Unexpected behavior of cross sections of high energy protons

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If a cap falls to the floor, it breaks up to pieces but sometimes stays intact. The stronger it hits the floor, the less chances to be unbroken.

If two high energy protons collide, many new particles (mostly pions) are produced, but sometimes they scatter elastically and retain their entity. It is surprising enough that at very high energies of collisions from ISR to LHC the share of elastic processes starts increasing with increase of energy.

This unexpected phenomenon and its consequences at present and higher energies are discussed in my talk.

Colliding protons are not destroyed but keep their entity with increase of energy!

$$\zeta(s) = \frac{\sigma_{tot}}{4\pi B} = \frac{4\sigma_{el}}{(1+\rho^2)\sigma_{tot}} \approx \frac{4\sigma_{el}}{\sigma_{tot}} \approx (4\pi)^{-0.5} \int_0^\infty d|t| \sqrt{d\sigma/dt}$$

$\sqrt{s}$, GeV	4.11	4.74	7.62	13.8	62.5	546	1800	7000
ζ	0.98	0.92	0.75	0.69	0.67	0.83	0.93	1.00-1.04
$G(s,0)$	1.00	0.993	0.94	0.904	0.89	0.97	0.995	1.00
					ISR			LHC
$\sigma_{inel}/\sigma_{el}$					**5**			**3**

EXPERIMENTAL FACT!

The share of elastic processes $\zeta/4$ decreases at energies below ISR and increases (why?) up to LHC energies! NOT EXPLAINED YET!

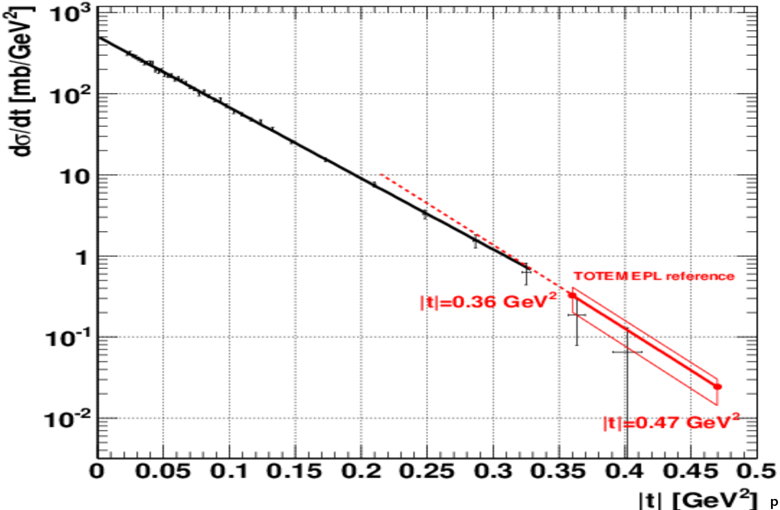
$\zeta = 1$ **CRITICAL!**

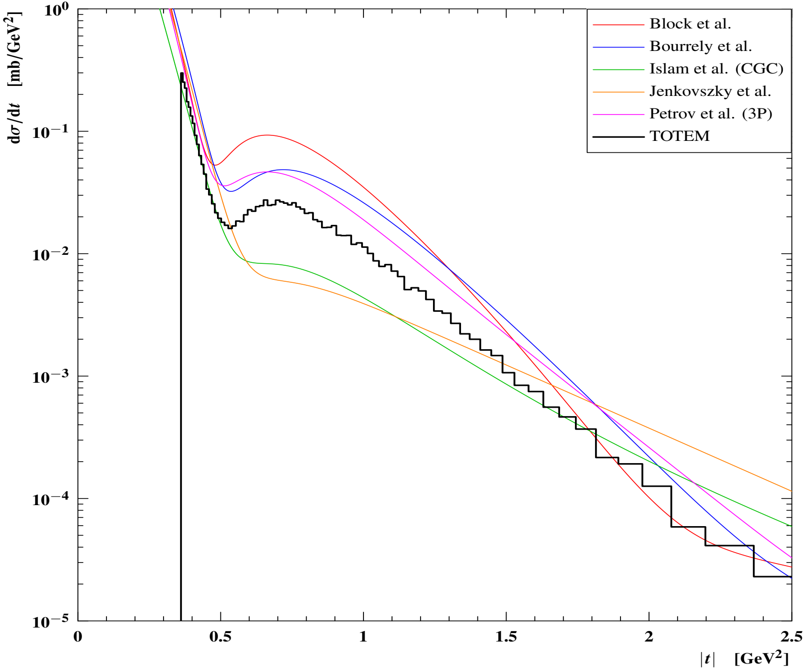
Elastic scattering variables:

$$s = 4E^2 = 4(p^2 + m^2), \quad -t = 2p^2(1-\cos\theta) \ [\approx p_\perp^2;\ \theta \ll 1]$$

$$\frac{d\sigma}{dt} = |f(s,t)|^2.$$

$|f| = \sqrt{d\sigma/dt} \approx |\mathrm{Im} f|$ if $\mathrm{Re} f$ neglected.





Block et al.
Bourrely et al.
Islam et al. (CGC)
Jenkovszky et al.
Petrov et al. (3P)
TOTEM
dσ/dt [mb/GeV^2]
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
0
0.5
1
1.5
2
2.5
|t| [GeV^2]

The unitarity condition

$$SS^+ = 1$$

$S = 1 + iT$

$$2\mathrm{Im}\, T_{ab} = \Sigma_n \int T_{an} T^*_{nb} d\Phi_n,$$

Elastic scattering $a = b = 2, \quad n \geq 2.$ $\quad \mathrm{Im} f(p,\theta) = I_2(p,\theta) + g(p,\theta) =$
$\frac{s}{8\pi^{3/2}} \int\int d\theta_1 d\theta_2 \frac{\sin\theta_1 \sin\theta_2 f(p,\theta_1) f^*(p,\theta_2)}{\sqrt{[\cos\theta - \cos(\theta_1+\theta_2)][\cos(\theta_1-\theta_2) - \cos\theta]}} + g(p,\theta$

Optical theorem at t=0: $\mathrm{Im} f(p,0) \propto \sigma_{tot} = \sigma_{el} + \sigma_{in}$

$$i\Gamma(s,b) = \frac{1}{2\sqrt{\pi}} \int_0^\infty d|t| f(s,t) J_0(b\sqrt{|t|}).$$

The unitarity condition in the b-representation (algebraic!)

$$G(s,b) = 2\mathrm{Re}\Gamma(s,b) - |\Gamma(s,b)|^2.$$

$$\frac{d^2\sigma_{inel}}{db^2} = \frac{d^2\sigma_{tot}}{db^2} - \frac{d^2\sigma_{el}}{db^2} \quad \rightarrow \quad \sigma_{inel} = \sigma_{tot} - \sigma_{el}.$$

$\mathrm{Re}\Gamma(s,0) = \zeta \approx (4\pi)^{-0.5} \int_0^\infty d|t| \sqrt{d\sigma/dt} \quad (\mathrm{Re}f \text{ neglected})$

Central collisions at $b = 0$

$$G(s, b = 0) = \zeta(2 - \zeta),$$

determined by the normalization factor ζ only!
Maximum at $\zeta = 1$ (see Table); $G(s, 0) = 1 - \epsilon^2$ for $\zeta = 1 \pm \epsilon$
Two branches of the unitarity condition for $\zeta < 1$ and $\zeta > 1$

$$\zeta(s) = 1 \pm \sqrt{1 - G(s, 0)}.$$

Branch with minus sign: $\zeta \approx G(s, 0)/2$ for $G \ll 1$ - elastic scattering interpreted as shadow of WEAK! inelastic processes - typical for electrodynamics ($ee \to ee\gamma$) and optics.
Strong interactions at present energies - large $G(s, 0)$ (see Table).
If $\zeta(s) < 1$, i.e. the share of elastic processes stays less than 0.25, - conservative situation with maximum value at $b = 0$.

Critical $\zeta(s) = 1$! BRANCH WITH PLUS SIGN for $\zeta > 1$!
Slight trend of ζ to increase and become larger than 1 at LHC:
TOTEM 7 TeV 1.00–1.02; 8 TeV 1.04 (accuracy ± 0.024);
13 TeV (high statistics, better accuracy; end 2016).
Extrapolations of fits of present data and theoretical speculations.
$\zeta(13\,TeV) = 1.05 - 1.06$; $\zeta(95\,TeV) = 1.12 - 1.15$

The geometry of the interaction region

$$\frac{d\sigma}{dt} = \frac{\sigma_{tot}^2}{16\pi} \exp(-B(s)|t|).$$

$$i\Gamma(s,b) \approx \frac{\sigma_t}{8\pi} \int_0^\infty d|t| \exp(-B|t|/2)(i+\rho) J_0(b\sqrt{|t|}).$$

$\rho \ll 1$ except near the minimum of $d\sigma/dt$.

$$\mathrm{Re}\Gamma(s,b) = \zeta \exp(-\frac{b^2}{2B}) \quad (= \zeta \; at \; b = 0)$$

Inelastic interaction region:

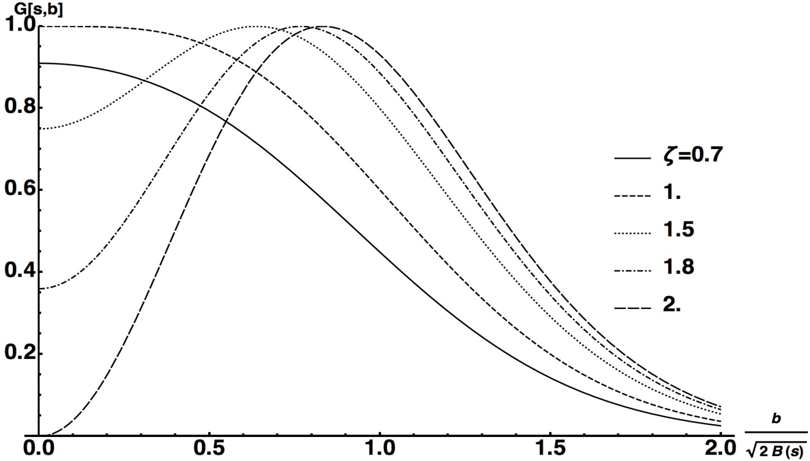
$$G(s,b) = \zeta \exp(-\frac{b^2}{2B})[2 - \zeta \exp(-\frac{b^2}{2B})].$$

Scaling in $b/\sqrt{2B}$. Typical $\sqrt{2B} \approx 6$ GeV$^{-1} \approx 1.2$ fm
Maximum at $b_m^2 = 2B \ln \zeta$ (for $\zeta < 1$ - maximal value at $b = 0$).
For $\zeta = 1$ maximum at $b_m = 0$ and plateau at $b^2 \ll 2B$ (LHC!)

$$G(s,b) = \zeta[2 - \zeta - \frac{b^2}{B}(1-\zeta) - \frac{b^4}{4B^2}(2\zeta - 1)].$$

For $\zeta > 1$ - maximum at $b_m > 0$. Full absorption $G(s, b_m) = 1$!
Inelastic processes stronger at periphery!

The evolution of the inelastic interaction region in terms of the survival probability. $\zeta = 0.7$ and 1.0 correspond to ISR and LHC energies. A further increase of ζ leads to the toroid-like shape with a dip at $b = 0$. The values $\zeta = 1.5$ are proposed in extrapolations of fits and $\zeta = 1.8$ in theoretical paper as asymptotical regimes. **No absorption at central collisions for $\zeta = 2$!** arXiv:1604.03469



Small cross sections at small b

$$\sigma_{el}(s, b \leq r) = \sigma_{el}(s)[1 - \exp(-r^2/B(s))],$$
$$\sigma_{tot}(s, b \leq r) = \sigma_{tot}(s)[1 - \exp(-r^2/2B(s))].$$
$$\sigma_{in}(s, b \leq r) = \pi r^2 G(s, 0) \quad (r^2 \ll B)$$

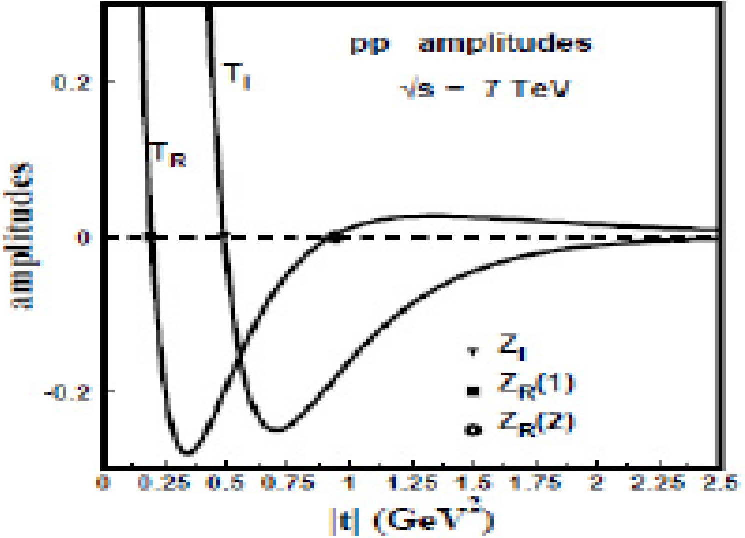
Effective impact parameters for elastic scattering

$$< b_{el}^2 >= \sigma_{el}(s)/\pi\zeta^2(s).$$

Inelastic processes are much more peripheral.

$$\frac{< b_{in}^2 >}{< b_{el}^2 >} = \zeta\frac{8-\zeta}{4-\zeta}.$$

Rare inelastic processes of central collisions at LHC energies -
very high multiplicities (tail of multiplicity distribution) -
jet creation as a signature of strong gluon fields.
New effects at very high multiplicities?
Accuracy of experiments at 13 TeV, 100 TeV? Statistics increases!



Real (T_R) and imaginary (T_I) parts of the proton-proton amplitude at 7 TeV according to a particular phenomenological model. Real part contributes to $d\sigma/dt$ only near the dip where $d\sigma/dt$ is small.

Discussion and conclusions

The intriguing increase of the share of elastic processes to the total outcome observed at energies from ISR to LHC attracts much attention nowadays. Its approach to 1/4 at LHC can become a critical sign of the changing character of processes of proton interactions if the above tendency of increase persists. The concave central part of the inelastic interaction region would be formed. The inelastic interaction region looks like a toroid hollowed inside and strongly absorbing in its main body at the edges. The role of elastic scattering in central collision becomes increasing. Inelastic processes are peripheral. That is surprising and contradicts somewhat to our theoretical prejudices. From the formal theoretical point of view it requires to consider another branch of the unitarity condition that asks for its physics interpretation.

It is hard to believe that protons become more penetrable at higher energies after being so dark in central collisions with $G(s,0)=1$ at 7 TeV unless some special coherence within the internal region develops. Moreover, it seems somewhat mystifying why coherence is more significant just in central collisions but not at other impact parameters. Is the string junction responsible for it?

One could imagine another classical effect that "black"protons start scatter backward like the billiard balls at head-on collisions. The similar situation happens if two unequal solitons collide. That can be checked if forward and backward scattered protons can be distinguished in experiment. Then they should wear different labels, The proton spin can be such a label. The polarization of scattered protons distinguishes if they are scattered forward or backward
Another hypothesis treats the hollowed internal region as resulting from formation of cooler disoriented chiral condensate inside it ("baked-alaska"DCC). The signature of this squeezed coherent state would be some disbalance between the production of charged and neutral pions noticed in some cosmic ray experiments. However the cross sections for central collisions seem to be extremely small as discussed above. The failure to find such events at Fermilab are probably connected with too low energies available.
The transition to the deconfined state of quarks and gluons in the central region could also be claimed responsible for new effects. The optical analogy with the scattering of light on metallic surface as induced by the presence of free electrons is used. Again, the special role of the central region remains unclear.