Philadelphia, August 3rd, 2008

QCD Experiment I

Structure Functions

Cristinel DIACONU

CPP Marseille & DESY

Outline

- Introduction
- News from HERA:
  - combined data and fits, F_L, heavy flavours
- Constraints from pp collisions at Tevatron
  - jets, W/Z
- Spin Measurements
- Conclusions

Not discussed:Diffraction, VM, photoproduction, strangeness,...
More on jets and photons in the next talk (C.Glasman)

A short experimental history

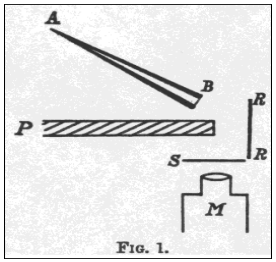
~100 years ago

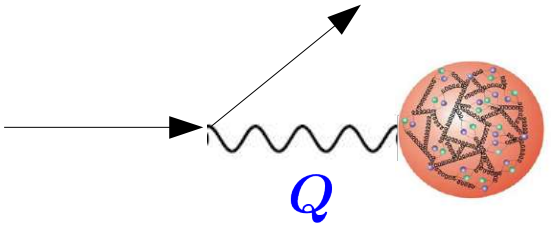
α-Au

Geiger, Marsden. (1909)

Rutherford(1911)

E_α=5.5 MeV





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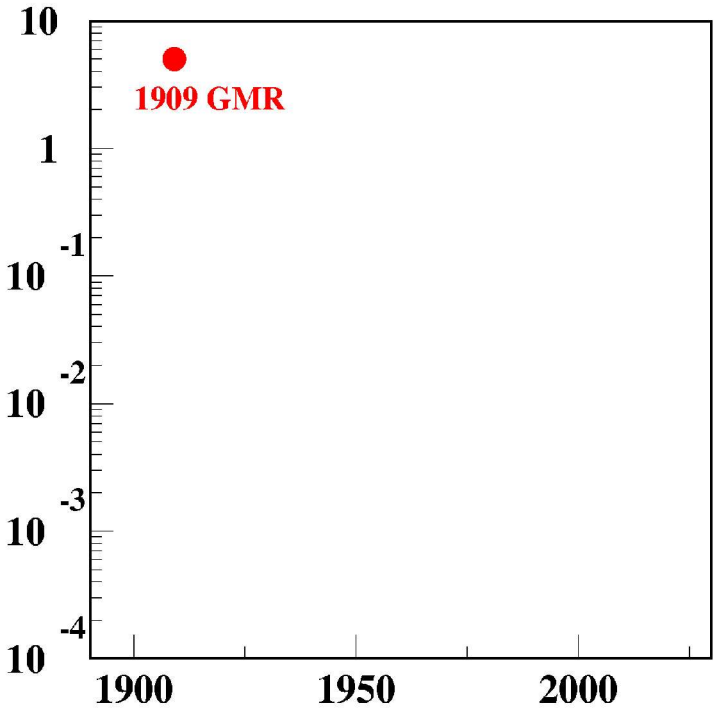

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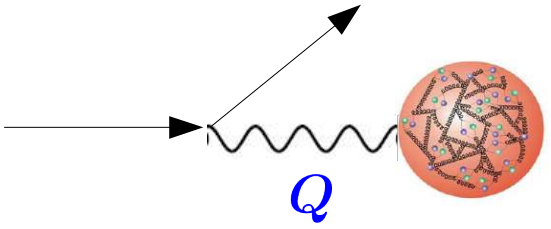

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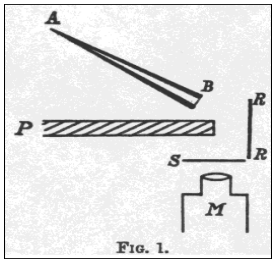

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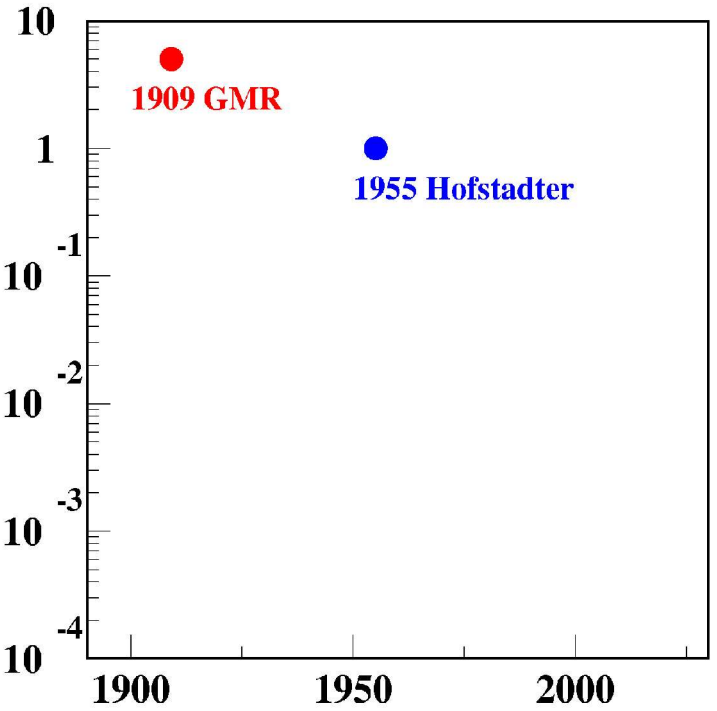
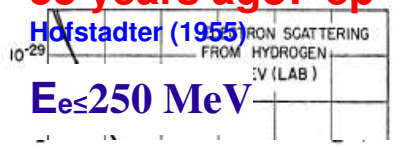


53 years ago: ep

Hofstadter (1955)

$E_e \leq 250$ MeV



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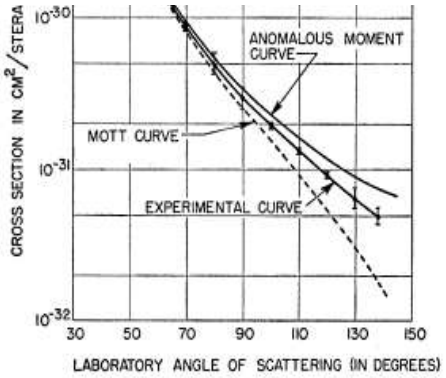

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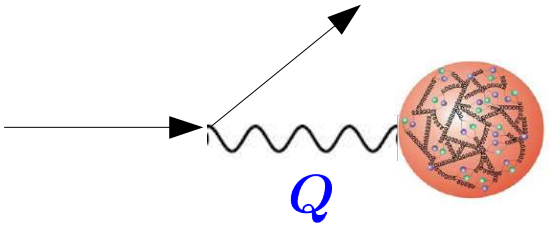

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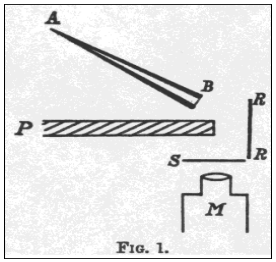

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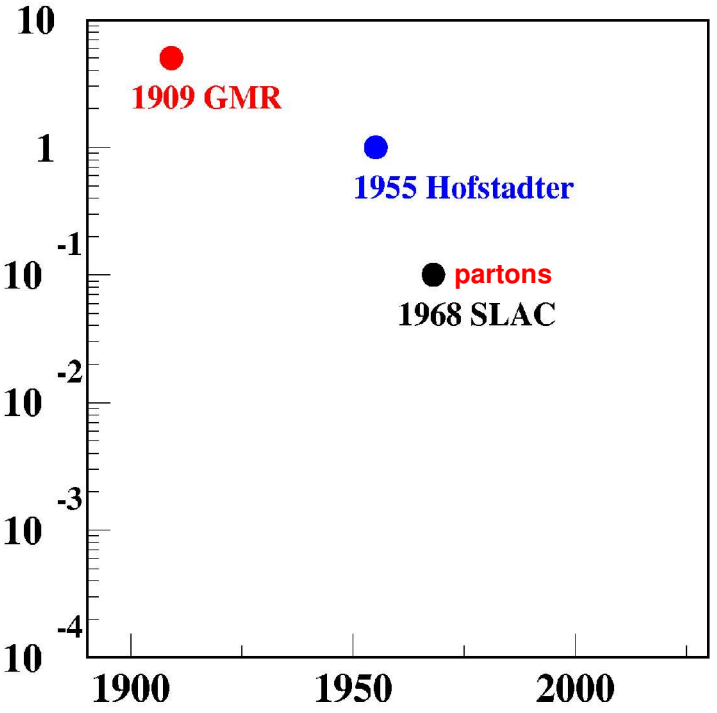
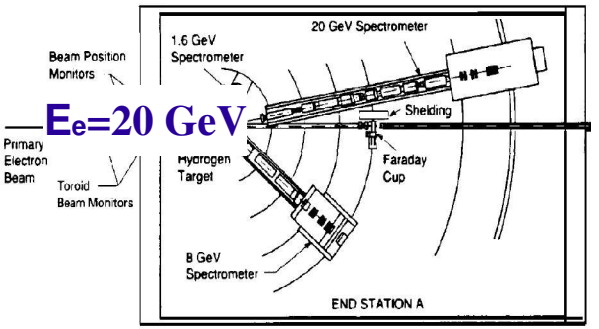


40 years ago ep: partons



E_e=20 GeV

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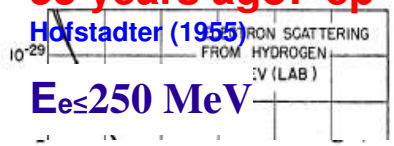

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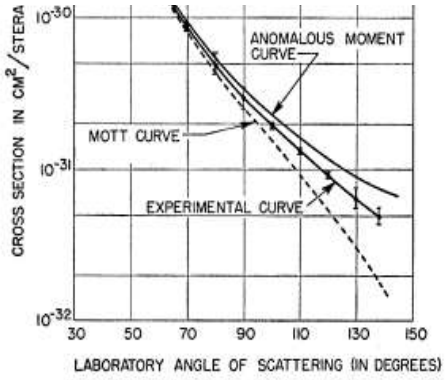

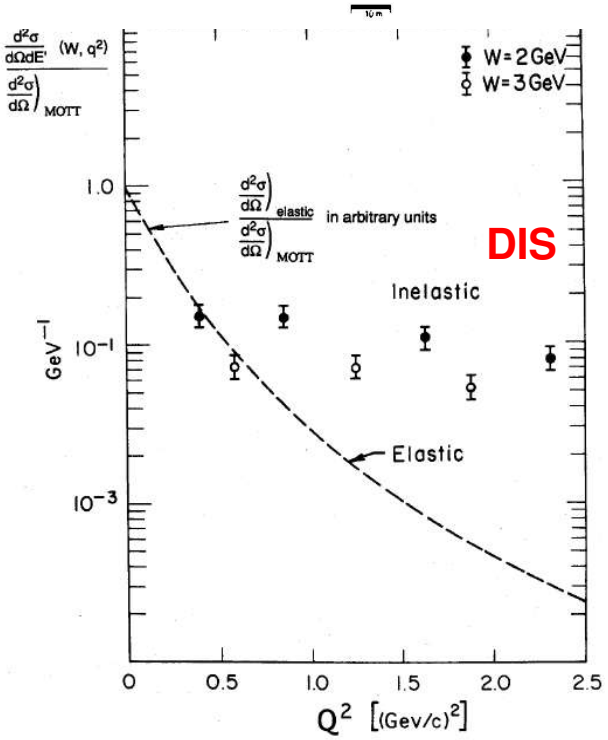

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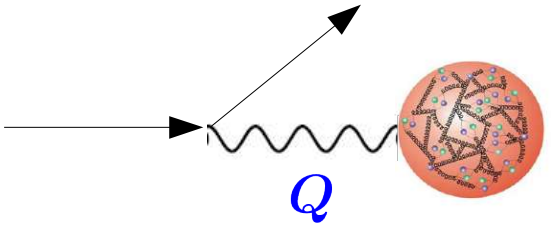

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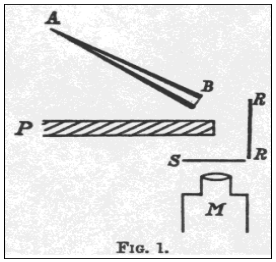

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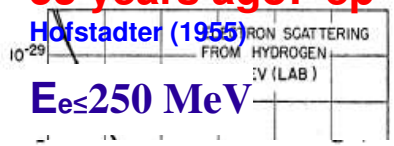

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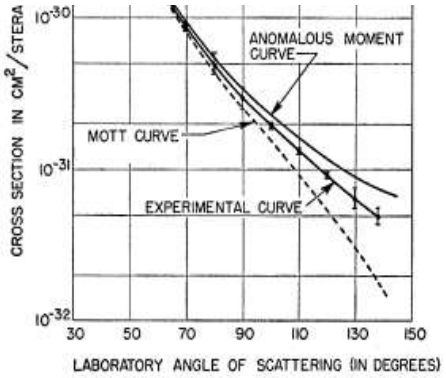
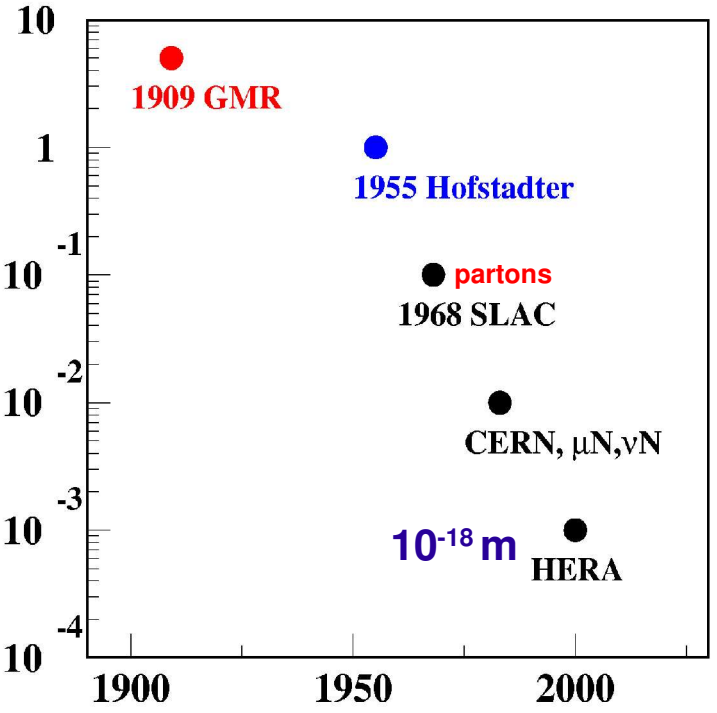
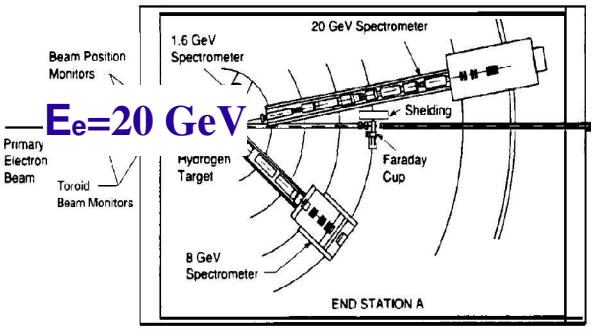


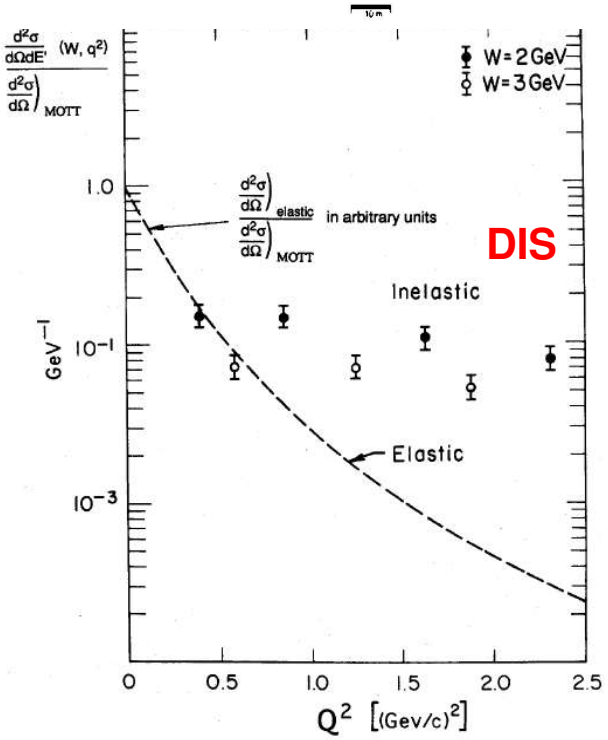


[polarised collisions since mid 70's]

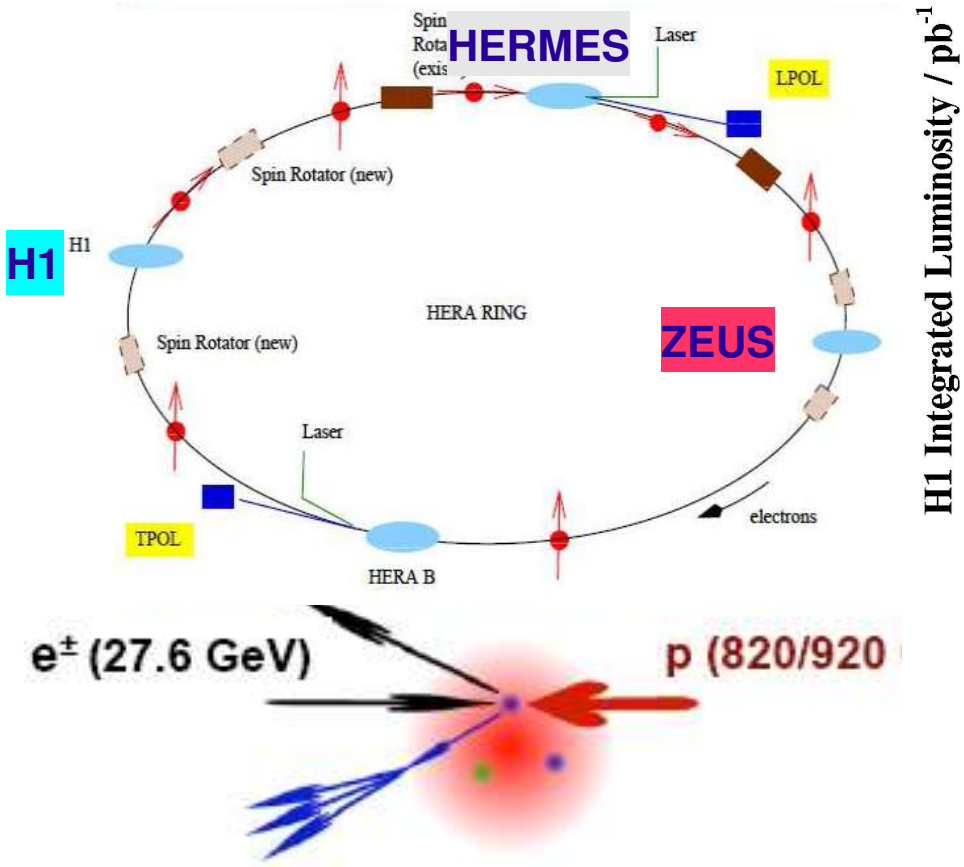
40 years ago ep: partons

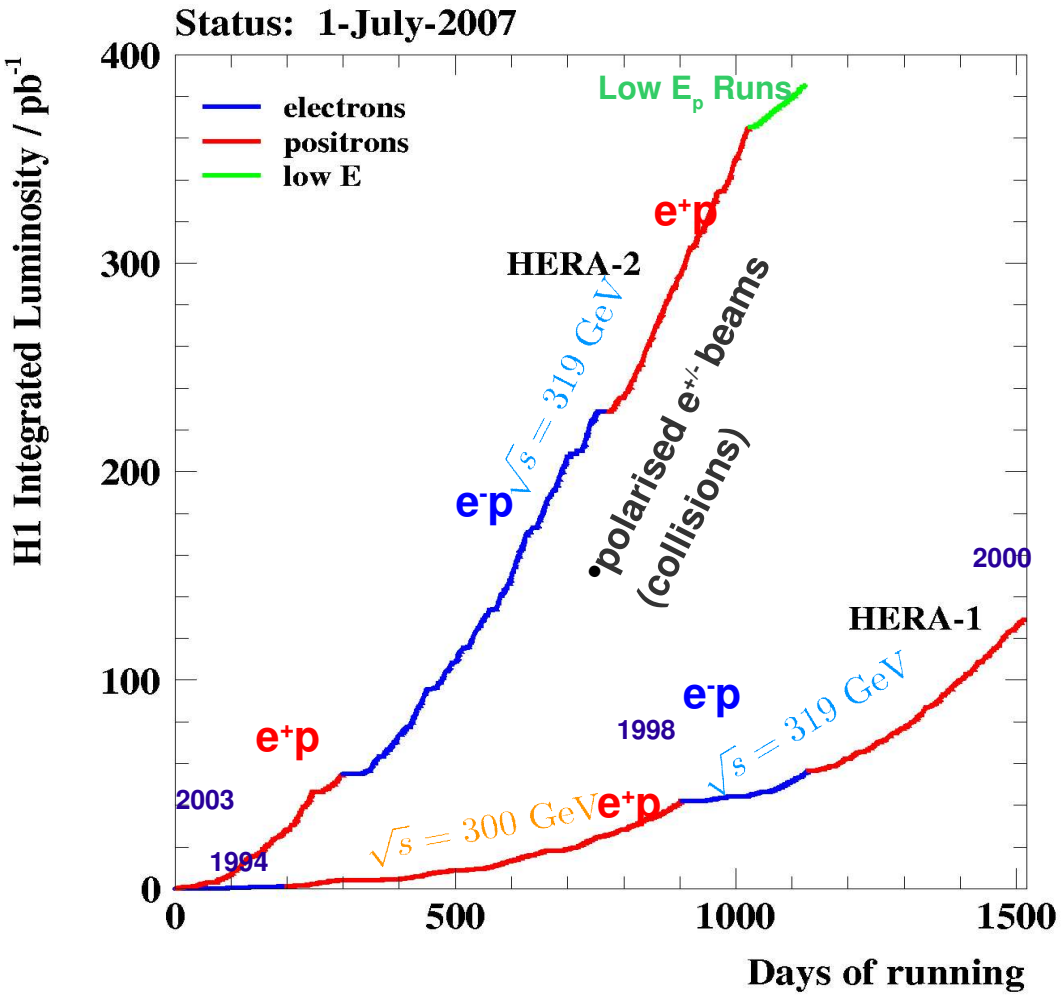


E_e=20 GeV



HERA Collider: end in 2007





- HERA 1: 1992-2000 ~120 pb^{-1}/expt
- HERA 2: 2003-2007

H1 ZEUS ~200 pb^{-1} e$^-$p

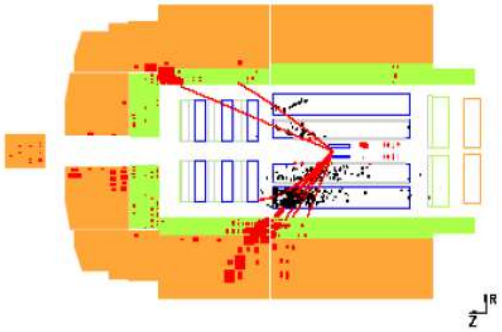
~300 pb^{-1} e$^+$p

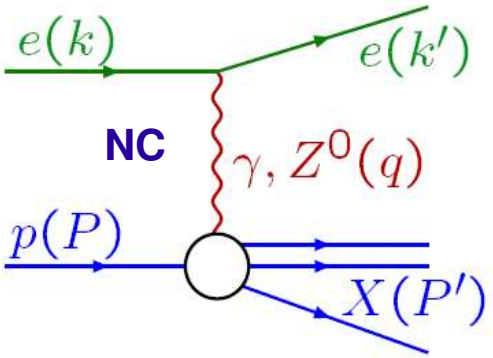
Low proton energy runs in 2007

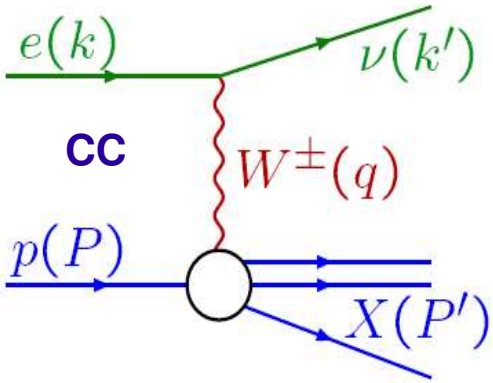
End of beams: June 30, 2007

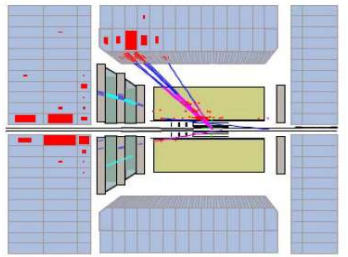
Deep-Inelastic Scattering (DIS)

Partons = Quarks (+ Gluons = QCD improved quark parton model)









$$Q^2 = -q^2 = -(k - k')^2$$

Boson Virtuality=1/Resolving power

$$x = \frac{Q^2}{2qP}$$

Momentum fraction of the scattered parton (Bjorken Scaling variable)

$$y = \frac{Q^2}{xs}$$

Inelasticity

DIS: Cross sections, structure functions, partons

$$e^{\pm}p \; : \tilde{\sigma}^{\pm}_{NC} = \frac{\mathrm{d}^2\sigma^{e^{\pm}p}_{NC}}{\mathrm{d}x\mathrm{d}Q^2}\frac{xQ^4}{2\pi\alpha^2 Y_+} = \tilde{F}_2 - \frac{y^2}{Y_+}\tilde{F}_L \mp \frac{Y_-}{Y_+}x\tilde{F}_3, \quad Y_\pm = 1 \pm (1-y)^2$$

Leading Order picture of the proton

F_2 $\left[F_2, F_2^{\gamma Z}, F_2^Z\right] = x\sum_q \left[e_q^2, 2e_q v_q, v_q^2 + a_q^2\right](q + \bar{q})$ **quarks**

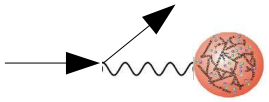
F_3 $\left[xF_3^{\gamma Z}, xF_3^Z\right] = 2x\sum_q \left[e_q a_q, v_q a_q\right](q - \bar{q})$ **(valence) quarks**

F_L $F_L = 0 (\sim x\alpha_s g \text{ at NLO})$ **gluons**

CC: similar decomposition, but different quarks combinations accessed

flavour sensitive (separate in e+p/e-p)

The PDF's mechanics: factorisation and evolution



$$\sigma_{DIS} \simeq F_2 \equiv \mathcal{C}_{\mathrm{lepton-parton}} \otimes f(x,Q^2)$$

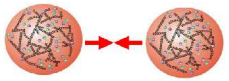
q,g

perturbative QCD

non-perturbative

Theory developed to NNLO
[W.van Neerven (†), J.Vermaseren, et al]

factorisation



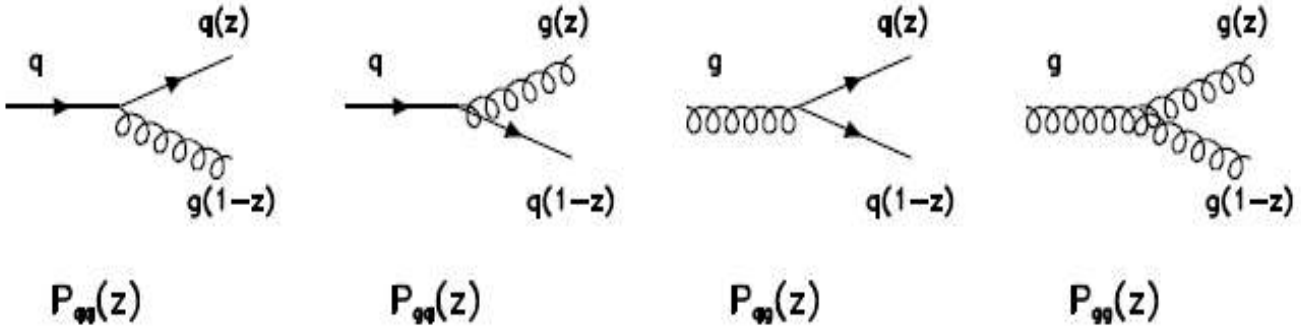
$$\sigma_{pp\to FS} \equiv \mathcal{C}_{\mathrm{parton-parton}} \otimes f(x,Q^2) \otimes f(x,Q^2)$$

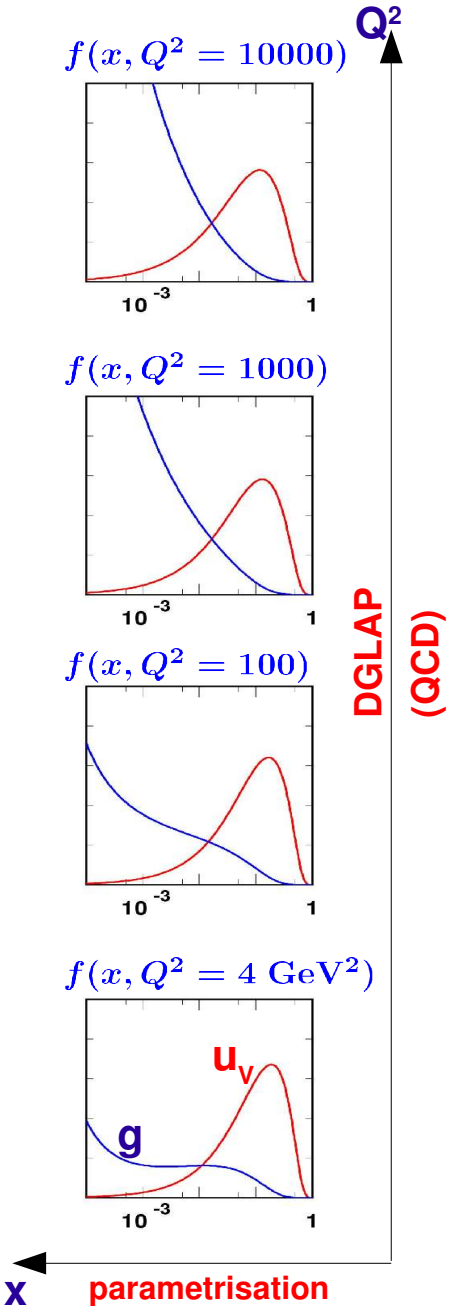
||

$E^2_{\text{CM parton-parton}}$

$f(x,Q^2)$ **Evolution in Q² calculable in QCD (DGLAP):**

$$\frac{\partial}{\partial Q^2} f_i(x,Q^2) = \sum P^{i,j} \otimes f_j(x,Q^2)$$





DIS versus hadronic colliders

Example:

pp: W (at rest) corresponds to

$Q2=M_W^2$ =6400 GeV^2

x=0.005 for LHC

x=0.2 for Tevatron

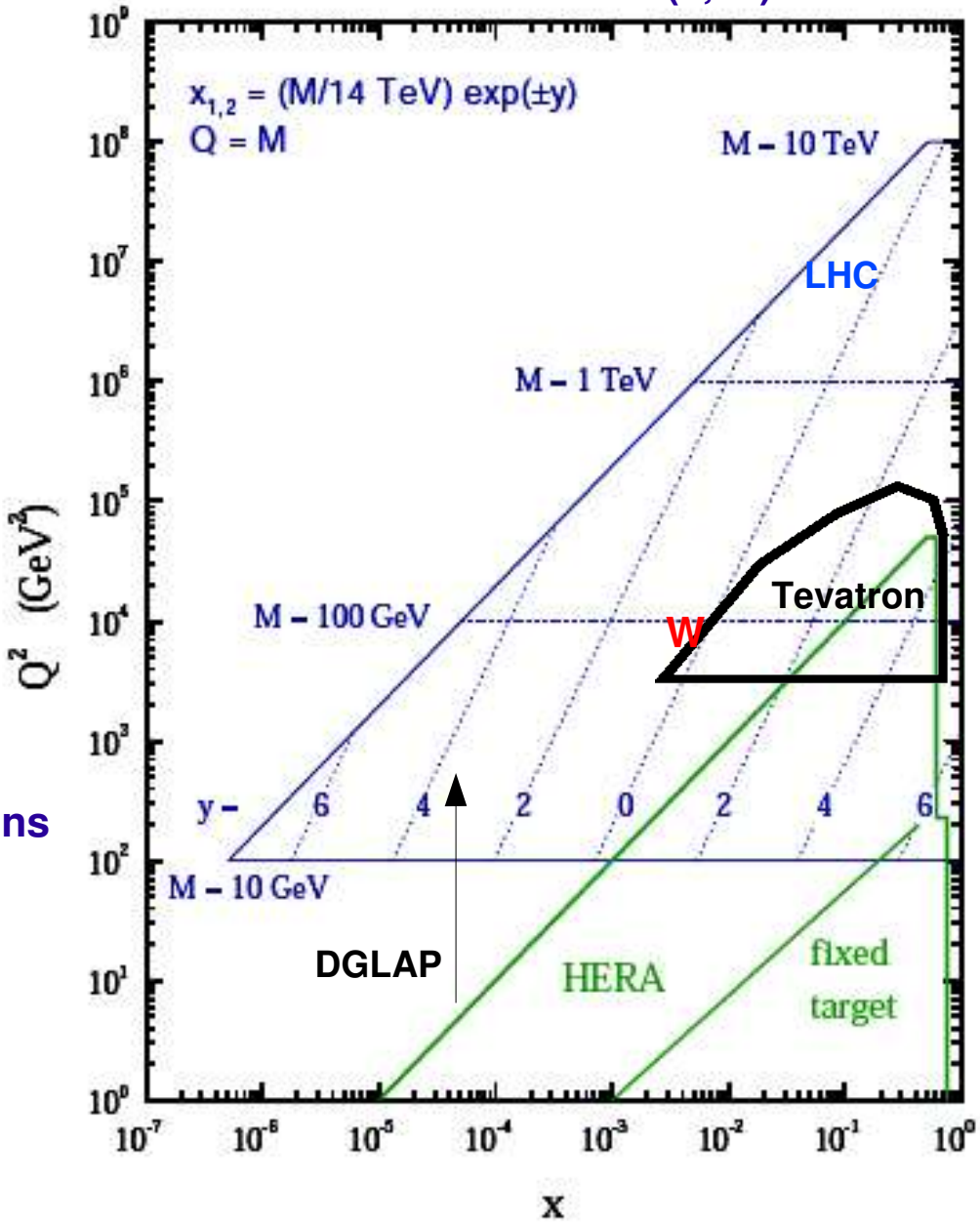
For M=1 TeV (LHC) x>0.005

DIS data is the support for LHC predictions

-beware the very low x

Improvements from Tevatron at high x

Kinematic Plane (x,Q^2)



The data for PDF's

Process	Experiments	Constraints
DIS Collisions	H1,ZEUS	q,g
DIS Fixed Target	BCDMS, NMC,E665,SLAC	q,g
pp collision :jets, W/Z asym.	CDF,D0	g, u/d at high x
DIS neutrino-N	NuTev,Chorus,CCFR	q,g (s)
pp/pN Drell Yan	E605,E702, E866/NuSea	q,g

Global fits: determination of PDF's using the available data sets

[Ex: MSTW08 uses 2743 measurements]

MSTW, CTEQ, AKP, NNPDF (DIS data), HERAPDF (HERA averaged data, see later)

PDF4LHC: Common effort to converge on technical and physics issues

Difficult issues:

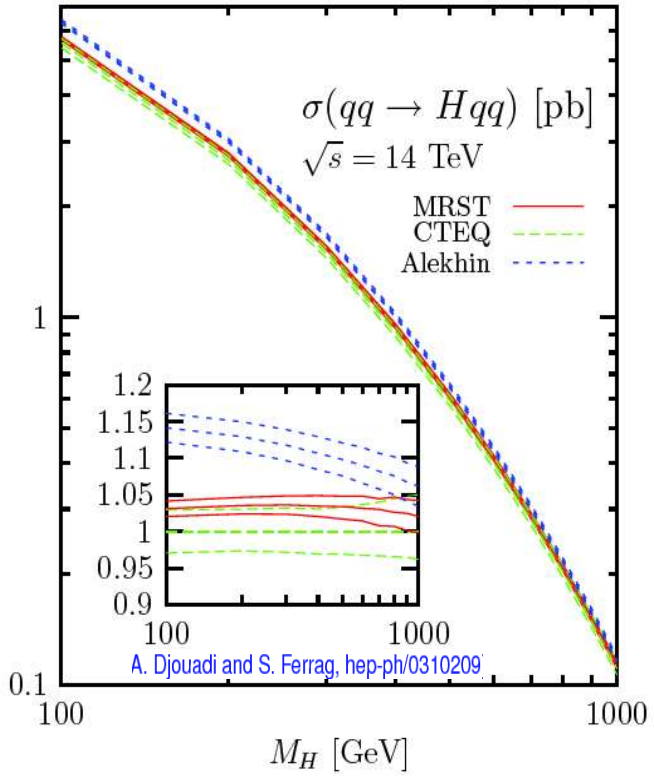
"model": low x, parametrisation, flavour/sea-valence decompositions...

data: "tensions" between data sets, tolerances

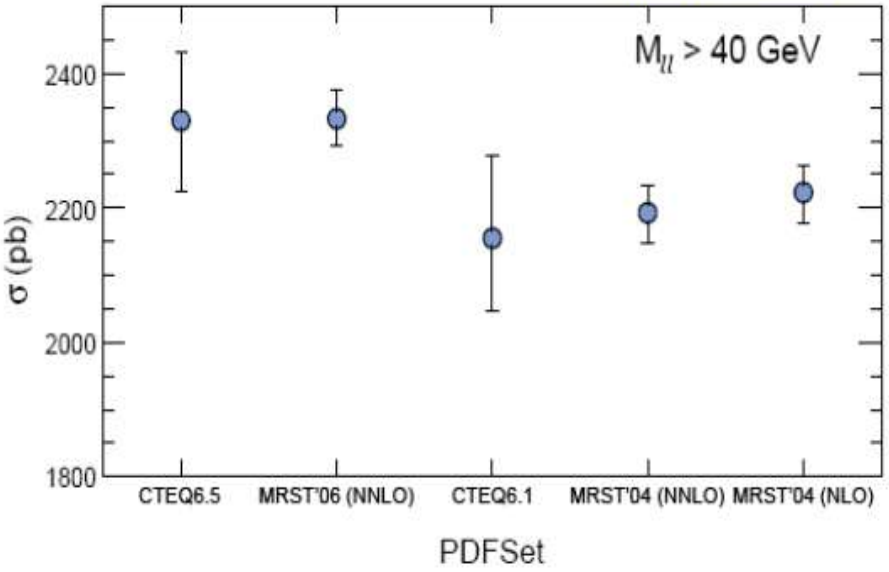
=> PDF uncertainties (determined in some global fits with $\Delta\chi^2$=~40 or more)

Predictions for LHC, some examples

$qq \to Hqq$



$pp \to Z \to \ell^+\ell^-$ N.Adam et al. arXiv:0802.3251



Total Theoretical Uncertainty (%)

Uncertainty	Cross-Section $\Delta\sigma$	Acceptance ΔA
Missing O(α) EWK	0.38 ± 0.26	0.96 ± 0.21
Total QCD Uncertainty	1.51 ± 0.75	2.55 ± 0.79
PDF Uncertainty	3.79	1.32
Total Uncertainty	4.1 ± 0.3	3.0 ± 0.7

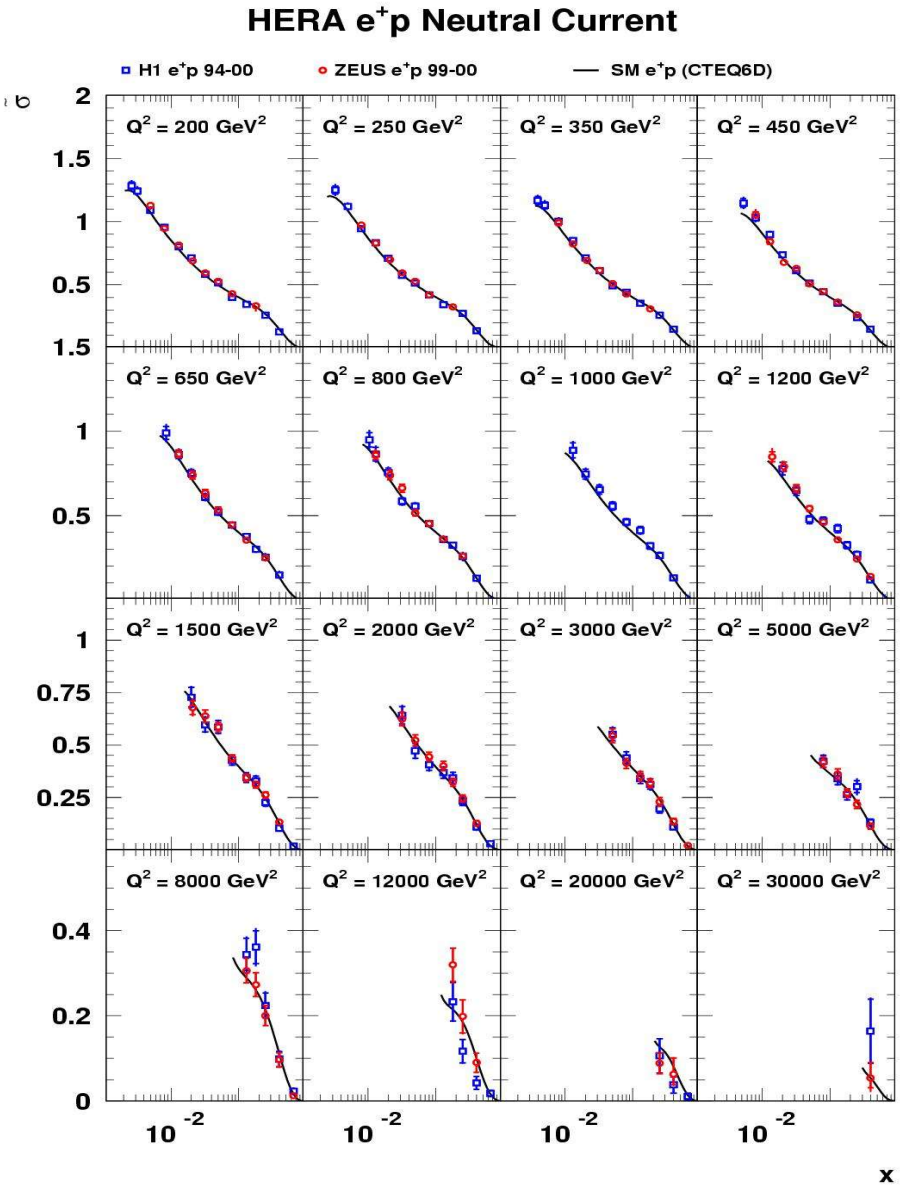
Various fits give incompatible results

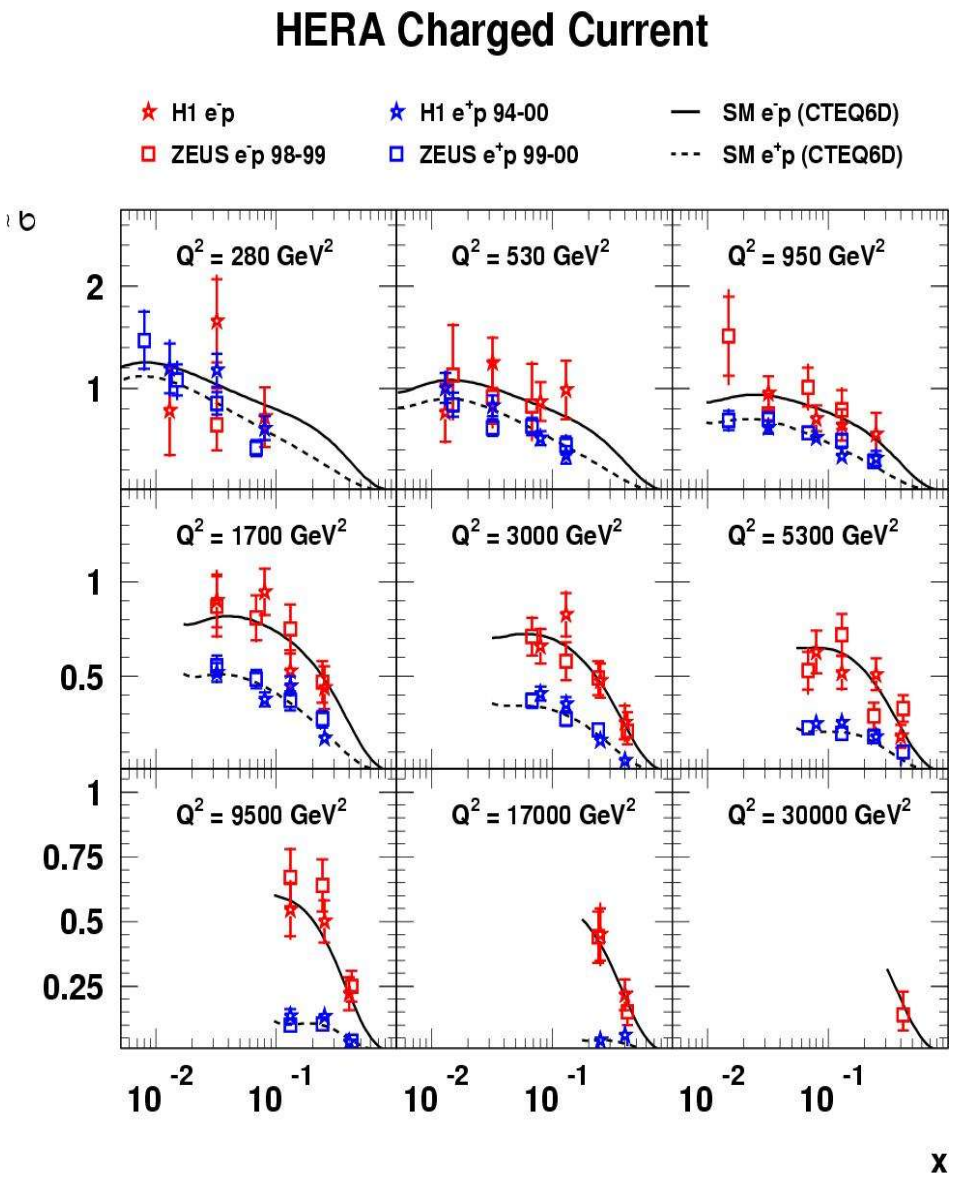
PDF error dominant for some standard signals

The variations in the P_T spectra due to PDF's can be limiting factor for non-resonant searches

More precise data for PDF's is the best medicine =>

DIS data from HERA





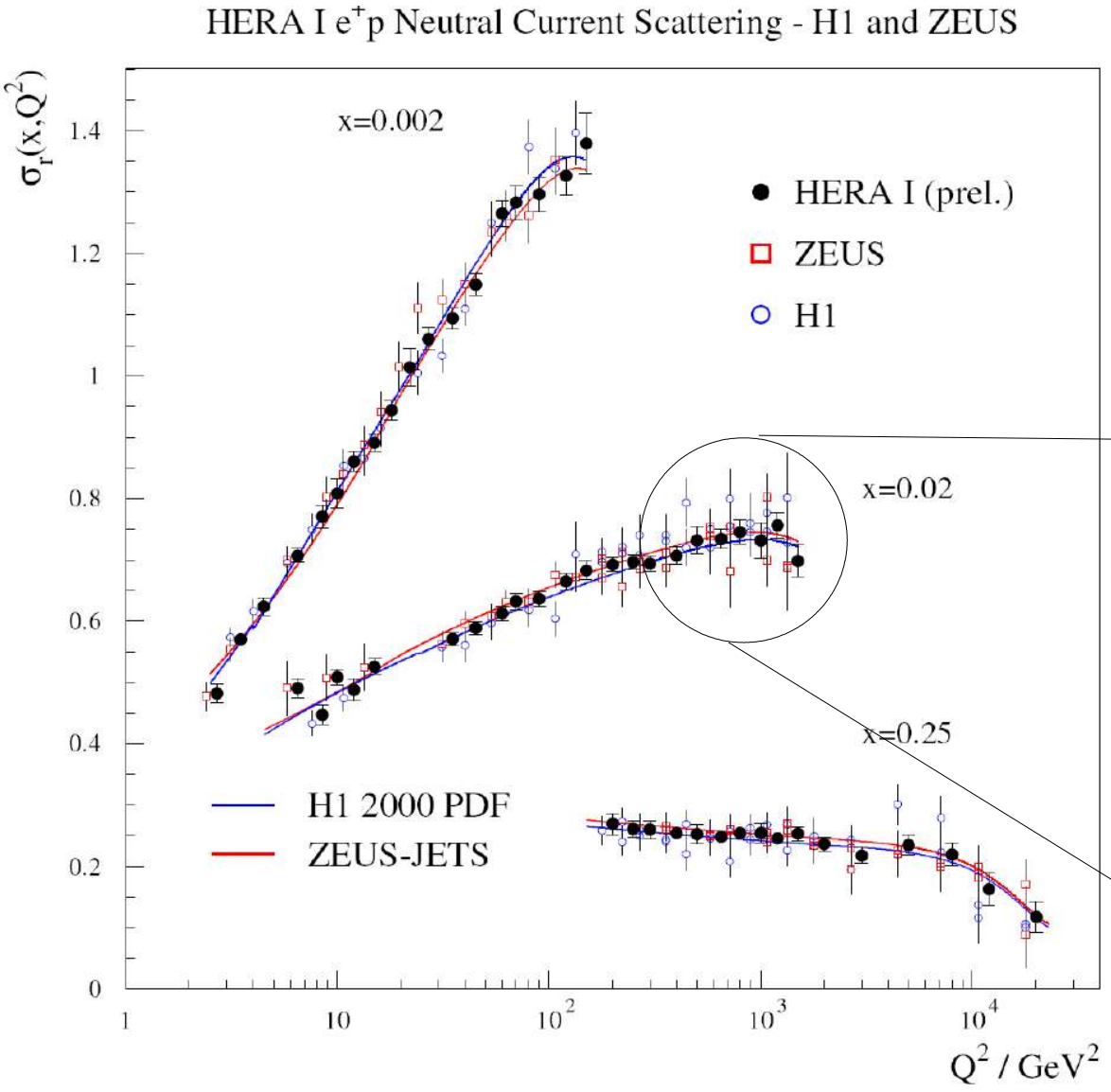
NC:precise and well in agreement with QCD

CC: provide flavour separation

H1/ZEUS data are compatible

H1-ZEUS cross section combinations

Coherent treatment of experimental effects in the average procedure (Lagrange multipliers method)



$$\chi^2(\{F_2^{true}\},\{\alpha\}) = \sum_i \frac{\left[F_2^{i,true} - \left(F_2^i + \sum_j \frac{\partial F_2^i}{\partial \alpha_j}\alpha_j\right)\right]^2}{\sigma_{F_2}^2} + \sum_j \frac{\alpha_j^2}{\sigma_{\alpha_j}^2}.$$

1153 individual NC/CC (HERA I data) averaged to 554 points

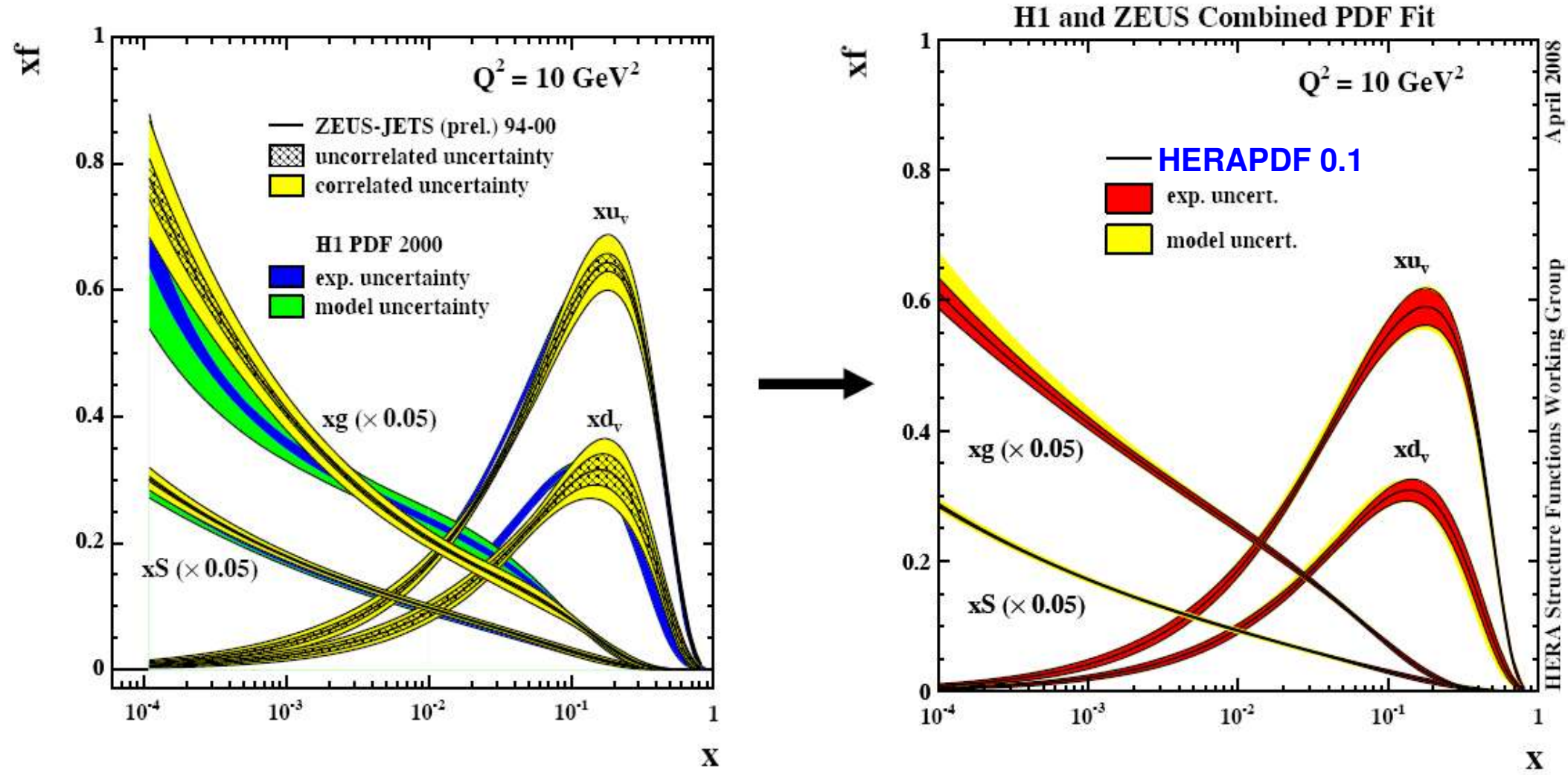
Improvements beyond the naively-expected sqrt(2): “cross calibration”

The common fit of the combined HERA I data

Partons parametrized at $Q_0^2 = 4$ GeV^2

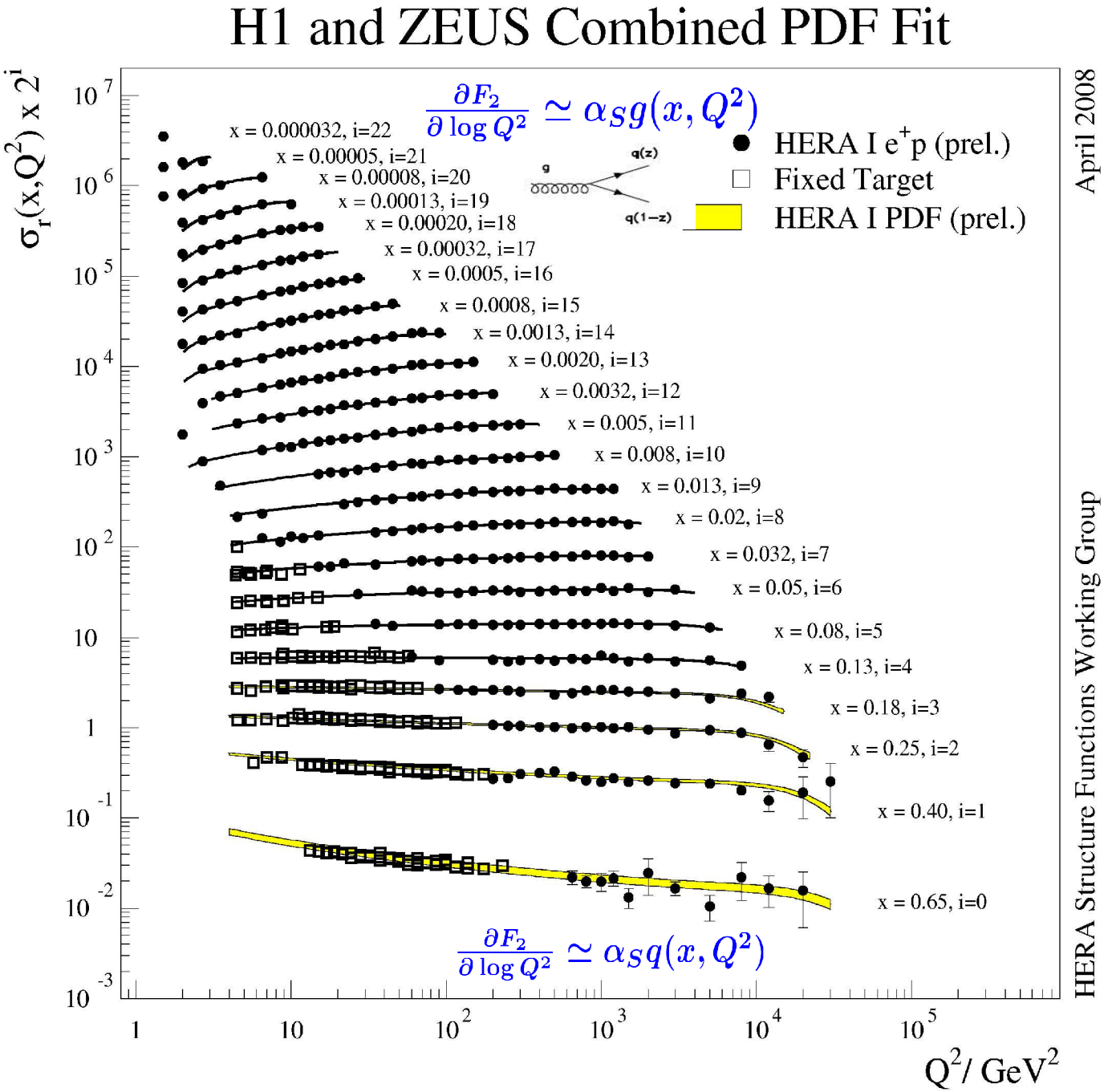
Experimental+Model uncertainties taken into account

Errors of the fit estimated using $\Delta\chi^2=1$



Improvement in precision is visible, originate mostly from data combination

The combined data compared to the fit



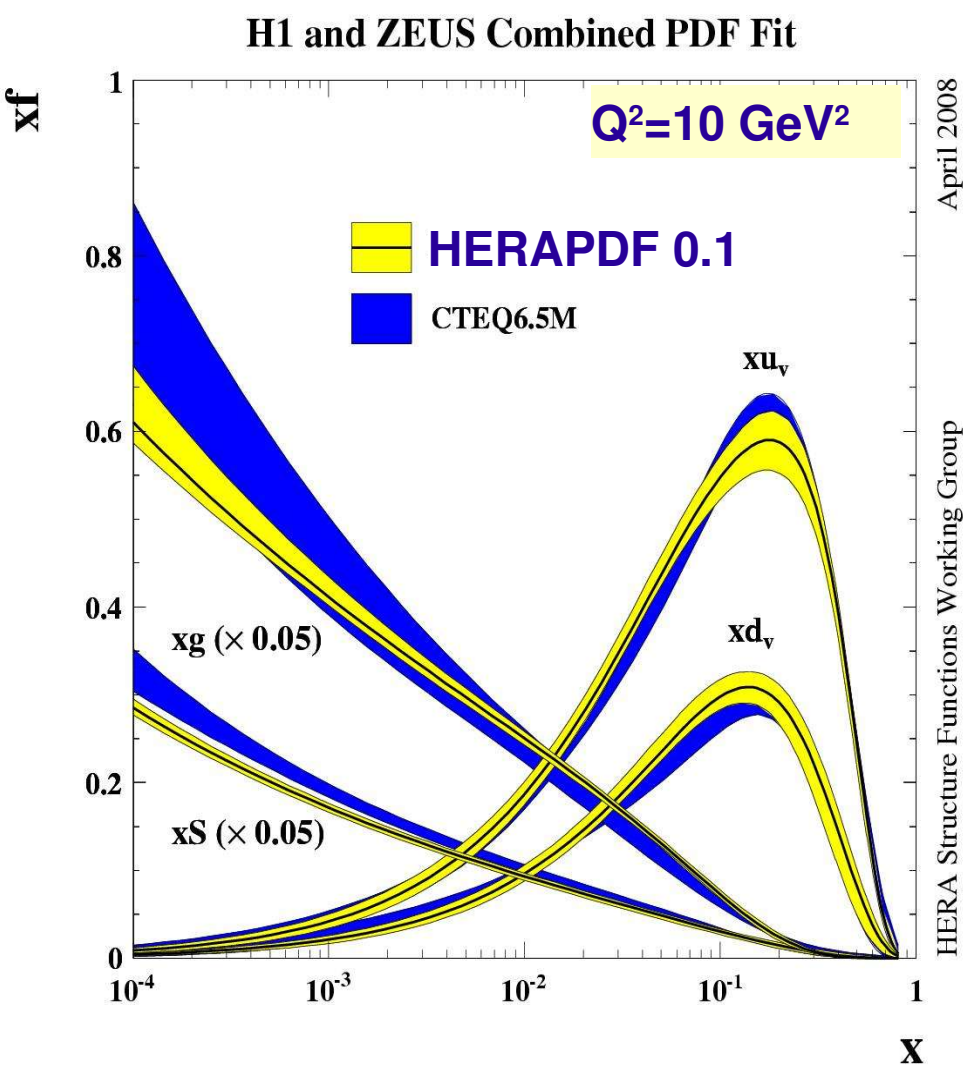
$$\tilde{\sigma}^{\pm}_{NC} = \frac{\mathrm{d}^2\sigma^{e^{\pm}p}_{NC}}{\mathrm{d}x\mathrm{d}Q^2}\frac{xQ^4}{2\pi\alpha^2 Y_+}$$

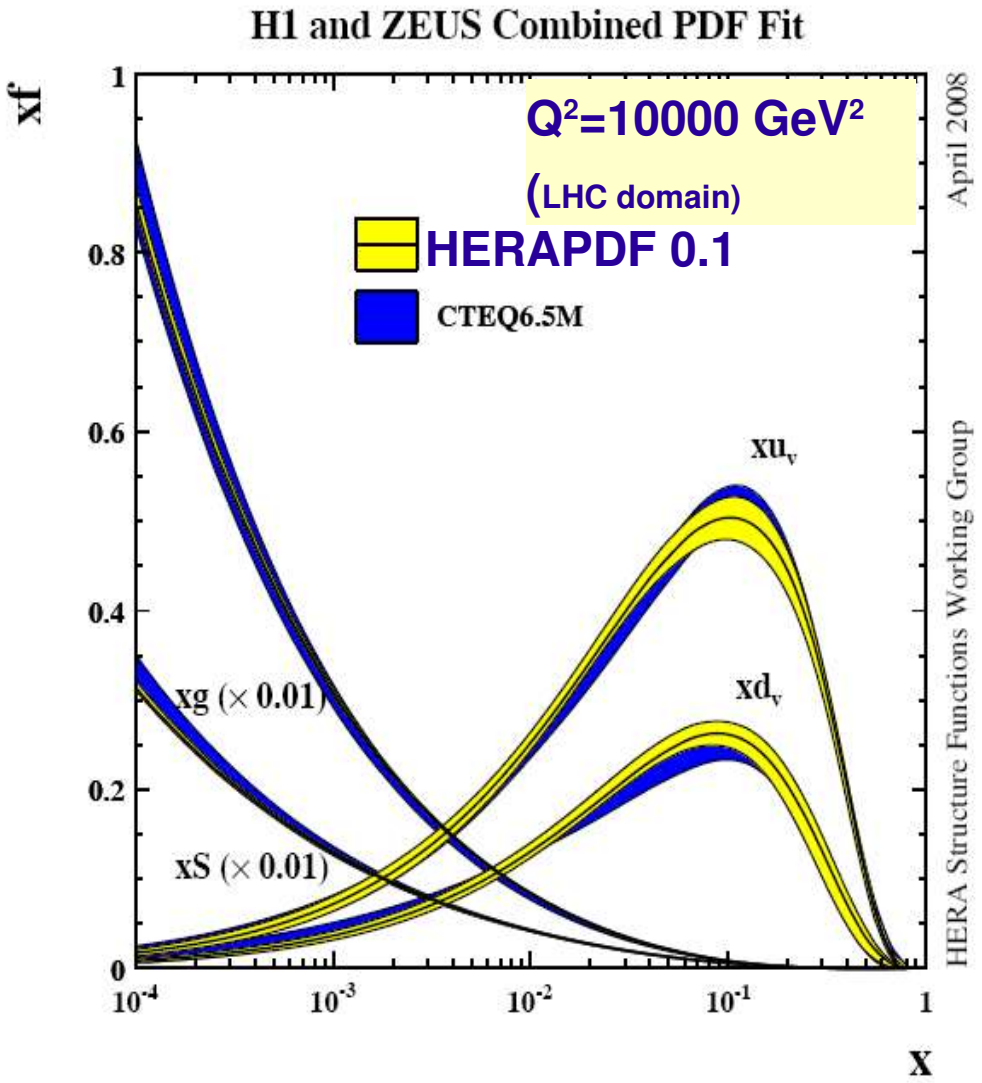
Vast coverage of the proton "map"

Dramatic increase in precision

QCD/DGLAP at work:
scaling violations from gluons

Side by side with global fits





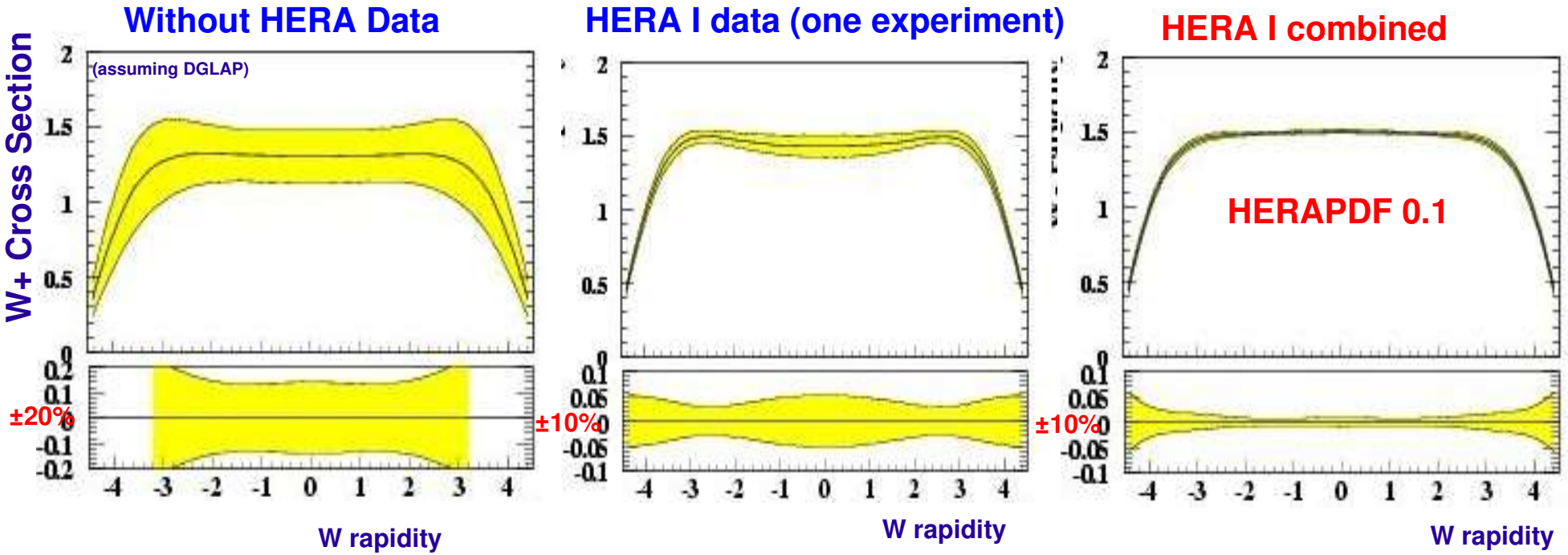
Improvement most notably at low x

The data precision is driving the improvement

Treatement of errors and parametrisation issues

Predictions for W/Z boson production at LHC

A.Cooper-Sarkar and E.Perez



Only the fit uncertainty shown here, no model variations

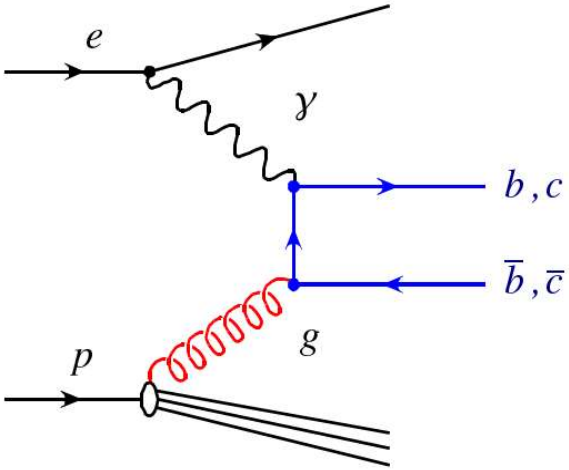
The step in experimental precision is significant ~2%

More HERA data to be included:

low Q2, HERA II data high x/Q^2, jets => ultimate precision

Proton's charm

$$\sigma_r^{cc/bb} = F_2^{cc/bb} - y^2/Y_+ F_L^{cc/bb}$$



Tags: D-mesons, lifetime

More QCD into the game

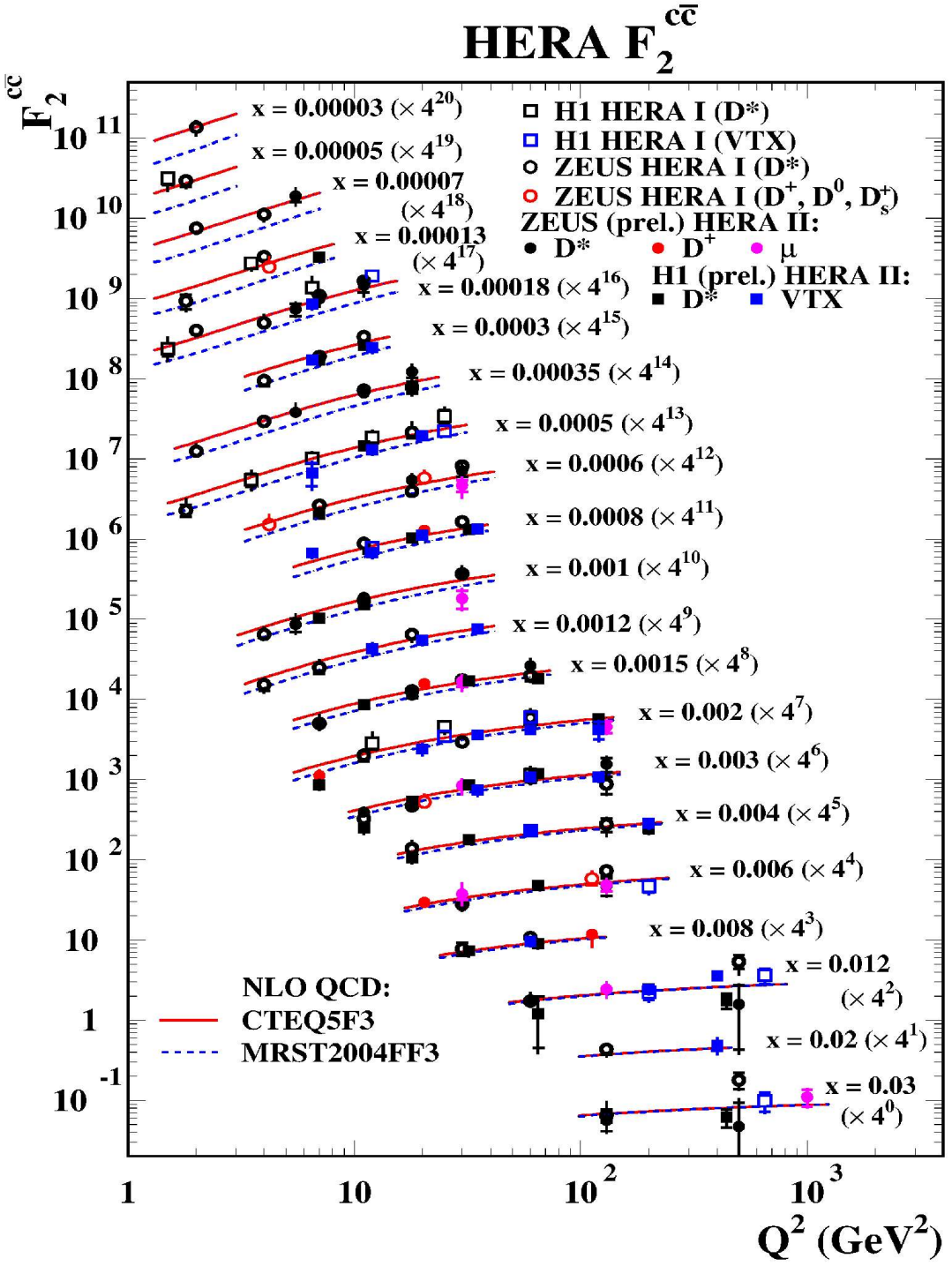
Fortunately, large quark mass helps

Produced via boson-gluon fusion

=>sensitivity to the gluon

Precision to 5% (or less) possible

=>challenges the theory



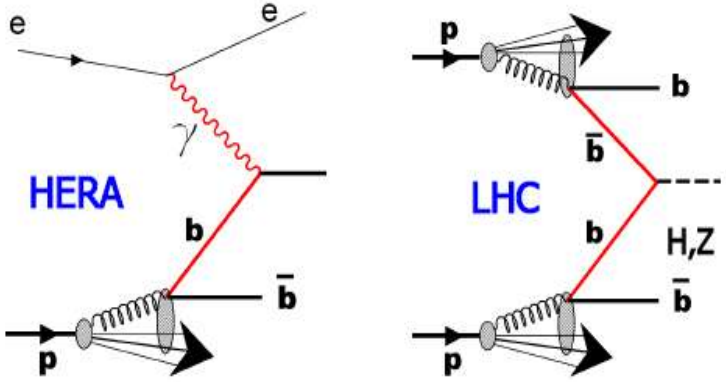
Proton's beauty

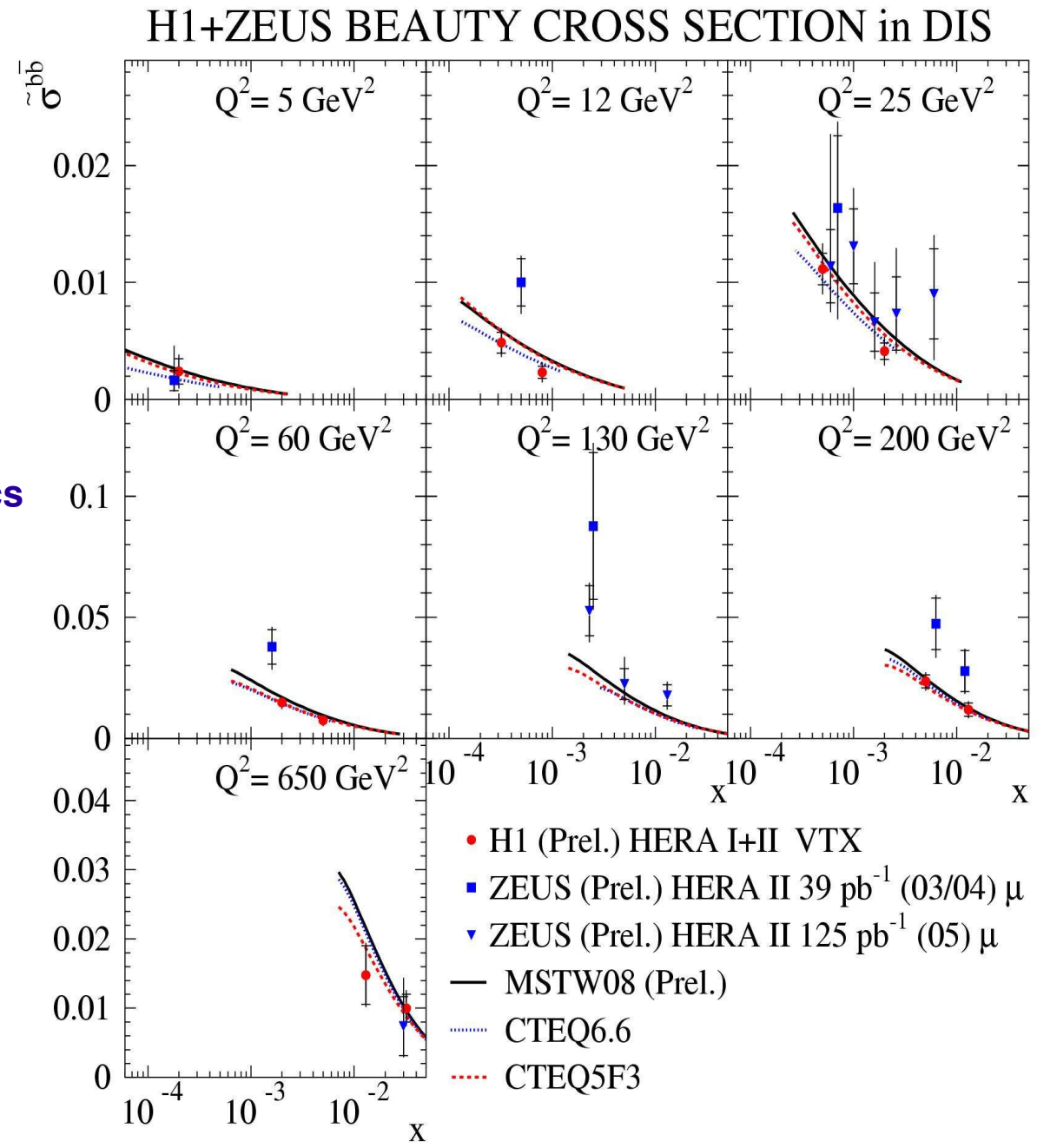
HERA II data with lifetime methods

More data available

Flavour control in PDF is crucial

for some aspects of the LHC physics





Longitudinal Structure Function F_L

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

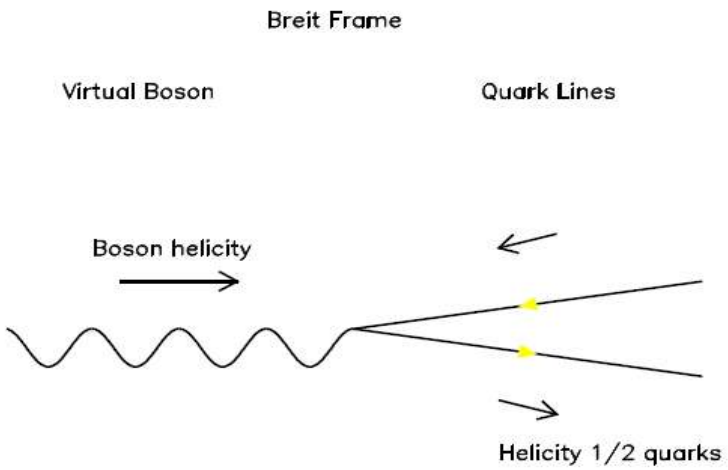
$$R = \sigma_L/\sigma_T = (F_2 - 2xF_1)/2xF_1 = F_L/2xF_1$$

=0 for spin ½ partons in QPM (Callan-Gross)

Fundamental form factor of the proton

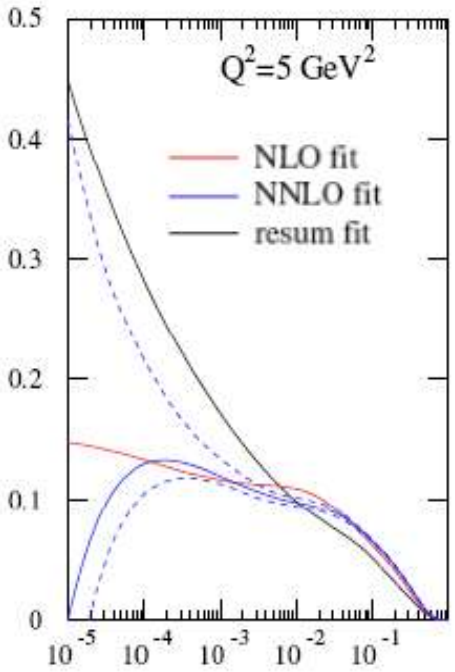
Proportional to the gluon, important for PDF's

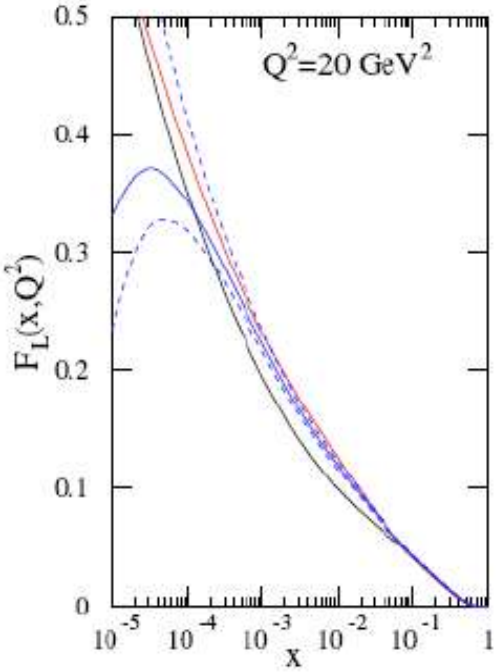
Discriminate between theoretical approaches



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

Altarelli, Martinelli, 1978





R.Thorne, DIS08

Direct F_L measurement

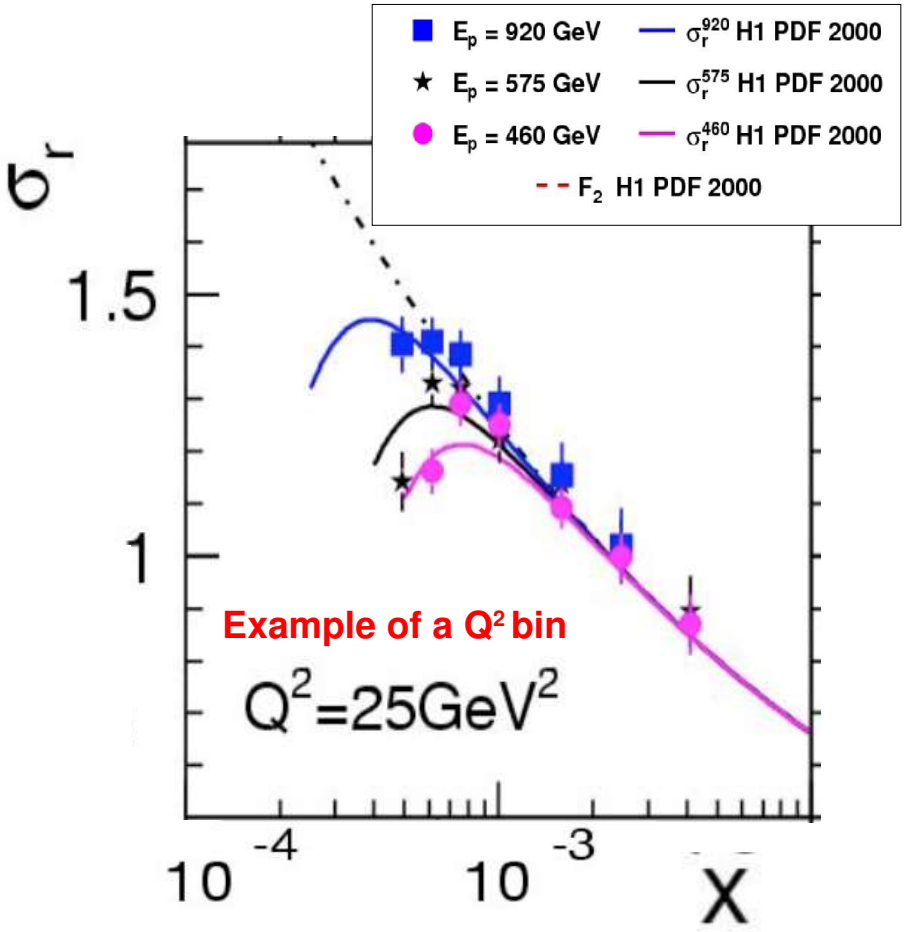
$$\sigma \sim F_2(x,Q^2) + f(y)\, F_L(x,Q^2)$$

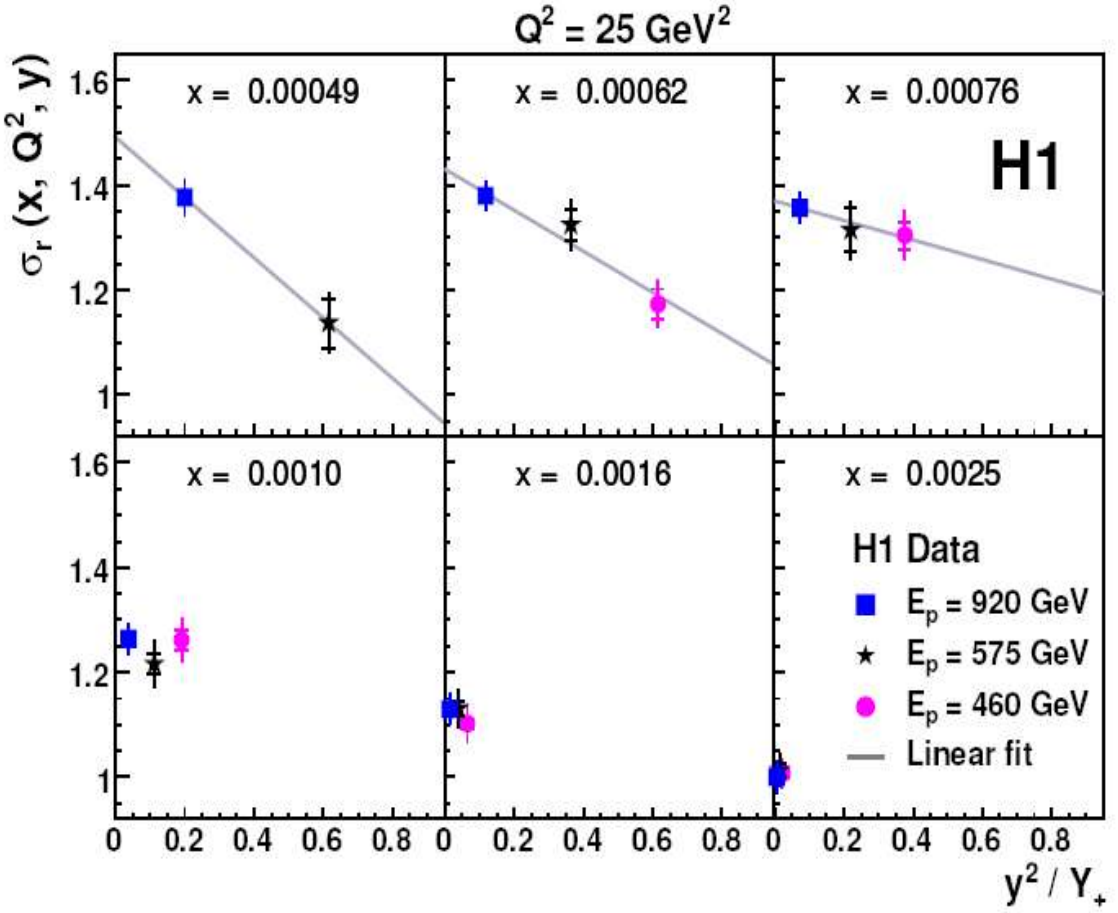
Method:

keep x,Q^2 constant, vary y: ys=y's'=Q^2/x

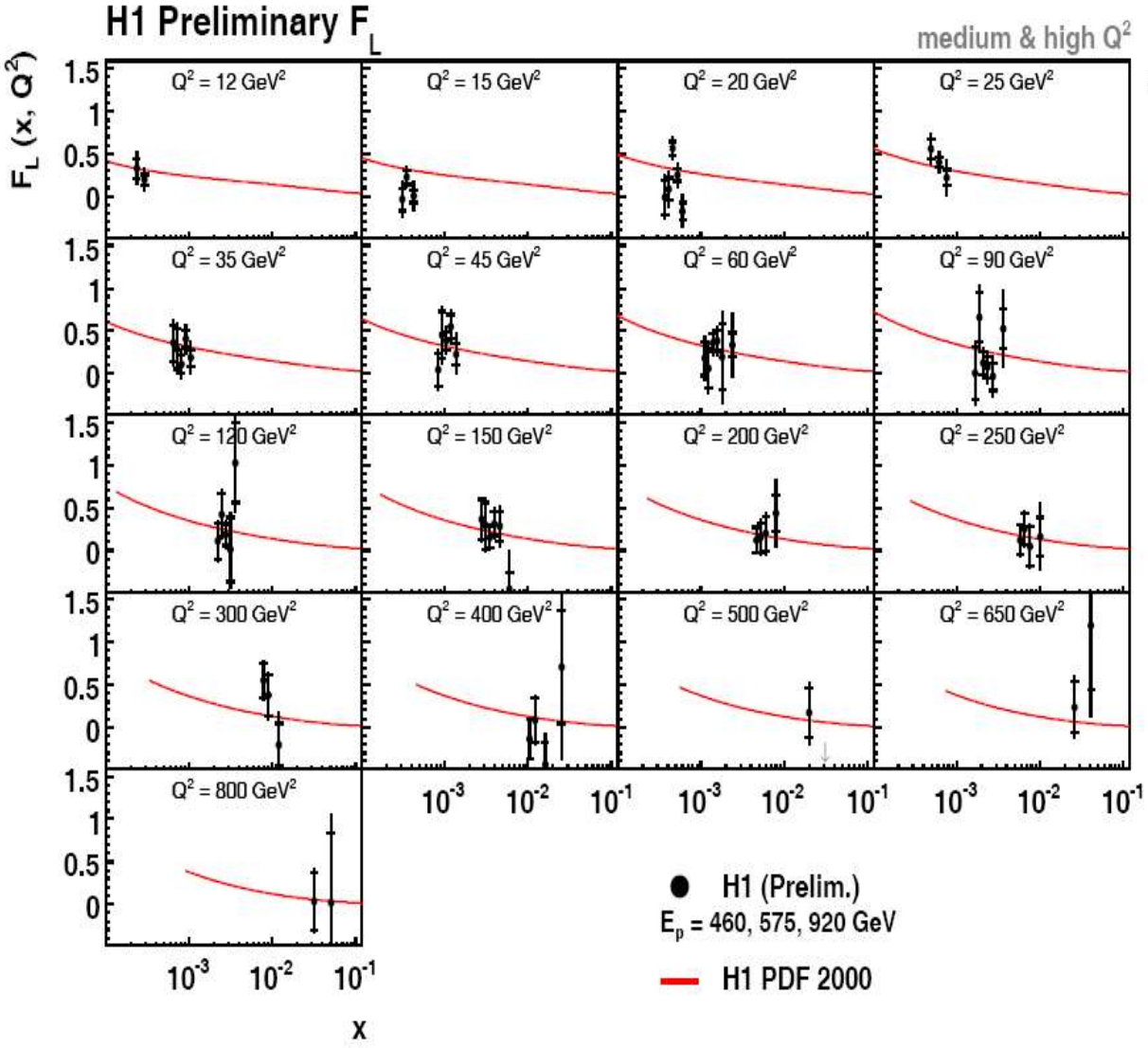
Vary s : Special Runs E_p=460,575 GeV

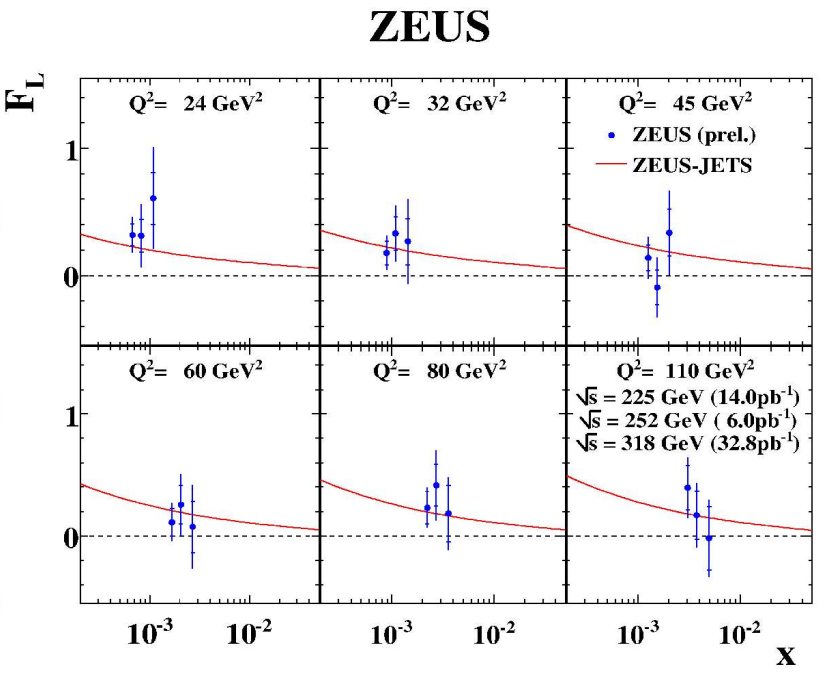
$$F_L \sim C(y) * (\sigma(E_p^1) - \sigma(E_p^2))$$





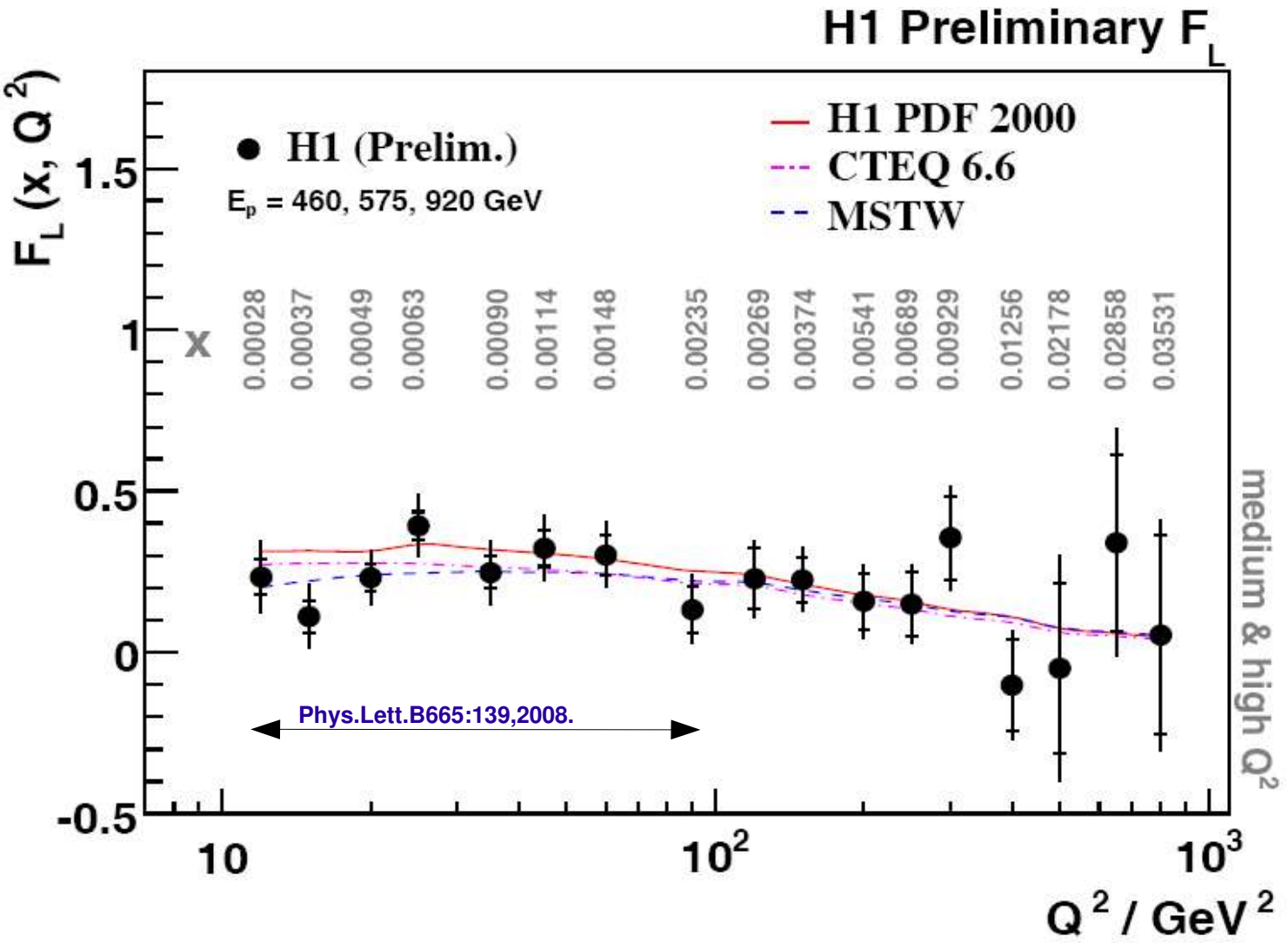
Direct F_L measurement





Measurements compatible with QCD predictions

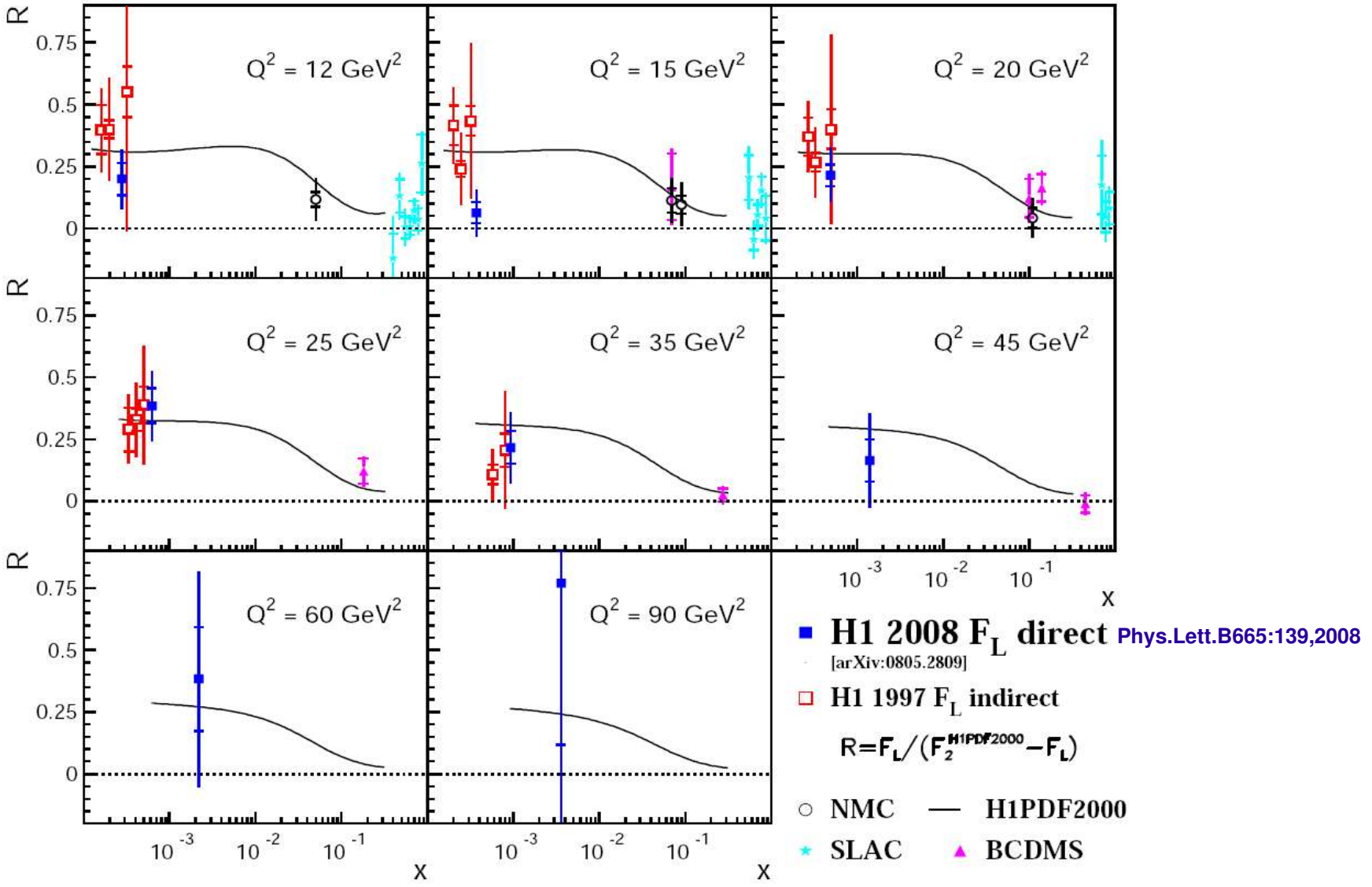
F_L averaged in each Q^2 bin



Work ongoing to extend to lower Q^2/x: test QCD, resummation, gluon

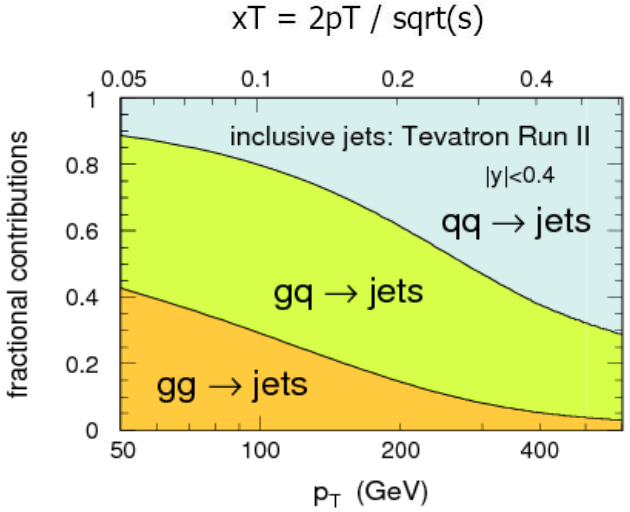
Comparison with target data and indirect determinations

Q^2 range of the first publication "medium Q^2"



The gluon "turn-on" at low x clearly visible

Jets production at Tevatron

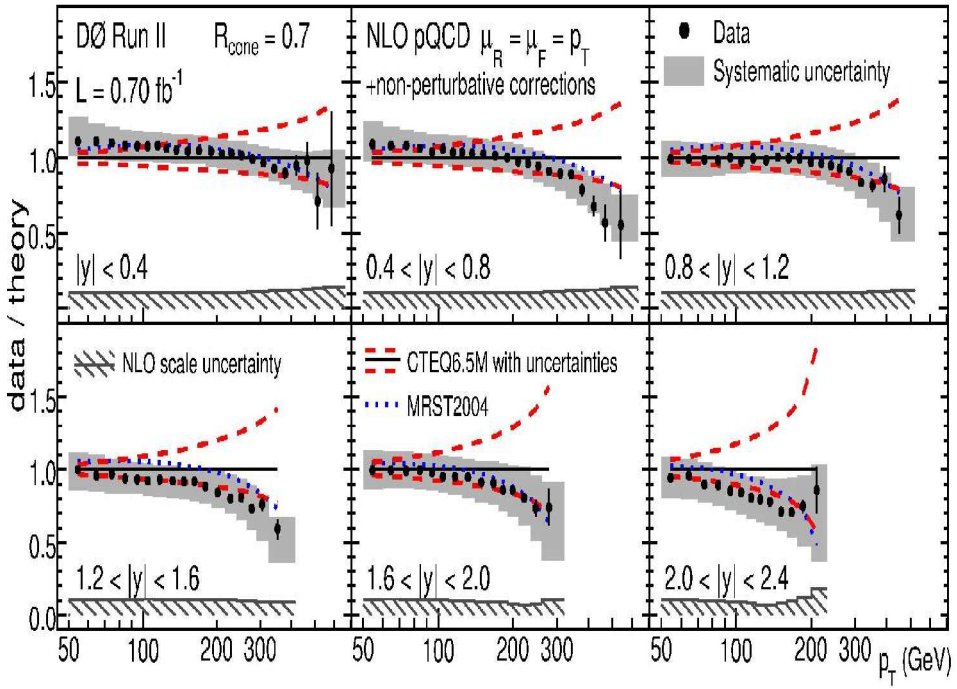


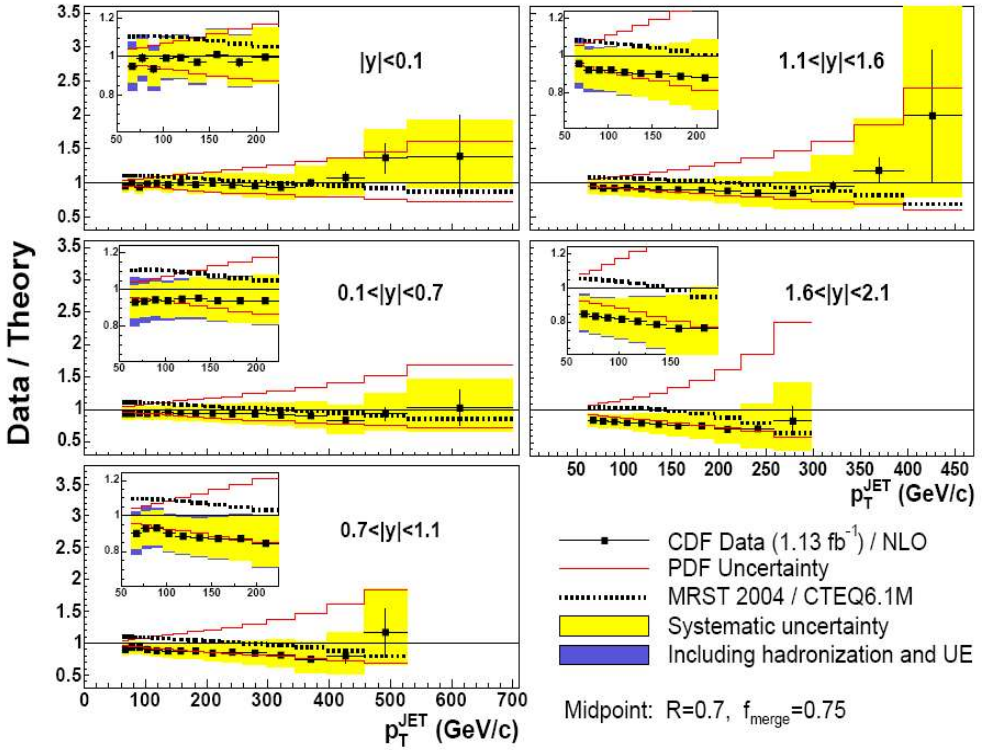
Impressive achievement in energy scale control (1%)

Sensitive to gluon at high x

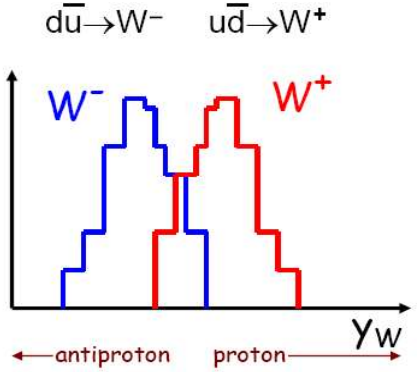
Precision with present global fits

Included in MSTW





W asymmetry at Tevatron

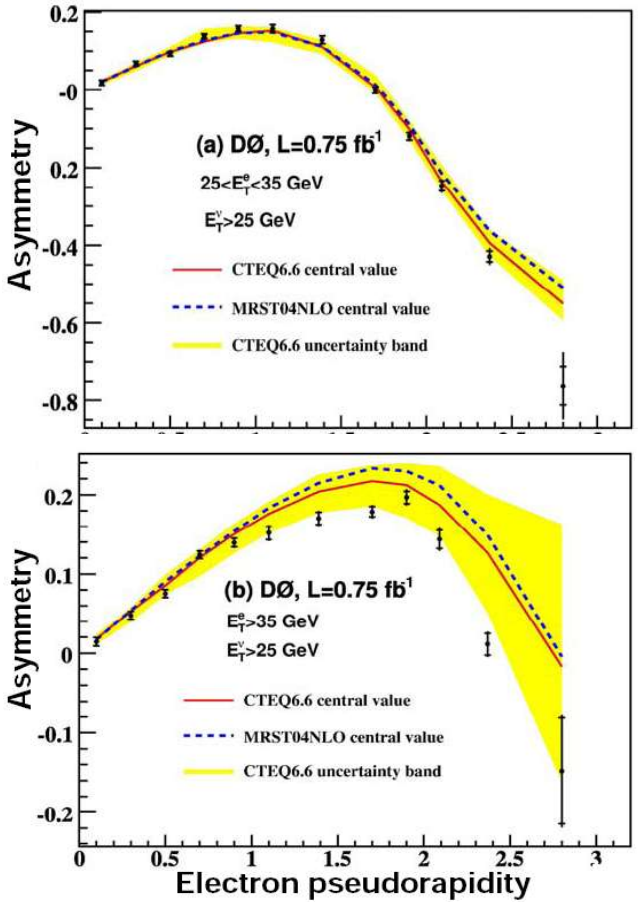


$$A_W(y) = \frac{\sigma^{W^+} - \sigma^{W^-}}{\sigma^{W^+} + \sigma^{W^-}} \sim \frac{d}{u}$$

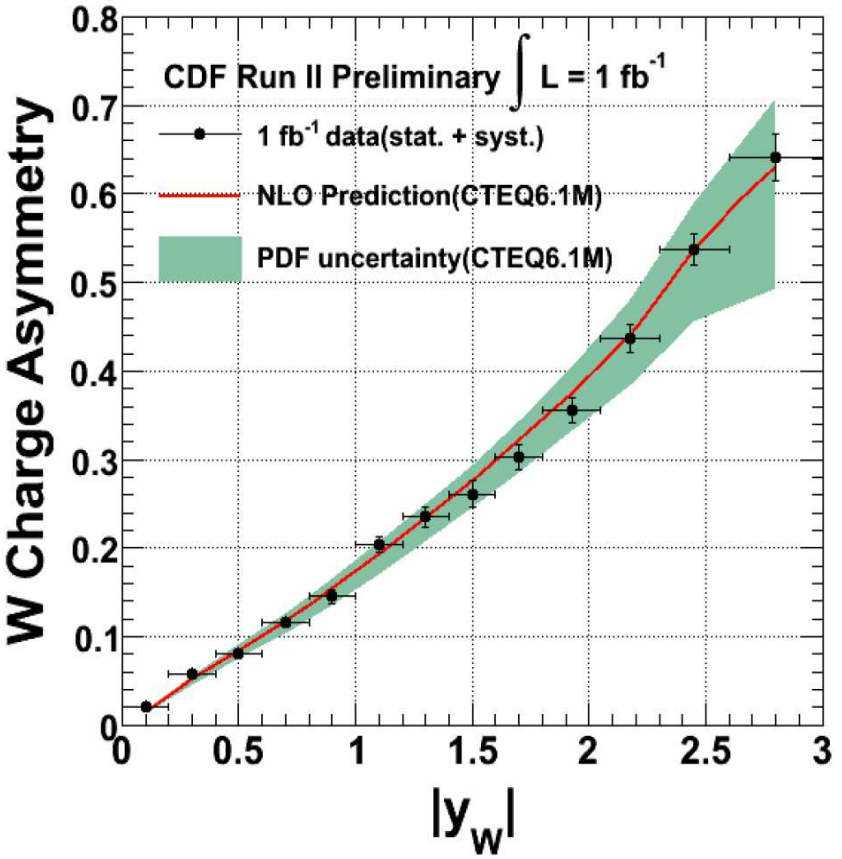
$$Q^2 = M_W^2 \quad x = \frac{M_W}{\sqrt{s}} e^{y_W}$$

$$0.002 < x < 0.8(1)$$

Use charged leptons (2 E_T bins)



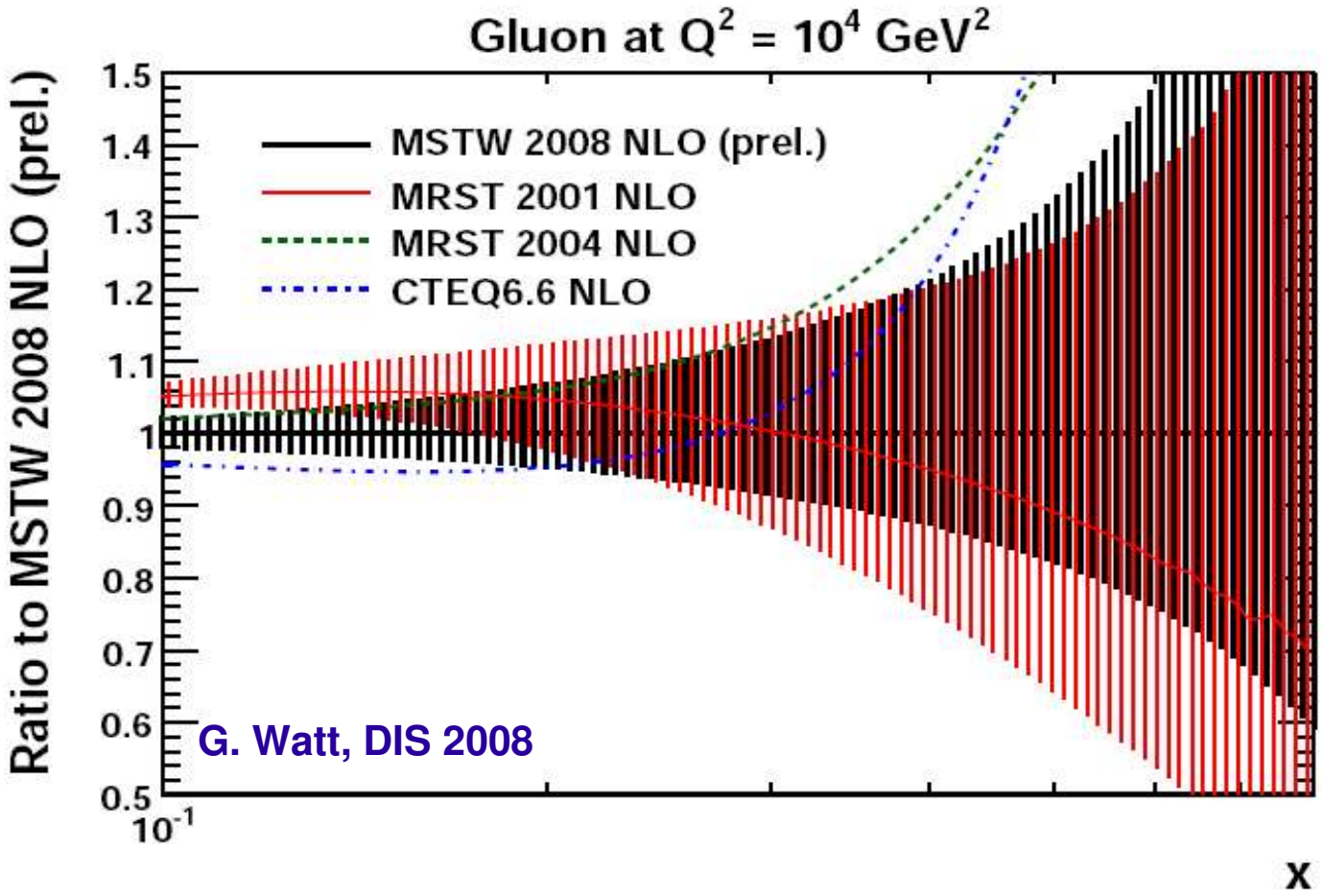
W full reconstruction



Expect to improve PDFs improvements at high x

The gluon at high x

MSTW 2008 analysis (including CDF and D0 run II data jets, W/Z asymmetries)

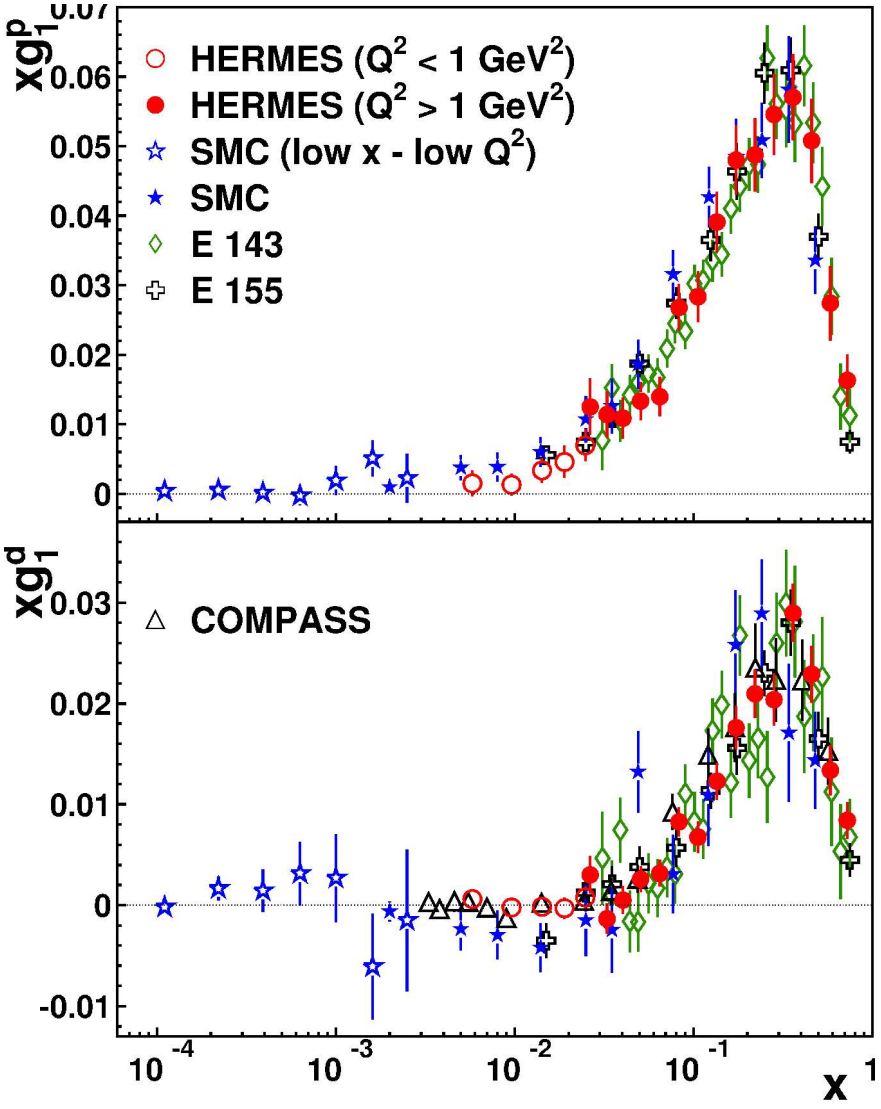


New data prefer smaller gluon at high x

The proton spin

Polarised lepton beam, polarised (H,D,...) targets

$$\sigma_{LL} \equiv \frac{1}{2}(\sigma^{\rightleftarrows} - \sigma^{\rightrightarrows})/2 \simeq g_1^{p,n}(x,Q^2) = \frac{1}{2}\sum_q e_q^2 \left[\Delta q^{p,n}(x,Q^2) + \Delta\bar{q}^{p,n}(x,Q^2)\right]$$



$$\Delta\Sigma = \int \Delta q \simeq 0.33$$

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_z^q + \Delta G + L_z^G$$

Level arm in Q^2 not large:

gluon contribution not constrained

=> semi-inclusive data

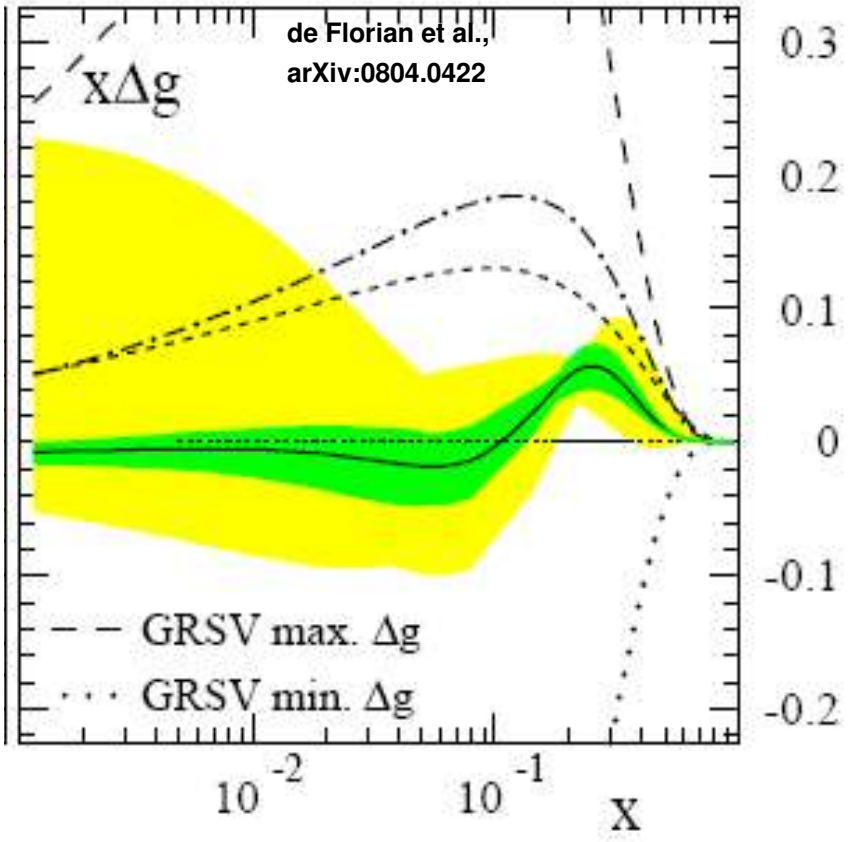
Use final states and angular distributions to further pin down the spin

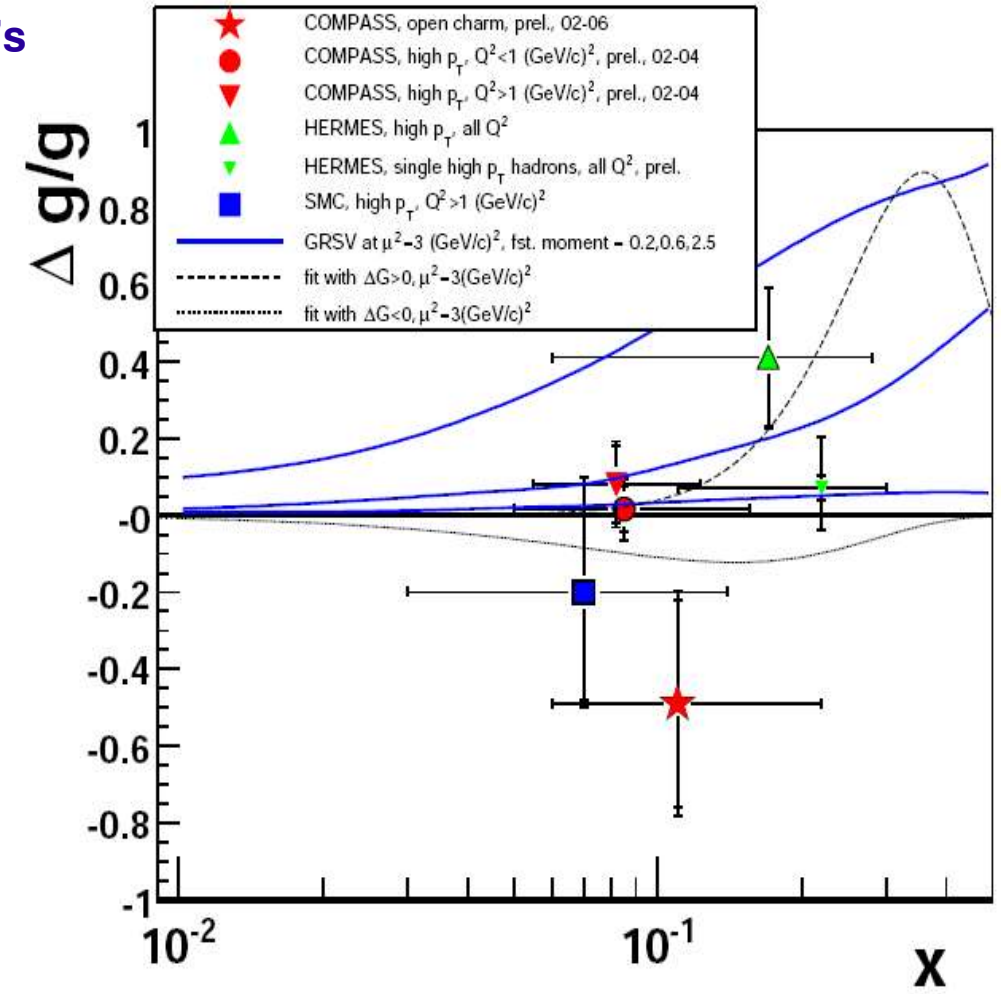
Gluon contribution to the spin

Understanding the gluon is crucial for the proton structure

Extracted via semi-inclusive processes: meson production in polarised DIS and pp (RHIC)

Global pol-analysis: extract polarised PDF's

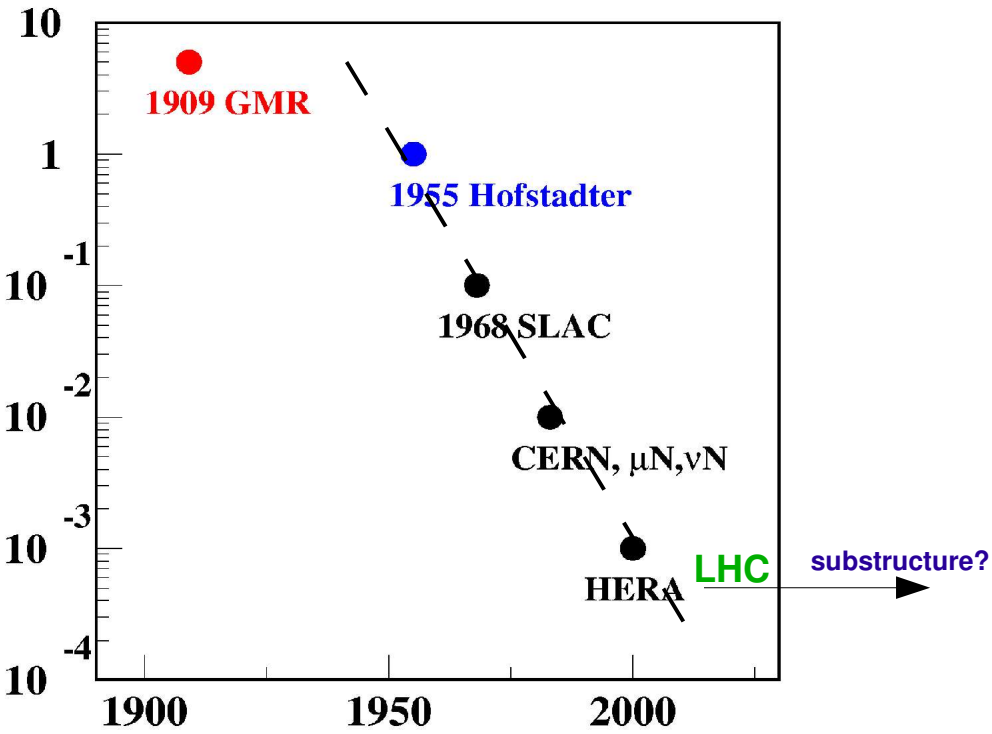




Extreme options now excluded
Extend x-range in pp at RHIC

Coda

LHC starts, precise data for proton "tuning" continue to come

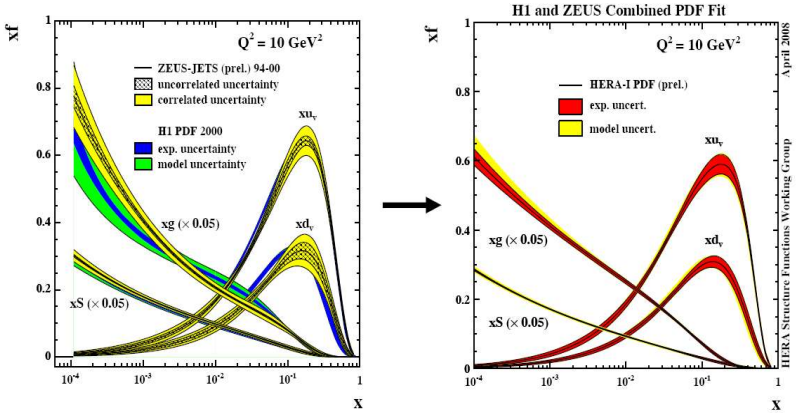


However: the proton structure and QCD are (unsolved) fundamental questions

More experiments planned: go deeper-inelastic (LheC) and extend spin studies (EIC)

Conclusions

- **The study of the structure of baryonic matter is a scene of fast progress**
  - inclusive DIS and PDF's, spin etc.
- **Precision (H)ERA :**
  - Fit of combined HERA data (HERAPDF 0.1)
  - First measurement of F_L at low x at HERA
  - Final analyses and H1/ZEUS combinations will lead to a significant step in precision



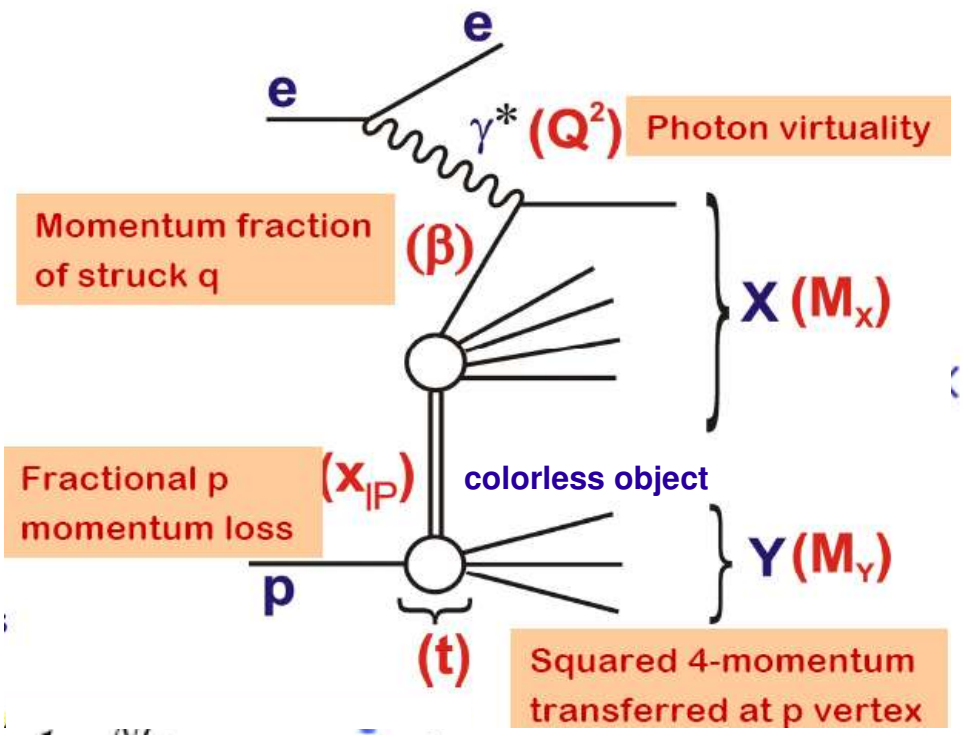
- **Tevatron run II :**
  - jets and W/Z studies offer new constraints on gluon, u/d at high x
- **Precise PDF's are an important ingredient for LHC analyses**
  - the perspectives are brilliant!

Thanks: A.Schoening, C.Vallee, E.Kinney,D.Lincoln,K.Hatakeyama,
A.Hillerbrand, T. Haas, U. Klein, A. Guffanti, S.Blessing, M. Wobisch

Backup

Hard Diffraction at HERA

10% of DIS events are diffractive:
produced via the exchange of an coulouless exchange



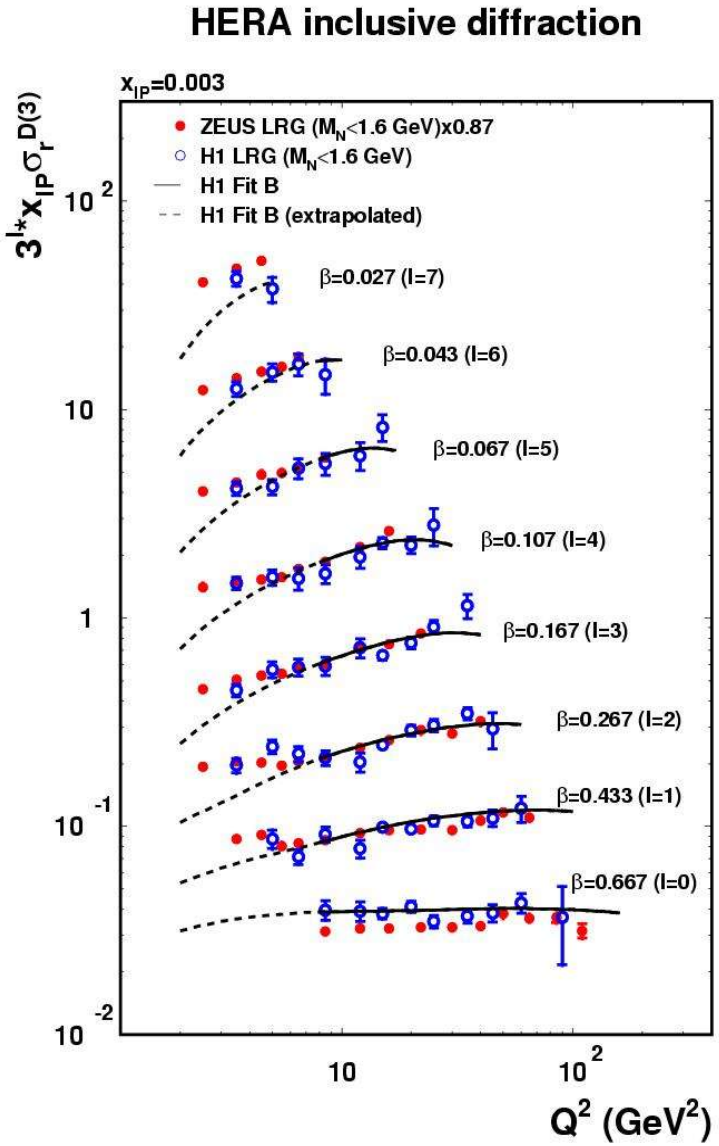
empty rapidity region (gap)

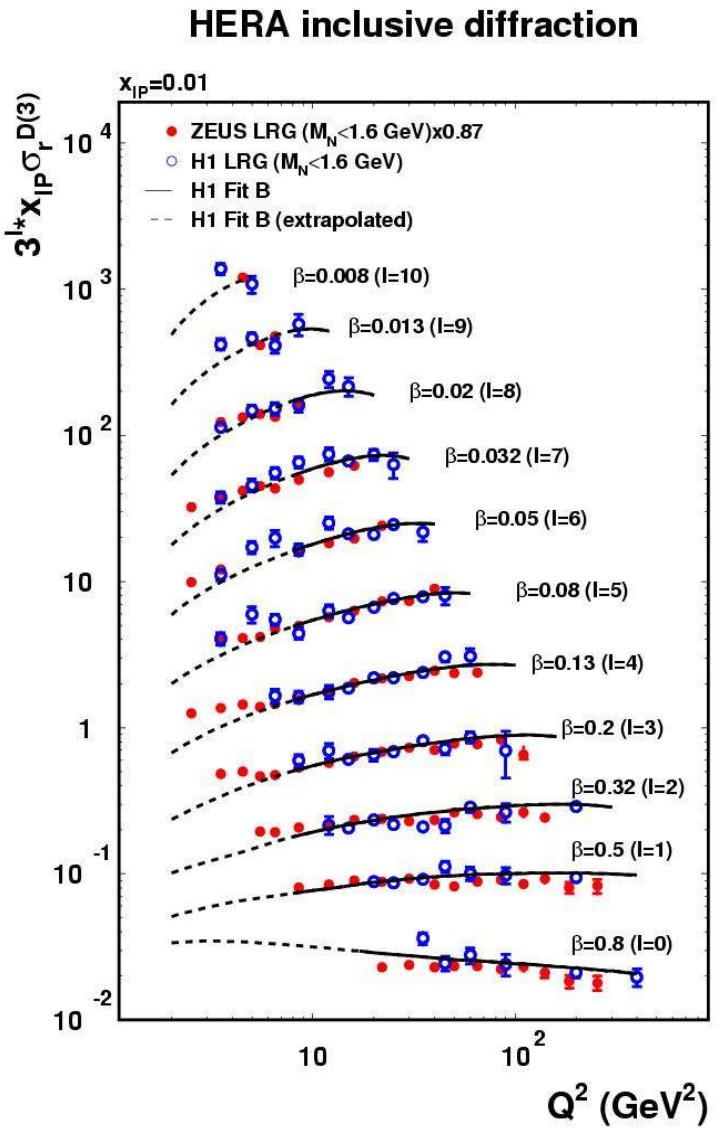
or intact proton detected down the beampipe (roman pots)

$$\frac{d\sigma^{NC}_{diff}}{dx_{IP}dtd\beta dQ^2} \propto \frac{1}{Q^4} F_2^{D(4)}(x_{IP}, t, \beta, Q^2)$$

assuming factorisation: structure of the diffractive echnage

H1 and ZEUS M_N<1.6 GeV





H1 and ZEUS corrected to the same phase space

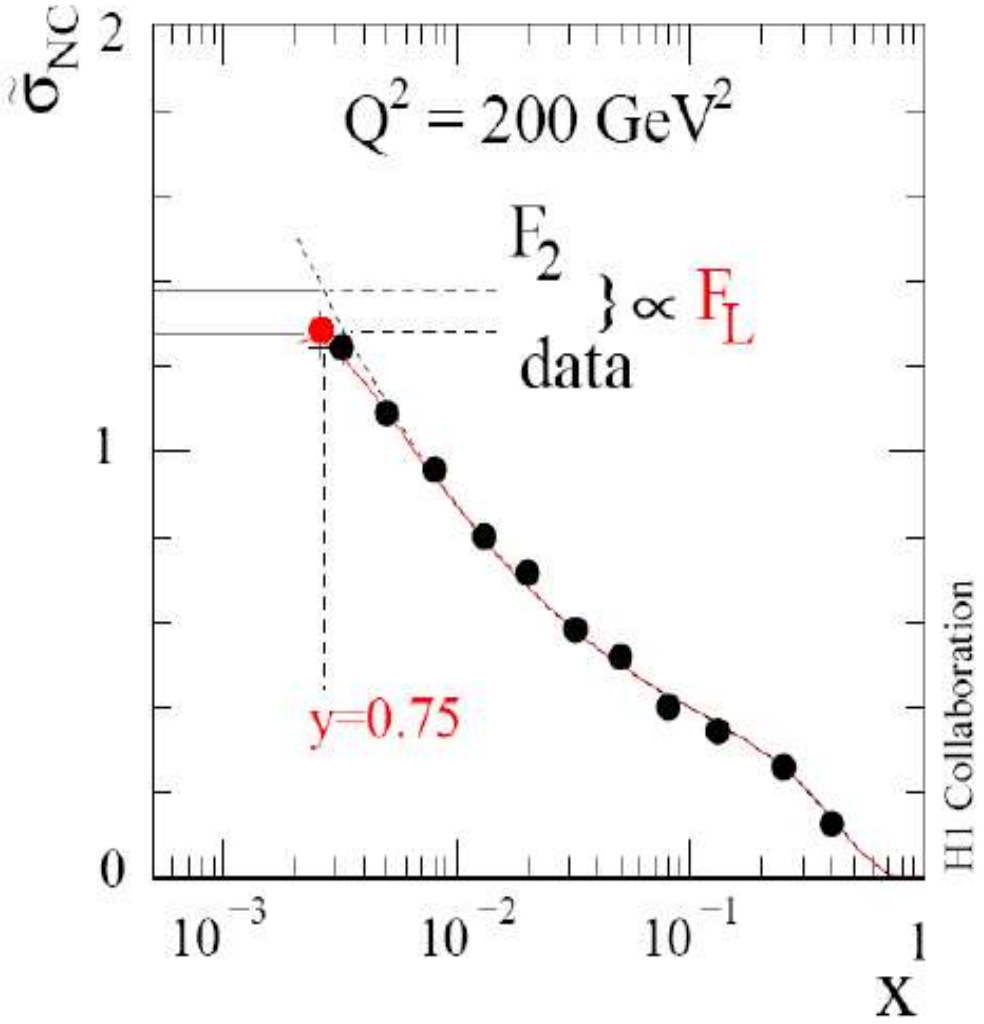
Ready for combination,more data to come

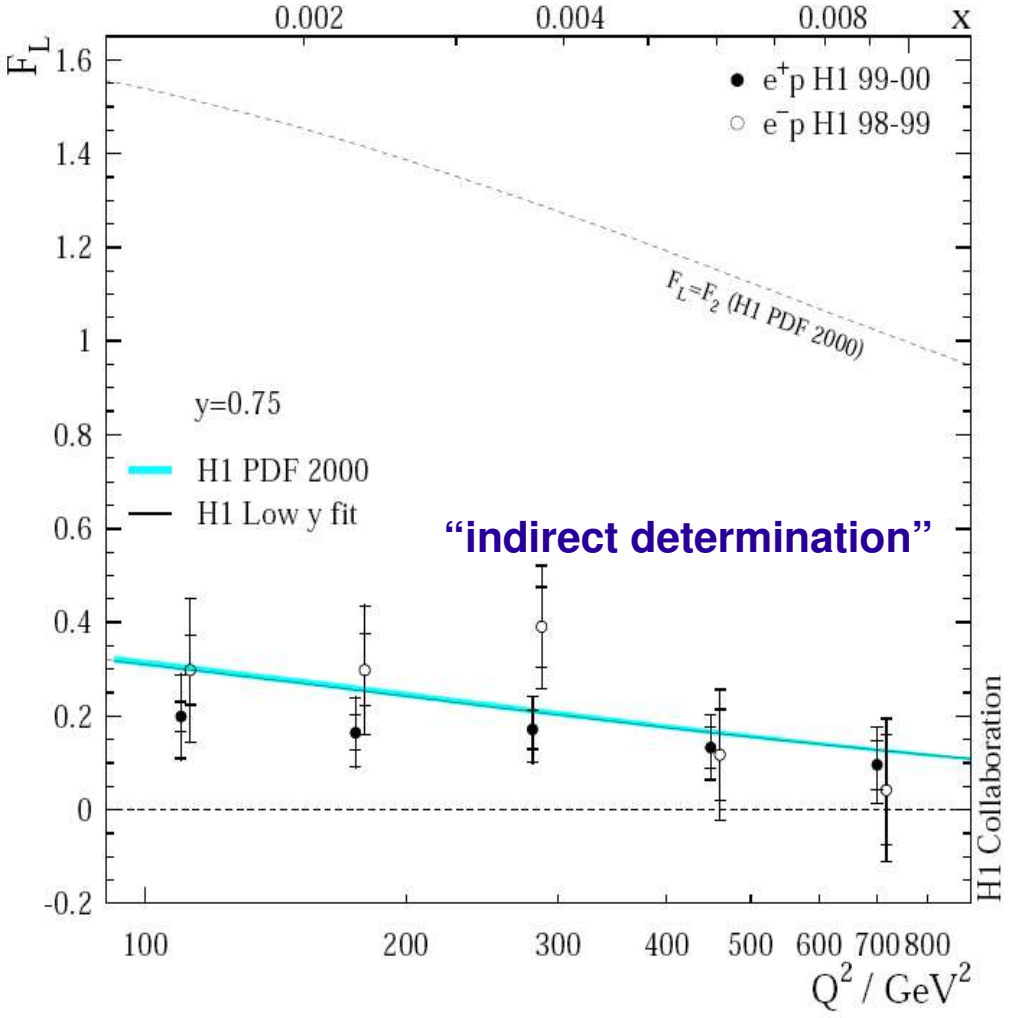
Indirect Determination

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

see bending at high y

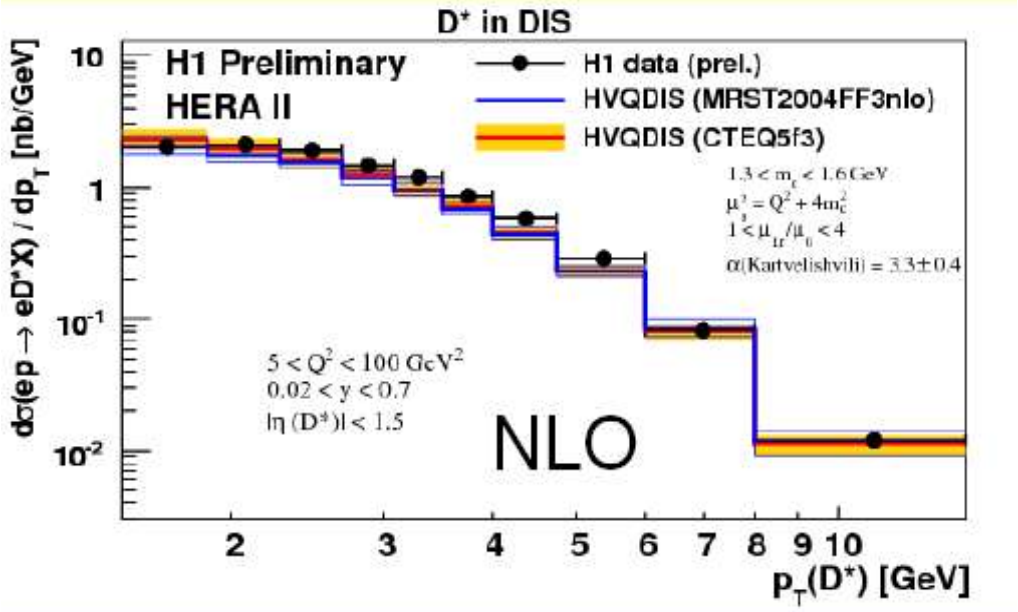
assume F2 -> extract FL



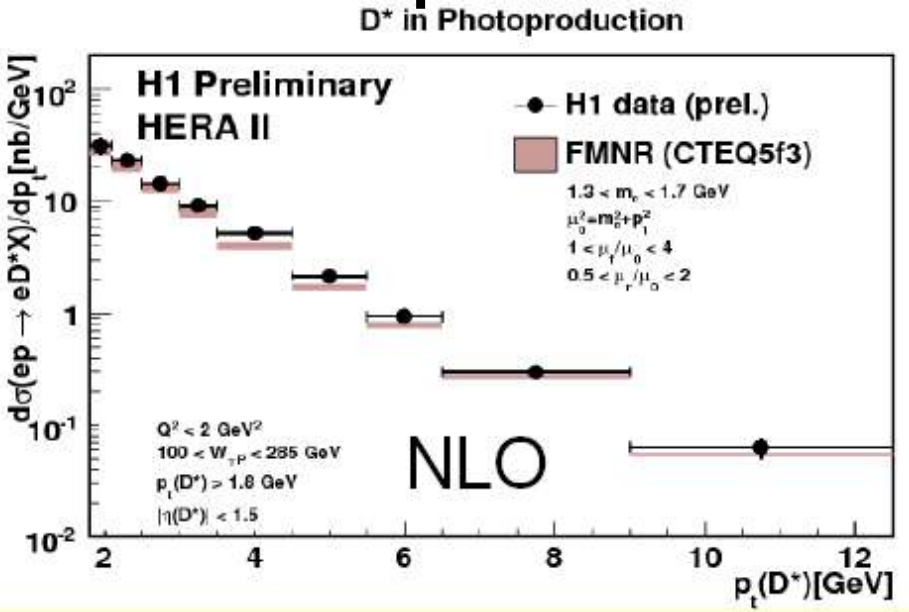


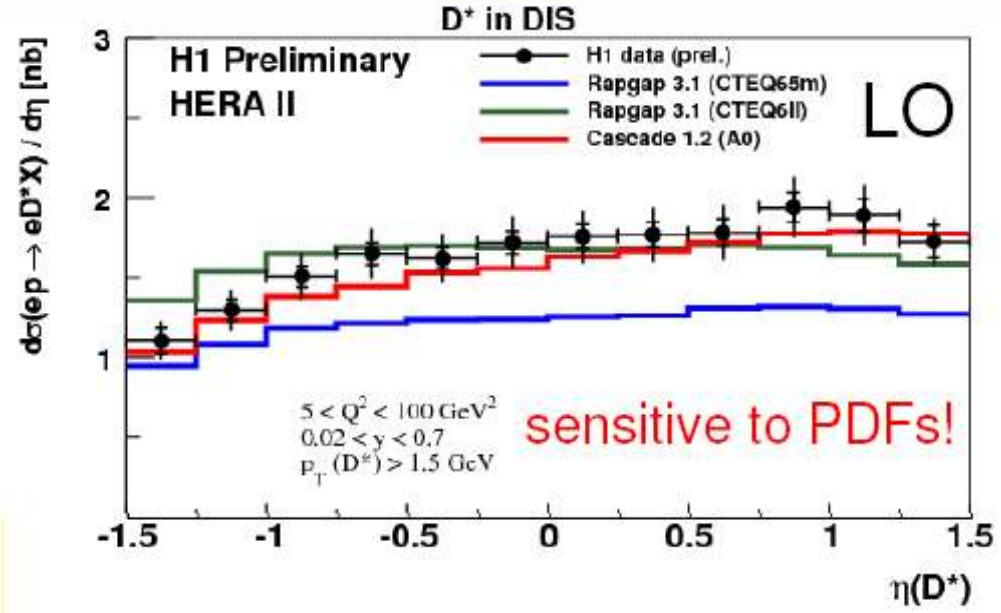
More charm with HERA II data

DIS



Photoproduction





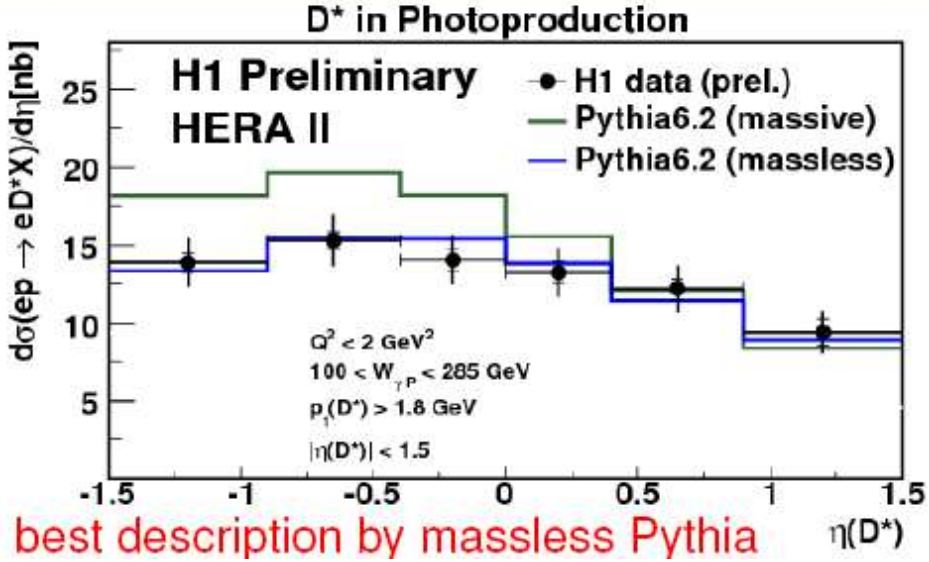
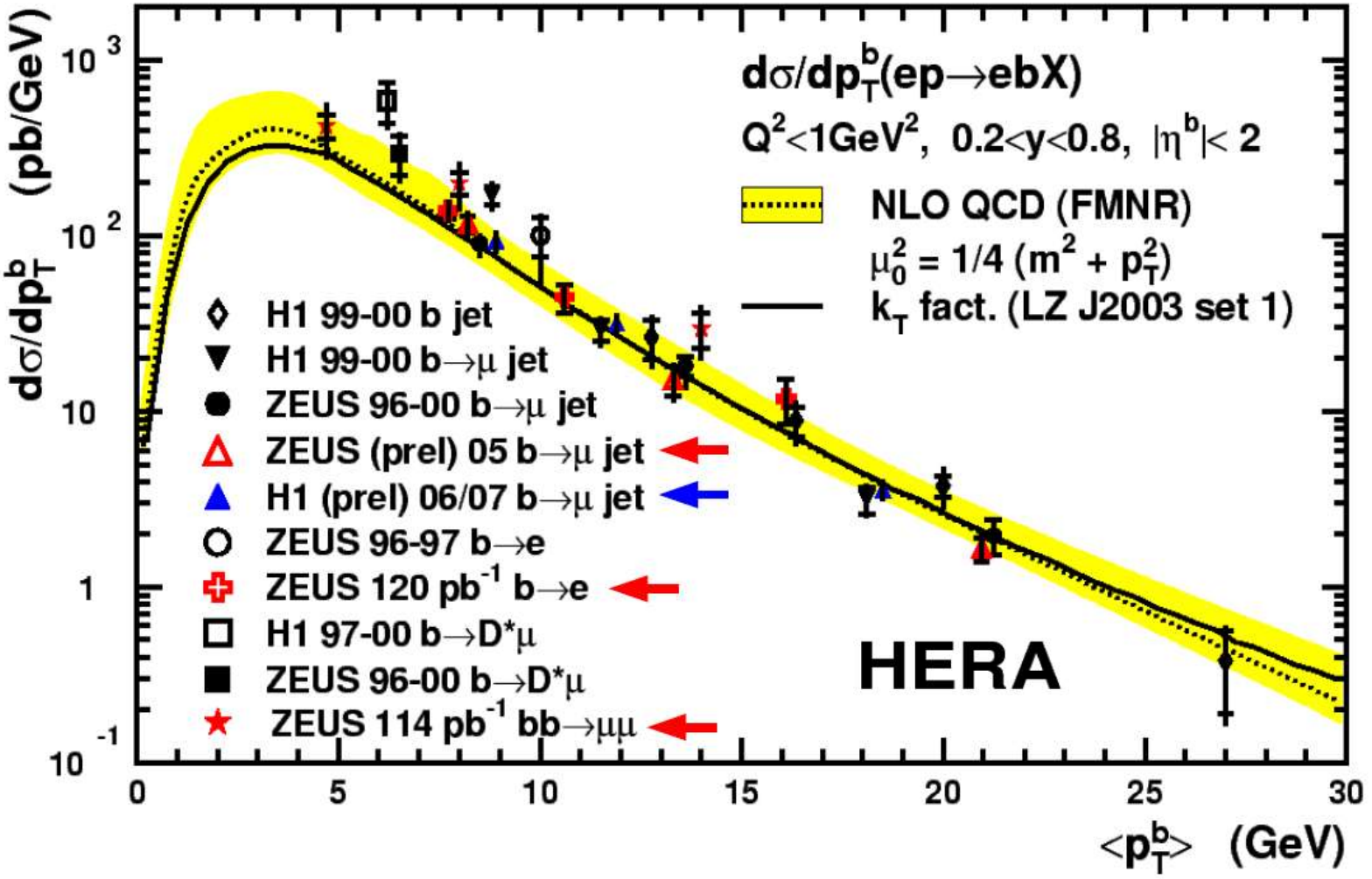
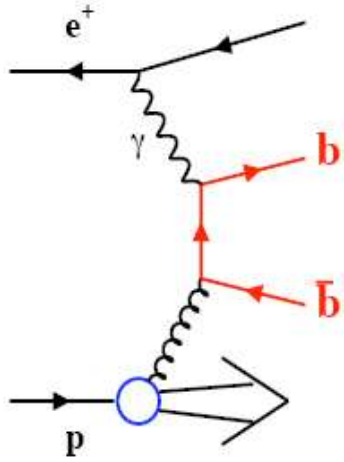
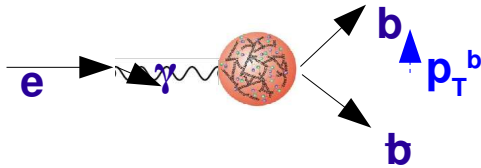


Photo-Produced Beauty





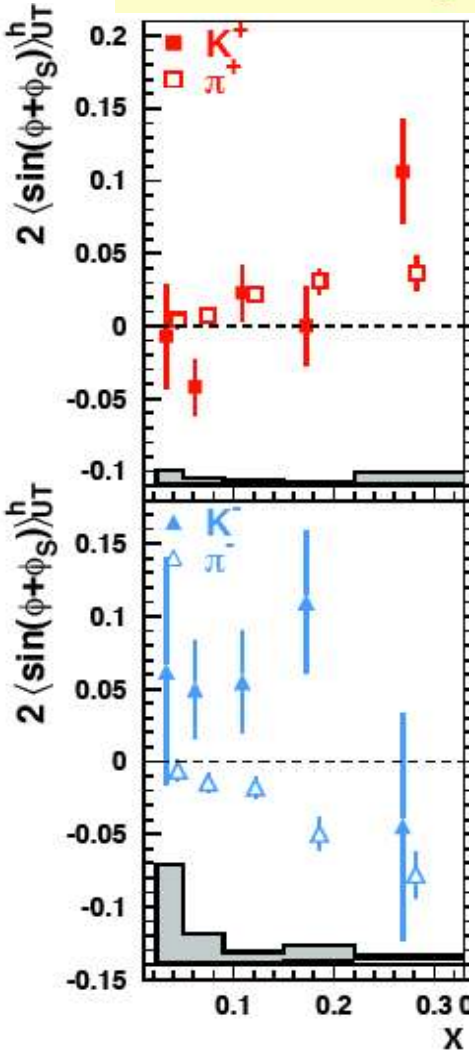


Recent precise measurements in agreement with theory

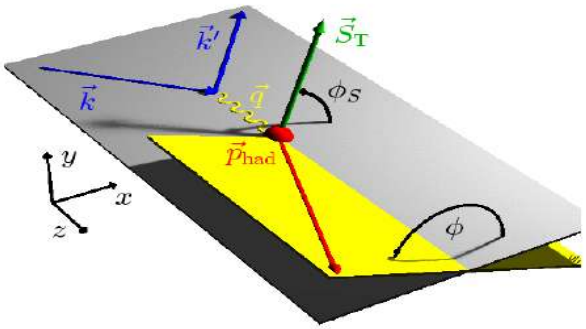
Asymmetries

Collins

$$A_C \propto \delta q \otimes H_1^{\perp}$$

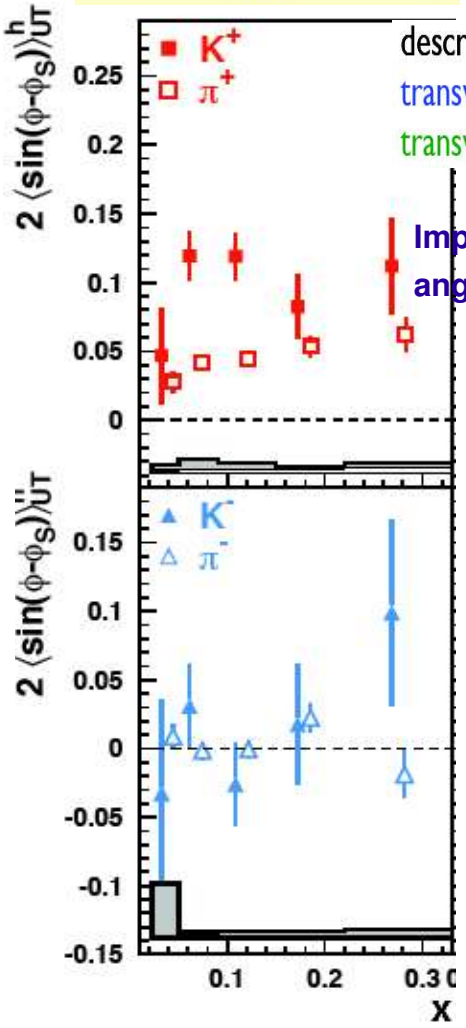


information from another process on Collins FF (BELLE) allows extraction of δq (eg Anselmino et al Phys.Rev.D75:054032,2007)



Sievers

$$A_S \propto f_{1T}^{\perp} \otimes D_1^q$$



describes correlation between intrinsic transverse quark momentum (p_T) and transverse nucleon spin

Implies non-zero angular momentum