Chiral symmetry breaking: Current experimental status and prospects

with a breaking new COMPASS result
on behalf of the Collaboration

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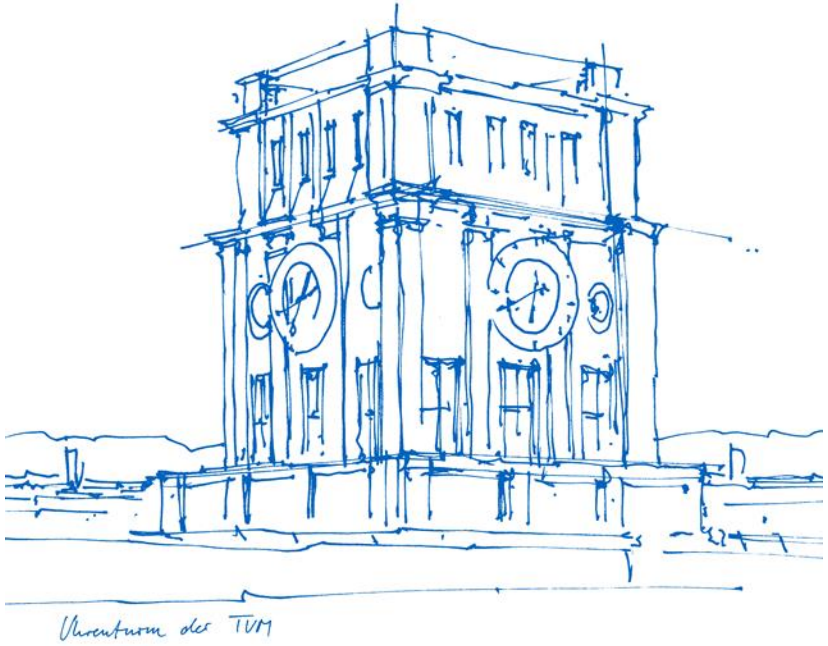

Quantum Chromodynamics

- Quantum Chromodynamics (QCD) as true theory of strong interaction
- Lagrangian of QCD

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

- 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?

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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:

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

flavor-symmetry breaking term

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- Approximate flavor symmetries:

Flavor symmetries of QCD

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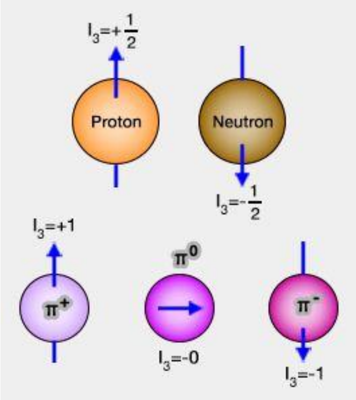
- Approximate flavor symmetries:

$\boldsymbol{SU(2)}$
$m_u \approx m_d$ -> isospin symmetry:



Flavor symmetries of QCD

- Lagrangian of QCD:

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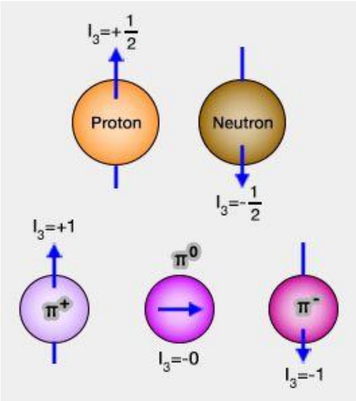
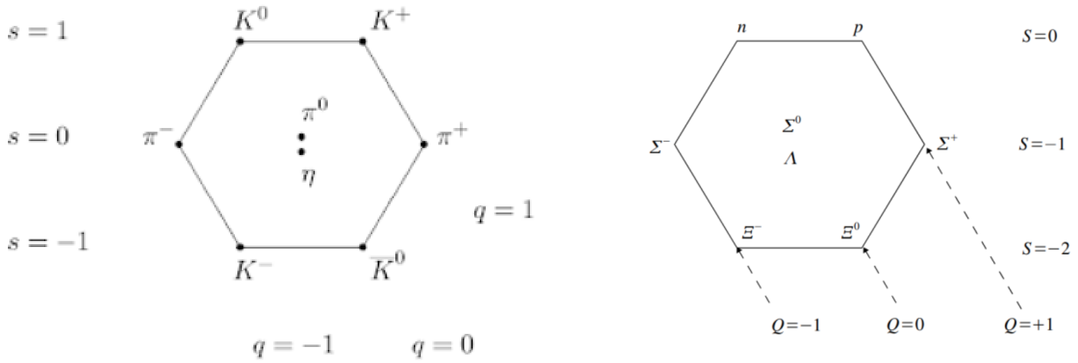
flavor-symmetry breaking term

- 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

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flavor-symmetry breaking term

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$m_c = (1.27 \pm 0.02)\,\mathrm{GeV}$ $m_b = (4.18 \pm 0.03)\,\mathrm{GeV}$ $m_t \approx 170\,\mathrm{GeV}$

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

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

- 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

Chiral symmetry of QCD

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

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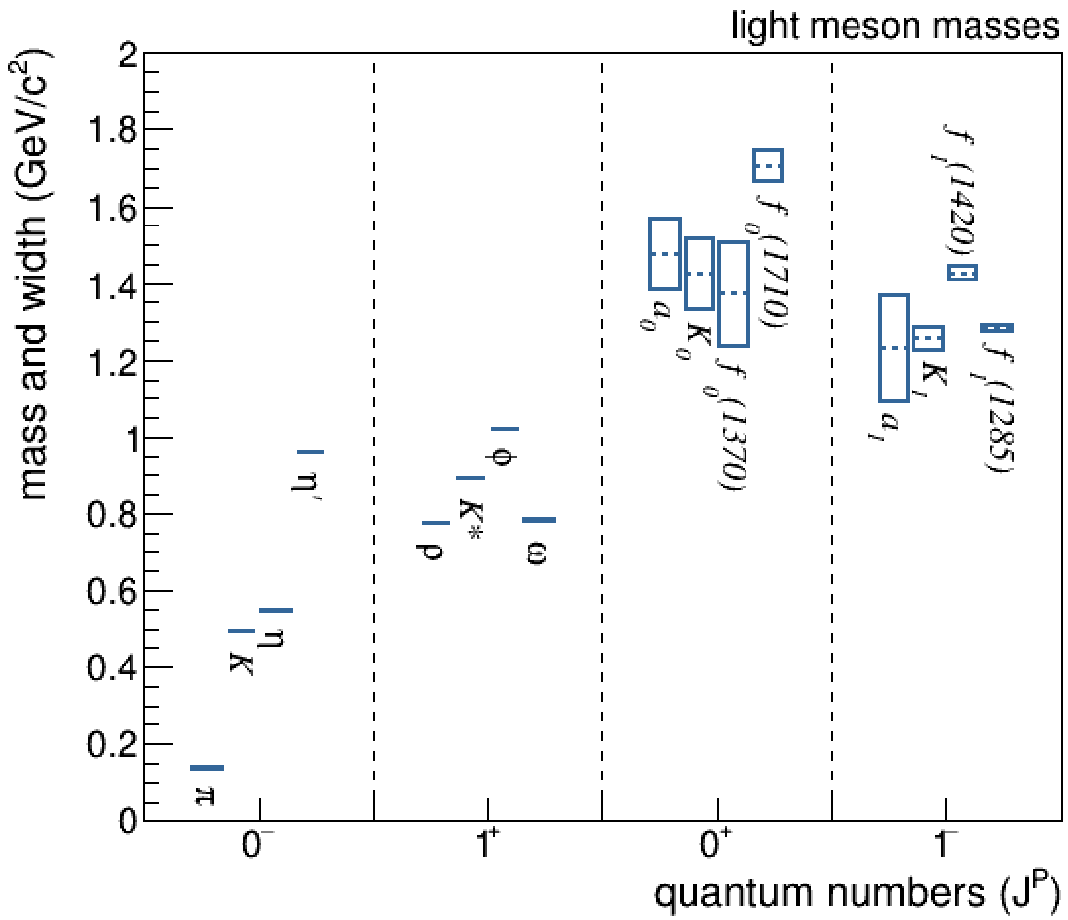
- Left- and right-handed fields decouple for massless particles
- Chirality can directly be translated to parity of particle
  → mass-degenerate doublets of states with opposite parity
- Why is chiral symmetry not manifested in the spectrum (in contrast to isospin and the eightfold way)?
  → Nambu-Goldstone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



Dynamic breaking of chiral symmetry

Spontaneous symmetry breaking

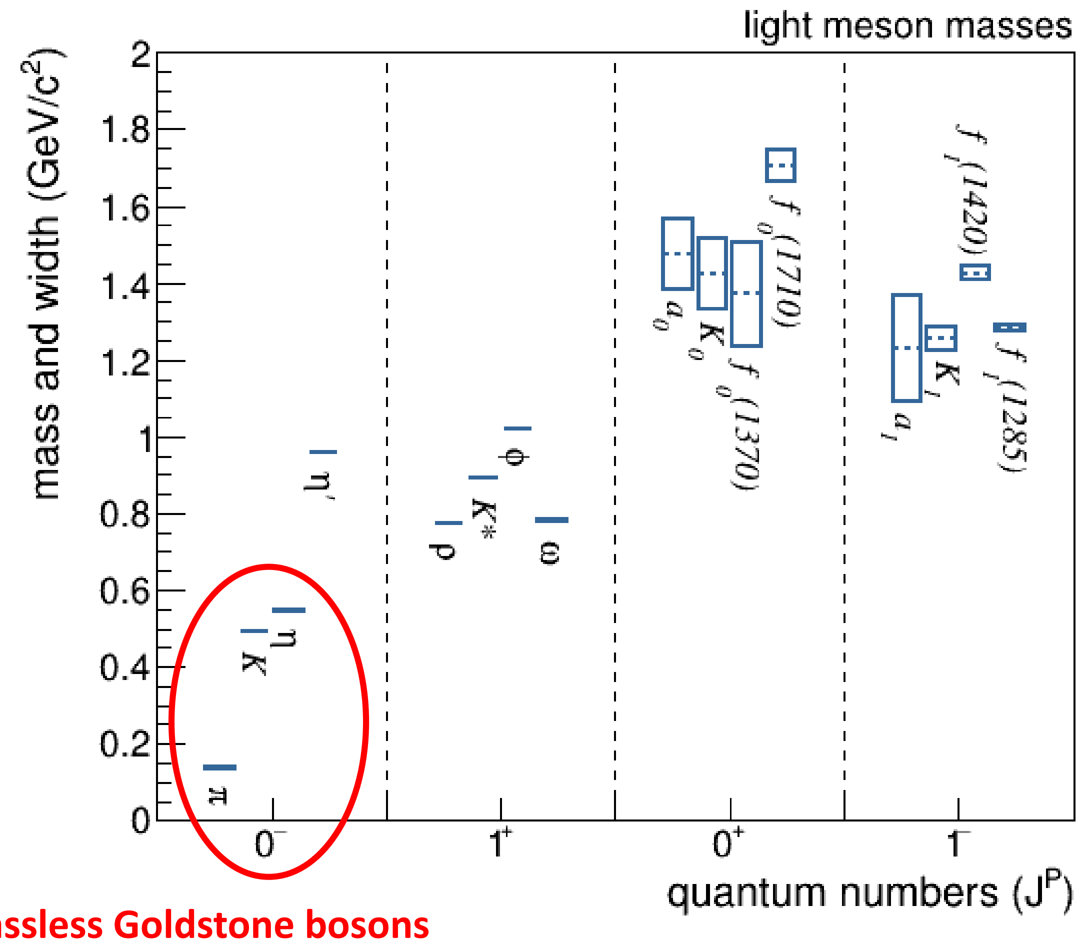
⇒ Eight massless, spinless Goldstone bosons

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

⇒ 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



The chiral anomaly

- Lagrangian of QCD

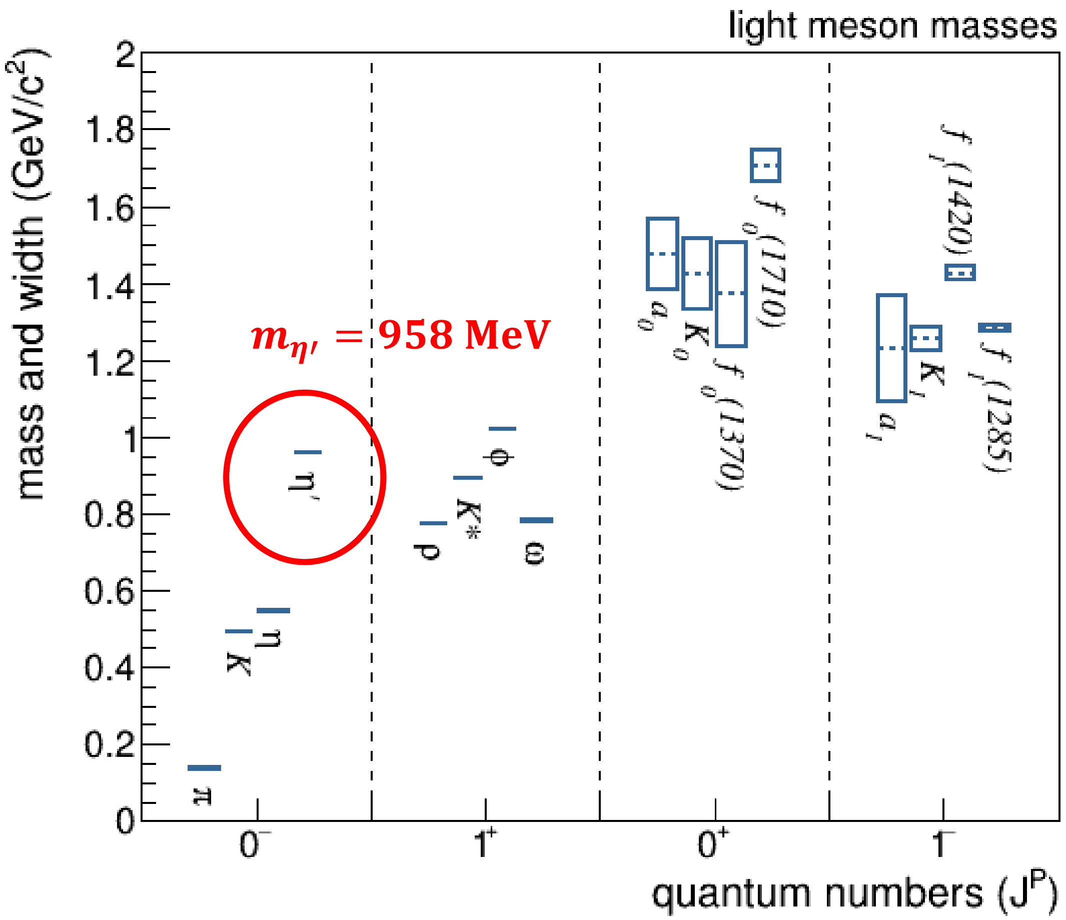
$$\mathcal{L}_{QCD} = \sum_{f=\substack{u,d,s,\\c,b,t}} \bar{q}_f\left(i\not{D} - m_f\right)q_f - \frac{1}{4}G^a_{\mu\nu}G_a^{\mu\nu}$$

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

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

- 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



Wess-Zumino-Witten term

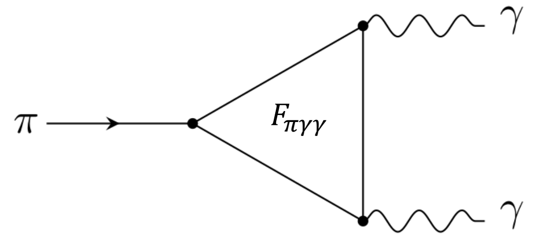
- Chiral anomaly in ChPT taken into account by Wess-Zumino-Witten (WZW) term

- 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.

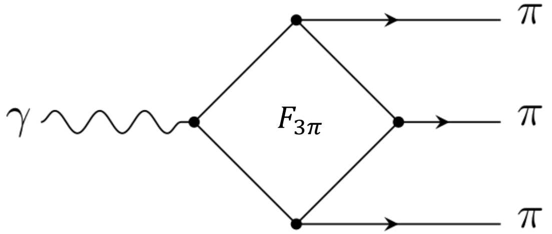
- Effective theory → pion decay constant F_π measured from leptonic decays of the charged pion $(\pi^\pm \to \mu^\pm + \nu)$

$F_{\pi\gamma\gamma}$



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

$F_{3\pi}$

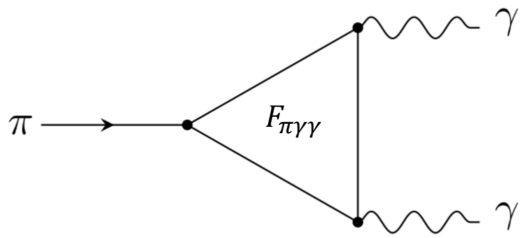


- $F_{3\pi} = \frac{e N_C}{12\pi^2 F_\pi^3} = (9.78 \pm 0.05)\,\mathrm{GeV}^{-3}$

Discovery of the chiral anomaly – π^0 lifetime

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

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



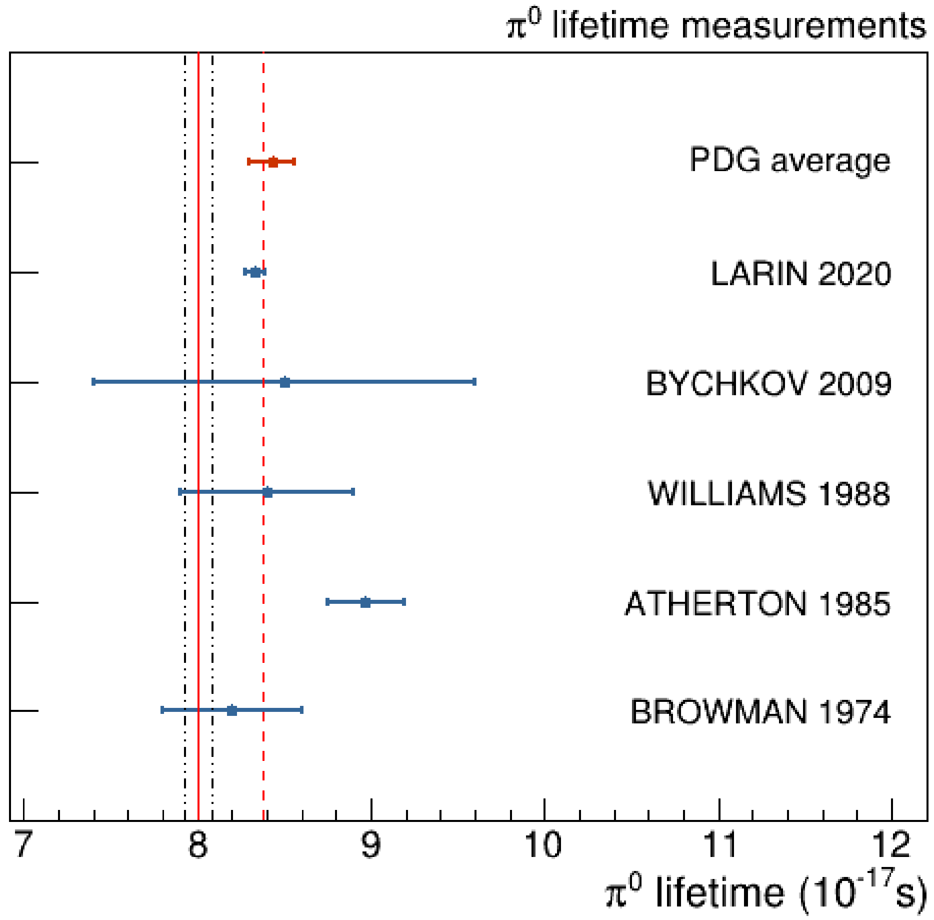
- Adler, Bell, Jackiw, Bardeen 1969: calculation of triangle diagram

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

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

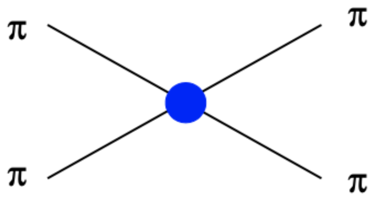
- Moussalam and Kampf 2009: NLO-calculation in chiral perturbation theory

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



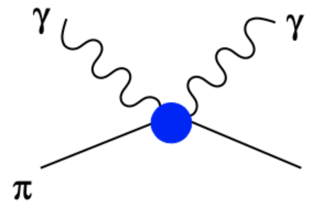
More predictions from ChPT

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

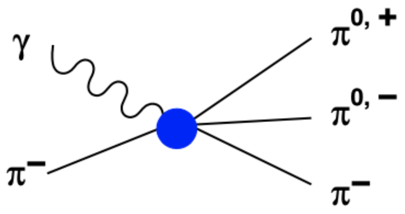


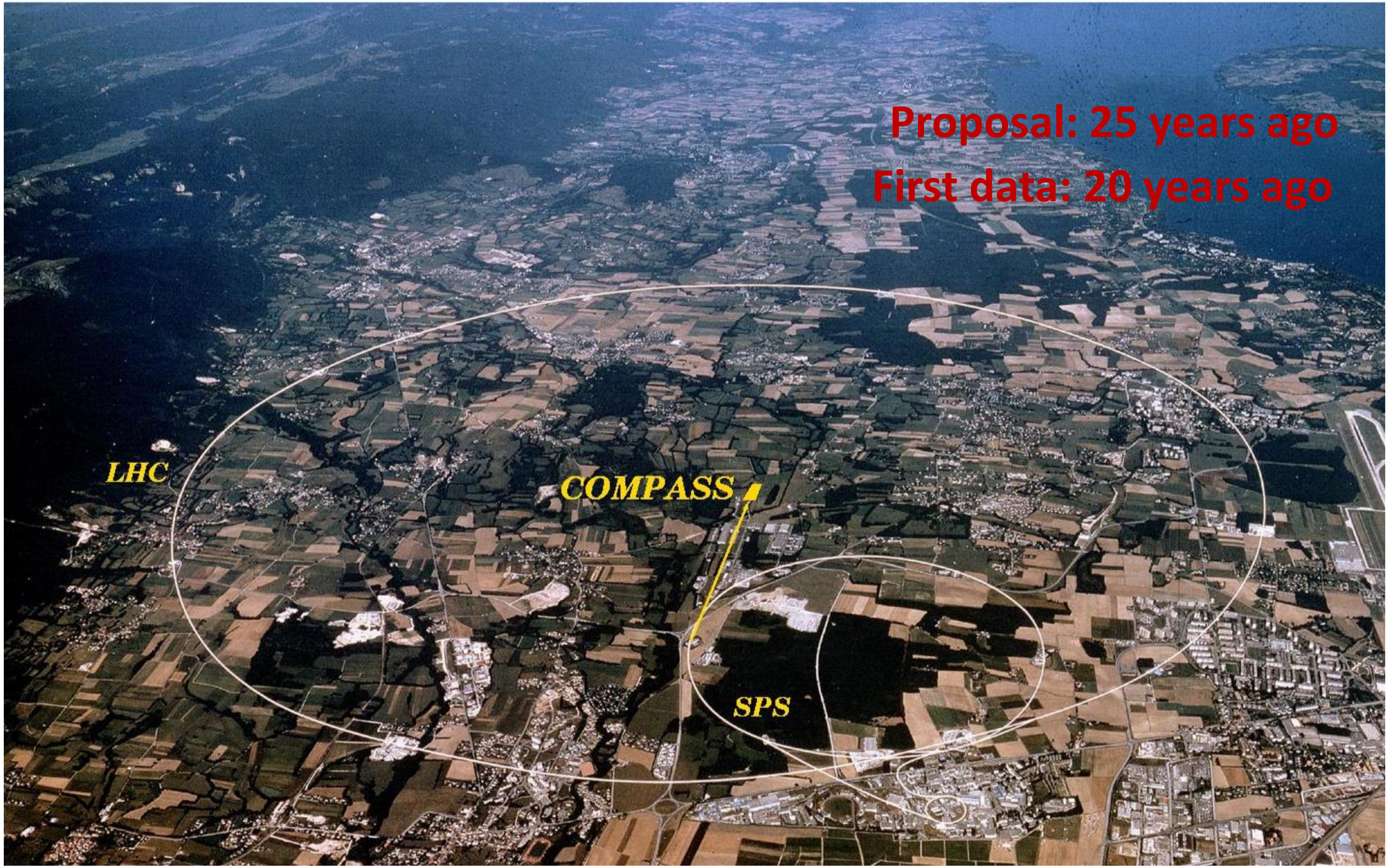
- pion polarisability: electric α_π, magnetic β_π
  - contribution to Compton scattering
  - ChPT prediction obtained by the relation to $\pi^+ \to e^+\nu_e\gamma$ [Gasser, Ivanov, Sainio, Nucl. Phys. B745, 2006]
    [PIBETA, M. Bychkov et al., PRL 103, 051802, 2009]

$$\alpha_\pi + \beta_\pi = (0.2 \pm 0.1) \cdot 10^{-4}\text{fm}^3$$
$$\alpha_\pi - \beta_\pi = (5.7 \pm 1.0) \cdot 10^{-4}\text{fm}^3$$



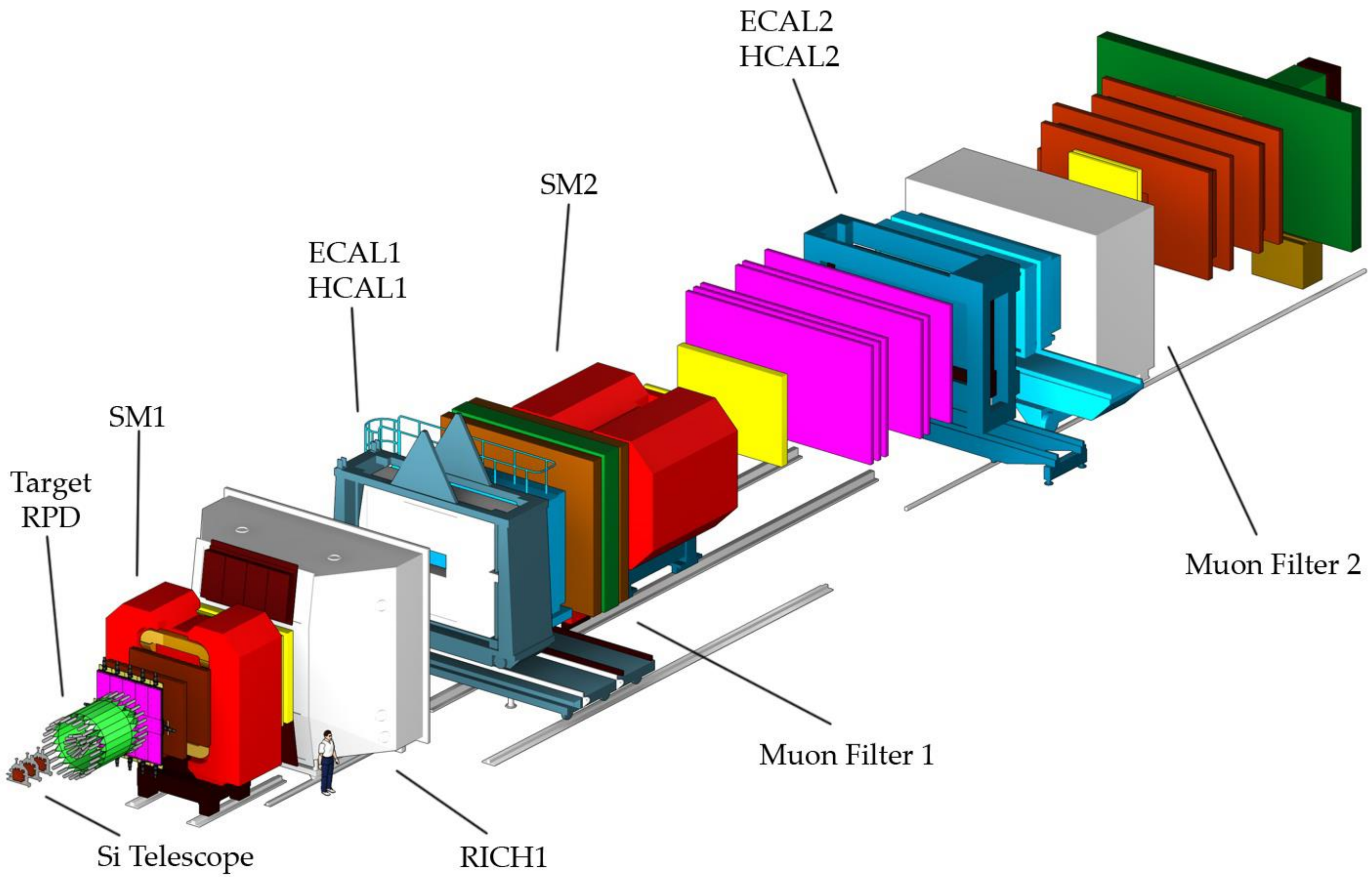
- Pion scattering including a real photon
  - Leading-order prediction from ChPT
    ↔ pion scattering lengths
    combined with photon coupling
  - chiral loop contribution
    theory prediction available, no measurement





Happy Birthday!

COMPASS spectrometer

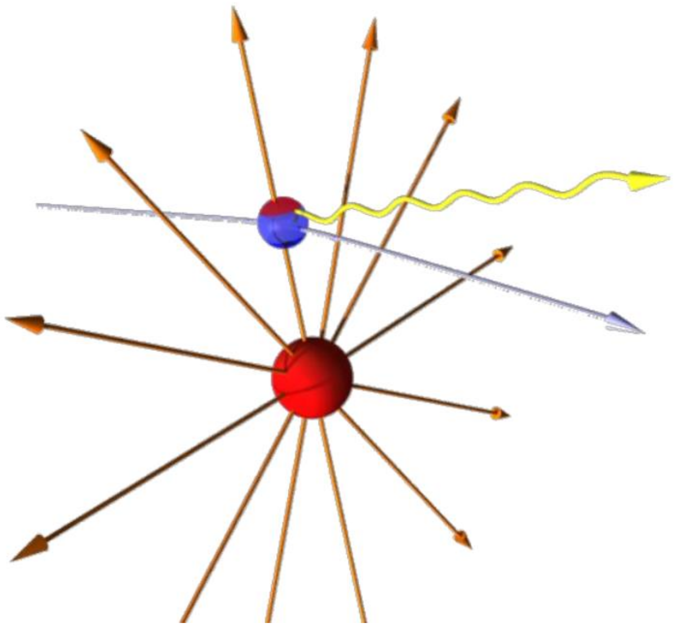


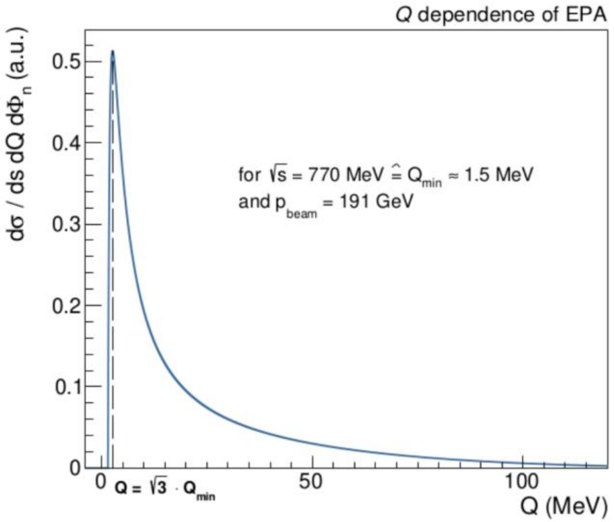
For the measurements presented in the following:

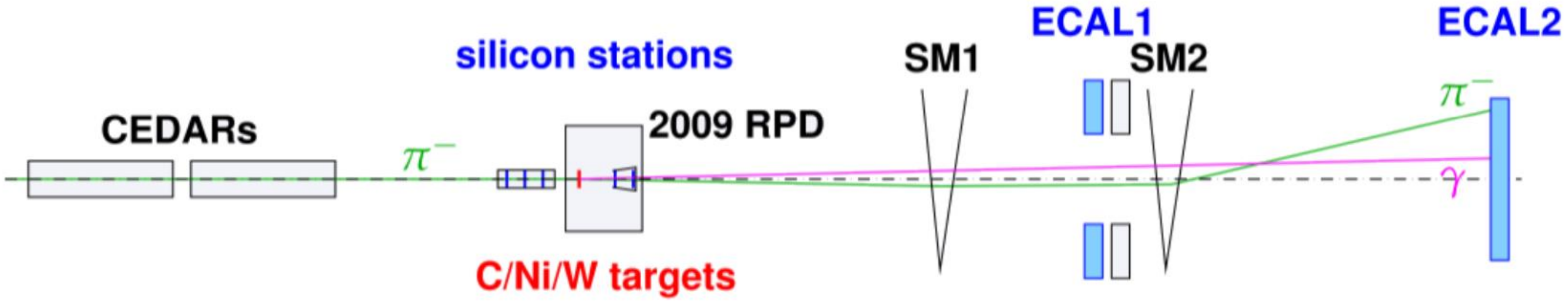
- 190 GeV negative hadron beam
- Beam PID
- Nuclear target(s): Ni and W
- Calorimetric trigger on neutrals
- Two stage spectrometer (LAS and SAS) with tracking and calorimeter

Pion-Photon reactions through the Primakoff technique

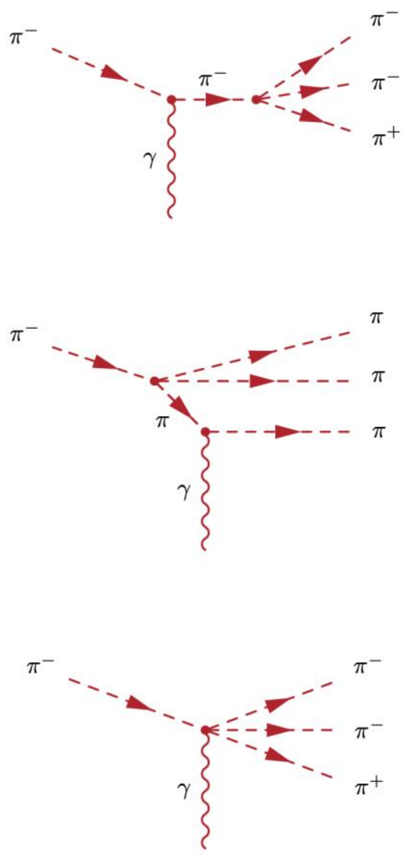
- Photon is provided by the strong Coulomb field of a nucleus (typical field strength at $d = 5R_{Ni}$: $E \approx 300$ kV/fm)
- Coulomb field of nucleus is a source of quasi-real ($P_\gamma^2 \ll m_\pi^2$) photons
- Large impact parameters (ultra-peripheral scattering)

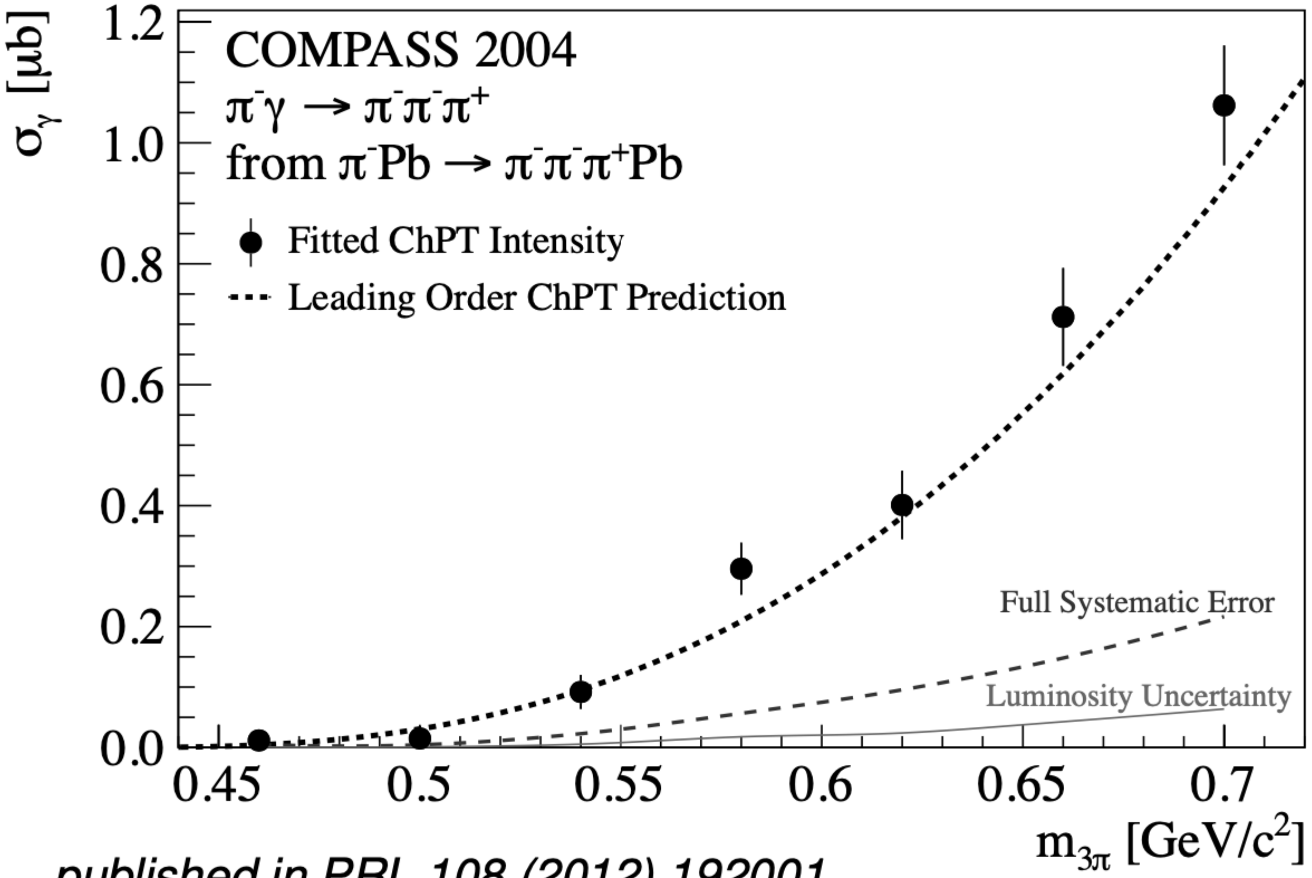






Measurement of the cross-section for $\pi^-\gamma \rightarrow \pi^-\pi^-\pi^+$

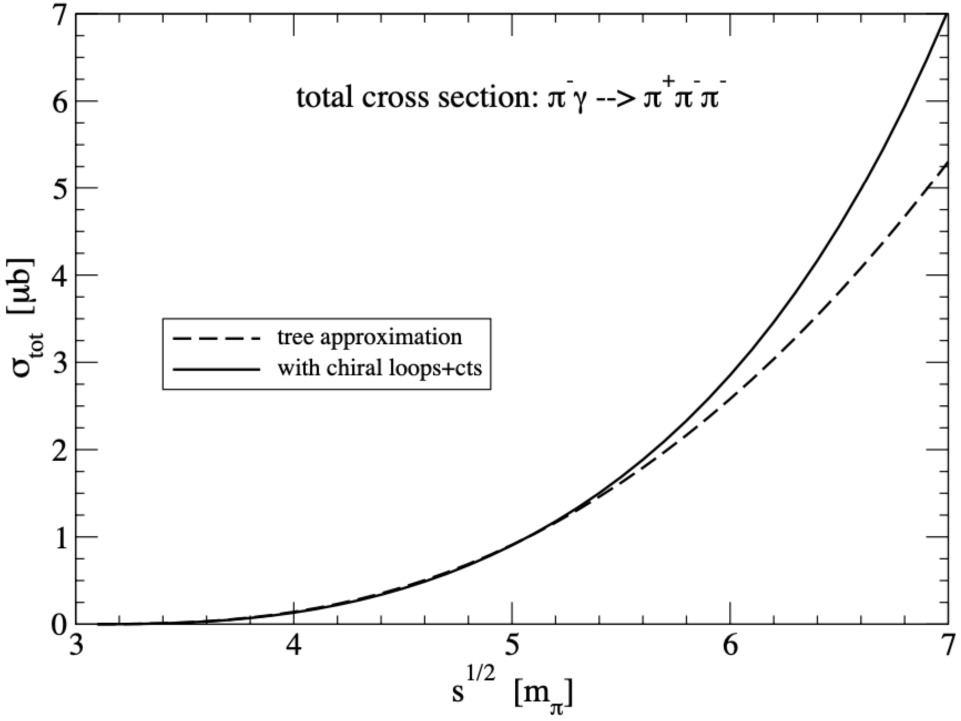


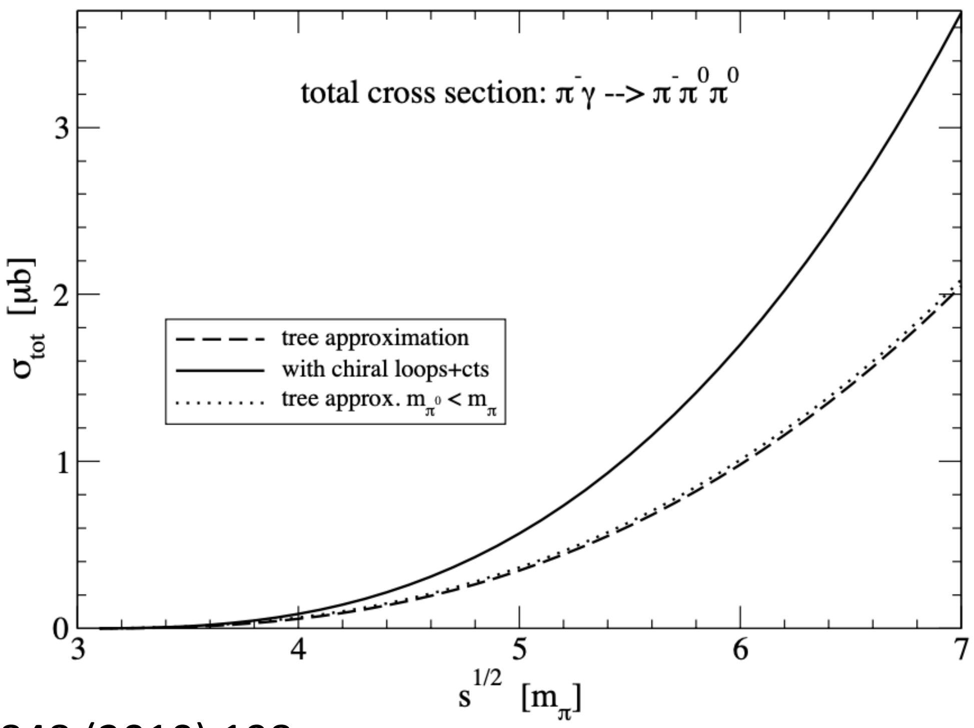


published in PRL 108 (2012) 192001

measurement up to $\sim 5m_\pi$

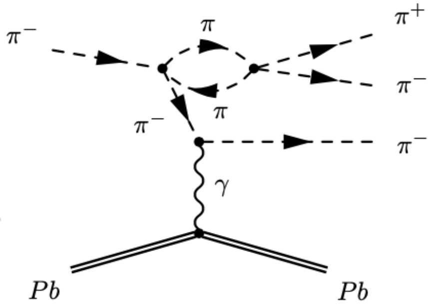
Higher chiral order for $\pi^- \gamma \rightarrow \pi^- \pi \pi$

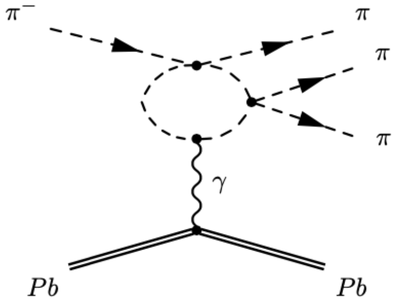




N. Kaiser, NPA848 (2010) 198

Chiral loops e.g.



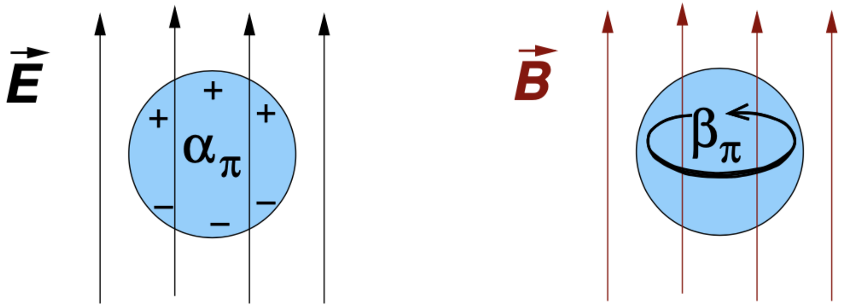


Also obtained in these analyses: radiative widths of $a_2(1320)$ and $\pi_2(1670)$
EPJ A50 (2014) 79

Pion polarisability: COMPASS measurement

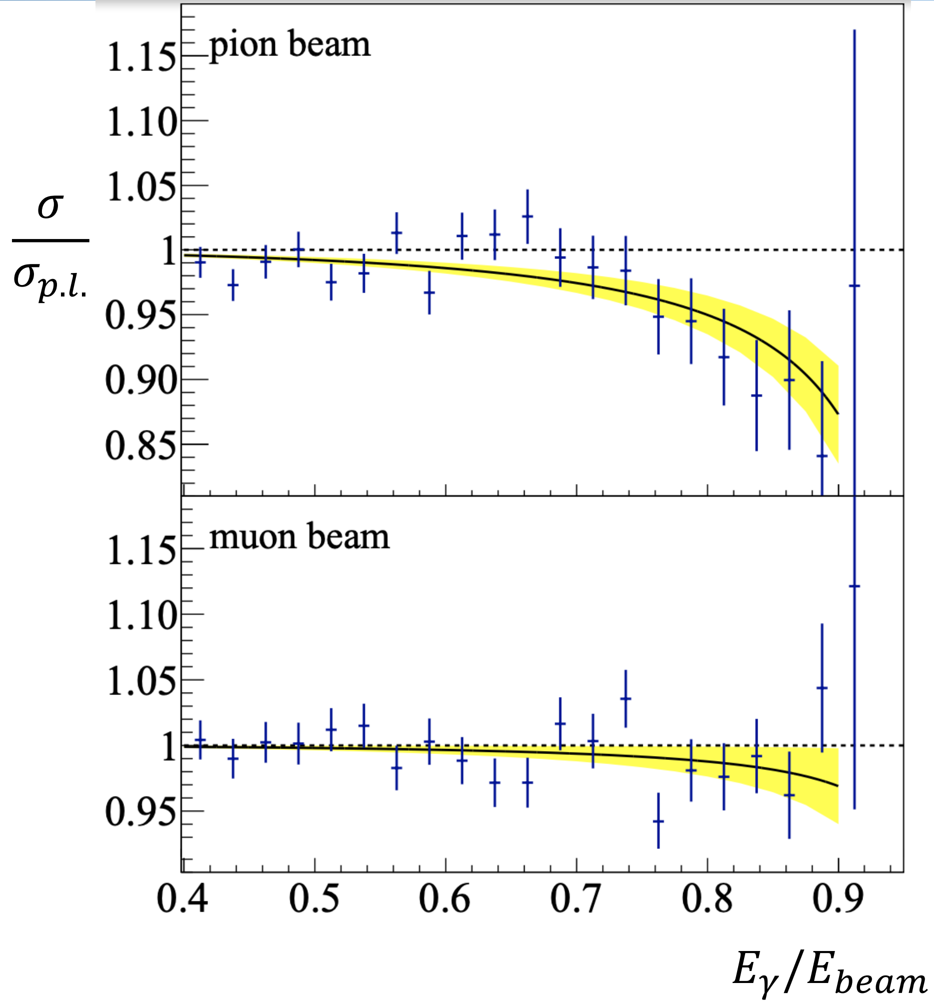
$$\pi + \gamma \rightarrow \pi + \gamma$$

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



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

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



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

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

- Processes described by WZW term:

$SU(2)$ flavor	$SU(3)$ flavor
$\pi^0 \to \gamma\gamma$	$K^+K^- \to \pi^+\pi^-\pi^0$
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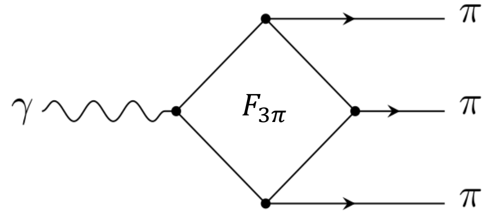
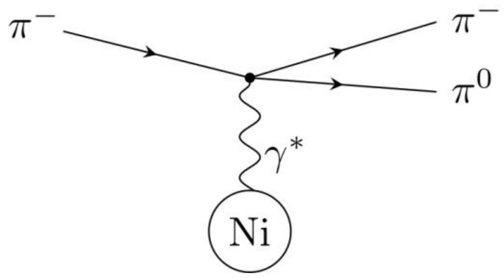
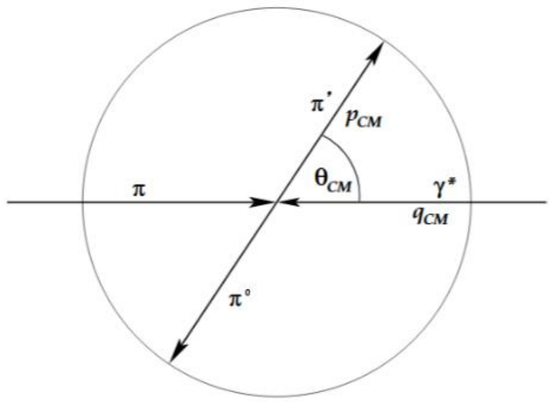


- $F_{3\pi}$: Direct coupling of γ to 3π - process proceeds primarily via the chiral anomaly => one of the most definitive tests of low-energy QCD



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



- Problem of explicit chiral symmetry breaking:

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

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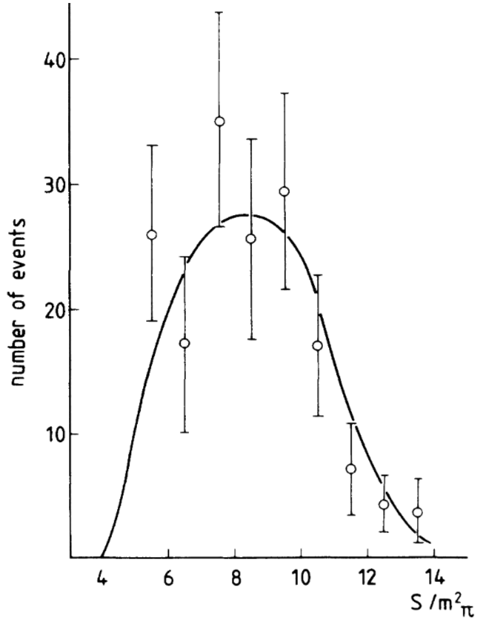
Previous measurement of $F_{3\pi}$:

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 $F^{3\pi} \simeq F^{3\pi}(0)$.

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



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

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

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Reanalysis of Serpukhov data:

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

- Using extrapolation & em corr:

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

- Compare to prediction from ChPT:

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

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

$\Rightarrow$ More precise experimental determination desirable

Analysis of COMPASS measurement

New result! – PhD theses of D. Ecker (TUM) and A. Maltsev (JINR)

- 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:

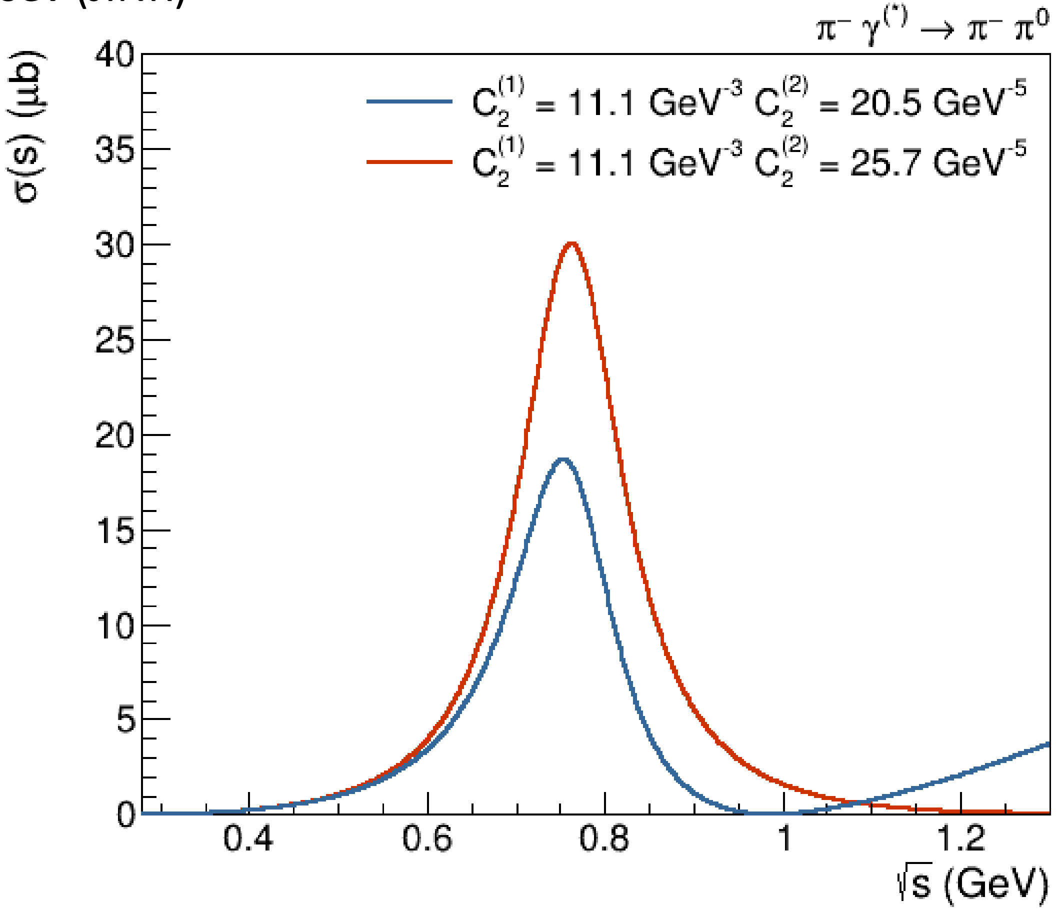
$$\sigma(s) = \frac{(s-4m_\pi^2)^{3/2}(s-m_\pi^2)}{1024\pi\sqrt{s}} \int_{-1}^{1} \mathrm{d}z(1-z^2)|\mathcal{F}(s,t,u)|^2$$

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

Key part: 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

$$K^- \rightarrow \pi^- \pi^0$$
$$K^- \rightarrow \pi^- \pi^0 \pi^0$$

$$N_K = \Phi_\pi \frac{n_K}{n_\pi} BR(K^- \rightarrow \pi^0 \pi^-)(1 - e^{-\frac{L}{\gamma c \tau}})\epsilon_K$$

- N_K: Number of detected kaon decays
- Φ_π: Pion flux
- $\frac{n_K}{n_\pi}$: Kaon/pion flux ratio
- $BR(K^- \rightarrow \pi^0 \pi^-)$: Branching ratio
- $(1 - e^{-\frac{L}{\gamma c \tau}})$: Probability of kaon decaying in region with length L
- ϵ_K: Acceptance for kaon decays for particular final state

Investigated 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 π/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

(dark green)	Used for luminosity determination
(light green)	Considered as background process

Luminosity from Kaon decays

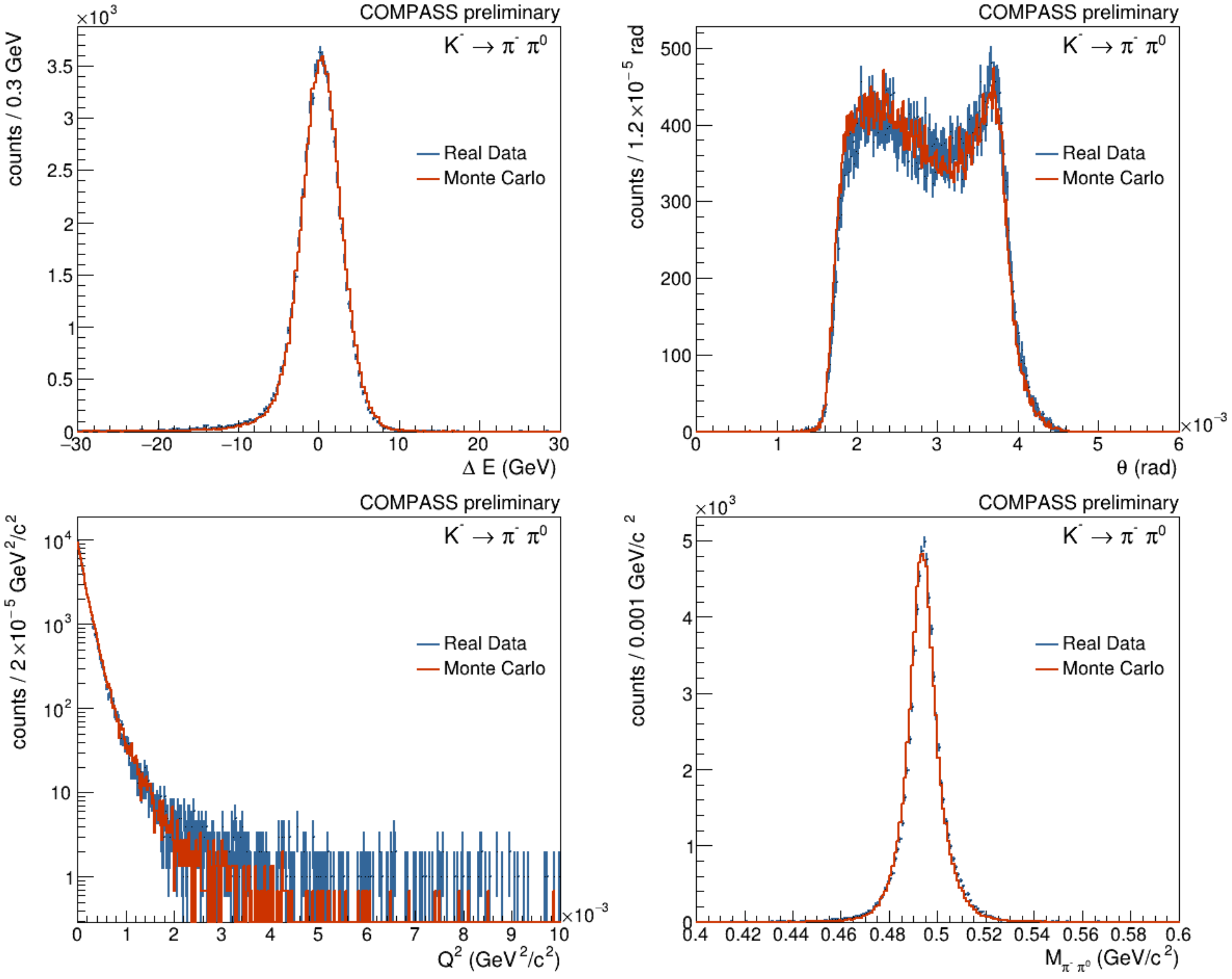
$$L_{2\pi,eff} = 5.21 \pm 0.04_{stat}\ nb^{-1}$$
$$L_{3\pi,eff} = 5.06 \pm 0.12_{stat}\ nb^{-1}$$

Largest contributions to systematic uncertainty:

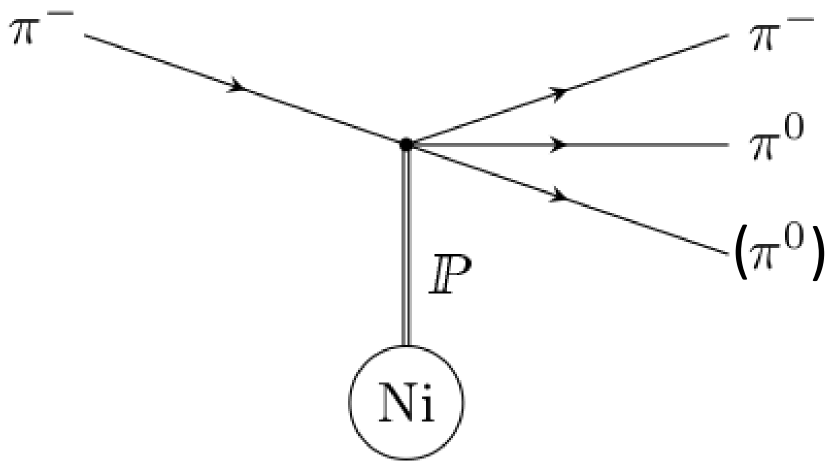
- CEDAR tag efficiency: 7%
- ECAL reconstruction: 5%
- kaon/pion beam ratio: 2.5%

Result:

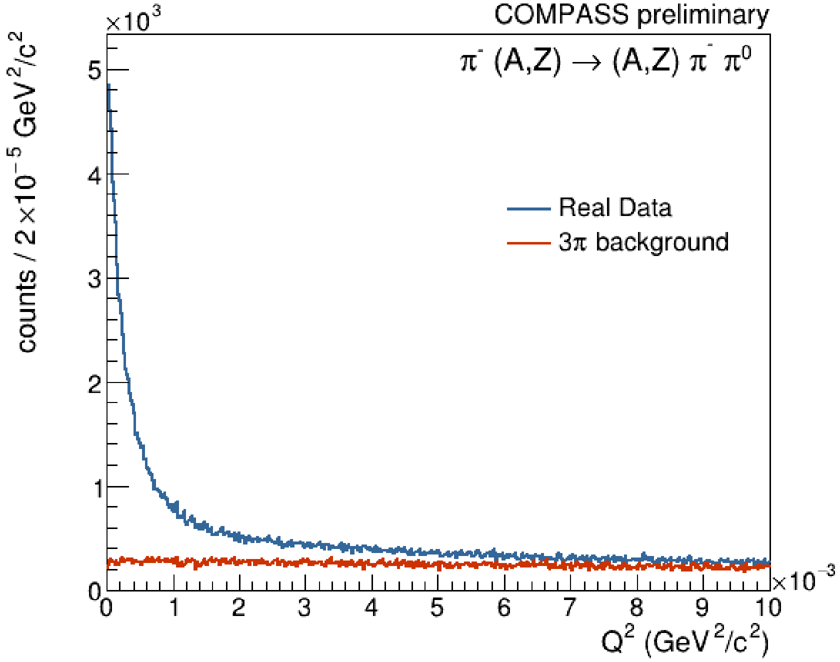
$$L_{eff} = 5.21 \pm 0.48_{syst} \pm 0.04_{stat}$$



The main background for π⁻γ → π⁻π⁰



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

Result of fitting with the Kubis-Hoferichter model

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

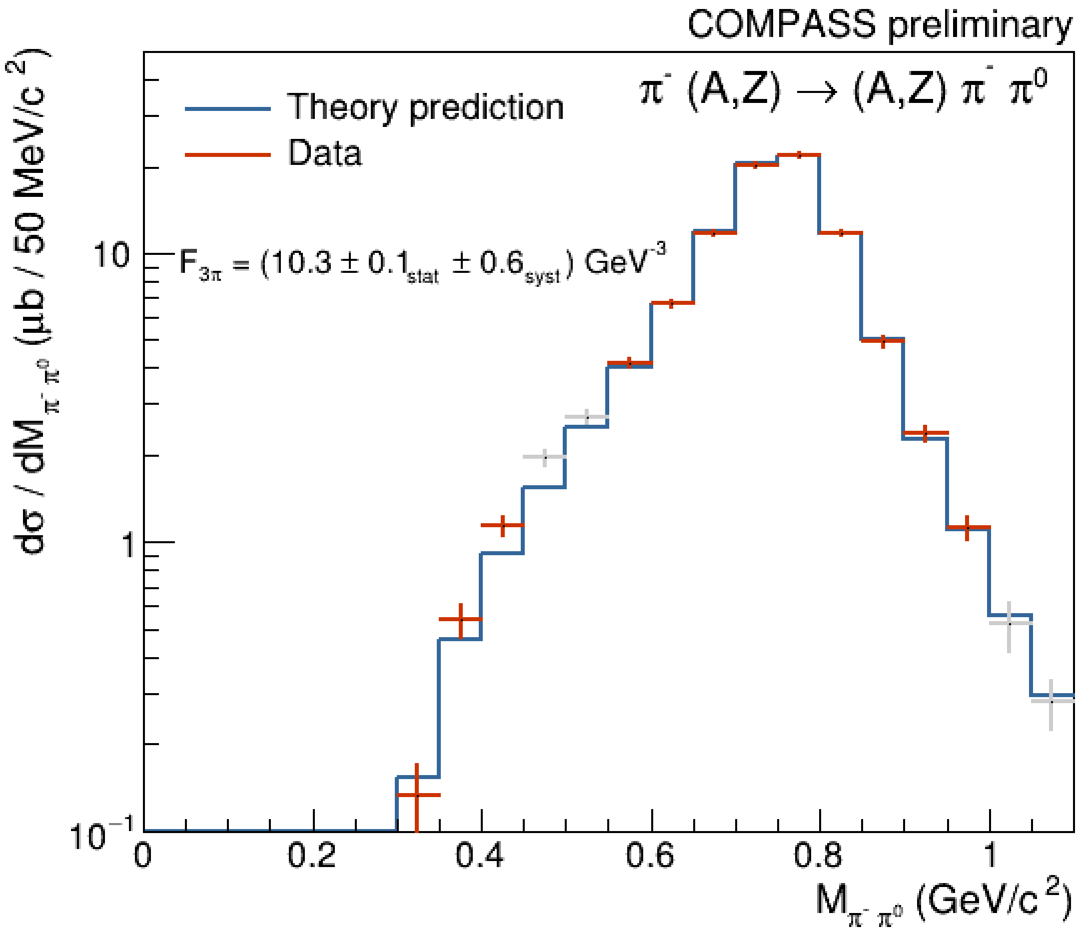
$$C_2^{(1)} = (10.5 \pm 0.1_{stat} \pm 0.6_{syst})\mathrm{GeV}^{-3}$$

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

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

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

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



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

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

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

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 π^-A → $\pi^-\pi^0$A
59.8±4.0	HUSTON	86	SPEC	+	202 π^+A → $\pi^+\pi^0$A
71 ±7	JENSEN	83	SPEC	−	156–260 π^-A → $\pi^-\pi^0$A

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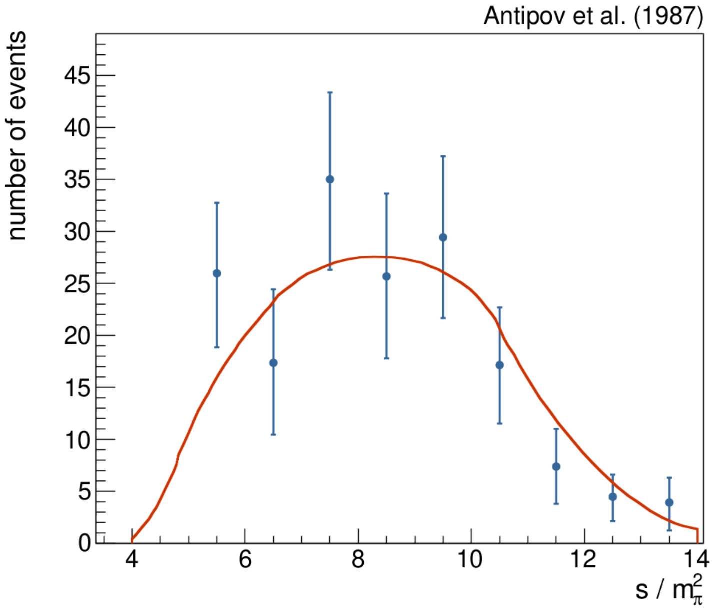
Antipov, Y. *et al.* PRD 36 (1987) 101103
and reanalyzed by
Ametller, L. *et al.* PRD 64 (2001) 094009

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

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



Conclusions and Outlook

- Chiral perturbation theory has, since its development in the 1980ies, 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

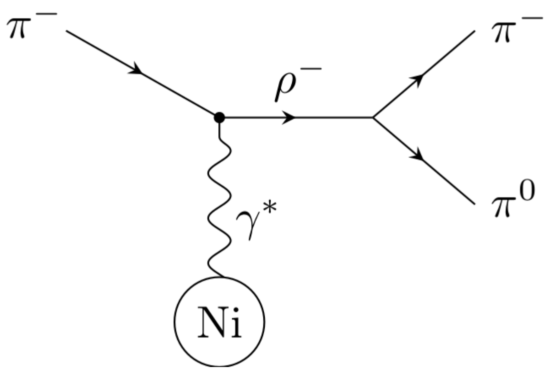
2004	$\pi^+\pi^-\pi^-$: published result	→ PRL 108 (2012) 192001
2009	$\pi^-\gamma$: pion polarizabilities	→ PRL 114 (2015) 06002
	$\pi^-\pi^0$: chiral anomaly	***new result!***
	$\pi^-\pi^0\pi^0$: chiral dynamics	
2012	$\pi^-\gamma$: pion polarizabilities $\pi^-\pi^0$: chiral anomaly $\pi^-\pi^0\pi^0$: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

- On the future program of the successor AMBER experiment: a similar program on the kaon sector

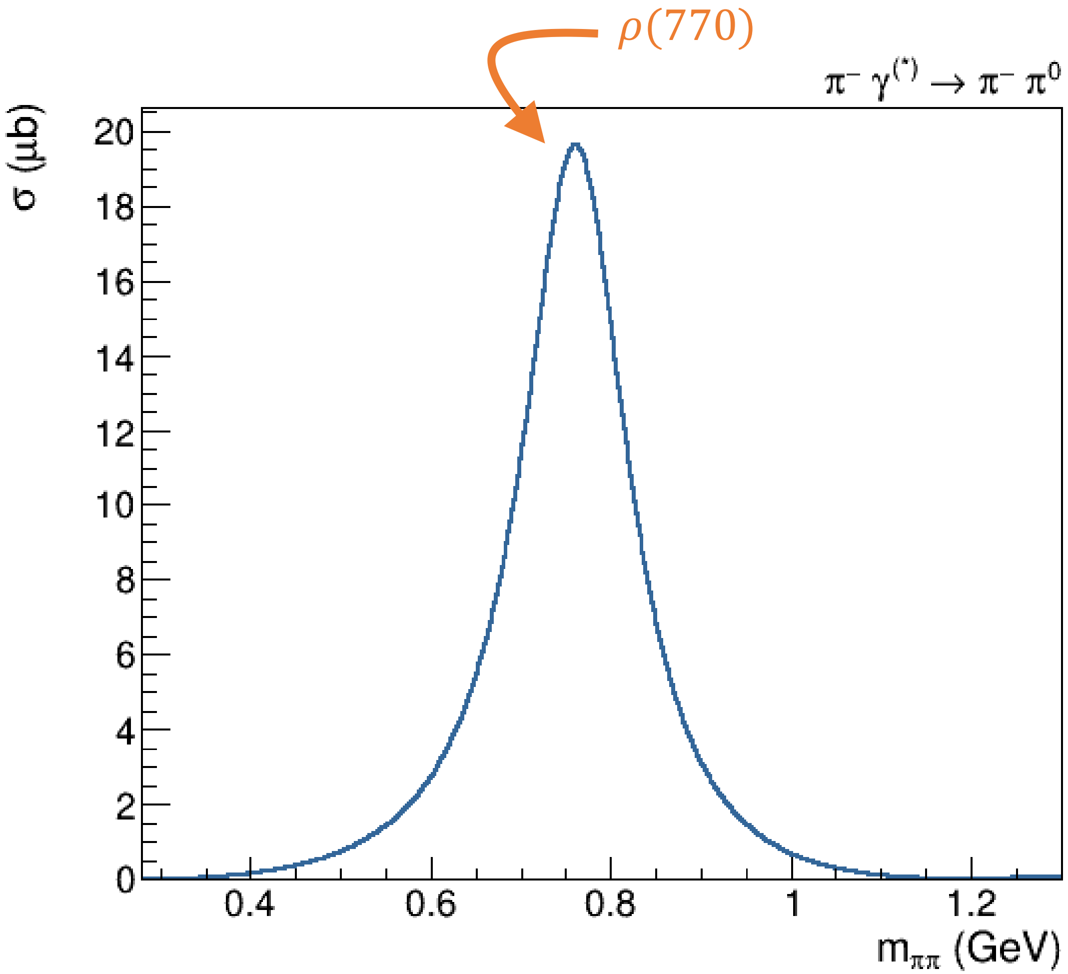
Thank you for your attention

Radiative width of ρ-meson

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



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



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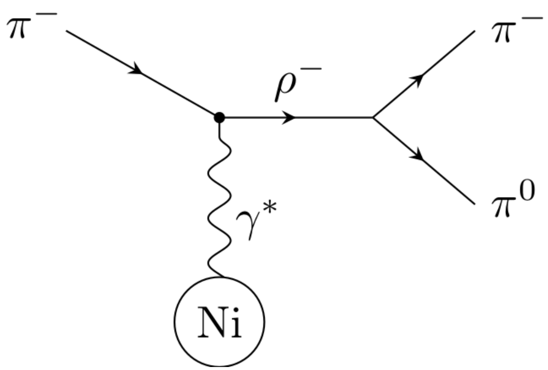

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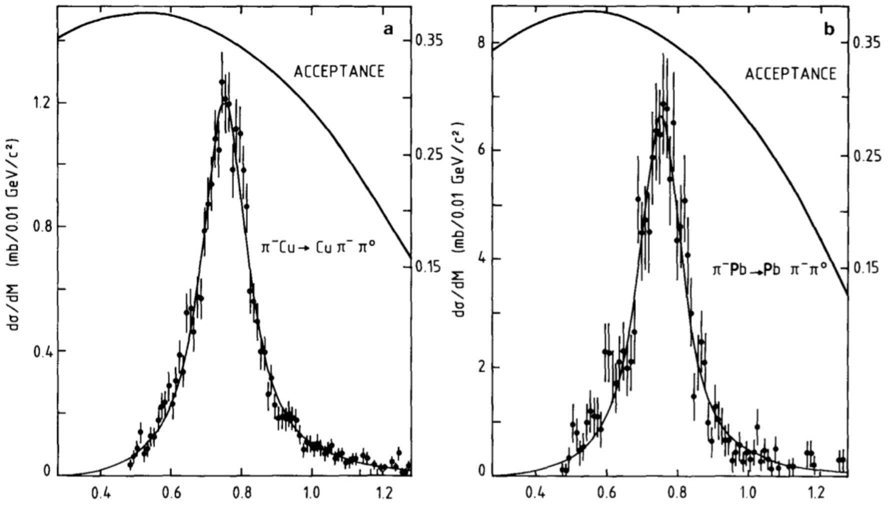

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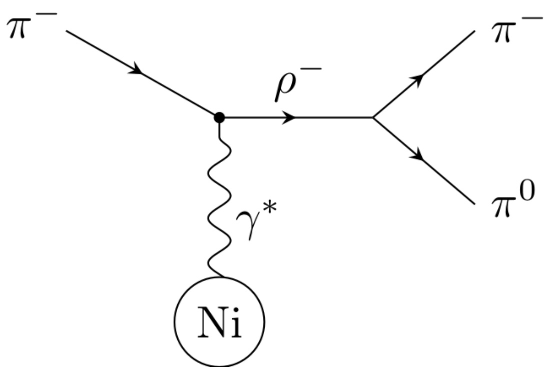

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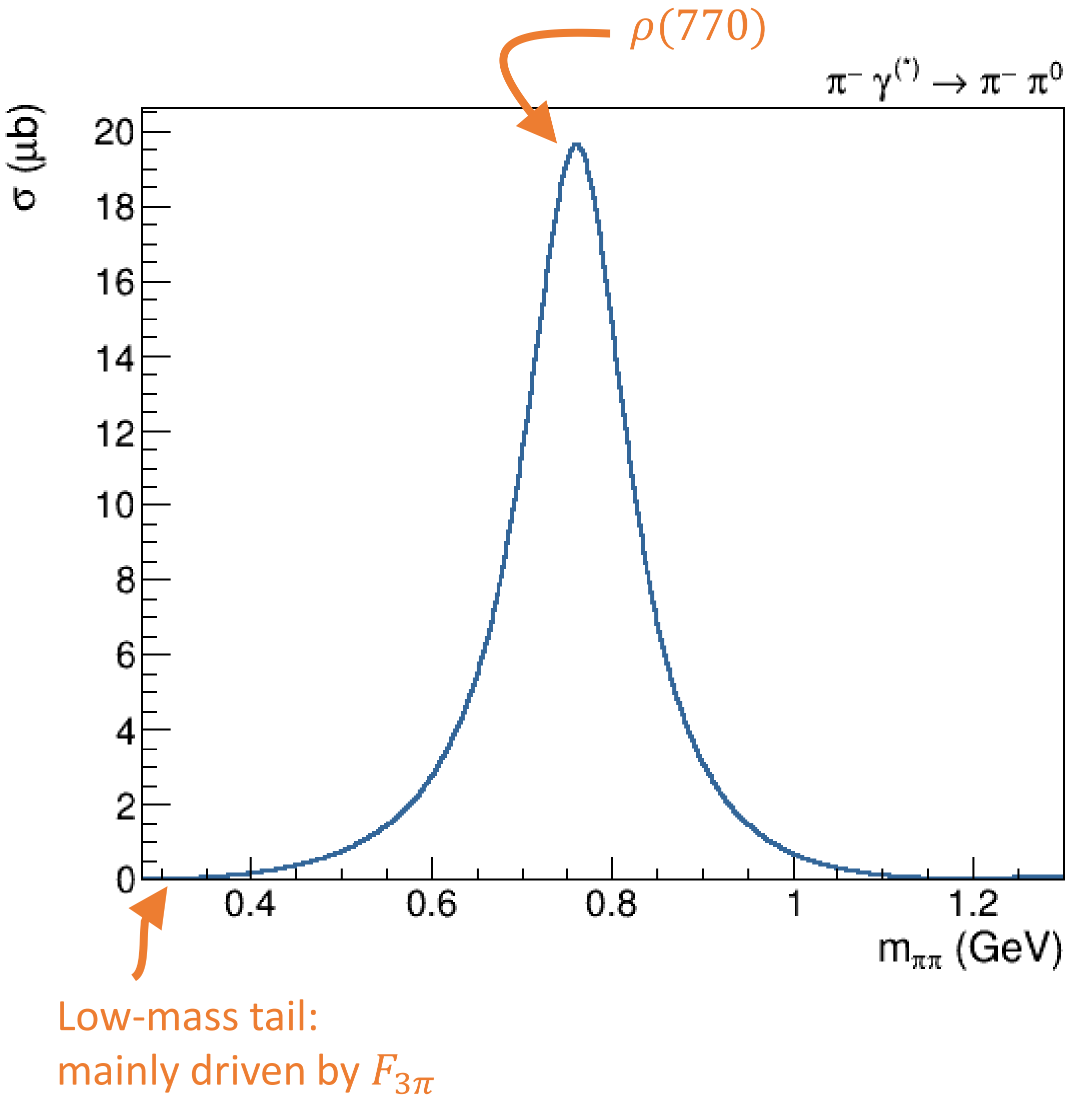
- At kinematic threshold: non-resonant behaviour but chiral anomaly (Serpukhov measurement)
- Interference between Chiral Anomaly and ρ gives additional information



Approach for 3π-leakage

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

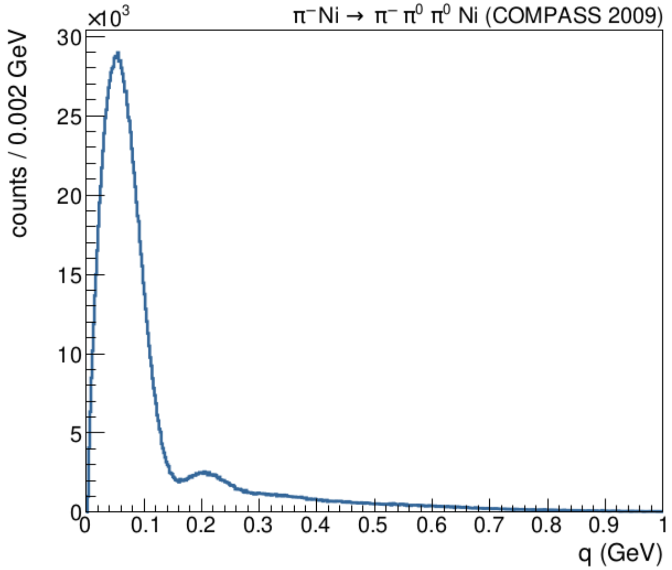
MC: $\pi^-\pi^0\pi^0$
- Phasespace distributed
- Generated by M.Kramer
- Weight PS distributed events according to model

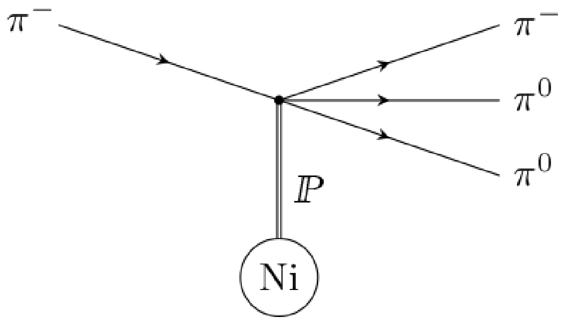
Develop PWA model

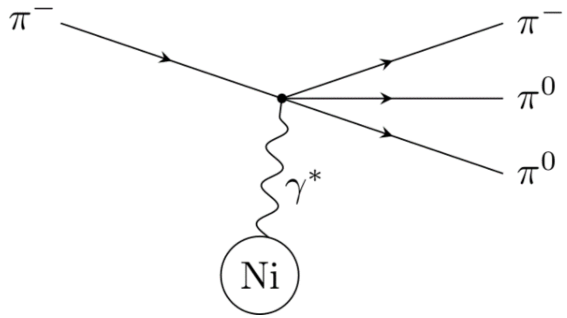
weight

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







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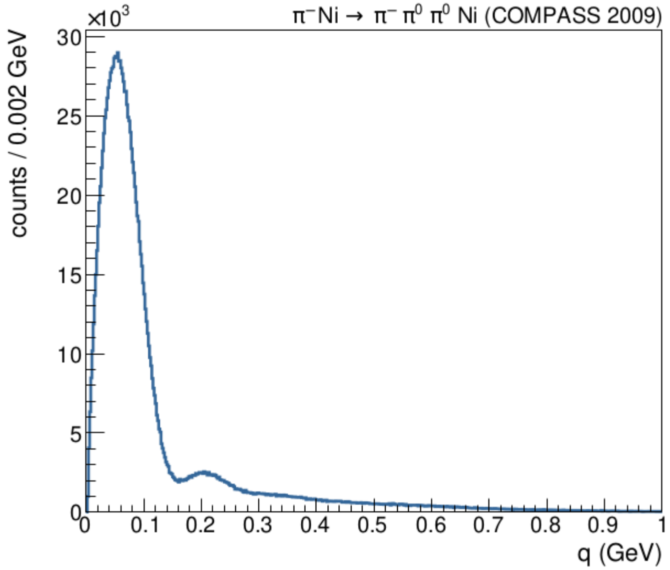

Issues so far: predicted background overshooting data