Pion/kaon structure study in Primakoff reactions

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On behalf of the COMPASS++/AMBER proto-Collaboration

Workshop on Pion and Kaon Structure Functions at the EIC

05 June 2020

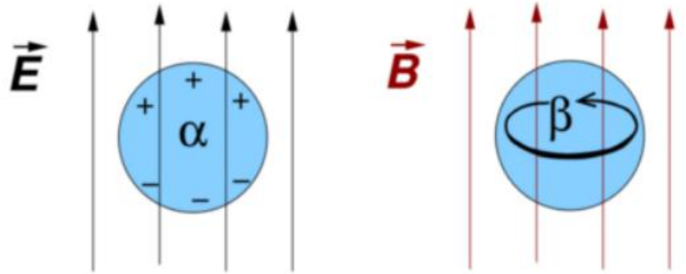
Introduction

- **QCD** has been an extremely successful theory of strong interactions, but it was **not yet possible to derive**, from the first principles, **fundamental properties** of the bound states (masses, spectra)
- **Effective QCD-based models were developed** and 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
- **End goal:** obtain the properties of the bound states from QCD

Polarizabilities

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

Analogy from classical physics:



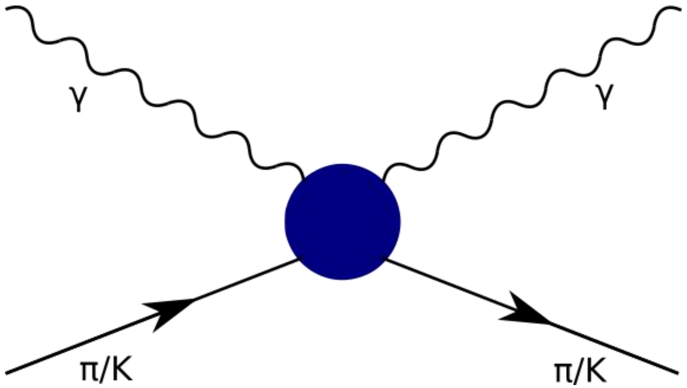
$$H_{em} = \ldots - \frac{1}{2}(\alpha \mathbf{E}^2 + \beta \mathbf{B}^2) + \ldots$$, α: electric polarizability, β: magnetic polarizability

Compton scattering cross-section:

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

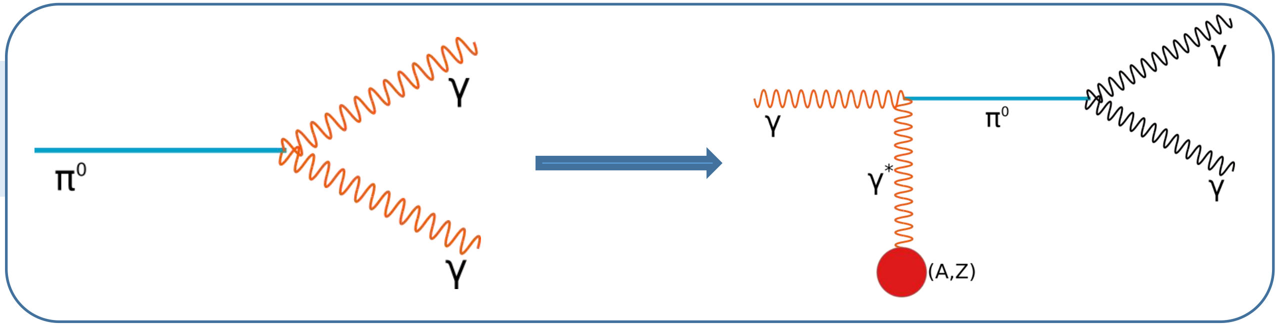
→ **point-like meson**

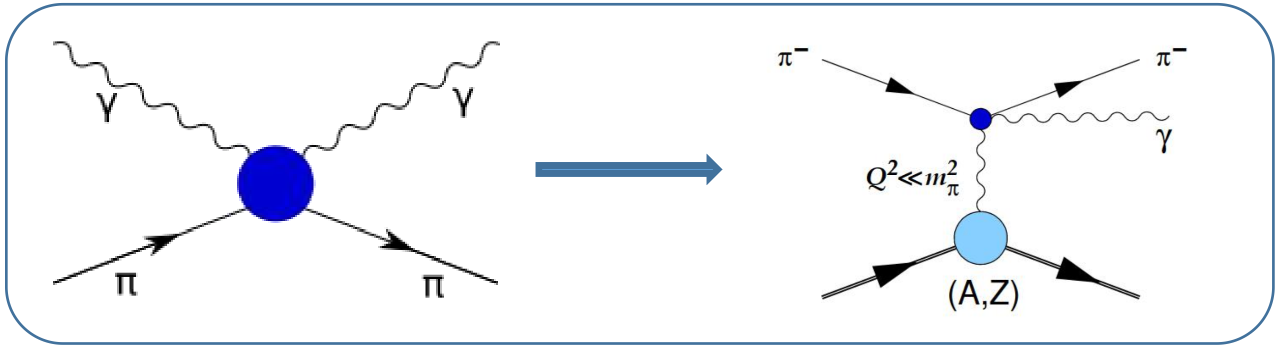
$$z_\pm = 1 \pm \cos\theta_{cm}$$



How to access polarizabilities in experiment?

Idea of Henry Primakoff:
EM field of nucleus = photon target!

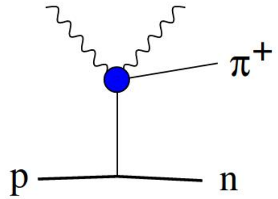




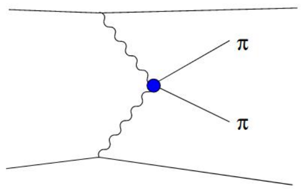
Assuming: one-photon exchange, $Q^2 \ll m_\pi^2$
Weizsäcker-Williams approximation:

$$\frac{d\sigma_{\pi^- + (Z,A) \to (Z,A) + \pi^-\gamma}}{ds\,dt\,dQ^2} = \frac{Z^2\alpha}{\pi(s - m_\pi^2)} \cdot F_{eff}^2(Q^2) \cdot \frac{Q^2 - Q_{min}^2}{Q^4} \cdot \frac{d\sigma_{\pi\gamma\to\pi\gamma}}{dt}$$

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



Radiative pion photoproduction



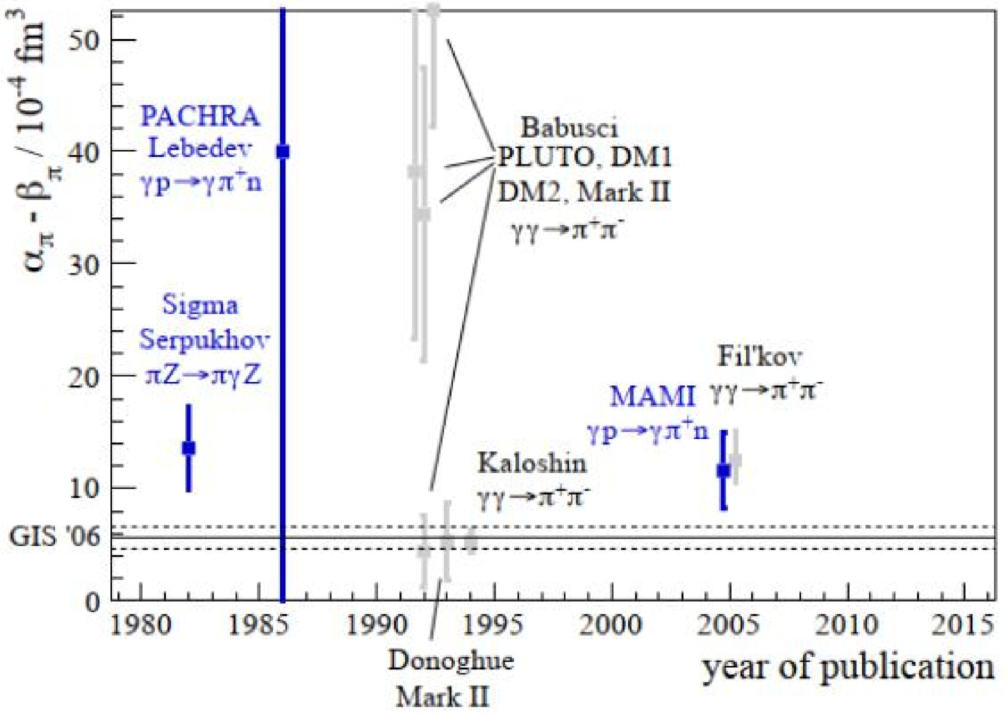
Photon-Photon fusion

Extract polarizabilities from $\pi^- + (Z,A) \to \pi^- + \gamma + (Z,A)$

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

World data on polarizabilities before COMPASS

Pion data



Dedicated measurements are shown in blue

Plot: T. Nagel, PhD TUM, 2012

Kaon 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 (two-loop, **pions**):
α_π-β_π = (5.7 ± 1.0)×10^{-4} fm^3
α_π+β_π = 0.16×10^{-4} fm^3

Most other low-energy models (chiral quark model,dispersion relations):
8×10^{-4} fm^3 < α_π-β_π < 12×10^{-4} fm^3

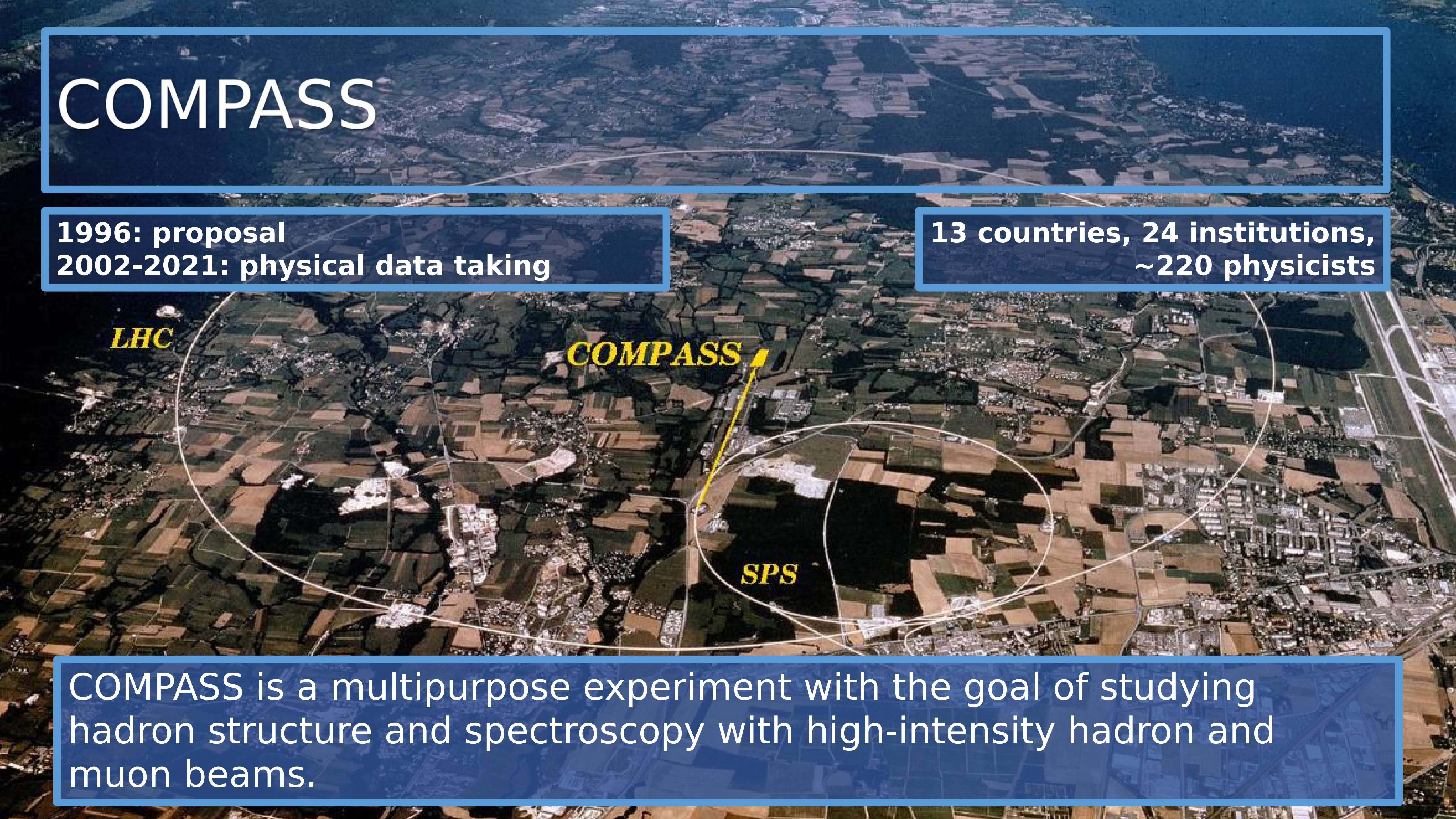
χPT (one-loop, **kaons**):
α_K-β_K = 1.16×10^{-4} fm^3

Quark confinement model:
α_K-β_K = 3.6×10^{-4} fm^3
α_K+β_K = 2.3×10^{-4} fm^3

COMPASS

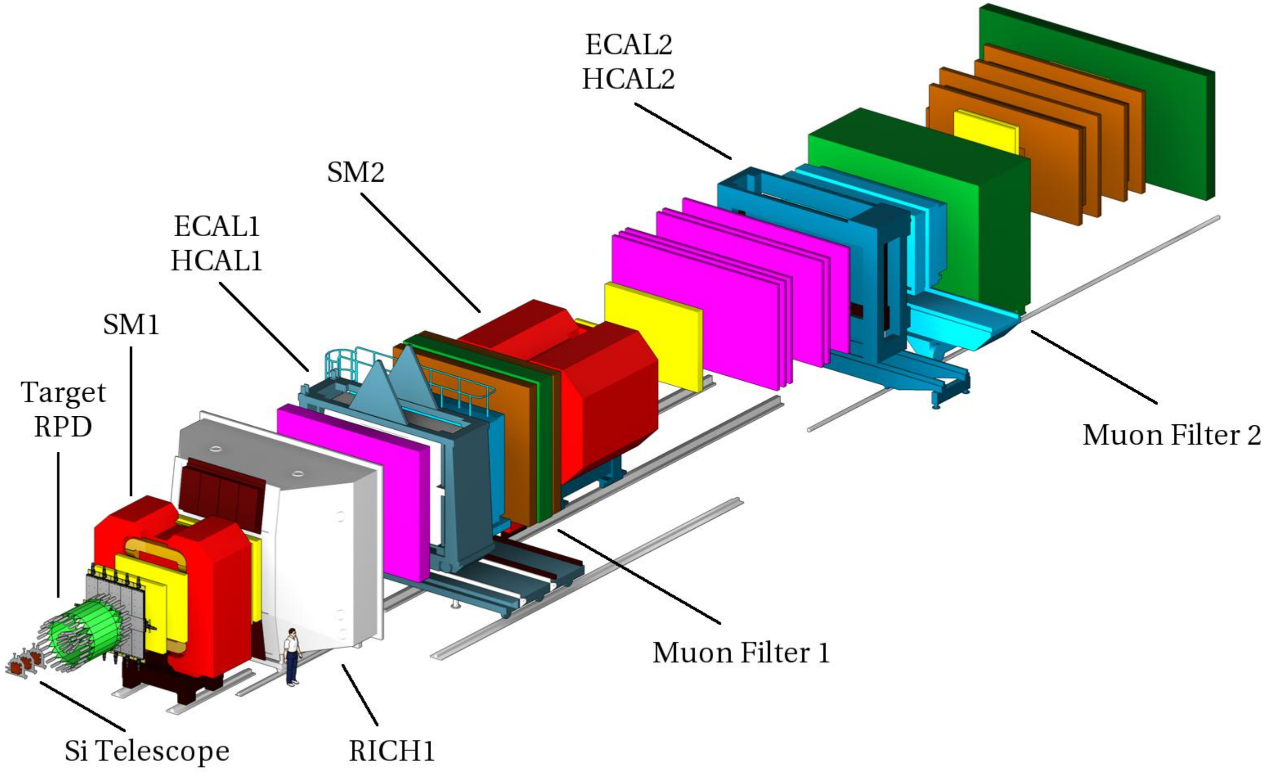
1996: proposal
2002-2021: physical data taking

13 countries, 24 institutions, ~220 physicists



COMPASS is a multipurpose experiment with the goal of studying hadron structure and spectroscopy with high-intensity hadron and muon beams.

COMPASS (2009 setup)



- Two-stage spectrometer, two ECALs
- CEDARs: beam PID
- Trigger: energy deposition in ECAL: $E_{ECAL} > 40/60$ GeV at small angles
- Trigger rate: 30 kHz
- Beam intensity: ~ 5×10^{6} s^{-1}
- Beam composition: 97% π^{-}, 2.4% K^{-}
- Beam momentum: 190 GeV/c
- Target: Nickel 4.2 mm (30% X_0, Z = 28)

Pion polarizability at COMPASS

Source of uncertainty	Estimated magnitude [10^{-4} 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

PRL 114, 062002 (2015)

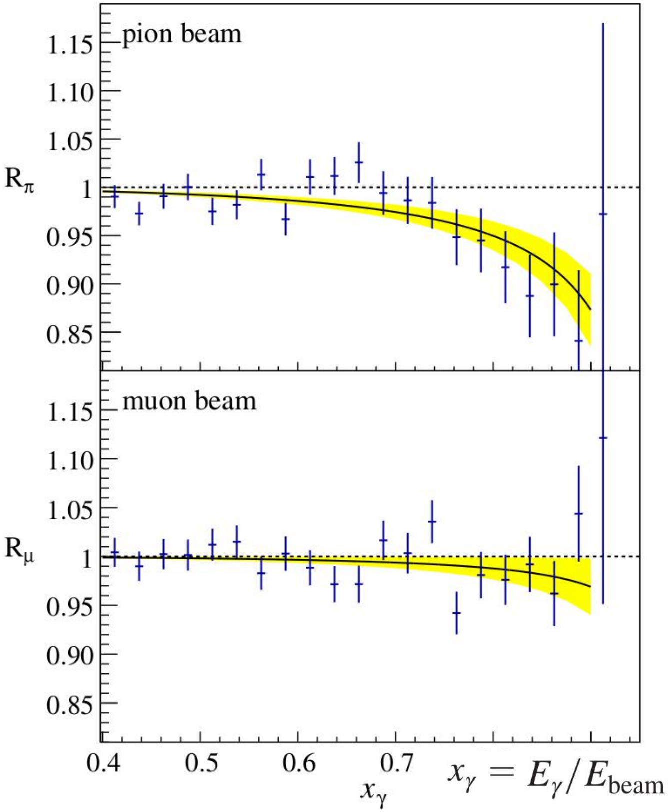
COMPASS 2009 Primakoff run:
~63000 selected $\boldsymbol{\pi^- Z \rightarrow Z \pi^- \gamma}$ events

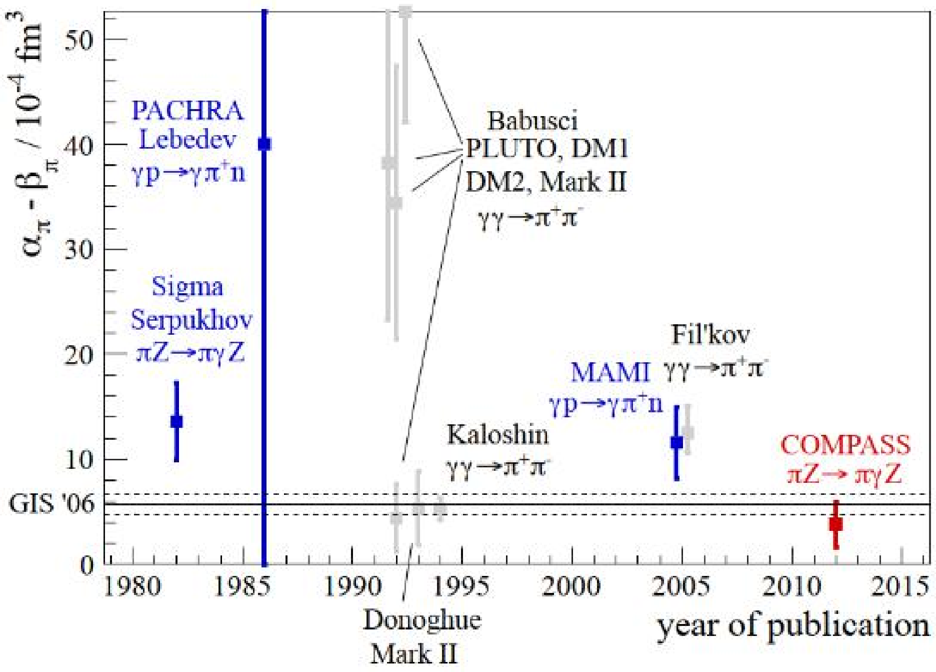
Previous measurement
using Primakoff reaction:

Serpukhov (~7000 events):
$\alpha_\pi = 6.8 \pm 1.4_{stat} \pm 1.2_{syst}\ 10^{-4}\ \mathrm{fm}^3$

Overall: better control and estimate of the background processes,
as well as corrections, in comparison with the Serpukhov experiment

Pion polarizability at COMPASS





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

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

χPT: $\alpha_\pi \approx 2.8 \times 10^{-4}$ fm^3

Serpukhov:
$\alpha_\pi = 6.8 \pm 1.4_{stat} \pm 1.2_{syst}\ 10^{-4}$ fm^3

PRL 114, 062002 (2015)

2012 data are still under analysis: new results on pion polarizability are expected

COMPASS++/AMBER

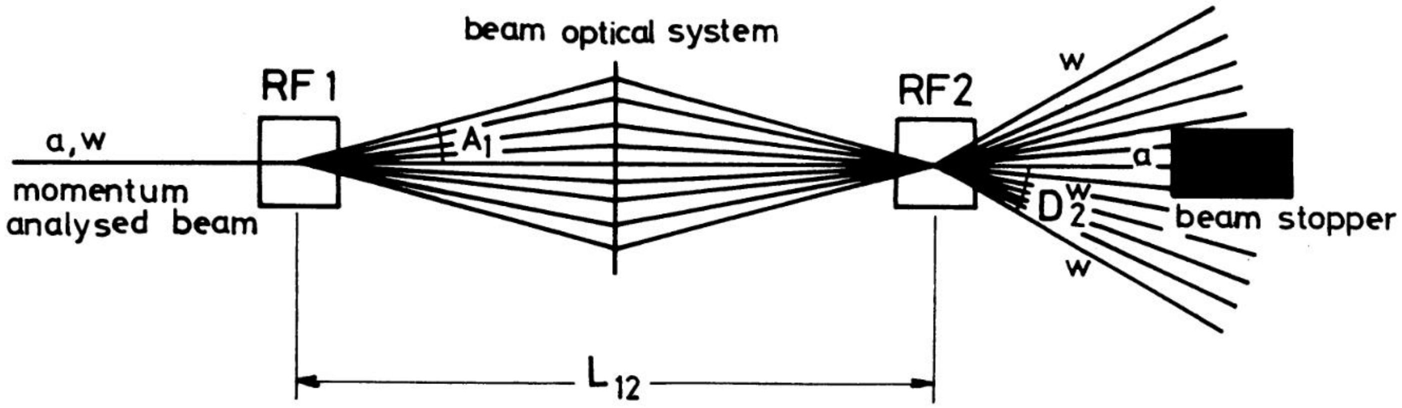
COMPASS | **COMPASS++/AMBER** (19 new institutions) **Oleg's talk**

2022 — **Phase 1**
- Proton radius
- Pion PDFs (DY) **Vincent's talk**
- GPD E
- Antiproton-induced spectroscopy

2026 — **Phase 2 (RF separated beam)**
- Primakoff: kaon polarizabilities, chiral anomaly **This talk**
- π^0 lifetime (direct measurement)
- Kaon PDFs (DY) **Vincent's talk**
- Prompt photons: meson gluon PDFs **Charles's talk**
- Kaon spectroscopy

Kaon polarizabilities: RF separated kaon beam at COMPASS++/AMBER

New possibilities to measure kaon polarizabilities due to increased statistics of beam kaons



P. Bernard et al., CERN 68-29

Two RF cavities (RF1, RF2) with frequency *f*
→ phase difference ΔΦ between particles of different masses (and therefore, different velocities):

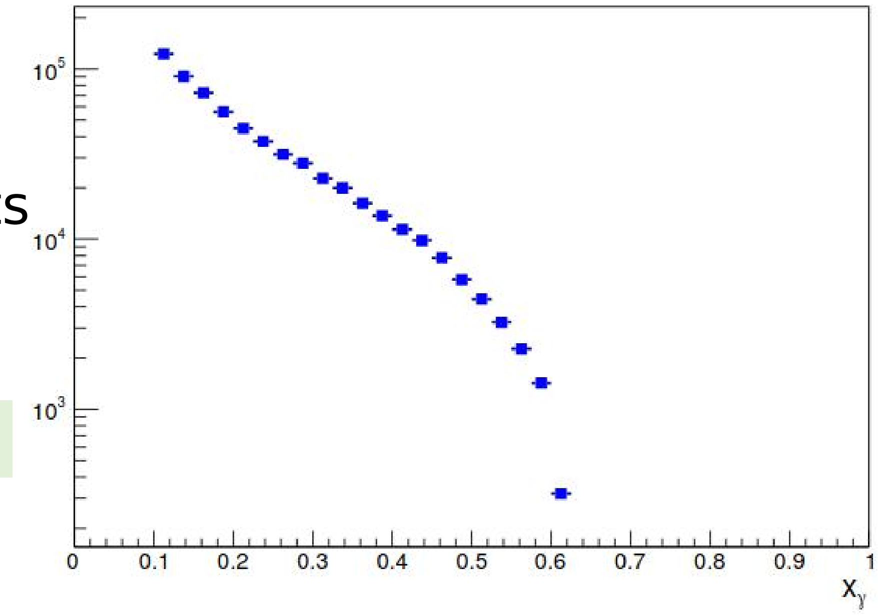
$$\Delta\Phi = 2\pi(Lf/c)\frac{m_1^2 - m_2^2}{2p^2}$$

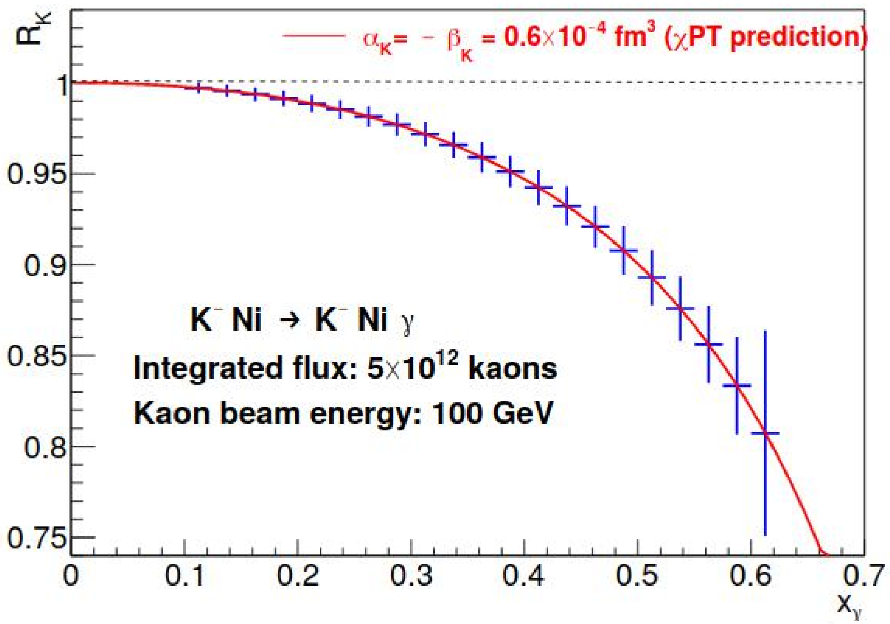
Kaon enriched beam: momentum $p_K \gtrsim$ 80 GeV,
intensity: ~ 5×10^6 s^{-1} (now: **kaons** @ COMPASS: ~ 10^5 s^{-1})

Kaon polarizabilities at COMPASS++/AMBER

Estimated number of **$K^-Z \rightarrow ZK^-\gamma$** events after 1 year of data taking:

hep-ex 1808.00848v6





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

- Assuming trigger rate improvement: 30 kHz (COMPASS) → **100 kHz (COMPASS++/AMBER)**
- Polarizability effects amplified: $(m_K/m_\pi)^3 \approx 44$
- 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:

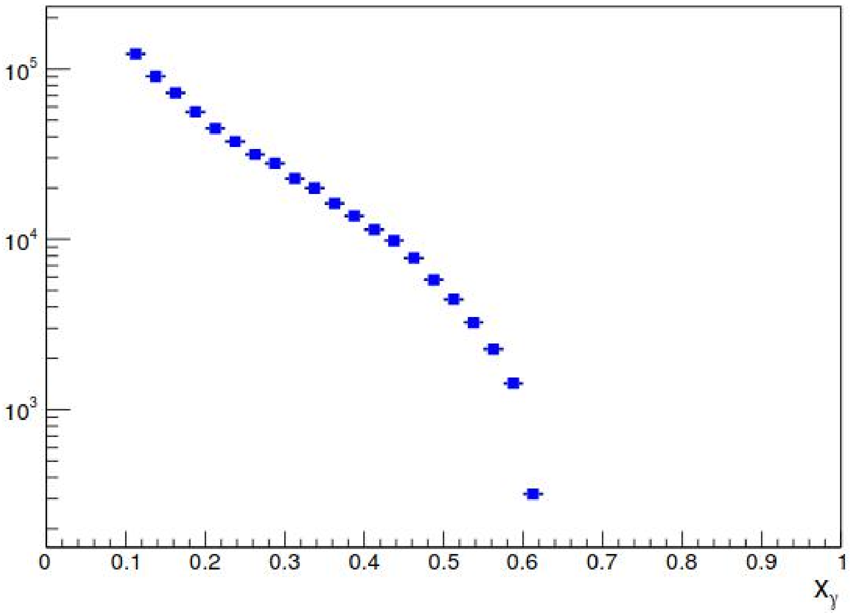
χPT (one-loop): α_K-β_K = 1.16×10^{-4} fm^3

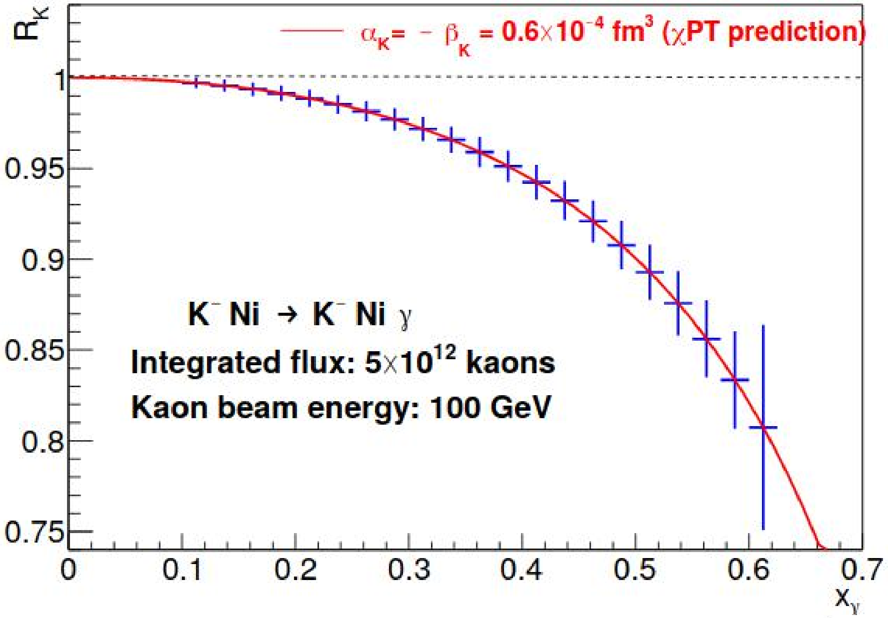
QCM: α_K-β_K = 3.6×10^{-4} fm^3

Kaon polarizabilities at COMPASS++/AMBER

Estimated number of $\mathbf{K^- Z \rightarrow Z K^- \gamma}$ events after 1 year of data taking:

hep-ex 1808.00848v6





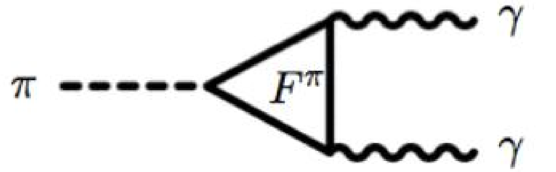
$$x_\gamma = E_\gamma / E_{\text{beam}}$$

More possible measurements (also for pions):

- separate measurements of α_K and β_K
- quadrupole polarizabilities

Chiral anomaly in γπ→ππ, γK→πK

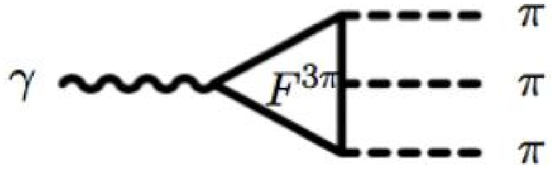
Chiral anomaly: describes **$\pi^0 \to \gamma\gamma$** decay width,
describes **γπ→ππ**, **γK→πK** vertices



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

only for s = t = u = 0
(unphysical point!)

f_π: pion decay constant



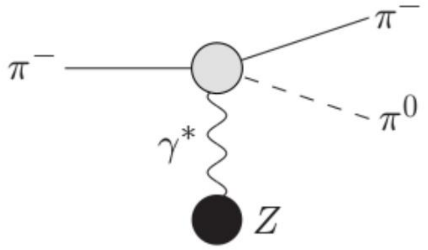
Access **γπ→ππ** experimentally: need to bridge the gap between s = t = u = 0 and physical region → χPT, dispersive framework

$\pi^- Z \to Z \pi^- \pi^0$
$K^- Z \to Z K^- \pi^0$
$\pi^- Z \to Z \pi^- \eta$
$K^- Z \to Z K^- \eta$

→ Test predictions of chiral anomaly, χPT

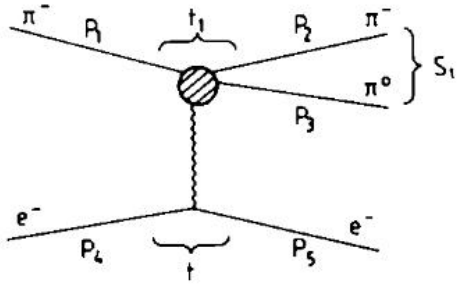
Chiral anomaly in γπ→ππ

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: $\pi^- e^- \to \pi^- e^- \pi^0$

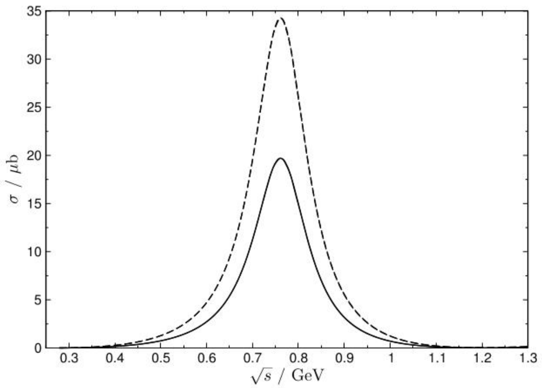


$F_{3\pi} = (9.6 \pm 1.1)\ \mathrm{GeV}^{-3}$
S. R. Amendolia et al., Phys.Lett.B155, 457(1985)
I.Giller et al., Eur.Phys.J.A25 229(2005)

Chiral anomaly: $F_{3\pi} = (9.78 \pm 0.05)\ \mathrm{GeV}^{-3}$

Experiment: precision at 10% level, data samples at ππ threshold (rejecting **interfering ρ sample**)

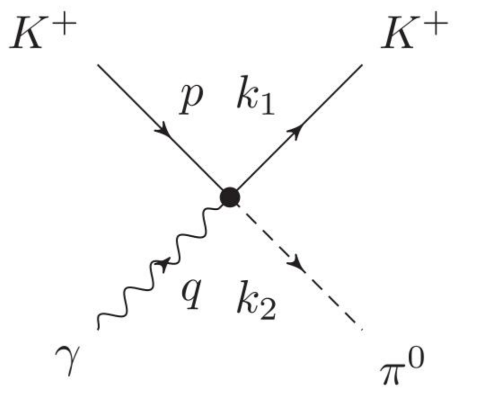
Plans at COMPASS: use a dispersive framework (M.Hoferichter et.al, Phys.Rev.D86, 116009(2012)) to incorporate the physics of the ρ(770) meson, increasing data sample
Allows to extract ρ radiative width from the same sample (same level of precision as $F_{3\pi}$)



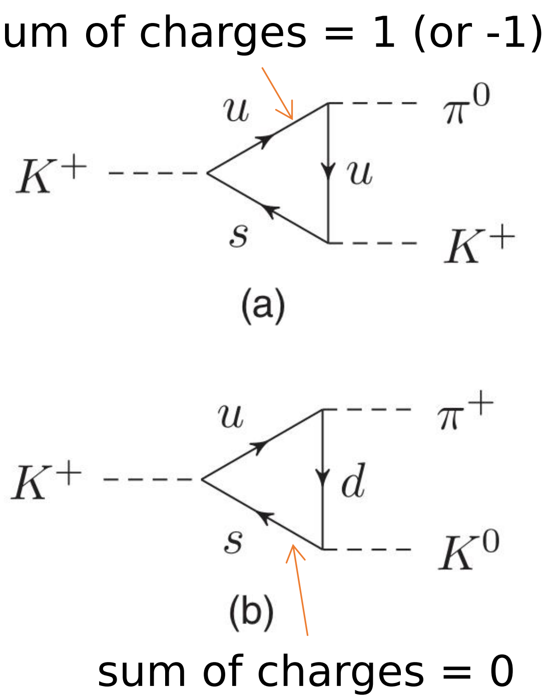
Cross section for γπ→ππ in the dispersive framework for two sets of free parameters

Chiral anomaly in γK→πK

As long as $m_s \ll \Lambda_{QCD}$ is considered, γK→πK amplitude could also be obtained from chiral anomaly:



$$A = -\frac{e}{4\pi^2 F_\pi^3}\varepsilon^{\mu\nu\rho\sigma} q_\mu \epsilon_\nu p_\rho k_{1\sigma}$$



Two processes with kaons:

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

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

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

- **only** **$K^-\gamma \to K^-\pi^0$** is influenced by the chiral anomaly
- contributions to **$K^-\gamma \to K^-\pi^0$** and **$\pi^-\gamma \to \pi^-\pi^0$** are equal

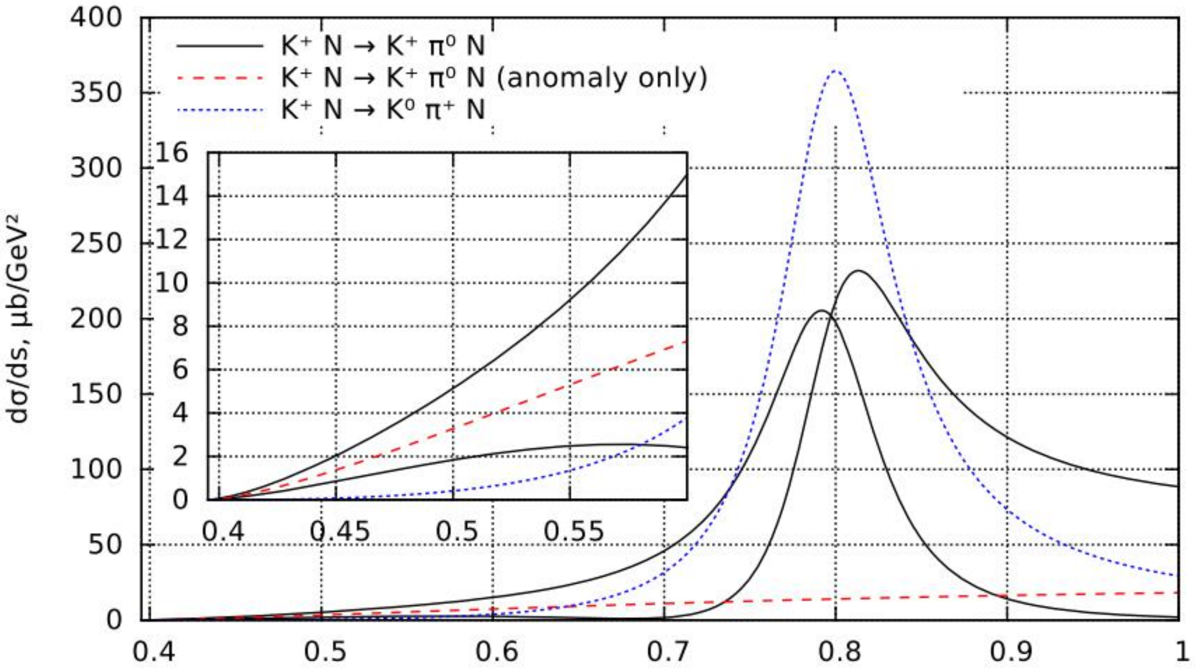
Chiral anomaly in $\gamma K \rightarrow \pi K$

Anomaly contribution could be determined from difference in cross section between $K^- \gamma \rightarrow K^- \pi^0$ and $K^- \gamma \rightarrow K^0 \pi^-$

Experiment planned at Serpukhov:
expected statistics ($L = 60\ \mu b^{-1}$):
~10 $K^- \gamma \rightarrow K^0 \pi^-$ **events**
~20-70 $K^- \gamma \rightarrow K^- \pi^0$ events
(for descructive/constructive interference)

An experiment with higher statistics would also test chiral anomaly predictions in the kaon sector.
COMPASS++/AMBER provides such opportunity.

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



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

Chiral anomaly in $\gamma\pi \to \pi\eta$, $\gamma K \to \eta K$

- Expression for $\gamma\pi \to \pi\eta$ coupling $F_{\eta\pi\pi\gamma}(0,0,0) = \frac{e}{4\pi^2 f_\pi^3}(\frac{f_\pi}{f_8}\frac{cos\theta_p}{\sqrt{3}} - \frac{f_\pi}{f_0}\sqrt{\frac{2}{3}}sin\theta_p)$

  where f_π, f_8, f_0: π / octet η / singlet η decay constants, θ_p: singlet-octet mixing angle

- Mixing parameters extracted from $\eta, \eta' \to \pi^+\pi^-\gamma;\ \eta, \eta' \to \gamma\gamma$

  Predicted value: $F_{\eta\pi\pi\gamma}(0,0,0) = 6.5 \pm 0.3\ \mathrm{GeV}^{-3}$ Phys.Rev.D57,7(1998)

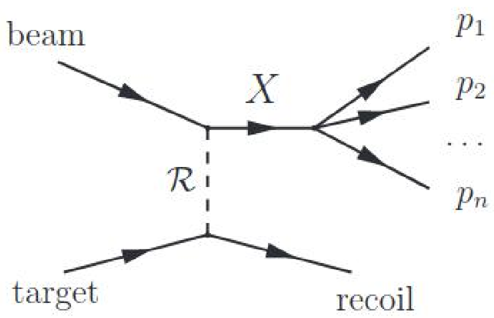
- **VES measurement** (1998): Primakoff reaction $\pi^- Be \to \eta\pi^- Be$, obtained result:

  $F_{\eta\pi\pi\gamma}(0,0,0) = 6.9 \pm 0.7\ \mathrm{GeV}^{-3}$ IHEP Preprint 98-62

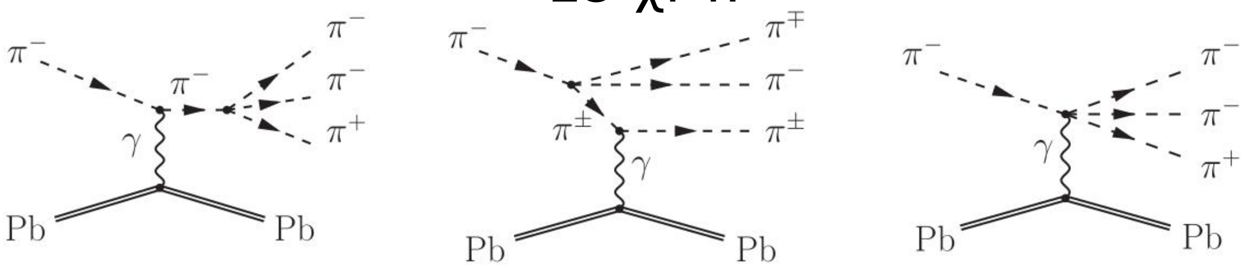
- More possibilities also with **$\gamma K \to \eta K$** vertex

Chiral dynamics in $\pi\gamma\to\pi\pi\pi$

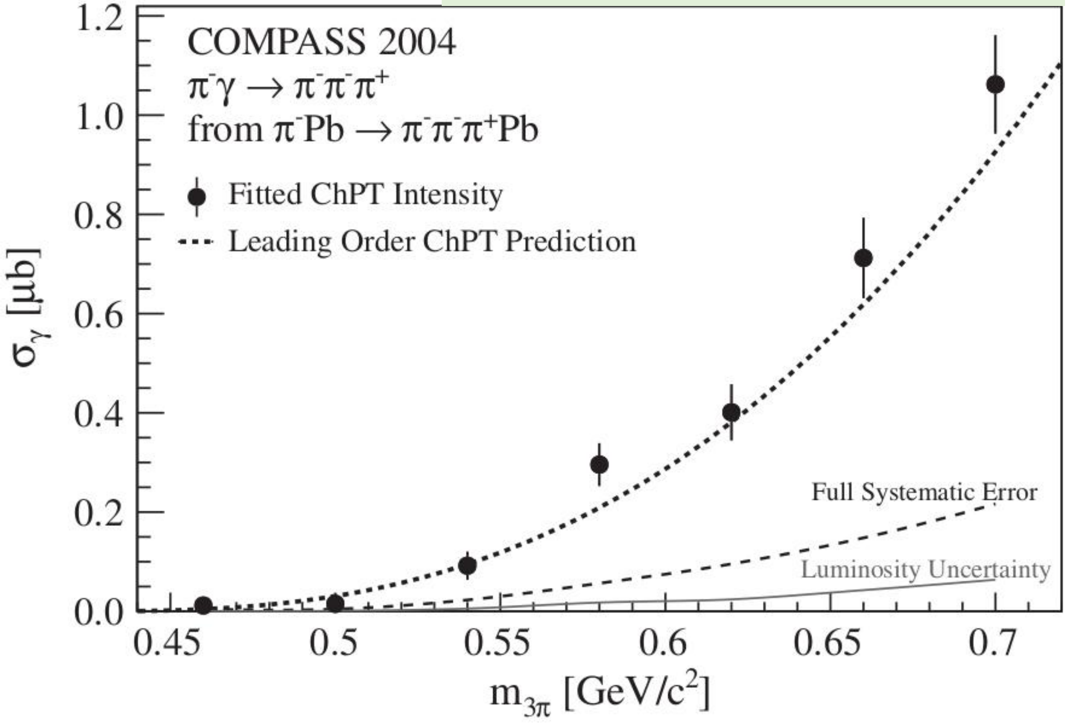
χPT test: **$\pi^-\gamma\to\pi^-\pi^-\pi^+$**
cross section at threshold



LO χPT:



PRL 108, 192001 (2012)



Also possible to study $\pi^-\gamma\to\pi^-\pi^0\pi^0$

Radiative widths of mesons

Access radiative width Γ(X→πγ) via Primakoff reaction πγ→X:

$$\sigma_{\mathrm{Primakoff},X} = \int_{m_1}^{m_2} \int_0^{t'_{\max}} \frac{\mathrm{d}\sigma}{\mathrm{d}m\,\mathrm{d}t'} \mathrm{d}t'\,\mathrm{d}m = \Gamma_0(X \to \pi\gamma) C_X .$$

COMPASS, **$\pi^-\gamma\to\pi^-\pi^-\pi^+$:** contributions from $a_2(1320)$, $\pi_2(1670)$ disentangled using PWA:

	$a_2(1320)$	$\pi_2(1670)$
This measurement	$(358 \pm 6 \pm 42)$ keV	$(181 \pm 11 \pm 27)$ keV $\cdot\ (0.56/\mathrm{BR}_{f_2\pi})$
SELEX [21]	$(284 \pm 25 \pm 25)$ keV	
S. Cihangir *et al.* [24]	(295 ± 60) keV	
E.N. May *et al.* [25]	(0.46 ± 0.11) MeV	
VMD model [1]	(375 ± 50) keV	
Relativ. Quark model [2]	324 keV	
Cov. Osc. Quark model [3]	235 keV	
Cov. Osc. Quark model [4]	237 keV	2 values: 335 keV and 521 keV

Possible to extract: **ρ** radiative width from γπ→ππ, **K*** radiative width from γK→πK

SPS, CERN: $\Gamma(\rho \to \pi\gamma) = (81 \pm 4 \pm 4)$ keV Nucl.Phys.B288, 659 (1987)

Summary

- Measurements of pion and kaon polarizabilities and quantitative studies of meson structure are of interest as a way to test the predictions of low-energy phenomenological models with the goal of controlling their regions of applicability.

- COMPASS collaboration has published the most precise result on pion polarizability using Primakoff reactions among specialized measurements, as well as first result on $\pi\gamma \to \pi\pi\pi$ cross section near threshold.

- More data is under analysis at COMPASS and new results on meson polarizabilities and chiral anomaly are expected.

- At **COMPASS++/AMBER experiment**, the new RF separated kaon-enriched beam will allow to measure **kaon polarizabilities with an unprecedented precision,** as well as study the chiral anomaly with kaons.