Pomeron - 50th Anniversary.
Age-related changes.

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The main points to be discussed :

1. The elastic scattering diffraction cone shrinkage speeds up with beam energy increase, approach to the Froissart limit.

2. Regge Field Theory , multiperipheral picture and implications to the elastic scattering and to multiparticle production at collider energies.

3. Charged particles radiation and proton radius increase.

4. LHC energy scan and soft physics QCD.

50 years ago the new object in Elementary Particle Physics - Pomeron - has appeared. The ”technology” was implemented by T.Regge and physics content was filled up by V.Gribov and I.Pomeranchuk and their coauthors. The motivation at that time was to provide a reasonable behavior at an ”asymptotic” energies of the elastic scattering amplitude and total cross sections. At high energies the hadron-hadron scattering are usually described by the Regge poles exchange. A popular parameterization of the elastic scattering amplitude at small momentum transfer takes into account only Reggeon and Pomeron poles exchange .

The ab elastic scattering amplitude reads

$$T_{ab}(t) = F_a(t)F_b(t)C_P s^{\alpha_P(t)} + F_R(t)C_R s^{\alpha_R(t)}$$

where the form factors F_a, F_b, $F_R(t)$ describes the matter distribution in the incoming hadrons a, b. C_P and C_R are the normalization constants. The contribution of the (secondary) Reggeon poles becomes negligible at $\sqrt{s} \sim 100GeV$.

The Pomeron pole has the UNIVERSAL nature, i.e. his contribution does not independent on the kind of elementary particle. However, at that time experimentally such universality was not yet established.

Experimental discovery of a universal shrinkage of the diffraction cone:

PNPI/CERN SPS experiments WA9 and NA8, 1976-1980

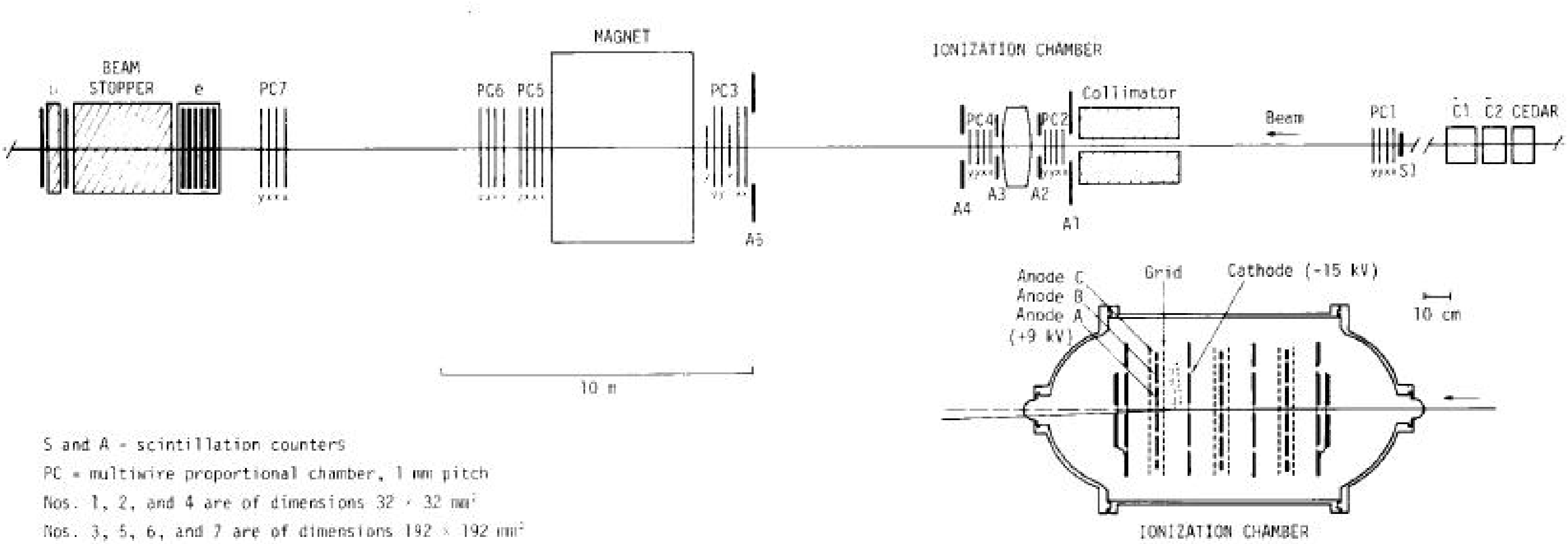
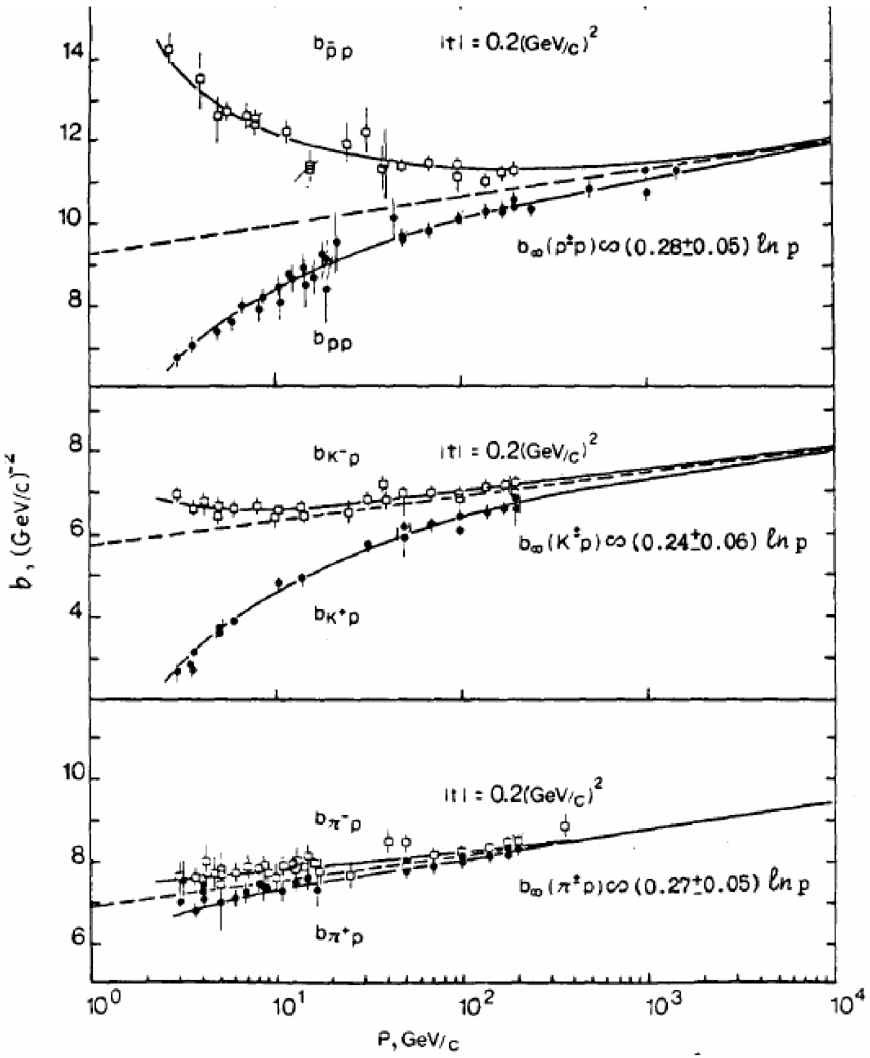


Figure 1: The view of the experiment set up



$b_{\bar{p}p}$
|t| = 0.2(GeV/c)^2
$b_\infty(p^\pm p) \propto (0.28 \pm 0.05)\ \ln p$
b_{pp}
b_{K^-p}
|t| = 0.2(GeV/c)^2
$b_\infty(K^\pm p) \propto (0.24 \pm 0.06)\ \ln p$
b_{K^+p}
|t| = 0.2(GeV/c)^2
b_{π^-p}
$b_\infty(\pi^\pm p) \propto (0.27 \pm 0.05)\ \ln p$
b_{π^+p}
b, (GeV/c)$^{-2}$
P, GeV/c

The conclusions were : **" The results of the slope parameters from this experiment together with the analysis of the available world data demonstrate that the existing experimental data are consistent with the hypothesis of a universal shrinkage of the hadronic diffraction cone at high energies. The value of the asymptotic shrinkage parameter α'_P was found to be independent of the kind of the incident hadron and of the momentum transfer in the $|t|$ range $|t| \leq 0.2 GeV^2; 2\alpha'_P = 0.28 \pm 0.03 GeV^{-2}$."**

It is interesting to make an extrapolation to LHC energy - $\sqrt{S} = 7TeV$. The slope of the pp-scattering diffraction cone at $\sqrt{S} = 24GeV$ - the highest energy of CERN SPS - was measured to be

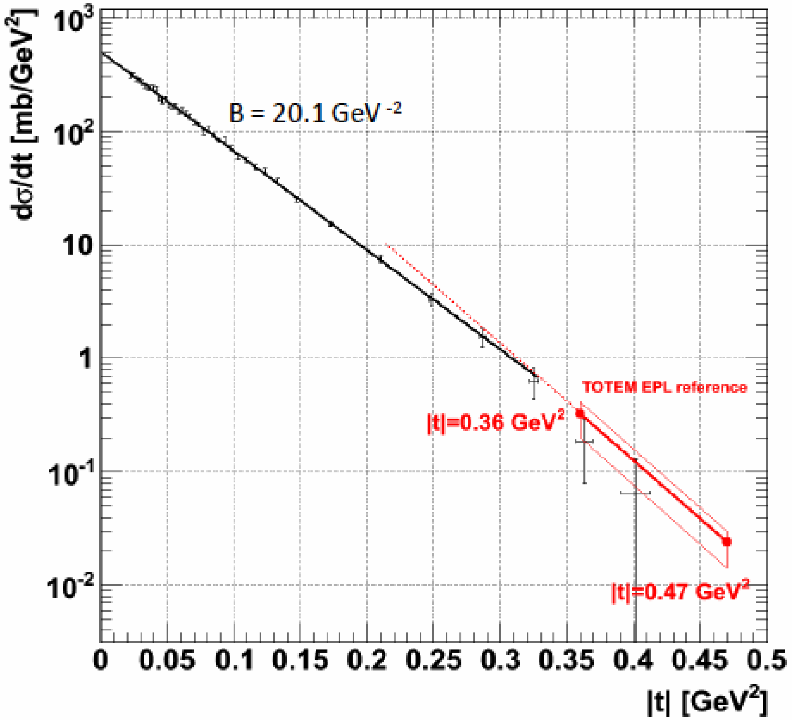
$$B_{el} = (12.4 \pm .3)GeV^{-2}.$$

Then at $\sqrt{S} = 7TeV$ one might expect

$$B_{el} = (15.7 \pm .7)GeV^{-2}.$$

The estimation of the extrapolation error might be considered as an optimistic guess. Moreover to describe the data only at a higher, CERN-ISR-, S$p\bar{p}$S-, Tevatron-collider energies($\sqrt{s}$ is up to 1800 GeV) Donnachie-Landshoff parametrization requires much larger $\alpha'_P = 0.25$ GeV^{-2}.

TOTEM: pp Elastic Cross-Section



Exponential slope:

$$B\Big|_{t=0} = 20.1\,\mathrm{GeV}^{-2}$$

Extrapolation to t = 0:

$$\frac{d\sigma}{dt}\Bigg|_{t=0} = 5.037\times10^{2}\,\mathrm{mb}/\mathrm{GeV}^{2}$$

Integral Elastic Cross-Section

$$\sigma_{EL} = 8.3\,\mathrm{mb}^{(\mathrm{extrapol.})} + 16.5\,\mathrm{mb}^{(\mathrm{measured})} = 24.8\,\mathrm{mb}$$

Of course, it is a bit naive to suppose that $\alpha_P^{\prime eff}$ is a constant value, i.e. independent on beam energy. Indeed, one clearly see that in the energy region $\sqrt{S} = 24 - 7000 GeV$ the slope is non-linear function, as one can expect from the multiperipheral picture of high energy hadron collisions .

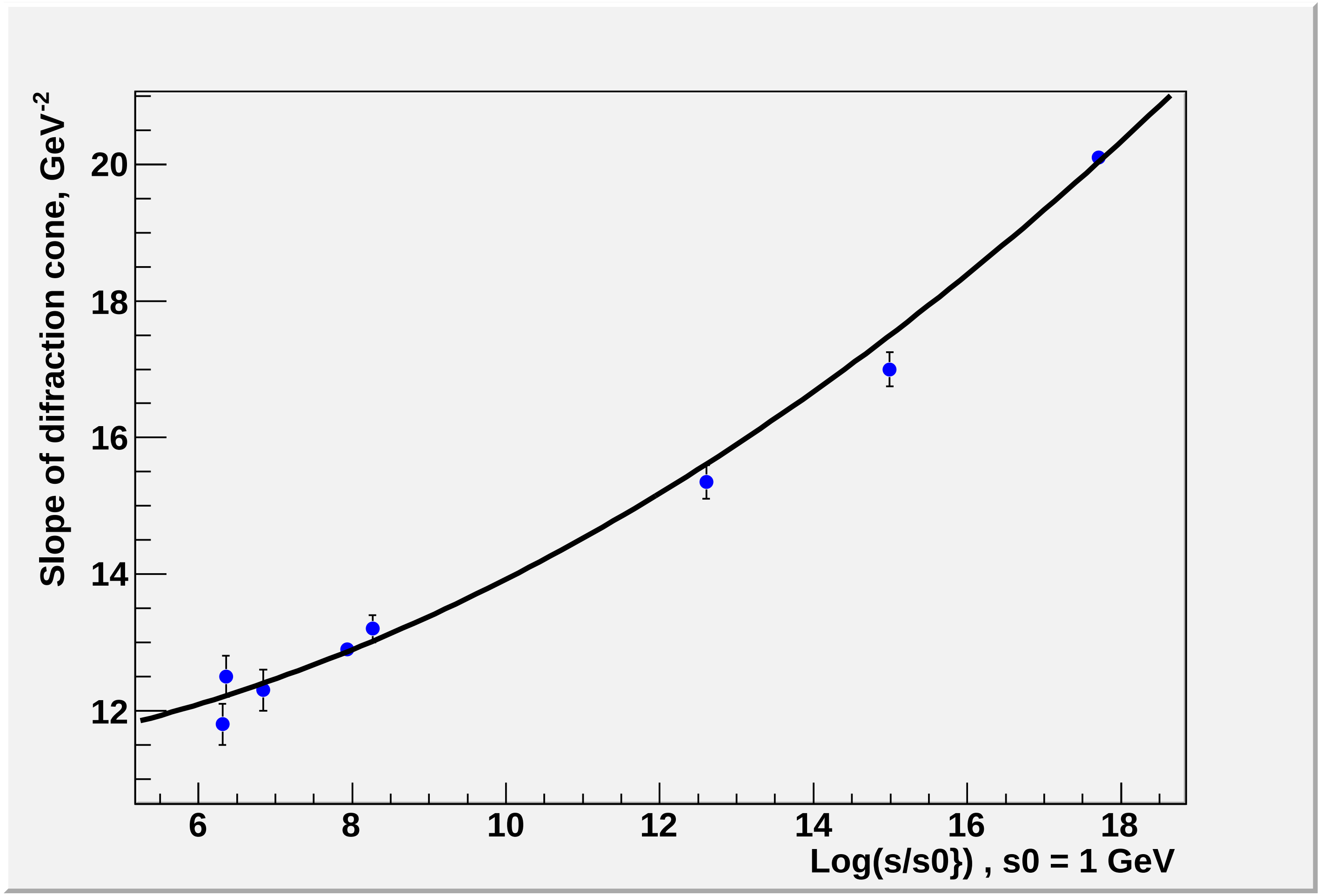


Figure 3: The diffraction cone slope at high energy

Fitting the $\ln s$ dependence of B_{el} by the second order polynomial

$$B_{el} = B_0 + b_1 \ln(s/s_0) + b_2 \ln^2(s/s_0)$$

we get

$b_1 = (-.22 \pm .17)GeV^{-2}$ and $b_2 = (.037 \pm .006)GeV^{-2}$.

The value of b_1 is equal zero with a large probability. The exclusion of this parameter and the fit with the function

$$B_{el} = B_0 + b_2 \ln^2(s/s_0)$$

gives

$$b_2 = (0.02860 \pm 0.00050)GeV^{-2}$$

and does not change statistical significance : $\chi^2/N_{df} = 1.49$ in the first fit and $\chi^2/N_{df} = 1.5$ in the second one.

The energy dependence of $\alpha'(eff)_P = dB_{el}/d(ln(s/s_0))$ is shown in Fig. 4 (of course, $\alpha'(eff)_P$ does not depends on s_0).

At $\sqrt{S}$ = 24 GeV the value of $\alpha_P^{eff} = (.343 \pm .006) GeV^{-2}$, found from $B_{el}(S)$ dependence at collider energies is in a fair agreement with PNPI-CERN value estimated from $B_{el}(S)$ at "low energy" $\alpha_P^{eff} = (.28 \pm .03) GeV^{-2}$, where contribution from the secondary Regge poles was significant.

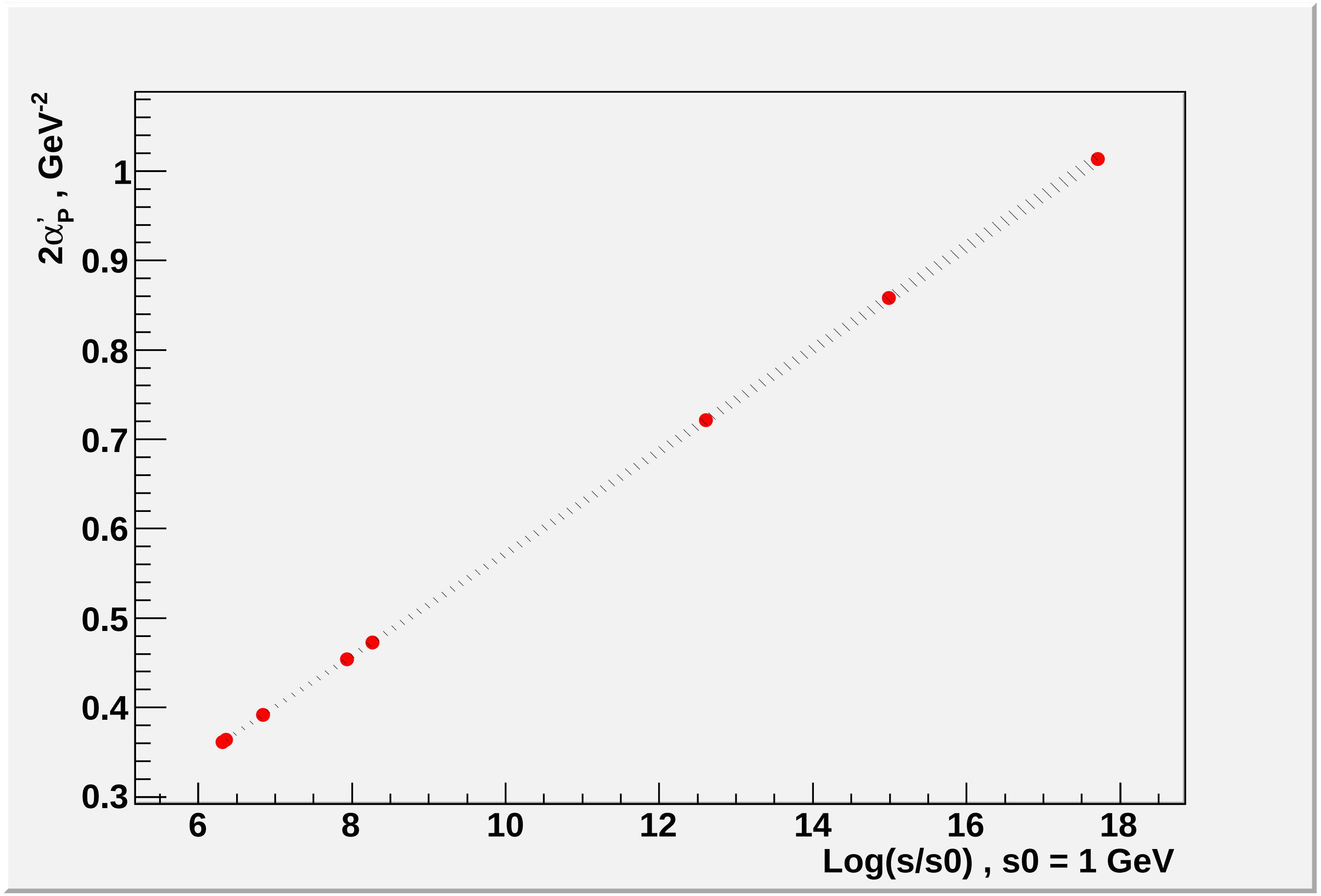


Figure 4: α_P^{eff} as a function of beam energy

Pomeron - these days status

Formally the Pomeron is defined as the rightmost pole of elastic scattering amplitude in complex moment, j, plane. From the microscopic viewpoint the Pomeron is described by the ladder-type diagrams

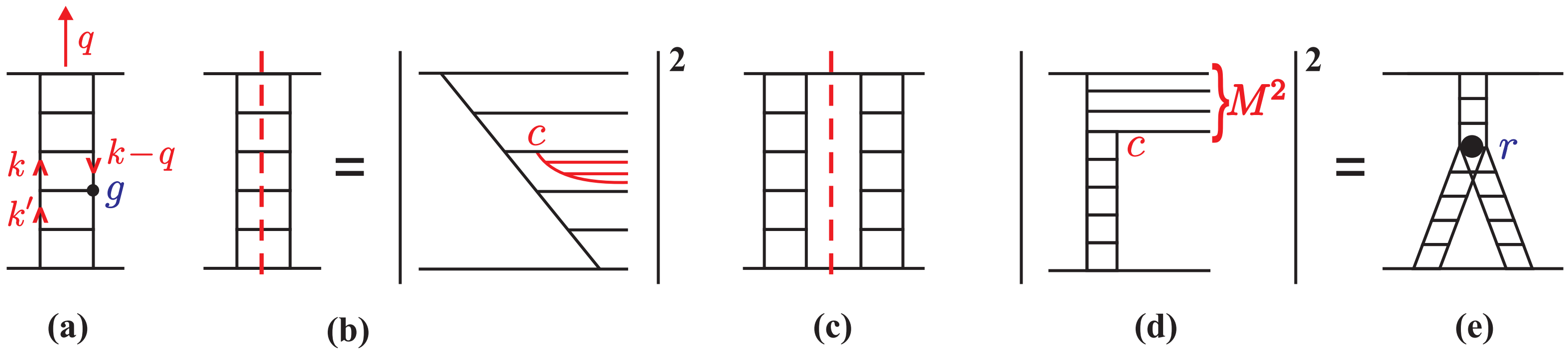


Figure 5: (a) The ladder diagram for one-Pomeron exchange; (b) cutting one-Pomeron exchange leads to the multiperipheral chain of final state particles;The parton branch shown in red does not interact with the target. It save the coherence and acts as the parton c self-energy, not producing a new secondaries. (c) a multi-Pomeron exchange diagram.

The energy (longitudinal momentum fraction) in each next cell is few times lower than that in the previous cell.To get the largest cross section we have to consider the chain (sequence) of interactions with relatively low partial sub-energies. On one hand in the resonance region the amplitude is close to its maximum value allowed by the unitarity, on another hand at each step the interaction radius changes (in one or another direction) by the value $\delta\rho \sim 1/m$ leading to the 'diffusion' in impact parameter plane. At each step the energy of incoming particle diminishes few times. Thus the number of steps $n \sim \ln s$ and the final radius $R^2 = R_0^2 + n \cdot (\delta\rho)^2$.

Such a sequence of the interactions provides a large (non-decreasing with energy) cross section $\sigma \propto s^{\alpha_P(0)-1}$. $\alpha_P(0) = 1 + \Delta$ is the intercept of the Pomeron trajectory and the present data indicate that the value of $\Delta > 0$.

The power growth of the "single Pomeron exchange" cross section is, indeed, generated by the ladder diagram (Fig. 5a). It reflects the growth of the vee parton (i.e. the partons which interact with the target directly since its energy in the target rest frame is low) multiplicity, N.

The mechanism is as follows: Since at each (ladder) step the longitudinal momentum decreases few times the mean number of steps $< n >\sim c * \ln s$. At each splitting (step) the multiplicity of parton increases two times. Thus the finall vee parton multiplicity $N \sim 2^{c \ln s} = s^{c \ln 2}$.

Recall that in Fig. 5 we show only one branch of the parton cascade, that is the branch where the parton coherence was spoiled by the target. All other branches which save the coherence and gather up into the parent partons/hadrons are implicit (not shown).

Saturation

At some stage with energy increasing the parton density becomes too large. The probability of two partons to one fusion exceeds the probability of the (one to two) splitting and the parton density reaches a saturation. However this does not happen simultaneously in all the points of the configuration space. Somewhere on the periphery (at large impact parameter ρ) the parton density continues to grow. As the result the interaction radius increases. Thus besides the diffusion in ρ (At each evolution step (ladder cell) the value of ρ may be changed by $\delta\vec{\rho} \sim 1/k_t$ in one or another direction. This leads to the growth of the interaction radius $R^2 = R_0^2 + n \cdot (\delta\rho)^2$ and therefore to the diffractive cone shrinkage $B_{el} = B_0 + 2\alpha' \ln s$).
In the case of increasing cross section ($\Delta > 0$) we get an additional source of the diffractive cone shrinkage – saturation of parton densities at low ρ.

Note that the partons with a low transverse momenta k_t reach saturation much before that with a high k_t since the probability of a fusion falls down with k_t; the cross section of fusion (i.e. the absorptive cross section) $\sigma^{abs} \propto 1/k_t^2$.
Therefore with energy increasing the partons start to fill the periphery of configuration space both in a large ρ and in a large k_t domains.

In terms of Regge Field Theory (RFT)[1] the fusion of two parton branches into the one branch is described by the multi-Pomeron (enhanced) diagram with the triple-Pomeron (two to one) vertex. Here the two branch of partons loose the coherence and produce the new secondaries. This way they become visible experimentally; therefore we draw these ladders in our diagrams. Another possibility is the so-called multiple interaction when the two different vee partons interact with the target and thus two branches of partons loose the coherence. In RFT this is described by the non-enhanced (eikonal-like) multi-Pomeron exchange.

It turns out that the *saturation effects start to reveal itself just in the "TeV" energy range*. In particular, using the popular Donnachie-Landshoff parametrisation[2] for the proton-proton elastic amplitude we see that in impact parameter ρ representation the amplitude $T(\rho = 0)$ exceeds the black disk limit $T(0) = 1$ between the Tevatron and the LHC (14 TeV) energies.

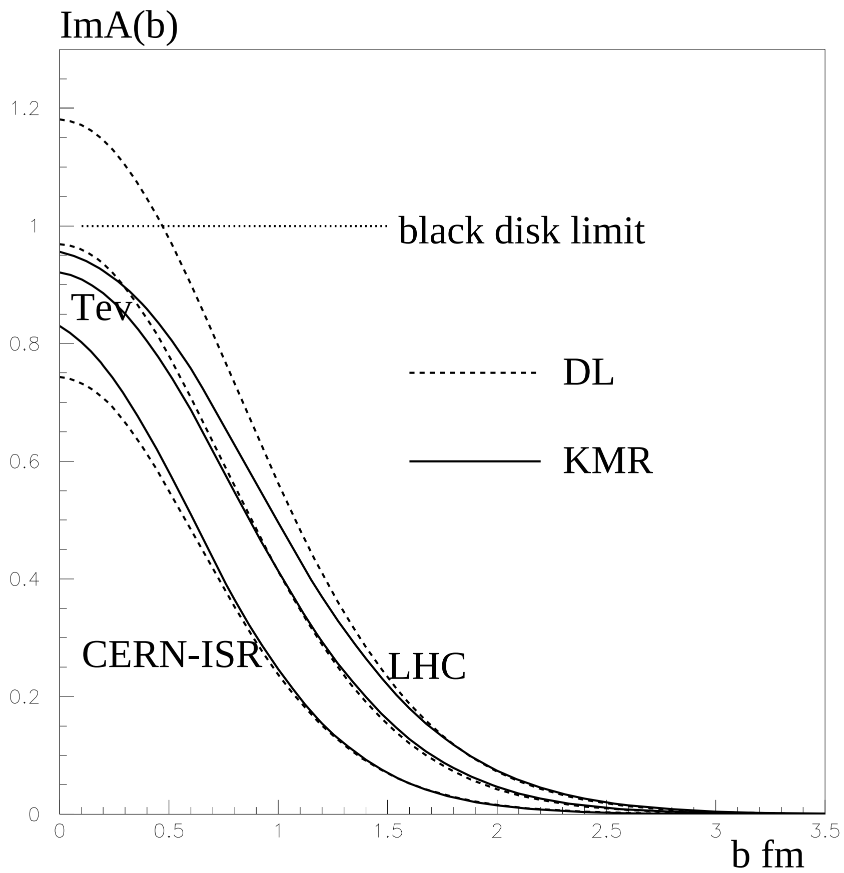


Figure 6: Amplitude $T(\rho)$ at the CERN-ISR, Tevatron and the LHC energies.

Actually in the ”TeV” range we observe an acceleration. Both the total pp-cross section and the t-slope, B_{el}, of elastic cross section start to grow faster than it was at a lower energies; in particular the Donnachie-Landshoff parametrisation[2] predicts $\sigma_{tot} = 90.7$ mb and $B_{el} = 18.5$ GeV^{-2} while the recent TOTEM results are 98.3 mb and $B_{el} = 20.1$ GeV^{-2} [3].

The acceleration of the interaction radius (i.e. B_{el}) growth is caused by the saturation at low impact parameters which enforce the partons to occupy a larger ρ domain. In the case of a total cross section a steeper energy behavior is most probably caused by the contribution of a larger k_t partons.

If we restore the amplitude $T(\rho)$ from the last elastic cross sections measured by TOTEM[3] and account for the s-channel two particles (elastic) unitarity

$$2\mathrm{Im}\mathrm{T}_{\mathrm{el}}(\rho) = |\mathrm{T}_{\mathrm{el}}(\rho)|^2 + \mathrm{G}_{\mathrm{inel}}(\rho)$$

which in the limit of $Re/Im << 1$ has the solution

$$T = 1 - exp(-\Omega/2)$$

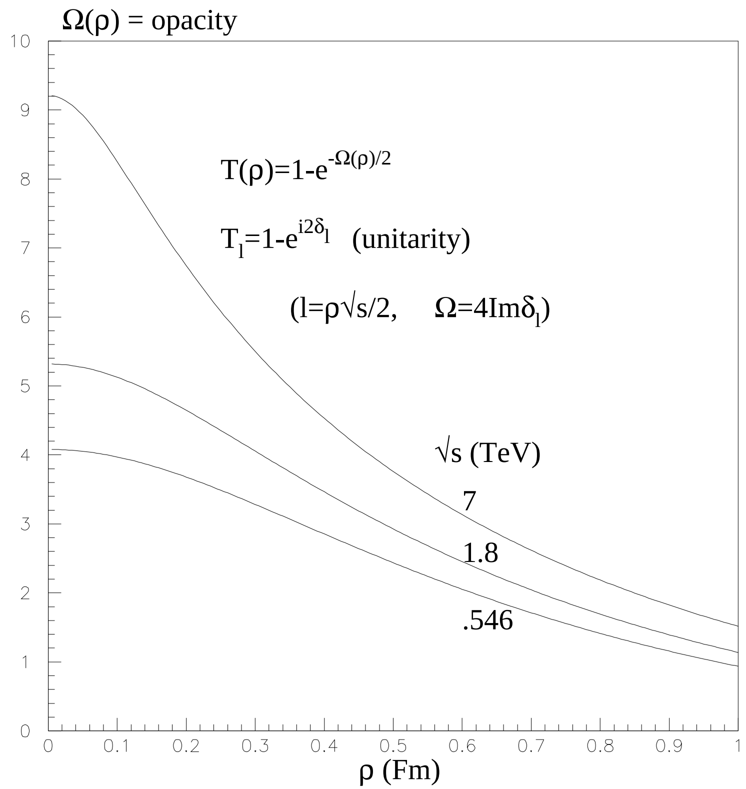


Figure 7: The opacity as a function of the impact parameter ρ for three proton-(anti)proton energies.

We see that the opacity Ω grows rapidly between the Tevatron and LHC especially at a low impact parameters $\rho < 0.2 - 0.3$ Fm. This indicates a fast increasing of parton densities. The fact that we observe a stronger effect at small ρ indicates also that the parton transverse momenta becomes larger.

Another hint in the same direction (k_t grows): to tune the Monte Carlo we need to enlarge the infrared cutoff $k_{min} = k_0 s^{0.12}$ with the energy increasing[4].

Less probable but not rejected yet possibility is that at a relatively small distances, $\rho \sim 0.2\mathrm{fm} = 1\mathrm{GeV}^{-1}$we observe a qualitatively new interaction which has a small coupling but rapidly increases with energy.

(see for example [6])

New regime

It looks that at the LHC we get the possibility to study a new, close to saturation, regime of strong interactions. In particular, it is quite important to measure the interaction radius both in elastic scattering (the diffractive cone slope B_{el}) and in miltiparticle production processes where this can be done with the help of identical particle (Bose-Einstein) correlations (BEC). It would be very interesting to study the radius and the transverse momentum distributions in diffractive dissociation events since thanks to the AGK cutting rules[5] the same triple-Pomeron diagrams describe both the absorptive effects due to the two to one parton branch fusion and the incoming proton high mass dissociation, that is the process where the coherence was destroyed in a single parton branch but was saved in two parallel branches - the cut between these two branches corresponds to the 'elastic' scattering of the intermediate parton.

Recall that the absorptive effects, which restore the unitarity and reduce the parton density growth, are described by the multi-Pomeron diagrams where we have to consider a few branches of parton cascade That is in the saturation region we have to observe an events with twice (and more) larger multiplicity than that created by a one branch – the events where few branches of parton cascade loose the coherence and produce a new secondaries. This means that at a large LHC energy we expect a wider multiplicity distribution. Moreover in a larger multiplicity events we expect the radius measured via the BEC to be larger since here we will observe the interference between two identical particles emitted by two different Pomerons (two branches of parton cascade) separated in ρ space by the distance up to the interaction radius R.

References

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[3] G. Antchev et al. Europhys. Lett. **96** (2011) 21002.

[4] T. Sjostrand, S. Marenna, P.Z. Skands, Comput. Phys. Commun. **178** (2008) 852. arXiv:0710.3820.

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[6] E. Levin, I. Potashnikova, JHEP 0906 (2009) 031

BEC were carefully studied with the first CERN hadron colliders - ISR and SPS. AFS experiment has observed BEC of pions produced in the collisions of proton-proton, proton-antiproton and helium nuclei. For the first time it was declared that the size of pions emitted region is independent on incident particles type, but does depend on the mean charged multiplicity. UA1 experiment performed BEC investigations with different hadron energies of SPS. In special so called rumping runs they collected statistics with SPS energies $\sqrt{S} =$ 200,260,380,500,620,790,900 GeV. The conclusions are : for a particular value of charged particle density in the pseudorapidity the size of the emitting region is independent on $\sqrt{S}$;at fixed $\sqrt{S}$ the size is increasing with particle densities.

High statistics was collected in LHC experiments - ALICE, ATLAS and CMS. Already the first analysis the universal features of BEC were confirmed: for the same multiplicity an average source radius is the same LHC $\sqrt{S}$ 900 Gev and 7 TeV .

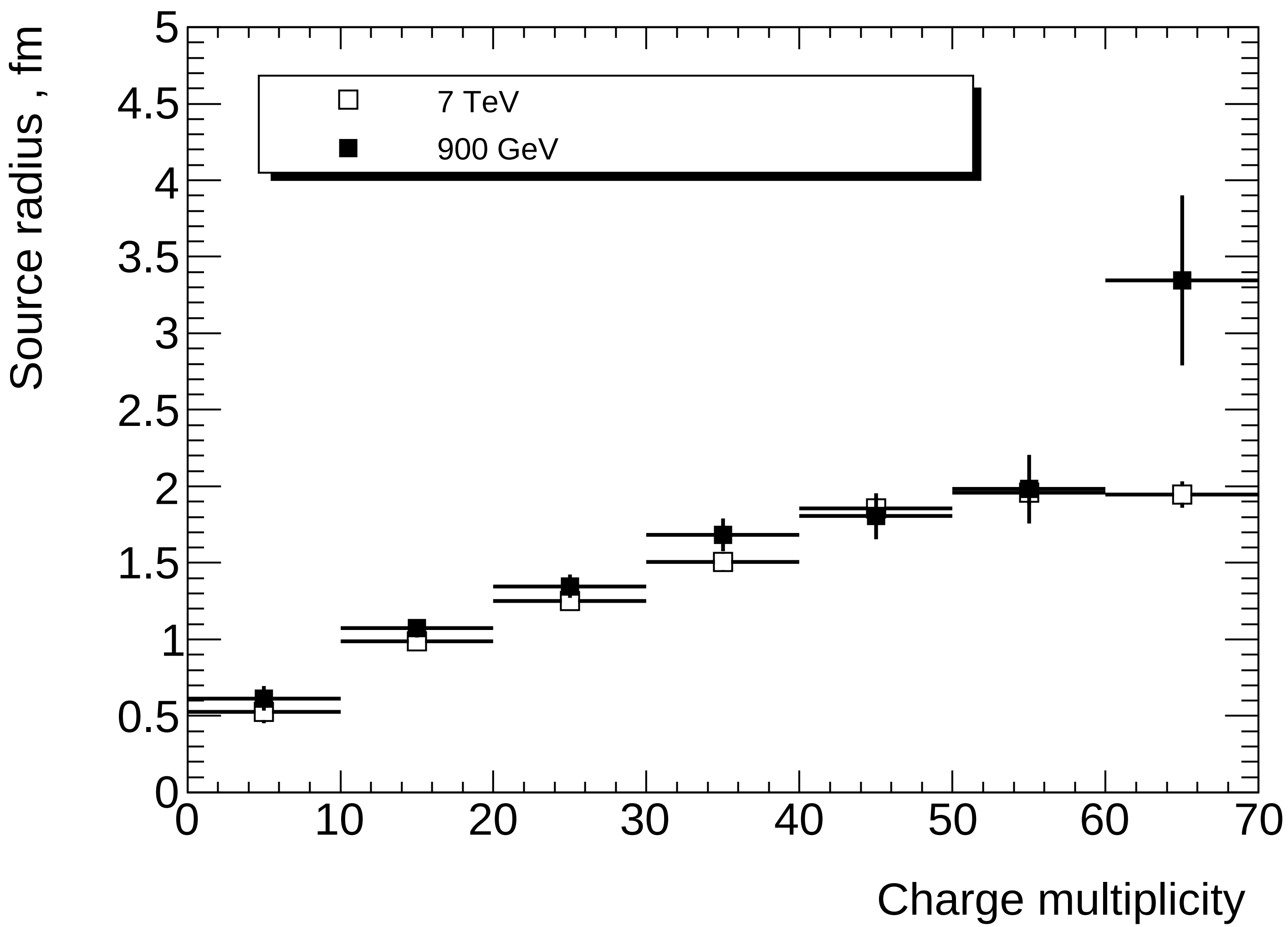

Figure 8: Source size as a function of particle multiplicity at $\sqrt{S}$ = 900 GeV and $\sqrt{S}$ = 7TeV

In terms of the Regge-Pomeron theory this can be described as follows: At high energies the multiparticle production is described by the emission from one or few cut Pomerons. Each cut Pomeron plays the role of the relatively small size source mentioned above. The low multiplicity corresponds to the case of only one cut Pomeron. Thus the smallest radius ~ 1 fm should be considered as the radius of one individual Pomeron (to be more precise – as the size of the source formed by a single Pomeron) At a higher multiplicities we deal with the events with a larger number of cut Pomerons and now via the identical particle correlation we measure the mean separation between the Pomerons.

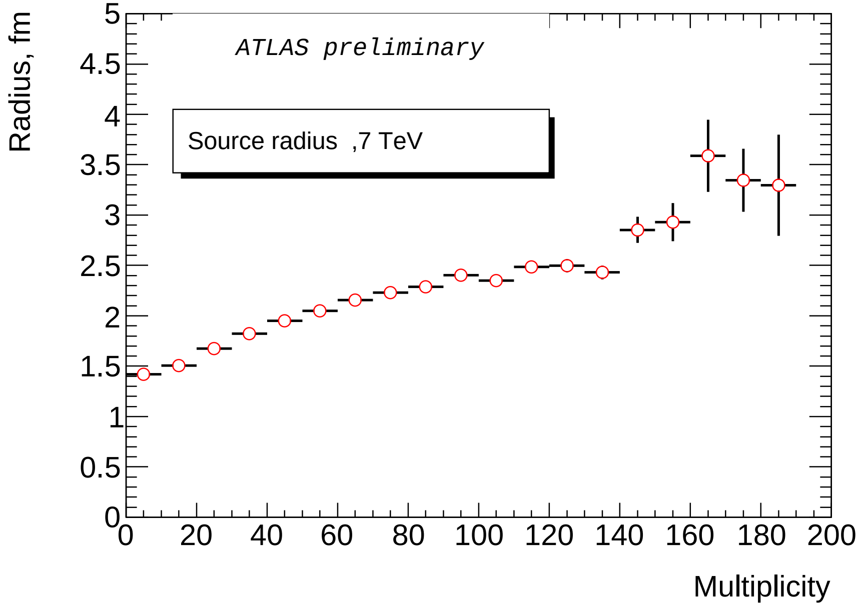

Figure 9: Source size as a function of particle multiplicity at $\sqrt{S}$ = 900 GeV and $\sqrt{S}$ = 7TeV

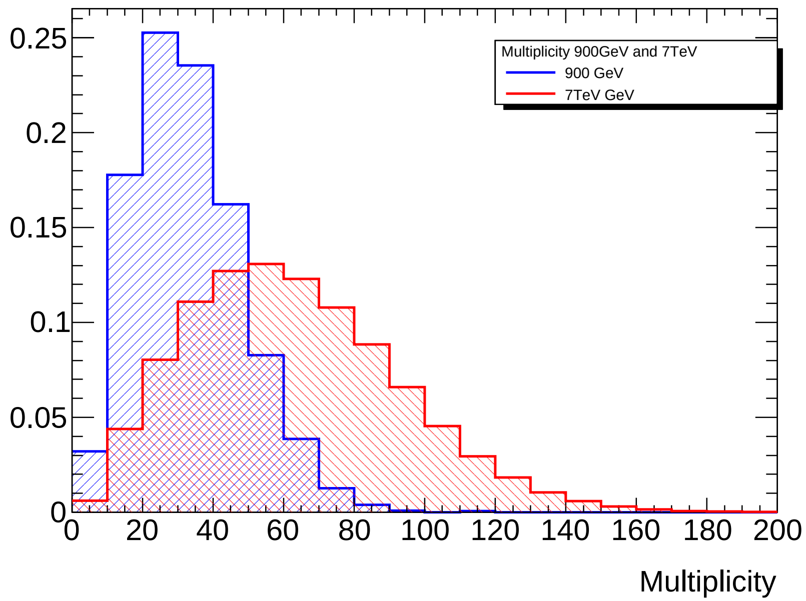

Figure 10: Charged particle multiplicity at $\sqrt{S}$ = 900 GeV and $\sqrt{S}$ = 7TeV

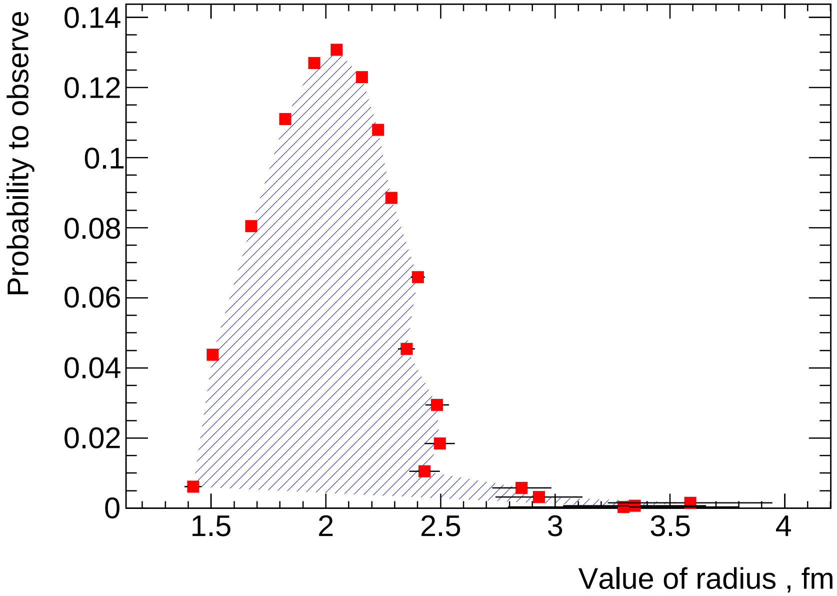

Figure 11: Radius probability function $\sqrt{S}$ = 7TeV

It is interesting to see that MEAN value of source radius is very close to TOTEM value and we have measured this value nearly one year before TOTEM.

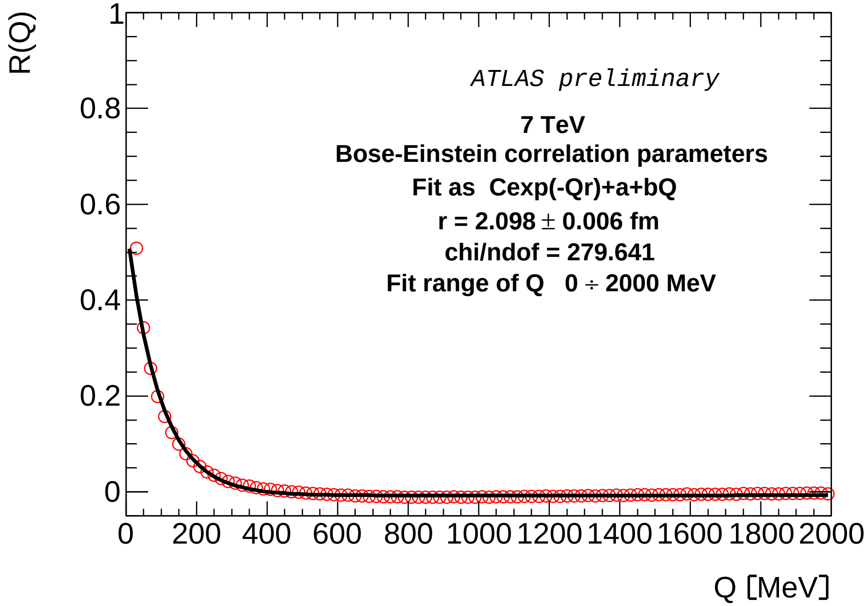

Figure 12: Proton radius no multipl selection $\sqrt{S}$ = 7TeV