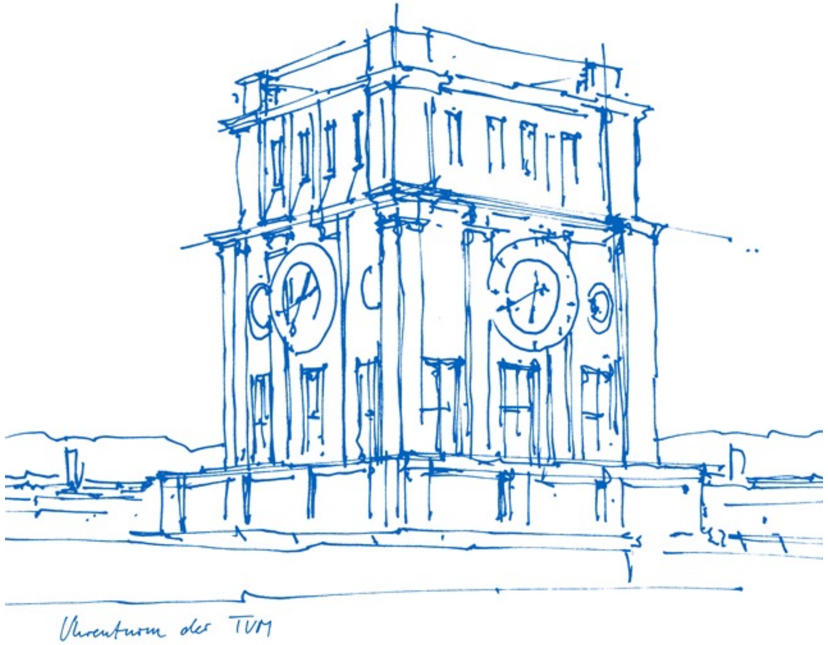
Testing Chiral Perturbation Theory in Soft Hadron-Photon Reactions at COMPASS and AMBER

Jan Friedrich
Institute for Hadronic Structures
and Fundamental Symmetries
Physik-Department,
School of Natural Sciences, TUM

WILHELM UND ELSE
HERAEUS-STIFTUNG

Brazilian-German WE Heraeus Seminar

Hadron spectroscopy and the new
unexpected resonances
Paraty, 22-28.9.2024



Quantum Chromodynamics

- Quantum Chromodynamics (QCD) as the underlying theory of strong interaction
- Lagrangian of QCD:

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

flavor-symmetry breaking term
($m_u \neq m_d \neq m_s$)

- Symmetries:

1. Local **color** symmetry (strong interaction couples equally to red, green, and blue color charges)
   → conservation of color charge, coupling to gluons

2. Flavor symmetries? → only **approximate** symmetries

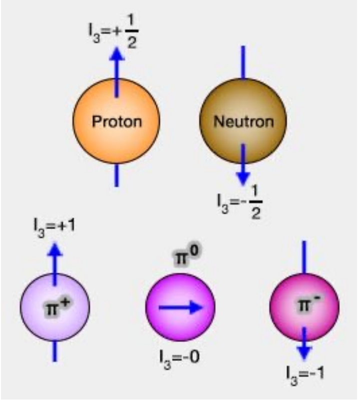
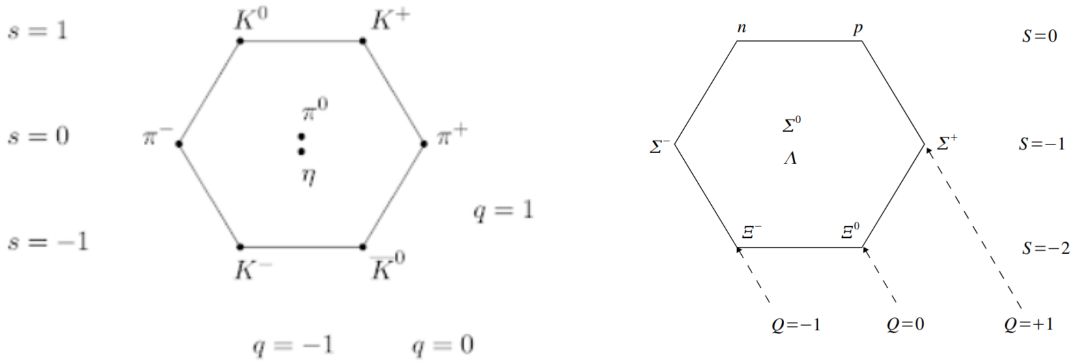
$$m_u = (2.16 \pm 0.49)\,\mathrm{MeV} \quad m_d = (4.67 \pm 0.48)\,\mathrm{MeV} \quad m_s = (93 \pm 11)\,\mathrm{MeV}$$
$$m_c = (1.27 \pm 0.02)\,\mathrm{GeV} \quad m_b = (4.18 \pm 0.03)\,\mathrm{GeV} \quad m_t \approx 170\,\mathrm{GeV}$$

Flavor symmetries of QCD

- Lagrangian of QCD:

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

- Approximate flavor symmetries:

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

Chiral symmetry of QCD

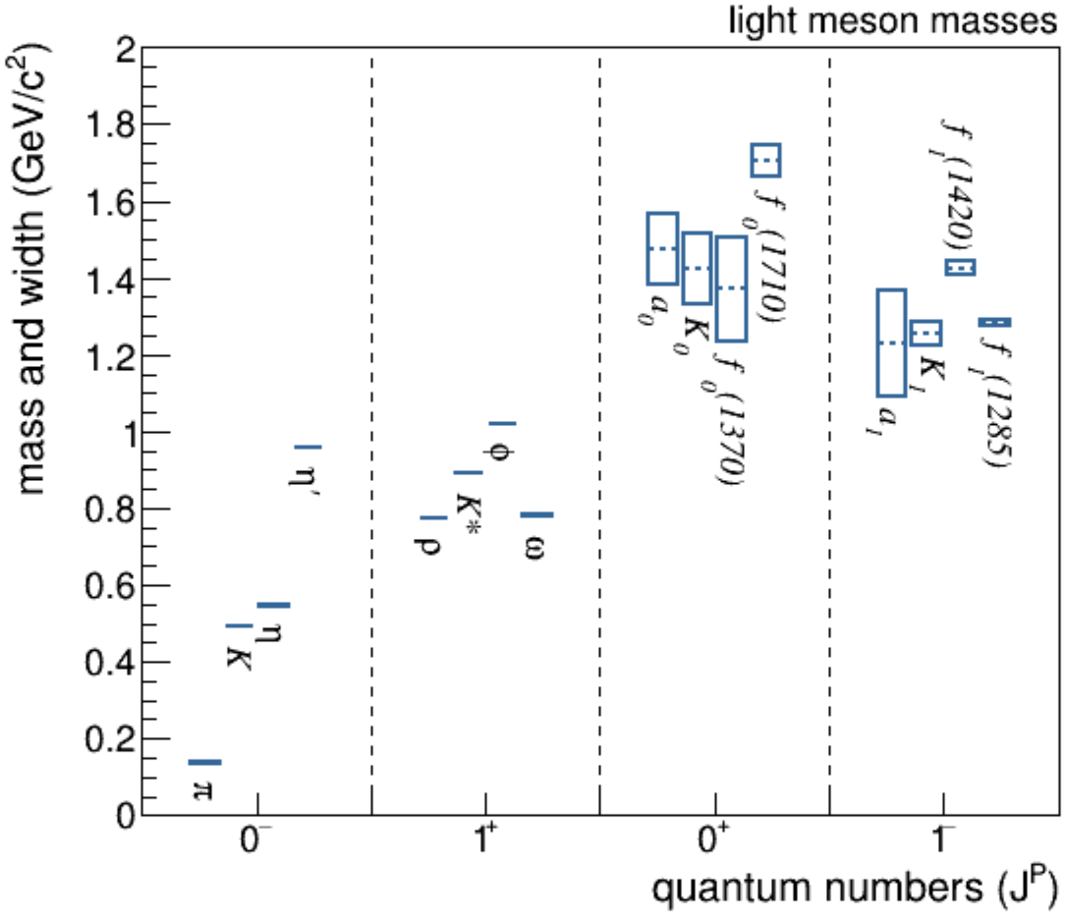
- Lagrangian of QCD:

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

- Flavor symmetries in chiral limit

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

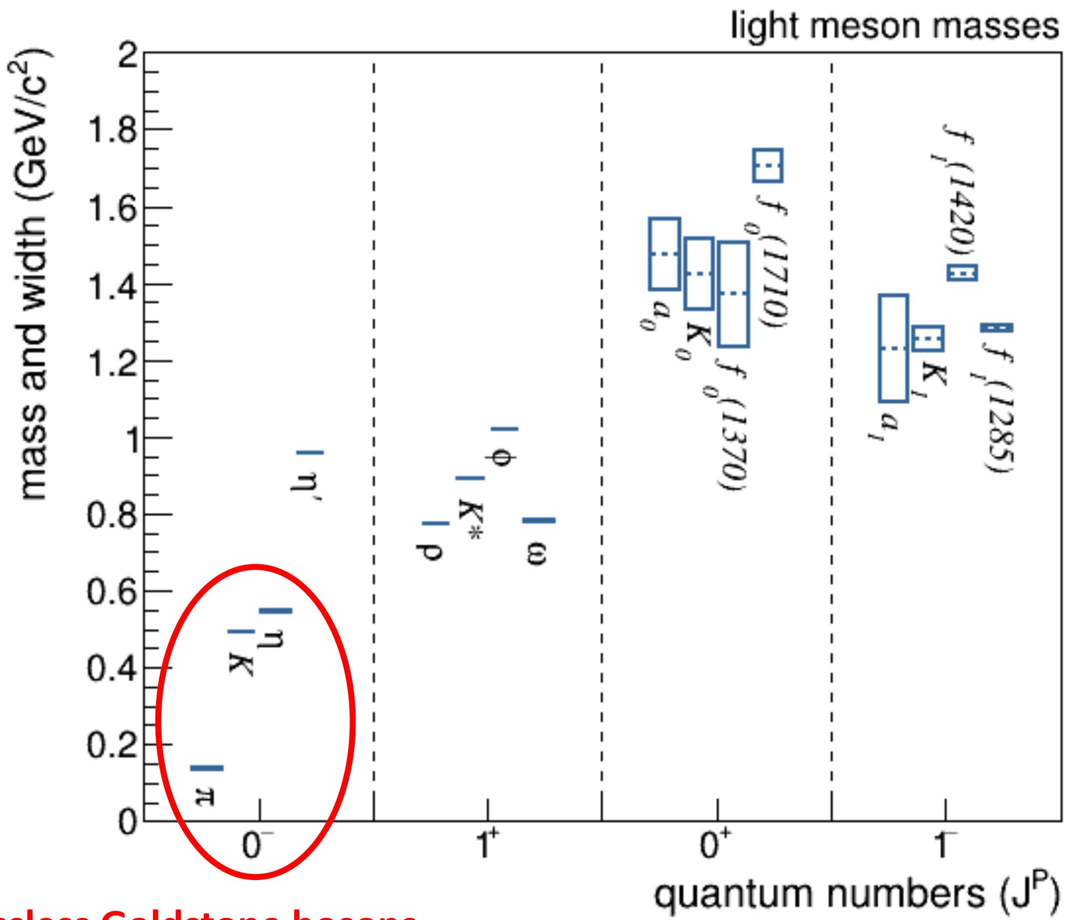
- Left- and right-handed fields decouple for massless particles
- Chirality can directly be translated to parity of particle
  → mass-degenerate doublets of states with opposite parity
- Why is chiral symmetry not manifested in the spectrum (in contrast to isospin and the eightfold way)?
  → Nambu-Goldstone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



Dynamic breaking of chiral symmetry

Spontaneous symmetry breaking

- ⇒ 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
- ⇒ $SU(3)_R \times SU(3)_L \rightarrow SU(3)_V$
- ⇒ Chiral Perturbation Theory: effective Lagrangian with power-counting scheme as low-energy theory for QCD makes use of chiral symmetry



(almost) massless Goldstone bosons

The chiral anomaly

- Lagrangian of QCD

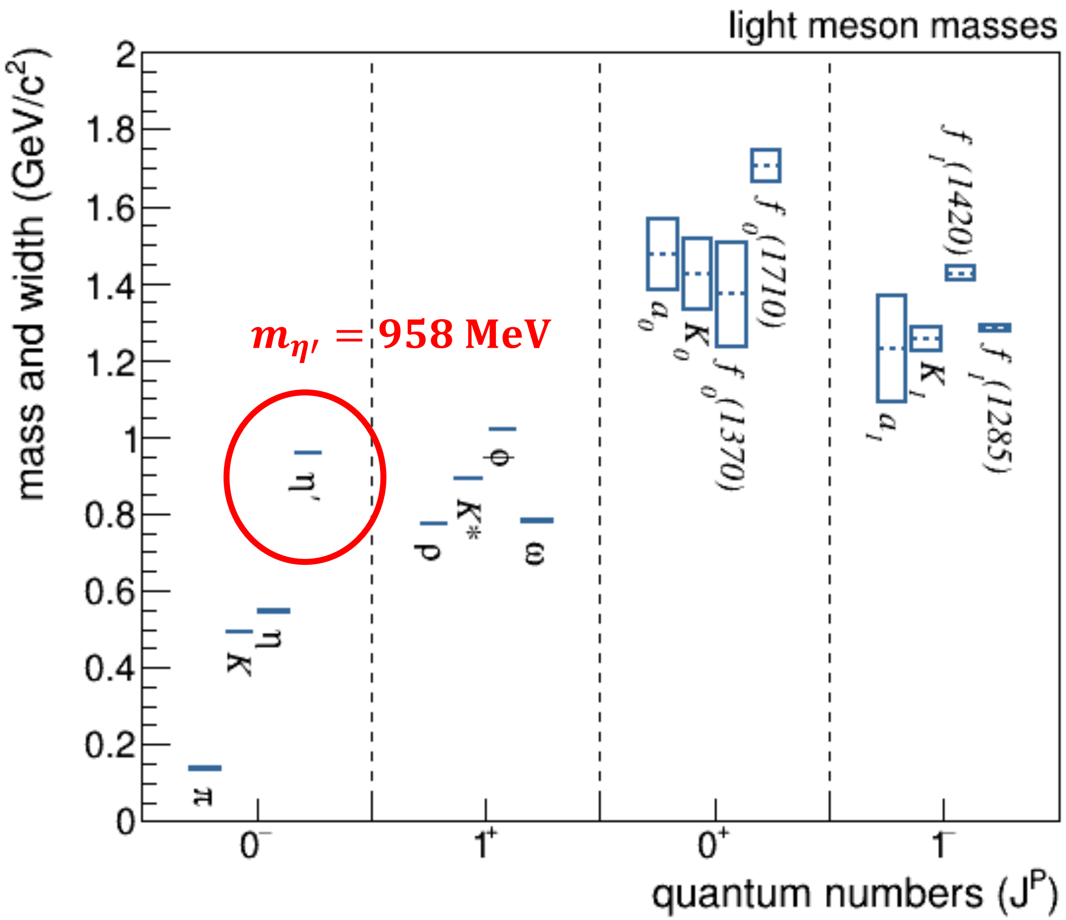
$$\mathcal{L}_{QCD} = \sum_{f=\substack{u,d,s,\\c,b,t}} \bar{q}_f\left(i\not{D} - m_f\right)q_f - \frac{1}{4}G^a_{\mu\nu}G_a^{\mu\nu}$$

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

$$q(x) \to e^{i\theta\gamma_5}q(x)$$

- No ninth “unnaturally light” meson

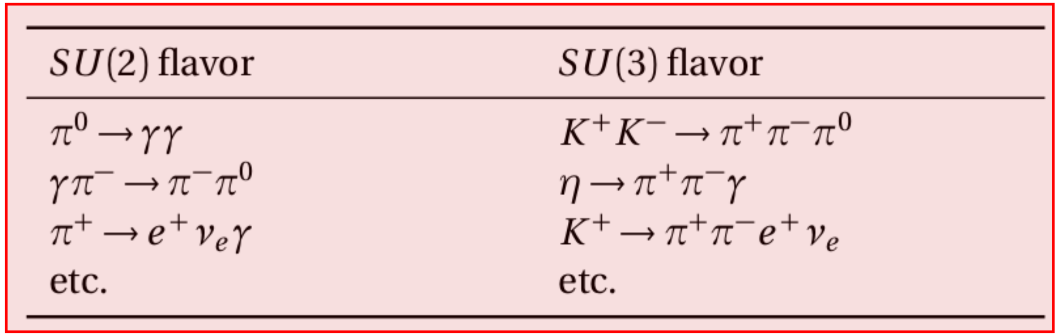
- **Anomalous** symmetry breaking: symmetry of the Lagrangian does not lead to conserved Noether currents
- **Anomaly:** Symmetry of classical Lagrangian violated at quantum level



$m_{\eta'} = 958\ \mathrm{MeV}$

Wess-Zumino-Witten term

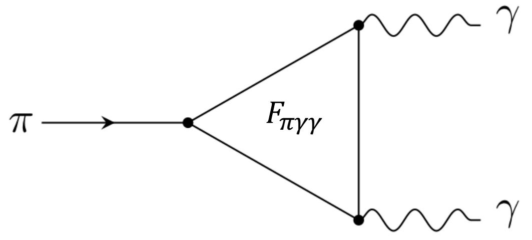
- Chiral anomaly in ChPT taken into account by Wess-Zumino-Witten (WZW) term
- Describes the coupling of an odd number of Goldstone bosons:



$SU(2)$ 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.

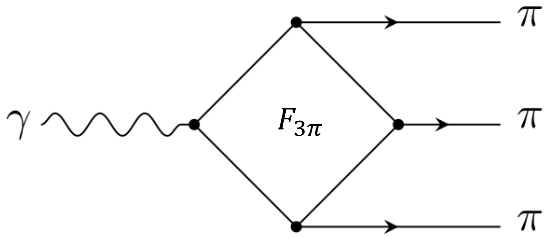
- Effective theory → pion decay constant F_π measured from leptonic $(\pi^\pm \to \mu^\pm + \nu)$ arged pion

$F_{\pi\gamma\gamma}$



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

$F_{3\pi}$

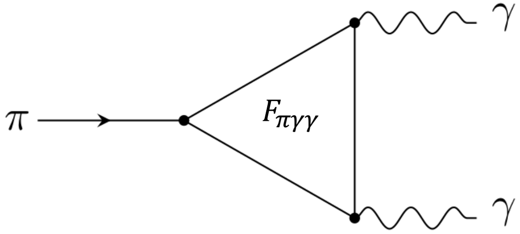


- $F_{3\pi} = \frac{e N_C}{12\pi^2 F_\pi^3} = (9.78 \pm 0.05)\text{GeV}^{-3}$

Discovery of the chiral anomaly: π^0 lifetime

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

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



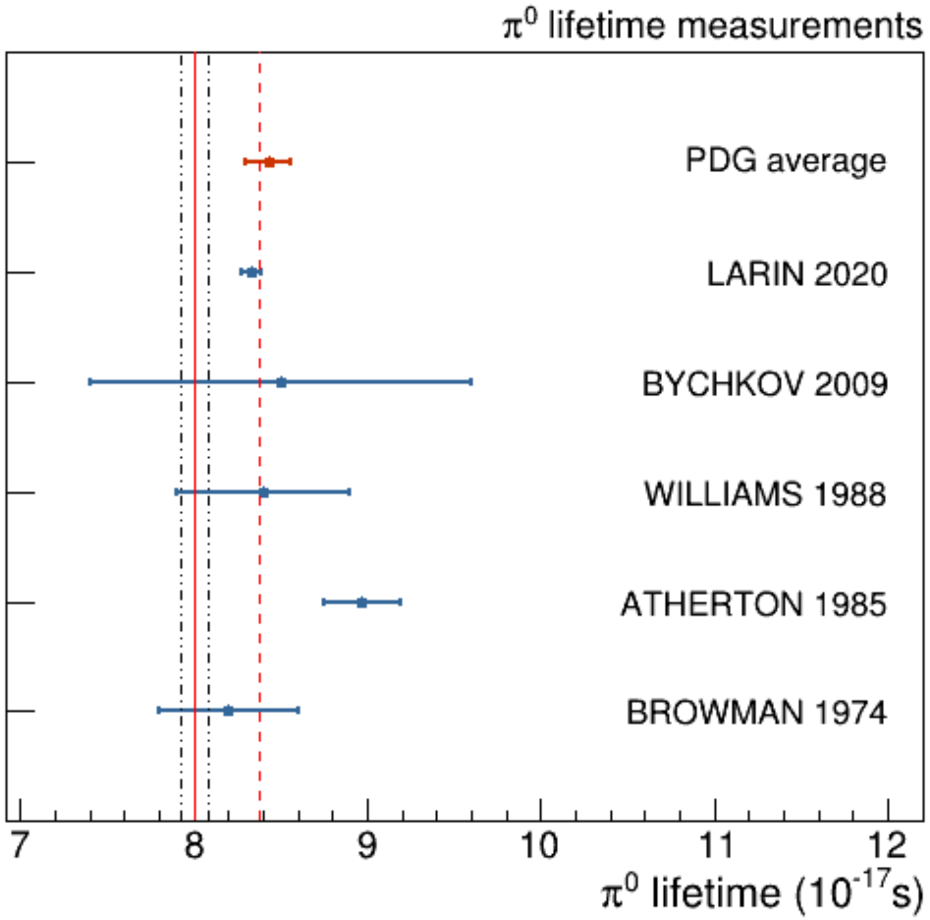
- Adler, Bell, Jackiw, Bardeen 1969: calculation of triangle diagram

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

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

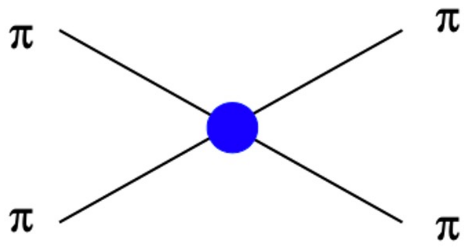
- Moussalam and Kampf 2009: NLO-calculation in chiral perturbation theory

$$\tau_{\text{NLO}}(\pi^0) = (8.04 \pm 0{,}11) \cdot 10^{-17}\text{s}$$

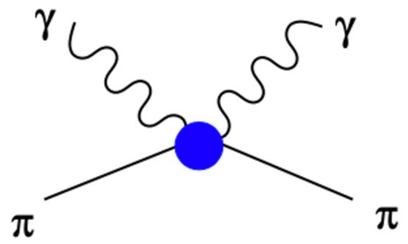


More predictions from ChPT

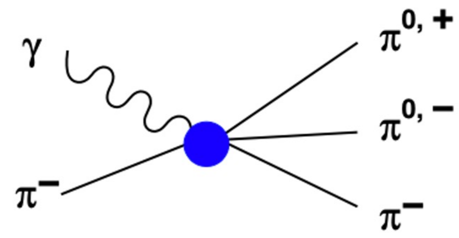
- pion scattering lengths predictions at 2 loops
  - $a_0^0 m_\pi = 0.220 \pm 0.005$ confirmed by E865 in $K^+ \rightarrow \pi^+\pi^- e^+ \nu_e$
  - $a_0^2 m_\pi = 0.264 \pm 0.006$ confirmed by NA48 in $K^+ \rightarrow \pi^+\pi^0\pi^0$ (0.268 ± 0.010)



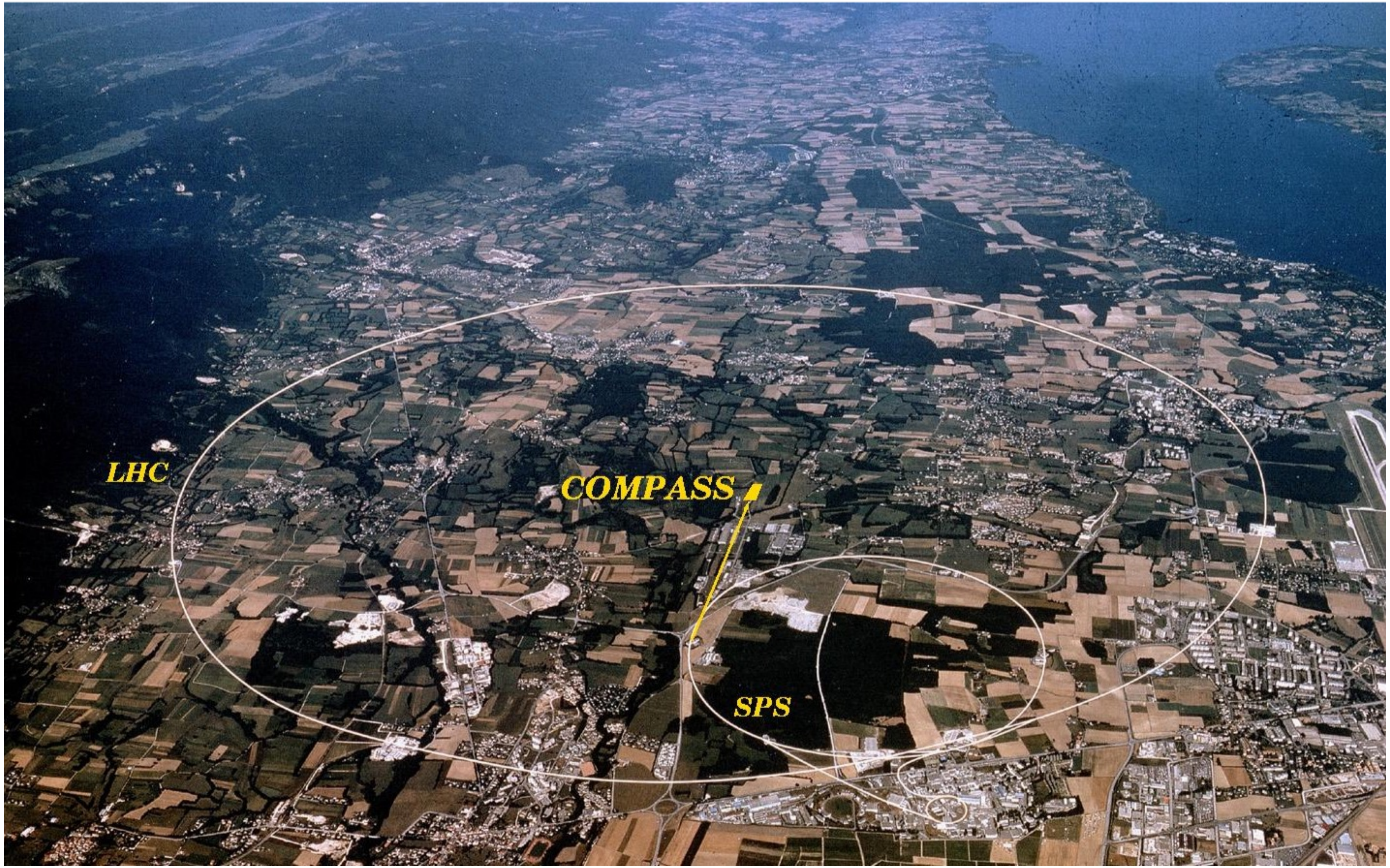
- pion polarisabilities: α_π (electric) and β_π (magnetic)
  - visible in Compton scattering cross-section
  - $\alpha_\pi + \beta_\pi = (0.2 \pm 0.1)\ 10^{-4}\ \mathrm{fm}^3$
  - $\alpha_\pi - \beta_\pi = (5.7 \pm 1.0)\ 10^{-4}\ \mathrm{fm}^3$
  - $\alpha_\pi = (2.9 \pm 0.5)\ 10^{-4}\ \mathrm{fm}^3$



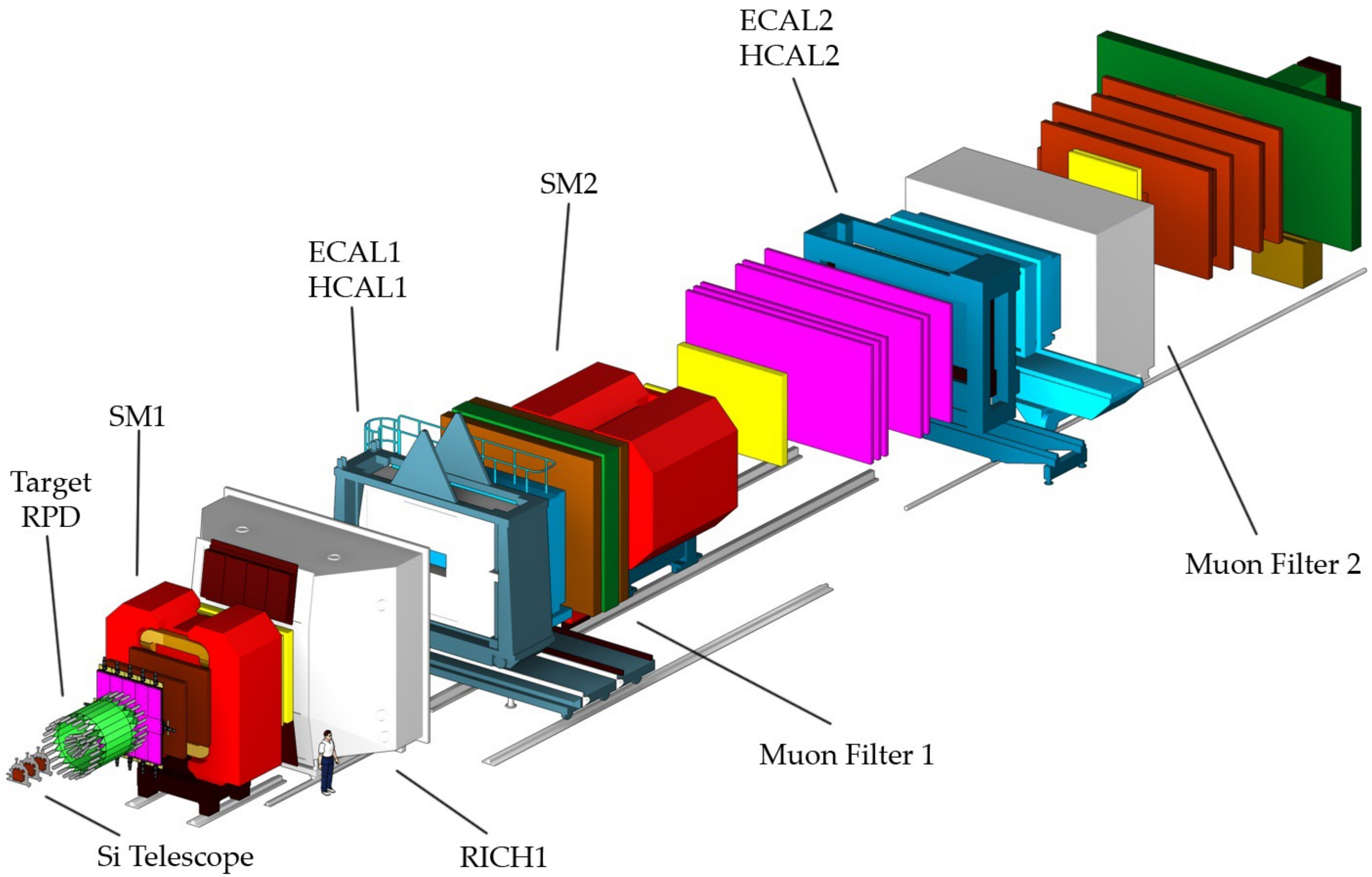
- pion-pion scattering with additional coupling to a photon
  - leading-order prediction from ChPT (scattering lengths + QED)
  - chiral-loop contributions: calculated, test with data pending



COmmon Muon and Proton Apparatus for Structure and Spectroscopy



COMPASS spectrometer

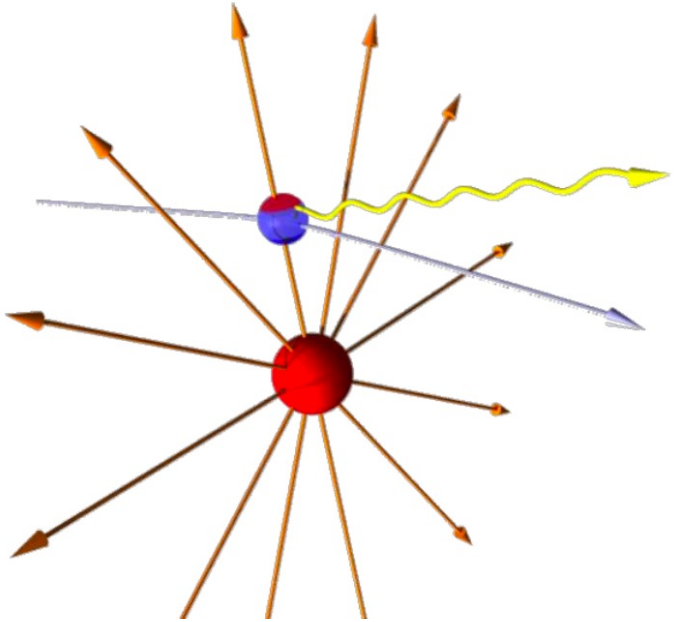


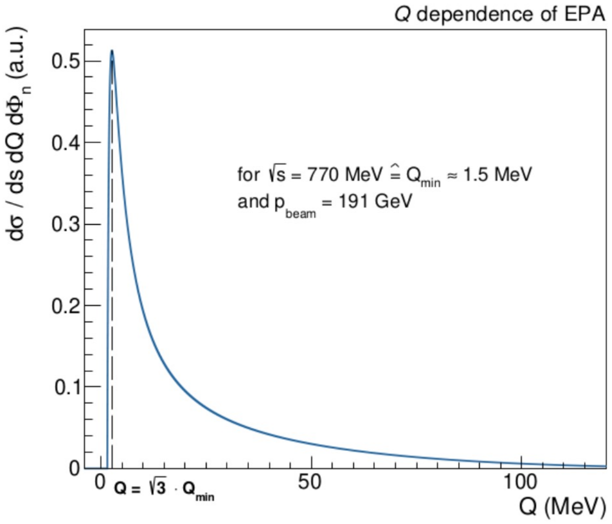
For the measurements presented in the following:

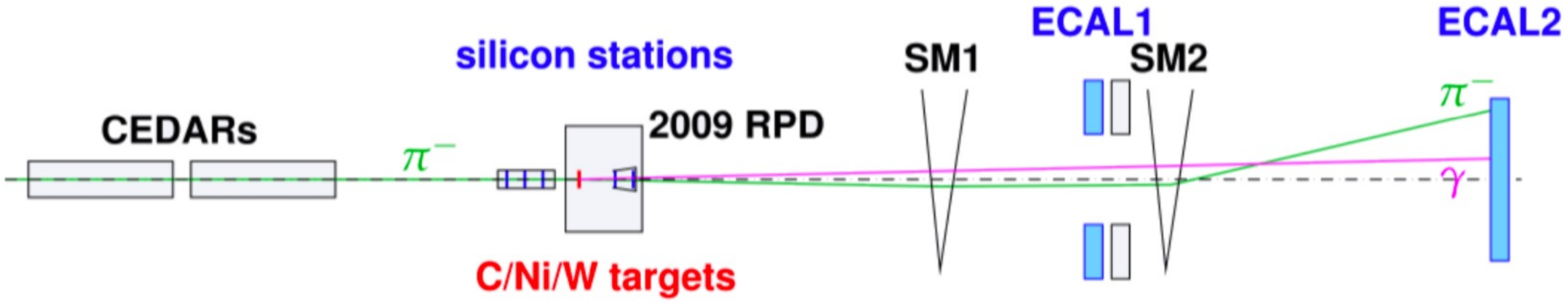
- 190 GeV negative hadron beam
- Beam PID
- Nuclear target(s): Ni and W
- Calorimetric trigger on neutrals
- Two stage spectrometer (LAS and SAS) with tracking and calorimeter

Pion-Photon reactions through the Primakoff technique

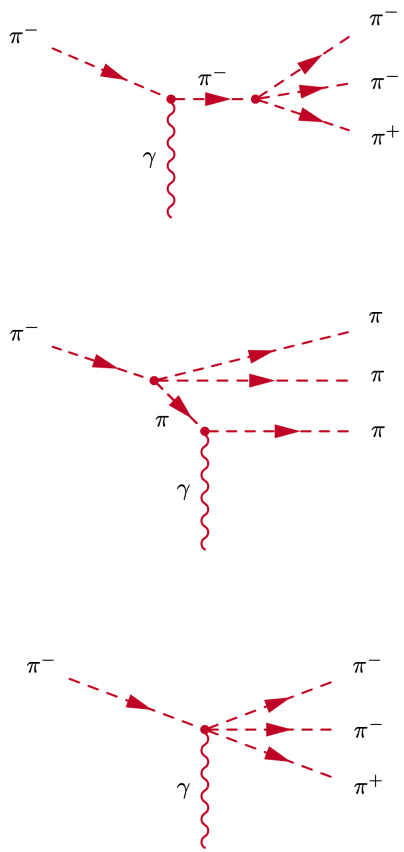
- Photon is provided by the strong Coulomb field of a nucleus (typical field strength at $d = 5R_{Ni}$: $E \approx 300\ \mathrm{kV/fm}$)
- Coulomb field of nucleus is a source of quasi-real ($P_\gamma^2 \ll m_\pi^2$) photons
- Large impact parameters (ultra-peripheral scattering)

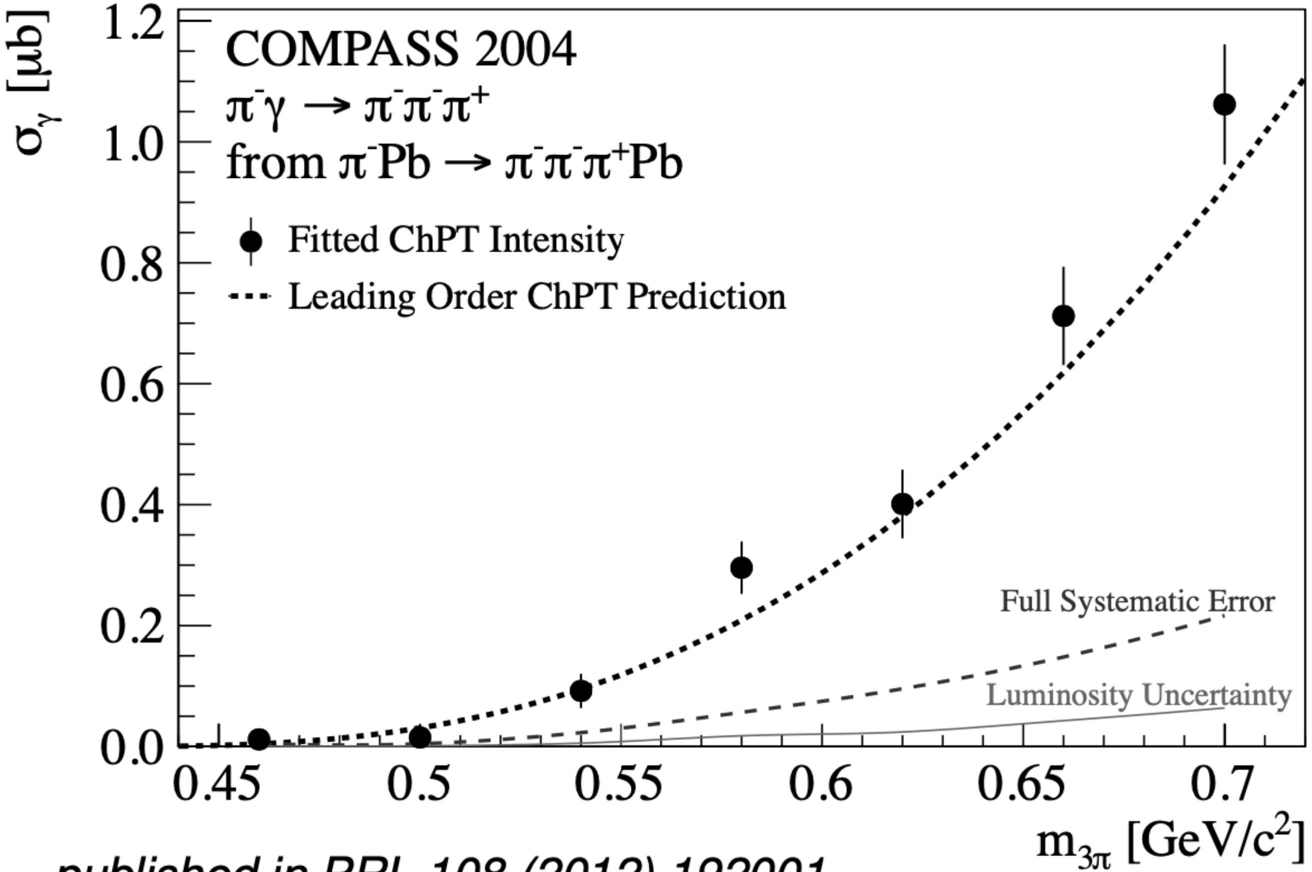






Measurement of the cross-section for $\pi^-\gamma \rightarrow \pi^-\pi^-\pi^+$

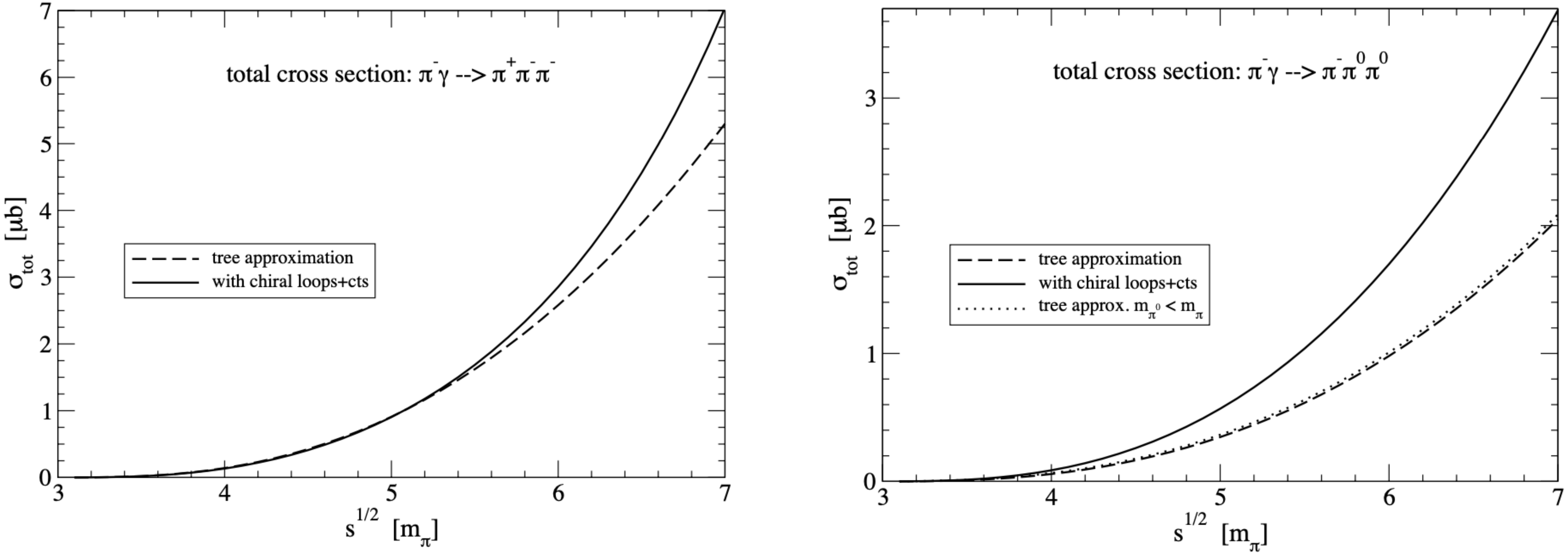




published in PRL 108 (2012) 192001

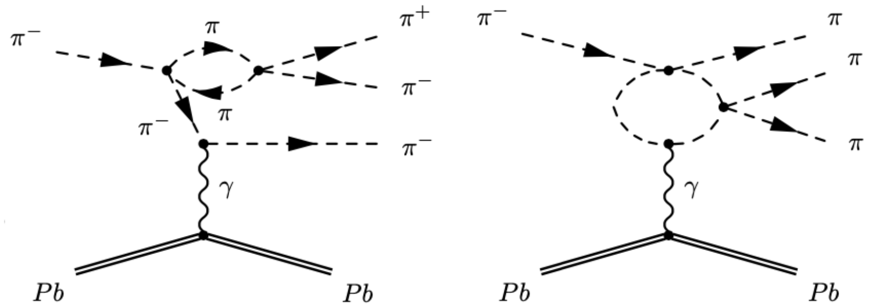
measurement up to $\sim 5m_\pi$

Higher chiral order for $\pi^-\gamma \rightarrow \pi^-\pi\,\pi$



N. Kaiser, NPA848 (2010) 198

Chiral loops e.g.

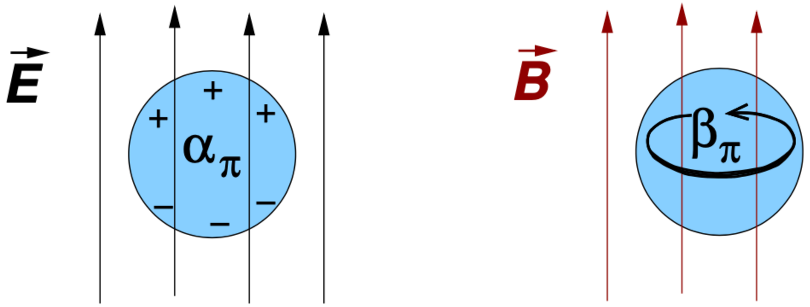


Also obtained in these analyses: radiative widths of $a_2(1320)$ and $\pi_2(1670)$
EPJ A50 (2014) 79

Pion polarisability: COMPASS measurement

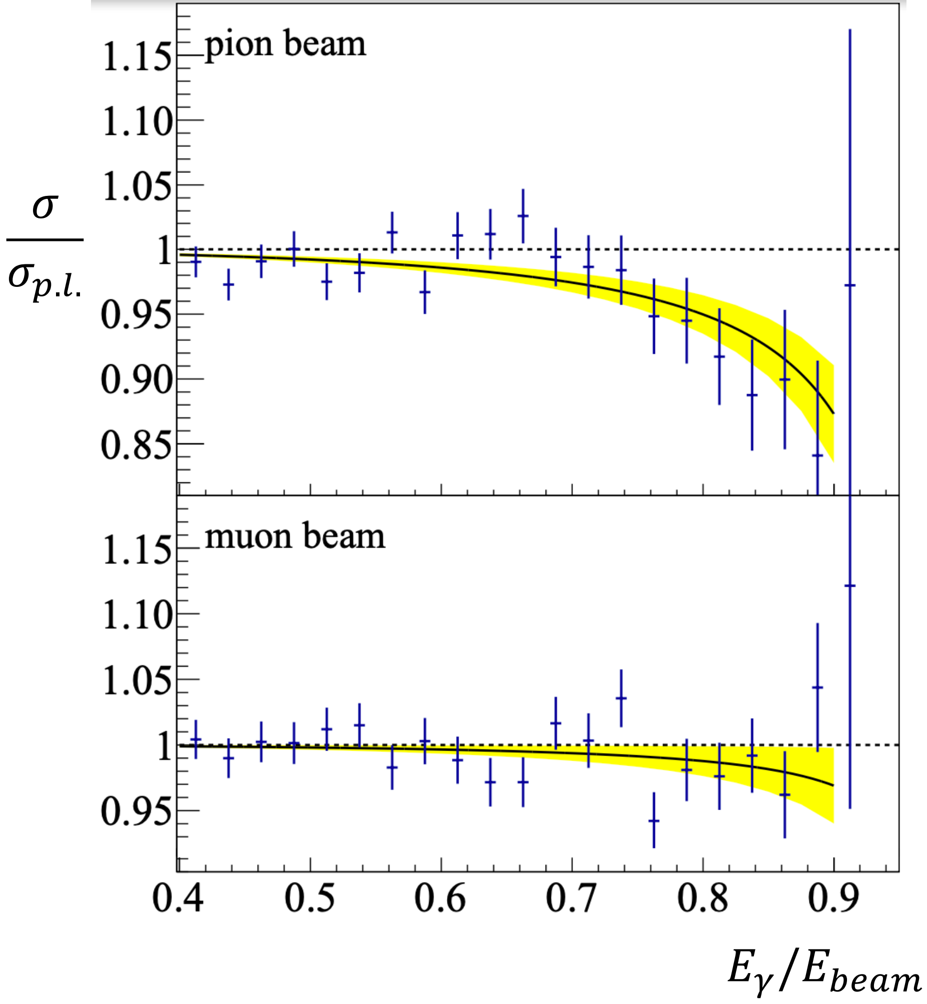
$$\pi + \gamma \rightarrow \pi + \gamma$$

Compton cross-section contains information about e.m. polarisability
(as deviation from the expectation for a pointlike particle)



polarisabilities α_π, β_π $[10^{-4}\ \mathrm{fm}^3]$

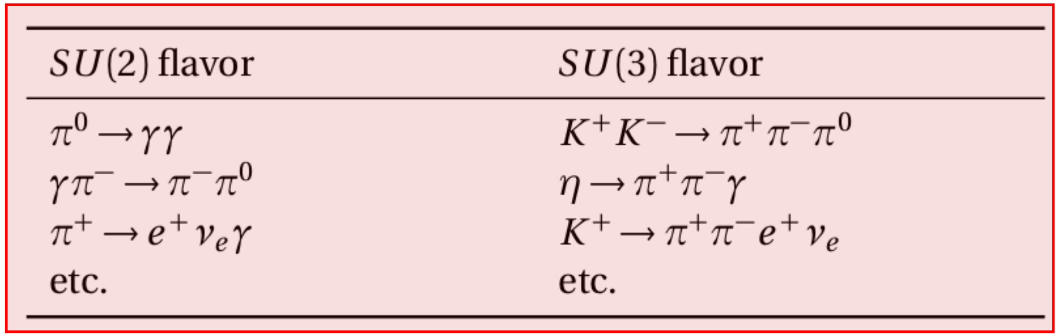
$$\boxed{\alpha_\pi = (2.0 \pm 0.6_{\mathrm{stat}} \pm 0.7_{\mathrm{syst}}) \times 10^{-4}\ \mathrm{fm}^3}$$



Phys. Rev. Lett. 114, 062002 (2015)

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

- Processes described by WZW term:



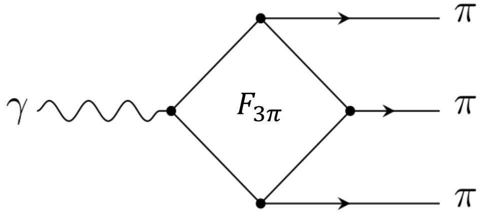
$SU(2)$ flavor	$SU(3)$ flavor
$\pi^0 \to \gamma\gamma$	$K^+K^- \to \pi^+\pi^-\pi^0$
$\gamma\pi^- \to \pi^-\pi^0$	$\eta \to \pi^+\pi^-\gamma$
$\pi^+ \to e^+\nu_e\gamma$	$K^+ \to \pi^+\pi^-e^+\nu_e$
etc.	etc.

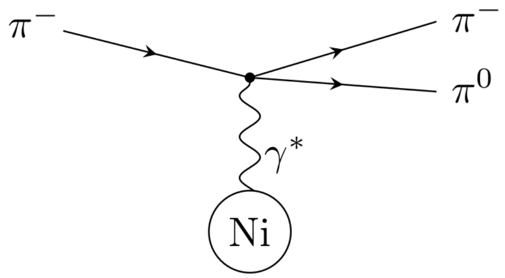
- $F_{3\pi}$: Direct coupling of γ to 3π - process proceeds primarily via the chiral anomaly => one of the most definitive tests of low-energy QCD

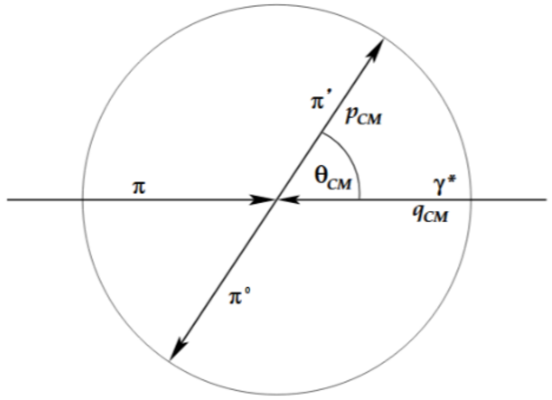
- Accessible in Primakoff reactions via: $\pi^-\gamma^* \to \pi^-\pi^0$

- Problem of explicit chiral symmetry breaking:

$$F_{3\pi} = \frac{eN_C}{12\pi^2 F_\pi^3} = (9.78 \pm 0.05)\mathrm{GeV}^{-3} = F(s = t = u = 0)$$

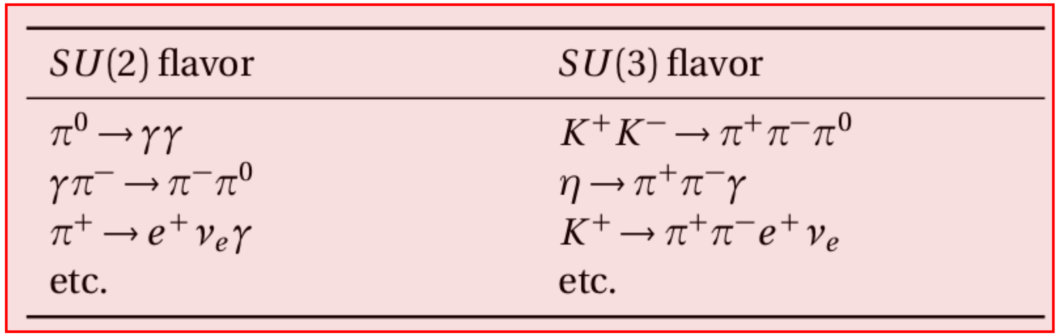






Testing the chiral anomaly - $F_{3\pi}$

- Processes described by WZW term:



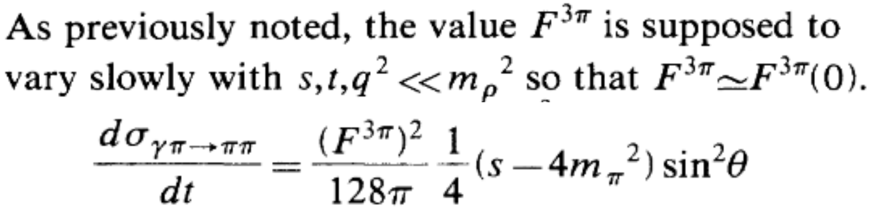
$SU(2)$ flavor	$SU(3)$ flavor
$\pi^0 \to \gamma\gamma$	$K^+K^- \to \pi^+\pi^-\pi^0$
$\gamma\pi^- \to \pi^-\pi^0$	$\eta \to \pi^+\pi^-\gamma$
$\pi^+ \to e^+\nu_e\gamma$	$K^+ \to \pi^+\pi^-e^+\nu_e$
etc.	etc.

- $F_{3\pi}$: Direct coupling of γ to 3π - process proceeds primarily via the chiral anomaly => one of the most definitive tests of low-energy QCD
- Accessible in Primakoff reactions via: $\pi^-\gamma^* \to \pi^-\pi^0$
- Problem of explicit chiral symmetry breaking:

$$F_{3\pi} = \frac{eN_C}{12\pi^2 F_\pi^3} = (9.78 \pm 0.05)\text{GeV}^{-3} = F(s = t = u = 0)$$

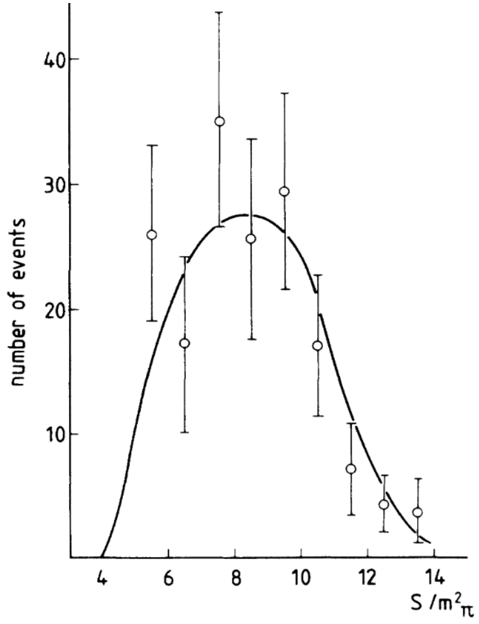
Previous measurement of $F_{3\pi}$:

Antipov, Y. *et al.* Phys.Rev. D36 (1987) 101103
from Serpukhov experiments



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

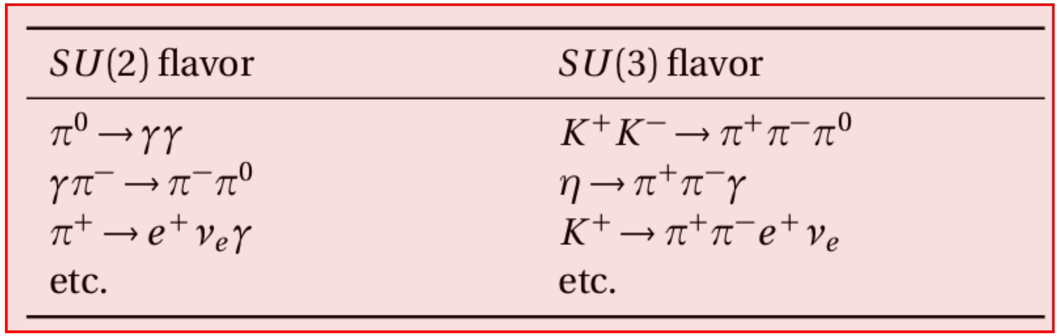
$$\frac{d\sigma_{\gamma\pi\to\pi\pi}}{dt} = \frac{(F^{3\pi})^2}{128\pi}\frac{1}{4}(s-4m_\pi{}^2)\sin^2\theta$$



$$\Rightarrow F_{3\pi} = (12.9 \pm 0.9 \pm 0.5)\ \text{GeV}^{-3}$$

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

- Processes described by WZW term:



$SU(2)$ 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.

- $F_{3\pi}$: Direct coupling of γ to 3π - process proceeds primarily via the chiral anomaly => one of the most definitive tests of low-energy QCD

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

- Problem of explicit chiral symmetry breaking:

$$F_{3\pi} = \frac{eN_C}{12\pi^2 F_\pi^3} = (9.78 \pm 0.05)\mathrm{GeV}^{-3} = F(s = t = u = 0)$$

Reanalysis of Serpukhov data:

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

- Using extrapolation & em corr:

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

- Compare to prediction from ChPT:

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

Precision of previous measurements: $\mathcal{O}(10\%)$

$\Rightarrow$ More precise experimental determination desirable

Analysis of 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:

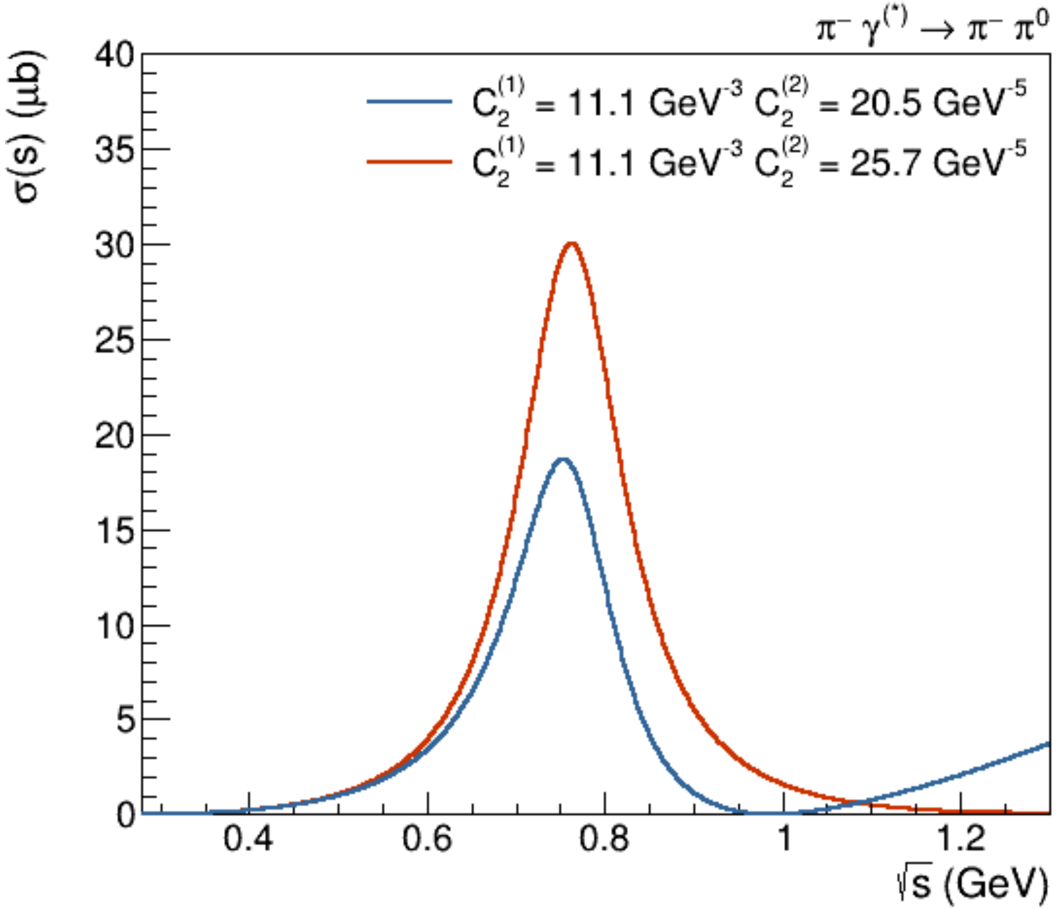
$$\sigma(s) = \frac{(s-4m_\pi^2)^{3/2}(s-m_\pi^2)}{1024\pi\sqrt{s}} \int_{-1}^{1} \mathrm{d}z(1-z^2)|\mathcal{F}(s,t,u)|^2$$

With

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

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

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



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

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

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

Number of detected kaon decays

Kaon/pion flux ratio

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

Pion flux

Acceptance for kaon decays for particular final state

Investigated Kaon decay channels

Decay channel	${}^{\Gamma_i}/_{\Gamma}$	**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
$K^- \to \pi^- \pi^- \pi^+$	$(5.583\ \pm 0.024)$ %	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
$\boldsymbol{K^- \to \pi^- \pi^0 \pi^0}$	$(1.760\ \pm 0.023)$ %	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

Luminosity from Kaon decays

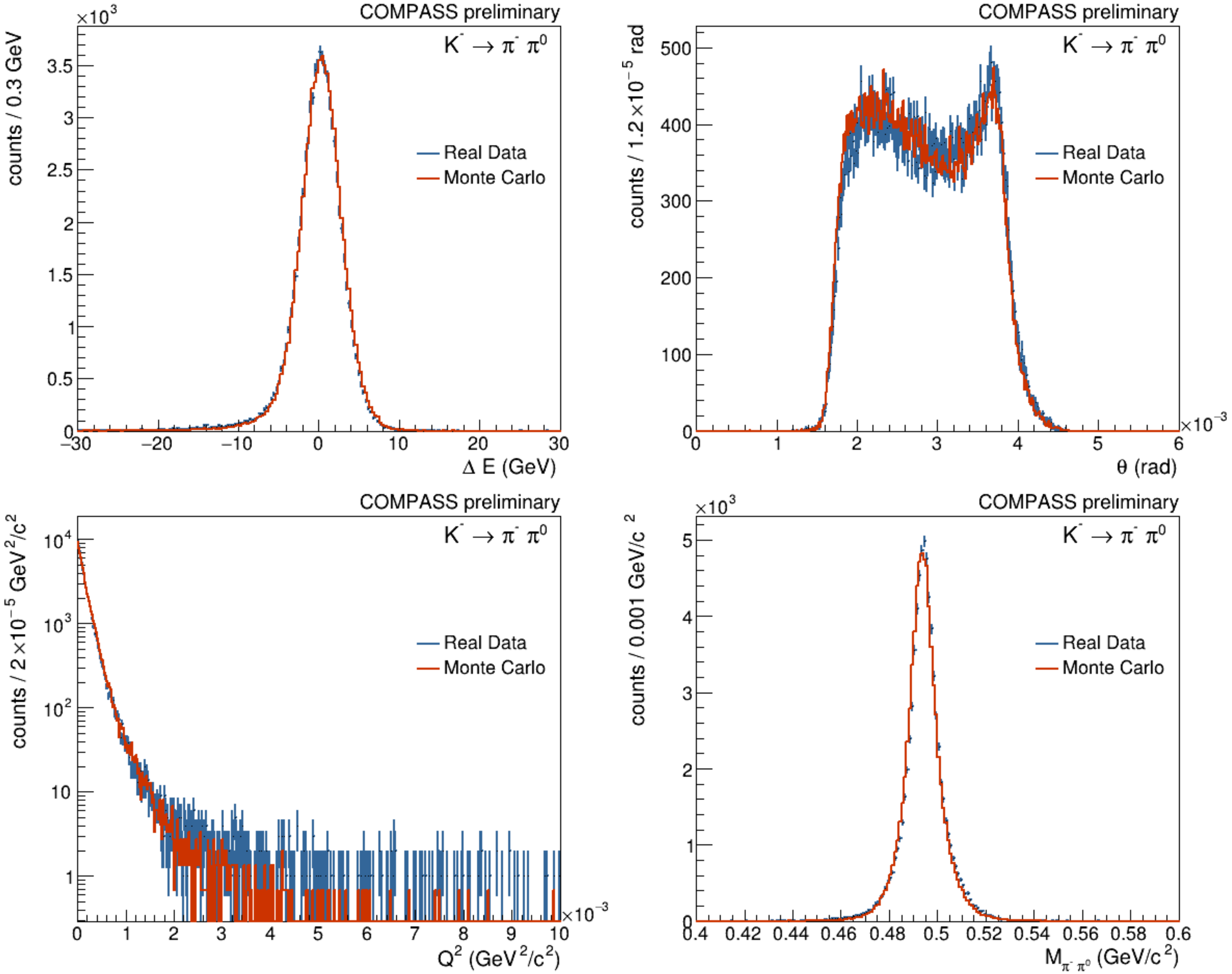
$$L_{2\pi,\mathrm{eff}} = 5.21 \pm 0.04_{\mathrm{stat}}\ \mathrm{nb}^{-1}$$
$$L_{3\pi,\mathrm{eff}} = 5.06 \pm 0.12_{\mathrm{stat}}\ \mathrm{nb}^{-1}$$

Largest contributions to systematic uncertainty:

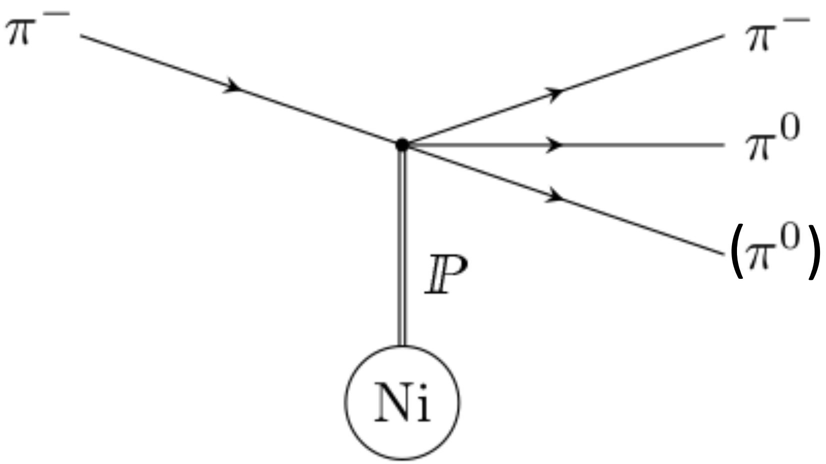
- CEDAR tag efficiency: 7%
- ECAL reconstruction: 5%
- kaon/pion beam ratio: 2.5%

Result:

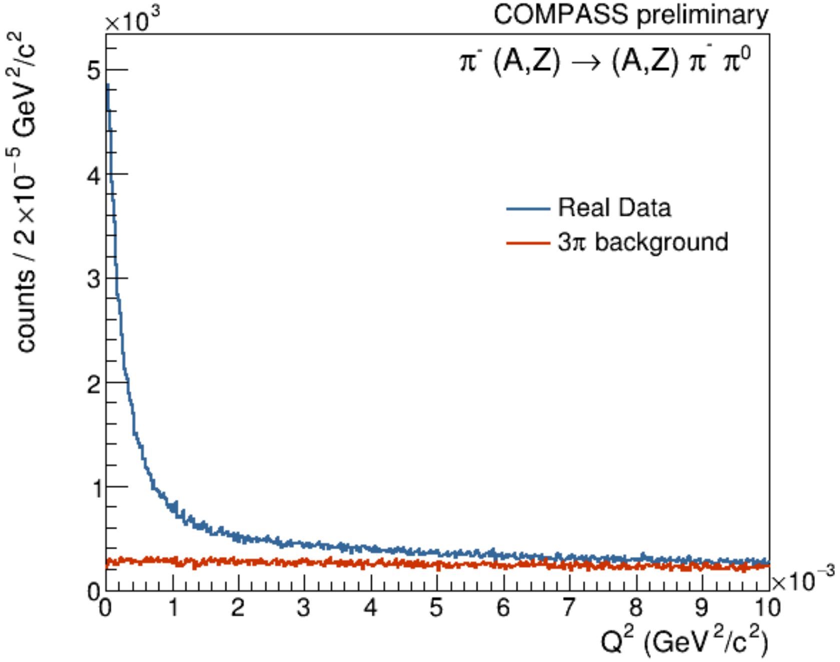
$$L_{\mathrm{eff}} = 5.21 \pm 0.48_{\mathrm{syst}} \pm 0.04_{\mathrm{stat}}$$



Main background for $\pi^-\gamma \rightarrow \pi^-\pi^0$: $\pi^-\pi^0\,\pi^0$ final states



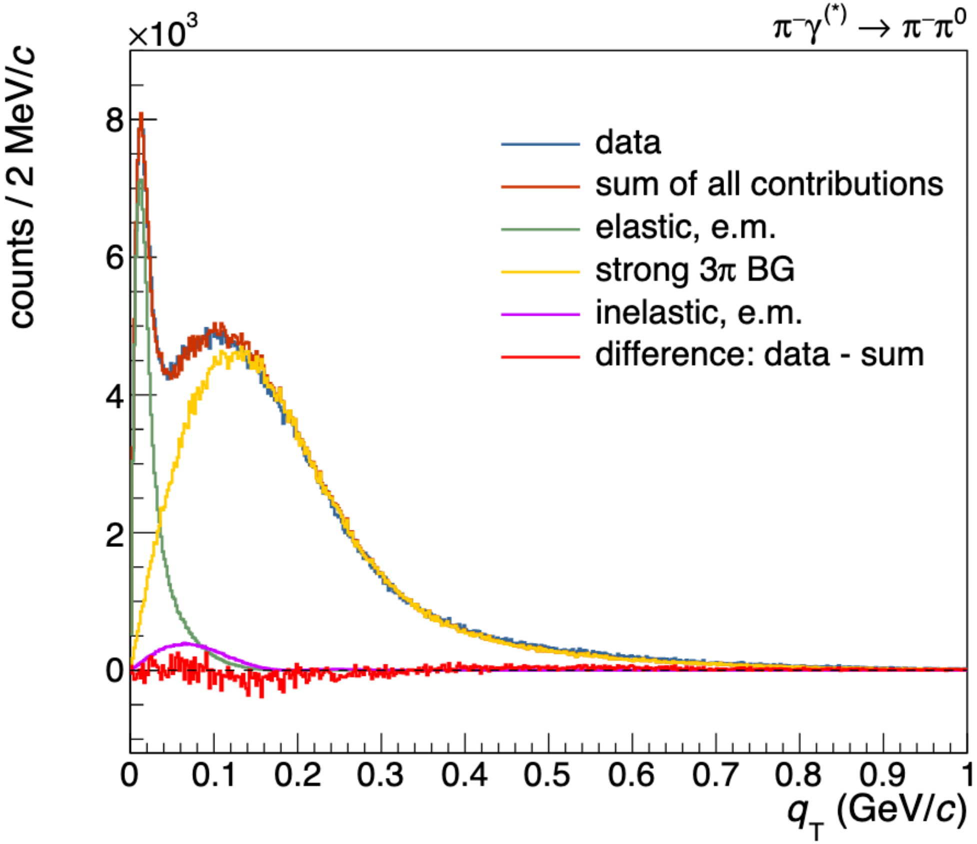
- $\pi^-\pi^0$-final state forbidden by G-parity conservation
- Large cross section for $\pi^-\pi^0\pi^0$ final state $\Longrightarrow$ loss of one (soft) π^0
- Approach: determine leakage from 3pi MC data with 2pi event selection



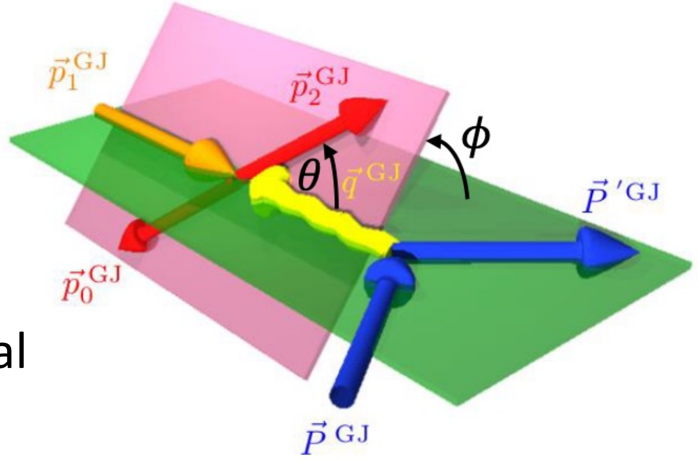
Approach for 3π leakage:

- Select diffractive 3π events
- Develop partial-wave model
- Weight 3π Monte Carlo data set according to model
- Subtract from 2π event sample

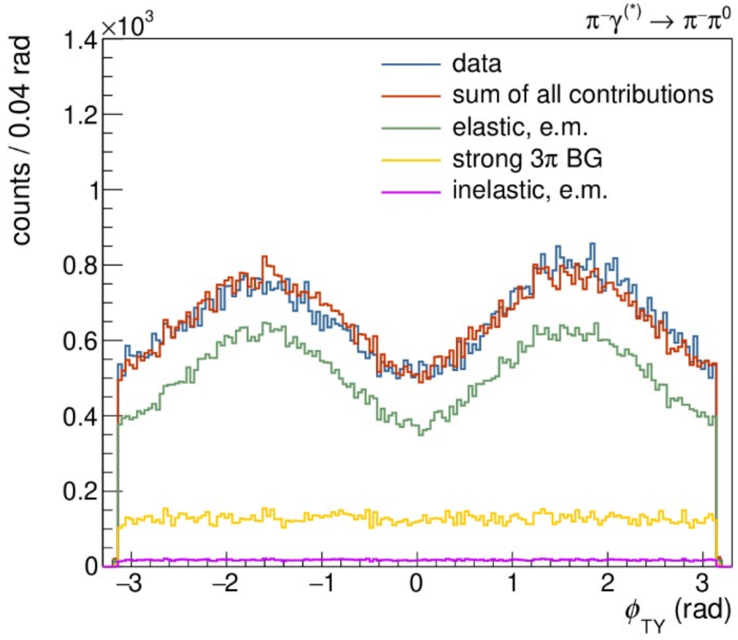
Background Subtraction



Dominik Ecker, PhD thesis

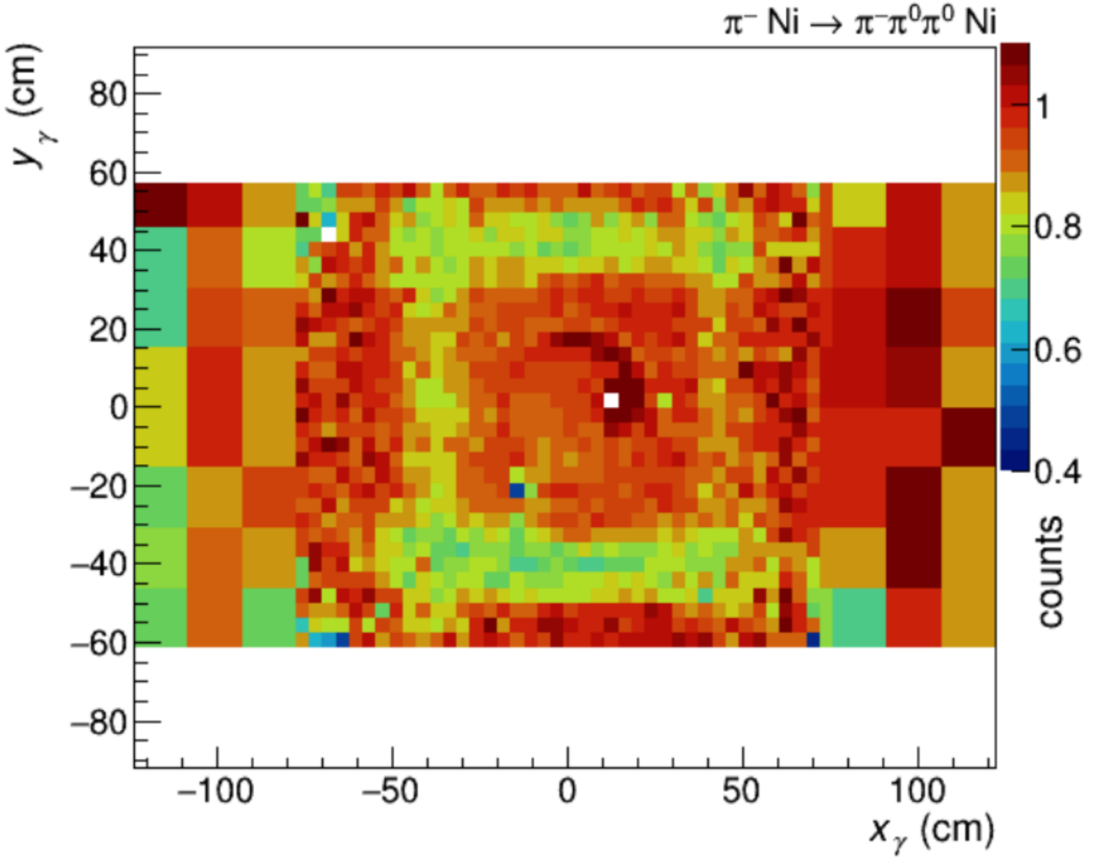


- Photon-exchange signature in azimuthal angular distribution allows alternative background subtraction



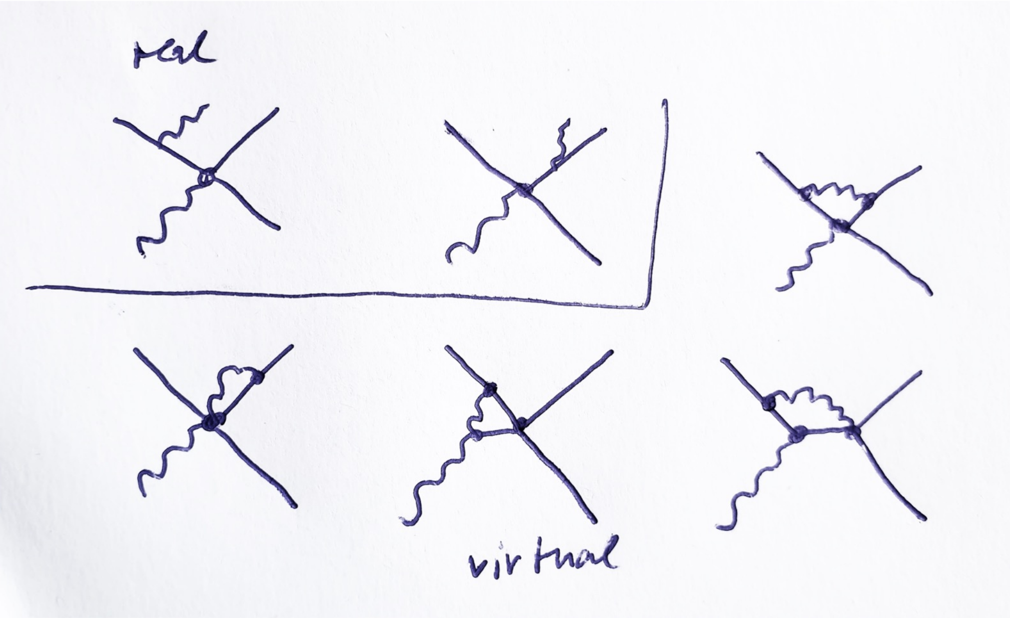
- Kinematic distributions of the 3-pion background fit well with the observed spectra
- some upscaling by 15-25% needed ?!

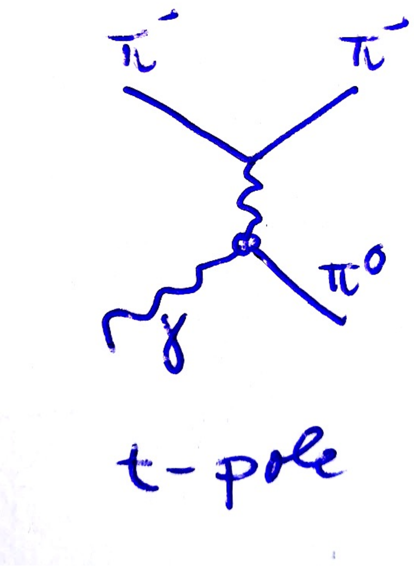
Challenges in Photon Detection

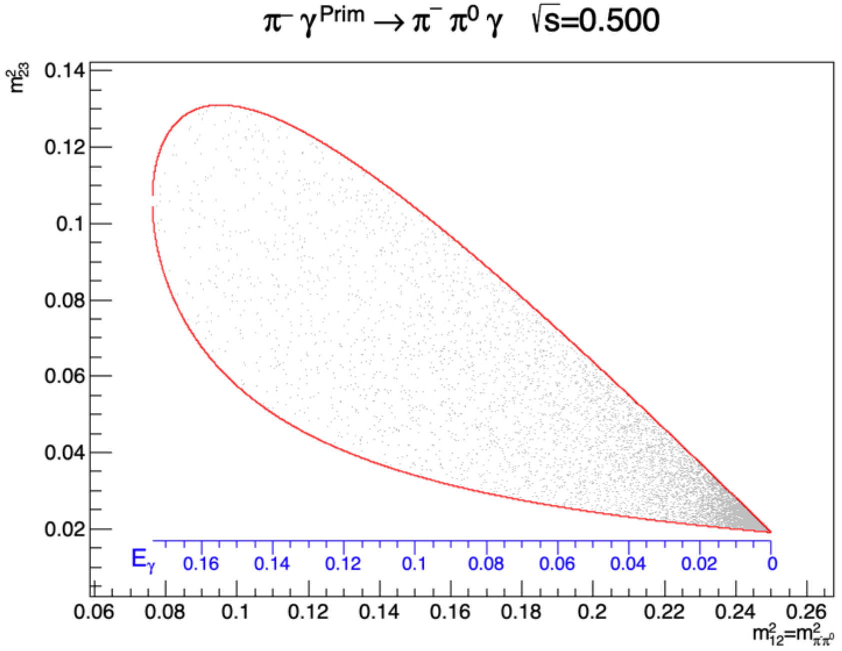


- Comparison of 3-pion PWA model with lab distributions shows clear inefficient structures for forward photons
- roughly consistent with the observed upscaling factor

QED Radiative Corrections

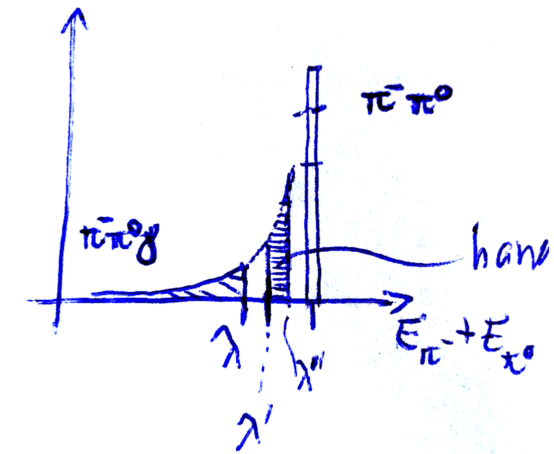




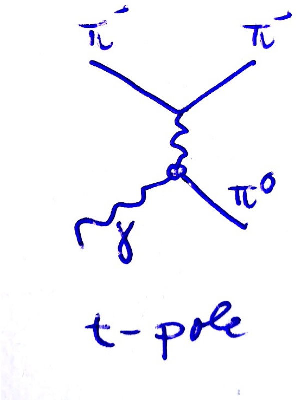


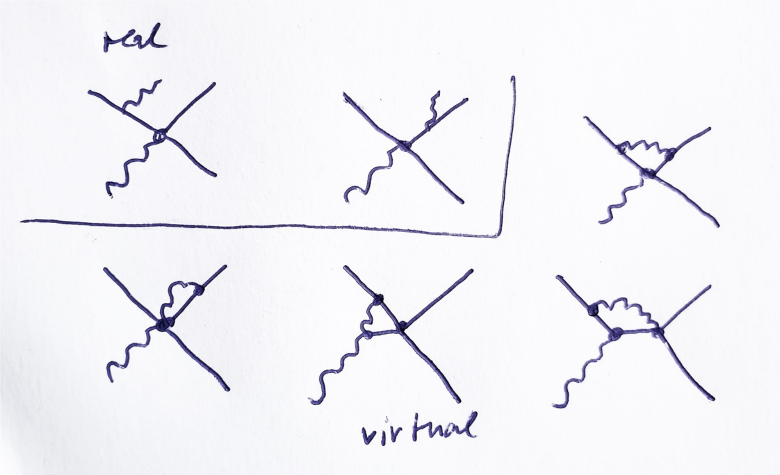
Implementation of QED radiative corrections:

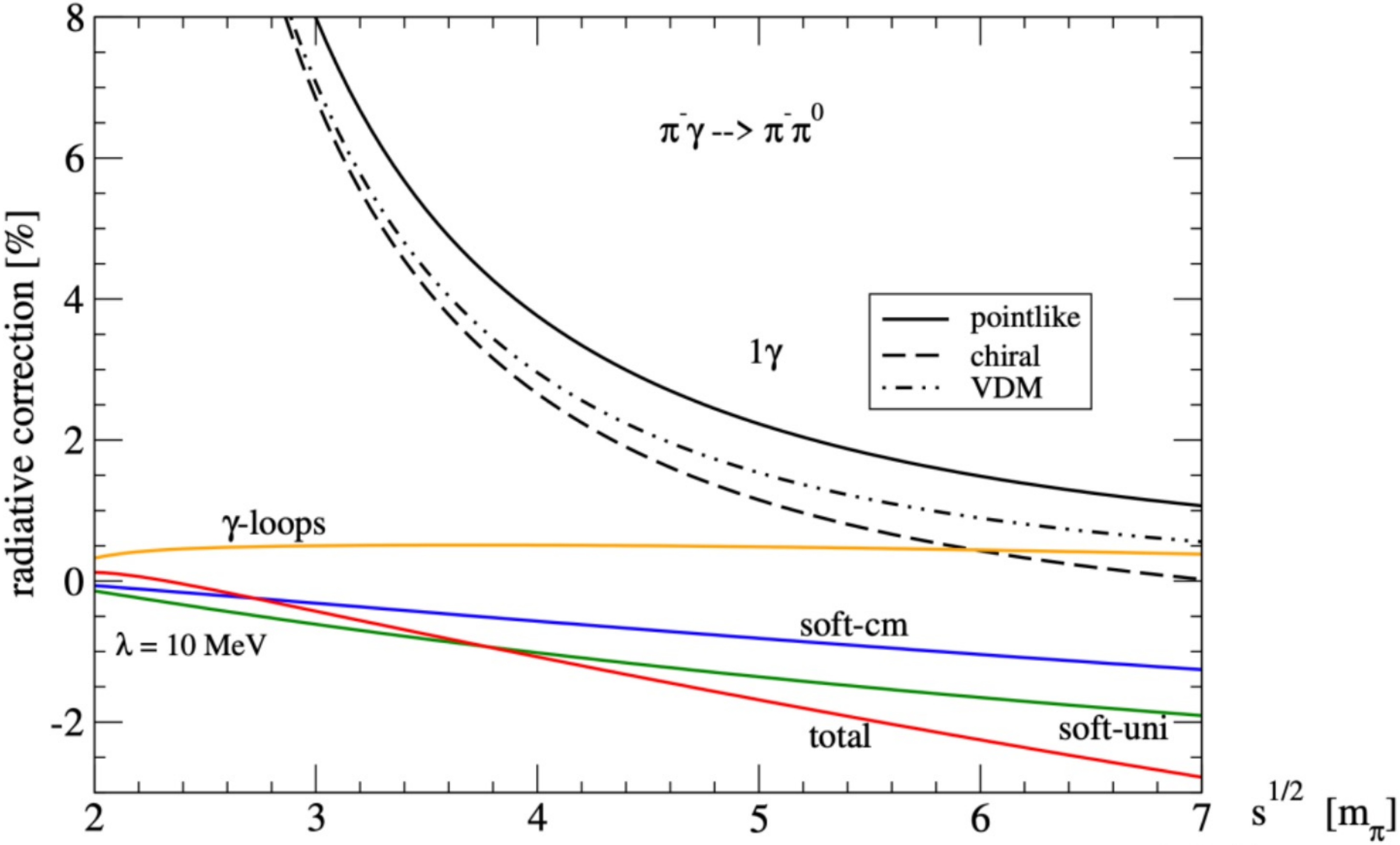
- Calculated on the base of the paper of Ametller et al. (extended and corrected by N. Kaiser, TUM)
- Included in MC generator: event distribution according to 1-photon emission spectrum, events in "hand-over" region replaced by correct fraction of purely elastic events (including virtual corrections)



QED Radiative Corrections







≈ 1 GeV

Result of fitting with the Kubis-Hoferichter model

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

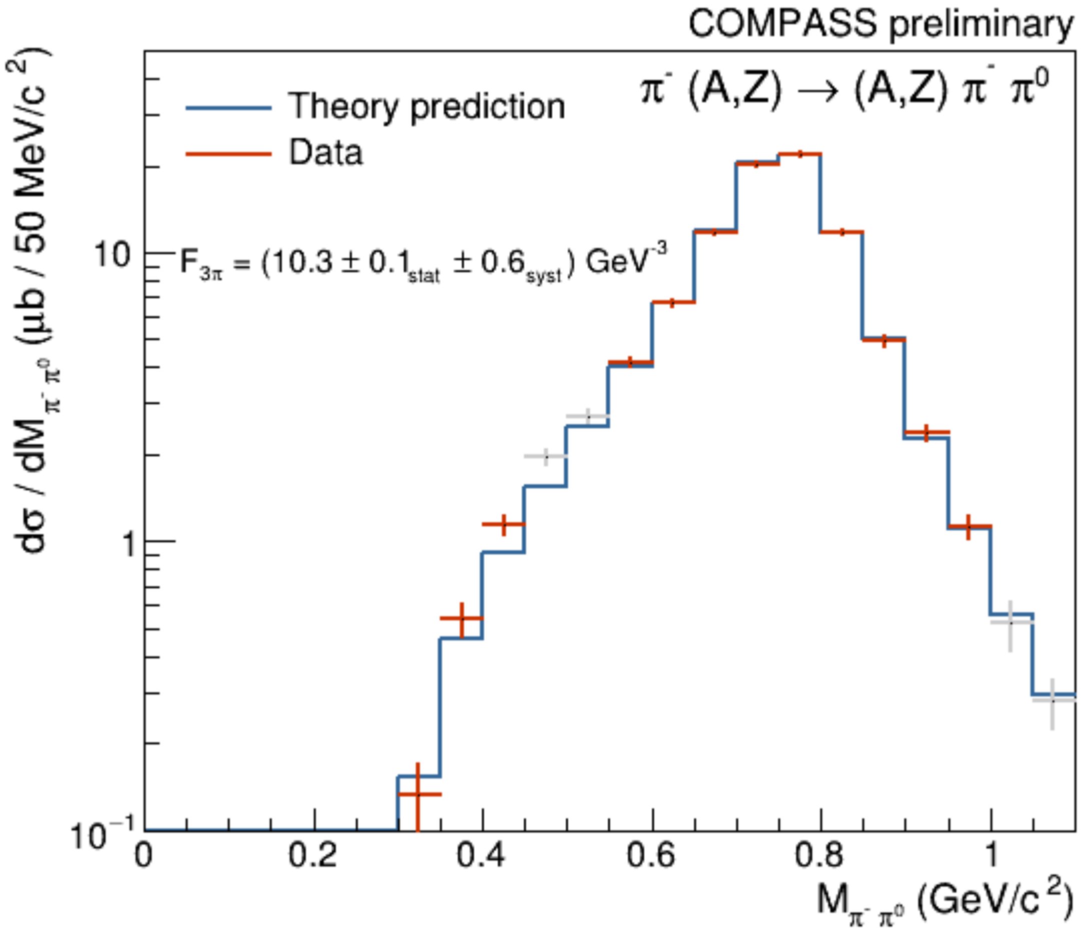
$$C_2^{(1)} = \left(10.5 \pm 0.1_{stat} \pm 0.6_{syst}\right)\mathrm{GeV}^{-3}$$

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

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

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

- Preliminary result for $F_{3\pi}$ in agreement with theory prediction from ChPT
- Lower systematics to be achieved



Interpretation of the new preliminary result

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

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

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

- Intensive test of systematics:
  - Different K^- decay channels
  - Studies on different background contributions (ω and π exchange)

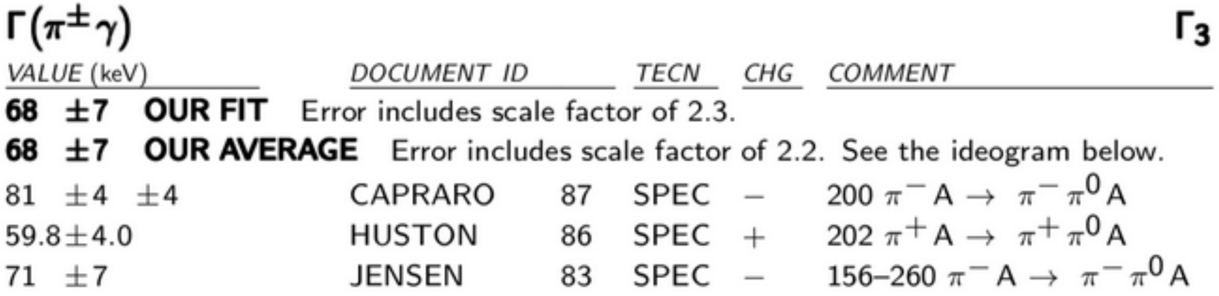
- Accompanied with intensive analysis of $\pi^-\text{Ni} \to \pi^-\pi^0\pi^0\text{Ni}$ for background estimation

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)



$\Gamma(\pi^\pm\gamma)$ **Γ_3**

VALUE (keV)	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
68 ±7	**OUR FIT** Error includes scale factor of 2.3.			
68 ±7	**OUR AVERAGE** Error includes scale factor of 2.2. See the ideogram below.			
81 ±4 ±4	CAPRARO 87	SPEC	−	200 $\pi^- A \to \pi^-\pi^0 A$
59.8±4.0	HUSTON 86	SPEC	+	202 $\pi^+ A \to \pi^+\pi^0 A$
71 ±7	JENSEN 83	SPEC	−	156–260 $\pi^- A \to \pi^-\pi^0 A$

Interpretation of the new preliminary result

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

$$F_{3\pi} = (10.3 \pm 0.1_{stat} \pm 0.6_{syst})\mathrm{GeV}^{-3}$$
$$\Gamma_{\rho\to\pi\gamma} = \left(76 \pm 1_{stat}{}^{+10}_{-8}{}_{syst}\right)\mathrm{keV}$$

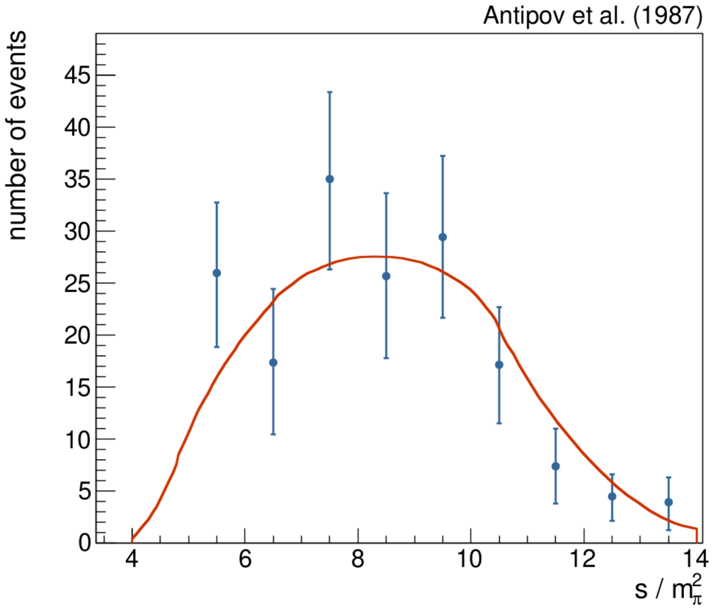
- Intensive test of systematics:
  - Different K^- decay channels
  - Studies on different background contributions (ω and π exchange)

- Accompanied with intensive analysis of $\pi^-\mathrm{Ni} \to \pi^-\pi^0\pi^0\mathrm{Ni}$ for background estimation

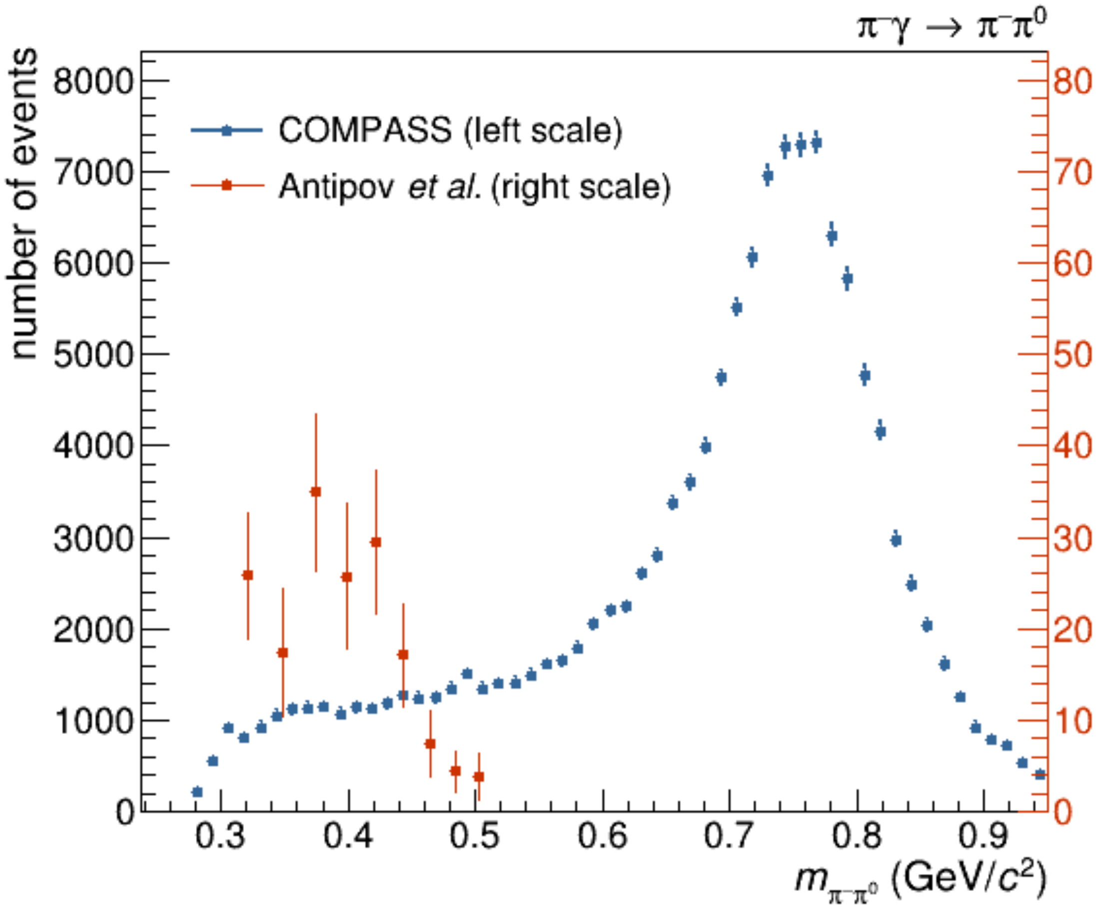
Antipov, Y. *et al.* PRD 36 (1987) 101103
and reanalyzed by
Ametller, L. *et al.* PRD 64 (2001) 094009

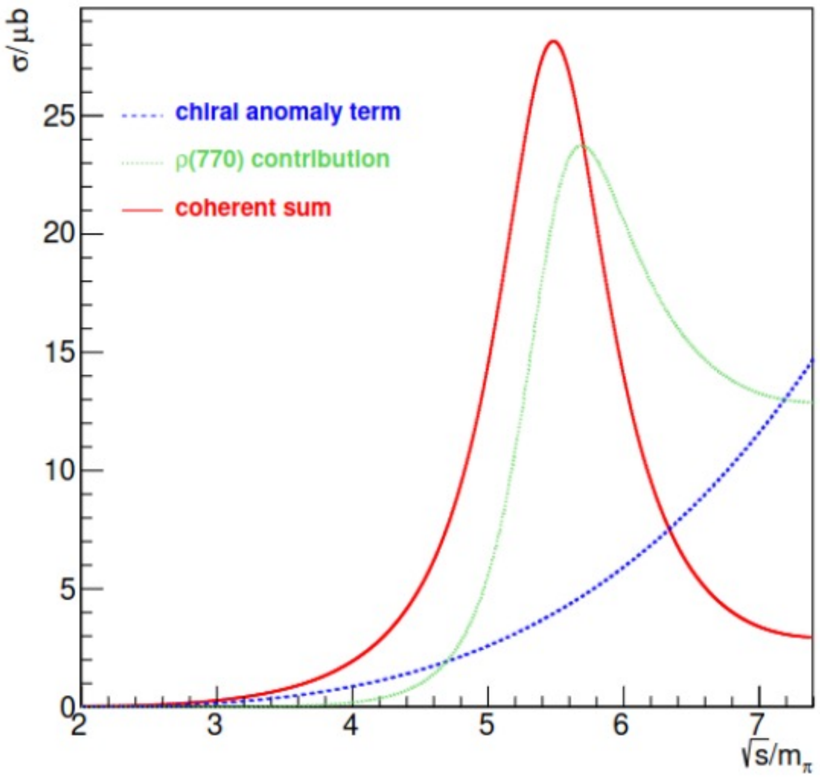
$$F_{3\pi} = (10.7 \pm 1.2)\ \mathrm{GeV}^{-3}$$

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

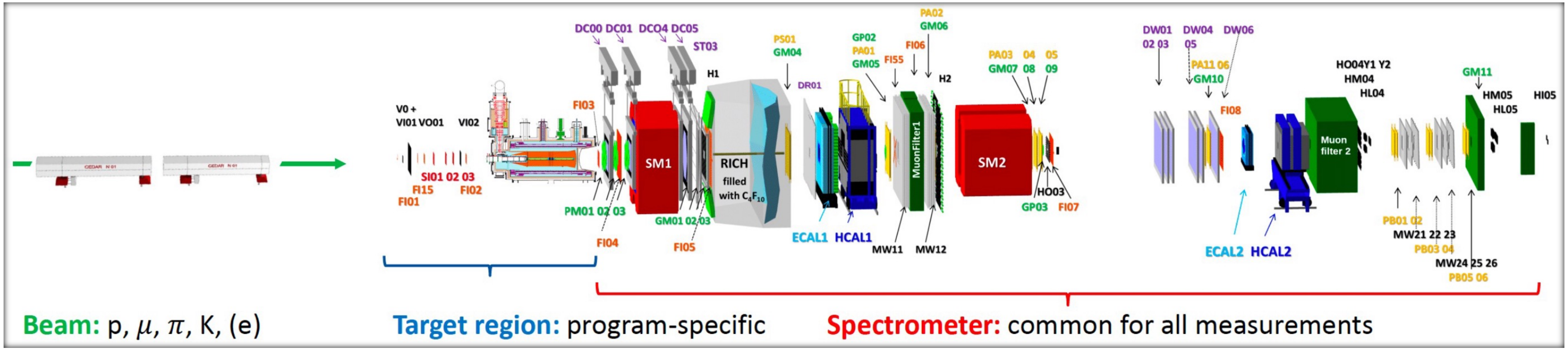


COMPASS vs. Serpukhov





AMBER



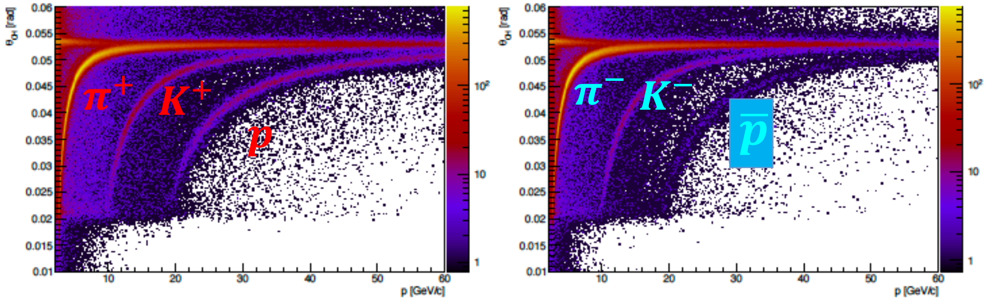
AMBER spectrometer (former COMPASS)

- currently 153 members from 36 institutions and 14 countries (plus master and bachelor students)
- Memorandum of Understanding July 2023
- Major contributions by Italian and German groups

Apparatus for Meson and Baryon Experimental Research

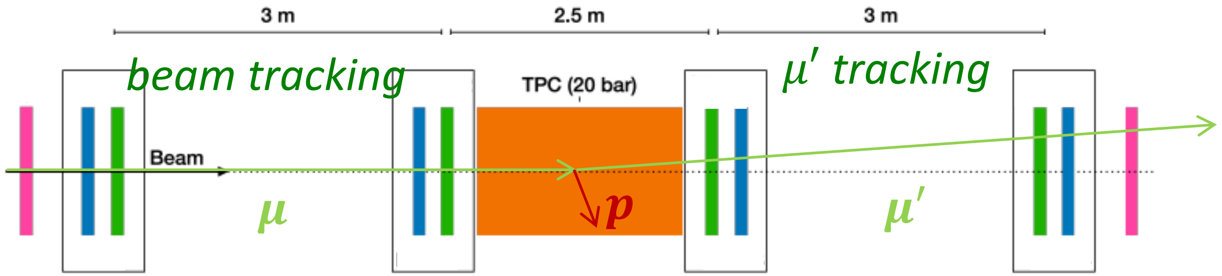
Phase-1 Program

- **Anti-proton production cross sections** in p-He and p-p collisions for constraining cosmic dark-matter search data: unique data sets in unexplored beam momentum range 60-250 GeV, successful p-He data taking in 2023

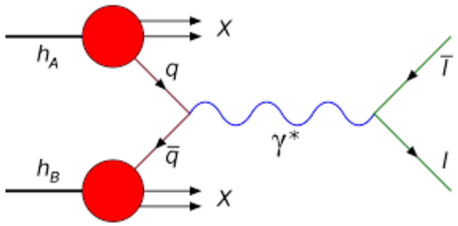


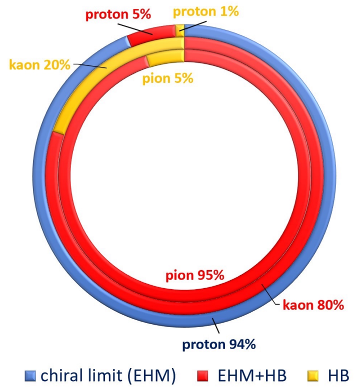
RICH PID: Cerenkov angle vs. momentum

- **Proton radius** via muon-proton scattering, recoiling proton and scattered muon are measured in coincidence: unique in terms of systematics control



- **Pion and kaon partonic structure** via Drell-Yan processes: separate valence and sea contributions in unprecedented precision





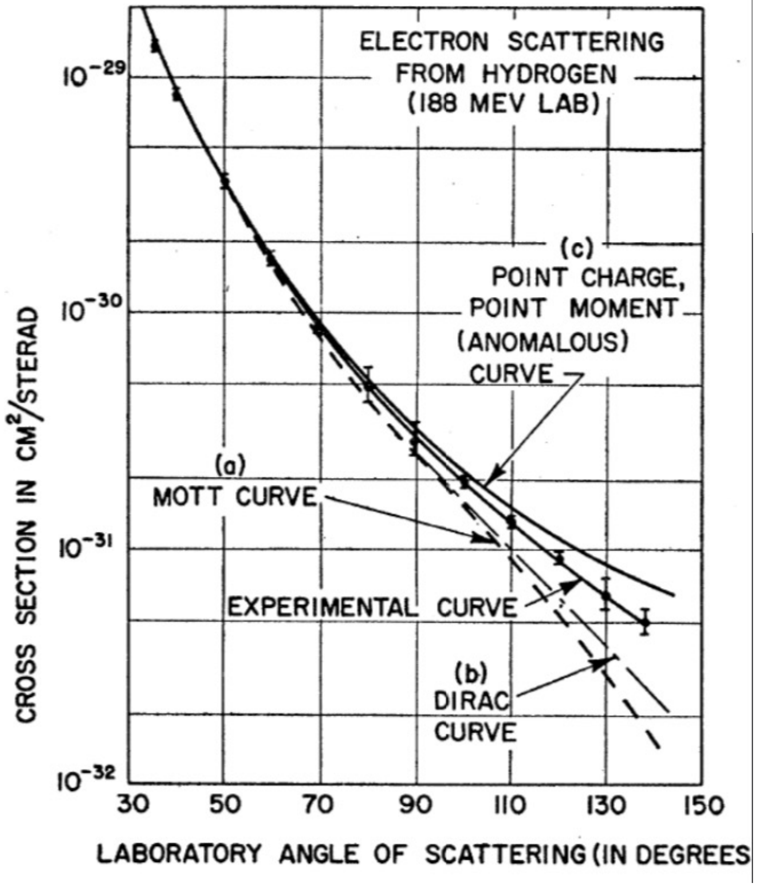
Mass budgets: **emergence** of the light-hadron masses is linked to both the QCD partonic structure and to confinement

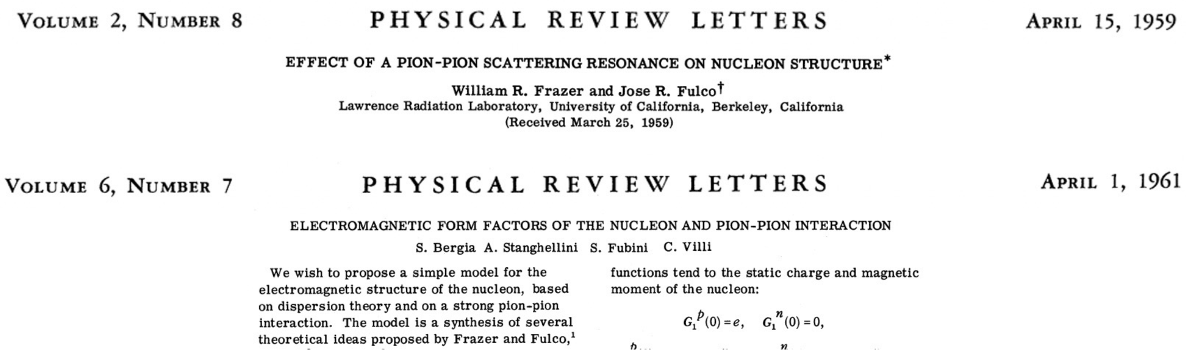
plot courtesy C. Robert

Size of the proton: experiment and theory ∼1960

1956 at SLAC,
few-hundred-MeV
electron scattering on the
proton reveals internal
structure effect,
$< r_p > \approx 0.8$ fm

R. Hofstadter





VOLUME 2, NUMBER 8 PHYSICAL REVIEW LETTERS APRIL 15, 1959

EFFECT OF A PION-PION SCATTERING RESONANCE ON NUCLEON STRUCTURE*

William R. Frazer and Jose R. Fulco†
Lawrence Radiation Laboratory, University of California, Berkeley, California
(Received March 25, 1959)

VOLUME 6, NUMBER 7 PHYSICAL REVIEW LETTERS APRIL 1, 1961

ELECTROMAGNETIC FORM FACTORS OF THE NUCLEON AND PION-PION INTERACTION

S. Bergia A. Stanghellini S. Fubini C. Villi

We wish to propose a simple model for the electromagnetic structure of the nucleon, based on dispersion theory and on a strong pion-pion interaction. The model is a synthesis of several theoretical ideas proposed by Frazer and Fulco,[1]

functions tend to the static charge and magnetic moment of the nucleon:

$$G_1^p(0) = e, \quad G_1^n(0) = 0,$$

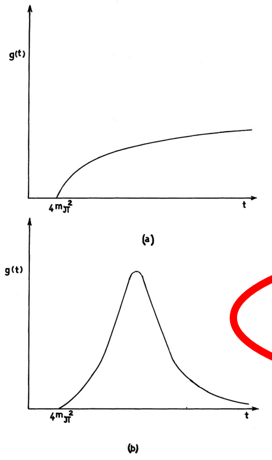
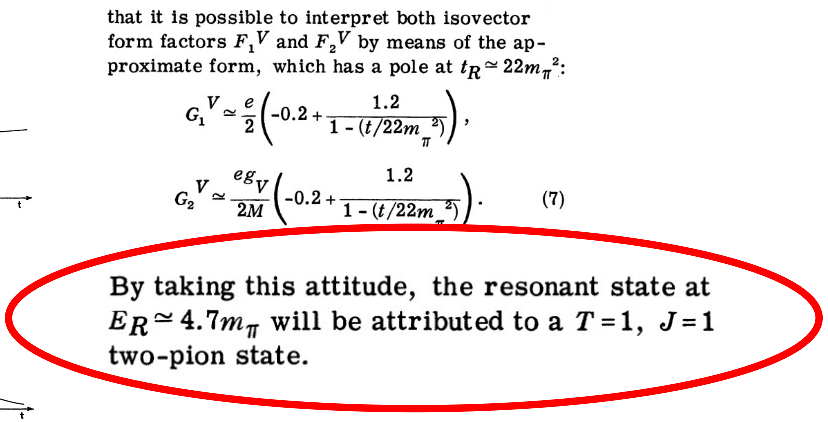


FIG. 1. Schematic representations of $g(t)$ in arbitrary scale. (a) Uncorrelated pions; (b) strong pion-pion resonance.



that it is possible to interpret both isovector form factors F_1^V and F_2^V by means of the approximate form, which has a pole at $t_R \simeq 22m_\pi^2$:

$$G_1^V \simeq \frac{e}{2}\left(-0.2 + \frac{1.2}{1-(t/22m_\pi^2)}\right),$$

$$G_2^V \simeq \frac{eg_V}{2M}\left(-0.2 + \frac{1.2}{1-(t/22m_\pi^2)}\right). \qquad (7)$$

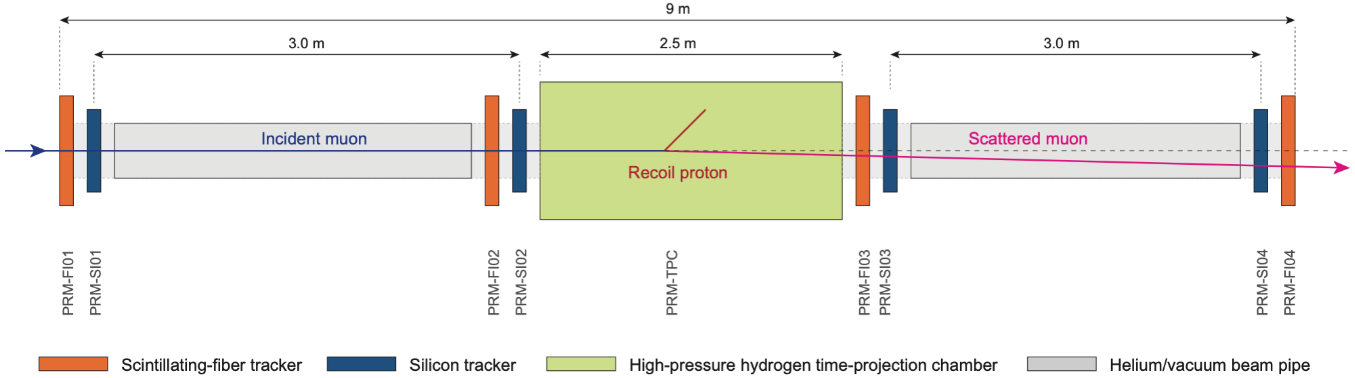
By taking this attitude, the resonant state at $E_R \simeq 4.7m_\pi$ will be attributed to a $T=1$, $J=1$ two-pion state.

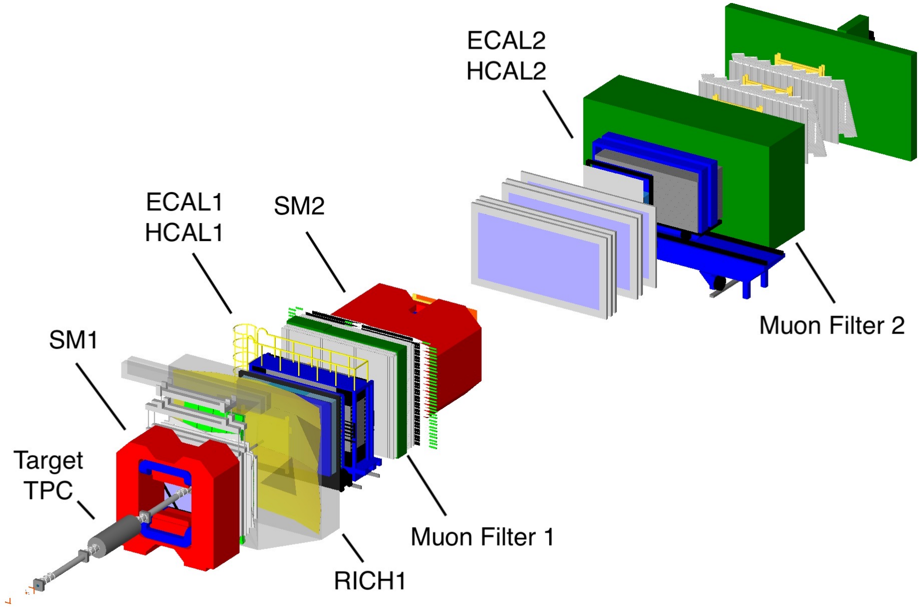
the new (unexpected?)
resonance of the time: $\rho(770)$

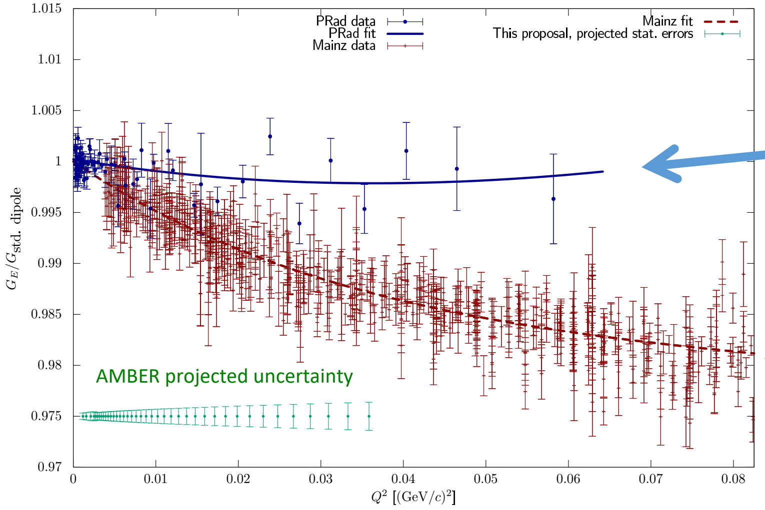
"Segrè blamed the theorists for their incorrect prediction of the resonant energy."
(from: J. David Jackson, Emilio Gino Segrè 1905-1989")

Proton Radius Measurement at AMBER

Apparatus for Meson and Baryon Experimental Research



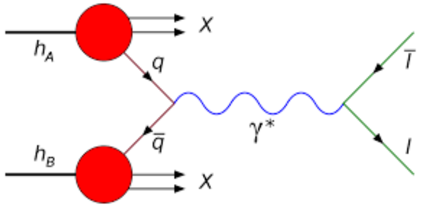




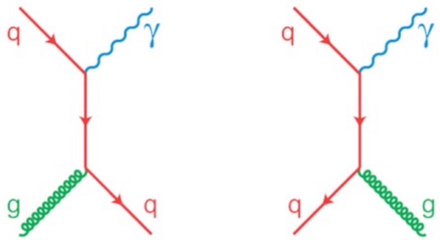
- 100 GeV **muon** beam, $2 \cdot 10^6$/sec
- Active-target TPC with high-pressure H_2
- high-precision tracking and spectrometer for muon reconstruction
- goal: 70 million elastic scattering events in $10^{-3} < Q^2 < 4{\cdot}10^{-2}$ GeV^2
- Precision on the proton radius ~0.01 fm
- Measurement under extreme forward conditions: demanding event recognition → **free-running data acquisition** with event selection on recorded data

Apparatus for Meson and Baryon Experimental Research

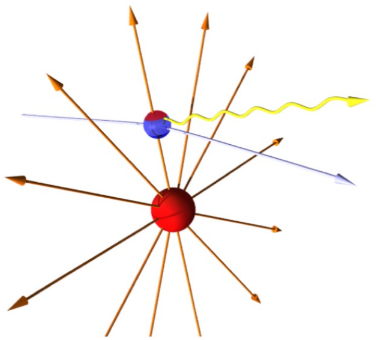
Ideas of the Phase-2 Program



- Kaon structure via the Drell-Yan process → feasible already in Phase-1 (?)

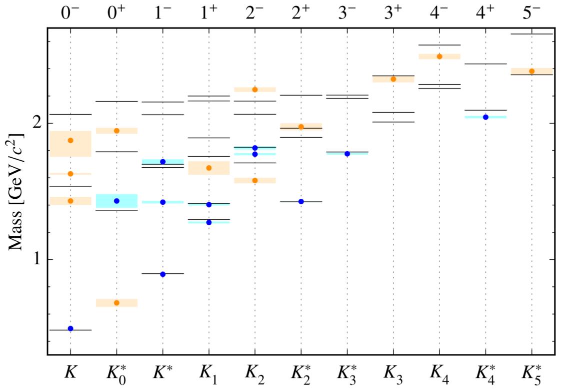


- Gluon structure of pions and kaons via prompt photons

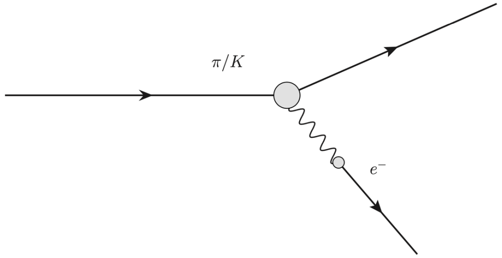


- Primakoff reactions to investigate kaon-photon coupling: kaon polarisability, $F_{KK\pi}$

- Generalized Parton Distributions in DVCS and HEMP



- Spectroscopy of mesons with strangeness



- Meson charge radii via electron scattering in inverse kinematics

- Diffractive production of vector mesons and di-jets to study distribution amplitudes

Conclusions and Outlook

- Chiral perturbation theory has, since its development in the 1980s, made **many correct predictions** in low-energy pion-nucleon dynamics, and thus proven its validity as **effective theory of QCD**
- The limits of predictive power and precision of ChPT are still to be challenged by experiment
- **COMPASS** has played a key role in the pion sector, and there are still data to harvest

2004	$\pi^-\pi^-\pi^+$	published result PRL108 (2012)
2009	$\pi^-\gamma$	pion polarisability PRL114 (2015)
	$\boldsymbol{\pi^-\pi^0}$, $\boldsymbol{\pi^-\eta}$	chiral anomaly
	$\pi^-\pi^0\pi^0$	chiral dynamics
2012	4x larger data set	

- New options in the **AMBER** Phase-2 program: extension of kinematic ranges and to the K sector

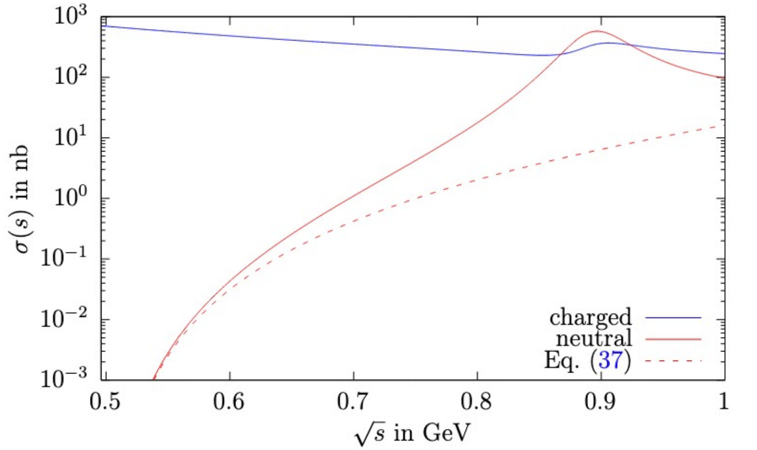


Fig. 8: Cross section for the charged (blue) and neutral (red) kaon Compton scattering. The dashed red line represents Eq. (37).

Stamen, Dammann, Korte, Kubis

https://arxiv.org/pdf/2409.05955

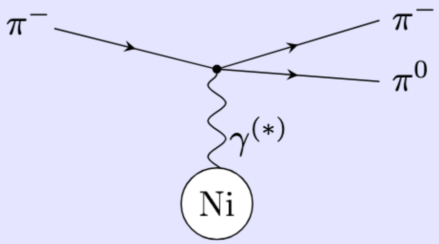
Thank you for your attention

Chiral anomaly in pi-eta

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

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

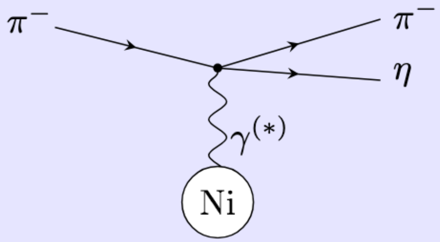
- access to $\gamma\pi \to \pi\pi$



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

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

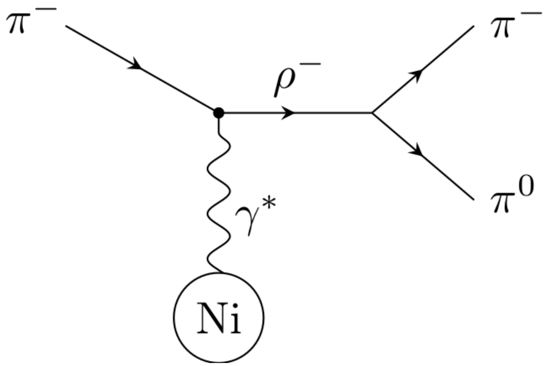
- access to $\gamma\pi \to \eta\pi$



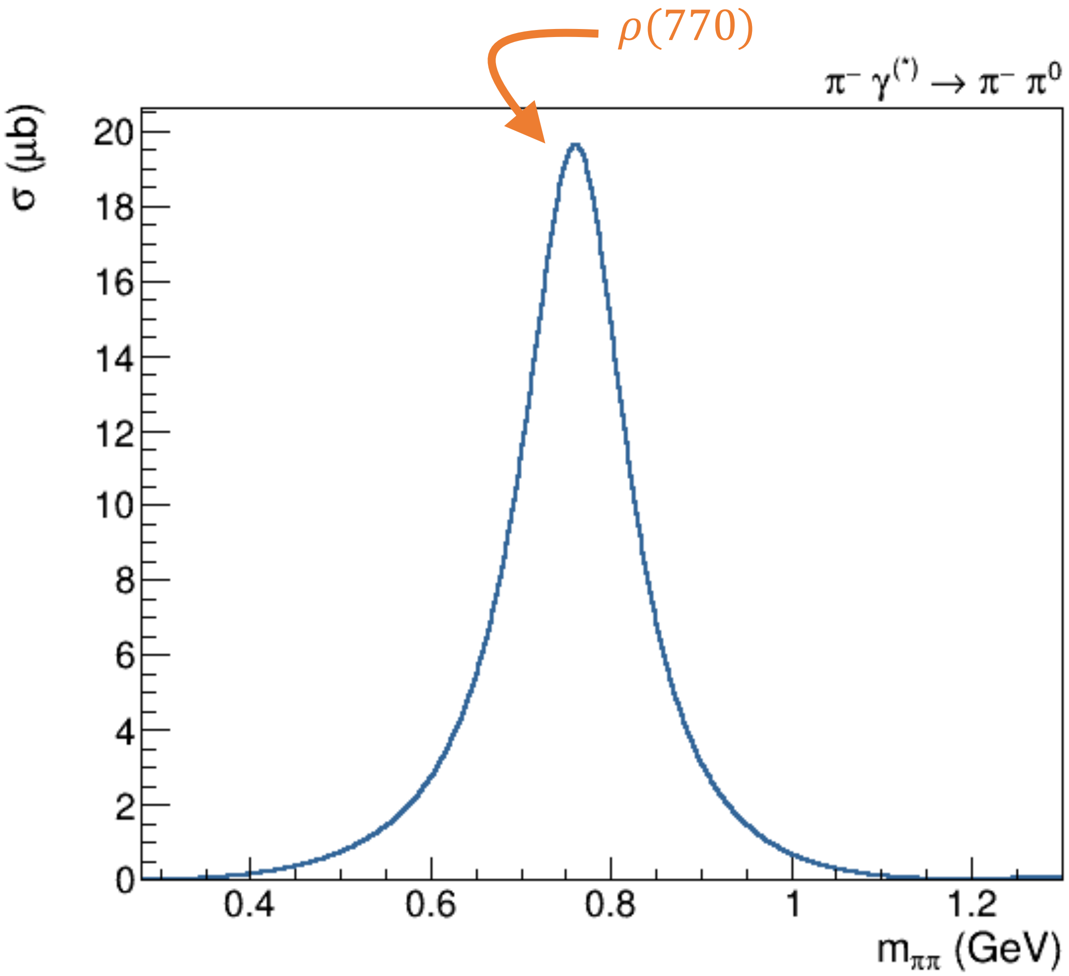
- final state production via $a_2(1320)$
- $F_{\eta\pi\pi\gamma} = \frac{e}{4\sqrt{3}\pi^2 f_\pi^3} =$ $5.65 \pm 0.03\ \mathrm{GeV}^{-3}$
- background from diffractive $\pi^- + (Z,A) \to \pi^- + \eta + (Z,A)$

Radiative width of $\boldsymbol{\rho}$-meson

- Coherent background of $\rho(770)$-production (strong and electro-magnetic)

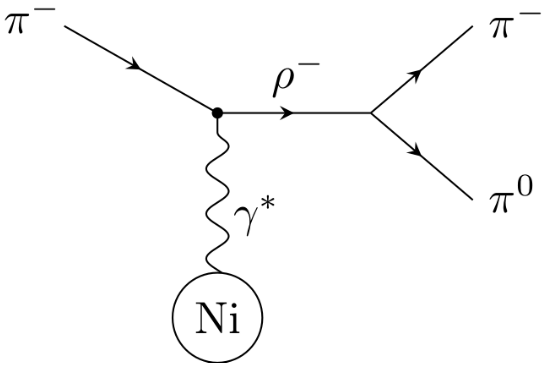


$\Rightarrow$ possibility of extraction of radiative width of ρ-meson: $\Gamma_{(\rho\to\pi\gamma)}/\Gamma_{\text{tot}} \approx 4.5 \cdot 10^{-4}$



Radiative width of $\boldsymbol{\rho}$-meson

- Coherent background of $\rho(770)$-production (strong and electro-magnetic)

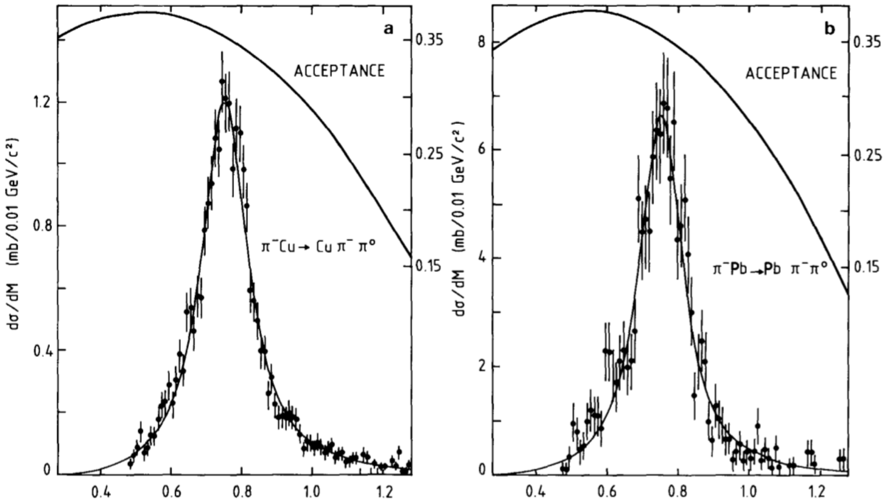


$\Rightarrow$ possibility of extraction of radiative width of ρ-meson: $\Gamma_{(\rho\to\pi\gamma)}/\Gamma_{\text{tot}} \approx 4.5\cdot 10^{-4}$

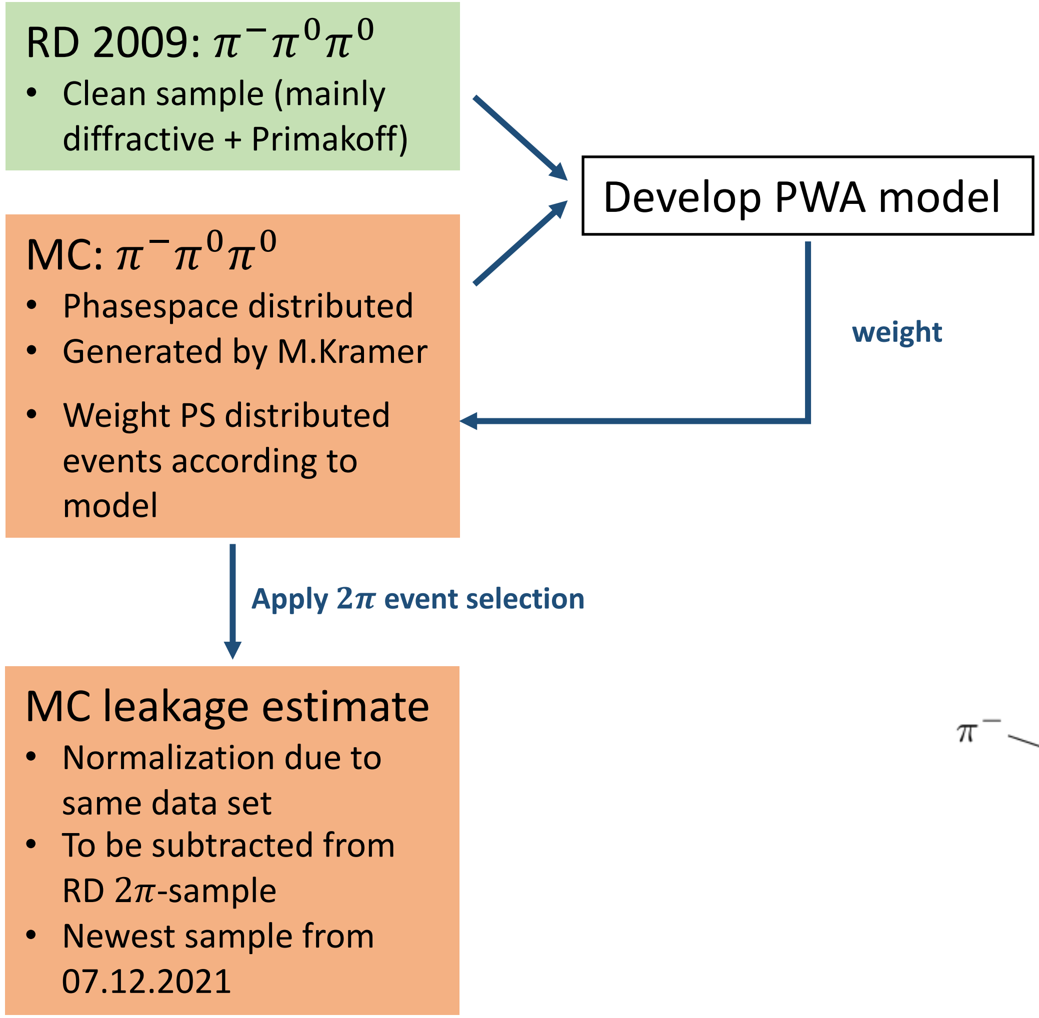
Radiative width of $\boldsymbol{\rho}$-meson:

[Capraro, L. *et al.* Nucl.Phys. B288 (1987) 659-680](#) at CERN (SPS):

- From fit of $\mathrm{d}\sigma/\mathrm{d}t$ for ρ production: $\Gamma(\rho\to\pi\gamma) = (81 \pm 4 \pm 4)\ \mathrm{keV}$



Approach for 3π-leakage



RD 2009: $\pi^-\pi^0\pi^0$
- Clean sample (mainly diffractive + Primakoff)

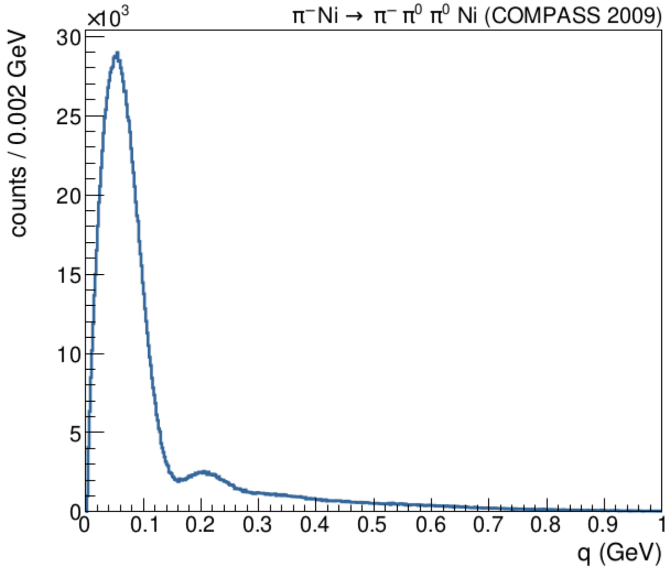
MC: $\pi^-\pi^0\pi^0$
- Phasespace distributed
- Generated by M.Kramer
- Weight PS distributed events according to model

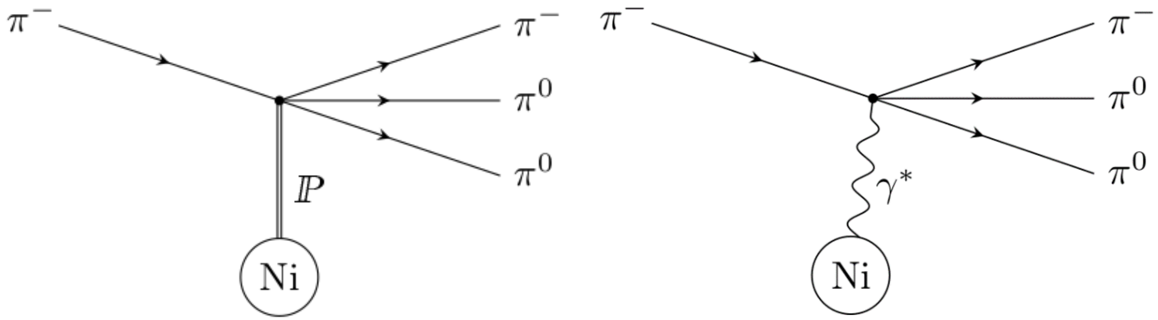
Develop PWA model

weight

Apply 2π event selection

MC leakage estimate
- Normalization due to same data set
- To be subtracted from RD 2π-sample
- Newest sample from 07.12.2021





Approach for 3π-leakage

RD 2009: $\pi^-\pi^0\pi^0$
- Clean sample (mainly diffractive + Primakoff)

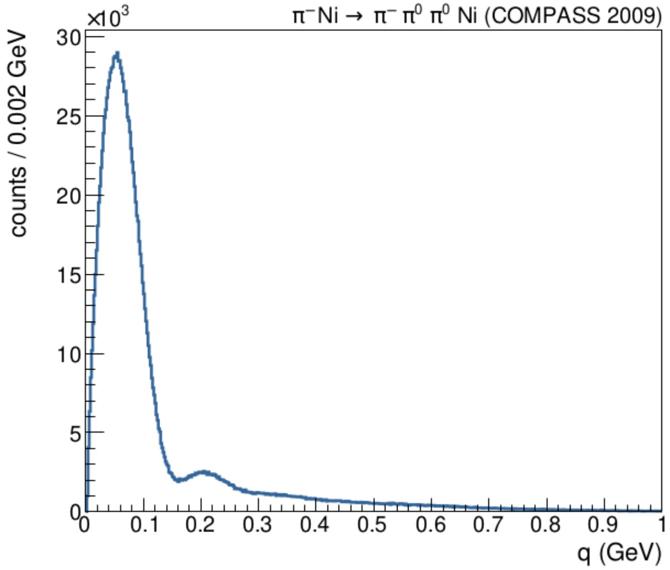
MC: $\pi^-\pi^0\pi^0$
- Phasespace distributed
- Generated by M.Kramer
- Weight PS distributed events according to model

Develop PWA model

weight

Apply 2π event selection

MC leakage estimate
- Normalization due to same data set
- To be subtracted from RD 2π-sample
- Newest sample from 07.12.2021



Issues so far: predicted background overshooting data