Pion polarisability: a new measurement by the COMPASS Collaboration at CERN

"CERN experiment brings precision to a cornerstone of particle physics"

Barbara Badełek
University of Warsaw

High Energy Physics Seminar

Warsaw, 27 .III. 2015

(based on COMPASS materials and conference talks; special thanks to J.Friedrich)

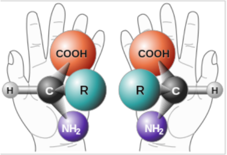
Introduction: Chiral Perturbative theory, χPT (in a nutshell)

- An object/system is chiral (Greek: $\chi\epsilon\iota\rho$/kheir $\equiv$ hand) if it is not identical with its mirror image (it cannot be superposed onto it), i.e. human hands. Conversely: achiral object (e.g. a sphere).

- First used in 1893 by Lord Kelvin.

- Enantiomorphs (-mers).

- Chirality (or handedness) in spin: chirality $\equiv$ helicity for massless objects



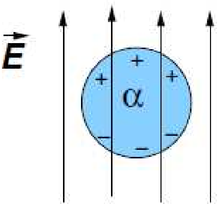
- QCD Lagrangian chiral symmetric in the limit $m_{\mathrm{u,d,s}} \to 0$. Explicit breaking of chiral symmetry $\Longrightarrow$ treated perturbatively; 8 light pseudo-Goldstone bosons: π, K, η.

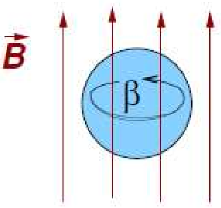
- Low-energy effective field theory with same symmetries as QCD; hadrons as fundamental degrees of freedom.

Definitions

Electromagnetic structure of a bound state

- total charge,
- charge distribution (radius, form factor),
- dipole (and higher order) polarisabilities: α, β





$$\vec{P} = \epsilon_0 \kappa \vec{E} = \alpha \vec{E} \qquad \vec{J} = \chi \vec{H} = \beta \vec{H} \approx \beta \frac{\vec{B}}{\mu_0}$$

- α, β measured in m^3 (fm^3)

Measurement of polarisabilities

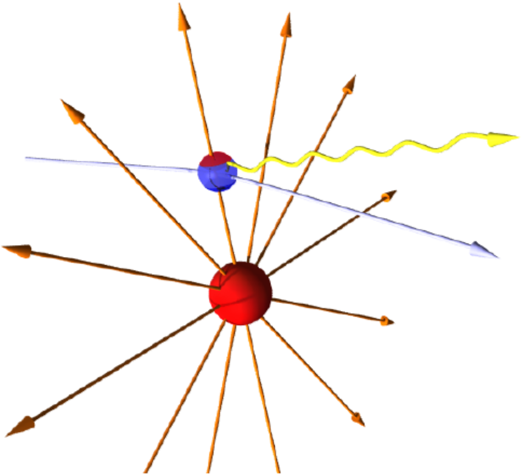
- For an extended object they are related to inner forces determinig the substructure $\longrightarrow$ QCD at low energy
- Lightest QCD bound state, the pion π, is of special interest
- Easiest way of polarisability determination:
  Compton scattering off an object; $\longrightarrow$ used for the proton
- In case of π ? The most direct method (exp. and th.) given by Primakoff (1951), originally for the $\pi^0 \to \gamma\gamma$ lifetime:
  using the electric field close to a nucleus as a source of quasi-real γ.
- Polarisabilities measured through modifications of the *bremsstrahlung* (or Primakoff) reaction: $\pi^- Z \to \pi^- \gamma Z$

Primakoff method of measuring $\pi\gamma \to \pi\gamma$

- Charged pion traversing the nuclear electric field
  - typical field strength at $r = 5R_{Ni}$: $E \sim 300\,\text{kV/fm}$

- Bremsstrahlung emission
  - particle scatters off *equivalent photons*
  - tiny momentum transfer $Q^2 \approx 10^{-5}\,\text{GeV}^2/c^2$
  - pion/muon (quasi-)real Compton scattering

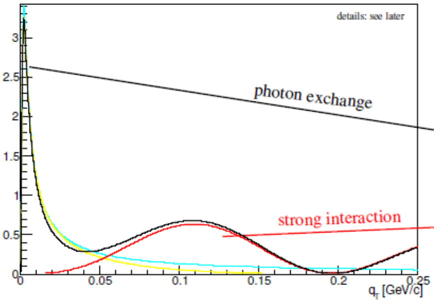
- Polarisability contribution
  - Compton cross-section typically diminished
  - expected charge separation $\sim 10^{-5}\,\text{fm} \cdot e$

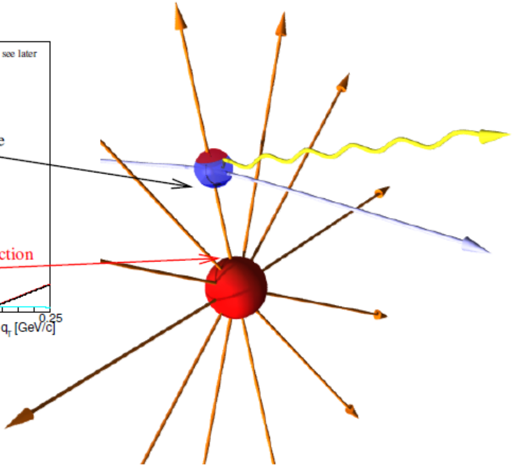


J. Friedrich, St. Petersburg, 2014

Primakoff method of measuring $\pi\gamma \to \pi\gamma$,... cont'd

- Charged pion traversing the nuclear electric field
  - typical field strength at





typically diminished

  - expected charge separation $\sim 10^{-5}$ fm $\cdot e$

J. Friedrich, St. Petersburg, 2014 (calculations: Fäldt, Tengblad, Phys.Rev. C **79** 0146607 + Erratum *ibid.* **87** 029903)

Cross section for the π Compton scattering

- π–Z reactions at very low $|Q|$ have a large component from (almost) real γ exchange; competes with strong interactions.
- In the Equivalent-photon Approximation (EPA) the $\sigma_{\pi Z}$ factorises into $\sigma_{\pi\gamma}$ and density of (quasi-real) photons provided by Z:

$$\frac{\mathrm{d}\sigma^{\mathrm{EPA}}_{\pi \mathrm{Z}}}{\mathrm{d}s\mathrm{Q}^2\mathrm{d}\Phi_n} = \frac{Z^2\alpha}{\pi(s-m_\pi^2)} F^2(Q^2)\frac{Q^2-Q^2_{\mathrm{min}}}{Q^4}\frac{\mathrm{d}\sigma_{\pi\gamma}}{\mathrm{d}\Phi_n}$$

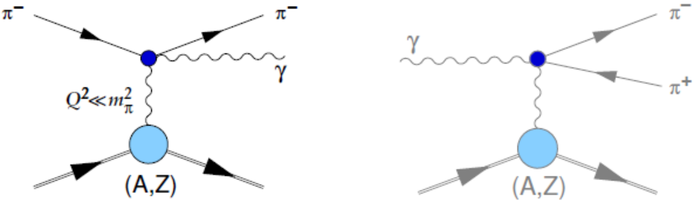
- At linear order:

$$\frac{\mathrm{d}\sigma_{\pi\gamma}}{\mathrm{d}\Omega} = \left(\frac{\mathrm{d}\sigma_{\pi\gamma}}{\mathrm{d}\Omega}\right)_{\mathrm{Born}} - \frac{\alpha m_\pi^3(s-m_\pi^2)^2}{4s^2(sz_+ + m_\pi^2 z_-)} \cdot \left(z_-^2(\alpha_\pi - \beta_\pi) + \frac{s^2}{m_\pi^4} z_+^2(\alpha_\pi + \beta_\pi)\right)$$

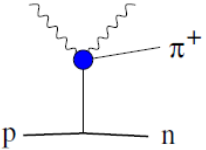
$$z_\pm = 1 \pm \cos\theta_{\mathrm{cm}}, \qquad \alpha \approx 1/137.04$$

(+ further multipole polarisabilities...)

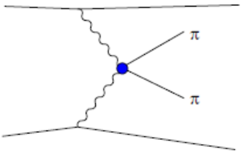
Compton scattering off the pion, $\pi\gamma \to \pi\gamma$: embedding the process



Primakoff processes



Radiative pion photoproduction



Photon-Photon fusion

J. Friedrich, St. Petersburg, 2014

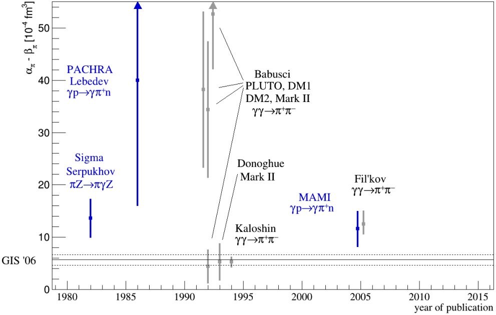
Predictions and world data prior to COMPASS

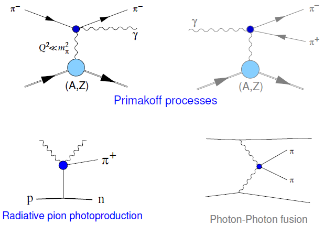
- Two-loop χPT calculations by Gasser, Ivanov, Sainio, Nucl. Phys. B**745** (2006) 84 (GIS)

$$\left.\begin{aligned}\alpha_\pi - \beta_\pi &= 5.7 \pm 1.0\\ \alpha_\pi + \beta_\pi &= 0.16\end{aligned}\right\} \Longrightarrow \begin{aligned}&\alpha_\pi = 2.93, \qquad \beta_\pi = -2.77\\ &(\text{assume}: \quad \beta_\pi \approx -\alpha_\pi)\end{aligned}$$

(polarisabilities in units of 10^{-4} fm ^{3})

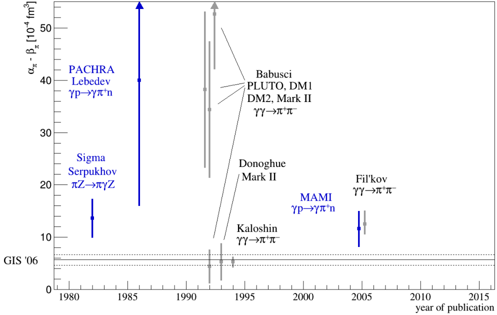
- World data prior to COMPASS

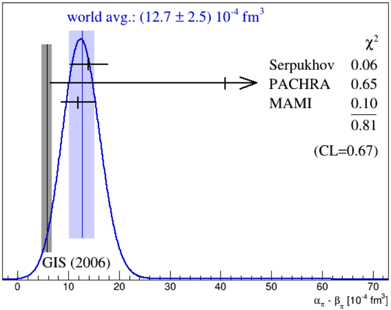




Plot: T. Nagel, PhD TUM, 2012; diagrams: J. Friedrich, St. Petersburg, 2014

Predictions and world data prior to COMPASS,...cont'd





T. Nagel, PhD TUM, 2012

COmmon Muon and Proton Apparatus for Structure and Spectroscopy

NA58, at the CERN SPS
$\sim$ 250 physicists
$\sim$ 30 institutes

COMPASS – past and future

- Located at CERN North Area beam line
  - Possible beams: μ^+, μ^-, π^+, π^-, K $\rightarrow$ Several physics programs
- Experiments with muon beam
- Experiments with hadron beams

COMPASS - I (2002 – 2011)

Experiments with muon beam:

- Spin structure, Gluon polarization
- Flavor decomposition
- Transversity
- Transverse Momentum-dependent PDF

Experiments with hadron beams:

- Pion polarizability
- Diffractive and Central production
- Light meson spectroscopy
- Baryon spectroscopy

COMPASS - II (2012 – 2017)

Experiments with muon beam:

- DVCS and HEMP
- Unpolarized SIDIS and TMDs

Experiments with hadron beams:

- Pion and Kaon polarizabilities
- Drell-Yan studies

A.Bressan, "POETIC V", 2014

COMPASS – past and future, ...cont'd

- Located at CERN North Area beam line
  - Possible beams: μ^+, μ^-, π^+, π^-, K → Several physics programs

- Experiments with muon beam
- Experiments with hadron beams

COMPASS - I (2002 – 2011)

- Spin structure
- p, d polarized target (L & T)

- Hadron spectroscopy
- Small LH_2 or nuclear targets

COMPASS - II (2012 – 2017)

- DVCS/Unpol SIDIS
- Long LH_2 target

- Drell-Yan studies
- Polarized target (T)

Reconfigurable target region - versatile experimental setup!

A.Bressan, "POETIC V", 2014

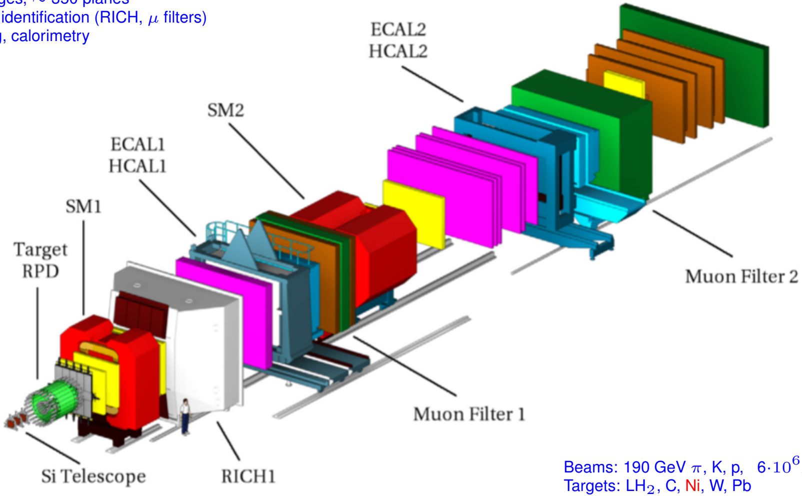
COMPASS II: tentative time table

- 2012 setup and tests: Primakoff 18 weeks, GPD 6 weeks
- 2013 SPS shutdown;
  polarised target movement and installation
- 2015 Drell-Yan, NH_3 target, $\perp$ polarised protons
- 2016
  – 2017 GPD (Phase 1) and SIDIS on liquid H_2 target
- $\geq$ 2017 Addendum ? Will comprise: D-Y, GPD with $\perp$ polarised protons (Phase 2), hadron programme.

COMPASS spectrometer for hadronic beams

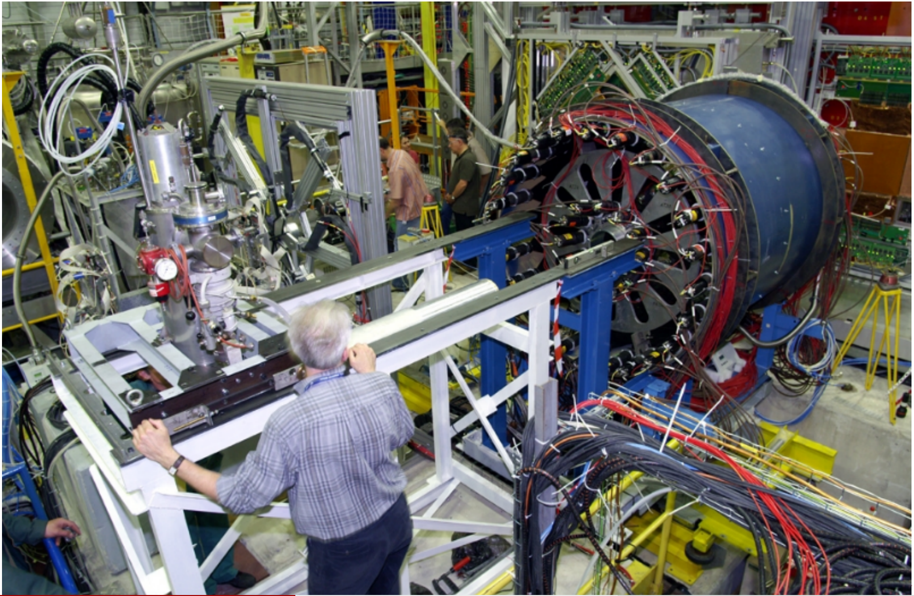
COMPASS, P. Abbon *et al.* NIM A **779** (2015) 69

Two stages, $\sim$ 350 planes
Particle identification (RICH, μ filters)
Tracking, calorimetry

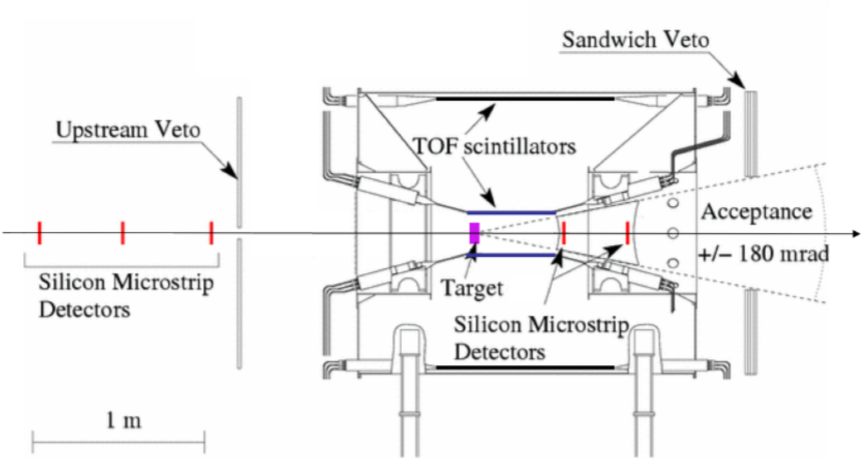


Beams: 190 GeV π, K, p, $6 \cdot 10^6$/s
Targets: LH_2, C, Ni, W, Pb
Silicon microstrips for vertex

LH_2 being inserted to RPD

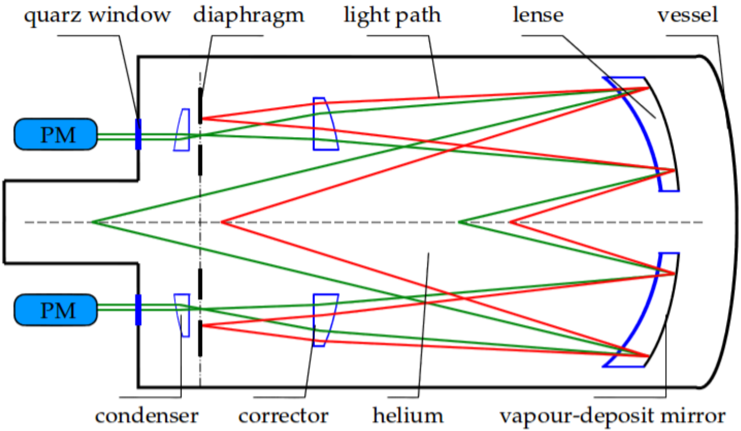


Target region



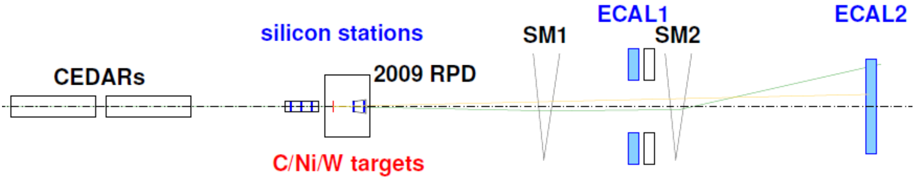
CEDAR to select pions (96.8%) in the beam

(ChErenkov Differential counter with Achromatic Ring focus)



P. Jasiński, PhD, Mainz, 2012

Principle of measurement (2009 data, 4mm Ni target)

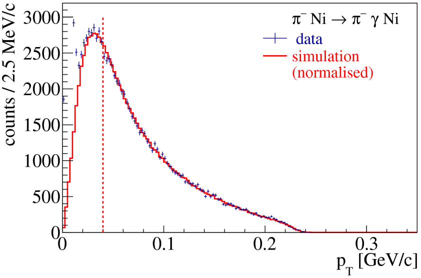


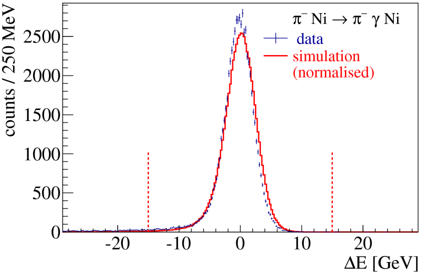
Event selection criteria:

J. Friedrich, St. Petersburg, 2014

- Trigger: (energy deposit of $>$ 70 GeV in ECAL2) AND incoming particle (π/μ)
- incident π^-, outgoing exactly one π^-, common interaction point
- exactly one energy cluster $>$ 2 GeV, NOT attributed to a charged particle $\rightarrow \gamma$
- only events with $p_T >$ 40 MeV accepted
  (removes multiple scattered outgoing π^- and e^-Ni $\rightarrow e^-\gamma$Ni, $\quad (e^- \equiv e^-_{\text{beam}})$
- energy balance in the reaction must be $|\Delta E| <$ 15 GeV,
  $\Delta E = E_\pi + E_\gamma - E_{\text{beam}}$ ($\Delta E_{\text{cal}} \sim 3$ GeV)
- tracks crossing $X > 15X_0 \Longrightarrow$ muons

Kinematic distributions



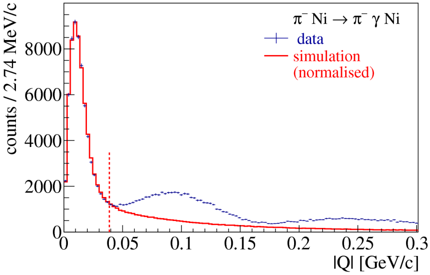


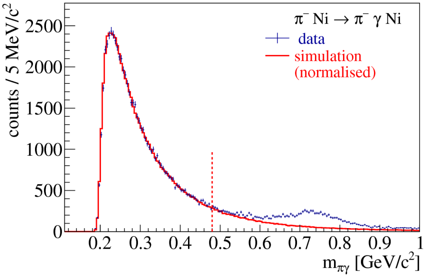
p_{T} w.r.t. incoming π

$$\Delta E = E_\pi + E_\gamma - E_{\mathrm{beam}}$$

Exclusivity peak $\sigma \approx$ 2.6 GeV (1.4%)

Kinematic distributions,...cont'd

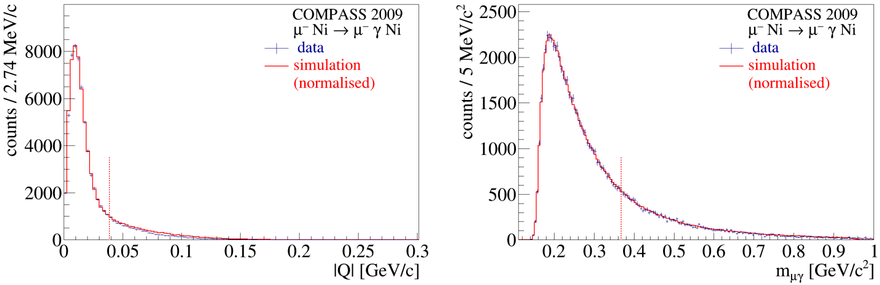




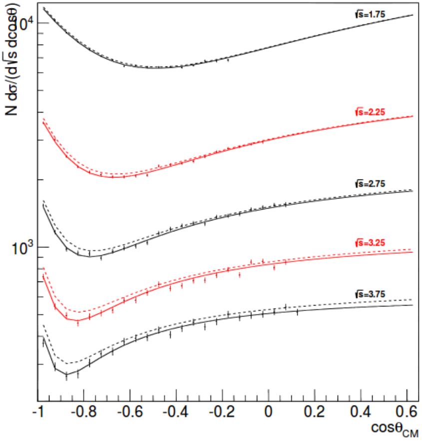
- $\sigma_{\mathrm{Q}} \approx$ 12 MeV $\approx 10 \cdot \sigma_{\mathrm{Coulomb}}$; size consistent with Z^2 (W, Si, C)
- At 190 GeV beam momentum, this requires $\sim$ few μrad angular resol.
- Accepted events with $Q^2 <$ 0.0015 GeV^2
- Background from intermediate $\rho^- \to \pi^-\pi^0$ removed by $m_{\pi\gamma} < 3.5 m_\pi$

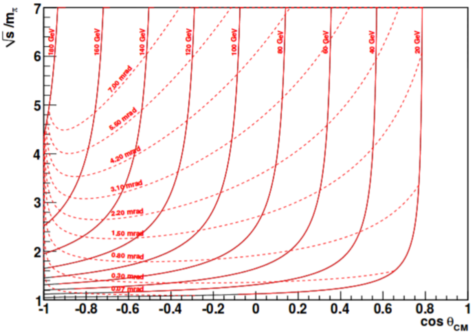
Kinematic distributions,...cont'd

Control plots for μ i.e. for pure electromagnetic interaction



Cross section and kinematics for $\pi\mathrm{Ni} \to \pi\mathrm{Ni}\gamma$





Statistics simulated for the 2012 run

(we cover -1$< \cos\theta_{\mathrm{cm}} <$ 0.15)

Final extraction

- Extract exclusive reaction $\pi^-\gamma\mathrm{Ni} \to \pi^-\gamma\mathrm{Ni}$
- For $x_\gamma^{\mathrm{lab}} = E_\gamma / E_{\mathrm{beam}}$ and assuming $\alpha_\pi + \beta_\pi = 0$ define:

$$\mathbf{R}_\pi(\mathbf{x}_\gamma) = \frac{\frac{\mathrm{d}\sigma_{\pi\gamma}}{\mathrm{d}x_\gamma}}{\frac{\mathrm{d}\sigma_{\pi\gamma}}{\mathrm{d}x_\gamma}\Big|_{\alpha_\pi=0}} = \frac{N_{\mathrm{meas}}(x_\gamma)}{N_{\mathrm{sim}}(x_\gamma)} = 1 - \frac{3}{2} \cdot \frac{m_\pi^3}{\alpha} \cdot \frac{x_\gamma^2}{1-x_\gamma}\alpha_\pi \quad \Longrightarrow \quad \alpha_\pi$$

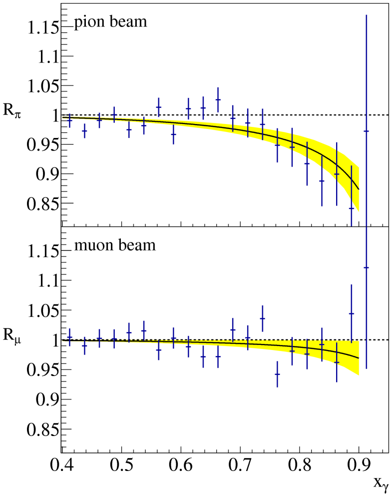
- Systematics estimated from:

$$\mu^-\gamma\mathrm{Ni} \to \mu^-\gamma\mathrm{Ni} \qquad \text{and} \qquad K^- \to \pi^-\pi^0 \to \pi\gamma\gamma \quad (K^- \equiv K^-_{\mathrm{beam}})$$

- COMPASS: about 63 000 exclusive events for 0.4$< x_\gamma <$ 0.9
  Serpukhov: about 7 000 events for $x_\gamma >$ 0.5

After J. Friedrich, St. Petersburg, 2014

x_γ distributions



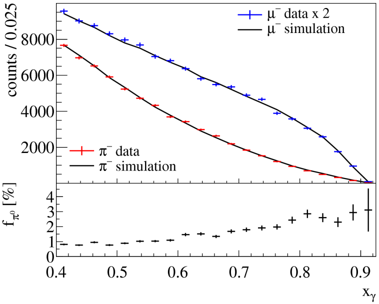


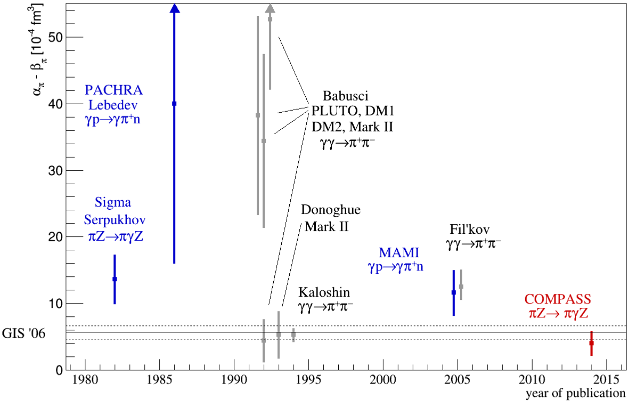
Table 1: Estimated systematic uncertainties at 68 % confidence level.

Source of uncertainty	Estimated magnitude $[10^{-4}\,\mathrm{fm}^3]$
Determination of tracking detector efficiency	0.5
Treatment of radiative corrections	0.3
Subtraction of π^0 background	0.2
Strong interaction background	0.2
Pion-electron elastic scattering	0.2
Contribution of muons in the beam	0.05
Quadratic sum	0.7

False polarisability from muon data: (0.5 ±0.5 (stat.))$\cdot 10^{-4}$ fm^3

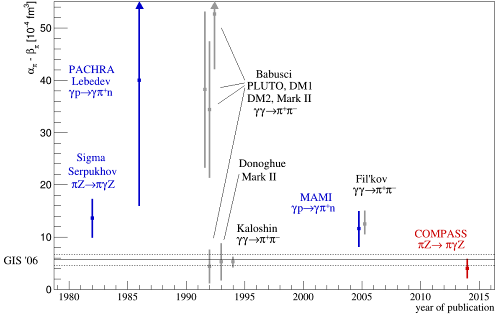
The final result for the pion polarisablity, assuming $\alpha_\pi + \beta_\pi = 0$

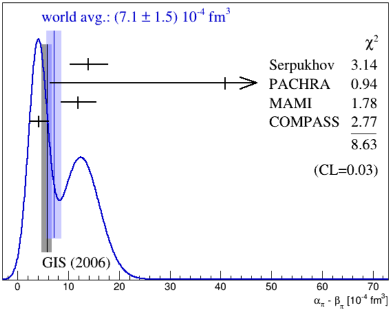
$$\alpha_\pi = (2.0 \pm 0.6 \pm 0.7) \cdot 10^{-4}\ \mathrm{fm}^3$$



COMPASS, C. Adolph *et al.* Phys. Rev. Lett. **114** (2015) 062002

Predictions and world data including COMPASS data





Plots: T. Nagel, PhD TUM, 2012

Polarisability measurements at COMPASS $\Longrightarrow$ future

via Primakoff reaction $\pi\gamma$ (Kγ)

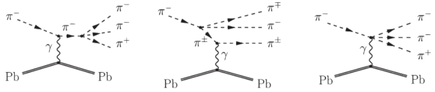
- 2004 pilot run, 1 week, 10 k events, 0.5X_0 Pb target
- 2009 3 weeks, 63 k events, 0.3X_0 Ni target
- 2012 3 months, 200–400 k events, 0.3X_0 Ni target
  - high statistics permits more extensive studies:
  - separate determination of α_π and β_π
  - quadrupole polarisabilities, α_2 and β_2
  - first measurement of the kaon polarisabilities

After J. Friedrich, St. Petersburg, 2014

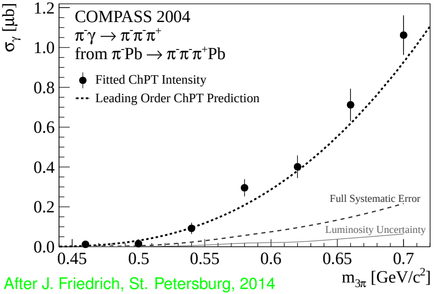
Primakoff $\pi^-\gamma$ reactions accessible at COMPASS

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

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



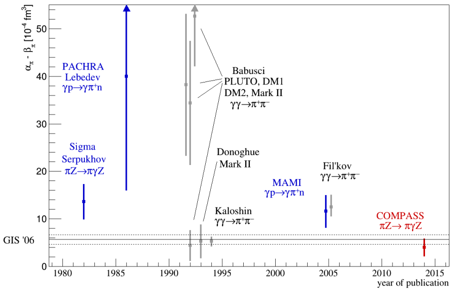
Results concerning $\pi^-\gamma \rightarrow \pi^+\pi^-\pi^-$ published in Phys.Rev.Lett. **108** (2012) 192001



After J. Friedrich, St. Petersburg, 2014

To remember ...before more precise results come

$$\alpha_\pi = (2.0 \pm 0.6 \pm 0.7) \cdot 10^{-4}\ \mathrm{fm}^3$$



COMPASS, C. Adolph *et al.* Phys. Rev. Lett. **114** (2015) 062002

One of the public statements: "...this constitutes one of the most important messages in experimental hadron physics of the past years"