Chiral symmetry breaking: Current experimental status and prospects

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with a breaking new COMPASS result on behalf of the Collaboration
Quantum Chromodynamics

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

\[
\mathcal{L}_{QCD} = \sum_{f=\{u,d,s,c,b,t\}} \bar{q}_f (i\slashed{D} - m_f) q_f - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a
\]

- 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?
Quantum Chromodynamics

• Quantum Chromodynamics (QCD) as true theory of strong interaction

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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) \( \rightarrow \) conservation of color charge, coupling to gluons

  2. Flavor symmetries? \( \rightarrow \) only **approximate** symmetries

    \[
    \begin{align*}
    m_u &= (2.16 \pm 0.49) \text{ MeV} & m_d &= (4.67 \pm 0.48) \text{ MeV} & m_s &= (93 \pm 11) \text{ MeV} \\
    m_c &= (1.27 \pm 0.02) \text{ GeV} & m_b &= (4.18 \pm 0.03) \text{ GeV} & m_t &\approx 170 \text{ GeV}
    \end{align*}
    \]
Flavor symmetries of QCD

- Lagrangian of QCD:

\[
\mathcal{L}_{\text{QCD}} = \sum_{f=u,d,s,c,b,t} \bar{q}_f (i\gamma^\mu - m_f) q_f - \frac{1}{4} G^a_{\mu\nu} G^{a\mu\nu}
\]

flavor-symmetry breaking term

- Approximate flavor symmetries:

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\end{align*}
\]
Flavor symmetries of QCD

- Lagrangian of QCD:

\[
\mathcal{L}_{\text{QCD}} = \sum_{f=u,d,s,c,b,t} \bar{q}_f \left( i\gamma_5 \partial - m_f \right) q_f - \frac{1}{4} G_{\mu\nu}^a G^{\mu\nu}_a
\]

flavor-symmetry breaking term

- Approximate flavor symmetries:

\[ SU(2) \]

\[ m_u \approx m_d \rightarrow \text{isospin symmetry:} \]
Flavor symmetries of QCD

• Lagrangian of QCD:

\[ \mathcal{L}_{QCD} = \sum_{f=u,d,s,c,b,t} \bar{q}_f (i\slashed{\partial} - m_f) q_f - \frac{1}{4} G_{\mu\nu}^a G^{\mu\nu}_a \]

flavor-symmetry breaking term

• Approximate flavor symmetries:

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<tr>
<th>SU(2)</th>
<th>SU(3)</th>
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<tr>
<td>(m_u \approx m_d) -&gt; isospin symmetry:</td>
<td>(m_u \approx m_d \approx m_s) -&gt; the eightfold way</td>
</tr>
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</table>

![Diagram of flavor symmetries](image)
Chiral symmetry of QCD

• Lagrangian of QCD:

\[ \mathcal{L}_{QCD} = \sum_{f=u,d,s,c,b,t} \bar{q}_f (i\gamma^\mu - m_f) q_f - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a \]

\( m_u = (2.16 \pm 0.49) \text{MeV} \quad m_d = (4.67 \pm 0.48) \text{MeV} \quad m_s = (93 \pm 11) \text{MeV} \)

\( m_c = (1.27 \pm 0.02) \text{GeV} \quad m_b = (4.18 \pm 0.03) \text{GeV} \quad m_t = 170 \text{GeV} \)

• Flavor symmetries in chiral limit \( (m_u = m_d = m_s = 0) \):

\[ SU(3)_R \times SU(3)_L \]

• Left- and right-handed fields decouple for massless particles

• Chirality can directly be translated to parity of particle

→ mass-degenerate doublets of states with opposite parity
Chiral symmetry of QCD

- Lagrangian of QCD:
\[ \mathcal{L}_{QCD} = \sum_{f=u,d,s,c,b,t} \bar{q}_f(i\gamma \cdot \mathbf{D} - m_f)q_f - \frac{1}{4} G^a_{\mu\nu} G^a_{\mu\nu} \]

- Flavor symmetries in chiral limit

\[ SU(3)_R \times SU(3)_L \]

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

⇒ \( SU(3)_R \times SU(3)_L \to SU(3)_V \)

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

\[ \text{(almost) massless Goldstone bosons} \]
The chiral anomaly

• Lagrangian of QCD

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

• 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

\[ m_{\eta'} = 958 \text{ MeV} \]
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:

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• Effective theory $\rightarrow$ pion decay constant $F_\pi$ measured from leptonic decays of the charged pion ($\pi^\pm \rightarrow \mu^\pm + \nu$)

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

$$F_3\pi = \frac{e N_C}{12 \pi^2 F_\pi^3} = (9.78 \pm 0.05) \text{GeV}^{-3}$$
Discovery of the chiral anomaly – $\pi^0$ lifetime

- First definitive measurement of $\pi^0$-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
  \[ \Gamma_{\text{anom}}(\pi^0 \to \gamma\gamma) = F_{\pi\gamma\gamma}^2 \cdot \frac{m_{\pi^0}^3}{64\pi} = \left( \frac{e^2 N_c}{12\pi^2 F_\pi} \right)^2 \frac{m_{\pi^0}^3}{64\pi} = 7.75 \text{eV} \]
  \[ \tau(\pi^0) = \text{BR}(\pi^0 \to \gamma\gamma) \cdot \frac{n}{\Gamma_{\text{anom}}(\pi^0 \to \gamma\gamma)} = 8.38 \cdot 10^{-17} \text{s} \]

- 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**
  - \( a_0^0 m_\pi = 0.220 \pm 0.005 \) \textit{confirmed} by E865 in \( K^+ \to \pi^+ \pi^- e^+ \nu_e \)
  - \((a_0^0 - a_0^2)m_\pi = 0.264 \pm 0.006 \) \textit{confirmed} by NA48 in \( 0.268 \pm 0.010 \ K^+ \to \pi^+ \pi^0 \pi^0 \)

- **pion polarisability: electric \( \alpha_\pi \), magnetic \( \beta_\pi \)**
  - 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
  - \( \leftrightarrow \) pion scattering lengths combined with photon coupling
  - chiral loop contribution
    - theory prediction available, no measurement
COmmom Muon and Proton Apparatus for Structure and Spectroscopy

Proposal: 25 years ago
First data: 20 years ago

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 $\pi^- \gamma \rightarrow \pi^- \pi^- \pi^+$

COMPASS 2004

$\pi^- \gamma \rightarrow \pi^- \pi^- \pi^+$

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

- Fitted ChPT Intensity
- Leading Order ChPT Prediction

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

Also obtained in these analyses: radiative widths of $\alpha_2(1320)$ 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 \( \alpha_\pi, \beta_\pi \) \( [10^{-4} \text{ fm}^3] \)

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

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

- Processes described by WZW term:

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

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

- Problem of explicit chiral symmetry breaking:

$$F_{3\pi} = \frac{eN_C}{12\pi^2 F_{\pi}^3} = (9.78 \pm 0.05)\text{GeV}^{-3} = F(s = t = u = 0)$$
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$$\Rightarrow F_{3\pi} = (12.9 \pm 0.9 \pm 0.5) \text{GeV}^{-3}$$

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

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

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

![Graph of number of events vs. $s/m_\pi^2$]
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$$F_{3\pi} = \frac{eN_C}{12\pi^2 F_{\pi}^3} = (9.78 \pm 0.05) \text{GeV}^{-3} = F(s = t = u = 0)$$

Reanalysis of Serpukhov data:


- 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: $O(10\%)$ 
$\Rightarrow$ 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:

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

With

$$\mathcal{F}(s,t,u) = C_2^{(1)} f_2^{(1)}(s,t,u) + C_2^{(2)} f_2^{(2)}(s,t,u) - \frac{2e^2 F_{\pi}^2 F_{3\pi}}{t}$$

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

$f_2^{(1)}(s,t,u), f_2^{(2)}(s,t,u)$: 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)

\[ L_{\text{eff}} = L \cdot (1 - \epsilon_{\text{DAQ}}) \]

- 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

\[ K^- \rightarrow \pi^- \pi^0 \]
\[ K^- \rightarrow \pi^- \pi^0 \pi^0 \]
### Investigated Kaon decay channels

<table>
<thead>
<tr>
<th>Decay channel</th>
<th>$\Gamma_i/\Gamma$</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^- \rightarrow \mu^- \bar{\nu}_\mu$</td>
<td>$(63.56 \pm 0.11)$ %</td>
<td>Does not deposit energy in ECAL2 (Primakoff-trigger)</td>
</tr>
<tr>
<td>$K^- \rightarrow \pi^- \pi^0$</td>
<td>$(20.67 \pm 0.08)$ %</td>
<td>Similar systematics as Primakoff $\pi^- \rightarrow \pi^- \pi^0$ channel</td>
</tr>
<tr>
<td>$K^- \rightarrow \pi^- \pi^- \pi^+$</td>
<td>$(5.583 \pm 0.024)$ %</td>
<td>Does not deposit energy in ECAL2 (Primakoff-trigger)</td>
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<tr>
<td>$K^- \rightarrow e^- \pi^0 \bar{\nu}_e$</td>
<td>$(5.07 \pm 0.08)$ %</td>
<td>Non exclusive, missing energy</td>
</tr>
<tr>
<td>$K^- \rightarrow \mu^- \pi^0 \bar{\nu}_\mu$</td>
<td>$(3.352 \pm 0.033)$ %</td>
<td>Non exclusive, missing energy</td>
</tr>
<tr>
<td>$K^- \rightarrow \pi^- \pi^0 \pi^0$</td>
<td>$(1.760 \pm 0.023)$ %</td>
<td>Used to determine $\pi/K$-ratio in the beam</td>
</tr>
<tr>
<td>others</td>
<td>$&lt; 10^{-4}$</td>
<td>No significant contribution to background expected</td>
</tr>
</tbody>
</table>

- 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

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

Largest contributions to systematic uncertainty:
- CEDAR tag efficiency: 7%
- ECAL reconstruction: 5%
- kaon/pion beam ratio: 2.5%

Result:
\[ L_{\text{eff}} = 5.21 \pm 0.48_{\text{syst}} \pm 0.04_{\text{stat}} \]
The main background for $\pi^-\gamma \rightarrow \pi^-\pi^0$

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

Approach for 3$\pi$ leakage:
- Select diffractive 3$\pi$ events
- Develop partial-wave model
- Weight 3$\pi$ Monte Carlo data set according to model
- Subtract from 2$\pi$ event sample
Result of fitting with the Kubis-Hoferichter model

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

\[ C_2^{(1)} = (10.5 \pm 0.1_{\text{stat}} \pm 0.6_{\text{syst}}) \text{GeV}^{-3} \]

\[ C_2^{(2)} = (24.5 \pm 0.1_{\text{stat}}^{+1.6}_{-1.4_{\text{syst}}}) \text{GeV}^{-5} \]

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

\[ \Gamma_{\rho \rightarrow \pi \gamma} = (76 \pm 1_{\text{stat}}^{+10}_{-8_{\text{syst}}}) \text{keV} \]

- 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 $\Gamma_{\rho\to\pi\gamma}$

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

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- Intensive test of systematics:
  - Different $K^-$ decay channels
  - Studies on different background contributions ($\omega$ and $\pi$ 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 $d\sigma/dt$ distribution
(separation of nuclear and Coulomb processes)

- Neglecting chiral production of $\pi^-\pi^0$
- Presumably underestimation of systematics
  (3$\pi$ leakage, beam composition)
Interpretation of the new preliminary result

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

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F_{3\pi} = (10.3 \pm 0.1_{\text{stat}} \pm 0.6_{\text{syst}}) \text{GeV}^{-3}
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Antipov, Y. et al. PRD 36 (1987) 101103
and reanalyzed by
Ametller, L. et al. PRD 64 (2001) 094009

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

- Neglecting $s$-channel production of $\rho$ 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

<table>
<thead>
<tr>
<th>Year</th>
<th>Reaction</th>
<th>Result</th>
<th>Reference</th>
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<tbody>
<tr>
<td>2004</td>
<td>$\pi^+\pi^-\pi^-$: published result</td>
<td>PRL 108 (2012) 192001</td>
<td></td>
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<td>2009</td>
<td>$\pi^-\gamma$: pion polarizabilities</td>
<td>PRL 114 (2015) 06002</td>
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- On the future program of the successor AMBER experiment: a similar program on the kaon sector
Thank you for your attention
Radiative width of $\rho$-meson

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

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


- From fit of $d\sigma/dt$ for $\rho$ production: $\Gamma(\rho \to \pi \gamma) = (81 \pm 4 \pm 4) \text{ keV}$
Radiative width of $\rho$-meson

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

\[ \pi^– \rightarrow \rho^– \rightarrow \pi^0 \]

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

- At kinematic threshold: non-resonant behaviour but chiral anomaly (Serpukhov measurement)

- Interference between Chiral Anomaly and $\rho$ gives additional information

Low-mass tail: mainly driven by $F_{3\pi}$
Approach for $3\pi$-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

**MC leakage estimate**
- Normalization due to same data set
- To be subtracted from RD $2\pi$-sample
- Newest sample from 07.12.2021

**Develop PWA model**
- Weight PS distributed events according to model
- To be subtracted from RD $\pi^-$ sample
- MC leakage estimate

**Apply $2\pi$ event selection**
- $\pi^-\pi^-\pi^0\pi^0\pi^0$ Ni (COMPASS 2009)
Approach for $3\pi$-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
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**Develop PWA model**
- Weight PS distributed events according to model

**Apply $2\pi$ event selection**

**MC leakage estimate**
- Normalization due to same data set
- To be subtracted from RD $2\pi$-sample
- Newest sample from 07.12.2021

**Issues so far: predicted background oversooting data**

- Predicted background overshooting data