

# Double Pomeron ( $\mathbb{P}$ ) Exchange as a Key to the Higgs Mechanism\*

## OUTLINE

1. The Sextet Quark Higgs Mechanism
2. High-Energy QCD Via Color Superconductivity
3. Anomalies in CSQCD - Confinement, Pions, & the  $\mathbb{P}$
4. The  $\mathbb{P}$ ,  $\pi$ 's, and  $\Pi$ 's, in QCD
5. The Sextet QCD Scale and Electroweak Masses
6. Direct Production of  $\Pi$ 's
7. DIS Diffractive Jet Production
8. Large  $x$  and  $Q^2$  at HERA
9. The  $\eta_6$  "Axion" & Large  $E_T$  Jets
10. Diffraction at Fermilab
11. Double  $\mathbb{P}$  Exchange at the LHC

\* Presented at the Workshop on Physics With Forward Proton Taggers at the Tevatron and the LHC, December 14-16, 2003, Manchester, England.

# The Sextet Quark Higgs Mechanism

## At first sight -

- sextet quark symmetry breaking is simply a special version of technicolor, with QCD as the technicolor gauge group.
- A doublet of sextet quarks,  $U$  &  $D$ , (+, perhaps, heavy leptons - to avoid an  $SU(2) \times U(1)$  anomaly) is added to the standard model. Breaking of the sextet chiral symmetry then gives a triplet  $\Pi^\pm$ ,  $\Pi^0$  of sextet pions and a “Higgs” - the  $\eta_6$ .
- The  $W^\pm$ , and  $Z^0$ , acquire masses by “eating” the  $\Pi$ 's.

## But -

- economically (and very beautifully) the electroweak scale is a second (higher color) QCD scale - no new interaction is needed.
- Electroweak symmetry breaking is intricately connected with QCD dynamics and, in addition, the direct QCD production of  $\Pi$ 's gives a range of new phenomena.

## Experimentally -

- the first evidence should be subtle deviations from standard QCD at the electroweak scale - which may have already been seen !
- At higher energies (LHC ! ) there should be a multitude of effects, with the  $\mathbb{P}$  prominently involved.
- Double  $\mathbb{P}$  exchange should be the most definitive and may be spectacular !!

Theoretically , I have argued that, within QCD, the sextet sector produces many attractive properties.

- With one sextet and three triplet families, an infra-red fixed point (in the massless theory) produces a distinctive high-energy S-Matrix via the chiral anomaly.
- There is confinement and chiral symmetry breaking, but (infinite momentum) physical states contain both quarks and a particular “anomalous wee gluon” component.
- The  $\mathbb{P}$  is ( $\approx$ ) a regge pole and the “Critical Pomeron” describes asymptotic high-energy cross-sections.
- Wee partons are “universal” and carry vacuum properties, allowing the parton model to be maximally valid.

However, also “at first sight”,

- the  $\eta_6$ , is a (Peccei-Quinn) light axion. (The  $\eta_6$  is both “the Higgs” and “the axion”).
- A light axion is well-known to be ruled out experimentally. This is generally thought to be a major (deadly!) problem for sextet quark symmetry breaking.

But, anomaly couplings, due to the gluon content of the states, violate the sextet axial U(1) symmetry, and so

- there should be no light axion in the “anomaly S-Matrix”.
- For related reasons, there should be no glueballs, no BFKL pomeron, and no odderon.
- The  $\eta_6$  should have an electroweak scale mass and is probably very broad. There may be “no Higgs” - in the conventional sense.

# High-Energy QCD Via Color Superconductivity

We construct the regge limit of QCD by

- starting from Color Superconducting QCD (CSQCD), in which  $SU(3)$  color is broken to  $SU(2)$ .
- CSQCD contains an  $SU(2)$  triplet of massless (reggeized) gluons, plus two  $SU(2)$  doublets and one singlet of massive (reggeized) gluons.
- Each  $SU(3)$  triplet quark gives one  $SU(2)$  doublet and one singlet quark. Each  $SU(3)$  sextet quark gives one  $SU(2)$  triplet, one doublet, and one singlet quark.

Originally,

- this construction was motivated only by Reggeon Field Theory (RFT) arguments that - the transition from CSQCD to unbroken QCD should be described (from the supercritical side) by the Critical Pomeron.

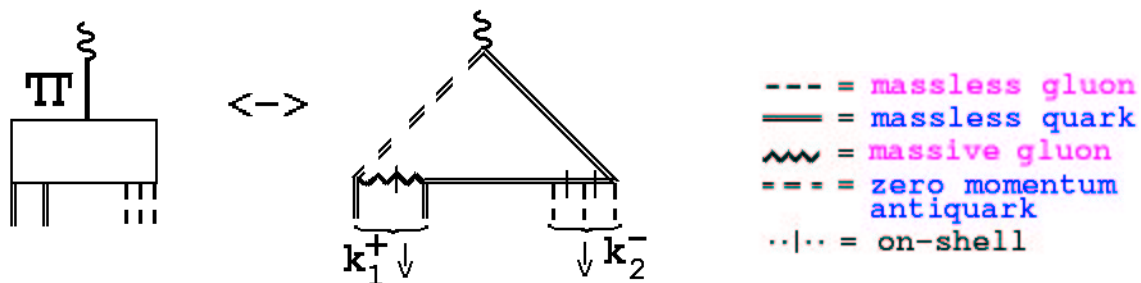
Additional, more direct, motivation is now provided by

- results obtained, via the chiral anomaly, on the structure, scattering, and production of infinite momentum Goldstone Bosons.
- From these results, QCD states and amplitudes can be obtained by restoring  $SU(3)$  gauge symmetry.

# Anomalies in CSQCD - Confinement, Pions, & the $\mathbb{P}$

- Within CSQCD, the triangle diagram “anomaly pole” gives important properties of Goldstone Boson Couplings.

First, the flavor anomaly



provides a coupling of a “pion” (triplet or sextet), with light-cone momentum  $k_1^+ \rightarrow \infty$ , to states containing

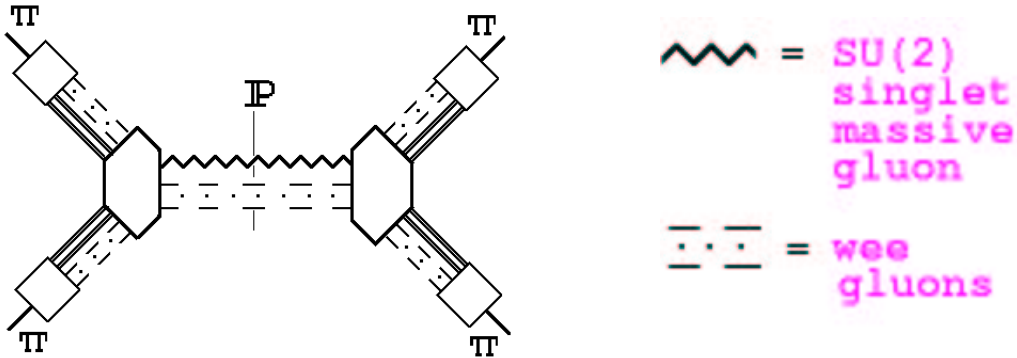
- a massless quark-antiquark pair with momentum  $k_1^+$  and vector-like spin
- massless “wee-gluons” with momentum  $k_2^-$  ( $k_2^- / k_1^+ \rightarrow 0$ )

Because of transverse momentum infra-red divergences produced by the wee gluons, such states dominate infinite momentum “physical” pion scattering amplitudes,

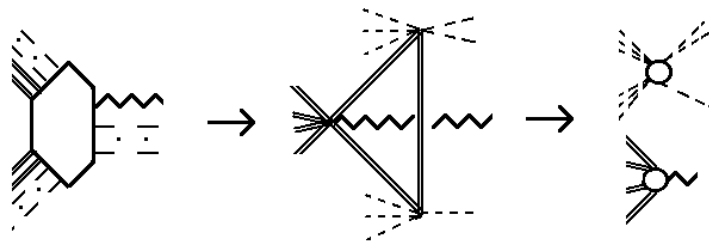
**As a consequence, there is no simple  $q\bar{q}$  component in the infinite momentum pion “wave function” !!**

*The triangle diagram anomaly pole can be interpreted as follows. A “pion” is created by the product of a physical quark field and a zero momentum “unphysical” antiquark field in which the Dirac sea is shifted. The antiquark becomes physical when it is accompanied by a wee gluon field that effectively moves the sea back to it's perturbative location.*

The simplest  $\pi - \pi$  scattering diagrams have the form



- The “anomaly pole” plays a second, crucial, role in the “ $\pi\pi\mathbb{P}$ ” vertex. The U(1) anomaly “pole” appears as a  $\delta$ -function that factorizes out the wee gluon interaction.





- With the IR fixed-point, regge exponentiation of divergences removes all colored wee gluon combinations.
- Physical amplitudes are selected by an overall divergence due to color zero, anomalous ( $C = -\tau = 1$ ) wee gluons (three as a minimum) that is not exponentiated.
- The divergence is factored out as a zero transverse momentum “condensate” in both the pion and the  $\mathbb{P}$ .
- The  $\mathbb{P}$  is an SU(2) singlet reggeized gluon + the condensate and is described by supercritical RFT.
- The only physical states are color zero Goldstone bosons, i.e. pions and nucleons !! (“nucleons” are  $qq$  and  $\bar{q}\bar{q}$  Goldstones.)

We can say that the condensate originates from a shift of the Dirac sea that produces states, and an S-Matrix, with both confinement of SU(2) color and chiral symmetry breaking.

# The $\mathbb{P}$ , $\pi$ 's, and $\Pi$ 's, in QCD

- With the sextet quark sector (and six triplet quarks), CSQCD has sufficient asymptotic freedom for SU(3) color to be smoothly restored via the Critical  $\mathbb{P}$  phase transition.
- As part of the transition, the condensate disappears and a corresponding dynamical contribution appears.
- Shifting of the Dirac sea becomes dynamical !!
- Simultaneously, the SU(2) singlet gluon becomes massless and decouples, as described by Supercritical RFT.

In unbroken QCD, the  $\mathbb{P}$  is (approximately)

1. (  ) a short-distance (gauge-invariant) reggeized gluon combined with
  2. (  ) a color compensating dynamical, anomalous, wee gluon contribution.
- $\pi$ 's and  $\Pi$ 's have the same wee gluon component, but with a short-distance quark-antiquark pair.

In the following, we will explicitly discuss hard diffractive, zero color, interactions (with a  $\gamma$ , a  $W$  or a  $Z$ ) in which the wee gluon component has only a limited role (no wee gluon interactions).

- For this, we can continue to represent the wee gluon component as a zero transverse momentum “condensate”.  
(In reality it is a much more complicated dynamical contribution of wee gluons over a range of infra-red transverse momenta.)
- Most importantly, distinct (wee gluon) dynamical scales for triplet and sextet quarks will be represented by distinct condensate couplings.

With the wee gluons treated as semi-classical,

- the anomaly mechanism will give a, **limited**, understanding of the production of  $\Pi$ 's and the resultant **production of  $W$ 's and  $Z$ 's in hard diffractive processes.**

Not surprisingly, the minimal representation of the dynamics of the wee gluon component will have major limitations.

- Most significantly, we will be able to apply the “**condensate anomaly mechanism**” only at large  $k_{\perp}$  and then (directly) only to the production of an “on-shell”  $\Pi$  carrying light-like momentum.
- **Dynamical wee gluons will produce  $\Pi$ 's at both small  $k_{\perp}$  and off-shell, but we will not try to discuss this explicitly.**

Instead, we first use the kinematic form given directly by the anomaly amplitude to go “off-shell”. This leads to

- **rough order-of-magnitude estimates and (some) qualitative kinematic features of hard diffractive phenomena.**

We can then combine

- the knowledge of hard diffraction that we obtain, with regge theory, to **discuss expectations for soft diffraction.**

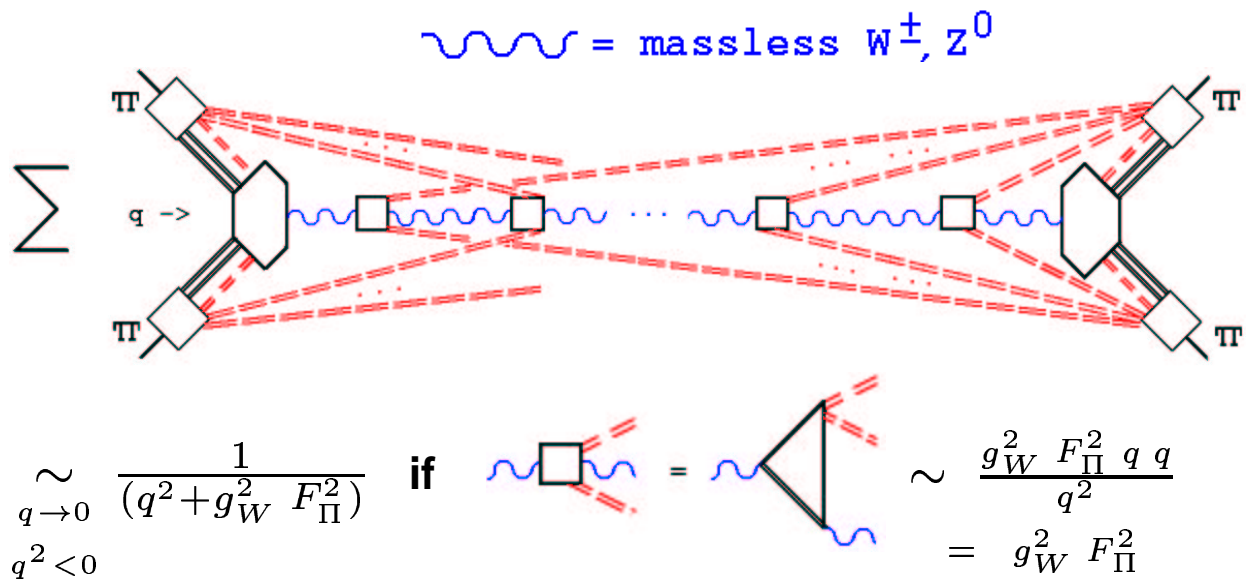
We will argue that

- the best place to see that new physics is in evidence is likely to be

**double  $\mathbb{P}$  exchange !!**

# The Sextet QCD Scale and Electroweak Masses

If (*suggestively*) we denote the sextet wee gluon coupling by  $F_{\Pi}$ , then, in the **regge limit**,  $W^{\pm}, Z^0$  mass generation can take place via a sum of anomaly diagrams. **This needs to be studied in more detail but, roughly,**



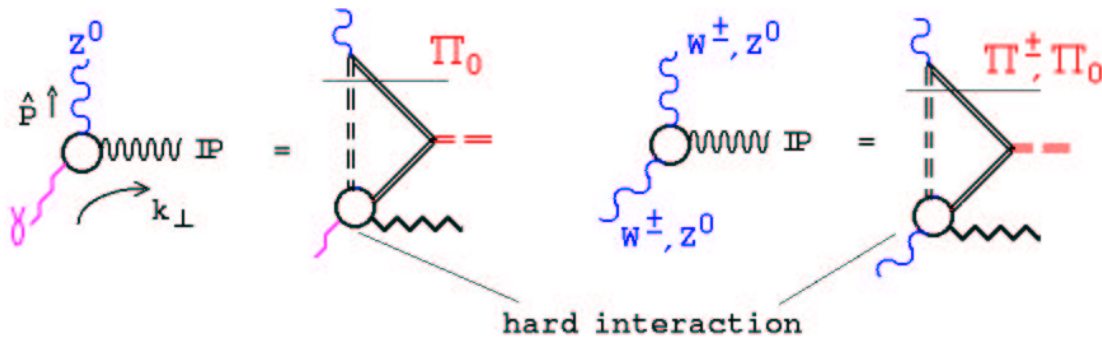
**From Feynman graph color factors, we expect triplet and sextet quark momentum scales for gluon interactions to be related (approximately) by “Casimir Scaling”, i.e.**

$$C_6 \alpha_s(F_{\Pi}^2) \sim C_3 \alpha_s(F_{\pi}^2) \quad C_6/C_3 \approx 3$$

- If  $\alpha_s$  evolves sufficiently slowly (e.g.  $\alpha_s(F_{\pi}^2) \sim 0.4$ )  $F_{\Pi}$  can indeed be the electroweak scale !
- This implies that the wee gluon component of the  $\mathbb{P}$  couples very strongly to sextet quarks.

# Direct Production of $\Pi$ 's

A  $\Pi$  can be directly produced via a **hard interaction (effectively pointlike at large  $k_{\perp}$ )** of the  $\mathbb{P}$  with a color neutral  $\gamma$ ,  $Z^0$ , or  $W^{\pm}$ .



- In this case, the  $\mathbb{P}$  provides, directly, the wee gluon component that is needed for the  $\Pi$  to appear via the anomaly pole.
- In addition to the large  $k_{\perp}$ , the hard gluon must also carry a large light-like momentum.

The anomaly amplitude has the form  $\frac{F_{\Pi} \hat{P}_+ \hat{P}_- \hat{P}_+}{\hat{P}_- \hat{P}_+} = F_{\Pi} \hat{P}_+$

Because of the anomaly pole, this is independent of  $\hat{P}_-$ , as we extrapolate away from  $\hat{P}^2=0$ . Combined with the  $Z^0$  propagator, and vertices  $g_w$ , the anomaly amplitude gives (using  $M=g_w F_{\Pi}$ )

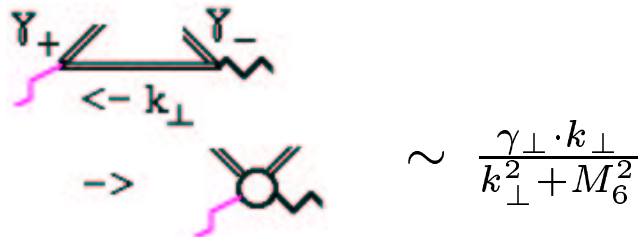
$$F_{\Pi} \hat{P}_+ g_w^2 \frac{(g_{-\nu} - \hat{P}_- \hat{P}_{\nu} / M^2)}{(\hat{P}^2 - M^2)} = -\frac{\hat{P}_-}{F_{\Pi}} \frac{\hat{P}^2}{\hat{P}^2 - M^2} \delta_{-, \nu} - \frac{\hat{P}_+}{F_{\Pi}} \delta_{+, \nu}$$

- The first term (which is present as soon as  $\hat{P}^2 \neq 0$ ) produces physical, longitudinal,  $W$ 's and  $Z$ 's.
- The second term has no pole, but is of comparable magnitude away from the pole. We use it to (crudely) estimate the background cross-section, on top of which the  $Z$  peak appears.

When  $\hat{P}_+ \sim F_{\Pi}$  ( $\hat{P}_- \ll \hat{P}_+$ ), the second term gives a direct coupling ( $\sim$  fermion masses) to fermion final states.

# DIS Diffractive Jet Production

In DIS a sextet quark loop can produce a  $\Pi_0$  via the hard interaction



$$\sim \frac{\gamma_{\perp} \cdot k_{\perp}}{k_{\perp}^2 + M_6^2}$$

where  $M_6$  is a dynamical sextet quark mass ( $\sim F_{\Pi}$ ).

Combined with the full “background amplitude”, this gives

$$\left( \frac{\hat{P}_+}{F_{\Pi}} \right) \left( \frac{\gamma_{\perp} \cdot k_{\perp}}{k_{\perp}^2 + M_6^2} \right)$$

The remainder of the amplitude compares (almost) directly with a standard two jet amplitude.

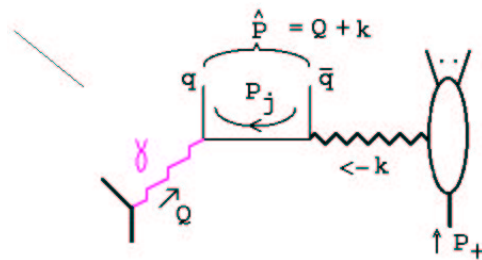
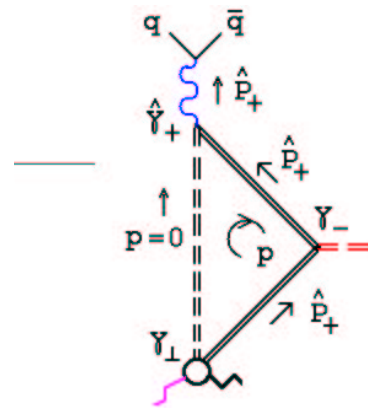
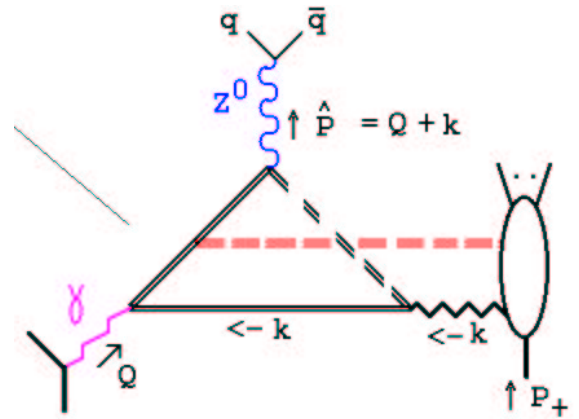
Kinematically, the only difference is that a (triplet) quark propagator (carrying momentum  $P_j$ ) replaces the triangle diagram factor.

In order-of-magnitude, therefore,

$$\sigma_{\Pi} \sim \left( \frac{\hat{P} P_j |k_{\perp}|}{F_{\Pi} (k_{\perp}^2 + F_{\Pi}^2)} \right)^2 \sigma_{2j}$$

and so  $\sigma_{\Pi}$  is suppressed, relative to standard jet cross-sections, until

$$\hat{P} \sim |k_{\perp}| \sim F_{\Pi} \sim P_j$$



# Large $x$ and $Q^2$ at HERA

Could there be observable events at HERA ?

- **At first sight, accessible kinematics might be**  
 $Q^2 \sim 30,000 \text{ GeV}^2$  and  $k_{\perp} \sim \hat{P} \sim 100 \text{ GeV}$ .  
**But,  $\hat{P}^2 \sim 0$  corresponds to  $x \sim 0.3$  and  $x$  increases further if  $\hat{P}^2$  is increased.**
- **Therefore, with  $x$  far from zero and  $-t/s \sim 0.2$  this is (at best) on the border of the regge region.**
- **Also, with  $\hat{P}^2 \sim 0$ , the electron will be produced close (but backwards) to the beam and will be unobservable.**

**For the electron to be observable,  $k_{\perp}$  must be smaller and/or  $\hat{P}^2$  must be larger**

- **Decreasing  $k_{\perp}$  decreases  $|t|$  and increases  $x$ . Increasing  $\hat{P}^2$  also increases  $x$ , but moves toward the  $Z^0$  pole.**

**In the diffractive region, with  $\hat{P}^2$  and  $Q^2$  fixed, the cross-section would be independent of  $x$  and grow as  $|t|$  decreases.**

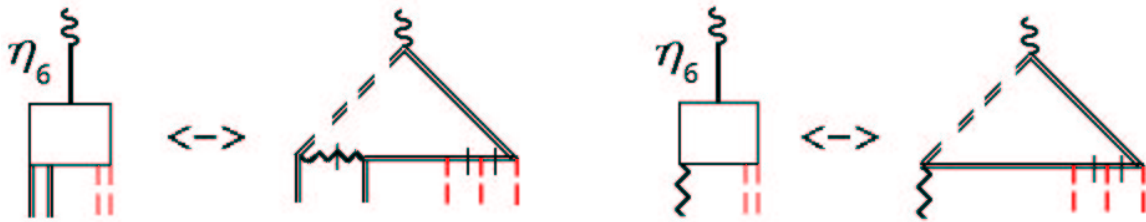
**In our case, the increase in  $x$  takes us further from the regge region. Although, this is compensated for, in part, by the decrease in  $|t|$  and the approach to the  $Z^0$  pole. Therefore, it is possible that**

**sextet pions could be responsible for jet events at HERA with  $Q \gtrsim$  electroweak scale and large  $x$  !!**

**In addition to the production of a (partly off-shell)  $Z^0$  it is also just possible that heavy quark jets could be produced.**

# The $\eta_6$ “Axion” & Large $E_T$ Jets

In CSQCD the  $\eta_6$  has **two** anomaly couplings to wee gluons



A  $Q\bar{Q}$  coupling (analogous to that of the  $\Pi$ ), and a second involving the SU(2) singlet gluon. As a result, in QCD,

- the  $\eta_6$  mixes with a pure glue state and (from the wee gluons) the coupling is  $\sim F_\Pi$ . Therefore,
- the  $\eta_6$  should acquire an electroweak scale mass.
- But, since it couples to the triplet sector via a gluon intermediate state, it may well produce only

**a broad enhancement of electroweak scale (large  $E_T$ ) jet cross-sections (at Fermilab ??)**

Unfortunately, we can not discuss these cross-sections using the present methods. Note that,

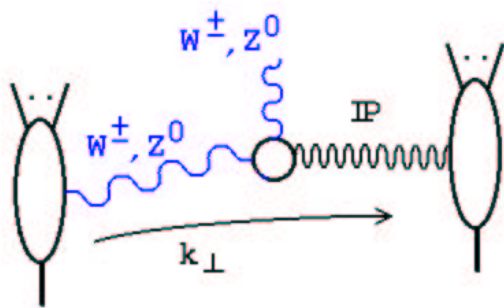
- To obtain the anomaly pole coupling, the helicity of the singlet gluon must be non-leading in the regge limit.
- Consequently, the full (reggeized) gluon state that mixes with the  $\eta_6$  is, initially, the “daughter of the pomeron”.

The fate of the axion is closely tied to the nature of the  $\mathbb{P}$  ! Since the wee gluons produce the  $\eta_6$  mixing with a pure glue state,

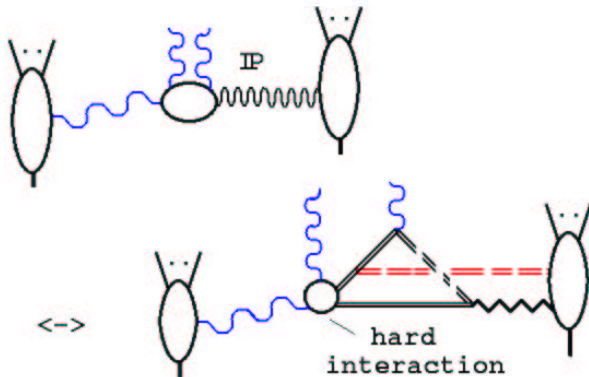
*“it is the dynamical shifting of the Dirac sea that breaks the sextet axial U(1) symmetry”.*

# Diffraction at Fermilab

Diffraction production of a  $\Pi$ , via the “condensate anomaly mechanism” requires an initial (perturbative)  $W$  or  $Z$  which (unlike the photon at HERA) will not be cleanly isolated  $\implies$  cross-sections will be relatively small and not easy to detect.



$\rightarrow$  enhanced diffractive  $W$  &  $Z$  cross-sections  
 $\rightarrow$  (large  $E_T$ ) jet cross-sections away from the central rapidity region.  
 - seen at Fermilab ??



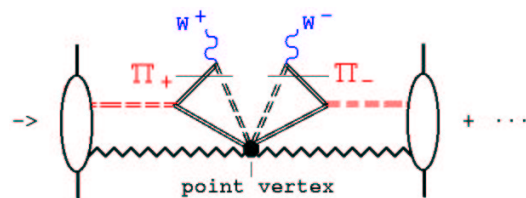
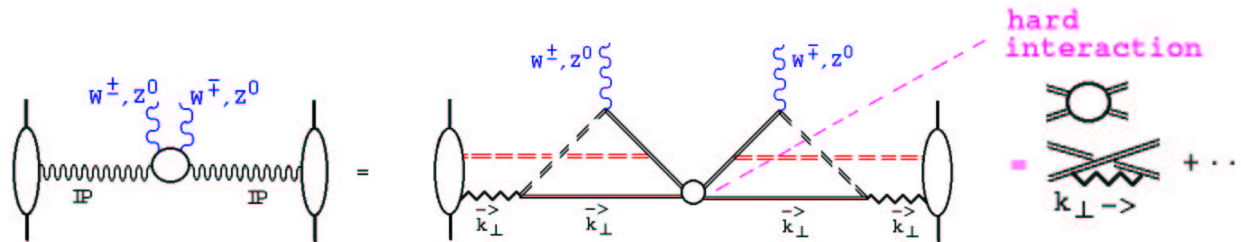
$\rightarrow$  enhanced  $W$  and  $Z$  pair cross-sections  
 $\rightarrow W + 2$  jet events (UA1?)  
 $\rightarrow W, Z +$  large  $E_T$  jets - seen at Fermilab ?

- Although the anomaly process takes place at large  $k_\perp$ , we expect the  $\Pi$  production vertex to continue to small  $t$  with little increase in magnitude.
- But, the  $\mathbb{P}$ /hadron vertex grows at small  $t$ , and so there could be “relatively large” cross-sections for the forward production of  $W$ 's and  $Z$ 's at Fermilab which remain undetected !

# Double $\mathbb{P}$ Exchange at the LHC

If each  $\mathbb{P}$  can be “cleanly isolated”, double  $\mathbb{P}$  exchange at the LHC should maximally expose the “new physics” of  $\Pi$  production.

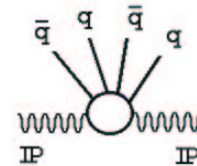
$\Pi$ 's can be pair-produced directly via the anomaly mechanism -



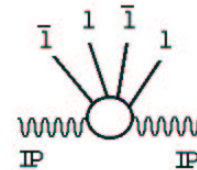
Order-of-magnitude arguments say that the large  $k_\perp$  production of  $W^+W^-$  and  $Z^0Z^0$  pairs should produce jet cross-sections that are at least as large as (and could be

considerably larger than) the inclusive cross-sections predicted by standard QCD.

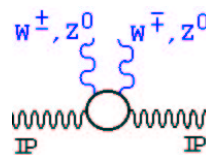
There should also be additional top quark production via a “background” anomaly vertex -



If new leptons exist, with electroweak scale masses, then there will similarly be large  $k_\perp$  anomaly vertices for their production.



- The boson/ $\mathbb{P}$  vertices will vary relatively slowly with  $k_\perp$ .



will vary relatively slowly

- But, the hadron/ $\mathbb{P}$  vertices (  ) will have strong  $k_\perp$  - dependence that should give large cross-sections at small  $t$ .

The first LHC evidence of sextet quark symmetry breaking is likely to be that, in general, diboson cross-sections are much larger than expected.

If forward protons can be tagged then it will be clear that,

- in particular, the double  $\mathbb{P}$  cross-section (for  $W^+W^-$  and  $Z^0Z^0$  pairs) is excessively large and, moreover, has the strong  $t$  dependence of a typical hadronic  $\mathbb{P}$  cross-section.

This would be very significant evidence that the electroweak sector is coupled strongly to the hadronic sector via

**sextet quark electroweak  
symmetry breaking.**

Possibly, there could be a substantial number of spectacular events in which the forward protons are tagged and only large  $E_T$  leptons are seen in the central detector !!