Recent results from the COMPASS hadron program

Precision studies of light mesons

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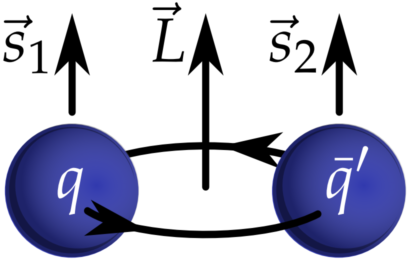
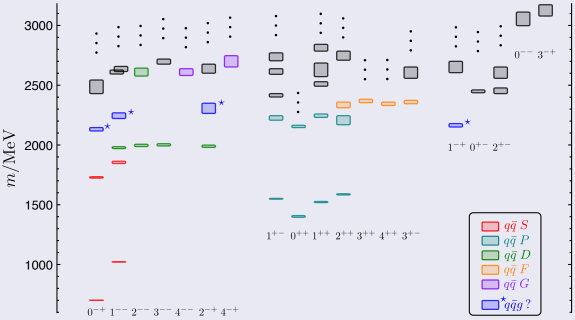
Naïve Constituent Quark Model

- Quark spins couple to total intrinsic spin $S = 0$ (singlet) or 1 (triplet)
- Relative orbital angular momentum $\vec{L}$ and total spin $\vec{S}$ couple to meson spin $\vec{J} = \vec{L} + \vec{S}$
- parity $P = (-1)^{L+1}$
- charge conjugation $C = (-1)^{L+S}$
- forbidden J^{PC}: 0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, 3^{-+}, ...



- Quark spins couple to t
  $S = 0$ (singlet) or 1 (tri
- Relative orbital angular
  and total spin $\vec{S}$ couple
  meson spin $\vec{J} = \vec{L} + \vec{S}$
- parity $P = (-1)^{L+1}$
- charge conjugation $C =$
- forbidden J^{PC}:
  0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, 3



J.Dudek, Phys.Rev.D84 (2011) 074023

Beyond the CQM: i.e. lattice QCD

isovector states

- prediction of states outside CQM
- hybrid candidate ($q\bar{q}g$)
- lightest candidate in 1^{-+}

in addition:

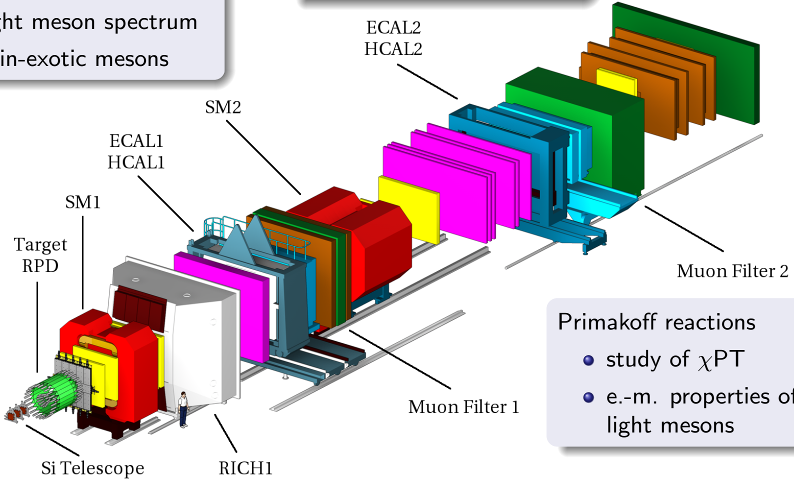
- (isoscalar) glueballs
- pure glue
- quantum numbers J^{PC}: 0^{++}, ...

central production

- glue-rich environment
- scalar resonances

diffractive dissociation

- light meson spectrum
- spin-exotic mesons



Primakoff reactions

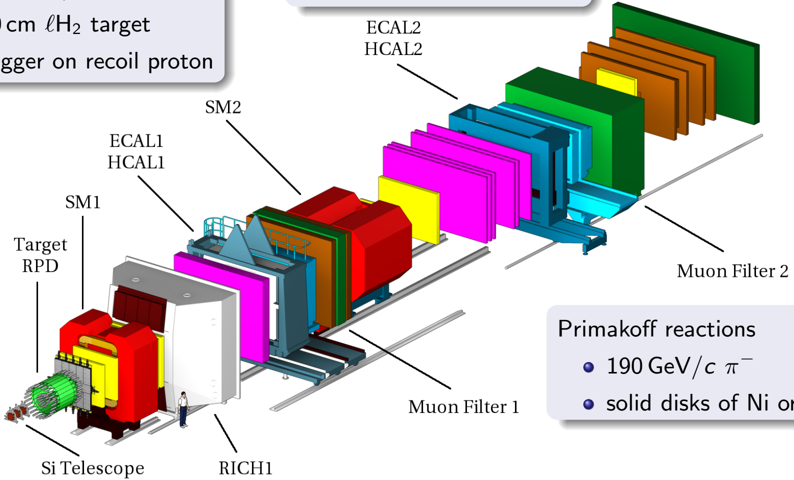
- study of χPT
- e.-m. properties of light mesons

central production

- 190 GeV/c p
- 40 cm ℓH_2 target
- trigger on recoil proton

diffractive dissociation

- 190 GeV/c π^-, K^-
- 40 cm ℓH_2 target
- trigger on recoil proton

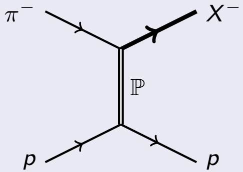


Primakoff reactions

- 190 GeV/c π^-
- solid disks of Ni or Pb

Diffractive Processes

diffractive dissociation

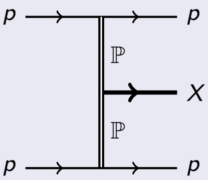


$0.1 < t' < 1\,\text{GeV}^2/c^2$

X^-:

- $\pi^-\pi^-\pi^+$
- $\pi^-\pi^0\pi^0$
- $\pi^-\eta$
- $\pi^-\eta'$

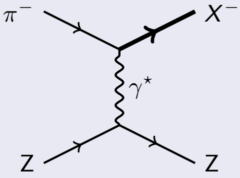
central production



X:

- $\pi^-\pi^+$
- K^-K^+

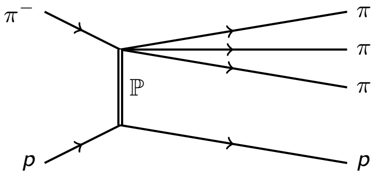
Primakoff reactions

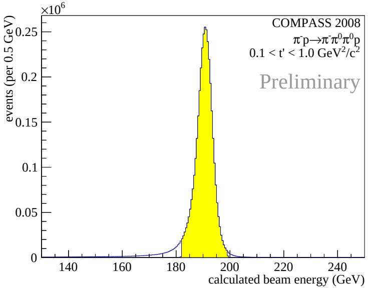


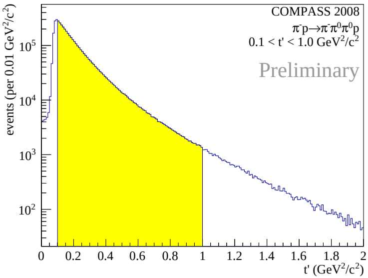
$t' < 0.001\,\text{GeV}^2/c^2$

X^-:

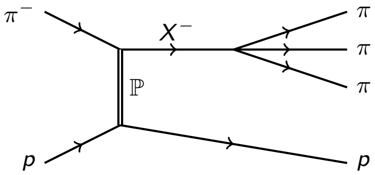
- $\pi^-\pi^-\pi^+$
- $\pi^-\pi^0\pi^0$
- $\pi^-\gamma$

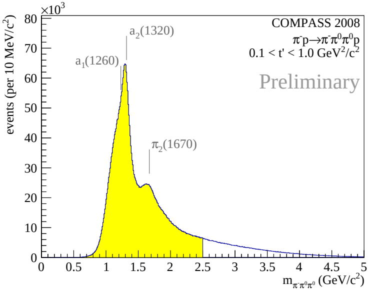






- exclusive $\pi^- p \to (3\pi)^- p$ reaction
- two channels in COMPASS
  - $\pi^-\pi^-\pi^+$
  - $\pi^-\pi^0\pi^0$
- high-t' region: $0.1 < t' < 1.0\,\text{GeV}^2/c^2$





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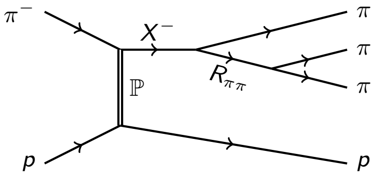
- high-t' region: $0.1 < t' < 1.0\,\mathrm{GeV}^2/c^2$
- huge dataset
  - 50 million $\pi^-\pi^-\pi^+$ events
  - 3.5 million $\pi^-\pi^0\pi^0$ events



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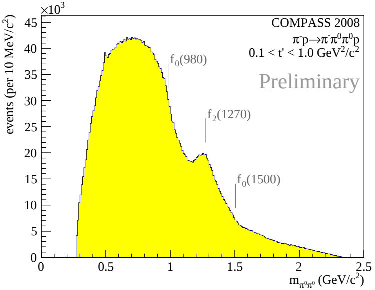
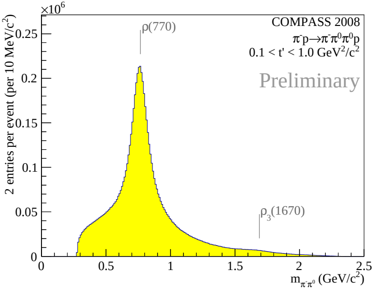
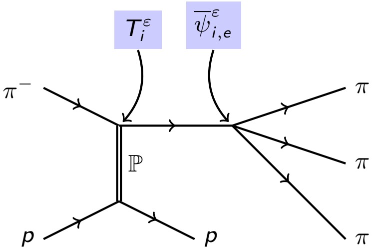
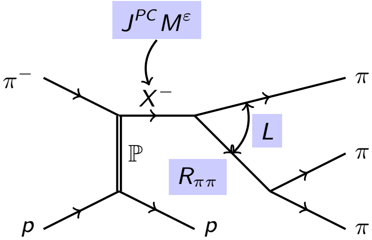
- partial-wave analysis using isobar model







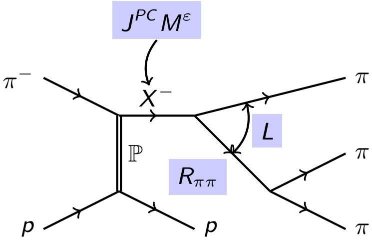
- process can be factorized
  - production T_i^ε
  - decay $\overline{\psi}_{i,e}^\varepsilon$



- process can be factorized
  - production T_i^{ε}
  - decay $\overline{\psi}_{i,e}^{\varepsilon}$

- 88 waves
  - 80 with positive reflectivity
  - 7 with negative reflectivity
  - flat wave
- spin J up to 6
- angular momentum L between bachelor π and isobar up to 6

- $(\pi\pi)_S$
- $f_0\,(980)$
- $f_2\,(1270)$
- $f_0\,(1500)$
- $\rho\,(770)$
- $\rho_3\,(1690)$
- for $\pi^-\pi^-\pi^+$ all isobars are $\pi^-\pi^+$
- for $\pi^-\pi^0\pi^0$ split to
  - $\pi^-\pi^0$: ρ, ρ_3
  - $\pi^0\pi^0$: $(\pi\pi)_S$, $2 \times f_0$, f_2



- process can be factorized
  - production T_i^{ε}
  - decay $\overline{\psi}_{i,e}^{\varepsilon}$
- two-step approach

1. fit in mass bins
   - extract production amplitudes T_i^{ε}

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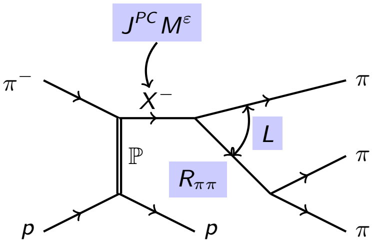

- process can be factorized
  - production T_i^{ε}
  - decay $\overline{\psi}_{i,e}^{\varepsilon}$
- two-step approach

1. fit in mass bins
   - extract production amplitudes T_i^{ε}
2. fit of mass dependence of spin-density matrix

- 88 waves
  - 80 with positive reflectivity
  - 7 with negative reflectivity
  - flat wave
- spin J up to 6
- angular momentum L between bachelor π and isobar up to 6

- $(\pi\pi)_S$
- $f_0\,(980)$
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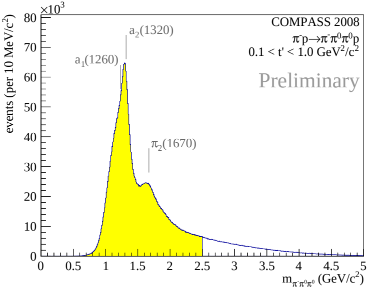
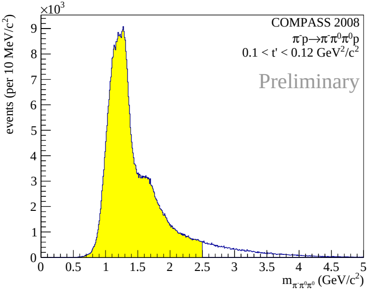
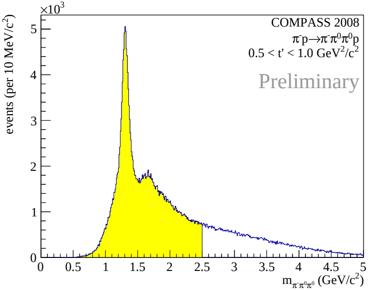
  - $\pi^-\pi^0$: ρ, ρ_3
  - $\pi^0\pi^0$: $(\pi\pi)_S$, $2 \times f_0$, f_2

Binning in t'

- mass spectrum depends on t'
- at low-t' ($0.1 < t' < 0.2\,\mathrm{GeV}^2/c^2$)
  - a_1 (1260) dominates low-mass region
  - a_2 (1320) hardly visible
- at high-t' ($0.5 < t' < 1.0\,\mathrm{GeV}^2/c^2$)
  - a_1 (1260) visible only as a shoulder
  - a_2 (1320) dominant
- no changes above π_2 (1670) region
- binning of data also in t'
  - 11 bins for $\pi^-\pi^-\pi^+$
  - 8 bins for $\pi^-\pi^0\pi^0$



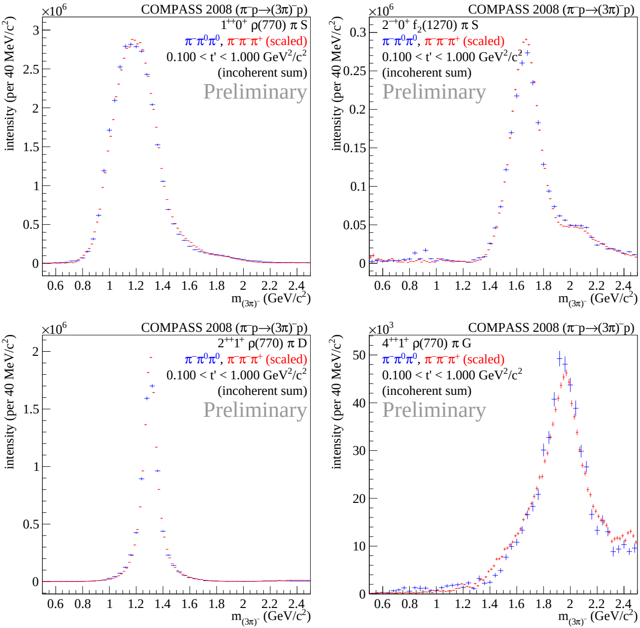




Mass-independent fit

major waves

- $1^{++}0^{+}\rho(770)\,\pi S$
- $2^{-+}0^{+}f_2(1270)\,\pi S$
- $2^{++}1^{+}\rho(770)\,\pi D$
- $4^{++}1^{+}\rho(770)\,\pi G$

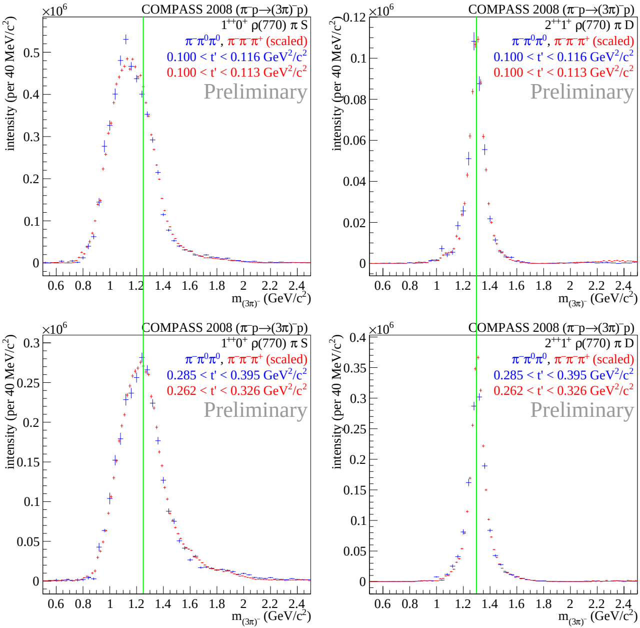


- $\pi^-\pi^0\pi^0$
- $\pi^-\pi^-\pi^+$ (scaled)
- scaled for each plot
- agreement between channels

Mass-independent fit

different t' bins

- $1^{++}0^{+}\rho(770)\,\pi S$
- $2^{++}1^{+}\rho(770)\,\pi D$
- position of peak in $1^{++}0^{+}$ changes
- a_2 not affected



- $\pi^-\pi^0\pi^0$
- $\pi^-\pi^-\pi^+$ (scaled)
- scaled for each plot
- agreement between channels

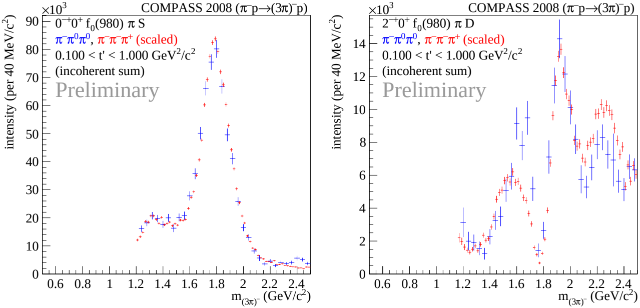
Mass-independent fit

f_0 (980) isobar

- $0^{-+}0^{+} f_0\,(980)\,\pi S$
- $2^{-+}0^{+} f_0\,(980)\,\pi D$

- stable fits also for non-ρ isobars

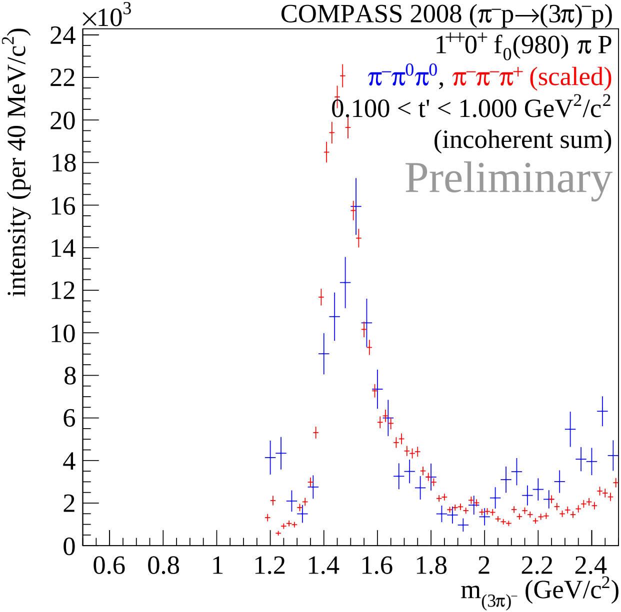
- $\pi^{-}\pi^{0}\pi^{0}$
- $\pi^{-}\pi^{-}\pi^{+}$ (scaled)
- scaled for each plot



f_0 (980) isobar

- $0^{-+}0^+ f_0\,(980)\,\pi S$
- $2^{-+}0^+ f_0\,(980)\,\pi D$
- $1^{++}0^+ f_0\,(980)\,\pi P$

- stable fits also for non-ρ isobars
- first observation of a signal in $1^{++}0^+ f_0\,(980)\,\pi P$ around 1.4 GeV/c^2



- $\pi^-\pi^0\pi^0$
- $\pi^-\pi^-\pi^+$ (scaled)
- scaled for each plot

Mass-dependent fit for $\pi^-\pi^-\pi^+$

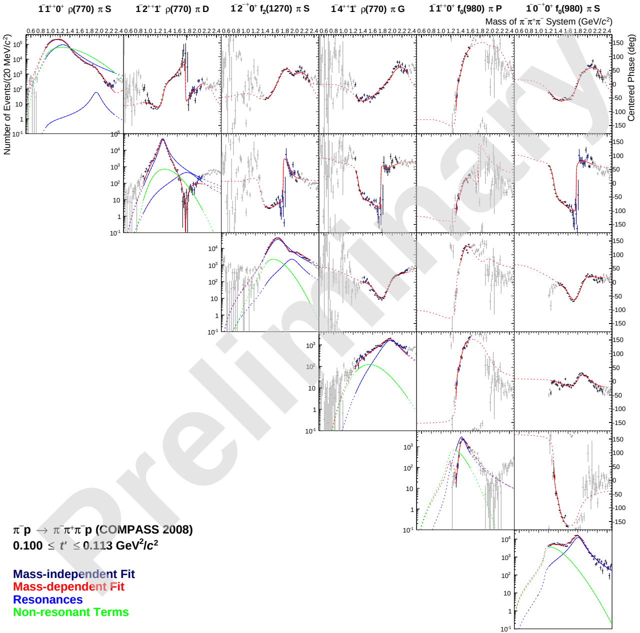
Model

- for the moment six waves
  - four major waves and two waves with $f_0\,(980)$ isobar
- describe spin-density sub-matrix with Breit-Wigner functions

$1^{++}0^+\rho\,(770)\,\pi S$	two BW:	$a_1\,(1260)$, a_1'
$2^{-+}0^+f_2\,(1270)\,\pi S$	two BW:	$\pi_2\,(1670)$, $\pi_2\,(1880)$
$2^{++}1^+\rho\,(770)\,\pi D$	two BW:	$a_2\,(1320)$, a_2'
$4^{++}1^+\rho\,(770)\,\pi G$	one BW:	$a_4\,(2040)$
$1^{++}0^+f_0\,(980)\,\pi P$	one BW:	$a_1\,(1420)$
$0^{-+}0^+f_0\,(980)\,\pi S$	one BW:	$\pi\,(1800)$

- non-resonant term for each wave
- 352 free parameters, around 15 000 data points

Mass-dependent fit for $\pi^-\pi^-\pi^+$

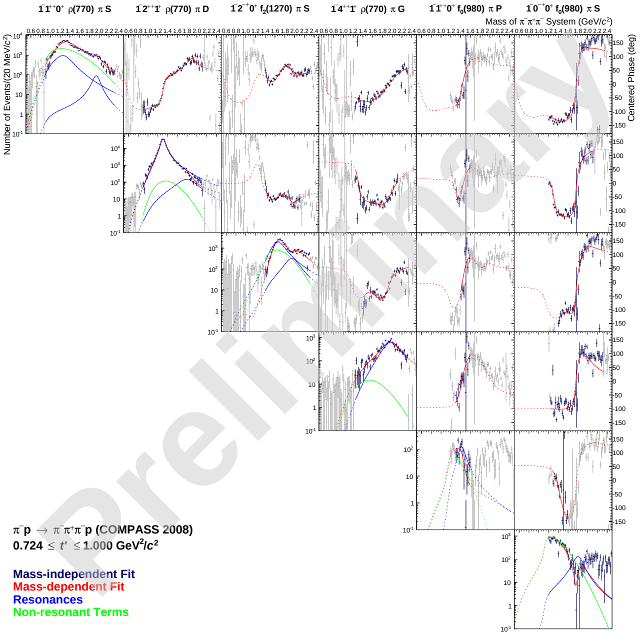


$\pi^- p \to \pi^-\pi^+\pi^- p$ (COMPASS 2008)

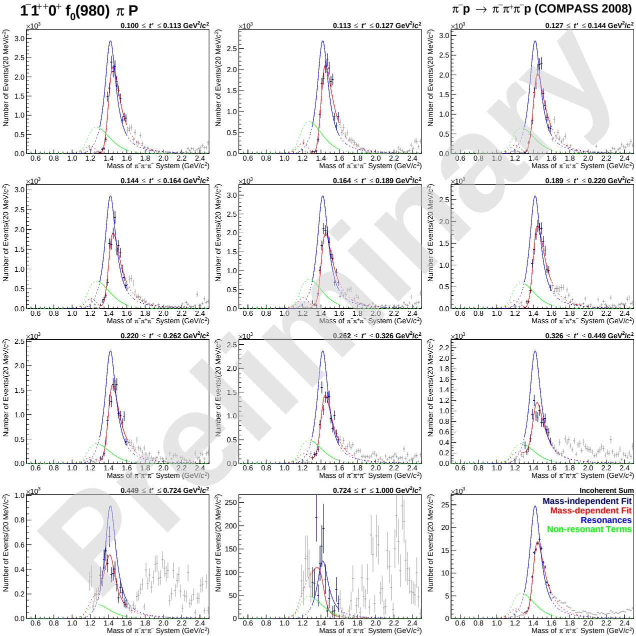
$0.100 \leq t' \leq 0.113$ GeV$^2/c^2$

Mass-independent Fit
Mass-dependent Fit
Resonances
Non-resonant Terms

Mass-dependent fit for $\pi^-\pi^-\pi^+$



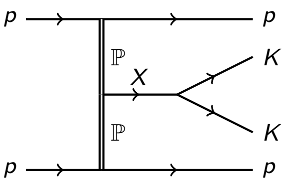
Mass-dependent fit of $1^{++}0^{+} f_0(980)\,\pi P$

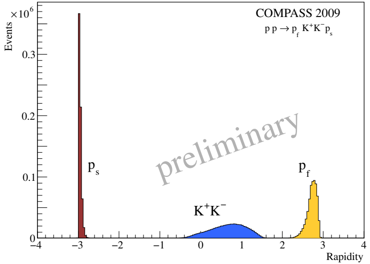


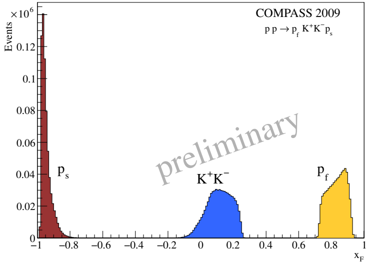
Mass-dependent fit for $\pi^-\pi^-\pi^+$

	J^{PC}	mass range (MeV/c^2)	width range (MeV/c^2)	PDG	
		major waves			
$a_1\,(1260)$	1^{++}	$1260 - 1290$	$360 - 420$	1230 ± 40	$250 - 400$
$a_2\,(1320)$	2^{++}	$1312 - 1315$	$108 - 115$	$1318.3^{+0.5}_{-0.6}$	$105^{+1.6}_{-1.9}$
$\pi_2\,(1670)$	2^{-+}	$1635 - 1663$	$265 - 305$	1672.2 ± 3.0	260 ± 9
$a_4\,(2040)$	4^{++}	$1928 - 1959$	$360 - 400$	1996^{+10}_{-9}	255^{+28}_{-24}
$\pi\,(1800)$	0^{-+}	$1790 - 1807$	$212 - 230$	1812 ± 12	208 ± 12
$\pi_2\,(1880)$	2^{-+}	$1900 - 1990$	$210 - 390$	1895 ± 16	235 ± 34
		states not in PDG summary table			
$a_1\,(1930)$	1^{++}	$1920 - 2000$	$155 - 255$	1930^{+30}_{-70}	155 ± 45
$a_2\,(1950)$	2^{++}	$1740 - 1890$	$300 - 555$	1950^{+30}_{-70}	180^{+30}_{-70}
$a_1\,(1420)$	1^{++}	$1412 - 1422$	$130 - 150$		

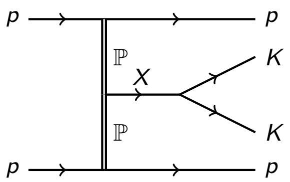
$pp \to pK^-K^+p$

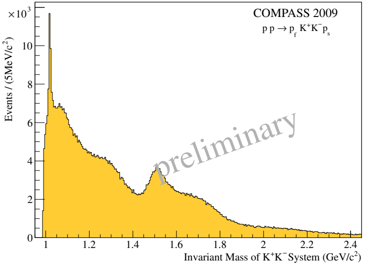






- exclusive $\pi^- p \to pK^-K^+p$ reaction
- rapidity gap to identify central system

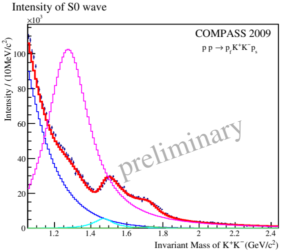


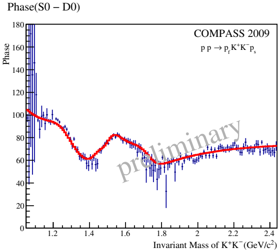


- exclusive $\pi^- p \to pK^-K^+p$ reaction
- rapidity gap to identify central system
- disentangle K^-K^+ mass spectrum
  - using PWA
  - identify isoscalar resonances
- further possible final states: $\pi^-\pi^+$, $\pi^0\pi^0$, $\eta\eta$, ...

Mass-dependent fit for $K^- K^+$

- focus on two most prominent waves
- resonances described by dynamic-width relativistic Breit-Wigner functions
- coherent background



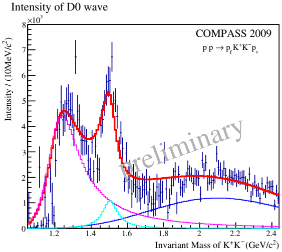


resonances in D_0^-

- $f_2\,(1270)$
- $f_2'\,(1525)$

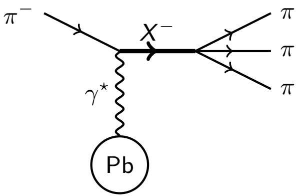
resonances in S_0^-

- $f_0\,(1500)$
- $f_0\,(1710)$
- $f_0\,(1370)$ as broad state
  - required to account for phase wrt. D_0^-



- decay $X \to \pi\gamma$ allows access to electromagnetic transitions
  - $a_2\,(1320) \to \pi\gamma$ magnetic quadrupole moment
  - $\pi_2\,(1670) \to \pi\gamma$ electric quadrupole moment
- direct measurement of $\pi\gamma$ decay is experimentally challenging
- inverse process: scattering of a π off a Coulomb potential
  - quasi-real photons in the vicinity of heavy nuclei
- cross-section for Primakoff produced X

$$\sigma_{\text{Primakoff},X} \propto \Gamma_0\,(X \to \pi\gamma)$$



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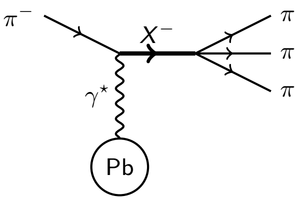


identify Primakoff contribution

- Primakoff produced states have spin projection $M = 1$
- cross-section for diffractively produced states

$$\sigma \propto t'^{M} e^{-bt'}$$

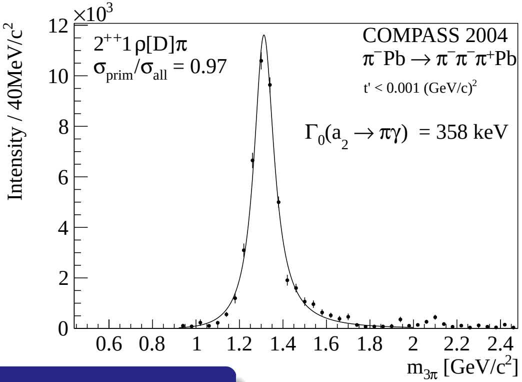
- at small t' $M = 1$ states are predominantly Primakoff produced
- partial-wave analysis to identify the $M = 1$ final states
- count number of final states to get cross-section

measurements

- SELEX (2001)
  $(284 \pm 25 \pm 25)$ keV
- E272 (1982)
  (295 ± 60) keV
- May et al. (1977)
  (0.46 ± 0.11) MeV

- COMPASS
  $(358 \pm 6 \pm 42)$ keV

EPJ A Highlight: EPJ A 50: 79 (2014)



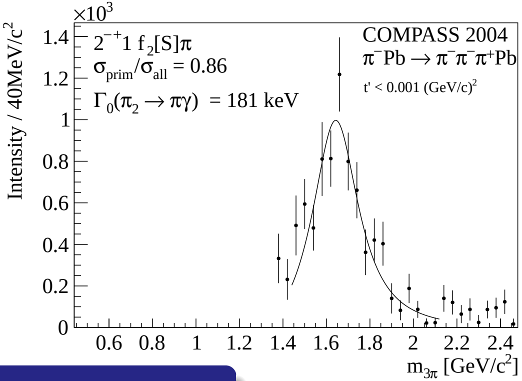
theoretical predictions

- Vector Meson Dominance Model
  375 keV (Rosner, 1981)
- Relativistic Quark Mode
  324 keV (Aznauryan and Ogamesyan, 1988)
- Covariant Oscillator Quark Model
  235 keV (Ishida et al., 1989)

Radiative width of $\pi_2(1670)$

EPJ A Highlight: EPJ A 50: 79 (2014)

first measurement

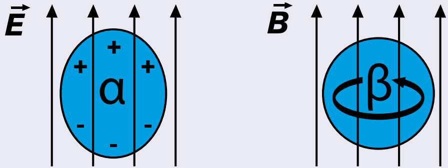


- COMPASS
  $(181 \pm 11 \pm 27)$ keV

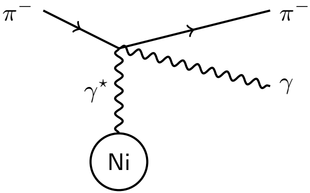
theoretical predictions

- Covariant Oscillator Quark Model
  335 keV and
  521 keV (both Maeda et al., 2013)

- π in strong electromagnetic field



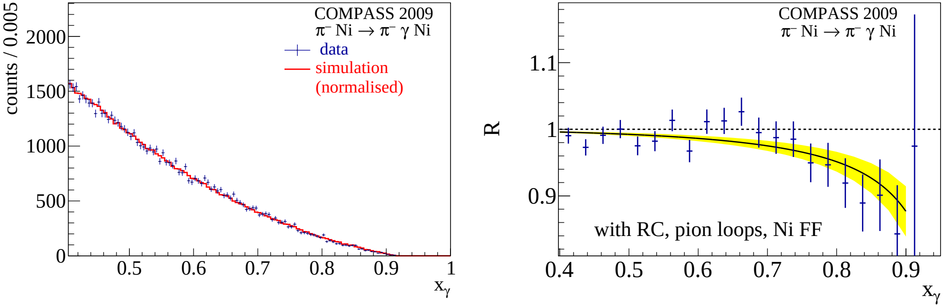
- prediction by χPT:
  $\alpha_\pi - \beta_\pi = (5.7 \pm 1.0) \times 10^{-4}\,\text{fm}^3$



- measure deviation of cross-section from expectation for point-like particle
- assumption

$$\alpha_\pi = -\beta_\pi$$

- use π and μ beams at COMPASS
- measure the fake-polarizability of the μ to verify simulation



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

- in tension with previous experiments
- in agreement with χPT predictions

Outlook

- more data taken in 2012
- separate measurement of α_π and β_π
- polarizability of K

Summary

COMPASS is a precision experiment to study light mesons

- unchallenged dataset for $\pi^-\pi^-\pi^+$
- charged and neutral particles with the same experimental setup

partial-wave analysis is a versatile tool for

- spectroscopy
  - various channels under study
  - t' resolved analysis, first mass-dependent fit in more than one t' bin
  - new resonance $a_1(1420)$:
    - $M_{a_1(1420)} = 1412 - 1422\,\text{MeV}/c^2$, $\Gamma_{a_1(1420)} = 130 - 150\,\text{MeV}/c^2$
    - full phase motion with respect to reference waves
- studies of light meson structure
  - measurement of radiative width of $a_2(1320)$ and $\pi_2(1670)$

tests of χPT

- measurement of π polarizability

Backup

data binned

- in 50 mass bins of 40 MeV/c^2 width
- in 8 t' bins with equal amount of statistics

in each mass and t' bin optimize

$$\log \mathcal{L} = -\sum_{e}^{\text{RD evts.}} \log \left(\sum_{\varepsilon}^{\text{refl.}} \left| \sum_{i}^{\text{waves}} T_i^{\varepsilon} \cdot \overline{\psi}_{i,e}^{\varepsilon} \right|^2 \right) + \sum_{\varepsilon}^{\text{refl.}} \left(\sum_{i,j}^{\text{waves}} T_i^{\varepsilon} \cdot \left(T_j^{\varepsilon}\right)^* \cdot \overline{\mathcal{A}}_{ij}^{\varepsilon} \right)$$

Spin-density matrix

$$\rho_{ij}^{\varepsilon} = T_i^{\varepsilon} \cdot \left(T_j^{\varepsilon}\right)^*$$

intensity

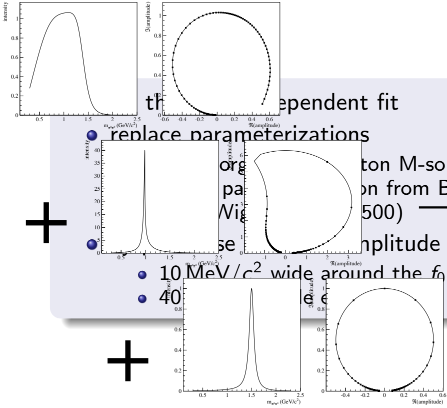
$$I_i^{\varepsilon} = \rho_{ii}^{\varepsilon}$$

absolute value and phase

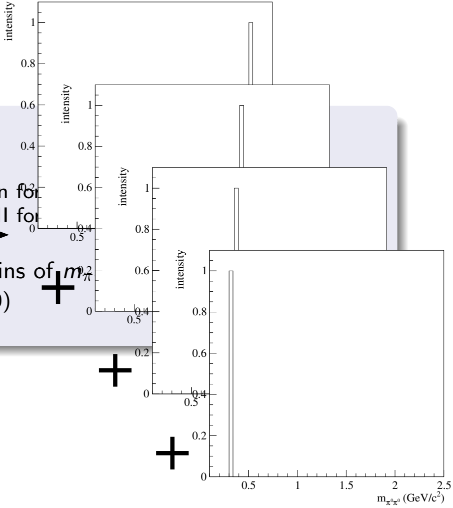
$$\rho_{ij}^{\varepsilon} = r_{ij}^{\varepsilon} e^{i \cdot \varphi_{ij}^{\varepsilon}}$$

Extraction of $(\pi\pi)_S$ wave from data

- for the mass-independent fit
- replace parameterizations
  - Au, Morgen, Pennington M-solution for $(\pi\pi)_S$ wave
  - Flatté parameterization from BES-II for $f_0\,(980)$
  - Breit-Wigner for $f_0\,(1500)$
- by piecewise constant amplitude in bins of $m_{\pi\pi}$
  - $10\,\mathrm{MeV}/c^2$ wide around the $f_0\,(980)$
  - $40\,\mathrm{MeV}/c^2$ wide elsewhere



- th… …ependent fit
- replace parameterizations
  - …org… …ton M-solution for…
  - …pa… …on from BES-II for…
  - …Wig… …500)
- …se… …nplitude in bins of m_{π}…
  - 10 MeV/c^2 wide around the $f_0(980)$
  - 40 … …le e…



- for the mass-independent fit
- replace parameterizations
  - Au, Morgen, Pennington M-solution for $(\pi\pi)_S$ wave
  - Flatté parameterization from BES-II for $f_0\,(980)$
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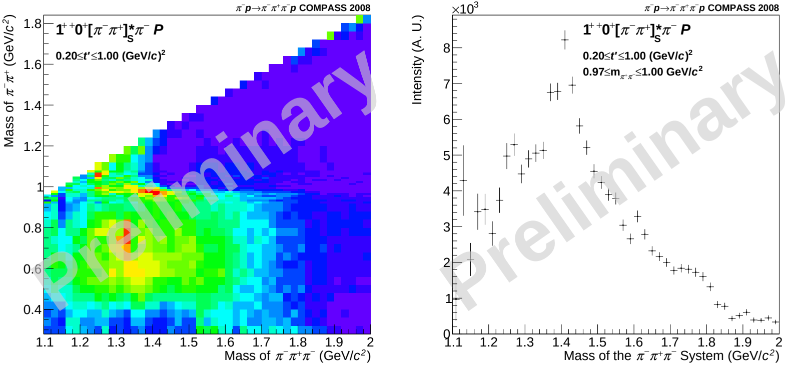
- by piecewise constant amplitude in bins of $m_{\pi\pi}$
  - $10\,\mathrm{MeV}/c^2$ wide around the $f_0\,(980)$
  - $40\,\mathrm{MeV}/c^2$ wide elsewhere

- increase in number of fit parameters
- requires a lot of data
- only done for 0^{-+}, 1^{++}, 2^{-+}



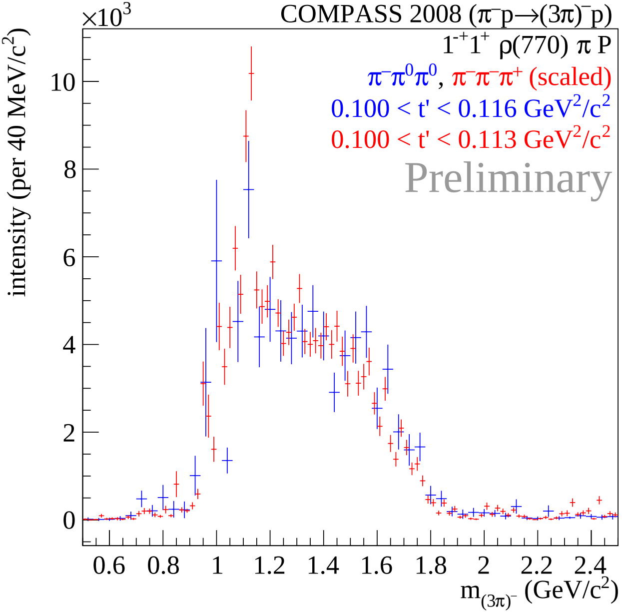
application to 1^{++}

- high-t': $0.2 < t' < 1.0\,\text{GeV}^2/c^2$
- select $m_{2\pi}$ region around $f_0(980)$
- correlation of $a_1(1420)$ with $f_0(980)$

Exotic $J^{PC} = 1^{-+}$ wave

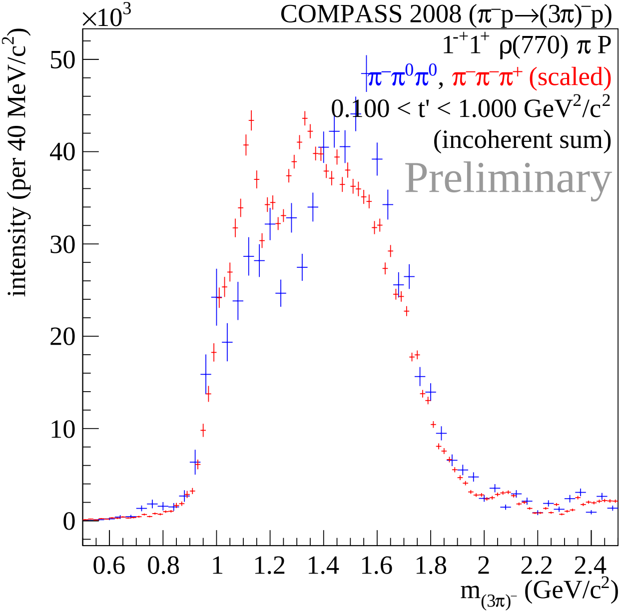
$1^{-+}1^{+}\rho(770)\,\pi P$

- agreement at low-t'

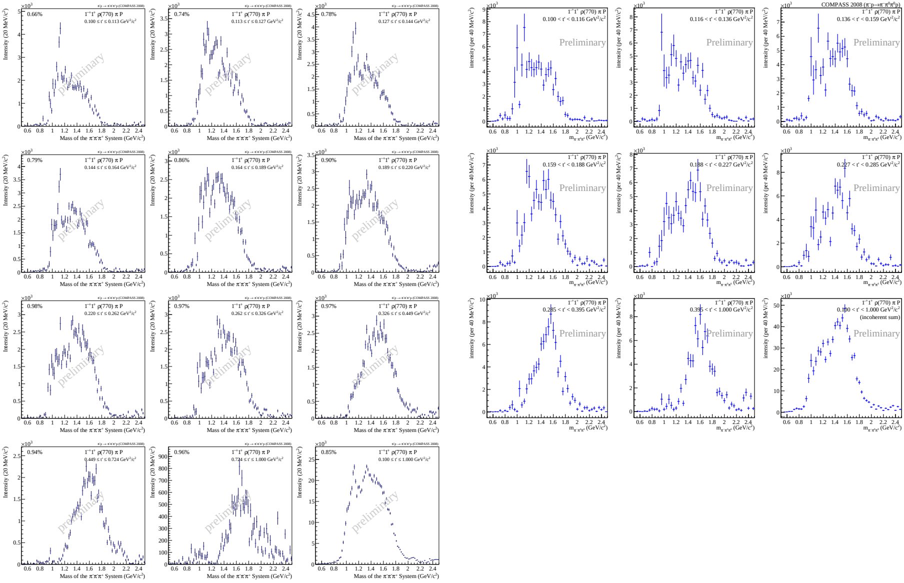


$1^{-+}1^{+}\rho(770)\,\pi P$

- agreement at low-t'
- differences for complete t' range

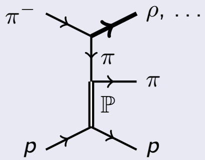


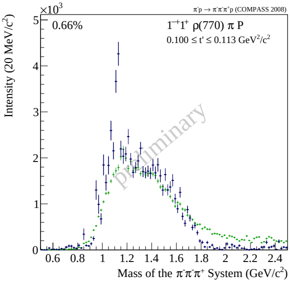
Exotic $J^{PC} = 1^{-+}$ wave

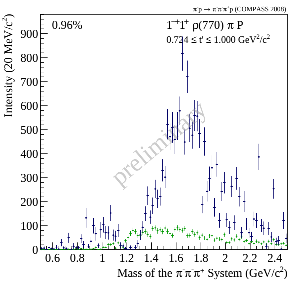


$1^{-+}1^{+}\rho(770)\,\pi P$

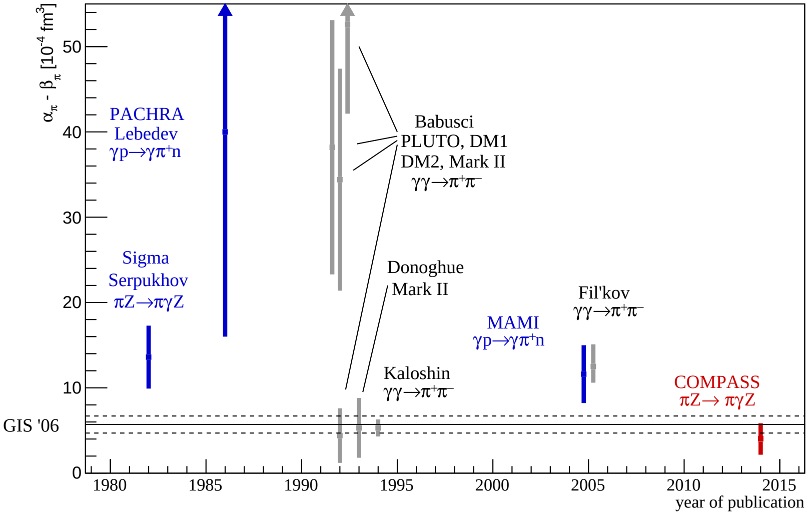
- agreement at low-t'
- differences for complete t' range
- non-resonant contribution
- especially at low-t'
- Deck-effect?

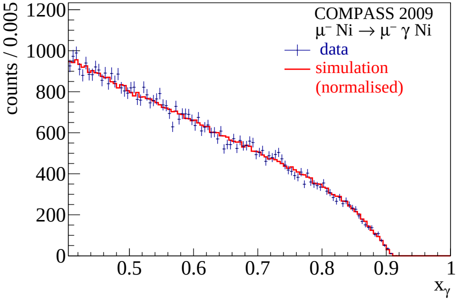


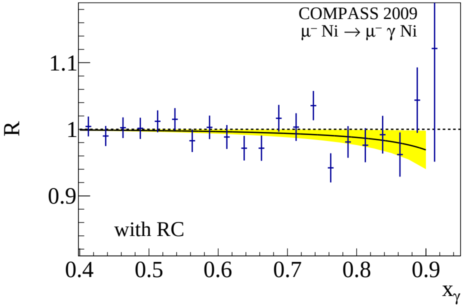




π polarizability







$$\alpha_\mu = (0.5 \pm 0.5) \times 10^{-4}\ \mathrm{fm}^3$$