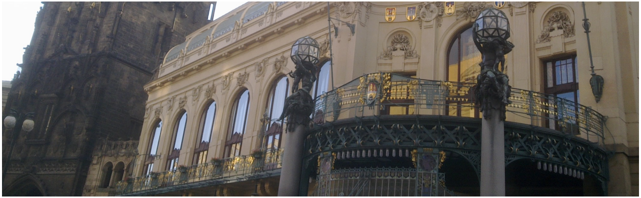
Measurement of the charged-pion polarisability and more on chiral dynamics from COMPASS

Jan M. Friedrich

on behalf of the COMPASS collaboration



Symmetries and Spin

Prague 2015, June 28

Bundesministerium für Bildung und Forschung

COmmon Muon and Proton Apparatus for Structure and Spectroscopy

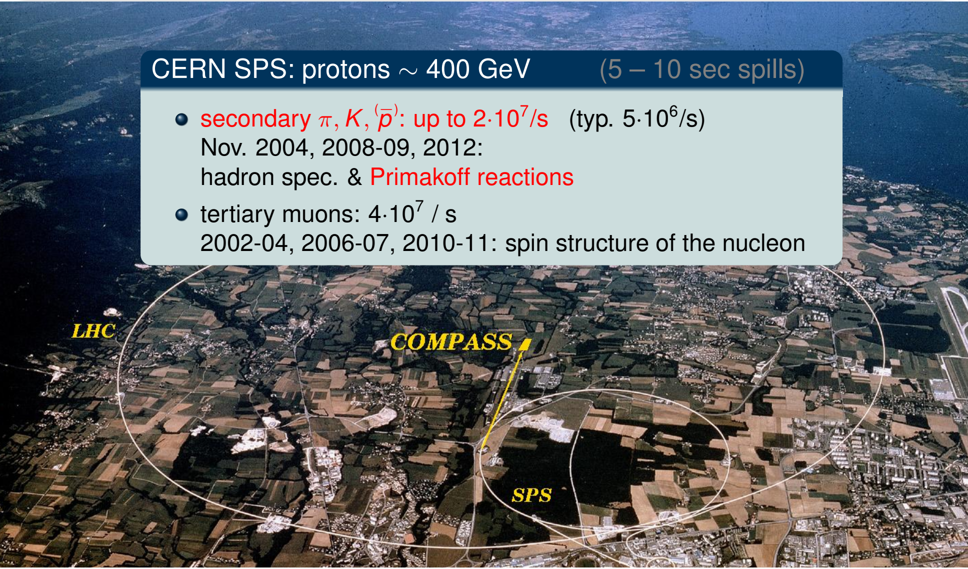
Technische Universität München

COmmon Muon and Proton Apparatus for Structure and Spectroscopy

Technische Universität München

CERN SPS: protons ~ 400 GeV (5 – 10 sec spills)

- secondary $\pi, K, \overset{(-)}{p}$: up to $2{\cdot}10^7$/s (typ. $5{\cdot}10^6$/s)
  Nov. 2004, 2008-09, 2012:
  hadron spec. & Primakoff reactions
- tertiary muons: $4{\cdot}10^7$ / s
  2002-04, 2006-07, 2010-11: spin structure of the nucleon



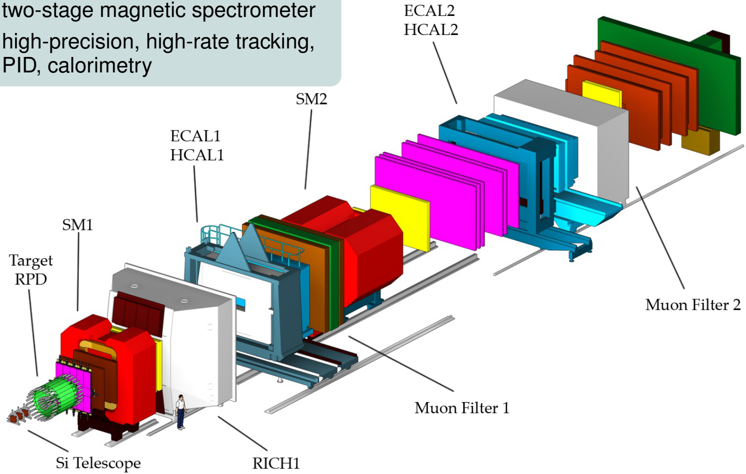
COMPASS

Technische Universität München

Experimental Setup

Fixed-target experiment

- two-stage magnetic spectrometer
- high-precision, high-rate tracking, PID, calorimetry



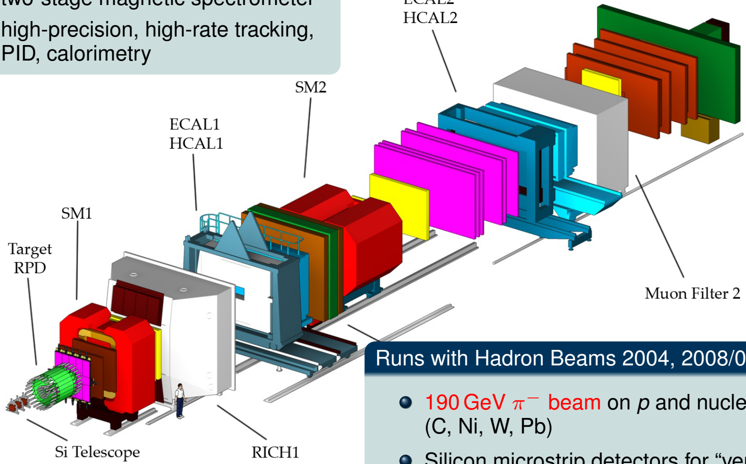
COMPASS

Technische Universität München

Experimental Setup

Fixed-target experiment

- two-stage magnetic spectrometer
- high-precision, high-rate tracking, PID, calorimetry

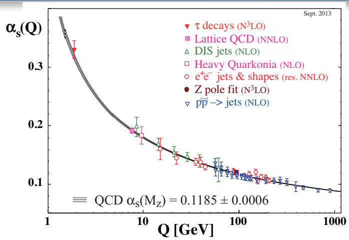


Runs with Hadron Beams 2004, 2008/09, 2012

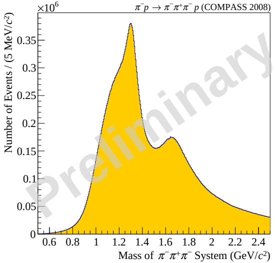
- 190 GeV π^- beam on p and nuclear targets (C, Ni, W, Pb)
- Silicon microstrip detectors for “vertexing”
- recoil and (digital) ECAL triggers

Physics fields at COMPASS

- lepton scattering at high Q^2
  $\rightarrow$ partonic structure of the nucleons
- since 2012: exclusive hard processes (DVCS, HEMP) for GPD, pol. Drell-Yan



from: PDG, S. Bethke et al.



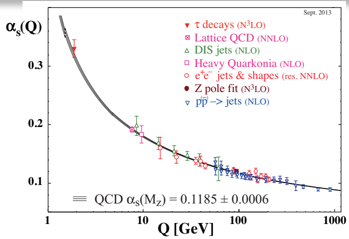
- diffractive dissociation of pions and kaons into multi-meson final states
  $\rightarrow$ meson spectrometry

- scattering of pions (and kaons) in nuclear Coulomb field
  $\rightarrow$ low-energetic meson-photon reactions
  $\pi\gamma \rightarrow \pi\gamma$ (pion polarisability), $\pi\gamma \rightarrow 3\pi$ (chiral dynamics, radiative couplings)

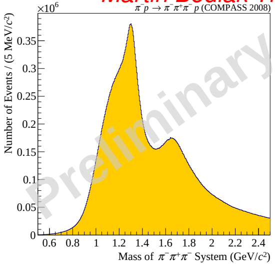
Physics fields at COMPASS

Technische Universität München

GPD's: *Oleg Kouznetsov tomorrow*
transverse spin: *Anna Martin tomorrow,*
Jan Matousek Thursday
pol. DY: *Riccardo Longo yesterday*
pol. DY target: *Michael Pesek tomorrow*
new DAQ: *Josef Novy tomorrow,*
Martin Bodlak Thursday



from: PDG, S. Bethke et al.

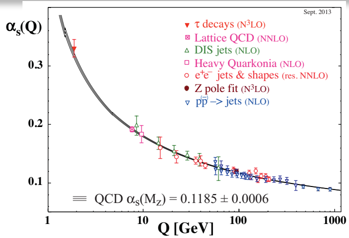


- diffractive dissociation of pions and kaons into multi-meson final states
  $\rightarrow$ meson spectrometry

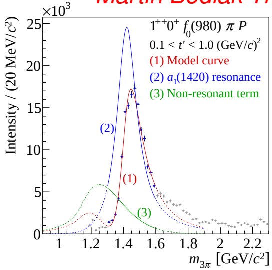
- scattering of pions (and kaons) in nuclear Coulomb field
  $\rightarrow$ low-energetic meson-photon reactions
  $\pi\gamma \rightarrow \pi\gamma$ (pion polarisability), $\pi\gamma \rightarrow 3\pi$ (chiral dynamics, radiative couplings)

Physics fields at COMPASS

GPD's: *Oleg Kouznetsov tomorrow*
transverse spin: *Anna Martin tomorrow,*
Jan Matousek Thursday
pol. DY: *Riccardo Longo yesterday*
pol. DY target: *Michael Pesek tomorrow*
new DAQ: *Josef Novy tomorrow,*
Martin Bodlak Thursday



from: PDG, S. Bethke et al.

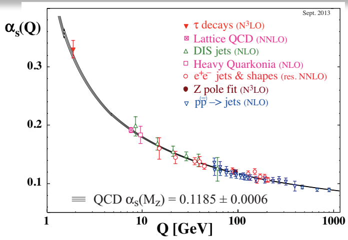


- diffractive dissociation of pions and kaons into multi-meson final states
  $\rightarrow$ meson spectrometry
  PRL on discovery of $a_1(1420)$ acc'd last week
  candidate for $s\bar{s}u\bar{d}$

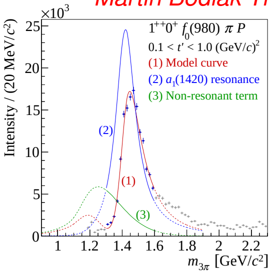
- scattering of pions (and kaons) in nuclear Coulomb field
  $\rightarrow$ low-energetic meson-photon reactions
  $\pi\gamma \rightarrow \pi\gamma$ (pion polarisability), $\pi\gamma \rightarrow 3\pi$ (chiral dynamics, radiative couplings)

Physics fields at COMPASS

GPD's: *Oleg Kouznetsov tomorrow*
transverse spin: *Anna Martin tomorrow, Jan Matousek Thursday*
pol. DY: *Riccardo Longo yesterday*
pol. DY target: *Michael Pesek tomorrow*
new DAQ: *Josef Novy tomorrow, Martin Bodlak Thursday*



from: PDG, S. Bethke et al.



- diffractive dissociation of pions and kaons into multi-meson final states
  $\rightarrow$ meson spectrometry
  PRL on discovery of $a_1(1420)$ acc'd last week
  candidate for $s\bar{s}u\bar{d}$

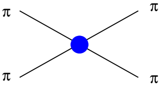
- scattering of pions (and kaons) in nuclear Coulomb field
  $\rightarrow$ low-energetic meson-photon reactions *(focus of this talk)*
  $\pi\gamma \rightarrow \pi\gamma$ (pion polarisability), $\pi\gamma \rightarrow 3\pi$ (chiral dynamics, radiative couplings)

Chiral symmetry

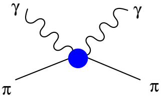
- decoupling of left- and right-handed massless quarks into $SU(N_f)_R \times SU(N_f)_L$
- hidden by spontaneous breaking
- explicit breaking by $m_q \neq 0$
- series expansion of QCD in chiral-symmetric terms
  and symmetry-breaking "perturbation"
- pion identified with the "Goldstone mode"

Quark-gluon dynamics when the interaction *is* strong

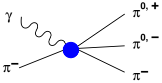
complicated system of interacting quarks and gluons $\xrightarrow{\text{ChPT}}$ effective degrees of freedom at low energy: mass, charge, spin, effective (self-)coupling



π only



$\pi-$photon

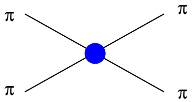


$\pi - \pi-$photon

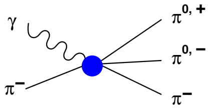
Chiral Perturbation Theory vs. Experiment

Technische Universität München

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



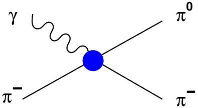
- pion scattering including a real photon
  - leading-order prediction from ChPT
    $\leftrightarrow$ pion scattering lengths
    combined with photon coupling
  - chiral loop contribution
    theory prediction available, no measurement



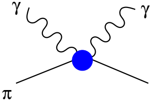
More pion-photon reactions

Technische Universität München

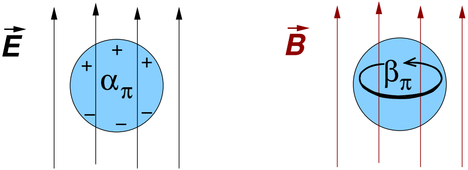
- chiral anomaly $F_{3\pi}$
  - established on 10% level
  - further development: inclusion of the ρ resonance theoretical work by Kubis, Hoferichter, Sakkas PRD86(2012)116009



- 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]
  - ChPT prediction contradicting the experimental findings (prior to our analysis)



Pion polarisability and ChPT



pion polarisabilities $\boldsymbol{\alpha_\pi}$, $\boldsymbol{\beta_\pi}$ in units of 10^{-4} fm^3

size of the pion $\sim$ 1 fm^3 [cf. atoms: polarisability $\approx$ size $\approx$ 1 Å^3]

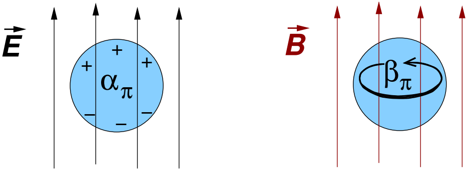
Theory: ChPT (2-loop) prediction:

$$\boldsymbol{\alpha_\pi} - \boldsymbol{\beta_\pi} = 5.7 \pm 1.0$$
$$\boldsymbol{\alpha_\pi} + \boldsymbol{\beta_\pi} = 0.16 \pm 0.1$$

experiments for $\boldsymbol{\alpha_\pi} - \boldsymbol{\beta_\pi}$ lie in the range $4 \cdots 14$

($\alpha_\pi + \beta_\pi = 0$ assumed)

Pion polarisability and ChPT



pion polarisabilities α_π, β_π in units of 10^{-4} fm^3

size of the pion $\sim$ 1 fm^3 [cf. atoms: polarisability $\approx$ size $\approx$ 1 Å^3]

Theory: ChPT (2-loop) prediction:

$$\alpha_\pi = 2.93 \pm 0.5$$
$$\beta_\pi = -2.77 \pm 0.5$$

experiments for α_π lie in the range $2 \cdots 7$

$(\alpha_\pi + \beta_\pi = 0$ assumed)

Pion Compton Scattering

$$\pi \;\gamma \;\rightarrow\; \pi\;\gamma$$

- Two kinematic variables, in CM: total energy $\sqrt{s}$, scattering angle θ_{cm}

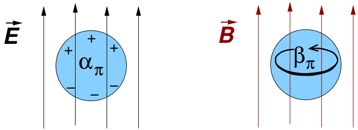
$$\frac{d\sigma_{\pi\gamma}}{d\Omega_{cm}} = \frac{\alpha^2(s^2z_+^2 + m_\pi^4 z_-^2)}{s(sz_+ + m_\pi^2 z_-)^2} - \frac{\alpha\, m_\pi^3\,(s-m_\pi^2)^2}{4s^2(sz_+ + m_\pi^2 z_-)} \cdot \mathcal{P}$$

$$\mathcal{P} = z_-^2(\alpha_\pi - \beta_\pi) + \frac{s^2}{m_\pi^4} z_+^2(\alpha_\pi + \beta_\pi) - \frac{(s-m_\pi^2)^2}{24s} z_-^3(\alpha_2 - \beta_2)$$

$$z_\pm = 1 \pm \cos\theta_{cm}$$

Pion Compton Scattering

$$\pi \quad \gamma \quad \rightarrow \quad \pi \quad \gamma$$



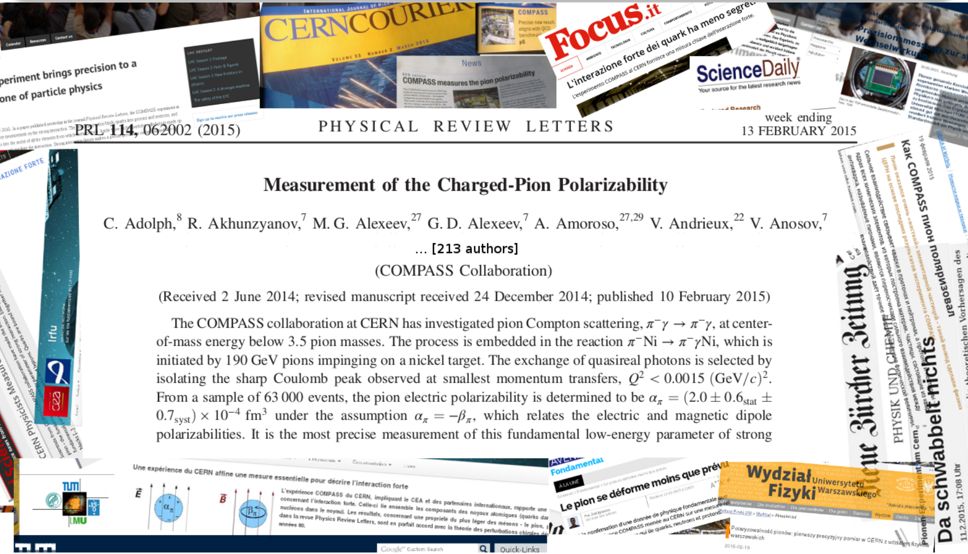
- Two kinematic variables, in CM: total energy $\sqrt{s}$, scattering angle θ_{cm}

$$\frac{d\sigma_{\pi\gamma}}{d\Omega_{cm}} = \frac{\alpha^2(s^2 z_+^2 + m_\pi^4 z_-^2)}{s(sz_+ + m_\pi^2 z_-)^2} - \frac{\alpha\, m_\pi^3\,(s - m_\pi^2)^2}{4s^2(sz_+ + m_\pi^2 z_-)} \cdot \mathcal{P}$$

$$\mathcal{P} = z_-^2(\alpha_\pi - \beta_\pi) + \frac{s^2}{m_\pi^4} z_+^2(\alpha_\pi + \beta_\pi) - \frac{(s - m_\pi^2)^2}{24s} z_-^3(\alpha_2 - \beta_2)$$

$$z_\pm = 1 \pm \cos\theta_{cm}$$

latest publication on the pion polarisability



PRL 114, 062002 (2015) PHYSICAL REVIEW LETTERS week ending 13 FEBRUARY 2015

Measurement of the Charged-Pion Polarizability

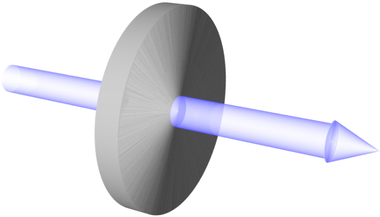
C. Adolph,[8] R. Akhunzyanov,[7] M. G. Alexeev,[27] G. D. Alexeev,[7] A. Amoroso,[27,29] V. Andrieux,[22] V. Anosov,[7]
... [213 authors]
(COMPASS Collaboration)

(Received 2 June 2014; revised manuscript received 24 December 2014; published 10 February 2015)

The COMPASS collaboration at CERN has investigated pion Compton scattering, $\pi^-\gamma \to \pi^-\gamma$, at center-of-mass energy below 3.5 pion masses. The process is embedded in the reaction $\pi^-\mathrm{Ni} \to \pi^-\gamma\mathrm{Ni}$, which is initiated by 190 GeV pions impinging on a nickel target. The exchange of quasireal photons is selected by isolating the sharp Coulomb peak observed at smallest momentum transfers, $Q^2 < 0.0015\ (\mathrm{GeV}/c)^2$. From a sample of 63 000 events, the pion electric polarizability is determined to be $\alpha_\pi = (2.0 \pm 0.6_{\mathrm{stat}} \pm 0.7_{\mathrm{syst}}) \times 10^{-4}\ \mathrm{fm}^3$ under the assumption $\alpha_\pi = -\beta_\pi$, which relates the electric and magnetic dipole polarizabilities. It is the most precise measurement of this fundamental low-energy parameter of strong

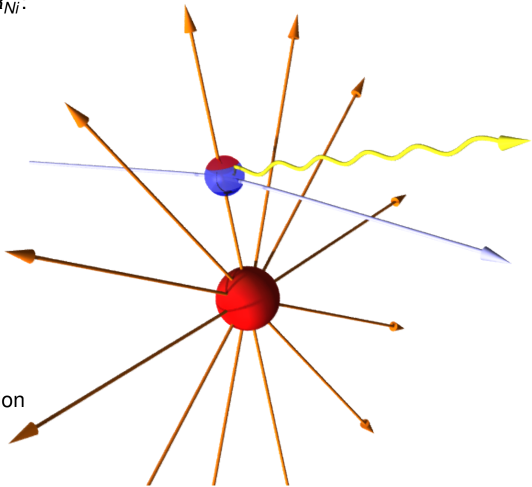
Principle of the COMPASS measurement

- high-energetic pion beam on 4mm nickel disk
- observe scattered pions in coincidence with produced hard photons
- study of cross-section shape



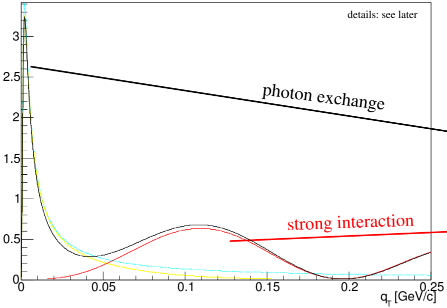
Polarisability effect in Primakoff technique

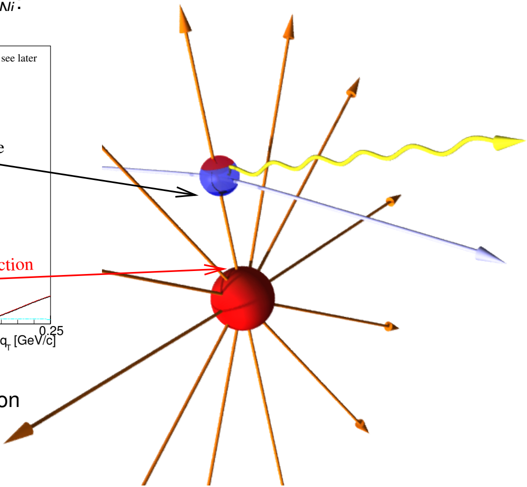
- Charged pions traverse the nuclear electric field
  - typical field strength at $d = 5R_{Ni}$: $E \approx 300\,\text{kV/fm}$
- Bremsstrahlung process:
  - particles scatter off *equivalent photons*
  - tiny momentum transfer $Q^2 \approx 10^{-5}\,\text{GeV}^2/c^2$
  - pion/muon (quasi-)real Compton scattering
- Polarisability contribution
  - Compton cross-section typically diminished
  - corresponding charge separation $\approx 10^{-5}\,\text{fm} \cdot e$



Polarisability effect in Primakoff technique

- Charged pions traverse the nuclear electric field
  - typical field strength at $d = 5R_{Ni}$:

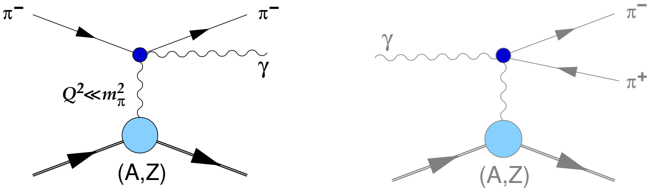




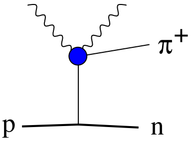
typically diminished

  - corresponding charge separation $\approx 10^{-5}$ fm $\cdot\, e$

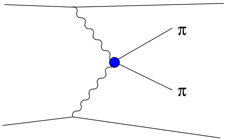
Pion Compton scattering: embedding the process



Primakoff processes

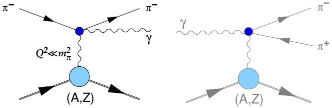


Radiative pion photoproduction

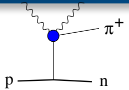


Photon-Photon fusion

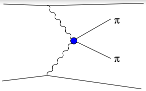
Pion polarisability: world data before COMPASS



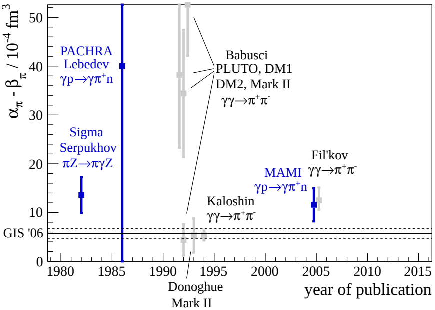
Primakoff processes



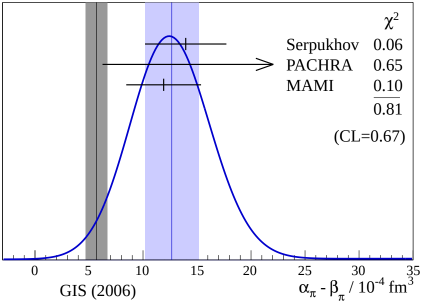
Radiative pion photoproduction



Photon-Photon fusion



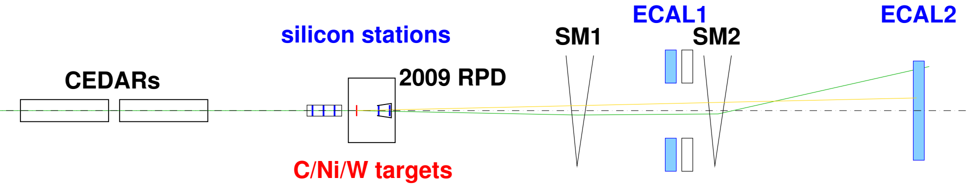
world avg.: 12.7 ± 2.5



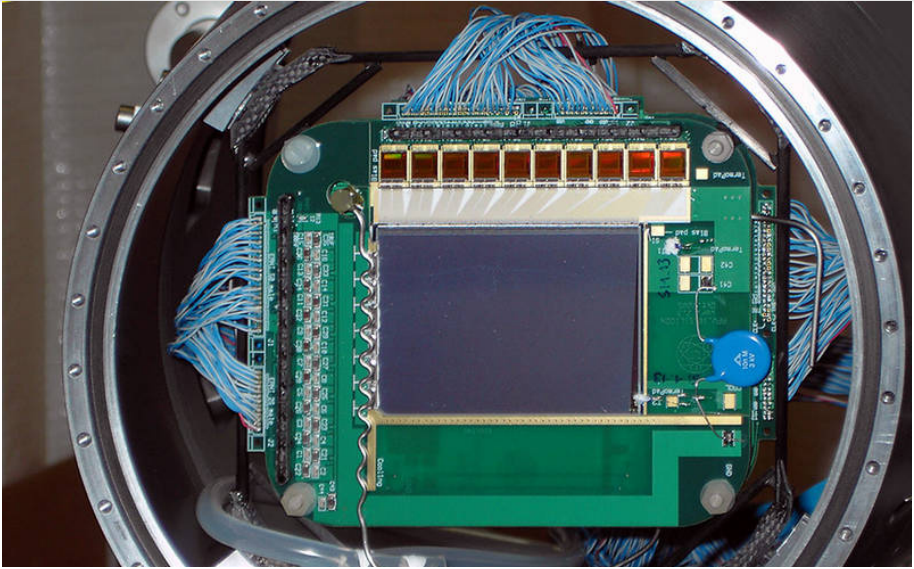
GIS'06: ChPT prediction, Gasser, Ivanov, Sainio, NPB745 (2006), plots: T. Nagel, PhD

Fil'kov analysis objected by Pasquini, Drechsel, Scherer PRC81, 029802 (2010)

Principle of the measurement

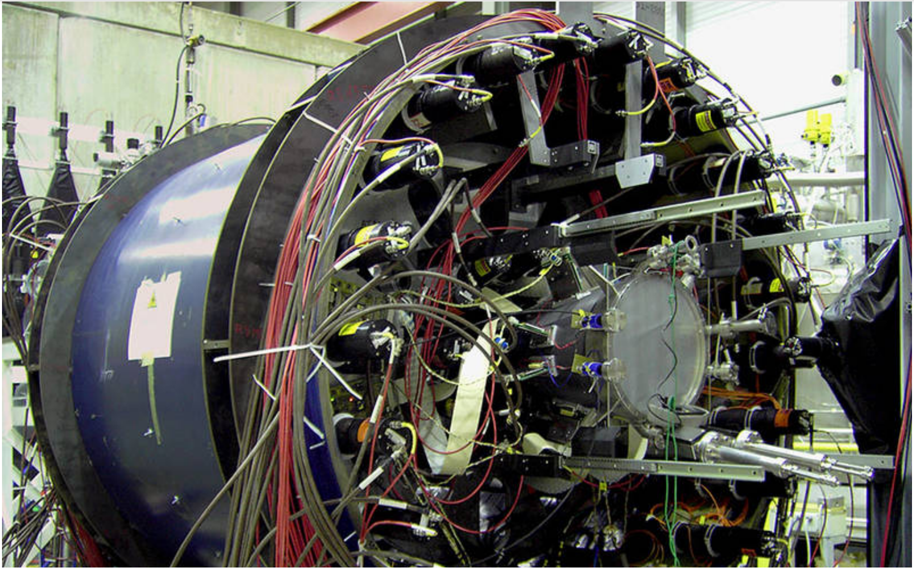


Silicon detector module, two-sided $\sigma_{x,y} \sim 5\mu m$



Silicon cryostat in the recoil detector

Technische Universität München



Extraction of the pion polarisability

- Identify exclusive reactions

$$\pi\gamma_{\{\mathrm{Ni}\to\mathrm{Ni}'\}} \to \pi\gamma$$

  at smallest momentum transfer $< 0.001\ \mathrm{GeV}^2/c^2$

- Assuming $\alpha_\pi + \beta_\pi = 0$, from the cross-section

$$R = \frac{\sigma(x_\gamma)}{\sigma_{\alpha_\pi=0}(x_\gamma)} = \frac{N_{meas}(x_\gamma)}{N_{sim}(x_\gamma)} = 1 - \frac{3}{2} \cdot \frac{m_\pi^3}{\alpha} \cdot \frac{x_\gamma^2}{1-x_\gamma}\, \alpha_\pi$$

  is derived, depending on $x_\gamma = E_{\gamma(lab)}/E_{Beam}$.
  Measuring R the polarisability α_π can be concluded.

- Control systematics by

$$\mu\gamma_{\{\mathrm{Ni}\to\mathrm{Ni}'\}} \to \mu\gamma$$

  and

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

Extraction of the pion polarisability

- Identify exclusive reactions

$$\pi\gamma_{\{\mathrm{Ni}\to\mathrm{Ni}'\}} \to \pi\gamma$$

at smallest momentum transfer $< 0.001\ \mathrm{GeV}^2/c^2$

- Assuming $\alpha_\pi + \beta_\pi = 0$, from the cross-section

$$R = \frac{\sigma(x_\gamma)}{\sigma_{\alpha_\pi=0}(x_\gamma)} = \frac{N_{meas}(x_\gamma)}{N_{sim}(x_\gamma)} = 1 - \frac{3}{2}\cdot\frac{m_\pi^3}{\alpha}\cdot\frac{x_\gamma^2}{1-x_\gamma}\,\alpha_\pi$$

is derived, depending on $x_\gamma = E_{\gamma(lab)}/E_{Beam}$.
Measuring R the polarisability α_π can be concluded.

- Control systematics by

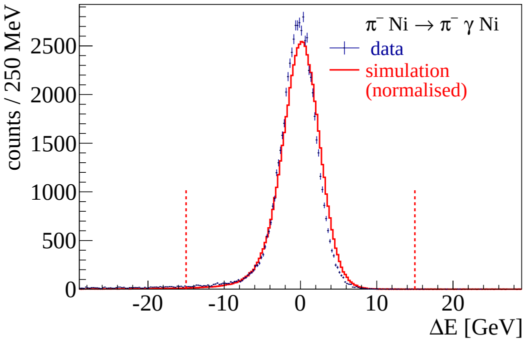
$$\mu\gamma_{\{\mathrm{Ni}\to\mathrm{Ni}'\}} \to \mu\gamma$$

and

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

Identifying the $\pi\gamma \rightarrow \pi\gamma$ reaction

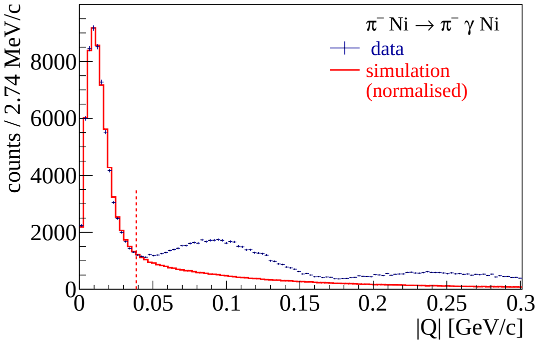
Phys. Rev. Lett. 114, 062002 (2015)



- Energy balance $\Delta E = E_\pi + E_\gamma - E_{\text{Beam}}$
- Exclusivity peak $\sigma \approx$ 2.6 GeV (1.4%)
- $\sim$ 63.000 exclusive events ($x_\gamma > 0.4$) (Serpukhov $\sim$ 7000 for $x_\gamma > 0.5$)

Primakoff peak

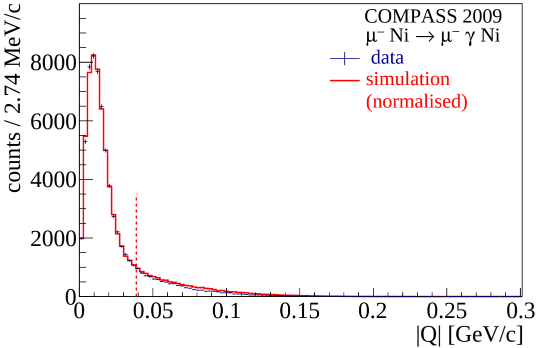
Phys. Rev. Lett. 114, 062002 (2015)



- $\Delta Q_T \approx 12$ MeV/c (190 GeV/c beam → requires few-μrad angular resolution)
- first diffractive minimum on Ni nucleus at $Q \approx 190$ MeV$/c$
- data a little more narrow than simulation → negative interference?

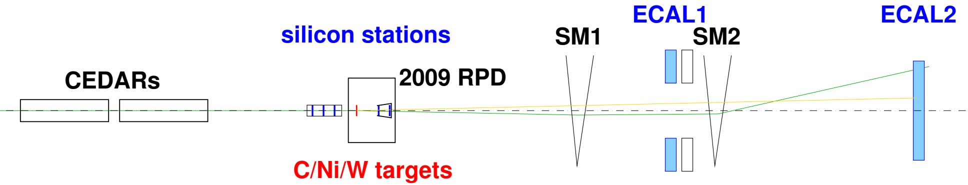
Primakoff peak: muon data

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



- muon control measurement: pure electromagnetic interaction
- e.m. nuclear effects well understood

Principle of the measurement



ECAL2: 3000 cells of different types

Technische Universität München

ECAL2: the quest for precision

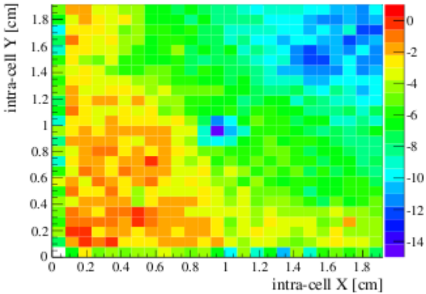


Figure 3.5: Profile of energy deviations shown for 1/4 of a shashlik block and for muon data photons within the range 133 GeV < E_γ < 152 GeV .

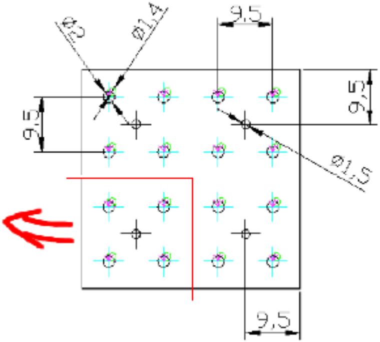
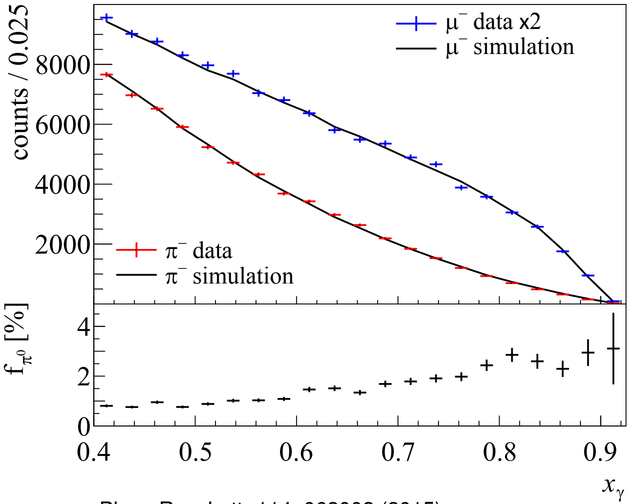


Figure 3.6: Technical drawing of a full shashlik cell to be compared with the figure to the left.

from: Th. Nagel, PhD thesis TUM 2012

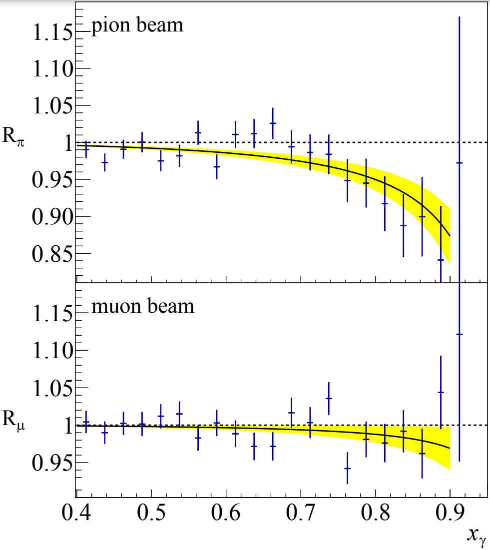
Photon energy spectra for muon and pion beam

Technische Universität München



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

Pion polarisability: COMPASS result



$$\boldsymbol{\alpha_\pi} = (\,2.0 \pm 0.6_{\text{stat}}\,) \times 10^{-4}\,\text{fm}^3$$

(assuming $\alpha_\pi = -\beta_\pi$)

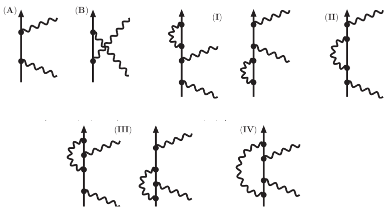
“false polarisability” from muon data:

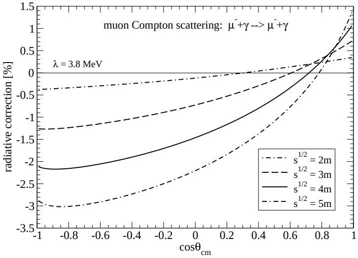
$$(\,0.5 \pm 0.5_{\text{stat}}\,) \times 10^{-4}\,\text{fm}^3$$

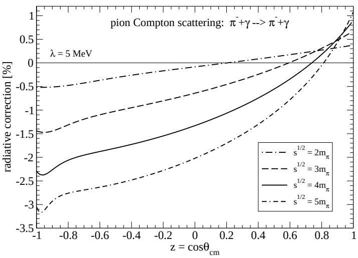
Phys. Rev. Lett. 114, 062002 (2015)

Radiative corrections (Compton scattering part)

Technische Universität München







Nucl.Phys. A837 (2010)   Eur.Phys.J. A39 (2009) 71

source of systematic uncertainty	estimated magnitude CL = 68 % [10^{-4} fm^3]
determination of tracking-detector efficiencies	0.5
treatment of radiative corrections	0.3
subtraction of π^0 background	0.2
strong interaction background	0.2
pion-electron elastic scattering	0.2
contribution of muons in the beam	0.05
quadratic sum	0.7

source of systematic uncertainty	estimated magnitude CL = 68 % $[10^{-4}\,\text{fm}^3]$
determination of tracking-detector efficiencies	0.5
treatment of radiative corrections	0.3
subtraction of π^0 background	0.2
strong interaction background	0.2
pion-electron elastic scattering	0.2
contribution of muons in the beam	0.05
quadratic sum	0.7

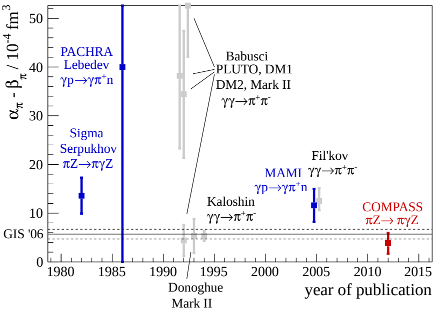
COMPASS result for the pion polarisability:

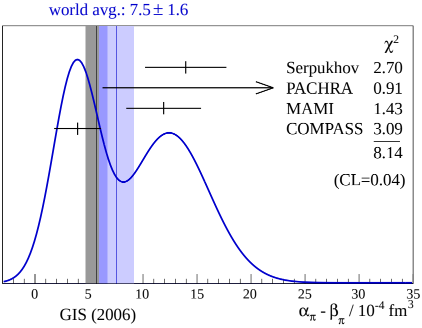
$$\alpha_\pi = (2.0 \pm 0.6_{\text{stat}} \pm 0.7_{\text{syst}}) \times 10^{-4}\,\text{fm}^3$$

with $\alpha_\pi = -\beta_\pi$ assumed

Pion polarisability: world data including COMPASS

Technische Universität München





- The new COMPASS result is in significant tension with the earlier measurements of the pion polarisability
- The expectation from ChPT is confirmed within the uncertainties

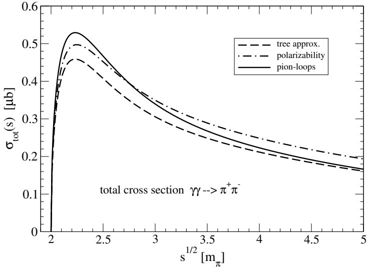
Photon-photon fusion process $\gamma\gamma \to \pi^+\pi^-$

Technische Universität München

- Planned measurements at ALICE and JLab

$$\sigma_{tot}(s) = \frac{2\pi\alpha^2}{\hat{s}^3 m_\pi^2}\Big\{\left[4+\hat{s}+\hat{s}|C(\hat{s})|^2\right]\sqrt{\hat{s}(\hat{s}-4)} + 8\left[2-\hat{s}+\hat{s}\,\mathrm{Re}\,C(\hat{s})\right]\ln\frac{\sqrt{\hat{s}}+\sqrt{\hat{s}-4}}{2}\Big\},$$

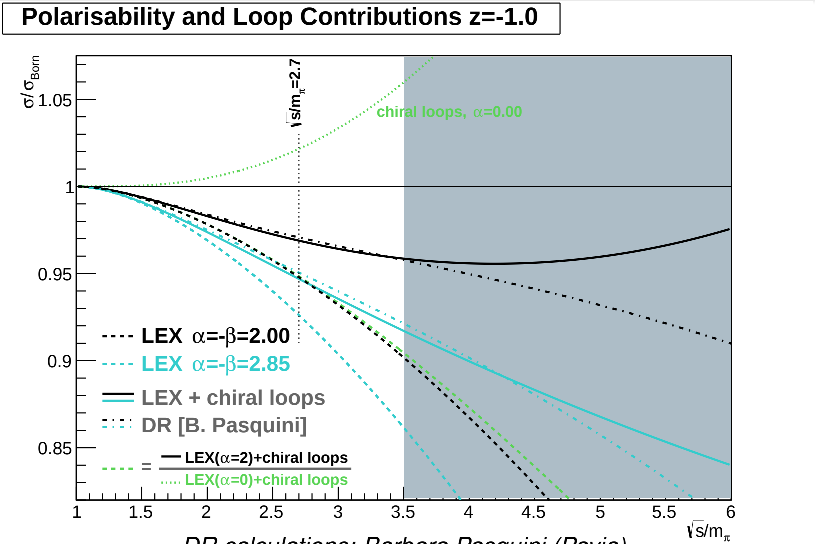
$$C(\hat{s}) = -\beta_\pi \frac{m_\pi^3}{2\alpha}\hat{s} - \frac{m_\pi^2}{(4\pi f_\pi)^2}\left\{\frac{\hat{s}}{2} + 2\left[\ln\frac{\sqrt{\hat{s}}+\sqrt{\hat{s}-4}}{2} - \frac{i\pi}{2}\right]^2\right\}$$



courtesy Norbert Kaiser (TUM)

limited sensitivity to the polarisability contribution

Dispersion relations and ChPT



DR calculations: Barbara Pasquini (Pavia)

Pion polarisability on the lattice

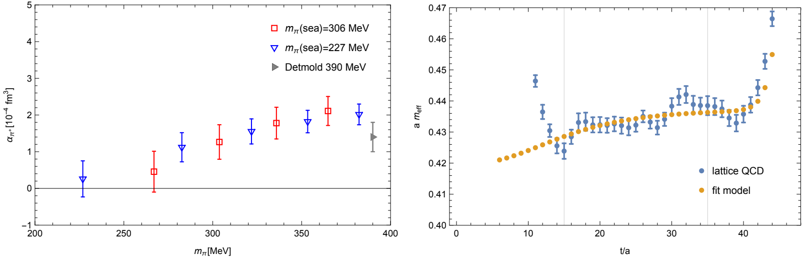


FIGURE 3. Left: electric polarizability for the charged pions as a function of the valence quark mass. The data for $m_\pi = 390\,\text{MeV}$ is taken from [5]. Right: effective mass for a charged pion correlator together with the scalar particle correlator determined from the fit. The fitting range is indicated by the vertical bars.

Alexandru *et al.*, Pion electric polarizability from lattice QCD, arXiv:1501.06516

Primakoff reactions accessible at COMPASS

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

chiral anomaly, delayed

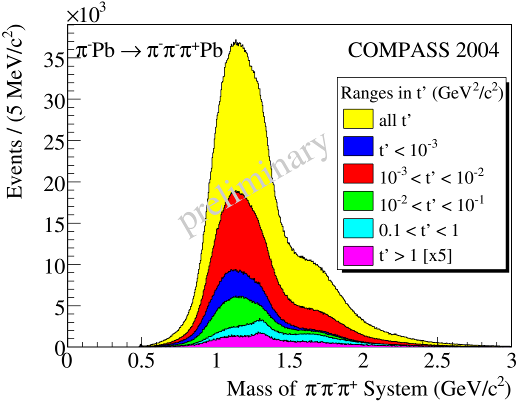
$\Longleftarrow$ ($\pi^- + \pi^0 + \pi^0$)

$\Longleftarrow$ ($\pi^- + \pi^- + \pi^+$)

analogous: Kaon-induced reactions $K^- + \gamma \to \cdots$

2004 Primakoff results

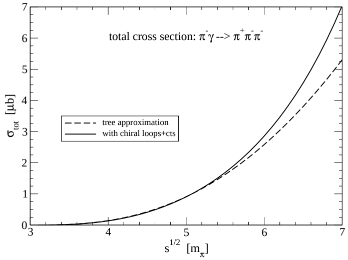
π^- Pb $\to$ Pb $\pi^-\ \pi^-\ \pi^+$

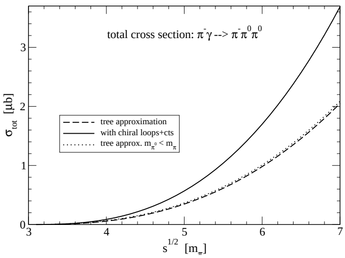


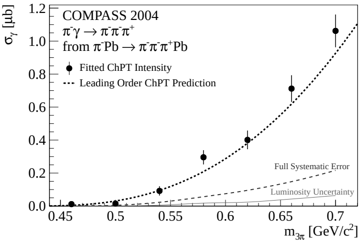
- "Low t'": $10^{-3}\,(\text{GeV}/c)^2 < t' < 10^{-2}\,(\text{GeV}/c)^2$ $\sim$ 2 000 000 events
- "Primakoff region": $t' < 10^{-3}\,(\text{GeV}/c)^2$ $\sim$ 1 000 000 events

Chiral dynamics in $\pi\gamma \to 3\pi$

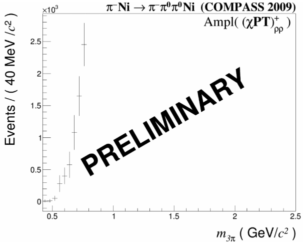
Technische Universität München







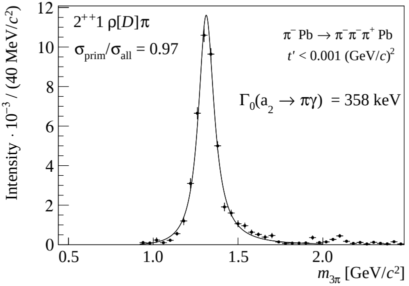
published in PRL 108 (2012) 192001



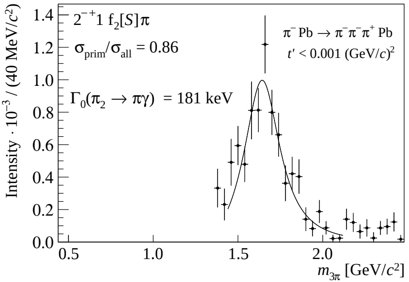
normalization: analysis ongoing

Radiative Coupling of $a_2(1320)$ and $\pi_2(1670)$

Technische Universität München



$\Gamma_0(a_2(1320) \to \pi\gamma)$ *M2*



$\Gamma_0(\pi_2(1670) \to \pi\gamma)$ *E2*

- radiative width for $a_2(1320)$: 358±6±42 keV larger than PDG value (287±30 keV)
- first measurement for $\pi_2(1670)$

published in EPJ A50 (2014) 79

Summary and Outlook

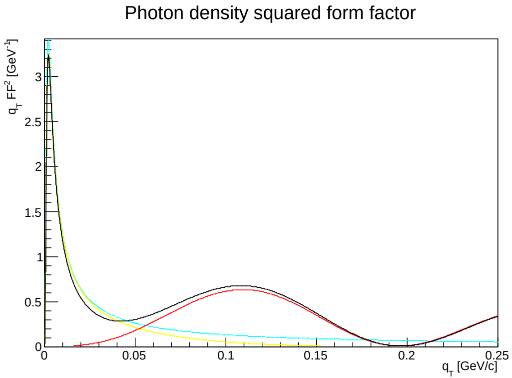
- COMPASS pursues a broad program in the field of strong interaction: partonic structure, hadron spectroscopy, precision measurements to test EFT
- Measurement of the pion polarisability at COMPASS
  - Via the Primakoff reaction, COMPASS has determined

$$\boxed{\alpha_\pi = (\,2.0 \pm 0.6_{\text{stat}} \pm 0.7_{\text{syst}}\,) \times 10^{-4}\,\text{fm}^3} \quad \text{assuming } \alpha_\pi + \beta_\pi = 0$$

  - most direct access to the $\pi\gamma \to \pi\gamma$ process
  - Most precise experimental determination
  - Systematic control: $\mu\gamma \to \mu\gamma,\ K^- \to \pi^-\pi^0$
- COMPASS measures more aspectes of chiral dynamics in $\pi^-\gamma \to \pi^-\pi^0$ and $\pi\gamma \to \pi\pi\pi$ reactions
- High-statistics run 2012
  - separate determination of α_π and β_π
  - $s-$dependent quadrupole polarisabilities
  - First measurement of the kaon polarisability

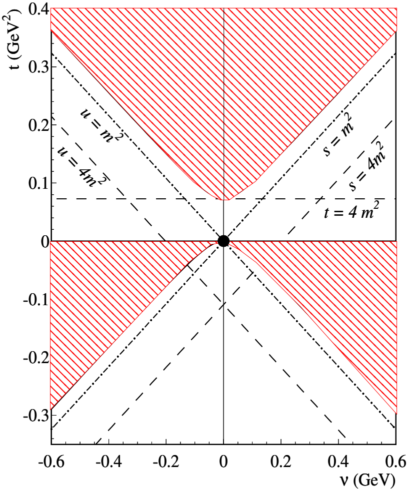
Thank you for your attention!

Coulomb-nuclear interference



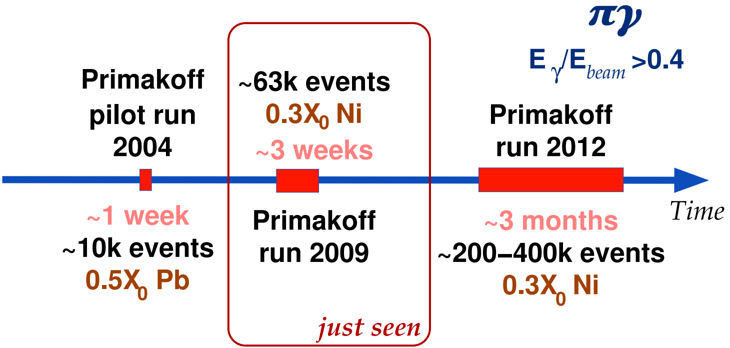
- calculation following G. Fäldt (Phys. Rev. C79, 014607)
- eikonal approximation: pions traverse Coulomb and strong-interaction potentials

About crossing



from: D. Drechsel, talk at IWHSS 2011 Paris

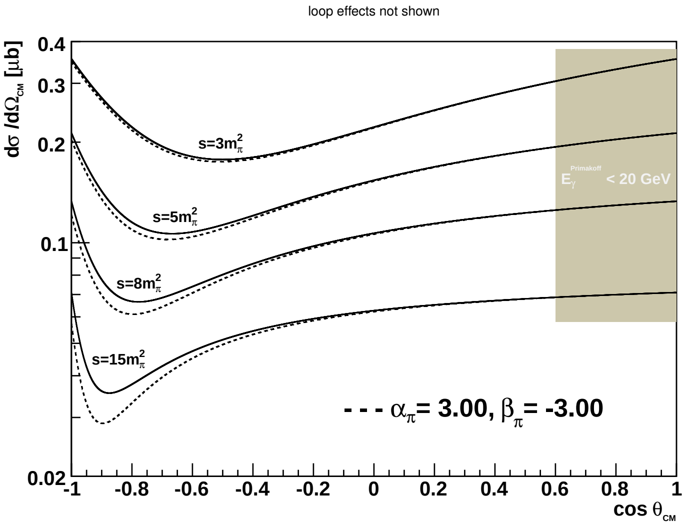
- red hatched: physical regions
  $\gamma + \gamma \to \pi + \pi$
  $\gamma + \pi \to \gamma + \pi$
- two-pion thresholds at $s = 4m_\pi^2$, $u = 4m_\pi^2$, $t = 4m_\pi^2$
- DR integration paths
  $t = 0$ (forward),
  $\theta = 180°$ (backward)
  $u = m_\pi^2$, $s = m_\pi^2$, ...



$$\mathcal{P} = z_-^2(\alpha_\pi - \beta_\pi) + \frac{s^2}{m_\pi^4} z_+^2(\alpha_\pi + \beta_\pi) - \frac{(s - m_\pi^2)^2}{24s} z_-^3(\alpha_2 - \beta_2)$$

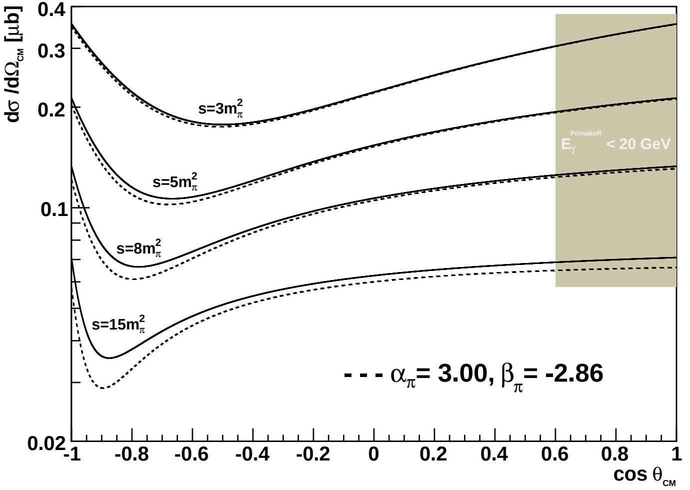
$$z_\pm = 1 \pm \cos\theta_{cm}$$

Polarisability effect (LO ChPT values)



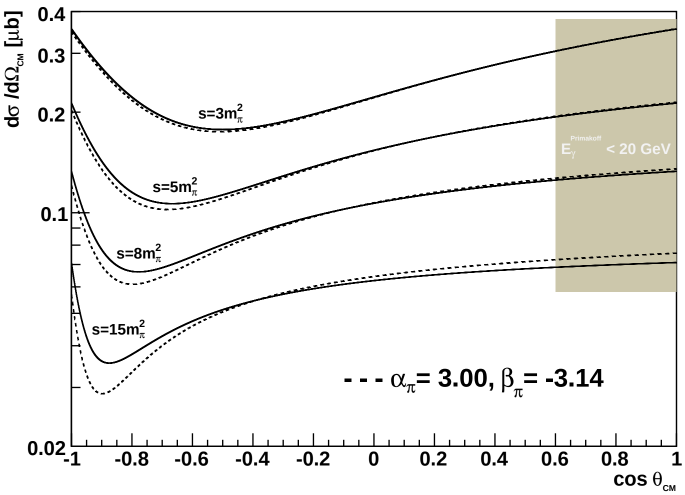
Polarisability effect (NLO ChPT values)

loop effects not shown

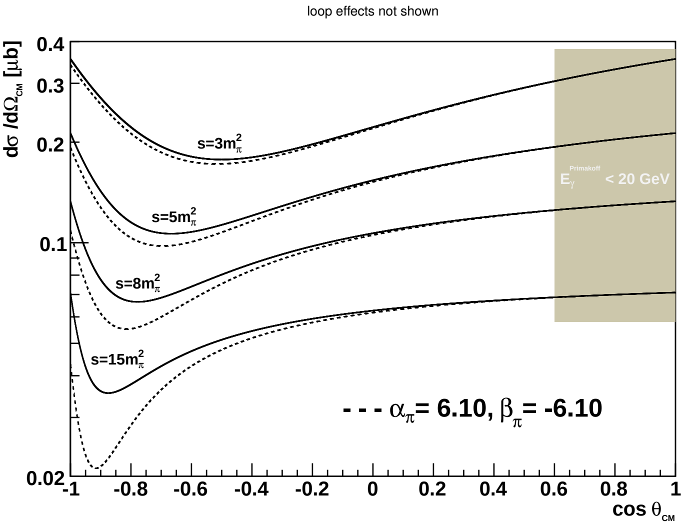


Polarisability effect with “wrong-sign” $\alpha_\pi + \beta_\pi < 0$

loop effects not shown



Polarisability effect (Serpukhov values)



- Radiative π^+ production on the proton:

$$\gamma\,\pi^{*} \longrightarrow \pi\,\gamma \qquad [\text{via } \gamma\, p \to n\,\pi^+\,\gamma]$$

Mainz (2005) measurement: $\alpha_\pi - \beta_\pi = 11.6 \pm 1.5 \pm 3.0 \pm 0.5$

"± 0.5": model error *only within the used ansatz*,

full systematics not under control

- Primakoff Compton reaction:

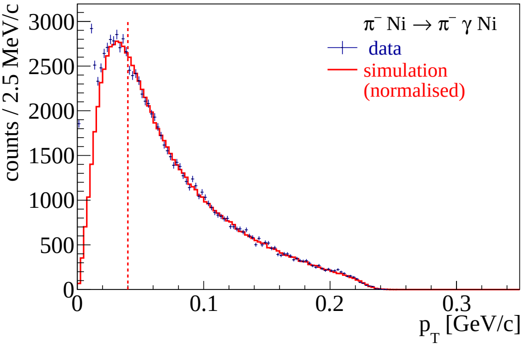
$$\gamma^{*}\,\pi \longrightarrow \pi\,\gamma \qquad [\text{via } \pi\, Z \to Z\,\pi\,\gamma]$$

tiny extrapolation $\gamma^* \to \gamma$ $\mathcal{O}(10^{-3} m_\pi^2)$

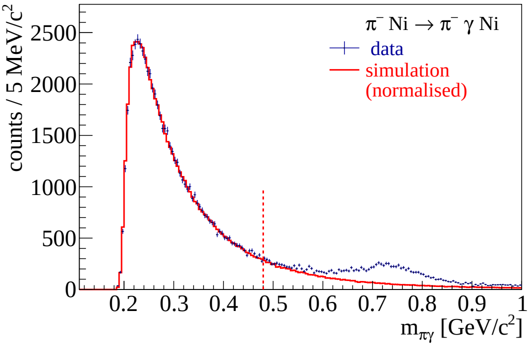
fully under theoretical control

[N. Kaiser, J.F., Nucl. Phys. A 812 (2008) 186]

Minimum transverse momentum of the charged particle

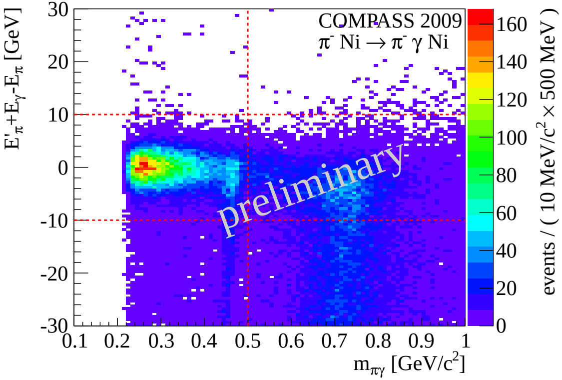


CM energy in $\pi\gamma \to \pi\gamma$



- ρ contribution from $\pi\gamma \to \pi\pi^0$

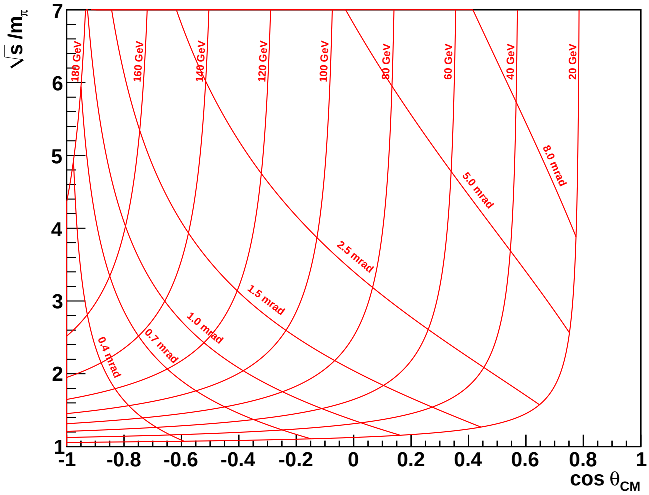
Exclusivity vs. $\sqrt{s}$



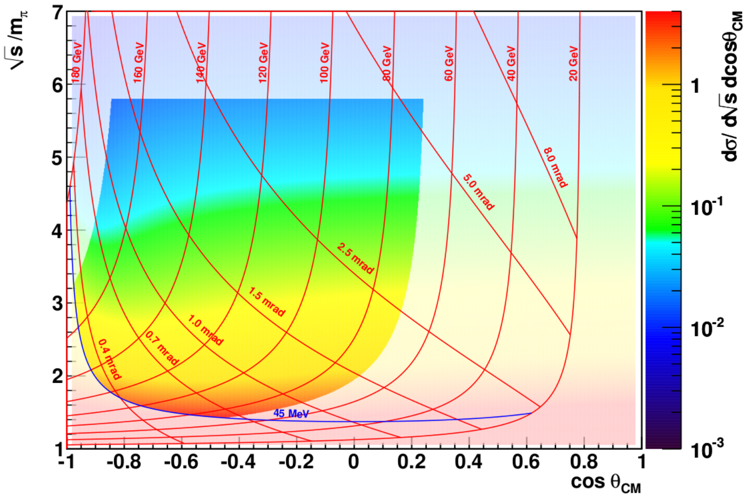
- ρ contribution from $\pi\gamma \to \pi\pi^0$

Mandelstam $\{s,t\} \leftrightarrow$ Laboratory $\{E_\gamma, \theta_\gamma\}$

for $\pi\gamma \to \pi\gamma$



Cross section

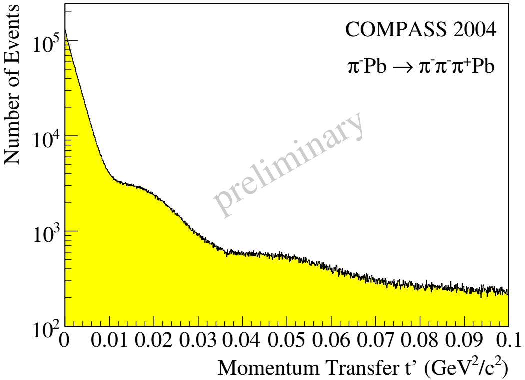


M.R. Pennington in the 2nd DAΦNE Physics Handbook,
"What we learn by measuring $\gamma\gamma \to \pi\pi$ at DAΦNE":

> All this means that the only way to measure the pion polarisabilities is in the Compton scattering process near threshold and not in $\gamma\gamma \to \pi\pi$. Though the low energy $\gamma\gamma \to \pi\pi$ scattering is seemingly close to the Compton threshold (...) and so the *extrapolation* not very far, the dominance of the pion pole (...) means that the energy scale for this continuation is m_π. Thus the polarisabilities cannot be determined accurately from $\gamma\gamma$ experiments in a model-independent way and must be measured in the Compton scattering region.

2004 Primakoff results

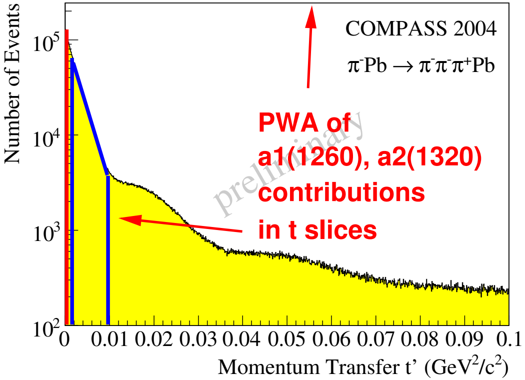
$\pi^- \text{ Pb} \rightarrow \text{Pb } \pi^- \ \pi^- \ \pi^+$



- "Low t'": $10^{-3}\,(\text{GeV}/c)^2 < t' < 10^{-2}\,(\text{GeV}/c)^2$ $\sim$ 2 000 000 events
- "Primakoff region": $t' < 10^{-3}\,(\text{GeV}/c)^2$ $\sim$ 1 000 000 events

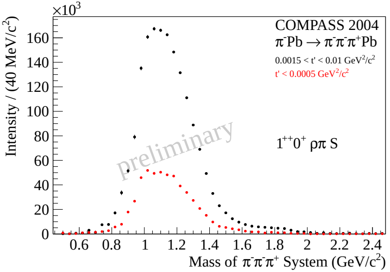
2004 Primakoff results

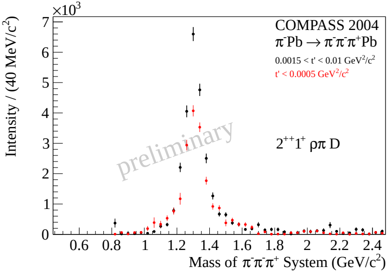
$$\pi^- \, \mathrm{Pb} \rightarrow \mathrm{Pb} \, \pi^- \, \pi^- \, \pi^+$$

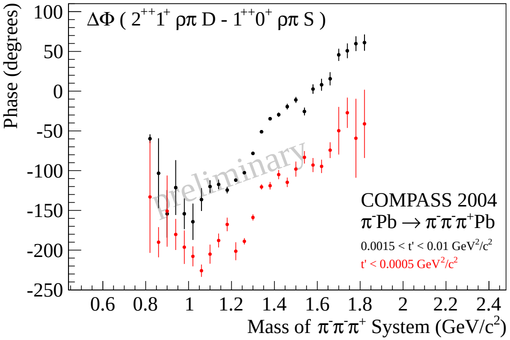


- "Low t'": $10^{-3}\,(\mathrm{GeV}/c)^2 < t' < 10^{-2}\,(\mathrm{GeV}/c)^2$ $\sim$ 2 000 000 events
- "Primakoff region": $t' < 10^{-3}\,(\mathrm{GeV}/c)^2$ $\sim$ 1 000 000 events

PWA: a_1, a_2 and $\Delta\Phi$ in separated t' regions

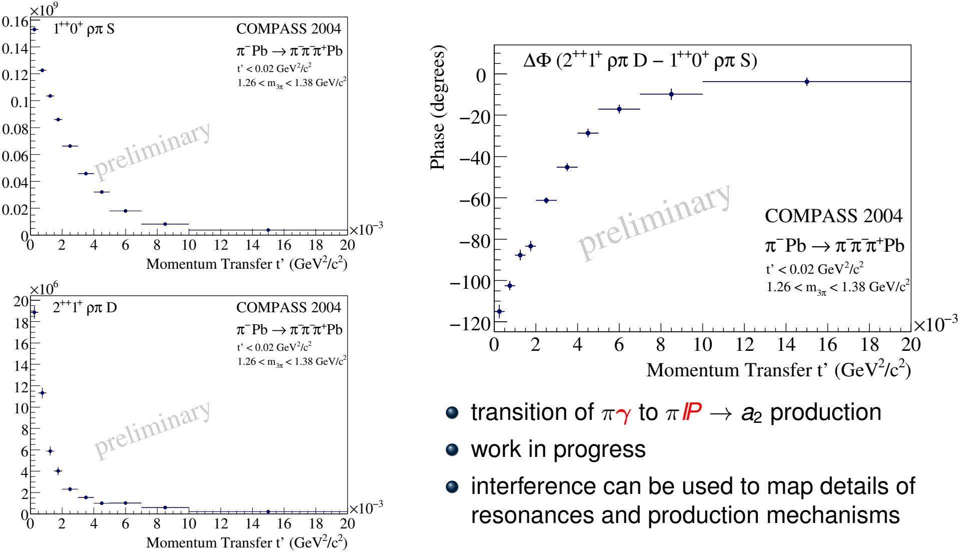






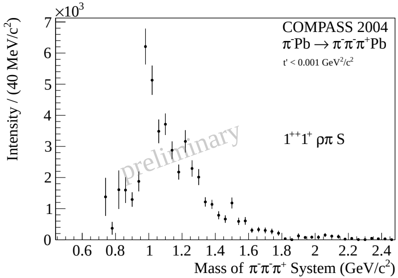
Phase $a_2 - a_1$ in detail: t' dependence

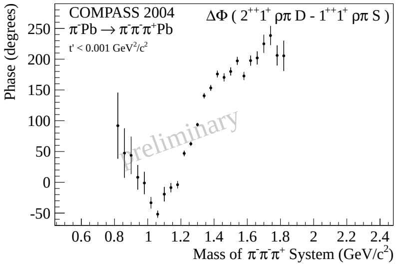
Technische Universität München

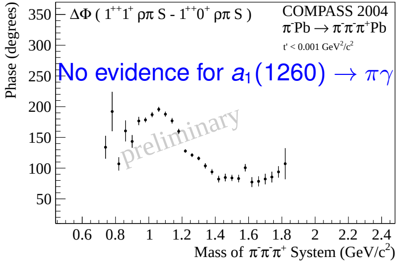


- transition of $\pi\gamma$ to $\pi I\!P \to a_2$ production
- work in progress
- interference can be used to map details of resonances and production mechanisms

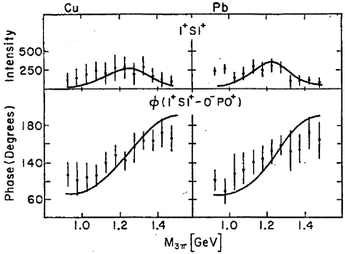
Primakoff production of a1(1260) vs. E272 result







No evidence for $a_1(1260) \to \pi\gamma$



M. Zielinski et al, Phys. Rev. Lett 52 (1984) 1195

- Mass-independent PWA (narrow mass bins):

$$\sigma_{\text{indep}}(\tau, m, t') = \sum_{\epsilon=\pm 1} \sum_{r=1}^{N_r} \left| \sum_i T_{ir}^{\epsilon} f_i^{\epsilon}(t') \psi_i^{\epsilon}(\tau, m) \Big/ \sqrt{\int |f_i^{\epsilon}(t')|^2 \mathrm{d}t'} \sqrt{\int |\psi_i^{\epsilon}(\tau', m)|^2 \mathrm{d}\tau'} \right|^2$$

  - Production strenght assumed constant in single bins
  - Decay amplitudes $\psi_i^{\epsilon}(\tau, m)$, with t' dependence $f_i^{\epsilon}(t')$
  - Production amplitudes T_{ir}^{ϵ} $\rightarrow$ Extended log-likelihood fit
  - Acceptance corrections included

- Spin-density matrix: $\rho_{ij}^{\epsilon} = \sum_r T_{ir}^{\epsilon} T_{jr}^{\epsilon *}$

$\rightarrow$ Physical parameters:

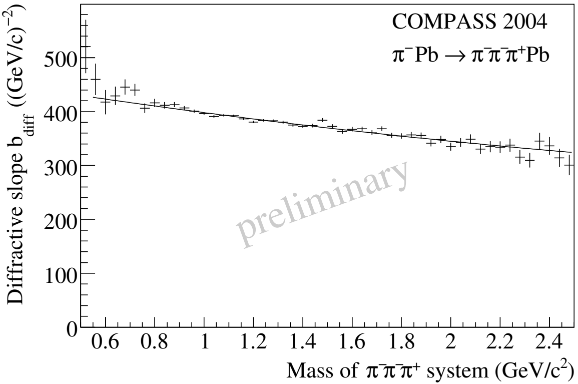
$$\text{Intens}_i^{\epsilon} = \rho_{ii}^{\epsilon},$$

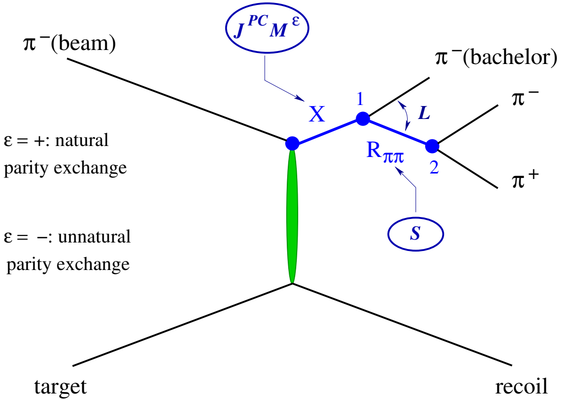
relative phase Φ_{ij}^{e}

$$\text{Coh}\;_{i,j}^{\epsilon} = \sqrt{(\text{ Re } \rho_{ij}^{\epsilon})^2 + (\text{ Im } \rho_{ij}^{\epsilon})^2} \Big/ \sqrt{\rho_{ii}^{\epsilon} \rho_{jj}^{\epsilon}}$$

- Mass-dependent χ^2-fit (not presented here):
  - X parameterized by Breit-Wigner (BW) functions
  - Background can be added

Mass dependence of the diffractive slope

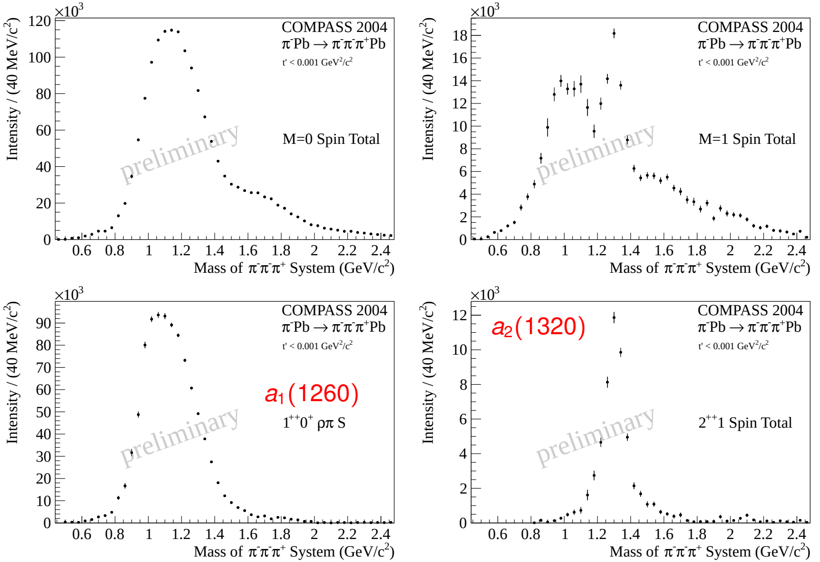




- Isobar model: Intermediate 2-particle decays
- Partial wave in reflectivity basis: $J^{PC}M^{\epsilon}[isobar]L$

- Mass-independent PWA (40 MeV/c^2 mass bins): 38 waves
  Fit of angular dependence of partial waves, interferences
- Mass-dependent χ^2-fit (Not presented here)

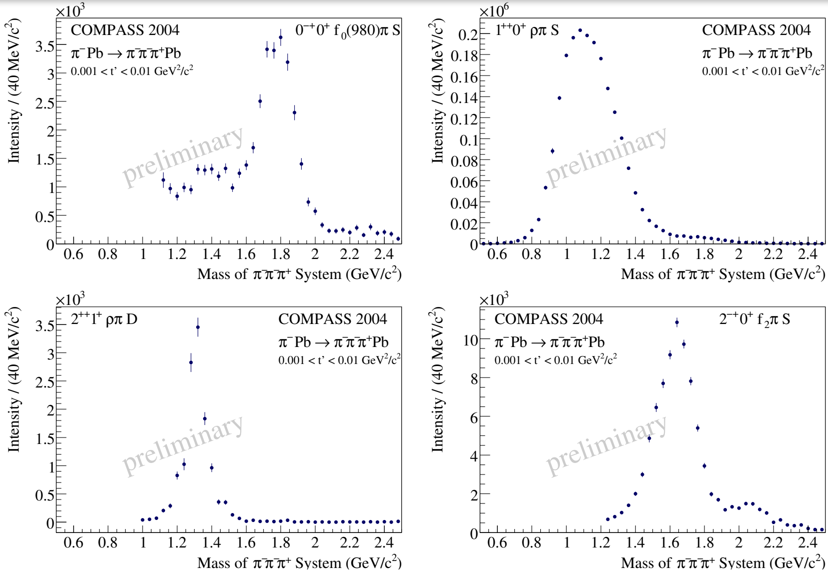
Major intensities in m(3π)-bins (acceptance corrected)



PWA of data with low t'

Technische Universität München

Intensity of selected waves: $0^{-+}0^{+} f_0(980)\pi S$, $1^{++}0^{+} \rho\pi S$, $2^{++}1^{+} \rho\pi D$, $2^{-+}0^{+} f_2(1270)\pi S$



Spin Totals for $t' < 10^{-3}$ (GeV/c)^2

Technische Universität München

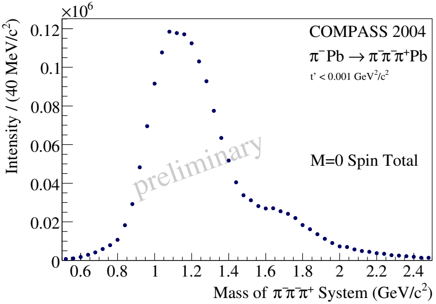
"Spin Totals": Sum of all contributions for given M (i.e. z-projection of J)

t'-dependent amplitudes:

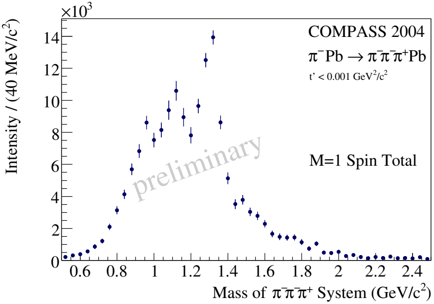
Primakoff production: M=1: $\sigma(t') \propto e^{-b_{\mathrm{Prim}} t'} \rightarrow$ arises at $t' \approx 0$ (resoluted shape!)

Diffractive production: M=0: $\sigma(t') \propto e^{-b_{\mathrm{diff}}(m) t'}$

M=1: $\sigma(t') \propto t' e^{-b_{\mathrm{diff}}(m) t'} \rightarrow$ vanishes for $t' \approx 0$

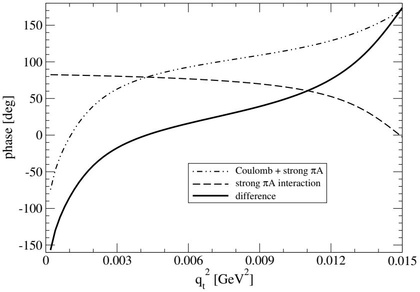


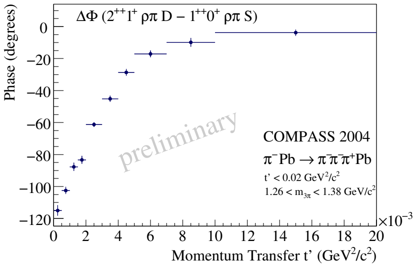
M=0



M=1

Theory: Phase a_2(strong+Coulomb)-a_1(strong)





Glauber modell

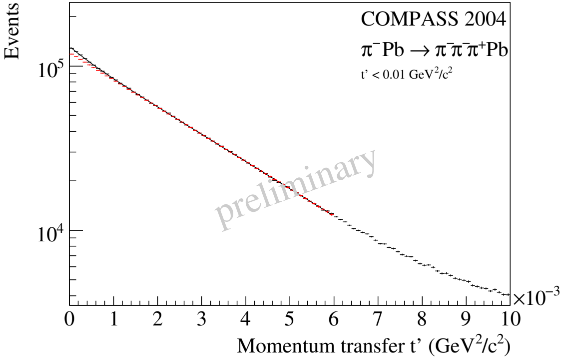
G. Fäldt and U. Tengblad, Phys. Rev. C79, 014607 (2009)

Plot: N. Kaiser (TU München)

- ⇒ indicates confirmation of interference Coulomb-interaction - strong interaction
- ⇒ detailed studies of the nature of resonances

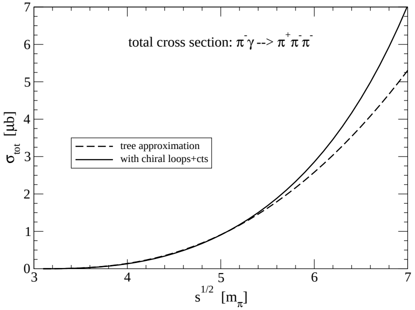
Primakoff contribution at $t' < 10^{-3}\,(\mathrm{GeV}/c)^2$

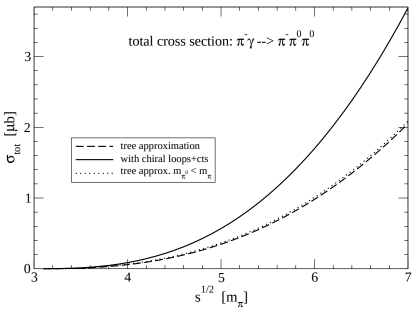
Primakoff: $\sigma(t') \propto e^{-b_{\mathrm{Prim}} t'}$, $b_{\mathrm{Prim}} \approx 2000\,(\mathrm{GeV}/c)^{-2}$ (mainly resolution)
Diffractive: $\sigma(t') \propto e^{-b_{\mathrm{diff}} t'}$, $b_{\mathrm{diff}} \approx 400\,(\mathrm{GeV}/c)^{-2}$ for lead target



(Mass) spectrum of this Primakoff contribution?
⇒ Statistical subtraction of diffractive background (for bins of $m_{3\pi}$)

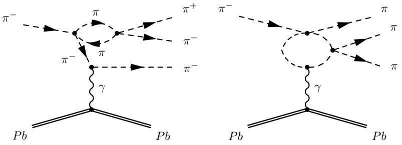
Higher-order effects



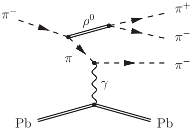


Chiral loops, e.g.

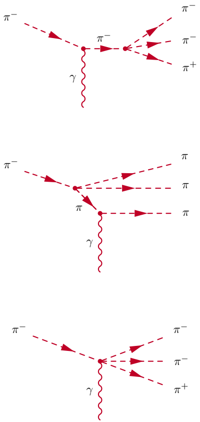
(N. Kaiser, NPA848 (2010) 198)



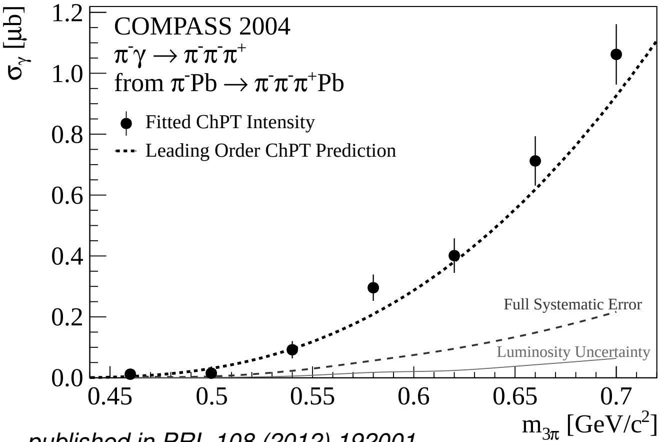
ρ terms:



First Measurement of $\pi\gamma \to 3\pi$ Absolute Cross-Section



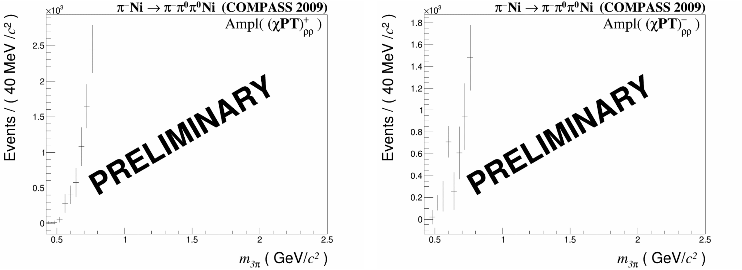
Measured absolute cross-section of $\pi^-\gamma \to \pi^-\pi^-\pi^+$



published in PRL 108 (2012) 192001

Partial Wave Analysis

Isobaric Model – Chiral Wave



Partial Wave Analysis

Chiral Model - Amplitudes