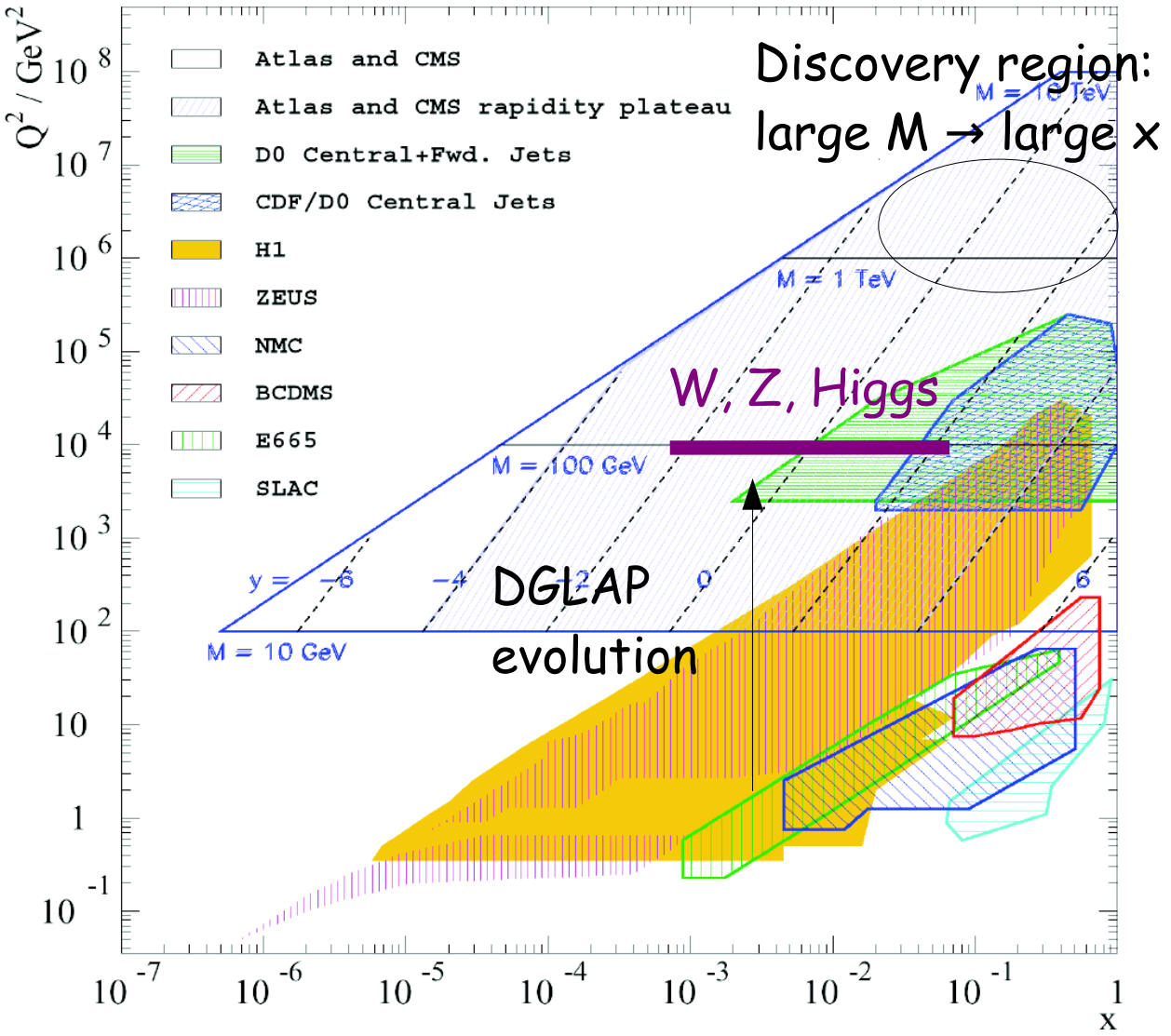




↘ Gluon and sea: QCD dynamics

[MSTW08 PDFs, G. Watt]

Proton structure for the LHC



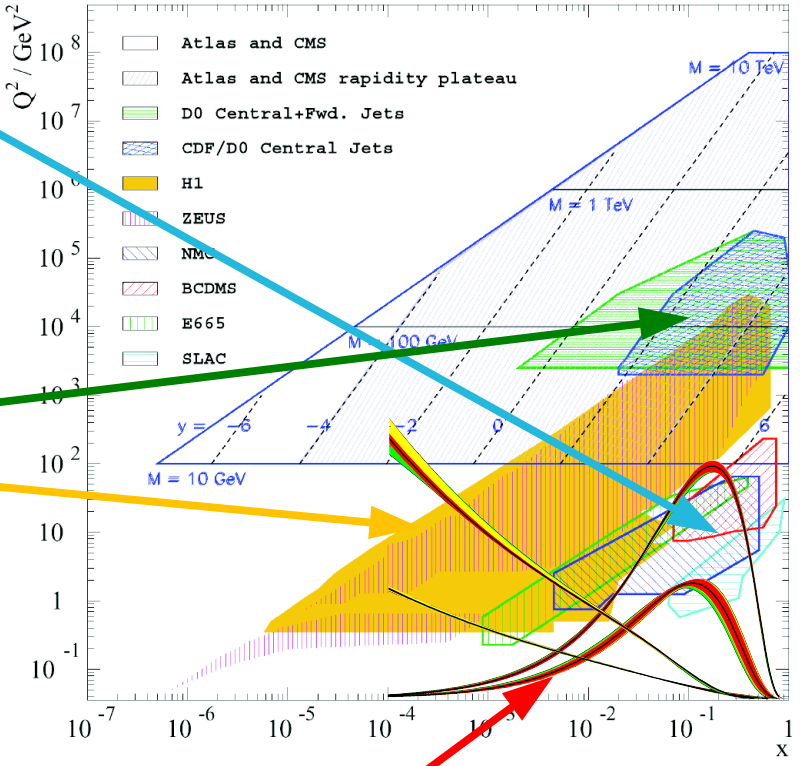
- Good knowledge of PDFs at large x is also important
  - ➔ Avoid "fake" discoveries
- Main SM processes at medium x ($\sim 5\ 10^{-4} < x < \sim 5\ 10^{-2}$)
  - ➔ Dominance of gluon and sea quark scattering at LHC

↘ Knowledge of the gluon is important for LHC physics

- LHC – HERA: same x-range, factor 100-1000 in Q^2

Experimental informations on PDFs

Process	Experiments	Partons
DIS Fixed target	BCDMS, NMC, E665, SLAC	q, g
DIS $\nu - N$	NuTeV, CHORUS, CCFR	q, s
pp, pN Drell Yan	E605, E772, E866/NuSea	q, g at high x
W, Z in $p\bar{p}$ collisions	CDF, D0	$d, u, d/u$ at medium x
DIS collisions	HERA	q, g
Jets in ep collisions	HERA	g, q
Jets in $p\bar{p}$ collisions	CDF, DO	g, q at high x
F_L in DIS	HERA	g
$c\bar{c}$ in ep collisions	HERA	g, c
$b\bar{b}$ in ep collisions	HERA	g, b



- Global fits: PDFs determination using available data sets

➔ Different extractions, based on different data sets

➔ Differences in theoretical treatments (α_s, heavy flavours, ...)

➔ "Global": MSTW, CTEQ, NNPDF

➔ DIS + DY: AKP, JR

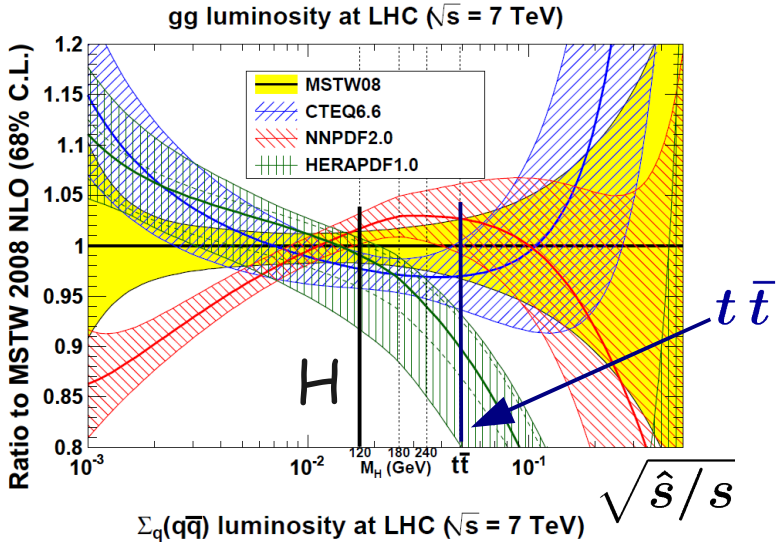
➔ HERA only: HERAPDF

The proton at the LHC

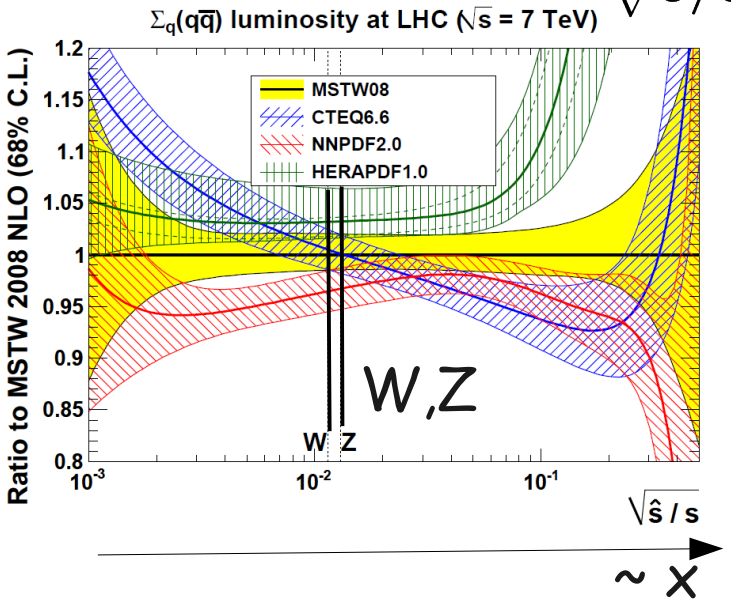
[G. Watt, A.M. Cooper-Sarkar]

- Partonic luminosities from different PDFs:

gg

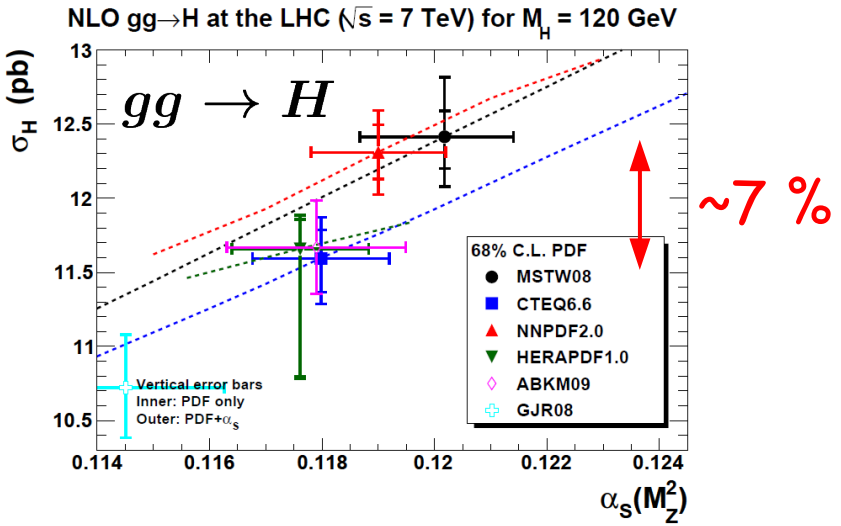


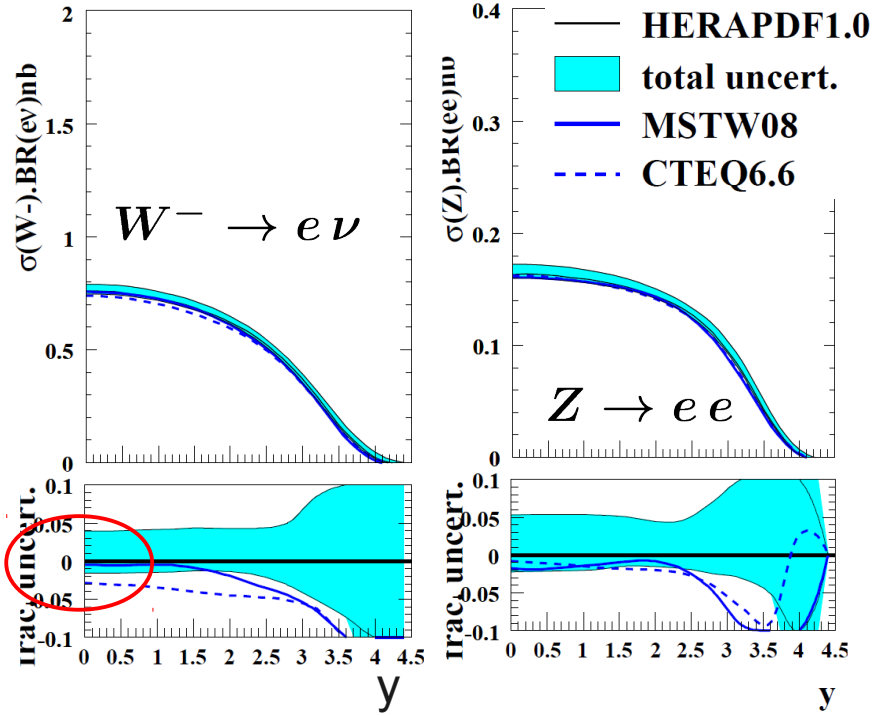
qq



~3-5 %

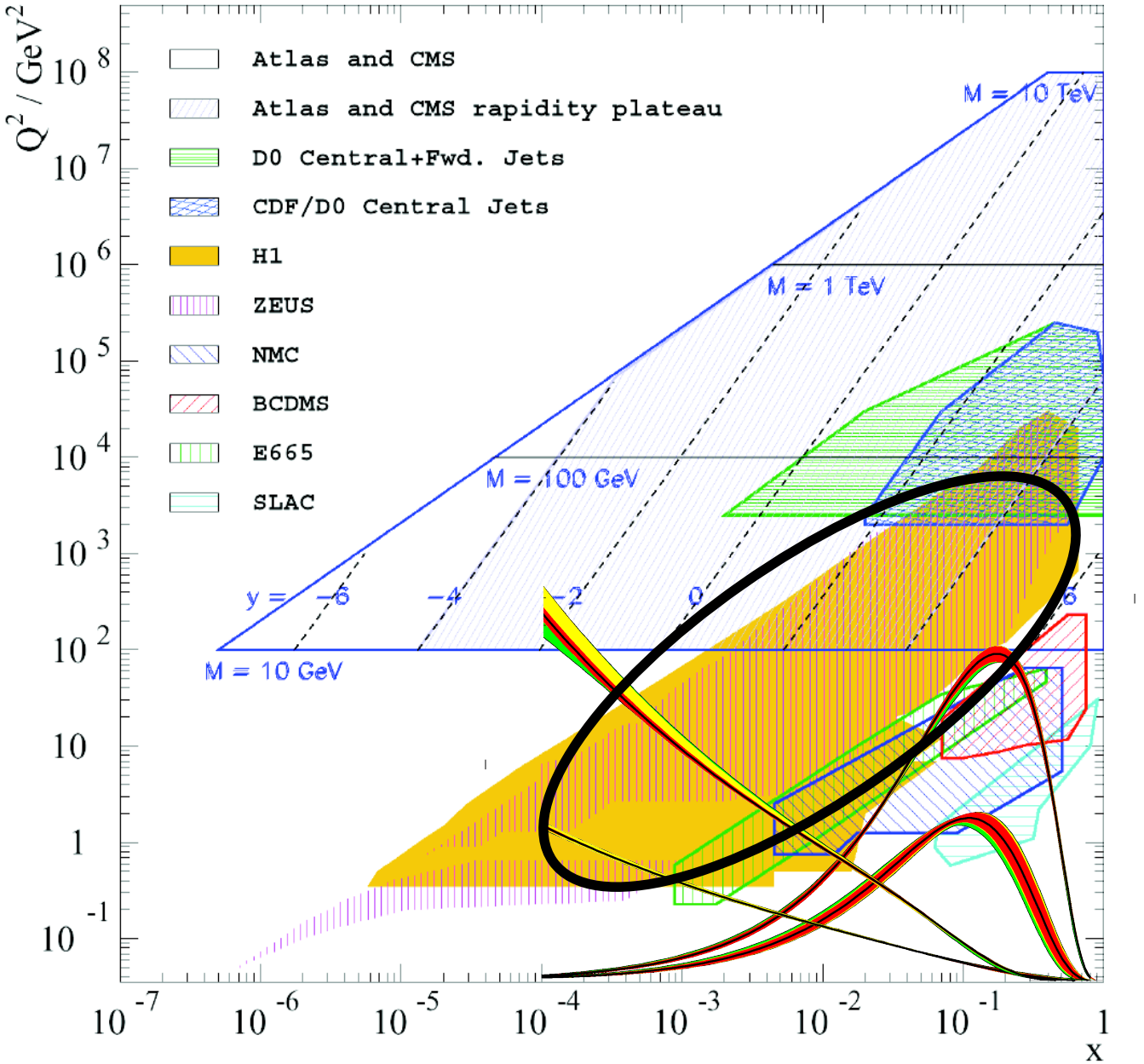
- Cross sections:





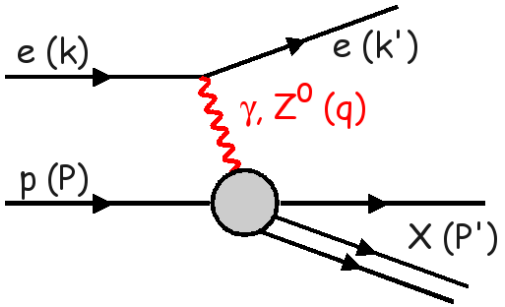
↘ Inputs of new data will help

Spine of PDF determinations: HERA



Spine of PDF determinations: HERA

- Neutral Currents (NC):



$$\sigma^{\pm}_{r,NC} = \frac{\mathrm{d}^2\sigma^{e^{\pm}p}_{NC}}{\mathrm{d}x\mathrm{d}Q^2}\frac{xQ^2}{2\pi\alpha^2 Y_+} = F_2 - \frac{y^2}{Y_+}F_L \mp \frac{Y_-}{Y_+}xF_3$$

$$y = \frac{Q^2}{xs}\ \text{(Inelasticity)} \qquad Y_{\pm} = 1 \pm (1-y)^2$$

(at LO)

$$\left[F_2^{\gamma}, F_2^{\gamma Z}, F_2^{Z}\right] = x\sum_i \left[e_{q_i}^2, 2e_{q_i}v_{q_i}, v_{q_i}^2 + a_{q_i}^2\right] (q_i + \bar{q}_i)$$

↘ F_2: quarks

$$\left[xF_3^{\gamma Z}, xF_3^{Z}\right] = 2x\sum_i \left[e_{q_i}a_{q_i}, v_{q_i}a_{q_i}\right] (q_i - \bar{q}_i)$$

↘ F_3: valence quarks

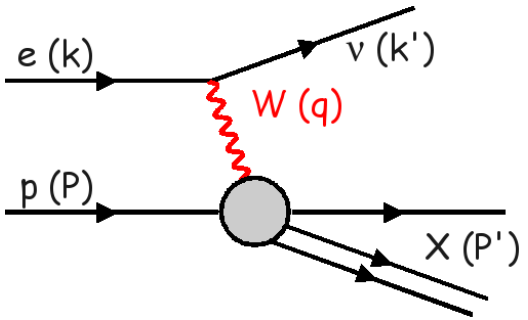
(beyond LO)

$$\partial F_2/\partial \ln Q^2 \sim \alpha_s \cdot xg$$

(scaling violations)

↘ Gluon density

- Charged Currents (CC):



$$\sigma_{CC}(e^+p) \propto x\left[(1-y^2)(d+s) + (\bar{u}+\bar{c})\right]$$

$$\sigma_{CC}(e^-p) \propto x\left[(u+c) + (1-y^2)(\bar{d}+\bar{s})\right]$$

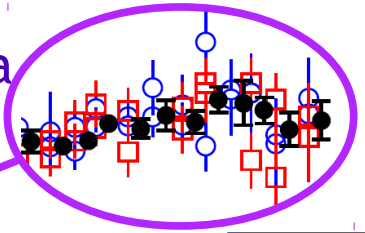
➔ e^+p most sensitive to d

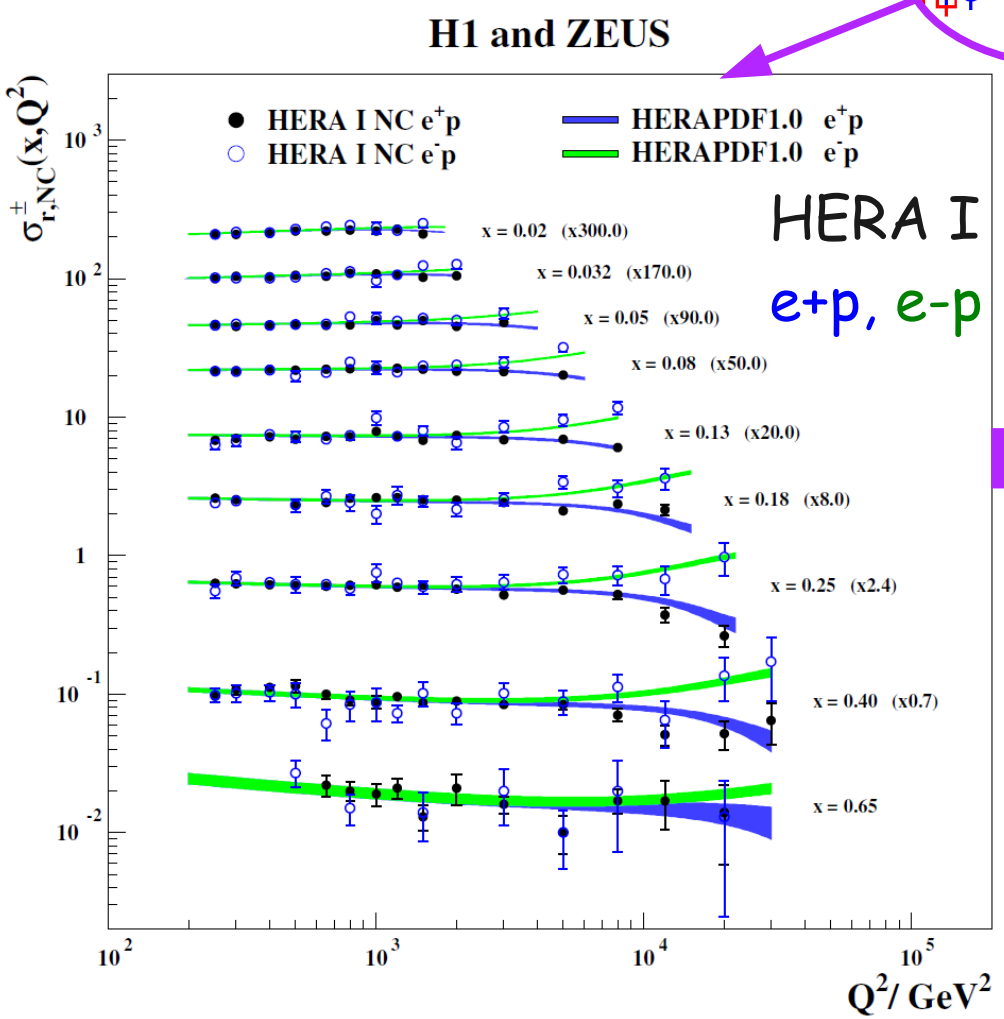
➔ e^-p most sensitive to u

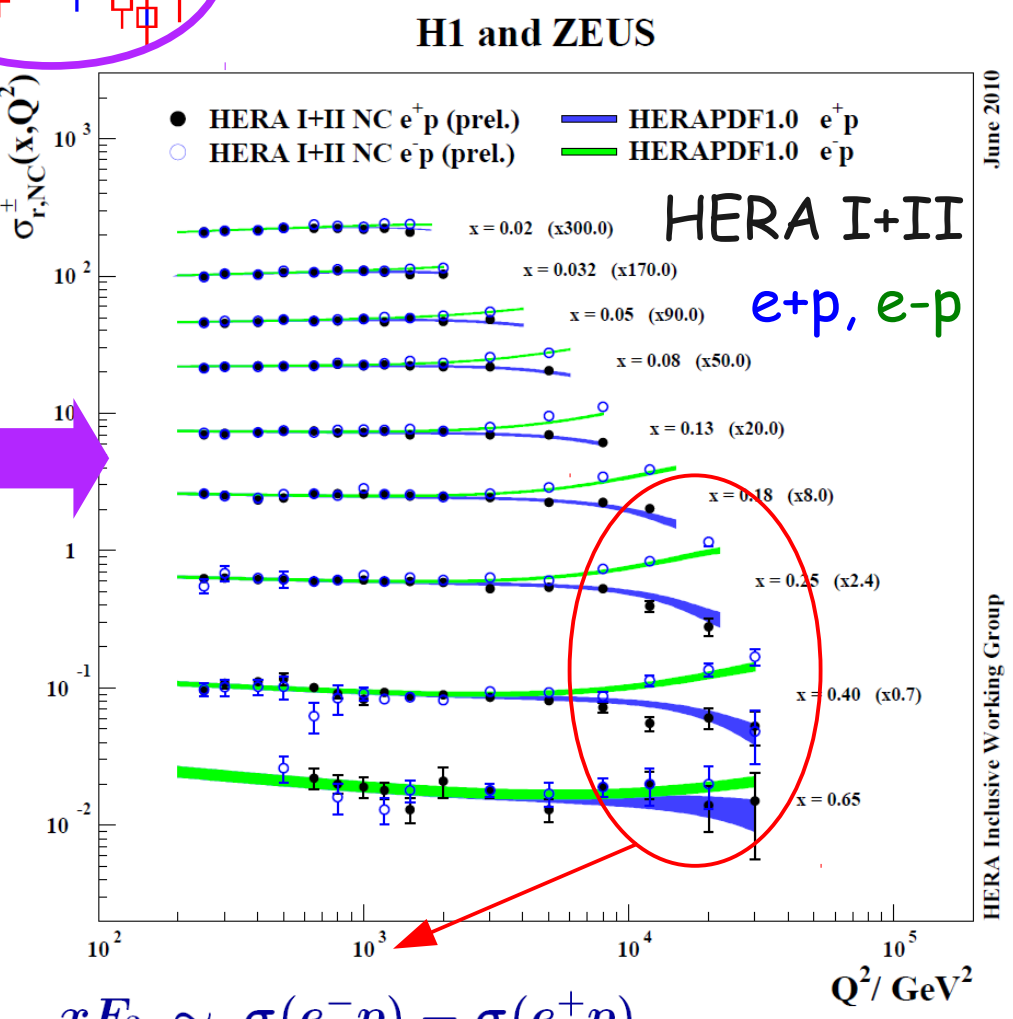
↘ Quark flavour separation

HERA NC: towards final precision

- Combination of H1 and ZEUS data







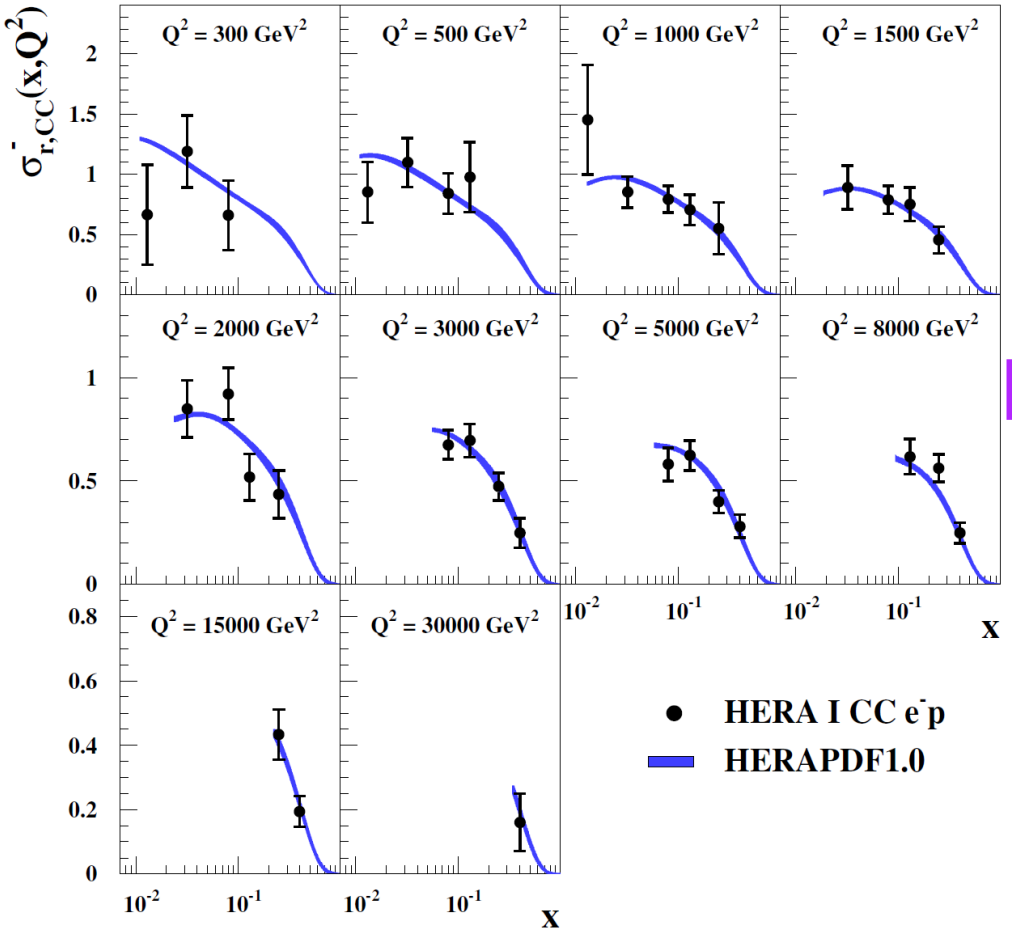
$$xF_3 \sim \sigma(e^-p) - \sigma(e^+p)$$
$$\sim (2u_v + d_v)$$

↘ Increased constraints on valence quarks from HERA data alone

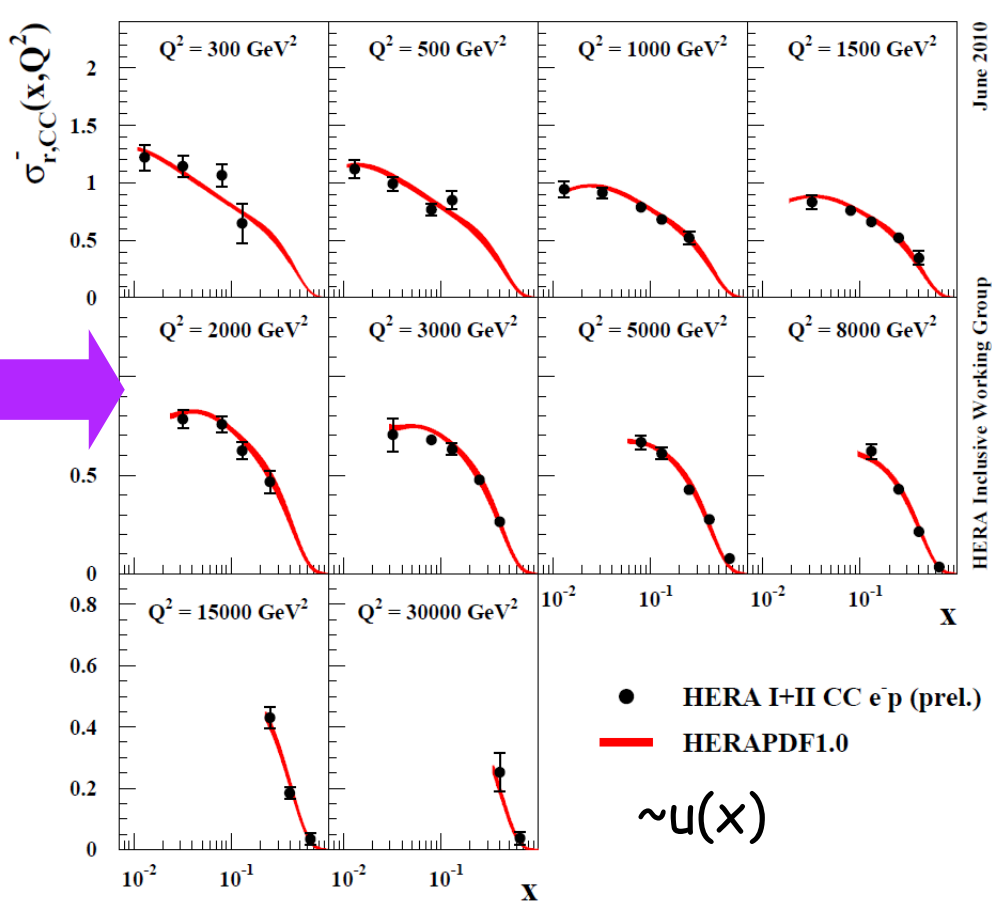
HERA CC: towards final precision

➔ Statistical precision also improved for CC's

CC, e-p HERA I



CC, e-p HERA I+II



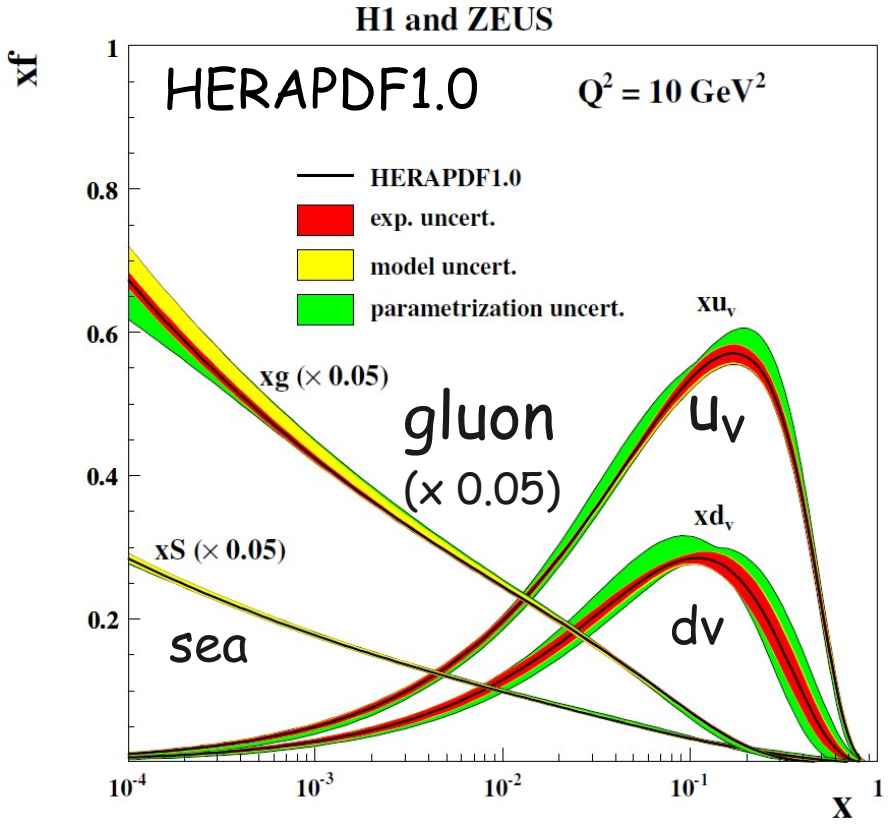
~u(x)

➔ Improves u/d separation

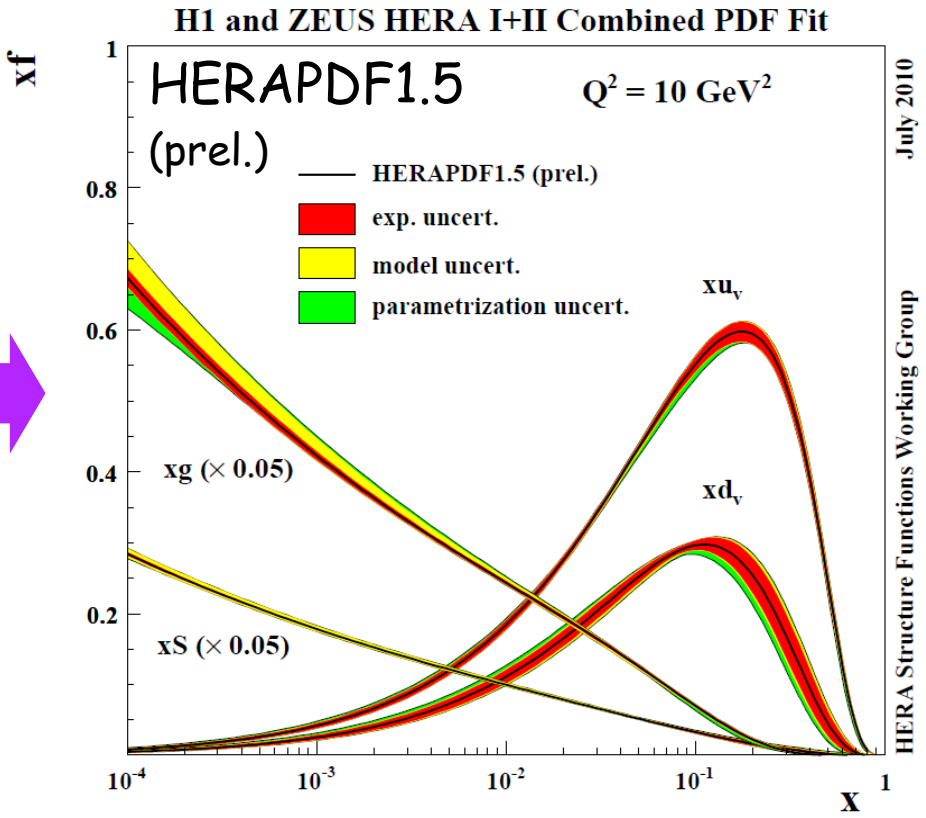
PDF determination from HERA alone

➔ HERA data are enough to determine PDFs of good precision

- HERA I combined data



- Including HERA II



- Advantage: controlled systematics
  - ➔ Errors estimated using $\Delta\chi^2 = 1$
  - ➔ Parametrisation error addressed

➔ Errors reduced at high x, mainly visible on valence distributions

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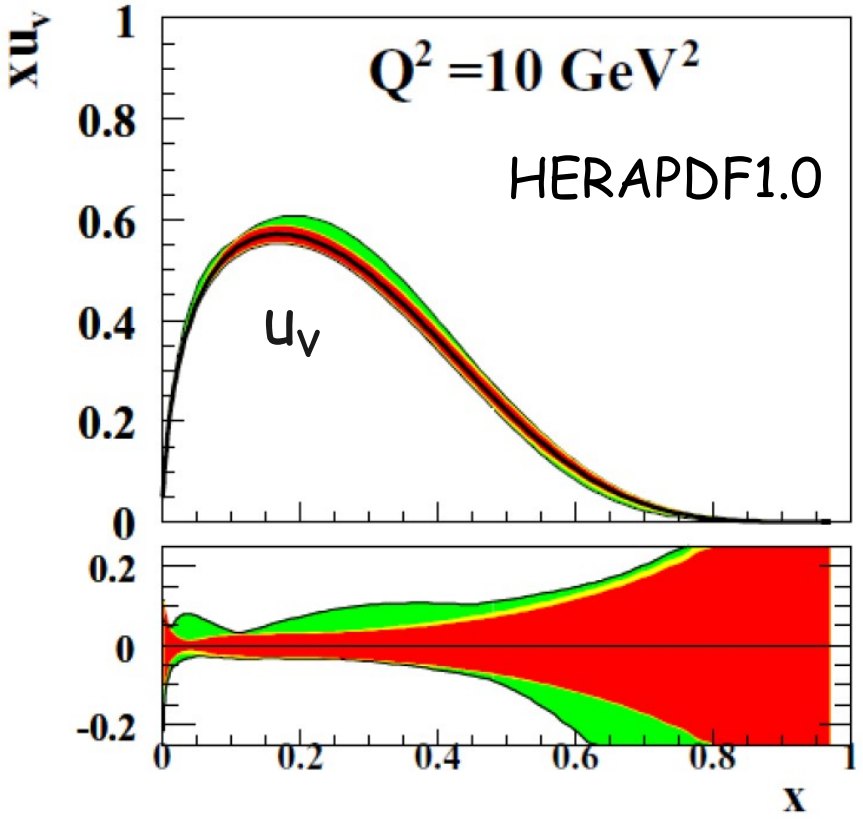

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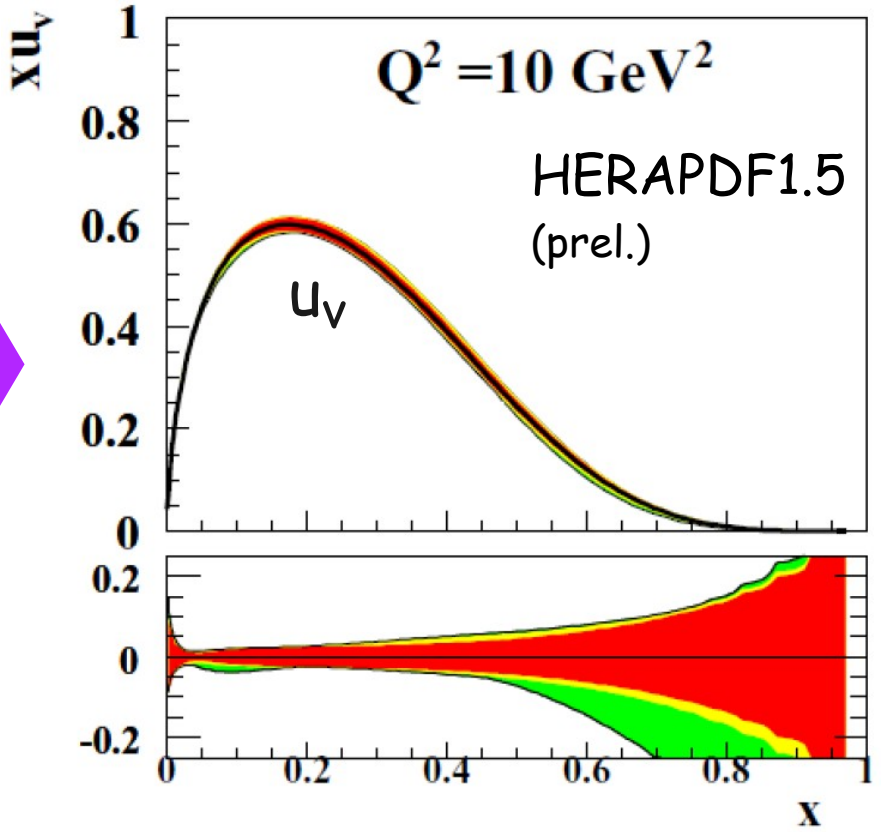

- Advantage: controlled systematics

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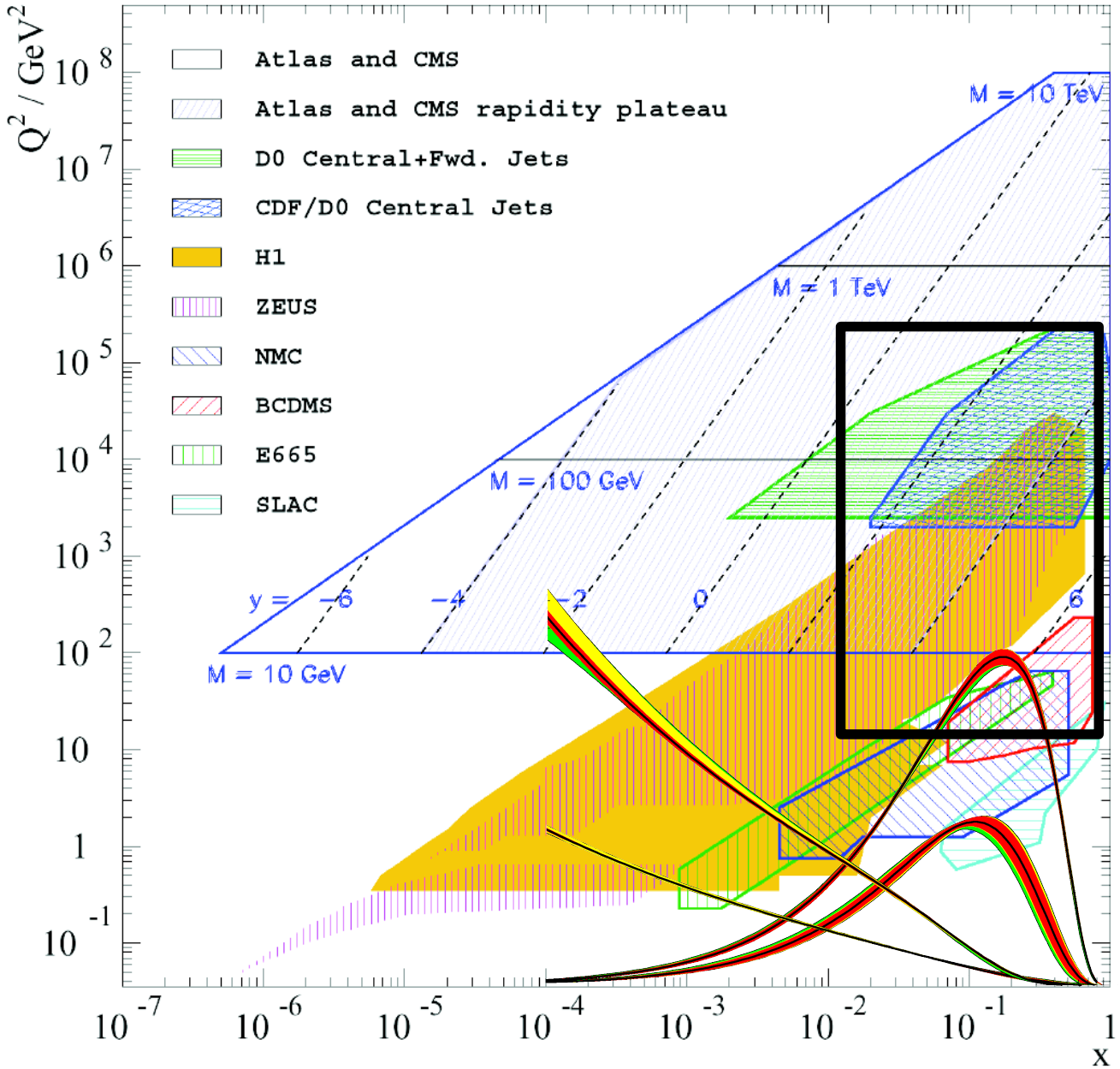
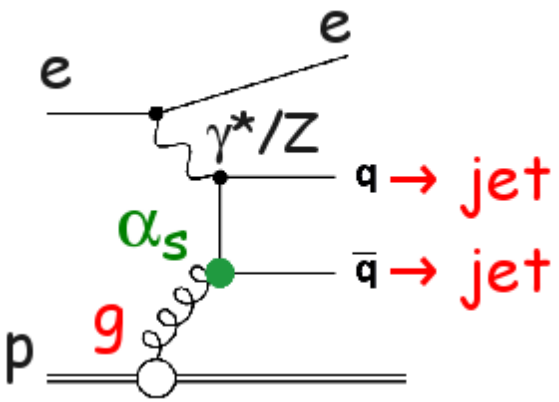
➔ Parametrisation error addressed

➔ Errors reduced at high x, mainly visible on valence distributions

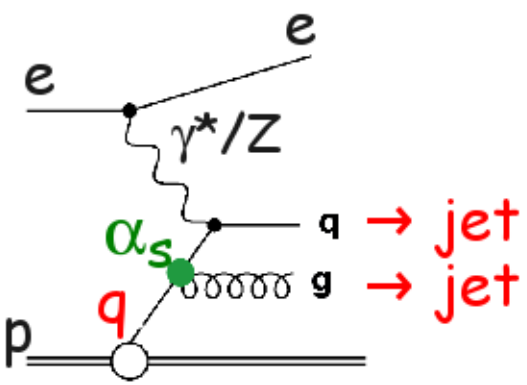
The gluon at medium and high x



The gluon: jets in ep collisions

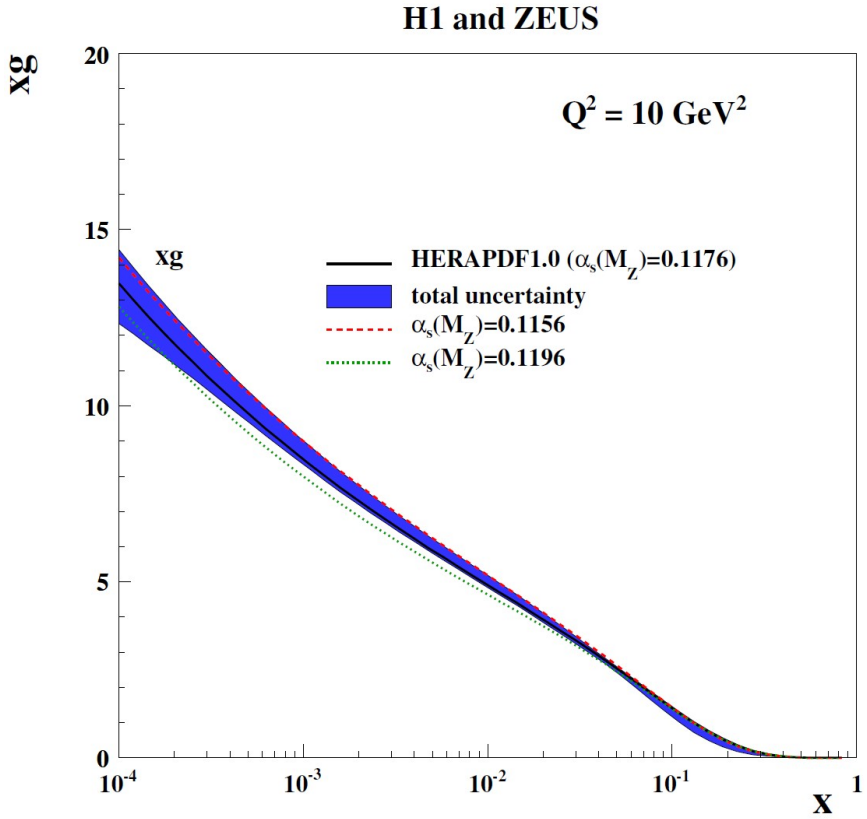


Boson-gluon fusion



QCD Compton

➔ Sensitive to α_s * (gluon + quark)



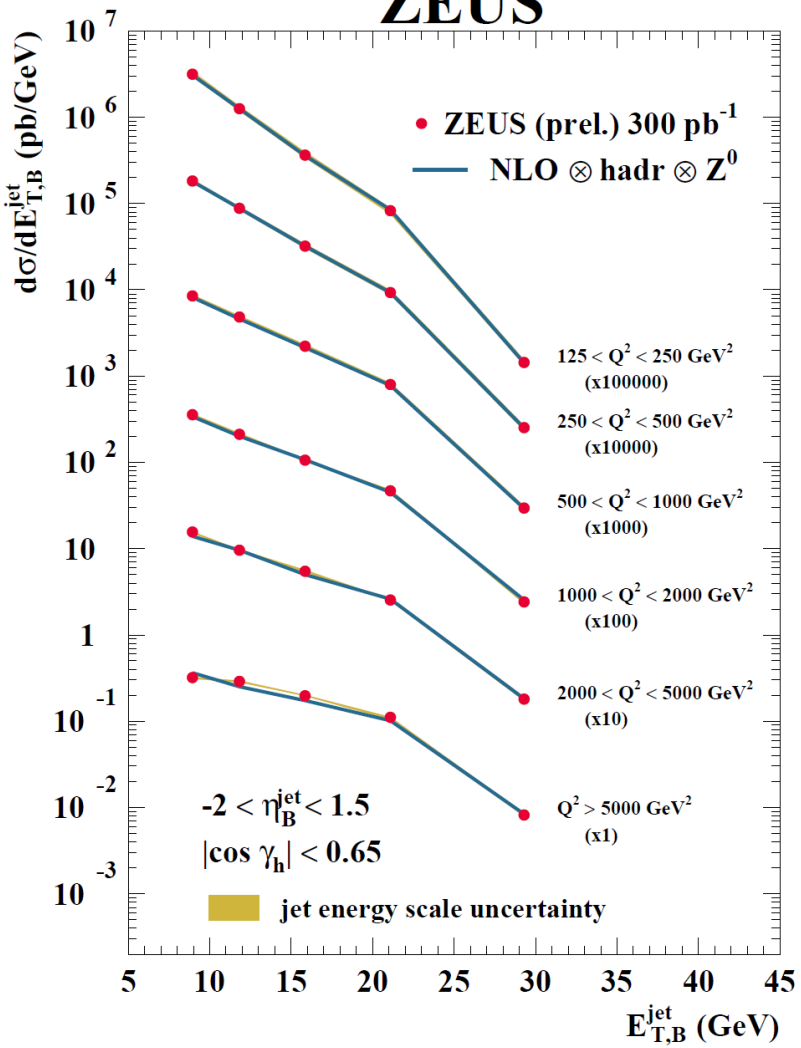
- At HERA, jet measurements constraint the gluon in 0.01 < x < 0.4
- Gluon distribution and α_s linked
  - ➔ Combined fit with DIS data expected to reduce gluon uncertainties
  - ➔ And α_s may also be extracted

The gluon from jets: ep collisions

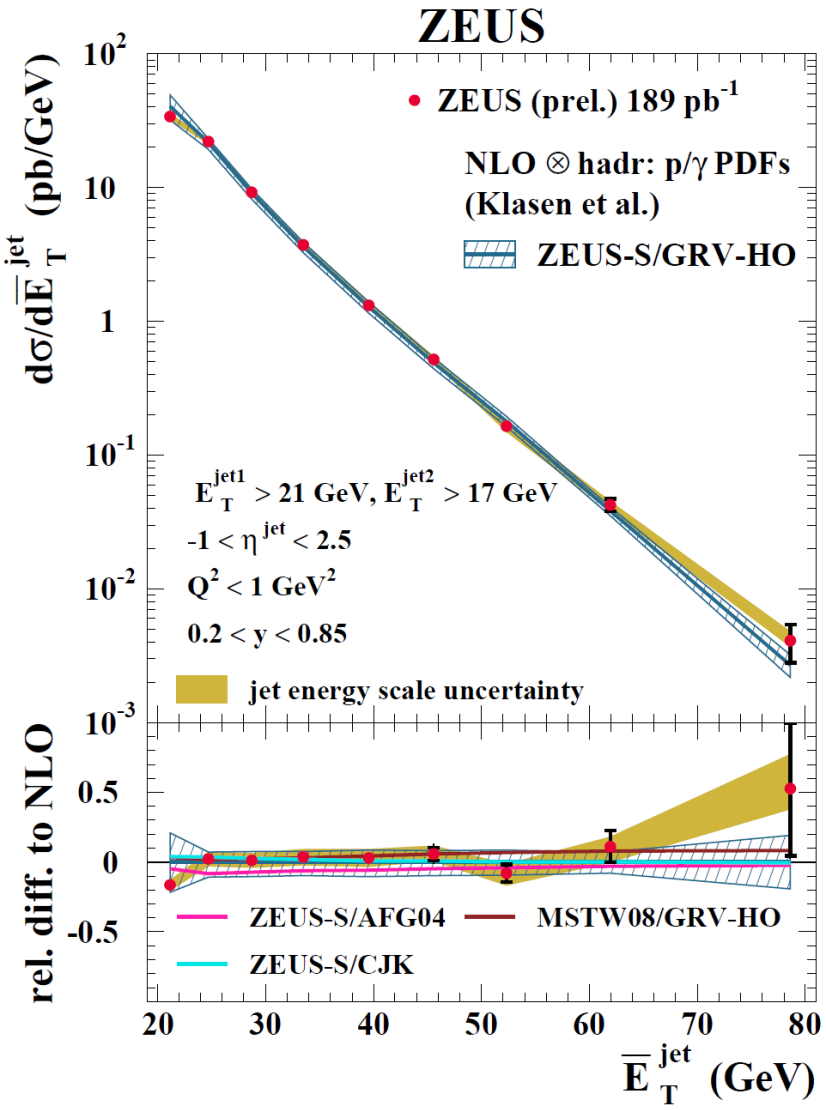
- Measurements of inclusive, 2 and 3 jets production in DIS and γP

➔ Jet energy scale uncertainty down to 1% for $E_T^{jet} > 10$ GeV

Inclusive jets in DIS

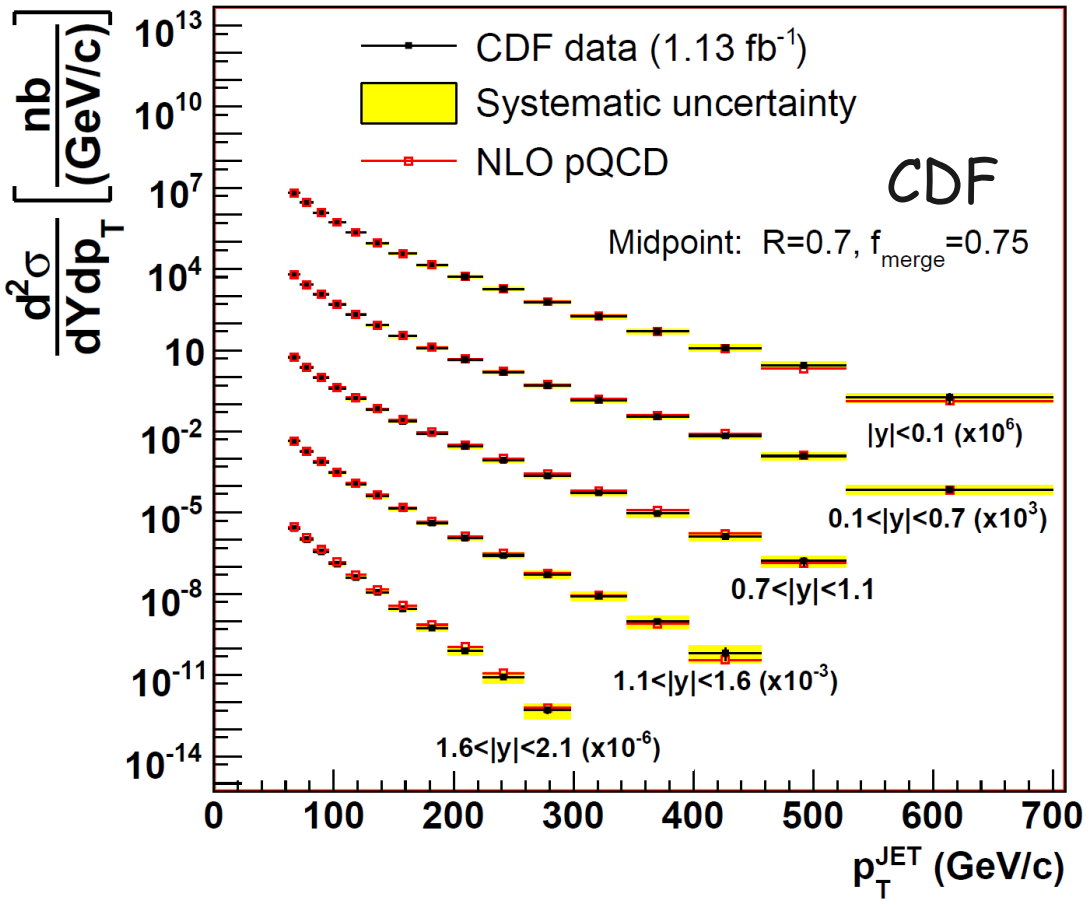


Di-jets in γP



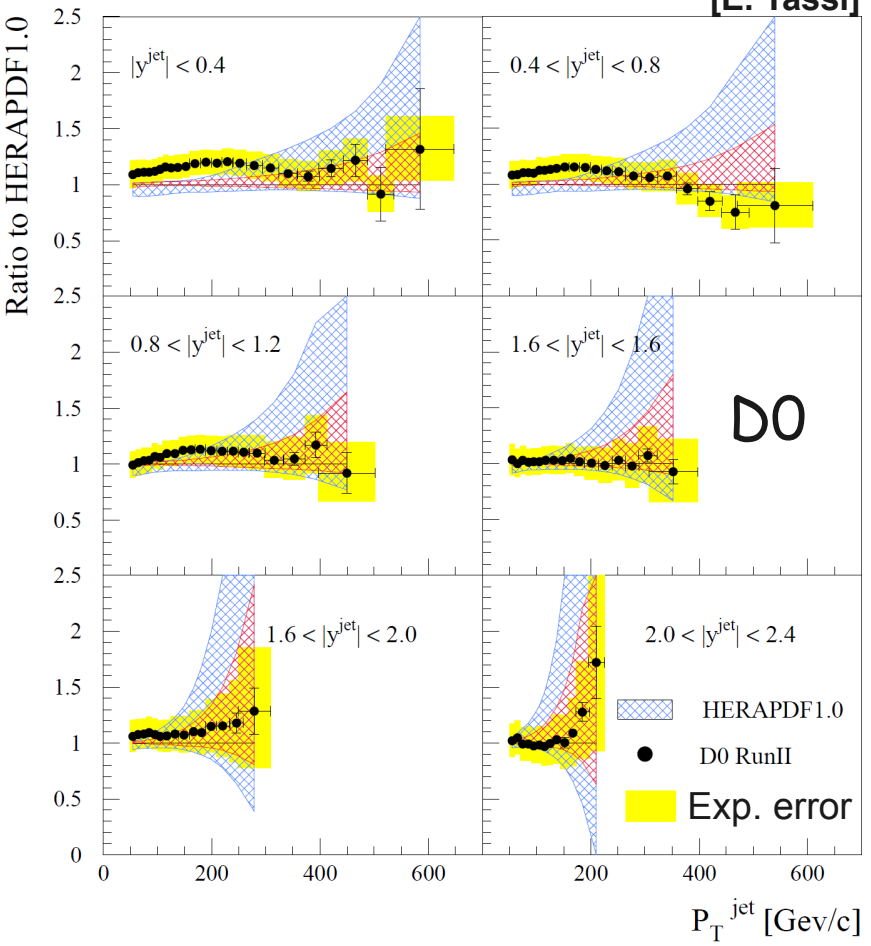
The gluon from jets: Tevatron

- Tevatron jets: constraint the gluon at high x
- Dominant exp. error:
  jet energy scale, now 1%



- Compared to HERAPDF:

[E. Tassi]



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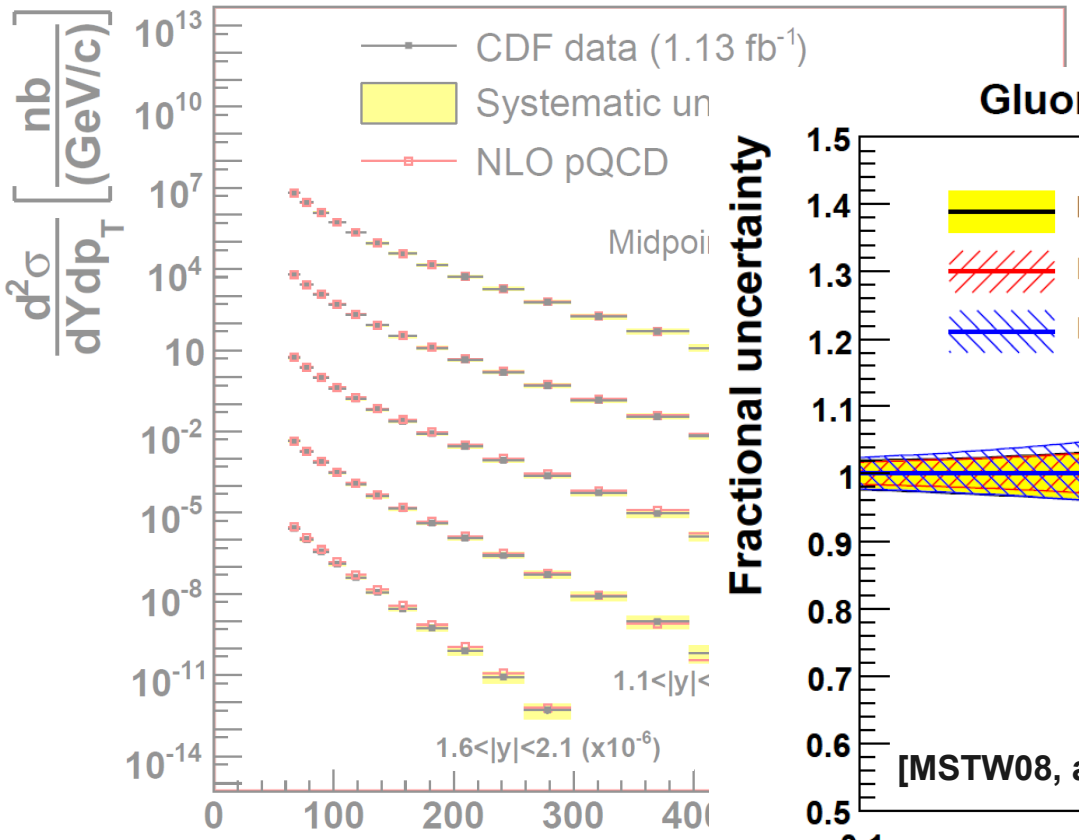
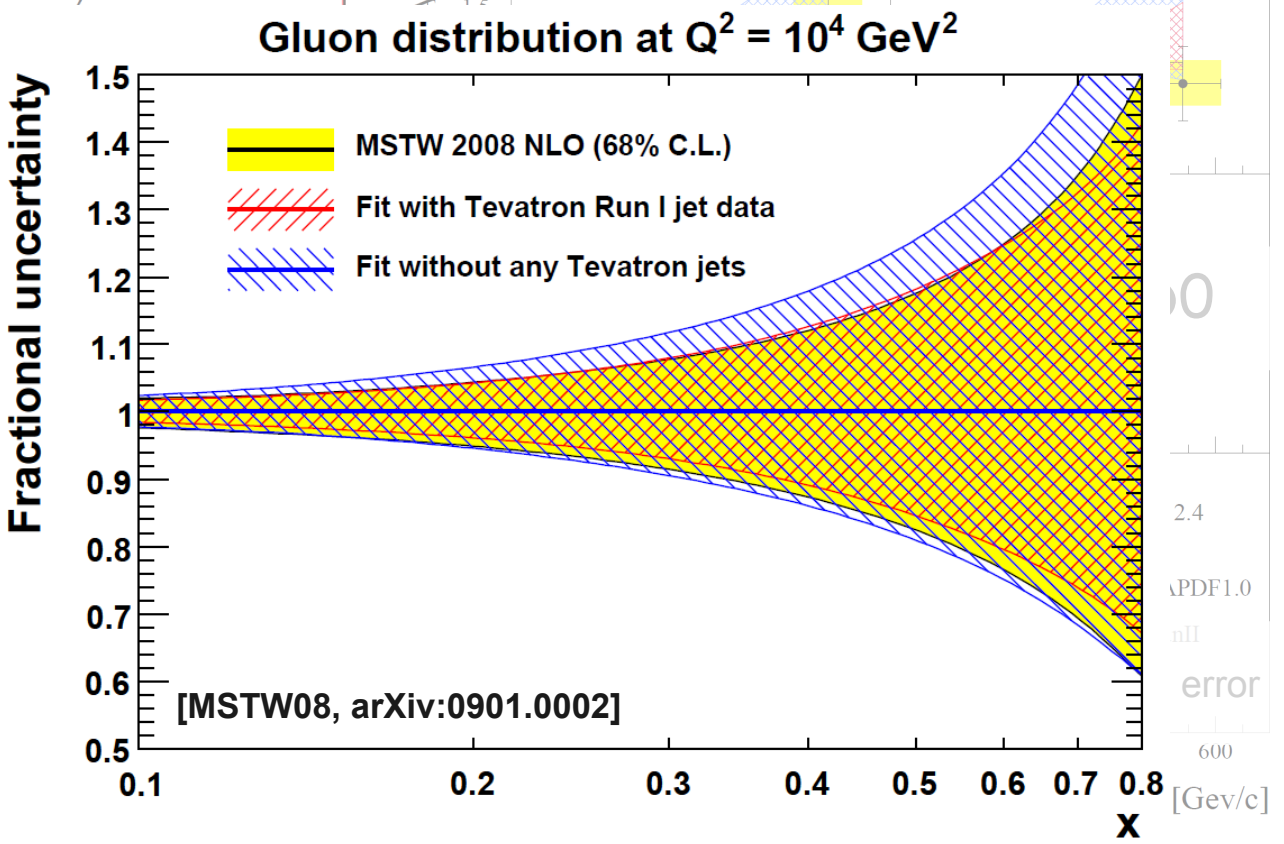




➔ Used in global fits to constraint the gluon in a region relevant to new physics at the LHC

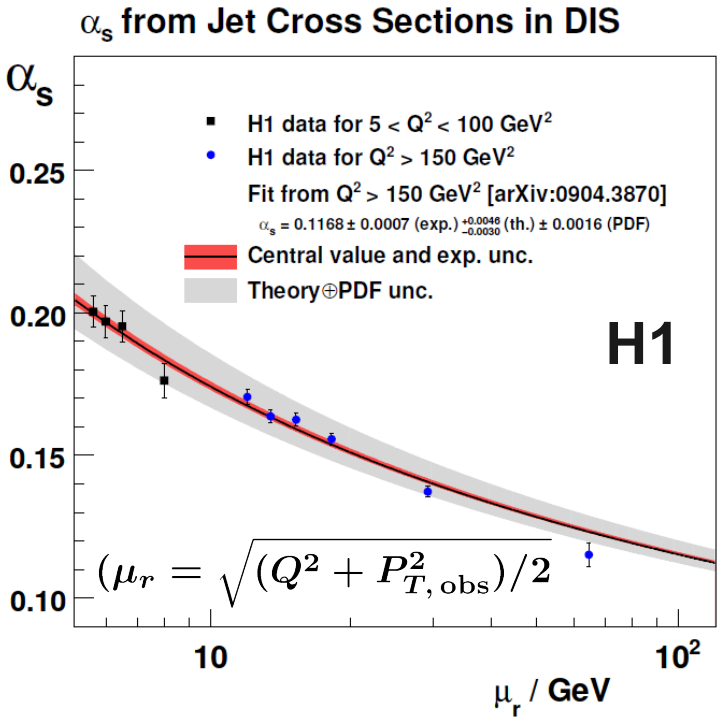
A fundamental parameter: α_s

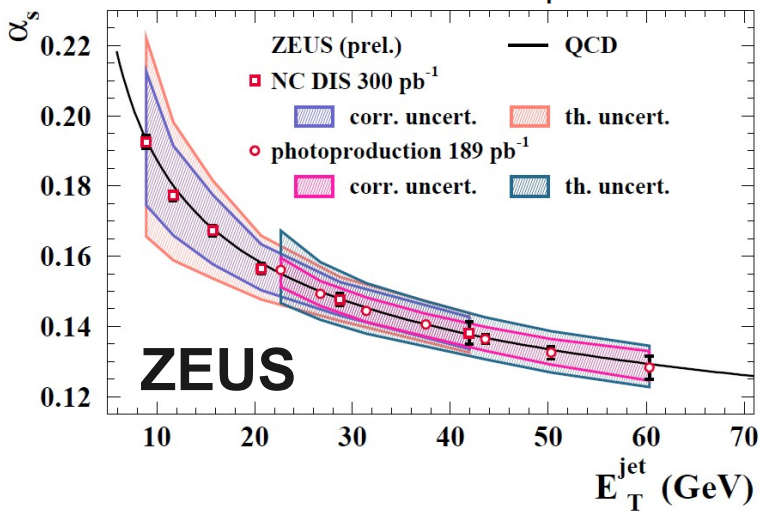
- Accessed from jet measurements

➔ From HERA

H1 $\alpha_s(M_Z) = 0.1168 \pm 0.0007\ (\text{exp.})\ ^{+0.0049}_{-0.0034}\ (\text{th.})$

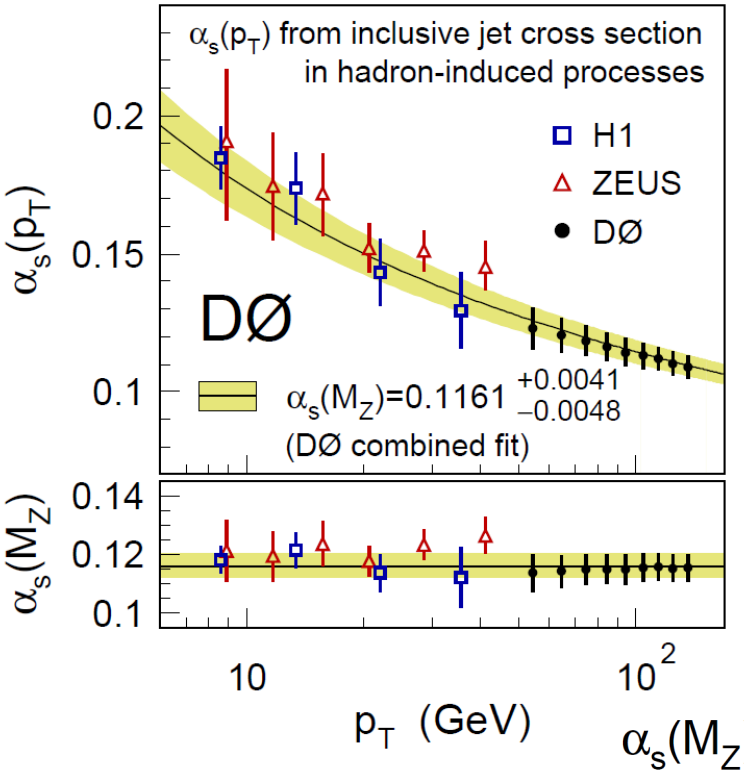
ZEUS $\alpha_s(M_Z) = 0.1208^{+0.0037}_{-0.0032}\ (\text{exp.})\ \pm 0.0022\ (\text{th.})$





➔ Further progresses require NNLO

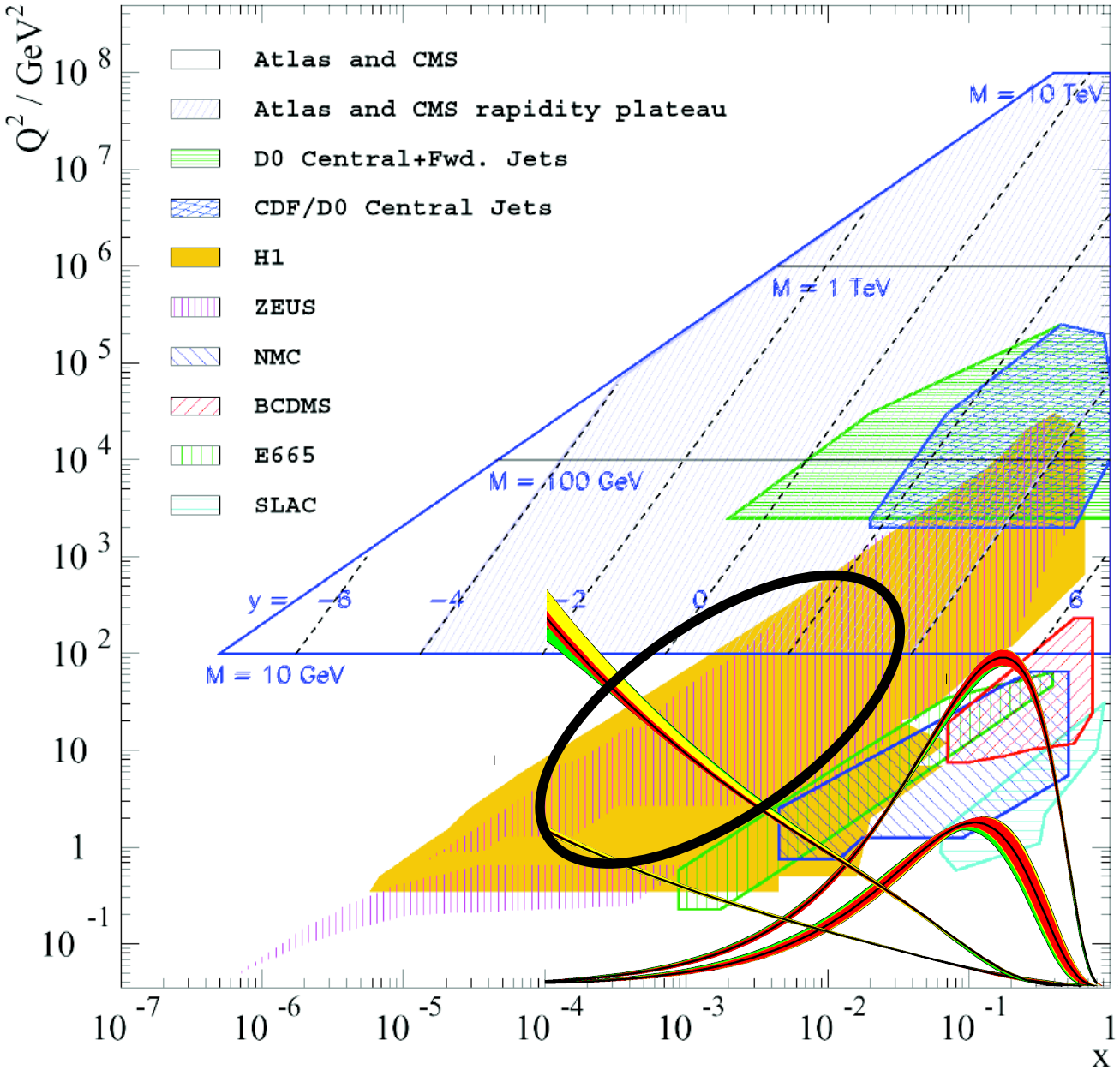
➔ From Tevatron



Using jet cross sections with $x < 0.2$-0.3

$\alpha_s(M_Z)=0.1161\ ^{+0.0041}_{-0.0048}$

The gluon towards low x

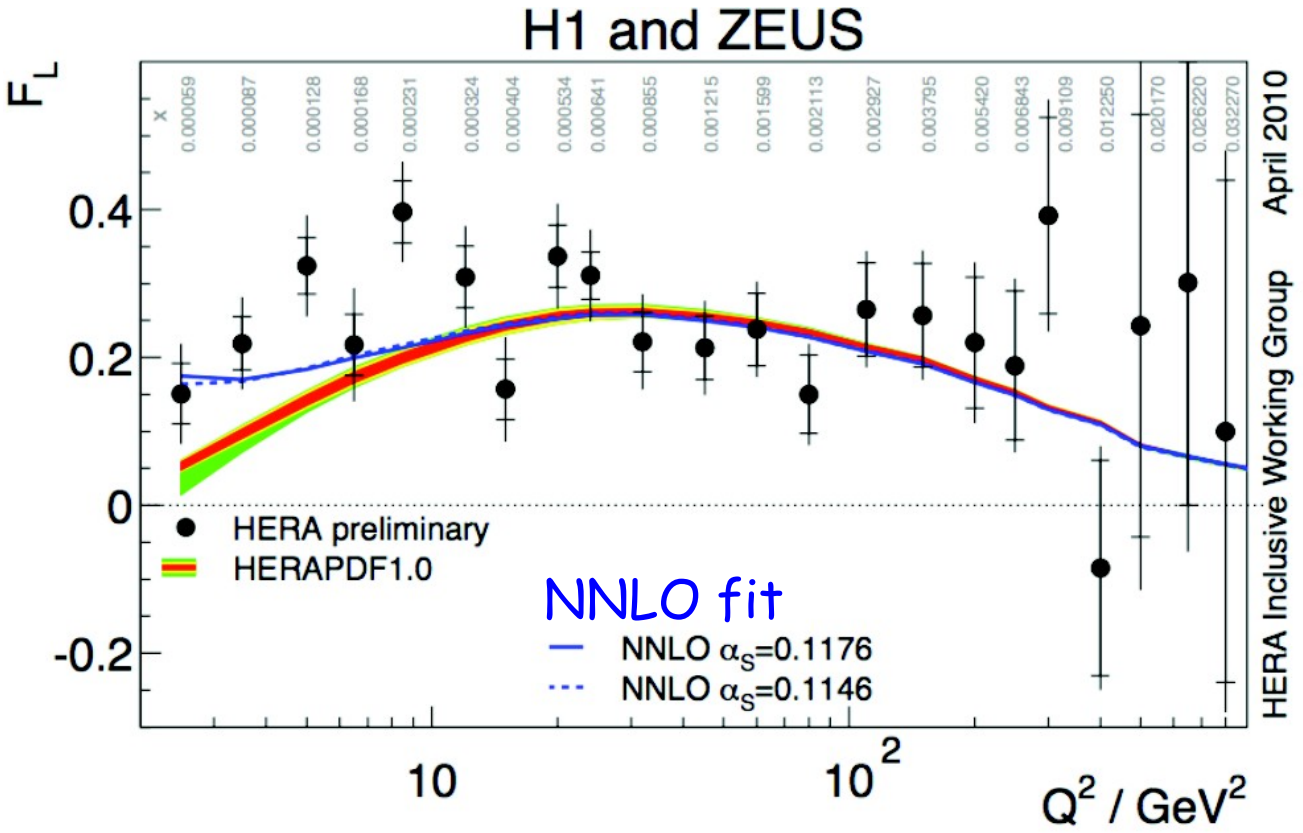


Direct F_L measurement at HERA

- In QCD, $F_L > 0$ due to gluon emissions ➔ Direct measure of the gluon density

$$\sigma_{r,NC} = F_2 - \frac{y^2}{1+(1-y)^2} F_L \qquad y = Q^2/sx$$

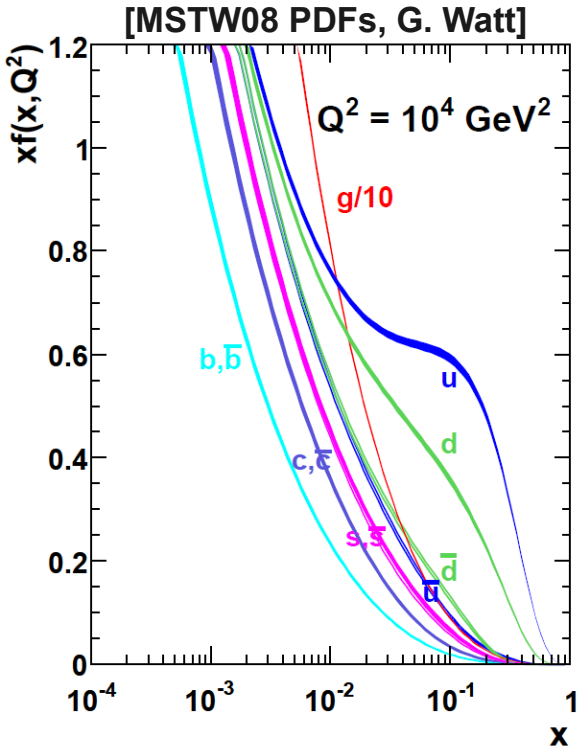
- Method: ➔ Keep x, Q^2 constant and vary y
  ➔ Vary s: special runs with E_p = 460, 575 GeV

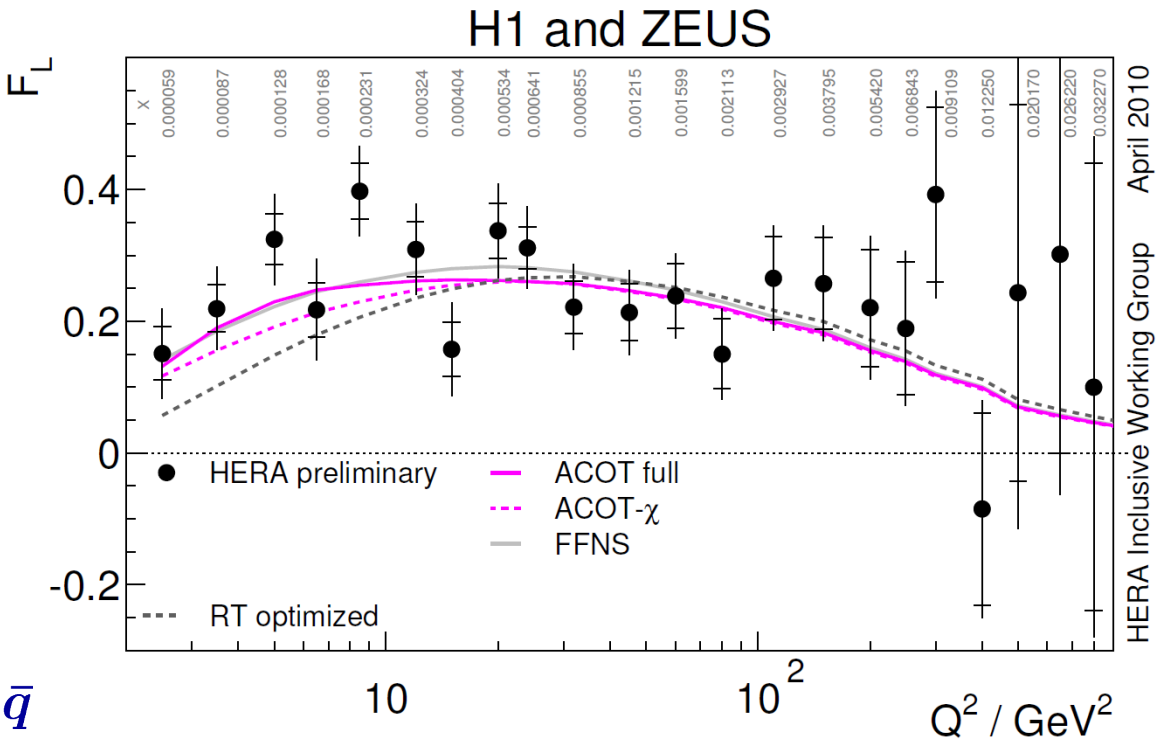


➔ Sensitive to the gluon distribution at low Q^2 and low x

➘ Evolution scheme (NNLO ?), QCD dynamics at low x?

Flavours in the proton



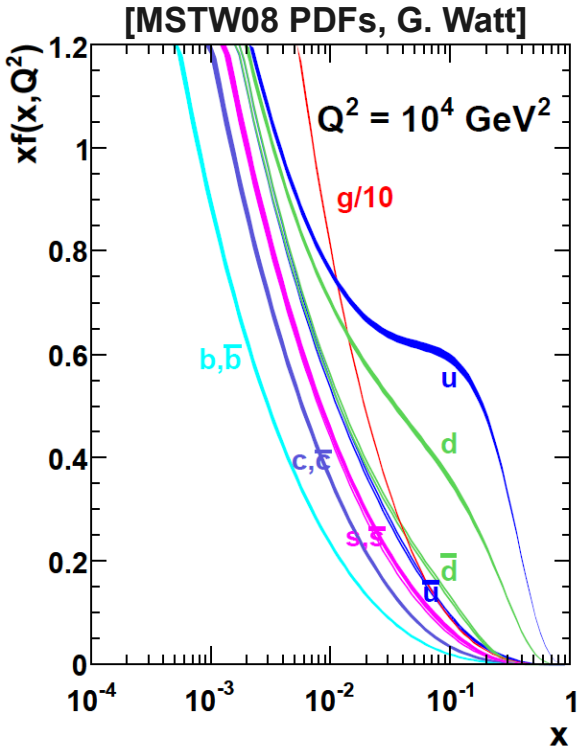


- Heavy quark flavours in the proton are radiatively generated from gluons $g \rightarrow q\bar{q}$

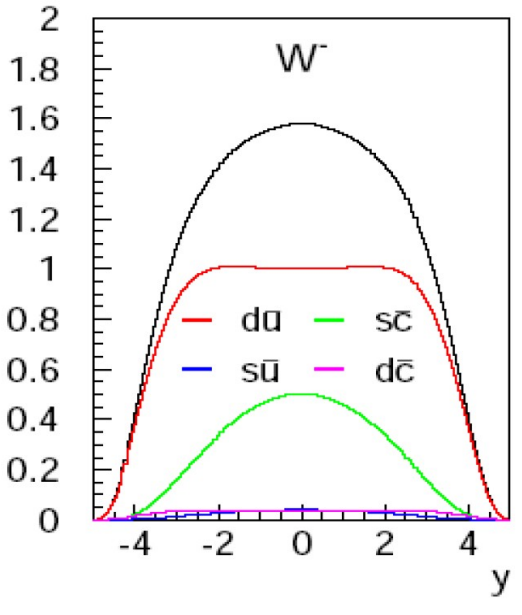
  ➔ Cross talk gluon ↔ sea quarks

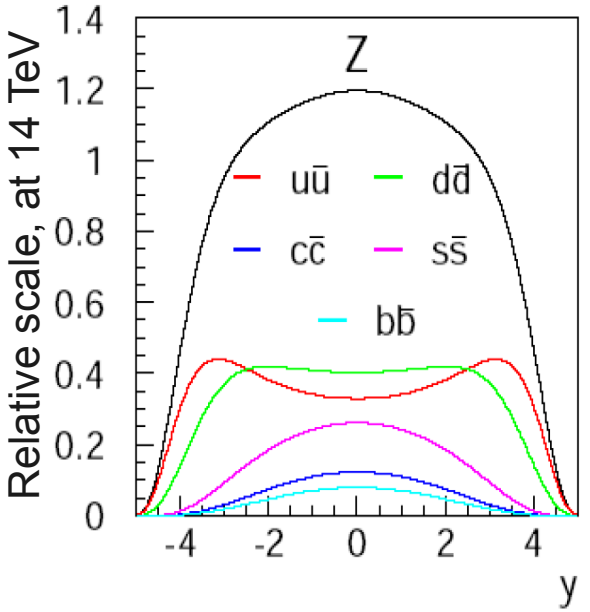
  ➔ Depends on the th. treatment of the transition $Q^2 \sim m_{c,b}$ / $Q^2 >> m_{c,b}$ (massive / massless)

Flavours in the proton



- LHC probe PDFs at small x: large fraction of heavy quarks





- Heavy quark flavours in the proton are radiatively generated from gluons $g \rightarrow q\bar{q}$

➔ At LHC, $W^{\pm}$, Z are mostly produced by sea $q\bar{q}$ collisions

➔ Cross talk gluon ↔ sea quarks

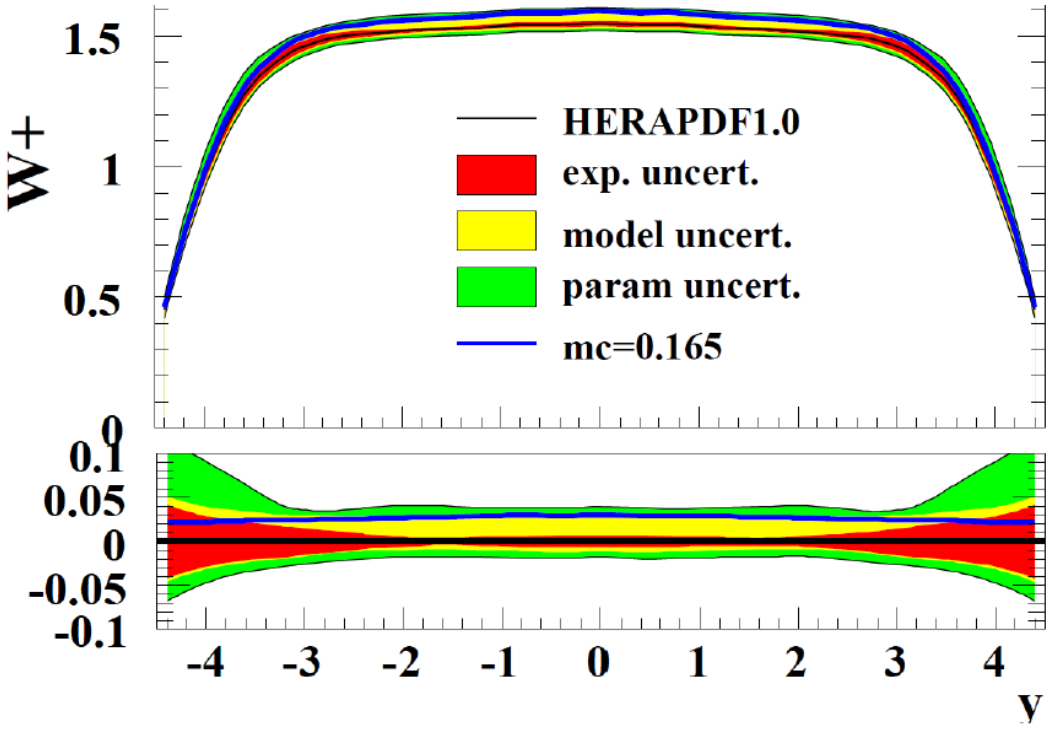
➔ Depends on the th. treatment of the transition $Q^2 \sim m_{c,b}$ / $Q^2 >> m_{c,b}$ (massive / massless)

➘ Exclusive measurements (c,b) sensitive to gluon + theoretical treatment (near $m_{c,b}$ threshold)

Impact on LHC cross sections

[A.M. Cooper-Sarkar]

- Low Q^2 changes in PDFs translate to high Q^2
- For example: variation of m_c in PDFs determination



- F_2 (DIS NC's) constraints xu+xc
- xc modified by charm treatment and m_c choice

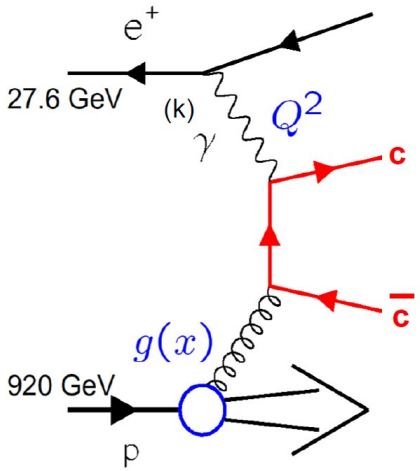
➔ Imply changes in xu

↘ Changes by possibly 3%, depending on heavy quark treatment

↘ Charm data help to constraint it

Charm of the Proton

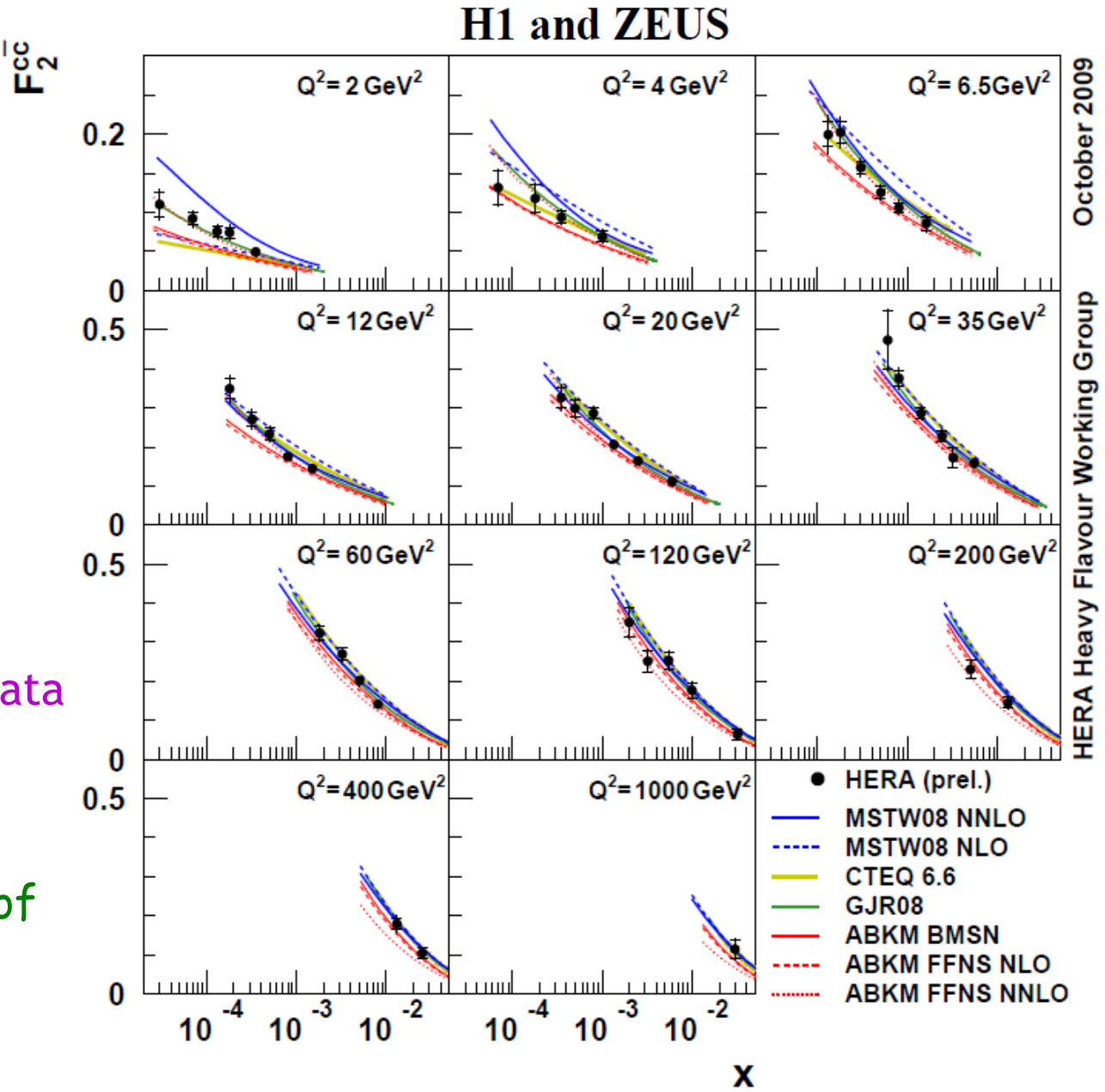
- At HERA: production by boson-gluon fusion



- Charm tagging with D*, D+, muons, impact parameter

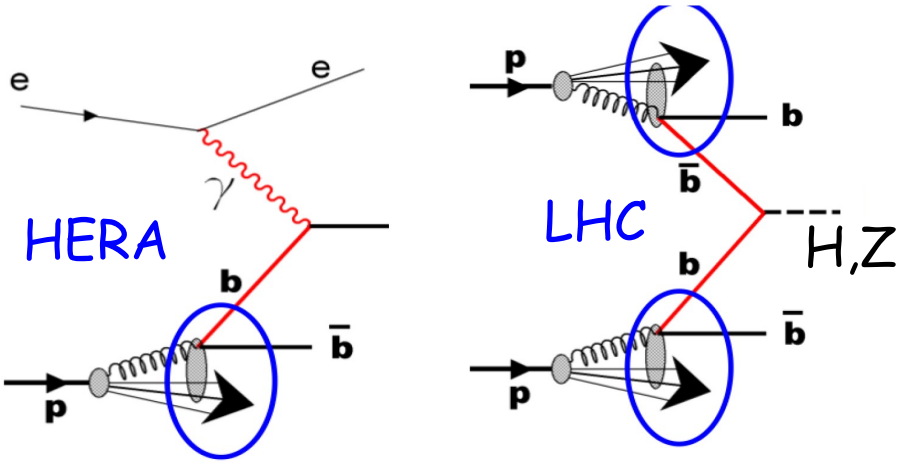
➔ New, precise, combined data

➘ New constraints on theoretical treatment of HF and m_c in PDF fits

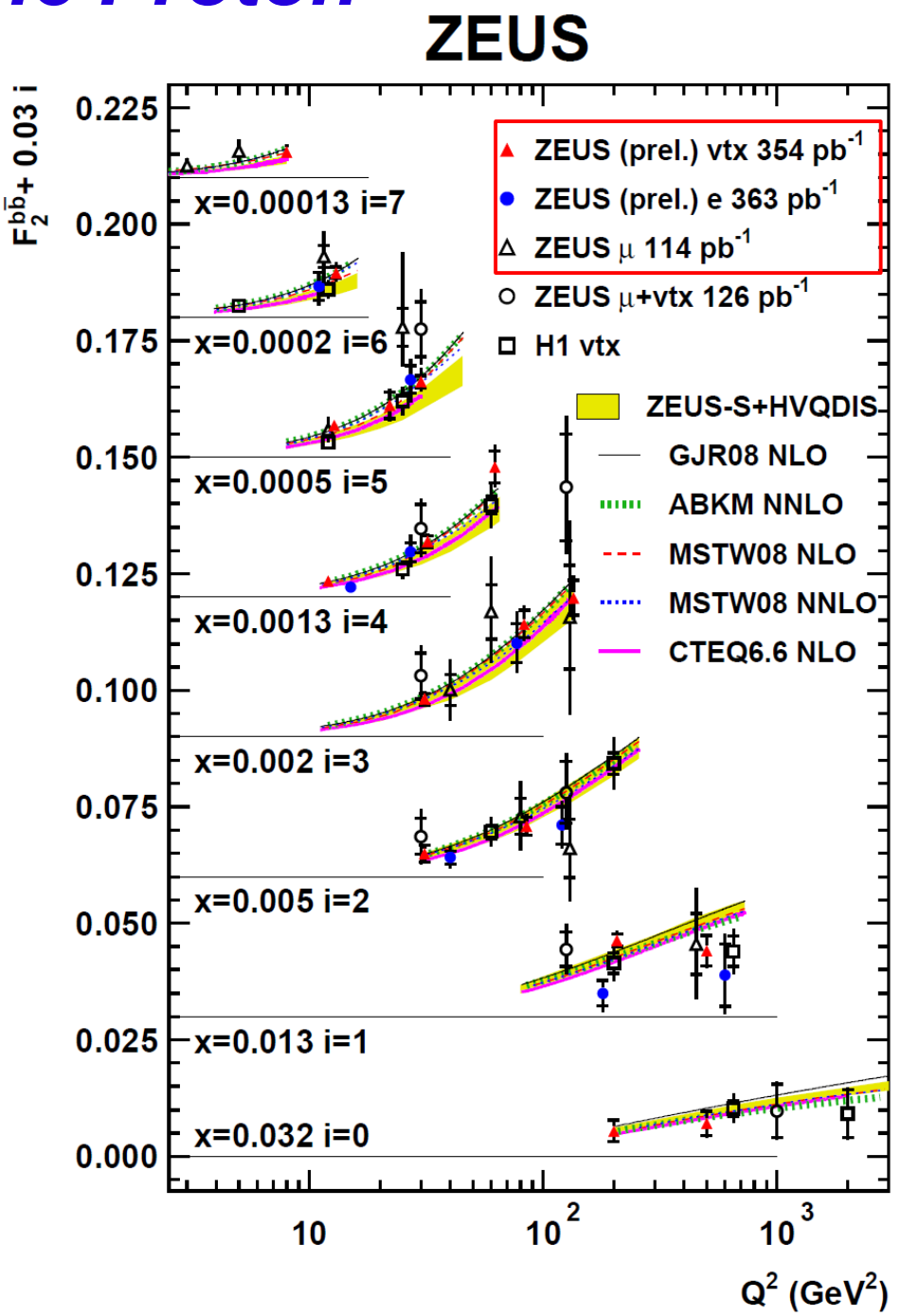


Beauty of the Proton

- Control of beauty is also important for some aspects of the LHC physics

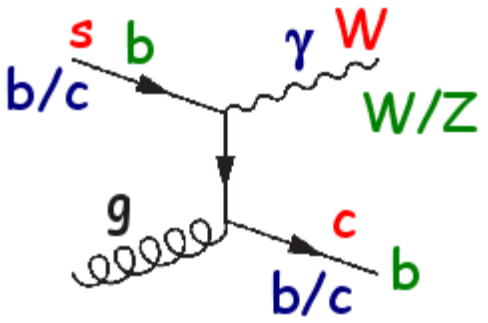


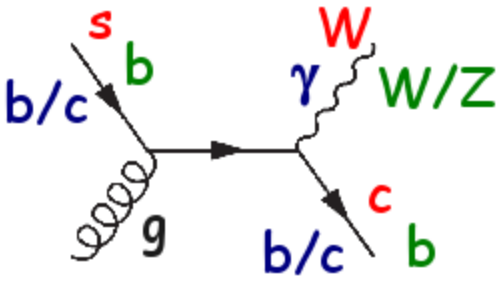
- New, precise measurements from HERA
  - ➔ Good agreement with calculations
  - ➔ Combination will further improve the precision

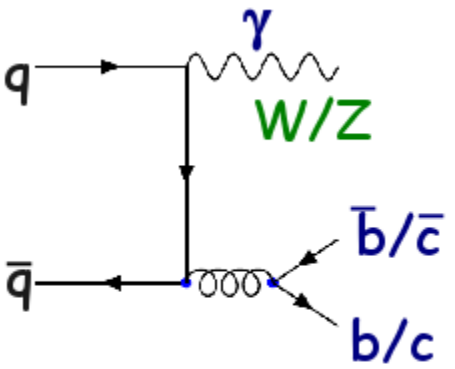


Testing proton's flavours at the Tevatron

➔ Associated boson – heavy quark production







- Direct measurements of:
  - Production of γ with b/c jets
  - Production of W/Z with b jets
  - Production of W with c jet

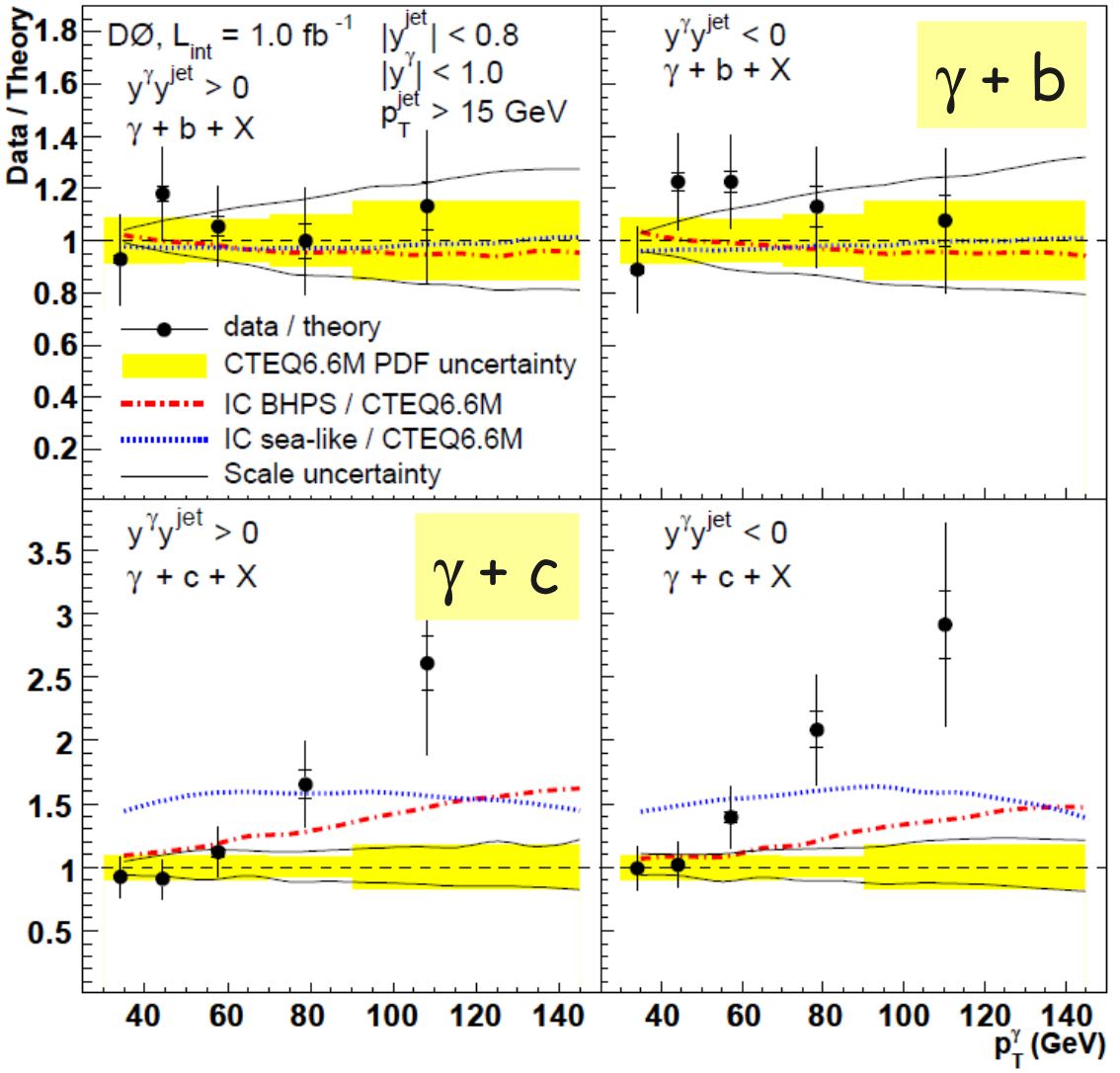
➔ Sensitive to g and s, c or b PDFs

➔ Backgrounds to Higgs, top, and new physics

➔ Tests of pQCD calculations

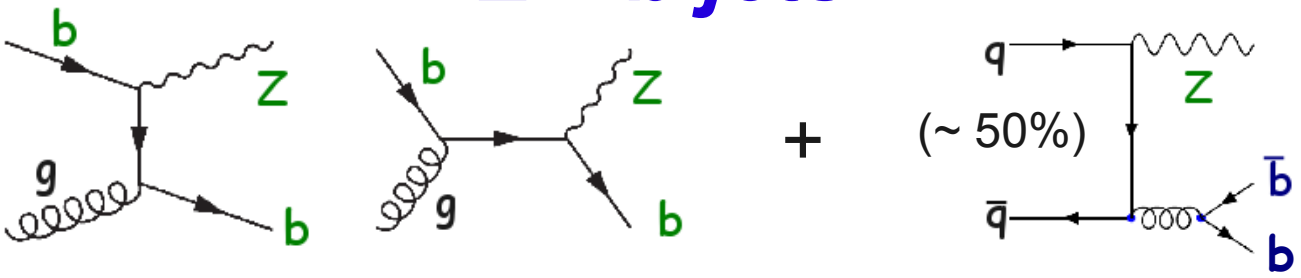
γ + c / b jets

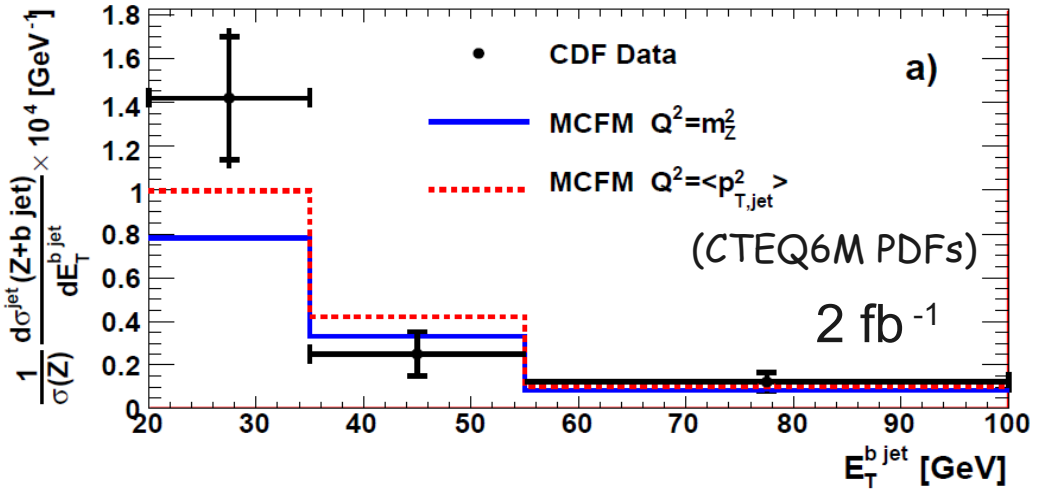
- Production of γ associated with b/c jets, compared to NLO predictions
  - ➔ PDFs probed in 0.01<x<0.3
- Good agreement for γ + b
  - ➔ But yet no sensitivity to PDFs
- Difference for γ + c with increasing P_T^{γ}
  - ➔ Intrinsic charm or uncertainties in $g \rightarrow c\bar{c}$?

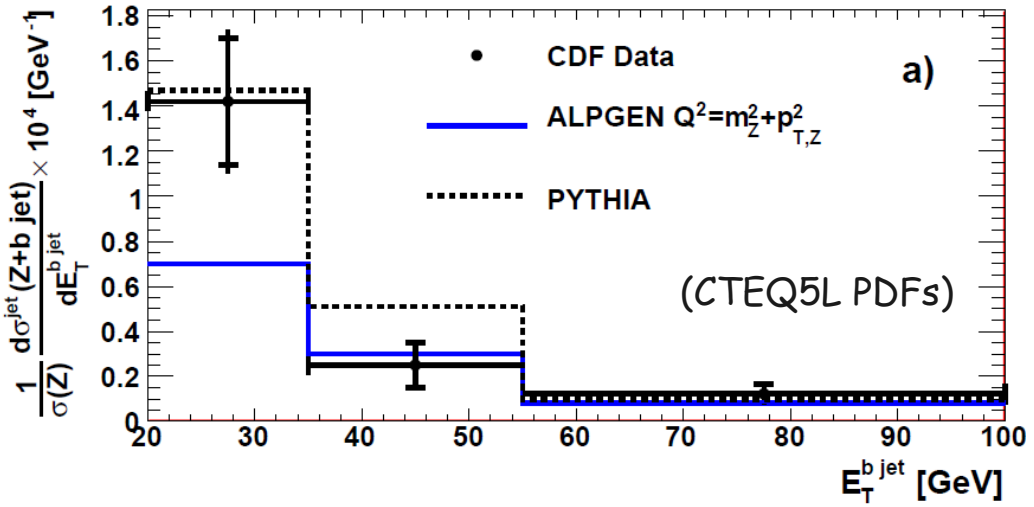


[D0, PRL 102 (2009) 192002]
[CDF, PRD 81 (2010) 052006]

Z + b jets







- First differential cross sections measured by CDF
  - ➔ Large spread of theoretical predictions
  - ➘ Needs of full NLO, importance of the choice of μ_R, μ_F

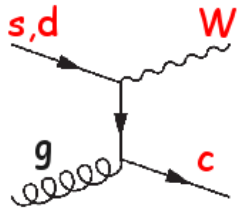
- Ratio (Z+b jets)/(Z+jets) measured by D0 with 4.2 fb^{-1}:

$$0.0176 \pm 0.0024(\text{stat.}) \pm 0.0023(\text{syst.})\ \text{pb}$$

NLO (MCFM): 0.0184 ± 0.0022 pb

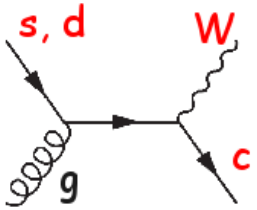
[CDF, PRD 79 (2009) 052008]

W + c / b jets



- W + c-jet production: dominated by s-g fusion (~90%)

➔ Sensitive to g and s PDFs at $\mu_R = M_W$

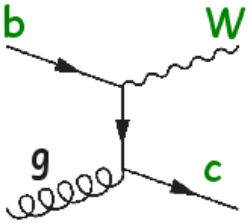


CDF measurement: $(p_T^c > 20\ \mathrm{GeV}, |\eta| < 1.5)$

$$\sigma_{W\,c} \times Br(W \to \ell\nu) = 21.1 \pm 7.1(\mathrm{stat.}) \pm 4.6(\mathrm{syst.})\ \mathrm{pb}$$

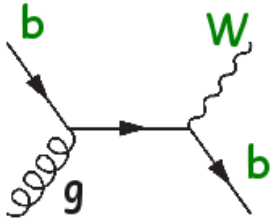
NLO (MCFM): $11.0\ ^{+1.4}_{-3.0}\ \mathrm{pb}$

↘ Fair agreement



- W + b-jet, CDF measurement:

$$\sigma_{b\ \mathrm{jets}} \times B(W \to \ell\nu) = 2.74 \pm 0.27(\mathrm{stat.}) \pm 0.42(\mathrm{syst.})\ \mathrm{pb}$$

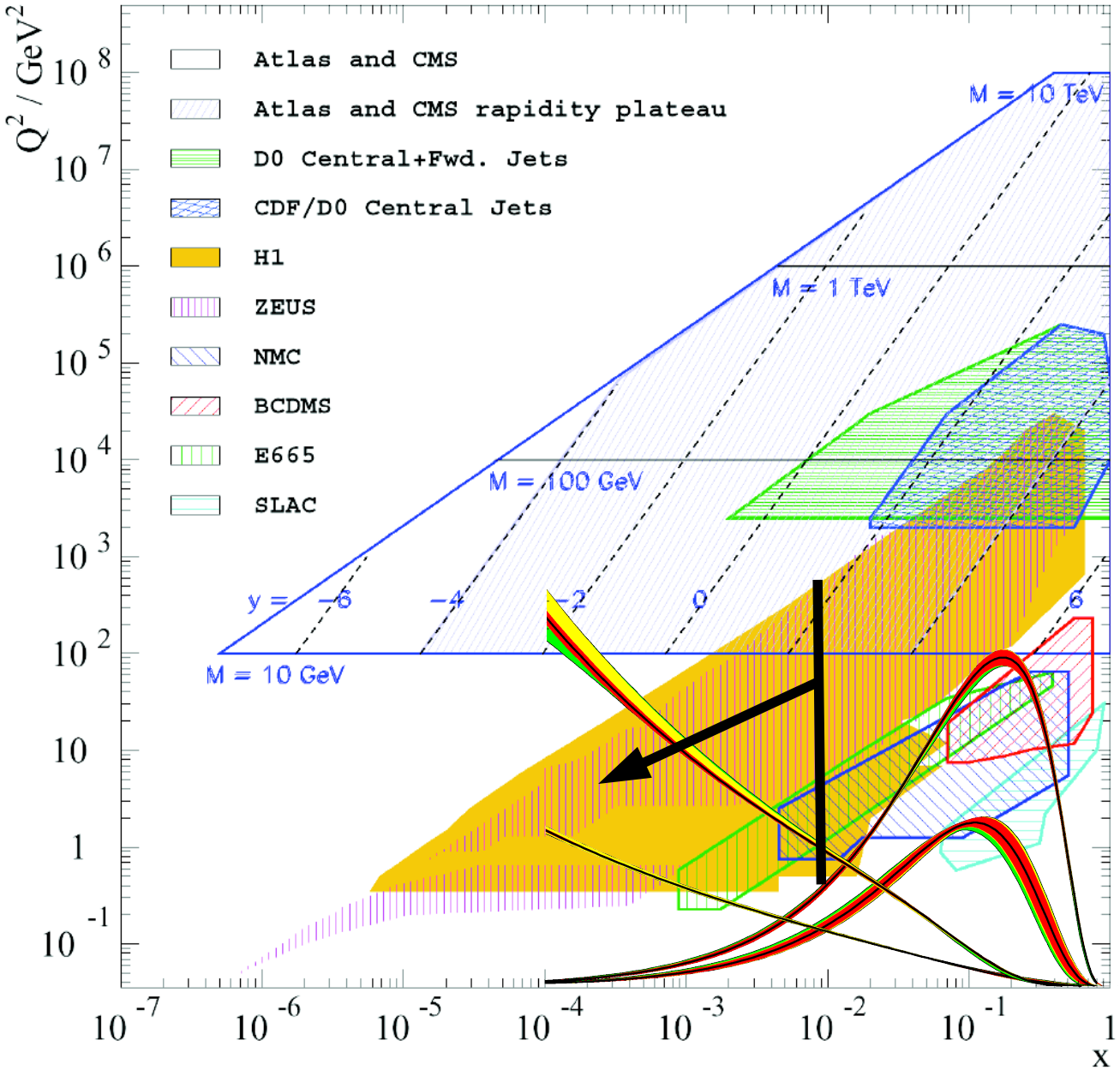


Theory: PYTHIA: 1.10 pb, ALPGEN: 0.78 pb,
NLO: 1.22 ± 0.14 pb

↘ All predictions lower

[CDF, PRL 100 (2008) 091803]
[CDF, PRL 104 (2010) 131801]

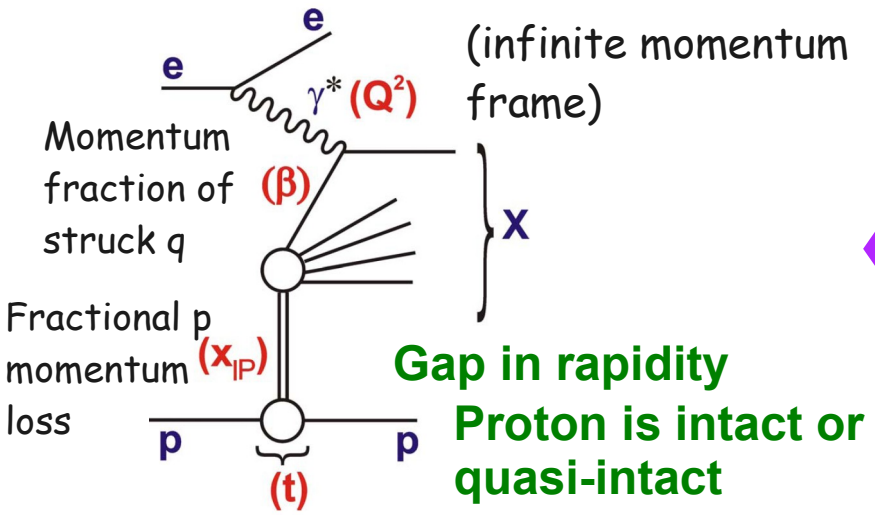
The gluon at low x



Another view on the gluon at small x: Hard Diffraction

➔ Results from a colorless exchange

- In ep collisions

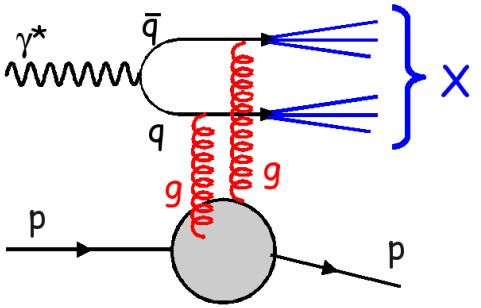


Gap in rapidity

Proton is intact or quasi-intact

- In pQCD, viewed as a 2-gluon exchange (at LO)

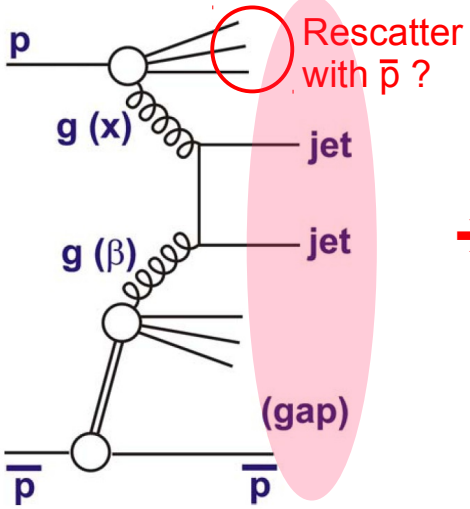
(proton rest frame)



➔ Process dominated by gluons

➔ Probes small x domain (x<0.01)

- In pp collisions



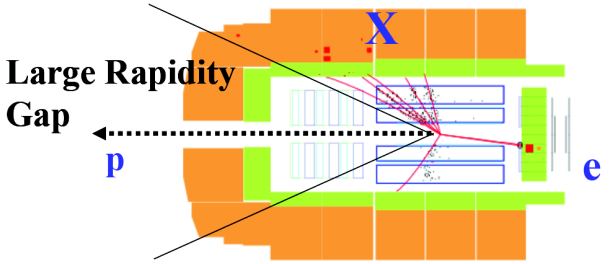
➔ Complicated by soft interactions, destroying the rapidity gap

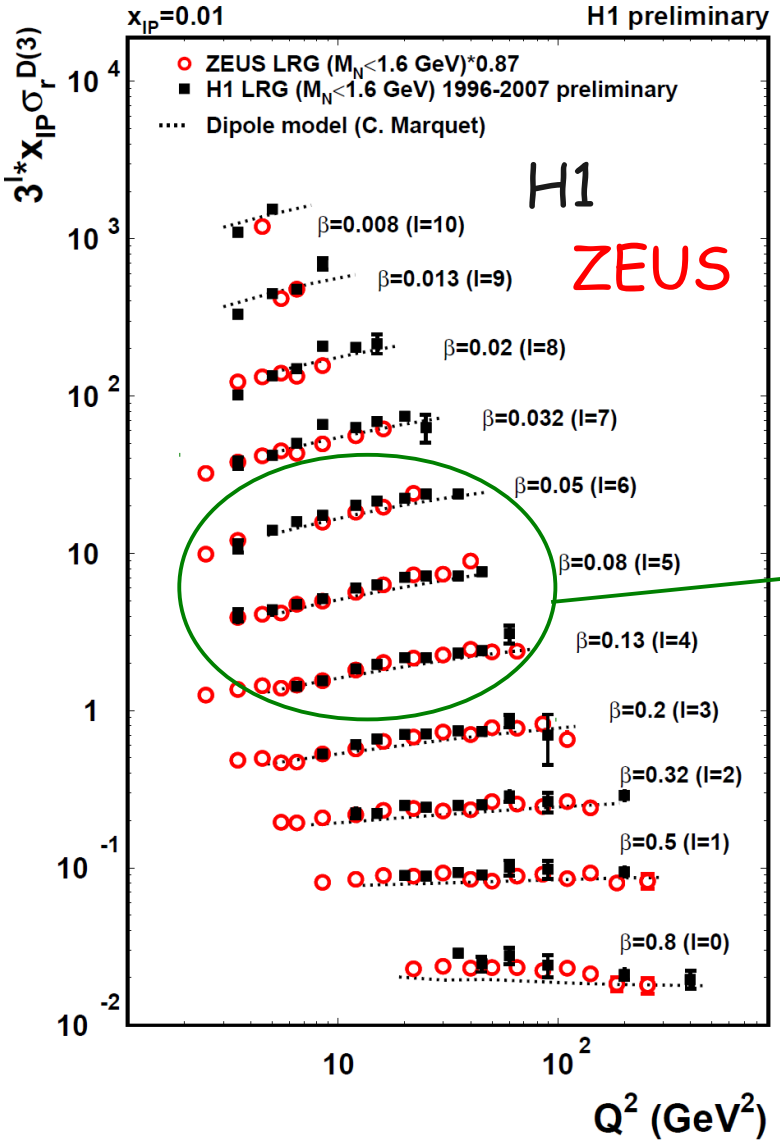
↘ Exact nature of the diffractive exchange ?

↘ HERA is the unique place to study it

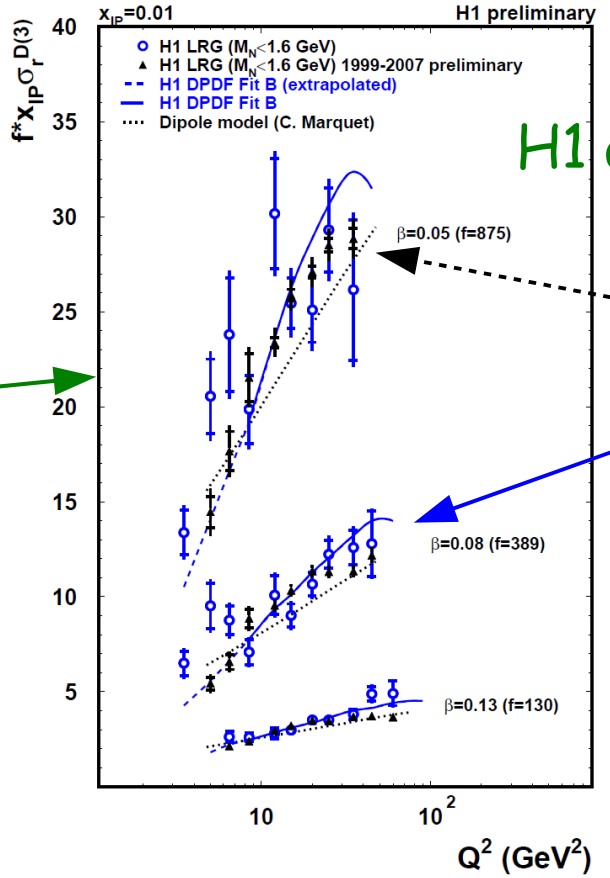
Inclusive diffraction at HERA

- Measurements based on a rapidity gap:





➔ Final data from the 2 experiments



H1 alone

Dipole model

Model of diffractive PDFs

➔ Positive scaling violations: gluons

➘ Entering in the precision era

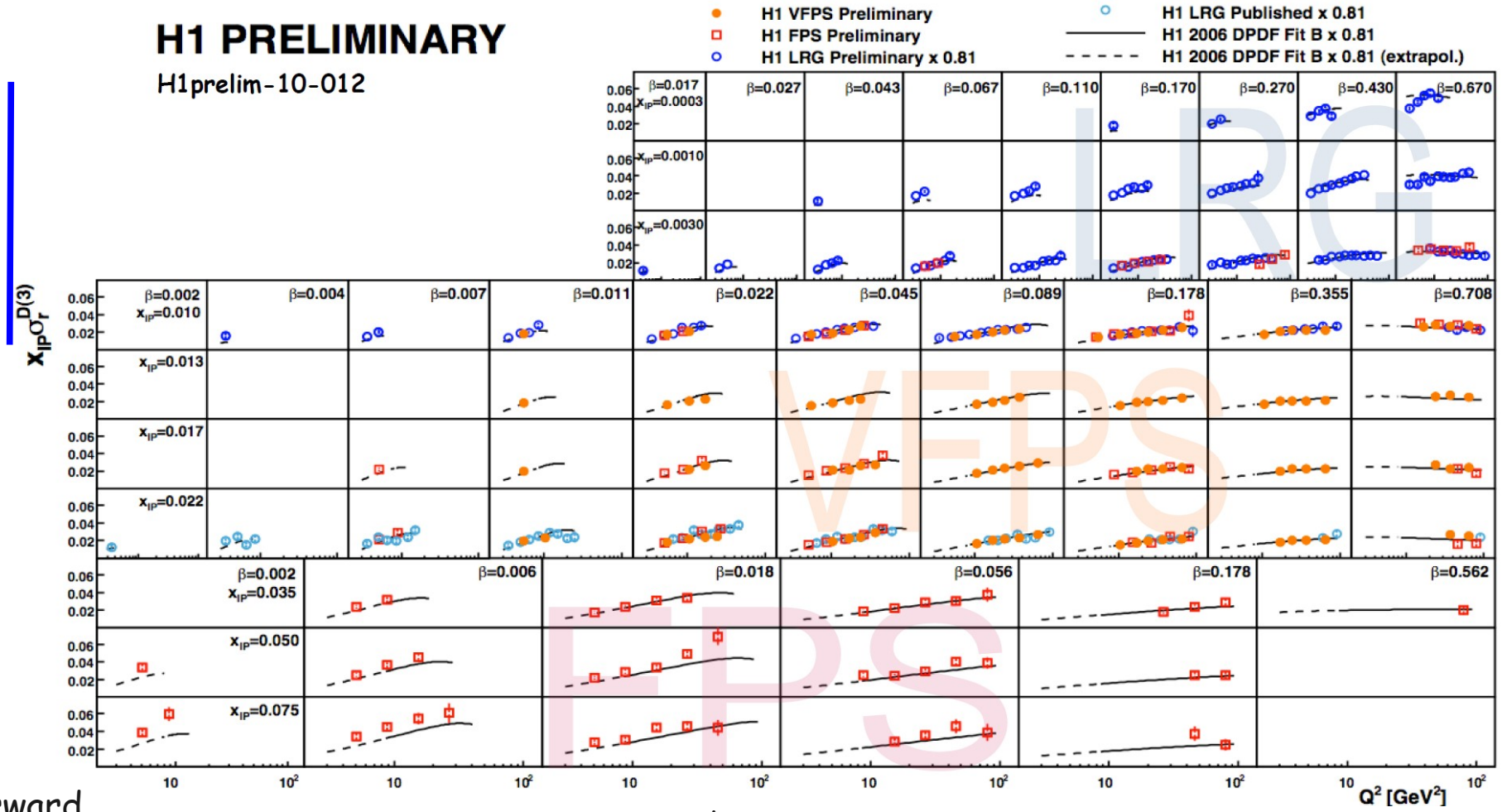
➘ A challenge for pQCD models

Inclusive diffraction at HERA

- Large coverage of the kinematic plane, using also proton taggers

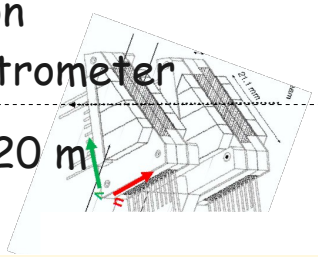
Large rapidity gap

Proton tagged

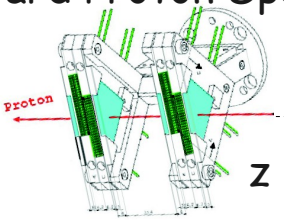


Very Forward Proton Spectrometer

z = 220 m

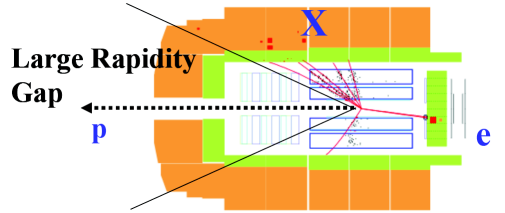


Forward Proton Spectrometer



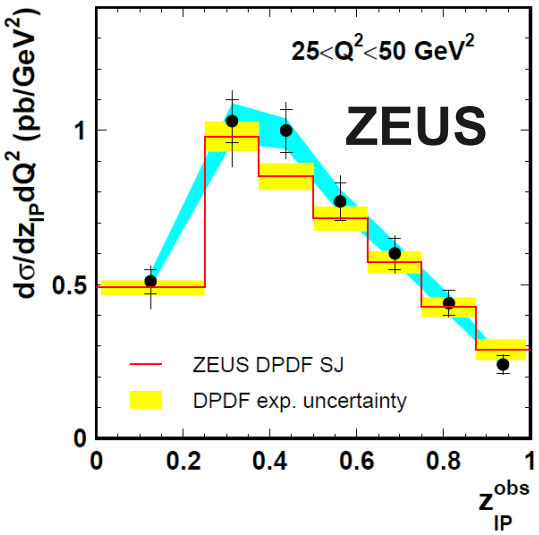
z = 64 m

p



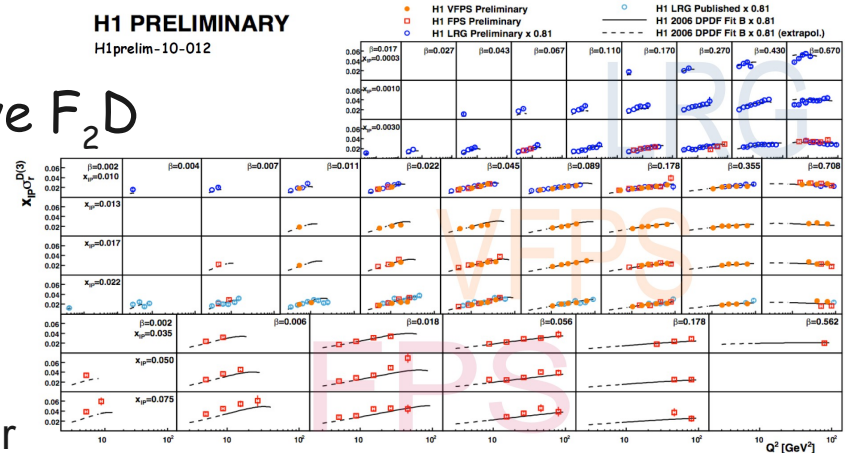
From HERA to LHC Diffraction

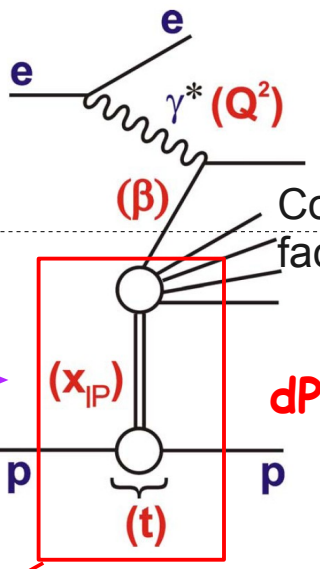
- HERA data may be used to determine diffractive PDFs (dPDFs)



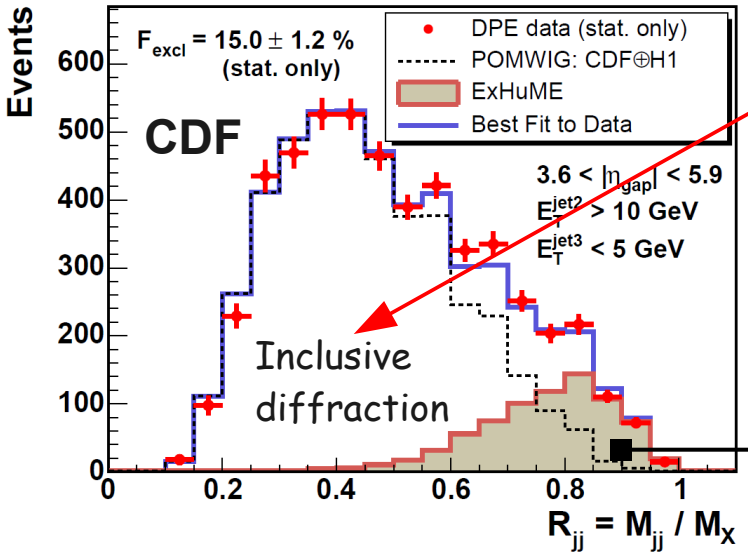
Diffractive jets

Inclusive F_2^D

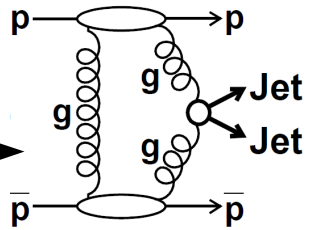




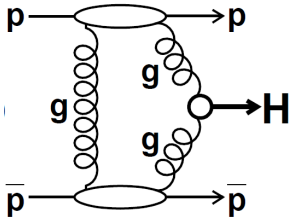
dPDFs: universal parton proton conditional probabilities



- Exclusive jet production at Tevatron



➔ Important inputs for the LHC forward physics program



Conclusions

- QCD dynamics of the proton plays a central role in LHC physics

  ➔ Hard cross sections calculation, underlying event, soft physics, ...

  ↘ Understanding of its structure being tighten up by HERA and Tevatron colliders

  (PDFs can only be measured and not predicted)

  - Increased precision of data

    ➔ HERA is delivering its final data with optimal precision

    ➔ More exclusive observables: jets, heavy flavours, ...

    ➔ Diffractive measurements now entering the precision era

↘ Numbers of measurements now challenging the theory precision

LHC experiments:

" We are at the top ....."

[Guido Tonelli]

Thank you for your attention !

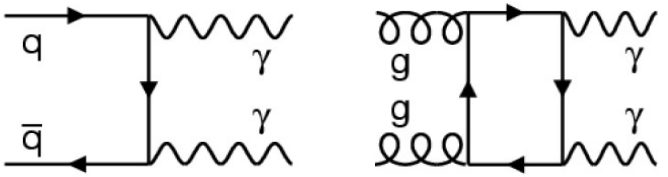
[Apologize for subjects or results not shown]

[Thanks to : all contributors to the results presented, the organisers, the speakers of the structure function and QCD sessions, C. Diaconu, A. Geiser, L. Schoeffel]

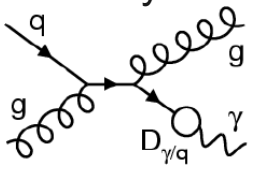
More ...

$\gamma\gamma$ production at Tevatron

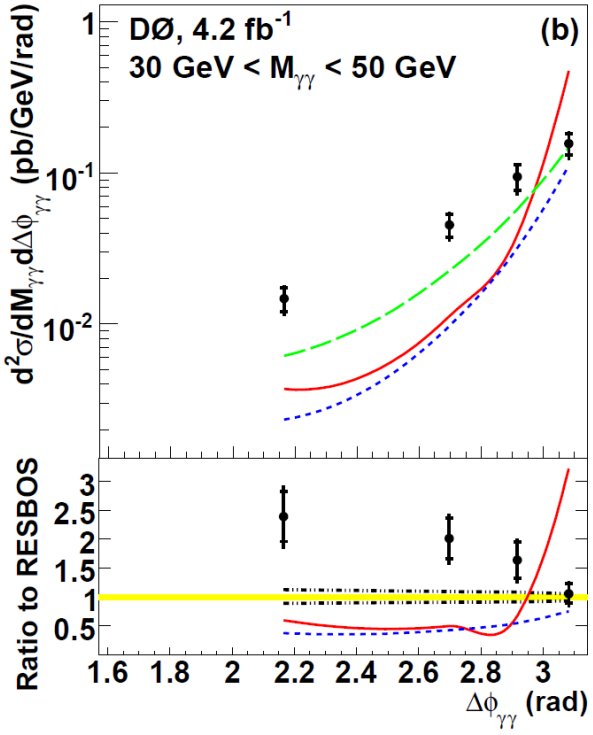
- Test of pQCD
- Major background to H → $\gamma\gamma$

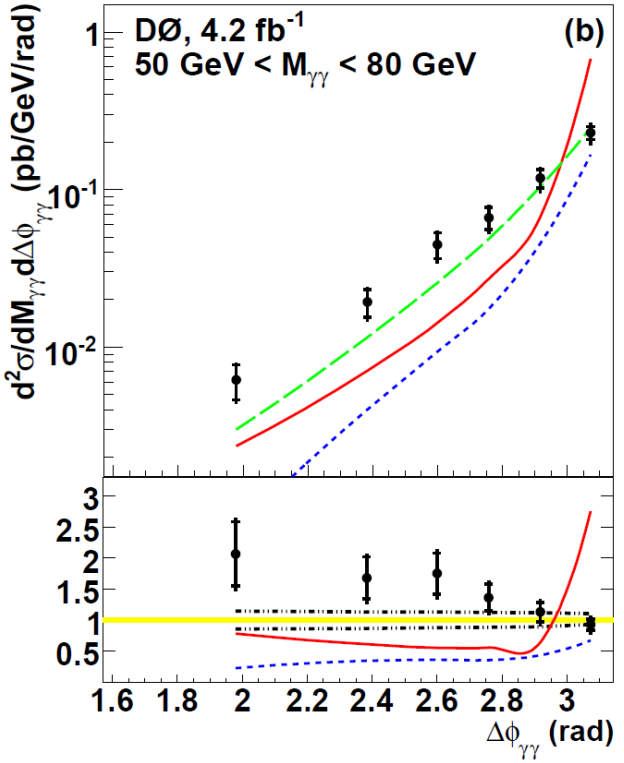


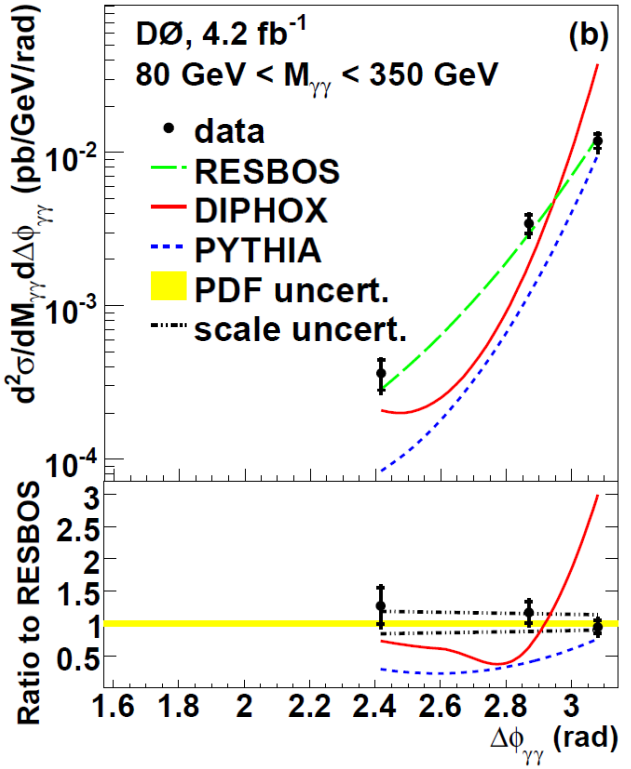
+ fragmentation
(reduced by isolation)



➔ First measurement of double differential cross sections





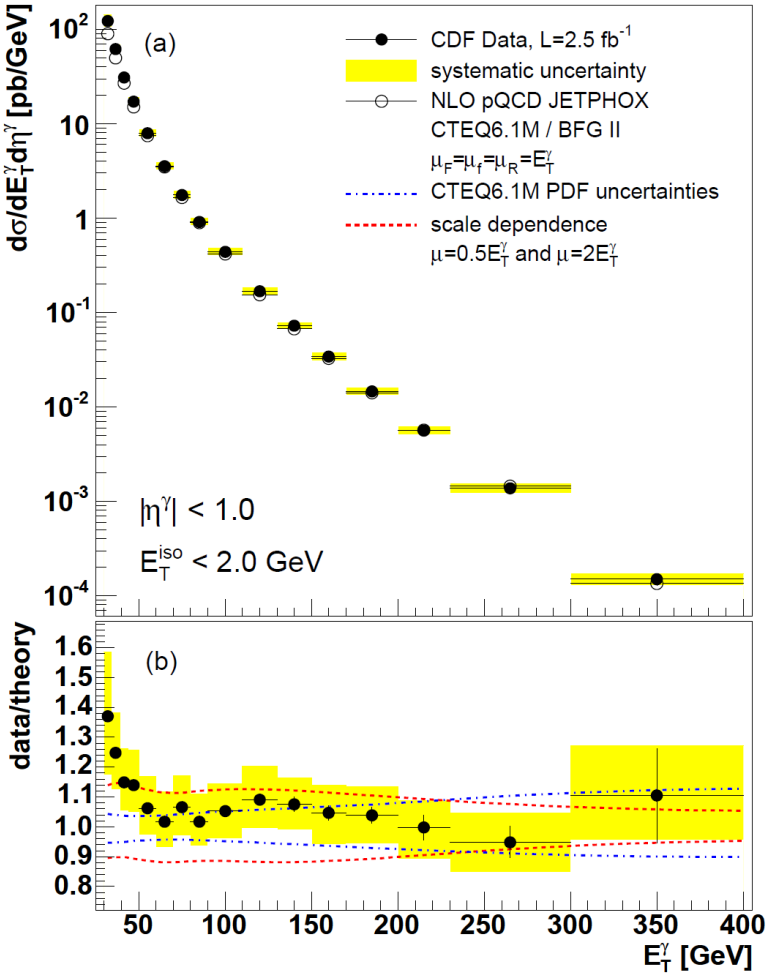


➔ No theoretical prediction describes data in the whole phase space

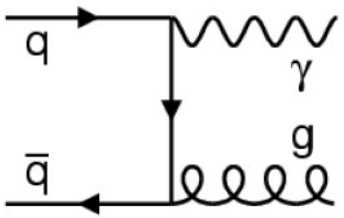
➔ Needs of NNLO ? Miss-modeling of fragmentation at low mass ?

[D0, arXiv:1002.4917]

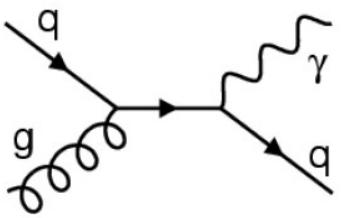
Inclusive Isolated photon at Tevatron



$$p\bar{p} \rightarrow \gamma + X$$

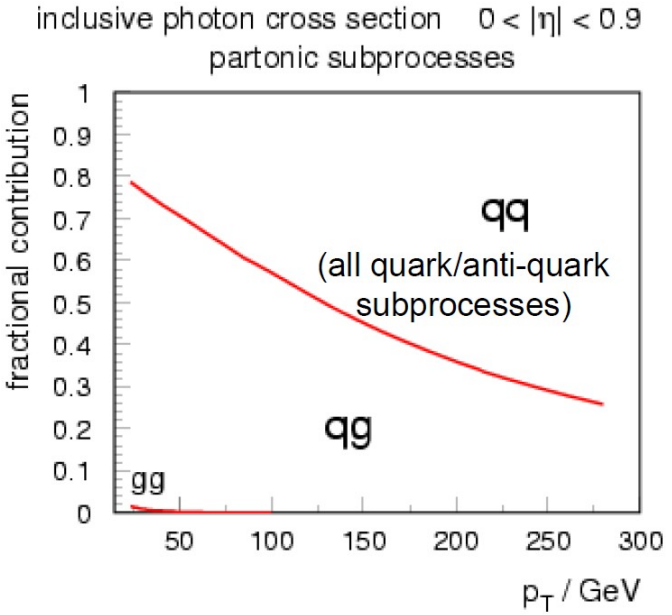


Annihilation



Compton

+ fragmentation



➔ Discrepancy at low E_T

➔ Experimental and theory uncertainties
~ PDF uncertainty

➘ No sensitivity to PDFs yet

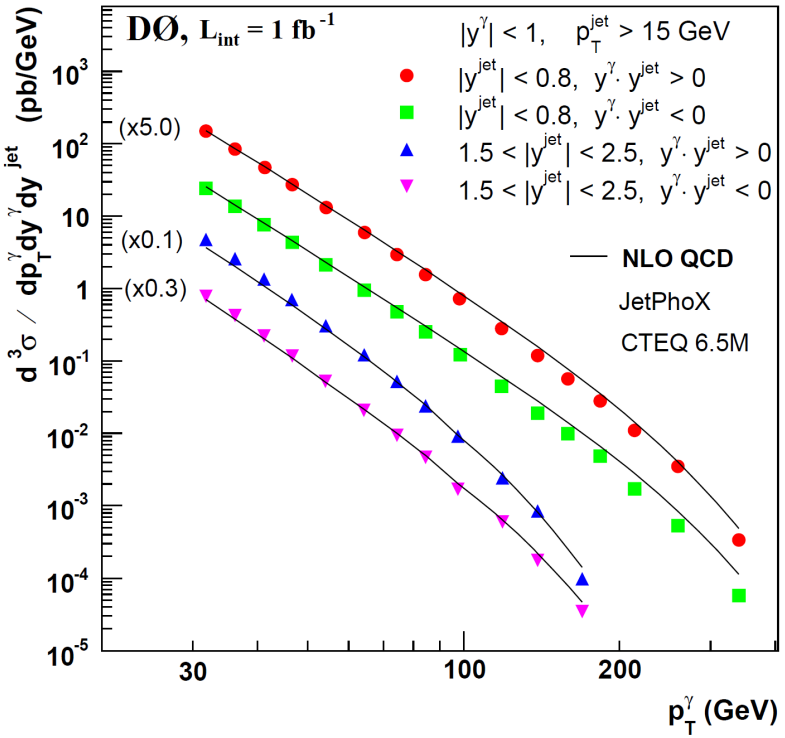
[CDF, PRD80 (2009) 111106]

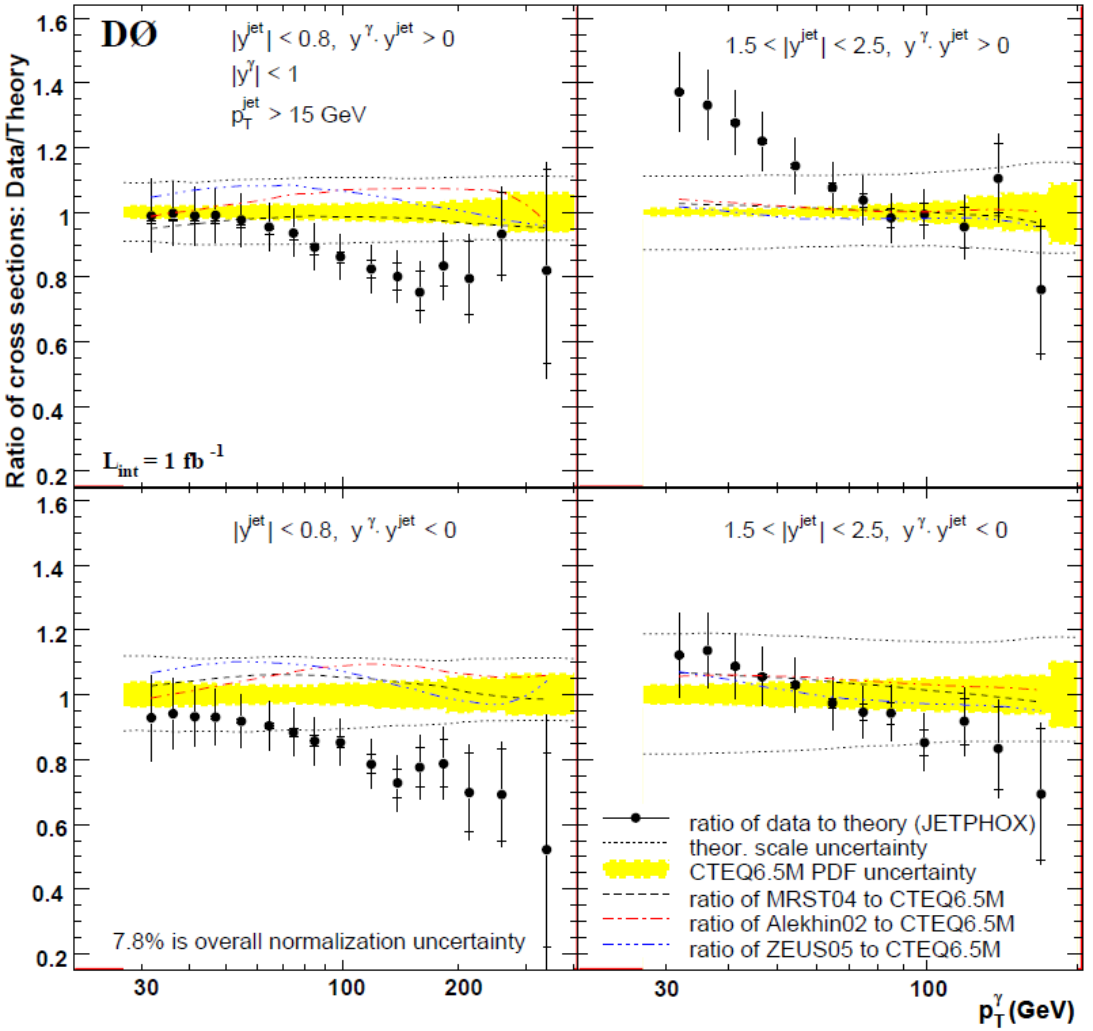
Prompt photon + jets at Tevatron

$$p\bar{p} \rightarrow \gamma + \text{jet} + \text{X}$$

- Measurement as a function of P_T^{γ} for different γ and jet rapidities

➔ Different angular configurations test different x and Q^2 regions



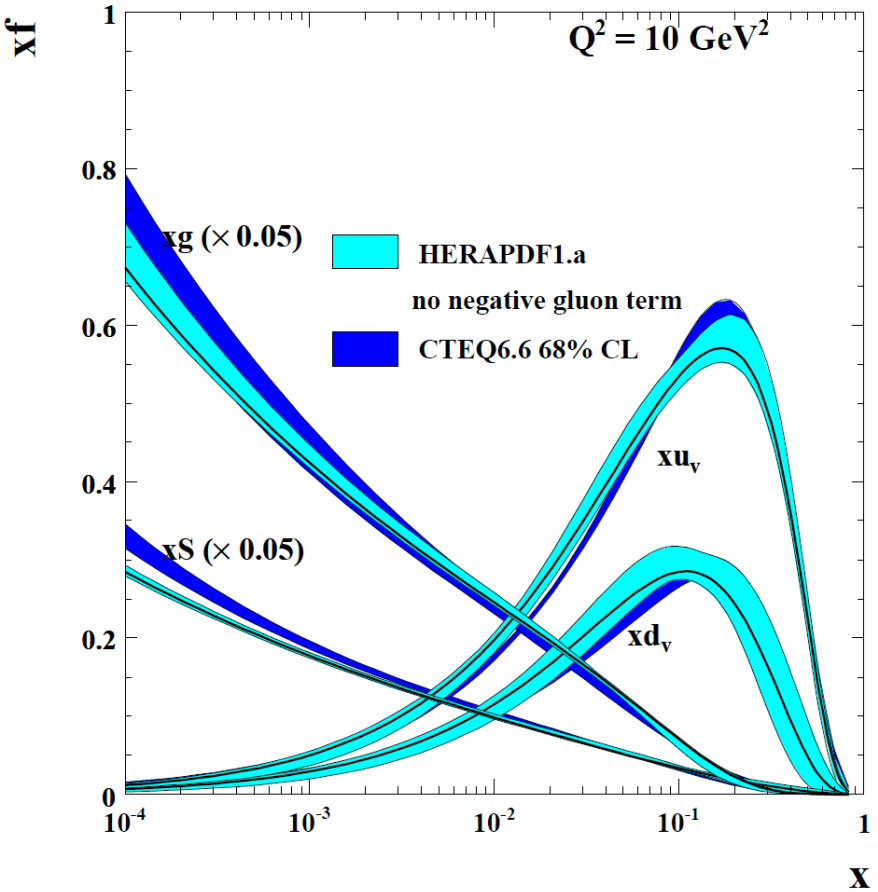


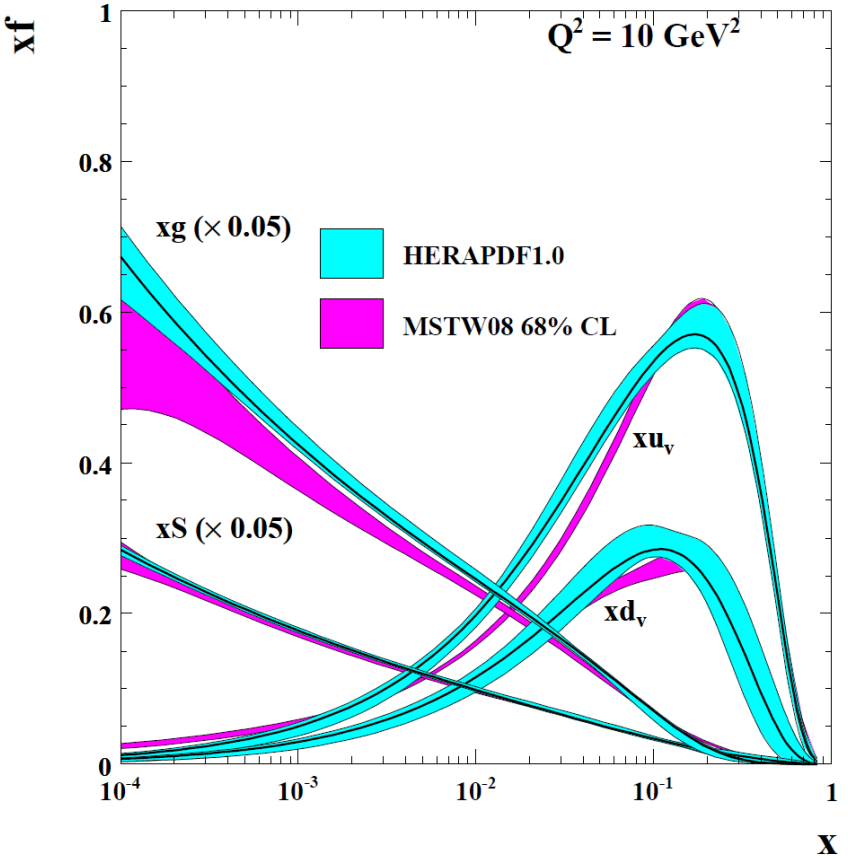
➔ Data not described by NLO predictions + different PDF sets

➘ Theory improvements needed

[D0, PLB666 (2008) 1435]

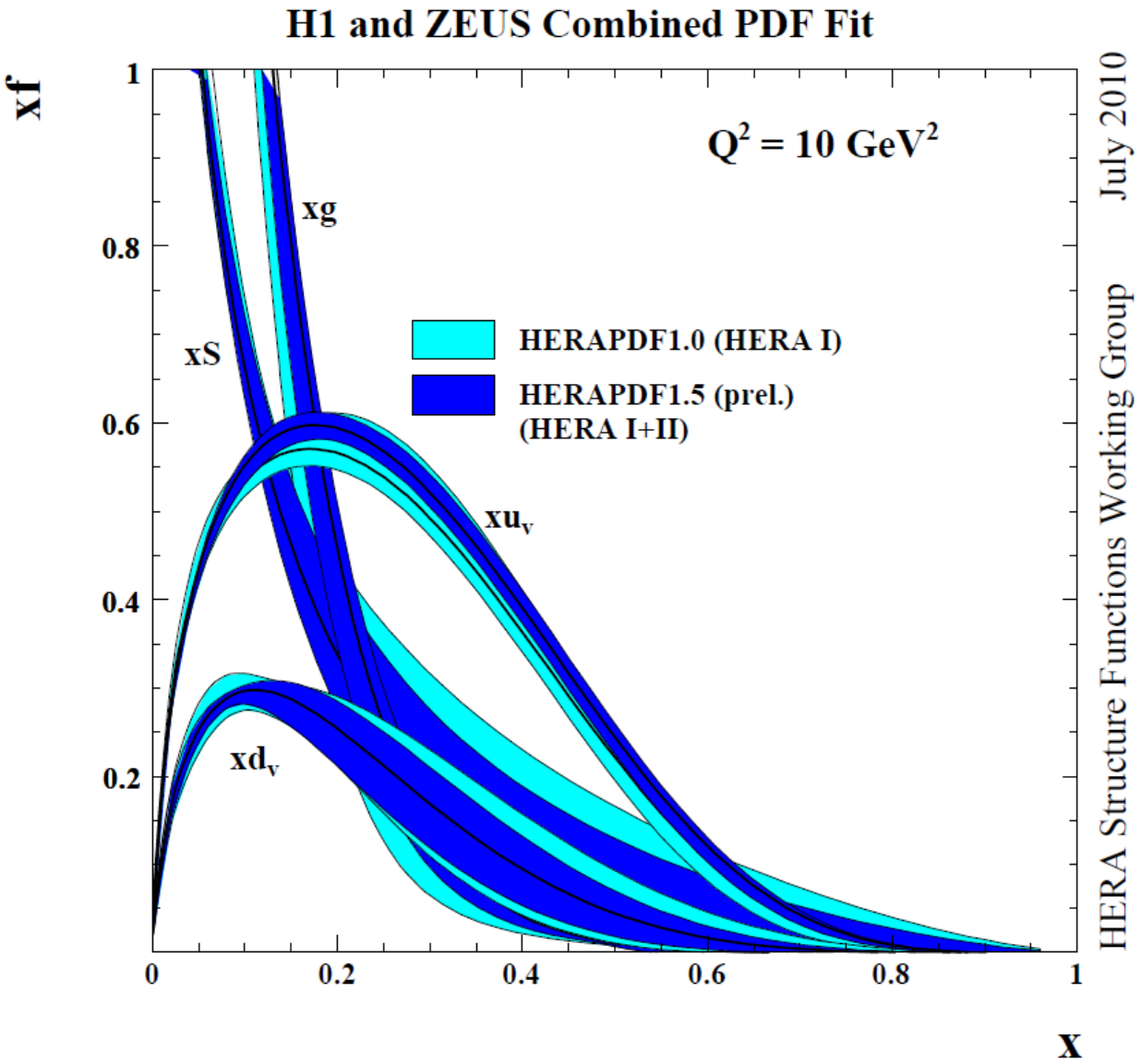
HERAPDF1.0 vs. Global Fits



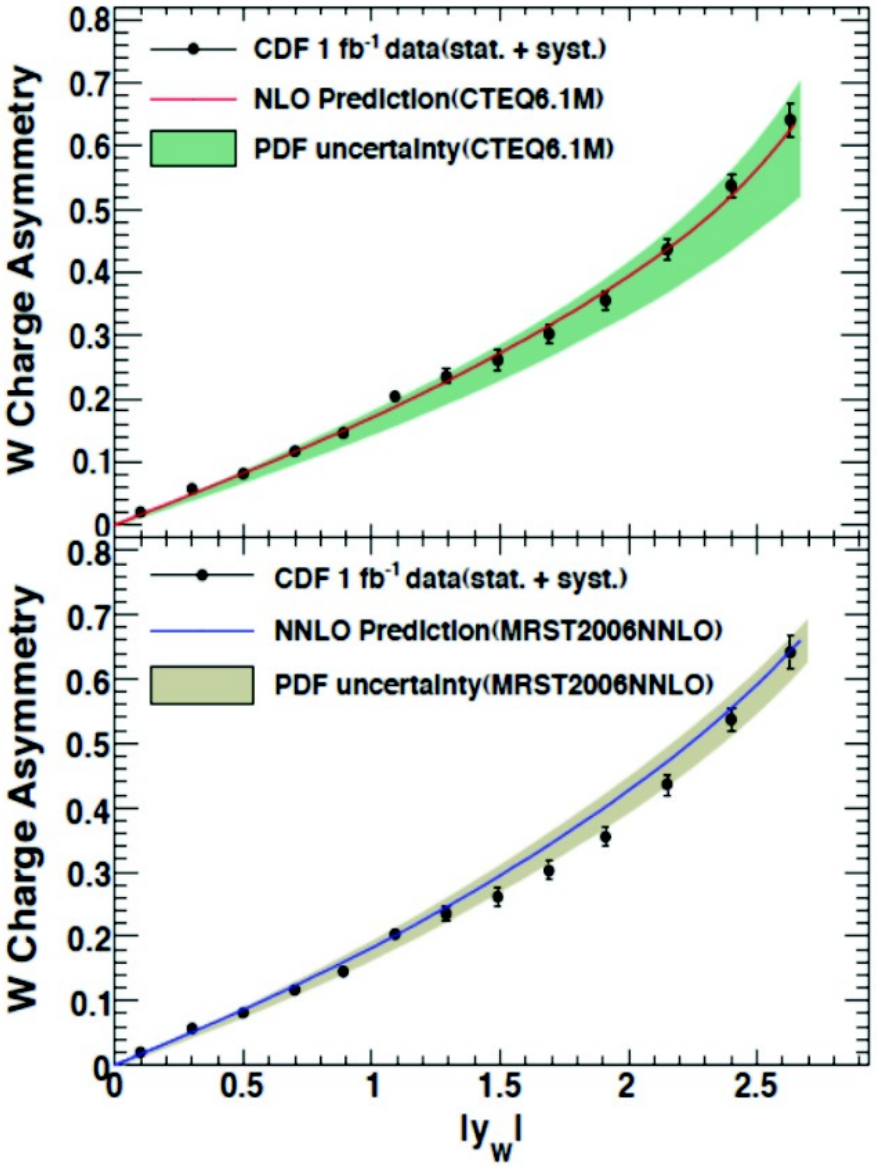


HERAPDF1.5

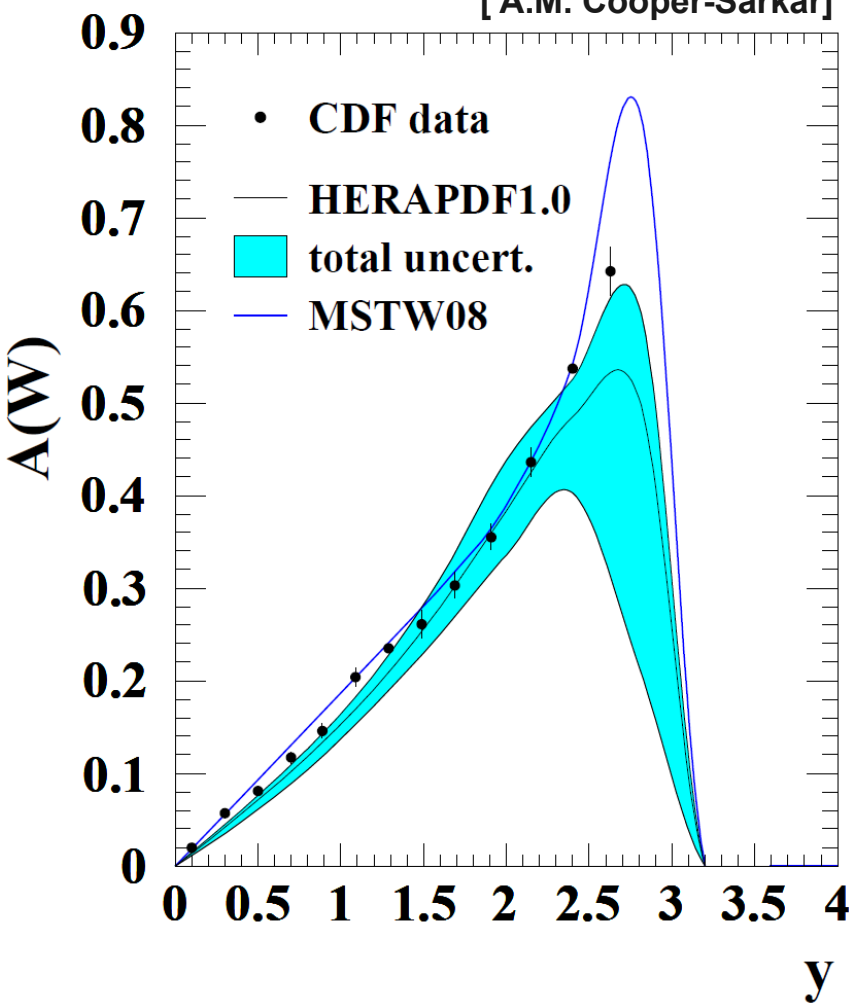
- Errors reduced on the valence and sea
- Sea is much softer at high x



W asymmetry at the Tevatron



[A.M. Cooper-Sarkar]



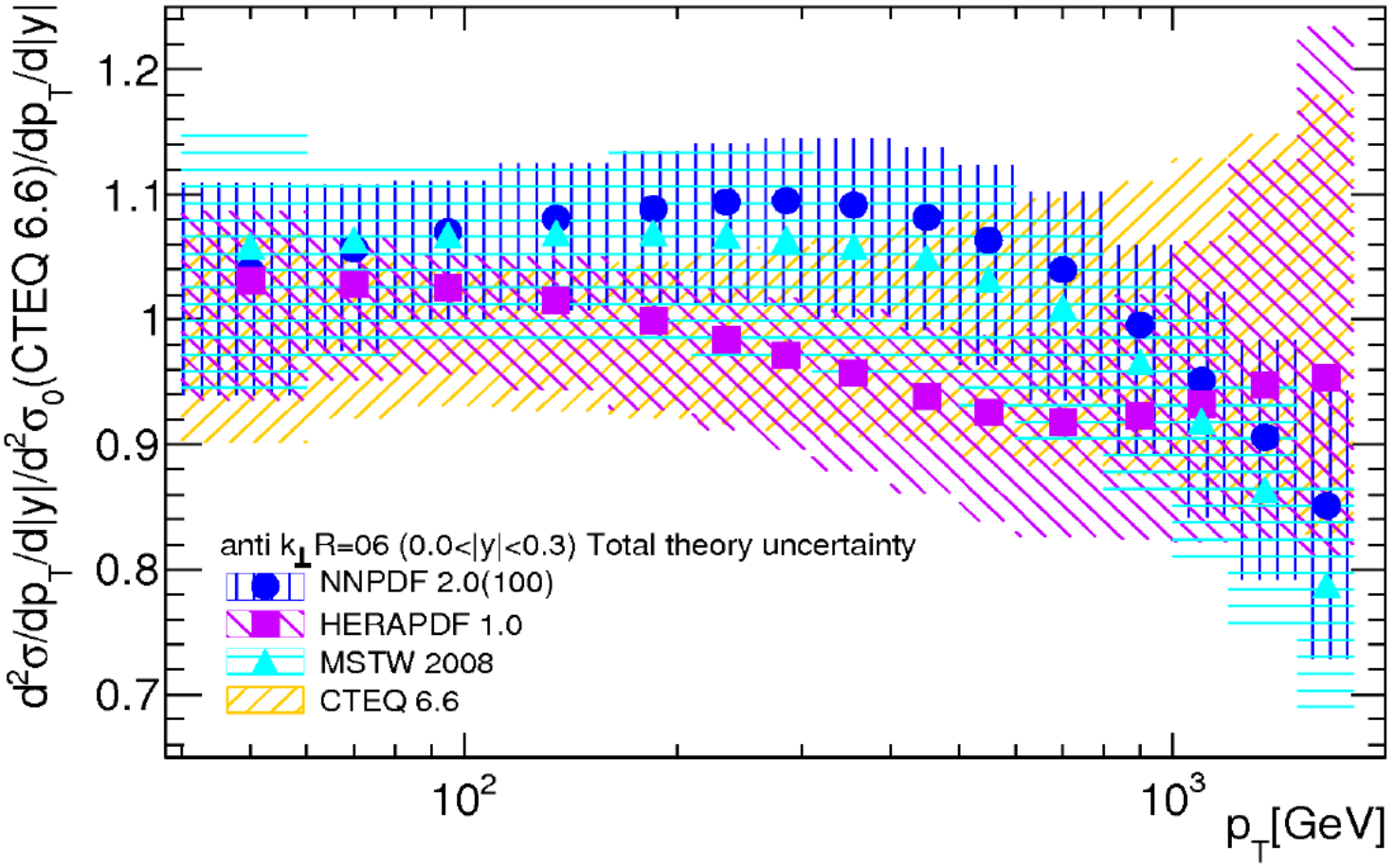
Jets at the LHC

[T. Carli]

NLO QCD Theory Calculation

Perturbative Predictions:

NLO pQCD calculated with NLOJET++,
efficient uncertainty calculation using: APPLGRID
default PDF: CTEQ6.6 variations: HERAPDF, MSTW2008, NeuralNet-PDF
Leading jet Pt as renormalisation and factorisation scale, independently varied by factor of 2



Theory uncertainty about 10% over measurable $P_{T,jet}$ range