DIFFRACTIVE SCATTERING

BASIC INTRODUCTION

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THE PLAN

- LECTURE 1:
  - WHAT DIFFRACTION?
  - SIGNATURES OF DIFFRACTIVE PROCESSES
- LECTURE 2:
  - EXPERIMENTS AT THE LHC
  - FUTURE PLANS

WHAT DIFFRACTION?

DIFFRACTIVE SCATTERING PROBES HADRONIC VACUUM

- DIFFRACTIVE SCATTERING IS CHARACTERIZED BY VACUUM FLUCTUATIONS IN THE PERIFERY OF INITIAL STATE HADRONS
- HOW TO QUANTIFY THESE FLUCTUATIONS, THEIR CONTENT AND DYNAMICS?

SOFT DIFFRACTION DEALS WITH QUARK-GLUON STATES CONFINED WITHIN HADRONS

- QCD IS THE THEORY BEHIND – BUT IT IS USEFUL ONLY IN CASE PERTURBATION THEORY CAN BE USED AT SMALL DISTANCES HAVING A HARD SCALE IN p_T^2, Q^2!

⇒ SOFT – LONG DISTANCE – PROCESSES CANNOT BE CALCULATED – NEED PHENOMENOLOGICAL MODELS FOR:

σ_{tot} $\sigma_{elastic}$ σ_{diff} $(= \sigma_{SD}+\sigma_{DD}+\sigma_{CD})$

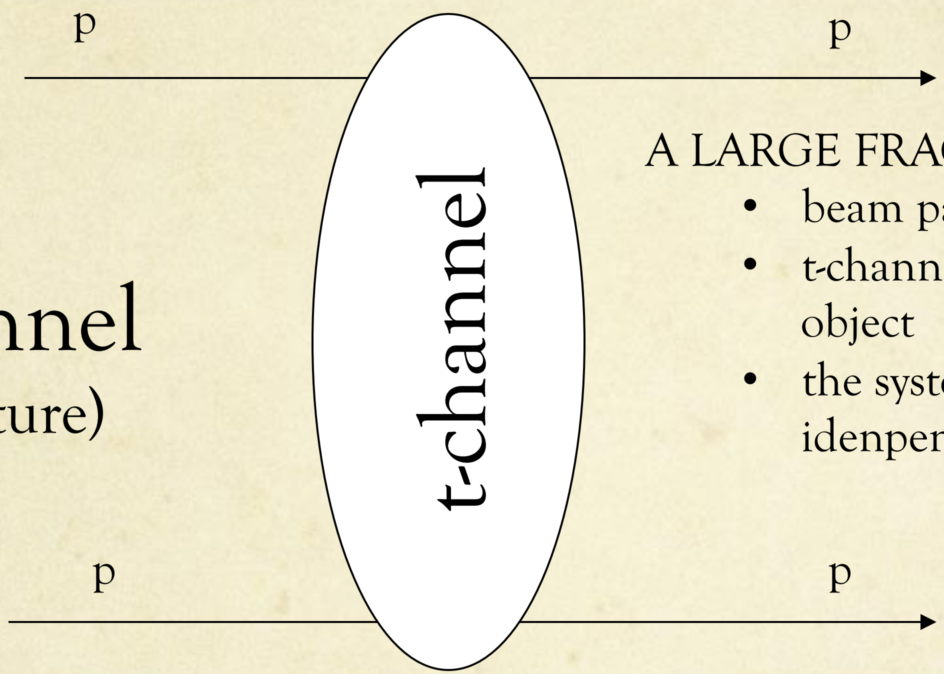
- AT LARGE DISTANCES CONFINEMENT FORCES TAKE OVER – BINDING FORCES BETWEEN QUARKS RESPONSIBLE FOR STATIC PROPERTIES OF HADRONS – DIFFRACTIVE SCATTERING TO PROBE THESE.

DIFFRACTIVE SCATTERING MAPS OUT CONFIGURATIONS OF PARTONS (QUARKS AND GLUONS) CONFINED WITHIN HADRONS

- SPACE-TIME EVOLUTION OF HADRON-HADRON SCATTERING

- QCD ASYMPTOPIA - QUARK-GLUON CONFINEMENT

DIFFRACTION IS DESCRIBED AS A PRODUCTION (s-channel) OR AS AN EXCHANGE (t-channel) PROCESS



s-channel
(this lecture)

A LARGE FRACTION OF EVENTS WITH:

- beam particles intact (elastic)
- t-channel exchange of a colourless object
- the systems created hadronize idenpendently, produce rap gaps

Bjorken’s definition (out of frustration?): ”A process which causes rapidity gaps that are not exponentially suppressed.”

Can be viewed as an exchange process (t-channel/Regge model) or as a production process (s-channel) $\Rightarrow$ Optical analogy: Fraunhofer scattering.

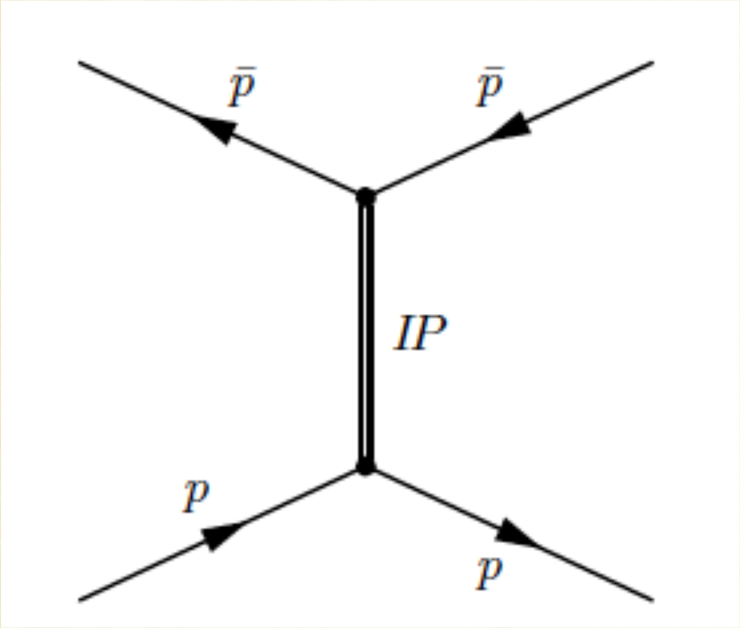
Remember the Mandelstam variables s, t, u?

DIFFRACTION HAS AN OPTICAL ANALOGY

- THE TWO APPROACHES BOTH USE AN ANALOGY TO (FRAUNHOFER) DIFFRACTION IN OPTICS:
  - MUELLER – REGGE MODEL
  - GOOD – WALKER FORMALISM

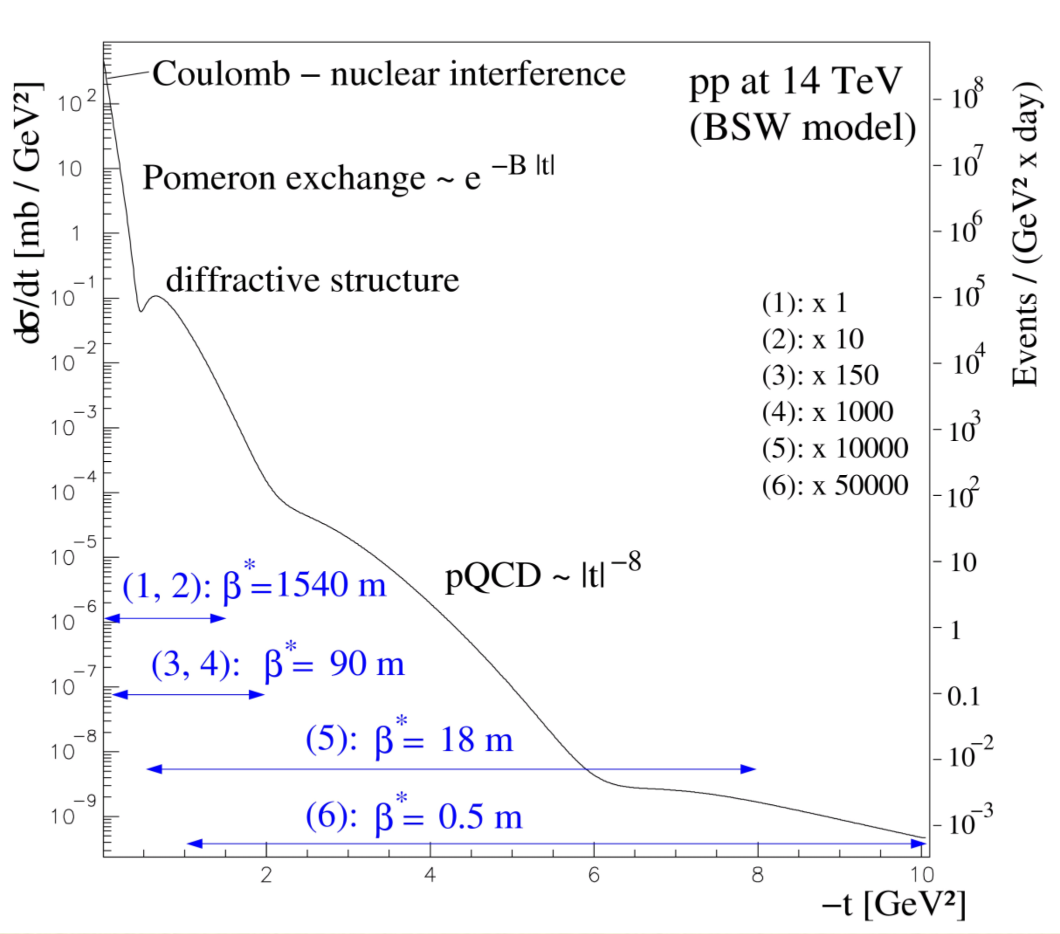
- THESE MODEL APPROACHES ARE SUPPLEMENTED BY:
  - saturation models, semiclassical approaches, dipole models, perturbative QCD – BFKL, colour connection…

ELASTIC SCATTERING IS DIFFRACTIVE



$$\bar{p}p \to \bar{p}p$$

ELASTIC CROSS SECTION PROJECTS THE SHADOW OF A COMPLEX PROTON



$d\sigma_{el}/dt$ yields:

- pp *interaction radius* (slope of the $d\sigma_{el}/dt$ distribution)
- with the measurement of the total inelastic rate - the *total pp cross section*,
- A test of the *Coulomb-nuclear Interference* (expected to have an effect over *large* interval in –t).
- A measurement of the *ratio of the real and imaginary parts* of the forward pp pscattering amplitude, ρ = ReA(s,t)/ ImA(s,t)

⇒ Through dispersion relations, a precise measurement of ρ will constrain σ_{tot} at substantially higher energies

⇒ "SHADOW SCATTERING"

LUMINOSITY AND ELASTIC CROSS SECTION ALLOW TOTAL CROSS SECTION TO BE MEASURED

Luminosity relates the cross section σ of a given process by:

$$L = N/\sigma$$

A process with well known, calculable and large σ (monitoring!) with a well defined signature? Need complementarity.

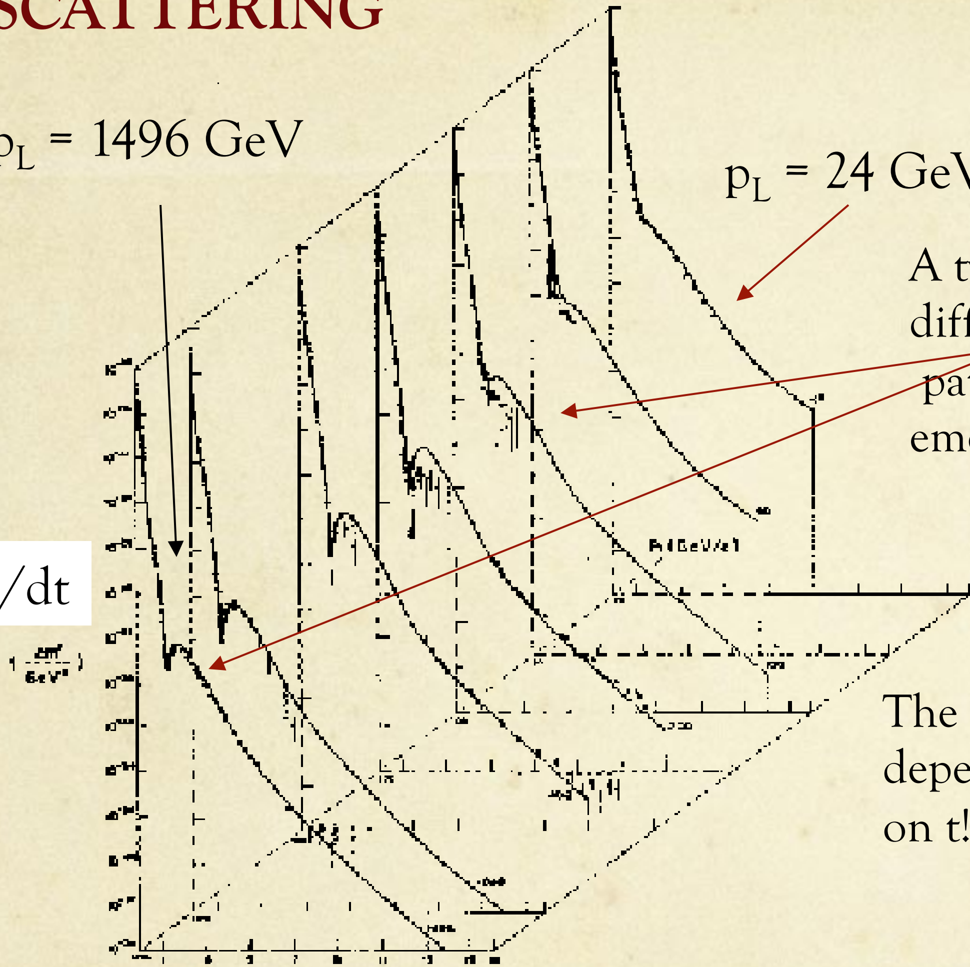
Measure simultaneously elastic (N_{el}) & inelastic rates (N_{inel}), extrapolate dσ/dt → 0, assume ρ-parameter to be known:

$$L = \frac{(1+\rho^2)}{16\pi} \frac{(N_{el} + N_{inel})^2}{dN_{el}/dt|_{t=0}}$$

N_{inel} = ? ⇒ Need a hermetic detector.

$dN_{el}/dt|_{t=0}$ = ? ⇒ Minimal extrapolation to t→0: $t_{min} \approx 0.01$

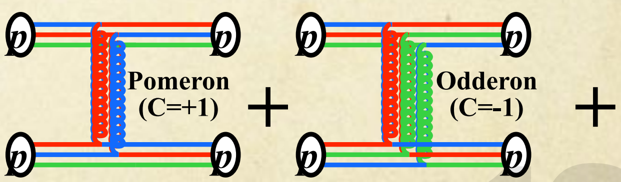
ISR RESULTS – CHARACTERISTICS OF ELASTIC SCATTERING



A typical diffraction pattern emerges

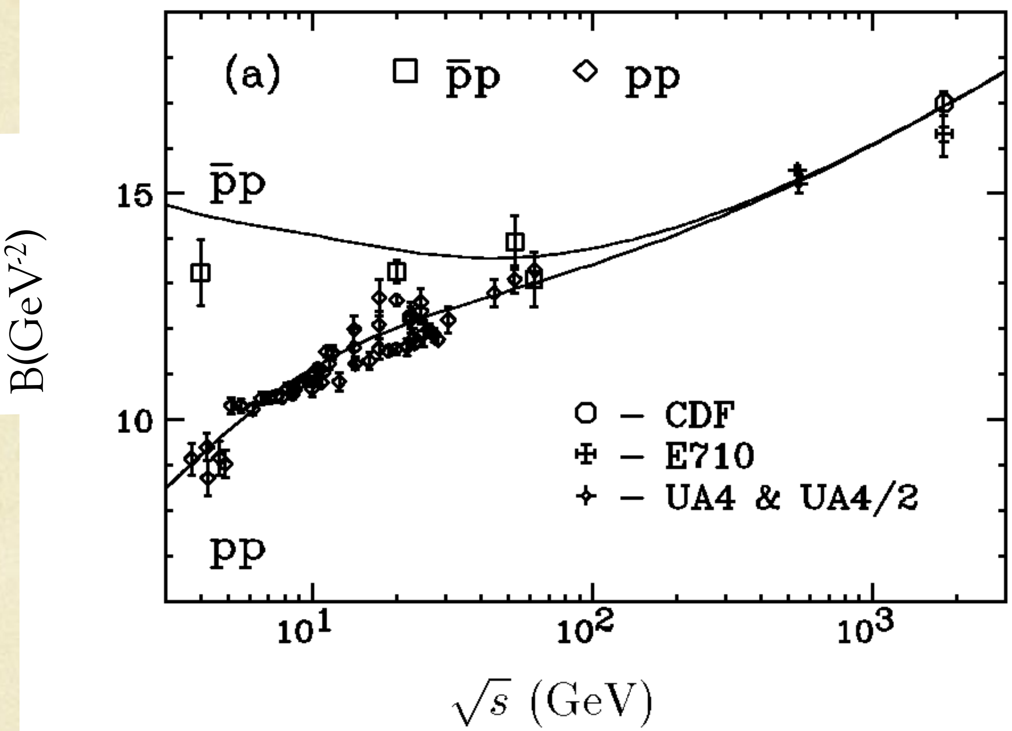
The local slope depends on t!

- diffractive peak *shrinks* – interference *dip* moves to smaller t
- at $-t \geq 1$ GeV² little $\sqrt{s}$ dependence, $d\sigma/dt \propto 1/t^8$ a la Donnachie&Landshoff
- exponential fall-off up to –t ≈ 10 GeV² ?
- Size of the interaction region ∝B(s)



-Where is the Odderon?

THE SLOPE PARAMETER B MEASURES THE pp INTERACTION RADIUS



$t < 0.13$ GeV^2

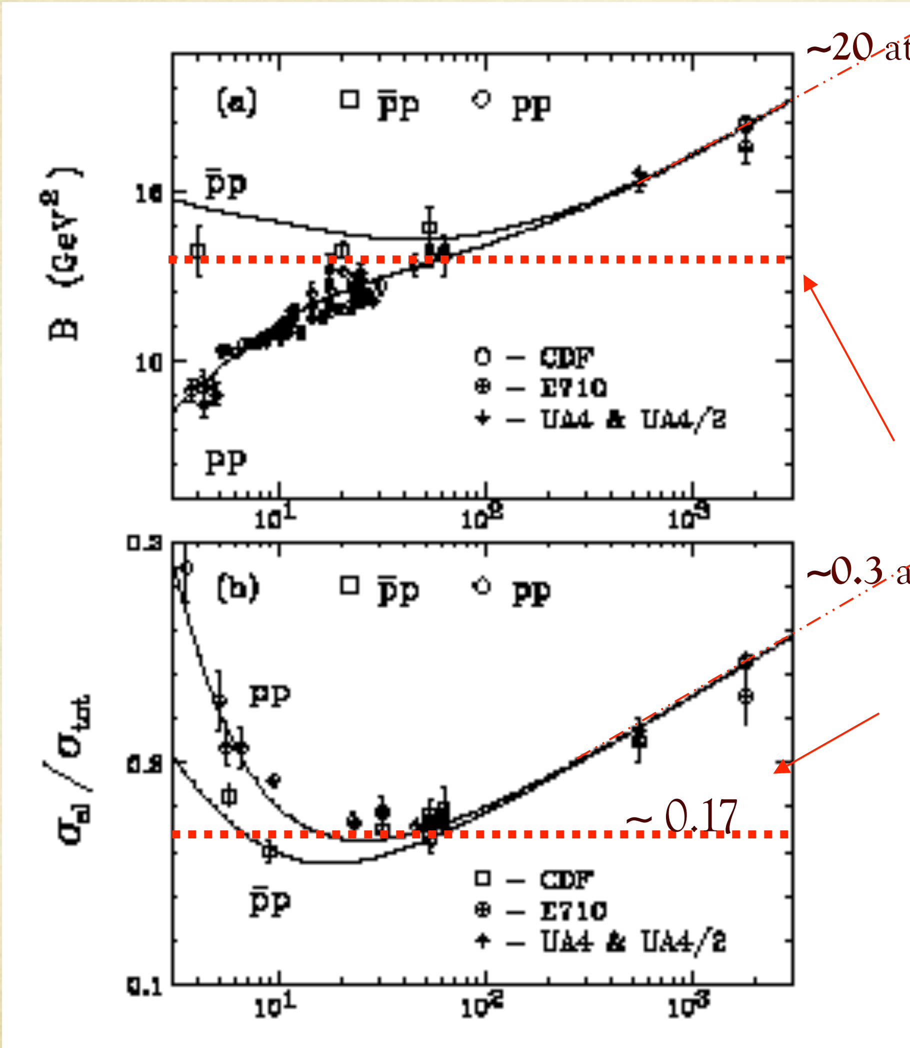
A.Covolan, J. Montanha and K. Goulianos, Phys. Lett. B 389(1996)176.

WHERE IS THE BLACK DISC LIMIT? – AN EARLY ESTIMATE

B~32 at the black disc limit?

The black disc limit reached at 10^8 GeV?

~20 at the LHC, $\langle b^2 \rangle \approx 1.6 fm^2$



Forward elastic slope shrinks
⇒ effective interaction radius of proton grows (∝ lns)

The values of the slopes agree with the optical picture, i.e. with a fully absorbing disc of radius R for which B = $R^2/4$.

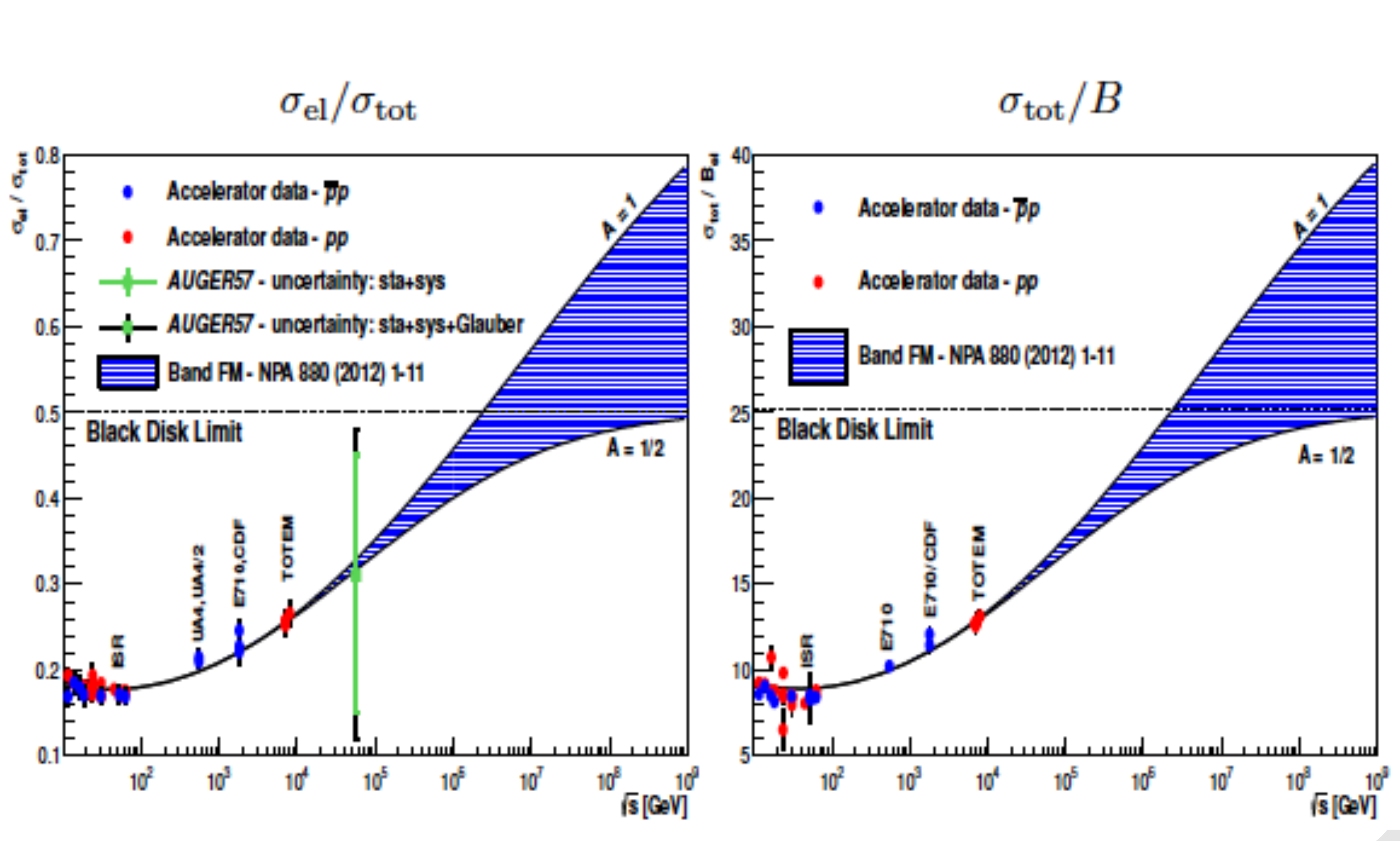
For a proton with R ≈ $1/m_\pi$ (m_π = π meson mass):
B ≈ 13 GeV^{-2}

~0.3 at the LHC

However: Scattering on a black disc: **σ_{el}/σ_{tot}** = ½, while the data (at √s corresponding to B ~13 GeV^{-2}) gives **σ_{el}/σ_{tot} = 0.17…**
⇒ the proton is semi-transparent
⇒ QCD colour transparency!

Mixture of scattering states with different absorption probabilities is required for diffractive scattering to take place.

BLACK DISC LIMIT



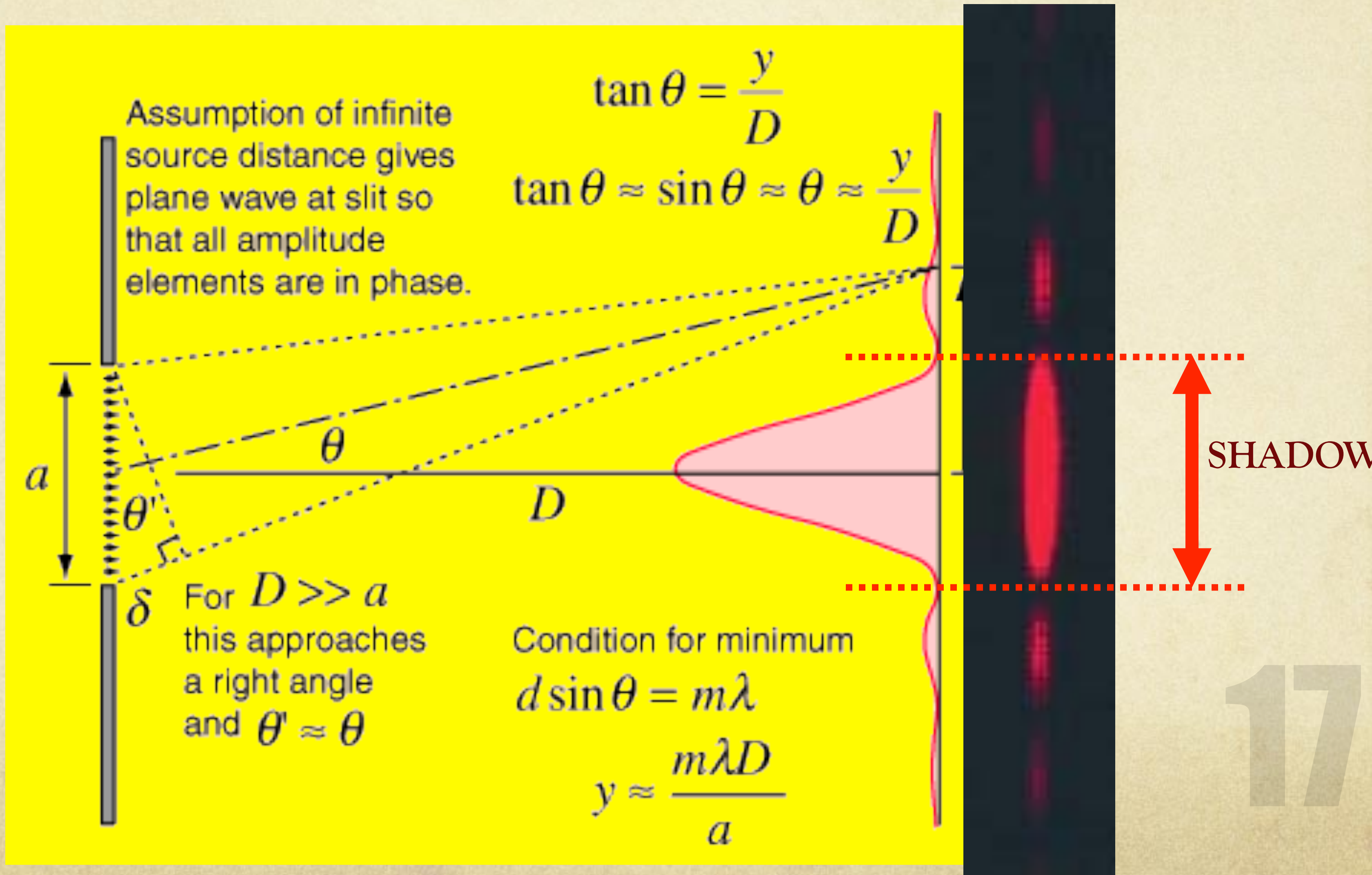
Paulo Silva in Diffraction 2014

MUELLER-REGGE AND GOOD-WALKER APPROACH BOTH HAVE AN OPTICAL ANALOGY – FRAUNHOFER SCATTERING

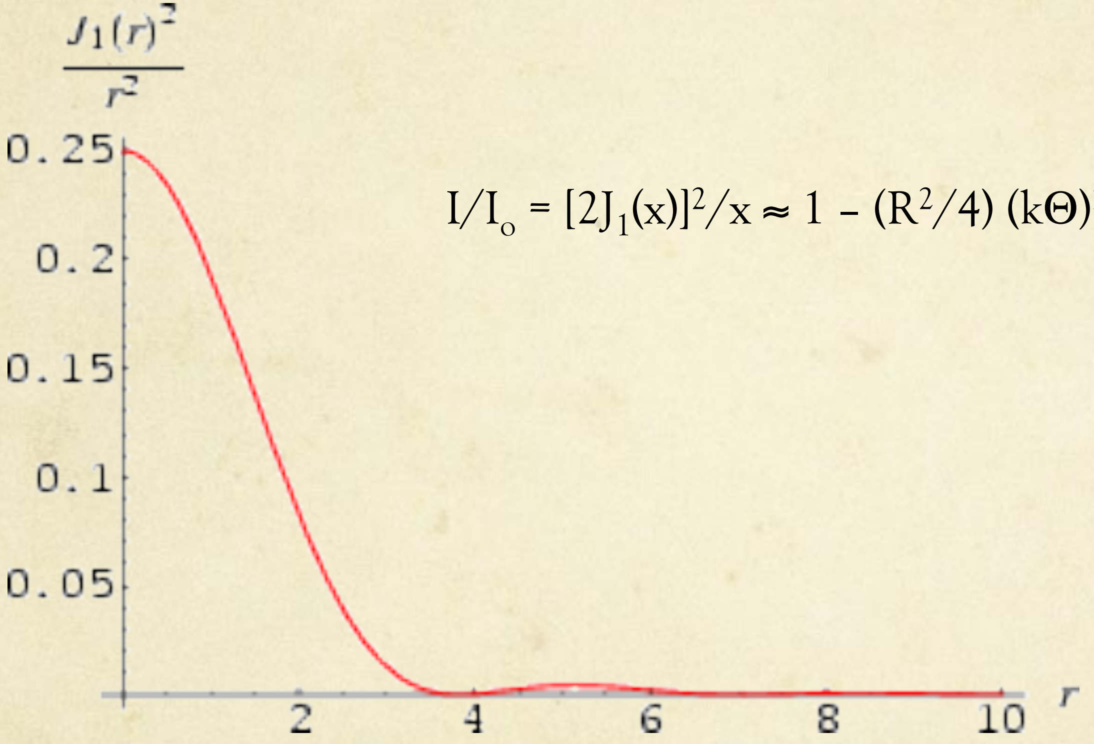
- **A coherent phenomenon** that occurs when a beam of light meets an obstacle with dimensions comparable to the wavelength of incoming light.
- As long as the *wavelength is much smaller than the dimension of an obstacle*, there is a geometrical **shadow**.

Optical analogy by the Landau school: (L.D. Landau and I.Y. Pomeranchuk, Zu.Eksper.Teor.Fiz.24(1953)505, E.Feinberg, NC suppl.3(1956)652, A.I. Akhiezer and Y.I. Pomeranchuk, Uspekhi, Fiz.Nauk.65(1958)593, A. Sitenko, Uspekhi, Fiz.Nauk. 67(1959)377, V.N. Gribov, Soviet Jetp 29(1969)377.)

PATTERN OF DIFFRACTION



BESSEL FUNCTION EXHIBITS MINIMA AND EXPONENTIAL SLOPES

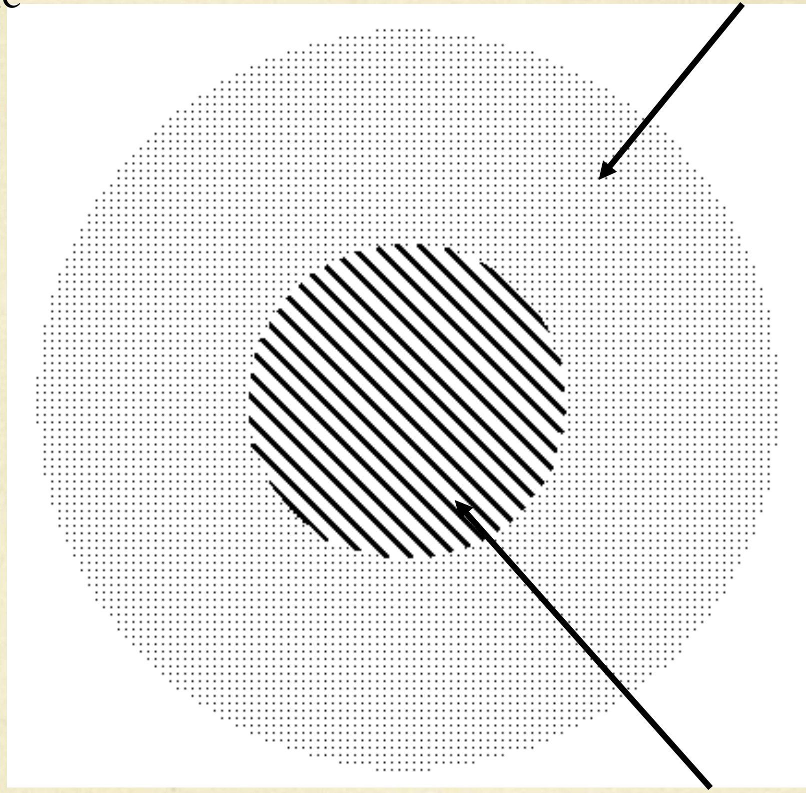


$I/I_o = [2J_1(x)]^2/x \approx 1 - (R^2/4)\,(k\Theta)^2$

"Airy disk": $x_1 = 2kR\sin\Theta = (\pi/\lambda)R\sin\Theta = (\pi/\lambda)D\sin\Theta = 3.83166...$

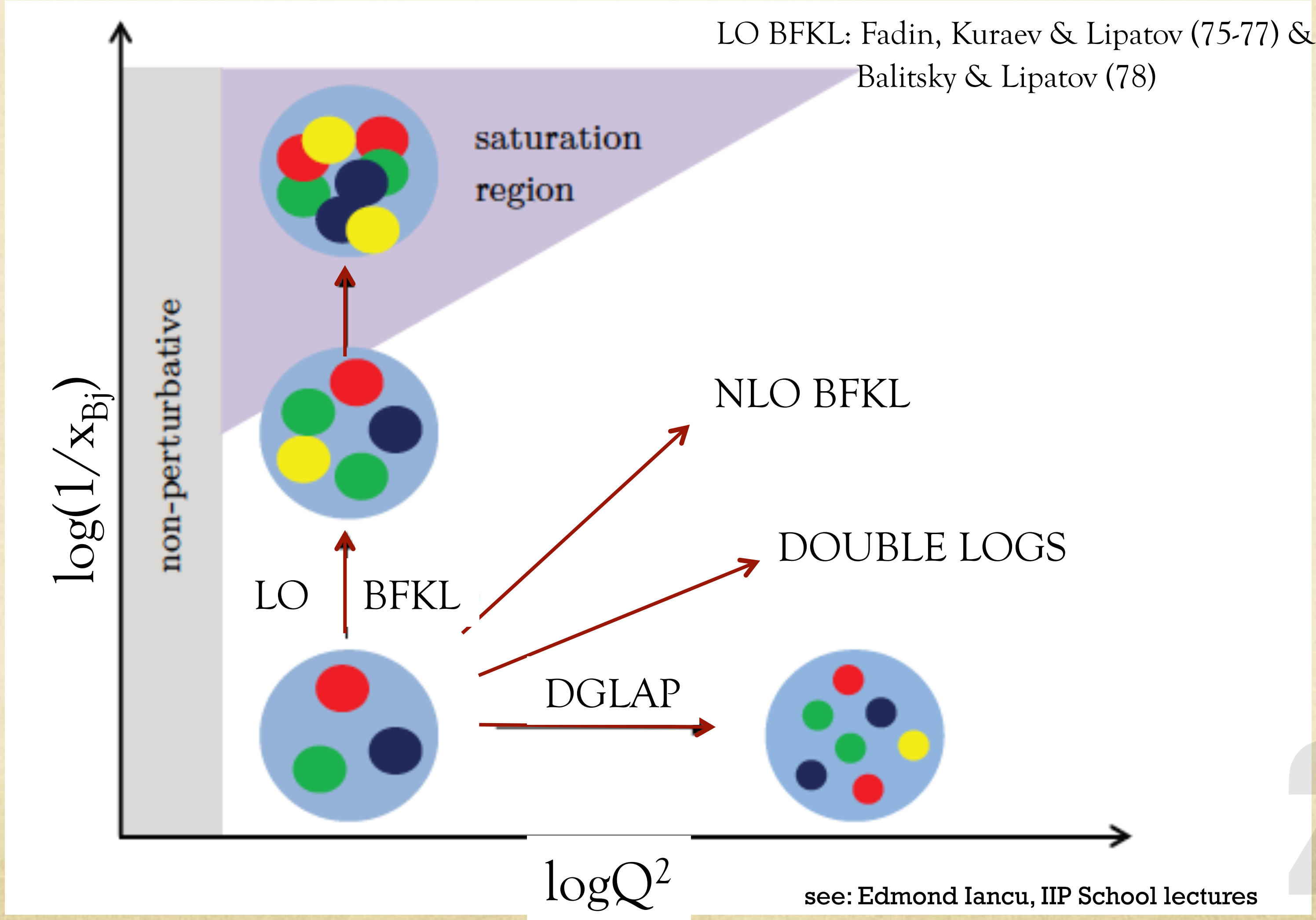
GEOMETRICAL PICTURE OF PROTON...

transverse plane

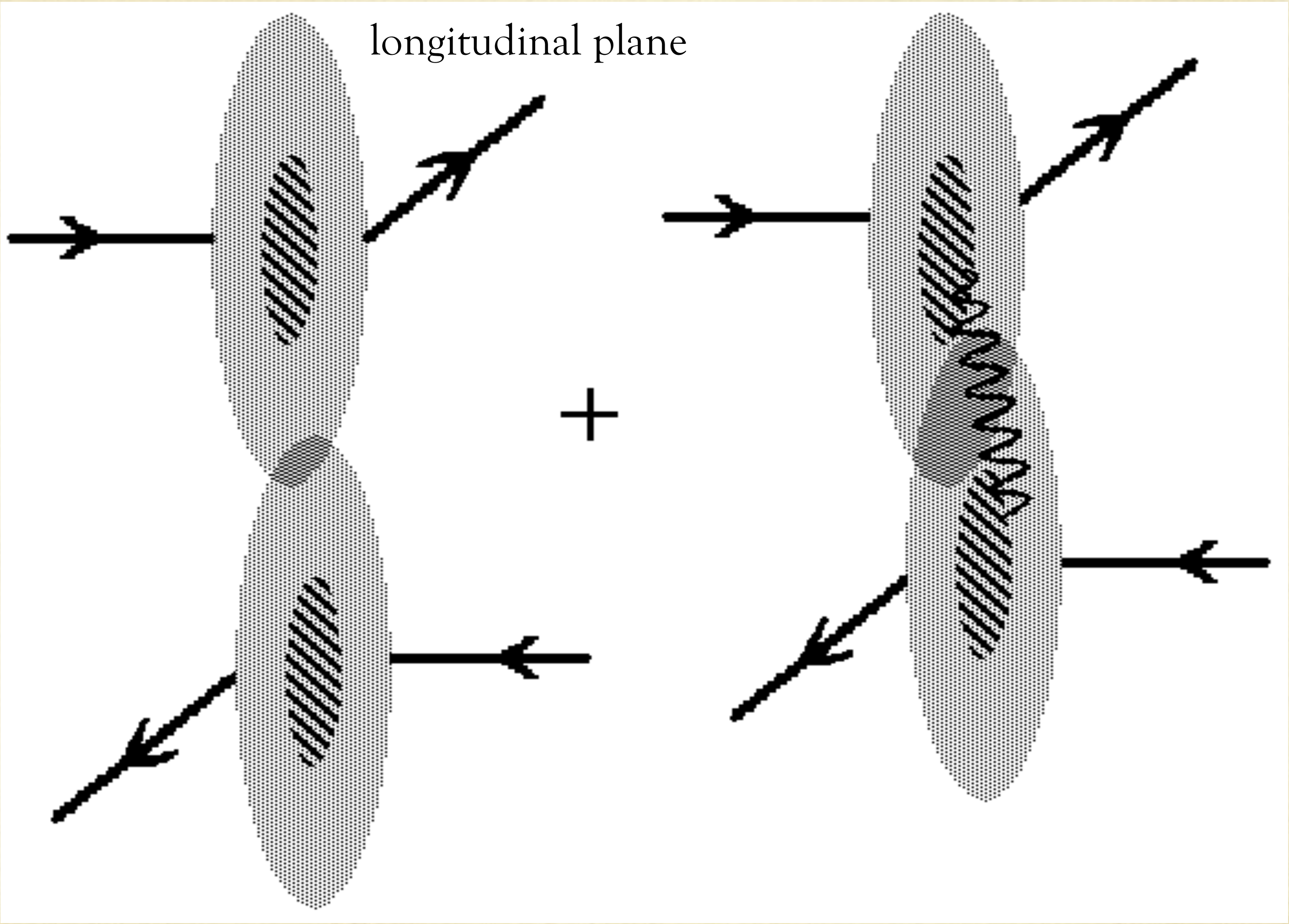


proton at rest – what happens in a high energy collision?

DIFFERENT PARTON CONFIGURATIONS ARE RESOLVED DEPENDING ON x_{Bj} and Q^2



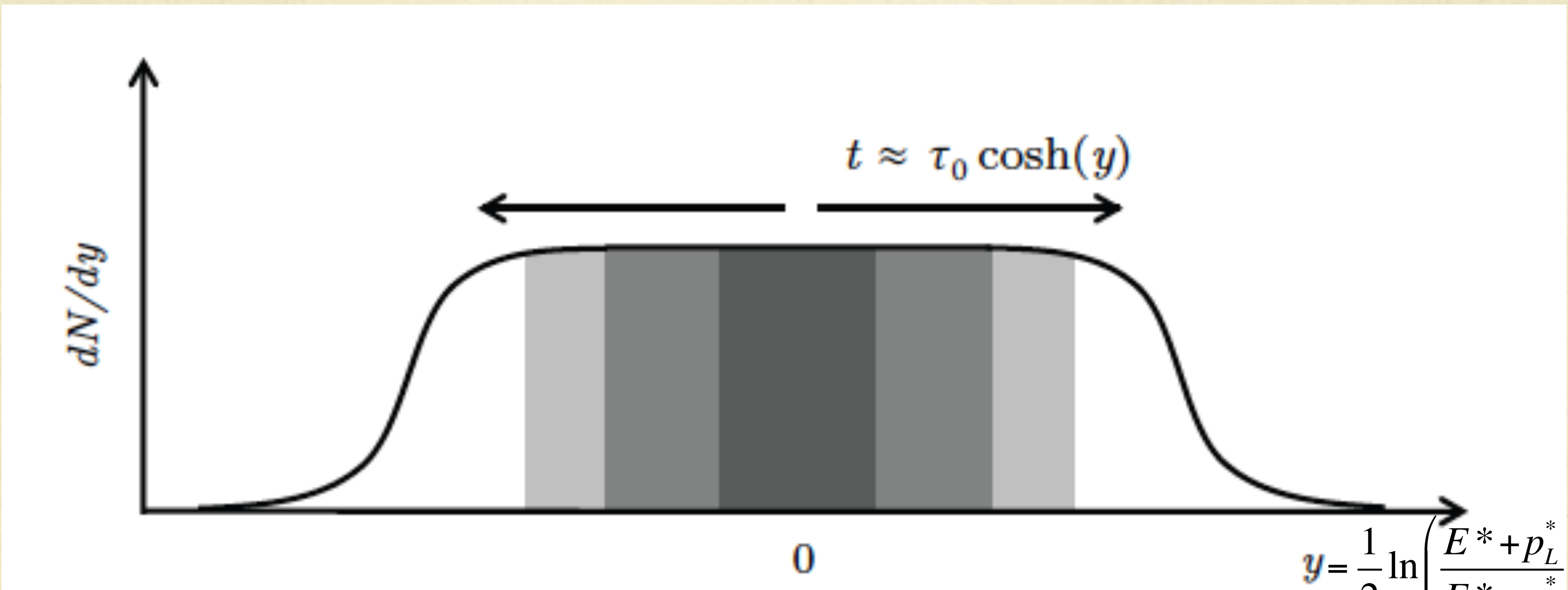
LORENTZ CONTRACTED PROTONS INTERACT



SOFT DIFFRACTION

HARD DIFFRACTION

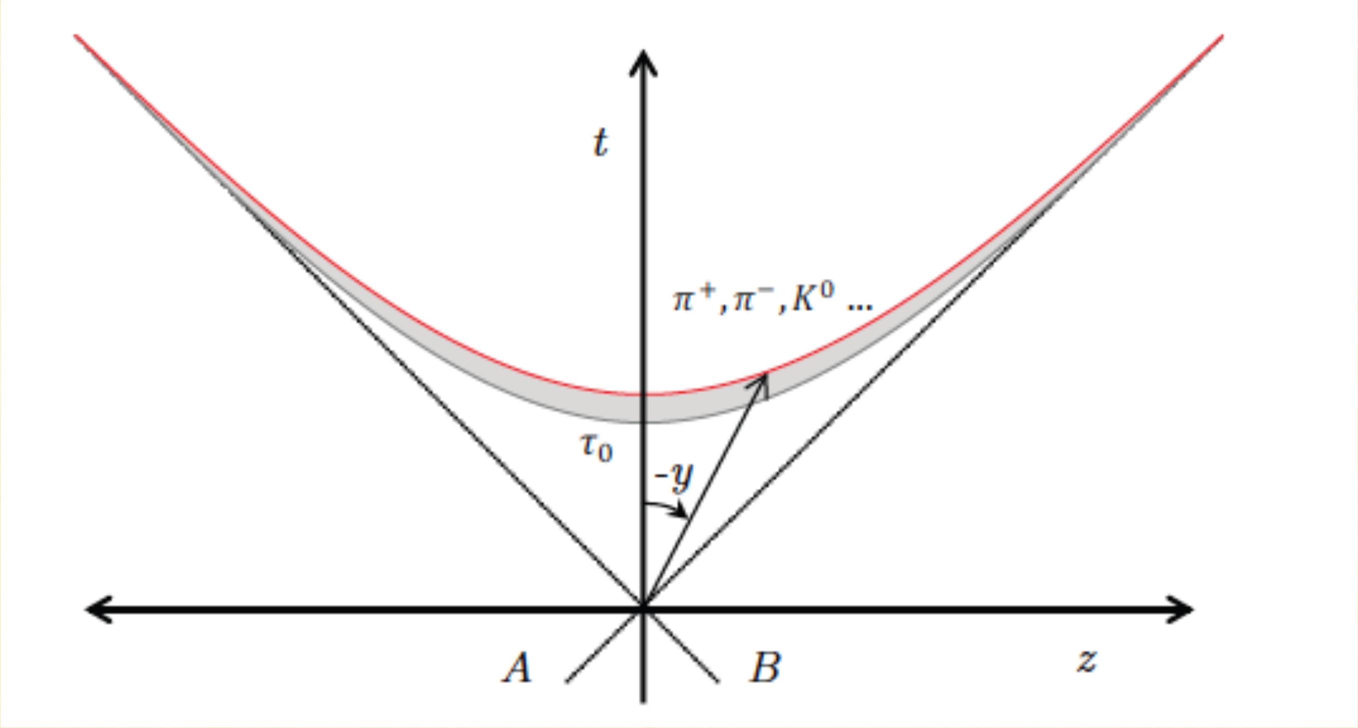
RAPIDITY SPACE – TIME WINDOW TO HADRON-HADRON SCATTERING



$$y = \frac{1}{2}\ln\left(\frac{E^* + p_L^*}{E^* - p_L^*}\right)$$

Assume that the colliding hadrons are Lorentz contracted into narrow discs. In collision, hadrons are formed and fill up the kinematically allowed longitudinal momentum space. A uniform rapidity distribution of final state particles results.

SPACE-TIME EVOLUTION (btw THERE ARE NO INDEPENDENT JET-PARTONS!)

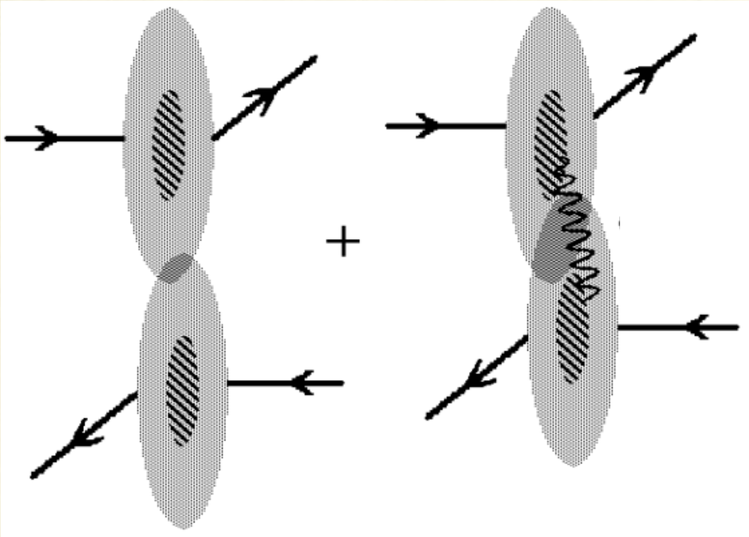


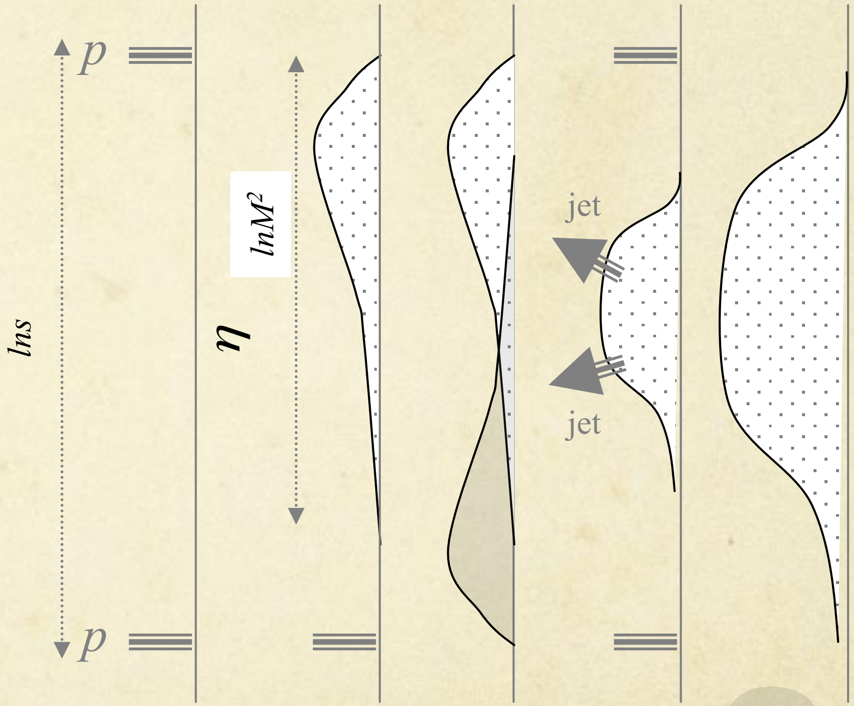
Hadron collision as a chain reaction initiated by wee partons: At first, only a small c.m.s. domain of partons within $|\Delta y| \approx 1$ around y=0 is excited. Subsequent to this initial excitation, de-excitation "cooling" takes place by $\boldsymbol{\tau}_0 \approx$ 1fm/c through hadron emission that, in turn, excites neighbouring domains with a characteristic time of t ≈ $\boldsymbol{\tau}_0$ cosh(y).

PROFILES OF DIFFRACTIVE SCATTERING AS SEEN IN THE RAPIDITY SCREEN

soft diffractive scattering

hard diffractive scattering

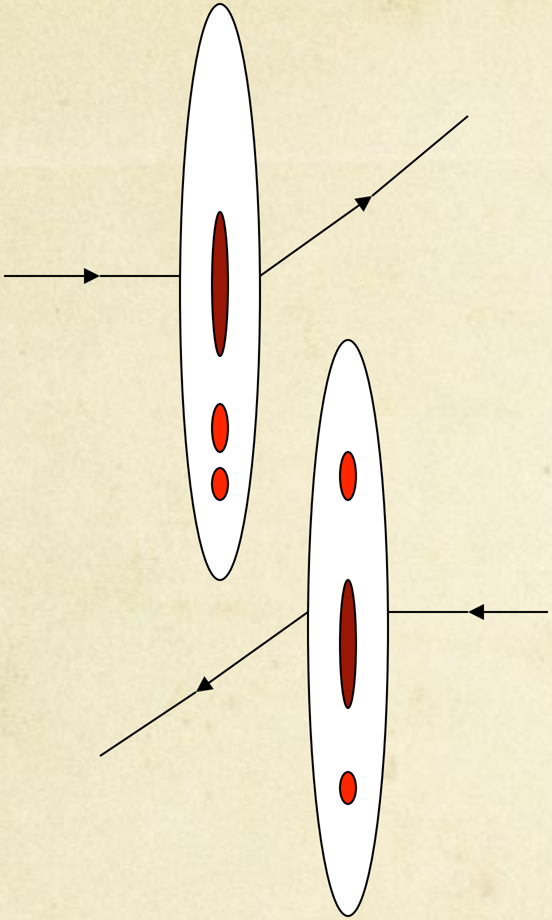


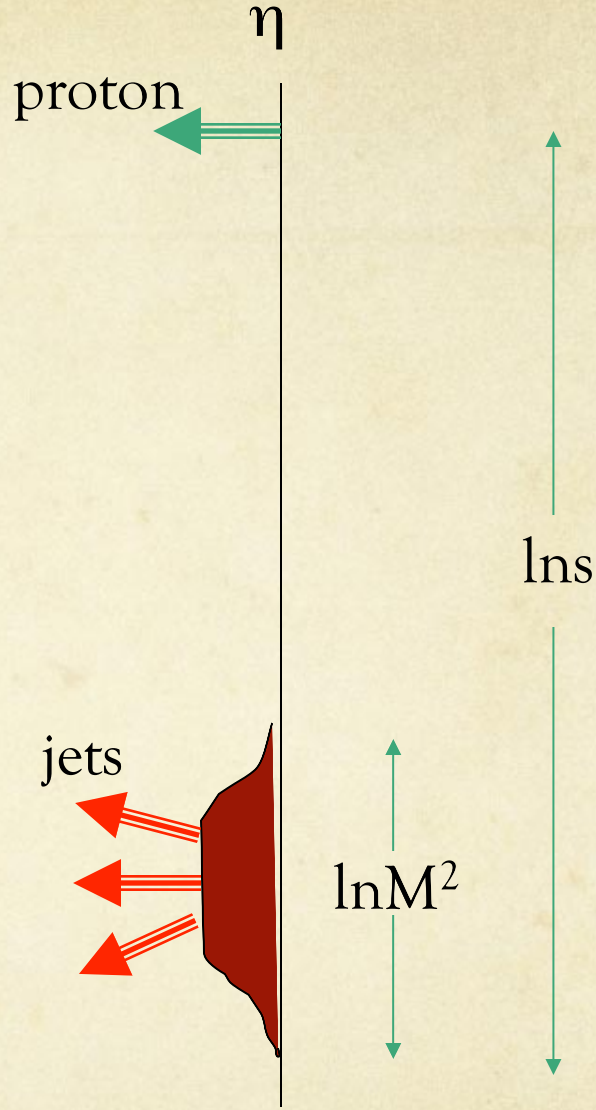


-low/high masses pose a problem!

pseudorapidity axis $\eta = -\ln(\tan(\theta/2))$

MULTIPLE GAPS IN RAPIDITY?





'hot spots' – vacuum fluctuations
of the 'wee' partons in the gluon cloud
of protons?

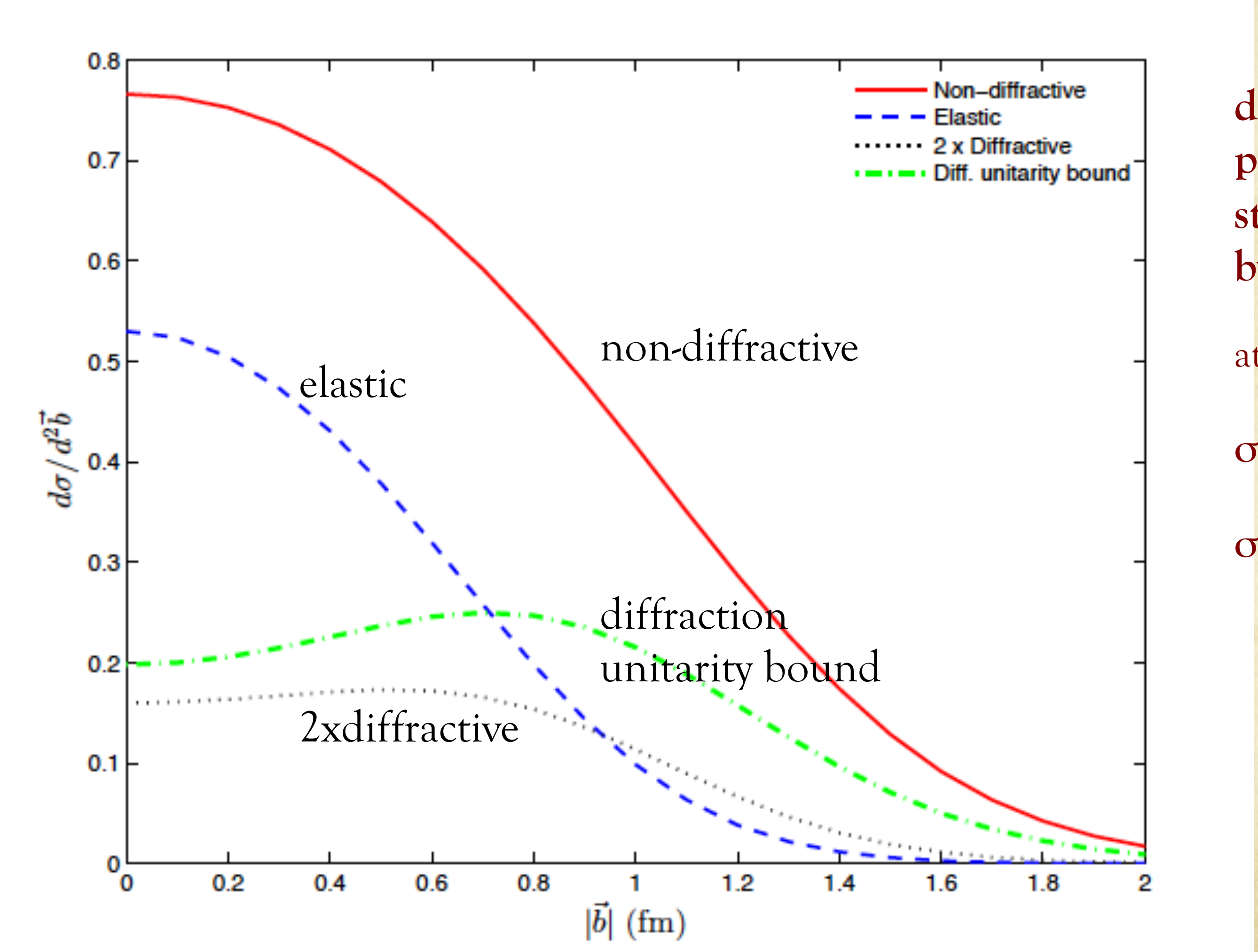
DIFFRACTION IN IMPACT PARAMETER SPACE

- The profile of diffractive scattering is a disc with an opacity depeding on b
- The mean radius of the disc = $\sqrt{B(s)}$
- B(s) contains an energy independent and a $\ln(s/s_o)$ term
- The radius of the disc expands with energy at a rate determined by α_P' ($\approx$0.25 GeV^{-2})
- The opacity – at fixed b – increases.

IN TERMS OF QCD:

- **The gluon density of the target – the interaction probability (blackness) – increases (but not without a limit!)**
- **Increase of σ_{tot} with energy due to the increase of 'wee' partons in colliding protons, controlled by $\alpha_P(0)$ (QCD multiplicity anomalous dimensions?)**
- **Proton is semi-transparent, even at b=0: wave functions of the hadrons entering the collision are a superposition of states – some will be fully absorbed, some pass through ⇒ 'colour transparency' in QCD**

PROTON-PROTON SCATTERING IN THE IMPACT PARAMETER SPACE



diffraction is peripheral – strongly influenced by unitarity

at $\sqrt{s} \approx$ 1TeV and $b \approx 0$,

$\sigma_{el} \approx ½\, \sigma_{tot} \approx ¼$

$\sigma_{diff}^{inel} \leq 0.01$

GOOD-WALKER APPROACH TO DIFFRACTIVE HADRON SCATTERING

- CONSIDER HADRONS AS QUANTUM MECHANICAL SUPERPOSITIONS OF QUARK-GLUON STATES
- HADRON-HADRON INTERACTIONS OCCUR BETWEEN THE QUARK-GLUON STATES EXTENDED IN SPACE AND TIME
- A HADRON-HADRON INTERACTION IS CALLED DIFFRACTIVE, IN CASE THE SCATTERING PROCESS CAN BE DESCRIBED AS AN ABSORPTION OF THE HADRON WAVE FUNCTION BY THE NUMBER OF AVAILABLE INELASTICS SCATTERING MODES – DIFFRACTION IS “SHADOW” SCATTERING”

GOOD-WALKER APPROACH

- WHAT ARE THE EIGENSTATES OF SOFT DIFFRACTION?
- HOW TO HANDLE LOW MASS (N*) STATES?
- TRANSITION BETWEEN SOFT AND HARD DIFFRACTION
- UNIFICATION OF THE s- AND t-CHANNEL DESCRIPTIONS?

DIFFRACTION - GOOD & WALKER INTERPRETATION

impact parameter

Diffractive part of the S-matrix: $iD_{ik}(s,b)$ can be diagonalized by an orthogonal matrix Q:

$D = QFQ^T$; $F_{ij} = F_i\delta_{ij}$

$\Psi_i = \sum_k Q_{ik}\varphi_k$; φ_k-eigenstates, which have elastic scattering only

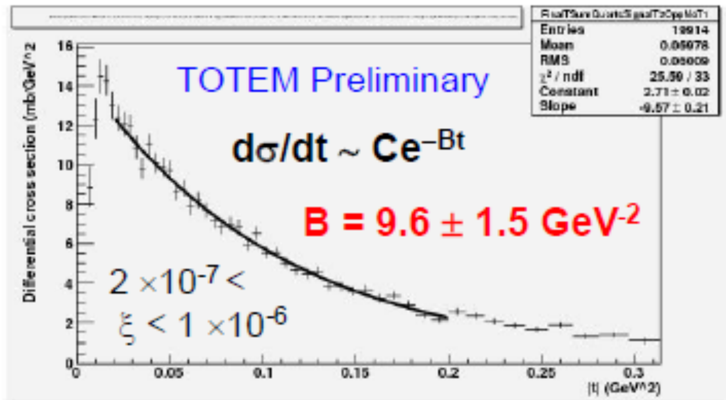
⇔ Quark configurations with fixed transverse separations.

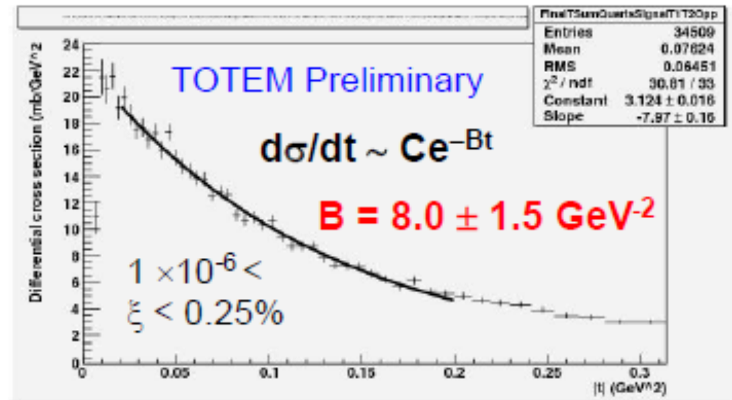
In diffractive scattering the final state is a new superposition of eigenstates, and thus contains (with i= 1,2,...,N).
If all $F_i = ½$ ($b \leq R$) – black disk limit – no inelastic diffraction.
For $F_i \leq ½$:

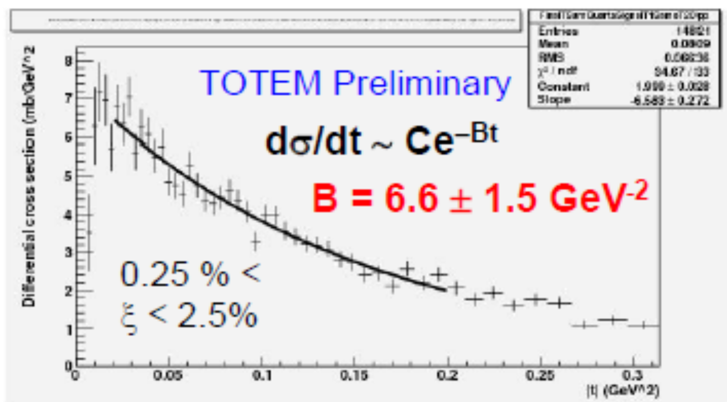
$$\sigma_{el}(b,s) + \sigma_D^{inel}(b,s) \leq ½\ \sigma^{tot}(b,s)$$

Pumplin's bound

SINGLE DIFFRACTION: $d\sigma/dt$ vs. ξ







t-distributions still to be corrected for beam divergence & effect of ξ on proton ϕ-acceptance correction

$$\frac{d\sigma_{SD}^{class\ i}}{dt} = e^{-B_i t} - \text{backgr.}$$

$$\sigma_{SD}(\xi > 2\times10^{-7}) = \sum_i \int_0^\infty dt \, \frac{d\sigma_{SD}^{class\ i}}{dt}$$

GOOD&WALKER APPROACH AS MODELED BY MIETTINEN & PUMPLIN

A superposition of diffractive states:

$$|B> = \sum C_k \, |\Psi_k>, \qquad (1)$$

which are eigenstates of the scattering operator ImT $|\Psi_k> = t_k|\Psi_k>$.

-**Different eigenstates absorbed by the target with different intensities** ⇒ the outgoing state is no longer $|B>$ ⇒ inelastic particle production (impact parameter space):

$$d\sigma_{el}/d^2b = |\langle B|ImT|B\rangle|^2 = |\sum |C_k|^2 \, t_k|^2 = \langle t\rangle^2,$$

$$d\sigma_{tot}/d^2b = 2\,\langle t\rangle,$$

$$d\sigma_{diff}/d^2b = \sum |\langle \Psi|ImT|B\rangle| \; - d\sigma_{el}/d^2b = \langle t^2\rangle - \langle t\rangle^2.$$

-Miettinen / Pumplin: The eigenstates of diffraction are **parton** states: $|\Psi_k> \equiv |\mathbf{b}_1,\ldots,\mathbf{b}_N, y_1,\ldots,y_N\rangle$,

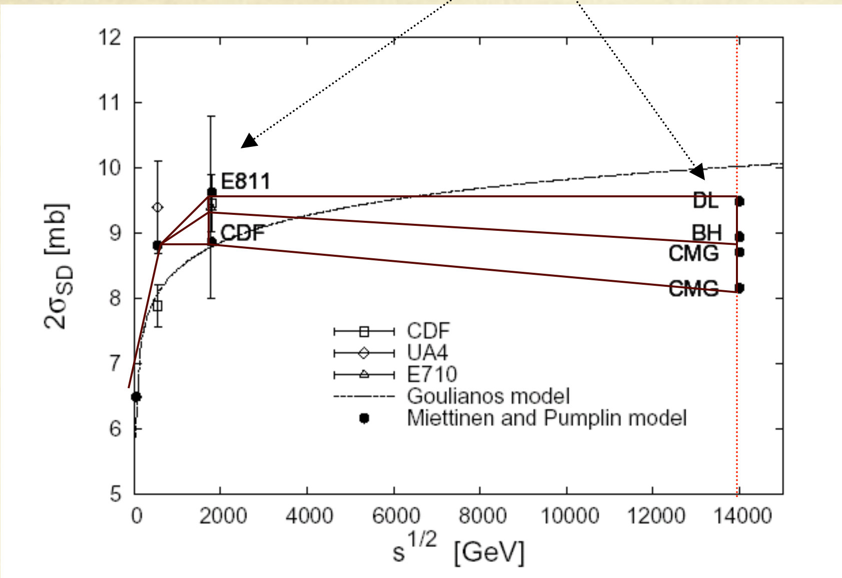
Where N is the number of partons; y_i is the rapidity of parton i and $\mathbf{b}_i$ is the impact parameter of parton i relative to the impact parameter of the incident particle. From Eq.(1):

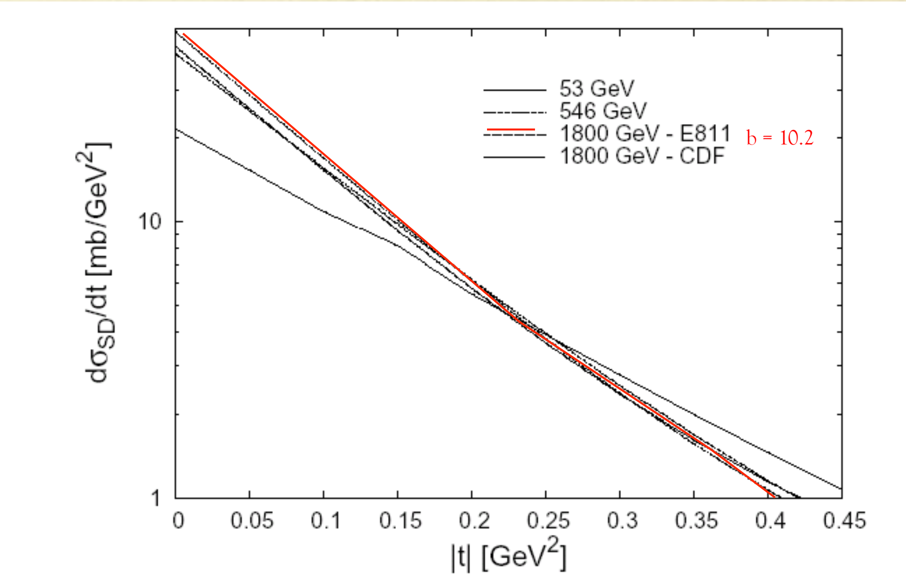
$$|B> = \sum \int \prod d^2\mathbf{b}_i \, dy_i \, C_N(\mathbf{b}_1,\ldots,\mathbf{b}_N, y_1,\ldots,y_N)|\mathbf{b}_1,\ldots,\mathbf{b}_N, y_1,\ldots,y_N\rangle$$

H.I.Miettinen and J. Pumplin, PRD18(1978)1696.

MIETTINEN & PUMPLIN MODEL PREDICTIONS

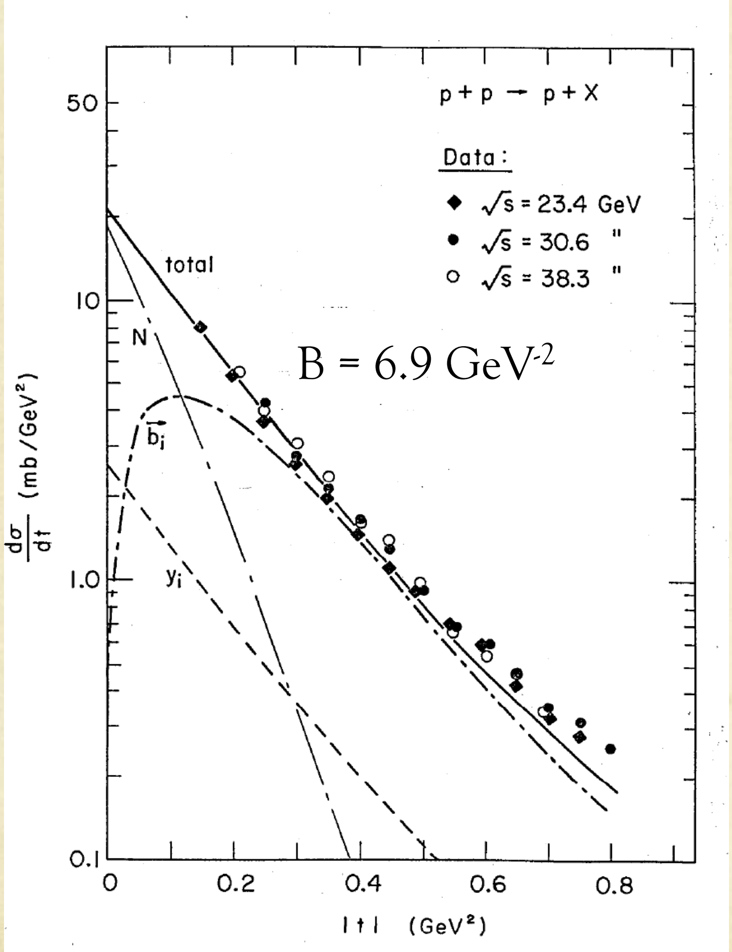
dependence on the input parameters σ_{tot} & σ_{el}





- Miettinen & Pumplin model predicts ≈ 8-9.5mb at the LHC
- Goulianos ('renormalized' Pomeron): 10mb
- $d\sigma_{diff}/dt$: slope increases with energy

DIFFRACTION AT THE ISR ($0.95 < x_F < 1.0$)



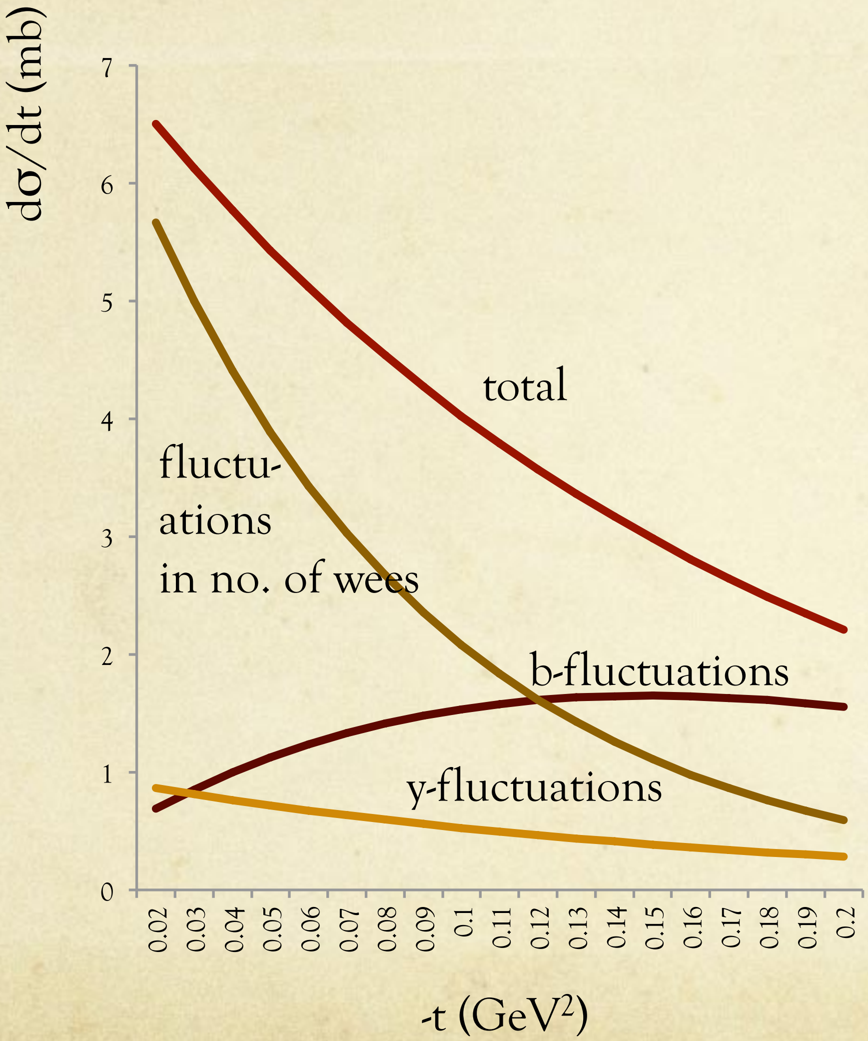
Miettinen & Pumplin, PRD 1978

Diffraction due to peripheral interactions; fluctuations in :

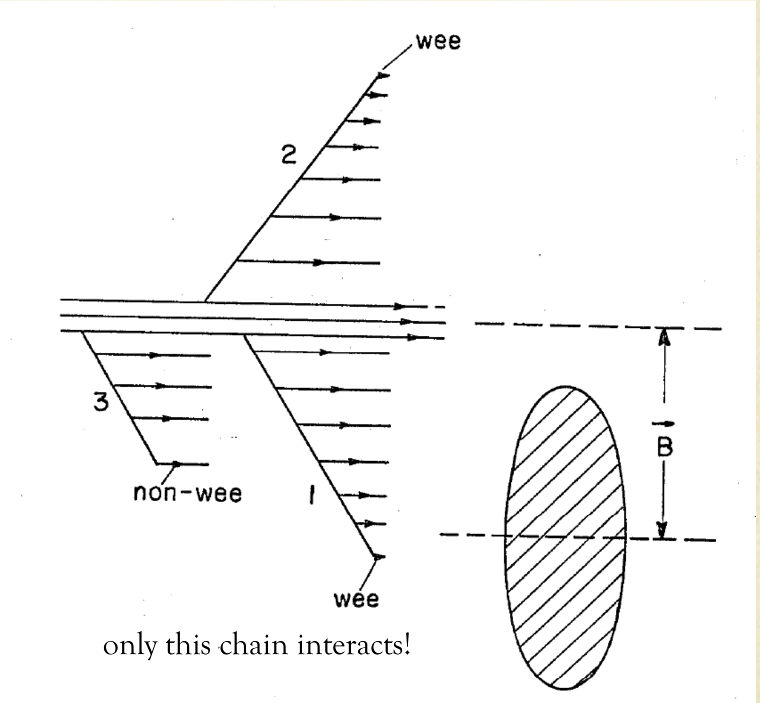
• impact parameter	45%
• number of	45%
• rapidities	10%

of the wee partons.

DIFFRACTION AT THE ISR ($0.95 < x_F < 1.0$)

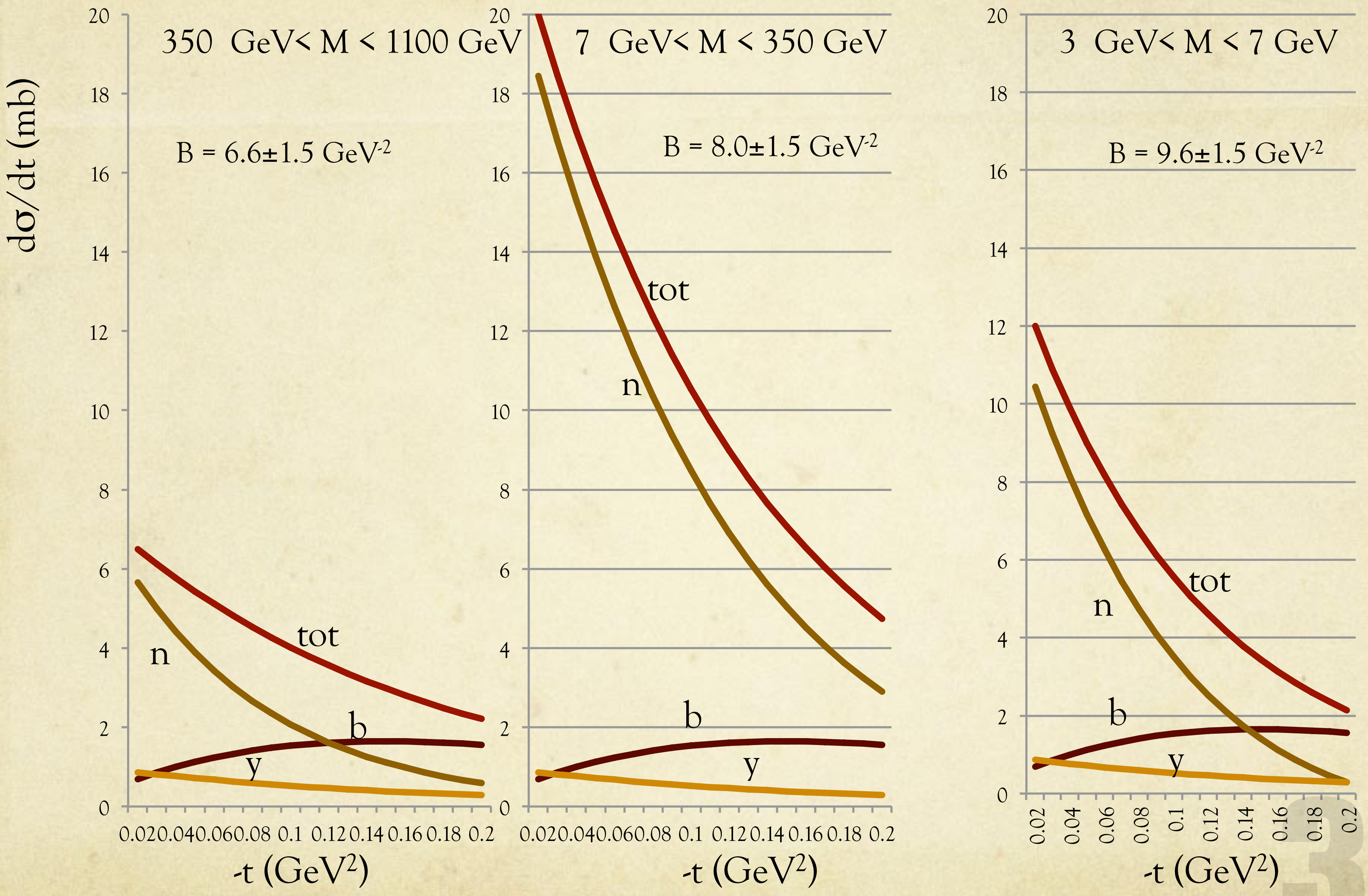


At small -t fluctuations in the no. of wee parton states dominate?



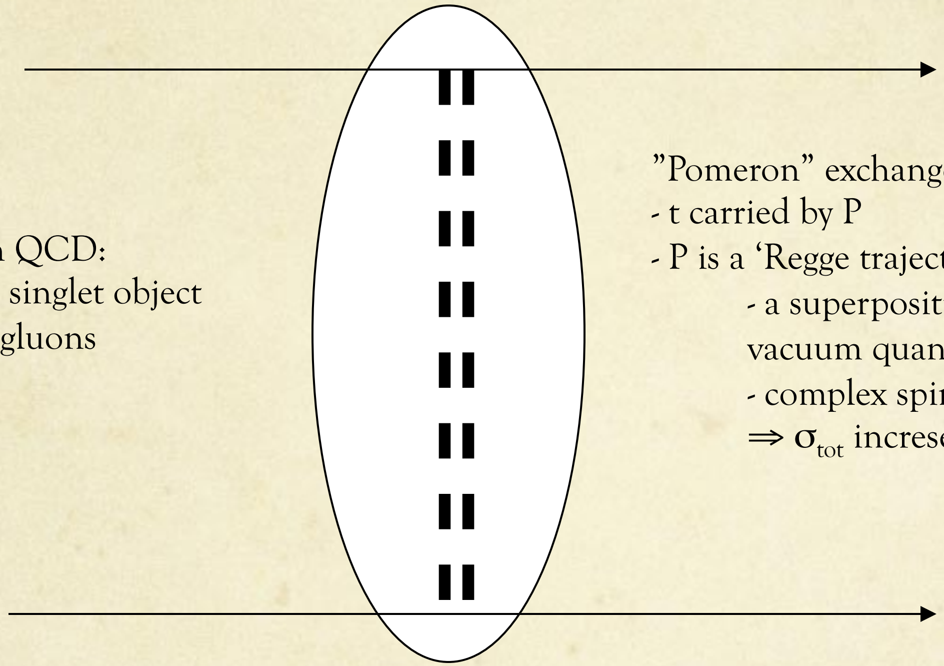
Miettinen & Pumplin, PRD 1978

DIFFRACTION at LHC vs. Miettinen&Pumplin model



At small diffractive masses (small ξ values), fluctuations in **number of wee states** grows in relative importance vs. b- or y- fluctuations

t-CHANNEL VIEW - POMERON EXCHANGE



If P existed in QCD:
-a new colour singlet object
 of quarks & gluons

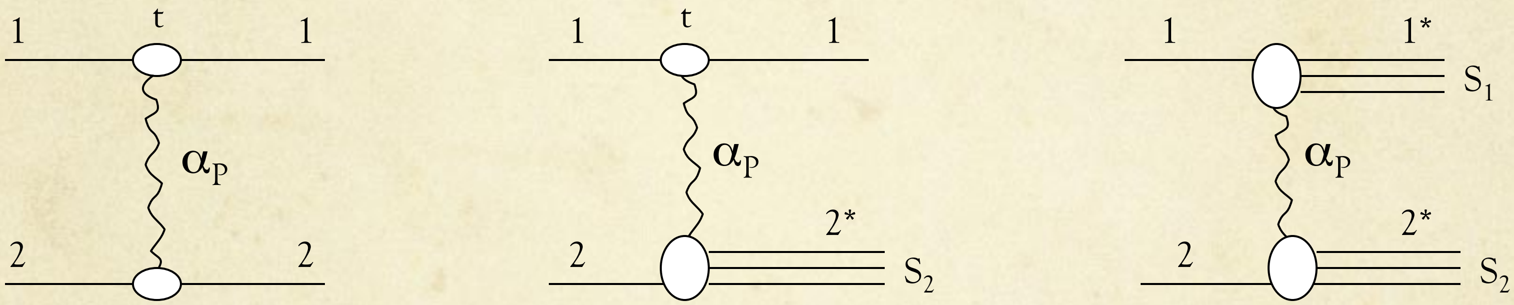
”Pomeron” exchange:
- t carried by P
- P is a ‘Regge trajectory’
  - a superposition of all possible exchange with the vacuum quantum numbers
  - complex spin $\alpha(t) = \alpha_o + \alpha' t$, α_o = 1.08-1.20 vs. Q^2
  $\Rightarrow \sigma_{tot}$ increses with s

-Several lectures on t-channel approach in this school.

DIFFRACTION – REGGE THEORY

t-CHANNEL DESCRIPTION

In the Regge pole model, diffractive processes are described in terms of the leading factorizable Regge pole having the vacuum quantum numbers – the *Pomeron.*



elastic

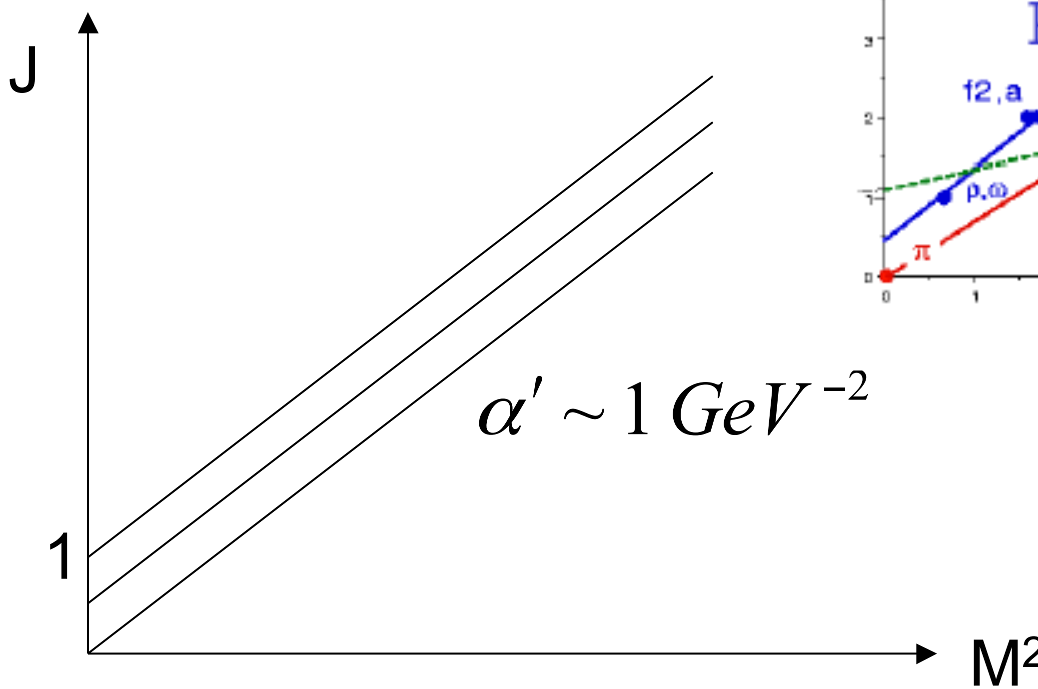
single diffractive dissociation

double diffractive dissociation

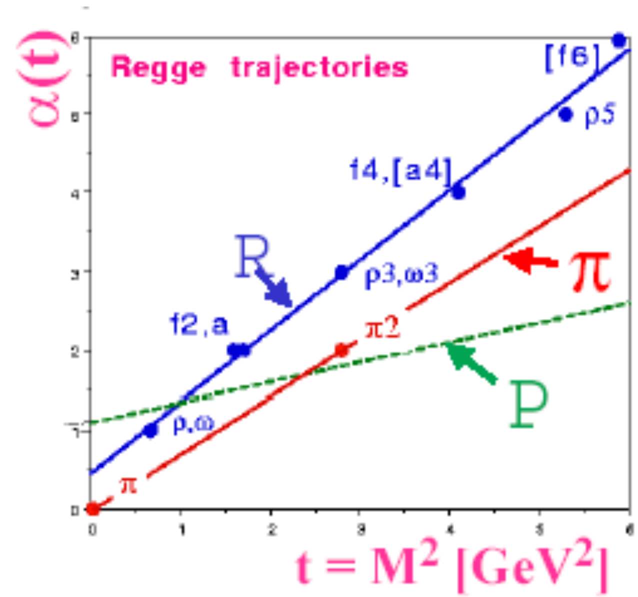
Regge Trajectories

- Empirical Observation by Chew and Frautschi
- Hadron Masses & Spins fall on linear trajectories in (J, M2) space

$$J(M) = \alpha(0) + \alpha' M^2$$



$$\alpha' \sim 1\, GeV^{-2}$$



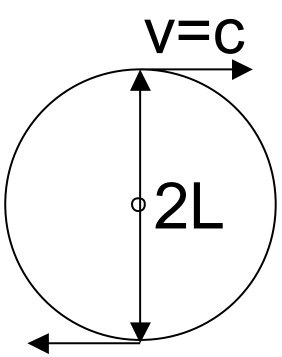
Peter Steinberg

String "Model" of Hadrons

Nambu 1970's

- Consider a hadron to be a rotating string of radius L and string tension κ
- The energy stored in the string is:

$$M = 2\int_0^L \gamma\kappa dx = 2\int_0^L \frac{\kappa dx}{\sqrt{1-(x/L)^2}} = \pi\kappa L$$



- The angular momentum is:

$$J = 2\int_0^L \gamma\kappa v x dx = 2\int_0^L \frac{\kappa v x dx}{\sqrt{1-(x/L)^2}} = \kappa L^2 \pi / 2$$

$$J = \frac{1}{2\pi\kappa} M^2$$

Regge trajectories

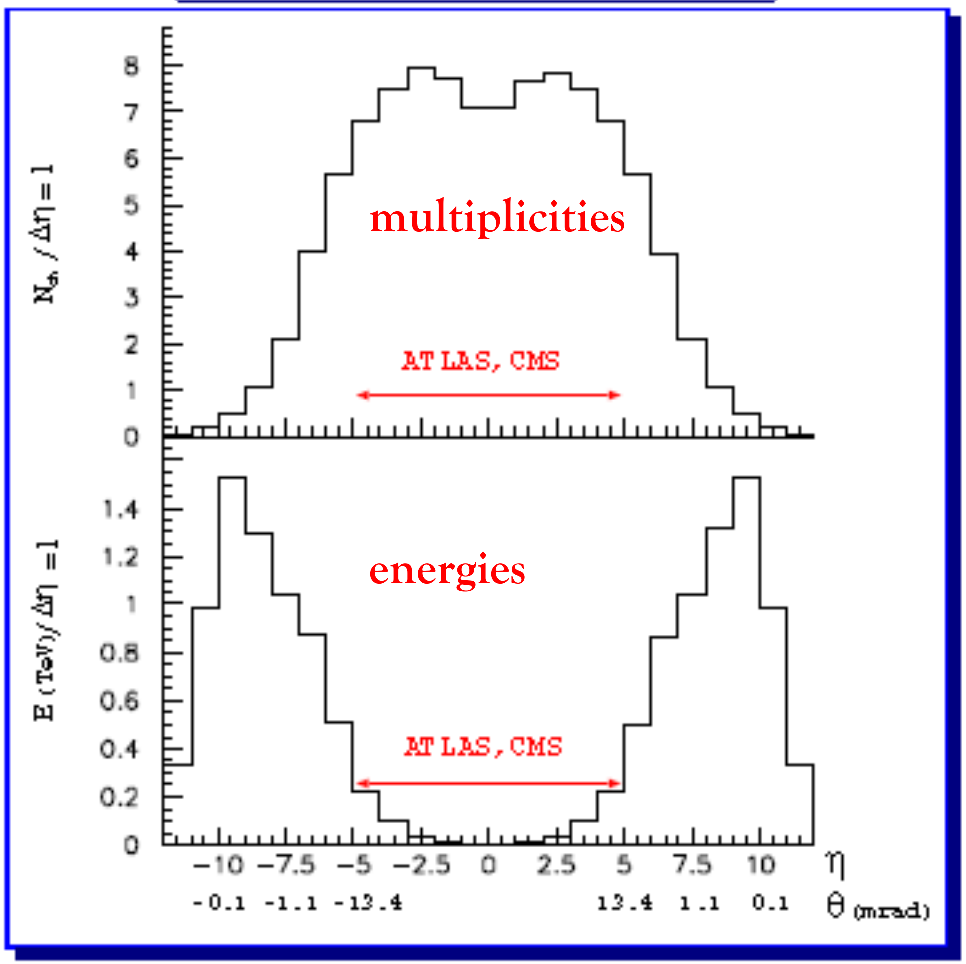
k = constant energy density per length ⇒ linear potential: V = kr ≈ 1 GeV/fm ≈ 16 ton!

SIGNATURES OF DIFFRACTIVE SCATTERING

SIGNATURES

- TRADITIONALLY, LOOK FOR LARGE RAPIDITY GAPS (LRGs) OF $\Delta\eta \geq 3$ UNITS
- CORRESPONDS TO $\xi = 1 - p_z^f/p_z^i = M_X^2/s \leq 0.05$
- REQUIRE NO TRACKS OR ENERGY DEPOSITS WITHIN THE LRG

Inelastic and diffractive events



$$\eta = -\ln \mathrm{tg}\Theta/2 \qquad y = \tanh^{-1} p_L/E$$

$$E = m_\perp \cosh y \sim \frac{m_\perp}{2} e^y \text{ for } y \gg 1 \qquad m_\perp^2 = p_t^2 + m^2$$

Fraction of total energy flow seen by:

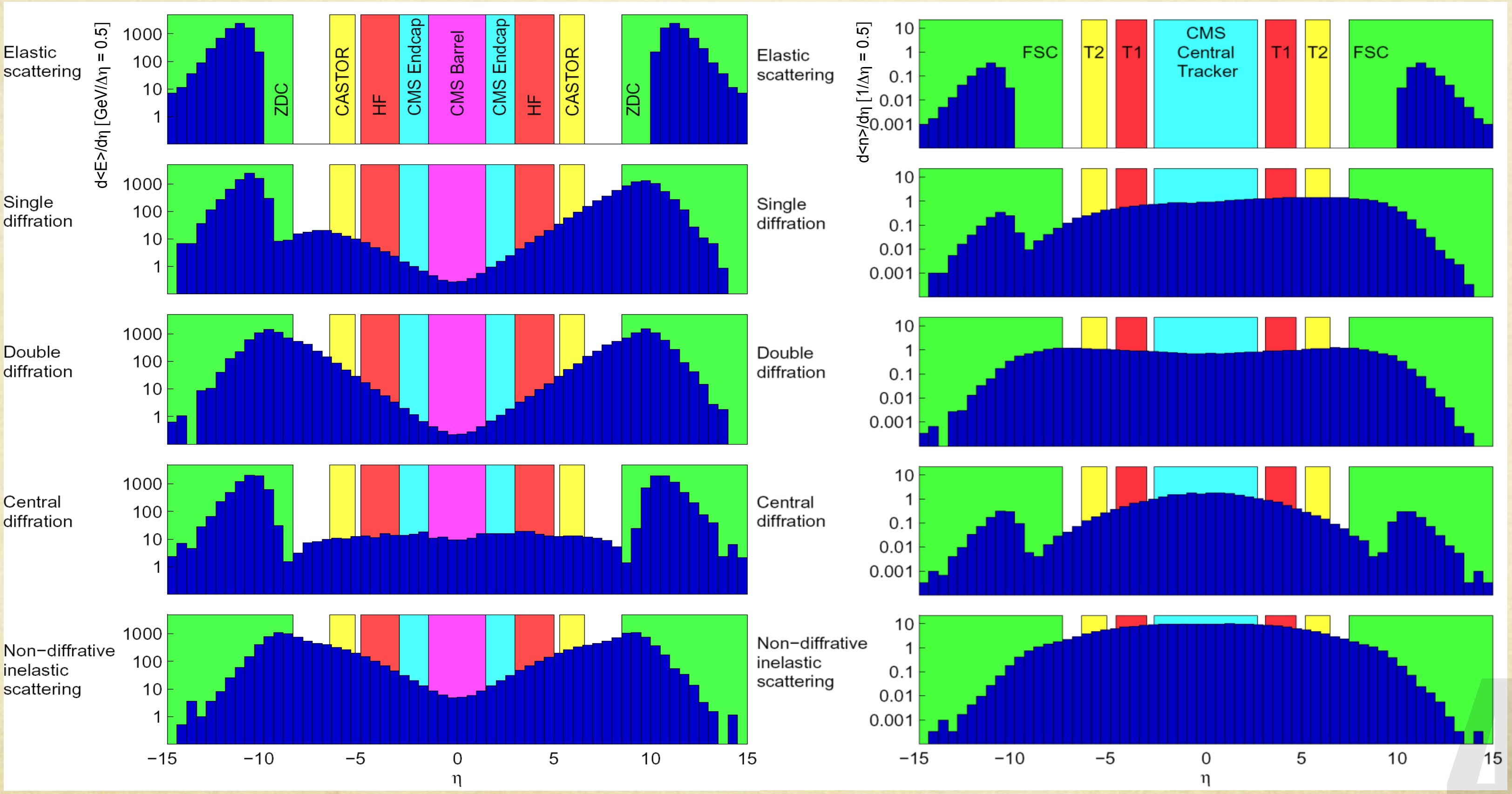
- ATLAS, CMS ~ 10%

NON-DIFFRACTIVE EVENTS FILL UP THE AVAILABLE RAPIDITIES BY LARGE NUMBER OF (MAINLY SOFT) PARTICLES

DIFFRACTIVE SCATTERING PRODUCES A FEW ENERGETIC SMALL ANGLE PARTICLES

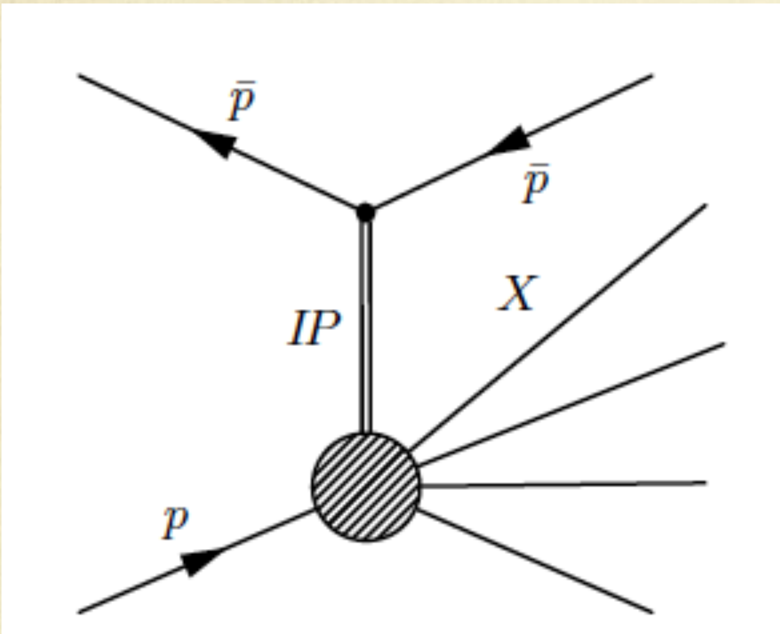
AVAILABLE DETECTOR INFORMATION vs. RAPIDITY – INPUT TO MULTIVARIATE EVENT CLASSIFICATION

ENERGIES MULTIPLICITIES



23 INPUTS FOR EVENT CLASSIFICATION

SINGLE DIFFRACTIVE SCATTERING IS "QUASI-ELASTIC"



$$\bar{p}p \to p + X$$

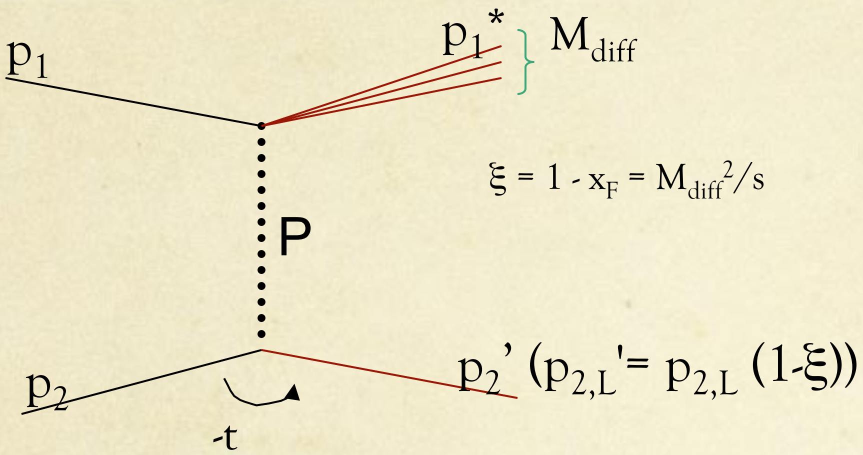
$$\xi = 1 - x_F = 1 - \frac{p_z^f}{p_z^i} = \frac{M_X^2}{s}$$

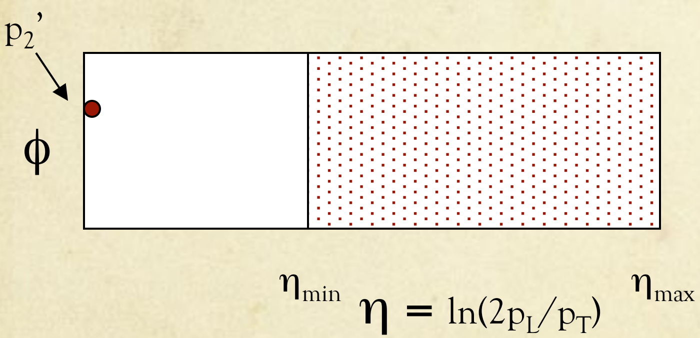
$$\frac{d\sigma_{SD}}{dM_X^2} \propto \frac{1}{M_X^2}$$

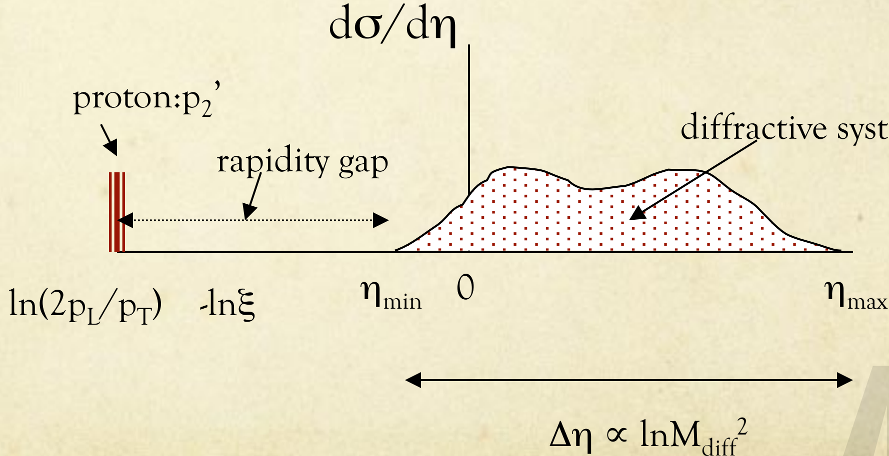
Note: the coherence condition $\xi \approx \frac{M_X^2}{s} < \frac{m_\pi}{m_p} \approx 0.1 - 0.2$ which is due to need to retain the coherence of the quasi elastically scattered target proton.

For zero angle production: $|t_{\min}| = \left[(M_X^2 - m_p^2)/2p\right]^2$ where p is the incident proton momentum in the target rest frame. The wave number, k, of the incident hadron varies by $\Delta k \propto \sqrt{|t_{\min}|}$

SINGATURES: SINGLE DIFFRACTION







$\Delta\eta \approx 2\ln(\sqrt{s}/M_{diff}) \geq 3$

Small Mass Diffractive States

SMALL MASS REGION DOMINATED BY N* RESONANCES

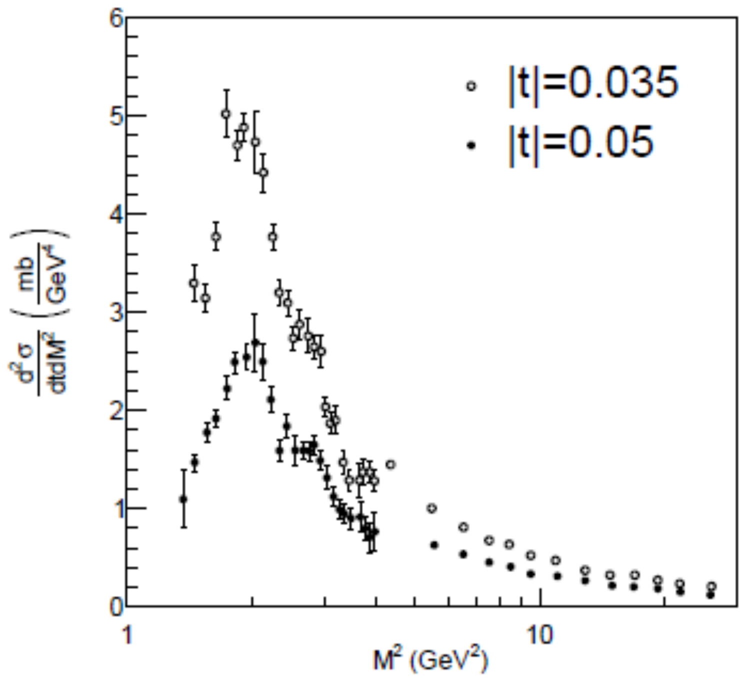
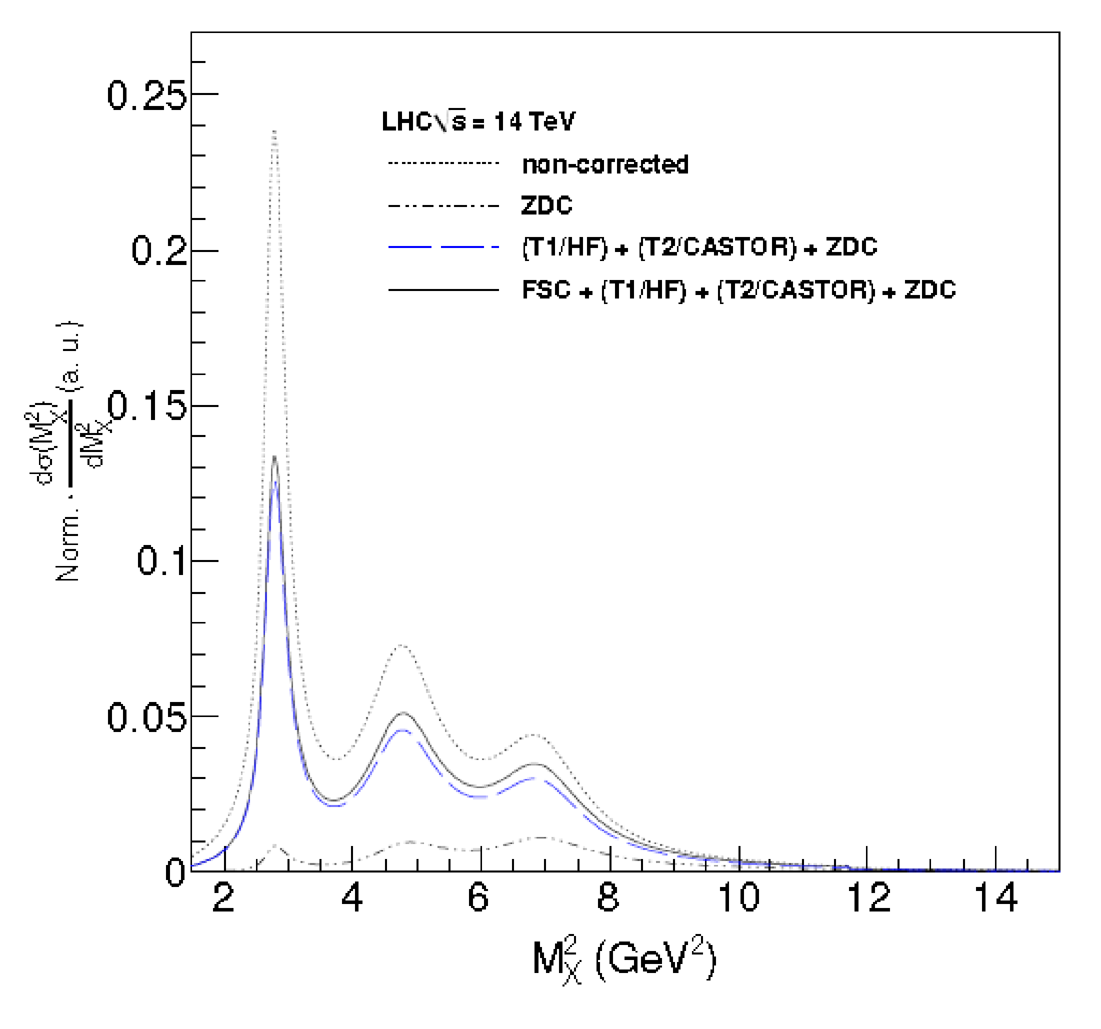


Fig. 1 Compilation of low-mass SD data form Fermilab experiments $p+d \to X+d$, $P_{lab} = 275\,\mathrm{GeV/c}$, see [2]. The first peak has the mean value of $M_{X,1} = 1400\,\mathrm{MeV}$ and the second bump has $M_{X,1} = 1688\,\mathrm{MeV}$, wich correspond to the masses of N^* resonances, see Sec. 4.2

N*(1680MeV)

SINGLE DIFFRACTION AT M_X < 10 GeV



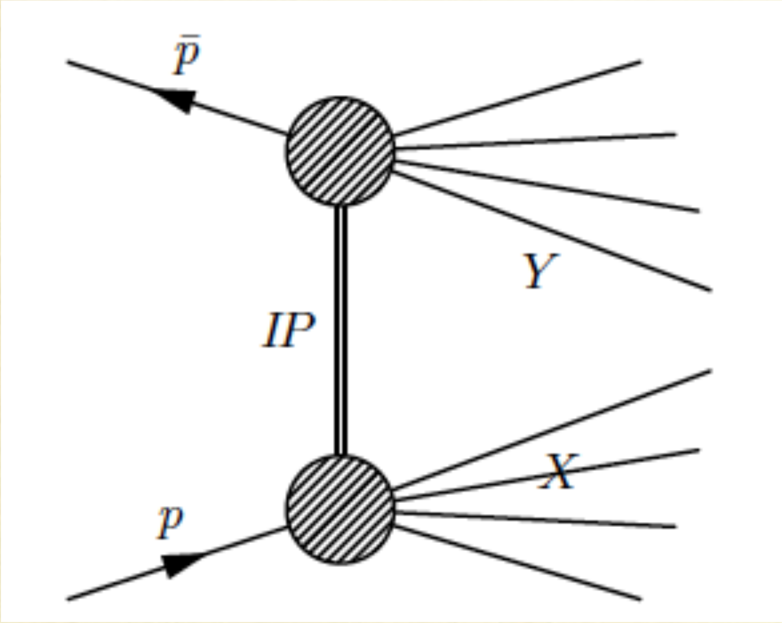
L.Jenkovzsky, O. Kuprash, J.W. Lämsä, V.Magas, RO

For σ_{tot}^{pp} via Optical Theorem need to measure the inelastic rate.

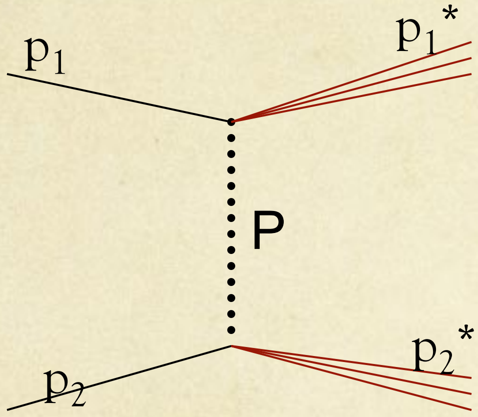
$\sigma_{SD}(M_X < 3$ GeV$) =?$

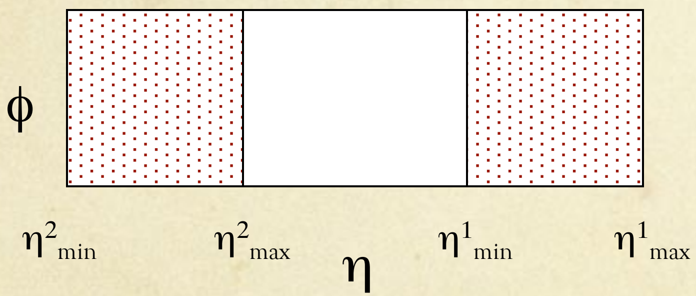
FSCs will solve the problem.

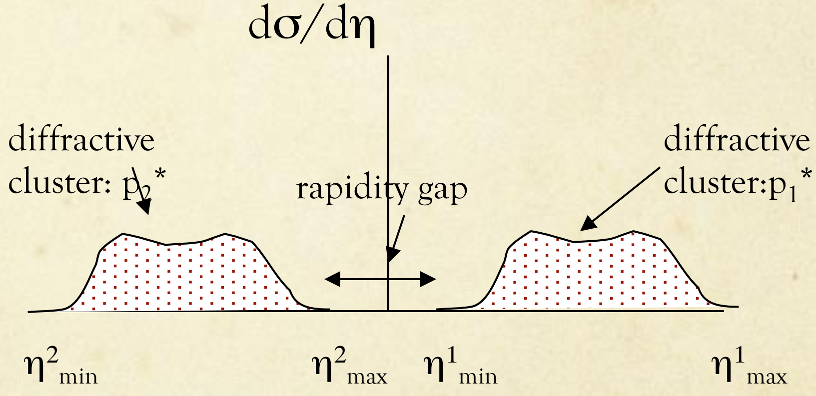
DOUBLE DIFFRACTION



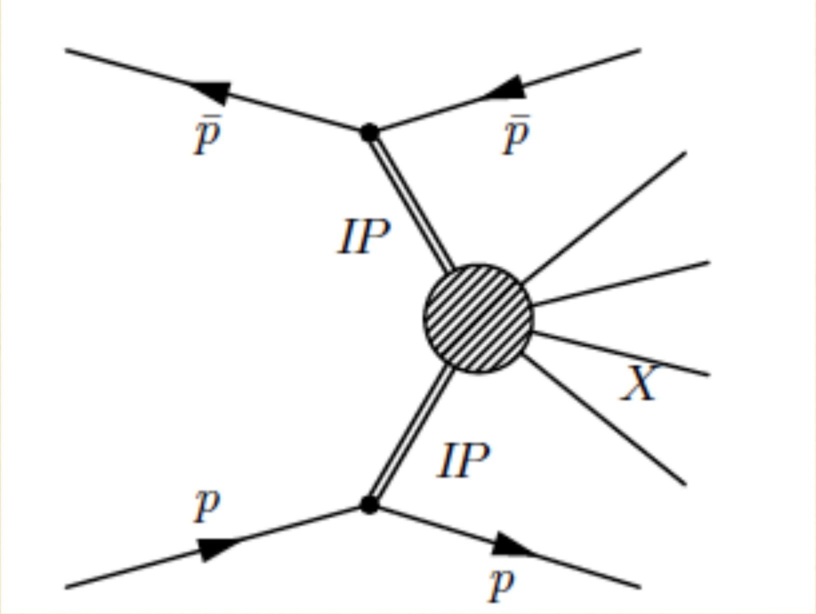
SIGNATURES: DOUBLE DIFFRACTION







CENTRAL DIFFRACTION IS A LABORATORY FOR $J^{PC} = 0^{++}$ NEW PARTICLE SEARCHES AND FOR HIGH PURITY GLUON JET STUDIES



$$\left[(p_i - p_f) + (\bar{p}_i - \bar{p}_f)\right]^2 = M_X^2$$

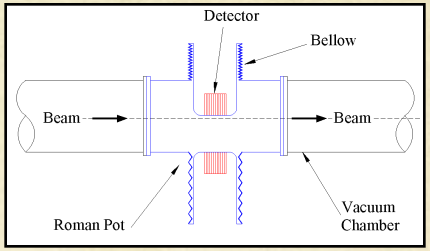
i.e.

$$M_X^2 = \xi_1 \xi_2 s$$

where $\xi_{1,2}$ is the fractional longitudinal momentum loss of the incident proton/antiproton

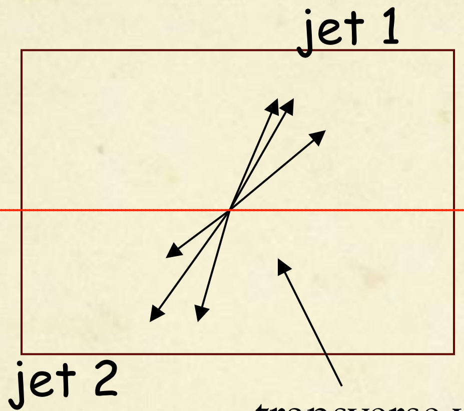
MASS X IN $p_1p_2 \rightarrow p_1' + X + p_1'$ MEASURED AS:

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

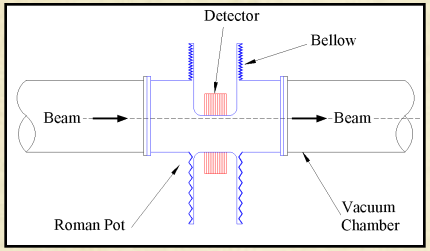


p_1'

- deflected proton measured here



p_2'



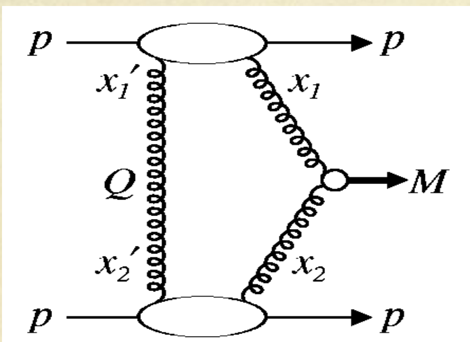
-beam energy spread?

- transverse vx position?

- leading protons on both sides (roughly symmetric) (aim at protons down to a of $\xi_{1,2} \approx 1‰$)
- a central system separated by rap gaps

CENTRAL EXCLUSIVE PRODUCTION:

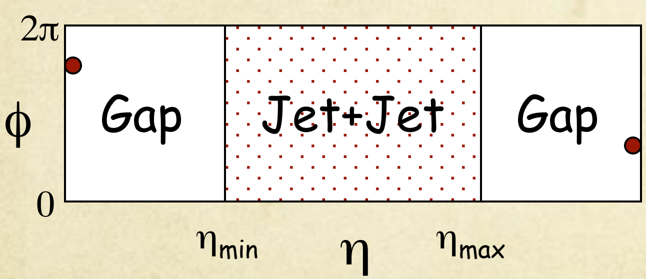
- FORWAR-BACKWARD PAIR OF PROTONS (or p*'s)
- FORWARD-BACKWARD PAIR OF RAP GAPS
- A CENTRAL HADRONIC SYSTEM
- BACKGROUNDS SUPPRESSED
- QUANTUM NUMBER FILTERING

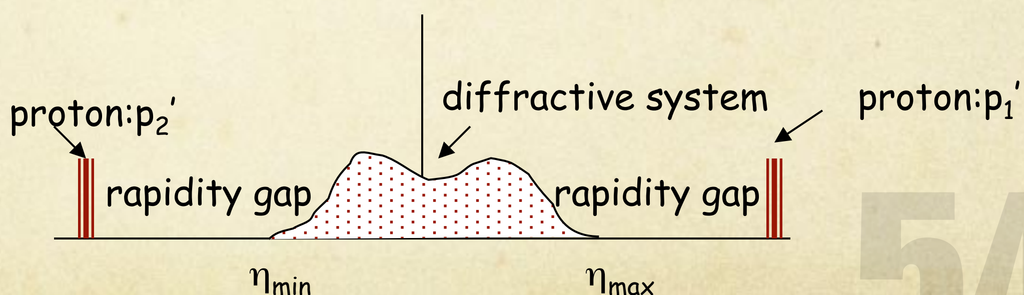


$M_X^2 \approx \xi_1 \xi_2 s$

Measure the parity P = (-1)^J:
$d\sigma/d\varphi \propto 1 + \cos 2\varphi$

$J^{PC} = 0^{++}\ (2^{++}, 4^{++}, \ldots)$



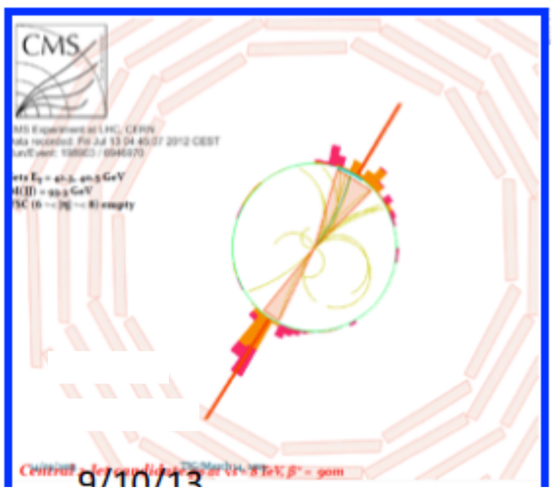


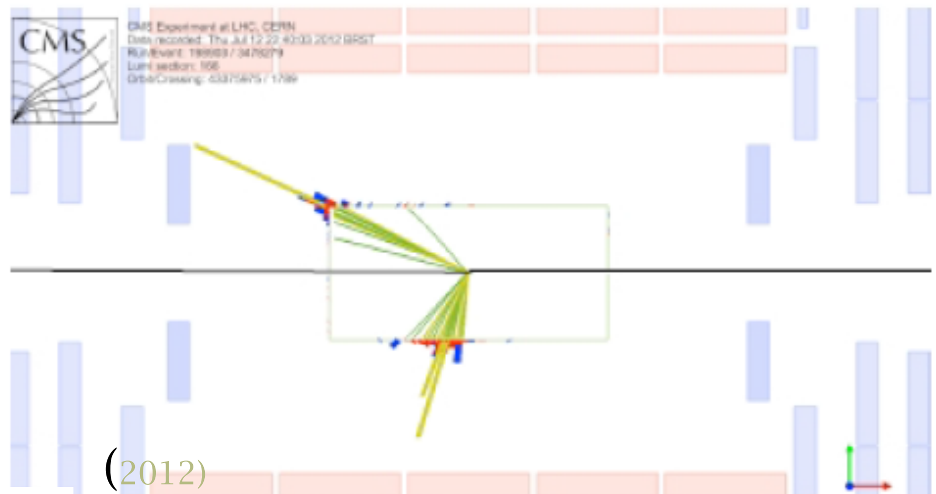
Rapidity Gap Survival Probability[1]

Gluon jet dominance

From the above considerations, we expect dijet events to be almost entirely (colour singlet) gg

$\longrightarrow$ CEP of dijets offers the possibility of observing the isolated production of gluon jets at the LHC.





CMS + TOTEM event displays

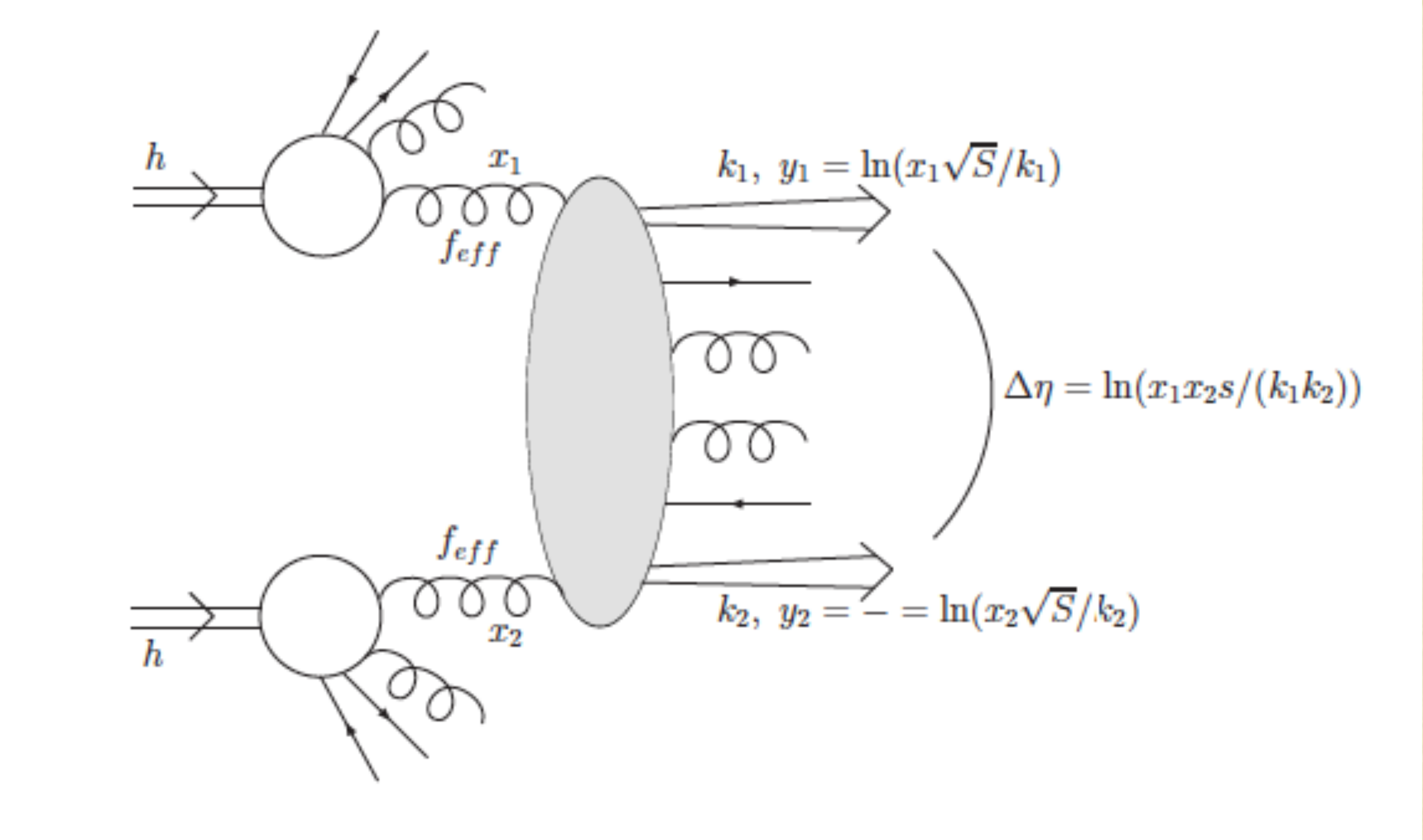
Dijet CEP as a gluon factory

Mike Albrow's EDS 2013 summary talk, arXiv:1310.7047 :

> These dijet and trijet events are the cleanest ever seen at a hadron collider, and remind one of LEP events. But these dijets are nearly all gg, while at LEP there were all $q\bar{q}$.

$\longrightarrow$ Clean probe of properties of gluons jets (multiplicity, particle correlations...)

MUELLER-NAVALET JETS

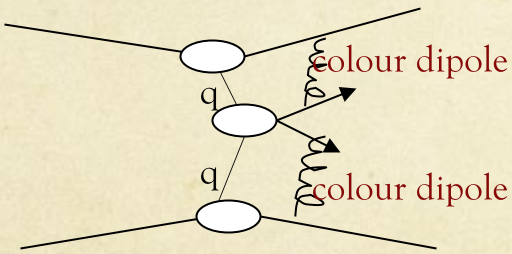


Christophe Royon in Diffraction 2014

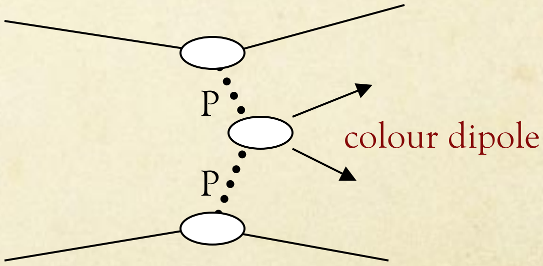
RECONSTRUCTION OF COLOUR DIPOLES?

CONSIDER A PAIR OF JETS AT LARGE p_T :

- in pQCD this is due to a gluon exchange in parton-parton scattering
- in hadronization, colour must be exchanged in order to make colour singletpre-clusters, i.e. there are colour dipole systems between the proton fragments and the hard scattering final states
- in diffractive scattering, a colour singlet Pomeron is exchanged, and colour dipoles are formed locally, between the closest jets and proton fragments, or in DPE, between the created jet-pairs.



Rapidity gaps filled by
soft gluon exchange



Rapidity gaps between
the colour dipole and protons

PDG on SCALAR MESONS

NOTE ON SCALAR MESONS

Revised April 2010 by C. Amsler (University of Zurich), T. Gutsche (University of Tübingen), S. Spanier (University of Tennessee) and N.A. Törnqvist (University of Helsinki).

I. Introduction: The scalar mesons are especially important to understand because they have the same quantum numbers as the vacuum ($J^{PC} = 0^{++}$). Therefore they can condense into the vacuum and break a symmetry such as a global chiral $U(N_f) \times U(N_f)$. The details of how this symmetry breaking is implemented in Nature is one of the most profound problems in particle physics.

In contrast to the vector and tensor mesons, the identification of the scalar mesons is a long-standing puzzle. Scalar resonances are difficult to resolve because of their large decay

From Mike Albrow in Diffraction 2014

RAP GAPS AS OBSERVABLES

- PARTON RE-SCATTERINGS
- CALORIMETER NOISE, LACKING TRACK E_T/p_T ACCEPTANCE...
- FLUCTUATIONS IN THE QCD CASCADES PRODUCED IN NON-DIFFRACTIVE EVENTS
- KINEMATICAL OVERLAPS IN RAPIDITY (DUE TO LIMITED PHASE SPACE)
- LACKING ANGULAR COVERAGE

SURVIVAL OF RAPIDITY GAPS

How do the rapidity gaps - created by colourless pomeron exchange - survive (1) inelastic interactions of the spectator partons, (2) soft "parasite" gluon emissions?

In impact parameter, b_t, space: The amplitude of the diffractive process under study is $M(s,b_t)$. The probability that there is *no extra inelastic interaction* is:

$$S^2 = \int |M(s,b_t)|^2 \exp[-\Omega(b_t)] d^2b_t / \int |M(s,b_t)|^2 N d^2b_t$$

where $\Omega(b_t)$ is the opacity (optical density) of the interaction and $N=\exp(-\Omega^o)$ the normalizing factor where Ω^o denotes the relevant opacity evaluated at $\Omega = 0$.

The survival probability, S^2, depends strongly on the spatial distribution of the constitutents of the relevant subprocess.

SURVIVAL OF RAPIDITY GAPS?

The survival probability S^2 is not universal but depends on the hard scattering process and kinematical configuration under study.

In particular, S^2 depends on the nature of the colour-singlet - Pomeron, W/Z-boson or photon - exchange which generates the gap as well as on the distribution of partons inside the proton in the b-space.

Probability of finding a rap gap (in inclusive QCD events) depends on the p_T cut-off

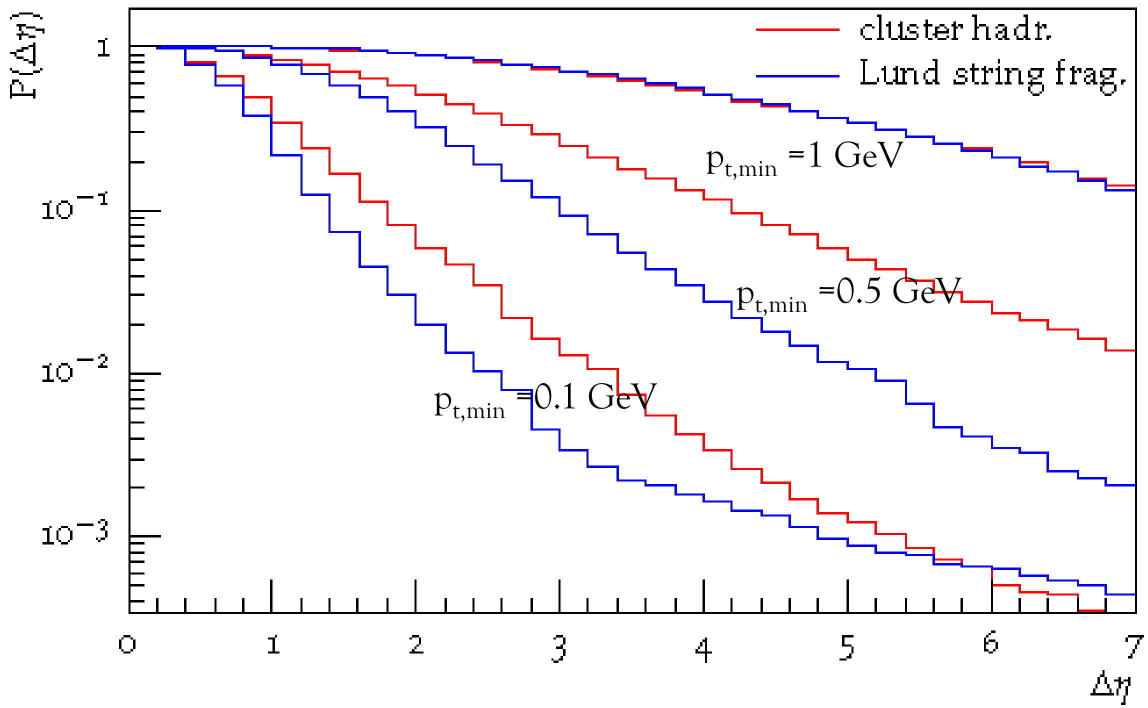
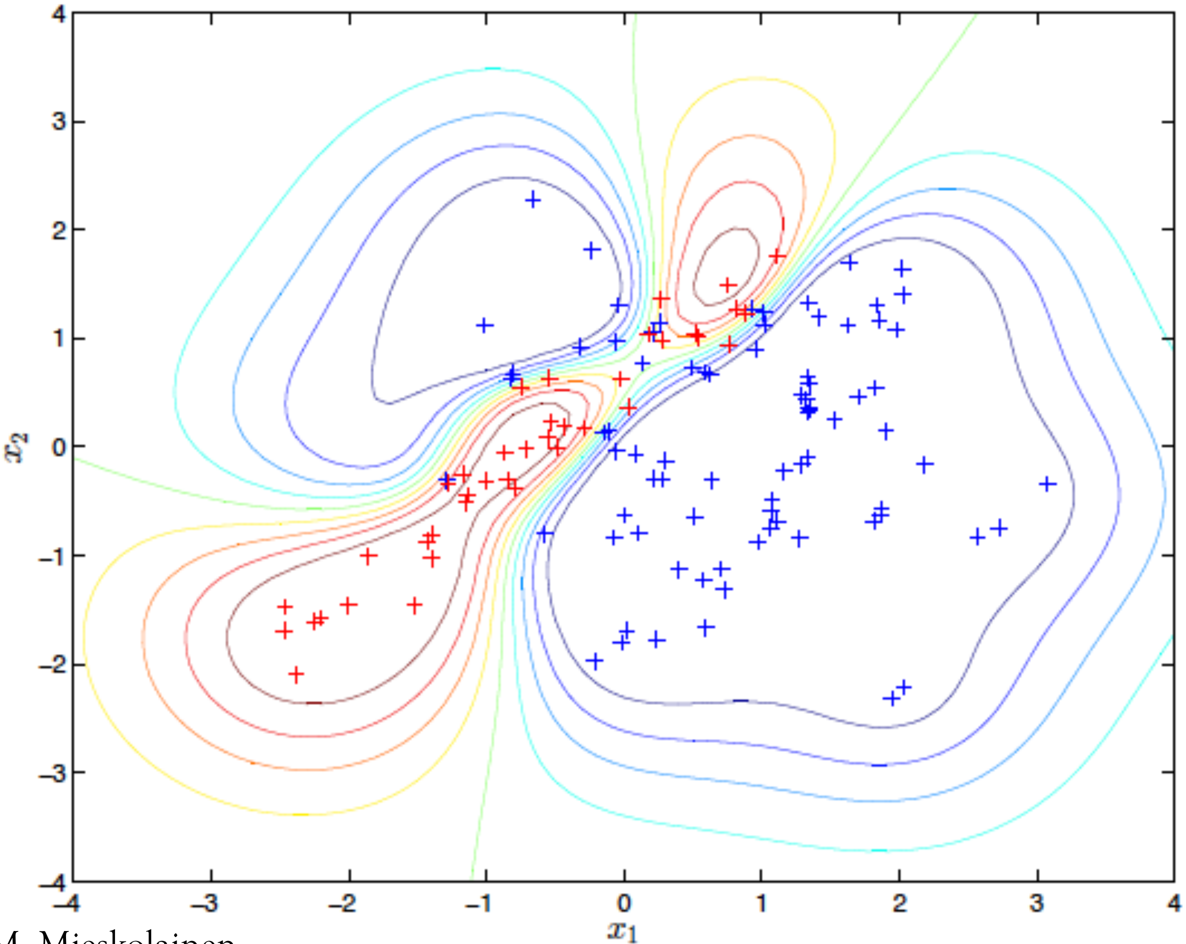


Fig. 4. Probability for finding a rapidity gap (definition 'all') larger than $\Delta\eta$ in an inclusive QCD event for different threshold $p_\perp$. From top to bottom the thresholds are $p_{\perp,\mathrm{cut}} = 1.0, 0.5, 0.1$ GeV. Note that the lines for cluster and string hadronisation lie on top of each other for $p_{\perp,\mathrm{cut}} = 1.0$ GeV. No trigger condition was required, $\sqrt{s} = 7$ TeV.

KKMRZ:

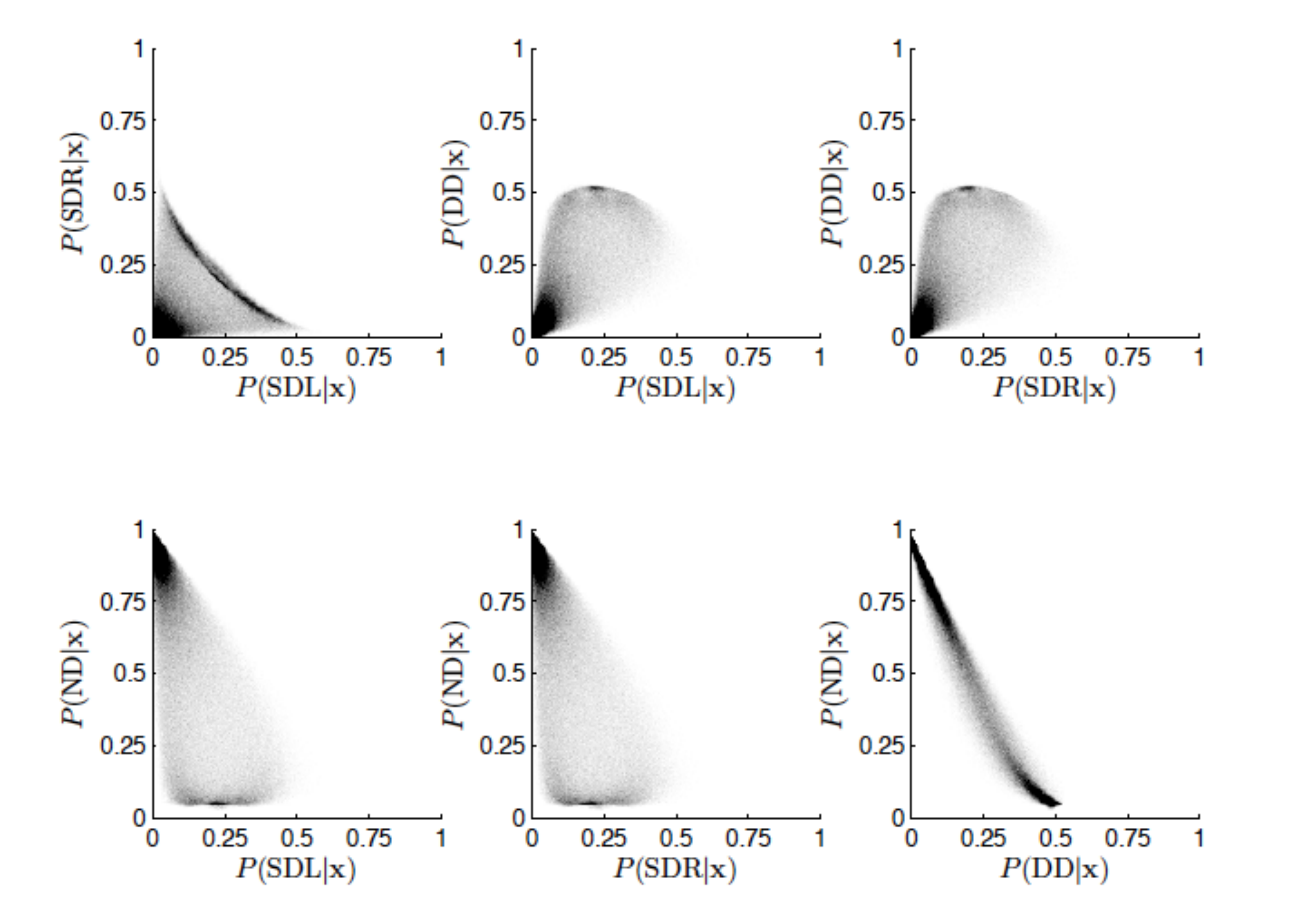
V.A. Khoze, (Durham U., IPPP & St. Petersburg, INP) , F. Krauss, A.D. Martin, (Durham U., IPPP) , M.G. Ryskin, (Durham U., IPPP & St. Petersburg, INP) , K.C. Zapp, (Durham U., IPPP) . IPPP-10-38, DCPT-10-76, MCNET-10-10, 2010. 19pp.

MULTIVARIATE CLASSIFICATION



M, Mieskolainen

MULTIVARIATE EVENT CLASSIFICATION



M, Mieskolainen & RO

APPENDIX 1:
FRAUNHOFER SCATTERING

FRAUNHOFER DIFFRACTION – AN ANALOGY OF HADRON DIFFRACTION

- ASSUME THAT A PLANE WAVE (wave length λ) HITS A SCREEN WITH A HOLE (radius R) AND THE WAVE NUMBER ($k = 2\pi/\lambda$) SATIFIES THE SHORT WAVE LENGTH CONDITION ($kR >> 1$).

- DUE TO THE HOLE IN THE SCREEN (Σ_o), EACH POINT BECOMES A NUCLEUS FOR A SPHERICAL WAVE WITH AN ENVELOPE THAT DESCRIBES THE DEFLECTED WAVE.

- NOW, ON PLANE ($\Sigma_,$) AT DISTANCE D, AN IMAGE OF THE HOLE APPEARS.

- SINCE THE INCIDENT BEAM OF LIGHT SEES THE HOLE AT VARYING DISTANCES AND ANGLES OF APPROACH, THE AMPLITUDES AND PHASES OF THE WAVELETS COLLECTED AT EACH POINT DIFFER FROM EACH OTHERS:

    - **CANCELLATIONS AND REINFORCEMENTS OCCUR AT DIFFERENT POINTS, i.e. DIFFRACTION OF LIGHT EMERGES**

    - THE INCIDENT ENERGY DISTRIBUTION (T_o on Σ_o) IS MAPPED AS T on Σ in point P(x,y,z) ON THE SURFACE OF THE DETECTOR.

    - MATHEMATICALLY THIS IS GIVEN BY THE **Fresnel-Kirchoff formula** (Born&Wolf, Principles of Optics, Pergamon Press, London (1959) p. 397):

$$T(x,y,z) = (-i/2\lambda)\, \exp(ik_o r_o)/r_o \int dS T_o (1 + \cos\Theta)\, \exp(i\mathbf{k}\bullet \mathbf{b})/s,$$

where s is the distance of point P from Σ_o and $\cos\Theta$ is the inclination of this vector with respect to the normal to Σ_o.

FRAUNHOFER DIFFRACTION AND IMPACT PARAMETER REPRESENTATION

- NOW, PLACE THE DETECTOR SUFFICIENTLY FAR, SO THAT ALL THE LIGHT RAYS FROM Σ_0 TO POINT P(x,y,z) ON Σ CAN BE TAKEN AS BEING PARALLEL.
- RESULTING OPTICAL DIFFRACTION IS EITHER FRAUNHOFER OR FRESNEL TYPE DEPENDING ON THE DETECTOR DISTANCE, CONSIDERED INFINITE OR NOT
- IN CASE OF PARTICLE INTERACTIONS, THE LARGE DISTANCE ASSUMPTION IS ALWAYS VALID.
- IF THE DISTANCE D SATISFIES THE LARGE DISTANCE CONDITION: $R/D \ll 1$, THE EXPONENTIAL exp(iks)/s CAN BE EXPANDED AS A SERIES IN ks, AND WE OBTAIN:
  - FRAUNHOFER DIFFRACTION WHEN $kR^2/D \ll 1$
  - FRESNEL DIFFRACTION WHEN $kR^2/D \approx 1$
  - GEOMETRICAL OPTICS WHEN $kR^2/D \gg 1$.
- IN PARTICLE PHYSICS, UPPER CONDITION HOLDS, AND IN **IMPACT PARAMETER** REPRESENTATION:

$$T(x,y,z) \approx (k/2\pi i)\{\exp(ikr_o)/r_o\} \int_{\Sigma} d^2b S(\mathbf{b}) \exp(i\mathbf{q}\cdot\mathbf{b})$$

Where q is the 2-dimensional momentum transfer: $|\mathbf{q}| = k\sin\Theta$, and the scattering matrix: $S(\mathbf{b}) \equiv 1 - \Gamma(\mathbf{b})$, in terms of the **profile function** of the target.

IMPACT PARAMETER REPRESENTATION, PROFILE FUNCTION AND DIFFRACTION AS "SHADOW SCATTERING"

Inserting S(**b**) into the expression for T(x,y,z), the complete amplitude with a term corresponding to the unperturbed (1) and perturbed ($\Gamma(\mathbf{b})$) waves is obtained.

The factor multiplying the outgoing spherical wave is the physically relevant quantity, i.e. the **scattering amplitude**:

$$f(\mathbf{q}) = (ik/2\pi)\int d^2b\, \Gamma(\mathbf{b}) \exp(i\mathbf{q}\cdot\mathbf{b}),$$

and the scattering amplitude is given by the **Fourier transformation of the profile function**, i.e. we can write:

$$\Gamma(b) = (1/2\pi ik)\int d^2q\, f(\mathbf{q}) \exp(-i\mathbf{q}\cdot\mathbf{b}).$$

If the profile function is spherically symmetric, f(**q**) can be written as the Bessel transform:

$$f(\mathbf{q}) = ik\int bdb\, \Gamma(b)\, J_o(qb).$$

If the profile function is a disk of radius R, we obtain the so-called **black disc** form:

$$f(q) = ikR^2\, J_1(qR)/qR.$$

DIFFRACTION IS NOW INTERPRETED AS THE SHADOW OF ALL INELASTIC CHANNELS OPEN AT THE ENERGY IN QUESTION.

APPENDIX 2: REGGE THEORY, POMERON EXCHANGE

DIFFRACTION AS POMERON EXCHANGE PROCESS

- One-gluon exchange: In leading order QCD qq-scattering proceeds by 1-gluon exchange, gluon carries (octet) colour, not gauge invariant
  ⇒diffractive scattering cannot be described as 1-gluon exchange

- Minimal rescue attempt: 2-gluons as a colour singlet exchange. –can be used as an effective model at sufficiently large masses

- "Reggeized gluon": Sum up infinite no. of gluon exchanges (including the q-loops).
  Reggeized gluon has t-dependent complex angular momentum (as the classical P) but carries net colour (octet in SU(3)).

- BFKL Pomeron: Colourless exchange between quarks can be constructed from two Reggeized gluons. These exchange gluons between each others ⇒ladder with quark loops = "BFKL (Balitsky-Fadin-Kuraev-Lipatov) Pomeron" ⇒Predictions about PDF evolution (in x_{Bj} rather than in Q^2 as DGLAP), very fwd jets with large Δy, minijets,…

Bj: Diffractive excitation is a process producing rapidity gaps that are not exponentially suppressed.

POMERON EXCHANGE...

- The standard approach: "Pomeron" emitted from a beam proton with an associated Pomeron "flux". Pomeron interacts with other beam proton with σ_{Pp} (Ingelman&Schlein). A useful - but not theoretically sound – paradigm!

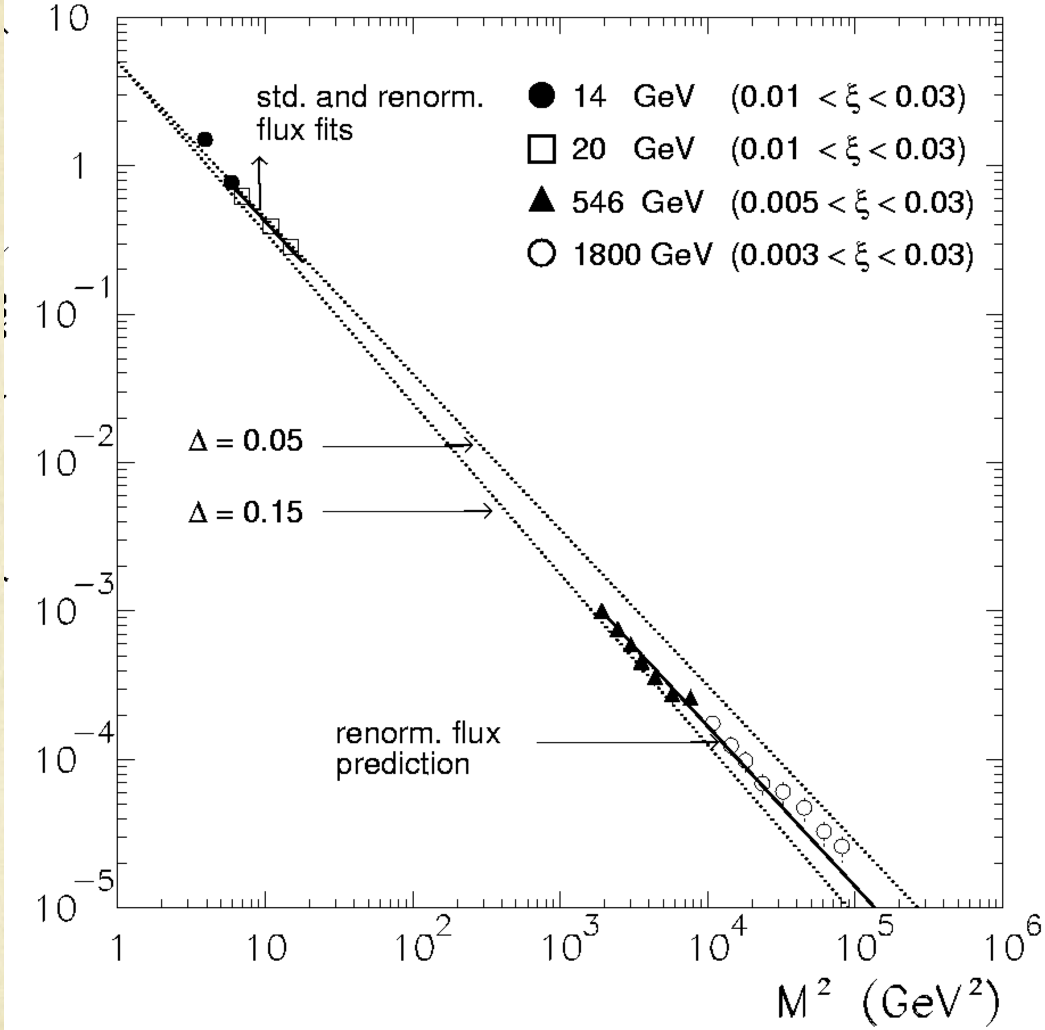
- Use the Pomeron "structure function" measured at HERA (γ-P collisions) and/or Tevatron (P-p collisions) for predictions at the LHC: If the quasi-elastically scattered proton is measured, the $-t$ and ξ ($=\Delta p/p < 0.05$) of the Pomeron is known together with the proton x_F ($= 1-\xi = 1-\Delta p/p \geq 0.95$).

- Production of high E_T jets, W's, Z's, Drell-Yan pairs, heavy flavour seen and measured at the Tevatron with typical cross sections of the order of 1% of the corresponding total cross section.

- By measuring two high E_T jets in P-p collisions, can reconstruct the momentum fractions of the proton (x_{Bj}) and Pomeron (β)

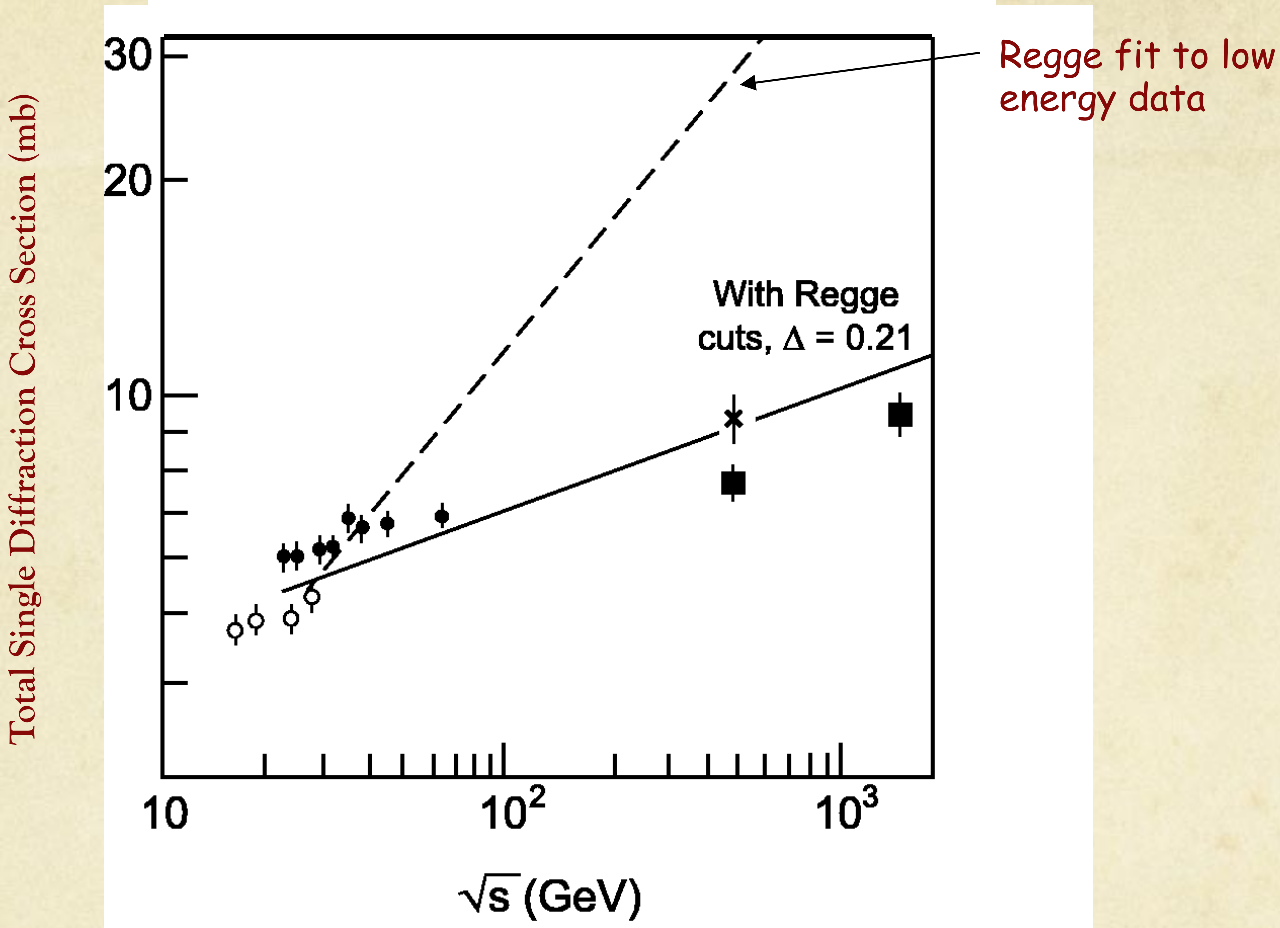
$\Rightarrow$ **"POMERON STRUCTURE FUNCTION"**

SDE – CROSS SECTION

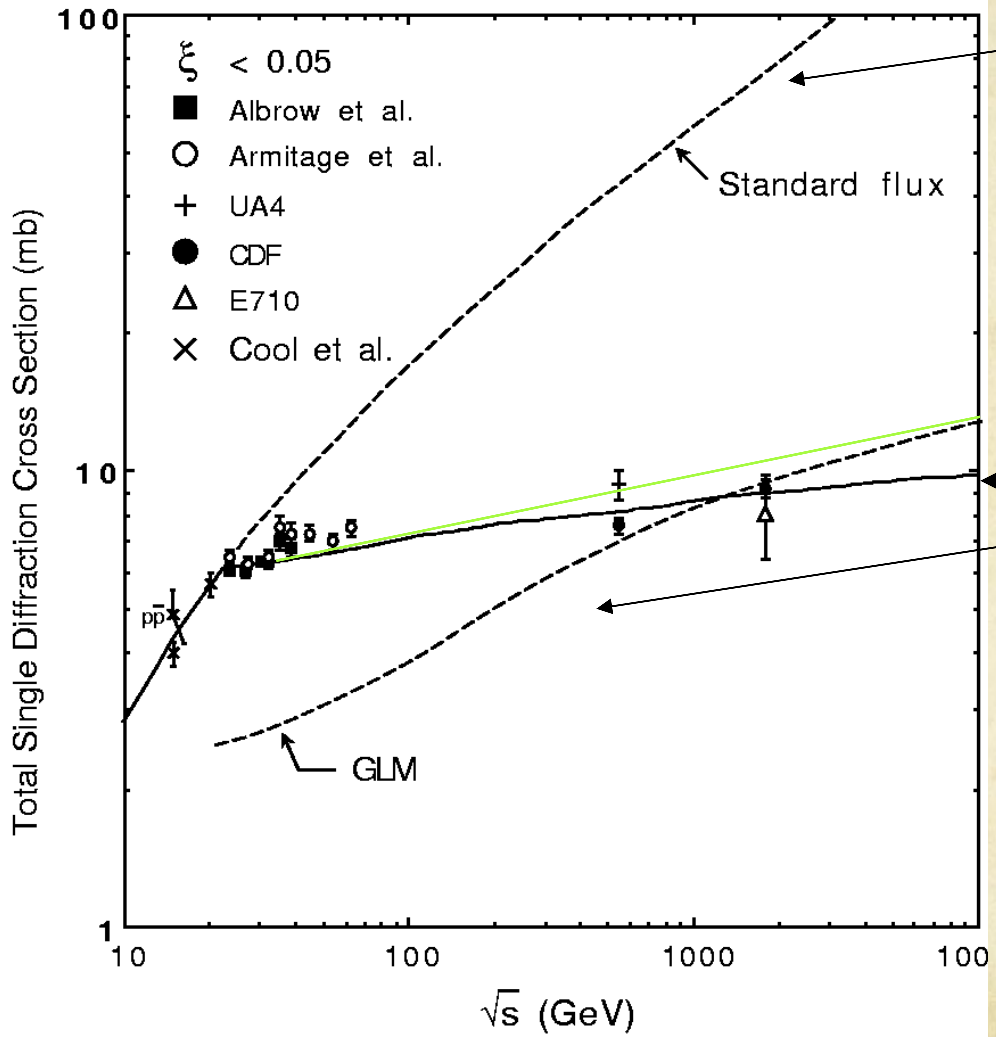


K. Goulianos, hep-ex/0011060, 18 November 2000.

SDE – CROSS SECTION



SDE – CROSS SECTION



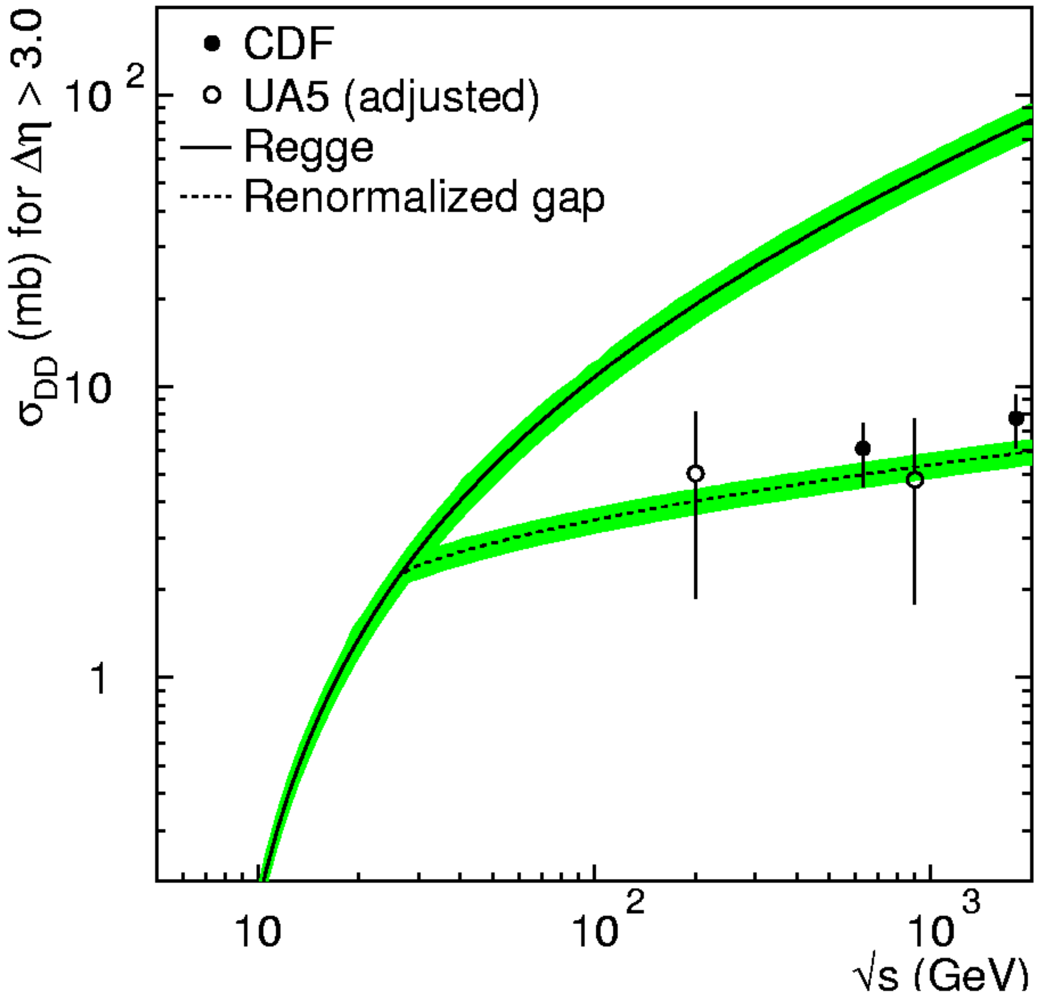
Regge fit to low energy data

K.Goulianos.

Eikonalized Regge prediction.

K. Goulianos, hep-ex/0011060, 18 November 2000.

DDE – CROSS SECTION



Triple-Pomeron amplitude+factorization

"Renormalized gap probability model" by Goulianos

K. Goulianos, hep-ex/0011060, 18 November 2000.

REGGE THEORY

- In Regge theory: 4-momentum transfer squared –t (GeV^2) in the t-channel exchange carried by a Pomeron P.

[Note: Because of the space-time structure of diffractive excitation, P cannot be a bound state – a particle.]

- It is described as a "Regge trajectory" which is a superposition of all possible t-channel exchanges with vacuum quantum numbers and a spin: $\alpha(t) = \alpha_o + \alpha' t$, where α_o is the intercept (related to the rise of σ_{tot} $\alpha_o \approx 1.08 - 1.20$) and α' the slope ($\alpha' \approx 0.25$ GeV^{-2}, trajectories appear to be linear).

⇒ Analytic theory of *hadronic* scattering described by the exchange of collective states: linear trajectories in the spin-energy (α,t) –plane. A trajectory for each: π, P, R.

But: Polarization data did not fit the scheme ⇒ unitarity corrections

⇒ complex angular momentum cuts (Mandelstam).

Further reading: Barone&Predazzi, HEP Diffraction, Springer (2002), Forshaw & Ross, QCD and the Pomeron, Cambridge UP(1997)m Donnachie et al., Cambridge UP (2002).

REGGE THEORY

Two fundamental and universal parameters describe the confining strong forces: $\alpha_P(0)$ and α_P'.

$$A_{el}^{ab}(s,t) = is\beta_a(t)(s/s_o)^{\alpha_P(t)-1}\,\beta_b(t)$$ (s_o mass scale, $\beta_{a,b}$ form factors $\propto \exp(Bt)$)

$\alpha_P(t) = \alpha_P(0) + \alpha_P' t$ (≥ 1), where $\alpha_P(0) = 1 + \varepsilon$ = 'intercept' which defines the energy

$$\sigma_{tot} = \beta_a(0)\beta_b(0)(s/s_o)^{\varepsilon} \propto (s/s_o)^{\varepsilon}$$

$$d\sigma_{el}/dt\,\big|_{t=0} = (1/16\pi)[\beta_a(0)\beta_b(0)]^2 (s/s_o)^{2\varepsilon} \propto (s/s_o)^{2\varepsilon}$$

At small t: $d\sigma_{el}/dt = (1/16\pi)[\beta_a(0)\beta_b(0)]^2 \exp(B(s)t)(s/s_o)^{2\varepsilon} = [\sigma_{tot}]^2/16\pi \exp(B(s)t)$

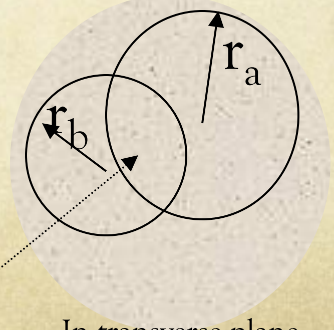
α_P' = 'slope' ($\approx 0.25\,GeV^{-2}$) which defines the rate of growth of the transverse extension of the scattering entity with energy:

$\approx 2\text{-}3\,GeV^{-2}$

$$R_{int}^2 = \langle b^2 \rangle = 2B(s) = 2(B_a + B_b + 2\alpha_P' \ln(s/s_o))$$

Diffraction!

fwd elastic peak "shrinks" with energy!



⇒ Confinement forces of the QCD!

TRIPLE REGGE

Triple Regge parametrization of the reaction: ab → c+X generalizes the Regge formalism to **inclusive** reactions. The Regge-Mueller expansion (based on the generalized Optical Theorem) states:

$$E(d^3\sigma/dp^3)\ (ab \rightarrow cX) \sim (1/s)\ \mathrm{Disc}_{M2}\ A(ab\mathbf{c} \rightarrow ab\mathbf{c}),$$

where the discontinuity is taken across the M_X^2 cut of the elastic Reggeized amplitude and A(ab**c** → ab**c**) is the elastic 'forward' three-body scattering amplitude.

For the triple Pomeron diagram, valid in the diffractive region of the phase space where the momentum fraction of particle c is close to unity, or $s >> W^2 >> (M_X^2, Q^2) >> (|t|, m_p^2)$:

$$E(d^3\sigma/dp^3)\ (ab \rightarrow cX) = (1/\pi) d^2\sigma/dtd\xi \cong (s/\pi) d^2\sigma/dtdM_X^2 = f(\xi,t)\ \sigma_{Pp}(M_X^2),$$

where the 'flux factor' $f(\xi,t)$ is given by: $f(\xi,t) = N\ F^2(t)\xi^{\,[1-2\alpha_P(t)]}$,

N is a normalization factor, F(t) the form factor of ppP-vertex, σ_{Pp} can be taken as the Pomeron-proton total cross section. By assuming that $\sigma_{Pp} \approx (M_X^2)^\varepsilon$, and by using the previous equations:

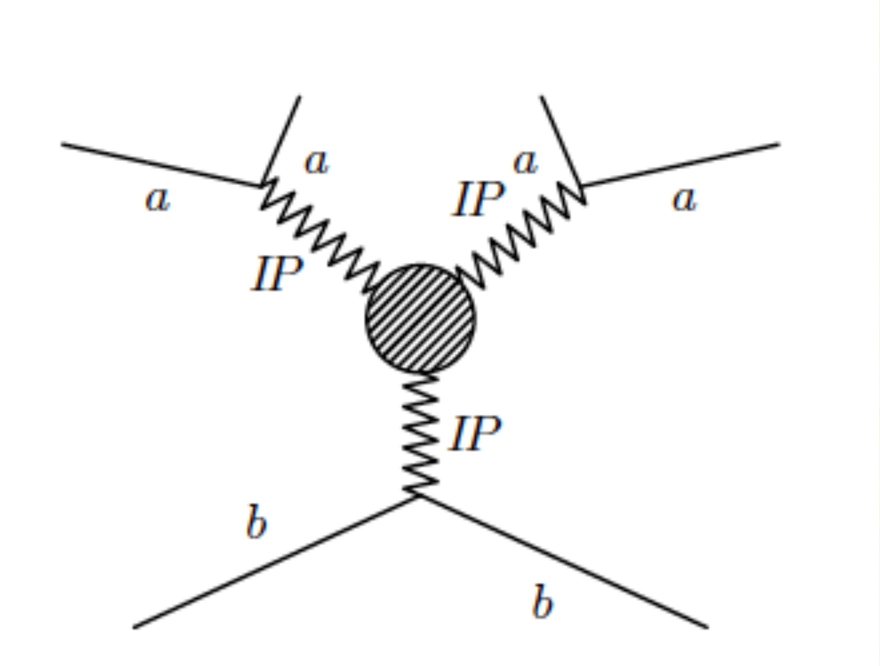
$$d^2\sigma/dtd\xi\,|_{t=0} \sim s^\varepsilon/\xi^{\,(1+\varepsilon)} = (M_X^2)^\varepsilon/\xi^{\,(1+2\varepsilon)}.$$

⇒ The triple-Regge PPP contribution in the region $\xi << 1$ is of the generic form: $d^2\sigma/dtd\xi\,|_{t=0} \sim 1/\xi^{\,(1+\delta)}$ with $\delta << 1$. This predicts a universal $1/\xi$ dependence as long as d is universal.

⇒ σ_{el}/σ_{tot} and $\sigma_{diff}/\sigma_{tot}$ increase as σ^ε ⇒ violation of unitarity since $\varepsilon > 0$.

⇒The total diffractive cross section $\sigma_{diff,tot}$ increases as $s^{2\varepsilon}$.

TRIPLE POMERON PROCESS DOMINATES HIGH MASS SINGLE DIFFRACTION



Triple Regge diagram with IPIPIP-vertex ~ squared amplitude of pp->p+X summed over system X, in the high mass limit of single diffraction ab → a˙+X.

- eight (2^3) possible combinations of Pomerons and Reggeons interact in the triple vertex
- at very high masses the (IPIPIP) vertex dominates
- at lower masses, a second triple coupling term replaces the Pomeron by a family of Reggeons family (like f_2 or ω) family
- in the intermediate range where ξ is not close to zero, triple vertices with one or both Pomerons are replaced with Reggeons

REGGE THEORY - PROBLEMS

The Regge theory is based on general properties of the scattering amplitudes, is a valid and elegant parametrization of the exchange processes in the **t-channel**

⇒ lacks in **predictive power**, cannot be used to derive the strong coupling limit of QCD, detailed structures of final states or to explain the free parameters.

⇒ leads to **unitarity problems** as $s \rightarrow \infty$ (especially in case of inelastic diffraction)

⇒ the power-law dependence $\sigma_{\tau ot} \propto s^{\varepsilon}$ violates the **Froissart-Martin bound**

⇒ the ratio $\sigma_{el}/\sigma_{tot} \propto s^{\varepsilon}/\ln s$ eventually exceeds the **blac-disc** geometrical bound ($\sigma_{el} \leq (1/2)\, \sigma_{tot}$)

⇒ the **ratio $\sigma_{tot,diff}$** increases as σ^{e} in disagreement with the experimental results (in DIS this is independent of W).

In the **s-channel** approach diffractive scattering is due to differential absorption – by the target particle – of the numerous open channels which coherently constitute the initial state hadron or the virtual photon (W/Z in case of weak interactions) in deeply inelastic scattering.

⇒ naturally incorporates **quantum mechanics** and **unitarity** and enables a unified description of the hadron, real and virtual photon (W/Z) scattering at short and long distances.

In the impact parameter space:

$$A_{el}^{ab}(s,\mathbf{b}) = i[\beta_a(0)\beta_b(0)/8\pi][(s/s_o)^{\varepsilon}/B(s)]\, \exp(-\mathbf{b}^2/2B(s))$$

The transverse size of the interaction region is Gaussian with $B(s) = \langle \mathbf{b}^2 \rangle$

⇒ the scattering profile is a disc with b-dependent opacity, the mean radius= $\sqrt{B(s)}$.

⇒ in pQCD language: **the gluon density in the proton rest frame increases** (& blackness ÷ interaction probability)

⇒ σ_{tot} increases with s: **number of 'wee' partons in the target & projectile increases:** $\alpha_P(0) \propto$ **'wee' parton density in rapidity** ($\propto$QCD multiplicity anomalous dimensions)

POMERON REVISITED

”Instanton Ladder” by Kharzeev, Kovchegov and Levin (2000):

Sturcture of soft Pomeron explained as a ladder consisting of instantons – spontaneous fluctuations of the hadronic vacuum:

Leads to the Regge-like energy dependence $\sigma \propto s^{\Delta}$

In the 1970’s Nambu argues that the linear Regge trajectories imply that the quarks inside are tied together by strings.

In Superstring theory the Regge trajectories are recovered again:
see ”Superstrings and the search for the theory of everything” by Peat.

APPENDIX 3: OPTICAL THEOREM

OPTICAL THEOREM

$$\langle f|S|i\rangle = \langle p_1' p_2' \ldots p_n'|S|p_1 p_2\rangle = \underbrace{\delta_{fi}}_{\text{no int.}} + \underbrace{i(2\pi)^4\delta^4(p^f - p^i)}_{\text{4-momentum cons.}} \underbrace{\langle f|T|i\rangle}_{\text{amplitude}},$$

$$\sum_f |f\rangle\langle f| = 1,$$

$$\langle j|Ti\rangle - \langle j|T^\dagger|i\rangle = (2\pi)^4 i \sum_f \delta^4(p^f - p^i)\langle j|T^\dagger|f\rangle\langle f|T|i\rangle.$$

$$\text{Re}\ \langle i|T|i\rangle + i\,\text{Im}\ \langle i|T|i\rangle - (\text{Re}\ \langle i|T|i\rangle - i\,\text{Im}\ \langle i|T|i\rangle) = 2\,\text{Im}\ \langle i|T|i\rangle$$

$$2\,\text{Im}\ \langle i|T|i\rangle = \sum_f (2\pi)^4\delta^4(p^f - p^i)|\langle f|T|i\rangle|^2.$$

OPTICAL THEOREM...

$$\frac{2\text{Im}\,\langle i|T|i\rangle}{F} = \frac{\sum_f (2\pi)^4\delta^4(p^f - p^i)|\langle f|T|i\rangle|^2}{F}$$

$$\frac{2\text{Im}\,\langle i|T|i\rangle}{F} = \sigma_{tot}$$

$$\frac{2\text{Im}\,\langle i|T|i\rangle}{4\sqrt{(p_1\cdot p_2)^2 - m_1^2 m_2^2}} = \sigma_{tot}.$$

$$\sigma_{tot} = \frac{\text{Im}\,A(s,t=0)}{2\sqrt{(p_1\cdot p_2)^2 - m_1^2 m_2^2}},$$

APPENDIX 4: MILESTONES IN DIFFRACTION

MILESTONES IN DIFFRACTION

- Events with **rapidity gaps** first observed in cosmic ray data. (Ciok et al., NC8(1958)166, Niu,NC10(1958)994, Cocconi, PR111(1958)1699)
- Idea of diffractive dissociation presented by **Good & Walker**. (PR 120(1960)1857)
- Inclusive and exclusive diffraction studied in fixed target experiments.
- **Optical theorem** proved by Al Mueller. (PRD2(1970)2963.)
- Elastic & Diffractive scattering through **Pomeron exchange**. (see: Donnachie&Landshoff PLB191(1987)309, NPB303(1988)634, Goulianos PR101(1983)169)
- Pomeron as **two gluon exchange**. (Low, PRD12(1975)163, Nussinov, PRD14(1976)246, PRL34(1976)1286, Nikolaev & Zakharov ZfPC49(1991)607, ZfPC53(1992)331)
- **BFKL Pomeron** (Kuraev,Lipatov,Fadin, Z.Eksp.Teor.Fiz.72(1977)199, Balitsky, Lipatov 28(1978)1957, Sov.J.Nucl.Phys.28(1978)822, Sov.Phys.JETP63(1986)904)
- **High p_T jets** observed at the CERN ISR could be of diffractive origin and could be used to probe the partonic structure of the Pomeron. (Ingelman & Schlein, PLB152(1985)256)
- Events with **rapidity gaps and jets** first observed by the CERN SPS experiment UA8. (Brandt et al., PLB297(1992)
- **Bjorken** predicts large rapidity gaps as signatures of diffraction (PRD47(1993)101.)
- **Jet production** in connection with rapidity gaps observed at the Tevatron. (D0:S.Abachi et al., PRL(72(1994)2332, PRL76(1996)734, CDF:F.Abe et al.,PRL74(1995)855, PRL80(1998)1156, PRL79(1997)2636), and at HERA (M.Derrick et al., PLB369(1996)55)

What is the relationship between <u>soft</u> and <u>hard</u> diffraction?
What is diffraction? Pomeron? Instantons? String theory - branes?
Forward physics at low-x. Physics beyond the Standard Model.