Measuring the Primakoff reaction and $F_{K2\pi}$ with AMBER phase-II

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Perceiving the EHM, AMBER@CERN,
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Motivation

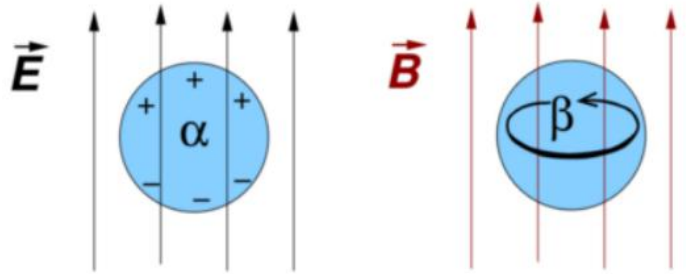
- **QCD:** extremely successful theory of strong interactions, **but** not yet possible to derive from the first principles, the **fundamental properties** of the bound states (masses, spectra)

- **Effective QCD-based models** are able to give quantitative predictions for processes at low energies *(chiral perturbation theory, quark confinement model, etc.)* → need to test applicability regions

- Simplest QCD objects: **pions & kaons** → obtain experimental results on their structure parameters → **control the applicability region** of these effective models

Polarizabilities

(Analogy from classical physics)



Interaction between **hadron** and **external electromagnetic field** described by parameters **α, β** (LO), encoding information about its internal structure

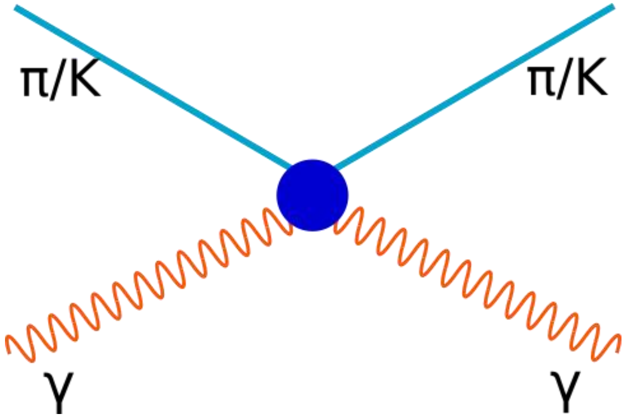
$$H_{em} = \ldots - \frac{1}{2}(\alpha \mathbf{E}^2 + \beta \mathbf{B}^2) + \ldots$$, α: electric polarizability, β: magnetic polarizability

Additional term into compton scattering cross-section:

$$\frac{d\sigma}{d\Omega_{\pi\gamma}} = \boxed{\frac{\alpha^2(s^2 z_+^2 + m_\pi^4 z_-^2)}{s(sz_+ + m_\pi^2 z_-)^2}} - \frac{\alpha m_\pi^3 (s - m_\pi^2)^2}{4s(sz_+ + m_\pi^2 z_-)}\left(z_-^2(\alpha_\pi - \beta\pi) + \frac{s^2}{m_\pi^4} z_+^2(\alpha_\pi + \beta\pi)\right)$$

point-like particle

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



How to access polarizabilities in experiment?

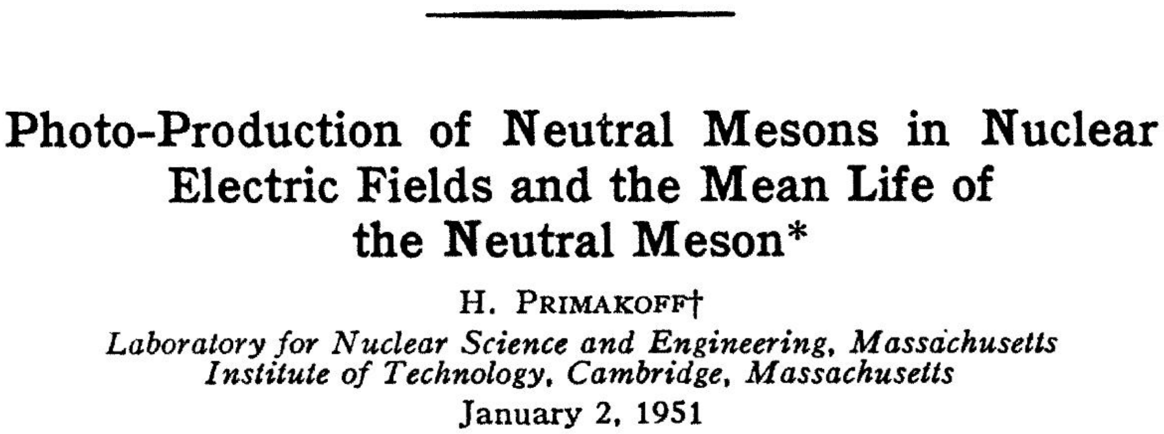


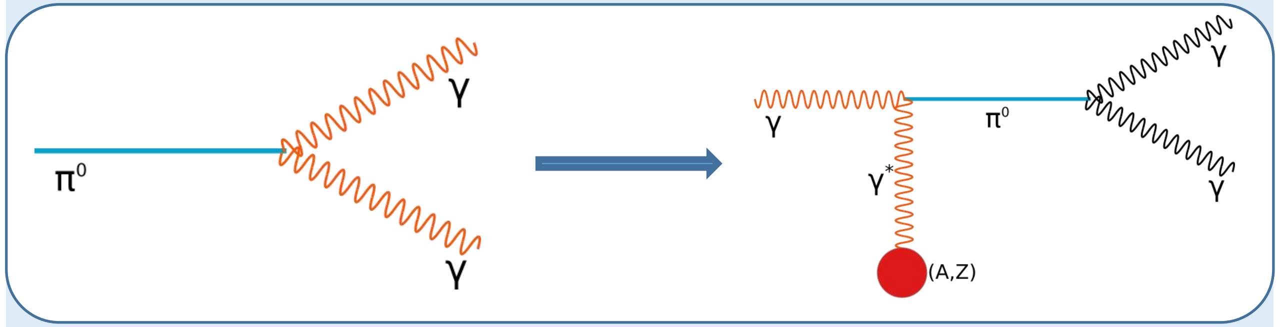
Photo-Production of Neutral Mesons in Nuclear Electric Fields and the Mean Life of the Neutral Meson*

H. PRIMAKOFF†

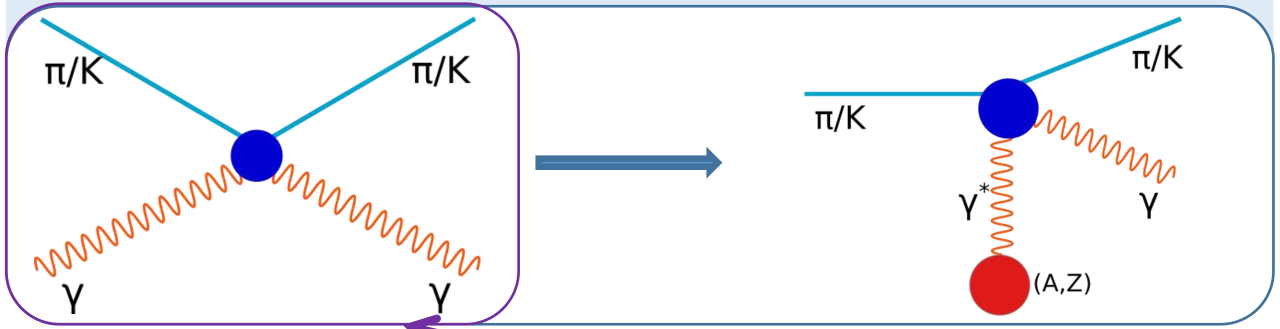
Laboratory for Nuclear Science and Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts

January 2, 1951

Initial idea of Henry Primakoff:
Electromagnetic field of nucleus = photon target!



Also applicable to compton scattering:



Scattering off equivalent photons
Assumption: $Q^2 \ll m^2_{\pi/K}$

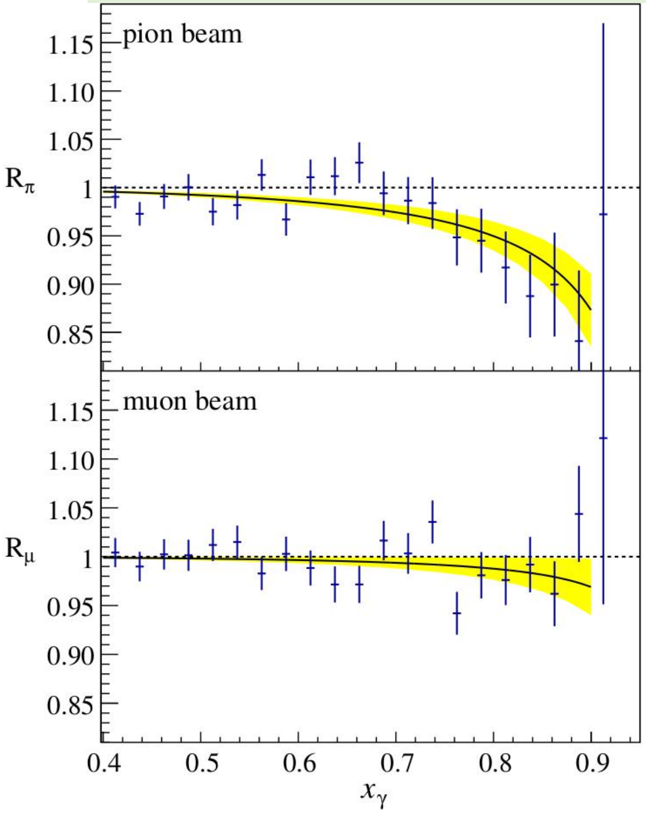
$$\frac{\mathrm{d}\sigma_{\pi^- + (Z,A)\to(Z,A)+\pi^-\gamma}}{\mathrm{d}s\mathrm{d}t\mathrm{d}Q^2} = \frac{Z^2\alpha}{\pi(s-m_\pi^2)}\cdot F_{eff}^2(Q^2)\cdot\frac{Q^2-Q^2_{min}}{Q^4}\cdot\boxed{\frac{\mathrm{d}\sigma_{\pi\gamma\to\pi\gamma}}{\mathrm{d}t}}$$

$$Q_{\rm min} = (s - m_\pi^2)/2E_{\rm beam}$$

Q is the virtual photon 4-momentum,
F(Q²) - nucleus form factor

Polarizability measurement @ COMPASS

PRL 114, 062002 (2015)



measured *simulated (α_π = 0)*

$$R_\pi = \left(\frac{d\sigma_{\pi\gamma}}{dx_\gamma}\right) \Big/ \left(\frac{d\sigma^0_{\pi\gamma}}{dx_\gamma}\right) = 1 - \frac{3}{2}\frac{m_\pi^3}{\alpha}\frac{x_\gamma^2}{1-x_\gamma}\alpha_\pi,$$

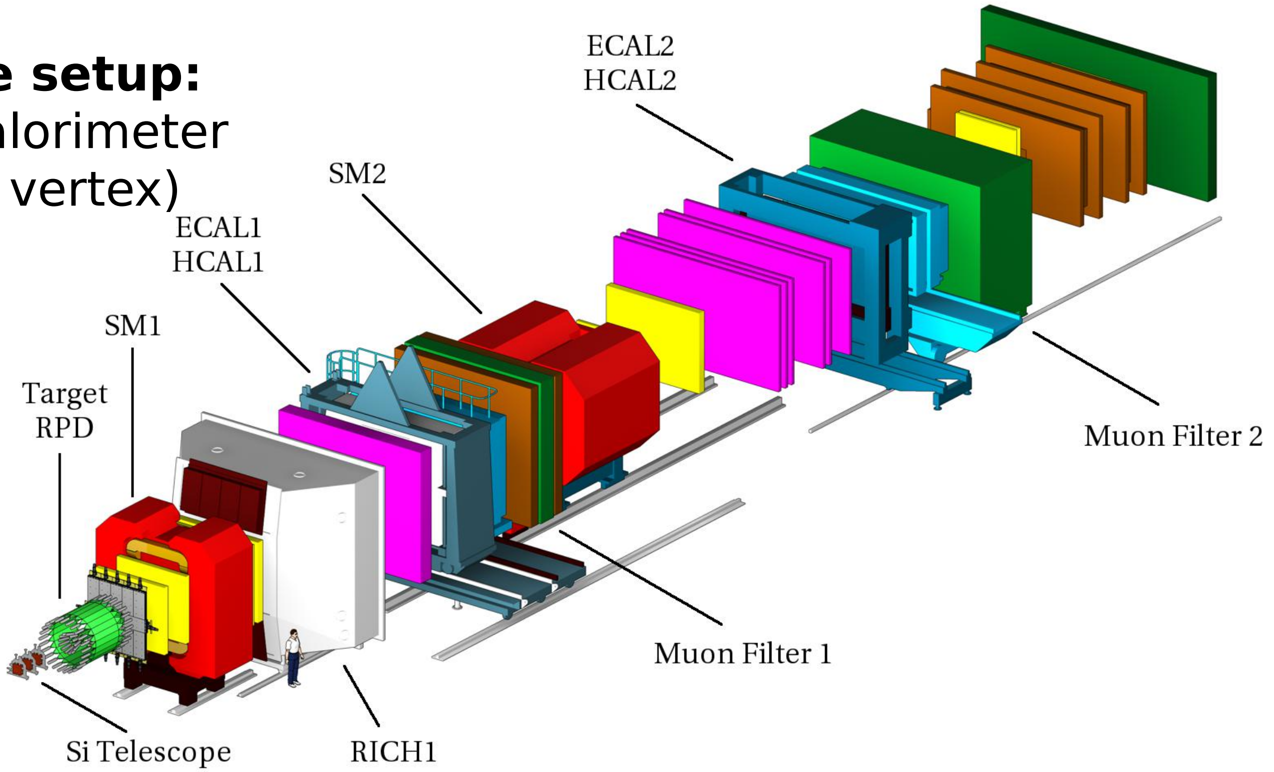
Assuming: $\alpha_\pi + \beta_\pi = 0$

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

Critical parts of the setup:

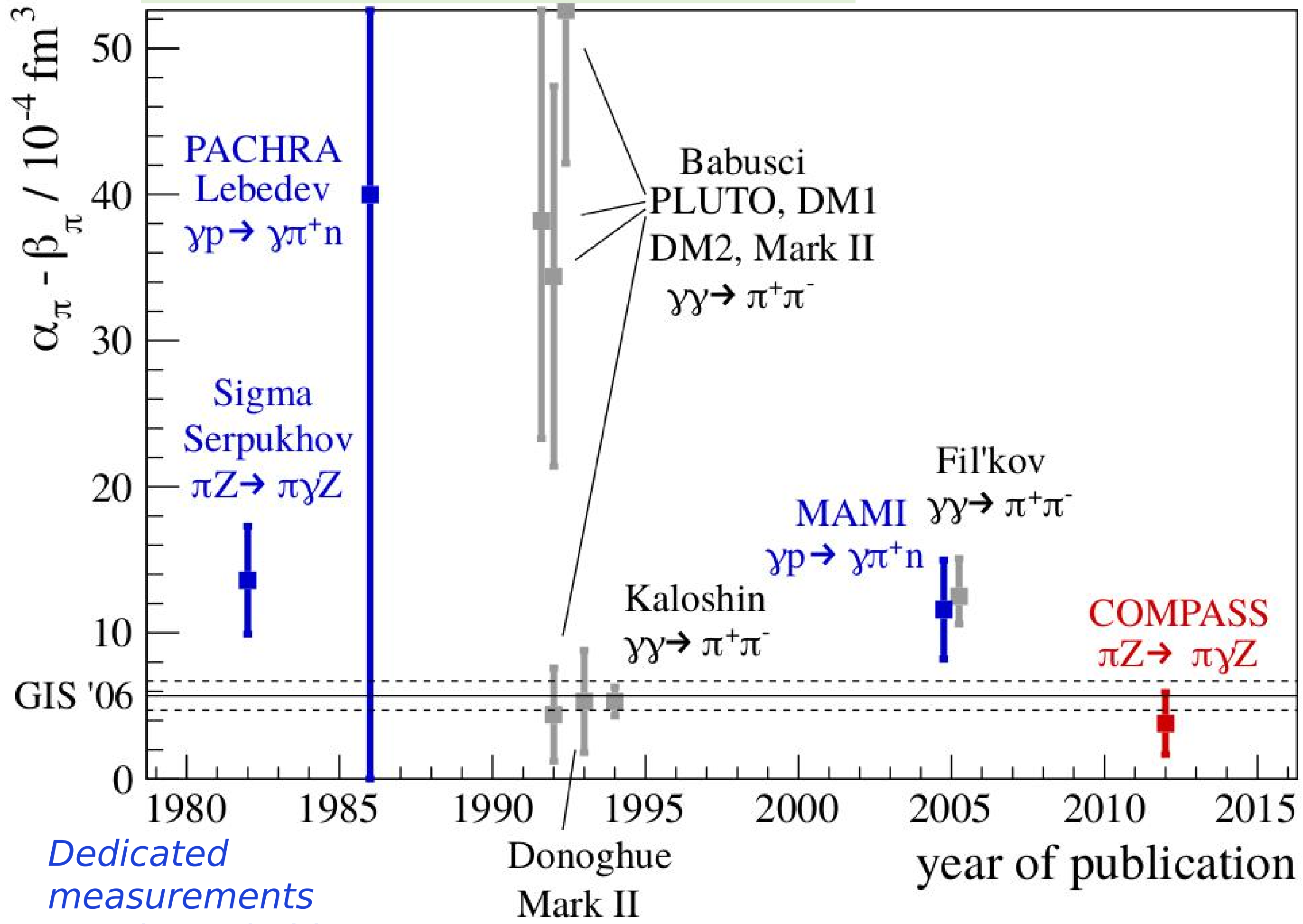
- electromagnetic calorimeter
- trackers (including vertex)

- **Polarizability** effects ~ **m³**
- Background from **π⁰**
- Background from same process via **strong interaction**



Pion polarizabilities: world data

Plot: T. Nagel, *PhD TUM, 2012*



Dedicated measurements are shown in blue

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

COMPASS:
$\alpha_\pi = (2.0 \pm 0.6_{stat} \pm 0.7_{syst}) \times 10^{-4}$ fm^3

Theory predictions:

χPT (two-loop, **pions**):
$\alpha_\pi - \beta_\pi = (5.7 \pm 1.0) \times 10^{-4}$ fm^3
$\alpha_\pi + \beta_\pi = 0.16 \times 10^{-4}$ fm^3

Most other low-energy models (chiral quark model,dispersion relations):
8×10^{-4} fm^3 $< \alpha_\pi - \beta_\pi <$ 12×10^{-4} fm^3

χPT (chiral perturation theory): low-energy expansion of QCD in particle momenta and quark masses

Kaon polarizabilities: world data

$|\alpha_K| < 200 \times 10^{-4}$ fm^3 (90% confidence)
(from kaonic atoms spectrum)

G. Backenstoss et. al, *Phys.Lett.43B, 5 (1973)*

Theory predictions:

χPT (one-loop):
$\alpha_K - \beta_K = 1.16 \times 10^{-4}$ fm^3

Quark confinement model:
$\alpha_K - \beta_K = 3.6 \times 10^{-4}$ fm^3
$\alpha_K + \beta_K = 2.3 \times 10^{-4}$ fm^3

Pion data: nice precision, COMPASS measurement in nice agreement with χPT
Kaon data: only vague estimates

χPT (chiral perturation theory): low-energy expansion of QCD in particle momenta and quark masses
Will it hold true also for strange quark sector?

There is a large demand for high-precision kaon data on polarizabilities

Chiral anomaly

Describes **$\pi^0 \to \gamma\gamma$** *(F^{π})* decay width
and **$\gamma\pi \to \pi\pi$** *($F^{3\pi}$)*,
$\gamma K \to \pi K$ *($F^{K2\pi}$)*,
$\gamma\pi \to \pi\eta$,
$\gamma K \to K\eta$ vertices

$$\frac{F^{3\pi}(0,0,0)}{F^{\pi}(0,0)} = \frac{1}{e f_\pi^2}$$

f_π: pion decay constant

Method of equivalent photons:

$$\frac{d\sigma_{\pi^- N \to N \pi^- \pi^0}}{ds dt dq^2} = \frac{Z^2\alpha}{\pi} \cdot \frac{q^2 - q^2_{min}}{q^4} \cdot \frac{1}{s - m_\pi^2} \cdot |F(q^2)|^2 \cdot \frac{d\sigma_{\gamma\pi \to \pi\pi}}{dt}$$

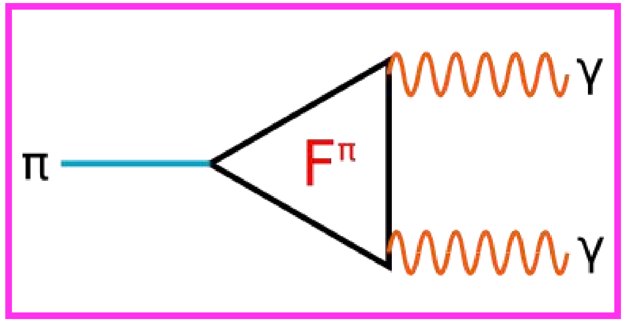
$$\frac{d\sigma_{\gamma\pi \to \pi\pi}}{dt} = \frac{F_{3\pi}(s,t,u)^2}{128\pi} \cdot \frac{s - 4m_\pi^2}{4} \sin^2\theta$$

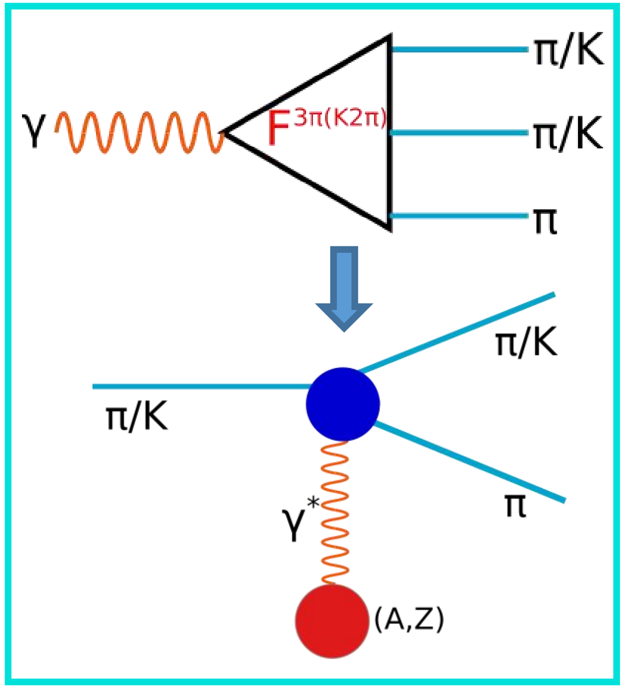
Problems with accessing ***$F^{3\pi}$***, ***$F^{K2\pi}$***:

- need to bridge the gap between s=t=q^2=0 and physical region

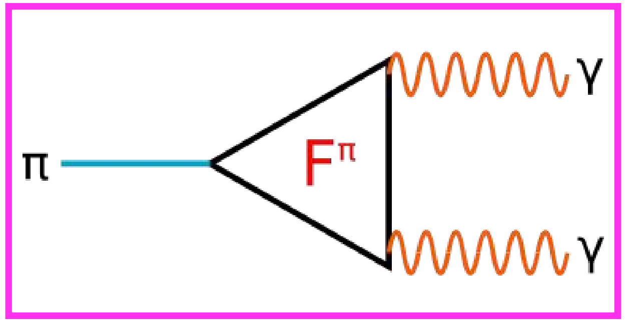
→ χPT, dispersive framework

- large background from γπ → πππ into γπ → ππ (Pomeron exchange) at high energies, and from ρ/K*(892) production





Chiral anomaly



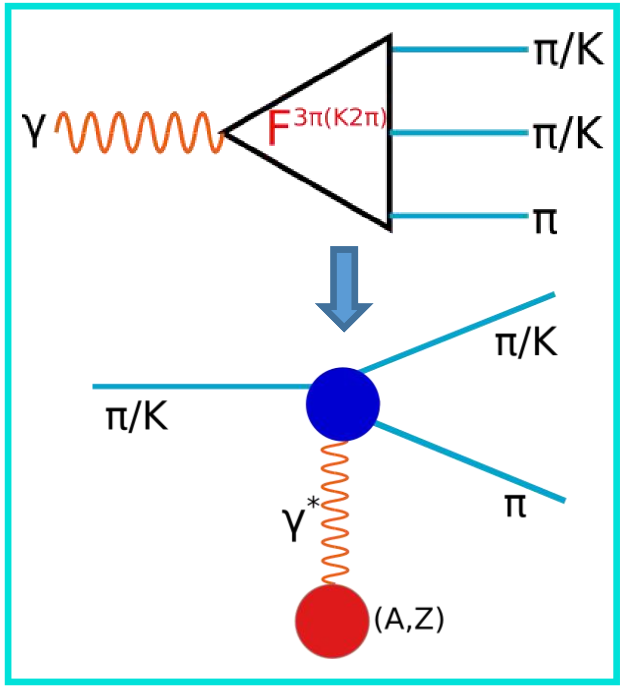
Theoretical prediction from chiral anomaly:

$$F_{K2\pi} = F_{3\pi} = \frac{e}{4\pi^2 F_\pi^3} = (9.78 \pm 0.05)\ \mathrm{GeV}^{-3}$$

Additional interest in γπ → ππ and γK → Kπ vertex studies:

- access to ρ/K*(892) radiative widths
- help link lattice QCD calculations to physical parameters

M. Niehus, M. Hoferichter, B. Kubis, *PoS CD2018, 076 (2019)*



Experimental results:

SIGMA (Serpukhov, 1980-s): $\pi^- Z \to Z \pi^- \pi^0$
$F_{3\pi} = (10.7 \pm 1.2)\ \mathrm{GeV}^{-3}$

Y. M. Antipov et al., *Phys.Rev.D36, 21(1987)*

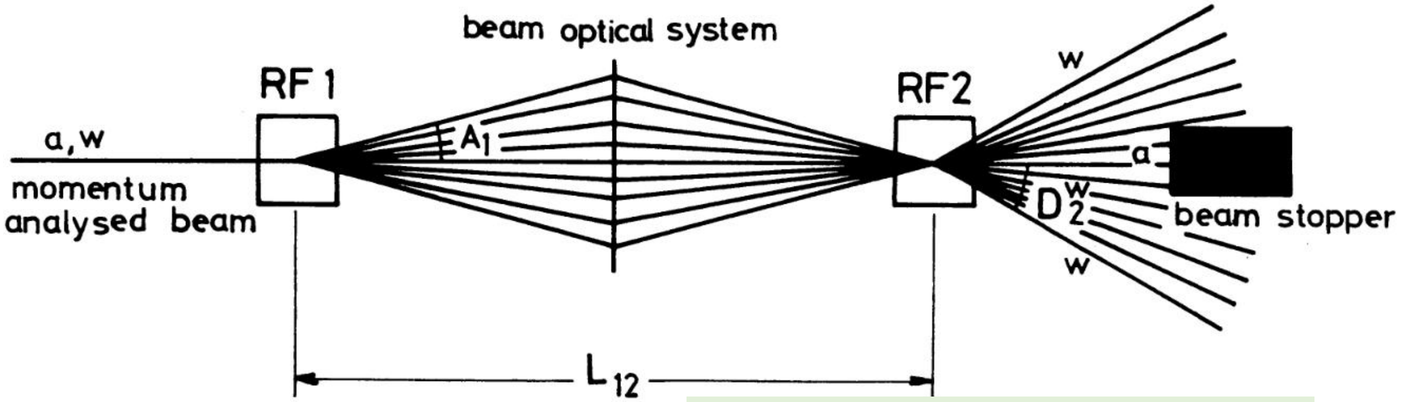
L. Ametller et al., *Phys.Rev.D64, 094009(2001)*

CERN SPS: $\pi^- e^- \to \pi^- e^- \pi^0$
$F_{3\pi} = (9.6 \pm 1.1)\ \mathrm{GeV}^{-3}$

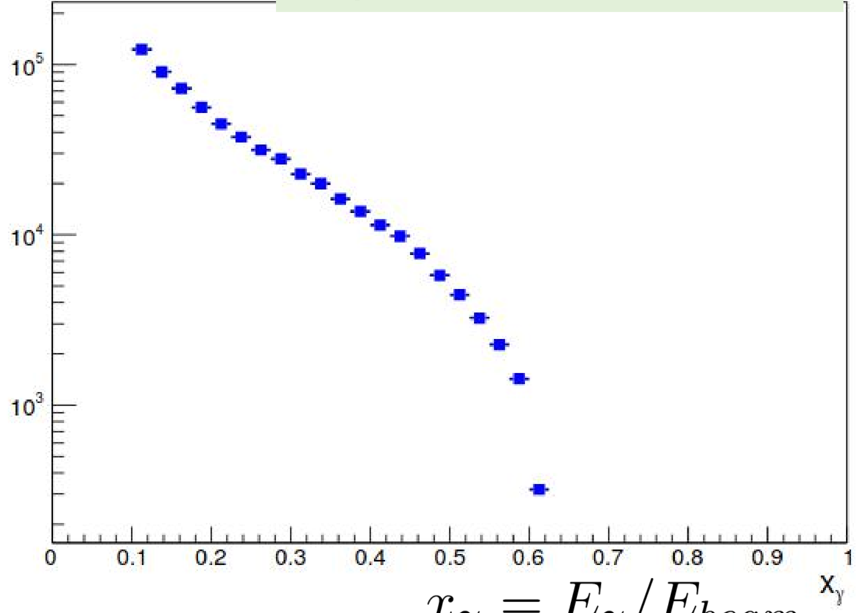
S. R. Amendolia et al., *Phys.Lett.B155, 457(1985)*

$F^{K2\pi}$: no measurement yet
(planned at IHEP, Protvino)

Polarisabilities with RF separated kaon-enriched beam at AMBER



P. Bernard et al., *CERN 68-29*



hep-ex 1808.00848v6

$x_\gamma = E_\gamma / E_{beam}$

Kaon enriched beam: momentum $p_K \sim 80$ GeV, intensity $\sim 5\times10^6\ s^{-1}$
(now: **kaons** @ COMPASS: $\sim 10^5\ s^{-1}$)

Estimated number of **$K^-Z \rightarrow ZK^-\gamma$** *("polarizability")* events after **1 year** of data taking

(Assuming trigger rate of **100 kHz**)

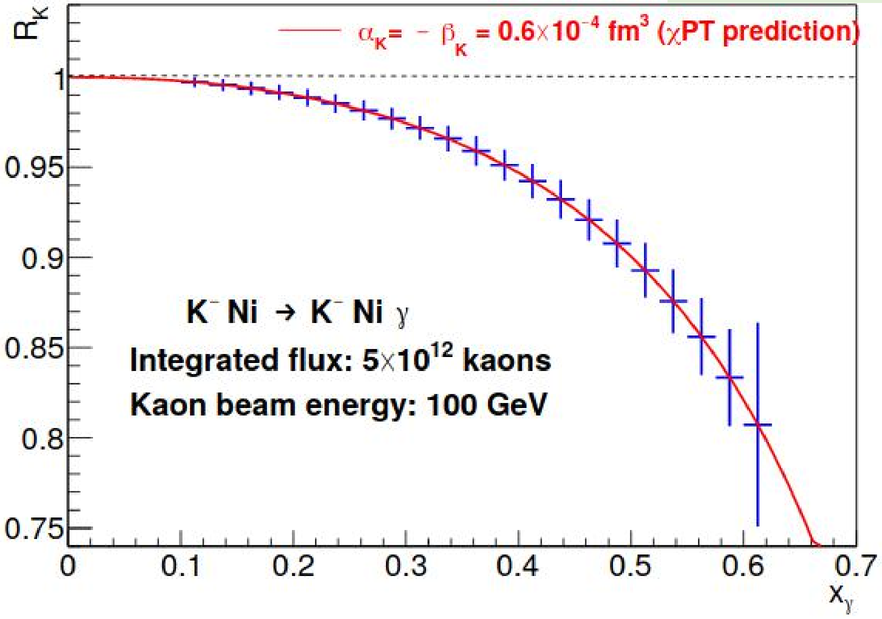
Critical parts of the setup:

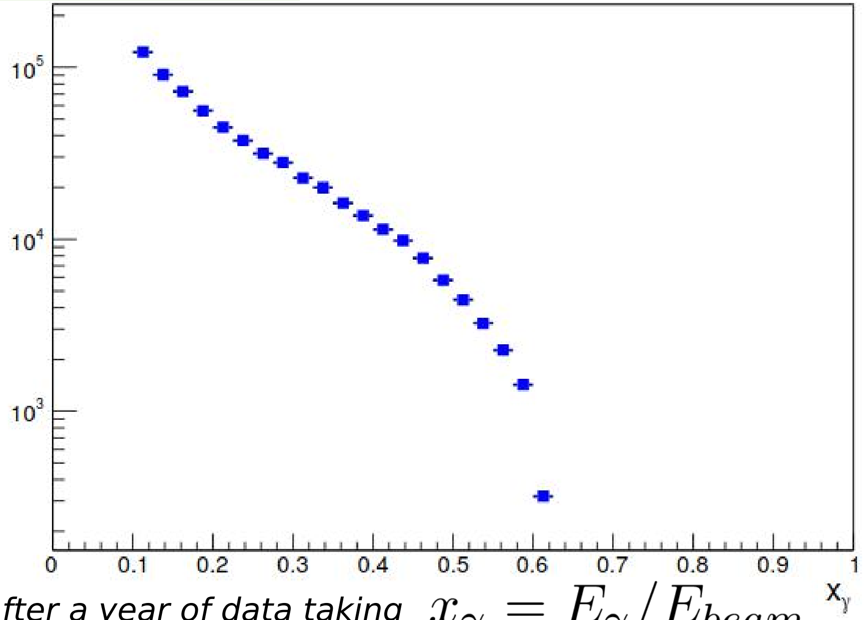
- electromagnetic calorimeter
- trackers (including vertex)
- performance similar to COMPASS

AMBER setup will provide all the needed elements for high-precision kaon polarizability measurements

Kaon polarizabilities at AMBER

hep-ex 1808.00848v6





after a year of data taking $x_\gamma = E_\gamma / E_{beam}$

Polarizability effects amplified:

$$(m_K/m_\pi)^3 \approx 44$$

$$R_\pi = \left(\frac{d\sigma_{\pi\gamma}}{dx_\gamma}\right) \Big/ \left(\frac{d\sigma^0_{\pi\gamma}}{dx_\gamma}\right) = 1 - \frac{3}{2}\frac{m_\pi^3}{\alpha}\frac{x_\gamma^2}{1-x_\gamma}\alpha_\pi,$$

- Expected statistical accuracy on **α_K - β_K**:
  σ_{stat} = 0.03×10^{-4} fm^3 ($\alpha_K + \beta_K = 0$):
- **No competitors so far**

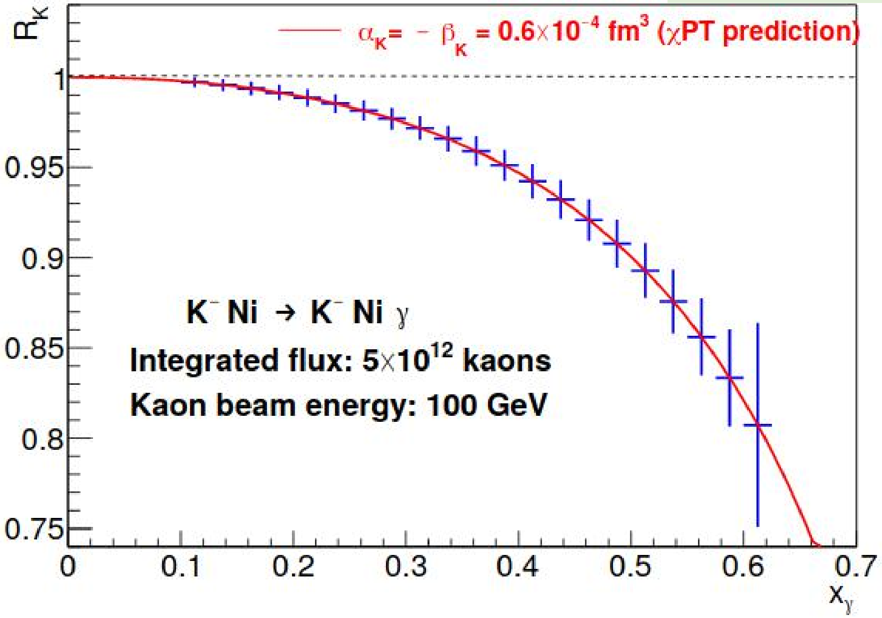
Theory predictions:

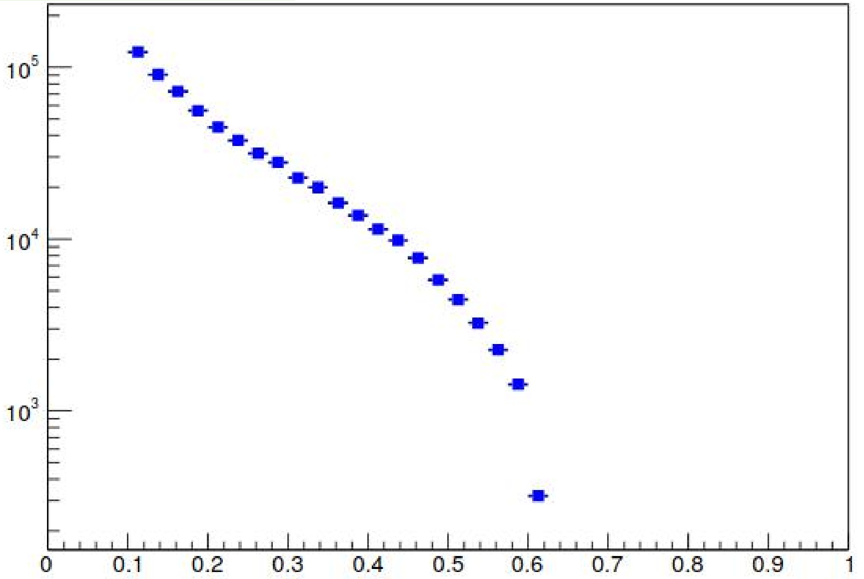
χPT (one-loop): α_K-β_K = 1.16×10^{-4} fm^3

QCM: α_K-β_K = 3.6×10^{-4} fm^3

Kaon polarizabilities at AMBER

hep-ex 1808.00848v6





$$x_\gamma = E_\gamma / E_{beam}$$

More possible measurements (also for pions):

- separate measurements of α_K and β_K
- quadrupole polarizabilities

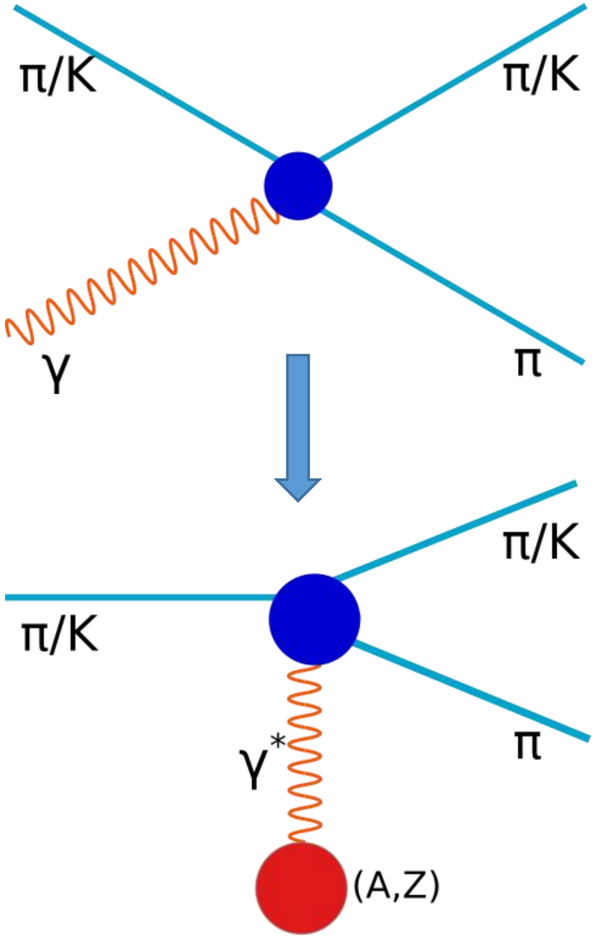
AMBER setup will allow to measure charged kaon polarizabilities with and unprecedented precision

Chiral anomaly in γK→πK

Idea: access **γK → Kπ** via $K^\pm + (Z,A) \to (Z,A) + K^\pm + \pi^0$
similarly to: **γπ → ππ** via $\pi^\pm + (Z,A) \to (Z,A) + \pi^\pm + \pi^0$

Anomalous contributions into **γπ → ππ** and **γK → Kπ** are equal:

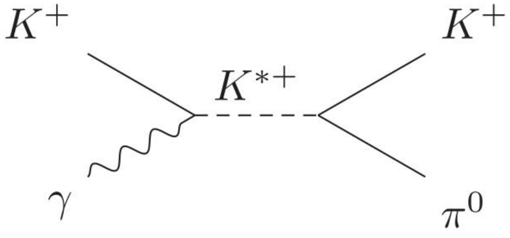
$$F_{K2\pi} = F_{3\pi} = \frac{e}{4\pi^2 F_\pi^3} = (9.78 \pm 0.05)\ \mathrm{GeV}^{-3}$$



BUT:

- with kaons, two processes are possible: **$K^-\gamma\to K^-\pi^0$** and **$K^-\gamma\to K^0\pi^-$**
- **only** **$K^-\gamma\to K^-\pi^0$** is influenced by the chiral anomaly
- anomaly contributions to **$K^-\gamma\to K^-\pi^0$** and **$\pi^-\gamma\to\pi^-\pi^0$** are equal
- physical region is further away from s=t=u=0 for kaons

How to incorporate K* production into analysis?



(a) s channel.

Chiral anomaly in γK→πK

M. I. Vysotsky and E. V. Zhemchugov *Phys.Rev.D93, 094029(2016)*

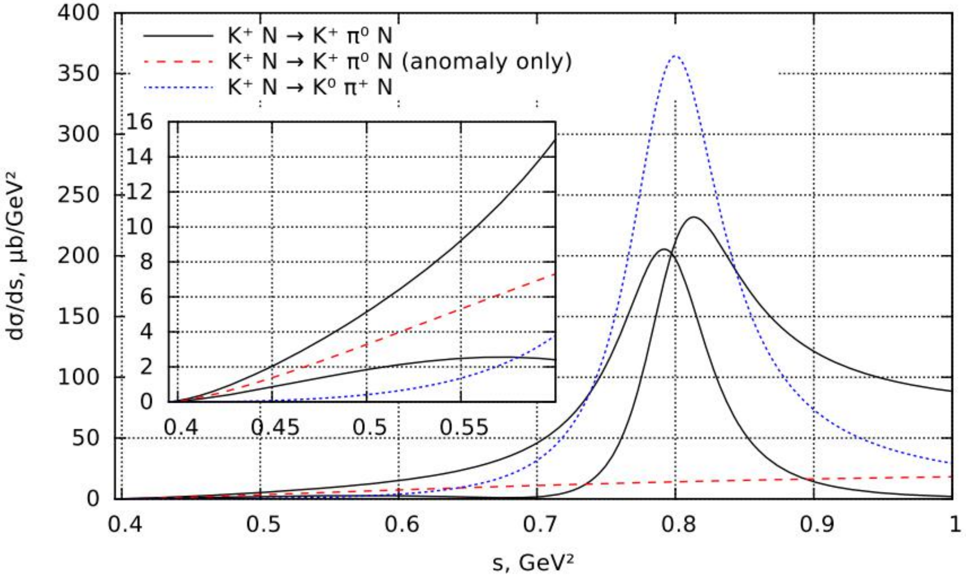
- Anomaly contribution + vector meson exchange (tree level)
- Anomaly dominates at low energies
- Extract anomaly from difference in **$K^-\gamma\to K^-\pi^0$** and **$K^-\gamma\to K^0\pi^-$** cross sections in the low-energy region

M. Dax, D. Stamen, B. Kubis *Eur. Phys. J. C (2021)81:221*

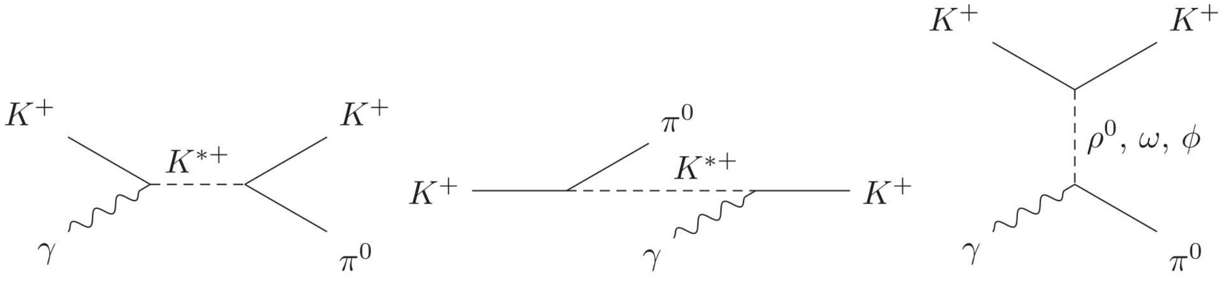
- Dispersive framework for all charge channels
- Fix subtraction constants using data on **$K^-\gamma\to K^-\pi^0$** and **$K^-\gamma\to K^0\pi^-$** → extract chiral anomaly
- Allows to utilize data up to s ~ $(1.2\ \mathrm{GeV})^2$
- Allows to obtain radiative coupling of $K^*(892)$

Phys.Rev.D93, 094029(2016)

Two solid lines: different interference phase between anomaly and resonance terms



s is the squared momentum sum of final state K,π



(a) s channel. (b) u channel. (c) t channel.

AMBER experiment could provide an opportunity to conduct precision measurements of γK→πK cross sections

Summary

- Pion and kaon **polarizabilities**, as well as coupling constants of **γπ → ππ** and **γK → Kπ** processes are of interest as a way to test the predictions of **low-energy phenomenological models** with the goal of controlling their regions of applicability.

- There are very few data on processes involving kaons at the moment, mainly due to absense of high-intensity kaon beams.

- At **AMBER experiment**, the new RF separated kaon-enriched beam will allow to measure **kaon polarizabilities with an unprecedented precision,** as well as study the γK→πK vertex to extract precise information on the chiral anomaly and $K^*(892)$ radiative width.