PION POLARIZABILITY AT CERN COMPASS

Murray Moinester

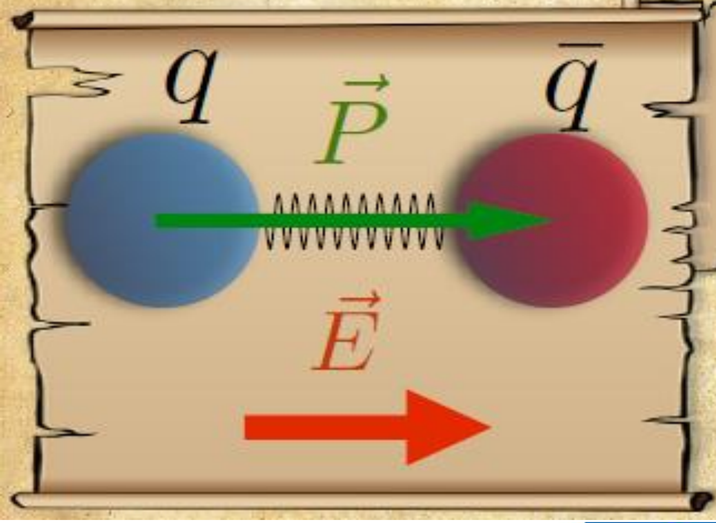
Tel Aviv University

for the COMPASS collaboration

COMPASS

APS Division of Nuclear Physics, October 23-26, 2013, Newport News, Virginia

Polarizabilities of particles



$$\vec{P} = \alpha_X \vec{E}$$

$$\vec{\mu} = \beta_X \vec{H}$$

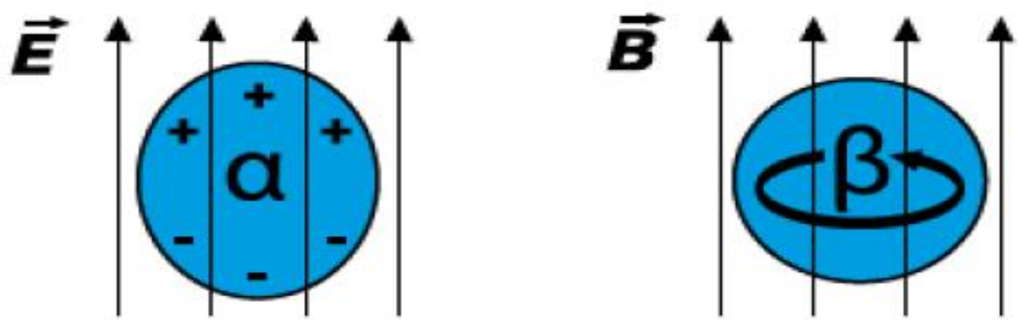
The electric and magnetic polarizabilities of a particle are the quantities characterizing the rigidity of QCD system

introduction

charged pion polarizabilities

$$\pi + \gamma \rightarrow \pi + \gamma$$

Compton cross-section contains information about e.m. polarisability
(as deviation from the expectation for a pointlike particle)



Theoretical predictions for a_π, β_π

Model	Parameter	$[10^{-4} fm^3]$
χPT (1 loop)	$\alpha_\pi - \beta_\pi$	5.4 ± 0.8
	$\alpha_\pi + \beta_\pi$	0
χPT (2 loops)	$\alpha_\pi - \beta_\pi$	5.7 ± 1.0
	$\alpha_\pi + \beta_\pi$	0.16
Nambu-Jona-Lasinio model	$\alpha_\pi - \beta_\pi$	9.8
Quark confinement model	$\alpha_\pi - \beta_\pi$	7.05
	$\alpha_\pi + \beta_\pi$	0.23
QCD sum rules	$\alpha_\pi - \beta_\pi$	11.2 ± 1.0
Dispersion sum rules	$\alpha_\pi - \beta_\pi$	13.60 ± 2.15
	$\alpha_\pi + \beta_\pi$	0.166 ± 0.024

The most of theoretical models are in agreement that $a_\pi - \beta_\pi \gg a_\pi + \beta_\pi \approx 0.2 \times 10^{-4} fm^3$. As for value $a_\pi - \beta_\pi$, predictions are quite different

Henry Primakoff

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:

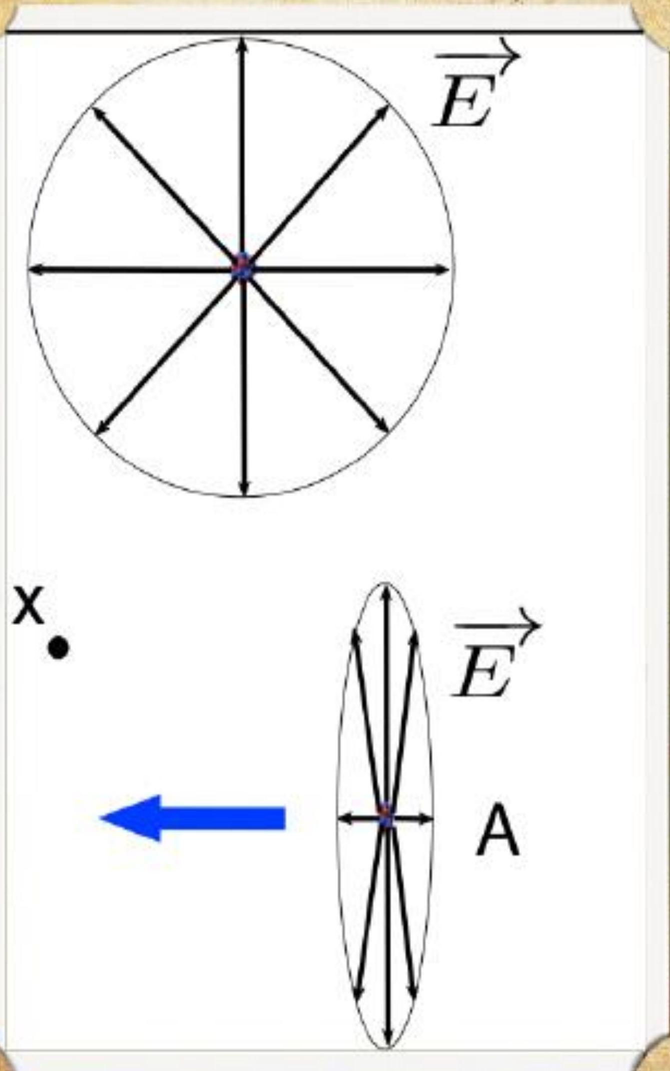
$$\text{Interaction Energy Density} = \eta(\hbar/\mu c)(\hbar c)^{-\frac{1}{2}}\varphi\mathbf{E}\cdot\mathbf{H}. \qquad (1)$$

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

Equivalent photon method

(Weizsaecker-Williams approximation)



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

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

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

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

density of equivalent photons

Primakoff reactions accessible at COMPASS

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

At smallest momentum transfers to the nucleus, high-energetic particles scatter predominantly off the electromagnetic field quanta ($\sim Z^2$)

$$\pi^- + \gamma \rightarrow \begin{cases} \pi^- + \gamma & \Leftarrow \\ \pi^- + \pi^0 \; / \; \eta \\ \pi^- + \pi^0 + \pi^0 \\ \pi^- + \pi^- + \pi^+ \\ \pi^- + \pi^- + \pi^+ + \pi^- + \pi^+ \\ \pi^- + \ldots \end{cases}$$

analogously: Kaon-induced reactions $K^- + \gamma \rightarrow \cdots$

Volume 121B, number 6 PHYSICS LETTERS 17 February 1983

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

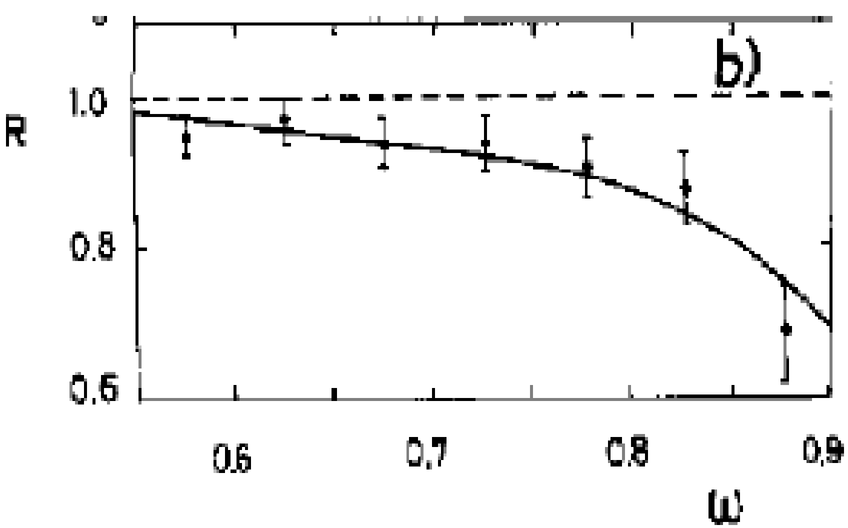
IHEP, Serpukhov, USSR

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.



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

"Serpukhov value"

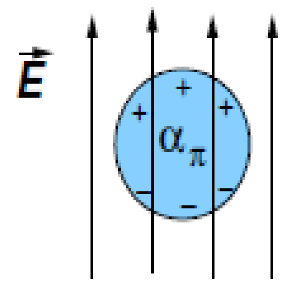
$\alpha_\pi \approx 7 \cdot 10^{-4}$ fm^3

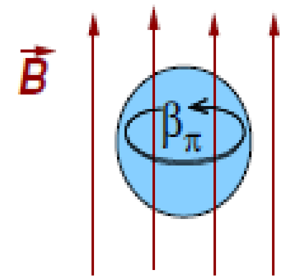
from the pion bremsstrahlung spectrum

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

Pion Compton Scattering

$$\underbrace{\pi \quad \gamma}_{\text{Ni} \to \text{Ni}',\ q^2 \approx 0} \quad \to \quad \pi \quad \gamma$$





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

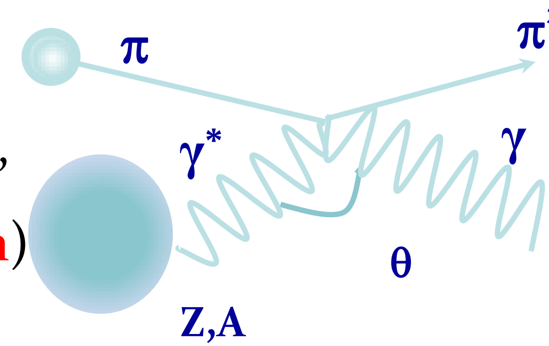
$$\frac{d\sigma_{\pi\gamma}}{d\Omega_{cm}} = \frac{\alpha^2(s^2 z_+^2 + m_\pi^4 z_-^2)}{s(sz_+ + m_\pi^2 z_-)^2} - \frac{\alpha\, m_\pi^3\,(s - m_\pi^2)^2}{4s^2(sz_+ + m_\pi^2 z_-)} \cdot \mathcal{P}$$

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

$z_\pm = 1 \pm \cos\theta_{cm}$ $\qquad$ $\alpha = 1/137$ fine structure constant (!)

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

The Primakoff reaction $\pi + Z \rightarrow \pi' + Z + \gamma$



Inverse kinematics for the Compton scattering: $\gamma^{*}\pi \rightarrow \gamma\pi'$
In the incoming pion rest frame (Anti-laboratory system)

$$\frac{d^2\sigma_{\gamma\pi}}{d\omega d\cos\theta} \propto Z^2 \left\{ F_{\gamma\pi}^{pt}(\theta) + \frac{m_\pi \omega}{\alpha} \cdot \frac{\alpha_\pi (1+\cos^2\theta) + 2\beta_\pi \cos\theta}{\left[1+\frac{\omega}{m_\pi}(1-\cos\theta)\right]^3} \right\}$$

α_π, β_π independently

ω is the energy of the virtual photon in the anti-laboratory sys.

Assuming $(\alpha_\pi + \beta_\pi) = 0$ in the Laboratory system:

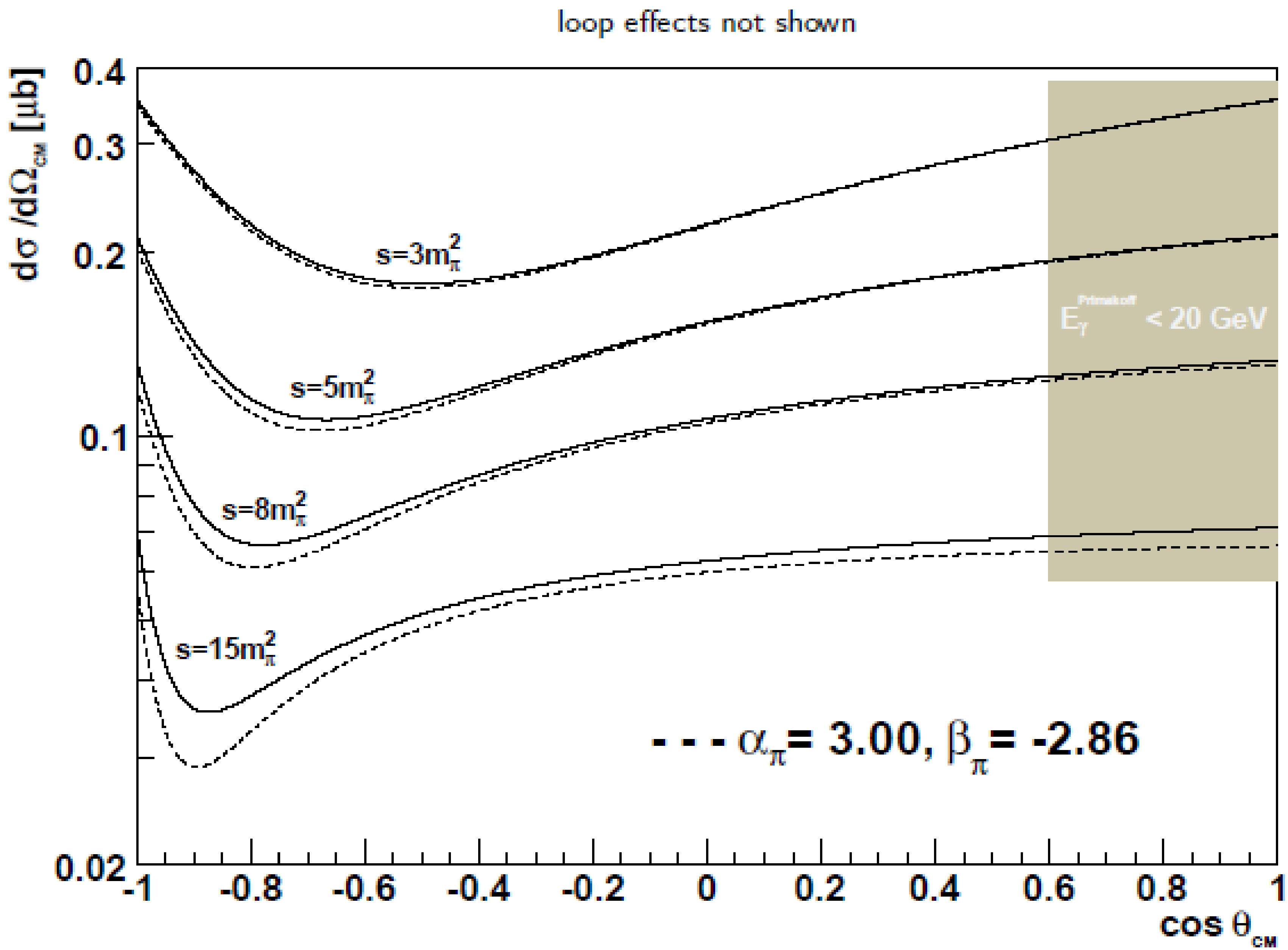
$$\frac{d\sigma_{\gamma\pi}}{dE_\gamma} = \frac{d\sigma_{\gamma\pi}^{pt}}{dE_\gamma} + 4Z^2\alpha^2 m_\pi \frac{E_\gamma}{E_{beam}^2} \beta_\pi \left(\ln \frac{Q^2_{\max}}{Q^2_{\min}} - 3 + 4\sqrt{\frac{Q^2_{\min}}{Q^2_{\max}}} \right)$$

β_π

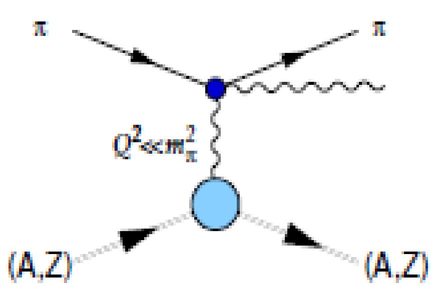
$$Q^2_{\min} = \left(\frac{E_\gamma m_\pi}{2E_{beam}(E_{beam} - E_\gamma)} \right)^2$$

Q^2_{max} depends on analysis cut
E_γ is the energy of the real photon

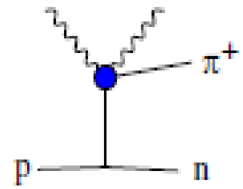
Polarisability effect (NLO ChPT values)



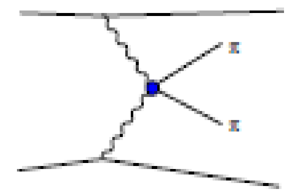
Pion polarisability: world data before COMPASS



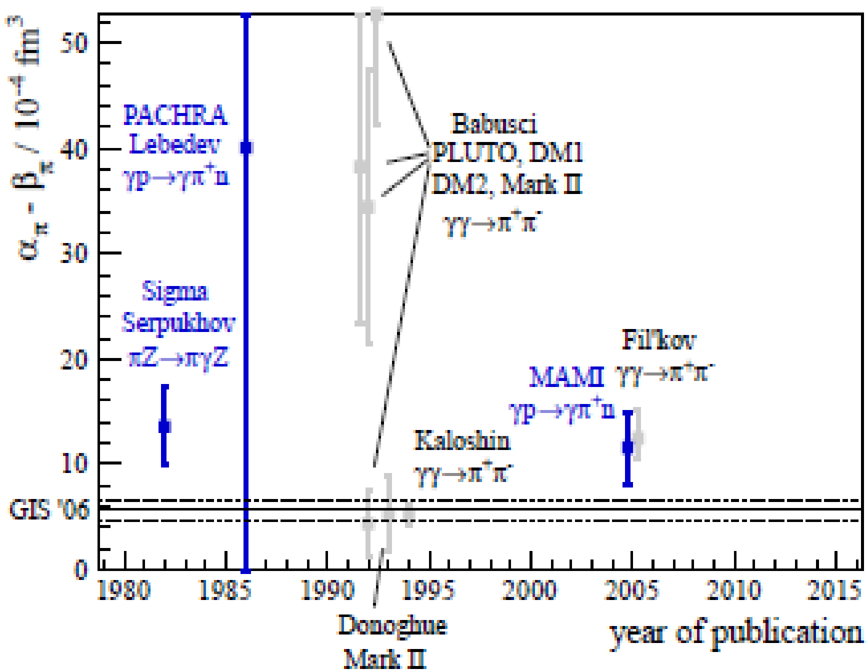
Primakoff process

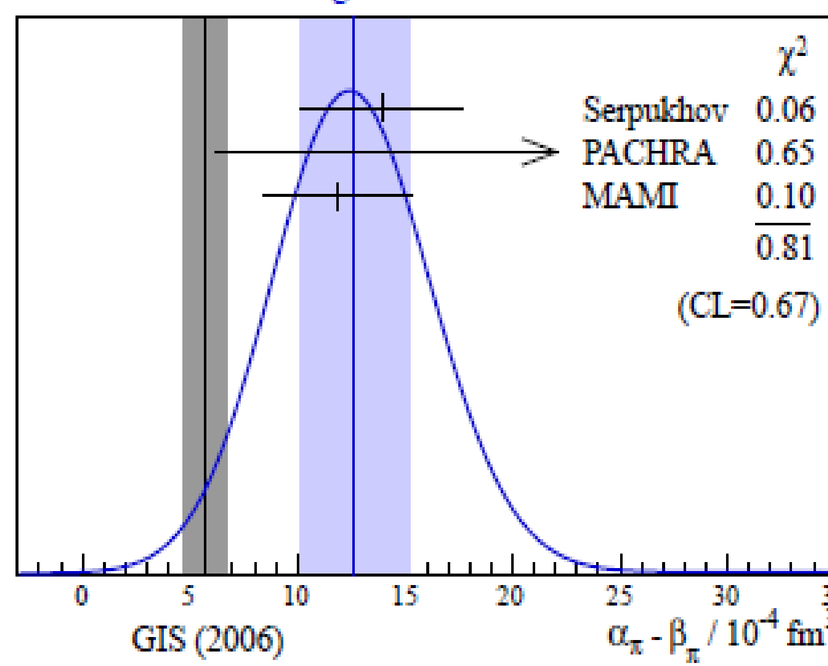


Radiative pion photoproduction



Photon-Photon fusion





GIS'06: ChPT prediction, Gasser, Ivanov, Sainio, NPB745 (2006)

plots from Thiemo Nagel, PhD thesis, TUM 2012

NA58 experiment at CERN SPS

COmmon
Muon and
Proton
Apparatus for
Structure and
Spectroscopy

20 Institutes/11 counties/~230 physicists

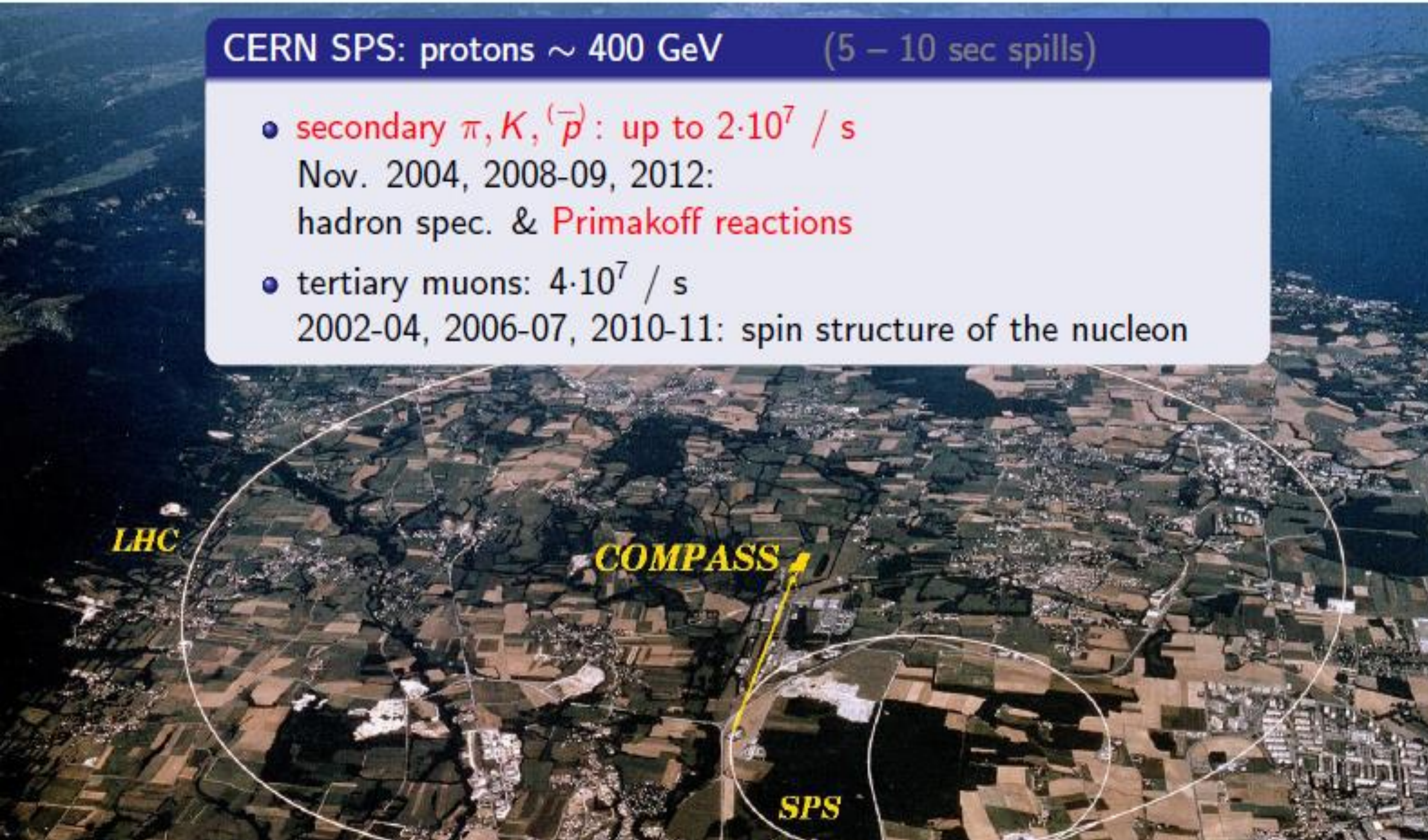
Czech Republic, Finland, France, Germany, India, Israel, Italy, Japan, Poland, Portugal and Russia

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

COmmon Muon and Proton Apparatus for Structure and Spectroscopy

CERN SPS: protons $\sim$ 400 GeV (5 – 10 sec spills)

- secondary $\pi, K, \overset{(-)}{p}$: up to $2{\cdot}10^7$ / 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

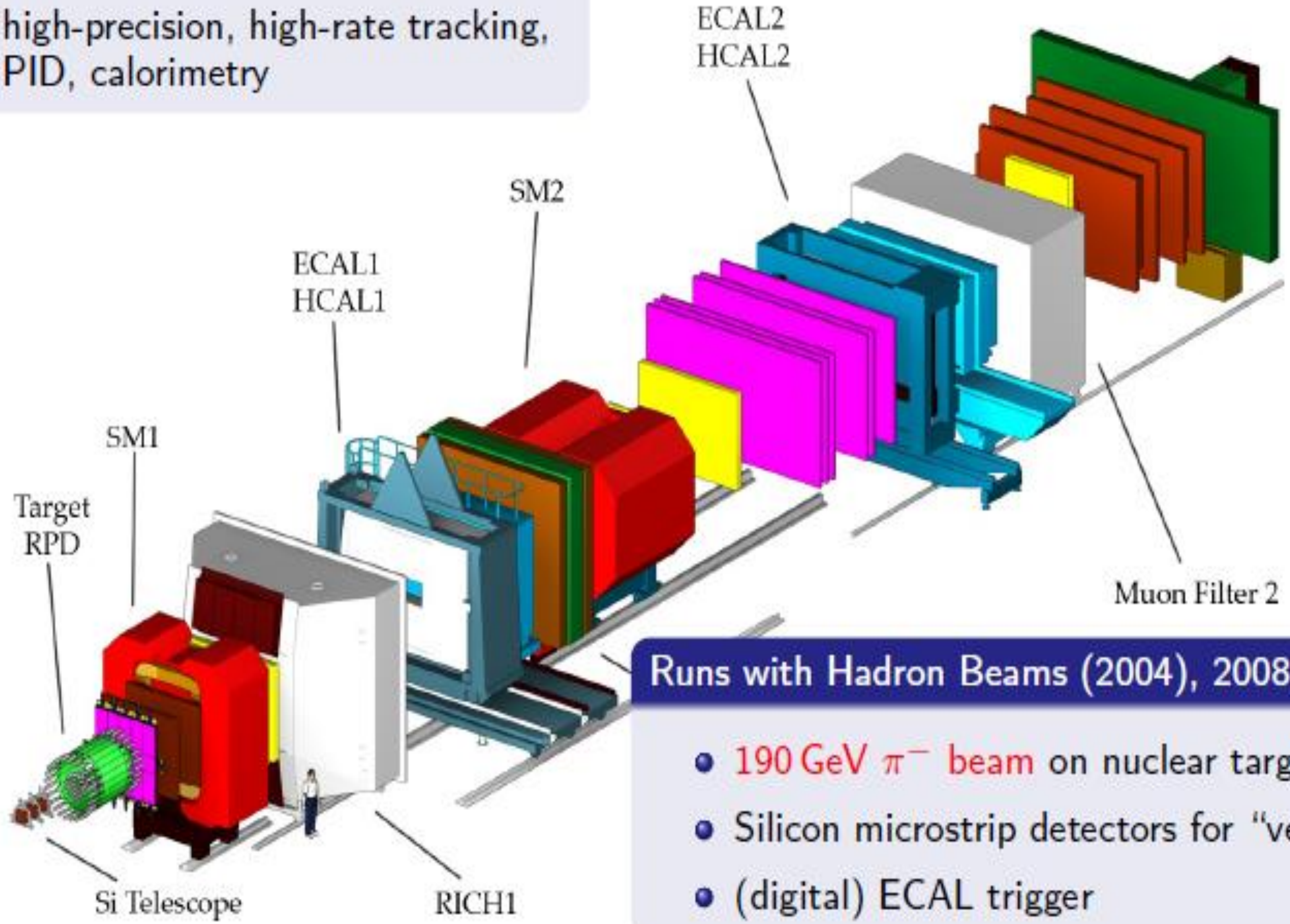


COMPASS

Experimental Setup

Fixed-target experiment

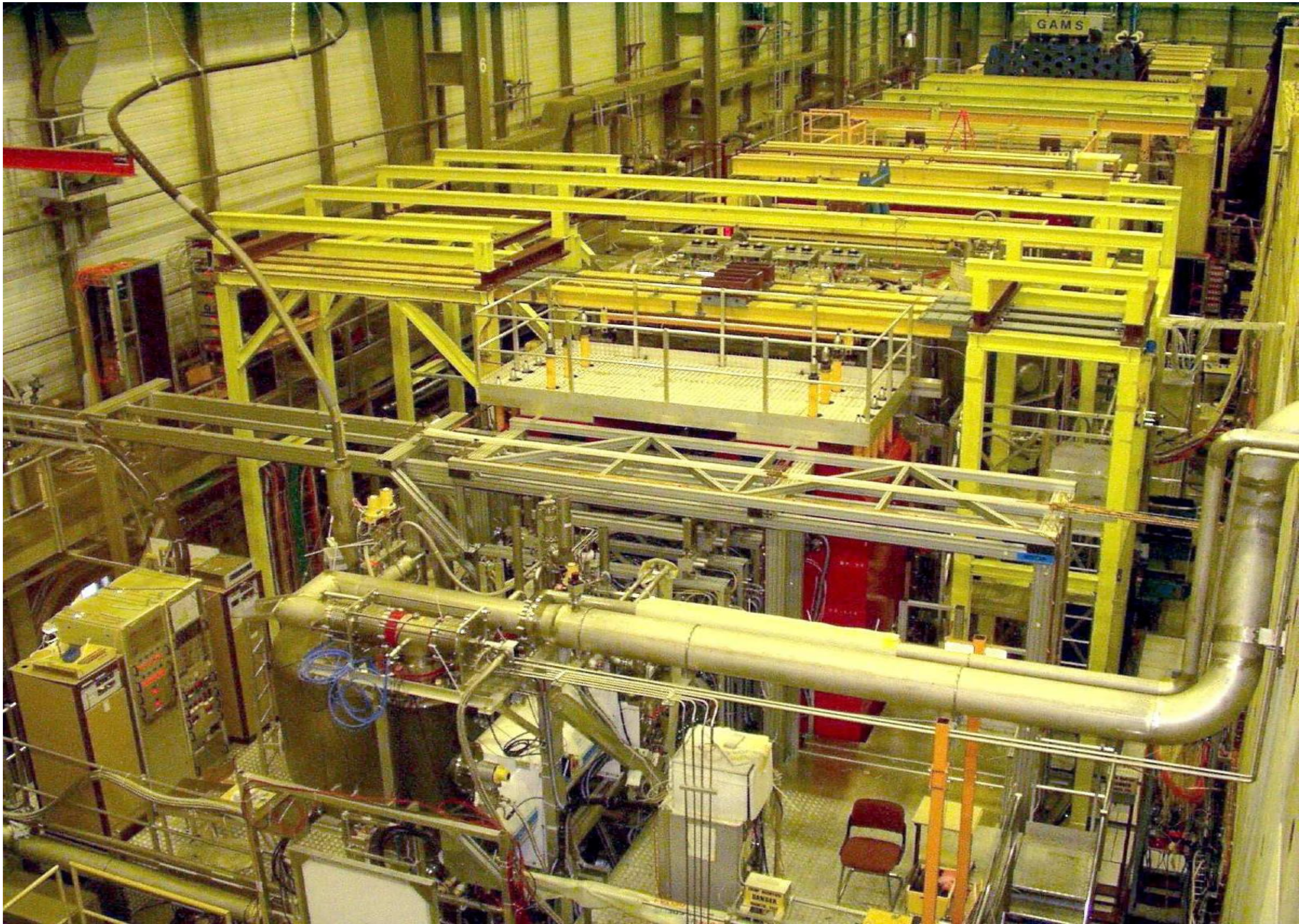
- two-stage magnetic spectrometer
- high-precision, high-rate tracking, PID, calorimetry



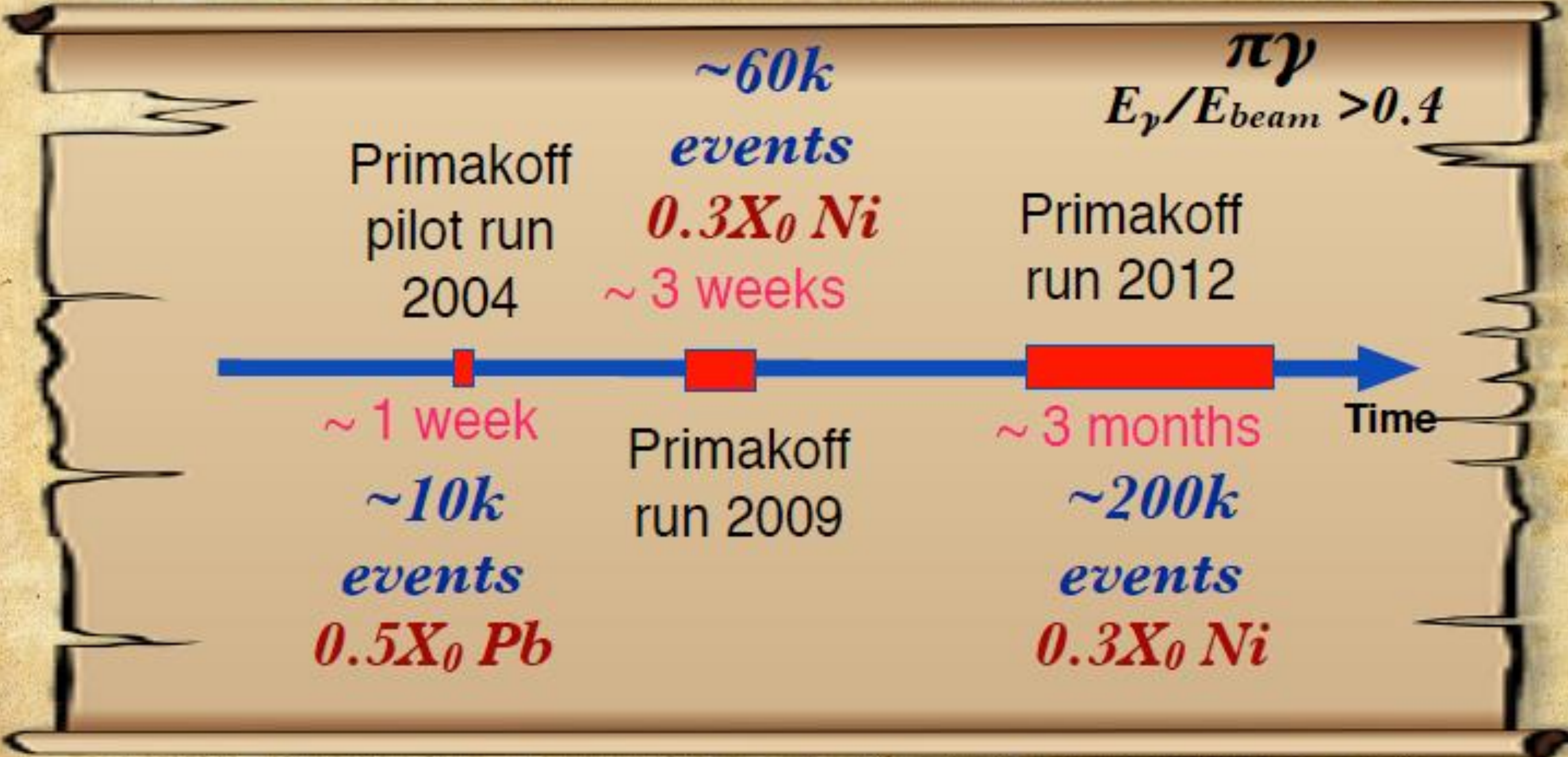
Runs with Hadron Beams (2004), 2008/09, 2012

- 190 GeV π^- beam on nuclear targets (Ni, W)
- Silicon microstrip detectors for "vertexing"
- (digital) ECAL trigger

The Compass Spectrometer



Pion polarizabilities at COMPASS



- *Precise silicon detectors to measure small scattering angles*
- *Electromagnetic calorimeter with good energy and spacial resolution for photon detection*
- *Calorimeter-based trigger on hard photon(s) in the final state*
- *Possibility to use hadron and muon beams with the same momentum 190 GeV/c*

Principle of the polarisability measurement

- 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.

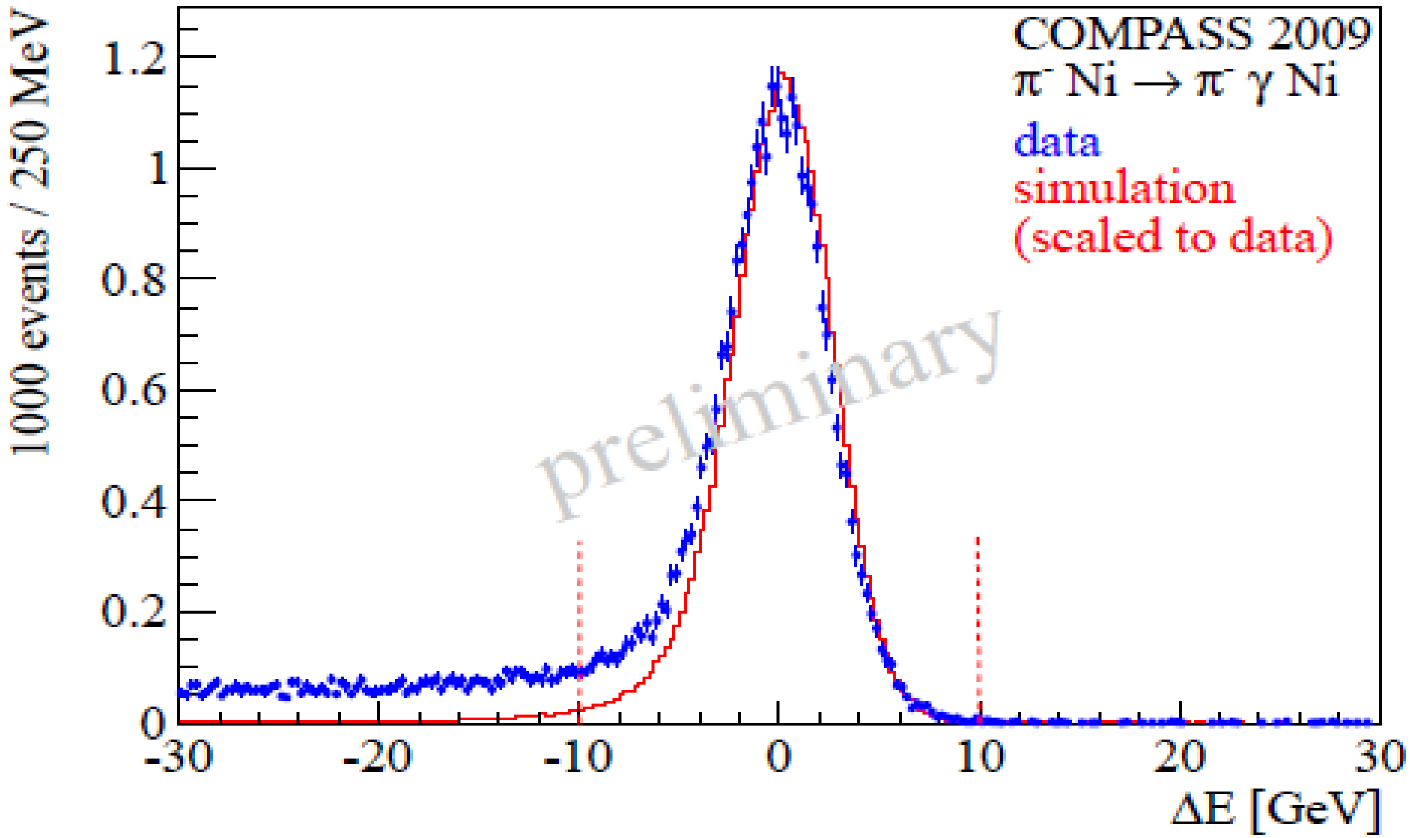
- Control systematics by

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

  and

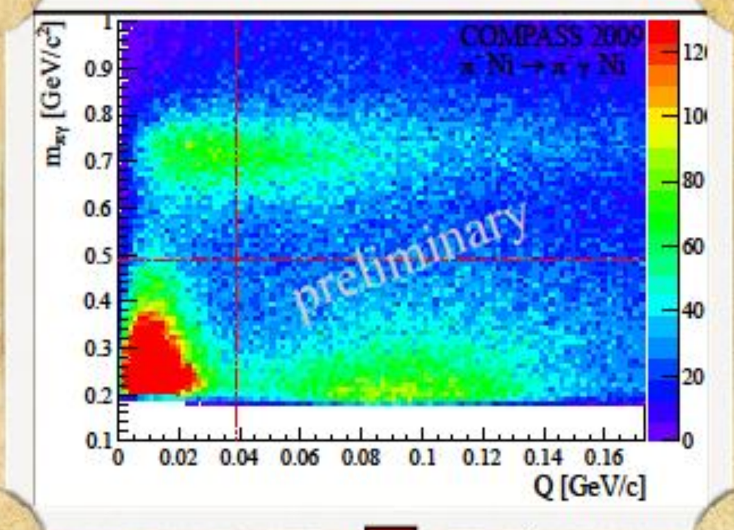
  $$K^- \to \pi^-\pi^0 \to \pi\gamma\gamma$$

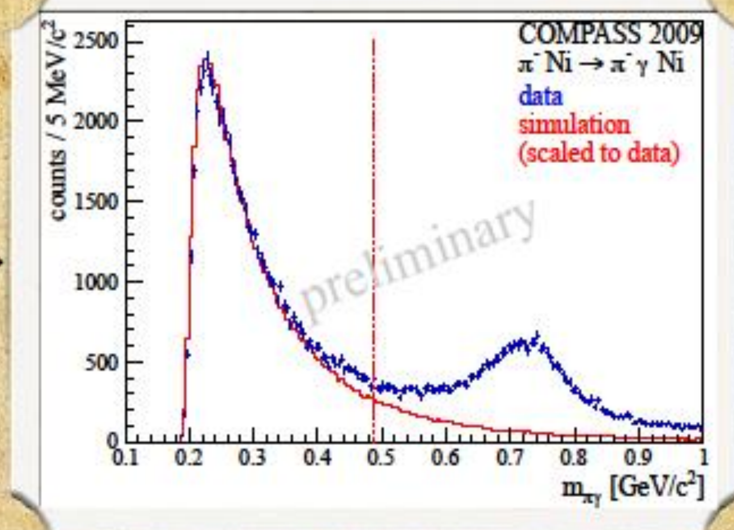
Identifying the $\pi\gamma \to \pi\gamma$ reaction

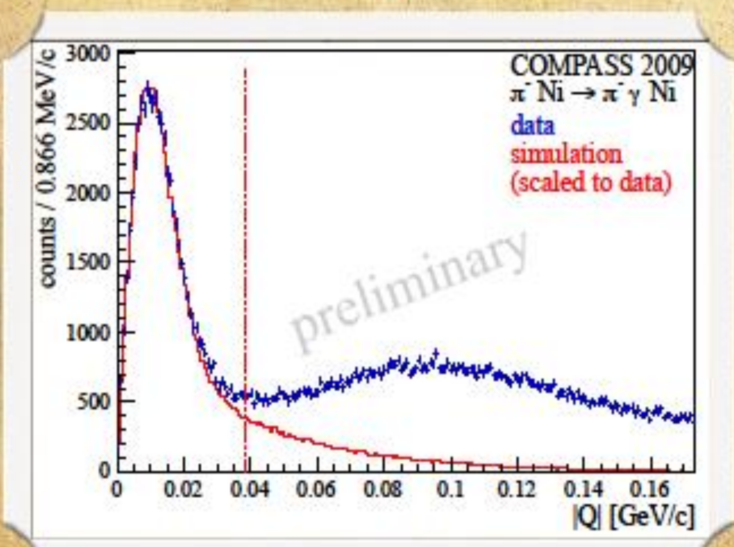


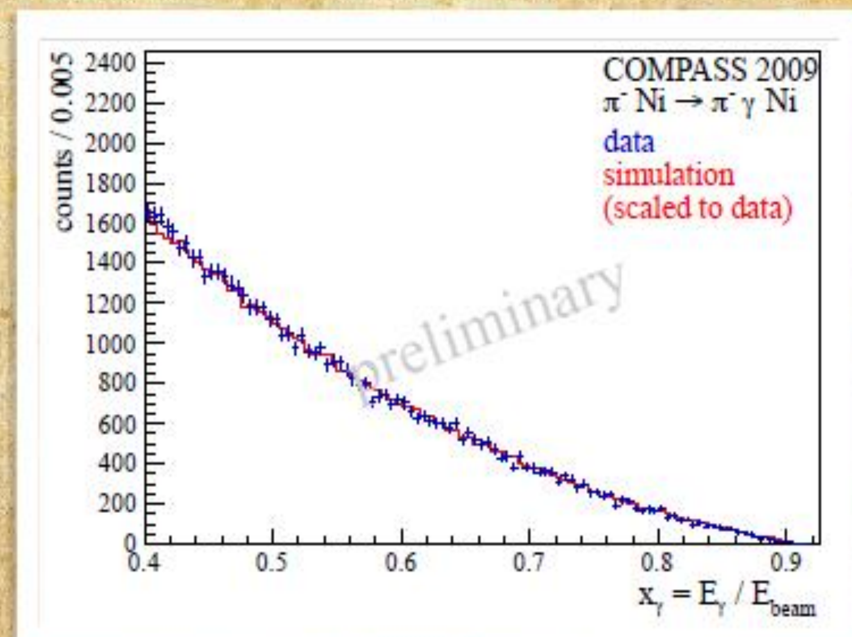
- Energy balance $\Delta E = E_\pi + E_\gamma - E_{\text{Beam}}$
- Exclusivity peak $\sigma \approx 2.6$ GeV
- $\sim$ 30.000 exclusive events (Serpukhov $\sim$ 7000)

Pion polarizabilities at COMPASS

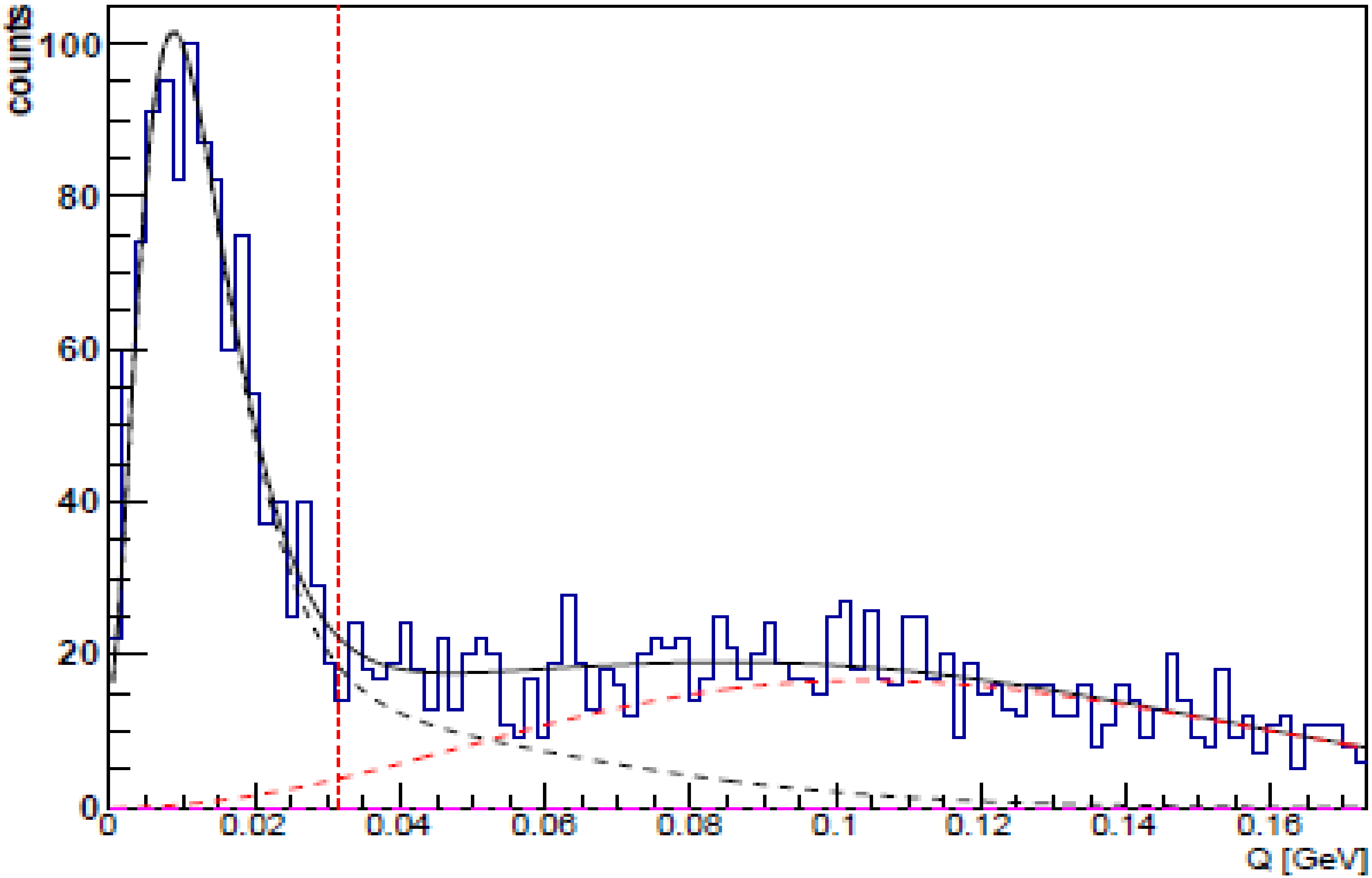








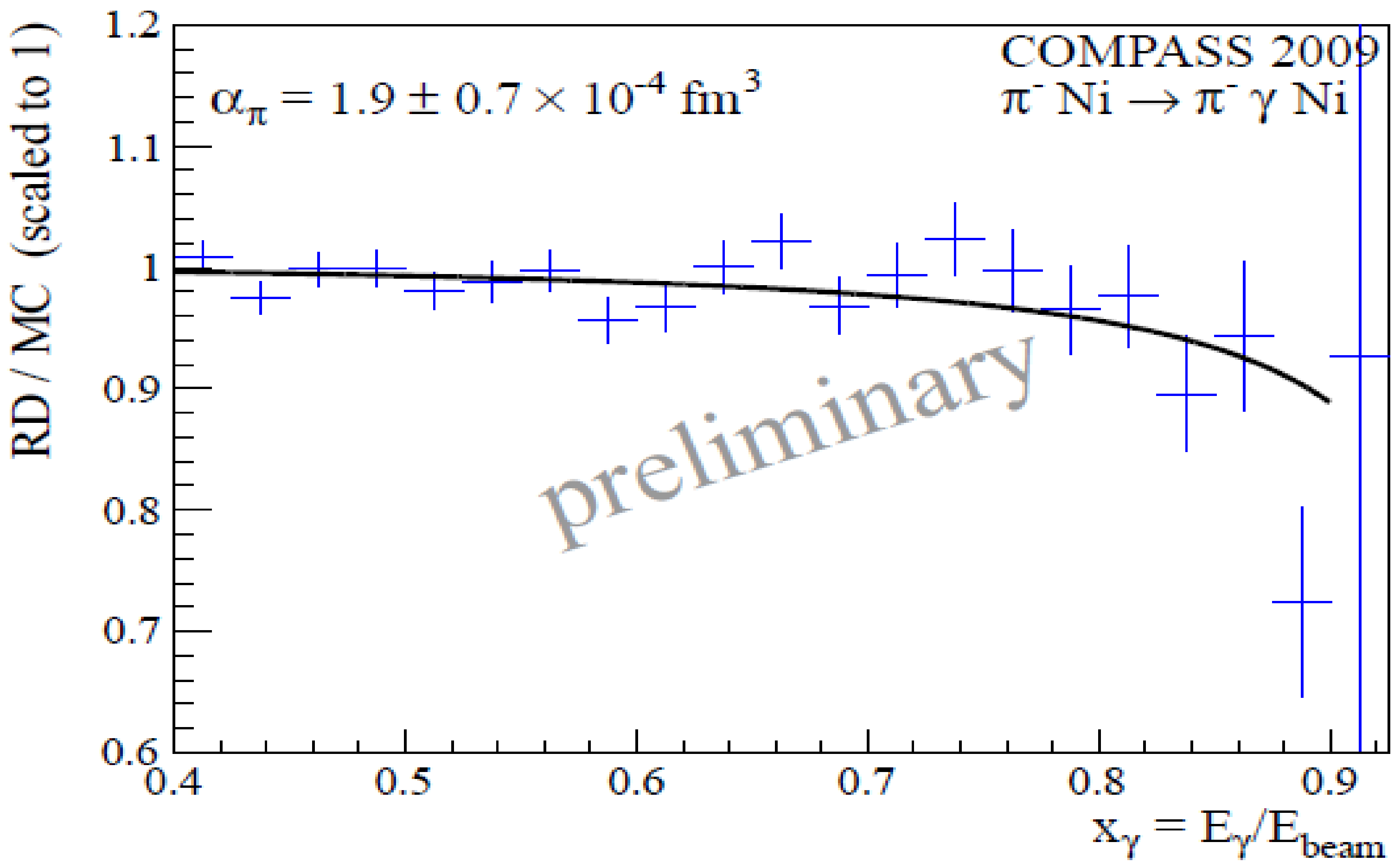
subtraction of strong and π^0 backgrounds



signal: $a_1 Q^2 e^{-b_1 Q} + a_2 e^{-b_2 Q^2}$

strong background: $a_3 Q^2 e^{-c Q^2}$

Pion polarisability – preliminary COMPASS result



Fit to the x_γ distribution of the ratio of Real Data (RD) to a Monte Carlo (MC) simulation (with zero polarizabilities), giving best value $\alpha_\pi=(1.9\pm0.7)\cdot10^{-4}$fm^3.

COMPASS

pion polarizability

2009 preliminary

determined under $\alpha_\pi + \beta_\pi = 0$ assumption:

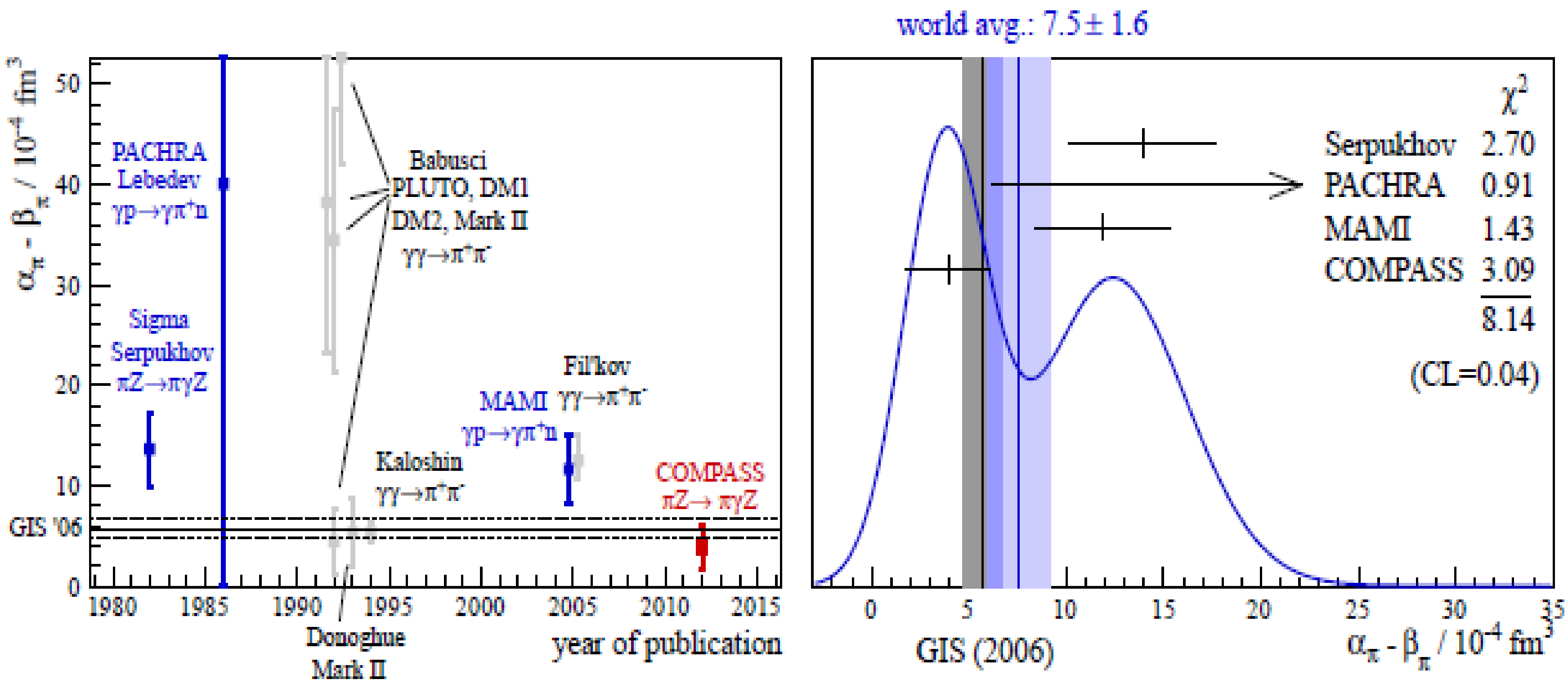
preliminary result

$$\alpha_\pi = 1.9 \pm 0.7_{\text{stat.}} \pm 0.8_{\text{syst.}} \times 10^{-4}\,\text{fm}^3$$

systematic error

description	estimated magnitude CL = 68 % $[10^{-4}\,\text{fm}^3]$
tracking	0.6
radiative corrections	0.3
background subtraction in Q	0.4
pion electron scattering	0.2
quadratic sum	0.8

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

COMPASS

2009

COMPASS preliminary result for pion polarizability is the most precise among dedicated measurements

Pion polarizabilities at COMPASS

>200k of $\pi\gamma$ events with $E_\gamma / E_{beam} > 0.4$

COMPASS

2012

Primakoff data collected in 2012 provide possibility:

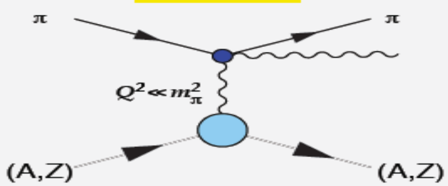
- to reduce uncertainty of α_π measurement to $\sim 0.3 \times 10^{-4}\ fm^3$ (χPT: 5.7)
- to measure $\alpha_\pi + \beta_\pi$ with accuracy $\sim 0.03 \times 10^{-4}\ fm^3$ (χPT: 0.16)
- to access quadrupole polarizabilities of pion $\alpha_{\pi 2}$ and $\beta_{\pi 2}$
- to study dynamics of pion polarizabilities $\alpha_\pi = \alpha_\pi(s,t,\ldots)$

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: $\pi + Z \rightarrow \pi + Z + \gamma$. COMPASS data analysis gives a value: $\alpha_\pi = -\beta_\pi = (1.9 \pm 0.7_{stat.} \pm 0.8_{syst.}) \times 10^{-4}\ fm^3$. 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.

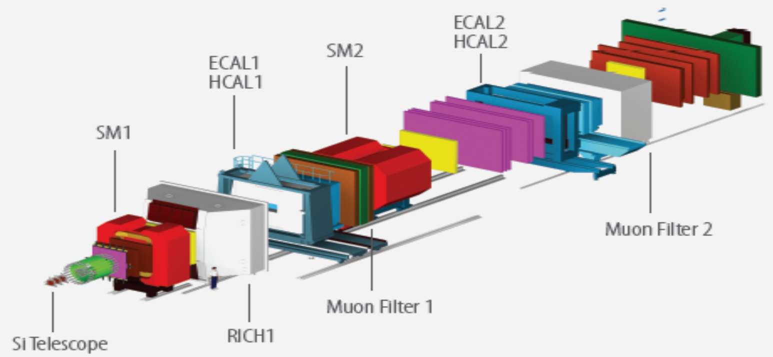
Primakoff Process



- Identify $\pi\, Ni \rightarrow \pi\, Ni\, \gamma$ 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 $\mu\, Ni \rightarrow \mu\, Ni\, \gamma$, $K^- \rightarrow \pi^- \pi^0$



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- 190 GeV π^- beam on nuclear targets
- Tracking: SMD for vertexing
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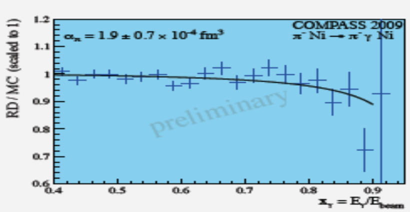
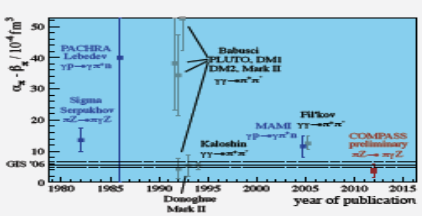
Fixed-target experiment

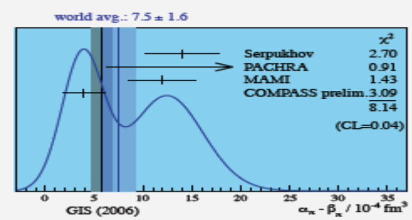
- Two-stage magnetic spectrometer
- High-precision, high-rate tracking, PID, calorimetry



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 $\alpha_\pi - \beta_\pi = (5.7 \pm 1.0) \times 10^{-4}$ fm^3



PDG style ideogram of polarizability data