Froissaron-Maximal Odderon approach and evidence for Odderon in TOTEM experiment

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Outline

Froissaron and Maximal Odderon are the model realization of

maximality principle for the strong interaction

The strong interactions at high energies are as strong as the main assumptions of theory (*S-matrix theory: unitarity, analyticity, crossing symmetry, ...*) and asymptotic theorems allow them to be. (G. Chew (1962) for simple Regge poles)

The cross sections at high energies should saturate the asymptotic bounds in their functional form.

Froissaron realises principle of maximality for the total hadron cross-sections. It was in 70-s, ISR experiments had confirmed the fast growth of total cross sections.

Maximal Odderon realises the idea of maximal growth of the difference particle-particle and antipartice-partice cross sections. No experimental evidences for rising $\Delta\sigma_t$. It was just a pure speculative idea! The first hint at difference in pp and $\bar{p}p$ differential cross sections in the dip region has been found later, in 1980.

The main asymptotic ($s \to \infty$ or $s \gg m^2$) theorems

- Froissart-Martin-Łukaszuk bound:

$$\sigma_t(s) \le \frac{\pi}{4m_\pi^2} \ln^2(s/s_0)$$

- Pomeranchuk theorems:

$$1.) \quad \sigma_t(s) \to \text{const} \quad \Rightarrow \quad |\sigma_t^{ab} - \sigma_t^{\bar{a}b}| \to 0$$

$$2.) \quad \sigma_t(s) \to \infty \quad \Rightarrow \quad \sigma_t^{ab}/\sigma_t^{\bar{a}b} \to 1$$

- Difference of ab and $\bar{a}b$ total cross sections:

$$\sigma_{\bar{a}b}^{ab}(s) \sim C \ln^\alpha(s/s_0) \pm D \ln^\beta(s/s_0), \quad \alpha \le 1, \quad \text{then} \quad \beta \le \alpha/2$$

$$\text{or} \quad |\Delta\sigma| \le 2D \ln^{\alpha/2}(s/s_0)$$

In FMO model: $\sigma_t(s) \propto \ln^2(s/s_0)$, $\quad |\Delta\sigma_t(s)| \propto \ln(s/s_0)$

- AKM theorem: at low $|t| \lesssim C/\ln^2(s/s_0)$

$$A(s,t) = s\ln^2(-is/s_0) f(\tau), \quad \tau = R\ln(-is/s_0)\sqrt{-t}$$

- Amplitudes satisfy the dispersion relations.
  Definitions for $\binom{pp\to pp}{\bar{p}p\to\bar{p}p}$:

$$F^{pp}_{\bar{p}p}(z_t,t) = F_+(z_t,t) \pm F_-(z_t,t), \quad z_t = 1 + \frac{2s}{t-4m^2},$$

$$F_\pm(-z_t,t) = \pm F_\pm(z_t,t)$$

Derivative form of the Dispersion Relations (DDR) at $s \gg 4m^2$

$$\mathrm{Re}[F_+(z_t,t)/s] = \left[\frac{\pi}{2}\frac{\partial}{\partial\xi} + \cdots\right]\mathrm{Im}[F_+(z_t,t)/s], \quad \xi = \ln(s/s_0)$$

FMO model: $\mathrm{Im}[F_+(z_t,0)/s] \propto \xi^2 \Rightarrow \mathrm{Re}[F_+(z_t,0)/s \propto \xi$

$$\frac{\pi}{2}\frac{\partial}{\partial\xi}\mathrm{Re}[F_-(z_t,t)/s] = -\left[1 - \frac{1}{3}\left(\frac{\pi}{2}\frac{\partial}{\partial\xi}\right)^2 + \cdots\right]\mathrm{Im}[F_-(z_t,t)/s]$$

FMO model: $\mathrm{Im}[F_-(z_t,0)/s] \propto \xi \Rightarrow \mathrm{Re}[F_-(z_t,0)/s] \propto \xi^2$

The first model of F+MO: L. Łukaszuk and B. Nicolescu, Letter al Nuovo Cimento 8 (1973) 405.
The name Odderon for the first time: D. Joynson, E. Leader, B. Nicolescu, C. Lopez, Il Nuovo Cimento 30A (1975) 345.

In the later papers the F and MO models were modified, improved, compared with the data.
The last papers (with the model named later as AGN) were published in 2007-2008:
R. Avila, P. Gauron, B. Nicolescu, Eur. Phys. J. C 49 (2007) 581 - In this paper the low values of ρ_{pp} at LHC (but with too high σ_t) were predicted;
E. M., B. Nicolescu, Eur. Phys. J. C 56, 57 (2008).
The alternative for AGN model was suggested: E.M., Phys. Rev. D 76 (2007) 074030.

Crossing even part, **Froissaron**.

Fact: $\sigma_t(s) \propto \ln^2(s/s_0)$.

Assumption: $\sigma_{el}(s)/\sigma_t(s) \to \text{const} \leq 1 \quad \text{at} \quad s \to \infty$

$\Rightarrow$ Singularity of partial amplitude cannot be triple pole with linear trajectory (in the case $\sigma_{el}/\sigma_t \to \infty$)

The only possibility for partial amplitude (no singularity at $t = 0, \quad j \neq 1$):

$$\varphi_+(\omega, t) \propto \frac{\beta_+(\omega, t)}{(\omega^2 + \omega_0^2)^{3/2}}, \quad \omega = j - 1, \quad \omega_0 = \pm i R_+ \tau, \quad \tau = \sqrt{-t/t_0}.$$

Then one can obtain a general form for $F_+(z_t, t)$ at not small s

$$F_+(z_t, t)/z_t = i \left[\xi^2 H_1 \frac{J_1(R_+\xi\tau)}{R_+\xi\tau} \beta_{1+}(t) + \xi H_2 f_{2+}(R_+\xi\tau)\beta_{2+}(t) + H_3 f_{3+}(R_+\xi\tau)\beta_{3+}(t) + \cdots \right]$$

Here $\xi = \ln(-iz_t), (= \ln(-is/2m^2) \quad \text{at} \quad t = 0), \qquad f_{2+,3+}(0) = 1.$

Crossing odd part, **Maximal Odderon**.

With the same argument as for Froissaron we have for Maximal Odderon

$$F_-(z_t,t)/z_t=\left[\xi^2 O_1\frac{J_1(R_-\xi\tau)}{R_-\xi\tau}\beta_{1-}(t)+\xi O_2 f_{2-}(R_-\xi\tau)\beta_{2-}(t)+O_3 f_{3-}(R_-\xi\tau)\beta_{3-}(t)+\cdots\right]$$

Evidently a choice of the functions $f_{n\pm},\beta_{n\pm}$ is not the unique.

I will not discuss now the model at $t\neq 0$. This work is in a progress.

Let me proceed to the results obtained after RRB meeting at CERN last year on 24-th October, when the newest TOTEM results on σ_t^{pp} and ρ^{pp} at 13 TeV

$$\sigma_t^{pp}=110.6\pm 3mb,\qquad \rho^{pp}=0.098\pm 0.01$$

had been announced.

Our analysis in FMO model was submitted to HEP arXiv on 9-th November 2017. Now the paper Evgenij Martynov, Basarab Nicolescu "Did TOTEM experiment discover the Odderon? " is published in Physics Letters B778 (2018) 414–418.

What is FMO model at $t = 0$?

Forward pp and $\bar{p}p$ amplitudes contain contributions of Froissron, Maximal Odderon, Standard Pomeron and Odderon with intercepts $\alpha_{P,O}(0) = 1$ and effective crossing even and crossing odd secondary reggeons:.

$$F_{\bar{p}p}^{pp}(z) = F_{+}^{H}(z) + F_{+}^{R}(z) \pm \left(F_{-}^{MO}(z) + F_{-}^{R}(z)\right),$$

$$z = |z_t(t=0)| = (s - 2m^2)/2m^2,$$

$$F_{\pm}^{R}(z) = -\begin{pmatrix} 1 \\ i \end{pmatrix} C_{\pm}^{R}(-iz)^{\alpha_{\pm}(0)},$$

$$F_{+}^{H}(z) = i(s - 2m^2)[H_1 \ln^2(-iz) + H_2 \ln(-iz) + H_3],$$

$$F_{-}^{MO}(z) = (s - 2m^2)[O_1 \ln^2(-iz) + O_2 \ln(-iz) + O_3].$$

Pomeron and Odderon are not shown because their contributions to $F_{\bar{p}p}^{pp}(z)$ at $t = 0$ are constants and they are inserted in terms H_3, O_3 which as well are constant. These terms would be distinguished at $t \neq 0$.

The observables:

$$\sigma_{tot}(s) = \mathrm{Im}F(z)/\sqrt{s(s-4m^2)}, \quad \rho(s) = \mathrm{Re}F(z)/\mathrm{Im}F(z).$$

We used in the fit the data at $\sqrt{s} > 5$ GeV from PDG set without Cosmic data. We added all data of TOTEM

but we did not used two points σ_t^{pp} of ATLAS because they are deviated strongly enough from the whole data at LHC. Accounting them does not change result qualitatively, increasing little bit χ^2.

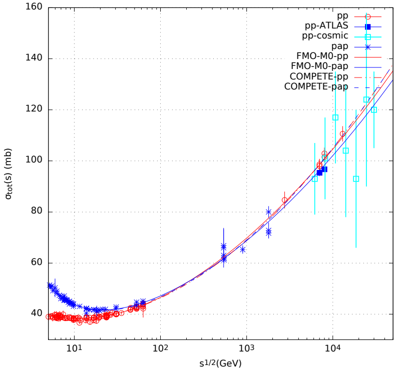
In total there were 246 data points, 10 free parameters.

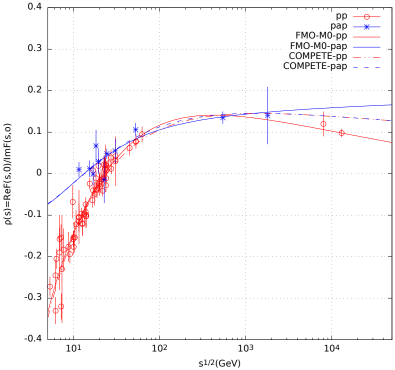
Observable	Number of points	χ^2/N_p
σ_{tot}^{pp}	110	0.8486
$\sigma_{tot}^{\bar{p}p}$	59	0.8662
ρ^{pp}	66	1.6088
$\rho^{\bar{p}p}$	11	0.5468
χ^2/dof		1.0871

Table: Number of experimental points N_p and χ^2/N_p for σ_{tot} and ρ in the fit with FMO model

$\sqrt{s}$ (TeV)	σ_{tot}^{pp} (mb)		ρ^{pp}	
	TOTEM	FMO	TOTEM	FMO
2.76	84.7± 3.3	83.66	-	0.123
7	98.6± 2.2 98.0± 2.5	98.76	-	0.109
8	101.5± 2.1 102.9± 2.3	101.09	0.12 ± 0.03	0.106
13	110.6± 3	109.92	0.098±0.01	0.0976

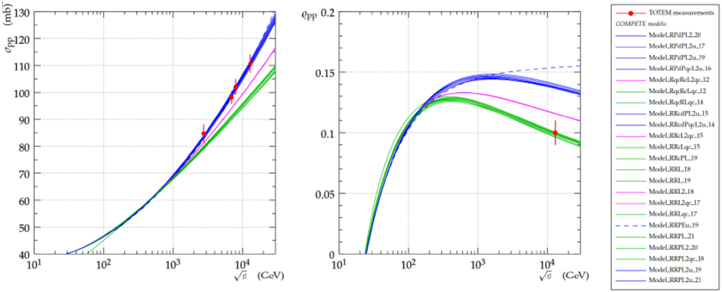
TOTEM data and the best fit values for the σ_{tot} and ρ in FMO model (from E. Martynov, B. Nicolescu, Phys. Lett. B778 (2018) 414)





pp and $\bar{p}p$ cross sections σ_t and ratios ρ in FMO model
(E. Martynov, B. Nicolescu, Phys. Lett. B778 (2018) 414).
Curves of the best COMPETE model without Odderon
(J.R. Cudell et al., COMPETE Collaboration, Phys. Rev. Lett. 89 (2002) 201801)
are shown for a comparison.

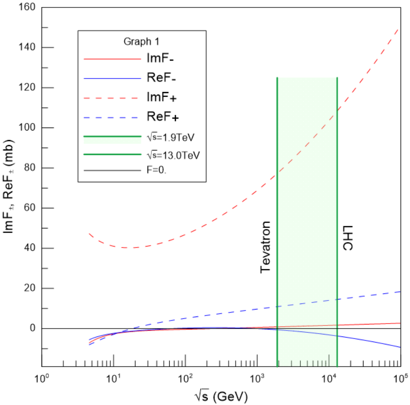
Part of the slide from the talk of S. Giani at RRB meeting on October 2017 with COMPETE results.



The set of COMPETE models cover almost all the models used for σ_t and ρ without Odderon, but they fail to describe simultaneously the new TOTEM data for σ_t and ρ at 13 TeV. It is possible to do that within the FMO model.

Thus the new data of the TOTEM can be considered as the clear evidence in favor of existence of Odderon

When our paper was already in HEP ArXiv we asked ourself "Why odderon was neglected in the most part of the models? Why various estimations allowed to do that? " Searching an answer we plotted the partial contributions to imaginary and real parts of amplitudes at $t = 0$.



Only at LHC energies the $\mathrm{Re}F^{MO}(s)$ (solid blue line) becomes to be visible!

We have considered recently the models of "Froissaron" and "Maximal Odderon" in a generalized form, including standard Pomeron and Odderon with free intercepts $\alpha_{P,O}(0) \leq 1$.

$$F_{+}^{H}(z) = i(s - 2m^2)[H_1 \ln^{\beta_F}(-iz) + H_2 \ln^{\beta_F - 1}(-iz) + H_3],$$

$$F_{-}^{MO}(z) = (s - 2m^2)[O_1 \ln^{\beta_O}(-iz) + O_2 \ln^{\beta_O - 1}(-iz) + O_3],$$

where $\beta_O = \beta_F/2 - \delta_{MO}, \quad \delta_{MO} \geq 0.$

$$F_{\pm}^{R}(z) = \begin{pmatrix} P, R_+ \\ O, R_- \end{pmatrix} = -\begin{pmatrix} 1 \\ i \end{pmatrix} C_{\pm}^{R}(-iz)^{\alpha_{\pm}(0)}.$$

The aim was to verify which values of parameters β_F, β_{MO} and Pomeron and Odderon intercepts $\alpha_{\pm}(0)$ are the best for agreement of the FMO model with experimental data on $\sigma_t(s)$ and $\rho(s)$ for pp and $\bar{p}p$ interactions.

The main result is that β_F and β_{MO} come back to the saturation values 2.

CONCLUSIONS

- The FMO model is based on general principles and theorems of QFT and S-matrix theory.
- The FMO model is in a very good agreement with the experimental data on the forward pp and $\bar{p}p$ scattering.

CONCLUSIONS

- The FMO model is based on general principles and theorems of QFT and S-matrix theory.
- The FMO model is in a very good agreement with the experimental data on the forward pp and $\bar{p}p$ scattering.
- To answer the question in the title of our paper

  " Did TOTEM experiment discover the Odderon? "

  we would like to say

  " Yes! "

Thank you!

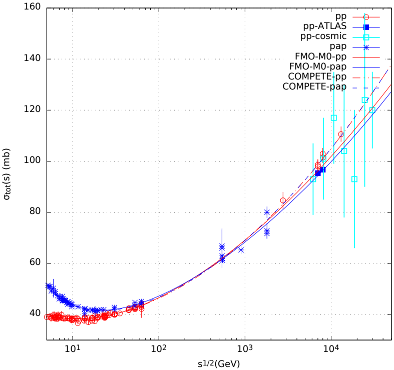
We have considered the FMO model with a various options for powers of $\ln(s)$ in $F_{\pm}(z,0)$ and for intercepts of Standard Pomeron and Odderon. In all cases we put unitary bounds on these parameters: M0-model is just to verify the code for more general form of FMO.

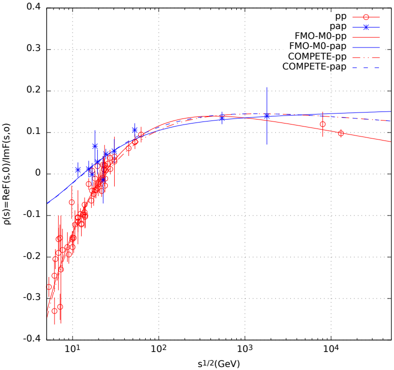
- In accordance with Froissart-Martin bound $\beta_F \leq 2$ and $\alpha_{P,O}(0) \leq 1$;
- From the theorem about maximal growth of $\Delta\sigma_t(s) = |\sigma_t^{pp}(s) - \sigma_t^{\bar{p}p}(s)|$ follows that $\beta_{MO} \leq \beta_F/2 + 1$.

1. **Model M0**. Model presented in the paper published in PLB. $\alpha_P(0) = \alpha_O = 1, \beta_F = 2, \beta_{MO} = 2$.
2. **Model M1**. $\alpha_P(0) = \alpha_O(0) = 1, \quad \beta_F, \beta_{MO}$ are free.
3. **Model M2**. $\alpha_P(0) = 1, \quad \alpha_O(0), \beta_F, \beta_{MO}$ are free.
4. **Model M3**. All above mentioned parameters are free.
5. **Model M4**. $\alpha_P(0) = 1, \beta_F = 2, \beta_{MO} = 2, \quad \alpha_O(0)$ is free.
6. **Model M4-A**. $\alpha_P(0) = 1, \beta_F = 2, \beta_{MO} = 2, \quad \alpha_O(0)$ is free. ATLAS points for σ_t are added to the data se.t
7. **Model M5**. Special case. The main term in $F_-^{MO}(z)$ is zero, $o_1 = 0$, other parameters are free.

Only conclusions, without details.

- In all models (excluding M0 and M5) free parameters β_F, β_{OM} are going to limits $\beta_F = \beta_{OM} = 2$;
- In all models intercept of Pomeron trajectory is equal or going to 1;
- the minimal χ^2 are obtained in the models with free Odderon intercept, which is surprisingly close to -1. For the best model, M4, $\chi^2/\text{dof} = 1.062$ (in the M0 model $\chi^2/\text{dof} = 1.087$);
- intercepts of the secondary reggeons are close to those in M0-model;
- inclusion of the ATLAS points to the data set leads to changes in behaviour of cross sections (Fig. 27, increases χ^2dof up to 1.122. However these two points do not change conclusion on ρ;
- Model M5 without the main Maximal Odderon term is unable to describe well the TOTEM data.





ATLAS point added at the fit.