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Diffractive Hadroproduction of W+, W- and Z0 bosons at high energies.

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(*) M. B. Gay Ducati, M. M. Machado, M. V. T. Machado, PRD 75, 114013 (2007)

Outline

- Diffractive Scattering
- Ingelman-Schlein Model
- Inclusive Cross Section
- Diffractive Cross Section
- Multiple Pomeron Corrections – Gap Survival Probability (GSP)
    - Khoze – Martin – Ryskin (KMR)
    - Gotsman – Levin – Maor (GLM)
- Tevatron Results
- LHC Prediction

This work

- Results from a phenomenological analysis of W and Z hard diffractive hadroproduction at high energies

- Use of Regge factorization approach

- Consider recent diffractive parton density functions extracted by the H1 Collaboration at DESY-HERA

- Multiple Pomeron exchange corrections considering gap survival probability factor

- Ratio of diffractive to non-diffractive boson production is in good agreement with the CDF and D0 data on central region

- Prediction for the future measurements at the LHC

Motivations

- Study of inclusive and diffractive cross section:
  - charged gauge boson W^+ and W^- → $p+\overline{p} \to p + W(\to e\nu)X$
  - neutral gauge boson Z^0 → $p+\overline{p} \to p + Z^0(\to e^+e^-)X$
- Study of Pomeron trajectory → phenomenology describes the diffractive scattering
- Study of hard diffractive process → Ingelman-Schlein model
- Investigation of the effects from multiple Pomeron scattering in the central region → gap survival probability factor (GSP)
- Analysis using recent parametrization for Pomeron structure function

$F_2^{D(3)}(x_{IP}, \beta, Q^2)$ → H1 Collaboration

Introduction

- Diffractive processes are a way of amplifying the physics program at proton colliders

- Inclusion of new channels searching for New Physics

- Investigation of these reactions gives important information on the structure of hadrons and their interaction mechanisms

- Diffractive production of massive eletroweak bosons allows the study of the interplay of the small- and large-distance dynamics within QCD

- In boson hadroproduction, single diffractive dissociation can occur characterized by the existence of large rapidity gap → IP exchange

General Aspects

- Expected that unitarity effects at high energies affect the results of diffractive cross sections

- Multiple-Pomeron contributions reduce the diffractive cross section

- Dependence on the particular hard process

- Tevatron energies ($\sqrt{s}=1.8$Tev) → suppression is in the range 0.05-0.2

- For LHC energy ($\sqrt{s}=14$ TeV) → suppression is in the range 0.08-0.1

- Adequate treatment of the multiple scattering effect is crucial for the reliability of theoretical predictions of the cross sections for diffractive processes

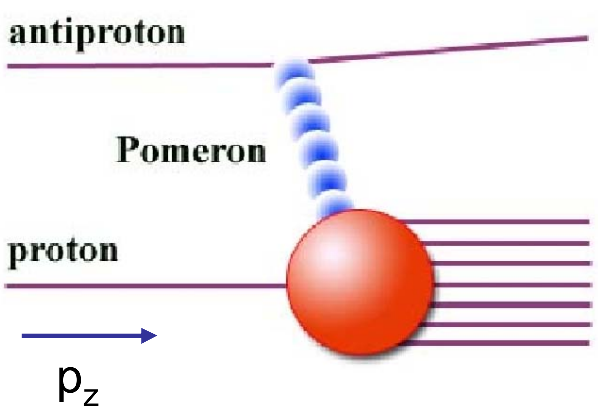
Diffractive Process

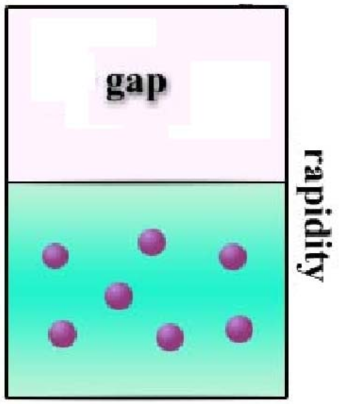
- Discovered at DESY (HERA) collider (H1 and Zeus Collaboration)

- Rapidity (y) gaps → no particle production

$$y = \frac{1}{2}\ln\left|\frac{E+p_z}{E-p_z}\right|$$

p_z proton momentum





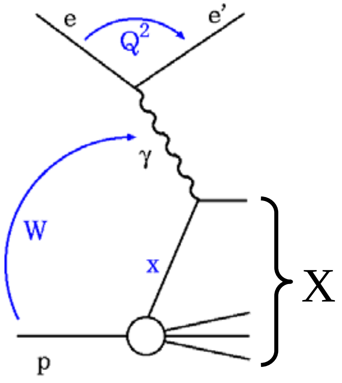
- Final state with same quantum numbers of initial state

- Pomeron → exchange of vacuum quantum numbers

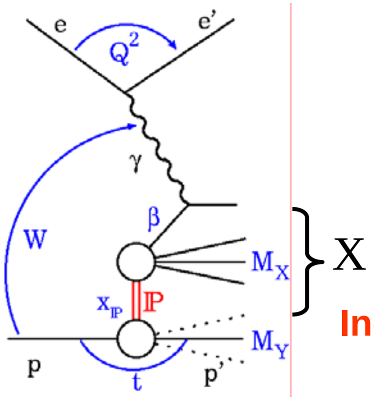
- M_W = 80 GeV, M_Z = 90.1 GeV

Diffractive DIS at HERA

- Diffractive Deep Inelastic Scattering (DDIS) contributes substantially to the cross section
- (~ 10% of visible low-x events)



Inclusive DIS:
Probes partonic structure of the proton



Diffractive DIS:
Probes structure of the exchanged color singlet

Ingelman-Schlein model

- Q^2: 4-momentum exchange
- W: γ p centre of mass energy
- x: fraction of p momentum carried by the struck quark
- x_{IP}: fraction of p momentum carried by the Pomeron (IP)

$$x_{IP} = \frac{q\cdot(p-p')}{q\cdot p} \approx \frac{Q^2+M_X^2}{Q^2+W^2}$$

- β: fraction of IP momentum carried by the struck quark

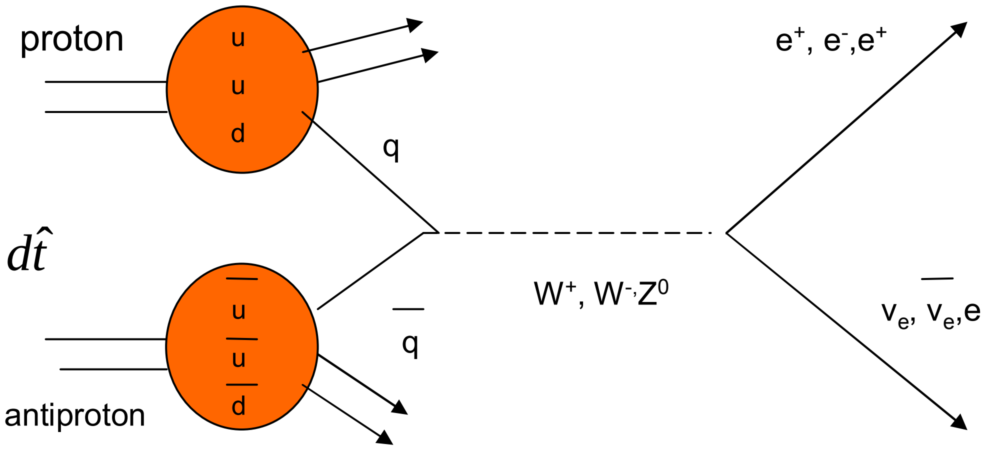
$$\beta = \frac{Q^2}{2q\cdot(p-p')} \approx \frac{Q^2}{Q^2+M_X^2} = \frac{x}{x_{IP}}$$

Inclusive cross section (I)

- Hard diffractive process, considering the Ingelman-Schlein model
- Pomeron structure (quark and gluon content) is probed
- Cross section for a process in which partons of two hadrons (A and B) interact to produce a massive eletroweak boson

$$A+B\rightarrow\left(W^{\pm}/Z^{0}\right)+X$$

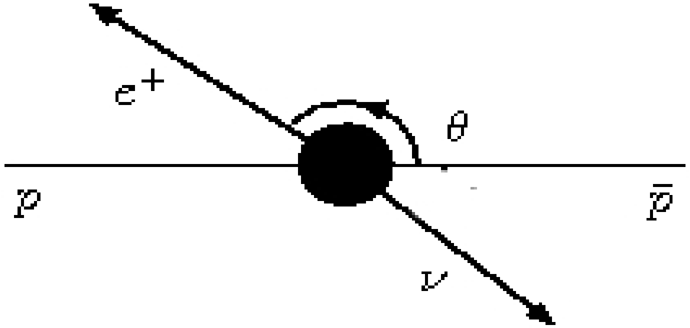
$$d\sigma=\sum_{a,b}\int dx_a\int dx_b\, f_{a/p}(x_a)\, f_{b/\bar{p}}(x_b)\,\frac{d\hat{\sigma}}{d\hat{t}}\,d\hat{t}$$



- x_a and x_b are the momentum fraction of nucleons carried by the partons
- $f_{i/h}$ is the parton distribution function (PDF) of a parton of flavor i = a,b in the hadron h = A, B

Inclusive cross section (II)

- $d\hat{\sigma}/d\hat{t}$ gives the elementary cross section of the corresponding subprocess
- The cross section is the usual leading-order QCD procedure to obtain the non-diffractive cross section
- Next-to-leading-order contributions are not essential, since corrections to W and Z production are small
- High energies ($m_p << E$) pseudo-rapidity → $\eta = -\ln tg\frac{\theta}{2}$
- θ is the electron scattering angle related to the proton beam direction



Energies and Mandelstan Variables

- Total Energy → $$E_e = \frac{\sqrt{s}}{4}\left[x_a(1+\cos\theta)+x_b(1-\cos\theta)\right]$$
- Longitudinal Energy → $$E_L = \frac{\sqrt{s}}{4}\left[x_a(1+\cos\theta)-x_b(1-\cos\theta)\right]$$
- Transversal Energy → $$E_T = \frac{M_W}{2} sen\theta$$
- Mandelstan variables of the process

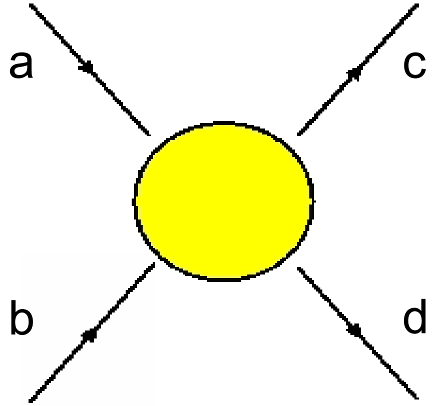
$$\hat{t} = (p_c - p_a)^2 = -\frac{\hat{s}}{2}(1-\cos\theta)$$

$$\hat{u} = (p_c - p_b)^2 = -\frac{\hat{s}}{2}(1+\cos\theta)$$

$$\hat{s} = (p_a + p_b)^2 = M_W^2$$

$$\cos\theta = \pm\frac{\sqrt{A^2-1}}{A}$$

$$A = M_W / 2E_T$$



W^- inclusive cross section

- General cross section for W and Z

$$\frac{d\sigma}{dx_a dx_b} = \sum_{a,b}\int dx_a\, f_{a/p}(x_a,\mu^2)\, f_{b/\bar{p}}(x_b,\mu^2)\,\frac{d\hat{\sigma}(p\bar{p}\to[W/Z]X)}{d\hat{t}}$$

- W^- inclusive cross section

$$\frac{d\sigma}{d\eta_{e^-}} = \sum_{a,b}\int dE_T\, f_{a/p}(x_a)\, f_{b/\bar{p}}(x_b)\left[\frac{V_{ab}^2 G_F^2}{6s\Gamma_W M_W}\right]\frac{\boxed{\hat{u}^2}}{\sqrt{A^2-1}}$$

- $\mu^2 = M_W^2$ hard scale in which the PDFs are evolved
- Total decay width → Γ_W = 2.06 GeV
- Fermi Constant $G_F = 1.166 \times 10^{-5}$ GeV^{-2}
- V_{ab} is the Matrix CKM element

W^+ inclusive cross section

- W^+ inclusive cross section

$$\frac{d\sigma}{d\eta_{e^+}} = \sum_{a,b} \int dE_T \, f_{a/p}(x_a)\, f_{b/\bar{p}}(x_b) \left[\frac{V_{ab}^2 G_F^2}{6 s \Gamma_W M_W} \right] \frac{\boxed{\hat{t}^2}}{\sqrt{A^2 - 1}}$$

- $\mu^2 = M_W^2$ $\qquad$ $\hat{t} = -E_T M_W \left[A + \sqrt{(A^2 - 1)} \right]$
- Total decay width ➡ Γ_W = 2.06 GeV
- G_F = 1.166 x 10^{-5} GeV^{-2}, V_{ab} is the CKM Matrix element
- W^+ ➡ dependence in t channel
- W^- ➡ dependence in u channel

W Diffractive cross sections

- W^- diffractive cross section

$$\frac{d\sigma}{d\eta_{e^-}} = \sum_{a,b} \int dx_{IP}\, g(x_{IP}) \int dE_T\, f_{a/IP}(x_a)\, f_{b/\bar{p}}(x_b) \left[\frac{V_{ab}^2 G_F^2}{6s\Gamma_W M_W} \right] \frac{\boxed{\hat{u}^2}}{\sqrt{A^2-1}}$$

- W^+ diffractive cross section

$$\frac{d\sigma}{d\eta_{e^+}} = \sum_{a,b} \int dx_{IP}\, g(x_{IP}) \int dE_T\, f_{a/IP}(x_a)\, f_{b/\bar{p}}(x_b) \left[\frac{V_{ab}^2 G_F^2}{6s\Gamma_W M_W} \right] \frac{\boxed{\hat{t}^2}}{\sqrt{A^2-1}}$$

- $f_{a/IP}$ is the quark distribution in the IP → parametrization of the IP structure function (H1)

- $g\ (x_{IP})$ is the IP flux integrated over t

Z^0 Diffractive cross sections

- Z^0 diffractive cross section

$$\sigma = \sum_{a,b} \int \frac{dx_{IP}}{x_{IP}} \int \frac{dx_b}{x_b} \int \frac{dx_a}{x_a} \bar{f}(x_{IP})\, f_{a/IP}(x_a, \mu^2)\, f_{b/\bar{p}}(x_b, \mu^2) \left[\frac{2\pi C^Z_{ab} G_F M_Z^2}{3\sqrt{2}s} \right] \frac{d\hat{\sigma}(ab \to ZX)}{d\hat{t}}$$

- $f_{a/IP}$ is the quark distribution in the IP

$$\bar{f}(x_{IP}) = \int_{-\infty}^{0} f_{IP/p}(x_{IP}, t)dt$$

- g (x_{IP}) is the Pomeron flux integrated over t

- $C^Z_{qq'} 1/2 - 2|e_q| \sin^2\theta_W + 4|e_q|^2 \sin^4\theta_W$

- θ_W is the Weinberg or weak-mixing angle

- Same result of H1 with LO Pomeron structure function (STIRLING 96)

Pomeron flux factor

- x_{IP} dependence is parametrized using a flux factor

$$f_{IP/p}(x_{IP},t) = A_{IP}\,\frac{e^{B_{IP}t}}{x_{IP}^{2\alpha_{IP}(t)-1}}$$

- IP trajectory is assumed to be linear → $\alpha_{IP}(t) = \alpha_{IP}(0) + \alpha'_{IP}\,t$

- $B_{IP,}$, α'_{IP}
  their uncertainties

obtained from the fits to H1 forward proton spectometer (FPS) data

Normalization parameter x_{IP} is chosen such that $x_{IP}\cdot\int_{t_{cut}}^{t_{\min}} f_{IP/p}\,dt = 1$ at $x_{IP} = 0.003$

- $|t_{\min}| \approx m_p^2 x_{IP}/(1-x_{IP})$ is the proton mass
- $|t_{cut}| = 1.0$ GeV^2 is the limit of the measurement

Pomeron structure function

- Pomeron structure function has been modeled in terms of a light flavor singlet distribution Σ(z)

- Consists of u, d and s quarks and antiquarks and a gluon distribution g(z)

- z is the longitudinal momentum fraction of the parton entering the hard subprocess with respect of the diffractive exchange

- ($z = \beta$) for the lowest order quark-parton model process and $0 < \beta < z$ for higher order processes

- Quark singlet and gluon distributions are parametrized at Q^2_0

$$zf_{i/IP}(z,Q_0^2) = A_i z^{B_i}(1-z)^{C_i}\exp\left[-\frac{0.01}{(1-z)}\right]$$

Pomeron structure function

- Experimental determination of the diffractive PDFs involves the following cuts

$$\beta < 0.8, M_X > 2GeV; Q^2 < 8.5GeV^2$$

- Quark singlet distribution, data requires inclusion of parameters A_q, B_q and C_q

- Gluon density is weakly constrained by data which are found to be insensitive to the B_g parameter

- **FIT A** - Gluon density is parametrized using only A_g and C_g parameters (Q^2_0 = 1.75 GeV^2)

- This procedure is not sensitive to the gluon PDF and a new adjustment was done with $C_g = 0$

- **FIT B** - Gluon density is a simple constant at the starting scale for evolution (Q^2_0 = 2.5 GeV^2)

Pomeron structure function

Parameter	*Value*
α'_{IP}	$0.06^{+0.19}_{-0.06} GeV^{-2}$
B_{IP}	$5.5^{+2.0}_{-0.7} GeV^{-2}$
$\alpha_{IR}(0)$	0.50 ± 0.10
α'_{IR}	$0.3^{+0.6}_{-0.3} GeV^{-2}$
B_{IR}	$1.6^{+1.6}_{-0.4} GeV^{-2}$
m_c	$1.4 \pm 0.2 GeV$
m_b	$4,5 \pm 0.5 GeV$
$\alpha_8{}^{(5)}(M_Z{}^2)$	0.118 ± 0.002

- Values of fixed parameters (masses) and their uncertainties, as used in the QCD fits.

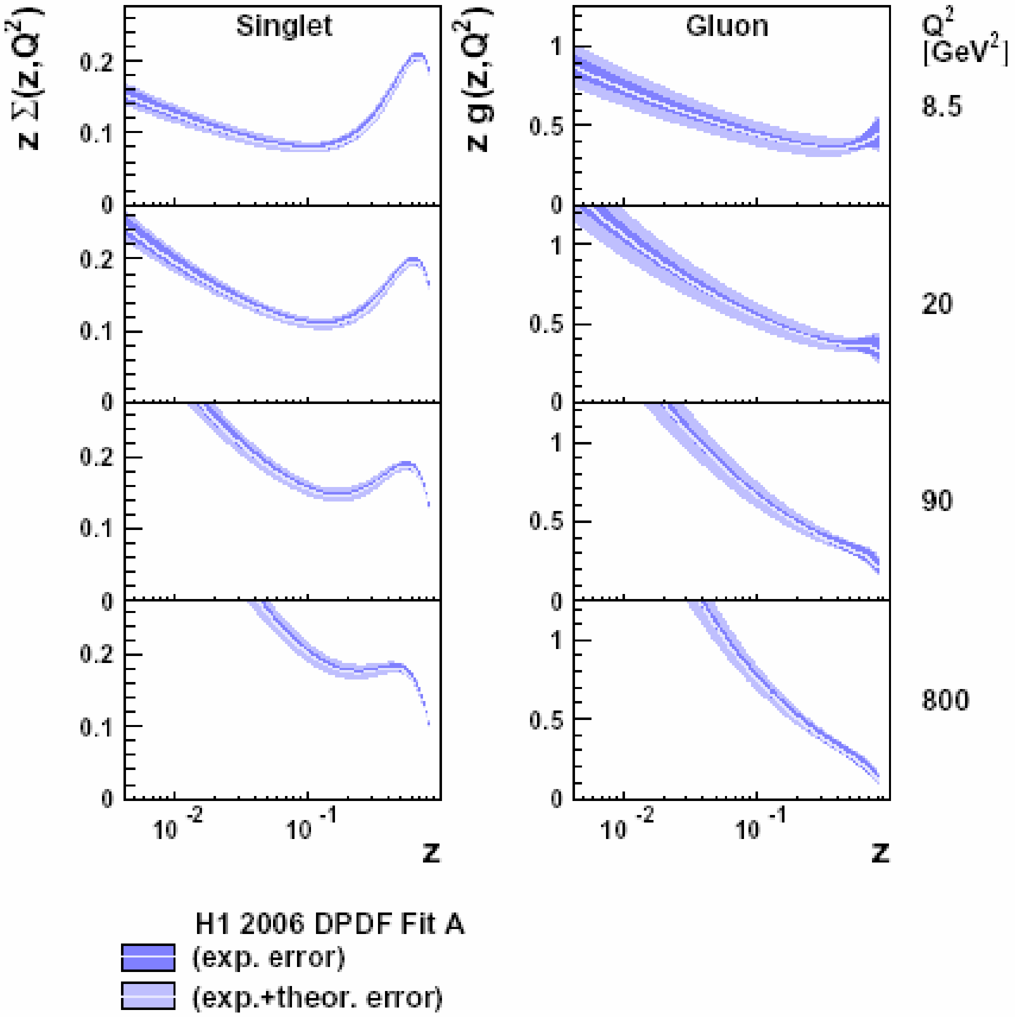
- α'_{IP} and B_{IP} (strongly anti-correlated) are varied simultaneously to obtain the theoretical errors on the fits (as well as α'_{IR} and B_{IR}).

- Remaining parameters are varied independently.

- Theoretical uncertainties on the free parameters of the fit are sensitive to the variation of the parametrization scale Q^2_0

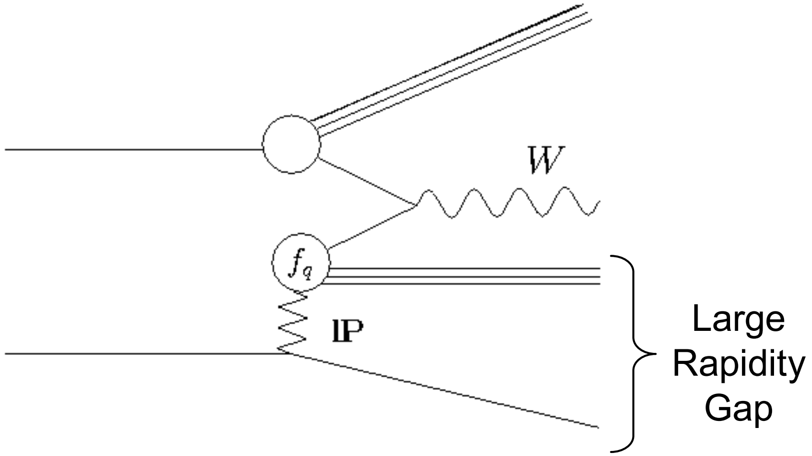
DESY – 06-049 May 2006

Quark and gluons distributions



- Total quark singlet and gluon distributions obtained from NLO QCD H1. DPDF Fit A,
- Range $0.0043 < z < 0{,}8$, corresponding approximately to that of measurement.
- Central lines are surrounded by inner errors bands corresponding to the experimental uncertainties and outer error bands corresponding to the experimental and theoretical uncertainties
- In this work, we use FIT A.
- Similar results are obtained with FIT B

Gap Survival Probability (GSP)



- Currently a subject of intense theoretical and experimental interest
- GAP – region of angular phase space devoid of particles
- Survival probability – fulfilling of the gap by hadrons produced in interactions of remanescent particles

$$<|S|>^2 = \frac{\int d^2b \, |A(s,b)|^2 \; P^s(s,b)}{\int d^2b \, |A(s,b)|^2}$$

- *A(s,b)* is the amplitude (in the parameter space) of the particular process of interest at center-of-mass energy $\sqrt{s}$
- *P^S(s,b)* is the probability that no inelastic interaction occurs between scattered hadrons

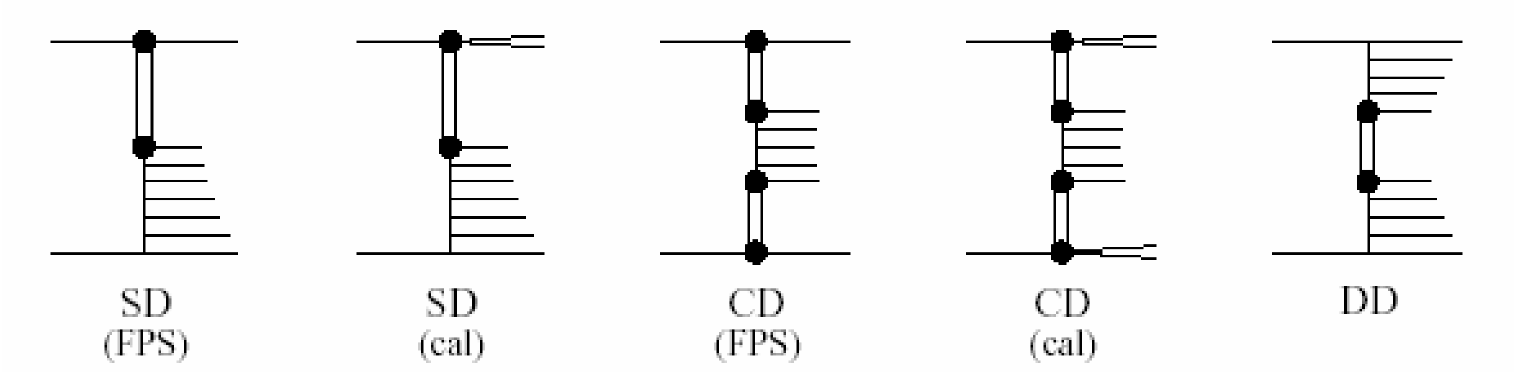
KMR - GSP

(*) Khoze-Martin-Ryskin Eur. Phys. J. C. 26 229 (2002)

- The survival probability of the rapidity gaps (associated with the Pomeron, represented by the double vertical line)

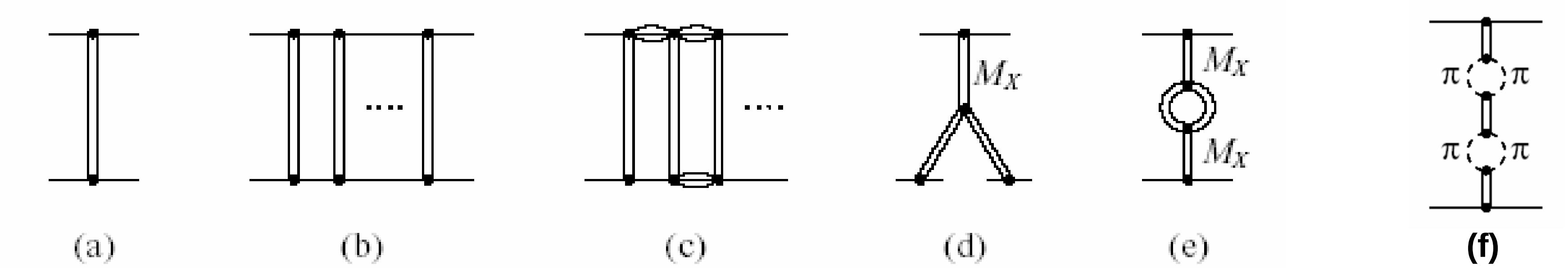
- Calculated
  - * single diffraction (SD)
  - * central diffraction (CD)
  - * double diffraction (DD)

- FPS or cal denotes “forward photon spectrometer” or “calorimeter”, and corresponds to the detection of isolated protons, or to events where the leading baryon is either a proton or a N* (symbolically, two lines emerging from the vertex)



KMR model

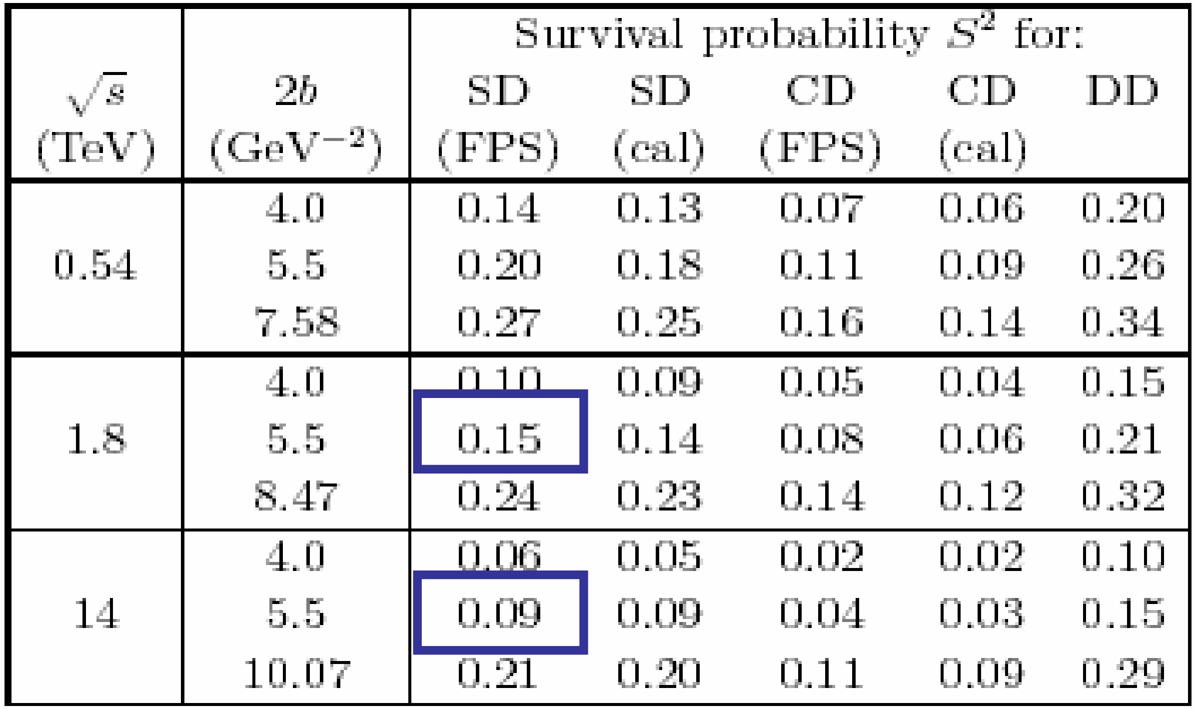
- t dependence of elastic pp differential cross section in the form exp (Bt)
  - pion-loop insertions in the Pomeron trajectory
  - non-exponential form of the proton-Pomeron vertex β (t)
  - absorptive corrections, associated with eikonalization, which lead to a dip in dσ/dt at |t| ~ 1 GeV^2, whose position moves to smaller |t| as the collider energy increases



- (a) Pomeron exchange contribution;
- (b-e) are unitarity corrections to the pp elastic amplitude.
- (f) is a two pion-loop insertion in the Pomeron trajectory

KMR model

- GSP KMR values

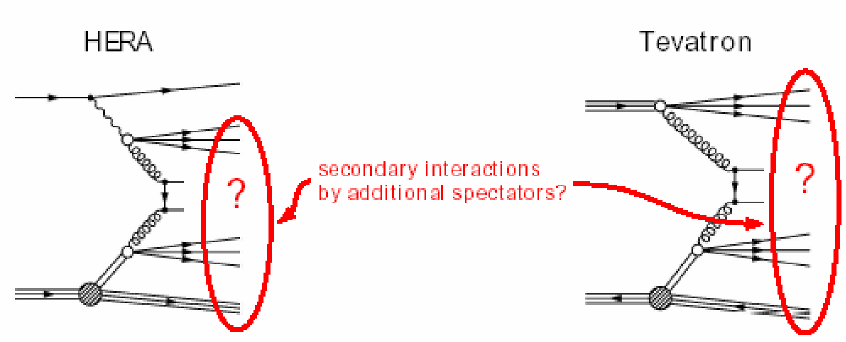


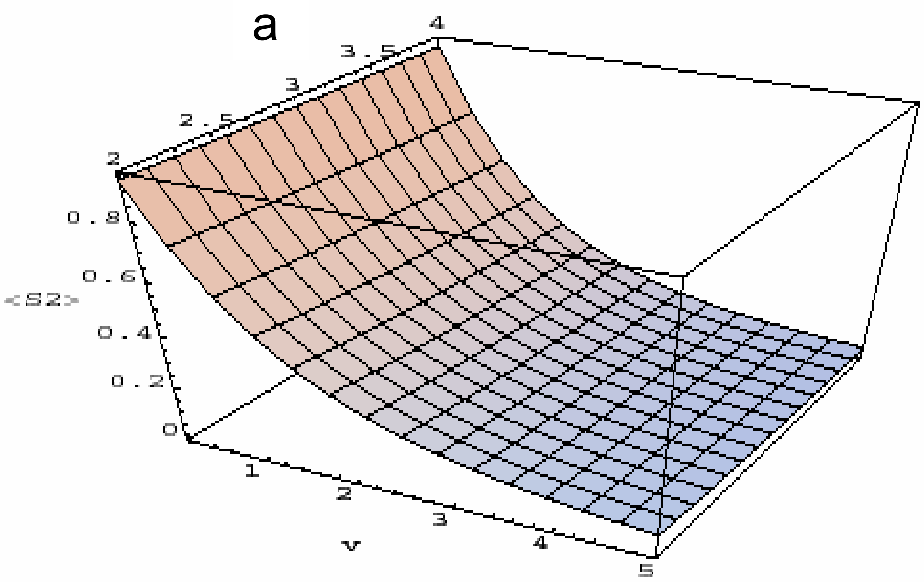
$\sqrt{s}$ (TeV)	$2b$ (GeV^{-2})	Survival probability S^2 for: SD (FPS)	SD (cal)	CD (FPS)	CD (cal)	DD
0.54	4.0	0.14	0.13	0.07	0.06	0.20
	5.5	0.20	0.18	0.11	0.09	0.26
	7.58	0.27	0.25	0.16	0.14	0.34
1.8	4.0	0.10	0.09	0.05	0.04	0.15
	5.5	0.15	0.14	0.08	0.06	0.21
	8.47	0.24	0.23	0.14	0.12	0.32
14	4.0	0.06	0.05	0.02	0.02	0.10
	5.5	0.09	0.09	0.04	0.03	0.15
	10.07	0.21	0.20	0.11	0.09	0.29

- GSP considering multiple channels

GLM - GSP

(*) Gotsman-Levin-Maor PLB 438 229 (1998)





- Suppression due to secondary interactions by additional spectators hadrons

$$<|S|^2>=\frac{\int |A(s,b)|^2\, e^{-\Omega(s,b)} d^2b}{\int |A(s,b)|^2\, d^2b}$$

- Survival probability as a function of v(s) = Ω (s,b = 0) (Ω is the opacity or optic density of interaction of incident hadrons and a, where a is the ratio of the radius in soft and hard interactions)

$$a = R_s / R_h$$

GLM model

- Eikonal model originally conceived so as to explain the exceptionally mild energy dependence of soft diffractive cross sections.

- Considers that the s-channel unitarization enforced by the eikonal model operates on a diffractive amplitude in a different way than it does on the elastic amplitude

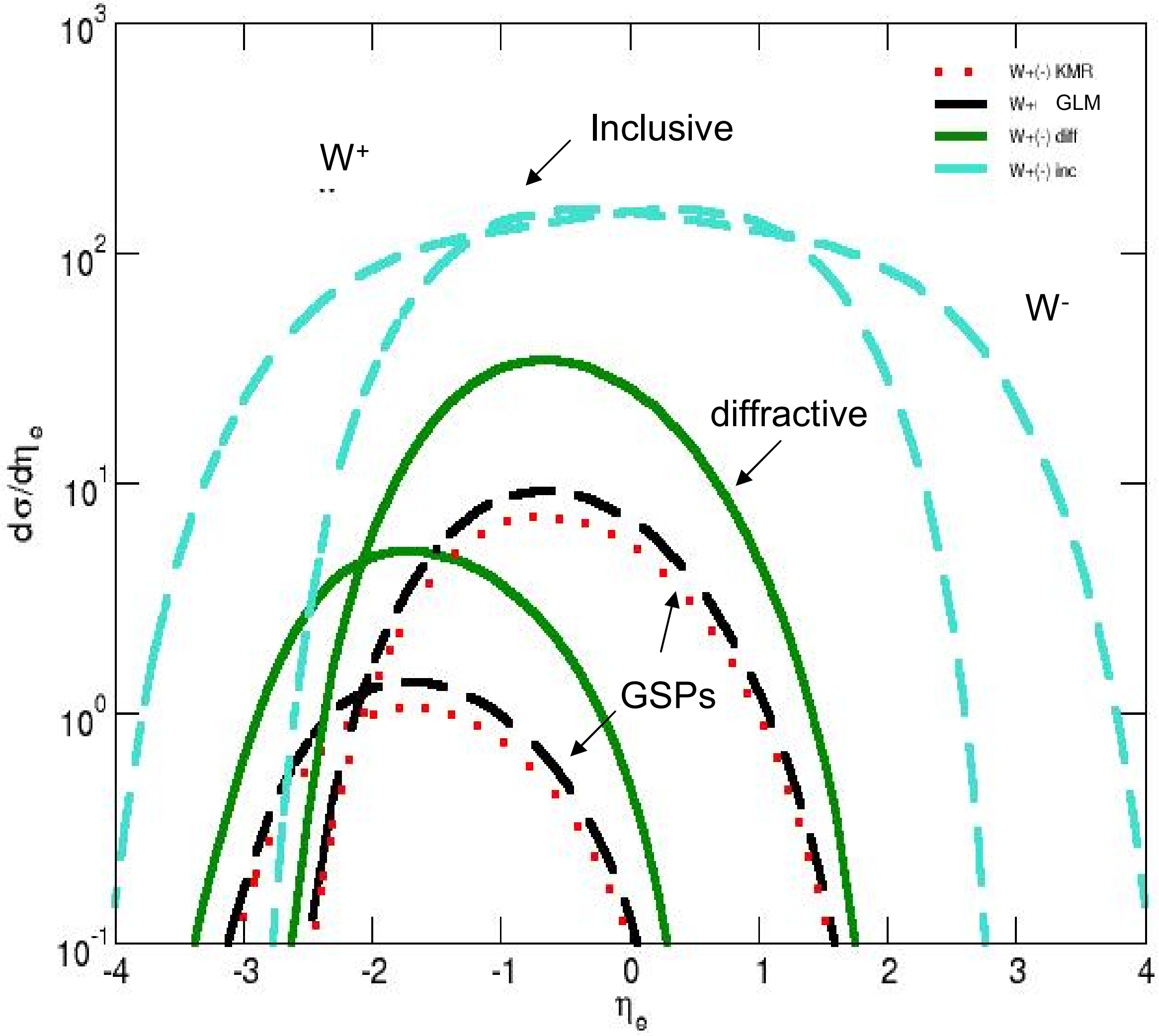
- We consider the single-channel eikonal approach

- Case where the soft input is obtained directly from the measured values of σ_{tot}, σ_{el} and hard radius R_H

$<\|S\|>^2$	GLM
Tevatron	**0.126**
LHC	**0.081**

W^+ and W^- Cross Sections

Tevatron



$$R = \frac{\int_{-\eta}^{\eta} \sigma_{diff}^{W^+} + \sigma_{diff}^{W^-}}{\int_{-\eta}^{\eta} \sigma_{inc}^{W^+} + \sigma_{inc}^{W^-}}$$

- Ranges $\begin{cases} |\eta_e| < 1.1 \\ 1.5 < |\eta_e| < 2.5 \end{cases}$

W^+, W^- and Z^0 Ratios

	Pseudo-rapidity	Data (%)	R(%)	
1.8 TeV	$\|\eta_e\| < 1.1$	1.15 ± 0.55	0.715 ± 0.045	**CDF**
		1.08 ± 0.25	0.715 ± 0.045	**D0**
	$1.5 < \|\eta_e\| < 2.5$	0.64 ± 0.24	1.7 ± 0.875	
	Total $W \to e\nu$	0.89 ± 0.25	0.735 ± 0.055	
	Total $Z \to e^+e^-(*)$	1.44 ± 0.80	0.71 ± 0.05	
14 TeV	$\|\eta_e\| < 1.1$	...	31.1 ± 1.6	**LHC**
	Total $Z \to e^+e^-(*)$	...	30.26 ± 1.41	

* $|\eta| < 1.1$

Average of KMR and GLM predictions

- **Tevatron, without GSP – 7.2 %**

Other GSPs results

- Diffractive W production

	Pseudo-rapidity	Model	R (%)	
1.8 TeV	$\|\eta_e\| < 1.1$	DGM 1 – 27.6	2.10 ± 0.065	
	$\|\eta_e\| < 1.1$	DGM 2 – 32.6	2.48 ± 0.129	
	$\|\eta_e\| < 1.1$	BH – 20.8	1.12 ± 0.075	
	$\|\eta_e\| < 1.1$	KMR – 15.0	0.67 ± 0.065	3 ch
	$\|\eta_e\| < 1.1$	GLM – 12.6	0.76 ± 0.055	1 ch

DGM – Dynamical Mass Gluon → Luna (2006)

BH – Block Halzen model → (2002)

GLM – Gotsman Levin Maor → (2001)

Conclusions

- Analysis of W and Z diffractive hadroproduction process and central rapidity distributions of produced leptons
- Using new Pomeron diffractive parton distributions (H1 Collaboration – DESY – HERA) and theoretical estimates for gap survival factor
- Very good agreement with experiment (D0 and CDF, Tevatron)
- Improvement of data description using gap survival probability
- Important subject to verify future IP PDF’s
- Estimates to be compared at LHC