PION POLARIZABILITY AT CERN COMPASS

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CERN COMPASS collaboration

The 2017 Division of Particles and Fields meeting, DPF17, Fermilab, Batavia, IL, July 31-Aug. 4, 2017

NA58 experiment at CERN SPS

COmmon
Muon and
Proton
Apparatus for
Structure and
Spectroscopy

20 Institutes/11 counties/~230 physicists

Czech Republic, Finland, France, Germany, India, Israel, Italy, Japan, Poland, Portugal and Russia

Bielefeld, Bochum, Bonn, Burdwan/Calcutta, CERN, Dubna, Erlangen, Freiburg, Lisbon, Mainz, Moscow, Munich, Prage,
Protvino, Saclay, Tel Aviv, Torino, Trieste, Warsaw and Yamagata

Dipole pion polarizabilities probe rigidity of pion's quark-antiquark structure.

Dipole moments induced by gamma's electric and magnetic fields during Gamma-Pion Compton scattering: $d=\alpha E \quad \mu=\beta H$.

COMPASS Tests of ChPT: Primakoff reactions

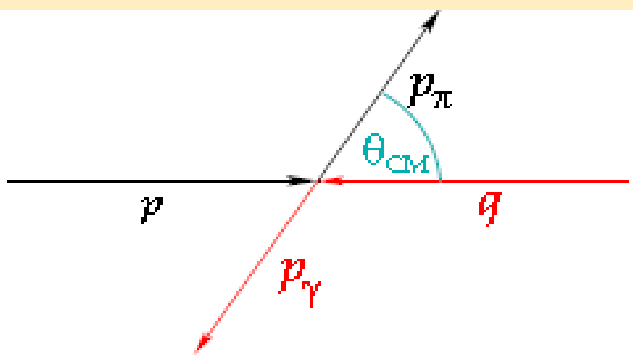
Access to $\pi + \gamma$ reactions via the Primakoff effect:

At small momentum transfer to the nucleus, high-energetic particles scatter predominantly off the el.mag. field quanta ($\sim Z^2$)

Compton Scattering

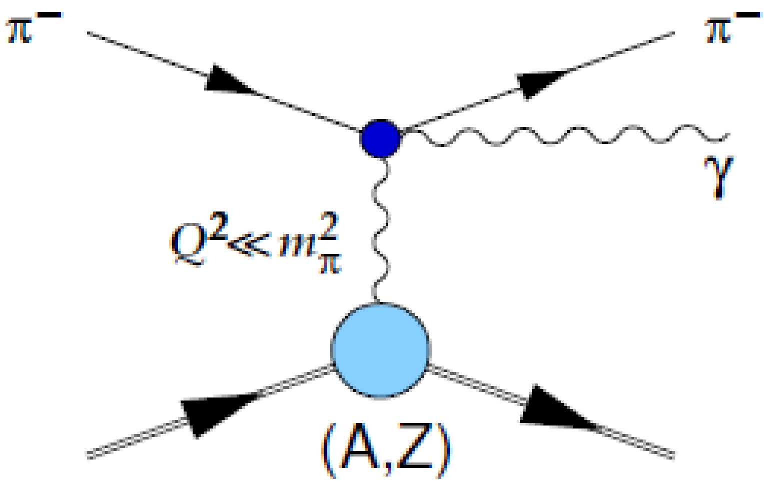
$$\pi^- + \gamma \to \begin{cases} \pi^- + \gamma & \text{Polarizability} \\ \pi^- + \pi^0 & \\ \pi^- + \pi^0 + \pi^0 & \\ \pi^- + \pi^- + \pi^+ & \text{or } \pi^- \rho^0 \\ \pi^- + \ldots & \end{cases}$$

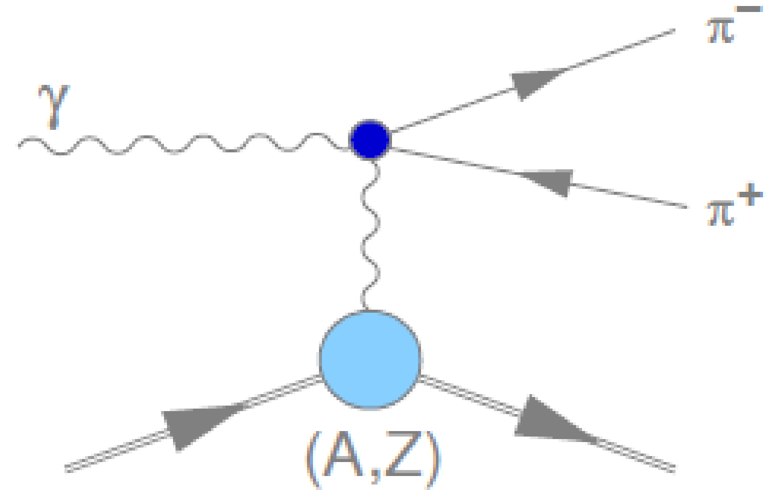
$$\pi + \gamma \to \pi + \gamma$$



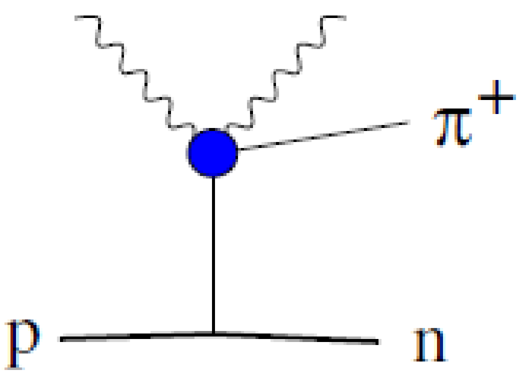
Low-energy LO deviation from pointlike particle $\leftrightarrow$ em. polarisability

Pion Compton scattering: embedding the process

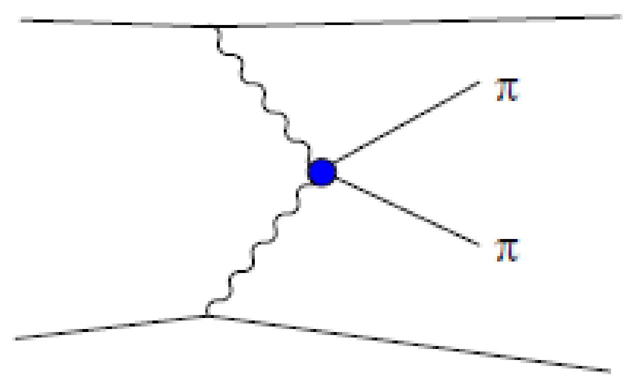




Primakoff processes



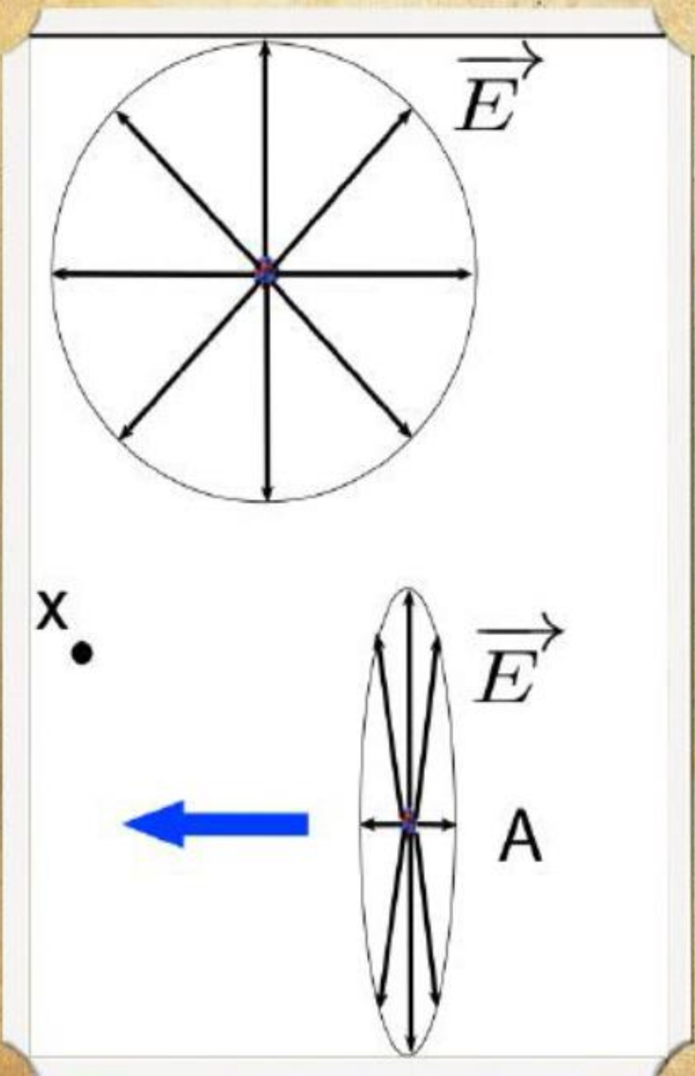
Radiative pion photoproduction



Photon-Photon fusion

Equivalent photon method

(Weizsaecker-Williams approximation)



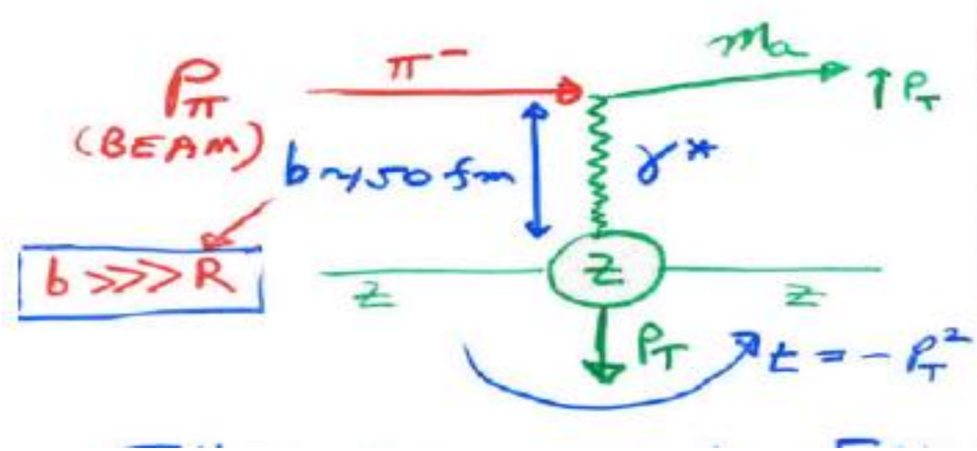
Electromagnetic field of fast charged particle is similar to a field of electromagnetic wave

$$\sigma_{x\gamma}(\omega, Q^2) \to \sigma_{x\gamma}(\omega, 0)$$

$$d\sigma_{xA} = \int n_\gamma(\omega) d\sigma_{x\gamma}(\omega) d\omega$$

$$n_\gamma(\omega) \sim \frac{Z^2\alpha}{\omega} ln \frac{E}{\omega}$$

density of equivalent photons



$$t_0 = -p_{T,MIN}^2 = -\frac{(m_a^2 - m_\pi^2)^2}{4\,p_\pi^2}$$

Primakoff scattering (pion Bremsthalung) of 200 GeV π from virtual photon target is a hypo-peripheral one-photon exchange reaction. Illustrate via production of a_1(1260), mass m_a, followed by $a_1 \rightarrow \pi\gamma$. Target Z intact with **low recoil energy**, **no FSI**, **separated from large p_T meson exchange reactions**. Minimal 4-momentum transfer t_0 to Z. For m_a=1 GeV, p_π = 200 GeV/c, t_0=5x10^{-6} GeV/c^2, **$p_{T,min}$= 2 MeV/c**. Uncertainty Principle: b $p_{T,min}$ = π/2 and **b ~ 150 fm**.

MEASUREMENT OF π^--MESON POLARIZABILITY IN PION COMPTON EFFECT

Yu.M. ANTIPOV, V.A. BATARIN, V.A. BESSUBOV, N.P. BUDANOV, Yu.P. GORIN, S.P. DENISOV, I.V. KOTOV, A.A. LEBEDEV, A.I. PETRUKHIN, S.A. POLOVNIKOV, V.N. ROINISHVILI[1], D.A. STOYANOVA
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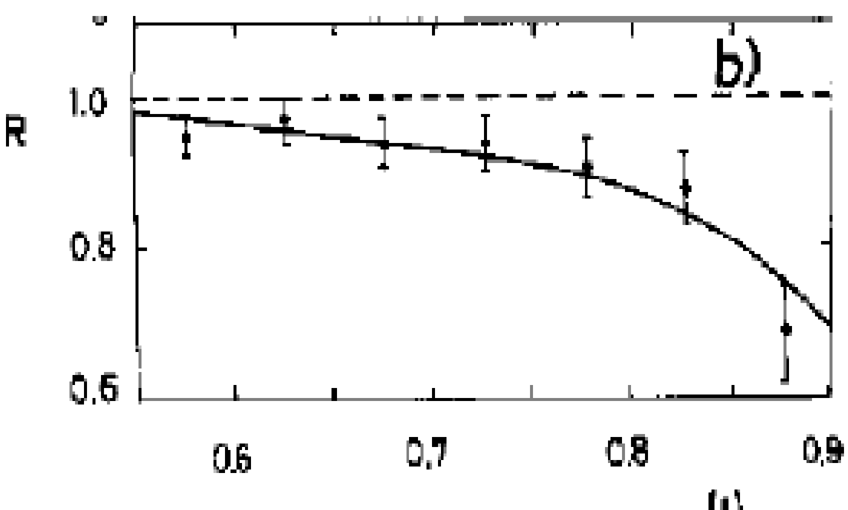
P.A. KULINICH, G.V. MECEL'MACHER, A.G. OL'SHEVSKI and V.I. TRAVKIN
JINR, Dubna, USSR

Received 11 November 1982

About 7×10^3 events of Compton effect on pion in the reaction $\pi^- A \to A\pi^-\gamma$ st 40 GeV/c were detected and for the first time the charged pion polarizability was obtained $\alpha_\pi = (6.8 \pm 1.4) \times 10^{-43}$ cm^3.



$x_\gamma = E_\gamma / E_{\mathrm{Beam}}$

"Serpukhov value"

$\alpha_\pi \approx 7 \cdot 10^{-4}$ fm^3

from the pion bremsstrahlung spectrum

assuming $\alpha_\pi + \beta_\pi = 0$

Experimental pion polarizabilities subject chiral symmetry and χPT **techniques of QCD to serious tests.** Major failure - χPT predicts pion polarizability significantly **stiffer** than previous measurements, and most other models. At one-loop level, electric and magnetic polarizabilities equal and opposite. Two-loop corrections small. Predictions below.

pion polarisabilities α_π, β_π in units of 10^{-4} fm^3

experiments for $\alpha_\pi - \beta_\pi$ lie in the range $4 \cdots 14$

ChPT (2-loop) prediction:

$$\alpha_\pi - \beta_\pi = 5.7 \pm 1.0 \qquad \alpha_\pi = 2.93 \pm 0.5$$

$$\alpha_\pi + \beta_\pi = 0.16 \pm 0.1 \qquad \beta_\pi = -2.77 \pm 0.5$$

INTERNATIONAL JOURNAL OF HIGH-ENERGY PHYSICS

CERN COURIER

MARCH 2015

QCD PHYSICS

COMPASS measures the pion polarizability

The COMPASS experiment at CERN has made the first precise measurement of the polarizability of the pion – the lightest composite particle built from quarks. The result confirms the expectation from the low-energy expansion of QCD – the quantum field theory of the strong interaction between quarks – but is at variance with the previously published values, which overestimated the pion polarizability by more than a factor of two.

Every composite system made from charged particles can be polarized by an external electromagnetic field, which acts to separate positive and negative charges. The size of this charge separation – the induced dipole moment – is related to the external field by the polarizability. As a measure of the response of a complex system to an external force, polarizability is directly related to the system's stiffness against deformability, and hence the binding force between the constituents.

The pion, made up of a quark and an antiquark, is the lightest object bound by the strong force and has a size of about 0.6×10^{-15} m (0.6 fm). So to observe a measurable effect, the particle must be subjected to electric fields in the order of 100 kV across its diameter – that is, about 10^{18} V/cm. To achieve this, the COMPASS experiment made use of the electric field around nuclei. To high-energy pions, this field appears as a source of (almost) real photons, on which the incident pions scatter.

The COMPASS experiment in the North Area on the Prévessin site at CERN studies hadron structure both with pion beams and with muon beams – a powerful combination. (Image credit: CERN-EX-1105182-01.)

Such pion–photon Compton scattering, also known as the Primakoff mechanism, was explored in the early 1980s in an experiment at Serpukhov, but the small data sample led to only an imprecise value for the polarizability of 6.8 ± 1.4 (stat.) ± 1.2 (syst.) $\times 10^{-4}$ fm^3, where the systematic uncertainty was underestimated, presumably.

COMPASS has now achieved a modern Primakoff experiment, using a 190 GeV pion beam from the Super Proton Synchrotron at CERN directed at a nickel target. Importantly, COMPASS was also able to use muons, which are point-like and hence non-deformable, to calibrate the experiment. The Compton $\pi\gamma \rightarrow \pi\gamma$ scattering is extracted from the reaction $\pi \mathrm{Ni} \rightarrow \pi\gamma\mathrm{Ni}$ by selecting events from the Coulomb peak at small momentum transfer. From the analysis of a sample of 63,000 events, the collaboration obtained a value of the pion electric polarizability of 2.0 ± 0.6 (stat.) ± 0.7 (syst.) $\times 10^{-4}$ fm^3 – that is, about 2×10^{-4} of the pion's volume. This value is in good agreement with theoretical calculations in low-energy QCD, therefore solving a long-standing discrepancy between these calculations and previous experimental efforts to determine the polarizability.

Although this measurement is the first to allow a self-calibration, the accuracy is still below the quoted uncertainty of the calculations. With more data already recorded, the COMPASS collaboration expects to improve on this result by a significant factor in the near future, and thereby probe further a benchmark calculation of non-perturbative QCD.

Further reading

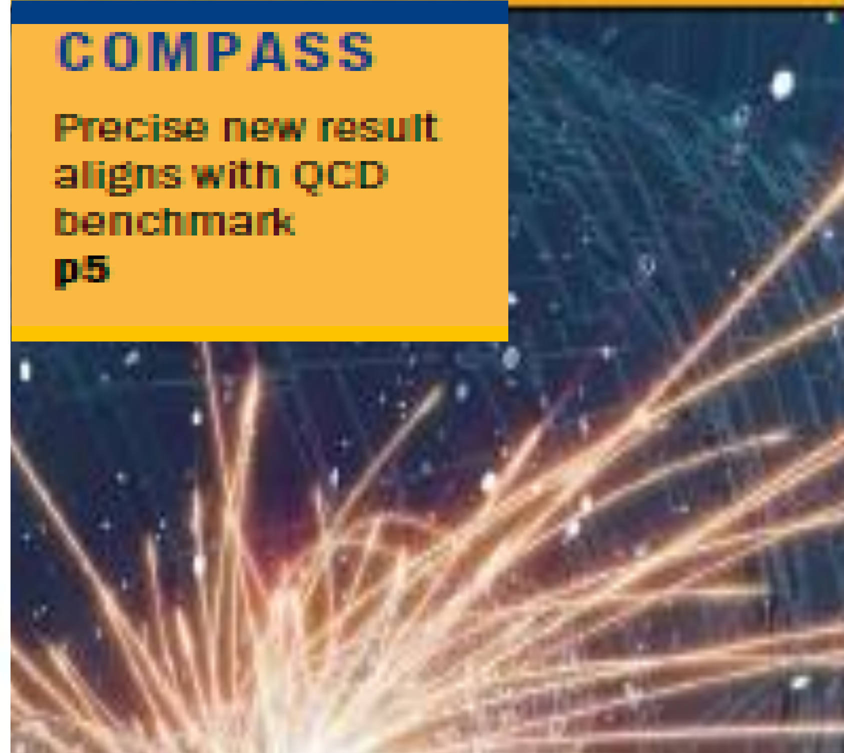
COMPASS Collaboration 2015 arXiv:1405.6377 [hep-ex], to be published in *Phys. Rev. Lett.*

Sommaire en français

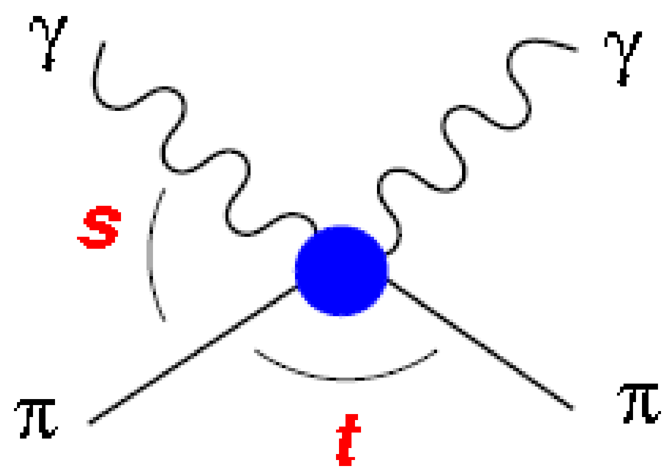
COMPASS

Precise new result aligns with QCD benchmark

p5



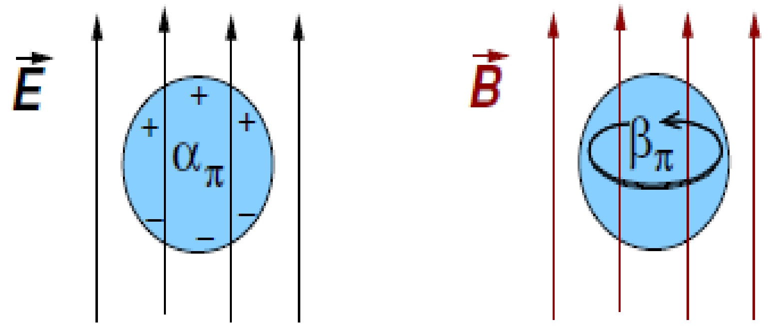
Compton cross section



- $s = (p + p_\gamma)^2$ (squared) CM energy of the $\pi\gamma$-system
- $t = (p - p_\pi)^2 \sim \cos\theta_{CM}$
- The polarisabilities α_π and β_π enter
  - with increasing s
  - as $\alpha_\pi - \beta_\pi$ in backward angles
  - as $\alpha_\pi + \beta_\pi$ in forward angles (small, but s-enhanced)
  - as $\alpha_2 - \beta_2$ with $(s - m_\pi^2)^2/s$ dependence

Pion Compton Scattering

$$\pi \;\; \gamma \;\; \rightarrow \;\; \pi \;\; \gamma$$



- Two kinematic variables, in CM: total energy $\sqrt{s}$, scattering angle θ_{cm}

$$\frac{d\sigma_{\pi\gamma}}{d\Omega_{cm}} = \frac{\alpha^2(s^2 z_+^2 + m_\pi^4 z_-^2)}{s(sz_+ + m_\pi^2 z_-)^2} - \frac{\alpha\, m_\pi^3\,(s - m_\pi^2)^2}{4s^2(sz_+ + m_\pi^2 z_-)} \cdot \mathcal{P}$$

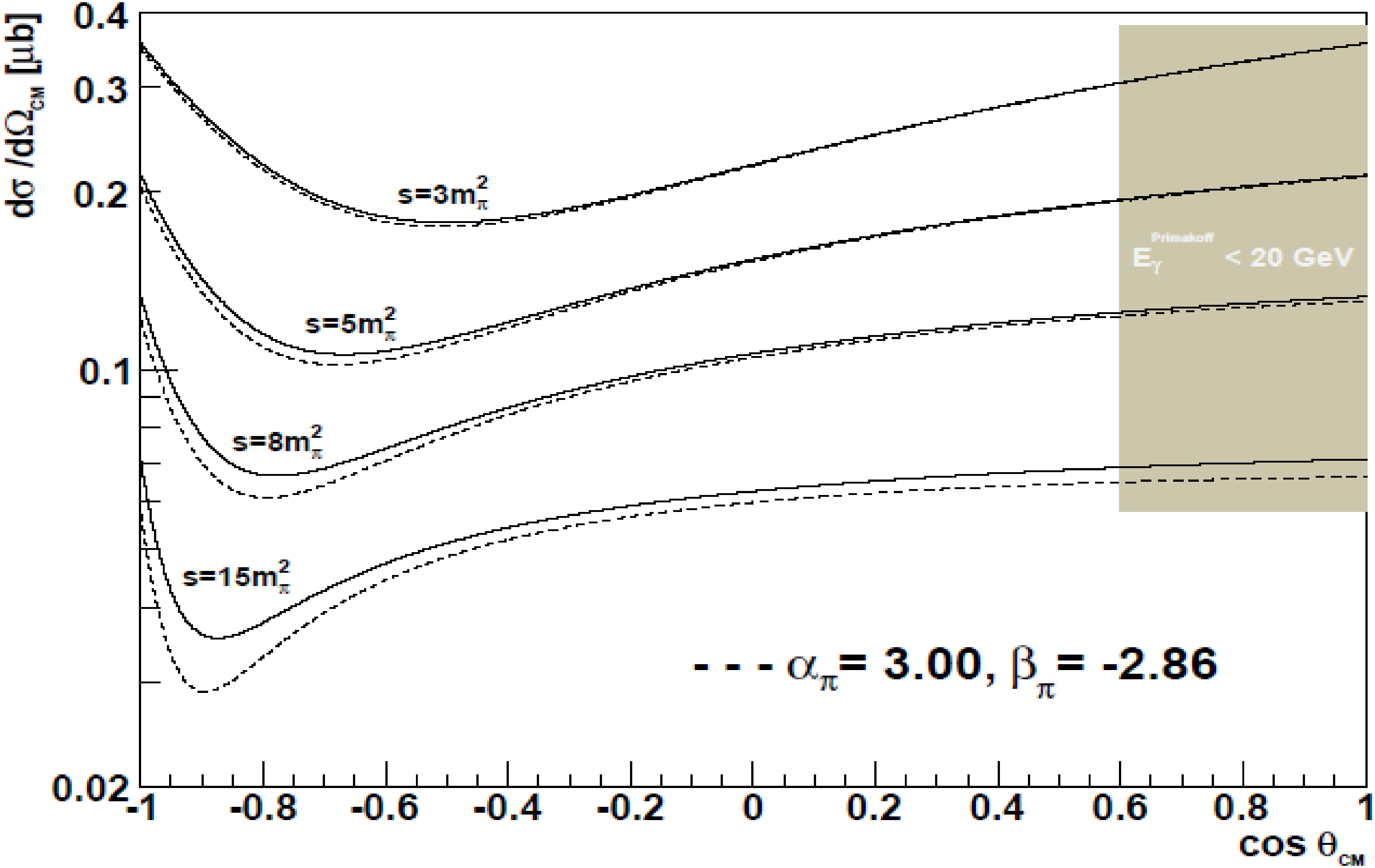
$$\mathcal{P} = z_-^2(\alpha_\pi - \beta_\pi) + \frac{s^2}{m_\pi^4} z_+^2(\alpha_\pi + \beta_\pi) - \frac{(s - m_\pi^2)^2}{24s} z_-^3(\alpha_2 - \beta_2)$$

$$z_\pm = 1 \pm \cos\theta_{cm}$$

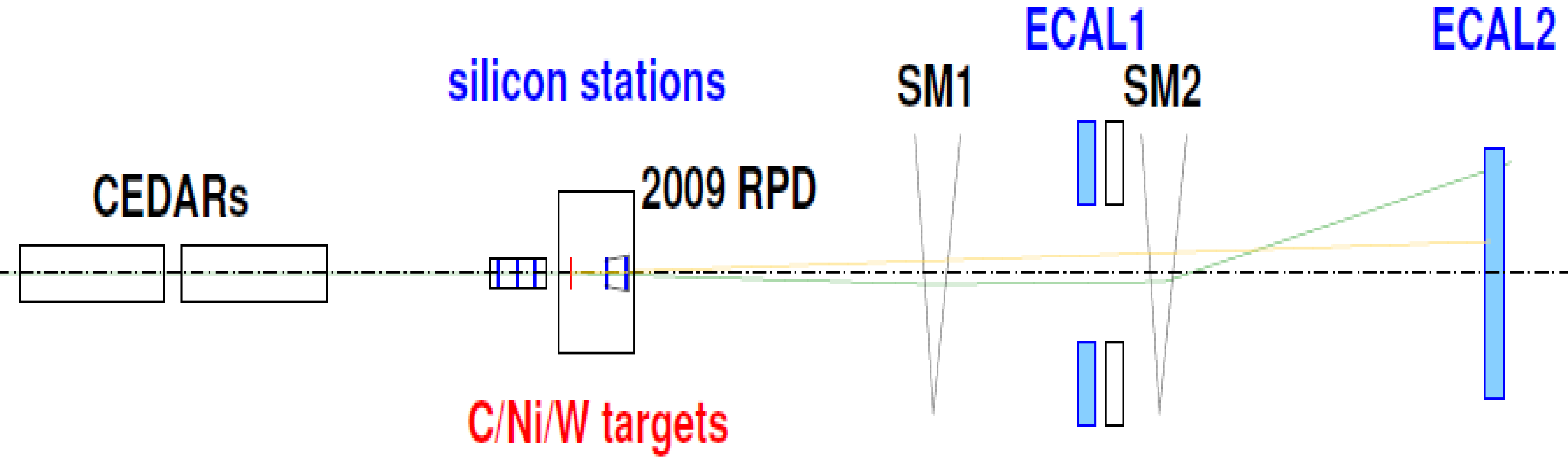
- $\sigma_{tot}(s)$ rather insensitive to pion's low-energy structure
- Up to 20% effect on *backward* angular distributions of $d\sigma/d\Omega_{cm}$

Polarisability effect (NLO ChPT values)

loop effects not shown



Principle of the measurement



Nuclear Instruments and Methods in Physics Research A 779 (2015) 69–115

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

The COMPASS setup for physics with hadron beams

Extraction of the pion polarisability

- Identify exclusive reactions

$$\pi\gamma_{\{\mathrm{Ni}\to\mathrm{Ni}'\}} \to \pi\gamma$$

at smallest momentum transfer $< 0.001\,\mathrm{GeV}^2/c^2$

- Assuming $\alpha_\pi + \beta_\pi = 0$, from the cross-section

$$\boxed{R = \frac{\sigma(x_\gamma)}{\sigma_{\alpha_\pi=0}(x_\gamma)} = \frac{N_{meas}(x_\gamma)}{N_{sim}(x_\gamma)} = 1 - \frac{3}{2}\cdot\frac{m_\pi^3}{\alpha}\cdot\frac{x_\gamma^2}{1-x_\gamma}\,\alpha_\pi}$$

is derived, depending on $x_\gamma = E_{\gamma(lab)}/E_{Beam}$.
Measuring R the polarisability α_π can be concluded.

- Control systematics by

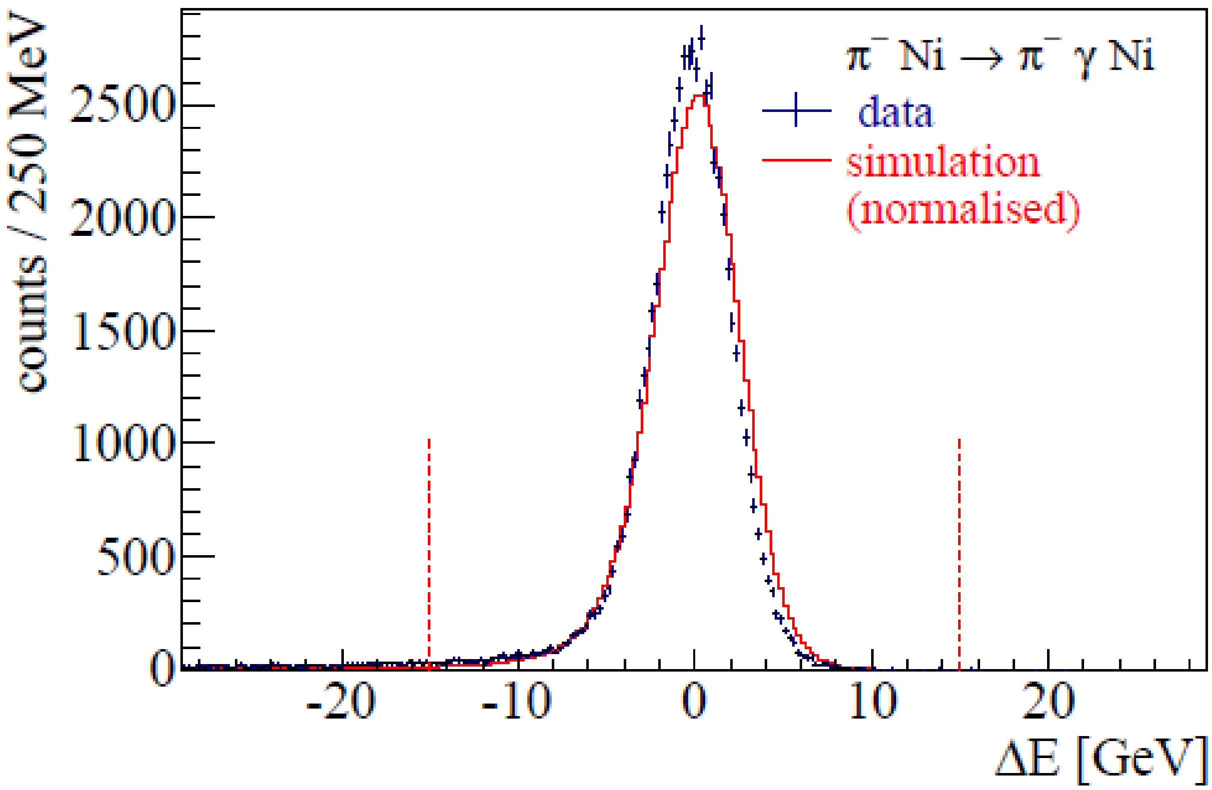
$$\mu\gamma_{\{\mathrm{Ni}\to\mathrm{Ni}'\}} \to \mu\gamma$$

and

$$K^- \to \pi^-\pi^0 \to \pi\gamma\gamma$$

Identifying the $\pi\gamma \to \pi\gamma$ reaction

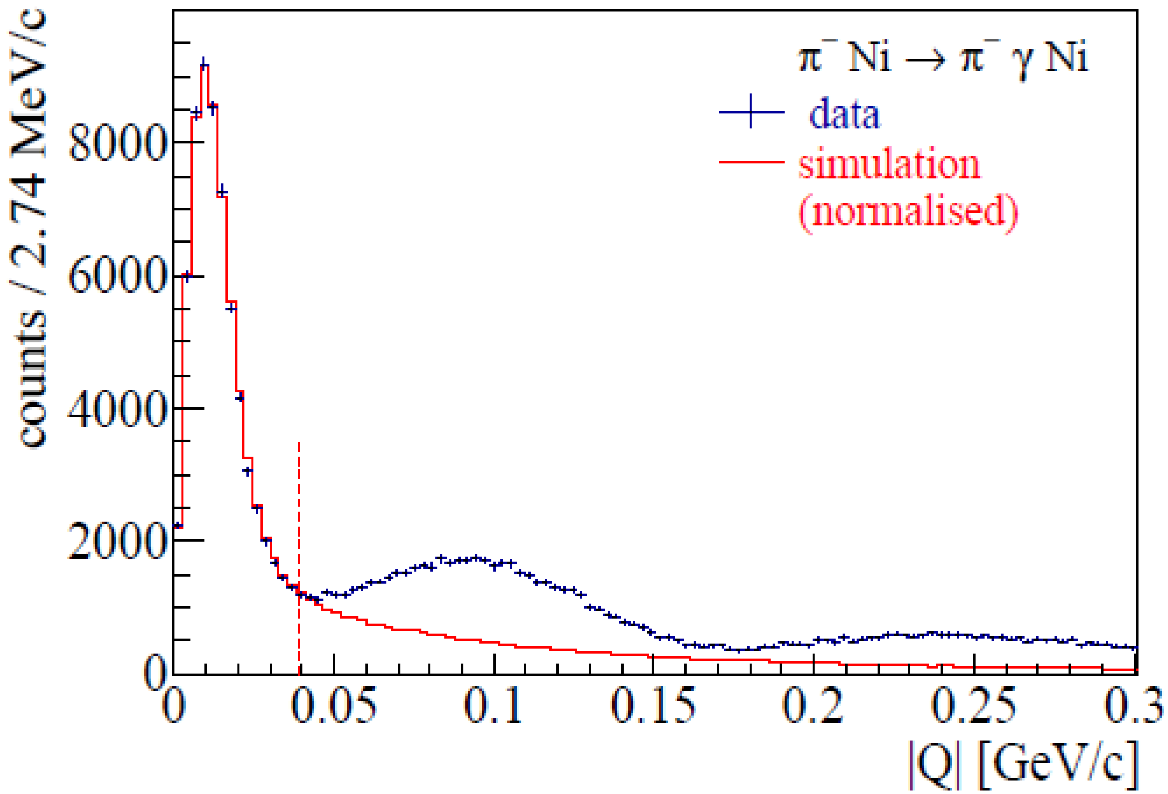
Phys. Rev. Lett. 114, 062002 (2015)



- Energy balance $\Delta E = E_\pi + E_\gamma - E_{\text{Beam}}$
- Exclusivity peak $\sigma \approx 2.6$ GeV (1.4%)
- $\sim$ 63.000 exclusive events ($x_\gamma > 0.4$) (Serpukhov $\sim$ 7000 for $x_\gamma > 0.5$)

Primakoff peak

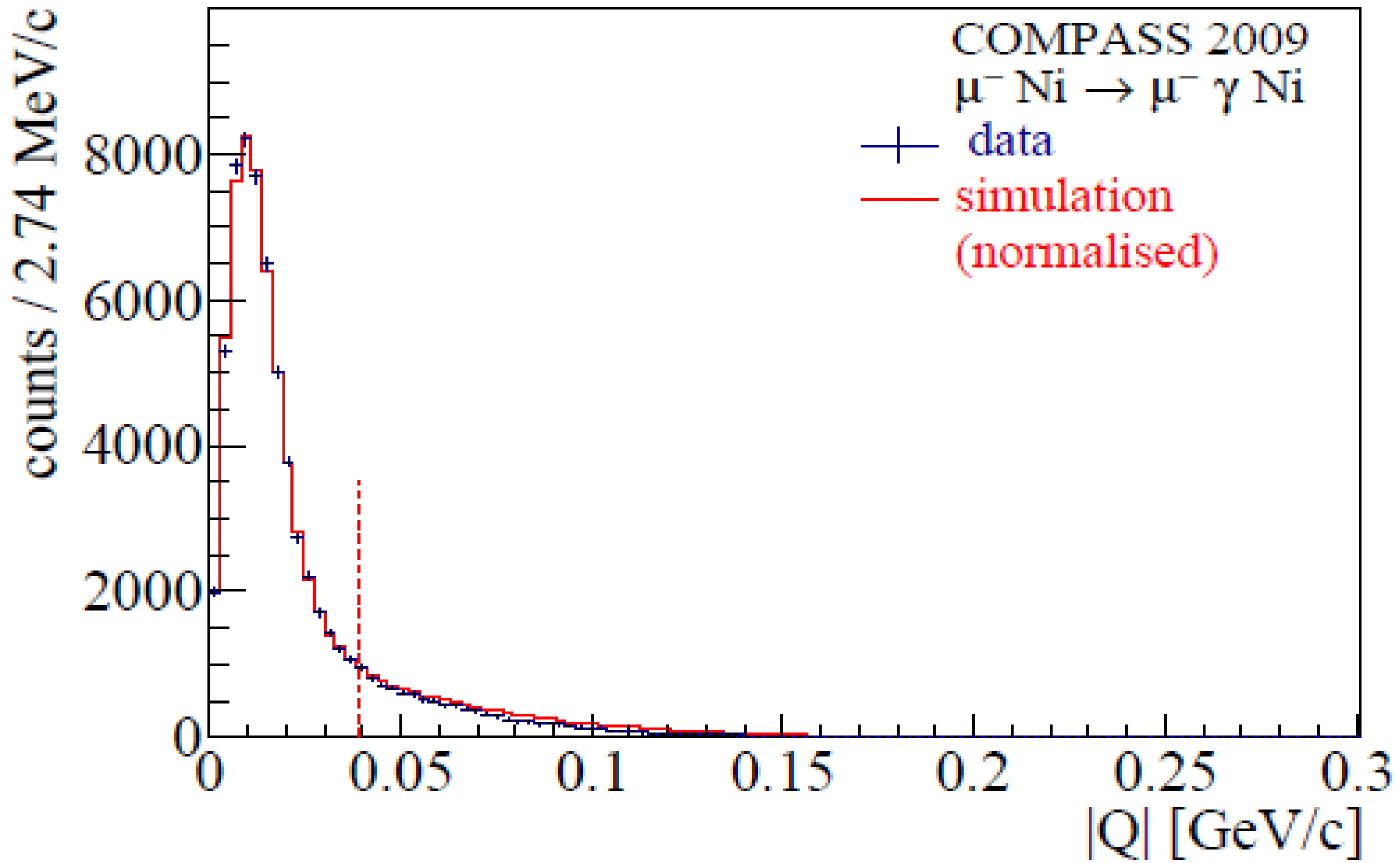
Phys. Rev. Lett. 114, 062002 (2015)



- $\Delta Q_T \approx 12$ MeV/c (190 GeV/c beam $\rightarrow$ requires few-μrad angular resolution)
- first diffractive minimum on Ni nucleus at $Q \approx 190$ MeV$/c$
- data a little more narrow than simulation $\rightarrow$ negative interference?

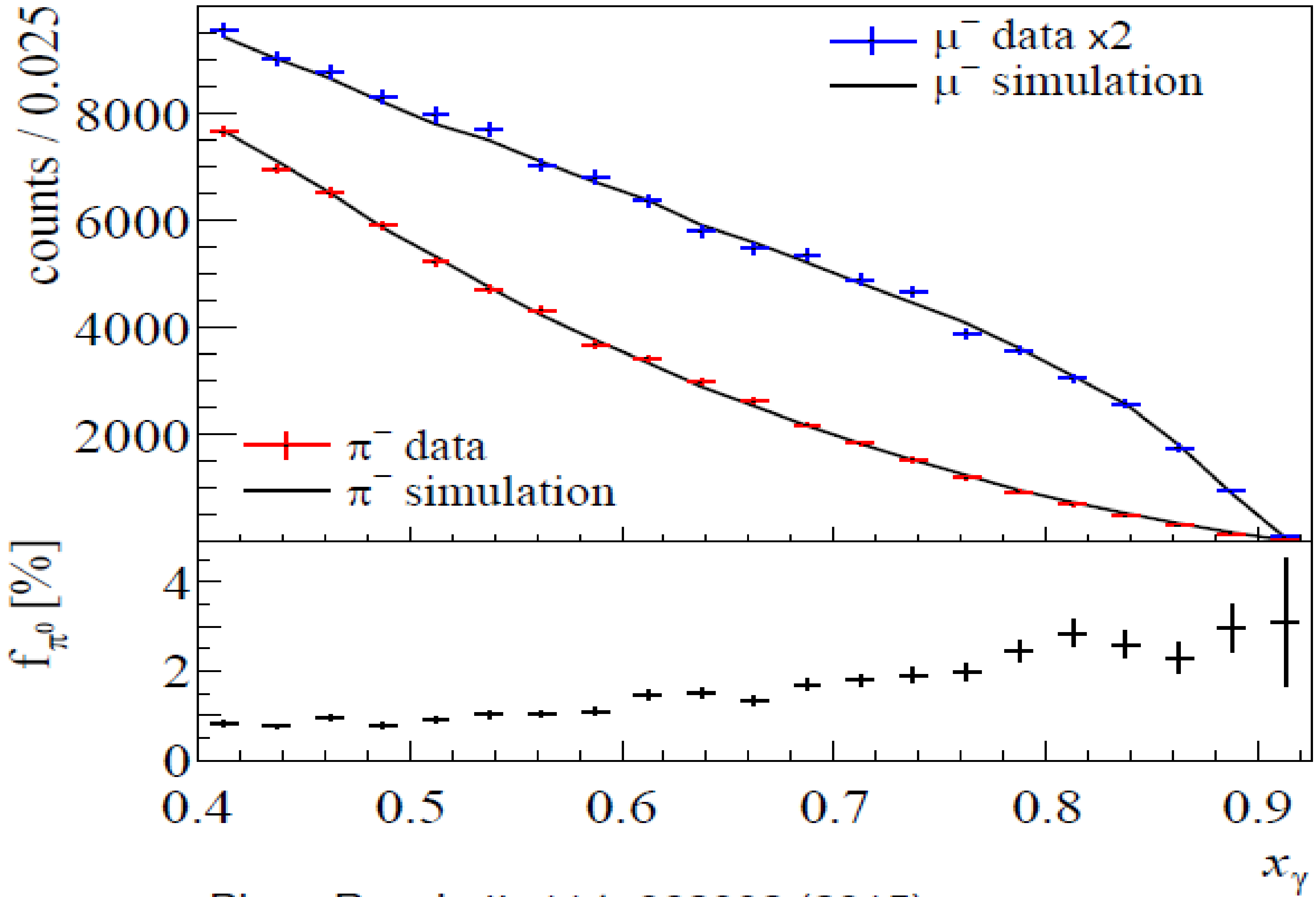
Primakoff peak: muon data

Phys. Rev. Lett. 114, 062002 (2015)



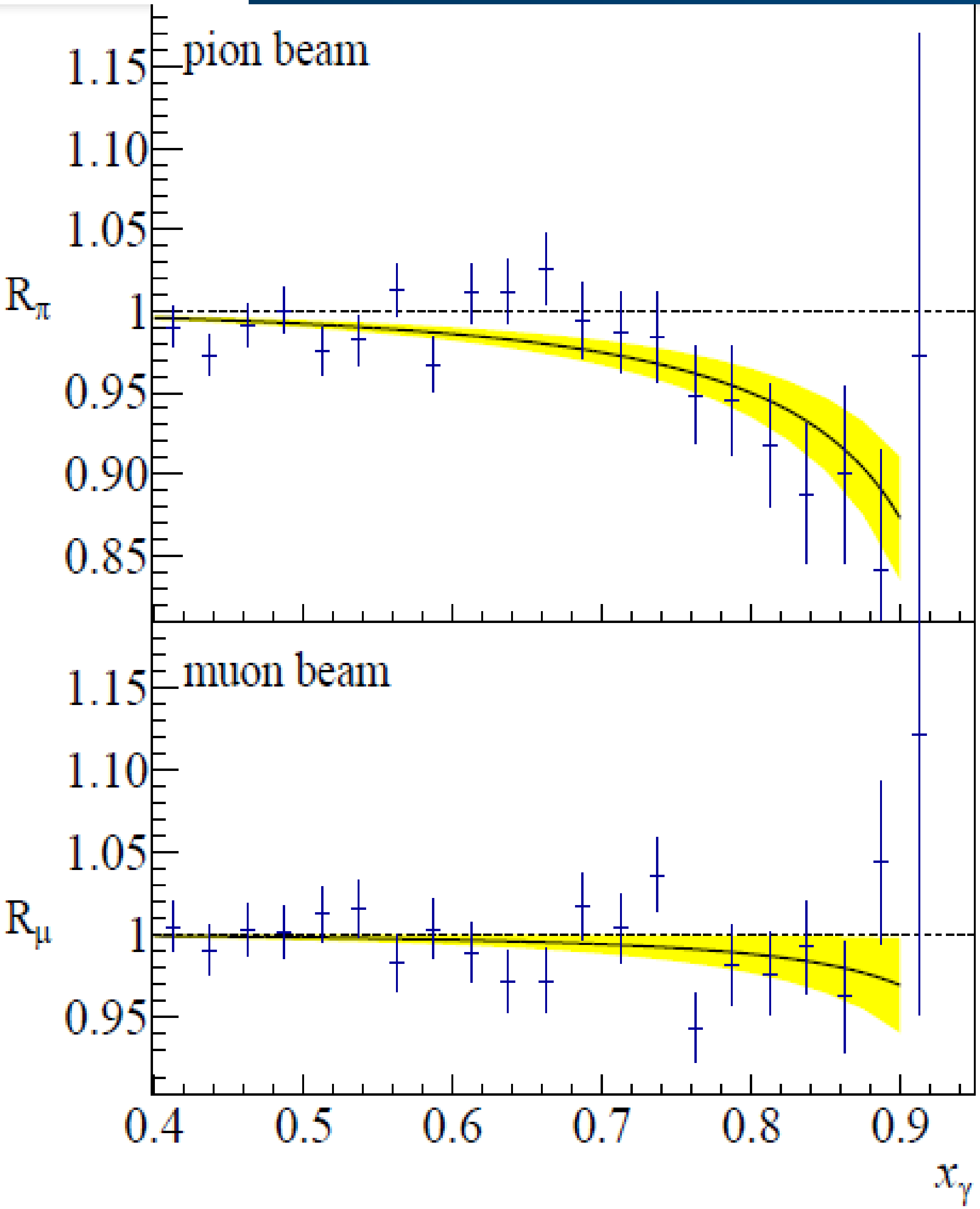
- muon control measurement: pure electromagnetic interaction
- e.m. nuclear effects well understood

Photon energy spectra for muon and pion beam



Phys. Rev. Lett. 114, 062002 (2015)

Pion polarisability: COMPASS result



$\alpha_\pi = (\, 2.0 \pm 0.6_{\mathrm{stat}}\,) \times 10^{-4}\,\mathrm{fm}^3$

(assuming $\alpha_\pi = -\beta_\pi$)

"false polarisability" from muon data:

$(\, 0.5 \pm 0.5_{\mathrm{stat}}\,) \times 10^{-4}\,\mathrm{fm}^3$

Phys. Rev. Lett. 114, 062002 (2015)

Pion polarisability

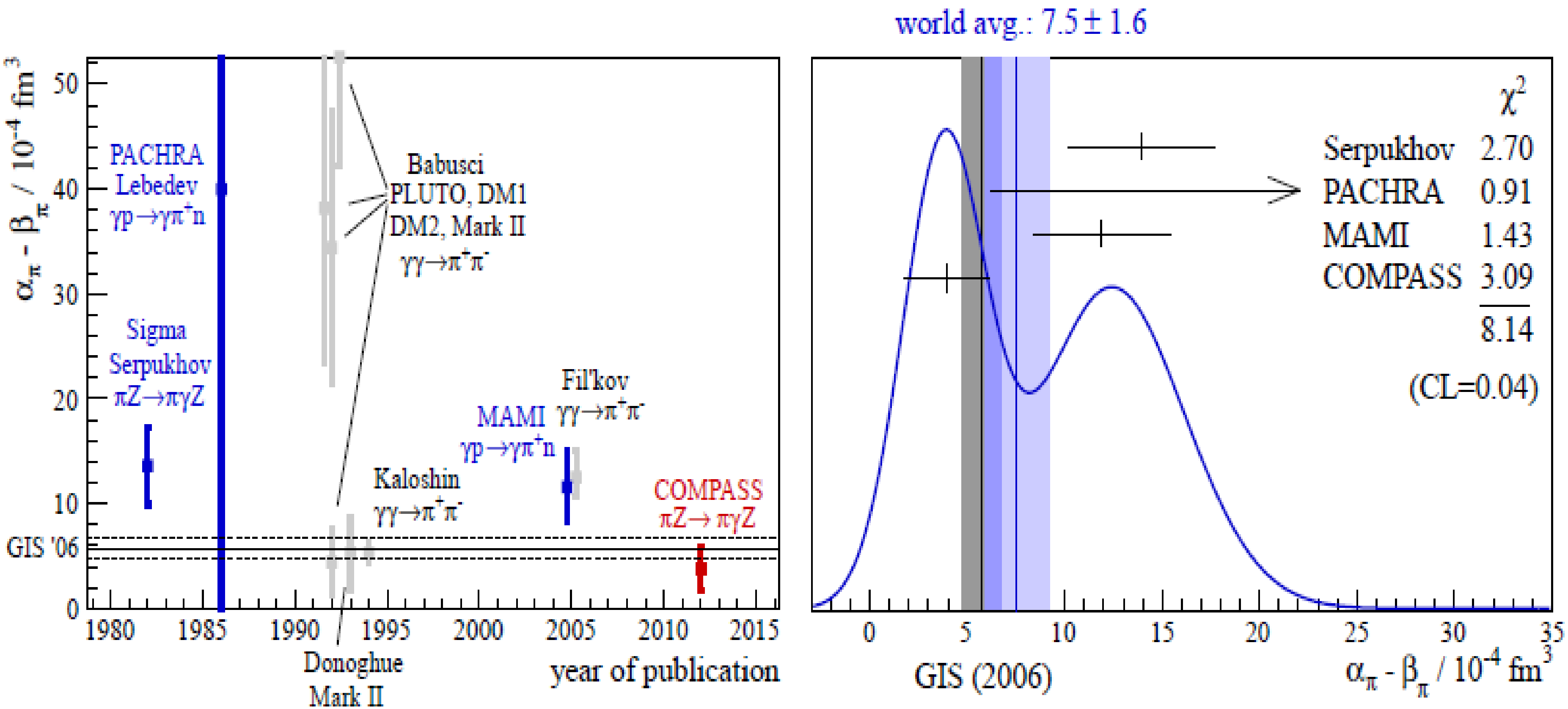
source of systematic uncertainty	estimated magnitude CL = 68 % $[10^{-4}\,\mathrm{fm}^3]$
tracking	0.5
radiative corrections	0.3
background subtraction in Q	0.4
pion electron scattering	0.2
quadratic sum	0.7

COMPASS result for the pion polarisability:

$$\boxed{\alpha_\pi = (\,\mathbf{2.0} \pm \mathbf{0.6}_{\mathrm{stat}} \pm \mathbf{0.7}_{\mathrm{syst}}\,) \times \mathbf{10}^{-4}\,\mathrm{fm}^3}$$

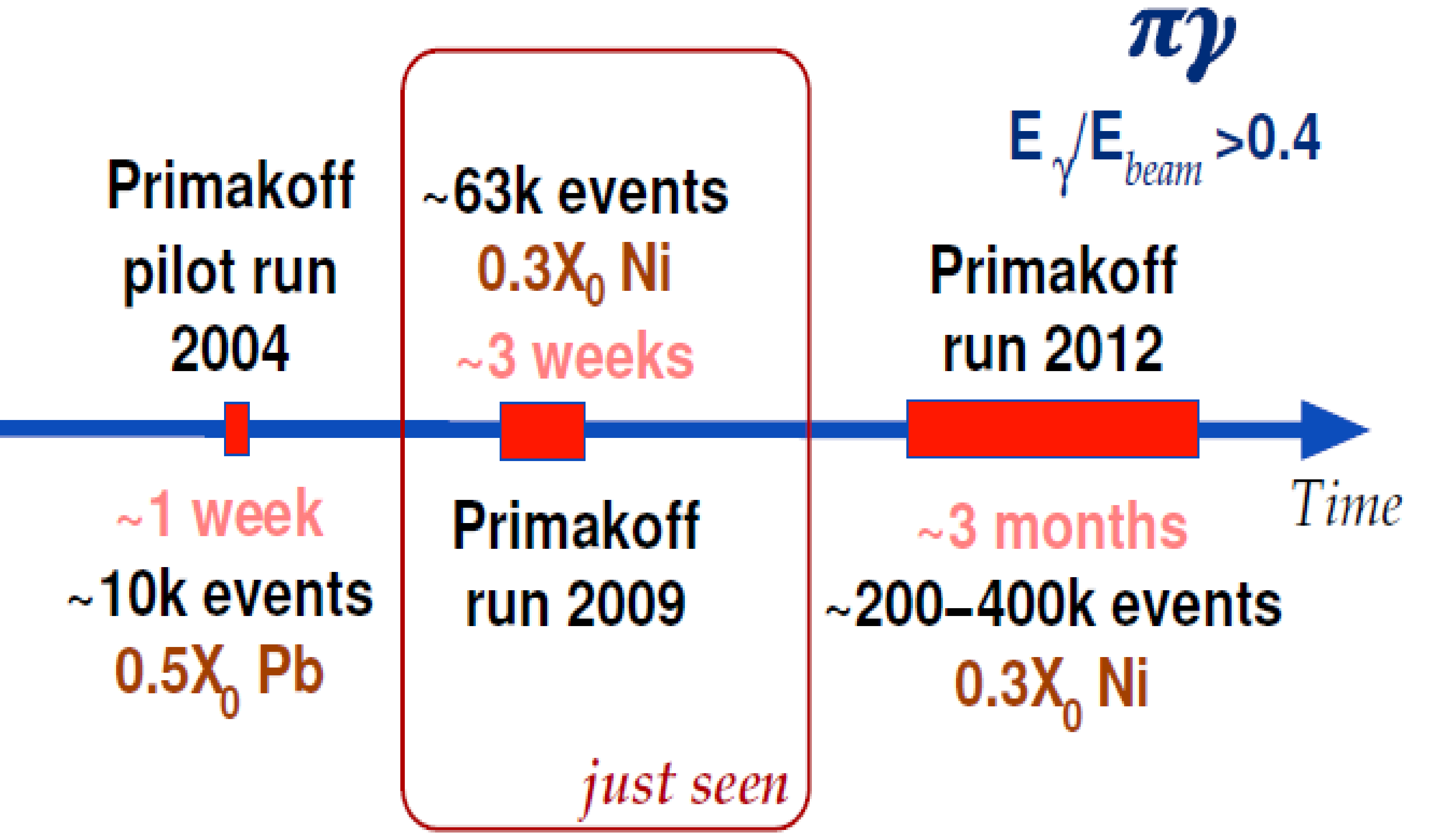
with $\alpha_\pi = -\beta_\pi$ assumed

Pion polarisability: world data including COMPASS



- The new COMPASS result is in significant tension with the earlier measurements of the pion polarisability
- The expectation from ChPT is confirmed within the uncertainties

Pion polarisability measurements at COMPASS



Summary and Outlook

- Measurement of the pion polarisability at COMPASS
  - Via the Primakoff reaction, COMPASS has determined

$$\boxed{\alpha_\pi = (2.0 \pm 0.6_{\text{stat}} \pm 0.7_{\text{syst}}) \times 10^{-4}\,\text{fm}^3} \quad \text{assuming } \alpha_\pi + \beta_\pi = 0$$

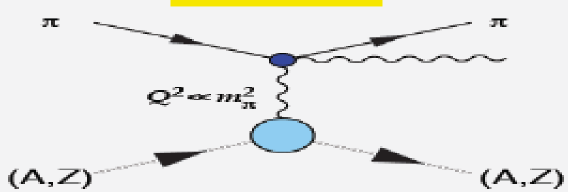
  - most direct access to the $\pi\gamma \to \pi\gamma$ process
  - Most precise experimental determination
  - Systematic control: $\mu\gamma \to \mu\gamma$, $K^- \to \pi^-\pi^0$
- (not shown today:) COMPASS measures other aspectes of chiral dynamics in $\pi^-\gamma \to \pi^-\pi^0$ and $\pi\gamma \to \pi\pi\pi$ reactions
- High-statistics run 2012
  - separate determination of α_π and β_π
  - $s-$dependent quadrupole polarisabilities
  - First measurement of the kaon polarisability

Pion Polarizabilities

Murray Moinester, Tel Aviv University
For the CERN COMPASS Collaboration

The electric α_π and magnetic β_π charged pion Compton polarizabilities provide stringent tests of Chiral Perturbation Theory. The combination $(\alpha_\pi - \beta_\pi)$ was measured at CERN COMPASS via radiative pion Primakoff scattering (190 GeV/c pion Bremsstrahlung) in the nuclear Coulomb field: $\pi + Z \to \pi + Z + \gamma$. COMPASS data analysis gives a value: $\alpha_\pi = (2.0 \pm 0.6_{\rm stat} \pm 0.7_{\rm syst}) \times 10^{-4}\ \mathrm{fm}^3$
The data were taken in 2009. Higher statistics data taken in 2012 will allow an independent determination of α_π and β_π, and a first determination of Kaon polarizabilities.

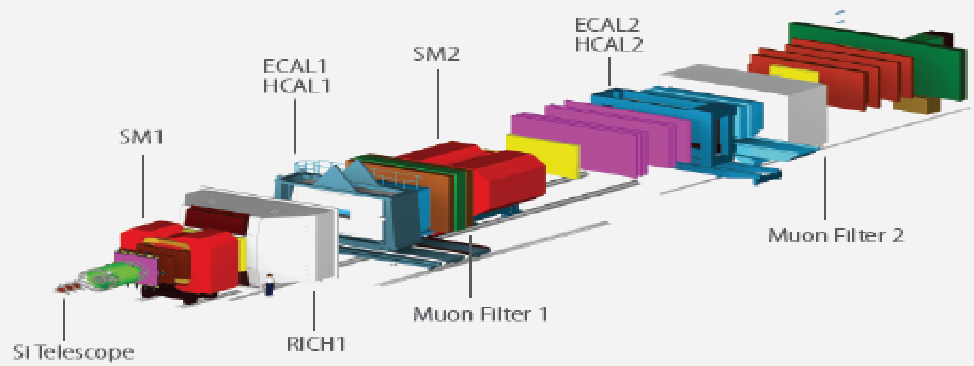
Primakoff Process



- Identify $\pi\, Ni \to \pi\, Ni\, \gamma$ exclusive reactions at smallest momentum transfer < 0.001 GeV $^2/c^2$
- Assuming $\alpha_\pi + \beta_\pi = 0$, the dependence on $x_\gamma = E_\gamma / E_{Beam}$

$$R = \frac{\sigma(x_\gamma)}{\sigma_{\alpha_\pi=0}(x_\gamma)} = 1 - \frac{3}{2} \cdot \frac{m_\pi^3}{\alpha} \cdot \frac{x_\gamma^2}{1 - x_\gamma}\, \alpha_\pi$$

  is used to determine the polarizability α_π
- Control systematics by investigating $\mu\, Ni \to \mu\, Ni\, \gamma$, $K^- \to \pi^- \pi^0$

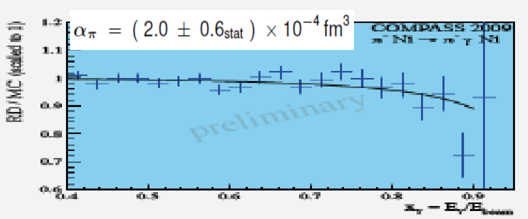


Runs with Hadron Beams 2004, 2008/09, 2012

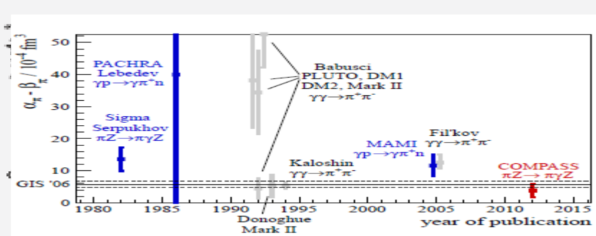
- 190 GeV π^- beam on nuclear targets
- Tracking: SMD for vertexing
- Trigger: Multiplicity trigger, (digital) ECAL trigger

Fixed-target experiment

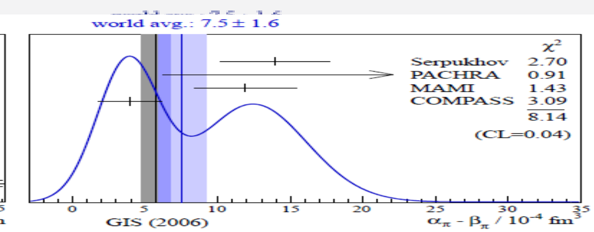
- Two-stage magnetic spectrometer
- High-precision, high-rate tracking, PID, calorimetry



Polarizability fit to the Xγ distribution of the ratio of real data (RD) to a Monte Carlo (MC) simulation with zero polarizabilities.



Overview of polarizability measurements; GIS'06 ChPT $\alpha_\pi - \beta_\pi = (5.7 \pm 1.0) \times 10^{-4}\ \mathrm{fm}^3$



PDG style ideogram of polarizability data

Polarizabilities are associated with the Rayleigh scattering cross section of sunlight photons on atomic electrons in atmospheric N_2 and O_2. The oscillating electric field of sunlight photons forces the atomic electrons to vibrate. The resulting changing electric dipole moment radiates energy as the square of it second derivative.**The radiated power is $P \sim \alpha^2\lambda^{-4}$, where α is the electric polarizability of the atom.** The scattering cross section depends on λ^{-4}. The intensity of scattered and transmitted sunlight is therefore dominated by blue and red, respectively. **The daytime sky is therefore blue, while sunrise and sunset are red.**

Henry Primakoff

http://virgo-physics.sas.upenn.edu/events/primakoff.html

Photo-Production of Neutral Mesons in Nuclear Electric Fields and the Mean Life of the Neutral Meson*

H. PRIMAKOFF†
Laboratory for Nuclear Science and Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts

January 2, 1951

IT has now been well established experimentally that neutral π-mesons (π^0) decay into two photons.[1] Theoretically, this two-photon type of decay implies zero π^0 spin;[2] in addition, the decay has been interpreted as proceeding through the mechanism of the creation and subsequent radiative recombination of a virtual proton anti-proton pair.[3] Whatever the actual mechanism of the (two-photon) decay, its mere existence implies an effective interaction between the π^0 wave field, φ, and the electromagnetic wave field, **E**, **H**, representable in the form:

$$\text{Interaction Energy Density} = \eta(\hbar/\mu c)(\hbar c)^{-\frac{1}{2}}\varphi\mathbf{E}\cdot\mathbf{H}. \qquad (1)$$

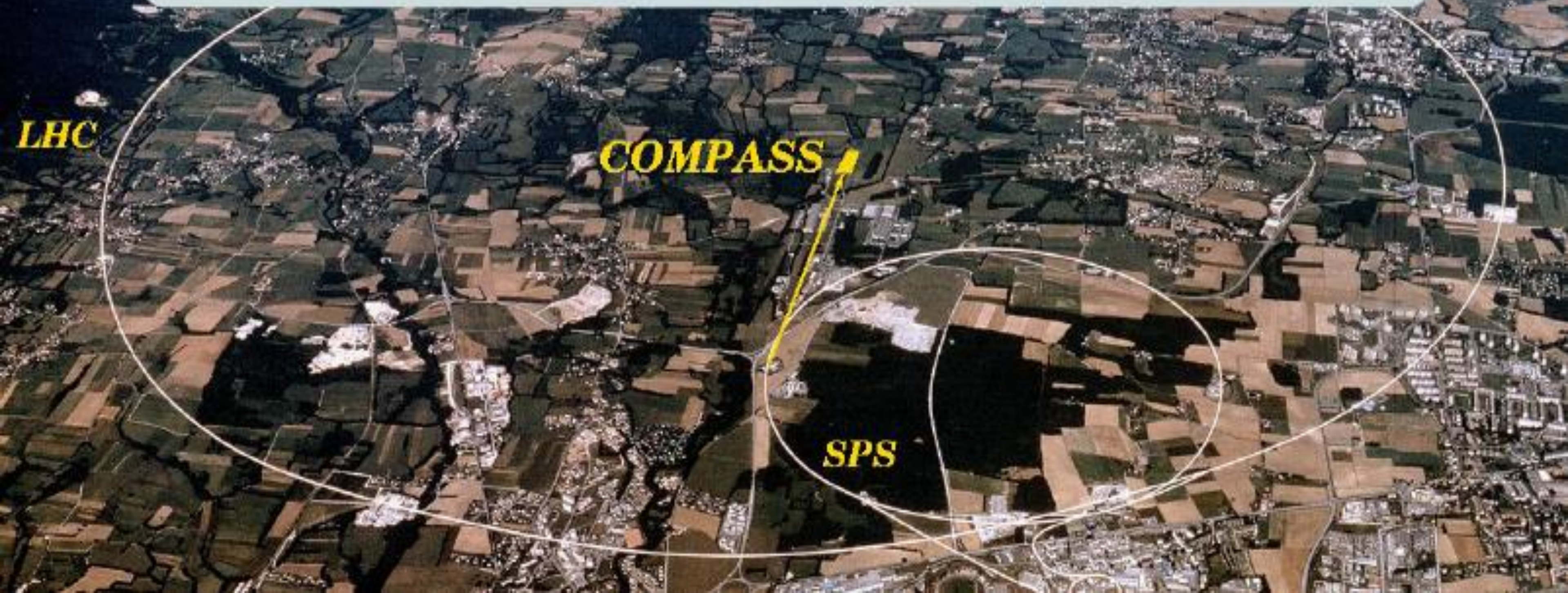
Here φ has been assumed pseudoscalar, the factors $\hbar/\mu c$ and $(\hbar c)^{-\frac{1}{2}}$ are introduced for dimensional reasons ($\mu \equiv$ rest mass of π^0),

Coulomb field of nucleus can be used as photon target

COmmon Muon and Proton Apparatus for Structure and Spectroscopy

CERN SPS: protons ~ 400 GeV (5 – 10 sec spills)

- secondary $\pi, K, \overset{(-)}{p}$: up to $2{\cdot}10^7$/s (typ. $5{\cdot}10^6$/s)
  Nov. 2004, 2008-09, 2012:
  hadron spec. & Primakoff reactions
- tertiary muons: $4{\cdot}10^7$ / s
  2002-04, 2006-07, 2010-11: spin structure of the nucleon



The COMPASS Experiment

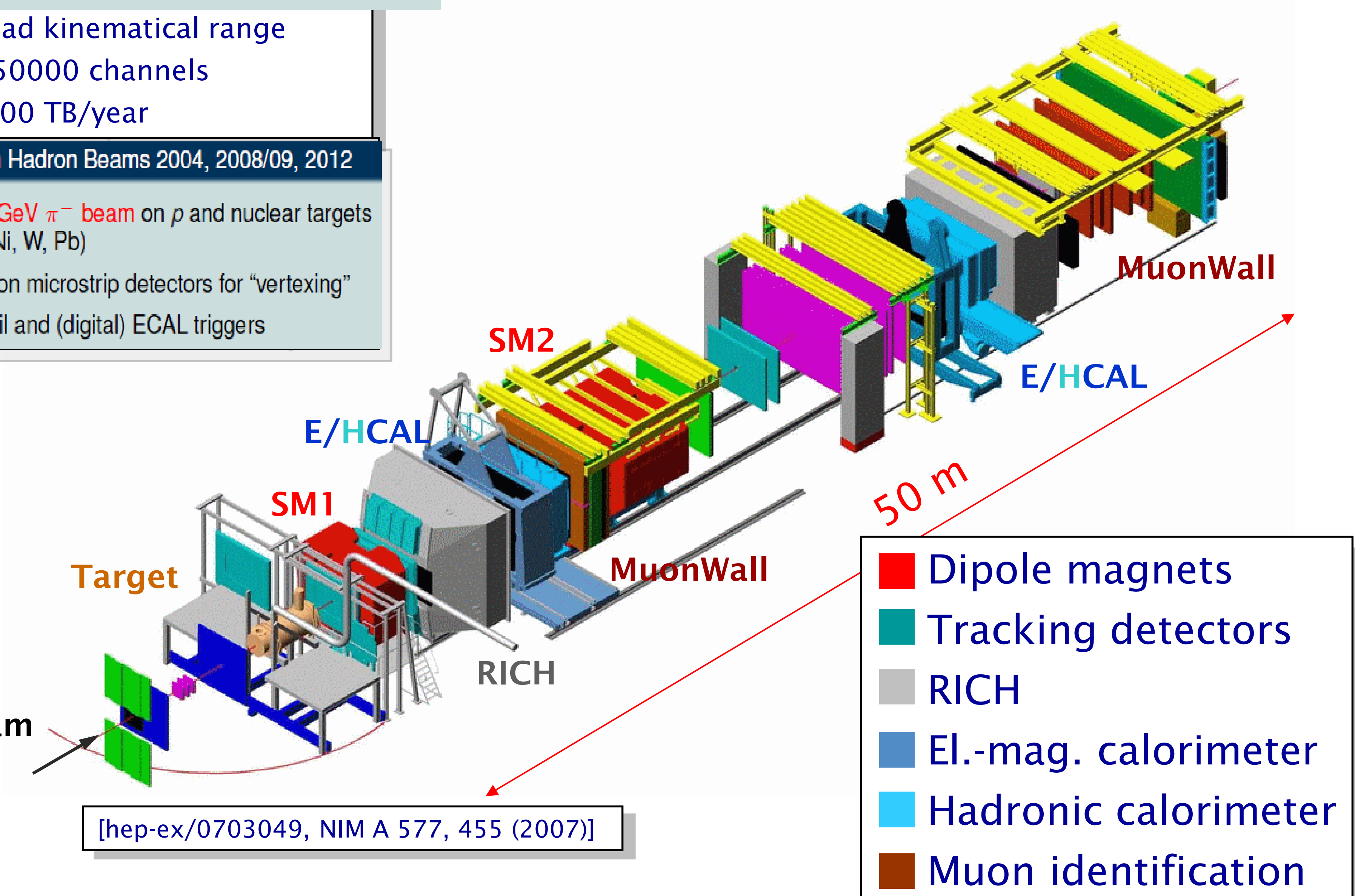
Fixed-target experiment

- two-stage magnetic spectrometer
- high-precision, high-rate tracking, PID, calorimetry

- broad kinematical range
- ~250000 channels
- > 800 TB/year

Runs with Hadron Beams 2004, 2008/09, 2012

- 190 GeV π^- beam on p and nuclear targets (C, Ni, W, Pb)
- Silicon microstrip detectors for "vertexing"
- recoil and (digital) ECAL triggers



[hep-ex/0703049, NIM A 577, 455 (2007)]

Measurement of the Charged-Pion Polarizability

C. Adolph,[8] J. Lichtenstadt,[23] M. A. Moinester,[23] et al. (COMPASS Collaboration)

The COMPASS collaboration at CERN has investigated pion Compton scattering, $\pi^-\gamma \to \pi^-\gamma$, at center-of-mass energy below 3.5 pion masses. The process is embedded in the reaction $\pi^-\mathrm{Ni} \to \pi^-\gamma\mathrm{Ni}$, which is initiated by 190 GeV pions impinging on a nickel target. The exchange of quasireal photons is selected by isolating the sharp Coulomb peak observed at smallest momentum transfers, $Q^2 < 0.0015\ (\mathrm{GeV}/c)^2$. From a sample of 63 000 events, the pion electric polarizability is determined to be $\alpha_\pi = (2.0 \pm 0.6_{\mathrm{stat}} \pm 0.7_{\mathrm{syst}}) \times 10^{-4}\ \mathrm{fm}^3$ under the assumption $\alpha_\pi = -\beta_\pi$, which relates the electric and magnetic dipole polarizabilities. It is the most precise measurement of this fundamental low-energy parameter of strong interaction that has been addressed since long by various methods with conflicting outcomes. While this result is in tension with previous dedicated measurements, it is found in agreement with the expectation from chiral perturbation theory. An additional measurement replacing pions by muons, for which the cross-section behavior is unambiguously known, was performed for an independent estimate of the systematic uncertainty.

Experimental Information and Data Analysis Backward polarizability $\alpha_{\pi^+} - \beta_{\pi^+}$ in units of $10^{-4}\,\mathrm{fm}^3$

reaction	analysis [experiment]	$\alpha_{\pi^+} - \beta_{\pi^+}$
$\pi^- Z \to \gamma\pi^- Z$	Serpukhov (1983)	$15.6 \pm 6.4 \pm 4.4$
	COMPASS(201?) 2015, 4.0 ± 1.2 ± 1.4	??±??±??
$\gamma p \to \pi^+ n$	Lebedev (1984)	40 ± 24
	Mainz (2005)	$11.6 \pm 1.5 \pm 3.0 \pm 0.5$
$\gamma\gamma \leftrightarrows \pi^+\pi^-$	D. Babusci *et al.* (1992) [PLUTO (1984)] [DM1 (1986)] [DM2 (1987)] [MARK II (1990)]	 $38.2 \pm 9.6 \pm 11.4$ 34.4 ± 9.2 52.6 ± 14.8 4.4 ± 3.2
	J.F. Donoghue & B. Holstein (1993) [MARK II (1990)]	5.4
	A. Kaloshin & V. Serebryakov (1994) [MARK II (1990), CBC (1990)]	5.25 ± 0.95
	L. Fil'kov (2005) [TPC/2γ (1986),MARK II (1990)] [CELLO (1992), VENUS (1995)] [ALEPH (2003), BELLE (2005)]	$13.0\ (+2.6, -1.9)$

Measurement of the π^+-meson polarizabilities via the $\gamma p \to \gamma\pi^+ n$ reaction

Eur. Phys. J. A **23**, 113–127 (2005)
DOI 10.1140/epja/i2004-10056-2

THE EUROPEAN PHYSICAL JOURNAL A

J. Ahrens[1], M. Moinester[5], I. Giller[5], et al., Mainz

$$(\alpha-\beta)_{\pi^+} = (11.6 \pm 1.5_{stat} \pm 3.0_{syst} \pm 0.5_{mod}) \times 10^{-4}\,\text{fm}^3.$$

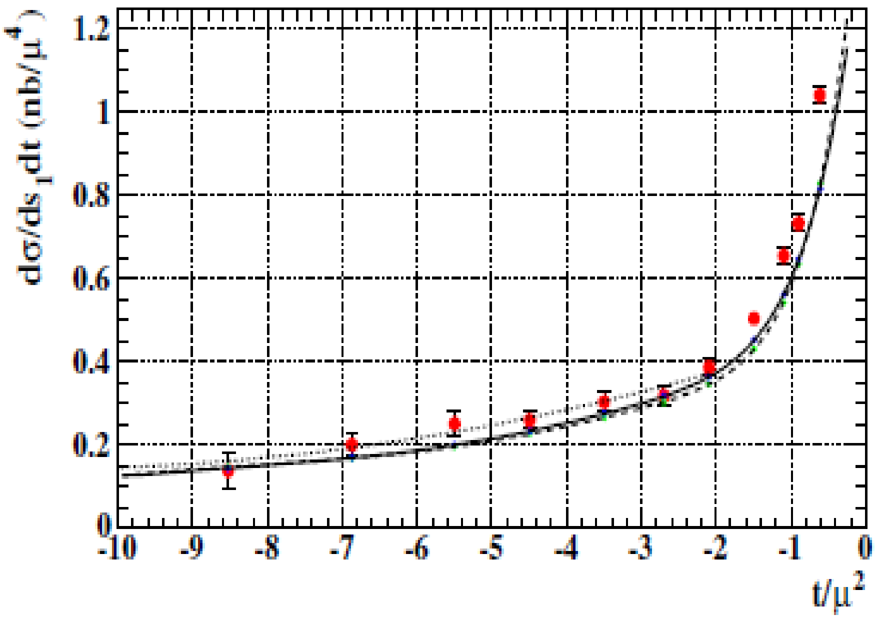


Fig. 10. The differential cross-section of the process $\gamma p \to \gamma\pi^+ n$ averaged over the full photon beam energy interval and over s_1 from $1.5m_\pi^2$ to $5m_\pi^2$. The solid and dashed lines are the predictions of model-1 and model-2, respectively, for $(\alpha-\beta)_{\pi^+} = 0$. The dotted line is a fit to the experimental data (see text).

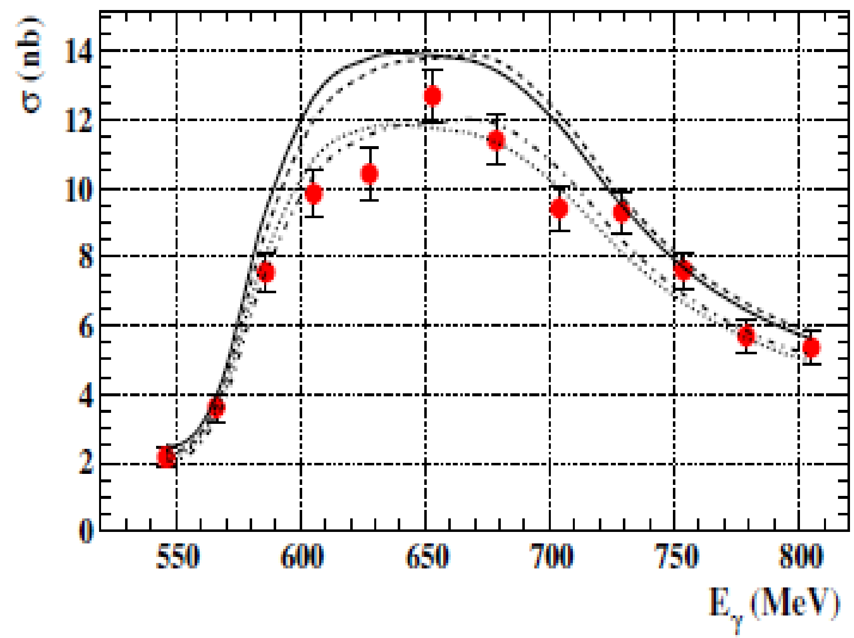


Fig. 11. The cross-section of the process $\gamma p \to \gamma\pi^+ n$ integrated over s_1 and t in the region where the contribution of the pion polarizability is biggest and the difference between the predictions of the theoretical models under consideration does not exceed 3%. The dashed and dashed-dotted lines are predictions of model-1 and the solid and dotted lines of model-2 for $(\alpha-\beta)_{\pi^+} = 0$ and $14 \times 10^{-4}\,\text{fm}^3$, respectively.

Physics Letters B 277 (1992) 158–162
North-Holland

PHYSICS LETTERS B

Chiral symmetry and pion polarizabilities

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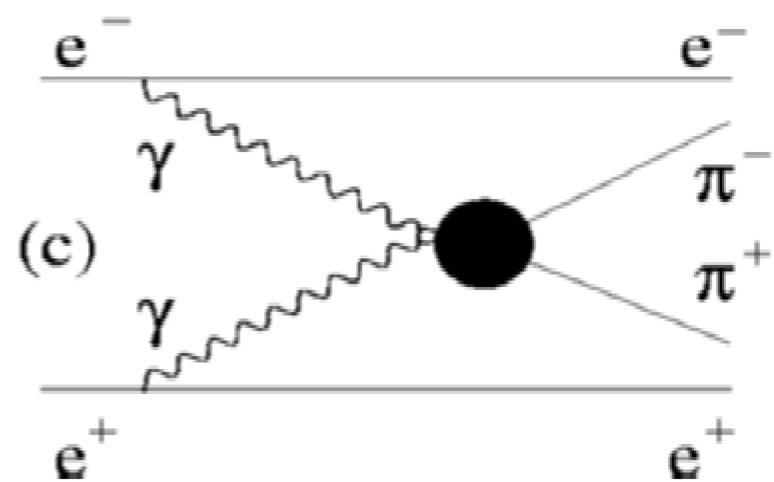
[c] *School of Physics and Astronomy, Raymond and Beverly Sackler Faculty of Exact Sciences, Tel Aviv University, 69978 Ramat Aviv, Israel*

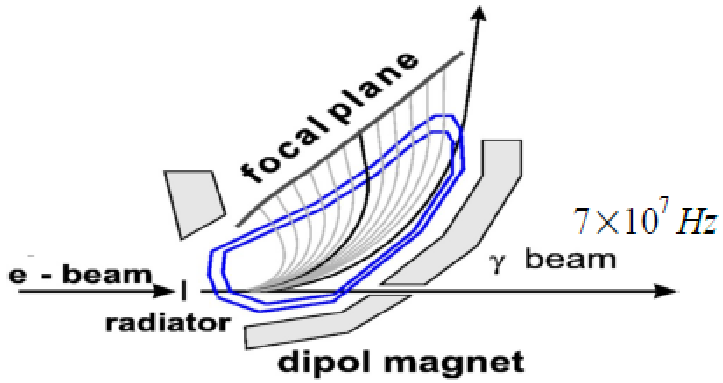
Received 8 November 1991

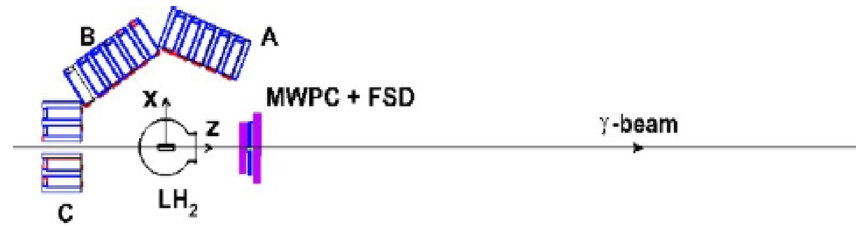
We use chiral perturbation theory including one-loop contribution to derive formulae needed to deduce pion polarizabilities for $\gamma\pi \to \gamma\pi$ and $\gamma\gamma \to \pi\pi$ data We deduce for the first time values for the $\pi^{\pm}$ and π^{0} polarizabilities from $\pi\pi$ production data, and compare these new results to chiral symmetry predictions

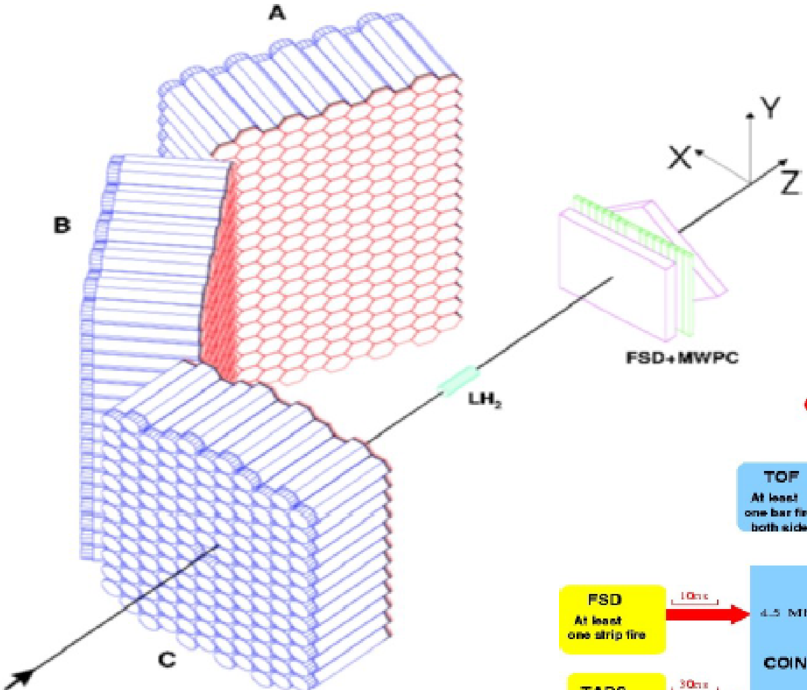
Table 1
Values for $\bar{\alpha}_{\pi}$ from data and theory

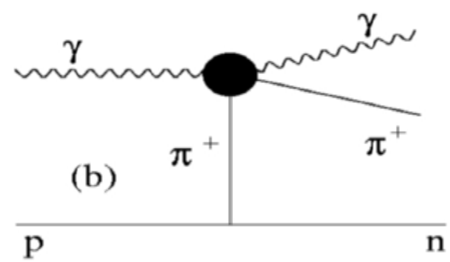
PLUTO	19 1	±4 8(stat)±5 7(syst)
DM1	17 2	±4 6(stat)
DM2	26 3	±7 4(stat)
LEBEDEV	20	±12 (stat)
MARK II	2 2	±1 6(stat +syst)

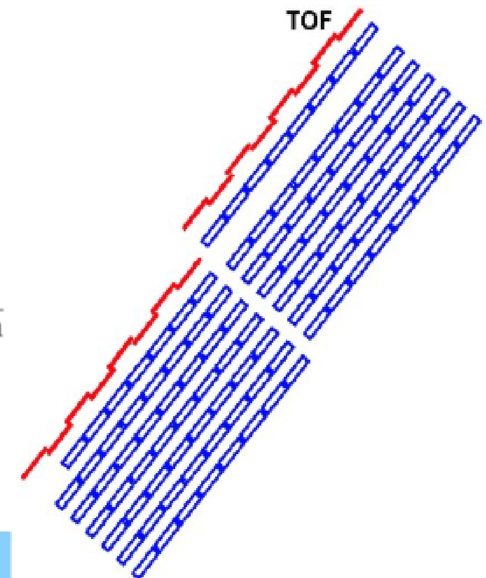


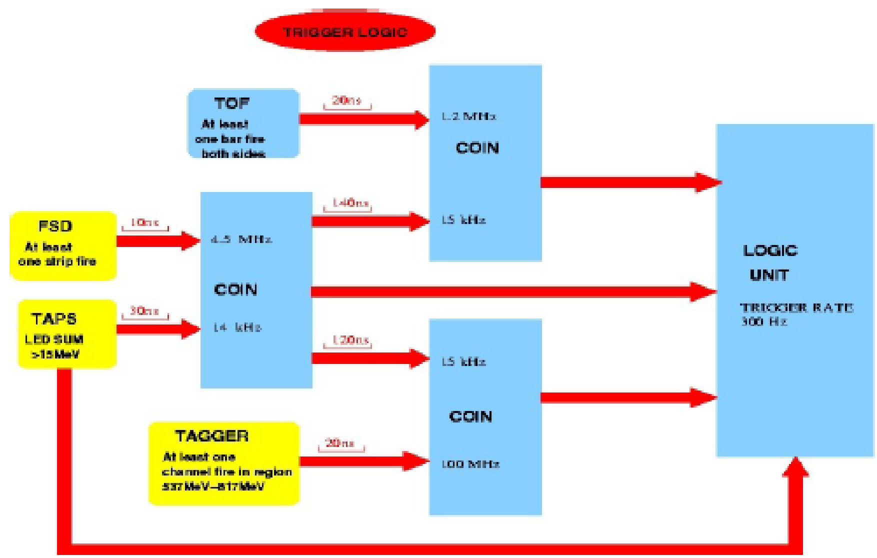

focal plane
$7\times10^7\ Hz$
e - beam
γ beam
radiator
dipol magnet

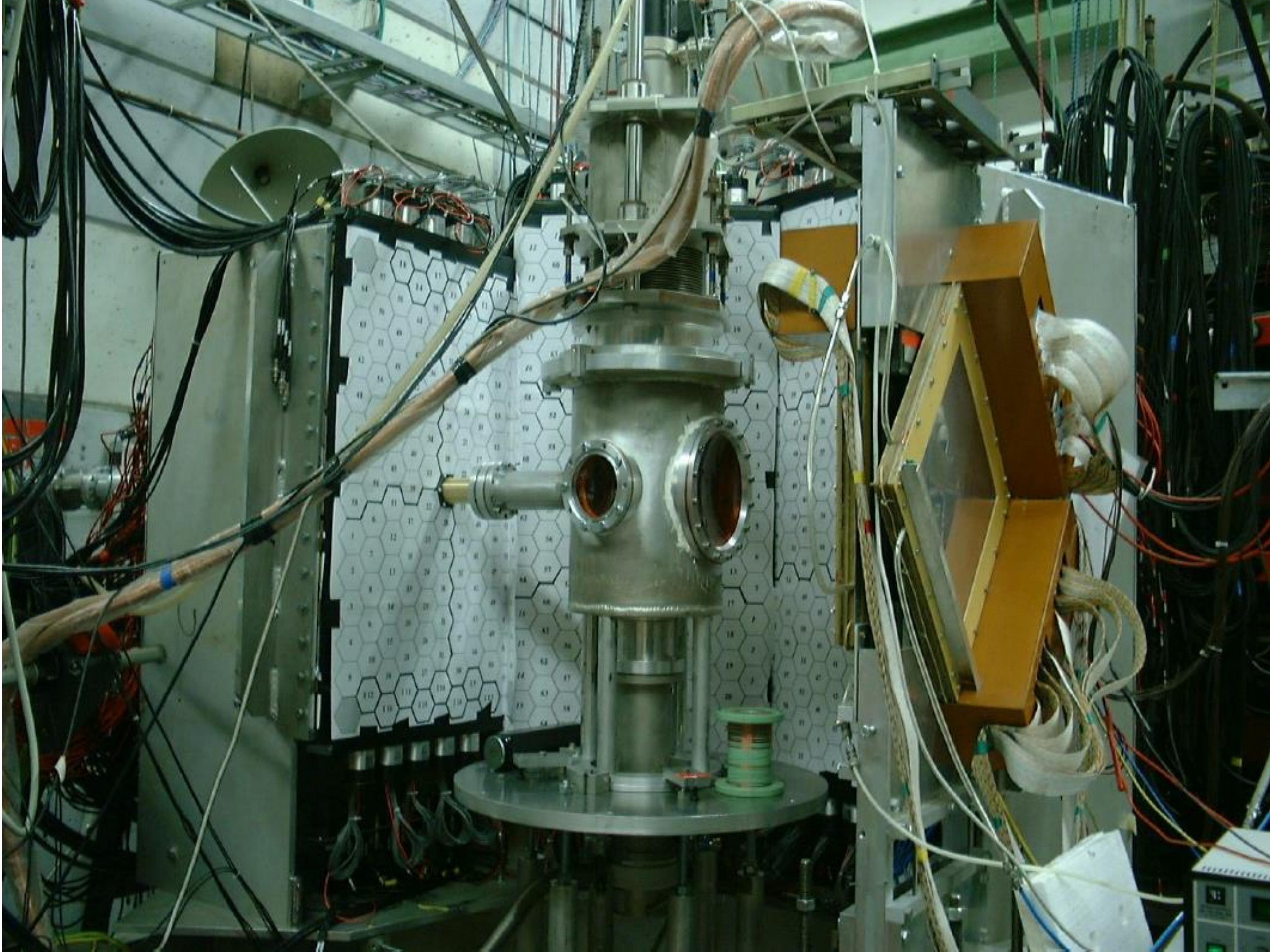

B
A
X
Z
MWPC + FSD
γ-beam
C
LH_2

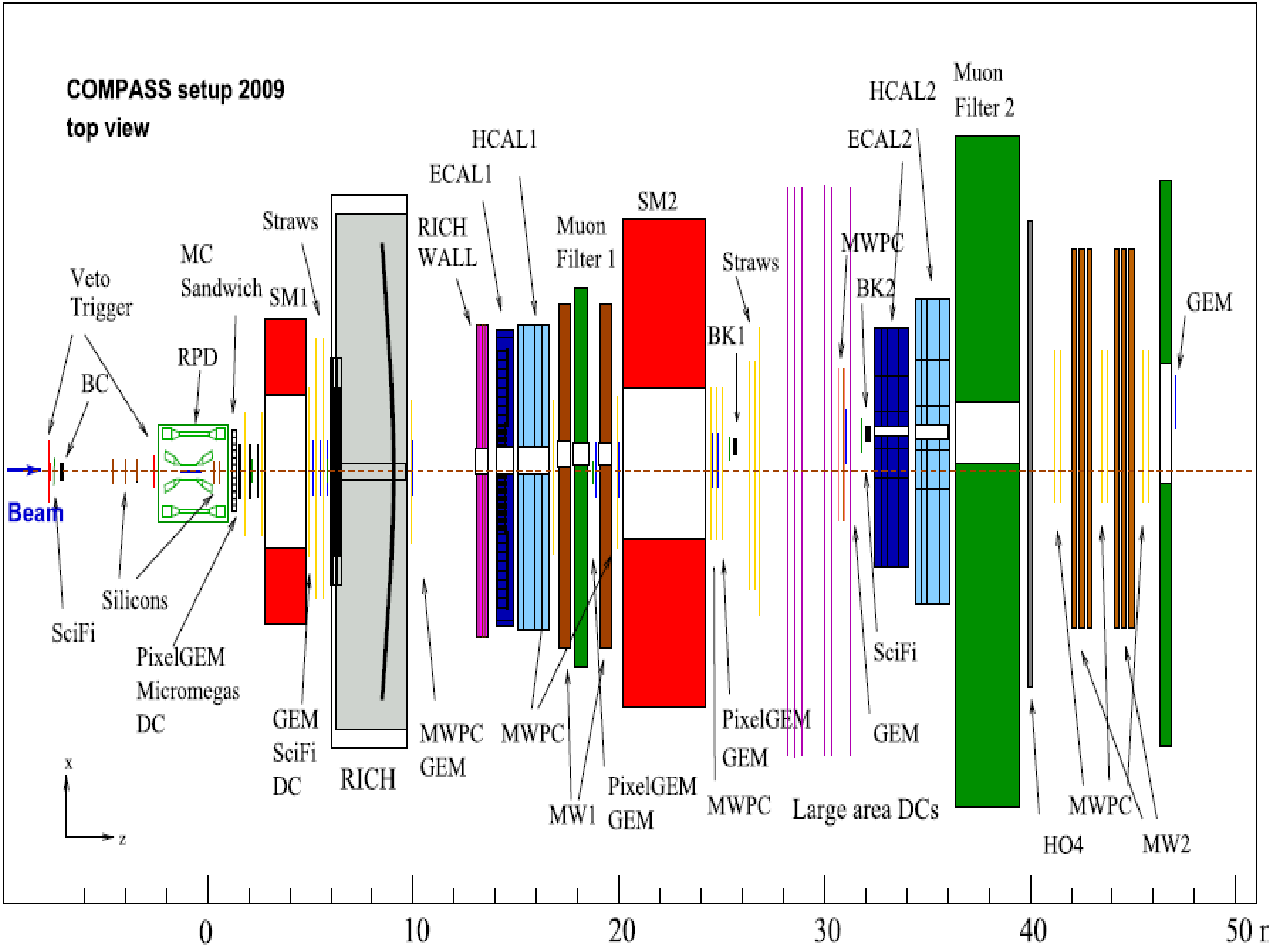

A
B
C
Y
X
Z
FSD+MWPC
LH_2


γ
γ
π^+
π^+
(b)
p
n


TOF

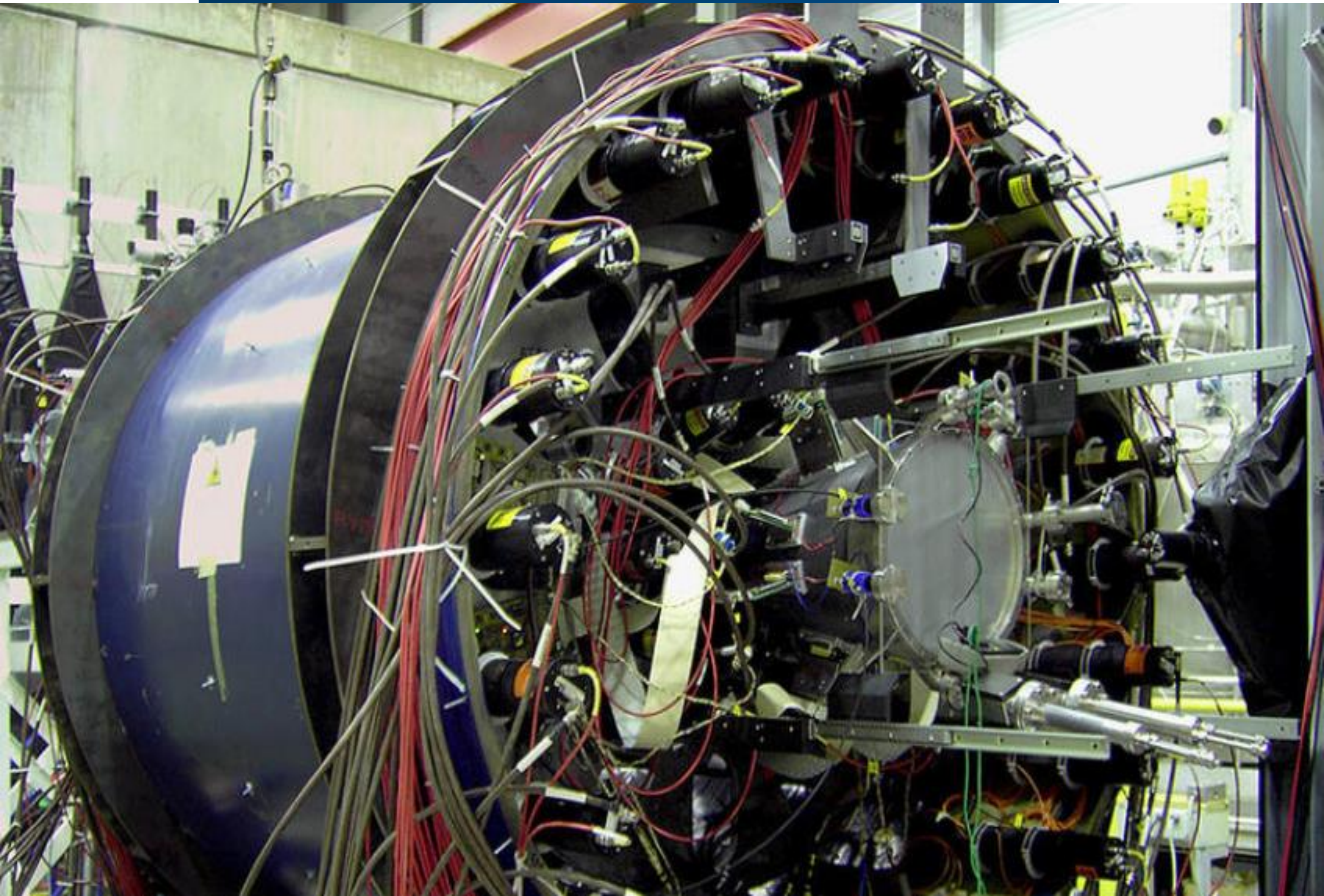

TRIGGER LOGIC
TOF
At least
one bar fire
both sides
20ns
1.2 MHz
COIN
FSD
At least
one strip fire
10ns
4.5 MHz
COIN
140ns
15 kHz
TAPS
LED SUM
>15MeV
30ns
14 kHz
120ns
15 kHz
COIN
TAGGER
At least one
channel fire in region
537MeV–817MeV
20ns
100 MHz
LOGIC
UNIT
TRIGGER RATE
300 Hz



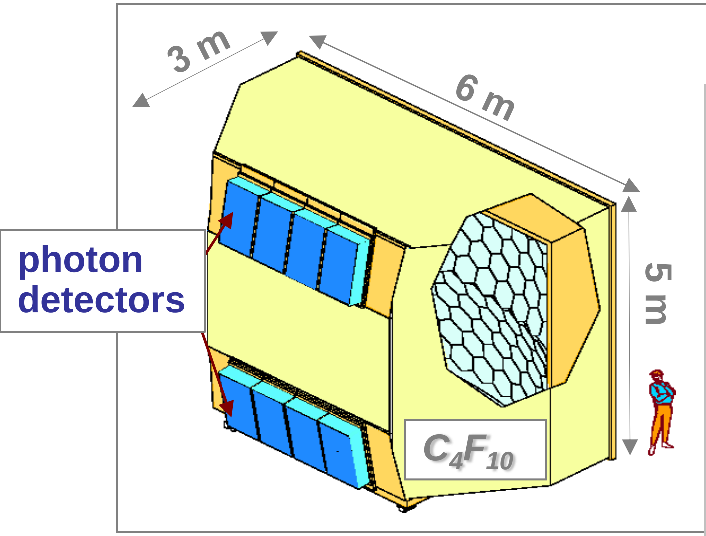

COMPASS setup 2009
top view
Veto
Trigger
BC
Beam
SciFi
Silicons
RPD
MC
Sandwich
PixelGEM
Micromegas
DC
Straws
SM1
GEM
SciFi
DC
RICH
RICH
WALL
MWPC
GEM
ECAL1
HCAL1
MWPC
Muon
Filter 1
MW1
PixelGEM
GEM
SM2
Straws
BK1
PixelGEM
GEM
MWPC
Large area DCs
MWPC
BK2
ECAL2
HCAL2
SciFi
GEM
Muon
Filter 2
HO4
MWPC
MW2
GEM
x
z
0
10
20
30
40
50 m

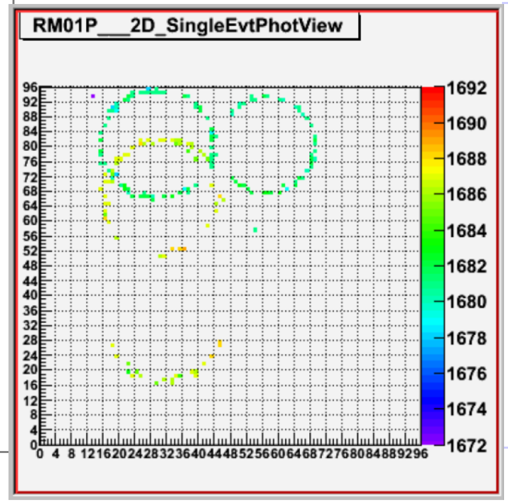
Silicon detector module

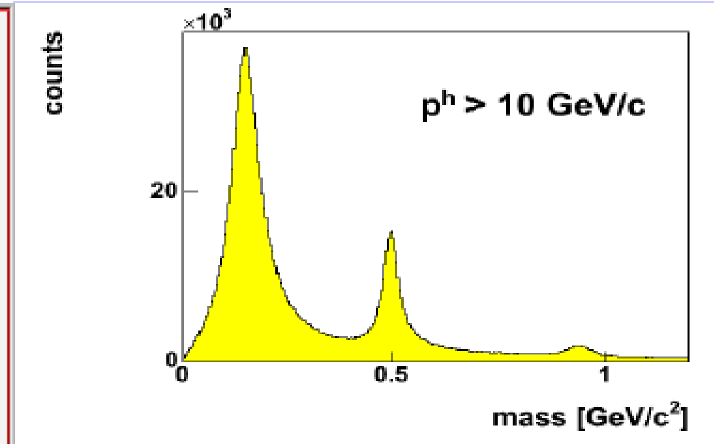
Silicon cryostat in the recoil detector

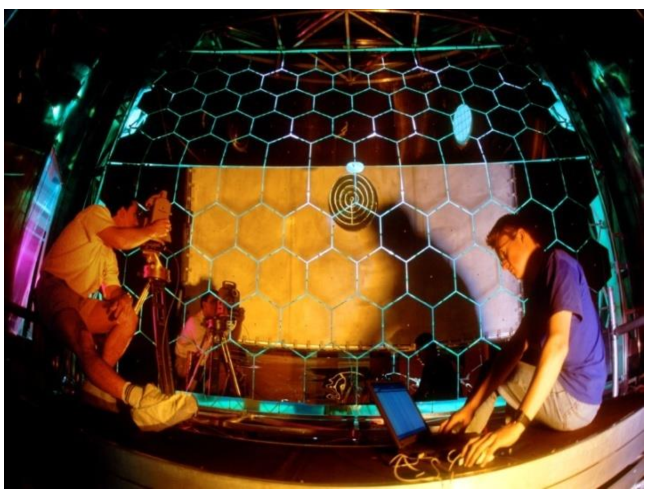


THE RICH DETECTOR









- radiator gas: C_4F_{10}
- mirror wall: 20 m^2 surface
- photon-detectors:
  - outer part (75%) MWPC(pad RO) with CsI cathode
  - inner part(25%) 576 MAPMTs with indiv. telescope

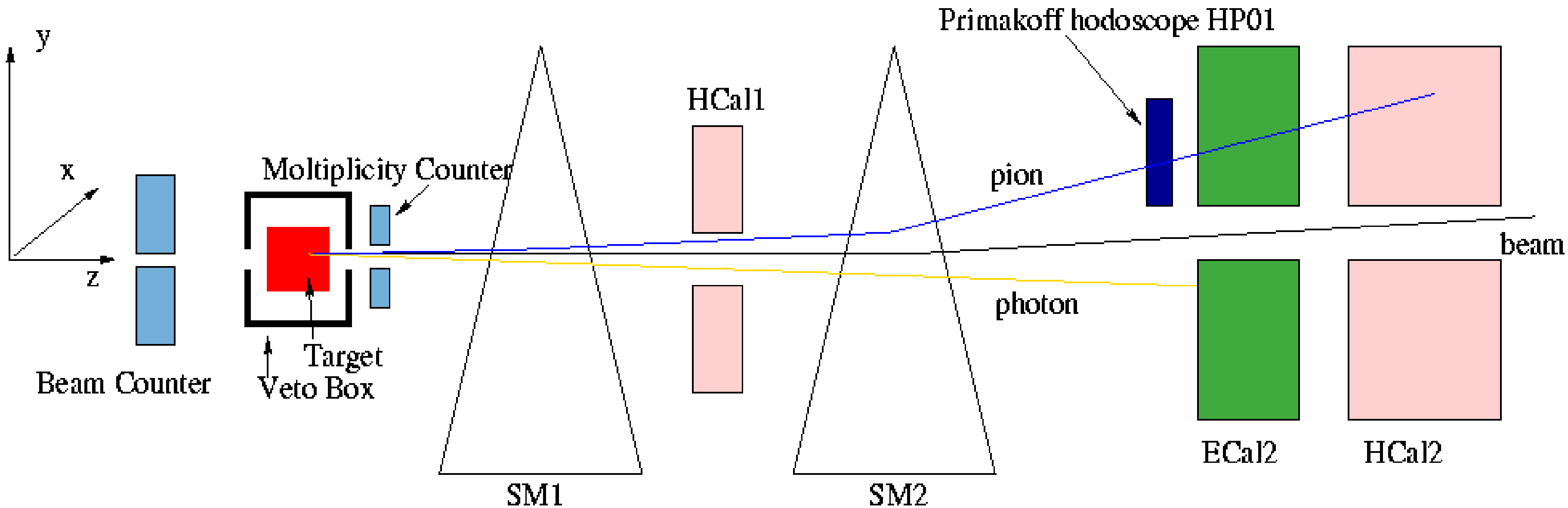
threshold momenta

- **p_π = 2 GeV/c**
- **p_K = 9 GeV/c**
- **p_P =17 GeV/c**

Installed in 2005,
Used in data taking from 2006

The Compass Spectrometer

Trigger



Experimental conditions during the 2004 hadron run (7 days)

- **Beam**: 190 GeV/c; ~10^6 π/s, 4.8 s / 16 s spill structure
  190 GeV/c; ~10^8 μ/s

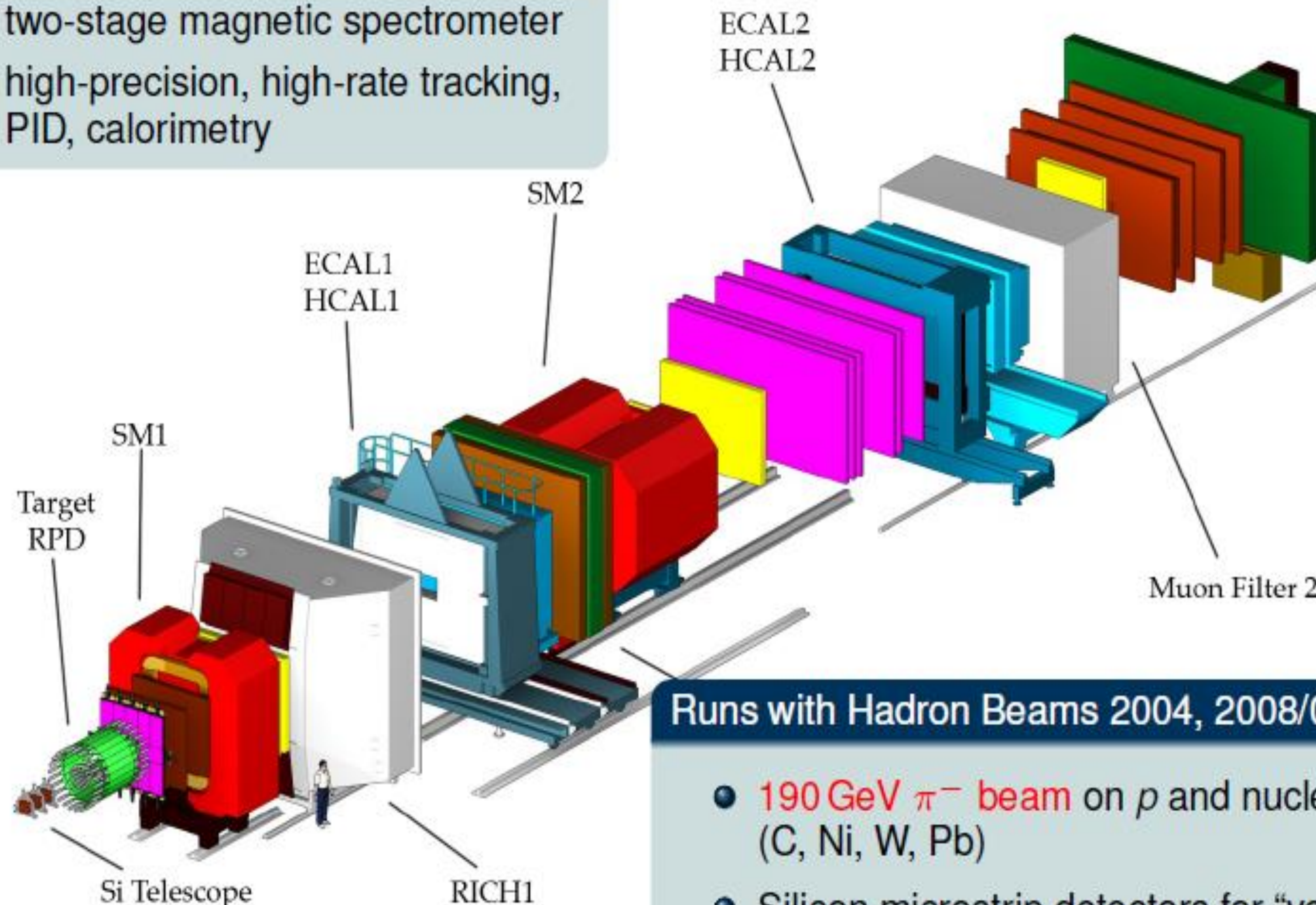
- **Targets**: 1.6 – (2+1) - 3 mm Pb , 7 mm Cu, 23 mm C

- **Triggers:**
  - Primakoff 1 = Hodoscope hit x ECal2 (E>50 GeV) x HCal2 (E>18 GeV)
  - Primakoff 2 = ECal2 (E>100 GeV)
- Saturated trigger rate (40-50k/spill)

COMPASS
Experimental Setup

Fixed-target experiment

- two-stage magnetic spectrometer
- high-precision, high-rate tracking, PID, calorimetry



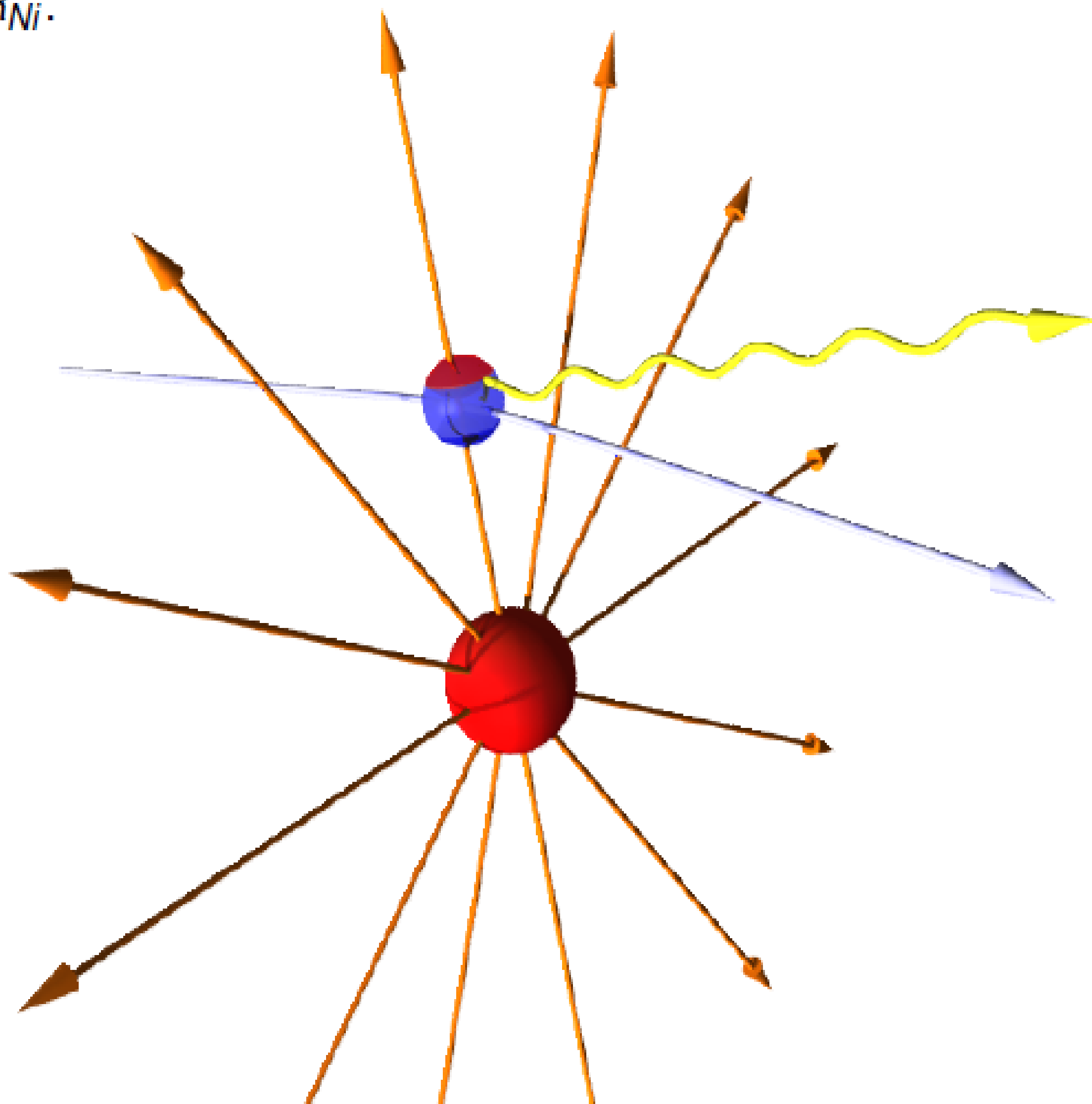
Runs with Hadron Beams 2004, 2008/09, 2012

- 190 GeV π^- beam on p and nuclear targets (C, Ni, W, Pb)
- Silicon microstrip detectors for “vertexing”
- recoil and (digital) ECAL triggers

ECAL2: 3000 cells of different types

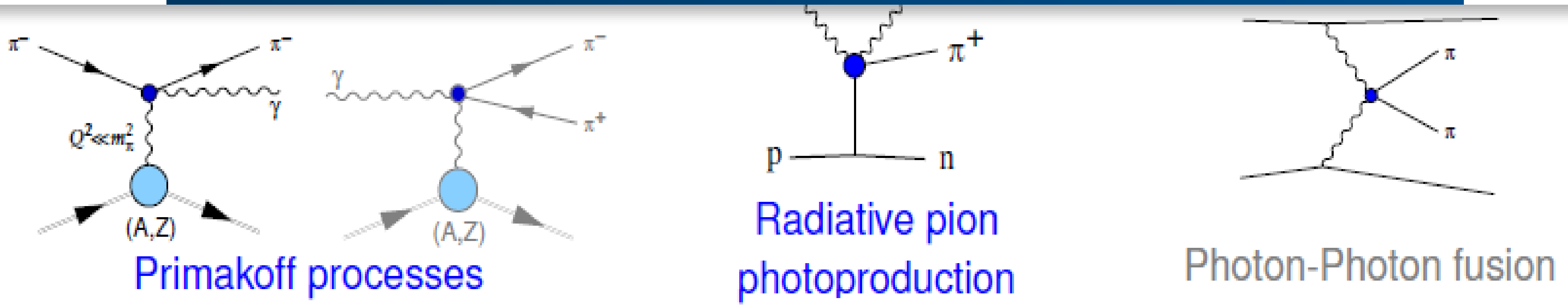
Polarisability effect in Primakoff technique

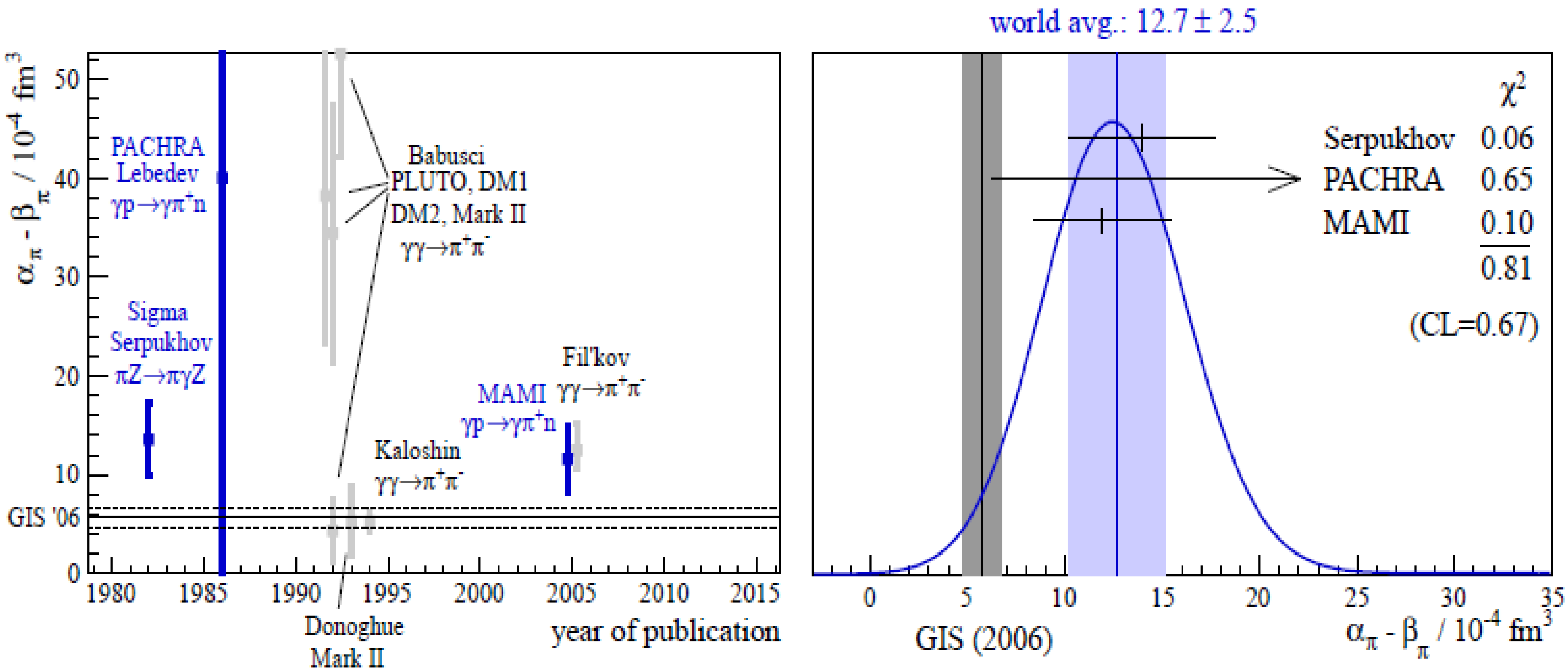
- Charged pions traverse the nuclear electric field
  - typical field strength at $d = 5R_{Ni}$: $E \approx 300\,\mathrm{kV/fm}$
- Bremsstrahlung process:
  - particles scatter off *equivalent photons*
  - tiny momentum transfer $Q^2 \approx 10^{-5}\,\mathrm{GeV}^2/c^2$
  - pion/muon (quasi-)real Compton scattering
- Polarisability contribution
  - Compton cross-section typically diminished
  - equivalent charge separation $\approx 10^{-5}\,\mathrm{fm} \cdot e$



Press echo in spring 2015

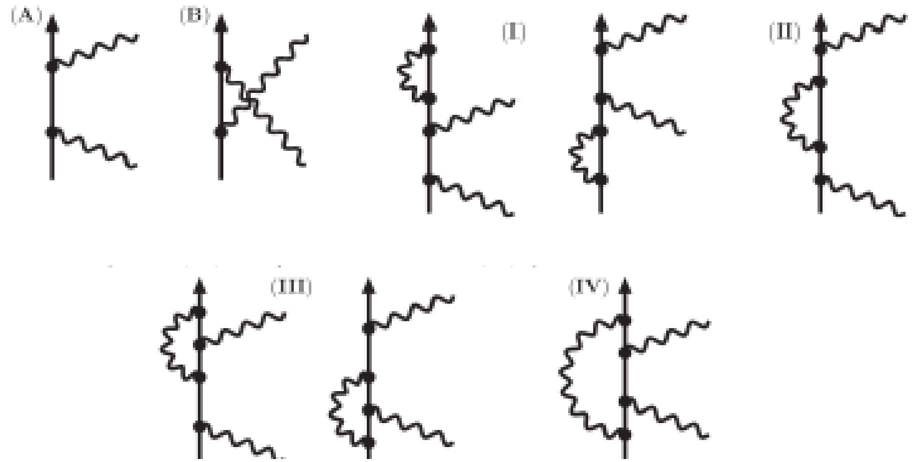
Pion polarisability: world data before COMPASS

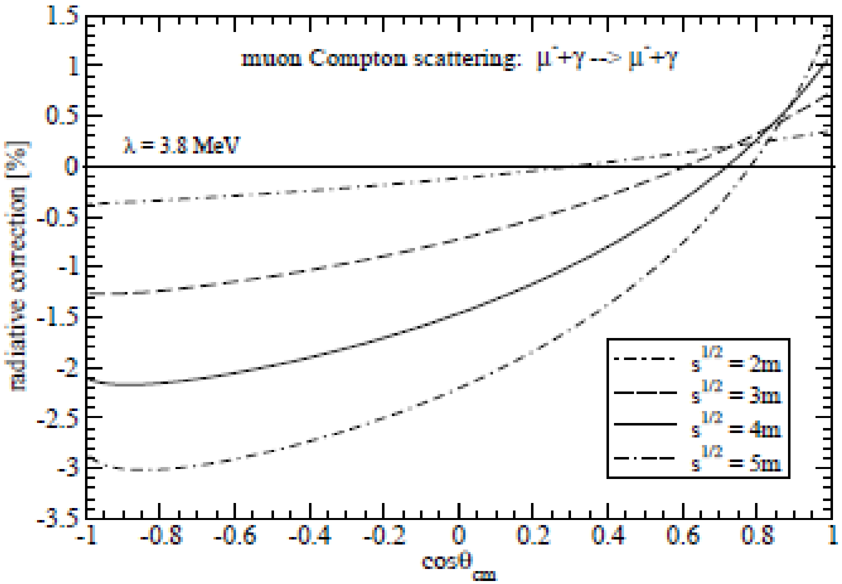




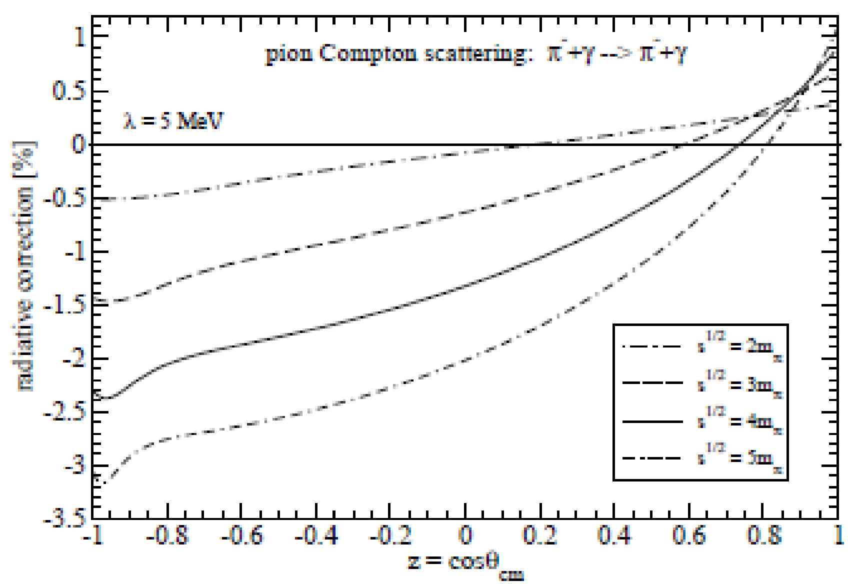
GIS'06: ChPT prediction, Gasser, Ivanov, Sainio, NPB745 (2006), plots: T. Nagel, PhD
Fil'kov analysis objected by Pasquini, Drechsel, Scherer PRC81, 029802 (2010)

Radiative corrections (Compton scattering part)



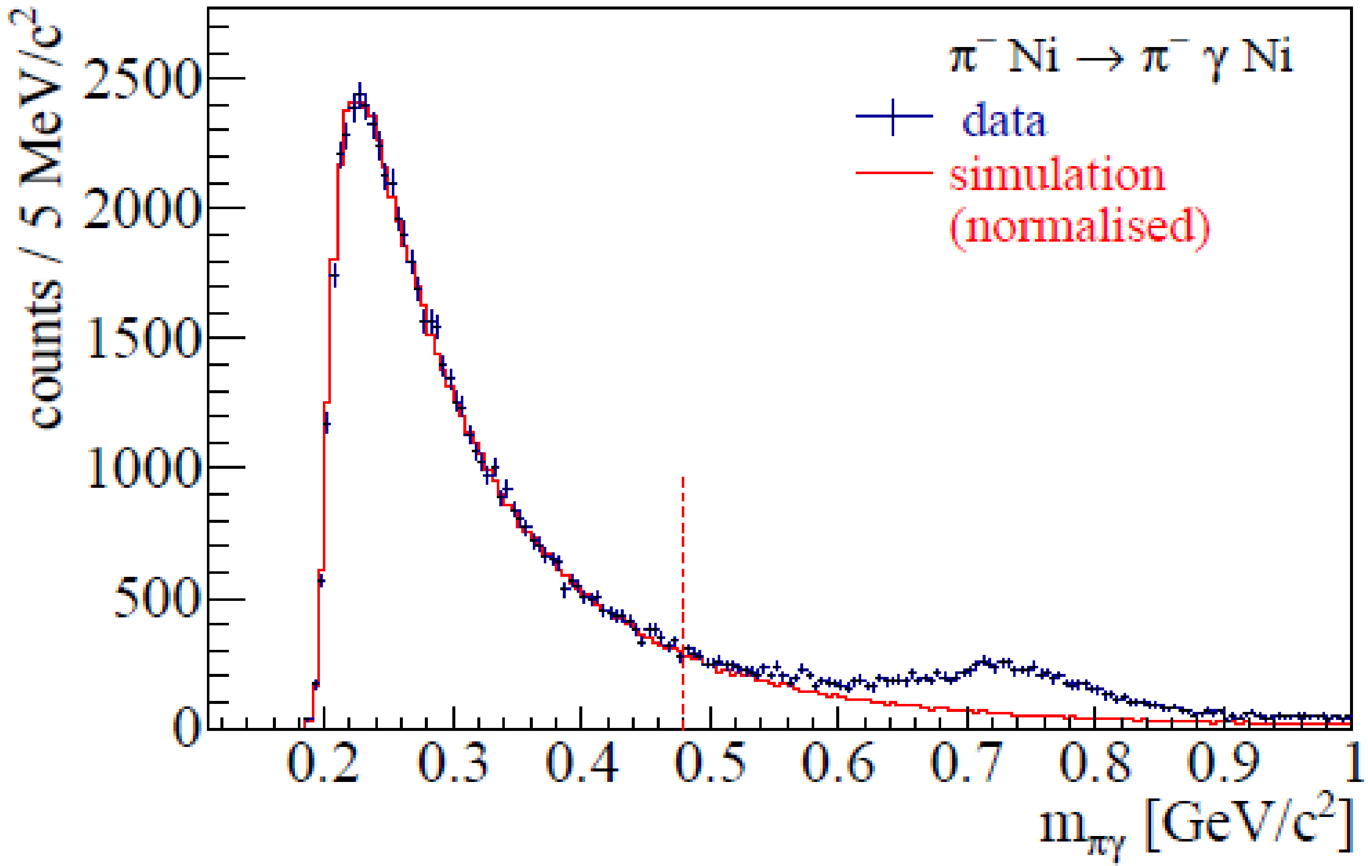


Nucl.Phys. A837 (2010)



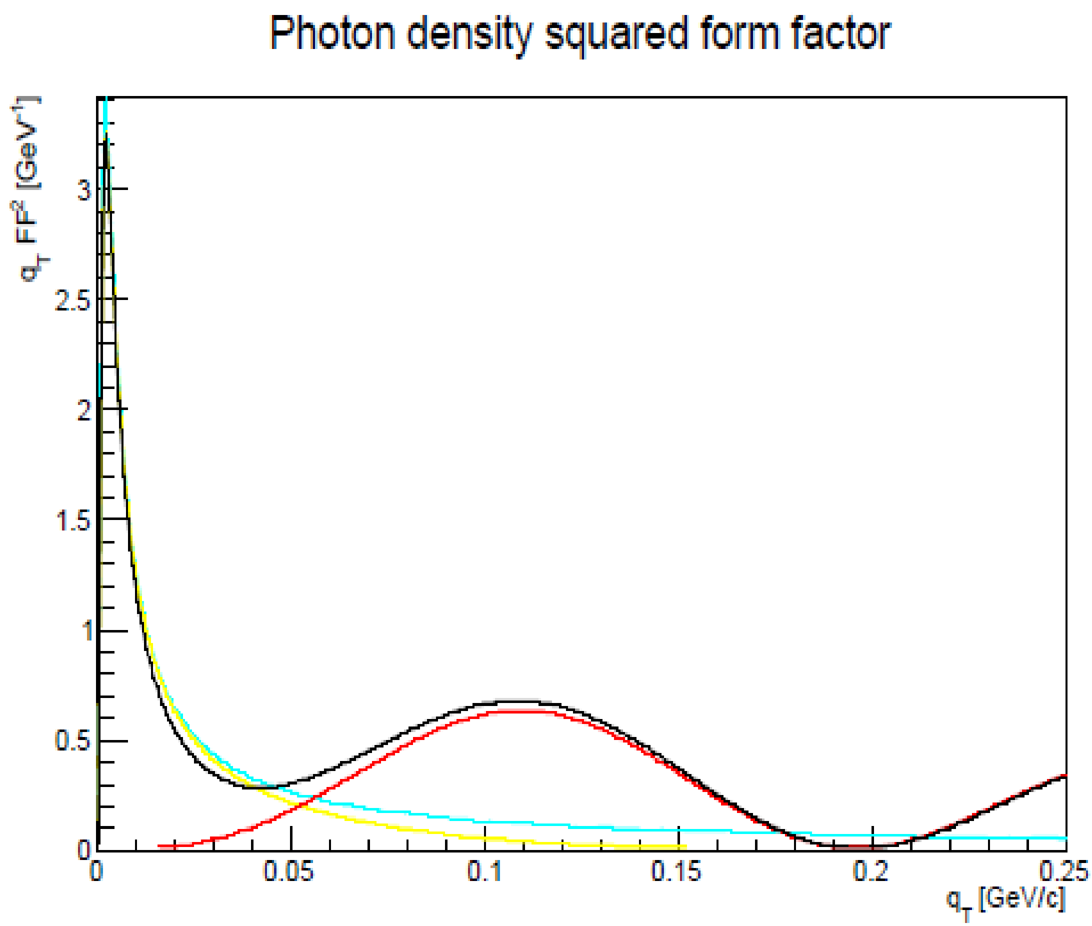
Eur.Phys.J. A39 (2009) 71

CM energy in $\pi\gamma \to \pi\gamma$



- ρ contribution from $\pi\gamma \to \pi\pi^0$

Coulomb-nuclear interference



- calculation following G. Fäldt (Phys. Rev. C79, 014607)
- eikonal approximation: pions traverse Coulomb and strong-interaction potentials

Pion Polarizability, Radiative Transitions, and Quark Gluon Plasma Signatures

Can one expect gamma ray rates from the QGP to be higher than from the hot hadronic gas phase. Xiong, Shuryak, Brown (XSB) calculate photon production from a hot hadronic gas via the reaction $\pi^- + \rho^0 \rightarrow a_1(1260) \rightarrow \pi^- + \gamma$. For $a_1(1260) \rightarrow \pi\gamma$, they assume a radiative width of 1.4 MeV. XSB use their estimated a_1 radiative width to calculate the pion polarizability, obtaining $\alpha_\pi = 1.8 \times 10^{-43}\ \mathrm{cm}^3$. Independently, Holstein showed that meson exchange via a pole diagram involving the a_1 resonance provides the main contribution ($\alpha_\pi = 2.6 \times 10^{-43}\ \mathrm{cm}^3$) to the polarizability. New Primakoff data for $\pi^-\gamma \rightarrow a_1(1260) \rightarrow \pi^- \rho^0$ should allow a reevaluation of the consistency of their expected relationship, and improved calculation of the gamma rate from the hot hadronic gas phase.

Compton Scattering: Kinematics

$$\gamma(k) + \pi(p) \to \gamma(k') + \pi(p')$$

3 Mandelstam variables:

$s = (k+p)^2, \quad t = (k-k')^2, \quad u = (k-p')^2$

(constraint $s + t + u = 2m_\pi^2$)

Mandelstam plane: Xing-symmetric $\nu = (s-u)/(4m_\pi)$ and t

$(\nu, t) \Leftrightarrow$ photon lab energies E_γ and E'_γ and lab scattering angle θ:

$\nu = E_\gamma + t/(4m_\pi) = \frac{1}{2}(E_\gamma + E'_\gamma)$

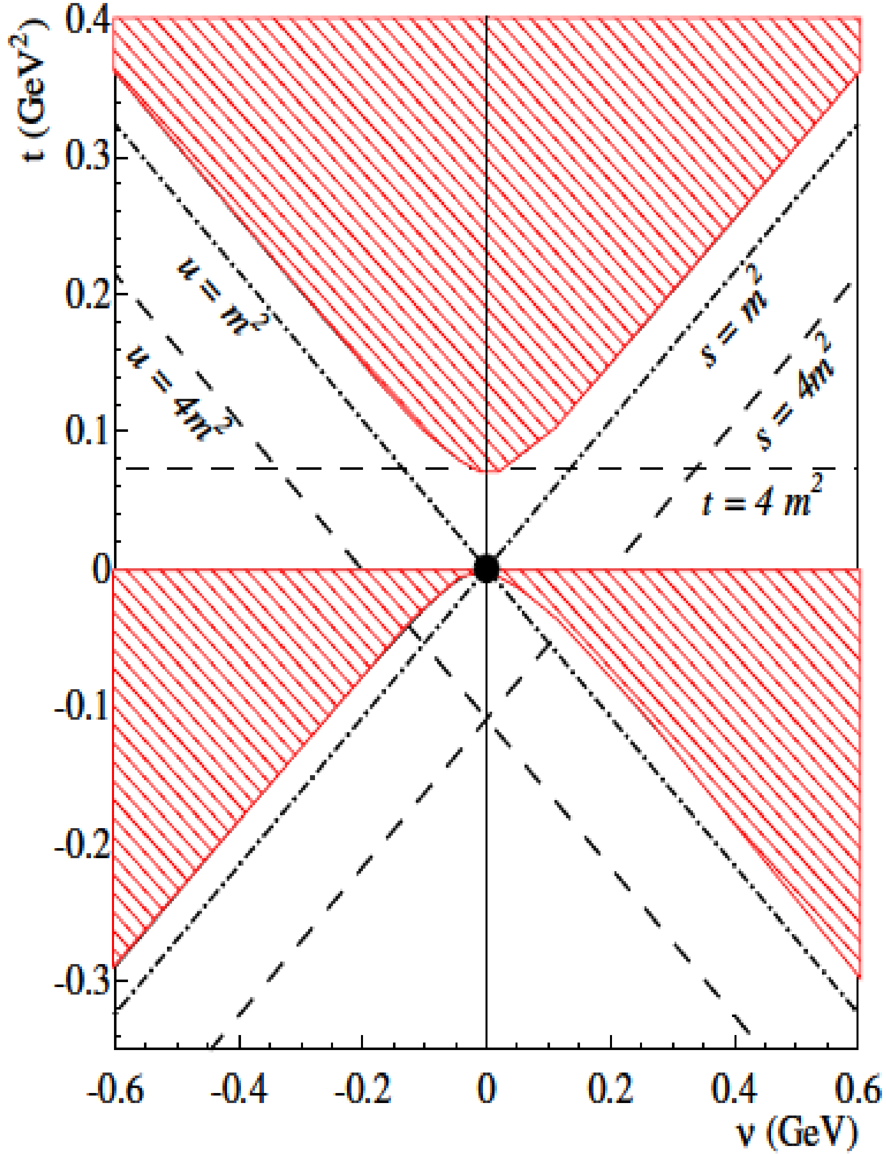
$t \ = -4E_\gamma E'_\gamma \sin^2(\theta/2) = -2m_\pi(E_\gamma - E'_\gamma)$

Scattering matrix has 2 independent amplitudes:

$M^{+-}(\nu, t)$ helicity-flip, forward scattering, $\Rightarrow \alpha + \beta$

$M^{++}(\nu, t)$ NO helicity-flip, backward scattering, $\Rightarrow \alpha - \beta$

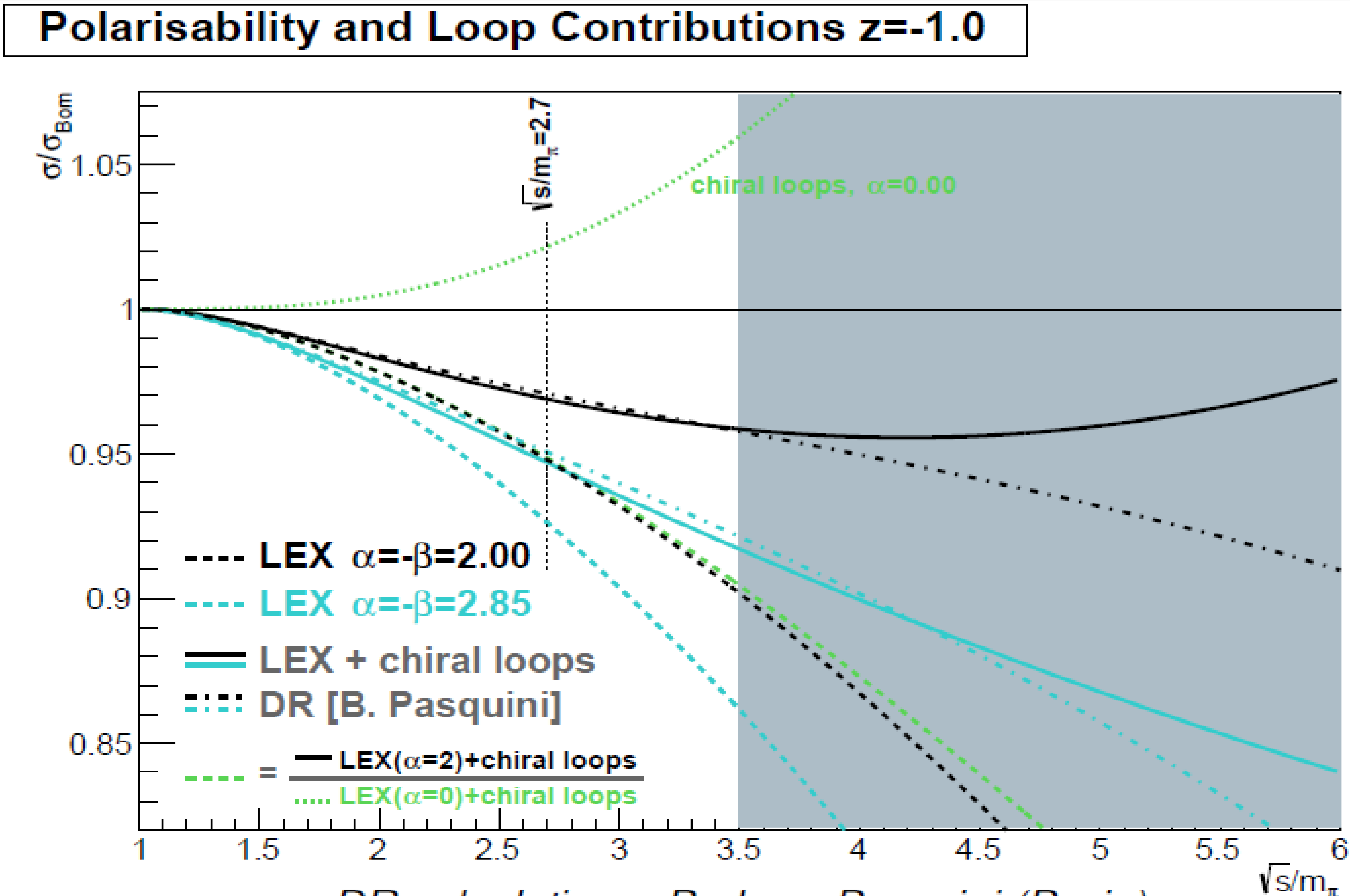
About crossing



- red hatched: physical regions $\gamma + \gamma \to \pi + \pi$ $\gamma + \pi \to \gamma + \pi$
- two-pion thresholds at $s = 4m_\pi^2$, $u = 4m_\pi^2$, $t = 4m_\pi^2$
- DR integration paths $t = 0$ (forward), $\theta = 180°$ (backward) $u = m_\pi^2$, $s = m_\pi^2$, ...

from: D. Drechsel, talk at IWHSS 2011 Paris

Dispersion relations and ChPT



DR calculations: Barbara Pasquini (Pavia)

Pion polarisability on the lattice

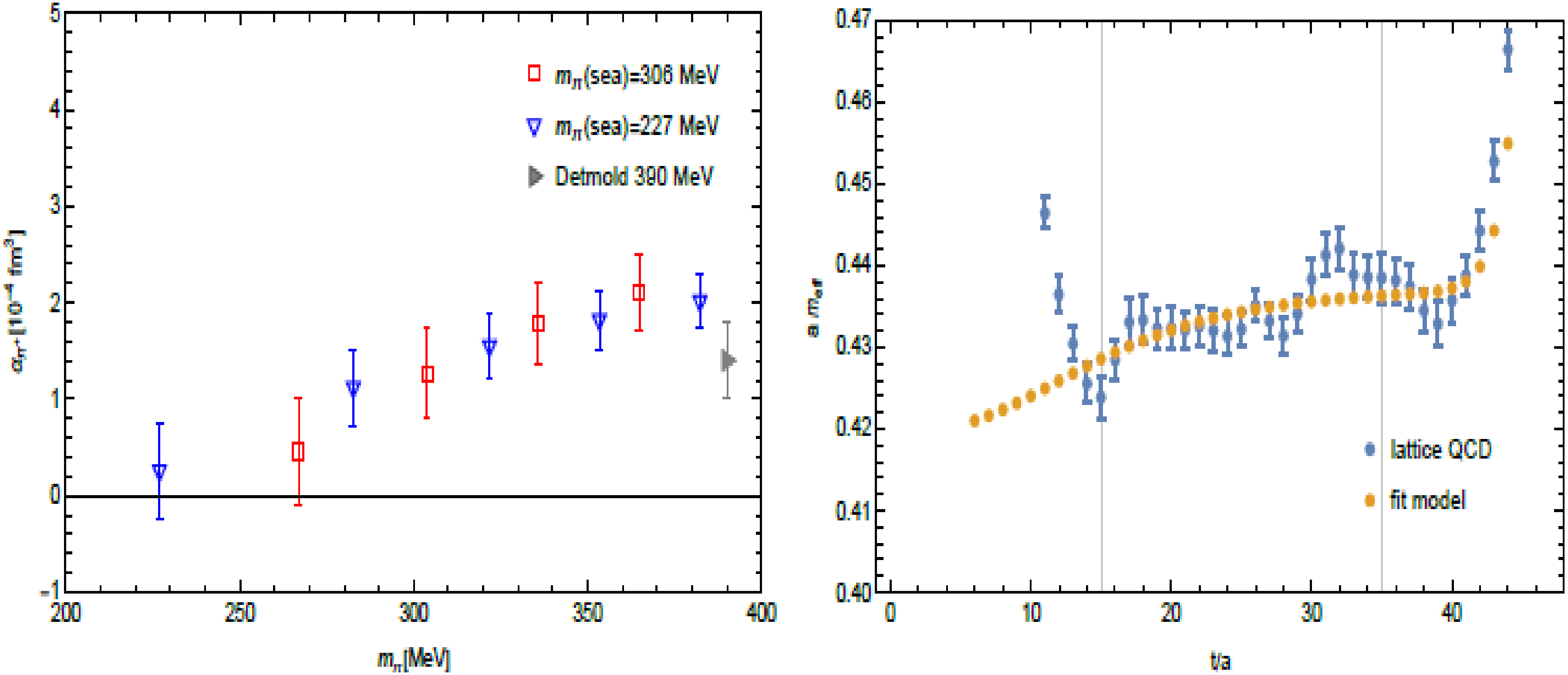


FIGURE 3. Left: electric polarizability for the charged pions as a function of the valence quark mass. The data for $m_\pi = 390$ MeV is taken from [5]. Right: effective mass for a charged pion correlator together with the scalar particle correlator determined from the fit. The fitting range is indicated by the vertical bars.

Alexandru *et al.*, Pion electric polarizability from lattice QCD, arXiv:1501.06516

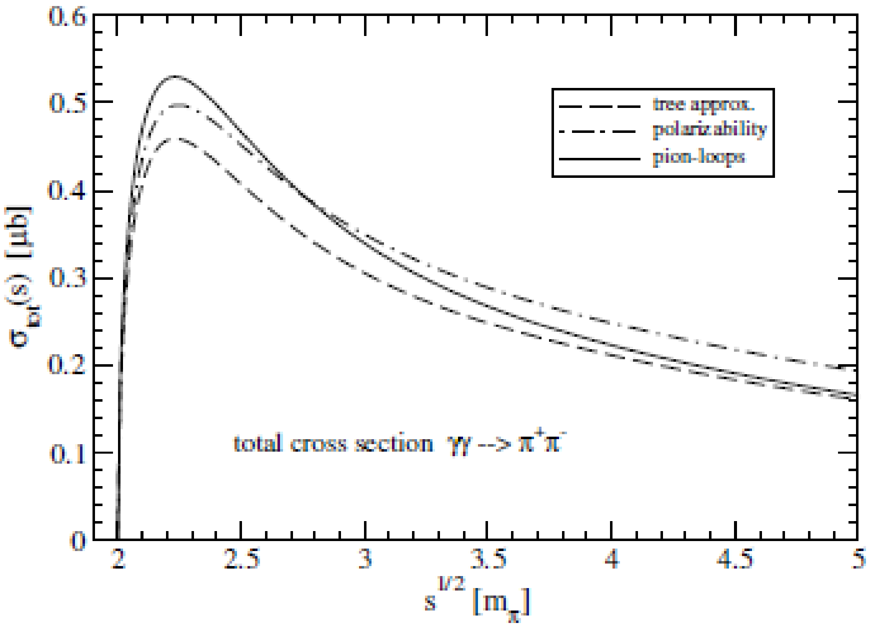
Photon-photon fusion process $\gamma\gamma \to \pi^+\pi^-$

- Planned measurements at ALICE and JLab

$$\sigma_{tot}(s) = \frac{2\pi\alpha^2}{\hat{s}^3 m_\pi^2}\Big\{\left[4+\hat{s}+\hat{s}|C(\hat{s})|^2\right]\sqrt{\hat{s}(\hat{s}-4)}$$

$$+8\left[2-\hat{s}+\hat{s}\,\mathrm{Re}C(\hat{s})\right]\ln\frac{\sqrt{\hat{s}}+\sqrt{\hat{s}-4}}{2}\Big\},$$

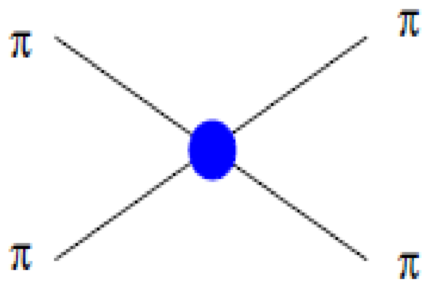
$$C(\hat{s}) = -\beta_\pi\frac{m_\pi^3}{2\alpha}\hat{s} - \frac{m_\pi^2}{(4\pi f_\pi)^2}\left\{\frac{\hat{s}}{2}+2\left[\ln\frac{\sqrt{\hat{s}}+\sqrt{\hat{s}-4}}{2}-\frac{i\pi}{2}\right]^2\right\}$$



courtesy Norbert Kaiser (TUM)

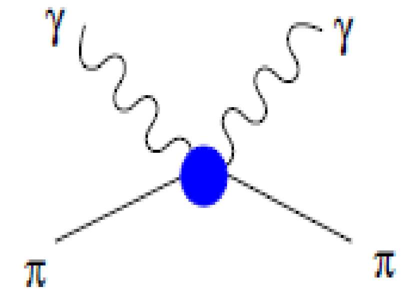
Chiral Perturbation Theory vs. Experiment

- pion scattering lengths: 2-loop predictions
  - $a_0^0 m_\pi = 0.220 \pm 0.005$ confirmed by E865 in $K^+ \to \pi^+\pi^- e^+\nu_e$
  - $(a_0^0 - a_0^2)m_\pi = 0.264 \pm 0.006$ confirmed by NA48 in 0.268 ± 0.010 $K^+ \to \pi^+\pi^0\pi^0$



- pion polarisability: electric α_π, magnetic β_π
  - leading structure-dependent contribution to Compton scattering
  - ChPT prediction obtained by the relation to $\pi^+ \to e^+\nu_e\gamma$ [Gasser, Ivanov, Sainio, Nucl. Phys. B745, 2006]

    [PIBETA, M. Bychkov et al., PRL 103, 051802, 2009]



- ChPT prediction contradicts the experimental findings (prior to this analysis)

For the γ–π interaction at low energy, chiral perturbation theory (χPT) provides a rigorous way to make predictions, because it stems directly from QCD and relies only on the solid assumptions of spontaneously broken $SU(3)_L \times SU(3)_R$ chiral symmetry, Lorentz invariance and low momentum transfer. Unitarity is achieved by adding pion loop corrections to lowest order, and the resulting infinite divergences are absorbed into physical (renormalized) coupling constants L_i^r (tree-level coefficients in $L^{(4)}$, see refs. [11,12]). With a perturbative expansion of the effective lagrangian limited to terms quartic in the momenta and quark masses ($O(p^4)$), the method establishes relationships between different processes in terms of the L_i^r. For example, the radiative pion beta decay and electric pion polarizability are expressed as [12]

$$h_A / h_V = 32\pi^2 (L_9^r + L_{10}^r) , \tag{4}$$

$$\bar{\alpha}_\pi = \frac{4\alpha_f}{m_\pi F_\pi^2} (L_9^r + L_{10}^r) , \tag{5}$$

chiral perturbation theory for light mesons

Chiral perturbation theory (CHPT) in its original form [1, 2, 3] describes the strong, electromagnetic (external photons) and semileptonic weak interactions at low energies for the light pseudoscalar mesons, pions only for chiral $SU(2)$, the light pseudoscalar octet for chiral $SU(3)$.

At NLO in CHPT, electric and magnetic polarizabilities are equal. In addition to the loop contribution, a single combination of $SU(2)$ LECs $2l_5 - l_6$ enters, which is accurately known from $\pi \to e\nu\gamma$ [2]. At NNLO the LECs l_1, l_2, l_3, l_4 (in one-loop diagrams) and three NNLO LECs contribute together with one-and two-loop contributions. It turns out that the difference $\alpha_\pi - \beta_\pi$ is not very sensitive to the NNLO LECs leading to the final result[1] $\alpha_\pi - \beta_\pi = 5.7 \pm 1.0$ [32]. The sum $\alpha_\pi + \beta_\pi \simeq 0.16$ is much smaller but the relative uncertainty is bigger than for the difference. Most experiments actually assume $\alpha_\pi = -\beta_\pi$ in their analyses.

$$\alpha_E^{\pi^+} = \frac{\alpha_{em}}{2M_\pi}\zeta = \frac{\alpha_{em}}{8\pi^2 M_\pi F_\pi^2}\frac{h_A}{h_V}.$$

$$\frac{h_A}{h_V} = 32\pi^2\left(L_9^r(\mu) + L_{10}^r(\mu)\right)$$

From Holstein & Scherer

Here, h_V arises from the anomaly and is exactly predicted at $\mathcal{O}(q^4)$ [98, 99, 100]. The ratio h_A/h_V is given in terms of a linear combination of LECs of the $\mathcal{O}(q^4)$ Lagrangian [92]. The renormalization scale is denoted by μ, but the linear combination $L_9^r(\mu) + L_{10}^r(\mu)$ is scale-independent. The coupling h_A has been measured with great precision by the recent PIBETA experiment [101], resulting in [26]

$$\left(\frac{h_A}{h_V}\right)_{\text{expt}} = 0.469 \pm 0.031 \tag{72}$$

which then corresponds to the one-loop prediction

$$\alpha_E^{\pi^+} = -\beta_M^{\pi^+} = (2.8 \pm 0.2) \times 10^{-4}\,\text{fm}^3. \tag{73}$$

Two-loop corrections are expected to be small by power-counting arguments,

$$\alpha_E^{\pi^+}|_{\text{two-loop}}/\alpha_E^{\pi^+}|_{\text{one-loop}} \sim \frac{4M_\pi^2}{\Lambda_\chi^2} \sim 0.1, \tag{74}$$

The constraint $\alpha_\pi + \beta_\pi = 0$

Coupling of scalar field to em. gauge field:

$$\mathcal{H}_{\text{int}} = g_1 \cdot \partial_\alpha \phi \partial_\beta \phi \, F^{\alpha\gamma} F^\beta_{\ \gamma} + g_2 \cdot \phi^2 F^2$$

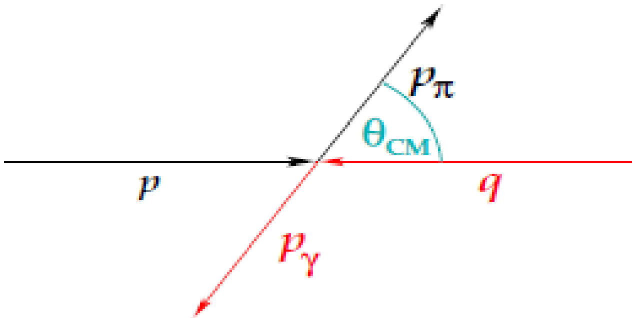
where

$$g_2 \cdot F^{\alpha\beta} F_{\alpha\beta} \sim g_2 \left(E^2 - B^2 \right) \stackrel{!}{=} \alpha_\pi \frac{E^2}{2} + \beta_\pi \frac{B^2}{2}$$

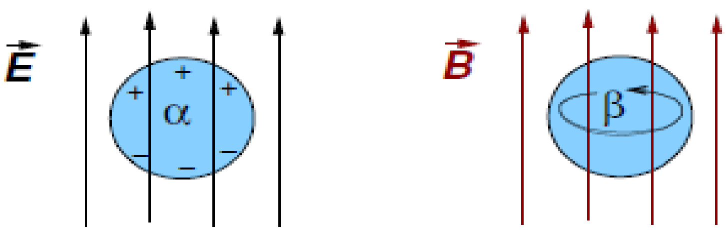
The term $g_1 = \frac{1}{2m}(\alpha_\pi + \beta_\pi)$ vanishes *to leading order* at low momenta.

Compton scattering and polarisability

$$\pi + \gamma \to \pi + \gamma$$



Low-energy LO deviation from pointlike particle $\leftrightarrow$ em. polarisability



$[10^{-4}\ \mathrm{fm}^3]$	$\alpha_\pi - \beta_\pi$	$\alpha_\pi + \beta_\pi$
ChPT LO	6.0	0
NNLO	5.7±1.0	0.16
experiments	4 — 14	—

ChPT (2-loop) prediction:
$$\alpha_\pi = 2.93 \pm 0.5$$
$$\beta_\pi = -2.77 \pm 0.5$$

experiments for α_π lie in the range $2 \cdots 7$

($\alpha_\pi + \beta_\pi = 0$ assumed)

Other models (dispersion sum rules, QCD sum rule, lattice calculations,…) predict different polarizability values: $0<(\alpha_\pi+\beta_\pi)<0.39$; $3.2<(\alpha_\pi-\beta_\pi)<11.2$

According to ChPT, the pion is significantly **stiffer** than shown by previous measurements, and most other models.