# Hadron Spectrospopy & Primakoff Reactions at COMPASS

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# Outline

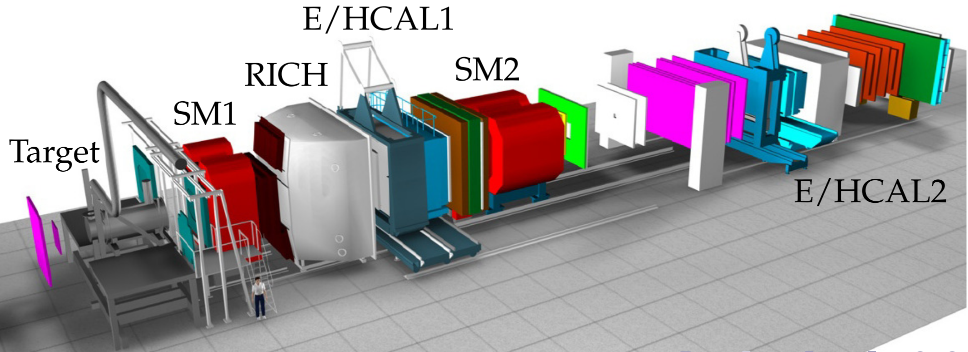
**Investigation of the strong interaction where it is strong**

- Formation of bound states of quarks and gluons
  $\rightarrow$ hadron spectroscopy
  COMPASS: high-statistics meson spectroscopy
- Hadron reactions at low relative momenta
  $\rightarrow$ manifestation of QCD by its symmetries
  COMPASS: pure pion-photon (Primakoff) reactions

NIM **A577**, 455 (2007)

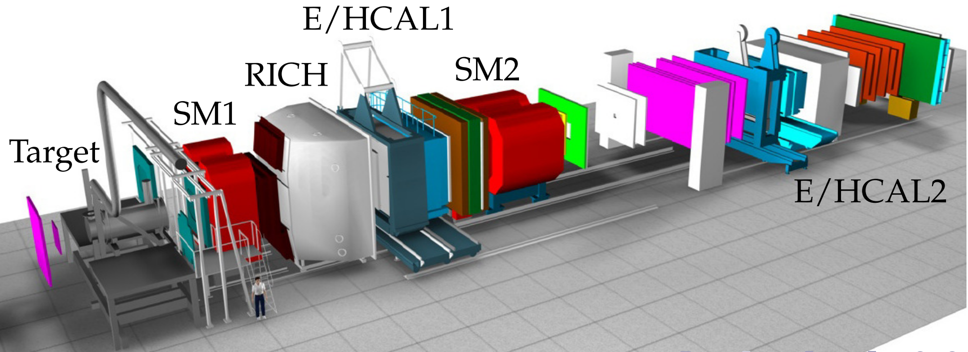
## Fixed-target experiment

- Two-stage spectrometer
- Large acceptance over wide kinematic range
- $> 1$ PByte/year



**Physics goals: Hadron spectroscopy**

- 190 GeV/$c$ secondary hadron beams
  - $h^-$ **beam:** 97% $\pi^-$, 2% $K^-$, 1% $\bar{p}$
  - $h^+$ **beam:** 75% $p$, 24% $\pi^+$, 1% $K^+$
- Various targets: $\ell H_2$, C, Ni, Cu, Pb, W



# Mesons in the Constituent Quark Model

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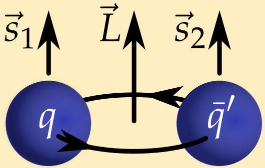
- Relative orbital $\vec{L}$ and $\vec{S}$ couple to meson spin $\vec{J} = \vec{L} + \vec{S}$



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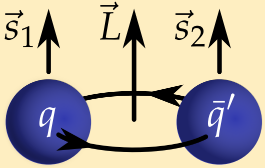
- Parity $P = (-1)^{L+1}$
- Charge conjugation $C = (-1)^{L+S}$
- **Forbidden $J^{PC}$ combinations:** $0^{--}$, $0^{+-}$, $1^{-+}$, $2^{+-}$, ...



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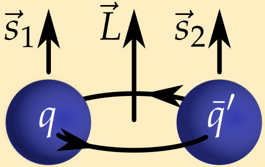
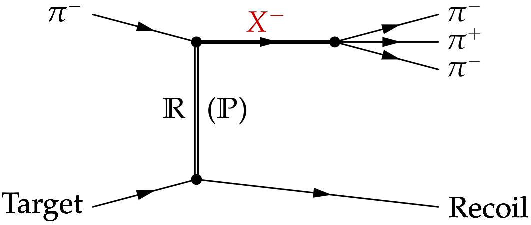



## QCD allows for states beyond the CQM

- Hybrid $|q\bar{q}g\rangle$, Glueball $|gg\rangle$, Multi-quark states $|q^2\bar{q}^2\rangle$, ...
- Physical mesons: superposition of all allowed basis states
- "Exotic" mesons with $|q\bar{q}\rangle$-forbidden $J^{PC}$

# Production of Hadrons in Diffractive Dissociation

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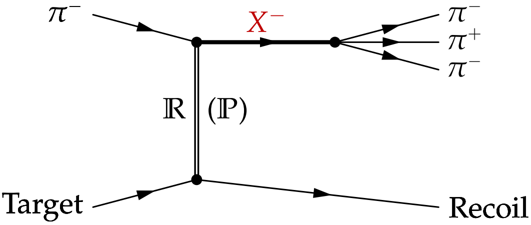


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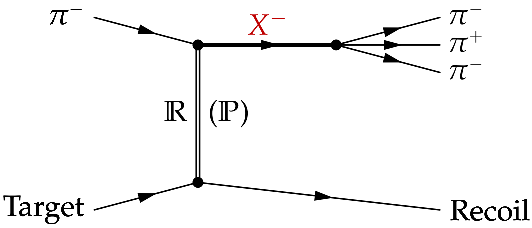
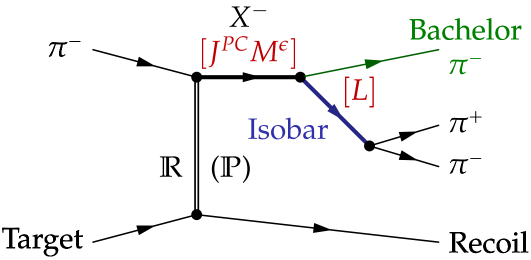



- Soft scattering of beam hadron off nuclear target
  - Excitation into resonance $X$
  - $X$ decays into $n$-body final state
- At high energies Pomeron exchange dominates
- Use kinematic distribution of outgoing particles
  - Disentangle all resonances $X$ $\rightarrow$ mass, width, $I^G J^{PC}$
  - **Method:** partial-wave analysis (PWA)

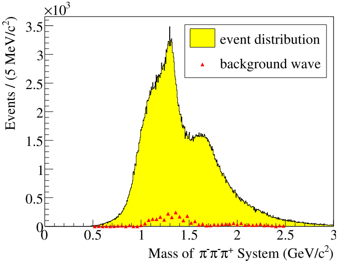
# Diffractive Dissociation of $\pi^-$ into $\pi^-\pi^-\pi^+$ Final State




**Isobar model:** $X^-$ decay is chain of successive two-body decays

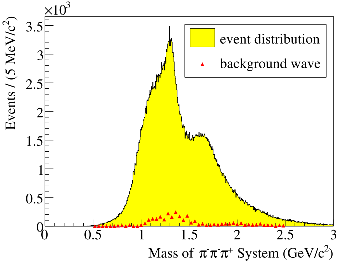
- Isobar with spin $S$ and bachelor $\pi^-$ have relative orbital $L$
  $L$ and $S$ couple to spin $J$ of $X^-$
- **"Wave":** unique combination of isobar and quantum numbers, specified by $J^{PC}M^{\epsilon}[\text{isobar}]L$
- PWA: disentangle waves using the angular distributions and interference

## $\pi^-\pi^-\pi^+$ mass spectrum

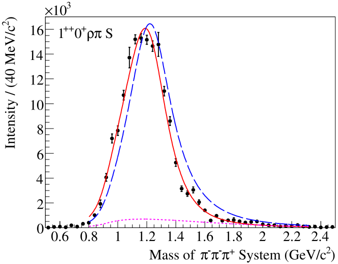


# 2004 Pilot Run: PWA of $\pi^-\pi^-\pi^+$ f.s. PRL 104 (2010) 241803

$\pi^-\pi^-\pi^+$ mass spectrum




$1^{++}0^+[\rho\pi]S \quad a_1(1260)$



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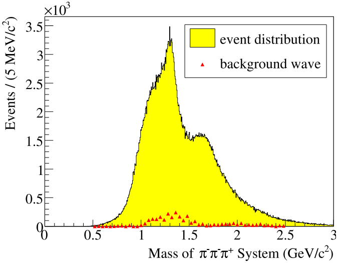
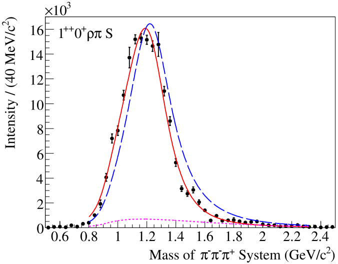
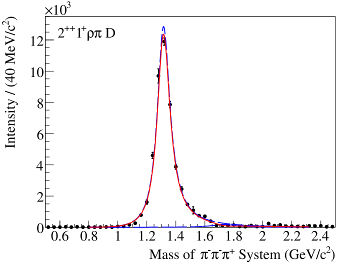



## $1^{++}0^+[\rho\pi]S$ $a_1(1260)$




## $2^{++}1^+[\rho\pi]S$ $a_2(1320)$



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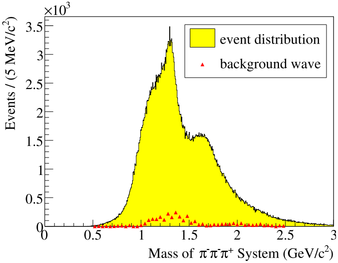


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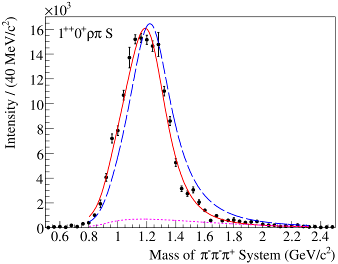


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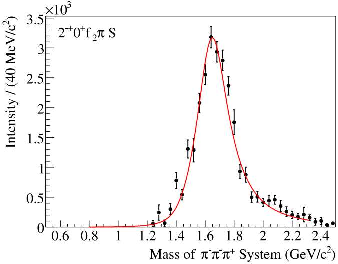


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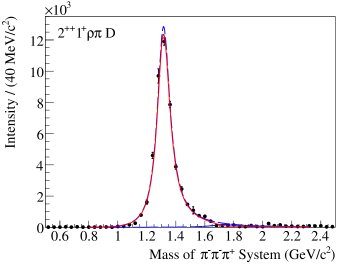

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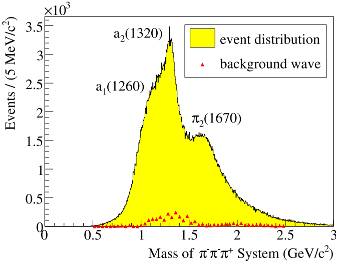


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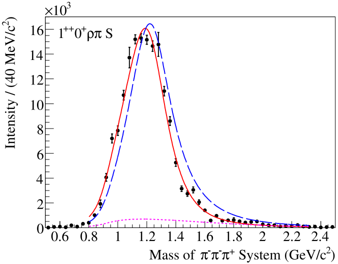


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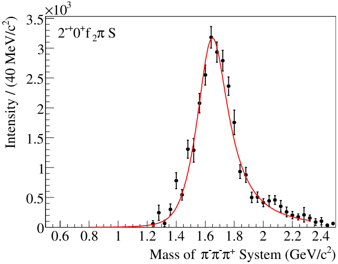


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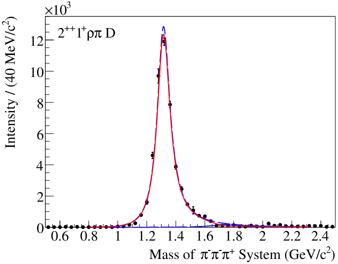

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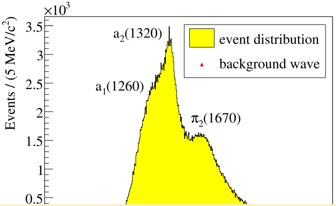


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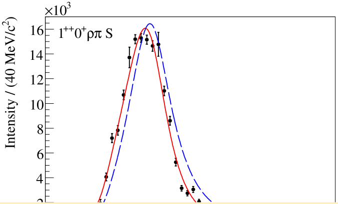
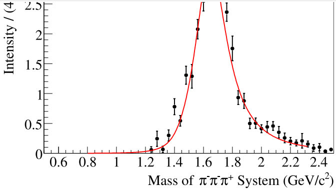
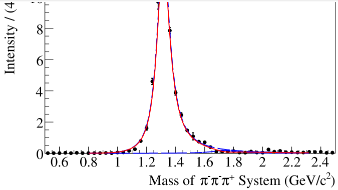



- Pb target
- Data described by model consisting of 41 waves + incoherent isotropic background
  - Isobars: $(\pi\pi)_S$, $f_0(980)$, $\rho(770)$, $f_2(1270)$, and $\rho_3(1690)$



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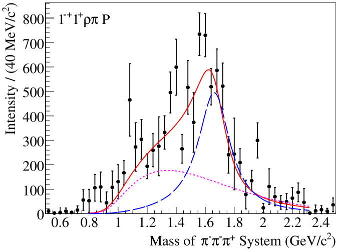
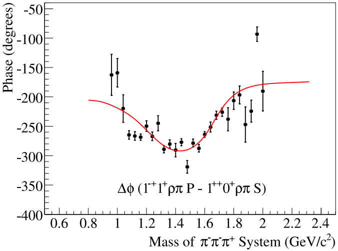
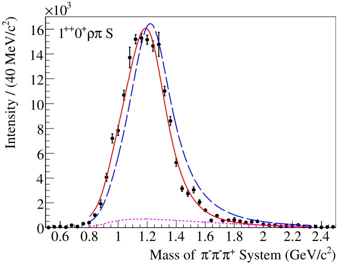
Spin-exotic $1^{-+}1^+[\rho\pi]P$




$1^{-+}1^+[\rho\pi]P - 1^{++}0^+[\rho\pi]S$



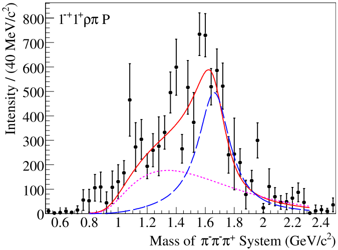

$1^{++}0^+[\rho\pi]S$ $a_1(1260)$



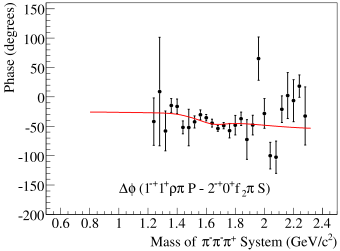

- Significant $1^{-+}$ amplitude

# 2004 Pilot Run: PWA of $\pi^-\pi^-\pi^+$ f.s. PRL 104 (2010) 241803

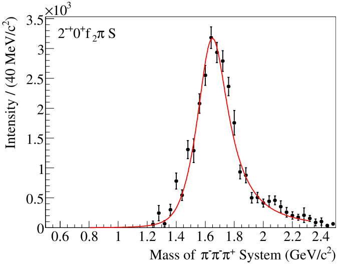
Spin-exotic $1^{-+}1^+[\rho\pi]P$




$1^{-+}1^+[\rho\pi]P - 2^{-+}0^+[f_2\pi]S$




$2^{-+}0^+[f_2\pi]S$ $\pi_2(1670)$




- Significant $1^{-+}$ amplitude
- $\pi_1(1600)$ BW + backgr.

$m = 1\,660 \pm 10^{+0}_{-64}\,\mathrm{MeV}/c$

$\Gamma = 269 \pm 21^{+42}_{-64}\,\mathrm{MeV}$

Intensity: $(1.7 \pm 0.2^{+0.9}_{-0.1})\%$

# 2008 Data using $H_2$ Target

## $\pi^-$ diffraction into $\pi^-\pi^-\pi^+$ final state

- **Spectrometer upgrade:** recoil proton detector, beam PID, calorimetry, tracking
- 190 GeV/$c$ negative hadron beam: 97% $\pi^-$, 2% $K^-$, 1% $\bar{p}$

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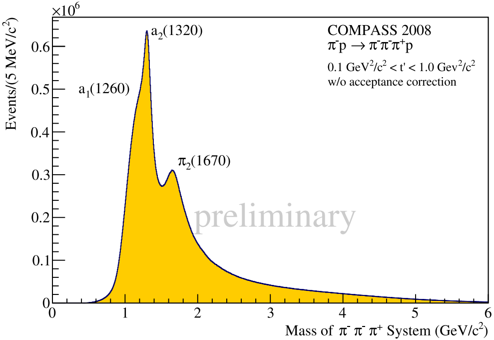
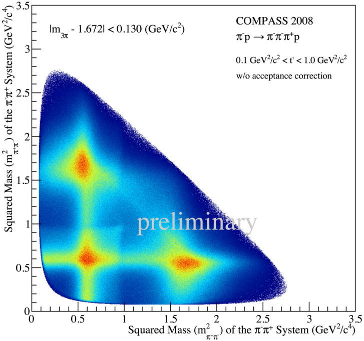
- **Spectrometer upgrade:** recoil proton detector, beam PID, calorimetry, tracking
- 190 GeV/$c$ negative hadron beam: 97% $\pi^-$, 2% $K^-$, 1% $\bar{p}$
- 200× 2004 statistics: $\approx 10^8$ events ⇒ challenging analysis

$\pi^-\pi^-\pi^+$ mass distribution




Dalitz plot for $\pi_2(1670)$ region

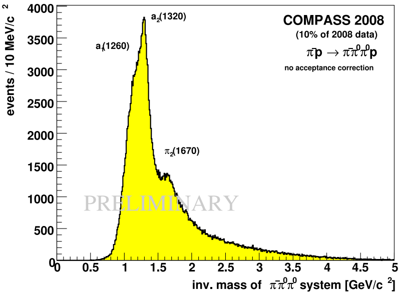


# Diffractive Dissociation into $\pi^-\pi^0\pi^0$ Final State

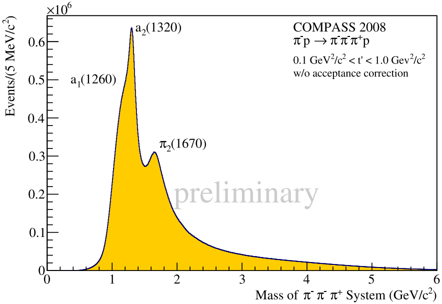
## Isospin partner to $\pi^- p \to \pi^-\pi^-\pi^+, p$

- Important consistency check
- Comparison with $\pi^-\pi^-\pi^+$: normalization to $a_2(1320)$

$\pi^-\pi^0\pi^0$ mass distribution




$\pi^-\pi^+\pi^-$ mass distribution



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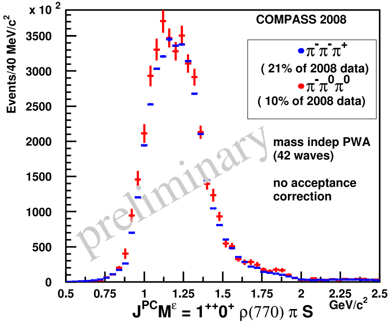
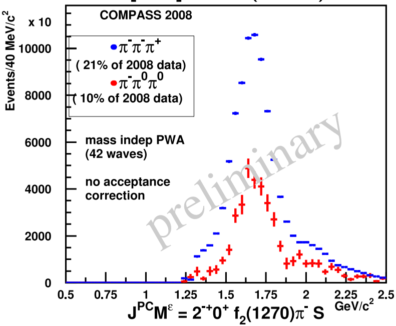
**Isospin partner to $\pi^- p \to \pi^-\pi^-\pi^+, p$**

- Important consistency check
- Comparison with $\pi^-\pi^-\pi^+$: normalization to $a_2(1320)$
- Isospin symmetry: $I = 1$ isobar $\Rightarrow$ same intensity
  $I = 0$ isobar $\Rightarrow$ half intensity

$1^{++}[\rho\pi]S$: $a_1(1260)$




$2^{-+}[f_2\pi]S$: $\pi_2(1670)$



# 2004 Pilot Run: PWA of $\pi^-\pi^-\pi^+$ Final State at low $t$

## Production mechanism depends on $t$ region

- $0.1 < t < 1\text{GeV}^2/c^2$ scattering on individual nucleons

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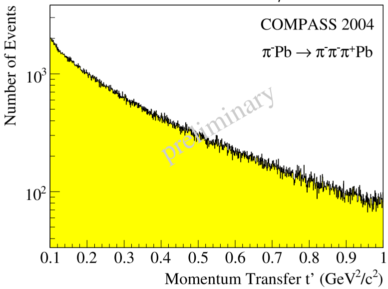

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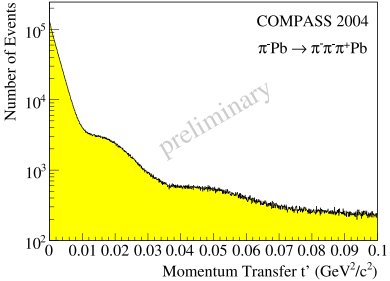
- $0.1 < t < 1\text{GeV}^2/c^2$ scattering on individual nucleons
- For $t \lesssim 0.01\text{GeV}^2/c^2$: coherent scattering on Pb nucleus

$t < 0.1\text{GeV}^2/c^2$

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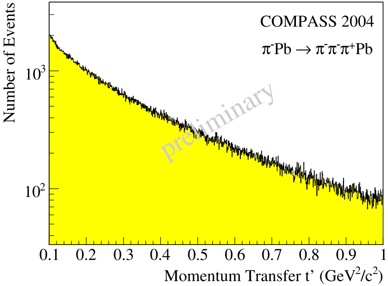

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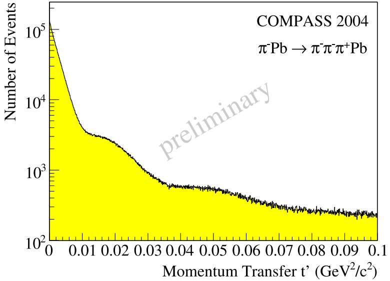
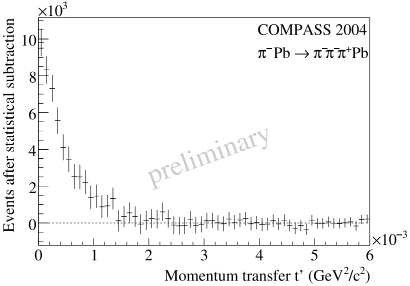
- $0.1 < t < 1\text{GeV}^2/c^2$ scattering on individual nucleons
- For $t \lesssim 0.01\text{GeV}^2/c^2$: coherent scattering on Pb nucleus
- For $t \lesssim 10^{-3}\text{GeV}^2/c^2$ Coulomb contribution

$t < 0.1\text{GeV}^2/c^2$



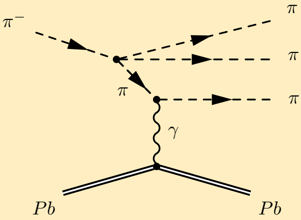

$t < 10^{-3}\text{GeV}^2/c^2$



# 2004 Pilot Run: PWA of $\pi^-\pi^-\pi^+$ Final State at low $t$

## Test of chiral perturbation theory (ChPT)

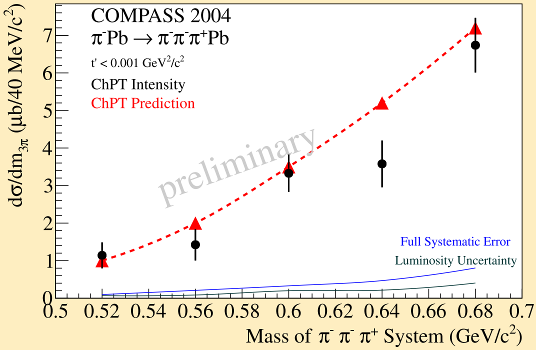
- $\gamma\pi^- \to \pi^-\pi^-\pi^+$ for $m_{3\pi} < 700\text{MeV}/c^2$
  ChPT parameter-free prediction [N. Kaiser, JF, EPJ A36 (2008) 181]




- $\pi^-\pi^-\pi^+$ Primakoff production at $t < 10^{-3}\text{GeV}^2/c^2$ probes strong interaction at low energies $\sim$ 100 MeV
- Use PWA to extract strength of ChPT amplitude as function of $m_{3\pi}$

## First measurement of $\gamma\pi^- \rightarrow \pi^-\pi^-\pi^+$ cross section

- Absolute cross section from beam flux measurement
  - Using $K^- \rightarrow \pi^-\pi^-\pi^+$ decays of beam $K^-$ (2.4%)




- Data confirm leading order ChPT calculation

# COMPASS – Analyzed Hadron Beam Channels

- $\pi^-\pi^-\pi^+$ large $t$ on various targets Pb, p, Ni, W *F. Haas*
- $\pi^-\pi^-\pi^+\pi^-\pi^+$ all $t$, 2004 Pb *S. Neubert*
- $\pi^-\pi^-\pi^+$ low $t$ *S. Grabmüller*
- $\pi^- K\bar{K}$ *T. Schlüter*
- $p\pi^-\pi^+$, $pK^-K^+$ baryon spectroscopy *A. Austregesilo*
- $p_s p_f \pi^-\pi^+\pi^-\pi^+$ *J. Bernhard*
- $K^-\pi^-\pi^+$ *P. Jasinski*
- $K\bar{K}\eta$, $K\bar{K}\pi^0$ *K. Schoenning*
- $\pi^-\pi^0\pi^0$ large $t$ *F. Nerling, S. Pflüger*
- $\pi^-\eta(\eta)$ large $t$ *S. Uhl, I. Uman, T. Schlüter*
- $\pi\gamma$ Primakoff *T. Nagel, J.F., A. Guskov*
- PWA, technical development *S.U. Chung, S. Gerassimov, B. Grube, S. Neubert, D. Ryabchikov*

# COMPASS Tests of ChPT: Primakoff reactions

Access to $\pi + \gamma$ reactions via the Primakoff effect:

At small momentum transfer to the nucleus, high-energetic particles scatter predominantly off the el.mag. field quanta ($\sim Z^2$)

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

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

# Primakoff reactions

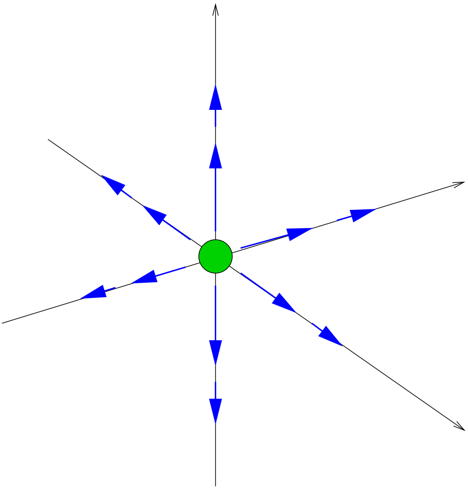
Key idea: Use Coulomb field of (heavy) nuclei as "photon target" for hadronic reactions

http://www.physics.upenn.edu/colloquium/Primakoff.html

[H. Primakoff, Phys. Rev. 81 (1951) 899]

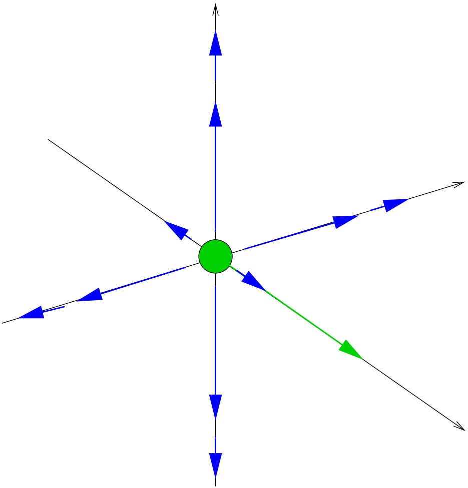
# Weizsäcker-Williams Method

Electric charge at rest

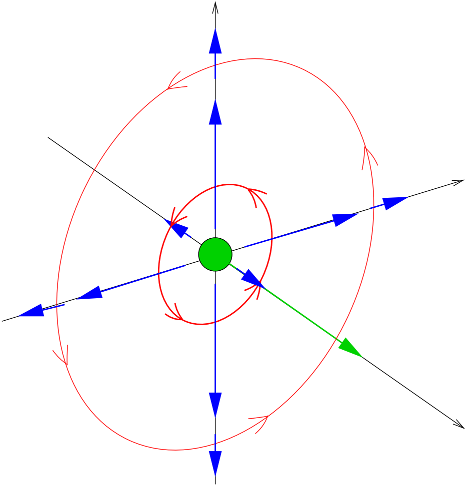


# Weizsäcker-Williams Method

Electric charge moving

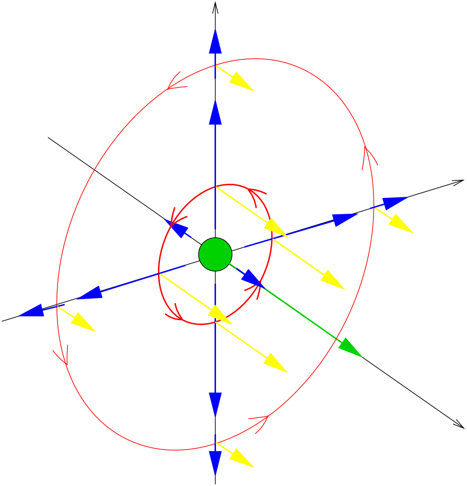


Electromagnetic field



# Weizsäcker-Williams Method

further reading: J. D. Jackson chapt. 11.10, 15.4



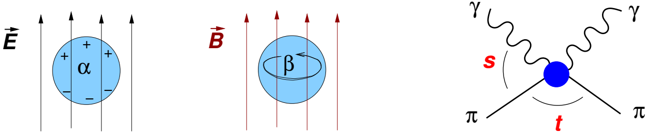
# Low-$t$ production mechanisms

- Production via photon and strong (pomeron) exchange
  - separable by different $t-$dependence
- e.g. resonance $a_2(1320)$ is produced both ways
  - radiative width
  - phase between the photon and strong amplitudes

# Compton scattering and polarisability

$$\pi + \gamma \to \pi + \gamma$$

Leading deviation from pointlike particle $\leftrightarrow$ e.m. polarisability

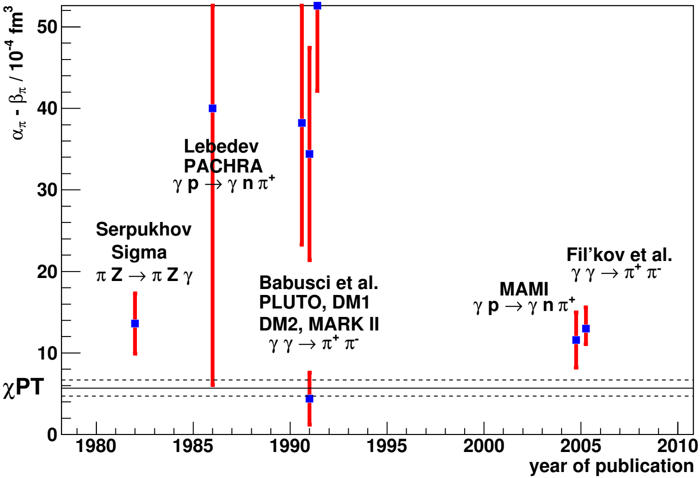



for $\alpha_\pi - \beta_\pi$ [$10^{-4}$ fm$^3$]: $(\alpha_\pi \approx -\beta_\pi)$

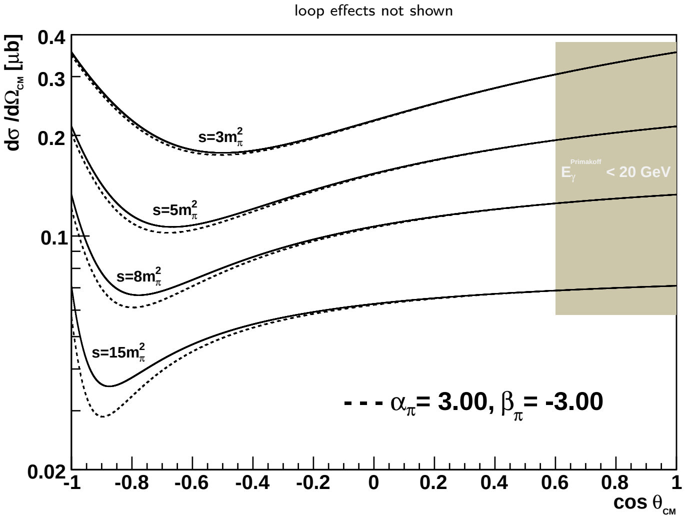
ChPT: 5.7±1.0

experiments: 4 — 14

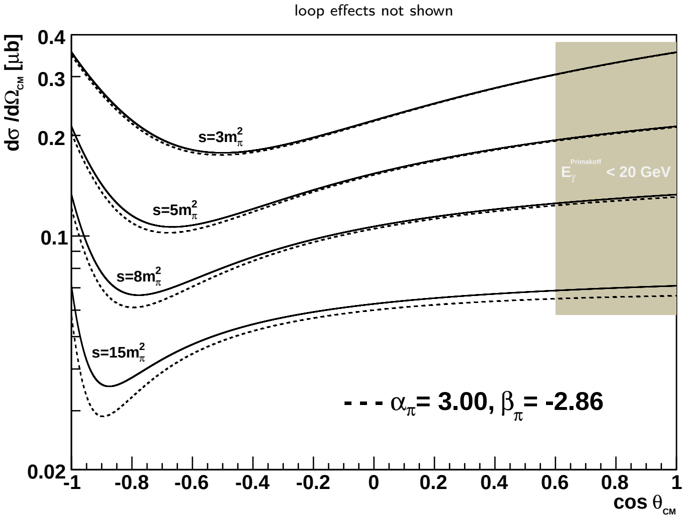
# Experiments



# Polarisability effect (LO ChPT values)

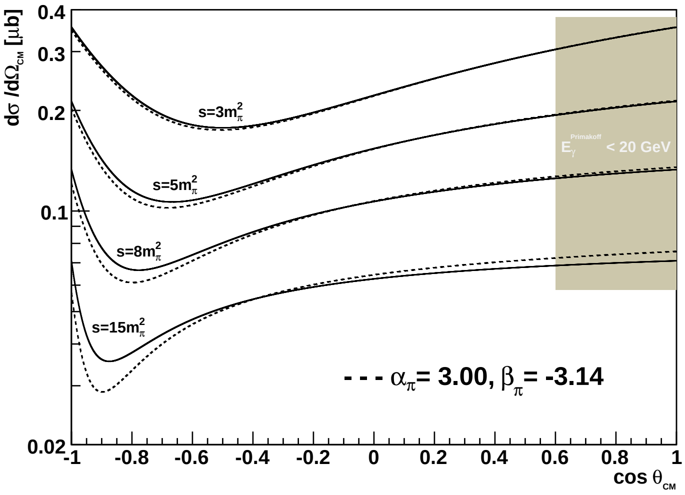


# Polarisability effect (NLO ChPT values)

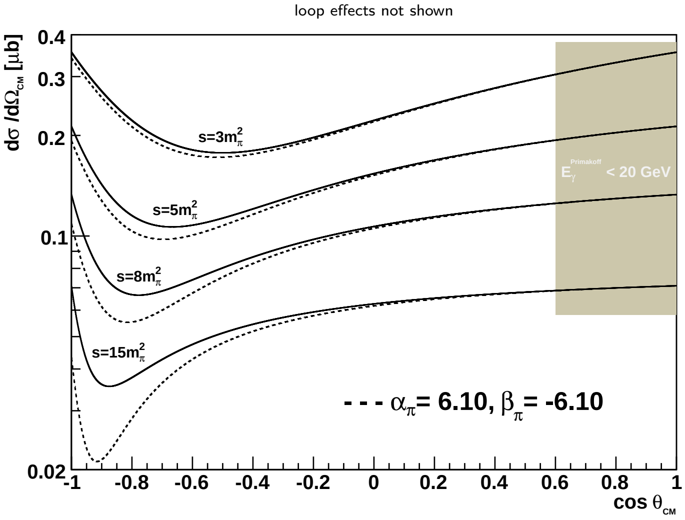


# Polarisability effect (wrong sign $\alpha_\pi + \beta_\pi$)

loop effects not shown



# Polarisability effect (Serpukhov values)



# Polarisability measurements at COMPASS

## Nov. 2004

- recorded statistics (eff. 3 days) competitive to Serpukhov
- setup not final $\rightarrow$ large estimated systematic error

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## $\geq$ 2012 `http://wwwcompass.cern.ch` $\rightarrow$ New proposal

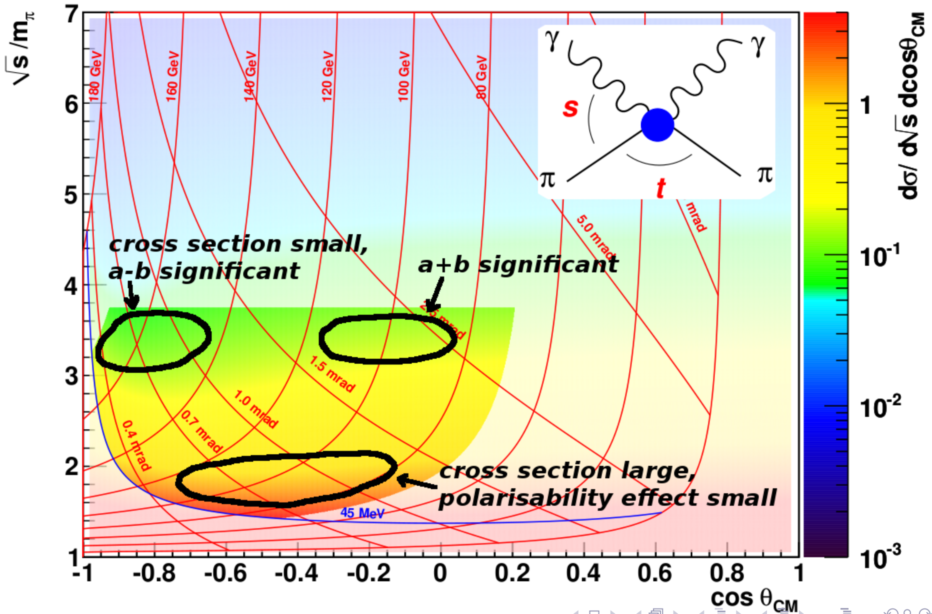
- COMPASS-II proposal for a high-statistics Primakoff run
- increase statistics by a factor $> 30$,
  uncertainty on $\alpha_\pi - \beta_\pi$: $\pm 0.66$ (ChPT: 5.7)
- First measurement of polarisability sum $\alpha_\pi + \beta_\pi$
  expected uncertainty $\pm 0.025$ (ChPT: 0.16)

# Summary and Outlook

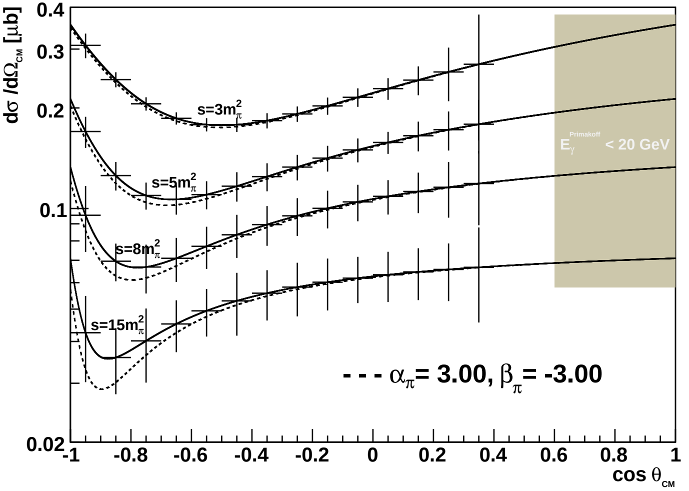
- COMPASS 2004: few days with 190 GeV hadron beam
  - Primakoff: calorimetry problems
  - diffractive: spin-exotic $\pi_1$ observation (PRL104)
  - still harvesting: chiral $\gamma\pi \to \pi^-\pi^-\pi^+$, radiative couplings ($a_2$,...), Pomeron/Photon interference
- 2008 and 2009 data with extended spectrometer
  - huge statistics on diffractive scattering (H, Pb, Ni)
  - central production with $p$ beam
  - Primakoff on Ni $\to$ pion polarisability result upcoming
- Future Primakoff run
  - determine $\alpha_\pi$ and $\beta_\pi$ pion polarisabilities independently, first value for forward polarisability $\alpha_\pi + \beta_\pi$
  - first experimental value for the Kaon polarisability

# BACKUP

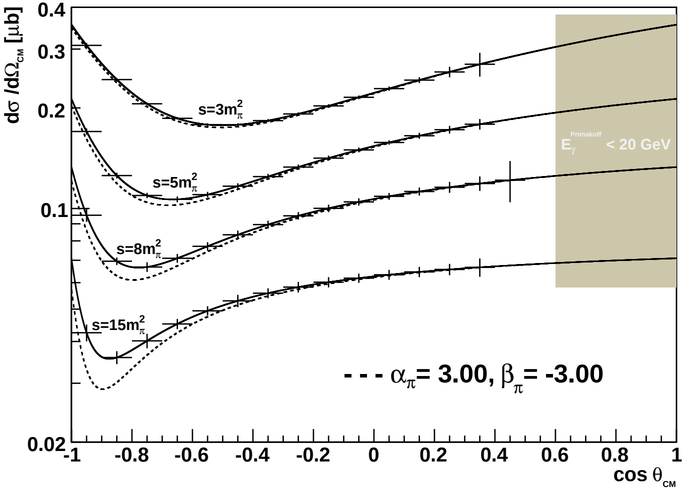
# Kinematics of the Primakoff Compton Reaction



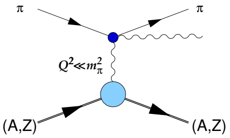
# Estimated errors on 20,000 Primakoff events



# Estimated errors on 500,000 Primakoff events

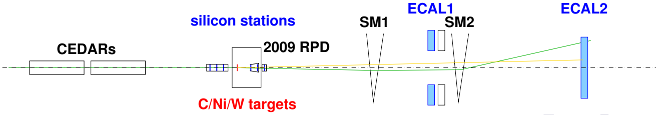


# Primakoff measurements: principle and goals

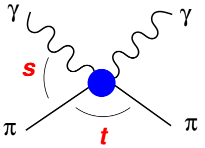



$\pi/K$ on Ni with $Q^2 < 10^{-3}$ GeV$^2/c^2$ dominated by $\gamma$-exchange $\leftrightarrow$ $\sum p_T \approx 0$

$$\pi/K + \gamma \rightarrow \begin{cases} \pi/K + \gamma & \rightarrow \textit{polarisabilities} \\ \pi/K + \pi^0/\eta & \rightarrow \text{chiral anomaly} \\ \pi/K + \pi^0/\eta + \pi^0/\eta & \rightarrow \text{chiral tree \& loops} \\ \pi/K + n \cdot [\pi/K]^{\pm} & \rightarrow \text{radiative couplings, exotics} \end{cases}$$



# Primakoff Compton: retrieving polarisabilities




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

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

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

- leading (non-pointlike) order: $(\alpha_\pi - \beta_\pi)$

  $\longrightarrow$ suppression of large $E_\gamma^{lab}$

- next ("$s$-dependent") order: $(\alpha_\pi + \beta_\pi)$ *and*