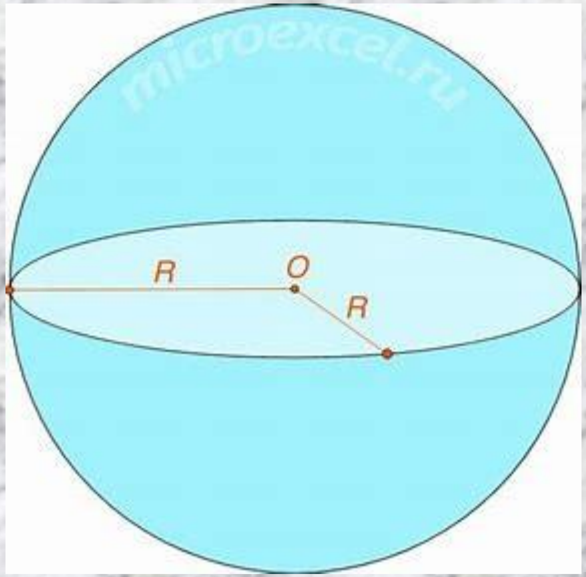
Семинар ОФВЭ
08.04.2025

О «радиусах» адронов



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Классический радиус протона

$$R_{\mathrm{CL}} = \frac{\alpha \hbar c}{M_p c^2} = \frac{\alpha}{M_p}$$

$$\boldsymbol{R_{CL} = 1,5 \cdot 10^{-3} fm}$$

Electron Scattering from the Proton*†‡

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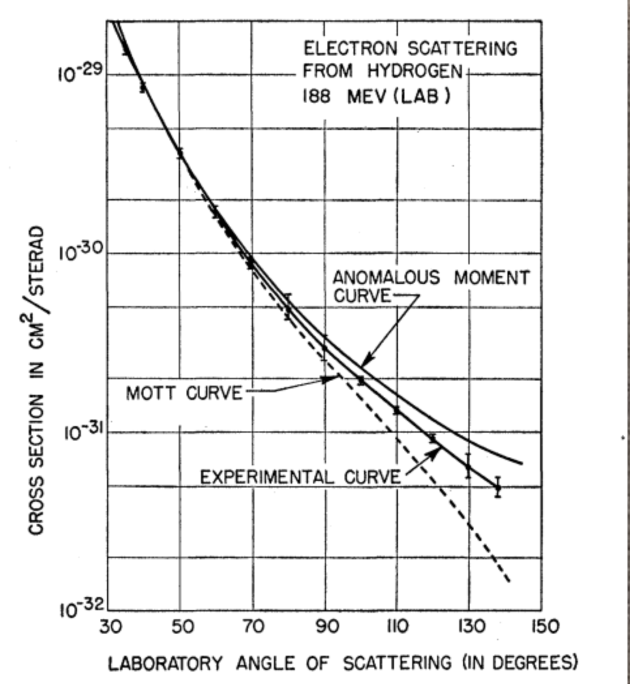
(Received January 24, 1955)



- "If the proton were a spherical ball of charge, this rms radius would indicate a true radius of $\mathbf{9.5 \times 10^{-14}}$**cm…" (0.95 fm)**

MEAN-SQUARE CHARGE RADIUS

Citation: S. Navas *et al.* (Particle Data Group), Phys. Rev. D **110**, 030001 (2024)

p CHARGE RADIUS

This is the rms electric charge radius, $\sqrt{\langle r_E^2 \rangle}$.

There are three kinds of measurements of the proton radius: via transitions in atomic hydrogen; via electron scattering off hydrogen; and via muonic hydrogen Lamb shift. Most measurements of the radius of the proton involve electron-proton interactions, the most recent of which is the electron scattering measurement $r_p = 0.831(14)$ fm (XIONG 19), and the atomic-hydrogen value, $r_p = 0.833(10)$ fm (BEZGINOV 19). These agree well with another recent atomic-hydrogen value $r_p = 0.8335(95)$ fm

$$\langle r^2 \rangle_{ch,p} = 0.707 \pm \ldots (fm)^2$$

sults available at the time, was 0.8751(61) fm. This differs by 5.6 standard deviations from the muonic hydrogen value, leading to the so-called proton charge radius puzzle. See our 2018 edition (Physical Review **D98** 030001 (2018)) for a further discussion of interpretations of this puzzle. However, reflecting the new electronic measurements, the 2018 CODATA, TIESINGA 21, recommended value is 0.8414(19) fm, and the puzzle appears to be resolved.

$$\langle r^2 \rangle_{ch,n} = -0.115 \pm \ldots (fm)^2$$

От зарядового «радиуса» к физическому радиусу нуклона

$$F(t) = \sum_{i \in val} e_i \int_0^1 dx\, f^i(x,t)$$

$$r_{ch}^2 = 6\frac{dF(t)}{dt}\Big|_{t=0}$$

$$f^i(x,t) = 2\pi \int_0^\infty db\, b J_0(b\sqrt{-t})\, \tilde{f}^i(x,b),$$

$$f^i(x, t=0) = f^i(x), i = u, d$$

$$F_p(t) = \frac{2}{3}\int dx\, u_p(x,t) - \frac{1}{3}\int dx\, d_p(x,t)\,,$$

$$F_n(t) = -\frac{1}{3}\int dx\, d_n(x,t) + \frac{2}{3}\int dx\, u_n(x,t)\,.$$

$$\langle r_u^2 \rangle = r_{\mathrm{ch},p}^2 + r_{\mathrm{ch},n}^2/2$$

$$\langle r_d^2 \rangle = r_{\mathrm{ch},p}^2 + 2r_{\mathrm{ch},n}^2\,.$$

$$\langle r_u^2 \rangle = (0.8056 \pm 0.0011 \text{ fm})^2\,, \quad \langle r_d^2 \rangle = (0.6891 \pm 0.0017 \text{ fm})^2$$

$$\sqrt{r_{nucleon}^2} \approx 0.77 fm.$$

$$\sqrt{r_{ch,proton}^2} \approx 0.84 fm.$$

Physical radii

$$r_{proton}^2 = r_{neutron}^2 \equiv r_{nucleon}^2 = r_{ch,proton}^2 + r_{ch,neutron}^2.$$

MESONS

$K^+ = u\bar{s}$

Charge radius

$\langle r \rangle = 0.560 \pm 0.031$ fm

$\langle r \rangle = \langle r^2 \rangle^{1/2}, \langle r^2 \rangle = 0.313 \pm 0.001\, fm^2$

$K^0 = d\bar{s}$

Mean square charge radius

$\langle r^2 \rangle = -0.077 \pm 0.010$ fm^2

$$F_{K^+}(t) = \frac{2}{3}\int dx\, u_{K^+}(x,t) + \frac{1}{3}\int dx\, \bar{s}_{K^+}(x,t), \quad F_{K^0}(t) = -\frac{1}{3}\int dx\, d_{K^0}(x,t) + \frac{1}{3}\int dx\, \bar{s}_{K^0}(x,t)$$

$$SU_f(3): d_{K^0}(x,t) = u_{K^+}(x,t);\ \bar{s}_{K^0}(x,t) = \bar{s}_{K^+}(x,t)$$

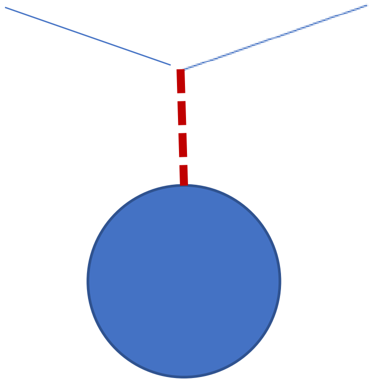
$$\langle r^2 \rangle_{\langle K^+ \rangle} = \frac{2}{3}\bar{r}_u^2(K^+) + \frac{1}{3}\bar{r}_{\bar{s}}^2(K^+);\ \langle r^2 \rangle_{\langle K^0 \rangle} = -\frac{1}{3}\bar{r}_u^2(K^+) + \frac{1}{3}\bar{r}_{\bar{s}}^2(K^+)$$

$\bar{r}_u^2(K^+) = 0.39 fm^2$ $\quad$ $\bar{r}_{\bar{s}}^2(K^+) = 0.16 fm^2$

Physical radii: $\bar{r}_{K^+}^2 = \bar{r}_{K^0}^2 = 0.275 fm^2 = (0.525\, fm)^2$

«Гравитационный радиус» протона. Сопромат внутри адрона?

- $$R_{grav}^{proton} = \frac{2Gm_{proton}}{c^2} \approx 2{,}5 \cdot 10^{-38}\ fm$$
- Взаимодействие гравитации с материей
- $$\int d^4\sqrt{-g}\, T_{\mu\nu} h^{\mu\nu}, \qquad g^{\mu\nu} \approx \gamma^{\mu\nu} + h^{\mu\nu}$$



$$\langle p' | T_{\mu\nu} | p \rangle = \sum_j \Lambda_{\mu\nu}^{j}\,(p', p) G_j(t)$$

$$r_g^2 = 6\frac{dG(t)}{dt}_{t=0} \approx (0.45\ fermi)^2 \to \sum_a \int dx x r_a^2(x) f_a(x, \mu^2)$$

“Mass structure and pressure forces inside the nucleon…”

Расстояние и время

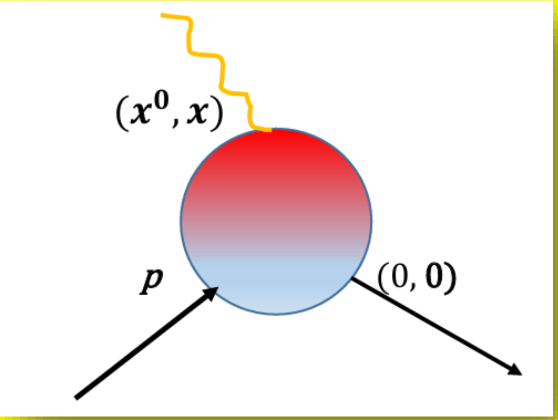
$$F(t) = \frac{2p_\mu}{4m^2 - t}\langle p'|J_\mu|p\rangle = \int d^4x\, e^{iqx}\left\langle \Omega\left|\frac{\delta J_\mu(x)}{\delta\varphi^+(0)}\right|p\right\rangle, t = q^2$$

$$\frac{\delta J_\mu(x)}{\delta\varphi^+(0)} = i\theta(-x^0)\left[J_\mu(x), I^+(0)\right],$$

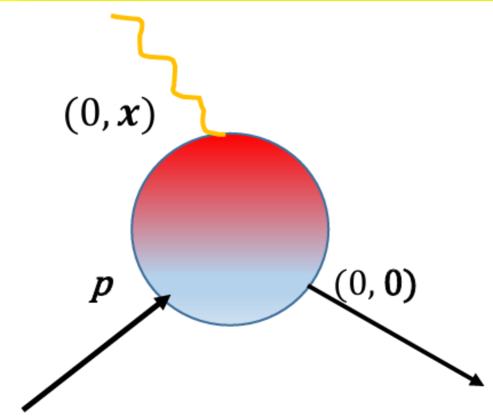
$$I^+(x) = (\partial^2 + m^2)\,\varphi^+(x)$$

$$r_{ch}^2 = \int d\,r\, r^2\,\rho_{ch}(r)$$

$$\rho_{ch}(r) = \frac{1}{2m}\int d\,x^0\left\langle \Omega\left|\frac{\delta J_0(x^0, r)}{\delta\varphi^+(0)}\right|p = 0\right\rangle$$



$$\left\langle \Omega\left|\frac{\delta J_0(x^0,\ r)}{\delta\varphi^+(0)}\right|p = 0\right\rangle_{c\to\infty} \sim \delta(x^0)$$



О пространственном размере

$$ds^2 = g_{\mu\nu} dx^\mu dx^\nu = c^2 d\tau^2 - dl^2$$

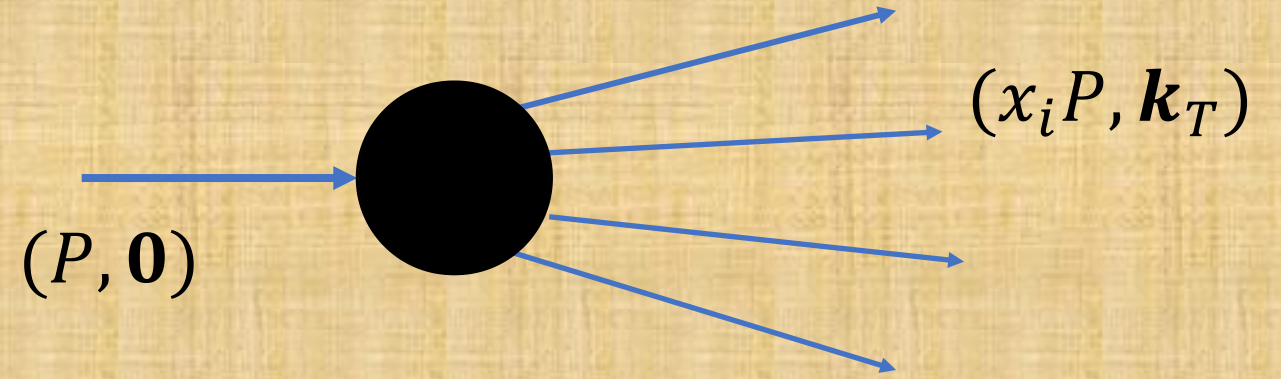
$$d\tau = \sqrt{g_{00}}dt + \frac{g_{0i}dx^i}{c\sqrt{g_{00}}}$$

$$dl^2 = (-g_{ik} + g_{0i}g_{0k}/g_{00})dx^i dx^k$$

$$dl^2 = -ds^2_{d\tau=0}$$

$$\left\langle \Omega \left| \frac{\boldsymbol{\delta J_0}(x^0, \ \boldsymbol{r})}{\boldsymbol{\delta\varphi}^+(\mathbf{0})} \right| \boldsymbol{p} \right\rangle ? \rightarrow \left\langle \Omega \left| \frac{\boldsymbol{\delta J_0}(\mathbf{0}, \ \boldsymbol{r})}{\boldsymbol{\delta\varphi}^+(\mathbf{0})} \right| \boldsymbol{p} \right\rangle$$

Parton picture (Bjorken-Feynman-Грибов)



$$\Delta t = \frac{2P}{\sum_i \frac{m_{T,i}^2}{x_i} - M^2}$$

$$\tilde{g}(x, \mathbf{b}) = c g(x, 0) \exp(-b^2/R^2(x))/\pi R^2(x).$$

$$\tilde{g} = \sum_n n \tilde{g}_n$$

$$R^2(x \ll 1) \approx 4\alpha'_{\mathbb{P}} ln(1/x) + b_0^2.$$

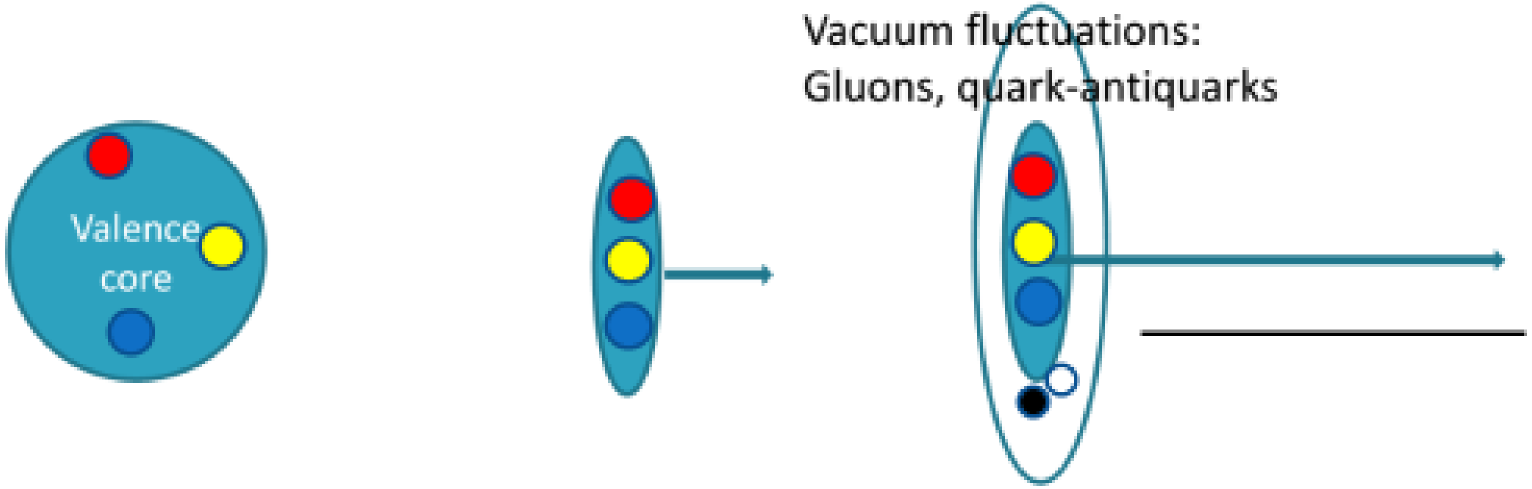
$$? \leftrightarrow \left(r_{nucleon}^{val}\right)^2$$

$$w = \sum_n \tilde{g}_n$$

$$r_{nucleon}^{val} = 0.77 fm.$$

$$w \rightarrow \sum_n n \tilde{g}_n / \langle n \rangle$$

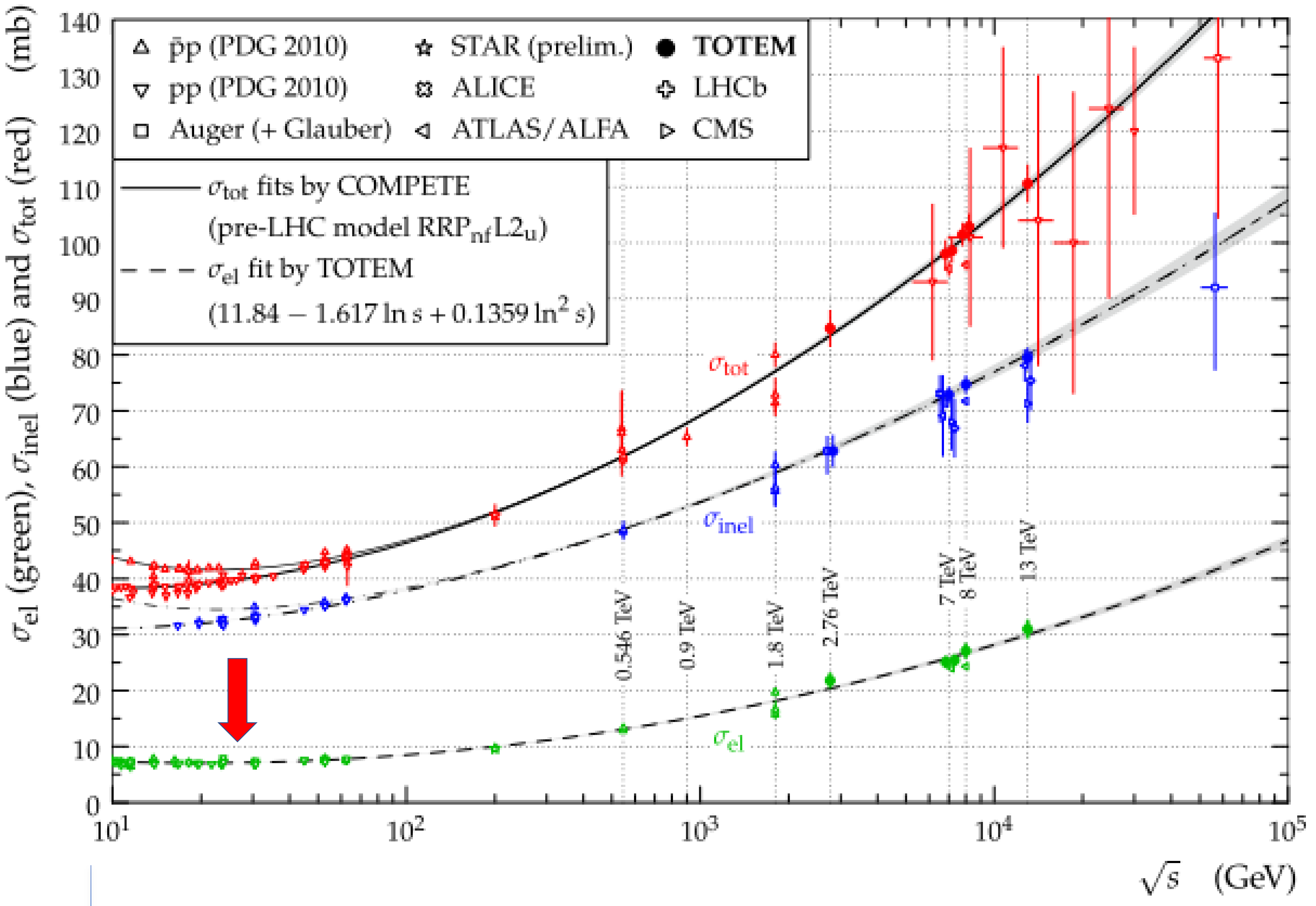
- **Moving nucleon's spatial structure**



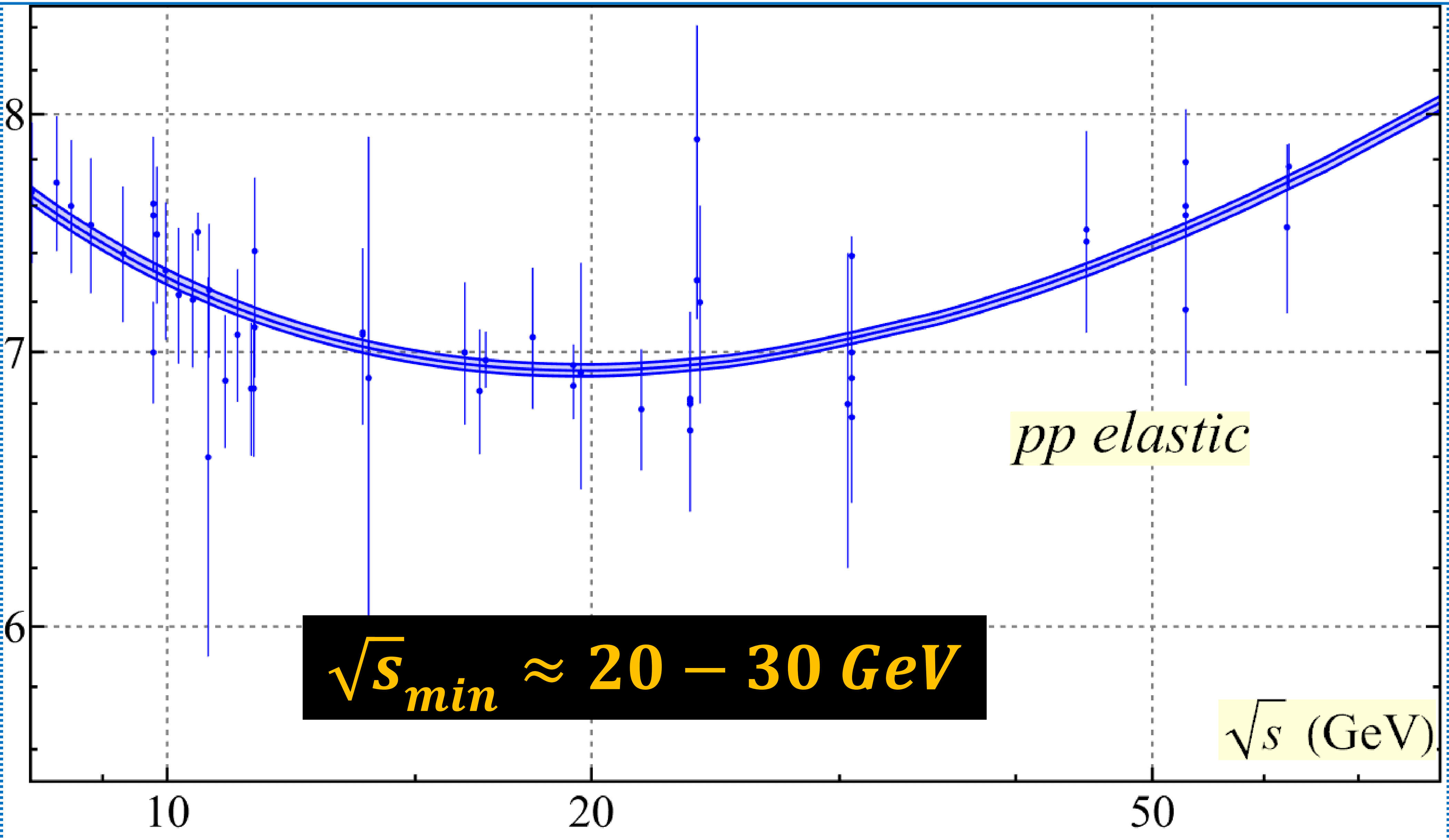
$$P = P^* \equiv \Lambda \exp\{(b_N^2 - b_0^2)/[4\alpha'_{\mathcal{P}}(0)\gamma(\Delta ln(P^*/\Lambda)]\}$$

$$\gamma(x) = \frac{e^x}{e^x - 1} - \frac{1}{x}.$$

$$\boldsymbol{P^* \approx 10\ \mathrm{GeV}}$$



p̄p (PDG 2010)
pp (PDG 2010)
Auger (+ Glauber)
STAR (prelim.)
ALICE
ATLAS/ALFA
TOTEM
LHCb
CMS
σ_{tot} fits by COMPETE
(pre-LHC model $RRP_{nf}L2_u$)
σ_{el} fit by TOTEM
$(11.84 - 1.617 \ln s + 0.1359 \ln^2 s)$
σ_{tot}
σ_{inel}
σ_{el}
0.546 TeV
0.9 TeV
1.8 TeV
2.76 TeV
7 TeV
8 TeV
13 TeV
σ_{el} (green), σ_{inel} (blue) and σ_{tot} (red) (mb)
$\sqrt{s}$ (GeV)



8
7
6
10
20
50
pp elastic
$\sqrt{s}_{min} \approx 20 - 30\ GeV$
$\sqrt{s}$ (GeV)

(Промежуточные) выводы

1. Физический (геометрический) радиус адрона не определяется, но выводится из «формфакторных радиусов».

Проблема : неодновременность.

Два факта:

2. Упругое сечение в протон – протонном рассеянии переходит в интервале энергий в с. ц. м $\mathbf{20 \div 30}$ ГэВ от убывания к росту.

3 . Глюонное облако выходит за пределы валентного кора при достижении протоном энергии порядка 10 ГэВ.