

# Sextet Quark Physics and the Pomeron at the LHC \*

Two sextet quarks added to QCD

→ “ $QCD_S$ ”

- has special solution, many attractive properties.

Sextet chiral symmetry breaking

→ electroweak symmetry breaking.

Longitudinal components of the  $W^\pm$  and  $Z^0$   
are sextet pions.

No new interaction required !!

**Experimentally** (the main focus of this talk) →

\* Presented at the Workshop on the Future of Forward Physics at the LHC, Manchester, England, December, 2004.  
Full details of everything I say in hep-ph/0412062

- **Strong  $\mathbb{P}$  coupling to sextet states**
  - large  $x$  and  $Q^2$  HERA events,
  - **diffractive**  $W^+W^-$ ,  $Z^0Z^0$ ,  $Z^0\gamma$ , **at Fermilab ?**
- **At Fermilab, also, sextet sector**
  - large  $E_T$  jet excess, non-evolution of  $\alpha_s$ ,
  - **top quark production via the  $\eta_6$  ?**
- *The sextet proton ( $P_6$ ) and neutron ( $N_6$ ) are the only new baryonic states. The  $N_6$  is absolutely stable.  $m_{N_6}$  could be as low as 500 Gev.*
- **Sextet states dominate at high energy.  $N_6$ 's can give (dominant) dark matter, and ultra high energy cosmic rays.**
- **The knee, and other cosmic ray phenomena, suggest that the sextet threshold is between Fermilab and LHC energies (as would be expected if the  $\mathbb{P}$  is involved).**
  - ⇒ large x-section effects expected at the LHC. Jet and multiple  $W$  and  $Z$  cross-sections will be much larger than expected.  $N_6$ 's and  $P_6$ 's should also be produced.*
- **Double  $\mathbb{P}$  produced states could provide definitive evidence in the initial low luminosity running of the LHC.**

## Properties of $QCD_S$

- High energy  $QCD_S$  can be constructed via “color superconducting”  $CSQCD_S$  (SU(3) color  $\rightarrow$  SU(2) )
- In  $CSQCD_S$  (with a  $k_{\perp}$  cut-off)

**perturbative reggeon diagrams  $\rightarrow$  supercritical RFT**

*A crucial infra-red fixed point (at small  $\alpha_s$ ) produces infra-red scaling of reggeon kernels.*

*Infra-red divergences coupled to triangle anomalies produced by longitudinal wee gluons, produce  $\mathbb{P}$  RFT diagrams.*

$\Rightarrow$  the  $QCD_S$   $\mathbb{P}$  is ( $\approx$ ) a regge pole and the

**“Critical Pomeron” describes asymptotic x-sections.**

- The physical states of  $QCD_S$  correspond to the Goldstone bosons of  $CSQCD_S$ .

- ⇒ triplet meson and nucleon states
- ⇒ no hybrid sextet/triplet quark states
- ⇒ sextet “pions” and “nucleons”
- ⇒ no additional bound states
- ⇒ no glueballs, no BFKL pomeron, and no odderon

- Infinite momentum states contain both quarks and an “anomalous wee gluon” component.

⇒ confinement and chiral symmetry breaking due to “universal wee gluons”.

⇒ (via Casimir effect) the sextet chiral scale can be the electroweak scale.

- Violation of sextet axial U(1) by wee gluon couplings

⇒  $m_{\eta_6}$  can be electroweak scale

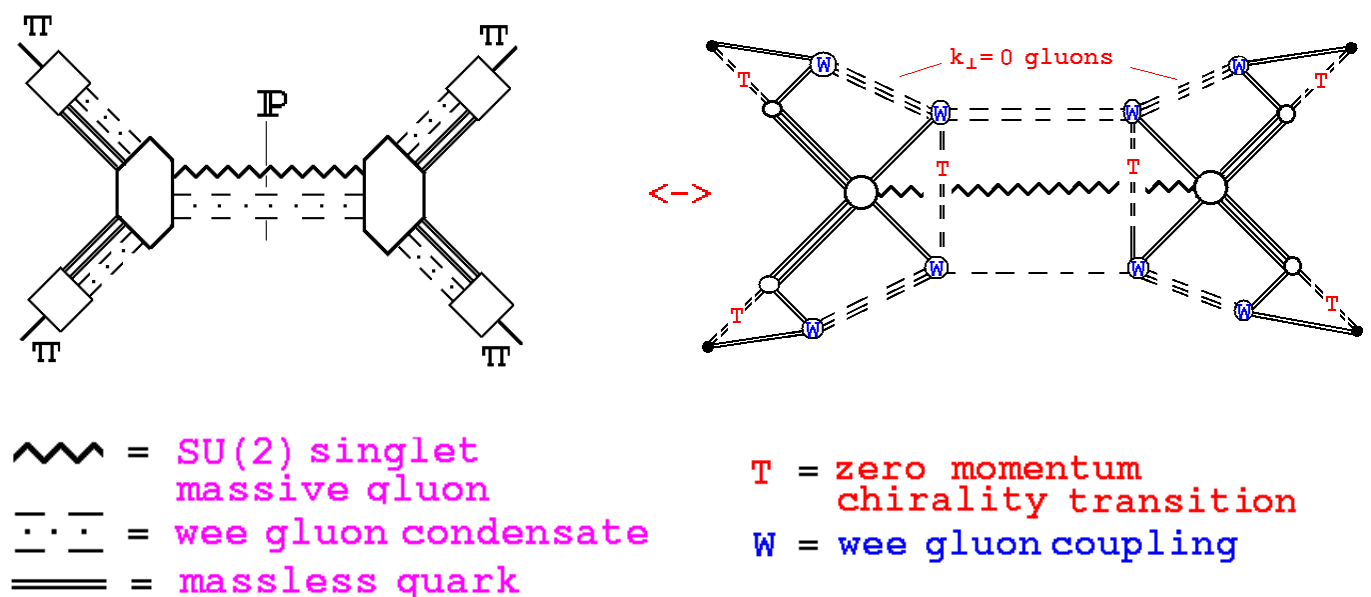
⇒ the  $\eta_6$  could give top quark production.

# Pions, & the $\mathbb{P}$ in $CSQCD_S$

When quarks are massless, particle and antiparticle propagator poles can combine to produce zero momentum chirality transitions, via the anomaly, in regge limit “effective vertex” triangle diagrams.

With a  $k_{\perp}$  cut-off, the chirality transitions produce wee gluon divergences at  $k_{\perp} = 0$  that select “anomaly pole” Goldstone bosons (“pions”) as physical states and determine the physical amplitudes.

The divergences are absorbed as a “wee gluon condensate” and the simplest  $\pi - \pi$  scattering diagrams have the form




- 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.  
(c.f. Gribov confinement)
- Via a chirality transition, the antiquark becomes physical in the presence of a compensating wee gluon field.
- In the scattering a further chirality transition realigns the initial state wee gluon field for absorption by the final state pion.
- There is no pure  $q\bar{q}$  component in the infinite momentum pion “wave function” - the  $q\bar{q}$  pair has vector-like spin !!

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

- $CSQCD_S$  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 wee gluon condensate disappears and a corresponding dynamical contribution appears, i.e.
- shifting of the Dirac sea becomes dynamical !!
- Simultaneously, the SU(2) singlet gluon becomes massless and decouples, as described by Supercritical RFT.
- The only remnant of the symmetry breaking is the anomaly couplings involving (longitudinal) wee gluons.

In unbroken  $QCD_S$ ,

- the  $\mathbb{P}$  is ( $\approx$ ) a short-distance (gauge-invariant) reggeized gluon () combined with a color compensating, dynamical, anomalous, wee gluon contribution ( $\equiv \equiv \equiv$ ).
- $\pi$ 's and  $\Pi$ 's have the same wee gluon component, but with a short-distance quark-antiquark pair.

Later, we will discuss *hard diffractive, zero color, interactions of the  $\mathbb{P}$  (with a  $\gamma$ ,  $W$  or  $Z$ ) 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.**



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.  $\alpha_s(F_{\pi}^2) \sim 0.4$ )

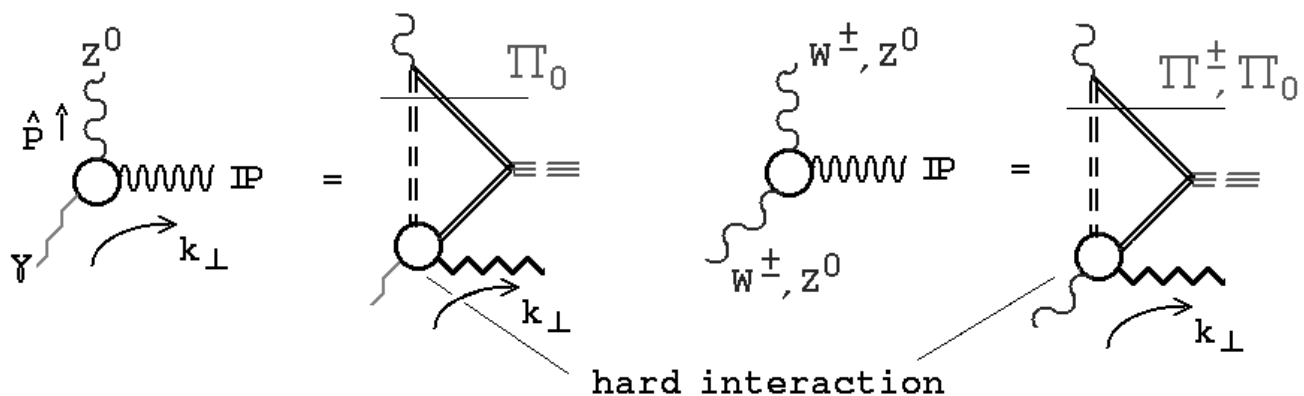
$F_{\Pi}$  can indeed be the electroweak scale !

- $\implies$  the wee gluon component of the  $\mathbb{P}$  couples very strongly ( $\sim F_{\Pi}$ ) to sextet quarks.

*We will not discuss whether effective quark masses can be generated by the sextet Higgs mechanism. (Significant shifting of the Dirac sea, perhaps as envisaged by Gribov, has to be involved)*

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

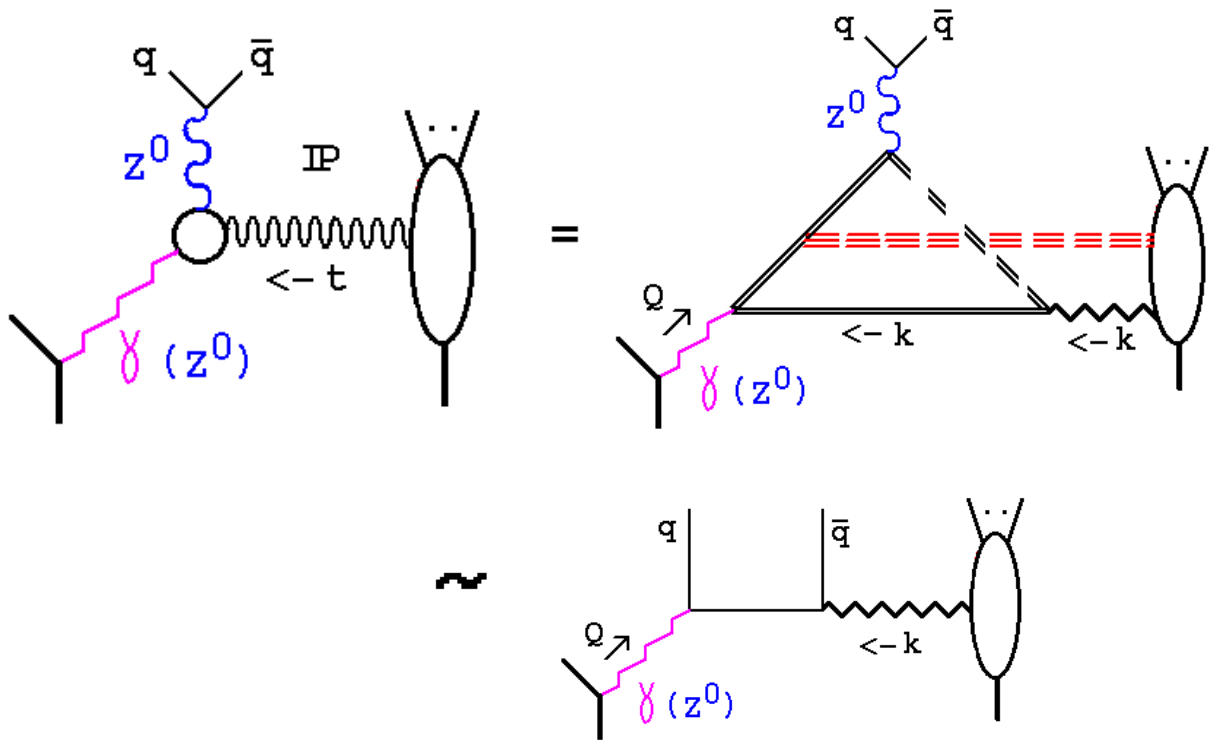
An anomaly pole  $\Pi$  can be produced via a large  $k_{\perp}$  “hard interaction” of the  $\mathbb{P}$  with a color neutral  $\gamma$ ,  $Z^0$ , or  $W^{\pm}$ , e.g.



- The  $\mathbb{P}$  provides, directly, the wee gluon component that is needed for a massless  $\Pi$  to appear via the anomaly pole.

*Could these vertices be seen at HERA ??*

If we consider the full DIS amplitude, it is strongly enhanced by the anomaly when  $k_{\perp}$  is electroweak scale and compares, in order of magnitude, with a standard two jet amplitude  $\rightarrow$



**At HERA,  $Q_{\perp} \gtrsim 100 \text{ GeV}$  requires**

$$Q^2 \gtrsim 30,000 \text{ GeV}^2, \quad x \gtrsim 0.5$$

**. But  $k_{\perp} \gtrsim 100 \text{ GeV}$  and  $\hat{P}^2 \sim M_{Z^0}^2$ , requires**

$$|t| \gtrsim 2k_{\perp}^2 \sim 20,000 \text{ GeV}^2$$

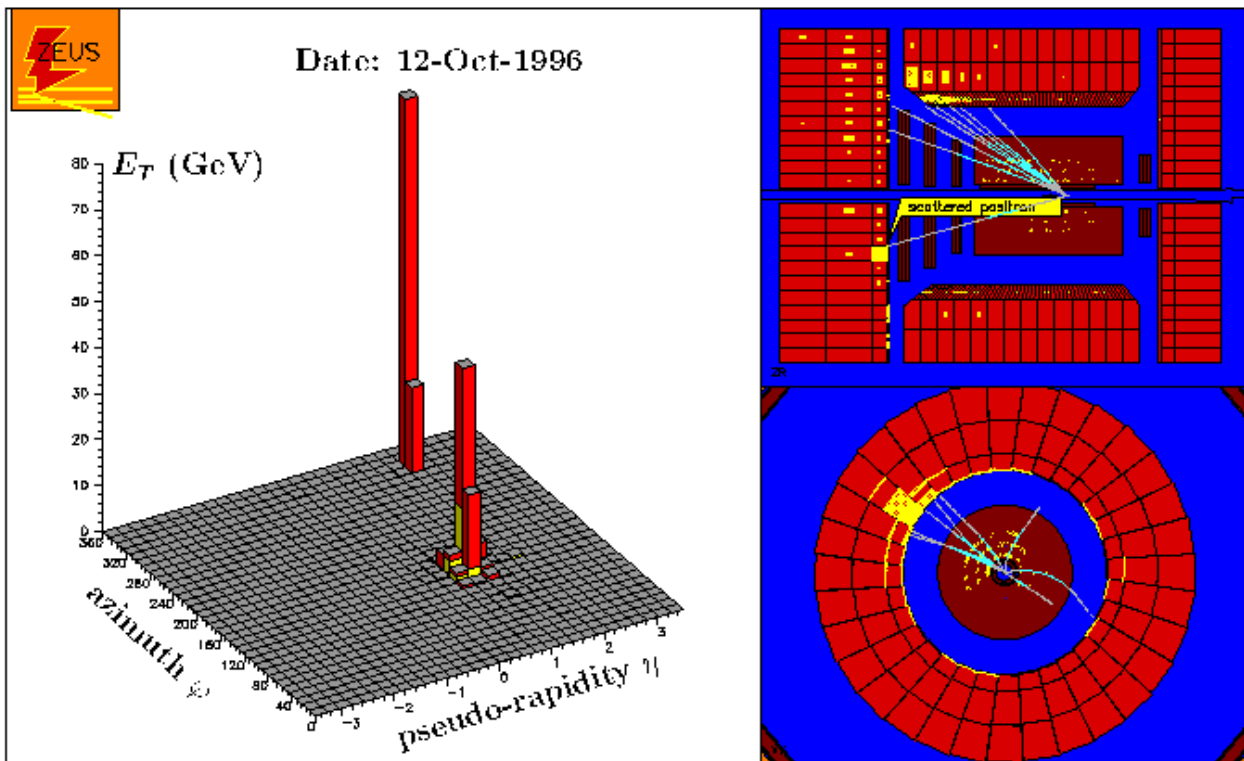
**and the two jet amplitude will be much too small.**

*But, the hadronic  $\mathbb{P}$  coupling will increase strongly as  $k_{\perp}$  (and  $|t|$ ) decreases, while the “non-perturbative”  $Z^0$  vertices should decrease only slowly (with a scale determined by  $F_{\mathbb{P}}$ ), and so, on the  $Z^0$  pole, there could be an observable x-section.*

**A high momentum longitudinal  $Z^0$  (produced via a sextet pion) has a higher probability (than a transverse  $Z^0$ ) to produce a jet (or lepton) pair sufficiently close together to appear as a single massive jet .**

$$\left. \begin{array}{l} \theta = 15.4^\circ \\ \gamma = 38.6^\circ \end{array} \right\} \rightarrow \begin{array}{l} x_{\text{DA}} = 0.709 \pm 0.034 \\ Q_{\text{DA}}^2 = 46,100 \pm 1,600 \text{ GeV}^2 \end{array}$$

$$\left. \begin{array}{l} \theta = 15.4^\circ \\ E' = 380 \text{ GeV} \end{array} \right\} \rightarrow \begin{array}{l} x_e = 0.605 \pm 0.060 \\ Q_e^2 = 41,000 \pm 3,000 \text{ GeV}^2 \end{array}$$



- For the largest  $Q^2 (> 40,000 \text{ GeV}^2)$  event seen by ZEUS (before 97) the 'double-angle' (DA) and direct 'positron measurement' (e) methods for reconstructing the event give significantly different results (outside the errors).
- But, the DA method assumes the jet is massless and so the two methods should agree only in this case !!

- The DA method, effectively, projects the experimental energies and momenta onto a (forced to be) massless jet and an additional momentum projected onto the positron direction.
- Subtracting the measured positron momentum, and adding the additional momentum to the massless jet gives (approximately) the true momentum of the (massive) hadronic state.
- **The result is a mass squared of**

$$8,077 \text{ GeV}^2 = (89.9 \text{ GeV})^2$$

**suggesting that a massive  $Z^0$  jet was indeed produced !!**

- The production angle is large enough ( $\sim 27.4^\circ$ ) for the jet to be clearly detected only because  $Q^2$  is so large.

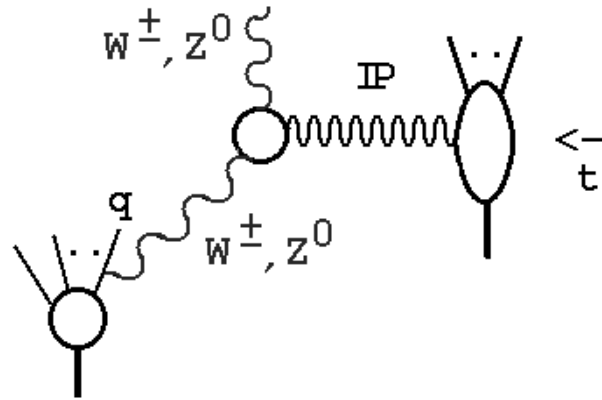
**One other ZEUS event (with much lower  $Q^2$ ) had a (not as bad) discrepancy between the two construction methods. It could, perhaps, have been a  $Z^0$  if a second, slower, jet went down the beam pipe.**

The kinematics of the H1 events were published in a more difficult form to analyze, but none had such a large  $Q^2$ .

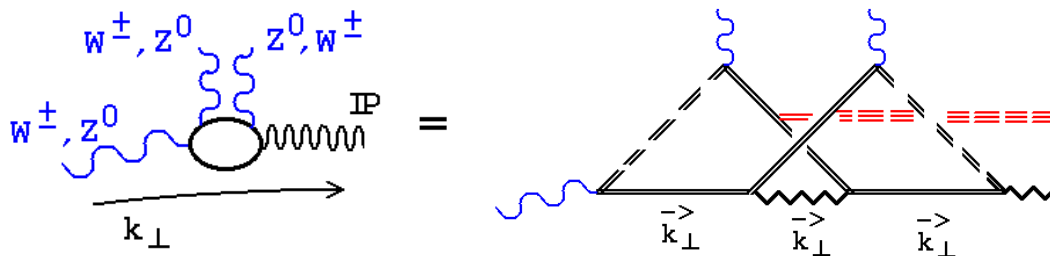
**Clearly, jet masses should be looked at directly and more recent events should be studied !!**

# Diffractive Physics at Fermilab

Diffractive, **sextet pion**, hard vertices will also appear in a hadron collider when a  $Z^0$ ,  $W^\pm$ , or  $\gamma$ , is emitted from a quark in a hadron. But, x-sections will be relatively small and not easy to detect.



*Diffractive production of a  $W$  or  $Z$  pair via a double anomaly pole vertex may give an anomalous x-section.*



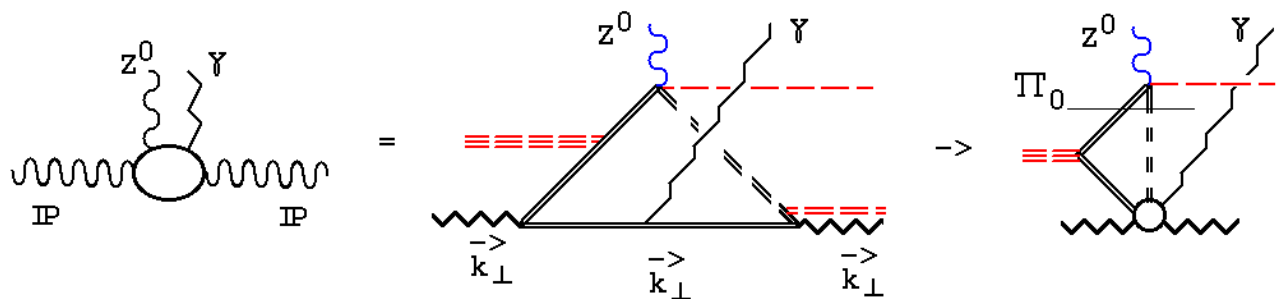
- An excess  $W$  pair x-section was apparently observed at the CERN  $S\bar{p}pS$  by UA1, why not at the Tevatron ??
- Hadronic jet decays can not be distinguished from the QCD background at the Tevatron (unlike at UA1).
- Lepton pairs less separated, makes detection of high momentum, longitudinal, bosons more difficult.
- Nevertheless, low or high associated multiplicities (wrt the Standard Model) could indicate anomalous x-sections that will become much larger at higher energies.

$$2\mathbb{P} \rightarrow W^+W^- \text{ (or } Z^0Z^0\text{)}$$

should be pre-eminent at the LHC but (probably) not at the Tevatron.

$$2\mathbb{P} \rightarrow Z^0\gamma$$

can proceed via a single sextet pion and so could be anomalously large at the Tevatron.



- Large  $k_{\perp}$  does not flow through the  $\gamma$  which, therefore, need not carry electroweak scale  $k_{\perp}$ .
- The two external  $\mathbb{P}$  couplings should greatly increase the x-section at smaller  $t$ .

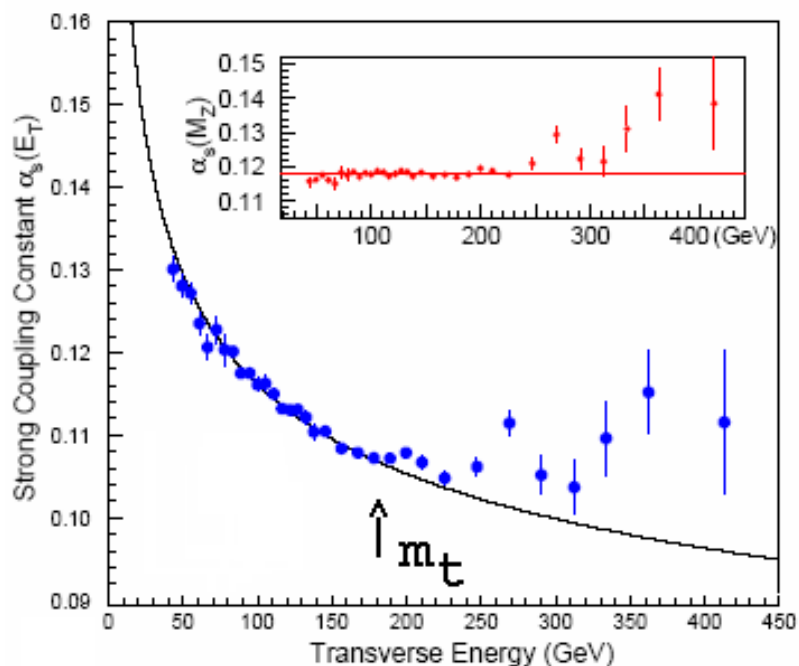
# The $\eta_6$ , $t\bar{t}$ , & Large $E_T$ Jets

- The sextet quark component of the  $\eta_6$  has octet color (compensated by wee gluons) and can be produced by a gluon.
- Consequently, the  $\eta_6$  mixes with a pure glue state (the daughter of the pomeron) and should have a mass determined by  $M_6$  (the sextet constituent mass scale).
- It will decay, primarily through  $t\bar{t}$ , via the gluon state.
- $t\bar{t}$  production could be via the  $\eta_6$  (resolving the paradox of the direct production of a confined, colored, quark), and yet be, essentially, “perturbatively calculable”.

$$\Rightarrow m_t \sim M_6, \quad m_{\eta_6} \sim 2m_t$$

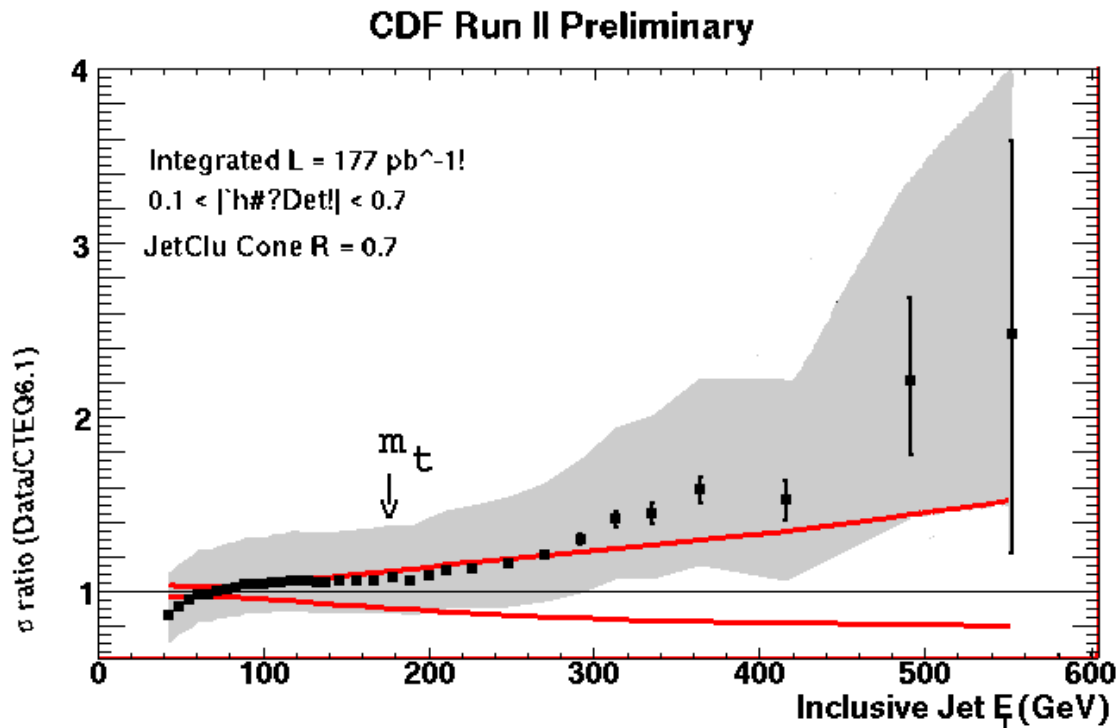
$\Rightarrow$  2 sextets  
( $\equiv$  10 triplets)  
stops  $\alpha_s$   
evolution  
at  $E_T \sim m_t$

$\Rightarrow$  a jet  
excess  
above  $E_T \sim m_t$



CDF Run 1  $\alpha_s$

To the innocent eye, the jet excess appears to persist in CDF run II data, for  $E_T > m_t$  !!



- Gluon distribution is fitted to Run I excess !!
- An excess in addition to  $\alpha_s$  not running => production of (longitudinal)  $W$  and  $Z$  jets contributing.

If the  $\eta_6$  produces  $t\bar{t}$  then “non-perturbative” decays should also be seen (at some level)

$$\eta_6 \rightarrow W^+ W^- Z^0 \rightarrow W^+ W^- b\bar{b} \text{ or } \dots !!$$

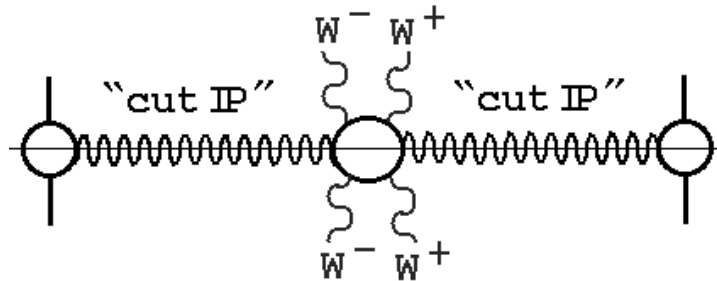
$$\eta_6 \rightarrow Z^0 Z^0 Z^0, \quad \eta_6 \rightarrow W^+ W^- \gamma, \quad \dots$$

$$\eta_6 \rightarrow \gamma\gamma, \quad \dots$$

# Dark Matter and Cosmic Ray Physics

- Because of the Casimir effect, the sextet sector will constitute a stronger coupling sector of  $QCD_S$ .
- Sextet states are produced by gluons. Large x-sections are obtained via the  $\mathbb{P}$  ( $\infty$  no. of gluons)
  - inclusive amplitudes give the largest effect.

e.g.



describes central, inclusive,  $W$  pair production. When this amplitude is large, pairs will be multiply produced across most of the rapidity axis - in analogy with low-energy pion production.

- Once there is enough energy for cut- $\mathbb{P}$  exchange to begin the production (perhaps  $\sqrt{s} \sim 5 \text{ Tev}$ ), sextet states will start to dominate the inelastic x-section

**Because of the absence of hybrid triplet/sextet states, the lightest sextet nucleon must be stable.**

- *Because  $m_u < m_d$  the triplet proton is lighter than the neutron.*
- *Sextet quark current masses must be zero for the sextet higgs mechanism to operate*

*$\Rightarrow$  the sextet mass difference is entirely electromagnetic*

*$\Rightarrow$  the  $N_6$  is stable.*

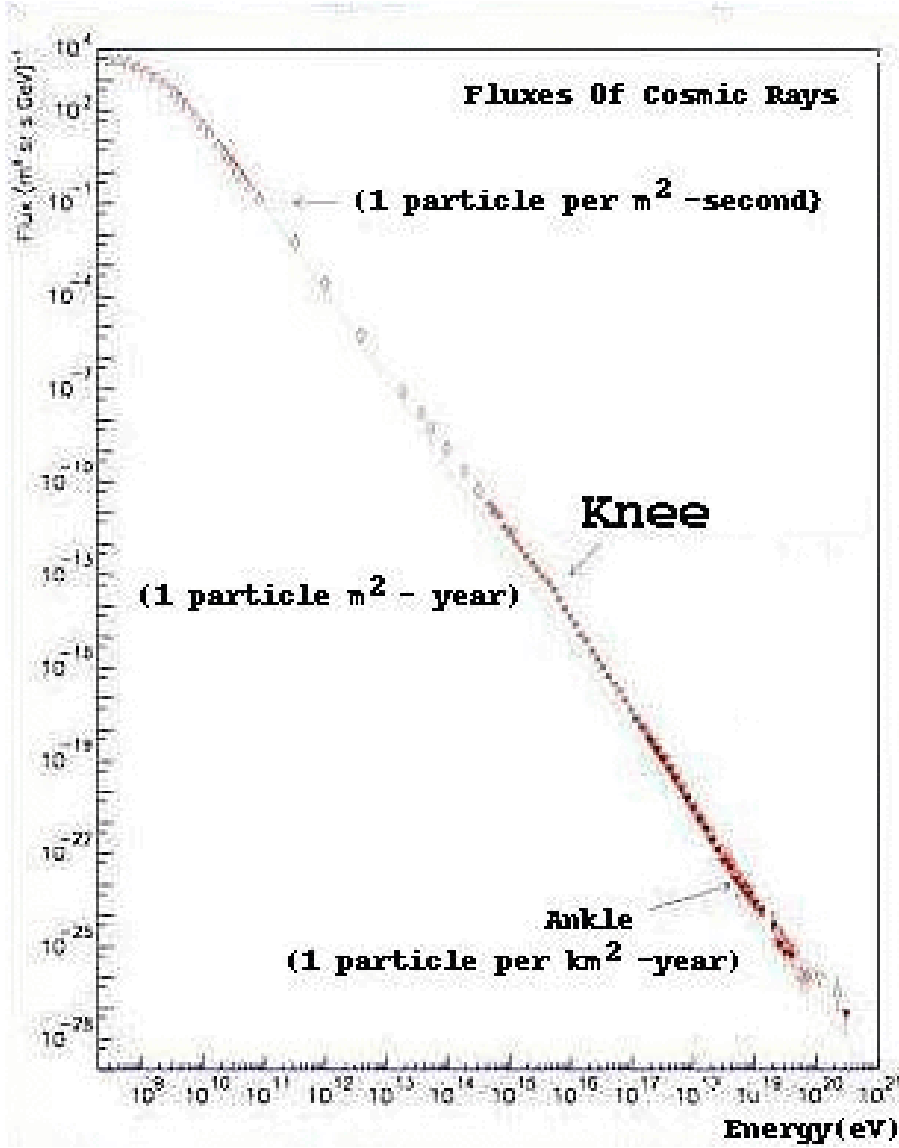
*If  $M_6 \sim m_t$  then  $m_{N_6} \approx 500 \text{ GeV}$ .*

**At high energy, the  $N_6$  will be the dominant stable state and will dominate the formation of matter in the early universe. It will abundantly form cold dark matter, as (sextet) nuclei, clumps, etc.**

- *For experimental evidence on the energy scale at which the dominance of sextet states appears, we turn to cosmic ray data.*
- *The “knee” in the cosmic ray spectrum suggests a major interaction change between Tevatron and LHC energies.*

The knee is an extraordinary phenomenon. A break in the slope that stands out, as the flux decreases by thirty orders of magnitude.

Looking more closely there is a "knee".



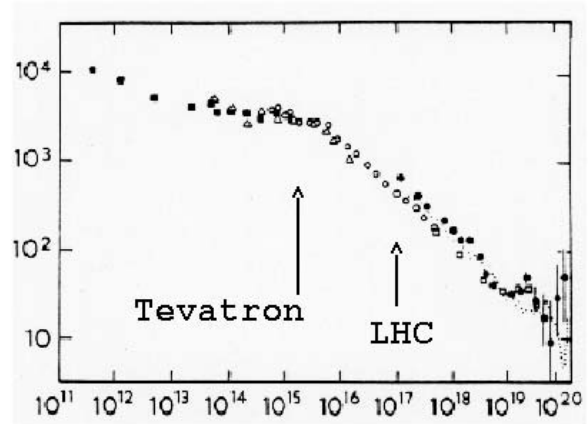
There is no agreement on it's origin !!

A priori, a conspiracy of external phenomena seems unlikely.

More plausibly, the atmospheric interaction is to blame.

Early on, a production threshold was suggested, for particles ( neutral ? ) not observed at ground level.

- => an underestimation of energies above the threshold
- => a pile-up of events below the threshold energy
- => a depletion of the spectrum above the threshold.



## The problem with the threshold proposal

- a major part of the x-section must be involved.

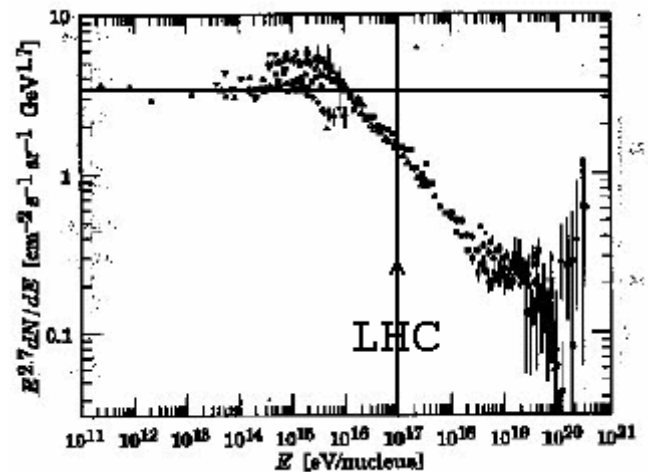
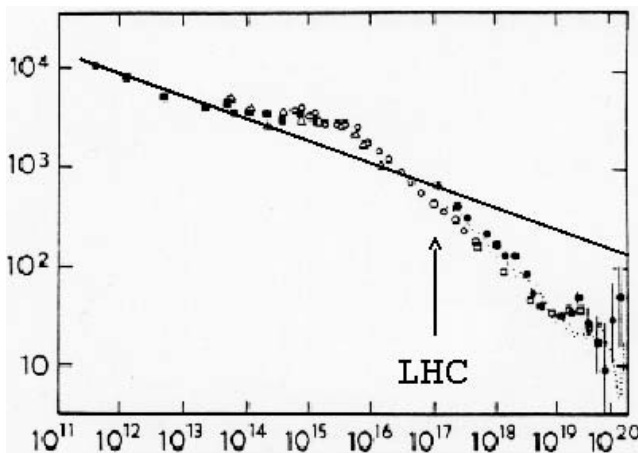
What physics could produce such a large effect ??

## Perhaps uniquely, the sextet threshold could be responsible

1. *As vector boson production becomes dominant it will increase the average transverse momentum enormously - an unexpectedly large fraction of shower particles will be undetected.*
2. *A huge increase of the large  $E_T$  jet x-section is the main effect.*
3. *There will also be major changes in lepton distributions, including a much larger fraction of (undetected) neutrinos.*
4. *Dark matter ( $N_6$ ) production will obviously take away energy and at high energy will be a major contribution to the loss of detected energy by most of the x-section.*

It is difficult to be sure exactly where the threshold is and how much of the cross-section has to be involved at a particular energy.

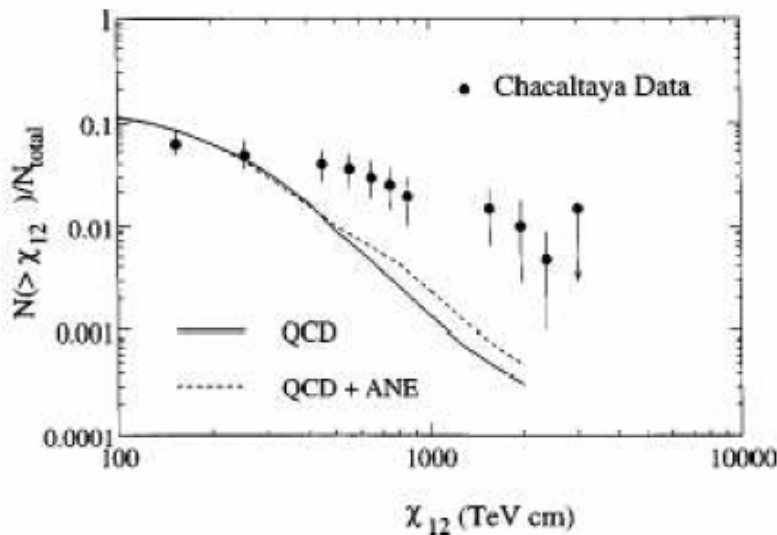
- Many experiments have now studied the knee
- The data from different experiments do not agree about the absolute value of the flux and cover different energy ranges.
- There must be a sufficient number of missing events above the threshold for the full knee to be formed by their movement (into the knee).



*The most reasonable conclusion is that the threshold should be below the LHC energy and that the physics involved should be visible at the LHC as a significant part of the hadronic cross-section ( $\sim 20\%$ ).*

Many effects seen in cosmic ray showers, with energies above the knee, suggest that new physics does indeed appear.

*In particular, dijet (cores) production is orders of magnitude above the QCD prediction.*



*Ultra high-energy events, with  $E_0 \gtrsim 10^{20}$  eV, have become of particular interest. This is because such energies exceed the GZK cut-off (from the proton interaction with the cosmic radiation.)*

- $N_6$ 's avoid the GZK cut-off (because they are both neutral and massive) and have large high-energy hadronic cross-sections.
- Ultra high-energy cosmic rays could be  $N_6$ 's - their origin would (perhaps) not be a mystery

**$\Rightarrow$  DARK MATTER, THE KNEE, UHE COSMICS, ALL RELATED !!!**

## What Should be Seen at the LHC ?

At high luminosity, major evidence for the sextet sector would be

- Multiple vector boson and large  $E_T$  jet x-sections much larger than expected, producing a dramatic rise in the average  $|p_\perp|$ .
- Because of longitudinal boson decays to close together jets or leptons, the true magnitude of boson cross-sections may not be detected.
- Will the increased magnitude of large  $E_T$  jet x-sections, alone, be sufficient evidence for the sextet quark sector ??

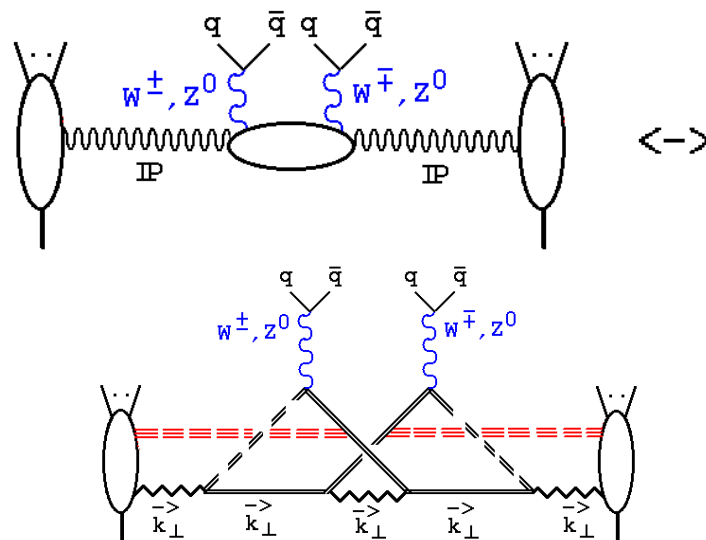
*A priori,*

- *the neutral  $N_6$  will be difficult to detect, since missing energies of several hundred  $GeV$  will be common.*
- *The  $P_6$ , assuming it is not too unstable, should be seen.*
- *Will a massive, charged, particle with a large production x-section be directly identified with the sextet sector ??*

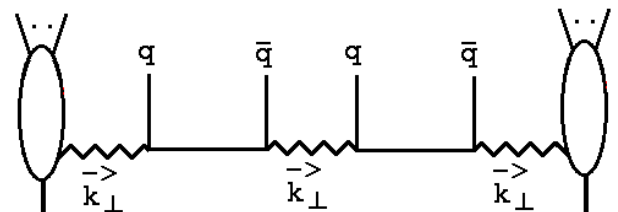
**The double  $\mathbb{P}$  x-section** may well be the most definitive early evidence for the existence of the sextet sector.

*If the  $\mathbb{P}$ 's are detected with Roman pots, the various phenomena can be looked for in a cleaner and much more controlled environment.*

**$W$  &  $Z$  pairs can be produced via sextet pion anomaly poles.**



When  $|k_{\perp}|$  is electroweak scale, the x-section is comparable with that given by a jet amplitude that has, apart from the anomaly loops, the same propagators and couplings.



*$\Rightarrow$  at large  $k_{\perp}$ , double  $\mathbb{P}$   $W$  &  $Z$  pairs will give jet cross-sections that are as large as the non-diffractive x-sections predicted by standard QCD.*

The large  $k_{\perp}$ , double  $\mathbb{P}$ ,  $W$  &  $Z$  pair x-section for producing jets is larger than the triplet sector x-section by a factor of  $\gtrsim O(10^{12})$ .

**As before, the central double  $\mathbb{P}$  vertices will vary only slowly with  $k_{\perp}$ .**

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

- *Central production of a mass  $2M$  requires*

$$t \sim -4M^2/S$$

- $\sqrt{S} = 14 \text{ TeV}$ , *and*  $M \sim 2M_W \sim 170 \text{ GeV}$   
*(c.f. pions) gives*  $t \sim 5 \times 10^{-4} \text{ GeV}^2$

*$\sim$  minimum for TOTEM, at low luminosity.*

- *If the CMS central detector is operational it should be straightforward to look for  $W$  &  $Z$  pairs in the central detector.*
- *Close to threshold minimizes “close together” decay problems.*
- *If x-sections are really large, could there be spectacular events in which protons are tagged and only (a multitude of) large  $E_T$  leptons are seen in the central detector ?*

## A large double $\mathbb{P}$ $W$ & $Z$ pair x-section

$\Rightarrow$  longitudinal components have direct strong interactions.

$\Rightarrow$  existence of the sextet sector and the sextet higgs mechanism.

This x-section can be looked for as soon as the LHC turns on.

$\Rightarrow$  best signature for the sextet sector !!!

*If we consider  $N_6$ 's and (to be well above threshold) set  $M = 1 \text{ TeV}$  we obtain  $t \sim 2 \times 10^{-2} \text{ GeV}^2$  which is detectable, if the x-section is large enough. Another spectacular process !*

- *Tagged protons determine a very massive state was produced.*
- *No charged particles seen in any of the detectors.*
- *Charged lepton comparison allows separation wrt neutrinos.*
- *If the x-section is too small for low luminosity, could the high luminosity “double  $\mathbb{P}$  higgs detectors” see it ??*