Testing the chiral anomaly and measuring the radiative width of the $\rho(770)$ at COMPASS

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New result on $F_{3\pi}$ and $\Gamma_{\rho\rightarrow\pi\gamma}$!
Primakoff reactions

- Idea dates back to Henry Primakoff ("photon target")

- 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 ($P^2_Y \ll m^2_\pi$) photons

- Large impact parameters (ultra-peripheral scattering)
Weizsäcker-Williams approximation

- Coulomb field of relativistic charge ≈ flux of quasi-real photons
  Equivalent photon approximation (single-photon exchange)

\[
\frac{d\sigma}{ds\,dQ^2\,d\Phi_n} = \frac{Z^2\alpha}{\pi(s - m^2_{\pi})} F^2(Q^2) \frac{Q^2 - Q^2_{\text{min}}}{Q^4} \cdot \frac{d\sigma_{\pi\gamma \rightarrow X}}{d\Phi_n}
\]

Flux of quasi-real photons \(\pi\gamma\) scattering cross section

- Beam pions scatter off equivalent photons

- Peak at tiny momentum transfers \(Q^2 \approx 10^{-5}\text{GeV}^2/c^2\)

\[Q = \frac{Q_{\text{min}}}{\sqrt{s}}\]

Q dependence of EPA

for \(s = 770\text{ MeV} \Rightarrow Q_{\text{min}} = 1.5\text{ MeV}\)
and \(p_{\text{beam}} = 191\text{ GeV}\)
## Requirements for Primakoff

- Fixed target setup with nuclear target ($Z$-dependence of WW approximation)
- Good $Q^2$-resolution to separate Coulomb processes (Primakoff) from other processes (strong processes)
- Neutral particles in final state $\rightarrow$ calorimetry with good position/energy resolution for good $Q^2$-resolution.

## Interesting $\pi + \gamma$ reactions:

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

### 2004

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- 4x larger data set compared to 2009
- Topic of this talk

**PRL 108 (2012) 192001**

**PRL 114 (2015) 06002**
Quantum Chromodynamics

- Quantum Chromodynamics (QCD) as true theory of strong interaction
- Lagrange density of QCD:

\[ \mathcal{L}_{QCD} = \sum_{f=[u,d,c,s,t,b]} \sum_{i,j=1}^{N_c} \overline{\psi}_f,i (i \gamma^\mu D^i_{\mu} - m_f \delta^i_j) \psi_f,i - \frac{1}{4} \sum_{a=1}^{N_c^2-1} G^a_{\mu \nu} G^{a\mu \nu} \]

Flavor symmetry breaking term \((m_u \neq m_d \neq m_s)\)

- Flavor symmetries? \(\rightarrow\) only approximate symmetries
  - \(SU(2): m_u \approx m_d\) \(\rightarrow\) isospin symmetry
  - \(SU(3): m_u \approx m_d \approx m_s\) \(\rightarrow\) the eightfold way
• Quantum Chromodynamics (QCD) as true theory of strong interaction
• Lagrange density of QCD:

\[ \mathcal{L}_{QCD} = \sum_{f=\{u,d,c,s,t,b\}} \sum_{i,j=1}^{N_c} \bar{\psi}_{f,j} \left( i \gamma^\mu D_{i,\mu}^j - m_f \delta^j_i \right) \psi_{f,i} - \frac{1}{4} \sum_{a=1}^{N_c^2-1} G_{\mu \nu}^a G^{a \mu \nu} \]

• Approximate 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 
  \( \rightarrow \) mass-degenerate doublets of states with opposite parity
Chiral symmetry of QCD

- Lagrange density of QCD:
  \[ \mathcal{L}_{QCD} = \sum_{f=[u,d,c,s,t,b]} \sum_{i,j=1}^{N_c} \bar{\psi}_f i(x) \gamma^\mu D^\mu_{i,j} \psi_f - m_f \bar{\delta}_f \psi_f - \frac{1}{4} \sum_{a=1}^{N_3^2-1} G^a_{\mu\nu} G^a_{\mu\nu} \]

- Approximate 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
  - Why does chiral symmetry not manifest itself in the spectrum (in contrast to isospin and eightful way)? → Nambu-Goldstone mechanism for spontaneous/dynamic breakdown 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 \(\rightarrow\) 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

Dynamic breaking of chiral symmetry

(light-meson masses)

(mass and width (GeV/c^2))

(0^+, 1^+ \rightarrow f_0(1370), f_0(1710), f_0(1285), a_0, \bar{K}_0, f_0, f_0^*, \phi, \rho, \omega, \eta, \eta', K, \bar{K}, \pi, \rho, \omega, \eta, \eta', K, \bar{K}, \pi, \rho, \omega)

(almost) massless Goldstone bosons
The chiral anomaly

• Lagrange density of QCD:

\[ \mathcal{L}_{QCD} = \sum_{f=u,d, c,s,t,b} \sum_{i,j=1}^{N_c} \bar{\psi}_f,\bar{j} (i \gamma^\mu D_{\mu}^j - m_f \delta^i_j) \psi^{f,i} - \frac{1}{4} \sum_{a=1}^{N_c^2-1} G^a_{\mu \nu} G^{a \mu \nu} \]

• Features \textit{axial} \( U(1) \)-symmetry in chiral limit:

\[ \psi(x) \rightarrow e^{i \theta \gamma_5} \psi(x) \]

• No ninth “unnaturally light” meson

• \textbf{Anomalous} symmetry breaking: symmetry of the Lagrangian does not lead to conserved Noether currents

• \textbf{Anomaly}: Symmetry of classical Lagrangian violated at quantum level
• Chiral anomaly in ChPT taken into account by Wess-Zumino-Witten (WZW) term

• Describes coupling of odd number of Goldstone bosons:

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

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

• Effective theory \(\rightarrow\) pion decay constant measured from leptonic decays of the charged pion \((\pi^\pm \rightarrow \mu^\pm + \nu)\)
Testing the chiral anomaly - $F_{3\pi}$

- $F_{3\pi}$: 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: $\pi^- \gamma^* \rightarrow \pi^- \pi^0$
- Challenges:
  1. Explicit chiral symmetry breaking:
     
     \[
     F_{3\pi} = \frac{eN_C}{12\pi^2 F_{\pi}^3} = (9.78 \pm 0.05)\text{GeV}^{-3} = F(s = t = u = 0)
     \]
  2. Coherent background from $\rho(770)$ production
Coherent background from $\rho(770)$ meson

- Background from $\rho(770)$ production (strong and electromagnetic)

$$\Rightarrow$$ possibility of extraction of radiative width of $\rho$-meson:

$$\Gamma_{(\rho \rightarrow \pi \gamma)} / \Gamma_{\text{tot}} \approx 4.5 \cdot 10^{-4}$$

$$\Rightarrow$$ contributes to hadronic vacuum polarization terms in calculations of $g - 2$ of $e$ and $\mu$

Radiative width of $\rho(770)$ meson

- Background from $\rho(770)$ production (strong and electromagnetic)

\[ \pi^- \rightarrow \rho^- \rightarrow \pi^0 \gamma \]

$\Rightarrow$ possibility of extraction of radiative width of $\rho$-meson:

\[ \Gamma(\rho \rightarrow \pi\gamma) / \Gamma_{\text{tot}} \approx 4.5 \cdot 10^{-4} \]

$\Rightarrow$ contributes to hadronic vacuum polarization terms in calculations of $g - 2$ of $e$ and $\mu$


- From fit of $d\sigma/dt$ for $\rho$ production:

\[ \Gamma(\rho \rightarrow \pi\gamma) = (81 \pm 4 \pm 4) \text{ keV} \]
Problem of explicit chiral symmetry breaking:

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

\[ \Rightarrow \bar{F}_{3\pi} = (12.9 \pm 0.9 \pm 0.5) \text{ GeV}^{-3} \]

Antipov, Y. et al. PRD 36 (1987) 101103 using data from Serpukhov experiments

![Graph showing number of events vs. s / m^2](image)
Reanalysis of Serpukhov data using chiral expansion:

\[ F_{3\pi}(s, t, u) = F_{3\pi}(s, t, u) + f^{(1)}(s, t, u) + f^{(2)}(s, t, u) + \ldots \]

- Extrapolation using one loop and two loop corrections:

\[ F_{3\pi} = (11.4 \pm 1.3) \text{ GeV}^{-3} \]
Previous measurement of $F_{3\pi}$ - Reanalysis

- Electro-magnetic corrections => significant contribution to $f^{(0)}(s, t, u)$ when isospin breaking effect are taken into account.

- Integrated correction amounts to 32% at threshold

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

- Precision of previous measurements: $O(10\%)$

$$\Rightarrow$$ More precise experimental determination desirable

\[\text{Ametller, L. et al. PRD 64 (2001) 094009}\]
The COMPASS experiment at CERN

- 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

Principle of Measurement

- 190 GeV negative hadron beam: 96.8% $\pi^-$, 2.4% $K^-$, 0.8% $\bar{p}$
- Beam particle identification by Cherenkov detectors
- 4mm Ni target disk ($\approx 25\% X/X_0$)
- Measure scattered $\pi^-$ and produced photons (number of photons depends on final state)
- Select exclusive events at very low $Q^2$
- For absolute cross-section measurements:
  Luminosity determination via free Kaon decays
  
  \[ (K^- \rightarrow \pi^-\pi^0 \text{ or } K^- \rightarrow \pi^-\pi^0\pi^0) \]
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

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

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

$f_2^{(1)}(s, t, u), f_2^{(2)}(s, t, u)$: provided by theory colleagues (Kubis, Hoferichter)

COMPASS measurement

Luminosity determination

- Needed for absolute cross section measurement: effective integrated luminosity (DAQ dead time taken into account)

  Effective luminosity: \( L_{\text{eff}} = L \cdot (1 - \epsilon_{\text{DAQ}}) \)

- 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

\[
N_K = \Phi_\pi \frac{n_K}{n_\pi} BR(K^- \to \pi^0 \pi^-)(1 - e^{-\frac{L}{\gamma c r}})\epsilon_K
\]
### Kaon decay channels

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

- Different channels may form background for each other, but give possibility to crosscheck results

Used for luminosity determination
Considered as background process
Effective integrated luminosity

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

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

Largest contributions to systematic uncertainty:

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

Result:

\[ L_{\text{eff}} = 5.21 \pm 0.48_{\text{syst}} \pm 0.04_{\text{stat}} \]
Main Background

- $\pi^-\pi^0$-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 $3\pi$ MC data with $2\pi$ 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
Scaling of $3\pi$ Monte Carlo background prediction

COMPASS preliminary

- $0.30 \text{ GeV}^2 < M_{\text{vis}}^2 < 0.35 \text{ GeV}^2$
- $0.35 \text{ GeV}^2 < M_{\text{vis}}^2 < 0.40 \text{ GeV}^2$
- $0.40 \text{ GeV}^2 < M_{\text{vis}}^2 < 0.45 \text{ GeV}^2$
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- $0.85 \text{ GeV}^2 < M_{\text{vis}}^2 < 0.90 \text{ GeV}^2$
- $0.90 \text{ GeV}^2 < M_{\text{vis}}^2 < 0.95 \text{ GeV}^2$
- $0.95 \text{ GeV}^2 < M_{\text{vis}}^2 < 1.00 \text{ GeV}^2$

Data
Primakoff MC
$3\pi$ MC
Sum of MC contributions
Results of dispersive fits

- 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
Comparison to previous measurements

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

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

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

- 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


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

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)
Comparison to previous measurements

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

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

- 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

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

- Neglecting $s$-channel production of $\rho$ meson
- No proper consideration of systematics

Thank you for your attention
### Primakoff data sets at COMPASS

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<tr>
<th>Year</th>
<th>Reactions</th>
<th>Notes</th>
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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
  \[ \Gamma_{\text{anom}}(\pi^0 \to \gamma\gamma) = F_{\pi\gamma\gamma}^2 \cdot \frac{m_{\pi^0}^3}{64\pi} = \left(\frac{e^2 N_C}{12\pi^2 F_\pi}\right)^2 \frac{m_{\pi^0}^3}{64\pi} = 7.75\text{eV} \]
  \[ \tau(\pi^0) = \text{BR}(\pi^0 \to \gamma\gamma) \cdot \frac{\hbar}{\Gamma_{\text{anom}}(\pi^0 \to \gamma\gamma)} = 8.38 \cdot 10^{-17}\text{s} \]

- Moussalam and Kampf 2009: NLO-calculation in chiral perturbation theory
  \[ \tau_{\text{NLO}}(\pi^0) = (8.04 \pm 0.11) \cdot 10^{-17}\text{s} \]
Production mechanisms for mesons at COMPASS

- Strong and electromagnetic production of mesons
- Electromagnetic production via Primakoff effect with sharp $Q^2$ distribution
- Pomeron exchange: $\pi^-\pi^0$ final state forbidden due to $G$-parity conservation, but: large cross-section for $\pi^-\pi^0\pi^0$-final state $\rightarrow$ loss of one (soft) $\pi^0$ as main background

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<th>$P$ (strong)</th>
<th>$R$ (strong)</th>
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<td>$\sigma(s)$</td>
<td>$\propto \ln(\sqrt{s})$</td>
<td>$\propto \text{const.}$</td>
<td>$\propto 1/\sqrt{s}$</td>
</tr>
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<td>$\sigma(A_{\text{target}})$</td>
<td>$\propto \text{const.}$</td>
<td>$\propto A^{2/3}$</td>
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<td>$\sigma(Z_{\text{target}})$</td>
<td>$\propto Z^2$</td>
<td>$\propto \text{const.}$</td>
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</tr>
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<td>$\sigma(t)$</td>
<td>$\propto \frac{Q^2-Q_{\text{min}}^2}{Q^4}$</td>
<td>$\propto e^{-b\hat{t}'}$</td>
<td>$\propto g(\hat{t}) \cdot e^{-b\hat{t}'}$ for small $\hat{t}$</td>
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Scaling of $3\pi$ Monte Carlo background prediction

COMPASS preliminary

$\pi^- (A,Z) \rightarrow (A,Z) \pi^- \pi^0$

$Q^2 < 0.01 \text{ GeV}^2/c^2$

$M_{\pi^-\pi^0} (\text{GeV}/c^2)$

Sum of MC contributions
• Direct (point-like) coupling of photon to 4 pions
• Prediction from ChPT at tree- and loop-level available

Grabmüller S. (2012). Cryogenic Silicon Detectors and Analysis of Primakoff Contributions to the Reaction $\pi^- Pb \rightarrow$

Krämer M. (2016) Evaluation and Optimization of a digital calorimetric trigger and analysis of $\pi^- Ni \rightarrow$
Covered kinematic range

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

- Trigger on energy deposit in central part of electromagnetic calorimeter ($E_{\text{trig}} > 68$ GeV)

- Minimum energy of $\pi^0 \rightarrow$ maximum scattering angle of $\pi^-$ in Gottfried-Jackson frame