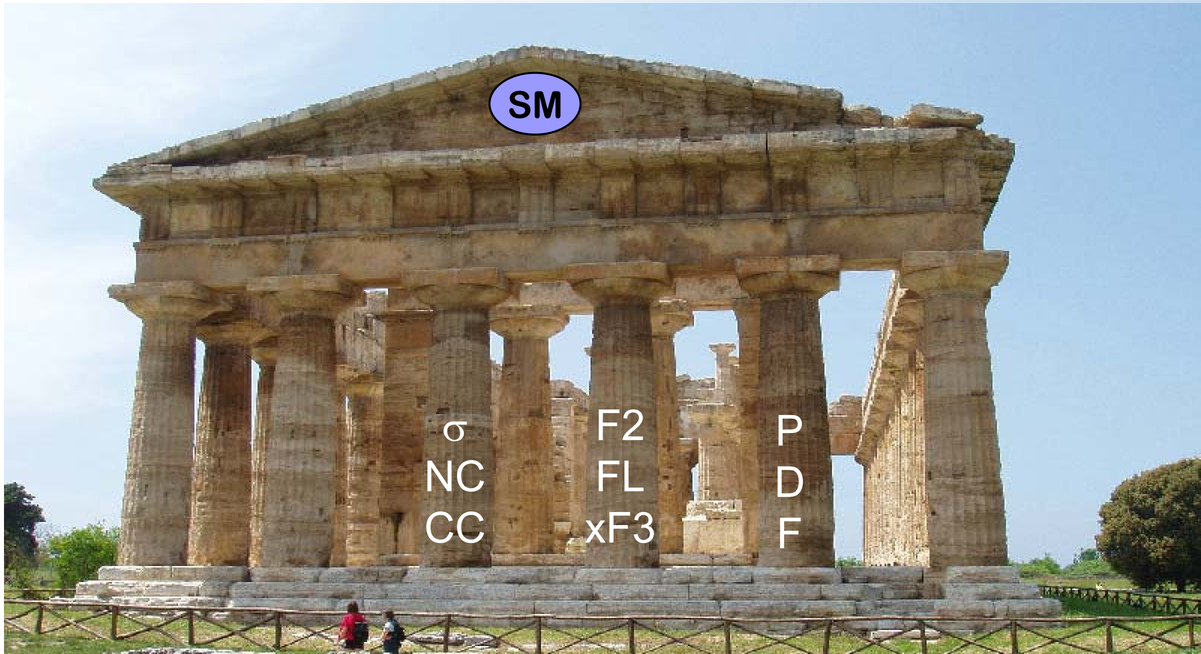
ICHEP 2008
QCD/Lattice

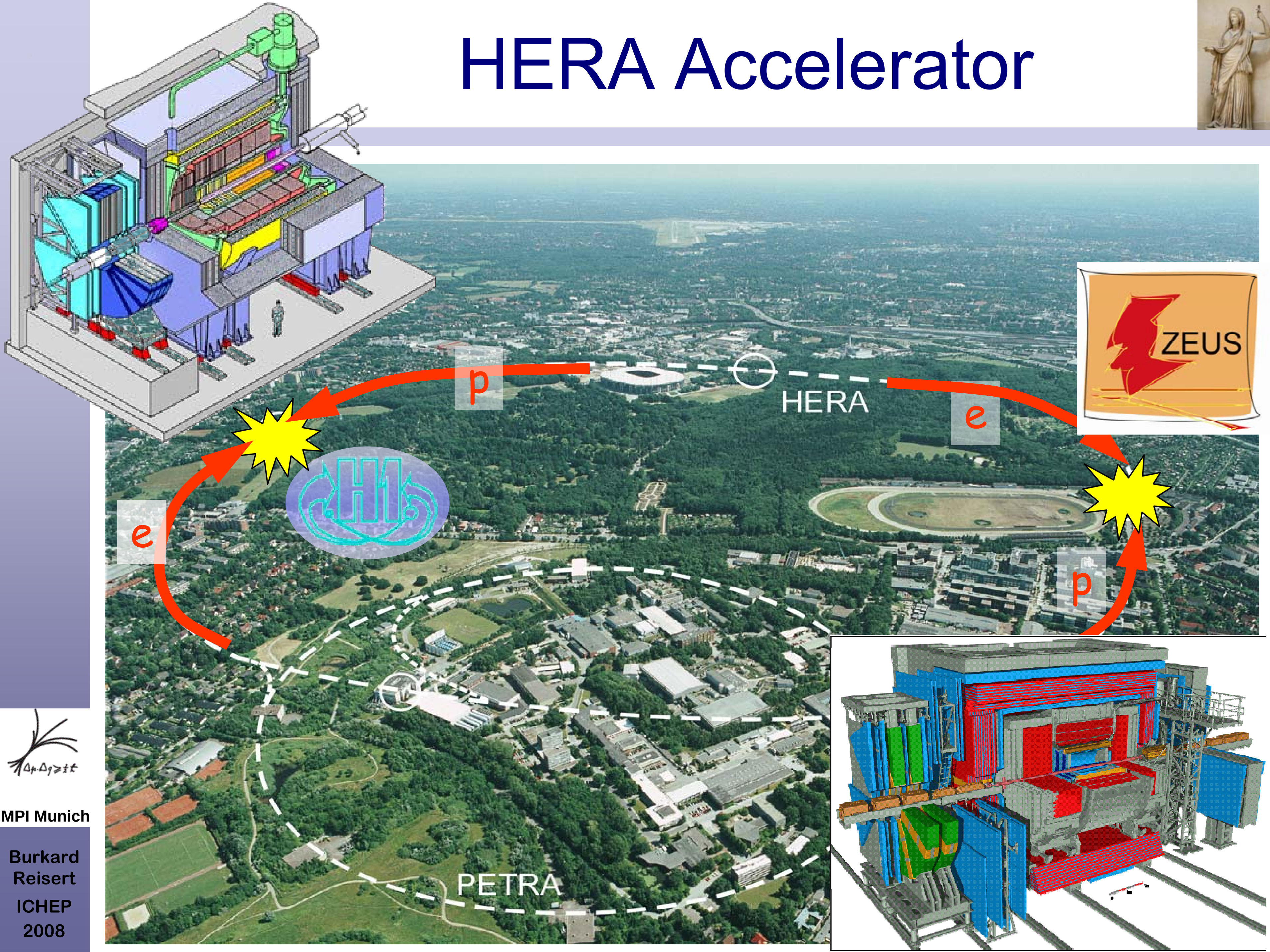
Burkard Reisert
for H1 and Zeus

F_2 and PDFs at HERA

Building up the HERA Legacy:



HERA Accelerator



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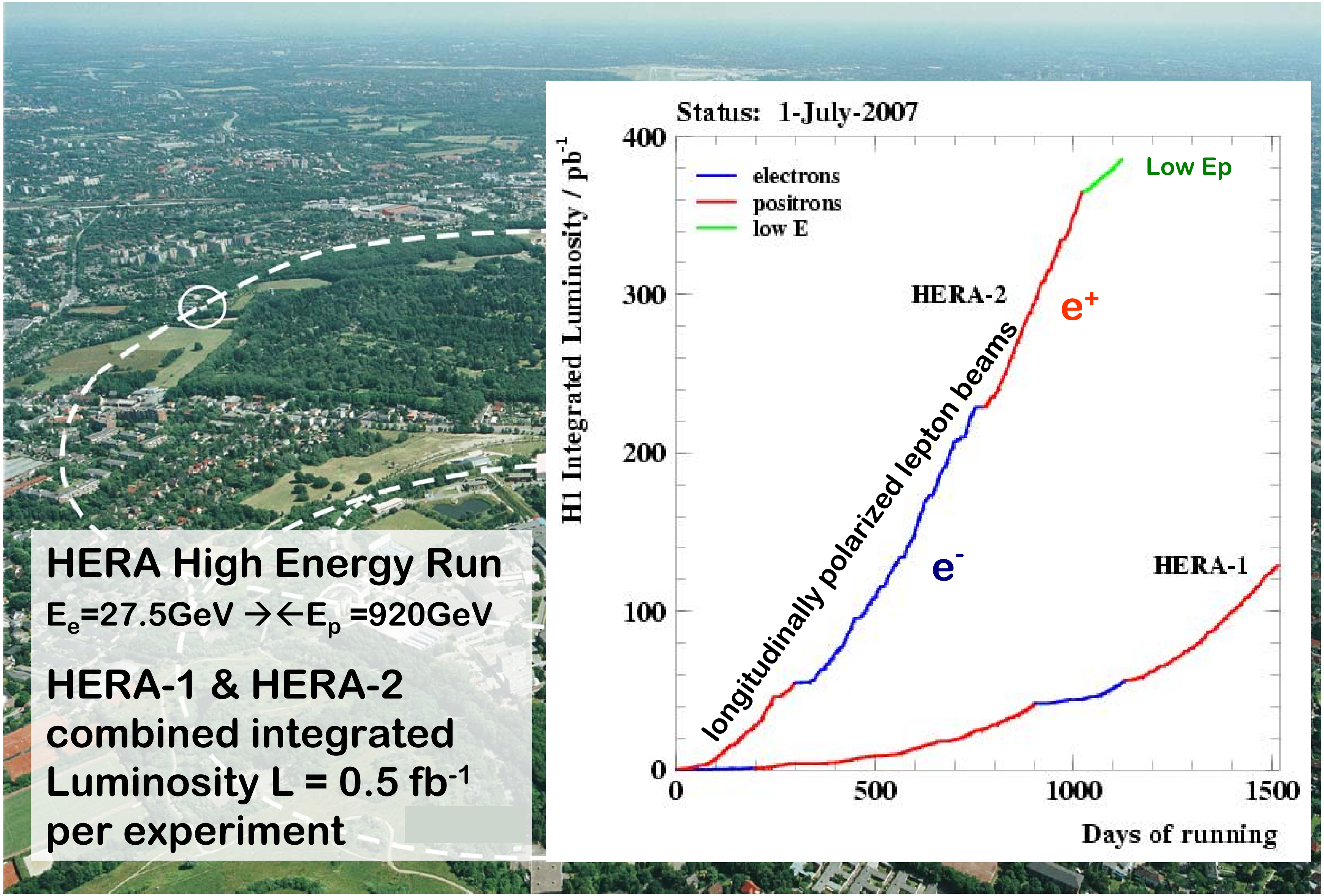
HERA Accelerator Performance

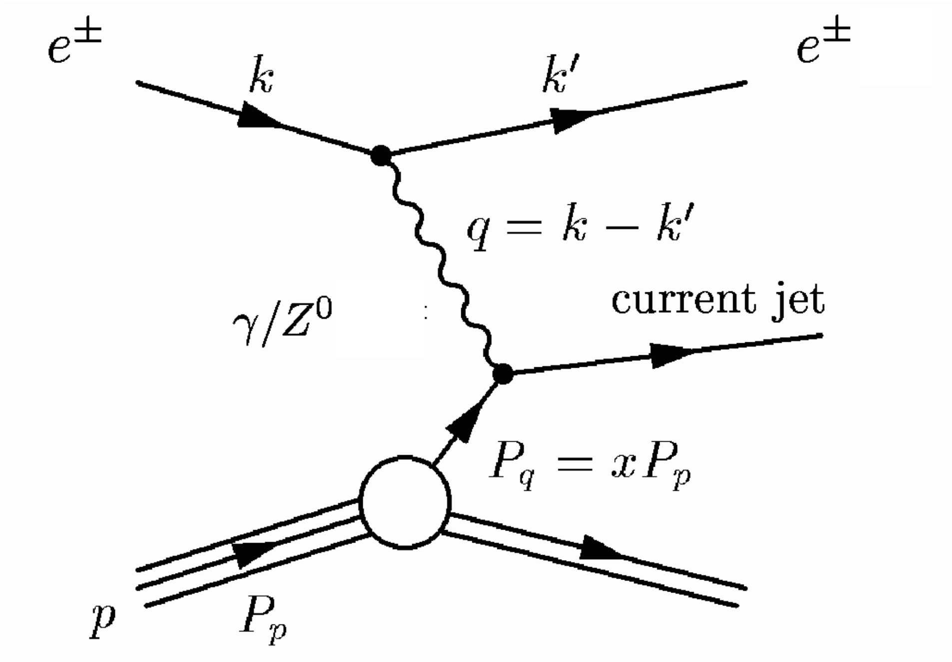


HERA High Energy Run

E_e=27.5GeV →← E_p =920GeV

HERA-1 & HERA-2 combined integrated Luminosity L = 0.5 fb^{-1} per experiment

Deep Inelastic Scattering



Kinematic Variables

- 4-momentum transfer
  resolving power

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

- Bjørken scaling variable
  momentum fraction
  of struck parton

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

- Inelasticity: $y = \frac{p\cdot q}{p\cdot k}$

Center of mass energy $\sqrt{s}$: $s = (k+p)^2$ relation for fixed s: $Q^2 = sxy$

- **Neutral current DIS cross section expressed by structure functions:**

$$\frac{d^2\sigma^{e^\pm p\to e^\pm X}}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}\underbrace{\left(1+(1-y)^2\right)}_{Y_\pm=1\pm(1-y)^2}\cdot\left(\boxed{F_2(x,Q^2)}-\frac{y^2}{Y_+}\boxed{F_L(x,Q^2)}\mp\frac{Y_-}{Y_+}\boxed{xF_3(x,Q^2)}\right)$$

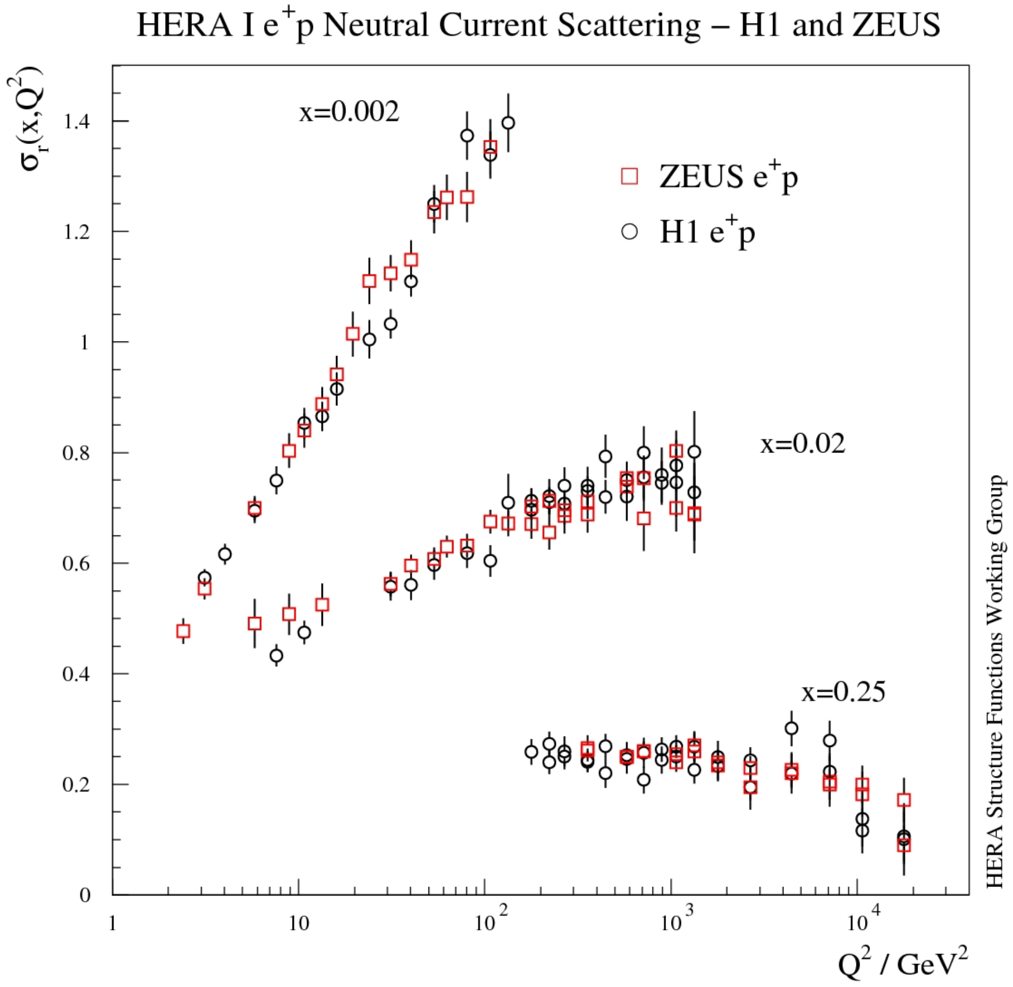
valence & sea quarks

gluons

valence quarks

Example NC cross sections

$$\sigma_r^{e^\pm p\to e^\pm X} = F_2 - \frac{y^2}{Y_+}F_L \mp \frac{Y_-}{Y_+}xF_3$$



- **Precise measurements from two experiments**
- **For $Q^2 \leq 100$ GeV^2**

  $\delta_{stat} \leq 1\%, \delta_{sys} \leq 3\%$

  for $Q^2 \geq 1000$ GeV^2

  $\delta_{stat} > \delta_{sys}$

- **Combine dataset from both experiments:**

  Key assumption

  H1 and ZEUS measure the same cross section at the same x, Q^2, y

- **Model independent combination by minimizing a χ^2 →**

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χ^2 Definition

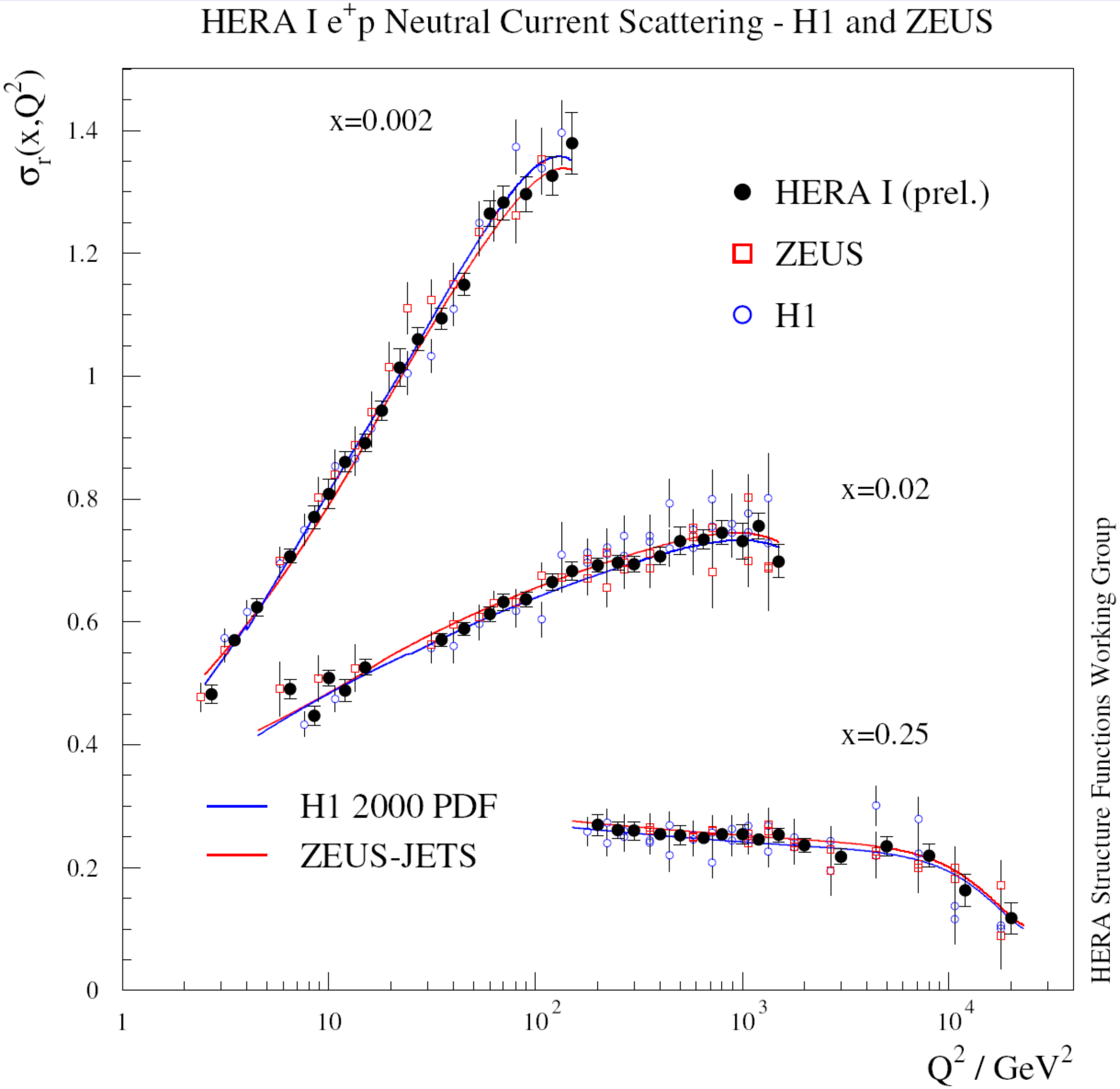
$$\chi^2_{\exp}(M^{i,\mathrm{true}},\Delta\alpha_j) = \sum_i \frac{\left[M^{i,\mathrm{true}} - \left(M^i + \sum_j \frac{\partial M^i}{\partial\alpha_j}\Delta\alpha_j\right)\right]^2}{\sigma_i^2} + \sum_j \frac{\Delta\alpha_j^2}{\sigma_{\alpha_j}^2}$$

M^i	**measured central values**
σ_i	**statistical and uncorrelated systematic uncertainties**
σ_{α_j}	**correlated uncertainty**
$\frac{\partial M^i}{\partial\alpha_j}$	**Sensitivity of the data to the systematic source *j***
$M^{i,\mathrm{true}}$	**Fitted H1-ZEUS combined cross section**
$\frac{\partial M^i}{\partial\alpha_j}\Delta\alpha_j$	**Fitted shift of the */*data due to the systematic source *j***

If $\Delta\alpha_j = 0$ it coincides with a standard average

Caution: Most errors are provided as relative errors, a smaller value of cross section has smaller absolute error bias toward smaller averages
Can be avoided by modified χ^2 definition: insert $M^{i,true}/M^i$

Averaged NC cross sections



Improved precision of combined H1 and ZEUS datasets

Total uncertainty includes ambiguity whether to use systematic errors as additive or multiplicative errors

Here predictions use PDFs of H1 and ZEUS separate NLO QCD PDF extractions.

Next step H1 and ZEUS combined fit

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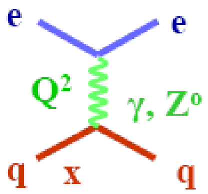
Input to HERA PDF Fits

- NC

$$\frac{d^2\sigma^{e^\pm p\to e^\pm X}}{dxdQ^2}=\frac{2\pi\alpha^2}{xQ^4}\underbrace{\left(1+(1-y)^2\right)}_{Y_\pm=1\pm(1-y)^2}\cdot\left(\tilde{F}_2\left(x,Q^2\right)-\frac{y^2}{Y_+}\tilde{F}_L\left(x,Q^2\right)\mp\frac{Y_-}{Y_+}x\tilde{F}_3\left(x,Q^2\right)\right)$$

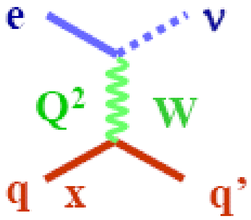


$$\tilde{F}_2=\sum_i A_i(Q^2)\left[xq_i+x\bar{q}_i\right]\Rightarrow F_2^{em}=\frac{4}{9}x\left(u+\bar{u}+c+\bar{c}\right)+\frac{1}{9}x\left(d+\bar{d}+s+\bar{s}\right)$$

$$x\tilde{F}_3=\sum_i B_i(Q^2)\left[xq_i-x\bar{q}_i\right]\Rightarrow xF_3^{em}=B_U x\left(u-\bar{u}+c-\bar{c}\right)+B_D x\left(d-\bar{d}+s-\bar{s}\right)$$

Electroweak Coefficient Functions $A_i(Q^2)$, $B_i(Q^2)$ (QED: $A_i=e_i^2$)

- CC



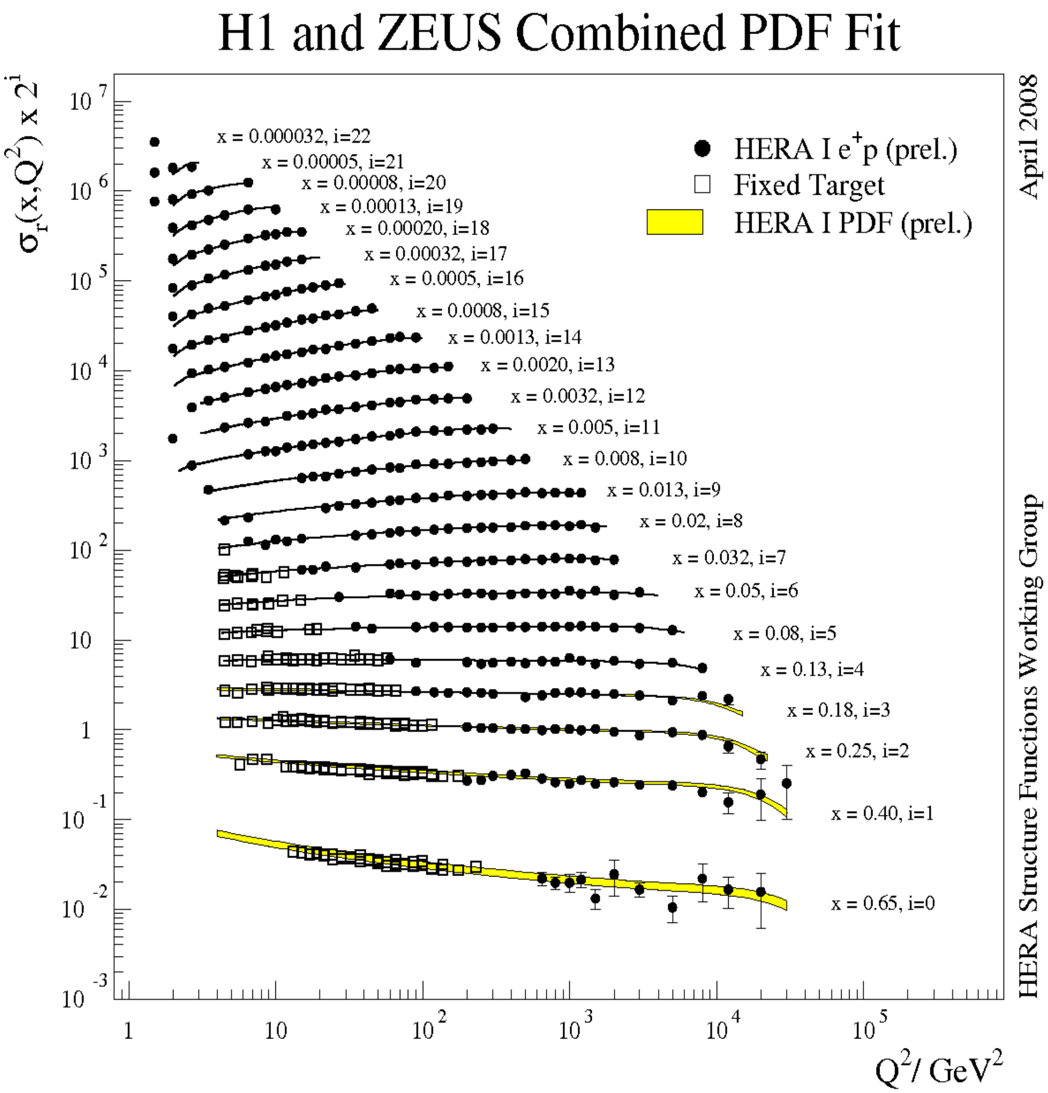
$$\sigma_{CC}(e^+p)\propto x\left[(1-y^2)\left(d+s\right)+\left(\bar{u}+\bar{c}\right)\right]\times(1+P_e)$$

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

PDF general form: $xPDF=Ax^B(1-x)^C\cdot(1+Dx+\ldots)$

Prameterize: g, u_v, d_v, U(=u+c), D(=d+s)

Structure Function F_2



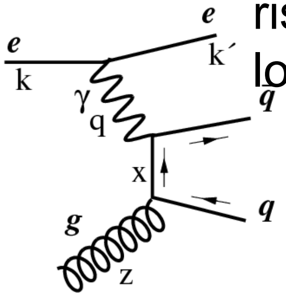
H1 and ZEUS Combined PDF Fit

April 2008

HERA Structure Functions Working Group

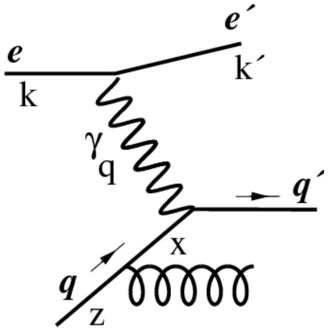
- H1 & ZEUS extended fixed target kinematic regime in x and Q^2 by 2 Orders
- Described by DGLAP

- Scaling violations

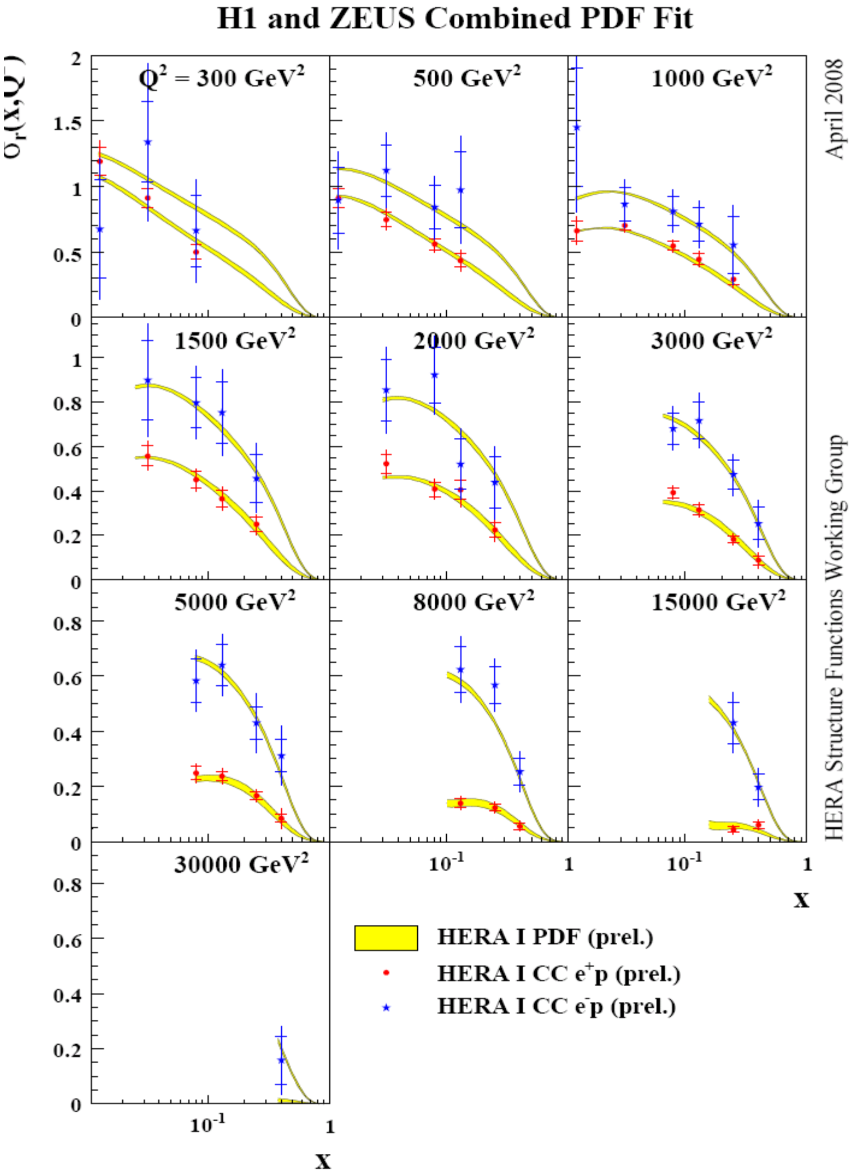


rise at low x

drop at high x



Charged Current Cross Section



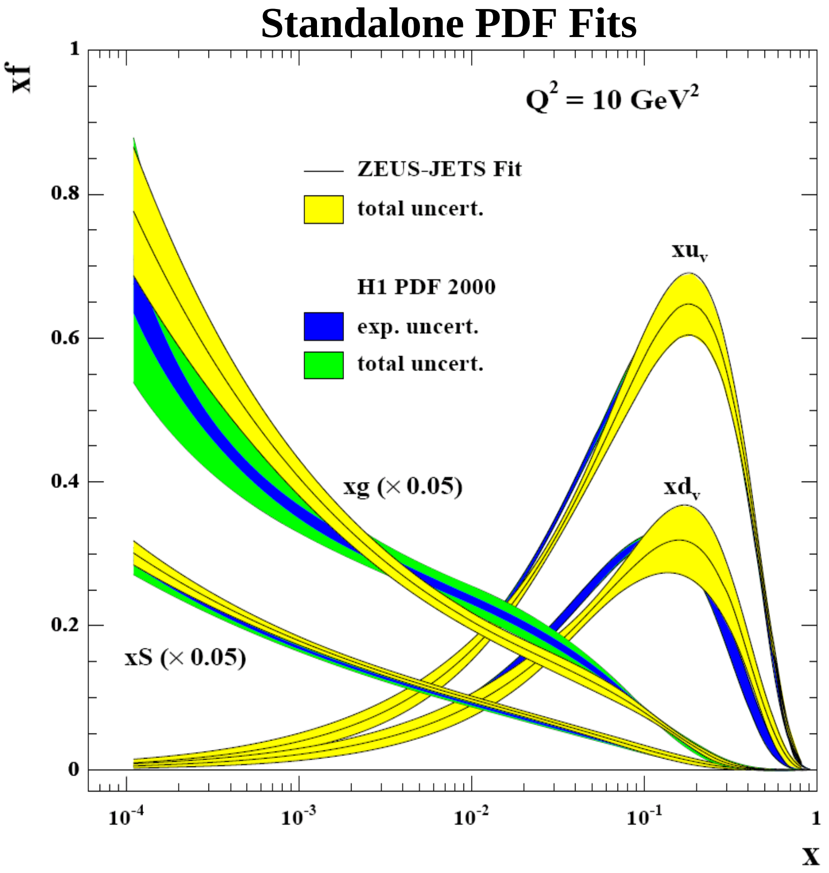
CC Cross section provide flavor sensible constrains at high x

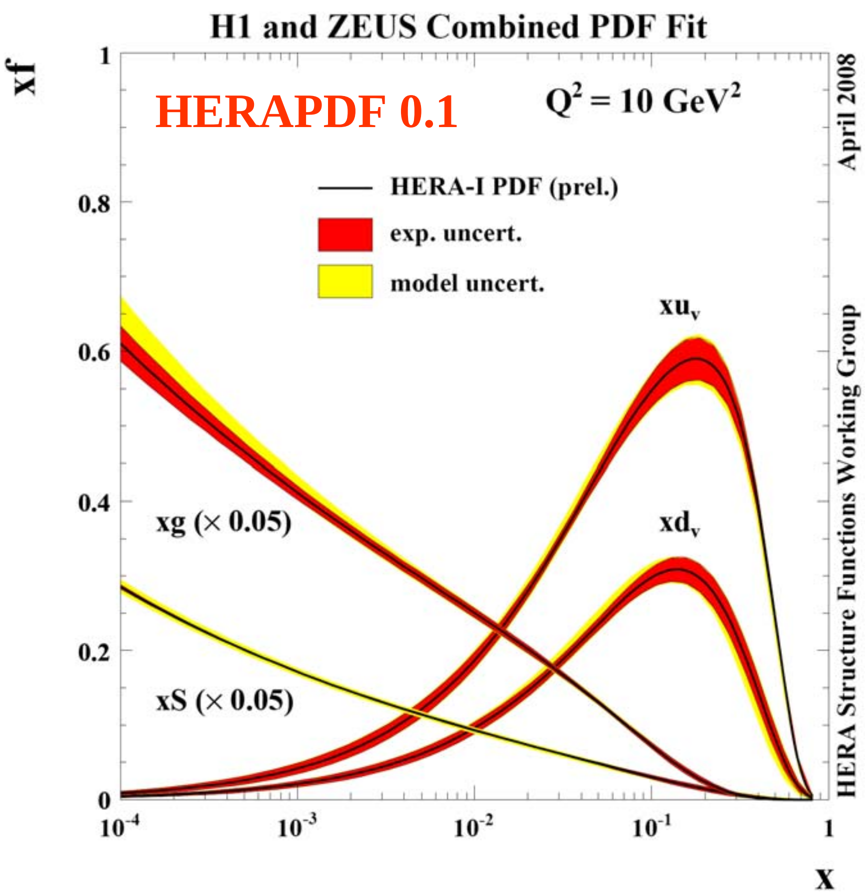
$$\sigma_{CC}(e^+p) \propto x\left[(1-y^2)D+\bar{U}\right]$$

$$\sigma_{CC}(e^-p) \propto x\left[U+(1-y^2)\bar{D}\right]$$

Improved precision of σ_{CC} By combining H1 and ZEUS

PDF Fits on HERA I Data

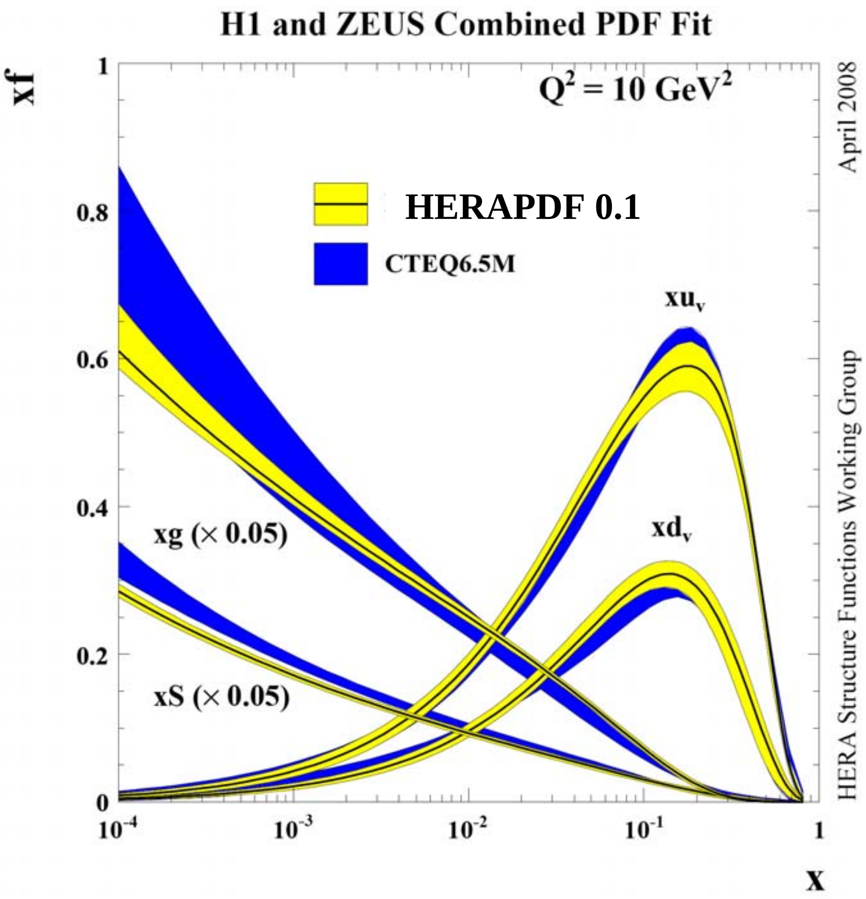


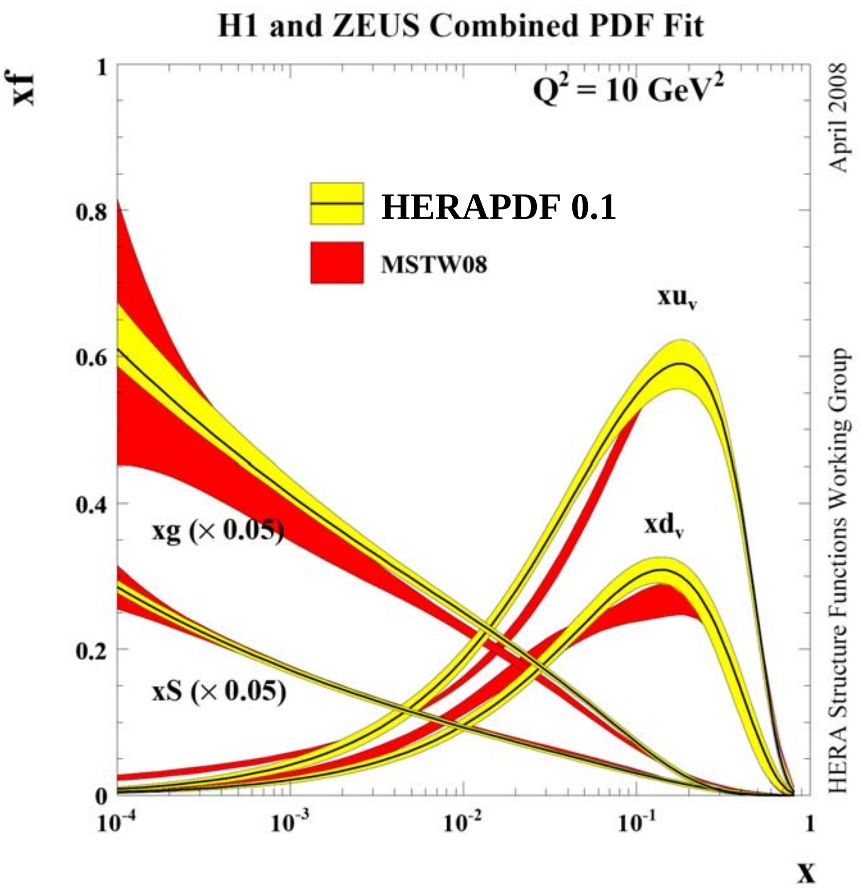


Impressive reduction of uncertainties of combined

Model uncertainty: variation of charm and bottom mass, starting scale Q_0^2, Q^2_{min} of included data, strange and charm fraction at starting scale

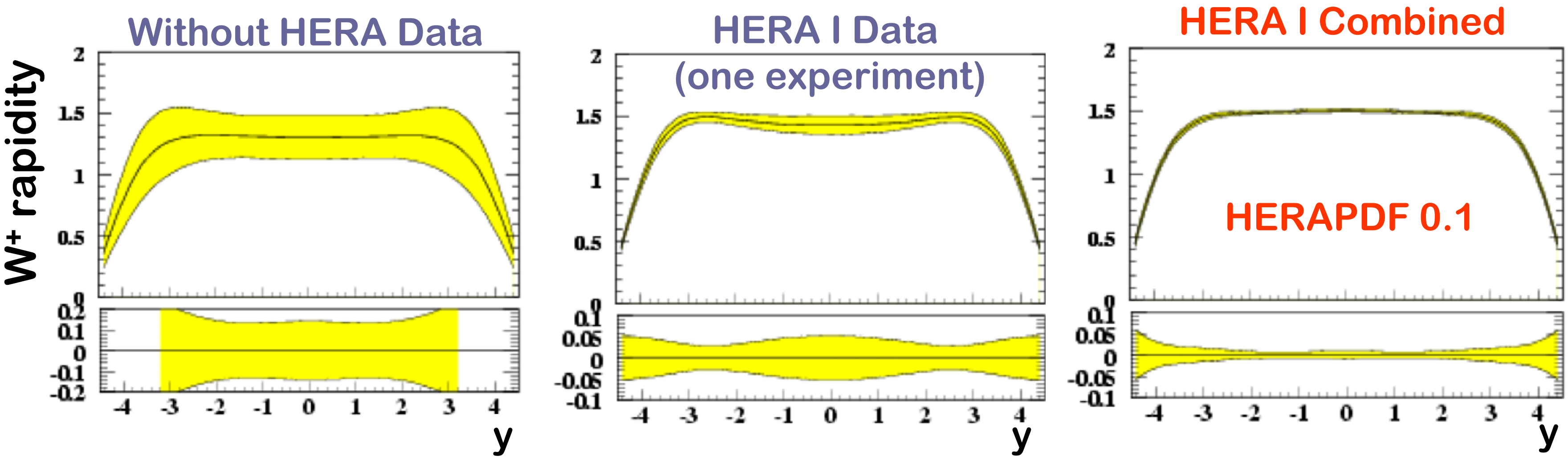
Comparison to Global Fits


H1 and ZEUS Combined PDF Fit


H1 and ZEUS Combined PDF Fit

Impact of HERA PDFs

Example: W+ production at the LHC (Study by A. Cooper-Sakar)


Without HERA Data

HERA I Data (one experiment)

HERA I Combined

HERAPDF 0.1

- HERA Combined Data and PDFs are an crucial input to predictions at the LHC
- Note: Error bands are experimental uncertainties only model uncertainty will become increasingly important

Summary

- Combining H1 and ZEUS reduces statistical and systematic uncertainties
- Model independent combination procedure
- HERA PDF fit on combined HERA I data
  - use ep data only → no need for nuclear corrections
  - results in a HERA PDF set with impressive precision compared to previous HERA analyses, and to the global fits
- HERAPDF0.1 is being implemented in LHAPDF
- Still to come: Use all of HERA II date

Backup Slides

- Data combination: Modified χ^2
- HERAPDF0.1 Parameterization
- Comparison of H1 and ZEUS PDF fits
- Model uncertainties

Modified c2 definition

Caution: Most errors are provided as relative errors, a smaller value of cross section has smaller absolute error bias toward smaller averages
Can be avoided by modified χ^2 definition:

$$\chi^2_{\exp}\left(M^{i,\mathrm{true}},\Delta\alpha_j\right)=\sum_i \frac{\left[M^{i,\mathrm{true}}-\left(M^i+\sum_j \frac{\partial M^i}{\partial\alpha_j}\frac{M^{i,\mathrm{true}}}{M^i}\Delta\alpha_j\right)\right]^2}{\left(\sigma_i\frac{M^{i,\mathrm{true}}}{M^i}\right)^2}+\sum_j\frac{\Delta\alpha_j^2}{\sigma^2_{\alpha_j}}$$

Normalization uncertainty is clearly a relative (multiplicative).

Are other systematic errors as additive or multiplicative errors?

Choice of best treatment is debatable. Does it matter?

Impact is mostly negligible, except at very large Q2 and x where statistical errors and fluctuation are largest.

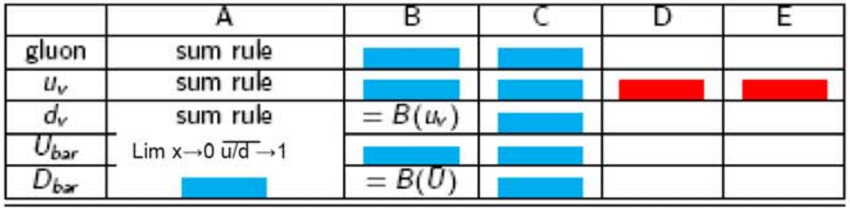
How to deal with this freedom in systematic error treatment?

→ Additional correlated uncertainty of averaged data points

Details on HERAPDF 0.1

Chosen form of the PDF parametrization at Q_0^2

$$xf(x) = Ax^B(1-x)^C(1+Dx+Ex^2+Fx^3\ldots)$$



	A	B	C	D	E
gluon	sum rule	🟦	🟦		
u_v	sum rule	🟦	🟦	🟥	🟥
d_v	sum rule	$= B(u_v)$	🟦		
U_{bar}	Lim x→0 $\overline{u/d}$ →1	🟦	🟦		
D_{bar}	🟦	$= B(\bar{U})$	🟦		

The number of parameters for each parton has been optimized

Optimization means starting with only BLUE parameters and adding D, E,F parameters until there is no further χ2 advantage

PDFs fiited: gluon, u_v, d_v, $U_{bar}=u_{bar}+c_{bar}$, $D_{bar}=d_{bar}+s_{bar}+b_{bar}$

Sea flavour break-up at Q_0: s = fs*D, c=fc*U , $AU_{bar}=(1-fs)/(1-fc)AD_{bar}$

Lim x→0 u_{bar}/d_{bar} →1

fs = 0.33D (s=0.5d), fc = 0.15U consistent with dynamical generation

mc=1.4 GeV mass of charm quark mb=4.75 GeV mass of beauty quark
Zero-mass variable flavour number heavy quark scheme (for now)

Q_0^2 = 4 GeV^2 input scale Q^2_{min} = 3.5 GeV^2 minimum Q^2 of input data

$\alpha_s(Mz)$ = 0.1176 PDG2006 value

Renormalization and factorization scales = Q^2

Comparison of Separate H1 and ZEUS PDF Fits

$$xf(x) = Ax^{B}(1-x)^{C}(1+Dx+Ex^{2}+Fx^{3}\ldots)$$

Alternative form of PDF parametrization: H1 style

	A	B	C	D	E	F
gluon	sum rule	🟦	🟦			
U	$\lim_{x\to 0} \bar{u}/\bar{d} \to 1$	🟦	🟦	sum rule	🟥	🟥
D	🟦	$= B(U)$	🟦	sum rule		
U_{bar}	$= A(U)$	$= B(U)$	🟦			
D_{bar}	$= A(D)$	$= B(U)$	🟦			

PDFs: gluon, U=u+c, $U_{bar}=u_{bar}+c_{bar}$, D=d+s+b, $D_{bar}=d_{bar}+s_{bar}+b_{bar}$

Sea flavour break-up at Q_0: s = fs*D, c=fc*U   AU=(1-fs)/(1-fc)AD

Alternative form of PDF parametrization: ZEUS style

	A	B	C	D	E!
gluon	From Sum Rule	🟦	🟦	🟦	0.
u_v	From Sum Rule	🟦	🟦	🟦	🟥
d_v	From Sum Rule	= B_{uv}	🟦		0.
u_{bar} - d_{bar}	from Z_S_11 fit	from Z_S_11 fit	from Z_S_11 fit	0.	0.
Sea	🟦	🟦	🟦	0.	0.

PDFs: gluon, u_v, d_v, Sea= $u_{sea}+u_{bar}+d_{sea}+d_{bar}+s+s_{bar}+c+c_{bar}$

Sea flavour break-up at Q_0: $s_{bar} = (d_{bar}+u_{bar})/4$, charm dynamically generated,

$d_{bar}-u_{bar}$ fixed to fit E866 data

Model Uncertainties

	Model Variation	Standard value	Upper limit	Lower limit
m_c	Mass c quark	1.4	1.35	1.5
m_b	B quark mass	4.7	4.3	5.0
f_s	Strange sea frac. (D) at Q_0^2	0.33	0.25	0.40
f_c	Charm sea frac. (U) at Q_0^2	0.15	0.12	0.18
Q_0^2	Starting scale	4.0	2.0	6.0
Q^2_{min}	cut of included data	3.5	2.5	5.0

- Correlated variations
  f_c varies when is m_c is varied
  variation Q_0^2 also changes f_s and f_c