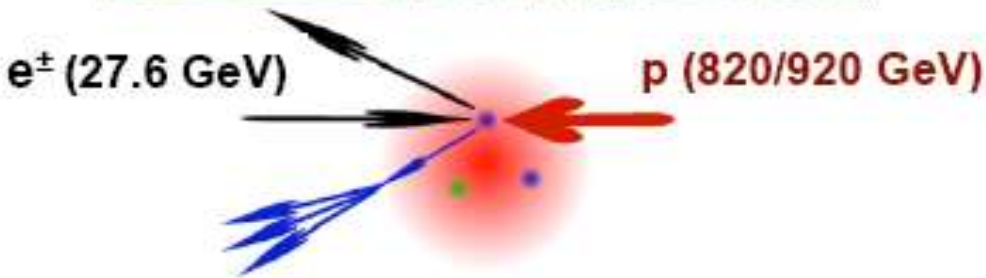
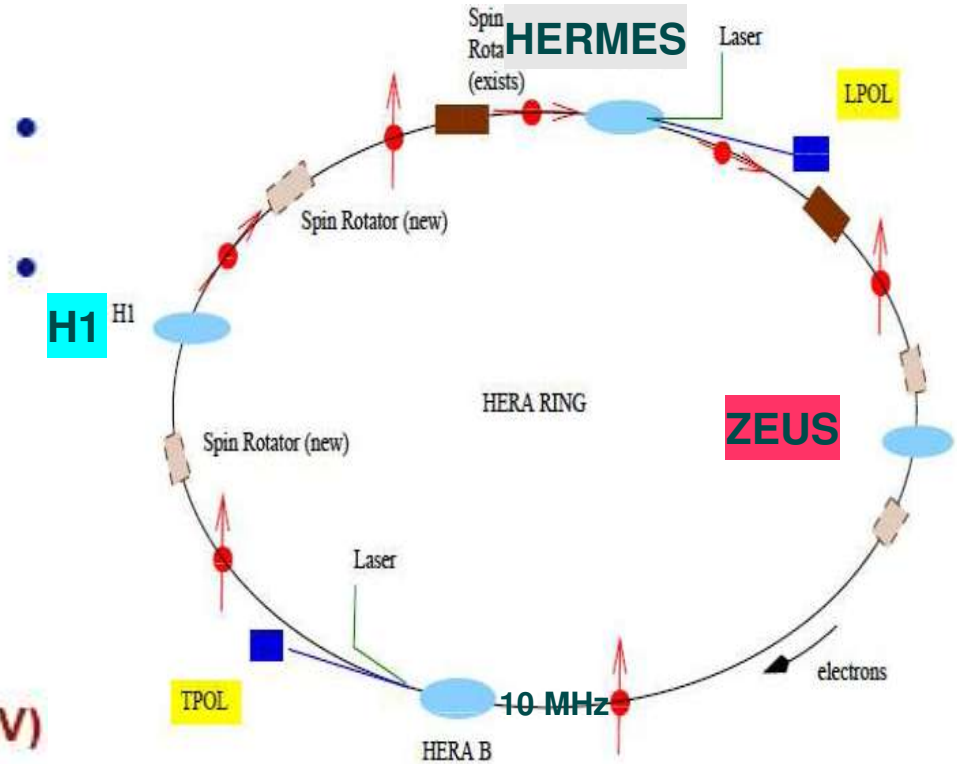
Recent Results from HERA

Cristinel DIACONU

CPP Marseille & DESY

HERA

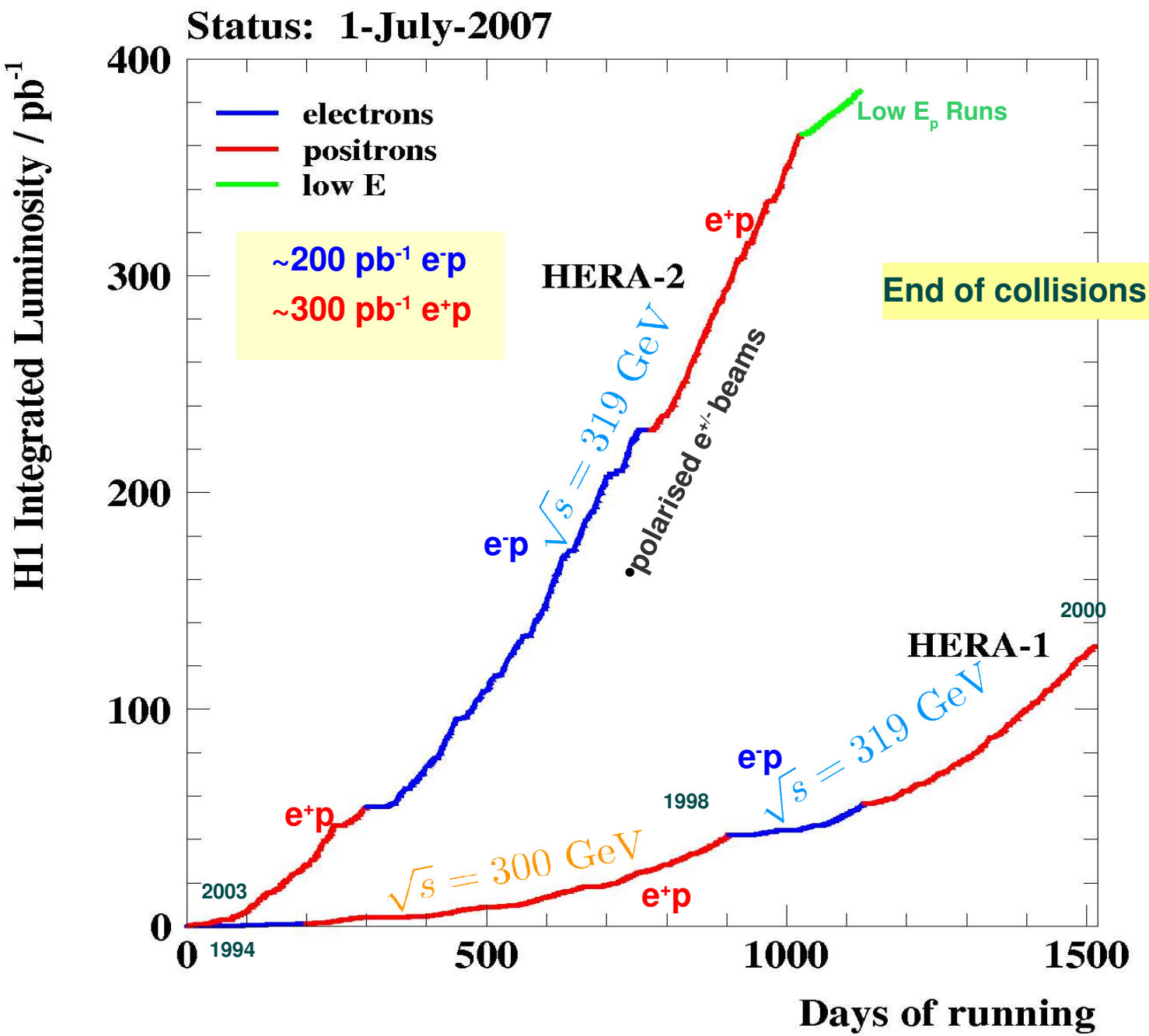




$\sqrt{(s)} = \mathbf{320}$ GeV
180 bunches
crossing 96 ns **(υ~LHC/4)**

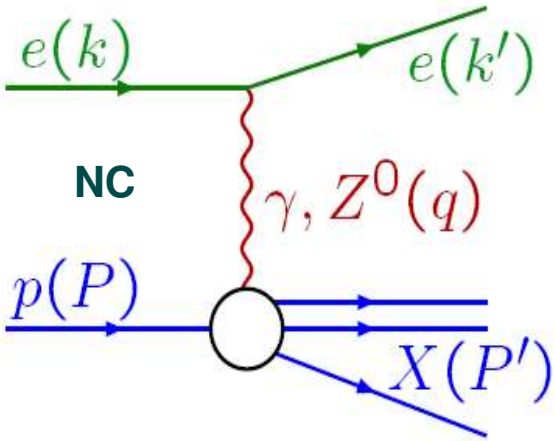
- **HERA 1: 1992-2000 ~120 pb^{-1}/expt**
- **HERA 2: 2003-2007**
  - **Luminosity upgrade (x3)**
  - **Polarised electrons/positrons**

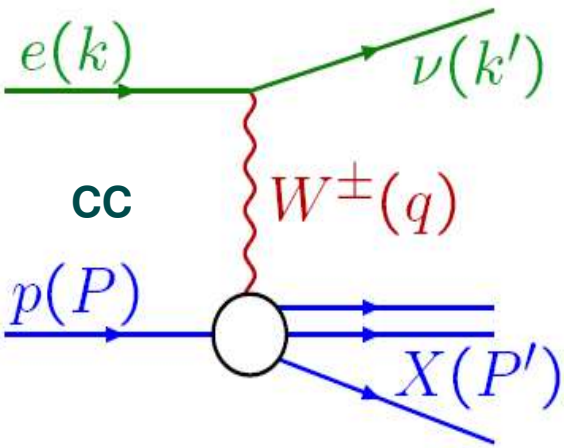
The harvest H1+ZEUS 2*0.5 fb^{-1}



End of collisions: June 30, 2007

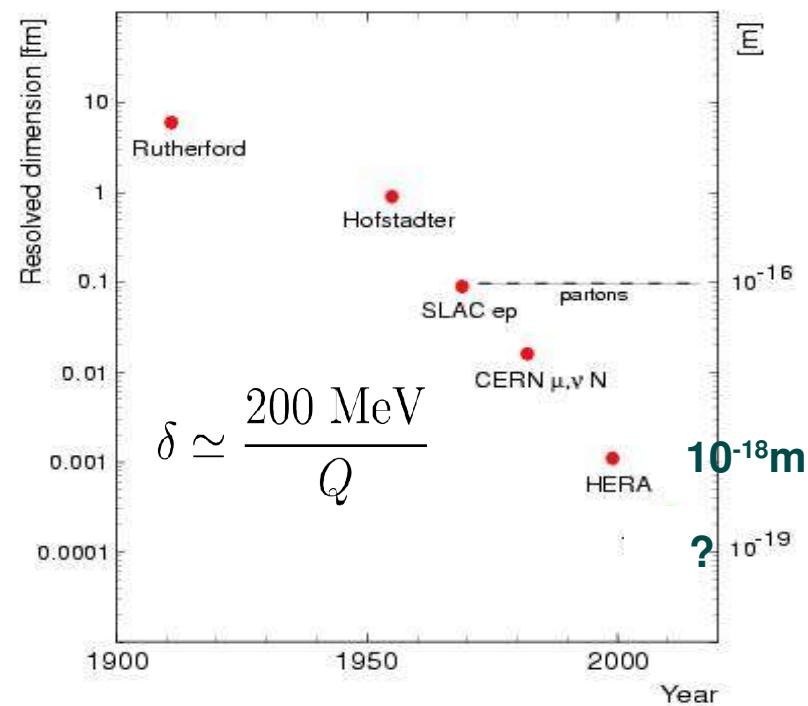
Deep-Inelastic Scattering





- $Q^2 = -q^2 = -(k-k')^2$ virtuality/resolving power
- $x = \frac{Q^2}{2P\cdot q}$ Bjorken scaling variable, momentum fraction of the scattered parton
- $y = \frac{q\cdot P}{k\cdot P}$ inelasticity

Related by $Q^2 = xys$



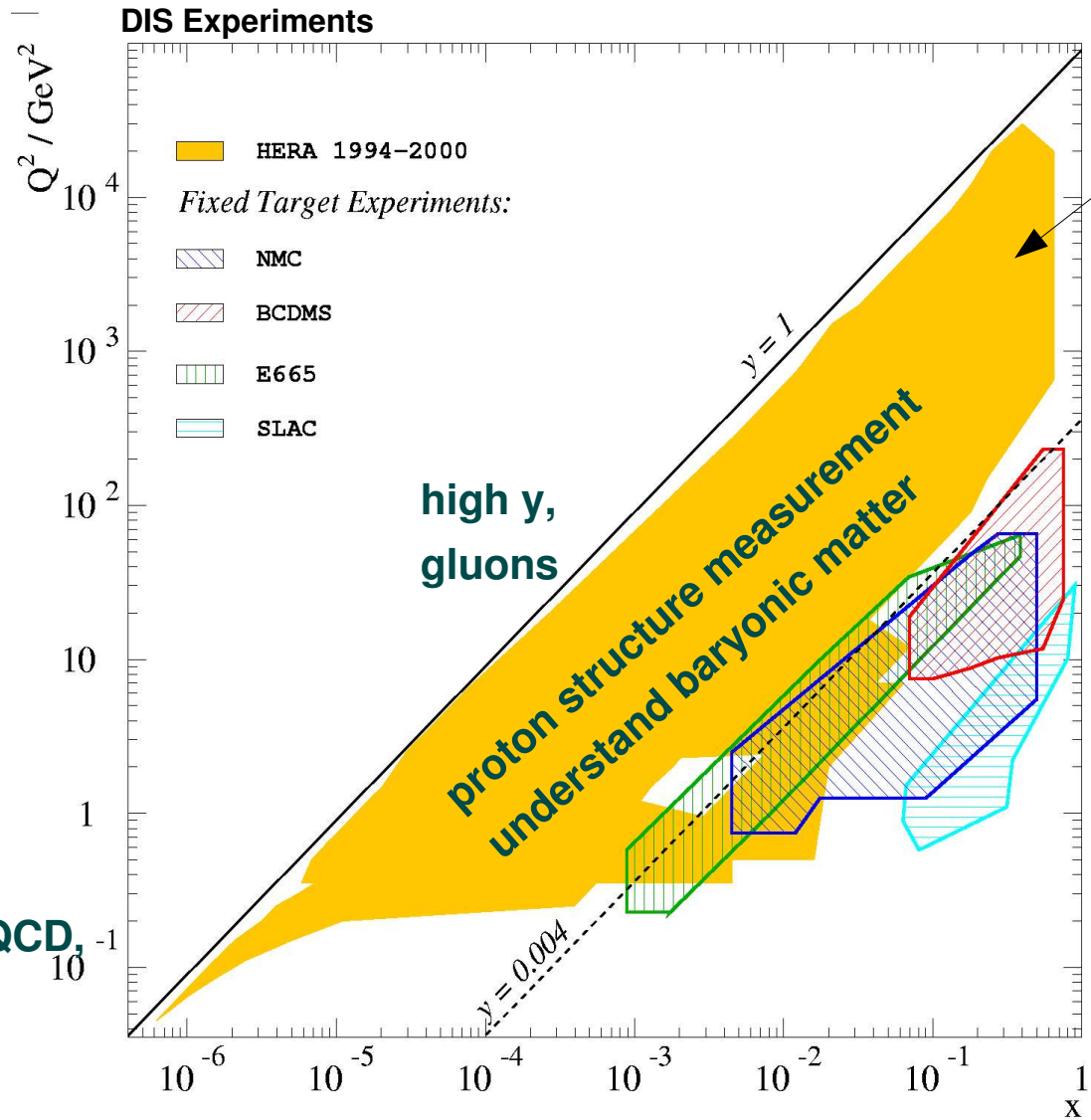
10^{-18}m

?

Kinematics reconstructed using measurements (E;θ)

lepton(NC)+hadrons(NC/CC)

The proton map in the kinematic plane



high y,
gluons

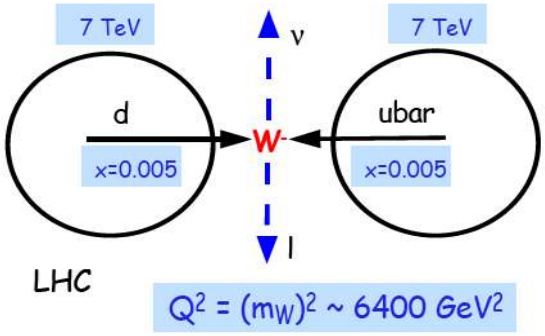
proton structure measurement
understand baryonic matter

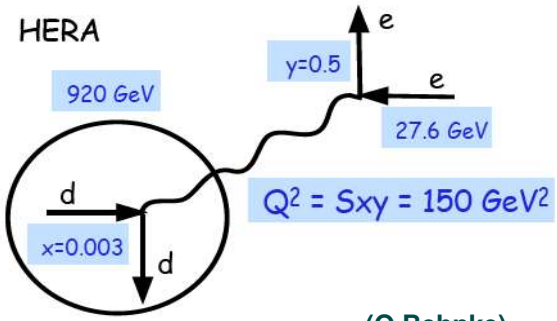
Highest
collision energy
EW+searches

Non-perturbative QCD,
transition

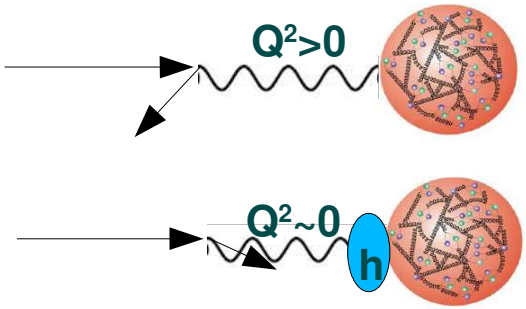
Use the final state processes (exclusive)
for more on QCD, for finer phase space

HERA4LHC

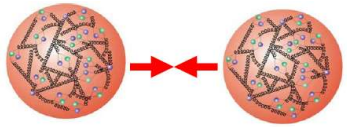


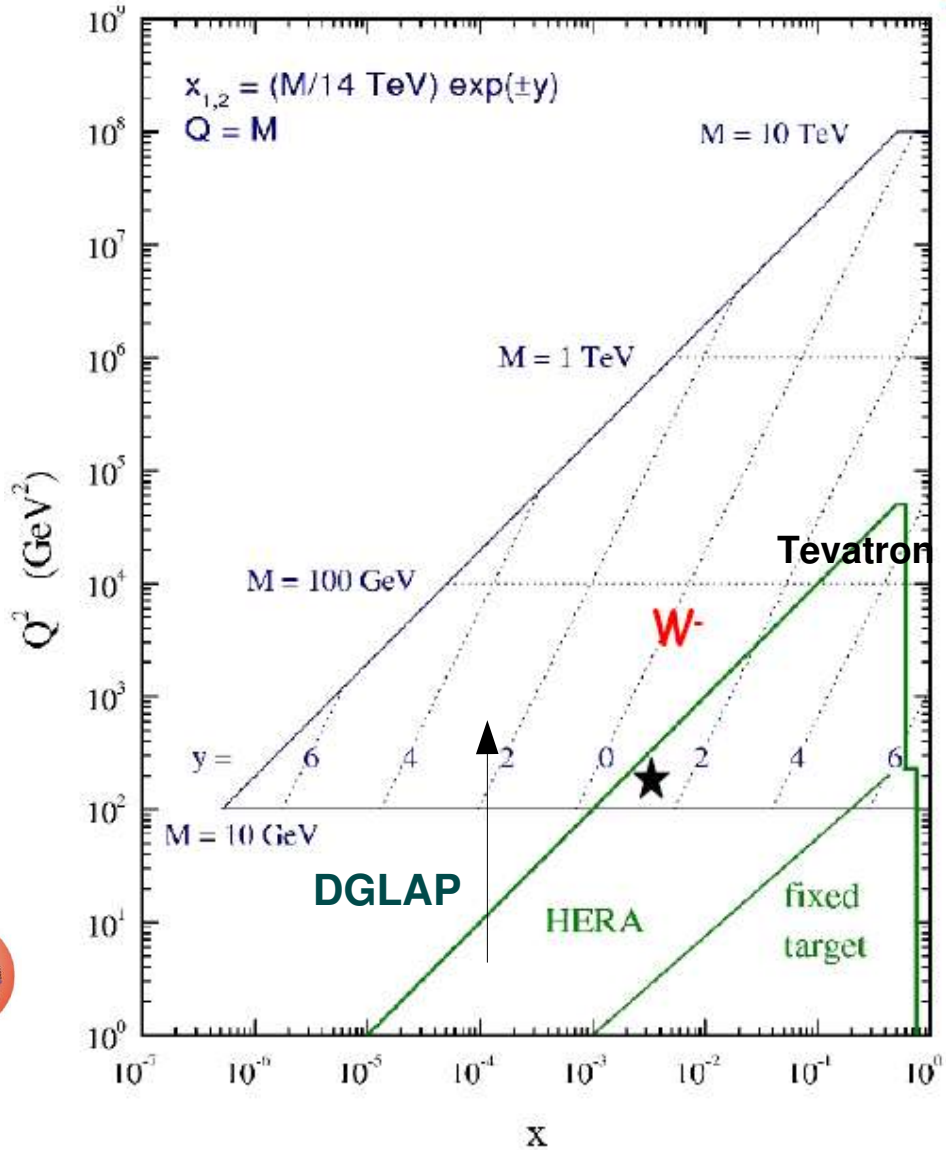


(O.Behnke)



photoproduction





QCD evolution, but also beyond

HERA is a clean QCD laboratory:heavy flavours, low x, diffraction etc.

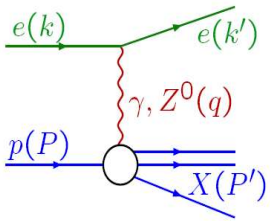
The menu

Structured around the three main directions of the HERA program:

- Proton Structure
  - Structure Functions and PDF's
  - Heavy flavours
- QCD studies
  - jets and α_s
  - inclusive diffraction
- High Energy Frontier
  - signatures and searches

Many other exciting subjects not covered:

exclusive processes, particles production, low x etc.



Cross sections, structure functions, partons

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

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**

gluons from scaling violations

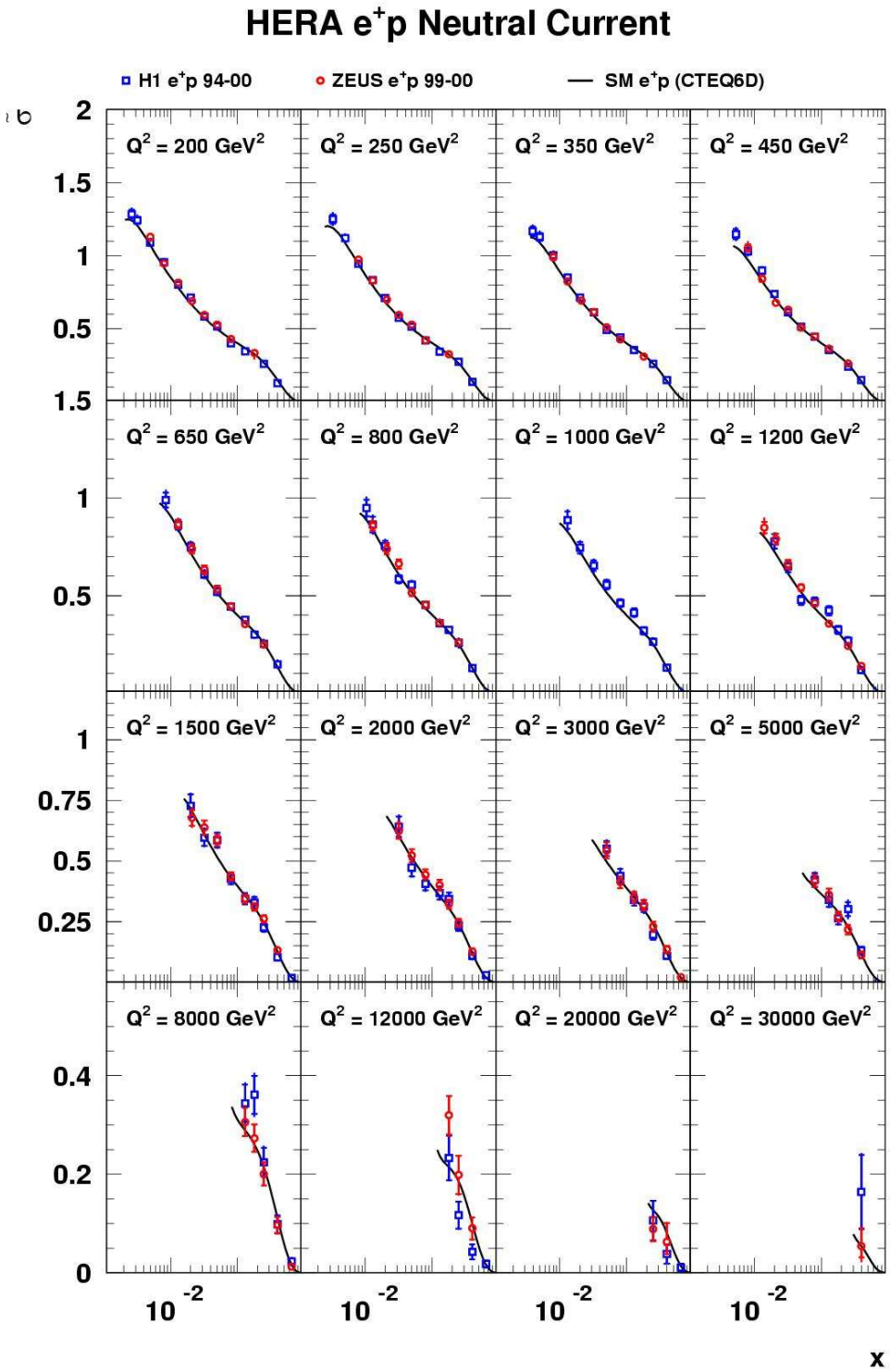
F_3 $$\left[xF_3^{\gamma Z}, xF_3^Z\right] = 2x\sum_q \left[e_q a_q, v_q a_q\right](q-\bar{q})$$ **(valence) quarks**

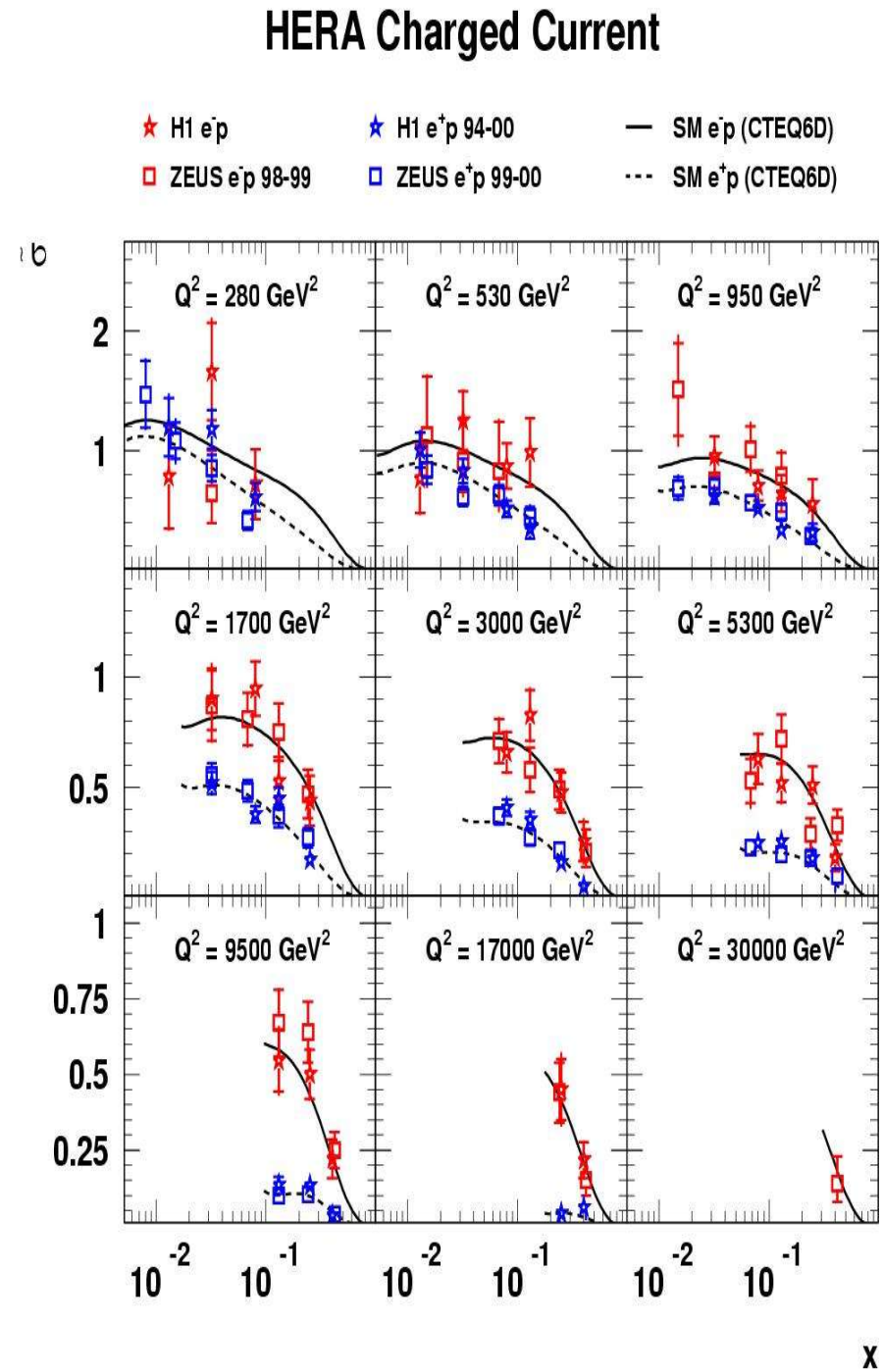
F_L $$F_L \sim x\alpha_s g$$ **gluons**

CC: similar decomposition, but different quarks combinatons accessed

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

CC+NC Double Differential cross sections: inputs for PDF's fits



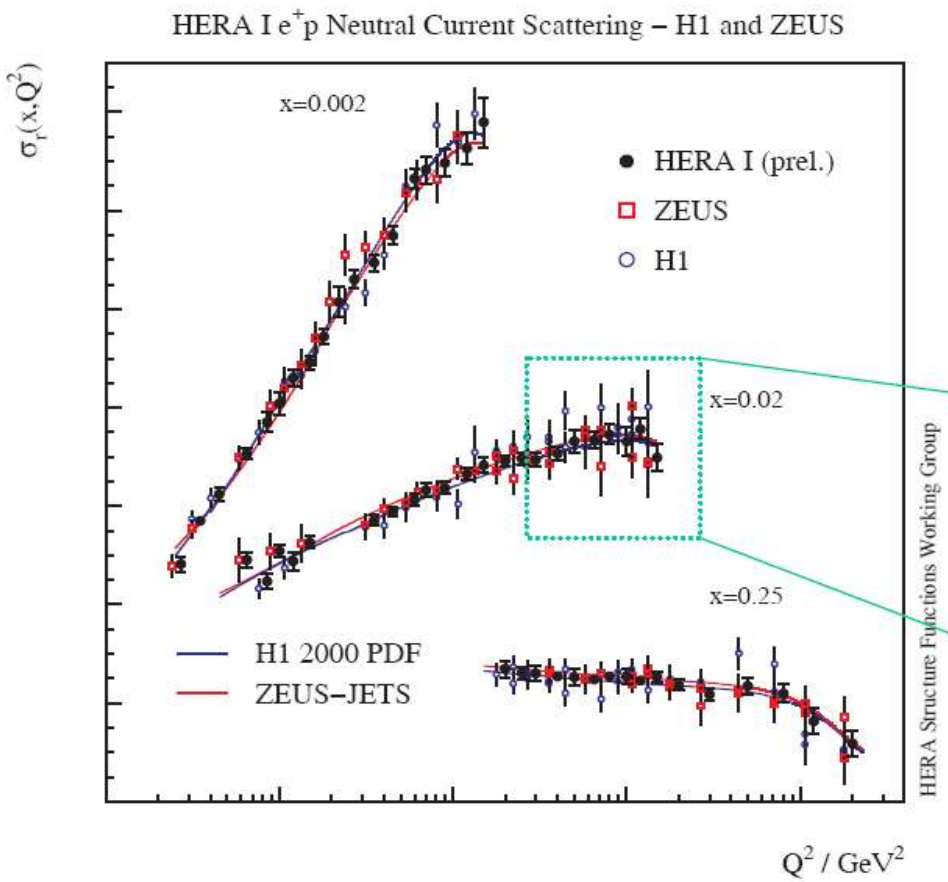


Used in pdf fits separately

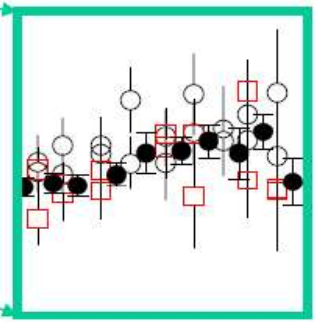
Cross section combination

Coherent treatment of experimental effects in the average procedure

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

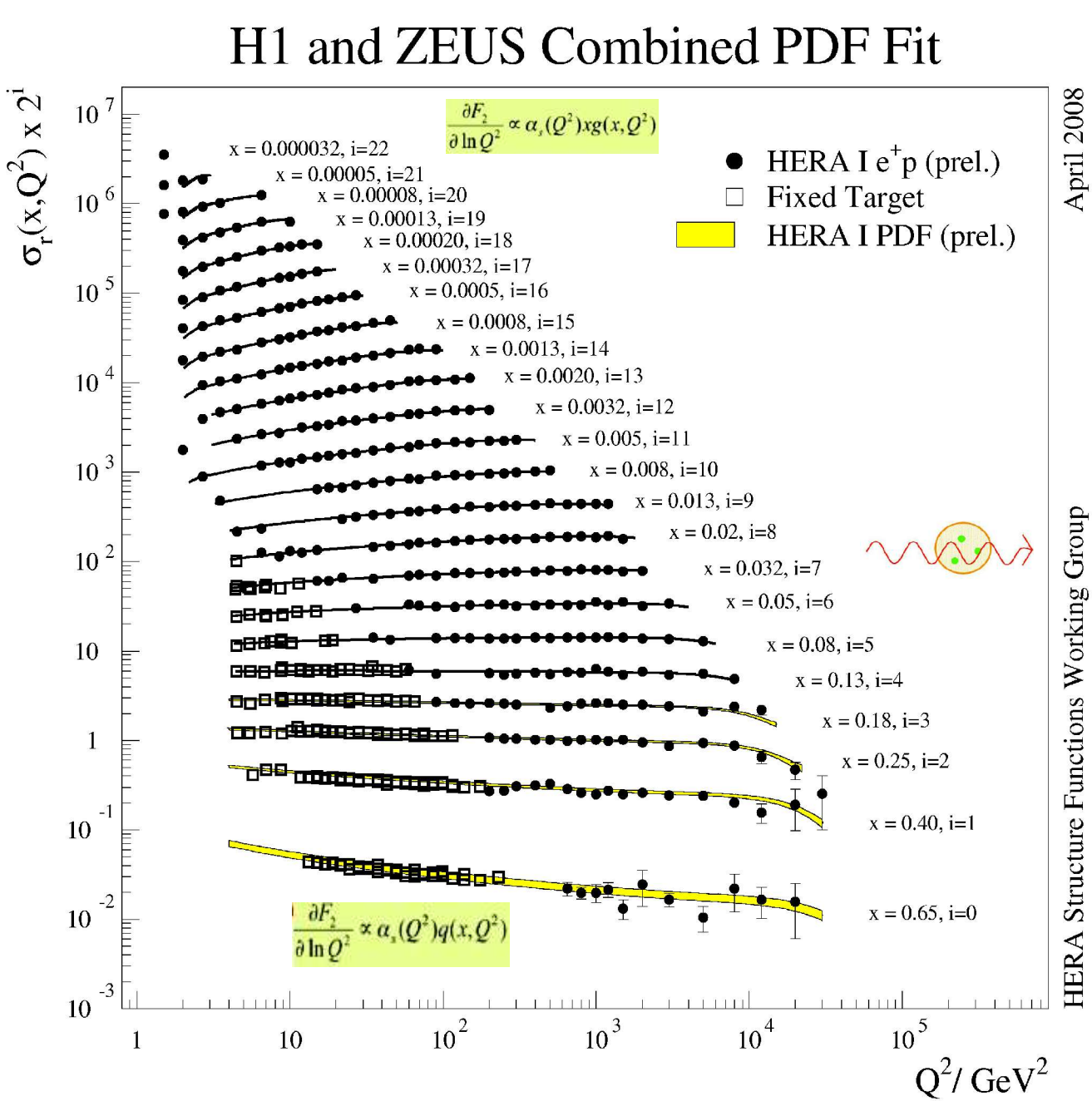


- 1153 individual NC and CC measurements are "averaged" to 554 unique points
  -- χ^2/dof = 510 / 599



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

The reduced cross section with novel precision



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

Coherent data sets combined:

vast coverage of the proton "map"

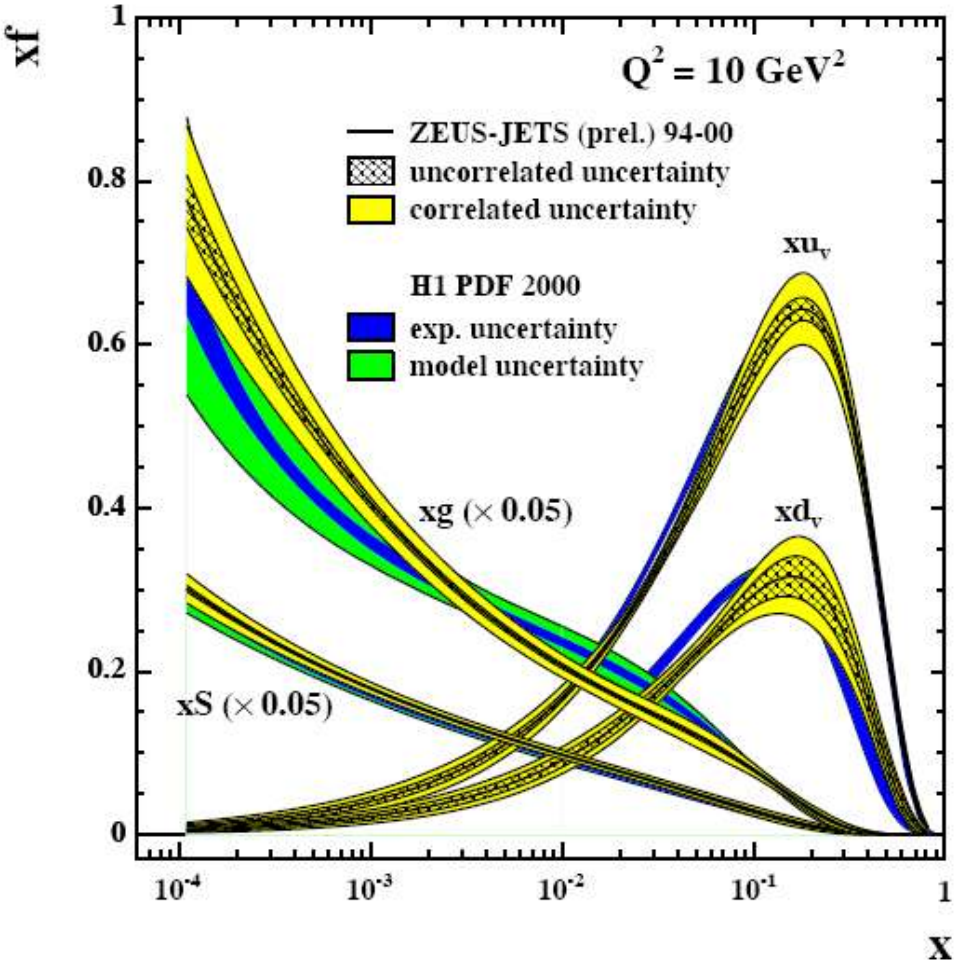
dramatic increase in precision

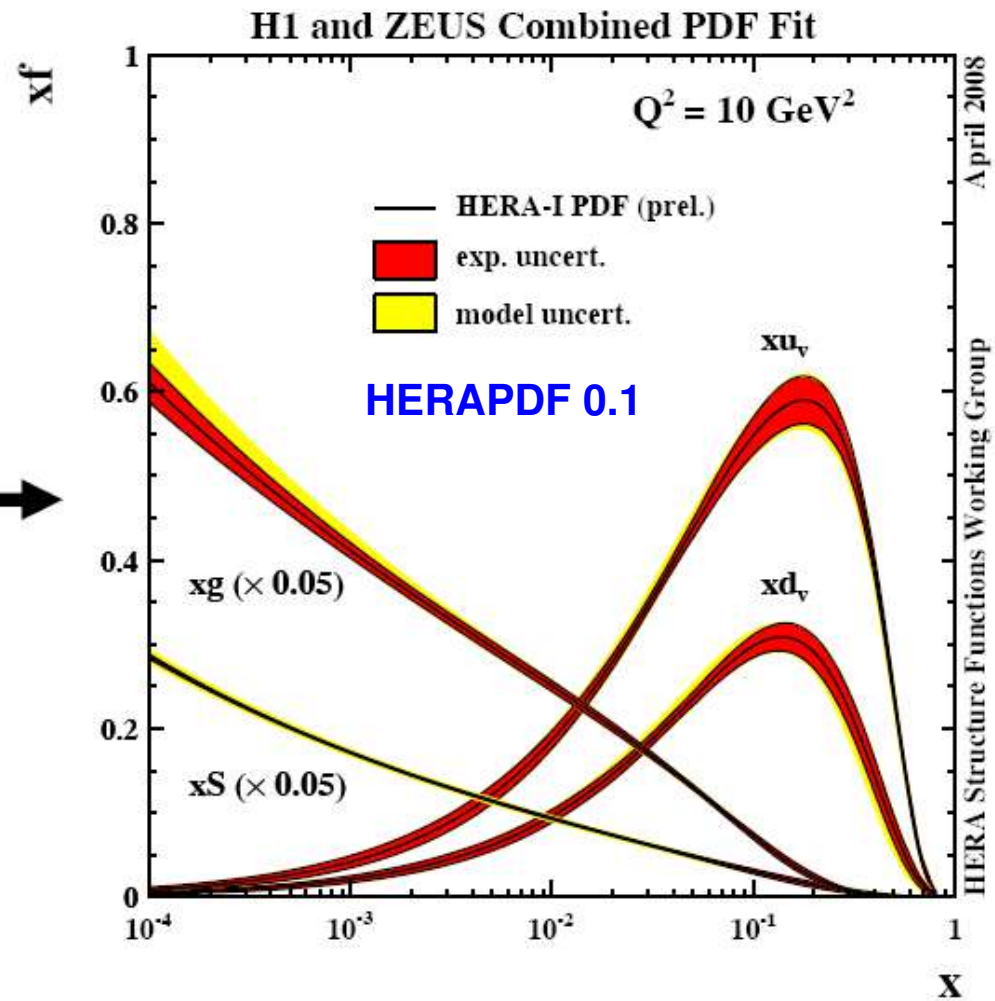
The common fit of the combined data

Partons parametrized at Q_0^2 = 4 GeV² (Data Q^2>3.5 GeV²)

Experimental+Model uncertainties taken into account

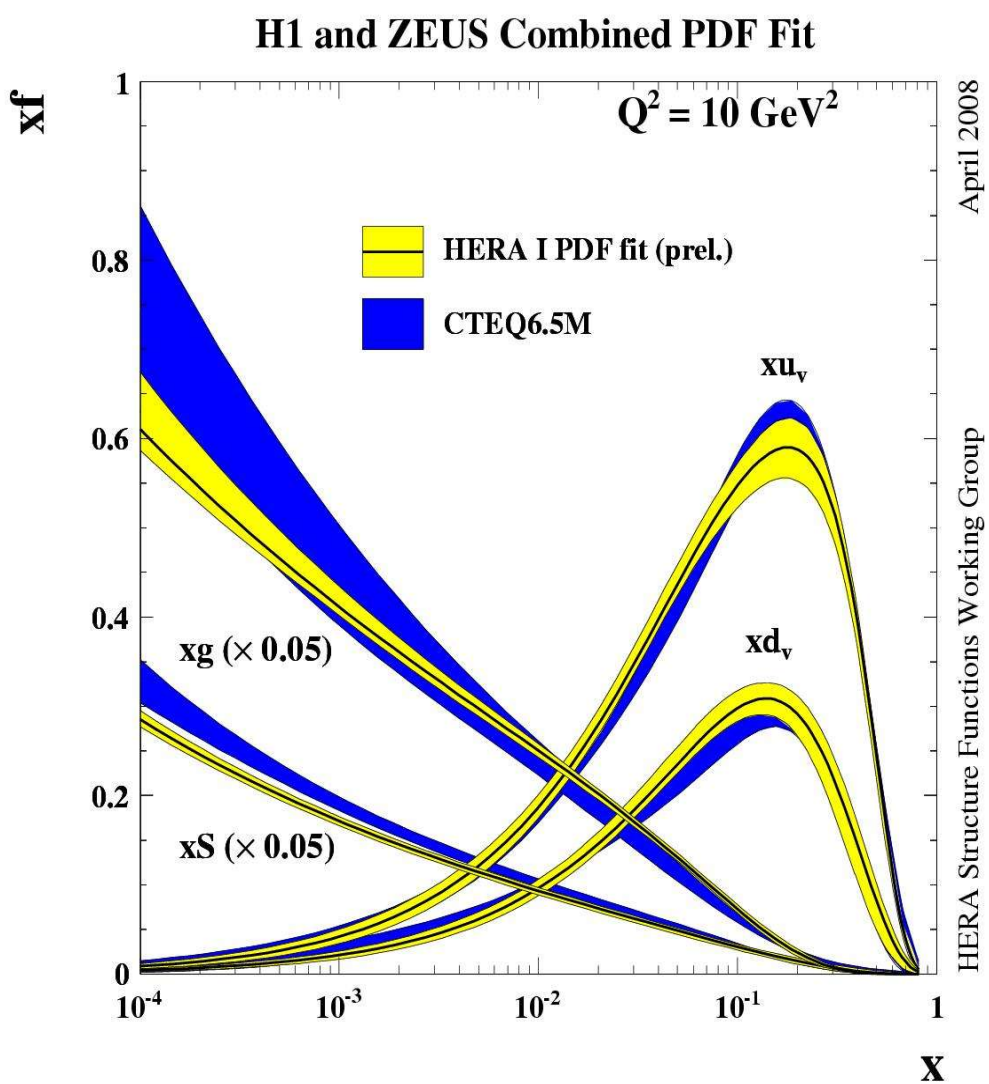
Errors of the fit estimated using $\Delta\chi^2=1$

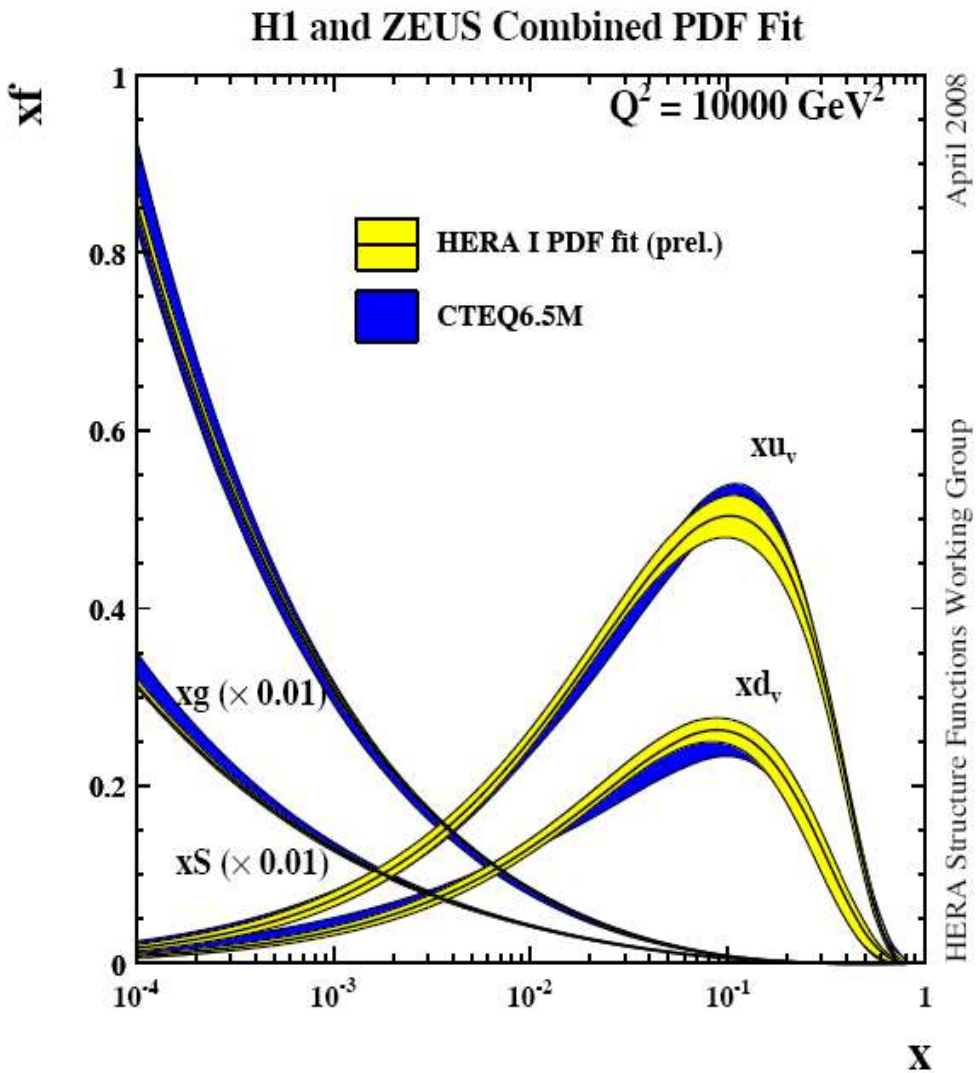




Improvement in precision is visible

The common fit of the combined data

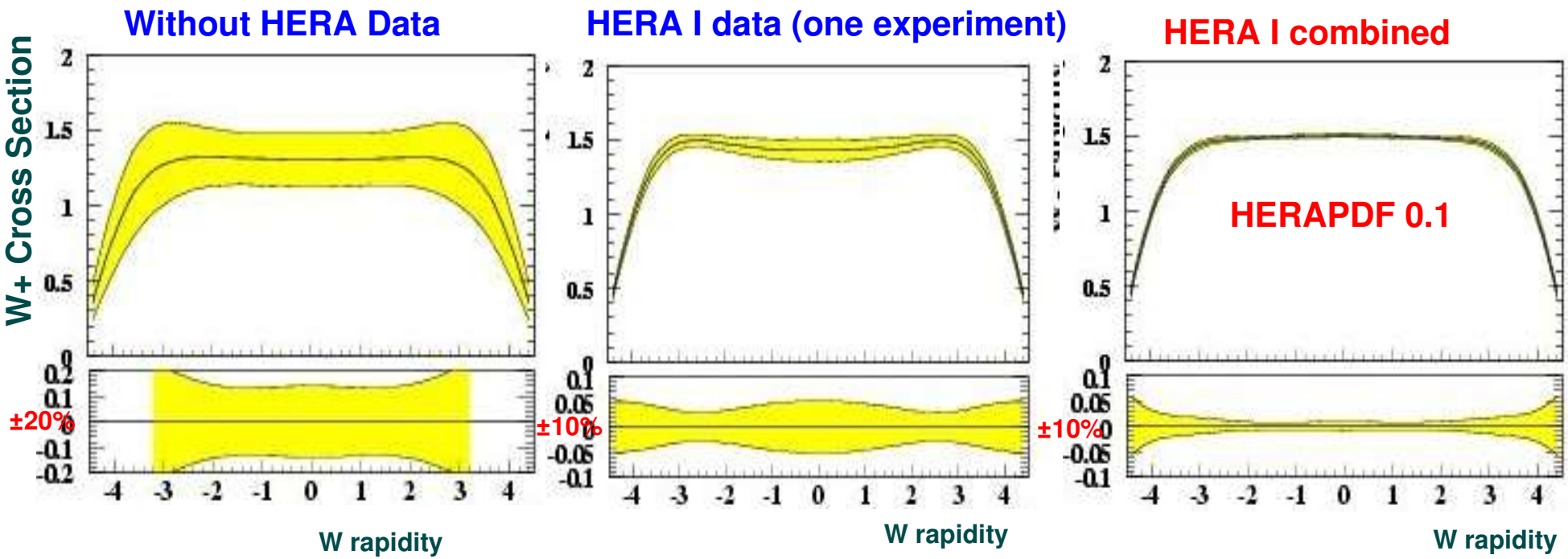




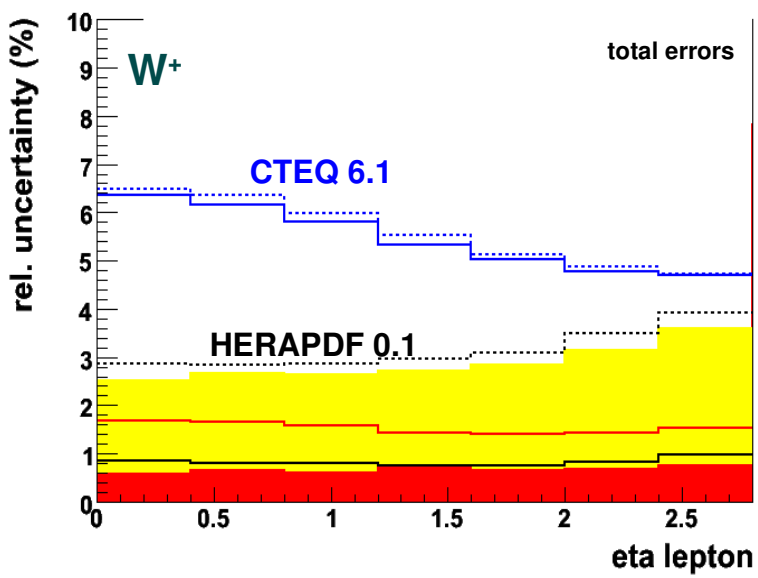
Improvement in precision most notably at low x remain also at high Q^2 (LHC domain)

HERAPDF 0.1: pdf's predictions using a coherent and precise data set=> LHC predictions

Predictions for W/Z boson production at LHC



only the fit uncertainty shown here,
no model variations



Impressive progress: from 5-6% to ~3%

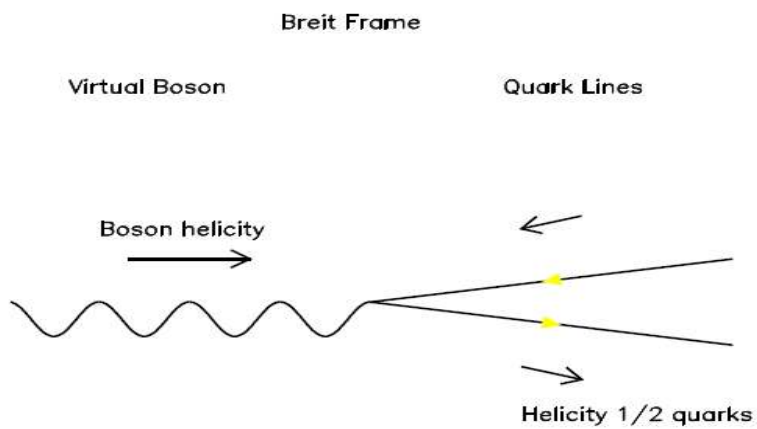
Much more data to be included
(low Q2, bulk, HERA II data high x/Q²)

A.Cooper-Sarkar and E.Perez in parallel session

Longitudinal structure function F_L

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

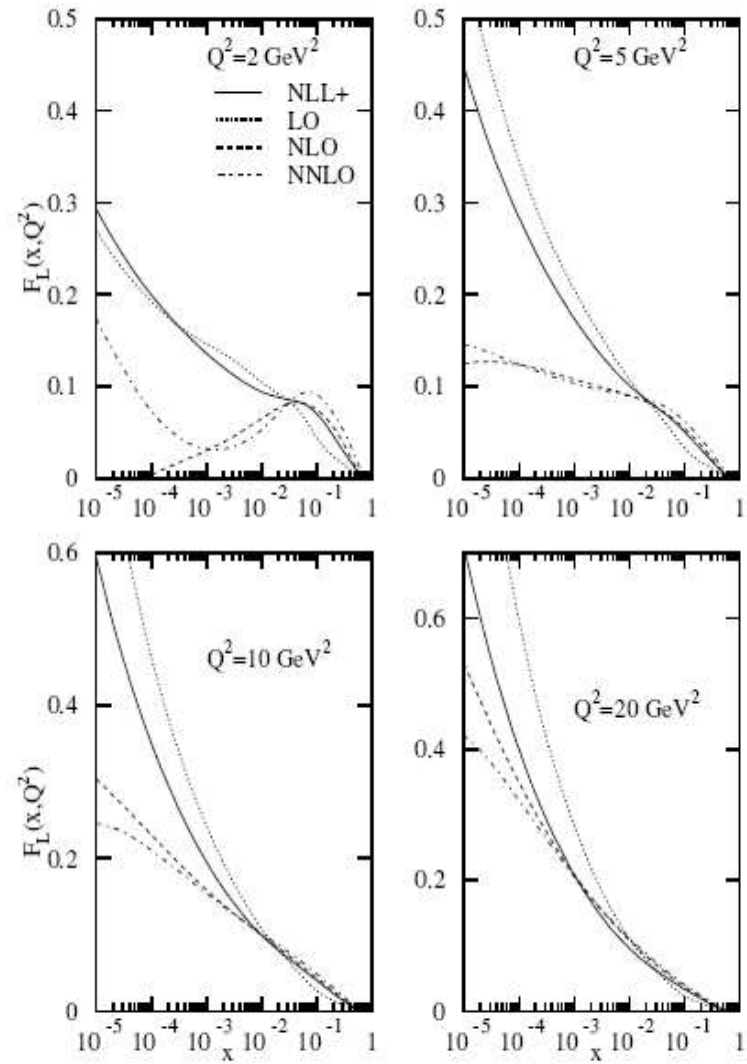
=0 for spin ½ partons
(Callan-Gross)



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

[low x effect]

Fundamental form factor of the proton
Test QCD
Proportional to the gluon, important for PDF's
Discriminate between theoretical approaches



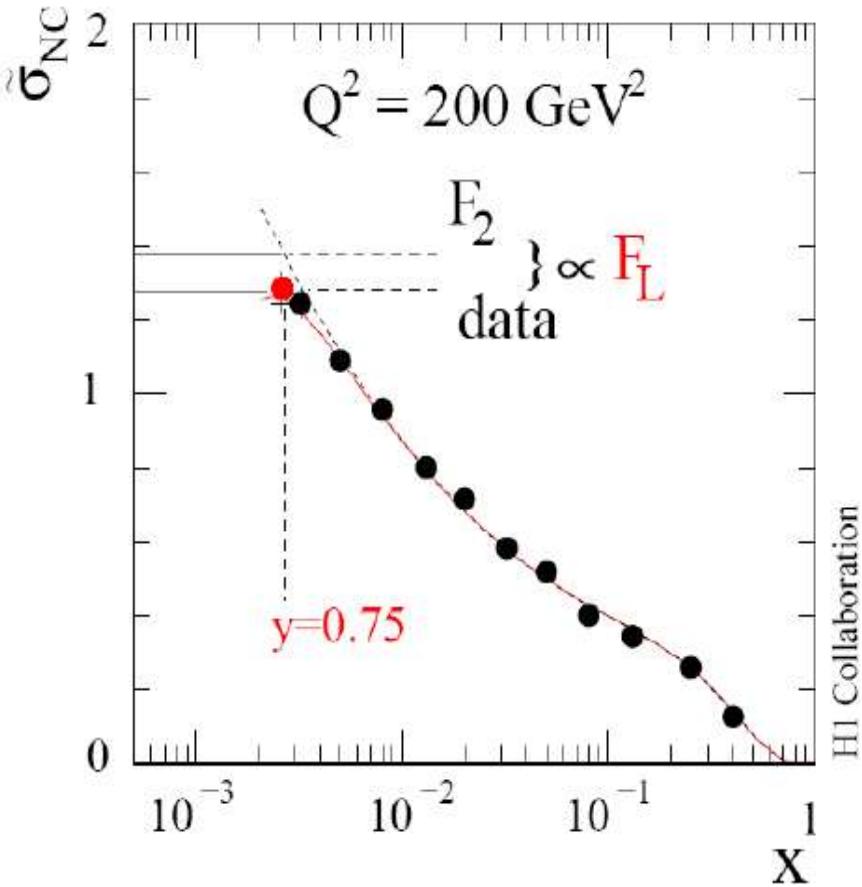
C. White, R. Thorne, 0706.2609 [hep-ph]

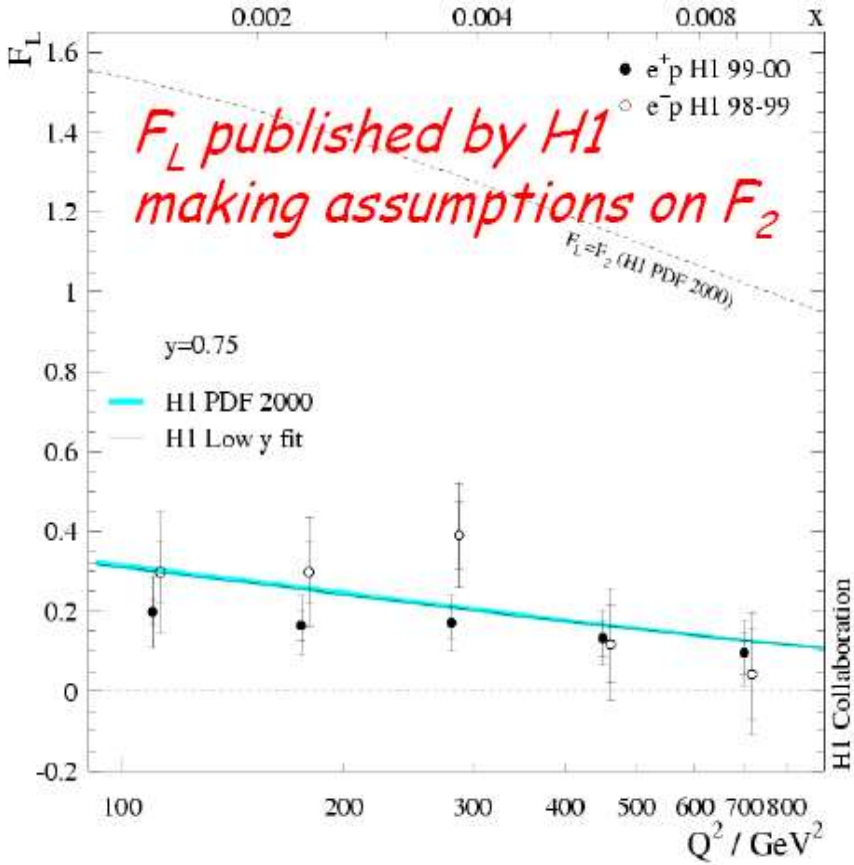
Indirect Determination

see bending at high y

assume F2 -> extract FL

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





Direct F_L measurement

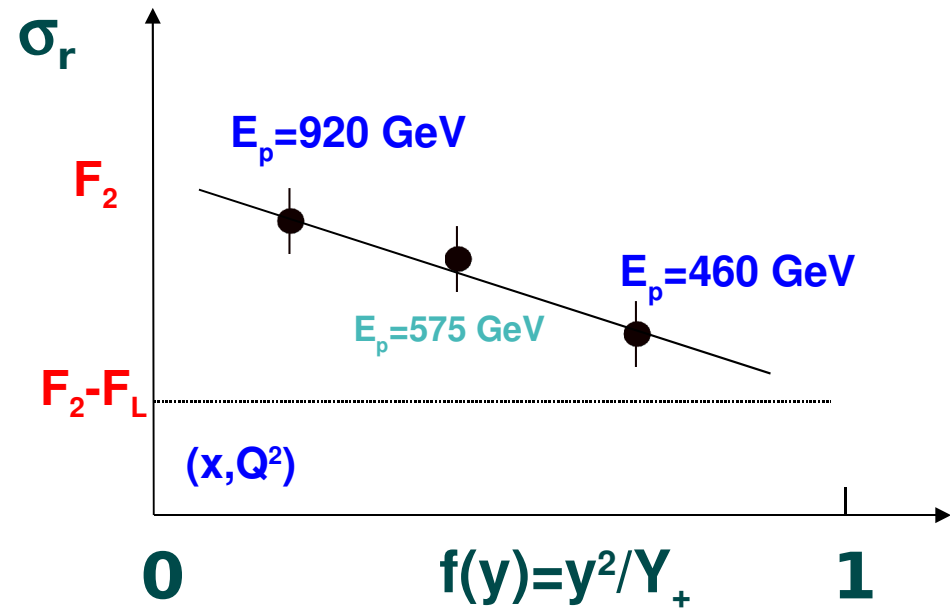
Method:

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

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

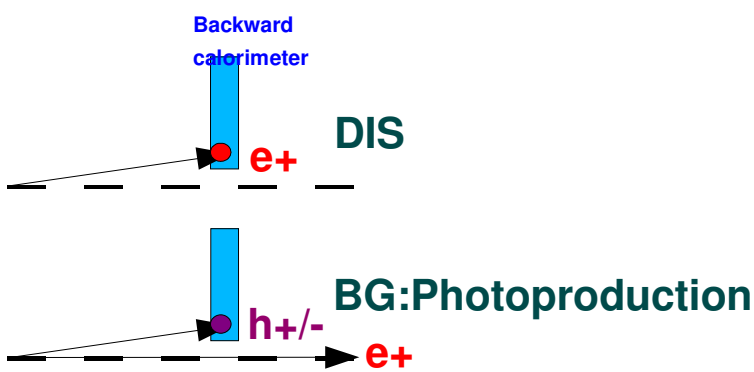
Vary s : Special Runs E_p=460,575 GeV

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



NB: At low E_p , same (x,Q2) and high y means lower energy of the detected electron

Have to fight the background from the hadronic final state (mostly from the photoproduction)



$$y \simeq \frac{E_e - E_e^0}{E_e}$$

high y = low E_e

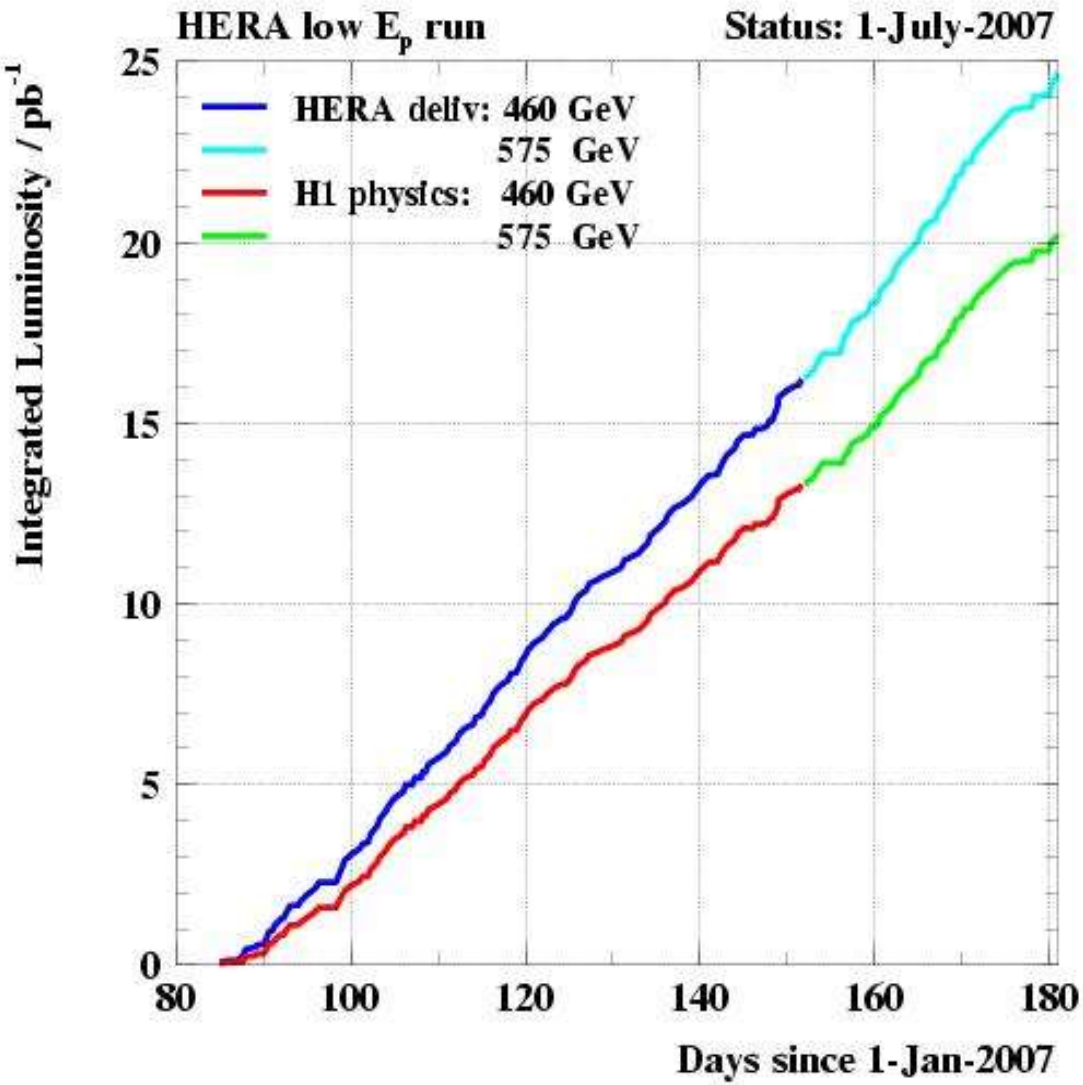
The low energy runs

$$\mathcal{L}_s(E) \sim \gamma(E)^2$$

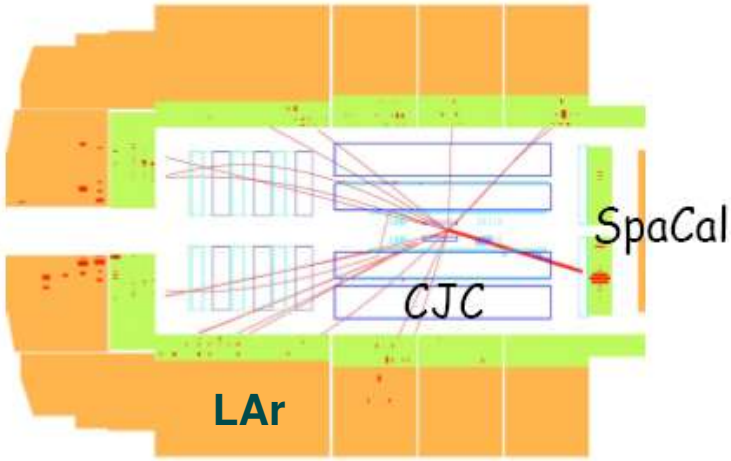
New optics, few days switching time:

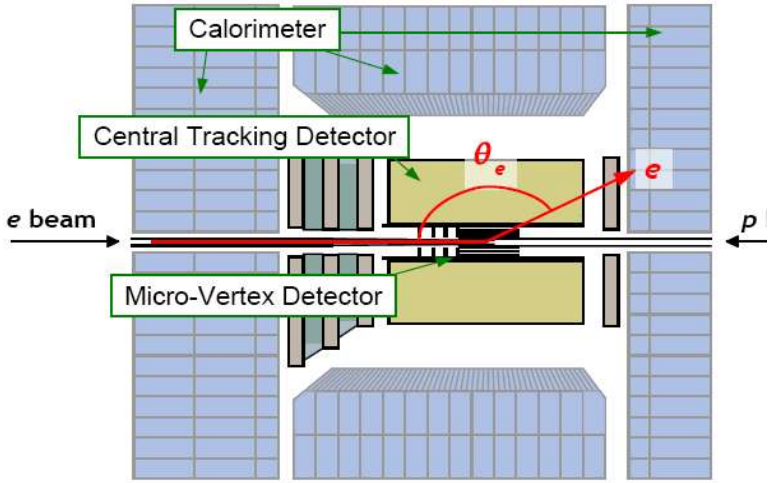
Impressive achievement of HERA crew!

$$\mathcal{L}_s(460) = \frac{1}{4}\,\mathcal{L}_s(920)\,!$$



The present measurements





H1:

E_p=920,575,460 GeV

Ee>3.4 GeV

y<0.9

ZEUS:

E_p=920,460 GeV

Ee>6 GeV

y<0.8

-Medium Q^2: 12 – 90 GeV^2 submitted to PLB

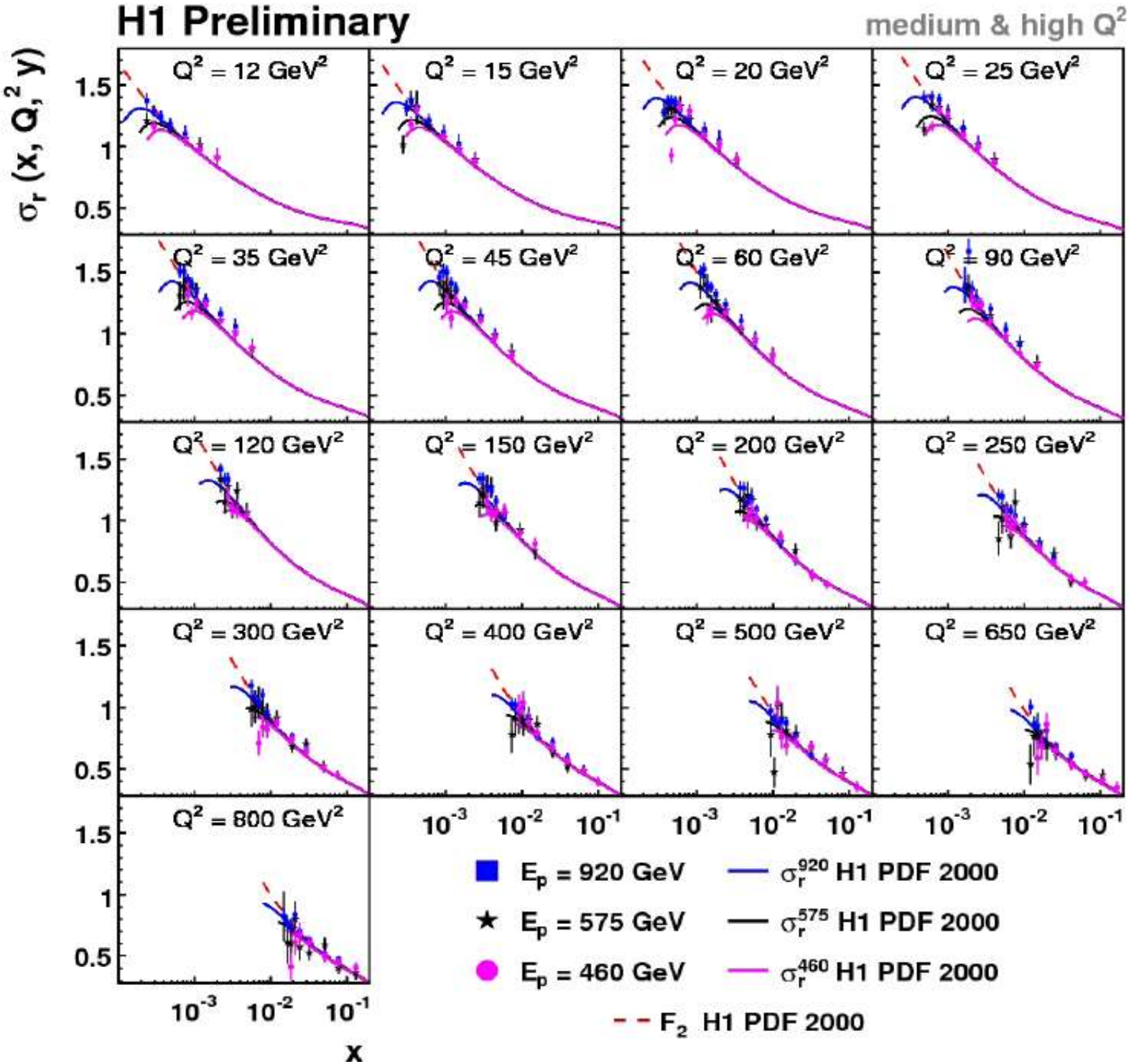
-High Q^2 : 90-800 GeV^2 preliminary measurements combined

-Low Q^2 : 5-12 GeV^2 (analysis in progress)

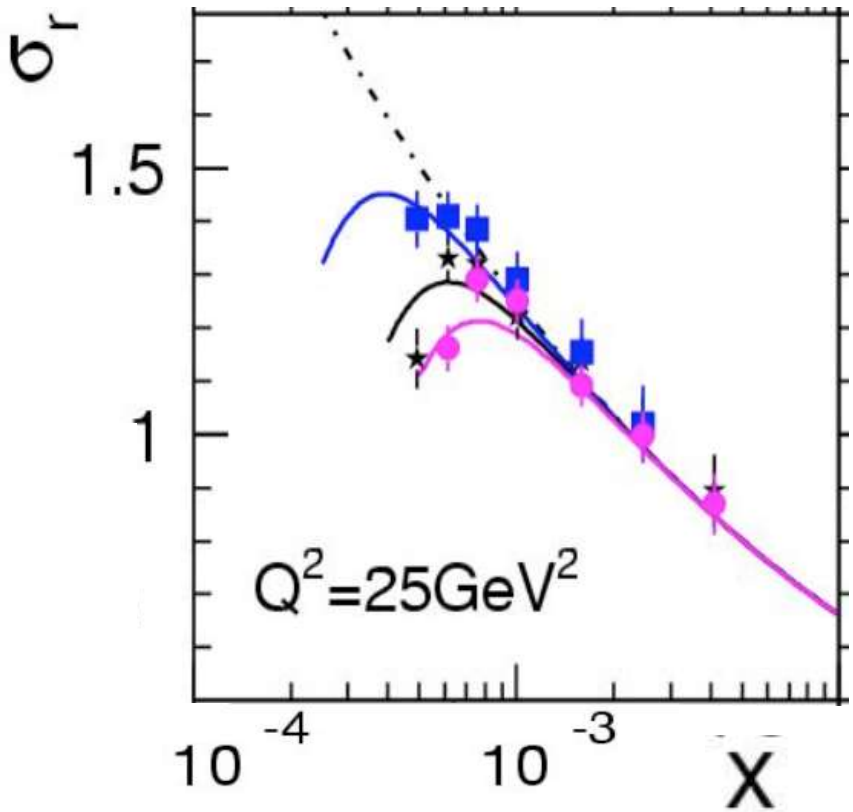
Q^2 : 24 – 110 GeV^2

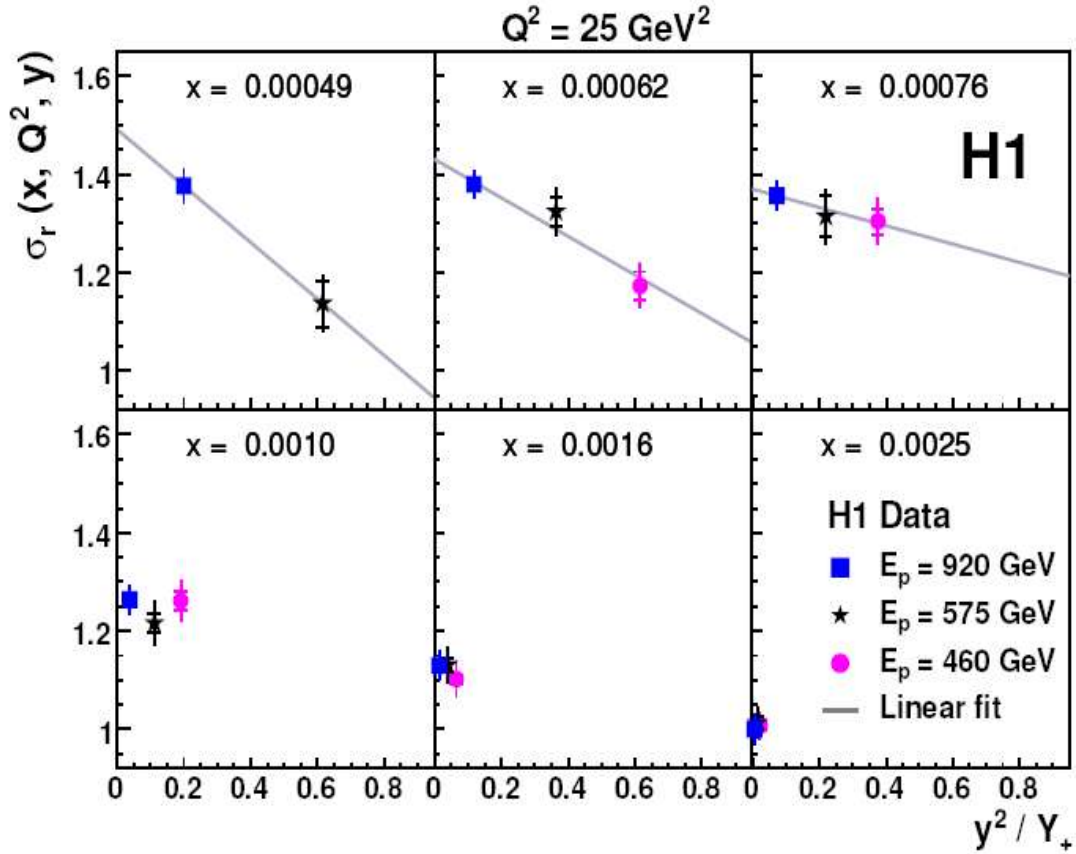
More details in the parallel session

Here only F_L results


H1 Preliminary
medium & high Q²
σr (x, Q², y)
Q² = 12 GeV²
Q² = 15 GeV²
Q² = 20 GeV²
Q² = 25 GeV²
Q² = 35 GeV²
Q² = 45 GeV²
Q² = 60 GeV²
Q² = 90 GeV²
Q² = 120 GeV²
Q² = 150 GeV²
Q² = 200 GeV²
Q² = 250 GeV²
Q² = 300 GeV²
Q² = 400 GeV²
Q² = 500 GeV²
Q² = 650 GeV²
Q² = 800 GeV²
1.5
1
0.5
10⁻³
10⁻²
10⁻¹
x
Ep = 920 GeV
Ep = 575 GeV
Ep = 460 GeV
σr920 H1 PDF 2000
σr575 H1 PDF 2000
σr460 H1 PDF 2000
F2 H1 PDF 2000

The F_L measurement



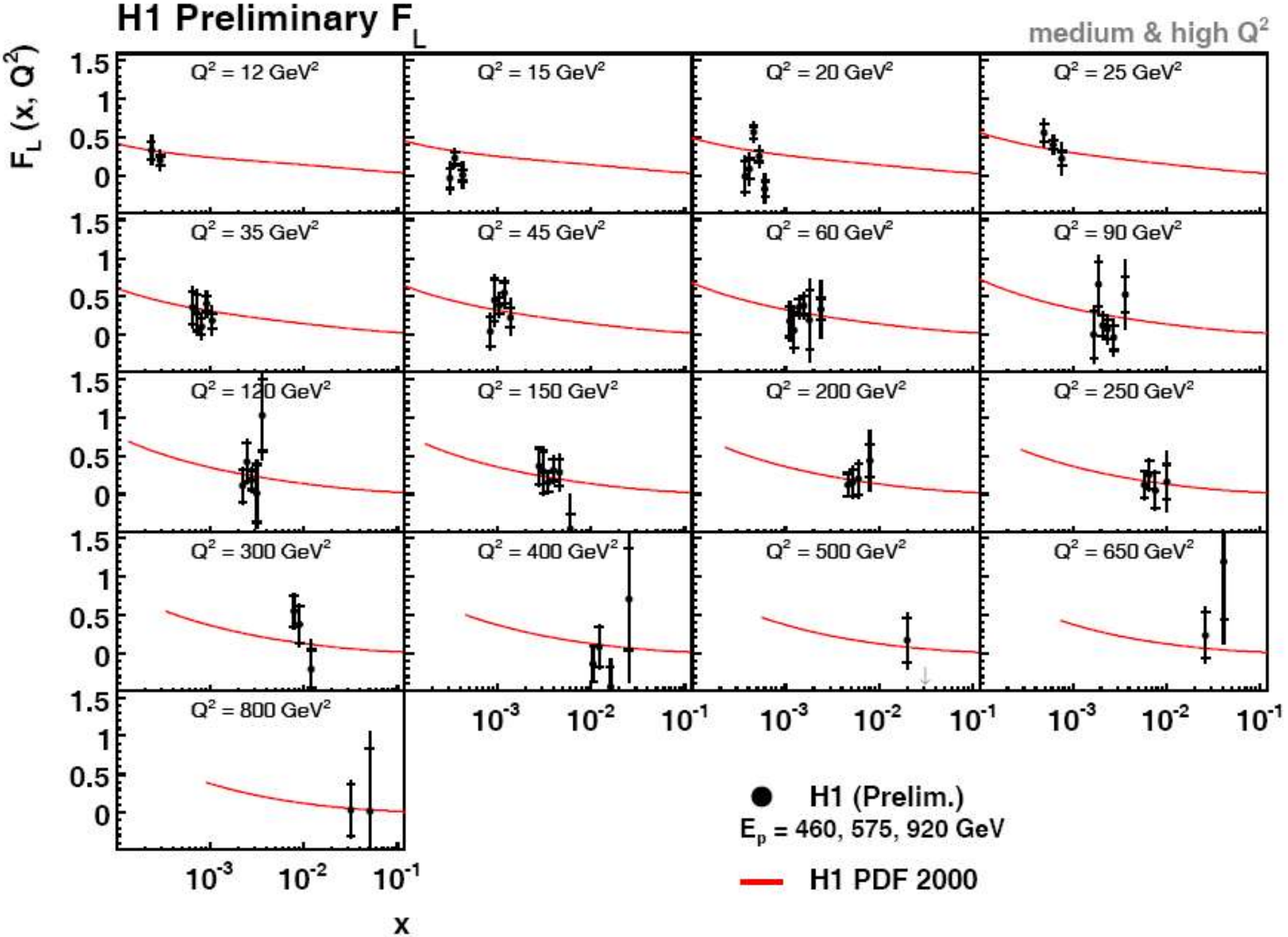


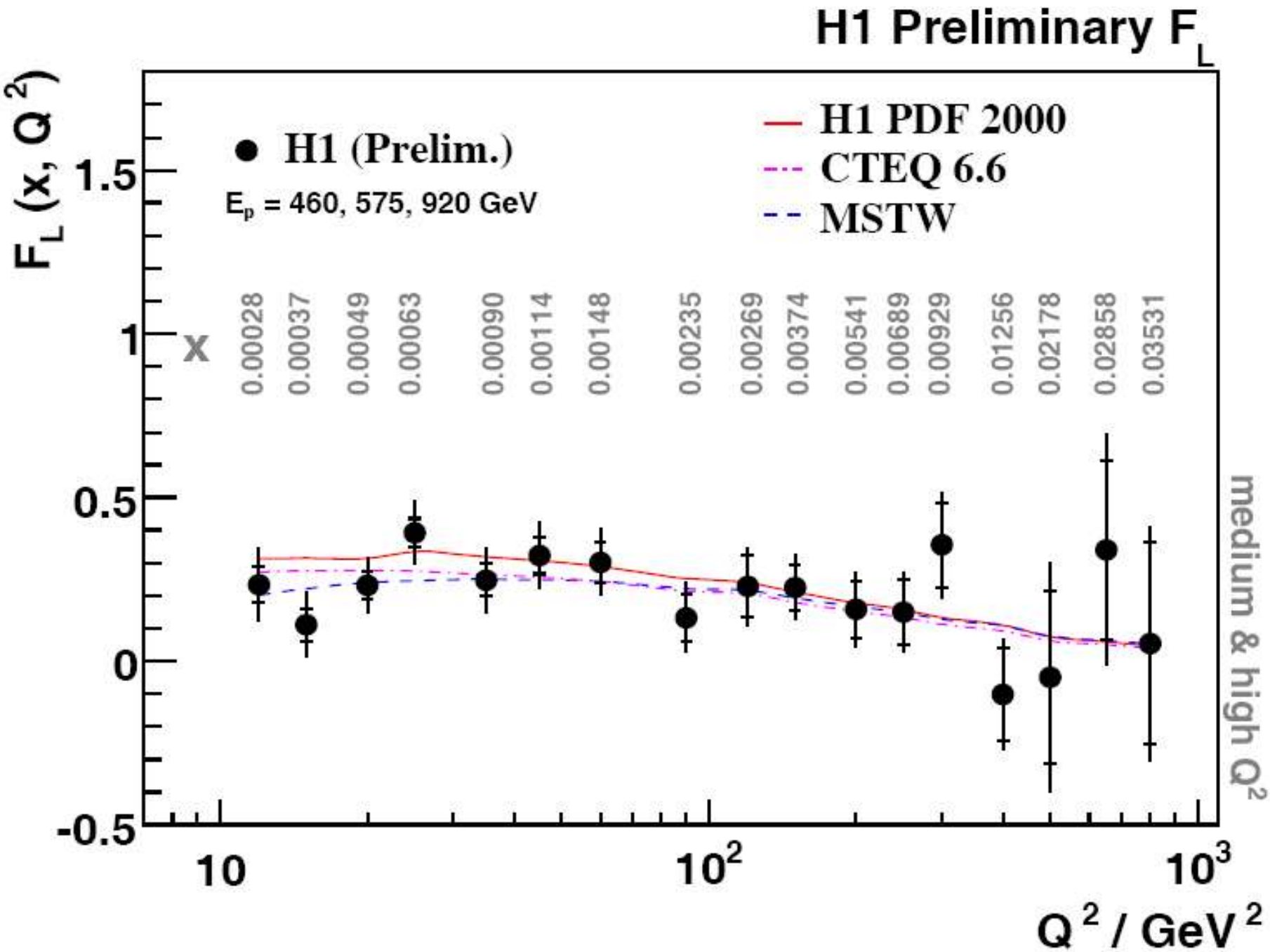
■ E_p = 920 GeV — σ_r^{920} H1 PDF 2000

★ E_p = 575 GeV — σ_r^{575} H1 PDF 2000

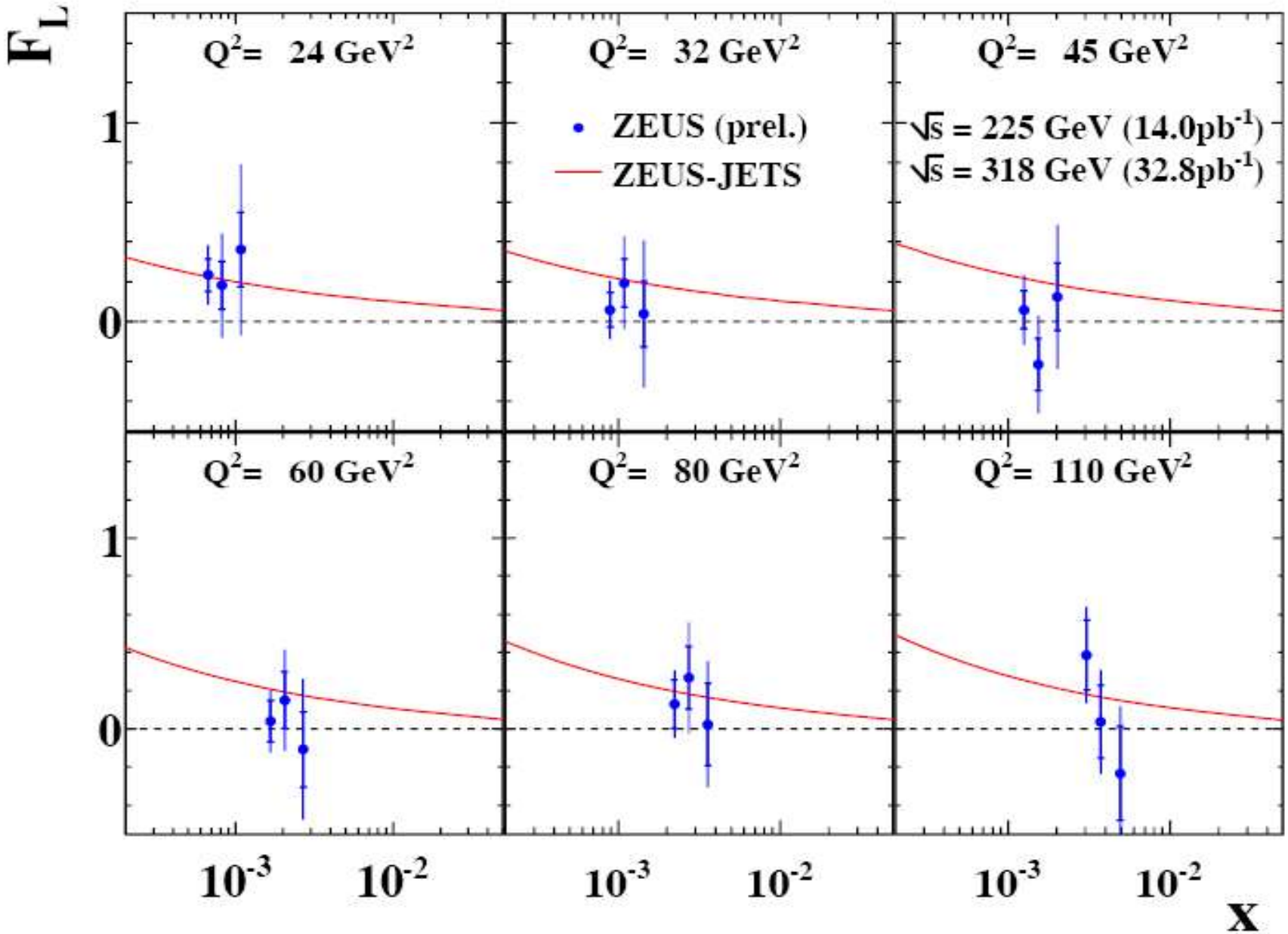
● E_p = 460 GeV — σ_r^{460} H1 PDF 2000

- - F_2 H1 PDF 2000

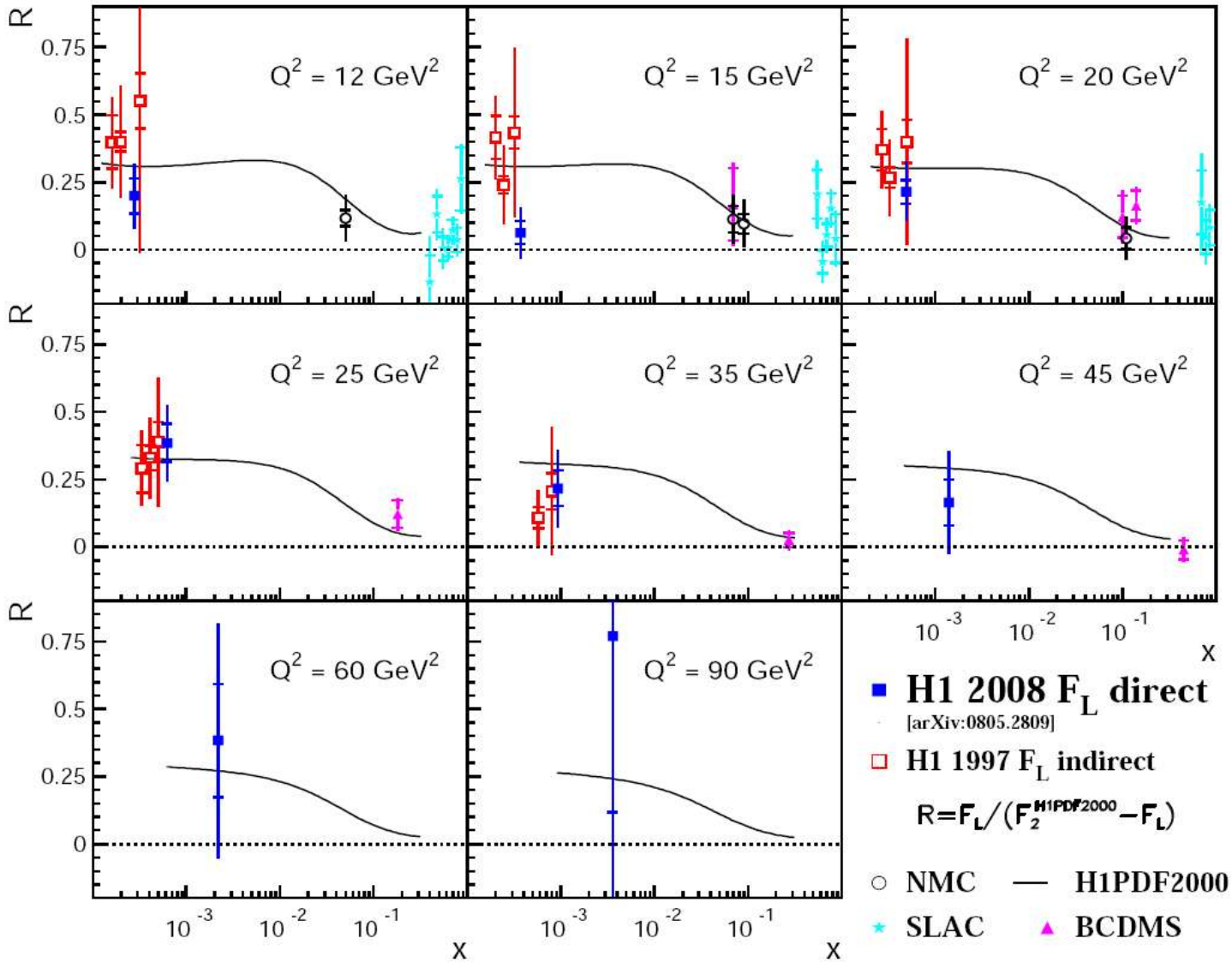

H1 Preliminary F_L
medium & high Q^2
$F_L(x, Q^2)$
Q^2 = 12 GeV^2
Q^2 = 15 GeV^2
Q^2 = 20 GeV^2
Q^2 = 25 GeV^2
Q^2 = 35 GeV^2
Q^2 = 45 GeV^2
Q^2 = 60 GeV^2
Q^2 = 90 GeV^2
Q^2 = 120 GeV^2
Q^2 = 150 GeV^2
Q^2 = 200 GeV^2
Q^2 = 250 GeV^2
Q^2 = 300 GeV^2
Q^2 = 400 GeV^2
Q^2 = 500 GeV^2
Q^2 = 650 GeV^2
Q^2 = 800 GeV^2
1.5
1
0.5
0
10^{-3}
10^{-2}
10^{-1}
x
H1 (Prelim.)
E_p = 460, 575, 920 GeV
H1 PDF 2000


H1 Preliminary F_L
$F_L(x, Q^2)$
H1 (Prelim.)
E_p = 460, 575, 920 GeV
H1 PDF 2000
CTEQ 6.6
MSTW
x
0.00028
0.00037
0.00049
0.00063
0.00090
0.00114
0.00148
0.00235
0.00269
0.00374
0.00541
0.00689
0.00929
0.01256
0.02178
0.02858
0.03531
1.5
1
0.5
0
-0.5
10
10^2
10^3
Q^2 / GeV ^{2}
medium & high Q^2

ZEUS

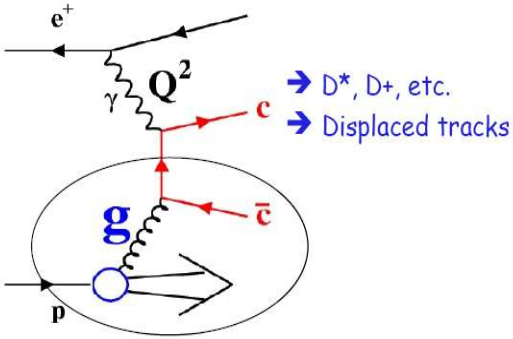

F_L
Q^2= 24 GeV^2
Q^2= 32 GeV^2
Q^2= 45 GeV^2
ZEUS (prel.)
ZEUS-JETS
$\sqrt{s}$ = 225 GeV (14.0pb^{-1})
$\sqrt{s}$ = 318 GeV (32.8pb^{-1})
Q^2= 60 GeV^2
Q^2= 80 GeV^2
Q^2= 110 GeV^2
1
0
1
0
10^{-3}
10^{-2}
x

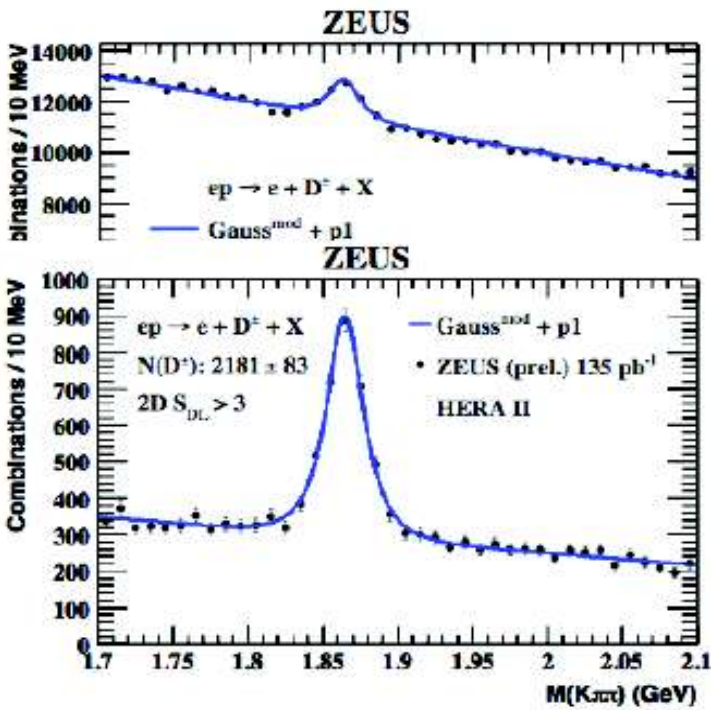
Comparison with target data and indirect determinations

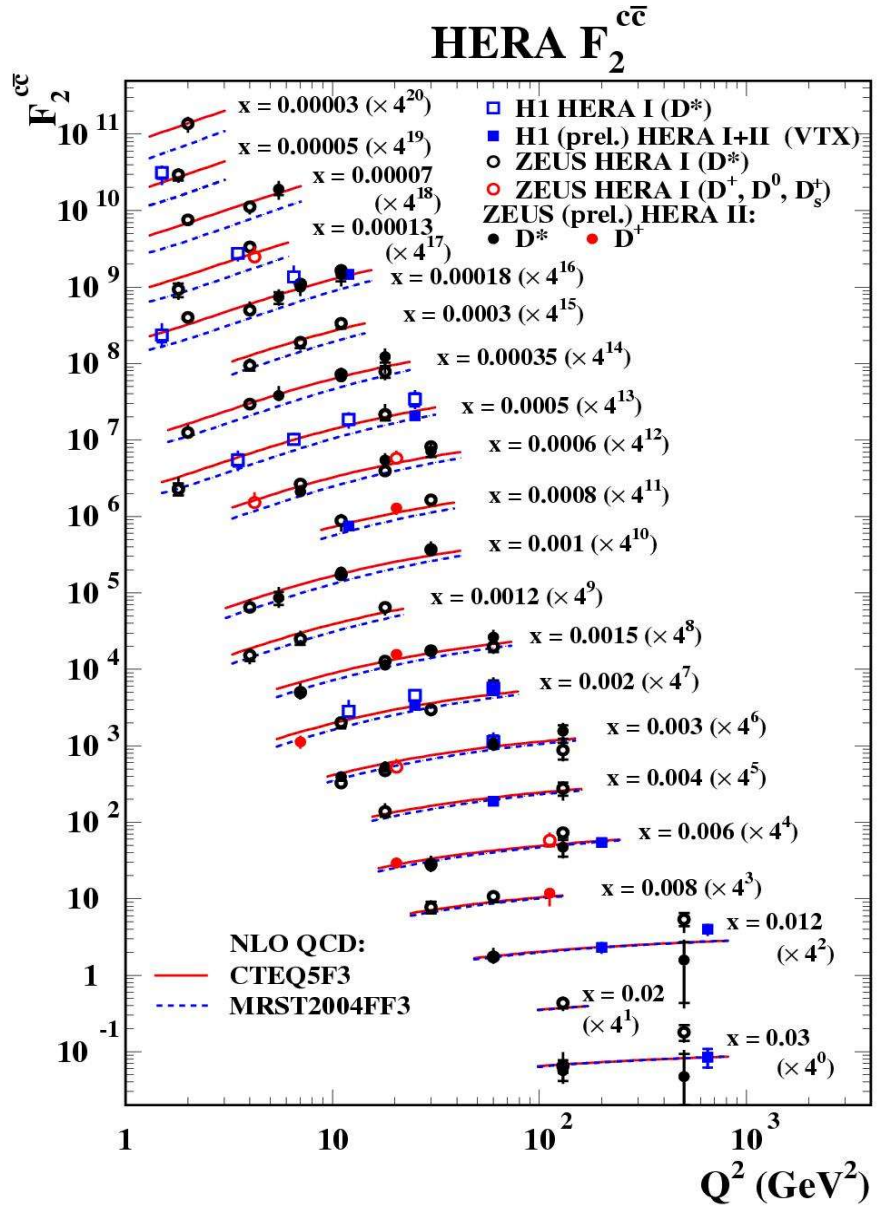


Q^2 range of the first publication "medium Q^2"

Proton's charm







A lot of analysis improvements still ahead

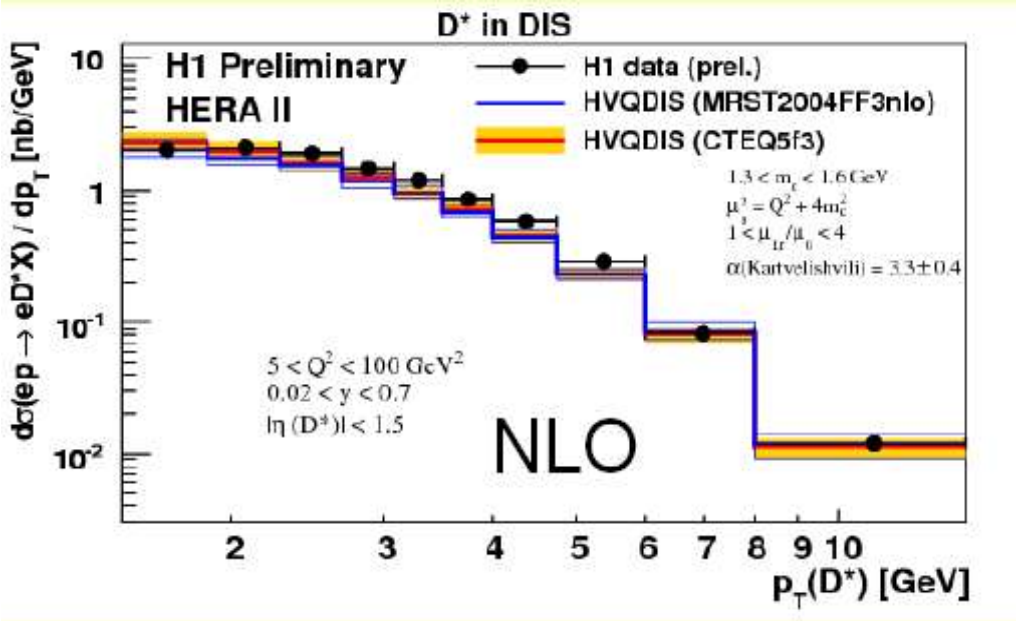
Experimental program in developement

Precision to 5% (or less) possible

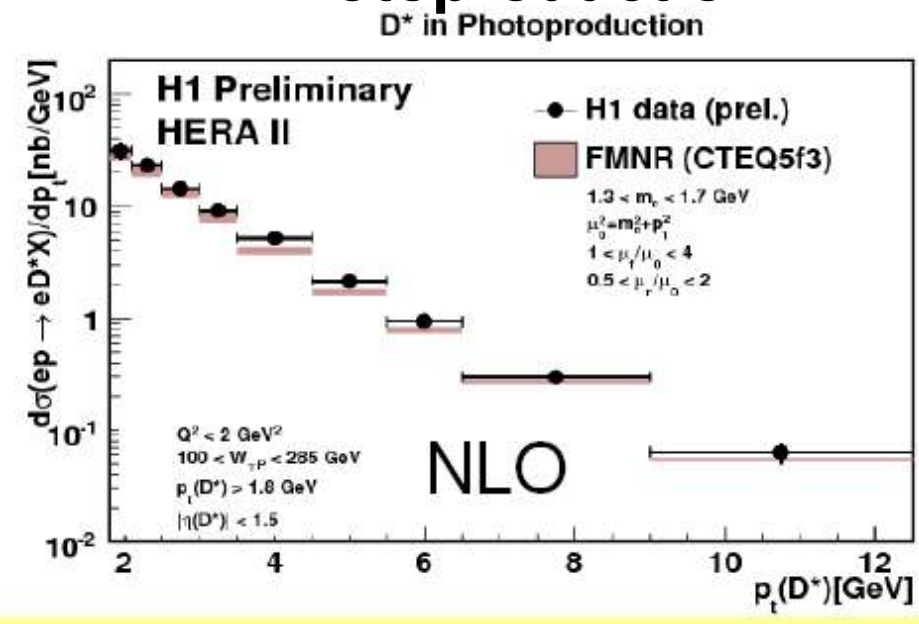
Test QCD, cross-check the gluon

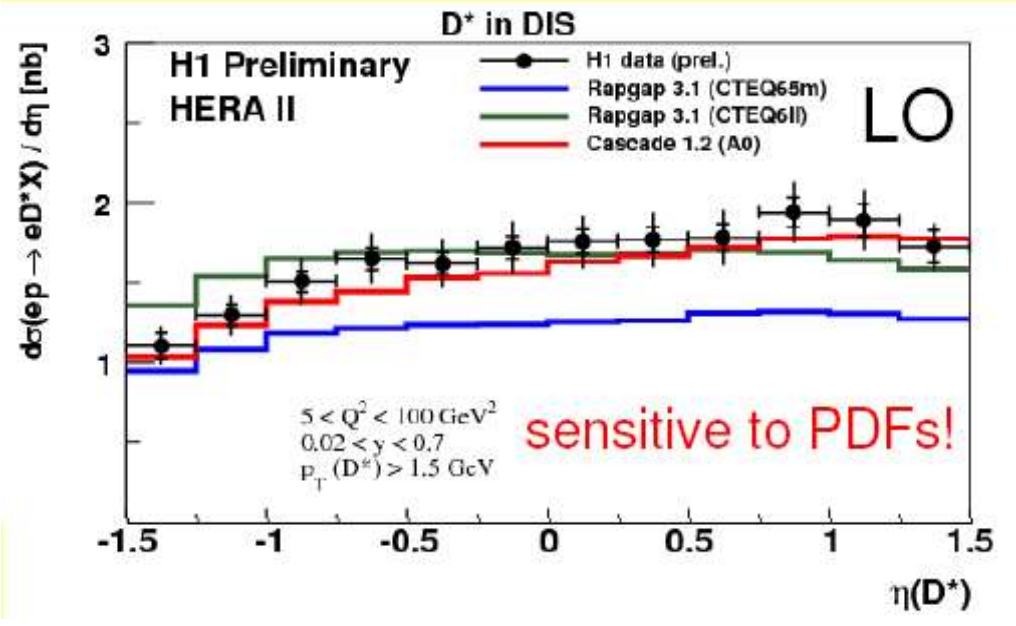
More charm with HERA II data

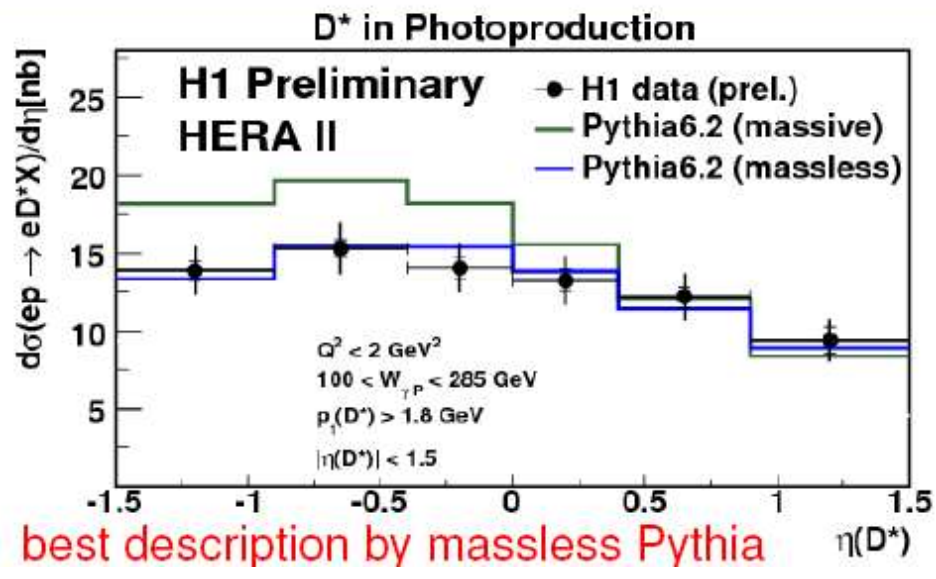
DIS



Photoproduction

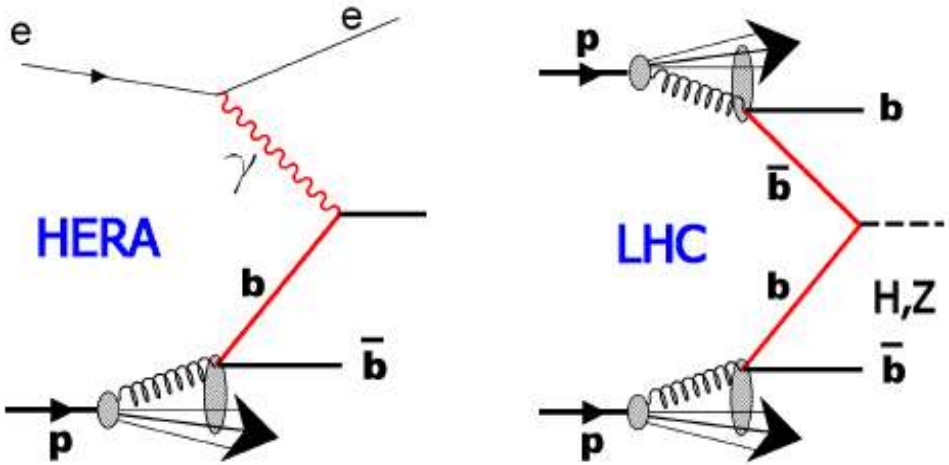


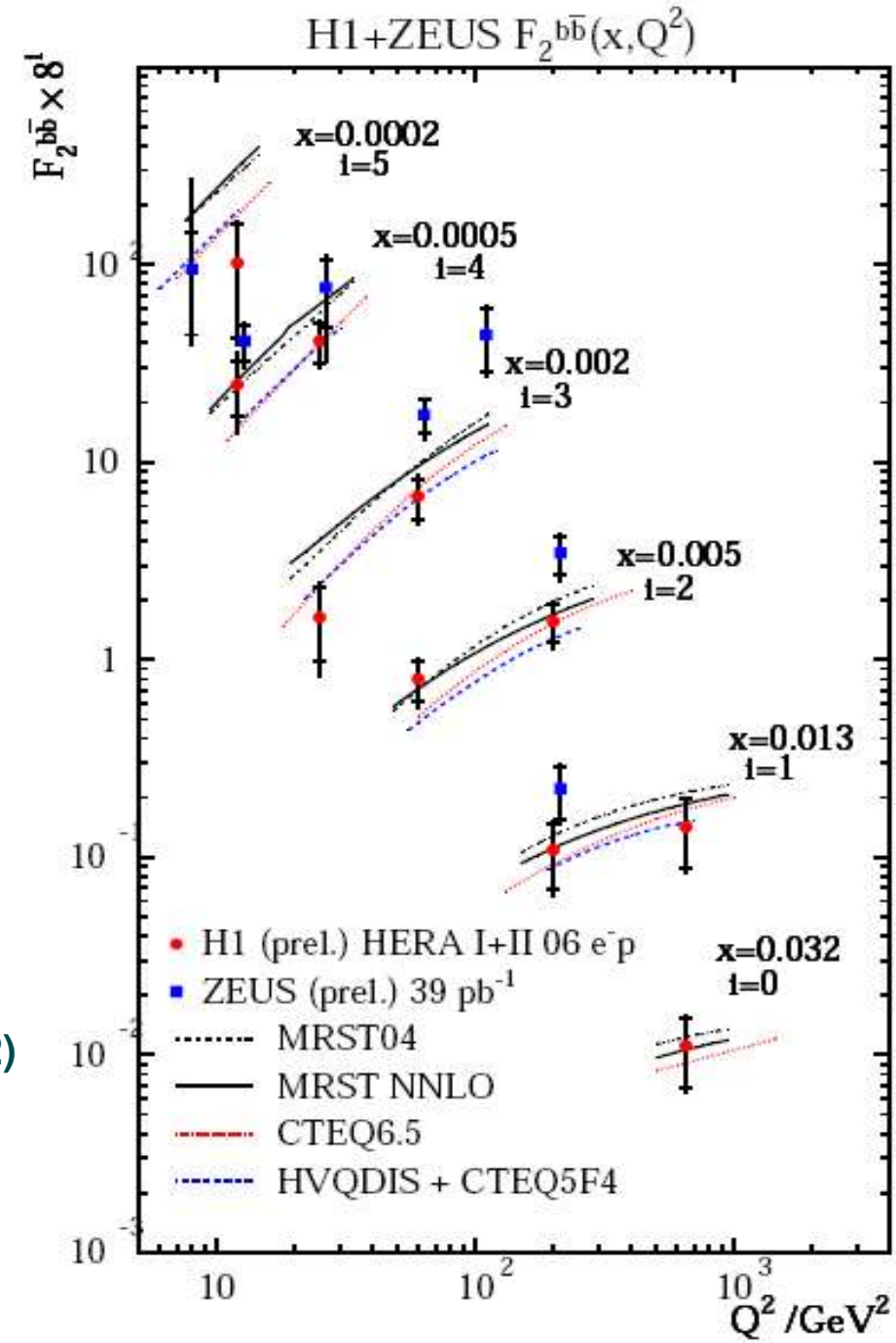




best description by massless Pythia

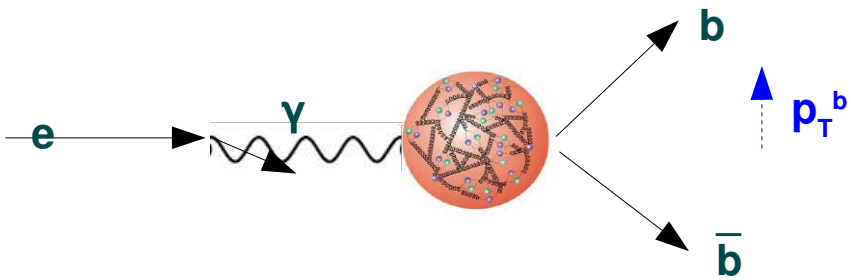
Proton's beauty

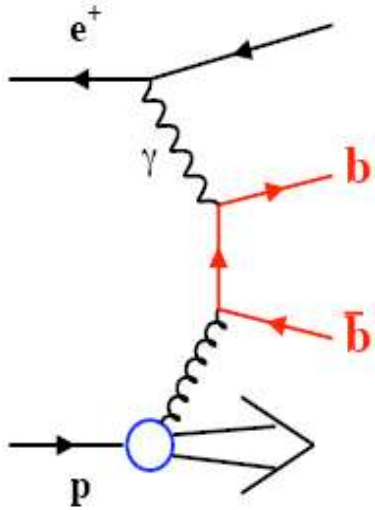


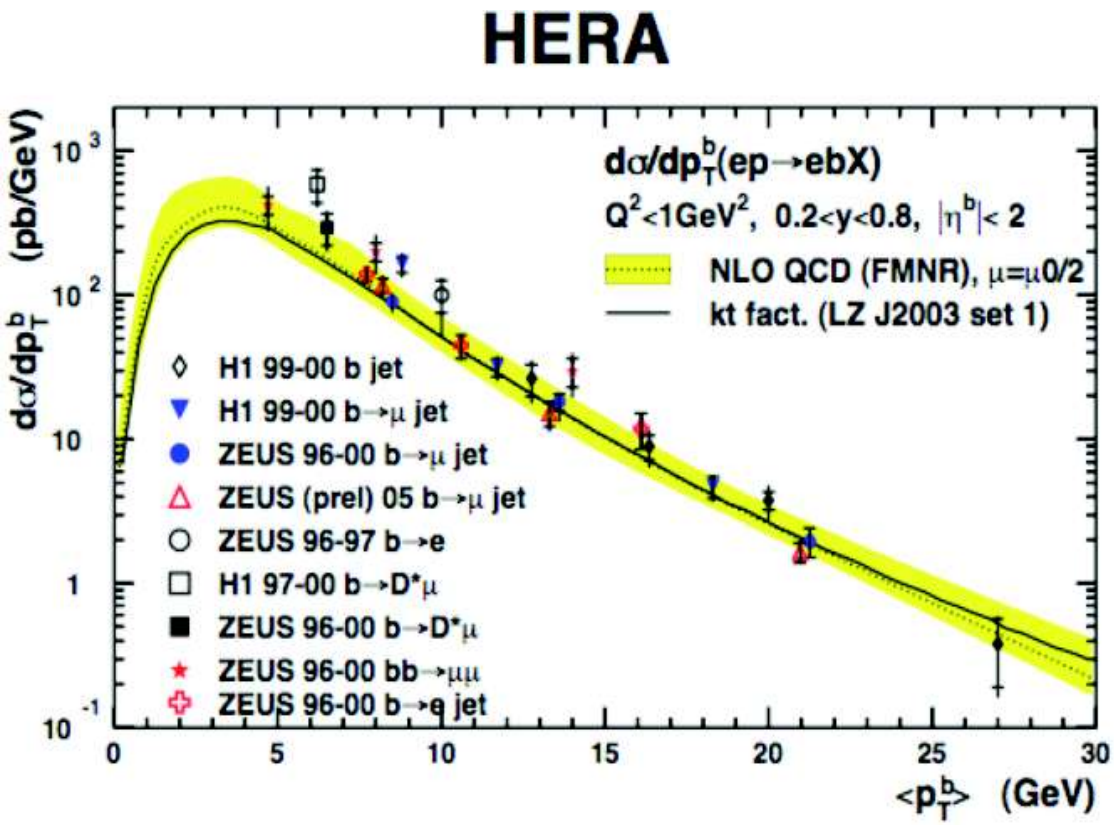


- HERA II data now investigated
- Precision is comparable with theory spread
- A significant improvement (more than a factor of 2) expected after final analyses

Photo-Produced Beauty







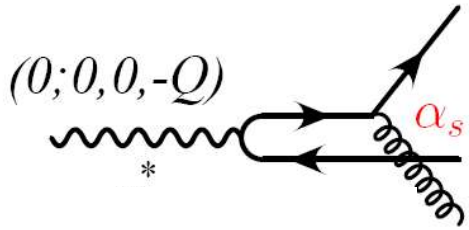
Recent precise measurements (HERA II) in agreement with theory

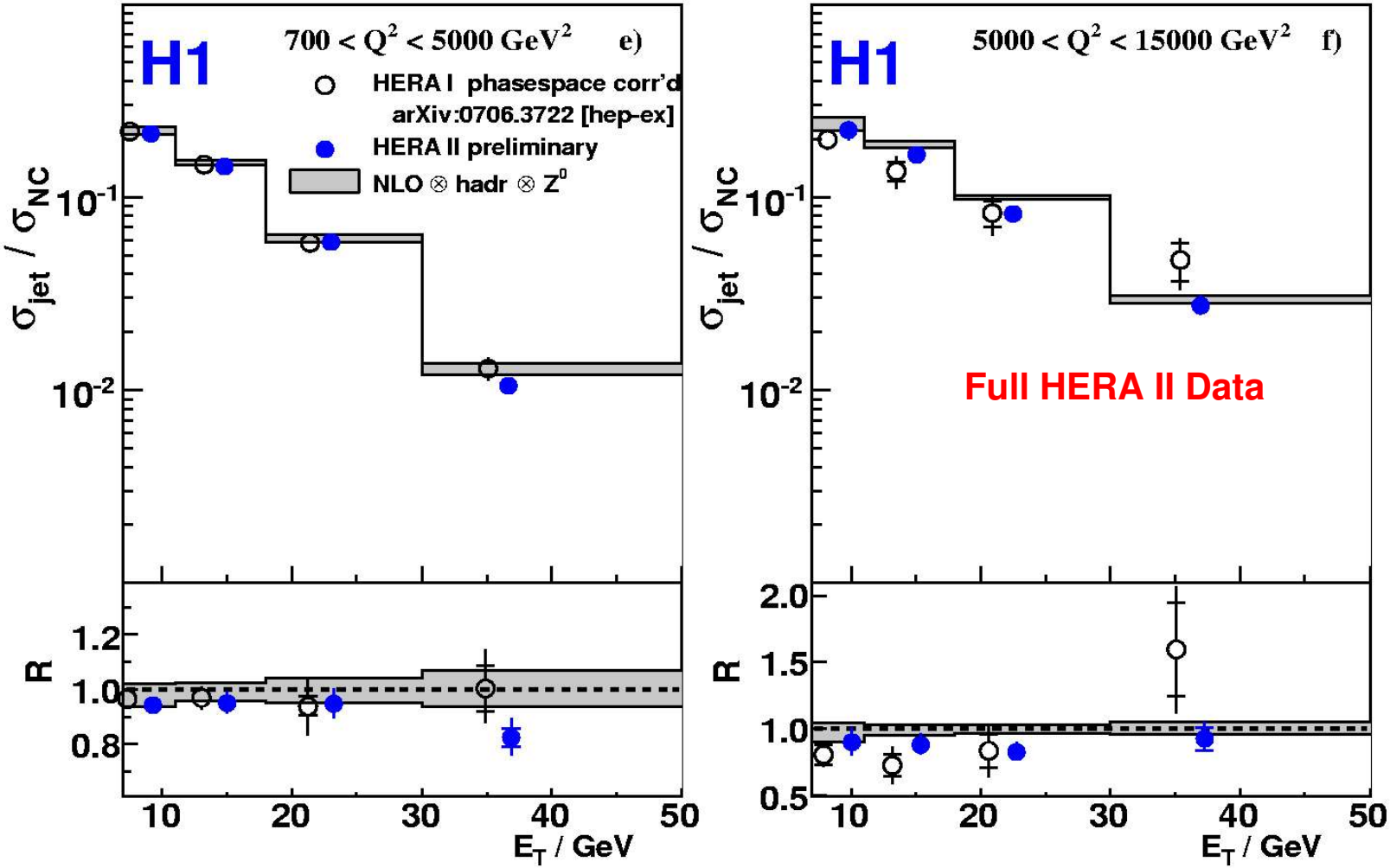
Precision to be improved with HERA II data

$150 < Q^2 < 15000\ \mathrm{GeV}^2$,

$0.2 < y < 0.7$,

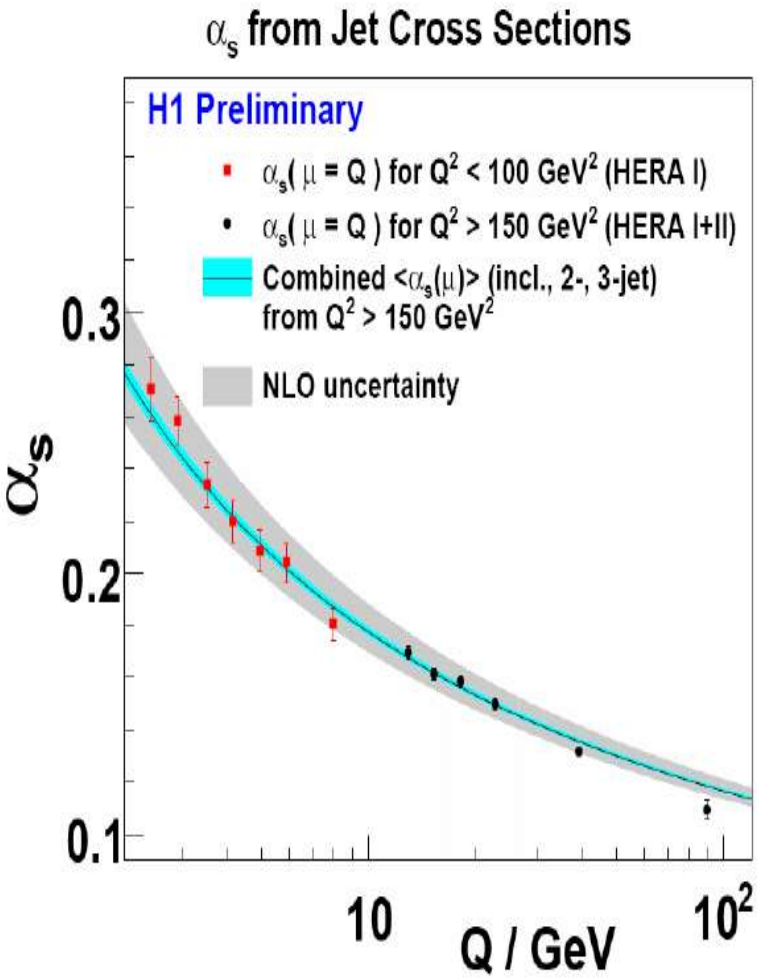
Jets in DIS

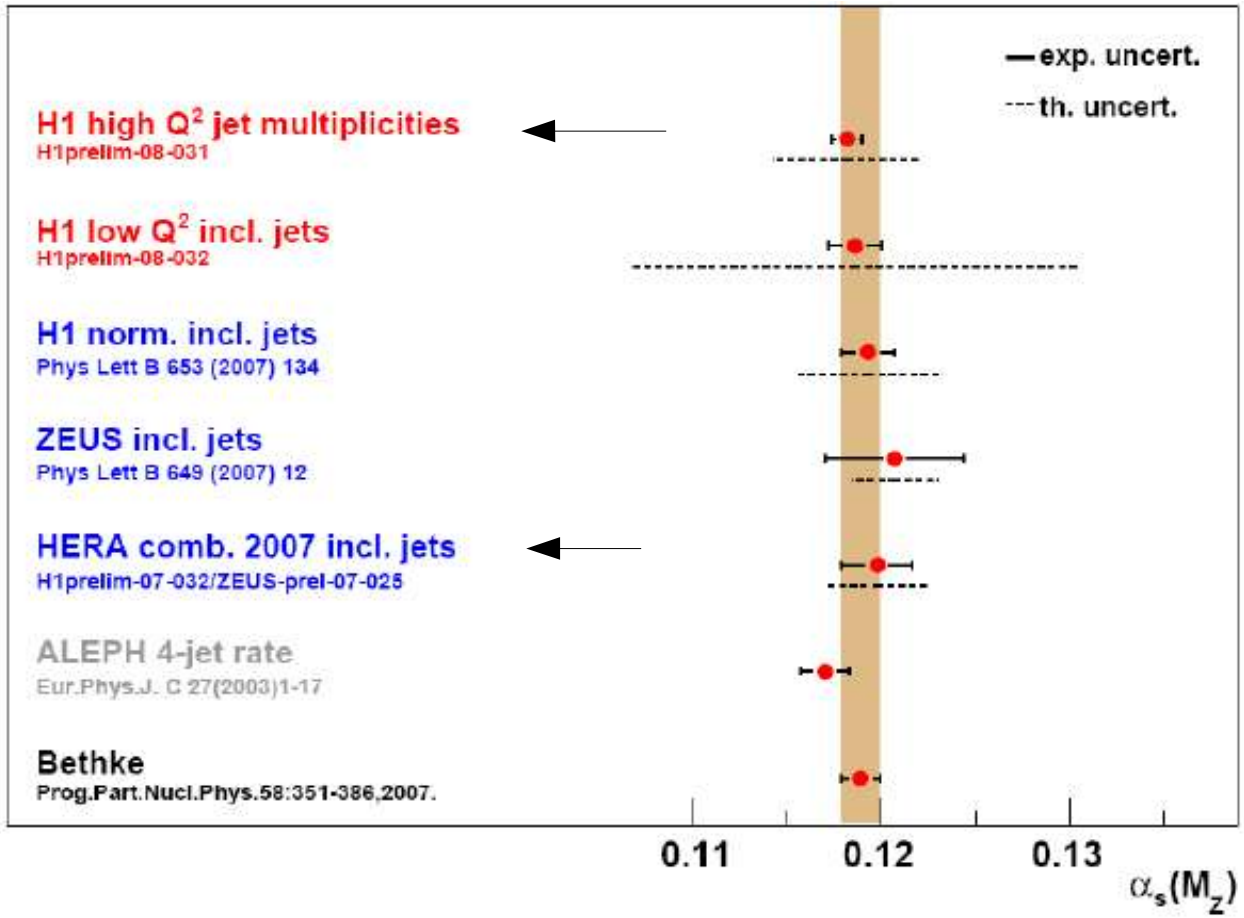




Clear improvement in precision, bright future for QCDs studies, gluon and α_s

Strong coupling: a sub-percent perspective?





H1/ZEUS combination (2007):

$$\alpha_S = 0.1198 \pm 0.0019(exp.) \pm 0.0026(theory)$$

NEW H1: high Q^2

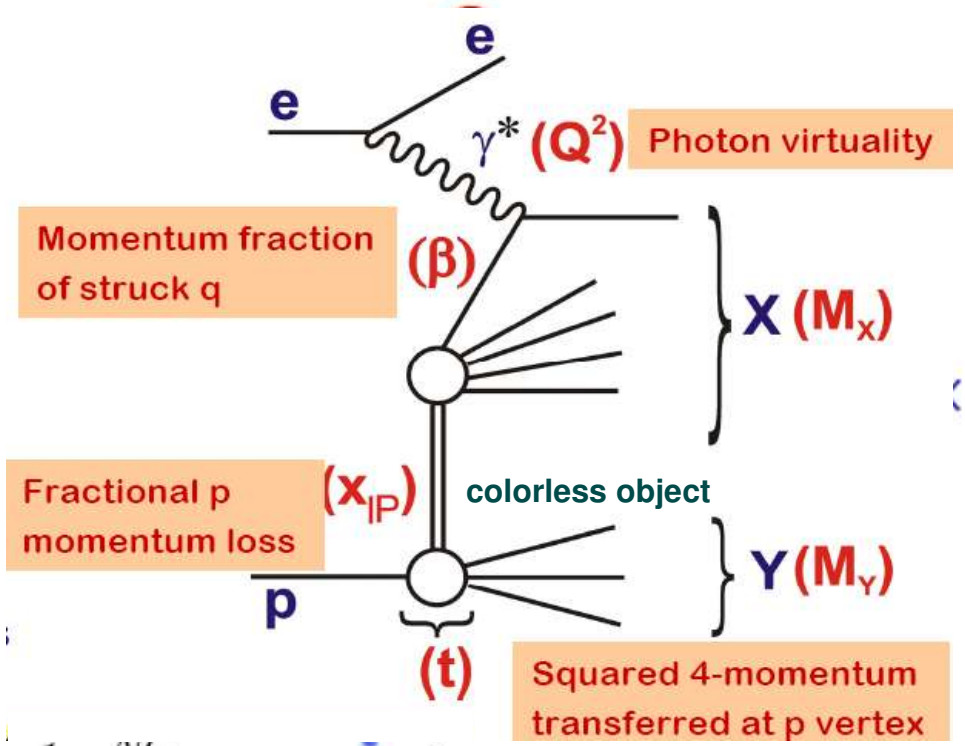
$$\alpha_S = 0.1182 \pm \boxed{0.0008(exp.)}\,^{+0.0041}_{-0.0031}(scale) \pm 0.0018(pdf)$$

NNLO theory is an absolute necessity now

Scales variation arbitrariness? Theory errors?

Hard Diffraction at HERA

~10% of NC DIS events have gap between p and central tracks. Measure gap or detect p with LPS/VFPS

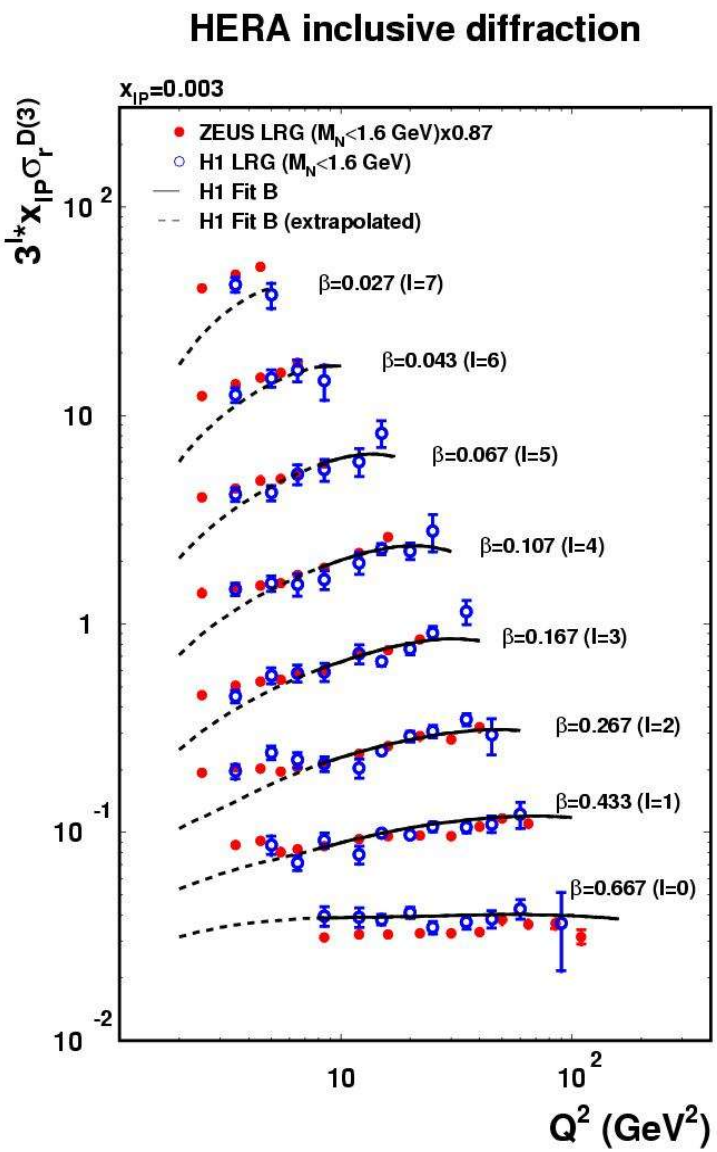


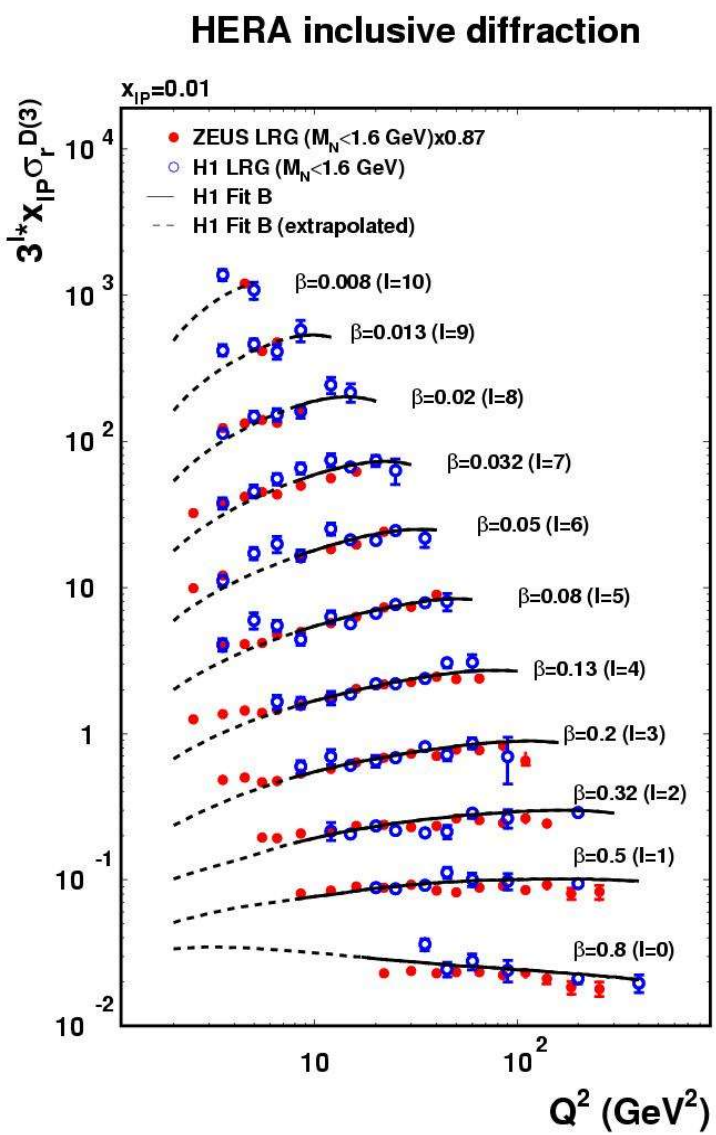
empty rapidity region (gap)

or intact proton detected down the beampipe (roman pots)

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

H1 and ZEUS M_N<1.6 GeV



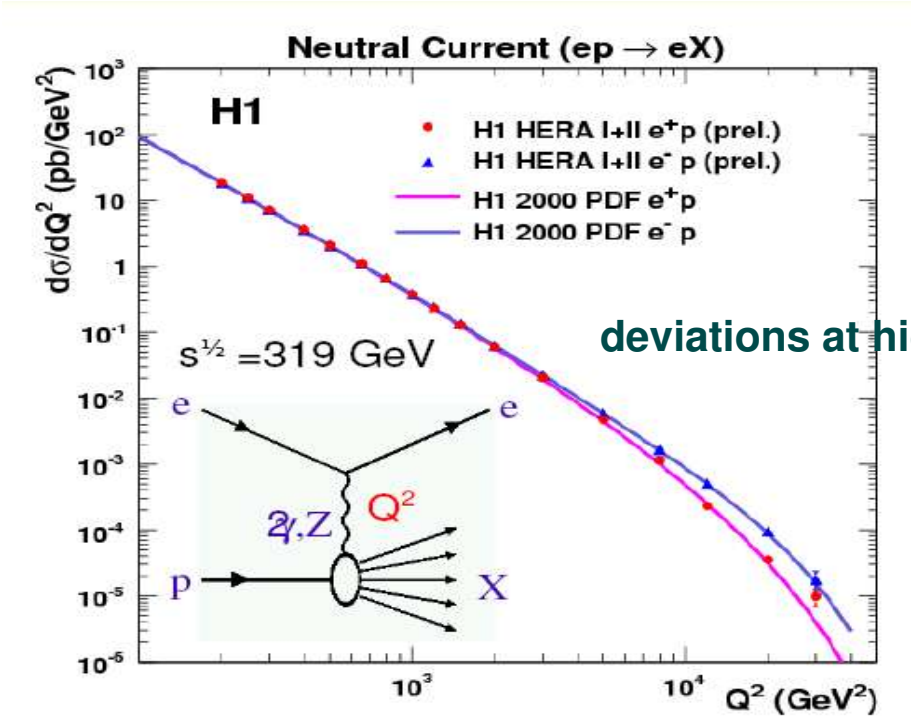


H1 and ZEUS corrected to the same phase space

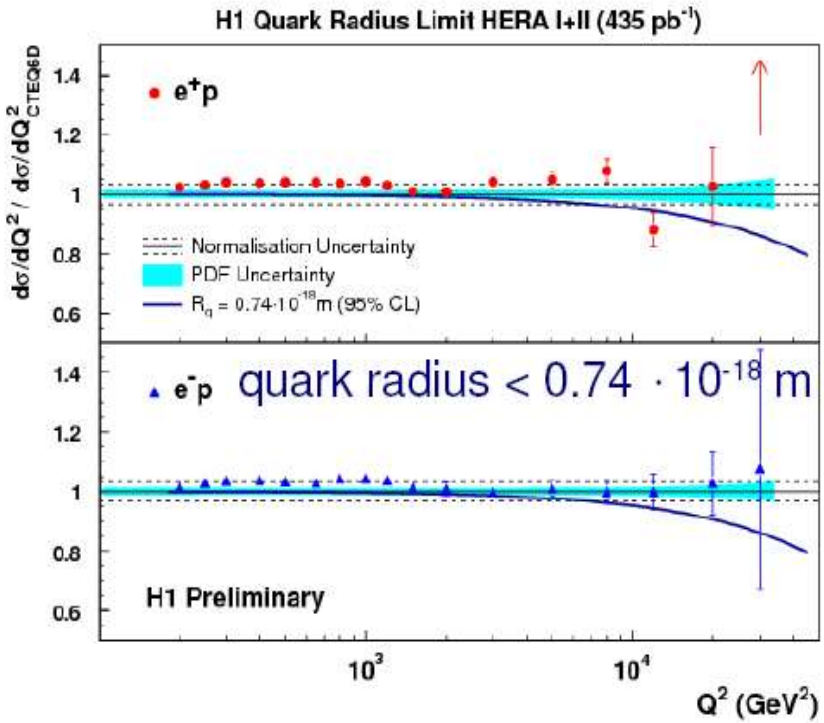
Ready for combination,more data to come

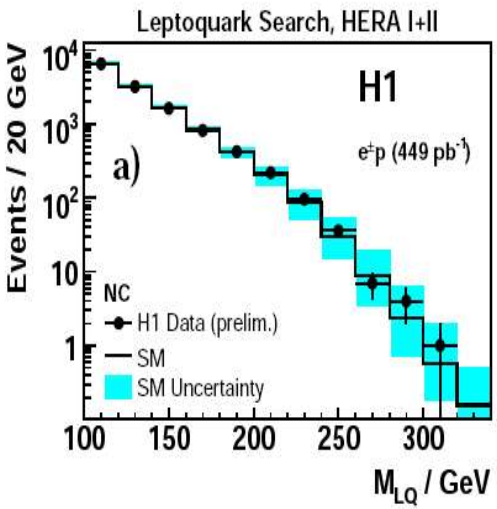
M.Ruspa in parallel session

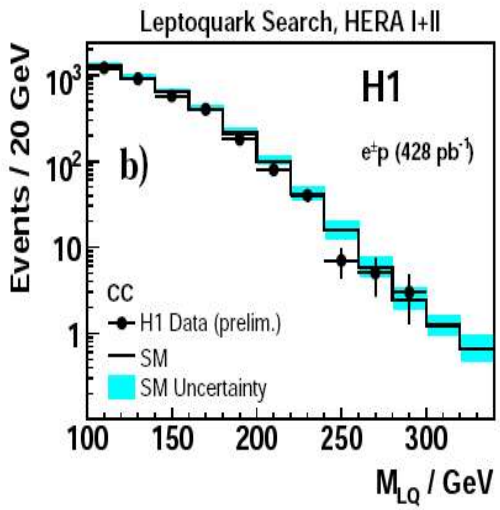
The searches for new physics



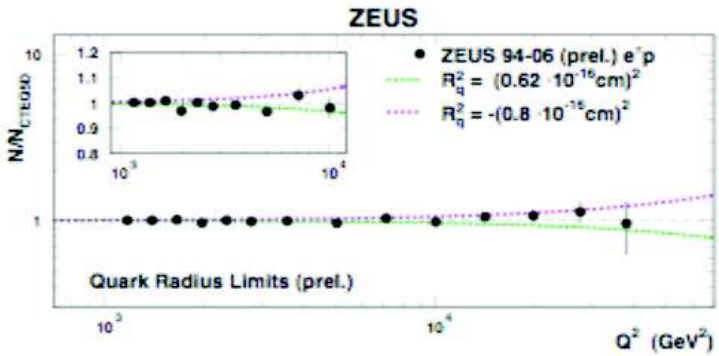
deviations at high Q2?







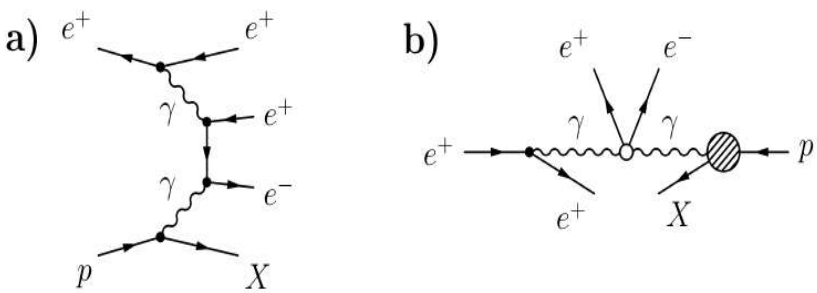
Mass peaks?

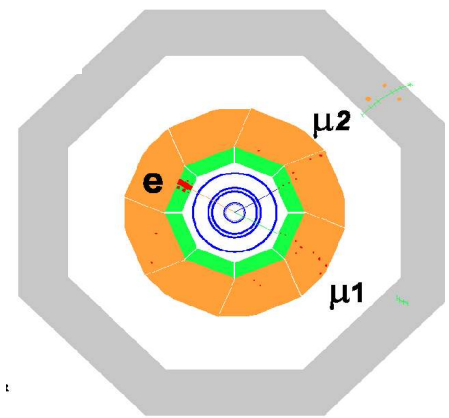


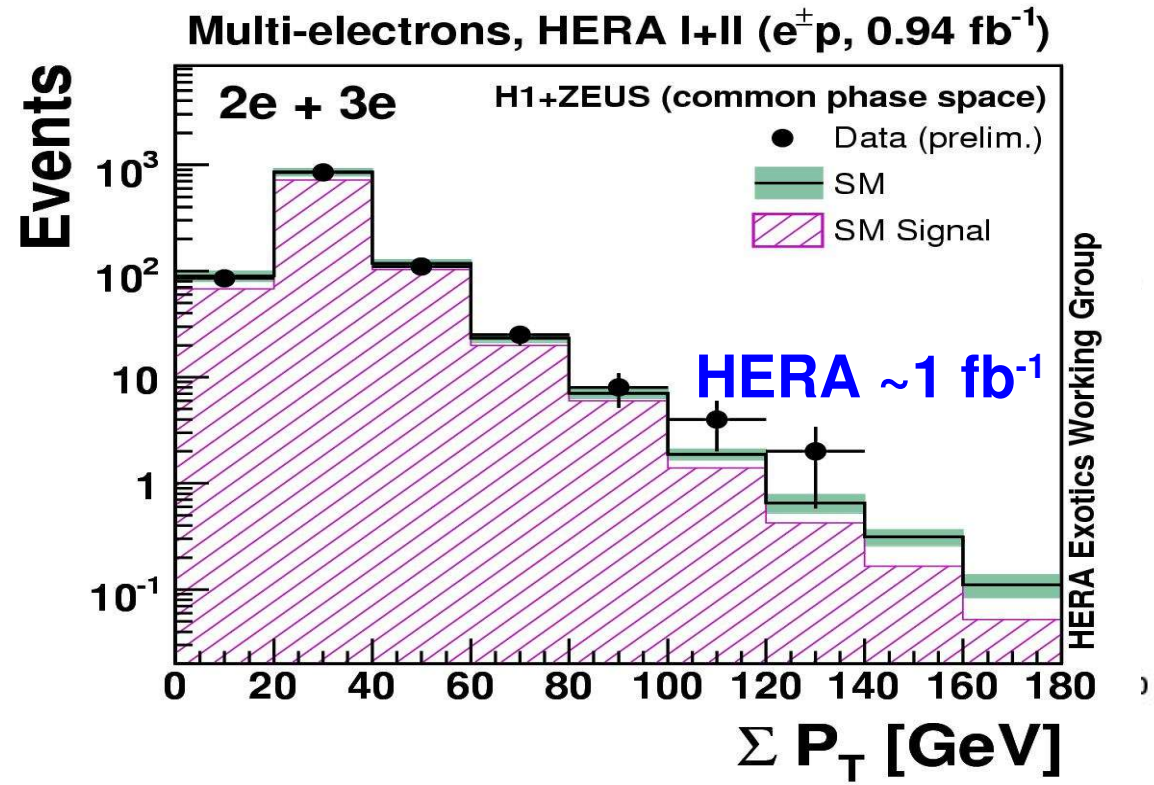
R_{quark}<0.62 10^{-18}m (ZEUS)

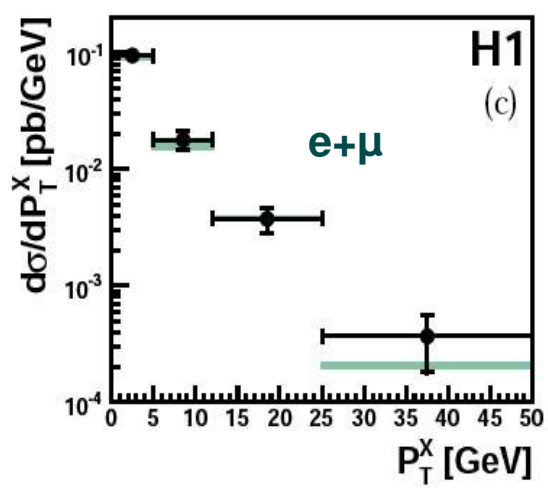
$R_{electron}$<0.28 10^{-18}m (LEP)

Multileptons in photon-photon collisions









$e\,p \to e\,\ell^+\ell^-X$

$P_T^{\ell_1} > 10$ GeV, $P_T^{\ell_2} > 5$ GeV

$20^\circ < \theta^{\ell_1,\ell_2} < 150^\circ$

$y < 0.82$, $Q^2 < 1$ GeV^2

H1 Data

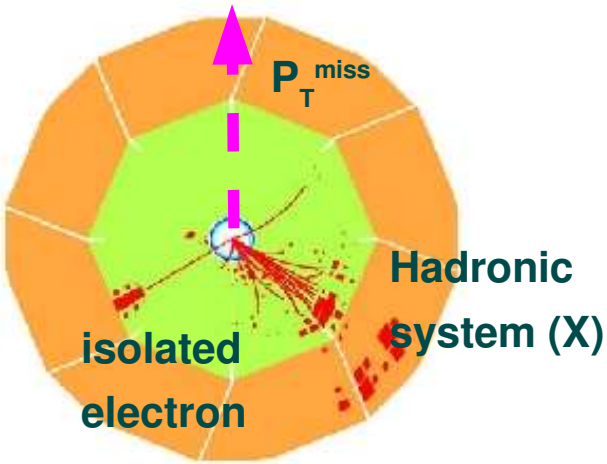
SM (GRAPE)

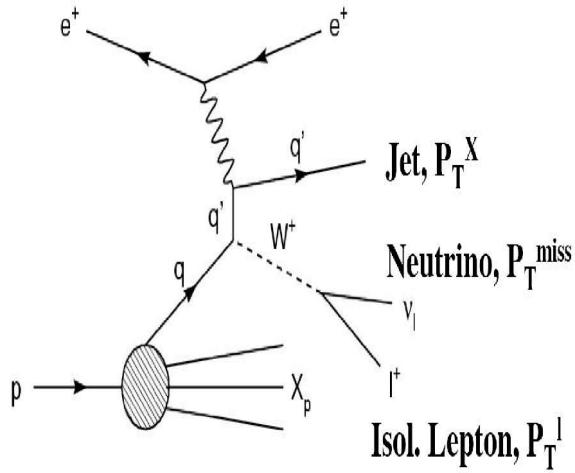
H1: 0.46 fb^{-1}

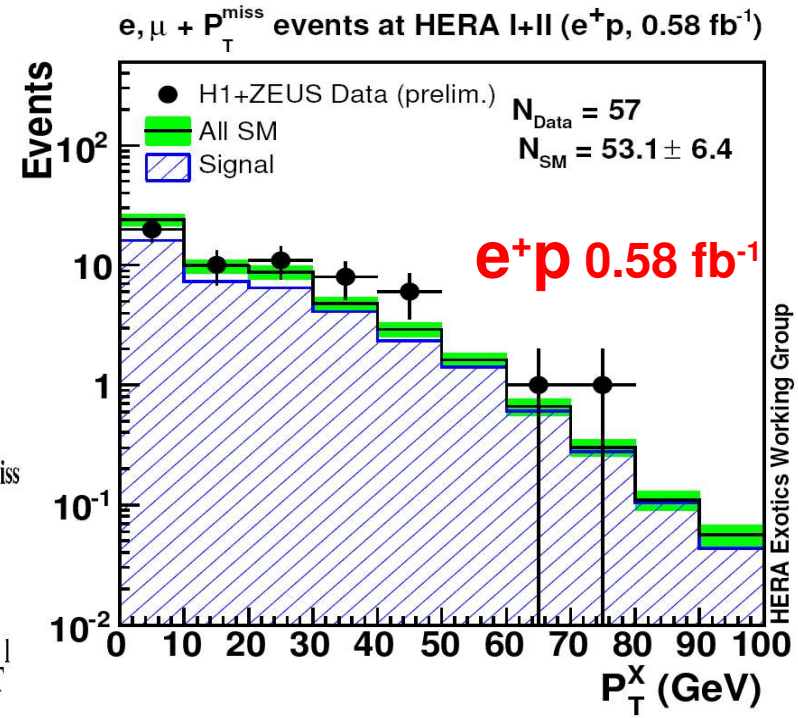
Measure elastic and inelastic di-leptons in photon-photon collisions

Search for high mass di-leptons

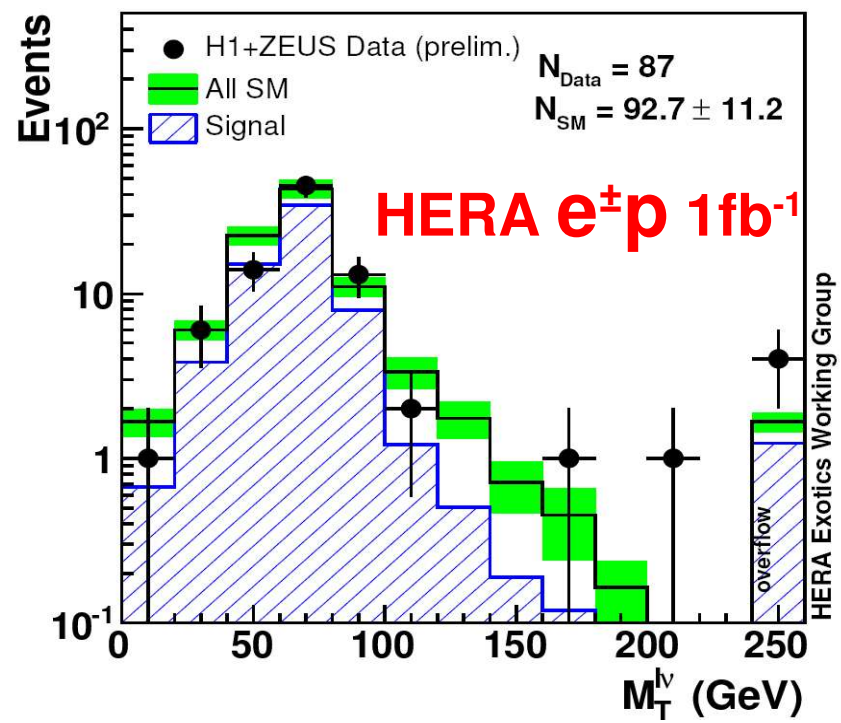
Isolated leptons+P_T^{miss}







P_T^X> 25 GeV		e+μ Data/SM	
H1	0.29 fb^{-1}	17/7.1±0.9	(2.9σ)
ZEUS	0.29 fb^{-1}	6/7.5±1.1	
H1+ZEUS	0.58 fb^{-1}	23/14.6±1.9	(1.8σ)



Anomaly at large P_T^X (H1) unsolved

Large statistics to measure and investigate

W production in ep collisions

General Searches

New result
Full HERA II

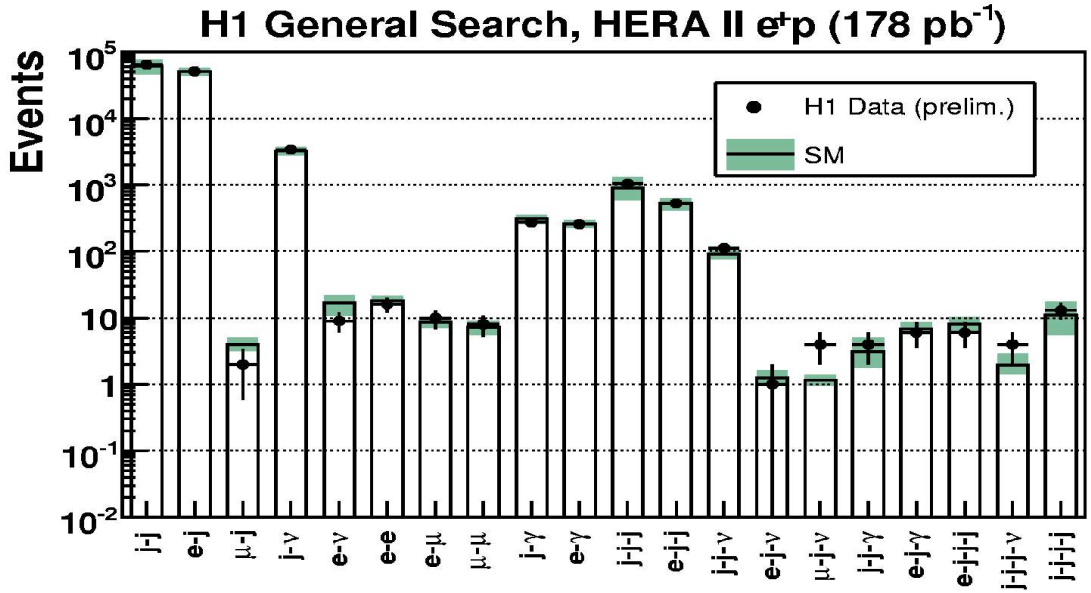
- Search for isolated particles at high P_T
- Electrons ,Photons, Muons, Hadronic Jets, Neutrinos

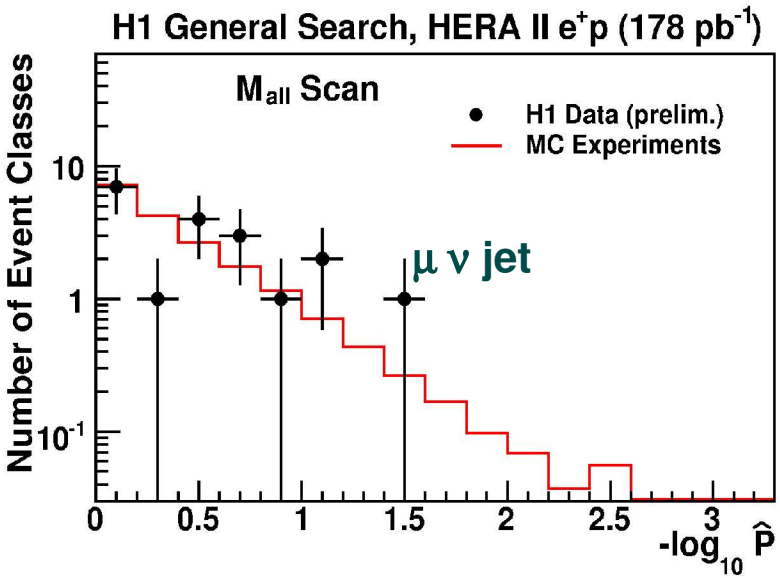
- Unique phase space:

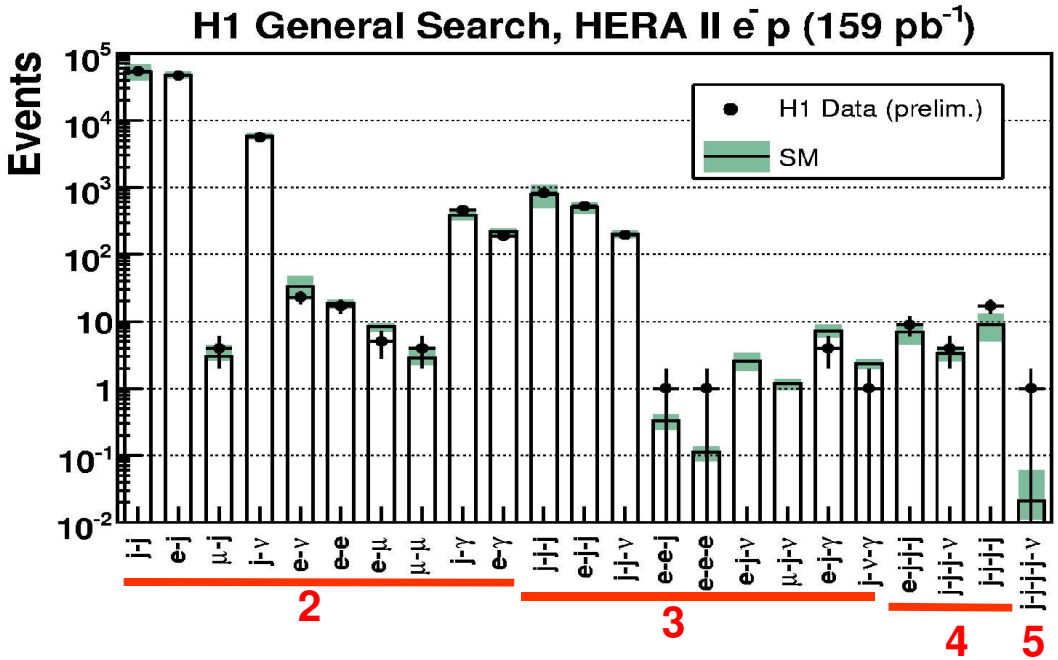
P_T >20 GeV

$10^o<\theta<140^o$

- Investigate Mass and ΣP_T
- Statistical Analysis (search for deviations)



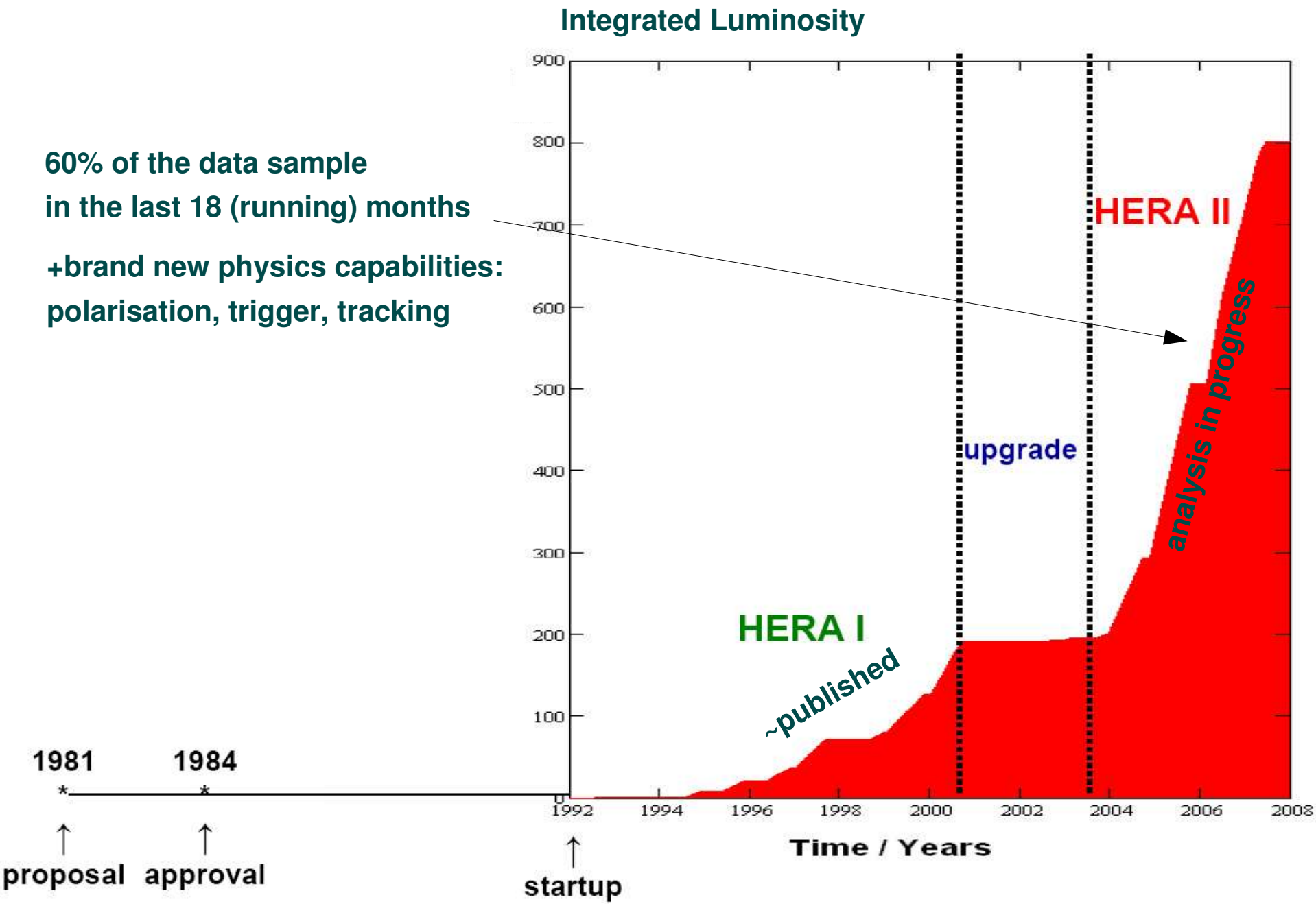




Outlook

60% of the data sample
in the last 18 (running) months

+brand new physics capabilities:
polarisation, trigger, tracking



Conclusions

HERA data is a (full) gold mine:

proton map, QCD laboratory, energy frontier searches

- Beginning of the precision era: final analyses in progress
  - Improvement in experimental precision: alignements, calibrations
  - significant progress in all HERA physics subjects expected in the next years.
- H1/ZEUS combinations => one step further in the precision
  - new inclusive combined data/fit display significant improvement in W/Z predictions for LHC
  - other subjects/data in the “combination pipeline”
- Results from HERA will stay for long
  - proton structure, QCD ...
- Input to LHC is essential and perspectives look brillant!

Backup

Slide from A. Cooper-Sarkar (DIS2008)

Form of the PDF parametrization at Q_0^2

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

	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 without D,E,F parameters and adding parameters until there is no further χ 2 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

α_s(Mz) = 0.1176 PDG2006 value

Renormalization and factorization scales = Q^2

Model uncertainties: to be added into the total PDF uncertainty

- mc 1.3 → 1.55 GeV variation of mass of c quark
- mb 4.3 → 5.0 GeV variation of mass of b quark
- fs 0.25→ 0.40 variation of strange sea fraction at Q_0
- fc 0.10→ 0.20 variation of charm sea fraction at Q_0
- Q_0^2 2.0 →6.0 GeV^2 variation of starting scale
- Model variations: to be compared with our results

Variation of $\alpha_S(Mz)$ 0.1156 → 0.1196

Variation of form of parametrization

Slide from A. Cooper-Sarkar (DIS2008)