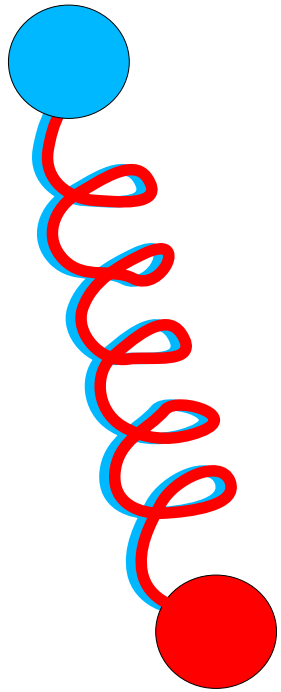
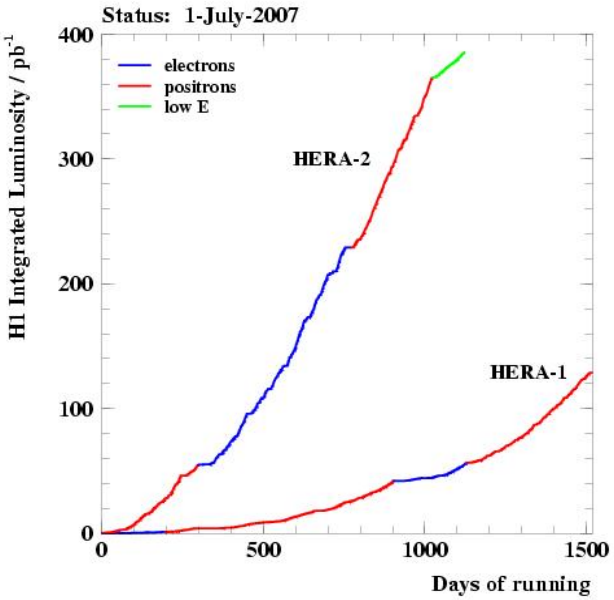
Experimental tests of QCD

- Proton structure
- α_s
- The real secrets of QCD:
  - Diffraction
  - Underlying event
  - Fragmentation
- Nucleon spin



July 23, 2007 @HEP2007, Manchester
Olaf Behnke (Heidelberg)

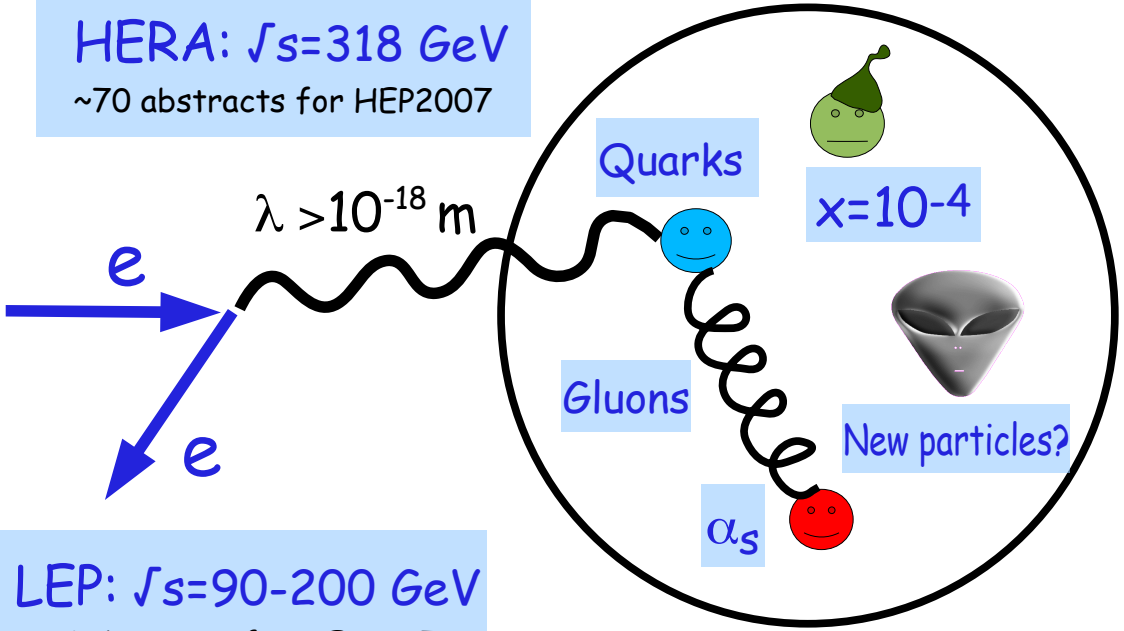
Hard QCD machines



30.6.2007: HERA-shutdown – the end of a unique machine for DIS at the high energy frontier

HERA: $\sqrt{s}$=318 GeV

~70 abstracts for HEP2007



LEP: $\sqrt{s}$=90-200 GeV

~5 abstracts for HEP2007

TEVATRON: $\sqrt{s}$=2 TeV

Run II: 3 fb^{-1} so far, aim for 8 fb^{-1} until 2009

~10 abstracts for HEP2007

Proton → ← Proton

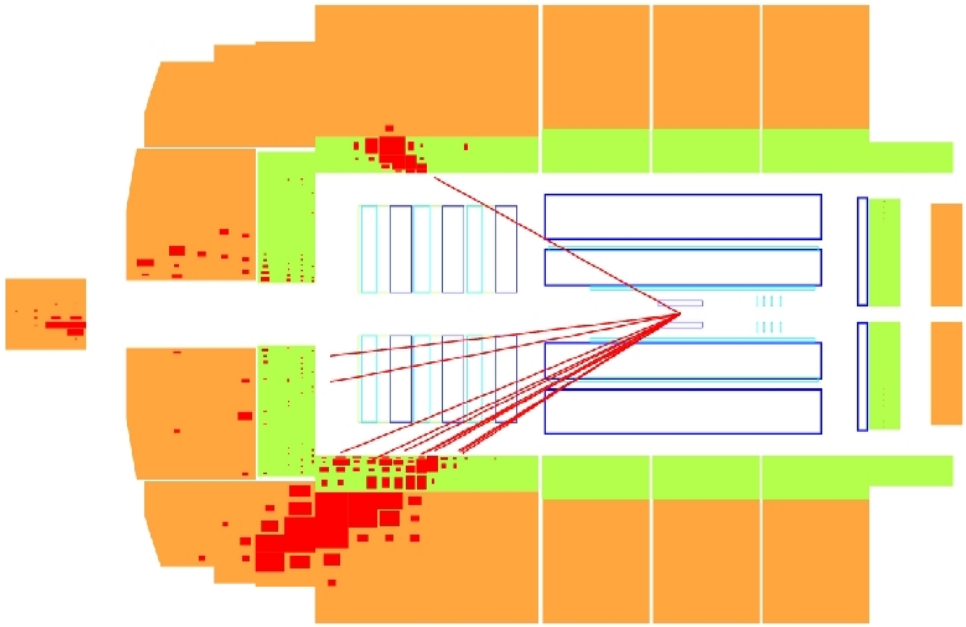
LHC: $\sqrt{s}$=14 TeV

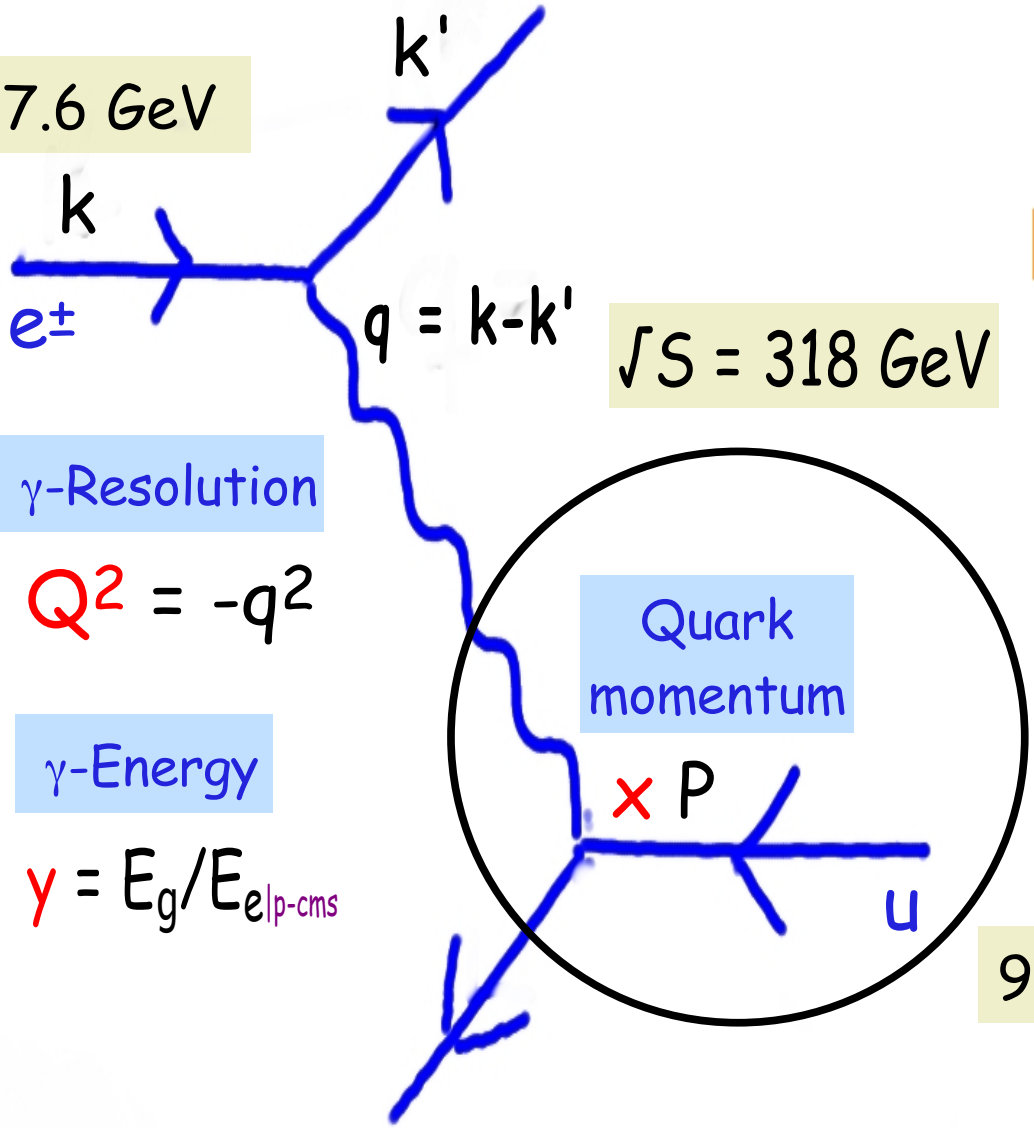
Start May 2008

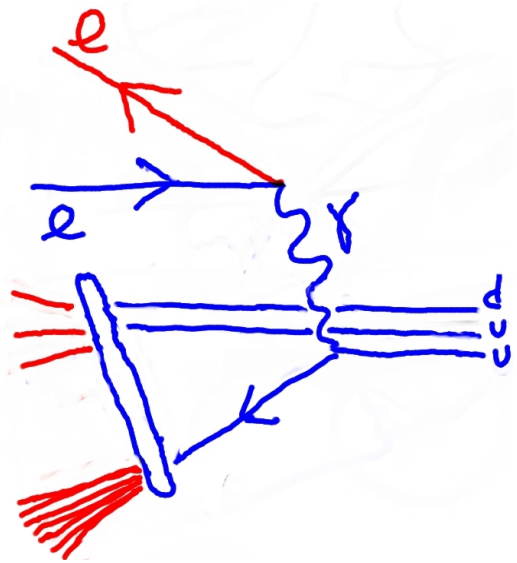
~5 abstracts for HEP2007

Deep inelastic scattering at HERA

Event in H1 detector:

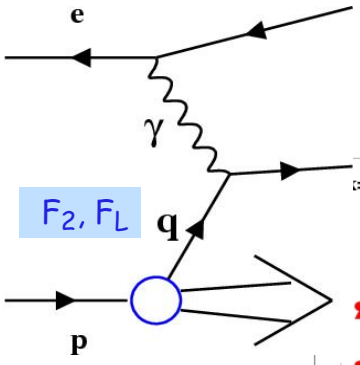




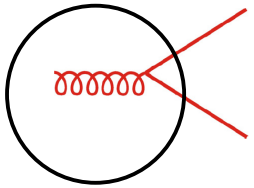


Relation: $Q^2 = Sxy$

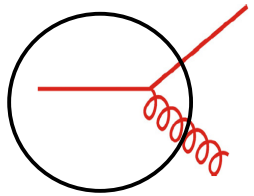
The HERA proton handbook



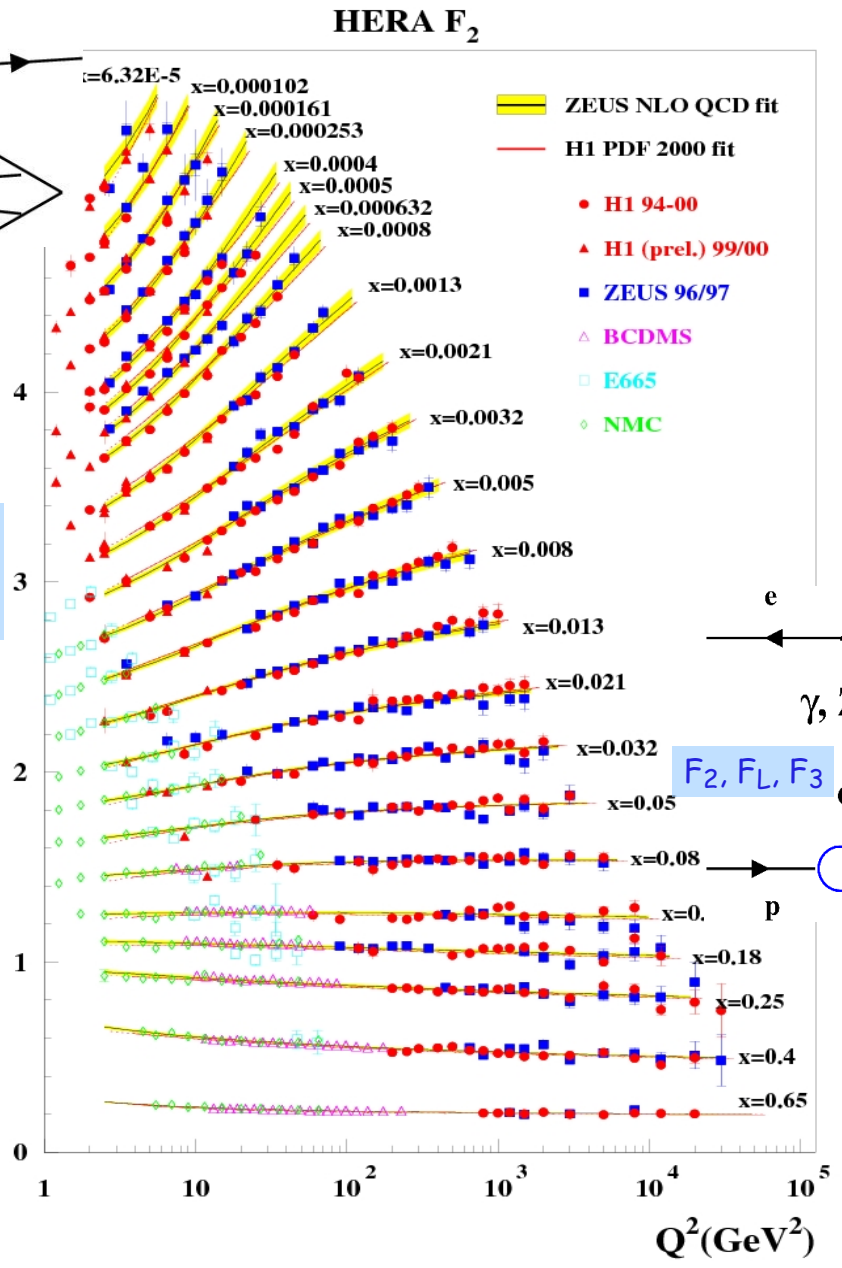
F_2, F_L

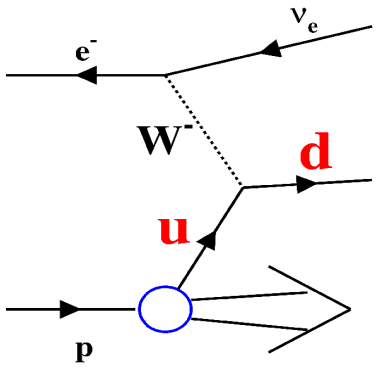


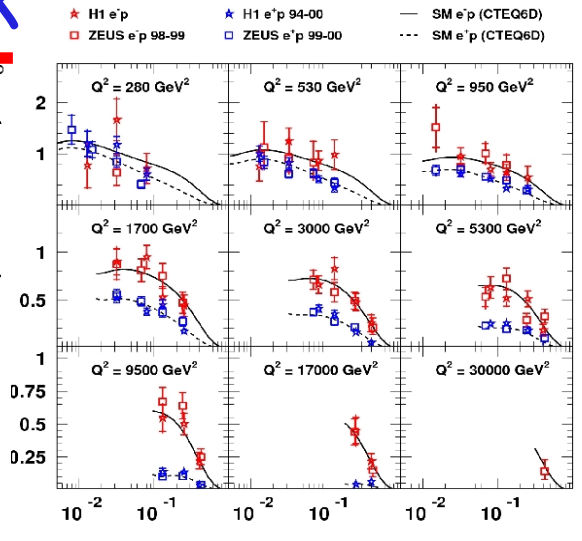
Scaling violations
~ $g(x,Q^2)$

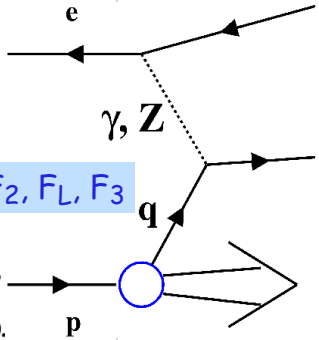


Bremsstrahlung of valence quarks



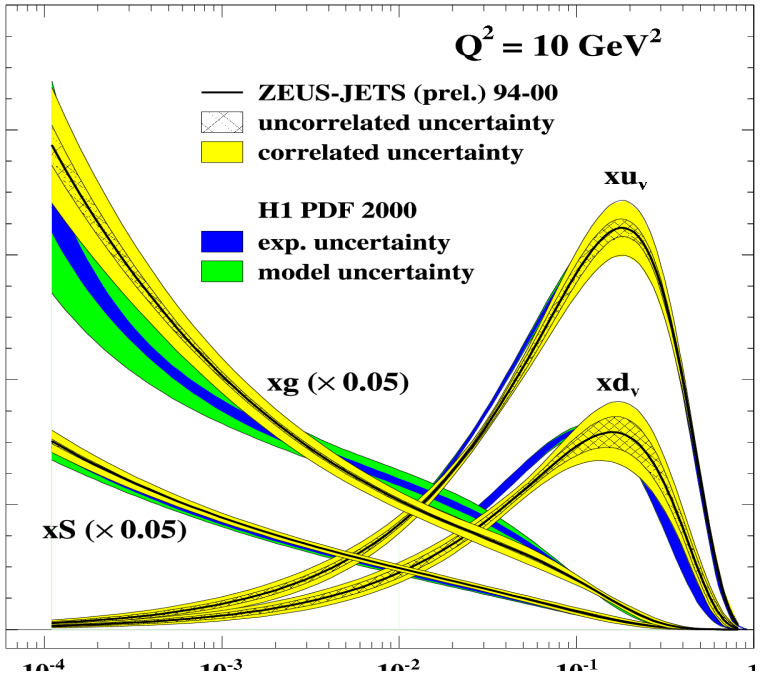




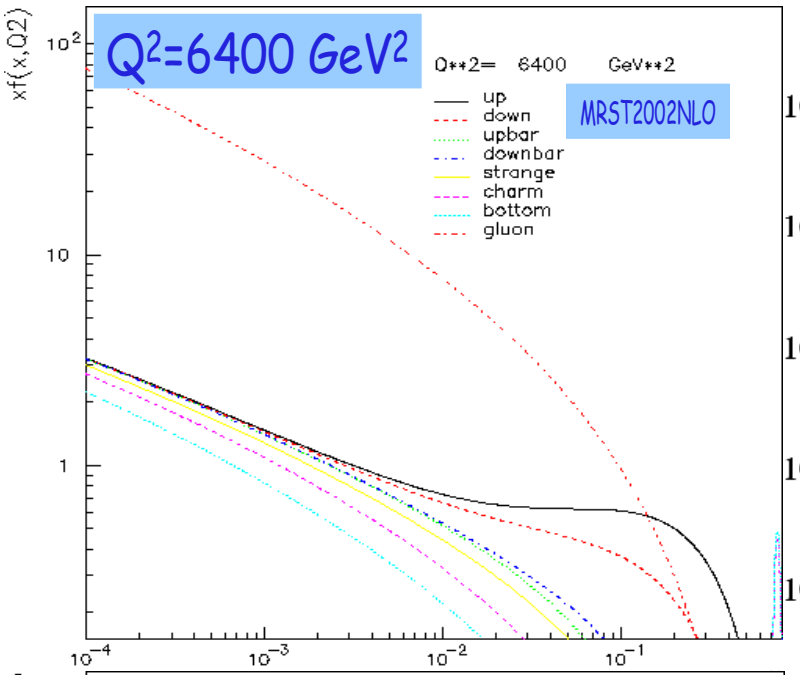


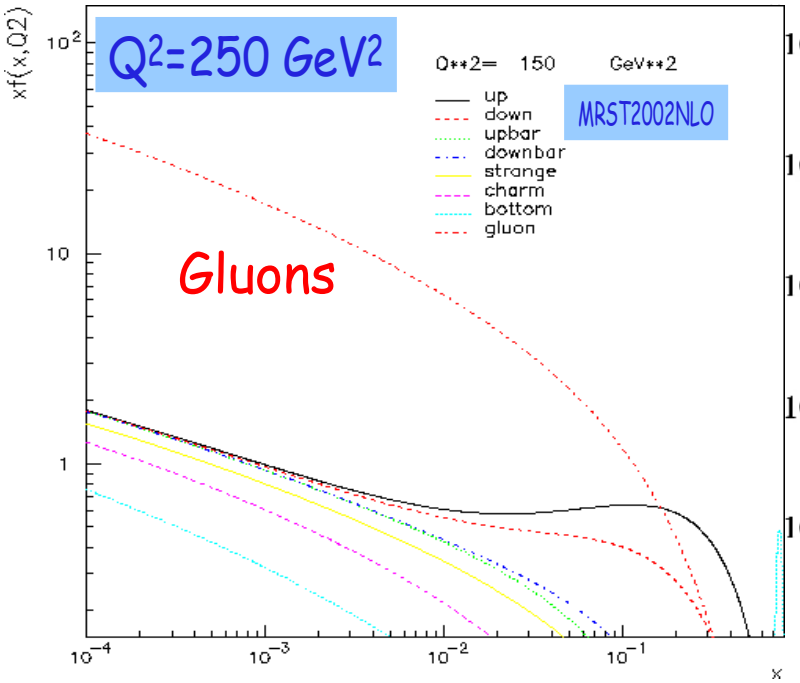
F_2, F_L, F_3

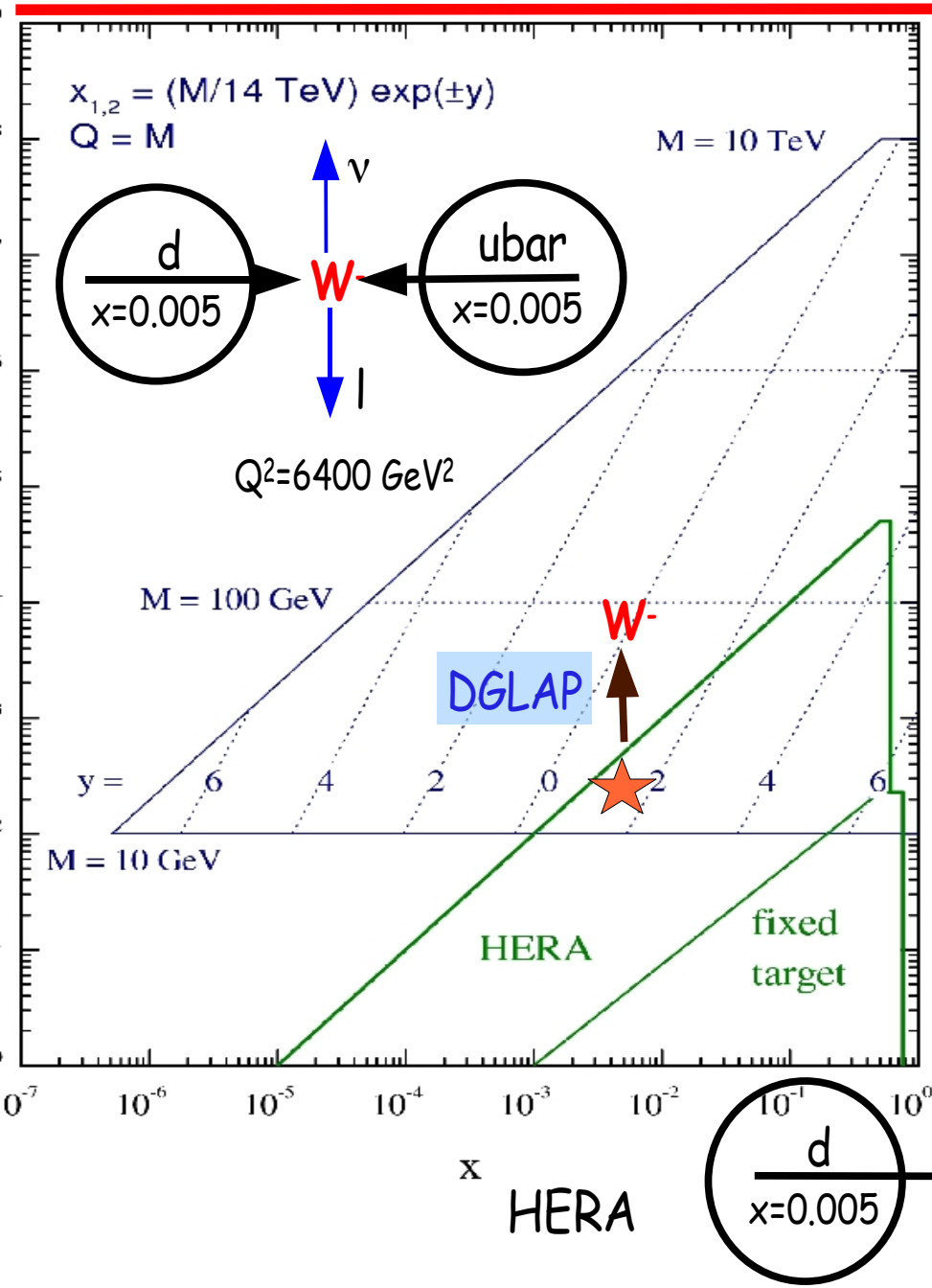
Using all info in an NLO QCD fit (DGLAP evolution) :



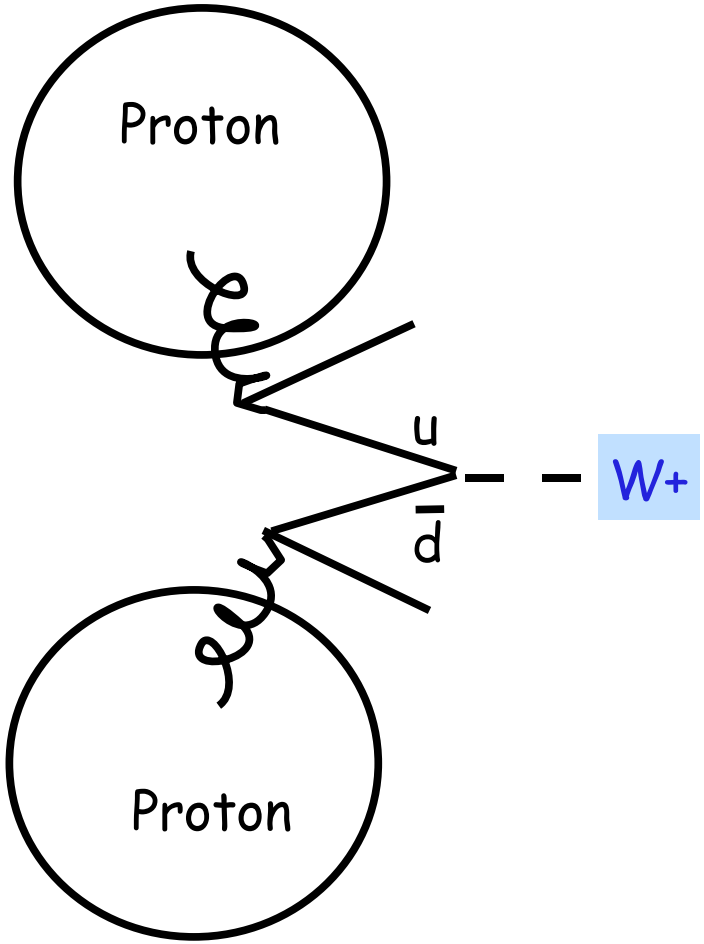
From HERA to LHC in a nutshell





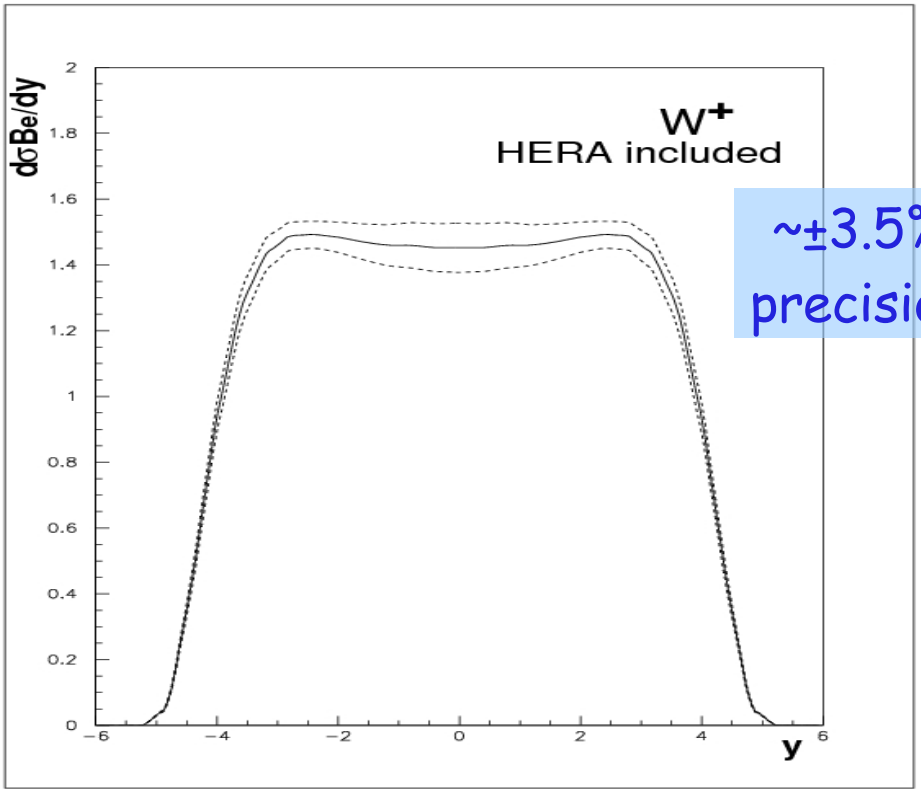


HERA proton PDF --> LHC W production



'Lumi' process for LHC

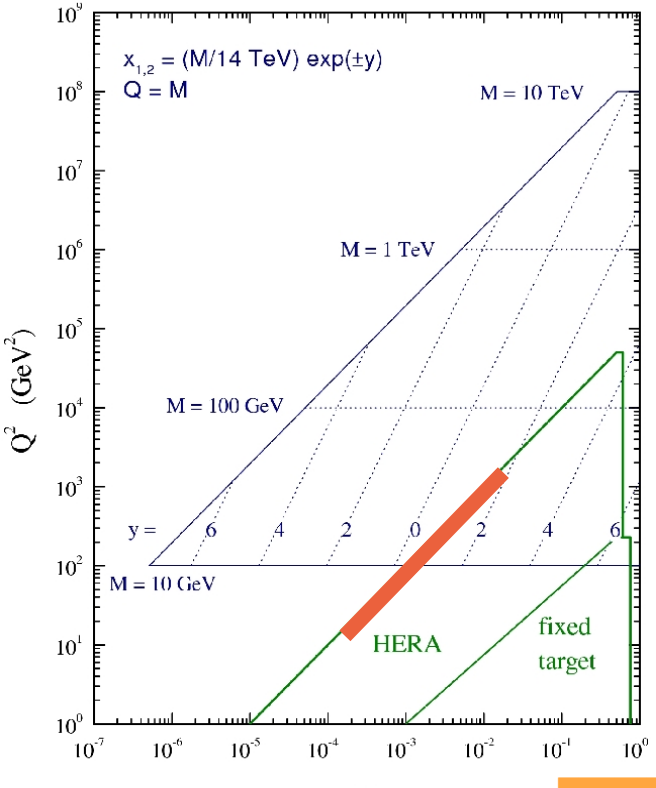
Prediction using ZEUS-S-PDF

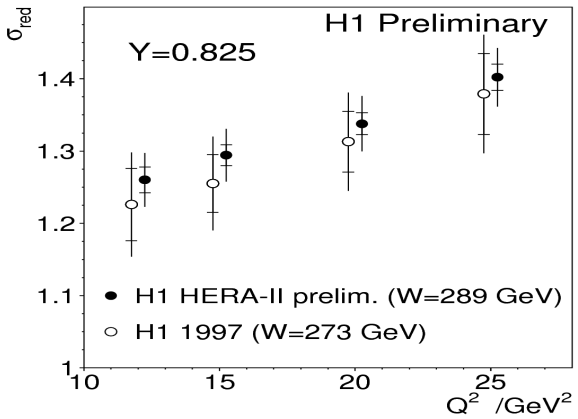


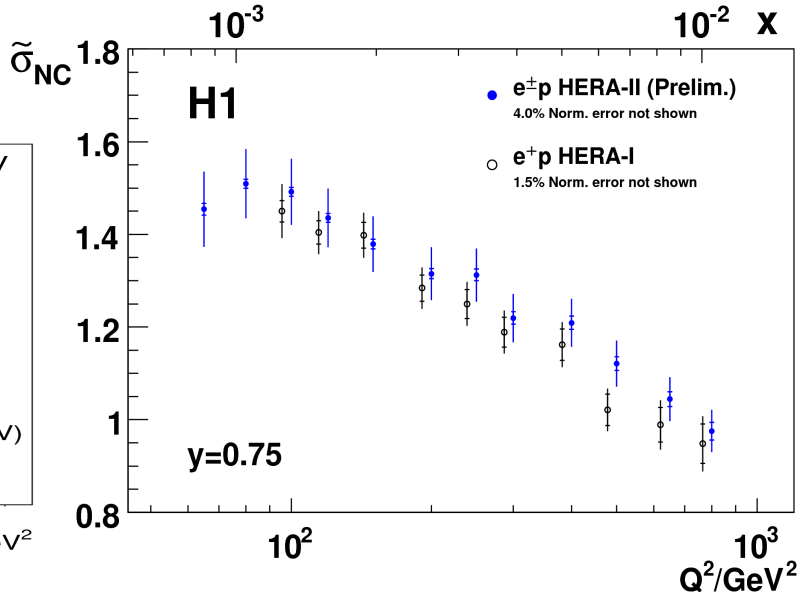
~±3.5% precision

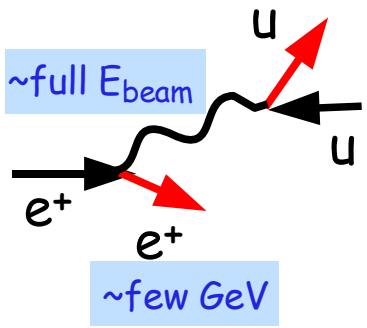
➔ HERA u, $\bar{d}$ and gluon determine precision
- how far can we improve this?

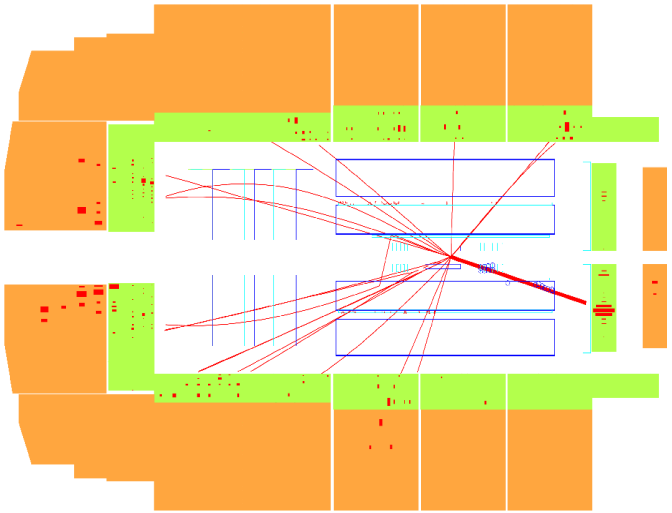
Inclusive DIS at highest Eγ (high y)

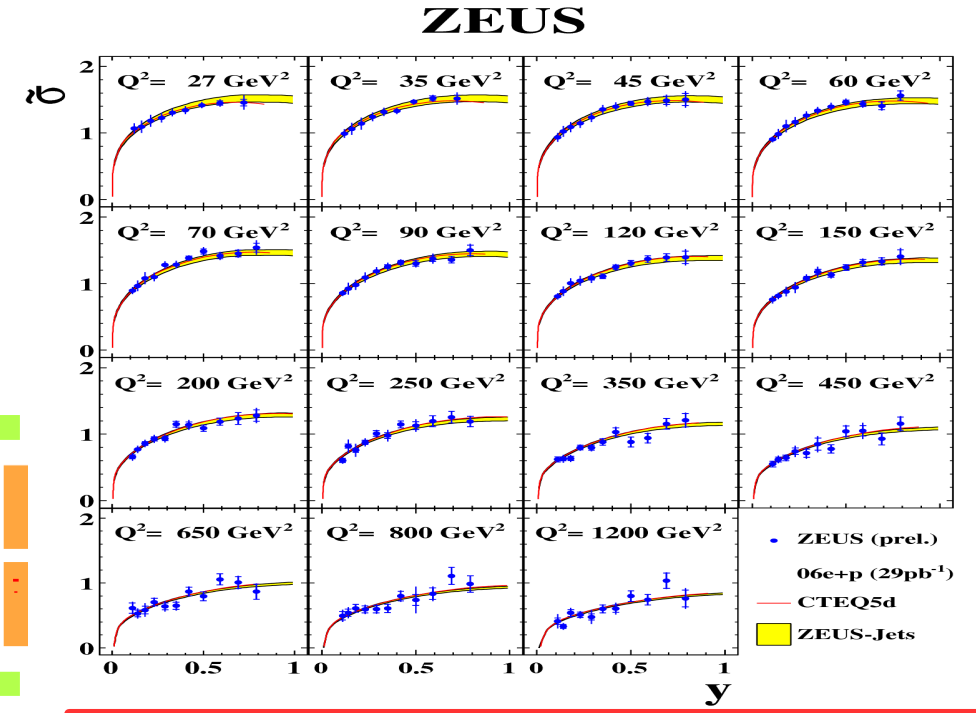






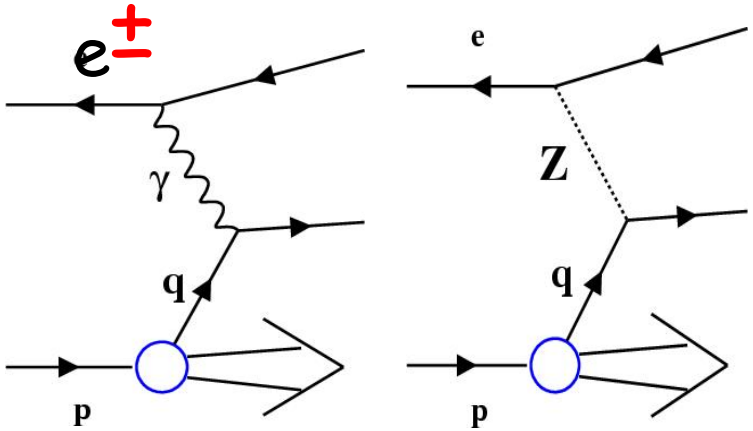




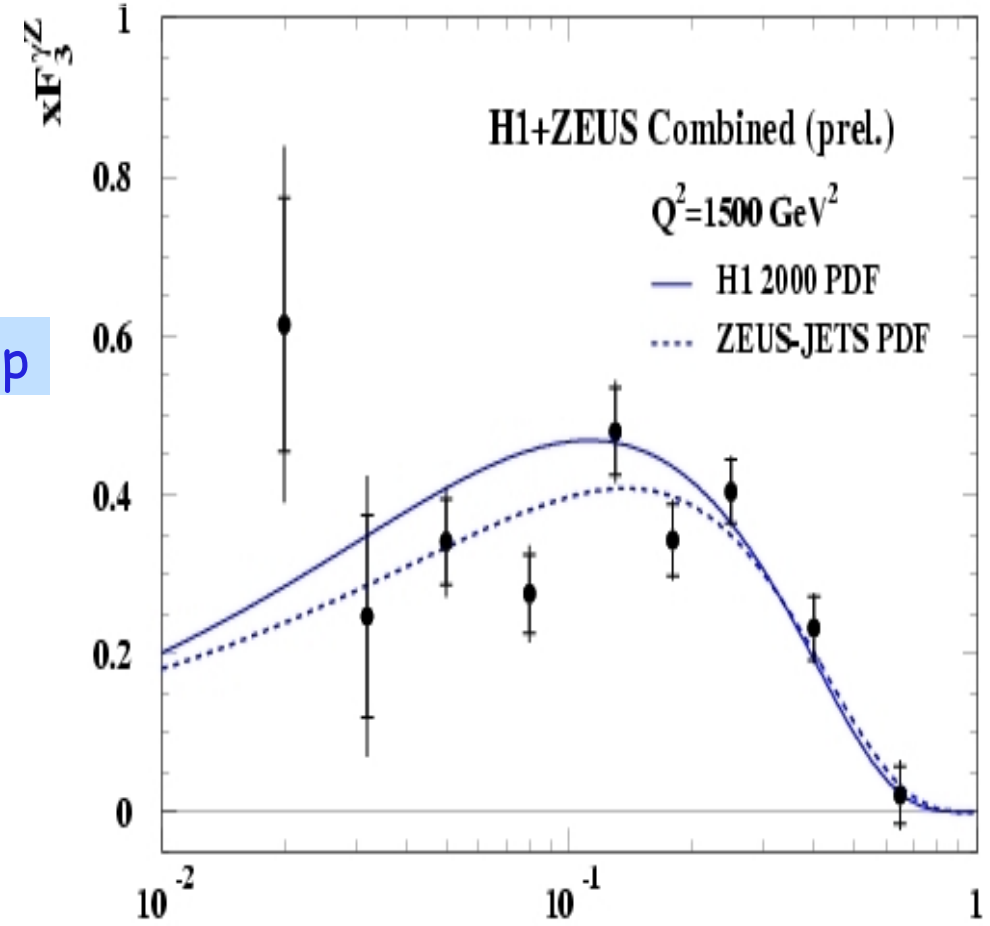


➔ Helps to extrapolate to LHC and to understand F_L

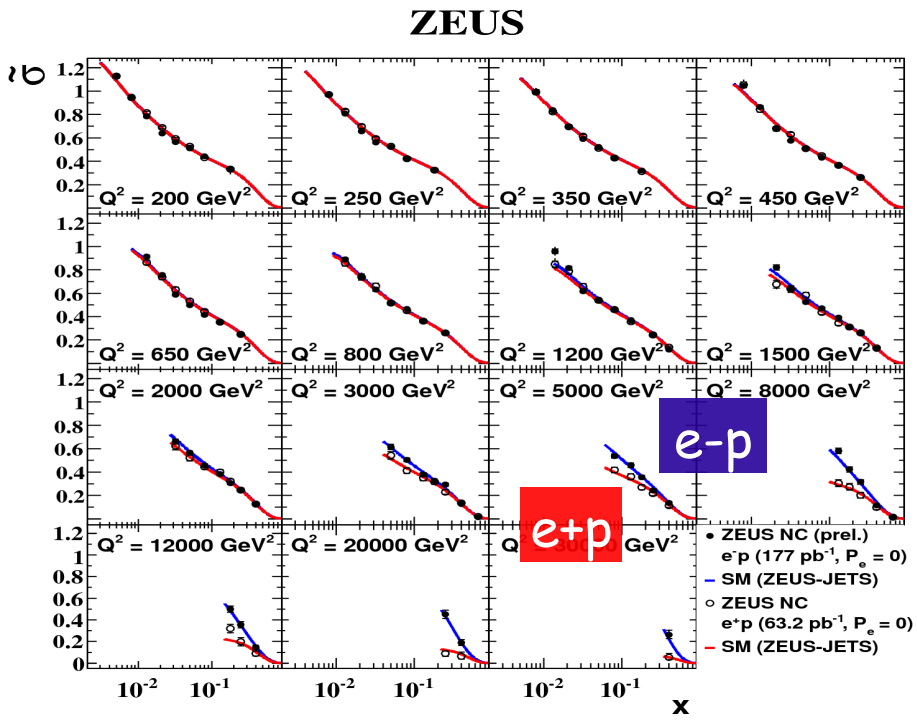
Valence quarks: xF_3



$xF_3 \sim \sigma(e^-p) - \sigma(e^+p) \sim 2u_v + d_v$

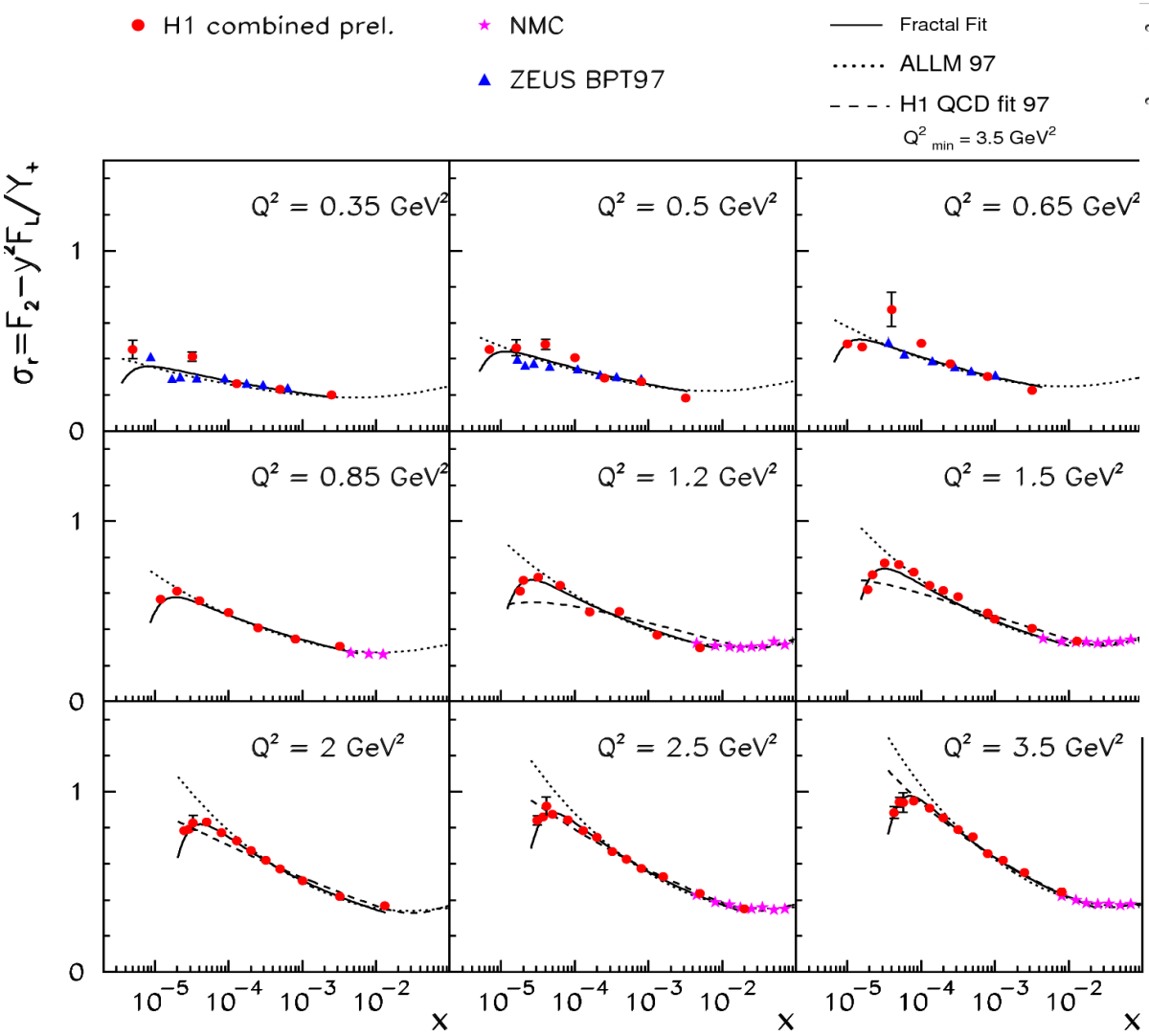


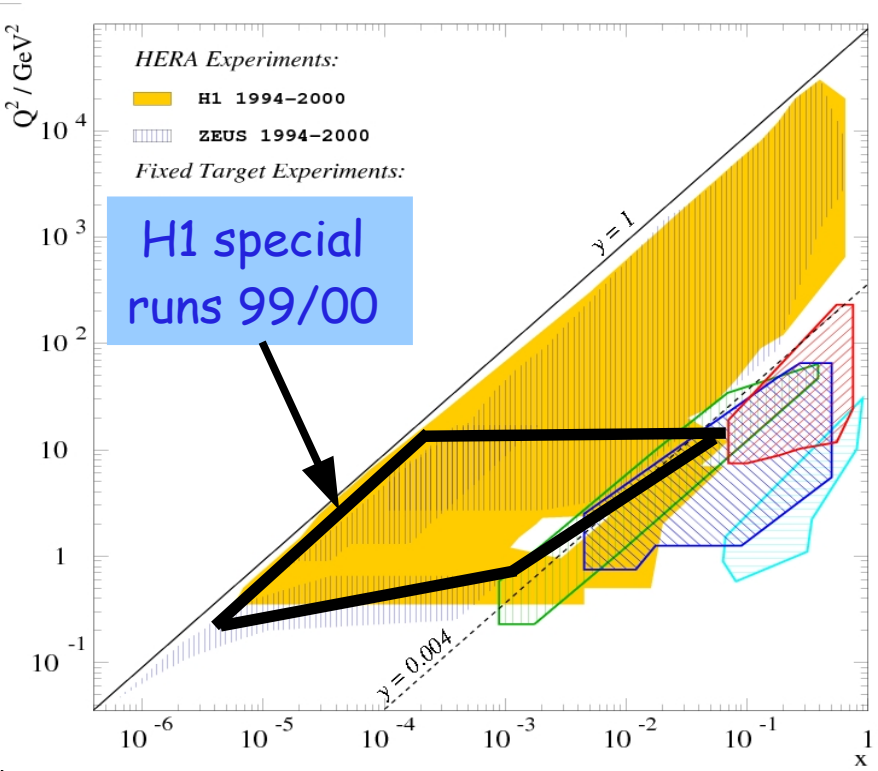
γZ interference flips sign for $e^+p \rightarrow e^-p$



➔ Valuable info on valence quarks at low x<0.1

The final word from HERA for low Q^2 <10 GeV^2

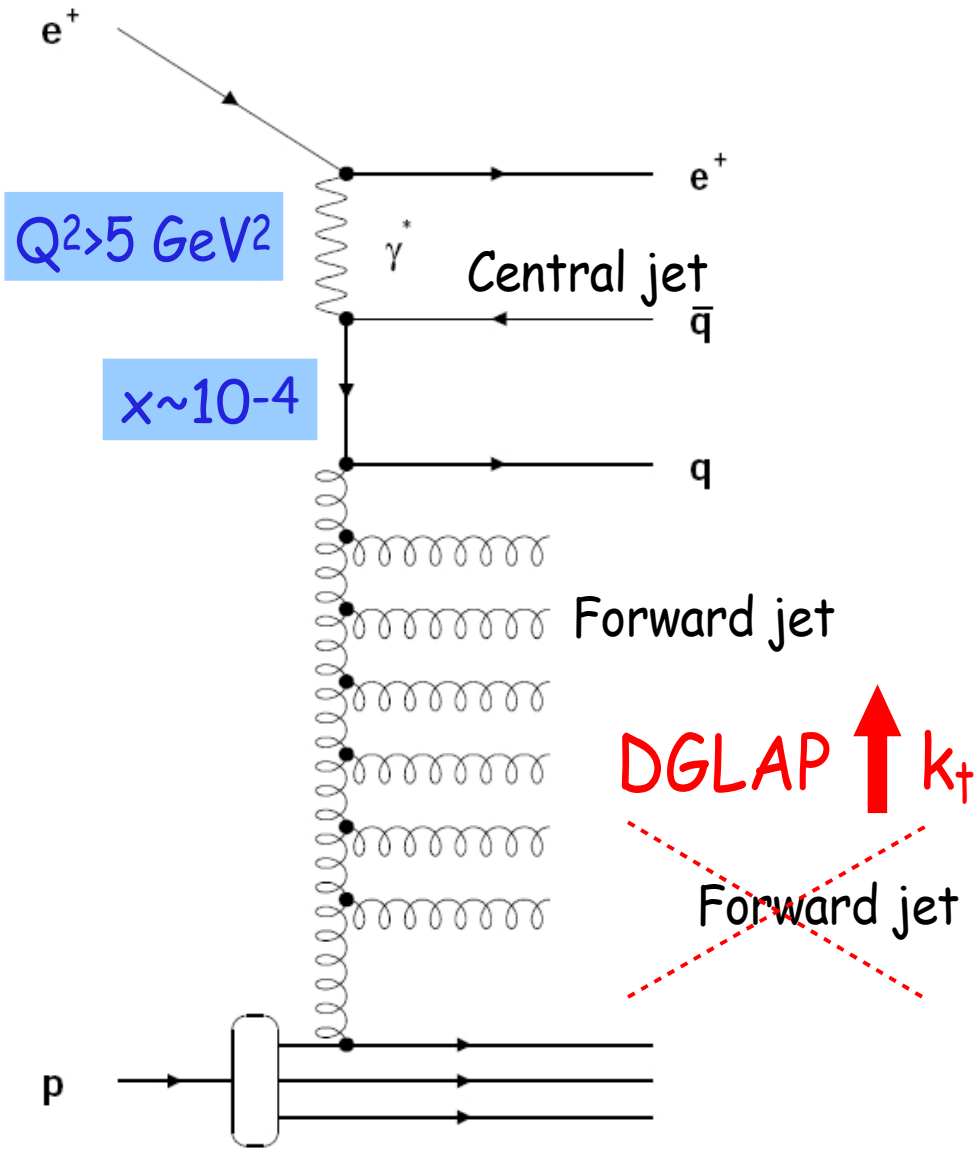


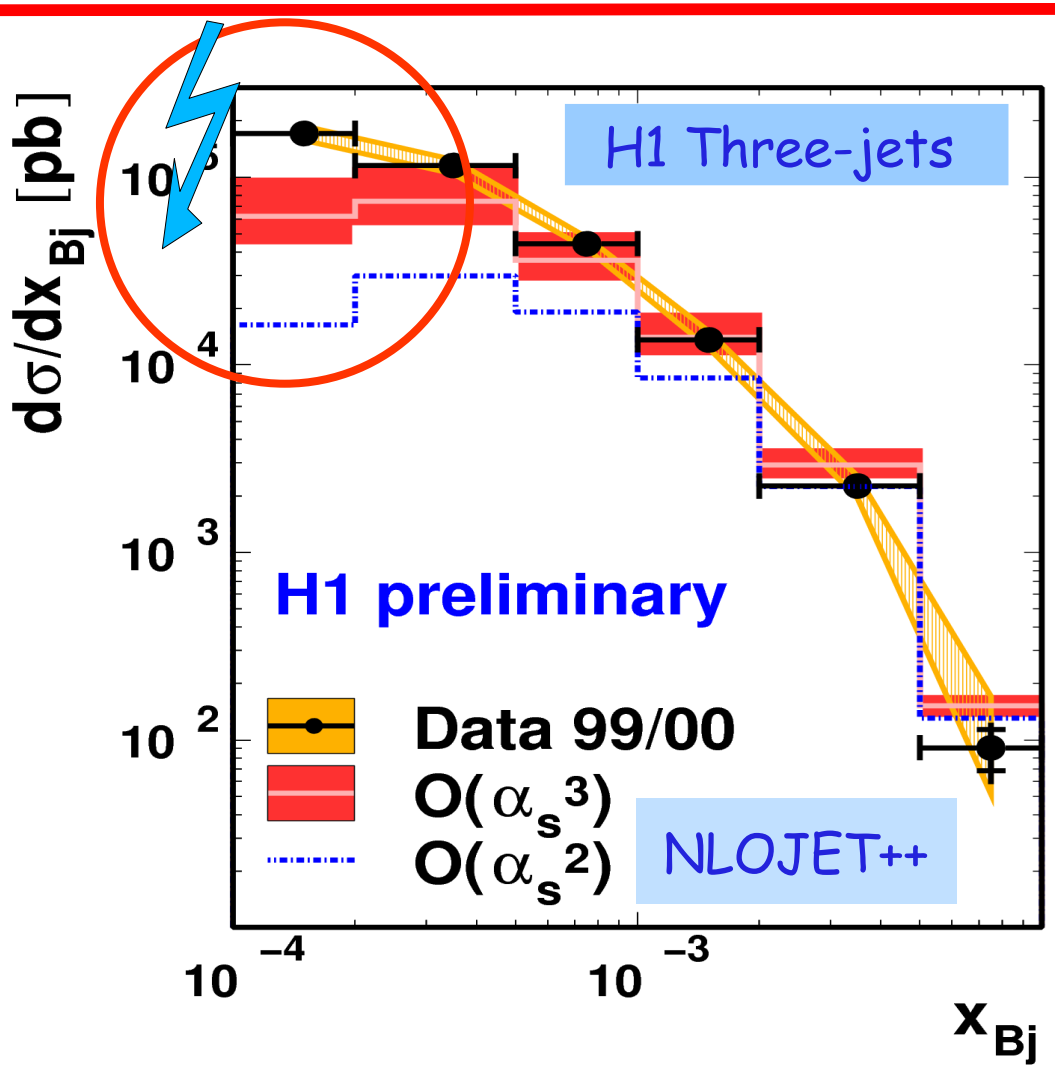


➔ Mapping the transition to the soft QCD regime (Q^2<1 GeV^2)

➔ Up to 3% precision reached – provides unique data for models

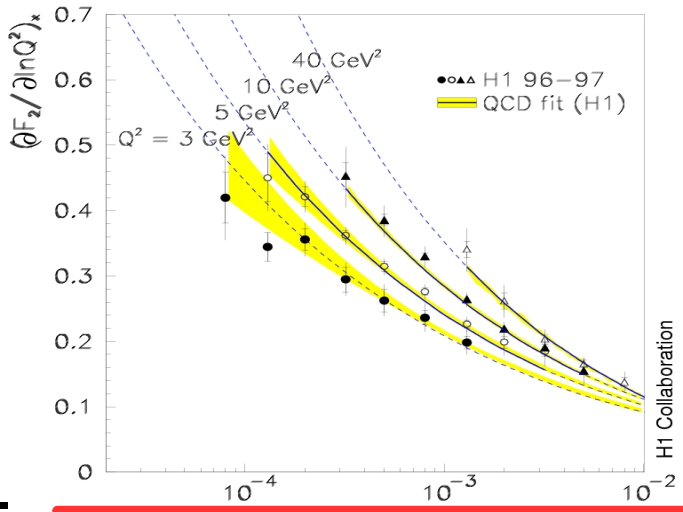
Warning: Signs of Breakdown of DGLAP at small x





➔ Strong hints for k_T unordered gluon emissions, neglected in DGLAP

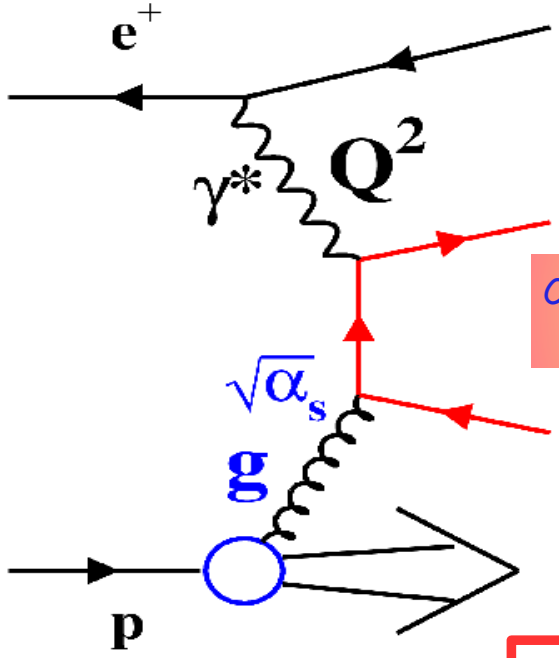
Gluon density determinations



Gluon	$\left.\frac{\partial F_2}{\partial \ln Q^2}\right\|_x \propto \alpha_s(Q^2) x g(x, Q^2)$ *Jet cross sections* $F_2^{c\bar{c}}$ F_L

➔ Still most precise - to be improved soon with the available HERA data

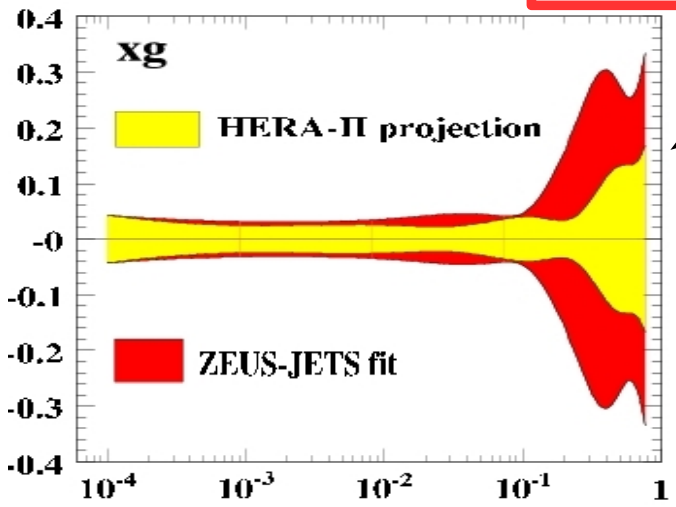
Gluon from jets @ HERA



Calibrate jet energy scale via pt balance with scattered e+

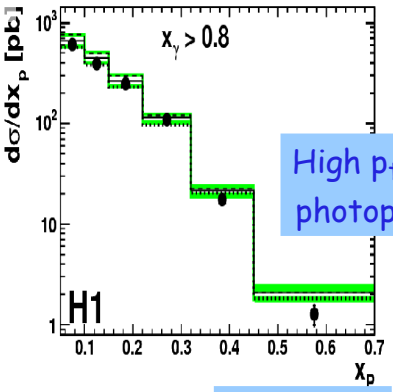
Wealth of new data to constrain g(x)

M. Cooper-Sakar: HERA-LHC workshop, 700 pb-1 HERA data simulation:



H1

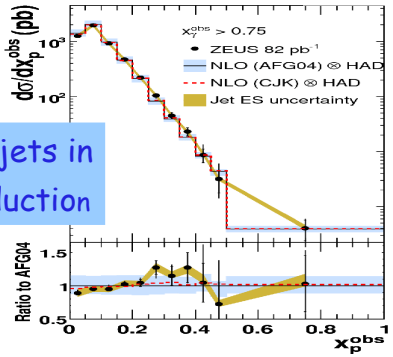
DESY-06-020



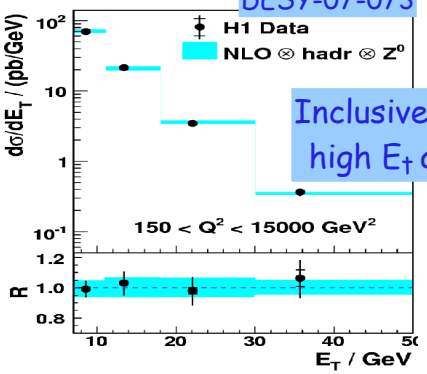
High p_t Dijets in photoproduction

DESY-07-092

ZEUS

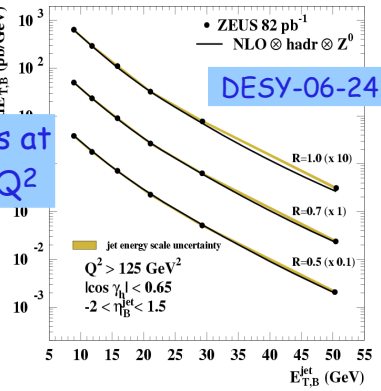


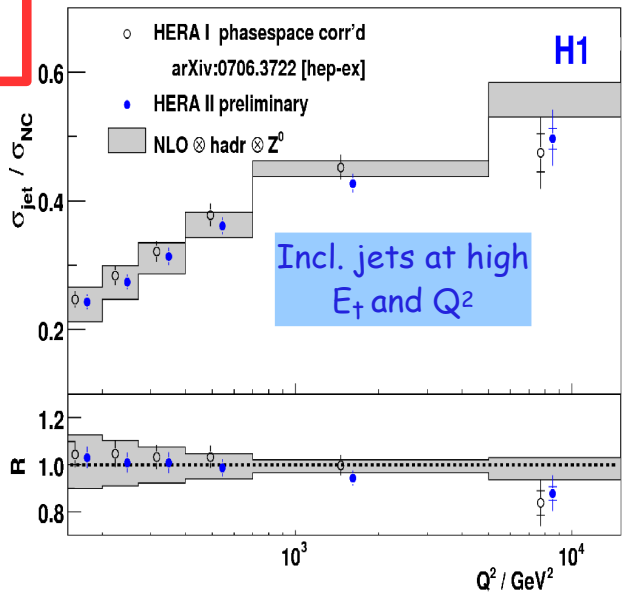
DESY-07-073

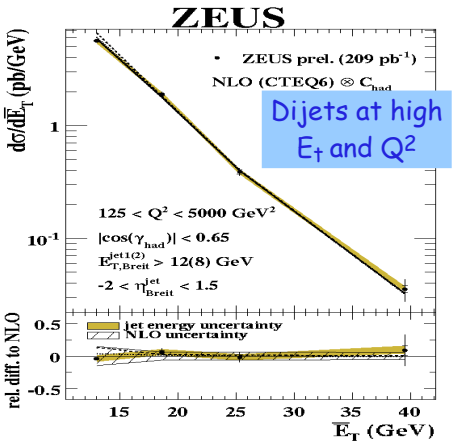


Inclusive jets at high E_t and Q^2

DESY-06-241

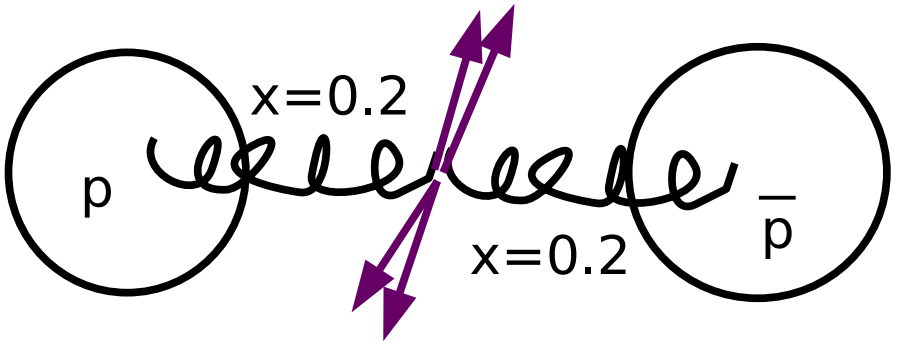






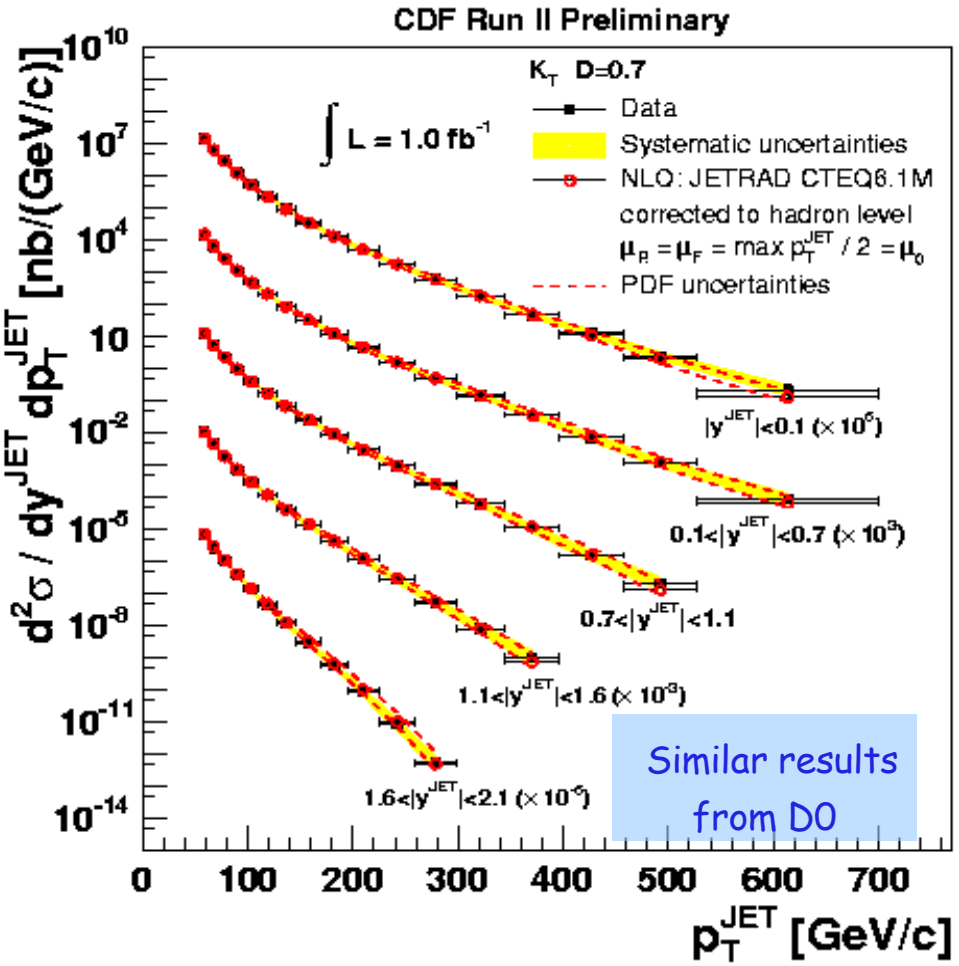
+ more to come from both experiments

Gluon from jets at Tevatron

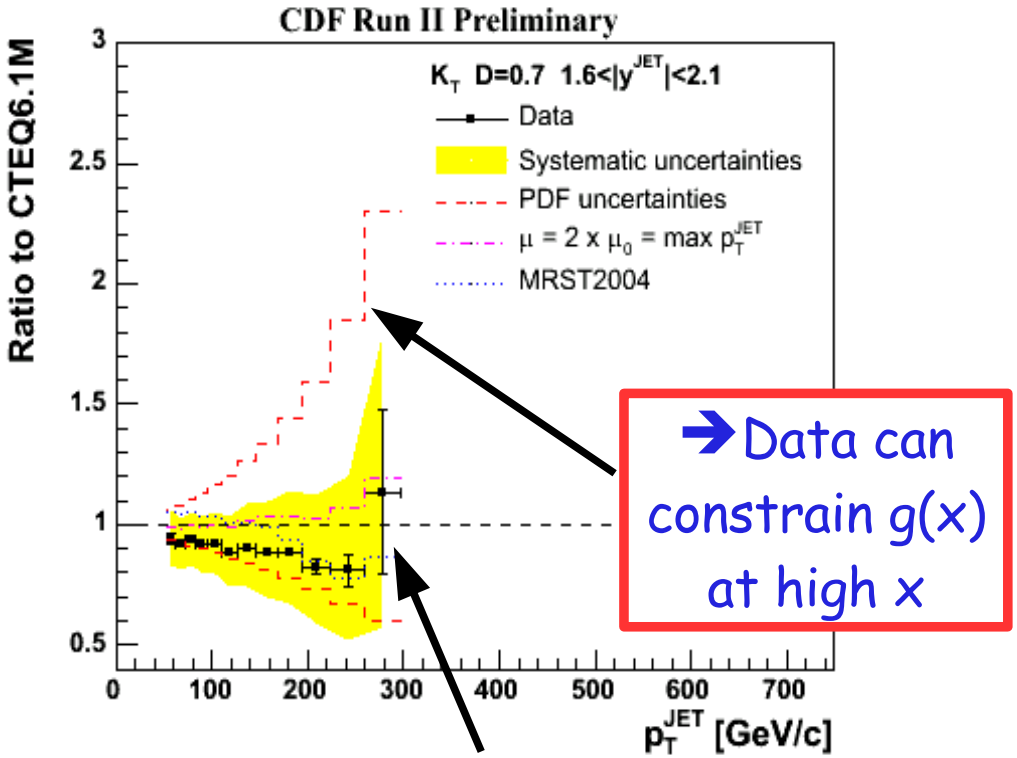


Deviation from NLO QCD could also signal new physics !

Can probe the *'most violent'* gluons!



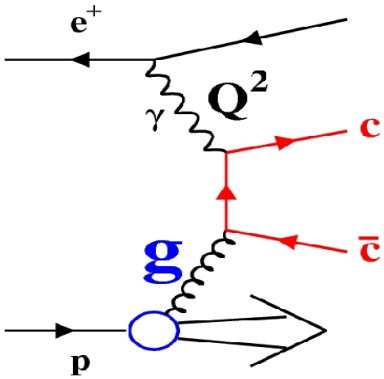
Similar results from D0



➔Data can constrain g(x) at high x

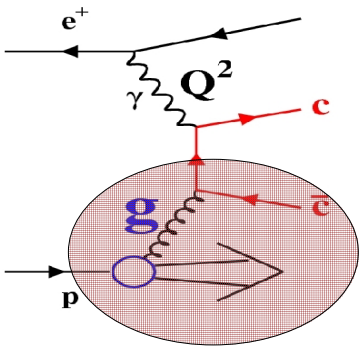
Hadronic energy scale dominates experimental uncertainty

Gluon via charm @ HERA



$Q^2 \sim m_c^2$

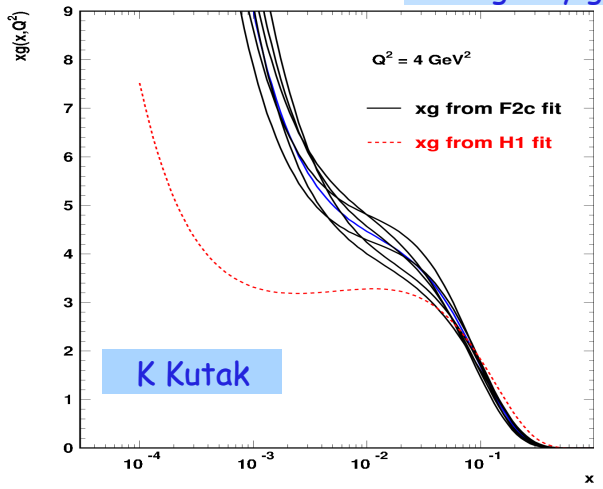
Massive c



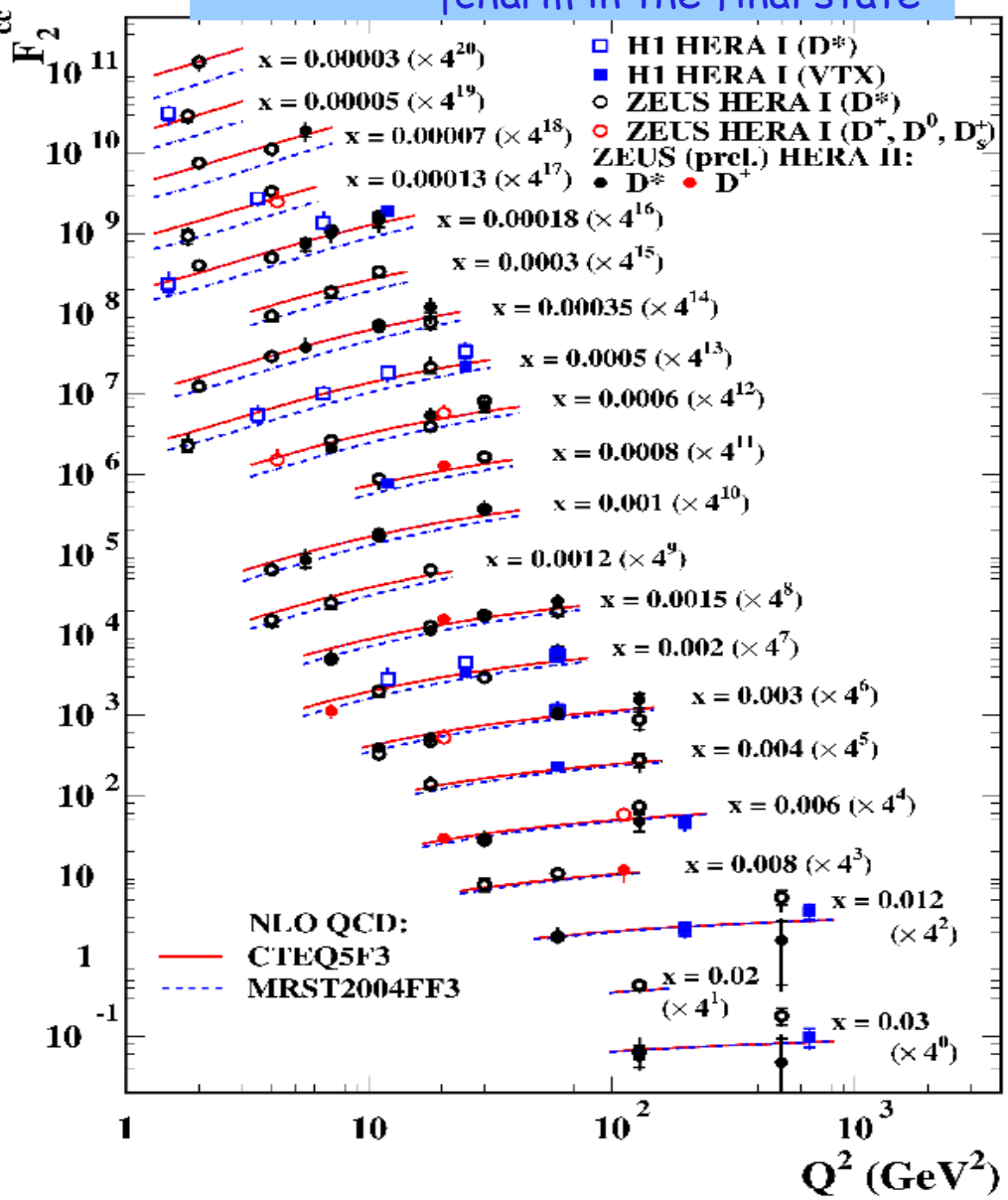
$Q^2 \gg m_c^2$

Massless c

NLO QCD fit using H1 F_2^{cc}, fitting only gluon



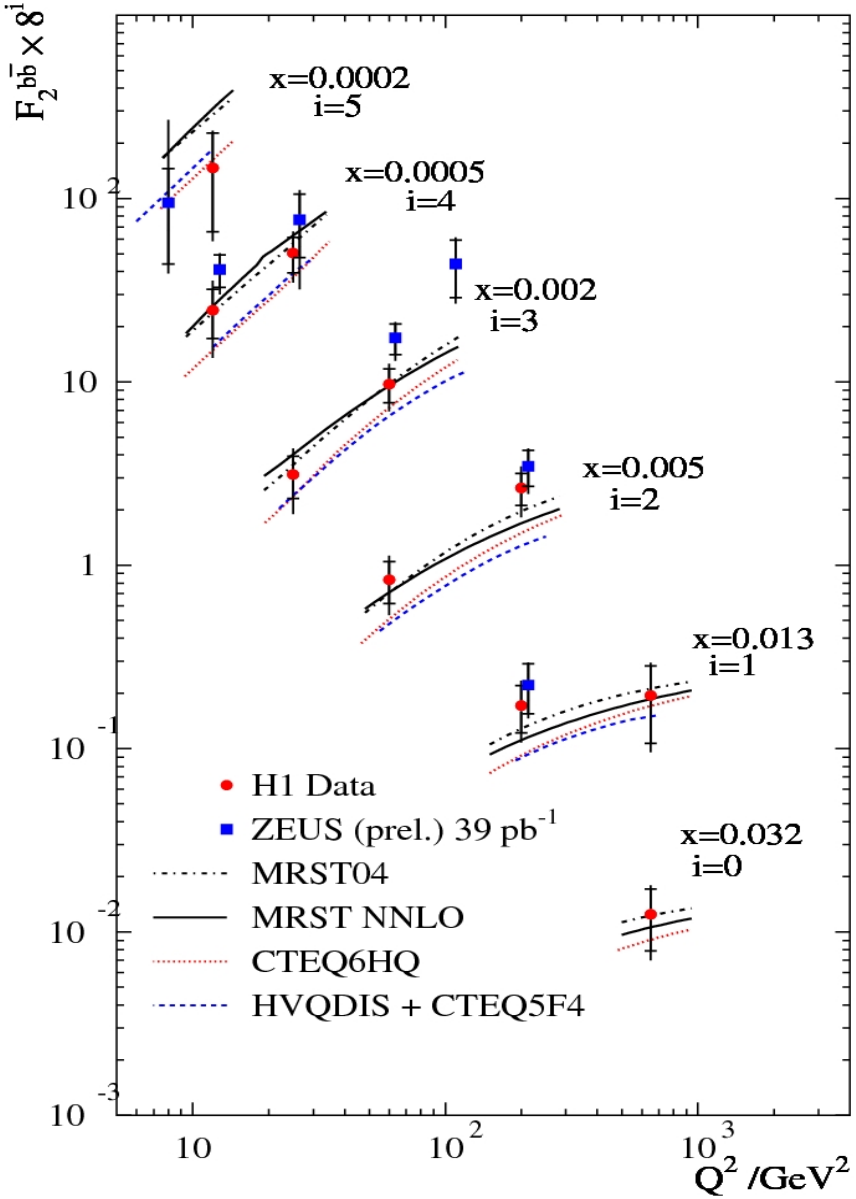
$F_2^{cc} = F_2|_{\text{charm in the final state}}$

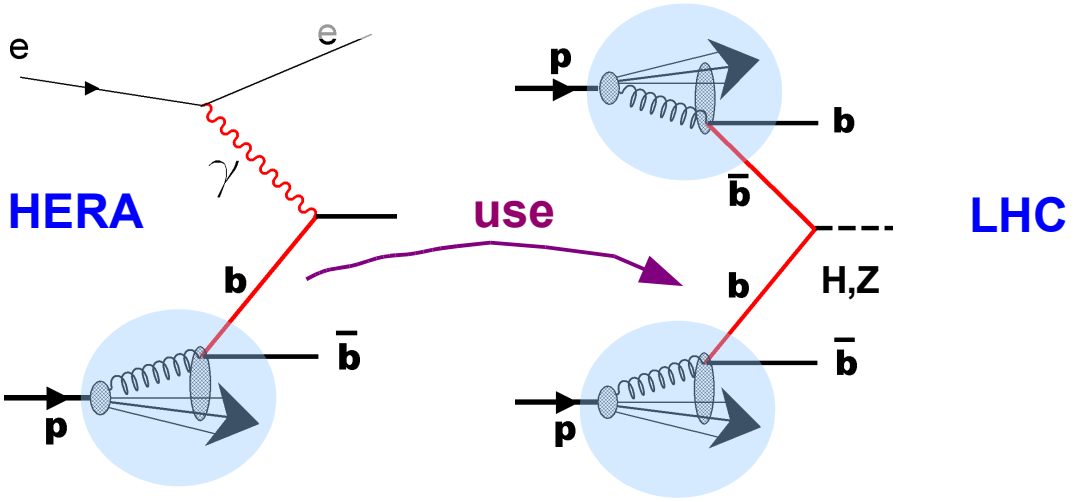


➔ F_2^{cc} data can constrain the proton gluon density at small x

HERA beauty density ... goes to LHC

Beauty contribution to F2

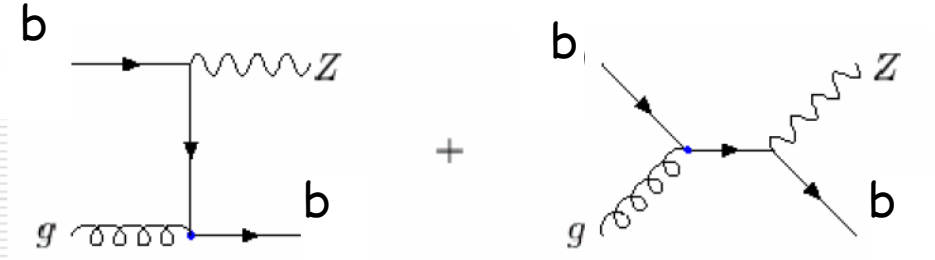


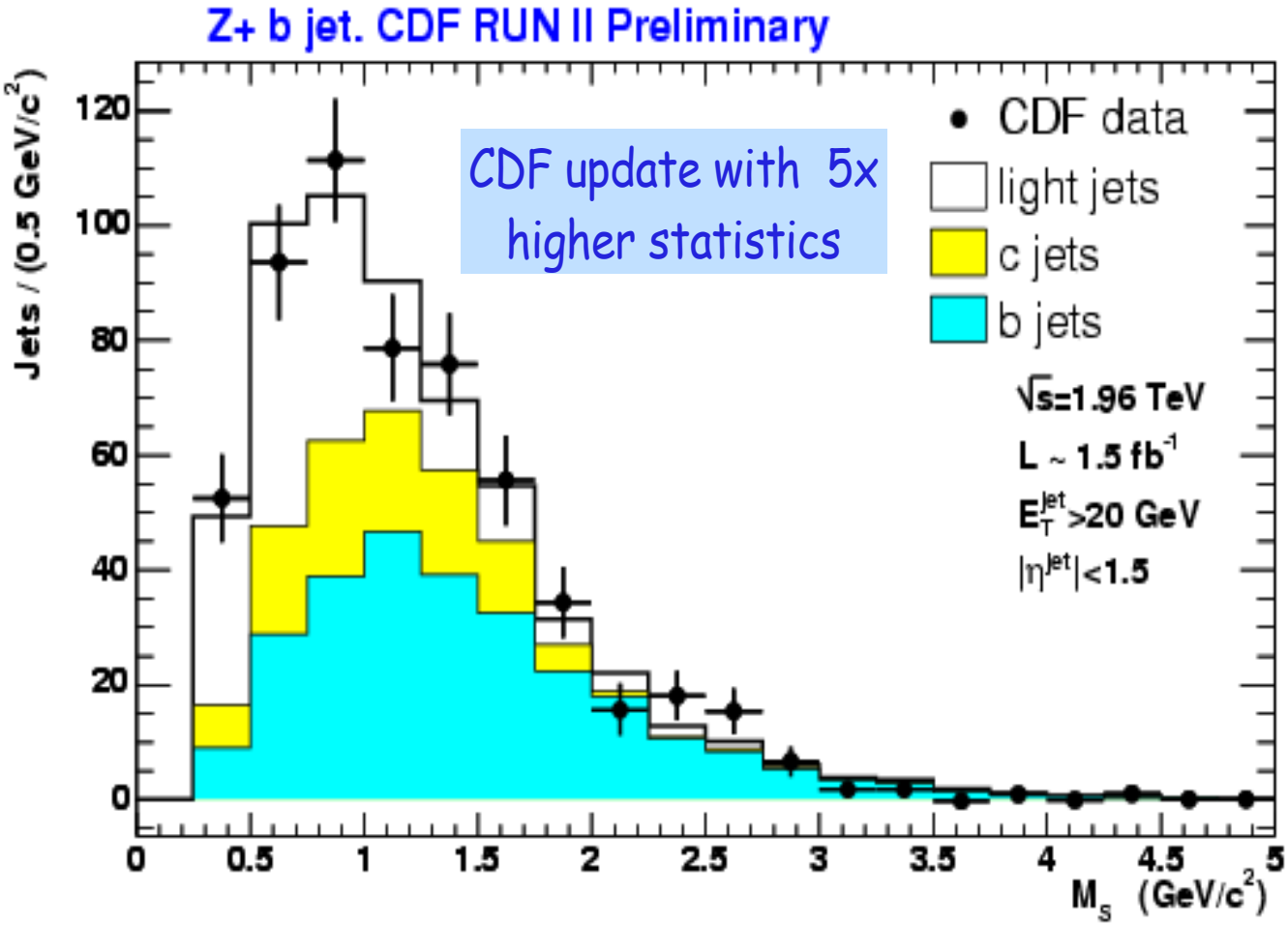


➔ 'Beautyful' new HERA II data

➔ Astonishing spread of model predictions!

Probe b PDF with Z+jet at Tevatron





Z+b-jet/Z+jet :

CDF: 2.35+-0.36(stat) +-0.45(sys) %

D0: 2.1+-0.4(stat) +0.3-0.2(sys) %

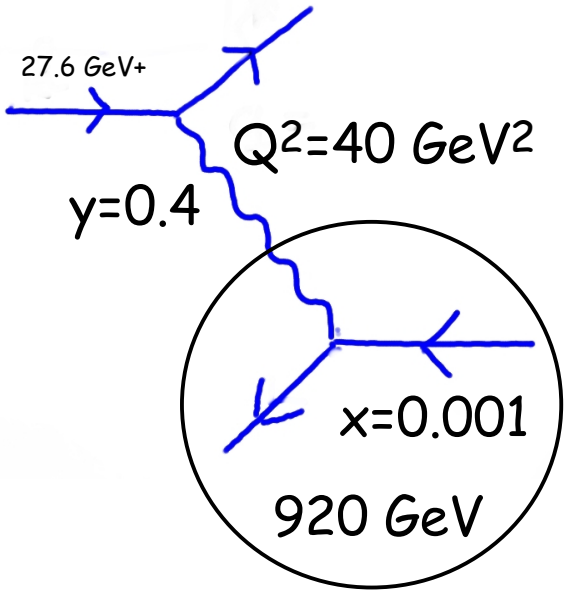
NLO: 1.8+-0.4 % (CTEQ6)

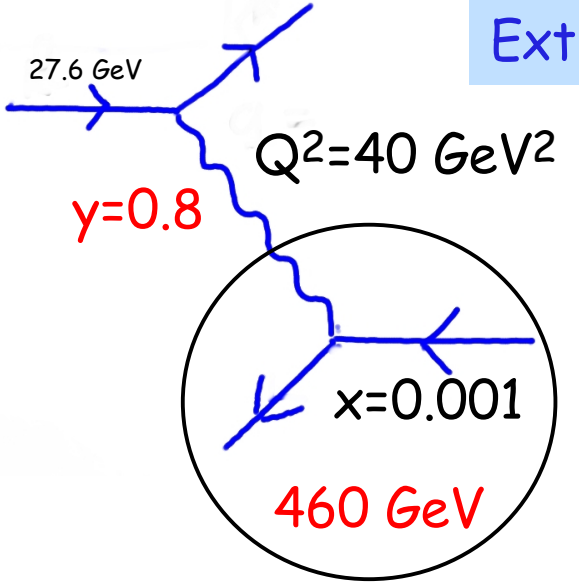
➔ More to come!

Gluon density via F_L at HERA

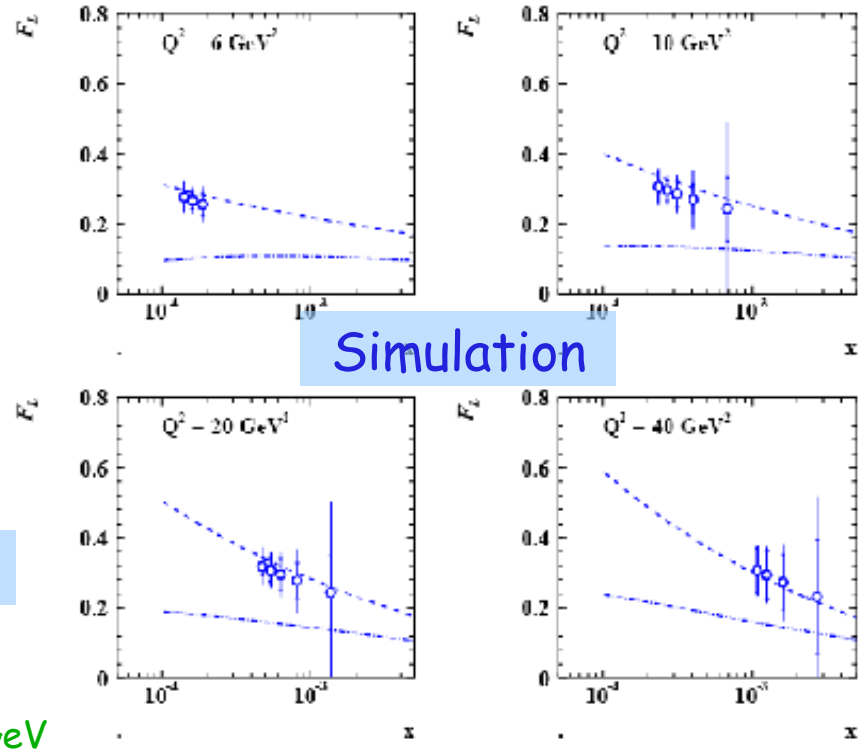
$$F_L = \frac{\alpha_S}{4\pi} x^2 \int_x^1 \frac{dz}{z^3}\left[\frac{16}{3}F_2 + 8\sum e_q^2 (1 - x/z) zg\right]$$

$\sigma_r(x,Q^2) = F_2(x,Q^2) - y^2/(1+(1-y)^2)\, F_L(x,Q^2)$ →



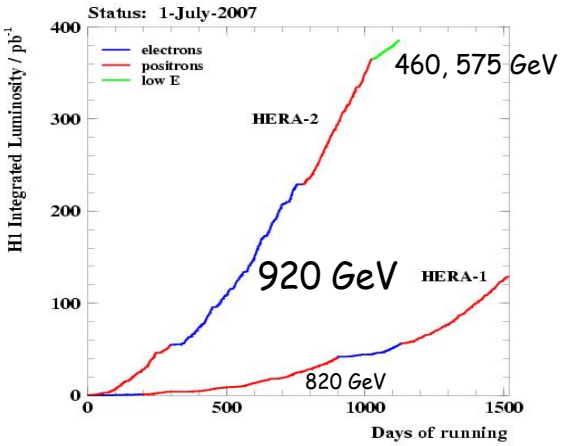


Extract F_L from $\sigma_r(x,Q^2)$ at different y

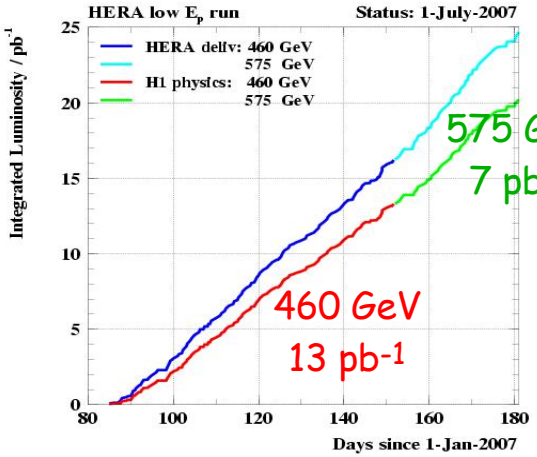


Simulation

HERA: All runs



Last 3 HERA months

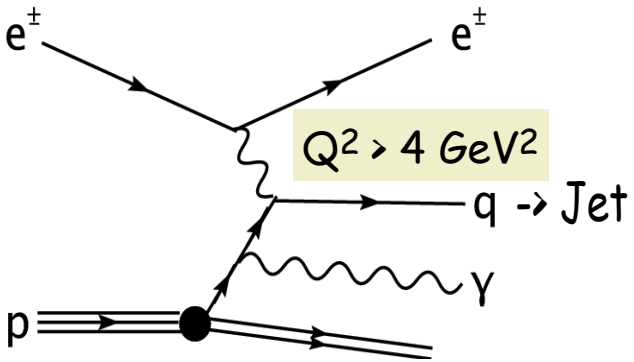


➔Nice low E_p data on tape

➔Final F_L should separate extreme gluon densities

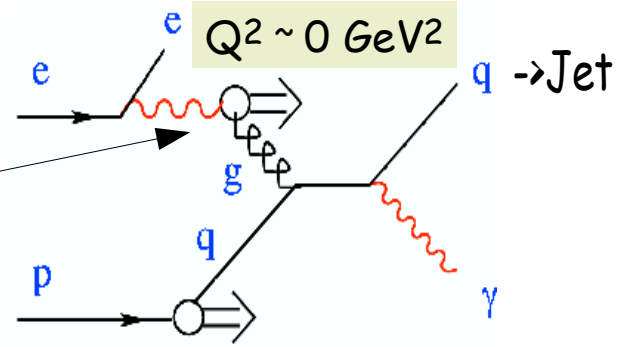
Prompt γ - sensitive probe of QCD!

HERA: ep

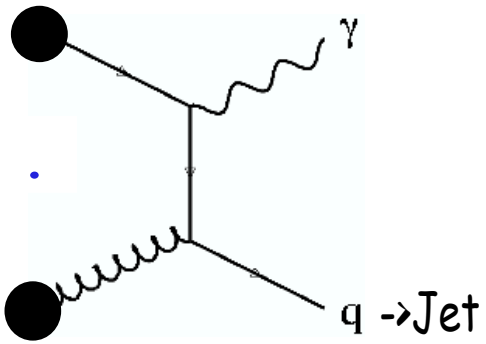


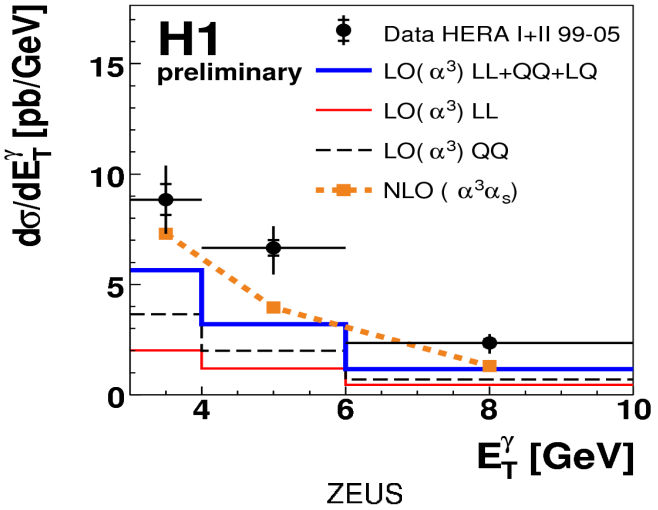
HERA: γp

resolved γ contributions

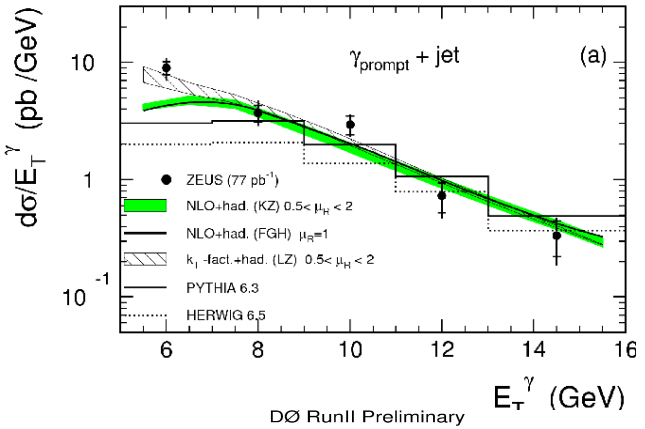


Tevatron: ppbar

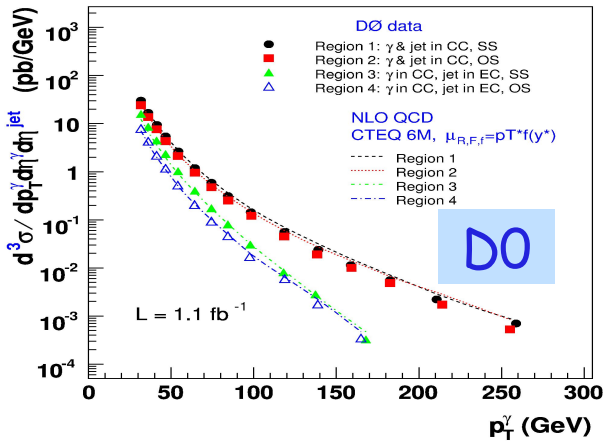




ZEUS



DØ RunII Preliminary

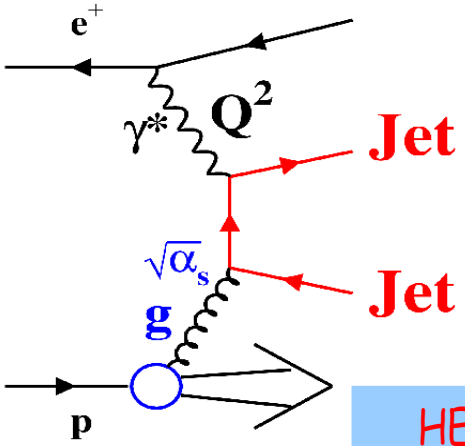


➔ Surprise: NLO too low

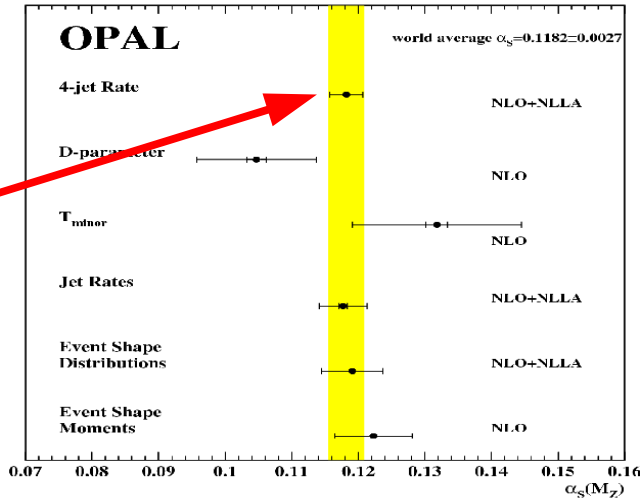
➔ ... too low at low E_T^γ

➔ High sensitivity to proton gluon density

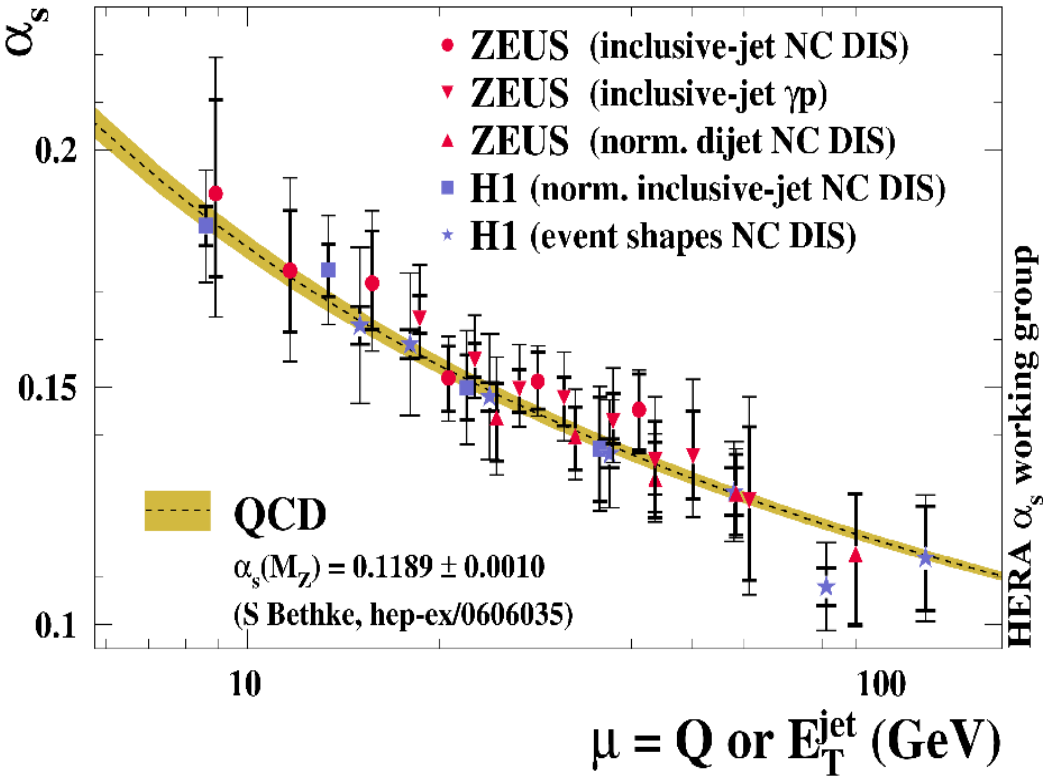
Strong coupling α_s

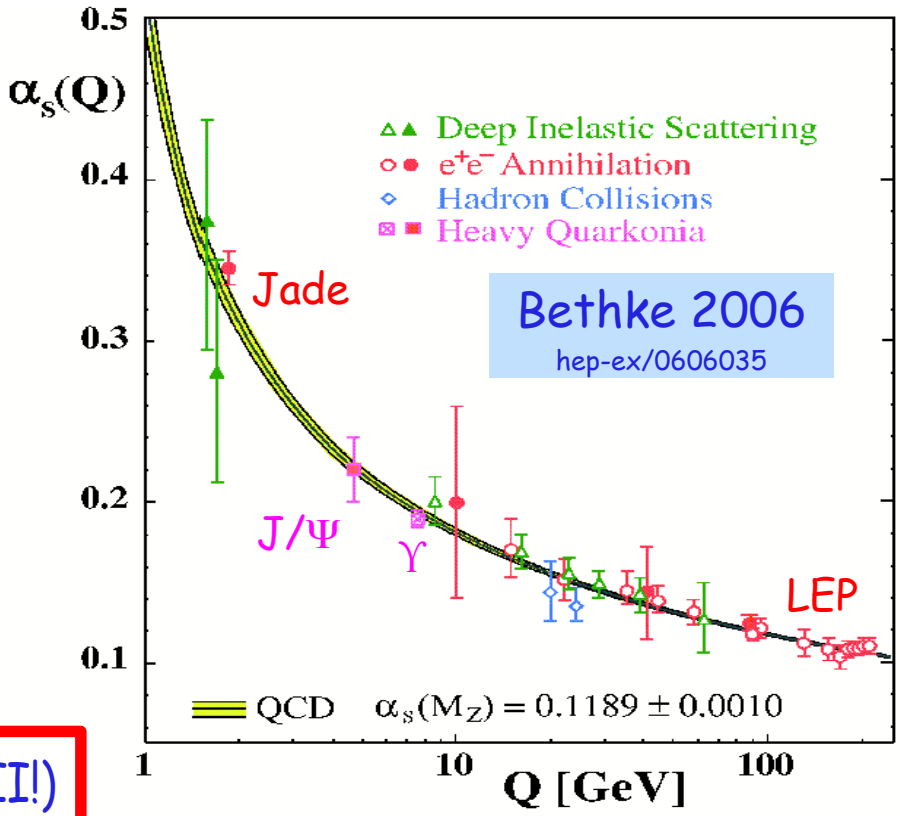


OPAL: ~400 k Four-jet events!
hep-ex/0601048



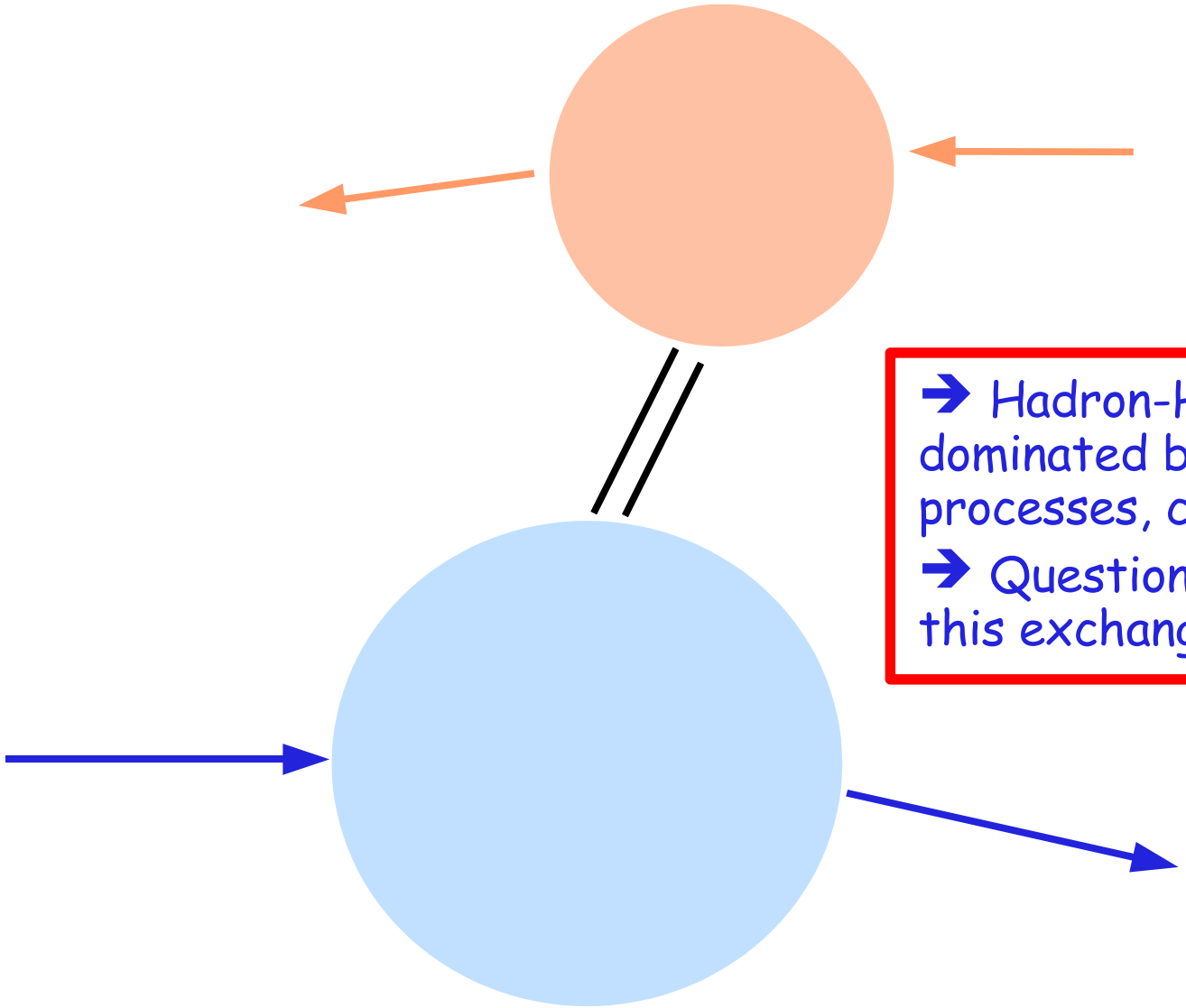
HERA α_s from fit to incl. Jet data
(H1: DESY-07-073, ZEUS: DESY-06-241)
$\alpha_s(m_Z)$= 0.1198±0.0019 (exp.)±0.0026 (th.)





➔ More to come from HERA incl. DIS and jets (HERA II!)

Diffraction: Intro

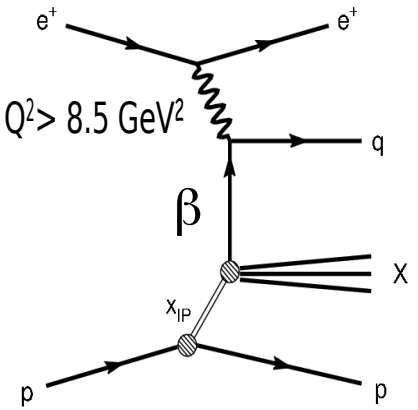


➔ Hadron-Hadron scattering dominated by soft elastic processes, called diffraction

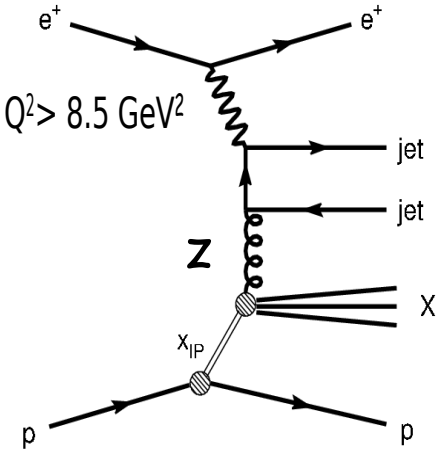
➔ Question: partonic nature of this exchange?

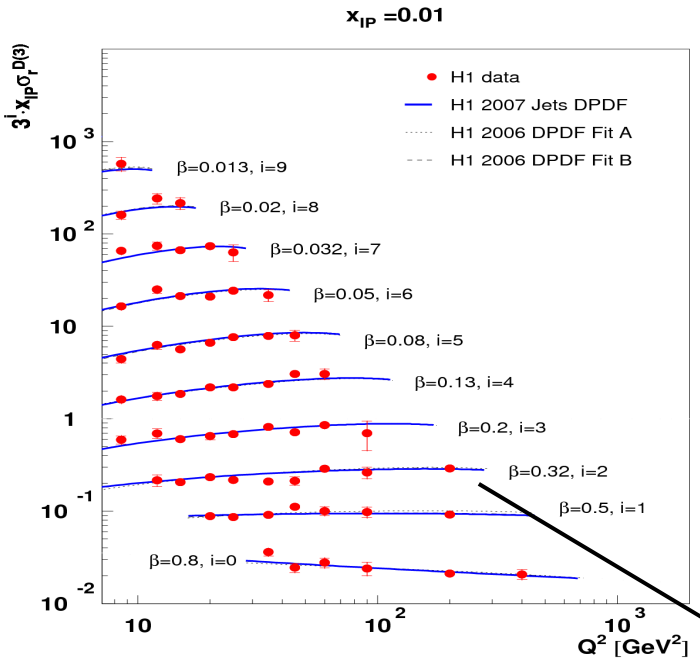
Hard diffraction at HERA - a key to the partonic nature

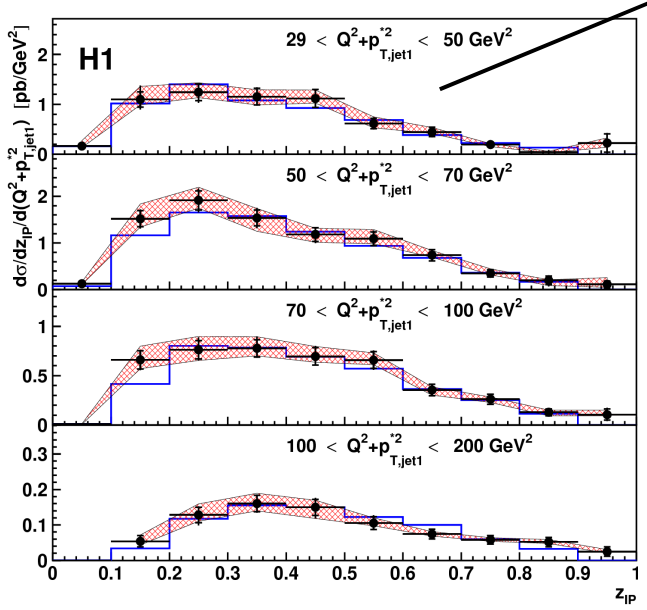
Inclusive diffr.



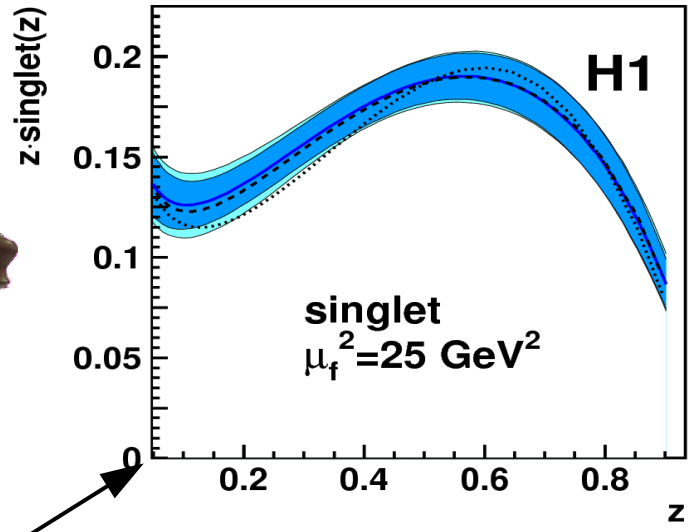
New: add info from diffractive dijets

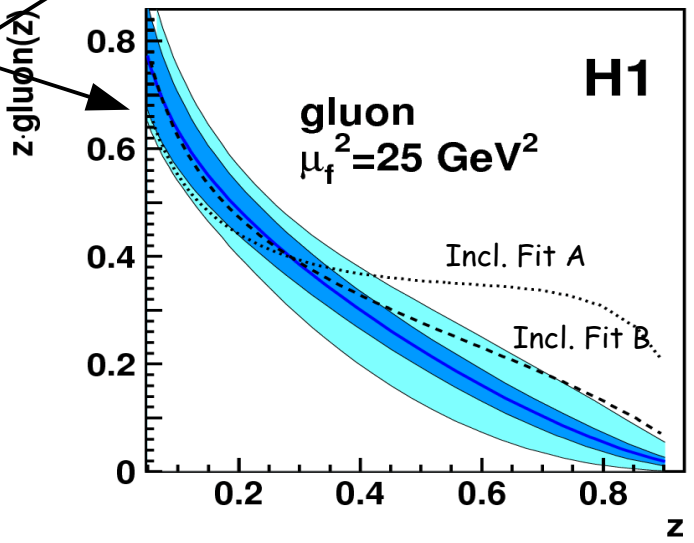






NLO FIT

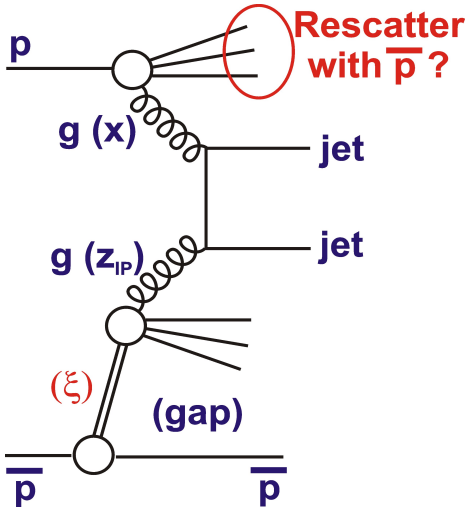


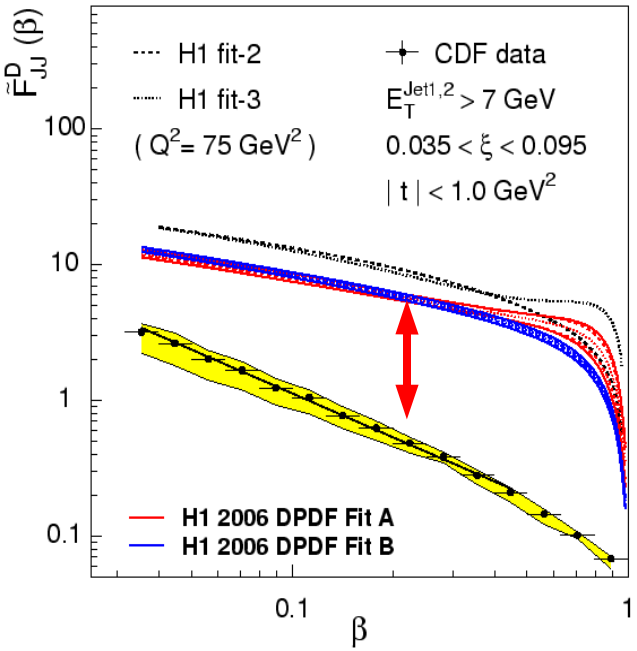


➔ Consistent picture, improved gluon density

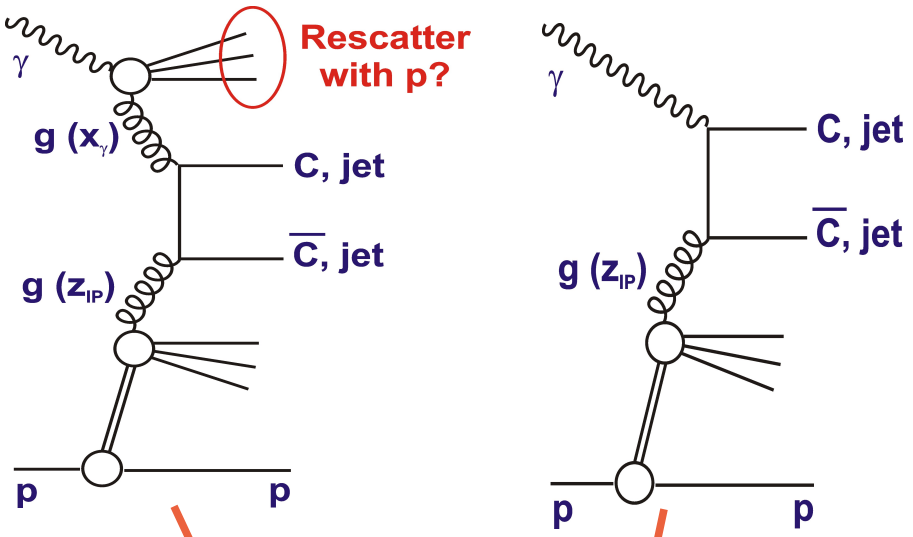
Does QCD factorisation hold? σ = Diffr. PDF $\otimes$ $\sigma_{\text{hard matrix el.}}$

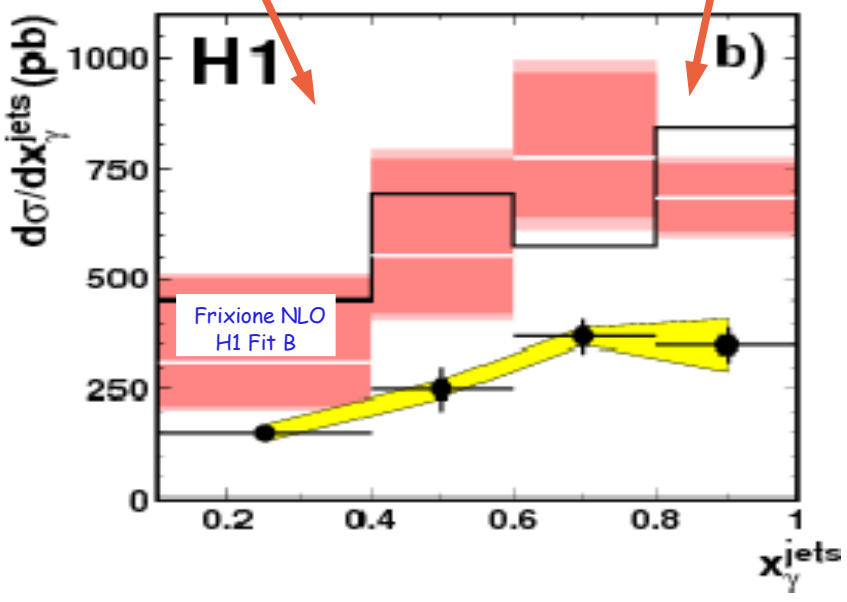
Tevatron





HERA photoproduction: $Q^2 \sim 0$

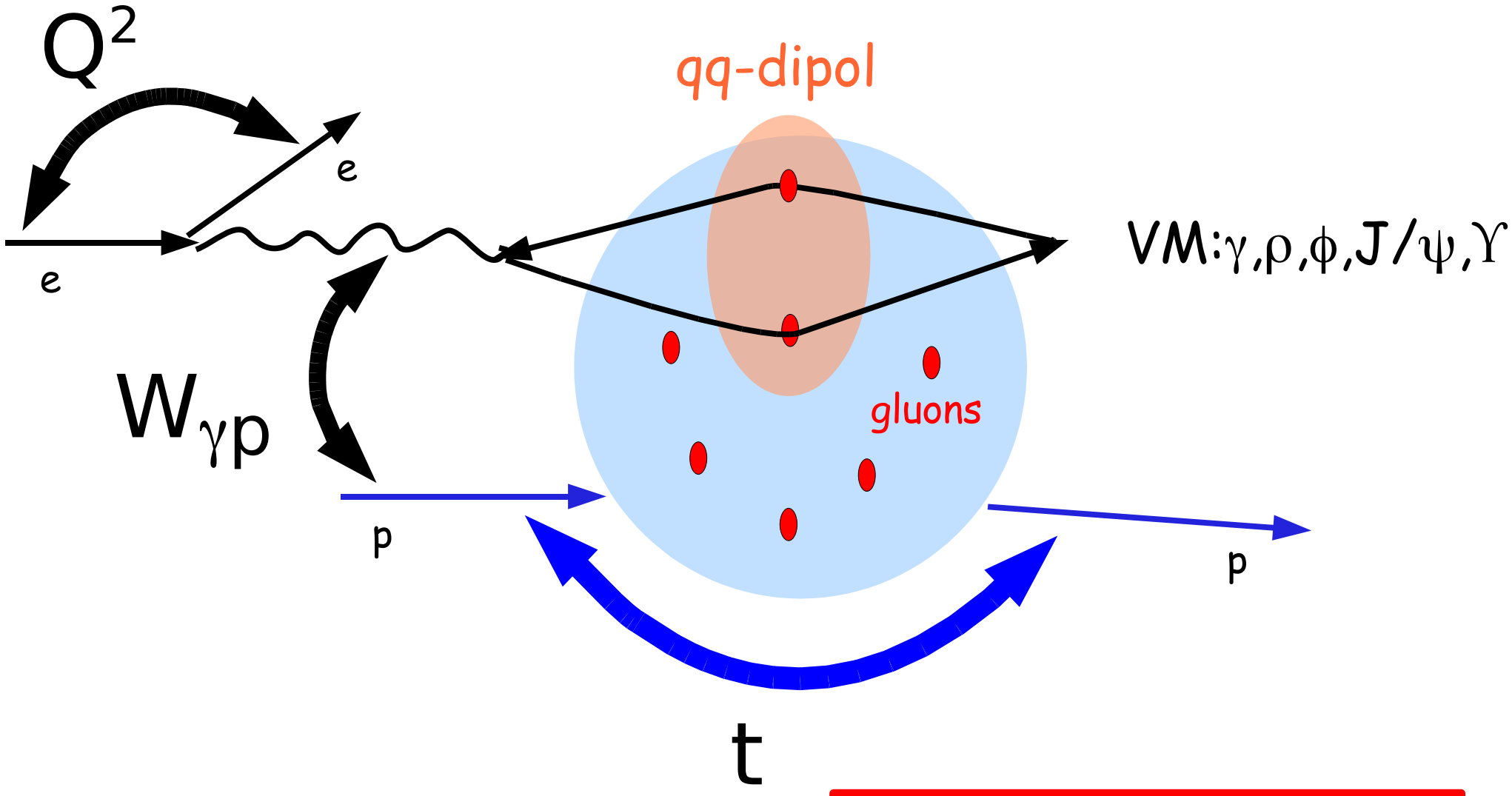




➔ H1 sees global suppression by ~0.5

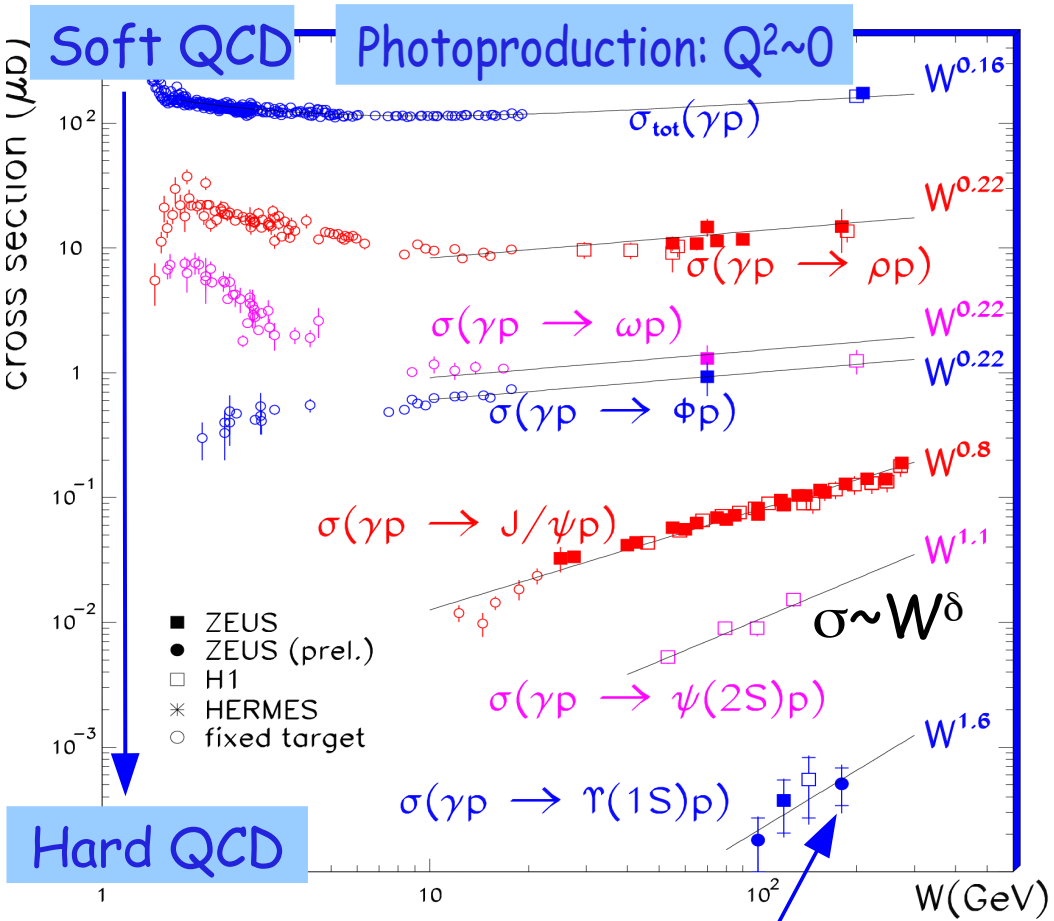
➔ Similar ZEUS analysis: sees much smaller suppression (due to harder jet p_t^{jet} cuts?)

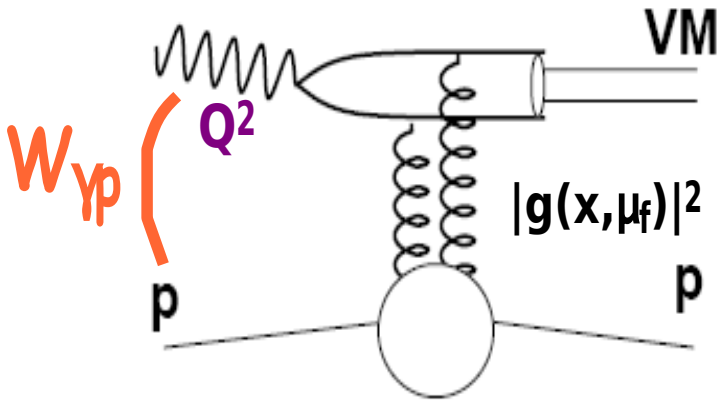
Elastic Vector meson production at HERA

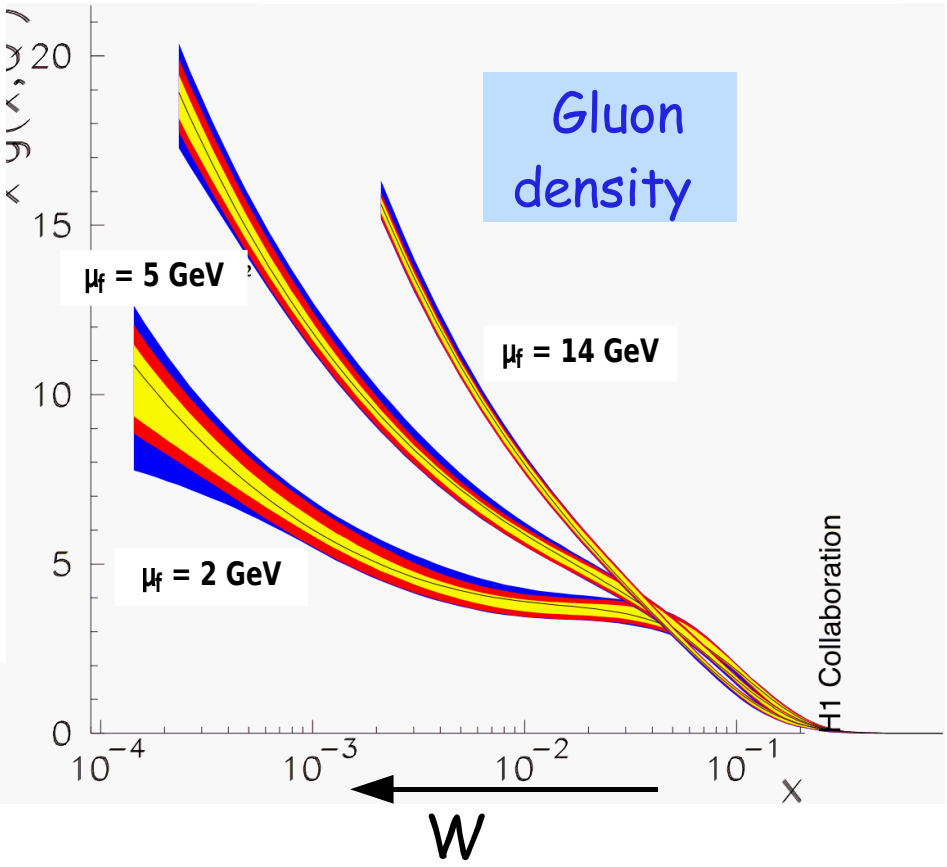


➔ Obtain 3d-picture of proton

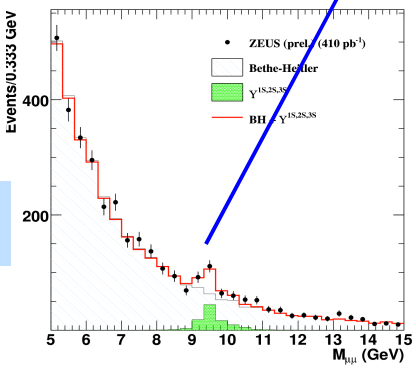
VM production: energy dependence







ZEUS: ϒ

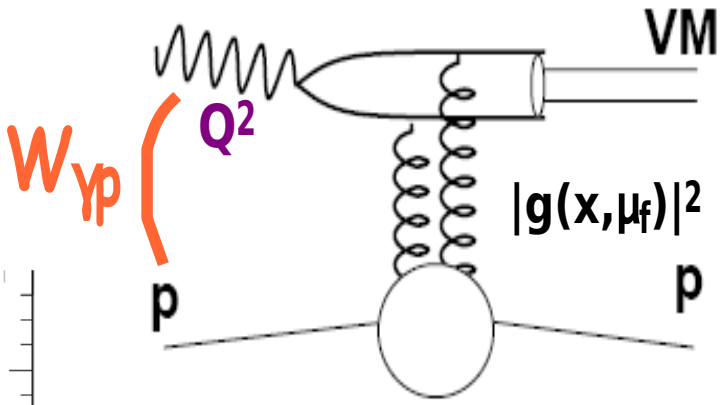


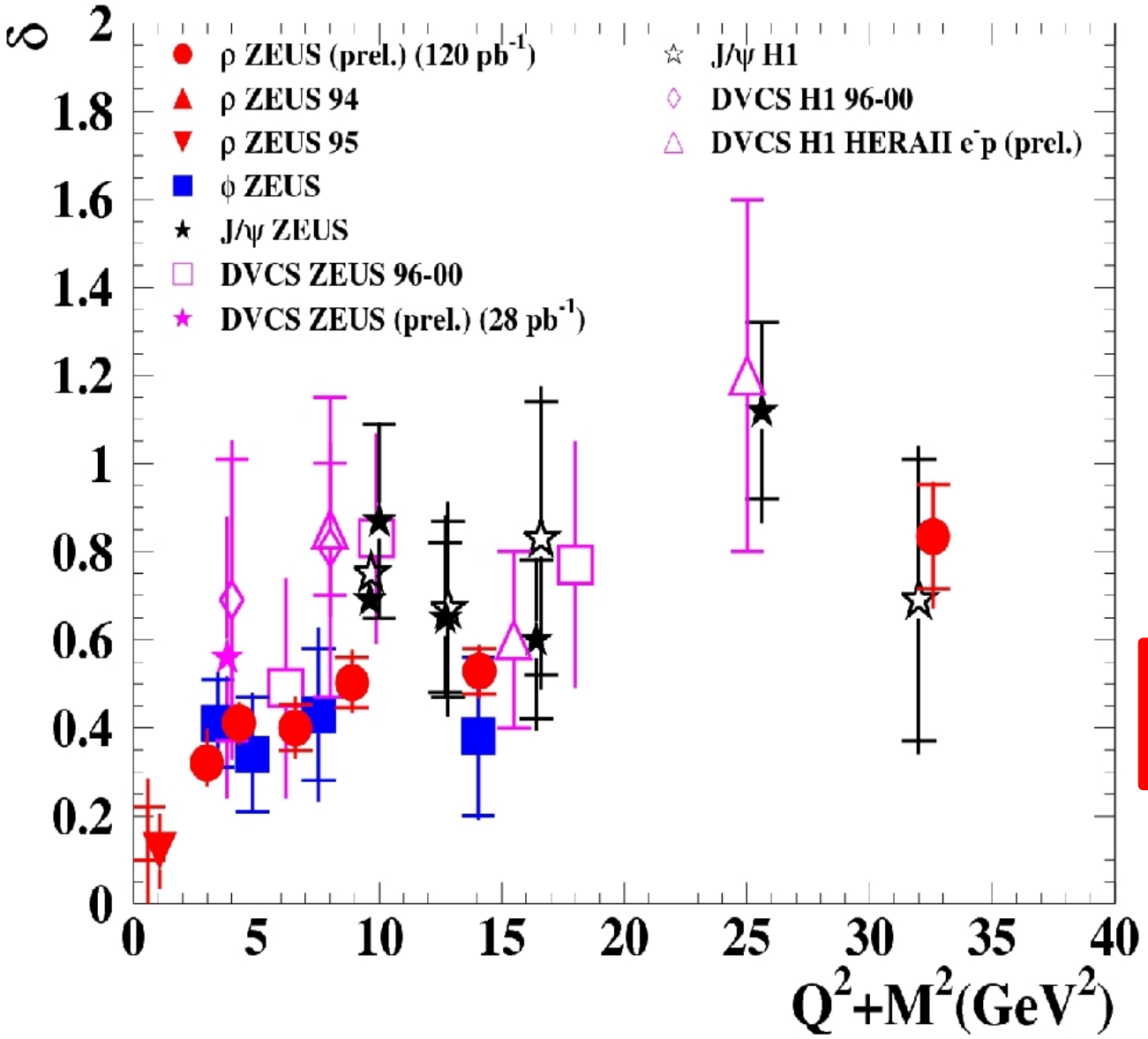
➔ VM mass sets hard scale of interaction

VM production: energy dependence

$\sigma \sim W^{\delta}$

DIS: $Q^2 > 1$ GeV^2

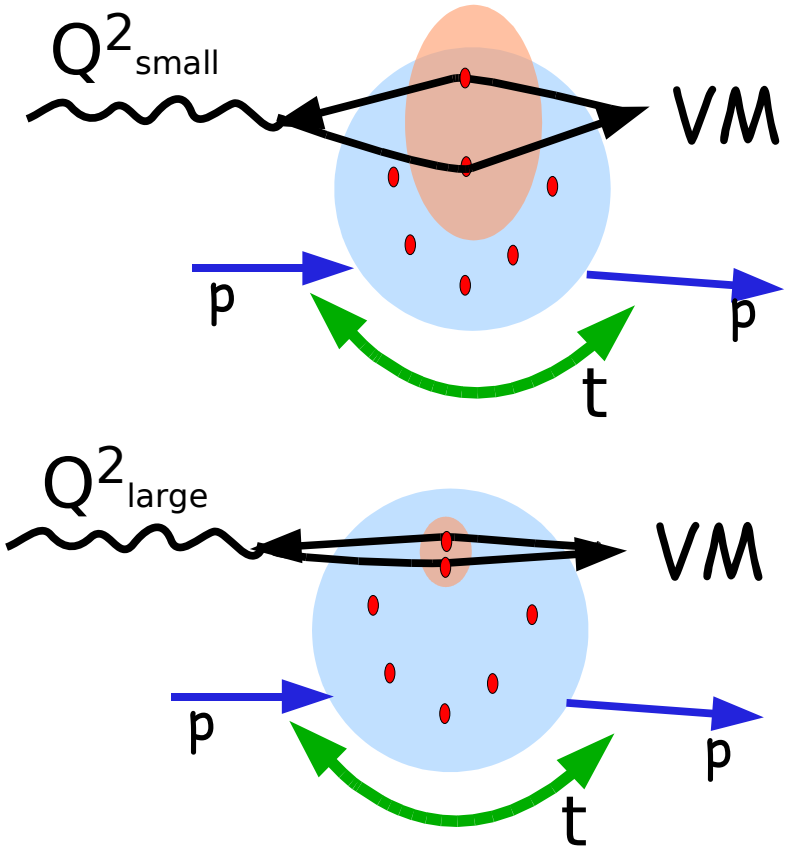


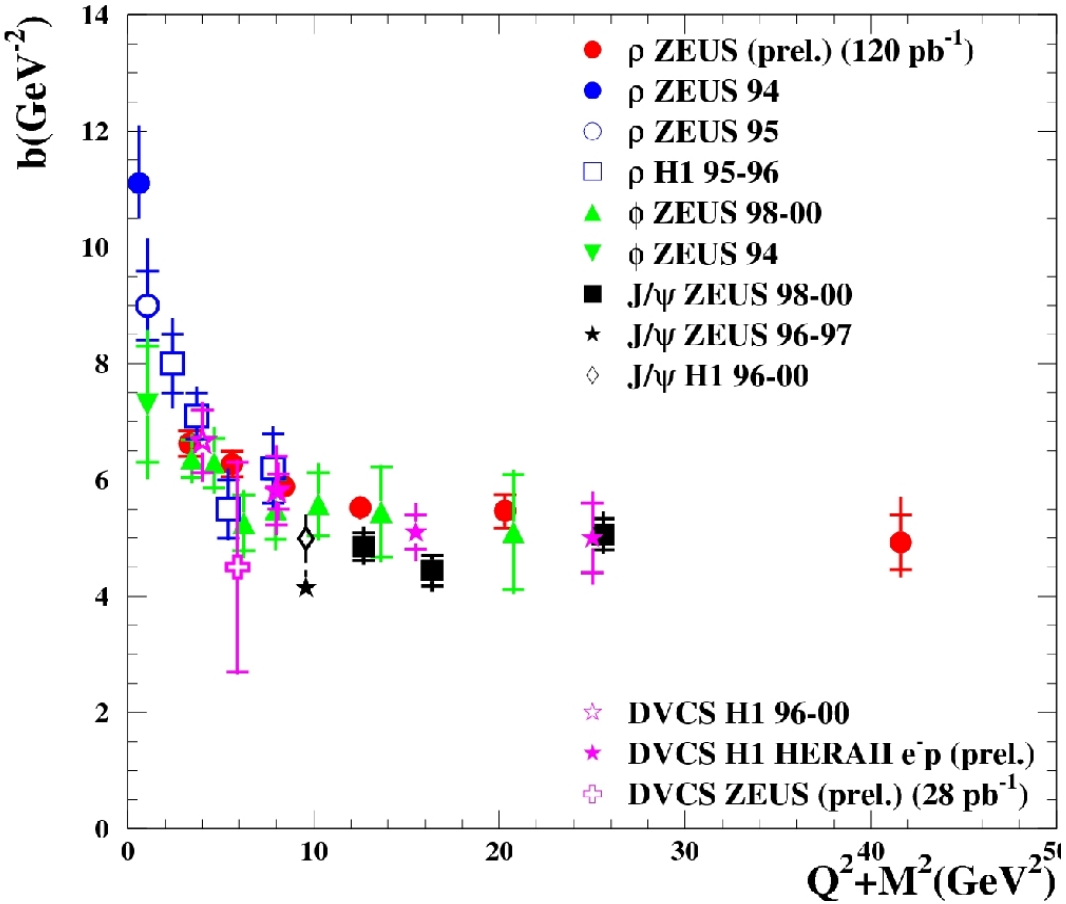


➔ VM mass and Q^2 'set' hard scale of interaction

Vector meson production: t-slope vs Q^2

$d\sigma/dt \sim e^{-b|t|}$ $\quad b \sim r_p^2 + r_{qq}^2$

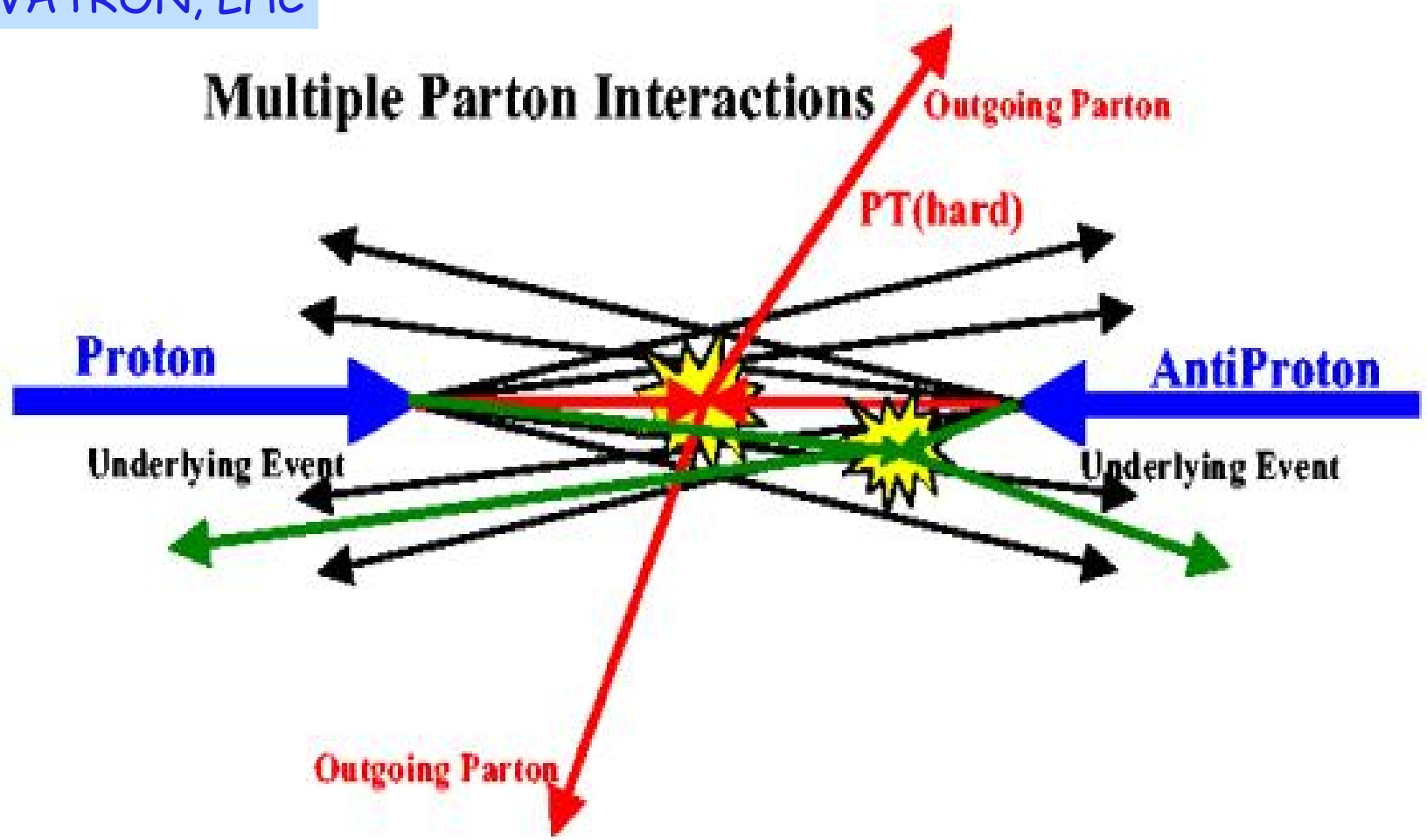




➔ Transverse extension of hard gluons in proton is ~0.6 fm, smaller than proton radius 0.8 fm!

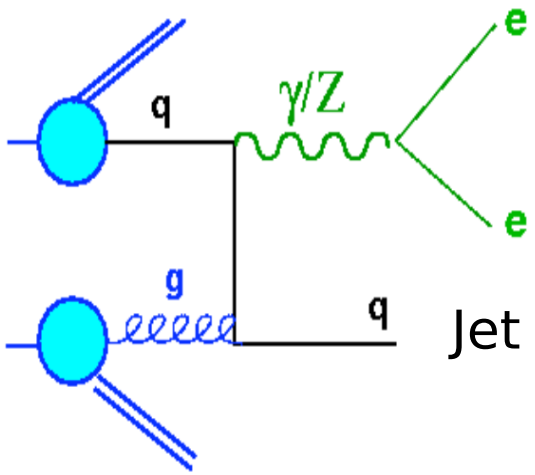
Underlying event

TEVATRON, LHC



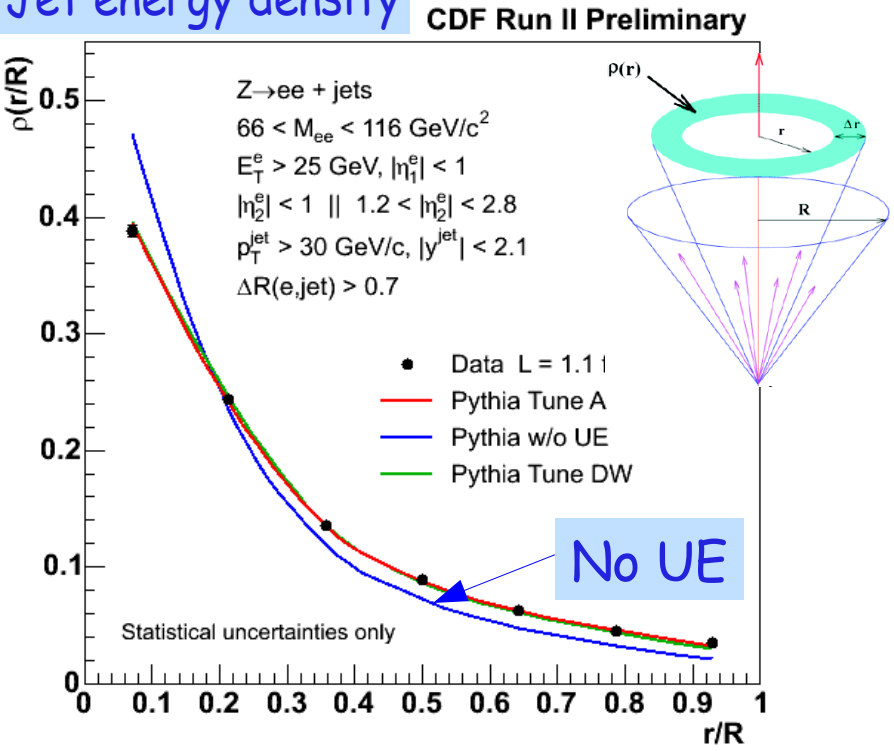
➔Physics interest is in hard primary interaction: need to understand & correct underlying event

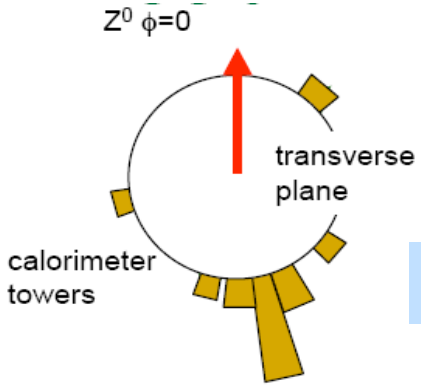
Underlying event: Z +jet at Tevatron



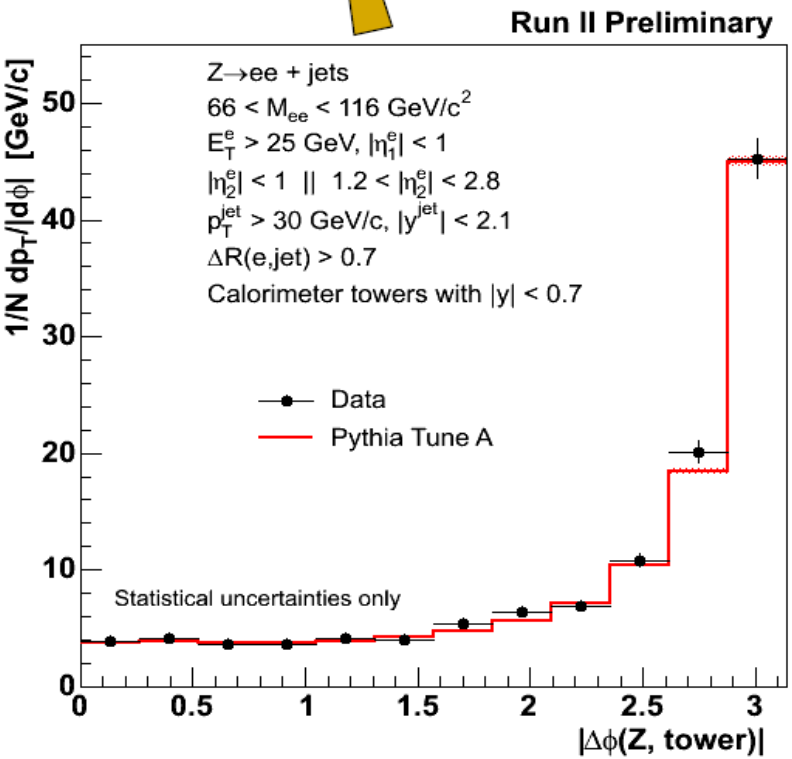
- Clean signal
- Well predictable

Jet energy density





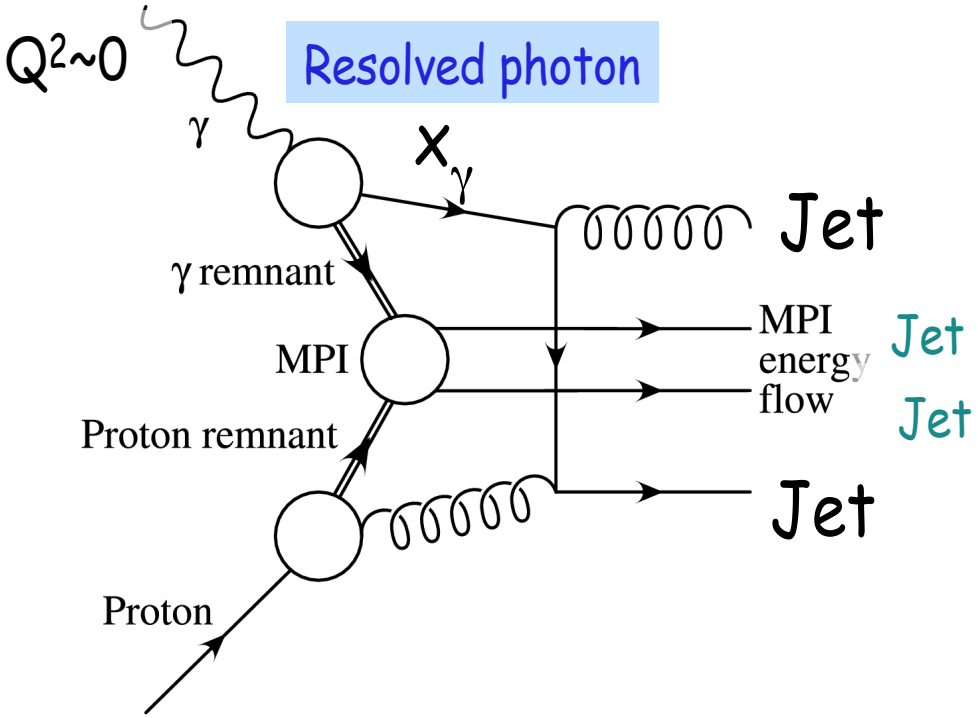
Energy flow



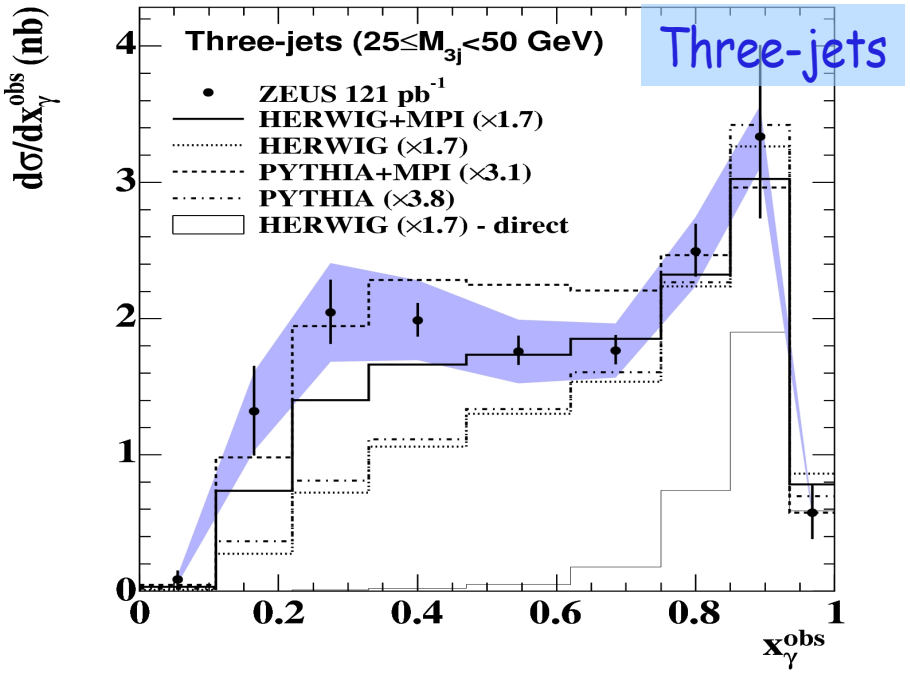
➔UE effects clearly visible

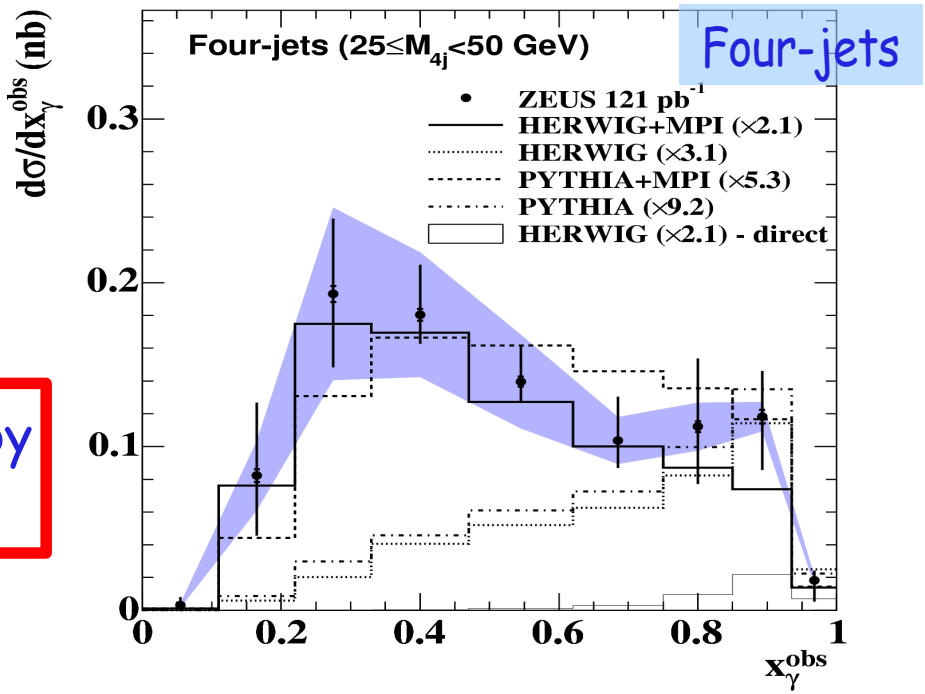
➔PYTHIA Tune A ☺

Underlying event at HERA



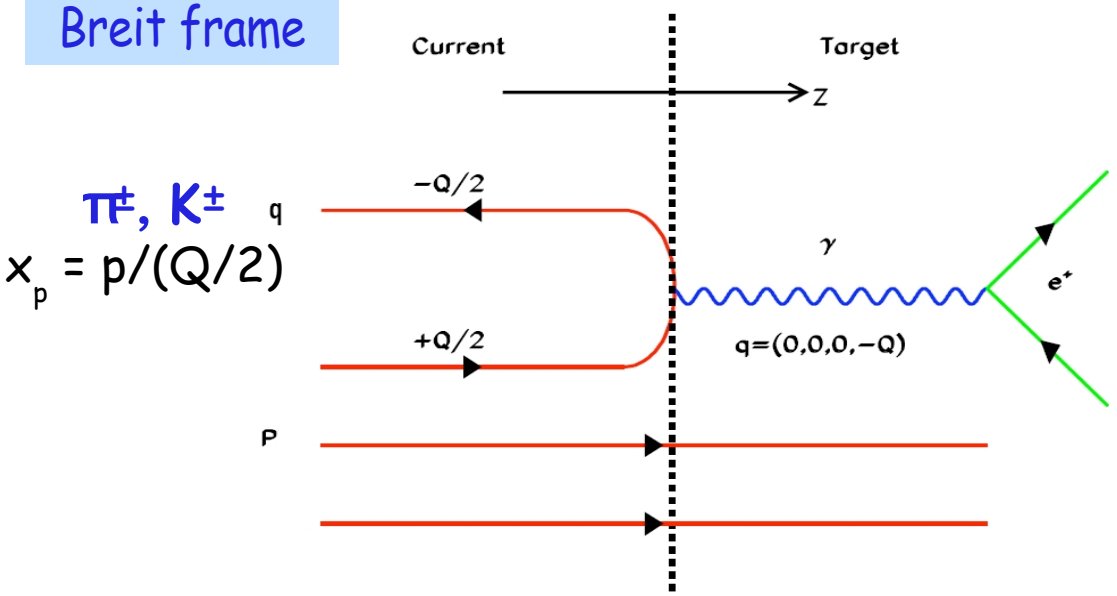
➔ Highly improved description by models with multiple interactions





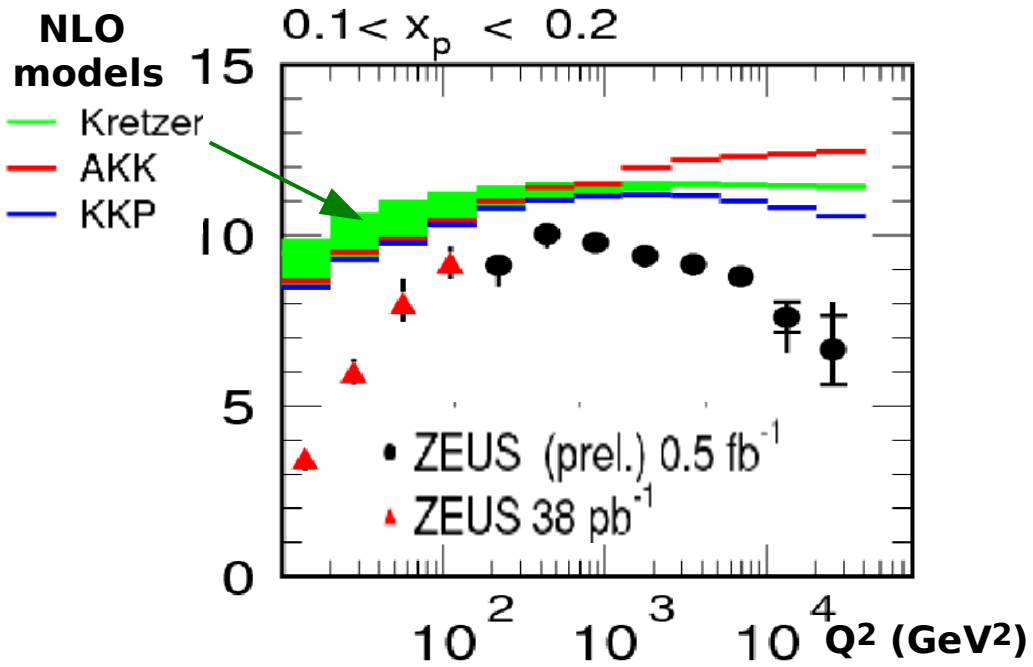
Charged particle momenta in DIS

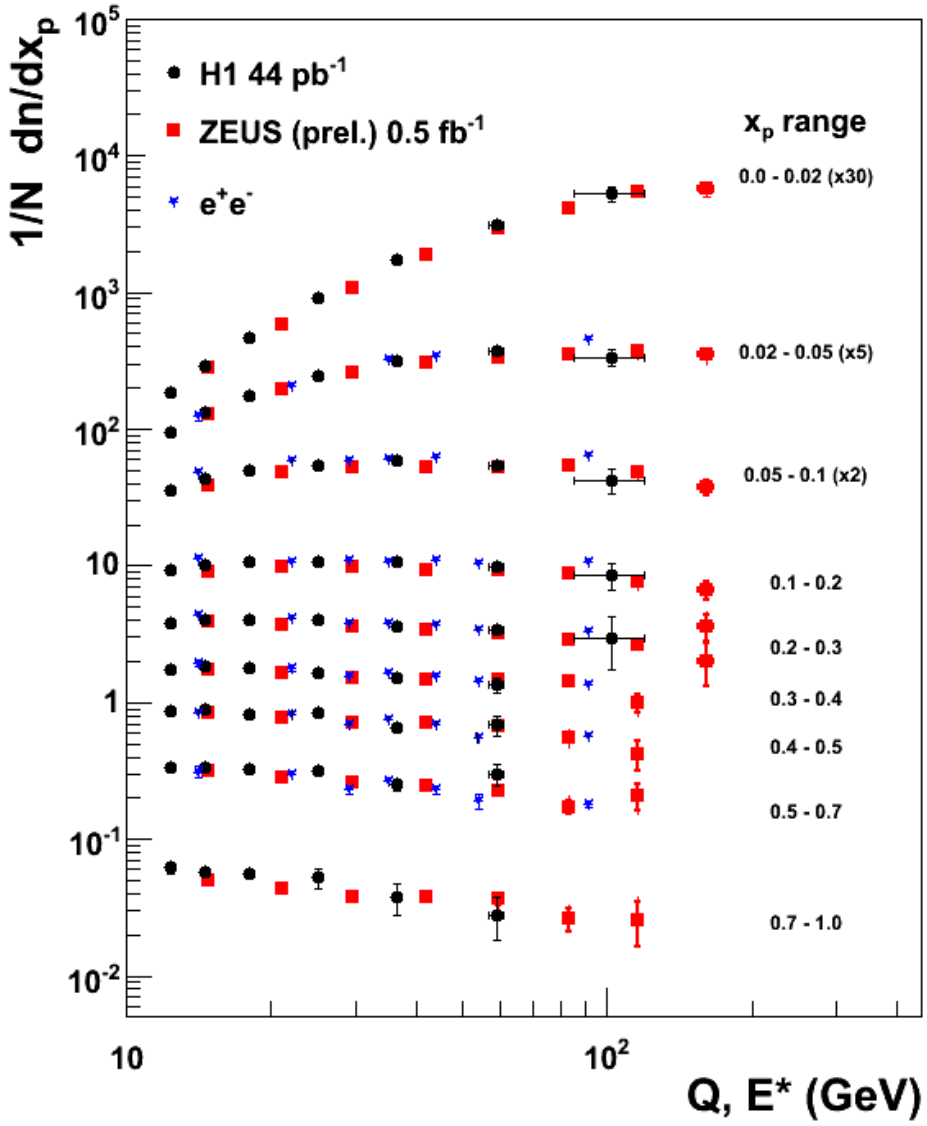
Breit frame



$\pi^{\pm}$, $K^{\pm}$ q

$x_p = p/(Q/2)$





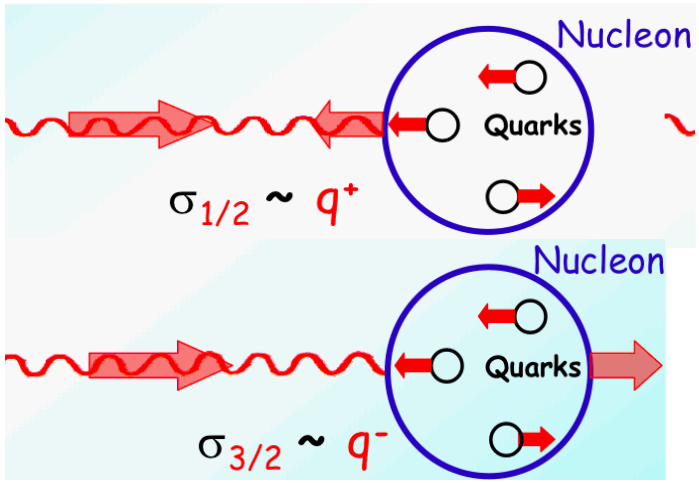
- Clear scaling violations
- Rough agreement with e^+e^- data
- Failure of NLO models

Nucleon Spin structure

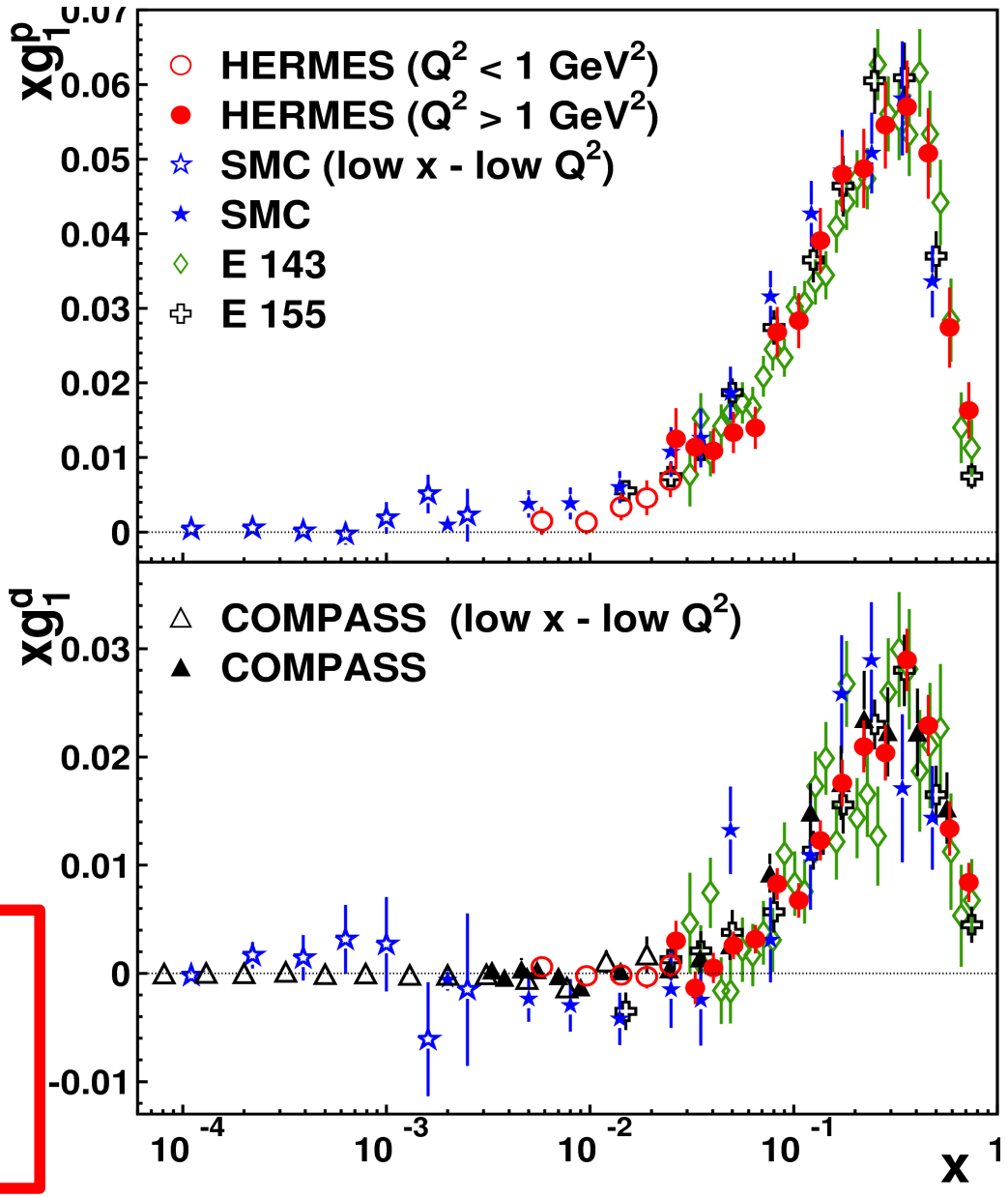
Quark-spin Gluon -spin Angular momentum

$$\tfrac{1}{2} = \tfrac{1}{2}\Delta\Sigma + \Delta G + L_z$$

DIS with pol. lepton beams on pol. targets



$$A_1 = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}} \cong \frac{g_1}{F_1}$$

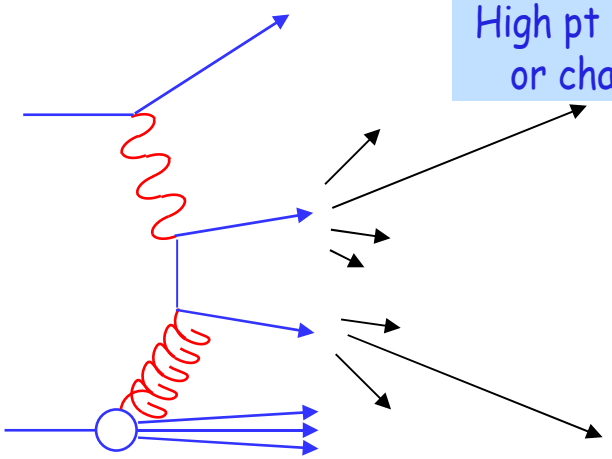


➔ HERMES final word on g1 (Most precise d data!)
QCD analysis: $\Delta\Sigma$ = 0.330 ± 0.011(th.) ± 0.025(exp.) ± 0.028(evol.)

➔ COMPASS: Precise measurements for $x<10^{-2}$
Also brand-new results for Valence quark polarisation from Semi-incl. DIS

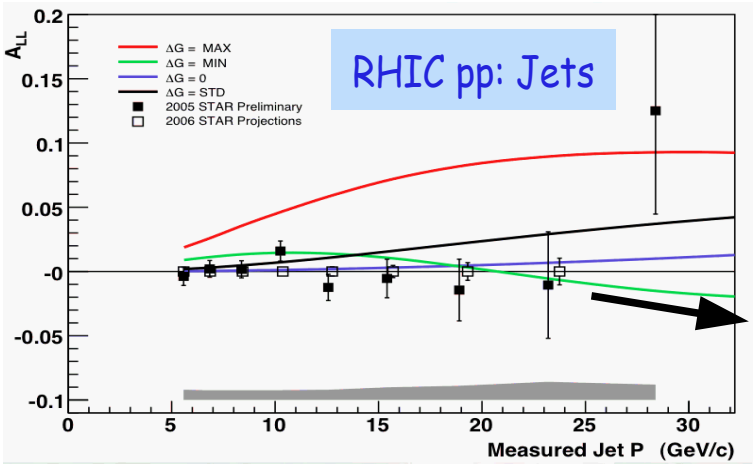
Contributions from gluon?

$$\tfrac{1}{2} = \tfrac{1}{2}\Delta\Sigma + \Delta G + L_z$$

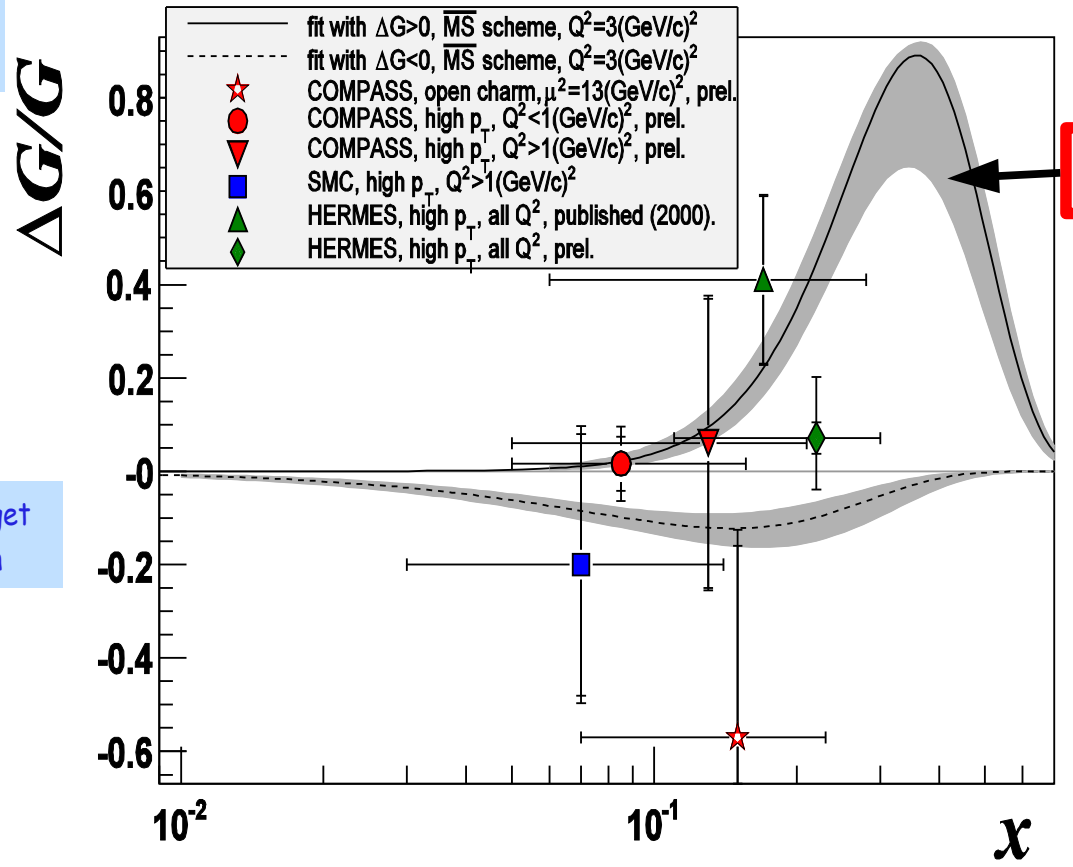


High pt Hadrons or charm tag

Use asymmetries between particle rates for nucleon target parallel and antiparallel polarised wrt beam polarisation



RHIC pp: Jets



ΔG ~0.2-0.3

Disfavour large ΔG, more data will come

➔ Δg not yet well constrained

$$\tfrac{1}{2} = \tfrac{1}{2}\Delta\Sigma + \Delta G + L_z$$

HERMES:

- ➔ results for transverse polarised target: Non-zero Sivers amplitudes for π -> L_z^q <>0
- ➔ DVCS target spin asymmetry: Ju+Jd/2.9 ~0.42
- ➔ Much more precise DVCS results to be expected from last HERA data periods

Summary

- HERA:
  - 30.6.2007 – end of a unique machine for DIS at the high energy frontier, successor?
  - Many new results at HEP2007, improved precisions 'challenge' QCD at new level!
  - Refine calibrations to achieve final results with full HERA statistics:
    - ✔ Proton content: gluon density (very important for LHC), charm & beauty
    - ✔ High precision α_s,
    - ✔ Diffraction (e.g. gain more insight on factorisation breaking)

Heavy flavour production at HERA and Tevatron covered in talk by A. S. Navarro

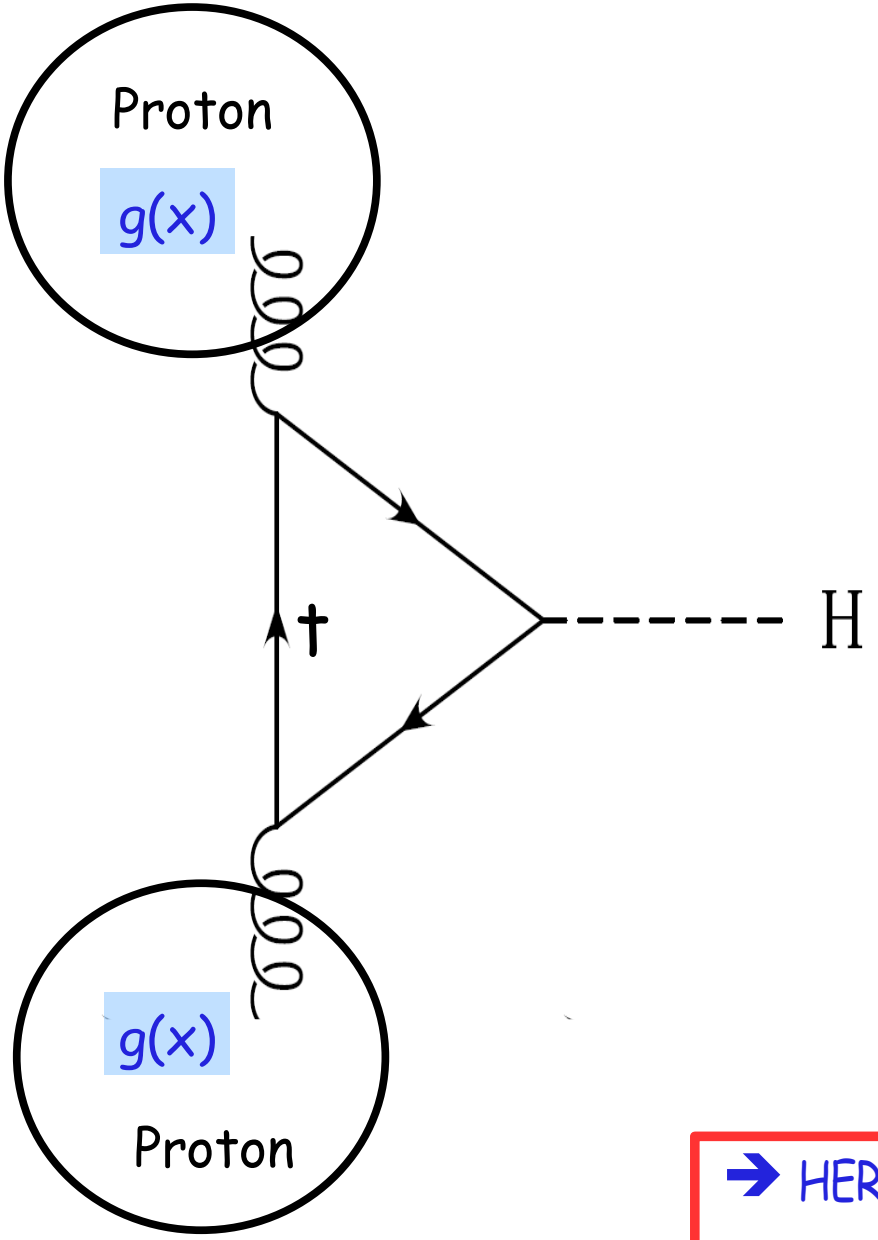
- Tevatron:
  - Accumulating (happily!) more lumi than ever
  - Unique QCD lab, complementary to HERA:
    - ✔ Proton content: access to the gluon density at highest x
    - ✔ Reveal complicate structure of hadron hadron collisions: Underlying event, multiple interactions

- HERMES, COMPASS, RHIC: hunting the 'contributors' to the nuclear spin
  - ✔ Nicely improving knowledge – but puzzle still not settled: gluons or orbital angular momentum?

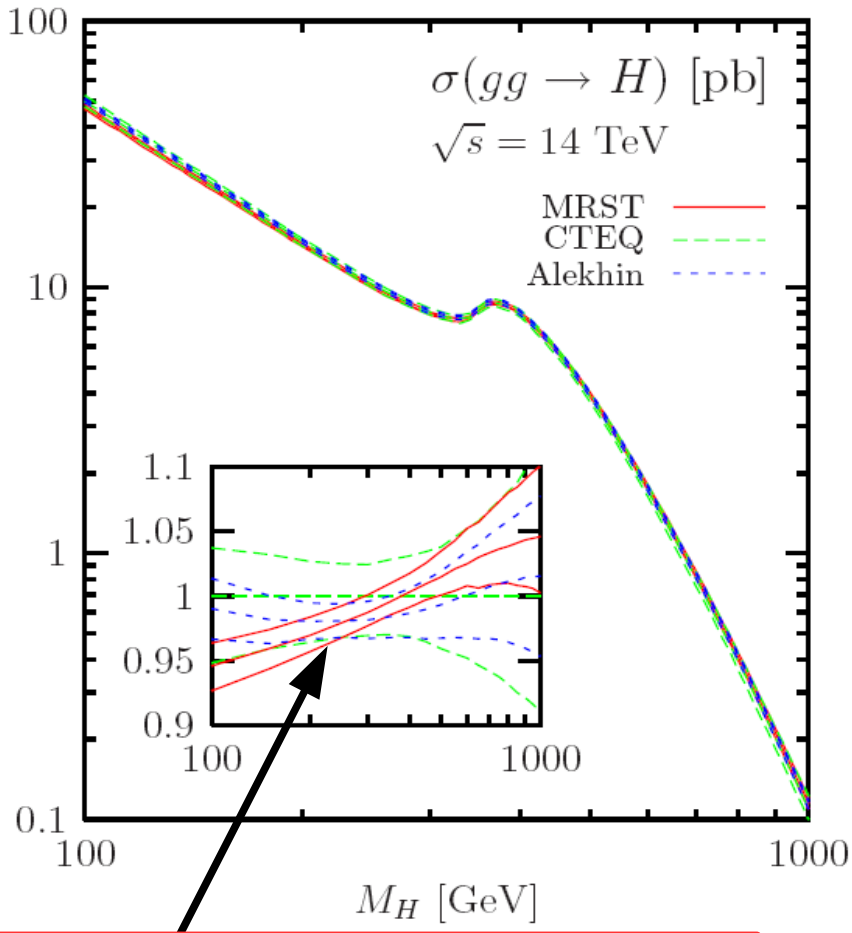
Thanks to: H. Abramowicz,, C. Diaconu, D. Hasch, R. Lefevre, A. Levy and all speakers in the QCD session

Backup

HERA Gluondensity --> LHC



gg-> H
prediction-uncertainty



➔ HERA Gluondensity determines precision! How far can we improve this???

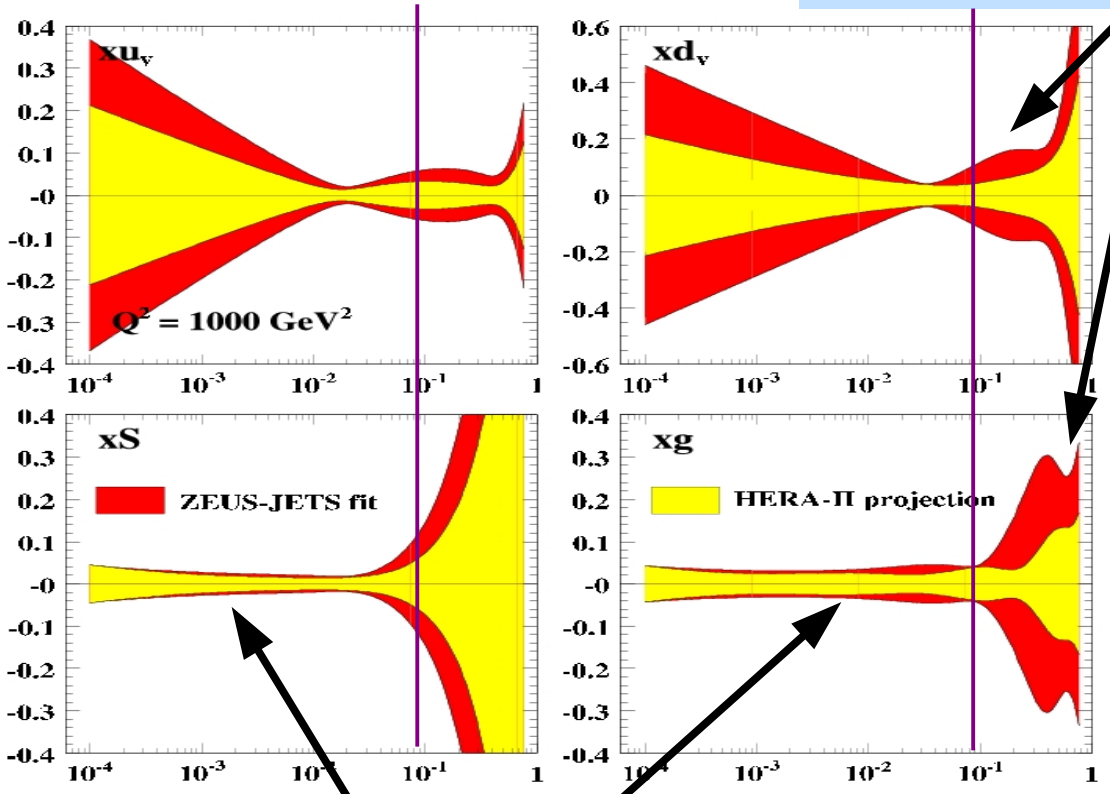
QCD fit prospects

Study by C. Gwenlan, A. Cooper-Sakar, C. Targett-Adams, HERA-LHC proceedings

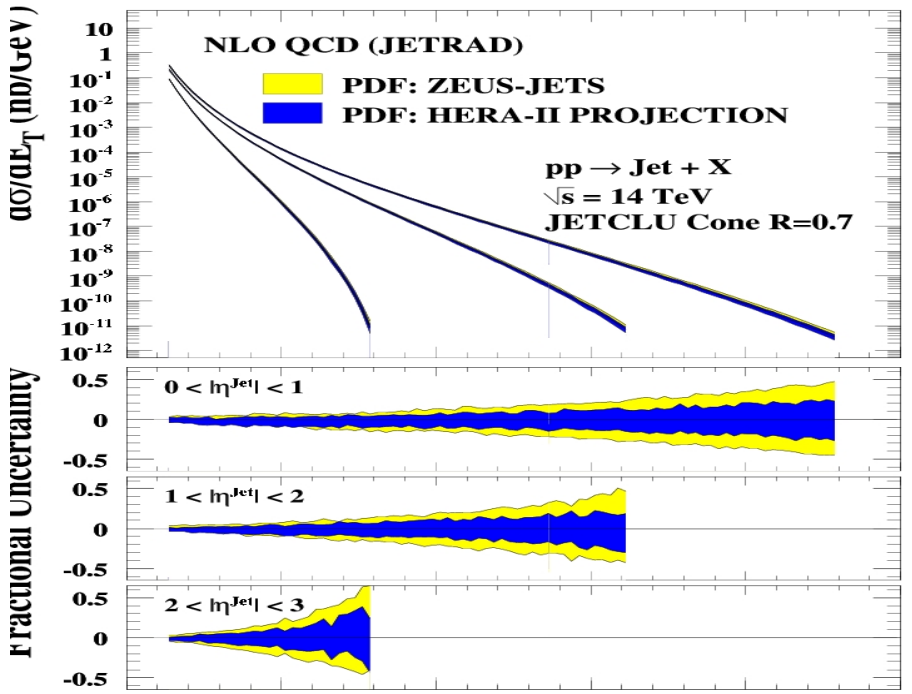
Assumptions:

- ➔ 700 pb^{-1} Lumi at HERA II ≈ reached by combining H1+ZEUS
- ➔ Inclusive data: Only high Q^2>100 GeV^2 taken into account
- ➔ Only statistical improvements, no systematical

x≈>0.1 still statistically limited



➔ more HERA statistics available (not taken into account here!)

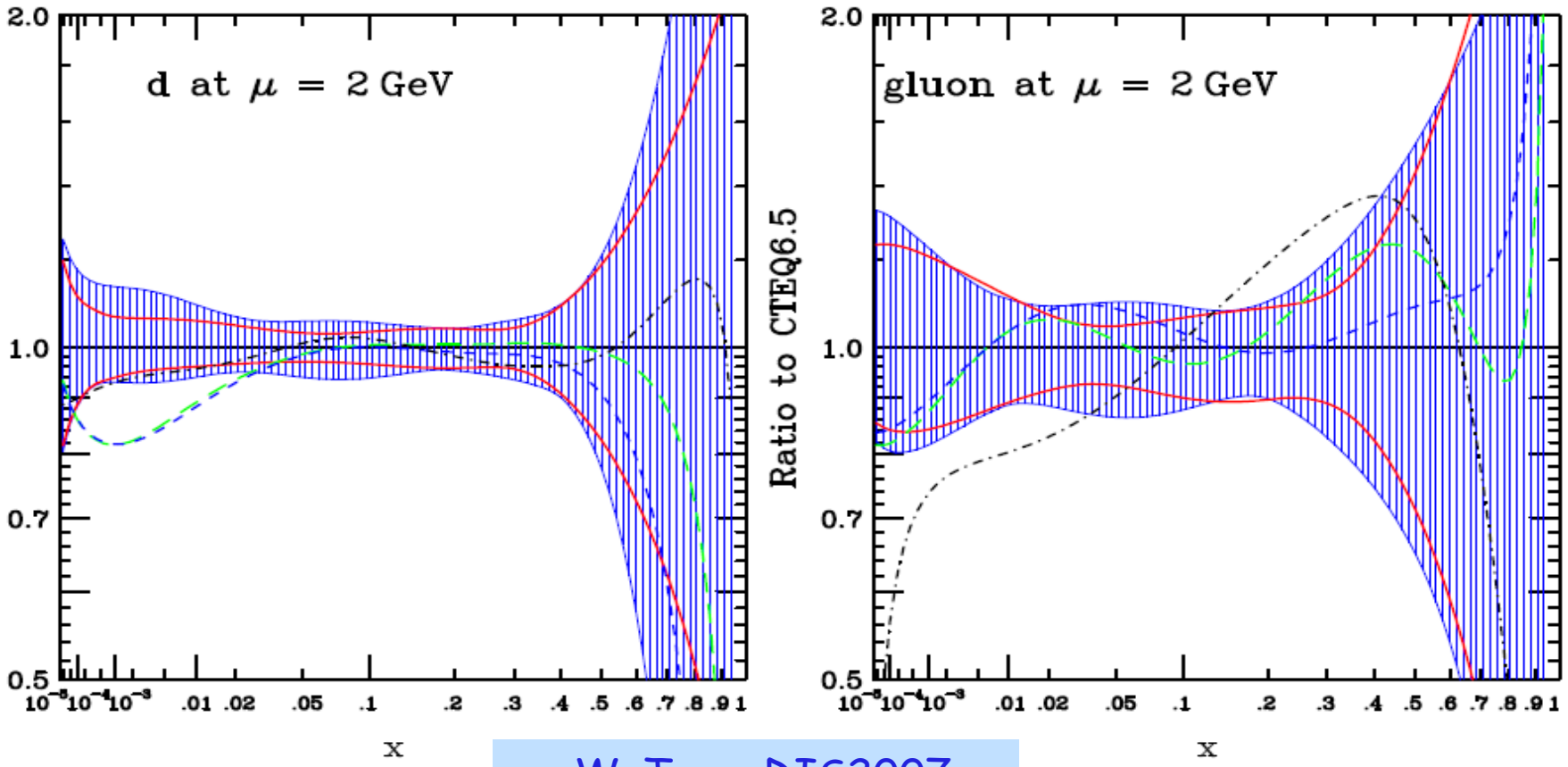


➔ Improvement of PDFs at high x reflected in jets cross sections at LHC

CTEQ global PDF fits: Effect of proper charm mass treatment in CTEQ6.5M

CTEQ6.1M: charm mass neglected in the kinematics of the processes

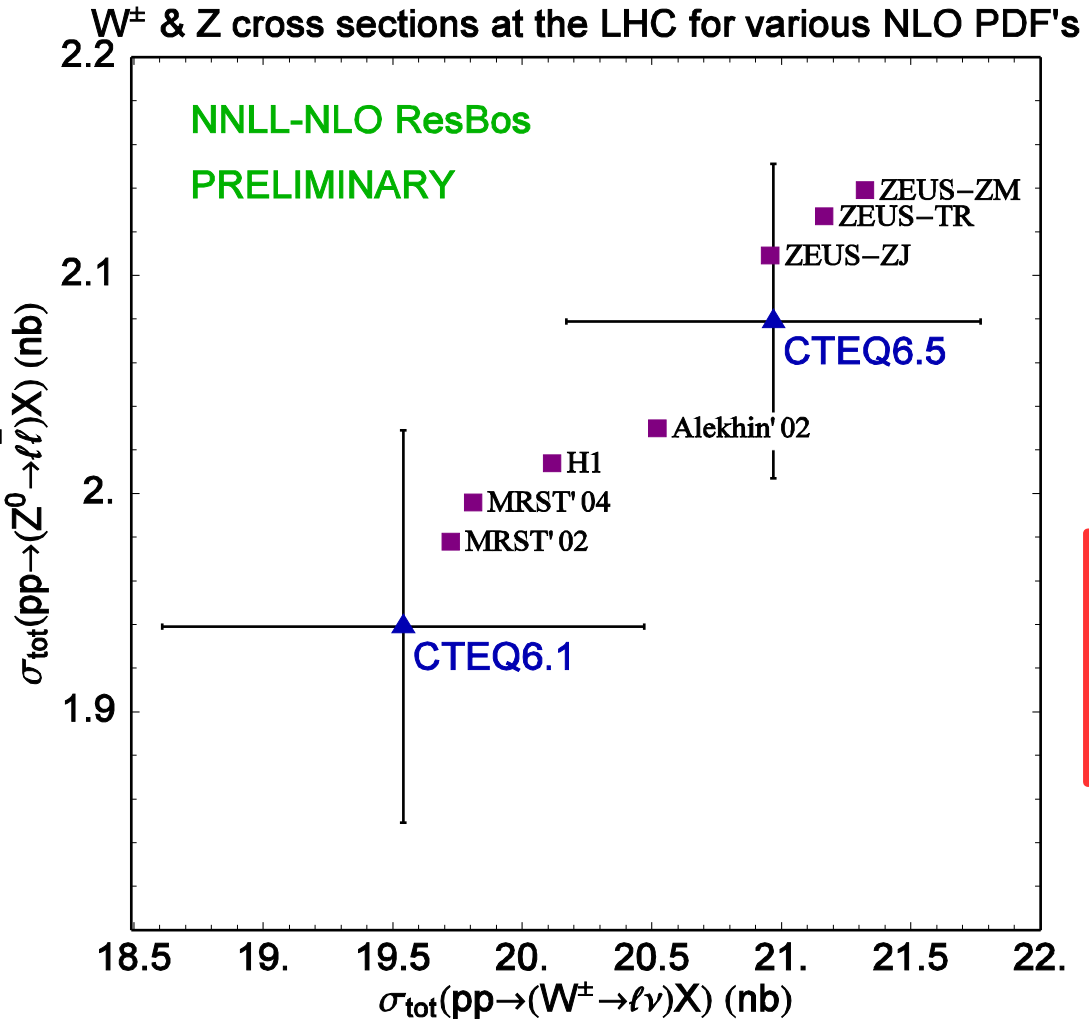
Shift of PDFs from CTEQ6.1M to CTEQ6.5M



W. Tung, DIS2007

Corresponding effect on LHC predictions

W/Z Production xSec @ LHC



➔ Correct charm mass treatment is crucial for accurate predictions of LHC xSecs!