Tribute to Henry Primakoff: Tests of Chiral Perturbation Theory via Primakoff Reactions

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Abstract: I review experimental tests of three-flavor (u,d,s) chiral perturbation theory (ChPT). These include measurements of pion and kaon polarizabilities, the chiral anomaly amplitudes for processes such as $\gamma \to \pi\pi\pi$, $\gamma \to \pi\pi\eta$ and $\gamma \to KK\pi$, as well as the lifetimes of the neutral pion and eta. These observables are extracted primarily through ultra-peripheral Primakoff scattering of high-energy particles from virtual photons in the Coulomb field of nuclei. Comparing data to two-flavor and three-flavor predictions allows us to evaluate how well ChPT describes light meson dynamics and the role of the strange quark in spontaneous chiral symmetry breaking.

Tests of Three-Flavor Chiral Perturbation Theory

IJMPA 40, 2530014, 2025 (https://arxiv.org/pdf/2412.03669)
and Primakoff Tribute: https://arxiv.org/pdf/2509.04649

Keywords: Chiral Symmetry; Chiral Lagrangian; Chiral Perturbation Theory; Primakoff Scattering; Pion and Kaon Polarizabilities; Chiral Anomaly; π^0 and η Lifetimes.

HENRY PRIMAKOFF

From S. Peter ROSEN's Biographical Memoir

TRIBUTE

Henry Primakoff, 1914–1983, was the first Donner Professor of Physics at U. Penn. He was a theoretical physicist well known for his contributions to condensed matter and high-energy physics. He helped develop the Holstein–Primakoff transformation, a mapping from boson creation and annihilation operators to spin operators, whereby spin waves in ferromagnets are treated as bosonic excitations. Primakoff became a leading authority in weak interaction phenomena by formulating a muon-nucleon effective Hamiltonian. Fujii and Primakoff calculated the partial muon capture rates in certain light nuclei, which were in good agreement with the experimental results. The Fujii-Primakoff Hamiltonian was also used to describe recoil nuclear polarization in muon capture. Primakoff also contributed to the understanding of double beta decay, neutrino-nucleus scattering, and shock waves in water.

Measuring the π^0 lifetime

The Primakoff Effect, $\gamma\gamma^* \to \pi^0$, is the resonant production of neutral pseudoscalar mesons (π^0 or η) by high-energy photons interacting with quasi-real photons γ^* in the Coulomb field of an atomic nucleus. It can be viewed as the inverse kinematics process of the π^0 decay into two photons, and has been used for the measurement of the decay width (lifetime) of neutral mesons

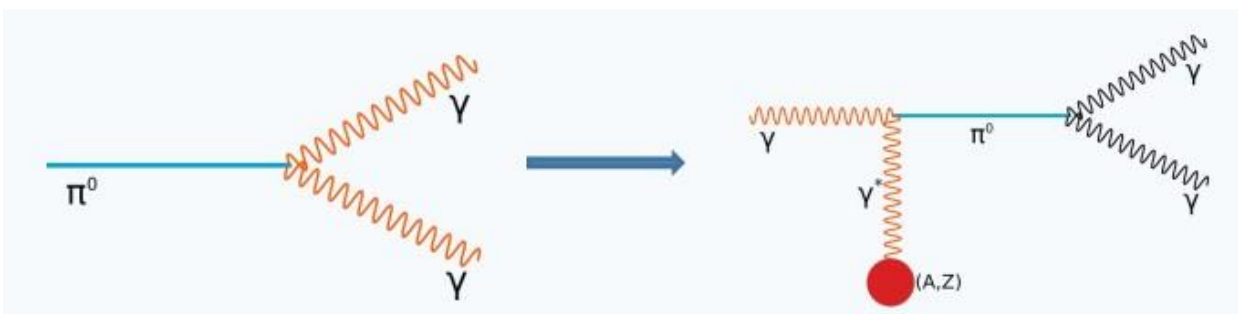


Photo-Production of Neutral Mesons in Nuclear Electric Fields and the Mean Life of the Neutral Meson*

H. PRIMAKOFF†

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

January 2, 1951

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 ($\sim Z^2$)

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

$\Longleftarrow$ Pion Polarizability

Chiral Anomaly
$F_{3\pi}$ ($\gamma \rightarrow 3\pi$), etc.

Meson Radiative Transitions
$\pi\gamma \rightarrow a^* \rightarrow \pi\,\pi\,\pi$ (etc.)

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

As COMPASS informal Primakoff spokesman, I drafted the Primakoff section of the proposal in 1996, **30 years ago**! Physics experiments started in 2002 with a muon beam and polarized proton and deuteron targets. ChPT tests via pion polarizability and chiral anomaly measurements began in 2009 using Primakoff scattering of pions.

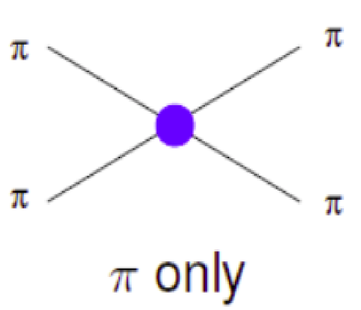
How to understand quark-gluon dynamics?

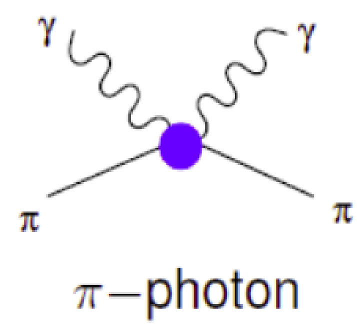
complicated system of interacting quarks and gluons

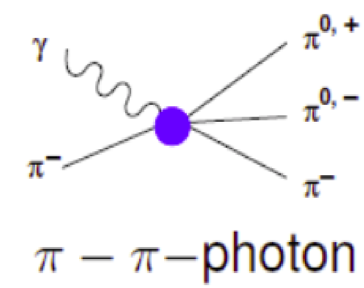
ChPT →

effective degrees of freedom at low energy: mass, charge, spin, effective (self-)coupling

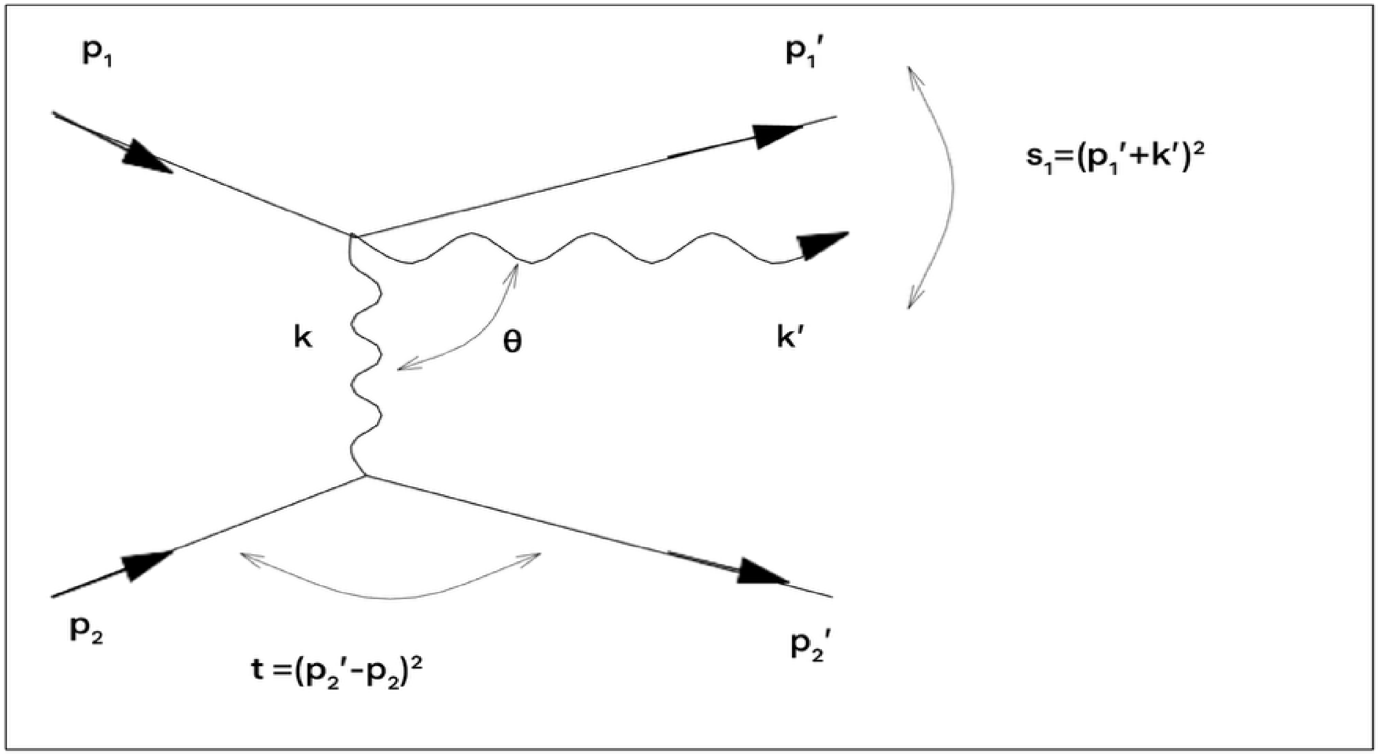
An approach pioneered by Weinberg and Goldstone, and worked out by Gasser and Leutwyler for the non-perturbative low-energy regime of the strong interaction.







The $\gamma\pi \rightarrow \gamma\pi$ Compton scattering cross section depends mainly on the pion charge. For γ energies in the range of $\omega = 60-780$ MeV (in pion rest frame) and scattering angles greater than 80°, approximately 5% of the differential cross section depends on the electric α_π and magnetic β_π charged pion polarizabilities.



Primakoff $\gamma\pi$ Compton process and kinematics. Four-momenta: p_1 (incoming pion), $p_{1'}$ (outgoing pion), p_2 (initial nucleus), $p_{2'}$ (recoiling nucleus), k (incoming virtual photon) and k' (outgoing real photon). θ is the photon scattering angle.

Determination of the pion polarizability by fitting the x_γ distribution of the Ratios $R_\pi=\sigma_E(x_\gamma,\alpha_\pi)/\sigma_{MC}(x_\gamma,\alpha_\pi=0)$ to the theoretical expression:

$$R_\pi = 1 - 72.7\,\frac{x_\gamma^2}{1-x_\gamma}\alpha_\pi.$$

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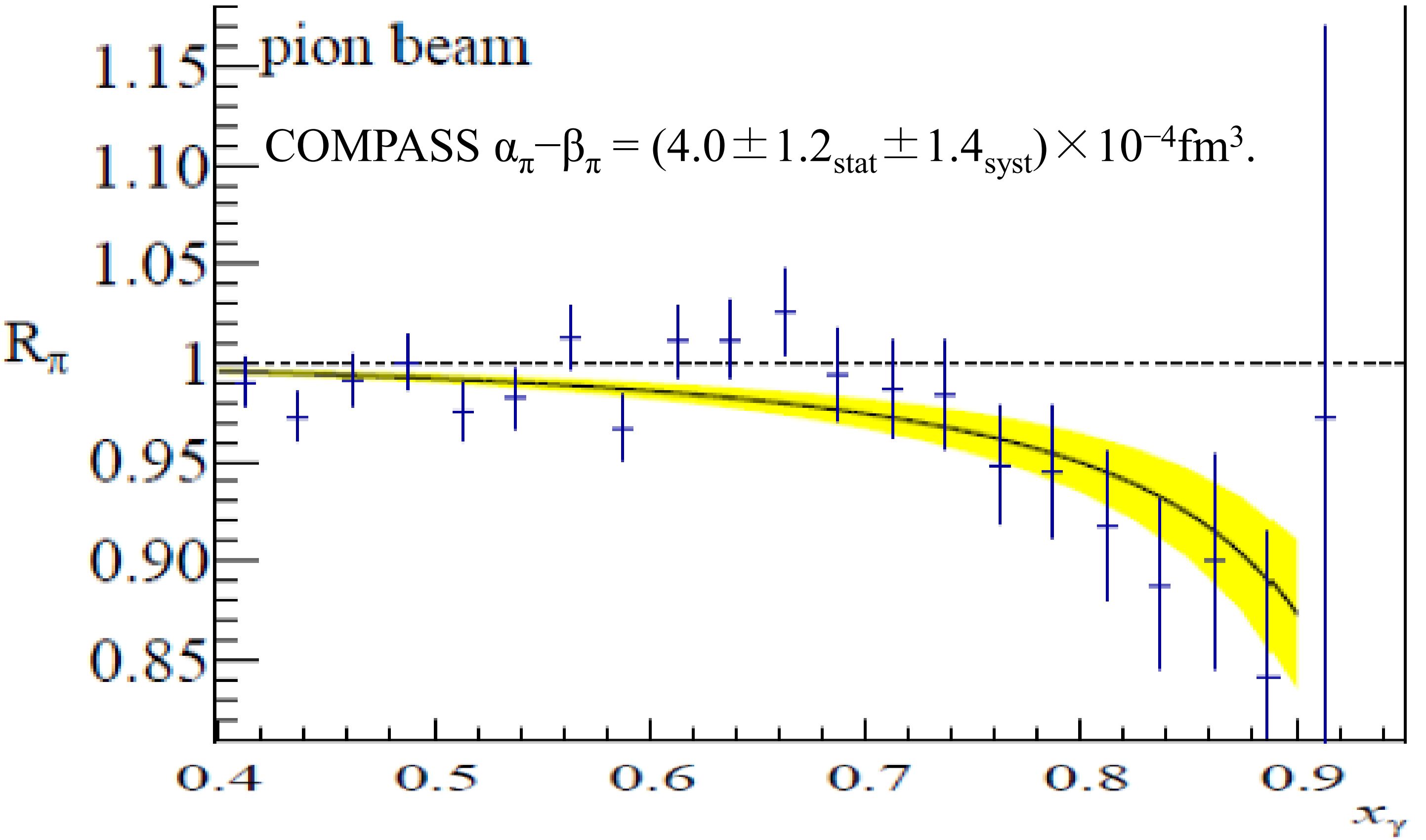
$x_\gamma=E_\gamma/E_\pi$ is the fraction of the beam energy carried by the final state γ.



Systematic uncertainties were estimated by measuring μ^- Ni → μ^- Ni γ cross sections & $K^- \rightarrow \pi^-\pi^0 \rightarrow \pi^-\gamma\gamma$. Statistics (63K events) 10X previously enabled this analysis.

Polarizability Summary

CERN COMPASS measured π^+ polarizabilities via radiative pion Primakoff scattering: $\boldsymbol{\alpha_\pi - \beta_\pi = 4.0 \pm 1.8}$

COMPASS π^+ Polarizabilities in good agreement with two-loop ChPT prediction $\boldsymbol{\alpha_\pi - \beta_\pi = 5.7 \pm 1.0}$, strengthening identification of the pion with the Goldstone boson of QCD.

Kaon Polarizability studies are planned at CERN AMBER.

The ChPT Chiral Anomaly

L_{eff} in ChPT must include Wess-Zumino-Witten (WZW) action terms. Classically the chiral (axial) current is conserved, but quantum effects (triangle diagram) produce the Adler–Bell–Jackiw Anomaly, whereby the divergence of the axial current is anomalous, not zero. The added WZW terms ensure that ChPT has the same anomalous behaviour as QCD. Chiral anomaly terms describe processes involving odd numbers of Goldstone bosons.

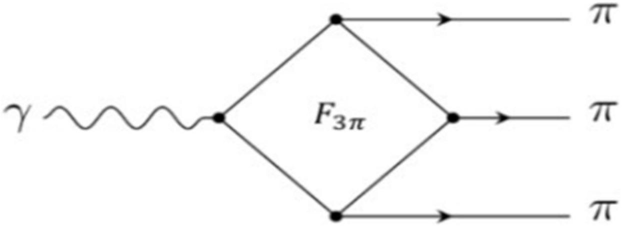
$\pi^0 \rightarrow \gamma\gamma$ Lifetime

1 pion

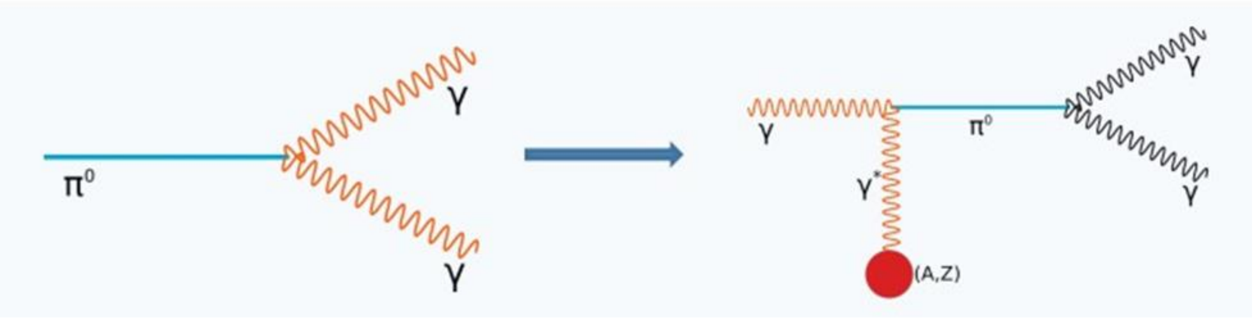
F_π

$\gamma\pi^- \rightarrow \pi^-\pi^0$

3 pions



Chiral Anomaly & the π^0 lifetime



The CA term controls the π^0 lifetime. 3-flavor ChPT is lower than 2-flavor ChPT by 4% due to mixing small η and η′ components into the π^0 wave function. Higher precision data and theory are needed to test ChPT.

- chiral anomaly, LO, 2-flavor $\tau(\pi^0) = \mathbf{8.48} \pm 0.02 \times 10^{-17} s$
- chiral anomaly, HO, 3-flavor $\tau(\pi^0) = \mathbf{8.14} \pm 0.11 \times 10^{-17} s$

- Experiment: $\tau(\pi^0) = (\mathbf{8.34} \pm 0.13 \text{ syst.}) \times 10^{-17}\text{s}$
  Larin et al., PrimEx, Jlab, 2020

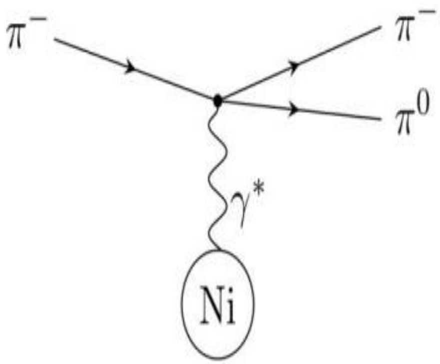
η Lifetime Primakoff Experiment is in progress at JLab

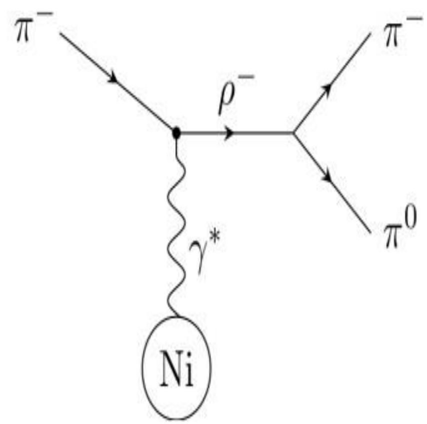
ChPT and experimental results for $\pi^0 \to 2\gamma$

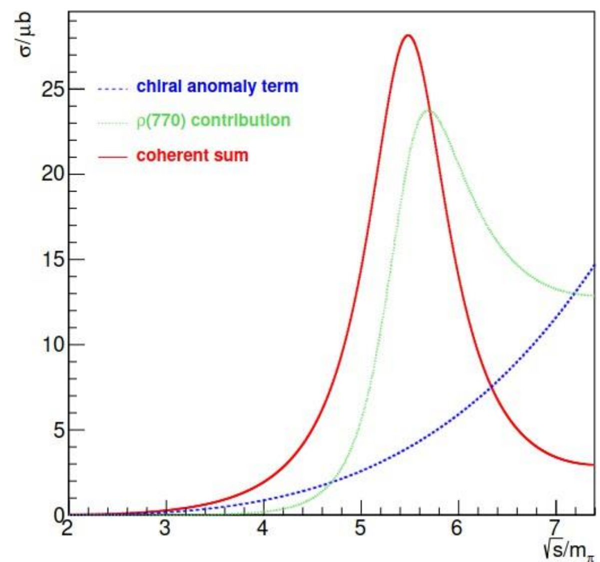
Theory(T), Exp(E)	$\tau(\pi^0)$ (10^{-17} s)
Theory 2-flavor	8.48±0.02
Theory 3-flavor	8.14±0.11
Exp, PrimEx	8.34±0.13

Jlab PrimEx is closer to 2-flavor (c,d) than 3-flavor ChPT; but agrees with both considering the uncertainties. Smaller uncertainties are needed. Overall, results confirm the ~applicability of ChPT in the CA sector. PrimEx studies of the η lifetime are planned at Jlab.

Primakoff $F_{3\pi}$ chiral anomaly $\pi\gamma \to \pi\pi$ and radiative ρ production $\pi\gamma \to \rho \to \pi\pi$ reactions both lead to a $\pi^-\pi^0$ final state







Contributions to the cross section for the reactions $\pi\gamma \to \pi\pi$ and $\pi\gamma \to \rho \to \pi\pi$ from the kinematic threshold where the chiral anomaly dominates, to the region of the ρ(770) resonance.

Extraction of the $F_{3\pi}$ and $\Gamma_{\rho\to\pi\gamma}$

Acceptance corrected number of Primakoff events in each bin are fitted with theoretical $\pi^- + Z \to \pi^- + \pi^0 + Z$ cross section. The data analysis extracts both the chiral anomaly amplitude and the radiative width of the ρ resonance, using a dispersive framework.

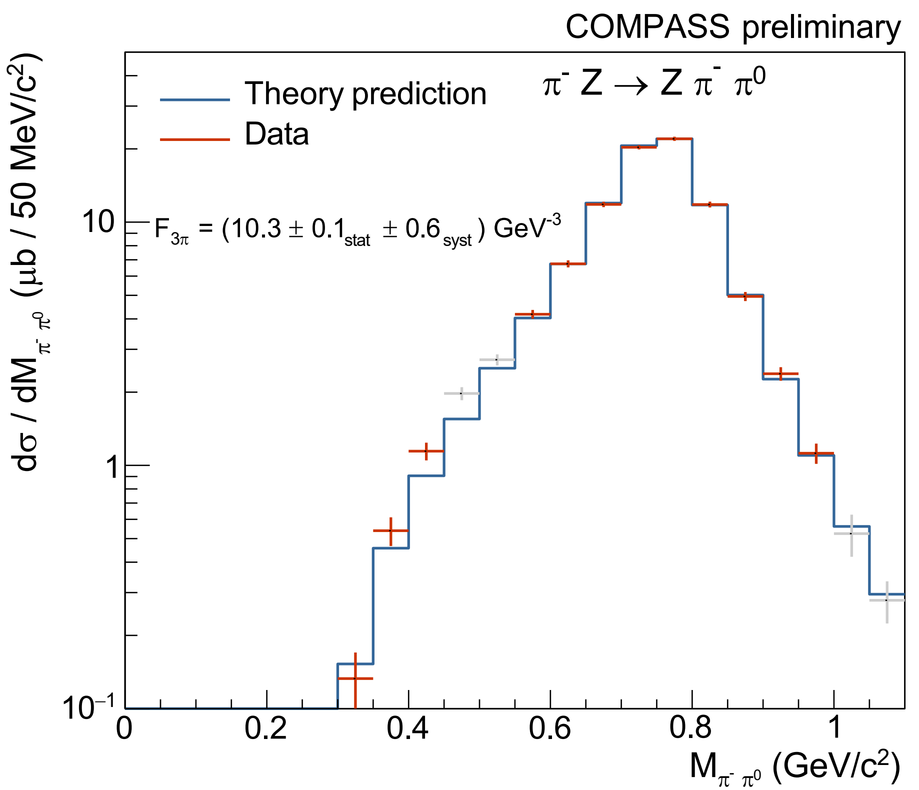


Table 2. Theoretical and experimental results for $\pi\gamma \rightarrow \pi\pi$

Theory(T), Exp(E)	$A_{3\pi}$ GeV^{-3}
E, COMPASS	10.3 ± 0.6
T, LO 2-flavor	9.7 ± 0.1
T, HO 3-flavor	10.7 ± 1.0

COMPASS $A_{3\pi}$ = 10.3 ± 0.6 GeV^{-3} aligns well with both the LO 2-flavor ChPT prediction $A_{3\pi} \approx 9.7 \pm 0.1$ GeV^{-3} and the HO 3-flavor ChPT prediction $A_{3\pi} \approx 10.7 \pm 1.0$ GeV^{-3}. Ongoing COMPASS analysis aims to reduce the uncertainty. PrimEx studies of the η lifetime and the COMPASS AMBER chiral anomaly reactions $\pi\gamma\rightarrow\pi\eta$ and $\gamma K\rightarrow \pi^0 K$ are being planned. More precise CA data are needed for comprehensive tests of 3-flavor ChPT.

Light-by-Light scattering measurement (I)

ATLAS EXPERIMENT

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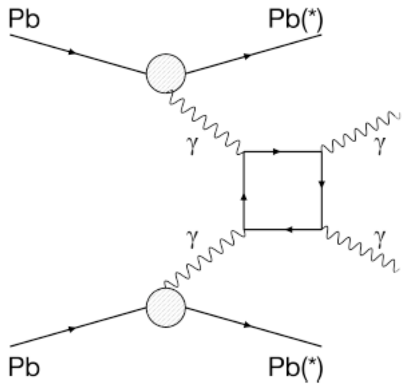
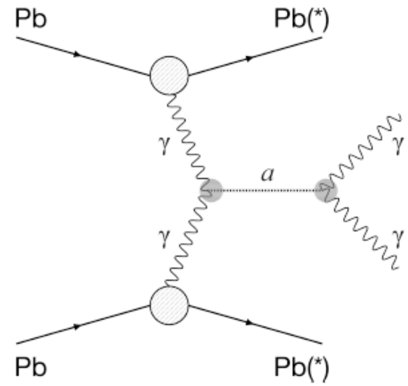
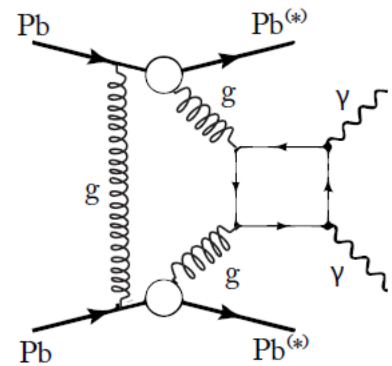
LbyL signal



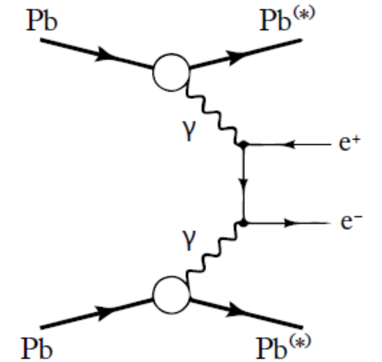
ALP signal



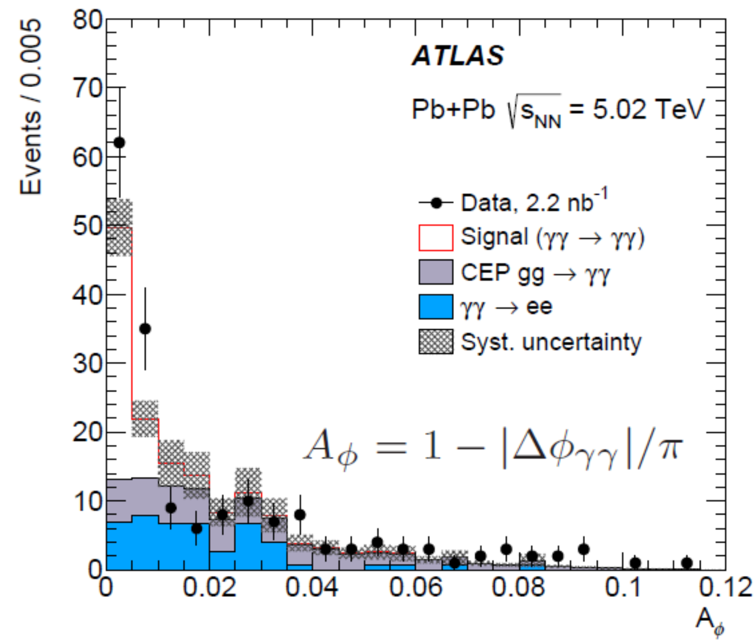
CEP background



$\gamma\gamma \to e^+e^-$ background



- Lowest order $\gamma\gamma \to \gamma\gamma$ scattering process in QED
- Involves virtual one-loop box via charged fermions and $W^\pm$ bosons
- Proposed as a **sensitive channel to study BSM processes** – axion-like particles (ALP) can modify $\gamma\gamma \to \gamma\gamma$ scattering rates in the form of narrow diphoton resonance
- Background: the central exclusive production (CEP), $gg \to \gamma\gamma$, and exclusive dielectron production, $\gamma\gamma \to e^+e^-$
- Modelling via SuperChic v3.0 (LbyL, CEP) and SuperChic v2.0 ($\gamma\gamma \to e^+e^-$, ALP)
- LbyL: **good agreement** with SM predictions



Summary: Details at https://arxiv.org/abs/2412.03669 and https://arxiv.org/pdf/2509.04649

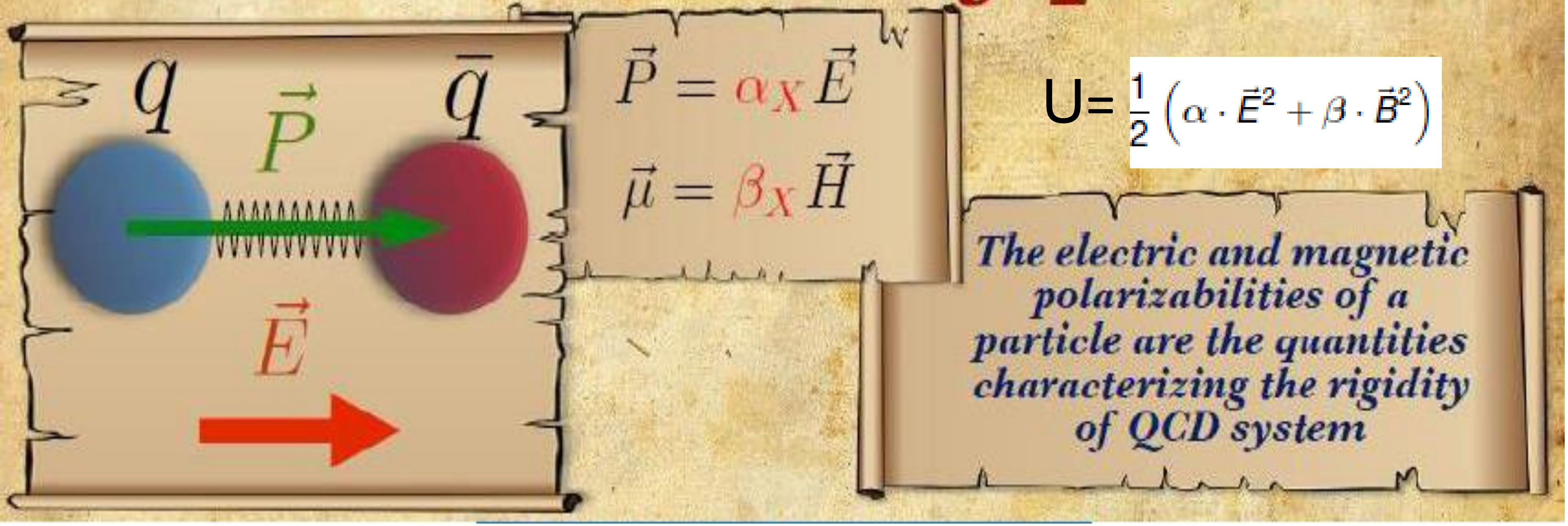
Henry Primakoff founded a field of study based on Primakoff reactions using virtual photons in the Coulomb field of an atomic nucleus, as targets.

Primakoff Reactions are being studied at CERN COMPASS and CERN AMBER and Jlab; for pion and kaon polarizabilities, the chiral anomaly $\gamma\pi \rightarrow \pi\pi^0$ reaction, radiative transitions of mesonic resonances, π^0 and η lifetimes, and $\pi\gamma \rightarrow \pi\eta$ and $K\gamma \rightarrow K\pi^0$ Primakoff Chiral Anomaly reactions.

The 1.5% π^0 lifetime and 6% $\gamma \rightarrow \pi\pi\pi$ CA preliminary results agree with chiral perturbation theory (ChPT) predictions.

High precision data and theory for all these processes are needed to fully test 2-flavor (u,d) and 3-flavor (u,d,s) ChPT.

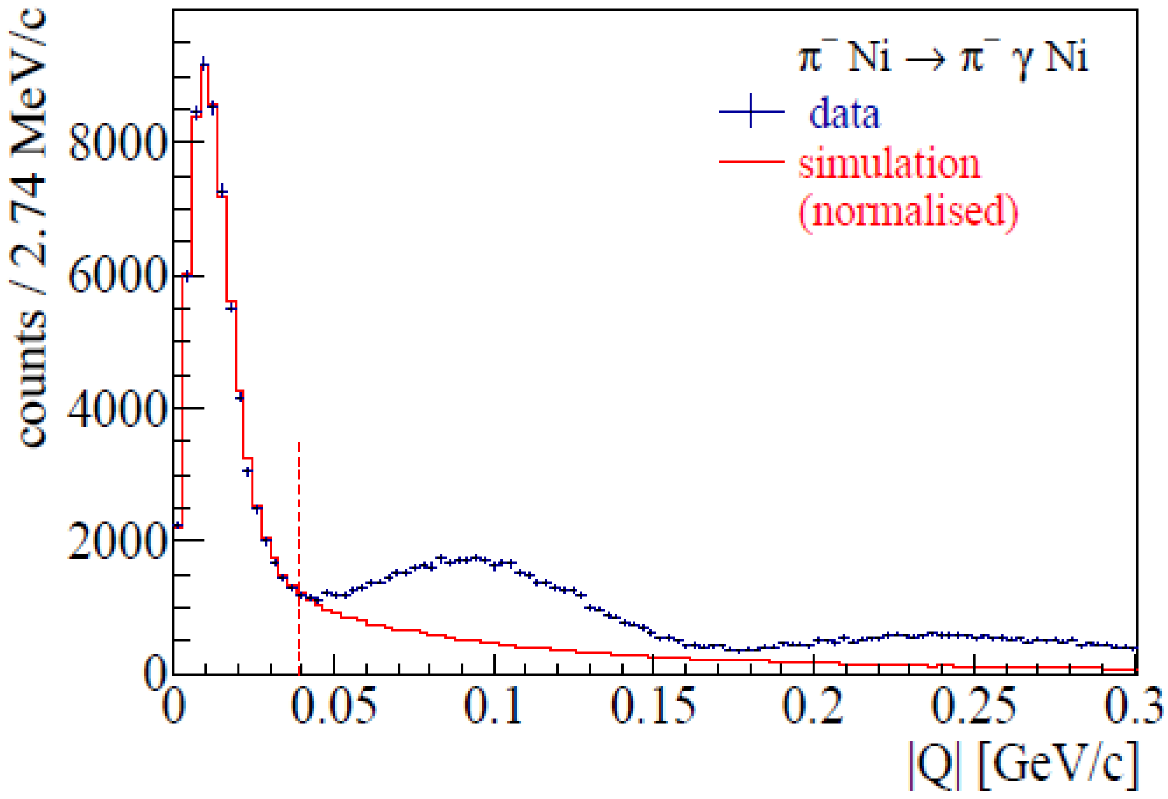
Polarizabilities of particles



- Pion Polarizabilities (α & β) are elementary structure constants, just as are its size and shape. For an electric field, the **induced electric dipole moment** is $\vec{P} = \alpha\overrightarrow{E}$.
- Pion Polarizabilities measure the amount of energy U stored in the deformation of the pion when exposed to an external EM field.
- Polarizabilities measure the pion’s stiffness against deformability, and hence the binding force between the constituent quarks.

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?

Light-by-Light scattering measurement (III)

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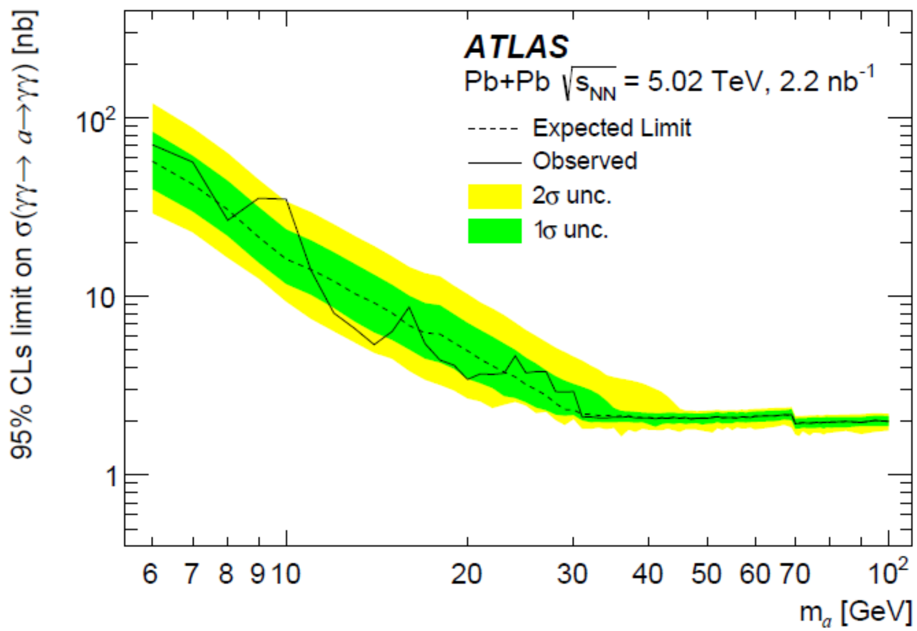
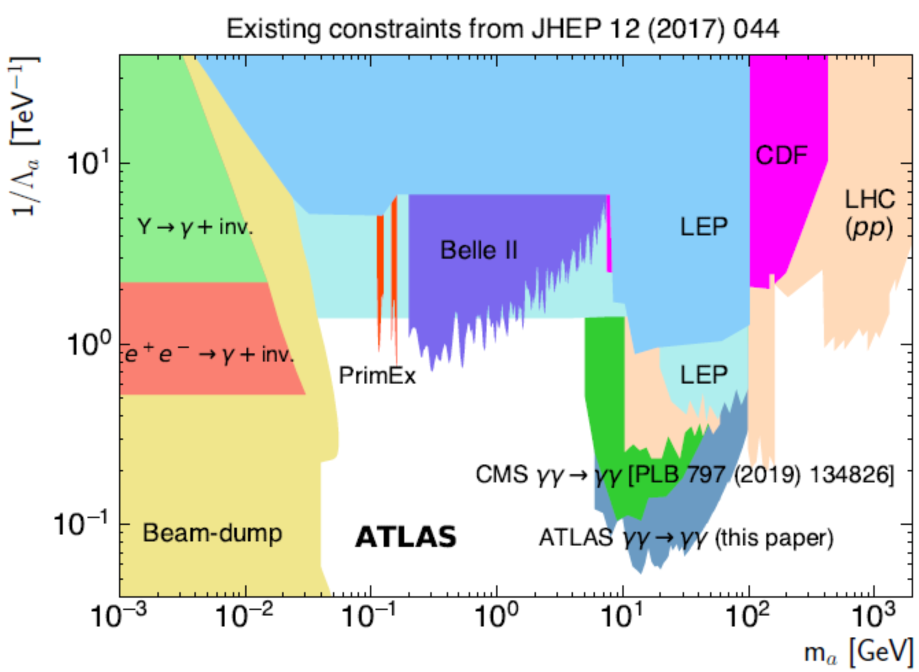
- Background: CEP, QED and SM LbyL
- MonteCarlo predictions with STARLIGHT v2.0
- Upper cross-section limits on ALP production in mass range between 6-100 GeV, with **the most stringent limits** between 10-100 GeV
- Recent CMS result [CMS-HIN-21-015] – better in very low mass range





Axion search at CERN ATLAS via γγ→γγ light-by-light scattering.

At CERN ATLAS LHC, Ultra-Peripheral Collisions, UPC, of 5.02 TeV heavy ions (Pb+Pb) allowed studying 2-photon light-by-light (LbL) reactions, using interacting virtual photons. The Z^4 enhanced photon-photon luminosity from the heavy ions provides a large exclusive production rate. This UPC LbL reaction was used to search for axions in the mass range 6-100 GeV. Axions are pseudoscalar (non-parity conserving) dark matter candidates predicted to occur in many extensions of the Standard Model (SM). Their existence would solve fundamental problems in physics, particularly the strong CP problem and the nature of dark matter. They are expected to have low mass and weak coupling to other particles. Across the mass range of 0.001 to 1000 GeV, over a wide range of axion-photon couplings, their existence was previously extensively constrained by a blend of astrophysical observations and dedicated experimental searches. ATLAS at CERN LHC conducted a low statistics (97 events) search for the axion via UPC γγ→γγ (LbL) scattering. An axion (a) produced as a resonance in the γγ→a→γγ subprocess would modify the LbL scattering cross section. Backgrounds from γγ→e+e−→γγ and gg→γγ were suppressed. In this experiment, axions should have showed up as a narrow resonance in the measured diphoton mass spectrum. But the measured LbL cross section was consistent with the SM prediction. No cross-section excess beyond the SM prediction was observed. The data allowed setting new exclusion limits at 95% CL on axions in the plane of axion-photon coupling strength (1/Λa) versus axion mass; in the mass range 6-100 GeV and coupling strength mass parameter Λa ≈ 2-15 TeV. Ongoing and upcoming experiments, including advancements in detection technologies and new experimental setups, are needed to detect axions or to improve constraints on their properties, particularly in unexplored regions of the parameter space. The ATLAS experiment effectively ruled out the mass region 6-100 GeV.