QCD Diffraction and Diffractive Dijets at HERA

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Louvain, 18/10/2007

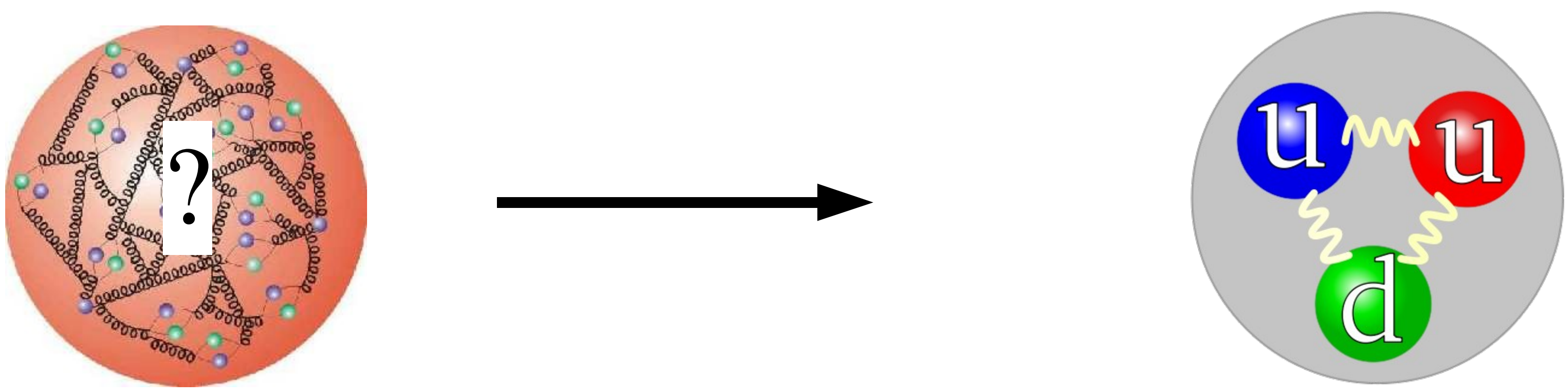
Outline

- QCD and DIS
- The ep collider HERA and the ZEUS detector
- Diffraction at HERA:
  - General features
  - Experimental techniques
  - QCD factorisation for diffraction
- Dijets in diffractive DIS:
  - Motivations
  - Analysis
  - Results
- Conclusions

QCD and the proton

SU(3) gauge symmetry. Massless vector bosons mediate the interaction (**gluons**).
Couple according to the color charge (RGB) (leptons are color singlets).
Asymptotic freedom: at high energies (short distances) intensity of the interaction vanishes.
This allows for sufficiently large scales to use perturbative calculation (pQCD).
Confinement: no colored particles free in nature. Quarks organize in colorless hadrons.

Proton: composite object (quarks+gluons)



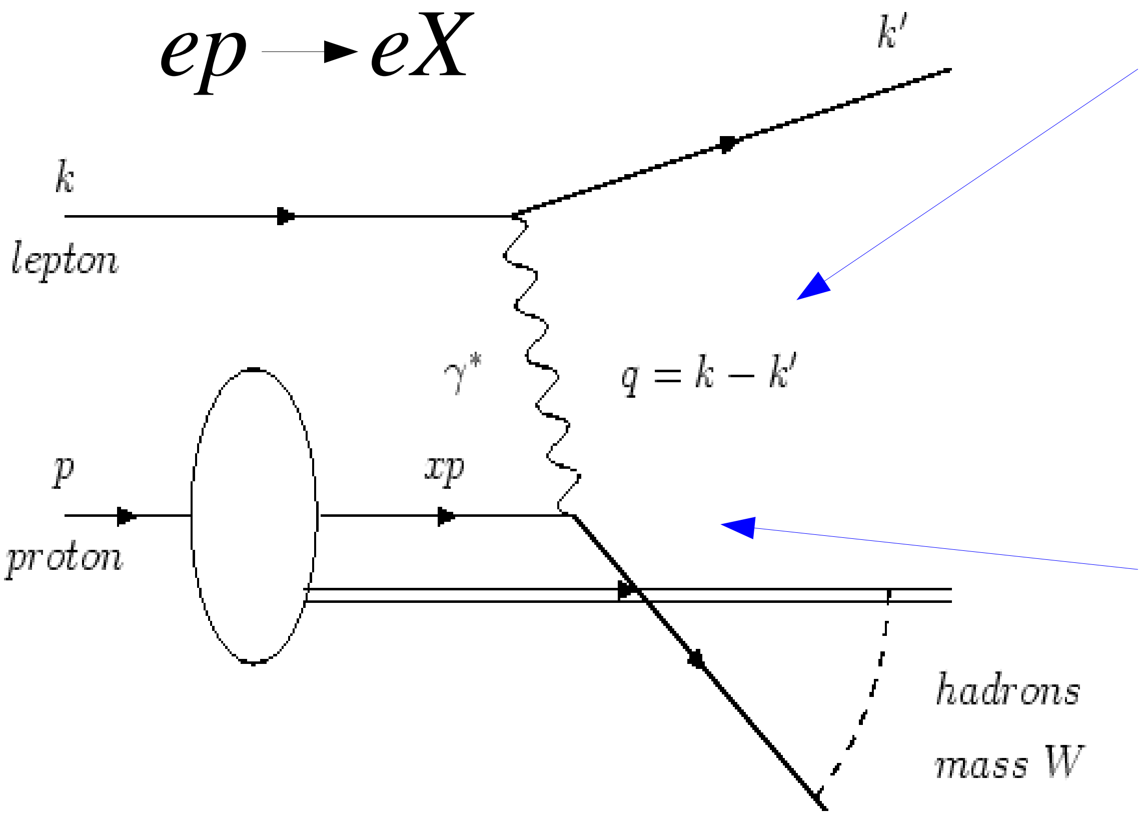
Three **valence quarks** (uud) + → p quantum numbers

gluons +

sea quarks → $q\bar{q}$ pairs, generated by strong int. backgr.

Deep Inelastic Scattering

ep-colliding experiments since '60s.



Virtual γ* emitted by lepton probes internal structure of p.

Virtuality of γ* : $Q^2 = -q^2$

"Size" of the probe ~ 1/Q

Assumption: partons don't interact one with each other in a fast moving p.

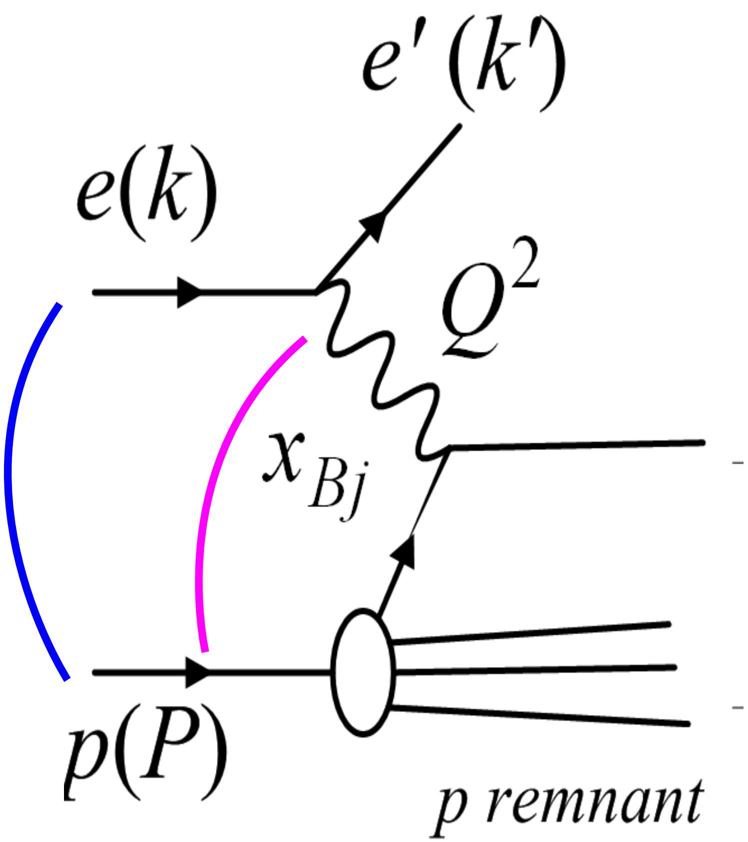
γ* interacts with a parton with *xp* momentum.

Q^2 and *x* measured from reconstructed final system.

Extracting informations about internal structure of p

(how the different kind of partons contribute to the final p)

DIS kinematics



Lorentz invariants (only 2 independent)

$s = (p+k)^2$ c.m. energy ep

$Q^2 \simeq 4 E_e E_{e'} \sin^2(\theta/2)$ **>> 0** (>1GeV²)

$W^2 = (p+q)^2$ c.m. energy γp

$$x = \frac{Q^2}{2pq} \simeq \frac{Q^2}{(Q^2+W^2)}$$

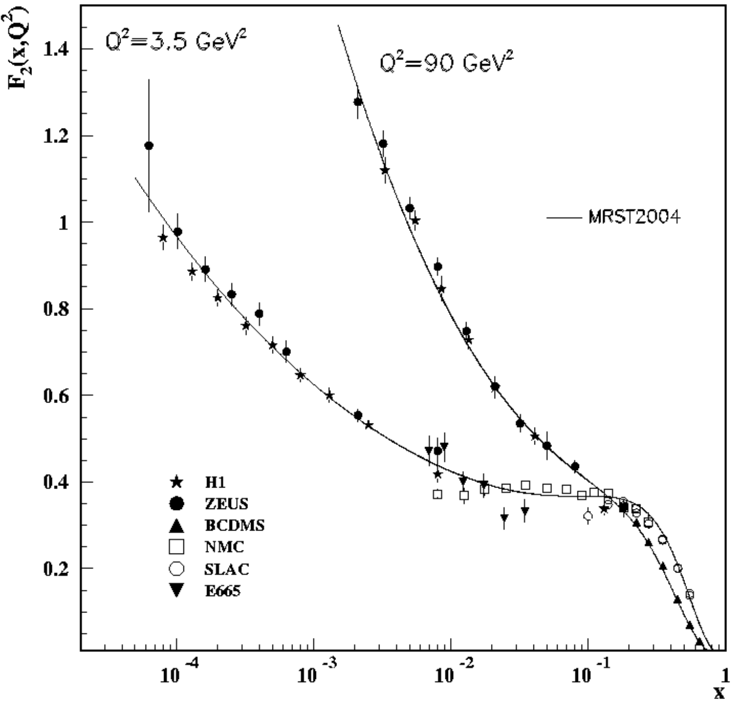
$$y = \frac{pq}{pk}$$ inelasticity

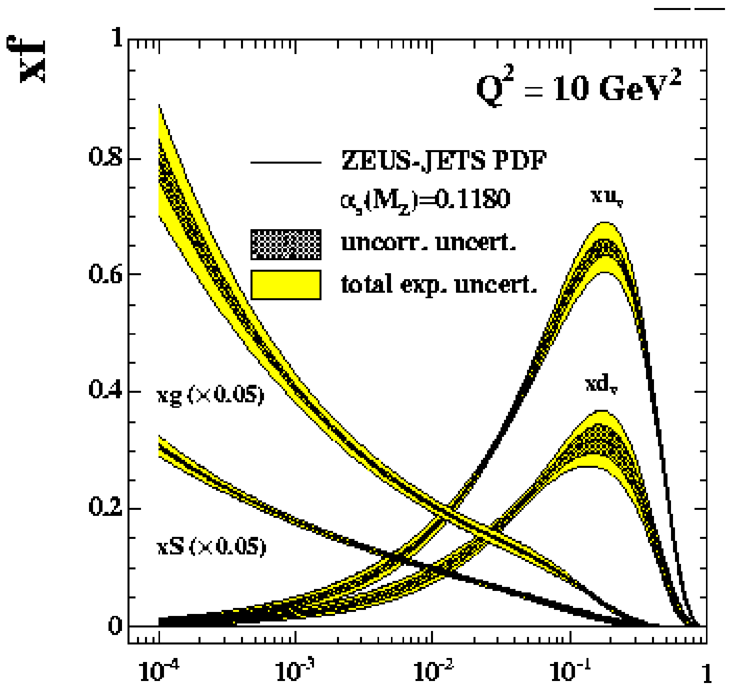
$$sxy = Q^2$$

$$\frac{d\sigma}{dQ^2\,dx} = \frac{2\pi\alpha}{xQ^4}[y_+ F_2(x,Q^2) + y^2 F_L(x,Q^2)] \qquad y_+ = [1+(1-y)^2]$$

Structure Functions: info on distribution of partons in p

DGLAP and PDF





QPM: only 3 valence quarks.
At high Q^2, $F_2(x,Q^2)$ -> $F_2(x)$ (scale invariance).

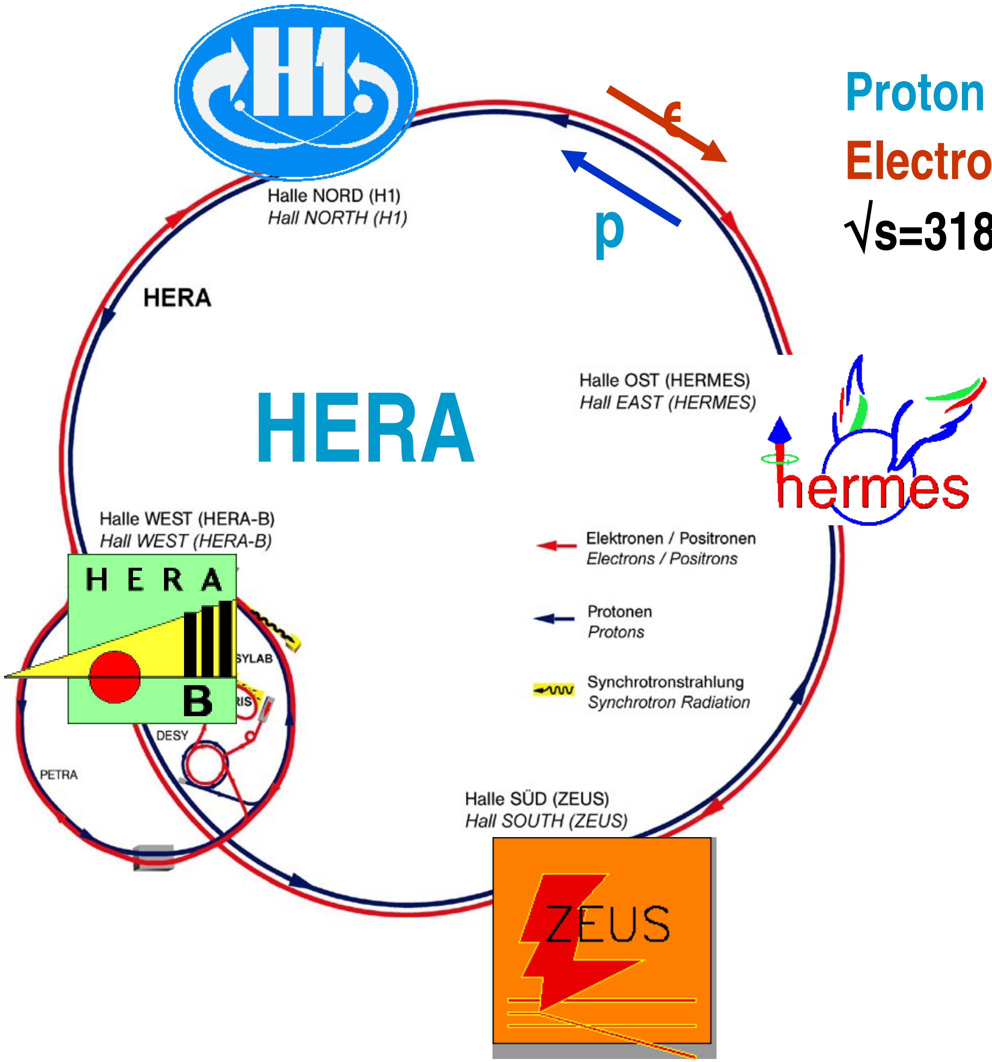
This is not the case! Gluons in the p violate this scaling. Rise of F2 at low x -> presence of gluons

DGLAP equations take in account gluon-quark splitting evolving F2 as a function of Q^2.

PDF: $q_f(x)$ prob to find parton type f with momentum xp

$$F_2(x,Q^2)=\sum_f e_f^2 x q_f(x,Q^2)$$

HERA



Proton energy = 920 GeV
Electron energy = 27.5 GeV
$\sqrt{s}$=318 GeV

5 T superconducting dipoles for p
Room temp dipoles for e

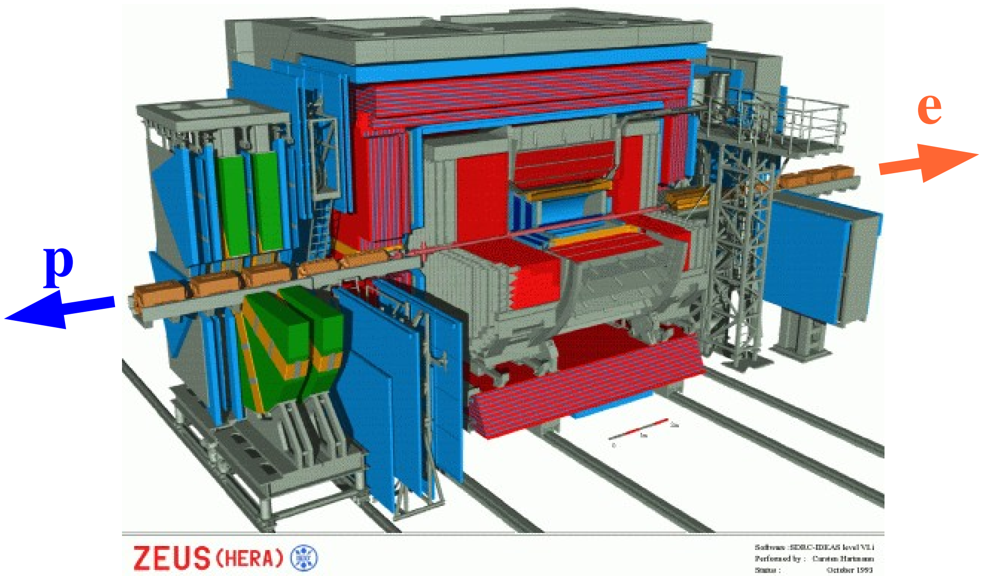
HERA I (1992 - 2000)

- Inst Luminosity: 1.8 x 10^{31} $cm^{-2}s^{-1}$
- Different p energies (820, 920 GeV)

HERA II (2003 – 2007)

- Inst Luminosity: 7.0 x 10^{31} $cm^{-2}s^{-1}$
- Polarised e-beams (~40%)
- Different p energies (920, 575, 460 GeV)

ZEUS detector



Asymmetric multi-purpose detector

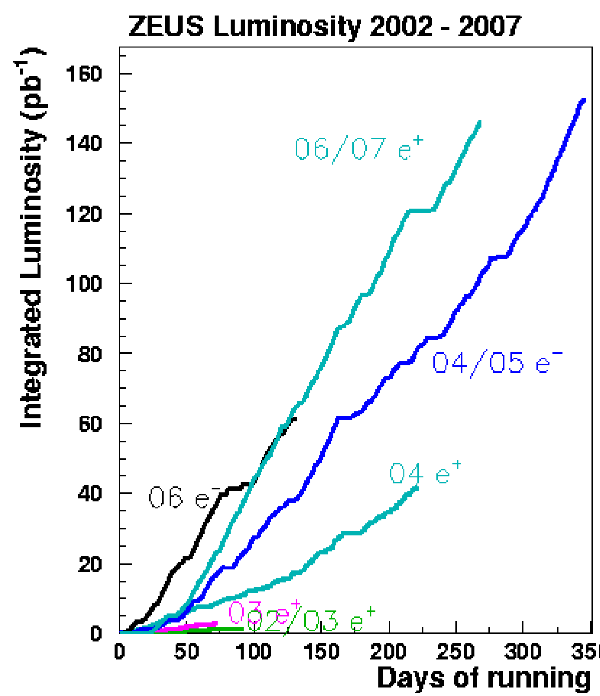
12x10x19 m, 3500 tons

1.43 T magnetic field

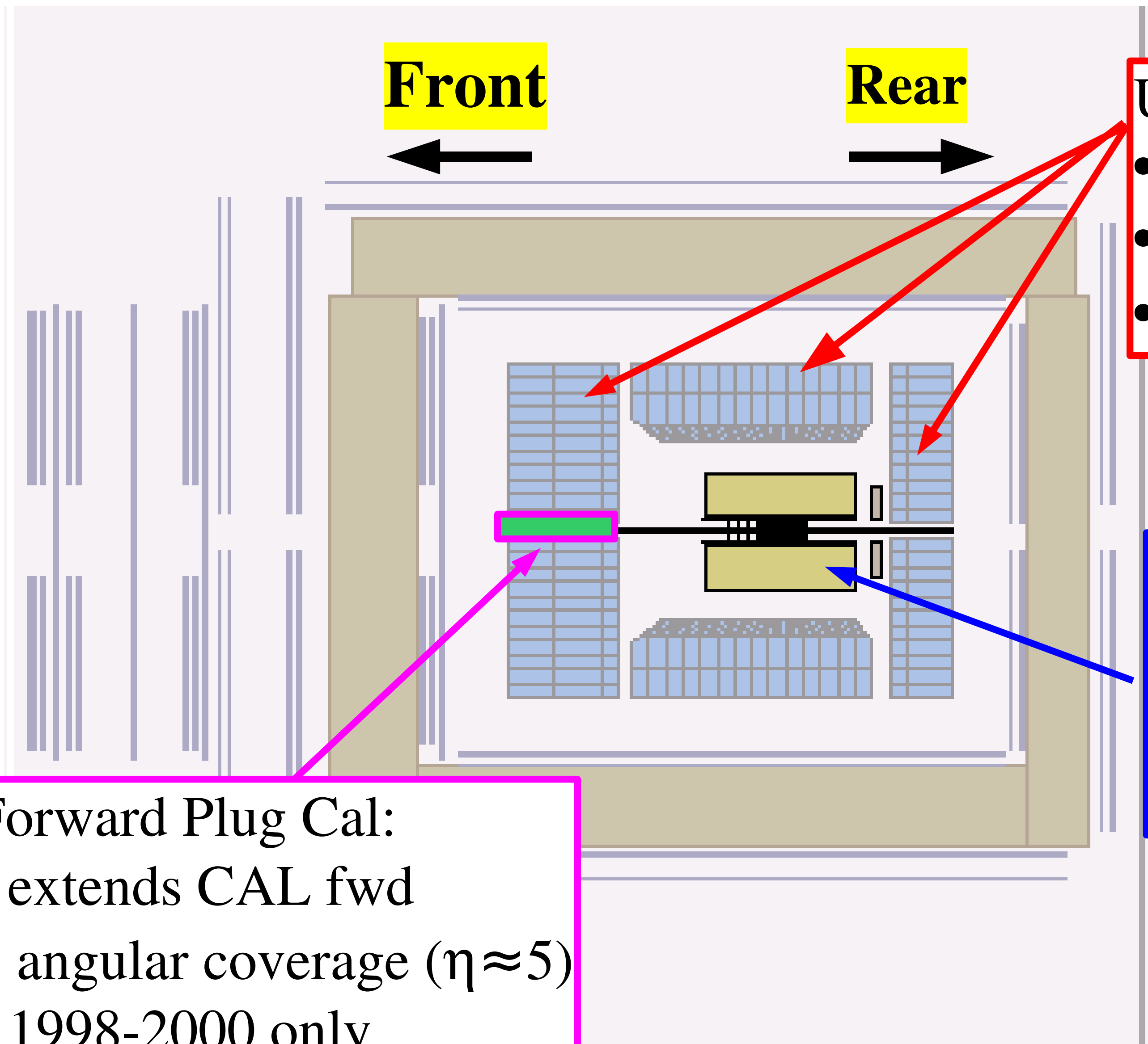
HERA HER delivered 755 pb^{-1}
ZEUS HER gated 550 pb^{-1}

Also Low (p @ 460 GeV) and Medium (p @ 575 GeV) Energy Runs

ZEUS LER gated 13.2 pb^{-1}
ZEUS MER gated 7.7 pb^{-1}



ZEUS components

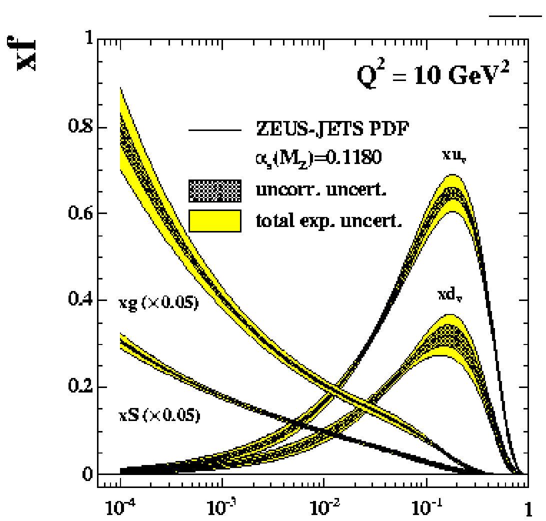


UCAL:
- Front, Barrel, Rear CAL
- $\delta(E)/E \sim 0.18 / \sqrt{E}$ for e-
- $\delta(E)/E \sim 0.35 / \sqrt{E}$ for had

Central Tracking Detector:
- drift chamber
- 72 layers
- $\delta(p_T)/p_T \sim (0.58 p_T \oplus 0.65)\%$

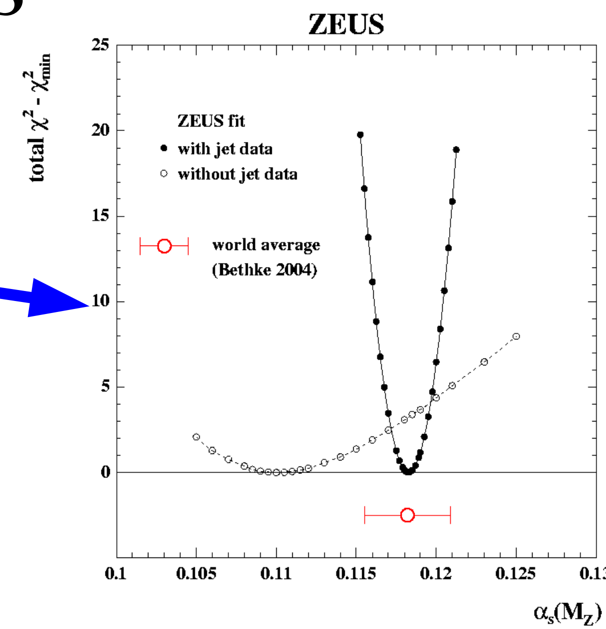
Forward Plug Cal:
- extends CAL fwd angular coverage ($\eta \approx 5$)
- 1998-2000 only

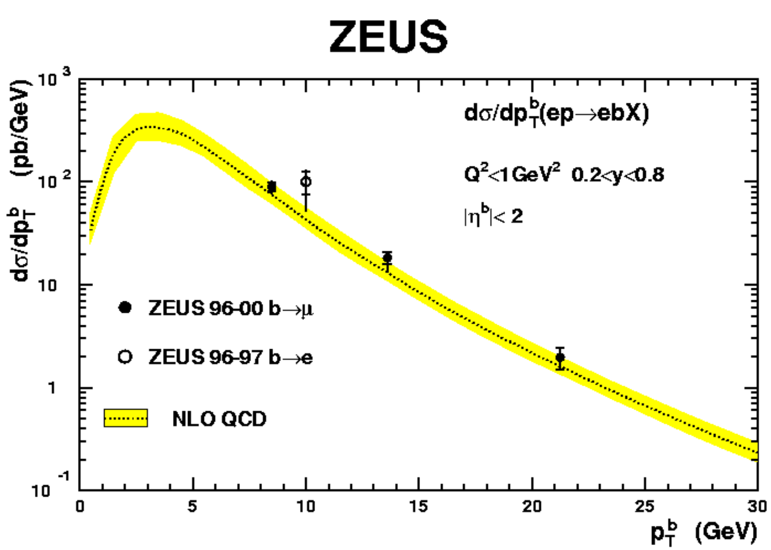
ZEUS Highlights



Determination of the **proton PDFs** and α_S

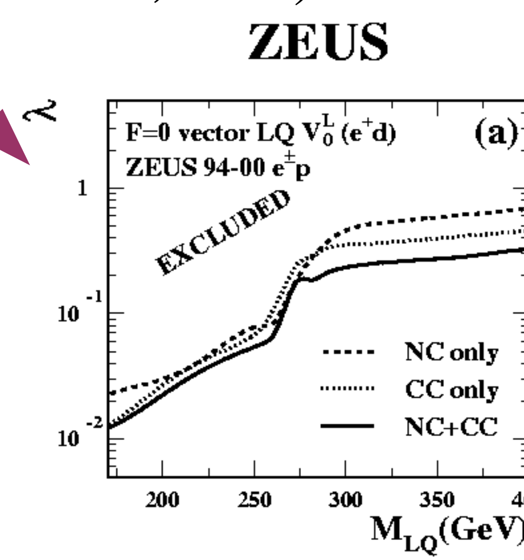
basic ingredients for ANY LHC analysis



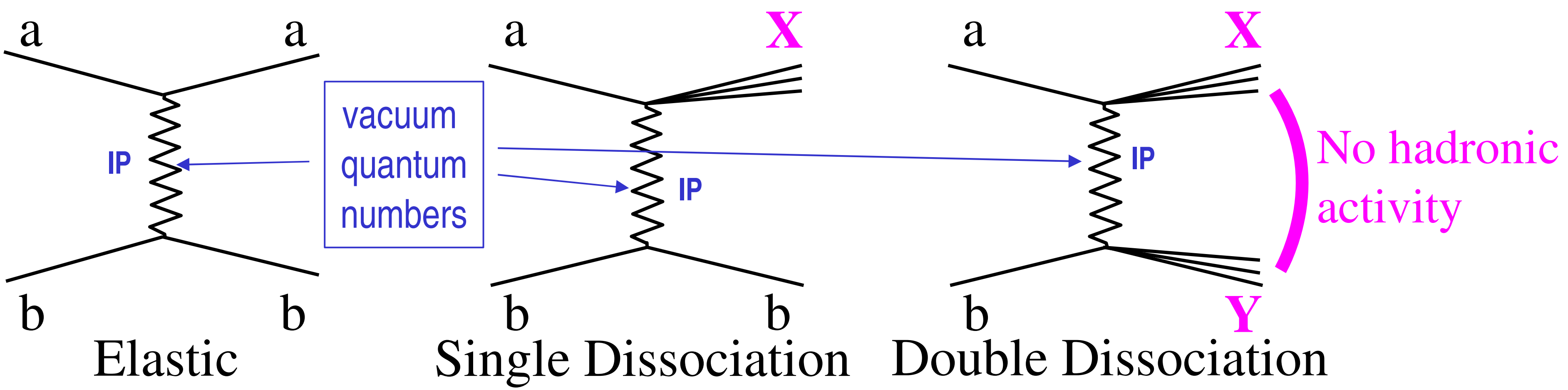


Heavy flavours physics

Searches for new physics (**LQ,** SUSY, CI...)

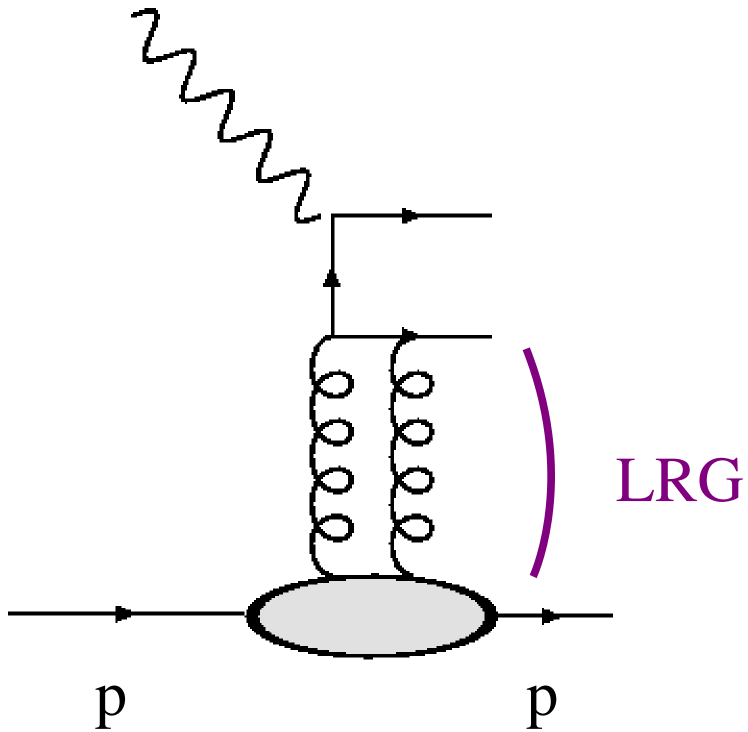


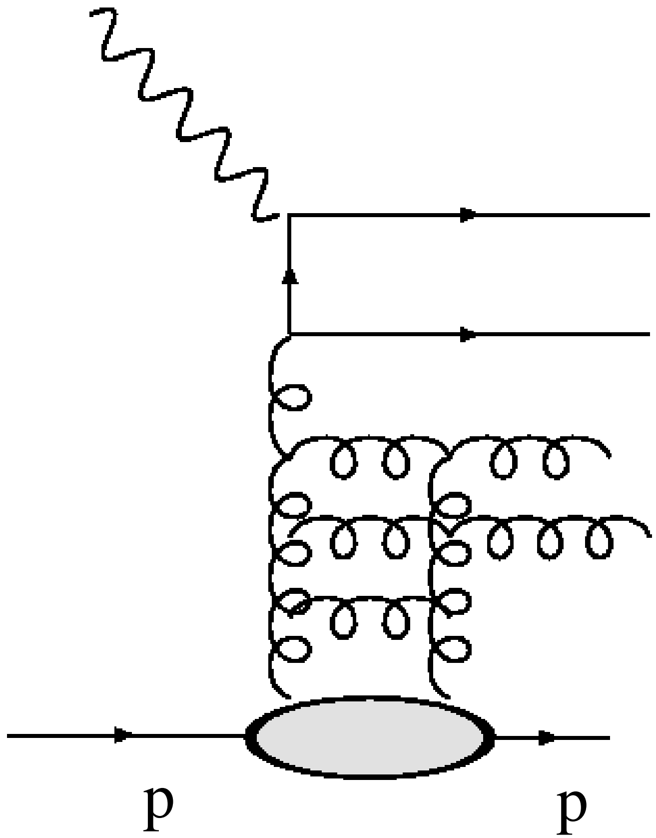
Diffraction



*For diffraction we mean all those types of processes in which no quantum numbers (charge, isospin, barion number, **color**,..) are exchanged between the interacting particles.*

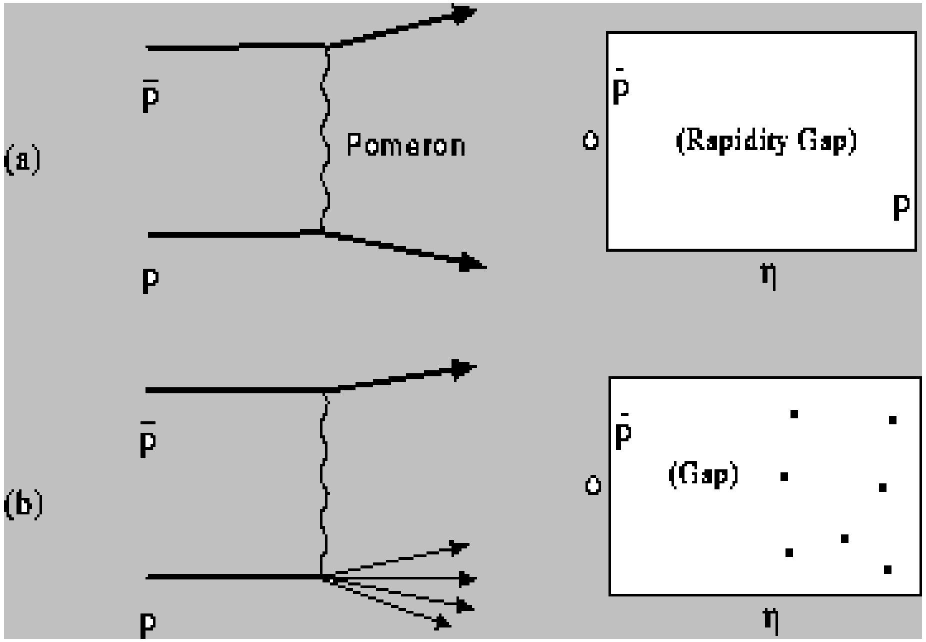
- Diffraction: no quantum numbers exchanged btw the incoming particles.
- Interaction is mediated by an exchanged object. In the case of diffraction this object carries the vacuum quantum numbers and is often called the "***pomeron***" (IP). In the easiest QCD picture, it can be thought as a gluon pair.

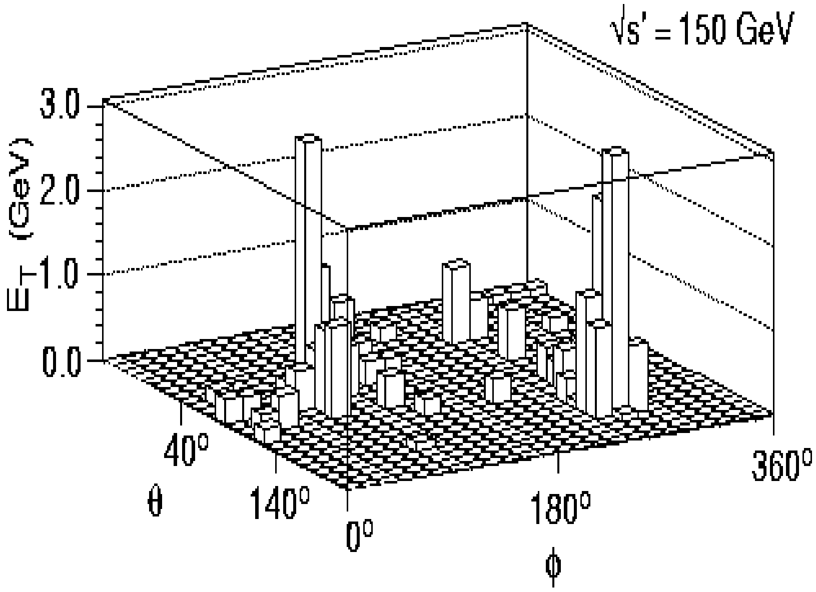




Experimental signatures

- Peculiar experimental signatures:
  - the incoming particles go out from the interaction only slightly perturbed: intact or low-mass resonant state, very low deflection angles, lose a few percent of initial momentum
  - presence of rapidity gaps in the detector: angular regions without hadronic activity.





A. Brandt et al., P.L. B 297 (1992) 417
(UA8 experiment)

A first summary

- Diffraction is known since a long time. It has very particular exp. signatures
- A lot of diffraction in soft processes (not described by pQCD).
- Diffractive process + hard scale -> pQCD. Richer information than standard DIS: correlations between partons in proton.

Some questions arise next:

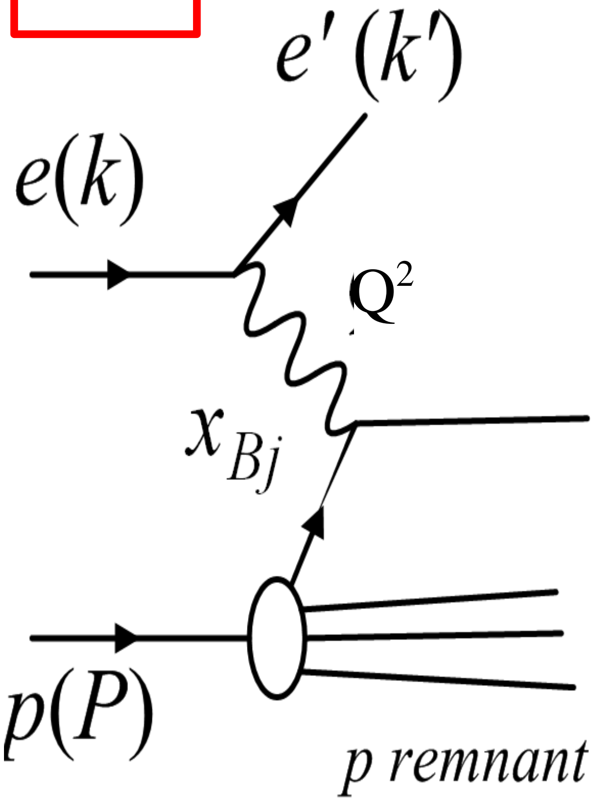
- It is a phenomenon involving the strong interaction. **We want to understand it using QCD tools (PDFs, DGLAP).**
- How is the IP exactly made? How many gluons? Quarks? Does it change with the scale of the process? How?
- Is it universal, i.e. is it the same for *pp* and *ep* collisions?

Diffraction at HERA. Why?

- HERA is an ideal place for studying QCD. Proton probed by the virtual photon γ^* emitted by the lepton (Deep Inelastic Scattering).
- Size of γ^* fixes the scale of the process. For sufficiently small sizes we can use perturbative theory (pQCD).
- Environment "cleaner" than pp colliders.
- *We can study diffraction within a pQCD framework by probing the diffractive exchange with the virtual photon.*
- Diffraction is a significant fraction of total DIS at HERA: **~10%**

$ep \longrightarrow epX$ kinematics

DIS



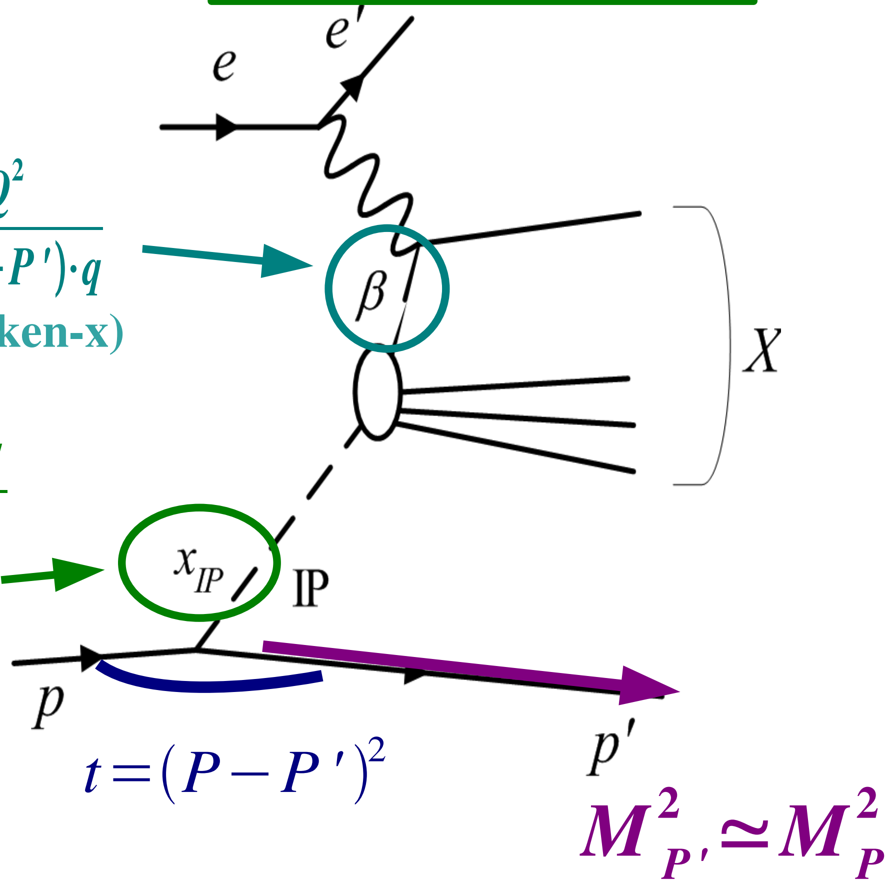
Diffractive DIS

$$\beta = \frac{Q^2}{2(P-P')\cdot q}$$

(~ Bjorken-x)

$$x_{IP} = \frac{(P-P')\cdot q}{P\cdot q}$$

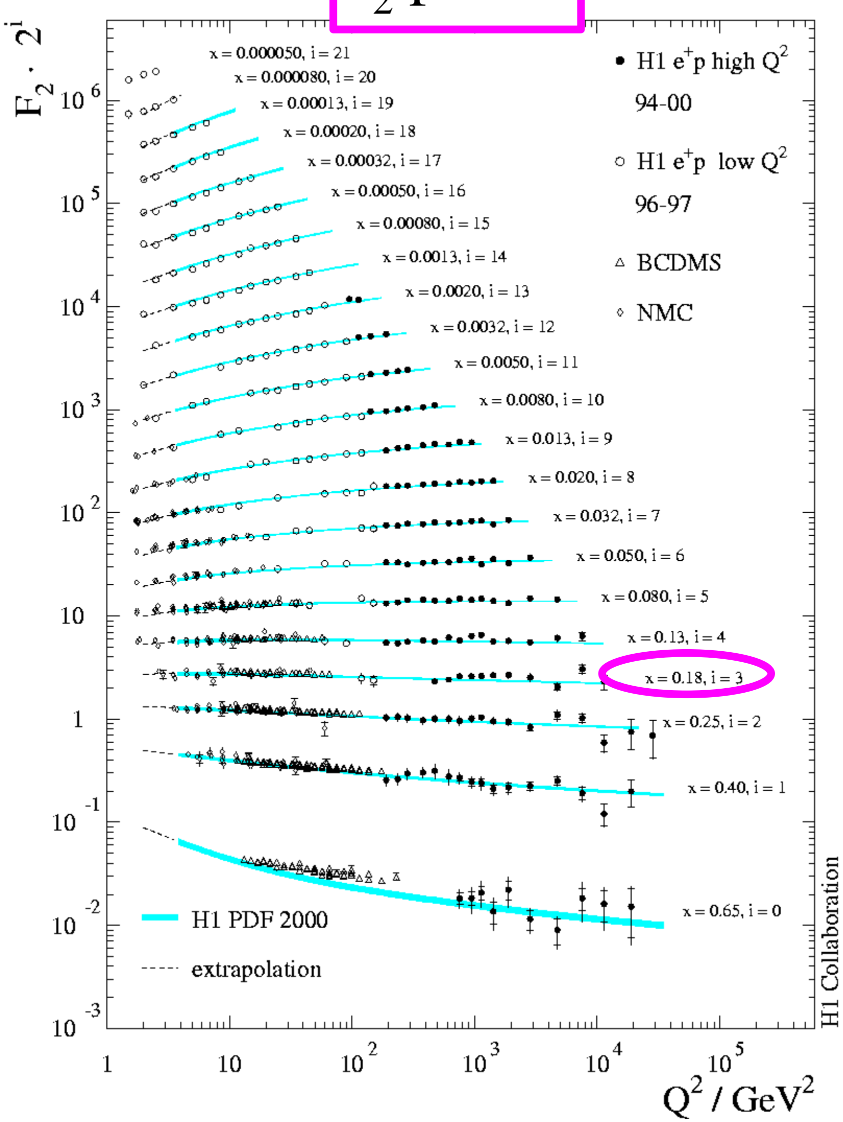
x_{IP} = fraction 4-mom lost by P



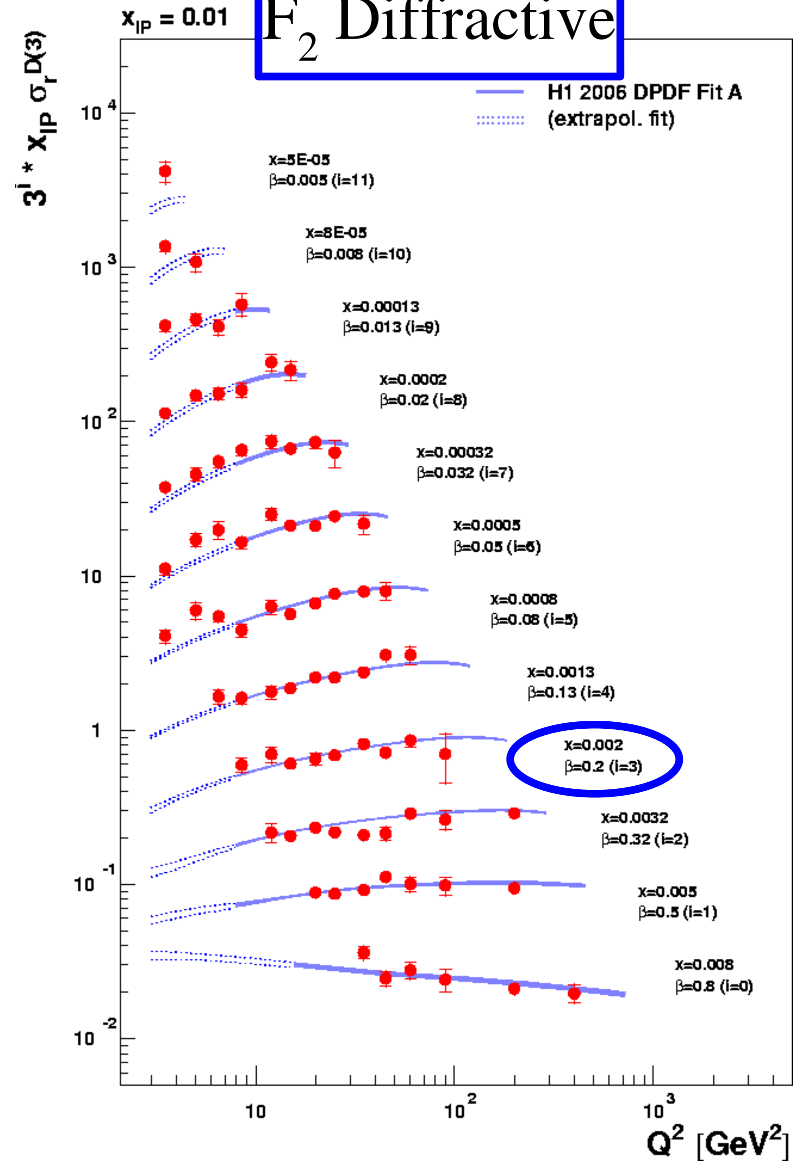
$$\frac{d\sigma^D}{d\beta\, dQ^2\, dx_{IP}\, dM_{P'}\, dt} = \frac{2\pi\alpha}{xQ^4}\left[y_+ F_2^D(x_{IP}, M_{P'}, t; \beta, Q^2) + y^2 F_L^D(x_{IP}, M_{P'}, t; \beta, Q^2)\right]$$

Diffractive Structure Functions

F_2 proton



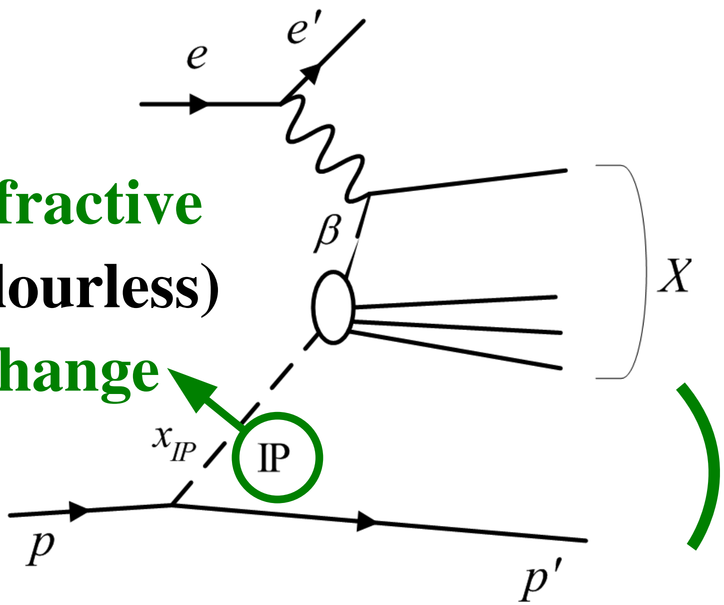
F_2 Diffractive



Positive scaling violations: lots of gluons !

Large Rapidity Gap

Diffractive
(colourless)
exchange



$$Y = \frac{1}{2}\,'\ln\frac{E+p_L}{E-p_L}$$ *Rapidity*

$$Y \approx \eta = -\ln\left(\tan\left(\frac{\theta}{2}\right)\right)$$ *Pseudorapidity*

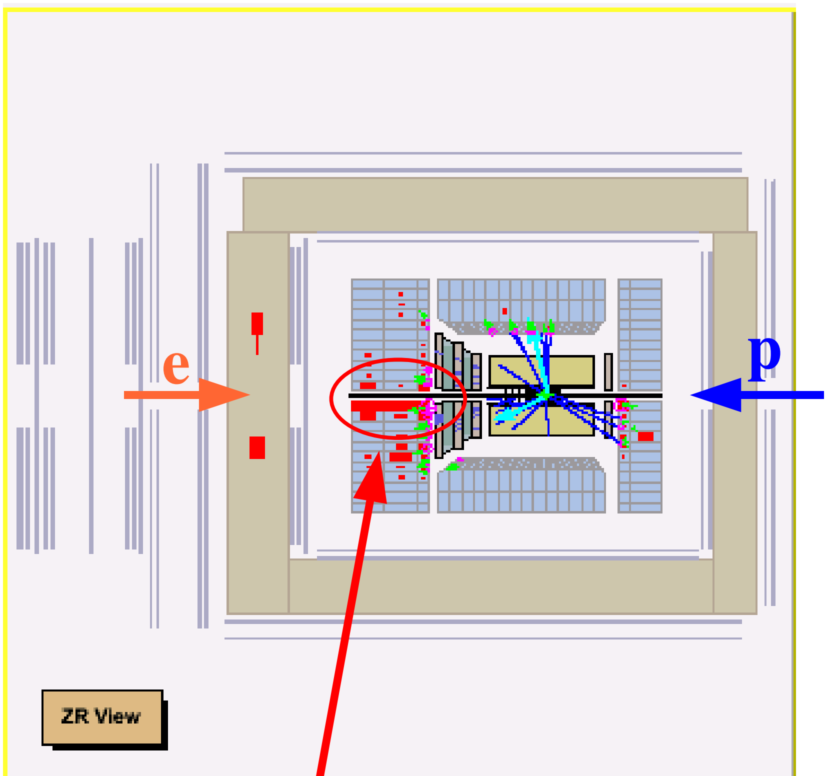
LRG: Large Rapidity Gap in the direction of the scattered proton with no hadronic activity

No colour flow   no hadr activity
no particles in a large angular region in direction of the outgoing proton

Non-diffr
$$\frac{dN}{d\eta} \simeq const$$

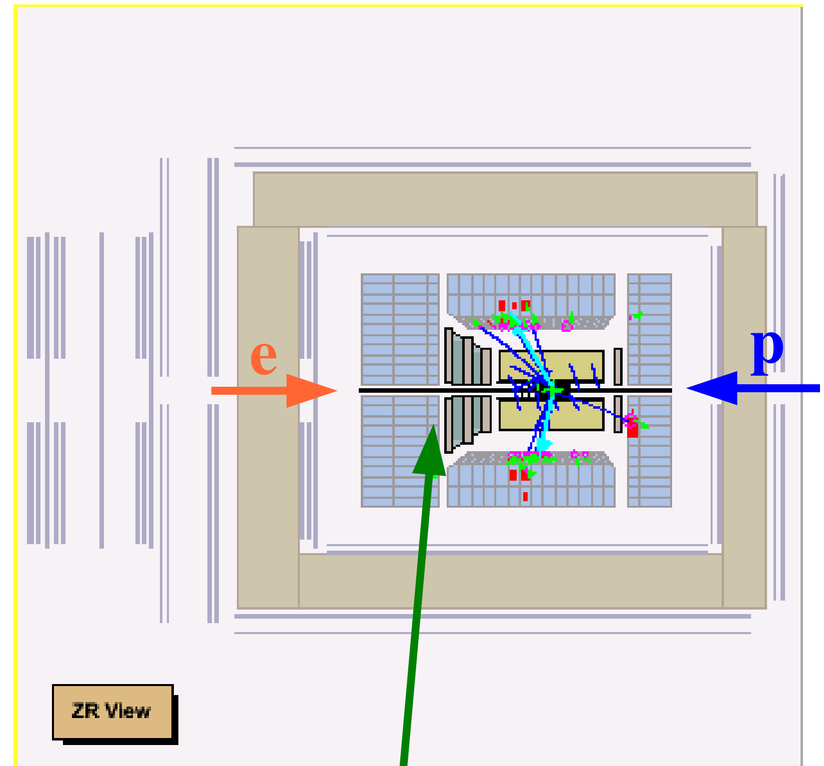
Diffractive events are identified by the presence of LRG
(size of gap exponentially suppressed for non-diff)

NON-DIFFRACTIVE



The proton breaks up
Activity in the forward direction

DIFFRACTIVE



A colourless object is exchanged
No activity in a large rapidity range

- Very easy tagging
- High statistics
- No detection of P': no info about t

QCD factorisation in Diffraction

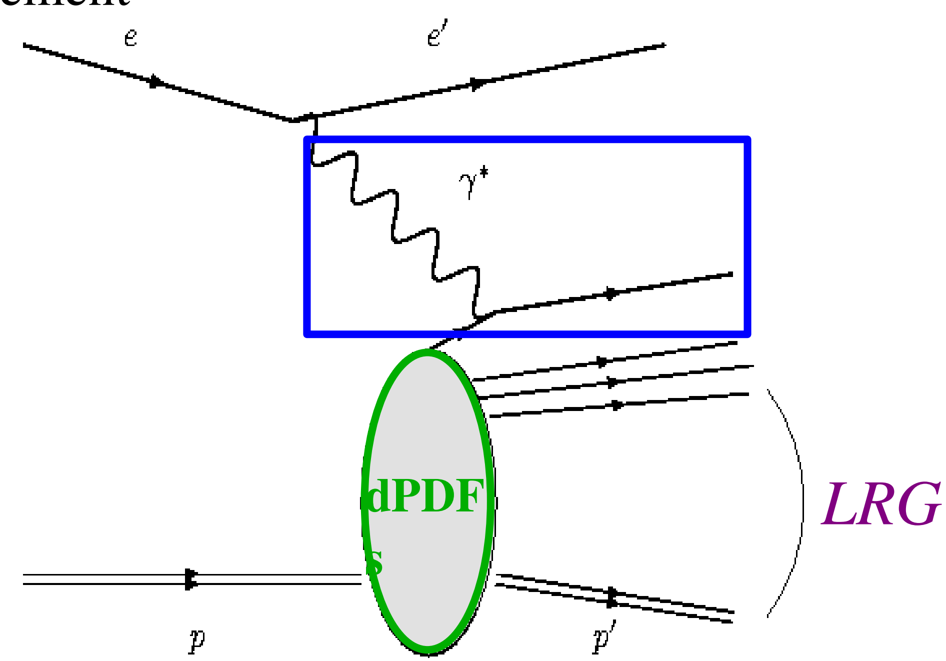
QCD Factorisation theorem

$$\sigma^D(\gamma * p \to Xp) \simeq \sum_{i=q,g} \hat{\sigma} \otimes f_i^D(t, x_{IP}, \beta, Q^2)$$

+ higher-twist terms
(non-leading powers of 1/Q)

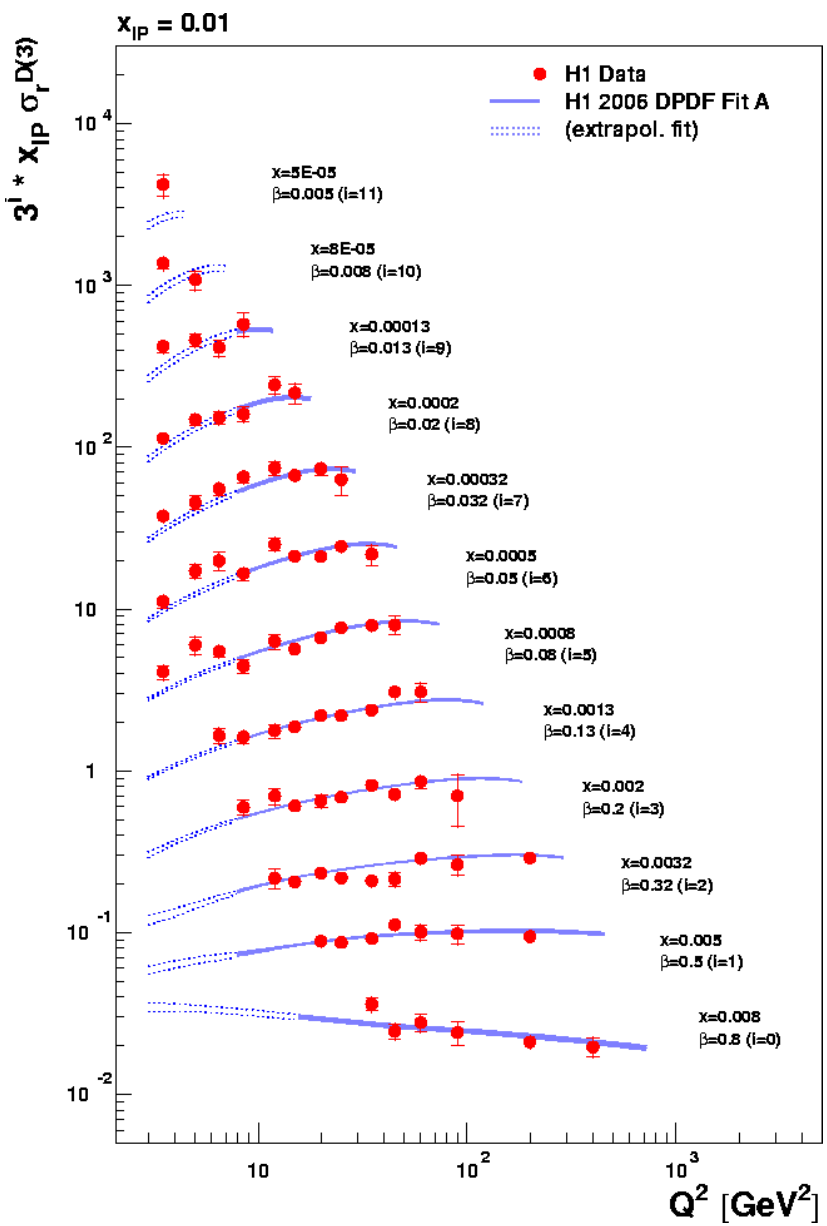
Hard subprocess ME
pQCD calculable

Diffractive PDFs
defined as the std PDFs +
diffractive requirement
Universal

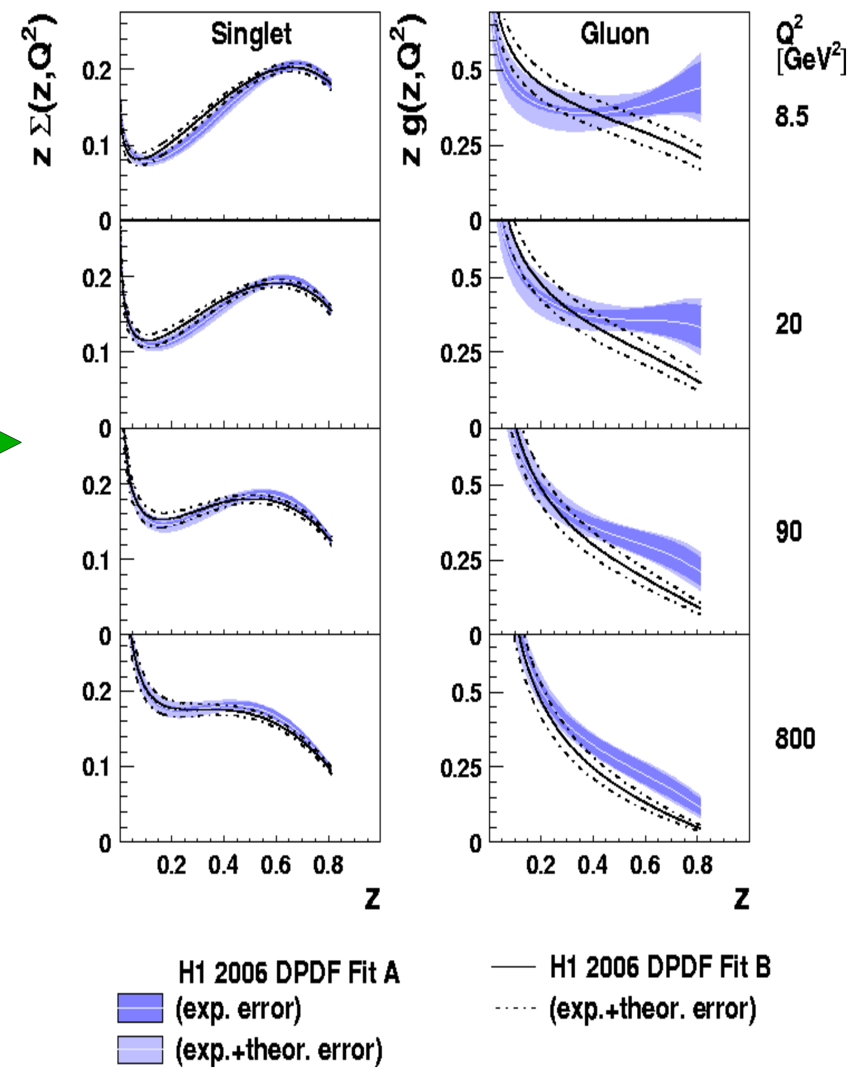


dPDFs can be used in calculations for different diffractive final states and different experiments.
This ansatz has to be validated experimentally.

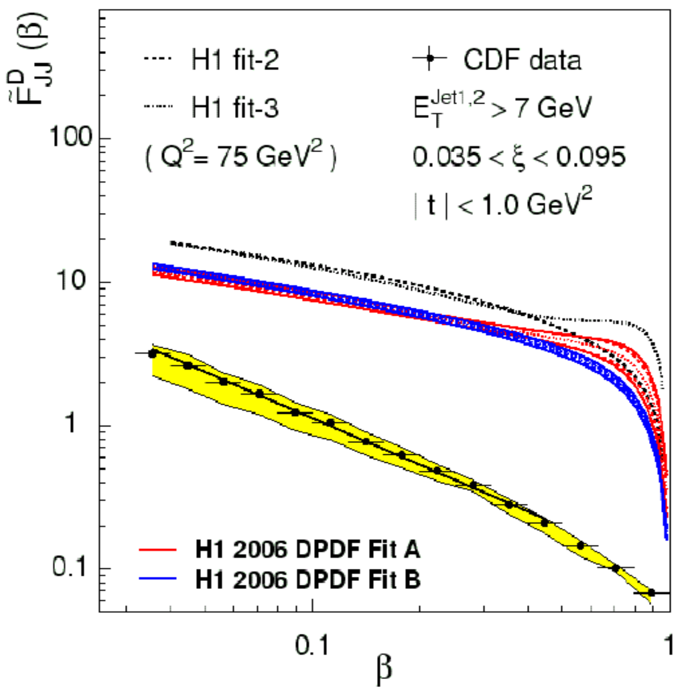
Diffractive PDFs



Extract the dPDFs via DGLAP fit

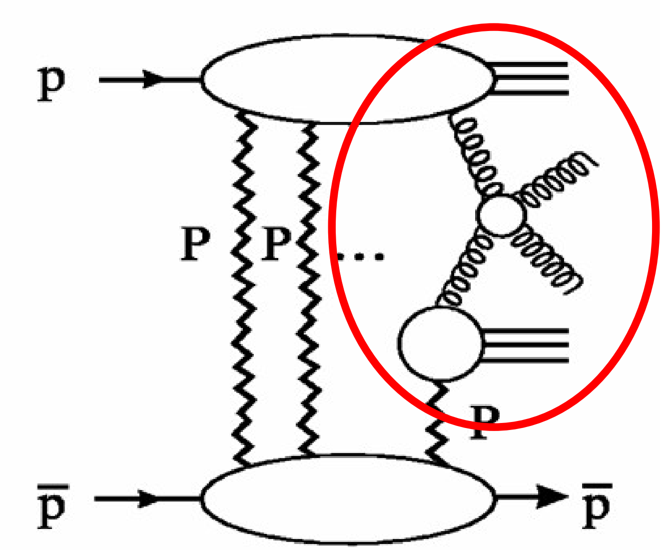


Factorisation breaking in *pp* collisions



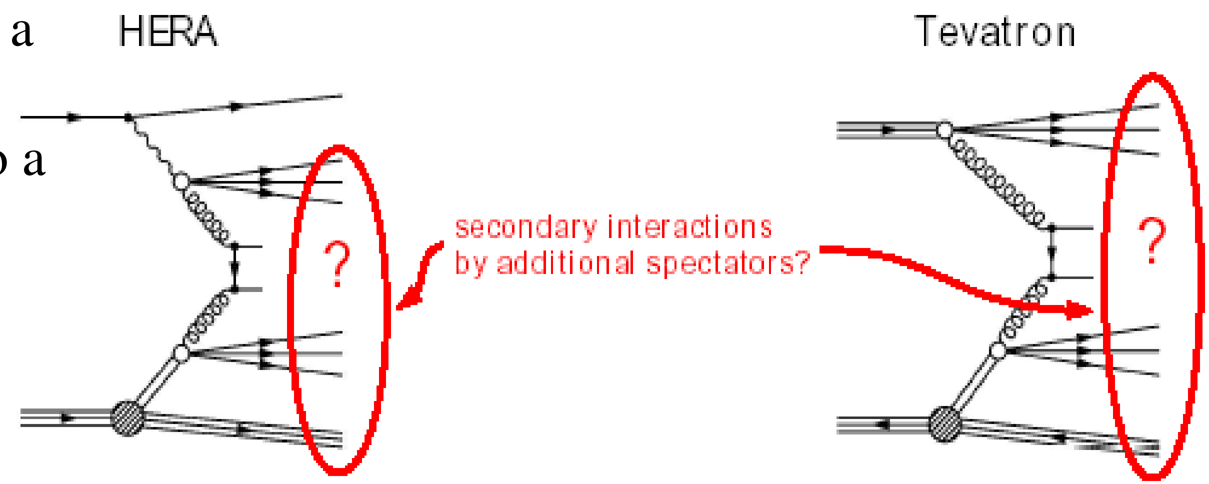
Diffractive dijet measurement by CDF.
Comparison with NLO prediction using as input dPDFs extracted at HERA .
Significant overestimation by NLO of the data.
The HERA dPDFs cannot be used directly at TeVatron.

Secondary interactions between spectator partons spoil the LRG, no diffractive tag anymore.
Models are able to describe the suppression observed at TeVatron.

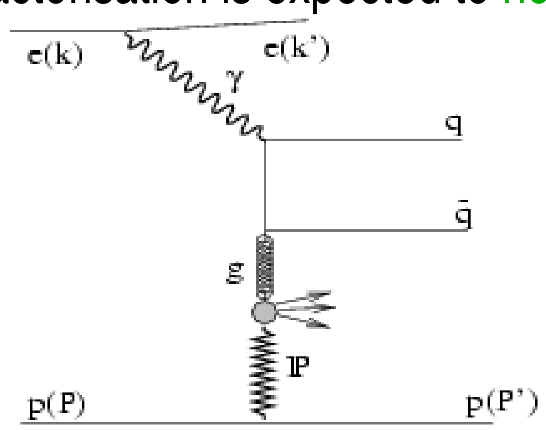


If things are in this way HERA has still a lot to teach.
At HERA we have something similar to a hadron: photoproduction (PhP) photon ($Q^2 \sim 0$).

Low Q^2 γ fluctuates in $q\bar{q}$ pairs and behave ~ vector meson

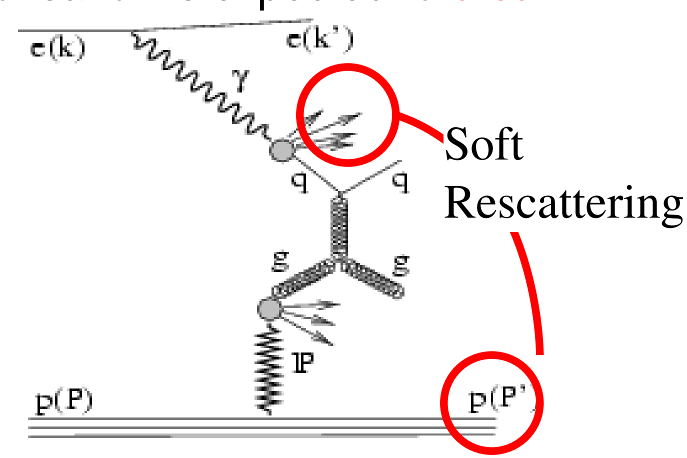


Direct γ^* (small γ^*) couples directly to parton (DIS and part of γp).
QCD factorisation is expected to hold.



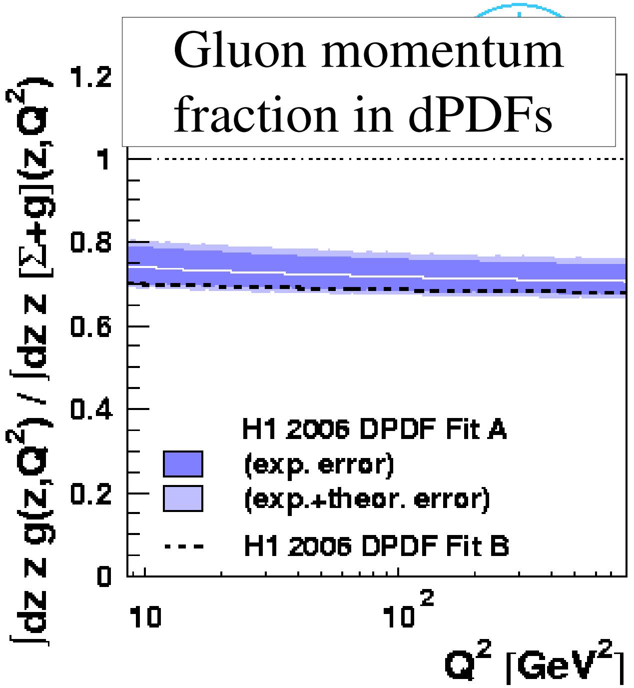
(a)

Resolved γ^* (large γ^*) behaves like a hadron (other part of γp).
QCD factorisation is expected to break



(b)

Dijets in diffraction



QCD factorisation test

- Measure a particular diffractive final state.
- Compare the measurement to NLO calculations using dPDFs previously extracted.

Improved fit to the dPDFs

- Gluon density from slope of the inclusive F_2^D (DGLAP equations, splitting func)
- Data limited in precision (especially at high β) –> limited sensitivity on the gluon density
- Exploiting the experience from the fit to the proton PDFs -> semi-inclusive data with a sensitivity to the gluon content for a more precise fit to the dPDFs.

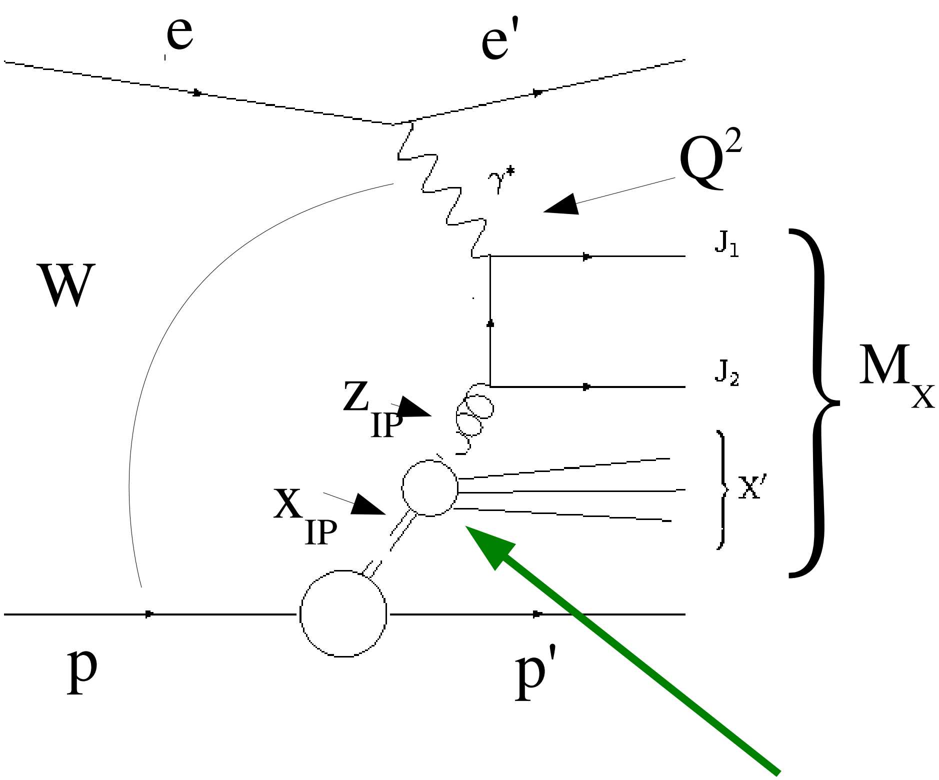
- What kind of final states?

  Processes with a **hard scale** (pQCD, DGLAP)

  Sensitive to gluons (gluons contribute to the main part of dPDFs)

Dijets

Dijets in dDIS



Q^2 = $-q^2$=- $(e-e')^2$ $W^2=(p+q)^2$

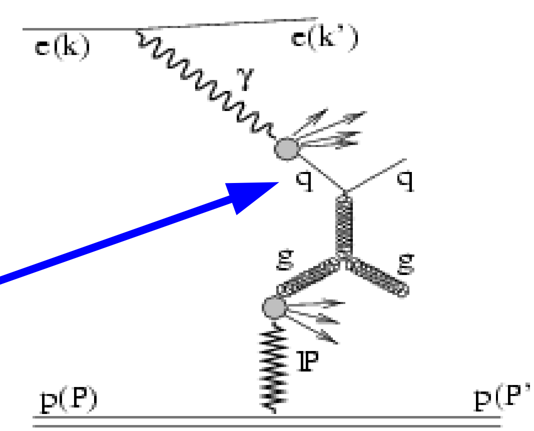
$$x_{IP} = \frac{(Q^2+M_X^2)}{(Q^2+W^2)}$$

$$z_{IP} = \frac{(Q^2+M_{jj}^2)}{(Q^2+M_X^2)}$$

sensitive to the dPDFs

$$x_\gamma = \frac{(\Sigma E - p_Z)_{JJ}}{(\Sigma E - p_Z)_{TOT}}$$

sensitive to direct / resolved γ



(b)

Data and MC samples

DATA: *Total $\mathscr{L}$ = 61.3 pb^{-1}*

- 1999 e-p runs (3.2 pb^{-1})
- 1999 e+p runs (12.9 pb^{-1})
- 2000 e+p runs (45.2 pb^{-1})

RAPGAP MC v2.08/13

- Proton vertex factorisation
- H1 fit2 dPDFs
- Matrix Element Parton Shower
- Three samples generated separately:

  direct γ LQ, direct γ charm, resolved γ

SATRAP MC

- Dipole model
- Interfaced to RAPGAP
- No resolved γ

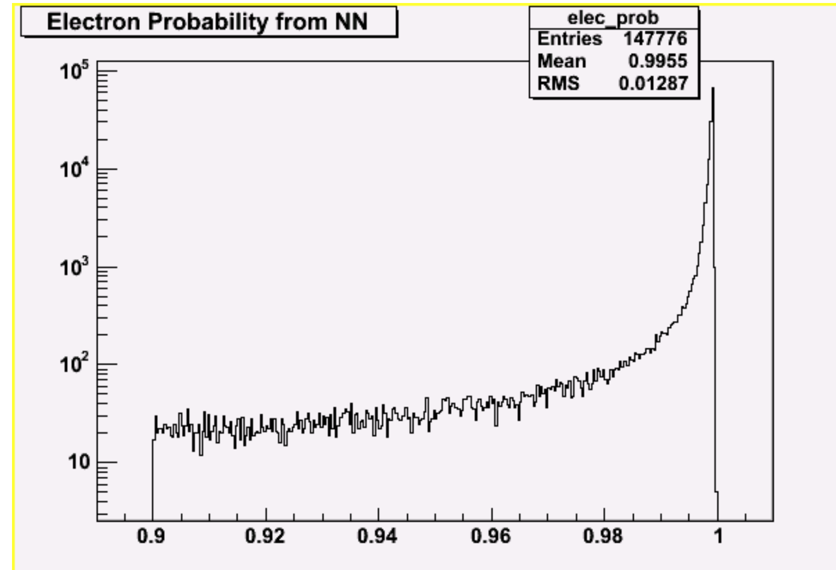
Inclusive DIS Background:
DJANGOH (-> LEPTO)

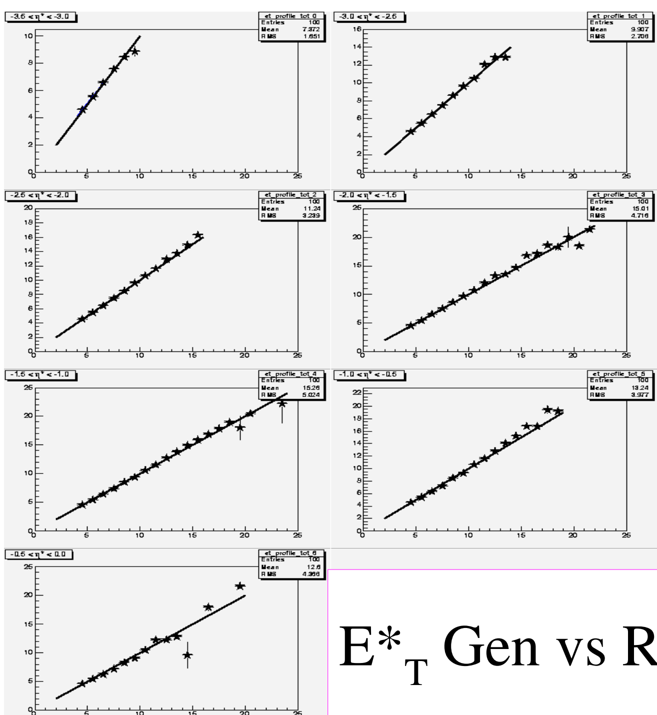
A.Bonato – Louvain, 2007/10/18

Selection of DIS and jet events

DIS selections:

- Electron identified from ECAL clusters with a neural network algorithm.
- $45 < E - p_Z < 65$ GeV
- $E'_{el} > 10$ GeV
- $-50.0 < Z_{vtx} < 50.0$ cm
- DIS electron outside fiducial box
- **$5 < Q^2_{DA} < 100$ GeV^2**
- **$100 < W_{DA} < 250$ GeV**





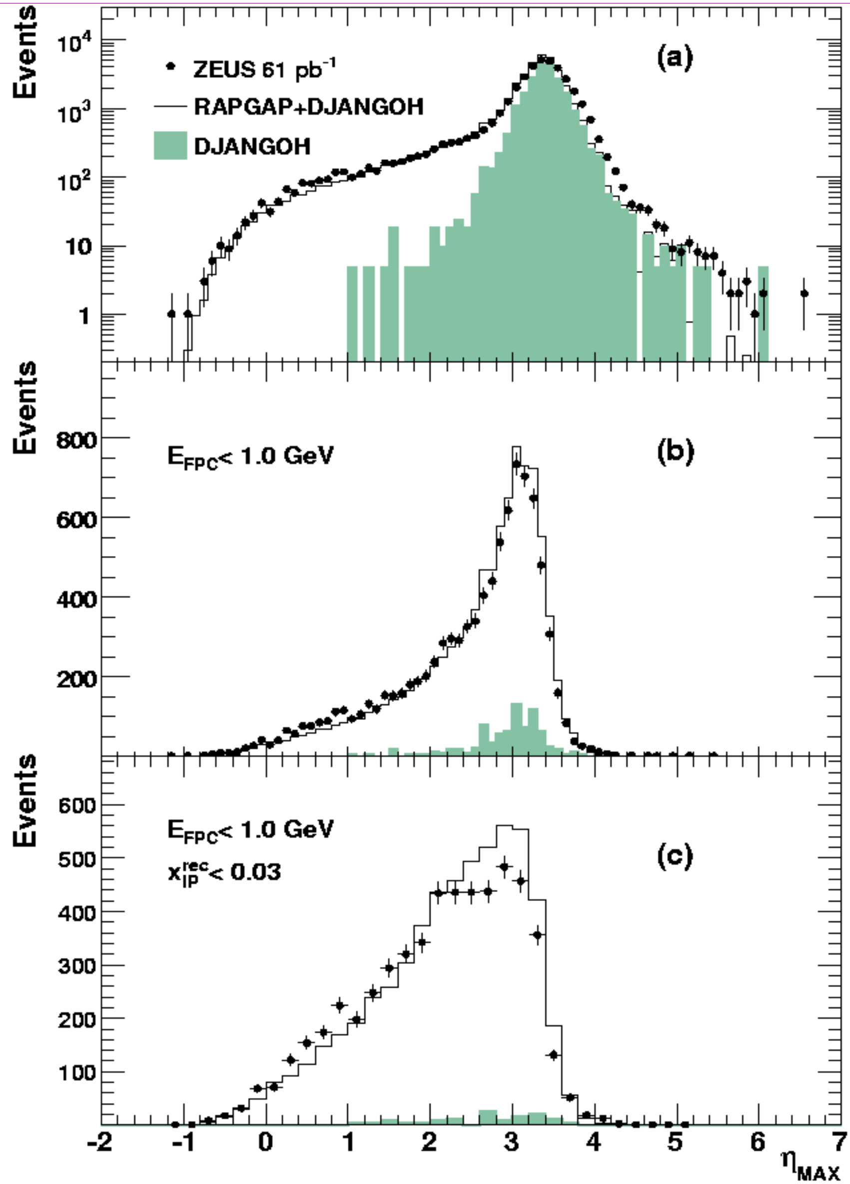
E^*_T Gen vs Rec

JET selections:

- Jets reconstructed from Energy Flow Objects (EFOs) mixing tracking+CAL informations
- K_T algorithm run on EFOs in the γ-proton c.m.s.
- Jets transverse energy (E_T) corrected for inactive material
- **Njets ≥ 2**
- E^*_T of jet with highest E^*_T : **$E^*_{T,jet1} > 5$ GeV**
- E^*_T of 2nd jet : **$E^*_{T,jet2} > 4$ GeV**
- η^* of all jets : **$-3.5 < \eta^* < 0$**
- η^{LAB} of all jets : **$-2 < \eta^{LAB} < 2$**

Diffractive selection

η_{MAX} : pseudorap. of most forward EFO



DIS dijets before diffractive selection

Non-diffractive dominates (log scale)

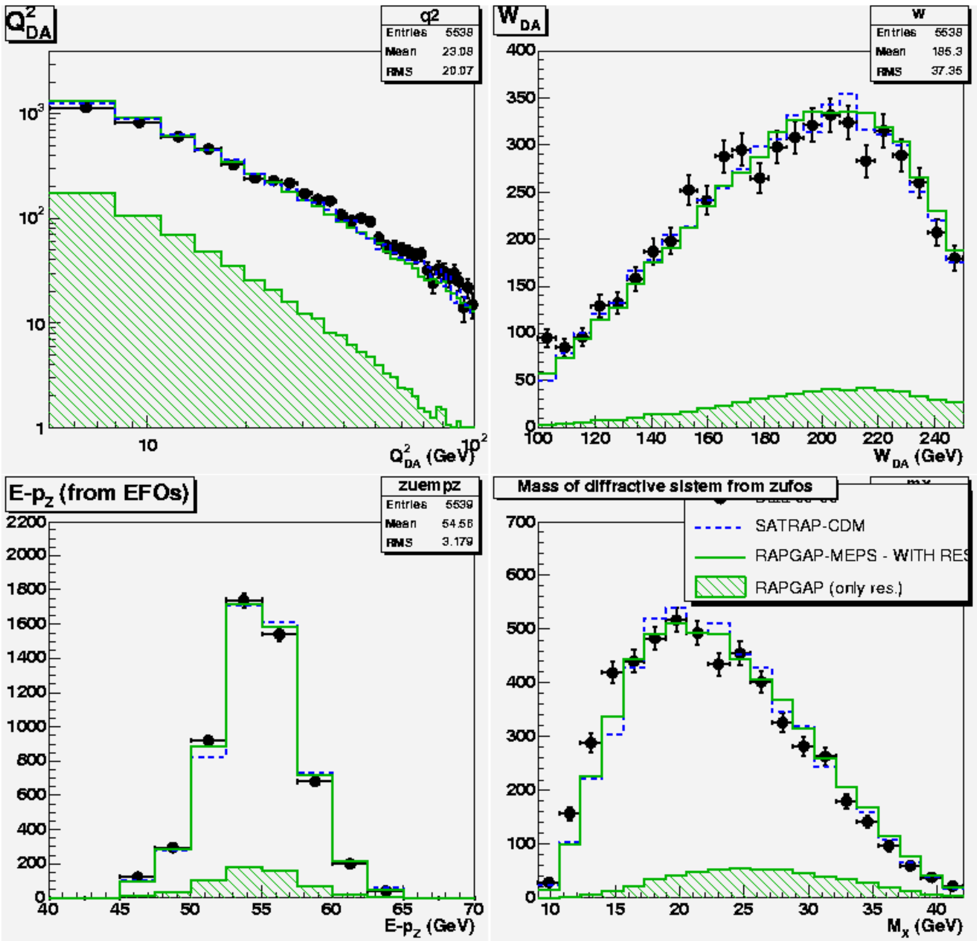
Diffractive tail at low η_{MAX}

No need of a cut on η_{MAX} with the FPC

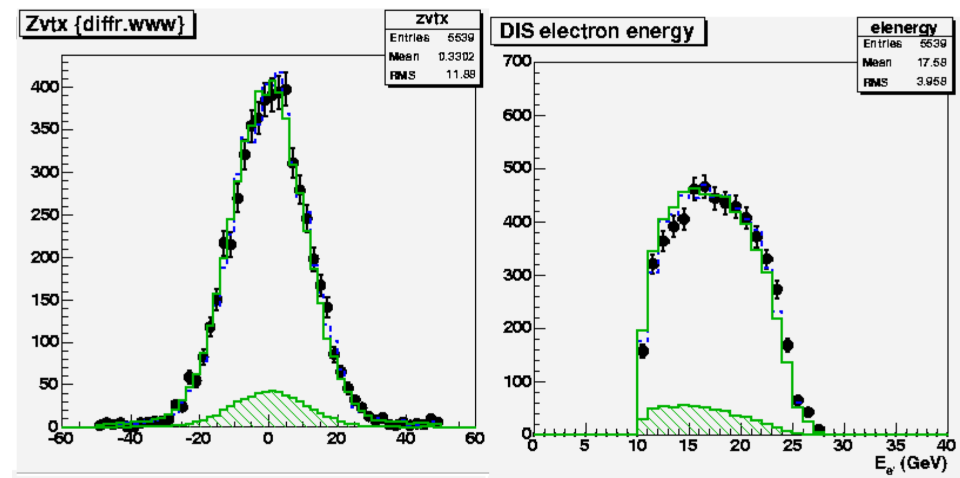
η_{MAX} distribution for DIS dijets after **$E_{FPC} < 1$ GeV**

Asking for **$x_{IP} < 0.03$** reduces further DIS non-diffr background (2.4% total events). Such background neglected.

Control plots

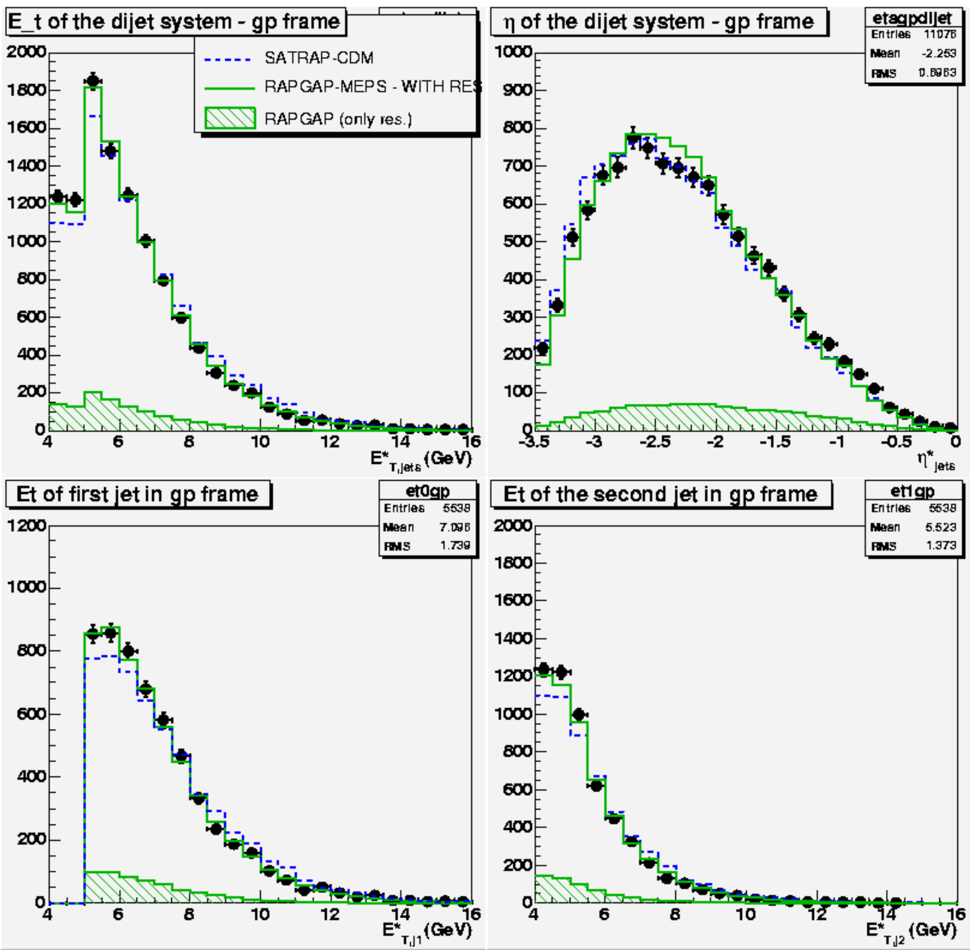


5539 events selected.
Comparing the distributions to the RAPGAP and SATRAP MC.

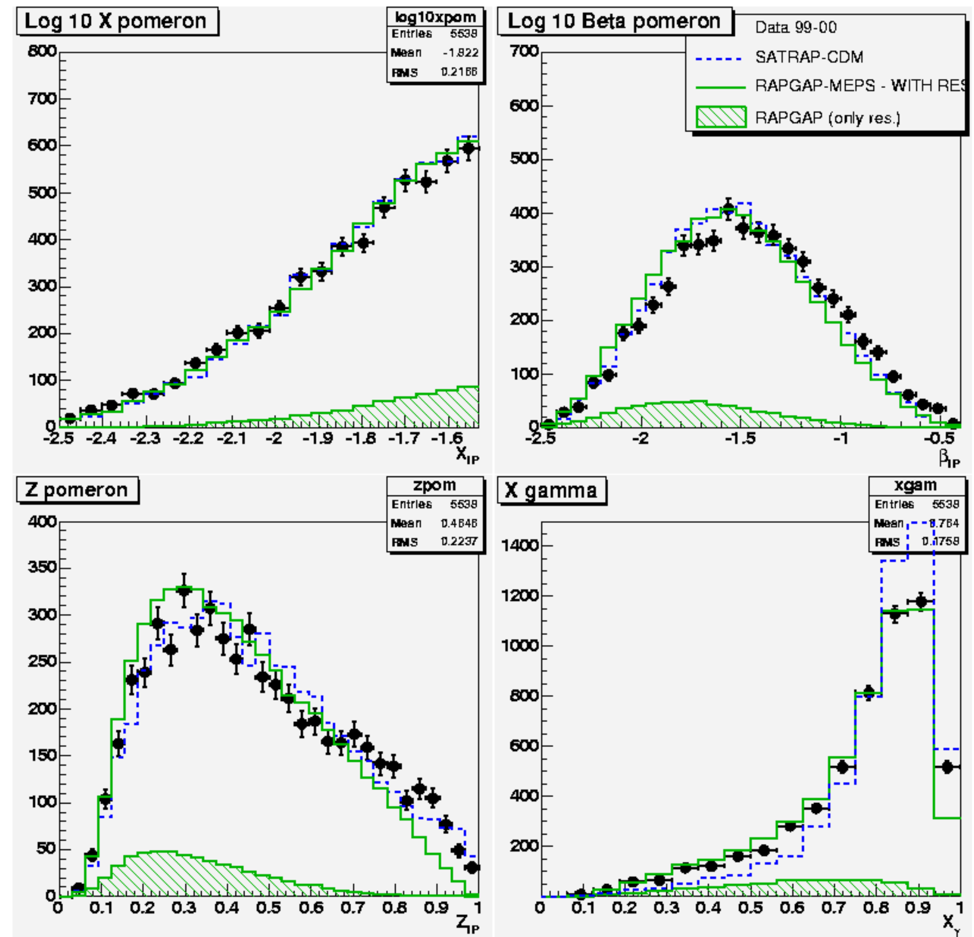


Good agreement between data and MC

Jet variables

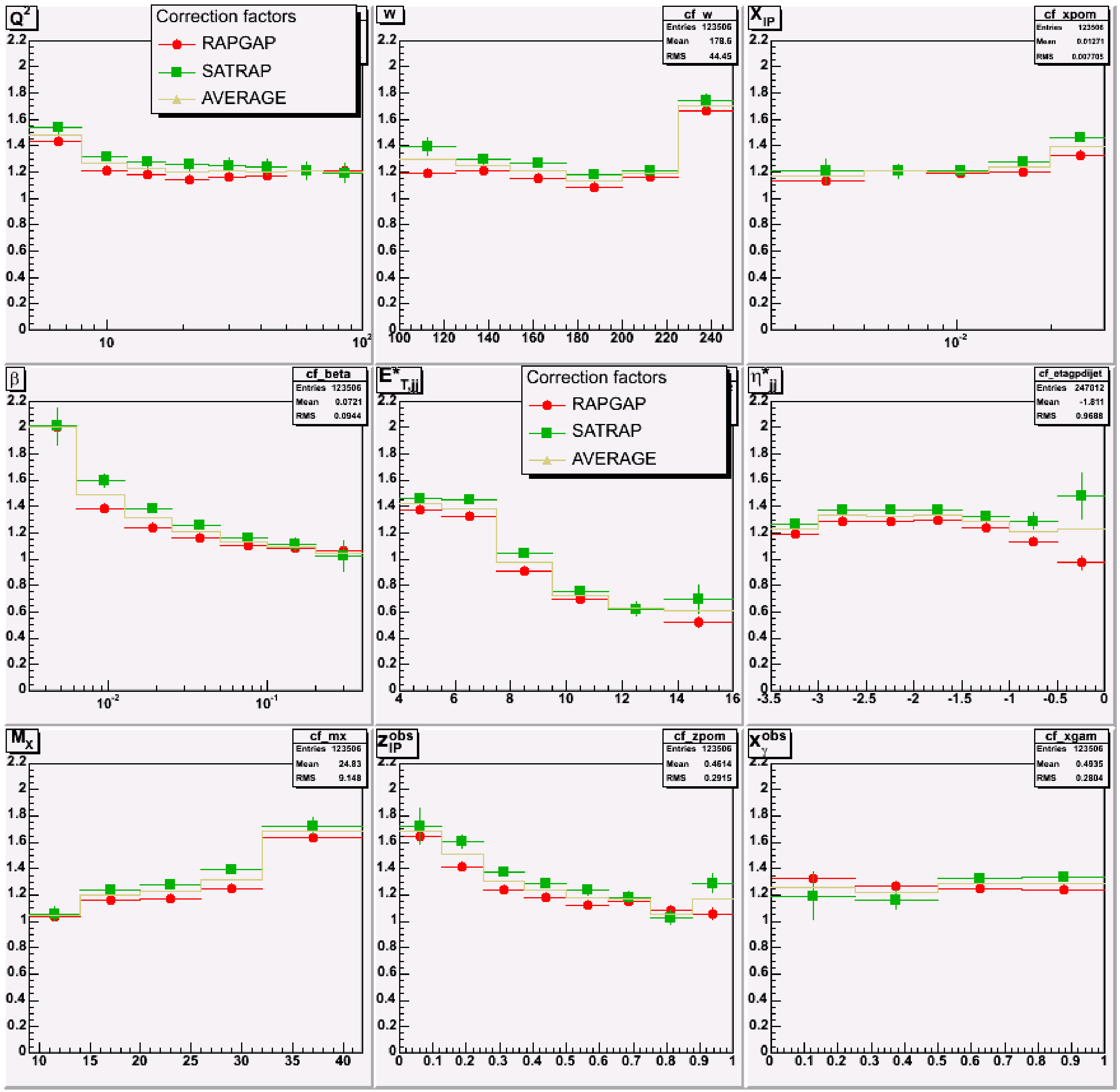


Diffractive variables



Good agreement between data and MC

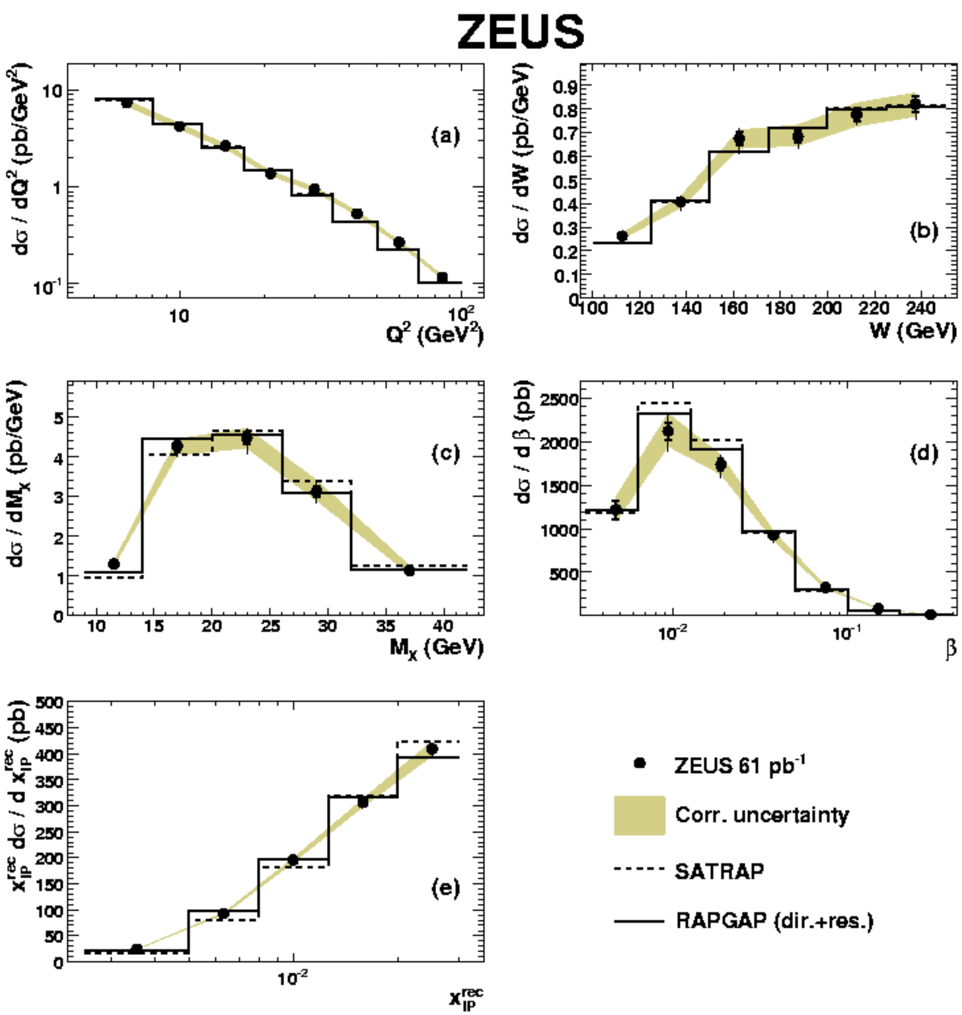
Acceptances

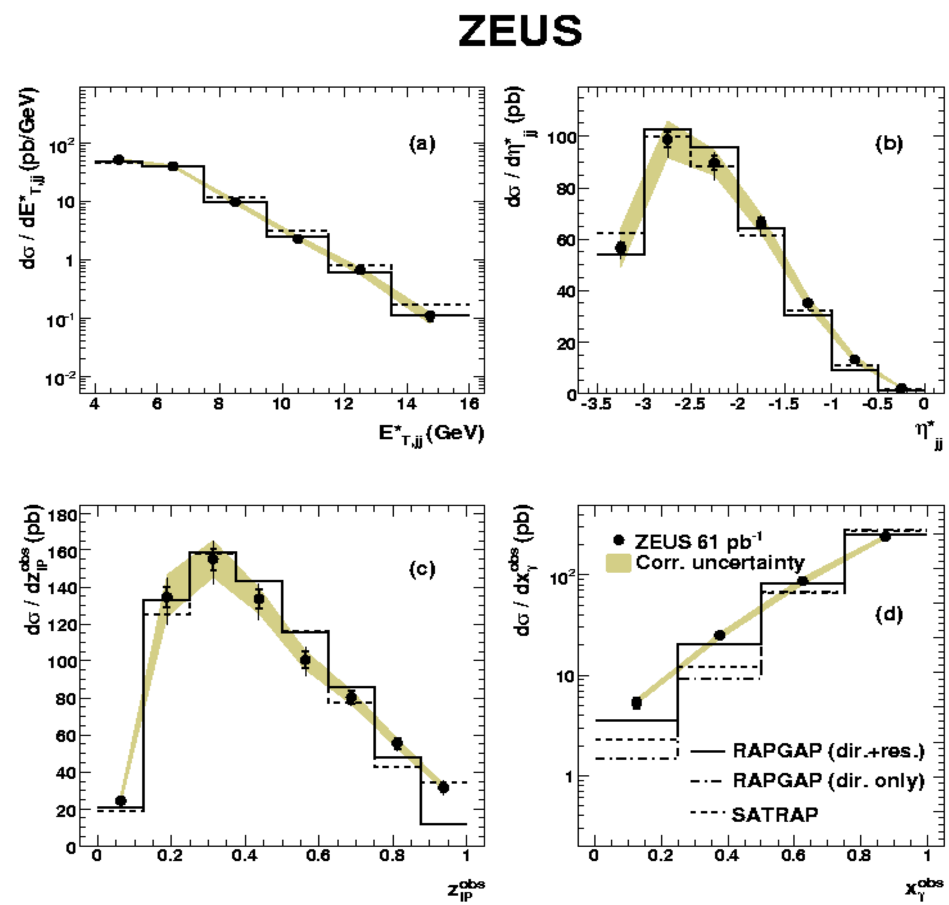


Systematic uncertainties

Systematic ID	Systematic uncertainty	Typical size
1	CAL energy scale ± 3%	± 5%
2	DIS electron energy ± 2%	± 3%
3	FPC energy veto ± 100 MeV	< 1%
4	SRTD z-position ± 2 mm	< 2%
5	Electron energy cut 8 GeV	-
6	Fiducial region electron detection ± 0.5 mm	< 2%
7	E-pz cut 43 GeV	< 2%
8	Unfolding using RAPGAP/SATRAP	± 5%

Cross sections





Data compared to LO MCs.

RAPGAP and SATRAP very similar.

Good agreement with the measurement.

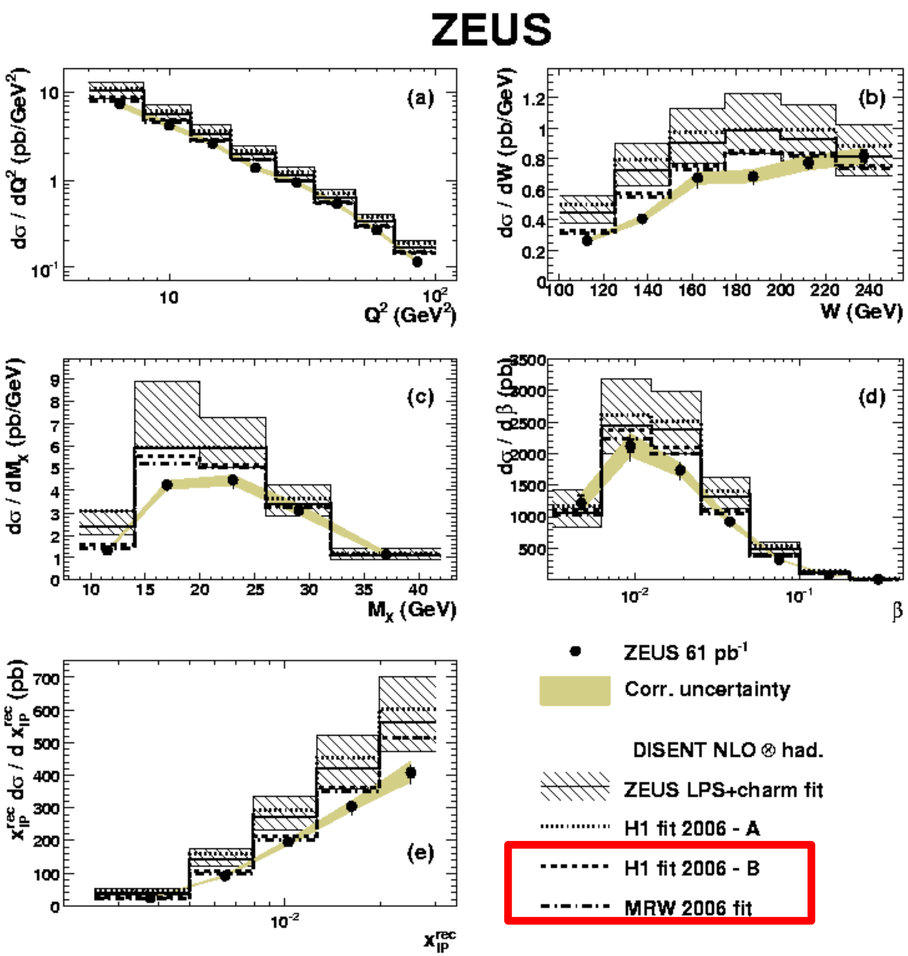
Introduction of a resolved photon improves low x_γ description.

NLO calculation

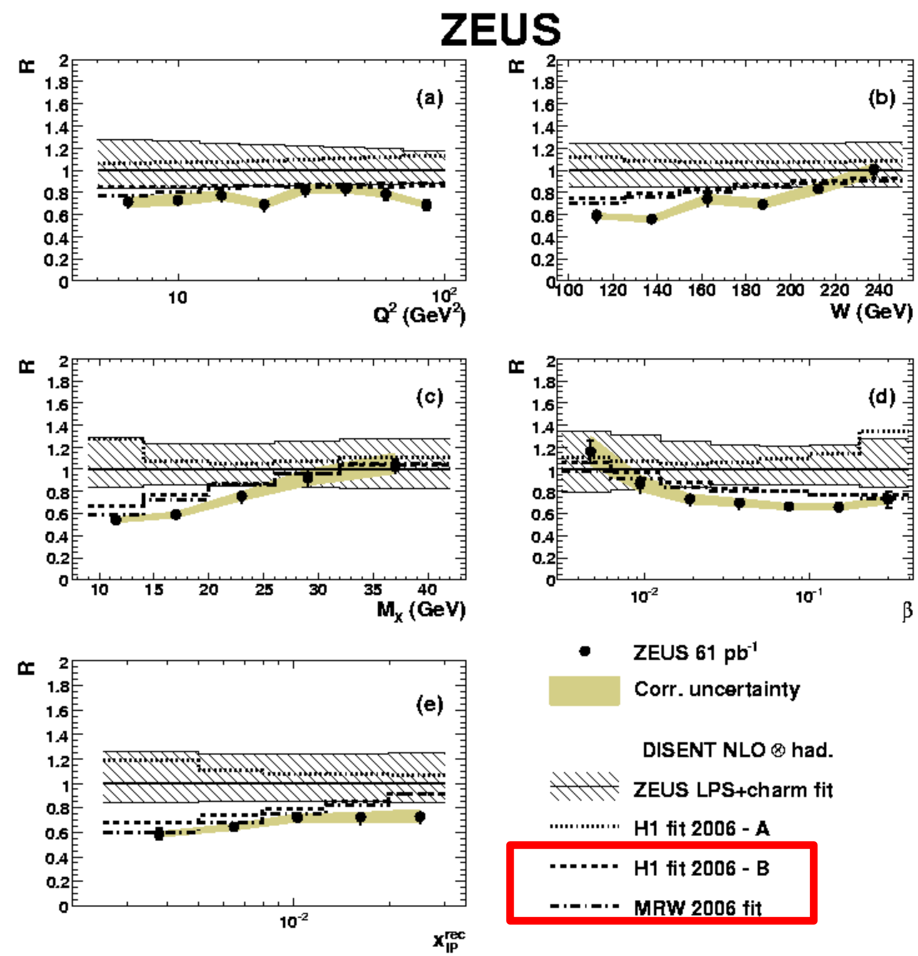
- Using dPDFs from inclusive F_2^D measurement for NLO calculation to dijets.
- Comparison with NLO prediction important for testing QCD factorisation.
- NLO gives prediction not only of the shapes but also of the normalisation.
- Using the program DISENT for the NLO calculation
  - DISENT written for non-diffractive processes (i.e. proton PDFs, not dPDFs)
  - Need to modify the code for plugging in the diffractive PDFs
- Several predictions using different dPDFs
  - **ZEUS LPS+charm** from ZEUS inclusive data
  - **H1 fit 2006** in two different parametrisations, “A” and “B”
  - **MRW 2006** by Martin-Ryskin-Watt fitting the same data as H1fit2006

Comparison to NLO

Cross sections



Ratio to ZEUS LPS prediction

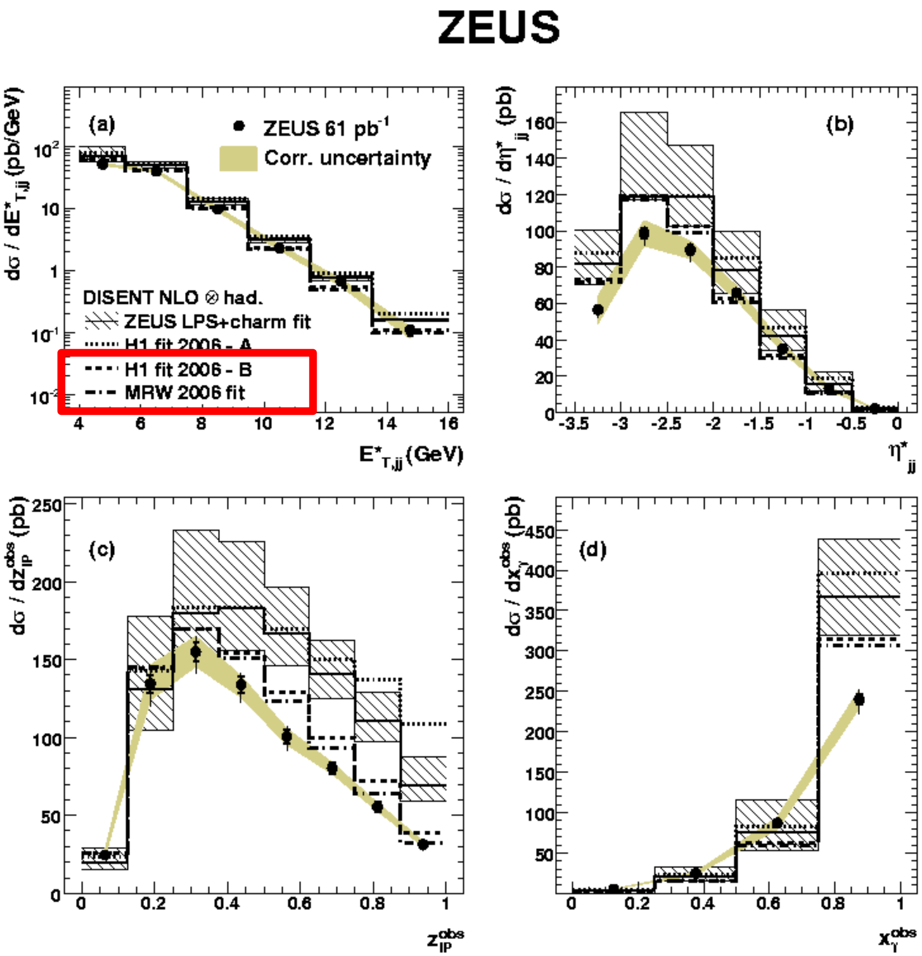


No evidence for QCD factorisation breaking (as expected).

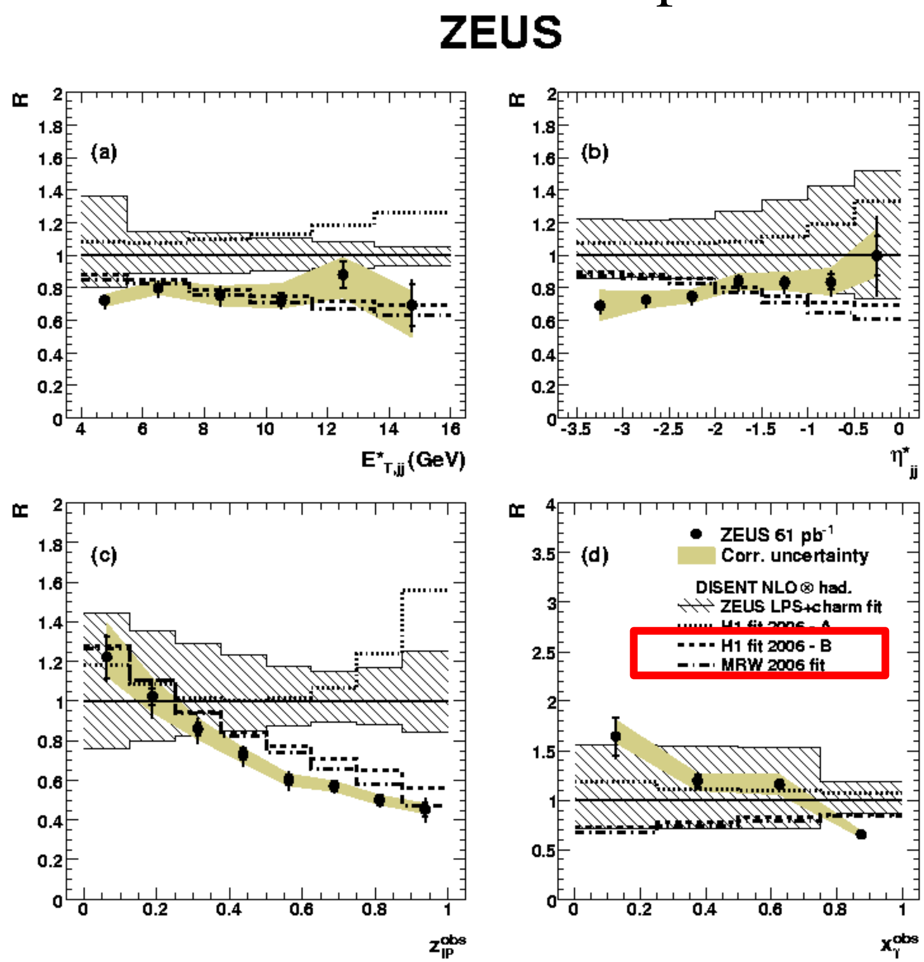
Remarkable precision of the measurement (~ 4% stat, 8% syst, 6% corr).

Data prefer strongly calculation using H1 fit B and MRW dPDFs

Cross sections



Ratio to ZEUS LPS prediction



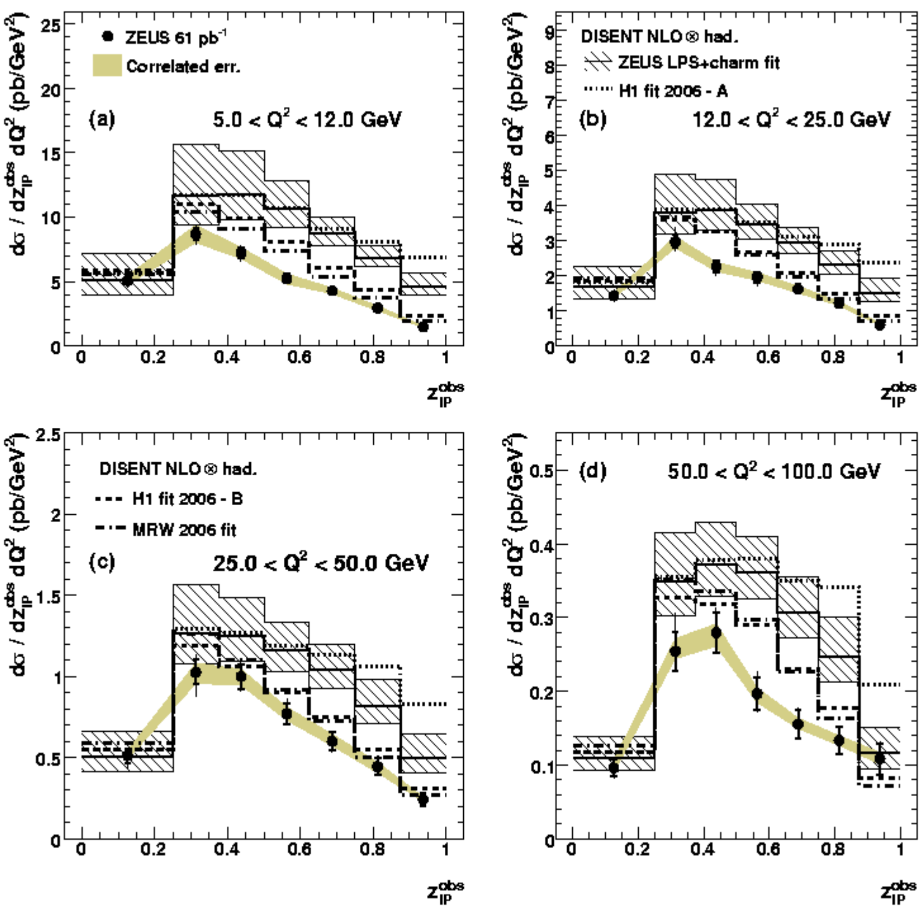
No evidence for QCD factorisation breaking (as expected).

Remarkable precision of the measurement.

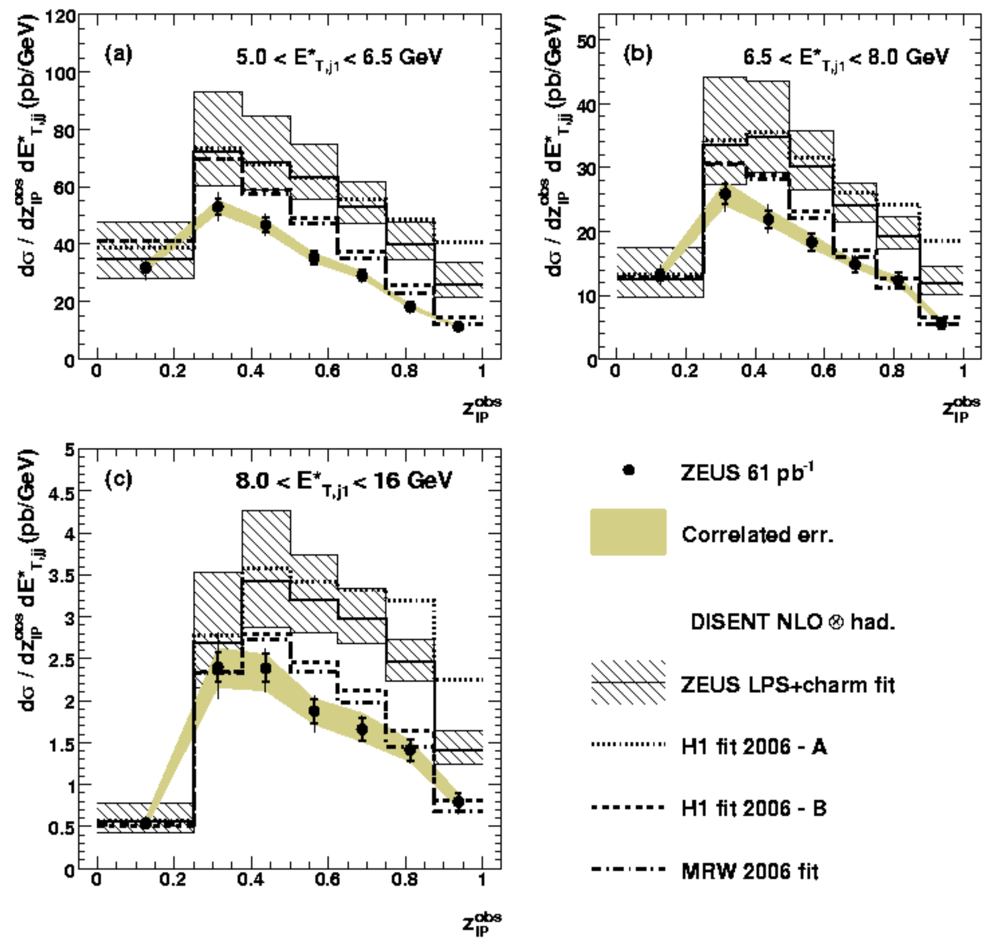
Data prefer strongly calculation using H1 fit B and MRW dPDFs

Double differential cross sections

Z_{IP} and Q^2



Z_{IP} and $E^*_{T,j1}$



Remarkable precision of the measurement.

These data can be used for a more constrained fit to the dPDFs

Summary

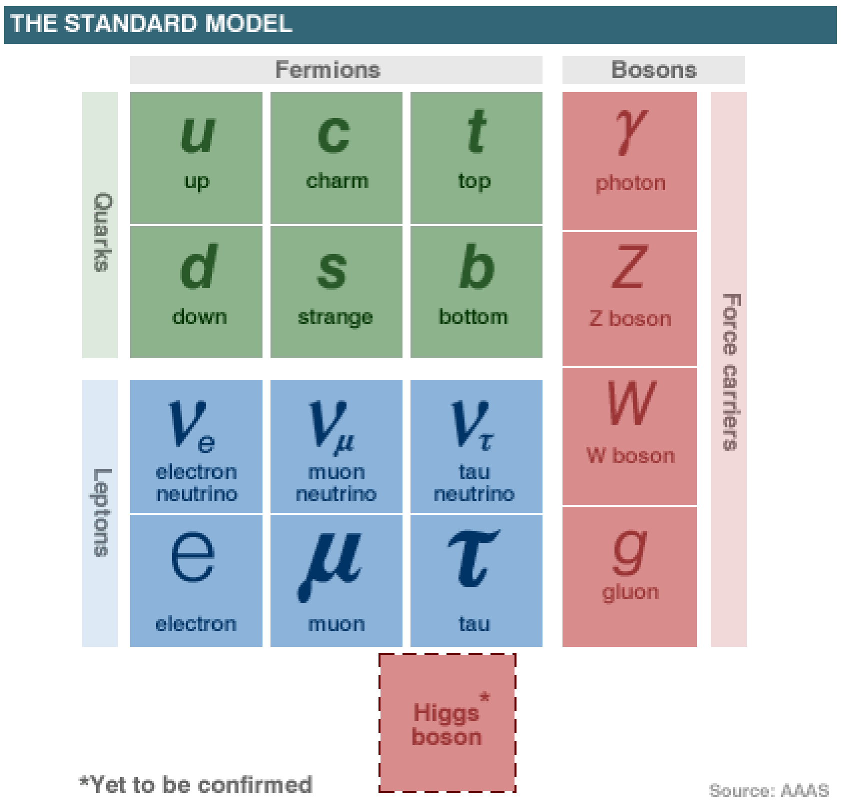
- Rich program of physics pursued at HERA. Fundamental for any other development (i.e. LHC). Diffraction is one of the main topics.
- Diffraction can be understood in terms of QCD (!!!) and can provide an even richer information than standard DIS.
- QCD factorisation is an important theorem for doing QCD studies in diffraction. Its test is mandatory.
- **Dijets in diffraction** are the best benchmark for that.
- An analysis of ZEUS data was presented here.
- The cross section was measured with (unprecedented) good precision.
- Data have strong discriminant power on the dPDFs used for the NLO.
- Data can be a precious **input to further fits to the dPDFs**.

Prospects

- This analysis has been recently released by ZEUS and accepted by Eur. Phys. J. (arXiv:0708.1415).
- The inclusion of these data in a QCD fit with the inclusive ones is an important step forward. It was already done by the H1 collaboration, showing how much the precision and stability of the fit can gain from it.
- Plenty of physics topics in diffraction at LHC (ATLAS, CMS, TOTEM, FP420) : exclusive Higgs, SUSY, QCD...
- Study of QCD factorisation breaking and soft rescattering at HERA are important for any of these diffractive analyses.

BACKUP SLIDES

The Standard Model



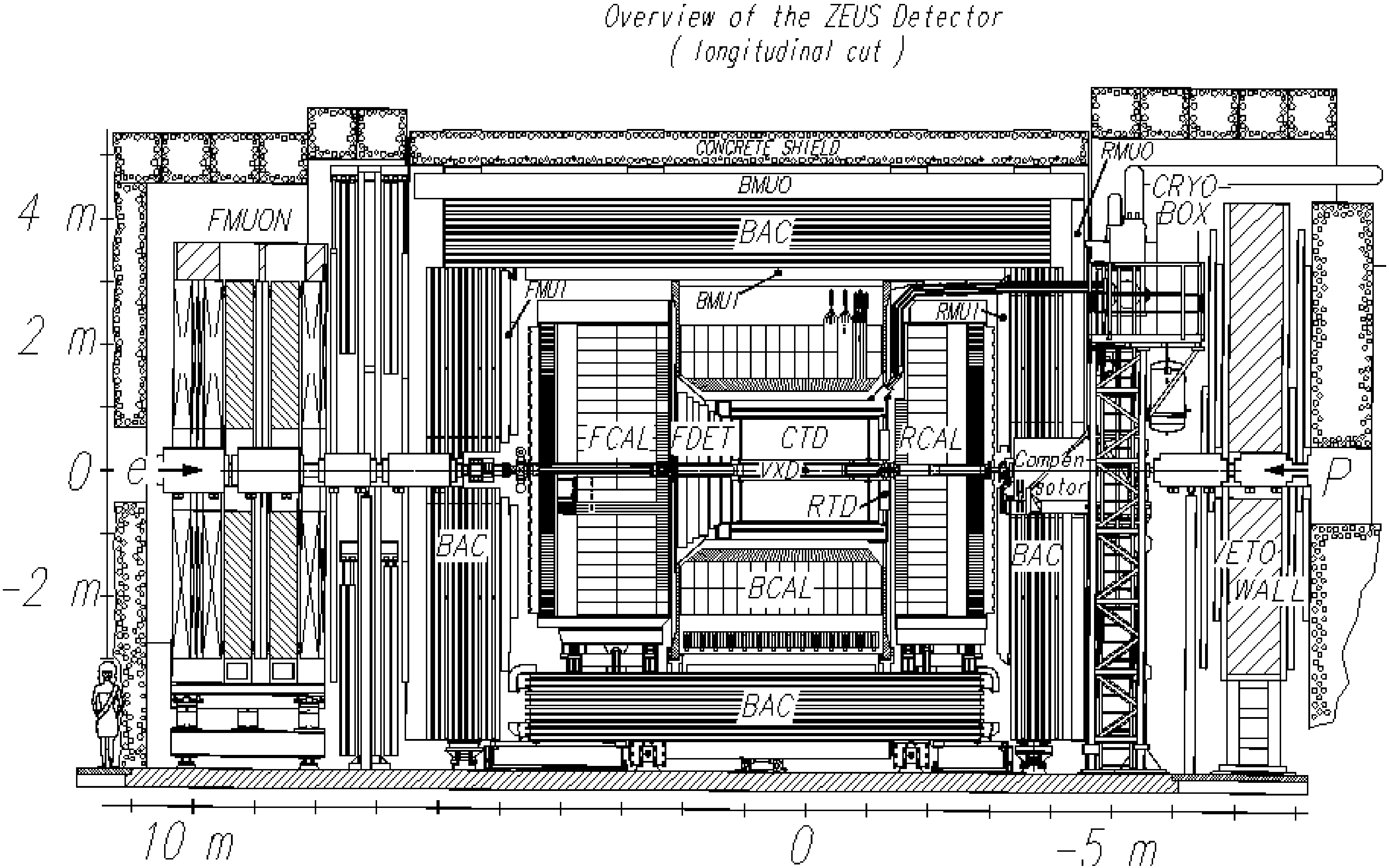
Lagrangian invariant under gauge transformations generated by $SU(3) \times SU(2)_L \times U(1)$.

Interactions mediated by Vector Bosons.

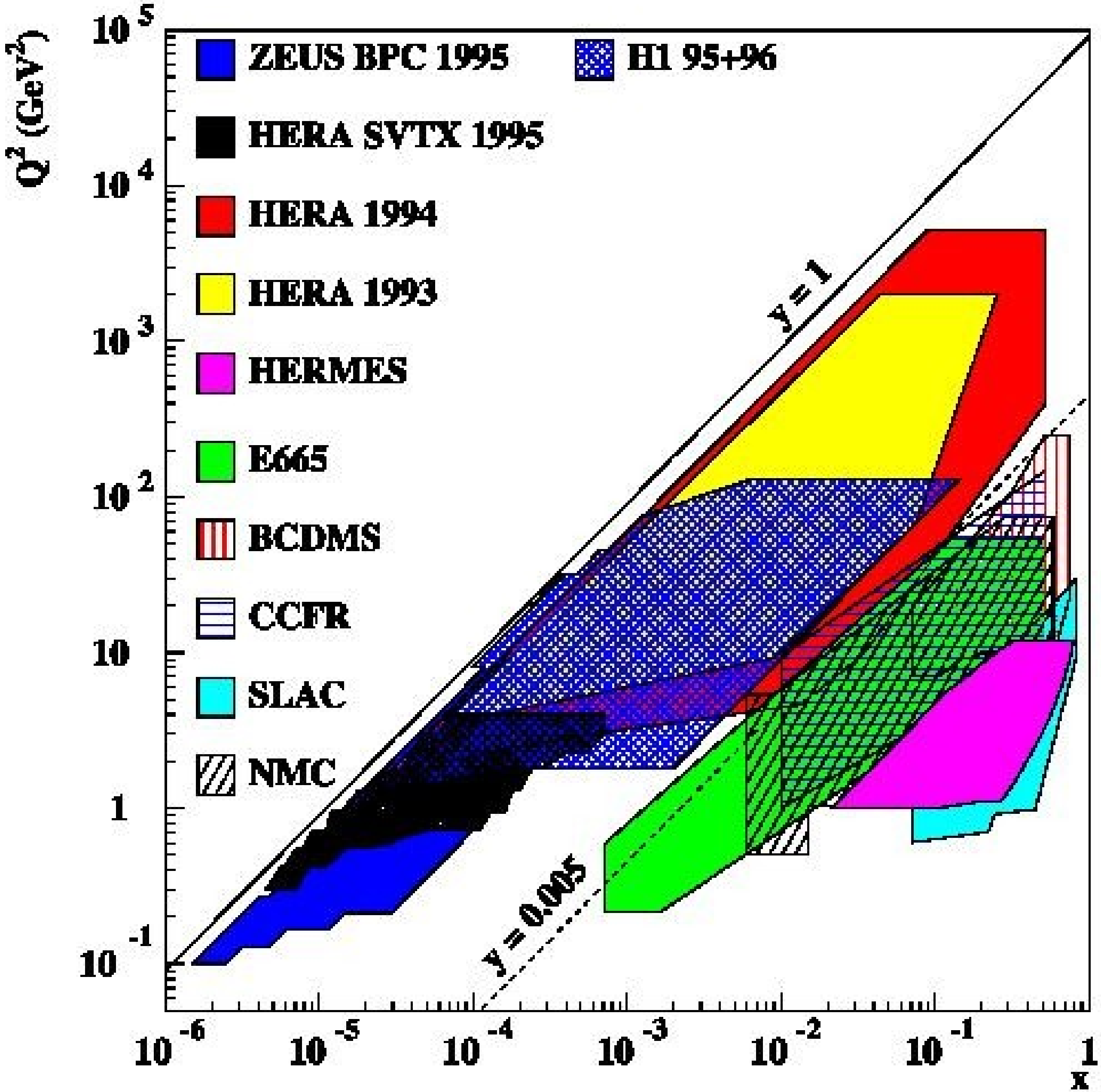
Leptons and quarks: basic constituents of the nature. Pointlike fermions.
Leptons: integer charge (0, -1), EM, weak interaction.
Quarks: fractional charge (+2/3, -1/3), subject to all interactions.

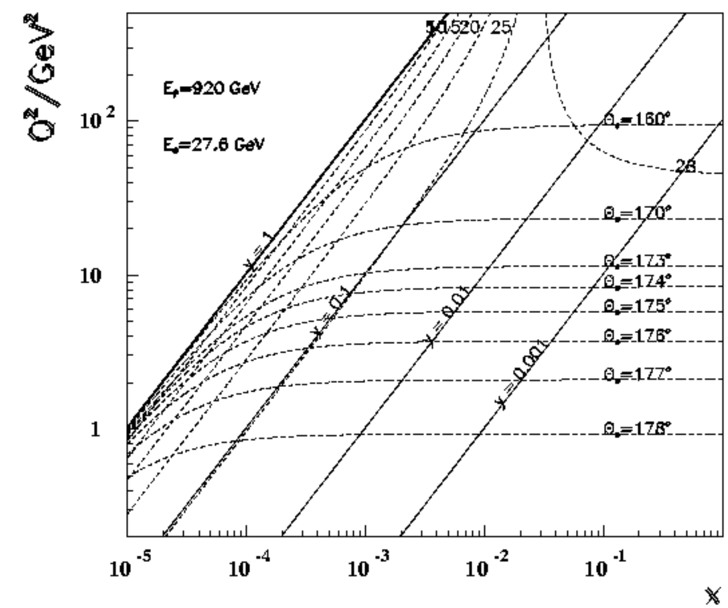
Strong interaction is responsible for the existence of hadrons and nuclei. Described by Quantum ChromoDinamics.

ZEUS components

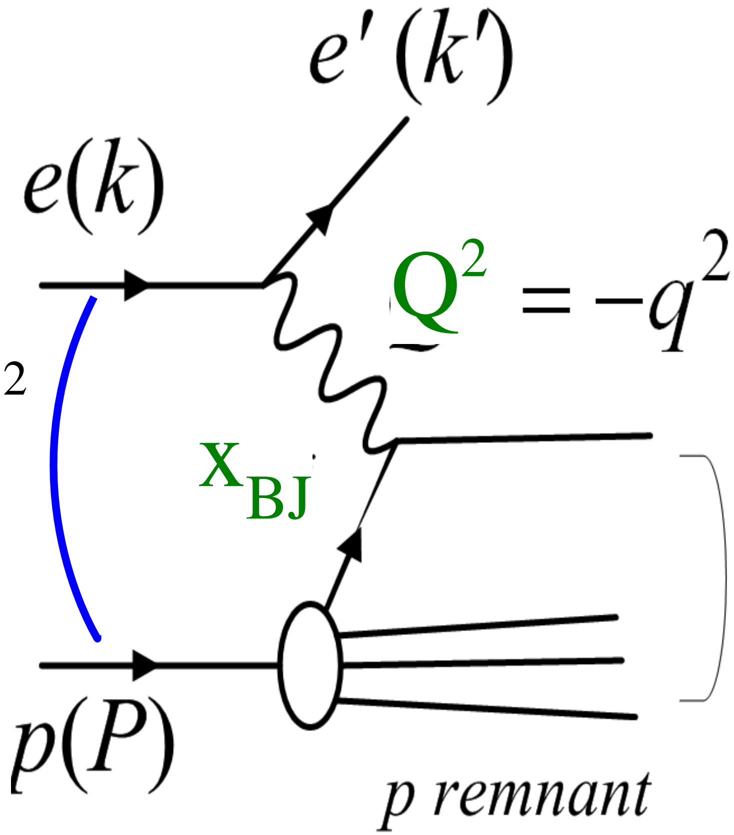


HERA kinematic range





DIS kinematics



$$Q^2 = -q^2 = -(k-k')^2 \simeq 4\, E_e E_{e'} \sin^2(\theta/2)$$

$$s = (p+k)^2$$

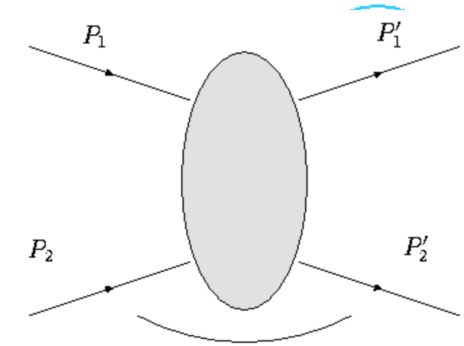
$$W^2 = (q+P)^2$$ c.m. energy of γp system

$$x = \frac{Q^2}{(Q^2+W^2)}$$

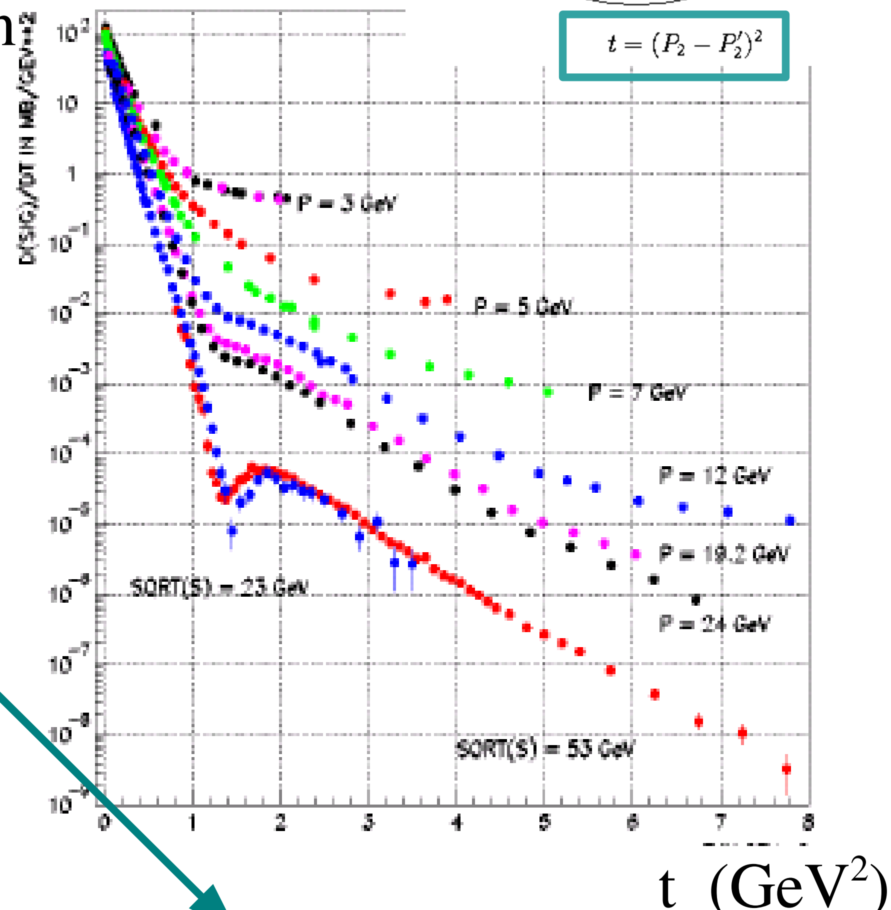
$$y = \frac{pq}{pk}$$ inelasticity

$$sxy = Q^2$$

Diffraction: Intro



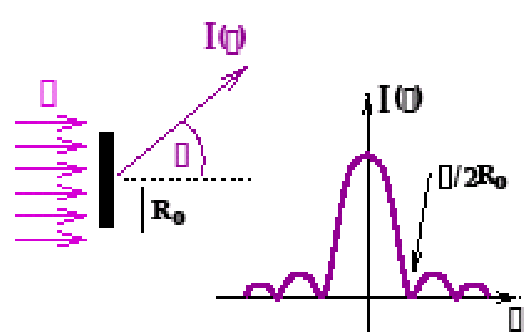
Known since '60s.
Feature of the elastic pp σ is the concentration at small t (-> small cosϑ): ***diffractive peak***



Elastic cross sect. in pp collisions:

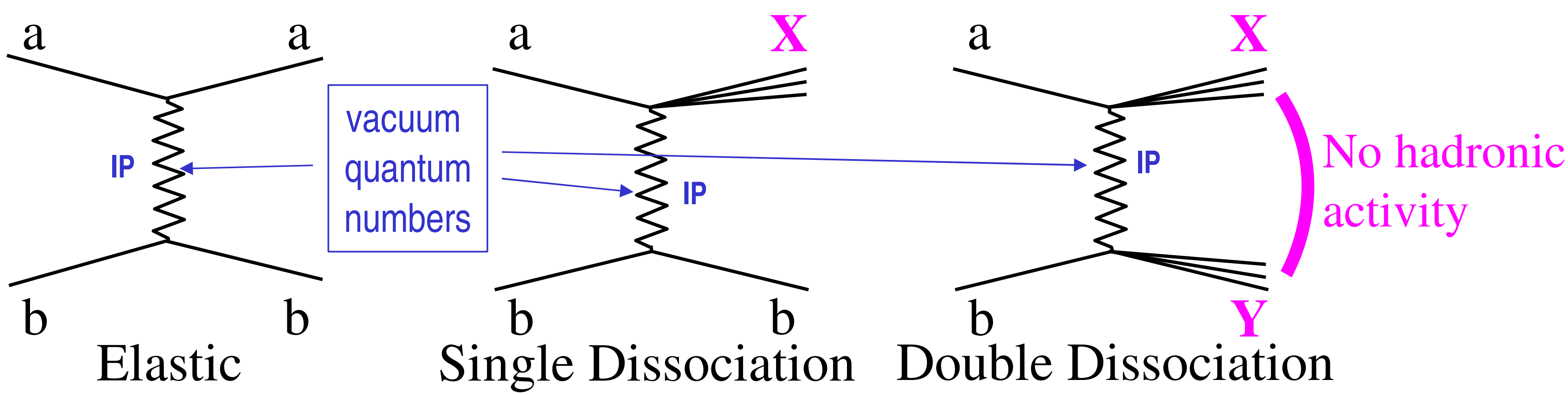
$$\frac{\dfrac{d\sigma_{el}}{dt}}{\dfrac{d\sigma_{el}}{dt}\Big|_{t=0}} \simeq e^{-b(s)|t|} \simeq \mathbf{1-b(s)\cdot(P\,\theta)^2}$$

Analogy with optics:
light on a black disk of radius ~ wavelenght



$$\frac{I(\theta)}{I(\theta=0)} = \frac{[2J_1(x)]^2}{x^2} \simeq \mathbf{1-\frac{R_0^2}{4}(k\,\theta)^2}$$

- Diffraction is involved in elastic processes, *i.e.* processes in which the final state is the same as the initial one, p + p → p + p . But not only that...
- One intact and the other breaks up (X). X has the same quantum numbers of the former particle - single diffractive dissociation.
- **Both** the particles go out from the interaction in a resonant state, (but quantum numbers stay the same) - double diffractive dissociation.



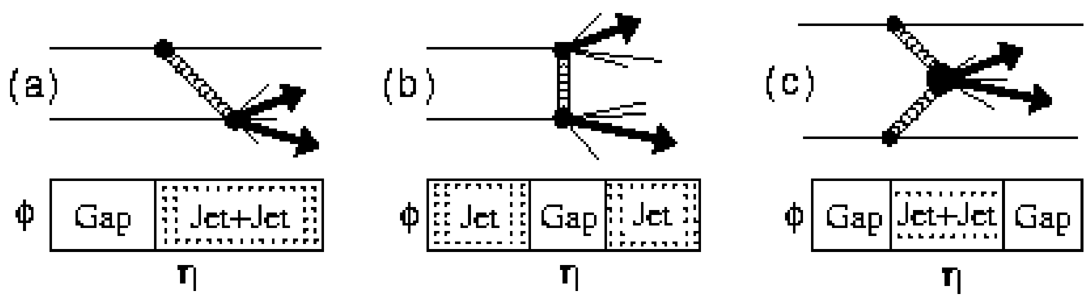
*For diffraction we mean all those types of processes in which no quantum numbers (charge, isospin, barion number, **color**,...) are exchanged between the interacting particles.*

Diffr 4

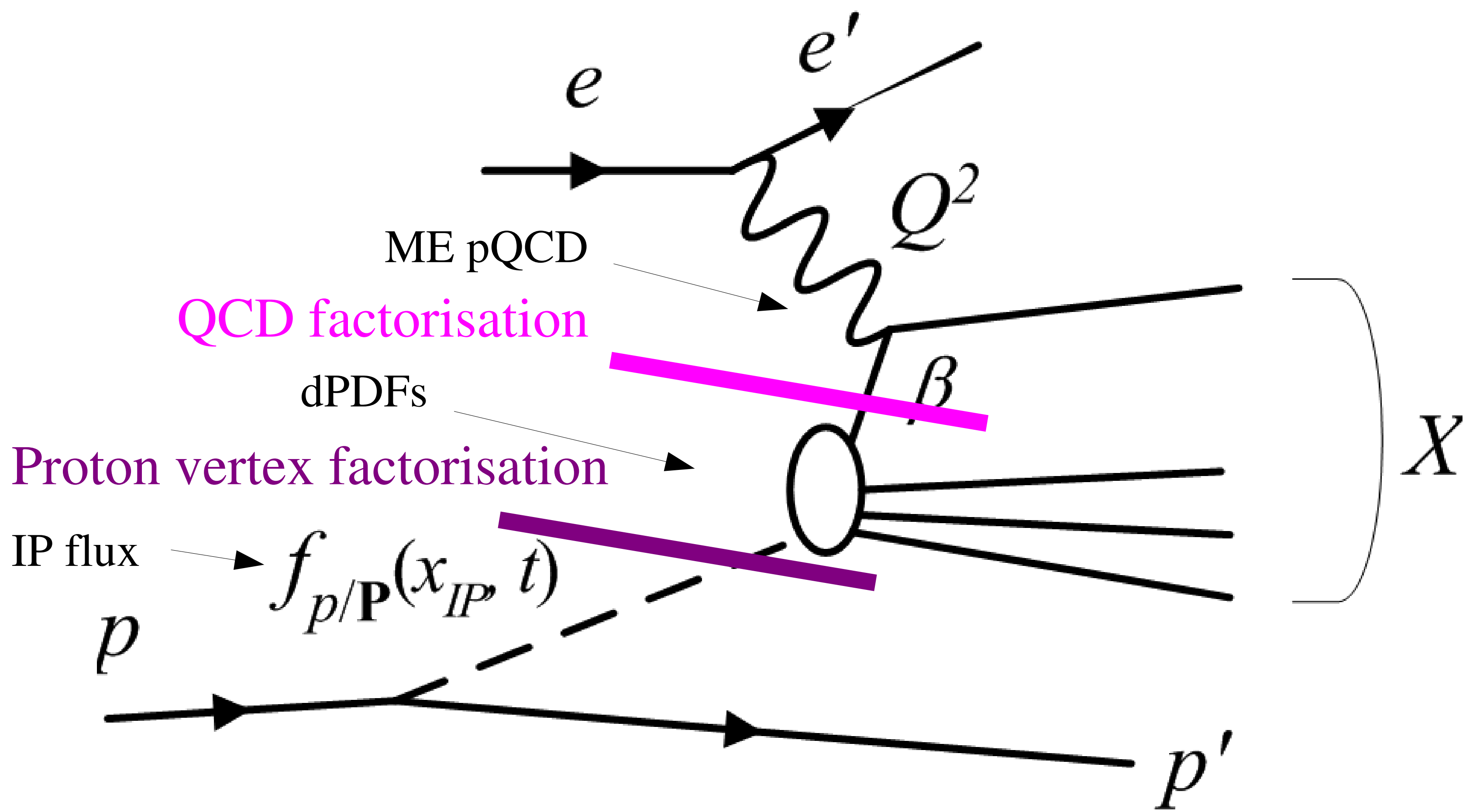
Elastic pp scattering   soft process. QCD is not in perturbative regime.

But what if we ask for a hard scale in the diffractive process, that is a process like

$$p + p \rightarrow p + X + p$$

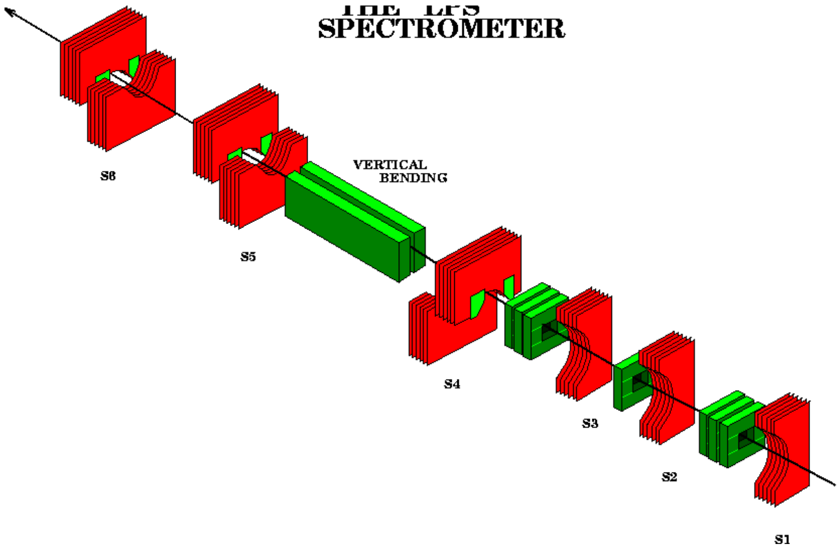


Hadronic system X contains a hard scale which allows the use of pQCD.
Final state quantum numbers = Initial state quantum numbers.



Proton vertex factorisation not needed in principle
but big theoretical simplification.

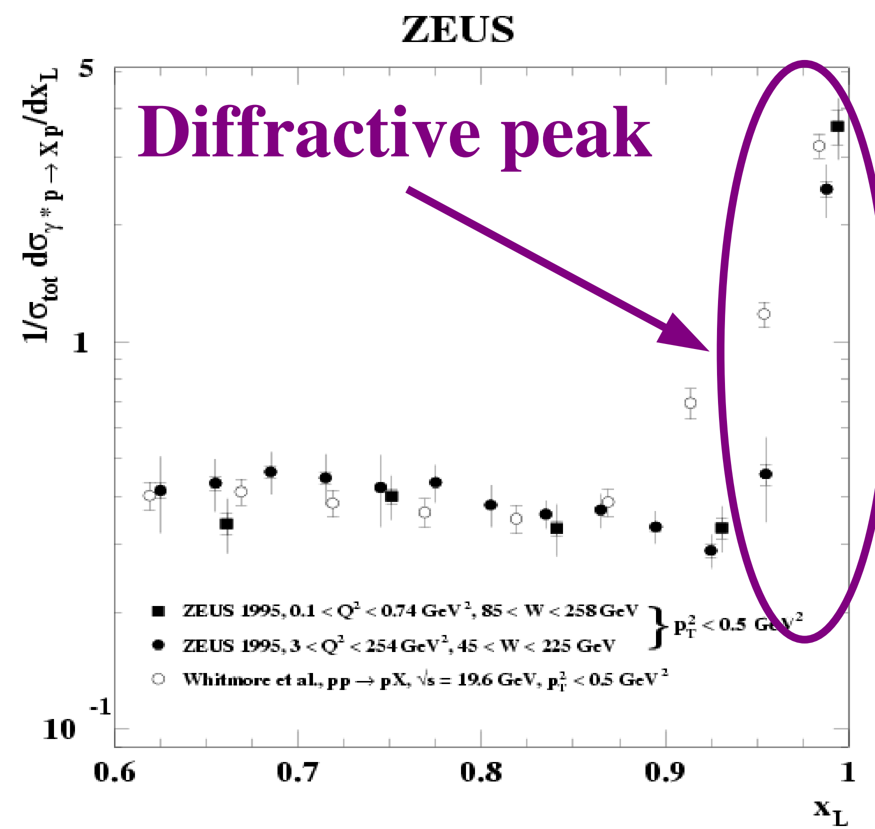
Diffr 8



Proton Spectrometer

Diffractive tag by detecting directly the scattered proton.

Tracking device close to the beam, far from the Interaction Point (p' only slightly perturbated). HERA dipoles for bending.



- Very clear diffractive tag
- Rich of informations (t measured directly)
- Low acceptance -> low statistics

x_L = fraction of p initial 4-mom kept

$$= \frac{|\vec{P}\,'|}{|\vec{P}|}$$

Strictly connected to the LRG method.

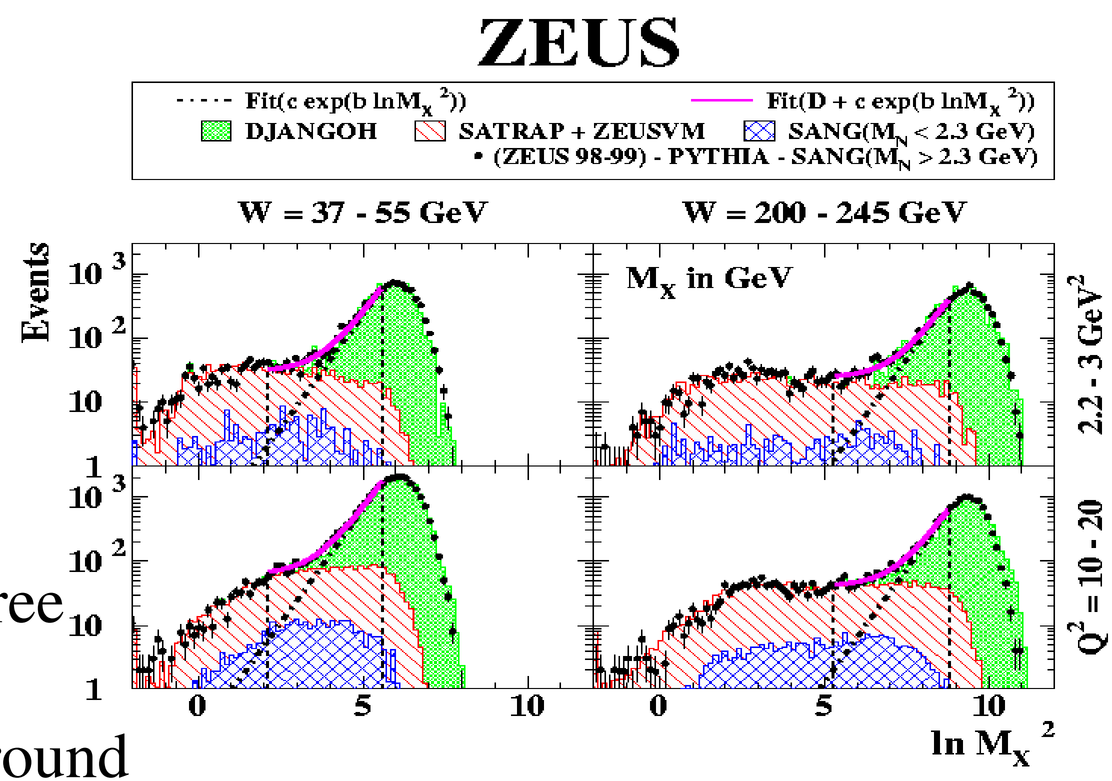
Hadronic radiation Poisson-distributed for non-diffr events

Rapidity gap in diffraction impose precise kinematic constraints on W and M_X.

The different M_X^2 dependence for diff and non-diff events is exploited in a fit for subtracting the non-diffr events to the total

diffr. non-diffr.

$$\frac{dN}{d\,lnM_X^2} = D + c\ \exp\left(b\ lnM_X^2\right)$$



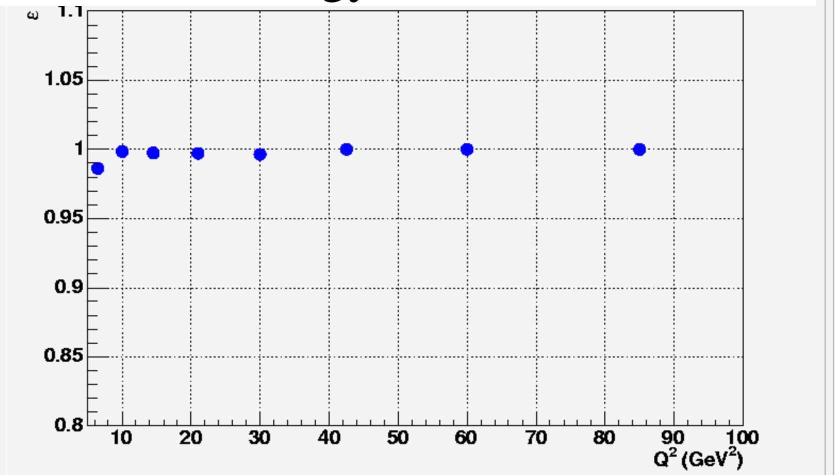
- High statistics
- Mesonic exchange background free
- No detection of P'
- Sensitive to P dissociation background

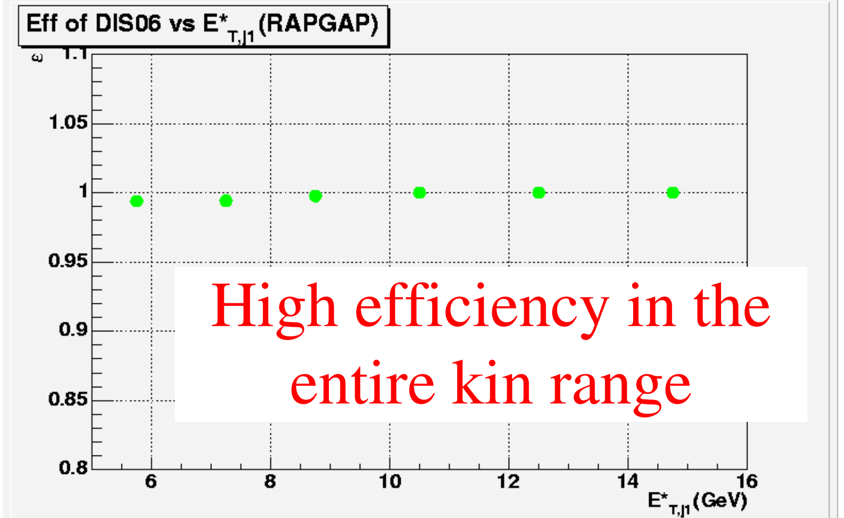
Trigger

- First Level selection:
  - Total energy in ECAL
  - Energy in rear ECAL
  - Transverse energy
- Second level selection:
  - Activity in the ECAL
  - E-Pz > 30 GeV
- Third level selection:
  - $E\text{-}P_z > 30$ GeV
  - $E_{e'} > 4$ GeV
  - Box cut 12×6 cm^2
  - $E_{FPC} < 20$ GeV

$$\varepsilon = \frac{(\#Events\,(Selected + Triggered))}{(\#Events\,(Selected\,))}$$

Trigger eff as function of Q^2 and transverse energy of jet with highest transverse energy





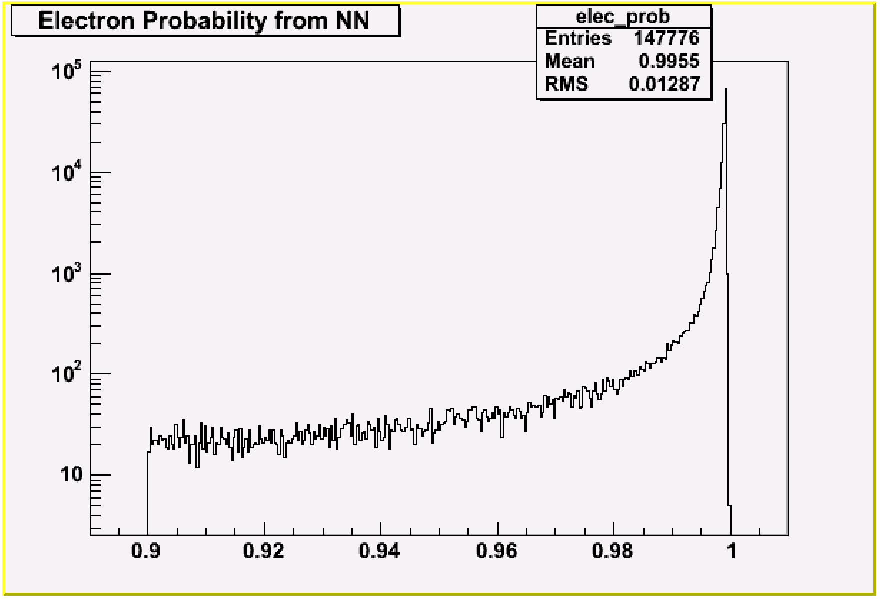
High efficiency in the entire kin range

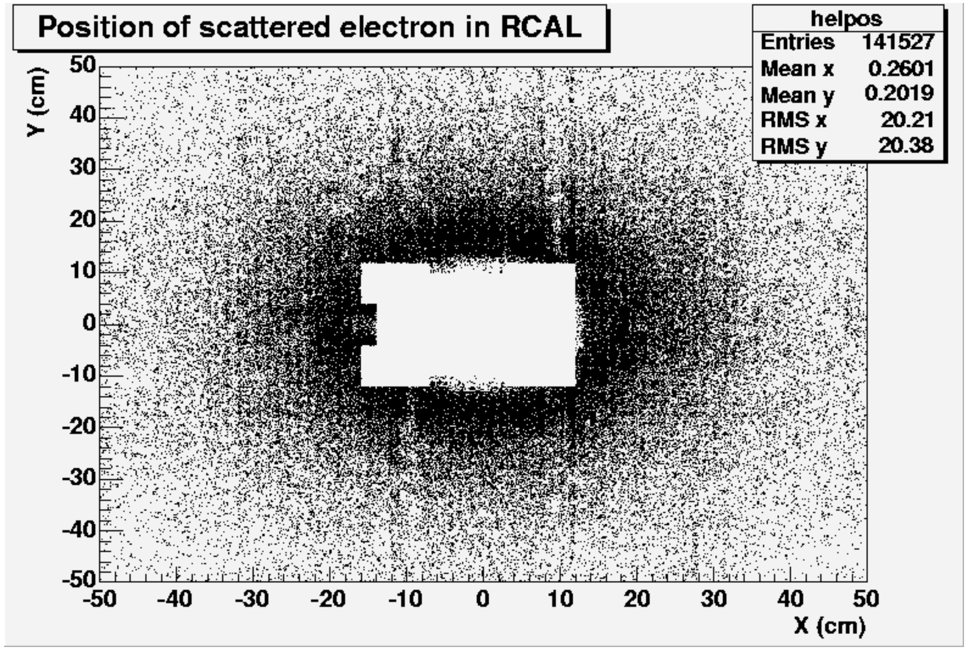
DIS selection

Electron identified from ECAL clusters with a neural network algorithm.

DIS selections:

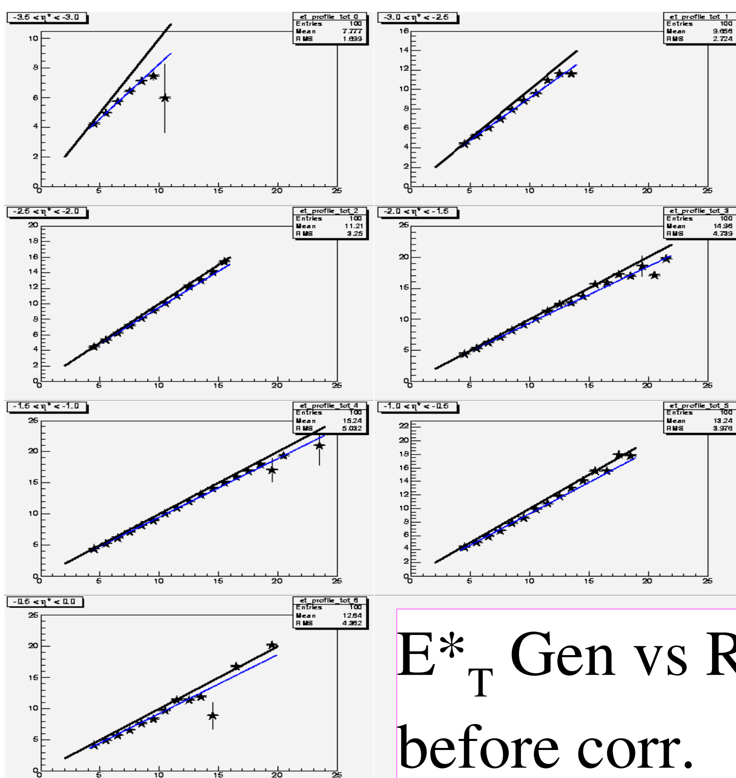
- $45 < E- p_Z < 65$ GeV
- $E'_{el} > 10$ GeV
- $-50.0 < Z_{vtx} < 50.0$ cm
- DIS electron outside fiducial box
- $5 < Q^2_{DA} < 100$ GeV^2
- $100 < W_{DA} < 250$ GeV



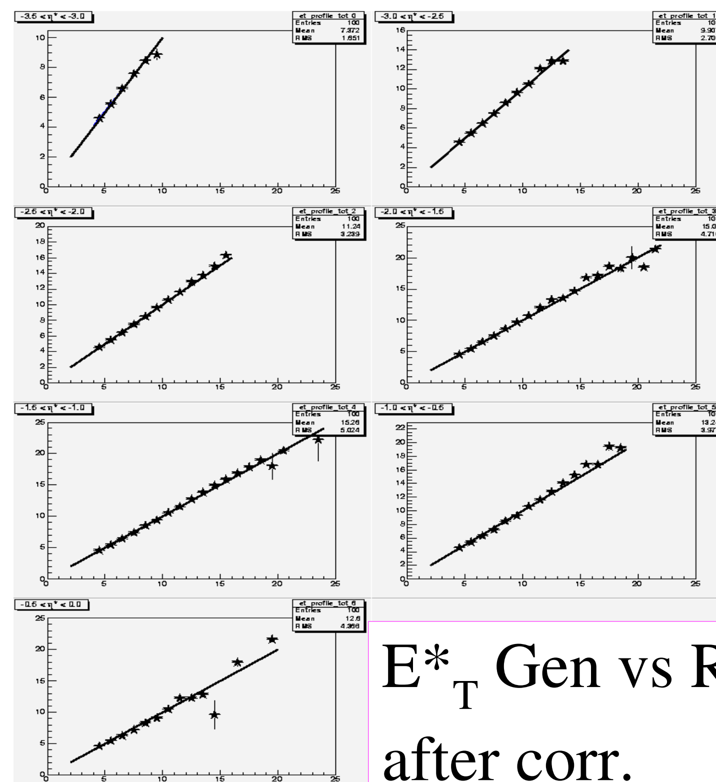


Jet selection

- Jets reconstructed from Energy Flow Objects (EFOs) mixing tracking+CAL informations
- K_T algorithm run on EFOs in the γ -proton c.m.s. (labeled with a star)
- Jets transverse energy (E_T) corrected for inactive material
- **Njets ≥ 2**
- E^*_T of jet with highest E^*_T : **$E^*_{T,jet1} > 5$ GeV**
- E^*_T of 2nd jet : **$E^*_{T,jet2} > 4$ GeV**
- η^* of all jets : **$-3.5 < \eta^* < 0$**
- η^{LAB} of all jets : **$-2 < \eta^{LAB} < 2$**



E^*_T Gen vs Rec before corr.



E^*_T Gen vs Rec after corr.