Physics with Hadronic Probes at COMPASS

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MESON 2008

10th International Workshop on Meson Production, Properties and Interaction

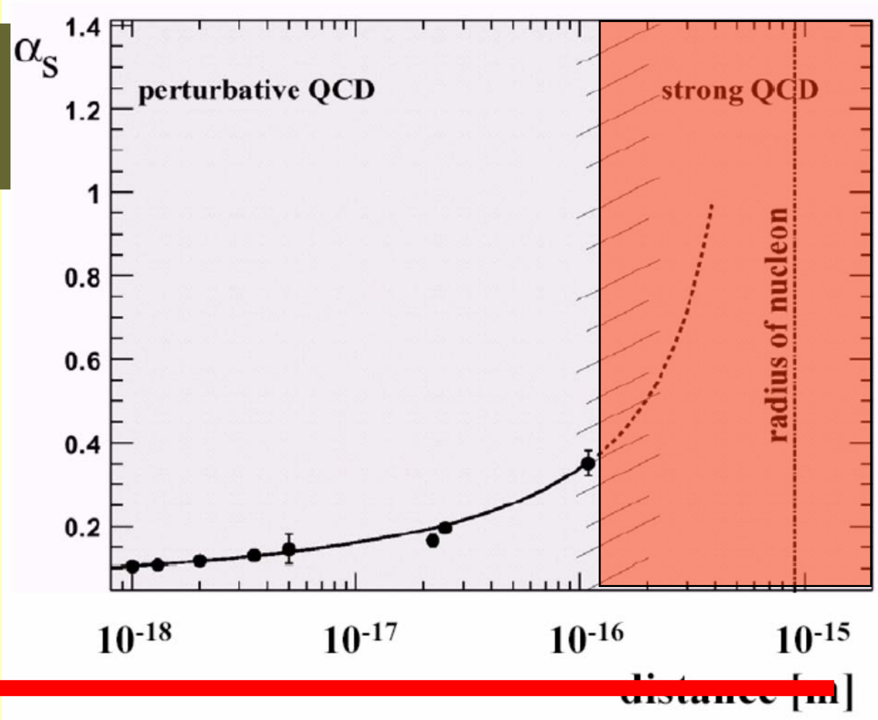
Krakow, Poland

6 June 2008

The Goal

Structure and dynamics of hadrons

⇨ non-perturbative regime of QCD



Theory:

- Models: QM, bag, flux tube, ...
- Effective theories: χPT, ...
- Lattice-QCD

Q^2 ←

Hard processes:

⇨ Nucleon structure
- Helicity
- Transversity
- GPDs

Spectroscopy:

⇨ Hadron mass spectrum

⇨ Gluonic excitations

⇨ Multi-quark systems

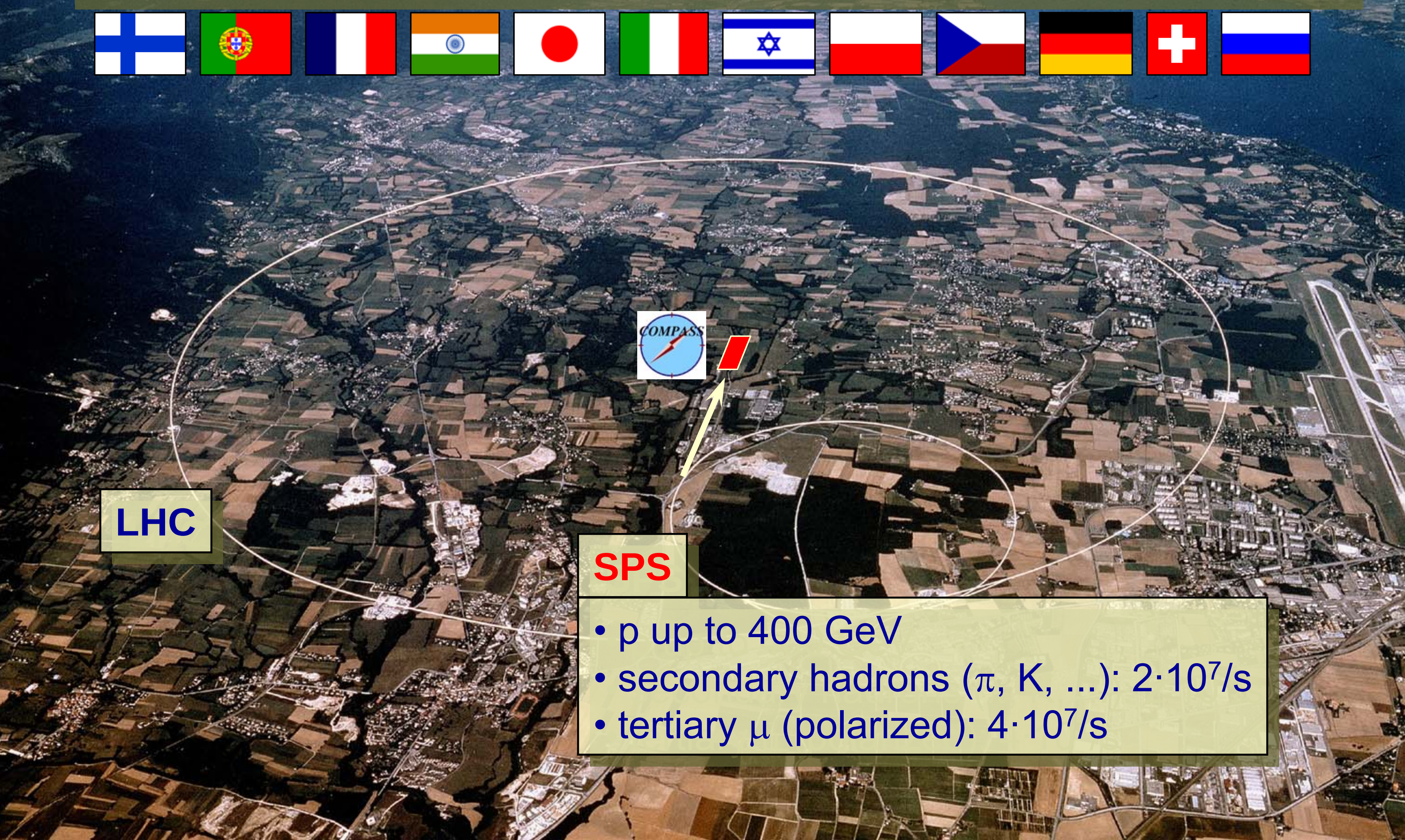
Scattering at very low Q^2:

⇨ Polarizabilities of π, K

⇨ Chiral anomaly: $F_{3\pi}$

COMPASS at CERN

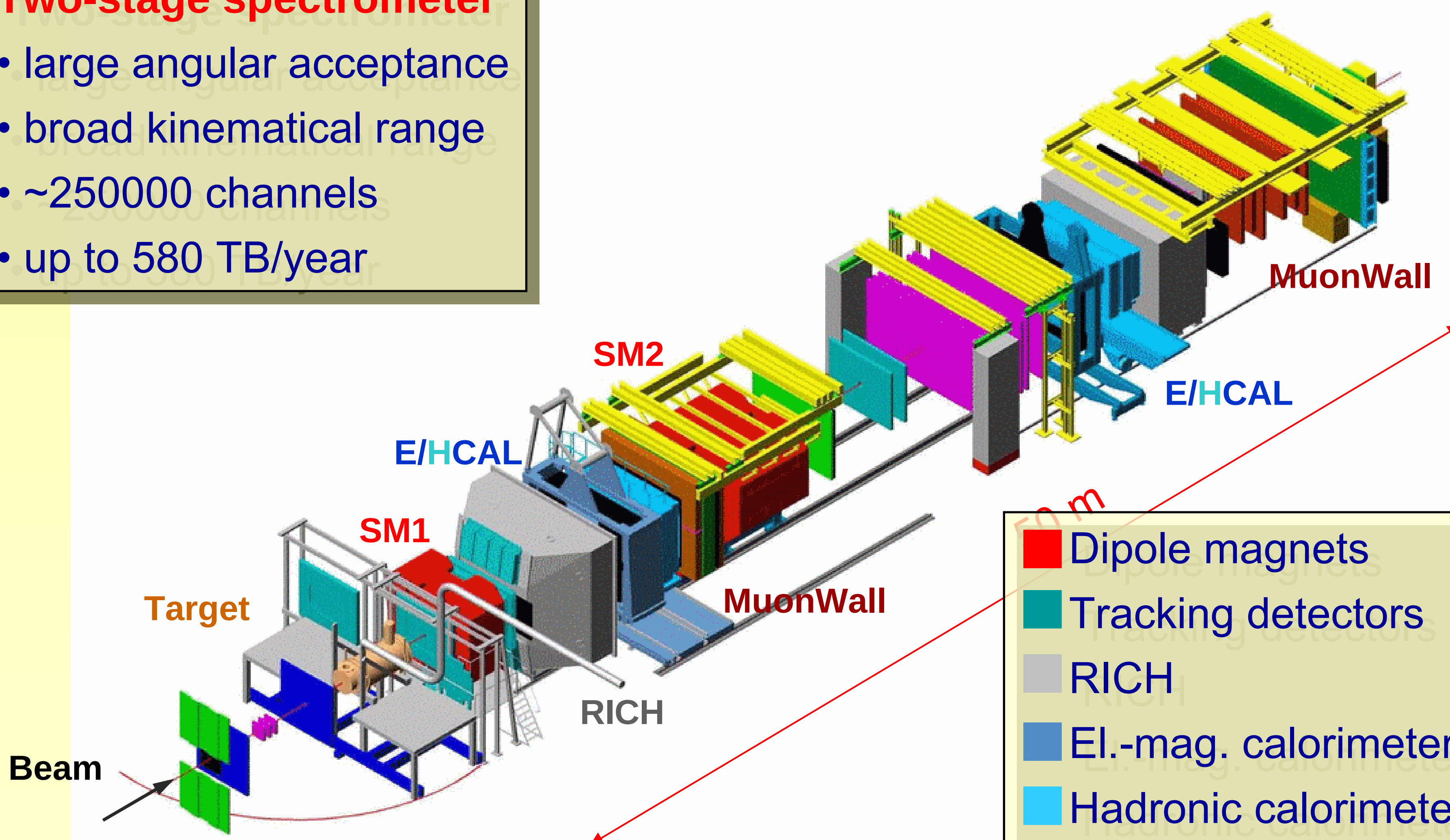
COmmon **M**uon and **P**roton **A**pparatus for **S**tructure and **S**pectroscopy



- p up to 400 GeV
- secondary hadrons (π, K, ...): $2 \cdot 10^7$/s
- tertiary μ (polarized): $4 \cdot 10^7$/s

The COMPASS Experiment

Two-stage spectrometer
- large angular acceptance
- broad kinematical range
- ~250000 channels
- up to 580 TB/year



- Dipole magnets
- Tracking detectors
- RICH
- El.-mag. calorimeter
- Hadronic calorimeter
- Muon identification

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

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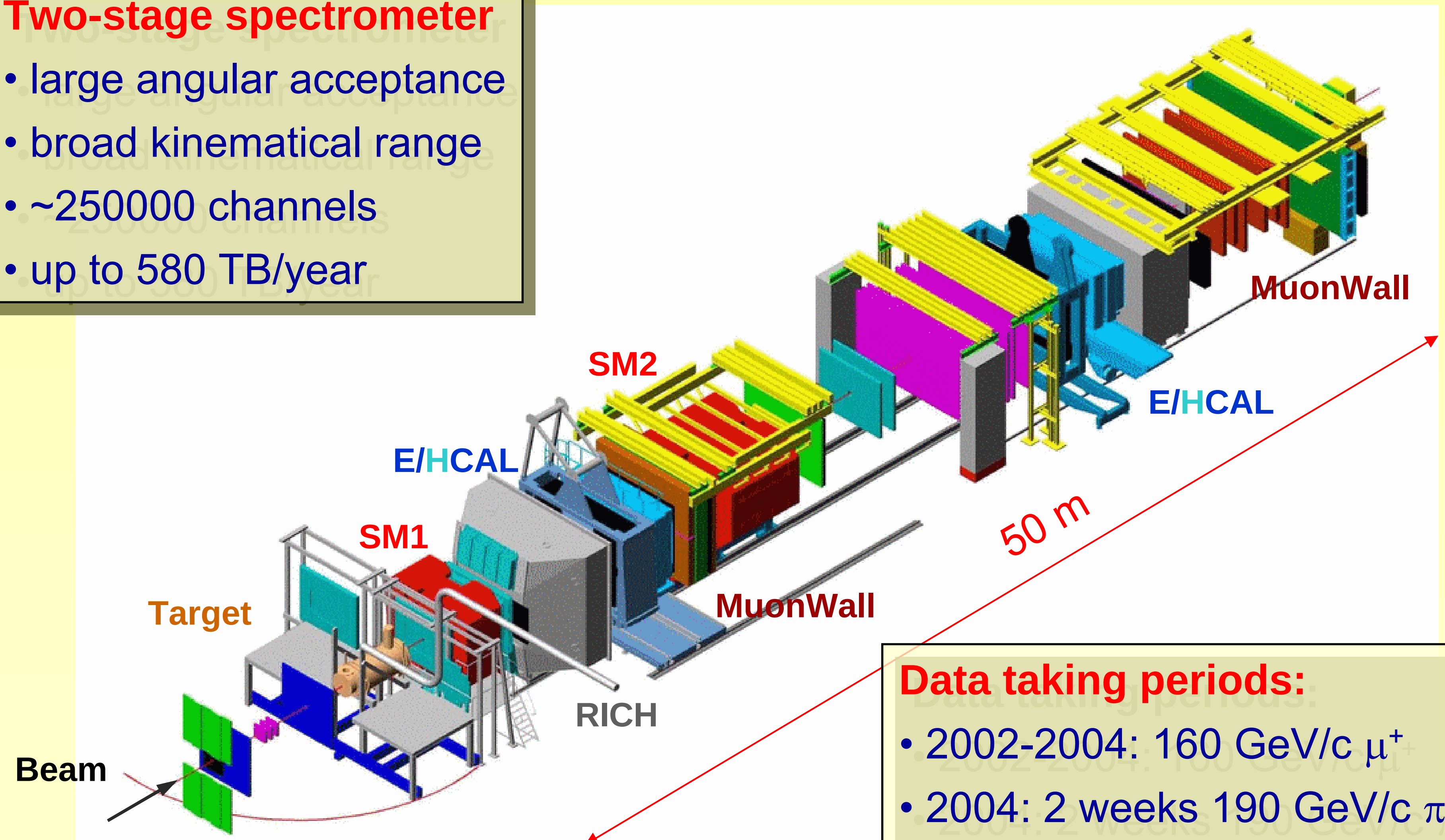

[hep-ex/0703049, NIM A 577, 455 (2007)]

Data taking periods:
- 2002-2004: 160 GeV/c μ^+
- 2004: 2 weeks 190 GeV/c π^-
- 2006-2007: 160 GeV/c μ^+

The COMPASS Experiment

Two-stage spectrometer
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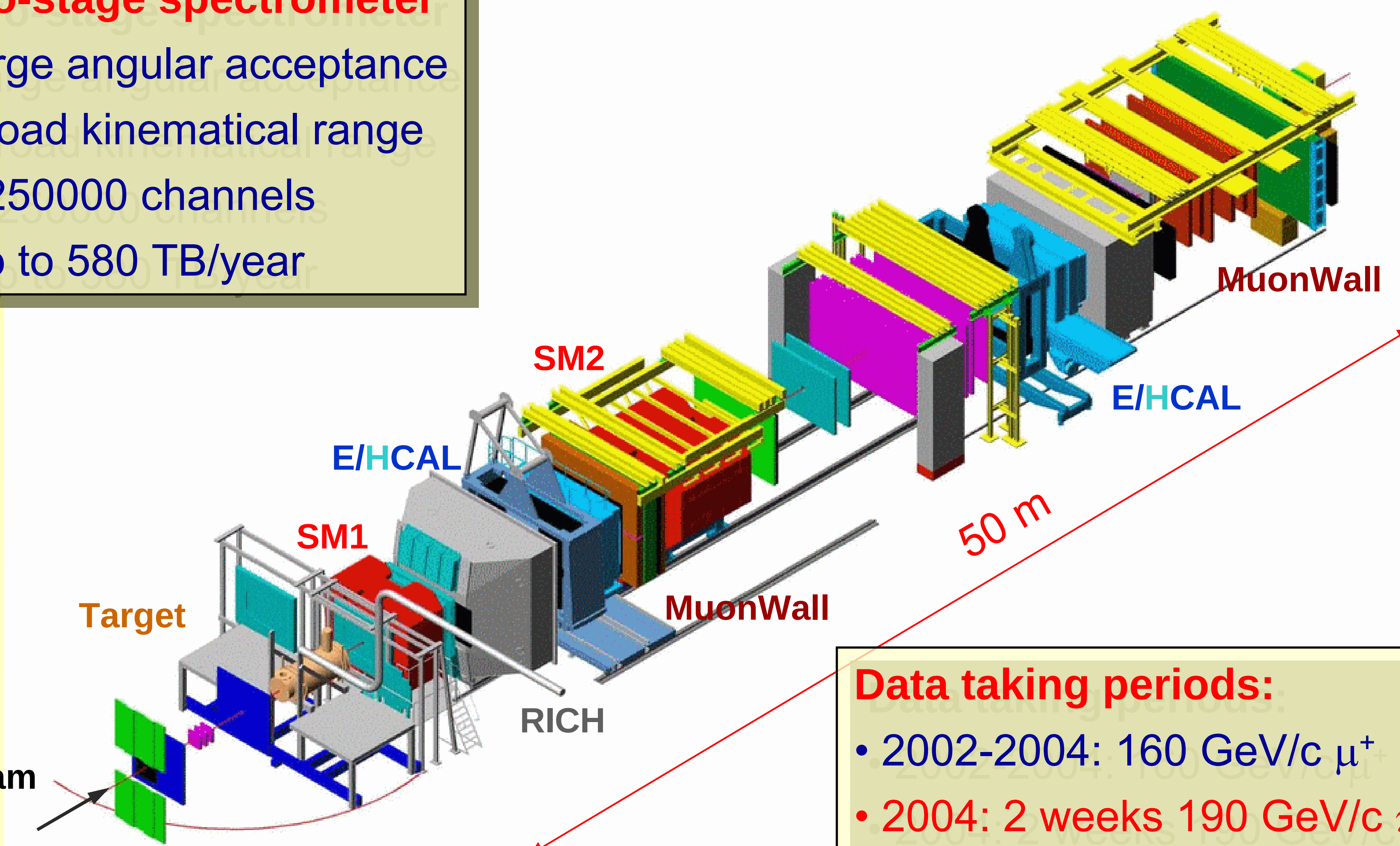

[hep-ex/0703049, NIM A 577, 455 (2007)]

Data taking periods:
- 2002-2004: 160 GeV/c μ^+
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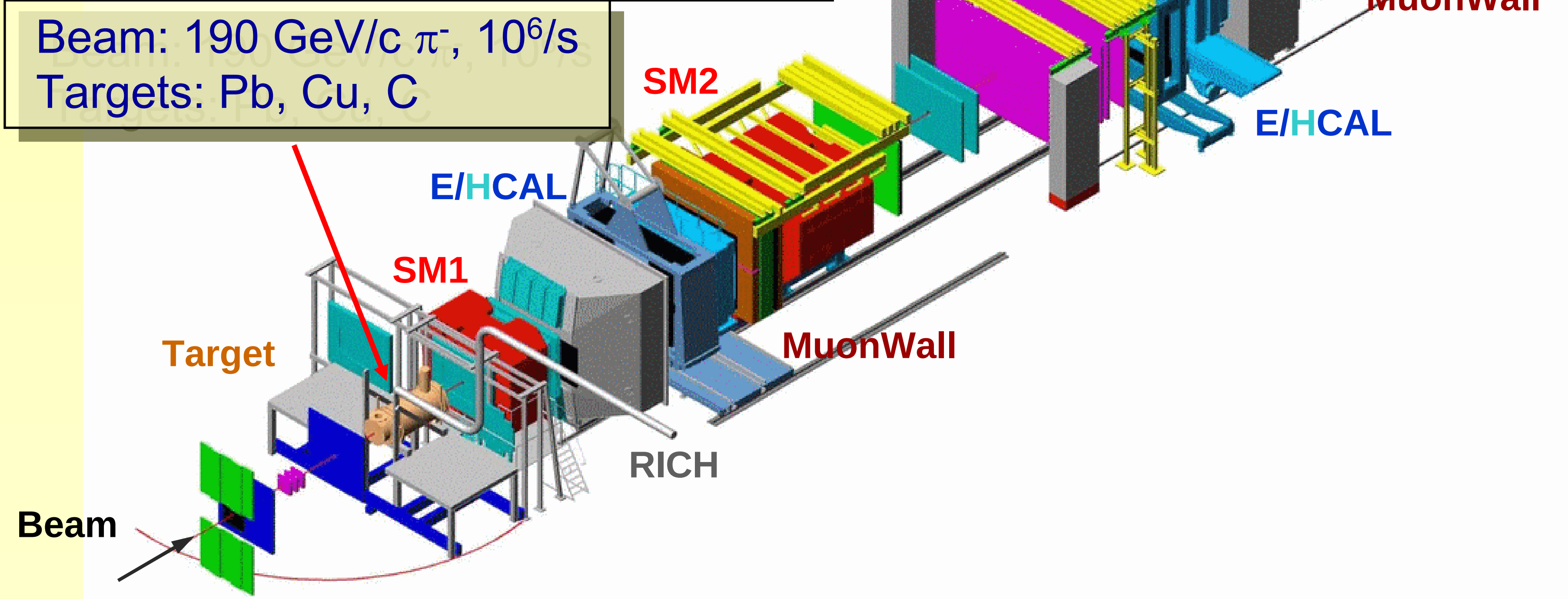
The COMPASS Experiment

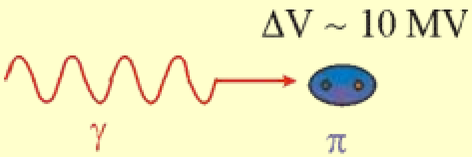
Beam: 190 GeV/c π^-, 10^6/s
Targets: Pb, Cu, C



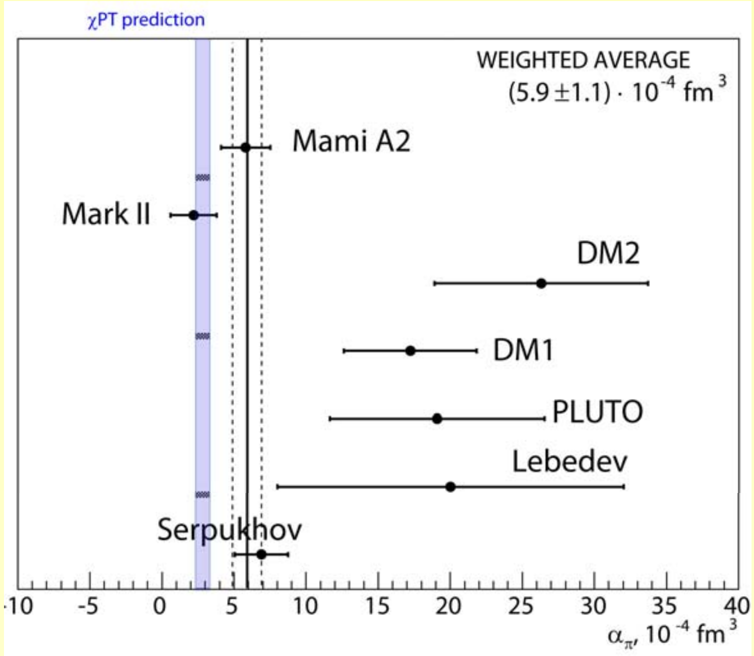
Pion Polarizabilities

Describe response to external e.m. fields ⇨ stiffness of system

- electric polarizability $\vec{d} = \overline{\alpha}\,\vec{E}$
- magnetic polarizability $\vec{\mu} = \overline{\beta}\,\vec{H}$

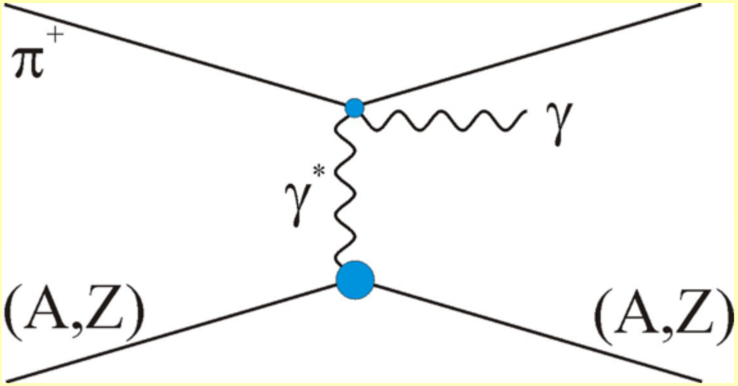


	α_π (10^{-4} fm^3)	$\alpha_\pi+\beta_\pi$ (10^{-4} fm^3)	$\alpha_\pi-\beta_\pi$ (10^{-4} fm^3)
χPT			
Buergi, Gasser		0.2±0.1	5.7±1.0
$\gamma p \to \gamma \pi^+ n$			
Lebedev (86)	20±12		
MAMI A2 (05)			11.6±1.5±3.0±0.5
$\gamma\gamma \to \pi^+\pi^-$			
PLUTO (84)	19.1±4.8±5.7		
DM1 (86)	17.2±4.6		
DM2 (86)	26.3±7.4		
Mark II (92)	2.2±1.6		
$\pi^- Z \to \gamma \pi^- Z$			
Serpukhov (85)	6.8±1.4±1.2	1.4±3.1±2.8	



Measurement of Polarizabilities

- Measurable in **Compton** scattering
- **Primakoff** reaction: inverse kinematics
- Assume $\bar{\alpha}_\pi + \bar{\beta}_\pi = 0$
- Cross section



$$\frac{d\sigma_{\gamma\pi}^{\mathrm{Prim}}}{d\omega} = \frac{d\sigma_{\gamma\pi}^{\mathrm{Thomson}}}{d\omega} + $$

$$+ 4Z^2\alpha^2 m_\pi \frac{\omega}{E_{\mathrm{beam}}} \bar{\beta}_\pi \left(\ln \frac{Q^2_{\mathrm{max}}}{Q^2_{\mathrm{min}}} - 3 + 4\sqrt{\frac{Q^2_{\mathrm{min}}}{Q^2_{\mathrm{max}}}} \right)$$

$$\omega = E_\gamma / E_{\mathrm{beam}}$$

$$Q_{\mathrm{min}} = \frac{m_\pi^2}{2E_{beam}} \frac{\omega}{1-\omega}$$

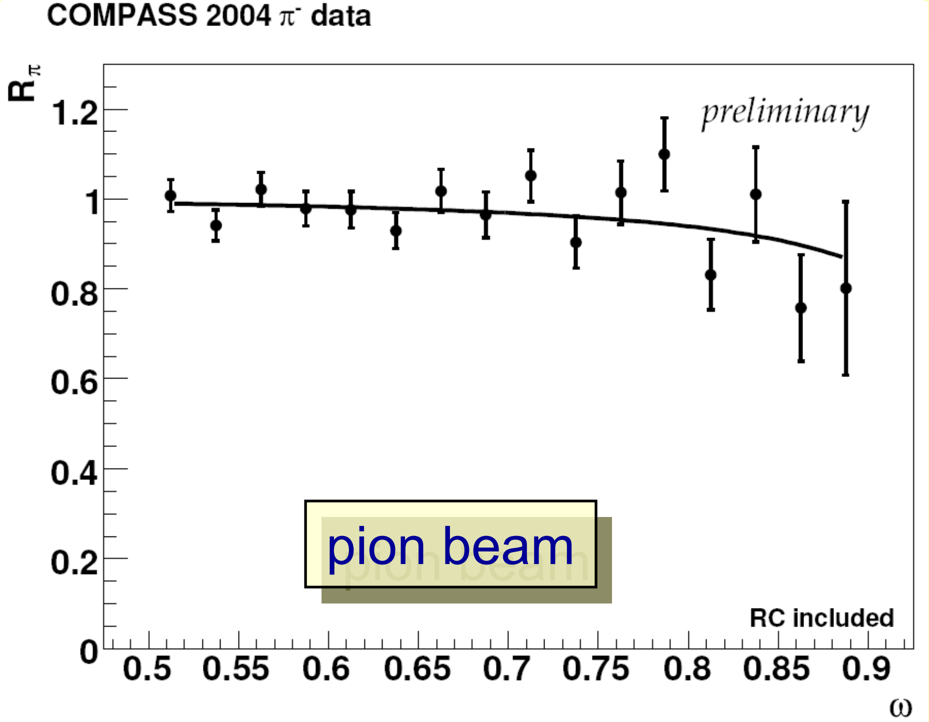
minimum Q to produce real photon

$$Q^2_{\mathrm{max}} = 0.0075\,(\mathrm{GeV}/c)^2$$

defined by analysis cut

Cross Section Ratios

$$R(\omega) = \frac{N_{\mathrm{exp}}(\omega)}{N_{\mathrm{MC}}(\omega)} = \frac{d\sigma_{\gamma\pi}^{\mathrm{Prim}}}{d\sigma_{\gamma\pi}^{\mathrm{Thomson}}} \cong 1 + \frac{3}{2}\frac{m_\pi^3}{\alpha}\frac{\omega^2}{1-\omega}\bar{\beta}_\pi$$

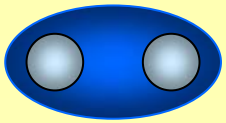


Status of analysis:

- Improve calibration of detectors (Si, ECAL)
- Improve MC description of setup
- Radiative corrections
  - π^- Compton
  - Pb nuclear form factor
- Suppress $\pi^-\pi^0$ background

waiting for final result...

Meson Spectroscopy

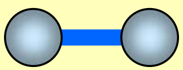


Quark model: bound state of $q\bar{q}$

Quantum numbers: $I^G\ (J^{PC})$

$$P=(-1)^{l+1},\ C=(-1)^{l+s},\ G=(-1)^{I+l+s}$$

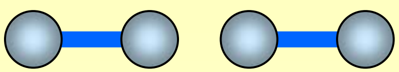
=



$(q\bar{q})_0$

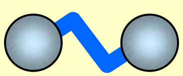
QCD: other color-neutral configurations with same quantum numbers ⇨ mixing

+



$(q\bar{q})(q\bar{q})$

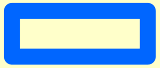
+



$(q\bar{q})_8\,g$

Hybrids

+



gg

Glueballs

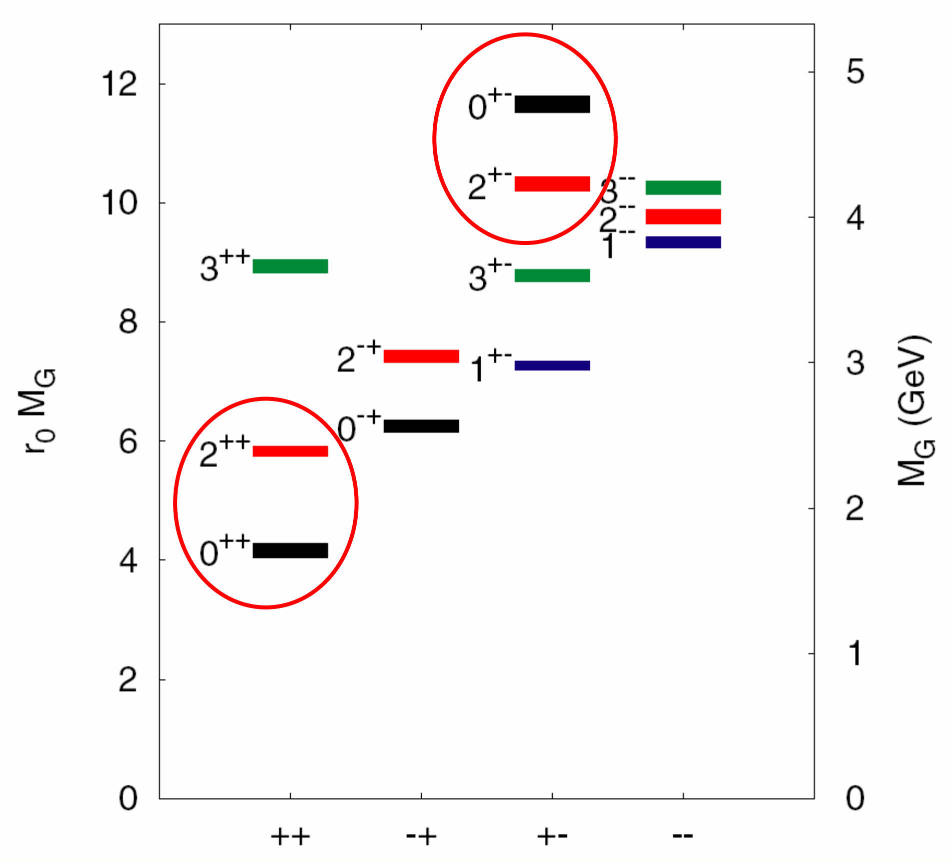
+ ...

Decoupling only possible for
- narrow states
- vanishing leading $q\bar{q}$ term

⇨ exotic $J^{PC}: 0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, \ldots$

Glueballs

Quenched L-QCD prediction



[Y. Chen et al., Phys. Rev. D 73, 014516 (2006)]

Lightest glueballs:

- $M \sim 1.7\,\mathrm{GeV}/c^2$ ($J^{PC} = 0^{++}$)
- $M \sim 2.4\,\mathrm{GeV}/c^2$ ($J^{PC} = 2^{++}$)

Experimental candidates:

- $f_0(1500)$ (Crystal Barrel, WA102)

  $J^{PC}=0^{++}$ ⇨ mixing with isoscalar mesons!

  ⇨ **COMPASS**

Higher masses:

- exotic: $J^{PC} = 2^{+-}, 0^{+-}$
- $M \sim 4.3\,\mathrm{GeV}/c^2$

  ⇨**PANDA**

  (talks by S. Lange et al.)

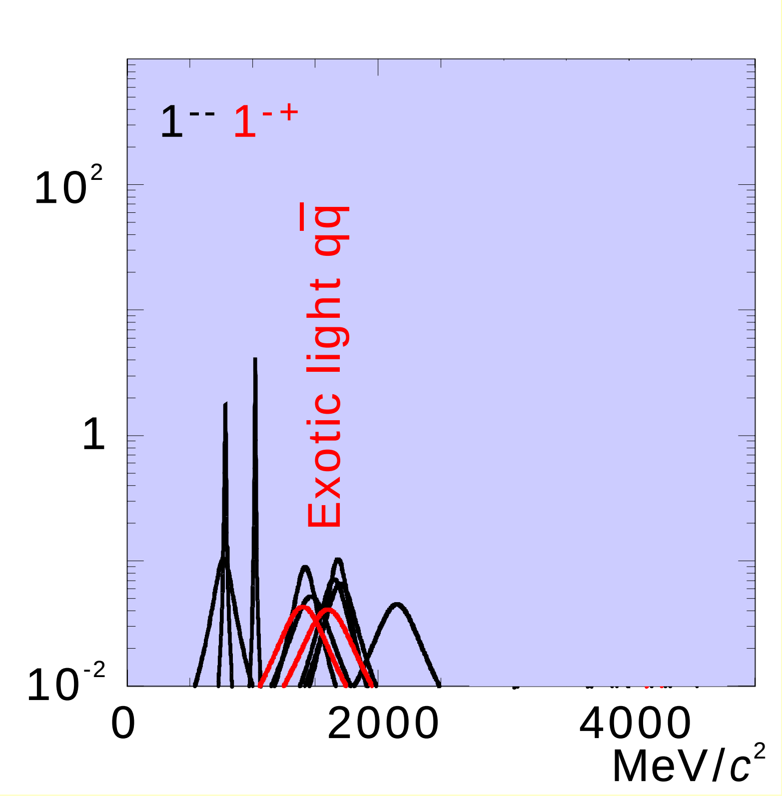
Hybrids

Light meson sector exotics $J^{PC}=1^{-+}$:

- $\pi_1(1400)$ (VES, E852, Crystal Barrel)
- $\pi_1(1600)$ (E852, VES)

still controversial...

⇨ **COMPASS**



Hybrids

Light meson sector (< 2.2 GeV/c²):

- $\pi_1(1400)$ (VES, E852, Crystal Barrel)
- $\pi_1(1600)$ (E852, VES)

still controversial...

⇨ **COMPASS**

Charmonium region: less populated

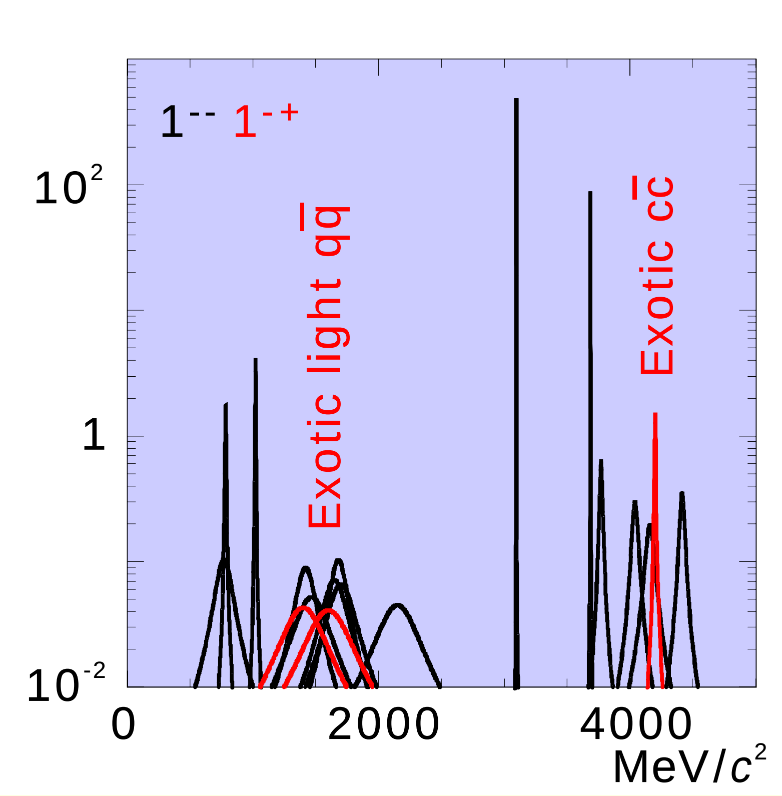
- $(c\bar{c})g$ ground state

predicted at 4.3 – 4.4 GeV/c²

exotic: $J^{PC}=1^{-+}$

narrow: 5 − 50 MeV/c² ?

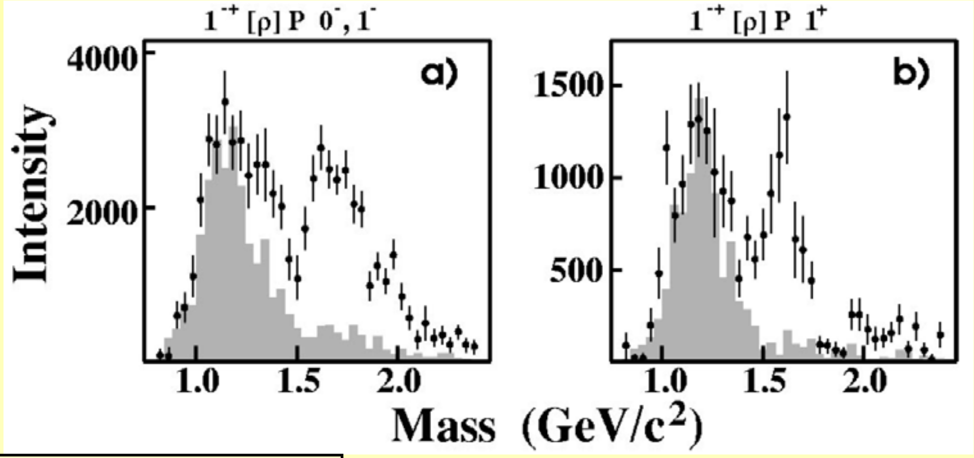
⇨**PANDA**



$\pi_1(1600)$ – Positive Results in 3π

BNL E852: $\pi^- + p \rightarrow \pi^+\pi^-\pi^- + p$

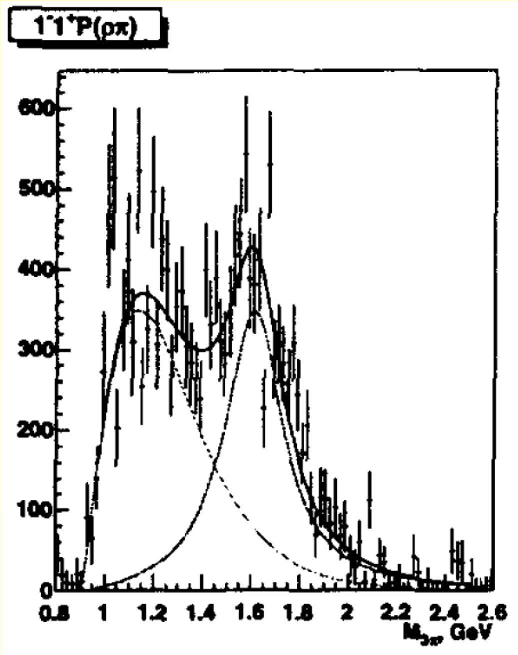
- p_π=18 GeV/c
- limited statistics: 250k ev.
- rank 2
- mass dependent fit



[S.U. Chung et al., Phys. Rev. D 65, 072001 (2002)]

VES: $\pi^- + A \rightarrow \pi^+\pi^-\pi^- + A$

- p_π=37 GeV/c
- full coherence

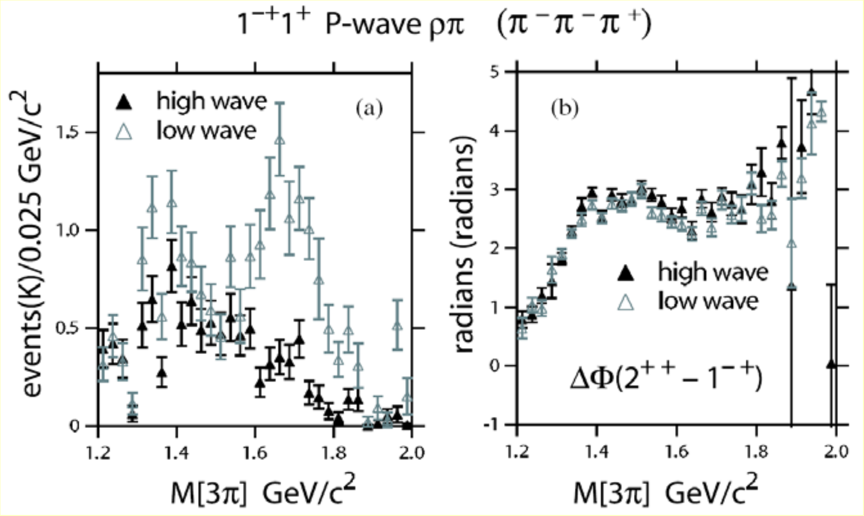


[Y. Khokhlov, Nucl. Phys. A 663, 596c (2000)]

$\pi_1(1600)$ – Negative Results in 3π

BNL E852: $\pi^- + p \rightarrow \pi^+\pi^-\pi^- + p$

- p_π=18 GeV/c
- full statistics: 2.6M ev.
- rank 1
- extended wave set (2-+ waves)
- no mass dependent fit



[A.R. Dzierba et al., Phys. Rev. D 73, 072001 (2006)]

VES: $\pi^- + A \rightarrow \pi^+\pi^-\pi^- + A$

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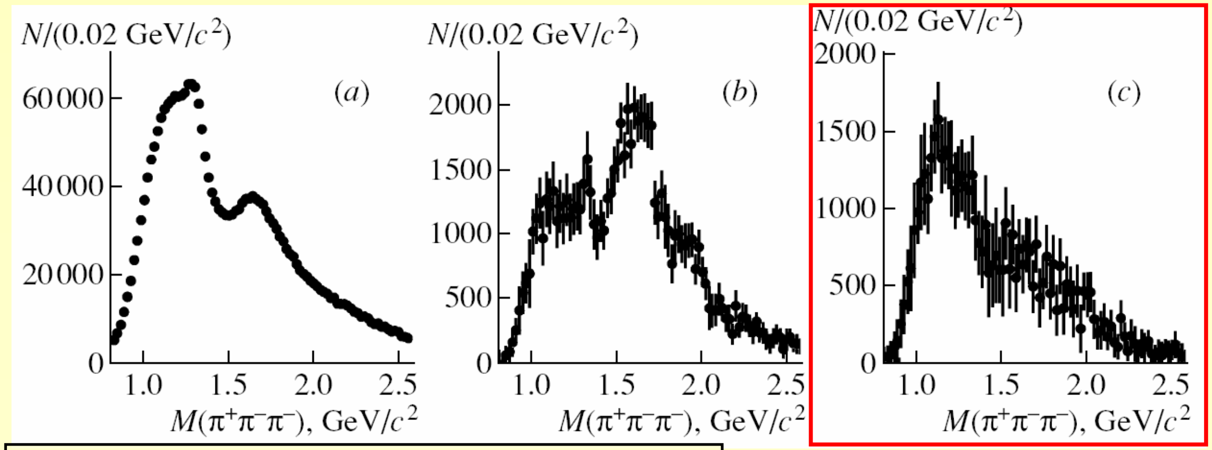


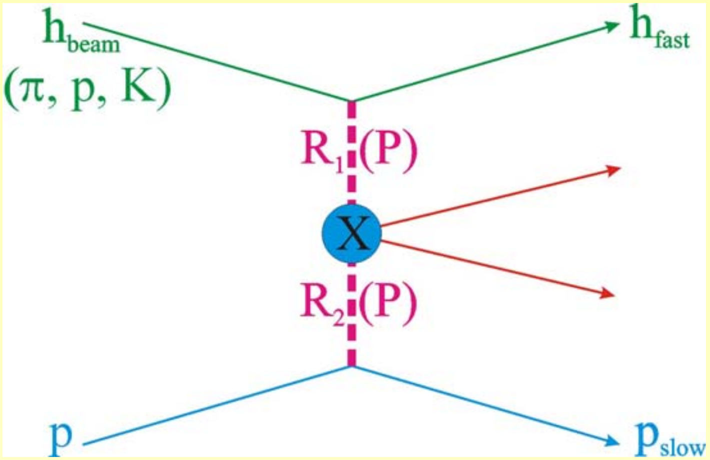
[D.V. Amelin, Phys. Atom. Nucl. 68, 359 (2005)]

Meson Spectroscopy at COMPASS

Two production mechanisms

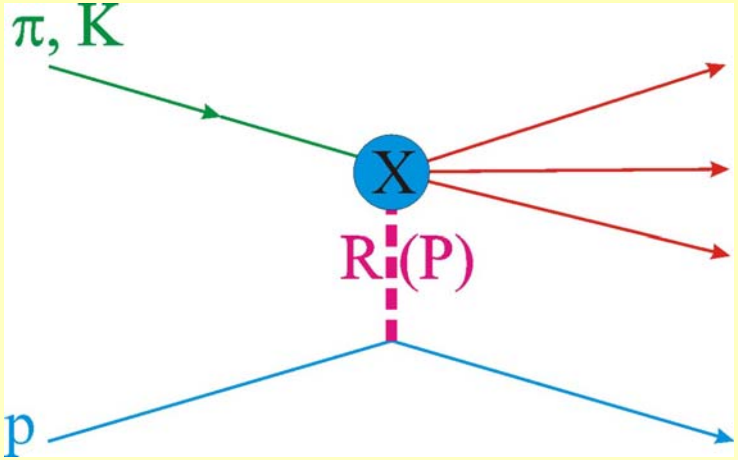
studied in parallel using proton, pion and kaon projectiles

Central production



- Large rapidity gap between p_{slow}, h_{fast}, X
- Beam particle looses ~10% of its energy
- Particles at large angles from X decays
- Possible source of glueballs

Diffractive scattering



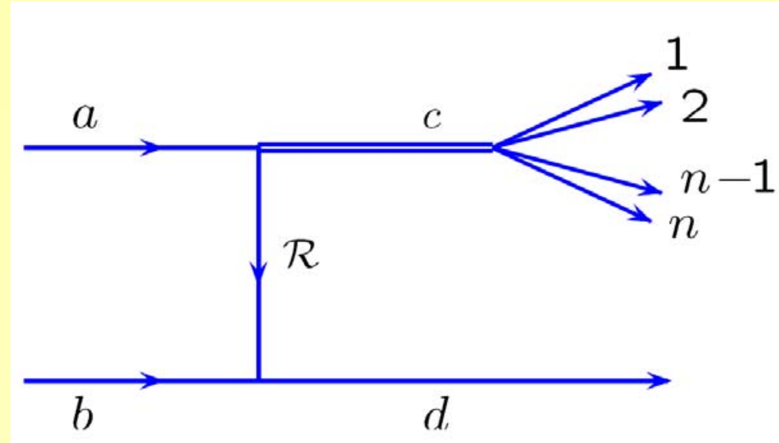
- Forward kinematics
- Large cross section (~mb)
- Need to separate particles at very small angles
- Study of J^{PC}-exotic mesons

Diffractive Reactions in COMPASS

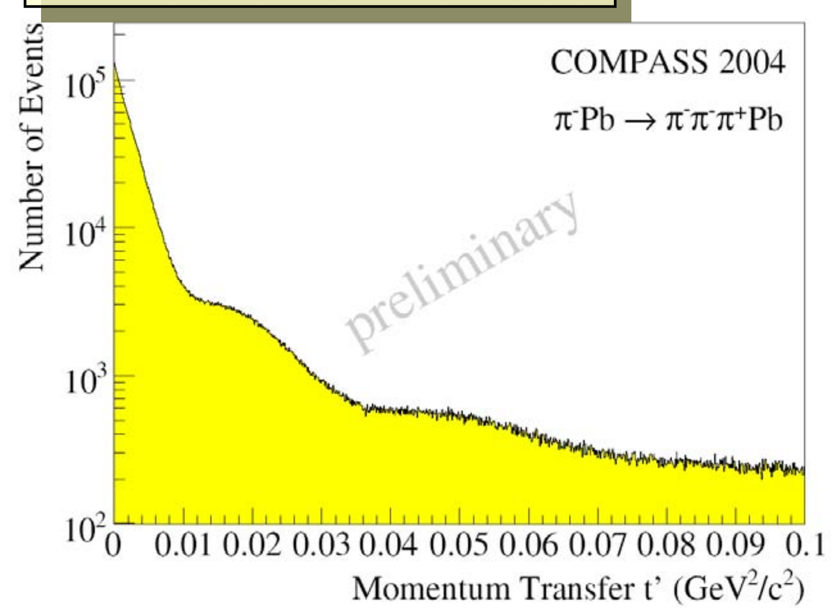
Example: $\pi^- + \mathrm{Pb} \rightarrow \pi^-\pi^-\pi^+ + \mathrm{Pb}$

- 4π vertex in Pb target
- Exclusivity ⇨ target stays intact
- Momentum transfer

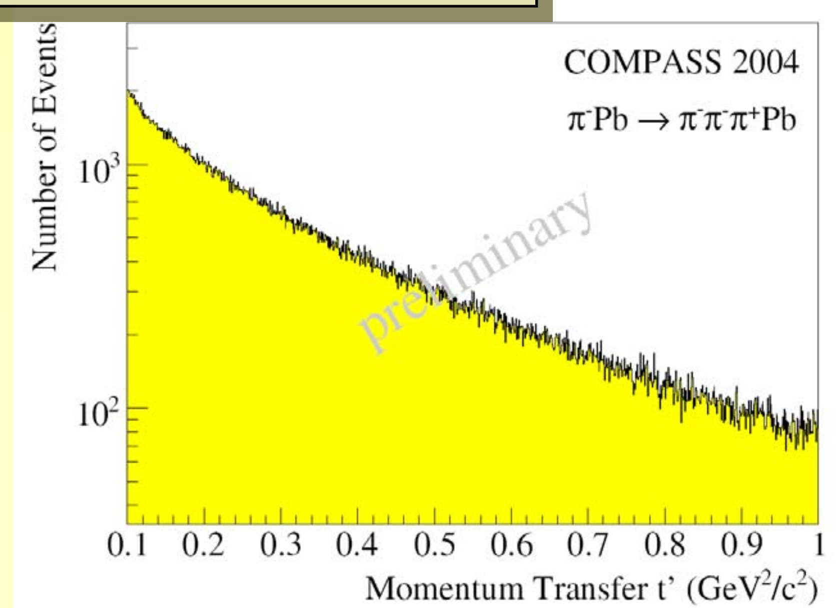
$$-t \equiv Q^2 = -(p_a - p_c)^2$$



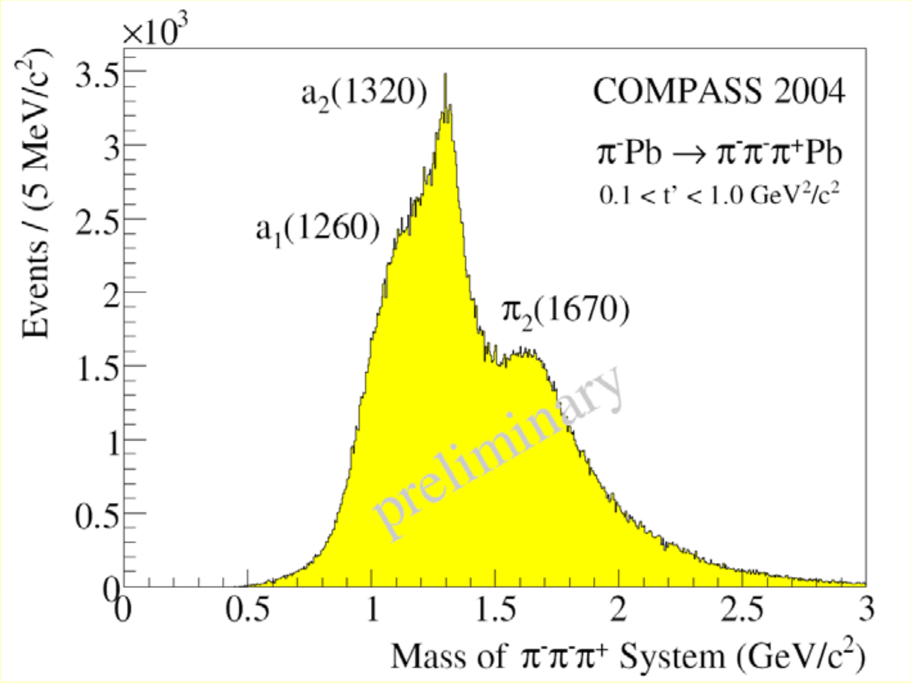
Diffraction on Pb nuclei

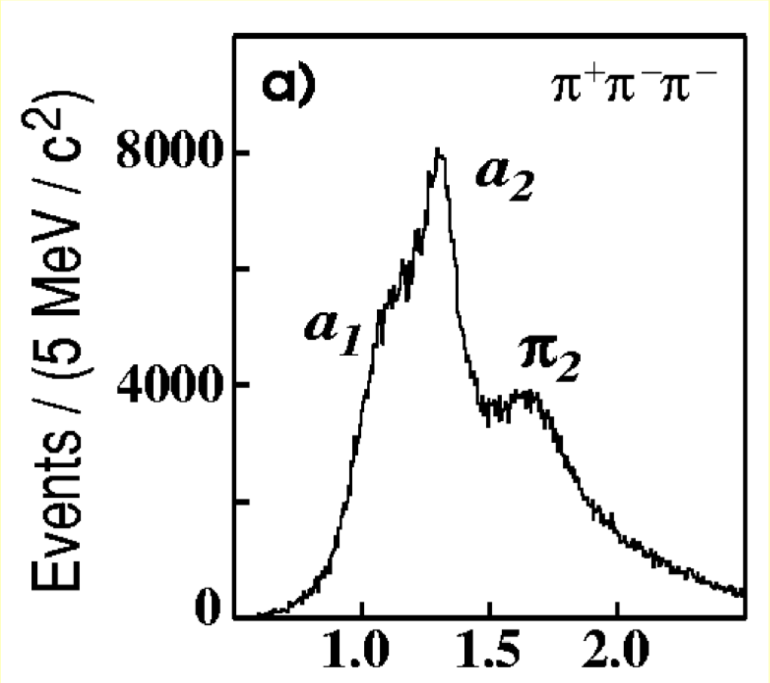


Diffraction on nucleons



Invariant Mass of 3π System

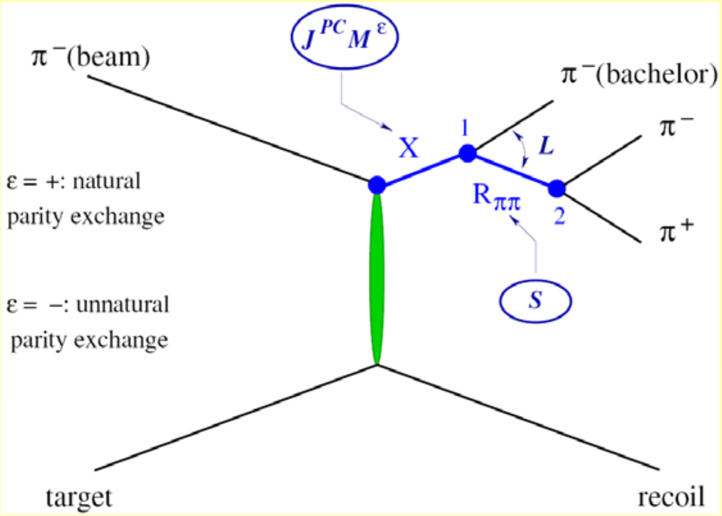




COMPASS: p_π=190 GeV/c
- No acceptance correction
- 4M events in 3 days (full t range)
- 450k events in 0.1<t'<1.0 GeV/c^2

BNL852: p_π=18 GeV/c
- PRD 65, 072001 (2002): 250k events ⇨ $\pi_1(1600)$

PWA Technique



- t-channel Reggeon exchange
- Reflectivity basis in G-J frame
- At high s: ε = η of Regge trajectory
- Isobar model

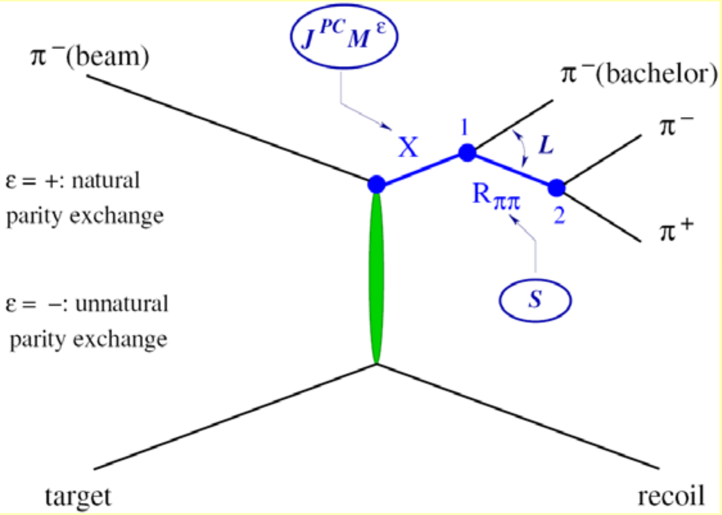
1. **Mass-independent PWA** of angular distributions in 40 MeV mass bins

$$\sigma_{\text{indep}}(\tau) = \sum_{\varepsilon=-1}^{1} \sum_{r=1}^{N_r} \left| \sum_i T_{ir}^{\varepsilon} \psi_i^{\varepsilon}(\tau) \Big/ \sqrt{\int \left|\psi_i^{\varepsilon}(\tau')\right|^2 d\tau'} \right|^2$$

- 42 partial waves ***i=J^PC M^ε[...]L***

[...]=isobar $(\pi\pi)_S$, $f_0(980)$, $\rho(770)$, $f_2(1270)$, $\rho_3(1690)$

PWA Technique



- t-channel Reggeon exchange
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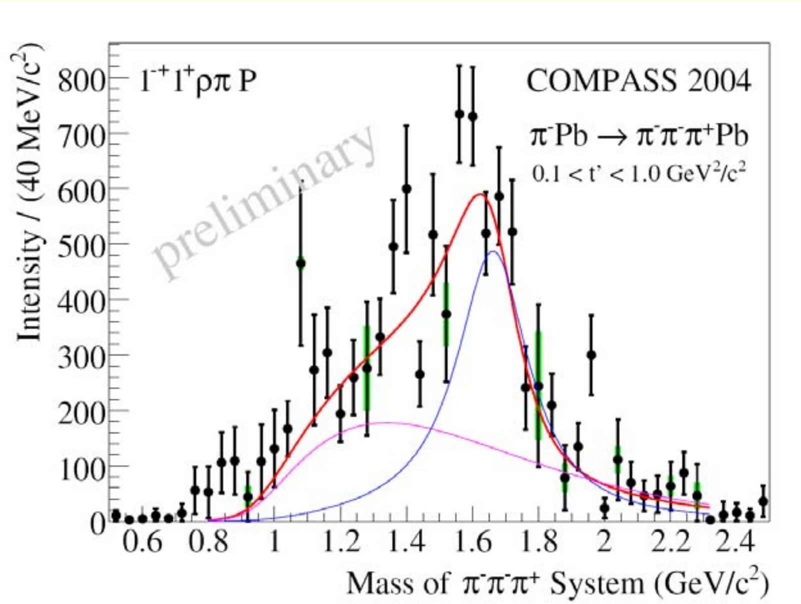
- Isobar model

1. **Mass-independent PWA** of angular distributions in 40 MeV mass bins

2. **Mass-dependent χ^2 fit** to results of step 1
   - 7 waves
   - Parameterized by BW
   - Coherent background for some waves

π_1(1600) in COMPASS

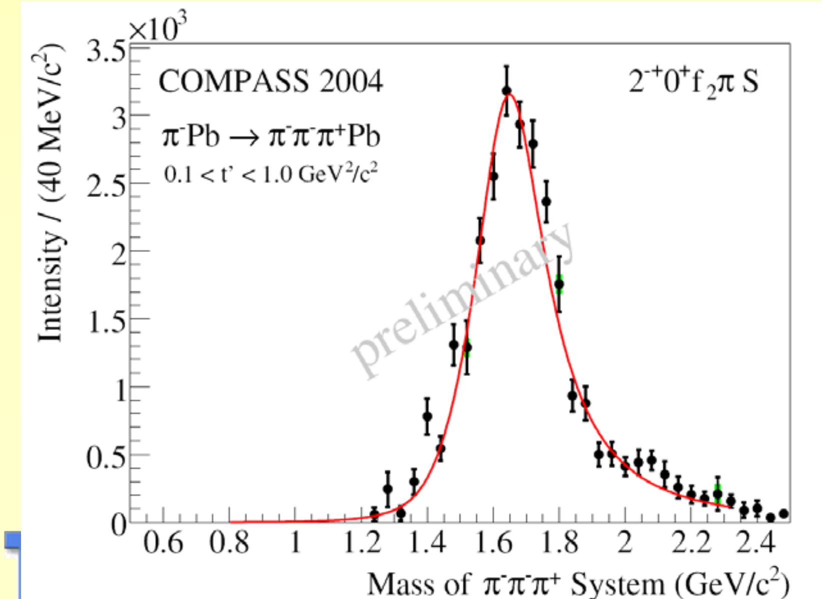


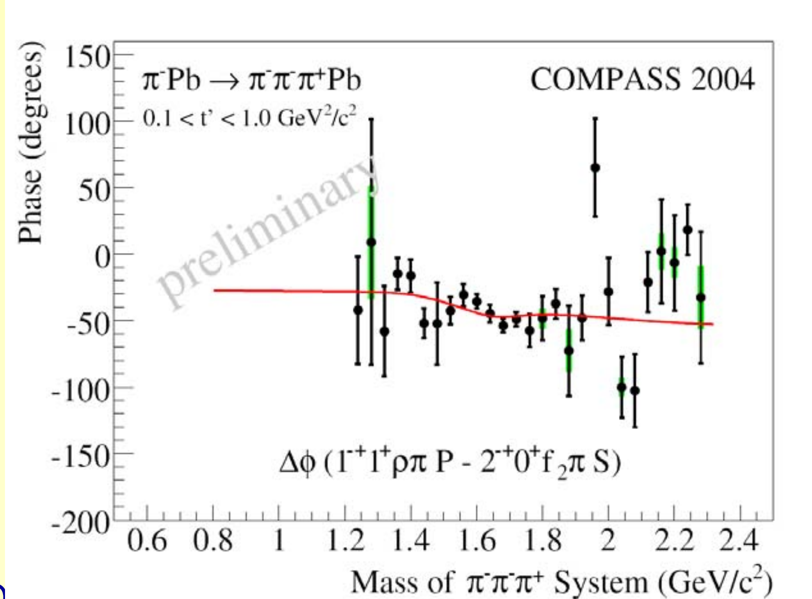
- BW parameters for π_1(1600)

$$M = \left(1.660 \pm 0.010 \,{}^{+0.000}_{-0.064}\right) \mathrm{GeV}/c^2$$

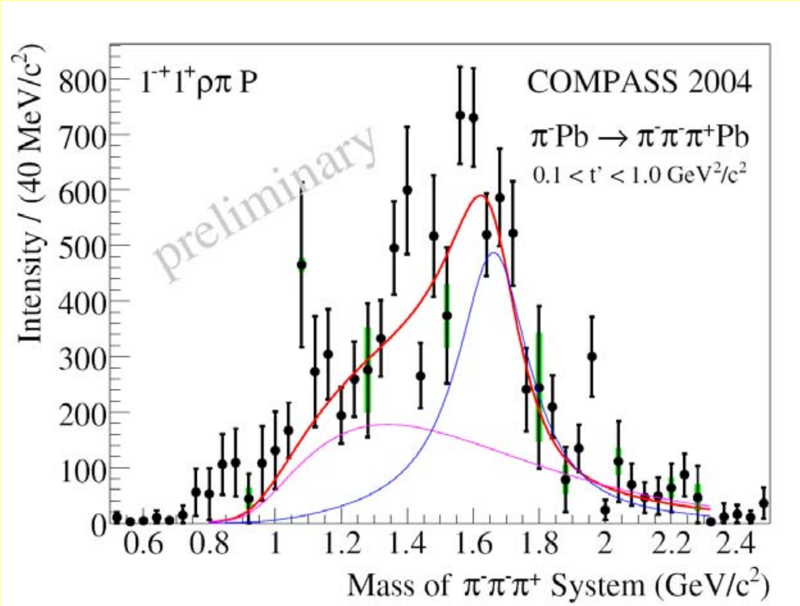
$$\Gamma = \left(0.269 \pm 0.021 \,{}^{+0.042}_{-0.064}\right) \mathrm{GeV}/c^2$$

- Leakage negligible





π_1(1600) in COMPASS



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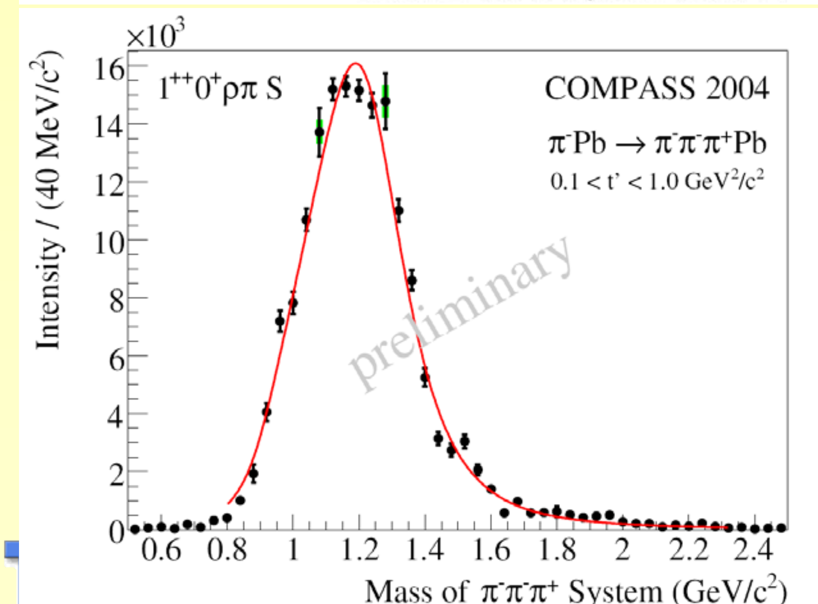
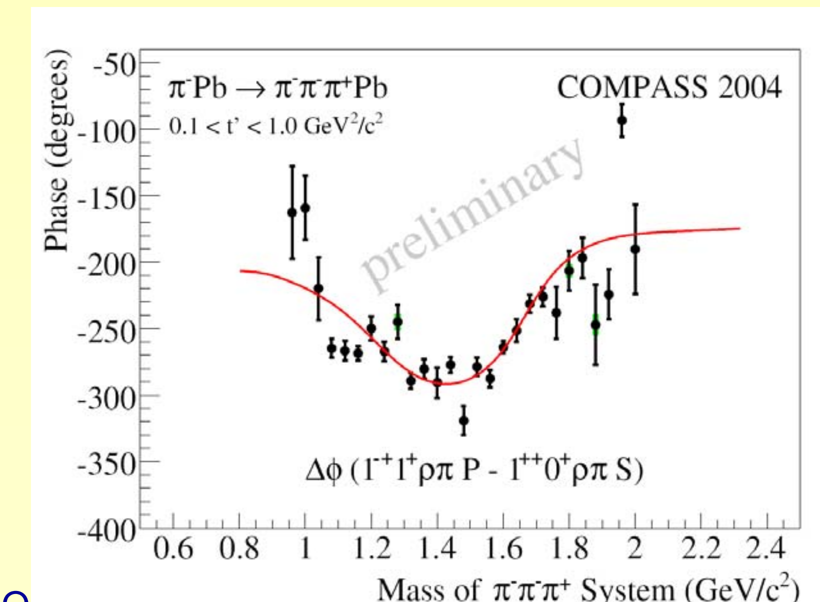


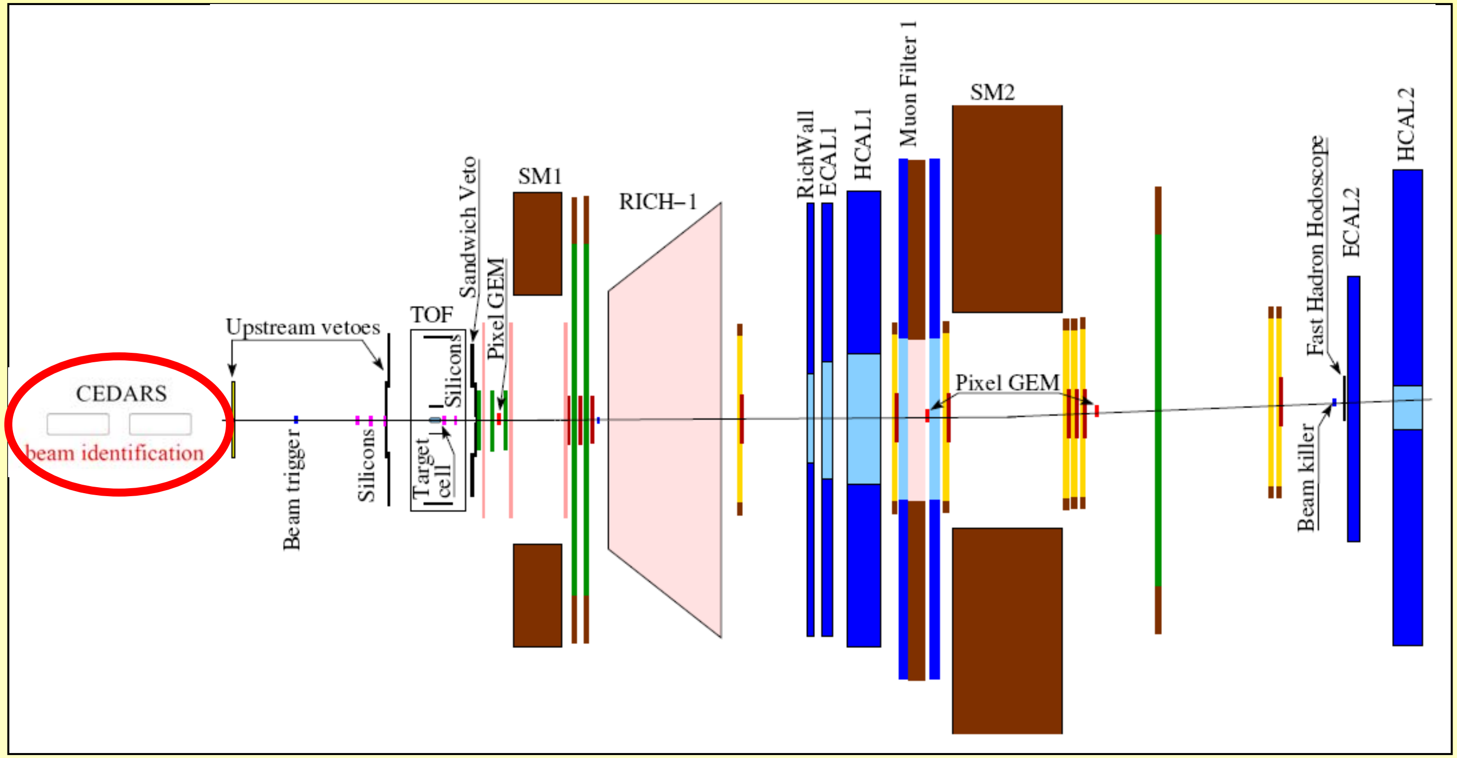


Summary of Waves

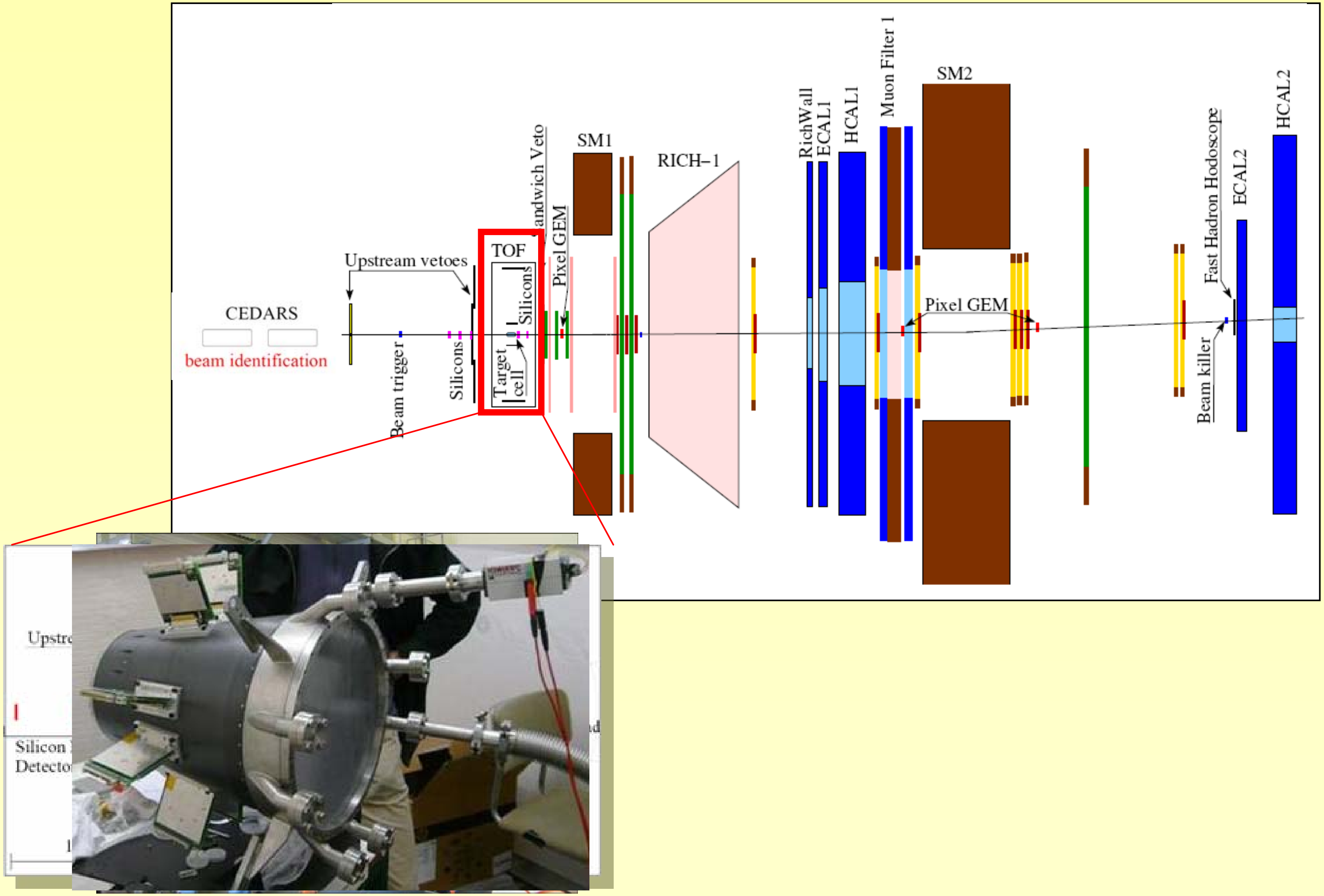
State	(GeV)	COMPASS ± stat ± syst	PDG
$a_1(1260)$	M	$1.256 \pm 0.006 + 0.007 - 0.017$	1.230 ± 0.040
	Γ	$0.366 \pm 0.009 + 0.028 - 0.025$	0.250 to 0.600
$a_2(1320)$	M	$1.321 \pm 0.001 + 0.000 - 0.007$	1.3183 ± 0.0006
	Γ	$0.110 \pm 0.002 + 0.002 - 0.015$	0.107 ± 0.005
$\pi_1(1600)$	M	$1.660 \pm 0.010 + 0.000 - 0.064$	$1.653^{+0.018}_{-0.015}$
	Γ	$0.269 \pm 0.021 + 0.042 - 0.064$	$0.225^{+0.045}_{-0.028}$
$\pi_2(1670)$	M	$1.659 \pm 0.003 + 0.024 - 0.008$	1.6724 ± 0.0032
	Γ	$0.271 \pm 0.009 + 0.022 - 0.024$	0.259 ± 0.009
$\pi(1800)$	M	$1.785 \pm 0.009 + 0.012 - 0.006$	1.812 ± 0.014
	Γ	$0.208 \pm 0.022 + 0.021 - 0.037$	0.207 ± 0.013
$a_4(2040)$	M	$1.884 \pm 0.013 + 0.050 - 0.002$	2.001 ± 0.010
	Γ	$0.295 \pm 0.024 + 0.046 - 0.019$	0.313 ± 0.031

Details: talk of Q. Weitzel, Sat 1C

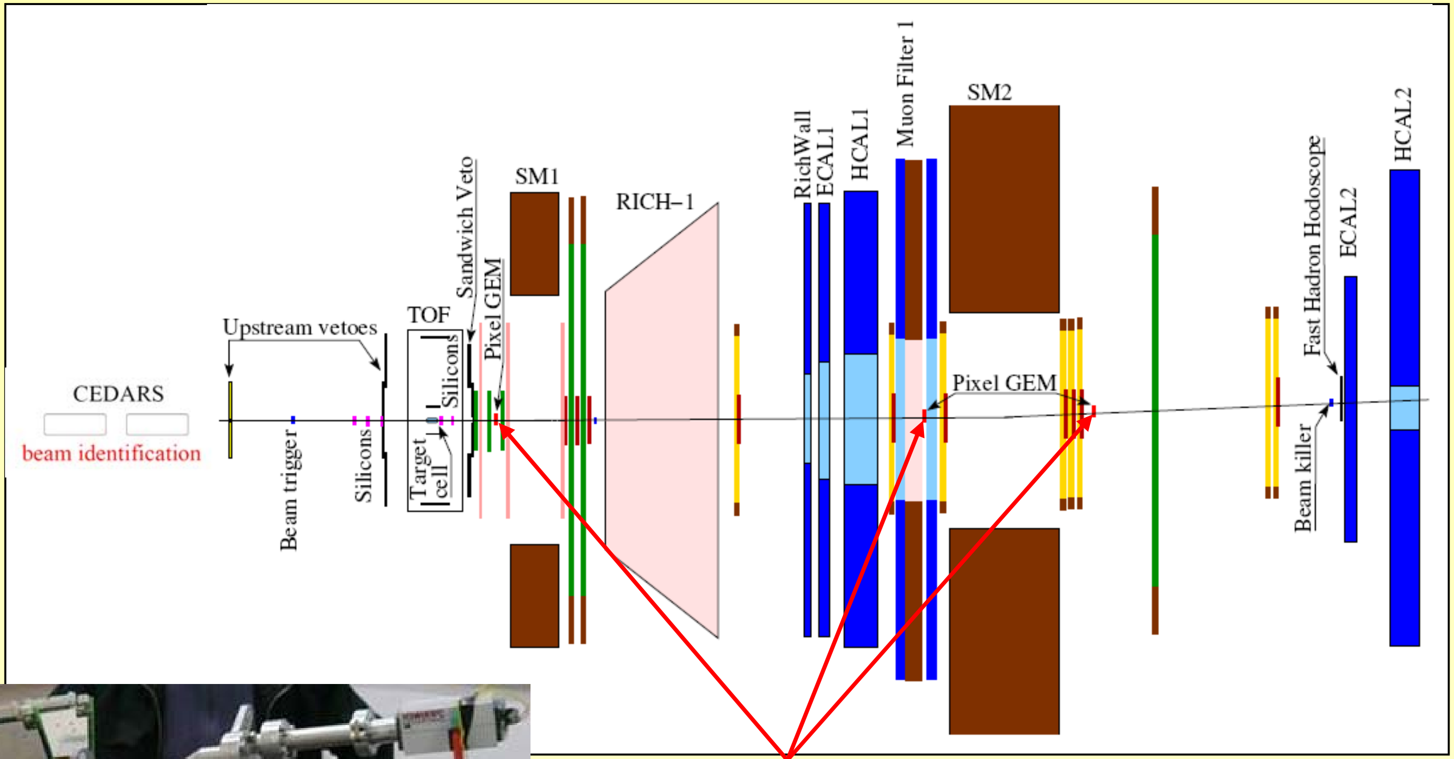
COMPASS in 2008

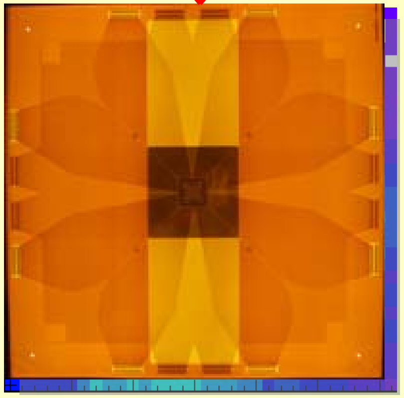


COMPASS in 2008

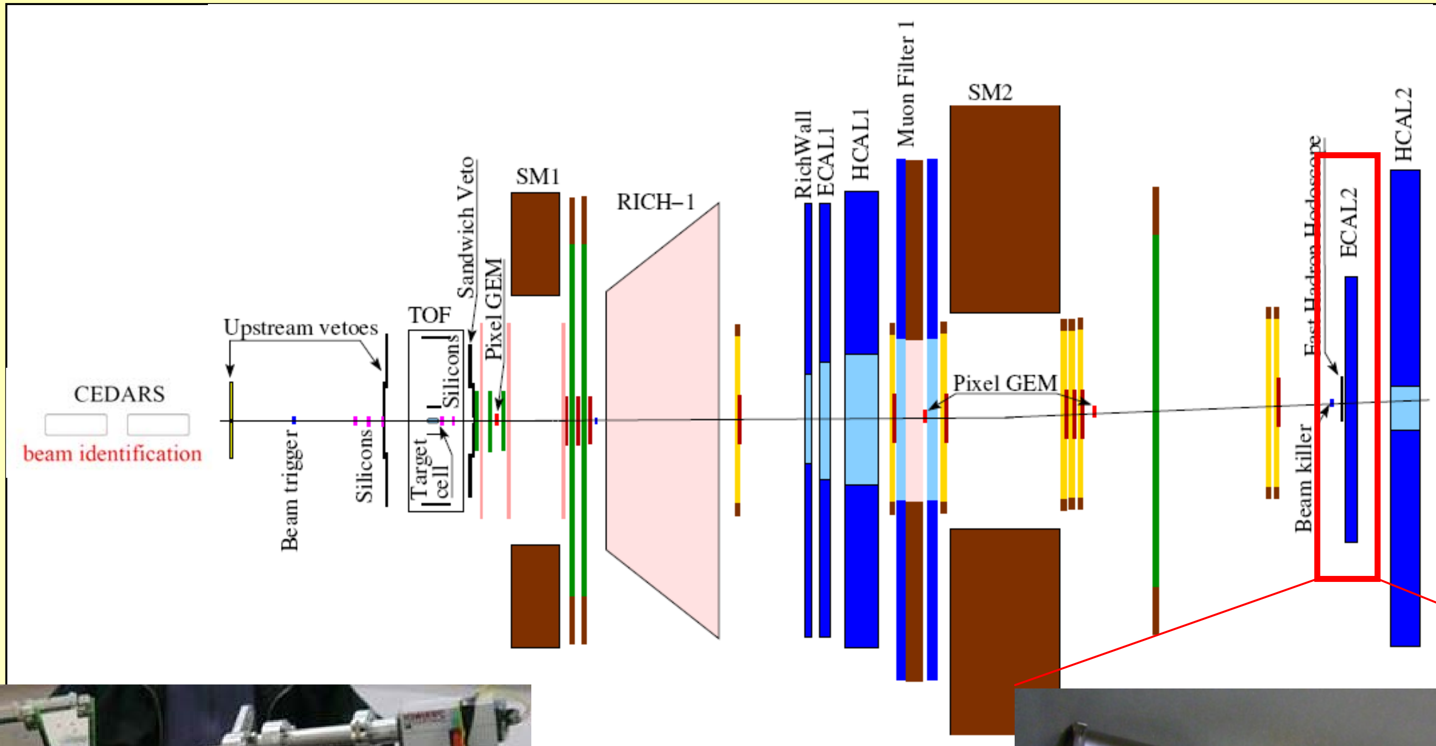


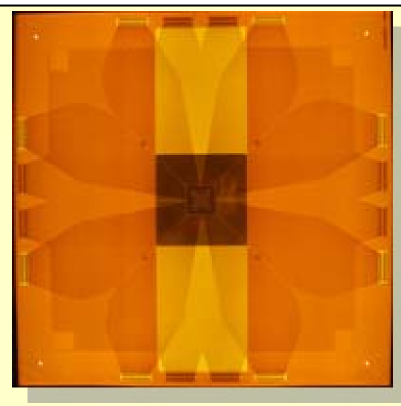
COMPASS in 2008

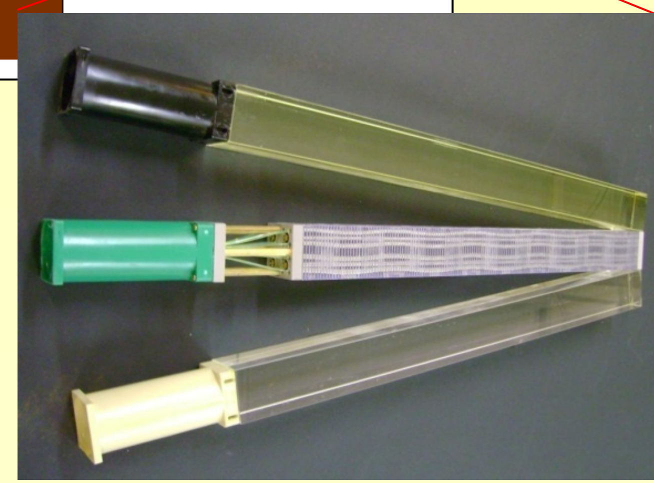




COMPASS in 2008







COMPASS in 2008

- 190 GeV/c hadron beam
  - positive: 75% p, 25% π^+
  - negative: 96% π^-, 3.5% K^-, 0.5% $\bar{p}$
- Beam intensity $5\cdot10^6$ /s, $5\cdot10^7$ /spill (10s)
- Target: 40cm liquid hydrogen
- $\mathcal{L}$=0.15 pb^{-1}/day
- Expected event rates:
  - $\pi^- p \rightarrow \pi_1(1600)\, p,\ \pi_1(1600) \rightarrow \pi^+\pi^-\pi^-$
    - $\sigma(\pi_1)\times BR(\pi_1\rightarrow\pi^+\pi^-\pi^-)=0.6\ \mu b$
    - $\varepsilon(DAQ)\times\varepsilon(reco)=5\%$

    ⇨ $4.5\cdot10^3$ ev./day

  $\pi^- p \rightarrow \pi^- f_0(1500)\, p,\ f_0(1500) \rightarrow \eta\eta \rightarrow 4\gamma$
    - $\sigma(f_0)\times BR(f_0\rightarrow\eta\eta\rightarrow4\gamma)=1.5\ \mu b\cdot5\%\cdot15\%=11nb$
    - $\varepsilon(DAQ)\times\varepsilon(reco)=2\%$

    ⇨ 30 ev./day

Conclusions

- **COMPASS:** data taking with μ beam: 2002-2004, 2006-2007
- Pilot run with π beam: 2004 **(3 days)**
  - **Coulomb interactions** being studied
    - Pion polarizability
    - $F_{3\pi}$ being studied

Stay tuned for new results from COMPASS...

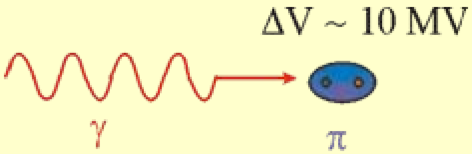
    - PWA for $\pi\pi\pi$ at high t' completed:
      - Statistics 2×higher than BNL E852 in 1 year
      - Strong signal in exotic 1^{-+} wave at 1.6 GeV/c^2
    - PWA for $\pi^+\pi^+\pi^-\pi^-\pi^-$ started
- **Hadron beam** running from 2008 on with IH2 target
  - Central production: 10× WA102 statistics in 60 days
  - Diffractive reactions: 10× BNL E852 statistics in 10 days

Spare Slides

Polarizabilities

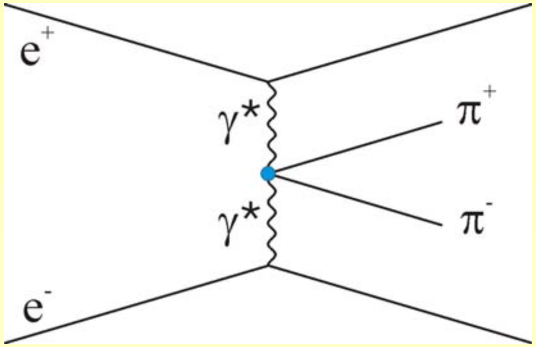
Describe response to external e.m. fields ⇨ stiffness of system

- electric polarizability $\vec{d} = \overline{\alpha}\,\vec{E}$
- magnetic polarizability $\vec{\mu} = \overline{\beta}\,\vec{H}$

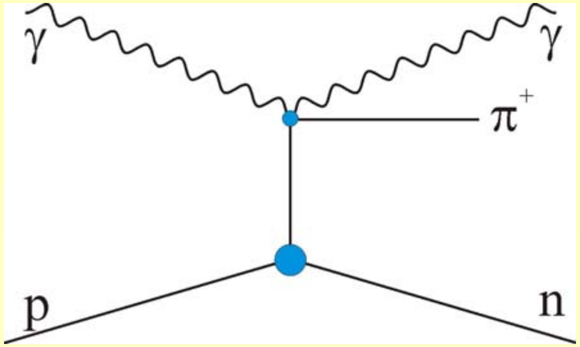


χPT (2-loop): $\overline{\alpha}_{\pi} = (2.9 \pm 0.5) \cdot 10^{-4}\ \mathrm{fm}^3$ $\overline{\beta}_{\pi} = (-2.8 \pm 0.5) \cdot 10^{-4}\ \mathrm{fm}^3$

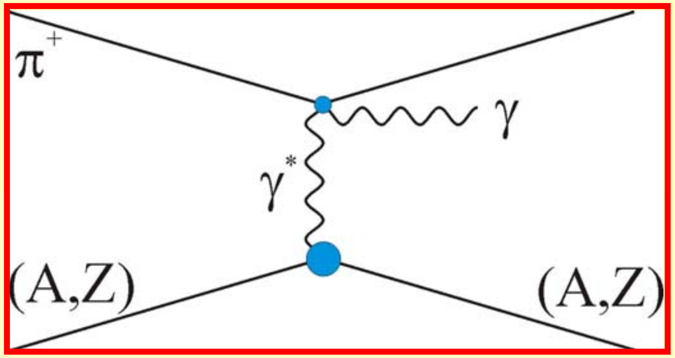
Experiments:



PLUTO
DM1
DM2
Mark II



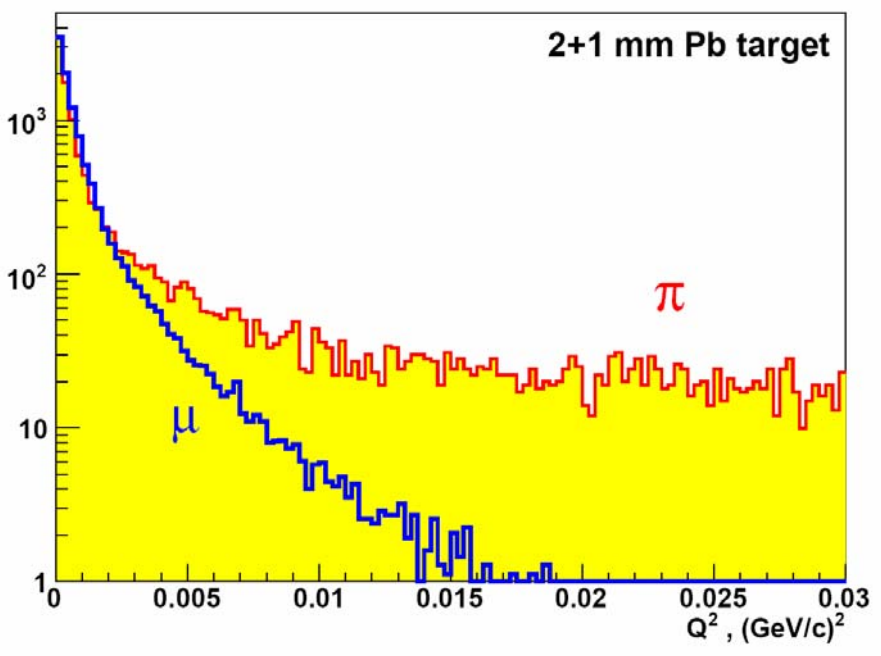
Lebedev
Mami A2

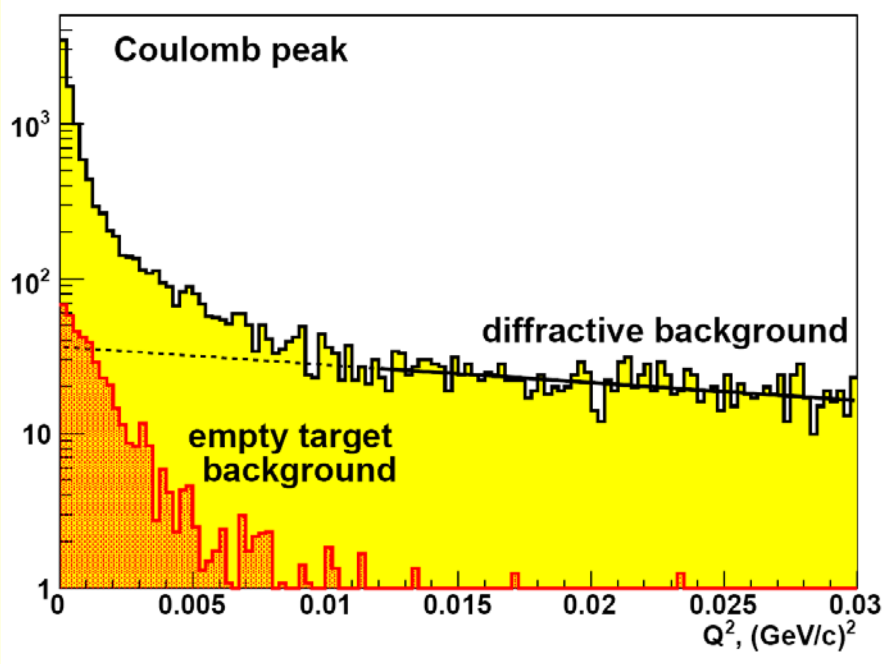


Serpukhov
COMPASS

Q^2 Distributions

$$\frac{d^3\sigma}{dQ^2\, d\omega\, d\cos\theta} = \frac{\alpha Z^2}{\pi\omega} \cdot \frac{Q^2 - Q^2_{\min}}{Q^4} \cdot \left|F_Z\left(Q^2\right)\right|^2 \cdot \frac{d\sigma_{\gamma\pi}(\omega,\theta)}{d\cos\theta}$$





Analysis Procedure

Selection of Primakoff events:

- One primary vertex in target
- One outgoing track with neg. charge and p<170 GeV/c
- One photon cluster in ECAL2 with $E_\gamma > 7$ GeV
- Exclusivity: $|E_\pi + E_\gamma - E_{beam}| < 25$ GeV
- $Q^2 < 0.0075$ GeV^2/c^2

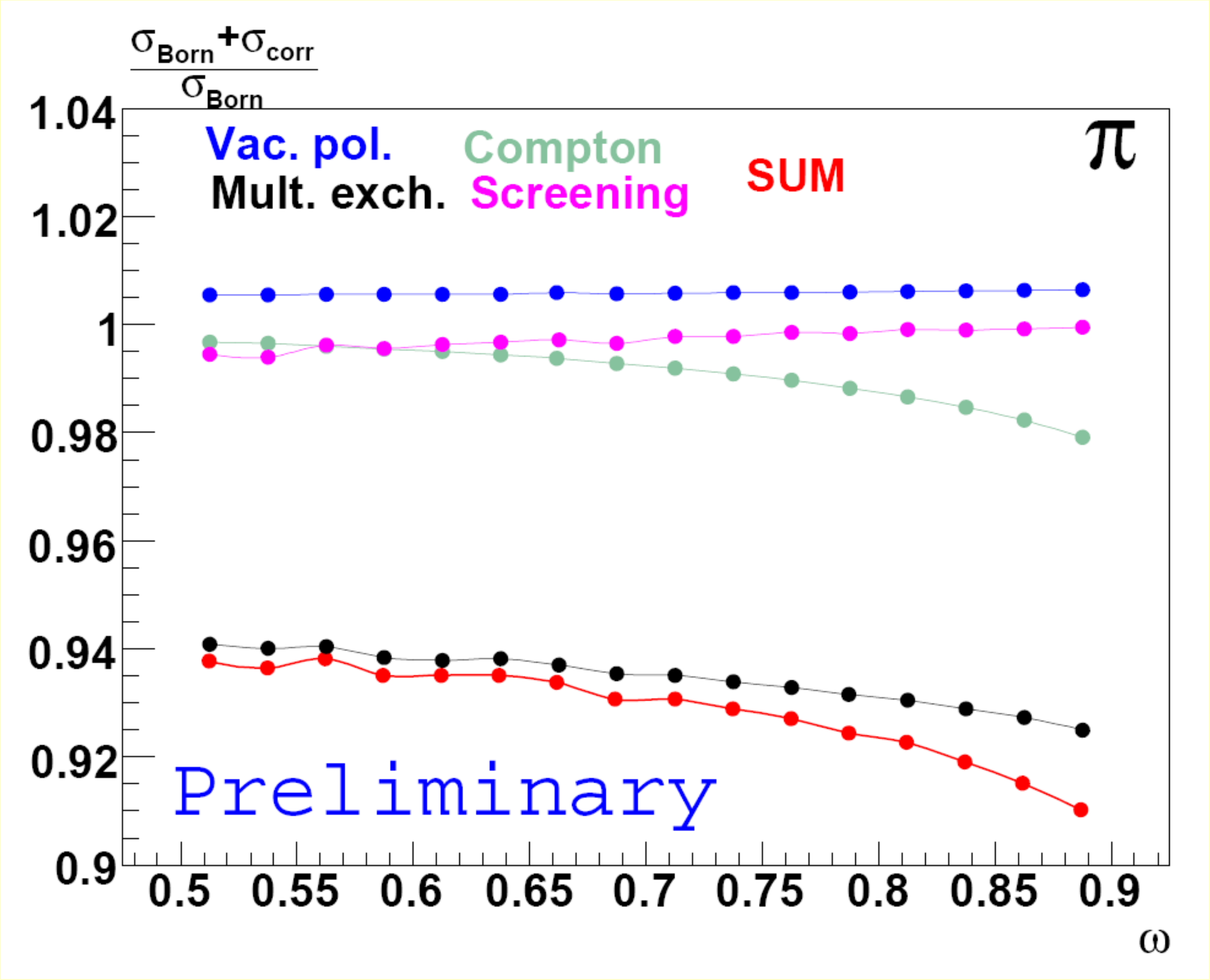
Background suppression:

- ρ decay: $M_{\pi\gamma} < 3.75\ m_\pi$
- Beam K decay: empty target subtraction
- Diffractive channels: different Q^2 dependence

Extraction of polarizability:

- Assume $\alpha_\pi + \beta_\pi = 0$
- Fit ratio $R(\omega) = 1 + d\sigma(\beta_\pi)/d\sigma_{pointlike}$
- $d\sigma_{pointlike}$ from Monte-Carlo, cross-checked with μ beam

Radiative Corrections

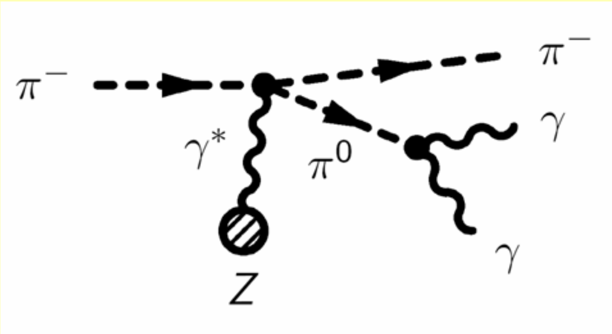


Systematic Error Estimate

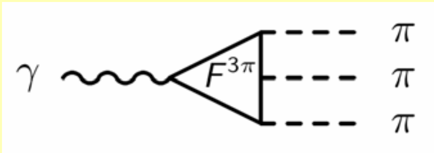
	Error, 10^{-4}fm^3
Setup description in MC (μ data)	± 0.5
Diffractive and empty target background subtraction	± 0.3
Muons background	$+0.2$
Electrons background	$<+0.1$
SYSTEMATIC TOTAL	± 0.6

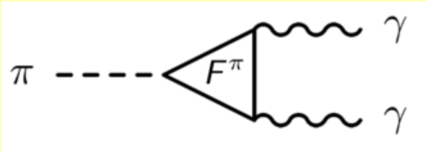
$F^{3\pi}$ Coupling Constant

Primakoff π^0 production



Chiral Perturbation Theory





$$F^{3\pi}(0) = \frac{F^{\pi}(0)}{\sqrt{\pi\alpha}\, f_{\pi^\pm}^2}, \quad f_{\pi^\pm} = (130.7 \pm 0.4)\,\text{MeV}$$

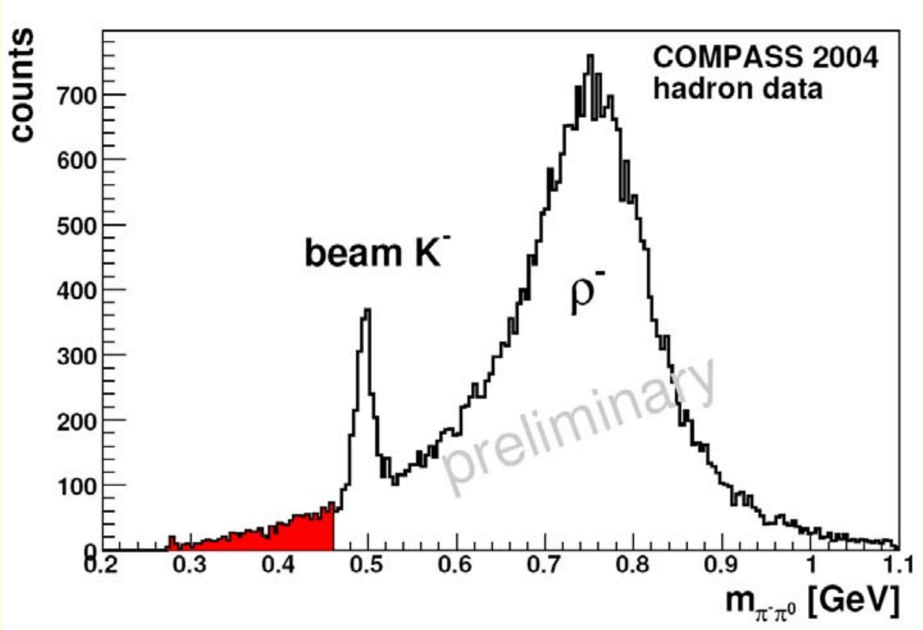
- Prediction:

  $F^{3\pi}(0)=9.7\pm0.1$ GeV^{-3}

- Experiment (Serpukhov):

  $F^{3\pi}(0)=12.9\pm0.9\pm0.5$ GeV^{-3}

⇨ **COMPASS**



Light Exotics

Experiment	Exotic	J^{PC}	Mass [MeV/c^2]		Width [MeV/c^2]		Decay
E852	$\pi_1(1400)$	1^{-+}	1359	$^{+16}_{-14}\ ^{+10}_{-24}$	314	$^{+31}_{-29}\ ^{+9}_{-66}$	$\eta\pi$
Crystal Barrel	$\pi_1(1400)$	1^{-+}	1400	$\pm 20 \pm 20$	310	$\pm 50\ ^{+50}_{-30}$	$\eta\pi$
Crystal Barrel	$\pi_1(1400)$	1^{-+}	1360	± 25	220	± 90	$\eta\pi$
Obelix	$\pi_1(1400)$	1^{-+}	1384	± 28	378	± 58	$\rho\pi$
E852	$\pi_1(1600)$	1^{-+}	1593	$\pm 8\ ^{+29}_{-47}$	168	$\pm 20\ ^{+150}_{-12}$	$\rho\pi$
E852	$\pi_1(1600)$	1^{-+}	1597	$\pm 10\ ^{+45}_{-10}$	340	$\pm 40 \pm 50$	$\eta'\pi$
Crystal Barrel	$\pi_1(1600)$	1^{-+}	1590	± 50	280	± 75	$b_1\pi$
Crystal Barrel	$\pi_1(1600)$	1^{-+}	1555	± 50	468	± 80	$\eta'\pi$
E852	$\pi_1(1600)$	1^{-+}	1709	$\pm 24 \pm 41$	403	$\pm 80 \pm 115$	$f_1\pi$
E852	$\pi_1(1600)$	1^{-+}	1664	$\pm 8 \pm 10$	185	$\pm 25 \pm 28$	$\omega\pi\pi$
E852	$\pi_1(2000)$	1^{-+}	2001	$\pm 30 \pm 92$	333	$\pm 52 \pm 49$	$f_1\pi$
E852	$\pi_1(2000)$	1^{-+}	2014	$\pm 20 \pm 16$	230	$\pm 32 \pm 73$	$\omega\pi\pi$
E852	$h_2(1950)$	2^{+-}	1954	± 8	138	± 3	$\omega\pi\pi$

Waves used in PWA

$J^{PC}M^{\epsilon}$	L	Isobar π	Cut [GeV]
$0^{-+}0^{+}$	S	$f_0\pi$	1.40
$0^{-+}0^{+}$	S	$(\pi\pi)_s\pi$	-
$0^{-+}0^{+}$	P	$\rho\pi$	-
$1^{-+}1^{+}$	P	$\rho\pi$	-
$1^{++}0^{+}$	S	$\rho\pi$	-
$1^{++}0^{+}$	P	$f_2\pi$	1.20
$1^{++}0^{+}$	P	$(\pi\pi)_s\pi$	0.84
$1^{++}0^{+}$	D	$\rho\pi$	1.30
$1^{++}1^{+}$	S	$\rho\pi$	-
$1^{++}1^{+}$	P	$f_2\pi$	1.40
$1^{++}1^{+}$	P	$(\pi\pi)_s\pi$	1.40
$1^{++}1^{+}$	D	$\rho\pi$	1.40
$2^{-+}0^{+}$	S	$f_2\pi$	1.20
$2^{-+}0^{+}$	P	$\rho\pi$	0.80
$2^{-+}0^{+}$	D	$f_2\pi$	1.50
$2^{-+}0^{+}$	D	$(\pi\pi)_s\pi$	0.80
$2^{-+}0^{+}$	F	$\rho\pi$	1.20
$2^{-+}1^{+}$	S	$f_2\pi$	1.20
$2^{-+}1^{+}$	P	$\rho\pi$	0.80
$2^{-+}1^{+}$	D	$f_2\pi$	1.50
$2^{-+}1^{+}$	D	$(\pi\pi)_s\pi$	1.20
$2^{-+}1^{+}$	F	$\rho\pi$	1.20

$J^{PC}M^{\epsilon}$	L	Isobar π	Cut [GeV]
$2^{++}1^{+}$	P	$f_2\pi$	1.50
$2^{++}1^{+}$	D	$\rho\pi$	-
$3^{++}0^{+}$	S	$\rho_3\pi$	1.50
$3^{++}0^{+}$	P	$f_2\pi$	1.20
$3^{++}0^{+}$	D	$\rho\pi$	1.50
$3^{++}1^{+}$	S	$\rho_3\pi$	1.50
$3^{++}1^{+}$	P	$f_2\pi$	1.20
$3^{++}1^{+}$	D	$\rho\pi$	1.50
$4^{-+}0^{+}$	F	$\rho\pi$	1.20
$4^{-+}1^{+}$	F	$\rho\pi$	1.20
$4^{++}1^{+}$	F	$f_2\pi$	1.60
$4^{++}1^{+}$	G	$\rho\pi$	1.64
$1^{-+}0^{-}$	P	$\rho\pi$	-
$1^{-+}1^{-}$	P	$\rho\pi$	-
$1^{++}1^{-}$	S	$\rho\pi$	-
$2^{-+}1^{-}$	S	$f_2\pi$	1.20
$2^{++}0^{-}$	P	$f_2\pi$	1.30
$2^{++}0^{-}$	D	$\rho\pi$	-
$2^{++}1^{-}$	P	$f_2\pi$	1.30
FLAT			