Testing Predictions of the Chiral Anomaly in Primakoff Reactions at COMPASS

Recent result on $F_{3\pi}$ and $\Gamma_{\rho\to\pi\gamma}$!

Dominik Ecker for the COMPASS collaboration
(dominik.ecker@tum.de)

DPG Frühjahrstagung - SMuK23

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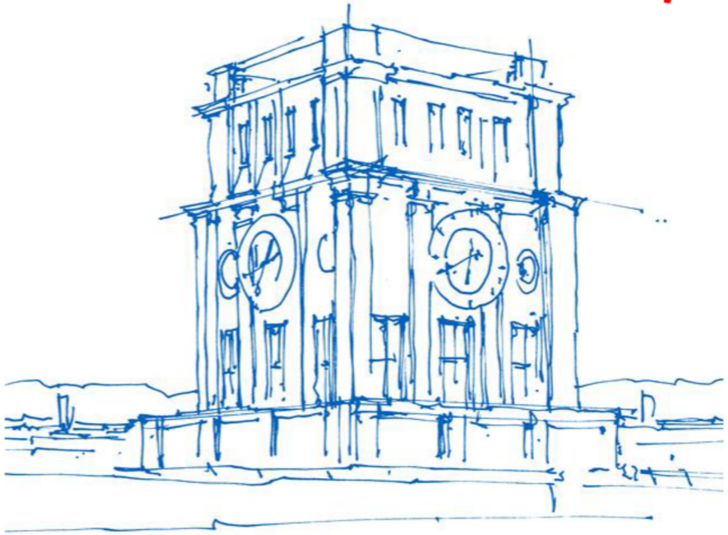

Uhrenturm der TUM

Quantum Chromodynamics

- Quantum Chromodynamics (QCD) - theory of strong interaction
- Lagrange density of QCD:

$$\mathcal{L}_{QCD} = \sum_{f=\substack{u,d,s,\\c,b,t}} \bar{q}_f (i\not{D} - \underbrace{m_f}_{\text{Flavor symmetry breaking term}}) q_f - \frac{1}{4} G^a_{\mu\nu} G_a^{\mu\nu}$$

- Flavor symmetries? -> only approximate symmetries
  - $\boldsymbol{SU(2)}$: $m_u \approx m_d$ -> isospin symmetry
  - $\boldsymbol{SU(3)}$: $m_u \approx m_d \approx m_s$ -> the eightfold way

Chiral symmetry of QCD

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- Approximate flavor symmetries in **chiral limit** ($m_u = m_d = m_s = 0$), left- and right-handed fields decouple for massless particles:

$$\boldsymbol{SU(3)_R \times SU(3)_L}$$

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$$\boldsymbol{SU(3)_R \times SU(3)_L} \longrightarrow \boldsymbol{SU(3)_V}$$

→ Dynamically broken (Goldstone bosons): $\pi^\pm, \pi^0, K^\pm, K^0, \bar{K}^0, \eta$

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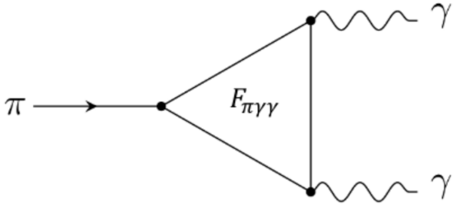
- Dynamically broken (Goldstone bosons): $\pi^{\pm}, \pi^0, K^{\pm}, K^0, \bar{K}^0, \eta$
- Underlying symmetry for effective Lagrangian of ChPT
  - Most general, chiral invariant, effective Lagrangian
  - Basic degrees of freedom: Goldstone boson fields of chiral symmetry breaking
  - Successful effective theory

Discovery of the chiral anomaly – π^0 lifetime

- First definitive measurement of π^0-lifetime in 1963:



$$\tau_{\text{exp}}(\pi^0) = (9.5 \pm 1.5) \cdot 10^{-17}\text{s} \neq \tau_{\text{theory}}(\pi^0) \approx 10^{-13}\text{s}$$

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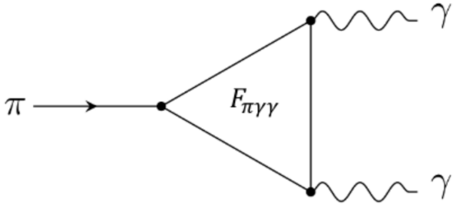

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- Features *axial* $U(1)$-symmetry in chiral limit**:**

$$\psi(x) \rightarrow e^{i\theta\gamma_5}\psi(x)$$

- **Anomalous** symmetry breaking: symmetry of the Lagrangian does not lead to conserved Noether currents
- **Anomaly:** Symmetry of classical Lagrangian violated at quantum level

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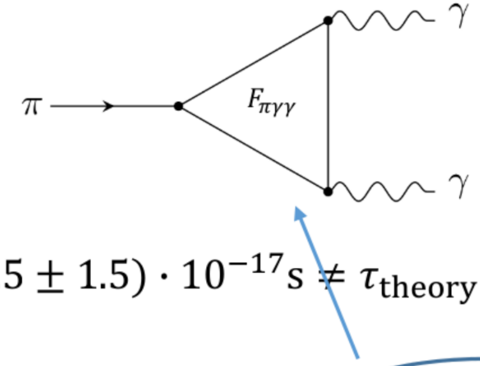

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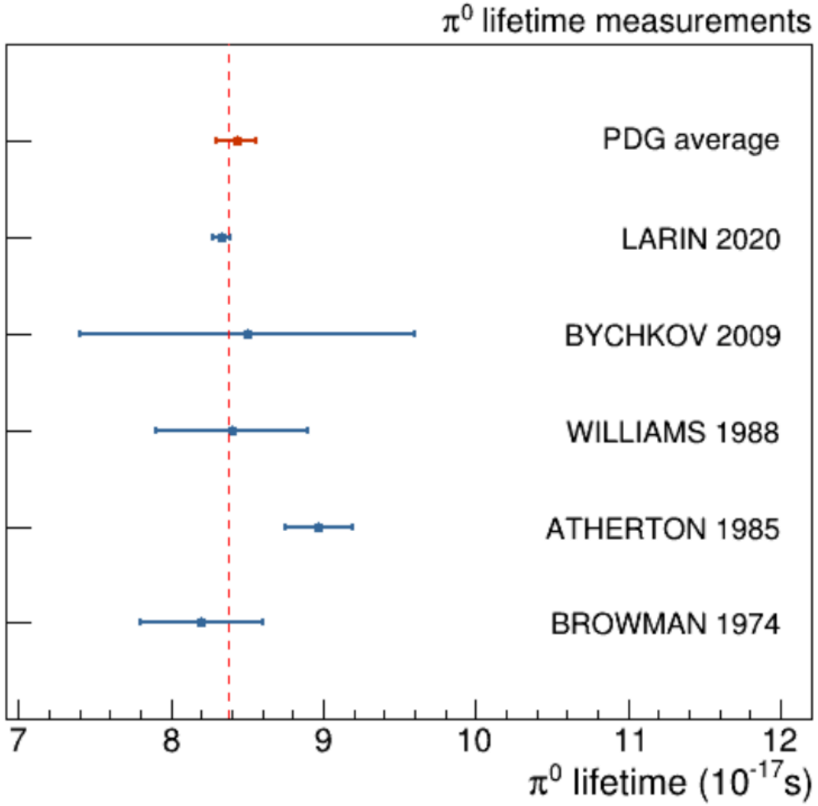
- Adler, Bell, Jackiw, Bardeen 1969: quark axial current **not** conserved:

$$\Gamma^{\text{anom}}(\pi^0 \to \gamma\gamma) = F_{\pi\gamma\gamma}^2 \cdot \frac{m_{\pi^0}^3}{64\pi} = \left(\frac{e^2 N_c}{12\pi^2 F_\pi}\right)^2 \frac{m_{\pi^0}^3}{64\pi} = 7.75\,\text{eV}$$

$$\tau(\pi^0) = \text{BR}(\pi^0 \to \gamma\gamma) \cdot \frac{\hbar}{\Gamma^{\text{anom}}(\pi^0 \to \gamma\gamma)} = 8.38 \cdot 10^{-17}\,\text{s}$$



Wess-Zumino-Witten term

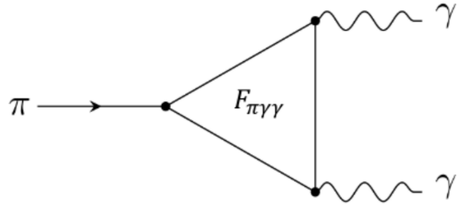
- Chiral anomaly in ChPT taken into account by Wess-Zumino-Witten (WZW) term

- Describes coupling of odd number of Goldstone bosons:

$SU(2)$ flavor	$SU(3)$ flavor
$\pi^0 \to \gamma\gamma$	$K^+K^- \to \pi^+\pi^-\pi^0$
$\gamma\pi^- \to \pi^-\pi^0$	$\eta \to \pi^+\pi^-\gamma$
$\pi^+ \to e^+\nu_e\gamma$	$K^+ \to \pi^+\pi^- e^+\nu_e$
etc.	etc.

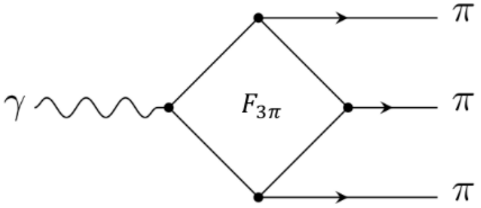
- Effective theory -> pion decay constant measured from leptonic decays of the charged pion ($\pi^\pm \to \mu^\pm + \nu$)

$F_{\pi\gamma\gamma}$



- $F_{\pi\gamma\gamma} = \frac{e^2 N_C}{12\pi^2 F_\pi} = 2.52 \cdot 10^{-2}\mathrm{GeV}^{-1}$

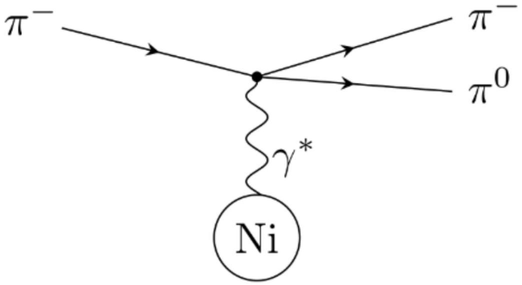
$F_{3\pi}$



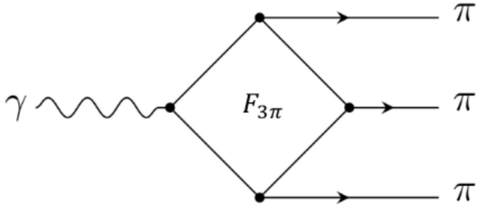
- $F_{3\pi} = \frac{e N_C}{12\pi^2 F_\pi^3} = (9.78 \pm 0.05)\mathrm{GeV}^{-3}$

Testing the chiral anomaly - $F_{3\pi}$

- Accessible in Primakoff reactions via: $\pi^-\gamma^* \rightarrow \pi^-\pi^0$



$F_{3\pi}$



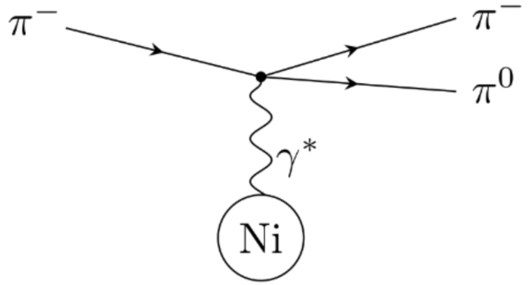
- $F_{3\pi} = \frac{eN_C}{12\pi^2 F_\pi^3} = (9.78 \pm 0.05)\text{GeV}^{-3}$

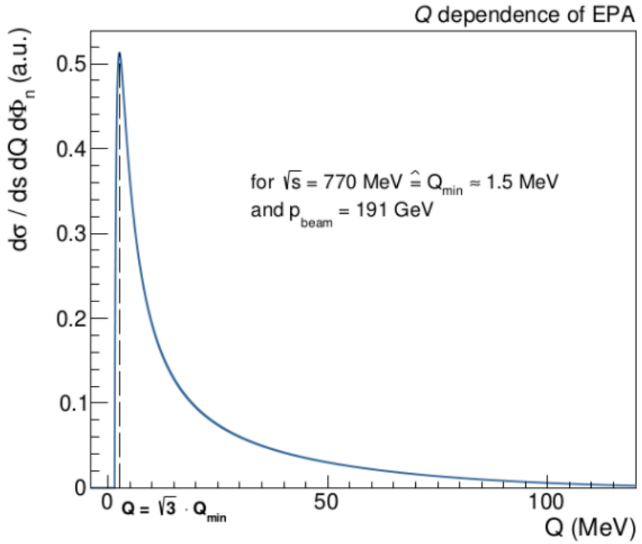
Pion-Photon reactions through the Primakoff technique

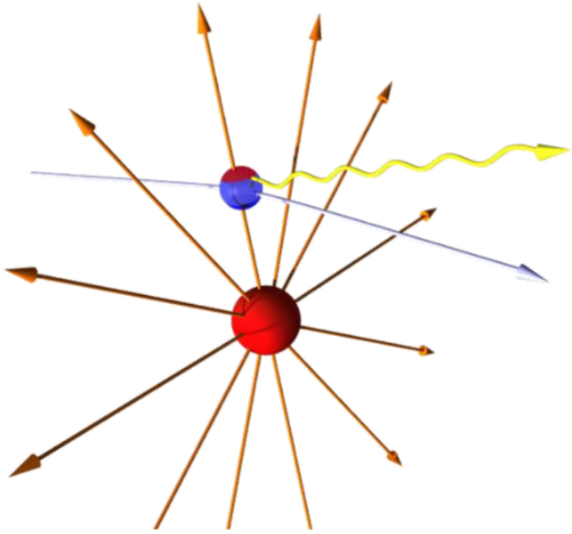
- Photon is provided by the strong Coulomb field of a nucleus

- Photons are quasi-real ($P_\gamma^2 \ll m_\pi^2$)

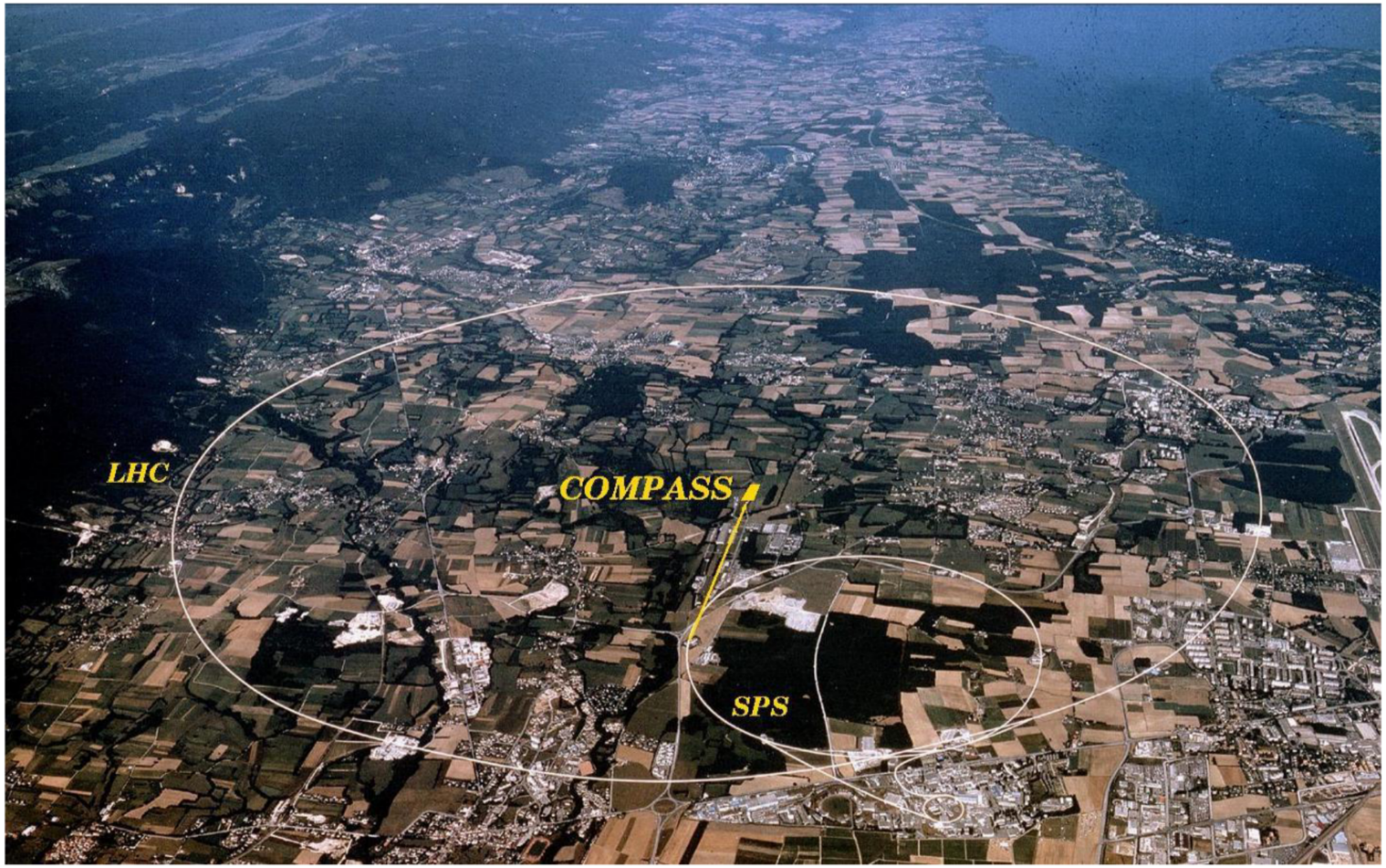
- Large impact parameters (ultra-peripheral scattering) -> low momentum transfer



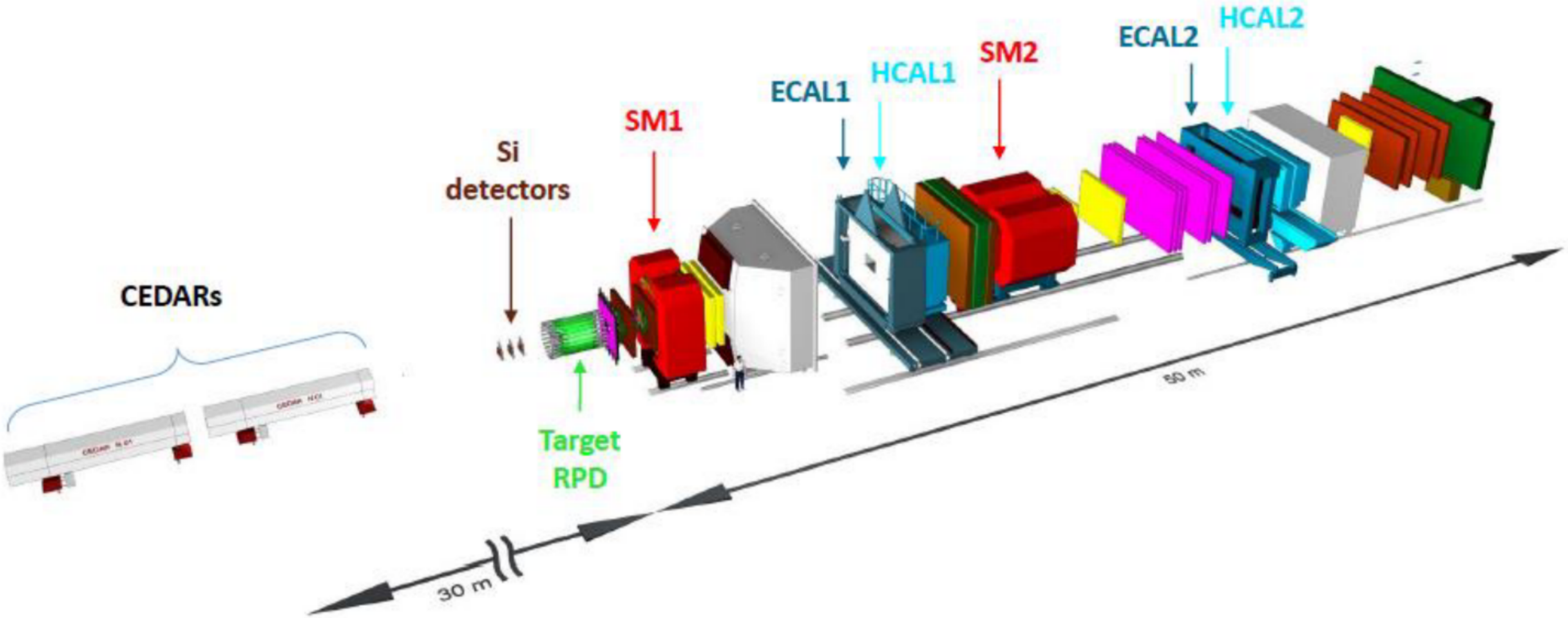




COmmon Muon and Proton Apparatus for Structure and Spectroscopy



COMPASS spectrometer

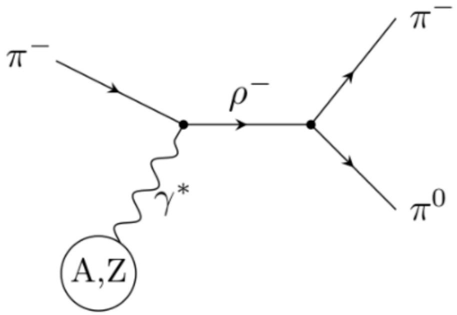


- 190 GeV negative hadron beam
- Beam PID
- Nuclear target(s): Ni and W
- Calorimetric trigger on photons
- Two stage magnetic spectrometer

Abbon, P. *et al.* NIM A 779 (2014) 69–115

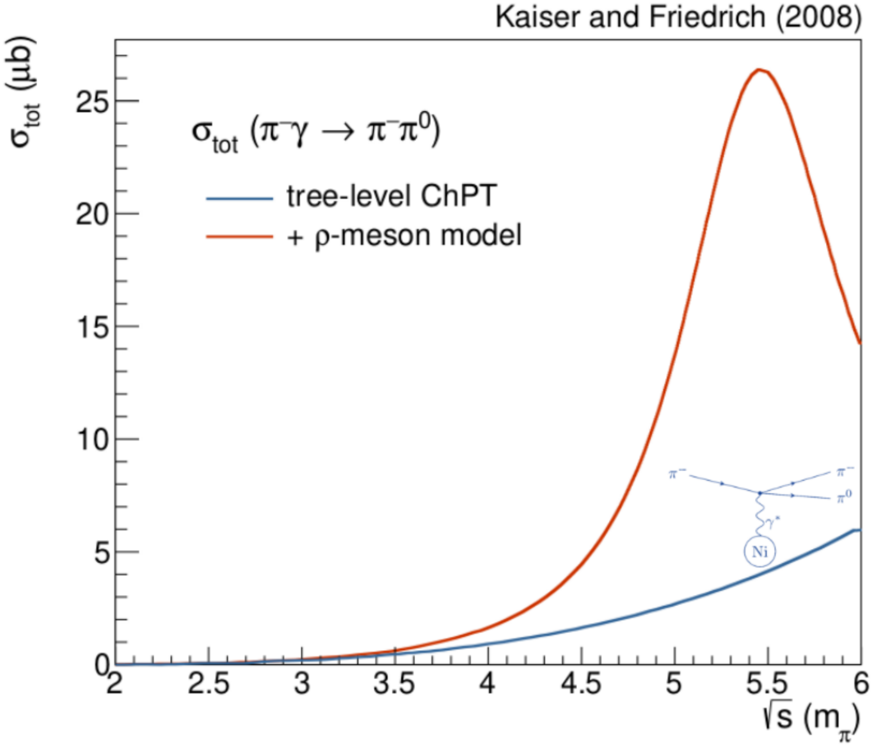
Coherent background from $\rho(770)$ meson

- Background from electromagnetic $\rho(770)$ production:



⇒ possibility of extraction of radiative width of ρ-meson:

$$\Gamma_{(\rho\to\pi\gamma)}/\Gamma_{\text{tot}} \approx 4.5\cdot 10^{-4}$$



Kaiser, N. and Friedrich, J. M., EPJA 36 no. 2, (2008) 181–188

COMPASS measurement

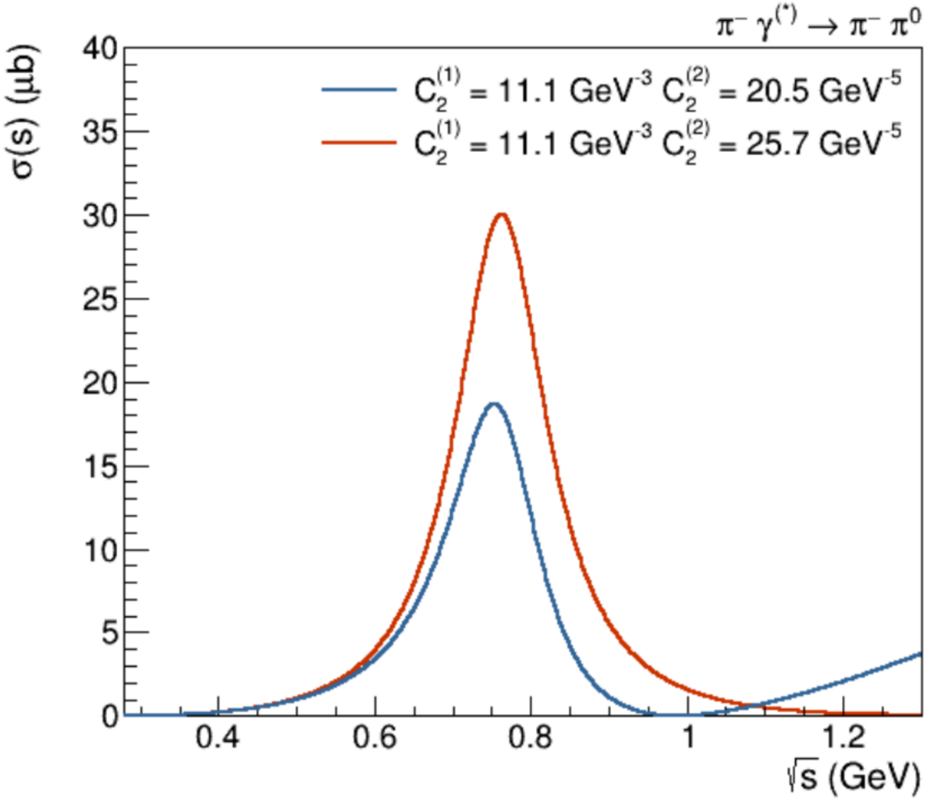
- Dispersive framework to deduce $F_{3\pi}$ from a fit to the $\pi^-\pi^0$ mass distribution up to 1.0 GeV including the $\rho(770)$-resonance

- Model form factor with two components

$$\mathcal{F}(s,t,u) = C_2^{(1)}\mathcal{F}_2^{(1)}(s,t,u) + C_2^{(2)}\mathcal{F}_2^{(2)}(s,t,u) - \frac{2e^2F_\pi^2F_{3\pi}}{t}$$

$C_2^{(1)}, C_2^{(2)}$: fit parameters (subtraction constants)

$\mathcal{F}_2^{(1)}(s,t,u)$, $\mathcal{F}_2^{(2)}(s,t,u)$: provided by theory colleagues (Kubis, Hoferichter)



M. Hoferichter, B. Kubis, and D. Sakkas, *PRD* **86** (2012) 116009

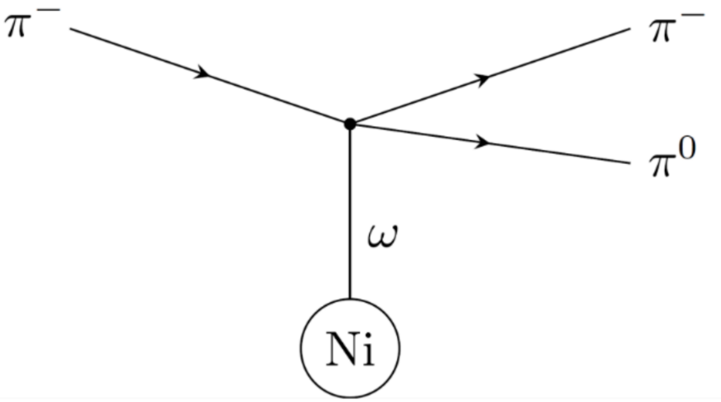
Background

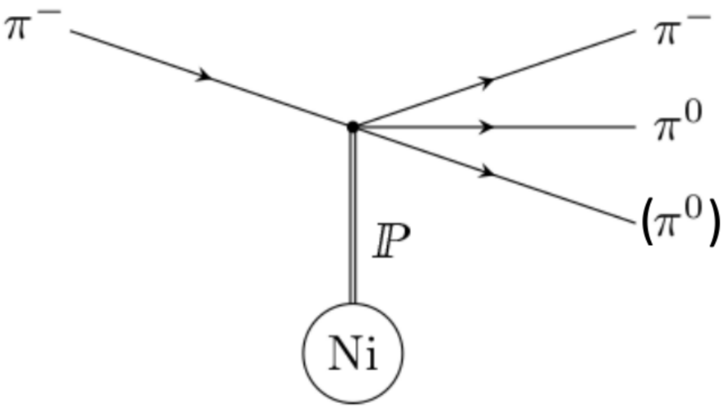
$\pi^-\pi^0$ via strong interaction

- Pomeron exchange: forbidden by G-parity conservation
- π and ω exchange: low cross section at COMPASS beam energies

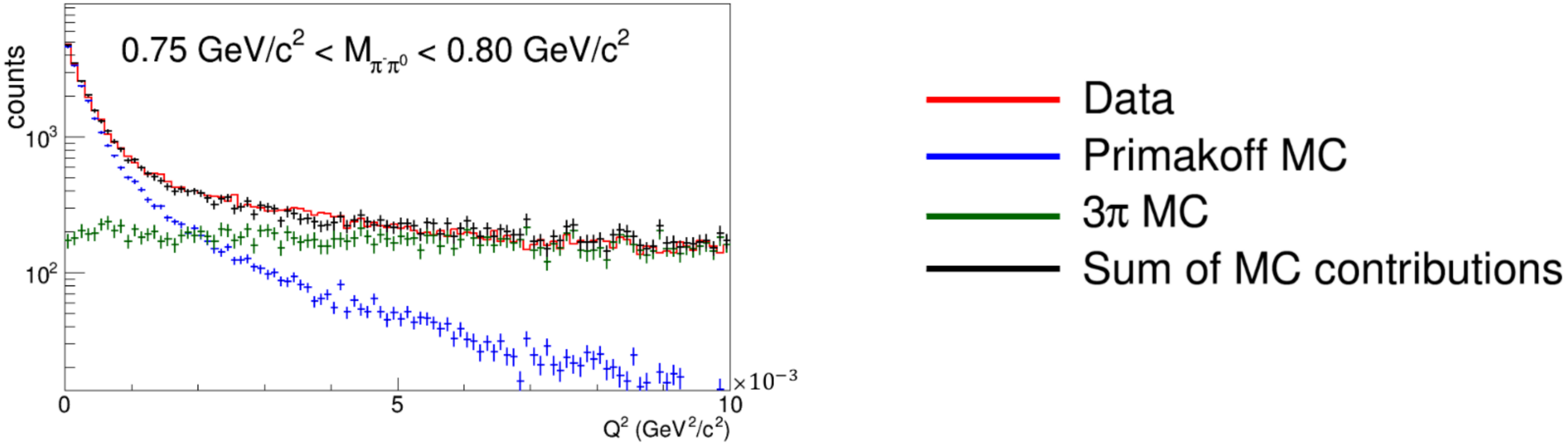
$\pi^-\pi^0\pi^0$ via Pomeron exchange

- Large cross section
- Main background: loss of one (soft) π^0
- Approach:
  - Using a model from COMPASS $\pi^-\pi^0\pi^0$ data
  - Apply $\pi^-\pi^0$ event selection -> realistic distributions of leakage in $\pi^-\pi^0$





Scaling of 3π background



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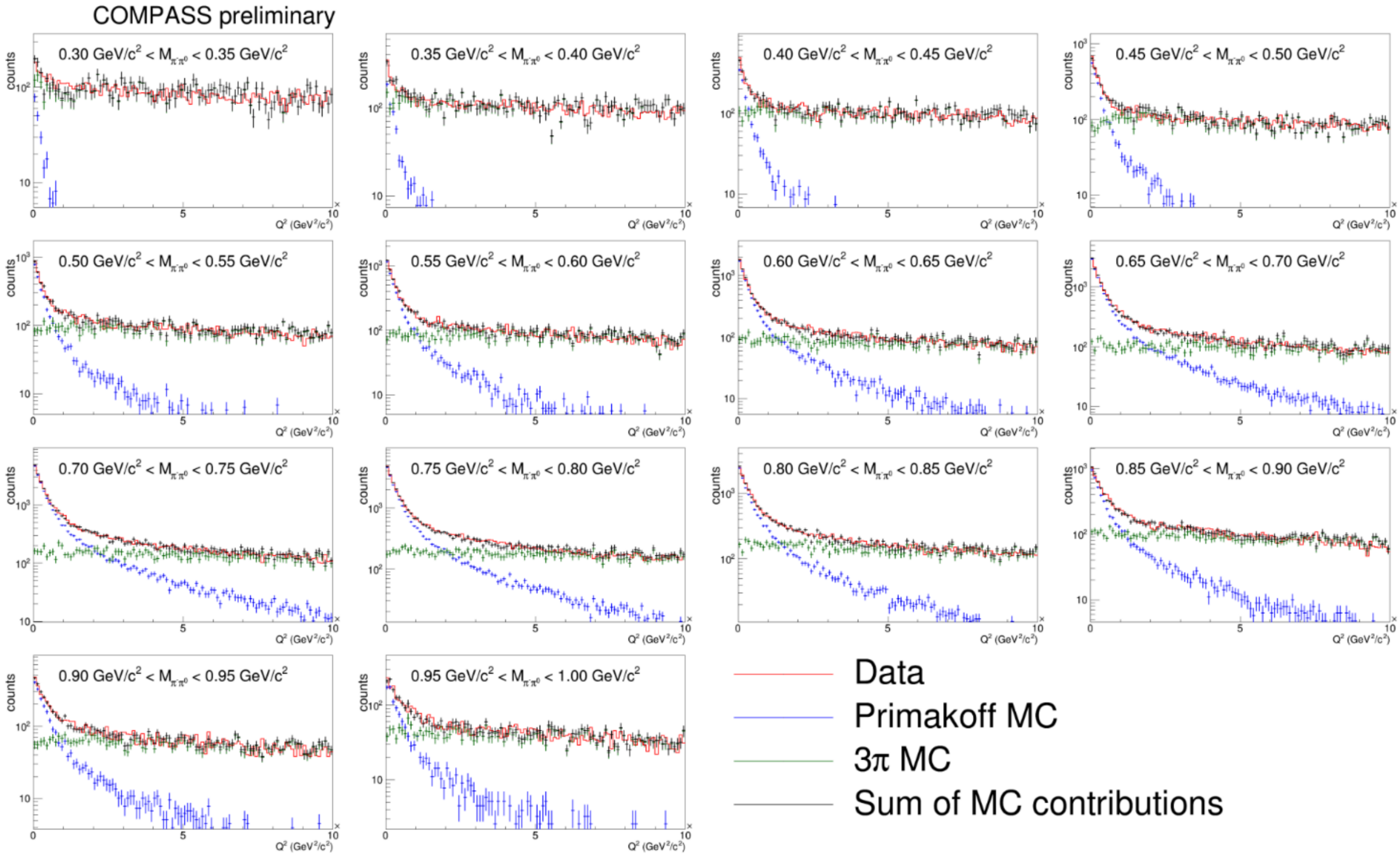


Results of dispersive fits

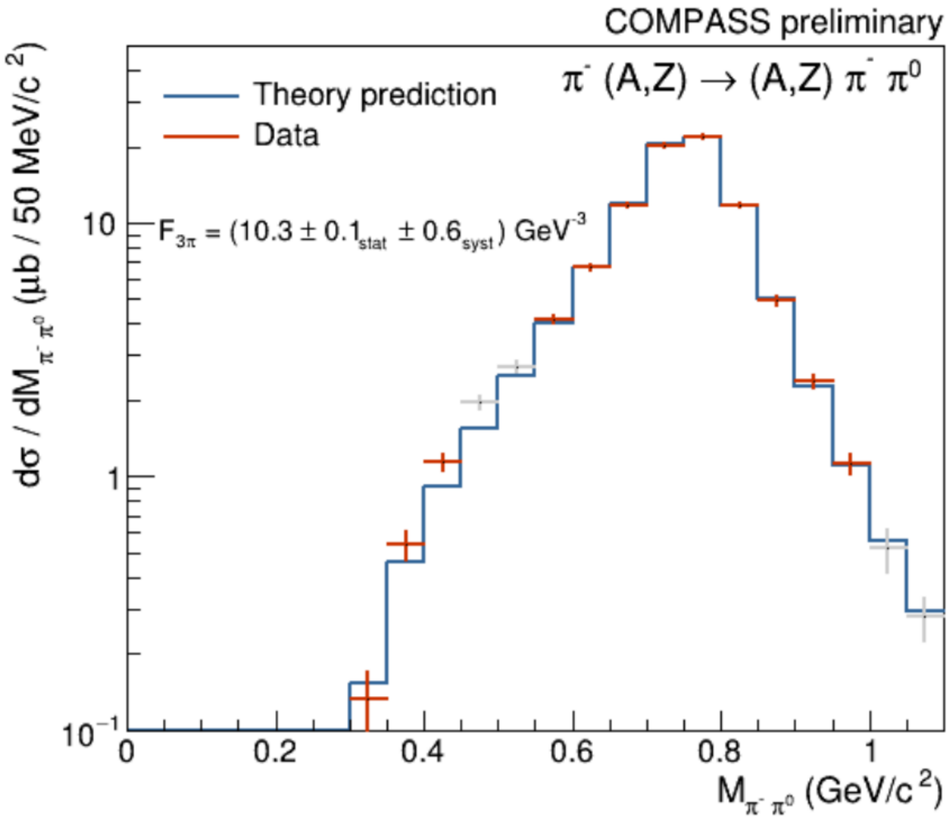
- Selection: $Q^2 < 1.296 \cdot 10^{-3}\,\mathrm{GeV}^2/c^2$

$$C_2^{(1)} = (10.5 \pm 0.1_{stat} \pm 0.6_{syst})\mathrm{GeV}^{-3}$$

$$C_2^{(2)} = \left(24.5 \pm 0.1_{stat}{}^{+1.6}_{-1.4}{}_{syst}\right)\mathrm{GeV}^{-5}$$

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

$$\Gamma_{\rho\to\pi\gamma} = \left(76 \pm 1_{stat}{}^{+10}_{-8}{}_{syst}\right)\mathrm{keV}$$



Comparison to previous measurements

- COMPASS: First combined measurement of $F_{3\pi}$ and $\Gamma_{\rho\to\pi\gamma}$

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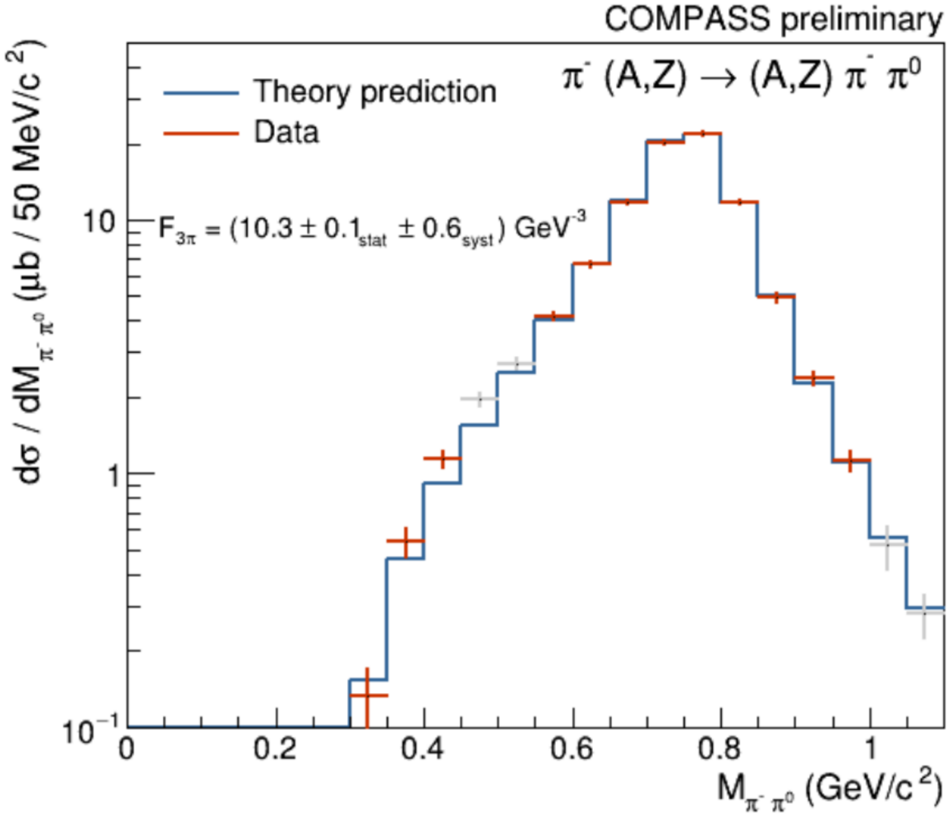
- Intensive test of systematics:
  - Studies on different background contributions (ω and π exchange)
  - Accompanied with intensive analysis of $\pi^-\mathrm{Ni} \to \pi^-\pi^0\pi^0\mathrm{Ni}$ for background estimation



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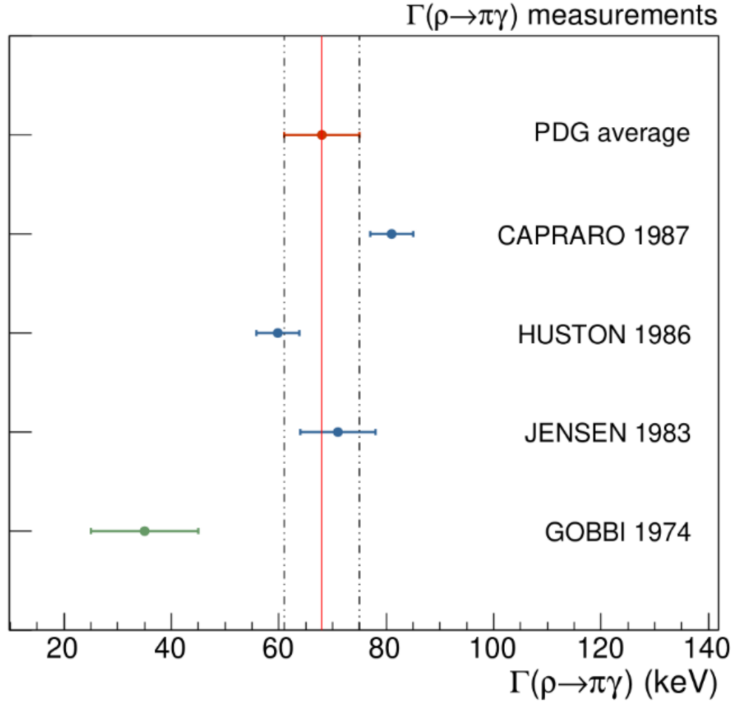

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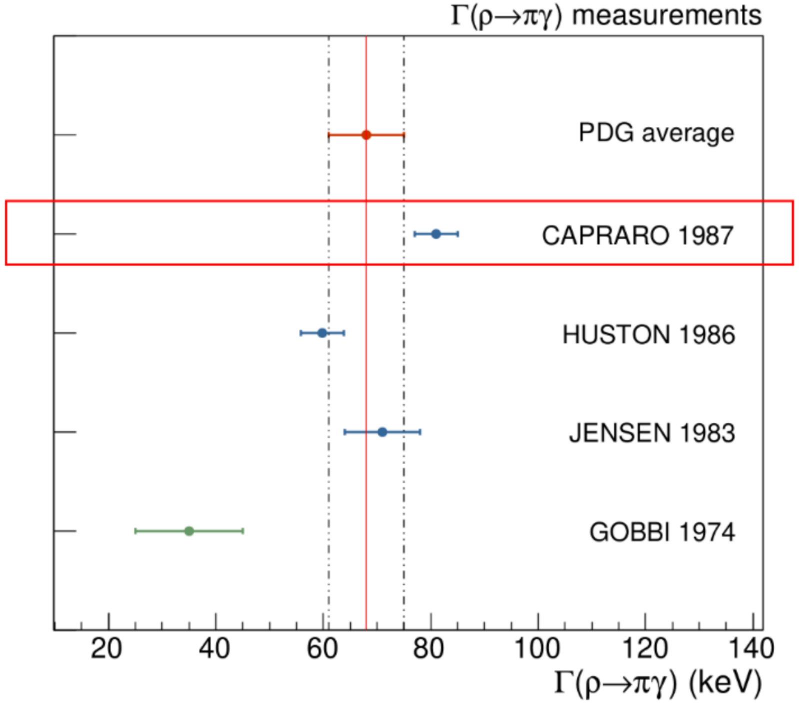
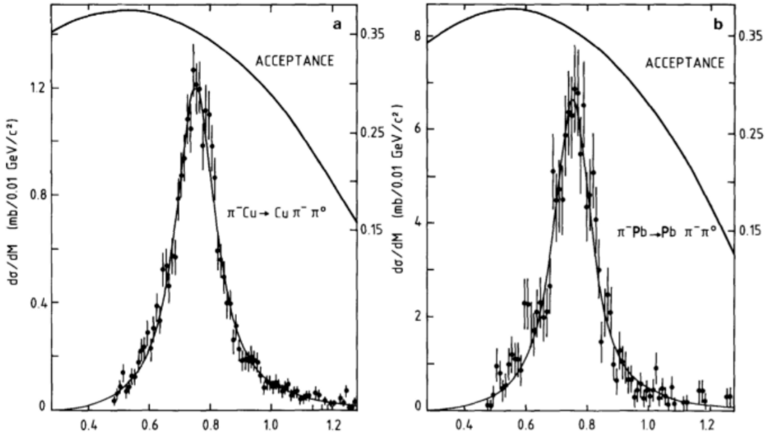


Comparison to previous measurements

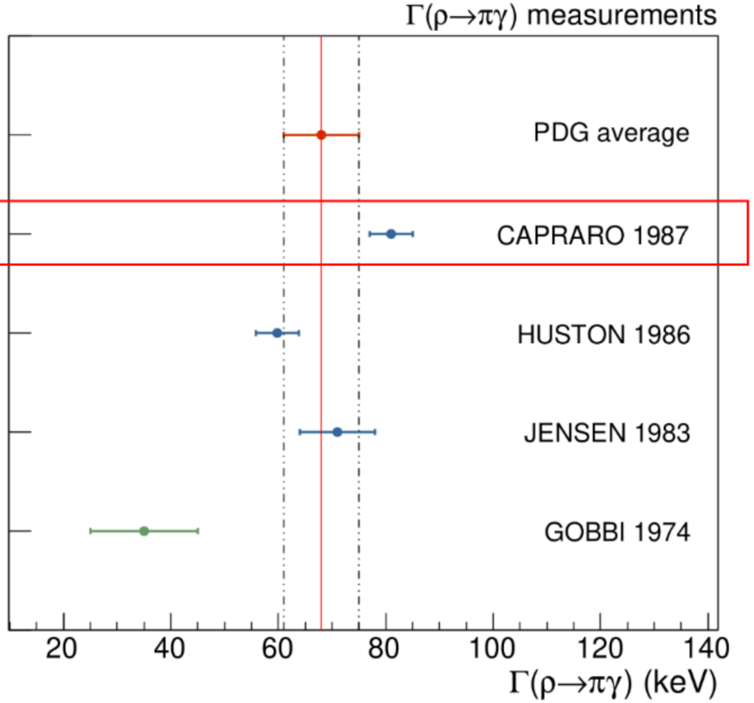
Capraro, L. *et al.* NPB 288 (1987) 659-680 at CERN (SPS):

$$\Gamma_{\rho\to\pi\gamma} = (81 \pm 4 \pm 4)\ \text{keV}$$

Obtained by fitting $\mathrm{d}\sigma/\mathrm{d}t$ distribution (separation of nuclear and Coulomb processes)



- Neglecting chiral production of $\pi^-\pi^0$
- Presumably underestimation of systematics (3π leakage, beam composition)



Comparison to previous measurements

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- Intensive test of systematics:
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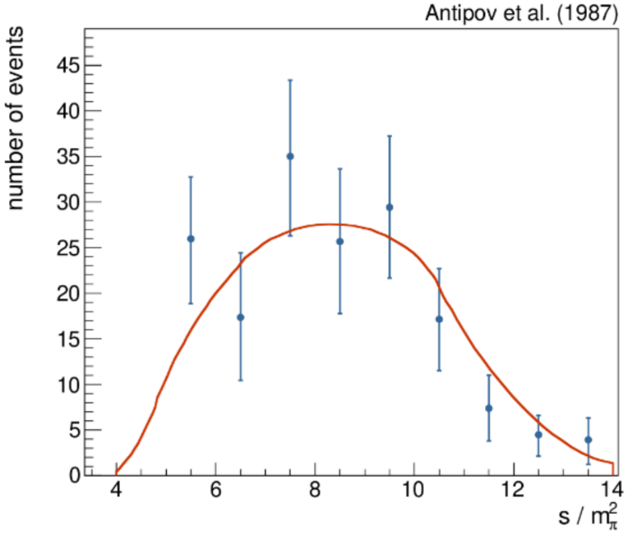
Antipov, Y. *et al.* PRD 36 (1987) 101103
and reanalyzed by
Ametller, L. *et al.* PRD 64 (2001) 094009

$$F_{3\pi} = (10.7 \pm 1.2)\ \mathrm{GeV}^{-3}$$

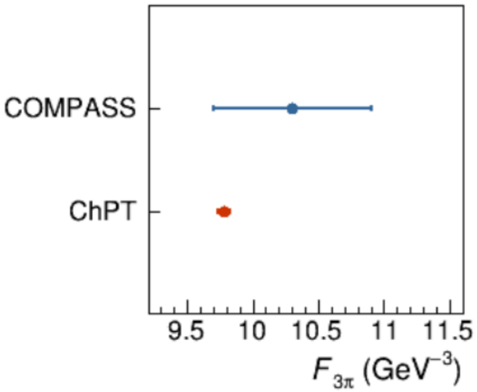
- Neglecting s-channel production of ρ meson
- No proper consideration of systematics



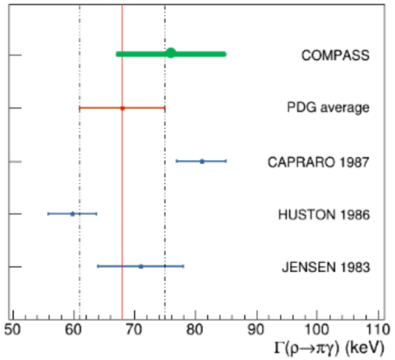
Conclusion and Outlook

- Recent results from COMPASS Primakoff data for $F_{3\pi}$ and $\Gamma_{\rho\rightarrow\pi\gamma}$ (first combined measurement):

chiral anomaly



ρ radiative width



- Result for $F_{3\pi}$ is in agreement with prediction from ChPT
- Results dominated by systematic uncertainties -> improvement expected
  - Background prediction
  - Luminosity determination
- On the future program of successor experiment AMBER: similar program on kaon sector

Backup

Chiral symmetry of QCD

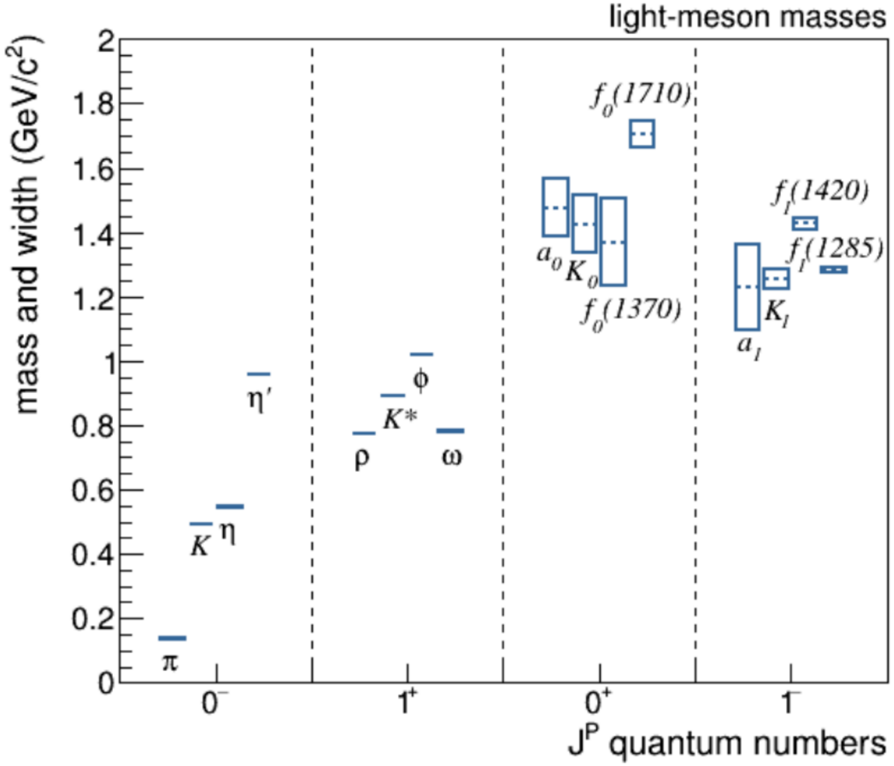
- Lagrange density of QCD:

$$\mathcal{L}_{QCD} = \sum_{f=\substack{u,d,s,\\c,b,t}} \bar{q}_f (iD - m_f) q_f - \frac{1}{4} G^a_{\mu\nu} G_a^{\mu\nu}$$

- Approximate flavor symmetries in chiral limit ($m_u = m_d = m_s = 0$):

$SU(3)_R \times SU(3)_L$

- Left- and right-handed fields decouple for massless particles
- Chirality can directly be translated to parity of particle
  → mass-degenerate doublets of states with opposite parity
- Why does chiral symmetry not manifest itself in the spectrum (in contrast to isospin and eightful way)?
  → Nambu-Goldstone mechanism for spontaneous/dynamic breakdown of chiral symmetry



Dynamic breaking of chiral symmetry

Spontaneous symmetry breaking:

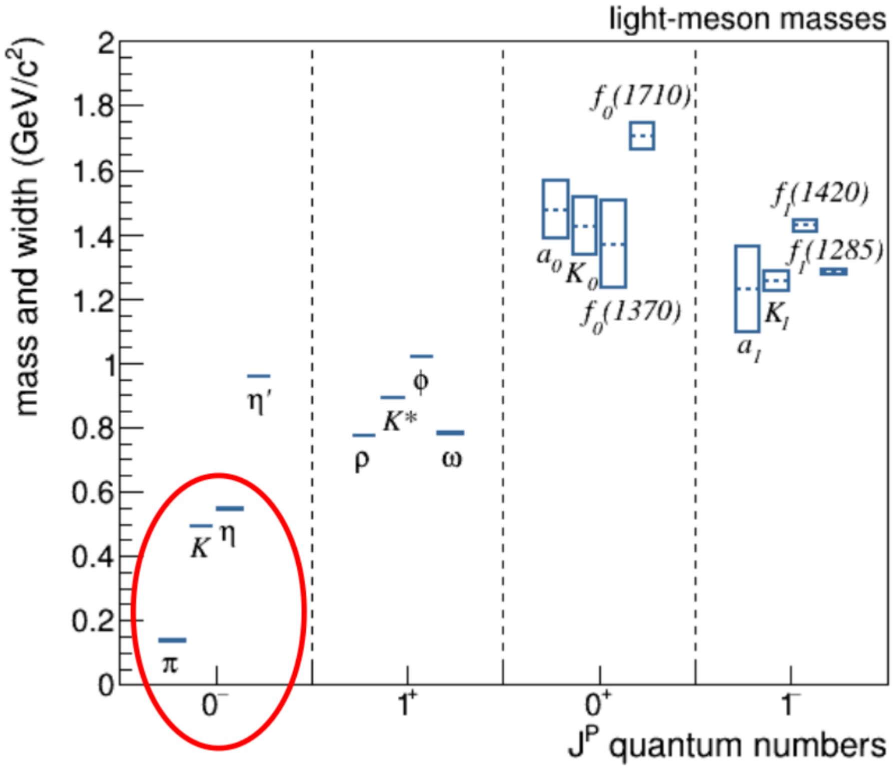
$$\boldsymbol{SU(3)_R \times SU(3)_L \rightarrow SU(3)_V}$$

⇒ Eight massless, spinless Goldstone bosons

$$(\pi^{\pm}, \pi^0, K^{\pm}, K^0, \bar{K}^0, \eta)$$

⇒ Explicit breaking of chiral symmetry due to the small quark masses -> Goldstone bosons acquire mass

⇒ Chiral Perturbation Theory: effective Lagrangian with power-counting scheme as low-energy theory for QCD makes use of chiral symmetry



(almost) massless Goldstone bosons

Chiral Perturbation Theory (ChPT)

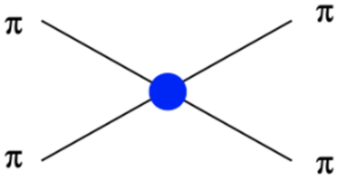
- Most general, chiral invariant, effective Lagrangian
- Basic degrees of freedom: Goldstone boson fields of chiral symmetry breaking

$$(\pi^\pm, \pi^0, K^\pm, K^0, \bar{K}^0, \eta)$$

- Describes: interactions of Goldstone boson fields with electromagnetic and other matter fields
- Power-counting scheme in masses and momenta

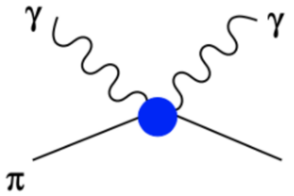
Predictions of ChPT

- Pion scattering lengths 2-loop predictions:
  confirmed by E865 in $K^+ \to \pi^+\pi^-e^+\nu_e$
  and by NA48 in $K^+ \to \pi^+\pi^0\pi^0$

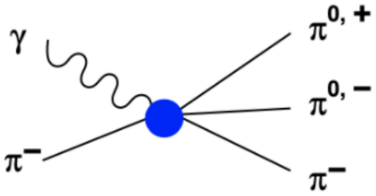


- Pion polarizability
  - Contribution to Compton scattering
  - ChPT prediction by relation to $\pi^+ \to e^+\nu_e\gamma$

[Gasser, Ivanov, Sainio, Nucl. Phys. B745, 2006]



- Pion scattering including a real photon
  - Leading-order predictions from ChPT
  - Chiral loop contribution available from ChPT



Weizsäcker-Williams approximation

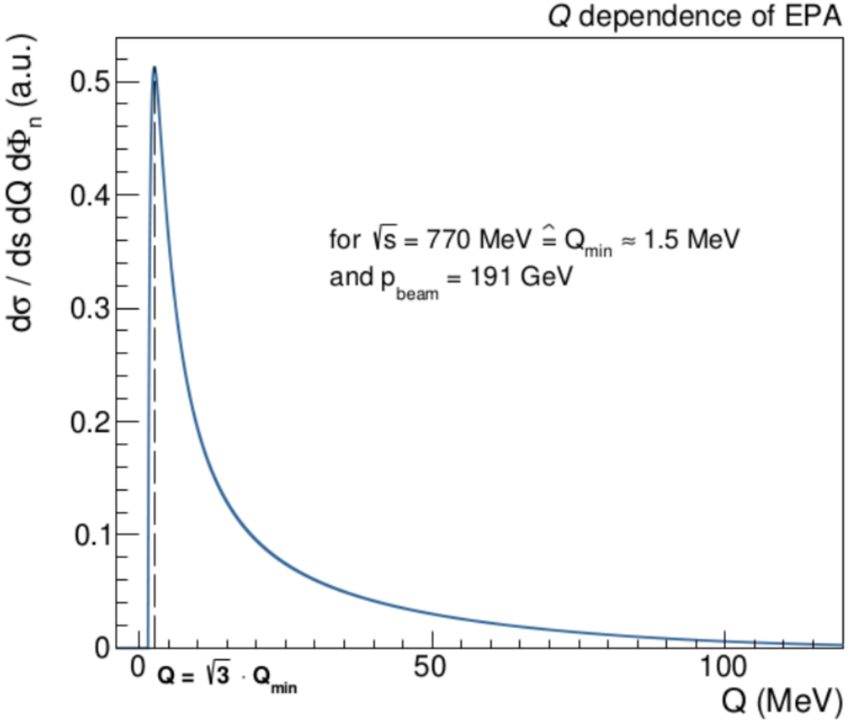
- Developed by Weizsäcker and Williams for description of Bremsstrahlung events.

- Coulomb field of relativistic charge ≈ flux of quasi-real photons
  Equivalent **p**hoton **a**pproximation (single-photon exchange)

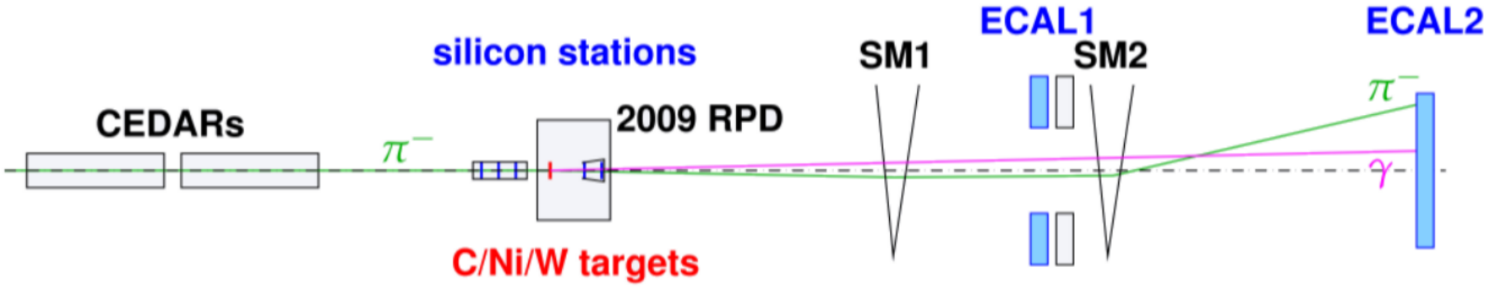
$$\frac{\mathrm{d}\sigma}{\mathrm{d}s\,\mathrm{d}Q^2\,\mathrm{d}\Phi_n} = \underbrace{\frac{Z^2\alpha}{\pi(s-m_\pi^2)}F^2(Q^2)\frac{Q^2-Q^2_{\mathrm{min}}}{Q^4}}_{\text{Flux of quasi-real photons}} \cdot \underbrace{\frac{\mathrm{d}\sigma_{\pi\gamma\to X}}{\mathrm{d}\Phi_n}}_{\pi\gamma\text{ scattering cross section}}$$

- Beam pions scatter off equivalent photons

- Peak at tiny momentum transfers $Q^2 \approx 10^{-5}\mathrm{GeV}^2/c^2$



Principle of Measurement



- 190 GeV negative hadron beam: $96.8\%\ \pi^-, 2.4\%\ K^-, 0.8\%\ \bar{p}$
- Beam particle identification by Cherenkov detectors
- 4mm Ni target disk $(\approx 25\%\ \ X/X_0)$
- Measure scattered π^- and produced photons (number of photons depends on final state)
- Select exclusive events at very low Q^2
- For absolute cross-section measurements:

  Luminosity determination via free Kaon decays

$$(K^- \longrightarrow \pi^-\pi^0 \text{ or } K^- \longrightarrow \pi^-\pi^0\pi^0)$$

Luminosity determination

- Needed for absolute cross section measurement: effective integrated luminosity (DAQ dead time taken into account)

Effective luminosity: $L_{eff} = L \cdot (1 - \epsilon_{DAQ})$

- Luminosity can be determined via free decays of beam kaons in the beam:
  - Use CEDARs to tag kaons
  - Measure free decays where no material
  - Exclusive events with zero momentum transfer

$$\overset{\text{Number of detected kaon decays}}{N_K} = \underset{\text{Pion flux}}{\Phi_\pi} \overset{\text{Kaon/pion flux ratio}}{\frac{n_K}{n_\pi}} \underbrace{BR(K^- \to \pi^0\pi^-)}_{\text{Branching ratio}} \overbrace{(1 - e^{-\frac{L}{\gamma c\tau}})}^{\text{Probability of kaon decaying in region with length L}} \underset{\text{Acceptance for kaon decays for particular final state}}{\epsilon_K}$$

Kaon decay channels

Decay channel	Γ_i/Γ	Remark
$K^- \to \mu^- \bar{\nu}_\mu$	(63.56 ± 0.11) %	Does not deposit energy in ECAL2 (Primakoff-trigger)
$\boldsymbol{K^- \to \pi^- \pi^0}$	(20.67 ± 0.08) %	Similar systematics as Primakoff $\pi^- \to \pi^- \pi^0$ channel
$K^- \to \pi^- \pi^- \pi^+$	(5.583 ± 0.024) %	Does not deposit energy in ECAL2 (Primakoff-trigger)
$\boldsymbol{K^- \to e^- \pi^0 \bar{\nu}_e}$	(5.07 ± 0.08) %	Non exclusive, missing energy
$\boldsymbol{K^- \to \mu^- \pi^0 \bar{\nu}_\mu}$	(3.352 ± 0.033) %	Non exclusive, missing energy
$\boldsymbol{K^- \to \pi^- \pi^0 \pi^0}$	(1.760 ± 0.023) %	Used to determine $^{\pi}/_{K}$-ratio in the beam
others	$< 10^{-4}$	No significant contribution to background expected

- Different channels may form background for each other, but give possibility to crosscheck results

🟩	Used for luminosity determination
▨	Considered as background process

Effective integrated luminosity

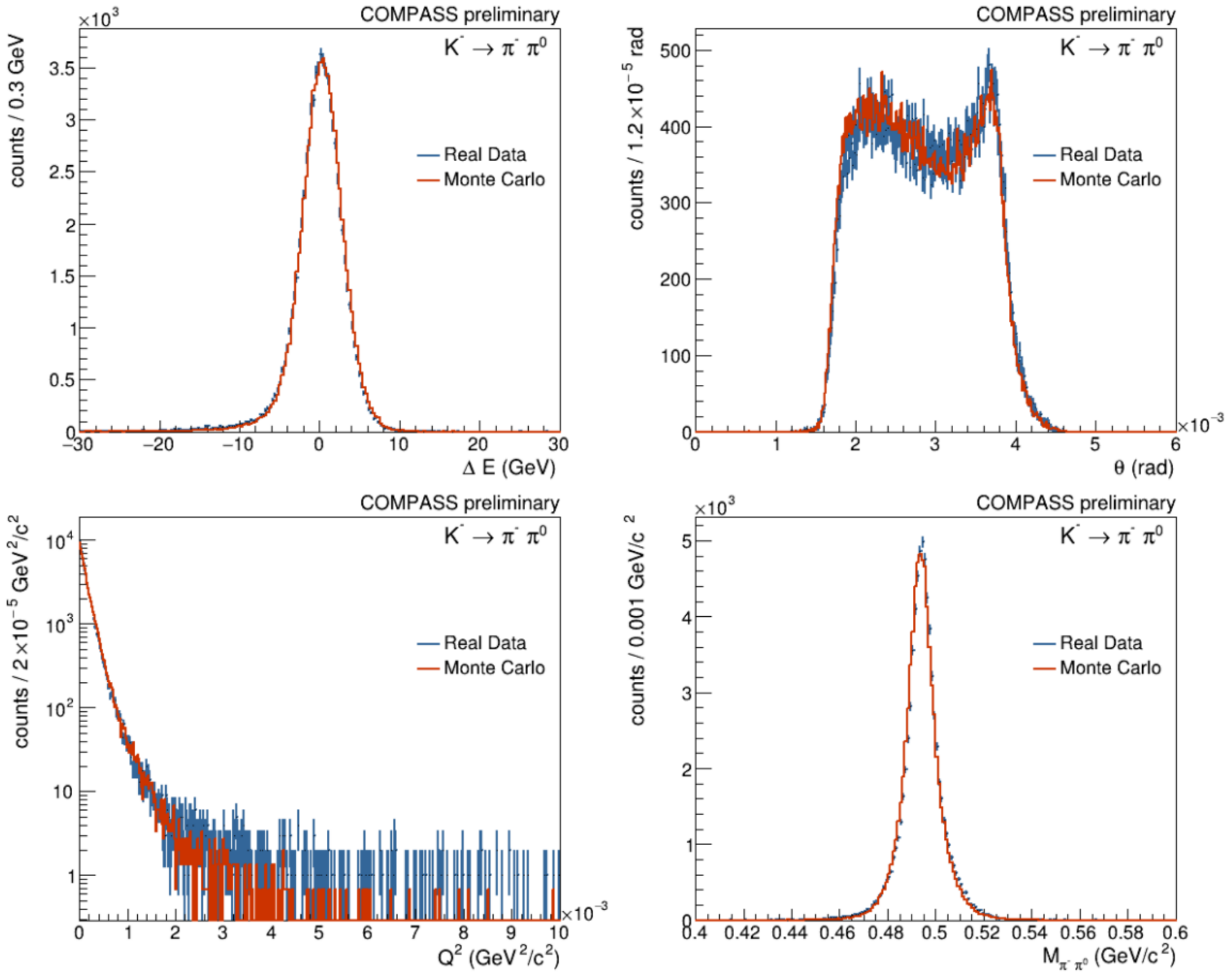
$$L_{2\pi,\mathrm{eff}} = 5.21 \pm 0.04_{\mathrm{stat}}\ \mathrm{nb}^{-1}$$
$$L_{3\pi,\mathrm{eff}} = 5.06 \pm 0.12_{\mathrm{stat}}\ \mathrm{nb}^{-1}$$

Largest contributions to systematic uncertainty:

- CEDAR tag efficiency: 7%
- ECAL reconstruction: 5%
- kaon/pion beam ratio: 2.5%

Result:

$$L_{\mathrm{eff}} = 5.21 \pm 0.48_{\mathrm{syst}} \pm 0.04_{\mathrm{stat}}$$



Primakoff data sets at COMPASS

2004

$\pi^+\pi^-\pi^-$: published result → PRL 108 (2012) 192001

2009

$\pi^-\gamma$: pion polarizabilities → Phys. Rev. Lett. 114 (2015) 06002

$\pi^-\pi^0$: chiral anomaly

$\pi^-\pi^0\pi^0$: chiral dynamics

} Presented in this talk

2012

$\pi^-\gamma$: pion polarizabilities

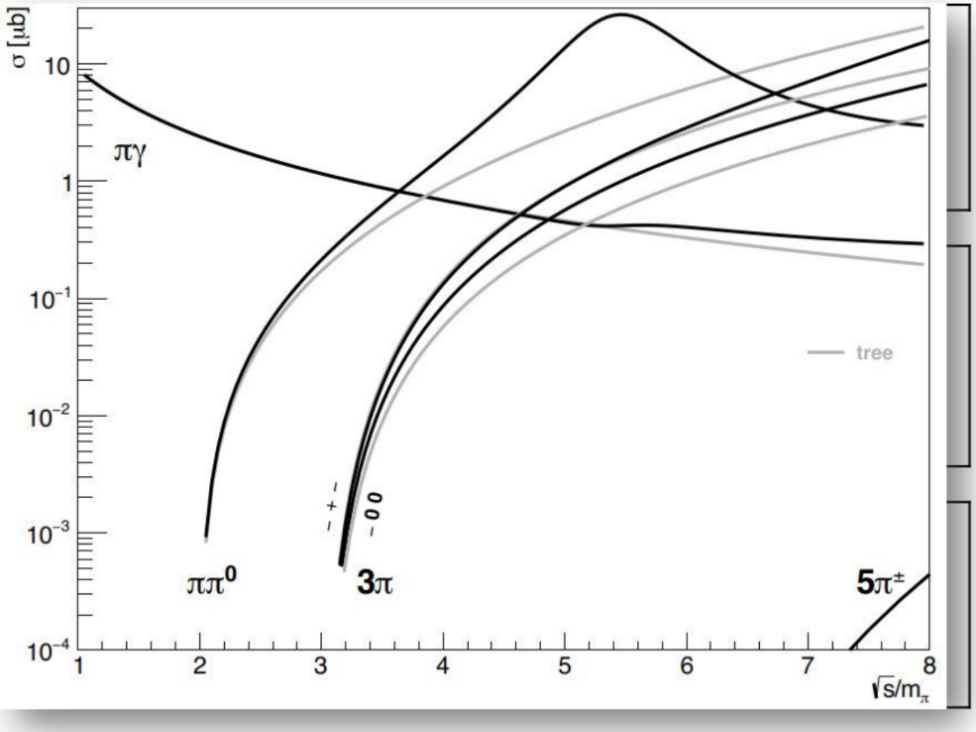
$\pi^-\pi^0$: chiral anomaly

$\pi^-\pi^0\pi^0$: chiral dynamics

} 4x larger data set compared to 2009
No results yet, MC still incomplete

Primakoff data sets at COMPASS

2004	$\pi^+\pi^-\pi^-$: pub
2009	$\pi^-\gamma$: pion pola $\pi^-\pi^0$: chiral ar $\pi^-\pi^0\pi^0$: chira
2012	$\pi^-\gamma$: pion pola $\pi^-\pi^0$: chiral ar $\pi^-\pi^0\pi^0$: chira



Primakoff Program at COMPASS

Requirements for Primakoff

- Fixed target setup with nuclear target (Z-dependence of WW approximation)
- Good Q^2-resolution to separate Coulomb processes (Primakoff) from other processes (strong processes)
- Neutral particles in final state ⟶ calorimetry with good position/energy resolution for good Q^2-resolution.

Interesting $\pi + \gamma$ reactions:

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

2004	$\pi^+\pi^-\pi^-$: published result	→ PRL 108 (2012) 192001
2009	$\pi^-\gamma$: pion polarizabilities	→ PRL 114 (2015) 06002
	$\pi^-\pi^0$: chiral anomaly	Topic of this talk
	$\pi^-\pi^0\pi^0$: chiral dynamics	
2012	$\pi^-\gamma$: pion polarizabilities	4x larger data set compared to 2009
	$\pi^-\pi^0$: chiral anomaly	
	$\pi^-\pi^0\pi^0$: chiral dynamics	

Previous measurement of $F_{3\pi}$

Antipov, Y. *et al.* PRD 36 (1987) 101103 using data from Serpukhov experiments

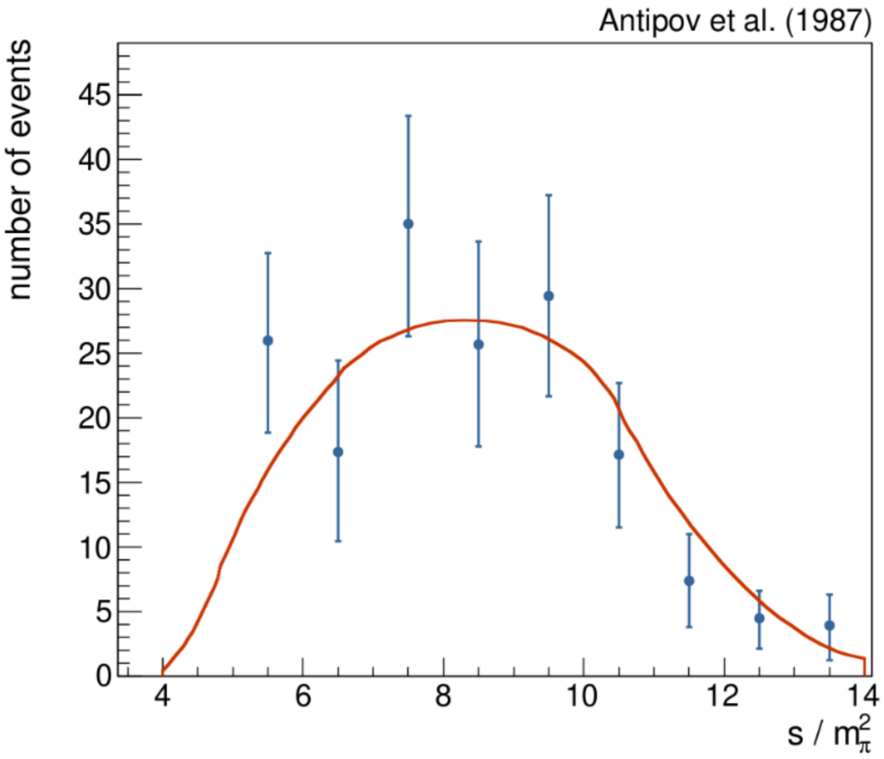
Problem of explicit chiral symmetry breaking:

As previously noted, the value $F^{3\pi}$ is supposed to vary slowly with $s,t,q^2 \ll m_\rho{}^2$ so that $F^{3\pi} \simeq F^{3\pi}(0)$.

$\Rightarrow \bar{F}_{3\pi} = (12.9 \pm 0.9 \pm 0.5)\ \mathrm{GeV}^{-3}$

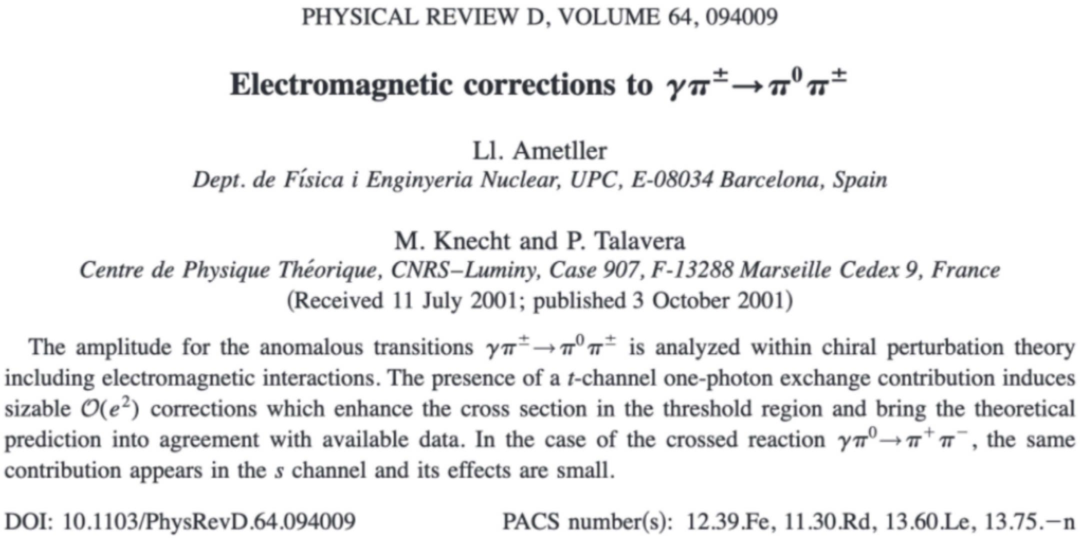
Reanalysis using ChPT to extrapolate to chiral limit (+ corrections):

$\Rightarrow F_{3\pi} = (10.7 \pm 1.2)\ \mathrm{GeV}^{-3}$



Previous measurement of $F_{3\pi}$ - Reanalysis

Ametller, L. *et al.* PRD 64 (2001) 094009



PHYSICAL REVIEW D, VOLUME 64, 094009

Electromagnetic corrections to $\gamma\pi^{\pm}\rightarrow\pi^{0}\pi^{\pm}$

Ll. Ametller
Dept. de Física i Enginyeria Nuclear, UPC, E-08034 Barcelona, Spain

M. Knecht and P. Talavera
Centre de Physique Théorique, CNRS–Luminy, Case 907, F-13288 Marseille Cedex 9, France

(Received 11 July 2001; published 3 October 2001)

The amplitude for the anomalous transitions $\gamma\pi^{\pm}\rightarrow\pi^{0}\pi^{\pm}$ is analyzed within chiral perturbation theory including electromagnetic interactions. The presence of a t-channel one-photon exchange contribution induces sizable $\mathcal{O}(e^{2})$ corrections which enhance the cross section in the threshold region and bring the theoretical prediction into agreement with available data. In the case of the crossed reaction $\gamma\pi^{0}\rightarrow\pi^{+}\pi^{-}$, the same contribution appears in the s channel and its effects are small.

DOI: 10.1103/PhysRevD.64.094009 PACS number(s): 12.39.Fe, 11.30.Rd, 13.60.Le, 13.75.−n

Reanalysis of Serpukhov data using chiral expansion:

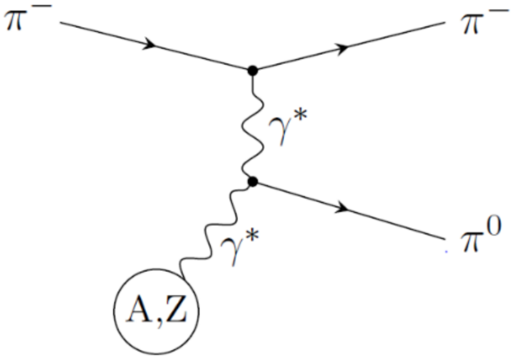
$$F_{3\pi}(s,t,u)=F_{3\pi}\left(f^{(0)}(s,t,u)+f^{(1)}(s,t,u)+f^{(2)}(s,t,u)+\ldots\right)$$

- Extrapolation using one loop and two loop corrections:

$$F_{3\pi}=(11.4\pm1.3)\ \mathrm{GeV}^{-3}$$

Previous measurement of $F_{3\pi}$ - Reanalysis

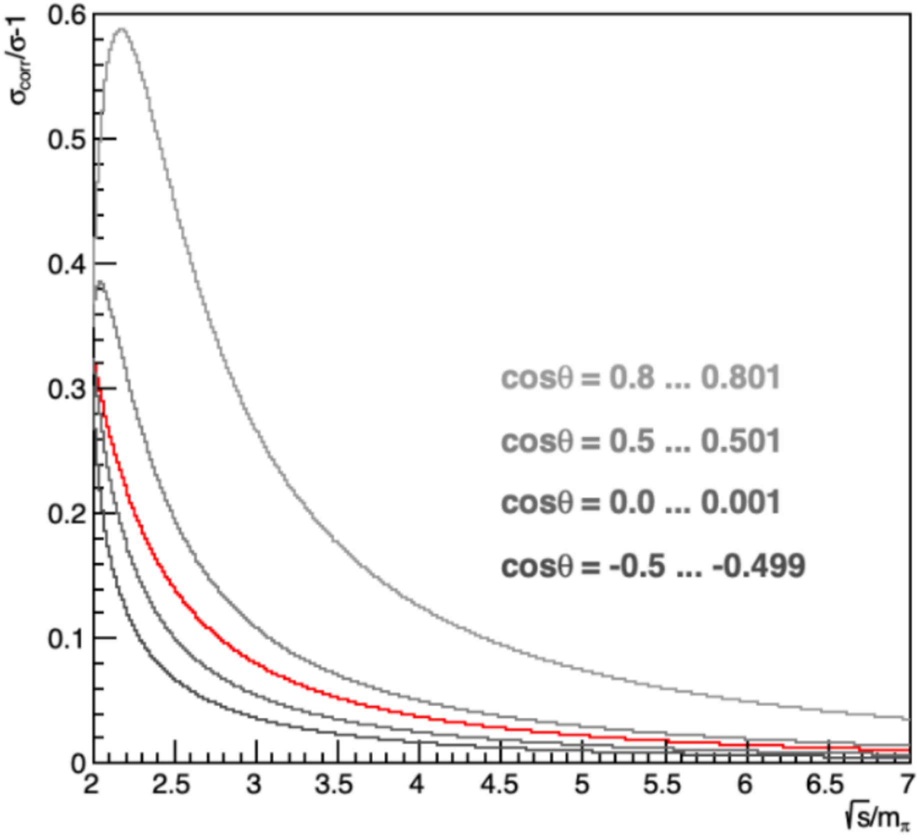
- Electro-magnetic corrections => significant contribution to $f^{(0)}(s,t,u)$ when isospin breaking effect are taken into account.



- Integrated correction amounts to 32% at threshold

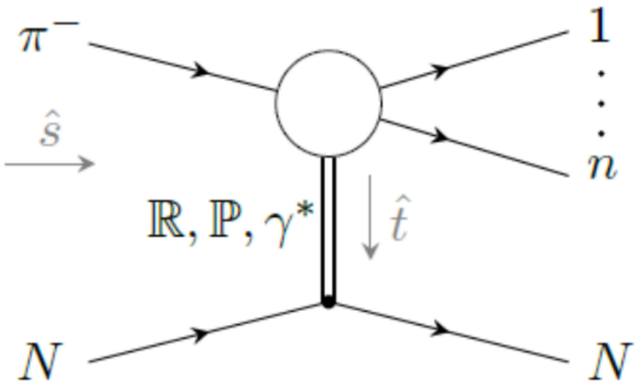
$$\Longrightarrow F_{3\pi} = (10.7 \pm 1.2)\ \mathrm{GeV}^{-3}$$

- Precision of previous measurements: $\mathcal{O}(10\%)$
  $\Rightarrow$ More precise experimental determination desirable



Ametller, L. *et al.* PRD 64 (2001) 094009

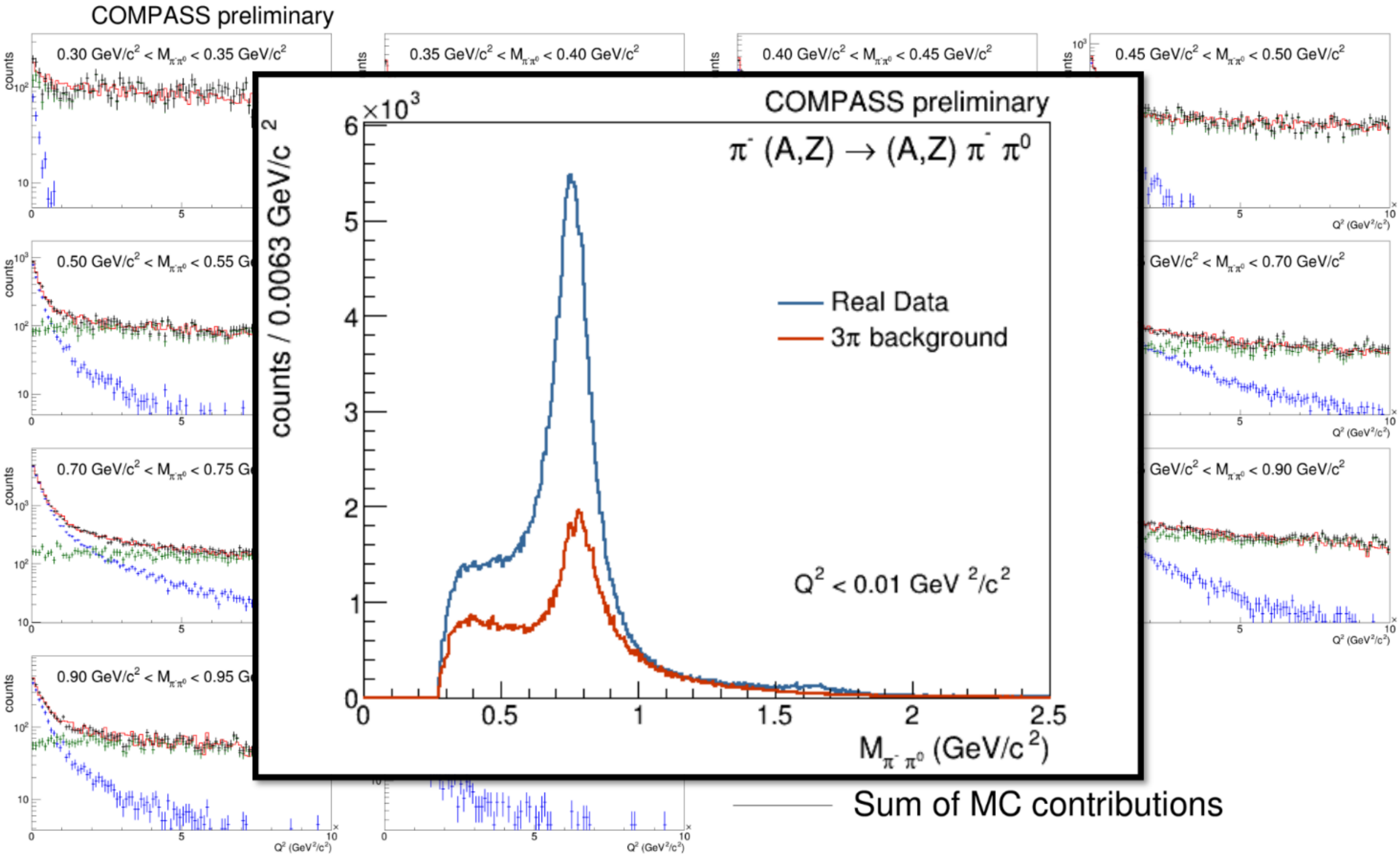
Production mechanisms for mesons at COMPASS



- Strong and electromagnetic production of mesons
- Electromagnetic production via Primakoff effect with sharp Q^2 distribution
- Pomeron exchange: $\pi^-\pi^0$ final state forbidden due to G-parity conservation, but: large cross-section for $\pi^-\pi^0\pi^0$-final state → loss of one (soft) π^0 as main background

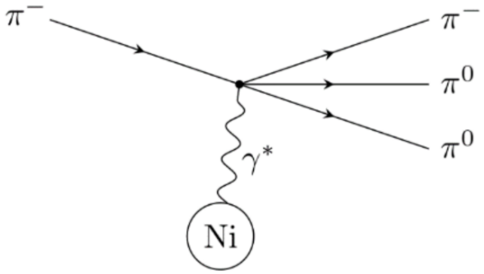
	Primakoff	$\mathbb{P}$ (strong)	$\mathbb{R}$ (strong)
$\sigma(s)$	$\propto \ln(\sqrt{s})$	$\propto$ const.	$\propto 1/\sqrt{s}$
$\sigma(A_{\text{target}})$	$\propto$ const.	$\propto A^{2/3}$	$\propto A^{2/3}$
$\sigma(Z_{\text{target}})$	$\propto Z^2$	$\propto$ const.	$\propto$ const.
$\sigma(t)$	$\propto \frac{Q^2-Q^2_{\text{min}}}{Q^4} = \frac{\hat{t}'}{\hat{t}^2}$	$\propto e^{-b\hat{t}'}$	$\propto g(\hat{t})\cdot e^{-b\hat{t}'}$ for small $\hat{t}$

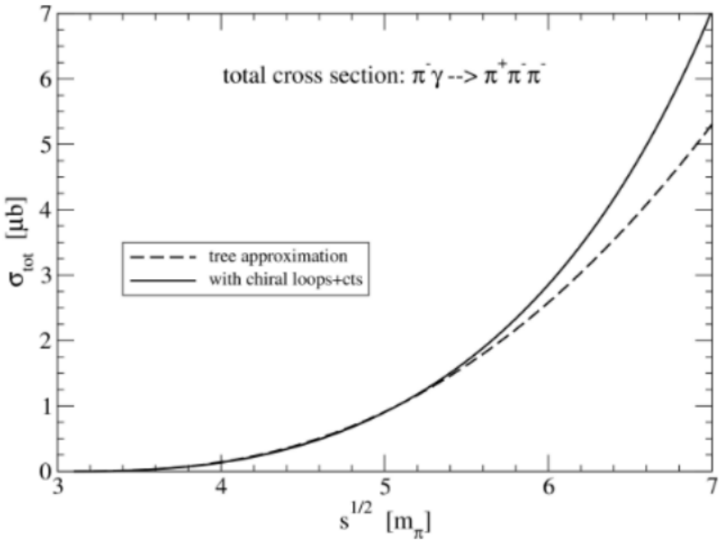
Scaling of 3π Monte Carlo background prediction



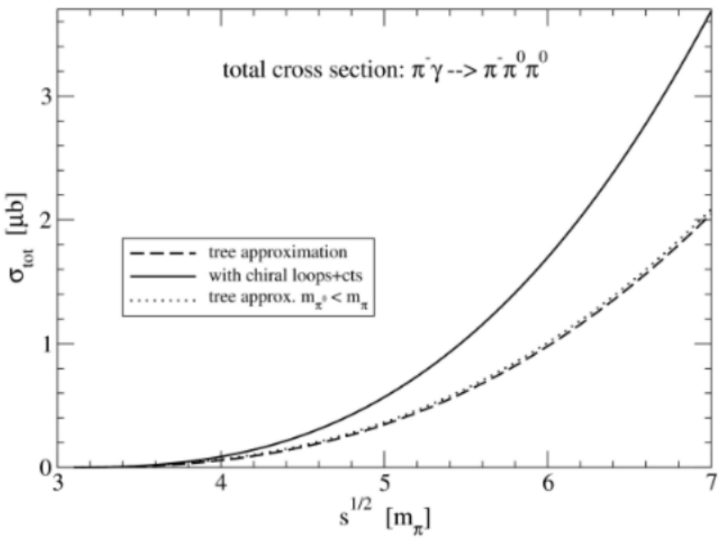
Chiral Tree, Chiral Loop

- Direct (point-like) coupling of photon to 4 pions
- Prediction from ChPT at tree- and loop-level available





Grabmüller S. (2012). Cryogenic Silicon Detectors and Analysis of Primakoff Contributions to the Reaction $\pi^- Pb \longrightarrow$



Krämer M. (2016) Evaluation and Optimization of a digital calorimetric trigger and analysis of $\pi^- Ni \longrightarrow$

Covered kinematic range

- Selection: $Q^2 < 1.296 \cdot 10^{-3}\,\mathrm{GeV}^2/c^2$
- Trigger on energy deposit in central part of electromagnetic calorimeter ($E_{\mathrm{trig}} > 68$ GeV)
- Minimum energy of π^0 → maximum scattering angle of π^- in Gottfried-Jackson frame