Outline:

• The COMPASS experiment:
• Diffractive dissociation into $3\pi$ final states
• First look into $3\pi$ neutral mode
  • Event selection
  • First PWA fits, main waves
The COMPASS experiment

**COmmon Muon Proton Apparatus for Structure and Spectroscopy**
(~270 physicists, 25 institutes, 12 countries)

### a) Nucleon spin structure:
- **polarised muon beam** (160 GeV/c \(\mu^+\))
  - data taken 2002-04, 2006/07

### b) Nucleon & meson spectroscopy:
- Diffractive production
- Central production
- Primakoff
- **Hadron beams** (190 GeV/c \(\pi^-, K^-\))

The COMPASS experiment

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  - see 3D

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- Central production
- Primakoff
  - Hadron beams (190 GeV/c $\pi^-,K^-$)


[hep-ex/0703049, NIM A 577, 455 (2007)]
COMPASS Hadron spectroscopy

- study of $J^{PC}$ exotic mesons
- t-channel Reggeon Exchange
- forwards kinematics, target stays intact

Light meson sector ($< 2.2$ GeV/c$^2$):
- exotics $J^{PC} = 1^{+-}$
  - $\pi_1(1400)$: VES, E852, Crystal Barrel
  - $\pi_1(1600)$: E852, VES

... still controversial $\rightarrow$ COMPASS

Also: photo-production, e.g.
$\mu + p \rightarrow \mu + p_{\text{slow}} + X^0$

- large rapidity gap between $p_{\text{slow}}$, $h_{\text{fast}}$, $X$
- possible source of glueballs
Diffraction:
- study of $J^{PC}$ exotic mesons
- t-channel Reggeon Exchange
- forwards kinematics, target stays intact

Diffractive pion dissociation:
- incoming $\pi^-$ excited to resonance $X^-$
- $X^-$ decays into final state, e.g. $(3\pi)^-$:
  $\pi^- p \rightarrow \pi^- \pi^+ \pi^- p$ (charged mode)

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**COMPASS Hadron spectroscopy**

-- Diffractive pion dissociation

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... still controversial $\rightarrow$ COMPASS

Submitted to Phys.Rev.Lett:

$J^{PC}$ exotic $\pi_1(1600)$ evidence in 2004 data (Pb):

$\left( 1660 \pm 10^{+42}_{-64} \ 269 \pm 21^{+42}_{-64} \right)$

![Graph showing mass distribution of $\pi\pi\pi^+$ system](image)
COMPASS Hadron spectroscopy
-- Diffractive pion dissociation

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  - *still controversial* → COMPASS

---

Submitted to Phys.Rev.Let:
$J^{PC}$ exotic $\pi_1(1600)$ evidence in 2004 data (Pb):

$$1660 \pm 10_{-64}^{+0} \quad 269 \pm 21_{-64}^{+42}$$

---

**Diagram:**
- Target $\rightarrow X^- \rightarrow \pi^-, \pi^+, \pi^-$
- Recoil

---

Frank Nerling
Diffractive pion production at COMPASS
01/12/2009
**COMPASS Hadron spectroscopy**

-- Diffractive pion dissociation

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- study of $J^{PC}$ exotic mesons
- t-channel Reggeon Exchange
- forwards kinematics, target stays intact

**Diffr. pion dissociation:**
- incoming $\pi^-$ excited to resonance $X^-$
- $X^-$ decays into final state, e.g. $(3\pi)^-$:
  - $\pi^- p \rightarrow \pi^-\pi^+\pi^- p$ (charged mode)
  - $\pi^- p \rightarrow \pi^-\pi^0\pi^0 p$ (neutral mode)

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\[
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\]

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... still controversial $\rightarrow$ COMPASS

---

**Analysis of 2008 data started (p-target)**
- **Simultaneous observation in neutral mode**
  $\rightarrow$ independent measurement (*same apparatus*)
  $\Rightarrow$ important cross check (*understand acceptance*)

1st look into neutral mode (*main waves, isospin sym.*)
all COMPASS trackers:
SciFi, Si, MM, GEM, DC, Straw, MWPC.

+Upgraded trackers close to beam:
ColdSilicons, PixelGEMs → Plenary

0.4m liquid H₂ target

π⁻,Κ⁻ Recoil detector (RPD) to trigger on reactions inside target

ECAL1 (2° ≤ θγ ≤ 12°)

ECAL2 (0.4° ≤ θγ ≤ 2°)

Electromagnetic calorimeters

CEDARS Beam particle PID

p’ (e.g. π° π°, ηη final states)
COMPASS spectrometer: Hadron setup 2008/09

ToF measurement: ~350ns

Diffractive Trigger = BT ∧ RPD ∧ !Veto

Recoil detector (RPD) to trigger on reactions inside target

Target full/empty ratio 14:1

COMPASS 2008
COMPASS spectrometer: Hadron setup 2008/09

Recoil detector (RPD) to trigger on reactions inside target

0.4m liquid H₂ target

Electromagnetic calorimeters:
- ECAL1 (2° ≤ θγ ≤ 12°)
- ECAL2 (0.4° ≤ θγ ≤ 2°)

All COMPASS trackers: SciFi, Si, MM, GEM, DC, Straw, MWPC

Shashlik counter

radhard GAMS

GAMS (ECAL1+2)

ECAL2:
- rad. hard shashlik counter
- 10bit SADC → 12bit MSADC
- DSP → timing info

Electromagnetic calorimeters
COMPASS spectrometer: Hadron setup 2008/09

COMPASS spectrometer: Hadron setup 2008/09

π⁻, Κ⁻

Recoil detector (RPD) to trigger on reactions inside target

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ECAL2 (0.4° ≤ θγ ≤ 2°)

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+ ColdSilicons, PixelGEMs

CEDARS Beam particle PID

Setting for Kaon separation in 2008

CEDARS Beam particle PID

01/12/2009
Event selection: $\pi^−p \rightarrow \pi^−\pi^0\pi^0 p$

$\sim$10% of 2008 data

<table>
<thead>
<tr>
<th>Type of cut applied</th>
<th>Nb of events</th>
<th>Remaining [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>All events</td>
<td>$6.98800 \times 10^8$</td>
<td>100.00</td>
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<tr>
<td>DT0</td>
<td>$5.07415 \times 10^8$</td>
<td>72.61</td>
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<td>NbPV$\equiv$1</td>
<td>$4.02453 \times 10^8$</td>
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<td>32.29</td>
</tr>
<tr>
<td>TargetCut</td>
<td>$1.80785 \times 10^8$</td>
<td>25.87</td>
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<td>ChargeSum</td>
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<tr>
<td>$N_\gamma = 4$</td>
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<td>$2\pi^0$ within $m_{\pi^0}(PDG) \pm 20$MeV</td>
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<td>exactly one $2\pi^0$ combination within $m_{\pi^0}(PDG) \pm 20$MeV</td>
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Table 1: Remaining statistics after cuts - Preselection.

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<tr>
<td>RPDtracks$\equiv$1 &amp; $p_{recoil} &gt; 250$MeV</td>
<td>$5.85308 \times 10^5$</td>
<td>65.06</td>
</tr>
<tr>
<td>$\Delta\Phi &lt; 0.2$</td>
<td>$3.95250 \times 10^5$</td>
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<td>$2.39511 \times 10^5$</td>
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Table 2: Remaining statistics after further cuts applied on preselected events, cf. Tab.1 - Final Selection.
Event selection: $\pi^- p \rightarrow \pi^- \pi^0 \pi^0 p$

~10% of 2008 data

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Main cuts for exclusive events: => *in terms of sigma (± 2\sigma)*
**All & Preselected gg pairs, circular cut on PDG $\pi^0$ mass**

$2\pi^0$ evt := exactly 4 clusters, exactly one $2\pi^0$ combi within PDG +/- 20 MeV
$\Delta \Phi$ (RPD-Spectro) vs. $E_{\text{beam}}$

COMPASS 2008
(10% of 2008 data)
$\pi p \rightarrow \pi \pi p$
no acceptance correction

COMPASS 2008
(10% of 2008 data)
$\pi p \rightarrow \pi \pi p$
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PRELIMINARY
ΔΦ (RPD-Spectro) vs. $E_{\text{beam}}$

-0.2 rad

+6 GeV

Frank Nerling

Diffractive pion production at COMPASS

01/12/2009
Preselected gg pairs, circular cut on PDG $\pi^0$ mass

After final cuts on $\Delta \Phi$ and exclusivity

$2\pi^0$ evt := exactly 4 clusters, exactly one $2\pi^0$ combi within PDG +/- 20 MeV
**Exclusivity w/wo $\Delta \Phi$ (RPD-Spectro) cut**

![Graph showing a peak in calculated beam energy with a label for events and no acceptance correction.]

**COMPASS 2008**
(10% of 2008 data)

$\bar{\pi}p \rightarrow \pi^0\pi^0p$

no acceptance correction

PRELIMINARY
t' distribution

COMPASS 2008
(10% of 2008 data)

πp → π^0 π^0 p

no acceptance correction

events

10^4

10^3

10^2

10^1

10

momentum transfer t' [GeV/c^2]

0 0.2 0.4 0.6 0.8 1 1.2 1.4

PRELIMINARY
Mass spectrum of $\pi^-\pi^0\pi^0$ final state

COMPASS 2008
(10% of 2008 data)

$\pi p \rightarrow \pi\pi^0\pi^0$
no acceptance correction
Mass spectrum of both $\pi^-\pi^0$ systems & the $\pi^0\pi^0$ system
Dalitz plots: $a_2$ & $\pi_2$ region

\begin{align*}
\text{COMPASS 2008} \\
(10\% \text{ of 2008 data}) \\
\pi p \rightarrow \pi^0 \pi^0 p \\
\text{no acceptance correction}
\end{align*}

\begin{align*}
\text{mass squared of } \pi^0 \text{ system [GeV}^2/{c^2}] \\
fabs(m_{3\pi} - 1.67) \leq 0.100 \text{ GeV}/c^2
\end{align*}
**PWA using isobar model**

**X** decay described using isobar model:
- Intermediate di-pion resonance (isobar)
  - Spin $S$ and rel. orbital angular momentum $L$ w.r.t bachelor $\pi^-$
  - $L+S$ couple to $J$
- Partial waves: $J^{PC} M^\epsilon$ [isobar] $L$

**PWA:**
- **program**: Illinois/Protvino/Munich (D.Ryabchikov) software (IHEP/VES, TUM/COMPASS)
- **Isobars**: $(\pi\pi)_S$ [broad $f_0(600)+f_0(1370)$], $f_0(980)$, $\rho(770)$, $f_2(1270)$, $\rho_3(1690)$
- **No acceptance correction yet** (assumed flat)

**Mass independent PWA:** (40MeV/c$^2$ bins, same waveset as used for 2004 data)

$$
\sigma_{\text{indep}}(\tau, m, t') = \sum_{\epsilon=\pm1} \sum_{r=1}^{N_r} \sum_i T^\epsilon_{ir} f_i^\epsilon(t') \psi_i^\epsilon(\tau, m) / \sqrt{\int |\psi_i^\epsilon(\tau', m)|^2 d\tau'}
$$
- Production amplitudes $T^\epsilon_{ir} \rightarrow$ extended maximum likelihood fit
- Decay amplitudes $\psi_i^\epsilon(\tau, m)$ (Zemach tensors, D functions)
PWA using isobar model

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- **Isobars:** $(\pi\pi)_S$ [broad $f_0(600)+f_0(1370)$], $f_0(980)$, $\rho(770)$, $f_2(1270)$, $\rho_3(1690)$
- **No acceptance correction yet** (assumed flat)

**Assumptions:**
- **factorisation** of beam & target vertex, no final state interactions
- $l^G$ conserved at beam vertex ($\pi^-$ beam: $l^G = 1^-$)
- **Scattering on nucleons:** helicity flip & non-flip amps at target vertex (*rank2*)
- **Using reflectivity basis** in Gottfried Jackson frame (at high CM energies: reflectivity $\varepsilon =$ naturality of $R$)

**Isospin symmetry:** neutral / charge mode
- isobar decaying into $f_2 \pi$: $1/2$ intensity expected
- isobar decaying into $\rho \pi$: $1/1$ intensity expected
First PWA fits – normalisation to a2

COMPASS 2008

mass Indep PWA
(42 waves)

no acceptance correction

PRELIMINARY
First PWA fits – check intensities $a_1$ to $\rho\pi$
First PWA fits – check intensities
\( \pi_2 \rightarrow f_2 \pi \)
First PWA fits – check intensities
$a_1$ to $\rho \pi$
a1/a2 mass region - neutral
(1.22 - 1.38 GeV/c²)

a1/a2 mass region - charged
(1.22 - 1.38 GeV/c²)
Conclusions & outlook

- COMPASS spectrometer well suited for Hadron Spectroscopy
  → Data taken with hadron beams on p target in 2008 & 09

- COMPASS measures Neutral & Charged channels

- First results on $3\pi$ final state -- neutral mode (diffr. dissociation)
  + Evt selection & 1st PWA fits (mass independent)
  + First look promising: mass spectra, main waves, isospin symmetry
  => Important cross-checks & independent confirmation of any new state observed

- Statistics less than charged mode
  → event selection presently limited to (exactly) 4γ events
  → will improve (allowing 5th => gain ~20%)
  → Ecals reconstruction under redevelopment

- Next steps:
  - Further development of Ecals reconstruction → MSADC info, DSP etc
  - Increase statistics, acceptance corrections, extend waveset, …
Backup
First PWA fits on $\pi^+\pi^-\pi^0$

**Theoretical expectation:** neutral / charge mode
- isobar decay into $f2\pi$ : 1/2 intensity expected
- isobar decay into $\rho\pi$: 1/1 intensity expected

Examples, ($J^{PC}$) $M^E$ [isobar] $L$ notation:
- $a2$: (2++)1+ rho pi D
  - a) $a2 \rightarrow \rho^+\pi^-$  
    - $\pi^-\pi^+$  
    - $\pi^-\pi^++\pi^-$
  - b) $a2 \rightarrow \rho^-\pi^0$  
    - $\pi^0\pi^-$  
    - $\pi^-\pi^0\pi^0$
- $\pi2$:
  - i) (2+)0+ f2 pi S: $\pi2 \rightarrow f2\pi^-$  
    - $\text{BR}(\pi^0\pi^+) / \text{BR}(\pi^-\pi^+)=1/3 / 2/3=1/2$
  - ii) (2+)0+ rho pi F
    - a) $\pi2 \rightarrow \rho^-\pi^0$  
      - $\pi^-\pi^0$
    - b) $\pi2 \rightarrow \rho^+\pi^-$  
      - $\pi^+\pi^-$

$\pi2$ intensity expected (neutral/charged): 1/2
(plus reduced acc. $\Rightarrow$ eff x eff for neutrals)

$\pi2$ intensity expected (neutral/charged): 1
First PWA fits on $\pi^-\pi^0\pi^0$

**Theoretical expectation:** neutral / charge mode
- isobar decay into f2 $\pi$: 1/2 intensity expected
- isobar decay into $\rho\pi$: 1/1 intensity expected

**Examples, General:**
- a2: (2++)1+ $\rho\pi$
  - a) a2 $\rightarrow \rho^-\pi^0\pi^+$
  - b) a2 $\rightarrow \rho^-\pi^0\pi^-

**Calculated / checked:**
- BR = $N(\pi^-\pi^0\pi^0)/N(\pi^-\pi^+\pi^-)$
  - BR(0-+ f0(1400) $\pi$ S) = 0.26 (at 1.3 GeV)
  - BR(0-+ f0(980) $\pi$ S) = 0.44 (at 1.8 GeV)
  - BR(2-+ f2(1270) $\pi$ S) = 0.50 (at 1.67 GeV = $\pi^2$ mass)

**General:** Branching not only from Clebsch-Gordon coeff., but also from Bose-Symmetrisation w bachelor $\pi$
- $\Rightarrow$ IsospinSym. holds for isobars going to $\rho\pi$ (same effect)
- $\Rightarrow$ "-" needs to be modified, BR may differ

**$\pi^2$:**
- (2-)0+ $\rho\pi$
  - a) $\pi^2$ $\rightarrow \rho^-\pi^0$ $\rightarrow \pi^-\pi^0$
  - b) $\pi^2$ $\rightarrow \rho^0\pi^-$ $\rightarrow \pi^+\pi^-$

**$\pi^2$ intensity expected** (neutral/charged): 1
Decay angles in G.J. frame
Full PhaseSpace Generated Prediction

Gottfried-Jackson frame:
• rest frame of resonance X
• z parallel to beam axis
• y normal to production plane

„PREDICT“:
• fit waveset to data
• fitted decay amplitudes used to calculate decay angles
• under assumption of uniform acceptance
• normalised per mass bin to data
Cut on energy of $\pi^-$ (plot after RPDcut)
(elastic events and background from e.g. pile-up)

$E_{\pi^-} < 185$ GeV
# Waveset used for the PWA

<table>
<thead>
<tr>
<th>$J^{PC} M^c$</th>
<th>$L$</th>
<th>Isobar $\pi$</th>
<th>Threshold (GeV/$c^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0^{-+}0^+$</td>
<td>$S$</td>
<td>$f_0(980)\pi$</td>
<td>1.25</td>
</tr>
<tr>
<td>$0^{-+}0^+$</td>
<td>$S$</td>
<td>$(\pi\pi)\pi$</td>
<td>-</td>
</tr>
<tr>
<td>$0^{-+}0^+$</td>
<td>$P$</td>
<td>$\rho\pi$</td>
<td>-</td>
</tr>
<tr>
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<td>-</td>
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<td>$1^{++}1^+$</td>
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<td>$G$</td>
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Table 5: List of the 42 waves used for the mass independent PWA.
Mass spectrum of $\pi^-\pi^0\pi^0$ final state

COMPASS 2008
(10% of 2008 data)

$\bar{\pi}p \rightarrow \pi^0\pi^0p$
no acceptance correction

COMPASS 2008
$\pi p \rightarrow \pi\pi\pi^+p$
$0.1 \text{ GeV}^2/c^2 < t^* < 1.0 \text{ GeV}^2/c^2$
w/o acceptance correction

(21% of 2008 data)
Mesons and Spin Exotic States

Constituent quark model
• color neutral qqbar systems
• Quantum numbers $I^G J^{PC}$
• $P = (-1)^{L+1}$, $C = (-1)^{L+S}$, $G = (-1)^{I+L+1}$
• $J^{PC}$ multiplets: $0^{++}$, $0^{--}$, $1^{--}$, $1^{+-}$, $1^{++}$, $2^{++}$, ...
• Forbidden: $0^{--}$, $0^{+-}$, $1^{--}$, $2^{+-}$, $3^{--}$, ...

QCD: Additional color-neutral objects
• Tetraquarks (qqbar)(qqbar)
• Hybrids (qqbar)g
• Glueballs gg

Spin Exotic States
• $J^{PC}$ forbidden $\rightarrow$ no simple qqbar state
• No mixing with quark model states