Parton Distribution Functions: Impact of HERA

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On behalf of
the H1 and ZEUS collaborations

Hadron Collider Physics Symposium 2008 (HCP08)
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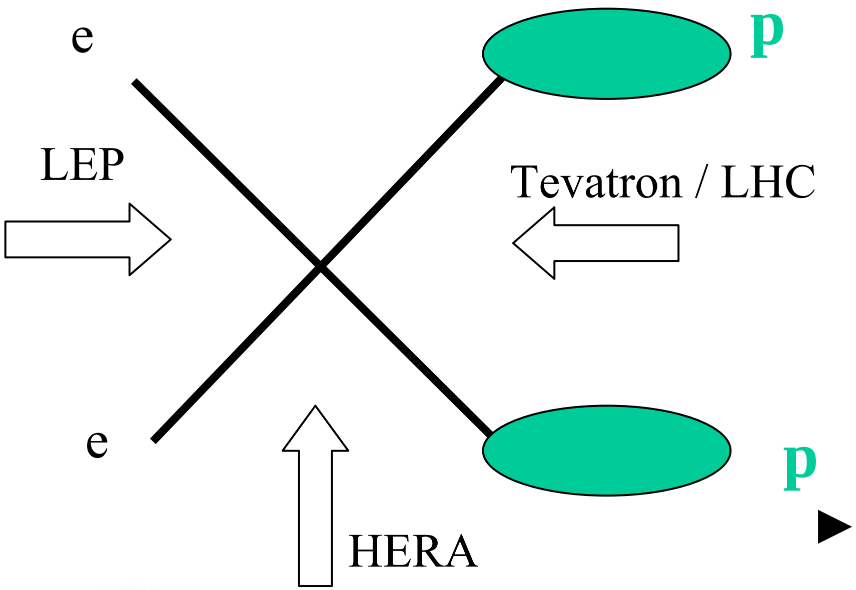
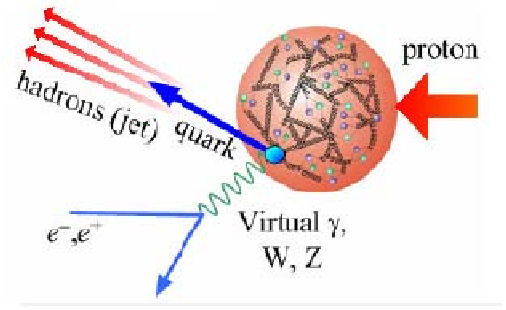
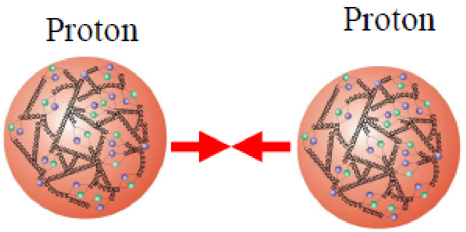
HERA and Hadron Colliders





$$\sigma = \sum_{pdf} \int dx_i [f_i(x_i) \times \Delta\sigma(eq_i \to X; x_i)]$$



$$\sigma = \sum_{pdf} \int dx_i dx_j [f_i(x_i) f_j(x_j) \times \Delta\sigma(q_i q_j \to X; x_i, x_j)]$$

► QCD Factorization Theorem

- -- Separate long- (‘soft’) and short-distance contributions
- -- Collinear divergence (‘soft contribution’) is absorbed into Parton Distribution Functions (PDFs)

If uncertainty in PDF:
→ “squared” impact at hadron colliders

Deep Inelastic Scattering: a straightforward tool to ”look” inside proton

Measured cross sections ➔ Structure Functions (SFs)

$$\frac{d^2\sigma}{dxdQ^2} \approx \frac{2\pi\alpha^2}{xQ^4} Y_+ F_2$$

Measure in terms of:
- ➢ **Mom.frac. of parton**
- ➢ **Spatial resolution**

- ● Virtuality: $Q^2 = -(k-k')^2$
  ➔ Spatial resolution of probe $\lambda \sim 1/\sqrt{Q^2}$
- ● Bjorken scaling variable: $x = Q^2/2pq$
  ➔ Momentum fraction of struck parton

If proton is point like → $\frac{d^2\sigma}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4} Y_+$

F_2 SF parameterize target structure, i.e how far from point-like

SFs ➔ PDFs : DGLAP evolution inspired Quark Parton Model

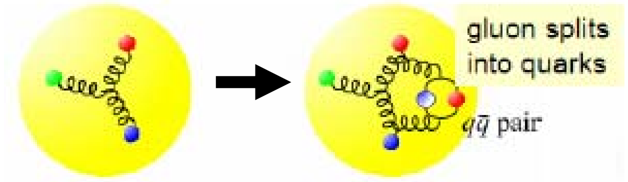
$$F_2 = x\Sigma e_q^{\,2}(q+\bar{q})$$

$$\frac{dF_2}{d\ln Q^2} \propto \alpha_s x g$$

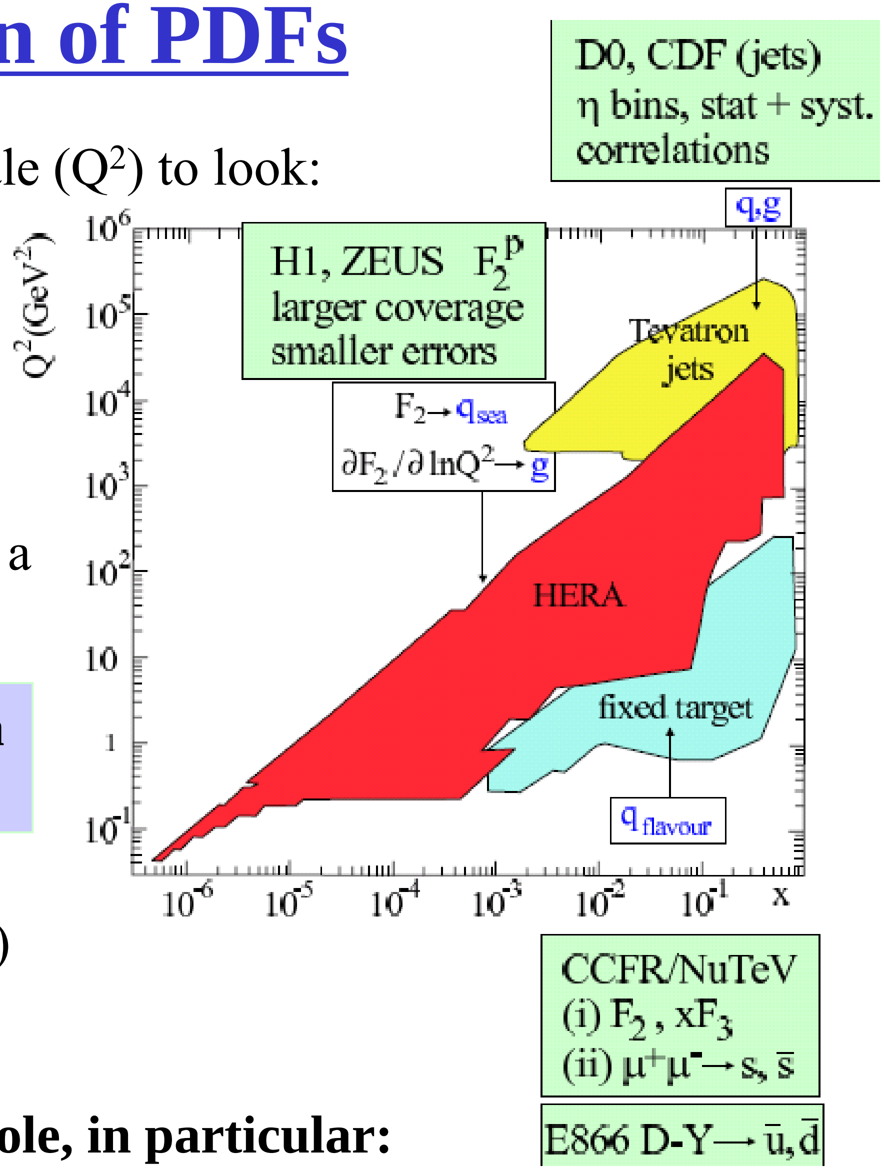
- ◆ **Quarks and antiquarks (spin ½) PDFs**
  → Directly sensitive to cross section
- ◆ **Gluon (spin 1) PDF**
  → Indirectly sensitive to cross section via Q^2 shape

Determination of PDFs

- QCD tells looking (PDFs) depends on scale (Q^2) to look:



- How PDFs evolves w.r.t Q^2 is given by “DGLAP equation”
- But no prediction power how PDFs are at a certain Q^2_0 where evolution starts



→ Initial PDFs at Q^2_0 are determined by a global fit to various experimental data.

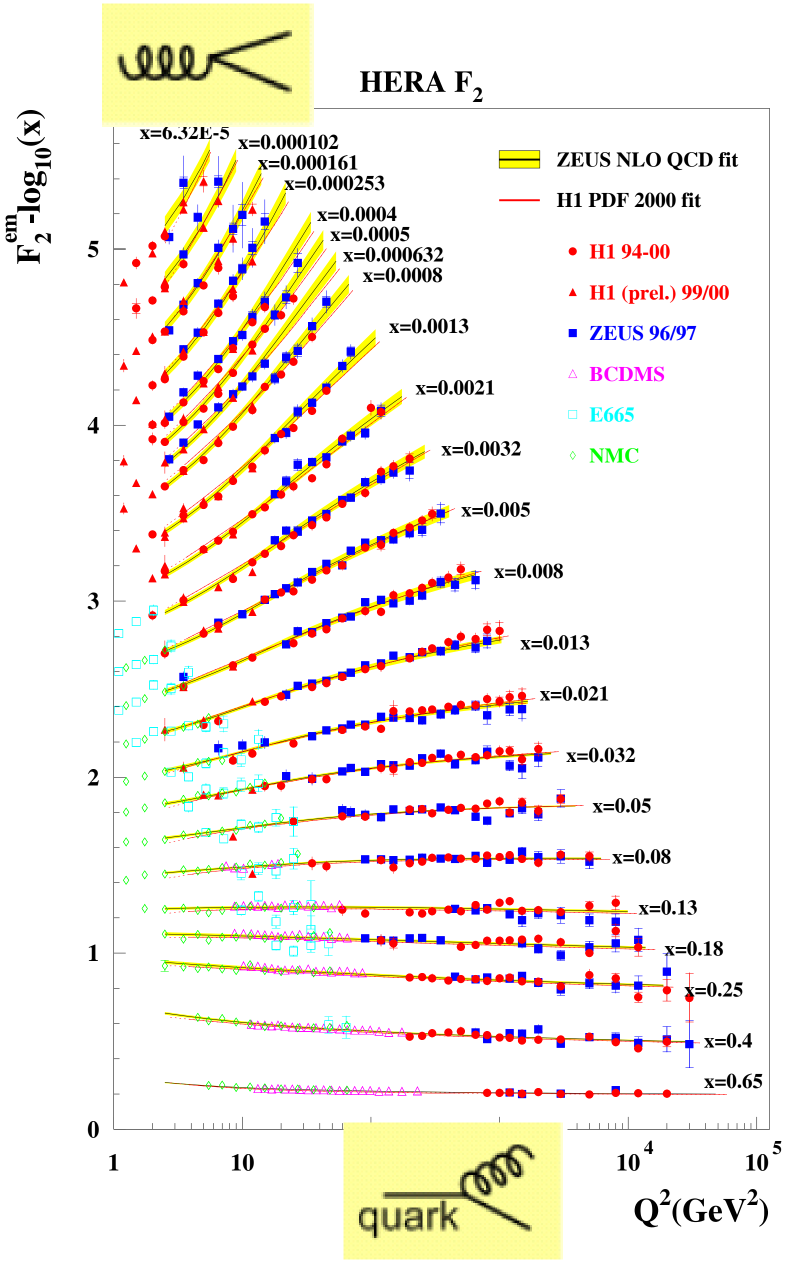
→ Needs wide kinematic range
(Notice: gluon is given by slope in *log* Q^2)
→ Universality should be checked in various processes

► **HERA plays significant role, in particular:**

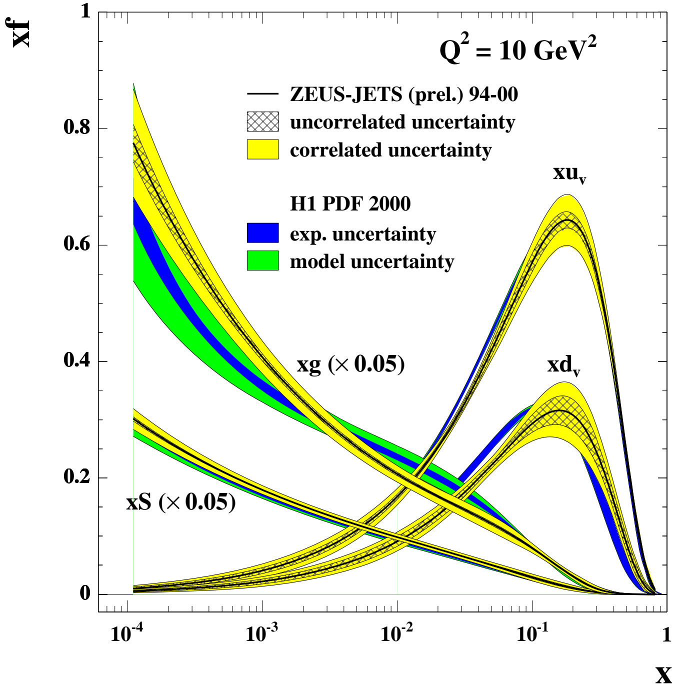
-- Gluon

-- Sea quarks

**At x=10^{-4} to 10^{-1}
(LHC main kinematic region; See later)**



Textbook figures from HERA-I (→year 2000)



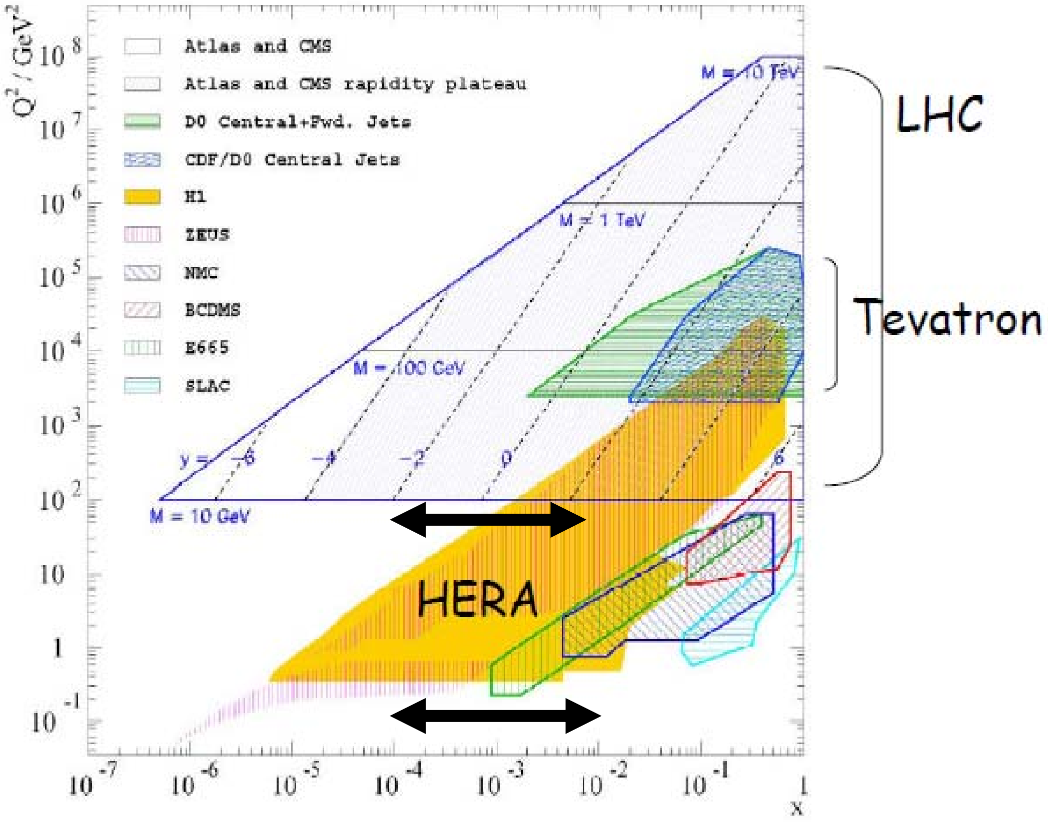
- ► Cross sections were precisely measured and NLO pQCD describes F_2 over:
  - -- 4 orders in Q^2
  - -- 3 orders in x
- ► PDFs were determined
  - → "Invisible" gluon as well

Impact to LHC

- LHC main body of phase space, i.e. ~1 TeV @ central rapidity corresponds to HERA's x region of $10^{-4} < x < 10^{-1}$

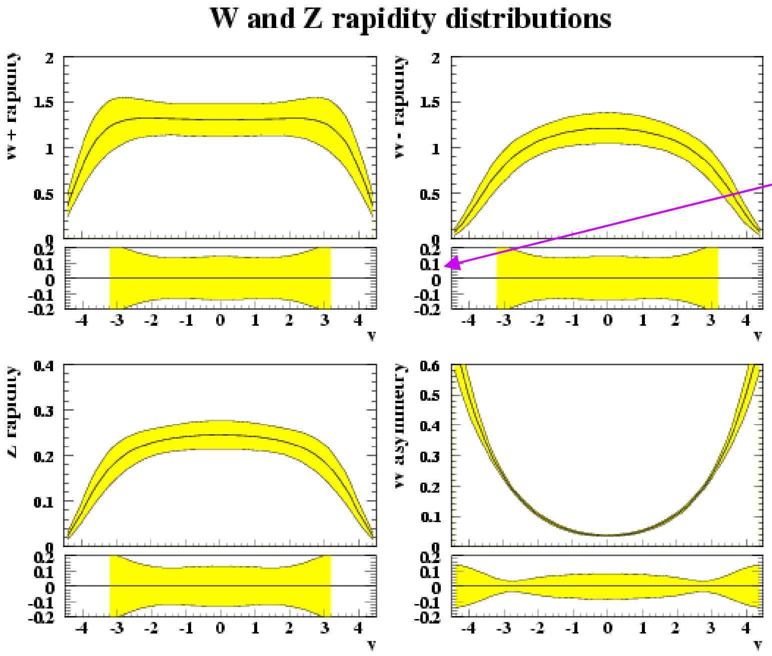
- At LHC most of the cross sections are due gluons, whose PDFs are mainly determined by HERA

HERA provides key and essential inputs to LHC



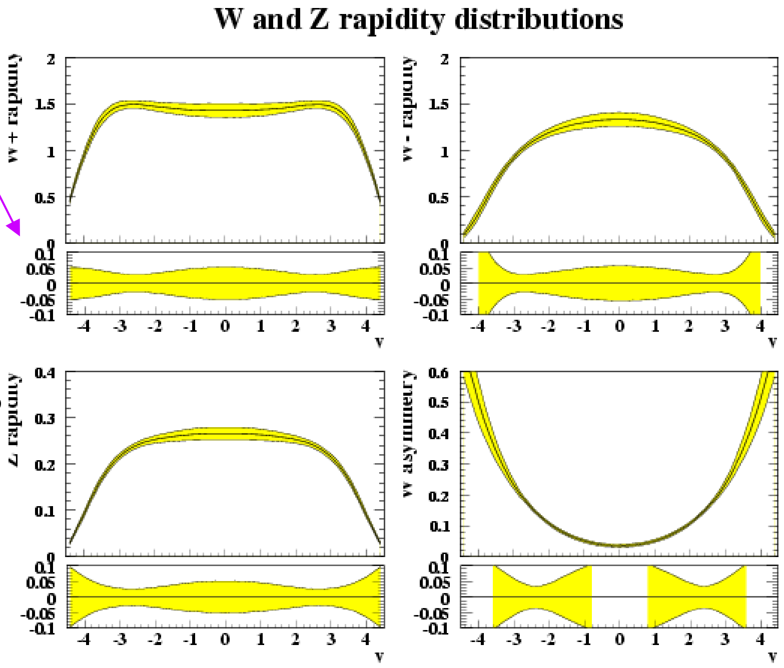
W/Z @ LHC

HERA data excluded



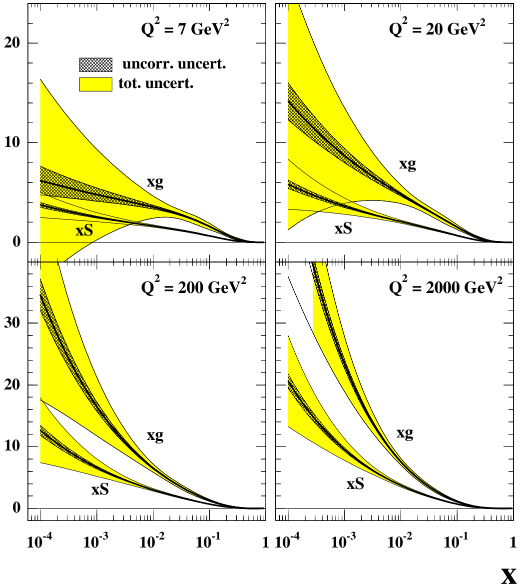
Note difference in scale for fractional errors

HERA data included

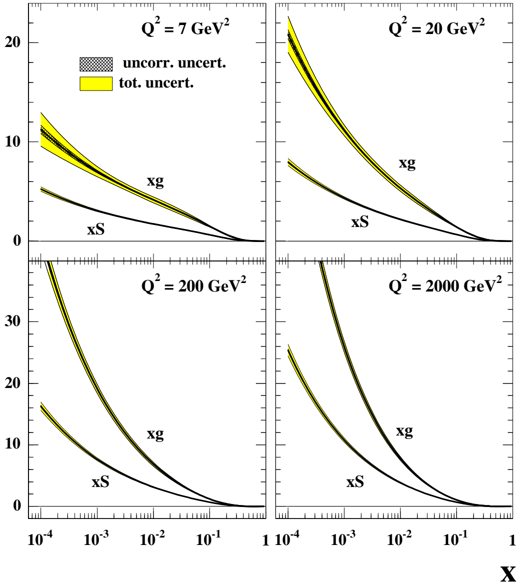


Note also: model errors are not included

HERA inclusion



- HERA brings big improvement in gluon/sea knowledge at small x
→ brings significant reduction of uncertainty of W/Z cross section @ LHC



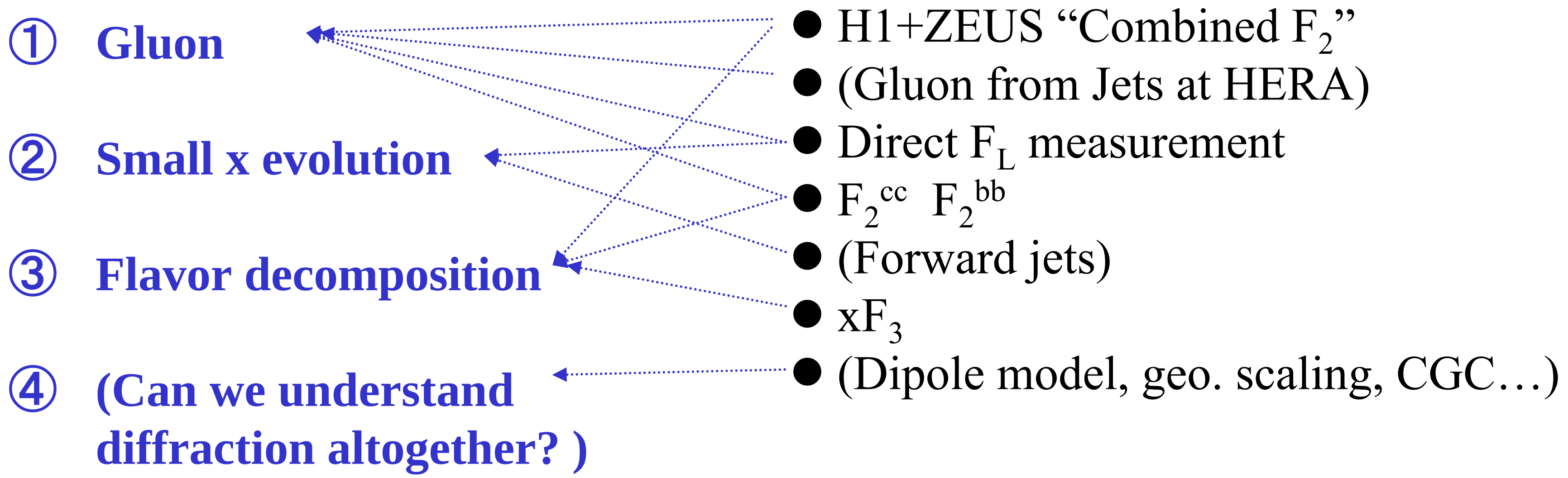
Main questions to current PDF knowledge

PDFs understanding and impact of HERA → So far, so good? Are we done?

If I would comment **in view of (now starting up) LHC era**

-- Main question is: Can we trust DGLAP and indirectly extracted gluon?

-- Further a lot to do! My possible shopping list could be:



① **Gluon**

② **Small x evolution**

③ **Flavor decomposition**

④ **(Can we understand diffraction altogether?)**

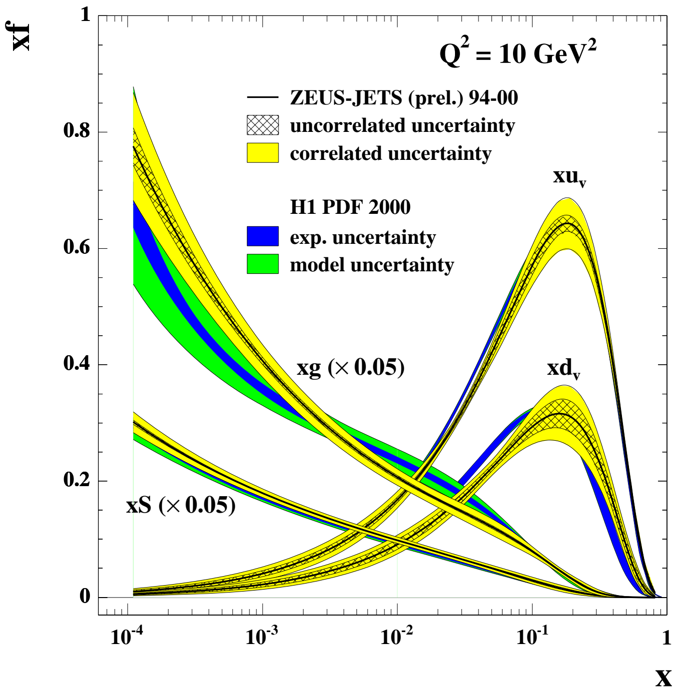
- H1+ZEUS "Combined F_2"
- (Gluon from Jets at HERA)
- Direct F_L measurement
- F_2^{cc} F_2^{bb}
- (Forward jets)
- xF_3
- (Dipole model, geo. scaling, CGC…)

Shown in previous slides are just introduction to what I will show you hereafter; New measurements, analyses are coming up

① Gluons
③ Flavor decomposition
-- “Combined F_2”

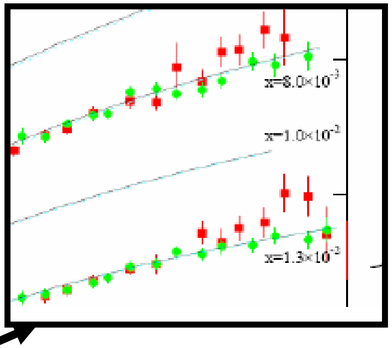
An issue in PDF fit

- **Measurement is “correlated” systematic error dominant, resulting in that extracted PDF errors are also systematic error dominant**



-- If we look the “Textbook” PDF plot, gluons from H1 and ZEUS are: “center values are different but consistent within large uncertainty” due to experimental errors (and model uncertainties)

-- Indeed, if we look carefully the “Textbook” F_2 plot there are some places where H1 and ZEUS data look “center values are different but consistent within large (correlated systematic) uncertainty”

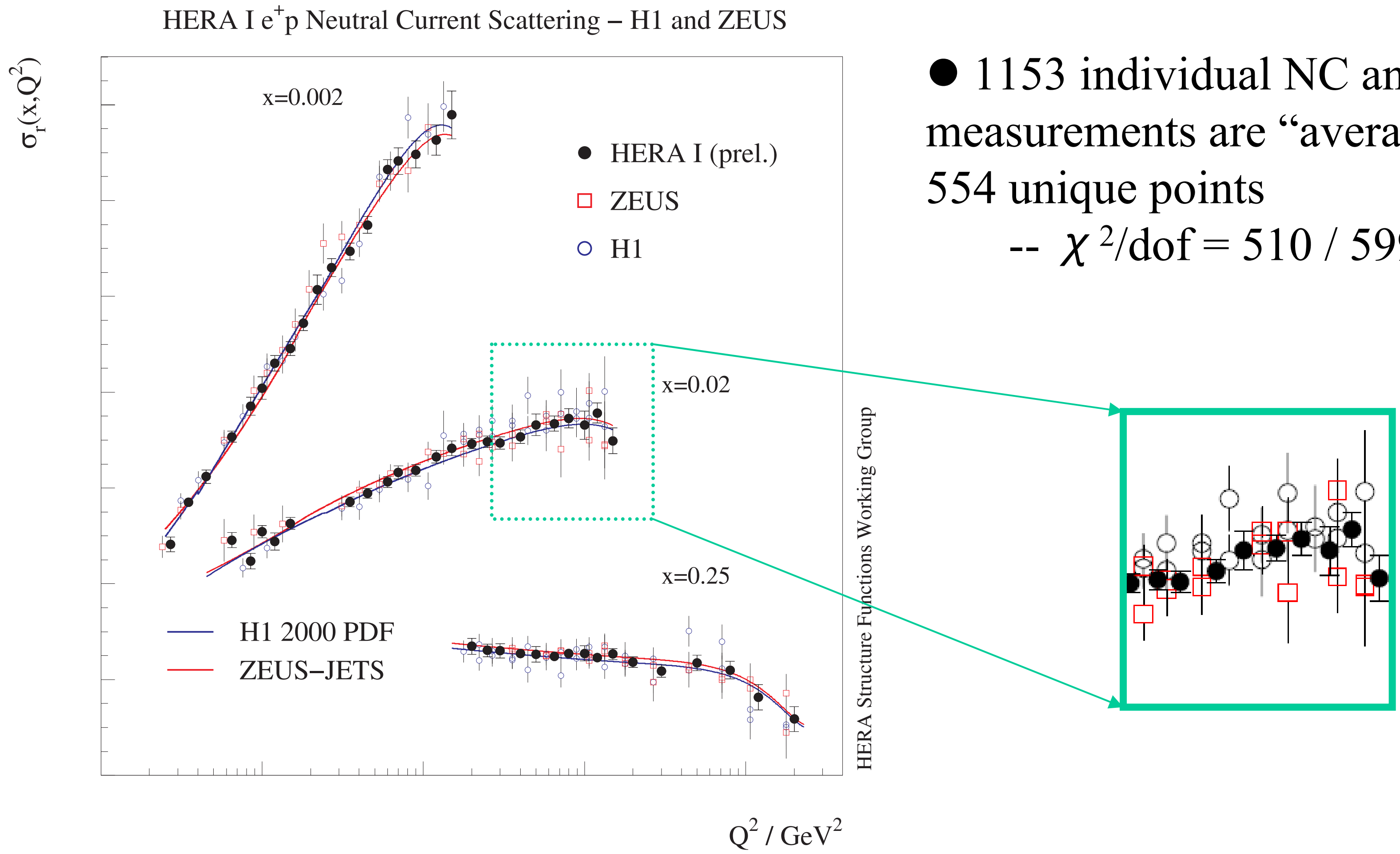


➔ Combine H1 and ZEUS cross sections by fully taking into account their correlated systematic uncertainties : “Cross-calibration between experiments”

① Gluons
③ Flavor decomposition
-- "Combined F_2"

Combined cross sections

★ NEW Prel.
@ LP '07



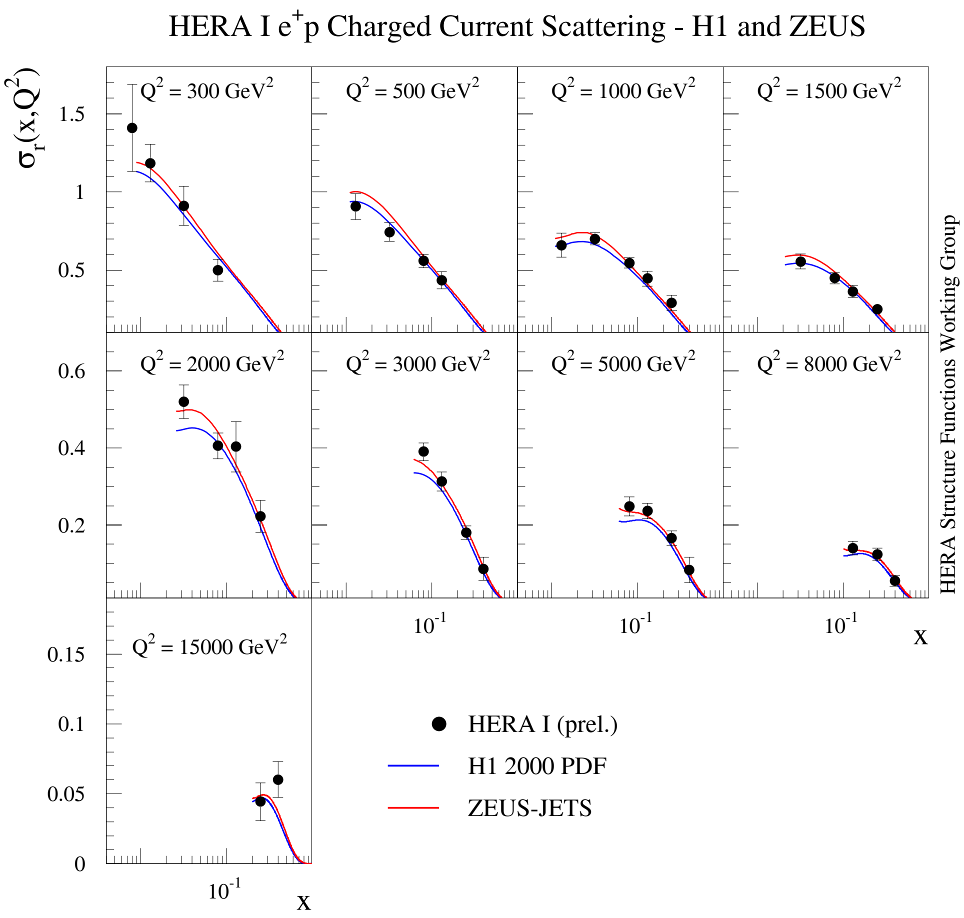
- 1153 individual NC and CC measurements are "averaged" to 554 unique points
  -- χ^2/dof = 510 / 599

Large reduction of systematic errors (significant than simple statistical gain of 1/sqrt(2))

① Gluons
③ Flavor decomposition
-- “Combined F_2”

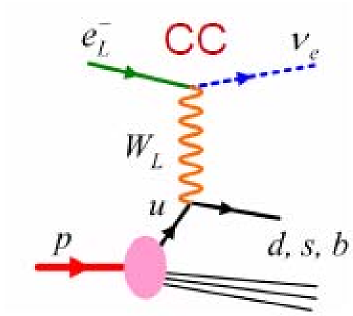
Combined cross sections at large Q^2

★ NEW Prel.
@ LP ‘07



- Not only “F_2” data (low- and mid-Q^2 NC) but also both NC and CC at large Q^2 are averaged

CC (Charged Current)
= Probe with W-boson



- Flavor selecting nature of CC

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

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

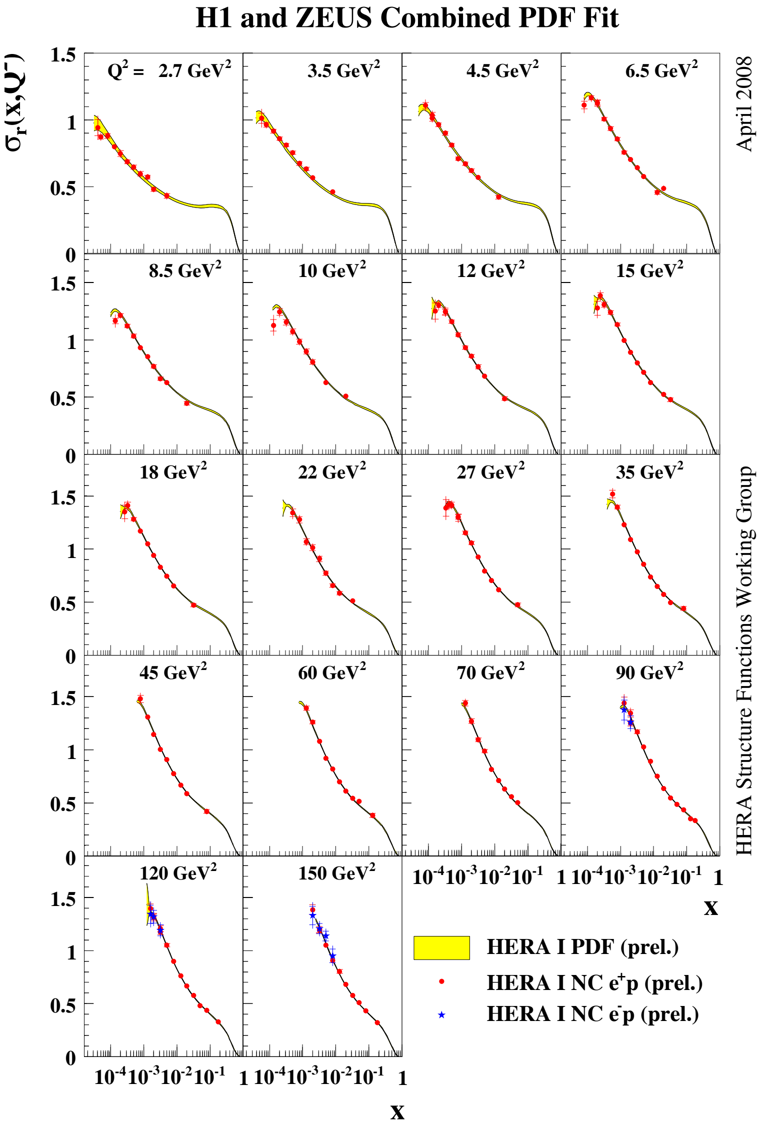
► HERA e+p CC will give cleanest determination (w/o heavy-target corr.) on d-quark PDFs

► Note: only ~230 pb^{-1} out of ~1 fb^{-1} is used for combination

① Gluons
③ Flavor decomposition
-- “Combined F_2”

★ **NEW Prel.**
@ DIS ‘08

QCD fit to combined cross sections



- A QCD fit was performed on the combined data
- Systematic uncertainties are smaller than statistical uncertainties
  → Handling of systematic errors is not an issue anymore
- Resulted in χ^2 / ndof = 476.7 / 562

① **Gluons**
③ **Flavor decomposition**
-- "Combined F_2"

"HERA PDF"

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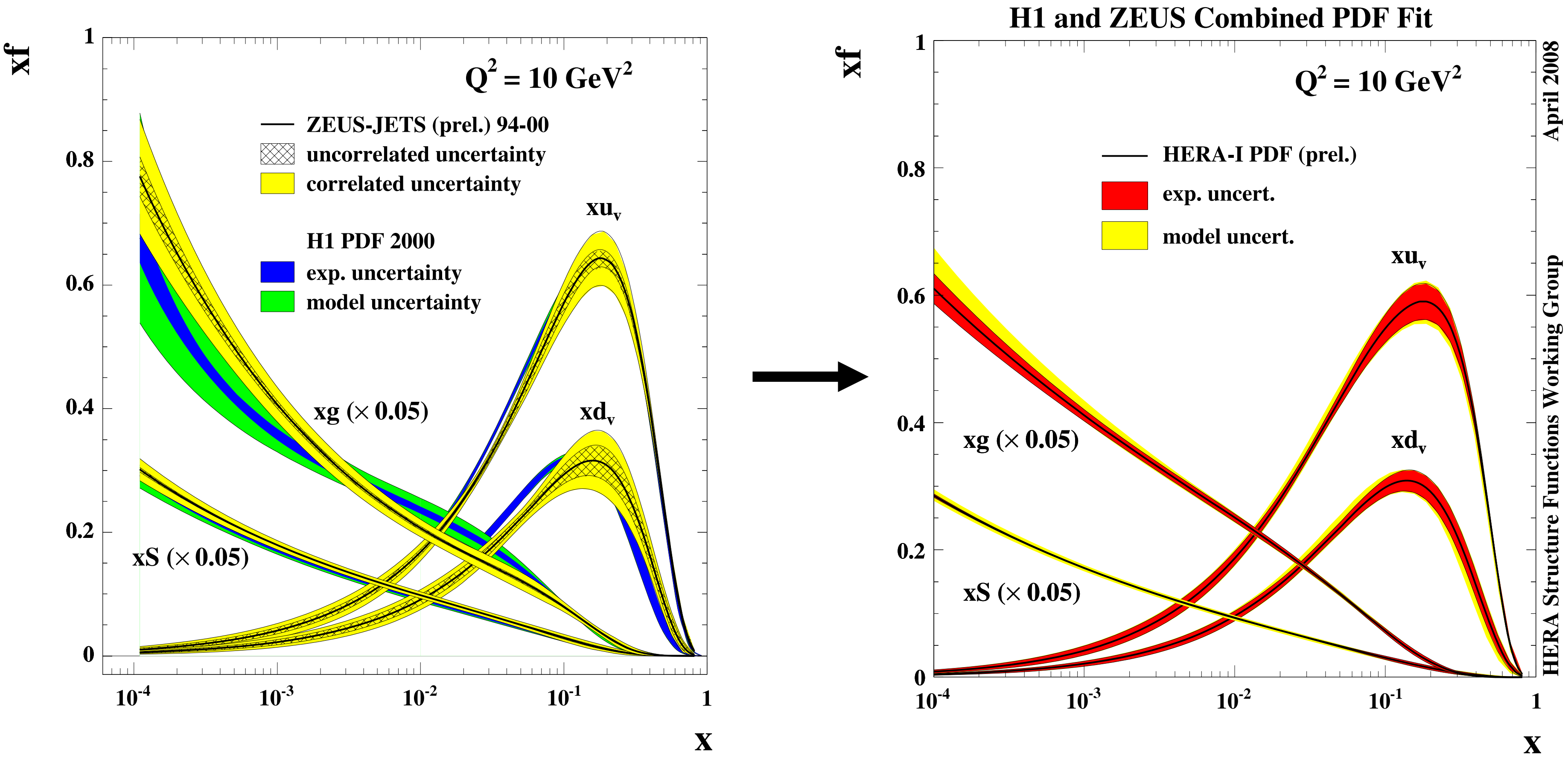
H1 and ZEUS Combined PDF Fit

- "H1 and ZEUS; consistent within large uncertainty" is now resolved in "single HERA PDF; with an improvement in level of uncertainty".

① Gluons
③ Flavor decomposition
-- “Combined F_2”

“HERA PDF”: Impact to LHC

★ NEW Prel.
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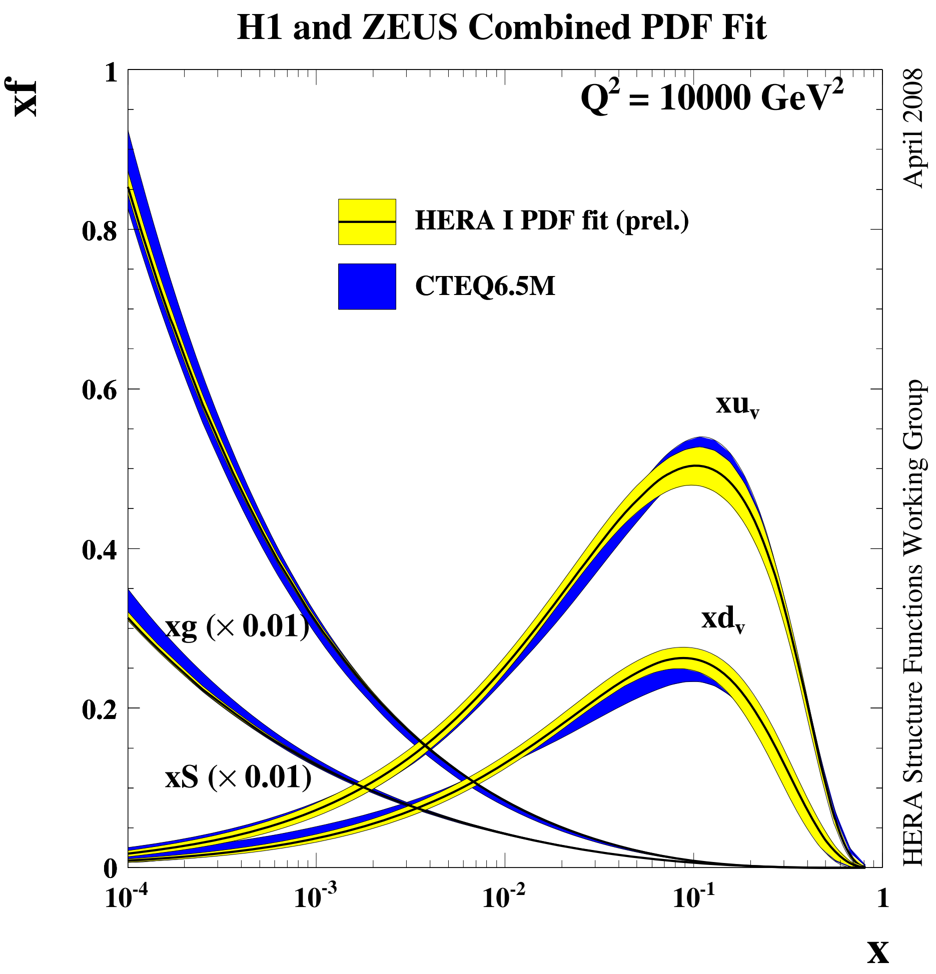

H1 and ZEUS Combined PDF Fit

- **Significant improvement in precision of PDF extraction holds even at large Q^2 of ~10000 GeV^2, where LHC concerns.**

- Remind: only partial data is used in combination
➔ Even more improvement will come!

See backup slides for a study of impact to LHC W/Z

① Gluon
② Small x evolution

Small x

- HERA PDF in previous slide would be the best-so-far determination of gluon
- However, gluon is mainly obtained indirectly via $d\ln F_2/d\ln Q^2$

  → Cross check with other processes which have direct sensitivity to gluon is vital

- There is also an another question: is DGLAP valid at small x in the first place ?

  * In QCD large log correction emerges if there are > 1 scales in the problem

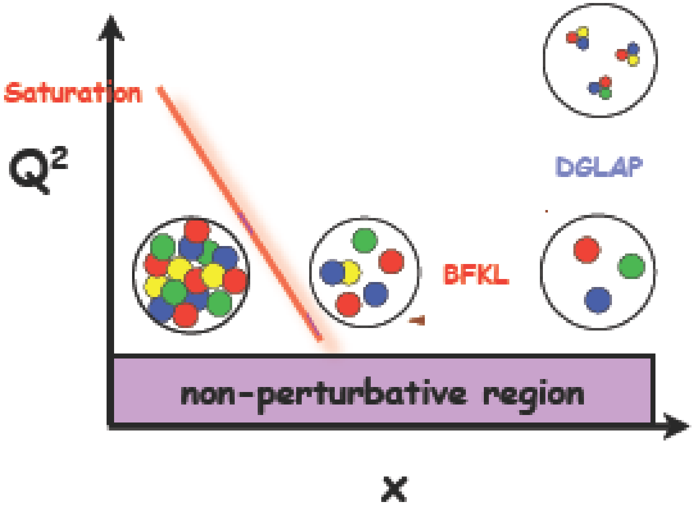
  -- If x is not so small, there is only one scale, $Q^2 \sim s$

  -- However, if x << 1, large log correction emerges in perturbative series, $\ln Q^2/s \approx \ln x$

$$\boxed{s = Q^2(1/x - 1)}$$

* DGLAP eq. accounts only for Q^2 evolution, i.e. resummation of ln Q^2

→ Effect due to resummation of ln x ("BFKL") may manifest itself at small x



① Gluon
② Small x evolution
-- Direct F_L measurement

F_L

Spin ½ parton contribution ➔

$$F_2 = \frac{Q^2}{4\pi\alpha^2}(\sigma_L + \sigma_R)$$

Spin 1 parton contribution ➔

$$F_L = \frac{Q^2}{4\pi\alpha^2}\sigma_L$$

- F_L is an another SF:

$$\frac{d^2\sigma}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}Y_+\{F_2 - \frac{y^2}{Y_+}F_L\}$$

※ Why two structures?

→ As seen differently from the two states of the probe γ^* (L, T)

- F_L =0 at naïve Quark-Parton-Model, i.e. w/o QCD
  → Non-zero F_L value can be directly related to parton dynamics inside proton
- F_L at small x is particularly interesting as it is a very good test of small x parton dynamics / evolution
  ➔ HERA is the only place where F_L can be measured at small x
- How can we measure?
  -- 2 unknowns in cross section formula → needs >= 2 values to solve
  ➔ Needs >= 2 cross sections at a same (x,Q^2), i.e. different center of mass energies (different y)

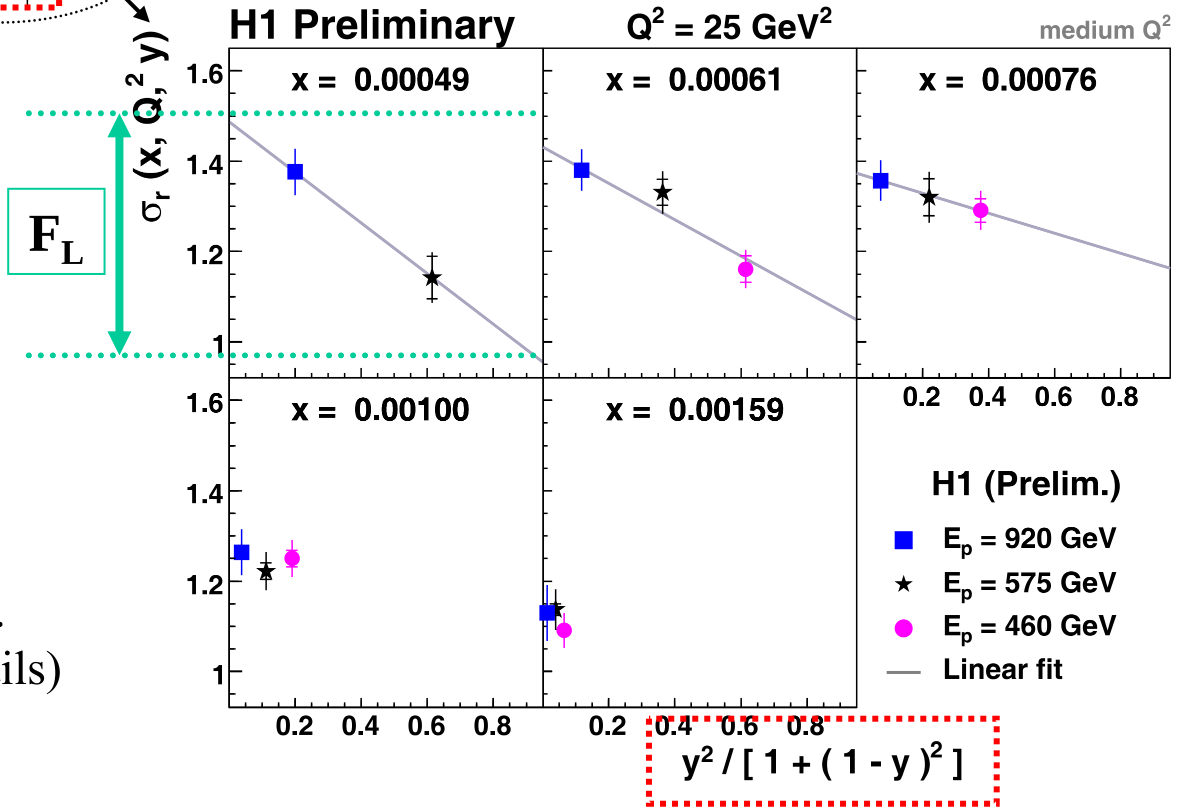
① **Gluon**
② **Small x evolution**
-- Direct F_L measurement

Direct measurement of F_L

★ **NEW Prel.**
@ DIS '08
("mid-Q2"
submitted to PLB)

- The last 3 months of HERA operations (Mar-June '07) were dedicated to special runs with lowered proton beam energy: -- Ep=460 GeV : ~ 15 pb^{-1}
  -- Ep=575 GeV : ~ 7 pb^{-1}
  (Nominal: Ep=920 GeV)

$$\frac{d^2\sigma}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4} Y_+ \{ F_2 - \boxed{\frac{y^2}{Y_+}} F_L \}$$

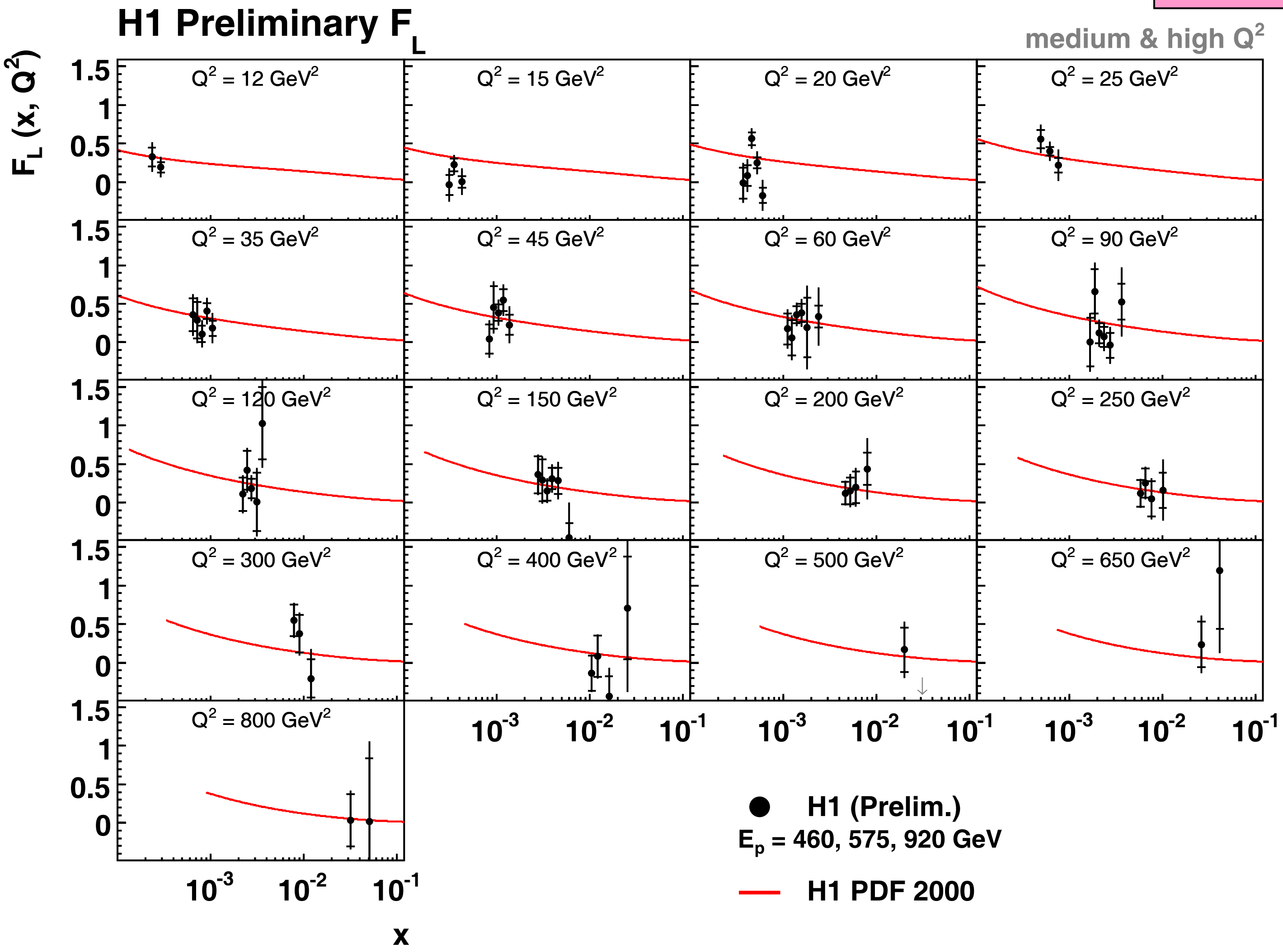


- Experimental challenges to measure cross sections up to large y
  - -- Large y corresponds to small energy of scattered electron
  - → Large backgrounds, energy scale, electron identification etc.
  (see backup slides for details)

① **Gluon**
② **Small x evolution**
-- Direct F_L measurement

Measured F_L

★ **NEW Prel.**
@ DIS '08
("mid-Q2"
submitted to PLB)

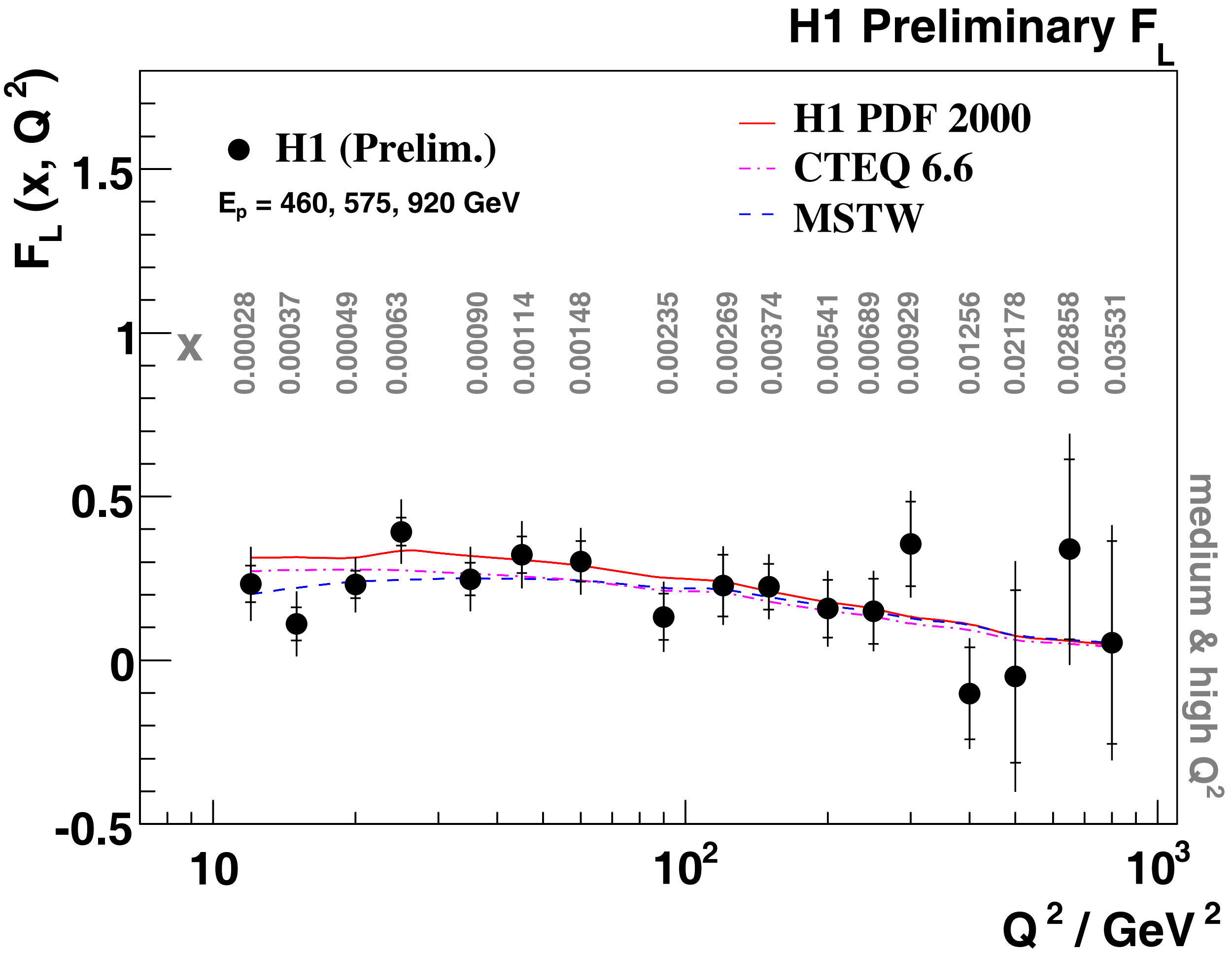


- First direct F_L measurement at small x

① Gluon
② Small x evolution
-- Direct F_L measurement

Measured F_L vs Q^2

★ NEW Prel.
@ DIS '08
("mid-Q2"
submitted to PLB)



- F_L predicted by QCD fits using gluon that was derived from scaling violation of F_2 is consistent with the measurement

① **Gluon**
② **Small x evolution**
-- Direct F_L measurement

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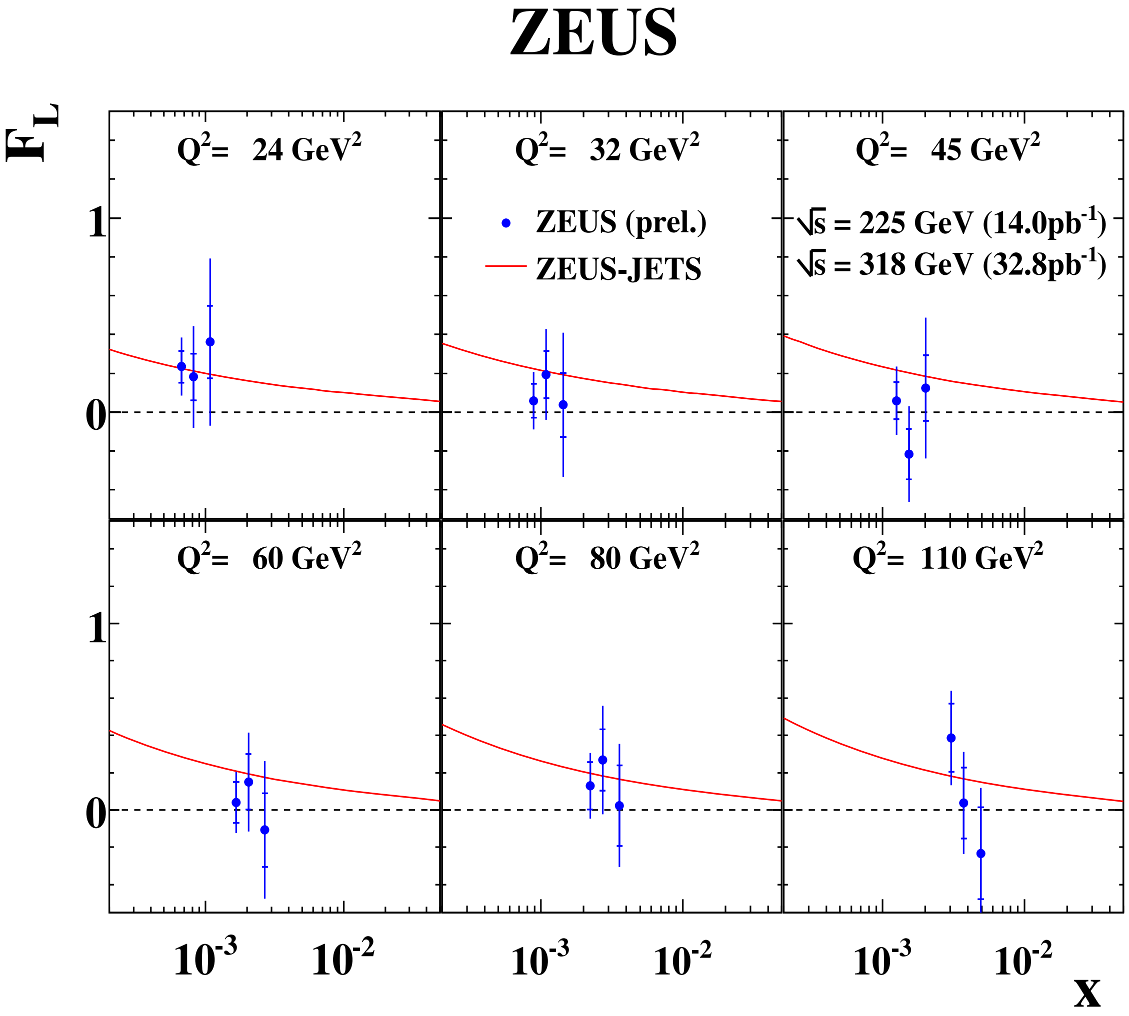
Measured F_L [ZEUS]

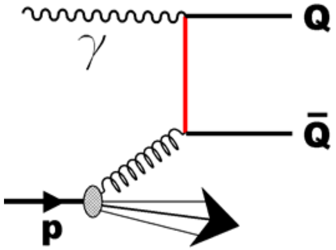


- Measurement consistent with QCD fit F_L prediction as well as with F_L=0 within large uncertainties

① Gluon
③ Flavor decomposition
-- F_2^{cc}, F_2^{bb}

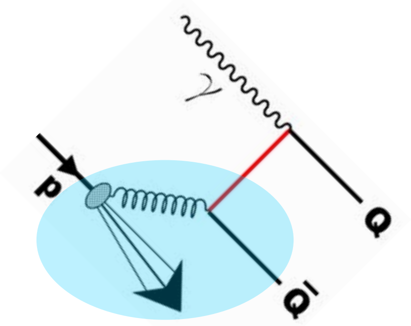
Heavy quark PDFs and gluons

- Other cross check of gluons and QCD dynamics : heavy-quarks
  -- Sensitive to gluon and heavy-quark PDFs altogether



c massive

→ **Test / determine gluon PDF**

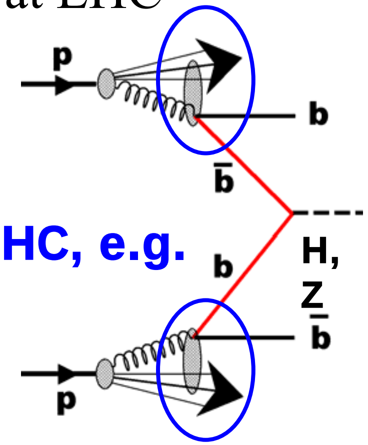


c massless
($Q^2 >> m_c^2$)

→ **Determine Heavy quark PDF**

- Heavy-quark PDFs at large scale is also important at LHC
  -- For particular type of new physics search

LHC, e.g.



① Gluon
③ Flavor decomposition
-- F_2^{cc}, F_2^{bb}

F_2^{cc} : Charm contribution to total F_2

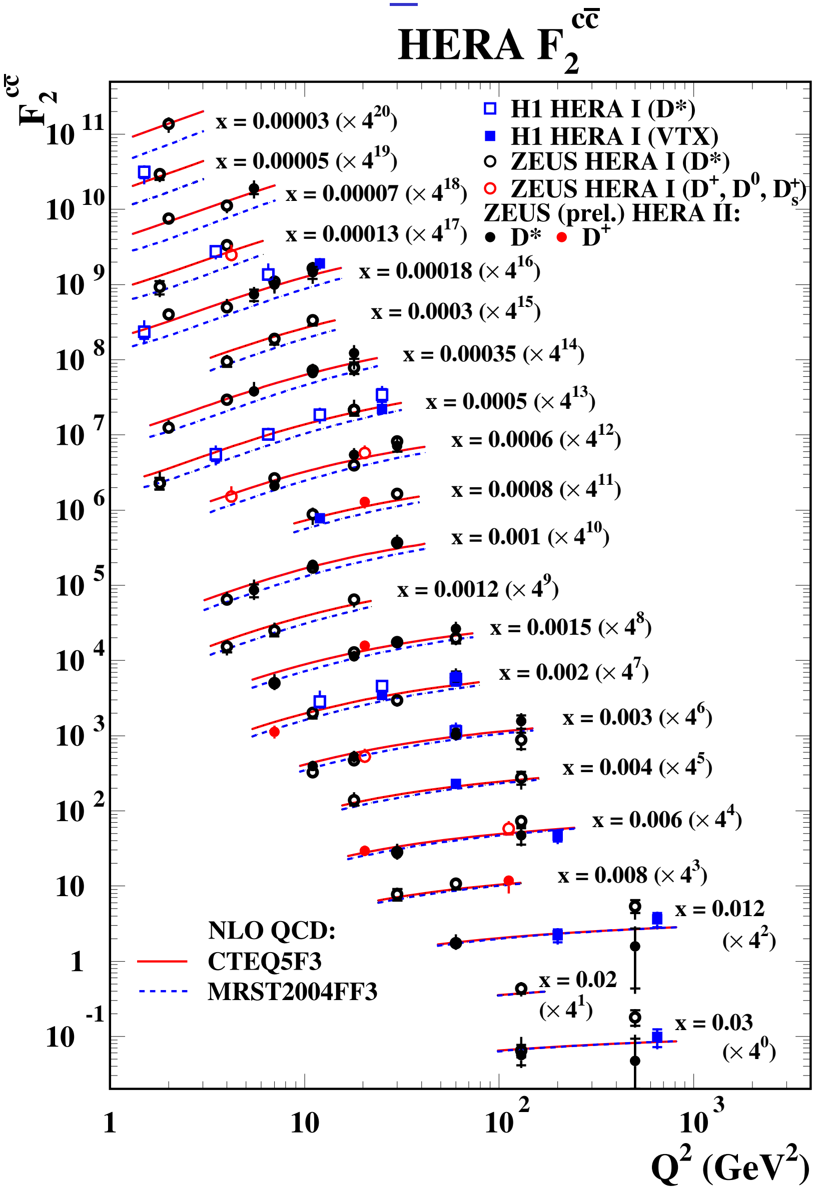
★ NEW Prel. @ LP '07

- D*→ K π π

- H1: Inclusive Impact Parameter tagging in VTX
- ZEUS: Signed 2D decay length in MVD to tag D^{+-}, D^0

→ Good agreement in different techniques
→ Agree with NLO within uncertainties (expect to start to constrain PDFs)

Note: only partial data is used
➔ Precision will improve (luminosity ~2-5 times)



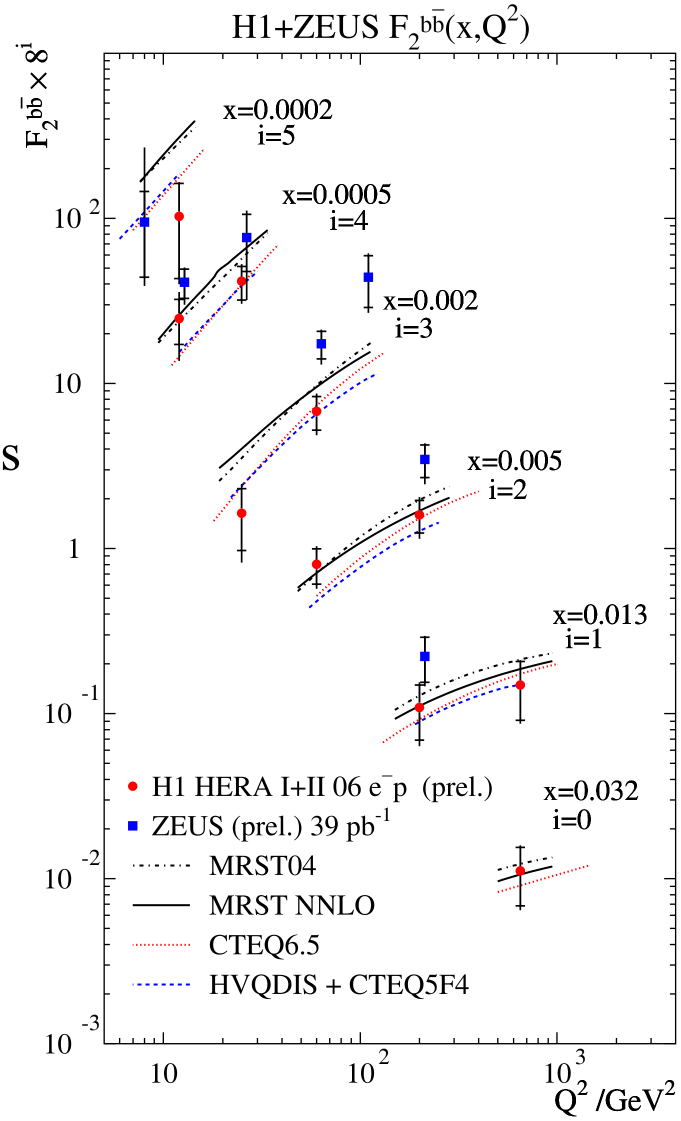
① Gluon
③ Flavor decomposition
-- F_2^{cc}, F_2^{bb}

★ NEW Prel.
@ LP '07

F_2^{bb} : Bottom contribution to total F_2

- H1: Impact Parameter tag
  ZEUS: μ + jet
- First measurement of F_2^{bb}
- Large spread in theoretical predictions
- Current data is not conclusive
  -- Only partial data is used

➔ Prospect in result with full statistics (luminosity ~5-10 times)



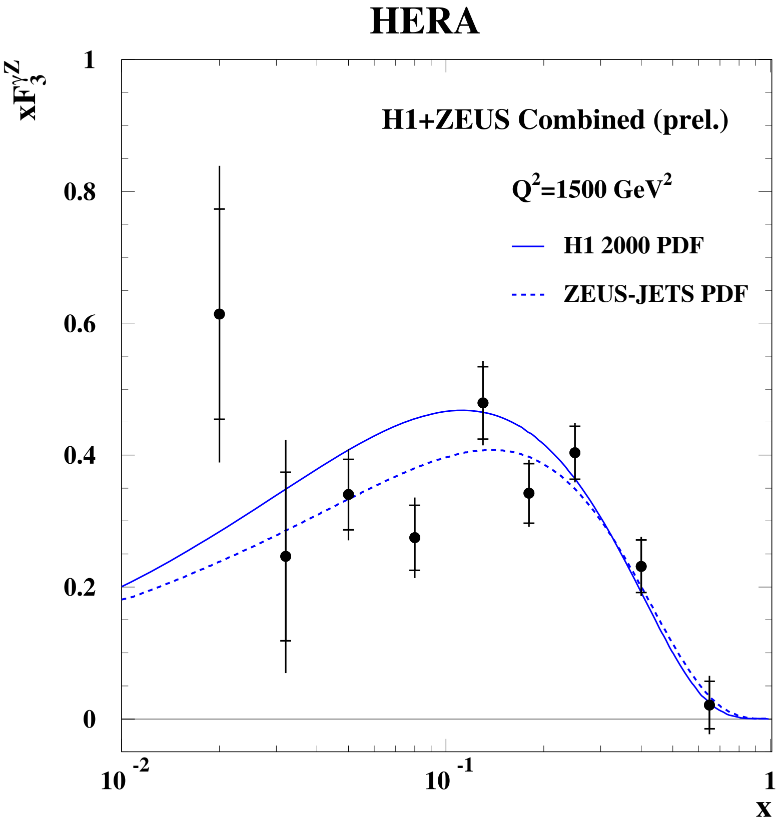
③ Flavor decomposition
-- xF_3

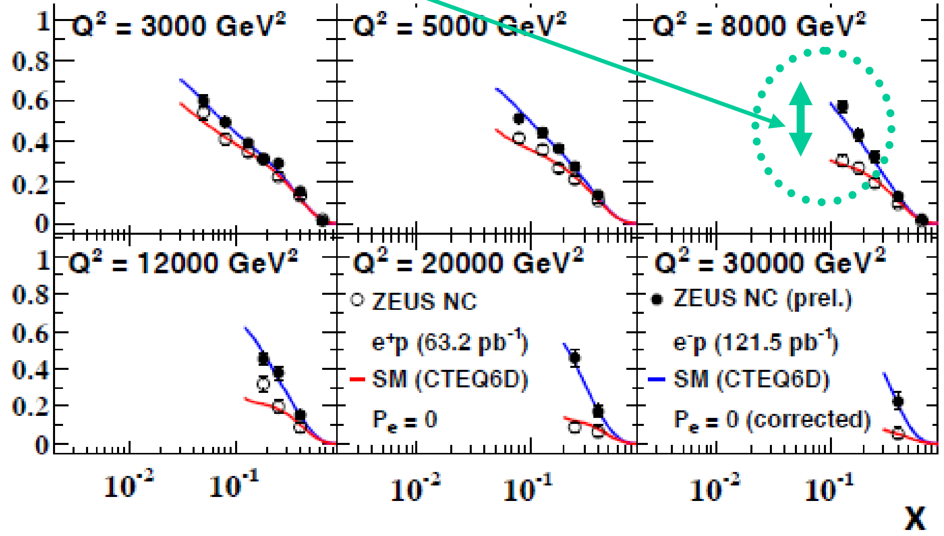
xF_3

- There is one more SF: xF_3 which is sensitive to valence quark PDFs

$$\frac{d^2\sigma(e\pm)}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4} Y_+ \left\{F_2 - \frac{y^2}{Y_+} F_L \boxed{\mp xF_3}\right\}$$

※ Why third SF?
→ As seen also by Z^0





← $$xF_3^{\gamma Z} \approx \frac{x}{3}(2u_V + d_V)$$

- Valence PDFs at small x which only HERA can access by now
  -- Impact to LHC W+/W- asymmetry

Prospect: stat will improve (~2 times) + H1&ZEUS “Combination”

Summary

- HERA ended its run at June 2007: ~1 fb^{-1} collected by H1 and ZEUS

- HERA has provided most precise inclusive structure function measurements, which brought significant improvements to our knowledge on proton structure
  - -- In particular, a key and essential inputs to LHC, e.g. gluons at small x

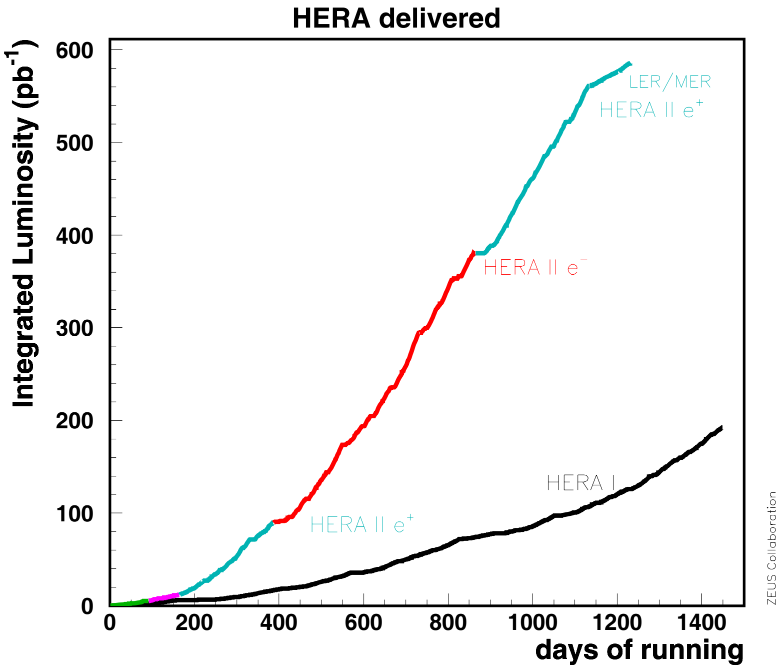
- HERA is still providing new high precision results which will further improve our understanding on proton structure
  - -- Combination of H1 and ZEUS cross-sections brought significantly improved precision of data, and hence best determined gluon
  - -- First direct measurement of F_L was performed
  - -- Precision of measurement on heavy-quark contribution to F_2 is improving

- Final publications with ultimate precision to come in the next years.

Backup

HERA Running

- HERA-I : Until year 2000
  - Unpolarized e^+ and e^- beams
- HERA-II : from year 2002 to Mar/2007
  - High luminosity to allow more statistical sensitivity for large Q^2
  - Longitudinally polarized e+ and e- beams to allow direct sensitivity to EW
- Low Energy Run : Mar – June 2007
  - A special run with low proton beam energy (460, 575 GeV) to measure "F_L" structure function

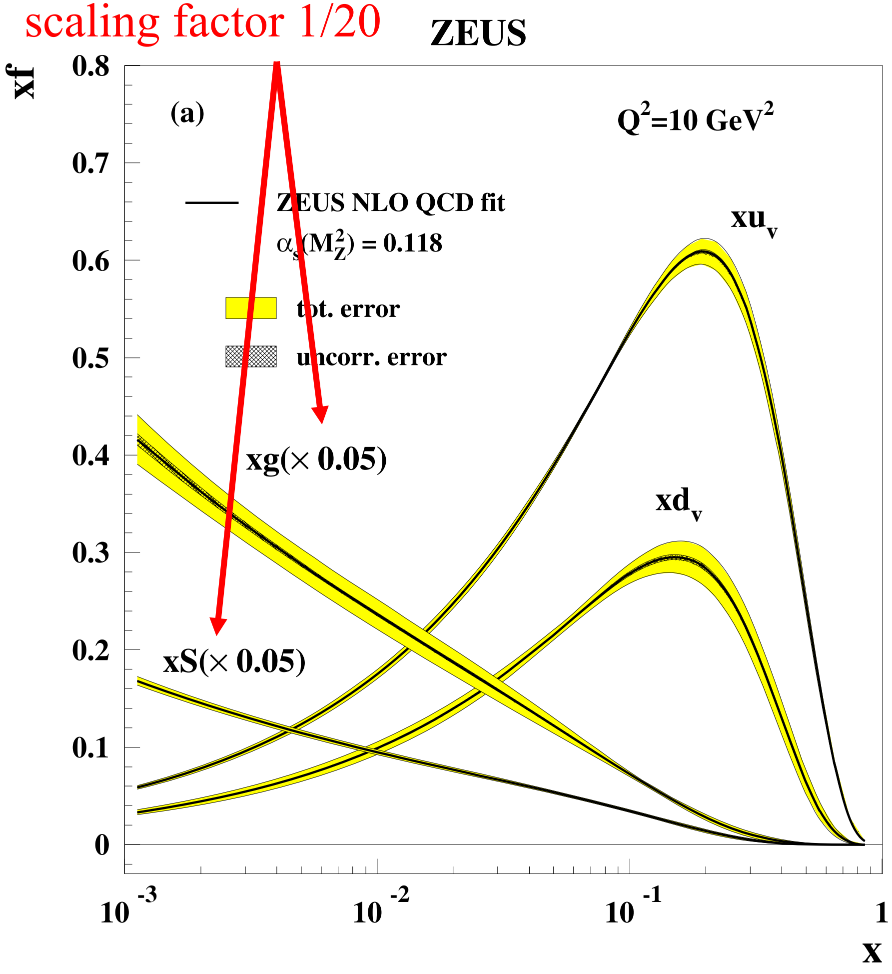


	HERA-I	HERA-II
e^-	~20 pb^{-1}	~200 pb^{-1}
e^+	~100 pb^{-1}	~200 pb^{-1}

1 fb^{-1} collected by H1+ZEUS

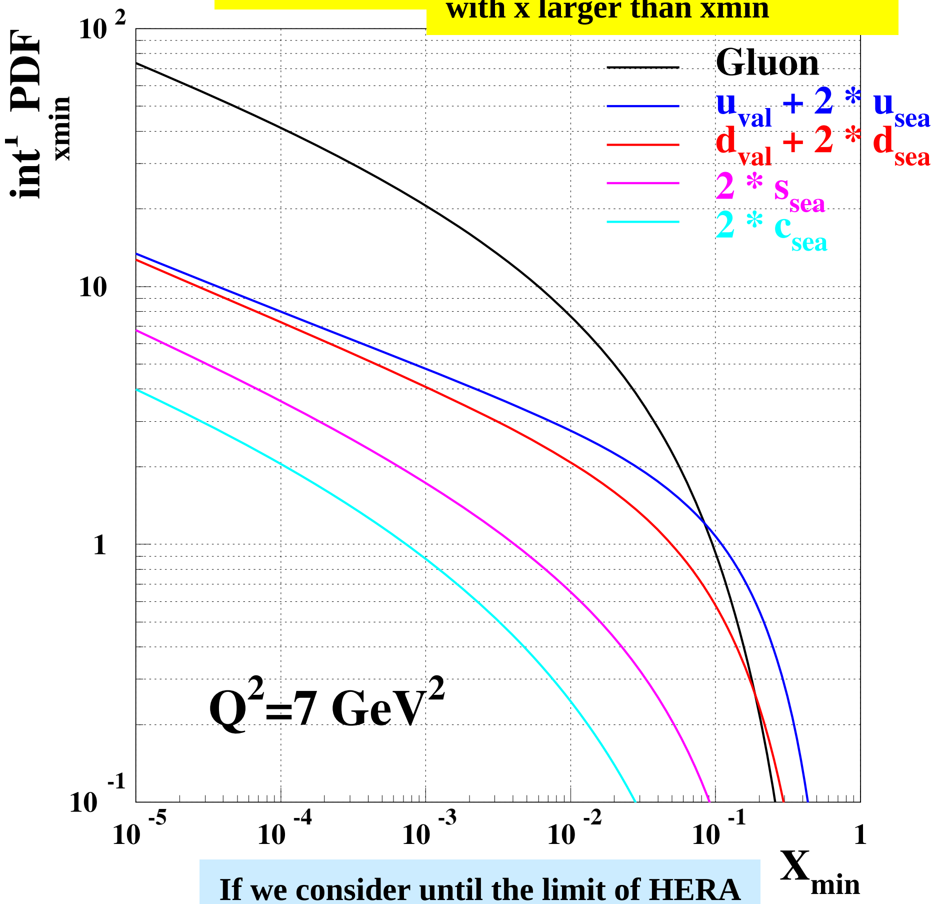
PDF

Notice that they are plotted with scaling factor 1/20



$$\int_{x_{min}}^{1} f_q(x)\,dx$$

i.e. how many partons are there with x larger than xmin



If we consider until the limit of HERA kinematic phase space, there are
~60 gluons
~30 quarks and anti-quarks
in a single proton

There are many of gluons and quarks with small x in a proton

Method to combine H1&ZEUS

► An idea to use Hessian method without theory assumption
-- Fit each cross section values at each (x, Q^2), rather than to fit theory parameters (PDFs for instance)

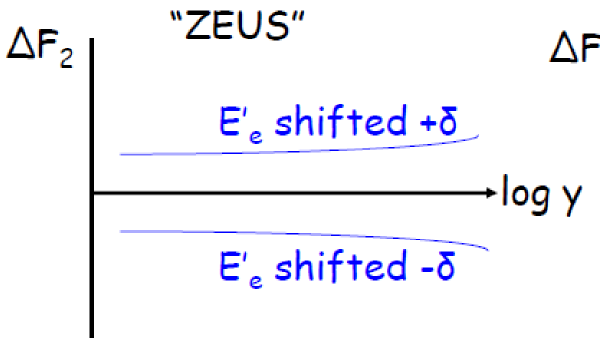
554 data points each from ZEUS and H1

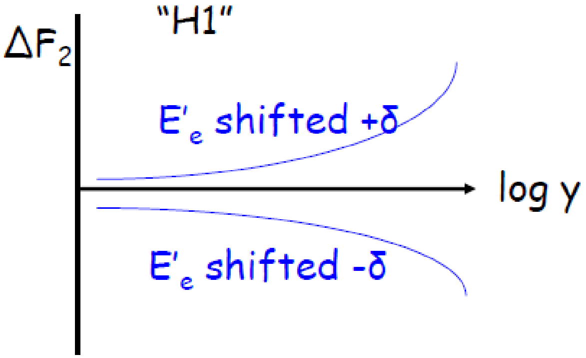
Fit for data points (554 of them)

And j systematic uncertainties

$$\chi_e^2(\{\mu\},\{r\}) = \sum_{i=1}^{N}\left(\frac{m_i^e - \mu_i - \sum_{j=1}^{Ke}\beta_{ji}^e r_j^e}{\sigma_i^e}\right)^2 + \sum_{j=1}^{Ke}\left(r_j^e\right)^2$$

m_i^e = measured cross section in bin i by exp e
μ_i^e = true cross section in bin i
σ_i^e = statistical uncertainty in bin i by exp e
β_{ji}^e = correlated syst. unc. in bin i by exp e
$s_i, r_j \sim N(0,1)$



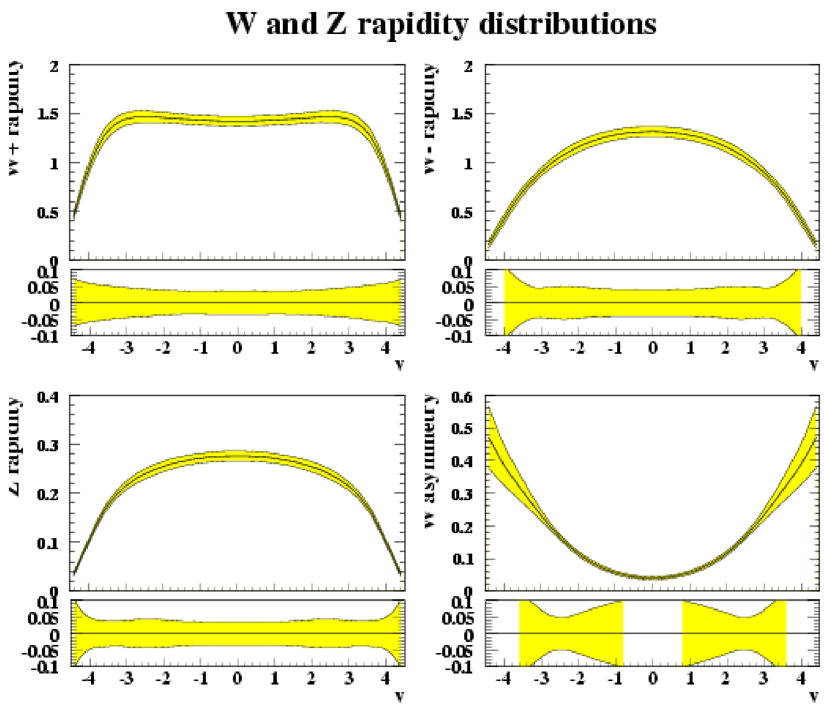


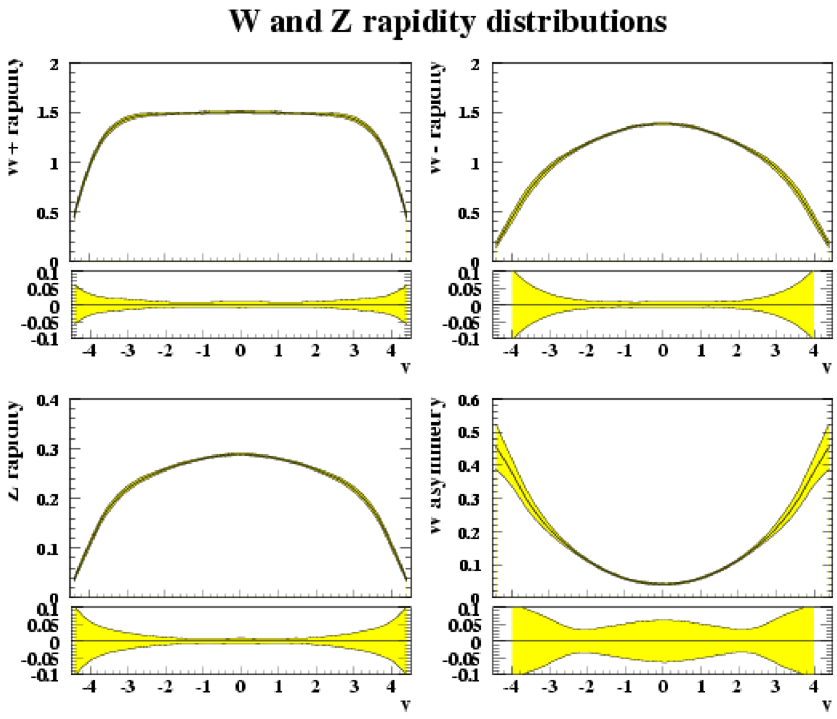
➔ Cross calibration. Can get reduction of systematic errors if
-- Similar size of errors but different “shape”

① Gluons
③ Flavor decomposition
-- “Combined F_2”

“HERA PDF”: Impact to LHC W/Z

★ Work by
A. M. Cooper-Sarkar
★ NEW
@ HERA-LHC WS ‘08


W and Z rapidity distributions


W and Z rapidity distributions

- Experimental uncertainty is now reduced to be ~1.5%
- Note: model uncertainty (systematics of QCD fit) is not yet included in the above figure. → It’s time we can think it.(Next slide)

① **Gluons**
③ **Flavor decomposition**
-- "Combined F_2"

"HERA PDF": Impact to LHC W/Z

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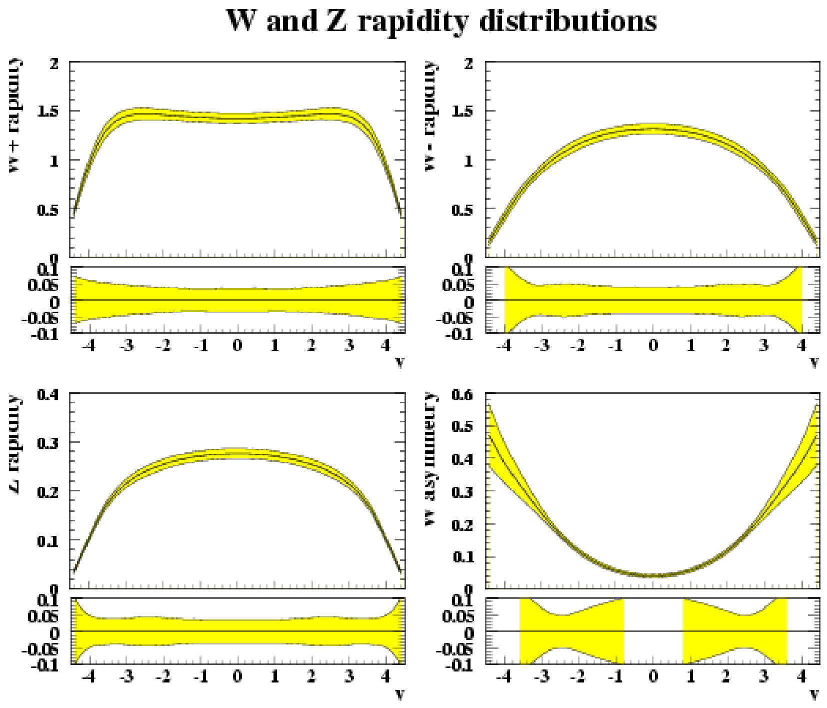
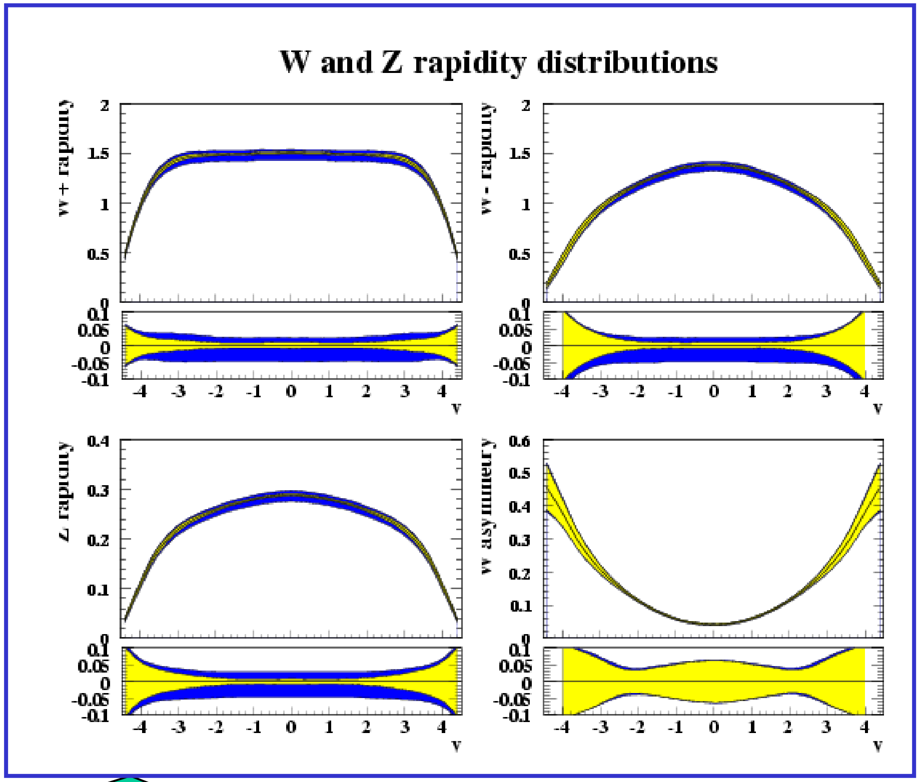




Model errors shown in blue

- Experimental uncertainty is now reduced to be ~1.5%, and they are now smaller than model uncertainty (~3%)

① Gluons

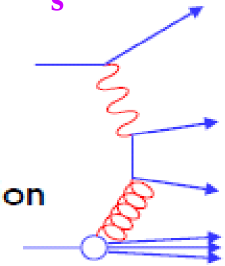
-- Gluons from Jets at HERA

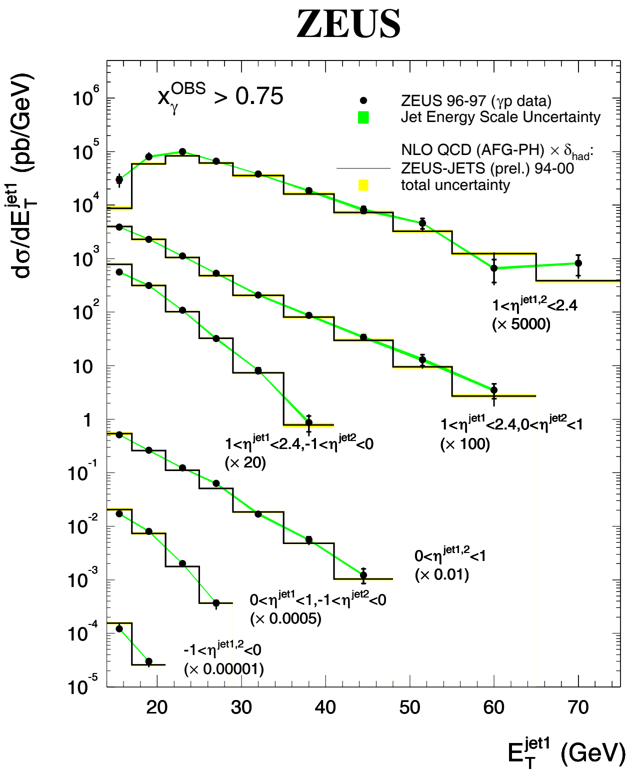
NLO QCD fit including Jets

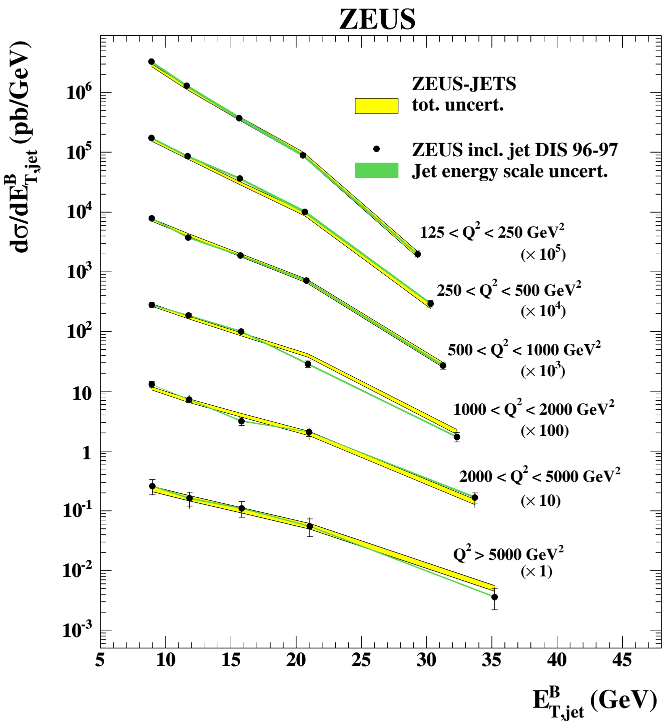
Photoproduction (Q^2=0) dijets gives direct access to gluon and α_s ➔

BGF

Boson Gluon Fusion







🡐 DIS Inclusive jet gives general sensitivity to gluon and α_s

※ A first fit to use HERA data only but HERA SFs + HERA Jets

① Gluons
-- Gluons from Jets at HERA

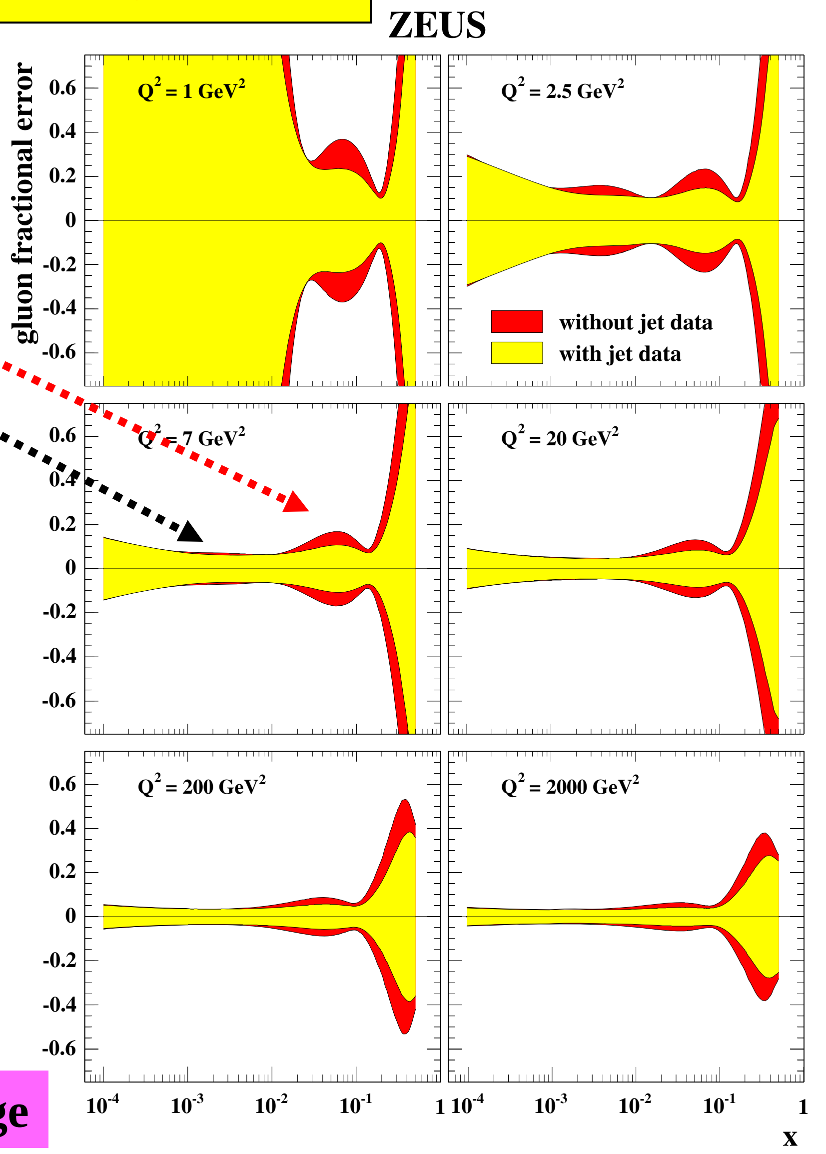
Errors of Gluon PDFs

► Gluon determination improved at Medium-x: 0.01-0.3 owing to Jets

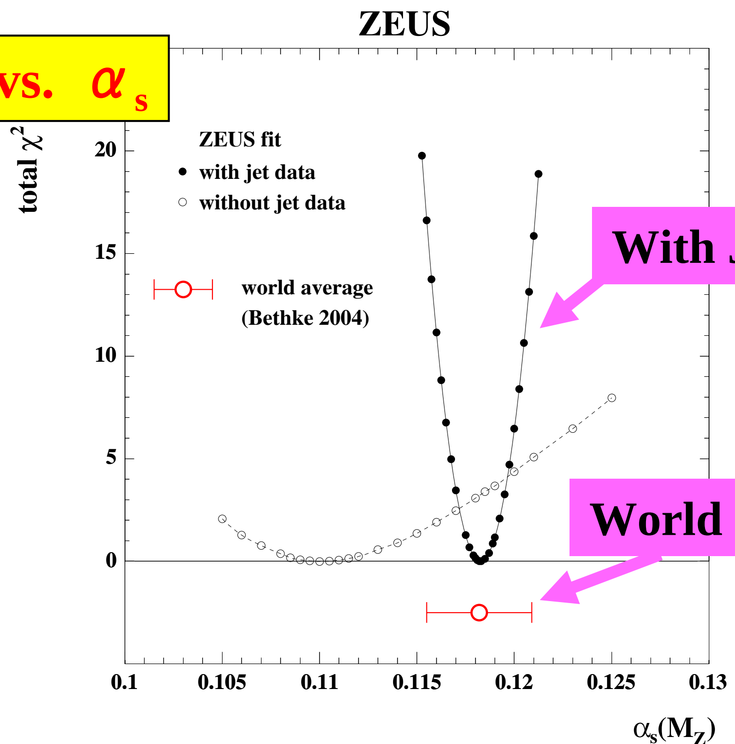
► Also, jet helps to constrain α_s :
➔ alpha_s was determined precisely compatible as the world average!

W/O Jets

With Jets



χ^2 vs. α_s



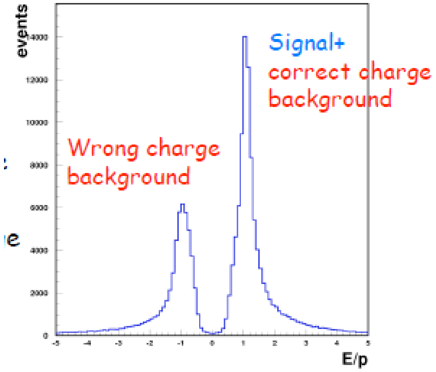
With Jets

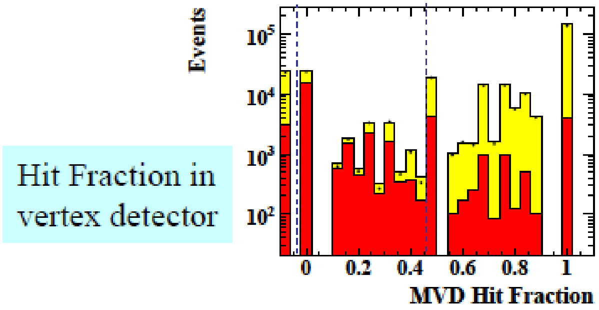
World average

① **Gluon**
② **Small x evolution**
-- Direct F_L measurement

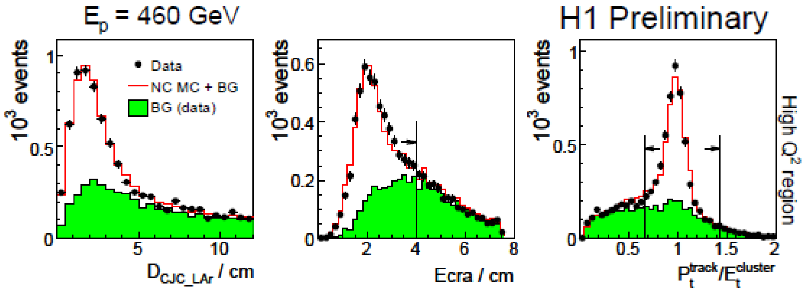
Technical issues in measuring F_L

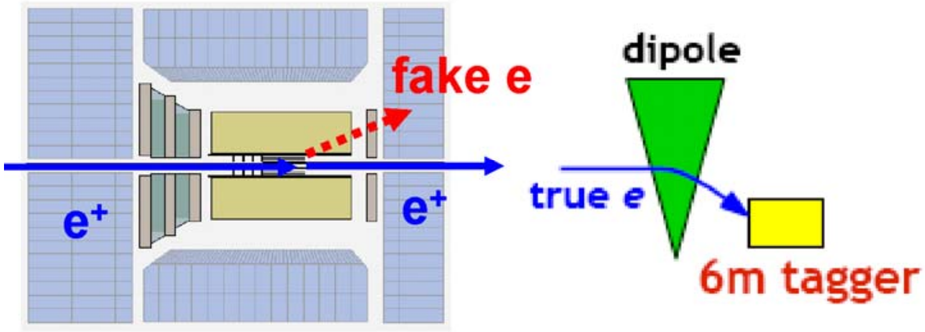
- High-y events are also experimentally very challenging, as huge photoproduction (Q^2=0) backgrounds are foreseen.





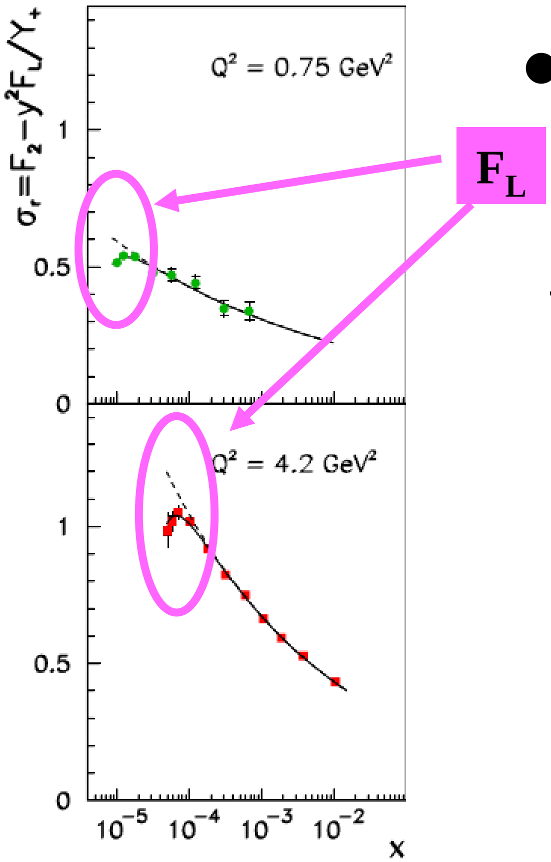
Slides still under construction





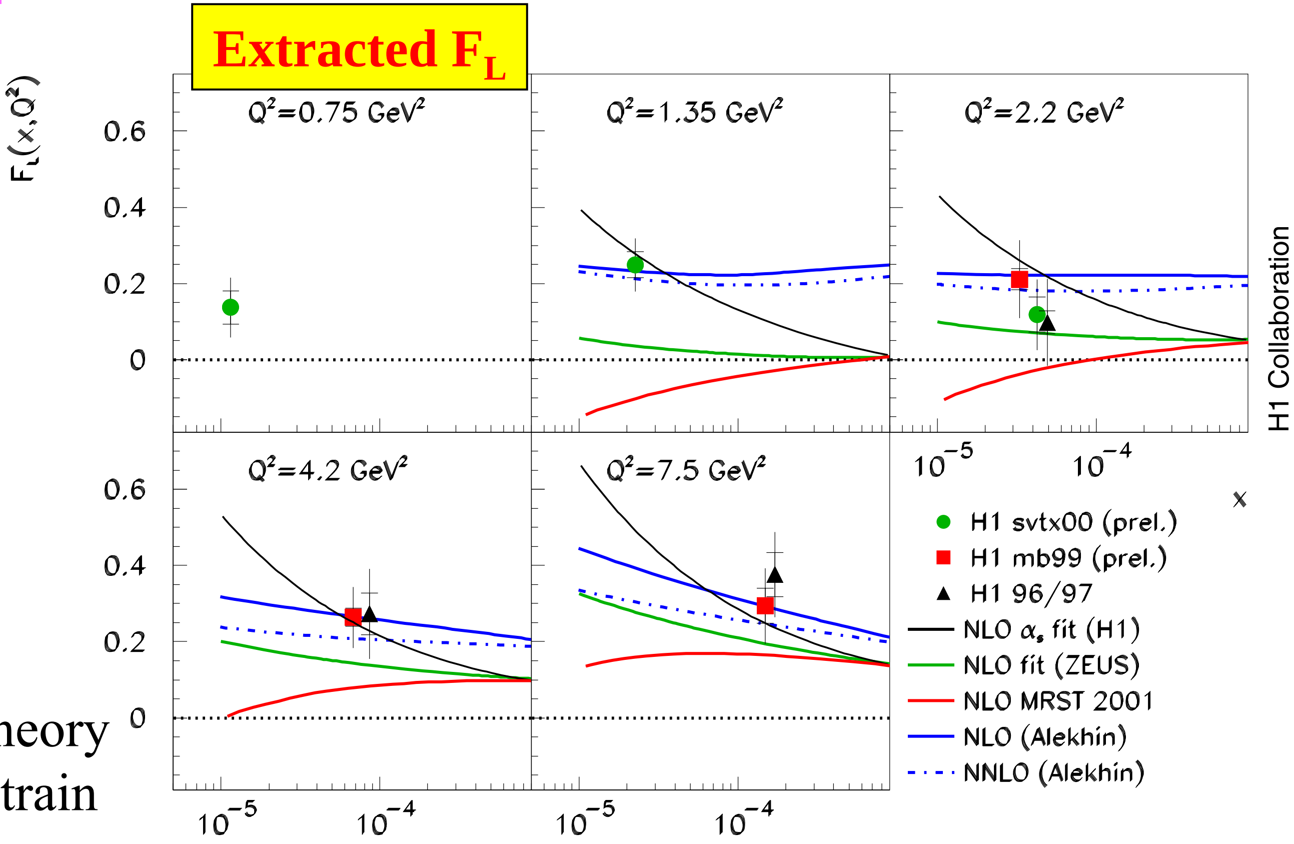
① Gluons
② Small x evolution
-- Direct F_L measurement

Model-dependent extraction of F_L



- "Shape Method" : Fit cross sections with: $\sigma = F_2 - \frac{F_L}{Y_+}$

  → λ is extrapolation from low-y $F_2 = x^{-\lambda}$

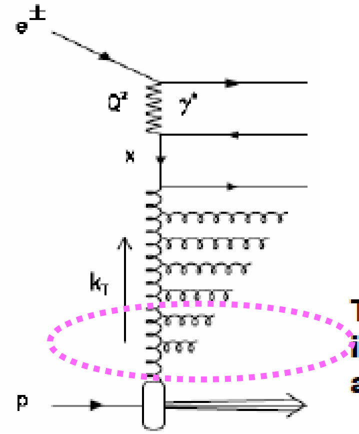


▶ Large uncertainty in theory

➔ Data will help to constrain

※ This is not a model-independent extraction

Small x and Forward Jet

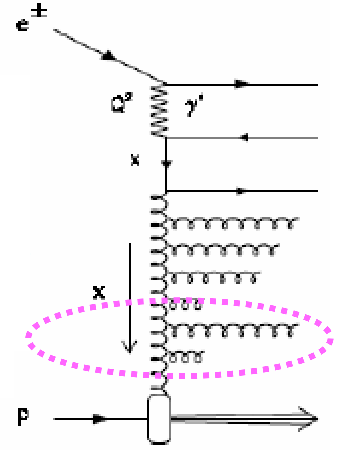


DGLAP

Evolution & resummation in powers of *lnQ2*

$$Q^2 >> k_{T,n}^2 >> \dots >> k_{T,2}^2 >> k_{T,1}^2$$

The DGLAP gluon cascade is strongly ordered in k_T and ordered in x



BFKL

Evolution & resummation in powers of *ln(1/x)*

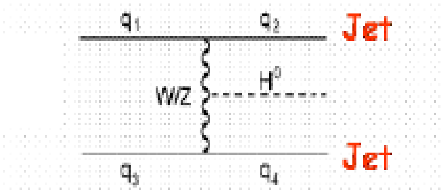
$$x_1 >> x_2 >> \dots >> x_n >> x$$

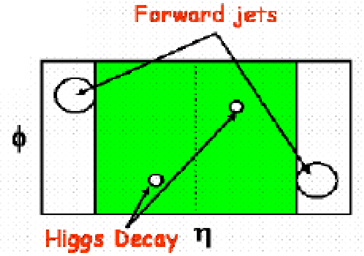
The BFKL is only strongly ordered in x

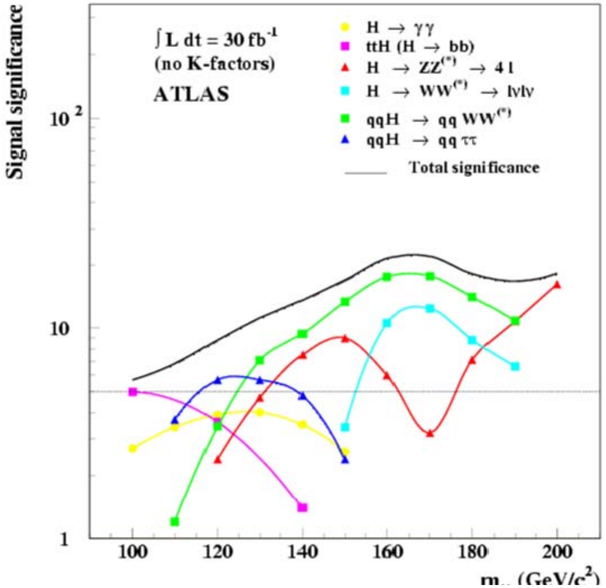
Forward jet:

$x_{jet} = E_{jet} / E_p$, large if BFKL

- ► How it relates to LHC?







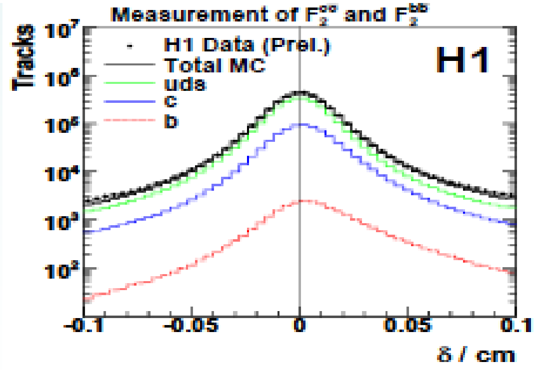
VBF is a most promising channel for Light Higgs search

-- Forward high p_T jet

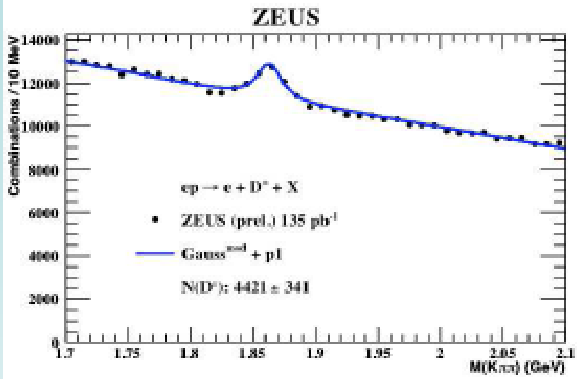
① Gluon
③ Flavor decomposition
-- F_2^{cc}, F_2^{bb}

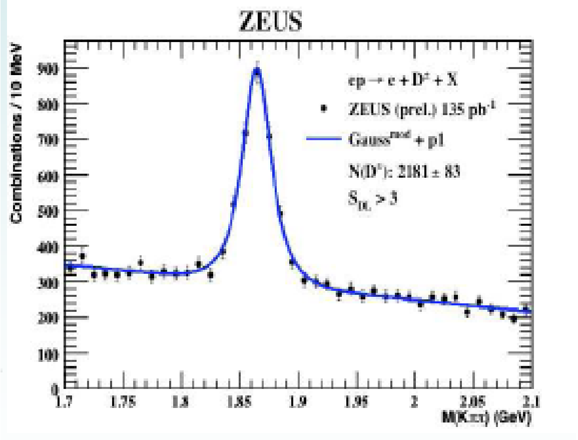
F_2^{cc}

- H1: Inclusive Impact Parameter tagging in VTX



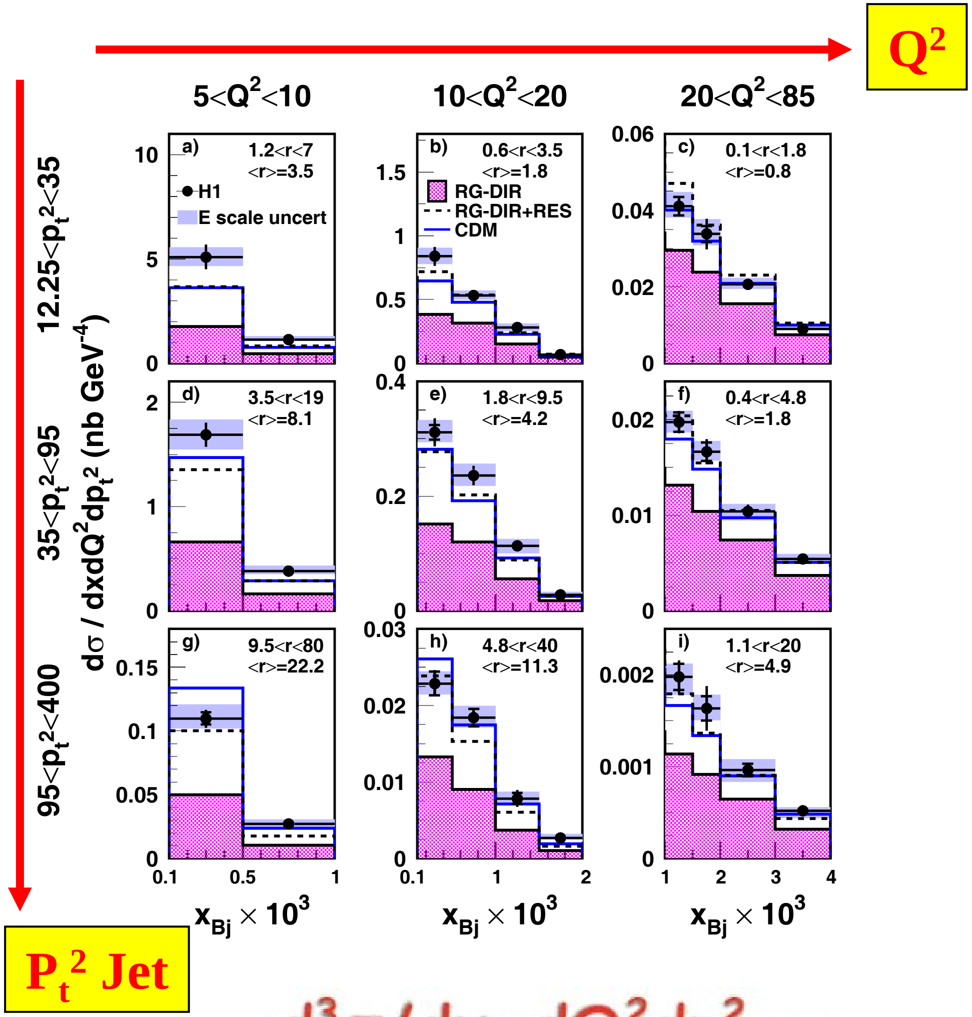
- ZEUS: Signed 2-D decay length in MVD for D+-, D0 identification





③ Small x
-- Forward Jet

Forward Jet @ HERA



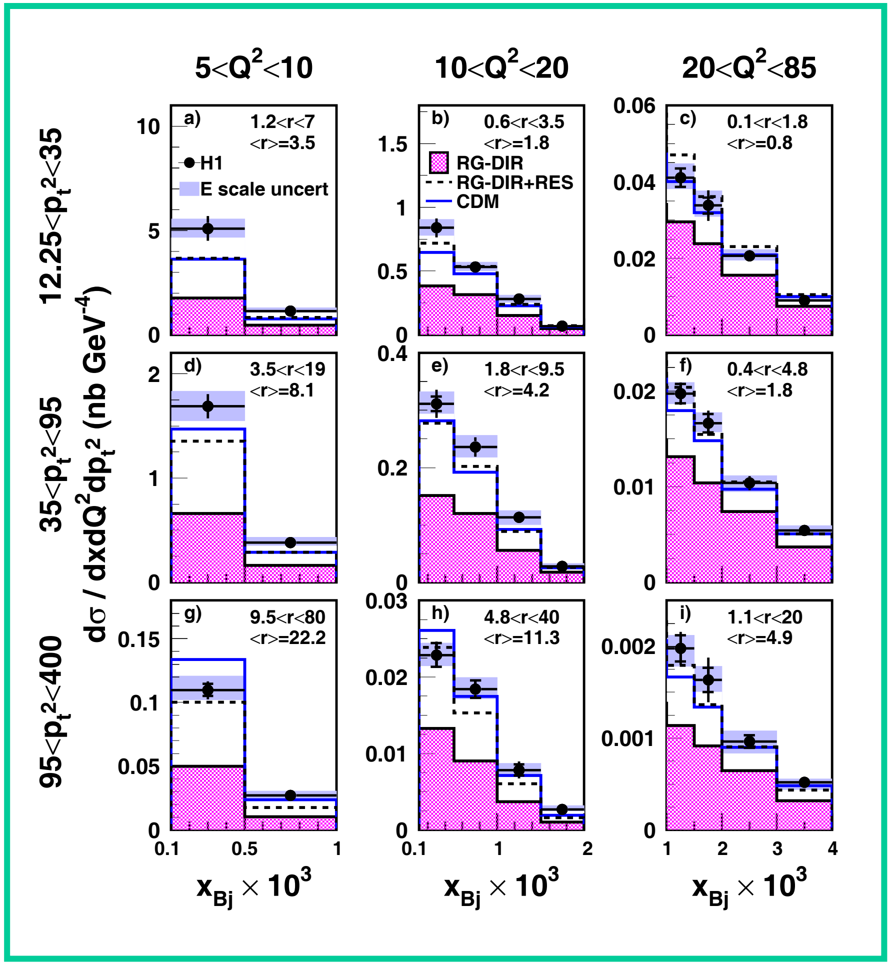
$d^3\sigma/dx_{Bj}dQ^2dp^2_{t,jet}$

- Large K-Factor
- Not sufficient yet with NLO

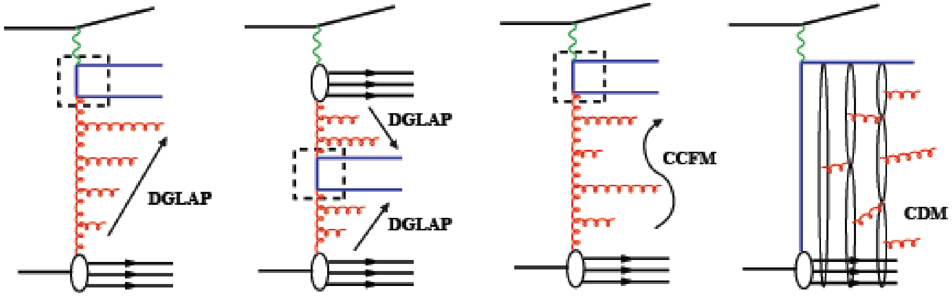
➔ How QCD Models describe (Next slide)

③ Small x
-- Forward Jet

Forward Jet @ HERA: QCD Models



(the same plot as in previous page)



Rapgap DIR

Rapgap DIR+RES

Cascade
CCFM

ARIADNE
CDM

- Resolved: Supply part of missing phase space as evolution from photon
- CDM: Emit gluons isotropically
- CCFM: Angular ordering evolution

→ CDM best describes data.

Higher order effects missing in NLO can be recovered by appropriate QCD models to some extent, but no conclusive theories / models