Physics with Hadron Beams at COMPASS

Bernhard Ketzer

Technische Universität München

MAMI and Beyond 2009

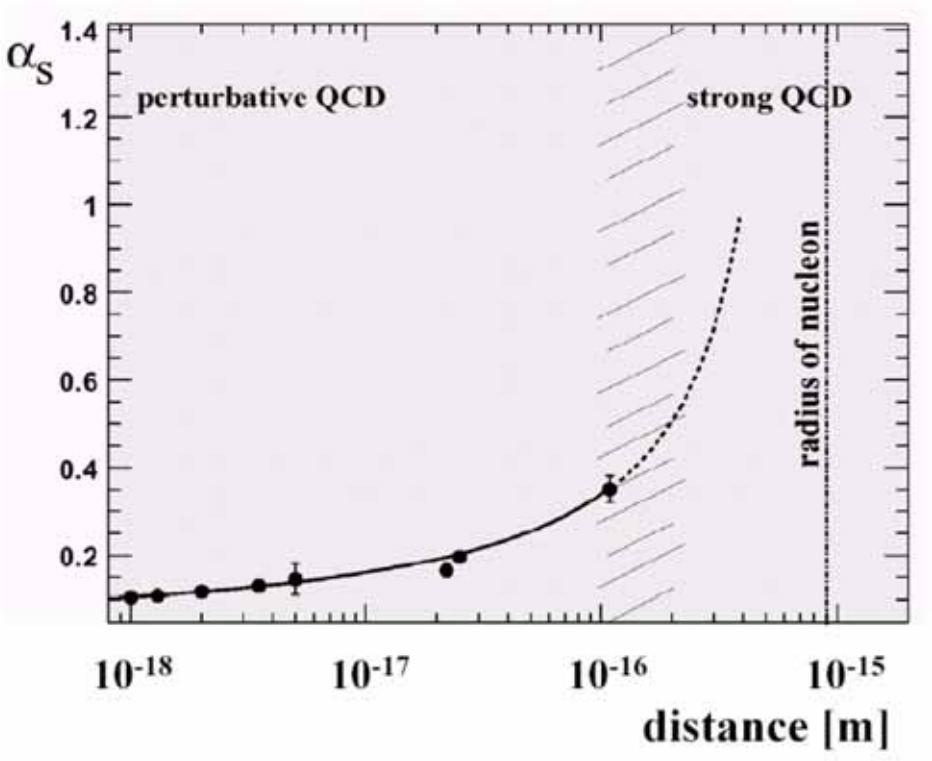
International Workshop on Hadron Structure and Spectroscopy 2009

30 March 2009

bmb+f - Förderschwerpunkt COMPASS Großgeräte der physikalischen Grundlagenforschung

The Goal

Understand hadrons from the dynamics of quarks and gluons



⇨ **non-perturbative regime of QCD**

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

Experimental Tools

Deep Inelastic Lepton Scattering

and related hard e.m. processes

Spectroscopy

Processes at low Q^2

Nucleon Structure

- Helicity
- Transversity
- GPDs

QCD Bound States

- Mass spectrum
- Gluonic excitations
- Multi-quark systems

Hadron Structure at Low Energies

- Polarizabilities
- Chiral anomaly

$$\lambda = 1/\sqrt{Q^2}$$

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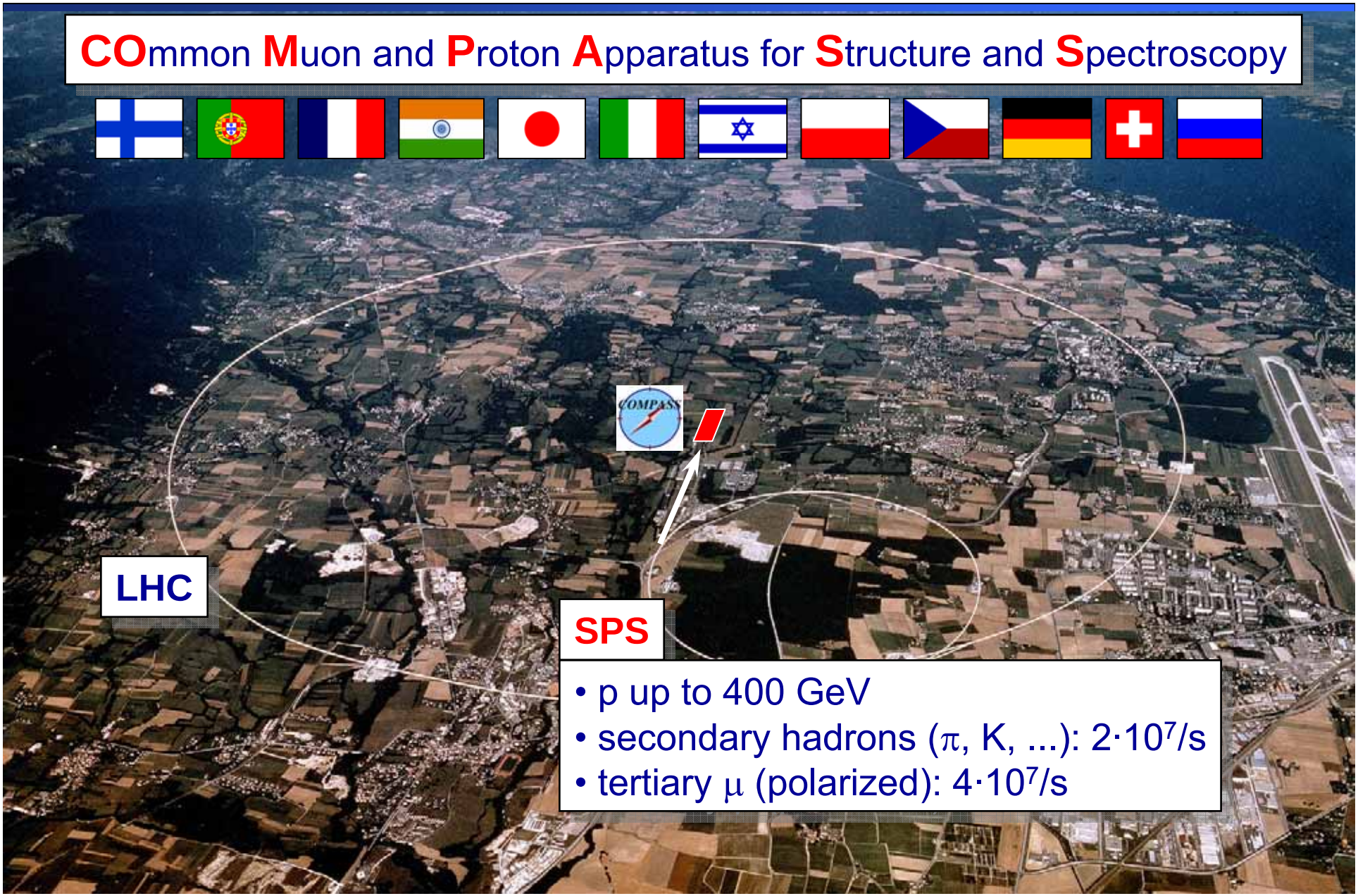
COMPASS at CERN

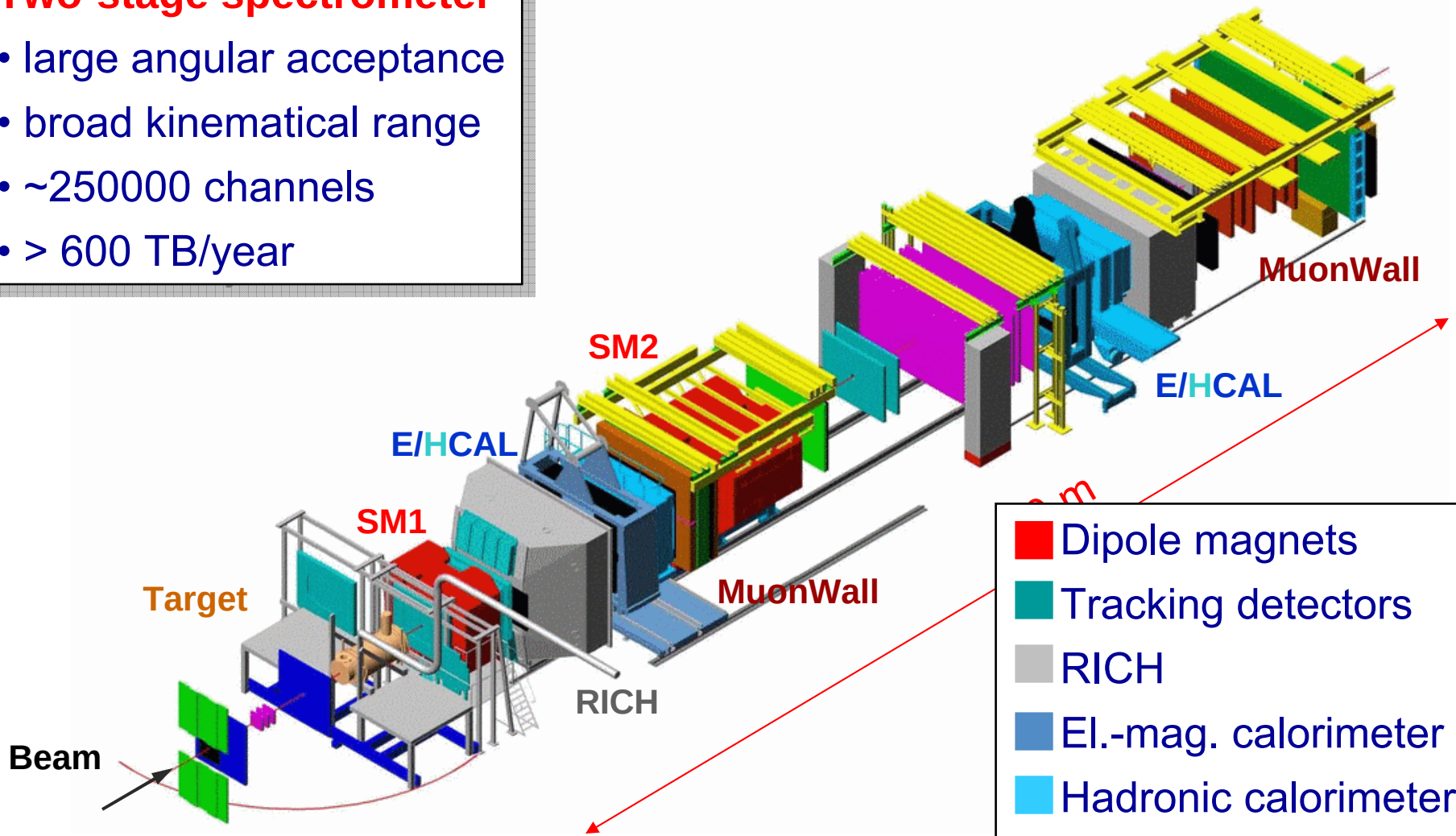
COmmon **M**uon and **P**roton **A**pparatus for **S**tructure and **S**pectroscopy



The COMPASS Experiment

Two-stage spectrometer

- large angular acceptance
- broad kinematical range
- ~250000 channels
- > 600 TB/year



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

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

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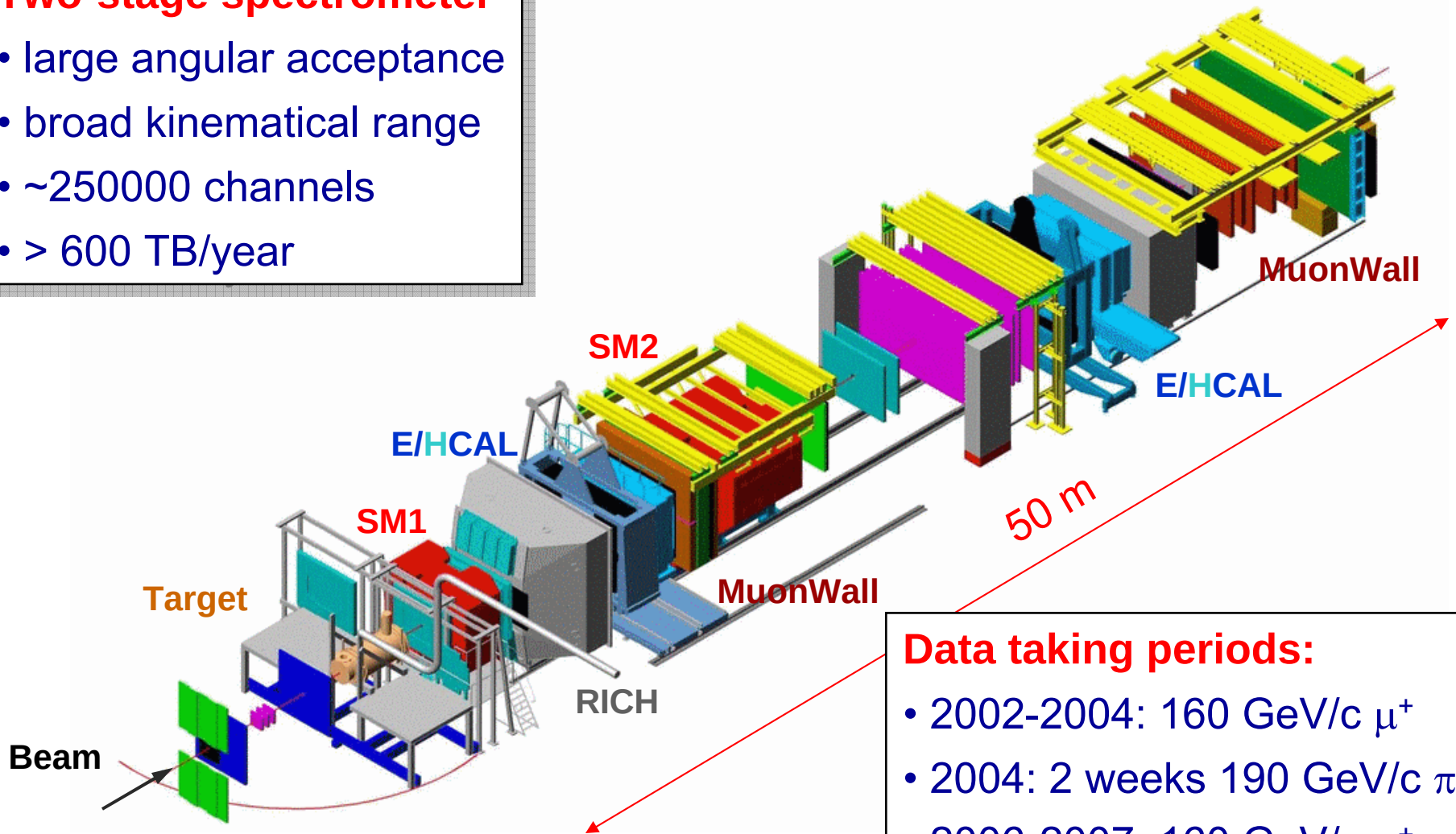

[hep-ex/0703049, NIM A 577, 455 (2007)]

Data taking periods:

- 2002-2004: 160 GeV/c μ^+
- 2004: 2 weeks 190 GeV/c π^-
- 2006-2007: 160 GeV/c μ^+
- ≥ 2008: 190 GeV/c π^-

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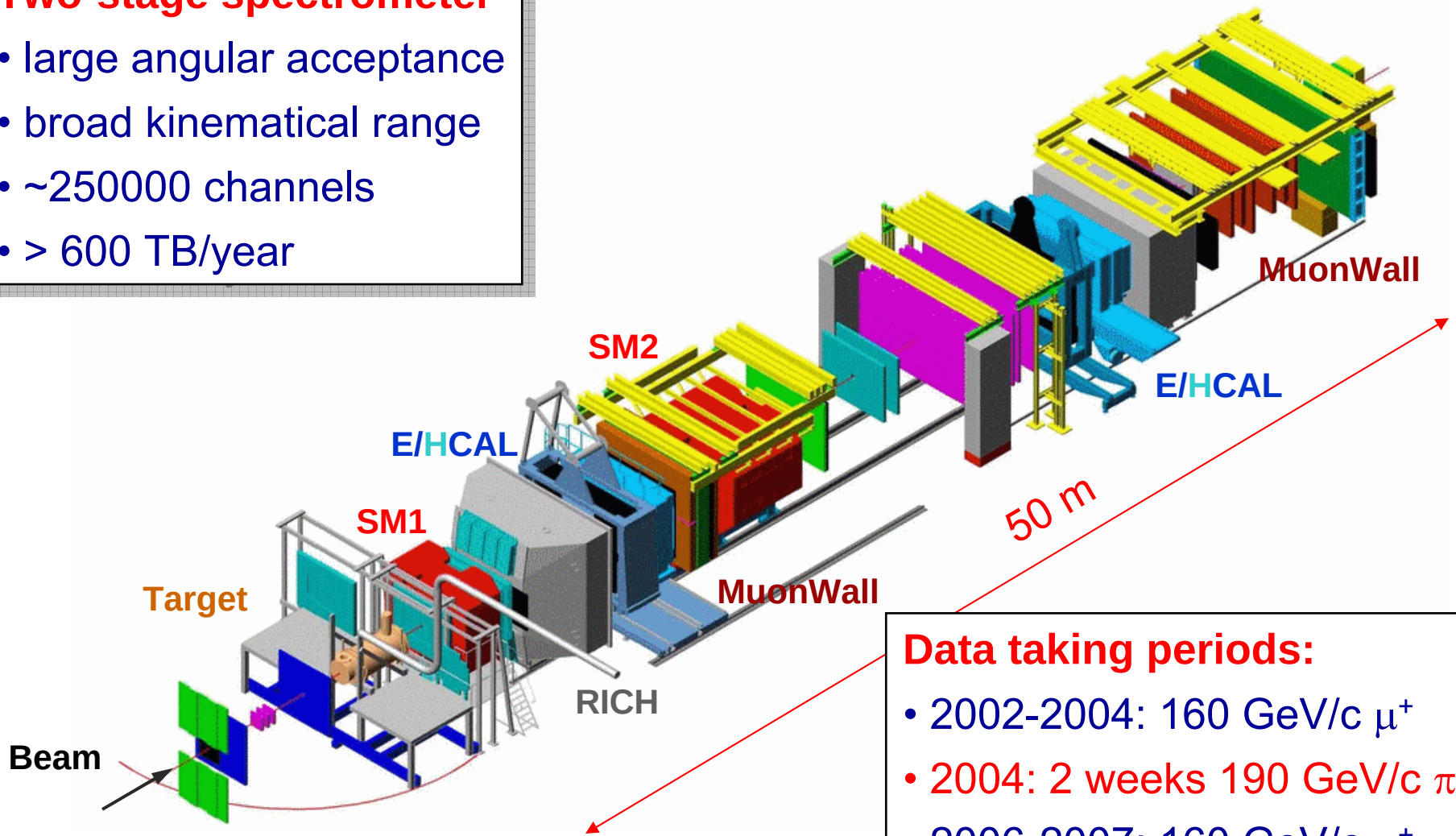

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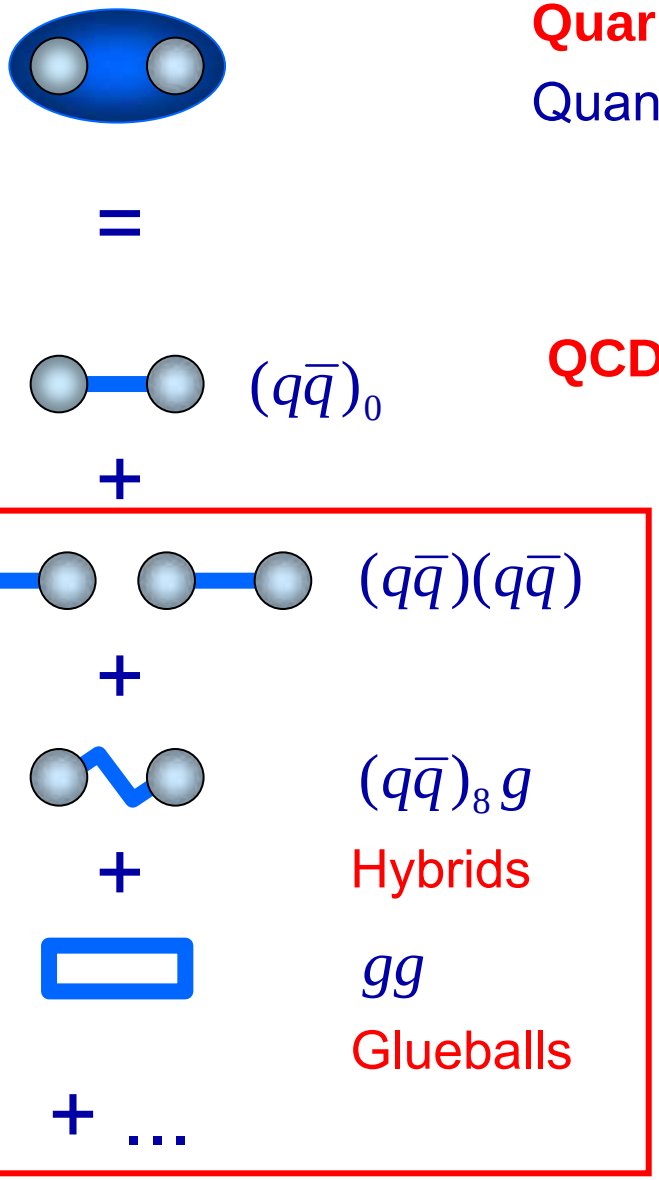
Meson Spectroscopy



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

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

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

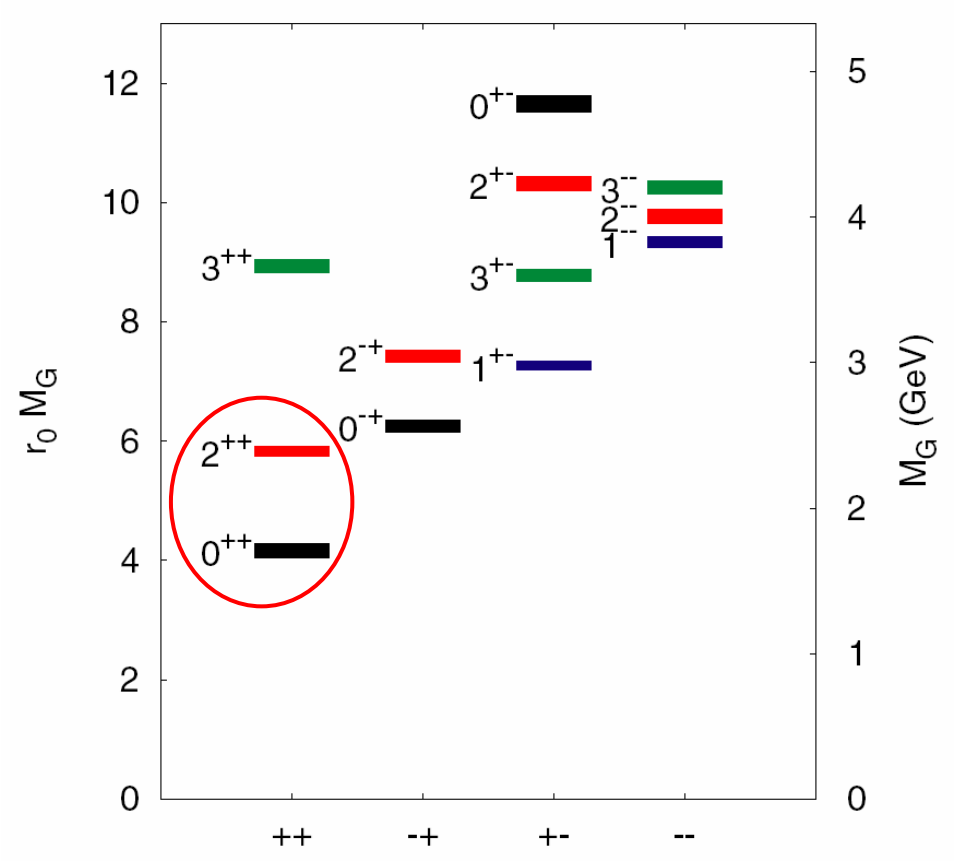
QCD: other color-neutral configurations with same quantum numbers ⇨ mixing

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)]

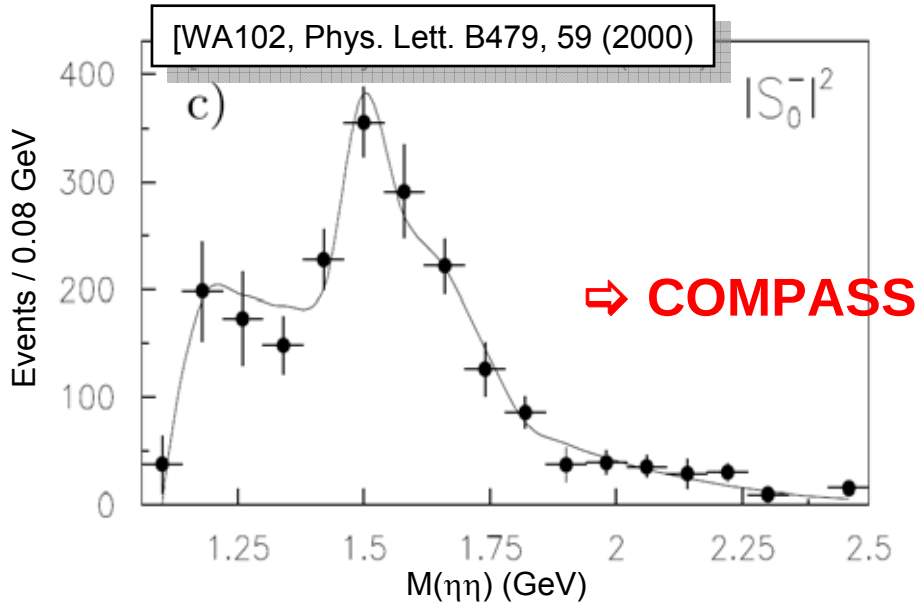
Lightest glueballs:

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

Experimental candidate:

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

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



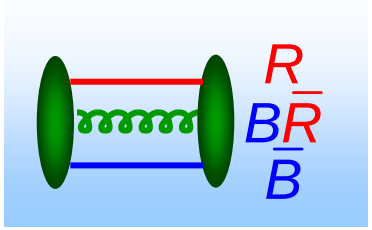
⇨ **COMPASS**

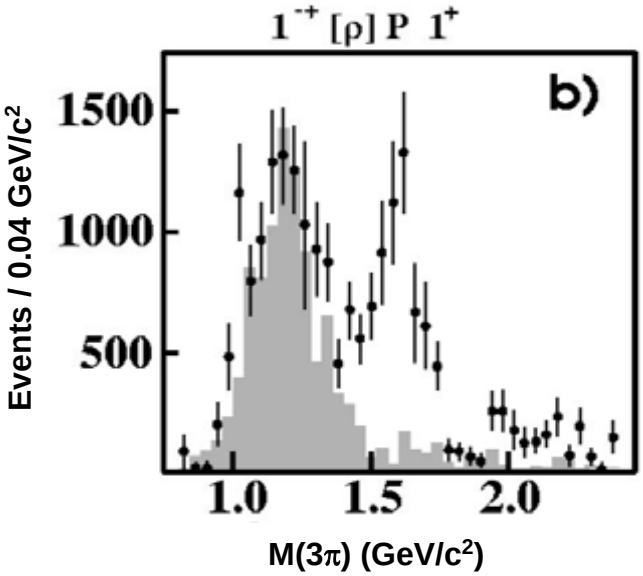
Hybrids

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

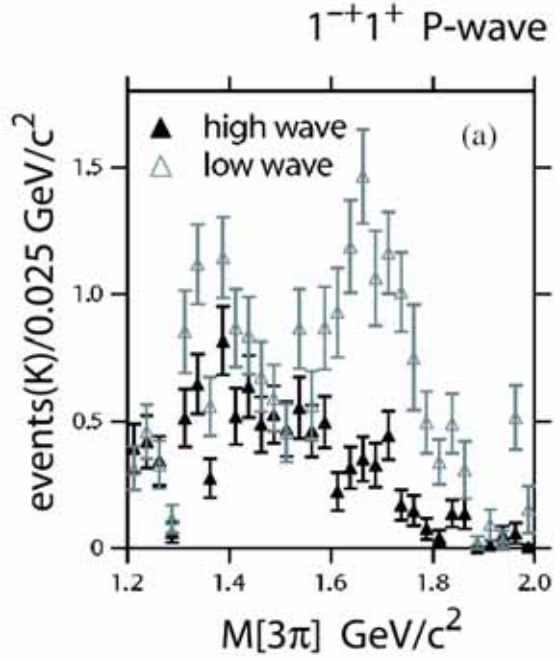
- $\pi_1(1400)$ (VES, E852, Crystal Barrel)
- $\pi_1(1600)$ (E852, VES)

  still controversial...





[S.U. Chung et al., PRD 65, 072001 (2002)]



[A.R. Dzierba et al., PRD 73, 072001 (2006)]

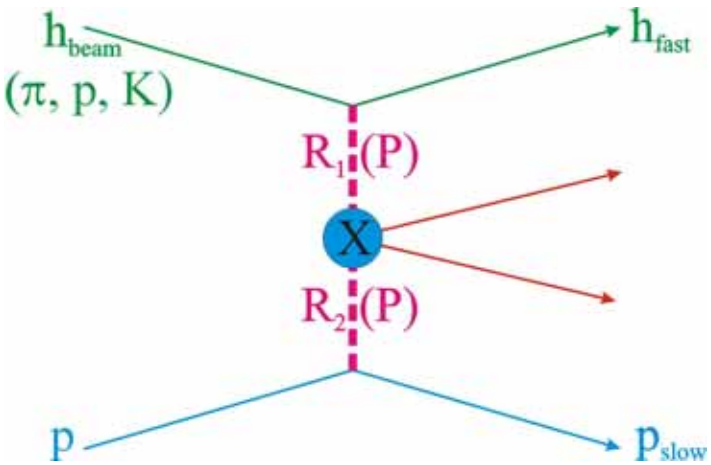
⇨ **COMPASS**

Hadron Reactions at COMPASS

Two production mechanisms

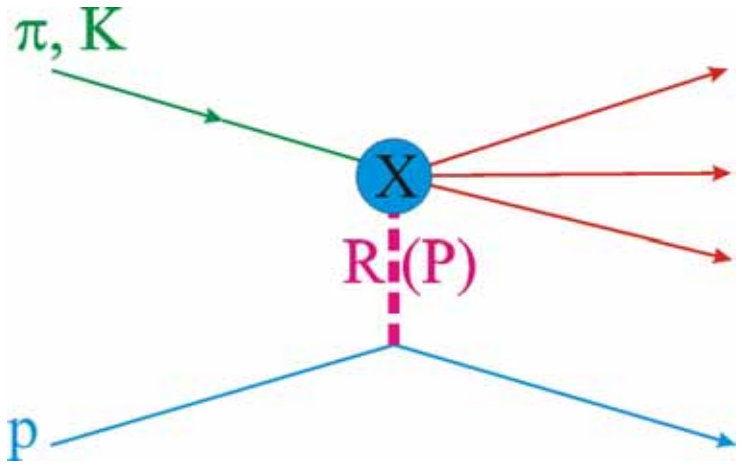
studied in parallel using **proton, pion** and **kaon** projectiles

Central production



- 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 (DPE)

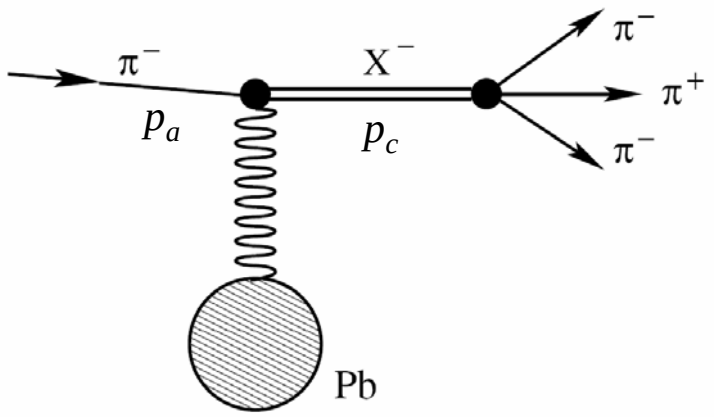
Diffractive dissociation



- Forward kinematics
- Need to separate particles at very small angles
- Study of J^{PC}-exotic mesons

Diffractive Reactions at COMPASS

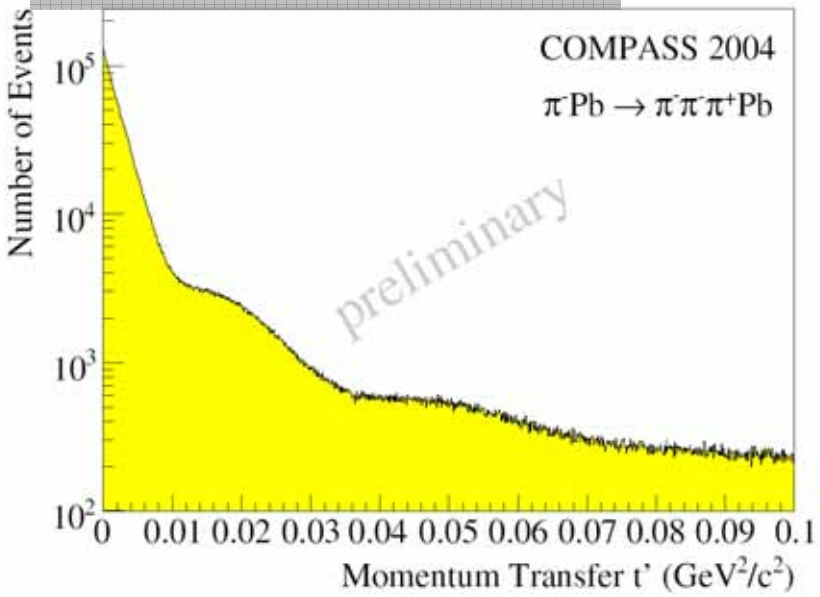
Example: $\pi^- + \mathrm{Pb} \rightarrow \pi^-\pi^-\pi^+ + \mathrm{Pb}$



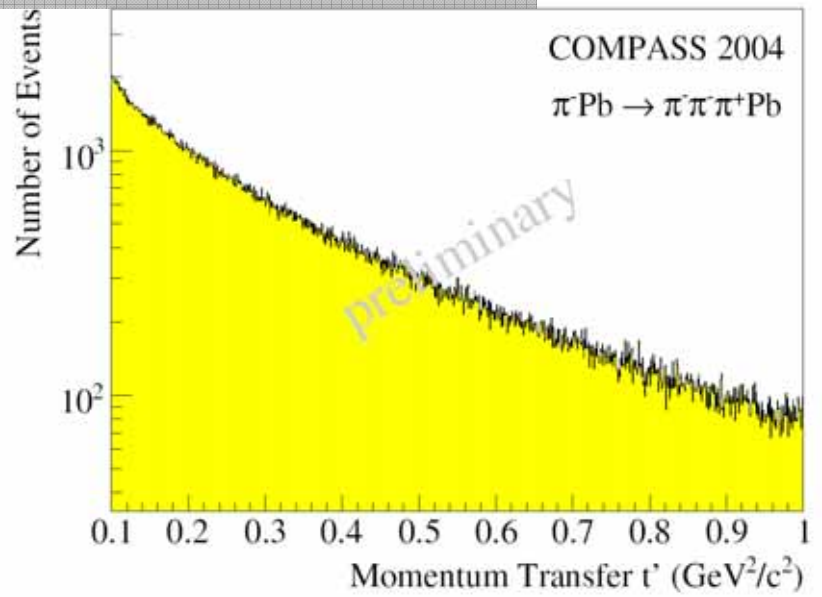
- 4π vertex in Pb target
- Exclusivity ⇨ target stays intact
- Momentum transfer

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

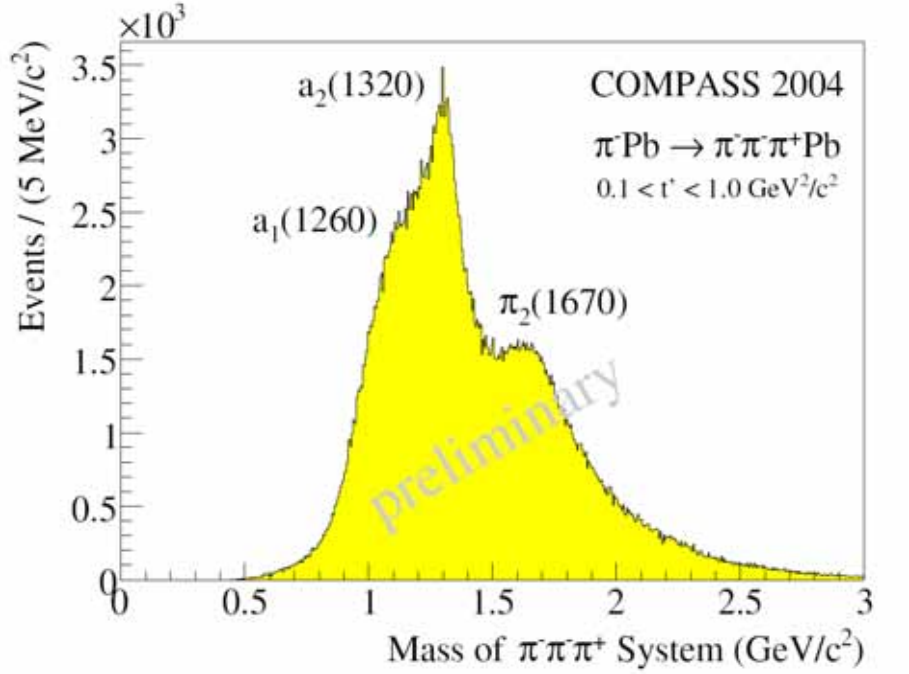
Diffraction on Pb nuclei

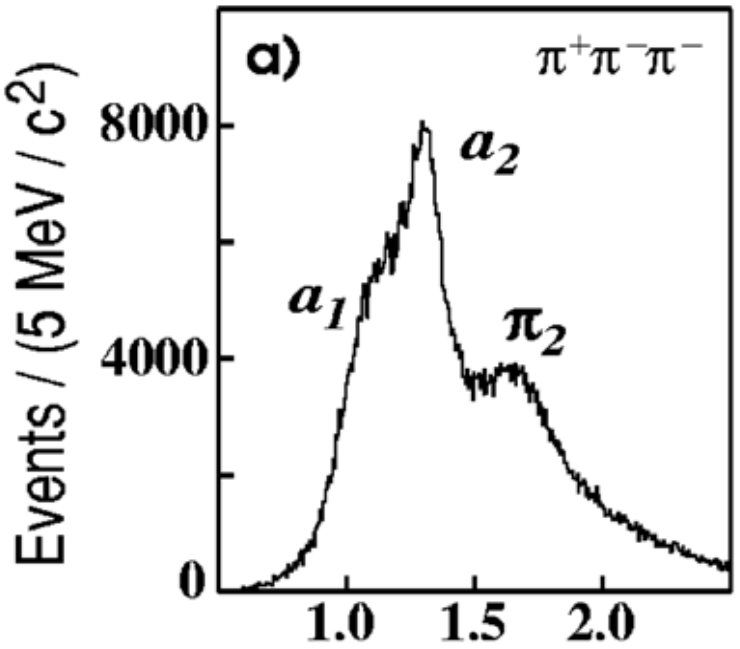


Diffraction on nucleons



Invariant Mass of 3π System





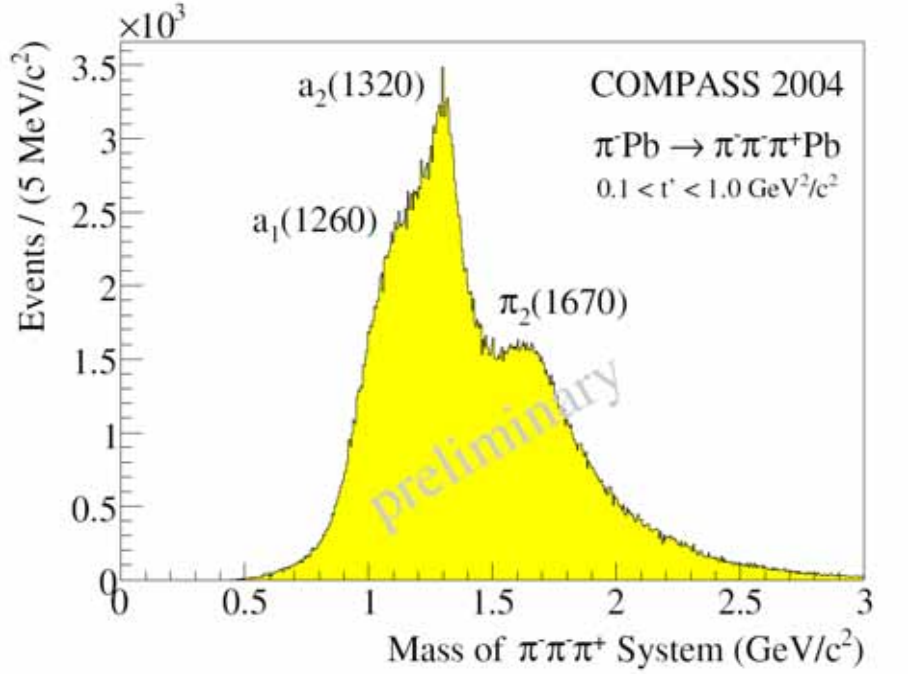
COMPASS: p_π=190 GeV/c

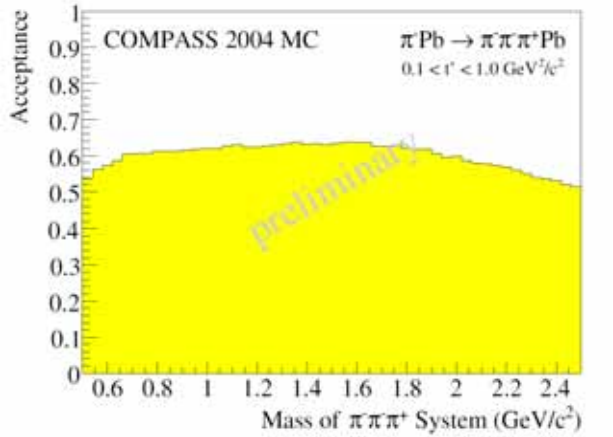
- 4M events in 3 days (full t range)
- 450k events in 0.1<t'<1.0 GeV²/c²

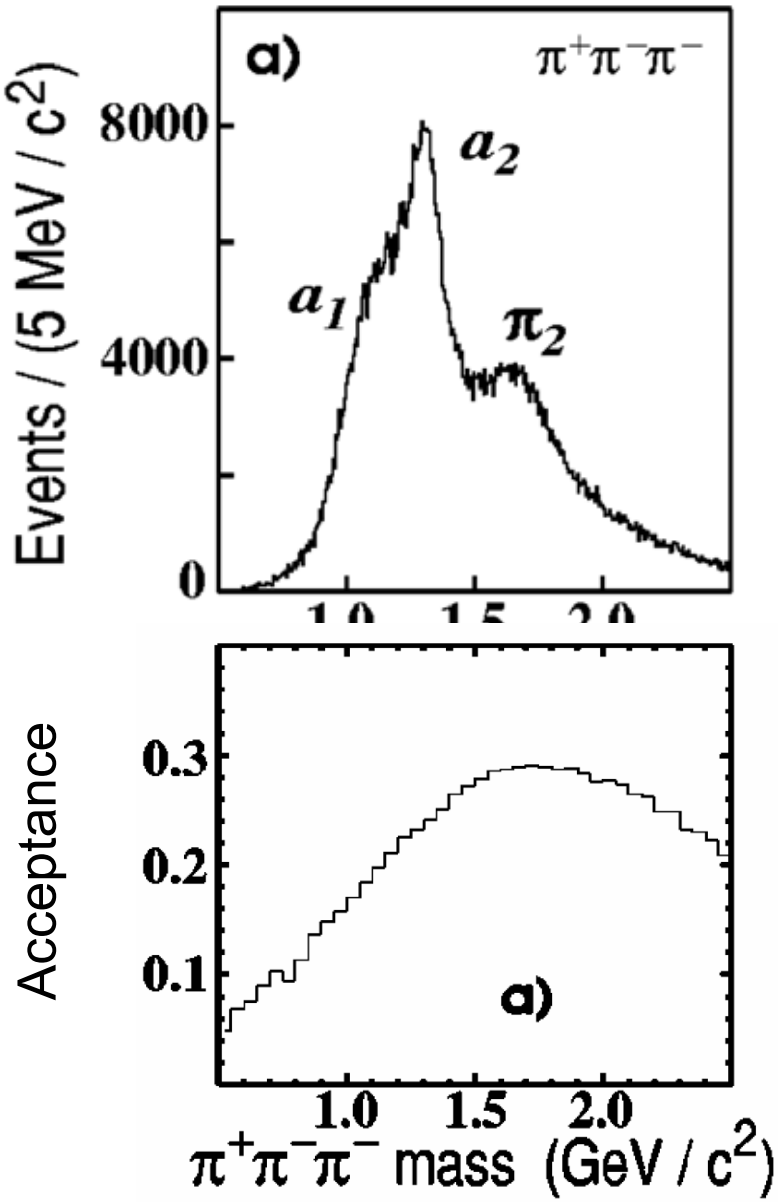
BNL852: p_π=18 GeV/c

- 250k events ⇨ $\pi_1(1600)$

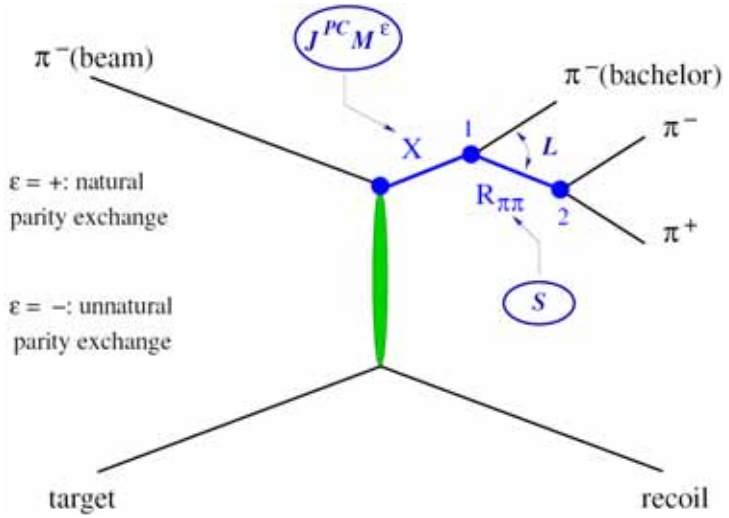
Invariant Mass of 3π System







PWA Technique



- high s: t-channel Reggeon exchange
- Reflectivity basis in G-J frame
- $\varepsilon = \eta$ of Regge trajectory
- Isobar model

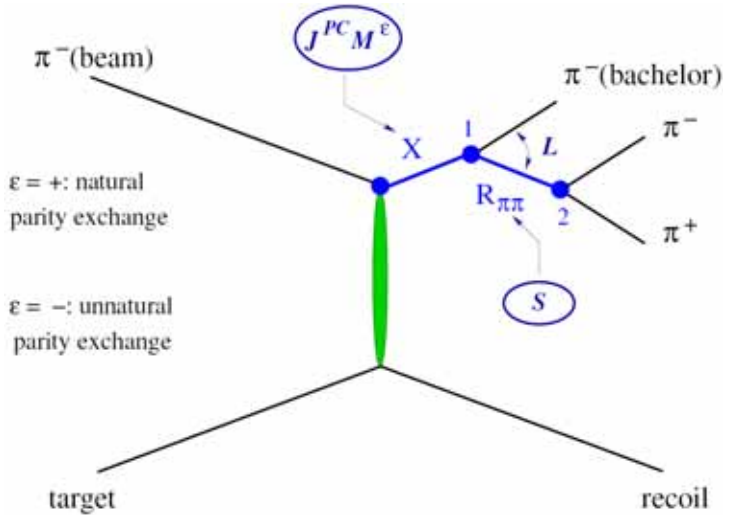
1. **Mass-independent PWA** of angular distributions in 40 MeV mass bins

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

- 42 partial waves ***$i=J^{PC}M^{\varepsilon}[\ldots]L$***

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

PWA Technique



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

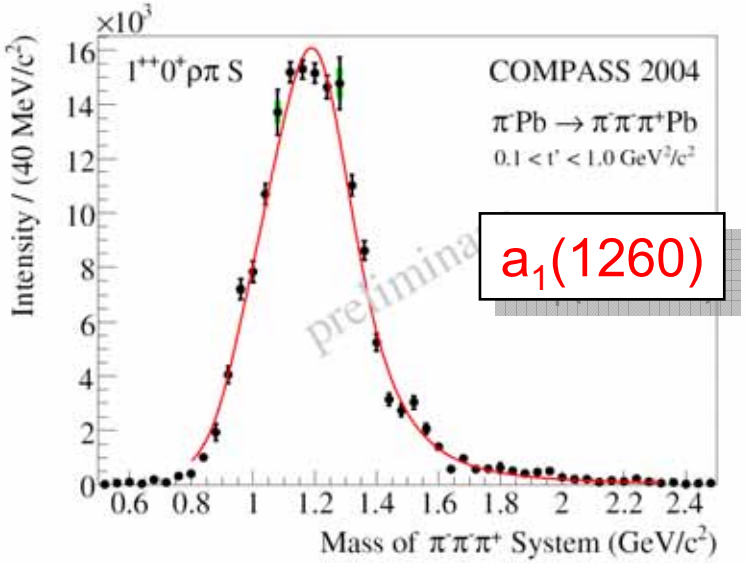
2. **Mass-dependent χ^2 fit** to results of step 1
   - 6 waves
   - Parameterized by BW
   - Coherent background for some waves

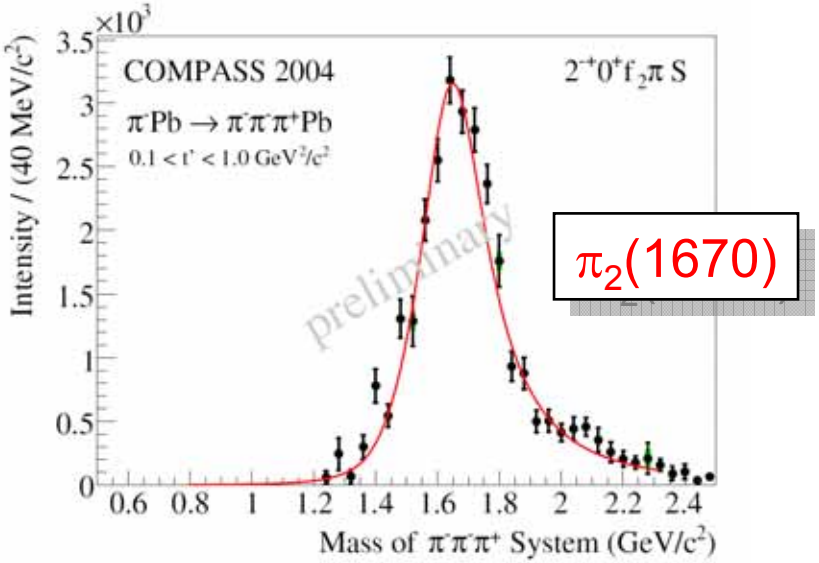
Waves used in PWA

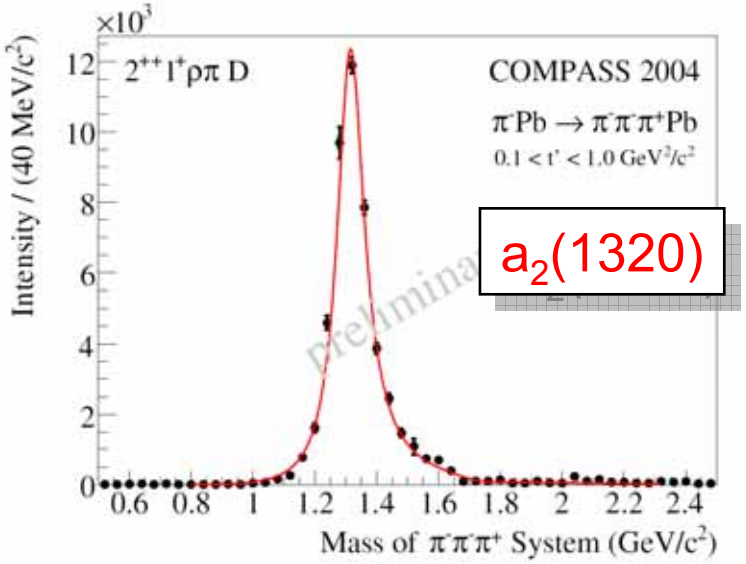
$J^{PC}M^{\epsilon}$	L	Isobar π	Cut [GeV]
$0^{-+}0^{+}$	S	$f_0\pi$	1.40
$0^{-+}0^{+}$	S	$(\pi\pi)_s\pi$	-
$0^{-+}0^{+}$	P	$\rho\pi$	-
$1^{-+}1^{+}$	P	$\rho\pi$	-
$1^{++}0^{+}$	S	$\rho\pi$	-
$1^{++}0^{+}$	P	$f_2\pi$	1.20
$1^{++}0^{+}$	P	$(\pi\pi)_s\pi$	0.84
$1^{++}0^{+}$	D	$\rho\pi$	1.30
$1^{++}1^{+}$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

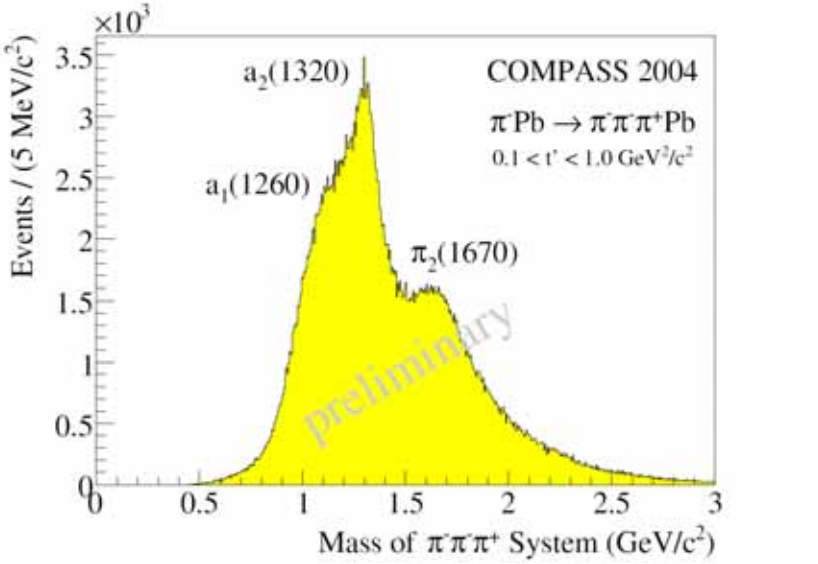
$J^{PC}M^{\epsilon}$	L	Isobar π	Cut [GeV]
$2^{++}1^{+}$	P	$f_2\pi$	1.50
$2^{++}1^{+}$	D	$\rho\pi$	-
$3^{++}0^{+}$	S	$\rho_3\pi$	1.50
$3^{++}0^{+}$	P	$f_2\pi$	1.20
$3^{++}0^{+}$	D	$\rho\pi$	1.50
$3^{++}1^{+}$	S	$\rho_3\pi$	1.50
$3^{++}1^{+}$	P	$f_2\pi$	1.20
$3^{++}1^{+}$	D	$\rho\pi$	1.50
$4^{-+}0^{+}$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

Major Waves

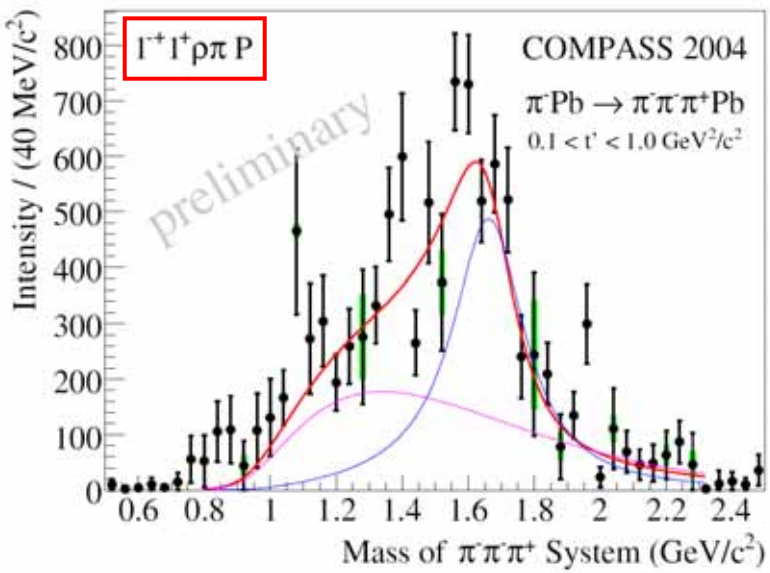

$1^{++}0^{+}\rho\pi$ S
COMPASS 2004
$\pi^-Pb \to \pi^-\pi^-\pi^+Pb$
$0.1 < t' < 1.0$ GeV$^2/c^2$
$a_1(1260)$
Intensity / (40 MeV/c^2)
Mass of $\pi^-\pi^-\pi^+$ System (GeV/c^2)
preliminary


COMPASS 2004
$2^{-+}0^{+}f_2\pi$ S
$\pi^-Pb \to \pi^-\pi^-\pi^+Pb$
$0.1 < t' < 1.0$ GeV$^2/c^2$
$\pi_2(1670)$
Intensity / (40 MeV/c^2)
Mass of $\pi^-\pi^-\pi^+$ System (GeV/c^2)
preliminary


$2^{++}1^{+}\rho\pi$ D
COMPASS 2004
$\pi^-Pb \to \pi^-\pi^-\pi^+Pb$
$0.1 < t' < 1.0$ GeV$^2/c^2$
$a_2(1320)$
Intensity / (40 MeV/c^2)
Mass of $\pi^-\pi^-\pi^+$ System (GeV/c^2)
preliminary


$a_2(1320)$
$a_1(1260)$
$\pi_2(1670)$
COMPASS 2004
$\pi^-Pb \to \pi^-\pi^-\pi^+Pb$
$0.1 < t' < 1.0$ GeV$^2/c^2$
Events / (5 MeV/c^2)
Mass of $\pi^-\pi^-\pi^+$ System (GeV/c^2)
preliminary

$\pi_1(1600)$

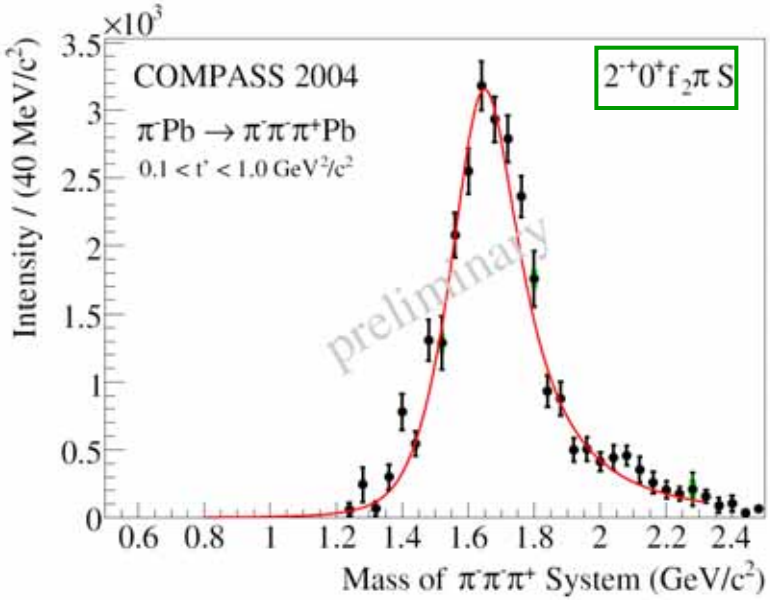


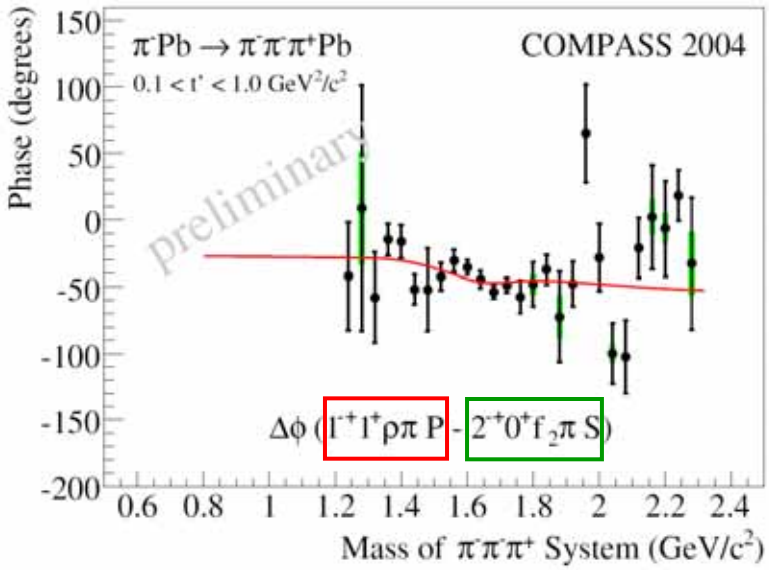
- BW parameters for $\pi_1(1600)$

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

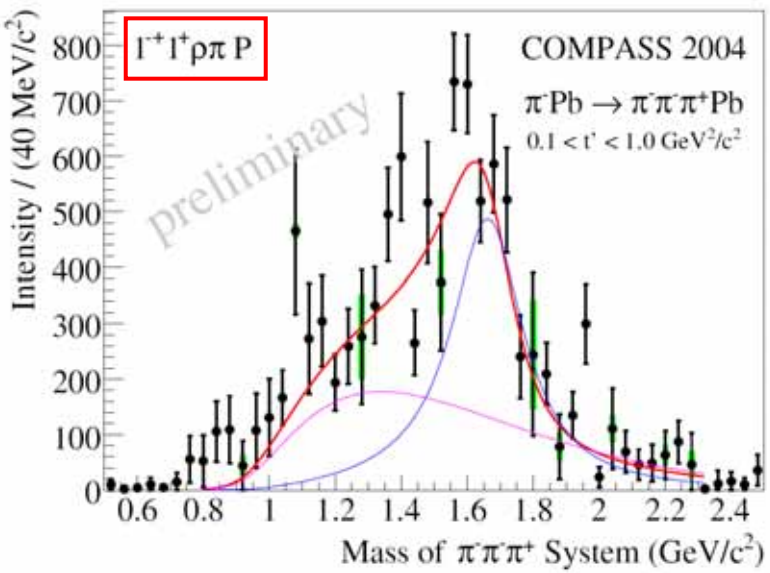
$$\Gamma = \left(0.269 \pm 0.021\,^{+0.042}_{-0.064}\right) \text{GeV}/c^2$$

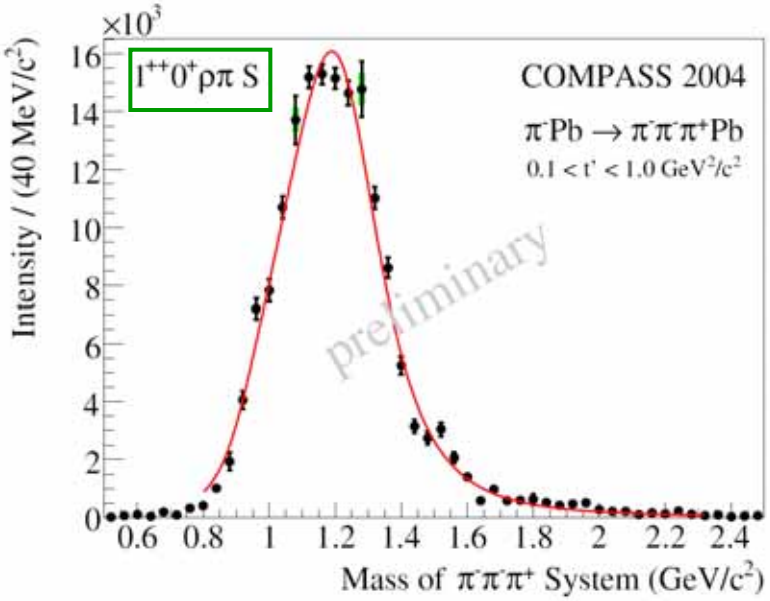
- Leakage negligible





$\pi_1(1600)$





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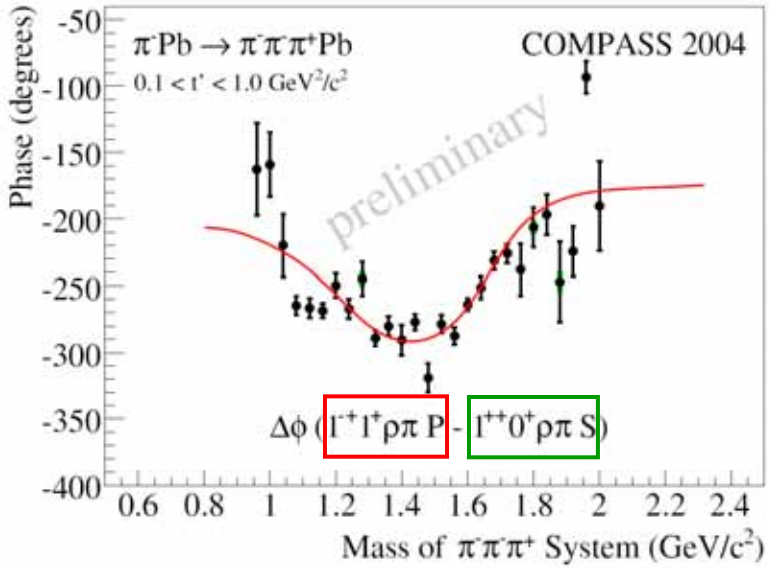
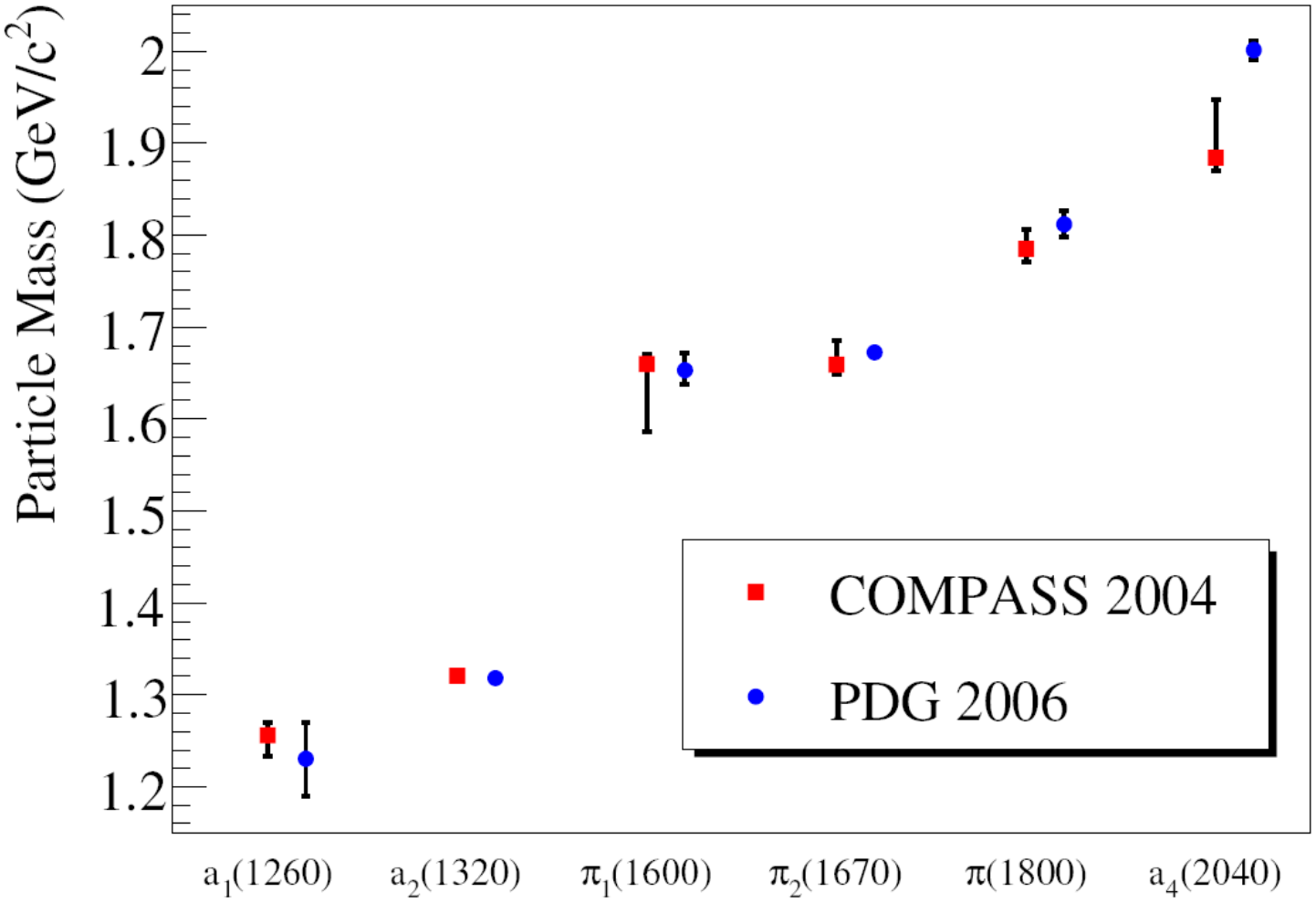
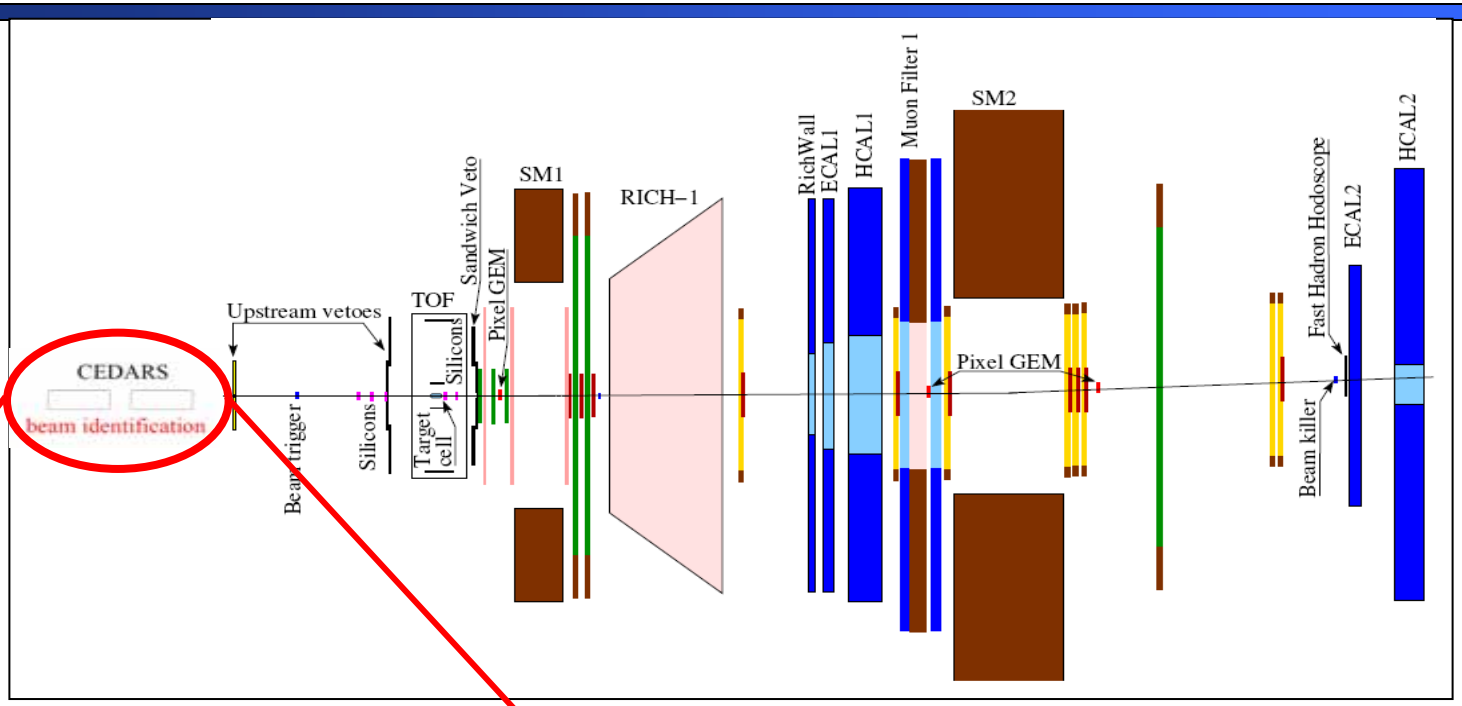


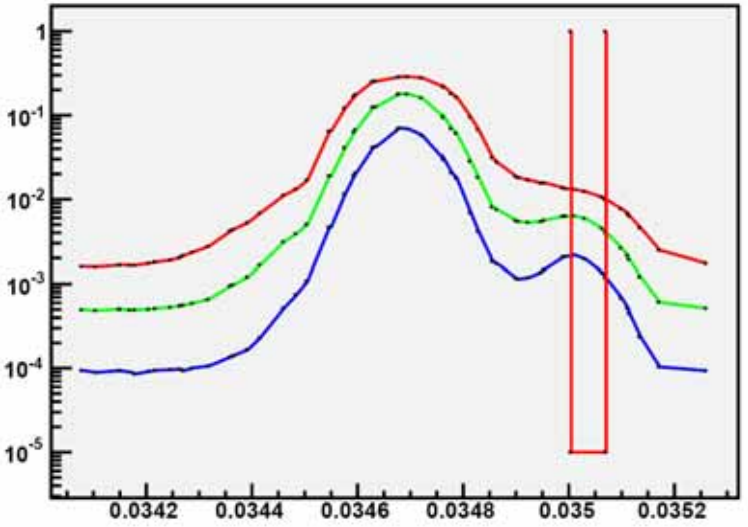
Summary of Waves



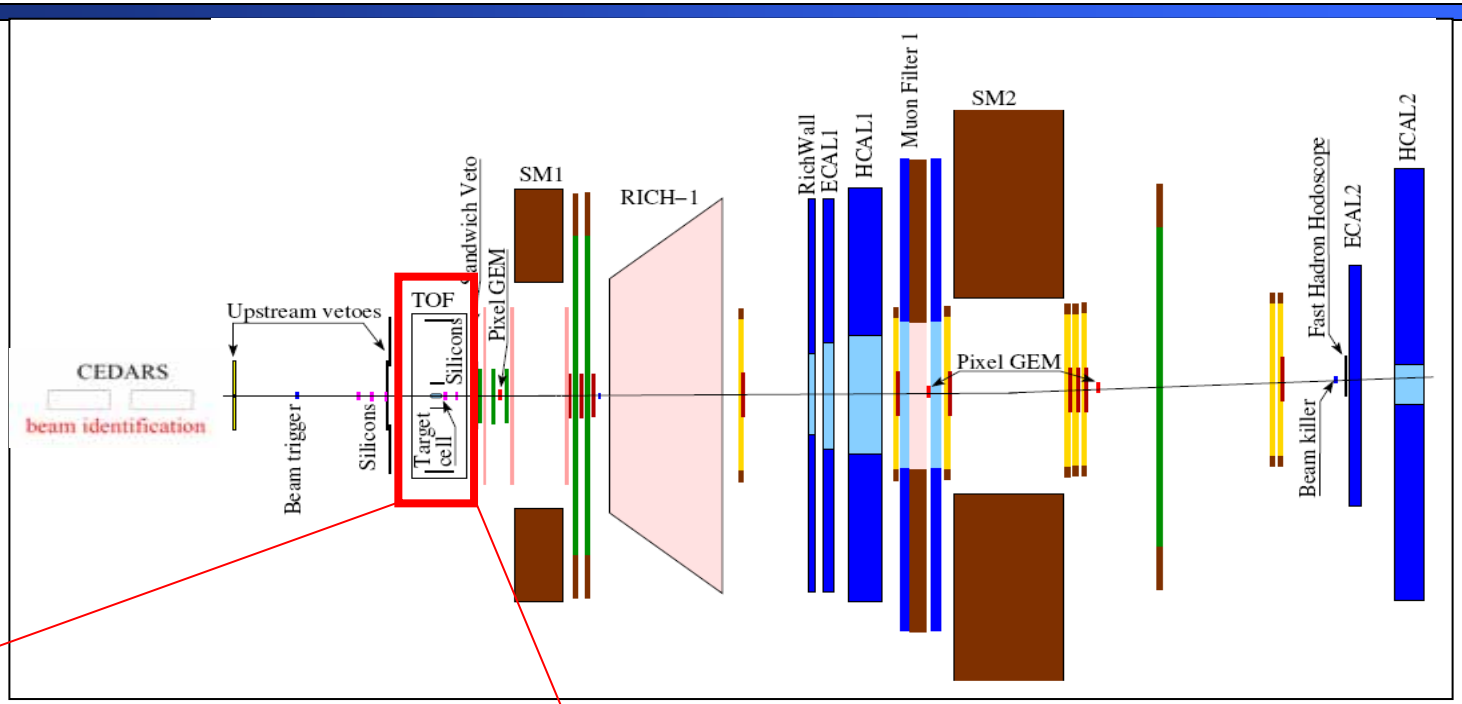
Publication being prepared, to be submitted to PRL

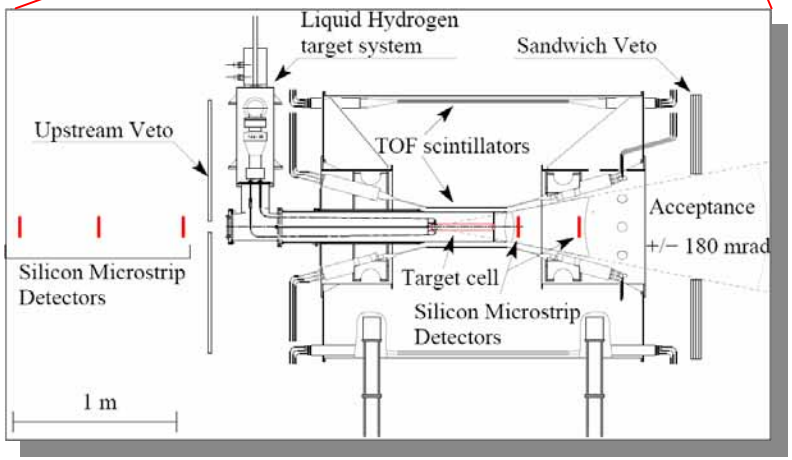
COMPASS in 2008

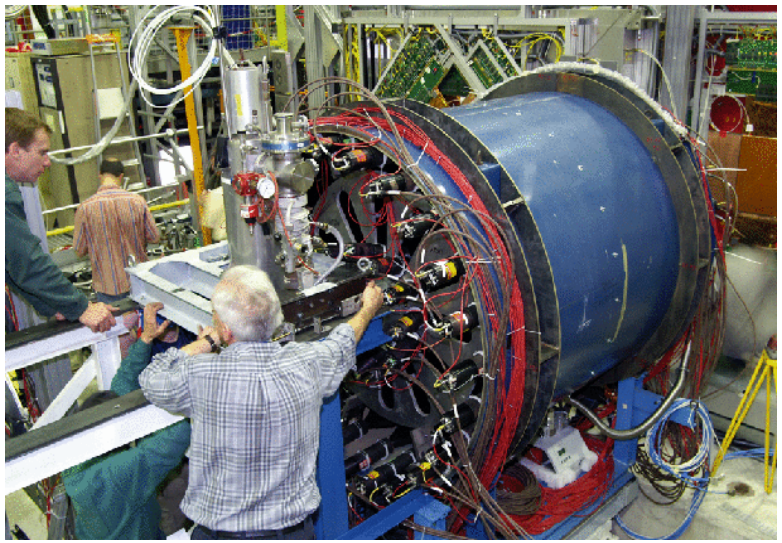




COMPASS in 2008







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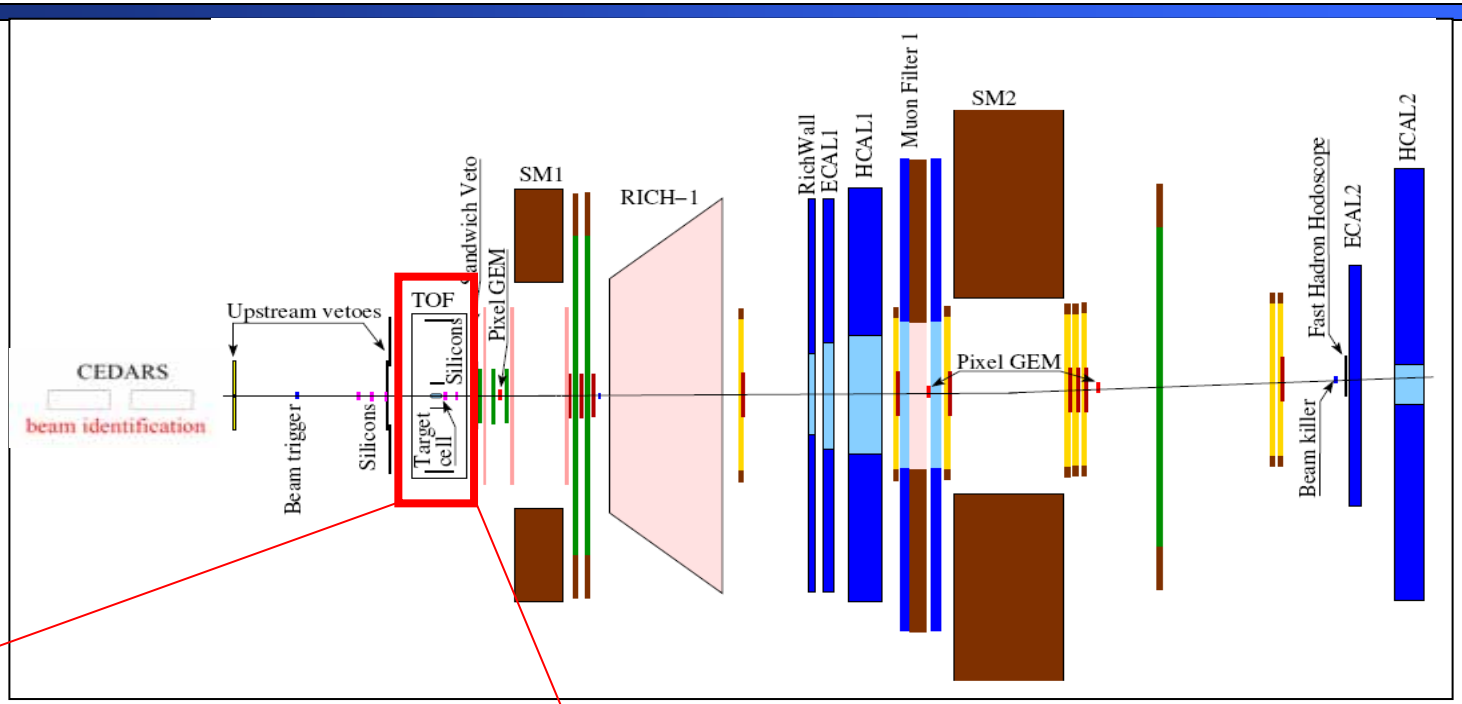
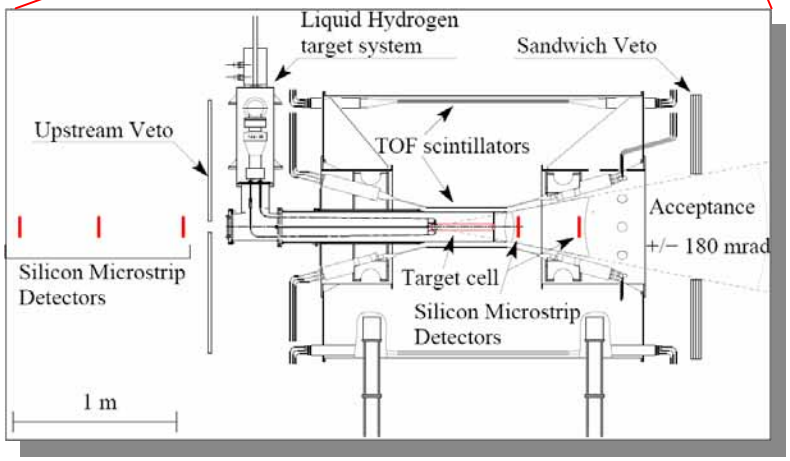
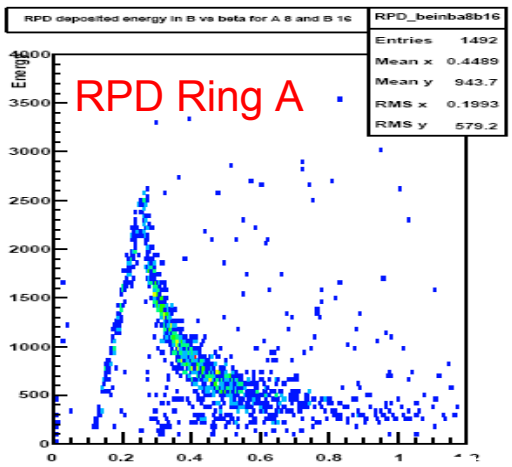
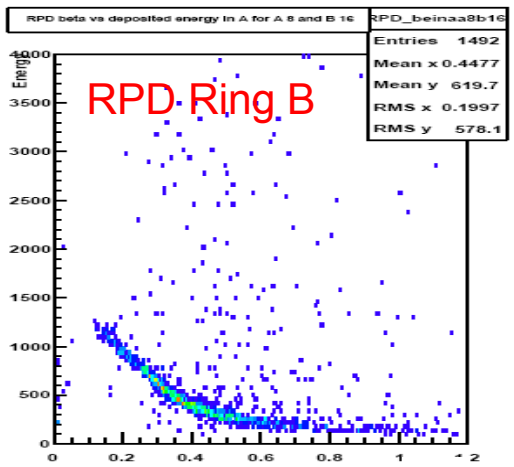
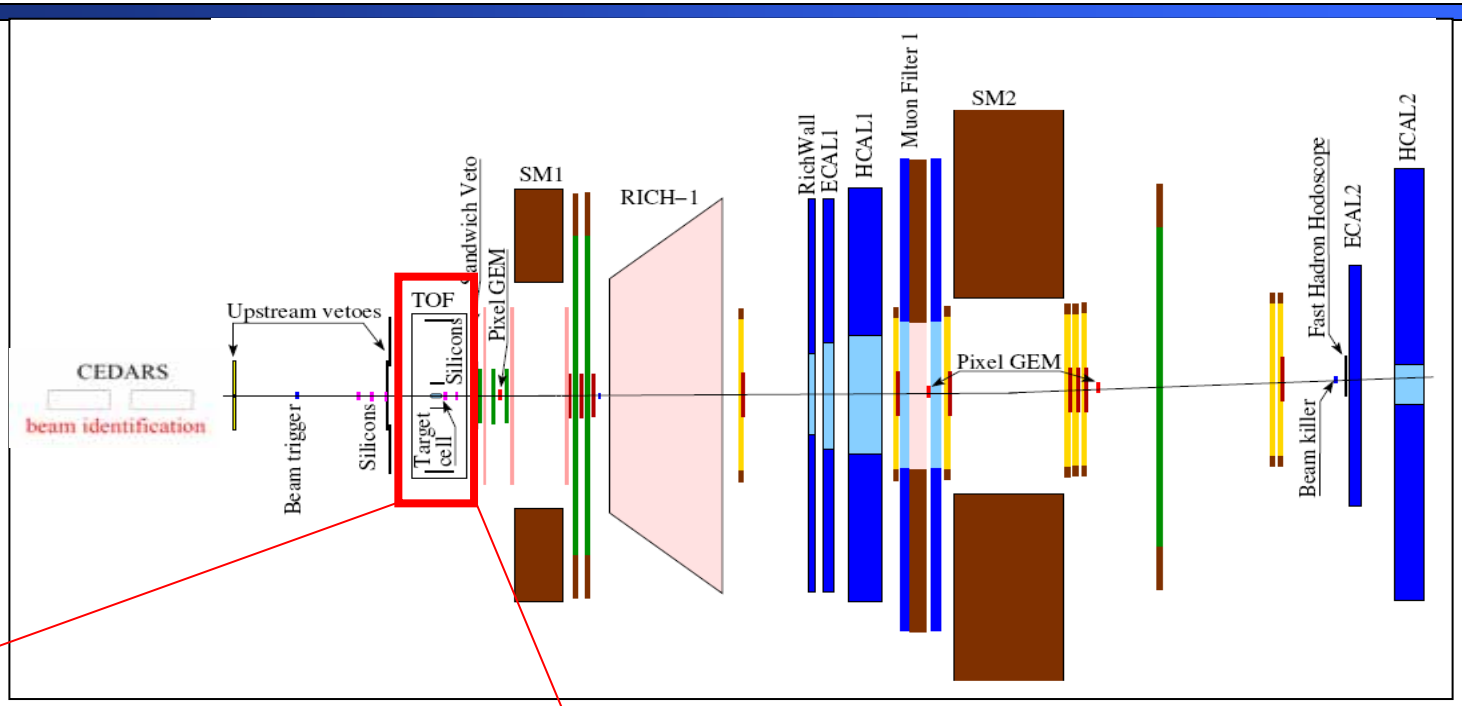


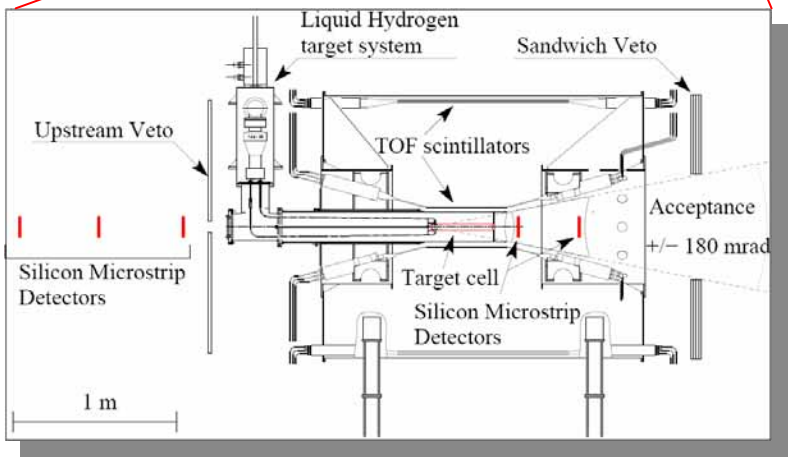






COMPASS in 2008





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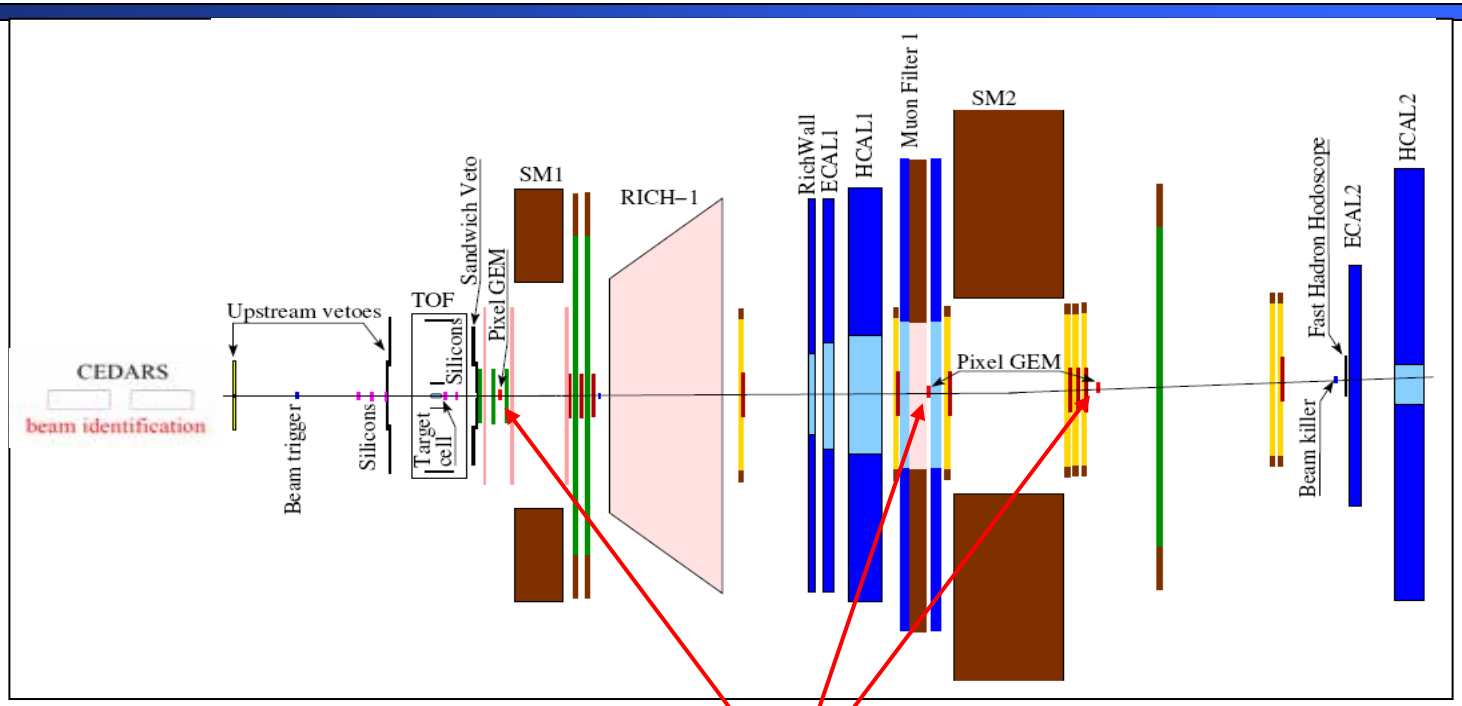
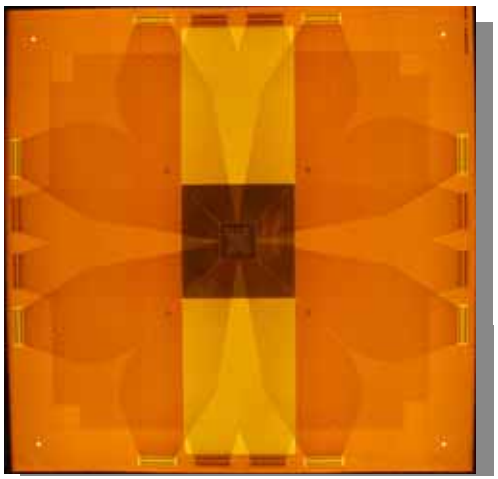
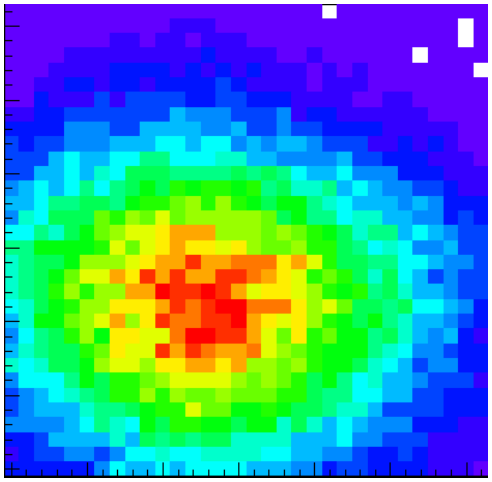


PixelGEM detectors:

- low mass
- high rates: ~10^5 $mm^{-2}s^{-1}$
- resolution: ~120 μm





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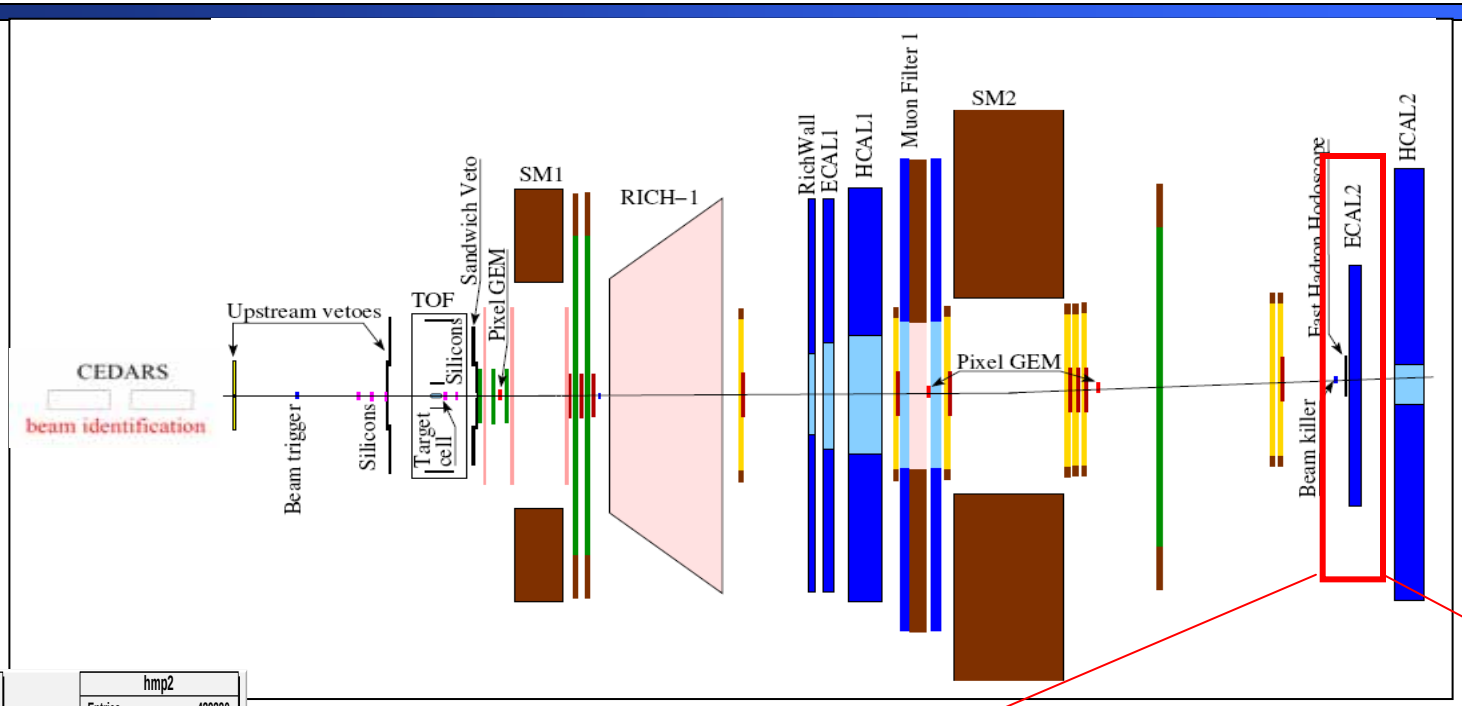

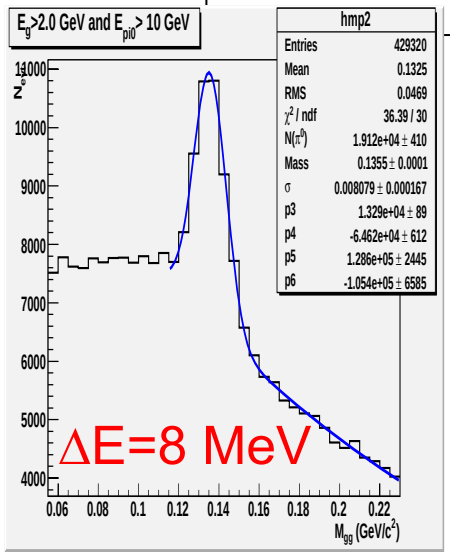

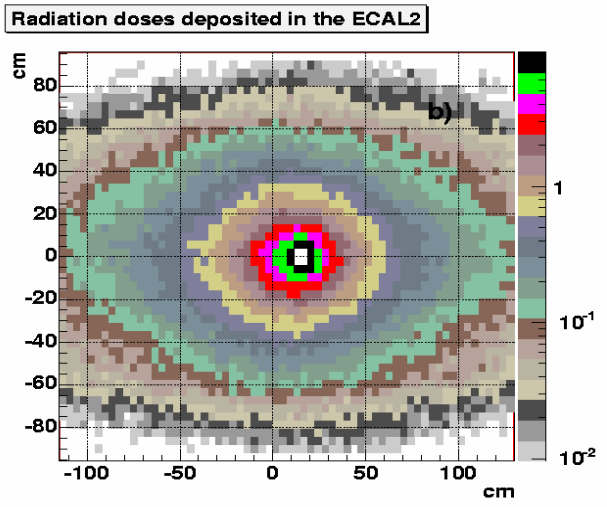

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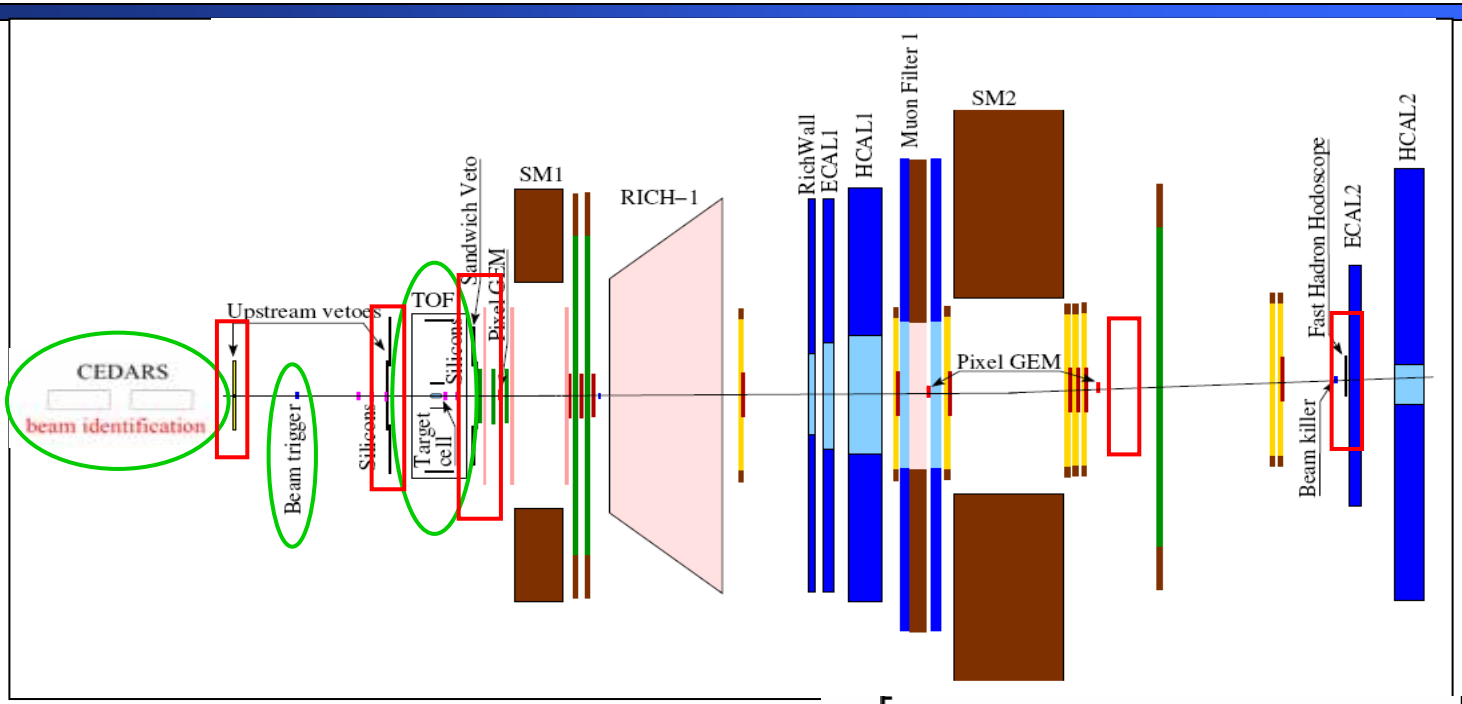
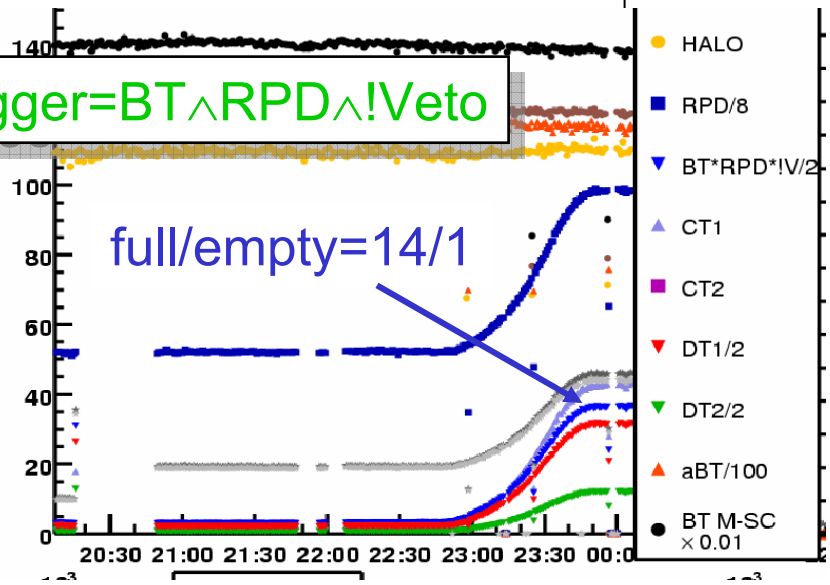


Trigger components:

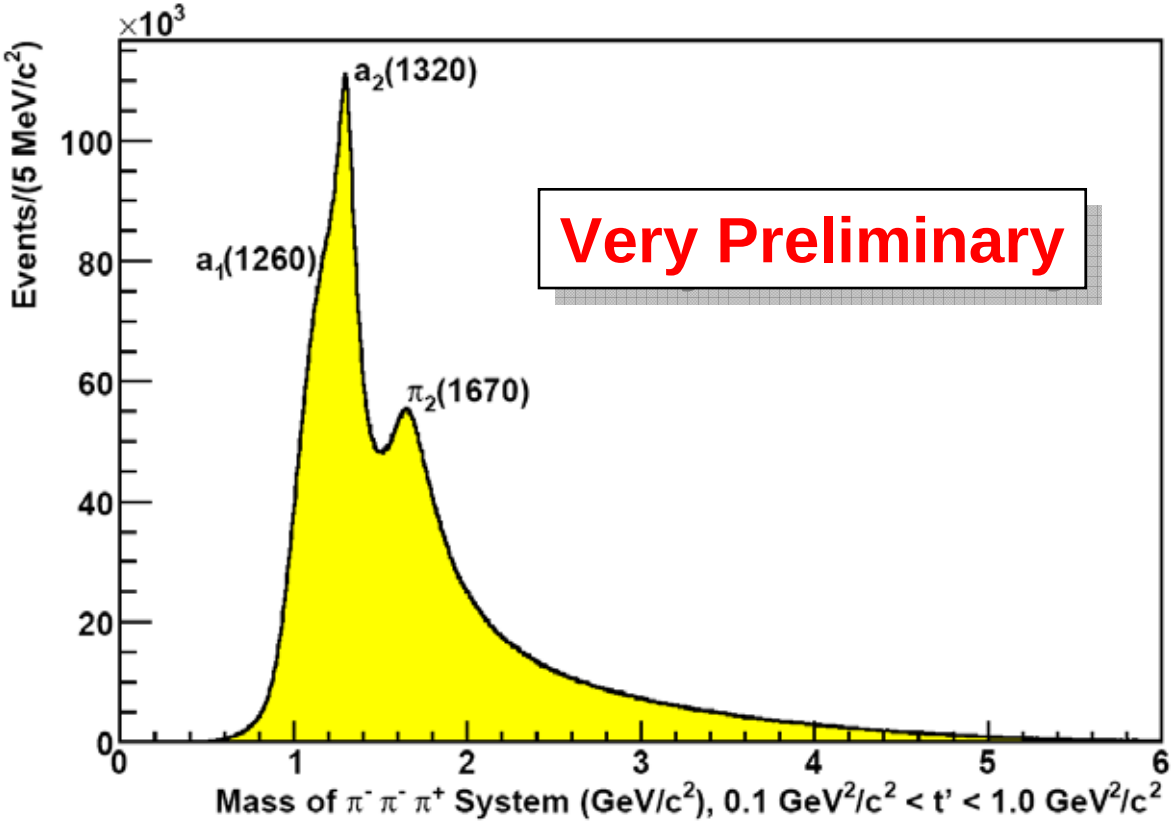
- Beam trigger
- RPD
- Cedars
- Veto: Hodo || Sandwich || BK
- Mainz Counter
- Forward Hodoscope

Diffractive Trigger=BT∧RPD∧!Veto



Statistics in 2008

- 190 GeV/c hadron beam
- Target: 40cm liquid hydrogen
- Diffractive dissociation: 96% π^-, 3.5% K^-, 0.5% $\bar{p}$
  - **$\pi^- p \rightarrow \pi_1(1600) p$, $\pi_1(1600) \rightarrow 3\pi$: 120000 events exp.** ≈✓



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- Central production: 75% p, 25% π^+
  - **$\pi^+ p \rightarrow \pi^+ f_0 p$, $f_0(1500) \rightarrow 4\pi$: 100000 events exp.**

Early North Area stop due to LHC problems

only a few days of testing...
to be done in 2009

Experimental Tools

Deep Inelastic Lepton Scattering

and related hard e.m. processes

Spectroscopy

Processes at low Q^2

Nucleon Structure

- Helicity
- Transversity
- GPDs

QCD Bound States

- Mass spectrum
- Gluonic excitations
- Multi-quark systems

Hadron Structure at Low Energies

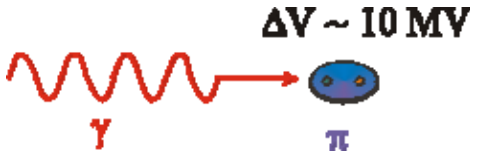
- Polarizabilities
- Chiral anomaly

$$\lambda = 1/\sqrt{Q^2}$$

Pion Polarizabilities

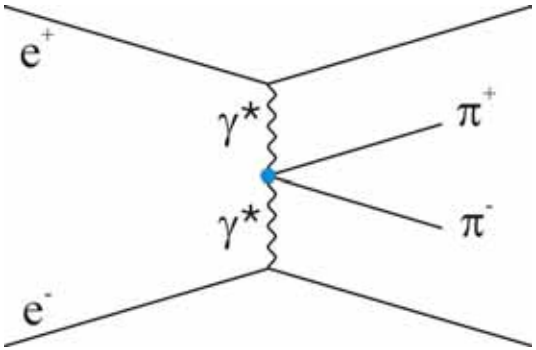
Describe response to external e.m. fields ⇨ stiffness of system

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

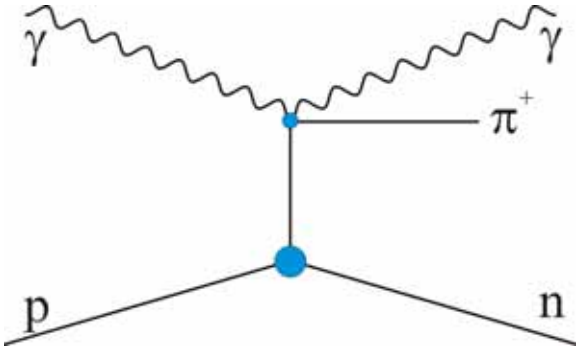


χPT (2-loop): $\overline{\alpha}_\pi = (2.9 \pm 0.5) \cdot 10^{-4}\ \mathrm{fm}^3$ $\overline{\beta}_\pi = (-2.8 \pm 0.5) \cdot 10^{-4}\ \mathrm{fm}^3$

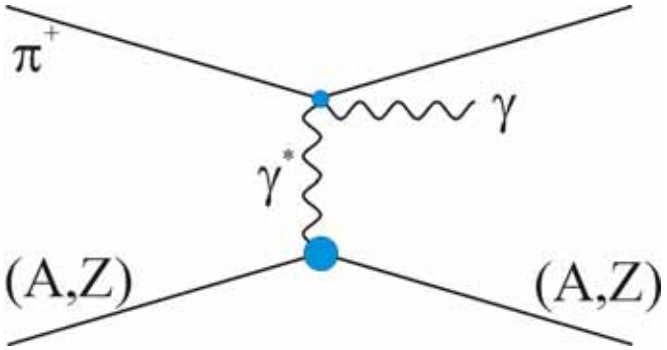
Experiments: pion Compton scattering $\pi^-\gamma \to \pi^-\gamma$



PLUTO
DM1
DM2
Mark II



Lebedev
Mami A2



Serpukhov

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- electric polarizability $\vec{d} = \bar{\alpha}\,\vec{E}$
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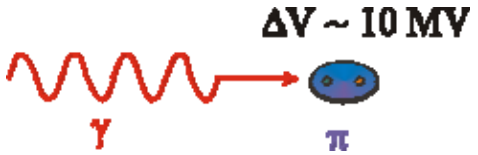

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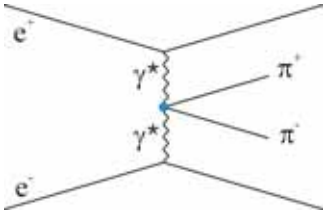

PLUTO
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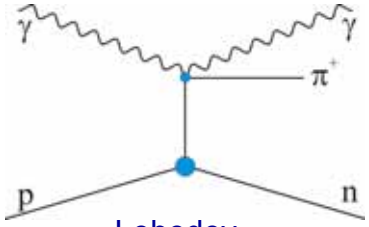
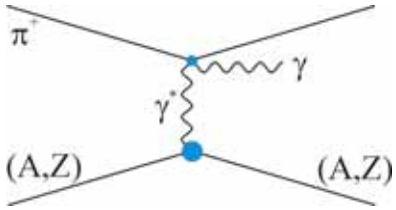
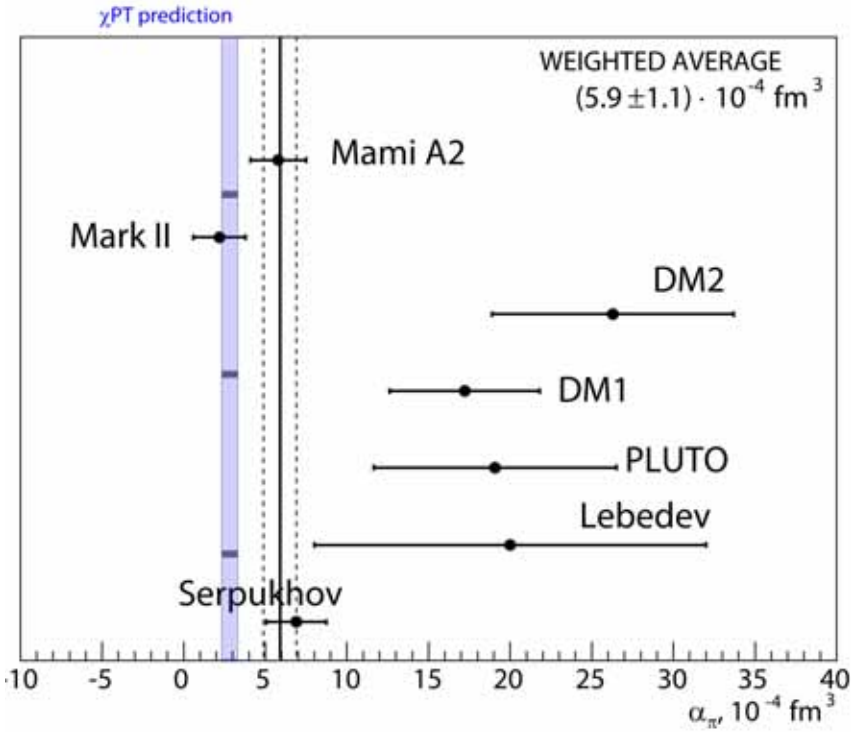


Lebedev
Mami A2



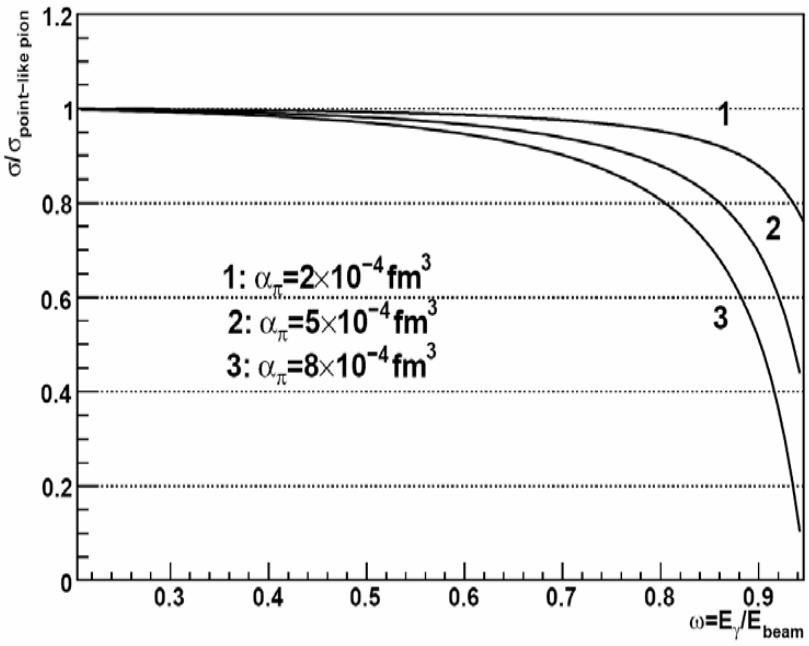
Serpukhov

COMPASS



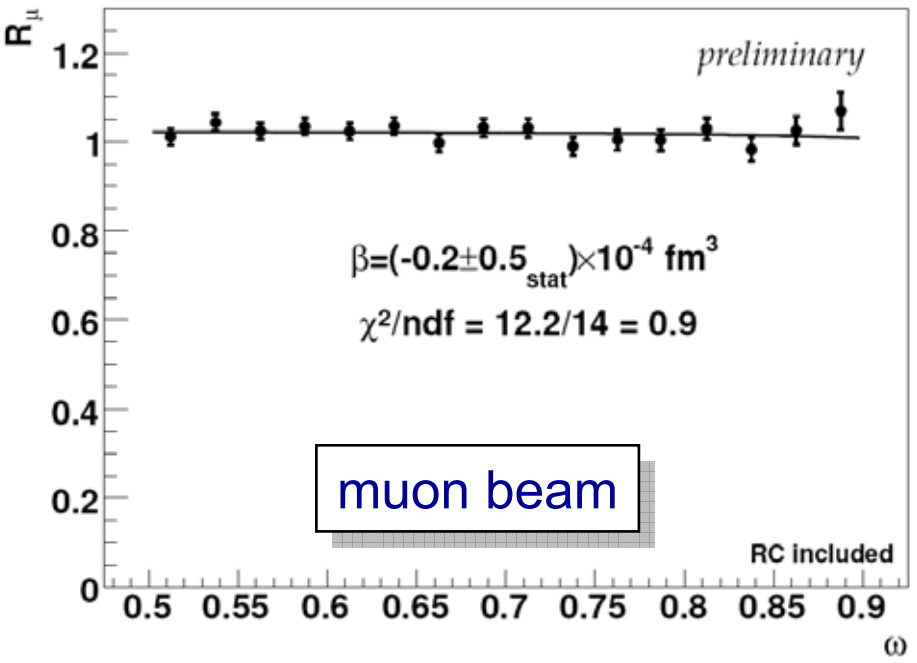
Cross Section Ratio

$$R(\omega) = \frac{N_{\mathrm{exp}}(\omega)}{N_{\mathrm{MC}}(\omega)} = \frac{\mathrm{d}\sigma_{\gamma\pi}^{\mathrm{Prim}}}{\mathrm{d}\sigma_{\gamma\pi}^{\mathrm{Thomson}}} \cong 1 + \frac{3}{2}\frac{m_\pi^3}{\alpha}\frac{\omega^2}{1-\omega}\bar{\beta}_\pi, \quad \left(\bar{\alpha}_\pi + \bar{\beta}_\pi = 0\right)$$



$R(\omega)$ for different values of α_π (β_π)

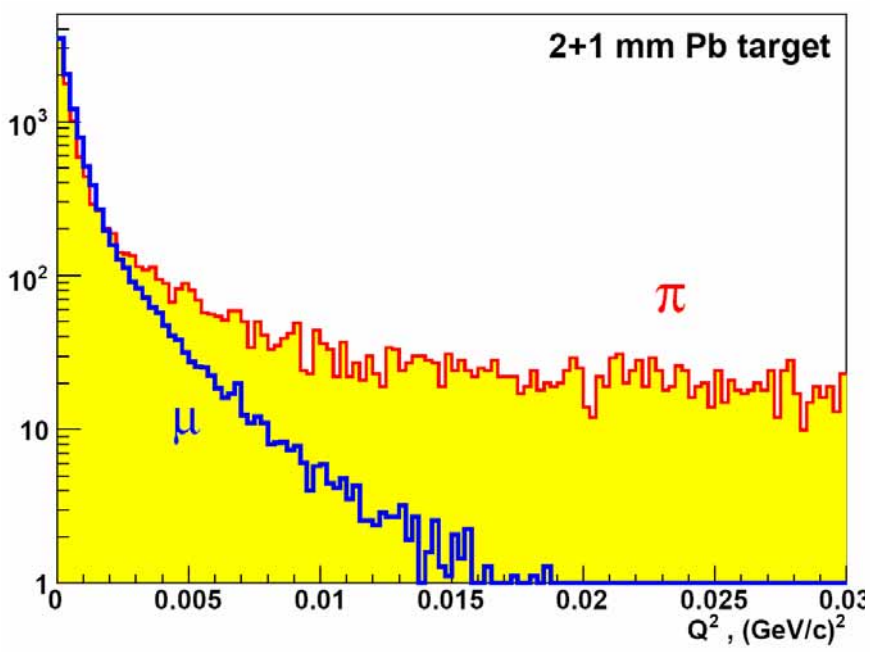
COMPASS 2004 μ⁻ data

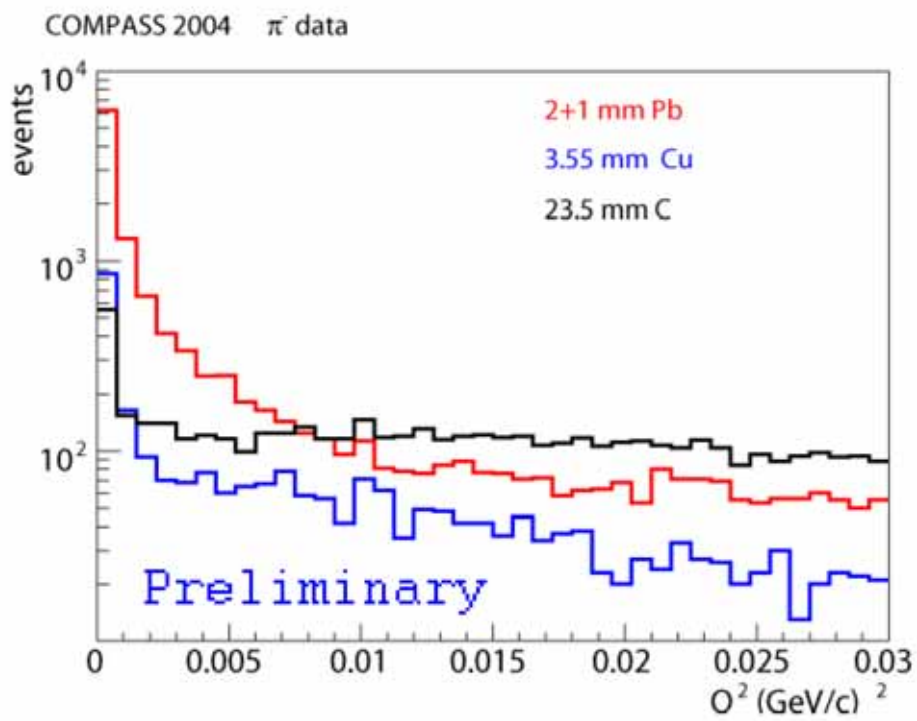


Cross check with μ beam

Q^2 Distributions from Pilot Run

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





Z^2 Dependence of Cross Section

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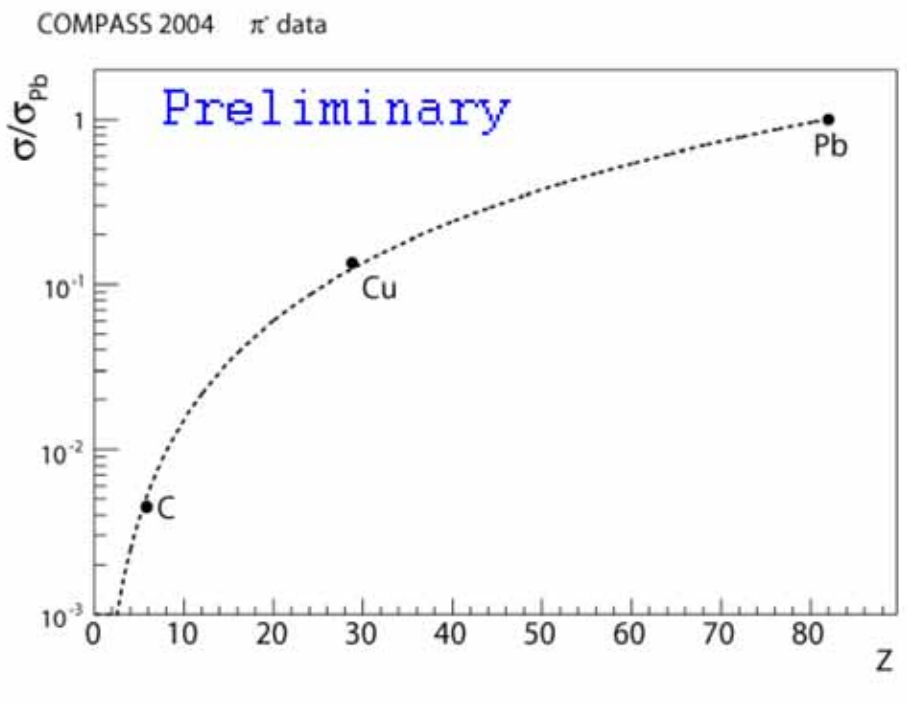
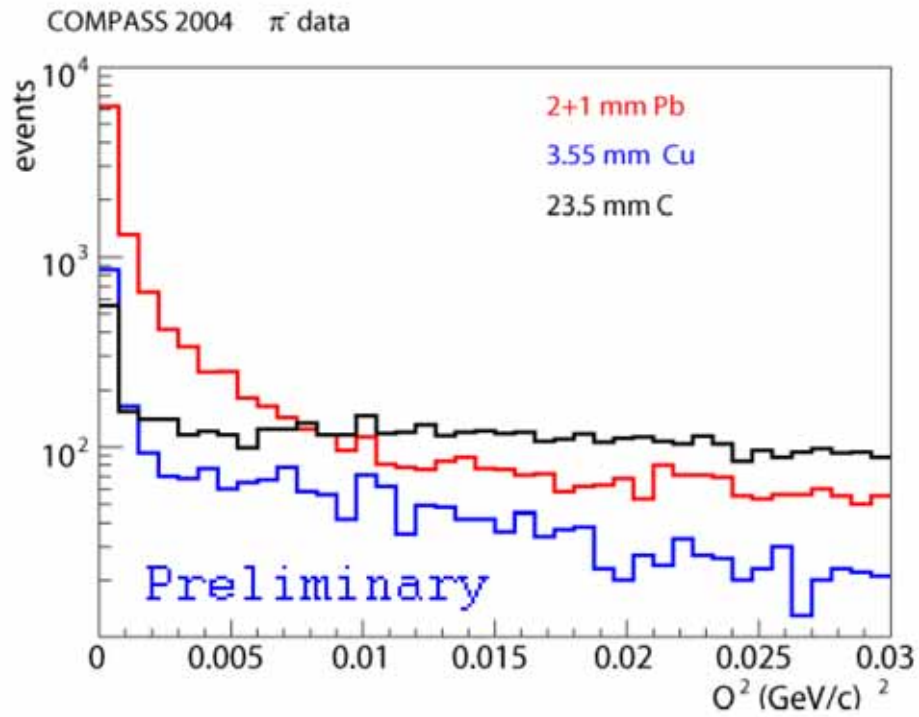




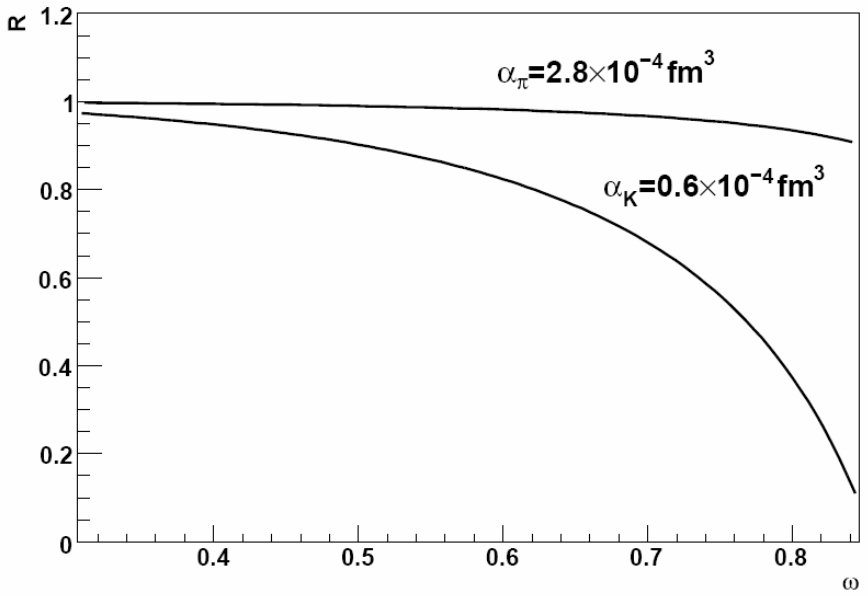
2009 Primakoff Measurement

Major improvements:

- Detector performance: ECAL, μID
- Optimized target: ^{58}Ni
- Radiative corrections
- Beyond Weizsäcker-Williams approach
- Interference with diffractive amplitudes
- Suppression of $\pi^-\pi^0$ background
- MC description of setup

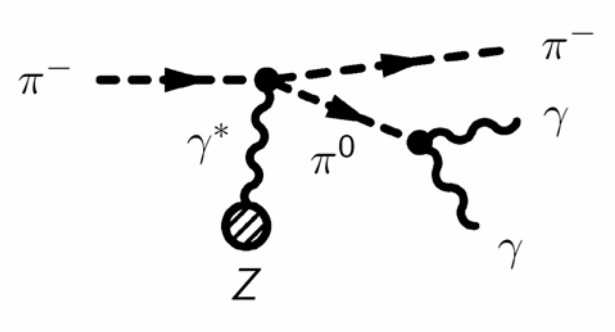
Prospects (4 weeks):

- σ_{stat}~0.33·10^{-4} fm^3
- σ_{sys}~0.16·10^{-4} fm^3
- independent extaction of α_π, β_π with σ_{stat}~0.5·10^{-4} fm^3
- α_π(s)
- first measurement of α_K

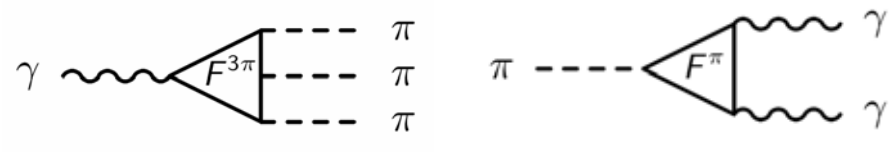


Primakoff Reactions with Neutral Mesons

Primakoff π^0 production



Chiral Perturbation Theory

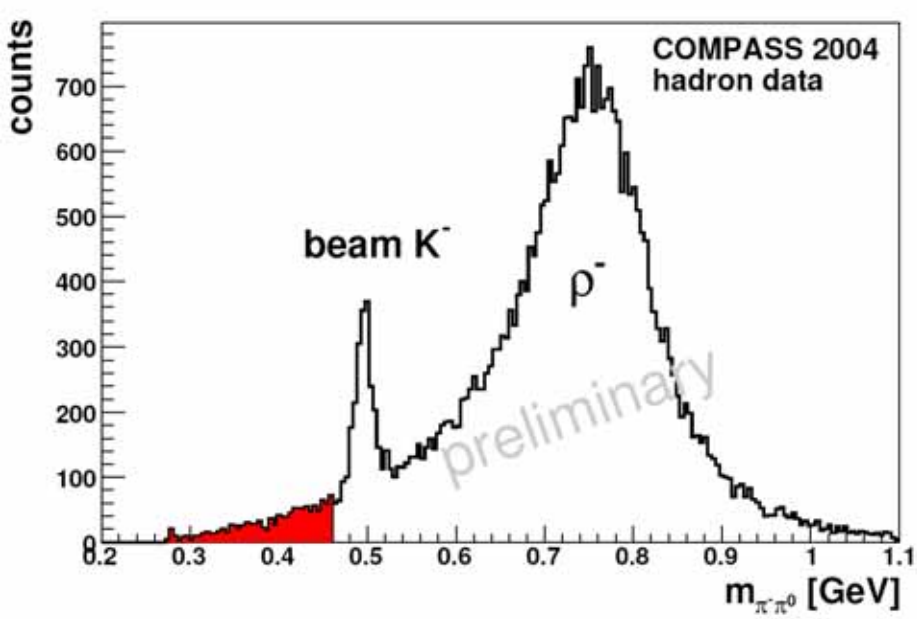


$$F^{3\pi}(0) = \frac{F^{\pi}(0)}{\sqrt{\pi\alpha}\, f_{\pi^{\pm}}^2}, \quad f_{\pi^{\pm}} = (130.7 \pm 0.4)\,\mathrm{MeV}$$

- 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}



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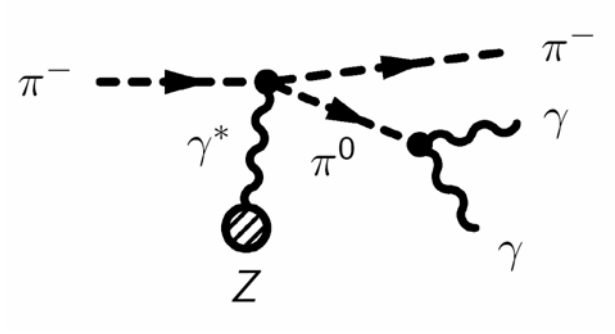

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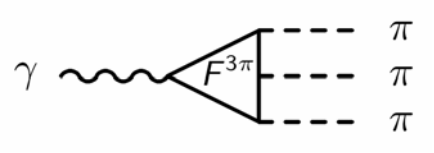

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- Further reactions channels studied in COMPASS: $\pi^- Z \to \pi^- Z \pi^0\pi^0$

  $\pi^- Z \to \pi^- Z \eta$

Conclusions

- **COMPASS** started physics program with hadron beams in 2008
  - High angular resolution for charged particles
  - Final states with neutral and charged particles
  - Observation of resonances in different production / decay channels
- **Light meson spectroscopy** with lH2 target
  - Experiment upgrade
  - Diffractive reactions: 10× BNL E852 statistics
  - Central production: 10× WA102 statistics
  - Analysis chain (PWA) ready and tested on MC / real data
- **Primakoff reactions**: polarizabilities of π and K, chiral anomaly
- New physics results from 2004 π **pilot run**
  - PWA for $\pi^+\pi^-\pi^-$ (high t'): strong signal in exotic 1^{-+} wave at 1.6 GeV/c^2
  - PWA for low t' ongoing
  - PWA for $\pi^+\pi^+\pi^-\pi^-\pi^-$ started: higher masses, $b_1\pi$, $f_1\pi$ decay channels