

Small x PDFs at HERA

Inclusive, Unintegrated, Diffractive



combined H1/ZEUS data and PDF fits
new inclusive analyses at low x
first F_L measurements
unintegrated PDFs
diffractive PDFs

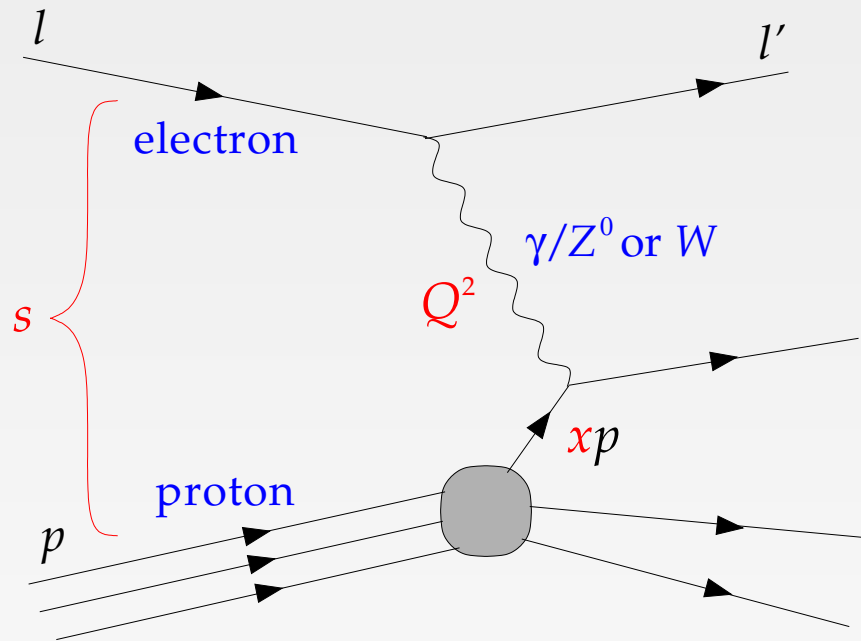


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KIP, Universität Heidelberg

MPI@LHC'08 Workshop
Perugia, 27–31.10.2008



Inclusive DIS Kinematics



boson virtuality
= resolution scale

$$Q^2 = -(l - l')^2$$

fractional momentum
of struck quark

$$x = \frac{Q^2}{2p \cdot q}$$

inelasticity

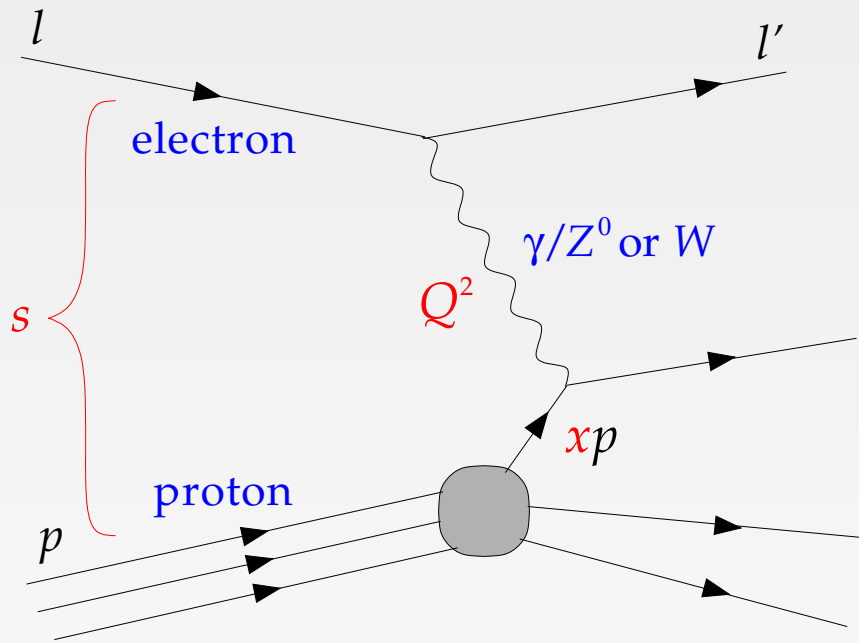
$$y = \frac{p \cdot q}{p \cdot l} \approx \frac{Q^2}{xs}$$

boson-proton
cms energy

$$W = \sqrt{ys - Q^2 + m_p^2}$$

low $x \iff$ high y, W

Inclusive DIS Cross Section



boson virtuality
= resolution scale

$$Q^2 = -(l - l')^2$$

fractional momentum
of struck quark

$$x = \frac{Q^2}{2p \cdot q}$$

inelasticity

$$y = \frac{p \cdot q}{p \cdot l} \approx \frac{Q^2}{xs}$$

boson-proton
cms energy

$$W = \sqrt{ys - Q^2 + m_p^2}$$

reduced cross section σ_r

Cross section:

$$\frac{d^2\sigma^\pm}{dx dQ^2} = \frac{2\pi\alpha^2}{Q^4 x} Y_\pm \left\{ F_2(x, Q^2) - \frac{y^2}{Y_+} F_L(x, Q^2) \mp \frac{Y_-}{Y_+} x F_3 \right\}$$

dominant

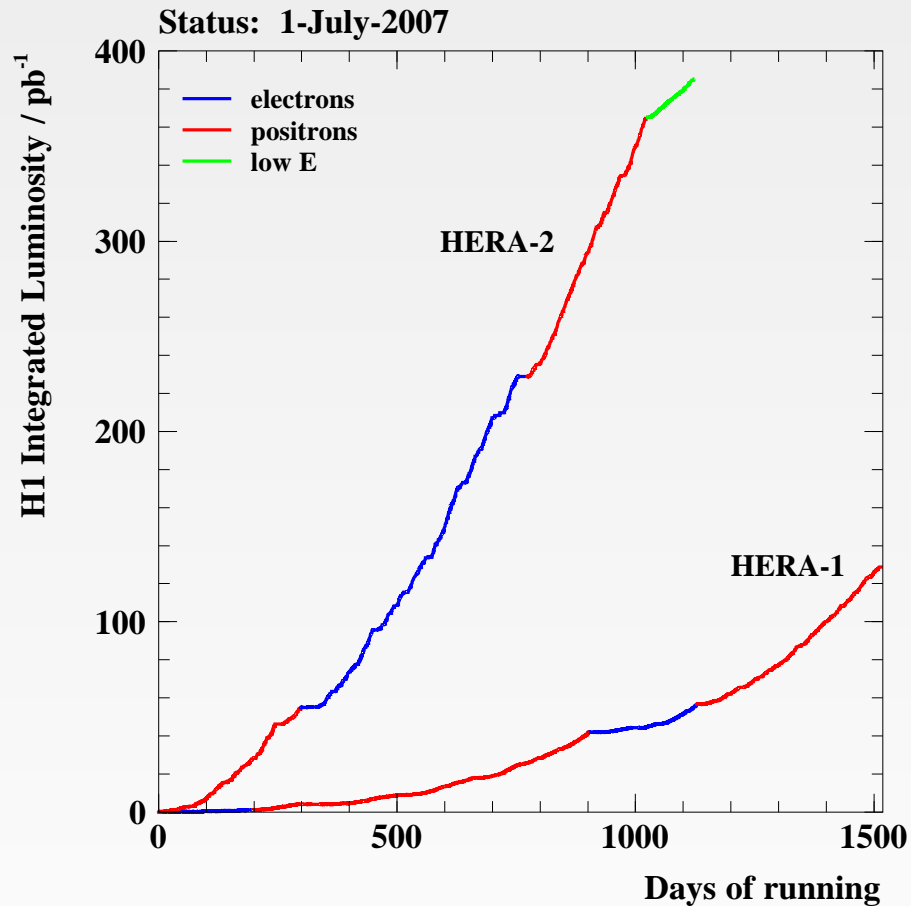
at high y

at high Q^2

$$Y_\pm = 1 \pm (1 - y)^2$$

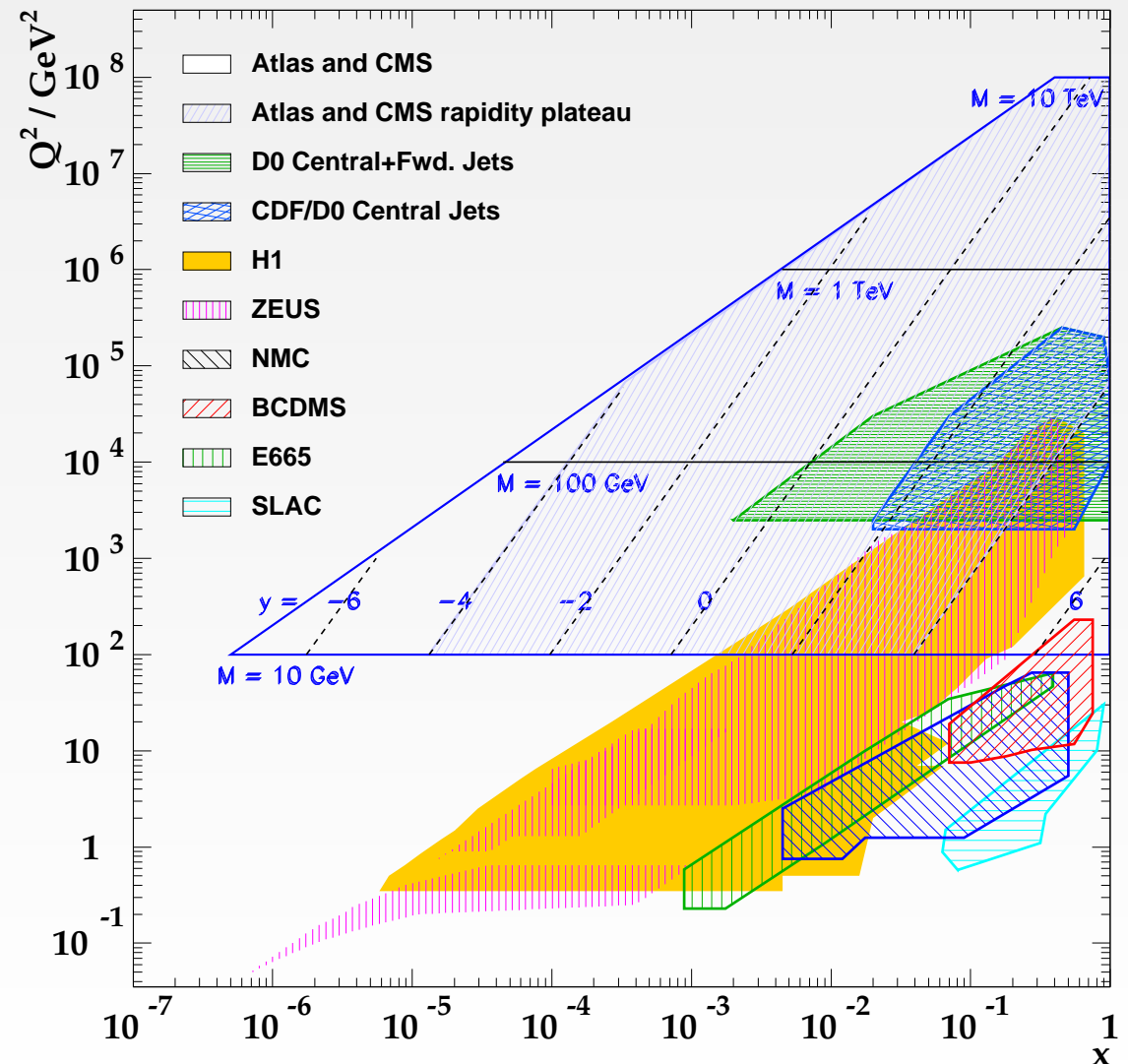
NC and CC σ_r are used to determine PDFs via pQCD fits

HERA Performance and Coverage



HERA I: $\sim 120 \text{ pb}^{-1} / \text{expt}$

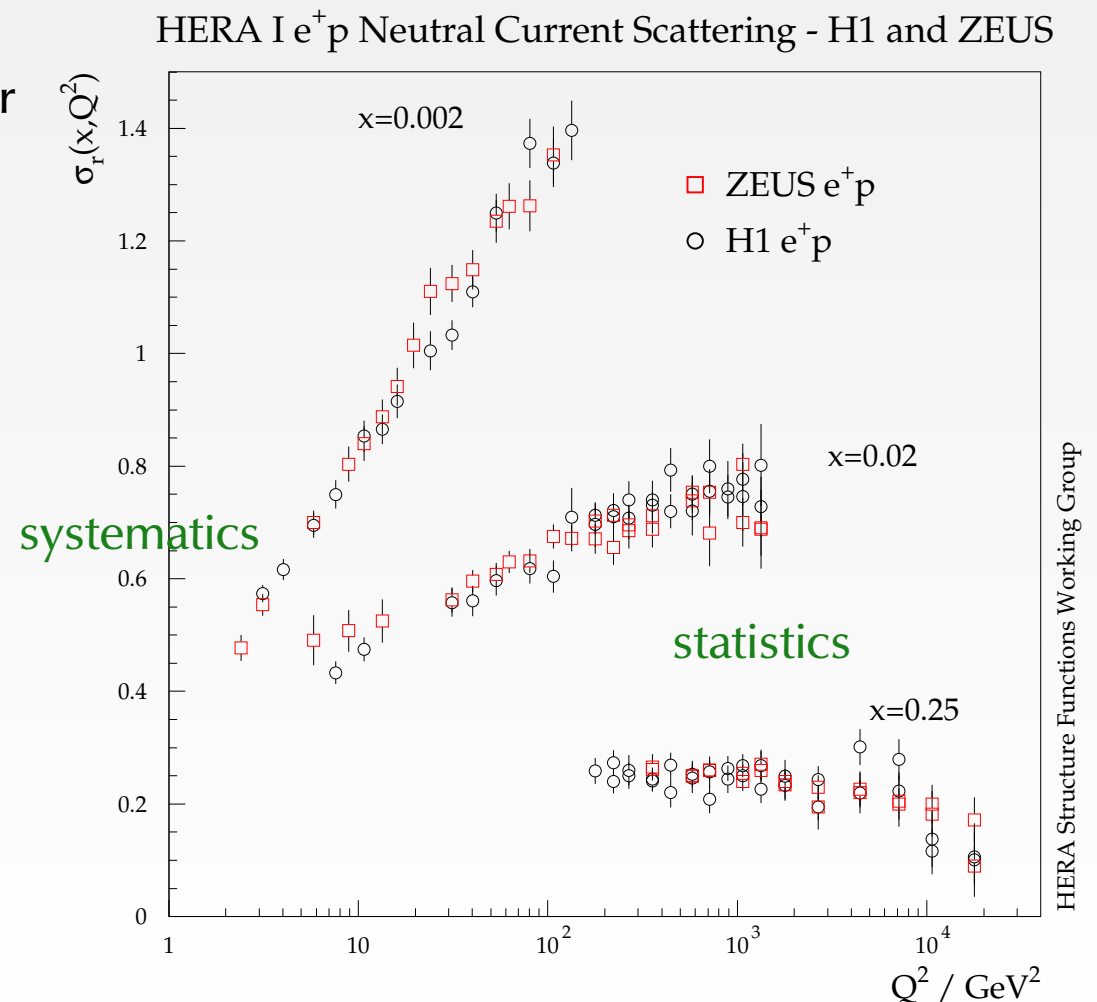
HERA II: $\sim 380 \text{ pb}^{-1} / \text{expt}$



$\mathcal{H}1 + \mathcal{ZEUS}$ Inclusive Data Combination

Goals

- ◆ Reduce statistical errors
- ◆ Reduce systematics by cross calibrating experiments to each other
- ◆ Study consistency of the data in a model independent way
- ◆ Allow more precise extraction of PDFs



Combination Procedure

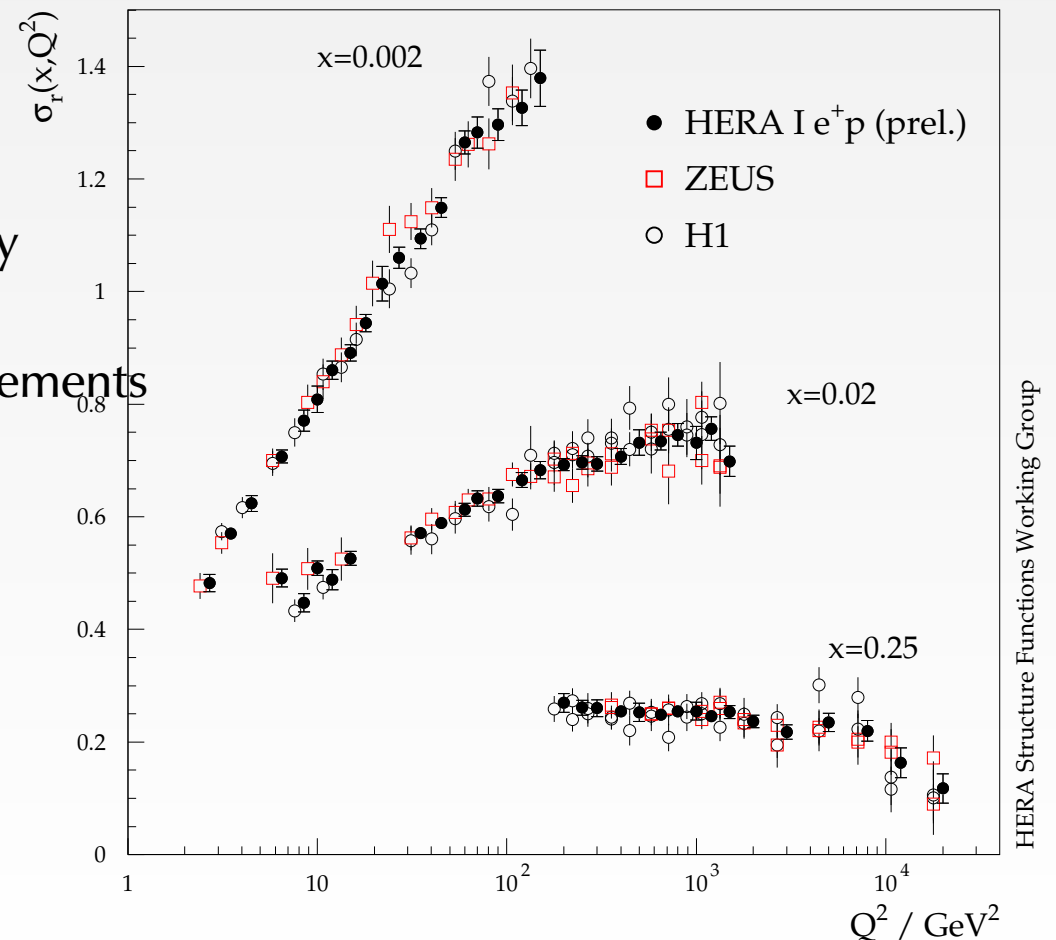
Combine all essential published HERA I NC and CC data
at $1.5 < Q^2 < 30000 \text{ GeV}^2$ and $6 \cdot 10^{-5} < x < 0.65$

Procedure

- ◆ Move all data points to common x - Q^2 grid
- ◆ Move 820 GeV data to 920 GeV beam energy
- ◆ Calculate average values and errors
accounting for correlations between measurements
- ◆ Evaluate uncertainties due to combination

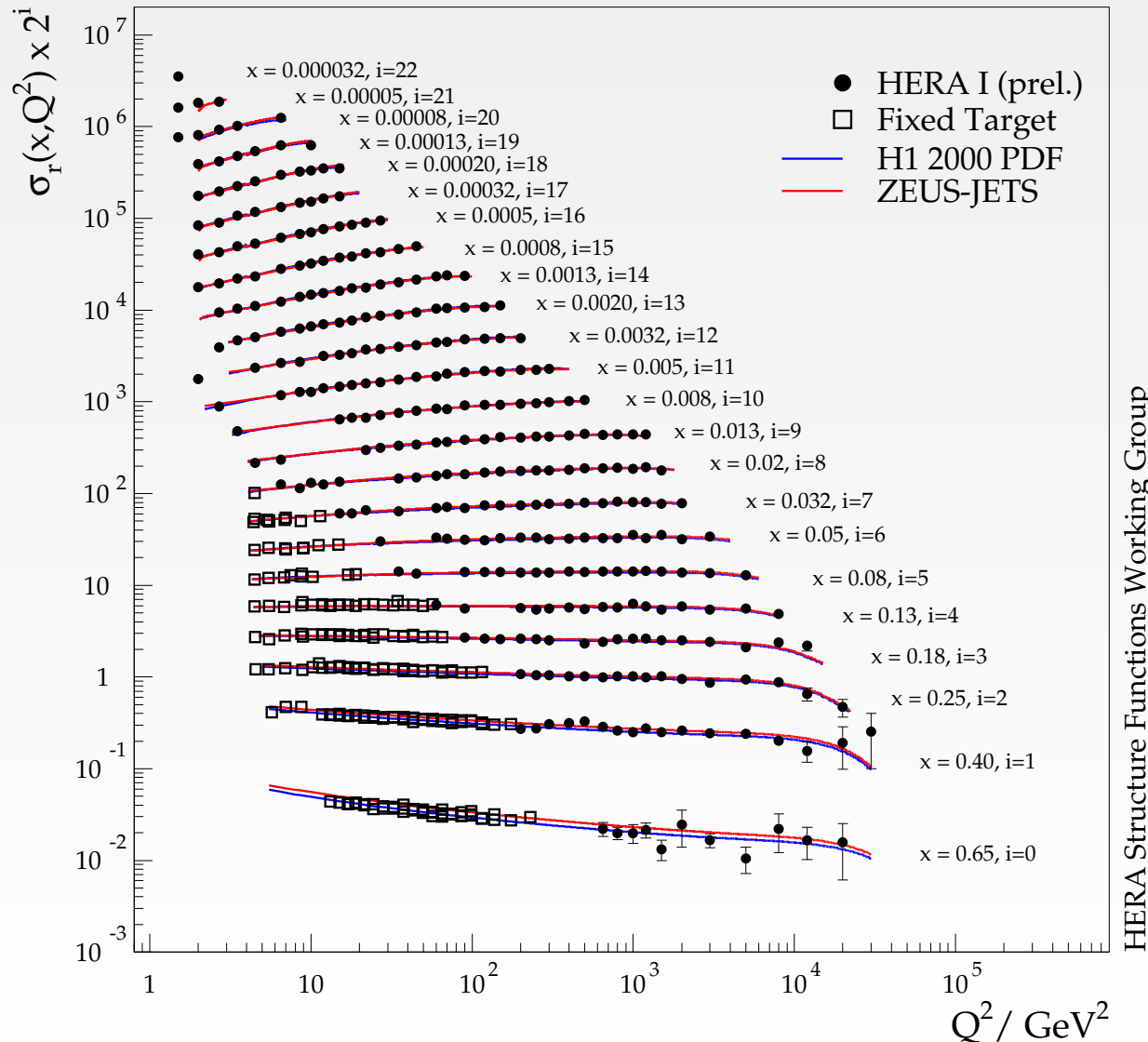
$$\chi^2 / \text{ndf} = 510 / 599$$

HERA I e^+p Neutral Current Scattering - H1 and ZEUS



H1 + ZEUS Combination Results

HERA I e^+p Neutral Current Scattering - H1 and ZEUS



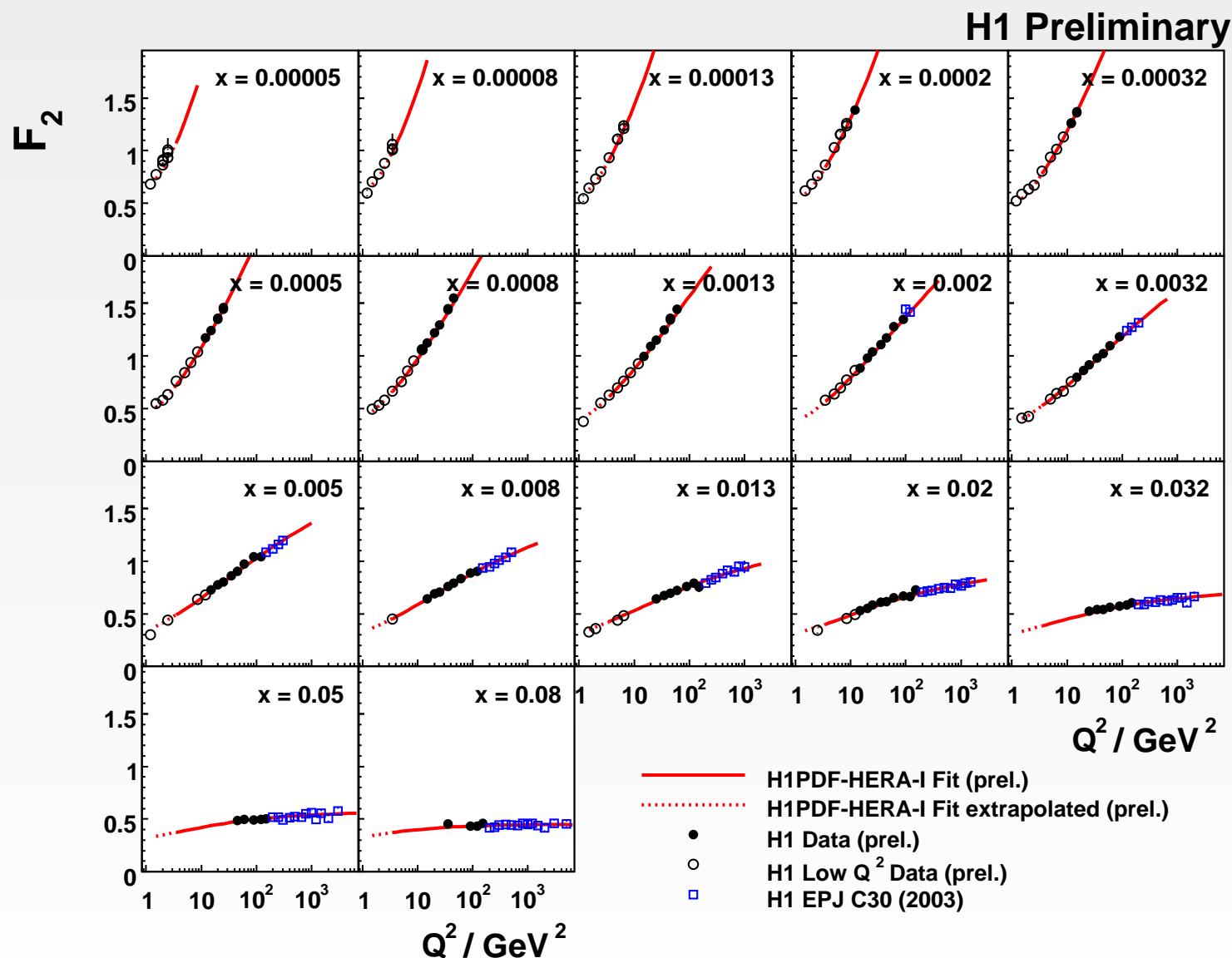
Agree well with both
 H1 2000 and ZEUS-JETS PDF fits

Systematic uncertainties are
 smaller than statistical ones
 across x - Q^2 plane

Outlook

- ◆ Add newest HERA I results
- ◆ Combine all HERA I / HERA II

Final H1 HERA I Set: Low-Medium Q^2

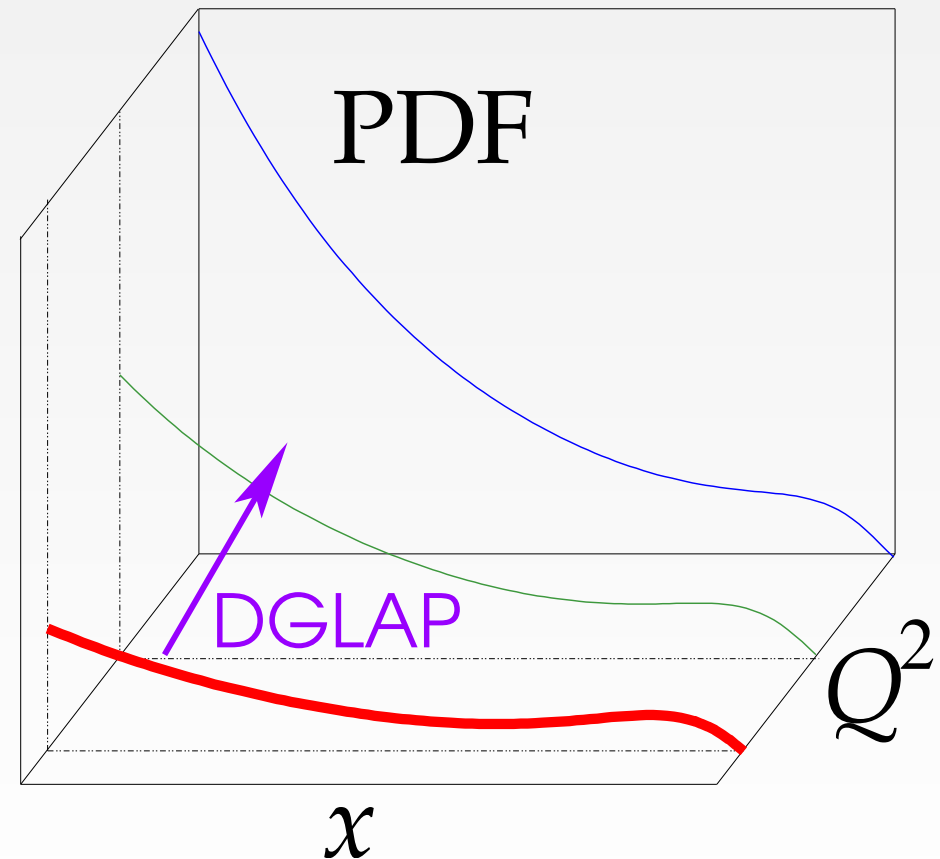


Total uncertainties in bulk region $\sim 1.5\%$ – improved by factor ~ 2 w.r.t. previous H1 data

pQCD PDF Fits

Procedure

- ◆ Assume parametric form of PDFs $q_i(x)$, $g(x)$ in x at starting scale Q_0^2
- ◆ Evolve to higher Q^2 using DGLAP
- ◆ Determine PDF parameters from χ^2 fit to experimental data



H1 + ZEUS Combined PDF Fit

Common choice

- ◆ Data set
- ◆ Choice of PDFs
- ◆ Starting scales
- ◆ Form in x at Q_0^2 and # parameters
- ◆ Treatment of heavy flavours
- ◆ Parameters and constraints
- ◆ Propagation of systematic errors
- ◆ Renormalisation / factorisation scales
- ◆ ...

Current decisions

Combined H1 + ZEUS

g , u_v , d_v , $\overline{U} = \overline{u} + \overline{c}$, $\overline{D} = \overline{d} + \overline{s} + \overline{b}$

$Q_0^2 = 4 \text{ GeV}^2$, data $Q_{\min}^2 = 3.5 \text{ GeV}^2$

$xf(x) = Ax^B(1-x)^C (1 + Dx + Ex^2 + \dots)$

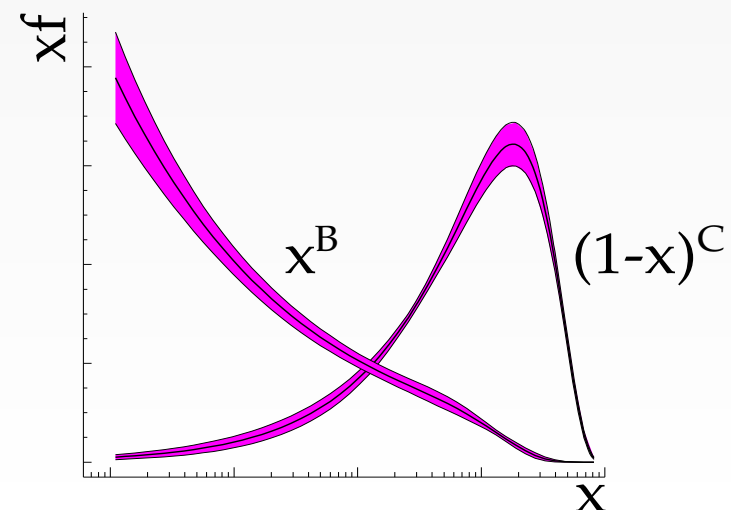
– optimize until no further χ^2 advantage

VFNS (Thorne) , $s = 0.33D$, $c = 0.15U$, ...

$\alpha_s(M_Z) = 0.1176$, $m_c = 1.4 \text{ GeV}$, $m_b = 4.75 \text{ GeV}$

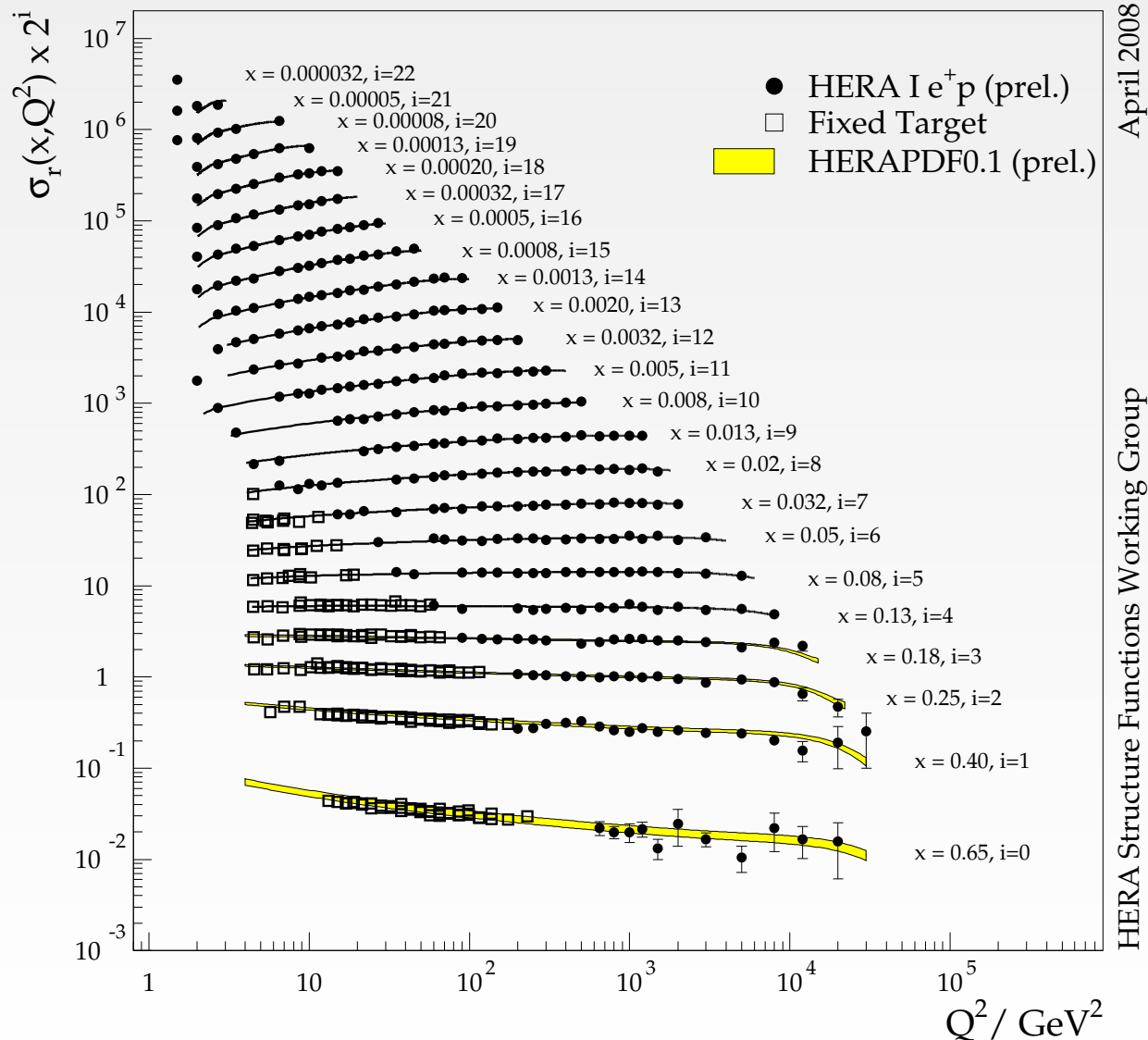
43 uncorrelated + 4 offset

Q^2



Results: $\mathcal{H}1 + \text{ZEUS}$ Combined PDF Fit

H1 and ZEUS Combined PDF Fit

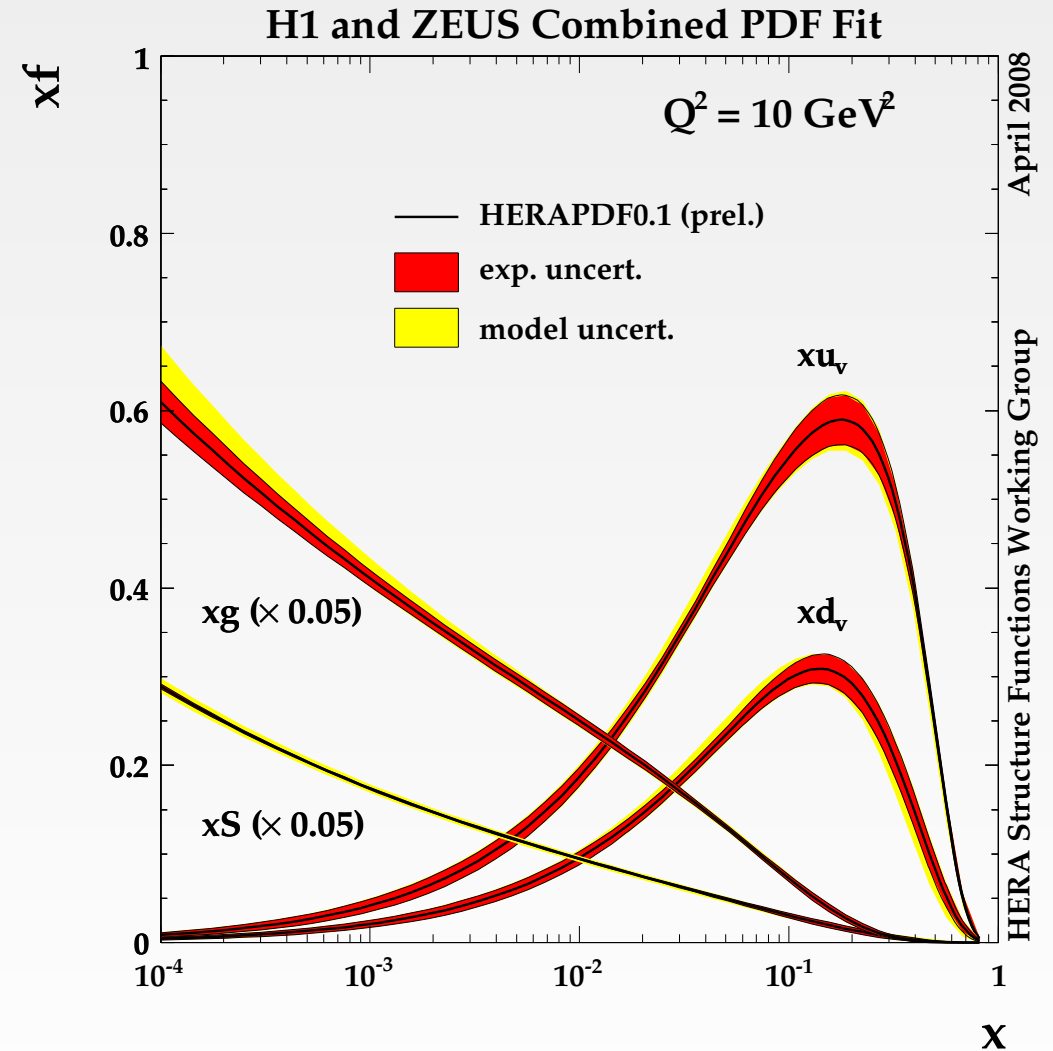
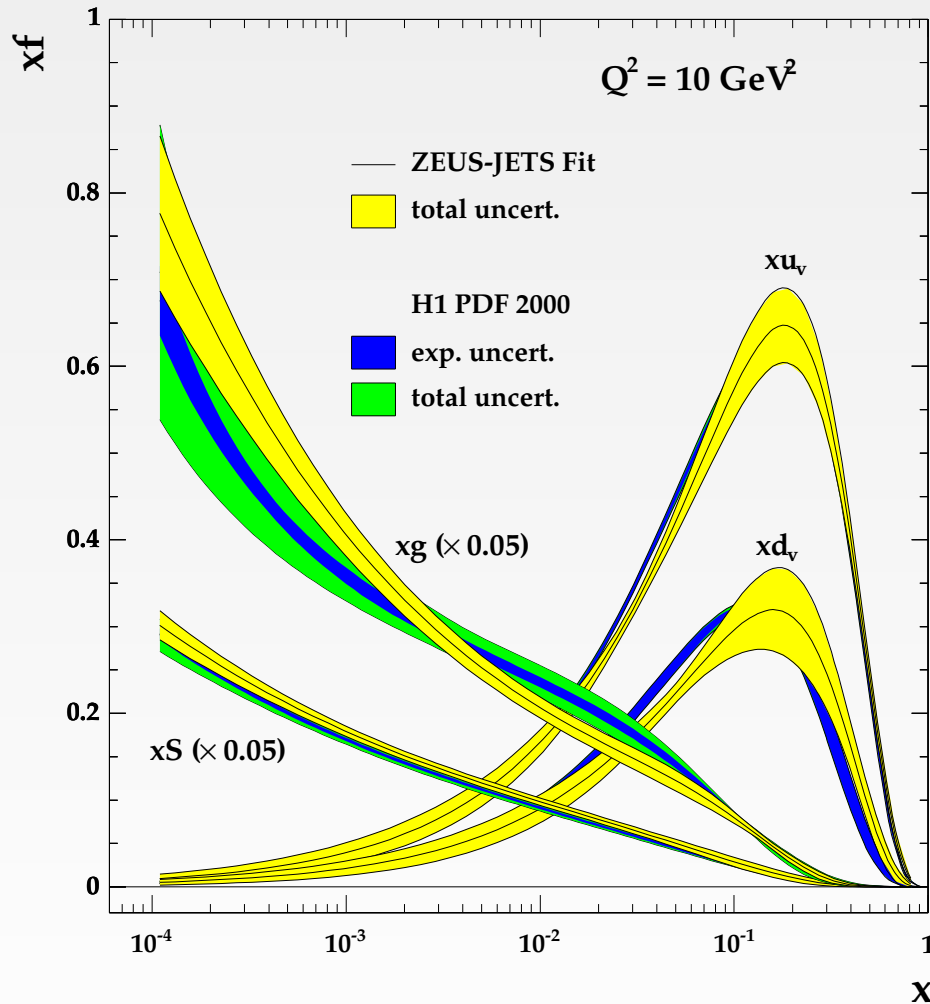


$$\chi^2 / \text{ndf} = 476,7 / 562$$

Total uncertainties shown
[including model uncertainties]

Comparison to Published H1/ZEUS Results

also based only on HERA data



Resolution of previous discrepancies, dramatic reduction of uncertainties

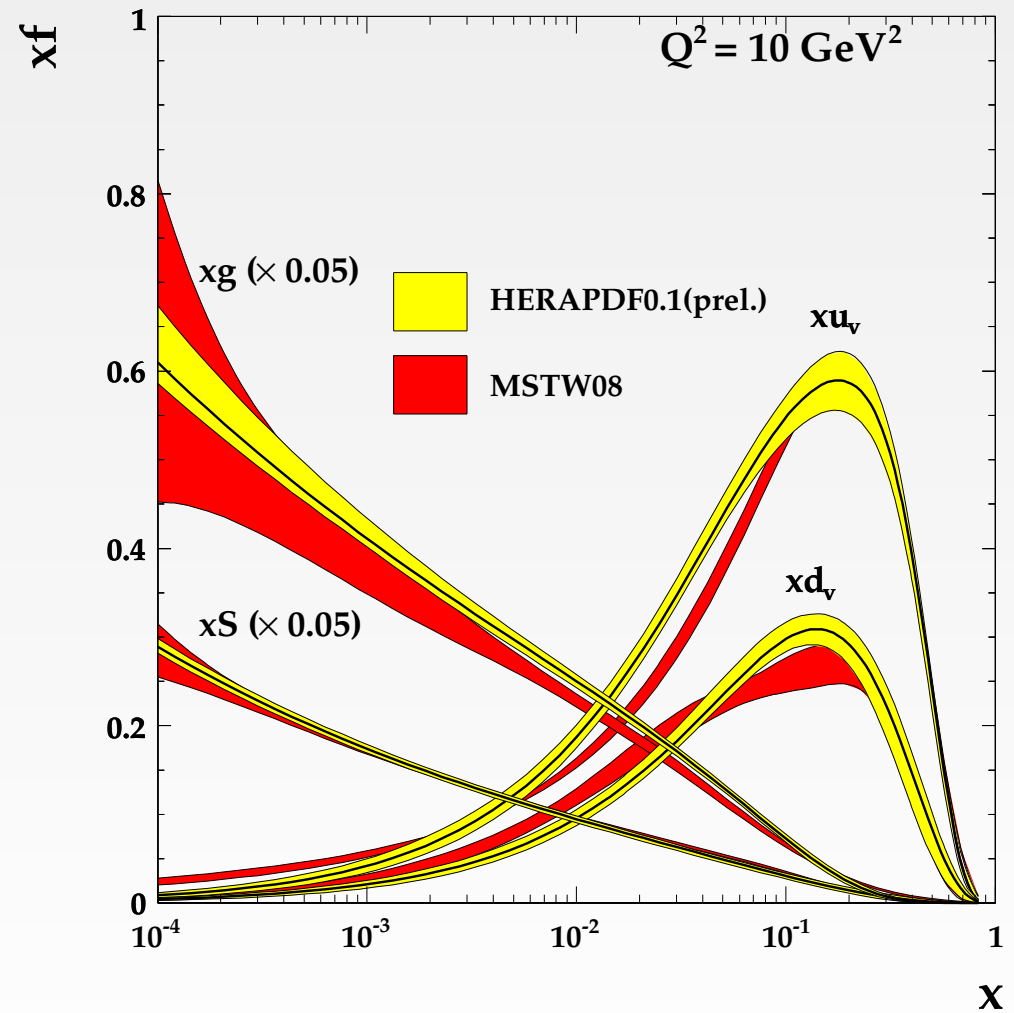
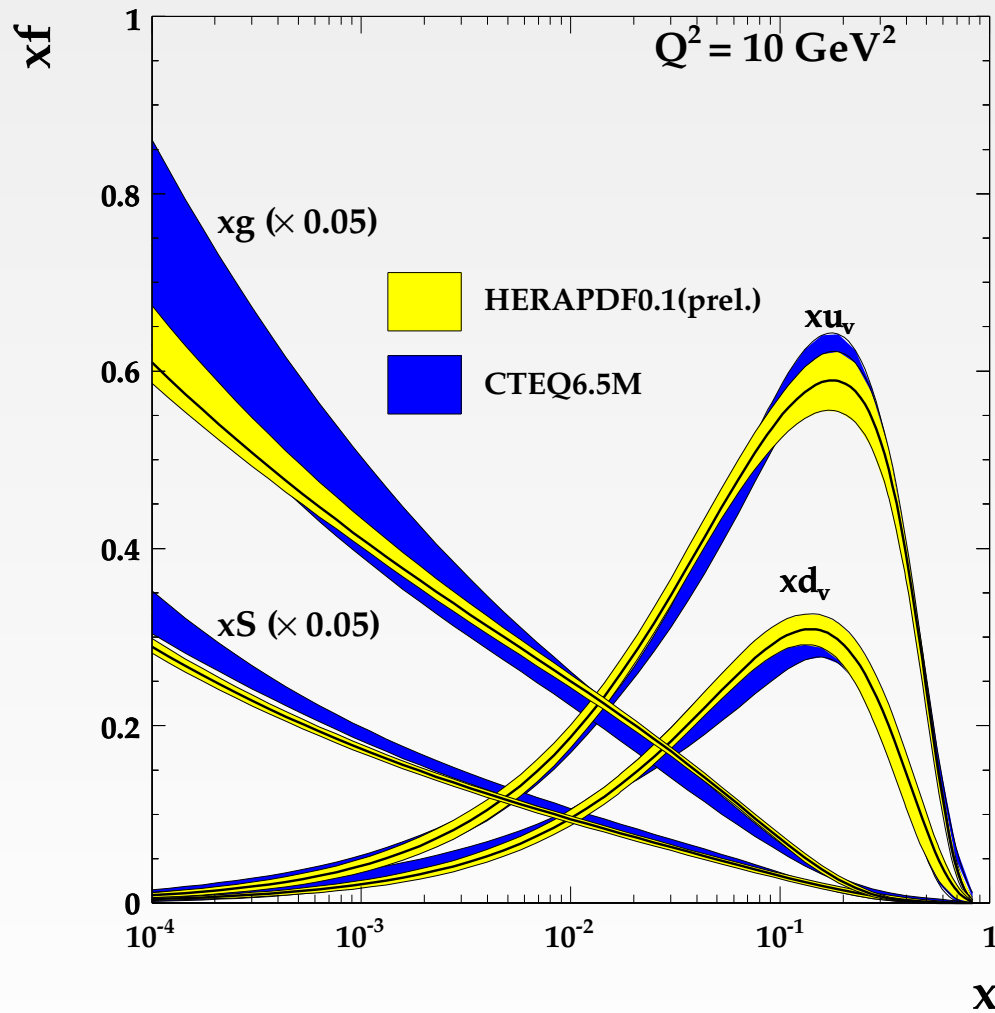
Increase of precision mostly from data combination

April 2008

HERA Structure Functions Working Group

x

Comparison to Newest Global Fits



Longitudinal Structure Function F_L

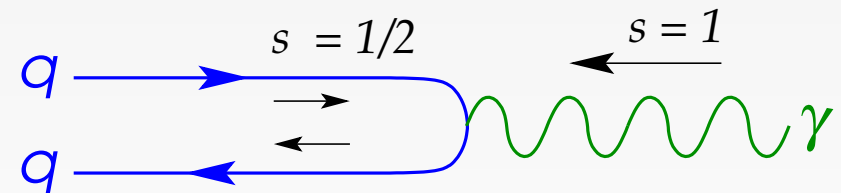
- ◆ NC DIS cross section [ignoring weak effects]

$$\sigma_r = F_2(x, Q^2) - \frac{y^2}{Y_+} F_L(x, Q^2) \quad Y_{\pm} = 1 \pm (1 - y)^2$$

F_L – independent structure function describing exchange of longitudinally polarised photons

- ◆ The last missing piece in HERA DIS measurements of proton structure functions

- ◆ In Quark–Parton Model $F_L = 0$ due to helicity and angular momentum conservation for spin $\frac{1}{2}$ quarks
[Callan–Gross relation]



- ◆ In QCD $F_L > 0$ due to gluon radiation

F_L measurement provides important test of pQCD

Directly sensitive to gluon distribution function: $F_L \propto \alpha_s x g(x)$

F_L in Theory

- ◆ Gluon pdf is otherwise known

from scaling violations $xg \sim \frac{\partial F_2}{\partial \ln Q^2}$
 → significant exp. and theor. uncertainty

- ◆ Most interesting at low x

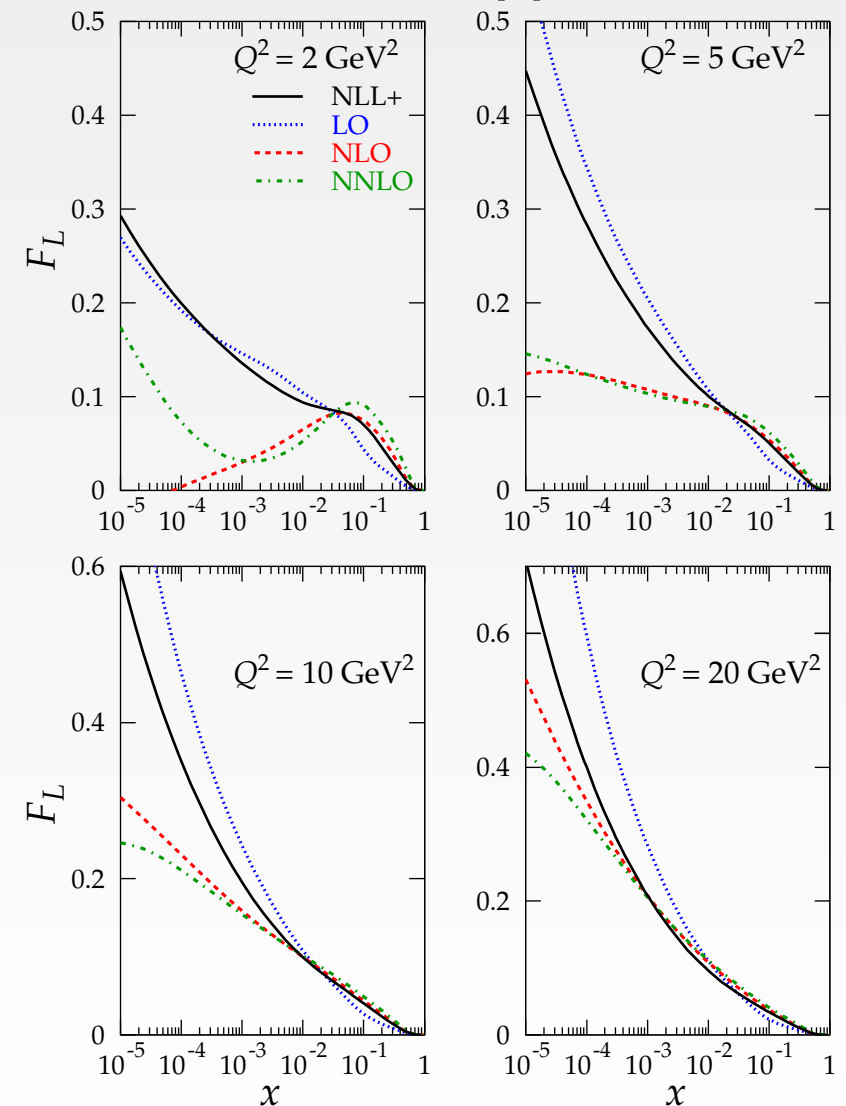
Critical corner – low Q^2 and low x , where
 $xg(x, Q^2)$ becomes valence-like or even negative

- ◆ Cross section is sensitive to F_L at high $y \rightarrow$ low x

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

with $Y_+ = 1 + (1 - y)^2$

White and Thorne, hep-ph/0611204



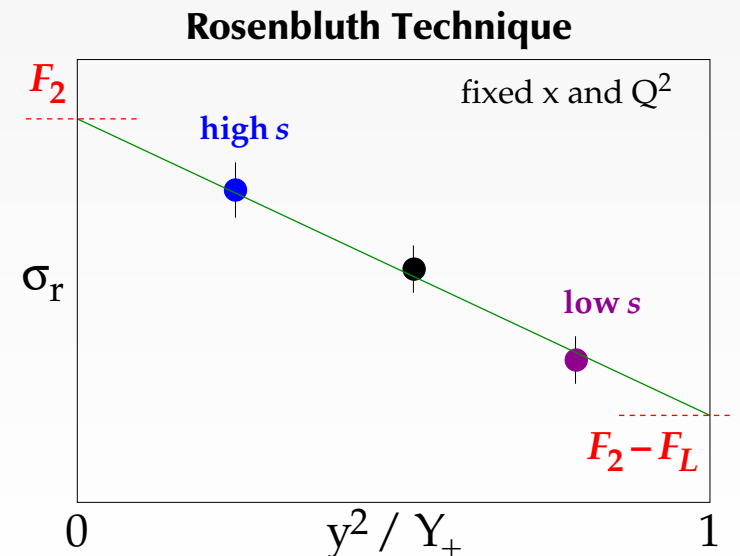
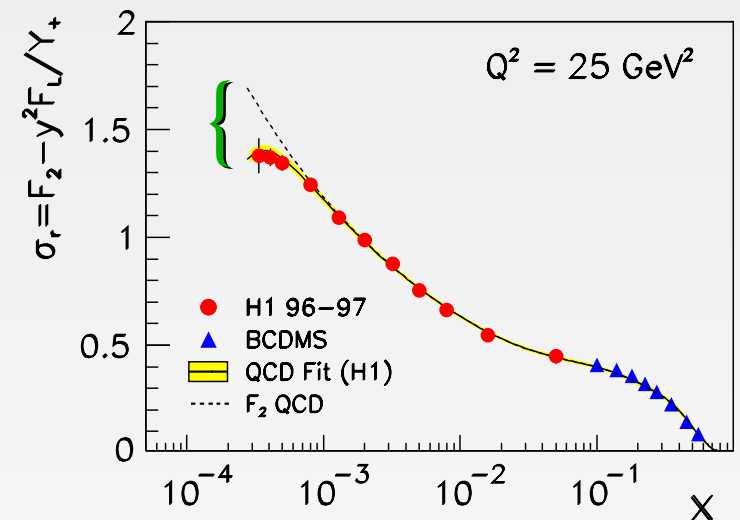
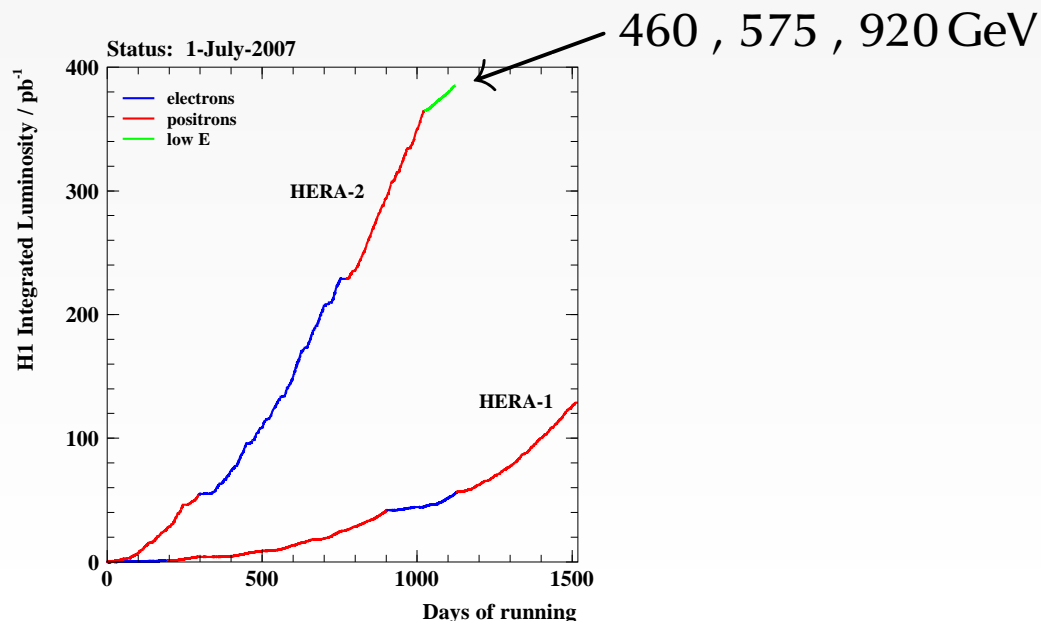
Basics of F_L Measurement

- Previous indirect F_L extractions – model dependent

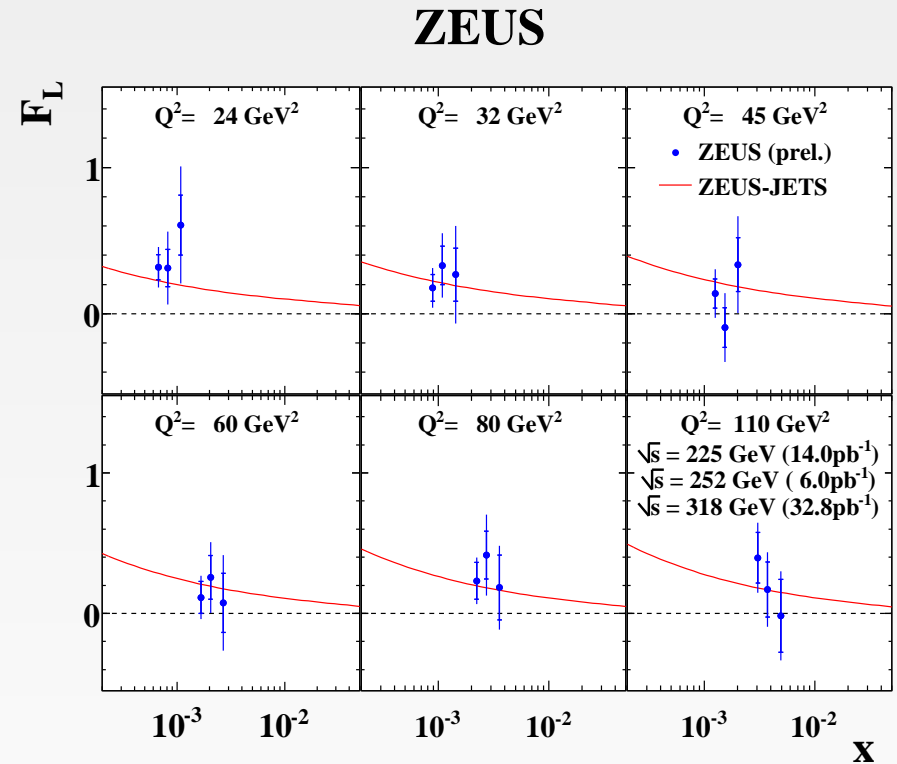
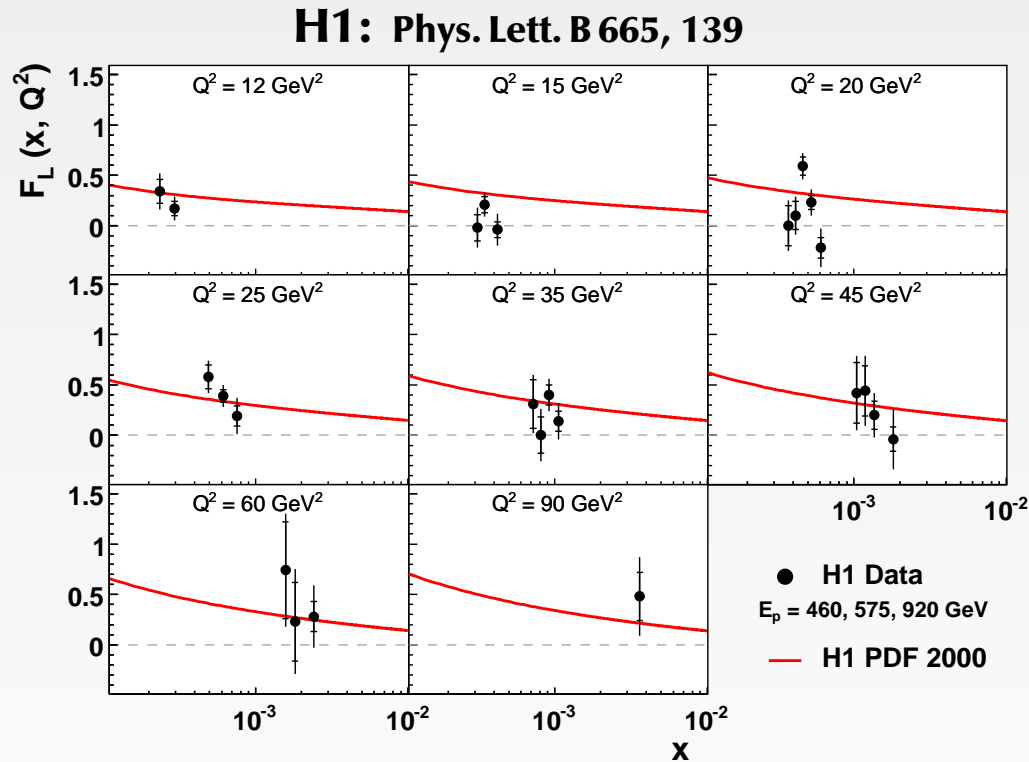
$$\sigma_r(x, Q^2) = F_2(x, Q^2) - \frac{y^2}{1 + (1 - y)^2} F_L(x, Q^2)$$

- Direct F_L requires σ_r at same x and Q^2 but at different y
 With $Q^2 = xys$: different $y \Rightarrow$ different s
 \Rightarrow low beam energy runs

- Collected e^+p data with 3 proton beam energies:



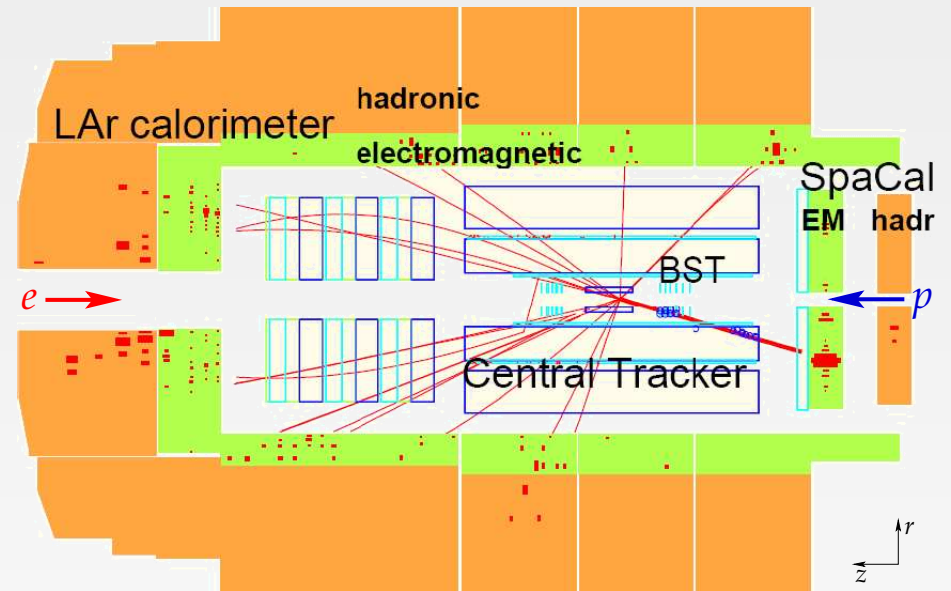
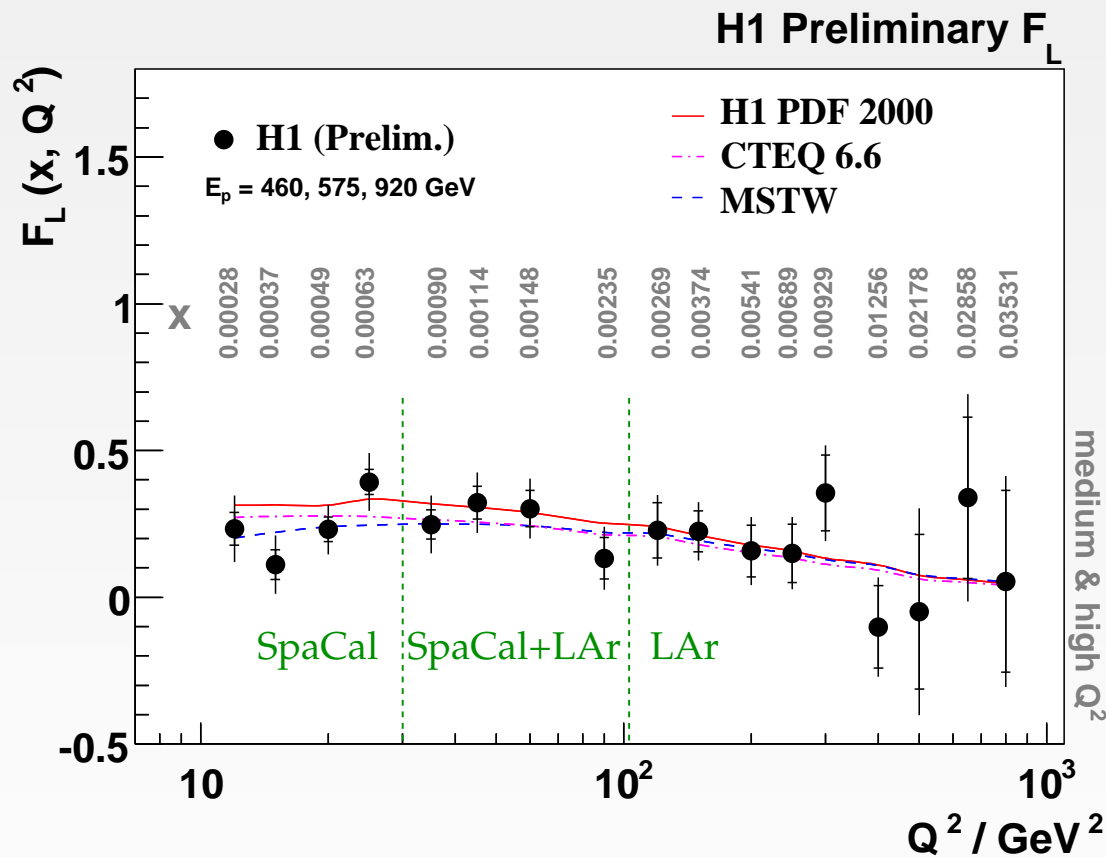
Results: $F_L(x)$ at Medium Q^2



Both measurements are consistent

Non-zero F_L is measured consistent with higher order pQCD predictions

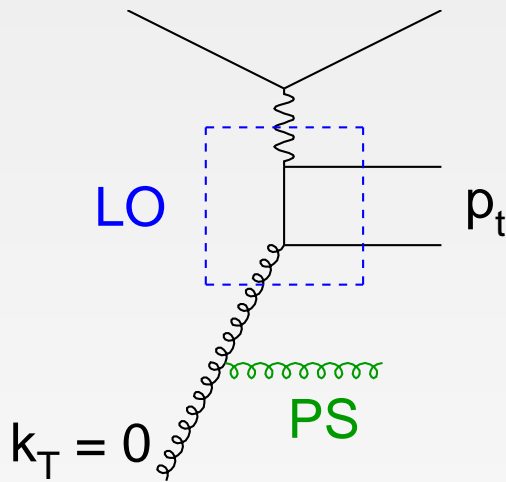
Preliminary F_L in Full Medium–High Q^2 Range



Data are consistent with NLO and NNLO QCD predictions

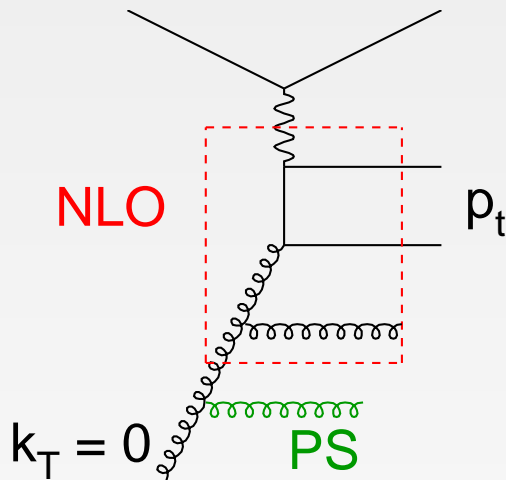
Looking forward for lower Q^2 / lower x using SpaCal + BST

Semi-Inclusive Measurements



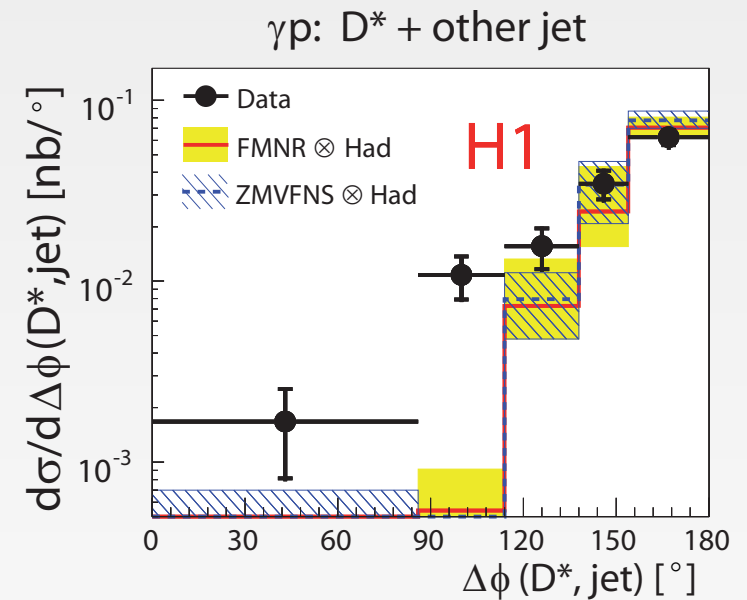
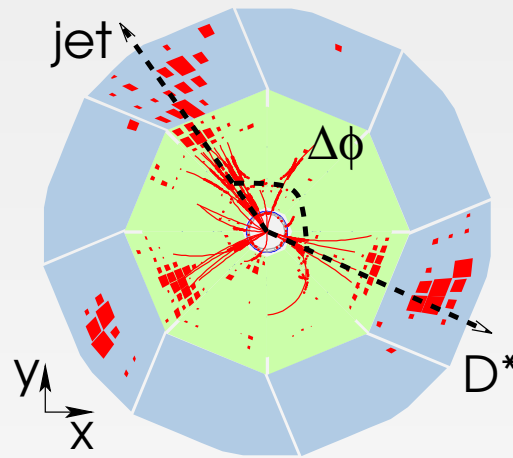
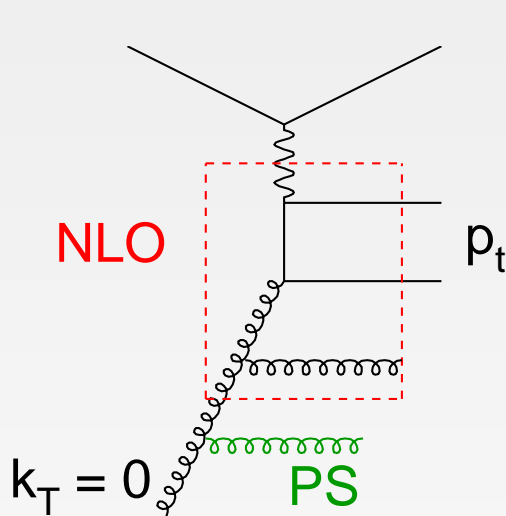
- ◆ In DGLAP, incoming parton $k_T = 0$
LO ME mostly insufficient to describe p_T
- ◆ MC PS adds soft gluons \Rightarrow small k_T

Semi-Inclusive Measurements



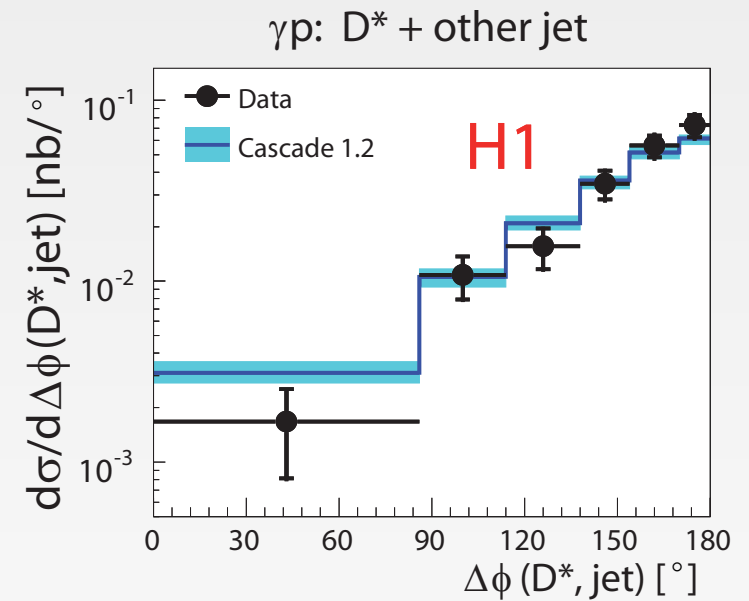
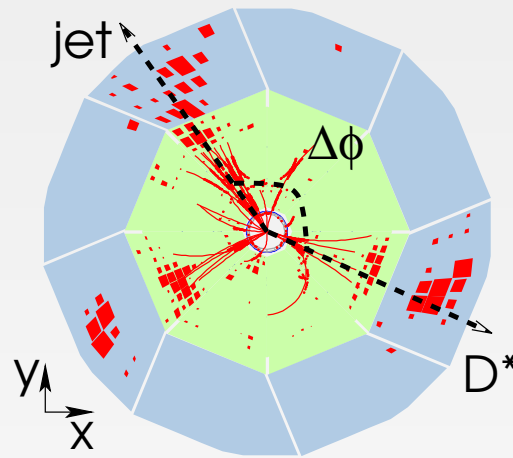
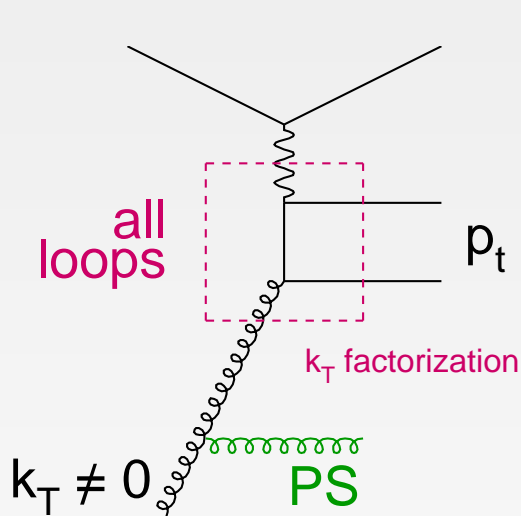
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- ◆ NLO usually much better, adds hard k_T , but PS are still required
- ◆ ME-PS matching difficult at NLO \Rightarrow NLO MC generators for only few processes
LO MC often used for hadronisation corrections \Rightarrow Significant uncertainties

Semi-Inclusive Measurements



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LO MC often used for hadronisation corrections \Rightarrow Significant uncertainties
- ◆ For some observables NLO is insufficient

k_T -Factorisation – Unintegrated PDFs



Better description of kinematics via

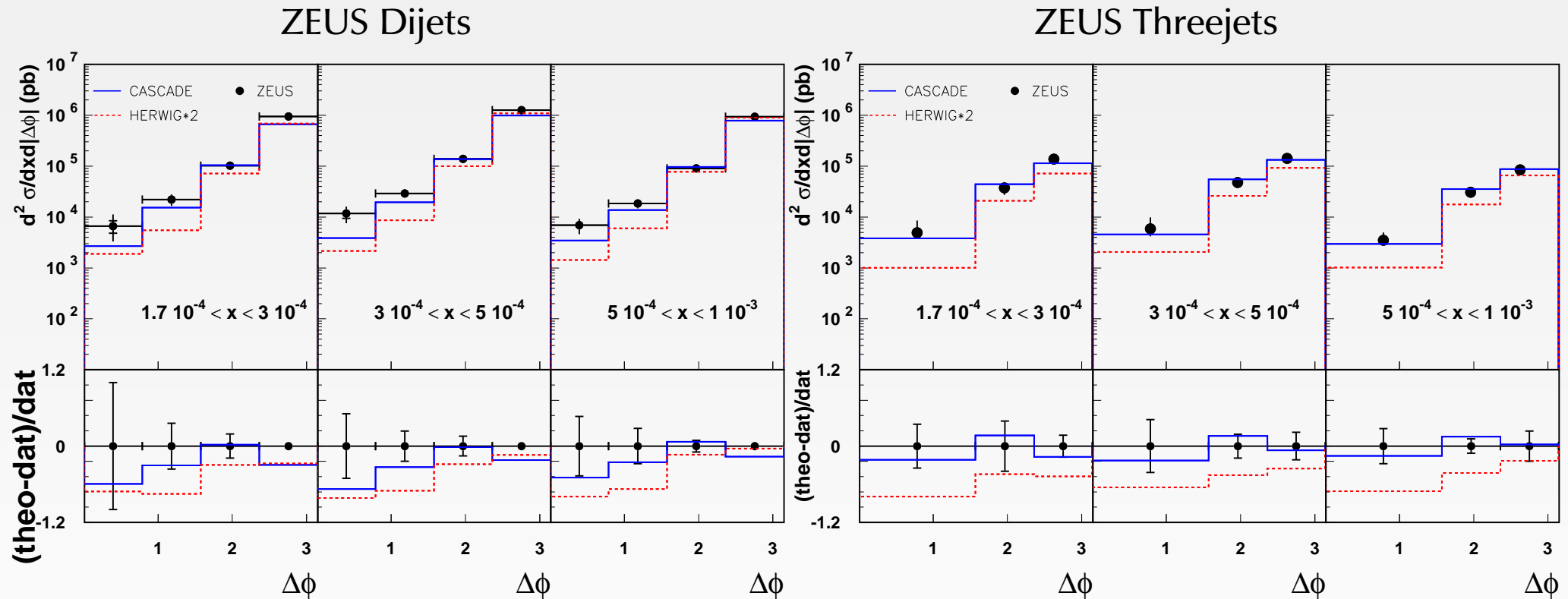
Unintegrated PDFs: $f_i(x, Q^2) \longrightarrow \mathcal{A}_i(x, k_T^2, Q^2)$ and off-shell ME

- ◆ Unintegrated PDFs are evolved using CCFM
- ◆ uPDF fits are available based on F_2 , dijets Δp_T
- ◆ Not yet as well established, as DGLAP
- ◆ MCs not as well developed as PYTHIA or HERWIG

Multijets in DIS

$$\Delta\phi = |\phi_1 - \phi_2|$$

Hautmann, Jung

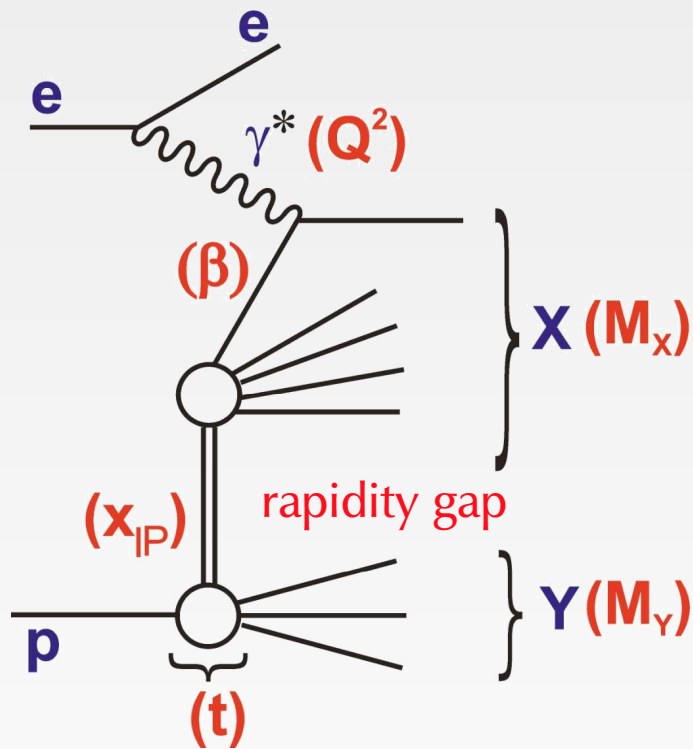


CASCADE is better both in normalisation and shape

uPDF MCs are additional tools for detailed semi-inclusive studies

⇒ Better understanding of hard interaction ⇔ multiple interactions

Diffraction



In addition to Q^2, x, y, W

momentum transfer squared
at proton vertex

$$t = (p - p_Y)^2$$

invariant mass of X (Y)

$$M_X = \sqrt{X^2} \quad (M_Y = \sqrt{Y^2})$$

fractional momentum
lost by proton

$$x_P = \frac{(p - p_Y) \cdot q}{p \cdot q} = \frac{Q^2 + M_X^2}{Q^2 + W^2}$$

fractional pomeron momentum
carried by struck quark

$$\beta = \frac{x}{x_P} = \frac{Q^2}{Q^2 + M_X^2}$$

reduced $\sigma_r^{D(4)}$

Cross section:

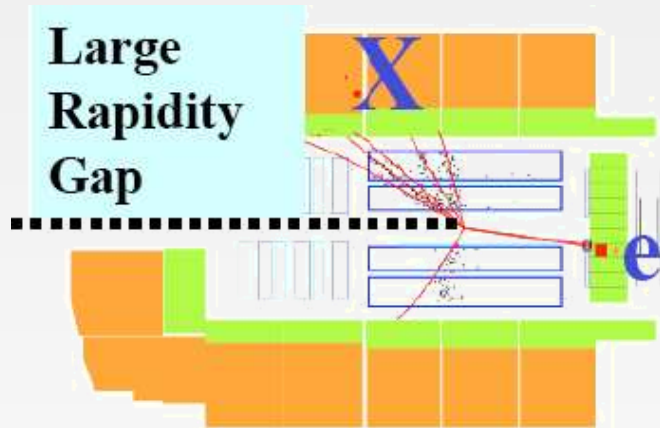
$$\frac{d^2 \sigma^{ep \rightarrow eXp}}{dx dQ^2 dx_P dt} = \frac{2\pi\alpha^2}{Q^4 x} Y_+ \left\{ F_2^{D(4)} - \frac{y^2}{Y_+} F_L^{D(4)} \right\}$$

In most analyses:

$$\sigma_r^{D(3)} \approx F_2^{D(3)} = \int \sigma_r^{D(4)} dt$$

Experimental Selections of Diffraction

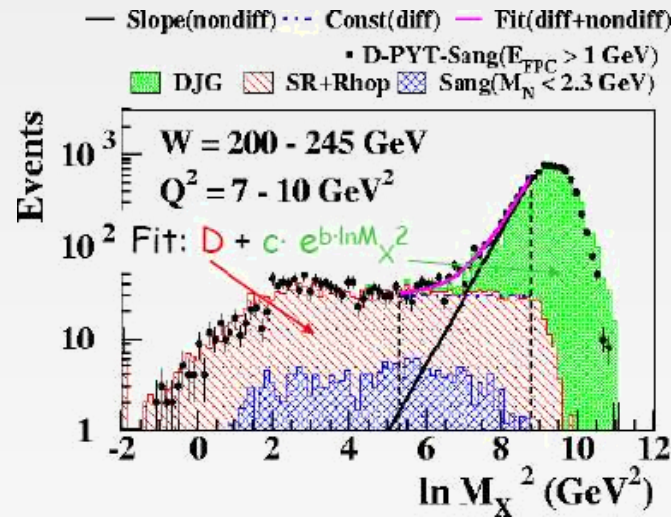
Large Rapidity Gap (LRG)



require LRG spanning
at least $3.3 < \eta < 7.5$

measure kinematics from X;
integrate over $|t| < 1 \text{ GeV}^2$
and $M_Y < 1.6 \text{ GeV}$

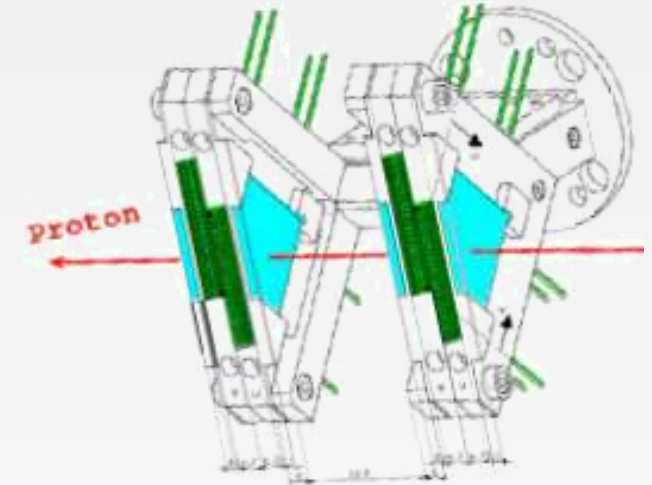
Fit of M_X distribution



extract diffractive sample
from fit $D + C \exp(b \ln M_X^2)$

measure kinematics from X;
integrate over $|t|$
and $M_Y < 2.3 \text{ GeV}$

Proton Tagging (FPS/LPS)



detect forward proton
 \Rightarrow no proton dissociation

measure kinematics from
proton momentum
 \Rightarrow direct measurement of t

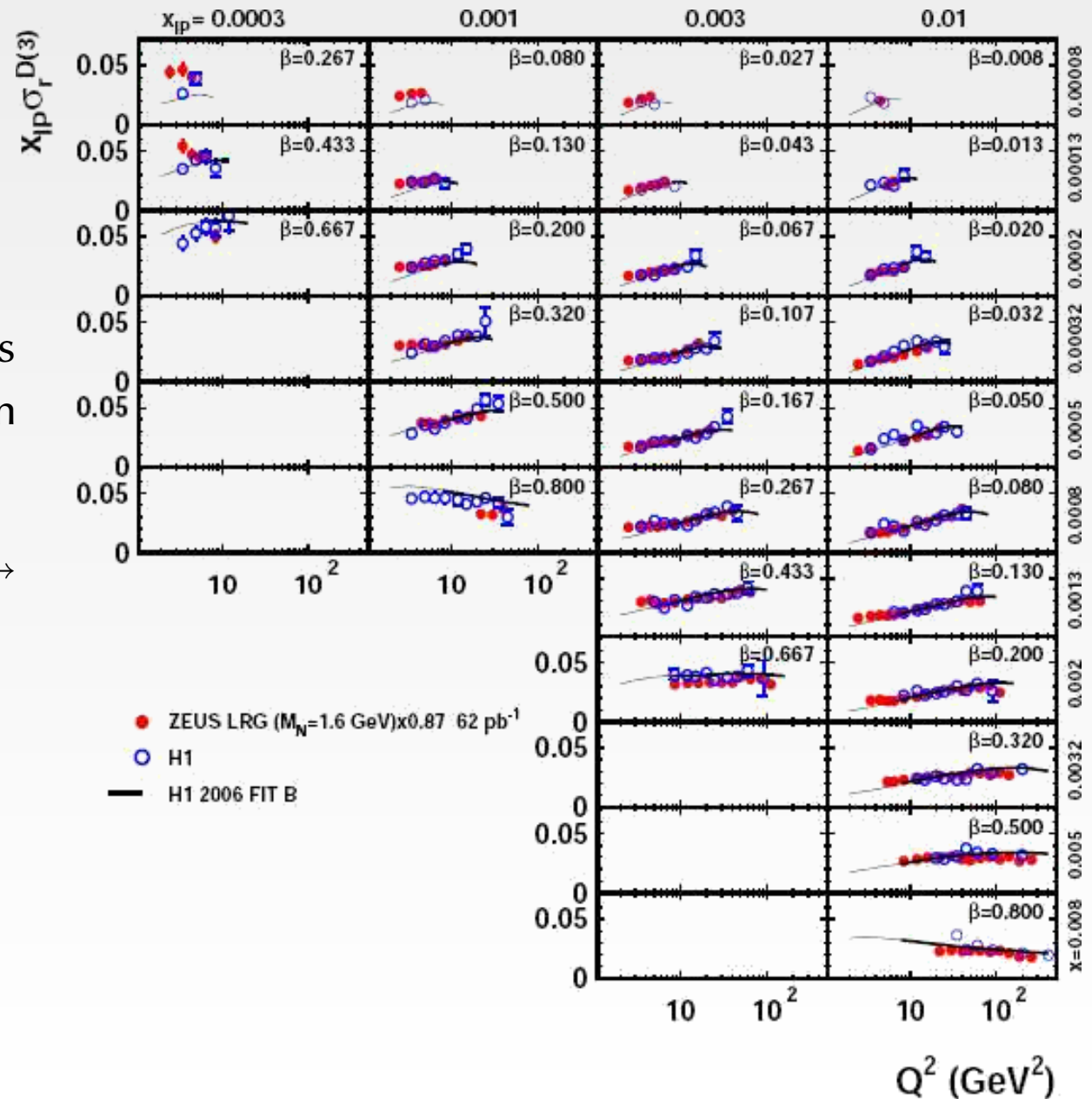
Different systematics and statistics

Cross Section Measurements

LRG, M_X and LPS/FPS measurements from H1 and ZEUS are consistent within uncertainties

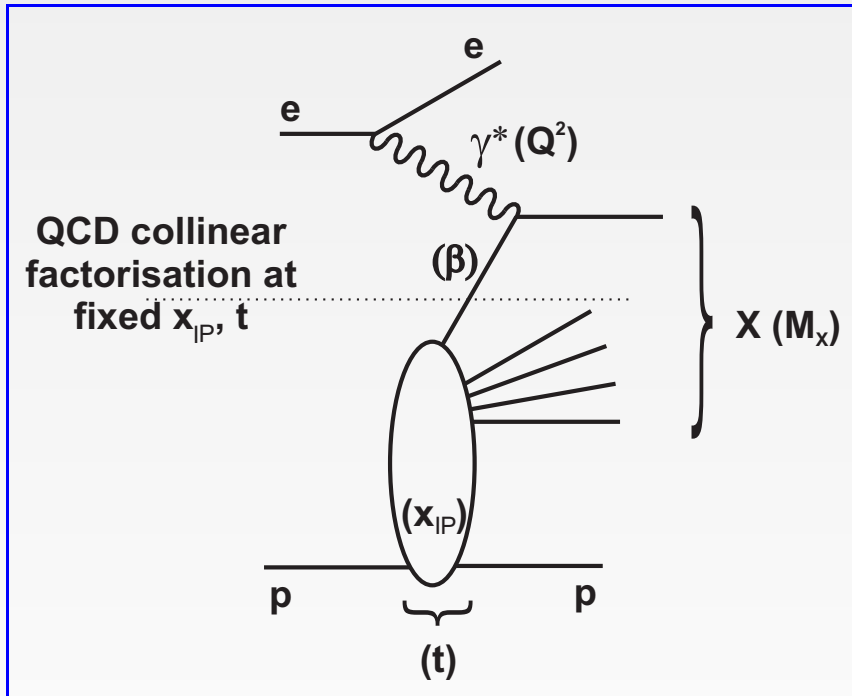
Note: here ZEUS normalised to H1 \longrightarrow

Discussions to combine data and produce common fits



Factorisation in Diffraction

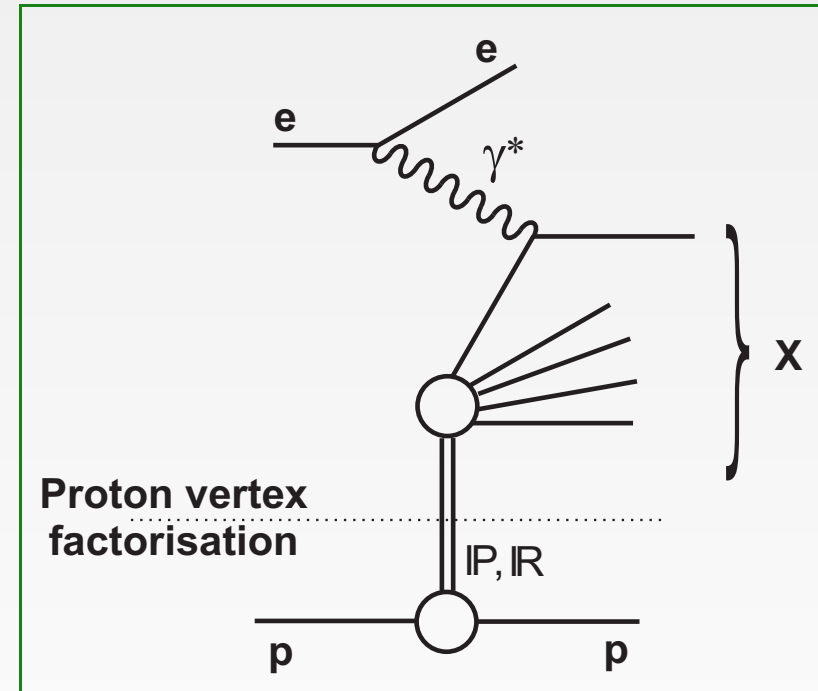
QCD collinear factorisation of hard scattering (Collins) – **exact**



DPDF

$$d\sigma^{ep \rightarrow eXY} = \sum_i f_i^D(x, Q^2, x_P, t) \otimes d\sigma^{ei}(x, Q^2)$$

Proton vertex factorisation (Regge) – **approximation**

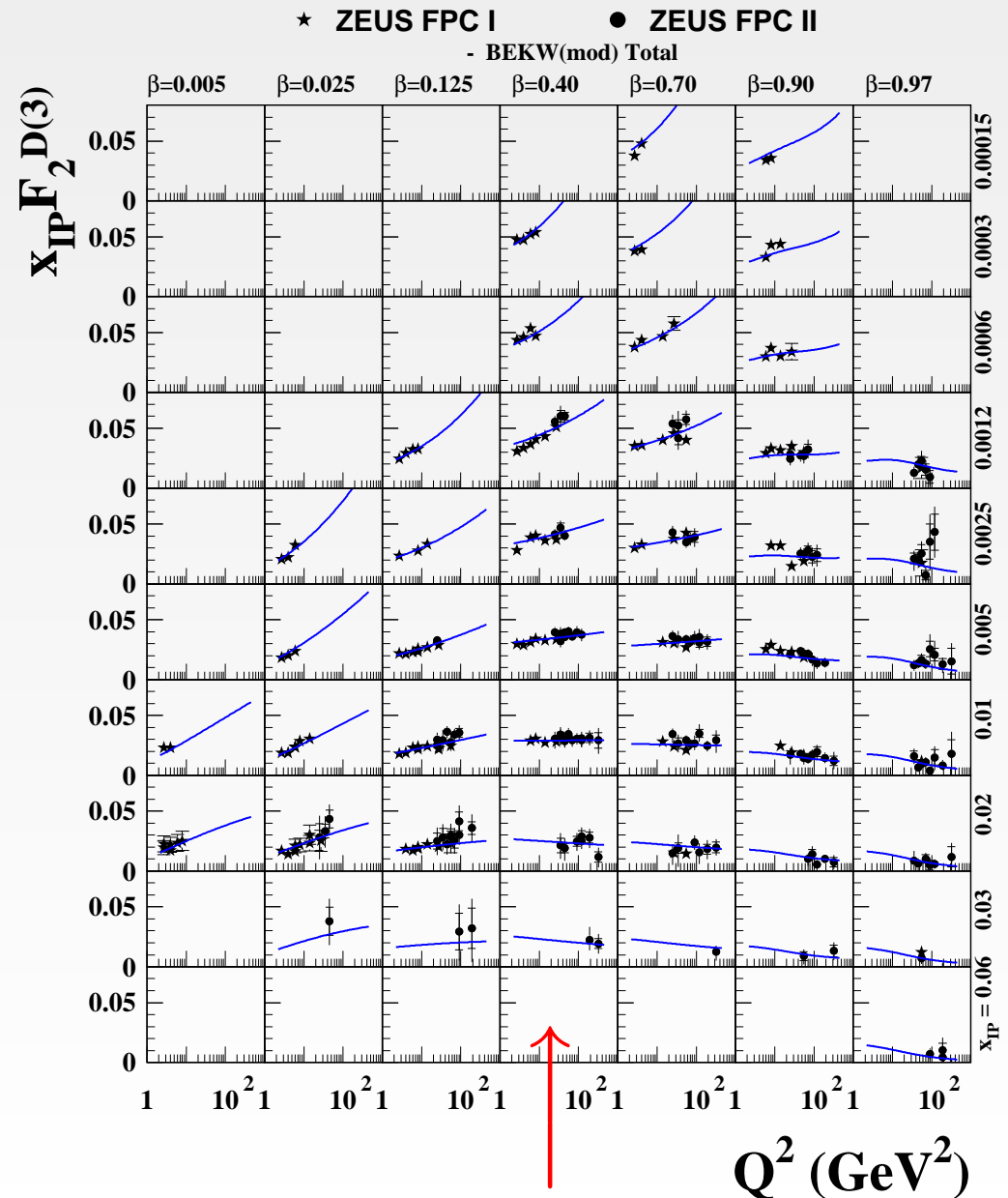


$$f_i^D(x, Q^2, x_P, t) = f_{P/p}(x_P, t) \cdot f_i^P(\beta = \frac{x}{x_P}, Q^2) \\ + n_R f_{R/p}(x_R, t) \cdot f_i^R(\beta = \frac{x}{x_R}, Q^2)$$

Factorisation in Detail

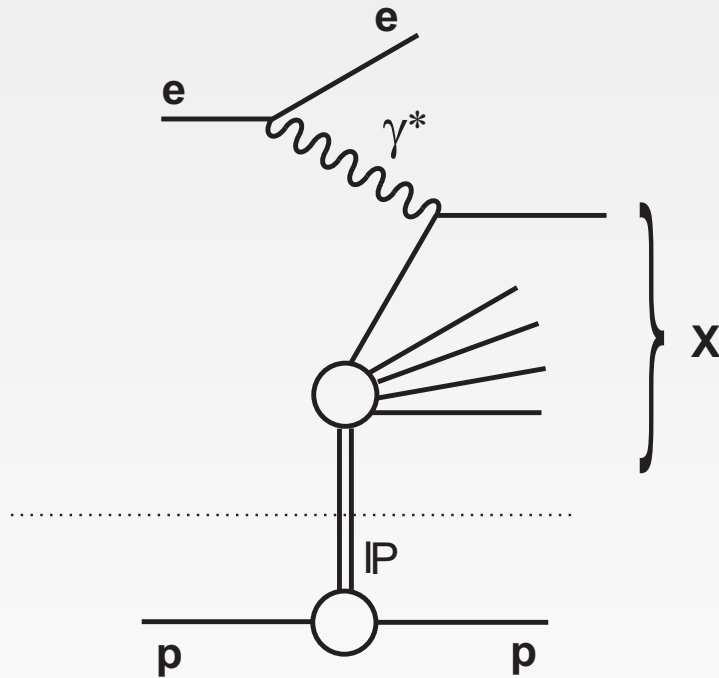
$$f_i^D(x_P, \beta, Q^2) \approx f_{P/p}(x_P) \cdot f_i^P(\beta, Q^2)$$

- ◆ For fixed β , dependence on Q^2 somewhat varies with x_P
 \Rightarrow Regge factorisation is broken
- ◆ Mild effect – should not strongly affect QCD fits which assume this

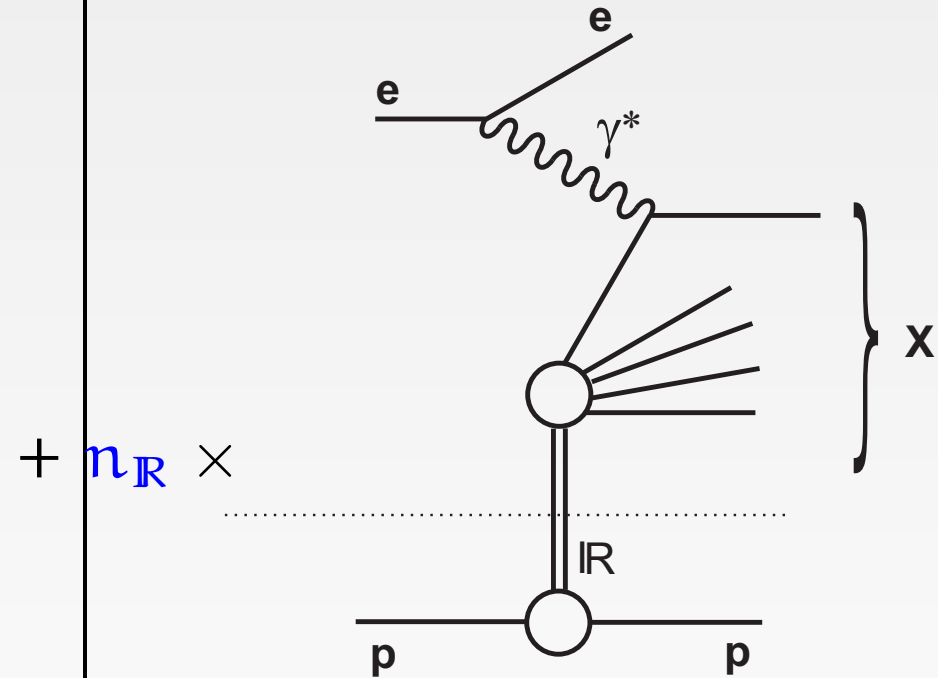


H1 DPD Fit Procedure

P component



R component



+ $n_{\mathbb{R}} \times$

- ◆ Fit $\alpha_{\mathbb{P}}(0) - \chi_{\mathbb{P}}$ dependence
- ◆ Simultaneously, fit 5 parameters of DPDs – β and Q^2 dependences – using NLO QCD

- ◆ Fit $n_{\mathbb{R}}$ – one parameter for normalisation
- ◆ All flux parameters from previous H1 data. PDFs taken from Owens-pion

DPDFs from Inclusive Diffraction

H1 2006 DPDF NLO QCD fit

$$zf_i(z, Q_0^2) = A_i z^{B_i} (1 - z)^{C_i}$$

[$z = \beta$ in QPM; $z \geq b$] $Q_0^2 \approx 2 \text{ GeV}^2$

Fitted data: $8.5 < Q^2 < 1600 \text{ GeV}^2$

Data insensitive to gluon $B_g \rightarrow$ omitted

◆ Fit A

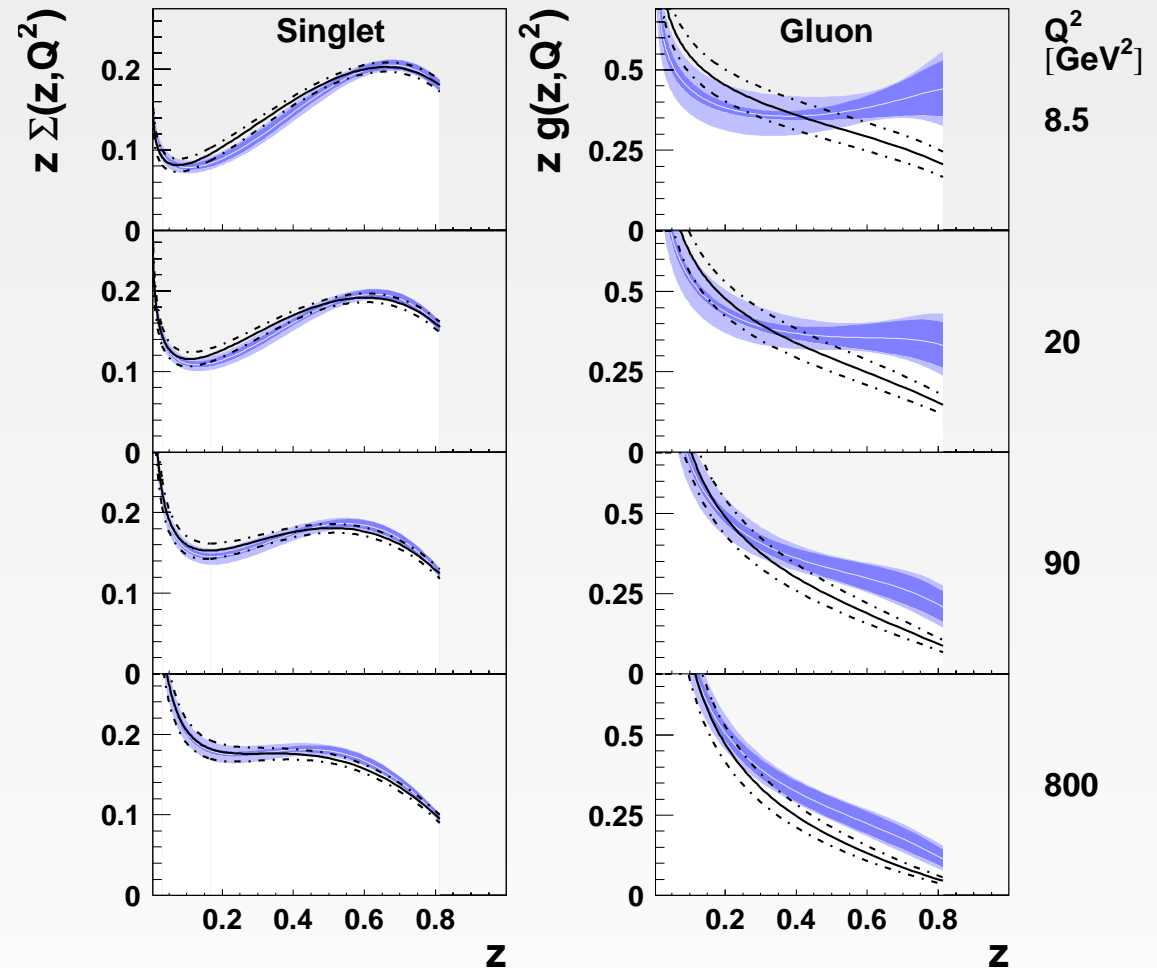
$$\chi^2 / \text{ndf} = 158 / 183$$

◆ Fit B

C_g dropped – gluon parameterised as constant at starting scale

$$\chi^2 / \text{ndf} = 164 / 184$$

- Quarks very stable
- Gluon similar at low z but no sensitivity at high z



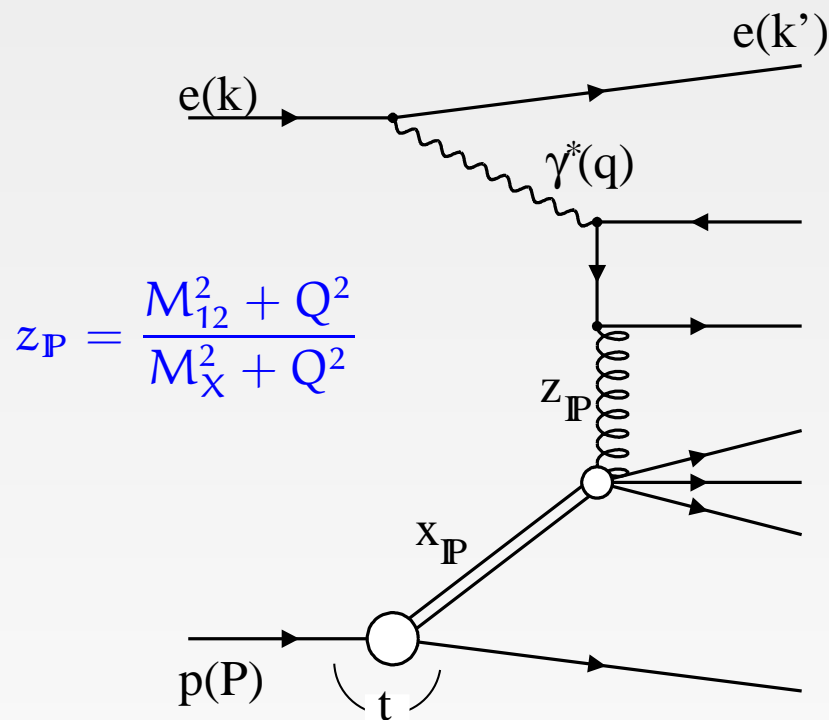
H1 2006 DPDF Fit A
 (exp. error)
 (exp.+theor. error)

H1 2006 DPDF Fit B
 (exp.+theor. error)

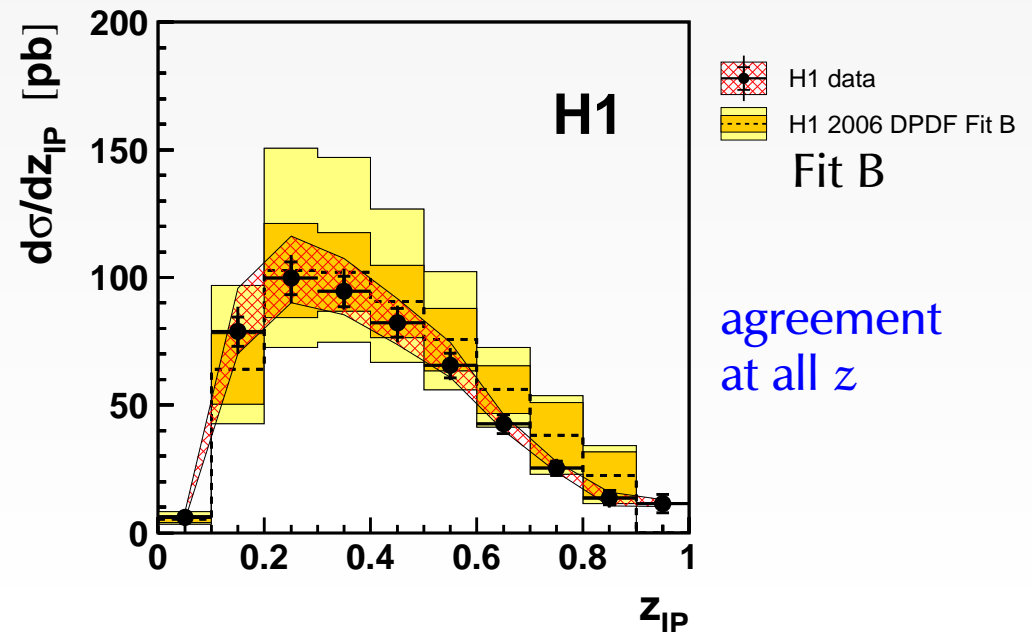
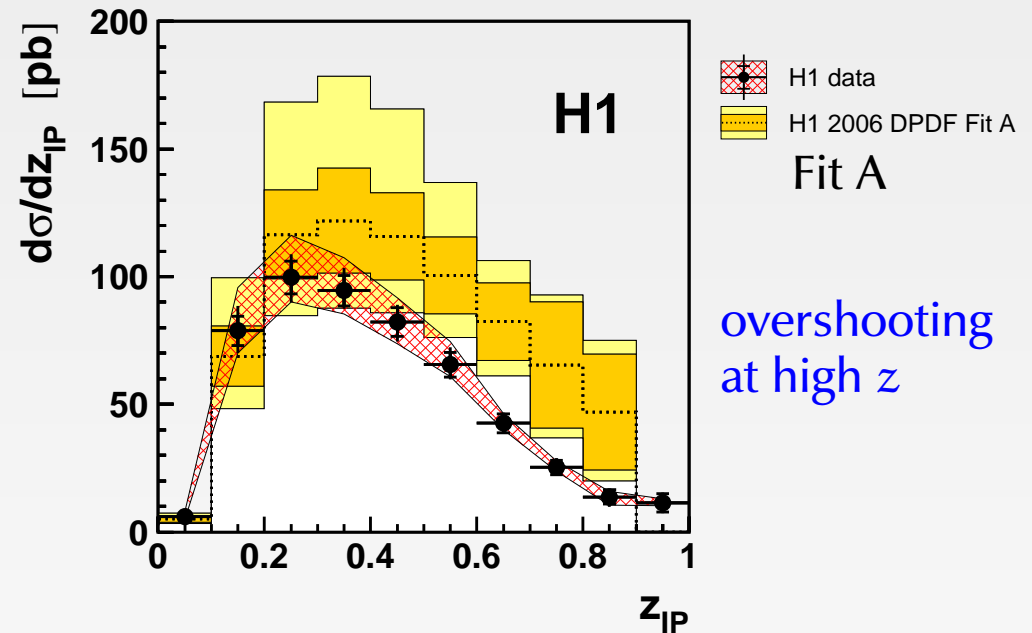
$$zg(z, \mu_{f,0}^2) = A_g (1 - z)^{C_g}$$

$$zg(z, \mu_{f,0}^2) = A_g$$

Comparison to Diffractive Dijets in DIS



- ◆ Sensitive to gluon at high z
- ◆ QCD factorisation holds in DDIS
Tested differentially in many variables
Similar observation by ZEUS
- ◆ Fit B preferred by DDIS dijets



Combined Diffractive PDF Fit

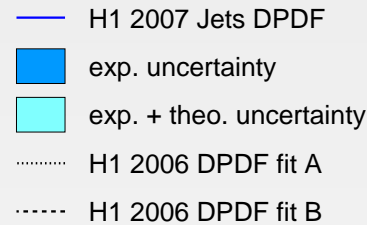
H1 Jets 2007 DPDF NLO QCD fit

use Diffractive DIS dijet data
as additional constraint

$$\chi^2 / \text{ndf} = 196 / 218$$

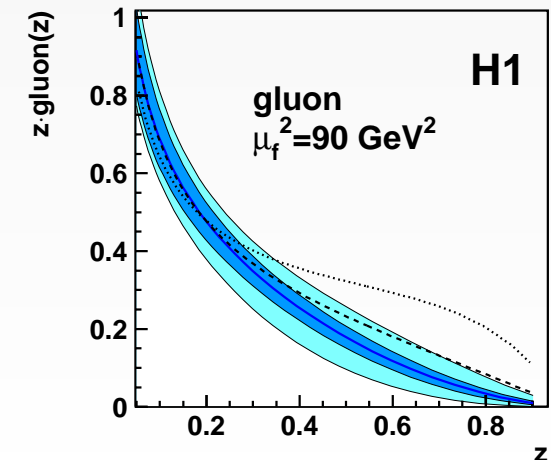
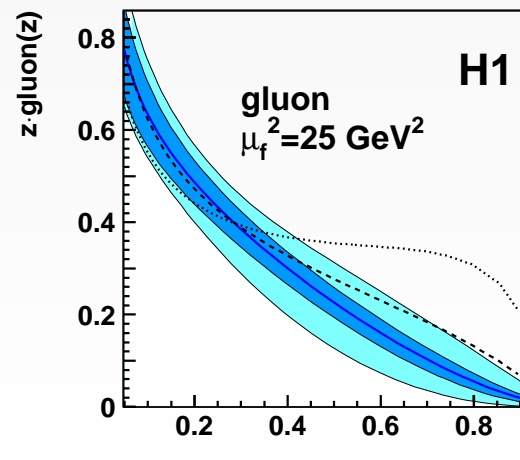
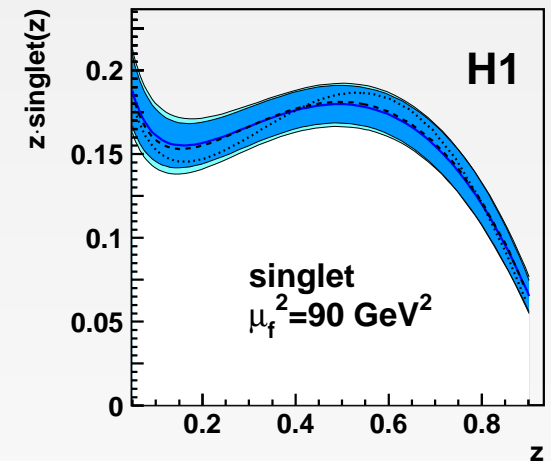
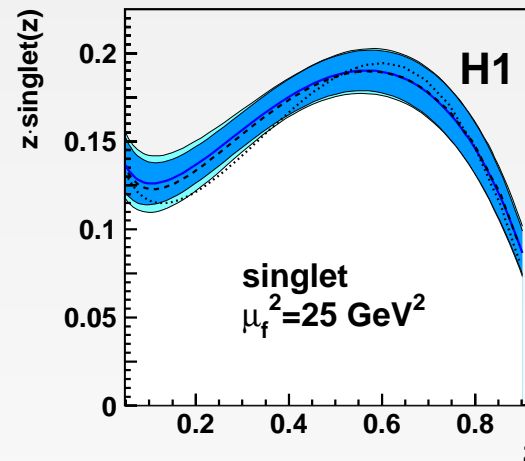
Combined fit constrains both
quark and gluon DPDFs
to similar good precision

⇒ **Most precise DPDFs to date**



$$z\Sigma(z, \mu_{f,0}^2) = A_q z^{B_q} (1-z)^{C_q}$$

$$zg(z, \mu_{f,0}^2) = A_g z^{B_g} (1-z)^{C_g}$$



Summary

Inclusive PDFs

- ◆ Averaging H1 and ZEUS data greatly improved precision
model independent tool to study consistency
- ◆ New HERA PDF set with impressive precision
No need for an inflated $\Delta\chi^2$ in setting errors on PDFs
- ◆ Final data analyses in preparation
H1 low and medium Q^2 ; H1 and ZEUS HERA II

Unintegrated PDFs

- ◆ Alternative approach to describe semi-inclusive distributions
Potentially advantageous over fixed-order MEPS predictions

Diffraction PDFs

- ◆ A wealth of inclusive data in diffraction using different methods
Generally consistent picture
- ◆ Diffractive dijets agree well with fits to inclusive diffraction
Factorisation holds in DDIS
- ◆ Fit based on inclusive diffraction + diffractive dijets
H1 2007 Jets DPDF – most precise diffractive partons to date

Additional Information

H1 + ZEUS Combined PDF Fit

Common choice

- ◆ Data set
- ◆ Choice of PDFs
- ◆ Starting scales
- ◆ Form in x at Q_0^2 and # parameters
- ◆ Treatment of heavy flavours
- ◆ Parameters and constraints
- ◆ Propagation of systematic errors
- ◆ Renormalisation / factorisation scales
- ◆ ...

Current decisions

Combined H1 + ZEUS

g , u_v , d_v , $\bar{U} = \bar{u} + \bar{c}$, $\bar{D} = \bar{d} + \bar{s} + \bar{b}$

$Q_0^2 = 4 \text{ GeV}^2$, data $Q_{\min}^2 = 3.5 \text{ GeV}^2$

$xf(x) = Ax^B(1-x)^C (1 + Dx + Ex^2 + \dots)$

VFNS (Thorne) , $s = 0.33D$, $c = 0.15U$, ...

$\alpha_s(M_Z) = 0.1176$, $m_c = 1.4 \text{ GeV}$, $m_b = 4.75 \text{ GeV}$

43 uncorrelated + 4 offset

Q^2

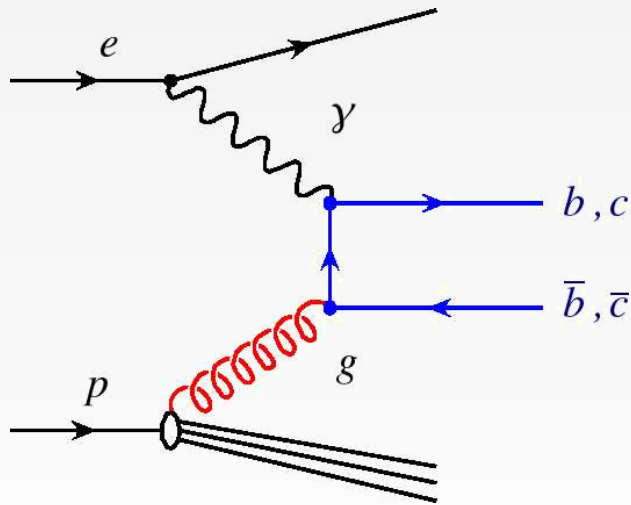
Optimize parameterisation until no further χ^2 advantage

PDF	A	B	C	D	E
g	sum rule	•	•		
u_v	sum rule	•	•	•	•
d_v	sum rule	$= B(u_v)$	•		
\bar{U}	$\lim_{x \rightarrow 0} \bar{u}/\bar{d} = 1$	•	•		
\bar{D}	•	$= B(\bar{U})$	•		

Heavy Flavour Measurements

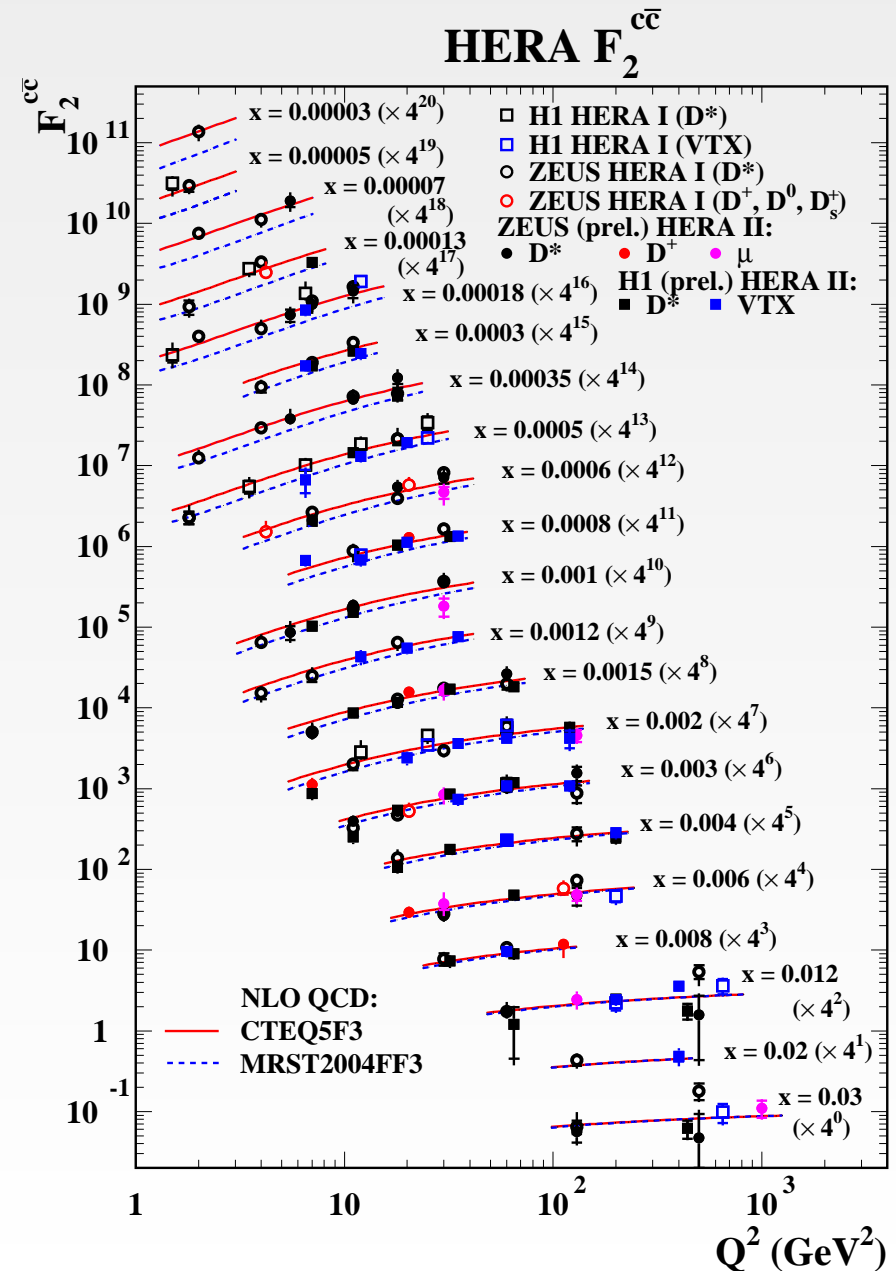
Wealth of precise measurements

- ◆ Inclusive c and b based on long lifetime [H1]
- ◆ $\mu p_T^{\text{rel}} + \text{lifetime}$ [ZEUS]
- ◆ Inclusive D^* production [H1, ZEUS]
- ◆ D^+, D^0, D_s cross sections [ZEUS]
- ◆ $D^+ + \text{lifetime}$ [ZEUS]

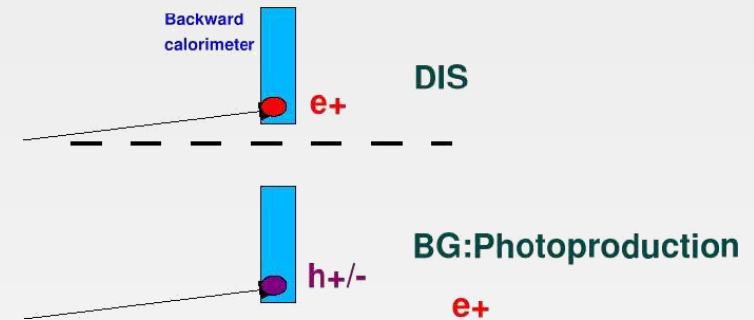
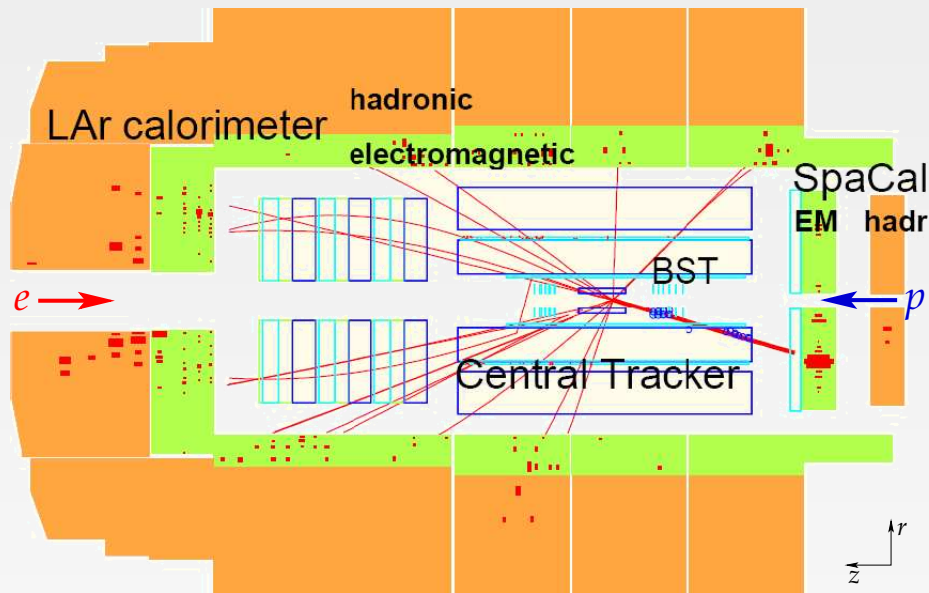


Impact on PDFs

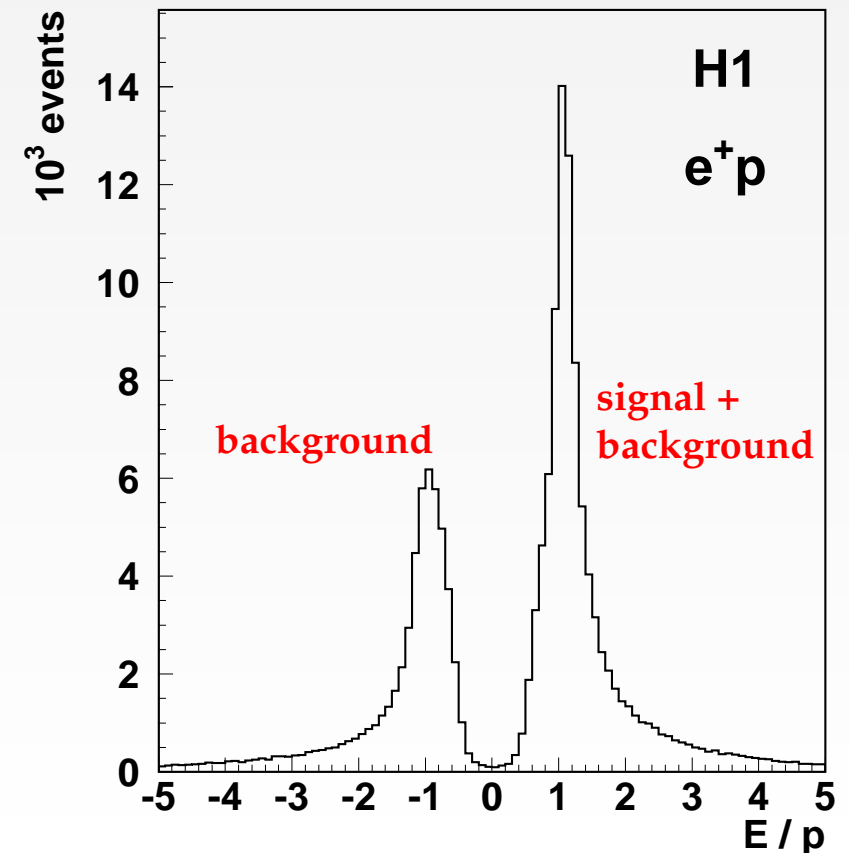
- ◆ Sea decomposition
- ◆ Improve gluon distribution?



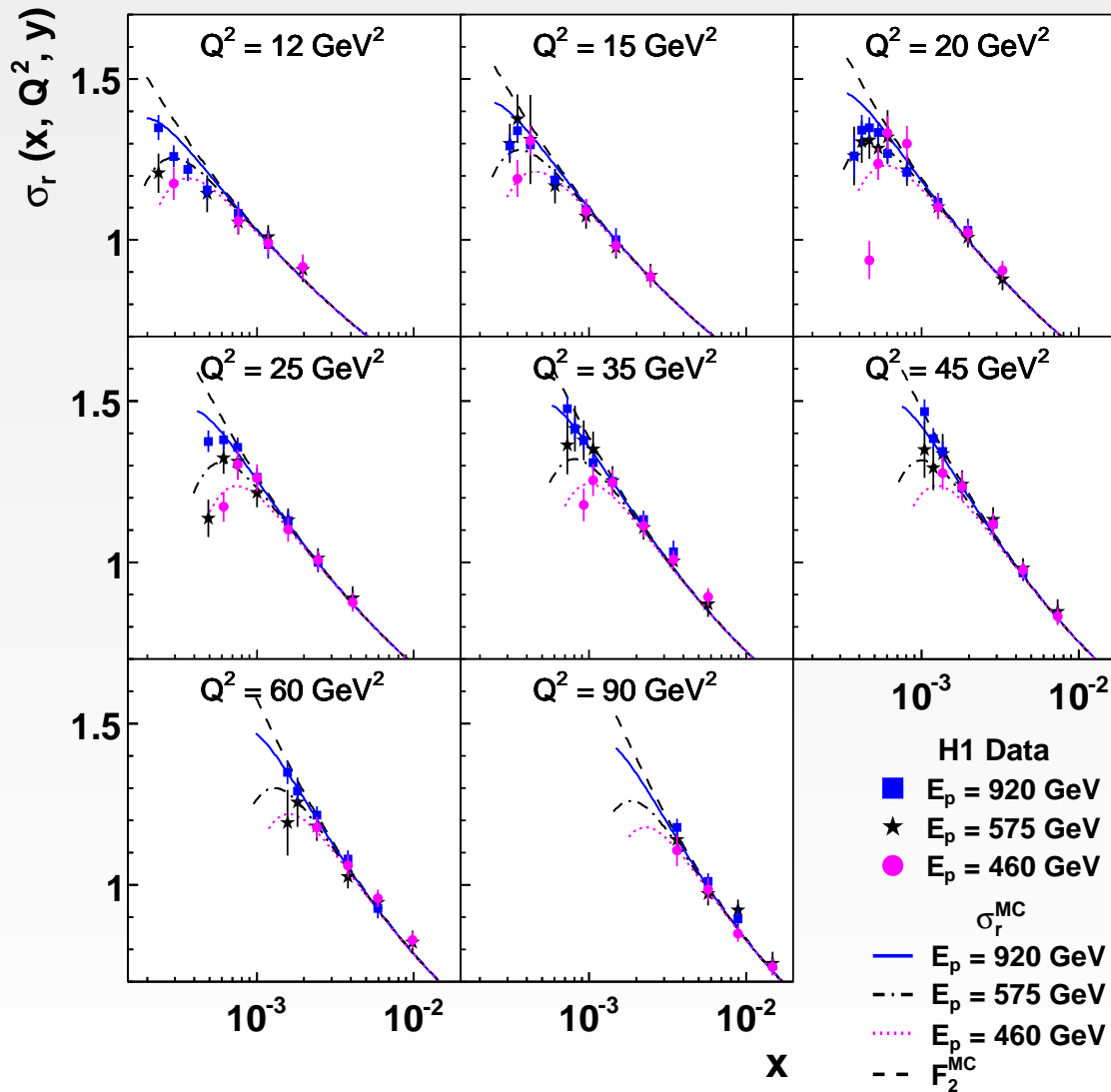
Hadronic Background at High γ



- ◆ H1 measured background using events with charge opposite to lepton beam charge
- ◆ Small **charge asymmetry** $\sim 5\%$ in background is due to difference of pA and $\bar{p}A$ cross sections – determined using e^+p and e^-p data 2003–2007
- ◆ Events with wrong sign tracks are rejected; Right sign background is statistically subtracted



Reduced Cross Section

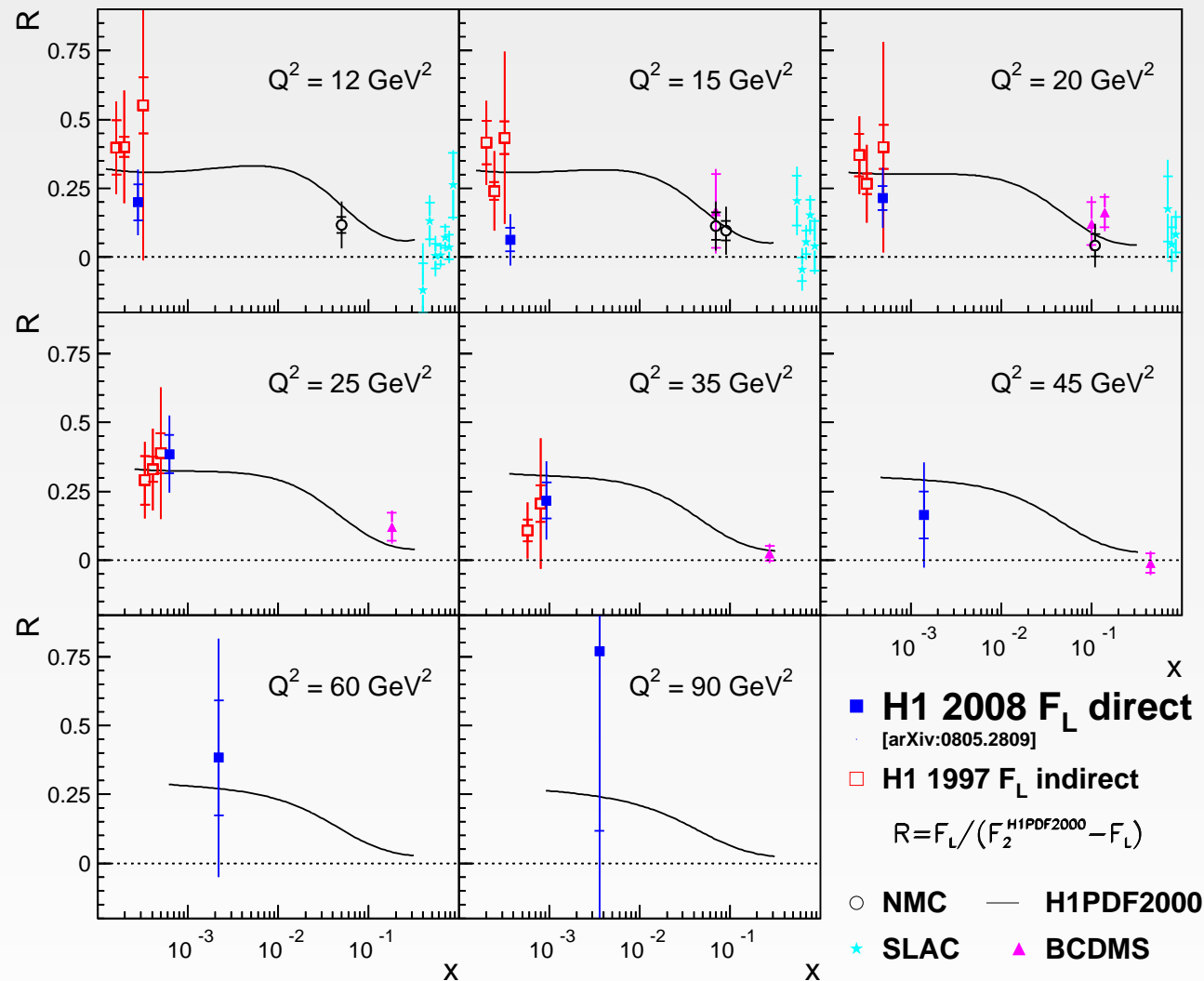


Flattening and turn over at high y
for different samples due to F_L

- ◆ Currently 5% luminosity uncertainty correlated for all samples
Uncertainty of F_L includes this value
- ◆ Samples were normalised to each other using F_2 at low y :
920, 575, 460 GeV : -2%, -0.5%, +1%
- ◆ Relative normalisation error: 1.6%

$\mathcal{H}1$ F_L Data at Medium Q^2

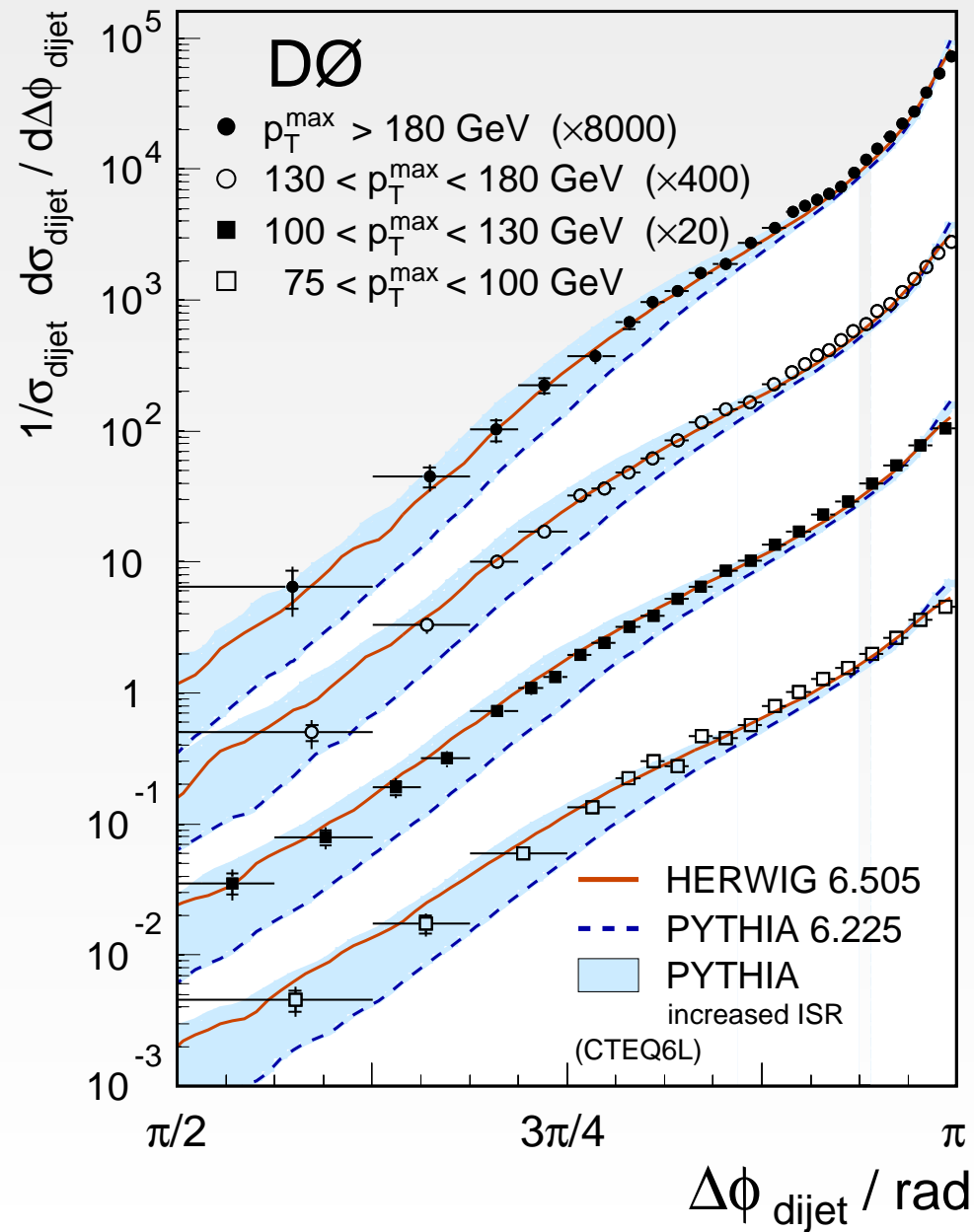
$$R = \frac{F_L}{F_2 - F_L}$$



New H1 data are in good agreement with previous indirect extractions

Observe increasing relative significance of F_L for low x due to rising gluon density

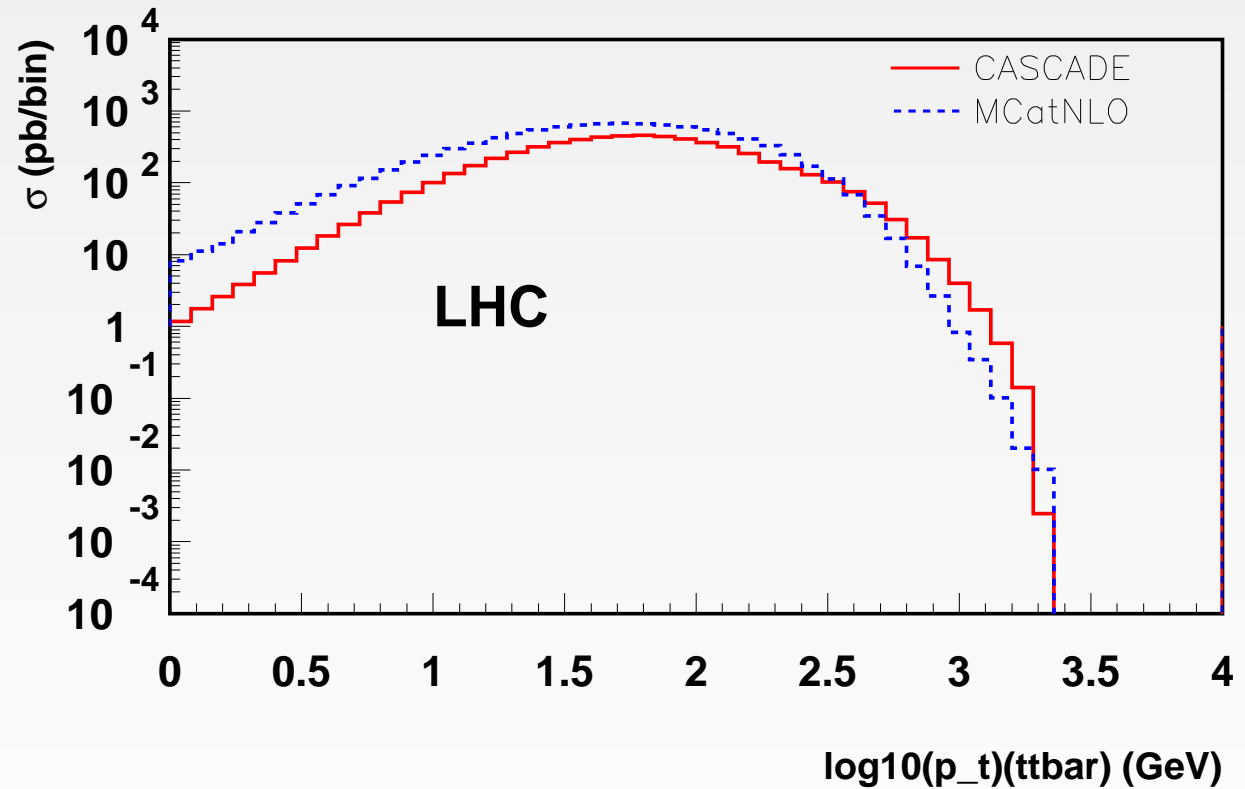
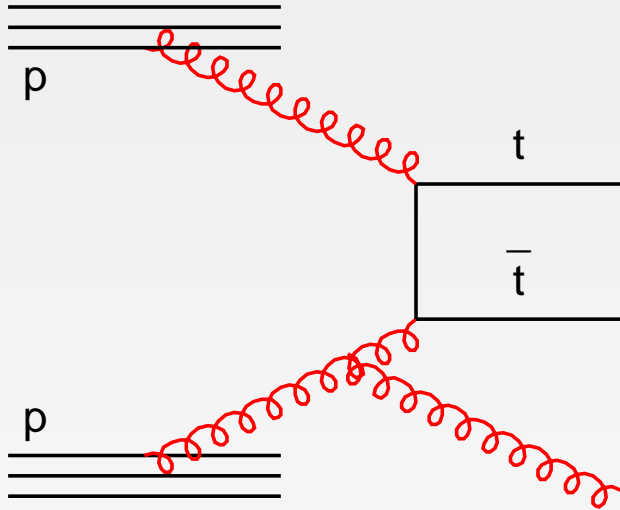
Dijets at Tevatron



Much stronger falling spectra at high $\Delta\phi$

$t\bar{t}$ Production at \mathcal{LHC}

Hautmann, Jung



k_T shower works up to high momentum scales (here $\sim t$ -mass)

Combined Diffractive PDF Fit

H1 Jets 2007 DPDF NLO QCD fit

use Diffractive DIS dijet data
as additional constraint

$$\mu_f^2 = Q^2 + p_{T,jet1}^{*2}$$

