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Double Pomeron Physics at the LHC

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Abstract. I discuss central exclusive production, also known as Double Pomeron Exchange, $DI\!PE$, from the ISR through the Tevatron to the LHC. There I emphasize the interest of exclusive Higgs and W^+W^-/ZZ production.

INTRODUCTION

In 1973, shortly after the CERN Intersecting Storage Rings (ISR) provided the first colliding hadron beams, “high mass" diffraction was discovered by the CERN- Holland-Lancaster- Manchester collaboration [1]. In this context “high mass" meant $\approx$ 10 GeV, much larger than the $\approx$ 2 GeV diffractive states seen hitherto. Then Shankar [2] and D.Chew and G.Chew [3] predicted in the framework of Triple-Regge theory double pomeron exchange, $DI\!PE$,where both beam hadrons are coherently scattered and a central hadronic system is produced. Later experiments, in particular at the Split Field Magnet [4] and the Axial Field Spectrometer (AFS) [5] discovered the processes: $I\!P\,I\!P \rightarrow \pi^+\pi^-, K^+K^-, p\bar{p}, 4\pi$ at $\sqrt{s}$ up to 63 GeV. In the case of the AFS we added very forward proton detectors to the large central high-p_T detector, motivated largely by a search for glueballs. Structures were indeed found in the $\pi^+\pi^-$ mass spectrum, not all understood and not, unfortunately, studied at higher $\sqrt{s}$. The absence of a ρ signal verified that $DI\!PE$ is indeed dominant at this energy, but not at lower (SPS) energies. Measuring the (coherently scattered) forward protons allowed a partial wave analysis to select $J = 0, 2$ central states.

Now we want to do a similar experiment on a much grander scale, adding very small forward proton detectors to the large central high-p_T detectors: CMS and ATLAS. At $\sqrt{s}$ = 14,000 GeV rather than 63 GeV we will be measuring W^+W^- and ZZ rather than $\pi^+\pi^-$ and looking for Higgs bosons or other phenomena (perhaps even more interesting, such as anomalous EWK-QCD couplings). What will the $M(W^+W^-), M(ZZ)$ spectra look like? As at the ISR, measurements of the (coherently scattered) forward protons will enable one to determine the quantum numbers of the central states, picking out the S-wave (scalars), D-wave (spin 2), etc. This is very powerful; even if, for example, a Higgs boson is discovered another way it may take central exclusive production to prove that it is a scalar. There will be forward roman pots around CMS at 220m for the TOTEM experiment to measure (in special runs) $\sigma_{TOT}, \frac{d\sigma}{dt}$ and other diffractive processes. To study central masses below 200 GeV (the favored Higgs region) in normal high luminosity low-β running we need to measure protons even farther from the

collision point, at 420m. Physicists from ATLAS, CMS and TOTEM have joined forces on an R&D project called FP420 to develop common technical solutions; we hope both large detectors will have this proton tagging capability.

In symmetric colliding beams the beam rapidity $y_{BEAM} = ln\frac{\sqrt{s}}{M_p}$, and a central produced state of mass M_{CEN} spans approximately $\Delta y_{CEN} = 2ln\frac{M_{CEN}}{M_0}; M_0 \approx 1$ GeV. Pomeron $I\!P$ exchanges begin to dominate (exceeding Reggeon exchanges) when a rapidity gap exceeds about 3 units, which is a good “rule-of-thumb", although 4 units is safer. Requiring two gaps of > 3 units, the maximum central mass follows from the above as simply $M_{CEN}(max) \approx \frac{\sqrt{s}}{20}$, which gives nominal limits of 3 GeV at the ISR (less at the SPS fixed target, which is therefore very marginal), 100 GeV at the Tevatron and 700 GeV at the LHC. The central exclusive mass spectra did indeed extend to $\approx$ 3 GeV at the ISR [5], and the Tevatron experiment CDF finds [6] $DI\!PE$ di-jets with masses up to $\approx$ 100 GeV. The Tevatron would be a perfect place for low mass $DI\!PE$ spectroscopy (glueballs, hybrids, odderon search) but this has not yet been done. At the $Sp\bar{p}S$ collider, with $\sqrt{s}$ = 630 GeV, a few $DI\!PE$ studies were done. UA1 had no forward proton detection but studied [7] charged multiplicity $n^{\pm}$ and p_T distributions up to $M_{CEN} \approx 60$ GeV using rapidity gaps. UA8 had roman pots, but studied mostly single diffraction, with some low mass $DI\!PE$ [8]. At the Tevatron ($\sqrt{s}$ = 630, 1800, 1960 GeV) CDF has forward proton (FP) detection (roman pots) on the $\bar{p}$ side only, and uses the gap criterion on the p side. As well as jet physics, searches are underway for exclusive χ_c and exclusive central $\gamma\gamma$ without, unfortunately, detecting the protons. D0 in Run 1 had no FP detection but studied jets with gaps. In Run 2 they now have FP detection on both sides but have not presented $DI\!PE$ data yet.

The extension of the $DI\!PE$ mass range from $\approx$100 GeV at the Tevatron to $\approx$700 GeV at the LHC is exciting, as it takes us into the $W, Z, H, t\bar{t}$ domain.

CENTRAL EXCLUSIVE PRODUCTION AT THE LHC

The main channel for Higgs boson production at the LHC is gg-fusion. Another gluon exchange can cancel the color and can even leave the protons intact: $pp \to p + H + p$ where the $+$ denote large rapidity gaps and there are *no* other particles produced (i.e. it is *exclusive*). If the outgoing protons are well measured, the mass $M_{CEN} = M_H$ can be determined by the missing mass method [9] with $\sigma_M \approx 2$ GeV, and its quantum numbers can be determined. Theoretical uncertainties in the cross section involve skewed gluon distributions, gluon k_T, gluon radiation, Sudakov form factors, etc. Probably [10, 11] for a Standard Model (SM) Higgs, $\sigma_{SMH} \approx 0.2$ fb at the Tevatron, which is not detectable, but at the LHC $\sigma_{SMH} \approx 3$ fb (within a factor 2-3) and with the higher luminosity (30-100 fb^{-1}) there should be enough events to be valuable. Some of the uncertainties in the cross section can be addressed by measuring related processes at the Tevatron. The process $gg \to H$ proceeds through a top loop. The same diagram with instead a $b(c,u)$ loop can give exclusive $\chi_b(\chi_c, \gamma\gamma)$, which can therefore be used to “calibrate" the theory now at the Tevatron and then in the early days of the LHC. There are predictions [12, 10] for exclusive $pp \to p + \chi_c + p \approx 600$ nb at the Tevatron, $\approx$ 20/sec! In reality requiring

decay to a useful channel ($\chi_c \to J/\psi\gamma \to \mu^+\mu^-\gamma$), no other interaction (for cleanliness), trigger efficiency and acceptance reduces this to effectively a few pb (still, thousands of events in 1 fb^{-1}). Candidates have been seen (also candidates for exclusive J/ψ which may be from photoproduction ($\gamma I\!P$)). Exclusive χ_b may also be possible but is marginal; the cross section is 5000 times smaller. It will be valuable to measure this early at the LHC (with TOTEM+CMS at high β^*?). Unfortunately in CDF we cannot detect the associated protons, which would provide a quantum number filter, selecting mainly $I^G J^{PC} = 0^+0^{++}$; $J^P = 2^+$ is forbidden at t = 0 for a $q\bar{q}$ state. D0 *may*, but they have $|t_{min}| \approx 0.7$ GeV^2 which limits the statistics.

The process $pp \to p + H + p$ with $H \to b\bar{b}$ with no other activity (e.g. no gluon emission) would have two and only two central jets. We can also have $pp \to p + gg + p$ or $pp \to p + b\bar{b} + p$ which we call "exclusive dijets", although it is clear that both experimentally and theoretically that is not a well defined state (unlike exclusive χ_c or exclusive W^+W^- production). Nonetheless we look in CDF for signs of "exclusive dijets" which we can define, with some arbitrariness, as events where two central jets as defined by a jet algorithm (again, not unique) have $R_{jj} = \frac{M_{jj}}{M_{CEN}} > 0.8$. (The events selected have a forward $\bar{p}$ detected and a rapidity gap on the p-side.) There is no R_{jj} = 1 "exclusive" peak, and probably none is expected; there may be a broad high R_{jj} enhancement but with respect to what? CDF look to see if at $R_{jj} > 0.8$ there is a depletion of quark (specifically b) jets as expected [12]; we can also look at the g/q-jet ratio using internal jet features vs R_{jj}. At the LHC, one could get very large samples (early, with low luminosity, tagging the protons) of exclusive dijets with $M_{CEN} = M_{jj} \approx$ 100-200 GeV. These should be very pure gluon jets, which could be used to study QCD (think of the large samples of quark jets studied at LEP on the Z).

A difficult issue with exclusive SMH(120-130 GeV) is that the 420m p-detectors are too far away to be included in the 1st level trigger, L1, and the central jets from the H-decay are completely overwhelmed by QCD jet production. Putting forward rapidity gaps in the L1 trigger can be done but only works with single interactions/low luminosity. The total integrated luminosity if only single interactions can be used is expected to be $\approx$ 2-3 fb^{-1} which is not enough for a SM Higgs, although it might be for some MSSM scenarios which can have a much bigger (factor $\approx$ 50) cross section. [J.Ellis, J.Lee and A.Pilaftsis discussed [13] diffractive production of MSSM Higgs at the LHC.] A solution might be to have a L1 trigger based on a 220m pot track and 2 jets with specific kinematics, such as 100 GeV $< M_{jj} <$150 GeV, small $\sum \vec{E_T}$ (the forward protons will have $\sum \vec{p_T} <\approx$ 2 GeV and the jets balance that), and with the jets in the same rapidity hemisphere as the 220m proton. Better, for the desired process $pp \to p + J_1 J_2 + p$ there is a relation between the rapidities of the jets y_1, y_2 and the momentum loss fractions ξ_1, ξ_2 of the forward protons: $\xi_{1(2)} = \frac{E_T}{\sqrt{s}}[e^{-(+)y_1} + e^{-(+)y_2}]$. If a (even a few-bit) measurement of ξ from the 220m pot track can be combined with the jets' (E_T, η, ϕ) at L1 it should help, but the technical feasibility (and value) remains to be studied. The 420m detectors can be included at L2. If the Higgs boson mass is 140 - 200 GeV W^+W^- and eventually ZZ decays come in, and can provide L1 triggers, so the forward detectors can be part of L2. They can again be of great value for quantum number determinations and for a good mass measurement ($\sigma(M_H)$ = 2 GeV *per event*) even in the mode $W^+W^- \to l^+\nu l^-\bar{\nu}$. These events are clean even with pile-up, as the

l^+l^- vertex has no other particles (the distribution of $n^\pm$ on the l^+l^- vertex will be broad but with a peak at 0). Two photon processes $\gamma\gamma \to W^+W^-$ give a continuum background for WW (not for ZZ) and the $|t|$ of the protons is smaller which helps the rejection.

PROMPT VECTOR BOSON PAIR PRODUCTION

By “prompt" I mean not from $t\bar{t}$ (a most prolific source) and not from Higgs, and by “vector boson" V I mean γ, W, Z. There are several production mechanisms. Approximately 90% of prompt W^+W^- are from $q\bar{q}$ annihilation with t-channel q exchange. This can produce any $Q = 0, 1$ pair. $q\bar{q}$ annihilation with an s-channel V can produce only $\gamma W, WW$ and WZ; it is important as a probe of the VVV vertex. Virtual V emission from quarks, rescattering to a real pair (any pair, even W^+W^+) is negligible at the Tevatron, but is $\approx$ 10% at the LHC (WW-scattering with a possible Higgs pole, something else, or unitarity violation!). Two photon production $\gamma\gamma \to W^+W^-$ is about 100 fb at the LHC, is well known and has the characteristic feature of very small t_1, t_2 for the protons. *DIPE* production of W-pairs has not been calculated, but whether inclusive or exclusive it should be very small in the SM. I address later the possibility of this being dramatically wrong. Note that in these various processes for VV production there are different color flows (color triplet annihilation, color singlet exchange, high p_T forward jets, low-p_T protons) which can give different hadronic activity. For single interactions that might be of interest.

At the Tevatron the (non-diffractive) cross sections agree with CTEQ NLO which predict: $\sigma(WW)$ = 12.4 pb, $\sigma(WZ)$ = 3.65 pb and $\sigma(ZZ)$ = 1.39 pb (the latter has not yet been measured). At the LHC the cross sections should be $\approx 10\times$ higher. At the Tevatron we found the following “rules-of-thumb" for diffractive production of hard final states (jets, W): about 1% (within a factor 2) are produced by single diffraction, and about 10^{-3} are produced by *DIPE* . This would imply 120 fb for SDE $\to W^+W^-$ and 12(1) fb for *DIPE* $\to WW(ZZ)$ (+ anything).

The WW decay mode of the SM Higgs rises through 10% at 120 GeV, through 50% at 140 GeV and is about 98% above 160 GeV. Let us consider three WW event classes at the LHC. In all cases consider only the $e\nu$ and $\mu\nu$ decay modes, which unfortunately gives a factor (4×0.106^2) = 0.045 (later we will relax this). The *DIPE* $WW \to l^+l'^-\nu\bar{\nu} + X$ cross section is $\approx$ 0.5 fb, small but perhaps not impossible to see; in any case this might be considered a background to the following more interesting signals. Exclusive W^+W^- with the two forward protons and nothing else can come from exclusive Higgs production or from $\gamma\gamma$ collisions. The former is predicted to be, for a 170 GeV Higgs, $\approx$ 3 fb $\times$ 0.045 (BR) $\approx$ 0.13 fb. The latter is larger, $\approx$ 100 fb $\times$ 0.045 = 4.5 fb. *However* (a) the $\gamma\gamma$ data is a mass continuum while the Higgs events are localised with the missing mass method in a $\approx$ 4 GeV bin (b) the t_1 and t_2 of the protons is more peaked at low values in the $\gamma\gamma$ case. For both classes of exclusive events, with the $pWWp$ missing mass method one can probably use also the $\tau\nu$ decay mode and even the dominant $W \to q\bar{q}$ decay mode for one of the W's. Note that there are potentially useful missing mass games one can play, e.g. in $p_1p_2 \to p_3 + WW + p_4 \to p_3 + l^\pm\nu j_1 j_2 + p_4$ the missing mass squared: $MM^2 = (p_1 + p_2 - p_3 - p_4 - p_e - p_{j_1} - p_{j_2})^2 = M_\nu^2 = 0$. Ability to use

$W \to q\bar{q}$ modes for one W would increase the statistics by a factor 7.4 over $e\nu, \mu\nu$ only. In $H \to ZZ \to \mu^+\mu^-\nu\bar{\nu}$ the invisible missing mass from $MM^2 = (p_1 + p_2 - p_3 - p_4 - p_{\mu_1} - p_{\mu_2})^2 = M_Z^2$ should help distinguish this from the $WW \to \mu^+\mu^-\nu\bar{\nu}$ state (of course we also have $(p_{\mu_1} + p_{\mu_2})^2 = M_Z^2$), as well as measuring $M(ZZ)$.

We cannot expect to see $DI\!PE \to W^+W^-$ at the Tevatron, but it may still be very interesting to study the associated hadronic activity in VV and also single V events. CDF and D0 each have around 20 $WW/WZ/ZZ$ events in Run 2 based on the first 0.2 fb^{-1}, with a factor ≈25 more to come. Counting associated hadrons in the CDF events we find a very large spread, with $n^{\pm}_{ass}$ in $p_T > 400$ MeV/c, $|\eta| < 1.0$ ranging from 0 to 34! More statistics and more studies are needed to say if there is anything anomalous, and the "super-clean" event cannot be called diffractive, but it is likely that the high $n^{\pm}_{ass}$ event was a small impact parameter collision and the super-clean event had large impact parameter *and yet produced a W-pair*.

DIFFERENT POMERONS

To 0th order soft (low $|t|$, low Q^2) diffractive interactions are due to a pair of gluons in a color singlet ... a classical Low-Nussinov soft pomeron. There can be a small (ggg) component which becomes relatively more important at larger $|t|$. These exchanges are equivalent to a sum over towers of virtual glueballs. As Q^2 increases, $q\bar{q}$ evolve in. Reggeons are predominantly towers of virtual $q\bar{q}$ mesons, summed over spins. There has been an ambitious attempt to calculate the pomeron in QCD as a "reggeized gluon ladder" ... the BFKL pomeron. It is known that the exchange of a single gluon between quark lines, the leading order qq-scattering QCD diagram, is 'sick"; it is not gauge invariant. A summing procedure over diagrams can result in a gauge invariant exchange, the "reggeized gluon". In the BFKL pomeron two reggeized gluons cancel each other's color. This "pomeron exchange between quarks" diagram enhances jet production in the forward direction (low $|t|$, high s). In the "White pomeron" [14] the color of the reggeized gluon is cancelled instead by an infinite number of wee gluons (they have no momentum even in the infinite momentum frame). The wee gluons have the properties of the vacuum; in a sense they *are* the vacuum. In White's theory asymptotic freedom requires a pair of very heavy color sextet quarks, which couple strongly to the pomeron *and* to the W and Z once the energy is high enough. Consequently at the LHC diffractive W, Z production should be prolific, including $pp \to p + WW/ZZ + p$ exclusive states.There should also be an *effective* $\gamma Z\,I\!P$ coupling through color sextet quark loops, and hence photoproduction of single Z seen as $pp \to p + Z + p$, which would be another surprise (effectively an anomalous EWK-QCD coupling).

FP420

The potentially rich physics program at the LHC with $DI\!PE$, especially with central states $WW, ZZ, H, jj, t\bar{t}, X$, needs the big central detectors CMS and ATLAS together with very forward proton detection and precision measurement. This can be partially

provided by the TOTEM detectors with CMS, but it is necessary to supplement them with detectors at 420m. At this place the relevant protons have been deflected out of the beam by $\approx$ 3-25 mm where they can be detected in small precision pixel tracking detectors. An international consortium of CMS, TOTEM and ATLAS physicists has been formed to develop this proposal, and a LOI for support for R&D will be sent to the LHCC in June.

The proposed precise very forward proton detectors may have a side benefit of calibrating the energy scale of the hadronic calorimetry. (At the Tevatron this gives the largest uncertainty in e.g. the top quark mass.) During a special run at low luminosity with less than one interaction per crossing, trigger on events with two forward protons and nothing else beyond (say) η = 4.0 ($\theta = 2^\circ$). The total central mass (e.g. $\approx$ 200 GeV) is contained in the main CMS/ATLAS detctors and is known to $\approx$ 1%. The electromagnetic calorimetry should already be well calibrated with $Z \to e^+e^-$, so this calibrates the hadronic energy scale, for jet or non-jet events. This should be competitive with other approaches (γ-jet balancing and $W \to$ jet+jet in top events).

CLOSING REMARKS

There are many other related talks at this meeting (e.g. Cox, Eggert, Klein, Kowalski, Piotrzowski, Royon, ...) demonstrating the interest in the field. This is sure to be a very exciting field at the LHC, *whether or not the Higgs boson is in reach*. It it exists and we see it, central exclusive production will be important for measurements of the mass, quantum numbers, couplings and other properties. If it does not exist, exotic new physics may manifest itself through this process. We will have come a long way from $pp \to p + \pi^+\pi^- + p$ at $\sqrt{s} = 63$ GeV to $pp \to p + W^+W^- + p$ at $\sqrt{s}$ = 14,000 GeV!

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