POMERON INDUCED PHYSICS AT LHC ENERGIES AND ABOVE

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Dedicated to the memory of Alyosha Kaidalov

The present vigorous studies of the Pomeron and its dynamics are based on sophisticated utilization of old theoretical ideas and models:

- **Reggeon Field Theory, Gribov(1968).**
- **Eikonal Model, Glauber(1959).**
- **Proton Wave Function Decomposition, Good and Walker(1964).**
- **Triple Pomeron Formalism, Mueller(1971).**
- **Multi Pomeron Interactions, Kaidalov et al.(1986).**

Updated Pomeron models have a few components:

- **A bare non screened Pomeron exchange amplitude.**
- **s-channel unitarity is enforced by eikonal re-scatterings of the incoming projectiles.**
- **These re-scatterings go through elastic and "low mass" diffraction implied by the GW mechanism.**
- **t-channel unitarity is maintained through multi $I\!\!P$ interactions leading to "high mass" diffraction and re-normalization of the Pomeron.**

GLMM, KMR07/08, LKMR and Ostapchenko (OS) models are based on the same principles, but utilize different modelings, parametrization data bases and analyses.

I shall summarize the GLMM Pomeron model, and its predictions. Compare it with KMR07/08 and comment on LKMR and OS, emphasising the interplay between data analysis and $I\!\!P$ theory.

GOOD-WALKER EIKONAL MODELS

Consider a system of two orthonormal states, a hadron Ψ_h and a diffractive state Ψ_D. The GW mechanism stems from the observation that these states do not diagonalize the 2x2 interaction matrix T. Assume that T is diagonalized by Ψ_1 and Ψ_2. We get,

$\Psi_h = \alpha\,\Psi_1 + \beta\,\Psi_2, \quad \Psi_D = -\beta\,\Psi_1 + \alpha\,\Psi_2, \quad \alpha^2 + \beta^2 = 1.$

The 4 elastic GW amplitudes are

$$A_{i,k}^{i',k'} = <\Psi_i\,\Psi_k|\mathbf{T}|\Psi_{i'}\,\Psi_{k'}>= A_{i,k}^s\,\delta_{i,i'}\,\delta_{k,k'}.$$

For initial $p(\bar{p})-p$ we have $A_{1,2}^s = A_{2,1}^s$.

The (i,k) s-channel unitarity equation is

$$Im\, A^s_{i,k}\,(s,b) = |A^s_{i,k}\,(s,b)\,|^2 + G^{in}_{i,k}(s,b).$$

$G^{in}_{i,k}$ **is the summed probability for all non GW inelastic processes induced by an initial (i,k) state. A general solution is written as**

$$A^s_{i,k}(s,b) = i\left(1 - \exp\left(-\frac{\Omega^s_{i,k}(s,b)}{2}\right)\right),$$

$$G^{in}_{i,k}(s,b) = 1 - \exp\left(-\Omega^s_{i,k}(s,b)\right).$$

The b space opacities,

$$\Omega^s_{i,k}\,(s,b) = \nu^s_{i,k}\,(s)\;\Gamma^s_{i,k}\,(s,b,...)\,,$$

are arbitrary.

In the eikonal approximation $\Omega^s_{i,k}$ are assumed to be real and are determined by the Born (non screened) input. Note that, $P^s_{i,k}(s,b) = \exp\left(-\Omega^s_{i,k}(s,b)\right)$ is the probability that the initial (i,k) projectiles reach the final diffractive interaction unchanged.

The elastic SD and DD amplitudes are

$$a_{el}(s,b) = i\{\alpha^4 A^s_{1,1} + 2\alpha^2\beta^2 A^s_{1,2} + \beta^4 \mathcal{A}^s_{2,2}\},$$

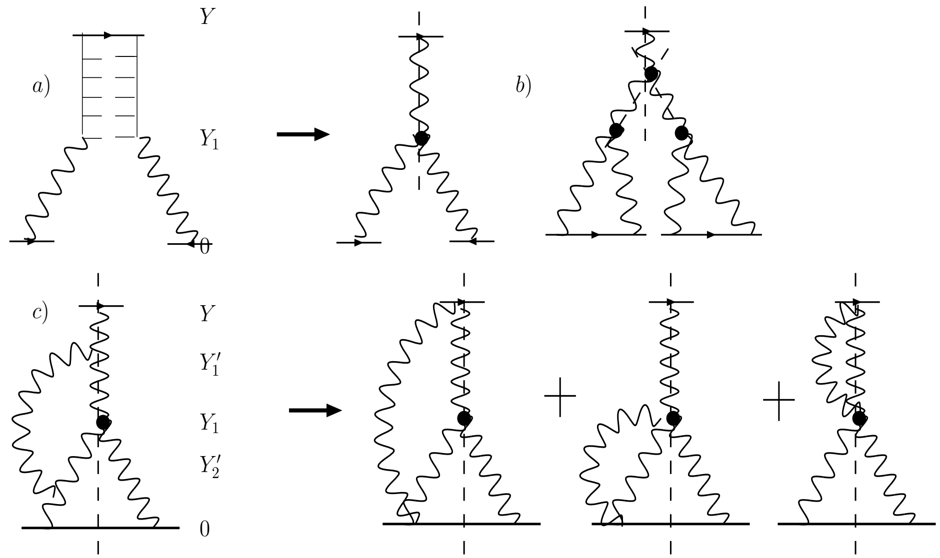
$$a_{sd}(s,b) = i\alpha\beta\{-\alpha^2 A^s_{1,1} + (\alpha^2 - \beta^2) A^S_{1,2} + \beta^2 A^s_{2,2}\},$$

$$a_{dd} = i\alpha^2\beta^2\{A^s_{1,1} - 2A^s_{1,2} + A^s_{2,2}\}.$$

The quoted eikonal models are multi channel in which the initial re-scatterings of the incoming projectiles are summed over the GW eigen states.
To this end we need a parametrization of $\Omega^s_{i,k}$. In GLMM $\nu^s_{i,k}(s) = g_i g_k (\frac{s}{s_0})^{\Delta_{I\!P}}$. $\Gamma^s_{i,k}$ are given as the b-transforms of two t-poles expressions $(t = -q^2)$, to which we add an explicit $\alpha'_{I\!P}$ dependence. The other models use different parametrizations which are numerically compatible with GLMM. All models reproduce $d\sigma_{el}/dt$ $(t \leq 0.5 GeV^2)$ in the ISR-Tevatron range.

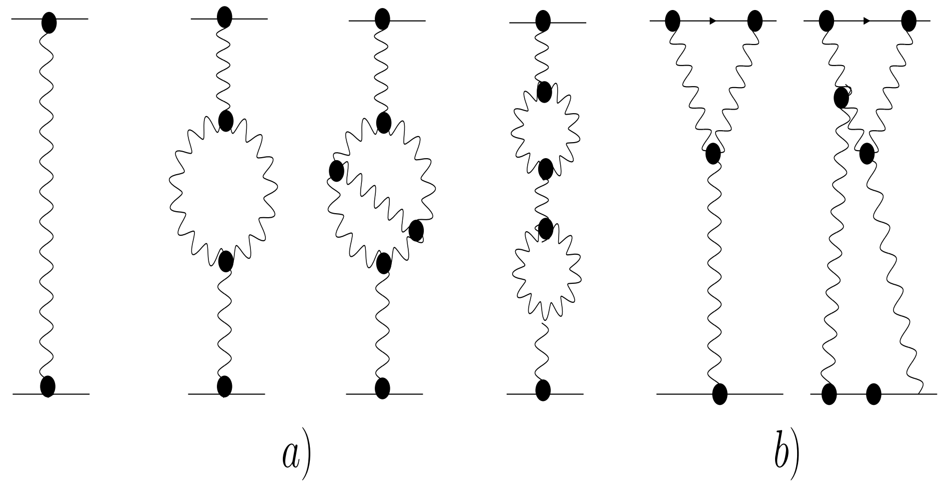
MULTI POMERON INTERACTIONS

Muller's $3I\!P$ approximation for "high mass" single diffraction is the lowest order of a very large family of multi Pomeron interactions (enhanced $I\!P$) which are not included in the GW mechanism. This dynamical feature is compatible with t-chaanel unitarity. It initiates additional screening resulting in additional reduction of the calculated soft cross sections and gap survival probabilities. Note, though, that these features become significant well above the Tevatron energy!



The figure shows examples of multi $I\!\!P$ interactions. The complexity of these diagrams requires summing algorithms which are model dependent.

The models I consider differ in their choice of summed diagrams.



The figure shows the low order $I\!\!P$ Green's function.

a) Enhanced diagrams which renormalize (in low order) the $I\!\!P$ propagator.

b) Semi-enhanced diagrams which renormalize (in low order) the $I\!\!P$-p vertexes.

1) DIAGRAM SUMMATION:

A key observation of the $I\!\!P$ models considered is that $\alpha'_{I\!\!P}$ smallness, be it fitted tuned or assumed, implies that the soft $I\!\!P$ has hard characteristics. As we shall see, reproducing the diffractive sector with a very small $\alpha'_{I\!\!P}$ implies a compensating large $\Delta_{I\!\!P}$.

- **GLMM is based on pQCD. It take into account only the enhanced diagrams. Since the SD lowest order diagram is semi enhanced, GLMM add, term by term, the relevant semi enhanced diagrams.**

- **KMR07/08 are motivated by a partonic interpretation. Only semi enhanced diagrams are considered.**
- **LKMR confine their calculations to the low order $3I\!\!P$ Mueller diagram and neglect higher orders.**
- **OS takes into account enhanced, semi enhanced and net diagrams. This model is significantly different from the previos listed models, as it is based on two Pomerons, soft and hard.**

2) MULTI $I\!P$ COUPLINGS:

- **KMR07/08** point coupling of $nI\!P \to mI\!P$ $(n+m>2)$ is $g_m^n = \frac{1}{2} g_N \, nm \, \lambda^{n+m-2} = \frac{1}{2} nm \, G_{3I\!P} \, \lambda^{n+m-3}$. λ is a free parameter and $G_{3I\!P} = \lambda g_N$. **Kaidalov et al.** have the same coupling with a different normalization.

- **GLMM** utilize the **pQCD MPSI procedure,** where $nI\!P \to mI\!P$ reduces to **a sequence of** $G_{3I\!P}$ **vertexes** (Fan diagrams).

	$1.8 \to 7.0$	$7.0 \to 14.0$	$14.0 \to 30.0$	$30.0 \to 60.0$	$60.0 \to 100.0$
$\Delta_{eff}(GLMM)$	0.059	0.049	0.043	0.040	0.037

3) POMERON RENORMALIZATION:

- $I\!P$ enhancement initiates a renormalization of the $I\!P$, in which $\Delta_{I\!P}^{eff}$ reduces with energy. This feature is common to GLMM, KMR07/08 and OS.
- The decrease of $\Delta_{I\!P}^{eff}$ raises the question if it may become eventually negative. In GLMM we have checked that $\Delta_{I\!P}^{eff} > 0$ up to $W = 100\,TeV$, which is the bound of validity of GLMM and KMR07/08.

4) POMERON PARAMETERS:

- **GLMM:** $\alpha_{I\!P} = 1 + 0.335 + 0.01t$.
- **KMR07:** $\alpha_{I\!P} = 1 + 0.55$.
- **KMR08:** $\Delta_{I\!P} = 0.3$ **and** $\alpha'_{I\!P} \propto 1/k_t^2$ **is approximated by 3 effective BFKL like trajectories with different** $\alpha'_{I\!P}$ **values.**
- **LKMR:** $\alpha_{I\!P} = 1 + 0.121 + 0.033t$.
- **OS:** $\alpha^s_{I\!P} = 1 + 0.14 + 0.14t, \quad \alpha^h_{I\!P} = 1 + 0.31 + 0.085t.$
  This is a dynamically different model with two Pomerons, soft and hard.

5) GLMM POMERON MODEL FEATURES:

- **GLMM have a single $I\!\!P$.**
- **The fitted $I\!\!P$ parameters are remarkably close to the BFKL $I\!\!P$ after NLL corrections are summed.**
- **The $I\!\!P$ parameters are in accord with Zeus and H1 fits to HERA DIS data.**
- **The fitted $\alpha'_{I\!\!P} \to 0$ is a necessary condition to connect the npQCD soft interactions with hard pQCD.**
- **Recall that, $\alpha'_{I\!\!P}(BFKL)$ relates to the saturation scale $\alpha'_{I\!\!P} \propto 1/Q_s^2 \to 0, \;\; as \; s \to \infty$.**

DATA ANALYSIS

There is a significant difference between the data analyses carried out by GLMM and KMR07/08. LKMR, which is a much simpler model, follows KMR07/08 methodology and is easier to decipher. The difference is reflected in the choices of data bases made by the groups and their procedure for adjusting their free parameters.

In my opinion, these choices determine, to a considerable extent, the models final dynamics.

1.8 TeV	GLMM	KMR07	KMR08	OS(C)	CDF	E710
$\sigma_{tot}(mb)$	73.3	74.0	73.7	73.0	80.03	71.71
$\sigma_{el}(mb)$	16.3	16.3	16.4	16.8	19.70	15.79
$\sigma_{sd}(mb)$	9.8	10.9	13.8	9.6	9.12	8.46
$\sigma_{dd}(mb)$	5.4	7.2		3.93	4.43	

1) FROM THE TEVATRON TO LHC AND ABOVE:

- **$I\!\!P$ enhancement voids the reliability of conventional extrapolations from the Tevatron to LHC and above. The table shows compatibility between the results of four $I\!\!P$ models and E710 data at** $W = 1.8\,TeV$,**.**

14 TeV	GLMM	KMR07	KMR08	OS(C)	Pythia	Phojet
$\sigma_{tot}(mb)$	92.1	88.0	91.7	114.0	101.5	119.1
$\sigma_{el}(mb)$	20.9	20.1	21.5	33.0	22.5	34.5
$\sigma_{sd}(mb)$	11.8	13.3	19.0	11.0	13.3	10.8
$\sigma_{dd}(mb)$	6.1	13.4		4.83		

- **Models which were mutually compatible at $W = 1.8\,TeV$ are non compatible at $W = 14\,TeV$. KMR08 neglects to present its σ_{dd} estimates.**

100 TeV	GLMM	KMR07	KMR08
$\sigma_{tot}(mb)$	108.0	98.0	108.0
$\sigma_{el}(mb)$	24.0	22.9	26.2
$\sigma_{sd}(mb)$	14.4	15.7	24.2
$\sigma_{dd}(mb)$	6.3	17.3	

- **The difference between GLMM and KMR07/08 high energy diffractive cross sections is traced to their different modellings of the $I\!P$ interactions sector. This supposition is supported by a comparison of GLMM and KMR07/08 gap survival factors.**

	$1.8\,TeV$			$14\,TeV$			$100\,TeV$		
	GLMM	**KMR07**	**KMR08**	**GLMM**	**KMR07**	**KMR08**	**GLMM**	**KMR07**	**KMR08**
$S^2_{2ch}(\%)$	**5.3**	**2.7-4.8**		**3.9**	**1.2-3.2**	**4.5**	**3.2**	**0.9-2.5**	
$S^2_{enh}(\%)$	**28.5**	**100**		**6.3**	**100**	**33.3**	**3.3**	**100**	
$S^2(\%)$	**1.51**	**2.7-4.8**		**0.24**	**1.2-3.2**	**1.5**	**0.11**	**0.9-2.5**	

2) SURVIVAL PROBABILITIES:

Denote the gap suvival factor initiated by s-channel eikonalization S^2_{2ch}, and the one initiated by t-channel multi $I\!P$ interactions S^2_{enh}. $S^2 = S^2_{2ch} \cdot S^2_{enh}$**.**

- **GLMM and KMR07/08 S^2_{2ch} outputs are compatible.**

	$1.8\,TeV$			$14\,TeV$			$100\,TeV$		
	GLMM	**KMR07**	**KMR08**	**GLMM**	**KMR07**	**KMR08**	**GLMM**	**KMR07**	**KMR08**
$S^2_{2ch}(\%)$	**5.3**	**2.7-4.8**		**3.9**	**1.2-3.2**	**4.5**	**3.2**	**0.9-2.5**	
$S^2_{enh}(\%)$	**28.5**	**100**		**6.3**	**100**	**33.3**	**3.3**	**100**	
$S^2(\%)$	**1.51**	**2.7-4.8**		**0.24**	**1.2-3.2**	**1.5**	**0.11**	**0.9-2.5**	

- $S^2_{enh}(GLMM)$ **is smaller and reduces faster than** $S^2_{enh}(KMR07)$ **and** $S^2_{enh}(KMR08)$**.**
  This is compatible with the enhanced $I\!P$ screening increasing faster than the semi enhanced.

3) DATA BASES:

- **The data base of GLMM contains diversified data points, so as to simultaneously investigate all the input elements of the model. The fitted 55 data points include** $\sigma_{tot}, \sigma_{el}, \sigma_{sd}, \sigma_{dd}\, and\, B_{el}$ **in the ISR-Tevatron energy range. The "cost" is that we have to include, also, secondary trajectories. We have added a consistency check of** B_{sd}**, CDF** $d\sigma_{el}/dt(t \leq 0.5\, GeV^2)$ **and** $d\sigma_{sd}/dtd(M^2/s)$ **at** $t = 0.05\, GeV^2$**.**

- **The approach of KMR07/08 and LKMR is different. Their data base contains just the measured values of $d\sigma_{el}/dt$, σ_{tot} and $d\sigma_{sd}/dtd(M^2/s)$.**

  In my opinion, this data base is too limited to substantiate a parameter rich model. This may explain the procedures they have adopted in their data analysis. $\alpha'_{I\!P} = 0$ is assumed in KMR07, and tuned in KMR08. $\Delta_{I\!P}$ is tuned in KMR07/08.

4) ADJUSTMENT PROCEDURES:

- **KMR07/08, and LKMR chose to adjust their parameters through a two step procedure. In the first step they determine the GW eikonal model parameters reproducing the GW sector of their data base. These parameters are frozen through the second step, in which they fix the $I\!P$ enhancement parametrs by adjusting the diffractive sector of their data base.**

  Recall that GLMM and KMR07/08 data base sets are not identical.

	$\Delta_{I\!P}$	β	$\alpha'_{I\!P}$ GeV^{-2}	g_1 GeV^{-1}	g_2 GeV^{-1}	m_1 GeV	m_2 GeV	$\chi^2/d.o.f.$
GW	**0.120**	**0.46**	**0.012**	**1.27**	**3.33**	**0.913**	**0.98**	**0.87**
GW+$I\!P_enh.$	**0.335**	**0.34**	**0.010**	**5.82**	**239.6**	**1.54**	**3.06**	**1.00**

- **The table compares the output of GLLM fits as applied in one or two strokes. GW denotes a GW eikonal applied to the elastic sector only. GW+**$I\!P_{enh}$ **denotes the output of a single stroke fit to the complete data base.**

- **A fit with a GW eikonal (no $I\!\!P_{enh}$), provides an excellent reproduction of the elastic sector. The reproduction of the diffractive sector is poor.**

- **A repeated fit with GW+$I\!\!P_{enh}$ results with a very good overall reproduction.**

- **The value of $\alpha'_{I\!\!P}$ is stable, reflecting that $\Gamma^s_{i,k}$ are determined by a fit of $d\sigma_{el}/dt$. Its model dependence is weak.**

- **$\Delta_{I\!\!P}$ obtained in GW+$I\!\!P_{enh}$ is much larger than in GW, so as to compensate the extra screening.**

- **Note that the values of $\Delta_{I\!P}$ and $\alpha'_{I\!P}$ obtained in GW are compatible with LKMR.**
- **An important observation is that $g_1\, and\, g_2$ are of the same order in the GW fit. A GW+$I\!P_{enh}$ fit results in a completely different $g_2 >> g_1$ output.**
- **This large difference has an important dynamical consequence. Recall that,**

$$a_{el}(s,b) = i\{\alpha^4 A^s_{1,1} + 2\alpha^2\beta^2 A^s_{1,2} + \beta^4 \mathcal{A}^s_{2,2}\}.$$

$a_{el}(s,b)$ **reaches unity when, and only when,** $A^s_{1,1}(s,b) = A^s_{1,2}(s,b) = A^s_{2,2}(s,b) = 1$.

When $a_{el}(s,b) = 1$**,** $a_{sd}(s,b) = a_{dd}(s,b) = 0$**.**

- **In GLMM, the 3 basic** $A^s_{i,k}$ **amplitudes reach the black disc bound at different energies, as** $g_2 >> g_1$**. GLMM predicts a very slow approach of** $a_{el}(s,b=0)$ **toward the black disc bound, reaching it well above the LHC energy.**

- **KMR07/08, LKMR, OS assume that** $g_2 \simeq g_1$**,. They predict, therefor, that** $a_{el}(s,b=0)$ **reaches blackness just above the LHC.**

CONCLUDING REMARKS

- Introducing multi Pomeron interactions, in addition to the conventional GW mechanism, secures both s and t channel unitarity and reproduce the data well.

- Updated $I\!P$ models predict a renormalization of the $I\!P$. It results in a reduction of soft cross sections relative to conventional extrapolations. This phenomenon becomes significant as of a few TeV. If correct, LHC simulations need to be revised!

- **Updated Pomeron poles have a diminishing $\alpha'_{\mathbb{P}}$ and a high $\Delta_{\mathbb{P}}$, simulating a NLL BFKL branch cut. It is tempting to connect the soft and hard $\mathbb{P}$ using this phenomenology. This issue is still in its infancy.**

- **Diffraction is not well defined. Experimentally, an agreed algorithm to define diffraction is missing. Theoretically, the distinction between "low" and "high" mass diffraction is model dependent.**

- **Model builders, be careful with your procedures.**

	0.9 TeV	7 TeV	10 TeV	14 TeV
σ_{tot} (mb)	66.6	86.0	89.2	92.1
σ_{el} (mb)	14.5	19.5	20.3	20.9
σ_{sd} (mb)	8.83	10.7	11.1	11.8
σ_{dd} (mb)	4.71	5.9	6.0	6.1