Measurements of the Chiral Anomaly at COMPASS

The 11th International Workshop on Chiral Dynamics,
Ruhr University Bochum, August 26-30 2024

Andrii Maltsev on behalf of the COMPASS collaboration[1]

Technical University of Munich, E18

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[1] andrii.maltsev@cern.ch

The chiral symmetry of QCD

- Description of low energy hadronic interactions: phenomenological models based on fundamental properties of QCD
- QCD Lagrangian density:

$$\mathscr{L} = \sum_{\substack{f=u,d,s,\\c,b,t}} \overline{q_f}(i\not{D} - m_f)q_f - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a$$

- Chiral limit ($m_f \to 0$):
  - left- and right-handed fields decouple
  - flavour symmetry $SU(3)_L \times SU(3)_R$
  - spontaneously broken → massless Goldstone bosons (π, K, η)
  - explicitly broken → Goldstone bosons obtain mass

The chiral anomaly of QCD

- QCD Lagrangian density:

$$\mathscr{L} = \sum_{\substack{f=u,d,s,\\c,b,t}} \overline{q_f}(i\not{D} - m_f)q_f - \frac{1}{4}G^a_{\mu\nu}G^{\mu\nu}_a$$

- Chiral limit ($m_f \to 0$): axial U(1) symmetry
- Chiral anomaly: symmetry of classical Lagrangian violated at quantum level
- π^0 lifetime explained by the chiral anomaly:
  - pre-chiral anomaly, PCAC: $\tau(\pi^0) \approx 10^{-13}s$
  - chiral anomaly, LO: $\tau(\pi^0) = 0.838 \times 10^{-16}s$

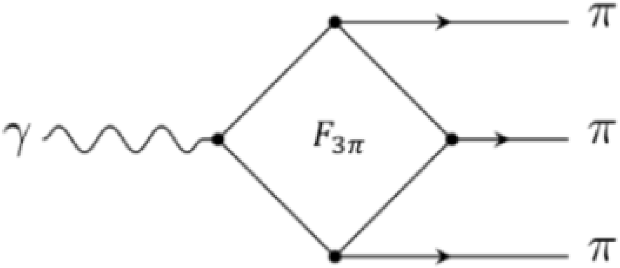
    [*J.Bell, R.Jackiw, Nuovo Cim. A60, 47 (1969)*]

    [*S.L.Adler, Phys.Rev. 177, 2426 (1969)*]
  - first measurement (CERN, 1963): $\tau(\pi^0) = (1.05 \pm 0.18) \times 10^{-16}s$

    [*C.von Dardel et al., Phys. Lett. 4, 51 (1963).*]

Predictions of the chiral anomaly

- Chiral anomaly governs processes with odd number of Goldstone bosons:
  - $\pi^0 \to \gamma\gamma$
  - $\gamma\pi^- \to \pi^-\pi^0$
  - $\gamma\pi^- \to \pi^-\eta$
  - $\gamma K \to K\pi^0$
- Chiral anomaly → predictions at the chiral limit, χPT → expansion to physical region
- χPT: effective perturbative Lagrangian constructed from Goldstone boson fields + low energy constants



Chiral anomaly at LO:

- $F_{3\pi} = F_{K\pi K\gamma} = \frac{e}{4\pi^2 f_\pi^3} =$ 9.78 ± 0.05 GeV^{-3}
- $F_{\eta\pi\pi\gamma} = \frac{e}{4\sqrt{3}\pi^2 f_\pi^3} =$ 5.65 ± 0.03 GeV^{-3}

[*Wess J., Zumino B. Phys. Lett. 1971, 37B, p.95.*]

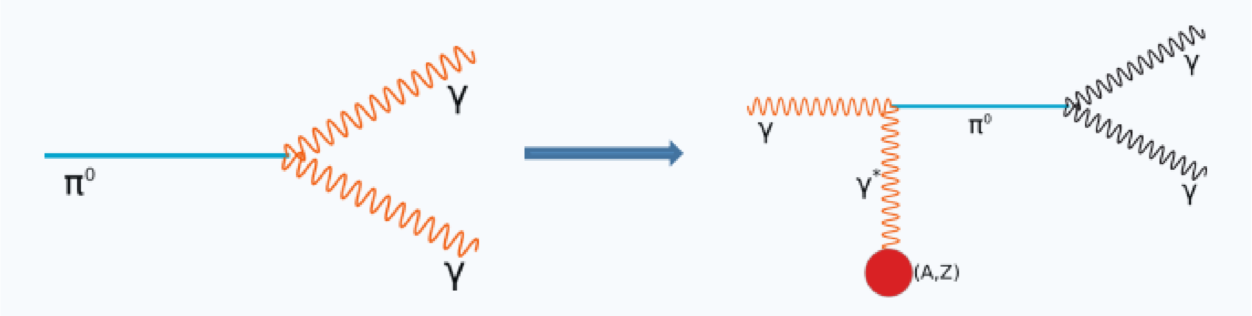
[*Witten E. Nucl. Phys. 1983, B223, p.422.*]

[*B.Kubis, J.Pletner (EPJC 75:283,2015)*]

Ways to access π^0 lifetime

Ideas for π^0 lifetime measurement:

- Direct: measure lifetime ($\gamma c \tau$)
- Inverse kinematics with quasi-real photons:
  - Primakoff: $\gamma^* \gamma \rightarrow \pi^0$, with γ^* from Coulomb field of the nucleus



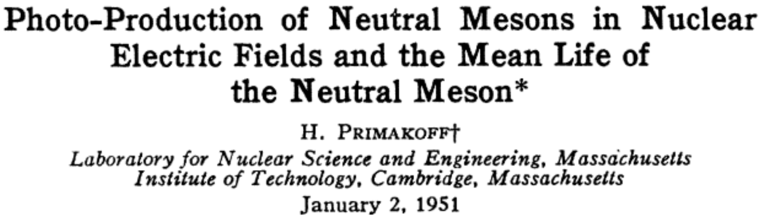


Photo-Production of Neutral Mesons in Nuclear Electric Fields and the Mean Life of the Neutral Meson*

H. PRIMAKOFF†

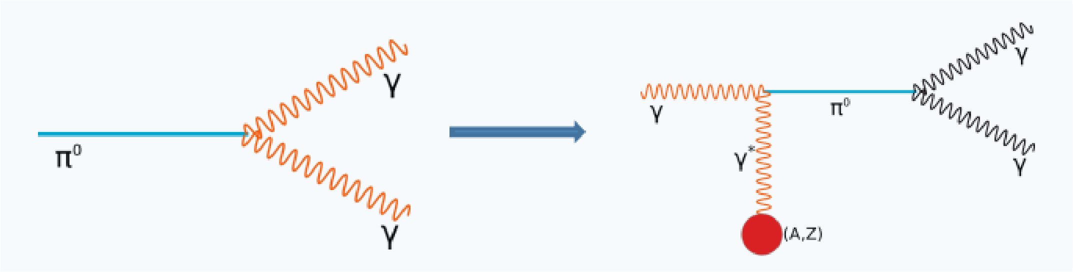
Laboratory for Nuclear Science and Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts

January 2, 1951

Nucleus Coulomb field is seen as a source of quasi-real photons

- This talk: Primakoff → processes with photons

The Primakoff technique

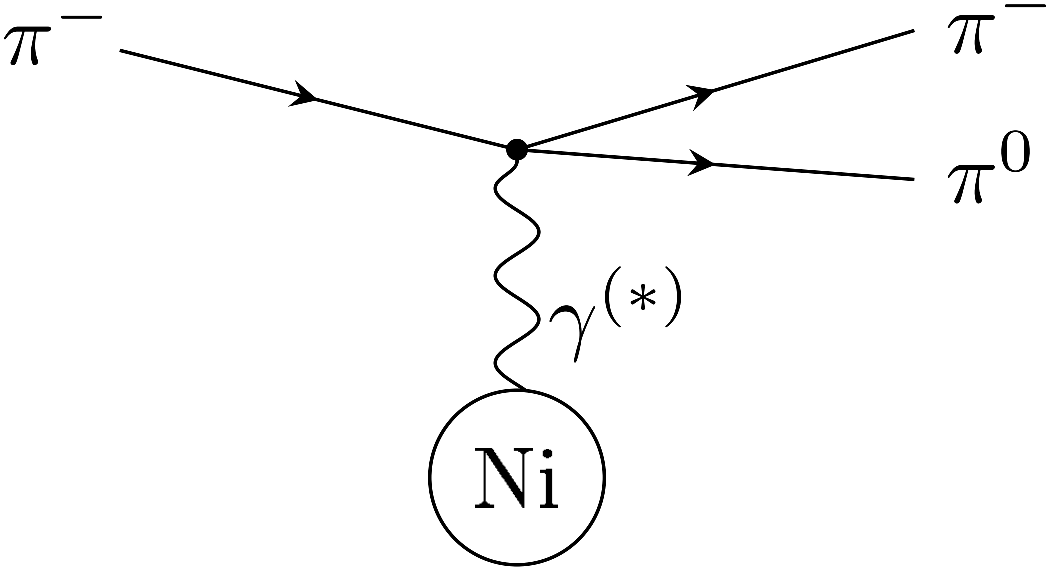


- Large distance interaction $\hat{=}$ low momentum transfer to the nucleus
- Access to the processes governed by chiral anomaly via electromagnetic reaction with the nucleus

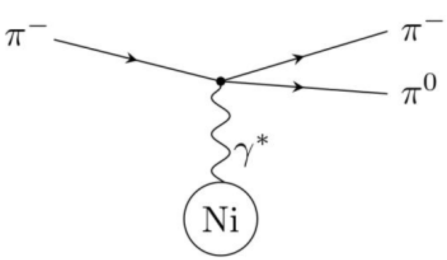
$$\frac{d\sigma_{Prim}}{dQ^2} \propto Z^2 \cdot \frac{(Q^2 - Q^2_{min}(p_{beam}))}{Q^4} \cdot |F_{em}|^2(Q^2)$$

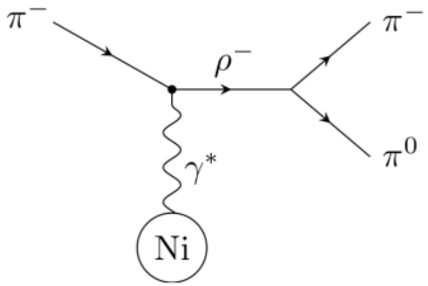
- Q: momentum transfer to the nucleus
- charge Z, electromagnetic form factor F_{em}: properties of the nucleus

The $\gamma\pi \to \pi\pi$ vertex

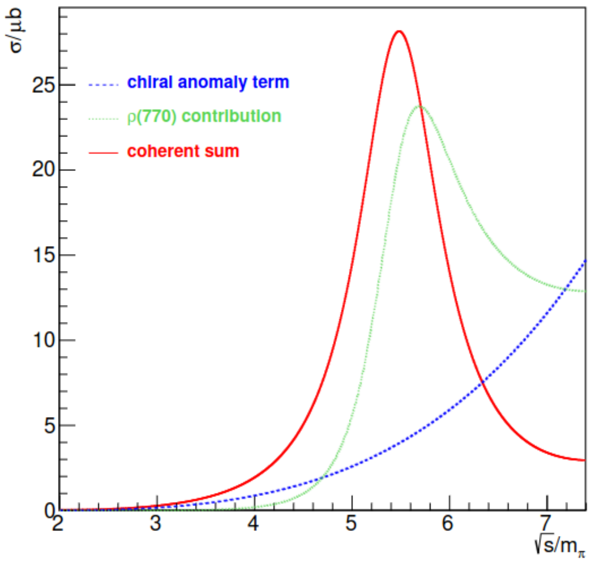


The $\gamma\pi \to \pi\pi$ vertex: production of the $\pi^-\pi^0$ final state



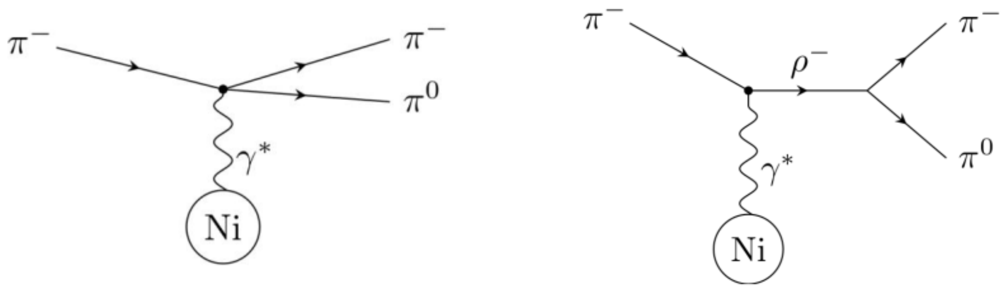


- dispersive approach to utilize the $\pi\pi$ P-wave phase shift: [*M.Hoferichter, B.Kubis, D.Sakkas (PRD 86:116009,2012)*]
- description of both:
  - effective 4-point $\gamma\pi \to \pi\pi$ coupling
  - $\gamma\pi \to \rho \to \pi\pi$ process
- two free parameters $C_2^{(1)}, C_2^{(2)}$ have to be constrained from experimental data
- information gained from interference of two contributions



[*A.Afanasev et al. arXiv:2306.14578*]

Bridging theory and experiment: $\gamma\pi \to \pi\pi$



- the dispersive description matched with NLO χPT:

  [*T.Hannah (Nuclear Physics B 593(3):577-595)*]
  - dispersive description: parameters $C_2^{(1)}, C_2^{(2)}$
  - NLO χPT: low energy constants
- $F_{3\pi}$ and $\Gamma_{\rho\to\pi\gamma}$ can be calculated from the two parameters

  [*M.Hoferichter, B.Kubis, M.Zanke (PRD 96, 114016, 2017)*]
- low energy constant in NLO χPT → 20% uncertainty → 1% uncertainty in $F_{3\pi}$

  [*J. Bijnens, A. Bramon, F. Cornet (Phys.Lett. B 237, issues 3-4 1990)*]

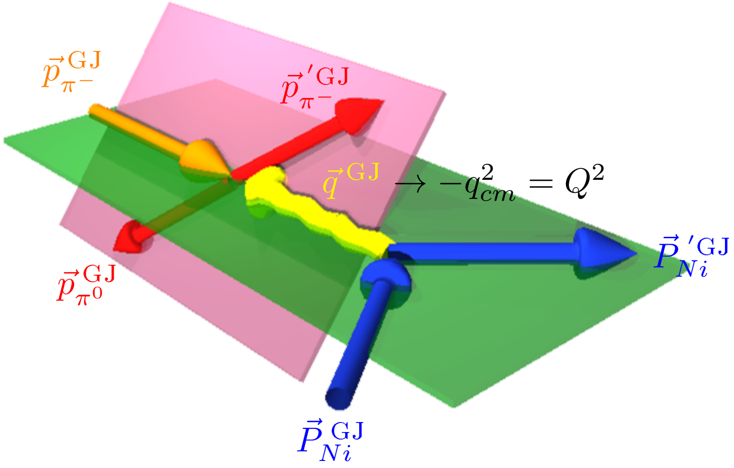
  [*M. Niehus, M. Hoferichter, B. Kubis (JHEP 12, 038, 2021)*]
- see also talk of Bai-Long Hoid (Monday 14:00 WG1)

Kinematic distributions for $\gamma\pi \to \pi\pi$

$$\sigma_{\gamma\pi\to\pi\pi}(s) = \frac{(s-4M_\pi^2)^{3/2}(s-M_\pi^2)}{1024\pi\sqrt{s}} \int_{-\pi/2}^{\pi/2} dcos\theta \sin^2\theta |F(s,t,u)|^2,$$

$$s = (p'_{\pi^-} + p_{\pi^0})^2, t = (p'_{\pi^-} - p_{\pi^-})^2, u = (p_{\pi^0} - p_{\pi^-})^2$$

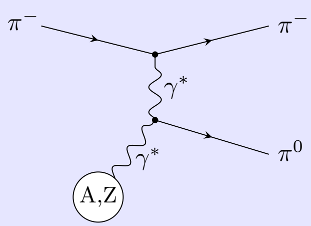
- amptitude $F(s,t,u)$: numerically calculated for fixed $C_2^{(1)}, C_2^{(2)}$, using input from [*M.Hoferichter, B.Kubis*]
- before including radiative corrections (see next slide): angles of π^- in Gottfried-Jackson frame $\propto sin^2\theta_{\pi^-}$, $\propto sin^2\phi_{TY}$



[*Picture by Dominik Ecker*]

Radiative corrections for $\gamma\pi \to \pi\pi$

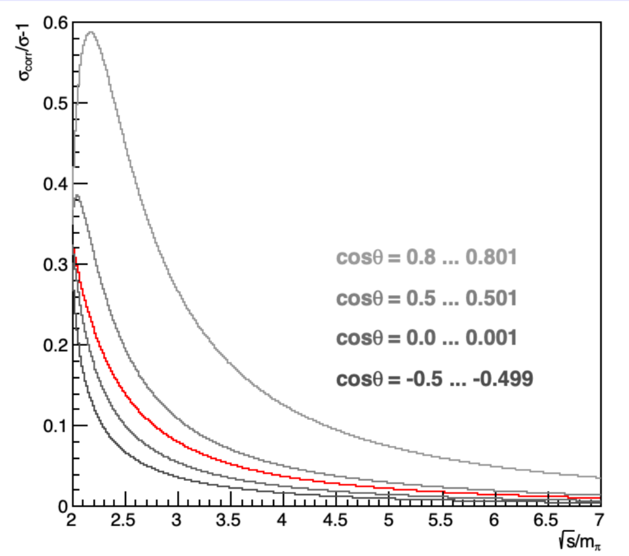
t-pole diagram



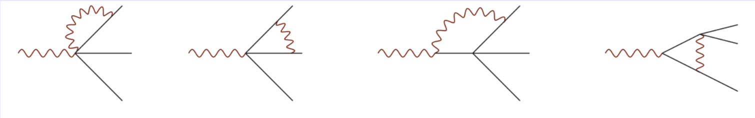
the dominant correction, modifies angular distributions

$$F(s,t,u) \to F(s,t,u) - \frac{2e^2F_\pi^2}{t}F_{3\pi}$$

[*J.Friedrich, Radiative Corrections from medium to high energy experiments (conference talk)*]



Real + virtual photon correction



[*Ametller et al. PRD 64 (2001) 094009*]

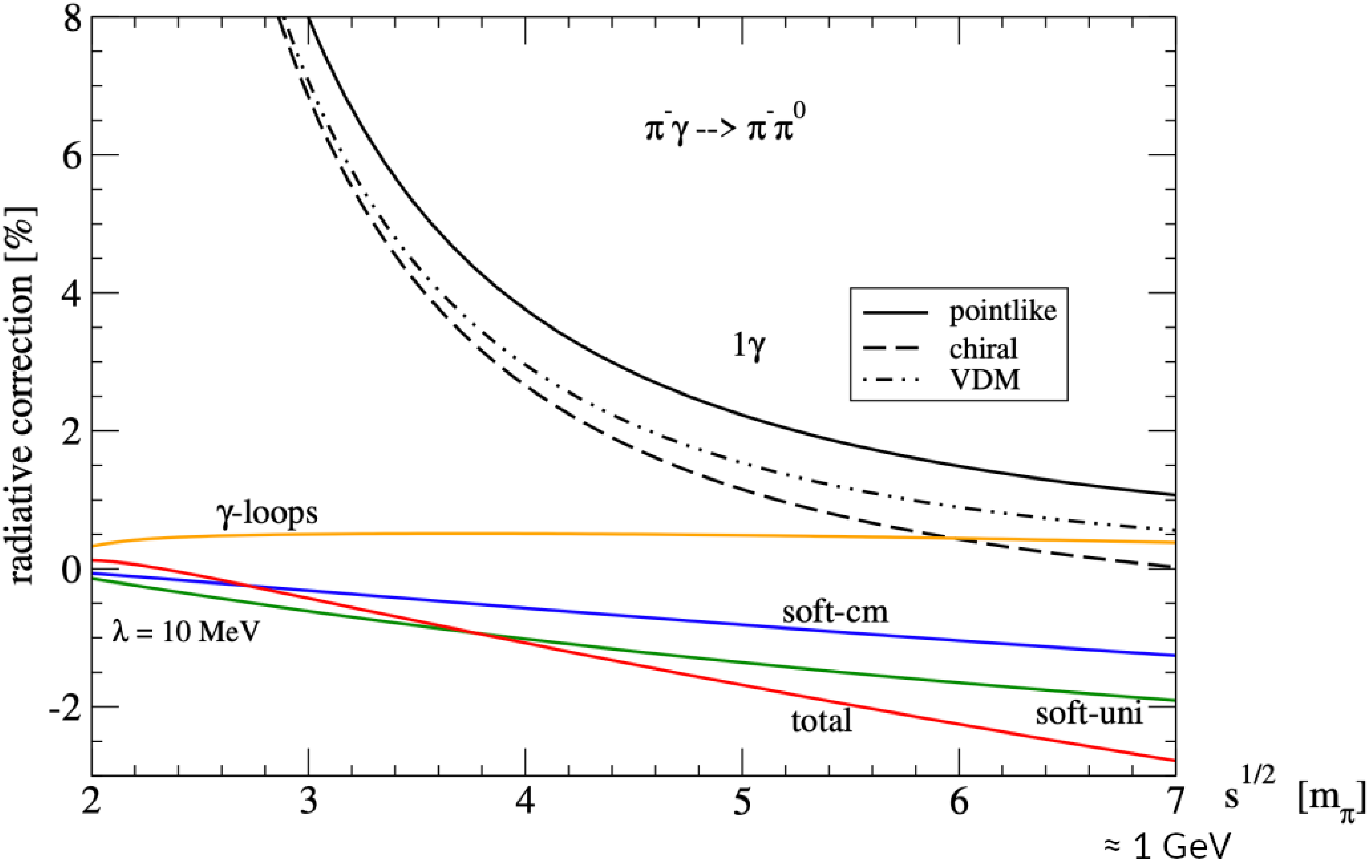
- Calculations:

  [*Ametller et al.*]

  [*PRD 64 (2001) 094009*]

- checked, extended and corrected by [*Norbert Kaiser*] (real photon contribution)

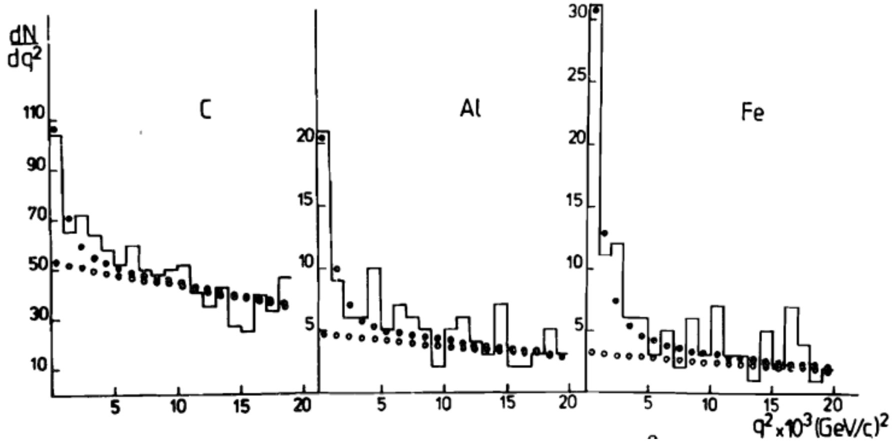
Radiative corrections for $\gamma\pi \to \pi\pi$

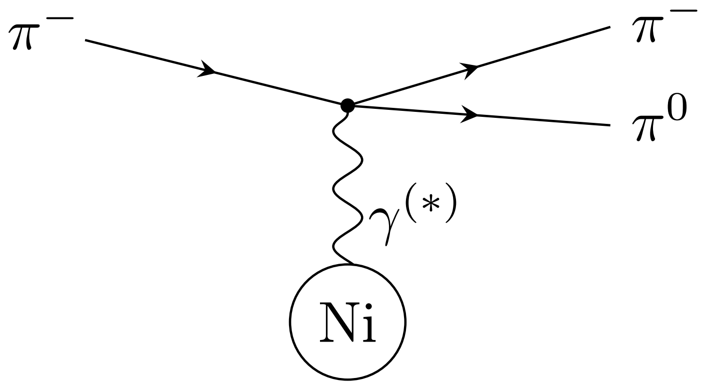


[*J.Friedrich, Radiative Corrections from medium to high energy experiments (conference talk)*]

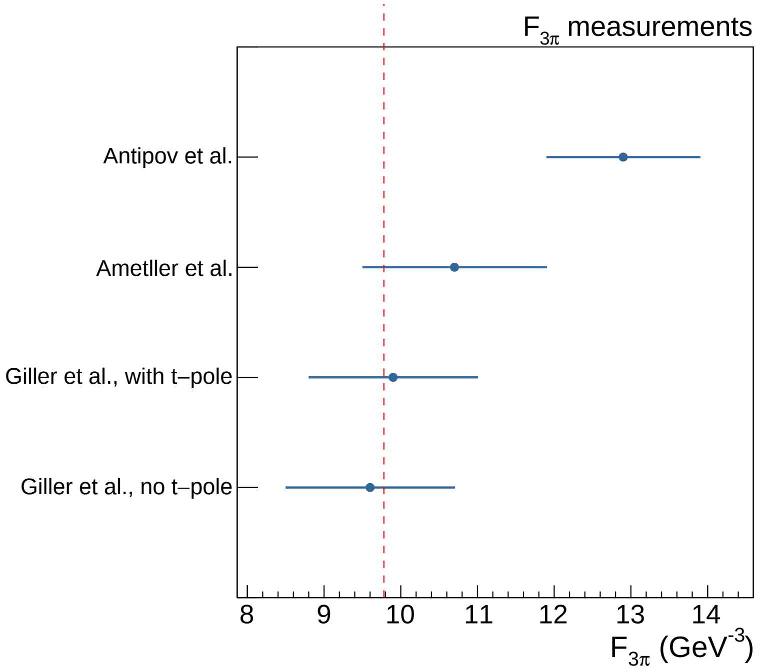
Measurement of $F_{3\pi}$ at SIGMA (Serpukhov)

- 40 GeV pion beam; C, Al, Fe targets
- Cut on threshold events: $M_{\pi^-\pi^0} < 0.427$ GeV/c^2
- Antipov et al.: $F_{3\pi} = 12.9 \pm 0.9_{stat} \pm 0.5_{syst}$ GeV^{-3}
- Radiative corrections not calculated in the original paper; poor control of systematics
- [*Ametller et al. PRD 64 (2001) 094009*] → re-analyzed experimental result with chiral corrections up to (p^8): $F_{3\pi} = 10.7 \pm 1.2$ GeV^{-3}





Comparison of results on $F_{3\pi}$



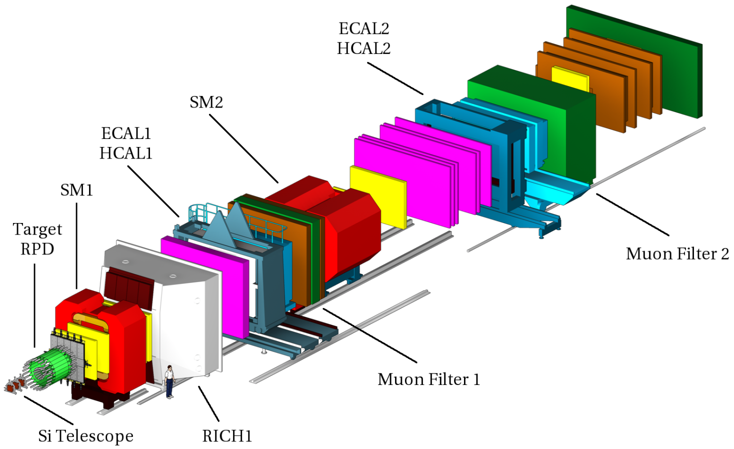
- Antipov et al.: $F_{3\pi} = 12.9 \pm 0.9_{stat} \pm 0.5_{syst}$ GeV^{-3}
- *[Ametller et al. PRD 64 (2001) 094009]* → reanalyzed experimental result with chiral corrections up to (p^8): $F_{3\pi} = 10.7 \pm 1.2$ GeV^{-3}

- $F_{3\pi}$ also measured in scattering of pions on electrons in an atomic orbit: $\pi^+ + e^- \to \pi^- + e^- + \pi^0$ *[Amendolia et al., Phys.Lett.155B, 5-6 (1985)]*
- $F_{3\pi} = 9.9 \pm 1.1$ GeV^{-3} without t-pole correction
- $F_{3\pi} = 9.6 \pm 1.1$ GeV^{-3} with t-pole correction

  [I.Giller, A.Ocherashvili, T.Ebertshauser, M.A.Moinester, S.Scherer, EPJA 25 (2005) 229-240]
- Chiral anomaly LO prediction: $F_{3\pi} = 9.78 \pm 0.05$ GeV^{-3}

The COMPASS experiment

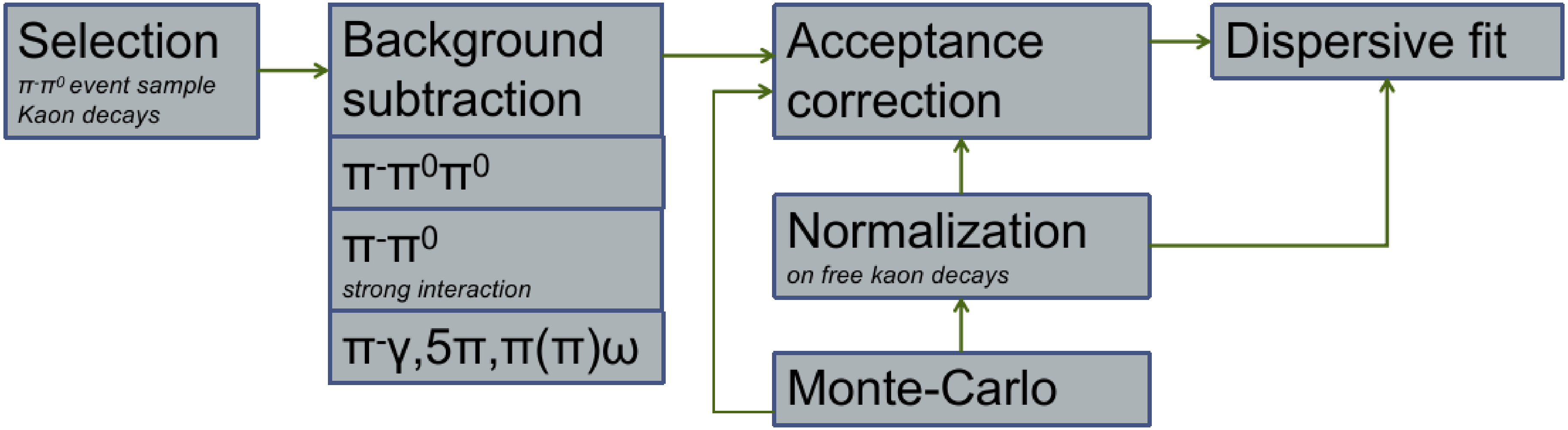
COMPASS setup for Primakoff runs



- Two-stage spectrometer → small-angle calorimeter for Primakoff (low-Q) processes
- Beam composition ($E_{beam} = 190$ GeV): 2.4% kaons, 97% pions + PID
- Three Primakoff data runs: 2004 (test run), 2009, 2012 (3x statistics of 2009)

- this talk → 2009 data
- Triggering on energy deposition in the center part of the calorimeter (E > 60 GeV)
- Nickel target with $X/X_0 = 0.3$, Z = 28 → trade-off between Primakoff cross section ($\propto Z^2$) and radiative corrections

The outline of the $F_{3\pi}$ measurement at COMPASS



Selection

$\pi^-\pi^0$ event sample
Kaon decays

Background subtraction

$\pi^-\pi^0\pi^0$

$\pi^-\pi^0$
strong interaction

$\pi^-\gamma, 5\pi, \pi(\pi)\omega$

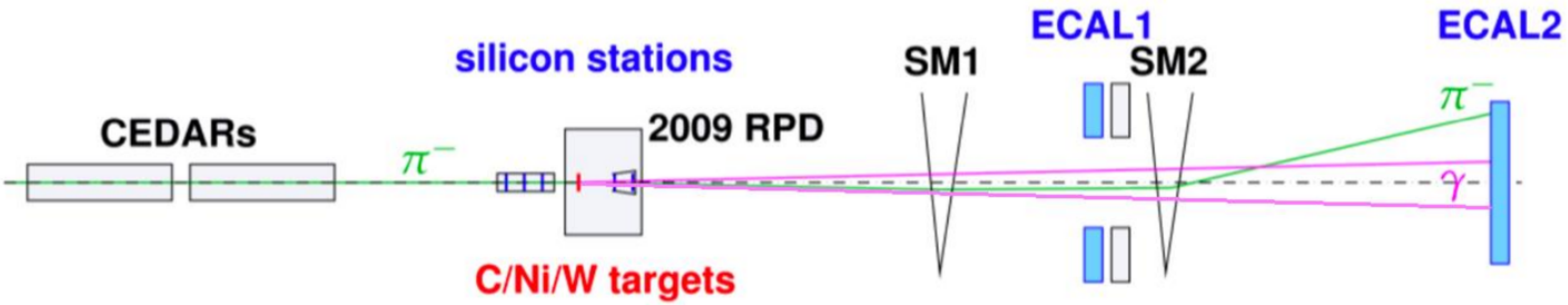
Acceptance correction

Dispersive fit

Normalization
on free kaon decays

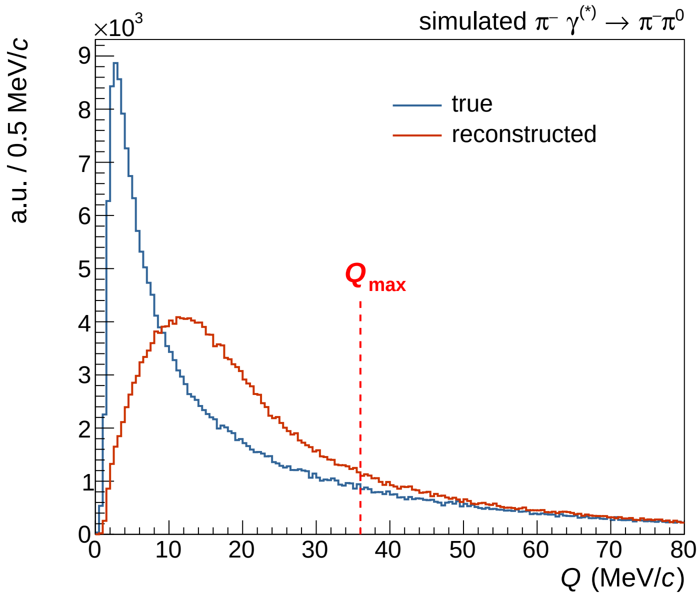
Monte-Carlo

Schematic of the measurement



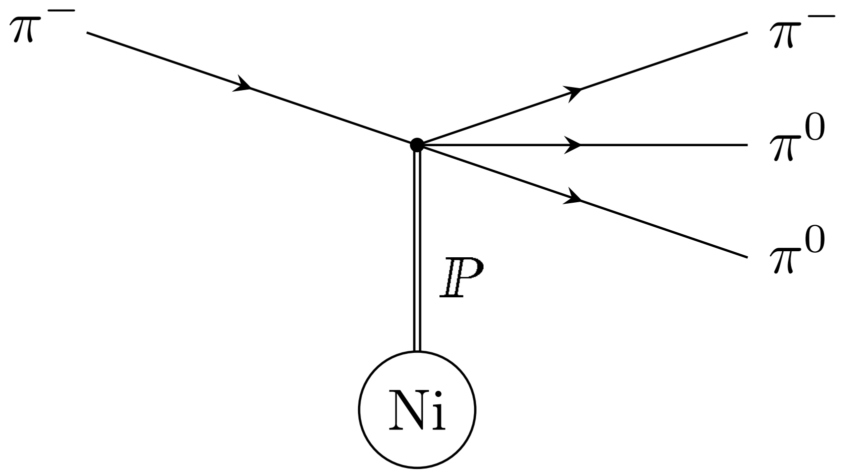
[*Picture by Dominik Ecker*]

- Selection: exclusive (-7.5 GeV $< \Delta E <$ 7.5 GeV) $\pi^-\pi^0$ events
- Q resolution $\approx$ 12 MeV $\rightarrow$ Primakoff peak at low Q_{reco}, selection: $Q <$ 36 MeV
- ECAL trigger: only events with forward π^0: $cos\theta_{\pi^-} < 0.2$



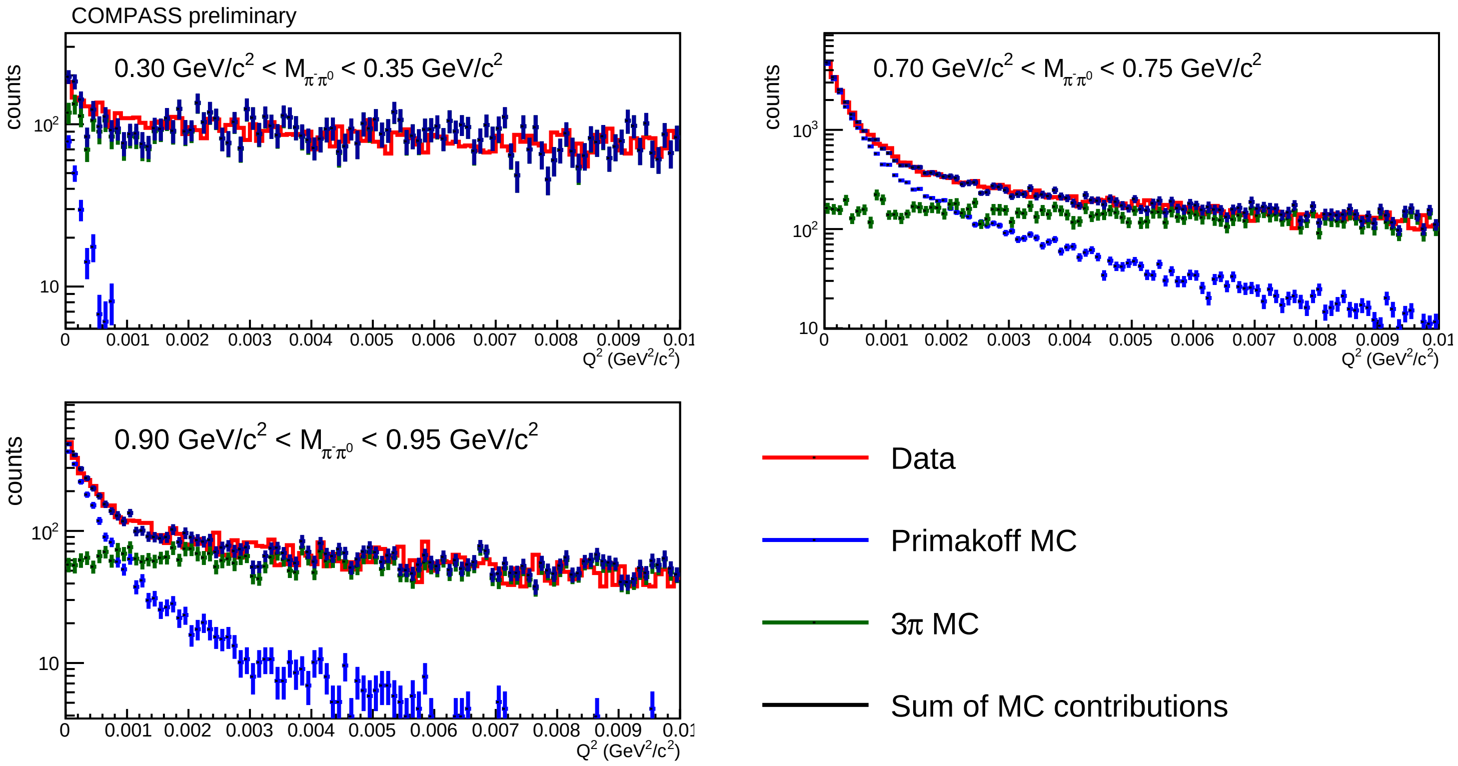
Background for the $\pi^-\pi^0$ final state

- Dominant background: $\pi^- + (Z, A) \rightarrow \pi^- + \pi^0 + \pi^0 + (Z, A)$
- not forbidden by G-parity conservation → large cross section
- partial wave analysis of $\pi^-\pi^0\pi^0$ final state → soft/undetected π^0 → reconstructed as $\pi^-\pi^0$ [*PhD thesis of Markus Krämer*]



Extraction of the number of Primakoff events

- Current approach: utilize the low-Q Primakoff peak



- Outlook: utilize ϕ_{TY}, $cos\theta_{GJ}$, energy balance

Normalization via kaon decays

- COMPASS Primakoff run: no direct measurement of beam particle flux
- beam contains 2.4% kaons → use $K^- \to \pi^-\pi^0$ selection to calculate kaon flux
- knowledge of kaon/pion beam composition ratio → pion flux
- same final state as $\pi^-\pi^0$: similar systematics + rigorous test of MC simulation

Number of detected kaon decays

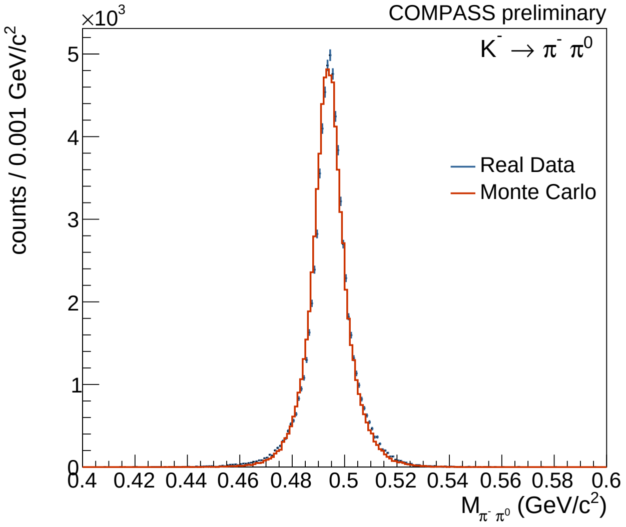
Kaon/pion flux ratio

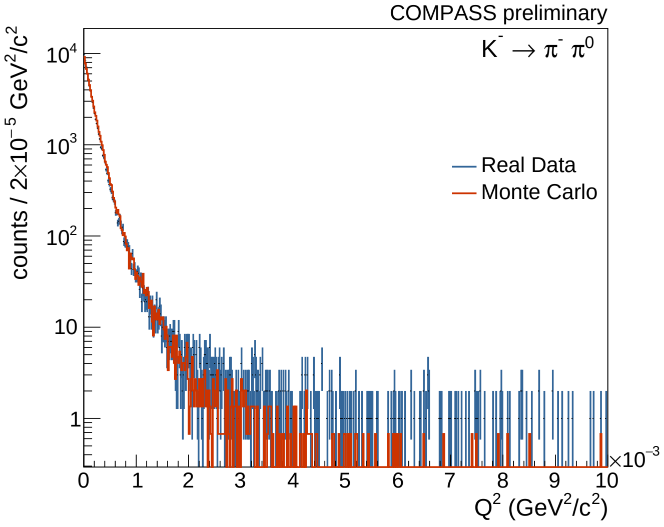
$$N_K = \Phi_\pi \frac{n_K}{n_\pi} \underbrace{BR(K^- \to \pi^0\pi^-)}_{\text{Branching ratio}} \overbrace{(1 - e^{-\frac{L}{\gamma c\tau}})}^{\text{Probability of kaon decaying in region with length L}} \epsilon_K$$

Pion flux

Acceptance for kaon decays for particular final state

Normalization via kaon decays





- well-understood kinematics: $M_{2\pi} = M_{K^-}$
- free kaon decay: $Q = 0 \rightarrow$ good control of setup resolution

Excellent agreement of MC and data

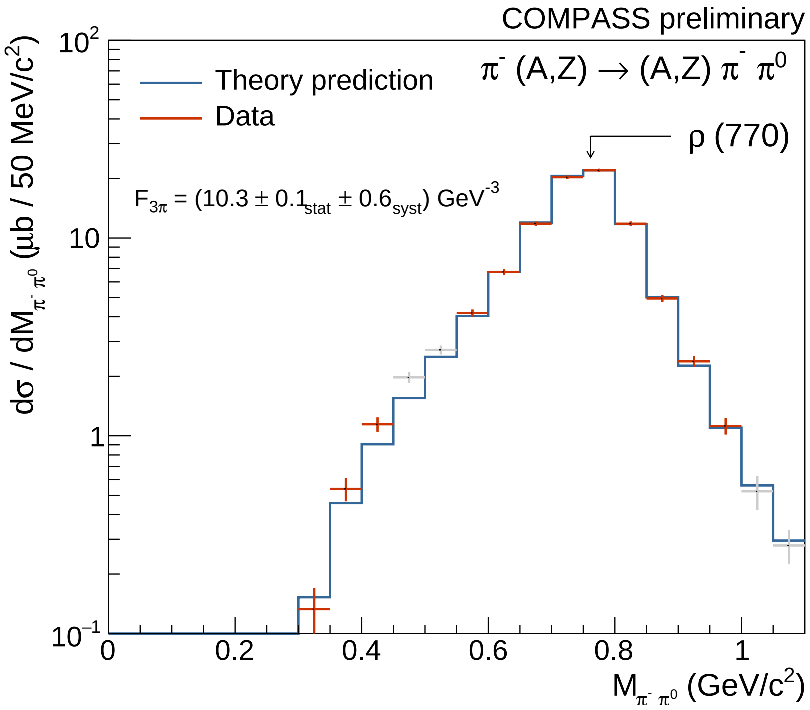
Extraction of the $F_{3\pi}$ and $\Gamma_{\rho\rightarrow\pi\gamma}$

- Acceptance corrected number of Primakoff events in each bin fitted with theoretical $\pi^- + (Z,A) \rightarrow \pi^- + \pi^0 + (Z,A)$ cross section

  [*M.Hoferichter, B.Kubis, D.Sakkas (PRD 86:116009,2012)*]

$$F_{3\pi} = 10.3 \pm 0.1_{stat} \pm 0.6_{syst}\ \text{GeV}^{-3}$$

$$\Gamma_{\rho\rightarrow\pi\gamma} = 76\ ^{+10}_{-8}\ \text{keV}$$



Systematics of the preliminary measurement

$F_{3\pi} = 10.3 \pm 0.1_{stat} \pm 0.6_{syst}$ GeV^{-3}

$\Gamma_{\rho\to\pi\gamma} = 76\ ^{+10}_{-8}$ keV

Contributions to the systematics:

- Normalization: 4.7% (PID efficiency, $K^- \to \pi^-\pi^0/K^- \to \pi^-\pi^0\pi^0$)
- Radiative corrections: 3% (were not yet applied)
- Extraction of Primakoff events, unaccounted background from ω/π exchange, nuclear excitations, $\omega\pi$, $\omega\pi\pi$ final states: 3%
- Contributions from $\pi\gamma$ final state (ECAL reconstruction): 2%

Potential of improvements of the COMPASS measurement (work in progress)

Focusing on 2009 dataset since dominated by systematics

- Normalization: 4.7% $\rightarrow$ use kinematics for kaon/pion PID
- Radiative corrections: 3% $\rightarrow$ control at generator level
- Extraction of Primakoff events, unaccounted background from ω/π exchange, nuclear excitations, $\omega\pi$, $\omega\pi\pi$ final states: 3% $\rightarrow$ use smaller Q range, $cos\theta_{GJ}$, ϕ_{TY}
- Control of discrepancies in material description in MC and data: impact on $\pi^-\pi^0\pi^0 \rightarrow \pi^-\pi^0$ leakage

The event generator: kinematic distributions

Preliminary result: only elastic, non-radiative events:

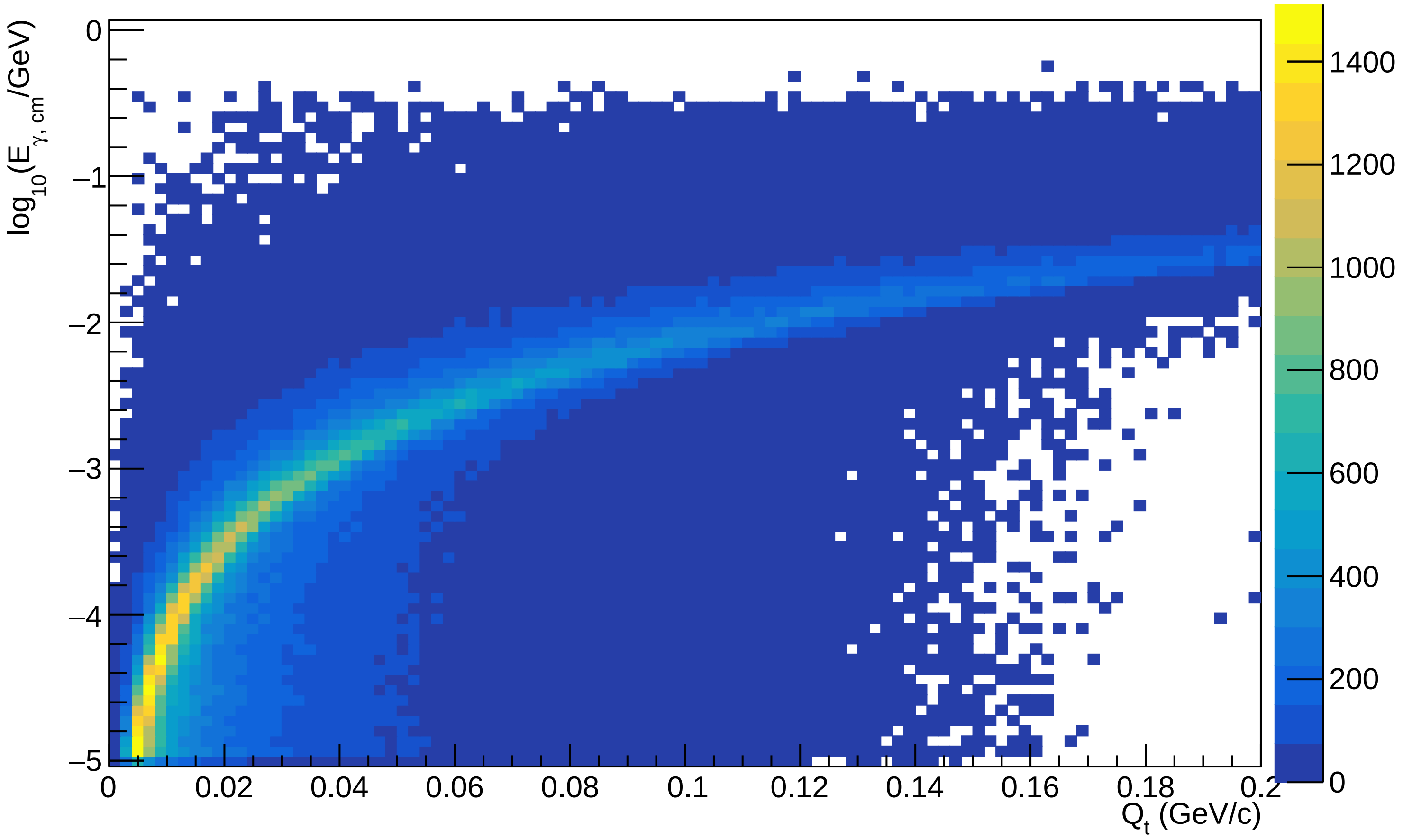
- $\frac{d\sigma}{ds} \propto \frac{1}{s - m_\pi^2} \int dQ^2 \frac{Q^2 - Q^2_{min}(s)}{Q^4} \sigma_{\gamma\pi\to\pi\pi}(s)$
- $\frac{d\sigma}{dQ^2} \propto \frac{Q^2 - Q^2_{min}}{Q^4}$
- $\frac{d\sigma}{dcos\theta_{GJ}} \propto sin^2\theta_{GJ}$
- $\frac{d\sigma}{d\phi_{TY}} \propto sin^2\phi_{TY}$

Analysis update (work in progress): include radiative corrections:

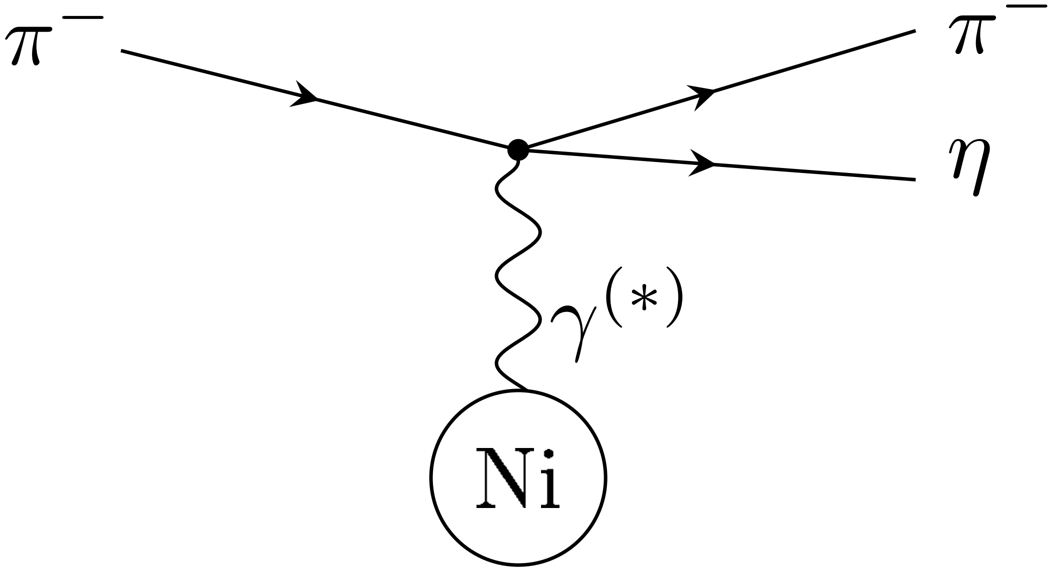
- t-pole, virtual photon corrections taken into account as weights
- real photon corrections (calculated by Norbert Kaiser): $E_\gamma : 1/E_{gamma}$, θ_{GJ} modified according to calculations

Updated event generator with radiative corrections

- implemented balancing of $\pi^-\pi^0$ and radiative $\pi^-\pi^0\gamma$ events according to calculations
- radiative $\pi^-\pi^0\gamma$ modify reconstructed momentum transfer Q for $\pi^-\pi^0$ final state ($\gamma \sim 1500$)



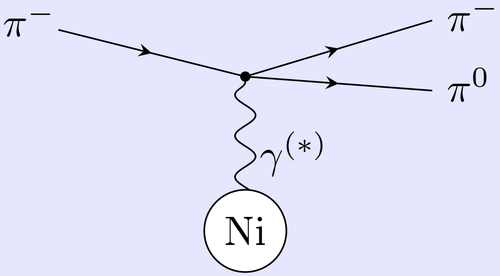
The possibility of $\pi^-\eta$ measurement



The possibility of $\pi^-\eta$ measurement

$\pi^- + (Z,A) \rightarrow \pi^- + \pi^0 + (Z,A)$

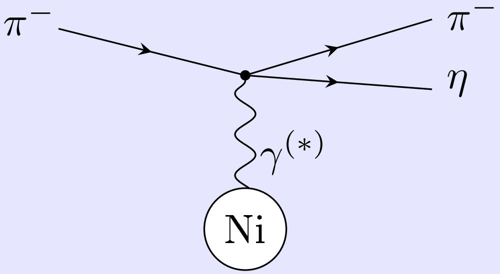
- access to $\gamma\pi \rightarrow \pi\pi$



- final state production via $\rho(770)$
- $F_{3\pi} = \frac{e}{4\pi^2 f_\pi^3} =$ 9.78 ± 0.05 GeV^{-3}
- dominant background from G-parity-conserving $\pi^-\pi^0\pi^0$

$\pi^- + (Z,A) \rightarrow \pi^- + \eta + (Z,A)$

- access to $\gamma\pi \rightarrow \eta\pi$



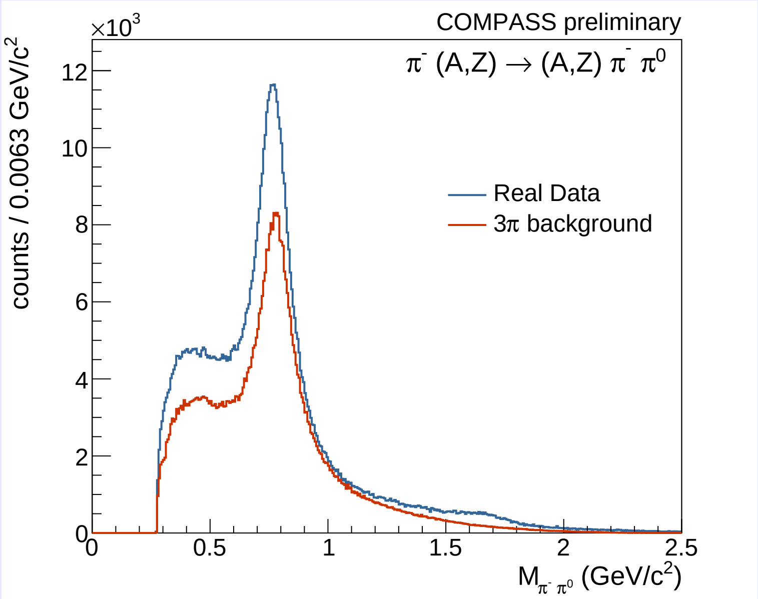
- final state production via $a_2(1320)$
- $F_{\eta\pi\pi\gamma} = \frac{e}{4\sqrt{3}\pi^2 f_\pi^3} =$ 5.65 ± 0.03 GeV^{-3}
- background from diffractive $\pi^- + (Z,A) \rightarrow \pi^- + \eta + (Z,A)$

The possibility of $\pi^-\eta$ measurement

Low-mass tail dominated by chiral anomaly events in both cases

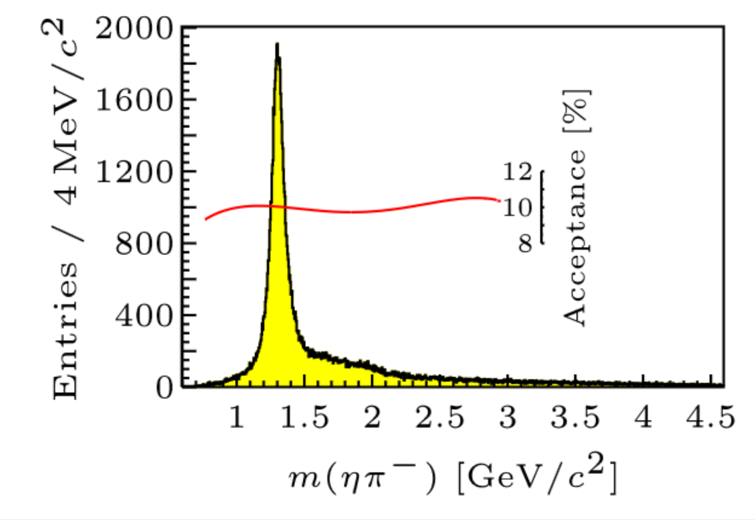
$$\pi^- + (Z,A) \to \pi^- + \pi^0 + (Z,A)$$

- access to $\gamma\pi \to \pi\pi$
- dominated by $\rho(770)$



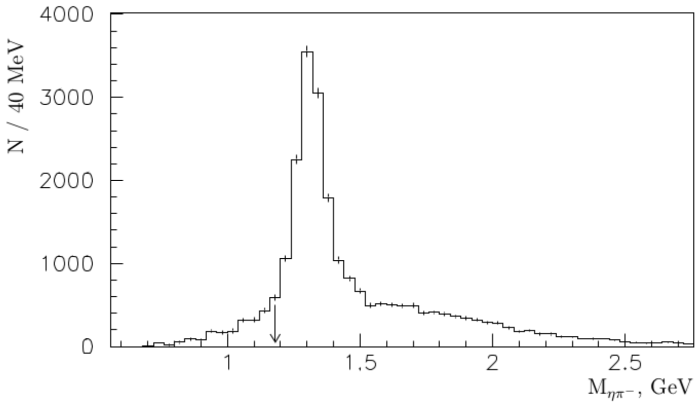
$$\pi^- + (Z,A) \to \pi^- + \eta + (Z,A)$$

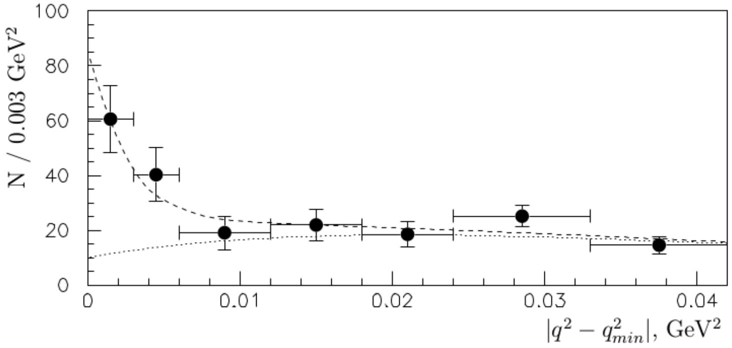
- access to $\gamma\pi \to \eta\pi$
- dominated by $a_2(1320)$

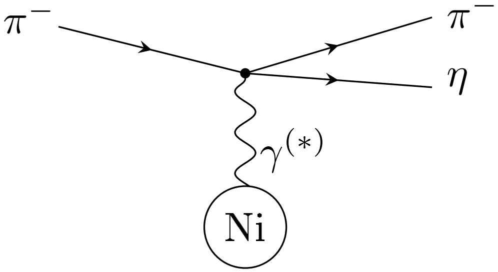


[*Phys.Lett.B 740 (2015) 303–311*]

VES measurement of $F_{\eta\pi\pi\gamma}$





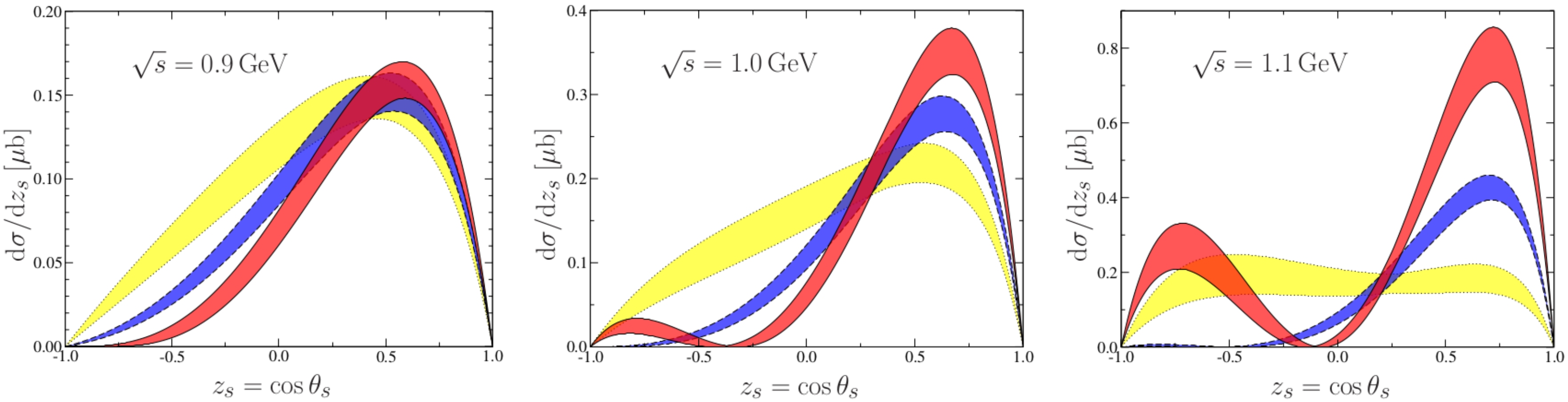


- $N_{Primakoff} = 109 \pm 23$ from fit of the Q^2 distribution
- Preliminary result shown on conference proceedings, not published
- Measured value: $F_{\eta\pi\pi\gamma} = 6.9 \pm 0.7$ GeV^{-3}
- Chiral anomaly LO prediction: $F_{\eta\pi\pi\gamma} = 5.65 \pm 0.03$ GeV^{-3}

[*Amelin et al.*]

[*International Europhysics Conference on HEP 1997 / IHEP-98-62*]

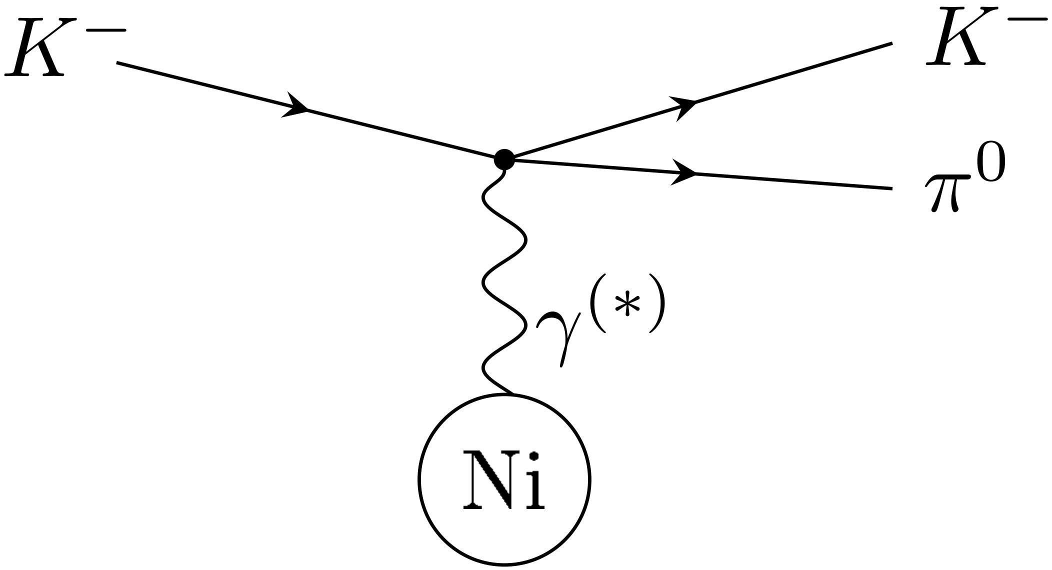
The possibility of $\pi^-\eta$ measurement



[B.Kubis, J.Pletner (EPJC 75:283,2015)]

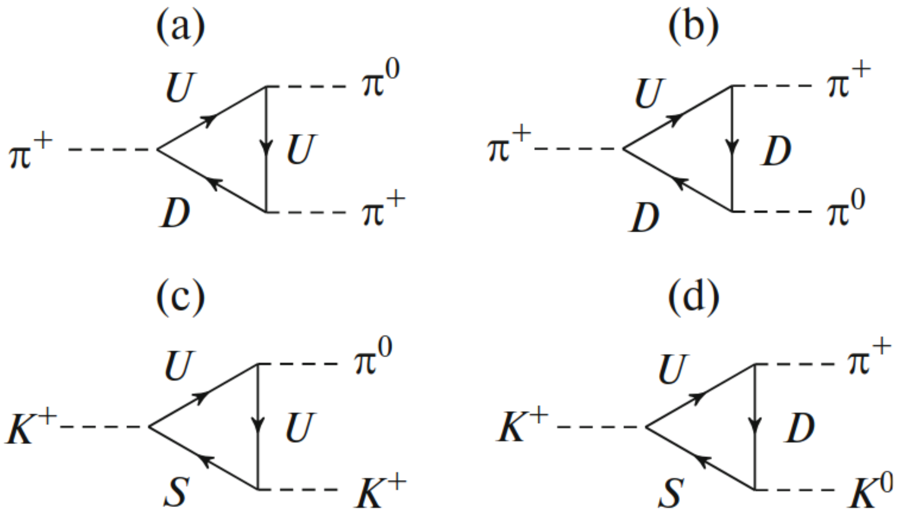
- Strategy: disentangle Primakoff production (Nickel target) + diffractive production
- Two COMPASS publication on $\eta\pi$ final state (Hydrogen target): [*EPJA (2014) 50: 79*] , [*PRB 779 (2018) 464–472*]
- [*B.Kubis, J.Pletner (EPJC 75:283,2015)*] → dispersive approach similar to $\pi^-\pi^0$

Chiral anomaly with kaons



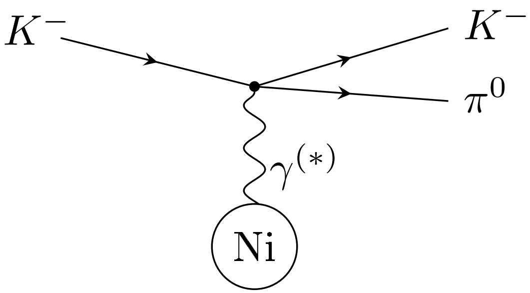
Chiral anomaly with kaons

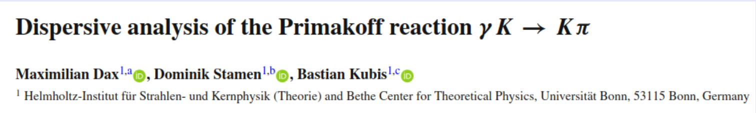
[PRD 93, 094029 (2016)]



- Fundamental difference from $\pi^-\pi^0$, $\pi^-\eta$: two possible final states $K^-\gamma \to K^-\pi^0$, $K^-\gamma \to \pi^-K^0$
- Chiral anomaly contributes to $K^-\gamma \to K^-\pi^0$, but not $K^-\gamma \to \pi^-K^0$

Chiral anomaly with kaons

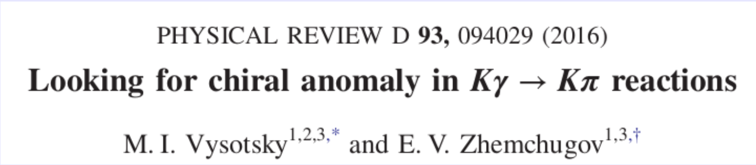



Dispersive analysis of the Primakoff reaction $\gamma K \to K\pi$

Maximilian Dax[1,a], Dominik Stamen[1,b], Bastian Kubis[1,c]

[1] Helmholtz-Institut für Strahlen- und Kernphysik (Theorie) and Bethe Center for Theoretical Physics, Universität Bonn, 53115 Bonn, Germany

[EPJC (2021) 81:22]


PHYSICAL REVIEW D **93,** 094029 (2016)

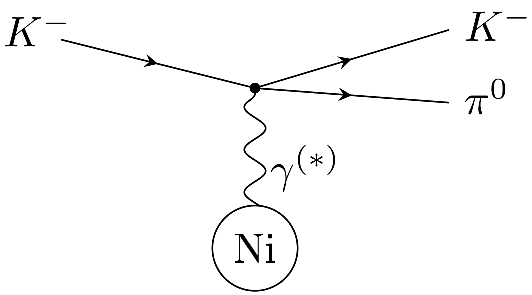
Looking for chiral anomaly in $K\gamma \to K\pi$ reactions

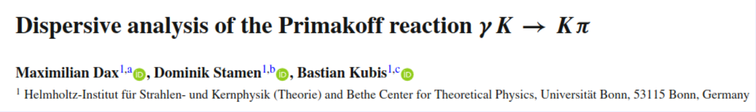
M. I. Vysotsky[1,2,3,*] and E. V. Zhemchugov[1,3,†]

[PRD 93, 094029 (2016)]

- Identical contributions to $K^-\gamma \to K^-\pi^0$ and $\pi^-\pi^0$
- Higher $K\pi$ threshold → higher order corrections potentially higher

Chiral anomaly with kaons

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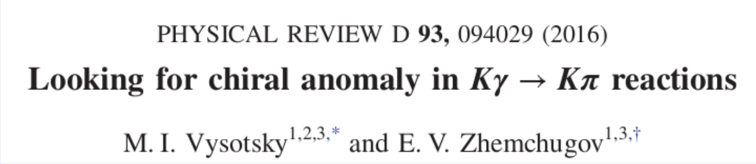
[*EPJC (2021) 81:22*]

- Dispersive approach similar to $\pi^-\pi^0$ case
- Higher order corrections estimated to be 25%


PHYSICAL REVIEW D **93,** 094029 (2016)

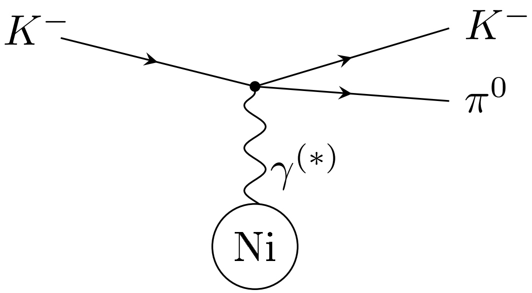
Looking for chiral anomaly in $K\gamma \rightarrow K\pi$ reactions

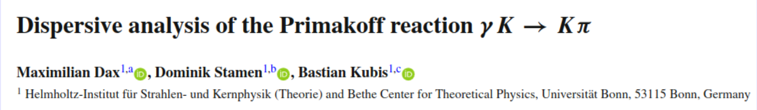
M. I. Vysotsky[1,2,3,*] and E. V. Zhemchugov[1,3,†]

[*PRD93, 094029 (2016)*]

- Extraction of the chiral anomaly from combined $K^-\gamma \rightarrow K^-\pi^0$ and $K^-\gamma \rightarrow \pi^-K^0$ analyses

Chiral anomaly with kaons




Dispersive analysis of the Primakoff reaction $\gamma K \to K\pi$

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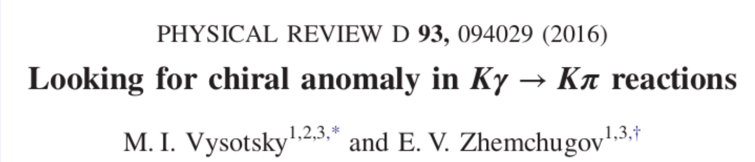

PHYSICAL REVIEW D **93,** 094029 (2016)

Looking for chiral anomaly in $K\gamma \to K\pi$ reactions

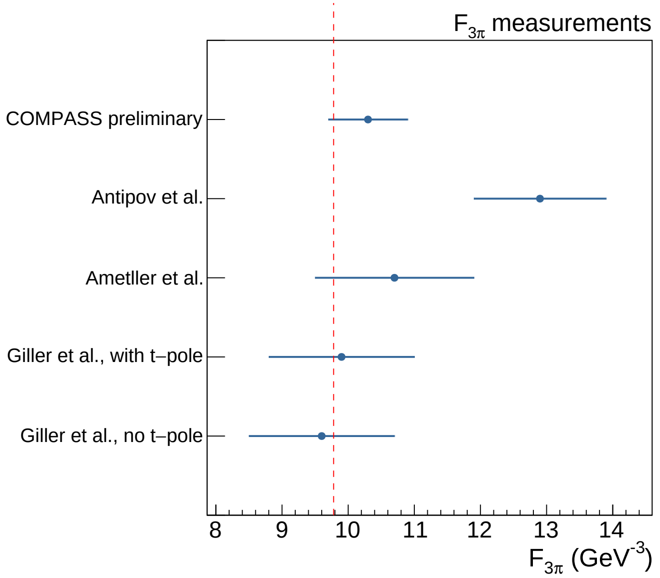
M. I. Vysotsky[1,2,3,*] and E. V. Zhemchugov[1,3,†]

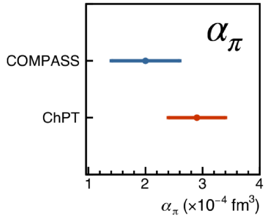
[PRD 93, 094029 (2016)]

- COMPASS: 2009, 2012 samples with beam kaons (2.4%)
- AMBER: plans for a dedicated Primakoff run
- plans for OKA detector at IHEP Protvino

Conclusions and outlook

- Preliminary results from COMPASS experiment:
  - $F_{3\pi} = 10.3 \pm 0.6$ GeV^{-3}
  - $\Gamma_{\rho\to\pi\gamma} = 76\ ^{+10}_{-8}$ keV
  - first combined measurement of $F_{3\pi}$ and $\Gamma_{\rho\to\pi\gamma}$
  - most precise $F_{3\pi}$ measurement to date
  - potential improvement on systematic uncertainty: more news soon!
- other χPT tests at COMPASS: polarizabilities, chiral dynamics in $\gamma\pi \to 3\pi$
- Outlook for future measurements:
  - $F_{\eta\pi\pi\gamma}$ from $\pi^-\eta$ final state
  - $F_{\pi KK\gamma}$ from $K^-\pi^0$



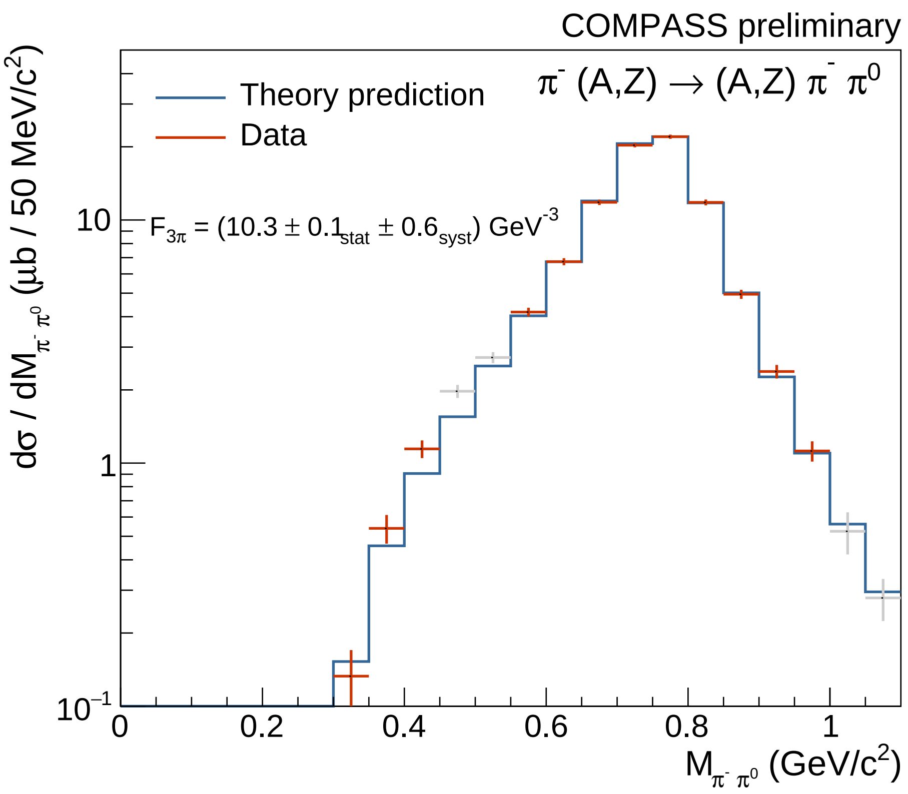


BACKUP

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

- Acceptance corrected number of Primakoff events in each bin fitted with theoretical $\pi^- + (Z,A) \to \pi^- + \pi^0 + (Z,A)$ cross section

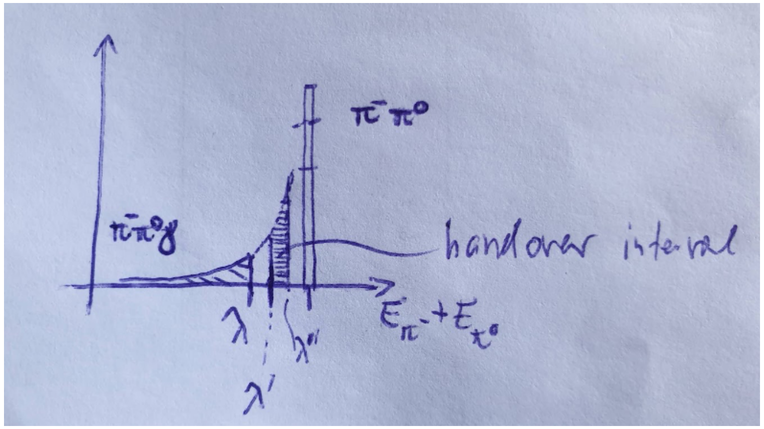
  [*M.Hoferichter, B.Kubis, D.Sakkas (PRD 86:116009,2012)*]
- $C_2^{(1)} = 10.5 \pm 0.1_{stat} \pm 0.6_{syst}$ GeV^{-3}
- $C_2^{(2)} = 24.5 \pm 0.1_{stat}{}^{+1.6}_{-1.4}{}_{syst}$ GeV^{-5}



Implementation of the radiative corrections

- Real photon radiative events: how to deal with infrared divergencies?
- Select λ' such that soft photons events below handover point λ' are indistinguishable from elastic $\pi^-\pi^0$ events in the experiment.

- Implementation procedure:
  - generate a real photon radiative event with soft photon energy E_γ
  - if $E_\gamma > \lambda' \rightarrow$ store the event as is
  - if $E_\gamma \leq \lambda' \rightarrow$ generate $N_{2\pi}$ elastic events with $N_{2\pi}$ calculated separately



[*Drawing of Jan Friedrich*]