Studying periphery of the nucleon in diffractive scattering at SPD

V. Baskov, O. Dalkarov, A. L’vov, V. Poliansky
LPI RAS, Moscow

Supported by the RFBR grant № 18-02-40061
(O. Dalkarov)

The Conference «RFBR Grants for NICA», JINR, 20-23 Oct 2020

Objectives of the RFBR grant 18-02-40061-mega

- LPI team: O. Dalkarov, V. Andreev, V. Baskov, S. Gerassimov, A. L'vov, P. Nechaeva, M. Negodaev, V. Polyansky, S. Souchkov, A. Terkulov, N. Topchiev

  - Development and implementation of components of reconstruction software for tracks, vertex and clusters in electromagnetic calorimeter, optimization of detectors for SPD experiment on NICA accelerator at Dubna. ⇒ V. Andreev, yesterday

  - Study of diffraction processes in small-angle scattering of polarized particles. ⇒ A. L’vov, present talk

  - Upgrade of the S-25R Pakhra calibration beam line. ⇒ V. Baskov, today

  - Deployment of setup for pixel detector and electromagnetic calorimeter prototypes tests. ⇒ P. Nechaeva, today

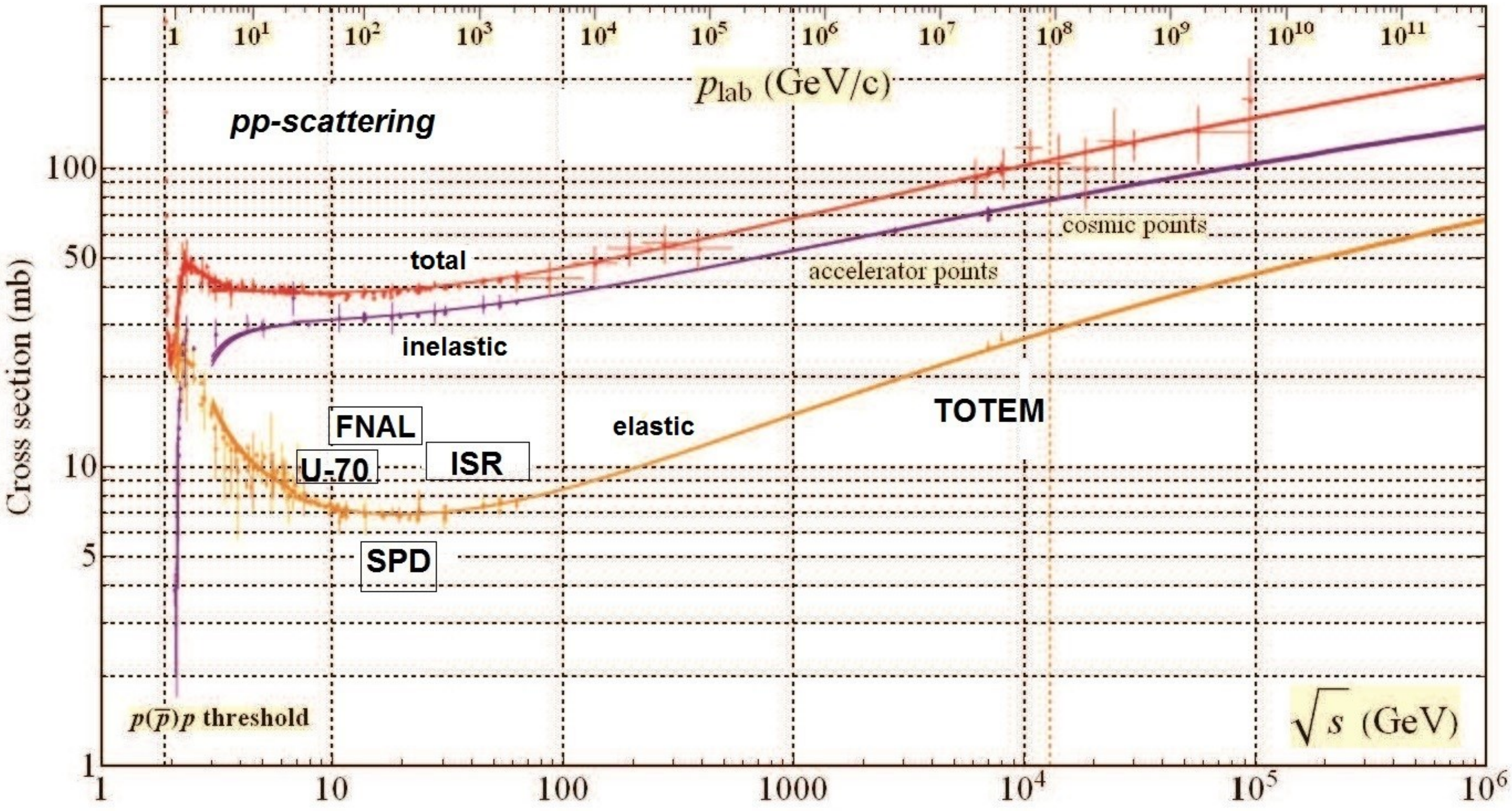
Data on the total cross section of high-energy pp interaction

- Energy range of SPD is in between that of U-70 (Protvino), old FNAL and ISR

- Registration of pp pairs in SPD can be used as a luminosity monitor of collisions

In the region of SPD, the most precise data are from U-70, ISR and FNAL.

Syst = 4%, 2-3.5%, 4%, resp.



Approximate scale of the diffractive scattering amplitude at low t (but beyond the Coulomb region):

Imaginary part of the amplitude (absorption) strongly dominates and

$$d\sigma/dt = |f(t)|^2 \approx A \exp(Bt)$$

Profile function $\Gamma(b)$ (amplitude distribution in the transverse plane)

$$\Gamma(b) \sim \int q\, dq\, f(q)\, J_0(qb) \sim \exp(-b^2/2B)$$

$$\sqrt{\langle b^2 \rangle} \approx \sqrt{B} \sim 0.7 \text{ fm} \quad \text{at energies of SPD.}$$

Rapid variations in t correspond to large distances (large impact parameter) b.

Differential cross sections of pp scattering (Protvino)

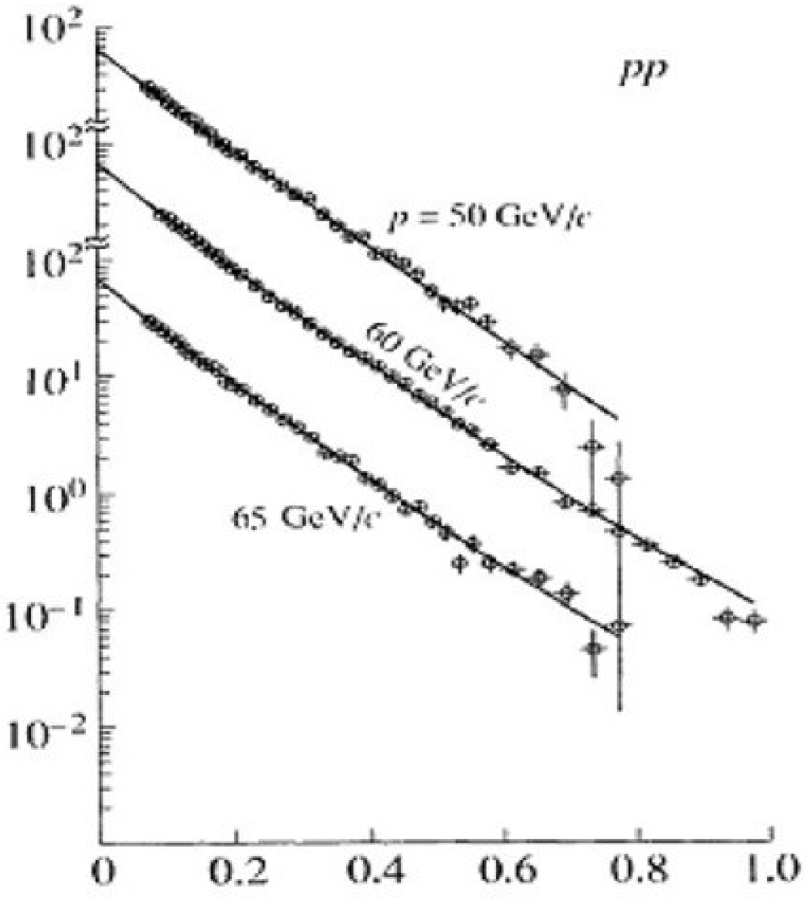
- Diff. cross sections and deviations from the reference exponential form *$\exp(Bt + Ct^2)$ at $\sqrt{s} \sim 11$ GeV.*

- Such deviations were observed on repeated occasions at various machines and energies.

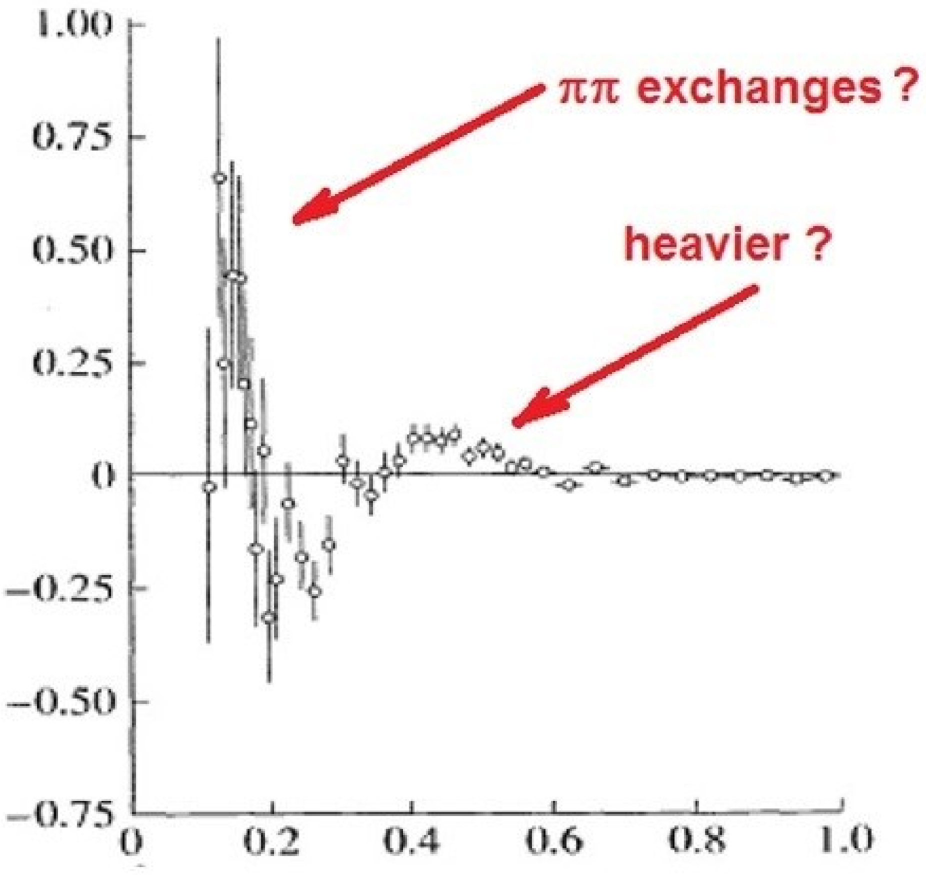
- Diff. cross sections fitted with a squared exponential (left) and the difference between the 60 GeV data and their fitted values (right)

- **Thanks to S.P. Denisov for introducing us to this problem !!**

$d\sigma/dt$, mb/(GeV/c)^2



$(d\sigma/dt) - (d\sigma/dt)_{fit}$, mb/(GeV/c)^2



$|t|$, (GeV/c)^2

Antipov et al. preprint 1976.
Denisov et al. Yad.Fiz. 79 (2016) 121.

pp scattering (Protvino)

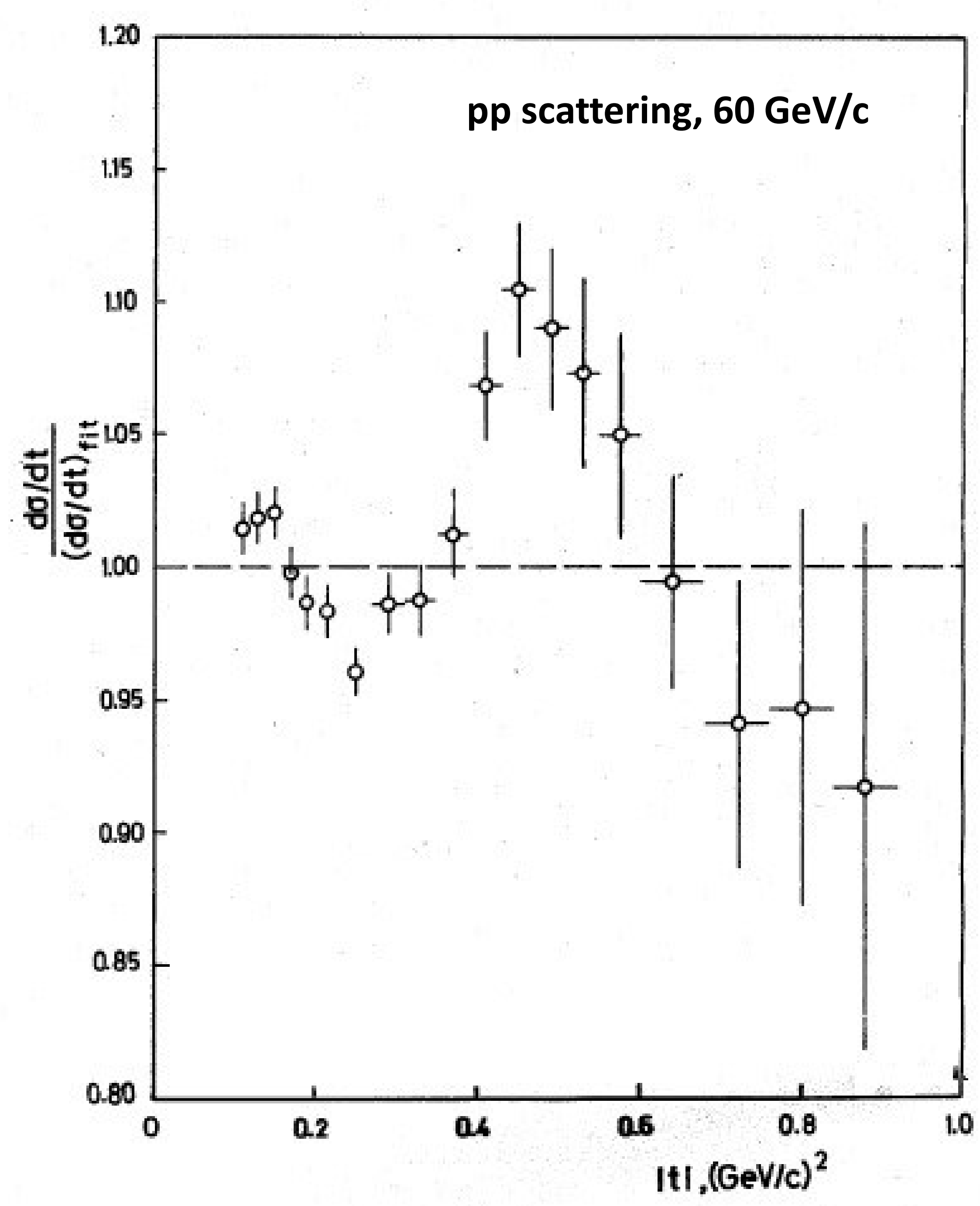
$$R = (d\sigma/dt)_{exp} \,/\, (d\sigma/dt)_{fit} \quad ;$$

$$(d\sigma/dt)_{fit} = A \exp(Bt + Ct^2)$$

Antipov et al. preprint 1976.

Dedicated data collected for testing observations of ISR of rapid variations at very low t ~ 0.1 GeV^2.

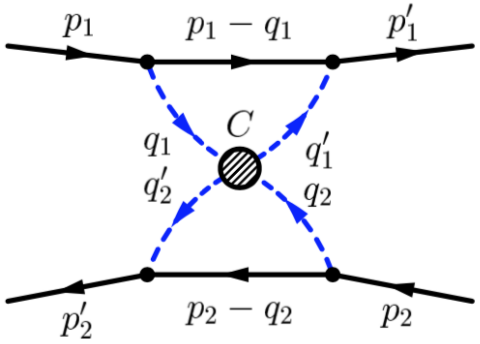
Surprise: another variation at higher t was also observed.



Two-pion effect at low t

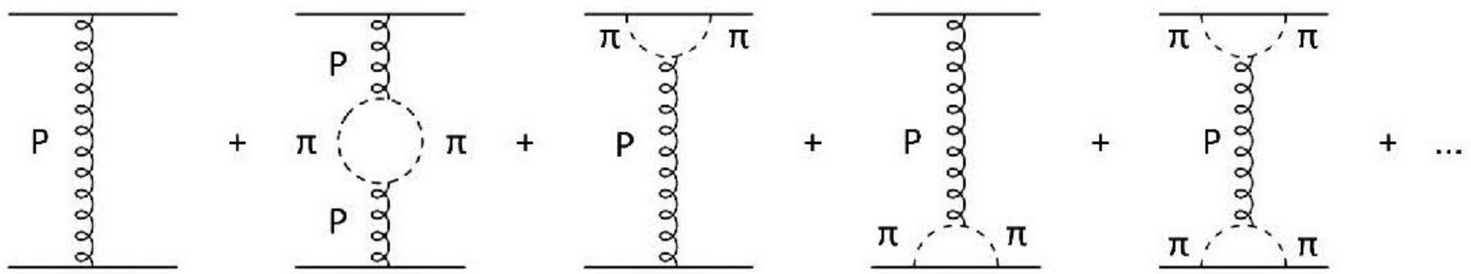
Large impact distances suggest that exchanges with light particles (pions) are responsible for irregularities in the differential cross section at small t.

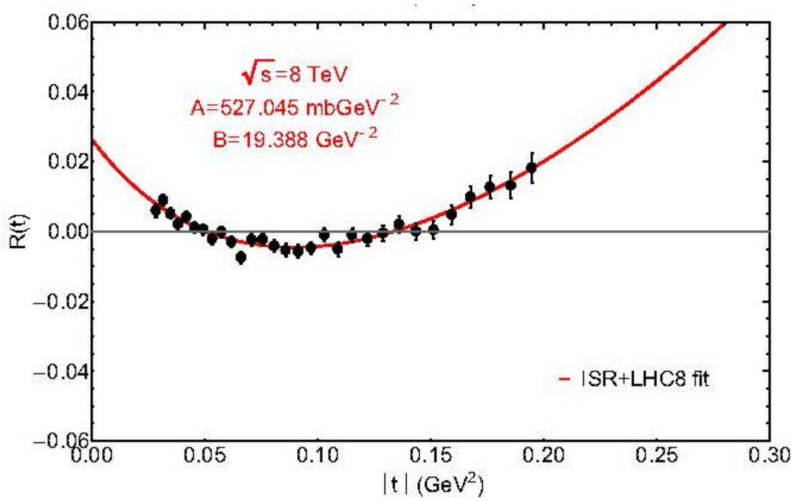
A. Anselm, V. Gribov. "Zero pion mass limit in interaction at very high energies". Phys. Lett. 40B (1972) 487.



Jenkovszky: Two-pion exchanges explain irregularities in diffractive high-energy data up to LHC energies.

L. Jenkovszky et al. "Shape of proton and the pion cloud". Eur. Phys. J A (2018) 54.





TOTEM

However, this concerns only very low -t ~ 0.1 GeV^2

Impact parameter interpretation of the second peak ?
(just an estimate)

In the impact parameter space

$$\frac{d\sigma}{dt} = |f(s,t)|^2 \approx \frac{\sigma_t^2}{16\pi} e^{Bt}, \qquad \mathrm{Im}\, f(s,0) = \frac{\sigma_t}{\sqrt{16\pi}},$$

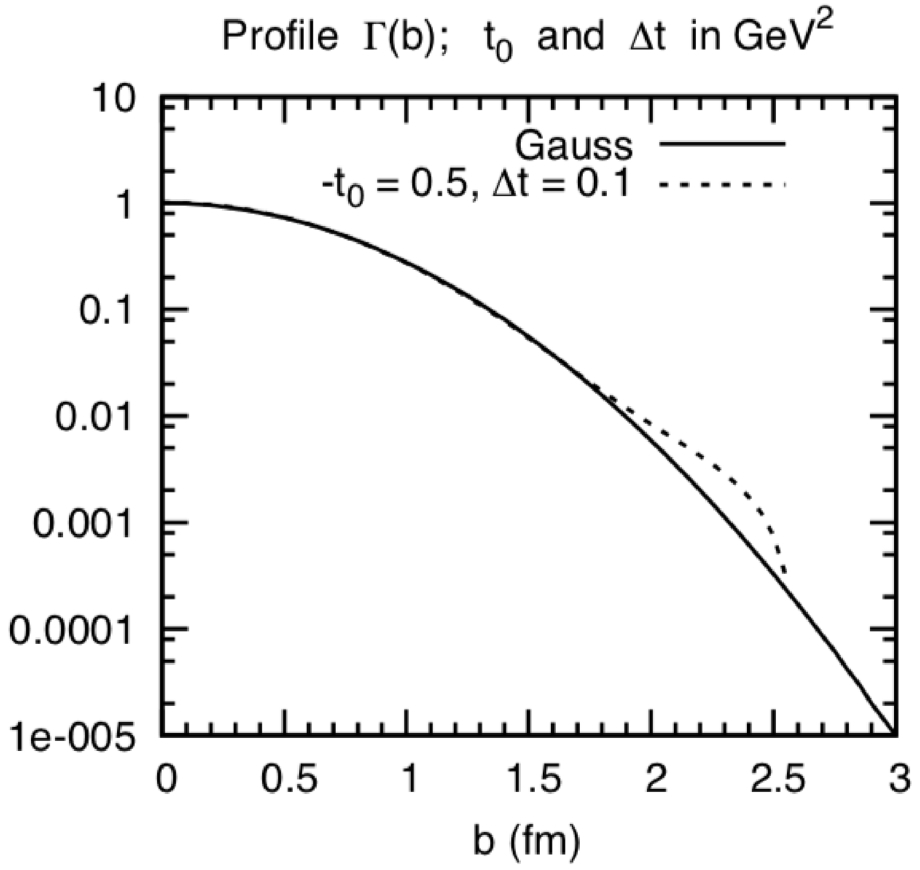
$$\Gamma(s,b) = \frac{1}{2i\sqrt{\pi}} \int_0^\infty f(s,t) J_0(b\sqrt{|t|})\, d|t|.$$

Let's assume $f(t) \propto ie^{Bt/2}$, therefore the corresponding $\Gamma(b) \propto \exp(-b^2/2B)$

If we add the local amplitude $f(t)$ enhancement at the point $t = t_0 = -0.5\ GeV^2$

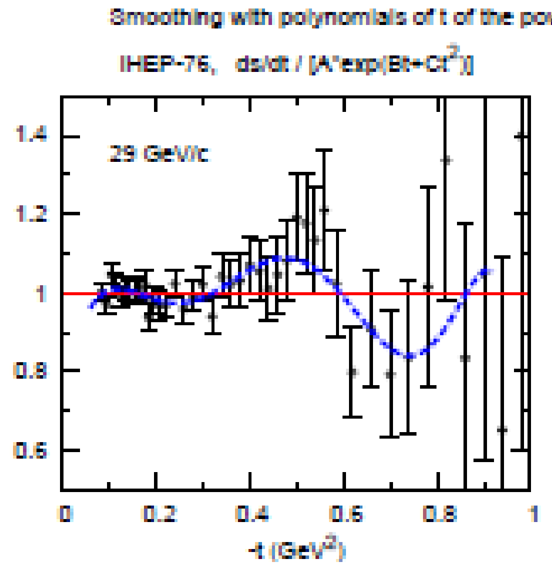
$$f(t) \to ie^{Bt/2}\left[1 + \epsilon\ \exp\left(-\frac{(t-t_0)^2}{2\Delta t^2}\right)\right]$$

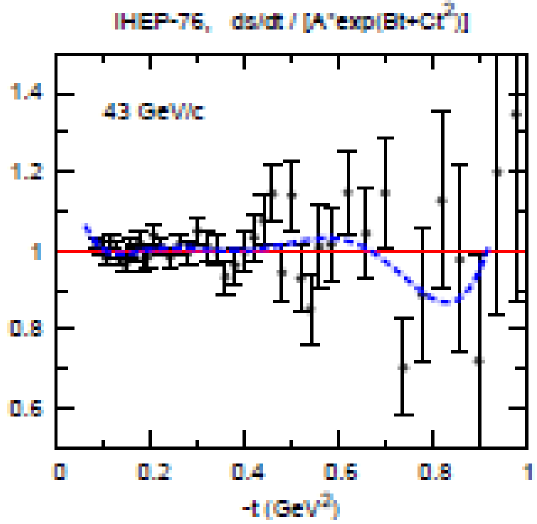
we'll see some enhancement in the corresponding $\Gamma(b)$ in the impact parameter region $b \sim 2\ fm$ $(\epsilon = 0.1)$

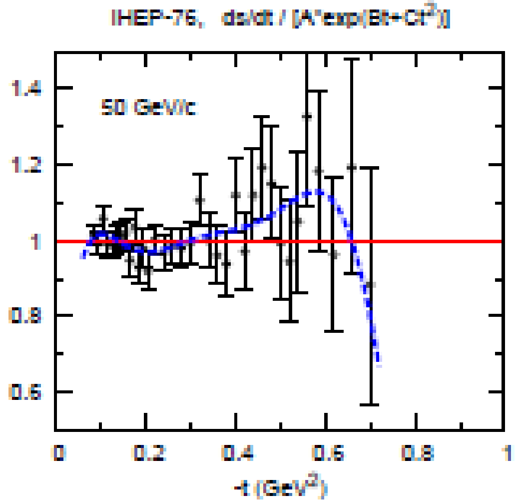


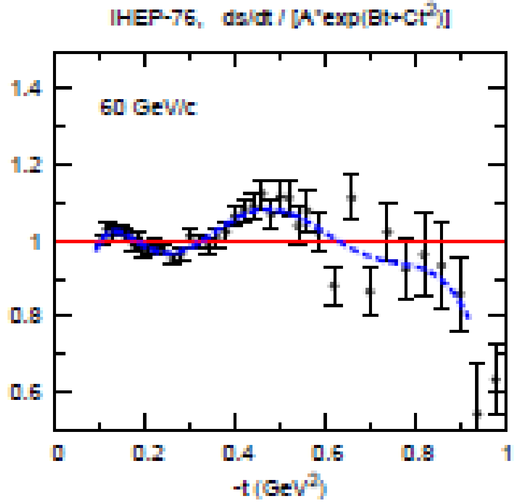
Data of several exps

pp scattering (Protvino 1976) - Antipov et al.

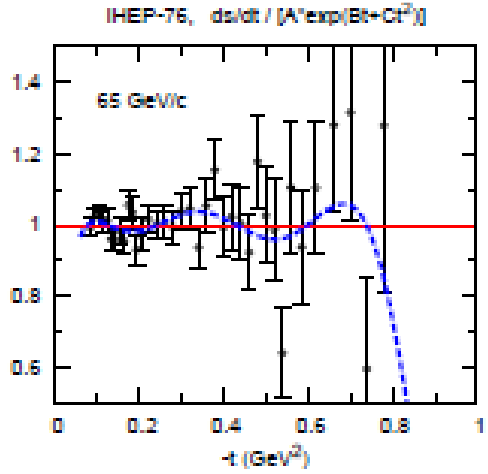








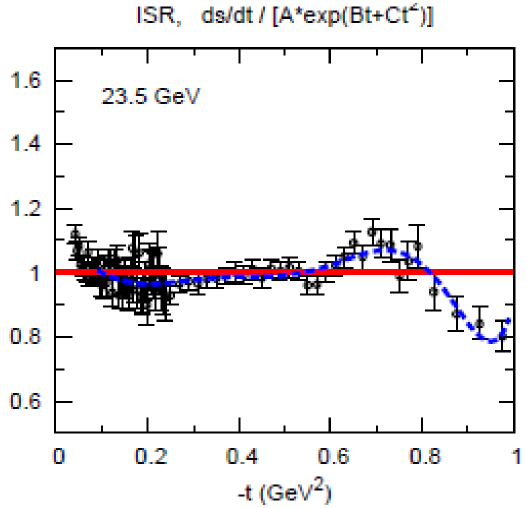
Specially high statistics !

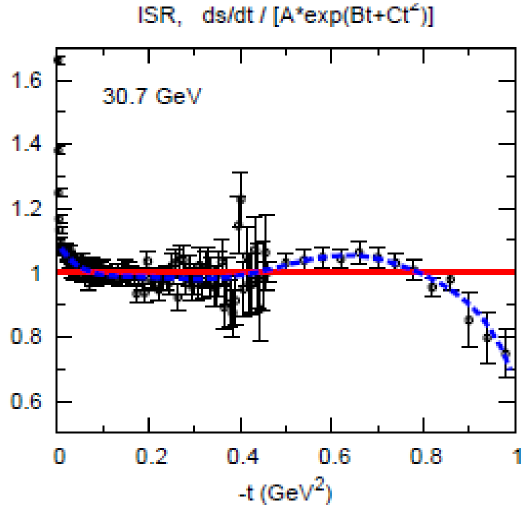


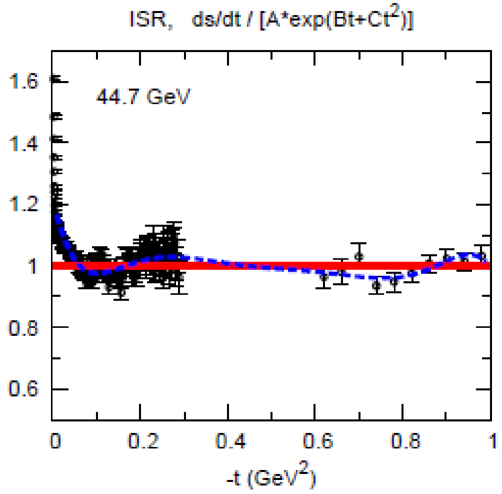
t dependence of (ds/dt)/exp_FIT

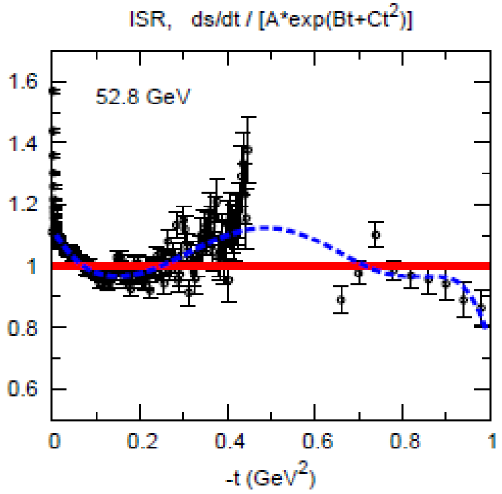
A polynomial smoothing (blue lines) is used in integration over t and finding the profile function Γ(b)

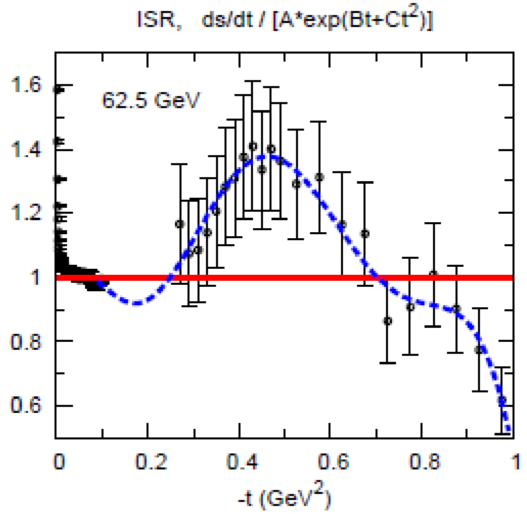
pp scattering, ISR – Amaldi et al





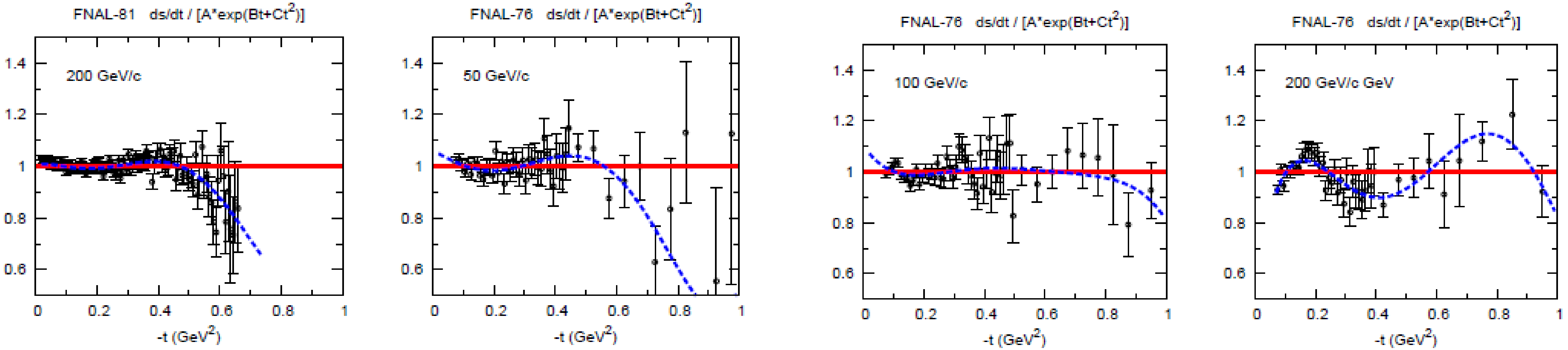






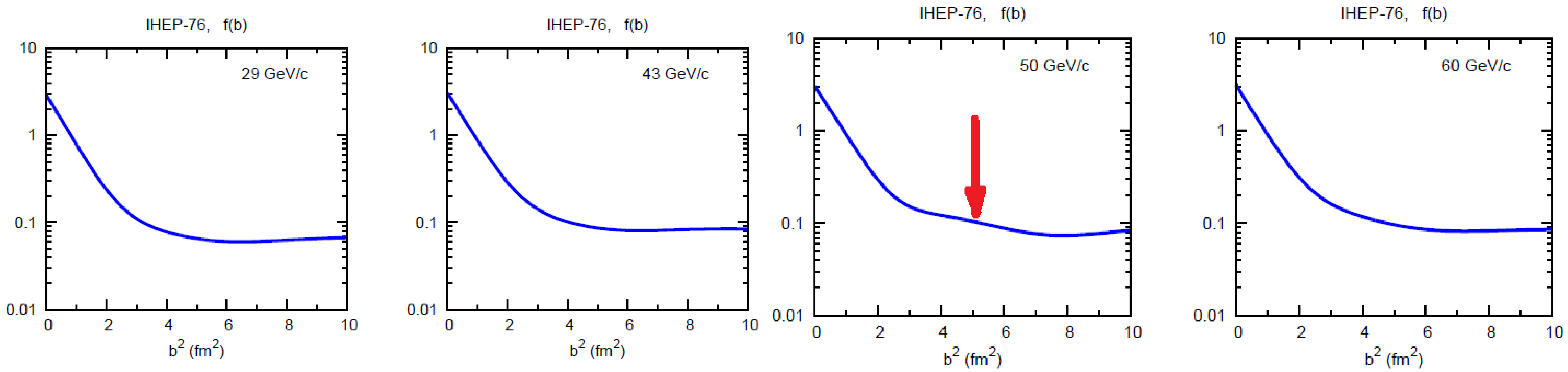
t dependence of (ds/dt)/exp_FIT

pp scattering, FNAL 1981, 1976 - Schiz et al, Akerlof et al.



t dependence of (ds/dt)/exp_FIT

Profile functions Γ(b) estimated from data



Gaussian distribution ~exp($-b^2/2B$) [straight line vs b^2 in log scale] is valid at small b.

At b > 2 fm there is a saturation ?! (meson tail?)

Very similar plots for Γ(b) arise from ISR and FNAL data sets too.

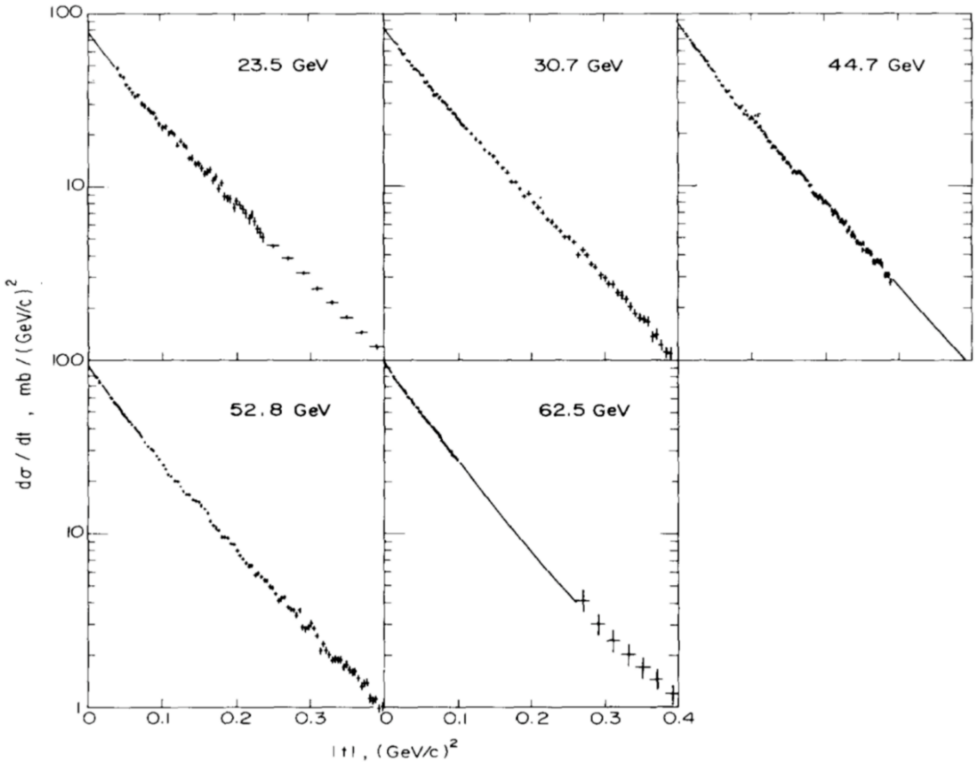
Impact parameter interpretation of the second peak ? (just an estimate)

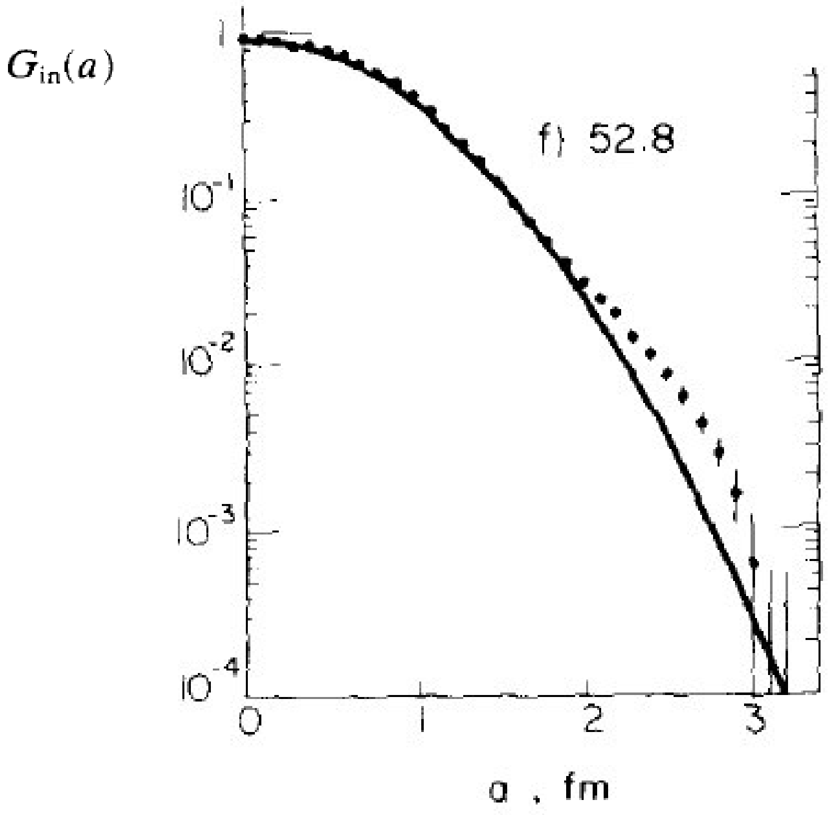
Data from U-70 and some others indicate anomaly in the differential cross section at $-t = 0.4 - 0.5$ GeV^2 ($\gg 4m_\pi^2$).
Perhaps it is relatied with heavier than pion exchanges existing in the proton structure (σ-meson??).

Physics of this phenomenon is a very good task for SPD experiment. In the range of $-t \sim 0.4 - 0.5$ GeV^2 there is almost no data on the diffractive pp-scattering: the accuracy decreases when $-t$ increases from $0.1 - 0.2$ GeV^2 to $0.4 - 0.5$ GeV^2.

The main experimental problem is getting good resolution in t (better than 0.01-0.02 GeV^2).

ISR data (pp collisions)





In the notations of the review paper of ref. [26], the unitarity condition is

$$2\,\mathrm{Re}\,\Gamma(a) = |\Gamma(a)|^2 + G_{in}(a)\,, \tag{6}$$

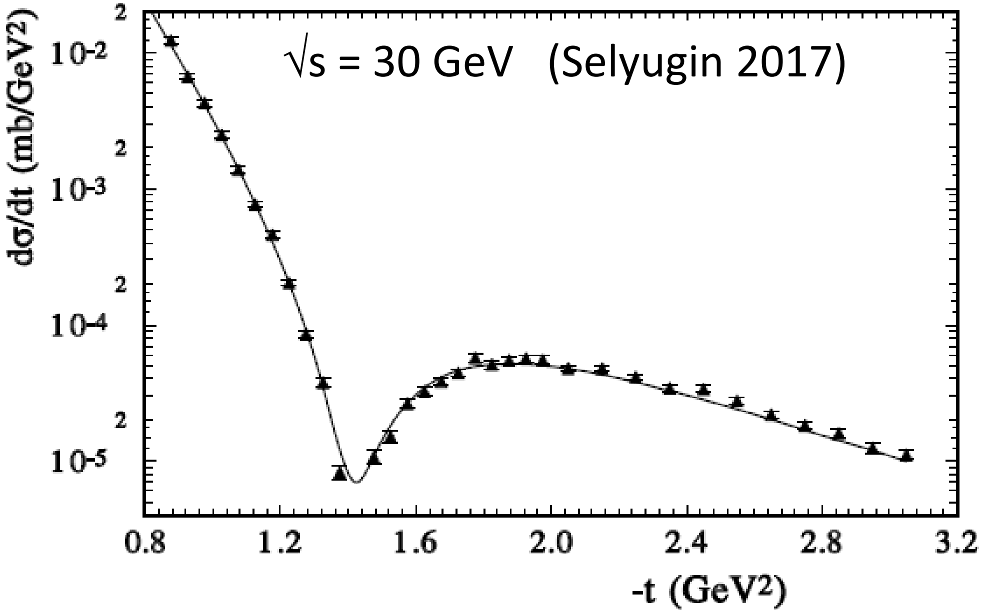
where $\Gamma(a)$ is the elastic "profile function" defined as

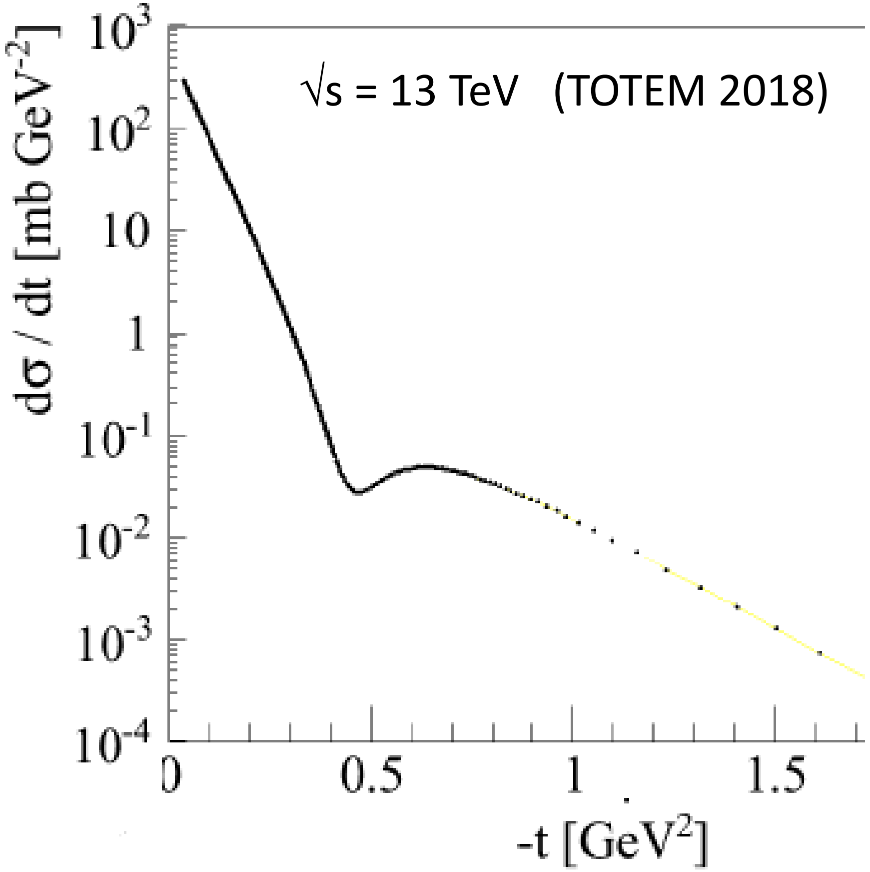
$$\Gamma(a) = \frac{1}{i\hbar c\sqrt{\pi}} \int_0^\infty \mathrm{d}q\, q f(q) J_0(qa/\hbar c)\,, \tag{7}$$

and $G_{in}(a)$ is the (real) inelastic overlap integral in impact parameter space; J_0 is the

U. Amaldi, K.R. Schubert. "Impact parameter interpretation of proton-proton scattering from a critical review of all ISR data ". Nucl. Phys. B166 (1980) 301.

pp-scattering at very high energies



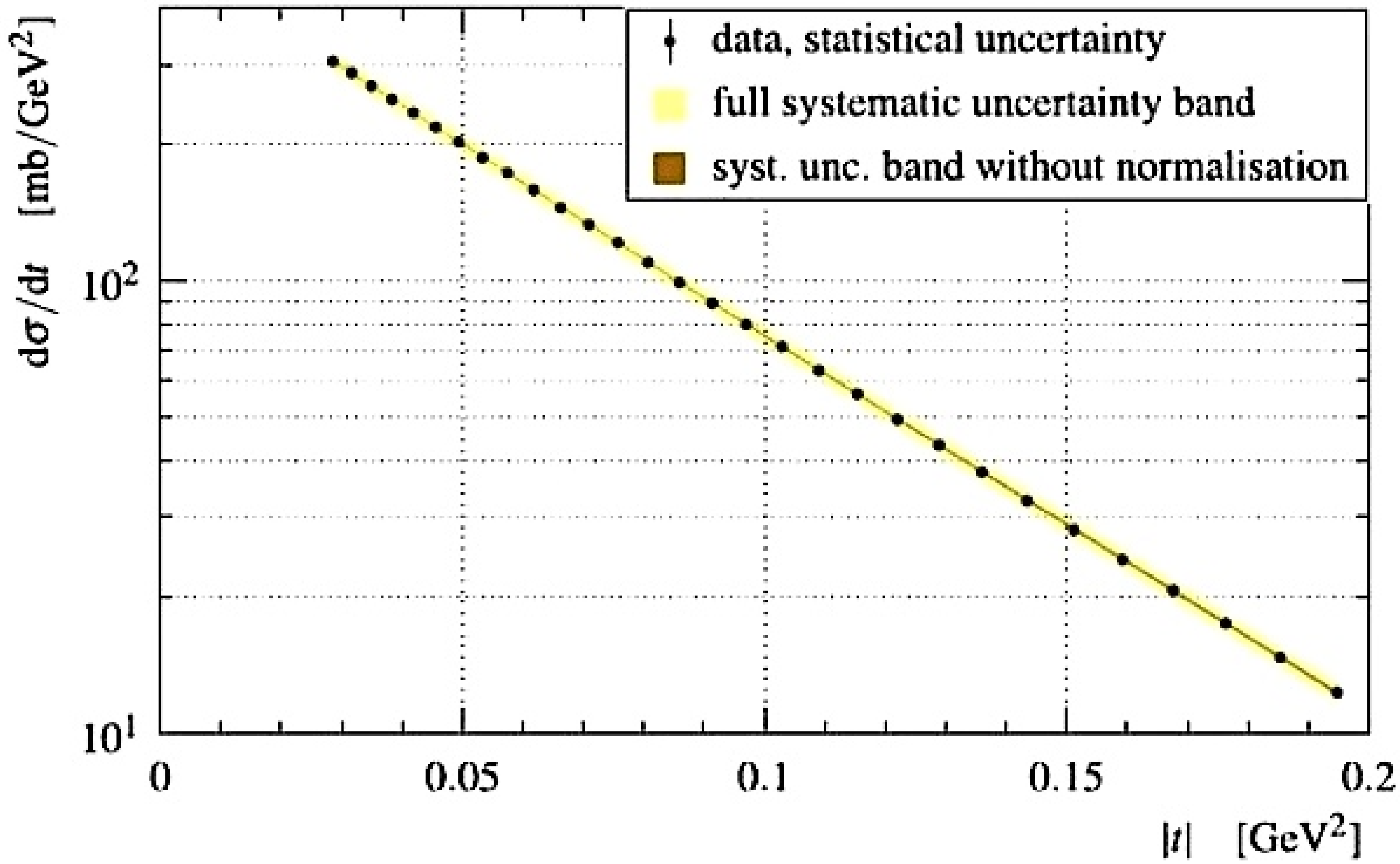


See also O.V.Selyugin. Arxiv: 2009.10129
“Anomaly in the differential cross sections at 13 TeV”

pp-scattering at very high energies

TOTEM data are very precise. In 2018 they have been extended to higher t.

Ref:
TOTEM Collab. (LHC), 2015
“Evidence for non-exponential elastic proton–proton differential cross-section at low |t | and √s = 8 TeV by TOTEM Collaboration”.
Nucl. Phys. B 899 (2015) 527.



ISR data (pp collisions)

U. Amaldi, K. R. Schubert / Review of all ISR data 317

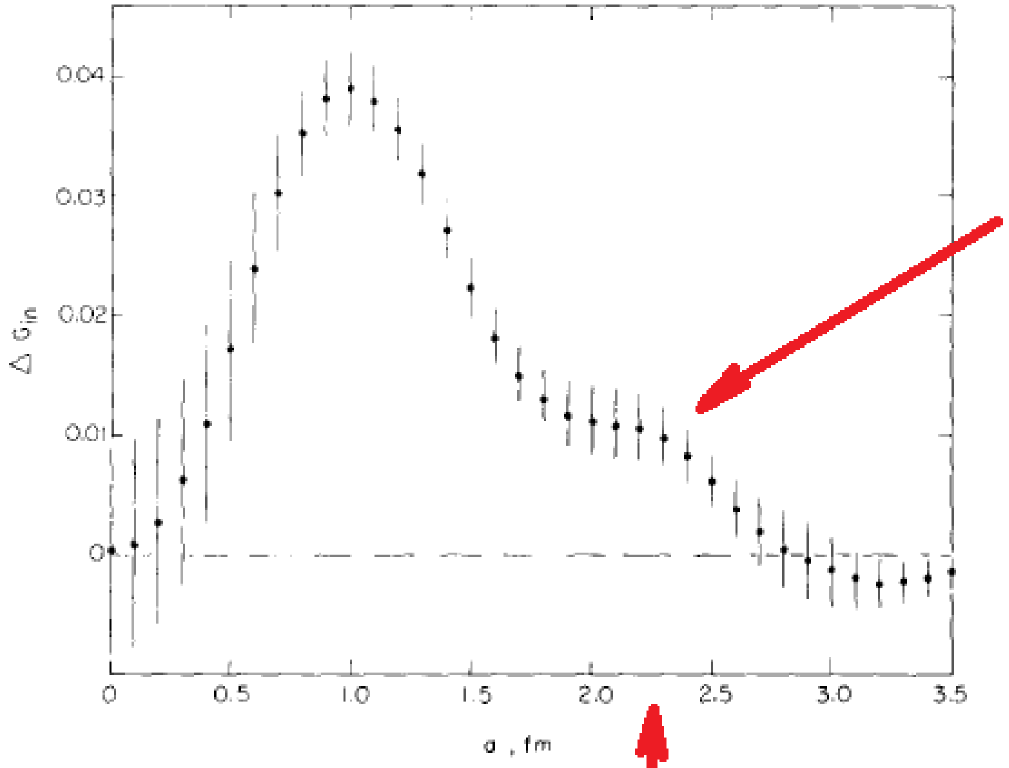
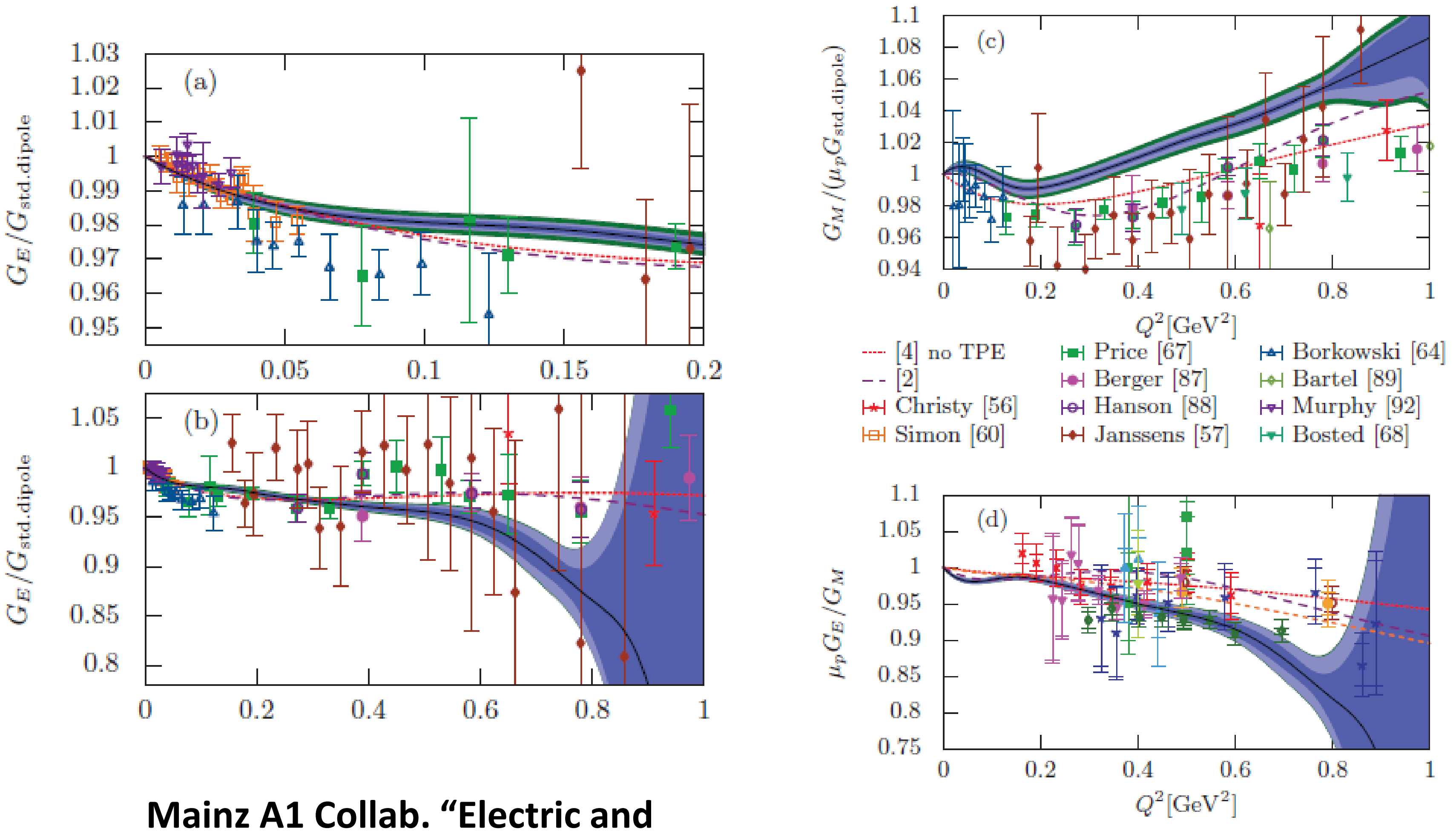


Fig. 8. Increase ΔG_{in} of the inelastic overlap function over the ISR energy range as a function of the impact parameter; ΔG_{in} is obtained by using eq. (14) and the results at all five energies.

U. Amaldi, K.R. Schubert. "Impact parameter interpretation of proton-proton scattering from a critical review of all ISR data ". Nucl. Phys. B166 (1980) 301.

Cf. EM form factors of the proton



In models using EM formfactors of the proton for describing proton-Reggeon couplings one has to remember an accuracy of available data on the formfactor.

At the scale of a few per cent, EM formafactors of the proton show irregularities at medium Q^2 below 1 GeV^2 (deviations from a simple dipole Ansatz).

Mainz A1 Collab. "Electric and magnetic form factors of the proton". Phys. Rev. C90 (2014) 015206.

Preliminary conclusion

Deviations from the Gaussian diffraction behavior of the differential cross section of elastic pp scatterimg are firmly established at very low $-t \sim 0.1$ GeV^2 ($\approx 4m_\pi^2$), both at medium and very high energies $\sqrt{s}$.
They are probably related with collisions of two pion clouds of the colliding protons.

At $-t \sim 0.4$-0.5 GeV^2 some smaller deviation are seen at medium energies in two experiments (p = 60 GeV/c at Protvino, $\sqrt{s}$ = 58.5 GeV at ISR). Meanwhile they are not found in Fermilab measurements at p = 200 GeV/c reaching statistical accuracy compatible with that of U-70 and ISR.

Anyway, diffractive pp scattering at low t is an interesting subject, and it certainly deserves a detailed study at NICA SPD which is quite suitable for that (see below).

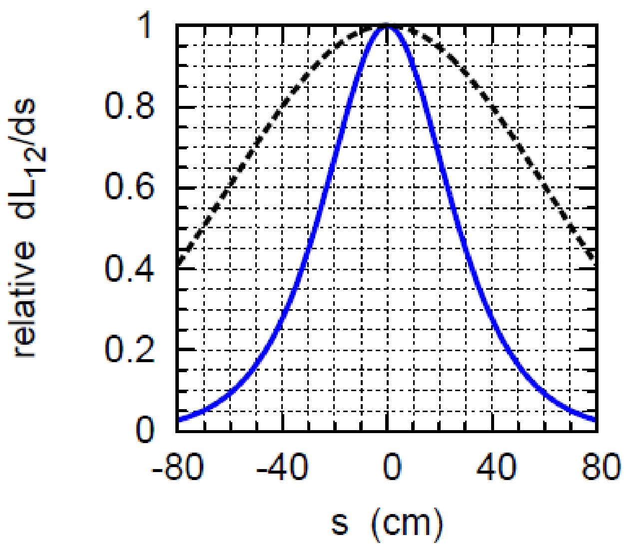
Diffractive pp-scattering @ SPD

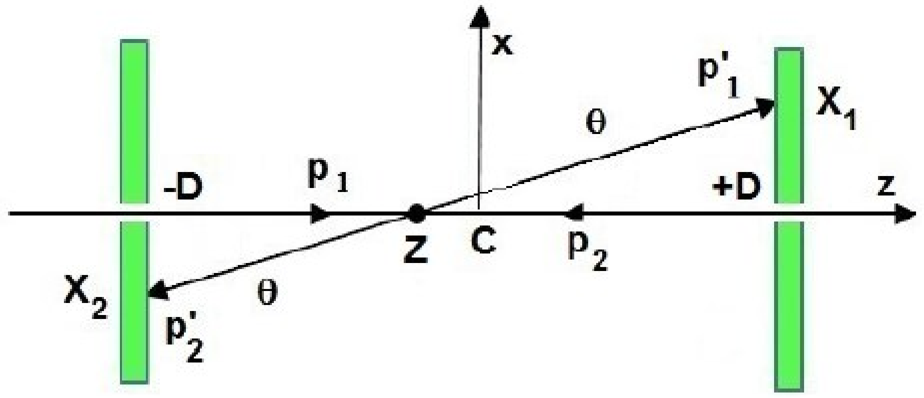
L = 10^{32} (begin with L = 10^{30})

pp collisions 4 MHz (average in time)
pp elastic 0.7 MHz
pp elastic with –t>0.2 GeV^2 95 kHz

proton's detectors at Endcaps

Collision zone (luminosity distribution)
Blue line – with hourglass effect. D.f. = 2.8%





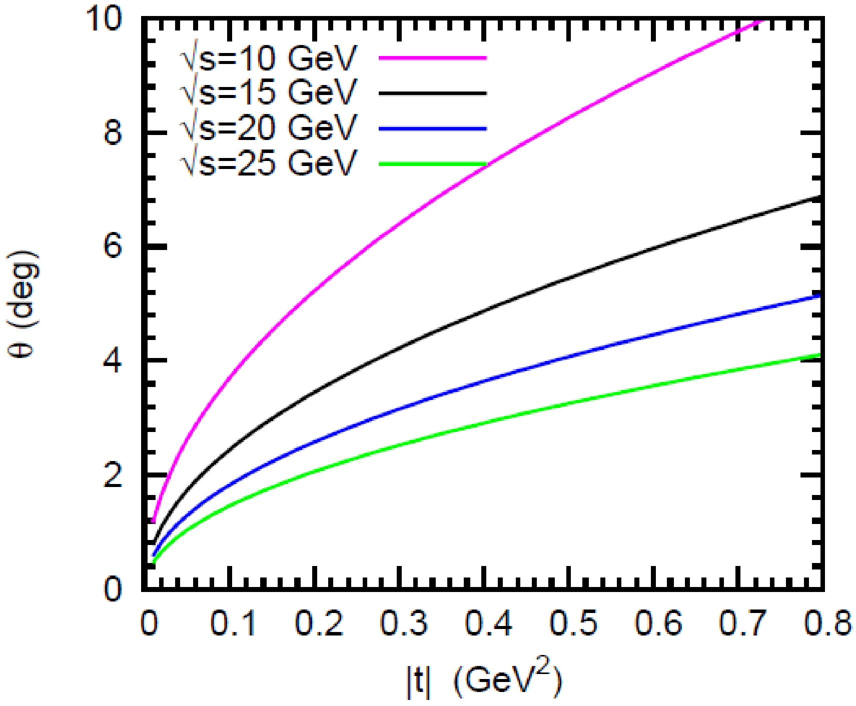
Ideal kinematics.
Collision point and angle (through coordinates)

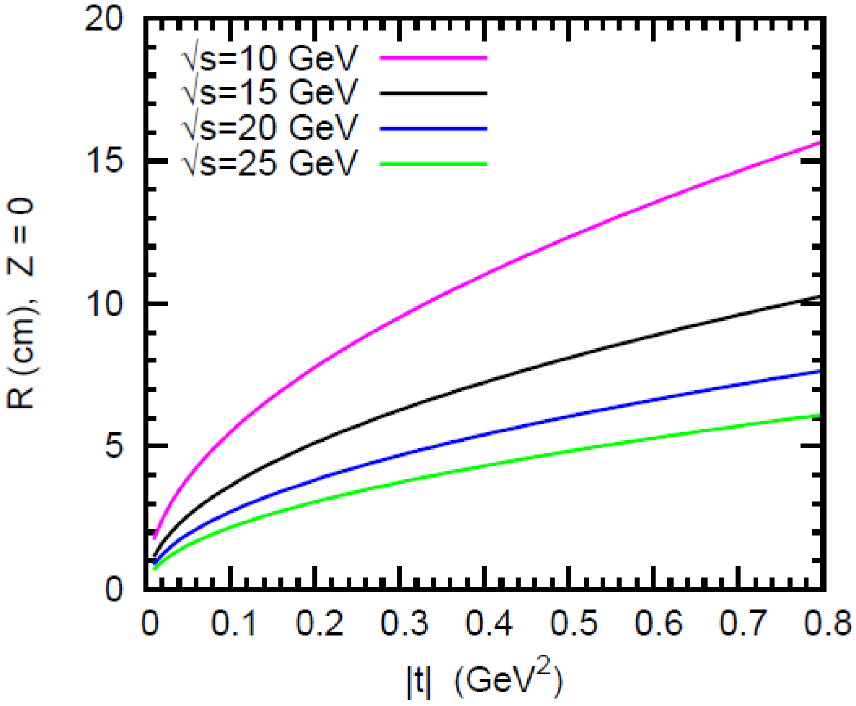
$$Z = -D\,\frac{X_1 + X_2}{X_1 - X_2}, \qquad \mathrm{tg}\,\theta = \frac{X_1 - X_2}{2D}$$

Collision point through times:

$$Z = \frac{v\cos\theta}{2}(T_2 - T_1), \qquad T = \frac{T_1 + T_2}{2} - \frac{D}{v\cos\theta}.$$

Measure: X1,X2 (and Y1,Y2) and T1-T2 $\Rightarrow$ overdetermine





Radial deviations of protons vs t

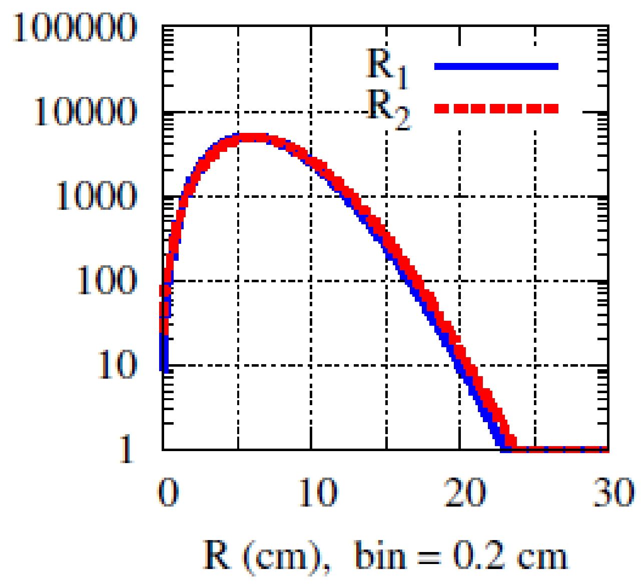
In order to cover 0.2 – 0.6 GeV^2
R = 3-15 cm

(D = 85 cm)

Fluctuations (errors in detectors, spread in beams):

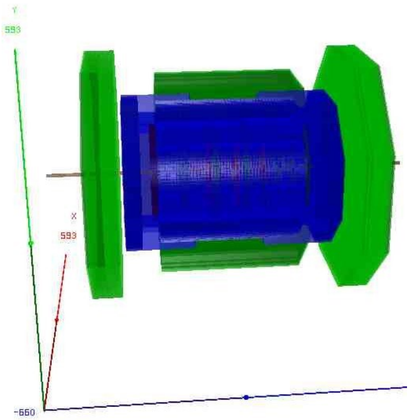
Leading contribution to $\delta\theta$ and δt comes from angular divergence of colliding beams (if $\varepsilon = 0.8\,\pi$ mm mrad)

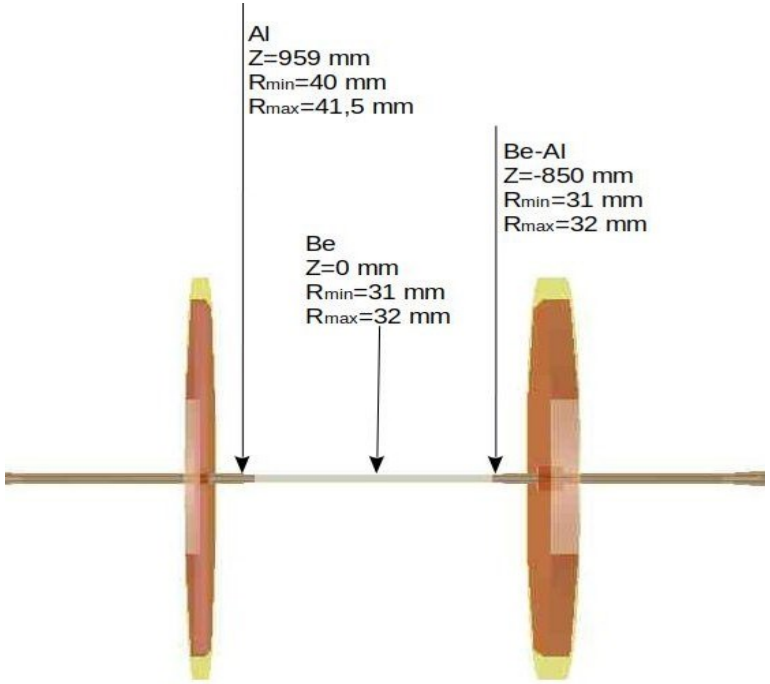
$$\sigma_{x'} = \sqrt{\frac{\epsilon_x}{\beta^*}} = 1.77 \text{ mrad}, \qquad \sigma_{y'} = \sqrt{\frac{\epsilon_y}{\beta^*}} = 1.51 \text{ mrad}.$$

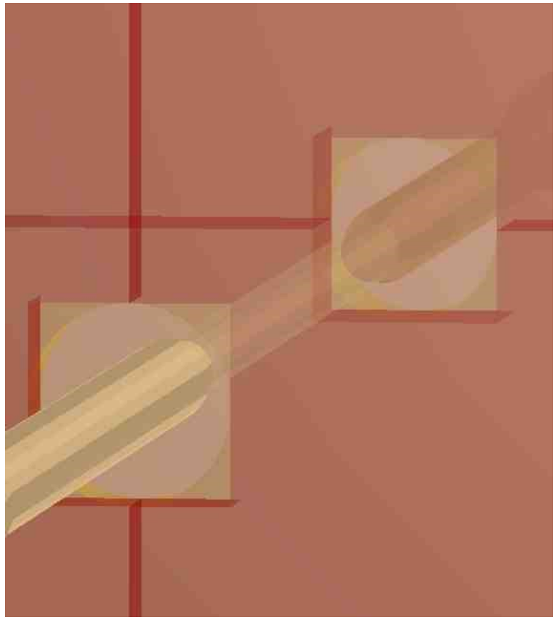


δt ~ 0.022 GeV^2 (we want to cover 0.3 – 0.5 GeV^2)

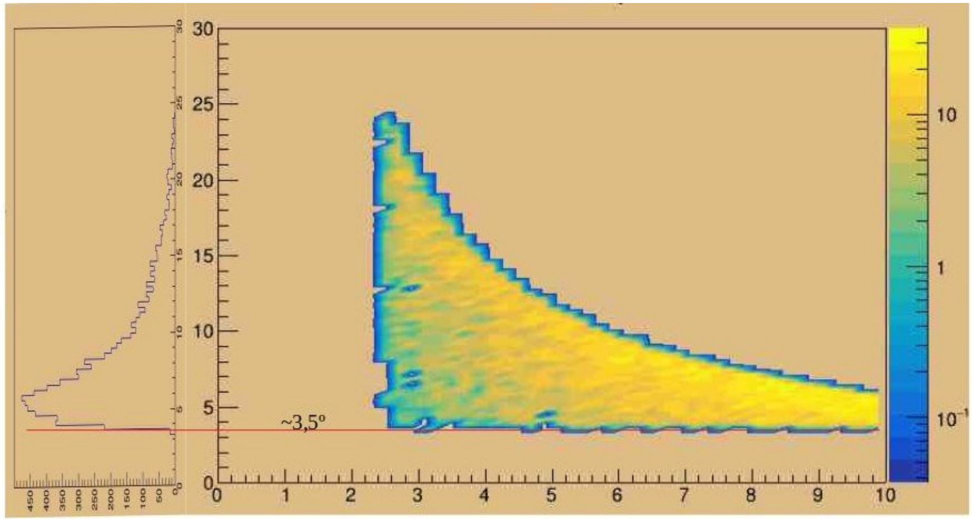
Optimal (economic) step in $\Delta R = \sigma_{x'} D = 0.5$ cm
that is sufficient for covering t with a small step.



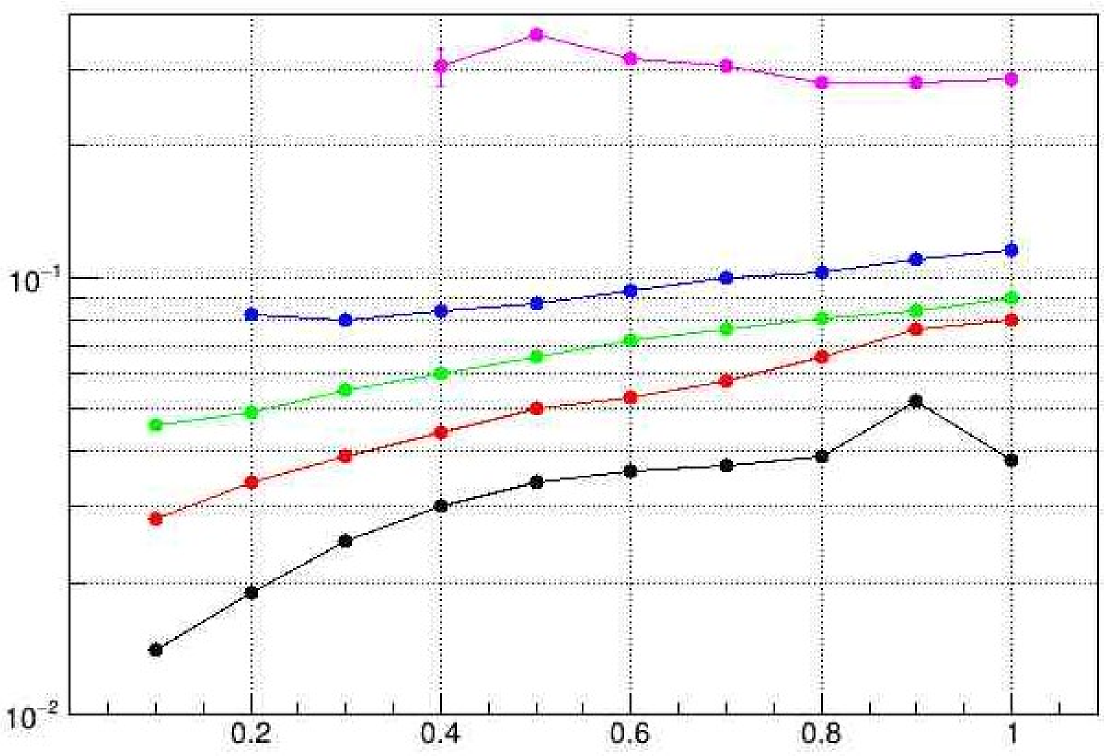

Al
Z=959 mm
Rmin=40 mm
Rmax=41,5 mm
Be-Al
Z=-850 mm
Rmin=31 mm
Rmax=32 mm
Be
Z=0 mm
Rmin=31 mm
Rmax=32 mm



Min Polar Angle with tracks reconstruction.



Resolutionto t, GeV^2



Preliminary conclusion:

Accuracy of order δt = 0.01 GeV^2 is hardly feasible when protons comes to Endcap through inner tracker.

It seems to better register particles with two Endcaps directly and have a success.

3 physical parameters of the pp-collision (Z and two angles) can be overdetermined through 5 measurements:
X1, X2, Y1, Y2, T1-T2
(avoiding uncertainties with inner tracker for particles coming too close to the tube).

Precausion:

Planned reducing β^* will increase the angular spread of beams and increase errors in t. Do the experiment before?

Slide from V.Baskov;s talk: Results of 2019-2020, articles

1. Алексеев В.И., Басков В.А., Дронов В.А., Львов А.И., Кречетов Ю.Ф., Малиновский Е.И., Павлюченко Л.Н., Полянский В.В., Сидорин С.С. «**КАЛИБРОВОЧНЫЙ КВАЗИМОНОХРОМАТИЧЕСКИЙ ПУЧОК ВТОРИЧНЫХ ЭЛЕКТРОНОВ УСКОРИТЕЛЯ С-25Р «ПАХРА»**» // ПТЭ. 2019. № 2. С.1-7; **DOI:** 10.1134/S0032816219020162

2. Алексеев В.И., Басков В.А., Дронов В.А., Львов А.И., Кречетов Ю.Ф., Малиновский Полянский В.В «**РЕГИСТРАЦИЯ НИЗКОЭНЕРГЕТИЧЕСКИХ ЭЛЕКТРОНОВ ЧЕРЕНКОВСКИМ СПЕКТРОМЕТРОМ ПОЛНОГО ПОГЛОЩЕНИЯ**» // arXiv.org > physics > arXiv: 1911. 12608; КСФ. 2019. №9. С. 31-37; **DOI:** 10.3103/S1068335619090057

3. Алексеев В.И., Басков В.А., Далькаров О.В., Кольцов А.В., Львов А.И., Мамонов И.А., Павлюченко П.Н., Полянский В.В «**МОНИТОР ЭЛЕКТРОННОГО ПУЧКА НА ОСНОВЕ ЧЕРЕНКОВСКОГО СЧЕТЧИКА**» // КСФ. 2019. №11. С. 37-43; **DOI:** 10.3103/S1068335619110071

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