# Opportunities for Experiments with Hadrons in the Regime of Chiral Dynamics at *COMPASS Beyond 2020*

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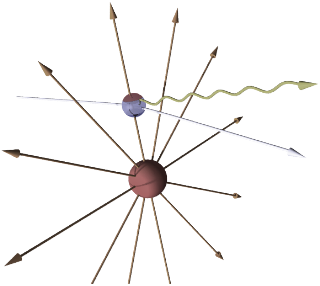
# Introduction & Outline

- *chiral dynamics* governs the low-energetic reactions of pions, nucleons, and all the hadron zoo
  pion-nucleon sector is already quite well explored and under study in many laboratories
- *pions-only* (+photons) reactions are explored via the Primakoff technique at COMPASS in a unique way (also: kaons, meson excitations)
- the *obvious* and the *less obvious* about future opportunities



# Cross Sections for $\pi^- \gamma \to \ldots$

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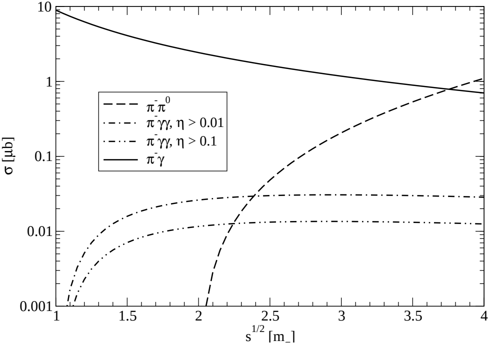
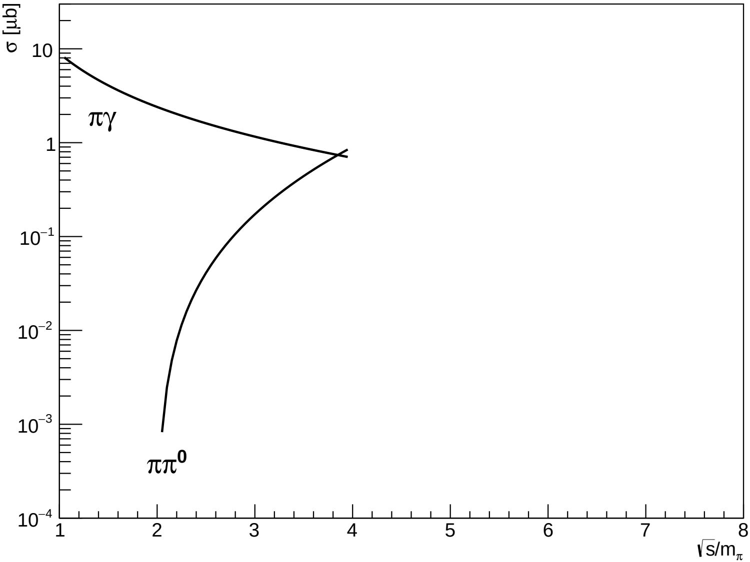
Perspective from 2008 (N. Kaiser, J.M.F., EPJA36, 181)




and also: "[Double-pion production $\pi^- \gamma \to \pi^- \pi^0 \pi^0$] has not been considered so far, mainly because of the lack of any experimental data. With the expected high statistics of the COMPASS experiment [15] this may change in the near future."

# Cross Sections for $\pi^-\gamma \rightarrow$ ...





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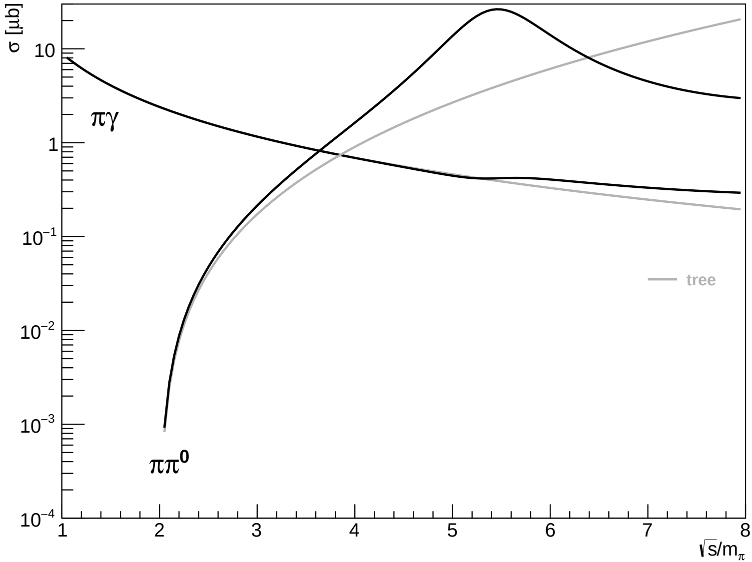

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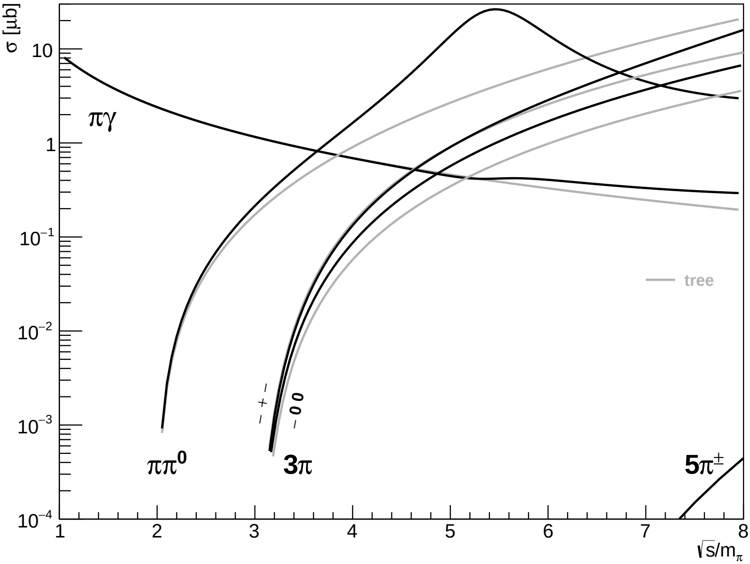

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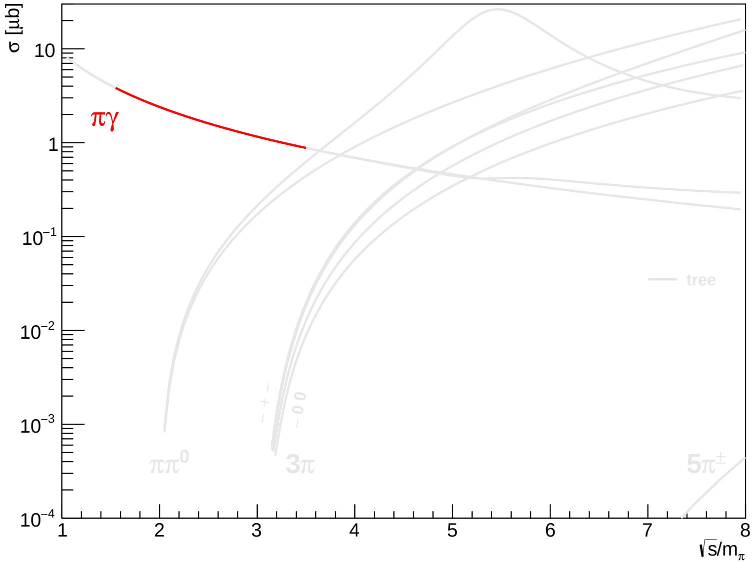

## Physics of Pion Compton Scattering $\pi^- \gamma \to \pi^- \gamma$

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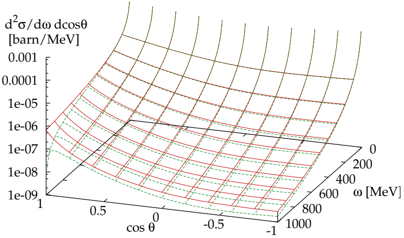
- leading structure-dependent parameter $\alpha_\pi - \beta_\pi$ determined from COMPASS 2009 data: $\alpha_\pi = (2.0 \pm 0.6_{\text{stat}} \pm 0.7_{\text{syst}}) \times 10^{-4}\ \text{fm}^3$
- goal of ongoing analyis of 2012 data: constrain $\alpha_\pi + \beta_\pi$ (assumed zero so far), i.e. determine $\alpha_\pi$ and $\beta_\pi$ separately
- future precision measurements should aim to fully map out the pion Compton scattering c.s., including *higher-order loop,* $\rho(770)$ *and quadrupole polarisability contributions*




$\alpha_\pi = \beta_\pi = 0$

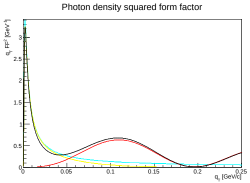
$\alpha_\pi = 7, \beta_\pi = -6$

*from: R. Kuhn, diploma thesis 2001*

- further extension of the kinematic range (mainly trigger issue)

for fighting the systematic uncertainties:

- different $Z$ of target nuclei: Be, C, Ni, Sn, W
- different beam energies: 140, 190, 240 GeV
- both polarities of the hadron beam
- separated kaon beam ($K^-$ polarisabilities)
- enhanced detector system: optimize spatial resolution of near-target tracking system, overall tracking efficiency, CEDAR3, RICH2



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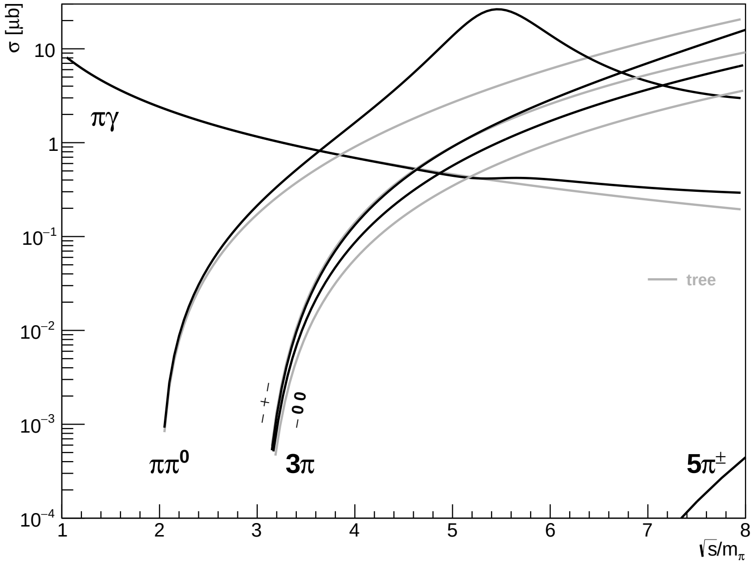
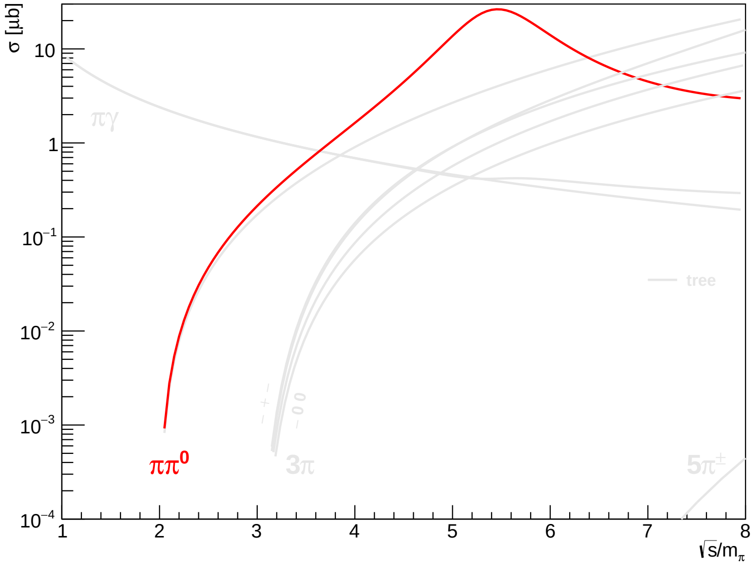


# Cross Sections for $\pi^-\gamma \to \ldots$

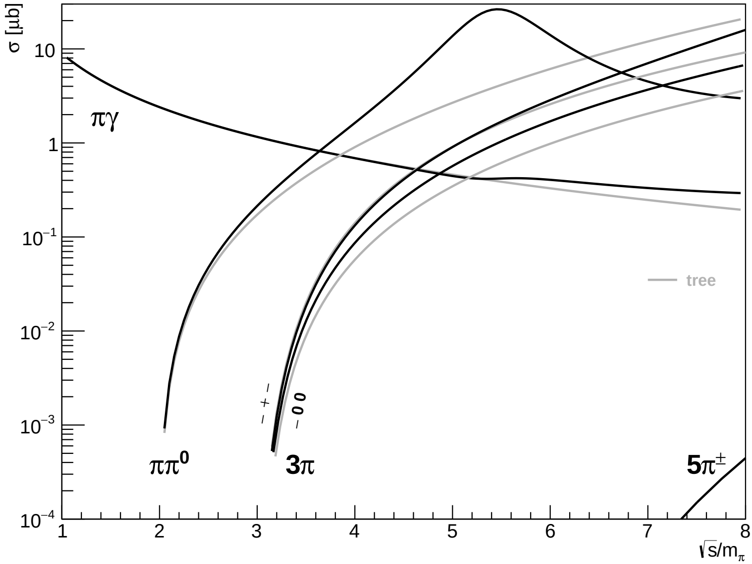




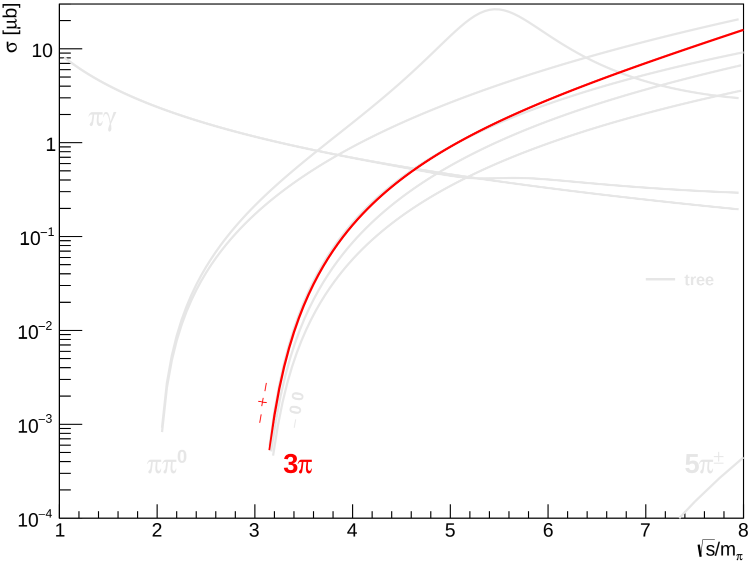
# Physics of $\pi^-\gamma \to \pi^-\pi^0$

- $\pi^-\gamma \to \pi^-\pi^0$ driven by chiral anomaly $F_{3\pi}$
- ChPT prediction $F_{3\pi} = (9.78 \pm 0.05)\,\mathrm{GeV}^{-3}$
- first experimental value $F_{3\pi}^{Serpukhov} = (12.9 \pm 0.9 \pm 0.5)\,\mathrm{GeV}^{-3}$
- e.m. and higher-order chiral corrections $F_{3\pi}^{Serpukhov,corr} = (10.7 \pm 1.2)\,\mathrm{GeV}^{-3}$
- alternatively via $e^-\pi^- \to e^-\pi^-\pi^0$: $F_{3\pi}^{e\pi} = (9.6 \pm 1.1)\,\mathrm{GeV}^{-3}$ (assuming ChPT)
- the large uncertainty of experimental determination should be readily outstripped by COMPASS data, analysis pending
- Hoferichter, Kubis, Sakkas (PRD 86, 116009 (2012)) have given a dispersive formulation for $\pi^-\gamma \to \pi^-\pi^0$

# Cross Sections for $\pi^-\gamma \to \ldots$



# Cross Sections for $\pi^- \gamma \to \dots$

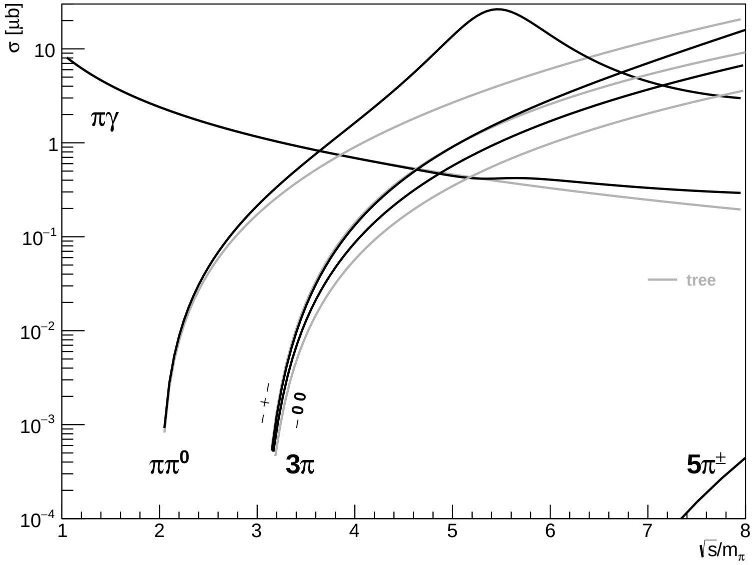


# Physics of the $\pi^-\pi^+\pi^-$ final state

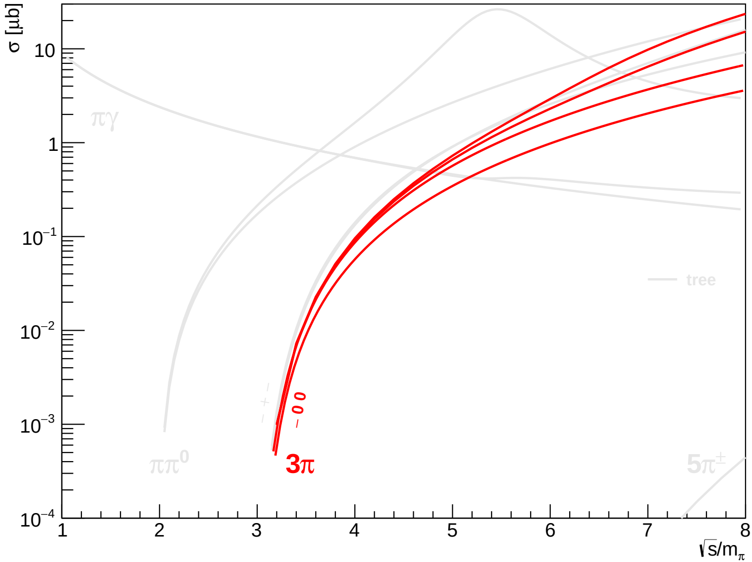
- analysis of 2004 data (Pb target):
  $3\pi^\pm$ threshold region largely dominated by tree diagrams,
  COMPASS PRL 108, 192001 (2012)
- $3\pi^\pm$ resonance region: radiative coupling of $a_2(1320)$, $\pi_2(1670)$ observed,
  COMPASS EPJA 50, 79 (2014)
- analysis of 2009 data (Pb target): ongoing
- for future measurement: both beam polarities required for measuring the Coulomb-nuclear interference

# Cross Sections for $\pi^-\gamma \to \dots$





# Cross Sections for $\pi^- \gamma \to \pi^- \pi^0 \pi^0$



# Physics of the $\pi^-\pi^0\pi^0$ final state

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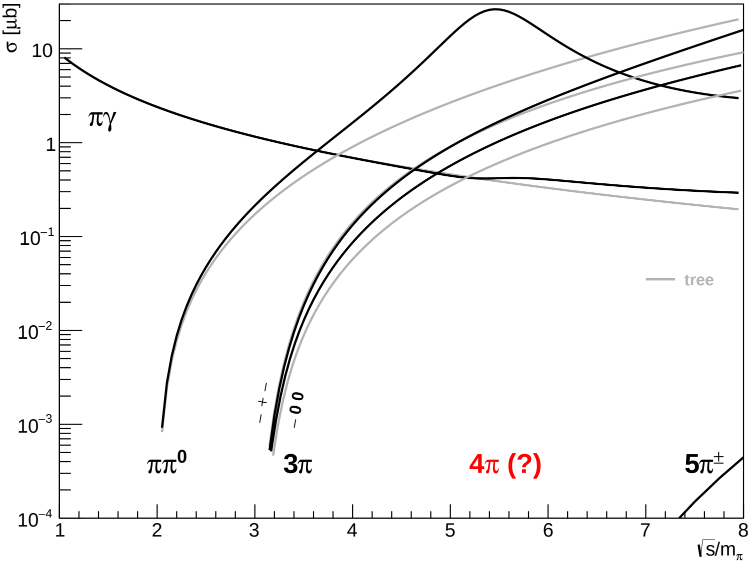
- threshold region: large (50%) contribution from chiral loops expected, promising study of 2009 data in Markus Kämer PhD
- resonance region: several radiative couplings visible,
  their determination requires the detailed understanding of the Coulomb-nuclear interference (Ni target)
- limited by low statistics
- most interesting: clarify the nature of the $a_1(1260)$
- 2012: trigger focused on Compton scattering (single photon)
- future measurement: dedicated triggers allowing higher beam intensities and better kinematic coverage, both beam polarities

# Cross Sections for $\pi^-\gamma \rightarrow \ldots$



# Speculative ideas on $\pi\gamma$ reactions

- $4\pi$ final states: mix of chiral anomaly, $\pi\pi$ chiral scattering, and loops (?) - to be worked out
- $\pi\pi^0\gamma$ final state with hard photon - and more in Max Duell's dimploma thesis (TUM, supervisor N. Kaiser)
  Complementary to the Pb-Pb (i.e. $\gamma\gamma$) program at ALICE
- more possibilities with higher intensity / separated beams: $\pi^- \leftrightarrow K^-$, $\pi^0 \leftrightarrow \eta$

# Neutral-Pion Lifetime

- explorative study with 2009 data on “double tungsten” target
- ongoing study with 2012 data on “(side-)segmented tungsten” target
- best future opportunity: measure $\pi^0$ decays

$$\pi^0 \to \gamma\gamma \qquad \text{and} \qquad \pi^0 \to \gamma\, e^+ e^-$$

from the (exclusive) $\pi^-\pi^0$ final state
on a double tungsten target with *varying distance*

- inspired by and extending the
1980’s “CERN direct measurement of the $\pi^0$ lifetime”
- competitive and complementary to the PRIMEX measurement

# Pion-Electron and Kaon-Electron Reactions

- electron scattering in inverse kinematics,
  corresponds to electron scattering on pions with $E_e \approx 700\,\mathrm{MeV}$
- in case of kaons $E_e \approx 200\,\mathrm{MeV}$
- explores momentum transfers up to about $Q^2 = 0.3\,\mathrm{GeV}^2/c^2$
- virtual Compton scattering off the pion $\pi^- e \to \pi^- e^- \gamma$
  C. Unkmeir, S. Scherer, A.I. L'vov, and D. Drechsel, PRD61, 034002 (2000)

# Primakoff Beam Times at COMPASS



2004: 3 days

# Primakoff Beam Times at COMPASS



2004: 3 days
2009: 3 weeks

# Primakoff Beam Times at COMPASS

| | |
|---|---|
| 2004: | 3 days |
| 2009: | 3 weeks |
| 2012: | 3 months |

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| beyond 2020: | *to be proposed* |

# Primakoff Beam Times at COMPASS

| | |
|---|---|
| 2004: | 3 days |
| 2009: | 3 weeks |
| 2012: | 3 months |
| beyond 2020: | *to be proposed with exciting prospects for a rich program* |

# *many thanks to*



Alexey Guskov *and Dubna colleagues*
Lau Gatignon
Maximilian Duell
Norbert Kaiser
Aron Bernstein
*and others*