DESY-Hamburg, January 27th 2009

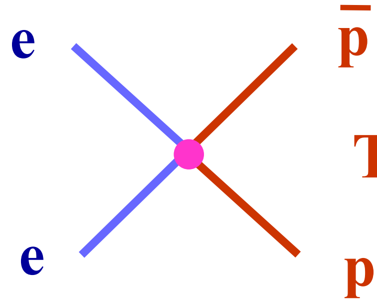
Claude Vallée
H1 experiment, CPPM-Marseille

Building up the HERA Legacy
Impact on LHC

The High Energy Frontier Landscape in the 1990-2010's

LEP

0.21 TeV, ~ 0.9 fb^{-1}/exp.



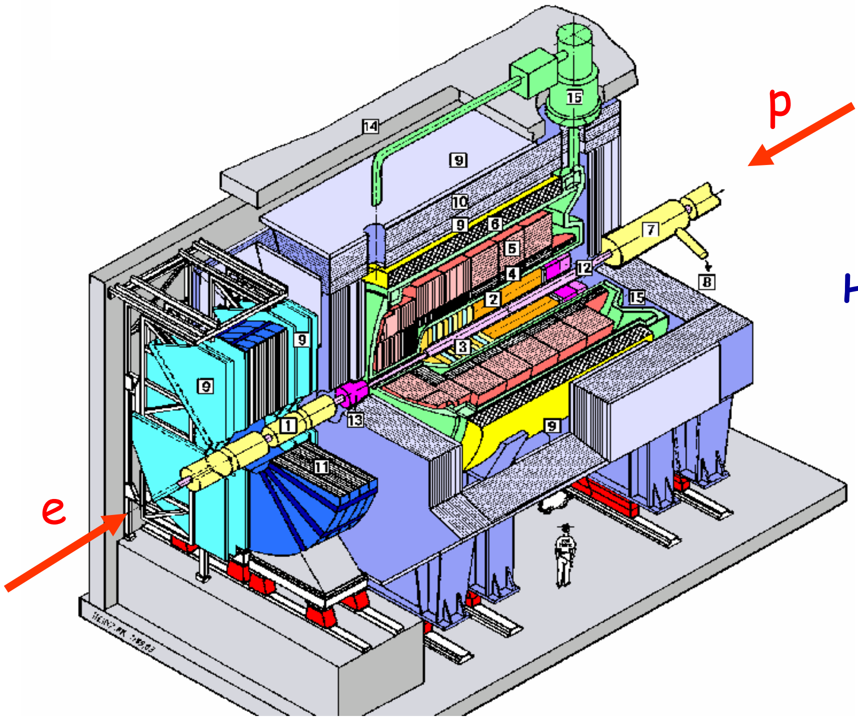
TEVATRON

1.96 TeV, ~ 4 fb^{-1}/exp.

~ twice more expected until 2010

HERA

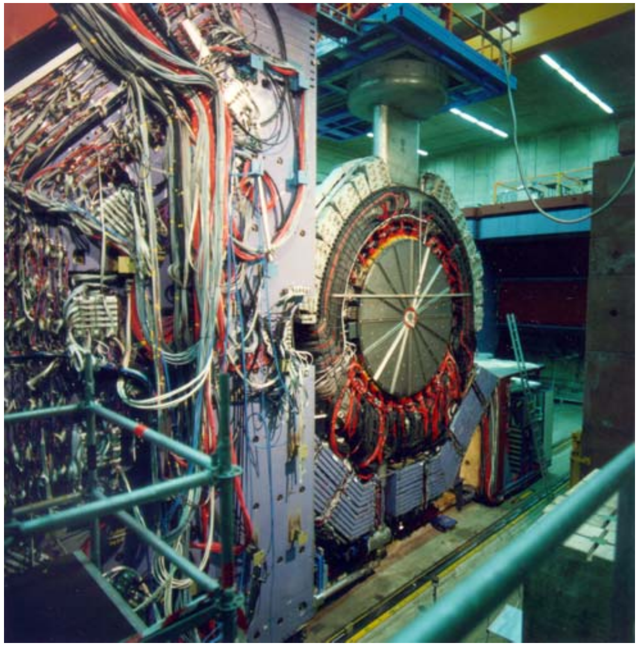
0.32 TeV, ~ 0.5 fb^{-1}/exp.

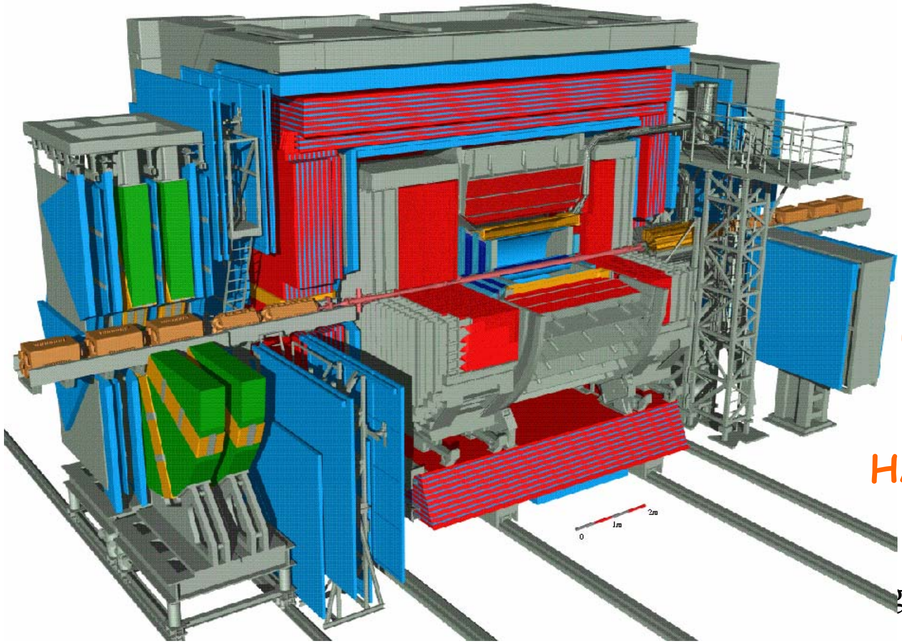


EM: $$\frac{\delta E}{E} = \frac{12\%}{\sqrt{E}}$$

HAD: $$\frac{\delta E}{E} = \frac{50\%}{\sqrt{E}}$$

LAr calorimeter

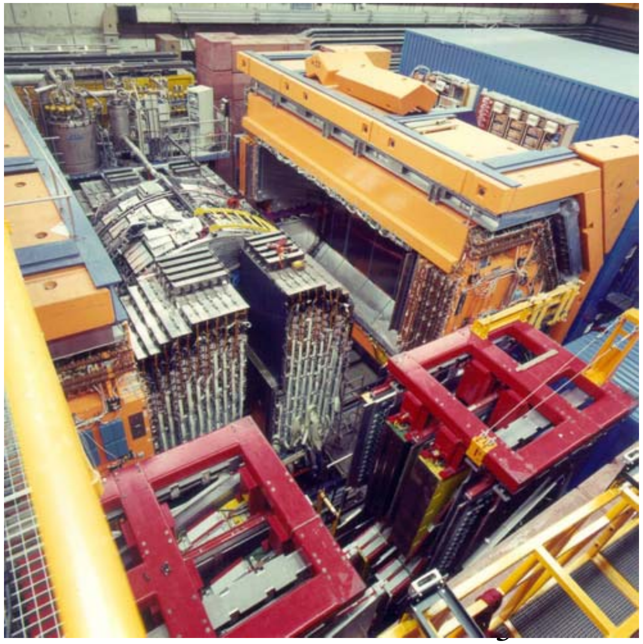




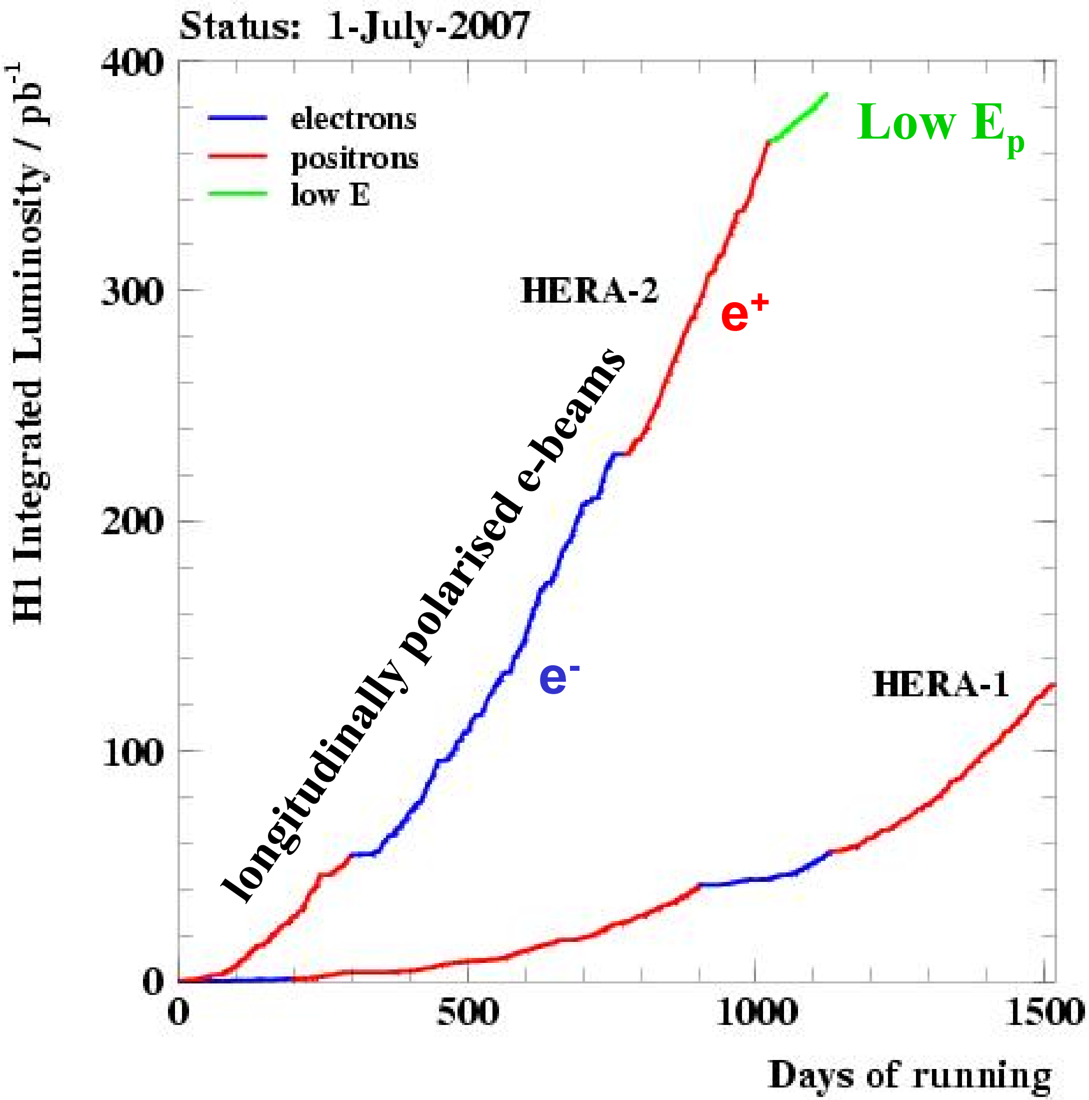
U-scint. calorimeter

EM: $$\frac{\delta E}{E} = \frac{18\%}{\sqrt{E}}$$

HAD: $$\frac{\delta E}{E} = \frac{35\%}{\sqrt{E}}$$



All good things come to an end…



The final HERA data samples

~0.5 fb^{-1} / experiment

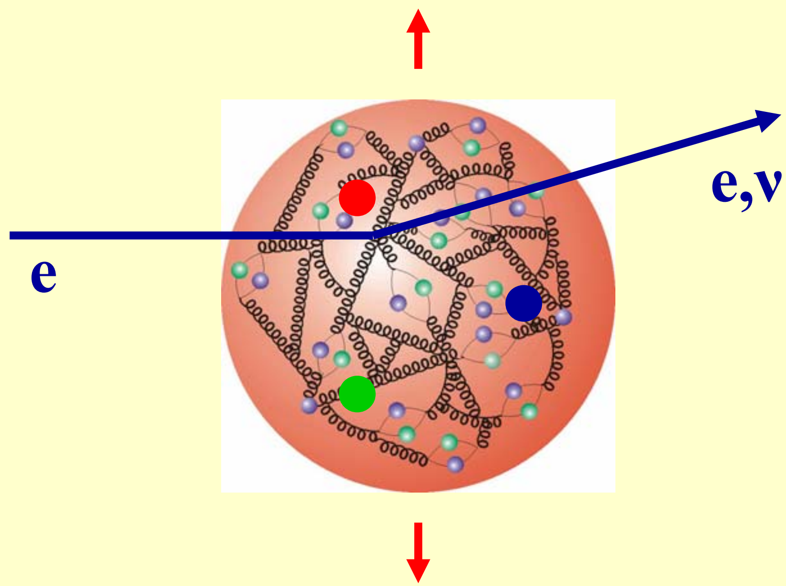
balanced e^+p and e^-p samples

~35% polarised e at HERA II

Low-E_p runs for F_L

Building up the HERA legacy

THE HIGH-ENERGY FRONTIER



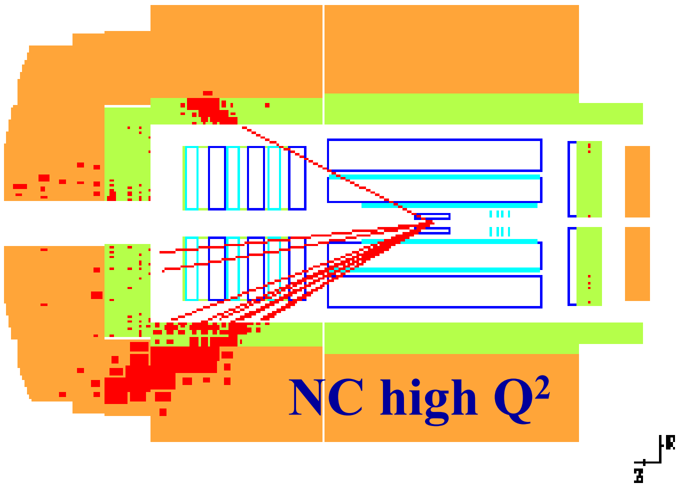
PRECISION MEASUREMENTS

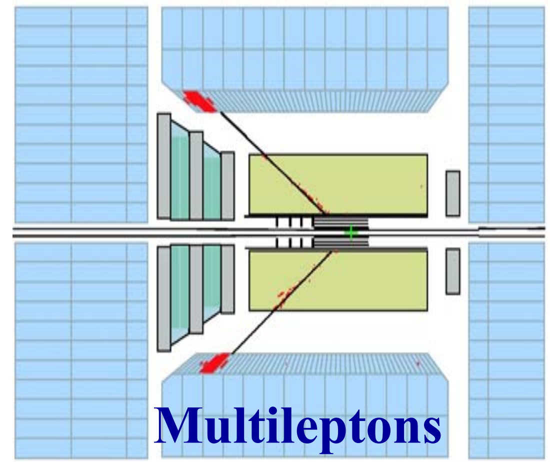
LHC needs

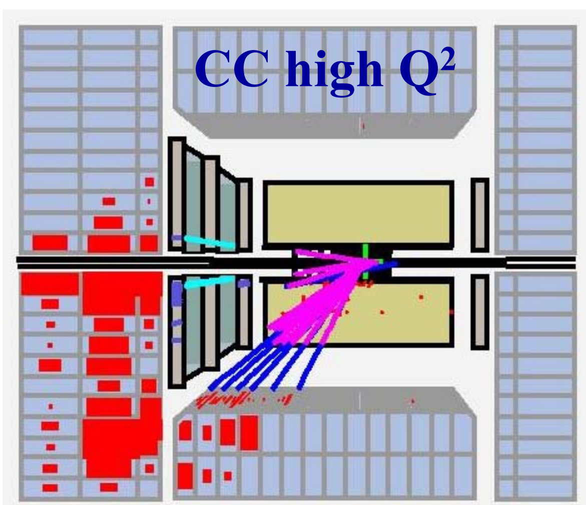
Proton structure and dynamics

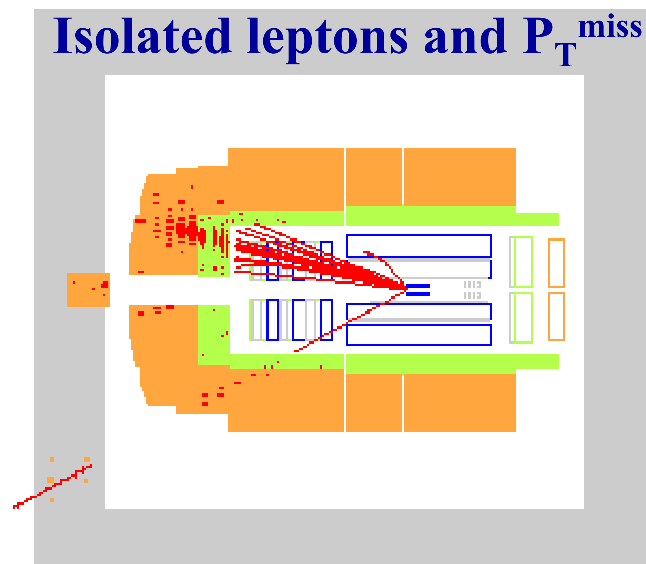
Diffraction and the low-x limit

THE HIGH-ENERGY FRONTIER

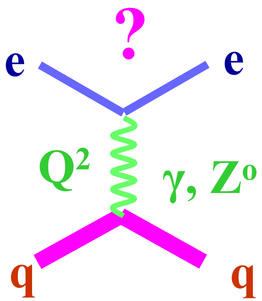




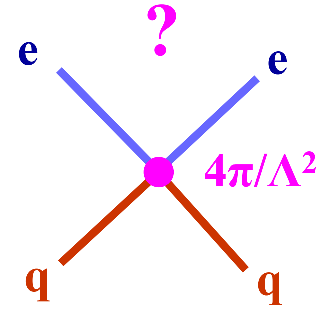


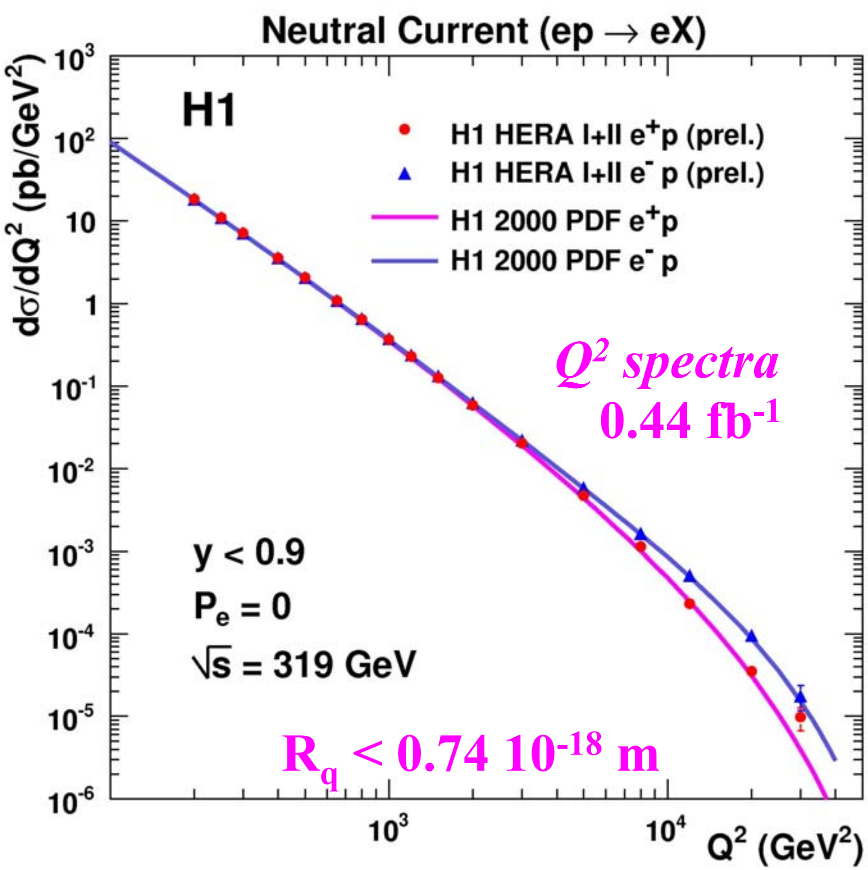


HIGH ENERGY FRONTIER: Quark sub-structure



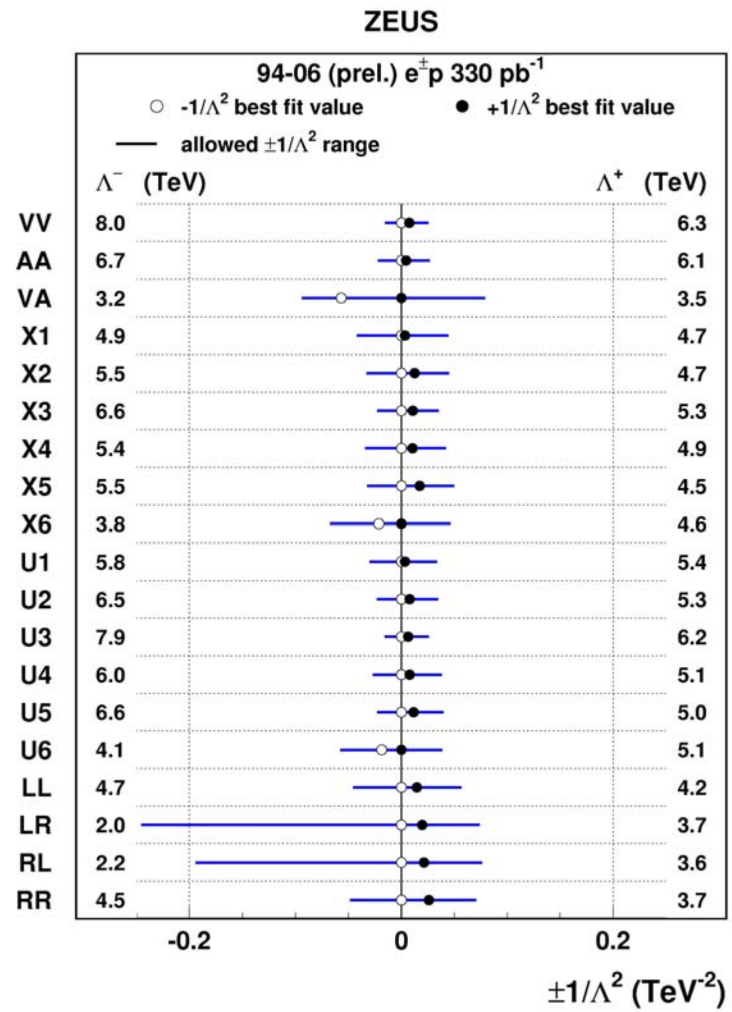
quark radius R_q
factor:$(1-R_q^2Q^2/6)$





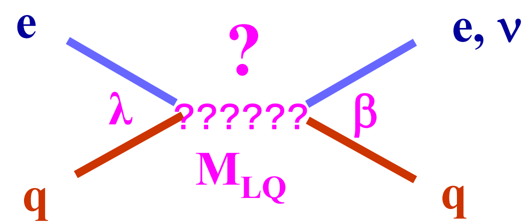
Q^2 spectra
$0.44\ fb^{-1}$

$R_q < 0.74\ 10^{-18}$ m

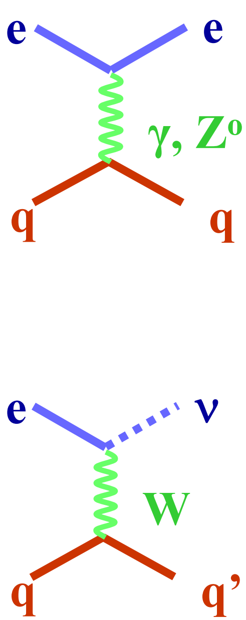


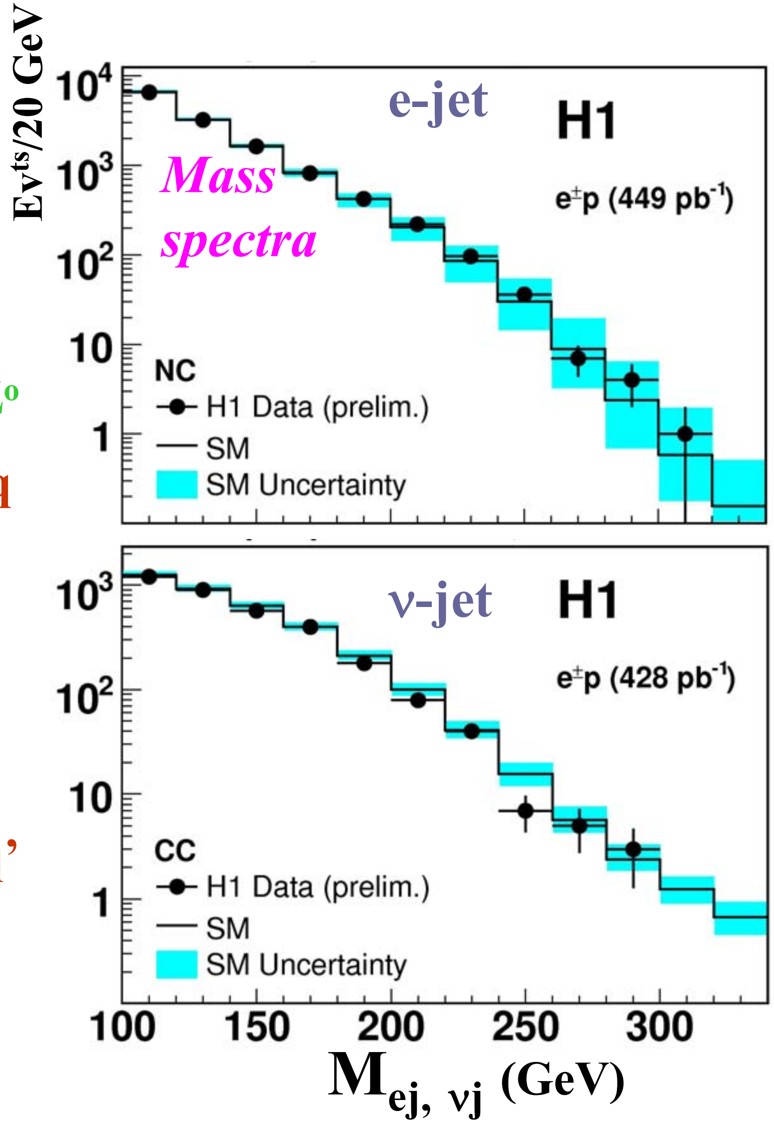
ZEUS $0.33\ fb^{-1}$: $R_q < 0.62\ 10^{-18}$ m

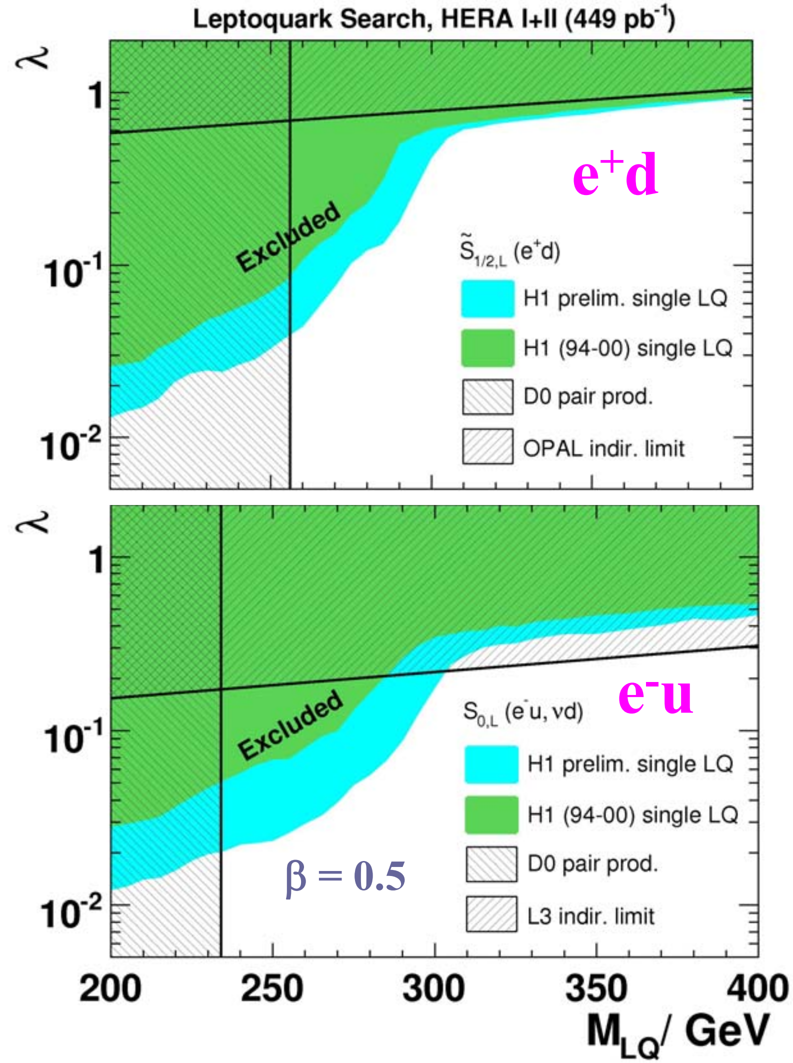
HIGH ENERGY FRONTIER: Leptoquarks



SM :

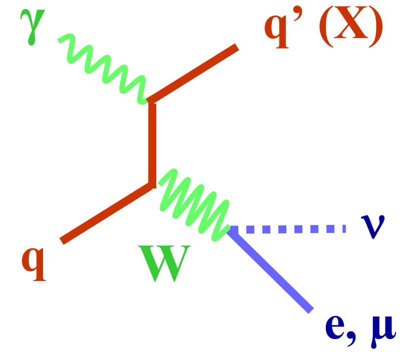


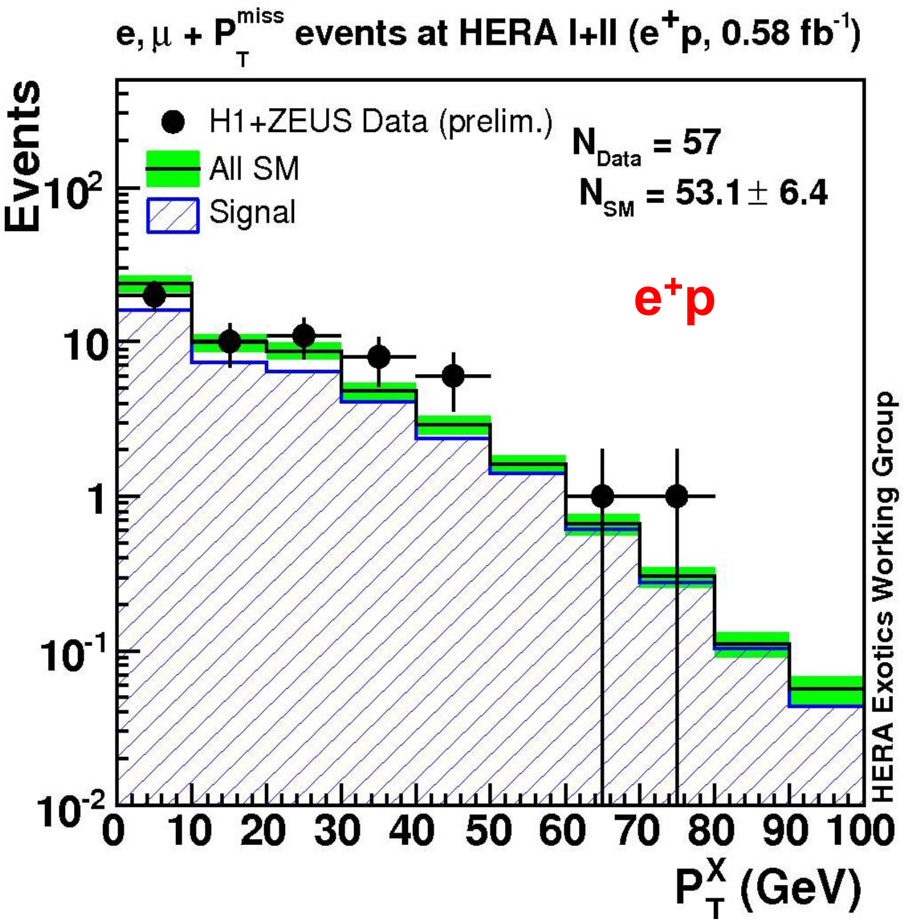


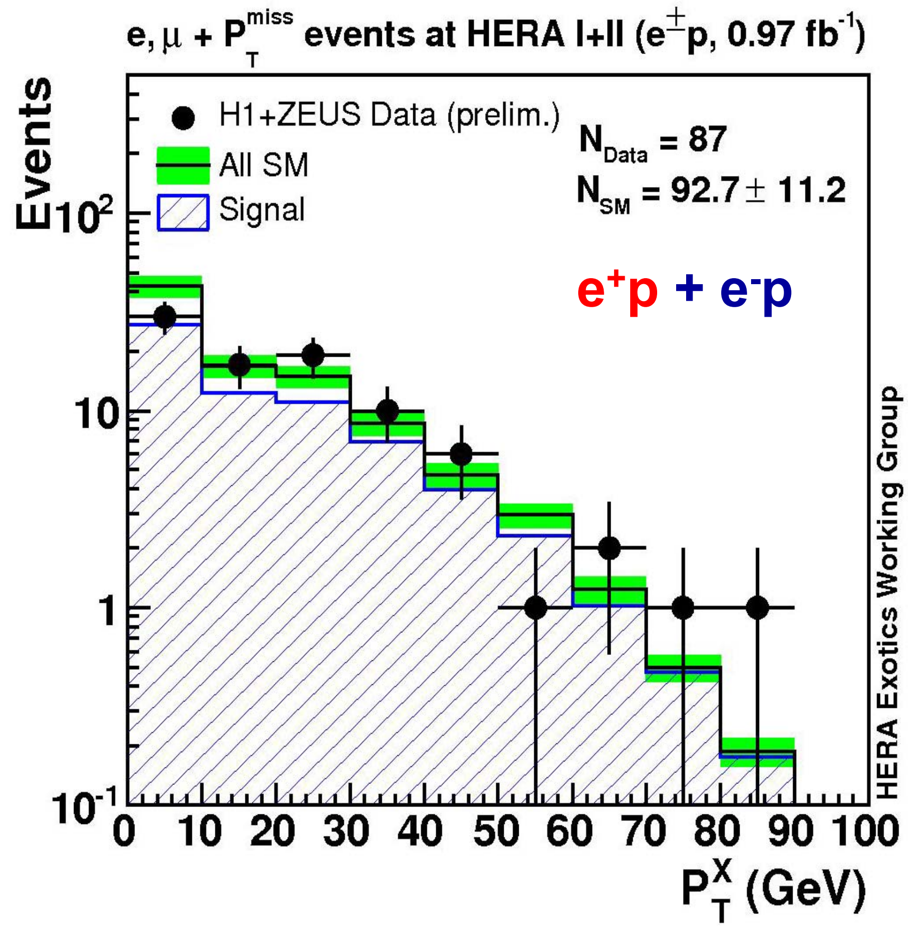


HIGH ENERGY FRONTIER: Isolated Leptons + Missing P_T

SM :

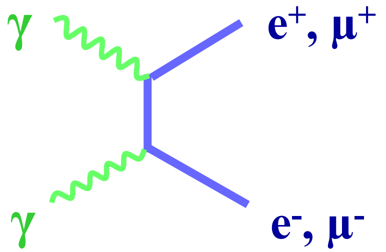


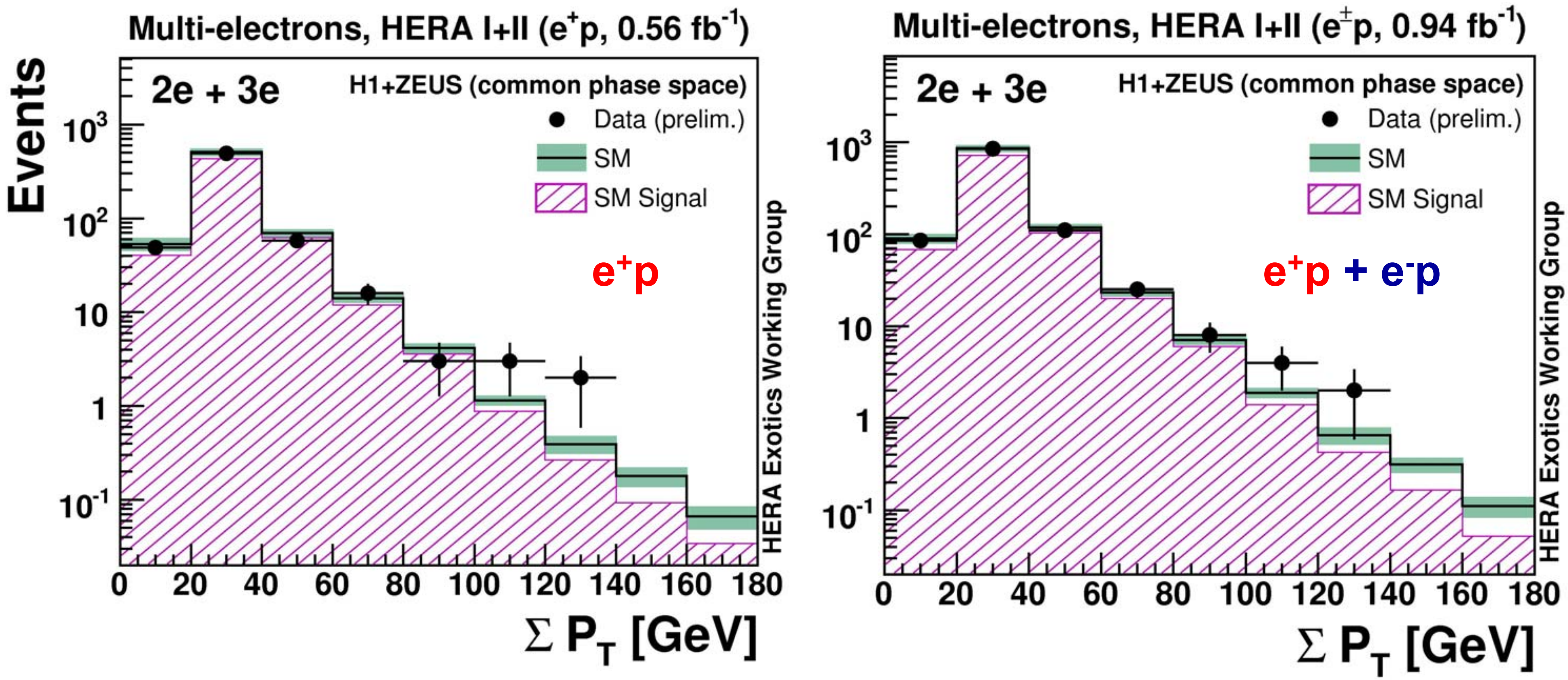




HIGH ENERGY FRONTIER: Multi-Leptons

SM :

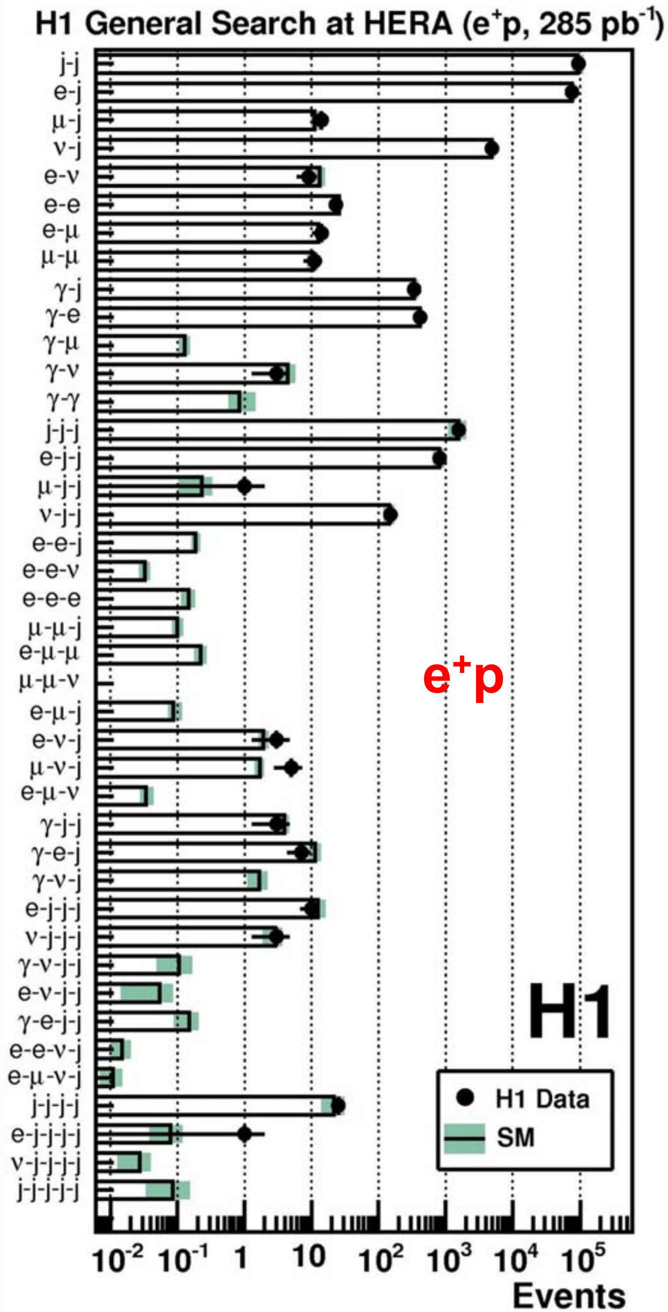


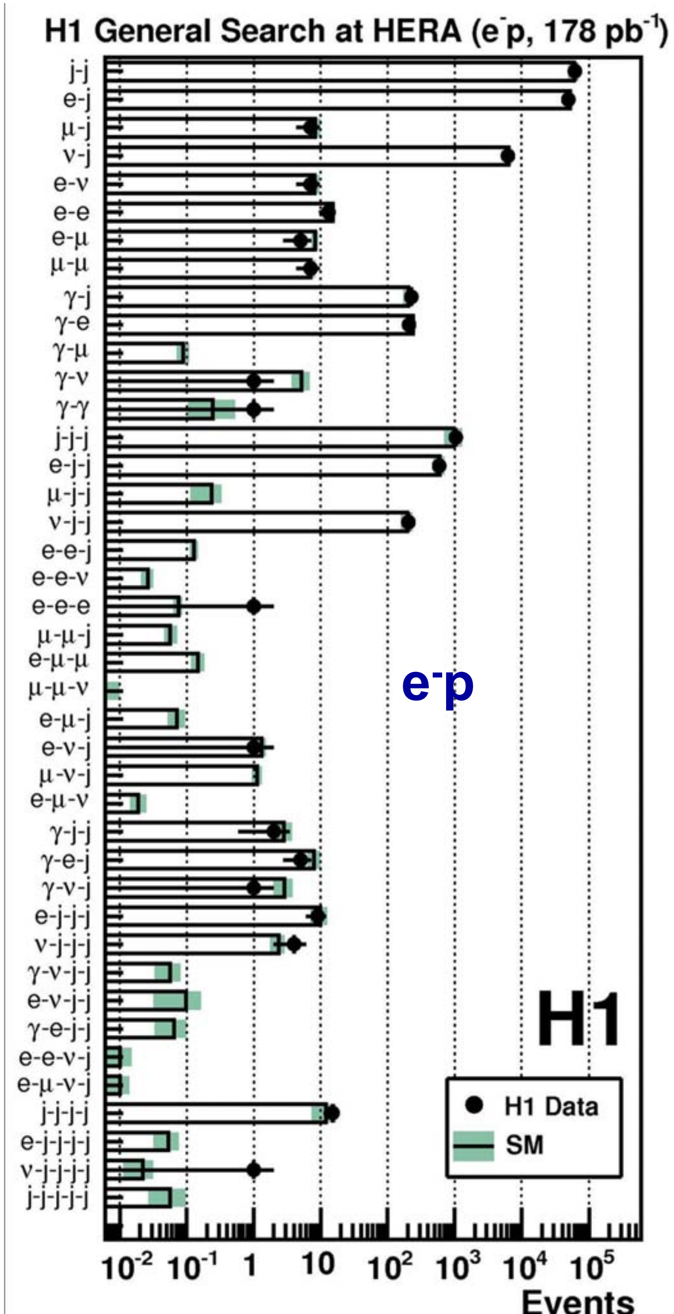


HIGH ENERGY FRONTIER:
Generic Search

Multi-body topologies
$P_T^i > 20$ GeV

SM OK

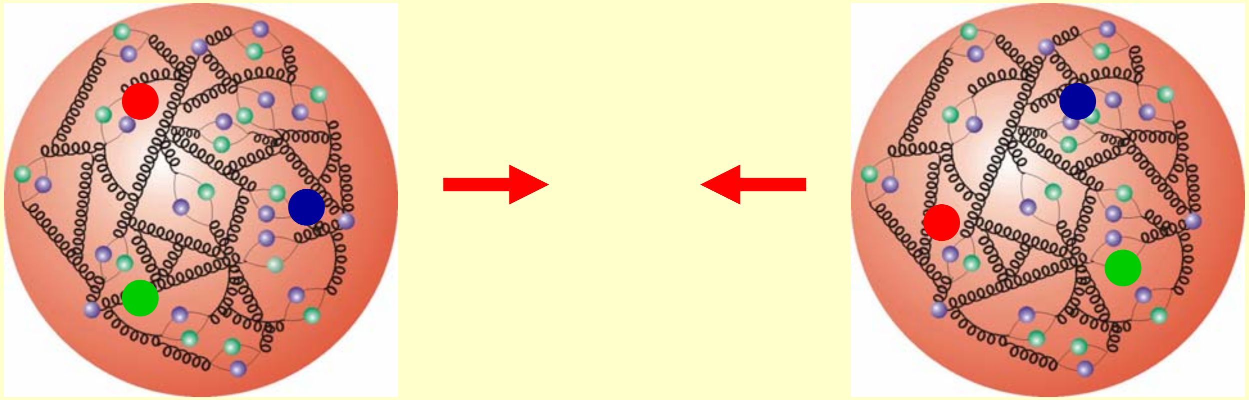




C. Vallee 27/01/09

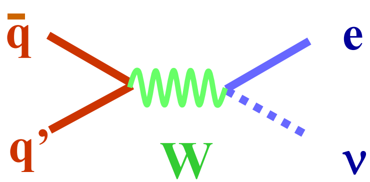
PRECISION MEASUREMENTS

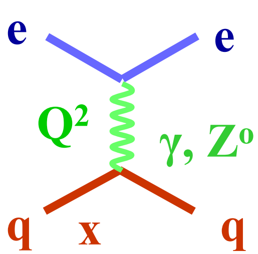
LHC needs

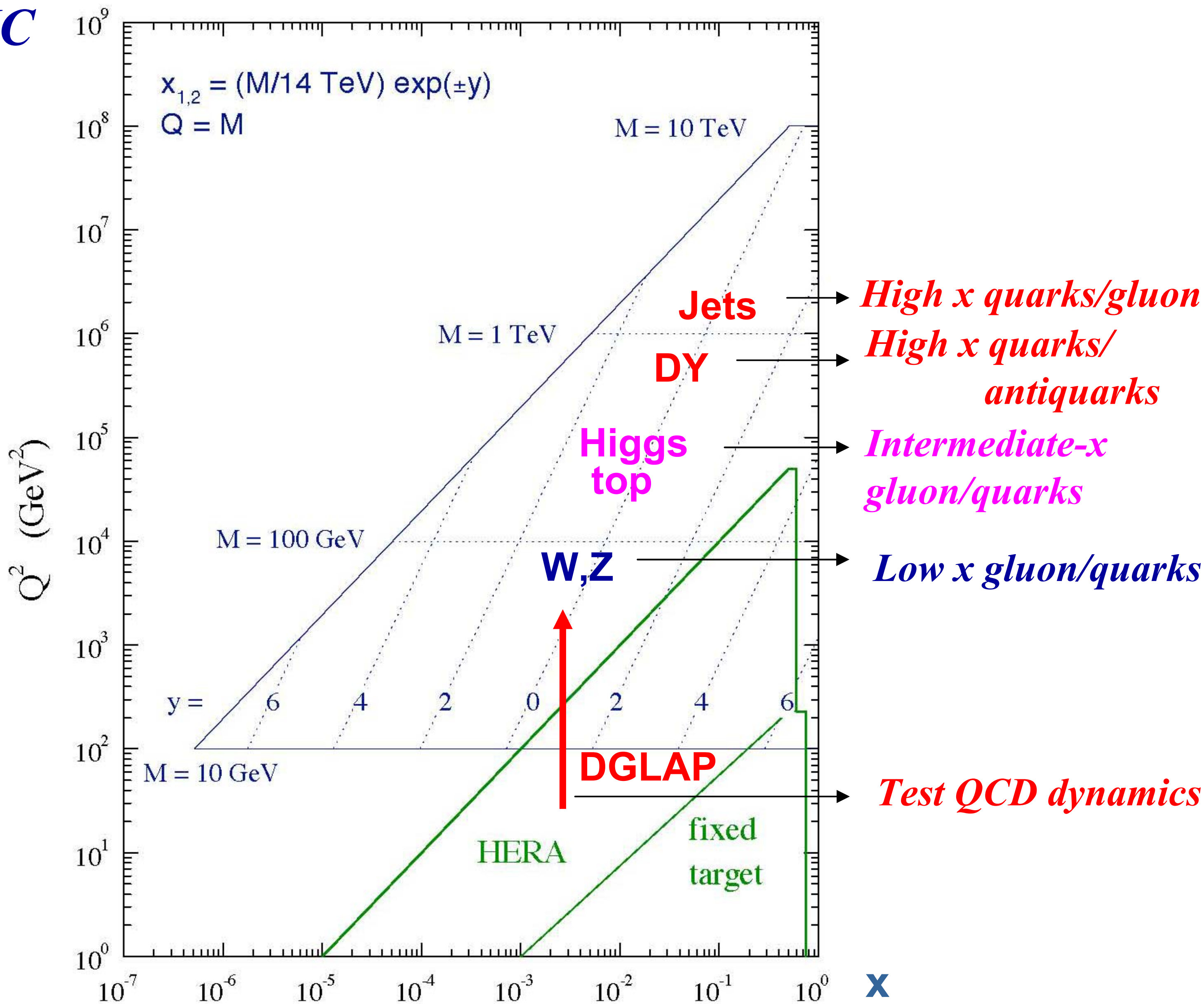


(plots from contributors to the PDF4LHC workshop)

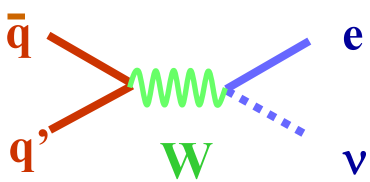
HERA ↔ LHC kinematics

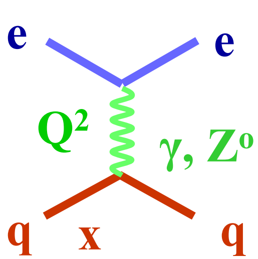


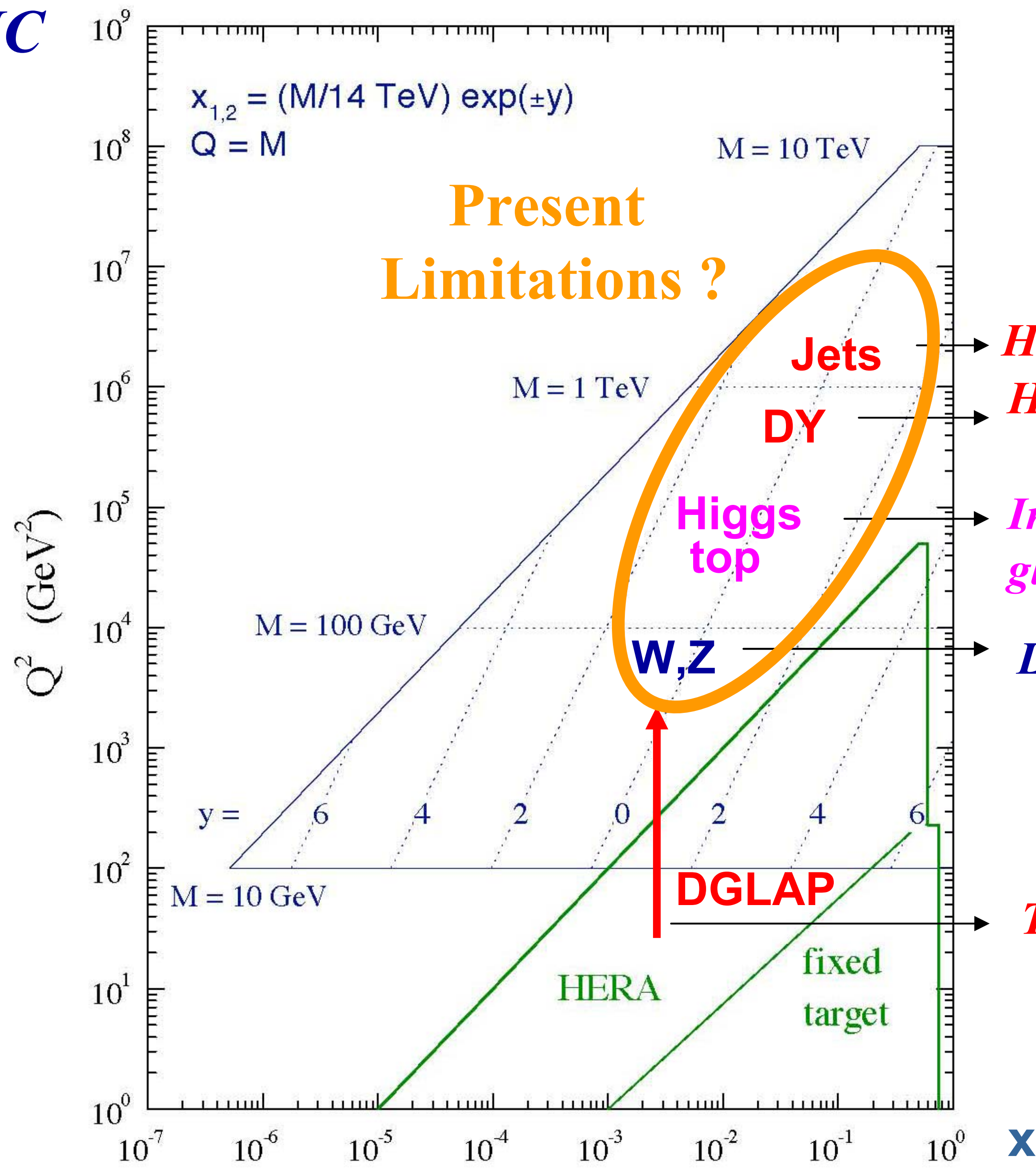




HERA ↔ LHC kinematics







High x quarks/gluon

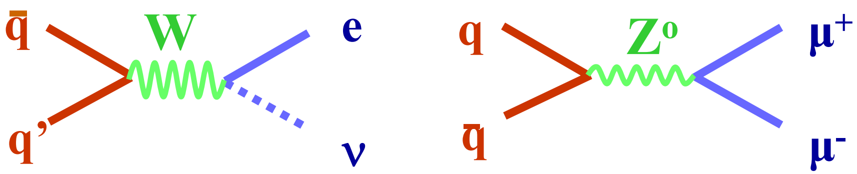
High x quarks/ antiquarks

Intermediate-x gluon/quarks

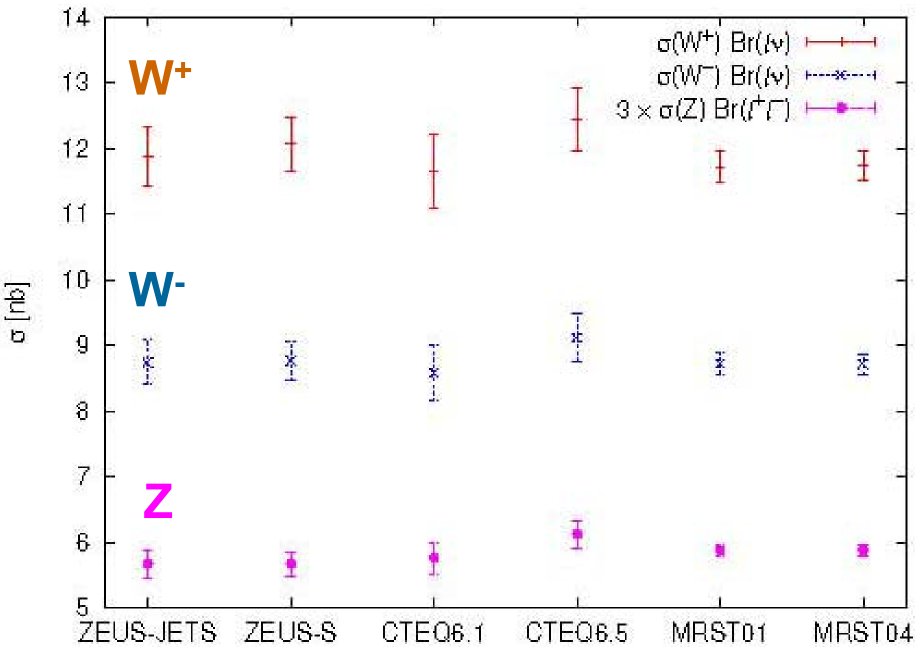
Low x gluon/quarks

Test QCD dynamics

LHC needs: W/Z production

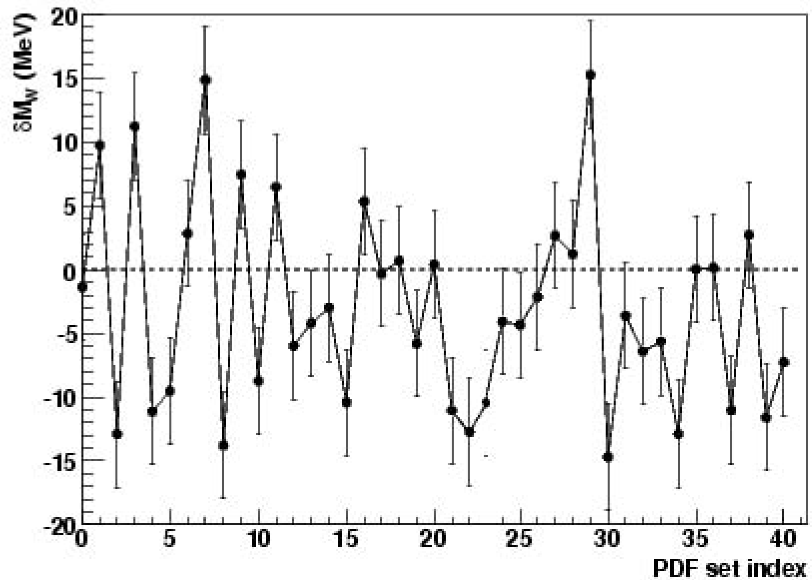


W/Z cross sections



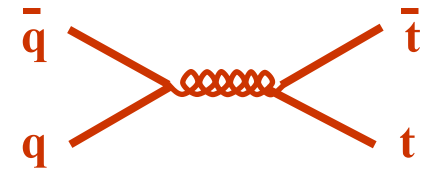
σ variations from PDF's at the level of ~5%

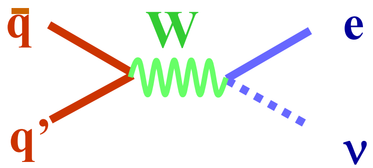
W mass determination

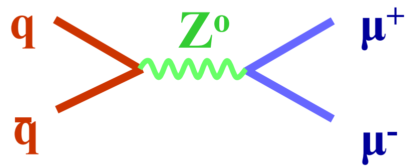


Spread of ~25 MeV in M_T mass fit due to PDF uncertainties in rapidity distribution (goal is ~1 MeV)

LHC needs: W ↔ Z ↔ top *PDF correlations*

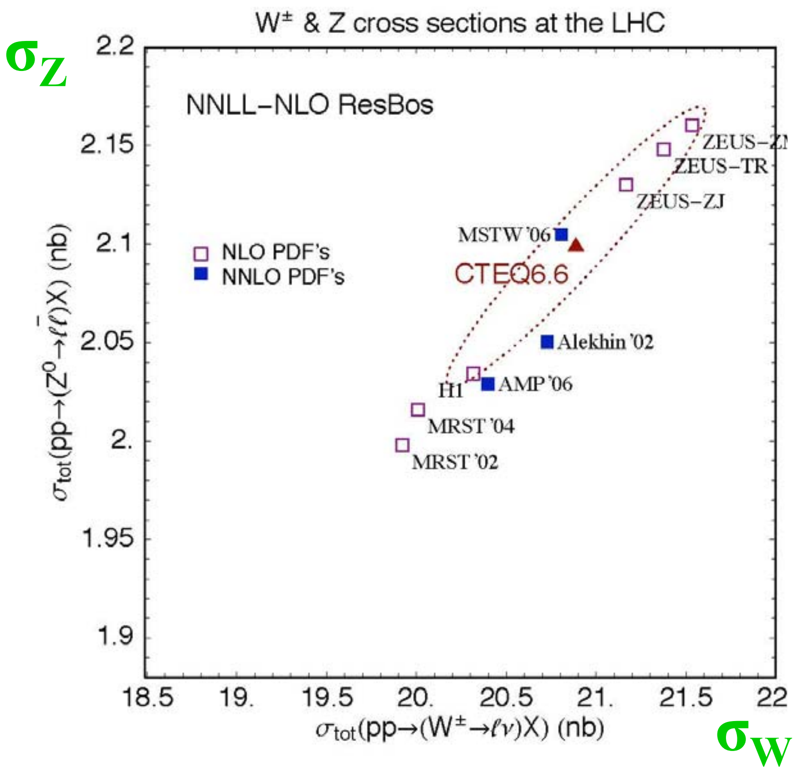


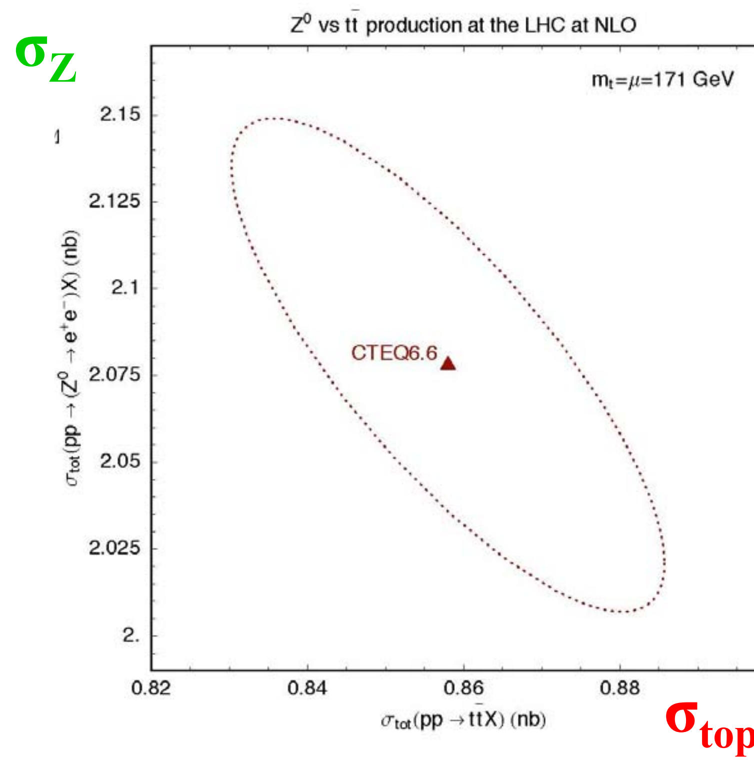




CTEQ6.5 $\sigma = 908\ ^{+82(9.0\%)}_{-85(9.3\%)}\ \text{(scales)}\ ^{+30(3.3\%)}_{-29(3.2\%)}\ \text{(PDFs) pb}$

MRSTW-06 $\sigma = 961\ ^{+89(9.2\%)}_{-91(9.4\%)}\ \text{(scales)}\ ^{+11(1.1\%)}_{-12(1.2\%)}\ \text{(PDFs) pb}$

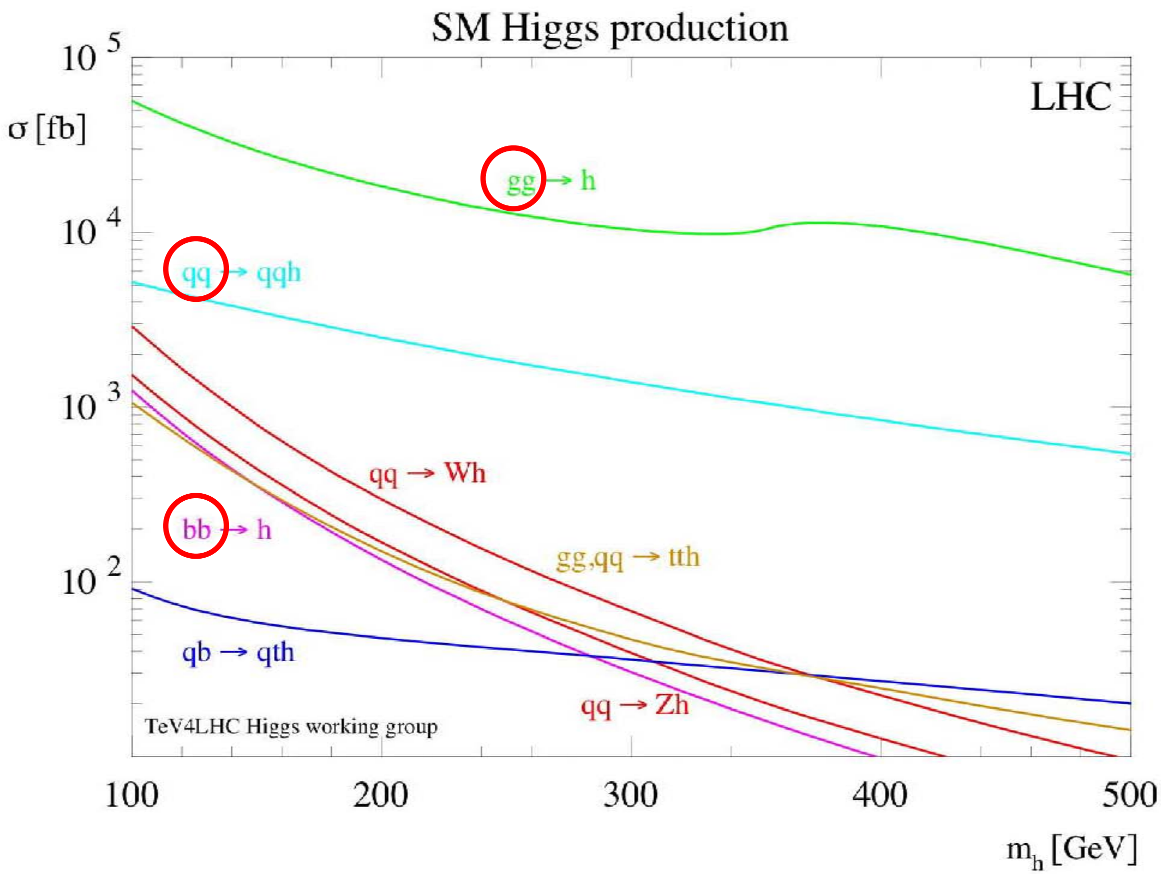


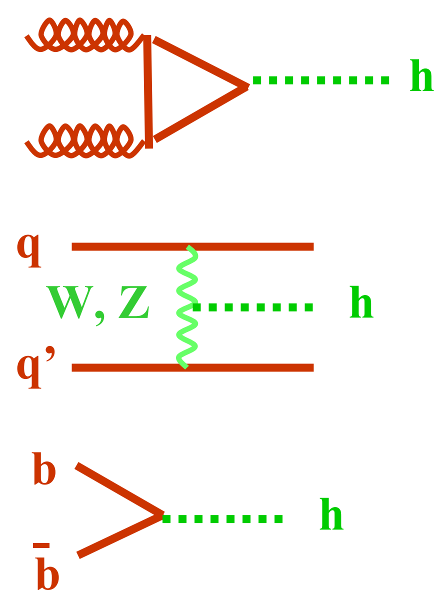


W and Z strongly correlated

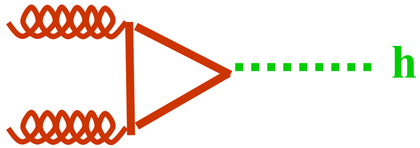
Top uncertainty ~5% anti-correlated with Z

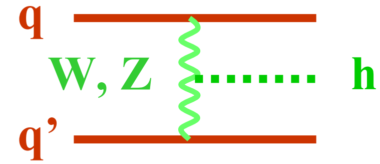
LHC needs: SM Higgs production

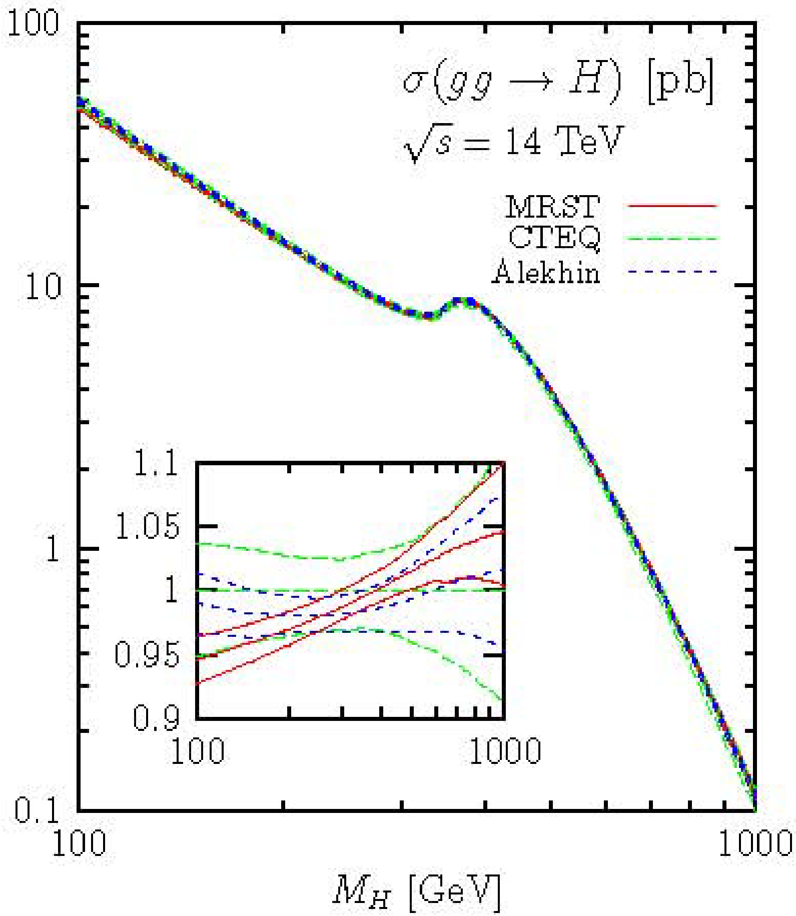


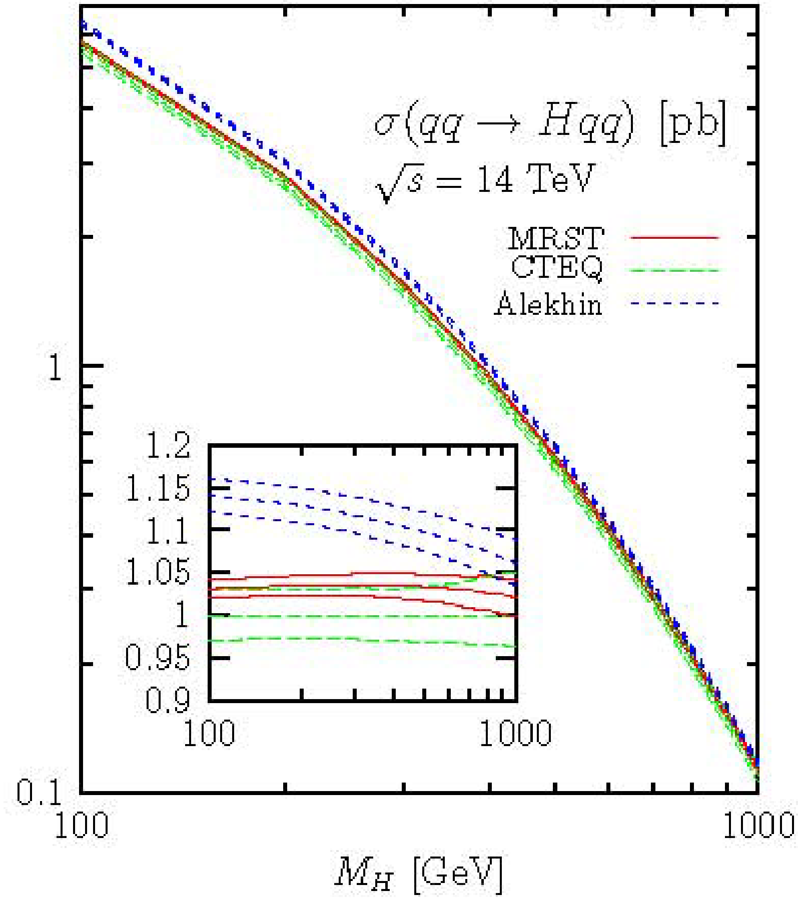


- Sensitive mainly to gluon and light quarks at low or intermediate x
- Beauty PDF contributes mainly at low mass for a SM Higgs



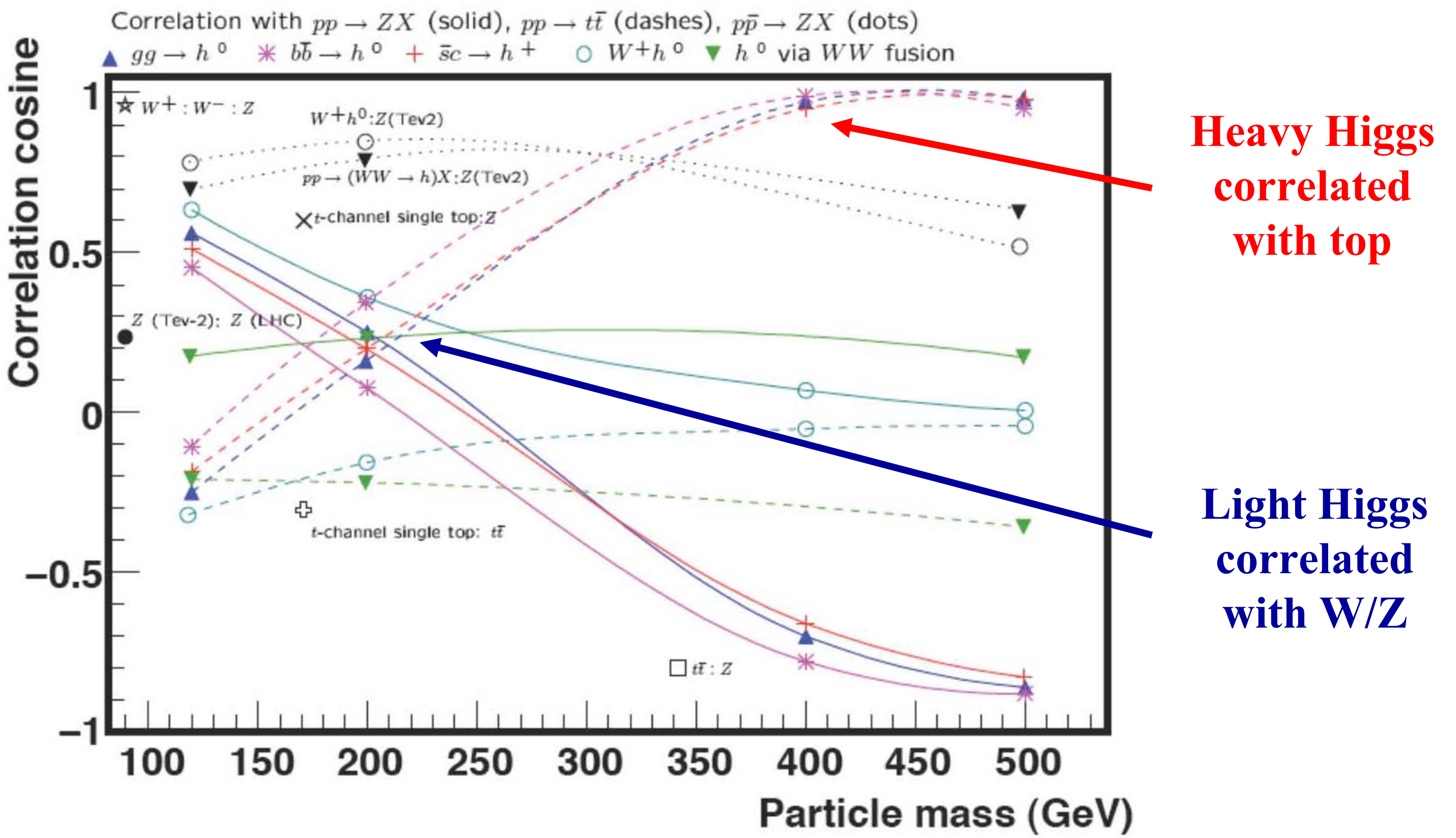






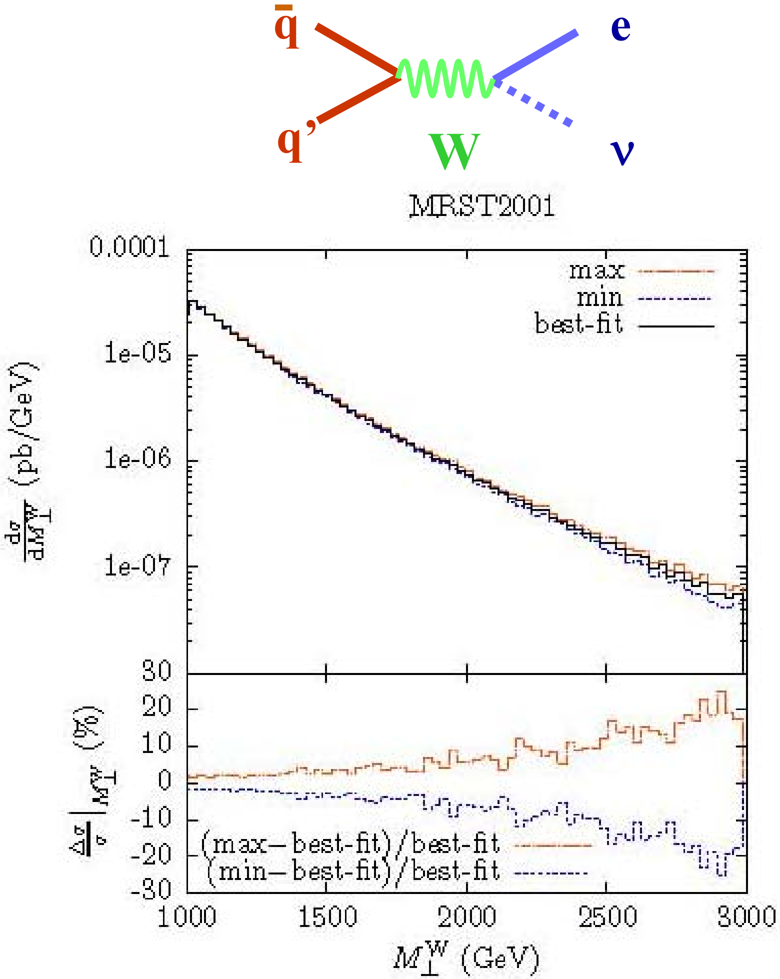
Higgs cross-section PDF uncertainty ~5-10 %

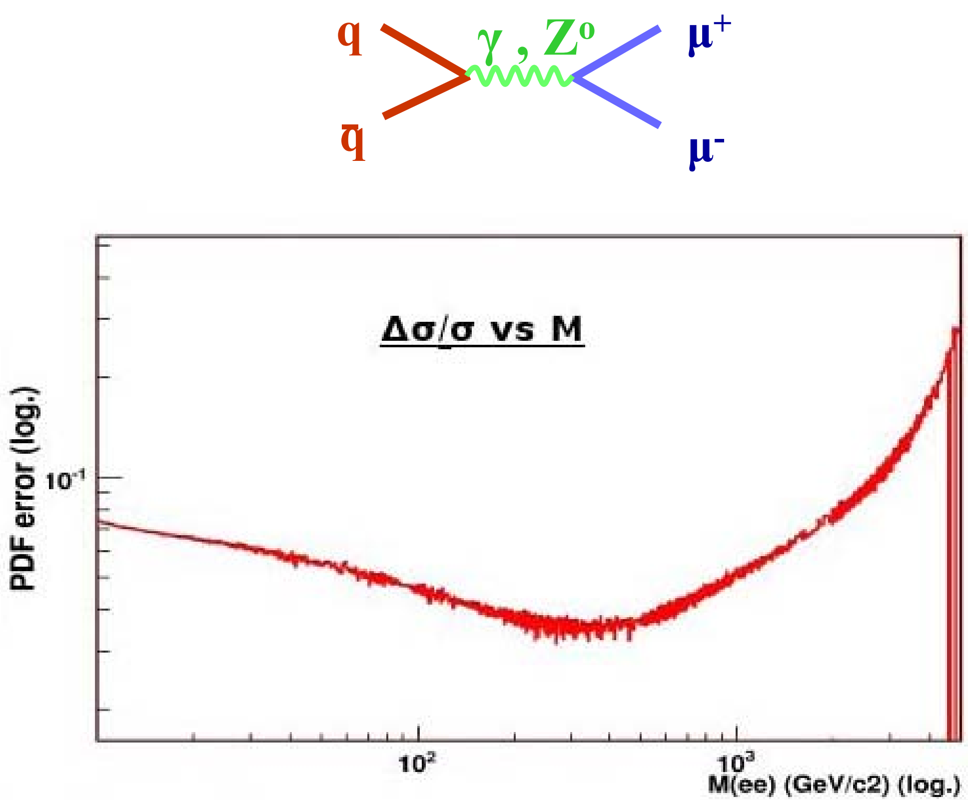
LHC needs: PDF cross-sections correlations



→ Best Standard Candle to which to renormalise may depend on mass

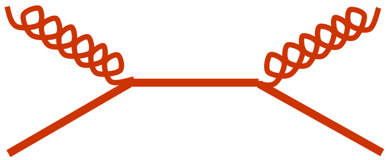
LHC needs: high-mass Drell-Yan cross-section

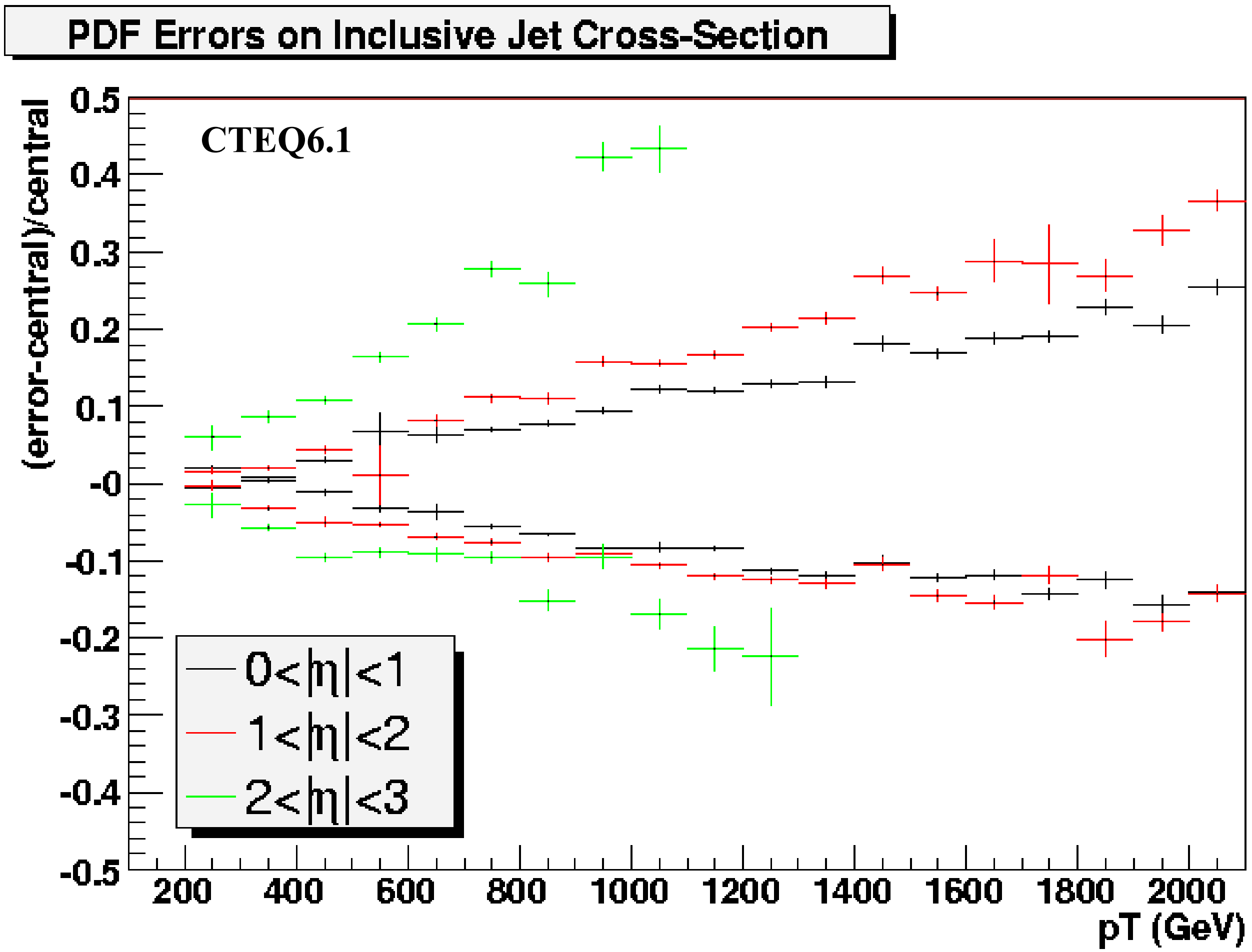




Uncertainty varies from ~5% to ~20% at high mass

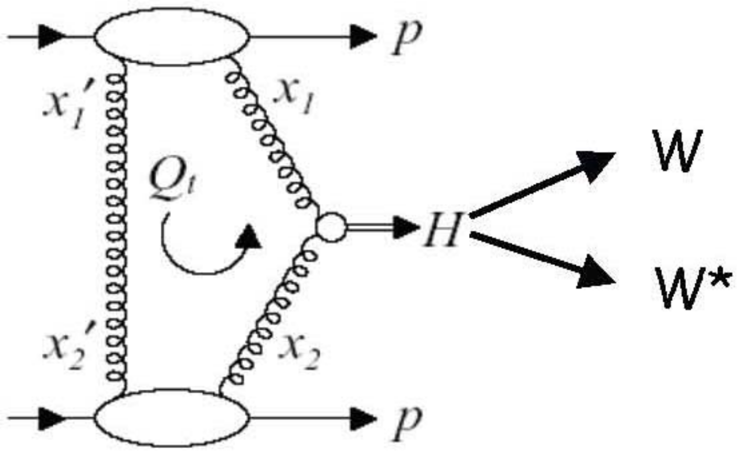
LHC needs: high-P_T jets cross-section

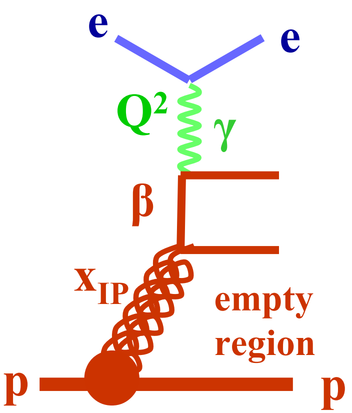




Uncertainty up to ~30% at high P_T

LHC needs: Diffractive Higgs production





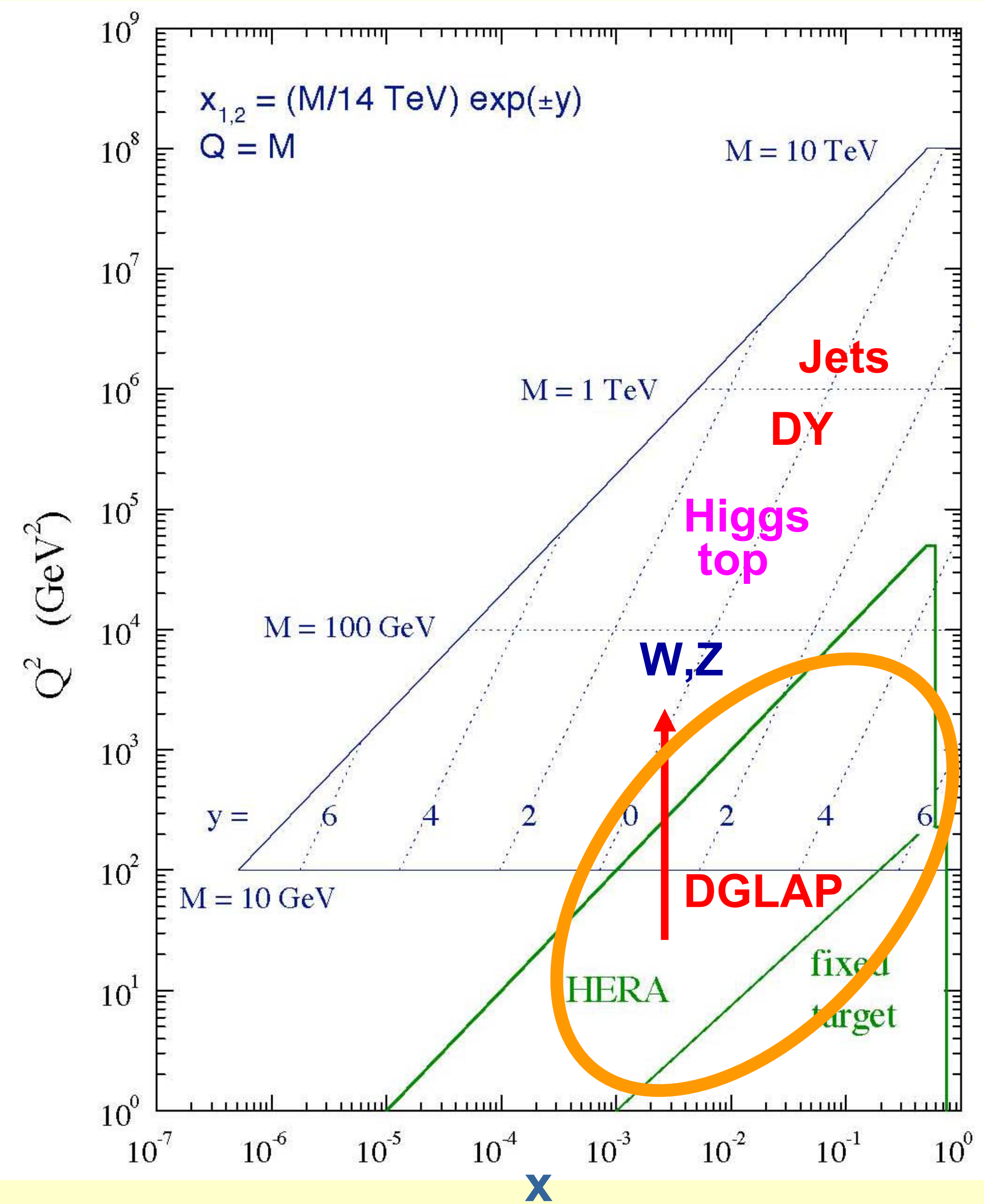
Cross-section depends on 2-gluon GPD's

Structure of inclusive colorless exchange also necessary for background (high β)

PRECISION MEASUREMENTS

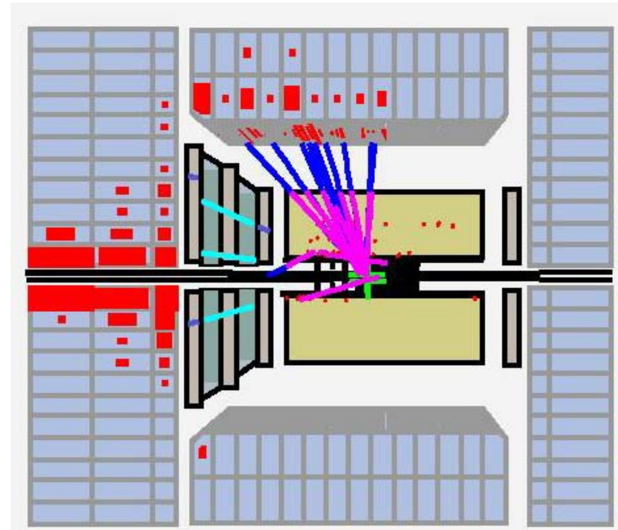
Proton structure and dynamics

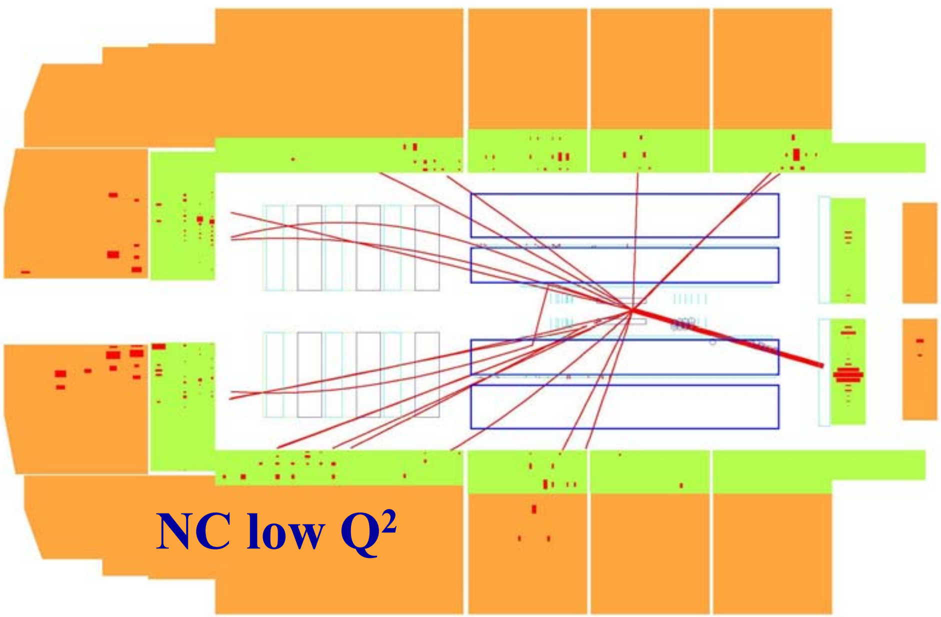
Latest HERA results



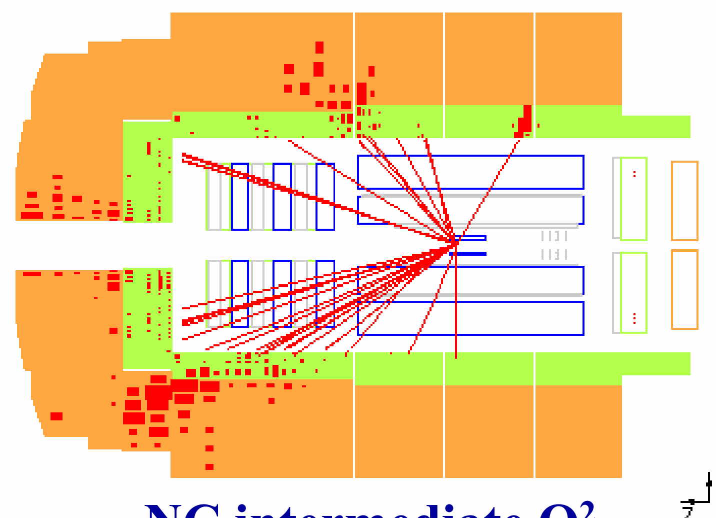
Typical interactions
for
precision measurements

CC intermediate Q^2



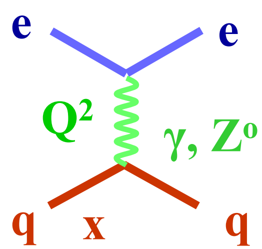


NC low Q^2

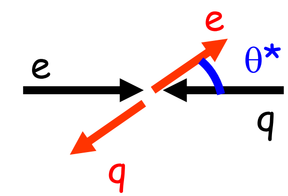


NC intermediate Q^2

MEASURING THE PROTON STRUCTURE



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



$y = Q^2/sx = (1\text{-}\cos\theta^*)/2$

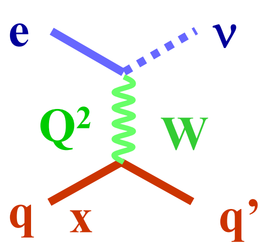
$$= \tilde{F}_2 - \frac{y^2}{Y_+}\tilde{F}_L \mp \frac{Y_-}{Y_+}x\tilde{F}_3$$

$$Y_\pm = 1 \pm (1-y)^2$$

valence + sea quarks

gluon

valence quarks

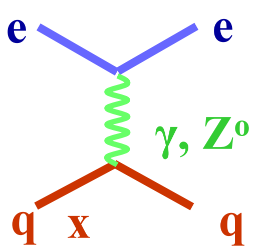


$$\sigma_{CC}(e^+p) \propto x[(1-y^2)(d+s)+(\bar{u}+\bar{c})] \quad \text{x } \mathbf{(1 + P_e)}$$

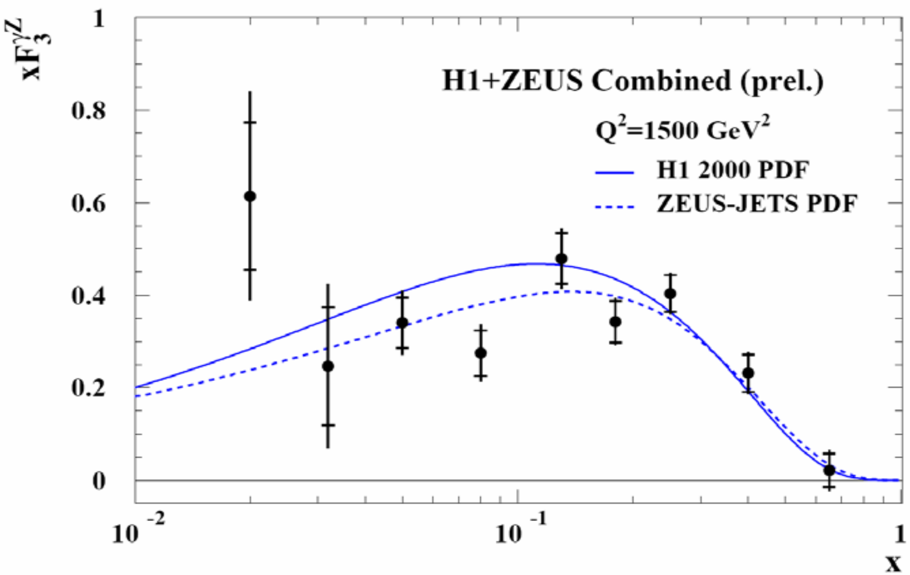
$$\sigma_{CC}(e^-p) \propto x[(u+c)+(1-y^2)(\bar{d}+\bar{s})] \quad \text{x } \mathbf{(1 - P_e)}$$

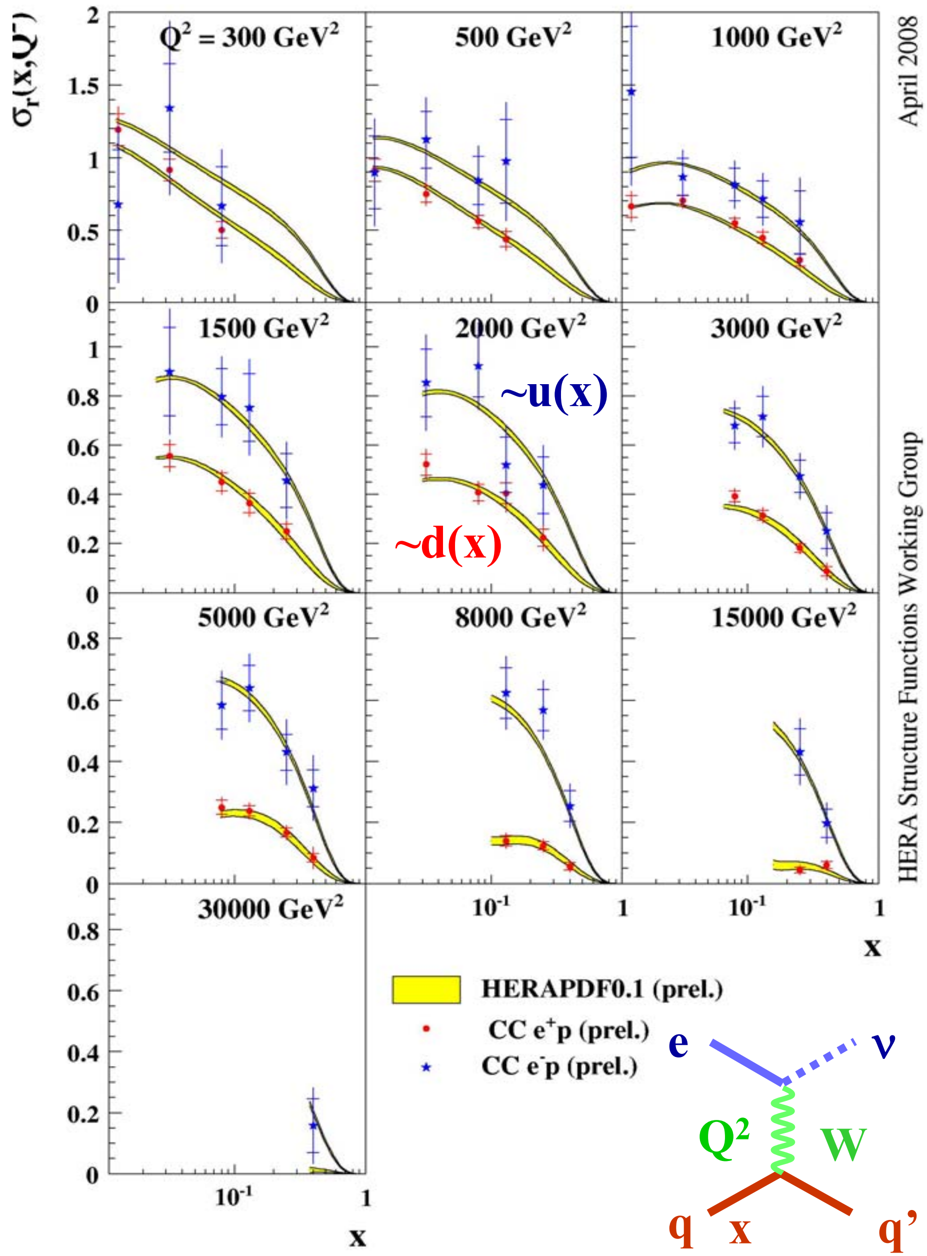
PROTON STRUCTURE

valence quarks



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

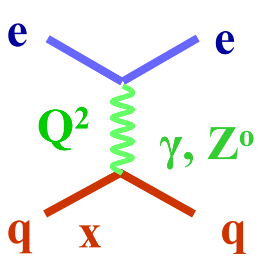




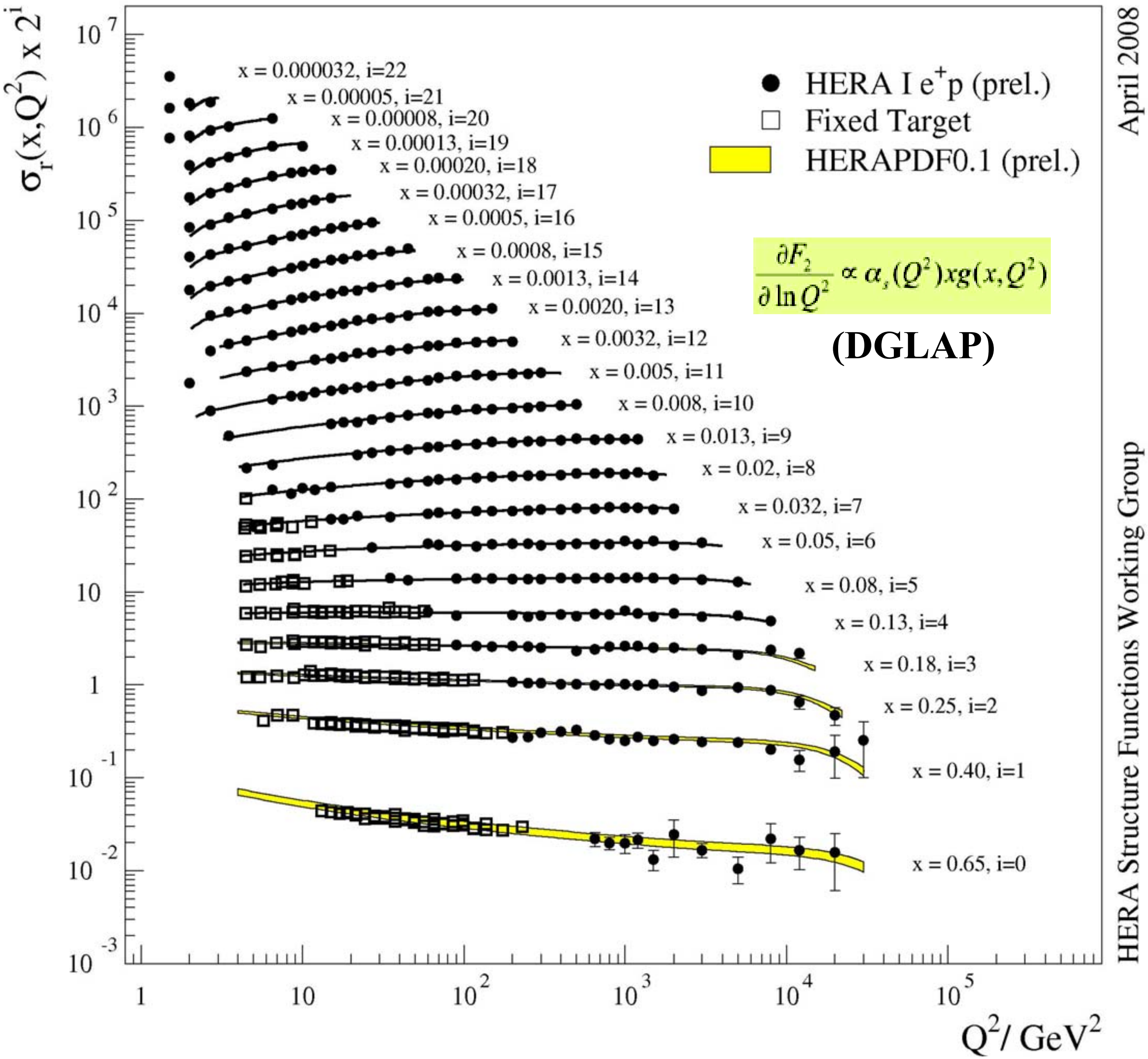
PROTON STRUCTURE

valence + sea quarks

$F_2(x,Q^2)$



DGLAP works on a very large phase space !



C. Vallee 27/01/09

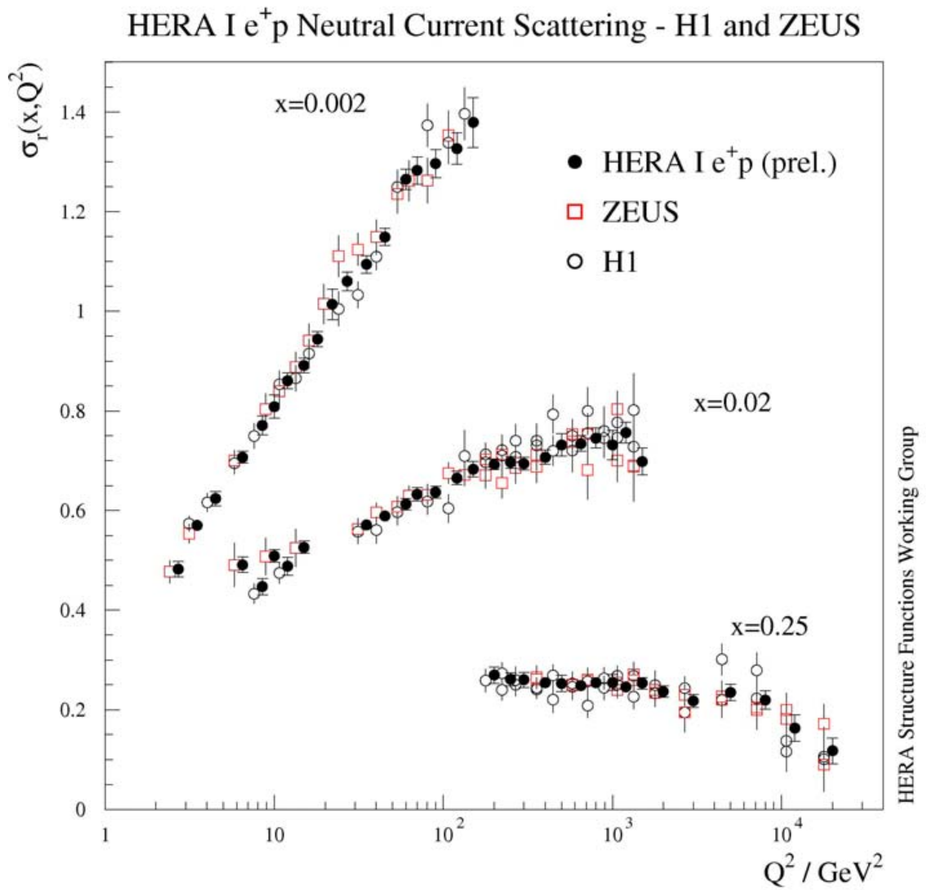
PROTON STRUCTURE: the power of combining

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

Cross-calibration of both experiments

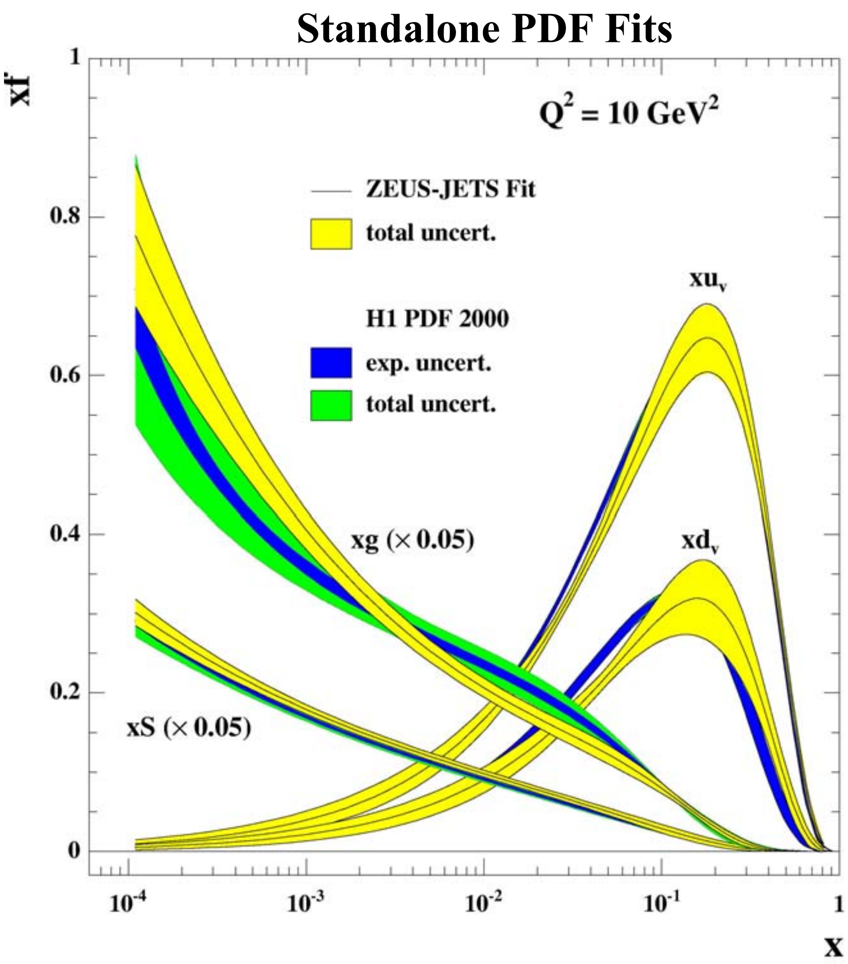
↓

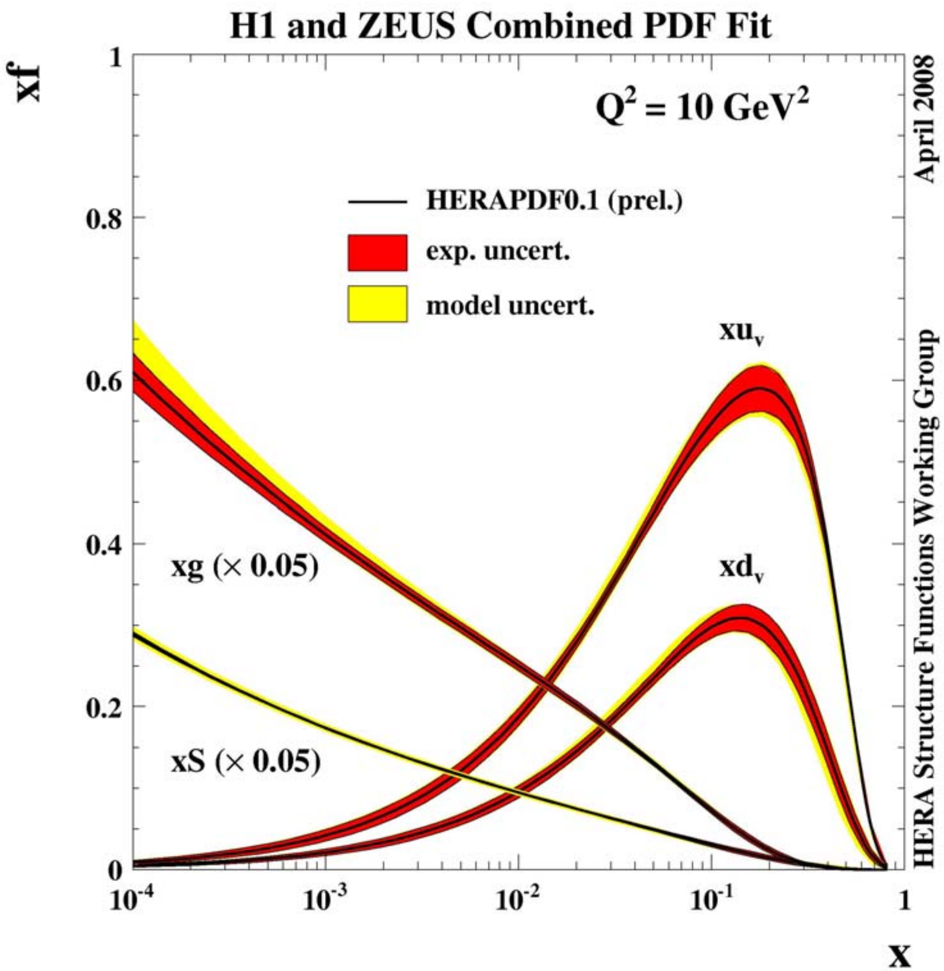
systematic uncertainties reduced together with statistical errors



Extracting the essence of Structure Functions

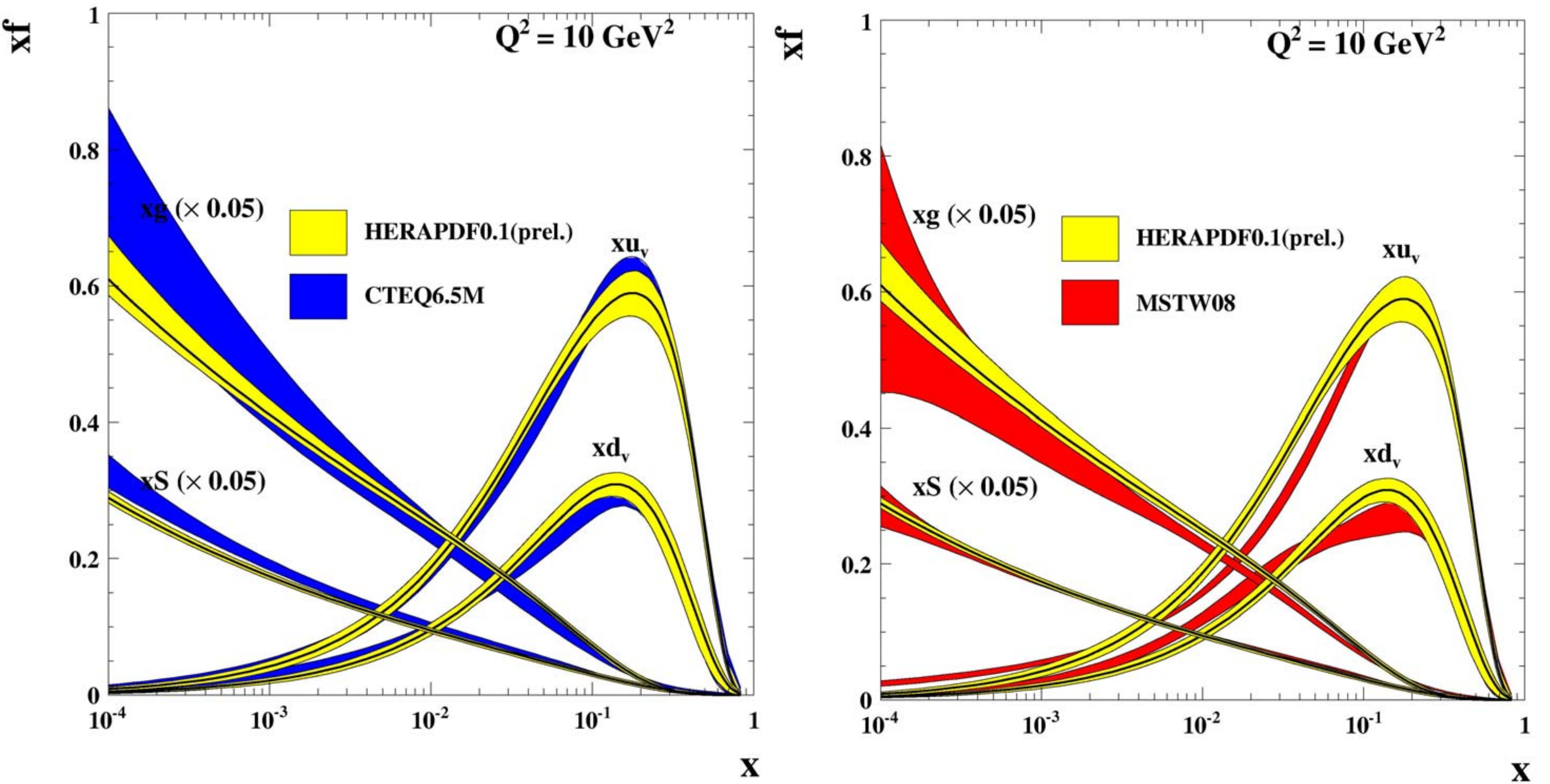
common PDF Fit on HERA I combined data

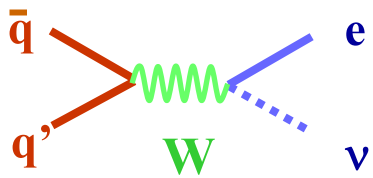




HERAPDF0.1 *versus* CTEQ *and* MSTW

uncertainty on low-x gluon and sea strongly reduced

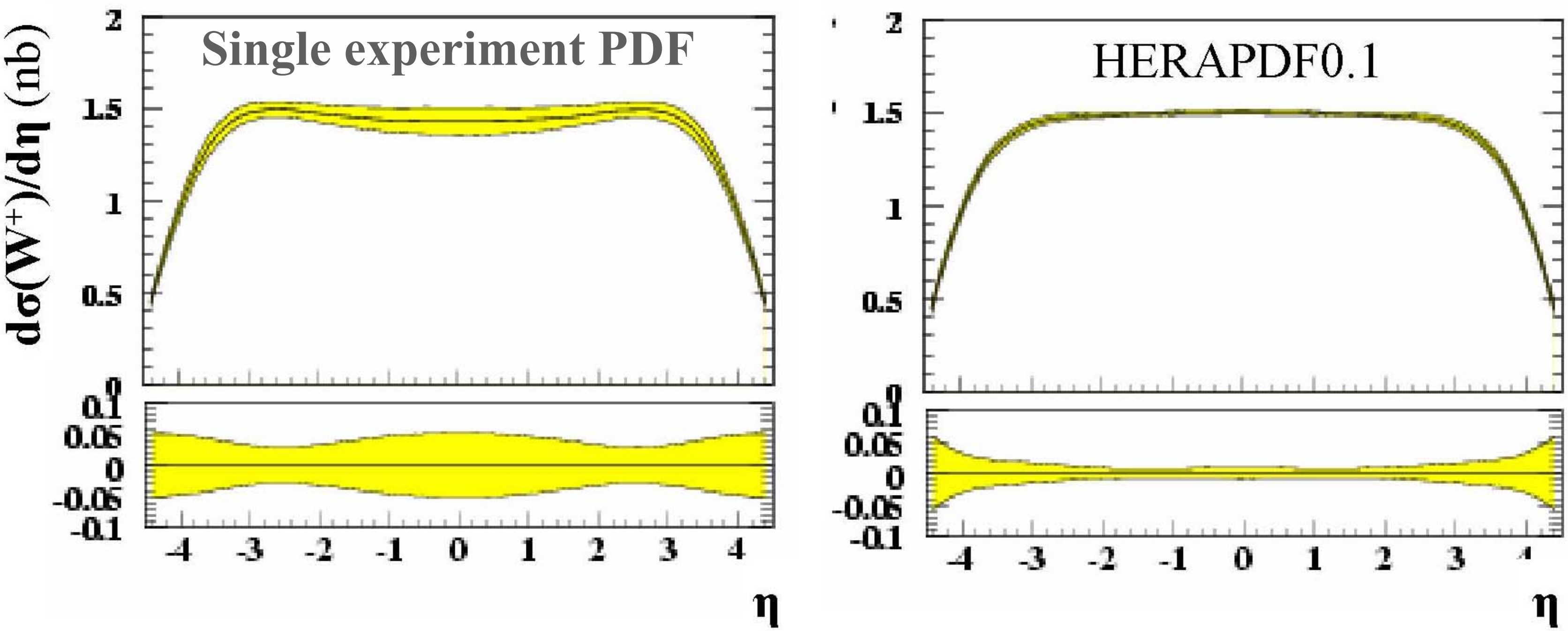




HERAPDF0.1 *impact on* LHC

the example of W production

M. Cooper / E. Perez

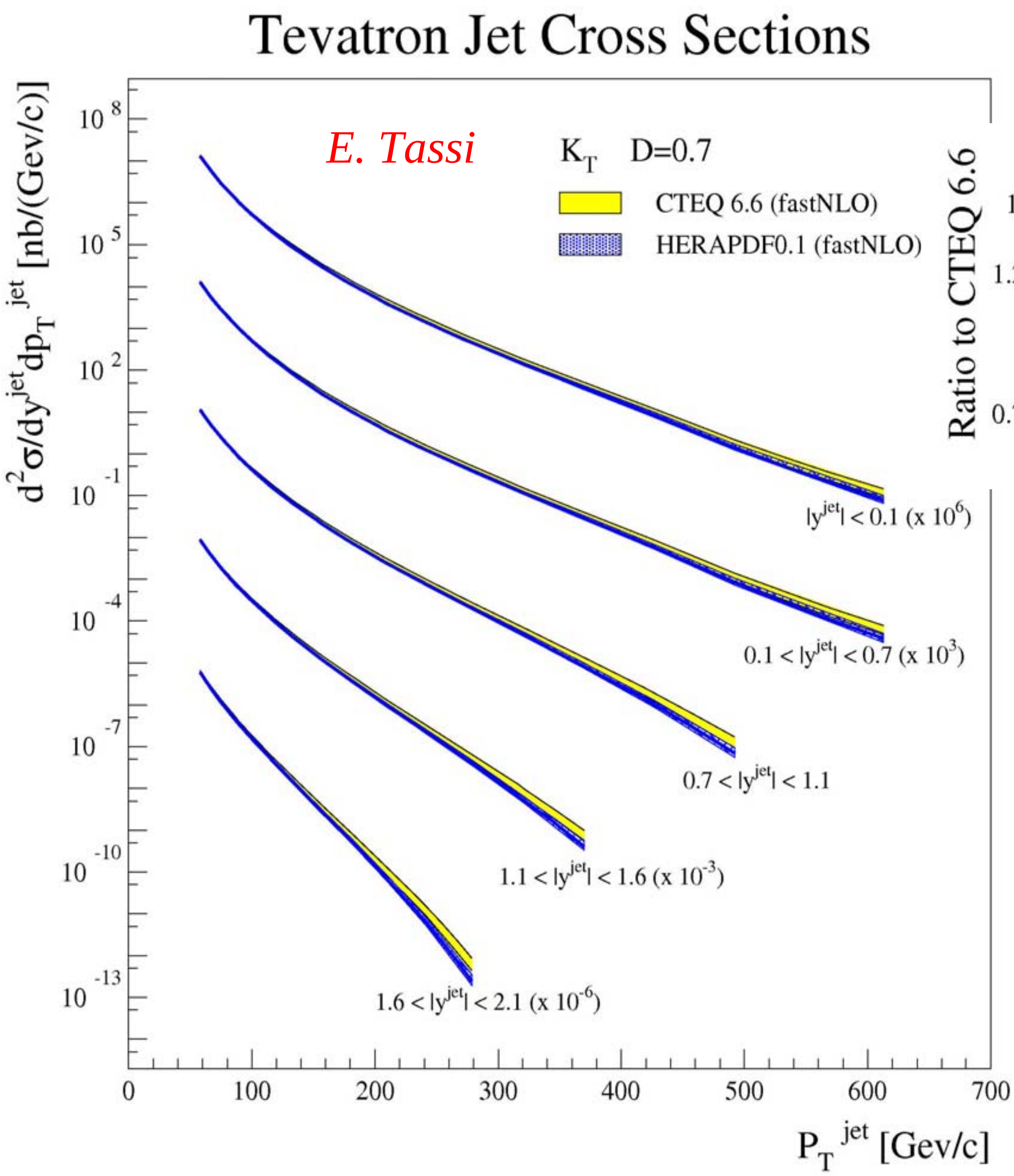


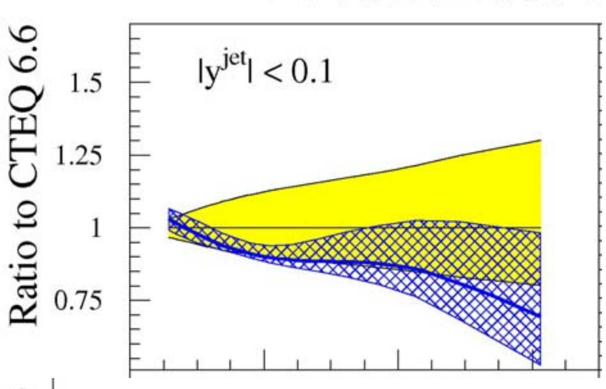
HERAPDF0.1 publicly released in LHAPDF (version 5.6.0)

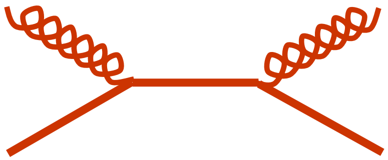
…to be exercised by the LHC experiments !

HERAPDF0.1 *impact on* LHC

the gluon at high x

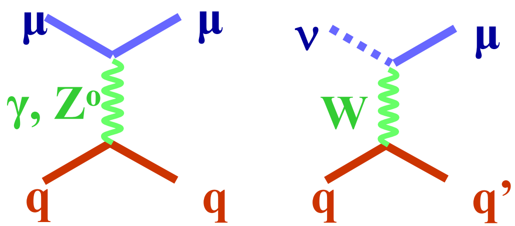




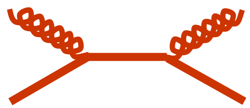


Reasonable behaviour at high x though no input from Tevatron High-P_T jets in the fit

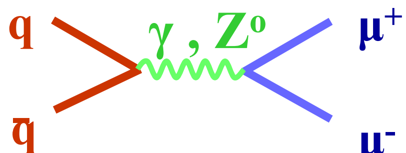
COMPLEMENTARY INPUTS to the PROTON PDF's



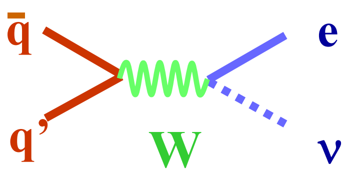
Fixed Target NC/CC
→ high-x quarks



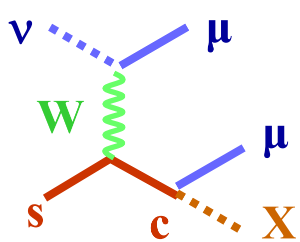
Tevatron High-P_T jets
→ high-x gluon



Fixed Target Drell-Yan
→ high-x antiquarks and ū/đ asymmetry

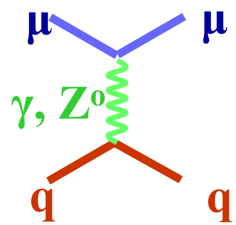


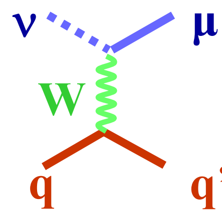
Tevatron W^+/W^-
→ u/d asymmetry at high x



Dimuons in Fixed Target CC
→ strange sea

COMPLEMENTARY INPUTS to the PROTON PDF's *(personal comments)*

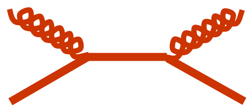




Fixed Target NC/CC

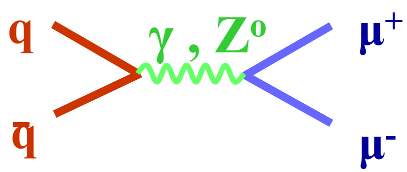
Nuclear corrections (CC) and possible Higher Twists (low Q^2)

Still needed with final HERA II high Q^2 NC/CC ?



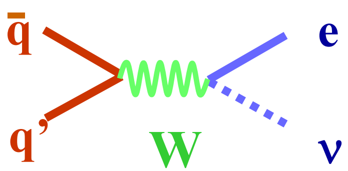
Tevatron High-P_T jets

Still needed with high precision HERA F_2 + jets ?



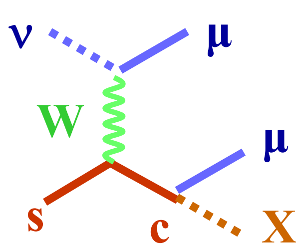
Fixed Target Drell-Yan

Nuclear corrections same as in DIS ?



Tevatron W^+/W^-

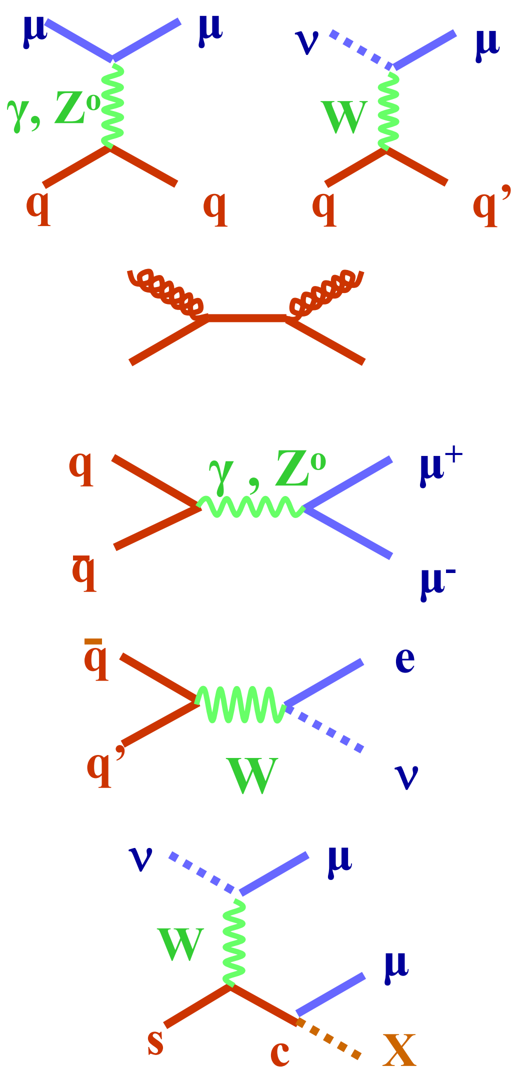
Special data will stay necessary for subtle asymmetry effects



Dimuons in Fixed Target CC

Increased tolerance needed in global fits

→ minimize number of experiments



TOWARDS OPTIMAL PROTON PDF's FOR LHC

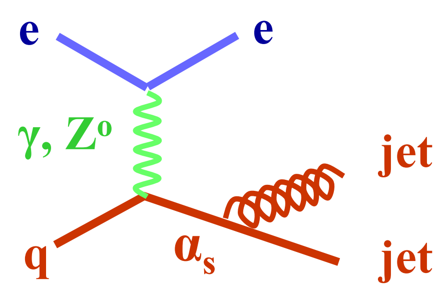
In the era of
high precision HERA results

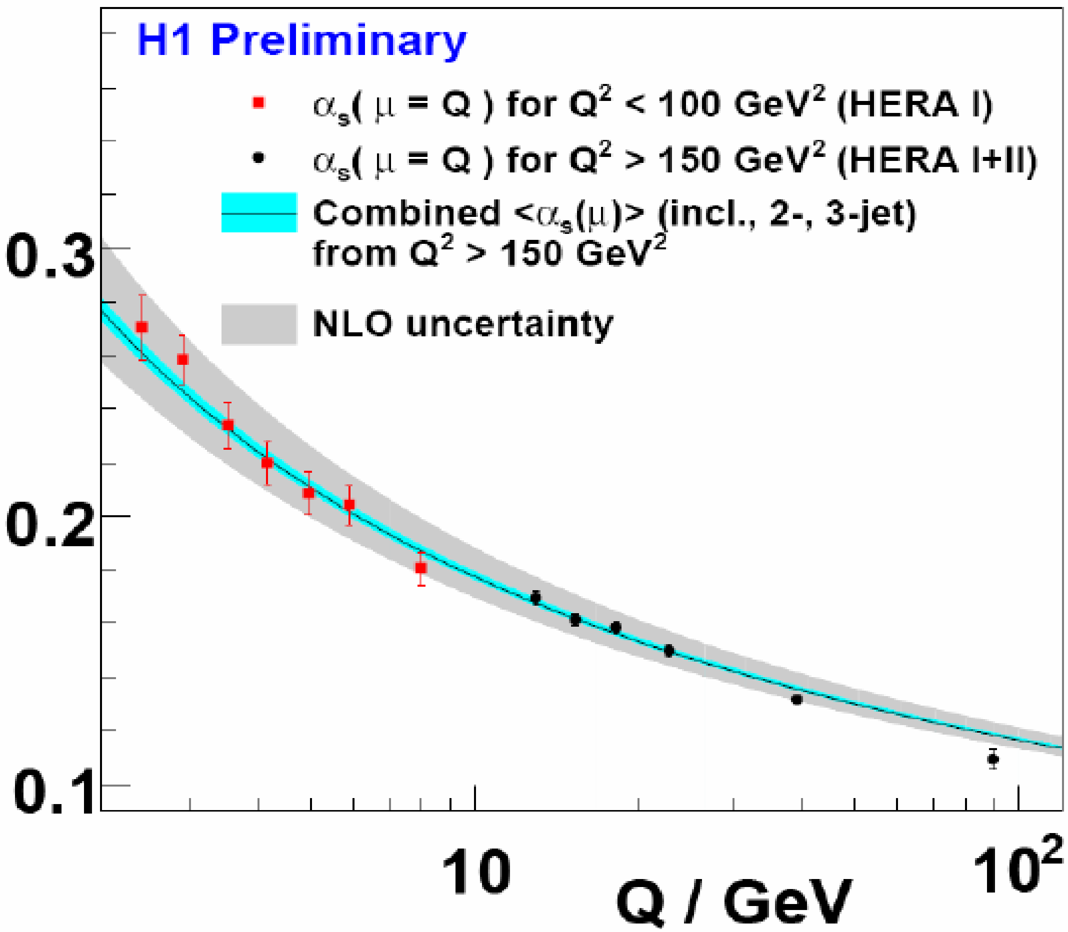
optimal inputs for LHC PDF's
and
PDF model uncertainties

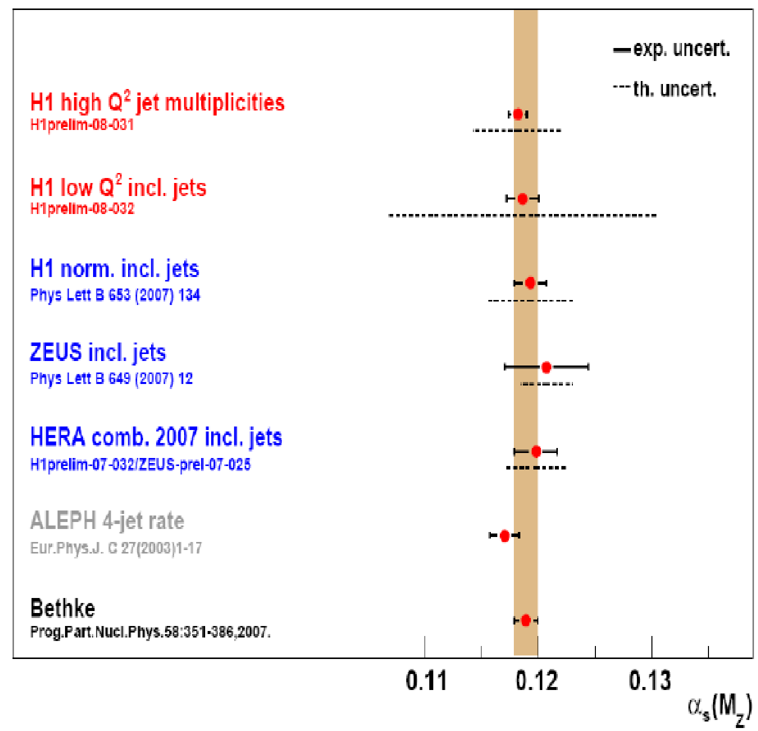
are essential questions
to be addressed by the
PDF4LHC workshop

PROTON DYNAMICS

the strong coupling α_s from multi-jet rates

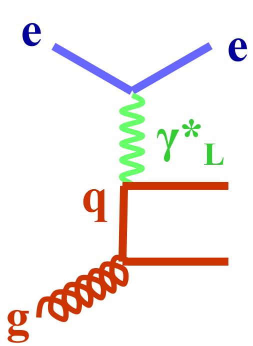






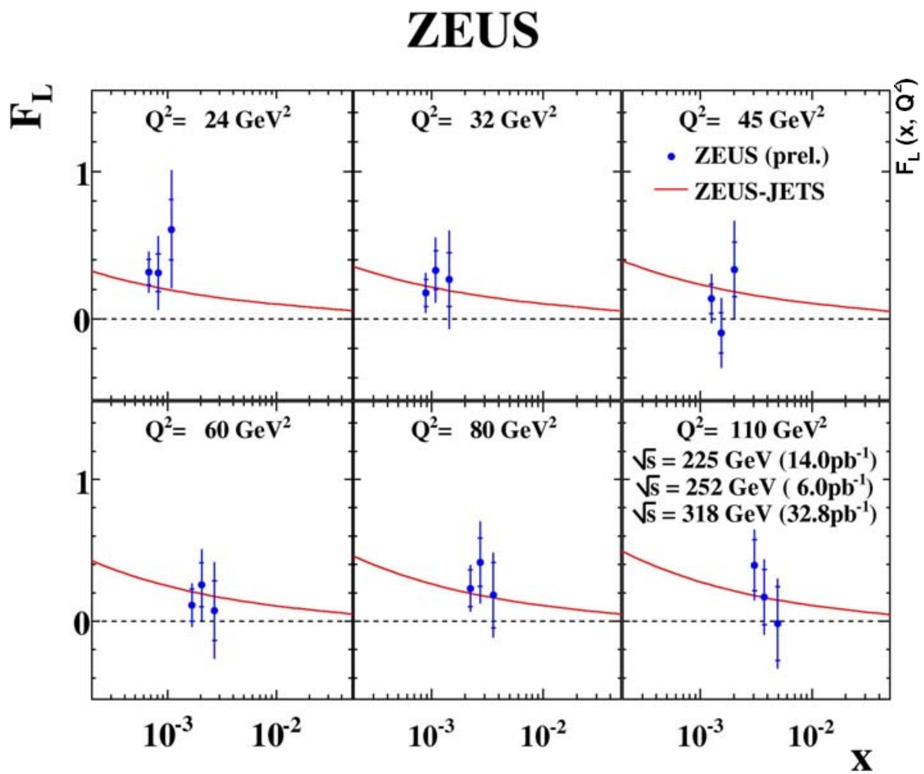
HERA exp. error ~ 0.7 %
a challenge for theory !

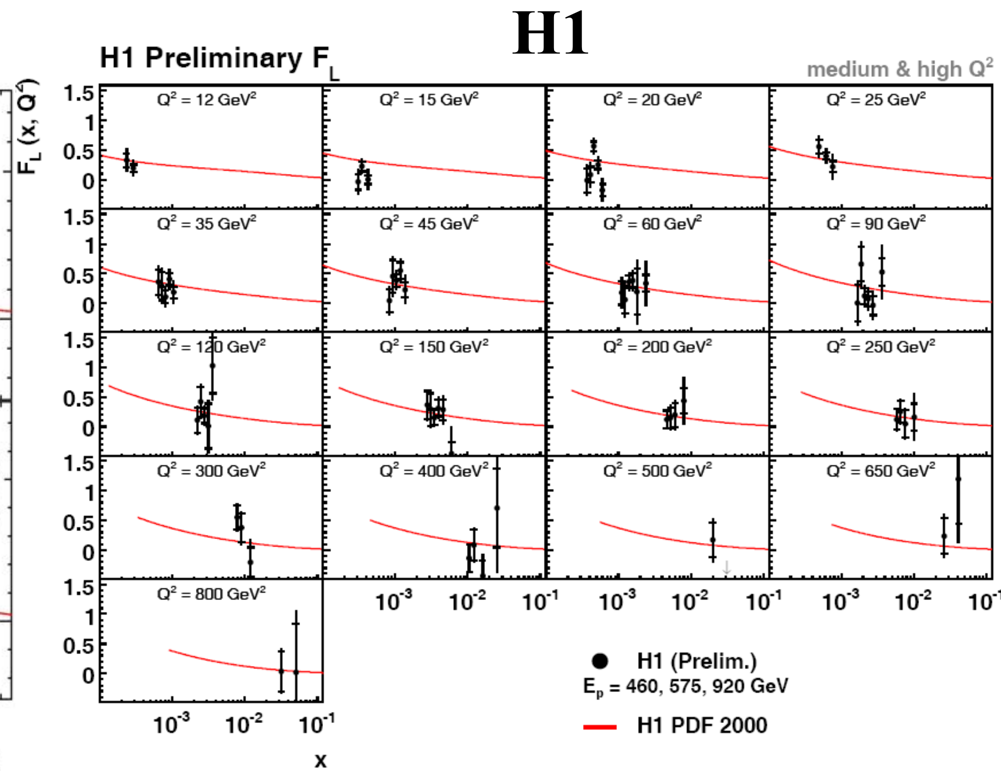
PROTON DYNAMICS: directly probing the gluon with F_L



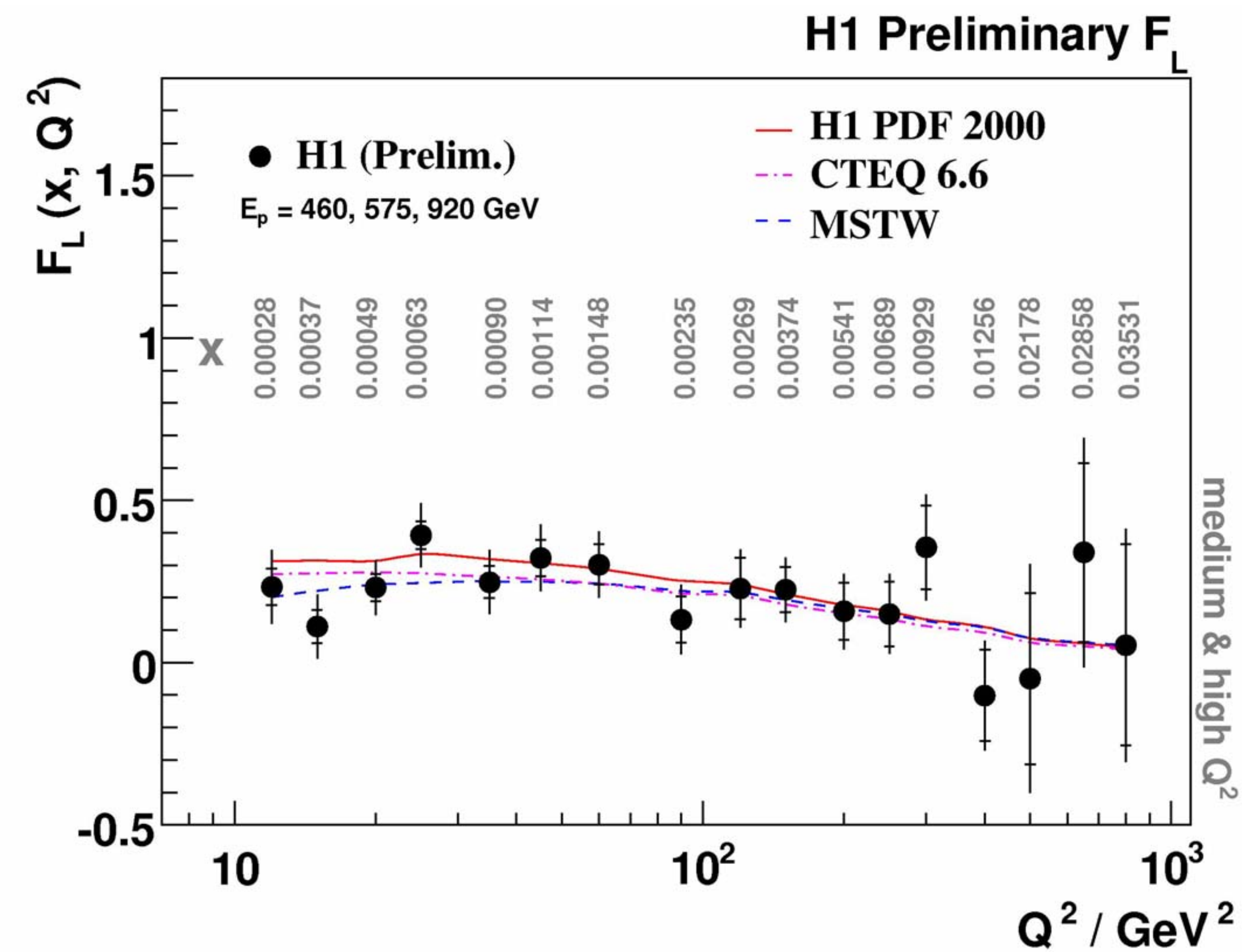
$$\tilde{\sigma}_{NC} = \frac{d^2\sigma^{ep}_{NC}}{dx dQ^2} / \left(\frac{2\pi\alpha^2}{xQ^4} Y_+ \right) = F_2 - \frac{y^2}{1+(1-y)^2} F_L$$

$y = Q^2/sx$

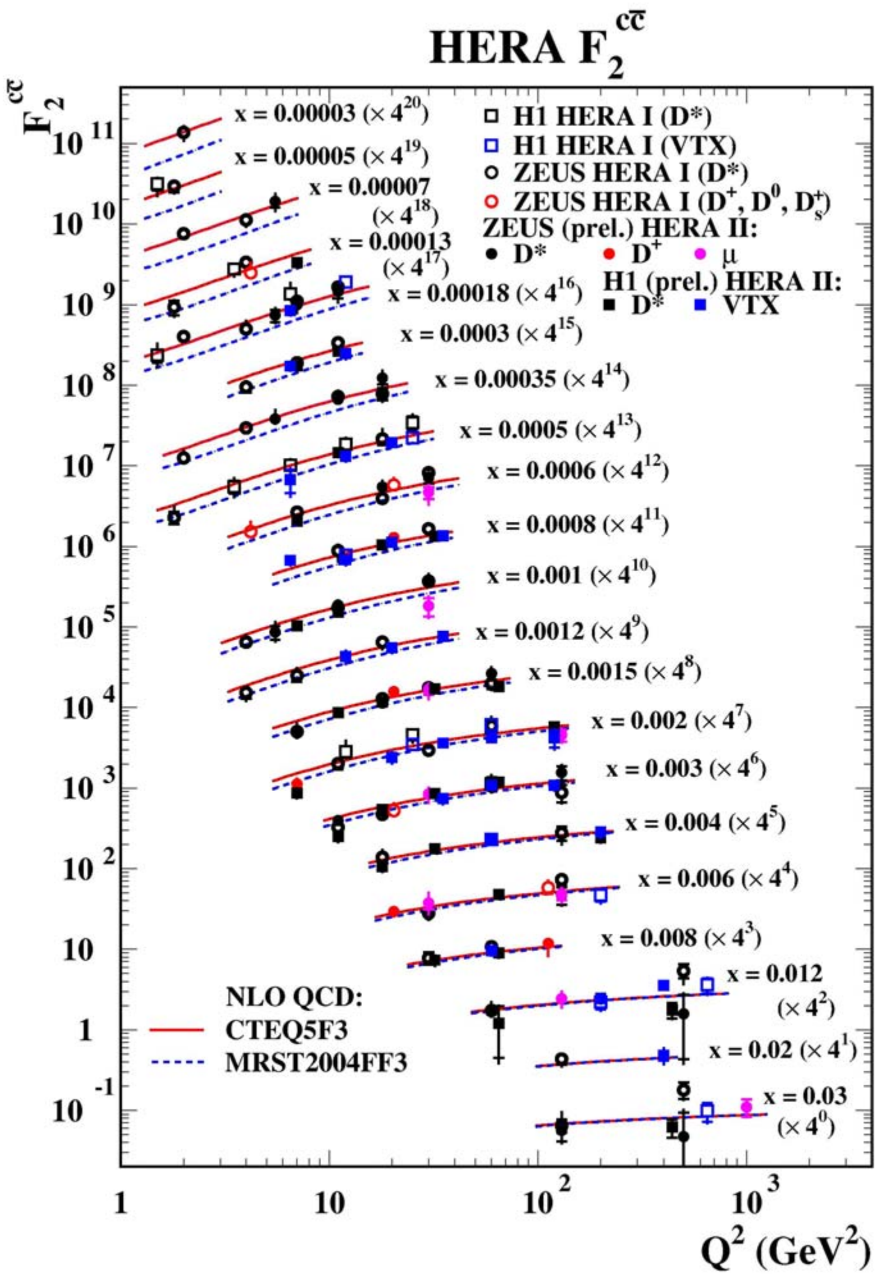


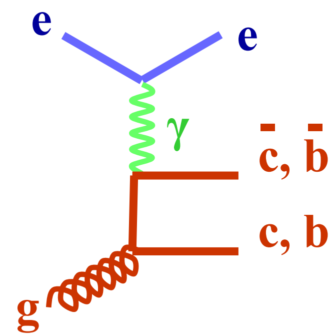


PROTON DYNAMICS: F_L compatible with NLO DGLAP predictions

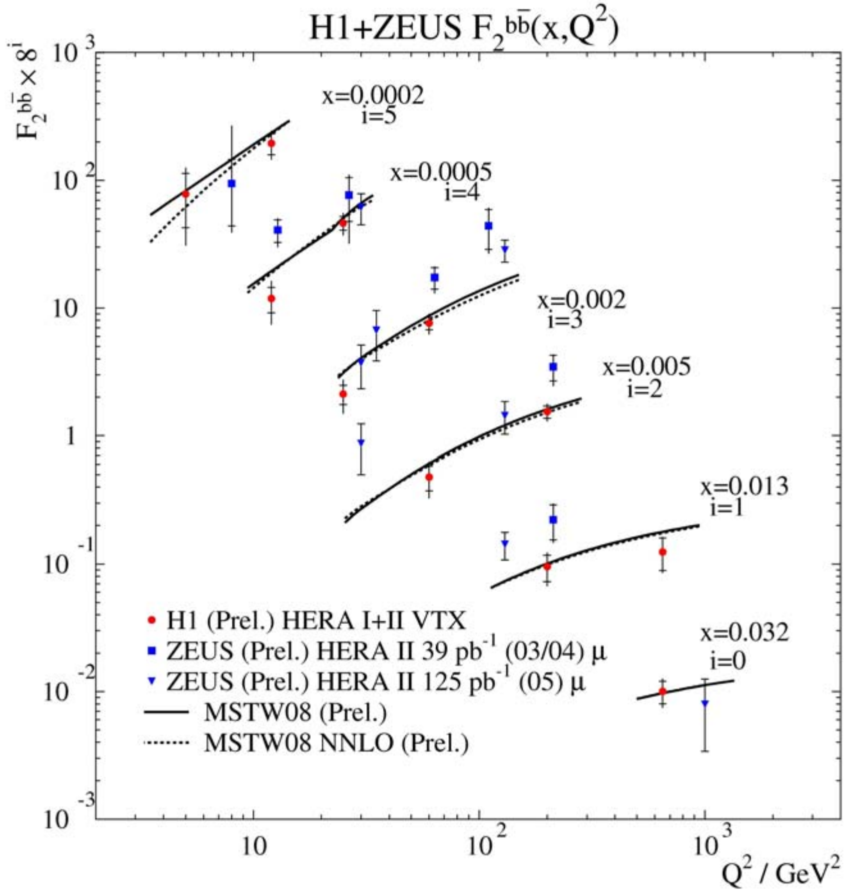


PROTON DYNAMICS: Heavy Quark generation well described by DGLAP





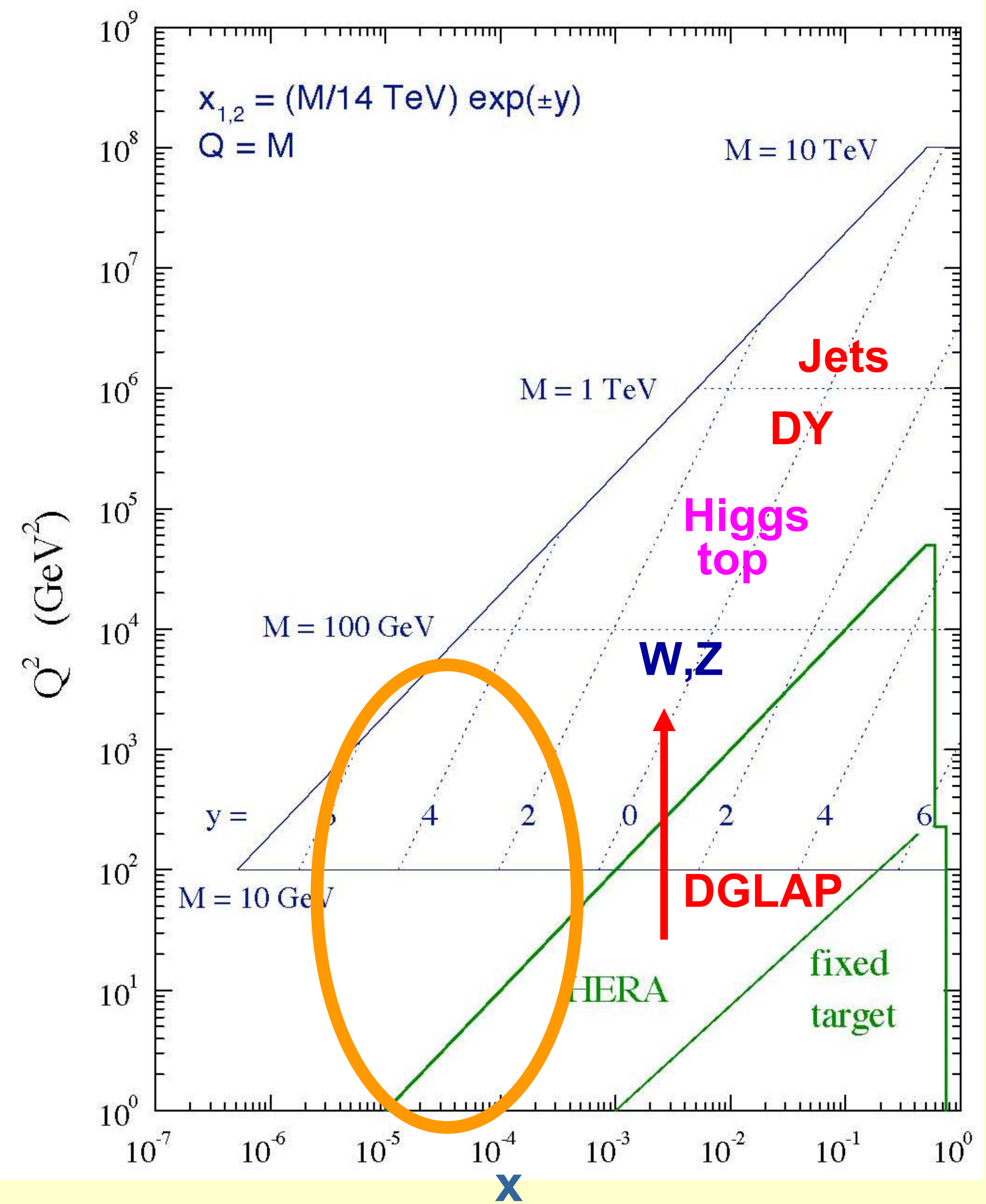
Heavy flavors tagged through $D^{(*)}$, decay muons or displaced vertices



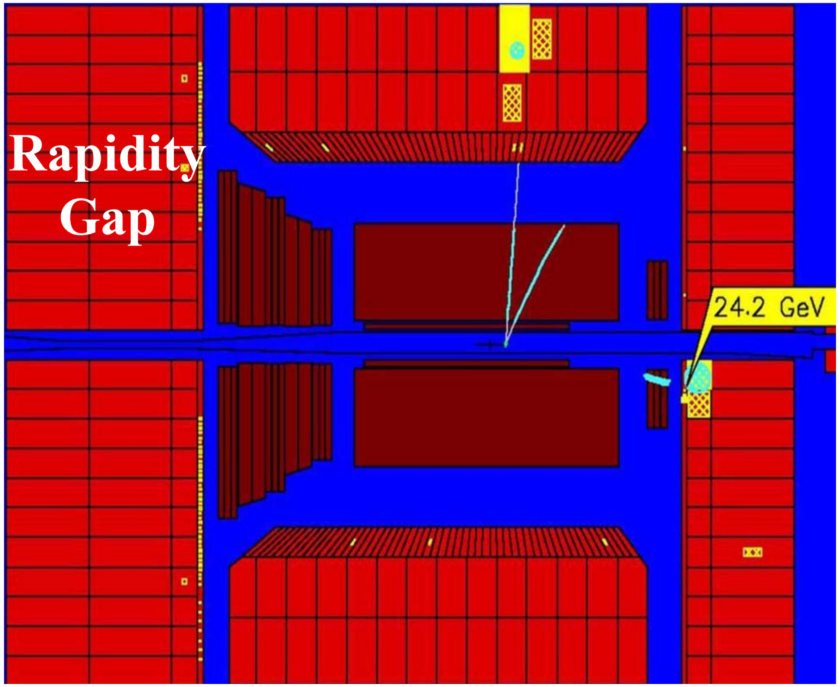
PRECISION MEASUREMENTS

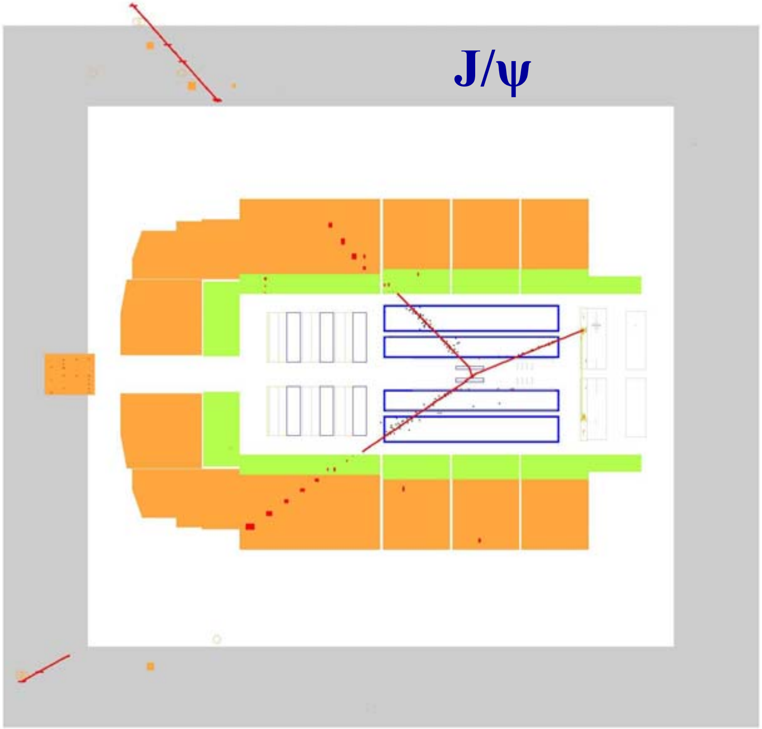
Closer insights from diffraction in proton dynamics

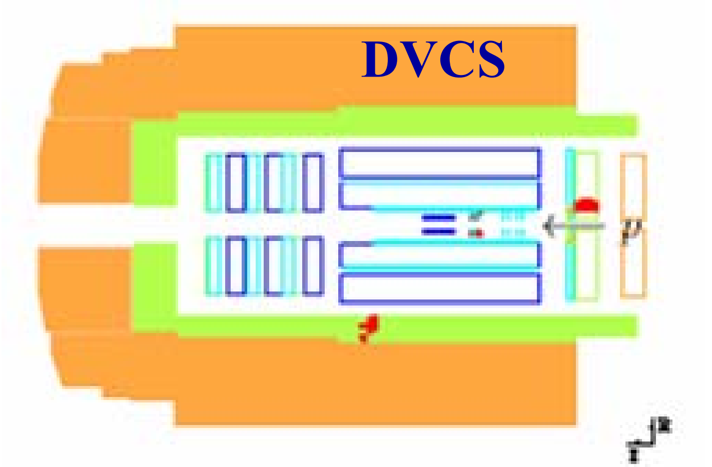
New effects at very low x ?



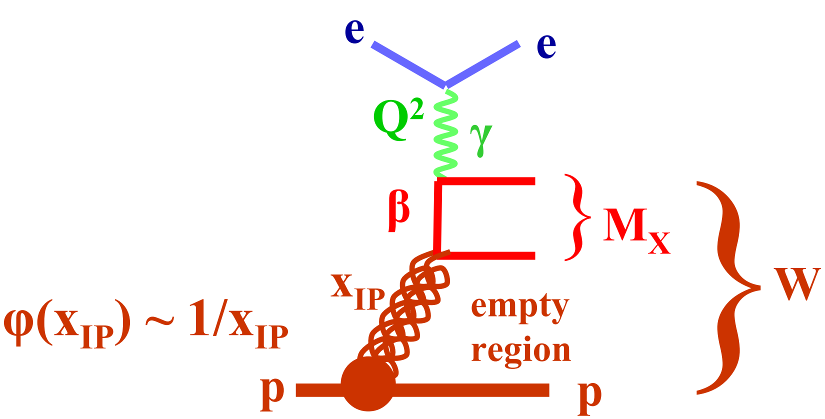
Typical diffractive interactions







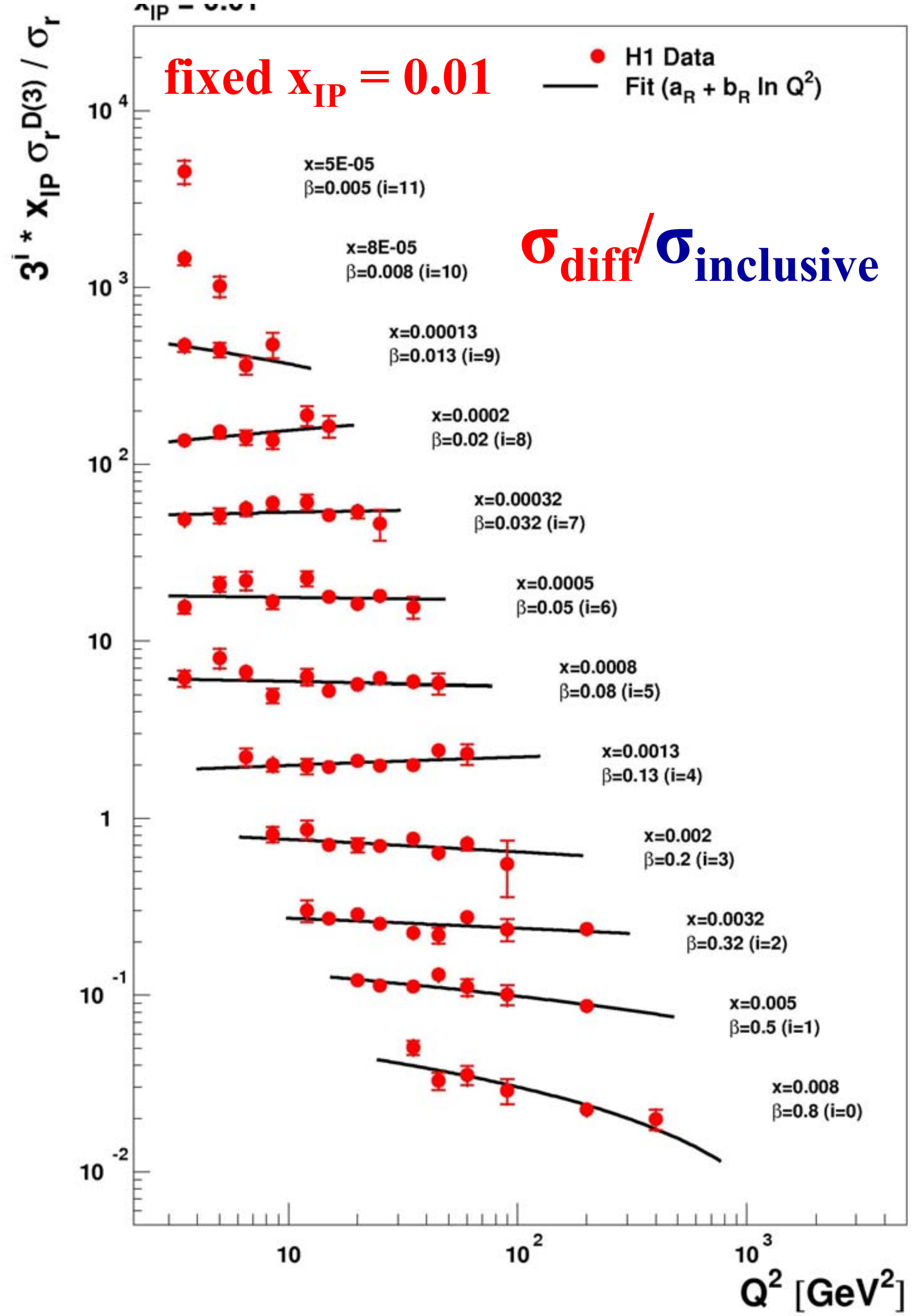
INCLUSIVE DIFFRACTION



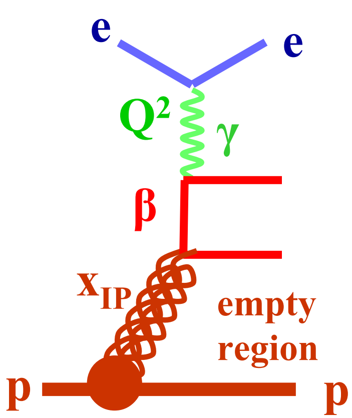
~10% of events are diffractive, logarithmic variation with Q^2

↓

diffraction is a leading-twist intrinsic part of the proton structure

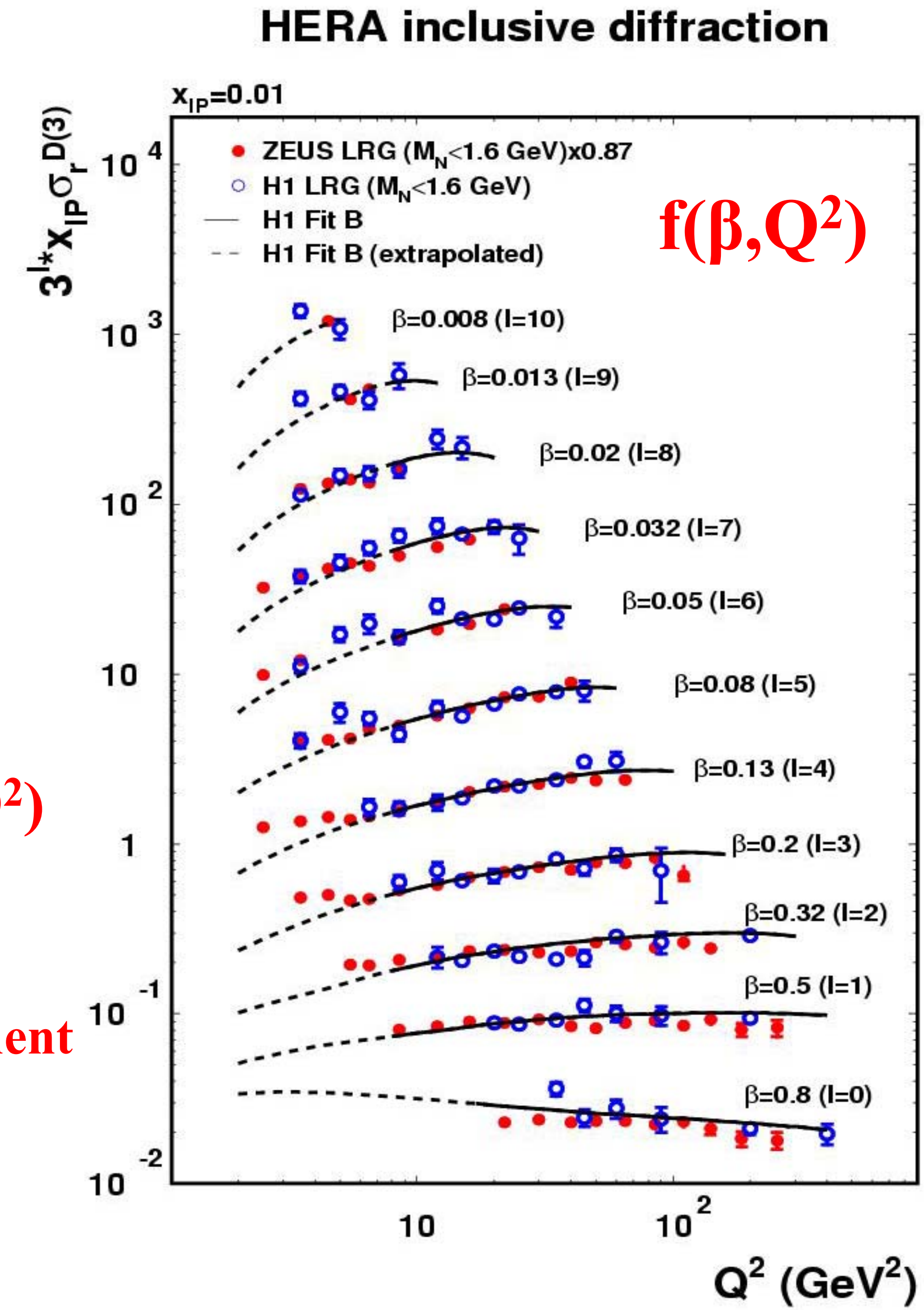


Perturbative structure of inclusive diffraction



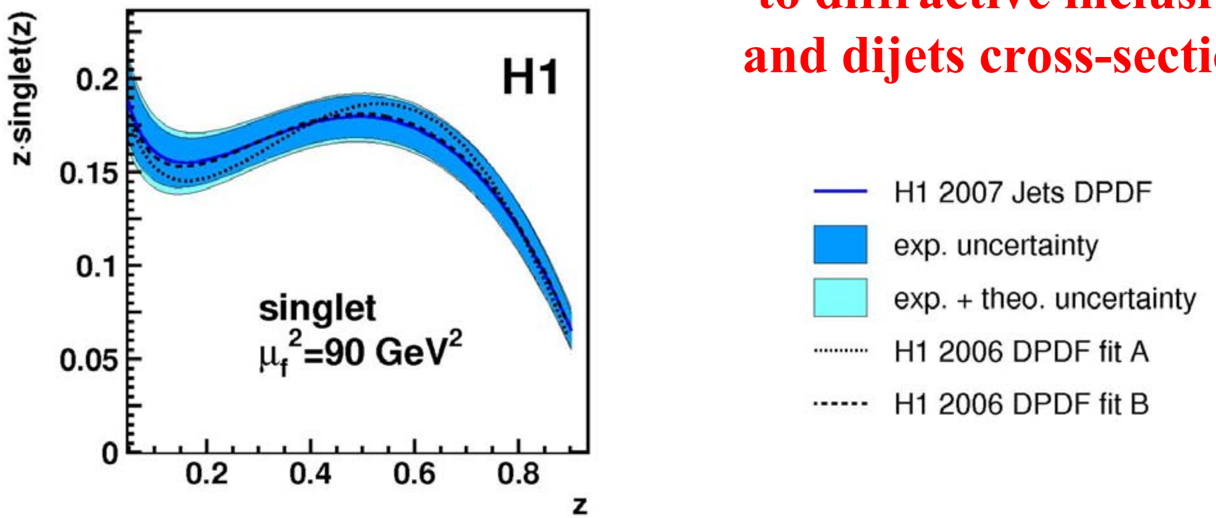
$$F_2^{D3}(x_{IP},\beta,Q^2) \sim \varphi(x_{IP}) \,.\, f(\beta,Q^2)$$

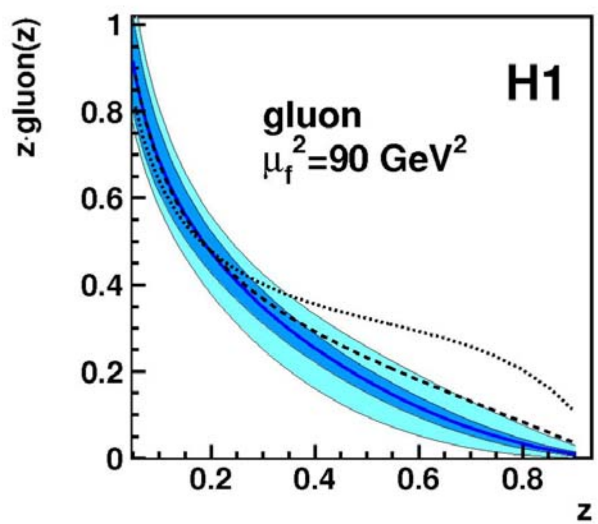
Strong positive scaling violations indicate a dominant gluonic component of the colorless exchange

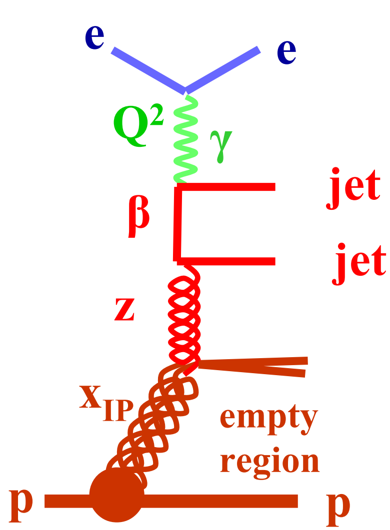


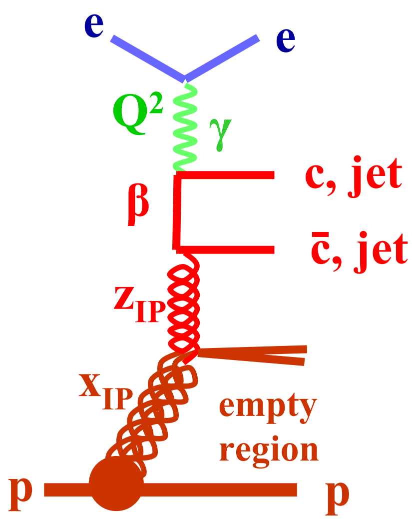
Diffractive PDF's

extracted from a common fit to diffractive inclusive and dijets cross-sections



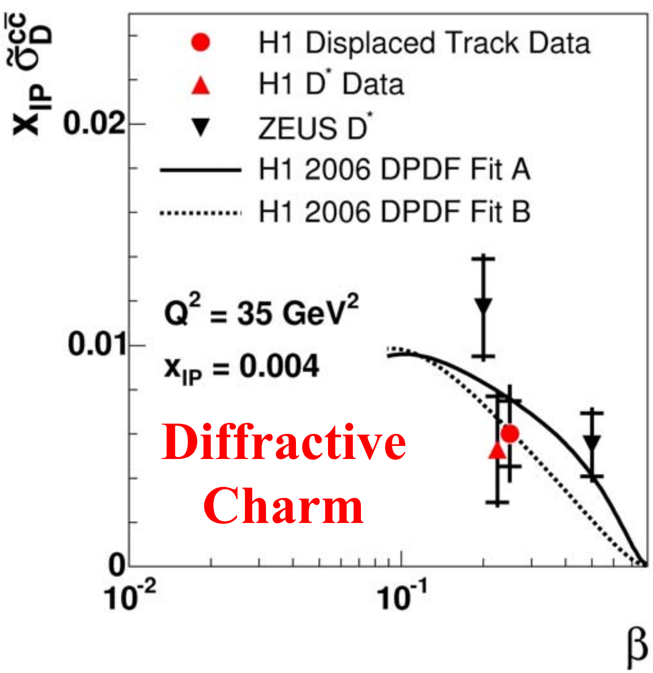


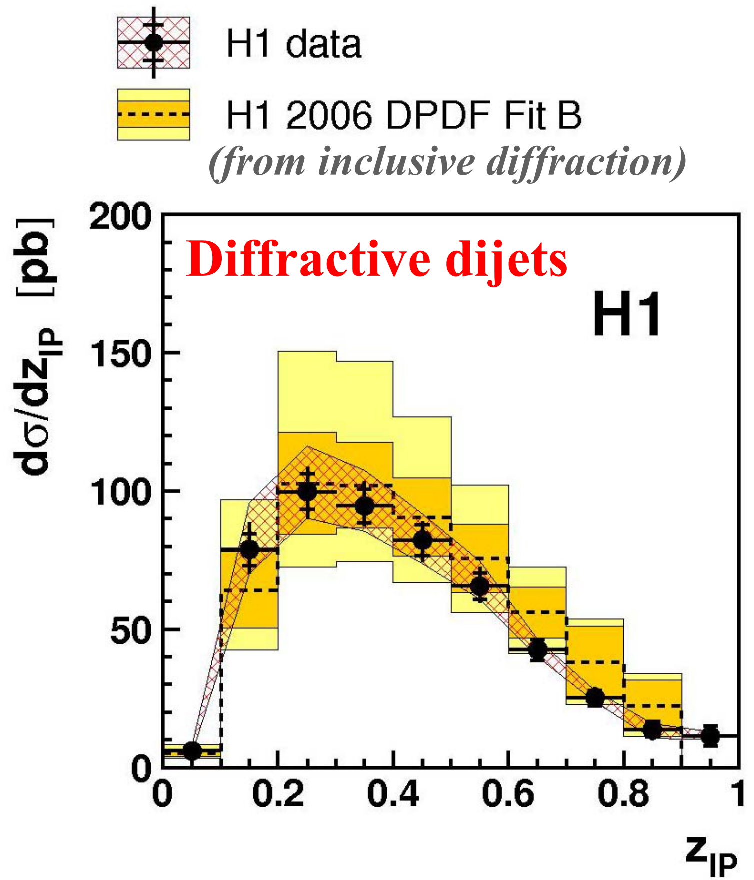




Factorisation of diffractive PDF's

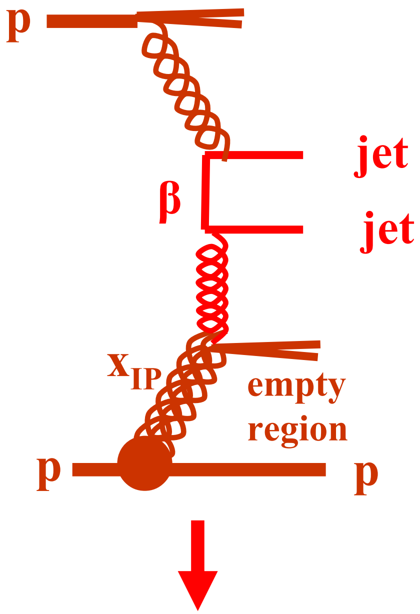
holds in DIS for charm and jets as predicted

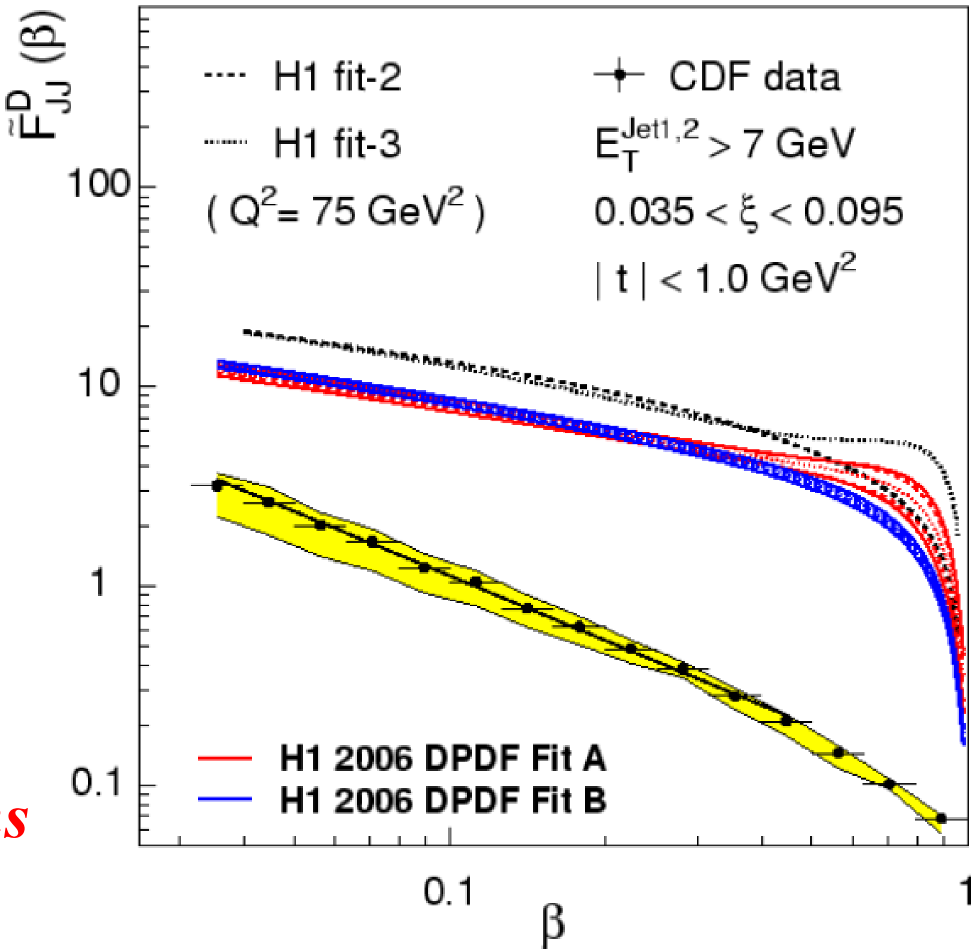




Factorisation of diffractive PDF's

broken by a factor ~7 for diffractive dijets at Tevatron



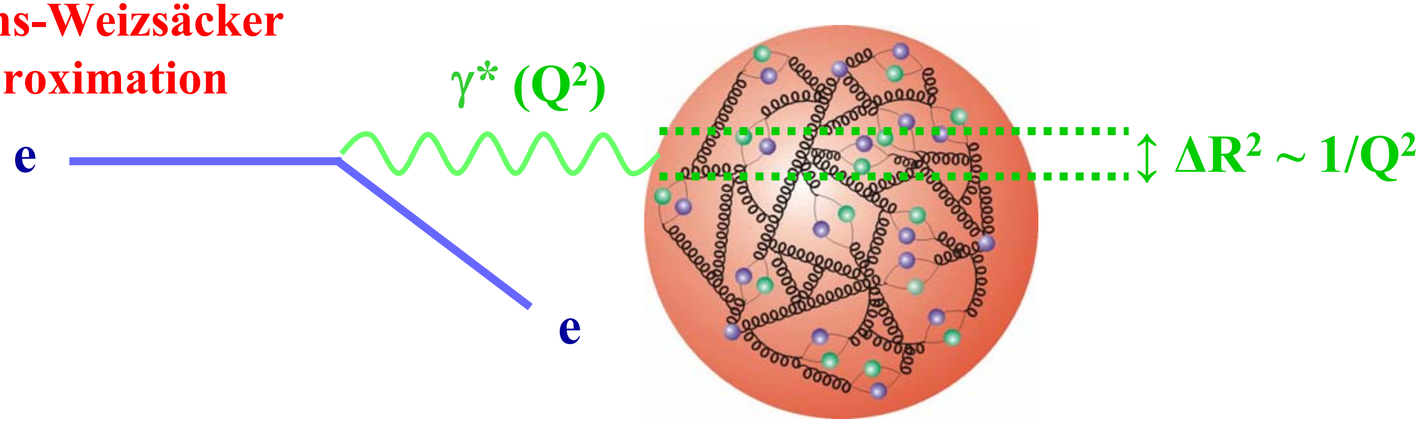


More studies on rapidity gap survival needed for LHC predictions

DIFFRACTION and LOW-X DYNAMICS

(experts please shut your eyes !)

Williams-Weizsäcker Approximation

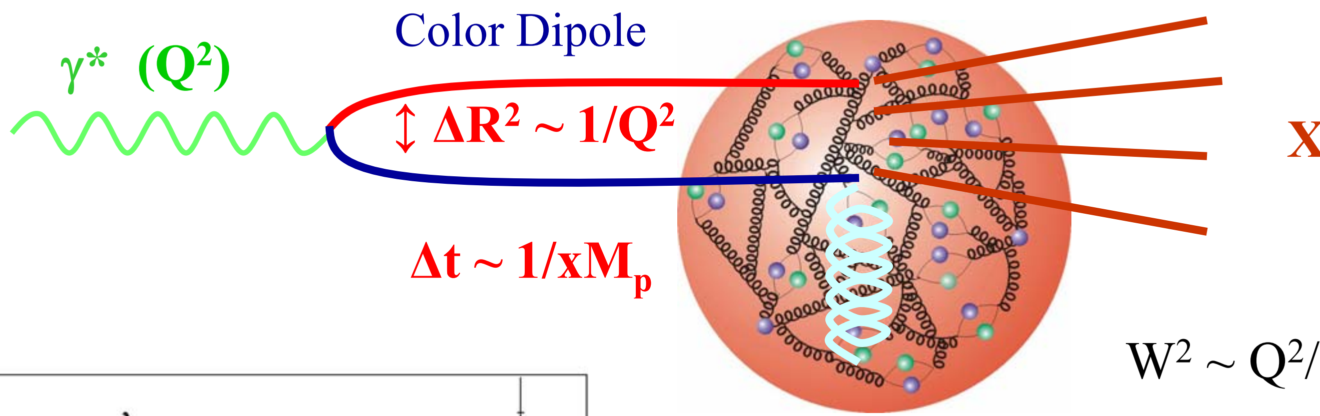


$d\sigma_{ep}/dydQ^2 \quad \sim \quad \Phi_{\gamma^*}(y,Q^2) \quad x \quad \sigma_{\gamma^* p}(W^2,Q^2)$ $\qquad W^2 \equiv E^2_{cms}(\gamma^* p) \sim Q^2(1-x)/x$

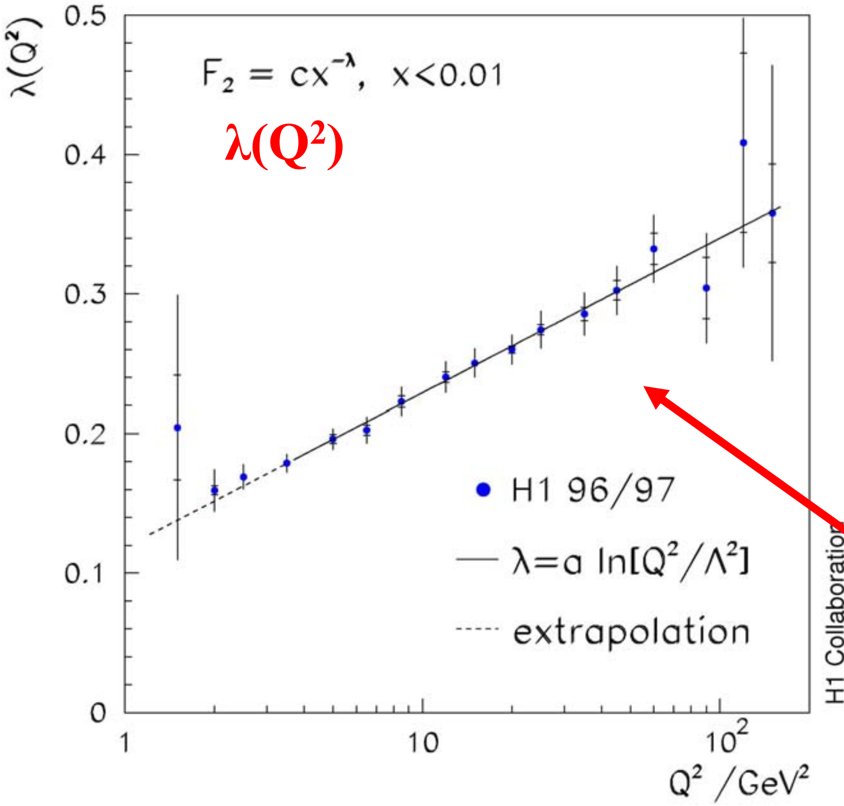
$\alpha/Q^2\ [1+(1-y)^2]/y \quad x \quad \alpha/Q^2\ xq(x)$ $\qquad$ scale invariance at high x

WWA allows to relate diffraction, photoproduction and deep inelastic scattering at low x in a unified frame.

Low-x limit: inclusive cross-section



$W^2 \sim Q^2/x$



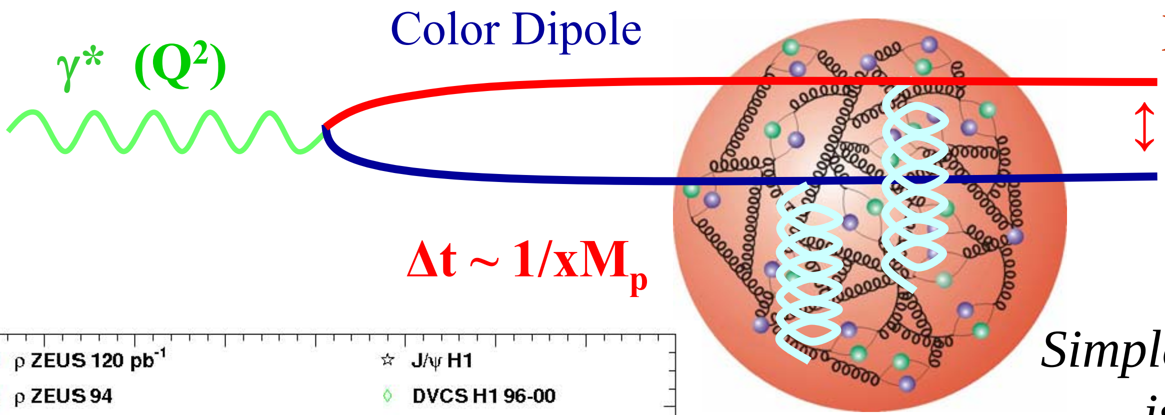
$$\sigma^{inc}_{\gamma^* p}(W^2,Q^2) \sim \alpha_s/Q^2 \; xg(x,Q^2)$$

$$\sim \alpha_s/Q^2 \quad x^{-\lambda(Q2)}$$

$$\sim \alpha_s/Q^2 \quad W^{2\lambda(Q2)}$$

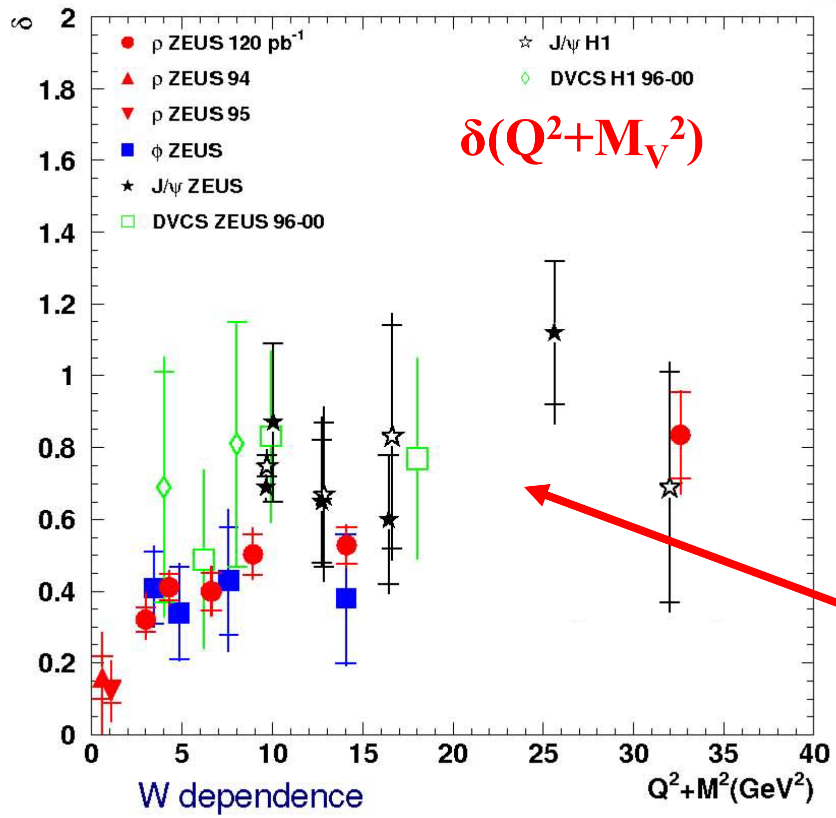
Rise of λ with Q² reflects increased low x gluon DGLAP radiation at high Q²

Low-x limit: diffractive cross-sections



$W^2 \sim Q^2/x$

Simplest colorless exchange is from two gluons



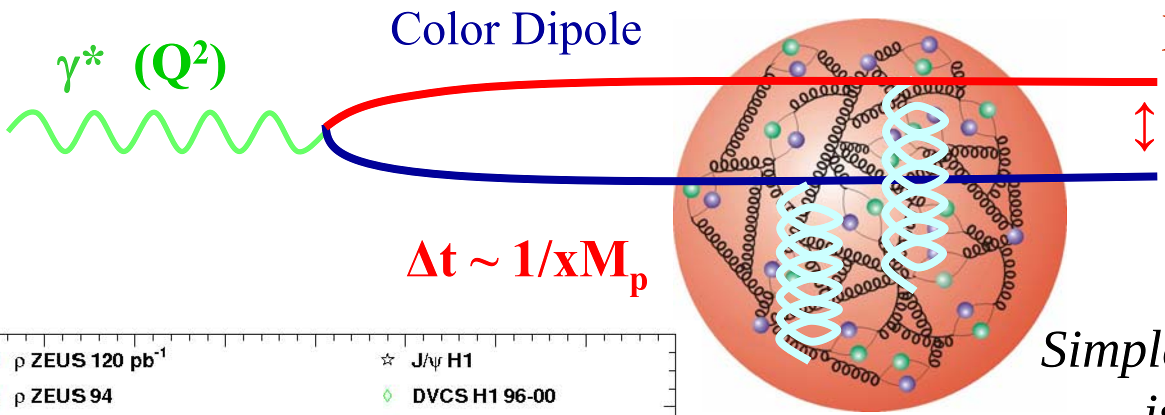
$$\sigma^{diff}_{\gamma^*p}(W^2,Q^2) \sim \alpha_s^2/Q^2\ [xg(x,Q^2+M_V^2)]^2$$

$$\sim \alpha_s^2/Q^2 \quad x^{-2\lambda\,(Q^2+M_V^2)}$$

$$\sim \alpha_s^2/Q^2 \quad W^{\delta(Q^2+M_V^2)}$$

Rise of δ with $(Q^2+M_V^2)$ reflects entering the hard diffraction regime with direct sensitivity to the gluon.

Low-x limit: diffractive cross-sections

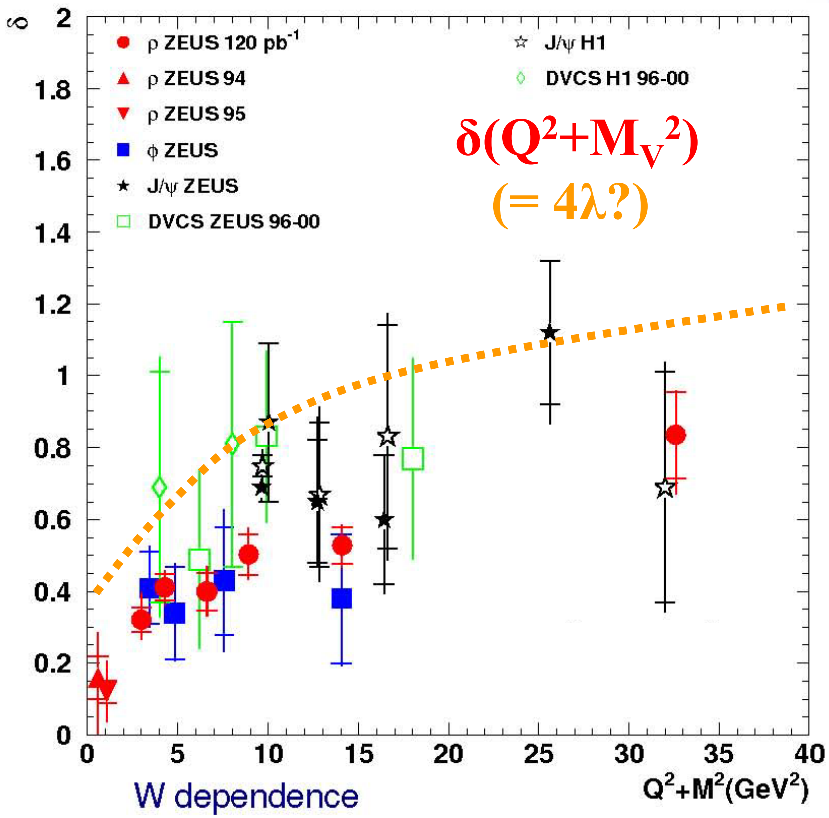


X, ρ, φ, J/ψ, Y, γ

↕ $\Delta R^2 \sim 1/(Q^2+M_V^2)$

$W^2 \sim Q^2/x$

Simplest colorless exchange is from two gluons



$$\sigma^{diff}_{\gamma^*p}(W^2,Q^2) \sim \alpha_s^2/Q^2\ [xg(x,Q^2+M_V^2)]^2$$

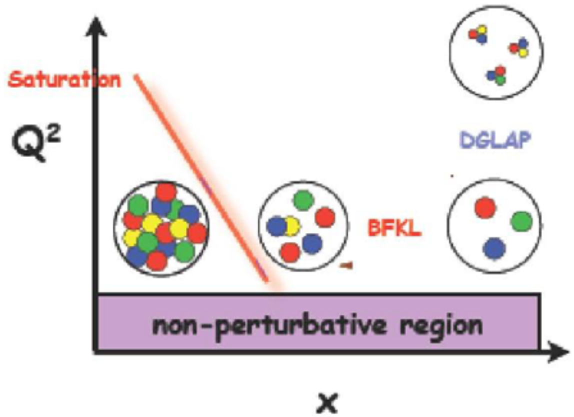
$$\sim \alpha_s^2/Q^2 \quad x^{-2\lambda\,(Q^2+M_V^2)}$$

$$\sim \alpha_s^2/Q^2 \quad W^{\delta(Q^2+M_V^2)}$$

Rise of δ with $(Q^2+M_V^2)$ reflects entering the hard diffraction regime with direct sensitivity to the gluon.

δ ~≤ 4 λ hints to saturation

Low x limit: is saturation observed ?



$\sigma_{\gamma^*p}(W^2,Q^2) \sim \alpha_s/Q^2\ xg(x)$

diverges at low x

↓

$R_p^2[1 - e^{-(\alpha_s/Q^2 R_p^2\ xg(x))}]$

saturates to the proton surface R_p^2

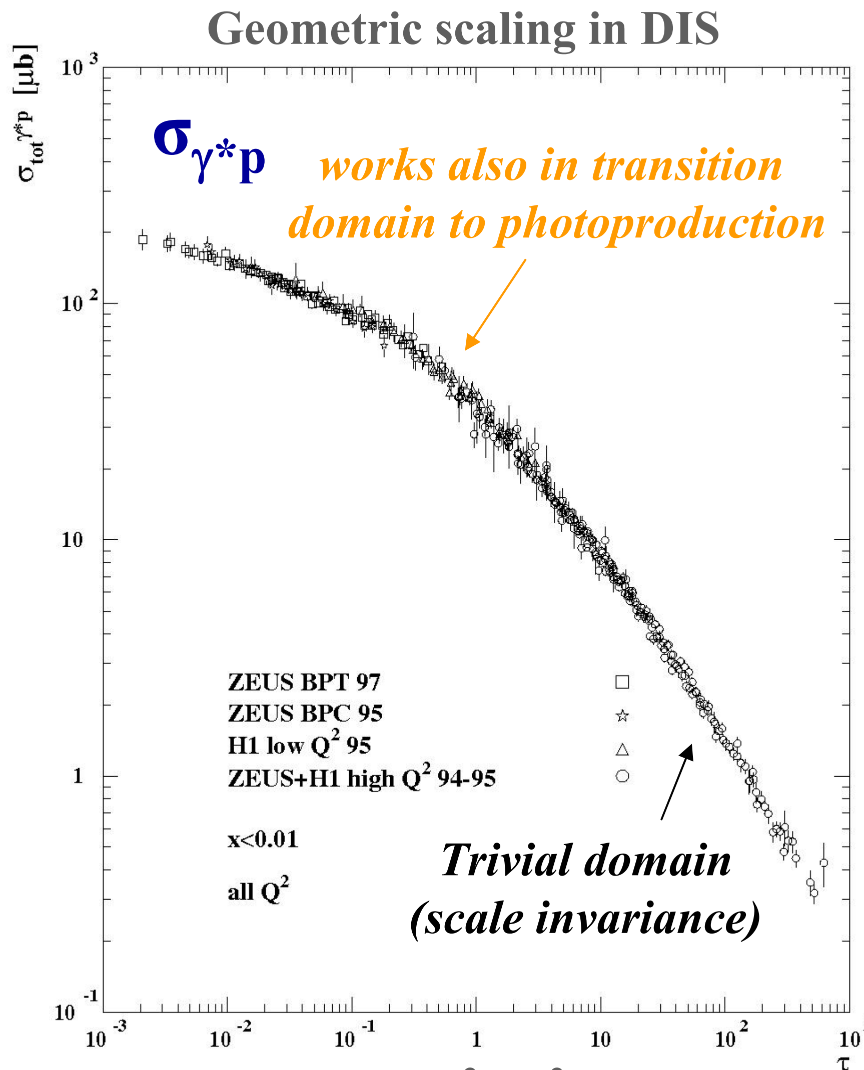
↓

Geometric scaling predicted:

$\sigma(x,Q^2) \rightarrow \sigma(\tau \equiv Q^2/Q_s^2(x))$

Universal saturation scale $Q_s^2(x) \sim \alpha_s/R_p^2\ xg(x)$

Geometric scaling in DIS



$\tau \equiv Q^2/Q_s^2(x)$

Paving the way towards optimal LHC PDF's

New insights in
low-x dynamics from hard diffraction

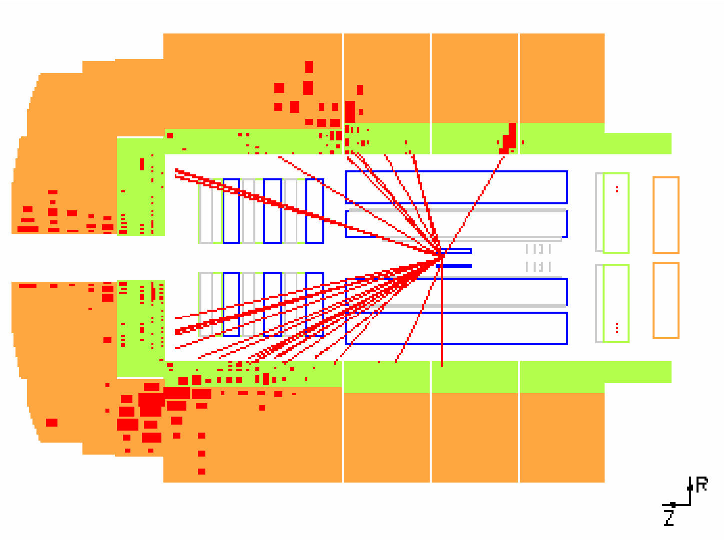
DGLAP OK in the bulk phase space

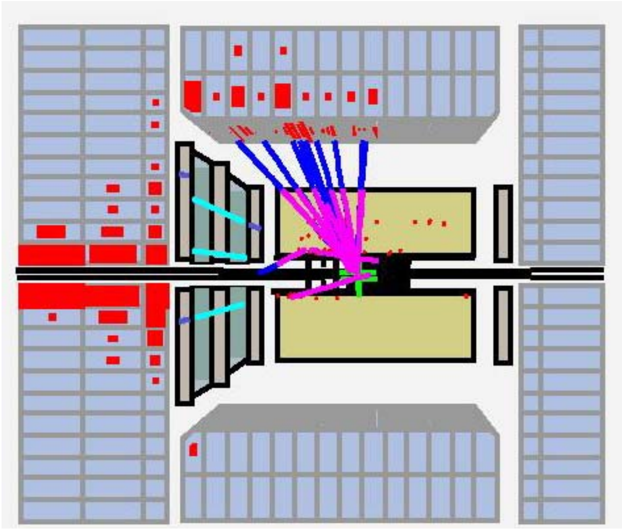
Recent breakthrough in precision at low x
from H1-ZEUS combinations

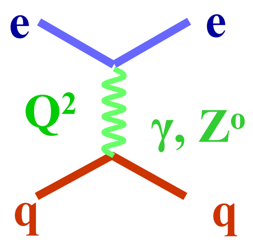
More to come at high x
with full HERA II data

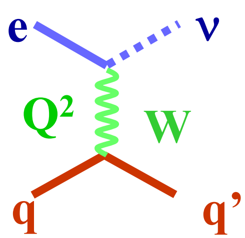
PRECISION MEASUREMENTS

More results



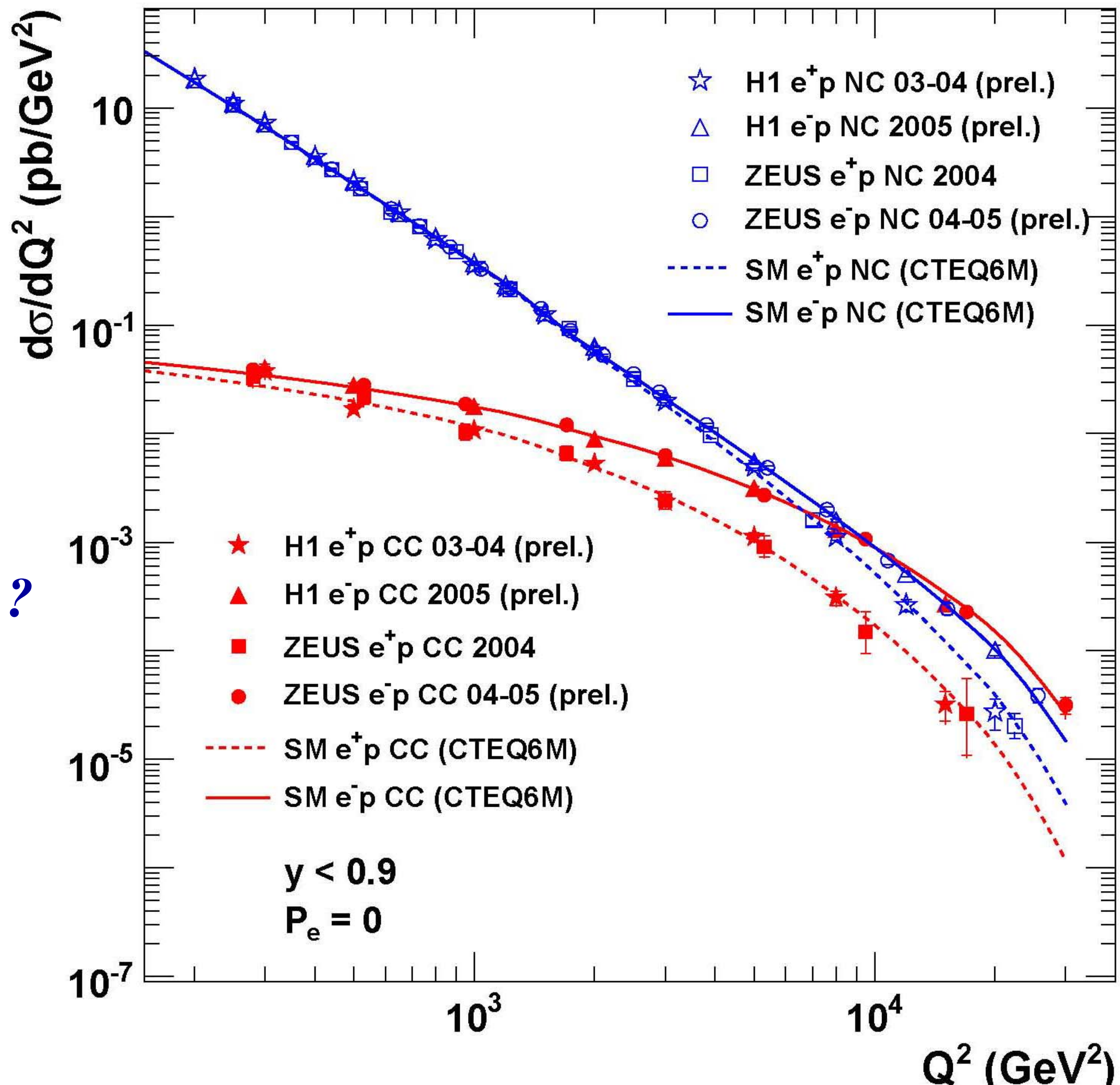




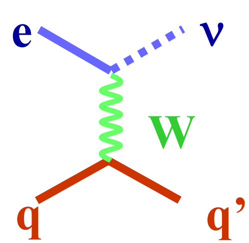


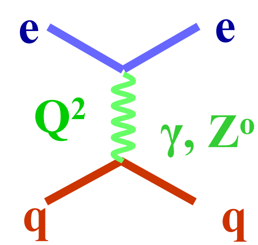
Does the e-probe behave as expected ?

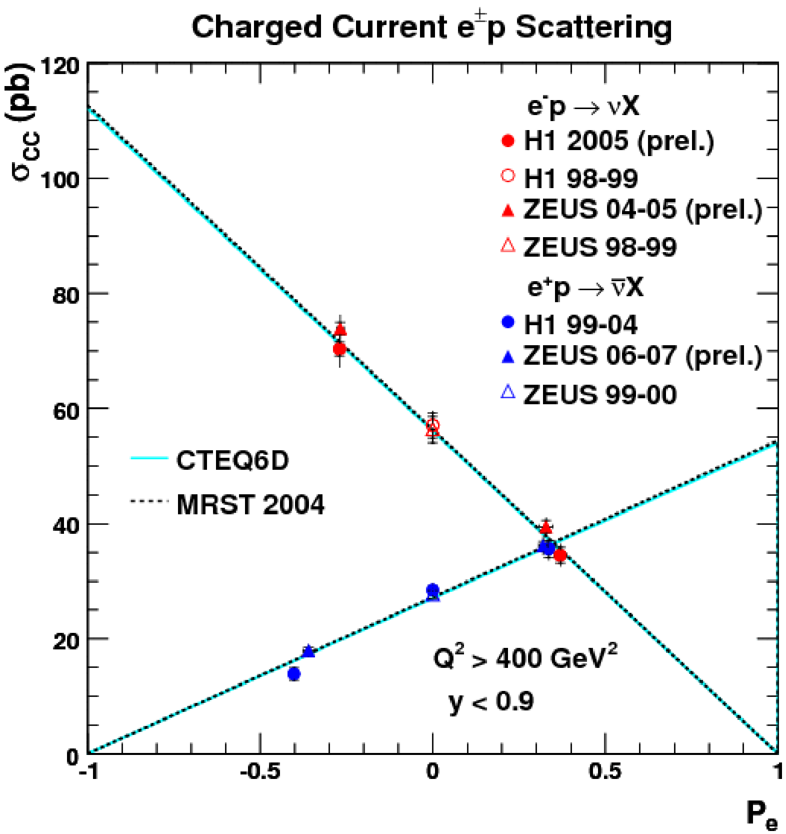
YES!
EW unification in the t-channel at the $M_{W,Z}$ scale



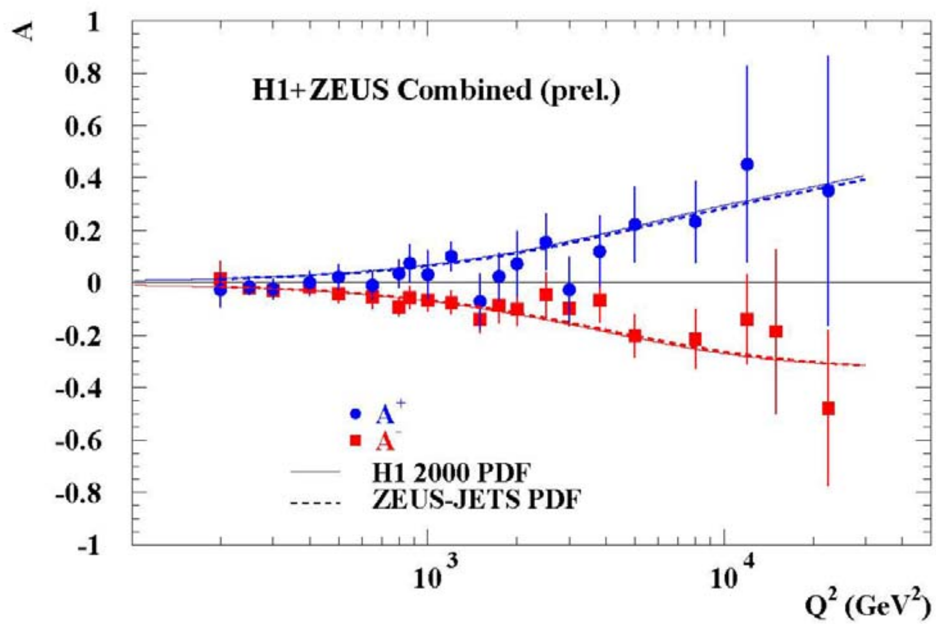
ELECTROWEAK POLARISATION ASYMMETRIES



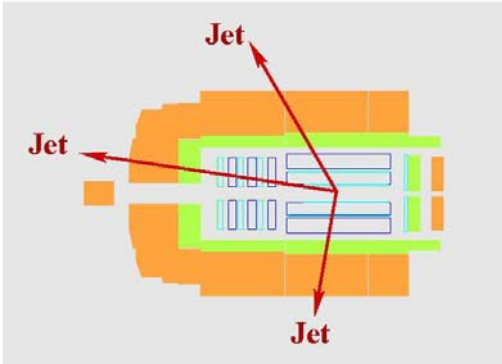


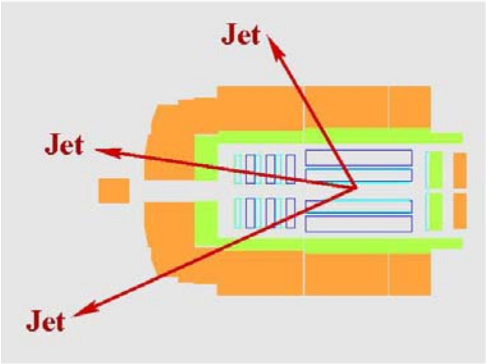


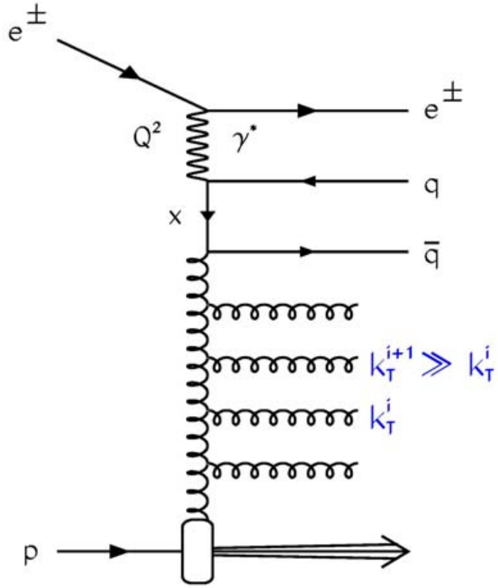
$$A^{\pm} = \frac{2}{P_R - P_L}\frac{\sigma^{\pm}(P_R)-\sigma^{\pm}(P_L)}{\sigma^{\pm}(P_R)+\sigma^{\pm}(P_L)}$$

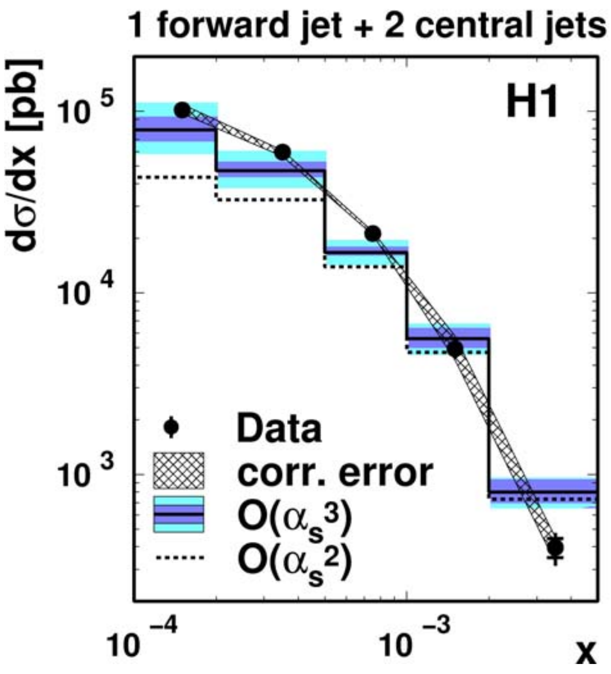


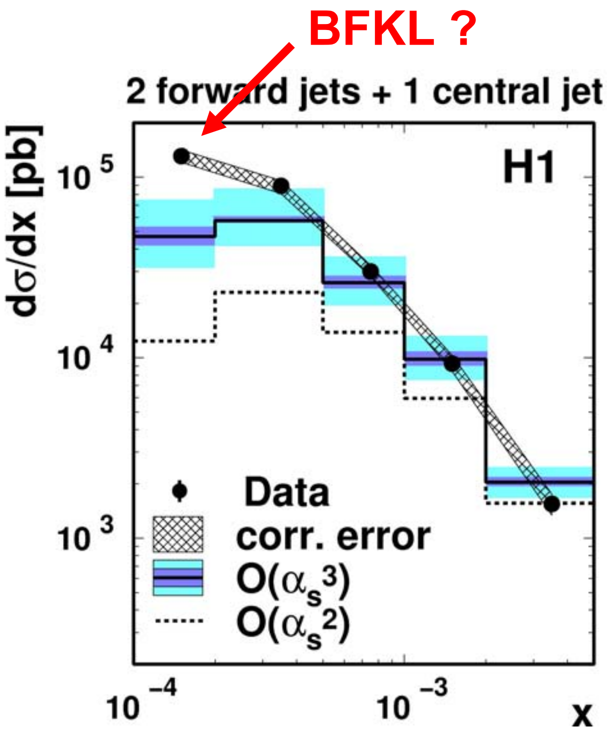
QCD Dynamics:
probing DGLAP with multijets at low x



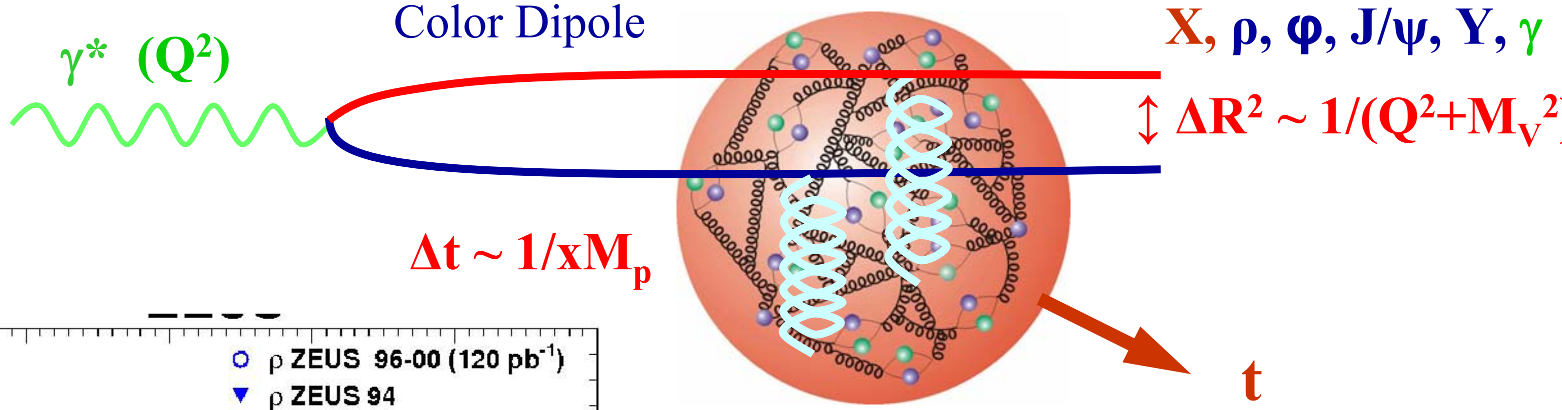




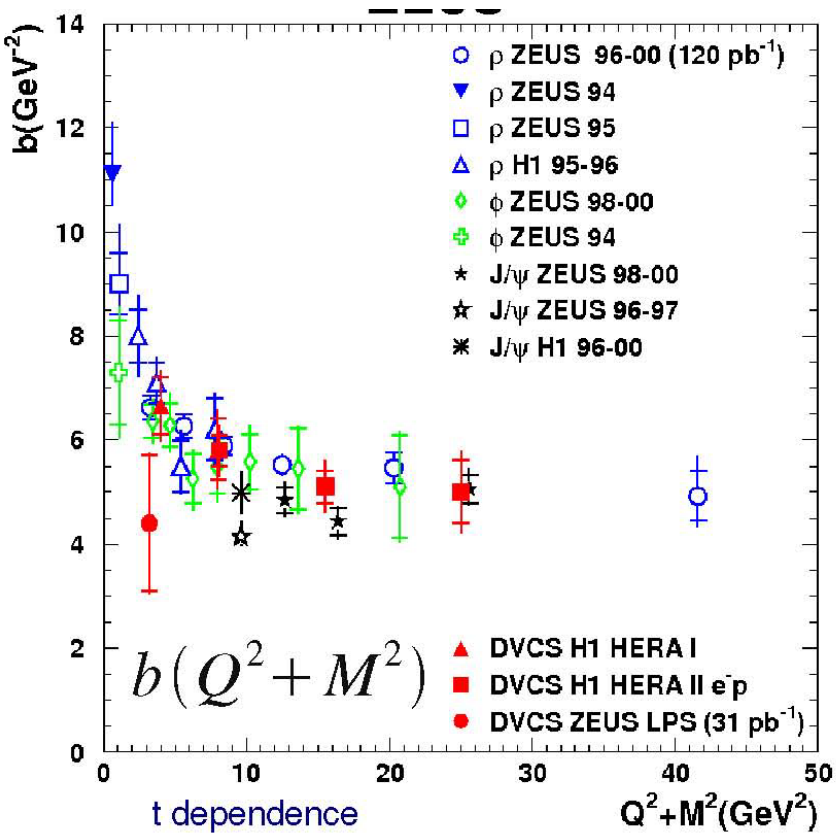




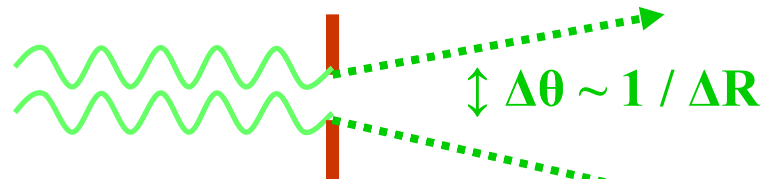
Diffractive processes: impact parameter



$d\sigma/dt \sim e^{bt}$

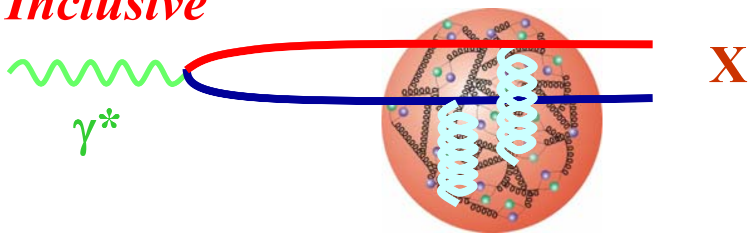


In the hard regime interaction size saturates down to the proton size



Perturbative QCD description of hard diffraction

Inclusive



DVCS