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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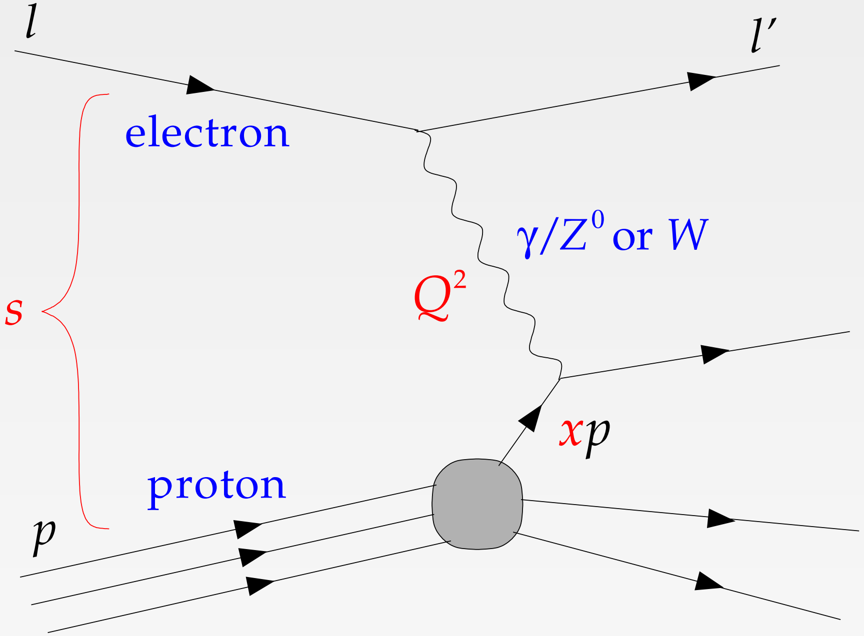
Inclusive DIS Kinematics



boson virtuality
= resolution scale $Q^2 = -(l - l')^2$

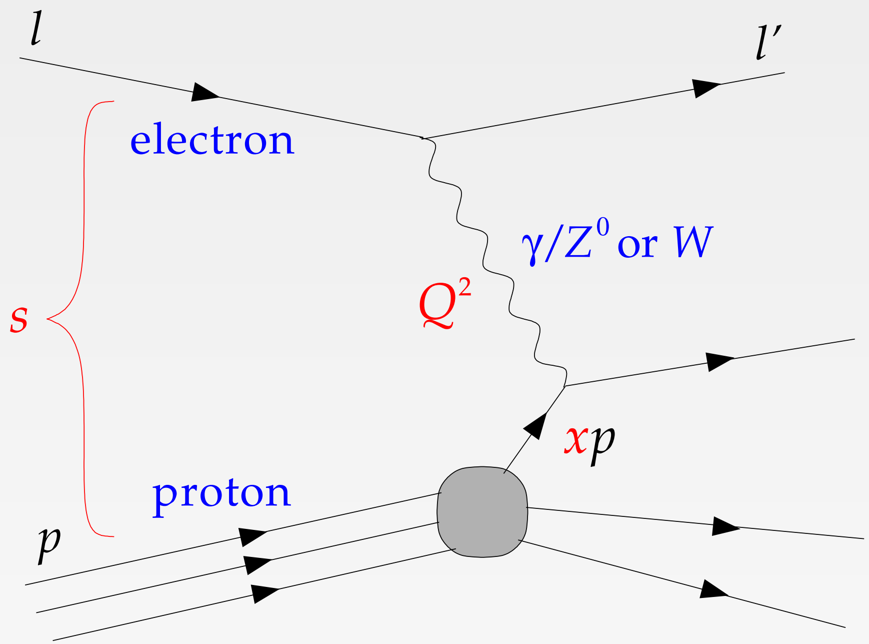
fractional momentum of struck quark $x = \frac{Q^2}{2p \cdot q}$

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 $x \Longleftrightarrow$ high y, W

Inclusive DIS Cross Section



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reduced cross section σ_r

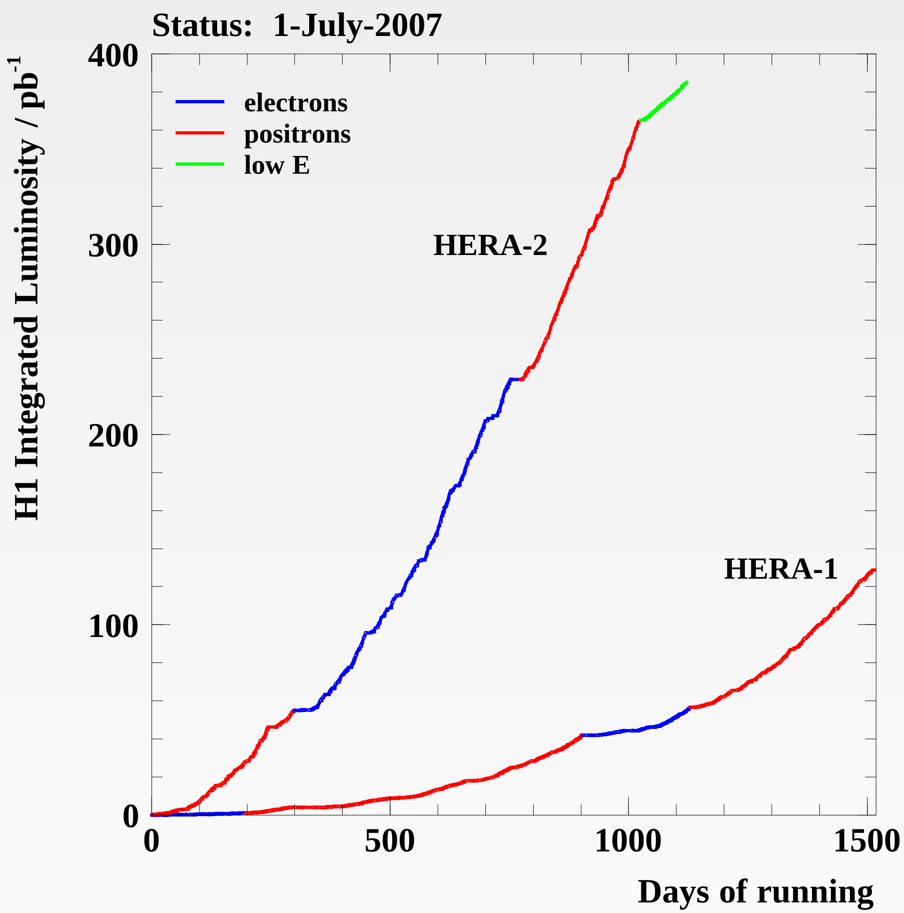
Cross section:

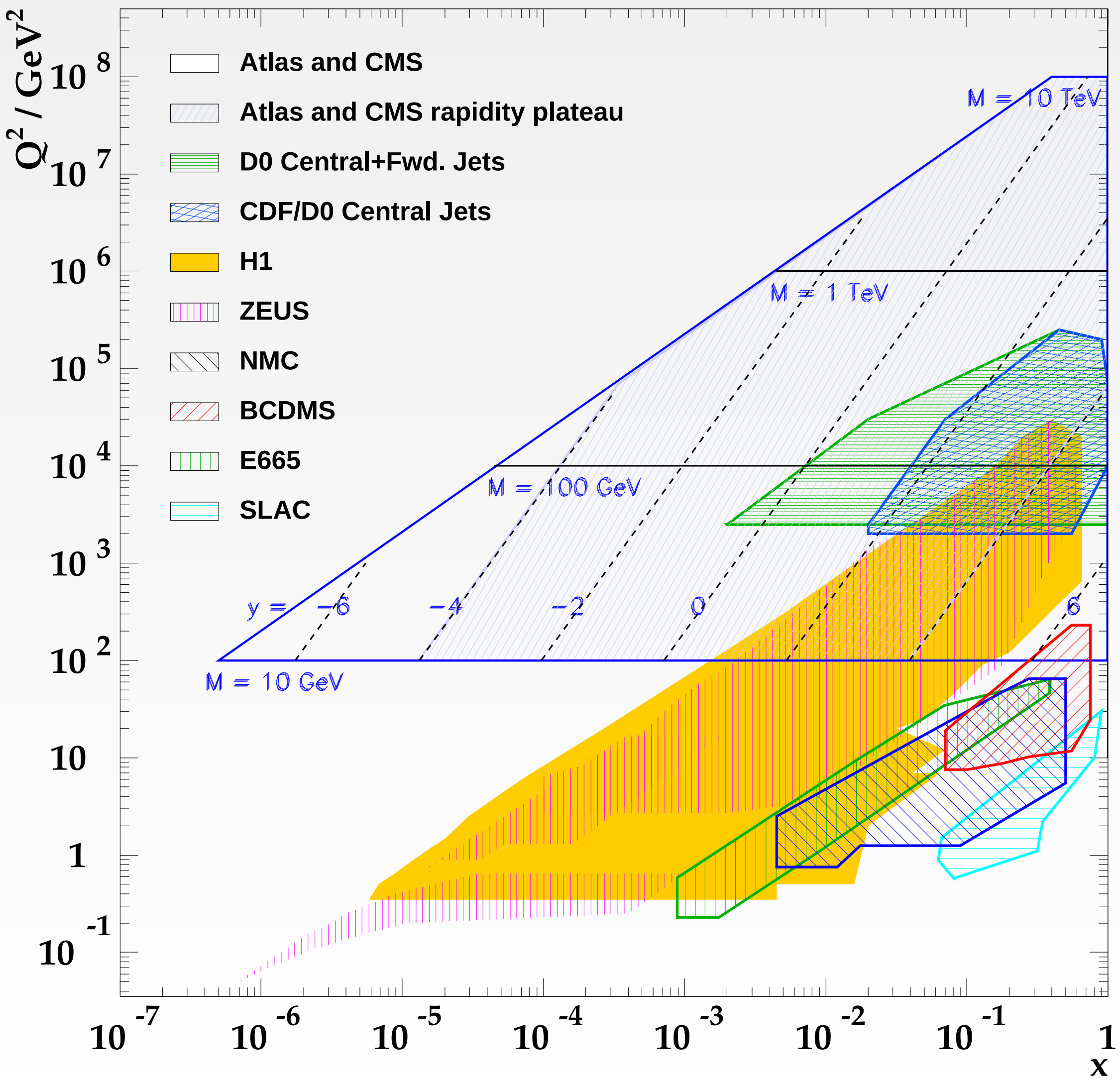
$$\frac{d^2\sigma^\pm}{dx\,dQ^2} = \frac{2\pi\alpha^2}{Q^4 x} Y_+ \left\{ F_2(x,Q^2) - \frac{y^2}{Y_+} F_L(x,Q^2) \mp \frac{Y_-}{Y_+} x F_3 \right\}$$

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





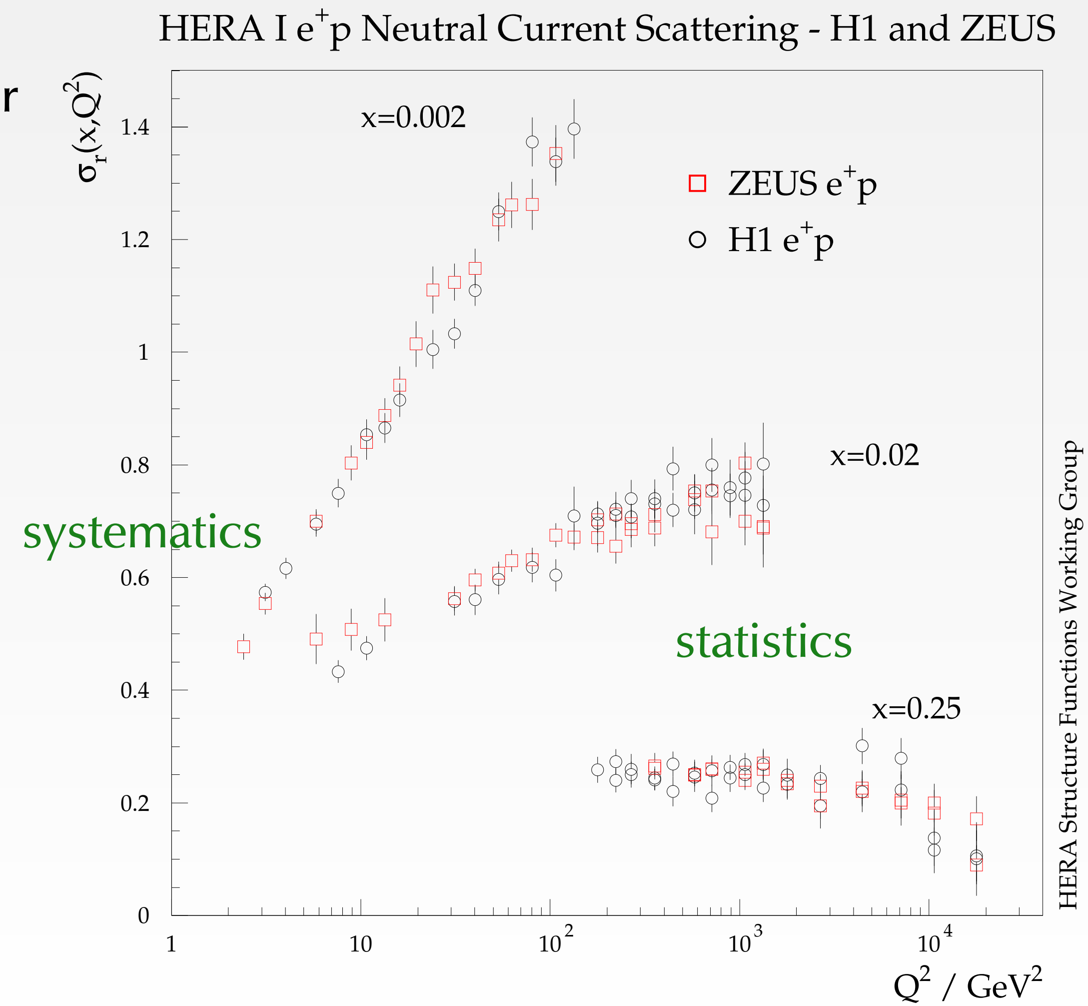
HERA I: $\sim 120\,\mathrm{pb}^{-1}$ / expt

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

H1 + 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



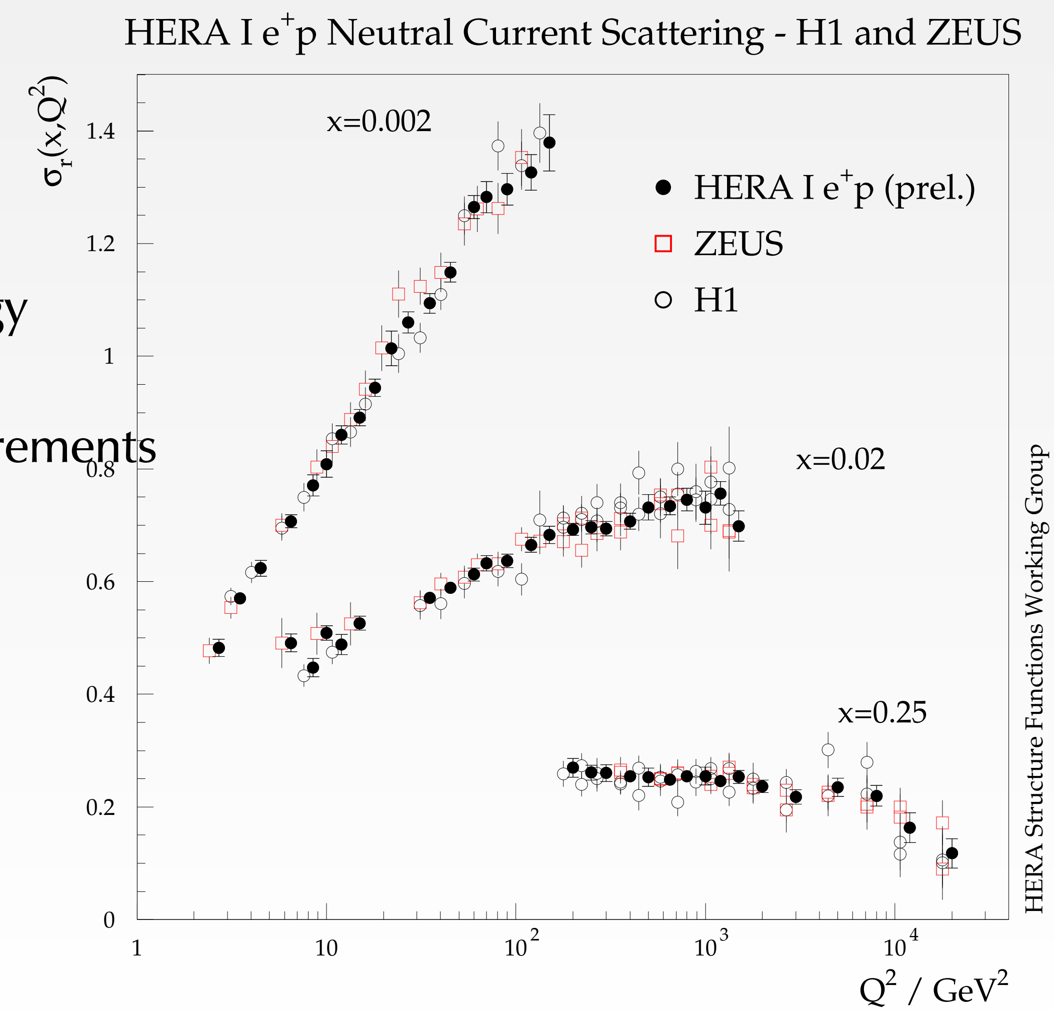
Combination Procedure

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

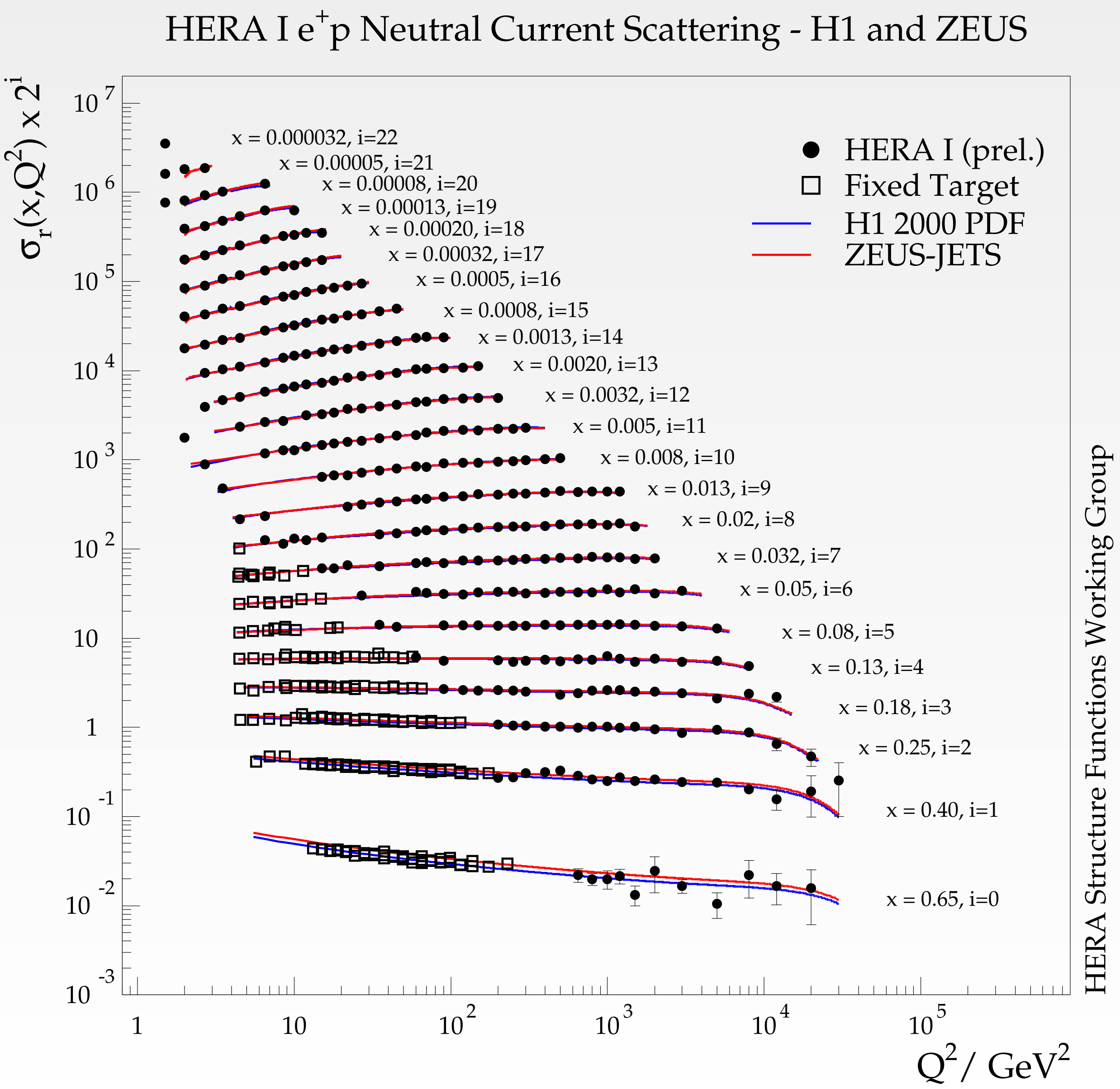
Procedure

- 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

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



H1 + ZEUS Combination Results



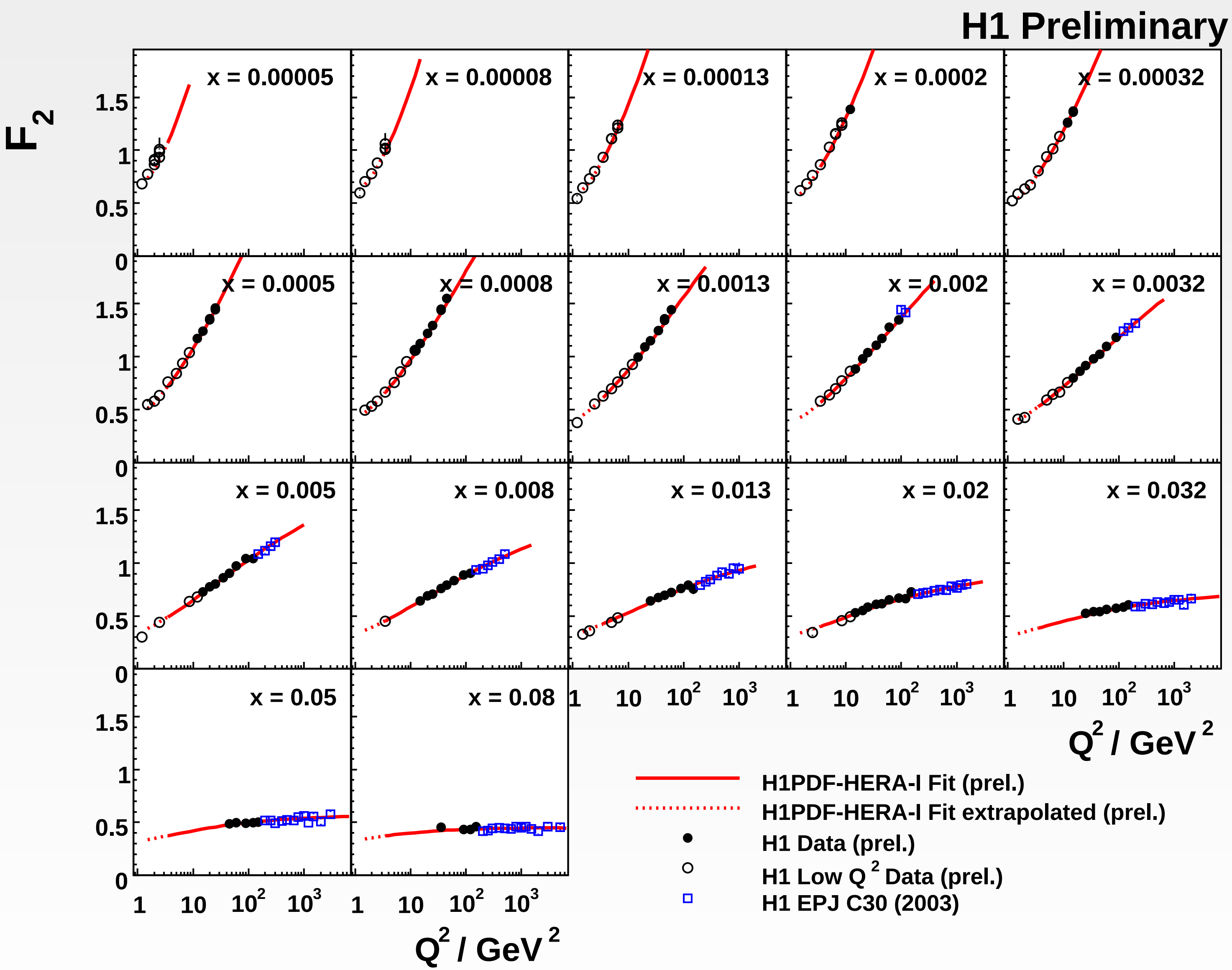
Agree well with both H1 2000 and ZEUS-JETS PDF fits

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

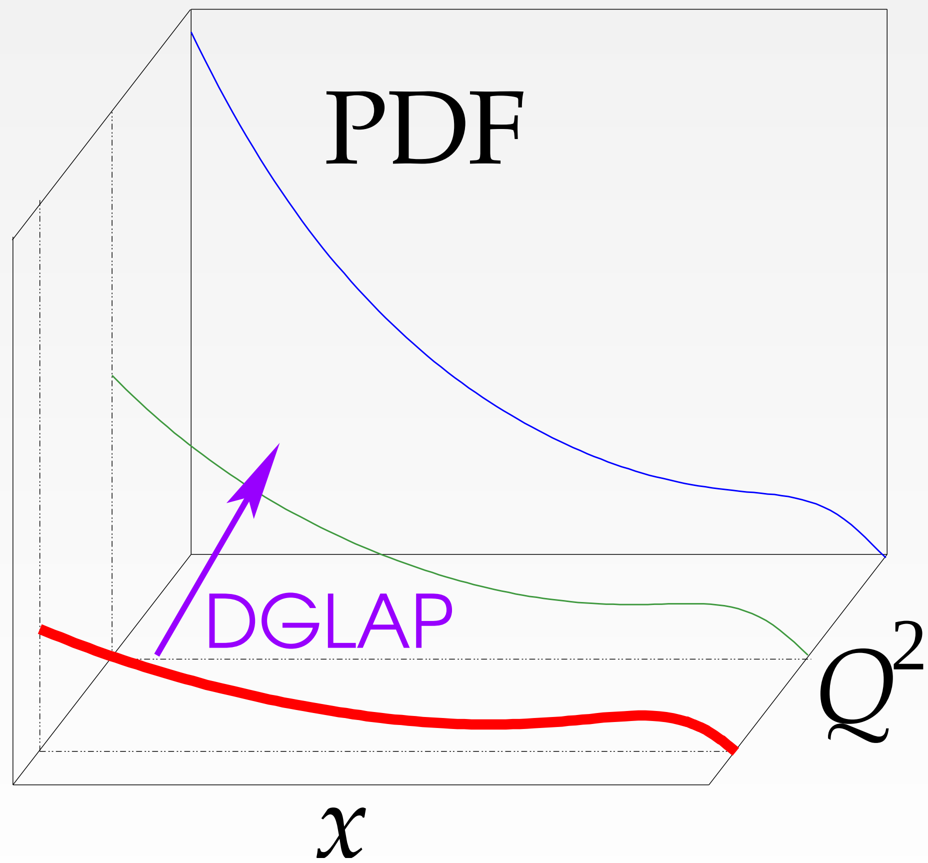


Total uncertainties in bulk region ~1.5% – improved by factor ~2 w.r.t. previous H1 data

pQCD PDF Fits

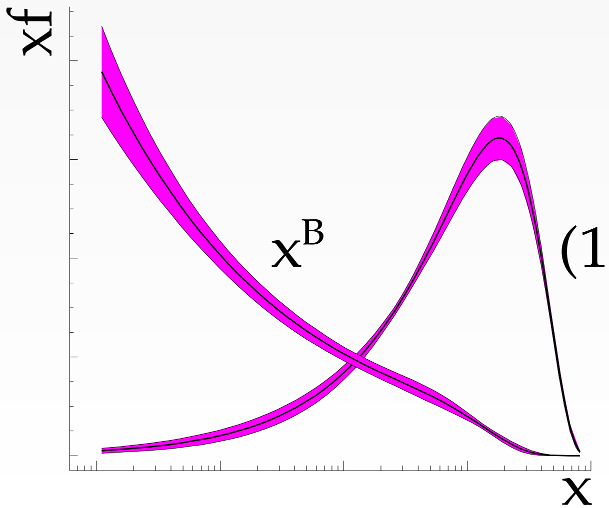
Procedure

- 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

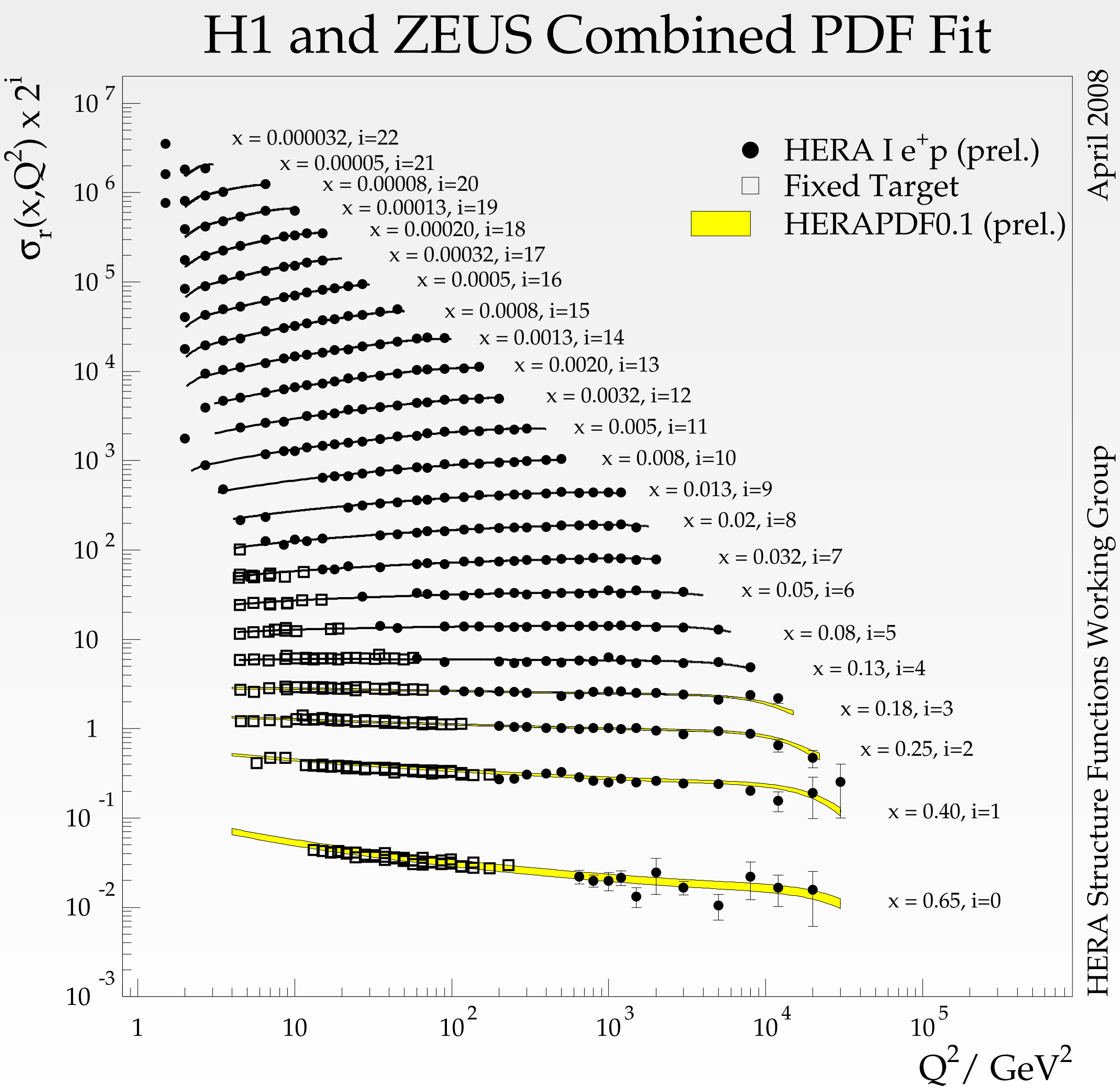


H1 + ZEUS Combined PDF Fit

Common choice	**Current decisions**
Data set	Combined H1 + ZEUS
Choice of PDFs	g , u_v , d_v , $\overline{U} = \overline{u} + \overline{c}$, $\overline{D} = \overline{d} + \overline{s} + \overline{b}$
Starting scales	$Q_0^2 = 4\,\mathrm{GeV}^2$, data $Q^2_{min} = 3.5\,\mathrm{GeV}^2$
Form in x at Q_0^2 and # parameters	$xf(x) = Ax^B(1-x)^C\,(1 + Dx + Ex^2 + \ldots)$ – optimize until no further χ^2 advantage
Treatment of heavy flavours	VFNS (Thorne) , $s = 0.33D$, $c = 0.15U$, ...
Parameters and constraints	$\alpha_s(M_Z) = 0.1176$, $m_c = 1.4\,\mathrm{GeV}$, $m_b = 4.75\,\mathrm{GeV}$
Propagation of systematic errors	43 uncorrelated + 4 offset
Renormalisation / factorisation scales	Q^2
...	



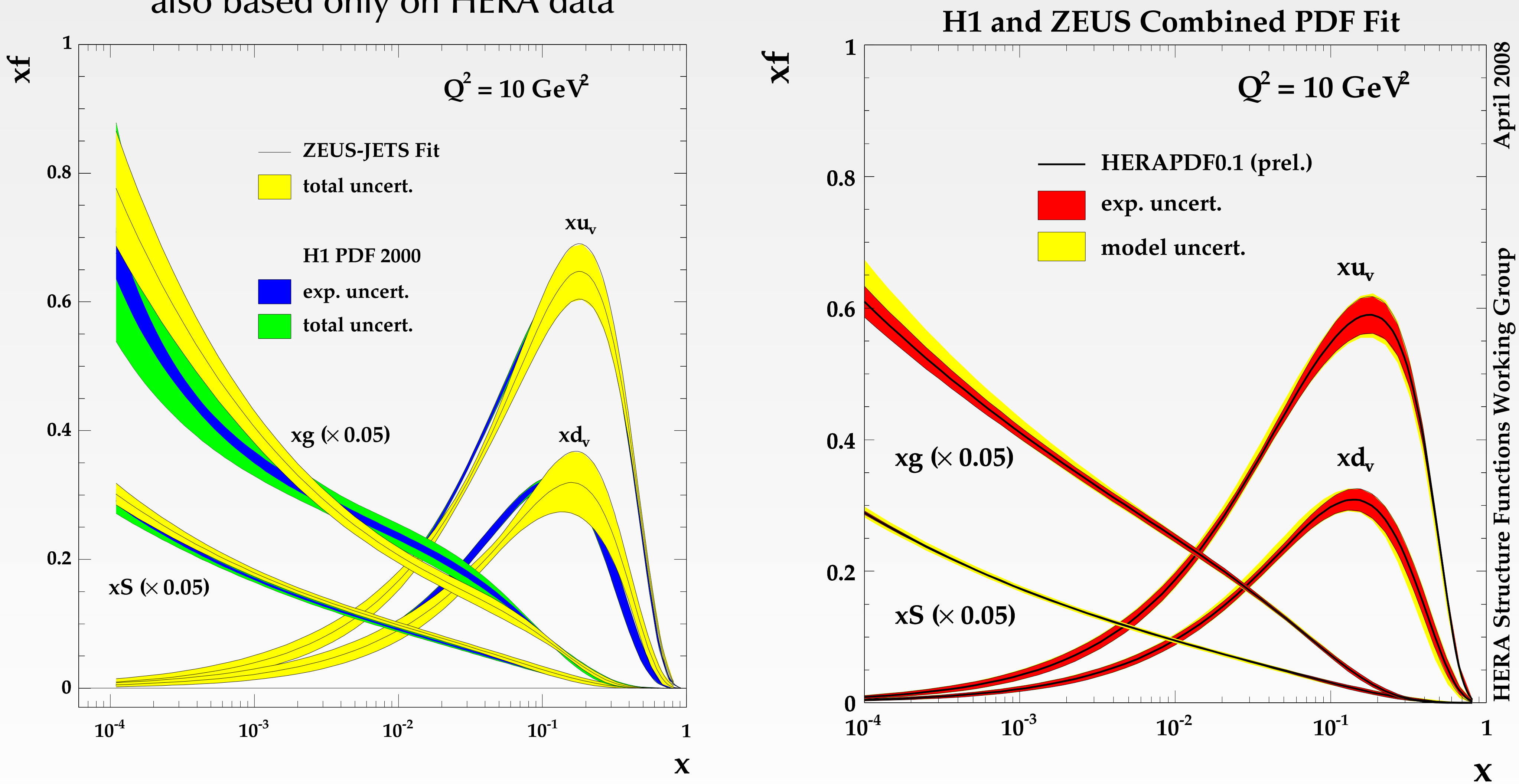
Results: H1 + ZEUS Combined PDF Fit



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

Total uncertainties shown
[including model uncertainties]

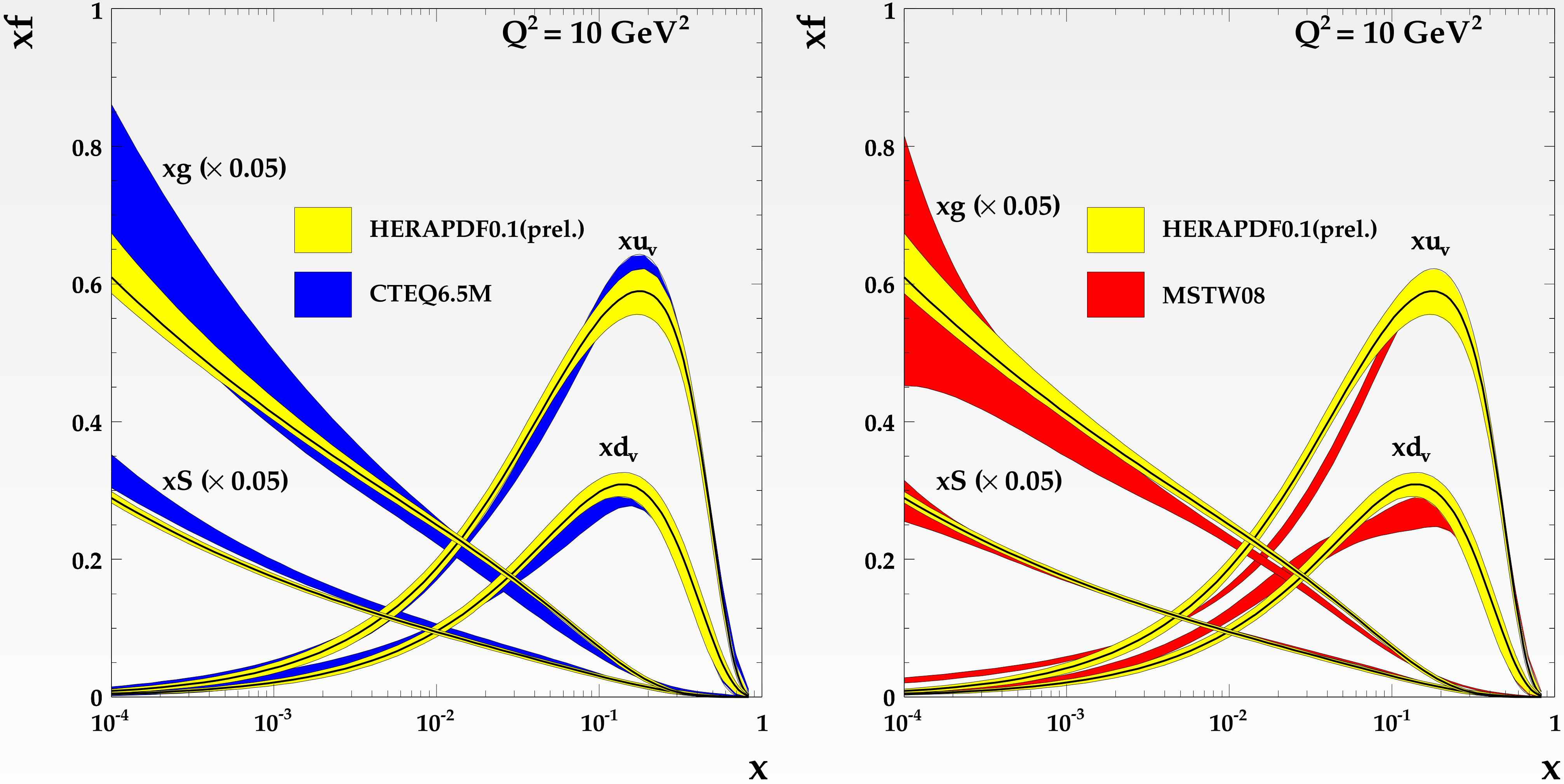
also based only on HERA data



Resolution of previous discrepancies, dramatic reduction of uncertainties

Increase of precision mostly from data combination

Comparison to Newest Global Fits



Longitudinal Structure Function F_L

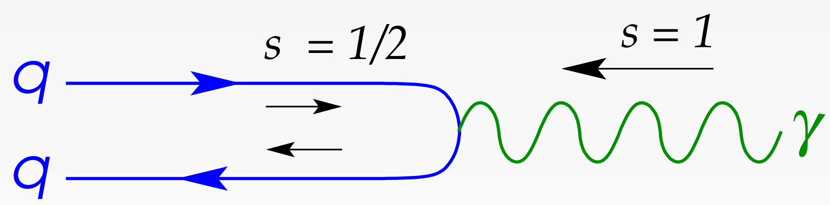
- NC DIS cross section [ignoring weak effects]

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

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 $xg \sim \frac{\partial F_2}{\partial \ln Q^2}$

  $\longrightarrow$ significant exp. and theor. uncertainty

- Most interesting at low x

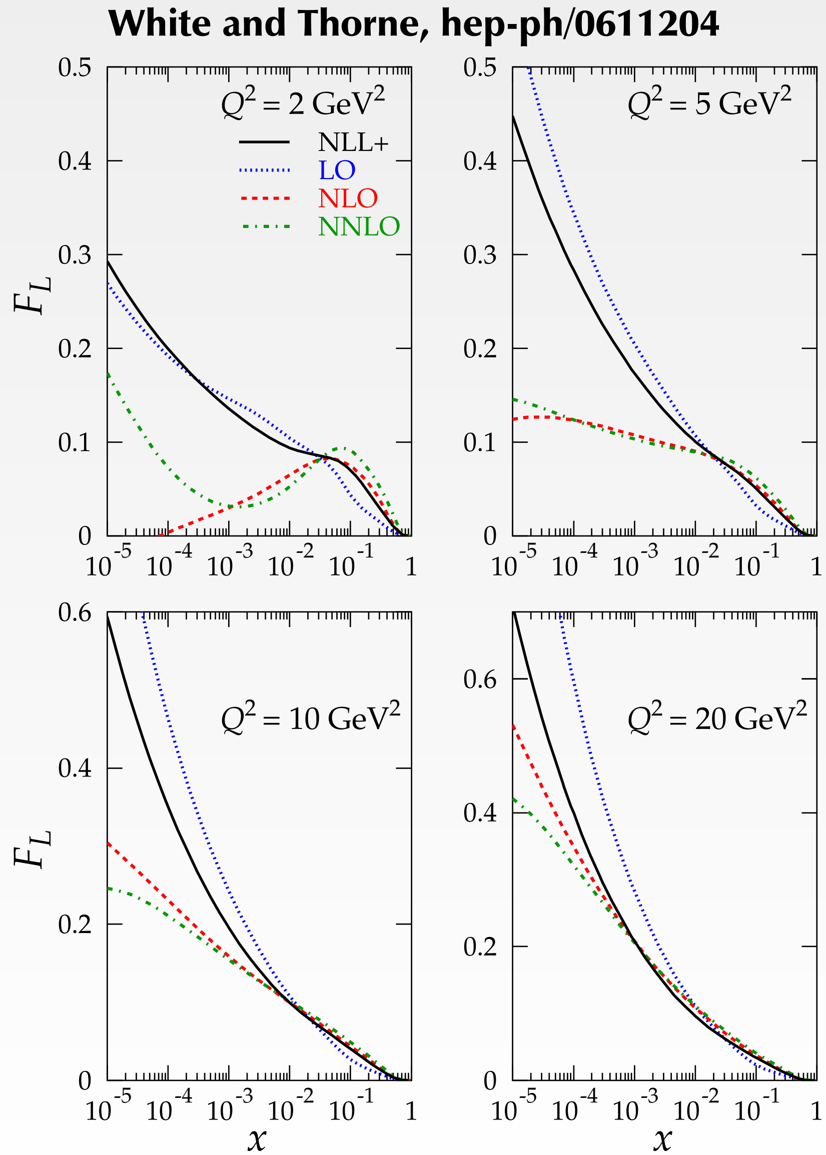
  Critical corner – low Q^2 and low x, where

  $xg(x, Q^2)$ becomes valence-like or even negative

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

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

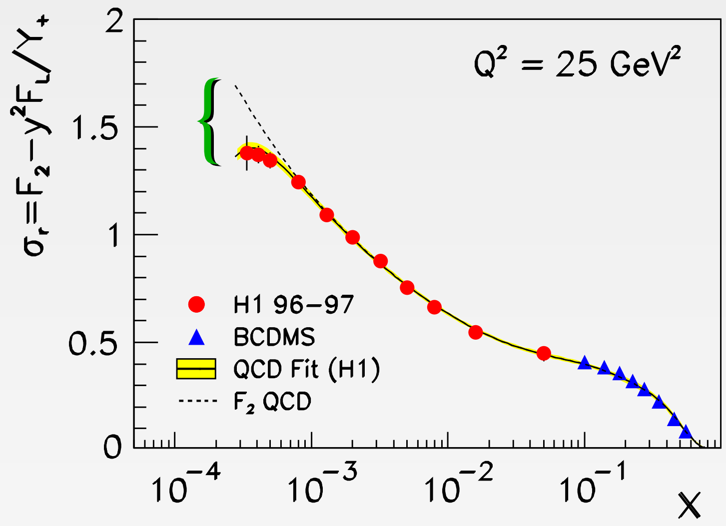
with $Y_+ = 1 + (1 - y)^2$



Basics of F_L Measurement

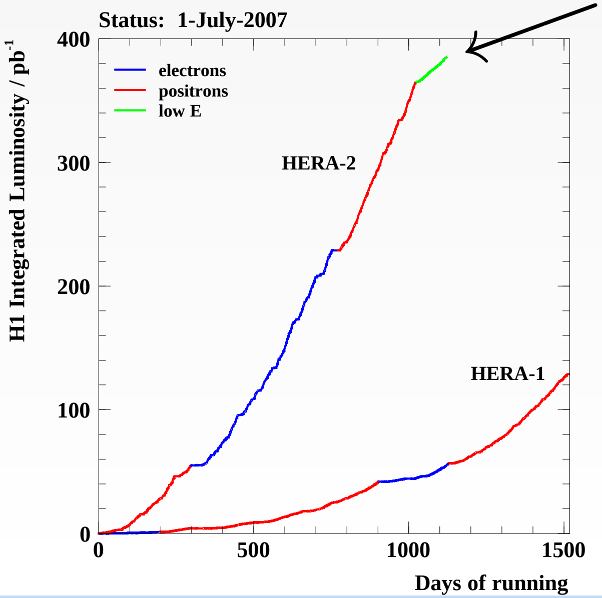
- Previous indirect F_L extractions – model dependent

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

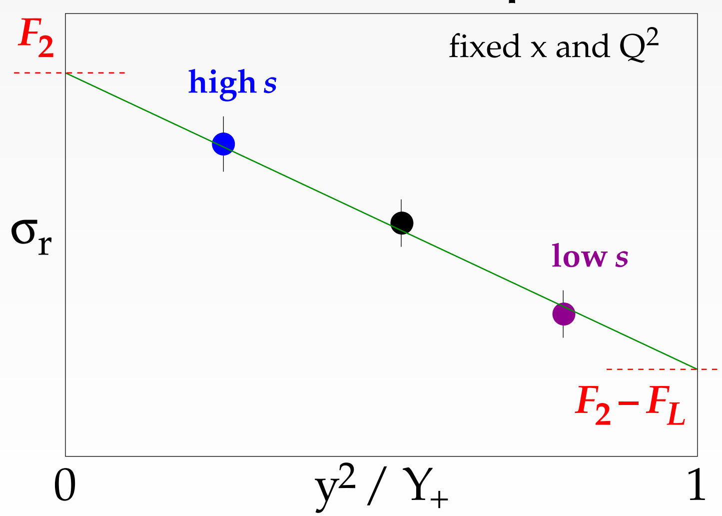


- Direct F_L requires σ_r at same x and Q^2 but at different y
  With $Q^2 = xys$: different $y \Longrightarrow$ different s
  $\Longrightarrow$ low beam energy runs

- Collected e^+p data with 3 proton beam energies:
  460 , 575 , 920 GeV

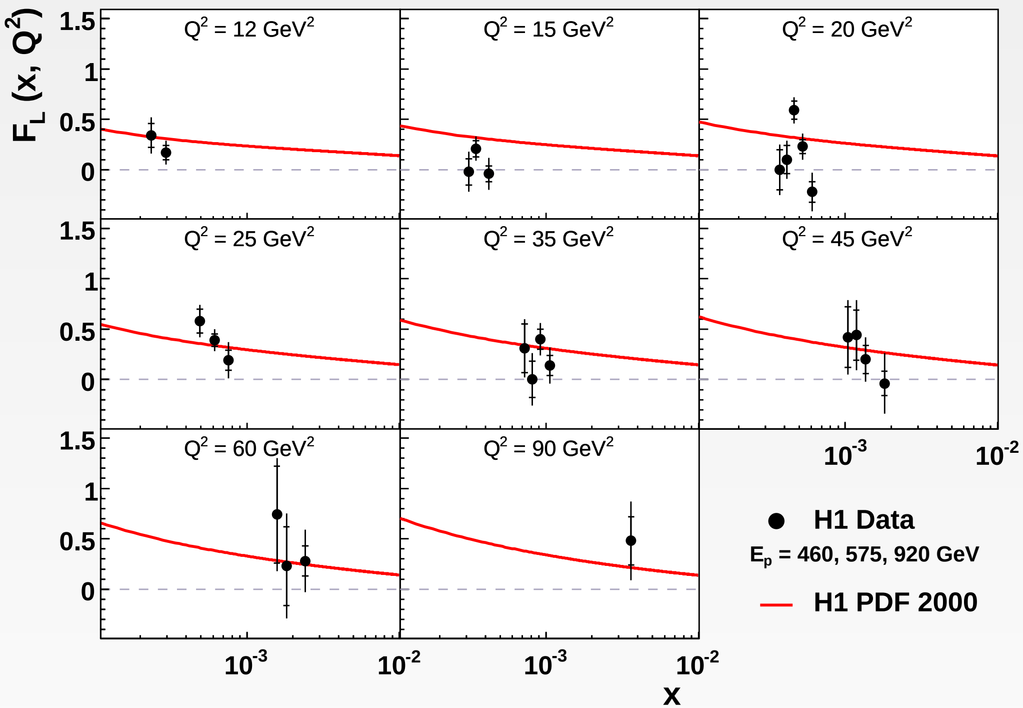


Rosenbluth Technique

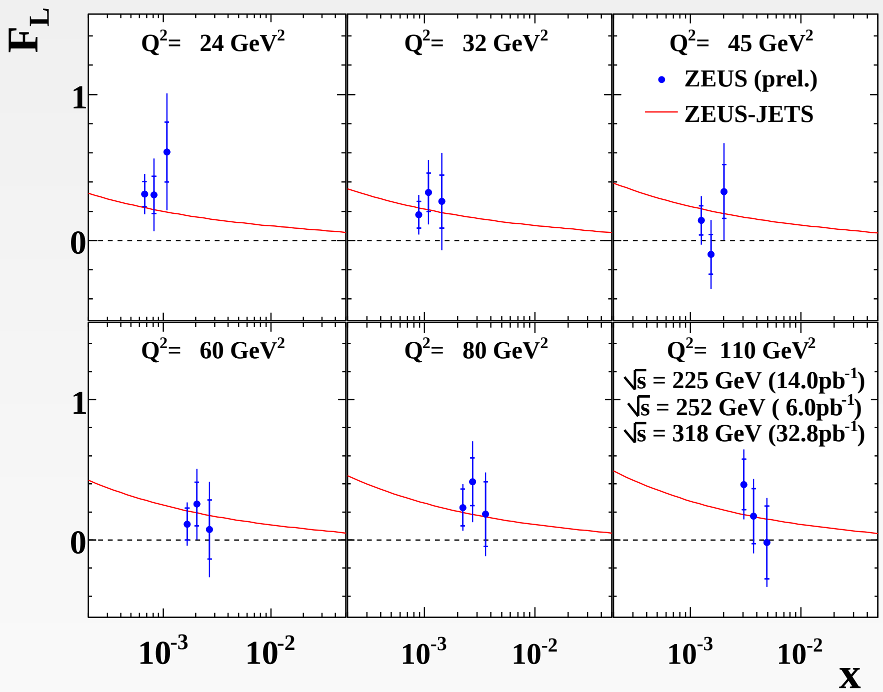


Results: $F_L(x)$ at Medium Q^2

H1: Phys. Lett. B 665, 139



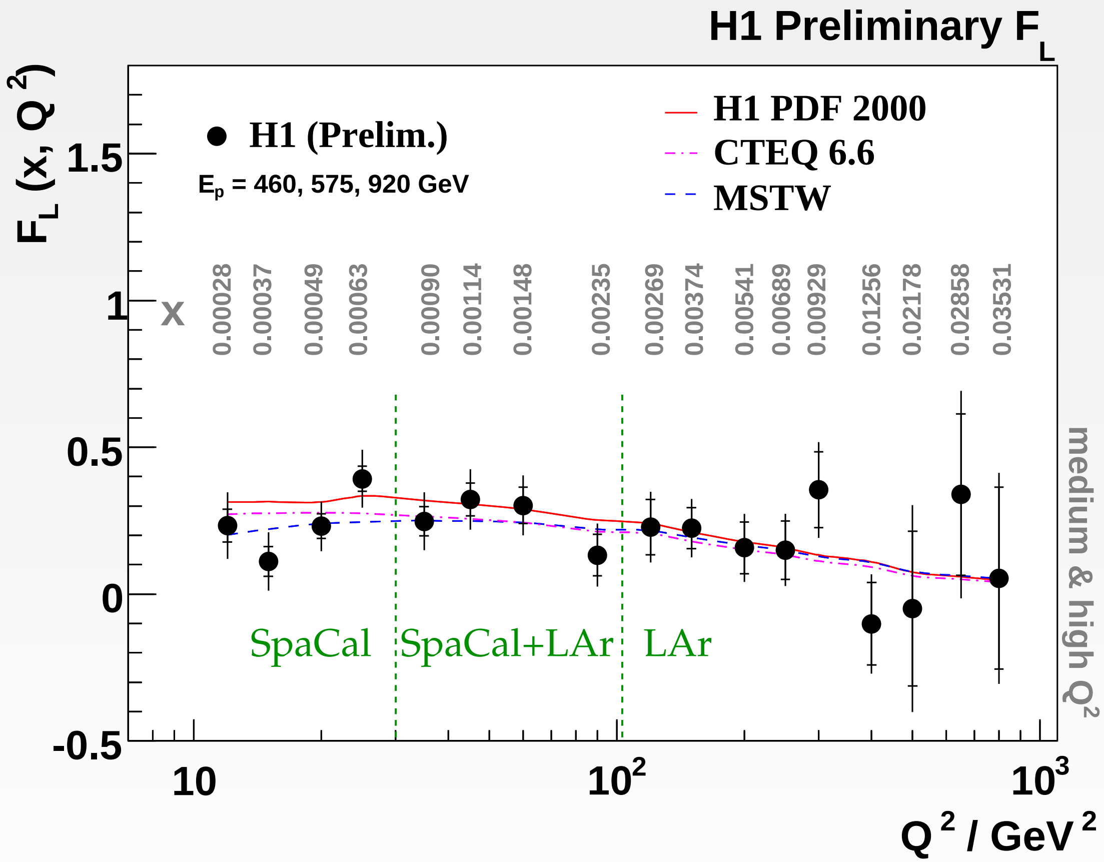
ZEUS

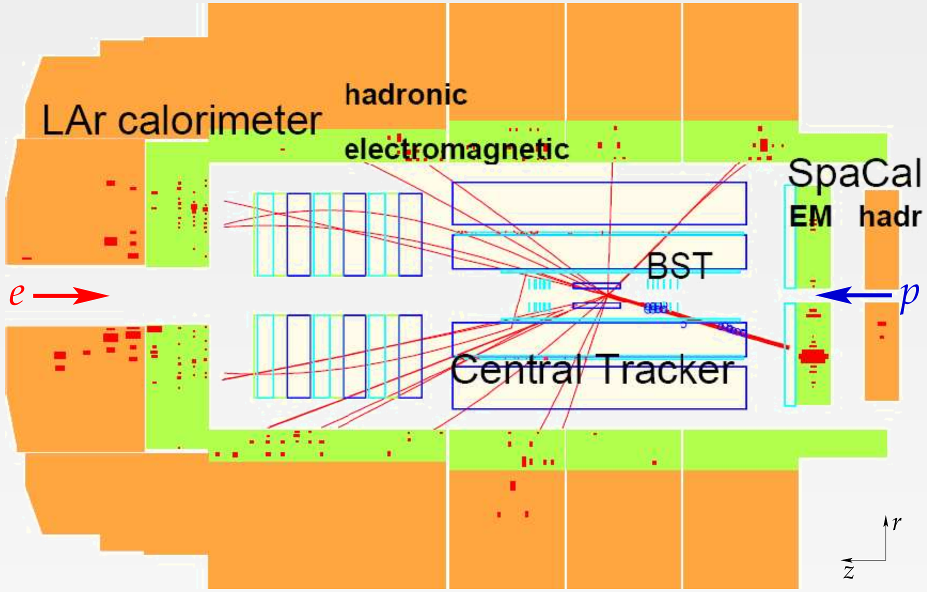


Both measurements are consistent

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

Preliminary F_L in Full Medium–High Q^2 Range

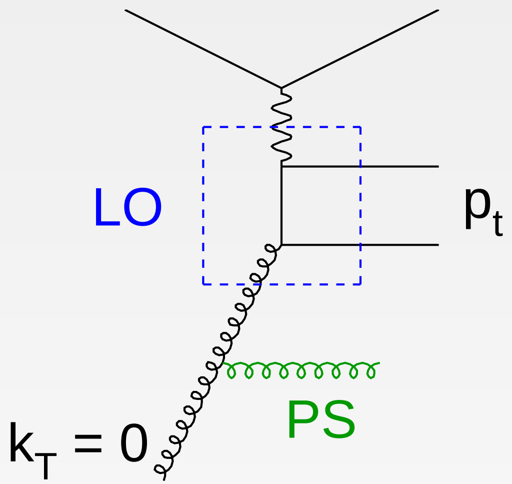




Data are consistent with NLO and NNLO QCD predictions

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

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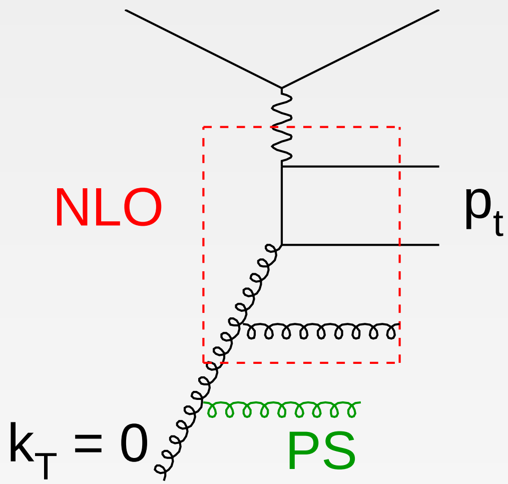

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- ME-PS matching difficult at NLO $\Rightarrow$ NLO MC generators for only few processes
  LO MC often used for hadronisation corrections $\Rightarrow$ Significant uncertainties

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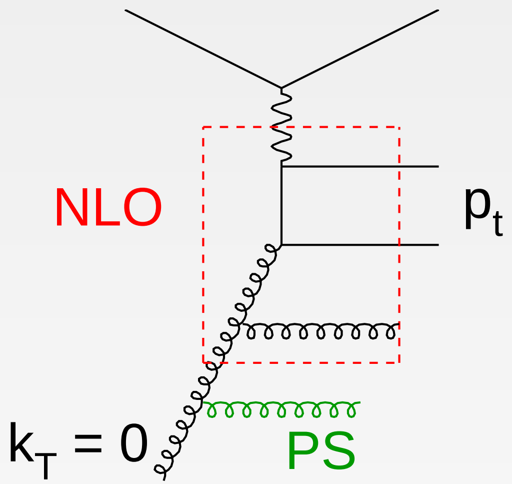

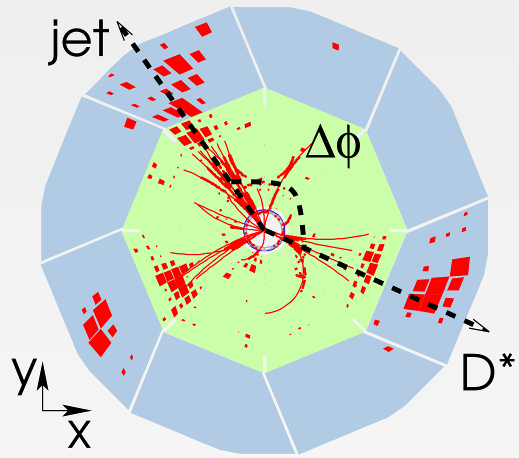

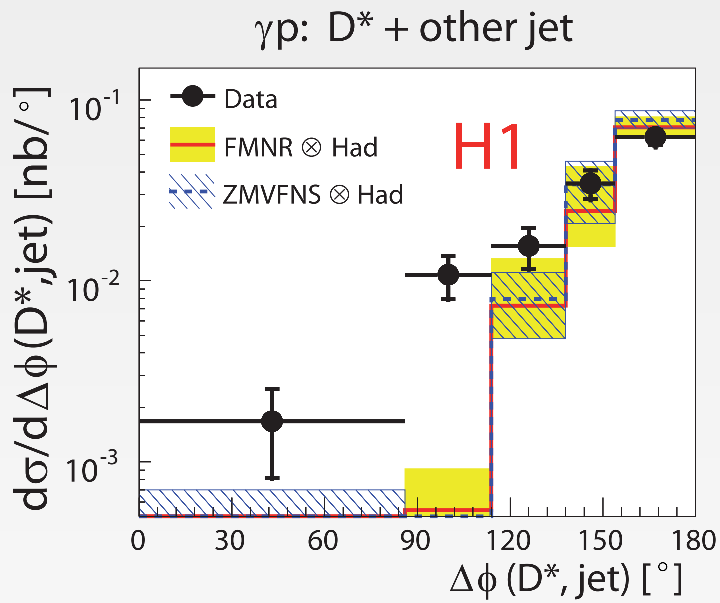

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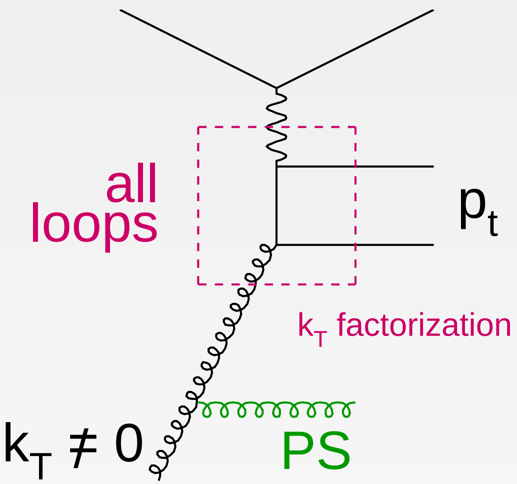
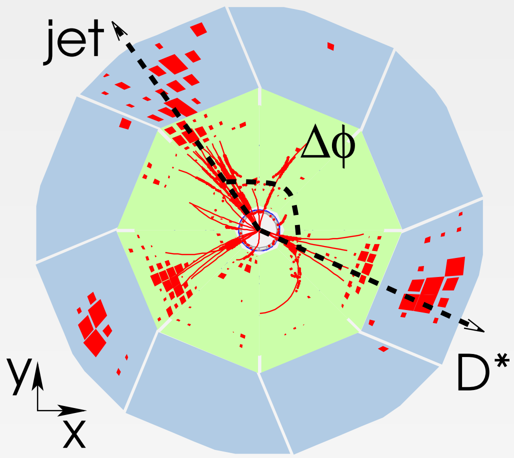
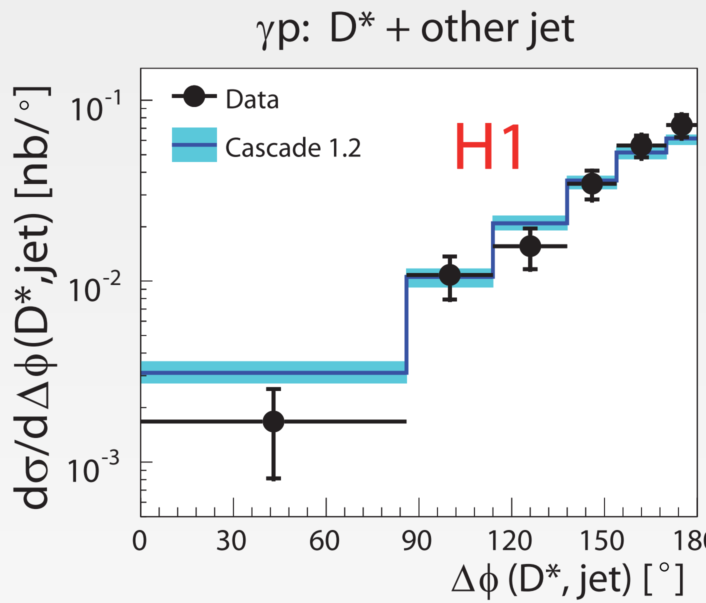
- For some observables NLO is insufficient

k_T-Factorisation – Unintegrated PDFs







Better description of kinematics via

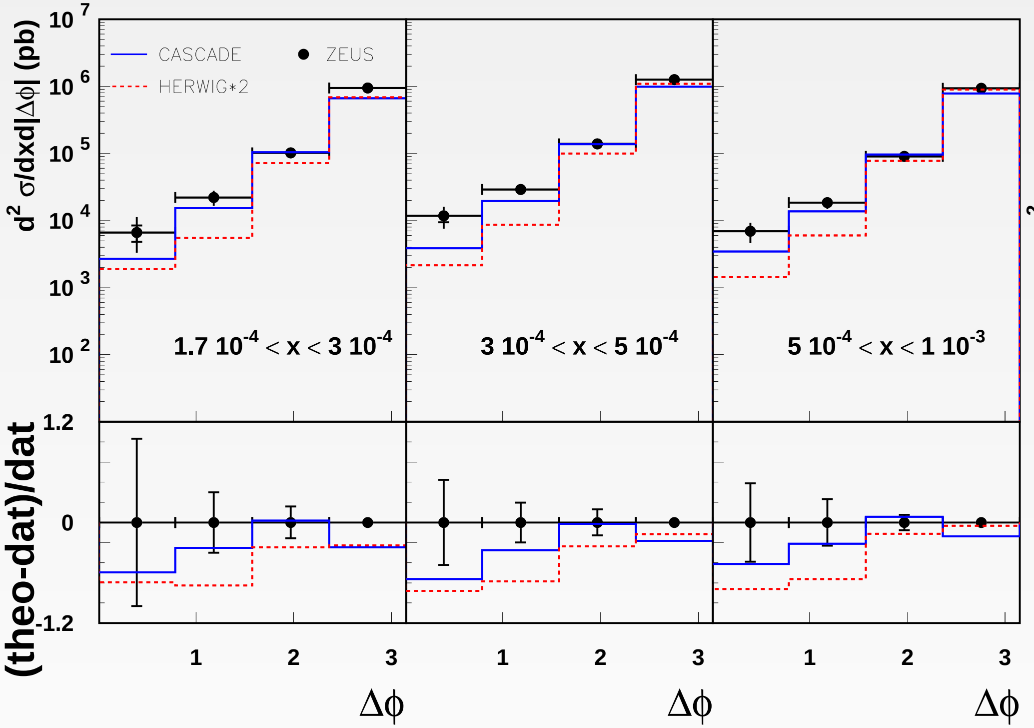
Unintegrated PDFs: $f_i(x, Q^2) \longrightarrow \mathcal{A}_i(x, k_T^2, Q^2)$ and off-shell ME

- 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

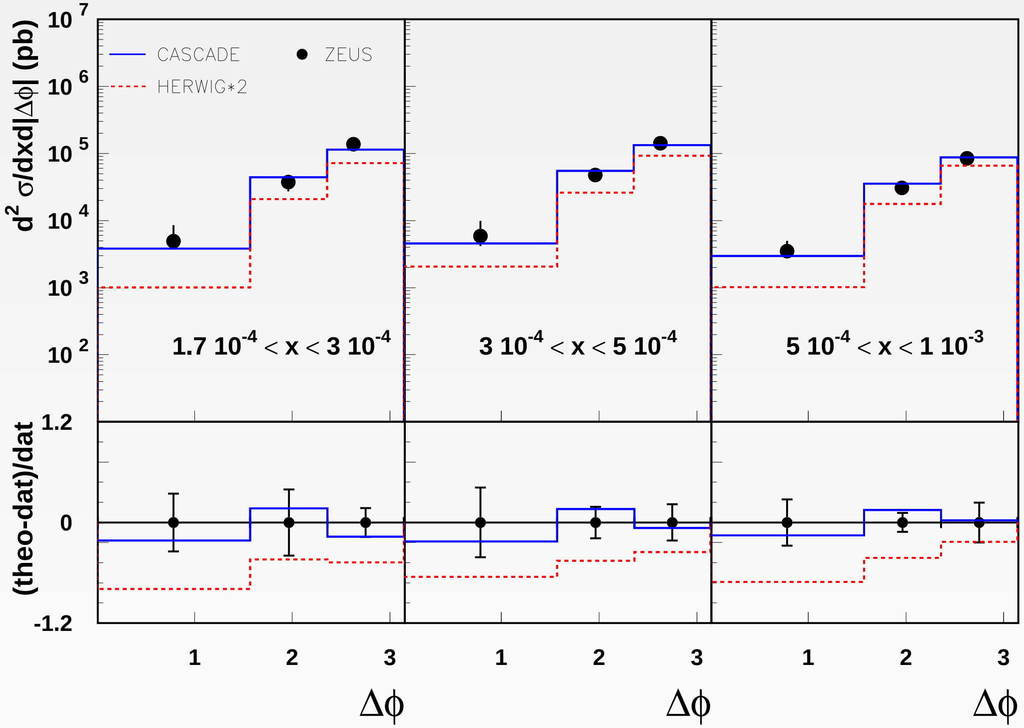
$\Delta\phi = |\phi_1 - \phi_2|$

Hautmann, Jung

ZEUS Dijets



ZEUS Threejets

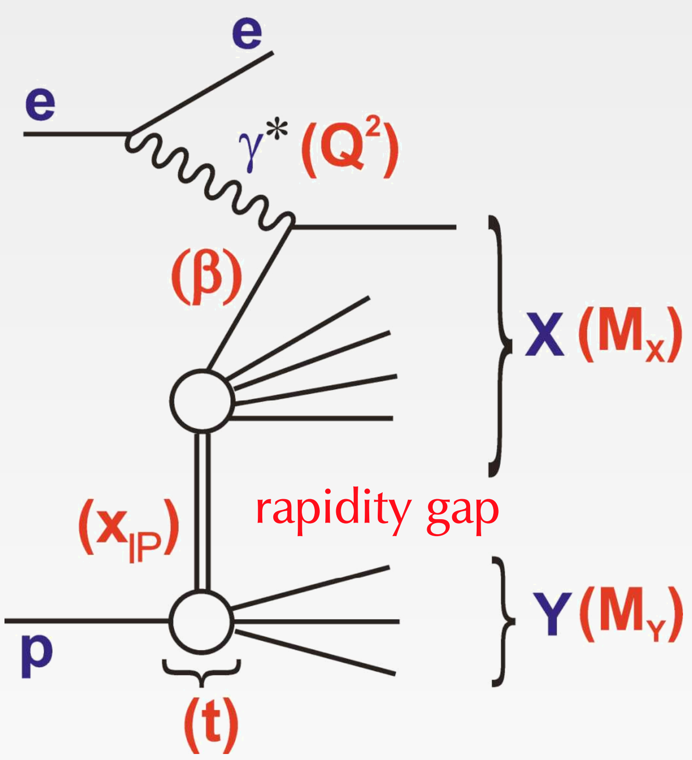


CASCADE is better both in normalisation and shape

uPDF MCs are additional tools for detailed semi-inclusive studies

$\Longrightarrow$ Better understanding of hard interaction $\Longleftrightarrow$ multiple interactions

Diffraction



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

momentum transfer squared at proton vertex $\quad t = (p - p_Y)^2$

invariant mass of X (Y) $\quad M_X = \sqrt{X^2} \qquad (M_Y = \sqrt{Y^2})$

fractional momentum lost by proton $\quad x_{\mathbb{P}} = \dfrac{(p - p_Y)\cdot q}{p \cdot q} = \dfrac{Q^2 + M_X^2}{Q^2 + W^2}$

fractional pomeron momentum carried by struck quark $\quad \beta = \dfrac{x}{x_{\mathbb{P}}} = \dfrac{Q^2}{Q^2 + M_X^2}$

Cross section:

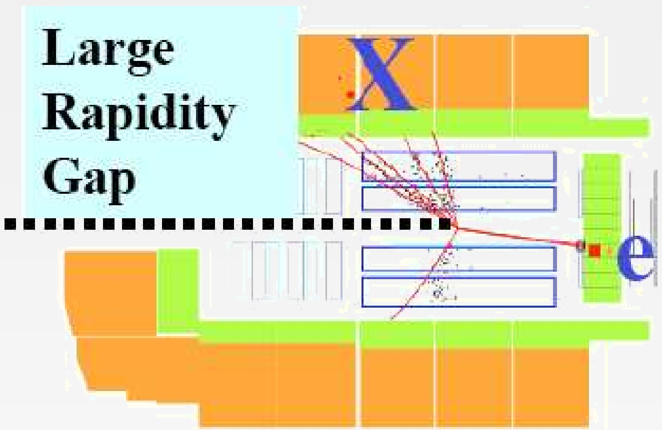
$$\frac{d^2\sigma^{ep\to eXp}}{dx\, dQ^2\, dx_{\mathbb{P}}\, dt} = \frac{2\pi\alpha^2}{Q^4 x} Y_+ \underbrace{\left\{ F_2^{D(4)} - \frac{y^2}{Y_+} F_L^{D(4)} \right\}}_{\text{reduced } \sigma_r^{D(4)}}$$

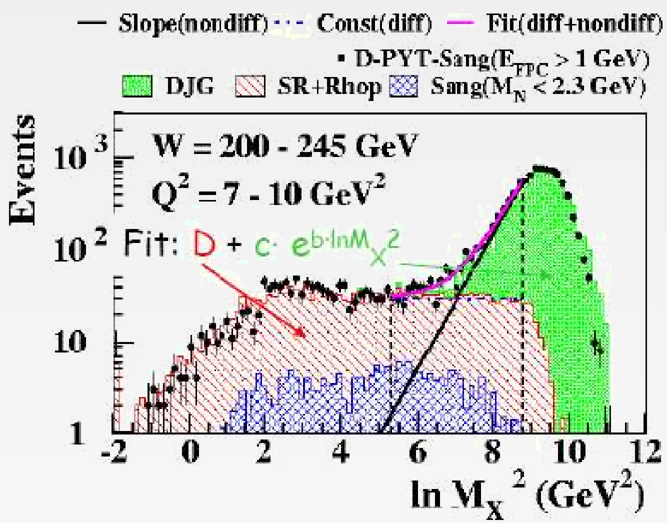
In most analyses:

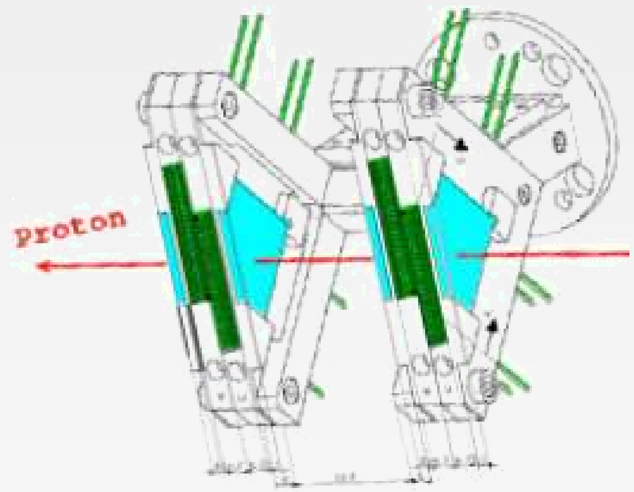
$$\sigma_r^{D(3)} \approx F_2^{D(3)} = \int \sigma_r^{D(4)}\, dt$$

Experimental Selections of Diffraction

Large Rapidity Gap (LRG)	Fit of M_X distribution	Proton Tagging (FPS/LPS)







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

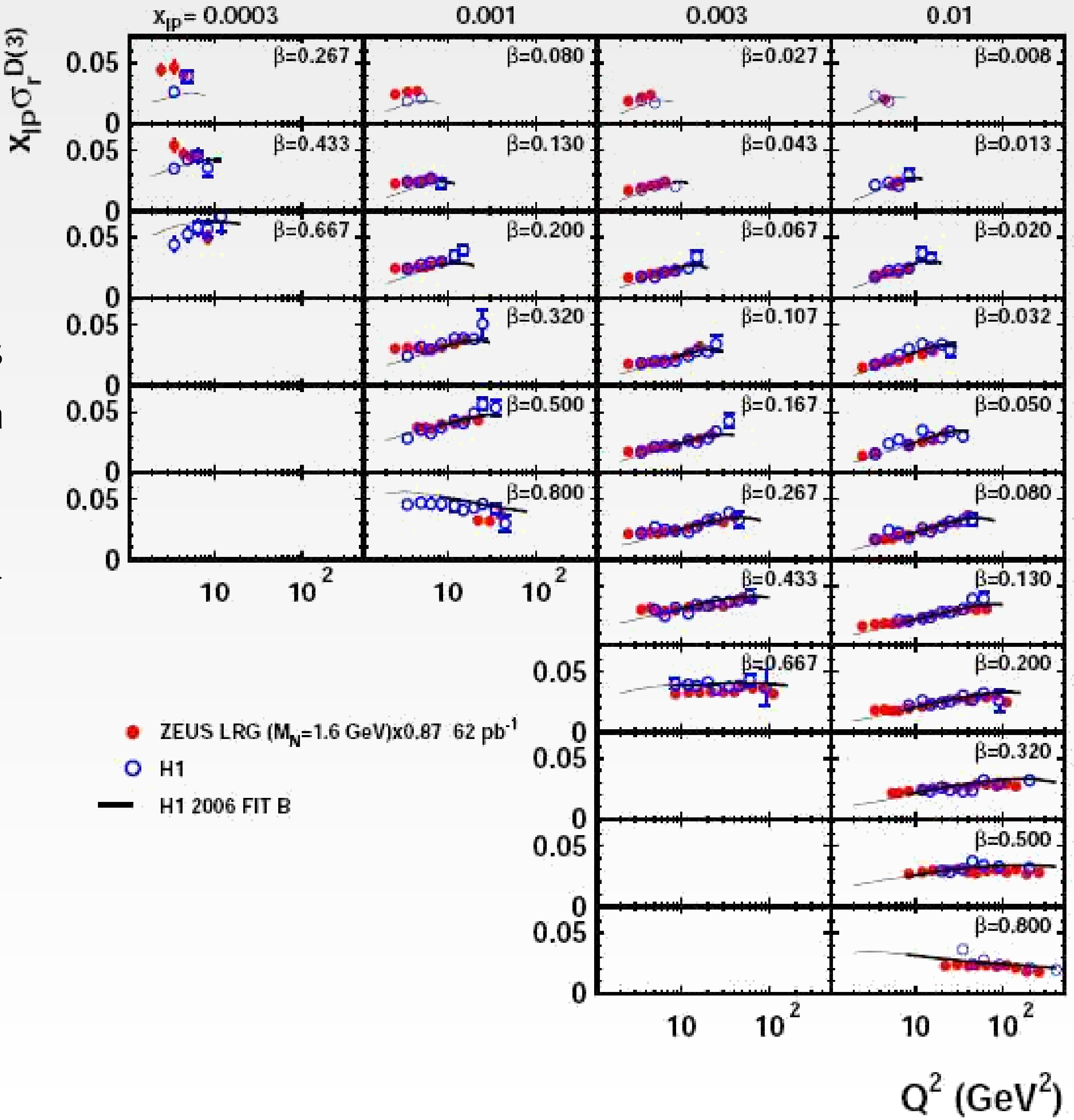
measure kinematics from proton momentum $\Rightarrow$ direct measurement of t

Different systematics and statistics

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

Note: here ZEUS normalised to H1 ⟶

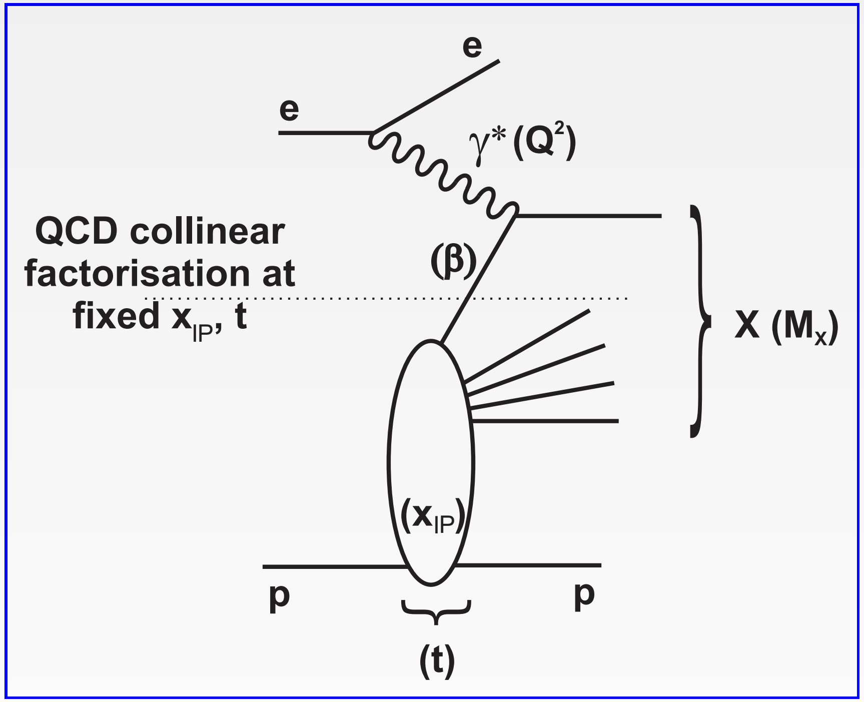
Discussions to combine data and produce common fits

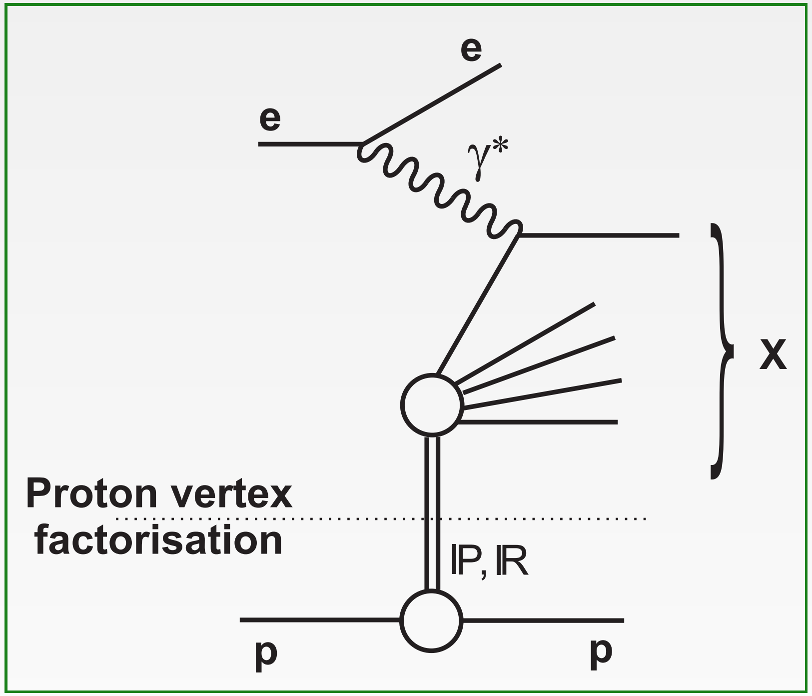


Factorisation in Diffraction

QCD collinear factorisation of hard scattering (Collins) – exact

Proton vertex factorisation (Regge) – approximation





DPDF

$$d\sigma^{ep\to eXY} = \sum_i f_i^D(x, Q^2, x_{\mathbb{P}}, t) \otimes d\sigma^{ei}(x, Q^2)$$

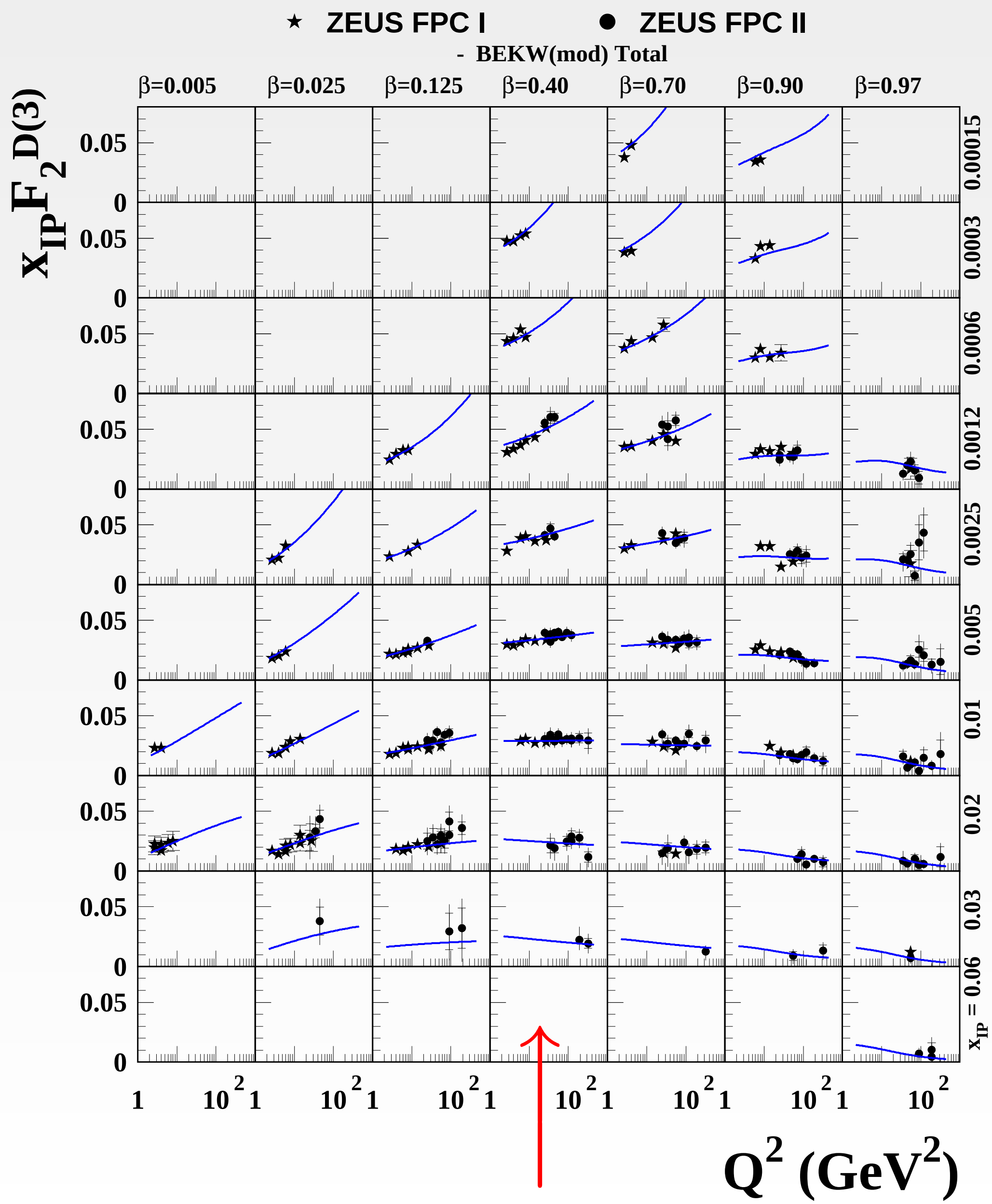
$$f_i^D(x, Q^2, x_{\mathbb{P}}, t) = f_{\mathbb{P}/p}(x_{\mathbb{P}}, t) \cdot f_i^{\mathbb{P}}(\beta = \frac{x}{x_{\mathbb{P}}}, Q^2)$$

$$+ n_{\mathbb{R}} f_{\mathbb{R}/p}(x_{\mathbb{R}}, t) \cdot f_i^{\mathbb{R}}(\beta = \frac{x}{x_{\mathbb{R}}}, Q^2)$$

Factorisation in Detail

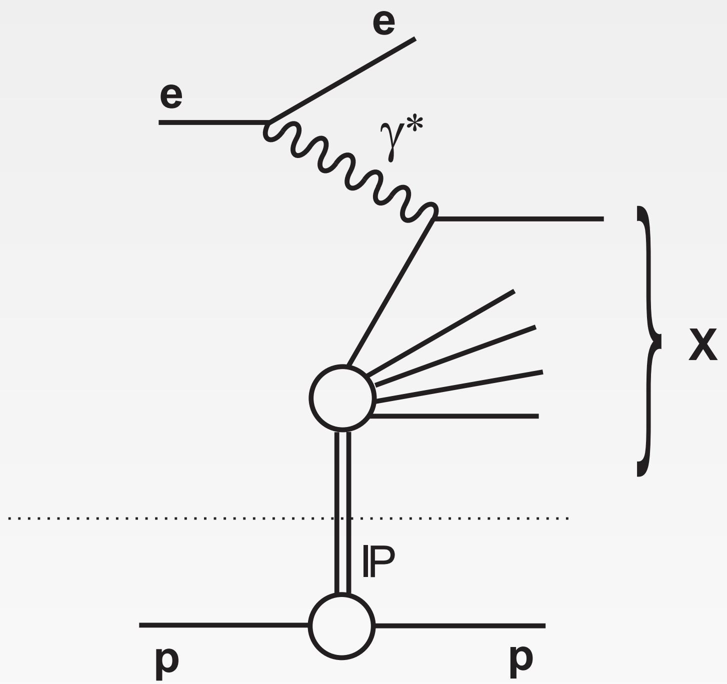
$$f_i^D(x_{\mathbb{P}}, \beta, Q^2) \approx f_{\mathbb{P}/p}(x_{\mathbb{P}}) \cdot f_i^{\mathbb{P}}(\beta, Q^2)$$

- For fixed β, dependence on Q^2 somewhat varies with $x_{\mathbb{P}}$
  $\Rightarrow$ Regge factorisation is broken
- Mild effect – should not strongly affect QCD fits which assume this



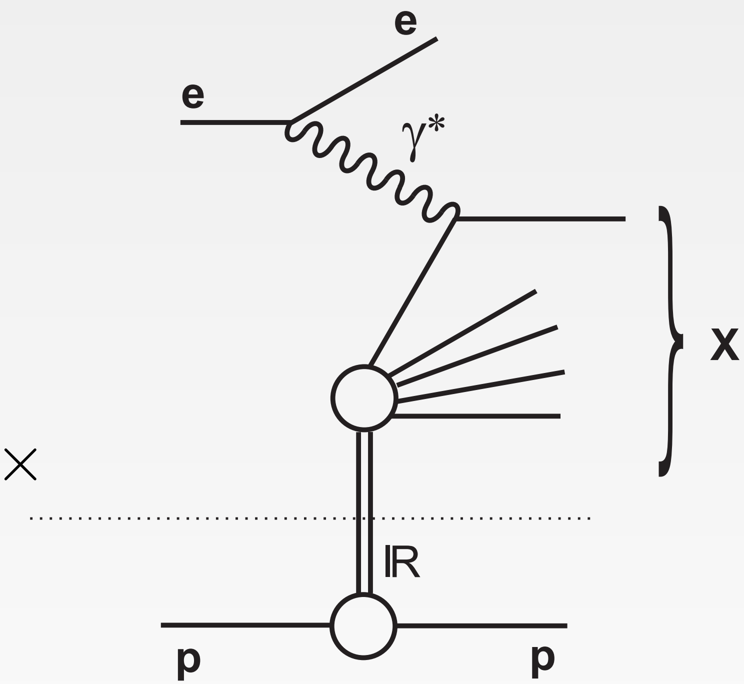
H1 DPDF Fit Procedure

$\mathbb{P}$ component



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

$\mathbb{R}$ component



- Fit $\alpha_{\mathbb{P}}(0)$ – $x_{\mathbb{P}}$ dependence
- Simultaneously, fit 5 parameters of DPDFs – 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; $z \geqslant b]$ $\quad Q_0^2 \approx 2\,\mathrm{GeV}^2$

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

Data insensitive to gluon $B_g \to$ omitted

- **Fit A**

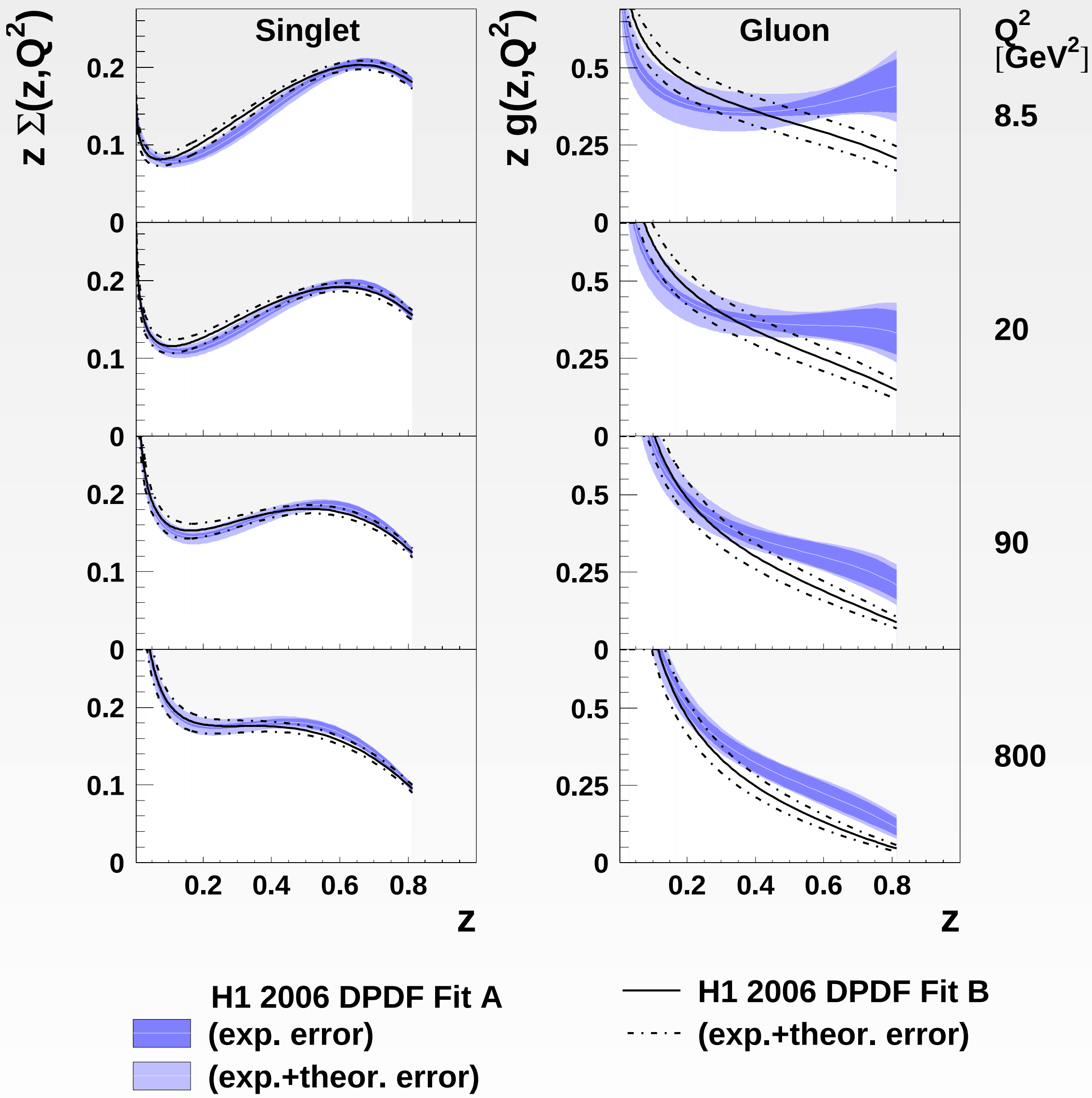
  $\chi^2/\mathrm{ndf} = 158/183$

- **Fit B**

  C_g dropped – gluon parameterised as constant at starting scale

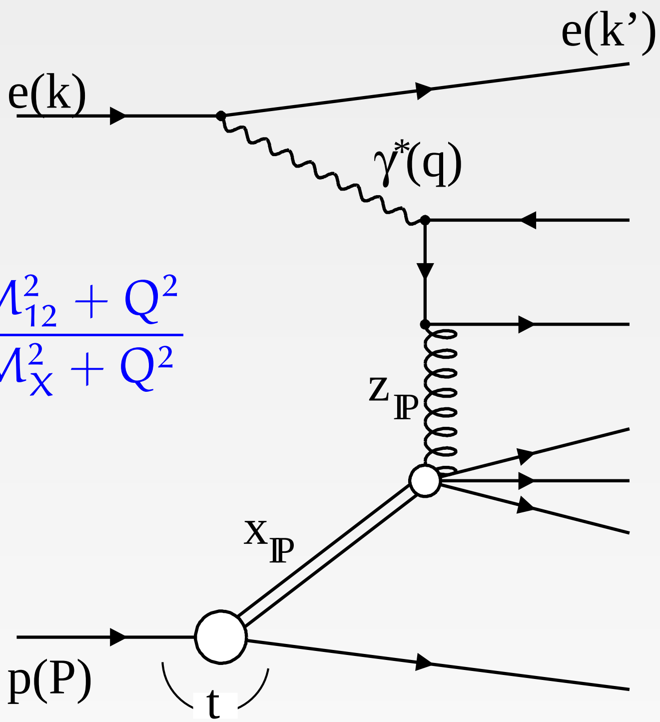
  $\chi^2/\mathrm{ndf} = 164/184$

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

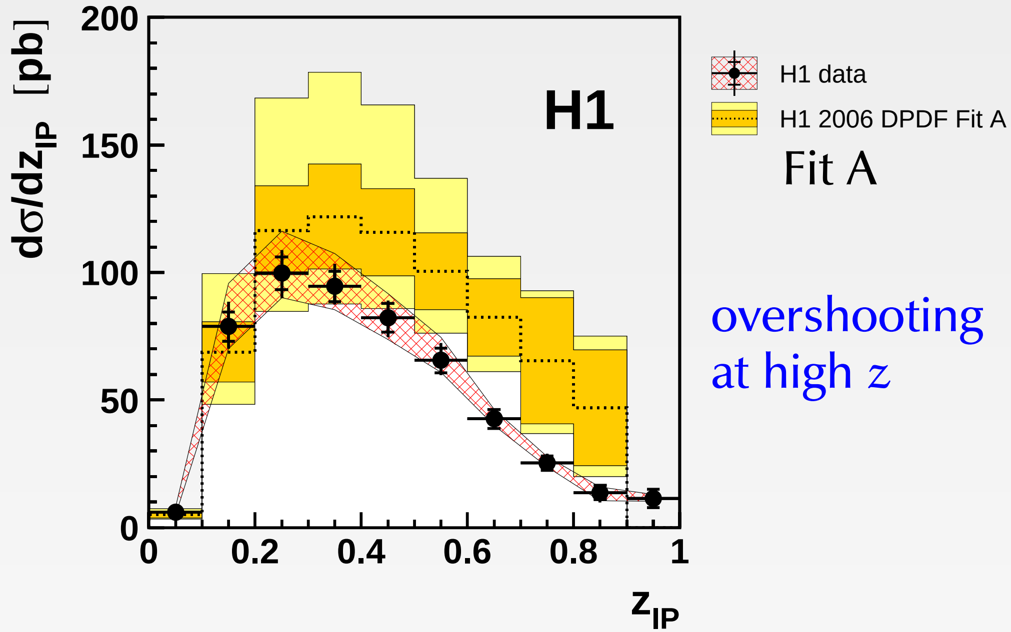


$zg(z, \mu_{f,0}^2) = A_g (1-z)^{C_g}$ $\qquad zg(z, \mu_{f,0}^2) = A_g$

Comparison to Diffractive Dijets in DIS

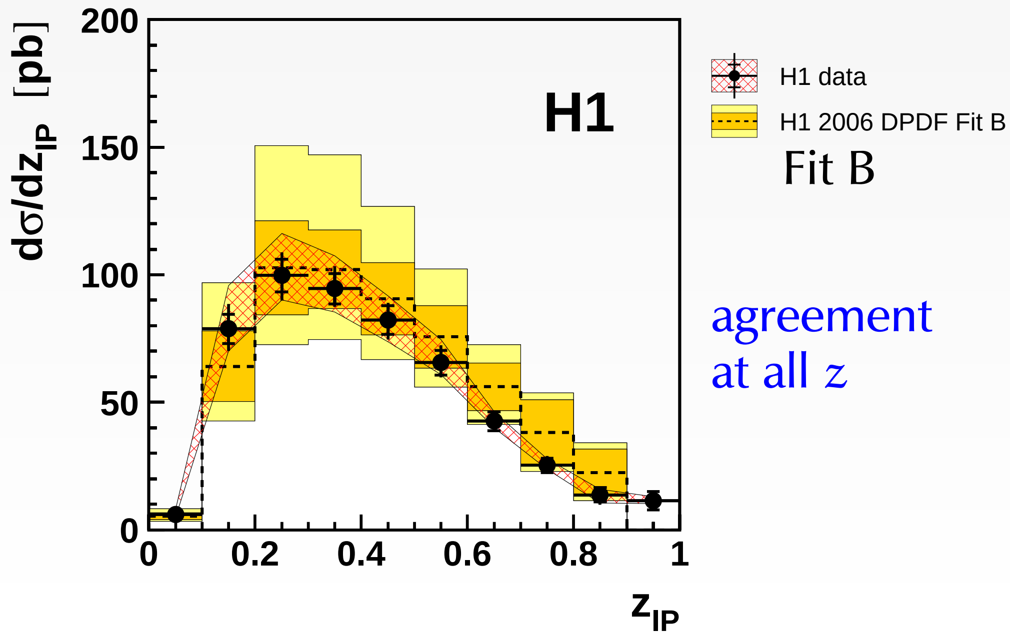


$$z_{\mathbb{P}} = \frac{M_{12}^2 + Q^2}{M_X^2 + Q^2}$$



Fit A

overshooting at high z



Fit B

agreement at all z

- 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

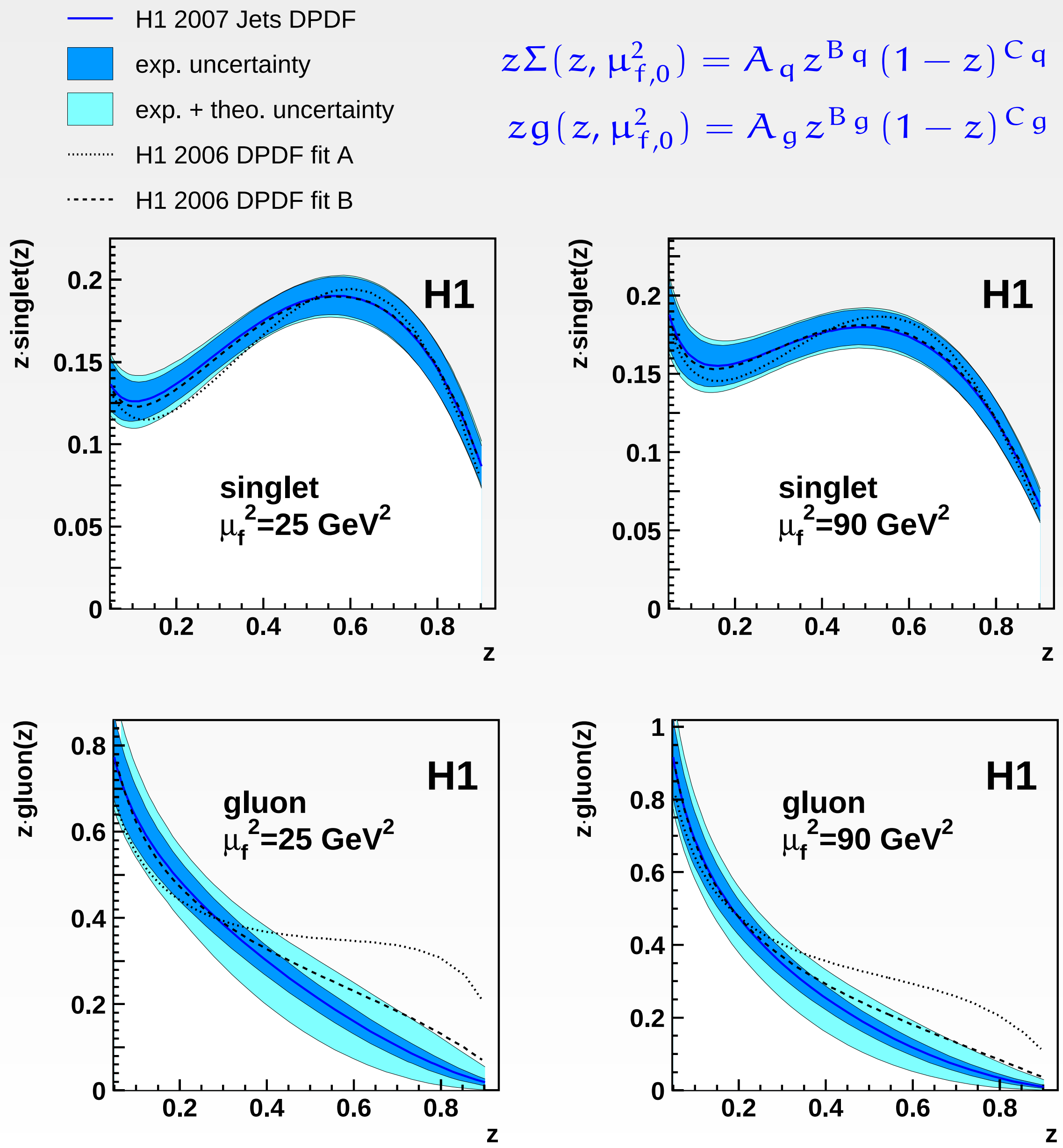
use Diffractive DIS dijet data

as additional constraint

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

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

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



Combined fit constrains both

quark and gluon DPDFs

to similar good precision

$\Longrightarrow$ Most precise DPDFs to date

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

Diffractive 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

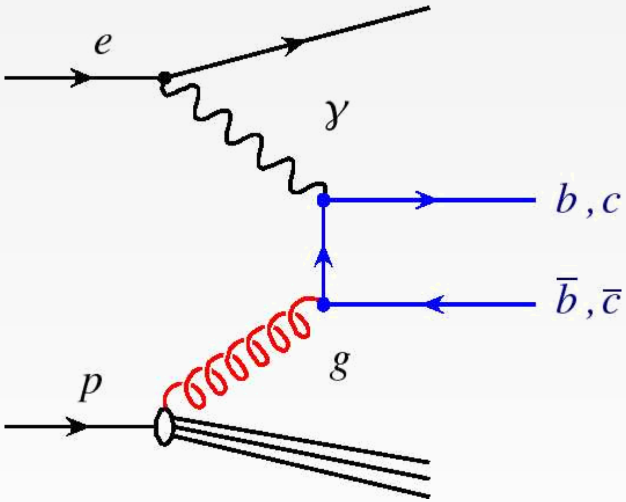
Common choice	**Current decisions**
♦ Data set	Combined H1 + ZEUS
♦ Choice of PDFs	g , u_v , d_v , $\overline{U} = \overline{u} + \overline{c}$, $\overline{D} = \overline{d} + \overline{s} + \overline{b}$
♦ Starting scales	$Q_0^2 = 4\,\mathrm{GeV}^2$, data $Q^2_{min} = 3.5\,\mathrm{GeV}^2$
♦ Form in x at Q_0^2 and # parameters	$xf(x) = Ax^B(1-x)^C\,(1 + Dx + Ex^2 + \ldots)$
♦ Treatment of heavy flavours	VFNS (Thorne) , $s = 0.33D$, $c = 0.15U$, ...
♦ Parameters and constraints	$\alpha_s(M_Z) = 0.1176$, $m_c = 1.4\,\mathrm{GeV}$, $m_b = 4.75\,\mathrm{GeV}$
♦ Propagation of systematic errors	43 uncorrelated + 4 offset
♦ Renormalisation / factorisation scales	Q^2
♦ ...	

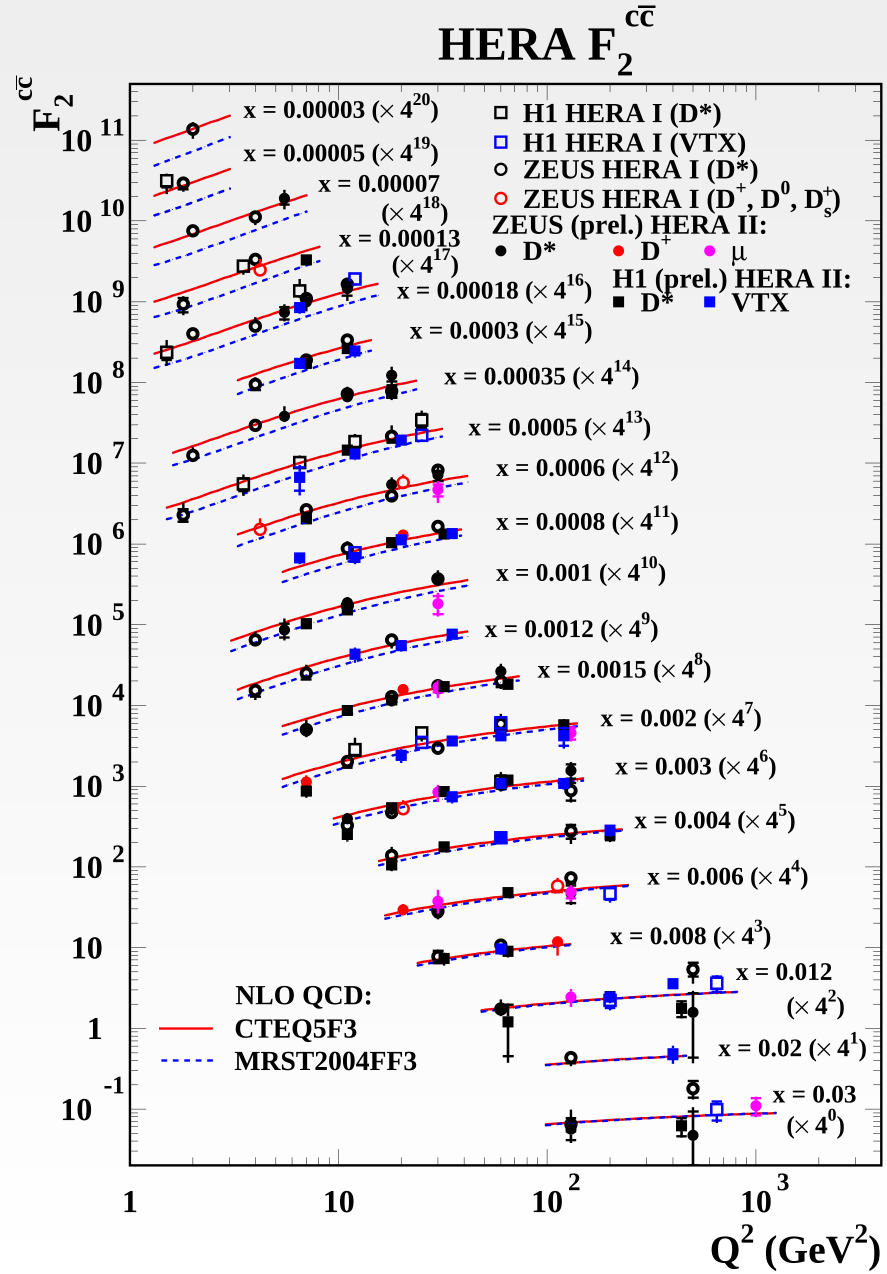
Optimize parameterisation until no further χ^2 advantage

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

Wealth of precise measurements

- Inclusive c and b based on long lifetime [H1]
- μp_T^{rel} + lifetime [ZEUS]
- Inclusive D^* production [H1, ZEUS]
- D^+, D^0, D_s cross sections [ZEUS]
- D^+ + lifetime [ZEUS]

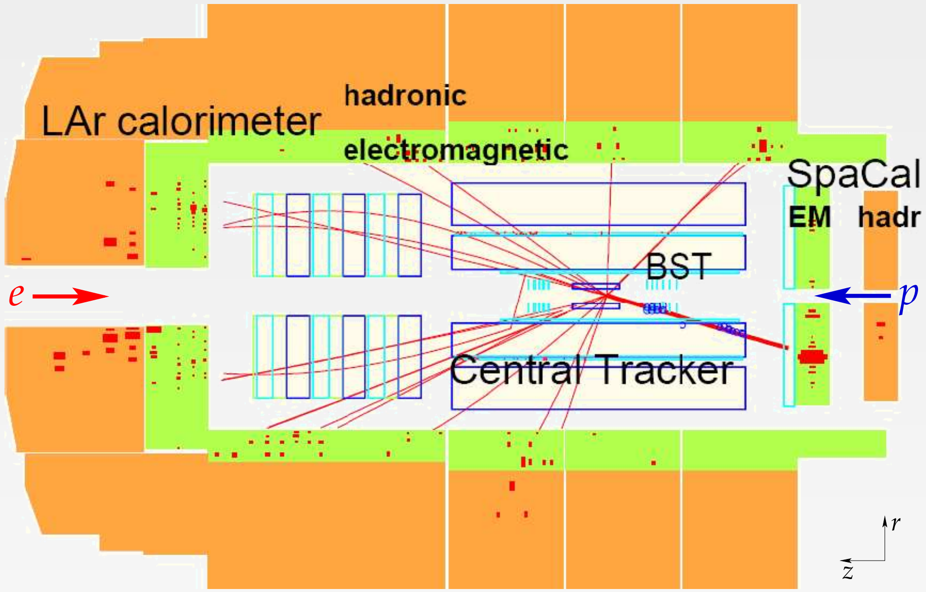


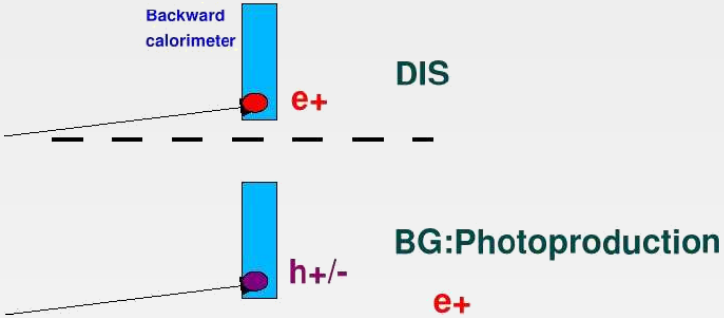


Impact on PDFs

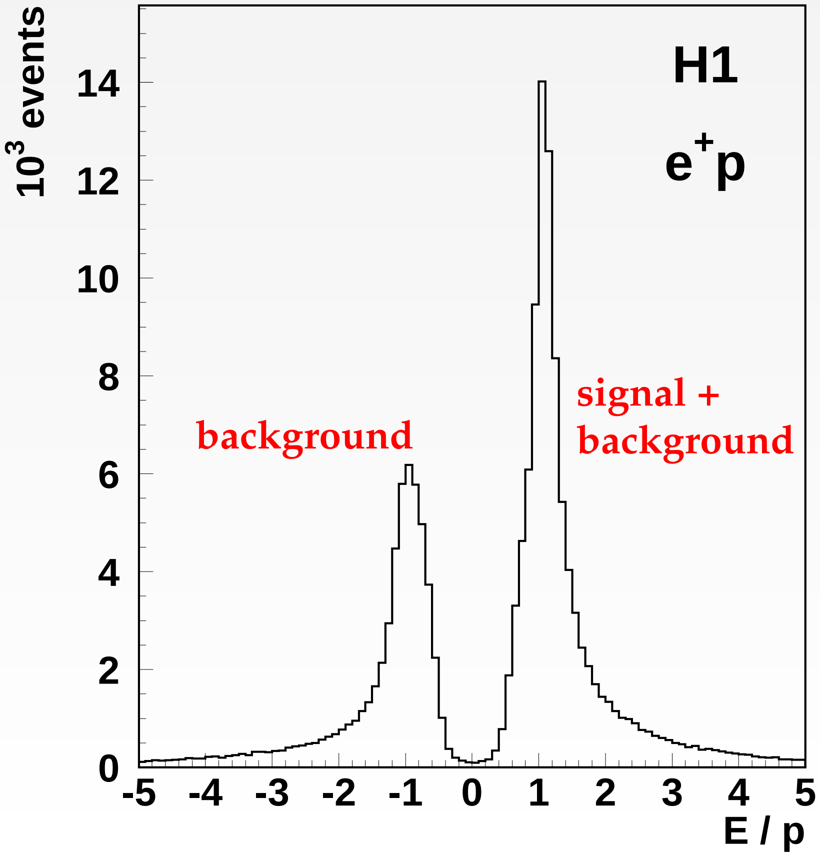
- Sea decomposition
- Improve gluon distribution?

Hadronic Background at High y

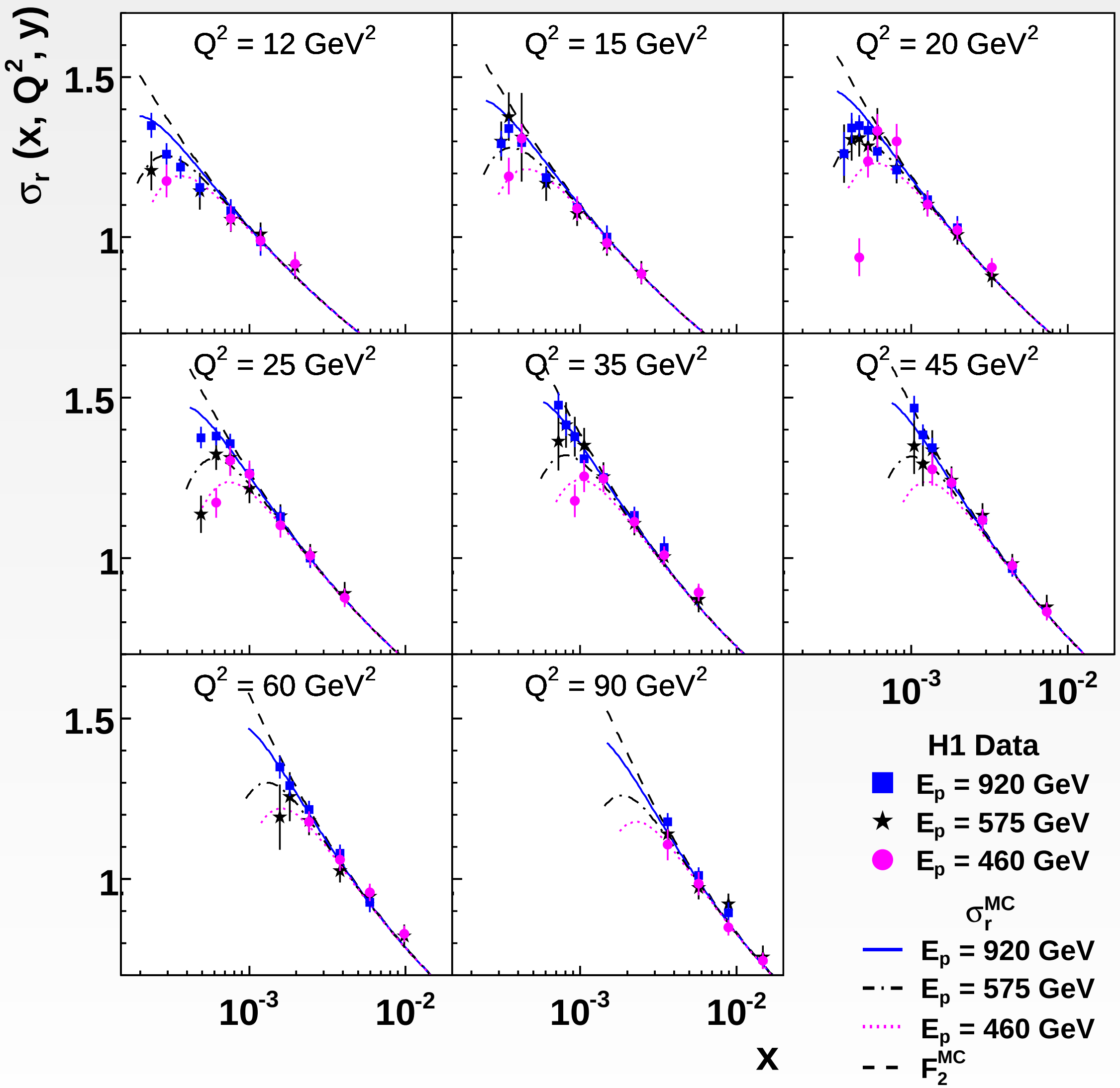




- H1 measured background using events with charge opposite to lepton beam charge
- Small charge asymmetry ~ 5% in background is due to difference of pA and $\overline{p}A$ cross sections – determined using e^+p and e^-p data 2003–2007
- Events with wrong sign tracks are rejected; Right sign background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



Reduced Cross Section

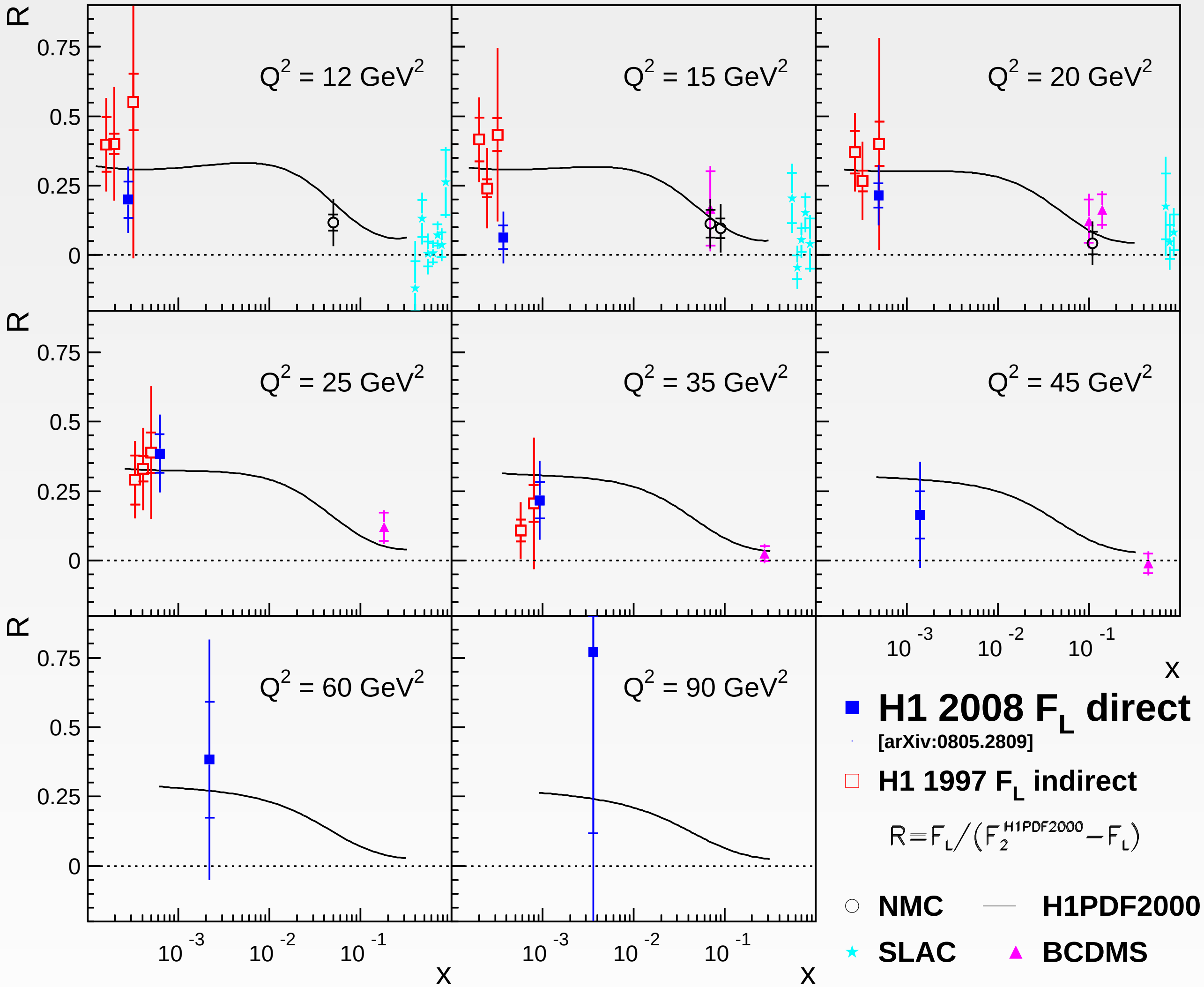


Flattening and turn over at high y for different samples due to F_L

- 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%

H1 F_L Data at Medium Q^2

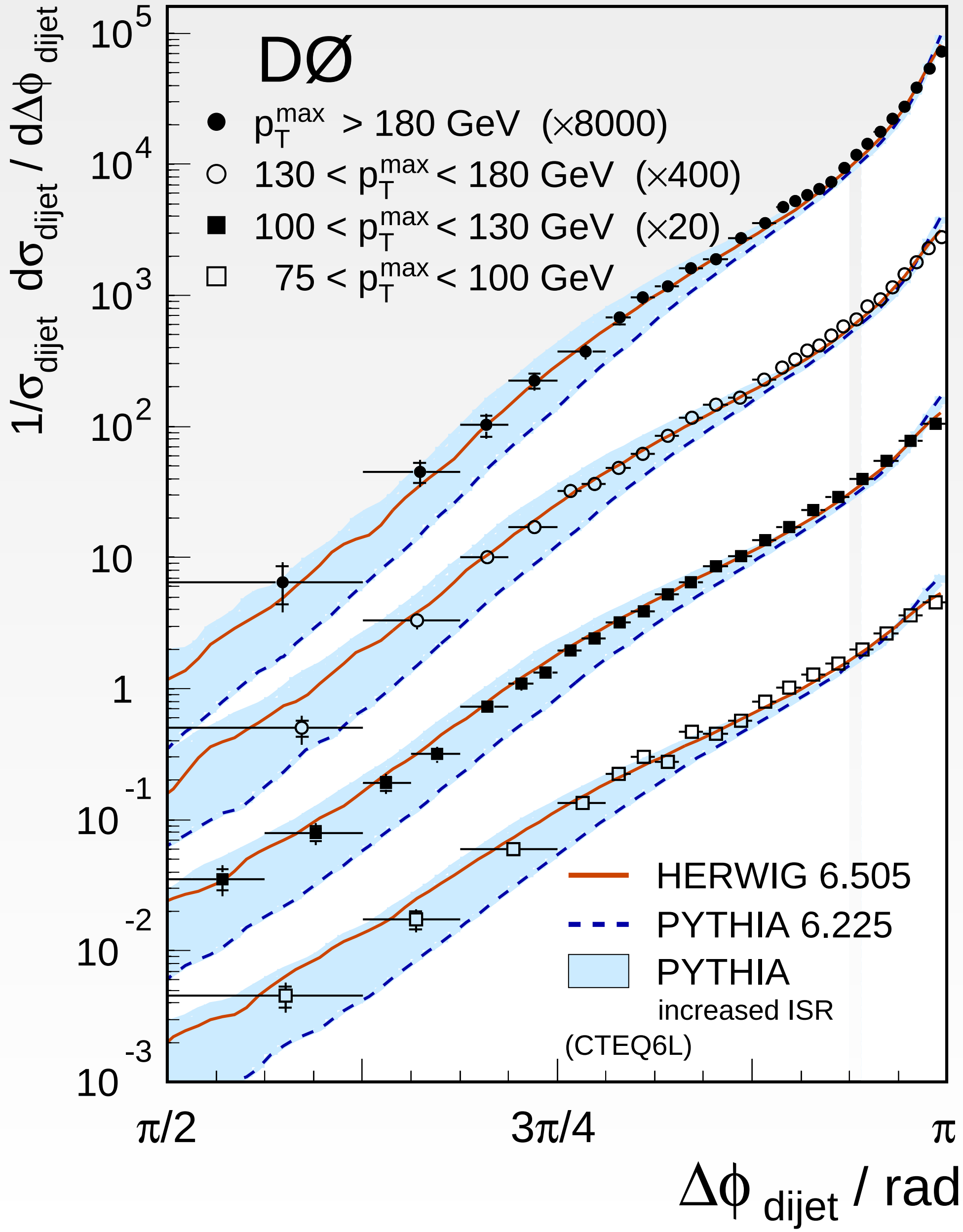
$$R = \frac{F_L}{F_2 - F_L}$$



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

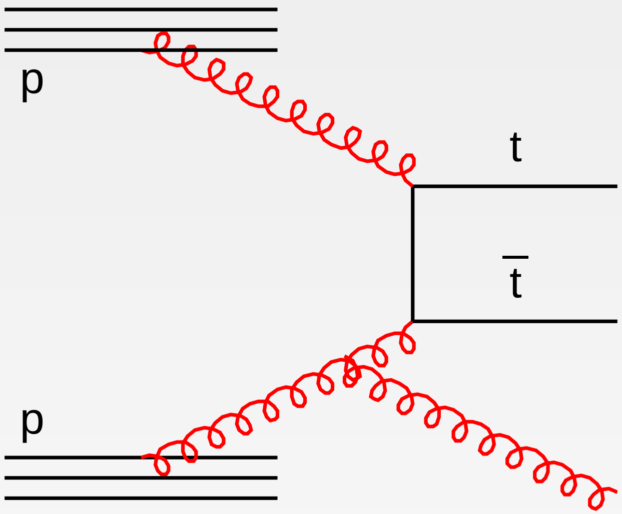
Dijets at Tevatron

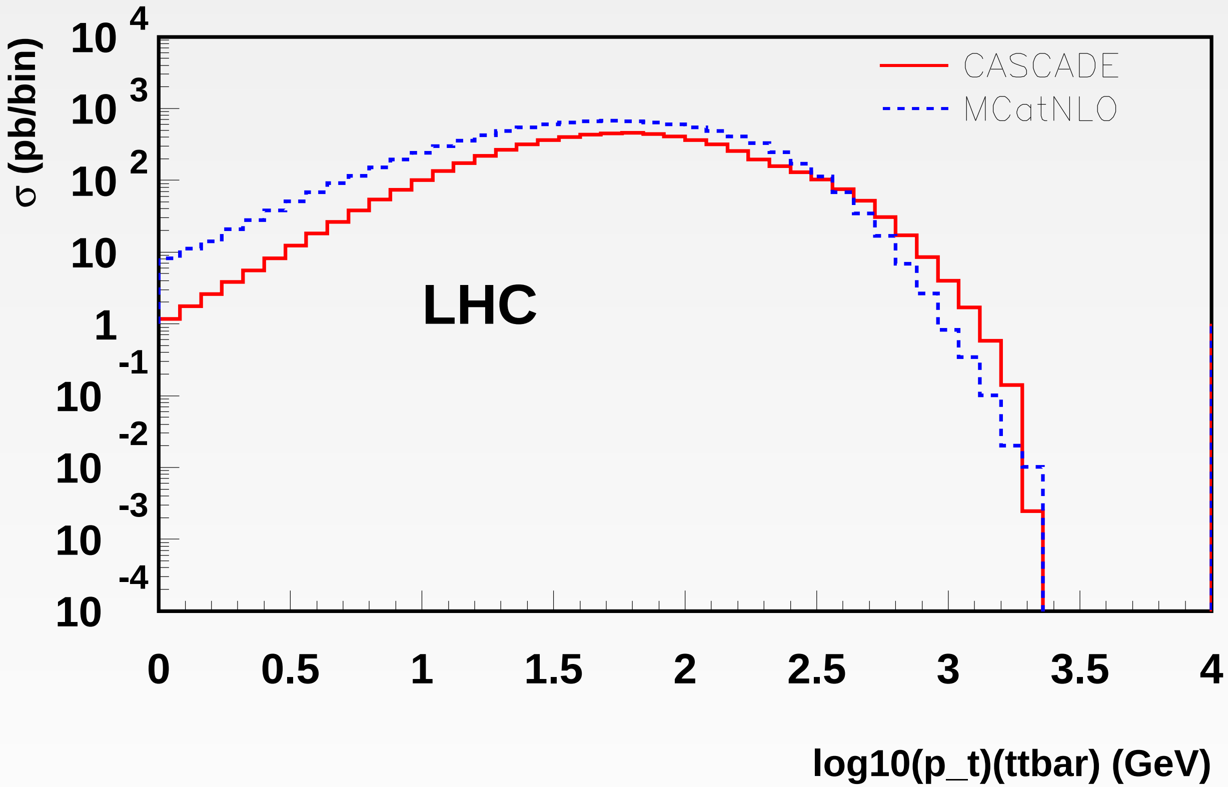


Much stronger falling spectra at high $\Delta\phi$

$t\bar{t}$ Production at LHC

Hautmann, Jung





k_T shower works up to high momentum scales (here ~ t-mass)

H1 Jets 2007 DPDF NLO QCD fit

use Diffractive DIS dijet data

as additional constraint

$$\mu_f^2 = Q^2 + p_T^{*2}$$