Collider Particle Physics
- Chapter 2 -

ISR – the first hadron collider and the "soft" physics

Claudio Luci

SAPIENZA
UNIVERSITÀ DI ROMA

last update : 070117

Chapter Summary

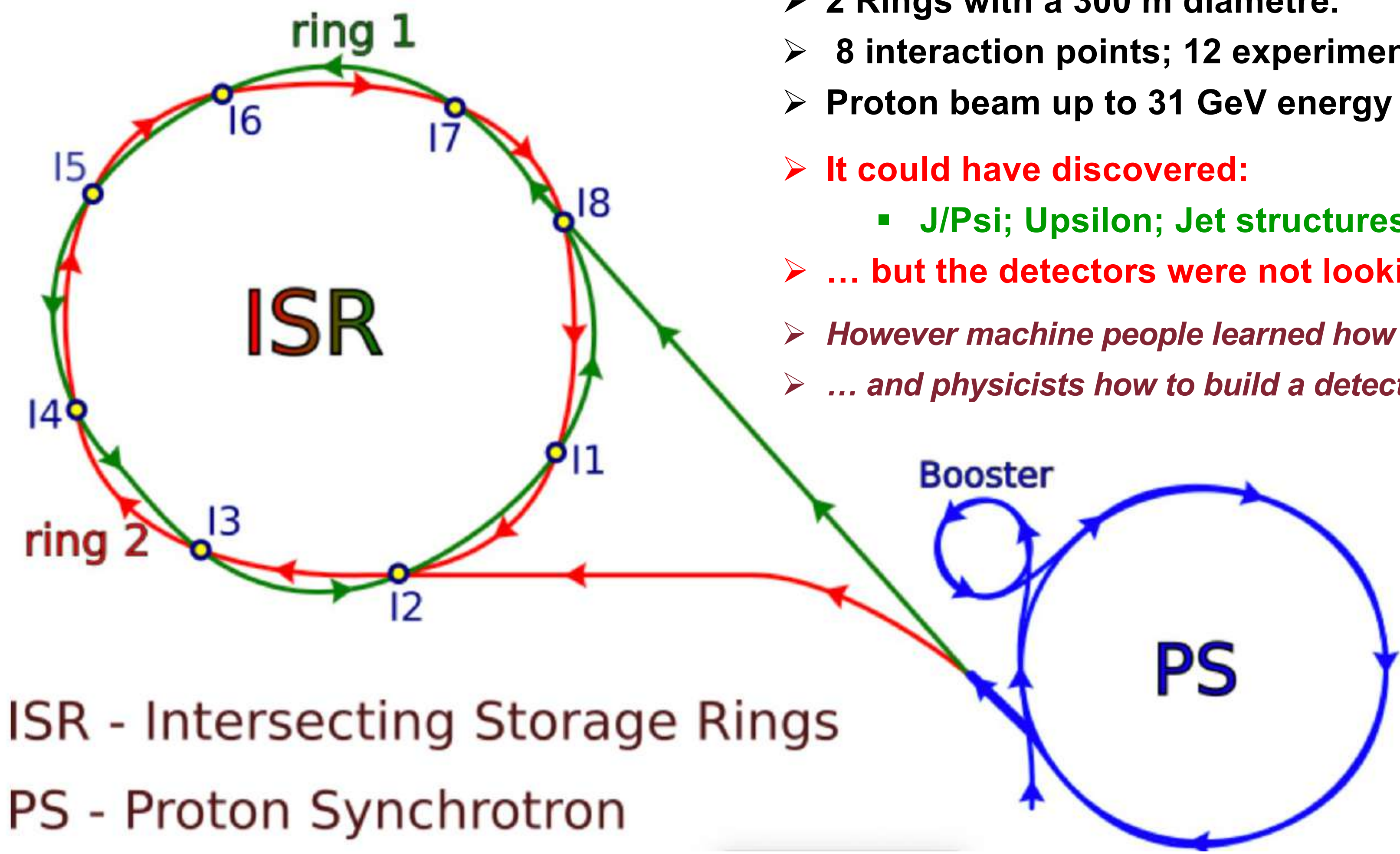
- ISR
- Theoretical framework of the strong interactions in the '60
- Partial wave, Optical theorem and total cross-section measurement.
- "Soft" Physics at the ISR: proton-proton total cross section.
- "Soft" Physics at LHC.
- "less soft" Physics at the ISR.
- Legacy of the ISR collider: Luminosity measurement and Stochastic cooling

"Blue" slides are taken from Ugo Amaldi presentation "ISR Physics" at The 50th Anniversary of Hadron Colliders at CERN – 14 October 2021- https://indico.cern.ch/event/1068633/timetable/

First hadron collider at CERN … the ISR

- In 1956, studies for the second generation of CERN accelerators began and gradually converged towards a proton–proton collider.
- From 1961 onwards, a study of a 300 GeV proton synchrotron was carried out. It was decided to construct the ISR first.
- In June 1965 ISR was approved and in December 1965 the construction started.
- First beams in 1971 and operation for Physics from 1971 to 1983.
- The ISR was the only CERN collider built without a specific physics goal.
- The program was shaped by the dominant view at the time:
  proton-proton collisions are SOFT processes
- The ISR Committee favoured the "PS approach":
  many experiments performed by small groups for a short time.

ISR (Intersecting Storage Rings)



- 2 Rings with a 300 m diametre.
- 8 interaction points; 12 experiments in 5 points
- Proton beam up to 31 GeV energy (62 GeV CoM energy)
- It could have discovered:
  - J/Psi; Upsilon; Jet structures …
- … but the detectors were not looking at high-Pt regions
- *However machine people learned how to build a hadron collider*
- *… and physicists how to build a detector for such a collider*

52 GeV ~ 1352 GeV	
CoM ISR (26 + 26)	*Fixed target beam*

One of the ISR key performance parameter: vacuum system

This is only an example of how many new technology challenges had to be overcome to build a collider.

- ❑ **the integrated luminosity was proportional to:**

$$\int \frac{I_1 \cdot I_2}{h}\, dt$$

(I is the beam current and h is the vertical separation at the interaction point)

with all three variables depending on time t.

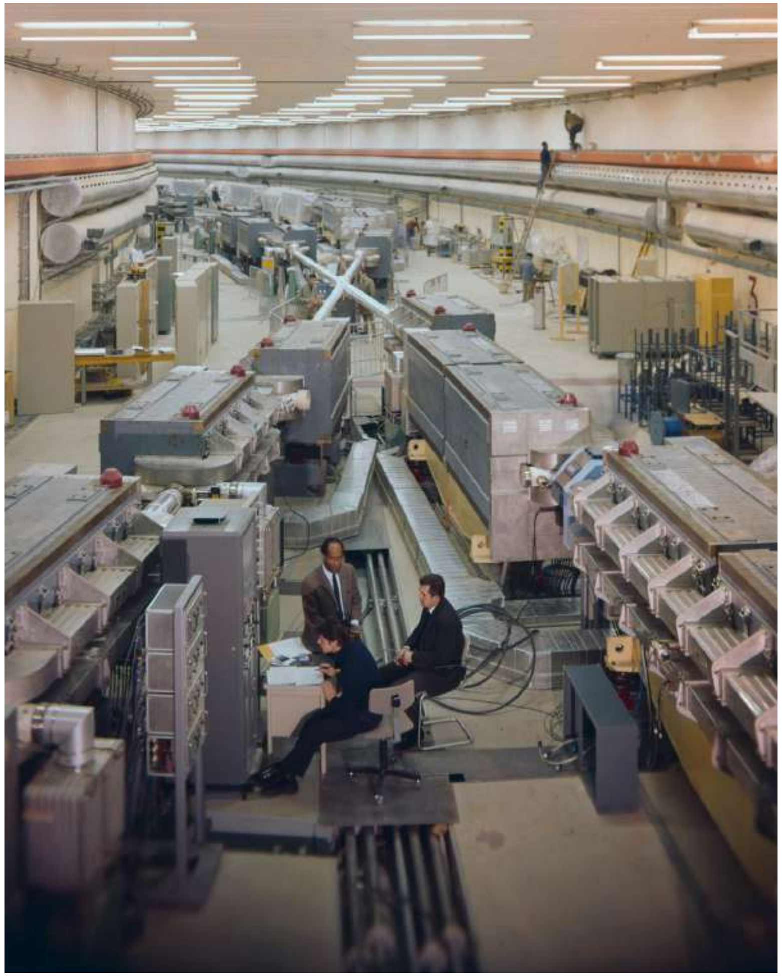
- ❑ **Protons in the beams are lost due to nuclear and Coulomb scattering with the residual gas in the beam pipe, and the effective beam height h_{eff} gets blown up by a similar mechanism.**

- ❑ **Imposing a beam loss of less than 50% and a growth of h_{eff} of less than 40% in 12 h, that will translate in a drop of less than 18% in luminosity after 12 h, the pressure should be less than 10^{-9} Torr over a total length of nearly 2 km (10^{-11} Torr at the interaction points) [1 atm = 760 Torr]**

- ❑ **Even new methods to measure such a low pressure had to be invented (*they succeeded*)**

I4 intersection point at the ISR

It hosted the split field magnet detector



ISR overview

”Blue” slides are taken from Ugo Amaldi presentation “ISR Physics” at
The 50th Anniversary of Hadron Colliders at CERN – 14 October 2021-
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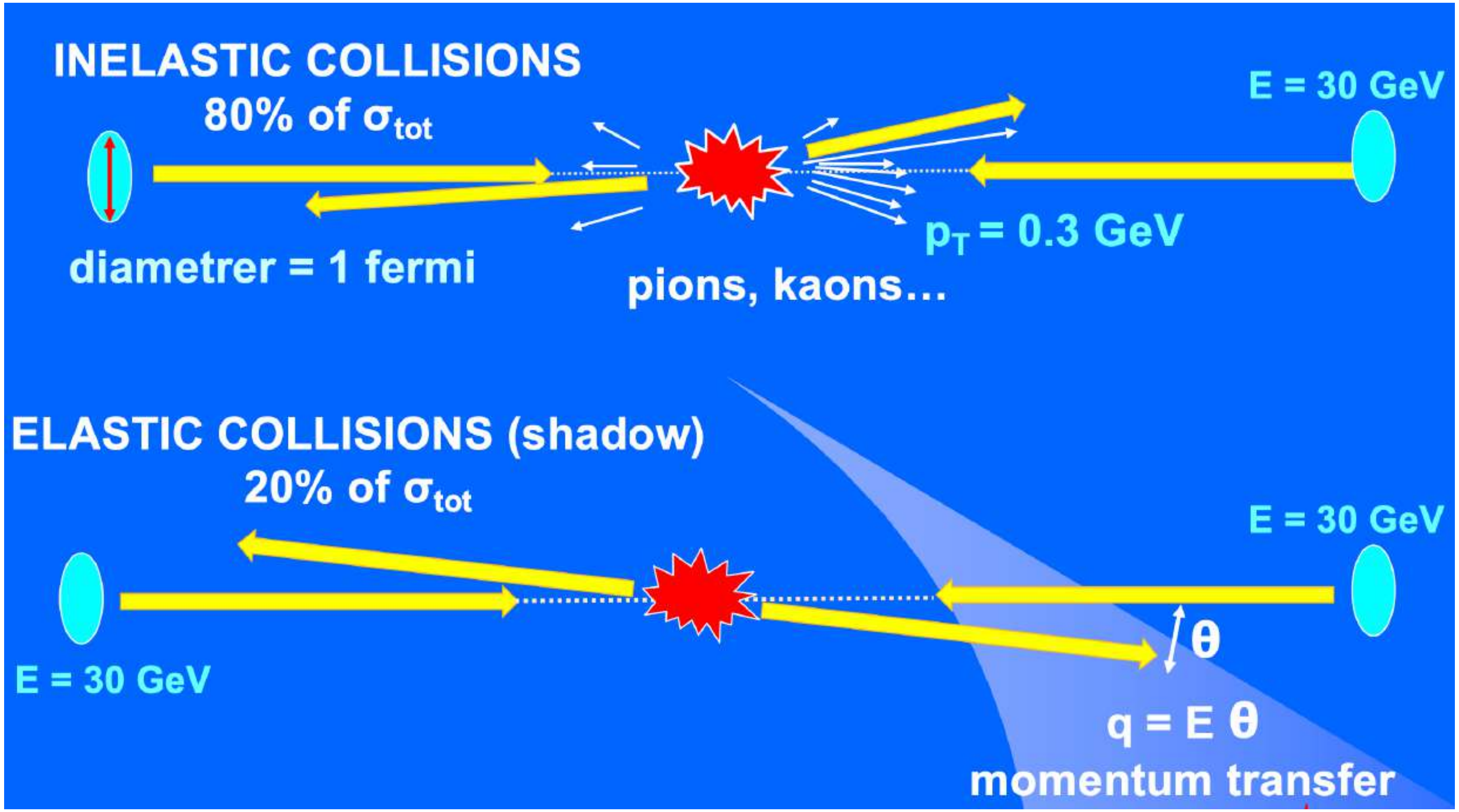
(This is not part of the exam program, but it is an important step toward the SppS physics)

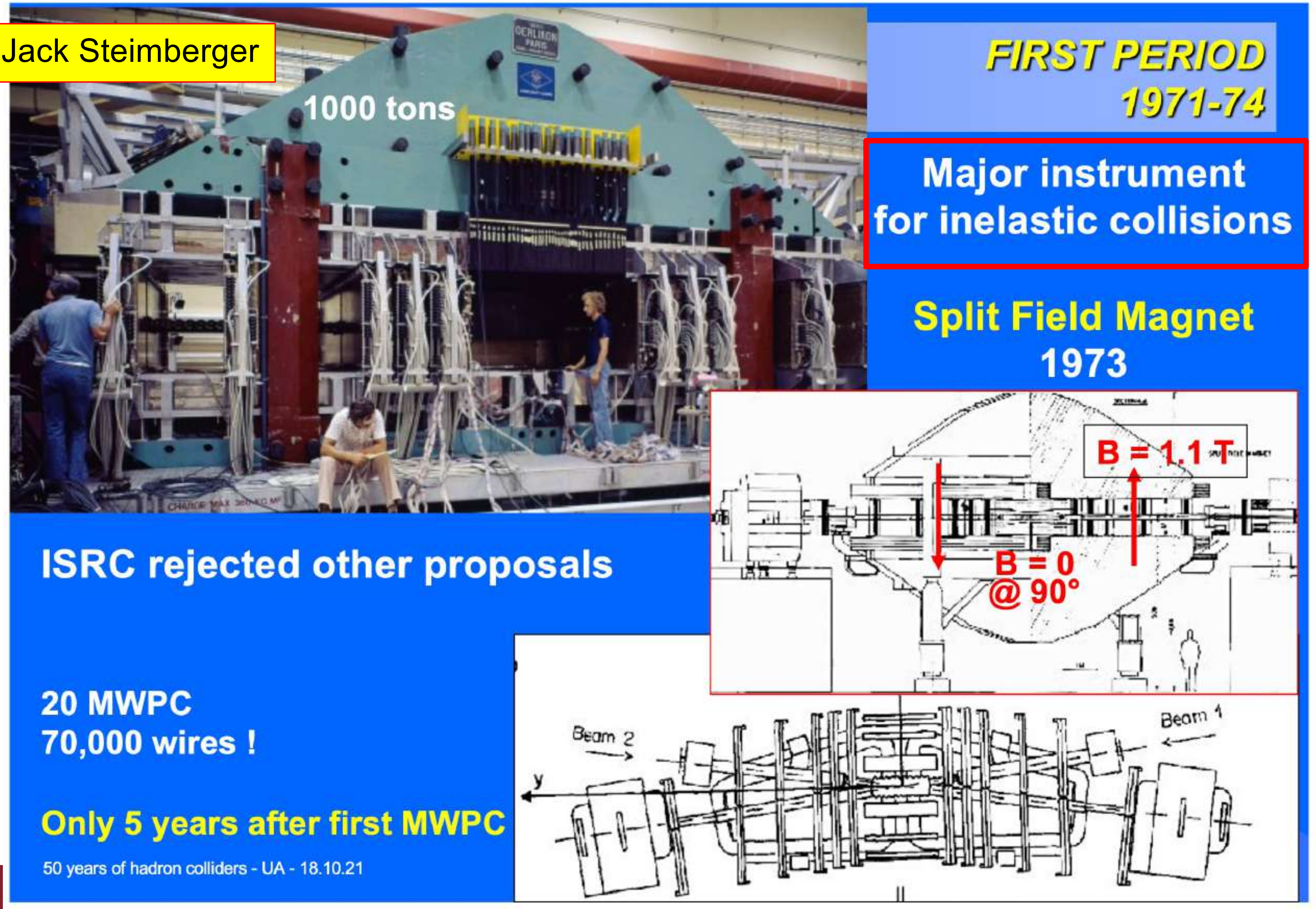
Dominant view: particles are created in SOFT processes



Reminder: elastic collisions: final state particles are equal to initial state particles
inelastic collisions: finale state particles are different from initial state particles

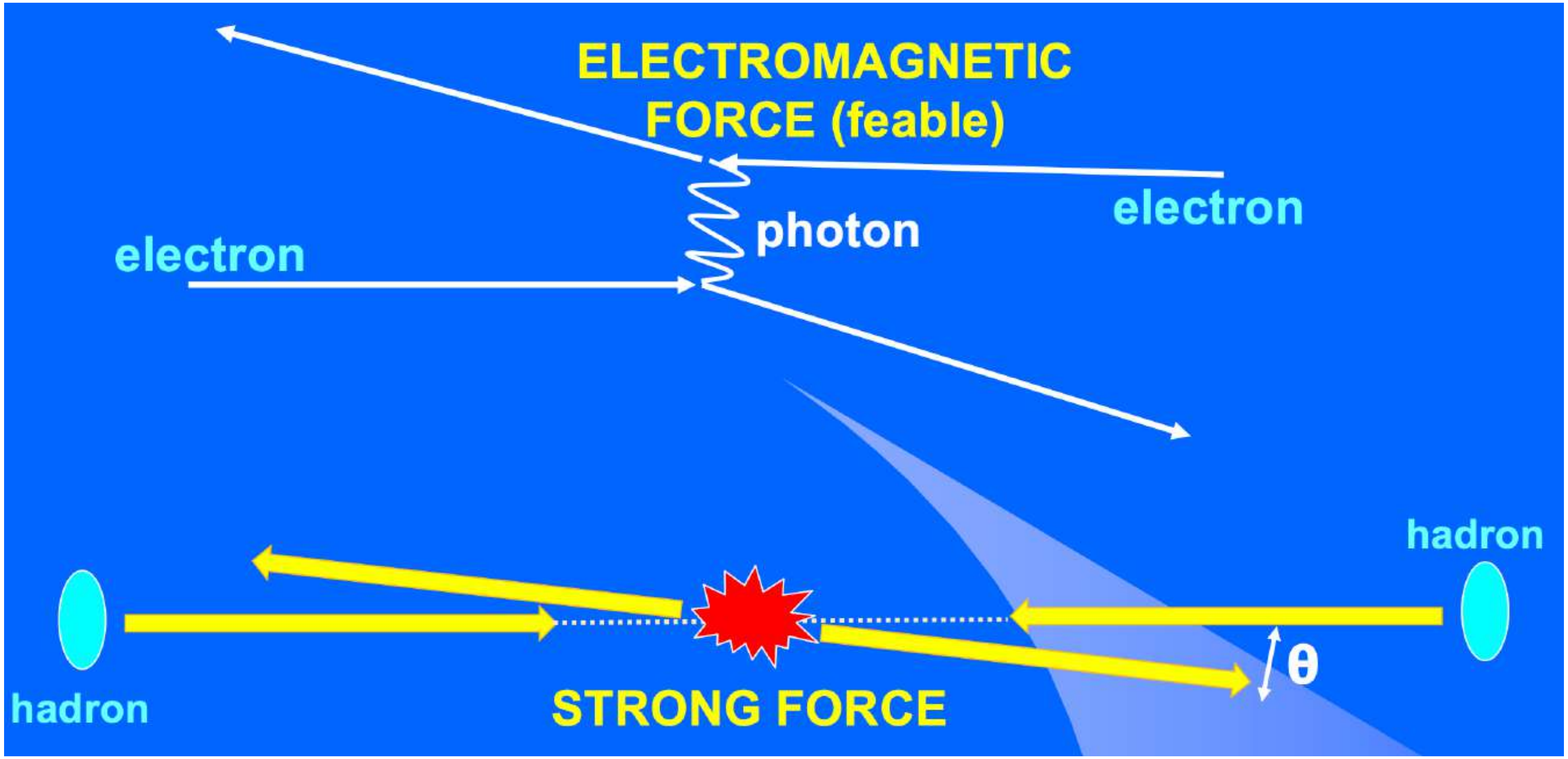
Split Field Magnet Detector

Team led by Jack Steimberger



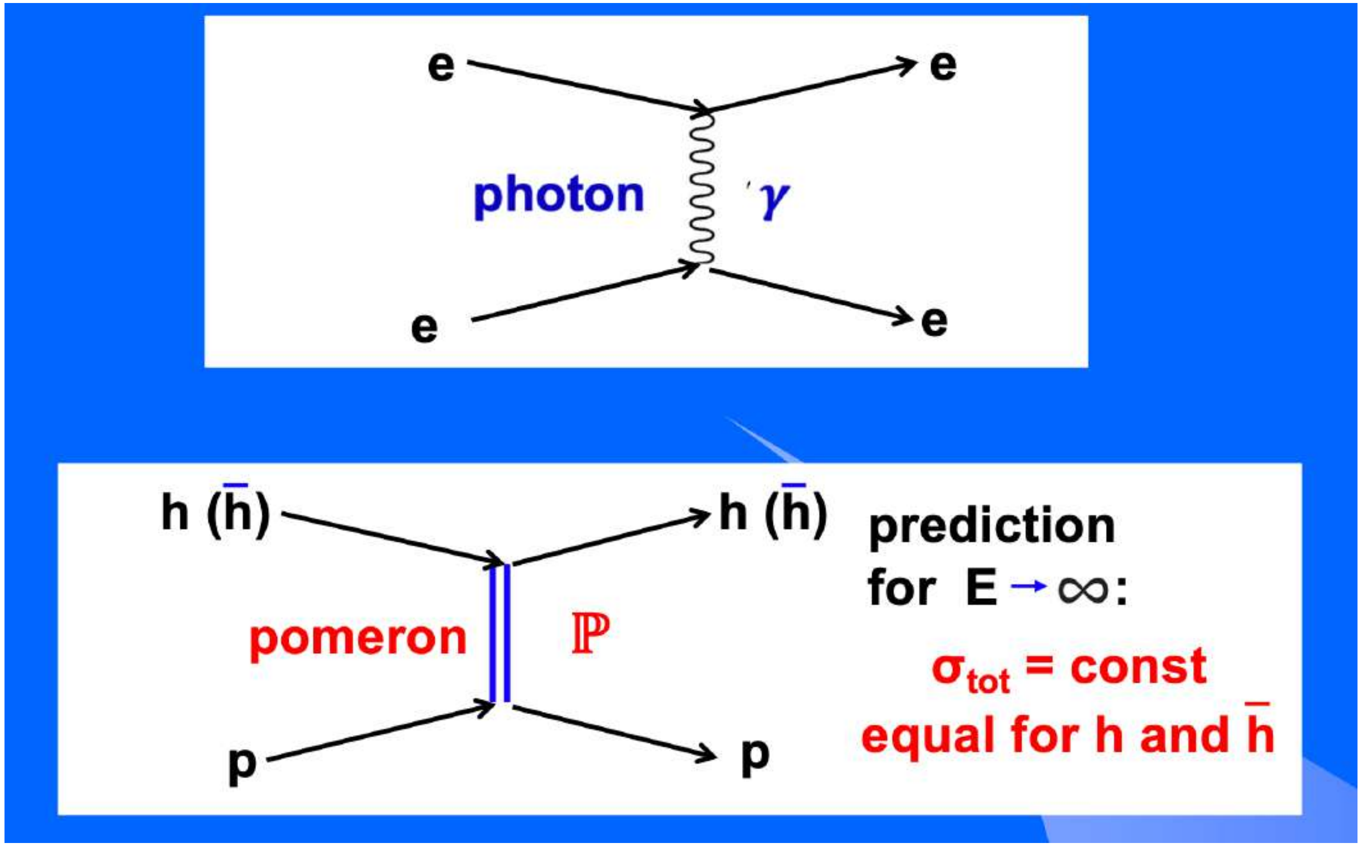
Close to the beam pipe

Hadron-hadron collisions were described in the framework of the Regge theory



(In a few slides I will tell you something about the Regge theory)

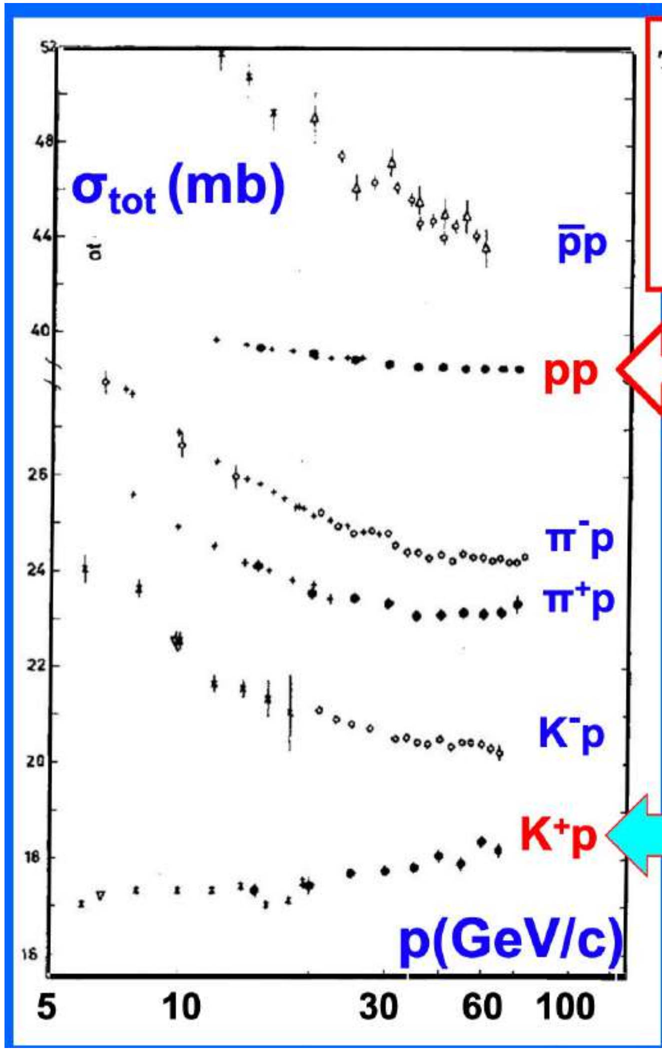
Elastic scattering between two hadrons is due to the exchange of the same Pomeron trajectory



Proton-proton total cross-section should be equal to proton-antiproton total cross-section

(The pomeron is still used in the modern description of the proton-proton elastic scattering)

In July 1971 Serphukov data confirmed the prediction



TOTAL CROSS SECTIONS OF π^+, K^+ AND p ON PROTONS AND DEUTERONS IN THE MOMENTUM RANGE 15-60 GeV/c

S. P. DENISOV, S. V. DONSKOV, Yu. P. GORIN, A. I. PETRUKHIN, Yu. D. PROKOSHKIN
D. A. STOYANOVA, J. V. ALLABY* and G. GIACOMELLI**
Institute of High Energy Physics, Serpukhov, U.S.S.R.

Received 30 July 1971

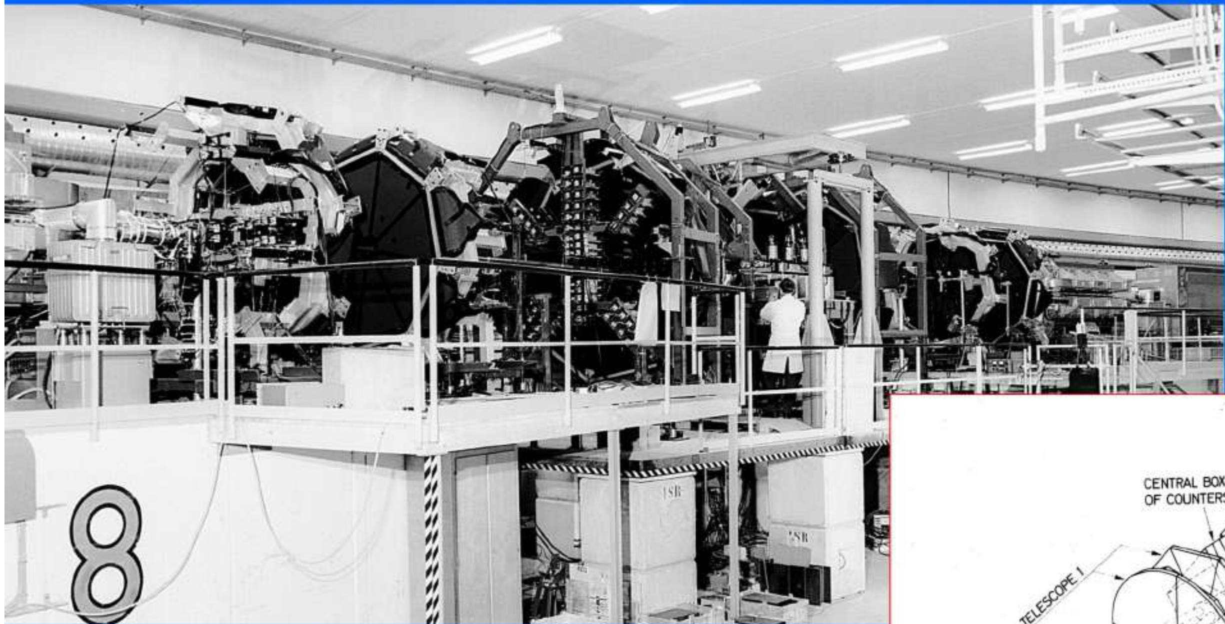
PROTON-PROTON ASYMPTOPIA IS ALREADY REACHED AT E_{beam} = 100 GEV

(total cross-section should remain constant according to the Regge theory)

This figure suggests that the total cross-section for K^+p will approach the asymptotic value from below

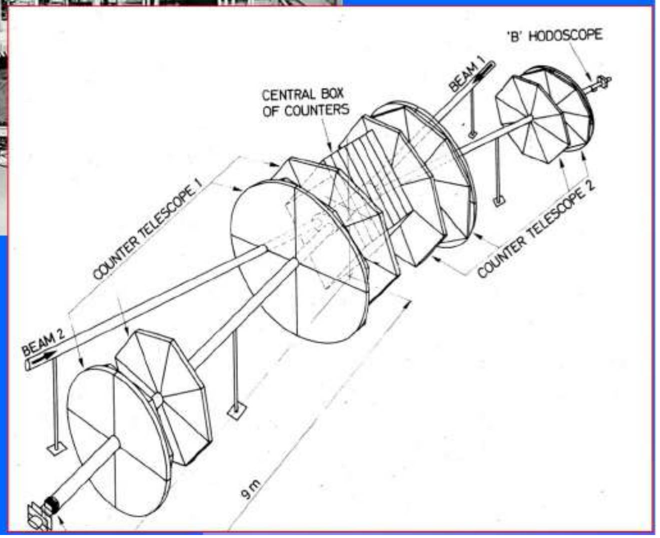
Total cross section measurement

In IR-8 the total cross section was measured by the Pisa - Stony Brook Coll.



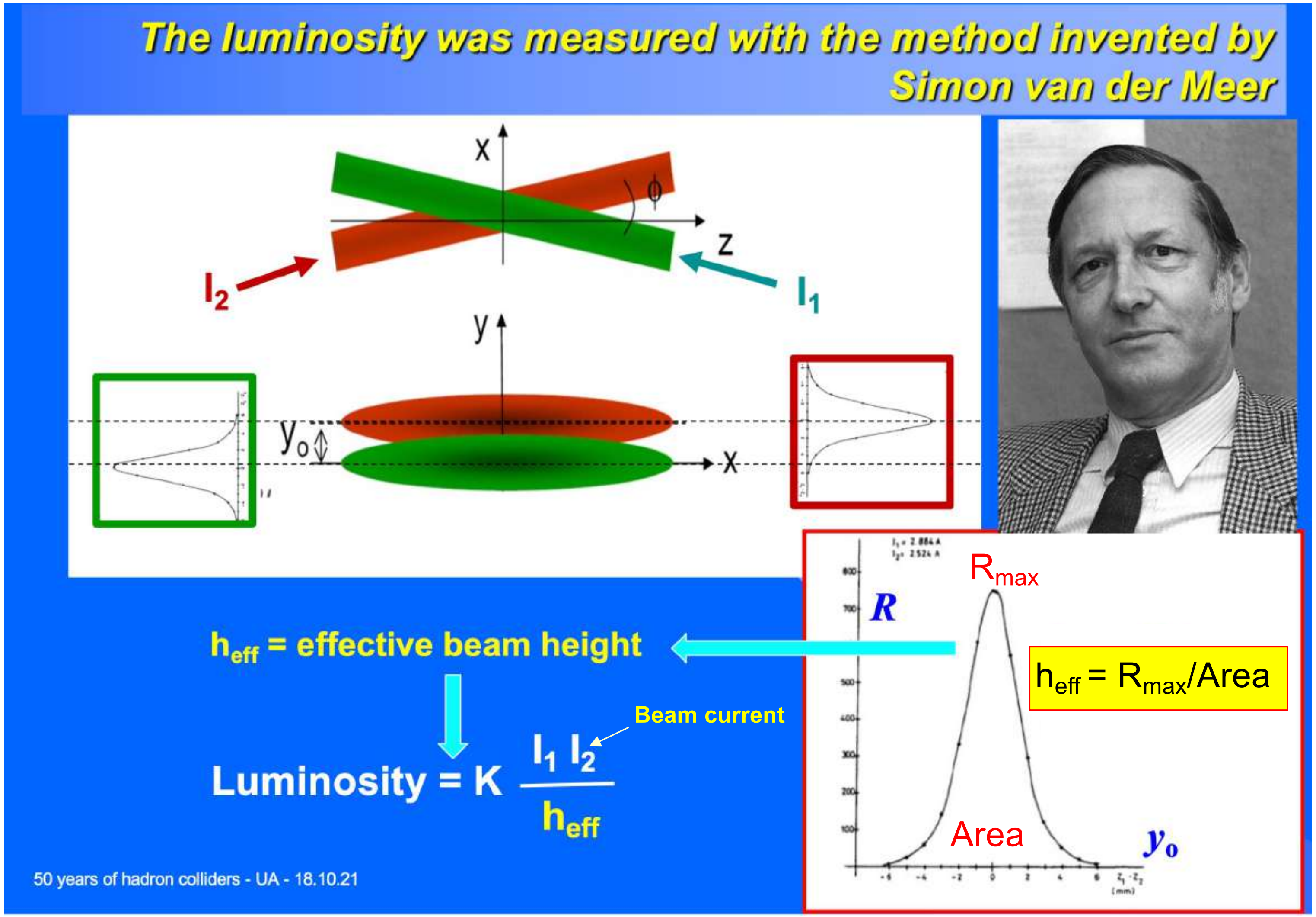
Measuring p-p total cross-section was one of the most important measurements in the early phase of the ISR.
Then, the knowledge of the luminosity was of a paramount importance.

$$\sigma = \frac{N_{events}}{Luminosity}$$



50 years of hadron colliders - UA - 18.10.21

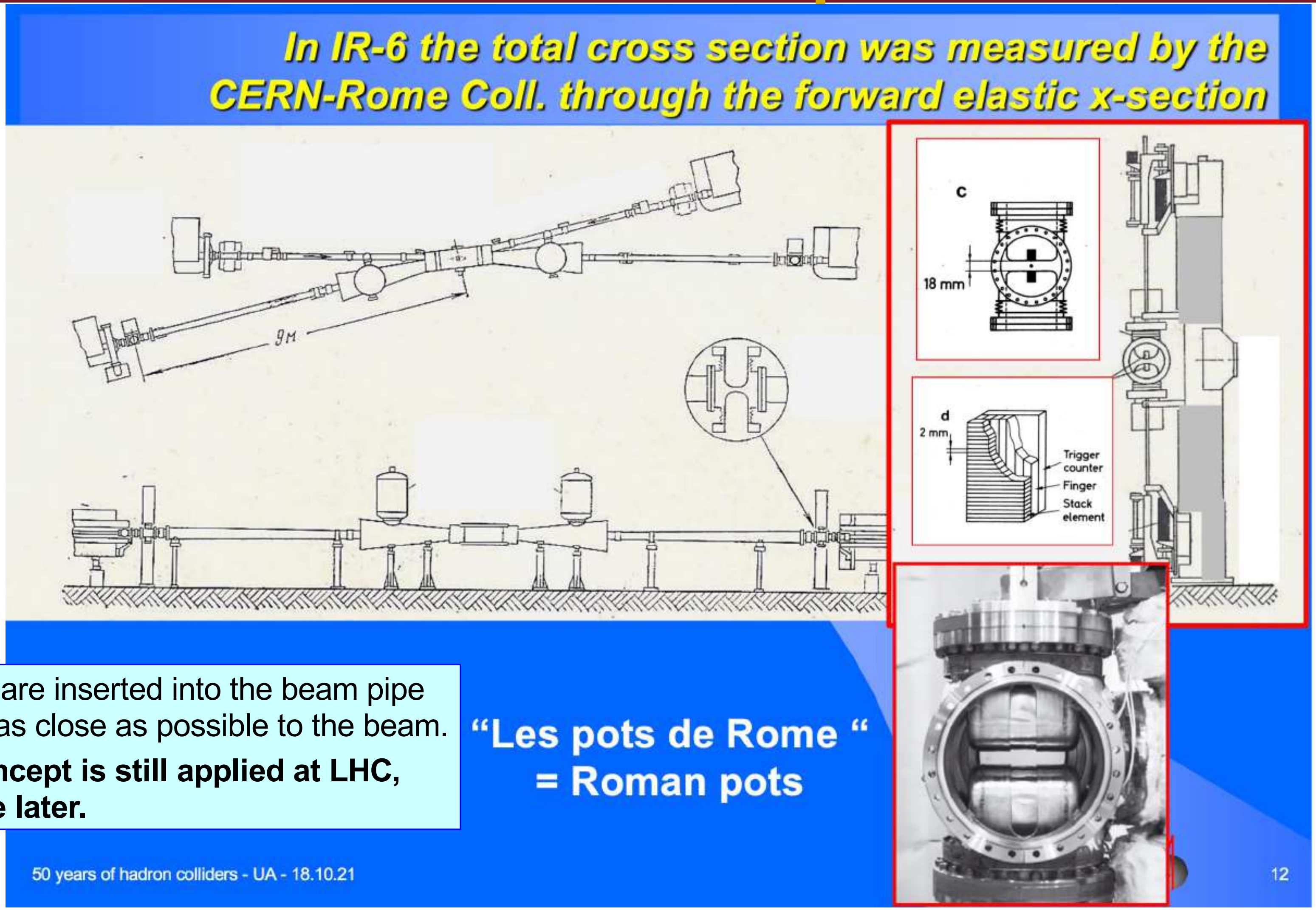
Luminosity measurement



- The luminosity is proportional to the overlap of two beams
- If the beams are very narrow, with a little displacement the counting rate goes to zero; on the contrary if the "bell" is large also the beams are large and the luminosity is small.

- R is the rate measured by a reference counter
- This is the method still used at LHC to measure the luminosity: ***van der Meer scan***

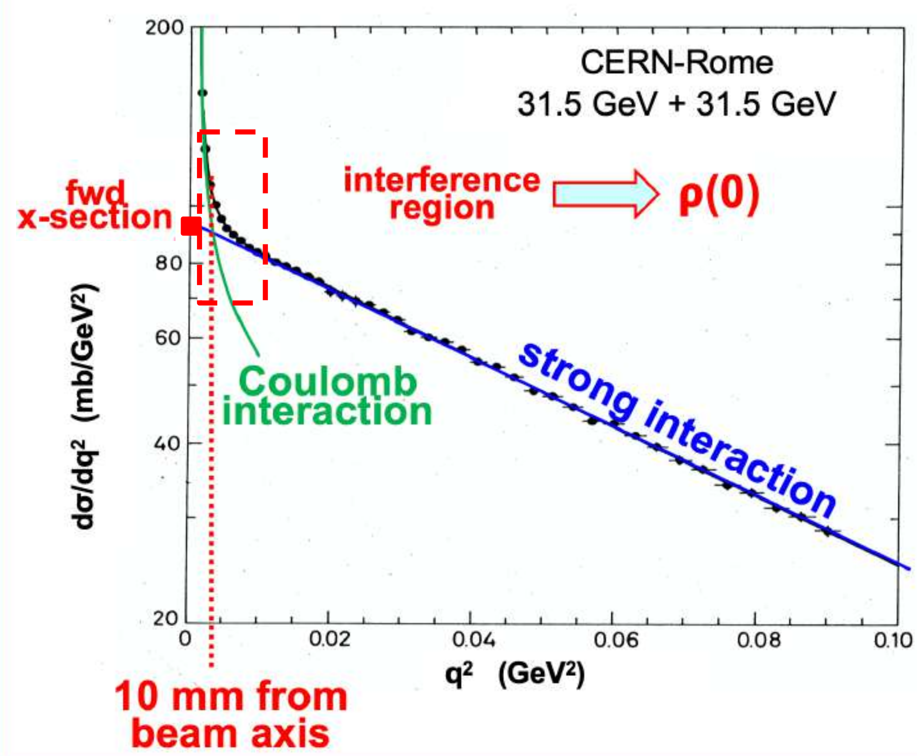
The Roman pots



(through the optical theorem. See later)

The detectors are inserted into the beam pipe in order to go as close as possible to the beam.
The same concept is still applied at LHC, as we will see later.

Roman Pots results



Behaviour of the elastic cross-section

S-matrix theory:

Scattering amplitude = $A(q^2)\ [\ i + \rho(q^2)\ ]$

(wait a few slides)

1. Optical theorem:

$\sigma_{tot} = C\,\sqrt{\text{fwd x-section}}$

2. Dispersion relation:

ρ(0) expressed as an integral over all energies of $\sigma_{tot}(E)$

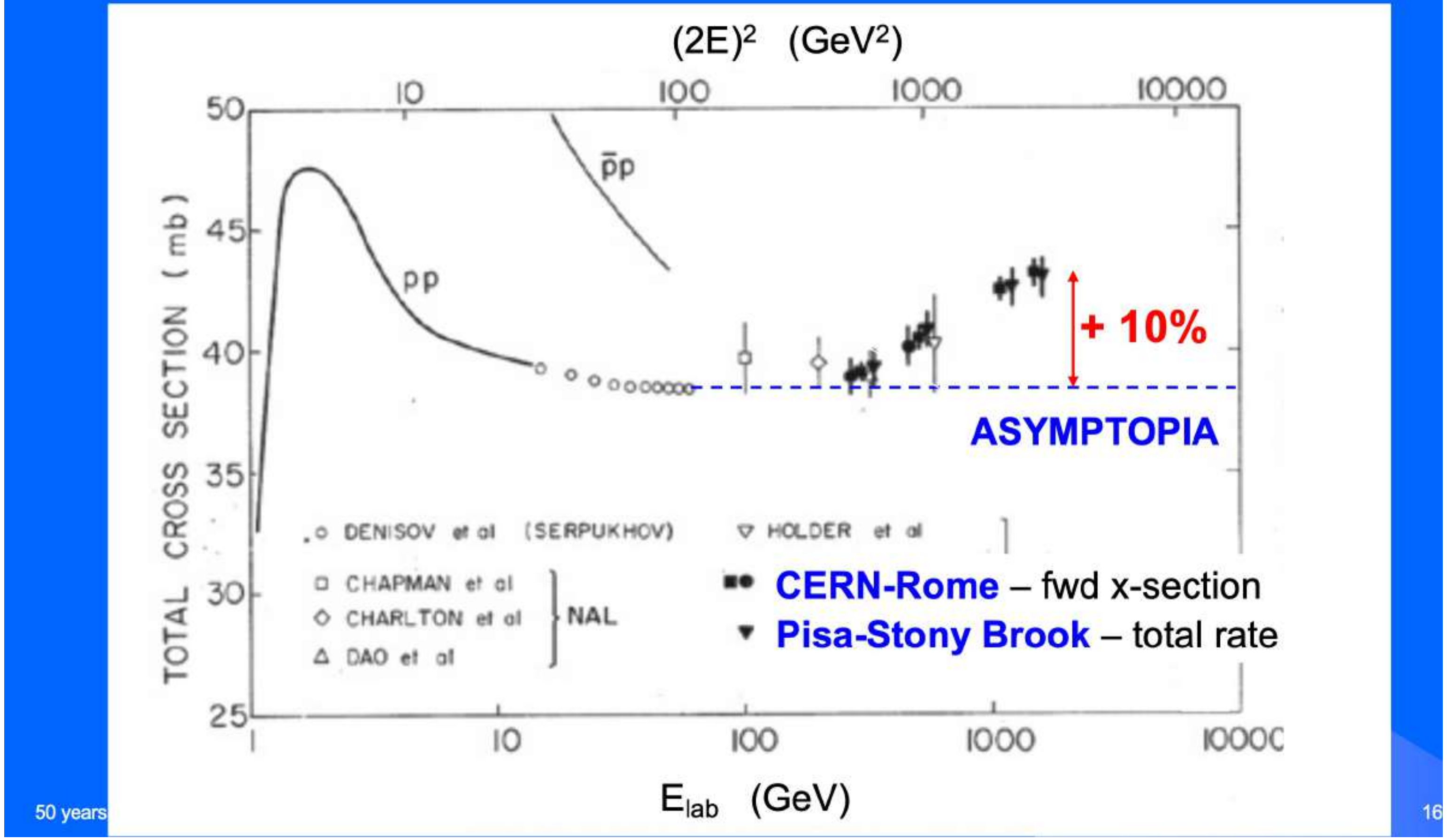
$$\rho = \mathrm{Re}[f_{el}(0)]/\mathrm{Im}[f_{el}(0)]$$

Wait for the optical theorem

(N.B. the optical theorem can be deduced also from the S-matrix theory)

First important ISR result on pp total cross-section

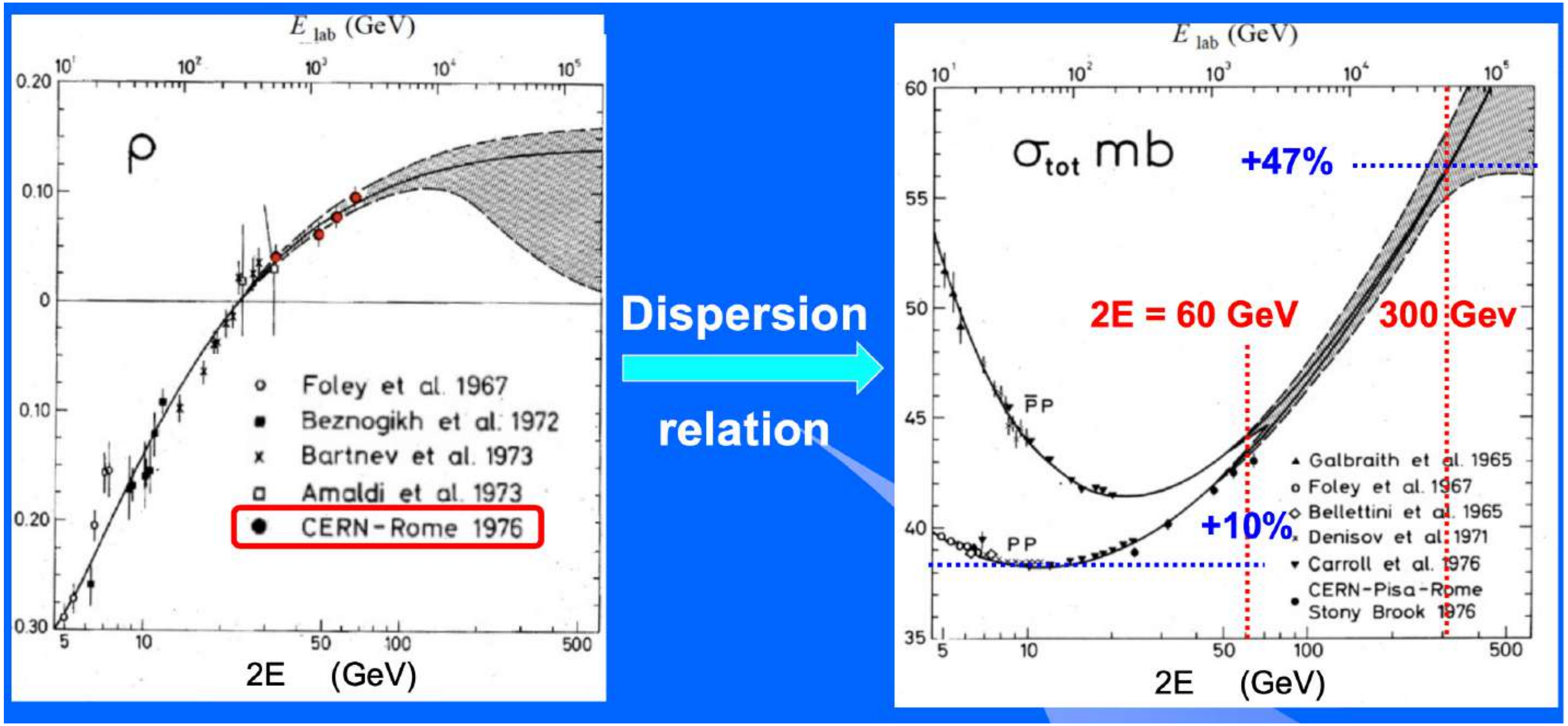
In 1973 the two Collaborations found that 1. Asymptopia does not apply to protons; 2. the Pomeron is much more complicated



Regge theory predicted that the pp cross-section should be constant for large energy.

Data do not agree with this prediction

pp cross-section measurements



"Soft" Physics: ISR experiments have shown that the proton-proton cross-section increases by 50% when the collision energy increases from 15 GeV + 15 GeV to 150 GeV + 150 GeV

A bit of theory/history: S matrix, Regge poles, pomeron…

(of course … this is not part of the exam program)

the S matrix

- We have an initial state |i> that evolves in the final state |f> due to an interaction;
- We work in the Dirac representation (interaction representation);
- $H = H_0 + V_I$, where H_0 is the free Hamiltonian and V_I is the interaction Hamiltonian;
- The S matrix (function of V_I) drives the state evolution from time t_0 until time t;

$$|\Psi_I(t)\rangle = S(t_0,t)|\Psi_I(t_0)\rangle$$

- where

$$S(t,t_0)=\exp\left[-\frac{i}{\hbar}\int_{t_0}^{t} V_I(t')dt'\right]$$

We have a conceptual problem to solve the integral because at different time t' the V_I are not granted that commute with each other. We introduce a procedure of time ordering (Time order product) that lead to the concept of "propagator".

- We want to evaluate the S Matrix between the time $-\infty$ and $+\infty$; that is we have a free state |i> and we would like to know how it evolves after the interaction:

$$|\Psi(\infty)\rangle = S(-\infty,\infty)|i\rangle$$

the S matrix

- the amplitude probability to find a particular final state |f> is:

$$\langle f|\Psi(\infty)\rangle = \langle f \mid S(-\infty,\infty)|i\rangle = \langle f \mid S|i\rangle = S_{fi}$$

- expansion of |Ψ(∞)> in a complete set of eigenstates:

$$|\Psi(\infty)\rangle = \sum_f | f\rangle\langle f |\Psi(\infty)\rangle = \sum_f | f\rangle S_{fi}$$

- Transition probability from the state |i> to the state |f>:

$$\left|\langle f|\Psi(\infty)\rangle\right|^2 = S_{fi}^2 \quad \text{(eigenstates normalized to 1)}$$

- Unitarity of the S Matrix (**probability conservation**):

$$\sum_f S_{fi}^2 = 1$$

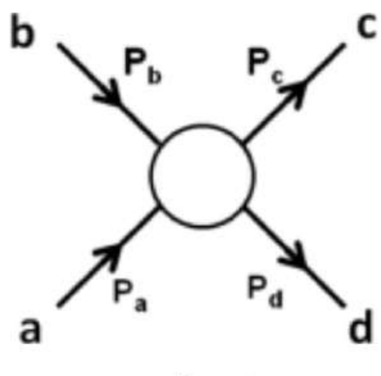
⇐ It can not be violated in any case and in any way!

N.B. to "compute" the single S_{fi} we need a lagrangian, that we didn't have for the strong interaction

The S matrix was then analysed in terms of its fundamental properties: unitarity, analyticity, crossing symmetry, without assuming anything about the strong potential responsible of the scattering.

Crossing simmetry

A process where a particle with a 4-momentum p_μ in the initial (final) state has the same amplitude **S_{fi}** of the process where it is replaced by its antiparticle in final (initial) state with the same 4-momentum



This graph describes these three processes

(s becomes t if you rotate the graph by 90°)

$a + b \rightarrow c + d$	s - channel
$a + \bar{d} \rightarrow \bar{b} + c$	t - channel
$a + \bar{c} \rightarrow \bar{b} + d$	u - channel

These processes involve different regions of the parameter space; variables s,t,u are the Mandelstam variables

$$s = (p_a + p_b)^2 \;;\; t = (p_a - p_d)^2 \;;\; u = (p_a - p_c)^2$$

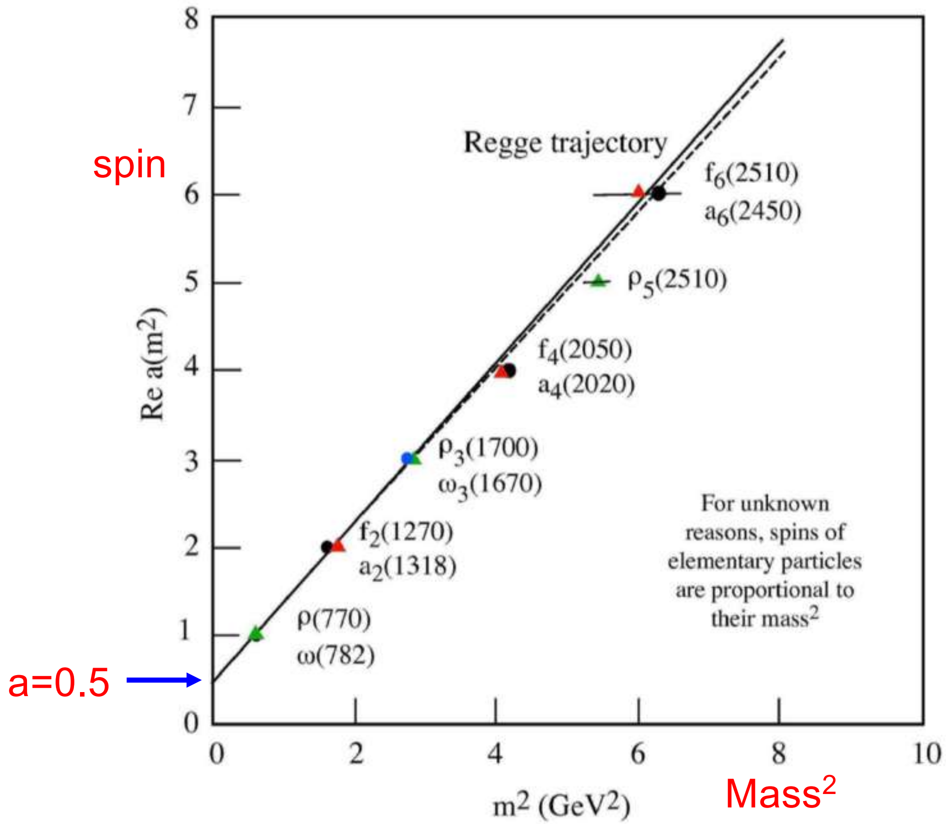
They are not independent because they obey at the following relationship:

$$s + t + u = m_a^2 + m_b^2 + m_c^2 + m_d^2$$

Conclusion: processes in the "s channel" (annihilation) and in the "t channel" (scattering) are related

Regge theory

- Tullio Regge studied the analytical properties of the scattering amplitude of the collision process between two particles. He considered (in 1959) the angular momentum as a complex variable and derived the singularities of the scattering amplitude that became universally known as Regge poles.



The present situation of the Chew–Frautschi plot shows that the Regge trajectory containing the ρ meson (mass = 770 MeV) is practically linear up to very large masses

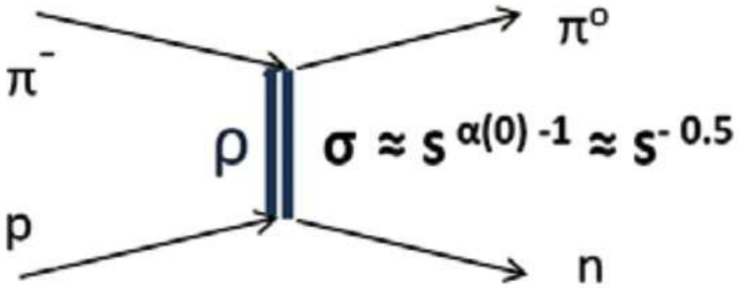
For unknown reasons, spins of elementary particles are proportional to their mass^2

In 1960 Chew and Frautschi conjectured that the strongly interacting particles had a very simple dependence of the squared-mass on the angular momentum: the particles fall into families where the Regge trajectory functions were straight lines with the same slope for all the trajectories. The straight-line Regge trajectories were later understood as arising from massless endpoints on rotating relativistic strings. Since a Regge description implied that the particles were bound states, Chew and Frautschi concluded that none of the strongly interacting particles were elementary

Regge theory: pion-proton scattering

- **The exchange of the ρ trajectory dominates the charge-exchange cross-section of the pion-proton interaction.**

According to the Regge theory the cross-section shoud varies as $s^{a(t=0)-1} = 1/E_{cm}$ [$\alpha(0) \approx 0.5$]



In the 1960s the experimental confirmation of this prediction was one of the strongest arguments in favour of the Regge description of the scattering of two hadrons. Such a description is still used because these phenomena cannot be computed with quantum chromodynamics

One of the many papers on this subject

Pion-Proton Charge-Exchange Scattering from 500 to 1300 MeV*

CHARLES B. CHIU, RICHARD D. EANDI, A. CARL HELMHOLZ, ROBERT W. KENNEY, BURTON J. MOYER, JOHN A. POIRIER,† AND W. BRUCE RICHARDS‡
Lawrence Radiation Laboratory, University of California, Berkeley, California

AND

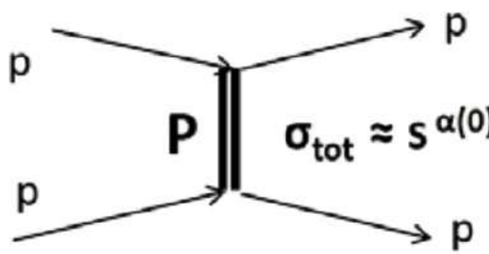
ROBERT J. CENCE, VINCENT Z. PETERSON, NARENDER K. SEHGAL, AND VICTOR J. STENGER
University of Hawaii, Honolulu, Hawaii

(Received 16 November 1966)

Differential cross sections for the reaction $\pi^- p \rightarrow \pi^0 n$ were measured at nine incident-pion kinetic energies in the interval from 500 to 1300 MeV. The negative pion beam from the bevatron was focused on a liquid-hydrogen target completely surrounded by a cubic array of six steel-plate spark chambers. The spark

Regge theory: proton-proton scattering

- **In the Regge model, the exchange of a pomeron trajectory is the dominant phenomenon in all high-energy elastic collisions.**
- **In the "t-channel view" $\alpha(t = 0) = 1 \rightarrow$ energy-independent total cross-section, as confirmed by experiments before ISR results.**



$$\sigma_{tot} \approx s^{\alpha(0)-1} = \text{const}$$

The pomeron itself was introduced by V. Gribov and he incorporated the Pomeranchum' theorem into the Regge theory.

The modern interpretation is that the pomeron has no conserved charges (electric charge or color charge) and the particles on his Regge trajectory ***have the quantum numbers of the vacuum****.*

S-channel description theorems:

- **Pomeranchum theorem**: in the the limit $s \rightarrow \infty$, the hadron–hadron and the antihadron–hadron cross-sections become equal.
- **Froissart-Martin theorem**: the total cross-section should satisfy the bound $\sigma_{tot} \lesssim C \ln^2(s/s_0) \approx 60 \text{ mb} \ln^2(s/s_0)$

where the numerical value $C = \pi(\hbar/m\pi)^2$ is determined by the mass of the pion, which is the lightest particle that can be exchanged between the two colliding hadrons, and s_0 is usually taken equal to 1 GeV^2.

One of the tasks of the ISR experiments was the measurement of the proton-proton cross-section

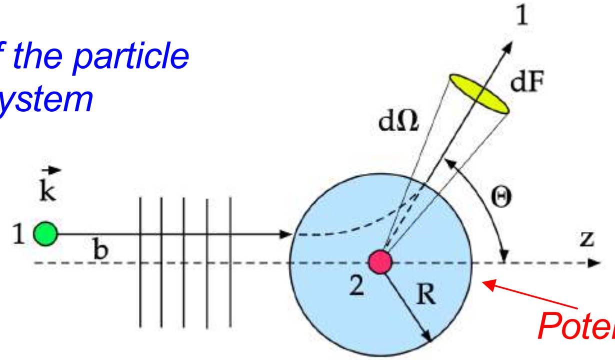
Partial wawe analysis, optical theorem and Total Cross-section Measurements

(this should be part of the exam program … even though it is difficult to remember the formulae)

Partial wawe analysis

- ❑ **elastic scattering between two particles of mass m_1 and m_2**

k: momentum of the particle in the CoM system



Potential of range R

At r >> R

$$\psi(r,\theta) = e^{ikz} + f(\theta)\frac{e^{ikr}}{r}$$

Incoming plane wawe (e^{ikz}); *scattering amplitude* ($f(\theta)$); *Scattered radial wawe* ($\frac{e^{ikr}}{r}$)

- ❑ **f(θ) can be parameterised in terms of partial wawes, that is as a function of angular momentum L.**

$$f(\theta) = \frac{1}{k}\sum_{\ell=0}^{\infty}(2\ell+1)\left[\frac{\eta_\ell e^{2i\delta_\ell}-1}{2i}\right]P_\ell(\cos\theta)$$

δ_l: phase shift; η_l : inelasticity parameter

Legendre Polynomials ($P_\ell(\cos\theta)$)

- ❑ **The total elastic cross-section is equal to:**

$$\sigma_e = \int |f(\theta)|^2 d\Omega \;=\; \frac{\pi}{k^2}\sum_{\ell=0}^{\ell_{\max}}(2\ell+1)|\eta_\ell e^{2i\delta_\ell}-1|^2$$

- ❑ **The inelastic cross-section is:**

$$\sigma_r = \frac{\pi}{k^2}\sum_{\ell=0}^{\ell_{\max}}(2\ell+1)(1-\eta_\ell^2)$$

$$\ell_{\max} = kR$$

η_l=1 (elastic); η_l<1 (inelastic)

Optical theorem

- The total cross-section (elastic plus inelastic) is: $$\sigma_t = \sigma_e + \sigma_r \; = \; \frac{2\pi}{k^2}\sum_{\ell=0}^{\ell_{\max}}(2\ell+1)(1-\eta_l\cos 2\delta_\ell).$$

- From the elastic scattering amplitude we find that the imaginary part at θ=0 is:

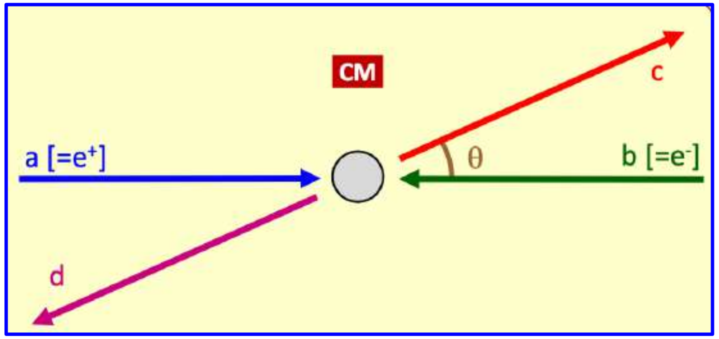
$$\mathrm{Im} f(0) = \frac{1}{2k}\sum_{\ell=0}^{\ell_{\max}}(2\ell+1)(1-\eta_\ell\cos 2\delta_\ell).$$

- If we compare the two expressions we find the optical theorem: $$\boxed{\sigma_t = \frac{4\pi}{k}\,\mathrm{Im} f(0)}$$

- This theorem is a wave mechanics relation between two unknown quantities: σ_t and Im *f*(0).
  The dynamics, carried by the potential scattering V(r), is contained in the scattering amplitude f(θ) or, in an analogous way, in the phase shifts δ_l and in the inelasticity parameters η_l

- The optical theorem is used to measure the total cross section in the hadron collider such as LHC (or ISR)

Mandelstam variables: s, t, u



CM system

- $p_a = [E, \quad p, \quad 0, \quad 0];$
- $p_b = [E, \quad -p, \quad 0, \quad 0];$
- $p_c = [E, p\cos\theta, p\sin\theta, \quad 0];$
- $p_d = [E, -p\cos\theta, -p\sin\theta, \quad 0];$

Lorentz-invariant variables for 2→2 processes.

Assume $E \gg m_i$, for the masses of all 4 bodies (otherwise, look for the formulæ in [PDG]).

s,t,u L-invariant

- $s \equiv (p_a + p_b)^2 = (p_c + p_d)^2 = 4E^2;$
- $t \equiv (p_a - p_c)^2 = (p_b - p_d)^2 \approx -\frac{1}{2}\, s\,(1 - \cos\theta) = -s \sin^2(\theta/2);$
- $u \equiv (p_a - p_d)^2 = (p_b - p_c)^2 \approx -\frac{1}{2}\, s\,(1 + \cos\theta) = -s \cos^2(\theta/2);$
- $s + t + u = 0$ (→ 1+1 independent variables, e.g. $[E,\theta]$, $[s, t]$, $[\sqrt{s},\theta]$)

If $\theta \to 0 \Rightarrow t \to 0$

Total cross section determination

$$\sigma_t = \frac{4\pi}{k}\,\mathrm{Im} f(0)$$

$$k = \frac{\sqrt{s}}{2} = \frac{\sqrt{4E^2}}{2}$$

Proton momentum in the CoM

$$\mathrm{Im}\, f(t=0) = \frac{\sqrt{s}}{8\pi}\sigma_t$$

- **We need to derive Im f(t=0) from the elastic scattering at very low angle.**

1. Define the differential cross-section in terms of $f_{el}(\theta)$: $\sigma_{el} = \int |f_{el}(\theta)|^2 d\Omega \Rightarrow \frac{d\sigma_{el}}{d\Omega} \equiv \frac{d^2\sigma_{el}}{d\varphi\, d\cos\theta} = |f_{el}(\theta)|^2$

2. We need the relationship between t and cos θ:

$$t = -\frac{s}{2}(1-\cos\theta) \rightarrow \cos\theta = 1 + \frac{2t}{s} \Rightarrow \frac{\partial \cos\theta}{\partial t} = \frac{2}{s}$$

$$\frac{\partial\sigma}{\partial t} = \frac{\partial\sigma}{\partial\cos\theta}\cdot\frac{\partial\cos\theta}{\partial t}$$

3. We integrate over ϕ, we change variable and we obtain the dependency of the cross section with respect to t:

$$\frac{d\sigma_{el}}{dt} = \int d\varphi \left(\frac{d^2\sigma_{el}}{d\varphi\, d\cos\theta}\right)\left|\frac{\partial\cos\theta}{\partial t}\right| = 2\pi |f_{el}(\theta)|^2 \frac{2}{s} = \frac{4\pi}{s}|f_{el}(s,t)|^2 \Rightarrow \left|f_{el}^{t=0}\right|^2 = \frac{s}{4\pi}\frac{d\sigma_{el}}{dt}\bigg|_{t=0}$$

It is an observable

Total cross section determination

$$\sigma_t = \frac{4\pi}{k}\,\mathrm{Im}f(0)$$ $$\mathrm{Im}\,f(t=0) = \frac{\sqrt{s}}{8\pi}\sigma_t$$ $$\Rightarrow \quad |\mathrm{Im}[f_{el}(0)]|^2 = \frac{s}{64\pi^2}\cdot\sigma_{tot}^2$$

4. Define: $\rho = \mathrm{Re}[f_{el}(0)]/\mathrm{Im}[f_{el}(0)]$ $\Rightarrow$ $|f_{el}(0)|^2 = |\mathrm{Re}[f_{el}(0)]|^2 + |\mathrm{Im}[f_{el}(0)]|^2 = |\mathrm{Im}[f_{el}(0)]|^2 \cdot (1+\rho^2)$

$$\Rightarrow \quad \left|f_{el}^{t=0}\right|^2 = \frac{\sigma_{tot}^2 s}{64\pi^2}\left(1+\rho^2\right)$$

5. In the previous slide we found: $$\left|f_{el}^{t=0}\right|^2 = \frac{s}{4\pi}\left.\frac{d\sigma_{el}}{dt}\right|_{t=0}$$

6. Combining the the two expression we find: $$\sigma_{tot} = \sqrt{\frac{16\pi}{1+\rho^2}\cdot\left(\frac{d\sigma_{el}}{dt}\right)_{t=0}}$$

7. We need the luminosity to measure the differential elastic cross section and we need ρ to measure σ_{tot}.

Total cross section determination without the Luminosity

- define R_{tot} as the total number of events (el. plus inelastic) per second and R_{el} the rate for elastic event:

$$R_{tot} = \mathfrak{L}\sigma_{tot}, \quad \sigma^2_{tot} = \sigma_{tot}R_{tot} / \mathfrak{L}, \qquad R_{el} = \sigma_{el}\,\mathfrak{L}, \quad d\sigma_{el}/dt = (dR_{el}/dt)/\mathfrak{L}$$

L: luminosity

- put together the various pieces:

$$\left|f_{el}^{t=0}\right|^2 = \frac{\sigma^2_{tot}s}{64\pi^2}\left(1+\rho^2\right) = \frac{R_{tot}\sigma_{tot}}{\mathfrak{L}}\frac{s}{64\pi^2}\left(1+\rho^2\right);$$

$$\left|f_{el}^{t=0}\right|^2 = \frac{s}{4\pi}\left.\frac{d\sigma_{el}}{dt}\right|_{t=0} \Rightarrow \left.\frac{d\sigma_{el}}{dt}\right|_{t=0} = \frac{1}{\mathfrak{L}}\left.\frac{dR_{el}}{dt}\right|_{t=0} = \frac{R_{tot}\sigma_{tot}}{16\pi\mathfrak{L}}\left(1+\rho^2\right).$$

$$\sigma = \frac{R}{\mathfrak{L}}$$

To measure R_{tot}, we have to make sure that, experimentally, we are counting all kind of proton-proton interactions. On top, we have to take into account all the efficiencies to record the events (geometrical acceptance, trigger efficiency, detector efficiency, etc…

- We can discard the luminosity in both terms and derive the final formula:

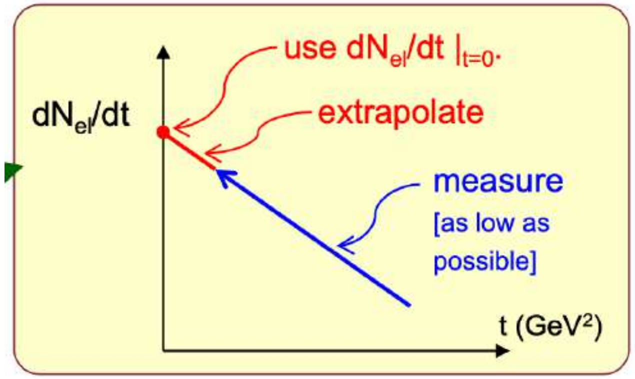
$$\sigma_{tot} = \frac{16\pi(\hbar c)^2}{1+\rho^2}\frac{1}{R_{tot}}\left.\frac{dR_{el}}{dt}\right|_{t=0}.$$

We don't need to know the luminosity

Total cross section determination (without Lum.)

$$\sigma_{tot} = \frac{4\pi}{k}\Im[f_{el}(\theta=0)] = \frac{16\pi(\hbar c)^2}{1+\rho^2}\frac{1}{R_{tot}}\frac{dR_{el}}{dt}\bigg|_{t=0}.$$

- Everyting (but ρ) is directly measurable → σ_{tot} can be measured without knowing the luminosity
- R_{el} and R_{tot}: only the ratio count → do the measurement in the same time interval (N_{el} and N_{tot})
- $dR_{el}/dt\,|_{t=0}$: do the following plot and extrapolate to zero:



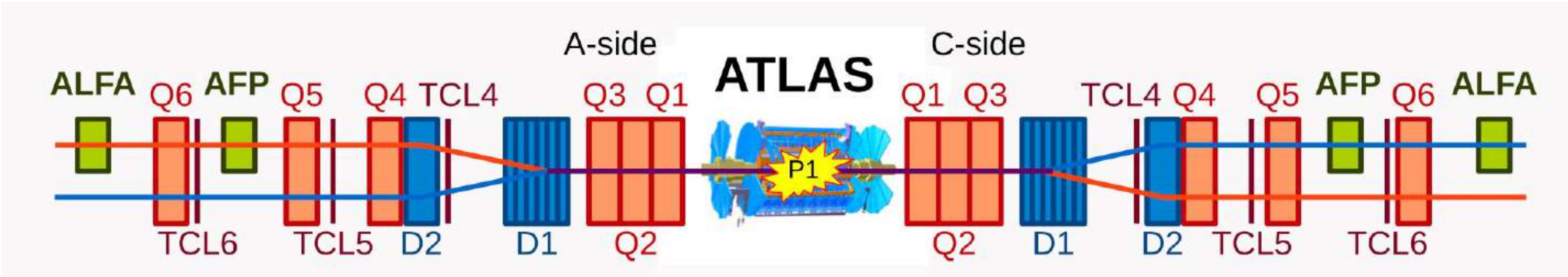
$$t = -\frac{s}{2}(1-\cos\theta)$$

To go to low t, we need to go to small θ, therefore the detectors for this measurement are placed far away from the interaction point and as close as possible to the beam.
Moreover, at LHC dedicated runs at high-β are done just for this measurement, to minimize the pile-up

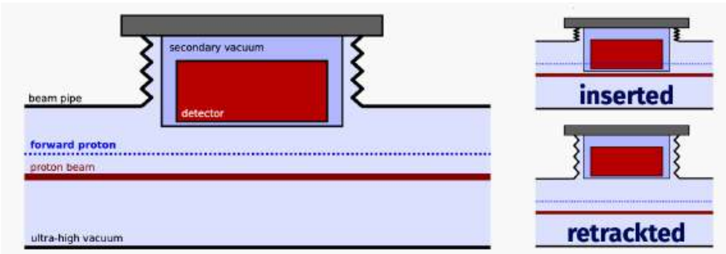
- The ratio ρ: it can be computed/guessed by first principle; at LHC it is about 0.14 with an error about 0.5%.

Soft Physics at LHC

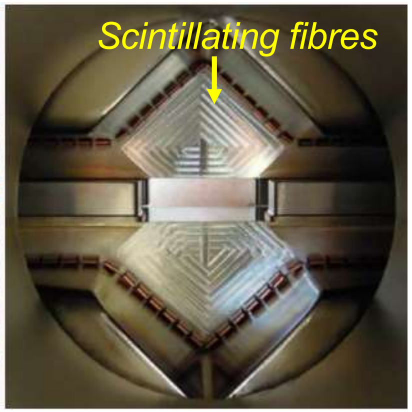
“soft” physics at LHC

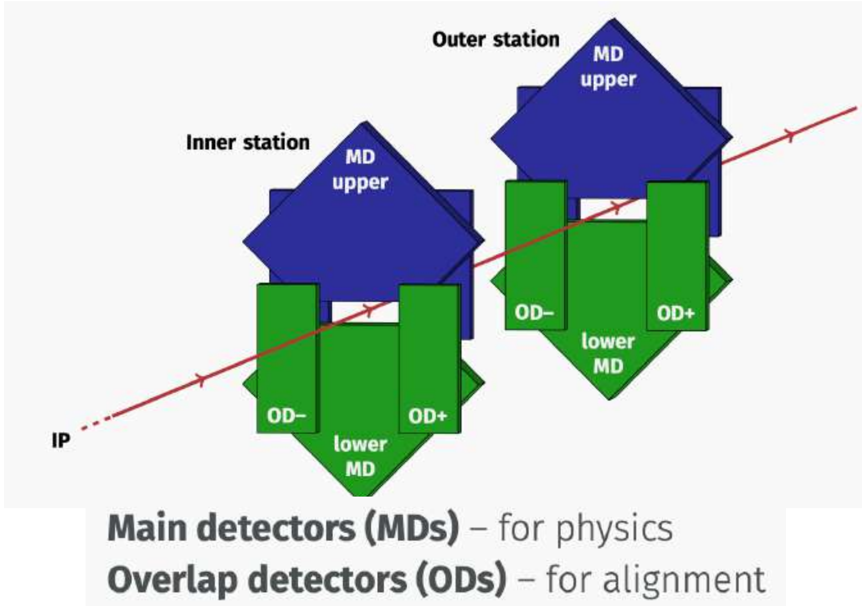


240 m



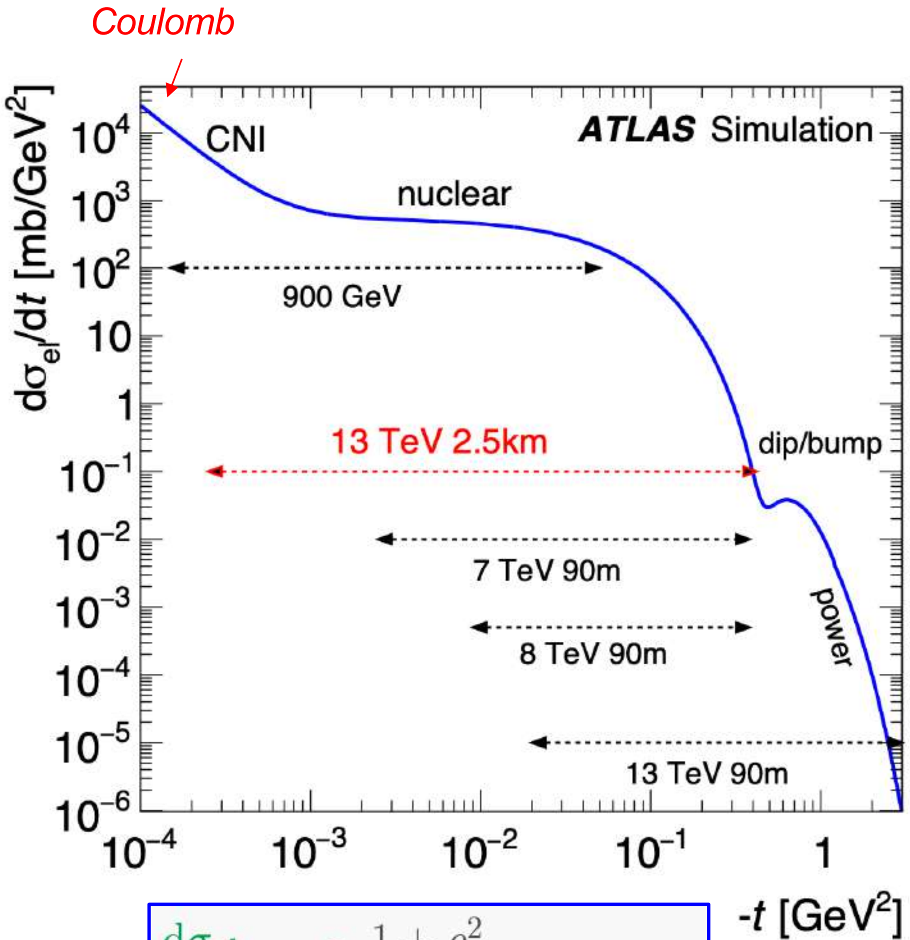
Roman pot



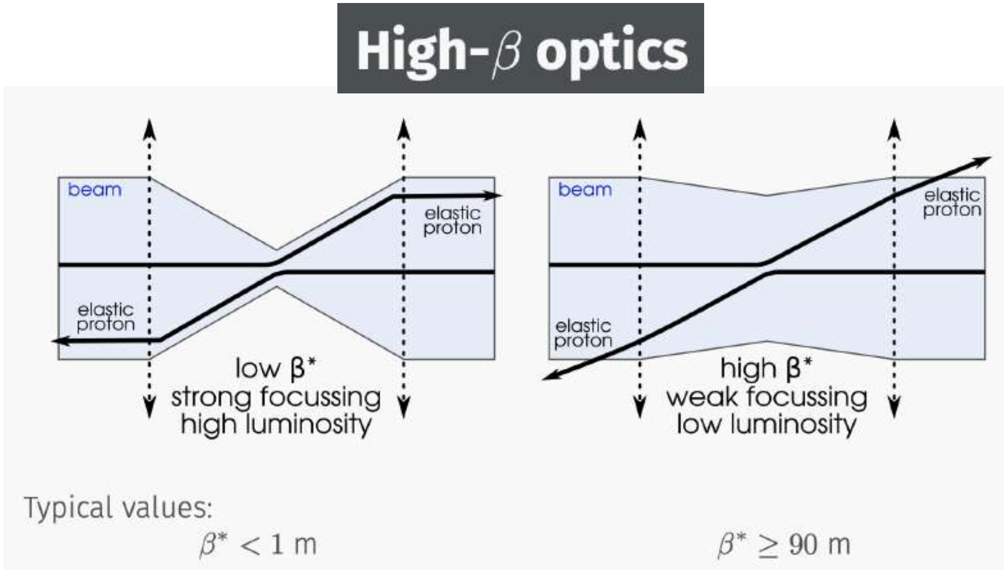


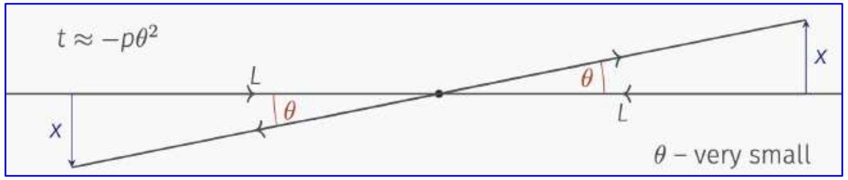
Near CMS we have the TOTEM detector

ALFA experimental reach



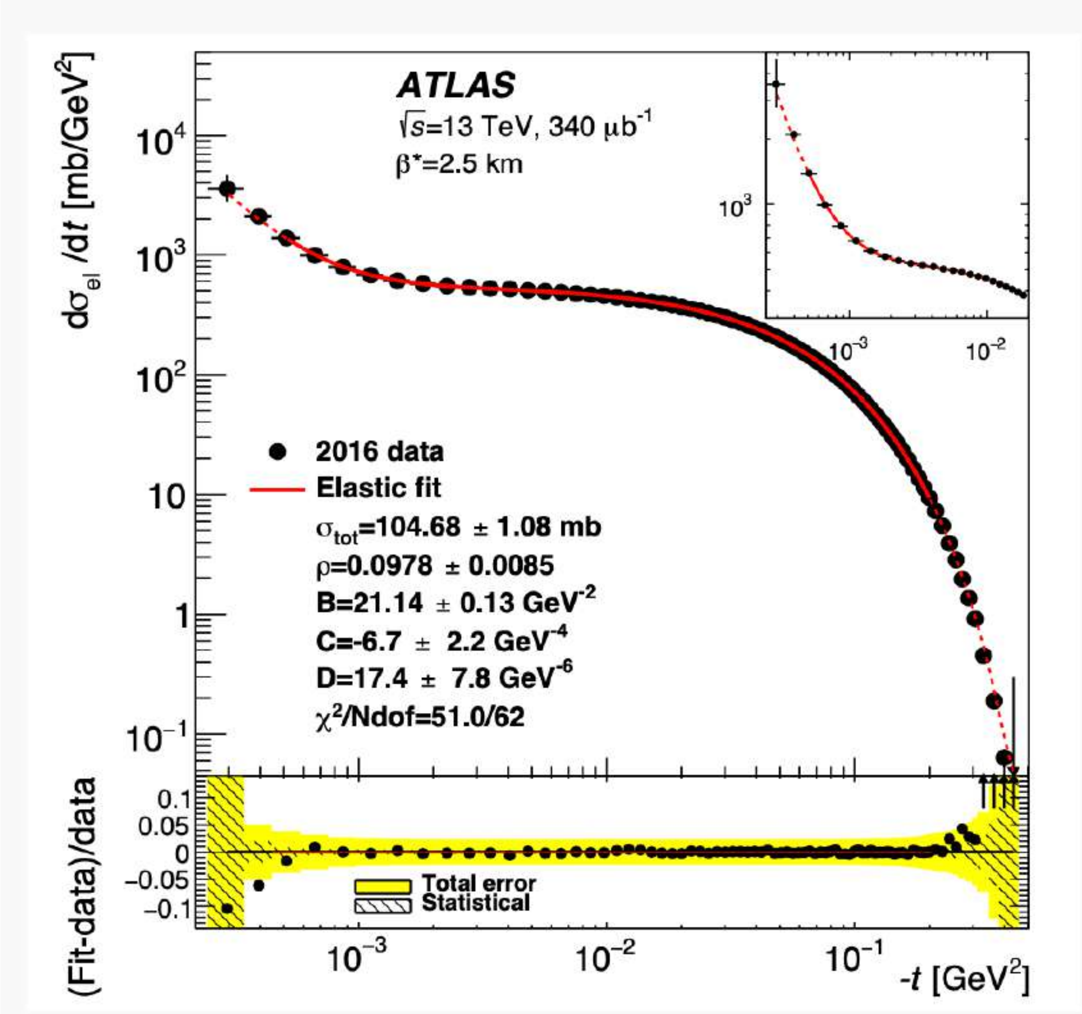
$$\frac{d\sigma_{\mathbf{el}}}{dt} = \sigma^2_{\mathbf{tot}} \frac{1+\rho^2}{16\pi} \exp(-B|t|)$$





Dedicated LHC runs with high beta for ALFA measurements

Differential cross section



Fitted function:

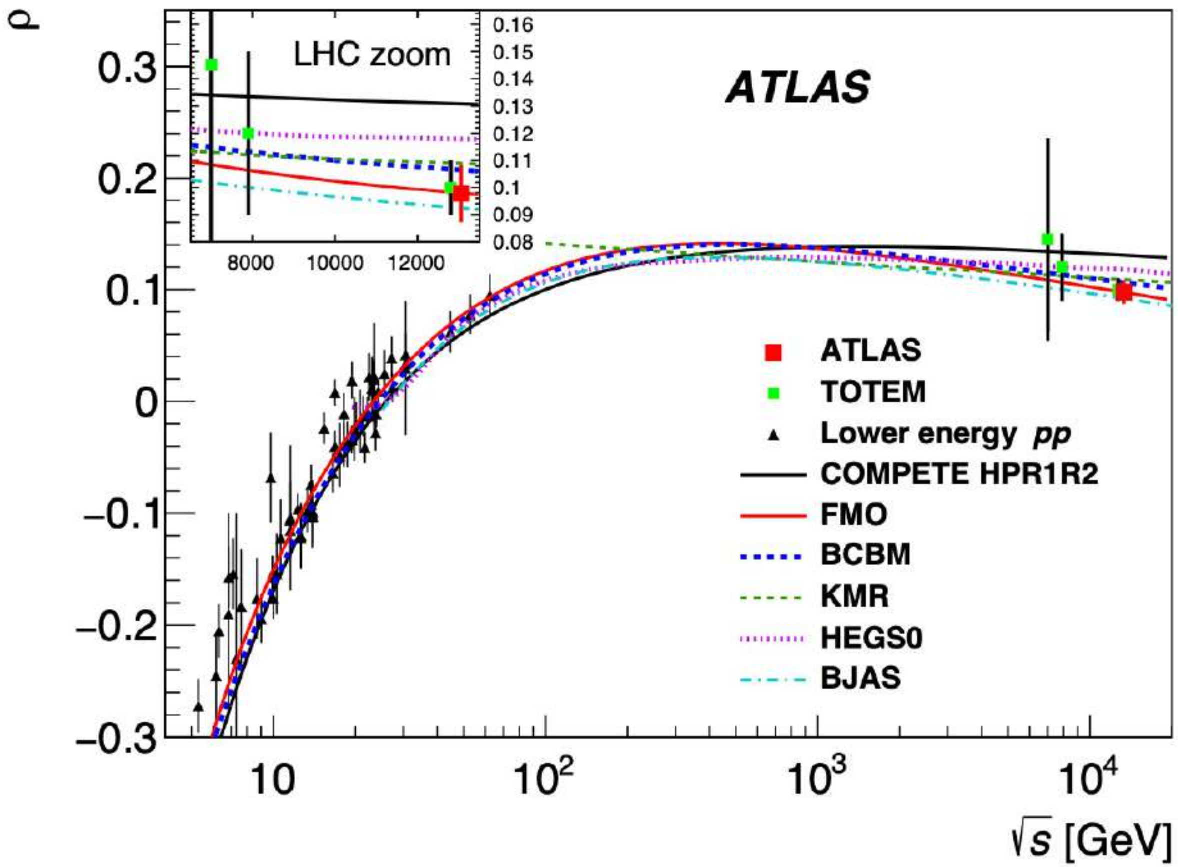
$$\frac{d\sigma}{dt} = \frac{1}{16\pi}\left|f_N(t) + f_C(t)e^{i\alpha\phi(t)}\right|^2$$

$$f_C(t) = -8\pi\alpha\hbar c\frac{G^2(t)}{|t|}$$

$$f_N(t) = (\rho + i)\frac{\sigma_{tot}}{\hbar c}e^{(-B|t| - C|t|^2 - D|t|^3)/2}$$

$$\rho = \frac{\mathrm{Re}\, f_N(0)}{\mathrm{Im}\, f_N(0)}$$

Results in interference region: ρ measurement



$$\rho = 0.0978 \pm 0.0043(\text{stat.}) \pm 0.0073(\text{exp.}) \pm 0.0064(\text{th.})$$

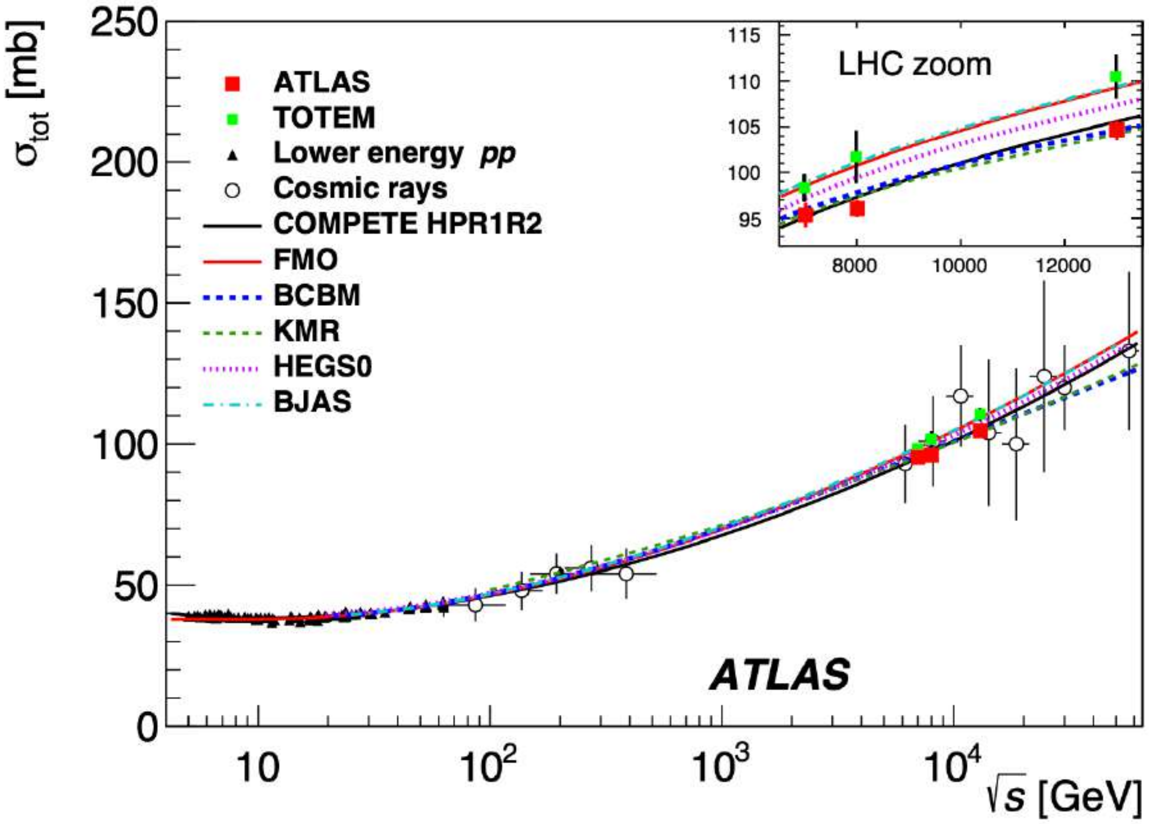
Result incompatible with COMPETE (community-standard semi-empirical fits) indicating Odderon exchange or a slowdown of σ_{tot} rise at high $\sqrt{s}$

Today view

Pomeron: two gluons exchange

Odderon: three gluons exchange

Results in nuclear region: σ_{tot}



$$\sigma_{tot} = 104.68 \pm 0.22(\text{stat.}) \pm 1.06(\text{exp.}) \pm 0.12(\text{th.})\ \text{mb}$$

Most precise σ_{tot} measurement. 2.2σ tension with TOTEM σ_{tot} result.

Method of σ_{tot} measurement

Luminosity-dependent (ATLAS)

$$\sigma^2_{\text{tot}} = \frac{16\pi}{1+\rho^2}\frac{1}{L}\frac{dN_{\text{el}}}{dt}\bigg|_{t\to 0}$$

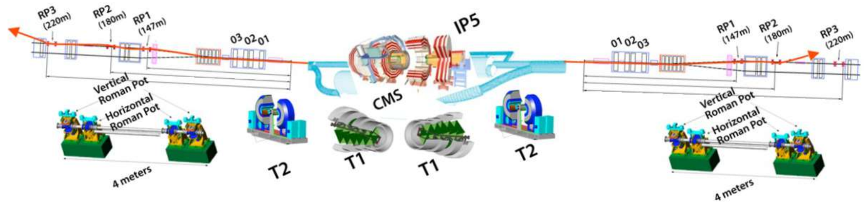
Requires a dedicated luminosity measurement

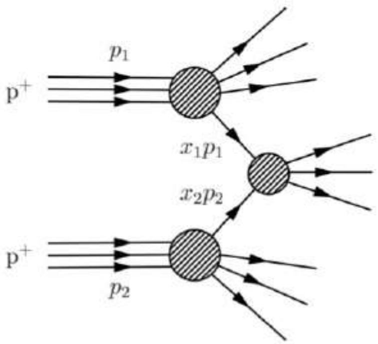
Luminosity-independent (TOTEM)

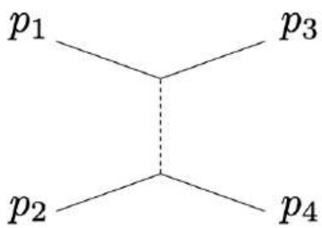
$$\sigma_{\text{tot}} = \frac{16\pi}{1+\rho^2}\frac{1}{N_{\text{el}}+N_{\text{inel}}}\frac{dN_{\text{el}}}{dt}\bigg|_{t\to 0}$$

Requires correction for not measured small-mass diffraction

Still on pp total cross section

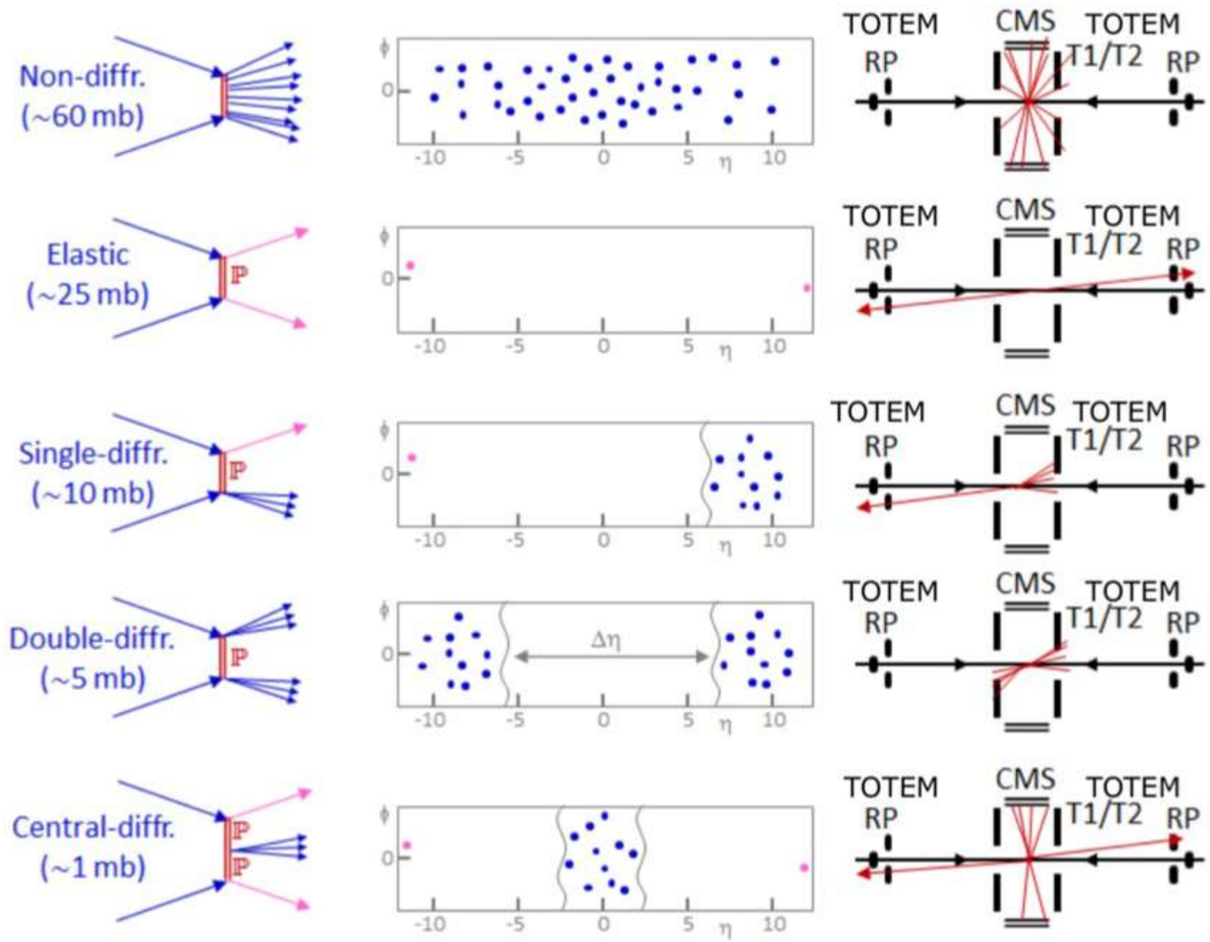




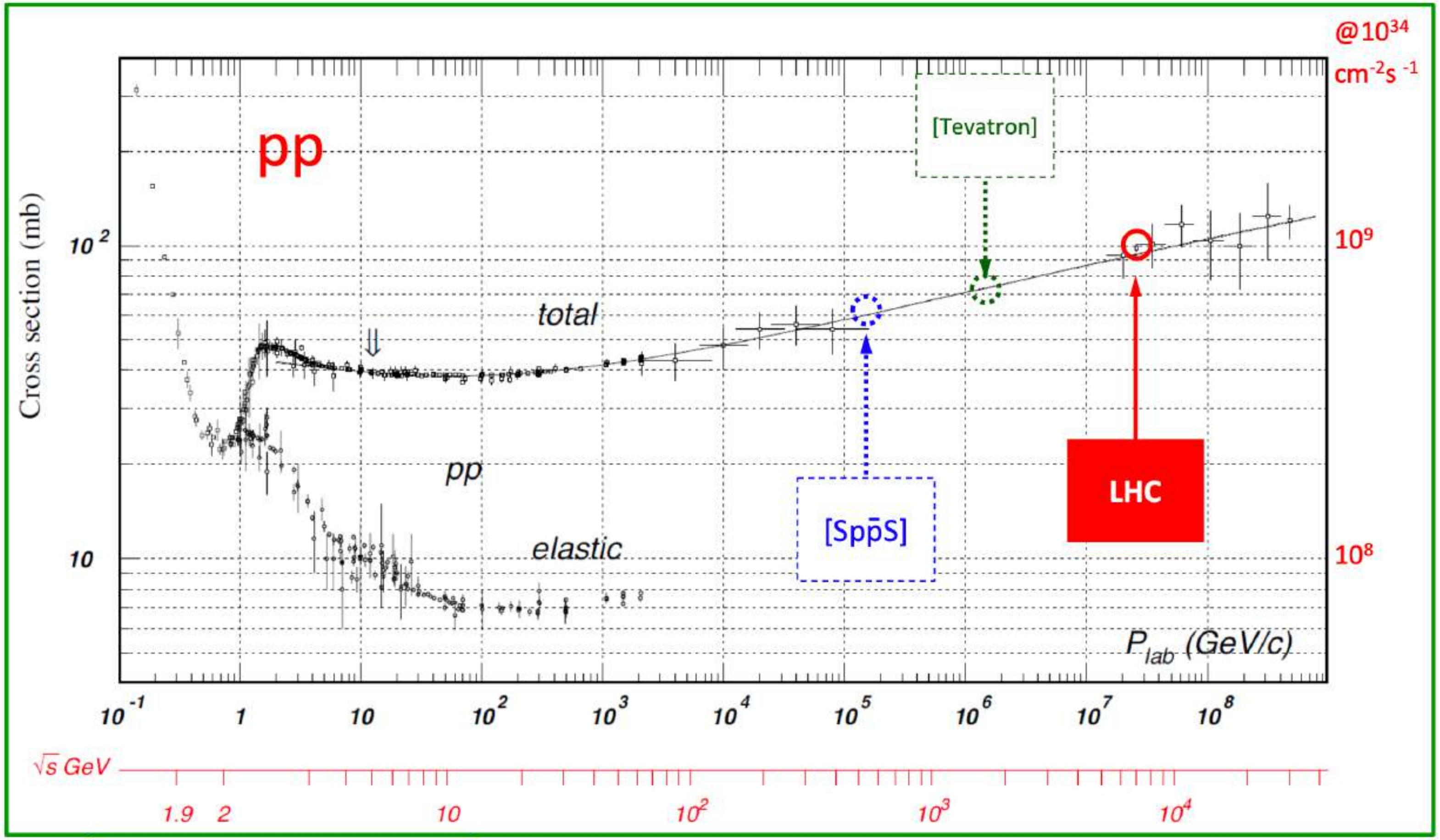


$$t = (p_1 - p_3)^2$$

(very naive view of the pomeron is a colorless pair of gluons)



pp σ_{tot} as a function of $\sqrt{s}$

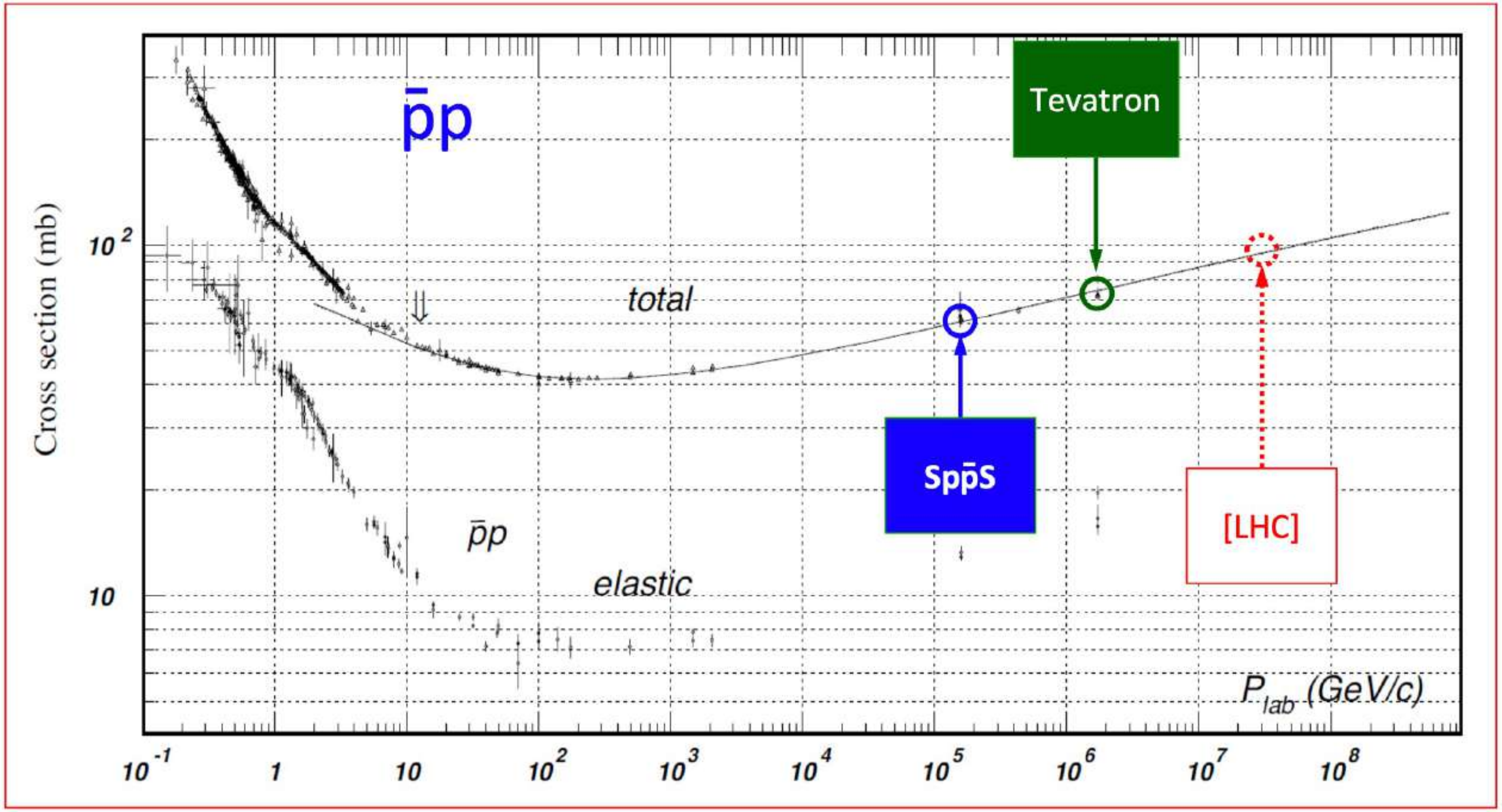


Rise as $ln^2(s)$

1 b = 10^{-28} m² = 10^{-24} cm²
1 mb = 10^{-31} m² = 10^{-27} cm²

The data of $\sigma(\bar{p}p)$, i.e. Sp$\bar{p}$S and Tevatron, are dashed, to show the similarity of the cross sections.

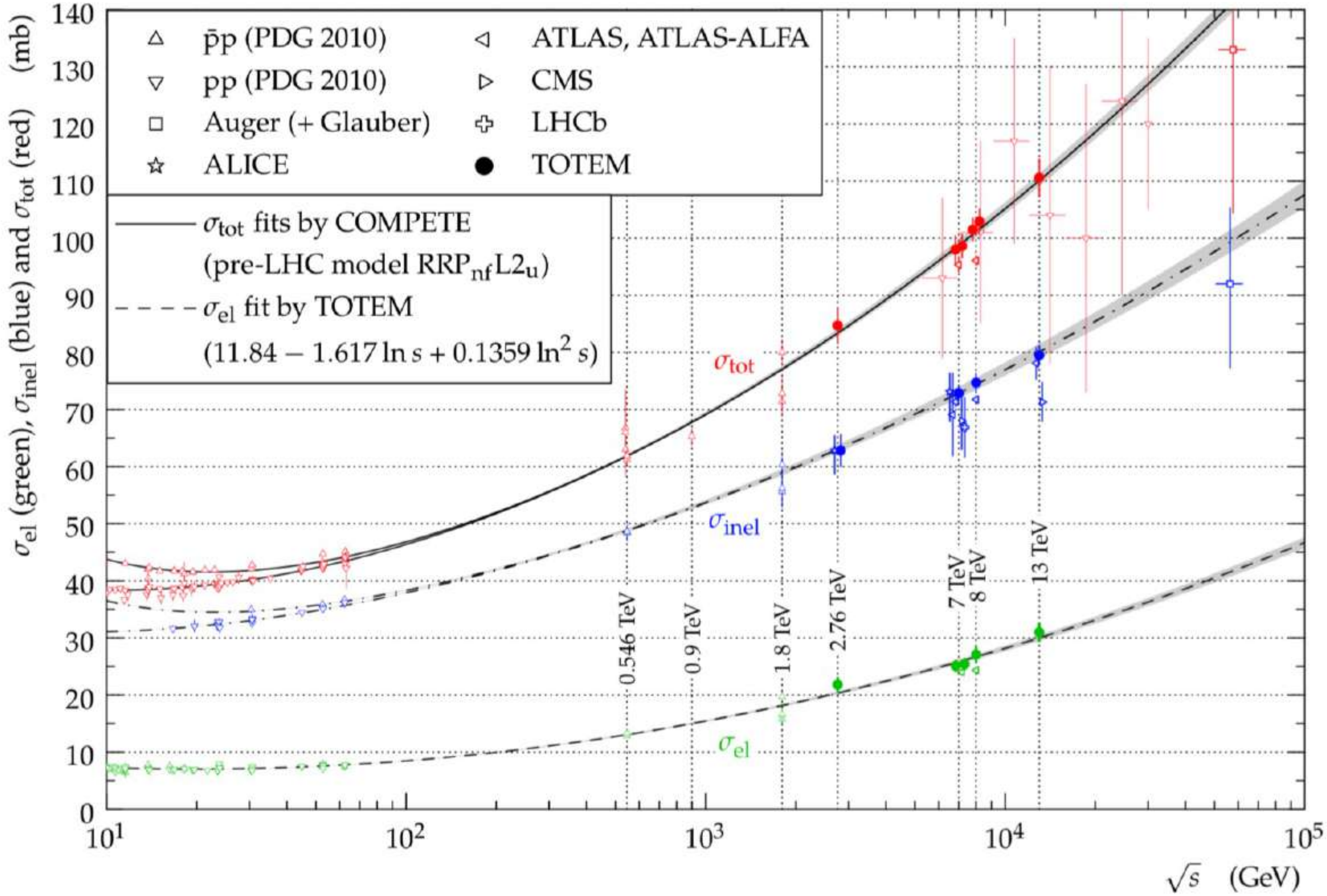
p̄p σ_{tot} as a function of $\sqrt{s}$



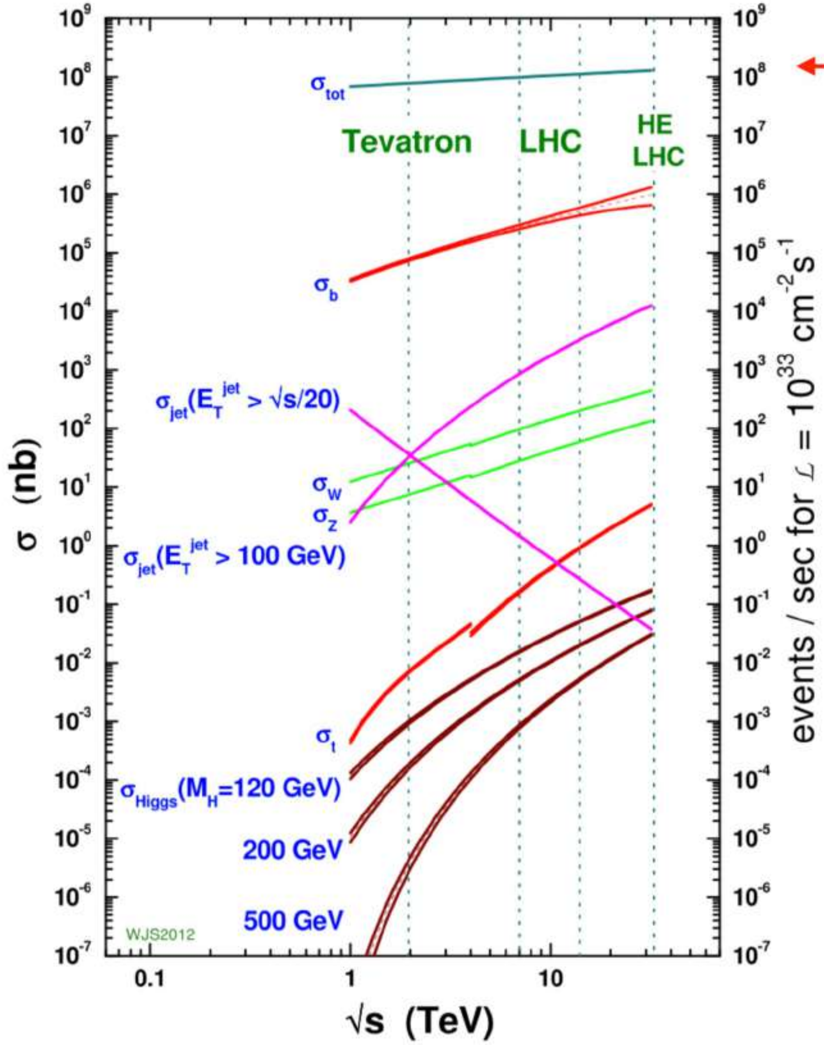
The data of σ(pp), i.e. LHC, do NOT belong to this plot; they are plotted dashed, to show the similarity of the cross sections ("Pomeranchuk theorem").

pp cross section: elastic, inelastic and total

Elastic
Inelastic
Total



Closer inspection to the total cross section



100 mb — Total cross section

60 mb — Start seeing events in the detector! Starting point of everything!!

(we don't see scattered protons in the beam pipe)

From the nominal LHC luminosity:

$$2 \times 10^{34} cm^{-2} s^{-1}$$

With a total cross section of approximately 100mb:

$$100 \times 10^{-27}\,(cm^2) \times 2 \times 10^{34}\,cm^{-2}s^{-1}$$

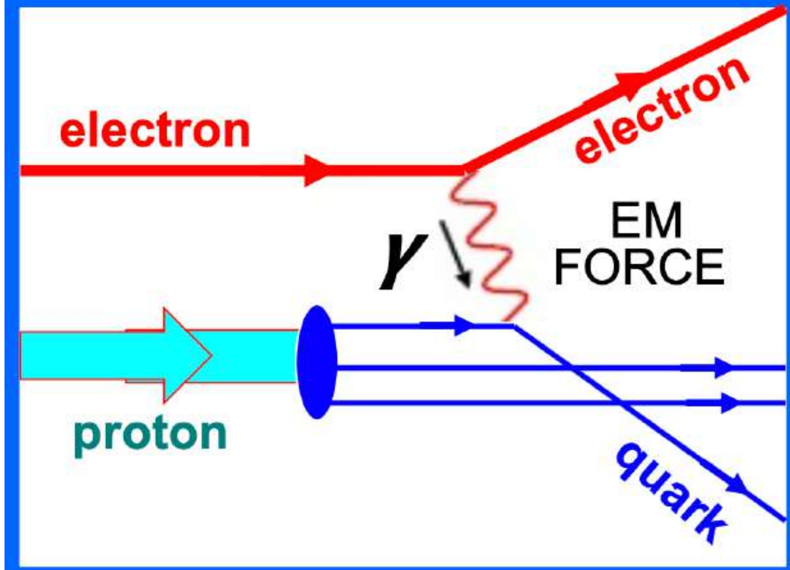
$$\sim 2 \times 10^9\,\text{evts/s}$$

The protons collide every 25 ns (40 MHz); what we should conclude?

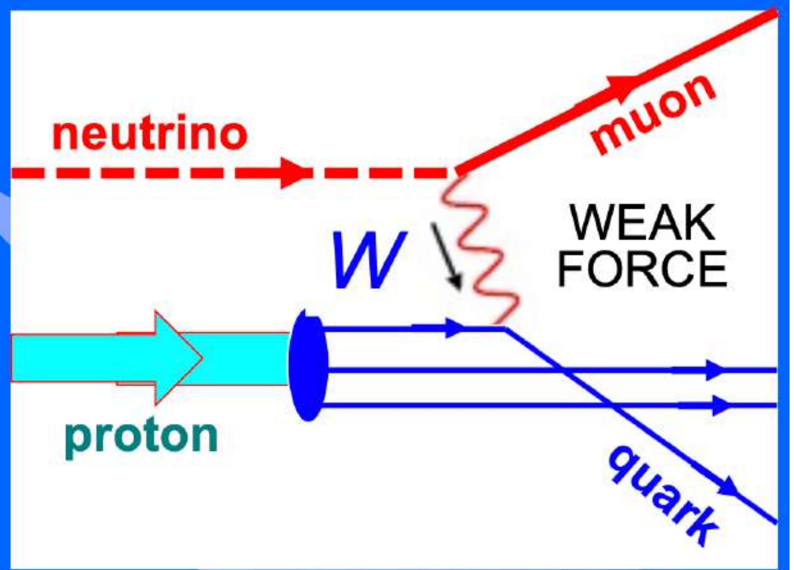
Back to "less soft" Physics at the ISR

This is not part of the exams, it is just for your fun

“HARD” PHYSICS: the XVI HEP Conference – 1972- Batavia



SLAC
ELECTRON deep inelastic scattering:
“partons” exist within protons
and partons are probably quarks

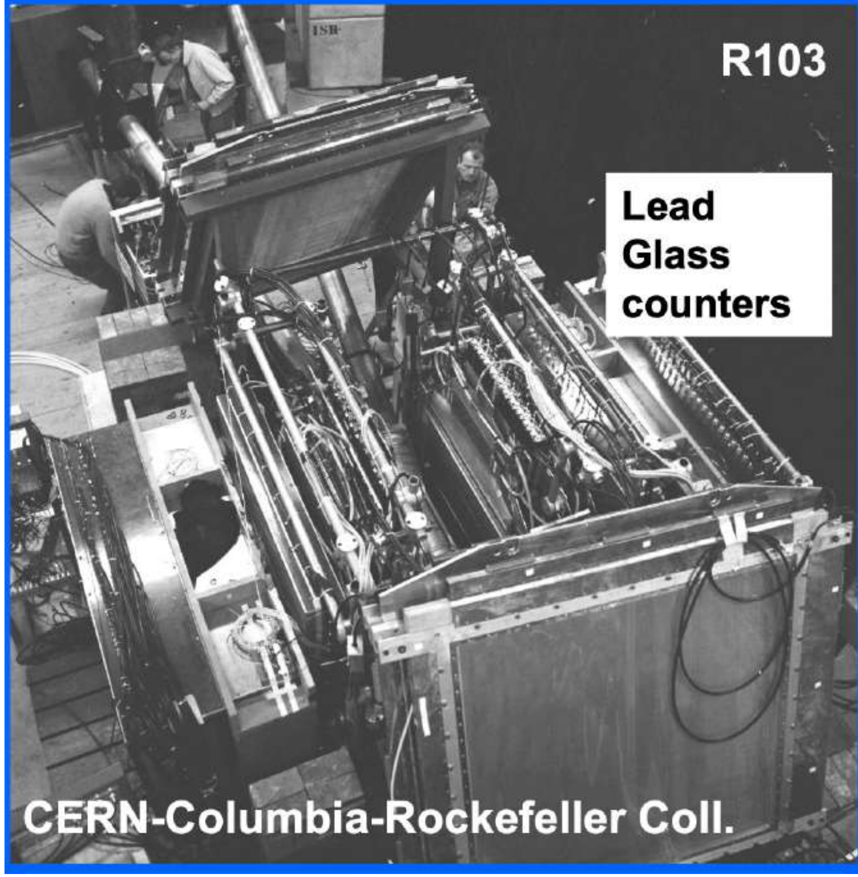


(bubble chamber experiment at CERN)

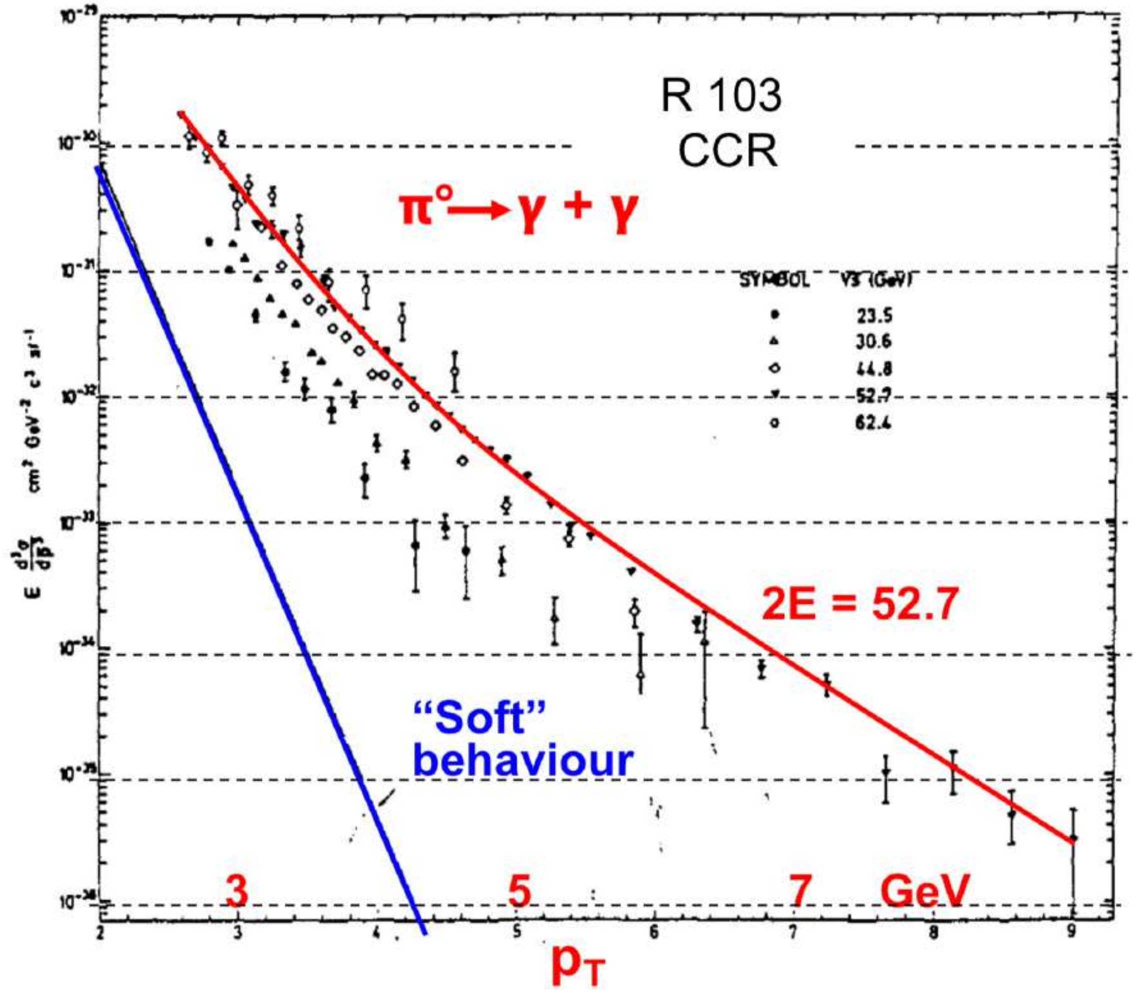
GARGAMELLE:
NEUTRINO ‘deep’ inelastic scattering:
first evidence that “partons” are quarks

“HARD” PHYSICS: the XVI HEP Conference – 1972- Batavia

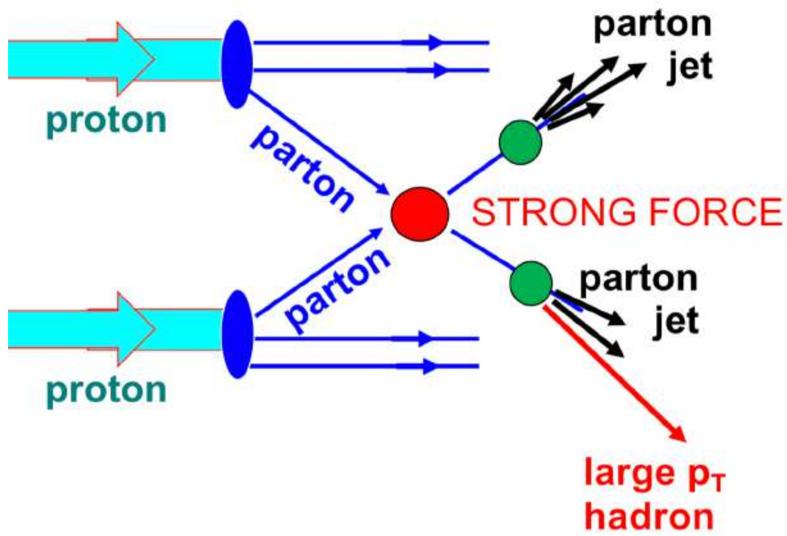
At the same Conference ISR Collaborations announced the discovery of large transverse momentum hadrons



Large p_T data presented by CCR at the 1972 conference



Parton interpretation of the new phenomena



"HARD PHYSICS"

ISR EXPERIMENTS HAVE SHOWN THAT PARTONS BEHAVE AS POINTLIKE OBJECTS ALSO WHEN THEY INTERACT THROUGH THE STRONG FORCE

NEXT: DETECT JETS

ISR disappointment

Frustration was felt in Sept 74 when J/psi was announced

Experiment R103

CERN-Columbia-Rockefeller Coll.

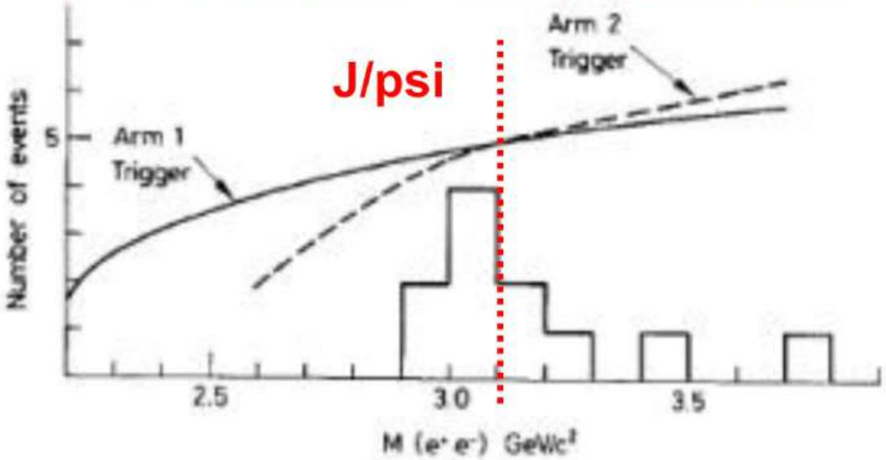
The two-arm trigger was dominated by $\pi^0 \longrightarrow \gamma + \gamma$

To write on tape less than 10 evts/s, cuts were set above 1.5 GeV thus excluding J/psi

Luigi Di Lella

"An ISR discovery prevented a more important discovery"

e^+e^- invariant mass distribution



R105 - December 1974

1975-1977:" A somewhat difficult time"

No instrument to trigger on jets and to study them

AND

ISRC was very hesitant in approving large coverage magnetic detectors

In 1976 organized a WG to evaluate Solenoid vs Toroid

The results were seminal for the Axial Field Spectrometer and for the detectors of the future proton-antiproton collider

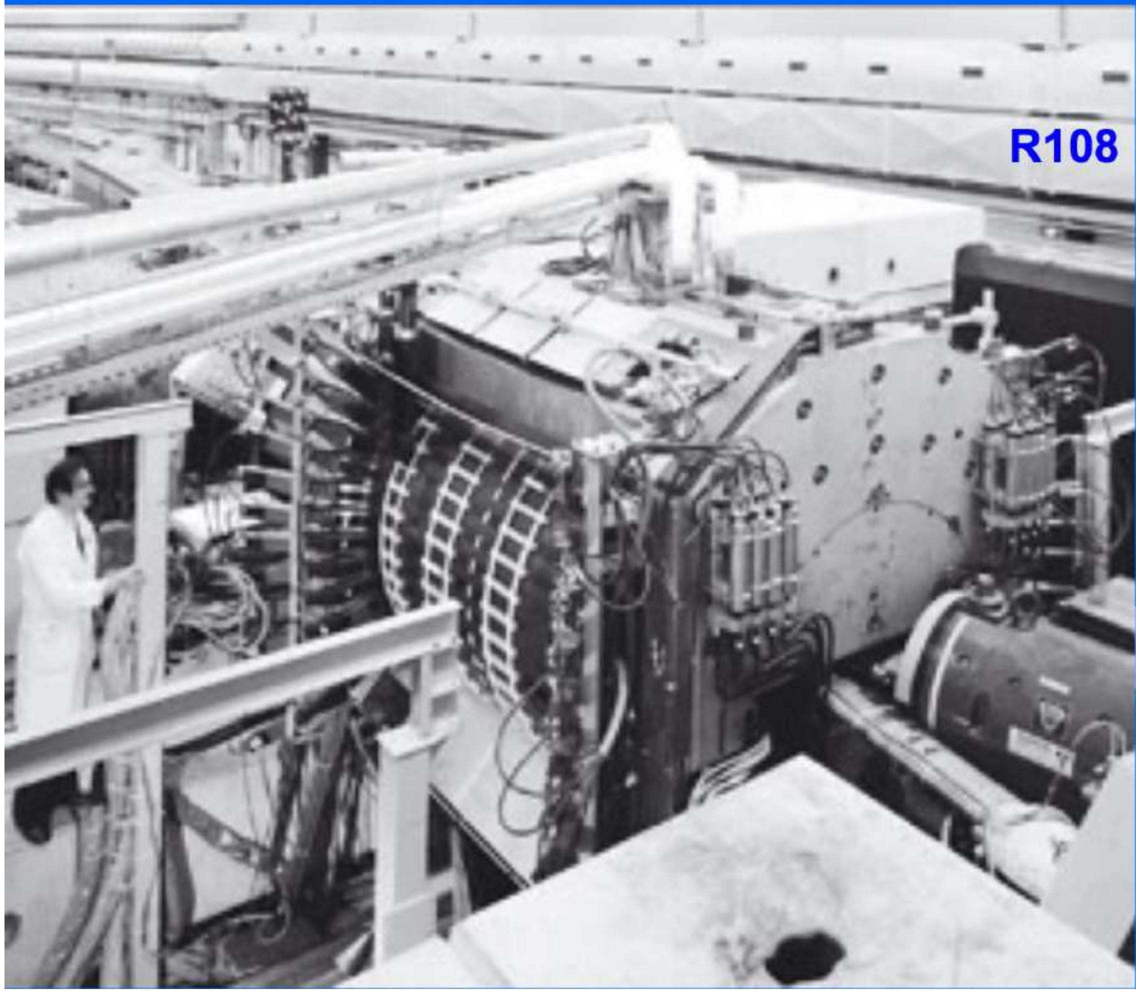
… and …

1976: LEP study group initiated

… in the mean while …

1977: SPS inauguration

1978-1983: “a very active and interesting program”

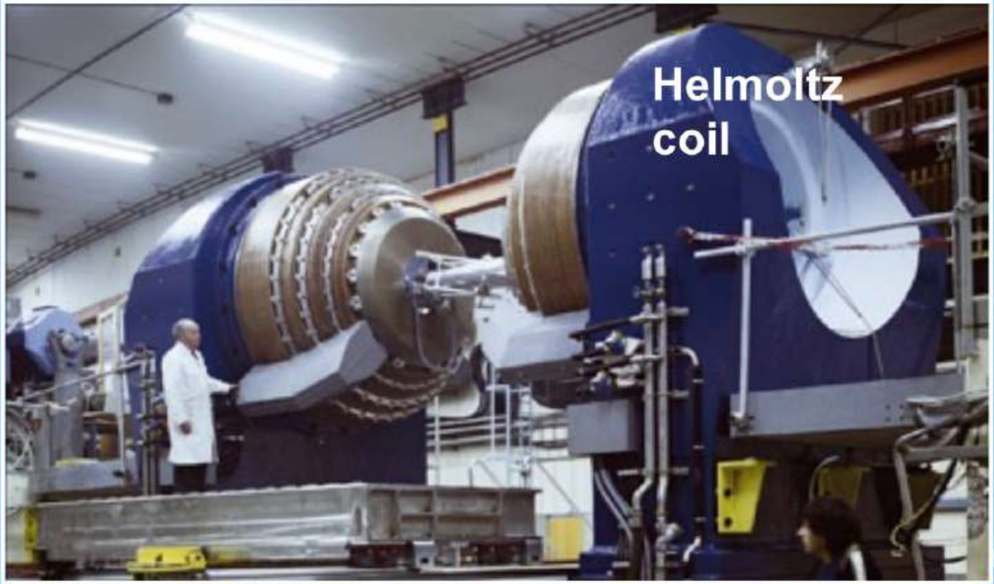


SUPERCONDUCTING SOLENOID

CERN-Columbia-Oxford-Rockefeller Collaboration

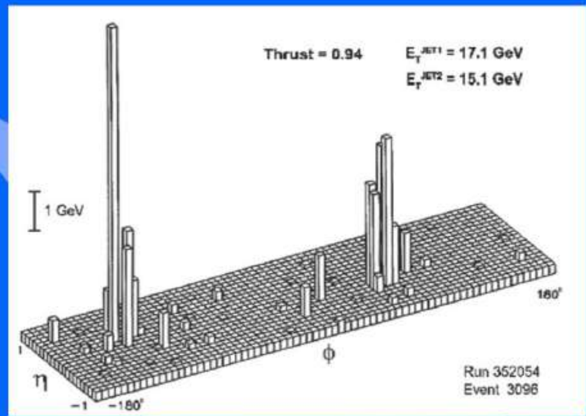
With cylindrical drift chambers and two arrays of glass Cherenkov counters

1978-1983: “a very active and interesting program”



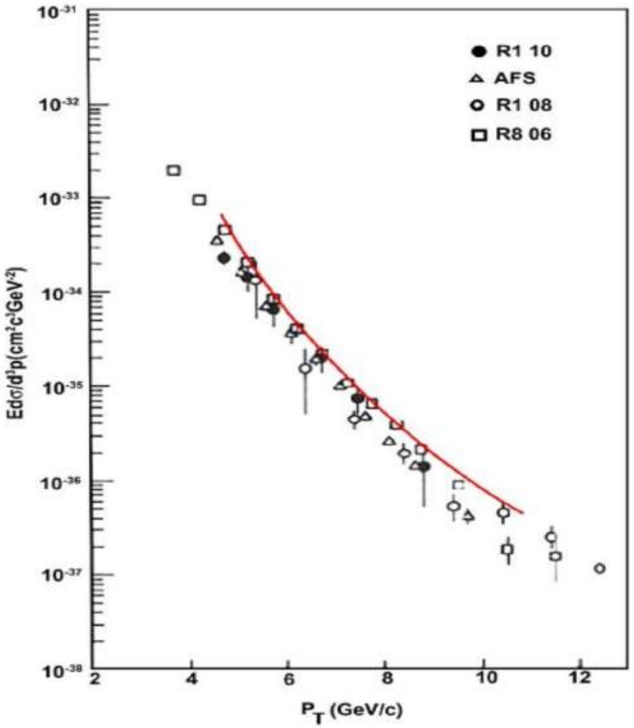
AXIAL FIELD SPECTROMETER
with liquid Ar calorimeter
And U hadron-calorimeter

BNL, CERN, Copenhagen,
Lund, Pennsylvania,
Rutherford, Tel Aviv



Evidence for jet production

An important discovery: single photons at large p_T

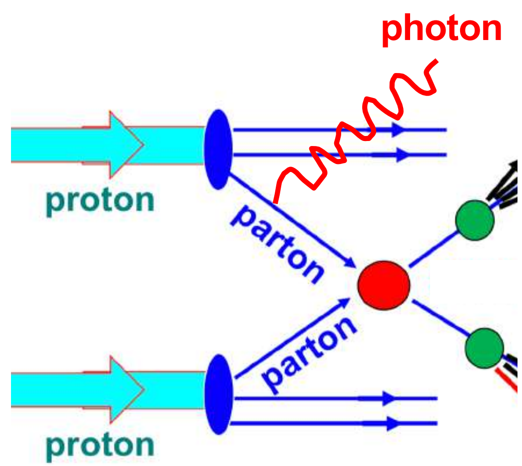


AFS
BNL, CERN, Copenhagen, Lund, Pennsylvania, Rutherford, Tel Aviv

R108
CERN, Oxford, Rockefeller

R110
CERN, Oxford, Rockefeller

R806
Athens, Brookhaven, CERN



High p_T single photons can not come from the final state. Most likely they are radiated by the initial parton state

Early experimental indication of the validity of QCD

BUT

lack of general recognition of the importance of ISR hard physics

In 1983 ISR were closed. They could not compete any longer with the “younger” and “stronger” $Sp\bar{p}S$ experiments.

1972: stochastic cooling paper by S. van der Meer

CERN/ISR-PO/72-31

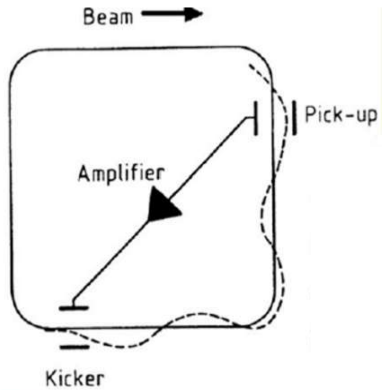
STOCHASTIC DAMPING OF BETATRON OSCILLATIONS

IN THE ISR

by

S. van der Meer

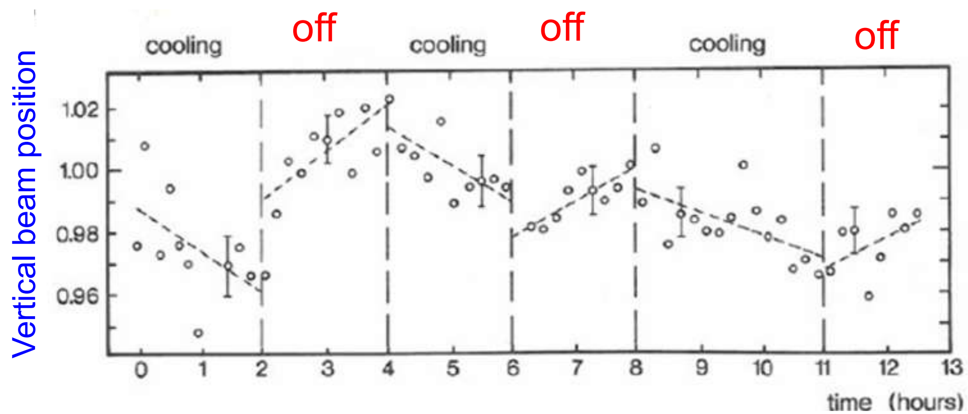
W. Schnell took the challenge and tried to implement the van der Meer proposal in the ISR.



A pick-up sensor detect the fluctuation of the average position of the protons with respect to the ideal orbit and send a signal to a kicker to push them "inside" the beam. In average the beam is "squeezed".

4. FINAL NOTE

This work was done in 1968. The idea seemed too far-fetched at the time to justify publication. However, the fluctuations upon which the system is based were experimentally observed recently. Although it may still be unlikely that useful damping could be achieved in practice, it seems useful now to present at least some quantitative estimation of the effect.



The cooling effect was visible

In 1918 W. Schottky described the spontaneous fluctuations from DC electrons beam (Schottky signal)

ISR: conclusion remarks

40th Anniversary of the First Proton-Proton Collisions in the CERN Intersecting Storage Rings (ISR)

CERN–2012–004
24 May 2012

10 years ago

Authors: U. Amaldi
P. J. Bryant
P. Darriulat
K. Hübner

PIERRE DARRIULAT

We, who worked at the ISR, tend not to attach much importance to this lack of recognition because for us the main legacy has been to have taught us how to make optimal use of the proton-antiproton collider….

We tend to see the ISR and the proton-antiproton colliders, both at CERN and at the Tevatron, as a lineage, father and sons, the success of the latter being indissociable from the achievements of the former.

SAPIENZA
UNIVERSITÀ DI ROMA

End of chapter 2