Hard Diffraction at ep and pp Colliders (HERA, TEVATRON, LHC)

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CERN EP-Seminar, April 2005

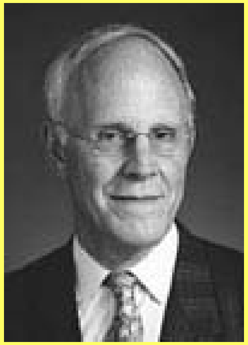
Recent results from HERA and the TEVATRON …

… and an outlook to the plans at the LHC

QCD as the theory of the strong force

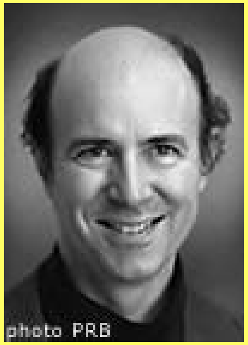
Quantum chromodynamics QCD established as theory of strong interaction

Nobel price 2004:
Asymptotic freedom:
Coupling small
at short distances

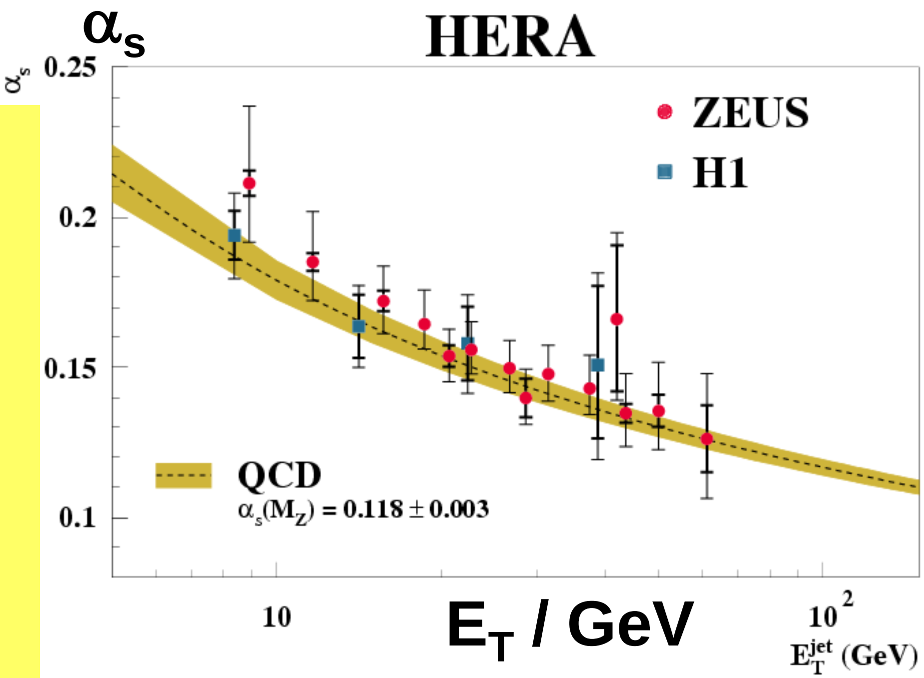


D. Gross

D. Politzer



F. Wilczek

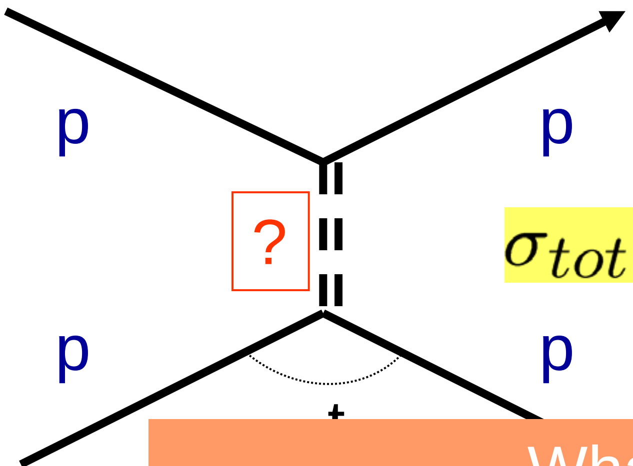


- Quark- and gluon exchange
- Gluons carry colour charge!

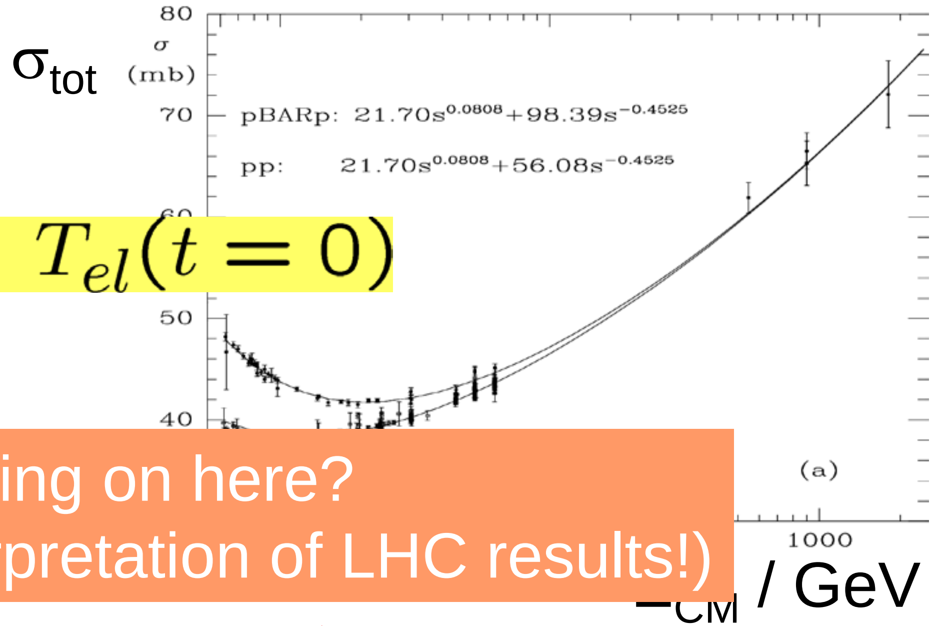
Hard scale → α_s small → Perturbative QCD calculations possible!

Proton scattering at high energies

B) Soft processes, in particular elastic scattering:



$$\sigma_{tot} \sim \text{Im}\ T_{el}(t=0)$$



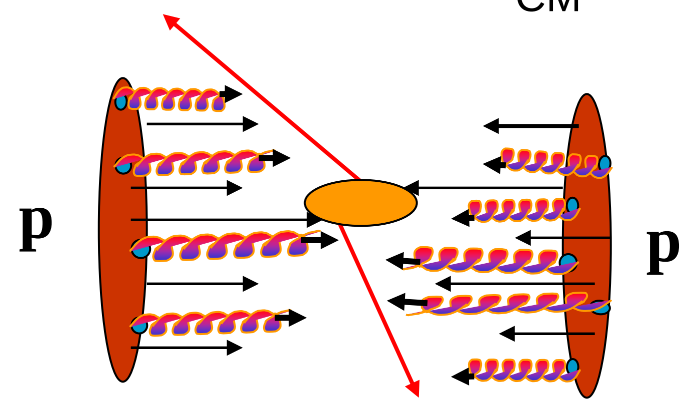
What is going on here?
(Also important for interpretation of LHC results!)

A) Hard QCD processes:

Jet, W, Z, t production

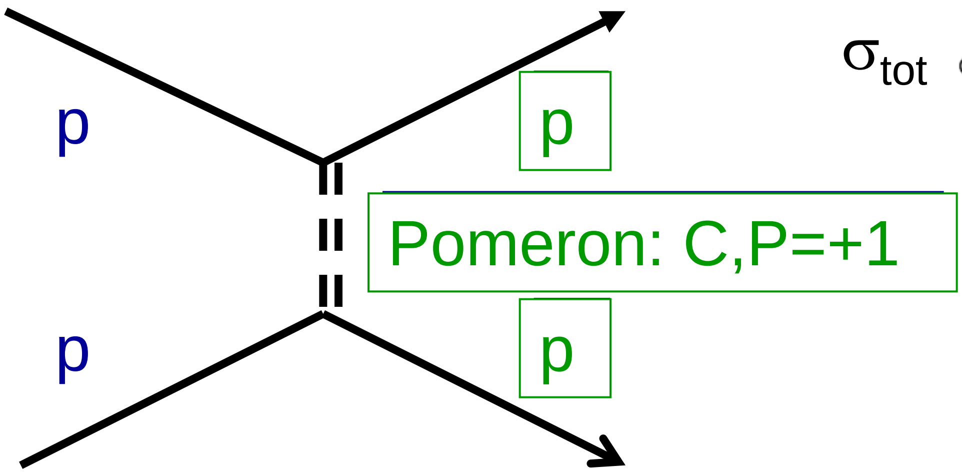
Perturbation theory successful

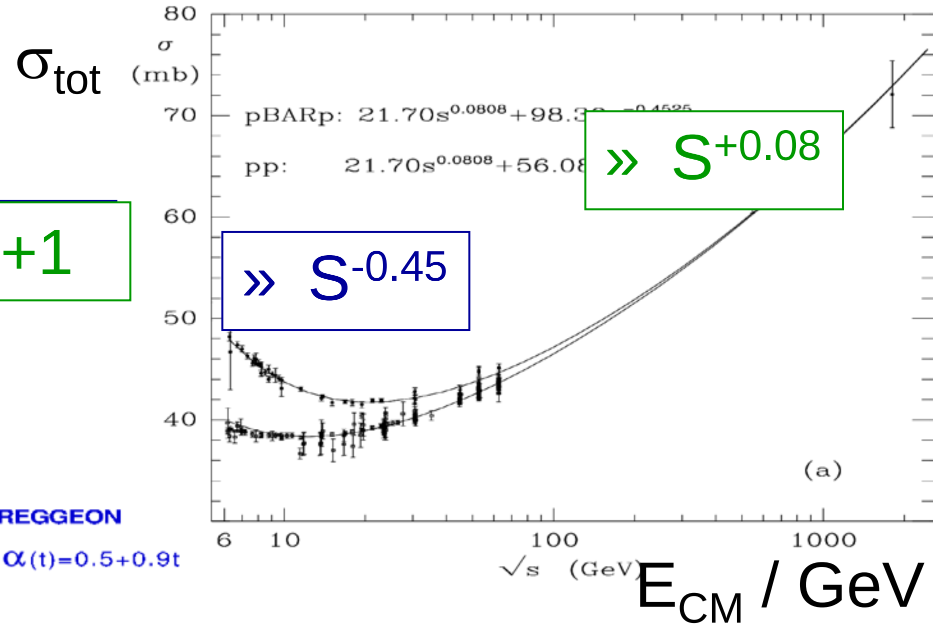
<u>But:</u> just small fraction of σ_{tot}

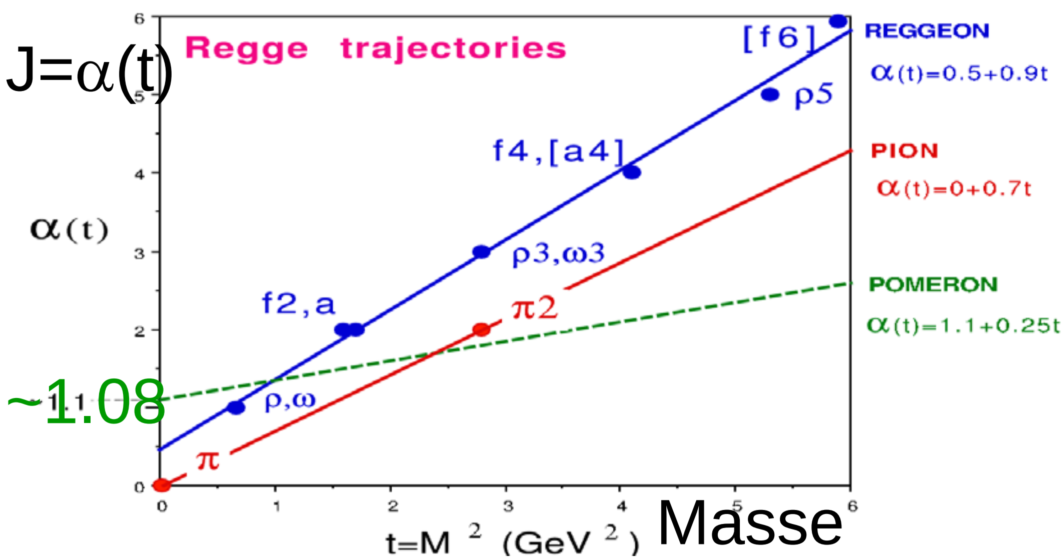


Proton scattering at high energies

t-channel exchange of mesons and their radial excitations:







$$\alpha(t) = \alpha(0) + \alpha' t$$

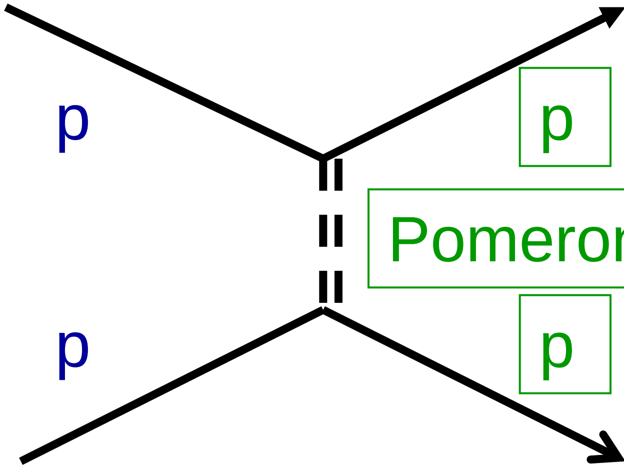
$$\sigma_{tot} \sim s^{\alpha(0)-1}$$

E_{CM}<20 GeV: Reggeon

E_{CM}>20 GeV: Pomeron

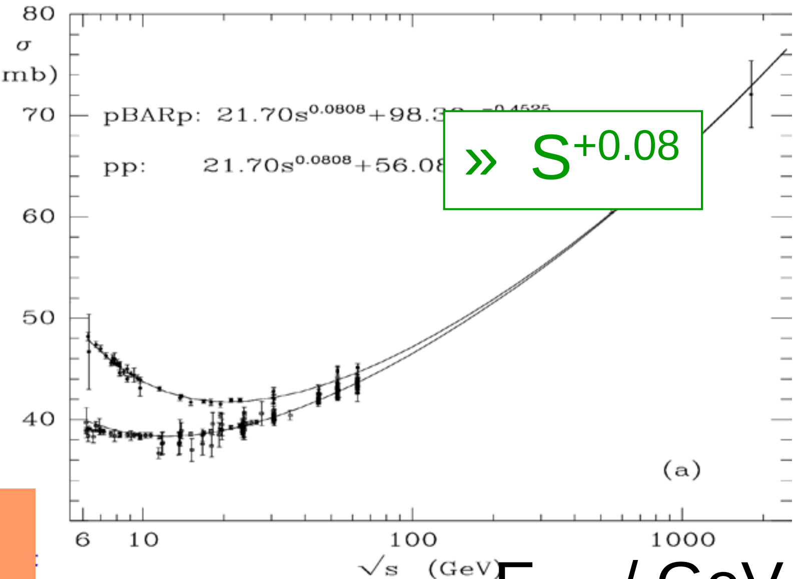
Proton scattering at high energies

t-channel exchange of mesons and their radial excitations:



Pomeron: C,P=+1

σ_{tot}



» $S^{+0.08}$

E_{CM} / GeV

- Ad hoc name: Pomeron
- No exchange particle known
- **α_{IP}(t)=1.08+0.25t**
- Elastic scattering: vacuum Q.N.

What is the QCD description?
(quarks / gluons)

$$\alpha(t) = \alpha(0) + \alpha' t$$

$$\sigma_{tot} \sim s^{\alpha(0)-1}$$

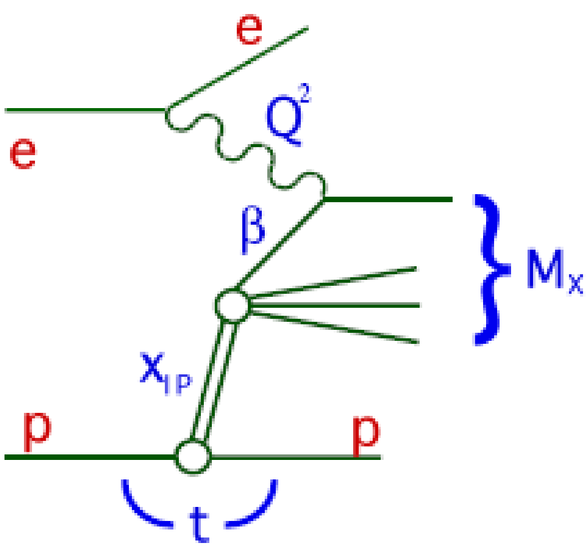
E_{CM}>20 GeV: Pomeron

Diffraction in deep-inelastic scattering (DIS) at HERA

Diffractive DIS: Kinematics

Deep-inelastic scattering with elastically scattered proton …

HERA advantage: point-like photon as a probe in DIS



Q^2,x: standard DIS variables $y = Q^2/sx$

x_{IP}: momentum fraction of diffractive exchange wrt incoming proton (typically <0.05)

β: fractional momentum of quark struck by the photon, i.e. **$x=x_{IP}\beta$**

$t=(p-p')^2$: 4-momentum transfer at p vertex

W: γp centre-of-mass energy

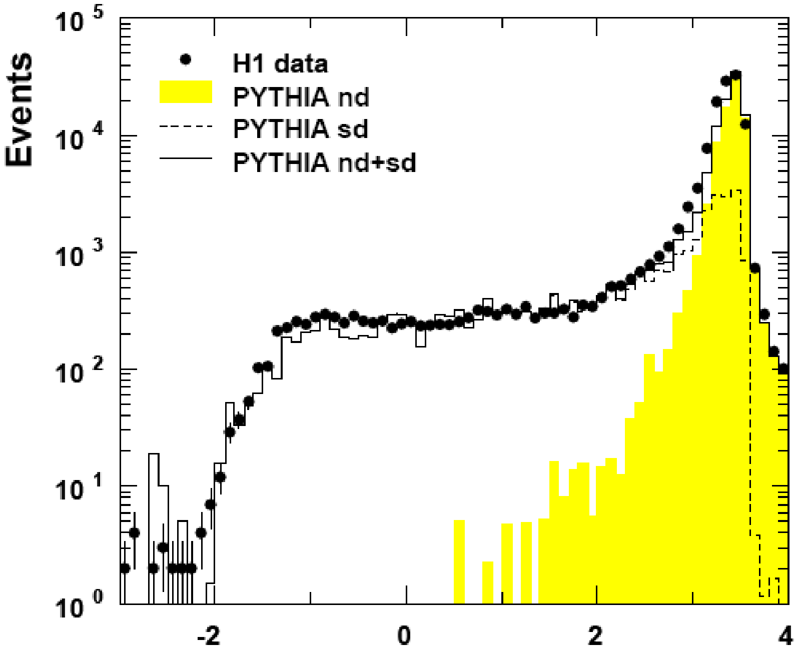
Diffractive structure function:

$$\frac{d^4\sigma^D}{dx_{I\!P}\ dt\ \ d\beta\ \ dQ^2} = \frac{4\pi\alpha^2}{\beta Q^4}\left(1 - y + \frac{y^2}{2}\right) F_2^{D(4)}(x_{I\!P}, t, \beta, Q^2)$$

Diffractive DIS at HERA: Measure structure of diffractive exchange!

Diffractive DIS at HERA

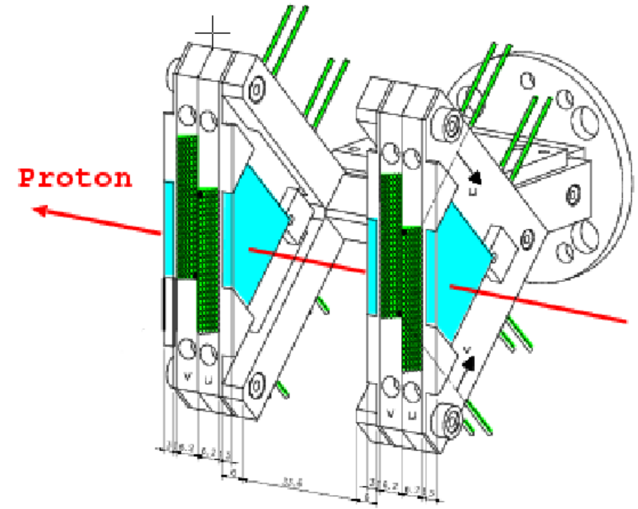
η_{max} Distribution



$$\eta_{max} = -\ln \tan \frac{\theta_{max}}{2}$$

Excess above non-diffractive contribution

Leading proton spectrometer: Direct measurement!

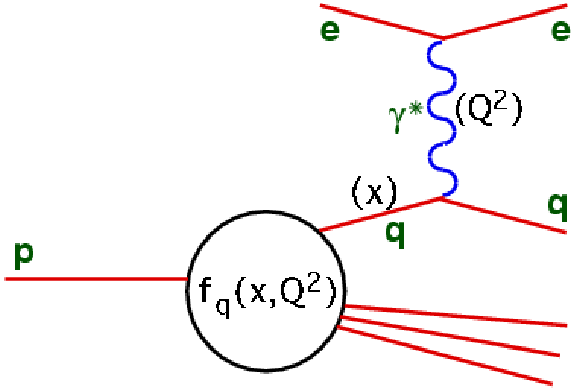


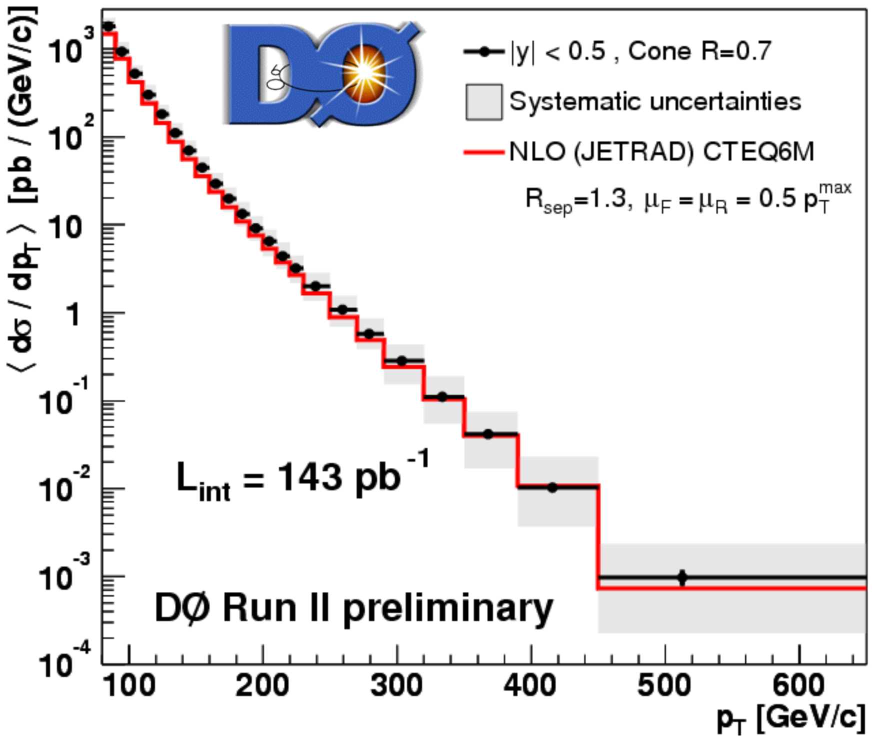
- ‘Roman Pot’ Detectors
- z=~100m; very close to beam!
- Machine dipoles as spectrometer

Measure full p kinematics!

QCD factorisation in DIS

Standard DIS





Factorisation theorem:

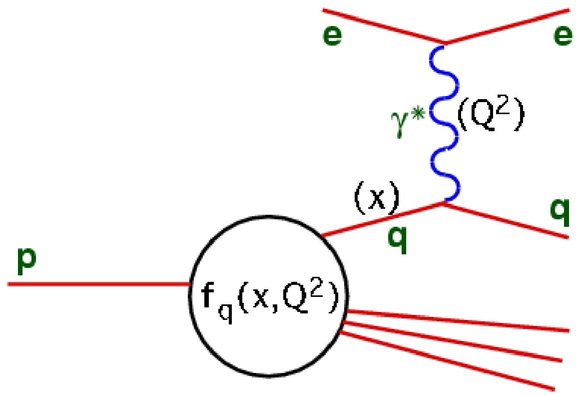
$$\sigma(x, Q^2)^{\gamma^* p \to X} \sim f(x, Q^2) \otimes \hat{\sigma}$$

e.g: Successful prediction of the TEVATRON jet cross section based on HERA parton densities!

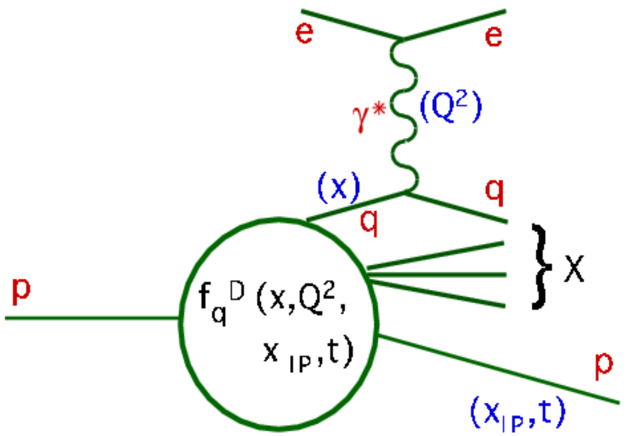
→Parton densities are universal!

QCD factorisation in diffractive DIS

Standard DIS



Diffractive DIS



Factorisation theorem:

$$\sigma(x,Q^2)^{\gamma^* p \to X} \sim f(x,Q^2) \otimes \hat{\sigma}$$

Factorisation theorem (Collins '97):

$$\frac{d^2\sigma(x,Q^2,x_{I\!P},t)^{\gamma^* p \to p' X}}{dx_{I\!P}dt} \sim f^D(x,Q^2,x_{I\!P},t) \otimes \hat{\sigma}$$

Standard DIS→ Proton structure!
Diffractive DIS→ Diffractive structure!

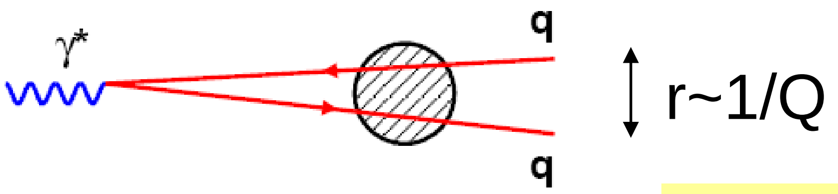
$f_i^D(x,Q^2,x_{IP},t)$: diffractive PDF:
Probab. to scatter off parton i with add. constraint that p stays intact

(Diffractive) parton densities universal: Final state predictions (e.g. jets)

NB: Factorisation in diffraction ONLY proved in DIS!

Alternative view:
DIS in the proton rest frame

Photon γ^* fluctuates into partonic states qq,qqg,…
long before the interaction with the proton:



$\tau_\gamma \sim 1/x$ $L_\gamma \sim$ 50fm!

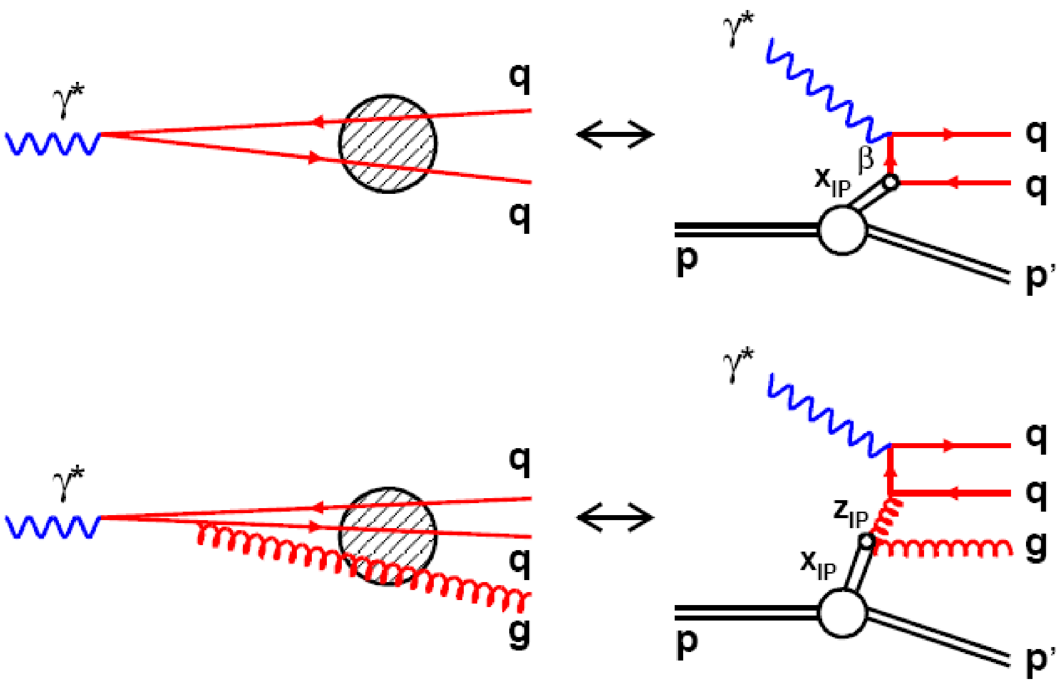
$$\sigma^{\gamma p}(x,Q^2) \sim \int d^2r \int d\alpha |\Psi(\alpha,r)|^2 \ \hat{\sigma}(x,r^2)$$

Dipole wave function   Dipole-p CS

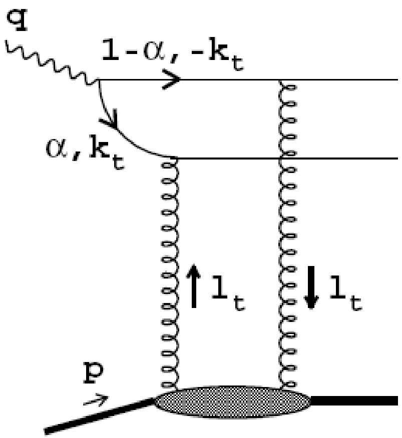
- **DIS at low x is the total cross section of a qq colour dipole with the proton at high energies**
- **The size of the dipole can be varied with Q^2 ('self made hadron')**
- **For small dipoles (large Q^2): perturbation theory applicable!**

Diffraction in the proton rest frame

Proton rest frame   Infinite momentum frame



Diffraction: that part of the total cross section in which dipole emerges as colour singlet from interaction!



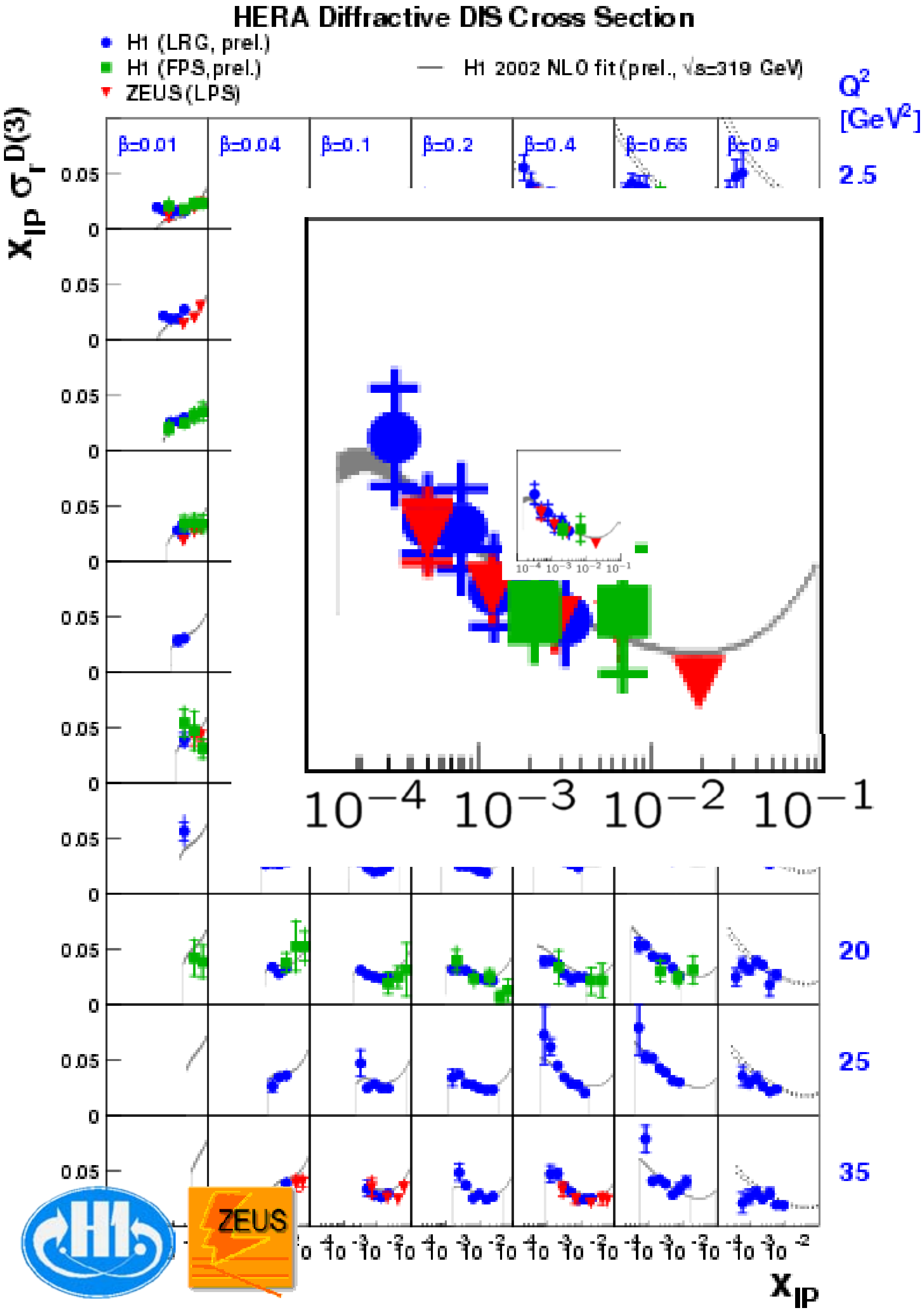
Calculation of the diffractive dipole cross section?

a) **Perturbative: simplest partonic configuration: 2-gluon exchange**

b) **Non-perturbative: colour neutralisation through the soft gluon field of the proton**

Die 'truth' should be somewhere these two extremes …

F_2^D Measurements



3-dimensional structure function **$F_2^{D(3)}$** (subset)
→precise measurements

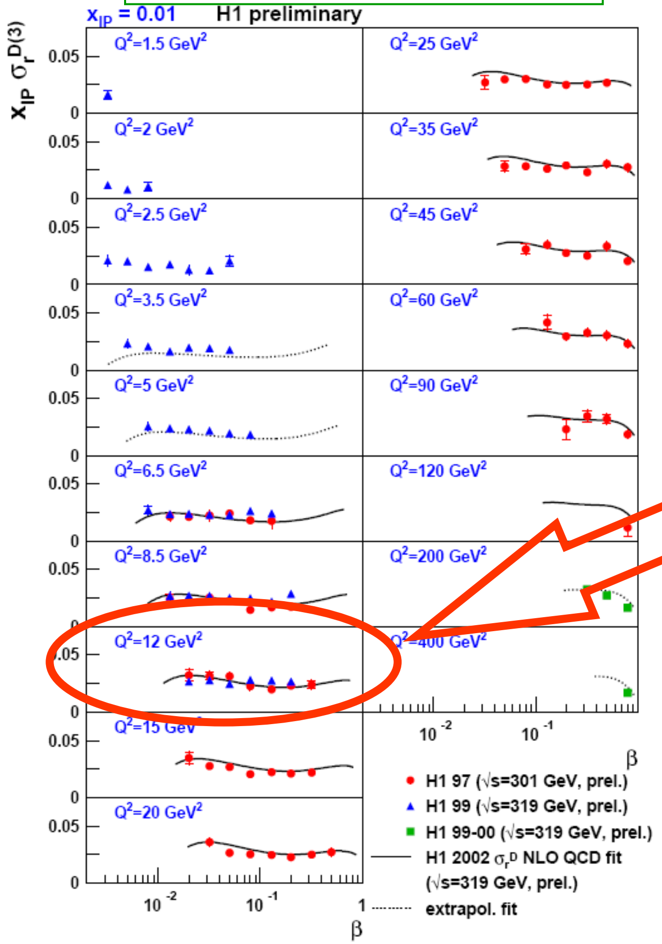
Full kinematic range:
$1.5<Q^2<2000$ GeV²
$10^{-2}<\beta<0.9$
$4*10^{-5}<x_{IP}<0.05$

Good agreement between ‘roman pot’ and ‘rapidity gap’ measurements!

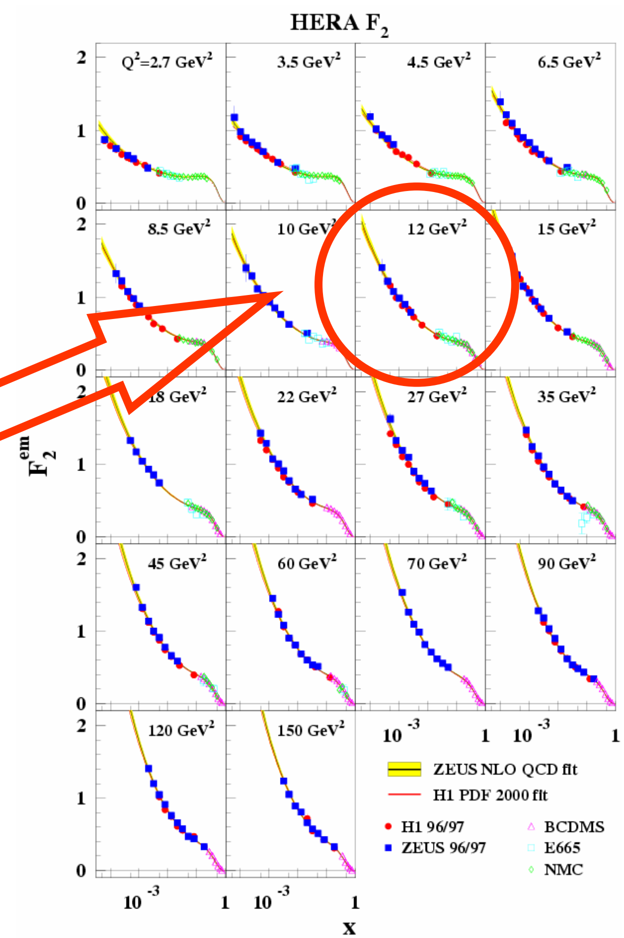
Characteristic rise with
$s_{\gamma^*p}=W^2$» 1/ x_{IP}
From fit: $\alpha_{IP}(0)\sim 1.2 > 1.08$

Comparison F_2^D with F_2: β-dependence

Diffractive vs β:



Proton vs x:

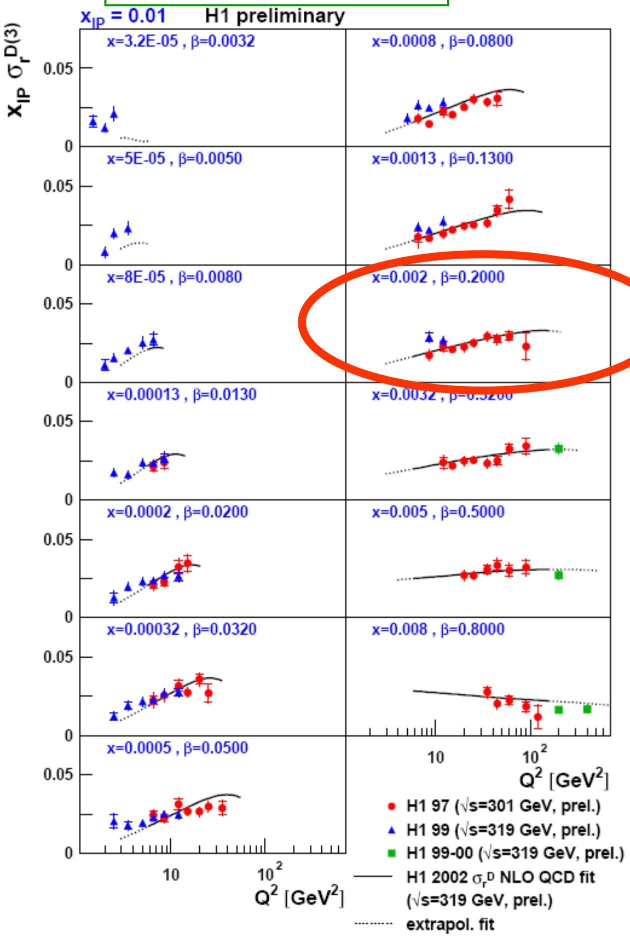


Only weak β dependence …

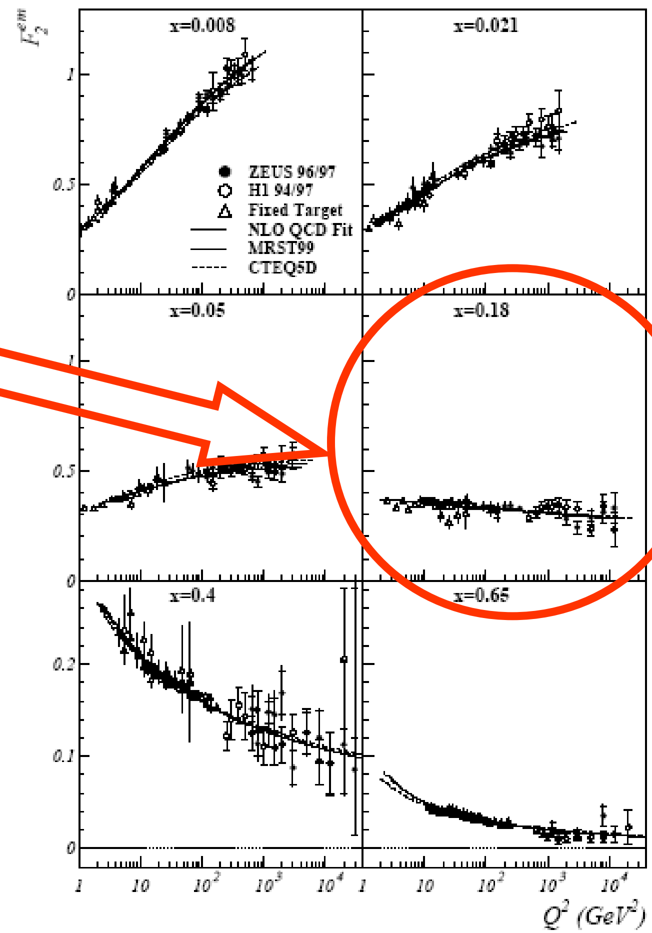
$$F_2^D \sim \sum_i e_i^2 (q_i^D + \bar{q}_i^D)$$

Comparison F_2^D with F_2: Q^2-dependence

Diffractive:



Proton:



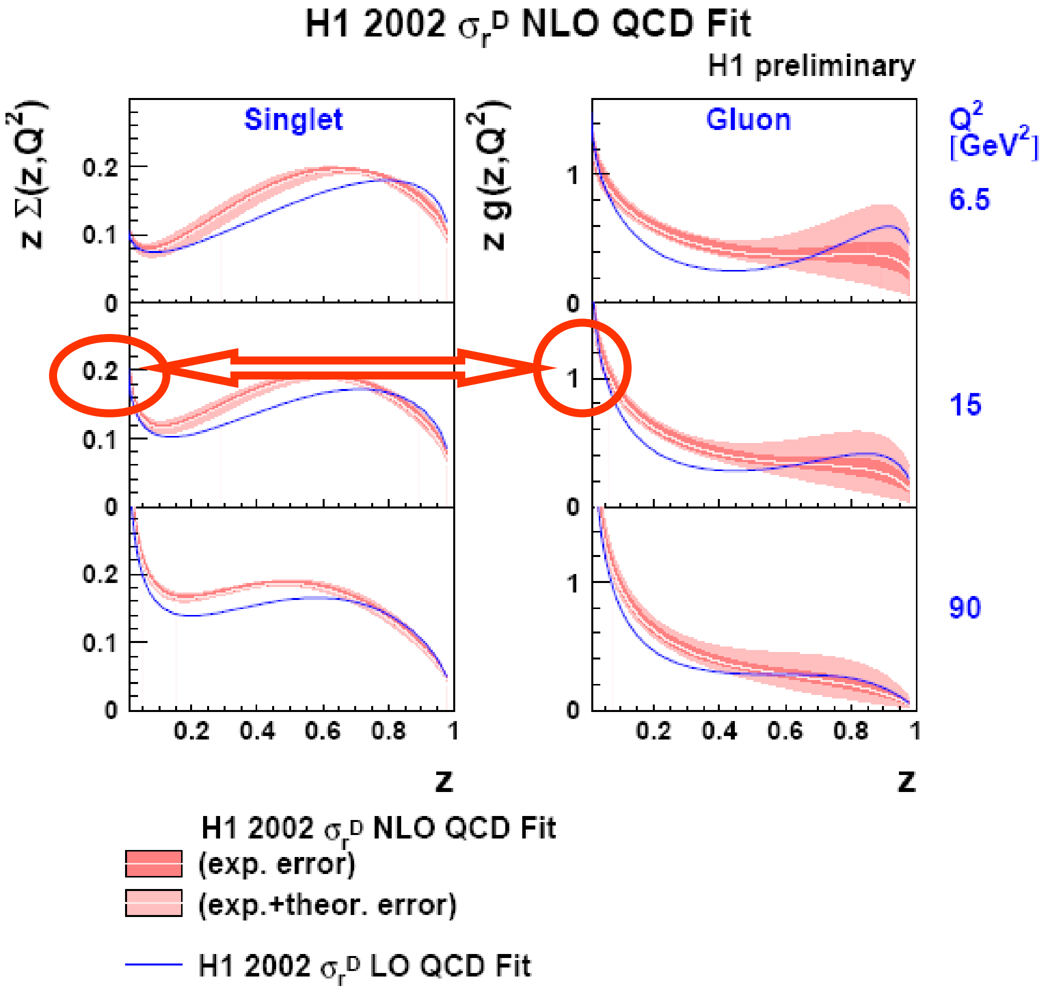
Positive scaling violations up to highest β

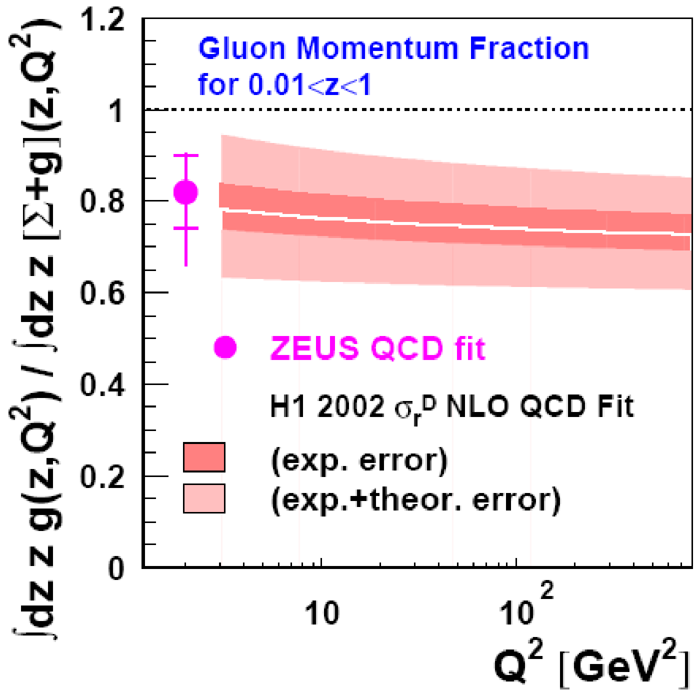
$$\frac{dF_2^D}{d\log Q^2} \sim \alpha_s \otimes g^D$$

QCD fit and diffractive parton densities

Diffractive pdf's extracted from DGLAP NLO QCD Fit:

Gluon dominated!



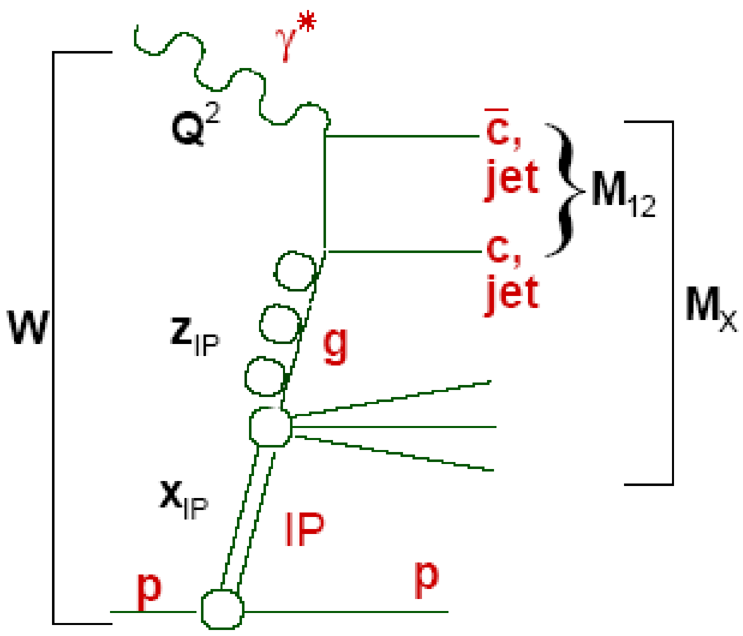


Gluons carry **75§ 15%** of momentum (at Q^2~10)!

Diffractive final states:
Jets, Charm

Diffractive dijets and charm in DIS

Test of QCD factorisation:
Do predictions based on diffractive pdf's also describe final states in diffractive DIS, e.g. jets, charm?



W: γ^*p centre-of-mass energy

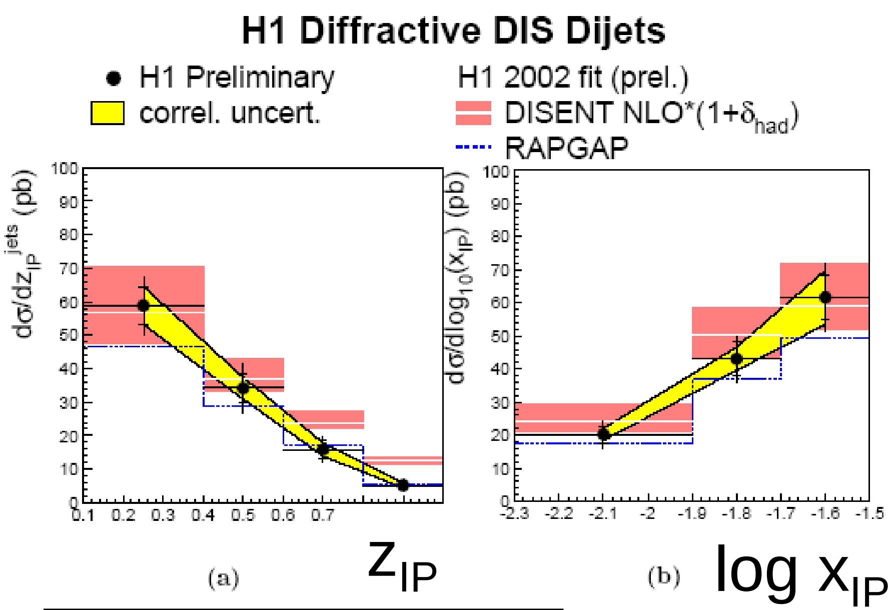
M_X: Mass of diffractively produced system

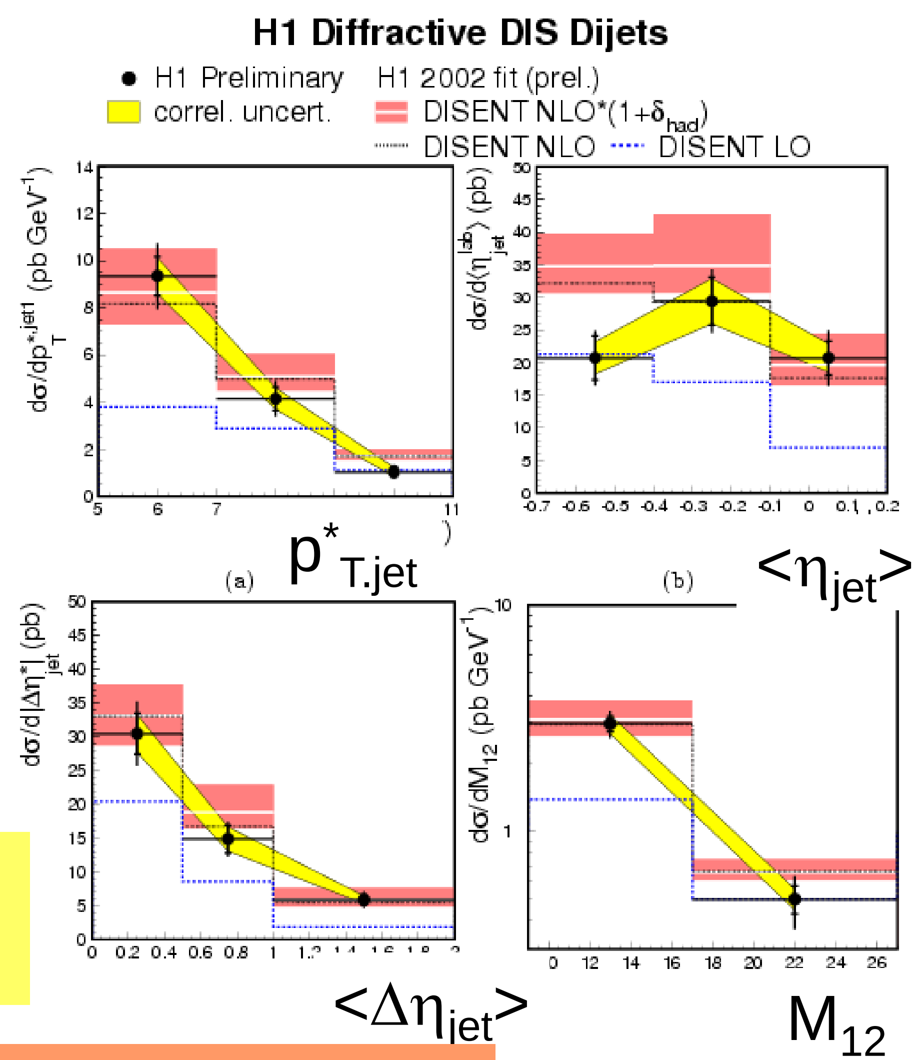
M_{12}: inv. mass of the two jets

Z_{IP}: momentum fraction of diffractive exchange entering the hard process

High sensitivity to diffractive gluon density!

Diffractive dijets in DIS





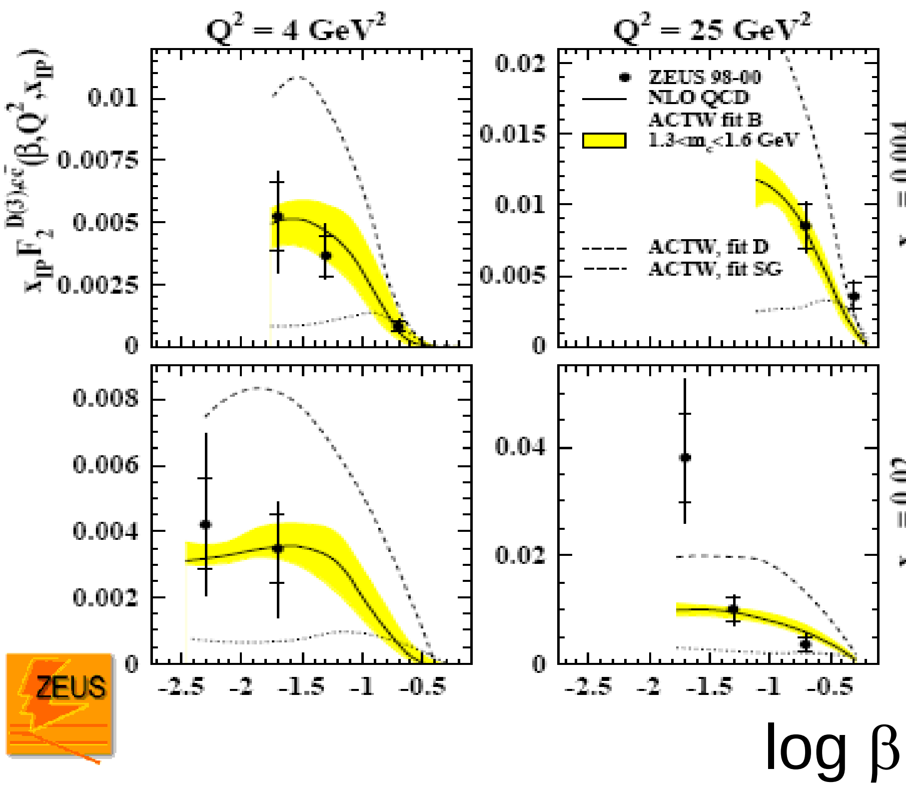
$4<Q^2<80$ GeV^2
$x_{IP}<0.03$
$E^*_{T,jet}(1,2)>5(4)$ GeV

NLO calculation based on H1 diffractive pdf's

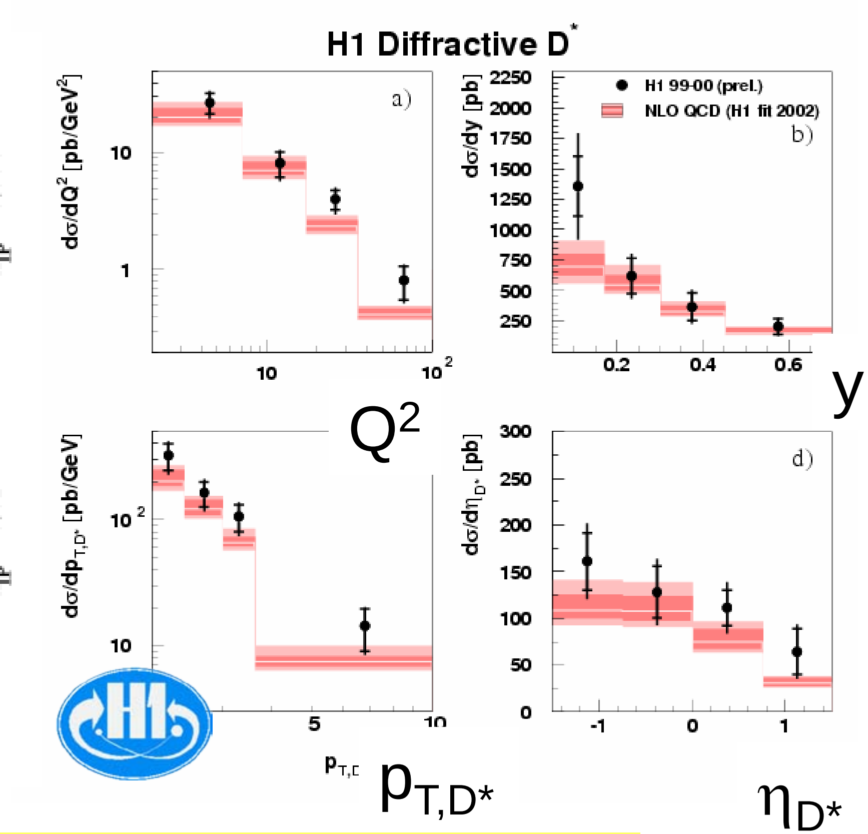
Consistent with QCD factorisation!

Diffractive charm production in DIS

Charm structure function $F_2^{D,c}$



D* cross section



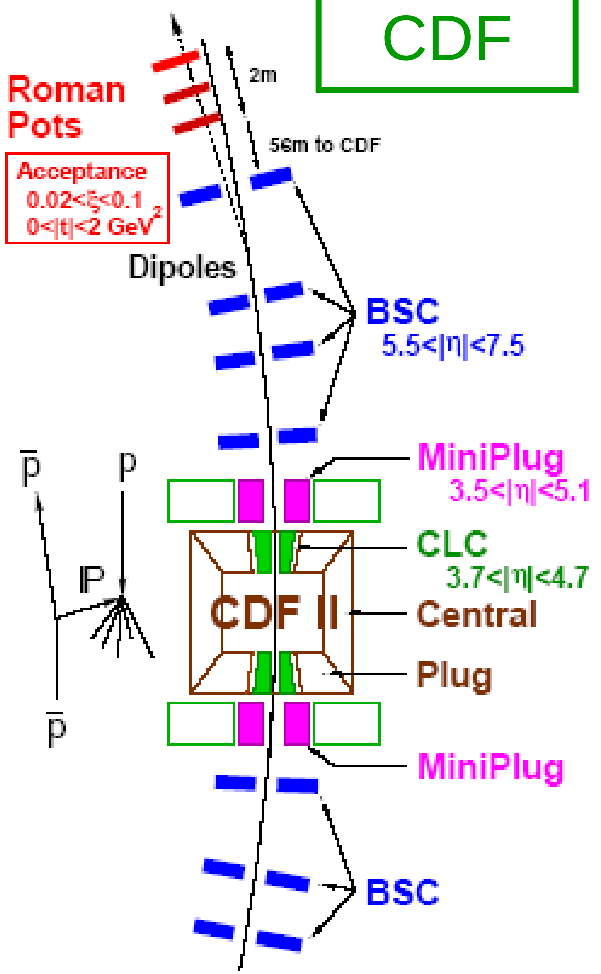
NLO calculations based on diffractive pdf's

Consistent with QCD factorisation!

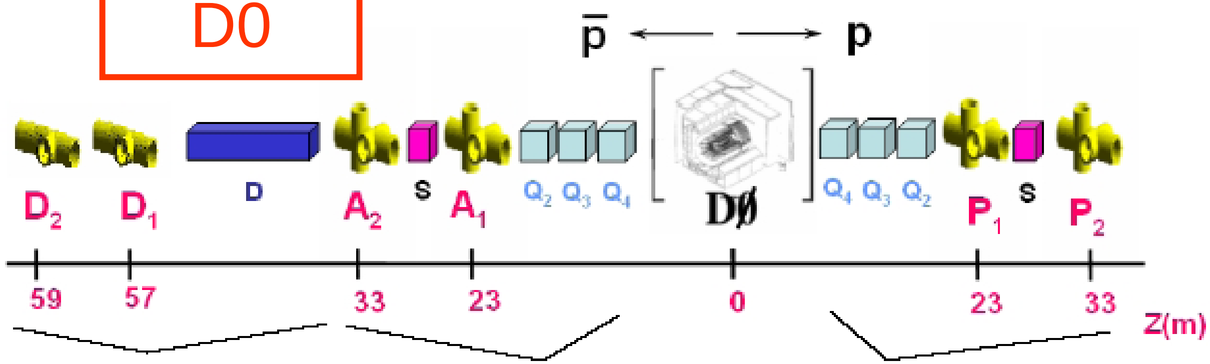
Diffraction at the Tevatron

Roman Pots at the Tevatron Run 2

CDF



D0



- **Dipole Spectrometer**
- inside the beam ring in the horizontal plane
- use **dipole magnet** (bends beam)

- **Quadrupole Spectrometers**
- surround the beam: up, down, in, out
- use **quadrupole magnets** (focus beam)
- also shown here: **separators** (bring beams together for collisions)

A total of 9 spectrometers composed of 18 Roman Pots

D0: New Roman Pots for Run 2

CDF: Roman Pots as for Run I
New: 'Beam Shower Counters' (BSC) and 'MiniPlug' calorimeter for increased fwd. aceptance: $5.1<\eta<7.5$

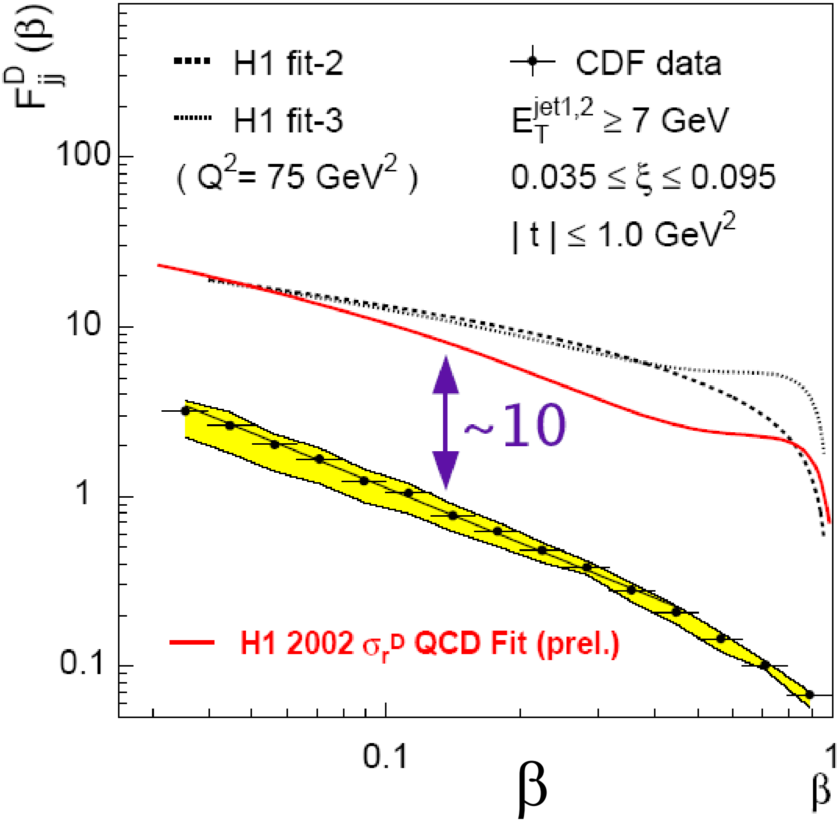
Diffractive dijets at the TEVATRON

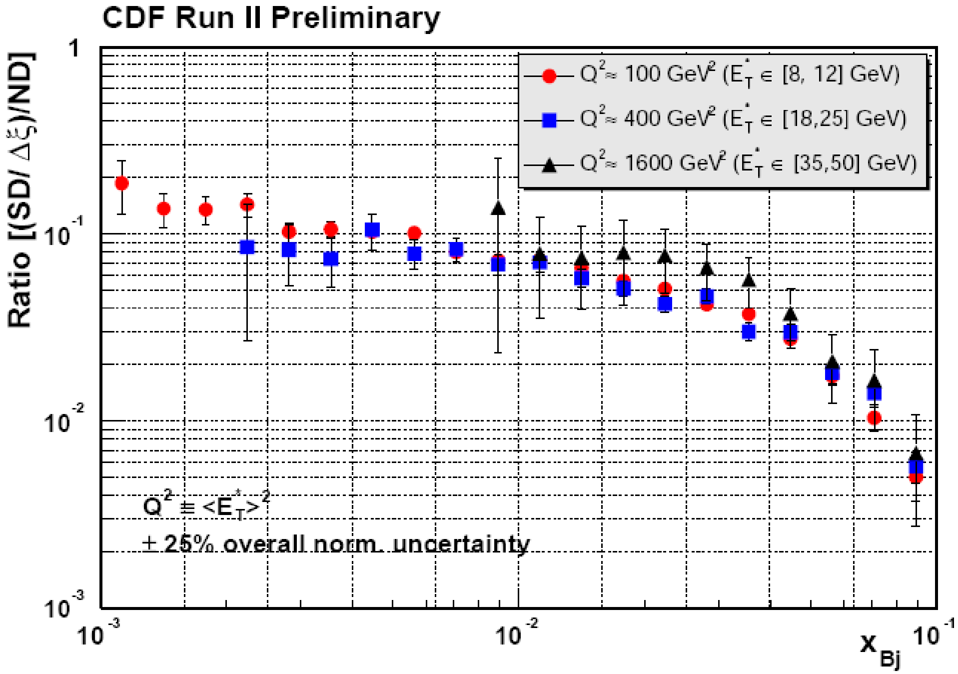
$$\bar{p}p \longrightarrow \bar{p} + \text{jet} + \text{jet} + X$$

Measurement lies faktor ~10 below prediction from HERA diffractive pdf's!
→Factorisation broken!

Effective structure function F_{jj}^{D}

$$F_{jj}^{D}(\beta,p_T^2) = \frac{4}{9}\left[q(\beta,p_T^2)+\bar{q}(\beta,p_T^2)\right]+g(\beta,p_T^2)$$





- **Confirmed in Run-2!**
- **No E_T dependence**

Rates of diffractive processes

Ratios diffractive / non-diffractive:

Diffractive W production $\quad q\bar{q} \to W,\ gq \to Wq$

$$R_W[\frac{SD}{ND}] = [1.15 \pm 0.51(stat) \pm 0.20(syst)]\%$$

$(p_T^e > 20\ \text{GeV/c}, |\eta^e| < 1.1, \not{E}_T > 20\ \text{GeV}, \xi < 0.1)$

Diffractive dijet production $\quad gg \to gg,\ qg \to qg$

$$R_{jj}[\frac{SD}{ND}] = [0.75 \pm 0.05(stat) \pm 0.09(syst)]\%$$

$(E_T^{jet} > 20\ \text{GeV}, 1.8 < |\eta^{jet}| < 3.5, \eta_1\eta_2 > 0, \xi < 0.1)$

Diffractive $b\bar{b}$ production $\quad gg \to b\bar{b},\ q\bar{q} \to b\bar{b}$

$$R_{b\bar{b}}[\frac{SD}{ND}] = [0.62 \pm 0.19(stat) \pm 0.16(syst)]\%$$

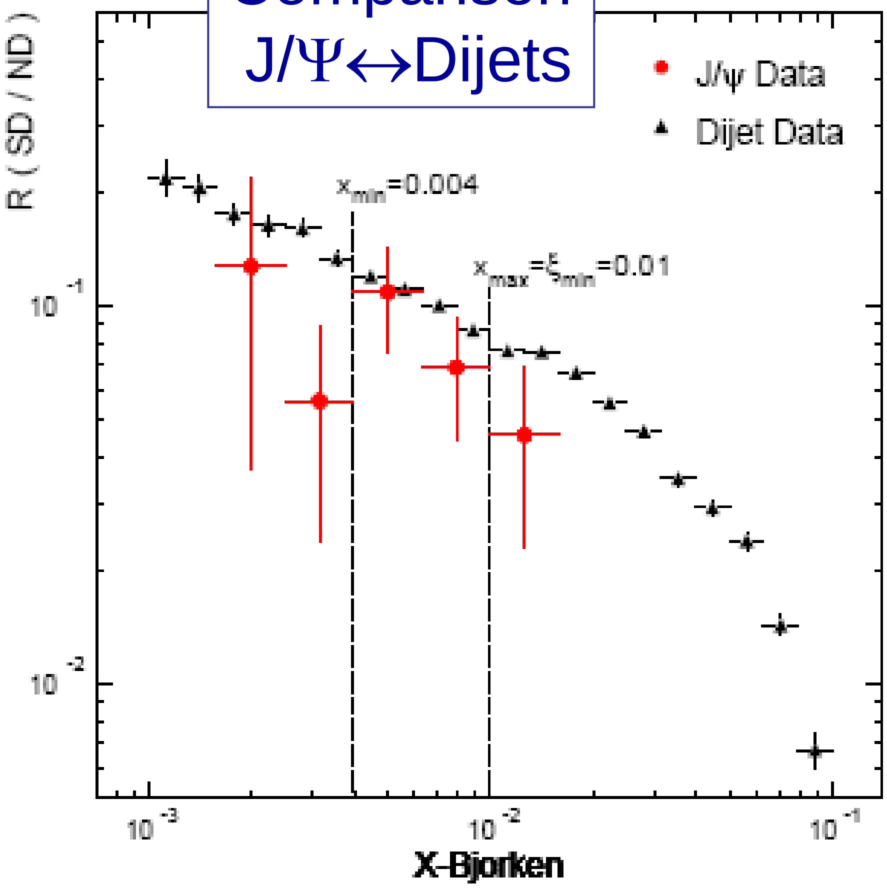
$(p_T^e > 9.5\ \text{GeV/c}, |\eta^e| < 1.1, \xi < 0.1)$

Diffractive J/ψ production $\quad gg \to J/\psi(g)$

$$R_{J/\psi}[\frac{SD}{ND}] = [1.45 \pm 0.25(stat \oplus syst)]\%$$

$(p_T^\mu > 2\ \text{GeV/c}, |\eta^\mu| < 1.0, \xi < 0.1)$

Comparison
J/Ψ↔Dijets



Ratios Diffractive / non-diffractive ~1% (HERA: 5-10%)!

Diffractive W§ and Z bosons

Sample	Gap Fraction (%) Diffractive/All (*)	Probability that Background would fluctuate to the Data in the (0,0) bin for W and Z Data	
W cent	1.08 + 0.19 - 0.17	1×10^{-14}	**7.7σ**
W fwd	0.64 + 0.18 - 0.16	6×10^{-8}	**5.3σ**
W All	**0.89 + 0.20 – 0.19**	3×10^{-14}	**7.5σ**
Z	**1.44 + 0.62 - 0.54**	5×10^{-6}	**4.4σ**

Diffractive contrib. ~1.0-1.5%

Intermediate summary on factorization

- QCD factorization theorem in diffractive DIS
  - Diffractive parton densities determined from DGLAP NLO QCD fit to F_2^D data
- Successful description of final state cross sections in diffractive DIS
  - diffractive dijets
  - diffractive D* production

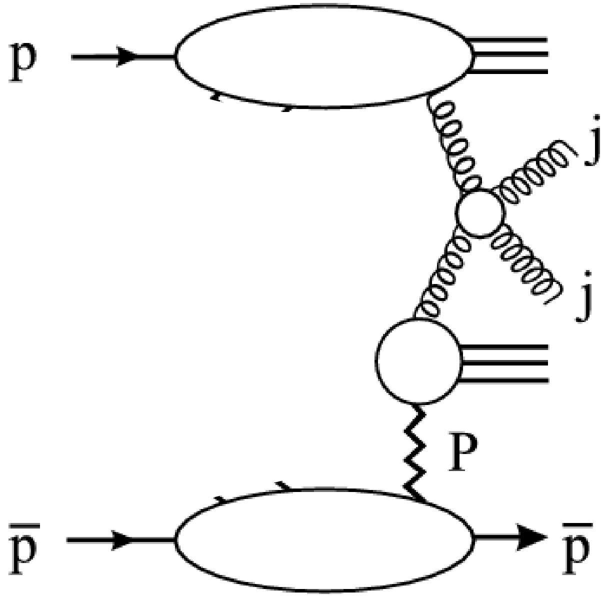
Factorization works in diffractive DIS!

- Prediction of diffractive rates at Tevatron fails!
  - HERA diffractive PDF’s+factorization: C.S. much too high!

Factorization HERA vs TEVATRON broken!

Factorization breaking: Reasons and models

Basic difference TEVATRON vs DIS:
2 vs 1 initial state hadrons!



$$\sigma \sim f_i^D(x,\mu^2,x_{I\!P},t) \otimes \hat{\sigma}_i^{jj}$$

$$\sigma \sim f_i^D(x,\mu^2,x_{I\!P},t) \otimes \hat{\sigma}_i^{jj} \otimes |S|^2$$

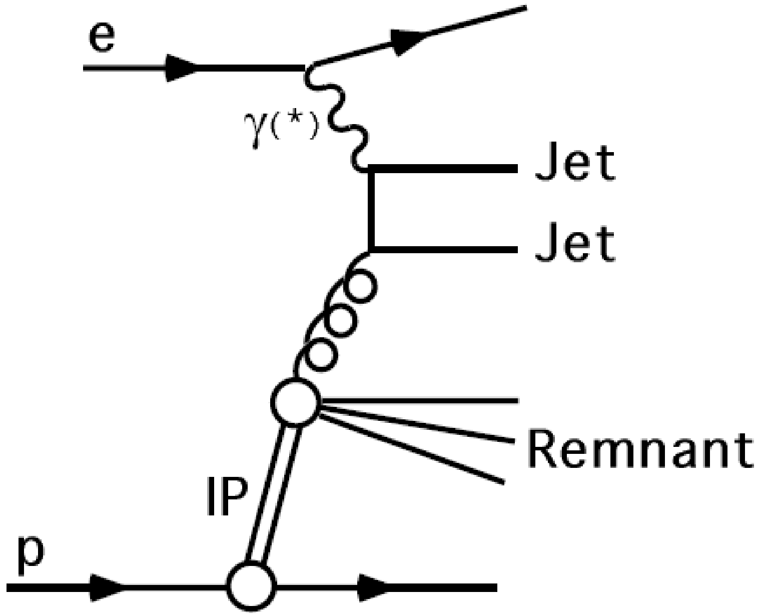
- Collins' factorization theorem is not valid for diffractive hadron-hadron scattering!
- **Suppression factor |s|^2** contains soft physics! – Phenomenological models exising …

Additional interactions between the remnants can destroy rapidity gaps: `Survival Probability' (Bjorken)

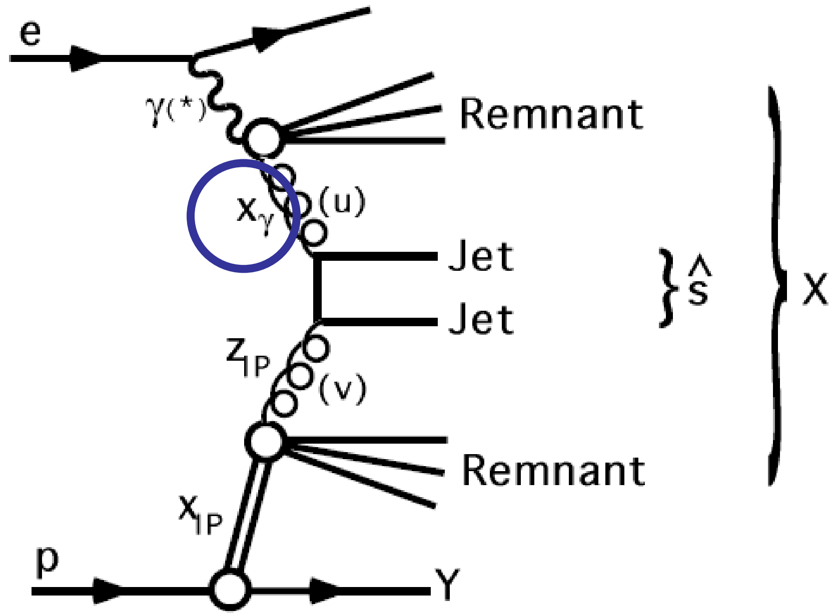
Jets in photoproduction at HERA: Key to the understanding of factorization breaking?

Jets in diffractive photoproduktion (Q^2~0) at HERA

DIS or direct process



'resolved' process

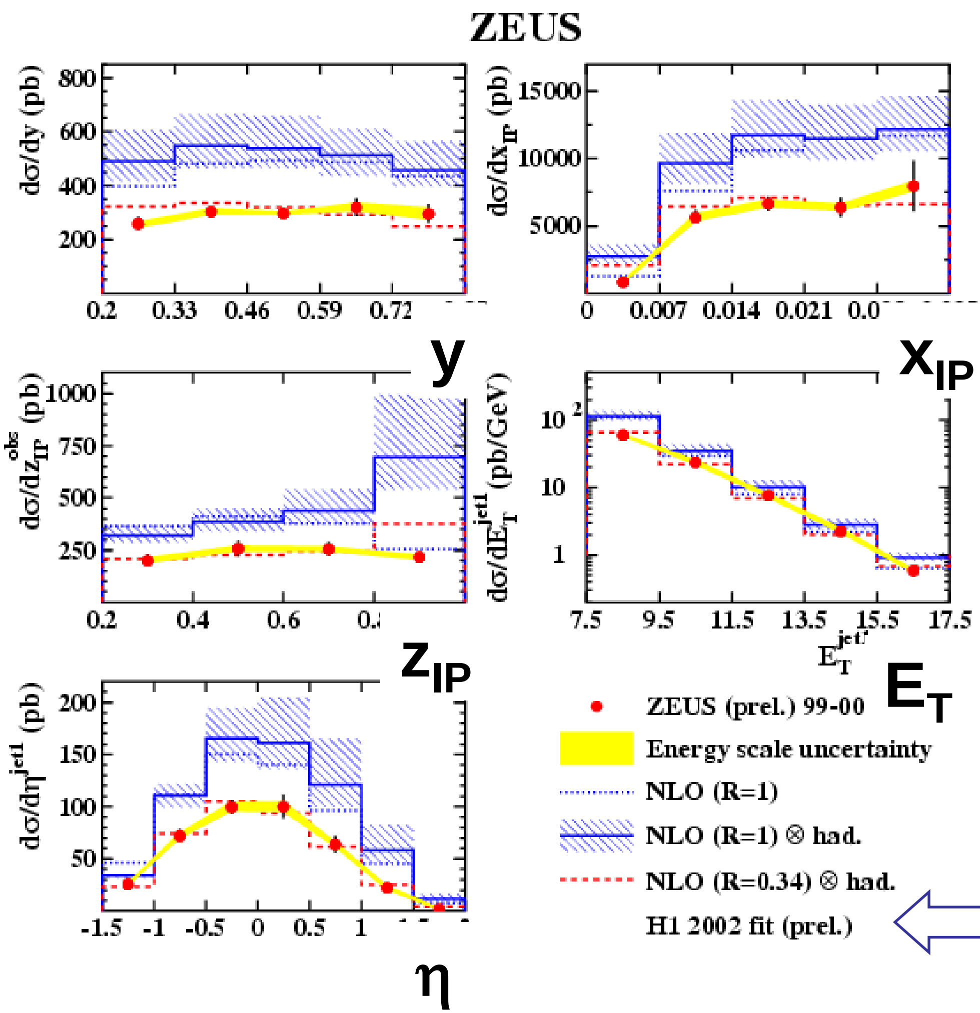


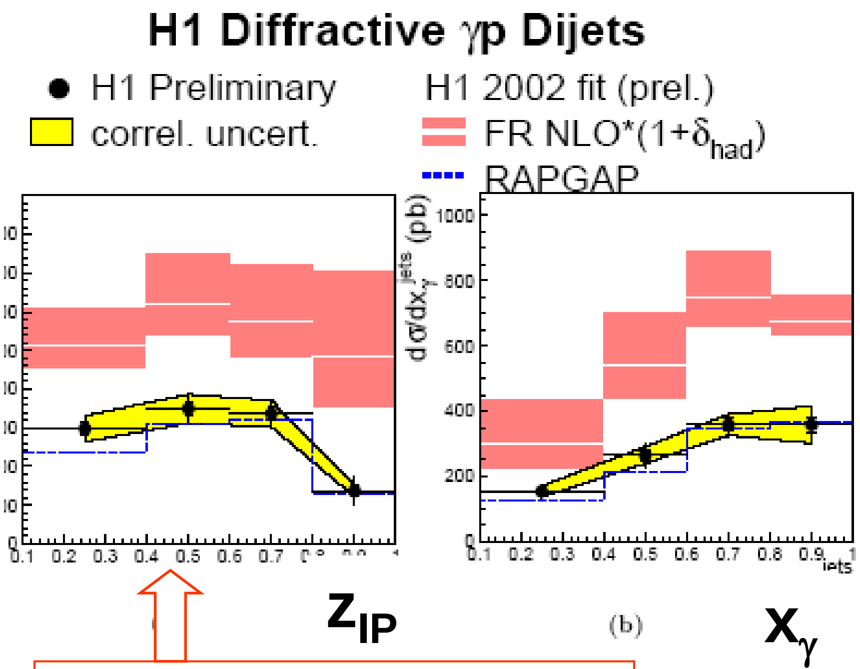
•Resolved γp similar to proton-proton

•Can study suppression in one experiment!

x_γ=1: direct
x_γ<1: resolved

Jets in diffractive photoproduction





$Q^2<0.01$ GeV^2; $x_{IP}<0.03$

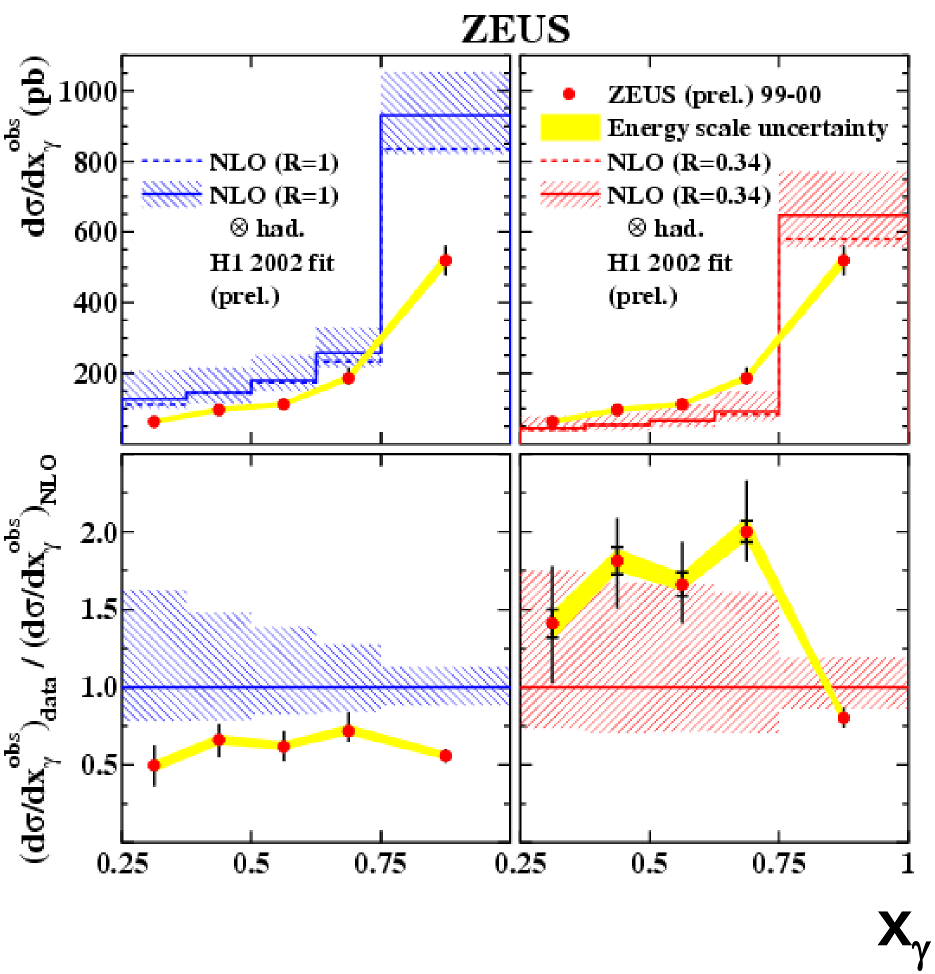
$E_{T,1(2)}>5(4)$ GeV

$Q^2<1$ GeV^2; $x_{IP}<0.035$

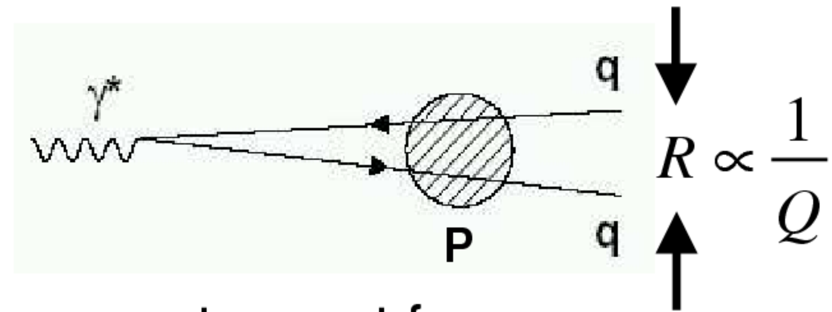
$E_{T,1(2)}>7.5(6.5)$ GeV

Data/NLO ~ 0.5! Factorization broken!

Jets in diffractive photoproduction



What is the dependence on x_γ? Are direct processes suppressed as well?



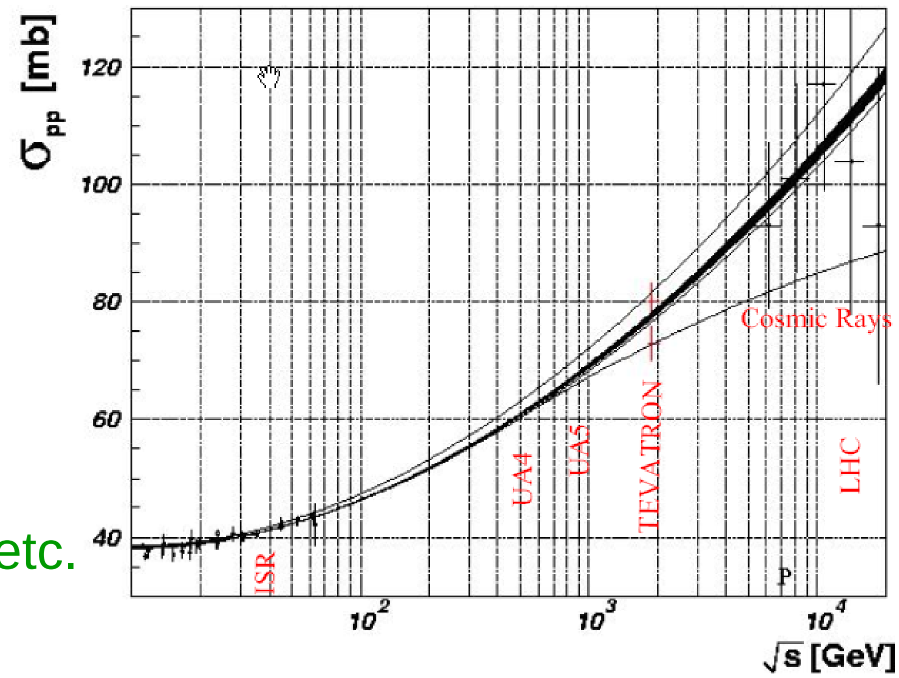
proton rest frame

Does the suppression at HERA only depend on the size of the photon?

Unexpected: Data favour suppression of resolved <u>and</u> direct! Not understood up to now …

Plans at the LHC

Diffraction at the LHC: Motivation

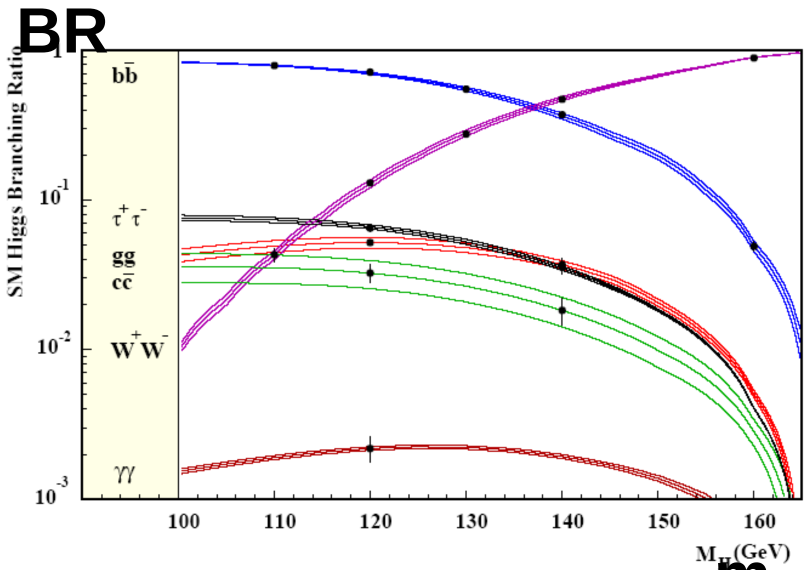


- Total cross section
- Elastic scattering
- Hard diffraction
  - Diffractive structure function and factorization breaking
  - Diffractive **Jets, W§, J/Ψ, b, t, γ** etc.
- Diffraction as 'gluon factory'
- Diffractive Higgs production
- Physics at small x: parton saturation, QCD dynamics etc.

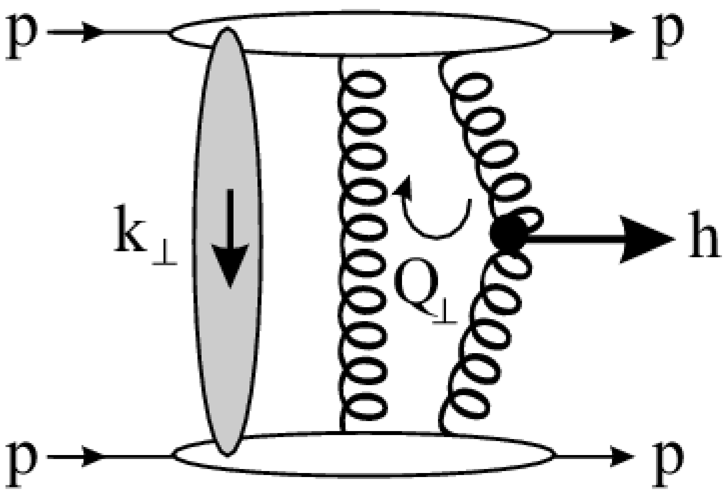
Many reasons to continue this research at the LHC!
(only possibility after shutdown of HERA andTEVATRON)

Diffractive Higgs production

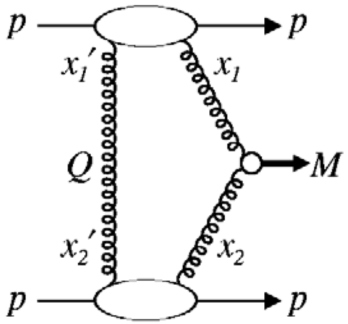
- Light SM Higgs m_H<130 GeV experimentally challenging at LHC:
  - Dominant decay H→bb:
  - huge QCD background
  - H→γγ challenging … (BR,S/B)

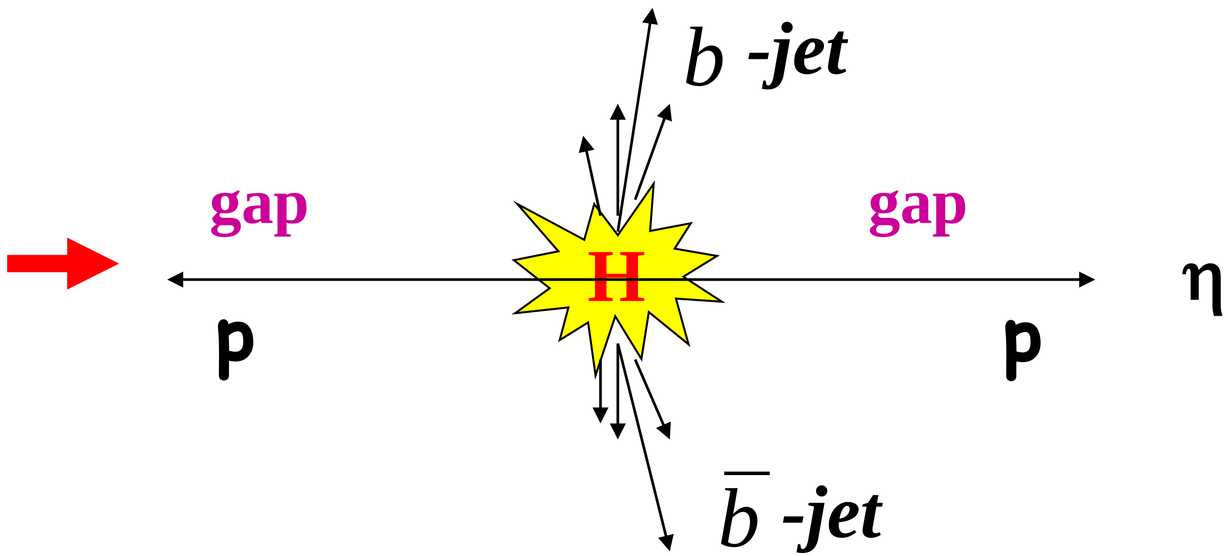


- New possibility: pp→p+H+p with double proton tag: 'exclusive double pomeron exchange'
  - (J_z=0, P even) selection rule suppresses gg->qq QCD background!
  - Higgs mass can be reconstructed from proton 4-vectors (missing mass mathod)



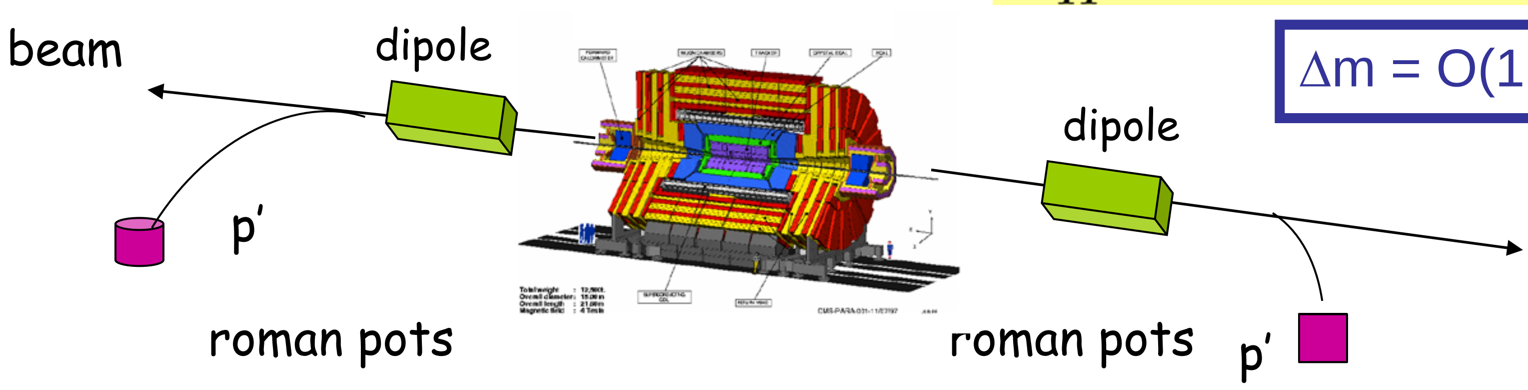
Diffractive Higgs production



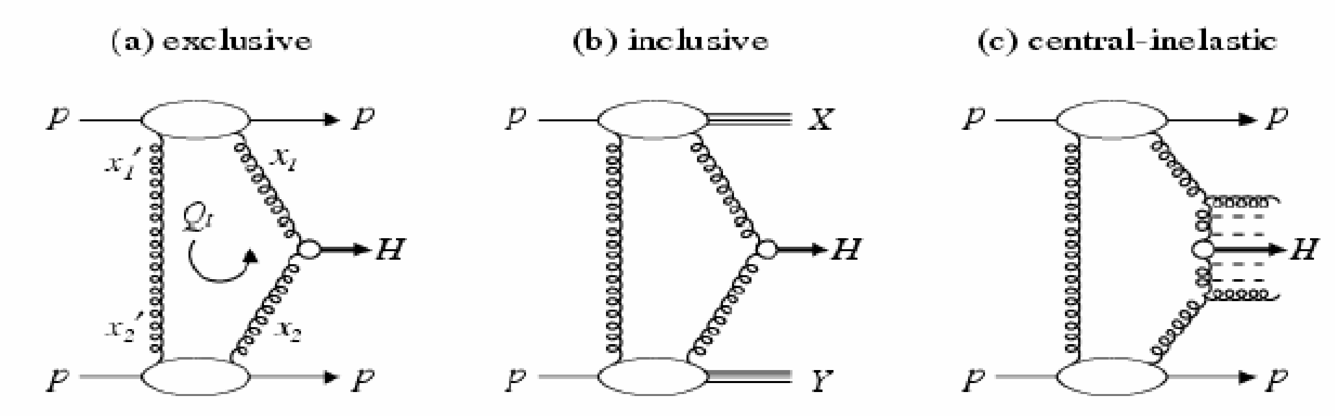


$$m_H^2 = (p_1 + p_2 - p_1' - p_2')^2$$

Δm = O(1.0 - 2.0) GeV



Diffractive Higgs production



Non-exklusive channel: larger cross section, but also higher background!

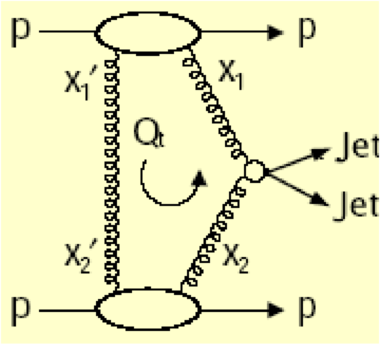
- Calculations of several theory groups
- Main problem: Normalization, 'Survival probability'

Consensus:
Exclusive channel pp → p H p : 3-10 fb
Inclusive channel pp → p+X+H+Y+p : 50-200 fb

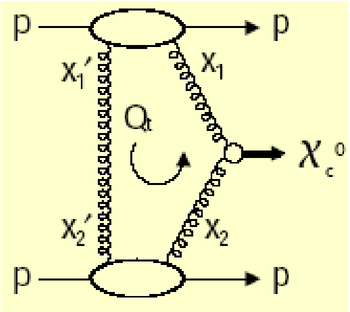
Example: m_H=120 GeV, L=30fb^{-1}, σ=3 fb (Khoze, Martin, Ryskin)
→ 90/10 events before/after cuts, signal / background: 3!

Calibration of the models at the Tevatron

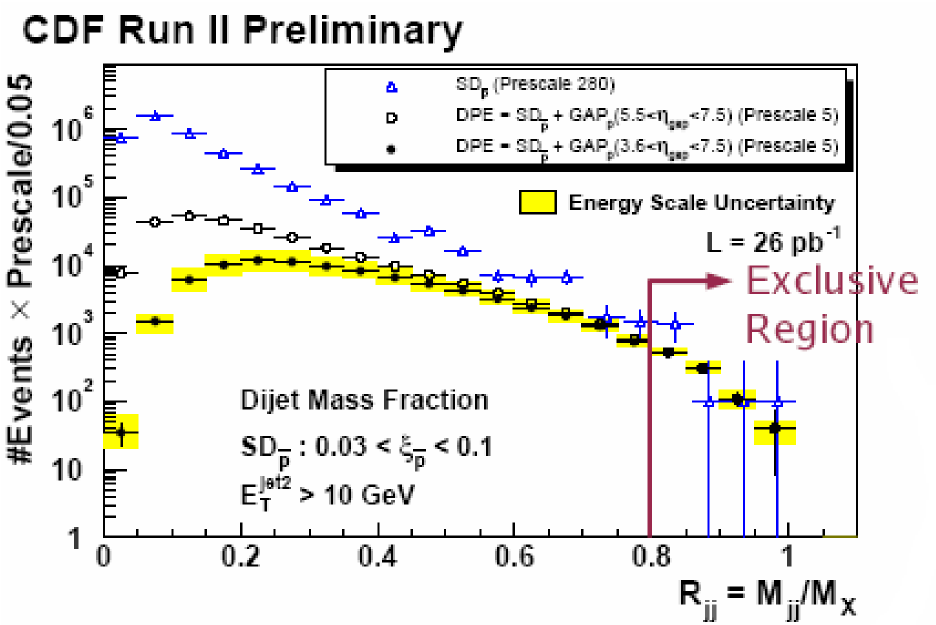
Cross section factorises → replace h with jj or $\chi_{c/b}$

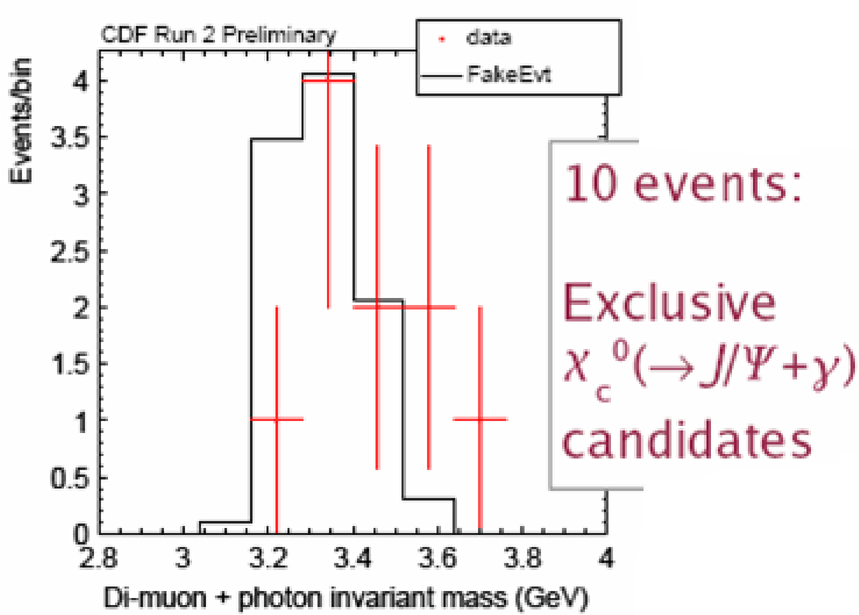


Exclusive dijets



X_c production



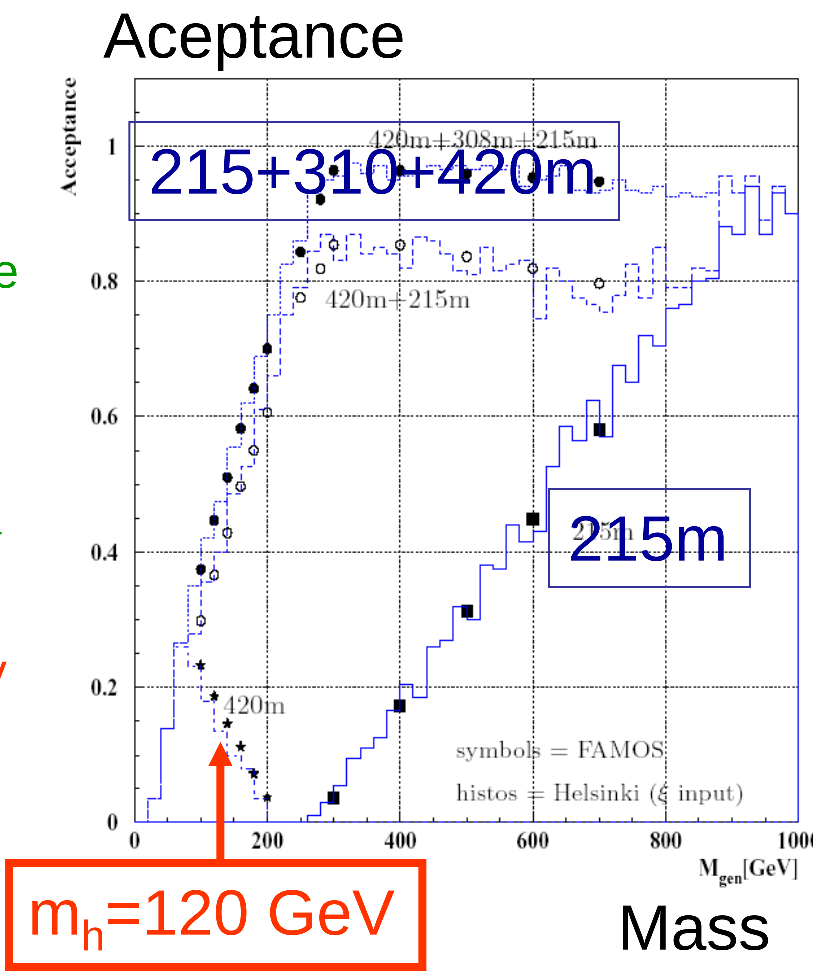


Consistent with Khoze, Martin, Ryskin Modell

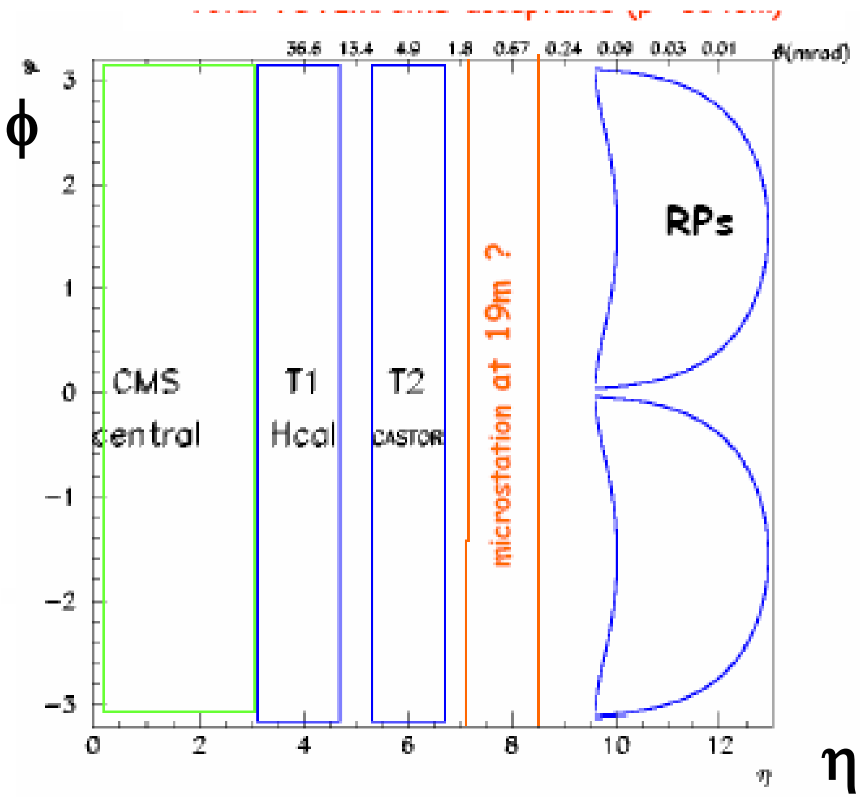
More data needed …

Plans of the LHC experiments: CMS+TOTEM

- Roman pots at z=150 und 215m
- Additional detectors at large η
- A) σ_{tot} and elastic scattering:
  - Data taking in special LHC optics where Roman Pot acceptance is high: β^*=1540m, L=$10^{28}cm^{-2}s^{-1}$ (few days!)
- B) Hard diffraction (incl. diffr. Higgs)
  - Standard LHC operation, L>$10^{33}cm^{-2}s^{-1}$
  - smaller acceptance for Roman Pots
  - Higgs: Pots at z=300 / 400m necessary (cold LHC section)
  - L1 trigger in time only for z<200m!
  - Selection with rapidity gap: Pileup: many interactions per bunch crossing!

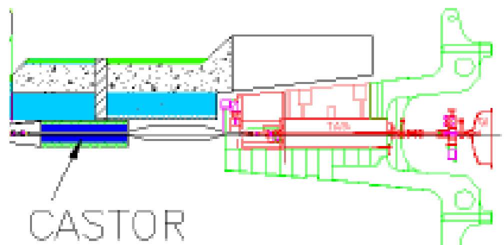


CMS+TOTEM detectors

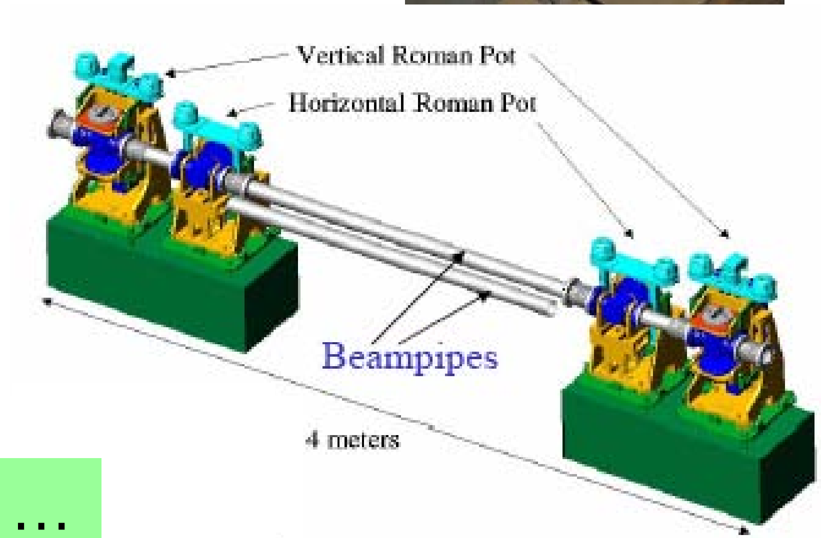


< η < 4.7

< η < 6.5



Roman Pot prototype



CMS+TOTEM: Detector mit with biggest ever acceptance at a hadron collider!
Large η important for small x!

Similar plans for ATLAS …

Summary

Diffraction at HERA:

- Pomeron 'Intercept' $\alpha_{IP}(0) \sim 1.2 > 1.08$! (different from 'soft Pomeron')
- Factorization theorem in diffractive DIS
- Precise F_2^D data, described by diffractive parton densities
- Successful prediction of diffractive final states in DIS
- Factorization broken in photoproduction (factor ~2)

- Diffraction at the TEVATRON:
  - Factorization broken (factor 5-10)
- Diffraction at the LHC
  - Rich physics program (e.g. diffractive Higgs production)
  - CMS/TOTEM and ATLAS plannings underway

Understanding of soft and elastic hadron scattering also important for the Interpretation of LHC results!