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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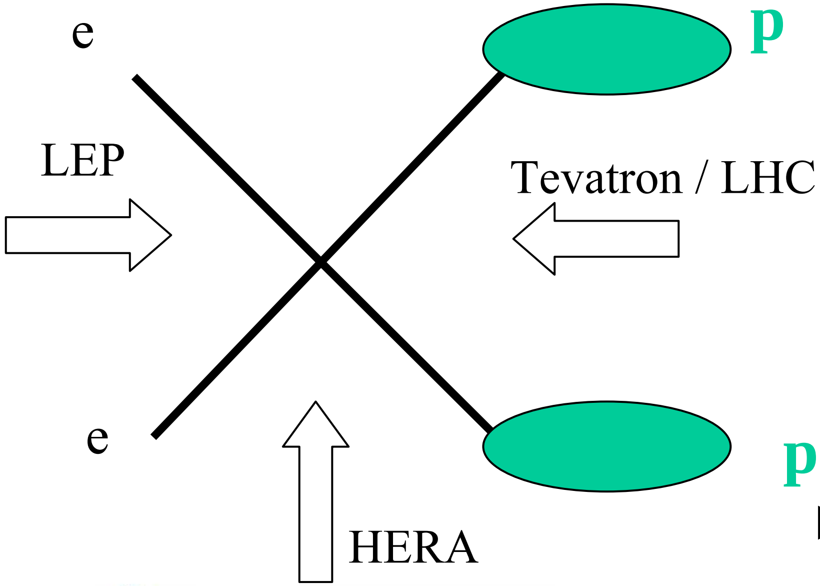
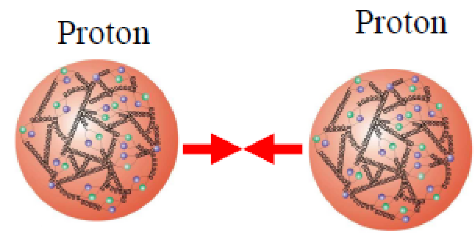
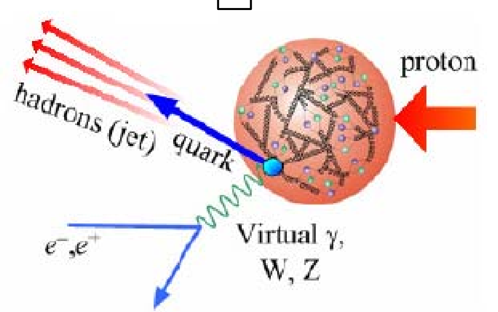
HERA and Hadron Colliders





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



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

- 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

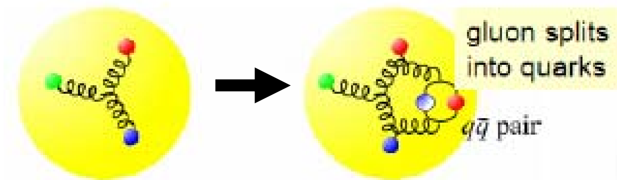
$$F_2 = x\Sigma e_q^2 (q + \bar{q})$$

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

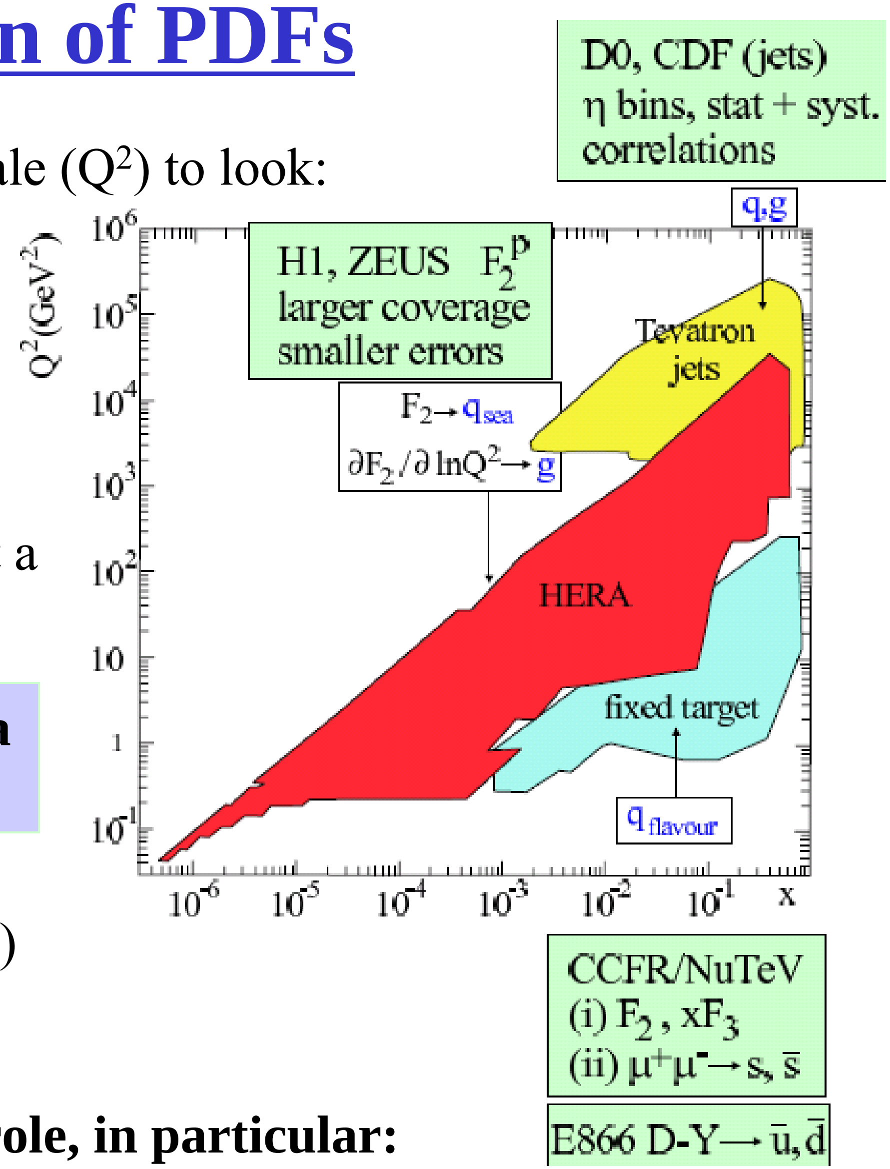
- **Quarks and antiquarks (spin ½) PDFs**
  → Directly sensitive to cross section
- **Gluon (spin 1) PDF**
  → Indirectly sensitive to cross section via Q^2 shape

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



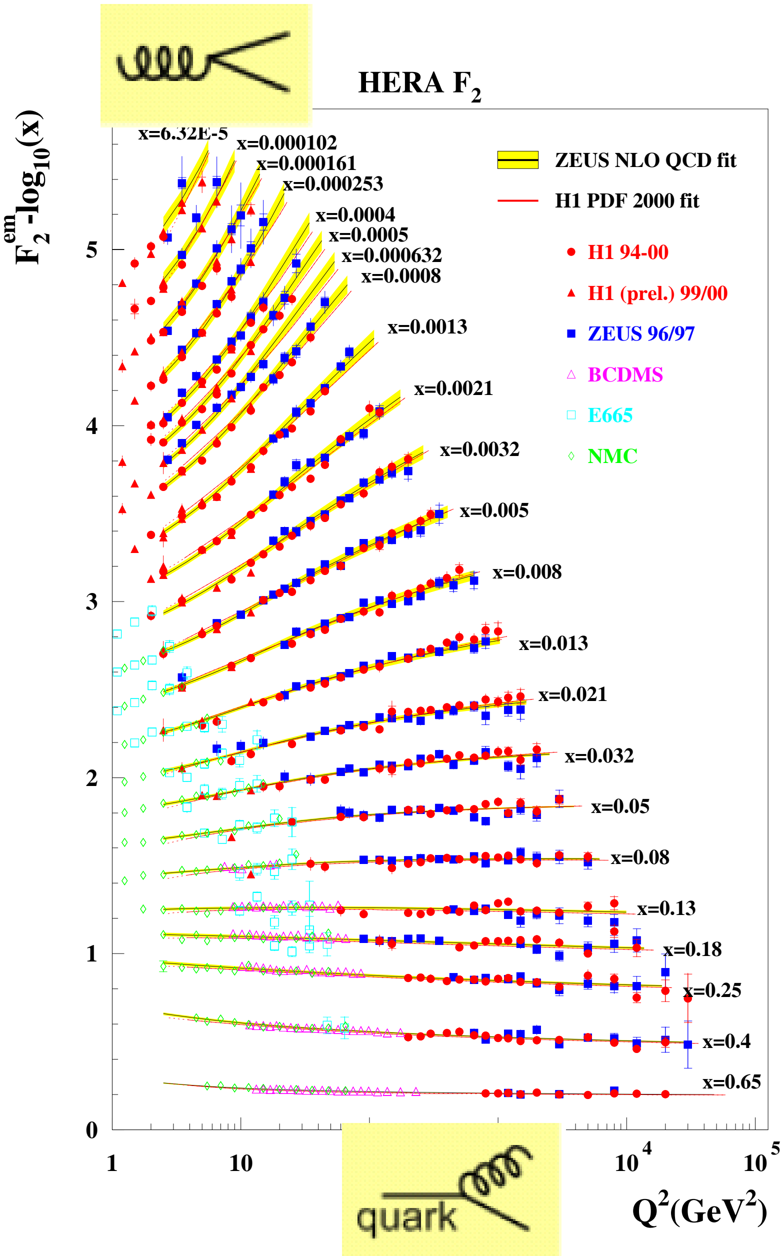
→ Initial PDFs at Q^2_0 are determined by a global fit to various experimental data.

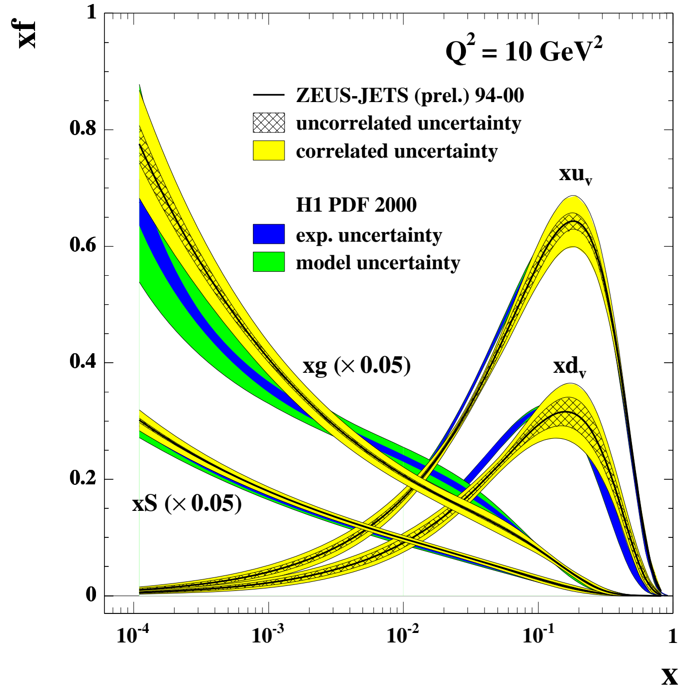
→ Needs wide kinematic range
(Notice: gluon is given by slope in *log* Q^2)
→ Universality should be checked in various processes

► **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

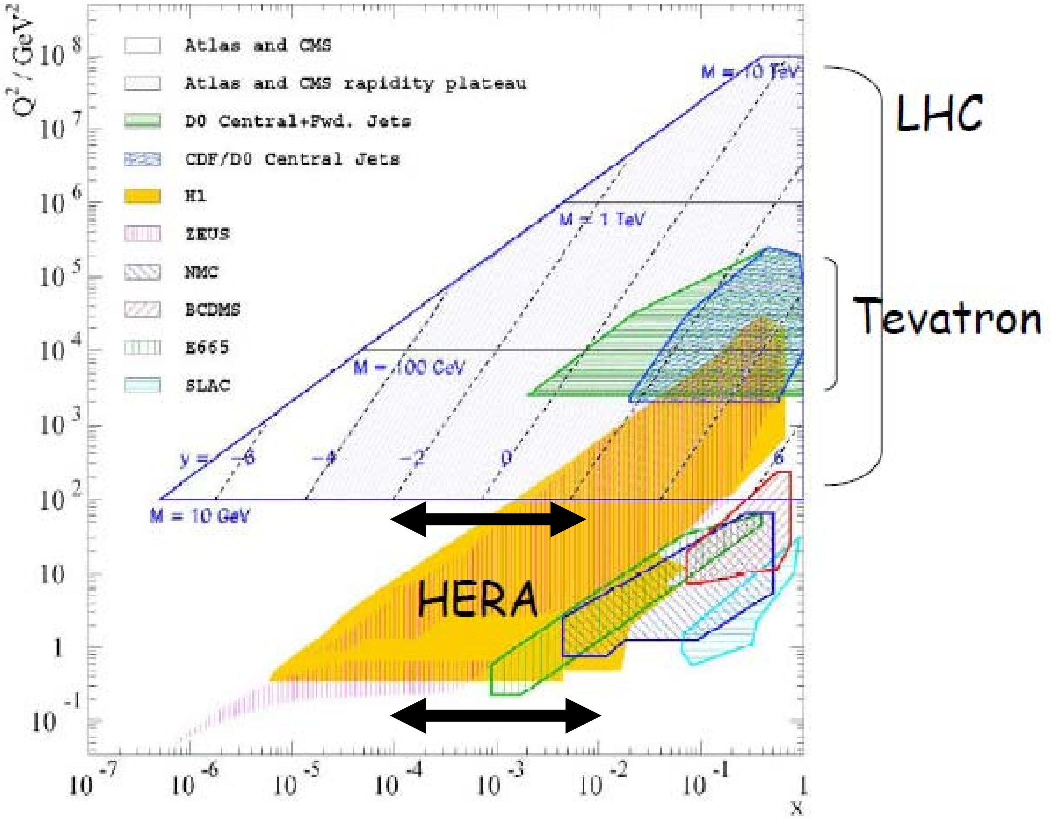
→ "Invisible" gluon as well

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

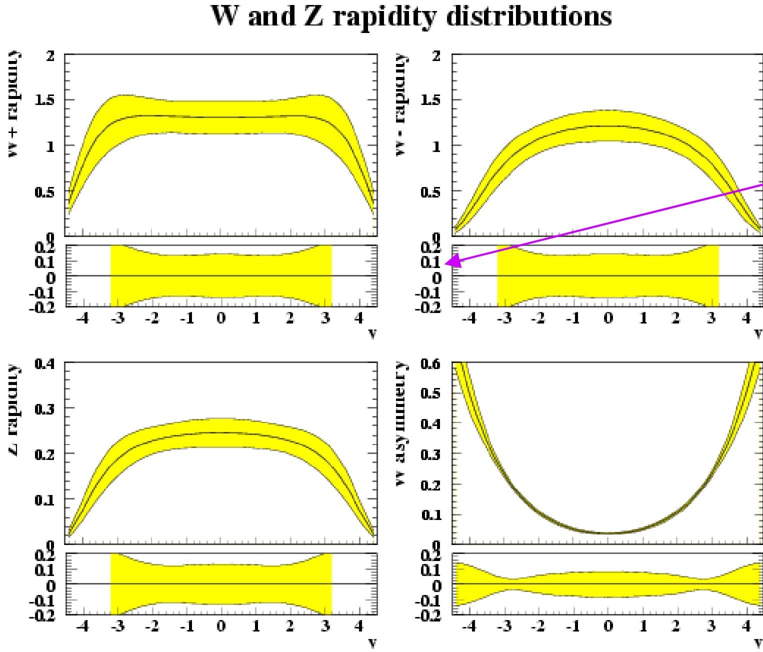
HERA provides key and essential inputs to LHC

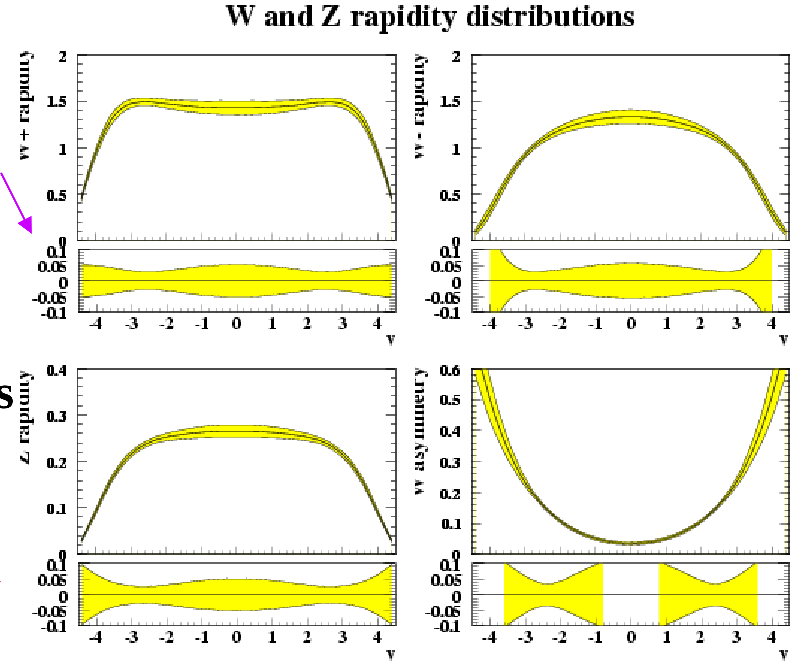


HERA data excluded

W/Z @ LHC

HERA data included

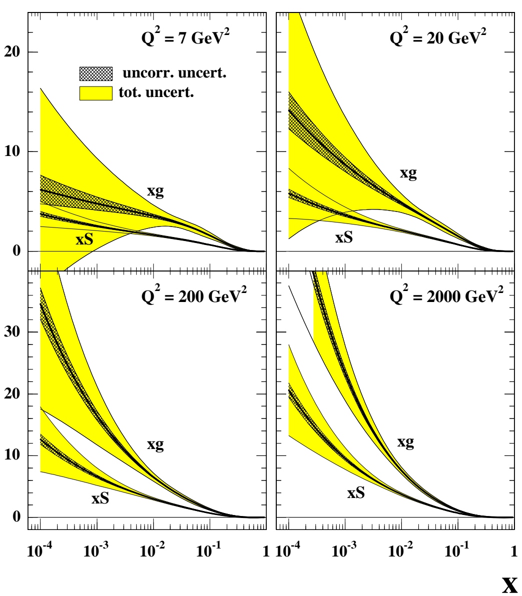




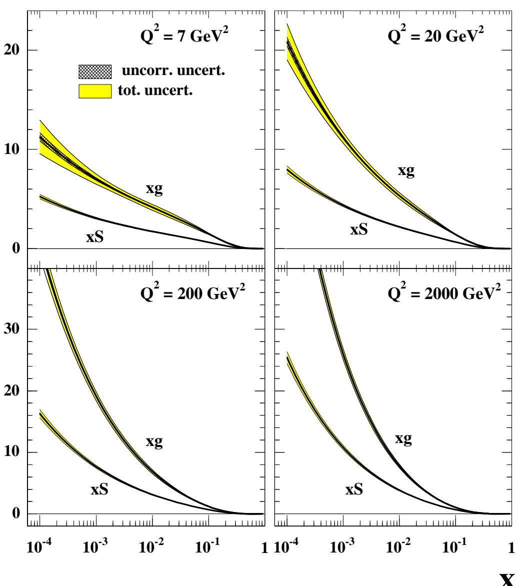
Note difference in scale for fractional errors

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?)**

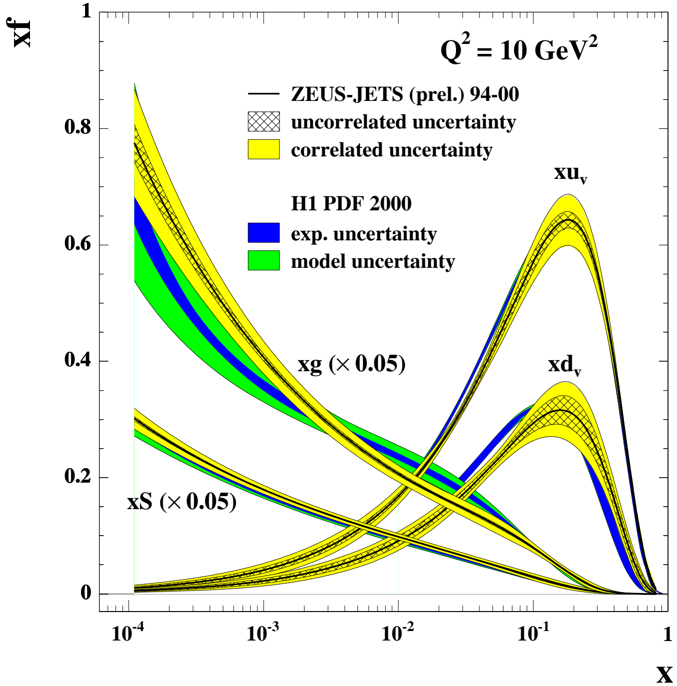
- H1+ZEUS "Combined F_2"
- (Gluon from Jets at HERA)
- Direct F_L measurement
- F_2^{cc} F_2^{bb}
- (Forward jets)
- xF_3
- (Dipole model, geo. scaling, CGC…)

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"

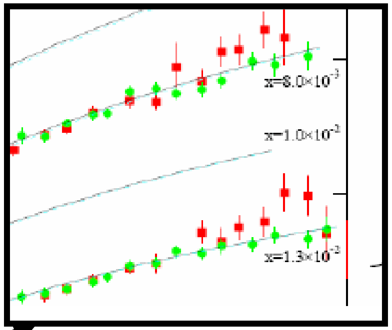
An issue in PDF fit

- **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"

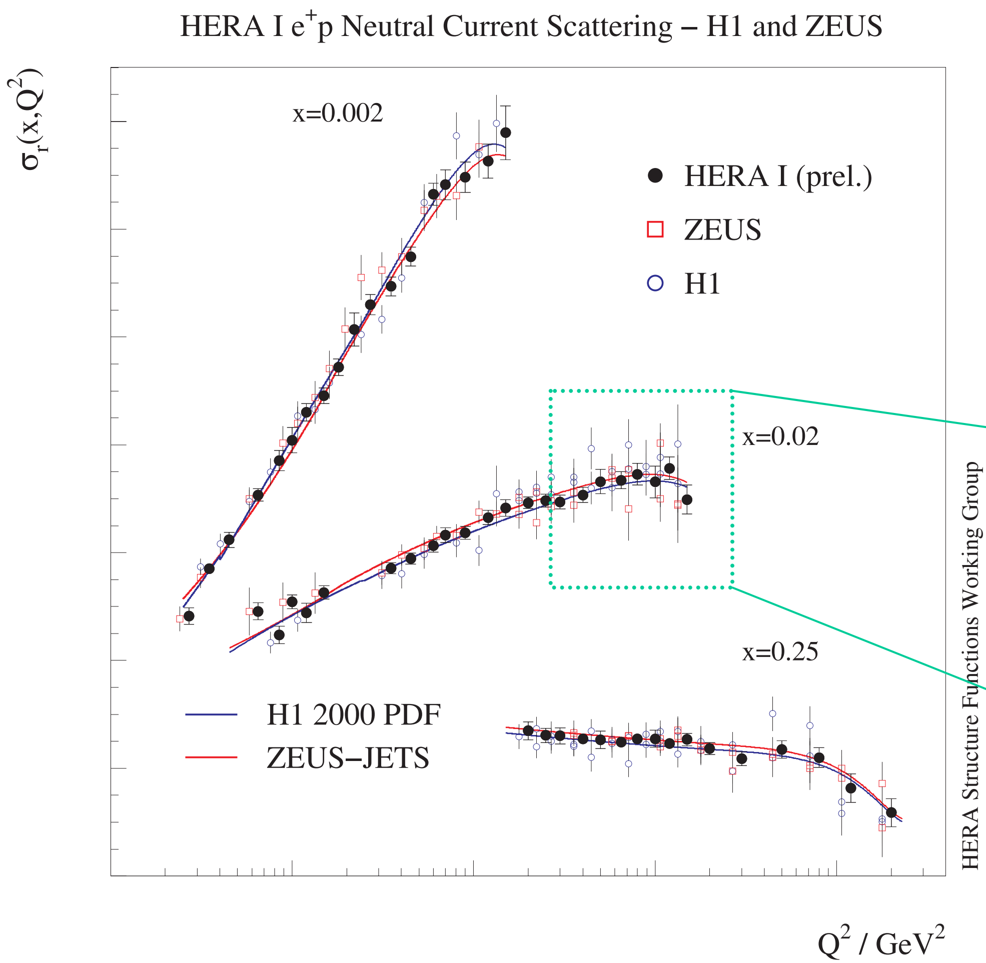


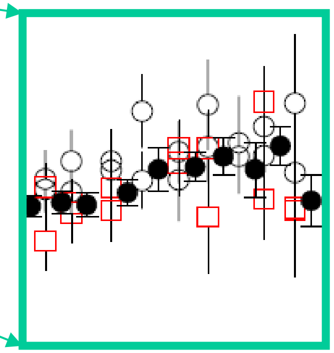
➔ Combine H1 and ZEUS cross sections by fully taking into account their correlated systematic uncertainties : "Cross-calibration between experiments"

① Gluons
③ Flavor decomposition
-- "Combined F_2"

Combined cross sections

★ NEW Prel. @ LP '07





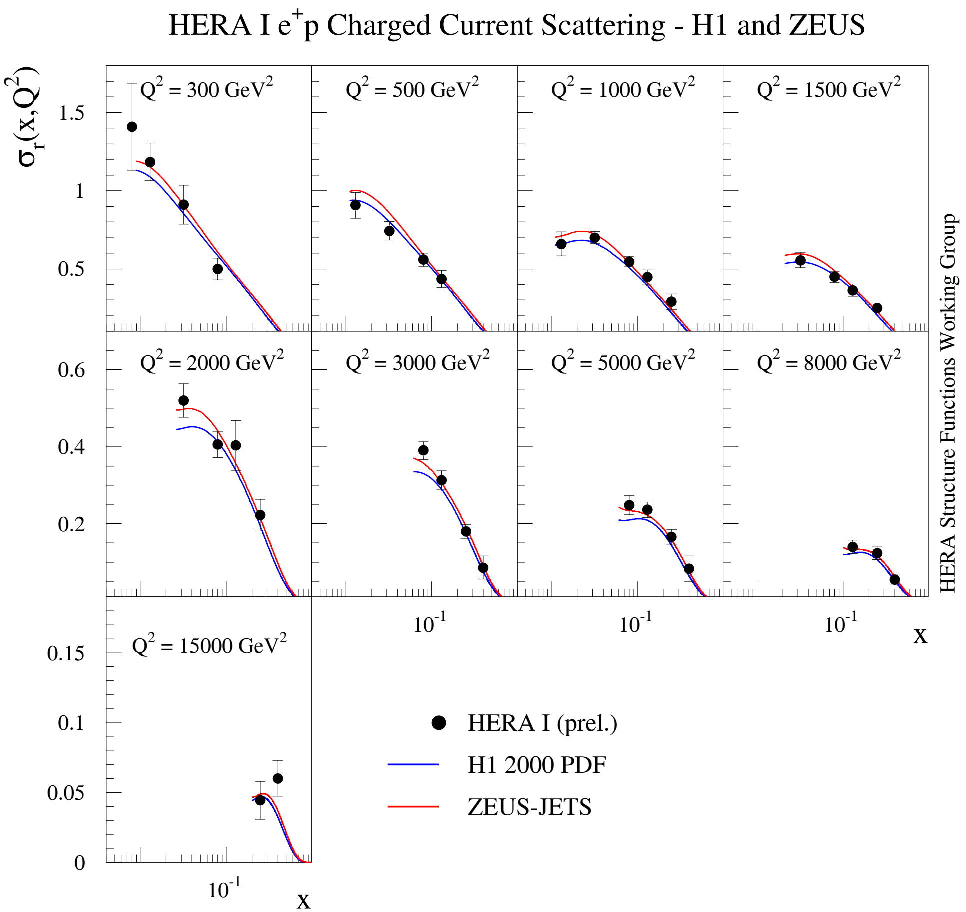
- 1153 individual NC and CC measurements are "averaged" to 554 unique points
  -- χ^2/dof = 510 / 599

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

① Gluons
③ Flavor decomposition
-- "Combined F_2"

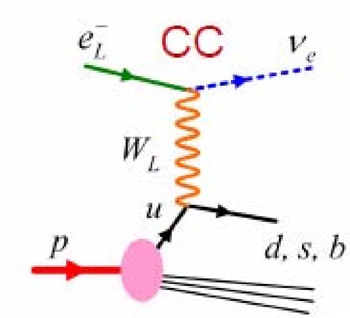
Combined cross sections at large Q^2

★ 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

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

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

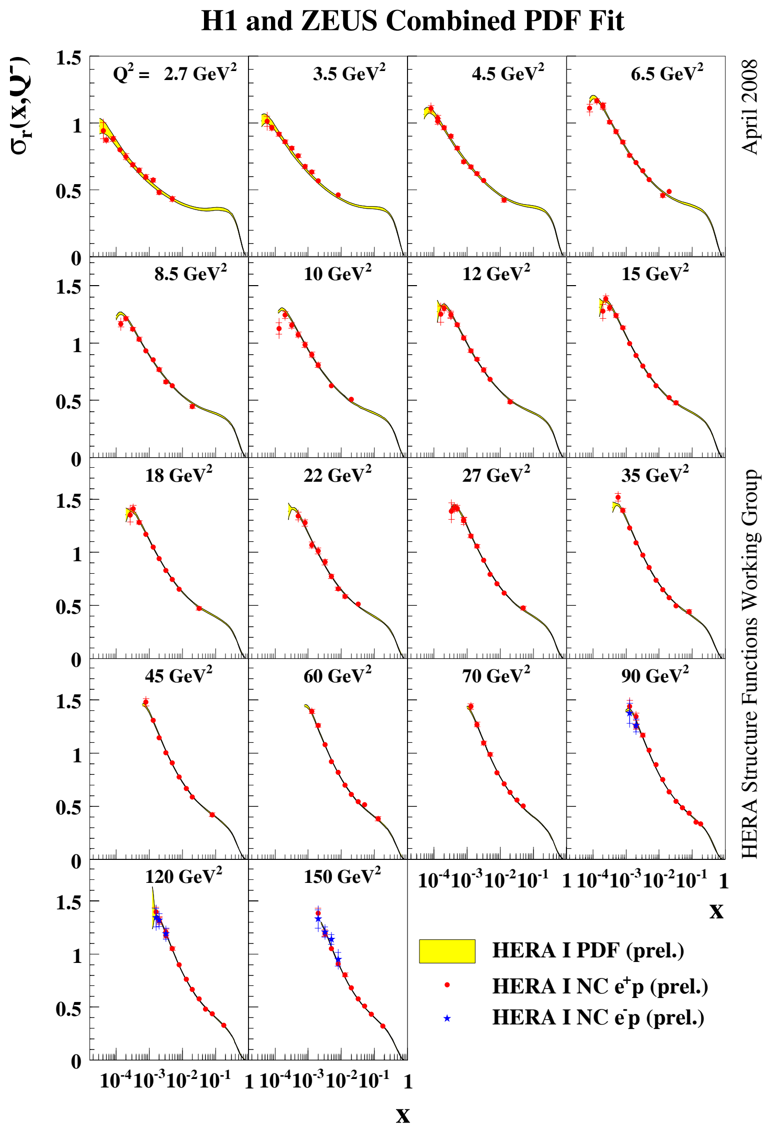
▶ HERA e+p CC will give cleanest determination (w/o heavy-target corr.) on d-quark PDFs

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

① Gluons
③ Flavor decomposition
-- “Combined F_2”

QCD fit to combined cross sections

★ NEW Prel. @ DIS ‘08

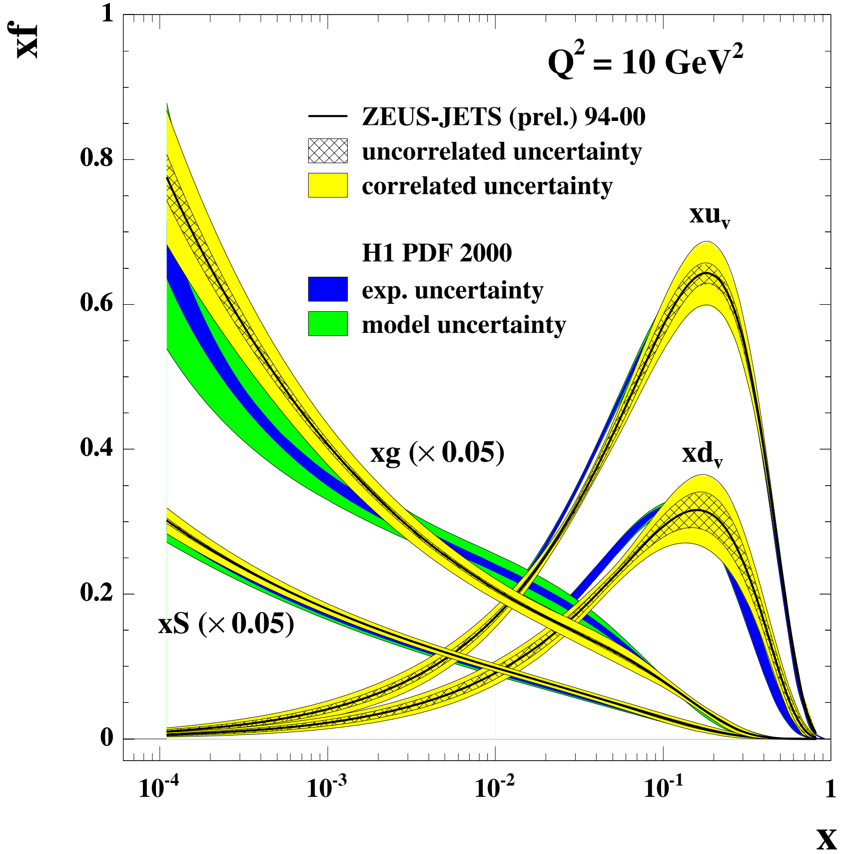


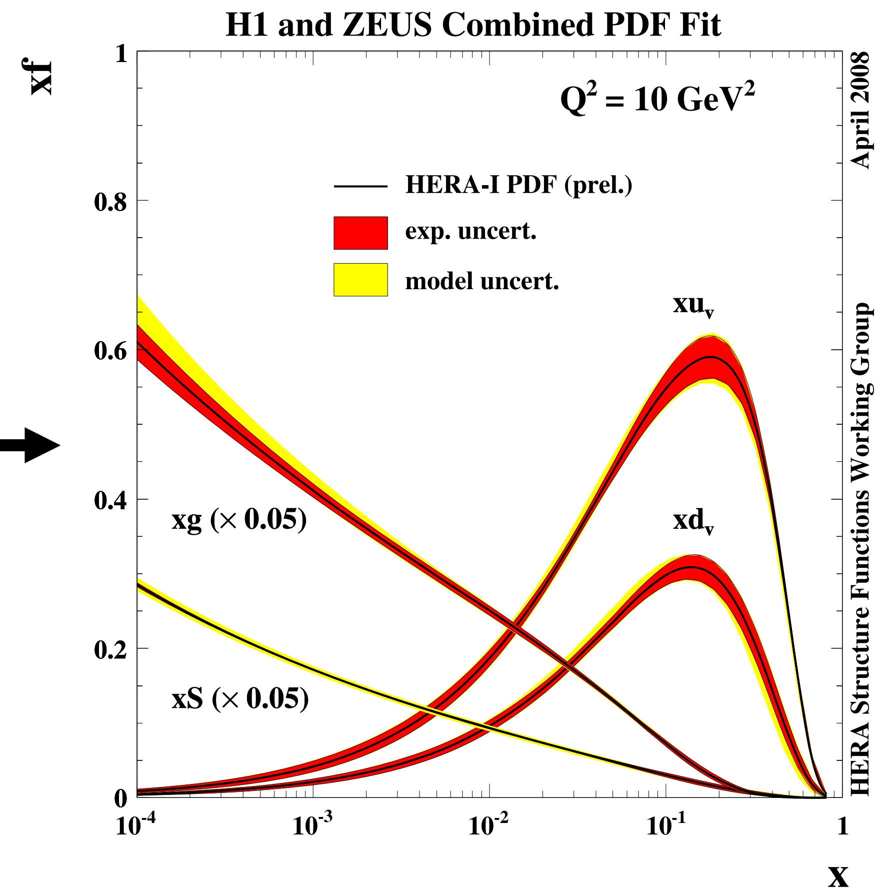
- A QCD fit was performed on the combined data
- Systematic uncertainties are smaller than statistical uncertainties
  → Handling of systematic errors is not an issue anymore
- Resulted in χ^2 / ndof = 476.7 / 562

① Gluons
③ Flavor decomposition
-- "Combined F_2"

★ NEW Prel.
@ DIS '08

"HERA PDF"



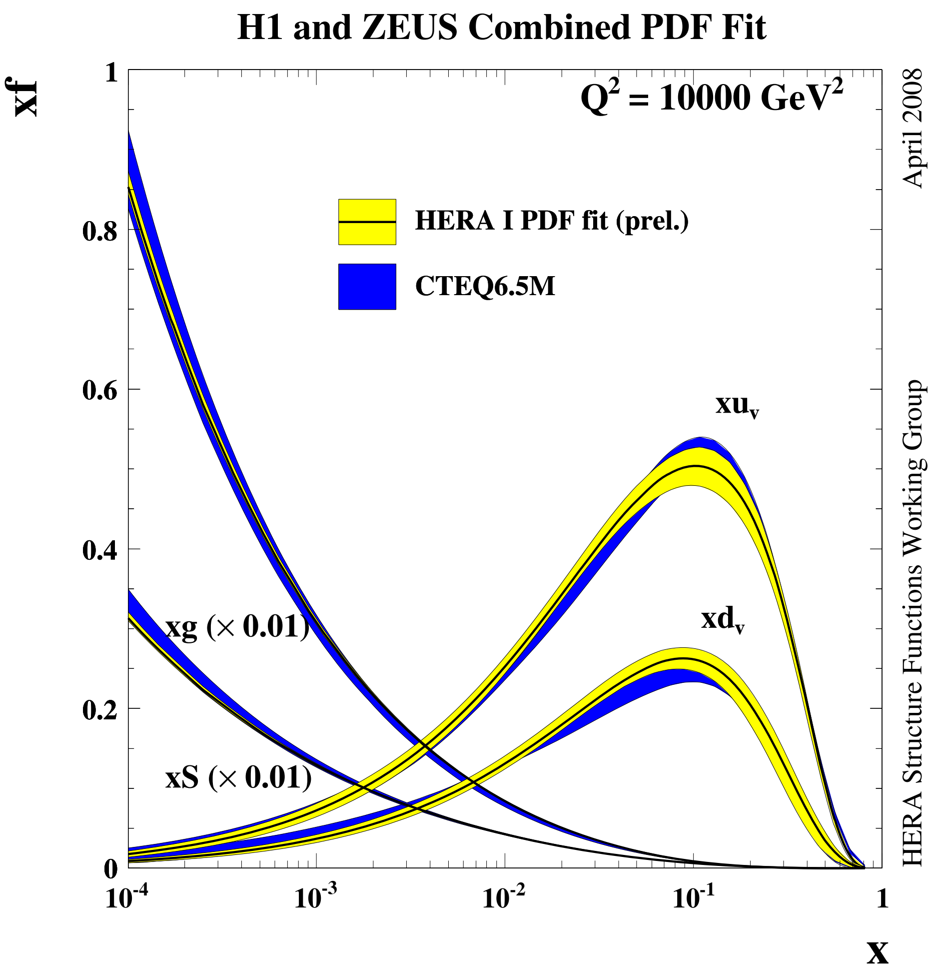


● "H1 and ZEUS; consistent within large uncertainty" is now resolved in "single HERA PDF; with an improvement in level of uncertainty".

① Gluons
③ Flavor decomposition
-- “Combined F_2”

“HERA PDF”: Impact to LHC

★ NEW Prel. @ DIS ‘08



- **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

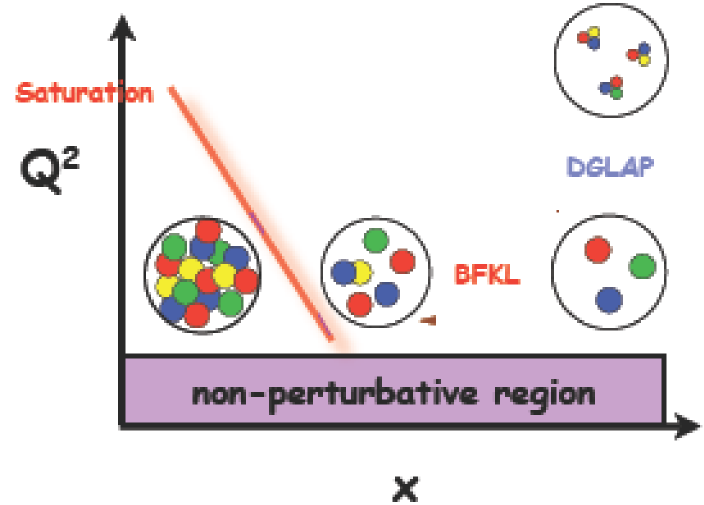
    -- If x is not so small, there is only one scale, $Q^2 \sim s$

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

$$s = Q^2 (1/x - 1)$$

  * 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

- F_L is an another SF:

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

Spin ½ parton contribution ➔ $F_2 = \frac{Q^2}{4\pi\alpha^2}(\sigma_L + \sigma_R)$

Spin 1 parton contribution ➔ $F_L = \frac{Q^2}{4\pi\alpha^2}\sigma_L$

※ 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

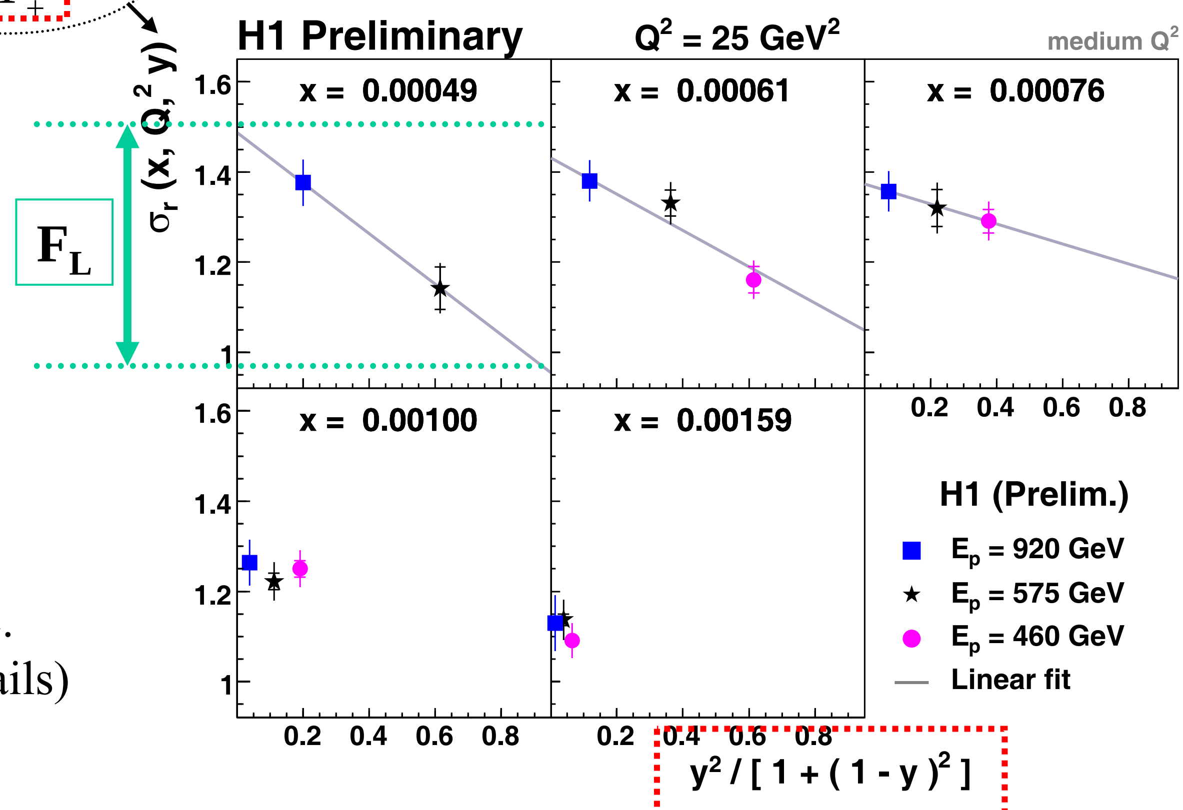
Direct measurement of F_L

★ **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)

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

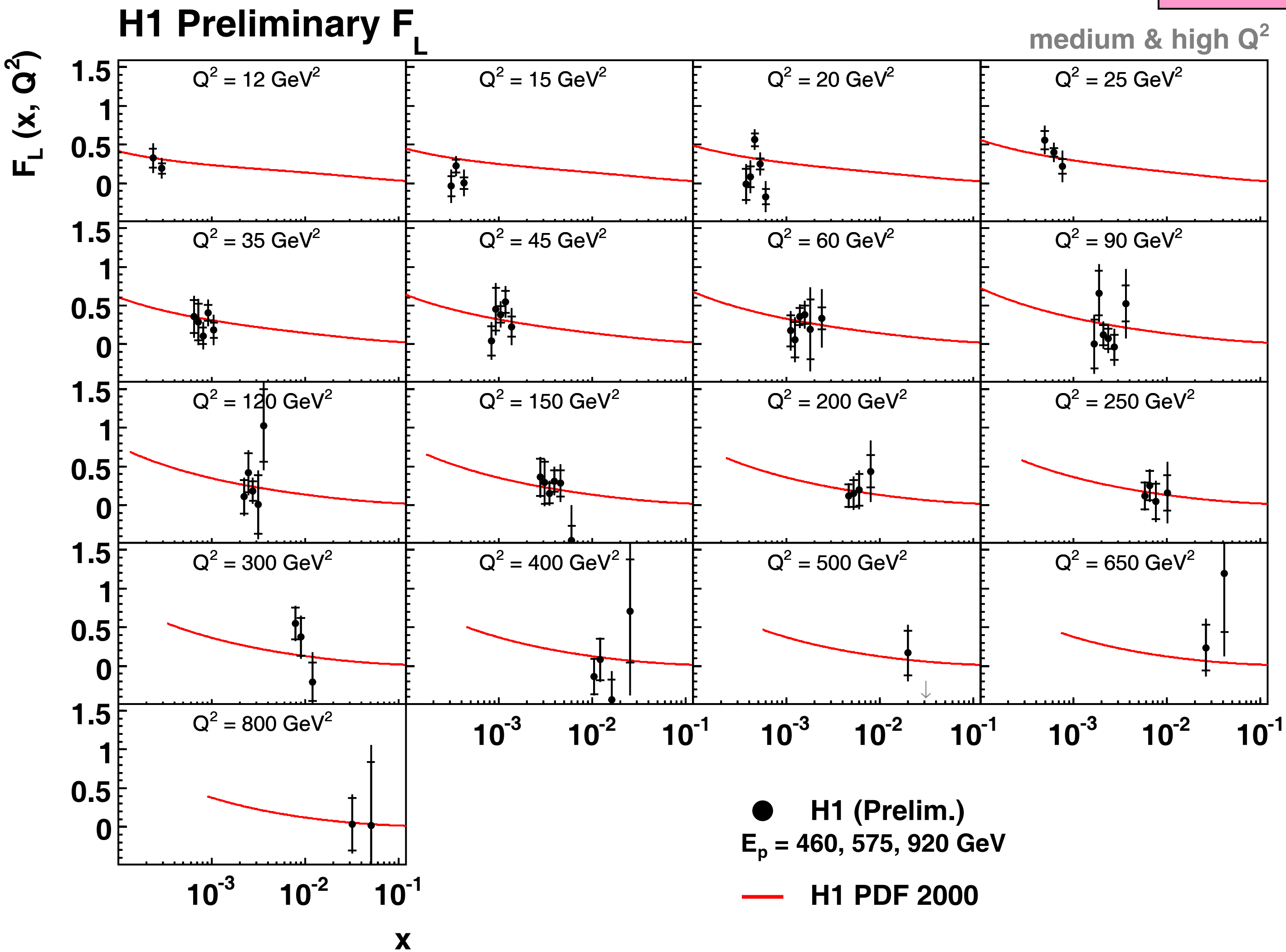
● Experimental challenges to measure cross sections up to large y
-- Large y corresponds to small energy of scattered electron
→ Large backgrounds, energy scale, electron identification etc.
(see backup slides for details)



① Gluon
② Small x evolution
-- Direct F_L measurement

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

Measured F_L

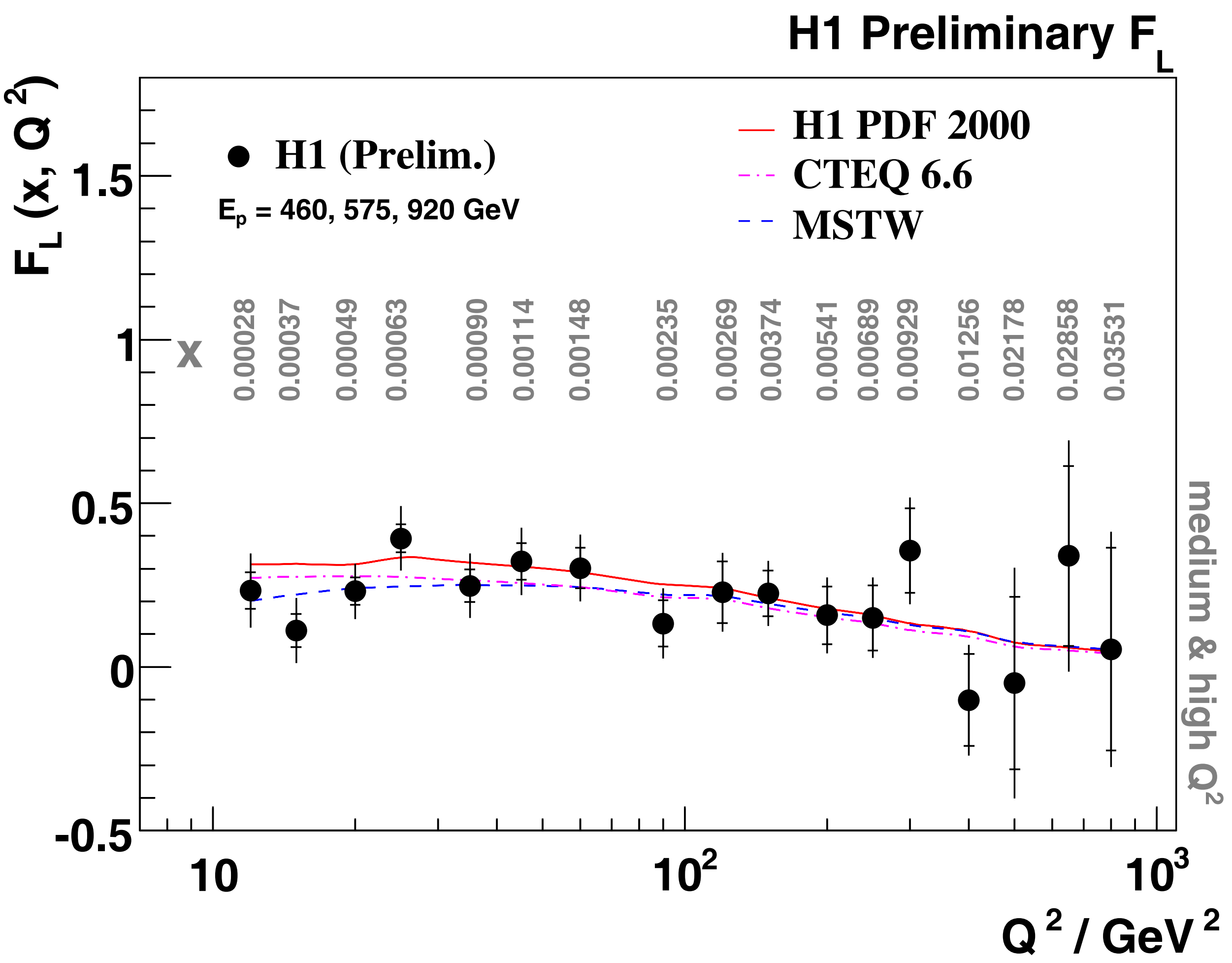


● First direct F_L measurement at small x

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)

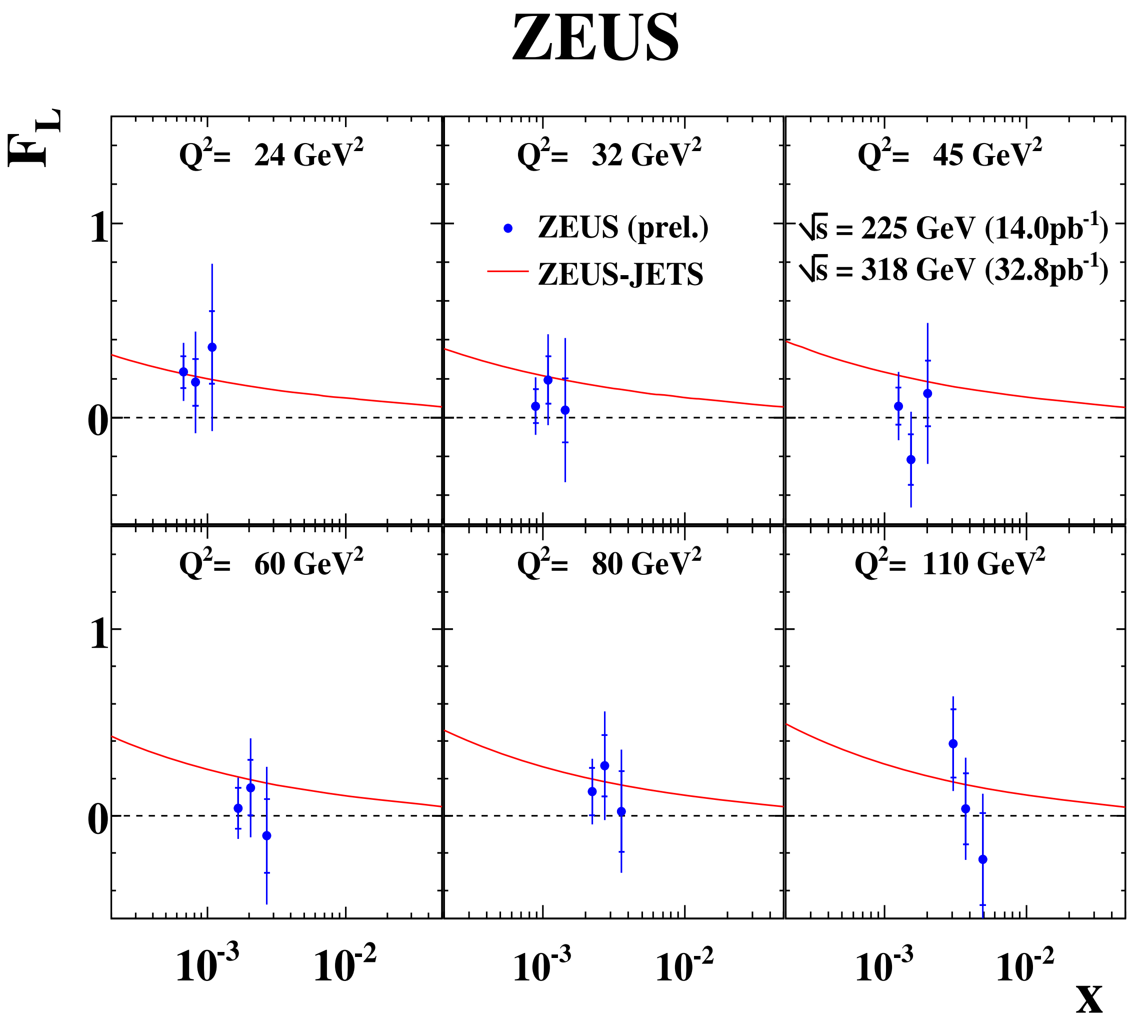


● F_L predicted by QCD fits using gluon that was derived from scaling violation of F_2 is consistent with the measurement

① Gluon
② Small x evolution
-- Direct F_L measurement

★ NEW Prel. @ DIS '08

Measured F_L [ZEUS]

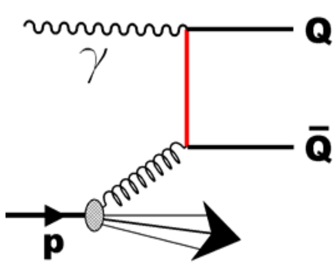


- Measurement consistent with QCD fit F_L prediction as well as with F_L=0 within large uncertainties

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

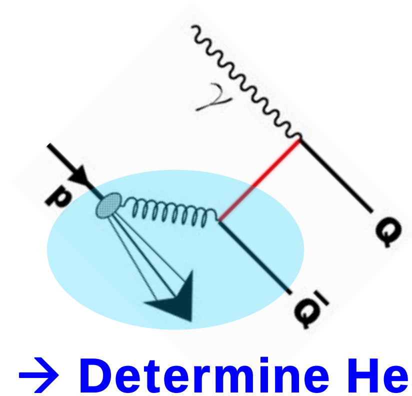
Heavy quark PDFs and gluons

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



c massive

→ **Test / determine gluon PDF**

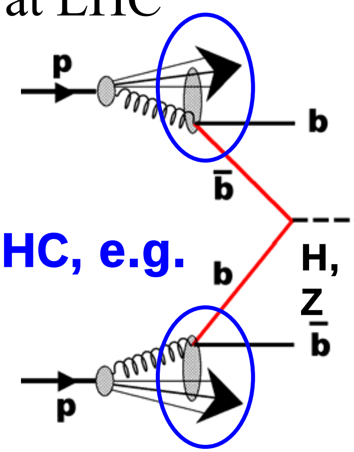


c massless
($Q^2 \gg m_c^2$)

→ **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

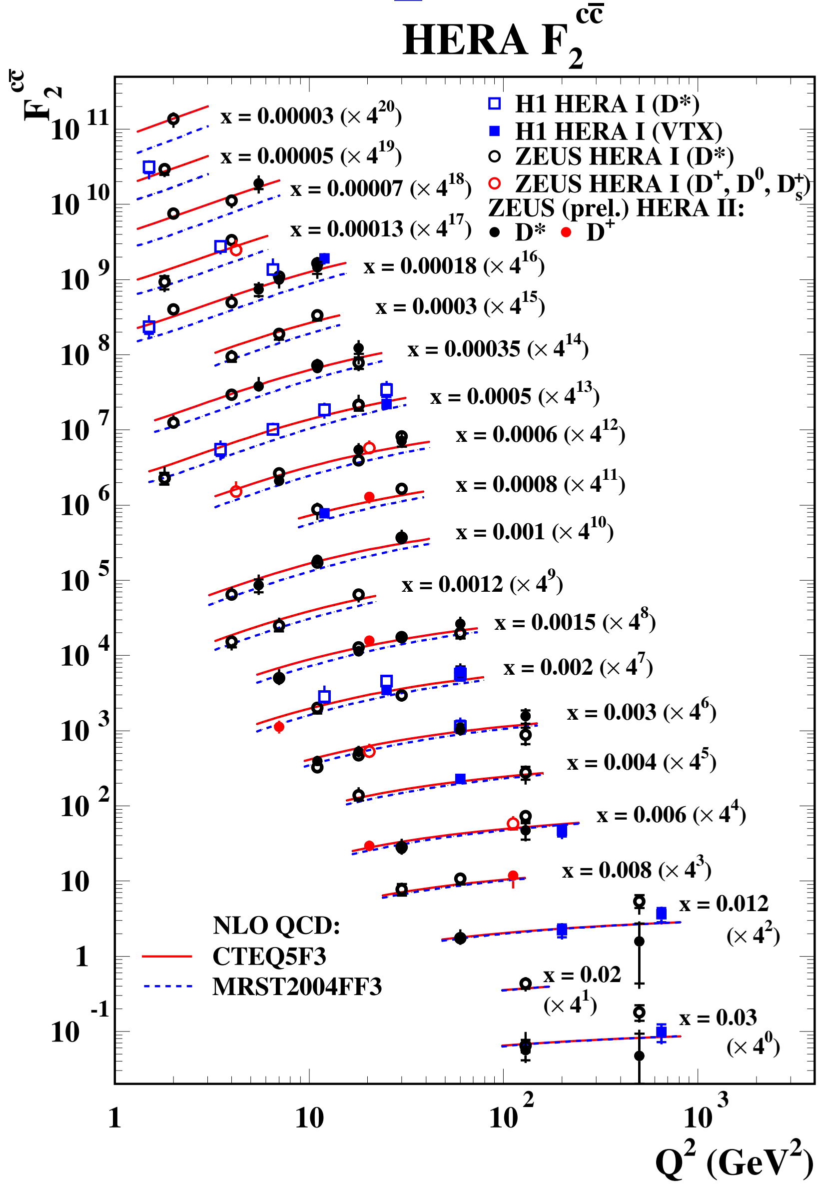
★ NEW Prel. @ LP '07

- $D^* \rightarrow K\pi\pi$

- 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)



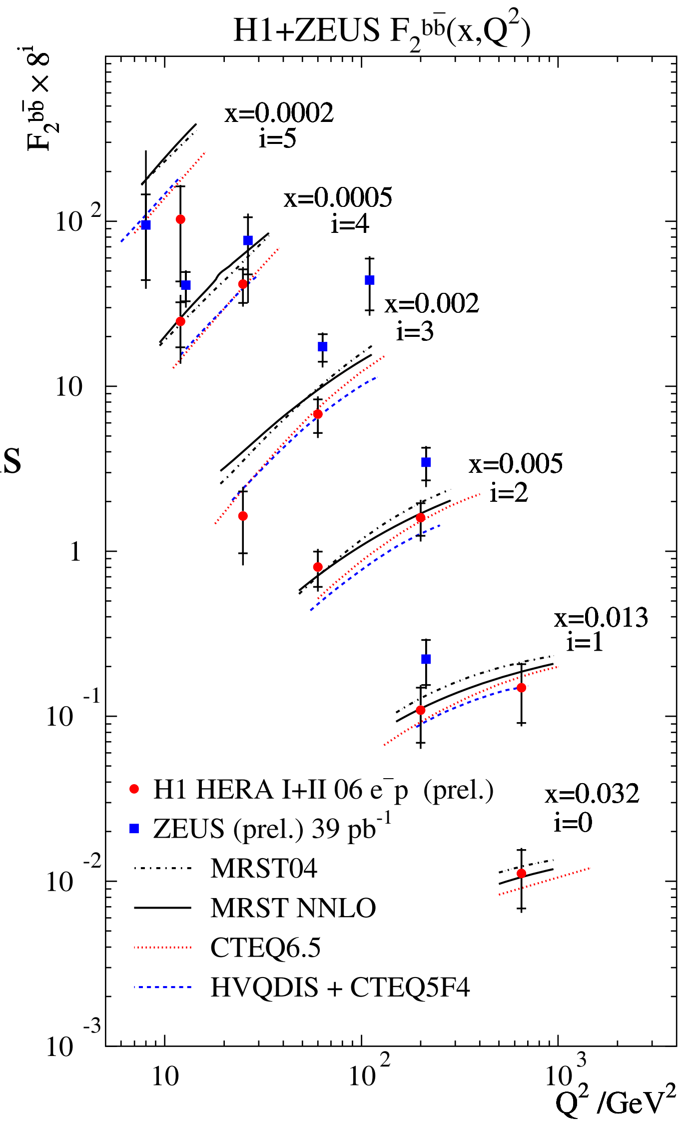
① Gluon
③ Flavor decomposition
-- F_2^{cc}, F_2^{bb}

★ 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)



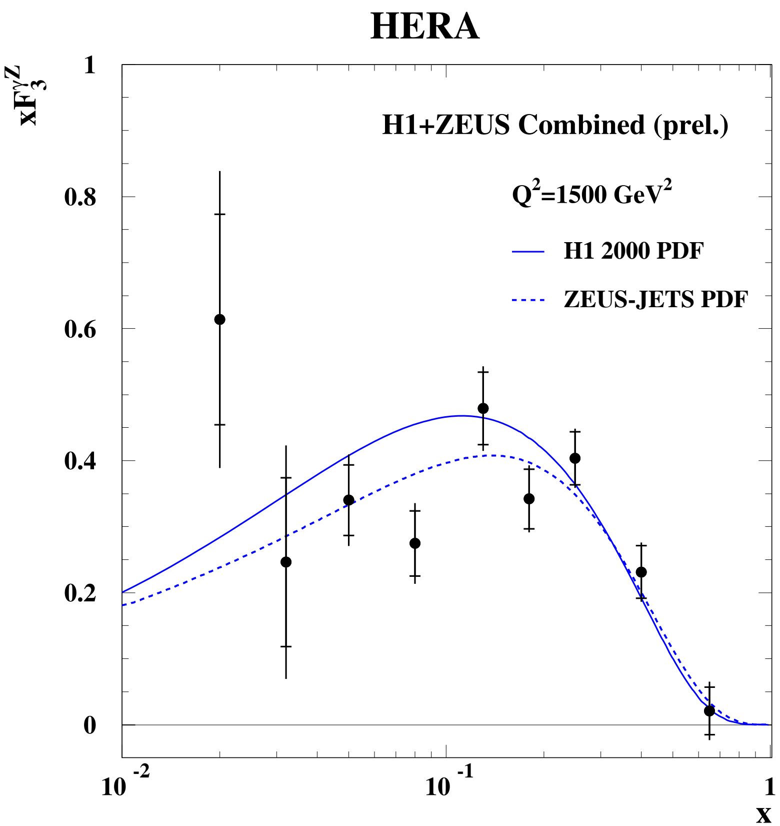
③ Flavor decomposition
-- xF_3

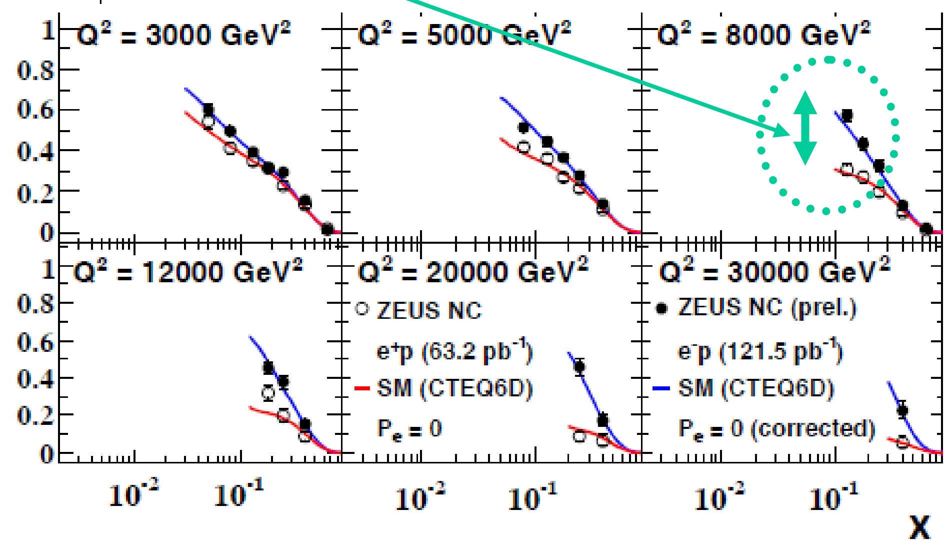
xF_3

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

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

※ 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

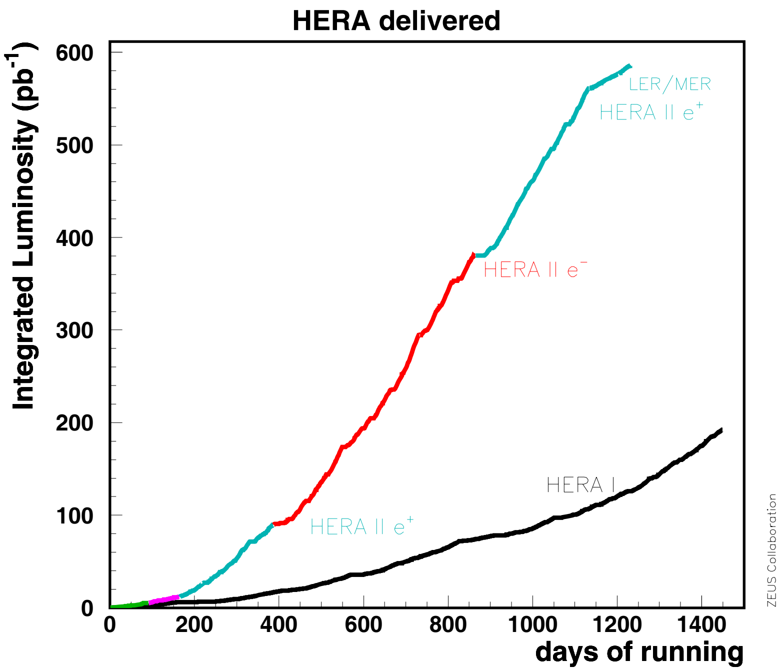
- HERA is still providing new high precision results which will further improve our understanding on proton structure
  -- Combination of H1 and ZEUS cross-sections brought significantly improved precision of data, and hence best determined gluon
  -- First direct measurement of F_L was performed
  --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

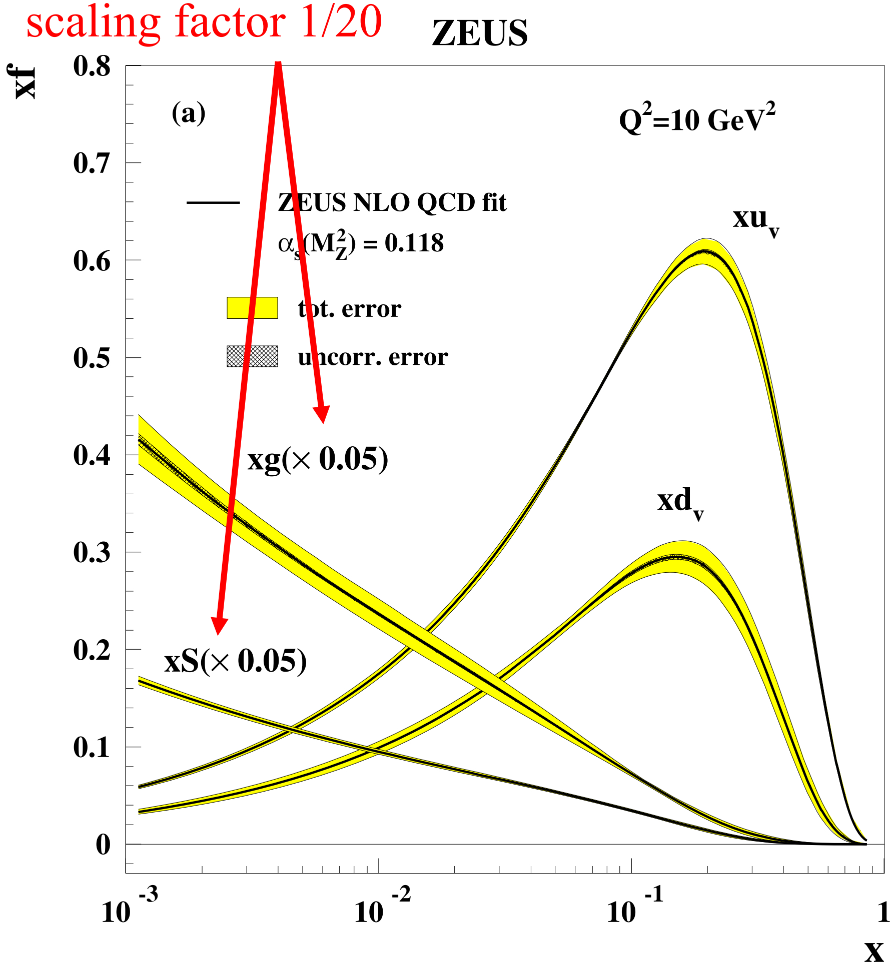
1 fb^{-1} collected by H1+ZEUS

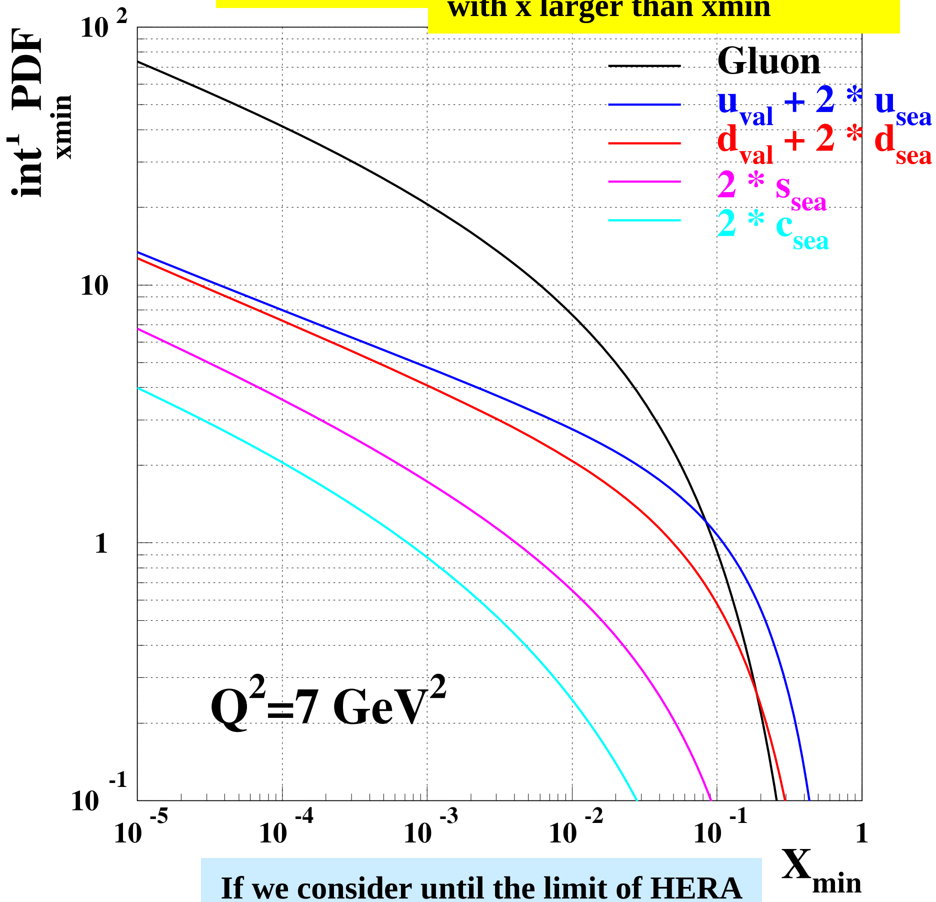
Notice that they are plotted with scaling factor 1/20

PDF

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

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

① **Gluons**
-- **“Combined F_2”**

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

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

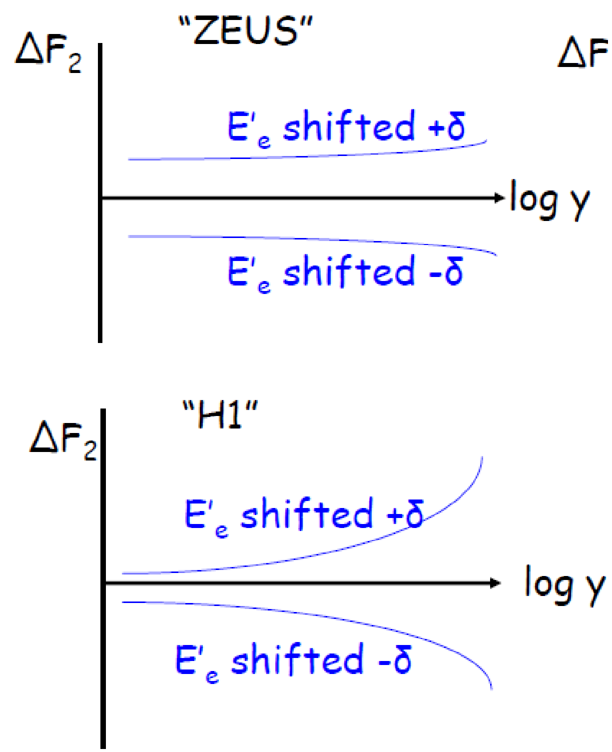
m_i^e = measured cross section in bin i by exp e

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

$s_i, r_j \sim N(0,1)$

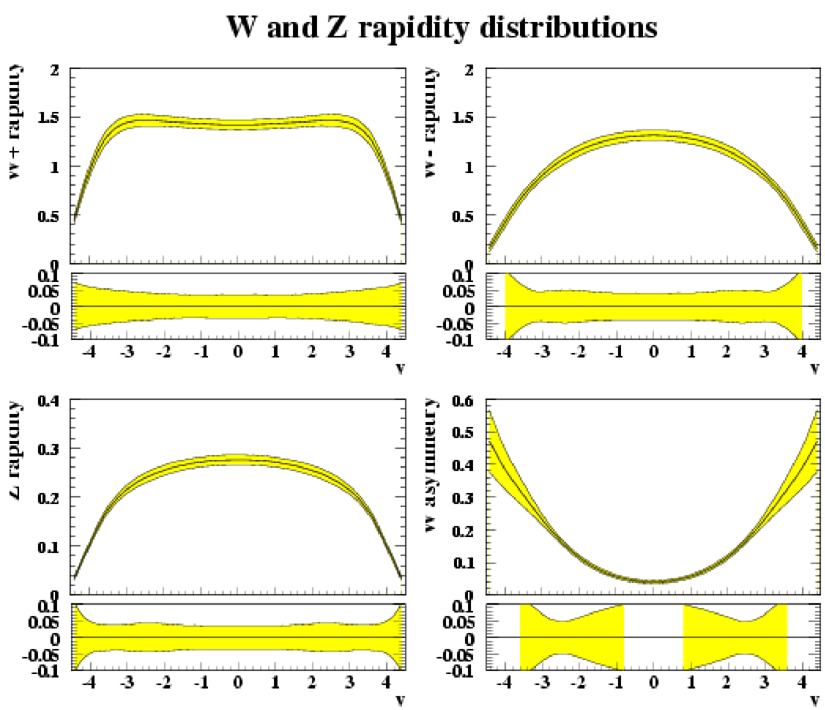


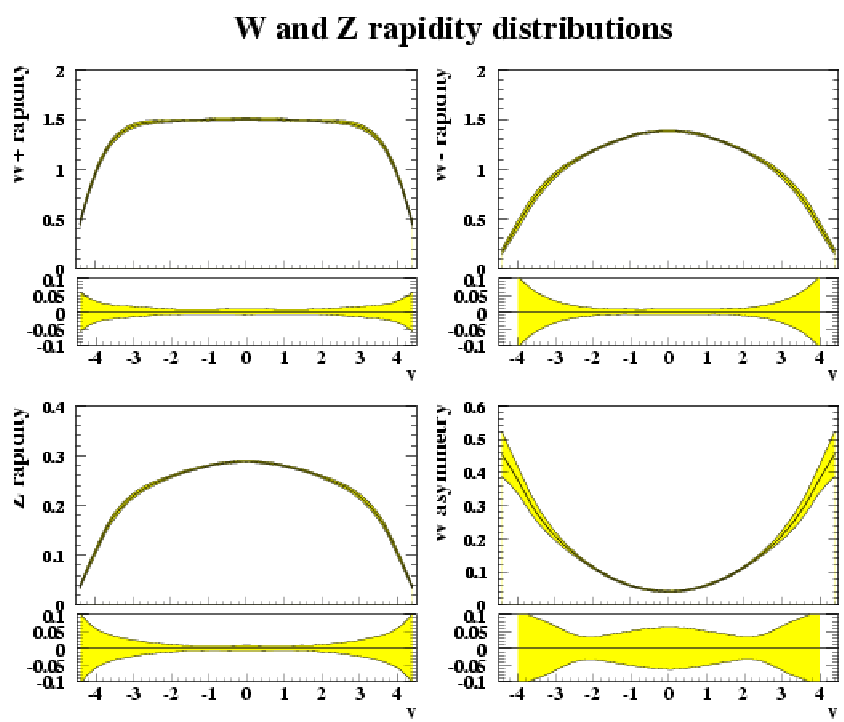
➔ Cross calibration. Can get reduction of systematic errors if
-- Similar size of errors but different “shape”

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





- 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

★ Work by A. M. Cooper-Sarkar
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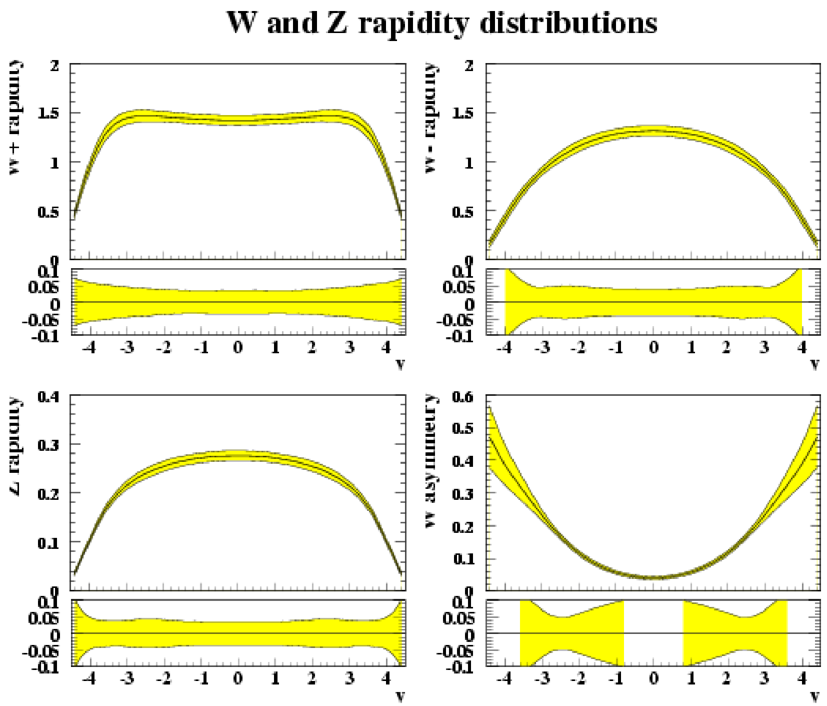
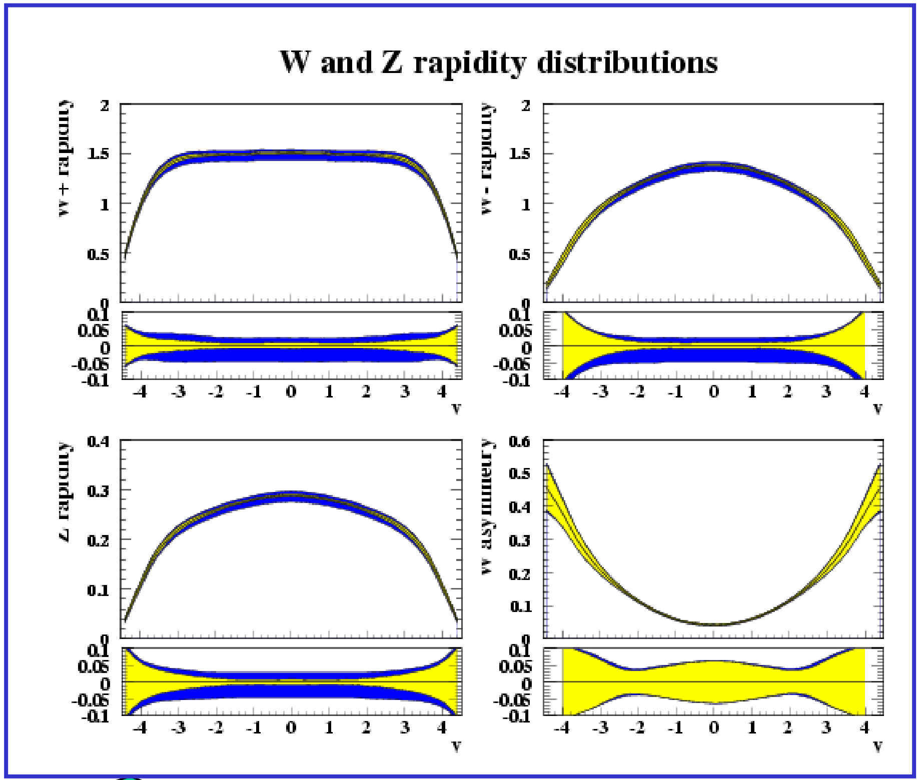




Model errors shown in blue

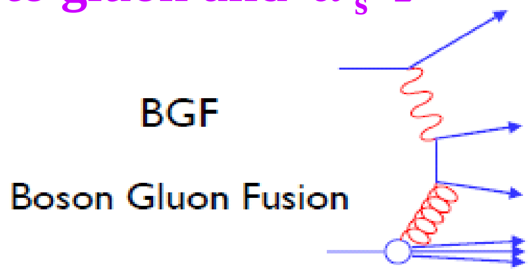
- Experimental uncertainty is now reduced to be ~1.5%, and they are now smaller than model uncertainty (~3%)

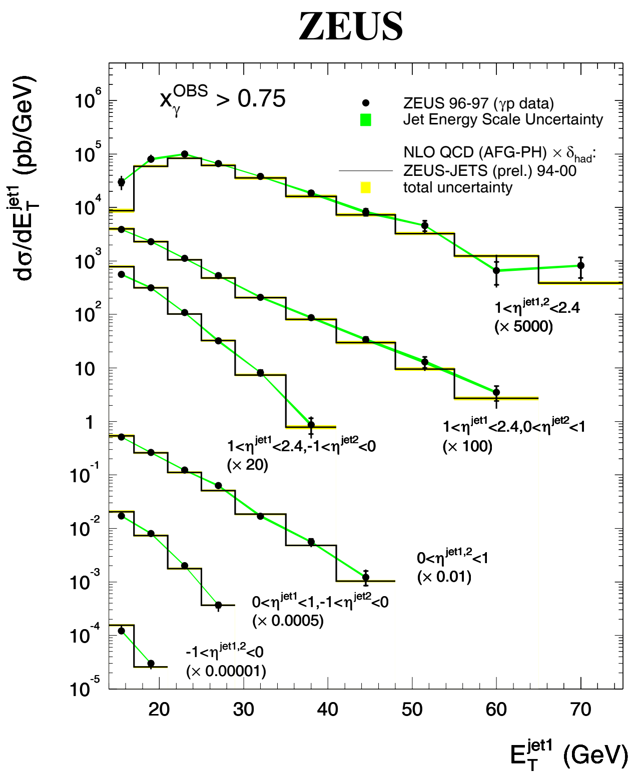
① **Gluons**

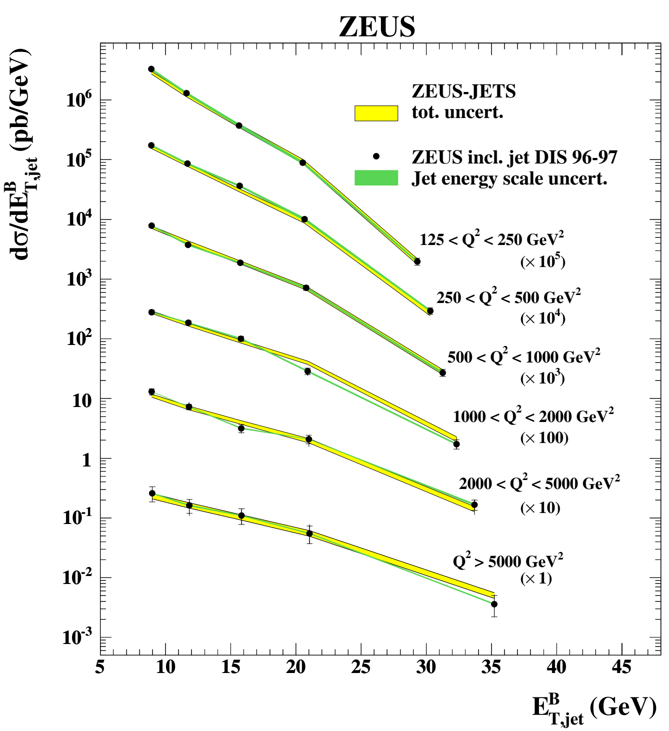
-- Gluons from Jets at HERA

NLO QCD fit including Jets

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





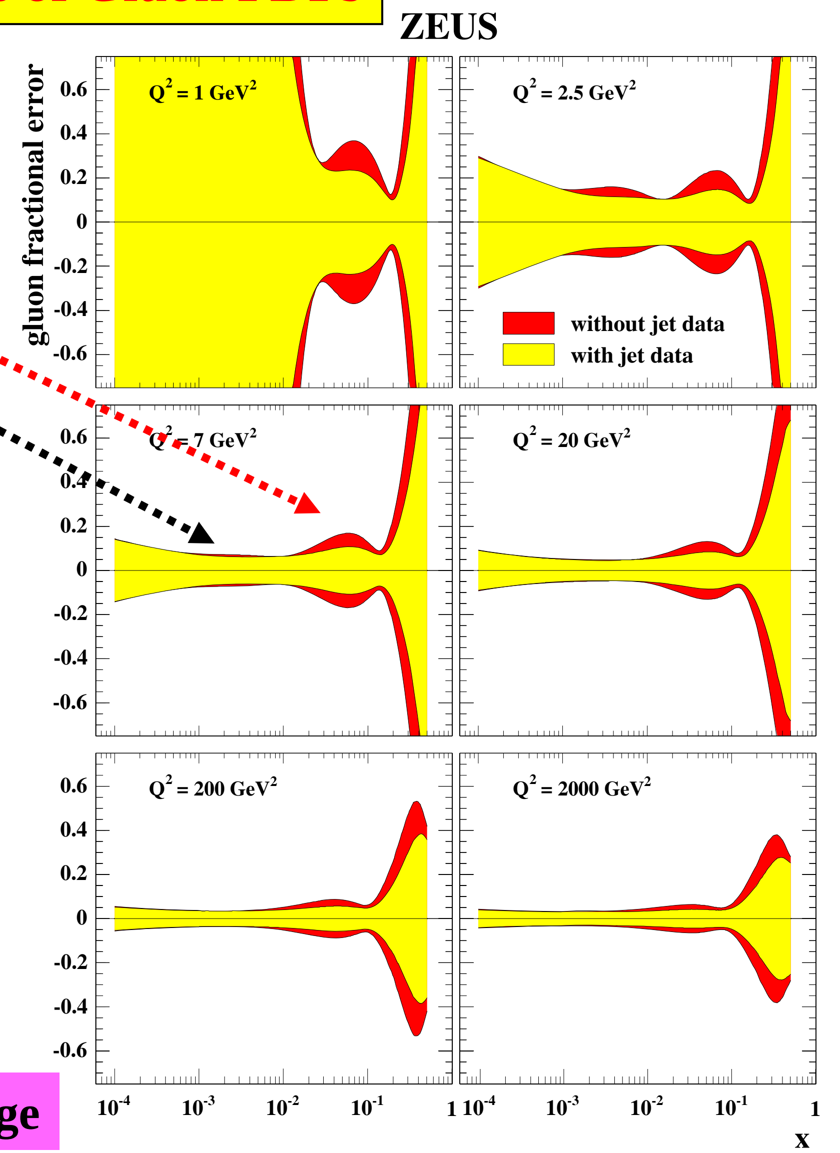


🡐 DIS Inclusive jet gives general sensitivity to gluon and α_s

※ 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

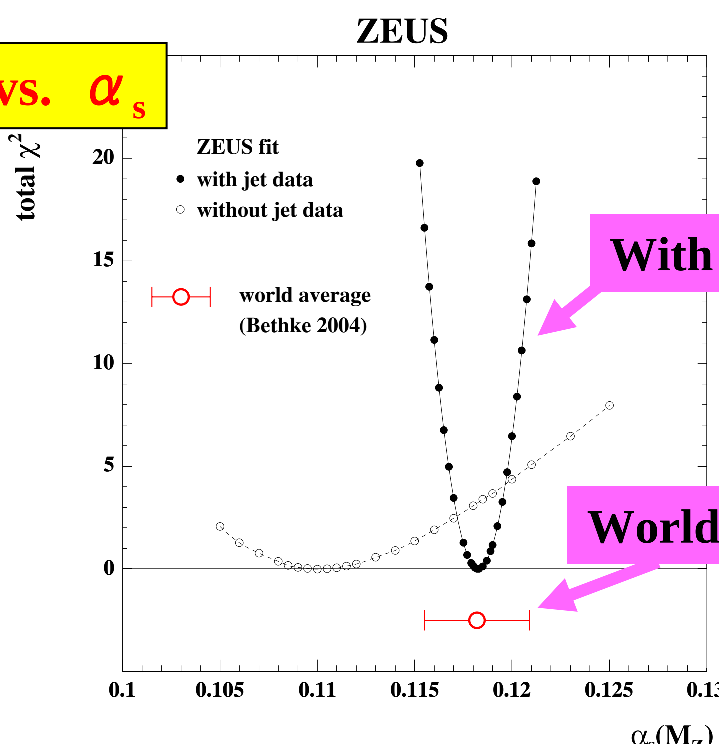
W/O Jets

With Jets

► Also, jet helps to constrain α_s :

➔ alpha_s was determined precisely compatible as the world average!

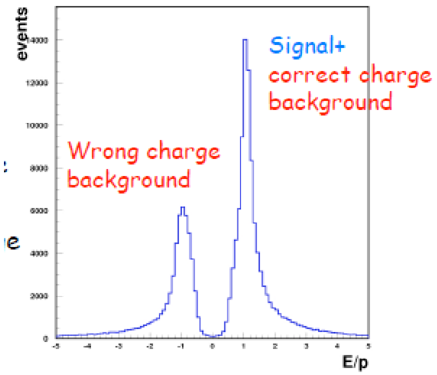
χ^2 vs. α_s



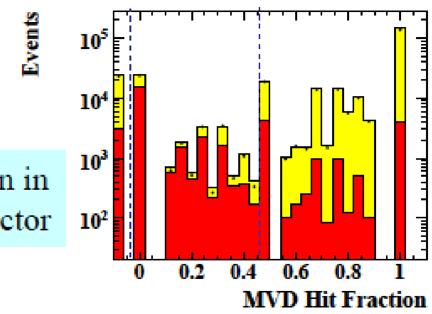
① Gluon
② Small x evolution
-- Direct F_L measurement

Technical issues in measuring F_L

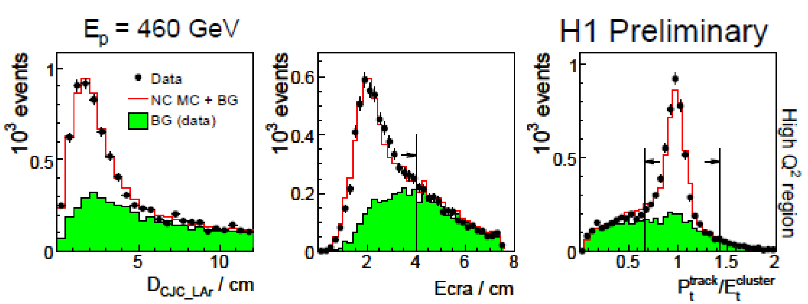
- High-y events are also experimentally very challenging, as huge photoproduction (Q^2=0) backgrounds are foreseen.

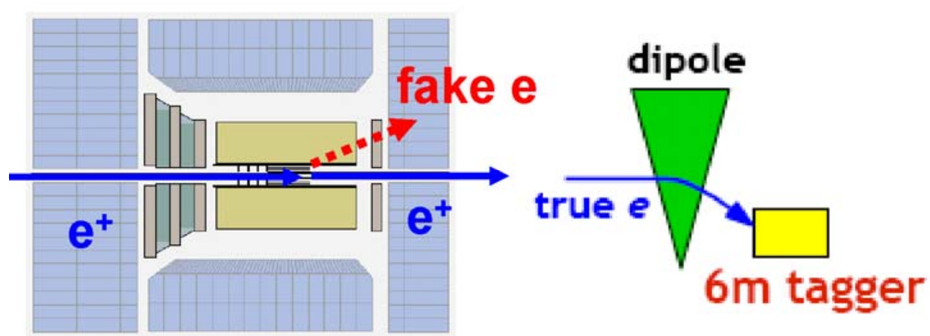


Hit Fraction in vertex detector



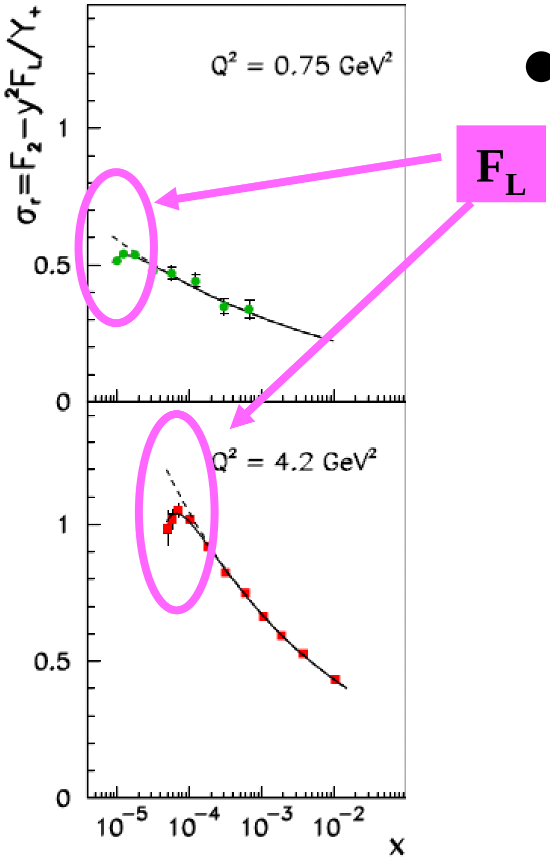
Slides still under construction





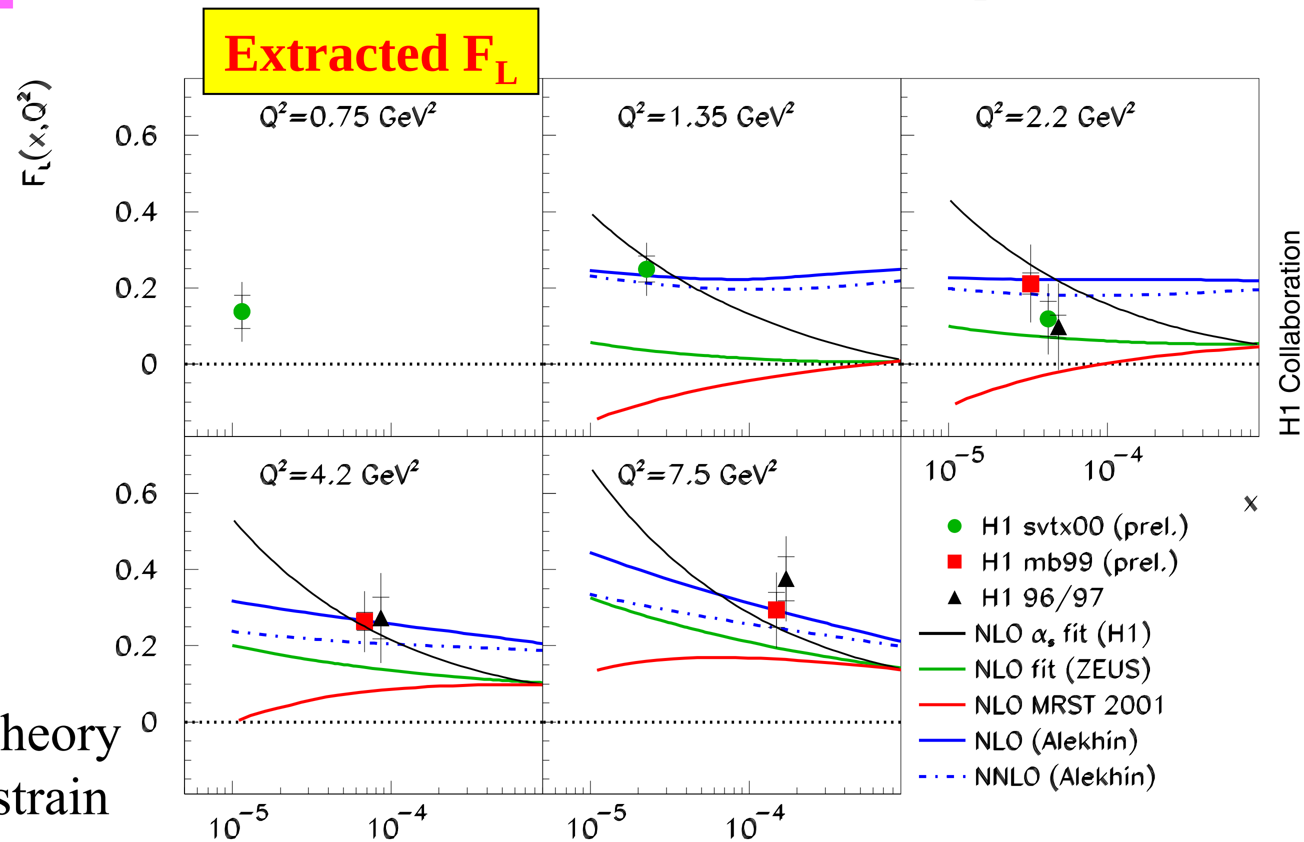
① Gluons
② Small x evolution
-- Direct F_L measurement

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 $F_2 = x^{-\lambda}$



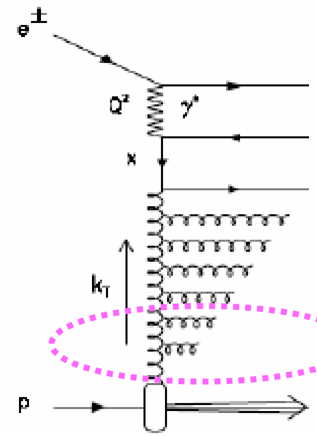
► Large uncertainty in theory

➔ Data will help to constrain

※ This is not a model-independent extraction

③ Small x
-- Forward Jet

Small x and Forward Jet

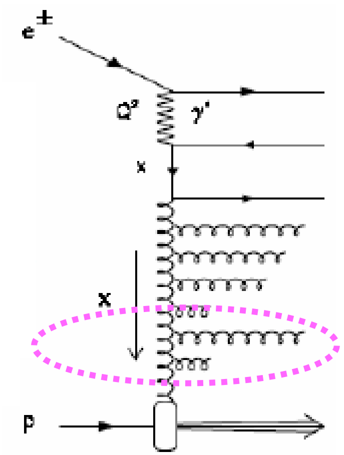


DGLAP

Evolution & resummation in powers of *lnQ2*

$$Q^2 >> k^2_{T,n} >> ... >> k^2_{T,2} >> k^2_{T,1}$$

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



BFKL

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

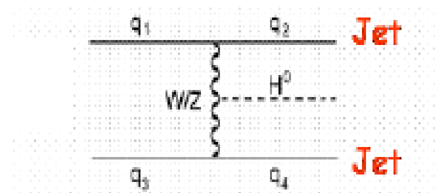
$$x_1 >> x_2 >> ... >> x_n >> x$$

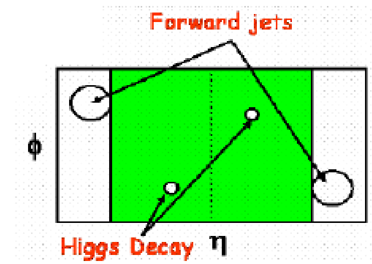
The BFKL is only strongly ordered in x

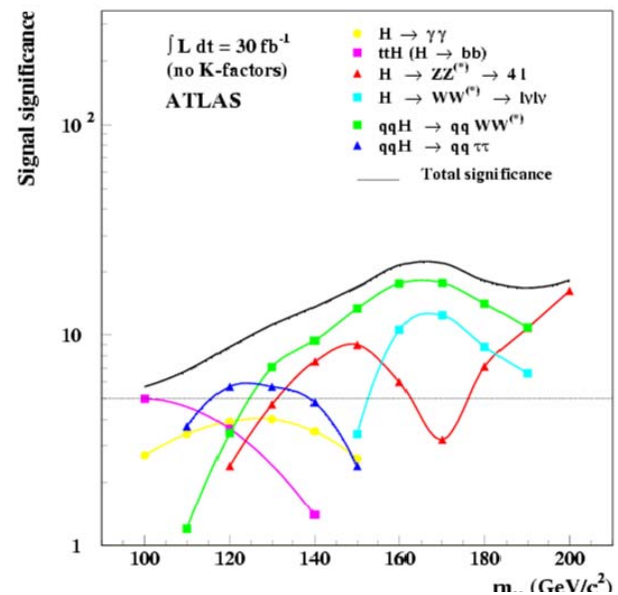
Forward jet:

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

► How it relates to LHC?







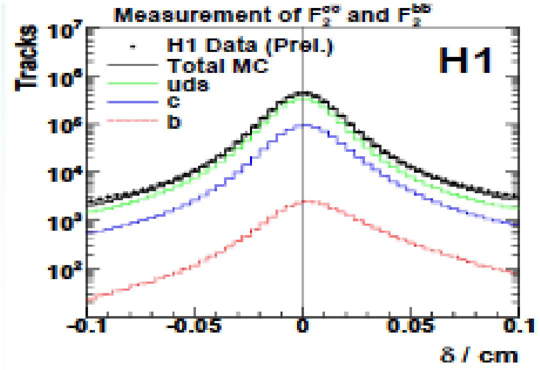
VBF is a most promising channel for Light Higgs search

-- Forward high p_T jet

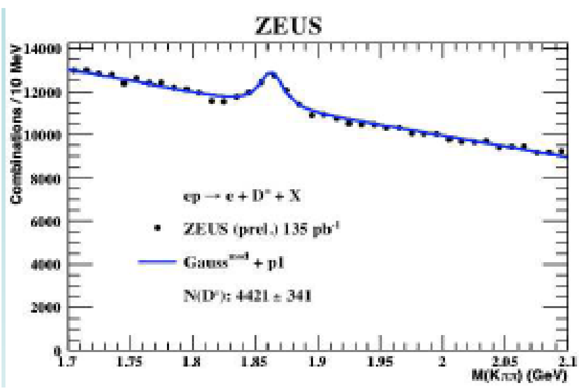
① Gluon
③ Flavor decomposition
-- F_2^{cc}, F_2^{bb}

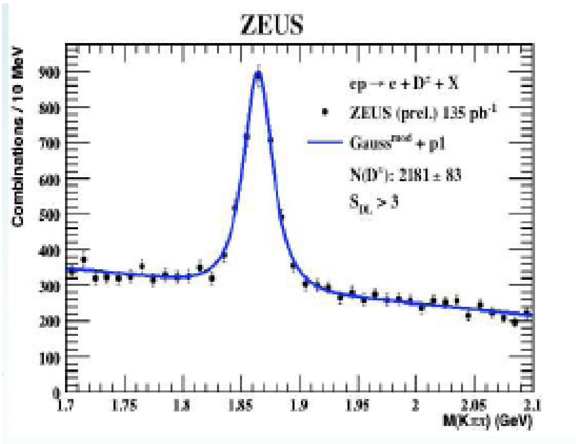
F_2^{cc}

● H1: Inclusive Impact Parameter tagging in VTX



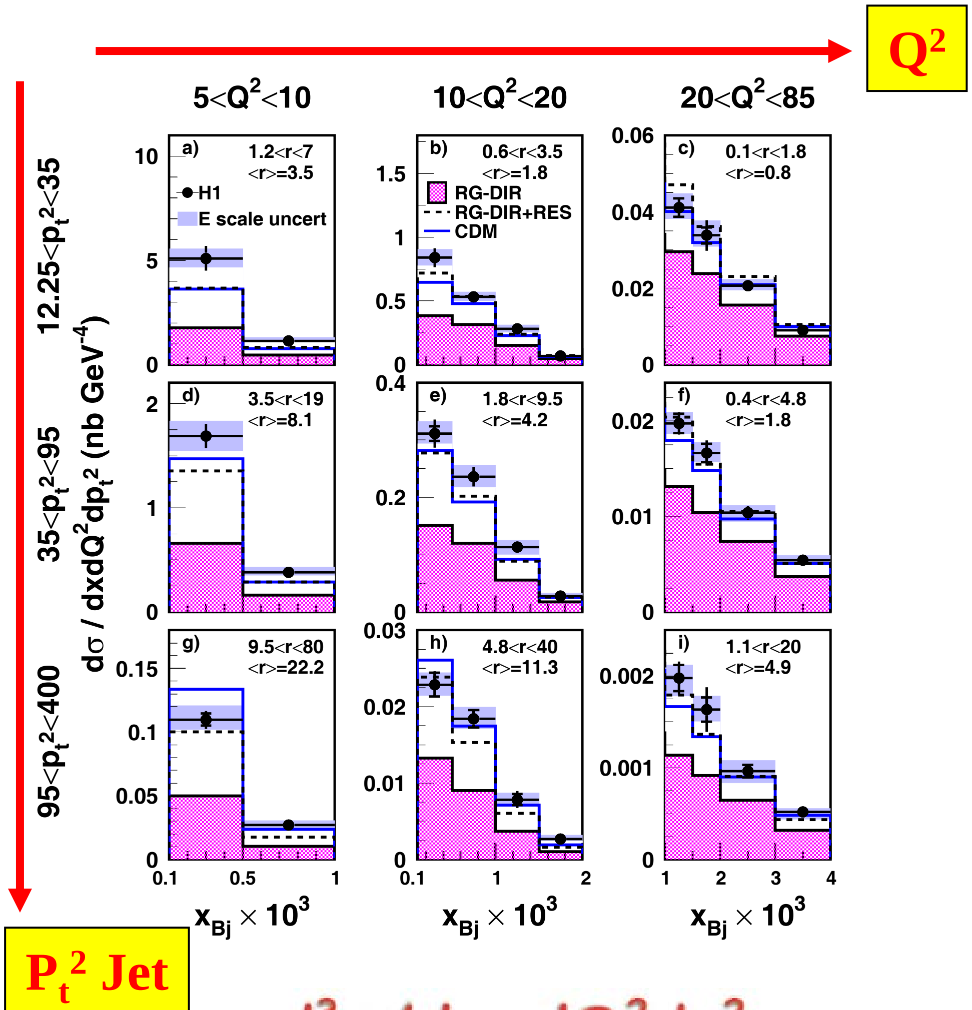
● ZEUS: Signed 2-D decay length in MVD for D+-, D0 identification





③ Small x
-- Forward Jet

Forward Jet @ HERA



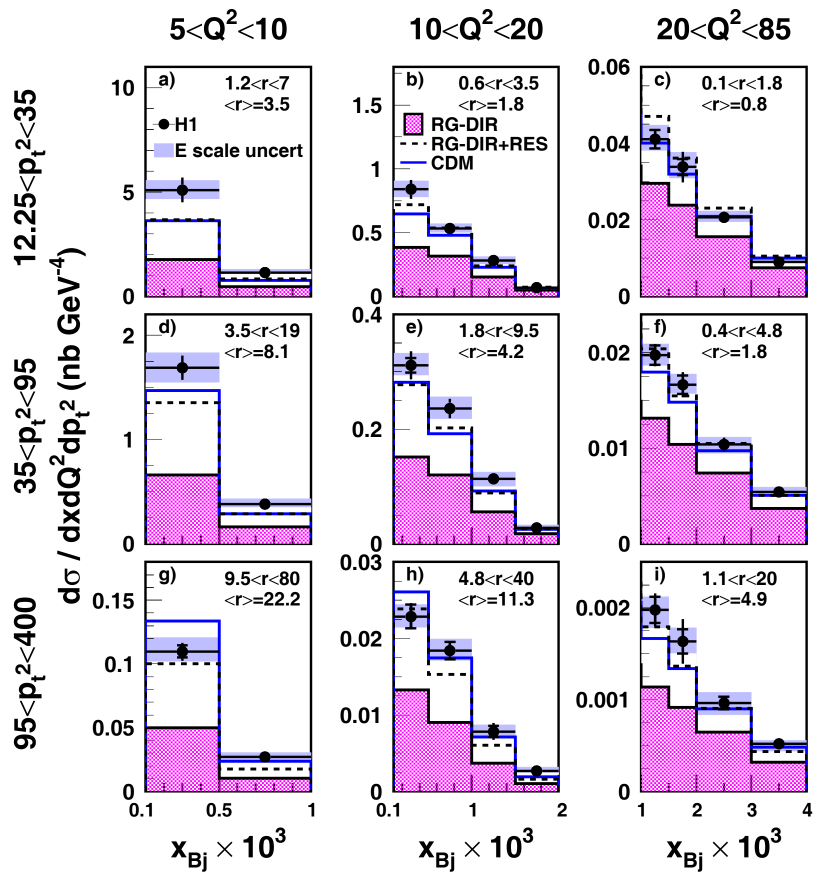
$$d^3\sigma/dx_{Bj}dQ^2dp^2_{t,jet}$$

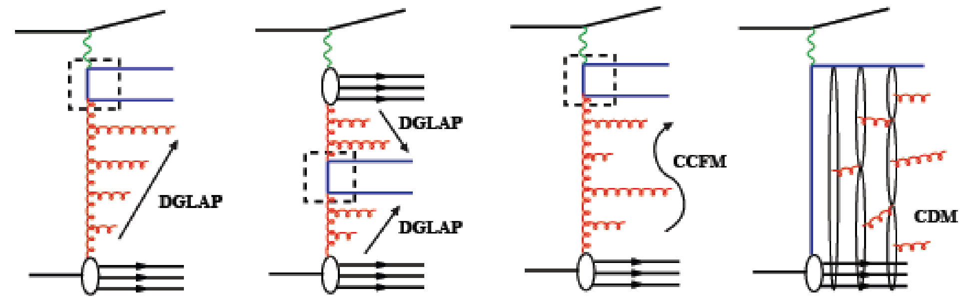
- Large K-Factor
- Not sufficient yet with NLO

➔ How QCD Models describe (Next slide)

③ Small x
-- Forward Jet

Forward Jet @ HERA: QCD Models





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.

(the same plot as in previous page)

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