Hadron Spectroscopy at COMPASS

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on behalf of the COMPASS Collaboration

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I) COMPASS

II) Hors d' oeuvre: spectrum of Kπ resonances from muon DIS

III) Some results from a short pilot run 2004:

Primakoff reaction and diffractive excitation of pions

IV) Goals, set up and data taken in 2008, Plans 2009 and beyond

GHP2009 in Denver, April 29, 2009

The Third Workshop of the APS Topical Group in Hadron Physics

I) Compass and Collaboration

CERN fixed target experiment North Area NA 58

COmmon
Muon and
Proton
Apparatus for
Structure and
Spectroscopy

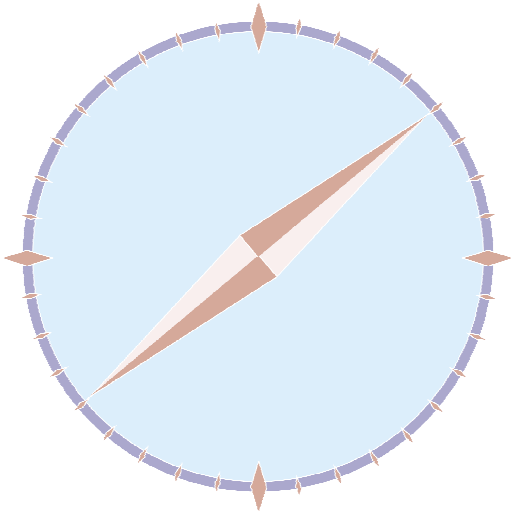
Collaboration: ~30 Institutes, ~230 physicists

from 22 towns : ***Bielefeld, Bochum, Bonn, Burdwan, Calcutta, CERN, Dubna, Erlangen, Freiburg, Lisbon, Mainz, Miyazaky, Moscow, Munich, Prague, Protvino, Saclay, Tel Aviv, Torino, Trieste, Warsaw, Yamagata***

and 11 countries: Czech Republic, Finland, France, Germany, India, Israel, Italy, Japan, Poland, Portugal, Russia

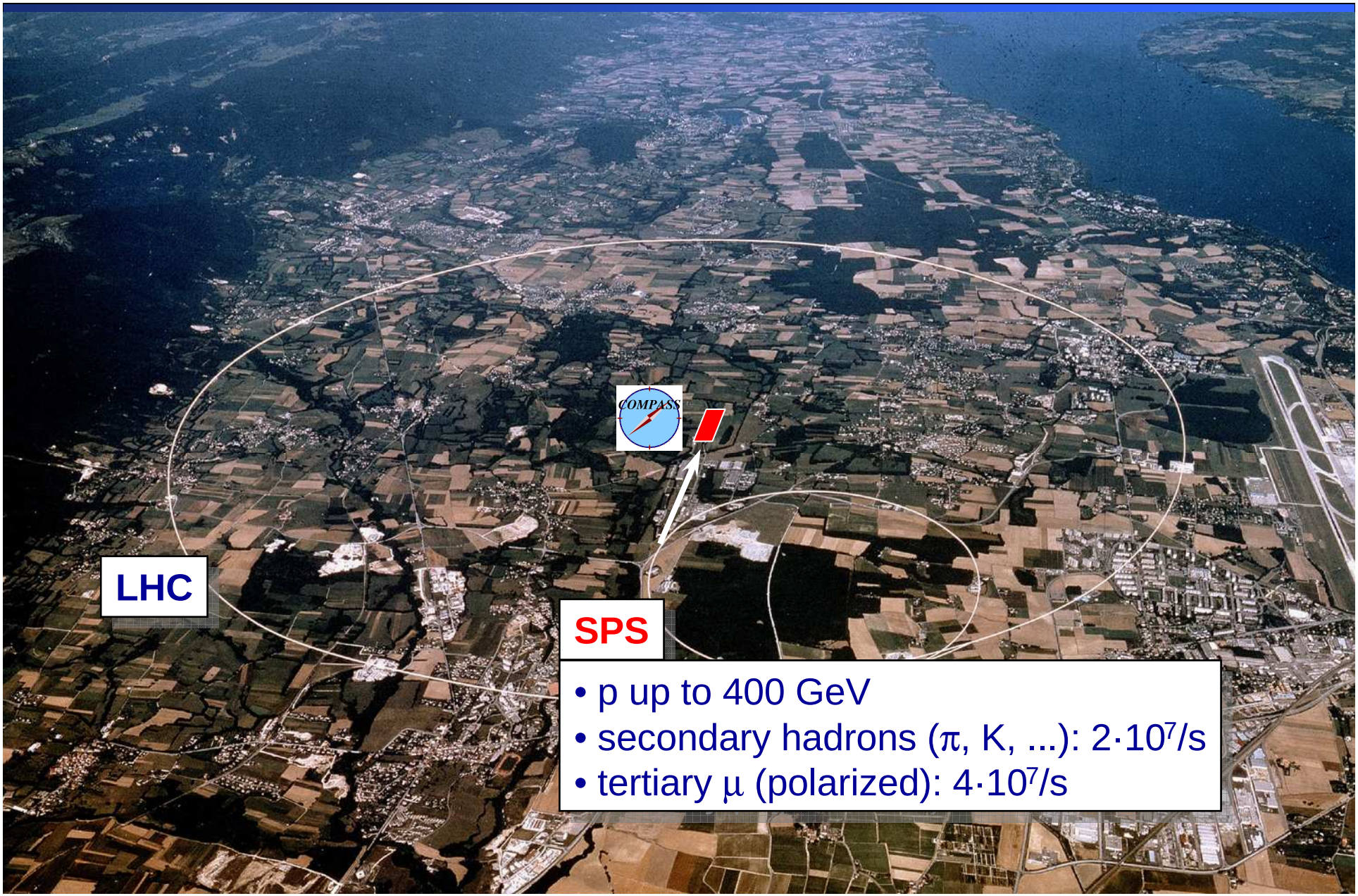
Muon and Proton : The 2 Programs of COMPASS

Hadron Program (2008, 2009, 2011,..):
190 GeV/c π, K , p
Search for exotics in
diffractive excitation
and
central production,
polarizability of π,K
Charm baryons?



Muon Program
(2002-2007, 2010,..):
Polarized muons, 160 GeV/c
Deep Inelastic Scattering on
polarized deuterons and protons

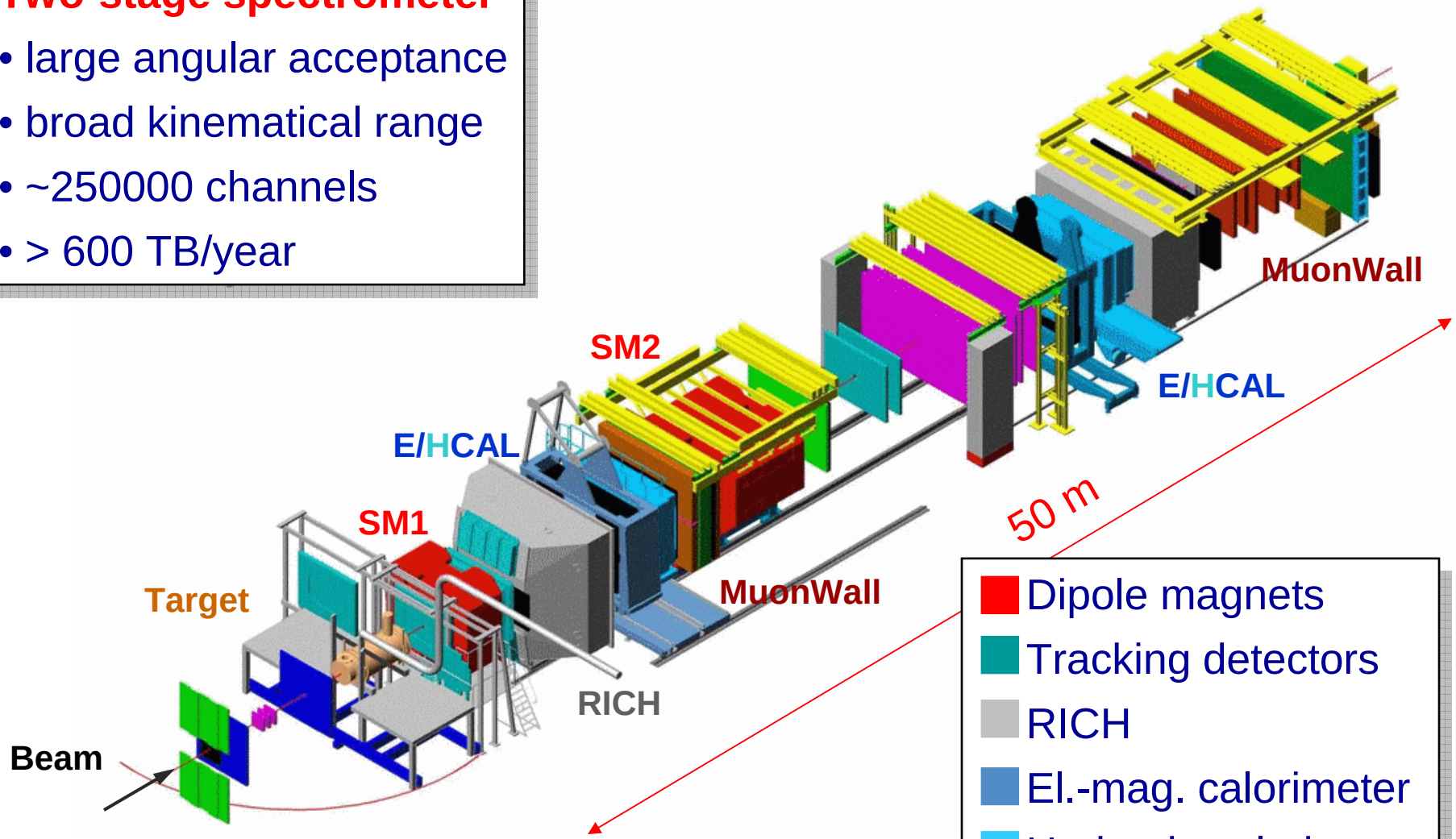
COMPASS at CERN



The COMPASS Experiment

Two-stage spectrometer

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

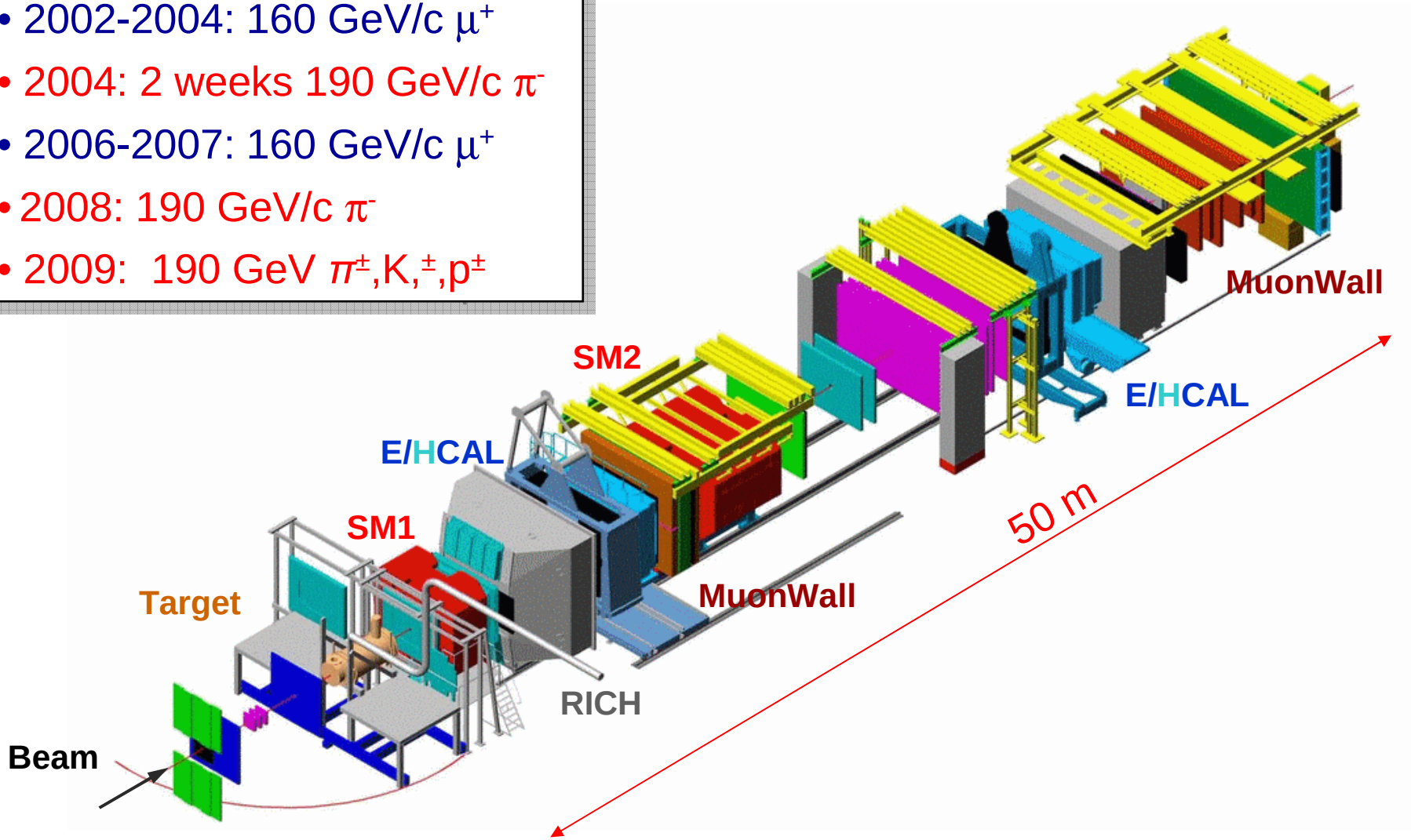


[hep-ex/0703049, NIM A 577, 455 (2007)]

The COMPASS Experiment

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^-
- 2009: 190 GeV $\pi^{\pm}$,K,$^{\pm}$,p$^{\pm}$



II) To start: A remarkable spectrum of some known hadrons produced by muons

Spectrum has been obtained in DIS of muons.

- Goal: measure **gluon polarisation** via cross section asymmetries for production of **charmed D** mesons in interactions of polarized muon on polarized nucleons.

(Underlying process supposed to be **photon-gluon fusion to charm –anticharm)**

Best suited decay : $\mathbf{D^0 \rightarrow K\pi}$

Select events with $\mathbf{\mu N \rightarrow \mu' + K + \pi +}$ **anything**

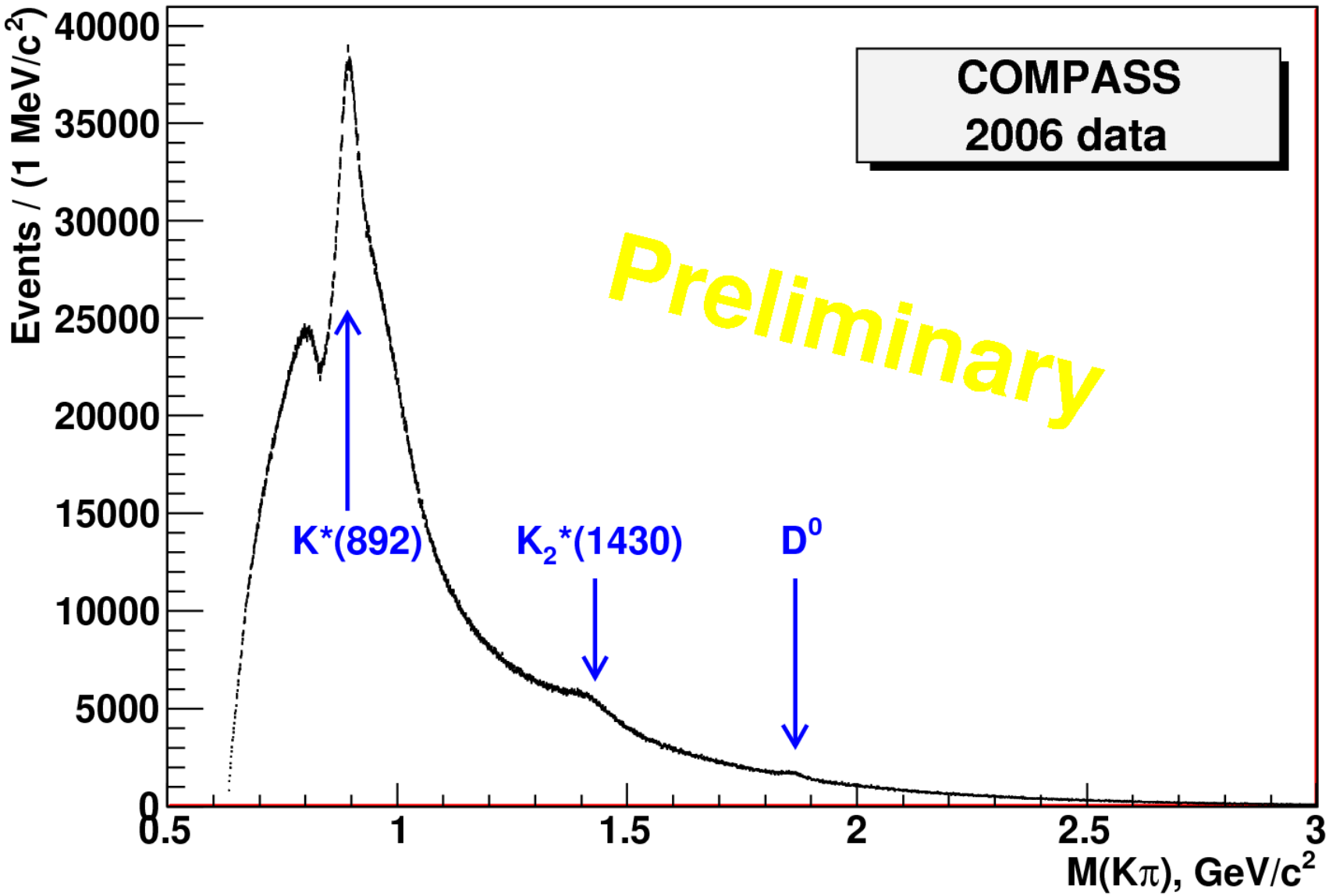
normally Kπ mass limited to ±400MeV around D^0

- In this context, we also looked for any **Kπ** (no mass constraints)

standard particle.id., but no kin cuts and only limited set of data:

1 year, 2006, about ¼ of all integrated luminosity 2002 to 2007

Kπ invariant mass spectrum from muon beam , no mass window, 2006



Comment to previous and following picture:

- It illustrates the large amount of data accumulated by COMPASS in order to collect enough D^0.

- Just 3 particles decaying to Kπ are easily seen, being narrow:

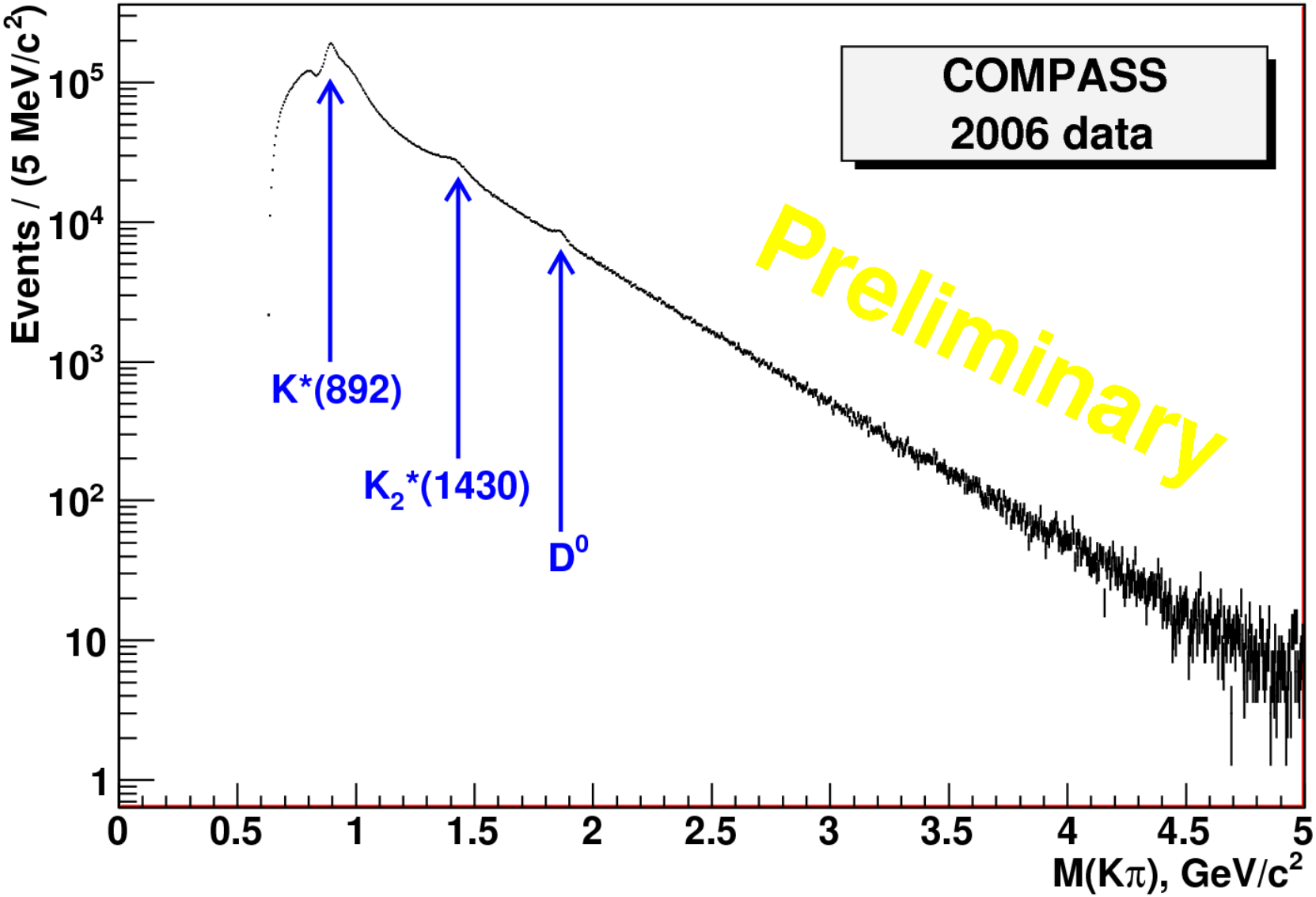
  D^0 (1865) $K_2^*(1430)$ K*(890)

- The K*(890) has an interesting line shape, interference with a broader K resonance? Why interference and which resonance? Kπ-S wave?

- Of course, there must be more kaonic resonances but they are broad and superimpose together with combinatorial background to a nearly perfect single exponential decrease,

  see next figure which shows the same spectrum but logarithmic vertical scale.

Same as before, but logarithmic vertical scale



III) Goals +results of short pilot hadron run 2004

Goals:

a) Measure Primakoff reaction on Pb, Cu and C: $\pi^- Z \rightarrow \pi^- \gamma Z$

hadron structure at very low Q^2 → • Pion Polarizability

b) Measure diffractive π excitation on nucleons $\pi N \rightarrow 3\pi N$

$\pi N \rightarrow 5\pi N$

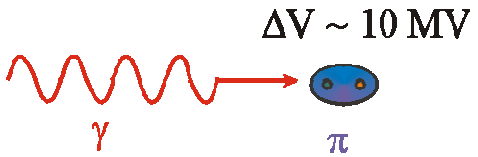
hadron spectroscopy at low Q^2 →

- search for exotics, i.e. non- qbarq bound states expected from QCD

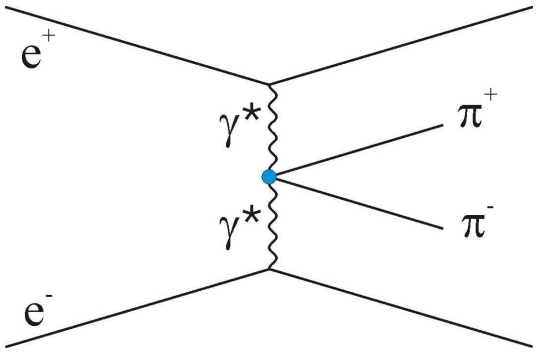
How to measure pion polarizabilities

Response to external e.m. fields ⇨ rigidity of system

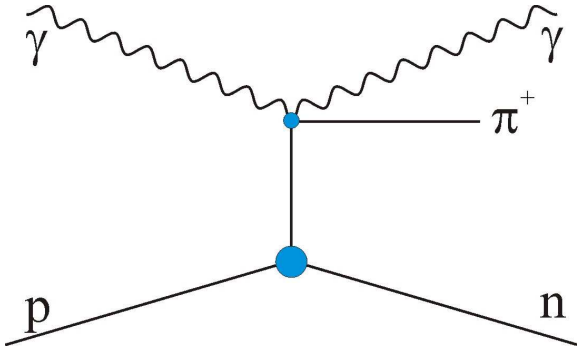
- electric polarizability $\vec{d} = \bar{\alpha}\,\vec{E}$
- magnetic polarizability $\vec{\mu} = \bar{\beta}\,\vec{H}$



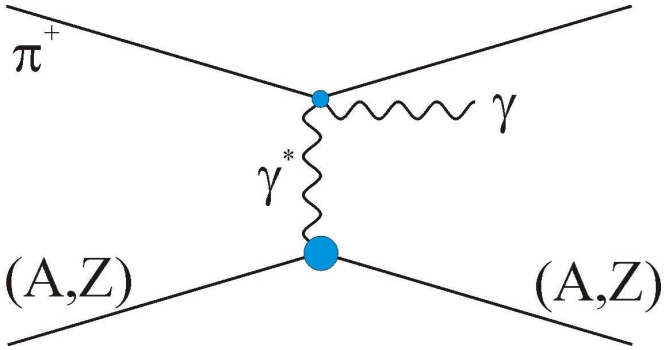
All **Experiments** study basic process pion Compton scattering $\pi^-\gamma \to \pi^-\gamma$



PLUTO
DM1
DM2
Mark II



Lebedev
Mami A2



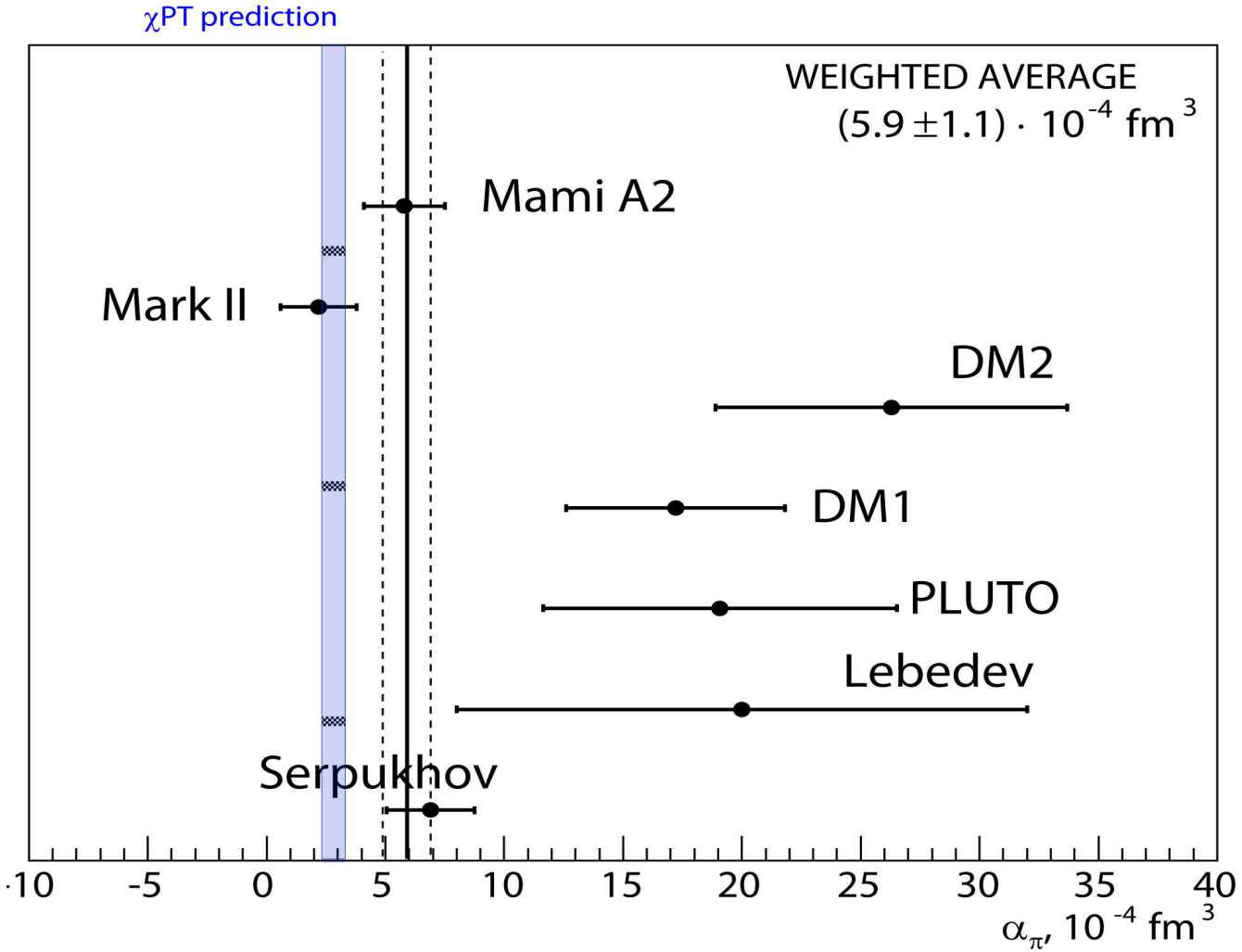
Serpukhov

COMPASS

Pion Polarizabilities

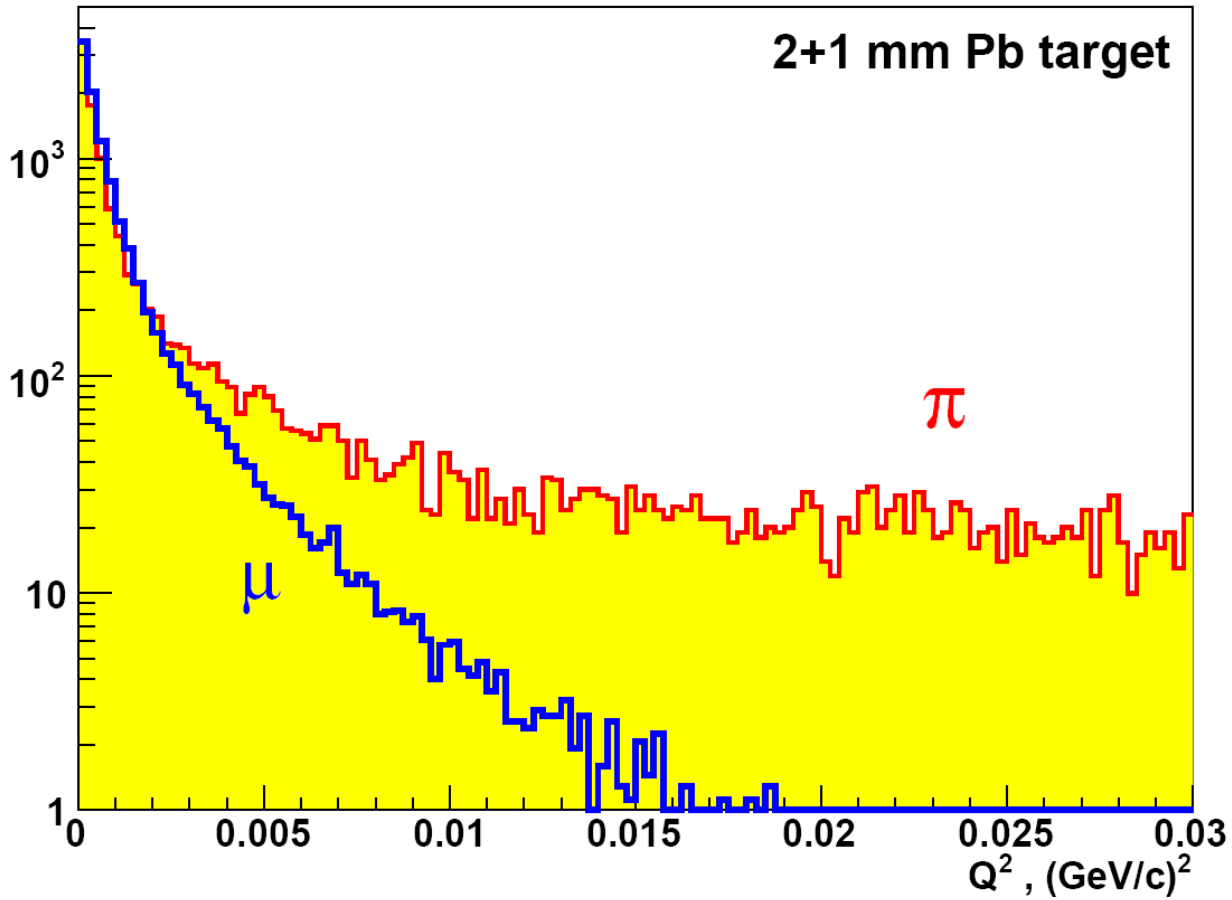
Prediction: χ**PT (2-loop):** $\bar{\alpha}_\pi = (2.9 \pm 0.5) \cdot 10^{-4}\,\mathrm{fm}^3 \qquad \bar{\beta}_\pi = (-2.8 \pm 0.5) \cdot 10^{-4}\,\mathrm{fm}^3$

Experimental results:



Q^2 Distributions for μ and π beam from Pilot Run 2004

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

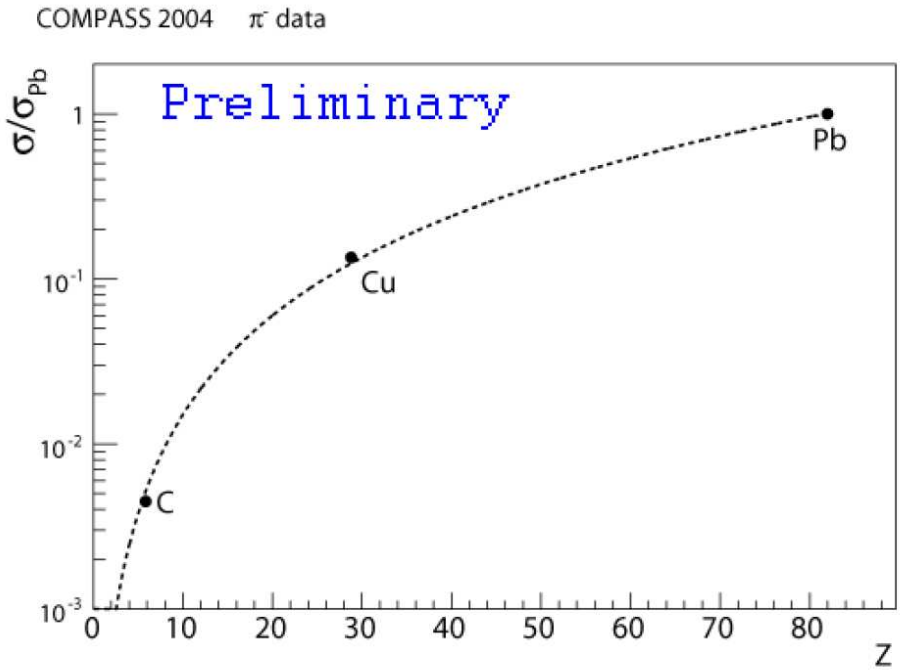


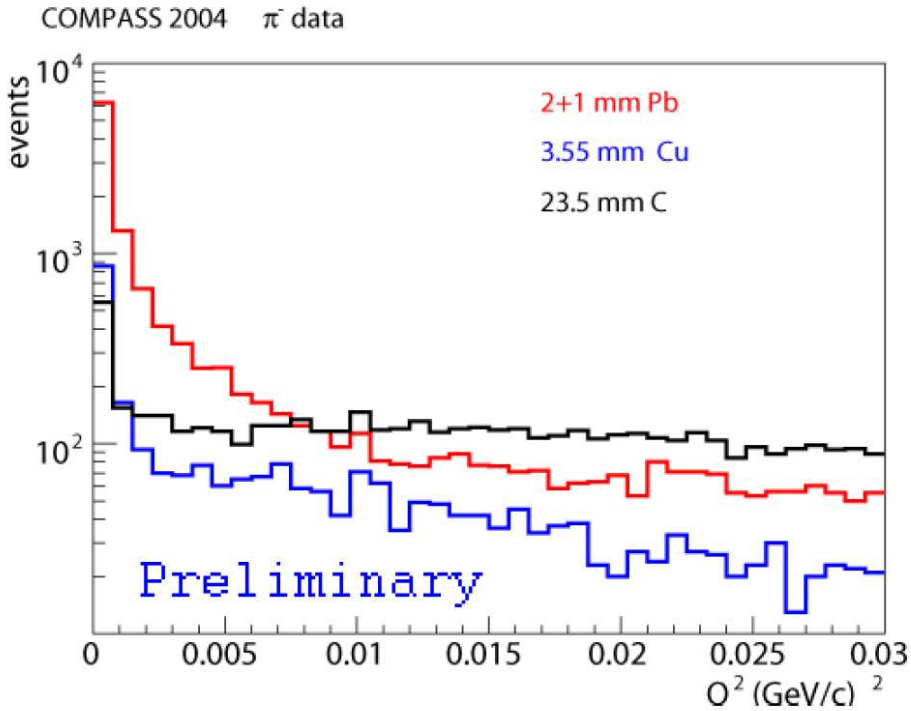
Cut

$Q^2 < 0.0075$ GeV^2

and subtract diffractive bgd

Measured Z^2 dependence of integrated Primakoff cross section

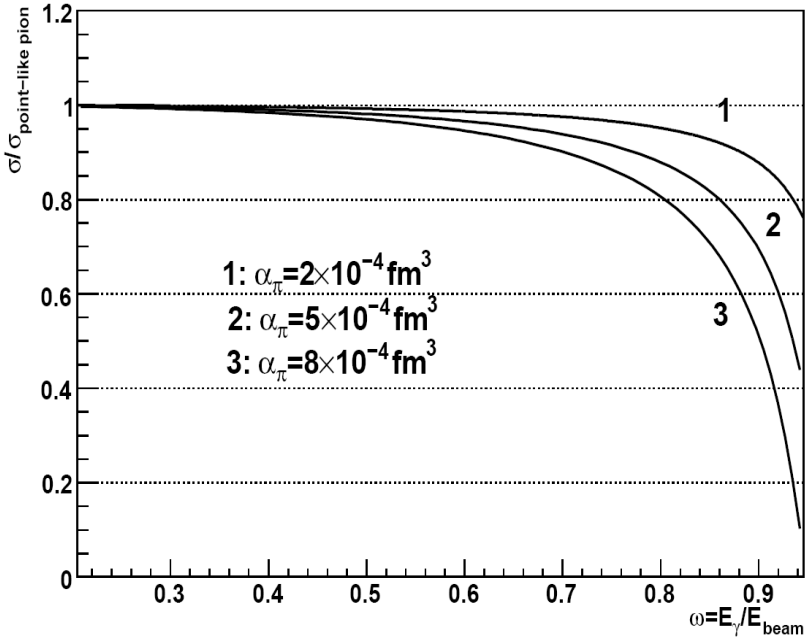




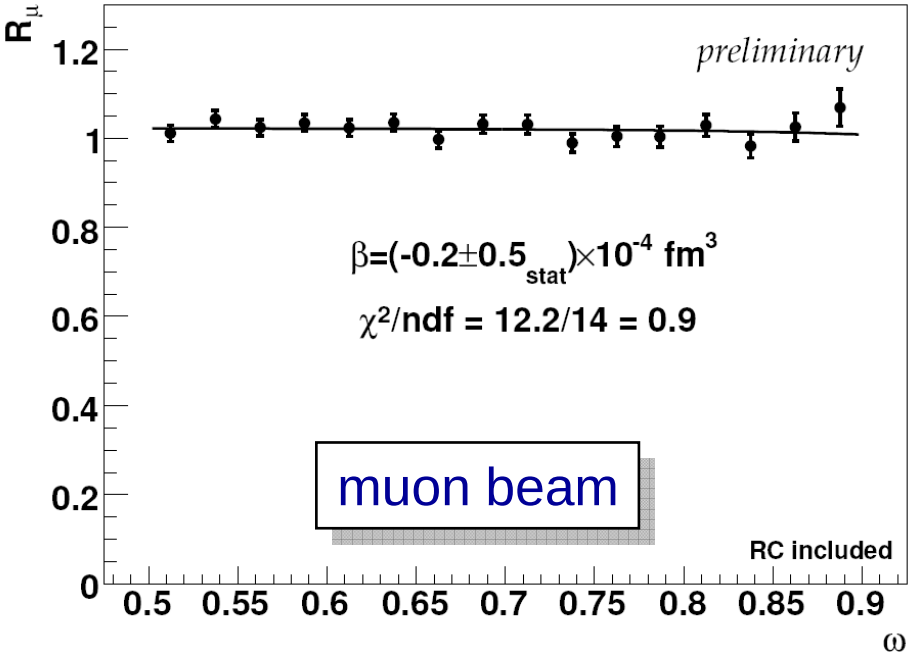
Born approximation, pointlike π, $0.5 < \omega < 0.9$: $\sigma_{Primakoff} = 21.5 \bullet Z^2$ nb

Cross Section Ratio as function of $\omega = E_\gamma / E_{beam}$

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



COMPASS 2004 μ^- data



$R(\omega)$ expected for pion,

for different values of α_π (β_π)

Cross check with μ beam

Ratio $R(\omega)$ = 1 as expected

For pointlike particle

Planned Primakoff Measurements 2009 or later

Prospects (4 weeks):

- $\sigma_{stat} \sim 0.33 \cdot 10^{-4}$ fm^3 and $\sigma_{sys} \sim 0.16 \cdot 10^{-4}$ fm^3
- independent extraction of α_π, β_π with $\sigma_{stat} \sim 0.5 \cdot 10^{-4}$ fm^3
- $\alpha_\pi(s)$ s up to 0.3 GeV^2
- first measurement of kaon polarizability α_K
- further Primakoff-like reactions to be studied: $\pi^- Z \rightarrow \pi^- \pi^0 Z$
  $\pi^- Z \rightarrow \pi^- \pi^0 \pi^0 Z$
  $\pi^- Z \rightarrow \pi^- \eta Z$

Major improvements:

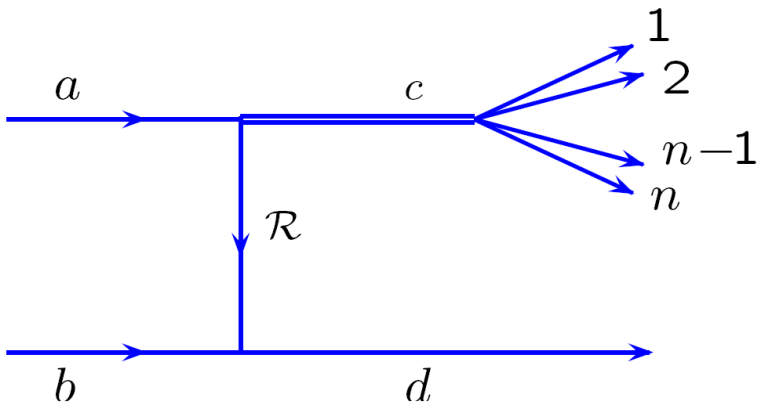
- Detector performance: ECAL, ID of incoming beam particle
- Optimized target: ^{58}Ni
- Suppression of $\pi^-\pi^0$ background
- MC description of setup

IIIb) Diffractive pion beam excitation 2004

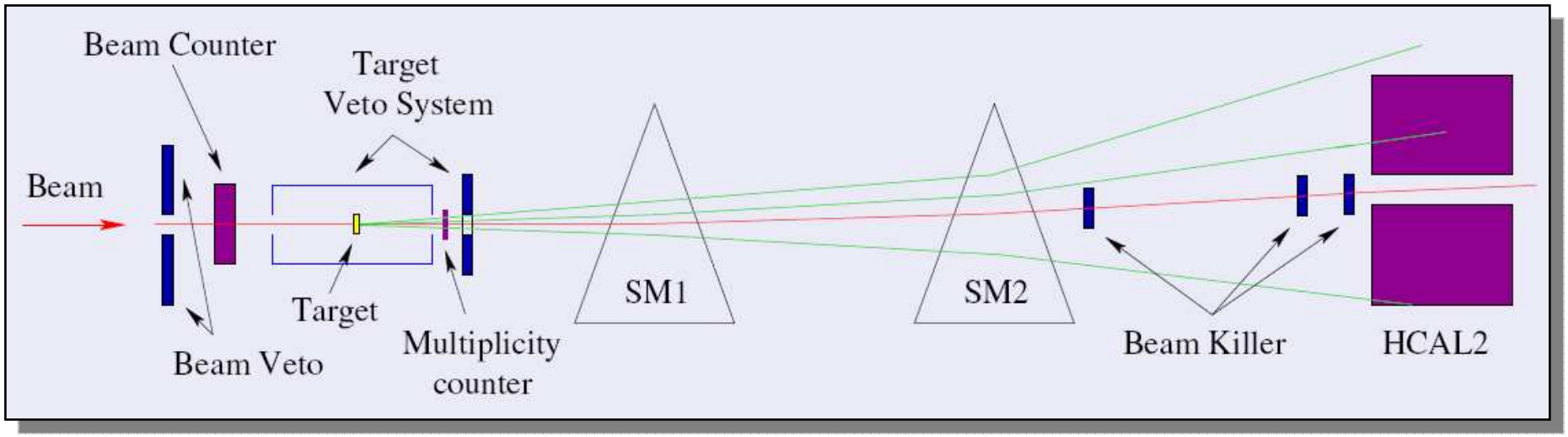
$$\pi^- + \mathrm{Pb} \rightarrow \pi^-\pi^-\pi^+ + \mathrm{Pb}$$

- 4 pion primary vertex in Pb target
- Exclusivity ⇨ target nucleon stays intact
- Momentum transfer

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



Diffractive Trigger

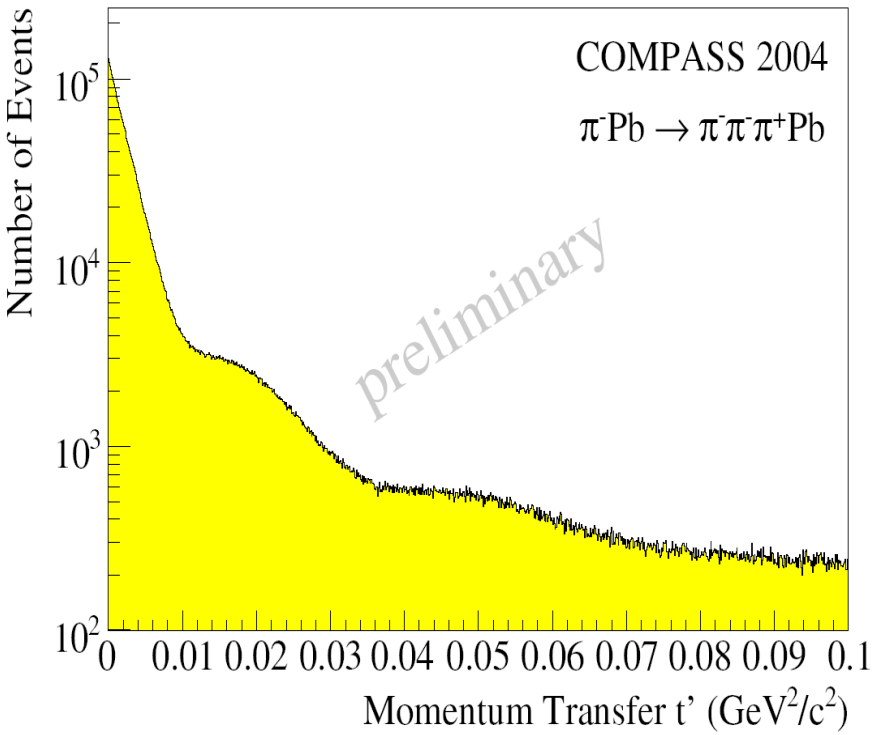


IIIb) Diffractive pion beam excitation 2004

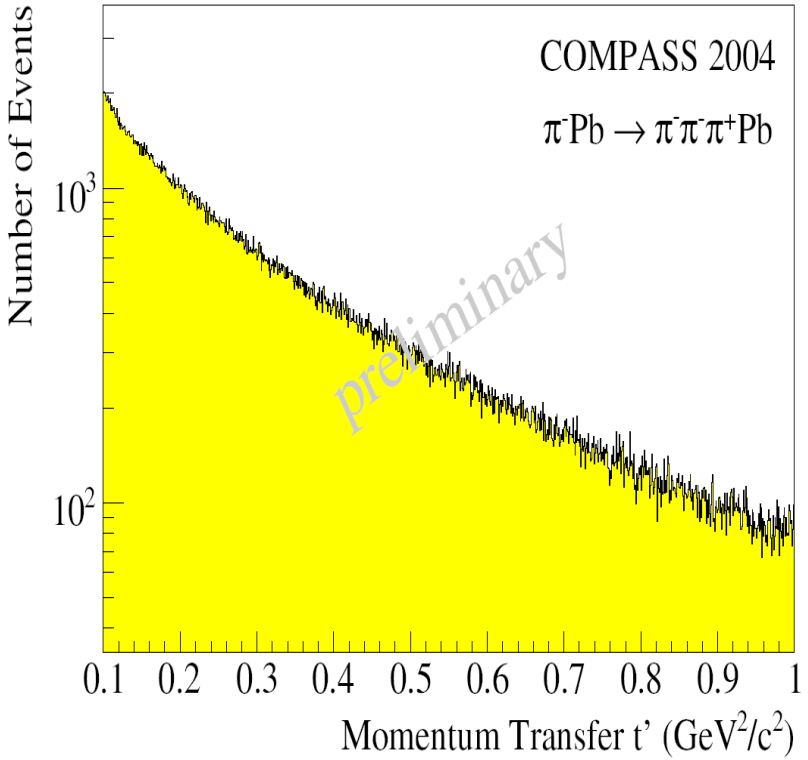
Momentum transfer distribution

$$t' = t - t_{min}$$

Diffraction on intact Pb nuclei

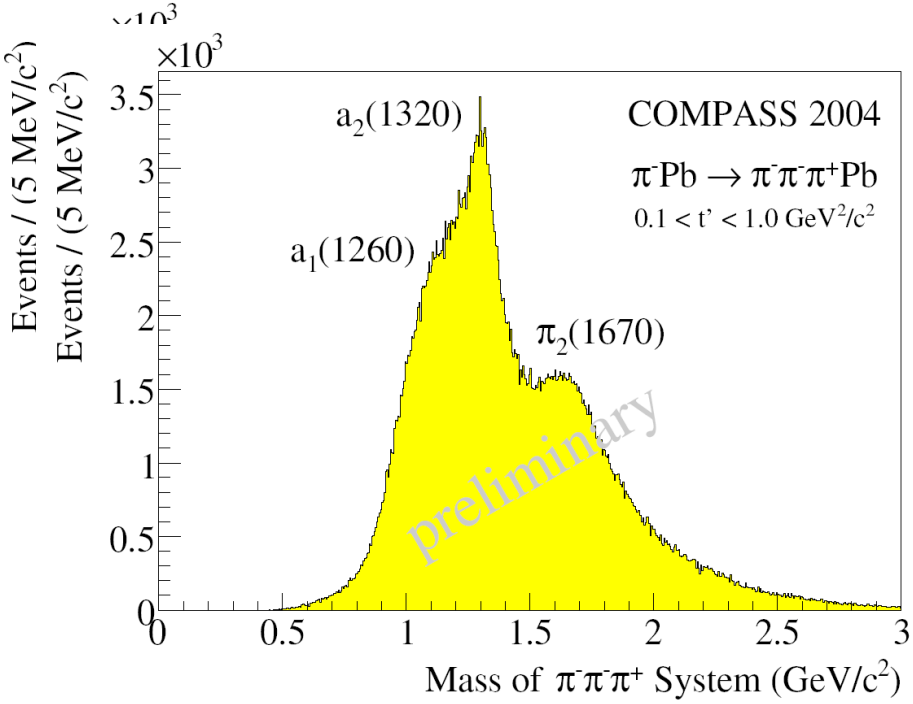


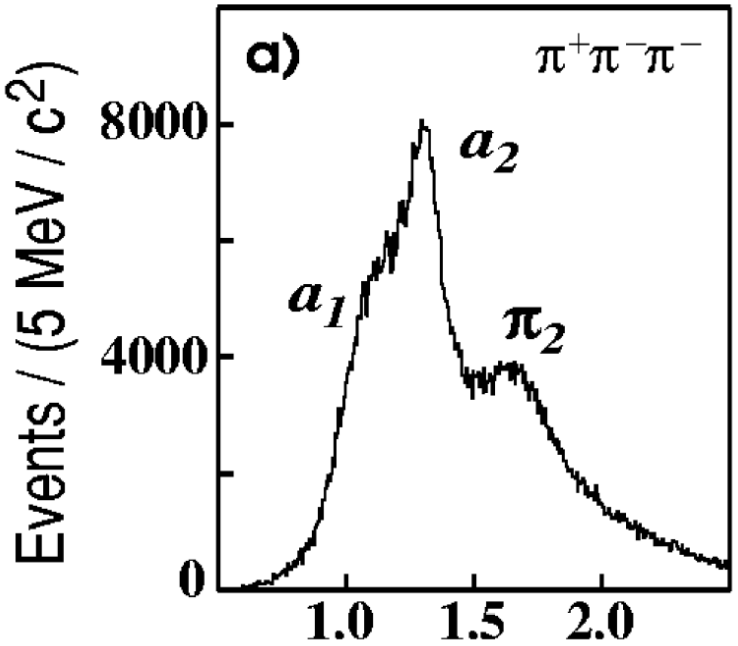
Diffraction on single nucleons



IIIb) Diffractive pion beam excitation 2004

Invariant Mass of 3π System





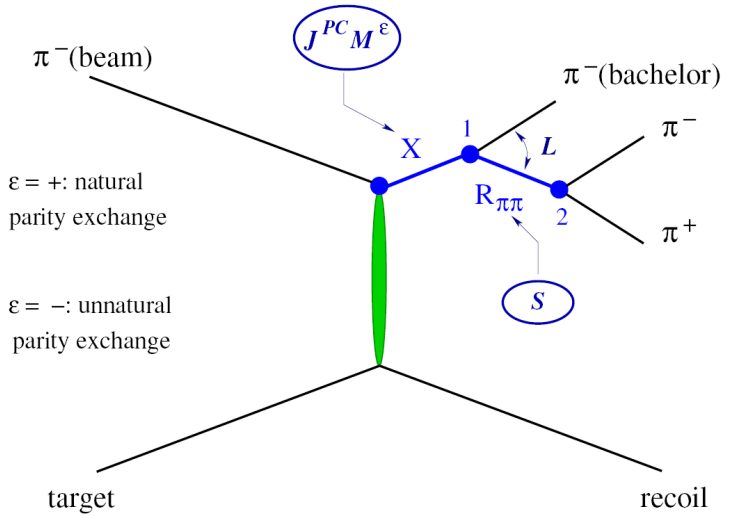
COMPASS: p_π=190 GeV/c

- 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 ⇨ $\pi_1(1600)$

PWA Technique Step 1



- t-channel Reggeon exchange
- Reflectivity ε basis, Gott-Jack frame
- Isobar model
- Non-relativistic Zemach Tensors

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

$$\sigma_{\text{indep}}(\tau) = \sum_{\varepsilon=\pm1}\sum_{r=1}^{N_r}\left|\sum_i T_{ir}^{\varepsilon}\psi_i^{\varepsilon}(\tau)\Big/\sqrt{\int\left|\psi_i^{\varepsilon}(\tau')\right|^2 d\tau'}\right|^2$$

- 42 partial decay amplitudes ψ_i where ***i=$J^{PC}M^{\varepsilon}$[...]L***

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

t´-dependent production amplitudes $T^{+}_{ir} = T^{+}_{iro}\ e^{-bt'}$ and $T^{-}_{ir} = T^{-}_{iro}\ t' e^{-bt'}$ with slopes b obtained from fit to data.
Extended max likelihood fit. Spin density matrix rank $N_r = 2$

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

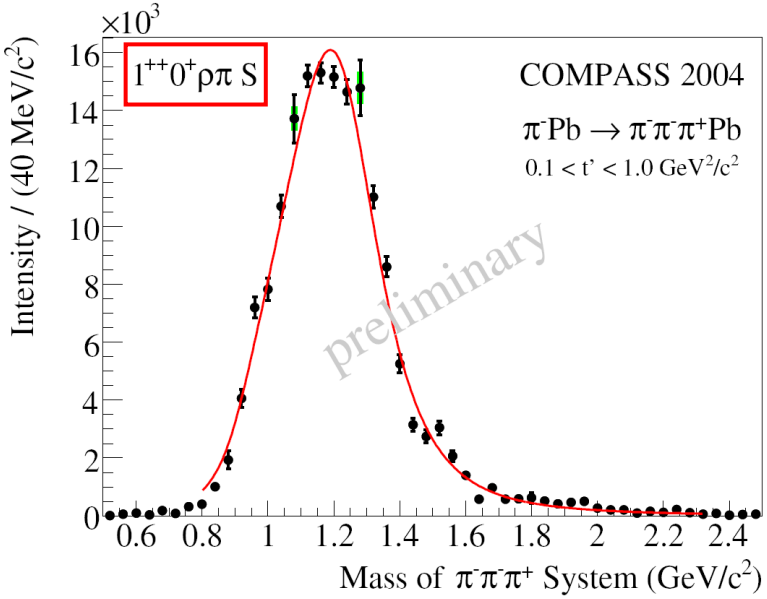
$J^{PC}M^{\epsilon}$	L	Isobar π	Cut [GeV]
$2^{++}1^{+}$	P	$f_2\pi$	1.50
$2^{++}1^{+}$	D	$\rho\pi$	-
$3^{++}0^{+}$	S	$\rho_3\pi$	1.50
$3^{++}0^{+}$	P	$f_2\pi$	1.20
$3^{++}0^{+}$	D	$\rho\pi$	1.50
$3^{++}1^{+}$	S	$\rho_3\pi$	1.50
$3^{++}1^{+}$	P	$f_2\pi$	1.20
$3^{++}1^{+}$	D	$\rho\pi$	1.50
$4^{-+}0^{+}$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

PWA Technique Step 2

2. **Mass-dependent χ^2 fit** (Breit-Wigner amplitudes) to decay amplitudes obtained in 40 mass bins from step 1
   - 6 waves
   - Coherent background for some waves

Results:

Results, points of reference : $a_1(1260)$ and $\pi_2(1670)$



- BW for $a_1(1260)$ + bgr

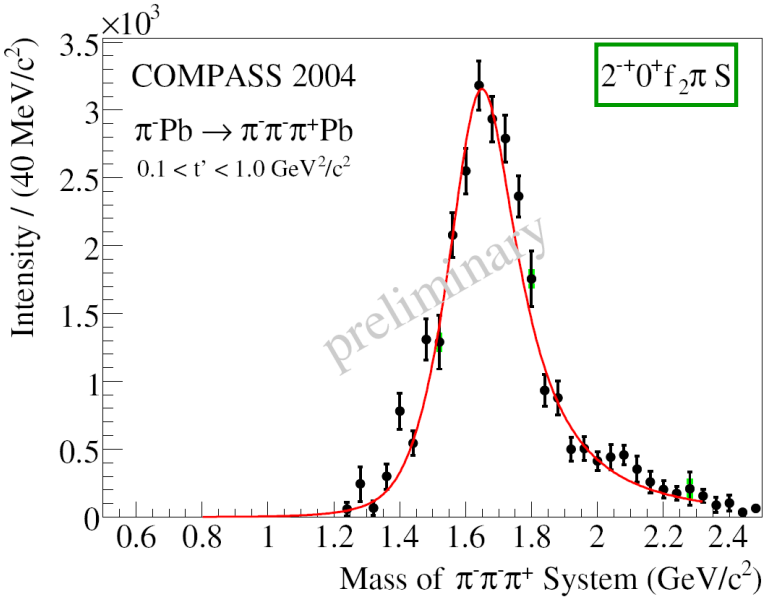
$$M = \left(1.256 \pm 0.006\,^{+0.007}_{-0.017}\right) \text{GeV}/c^2$$

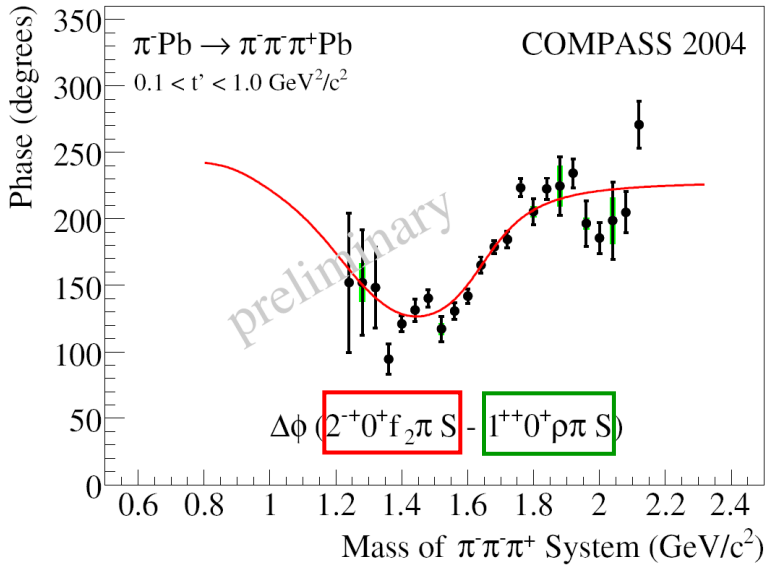
$$\Gamma = \left(0.366 \pm 0.009\,^{+0.028}_{-0.025}\right) \text{GeV}/c^2$$

- BW for $\pi_2(1670)$

$$M = \left(1.659 \pm 0.003\,^{+0.024}_{-0.008}\right) \text{GeV}/c^2$$

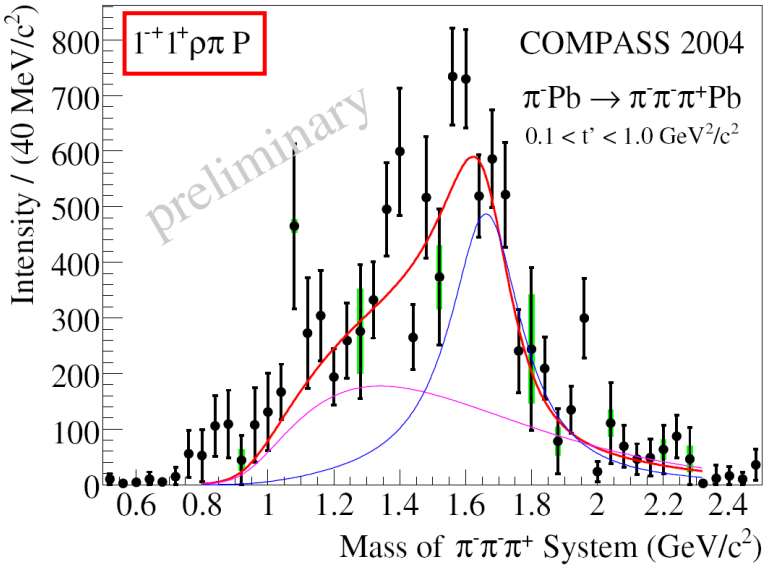
$$\Gamma = \left(0.271 \pm 0.009\,^{+0.022}_{-0.024}\right) \text{GeV}/c^2$$





A candidate for an exotic bound state: $\pi_1(1600)$

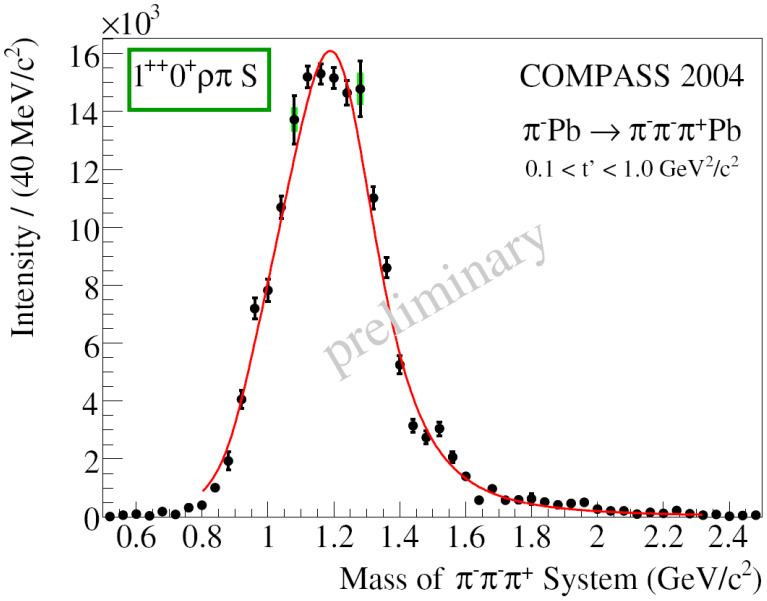
$\pi_1(1600)$ intensity and interference with $a_1(1260)$

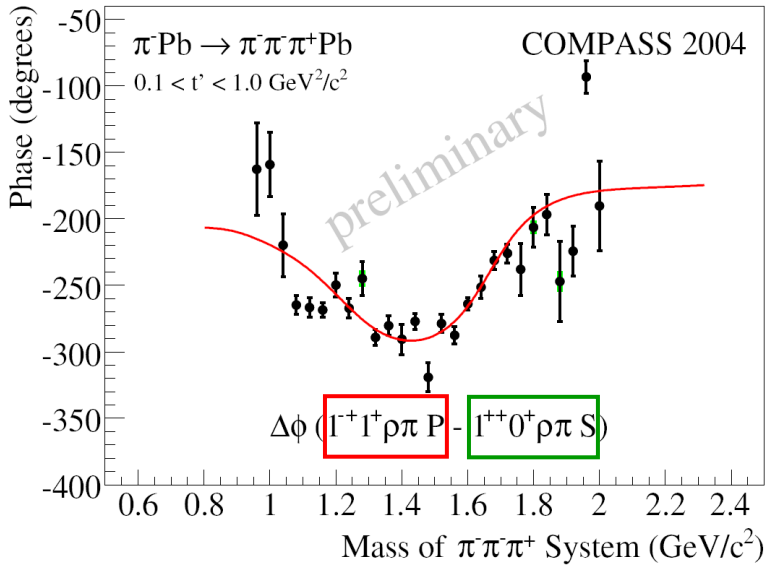


- BW parameters for $\pi_1(1600)$

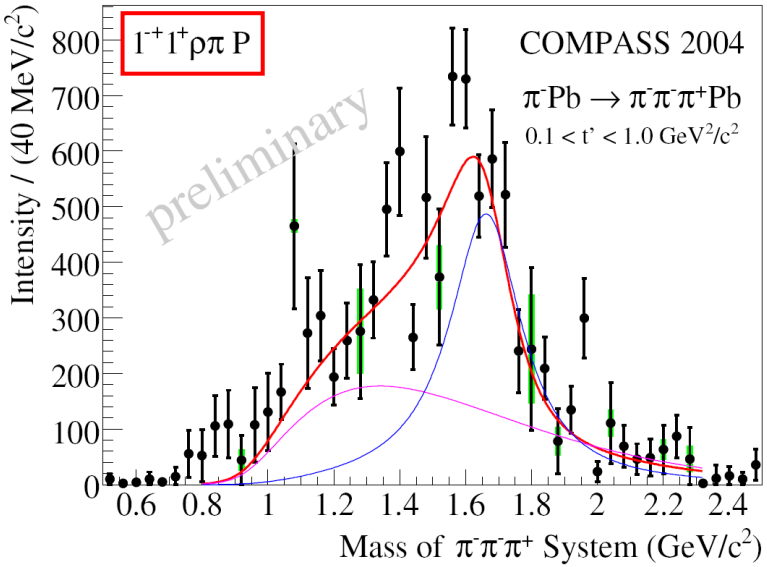
$$M = \left(1.660 \pm 0.010\,^{+0.000}_{-0.064}\right) \text{GeV}/c^2$$

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





$\pi_1(1600)$ intensity and interference with $\pi_2(1670)$



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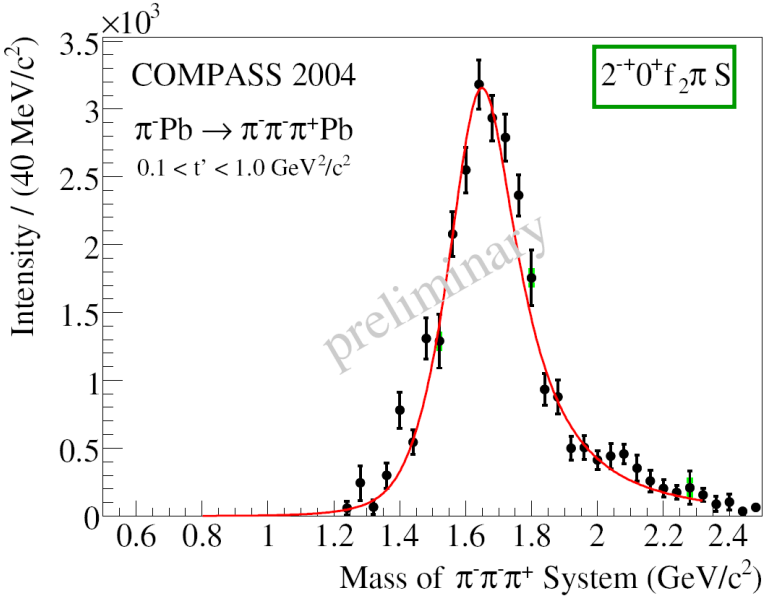
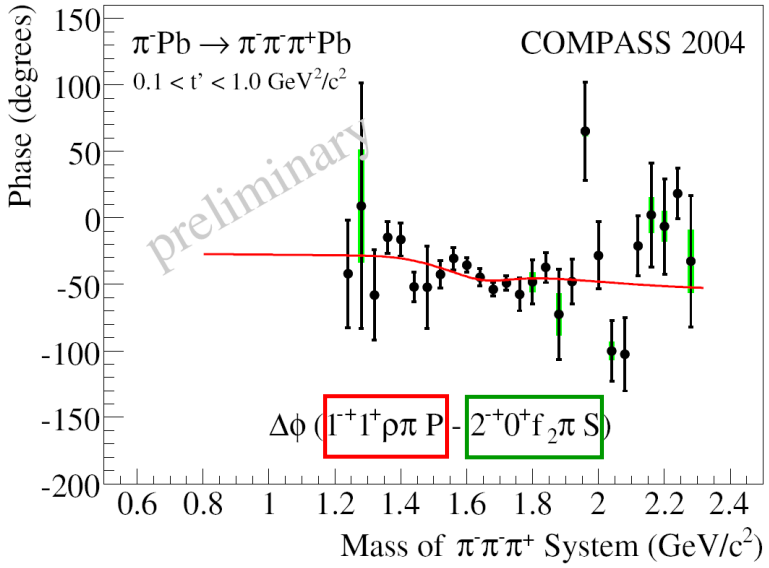




Summary of Breit Wigner amplitudes needed for mass dependent fit (preliminary)

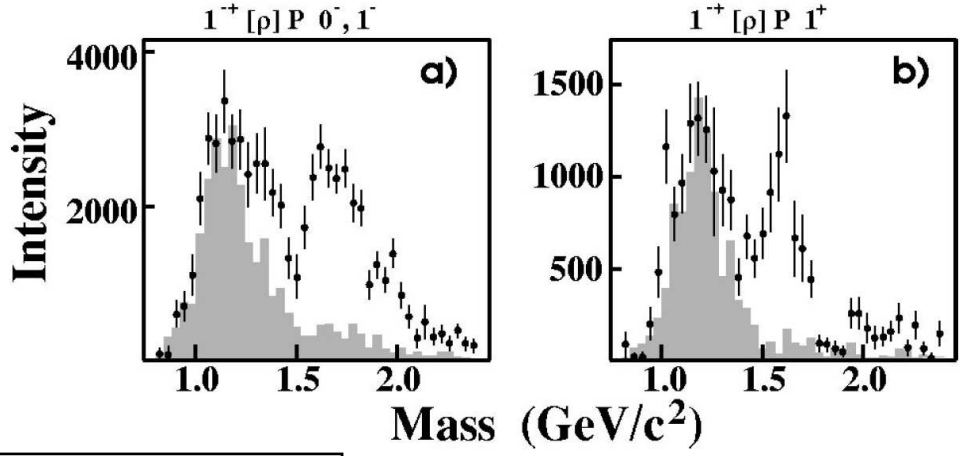
State	(GeV)	COMPASS ± stat ± syst	PDG
$a_1(1260)$	M	$1.256 \pm 0.006 + 0.007 - 0.017$	1.230 ± 0.040
	Γ	$0.366 \pm 0.009 + 0.028 - 0.025$	0.250 to 0.600
$a_2(1320)$	M	$1.321 \pm 0.001 + 0.000 - 0.007$	1.3183 ± 0.0006
	Γ	$0.110 \pm 0.002 + 0.002 - 0.015$	0.107 ± 0.005
$\pi_1(1600)$	M	$1.660 \pm 0.010 + 0.000 - 0.064$	$1.653^{+0.018}_{-0.015}$
	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

Publication being prepared, to be submitted

$\pi_1(1600)$ – Positive Results of previous experiments for same reaction $\pi A \rightarrow 3\pi A$

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

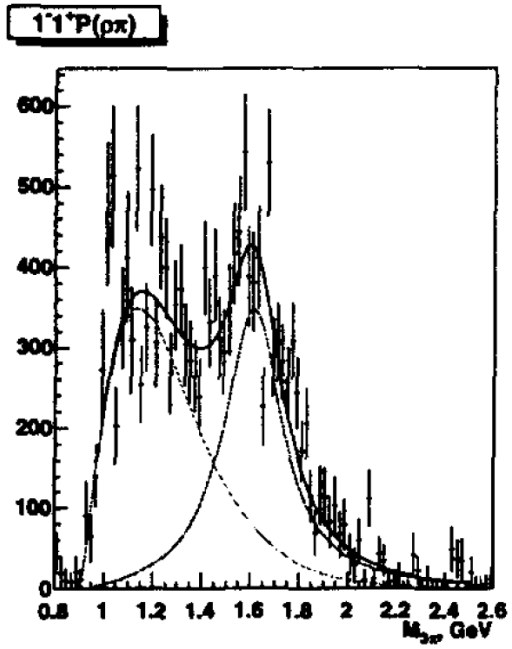
- p_π=18 GeV/c
- limited statistics: 250k ev.
- rank 2
- mass dependent fit



[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

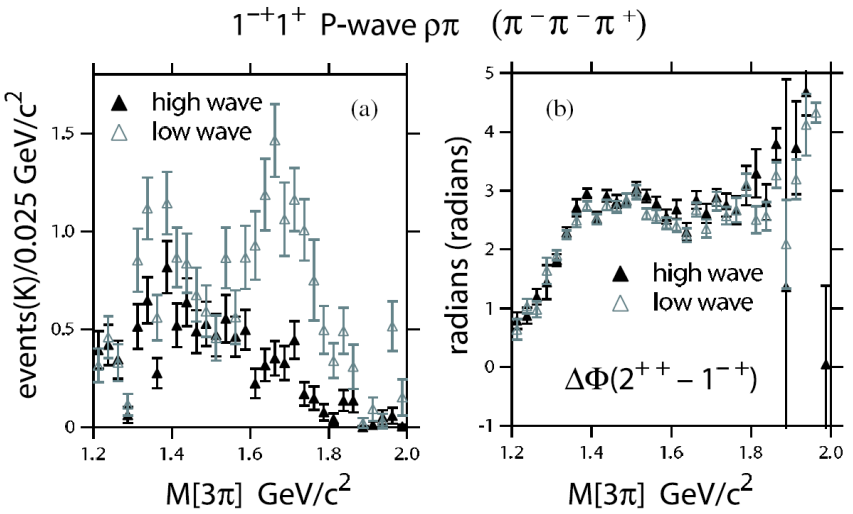


[Y. Khokhlov, Nucl. Phys. A 663, 596c (2000)]

$\pi_1(1600)$ – Negative Results of previous expts

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

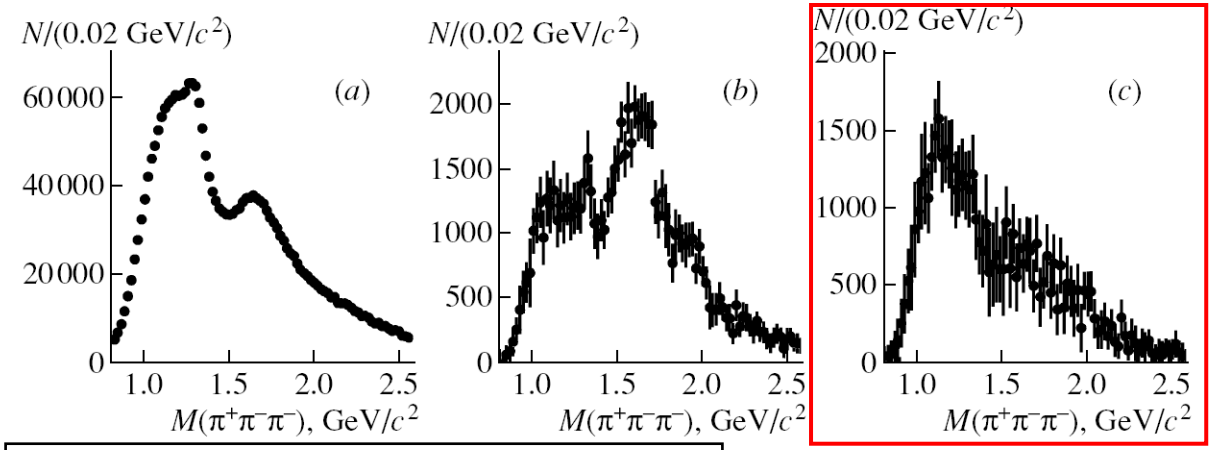
- p_π=18 GeV/c
- full statistics: 2.6M ev.
- rank 1
- extended wave set (2-+ waves)
- no mass dependent fit



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

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

- p_π=37 GeV/c
- unlimited rank



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

Hadron Run 2008/2009

Goal: Explore hadron spectrum up to 2.2 GeV/c^2

via **diffractive excitation** of π, K and p and

central production with π and p beams (up to 250 GeV/c)

- Collect 10× existing statistics compared to WA102
- Search for gluonic excitations (hybrids, glueballs)

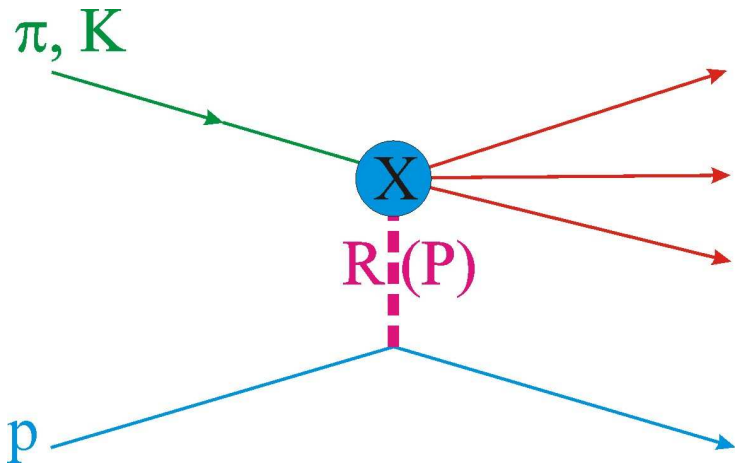
for new or disputed states

Hadron Reactions at COMPASS

Two production mechanisms

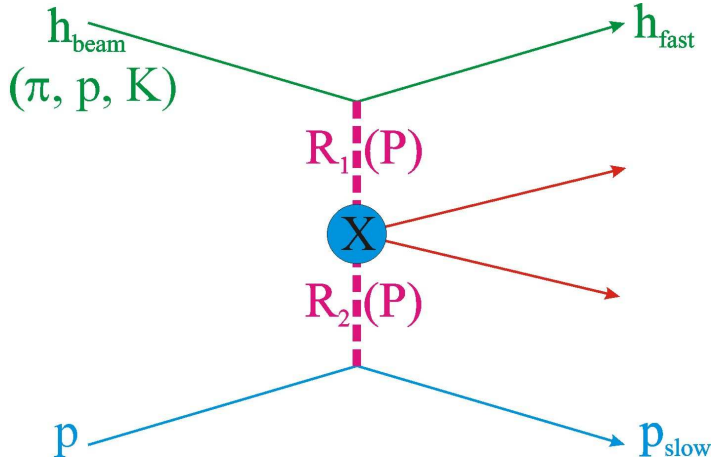
studied in parallel using **proton, pion** and **kaon** projectiles

Diffractive scattering



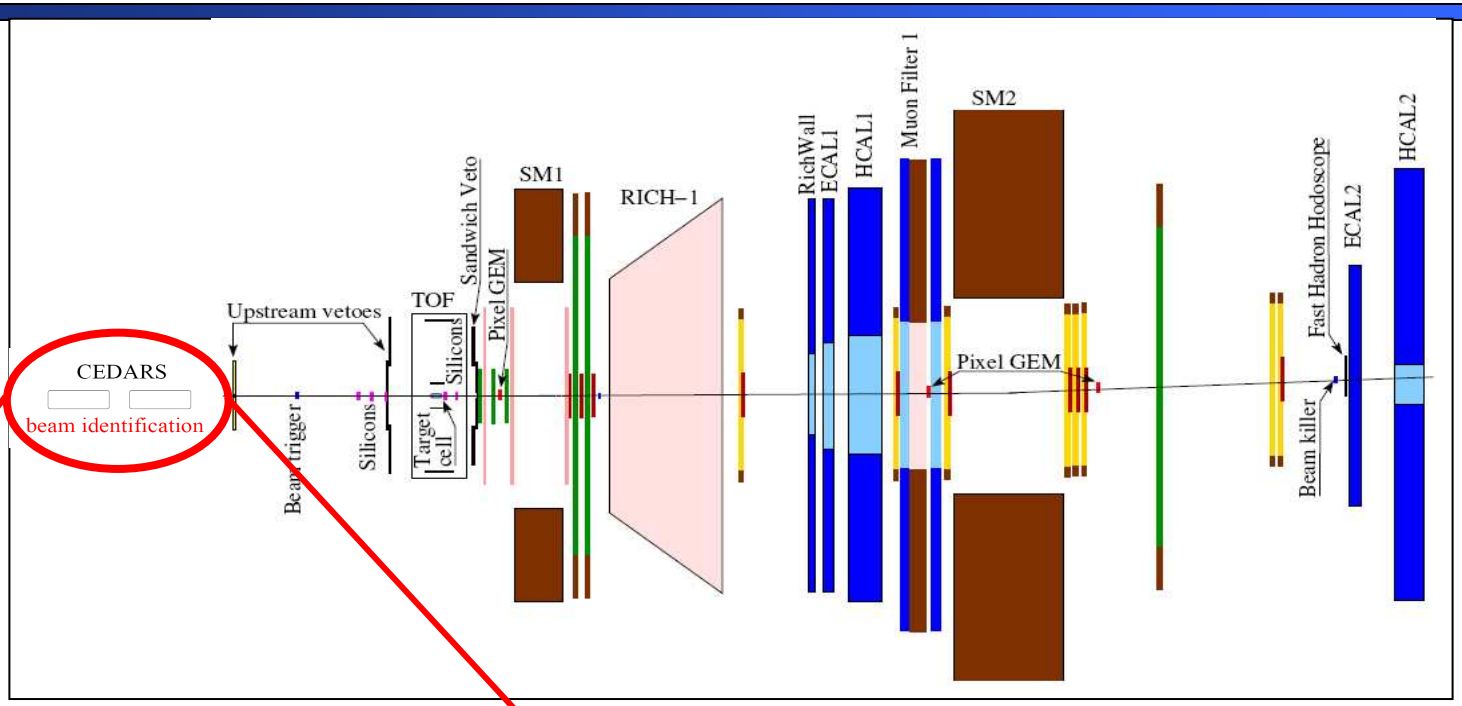
- "elastic" recoil proton
- Rapidity gap between p_{slow} and X
- X carries nearly all energy
- Large cross section (~mb)
- X decay particles at small angles
- Study of J^{PC}-exotic mesons

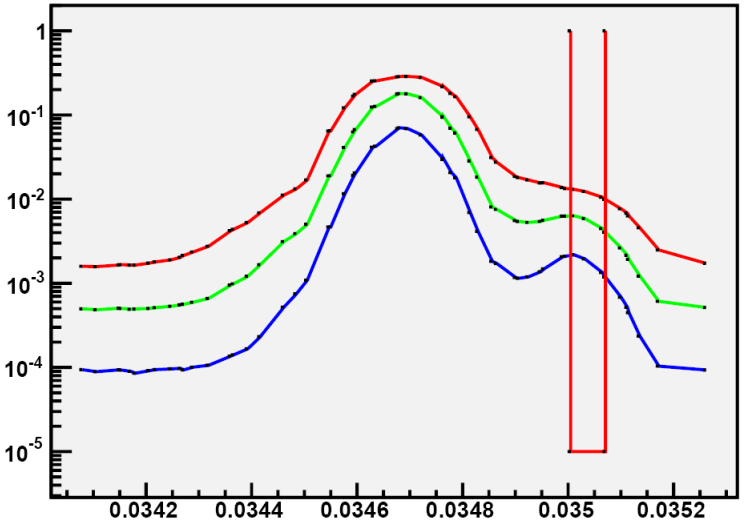
Central production



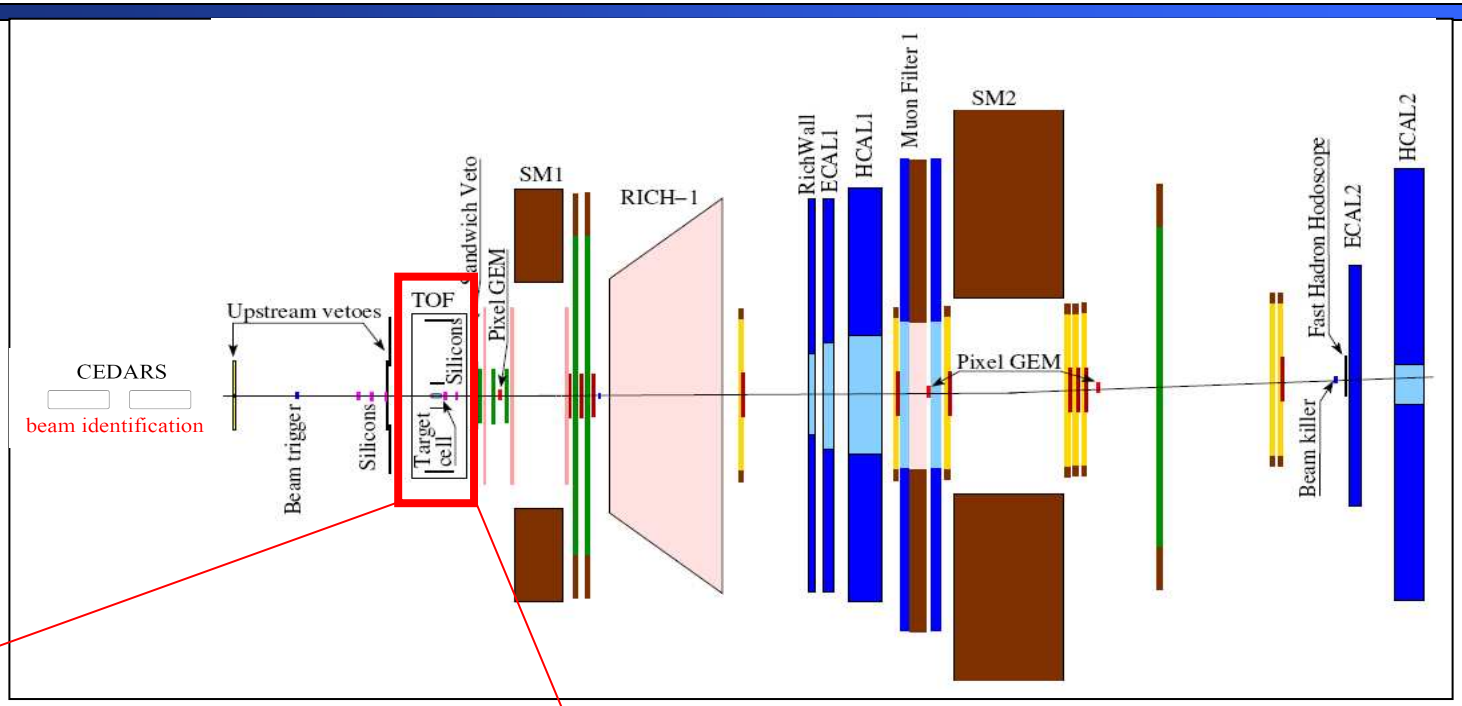
- "elastic" recoil proton
- Rapidity gaps between p_{slow}, h_{fast} and X
- X carries ~10% of incoming energy
- Cross section small (~10μb)
- …at large angles
- Possible source of glueballs (DPE)

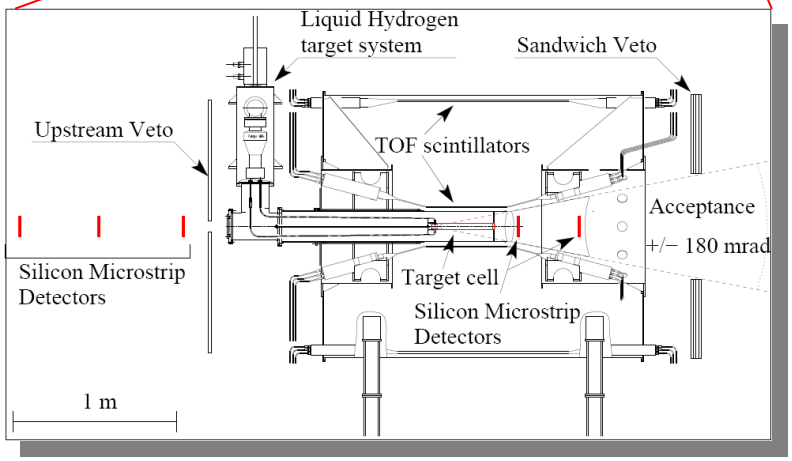
COMPASS in 2008





COMPASS in 2008

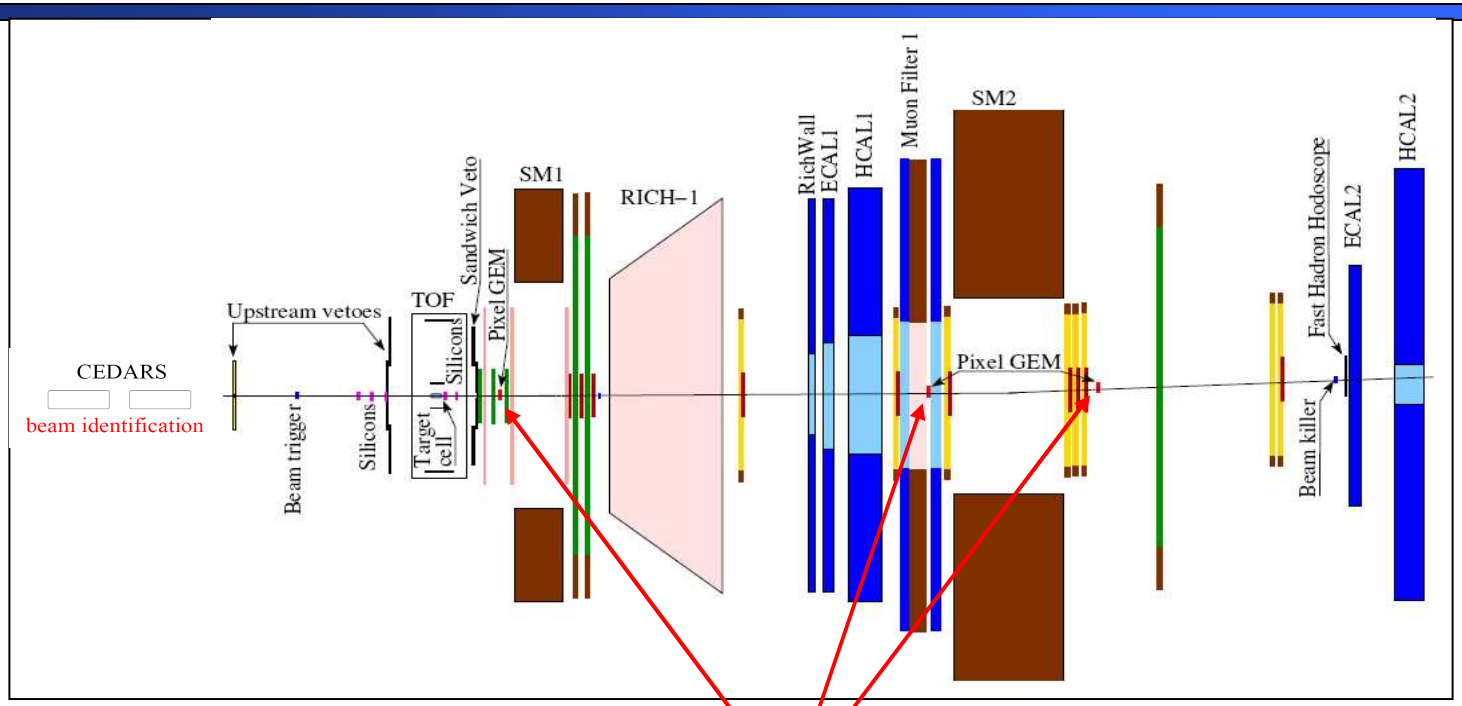


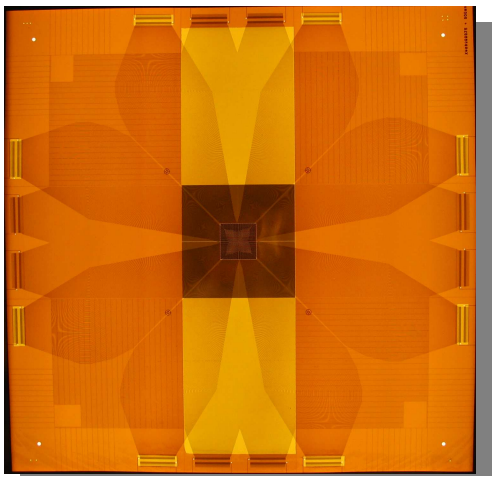


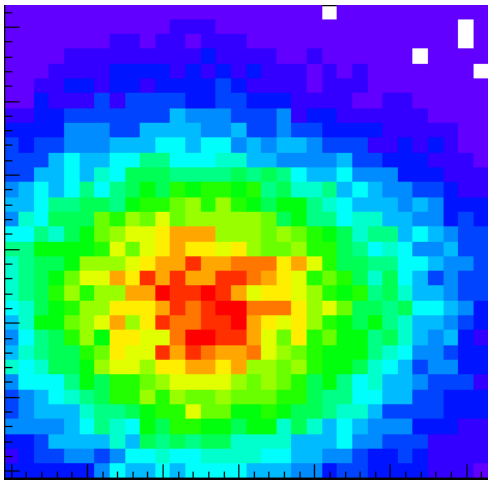
Target region:

- Recoil Proton Detector (TOF)
- 20 Silicon Microstrips Planes operated at 200 K to avoid radiation damage

COMPASS in 2008



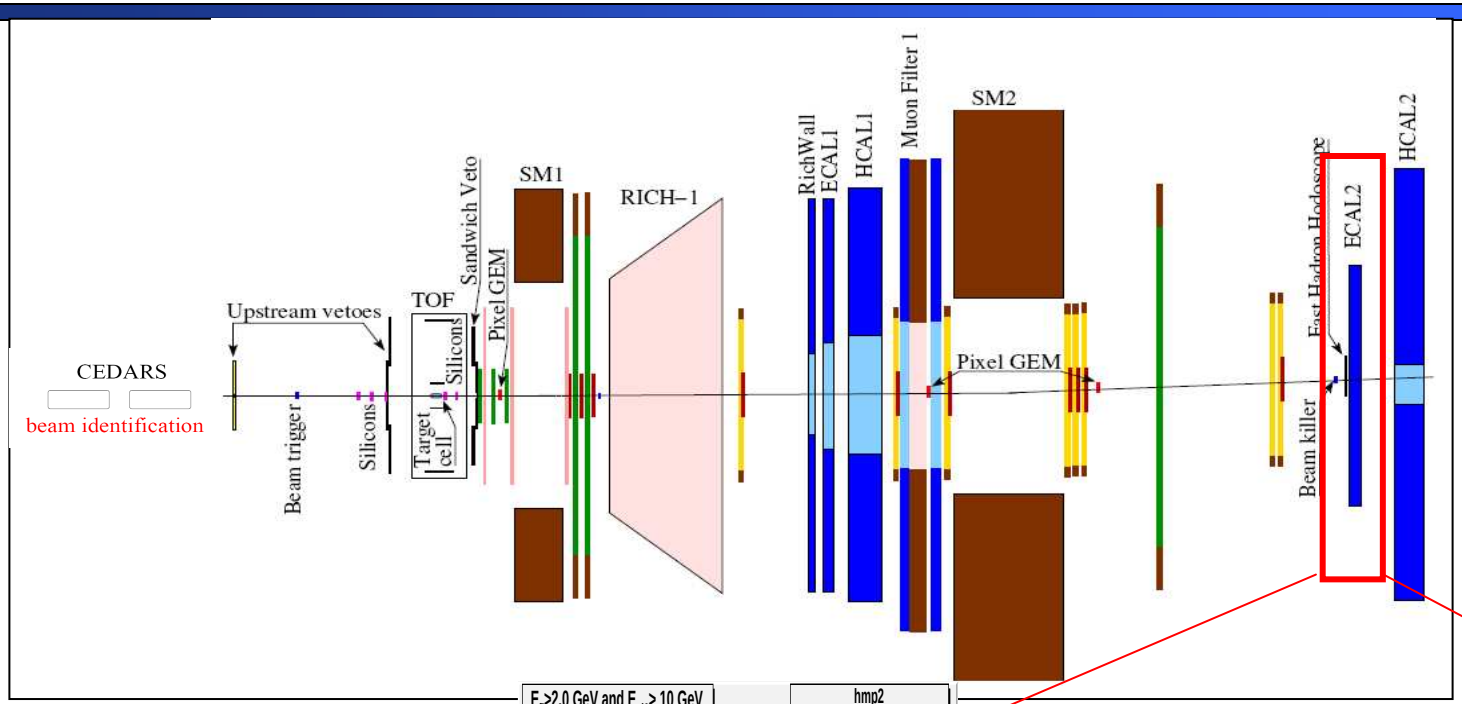




PixelGEM detectors:

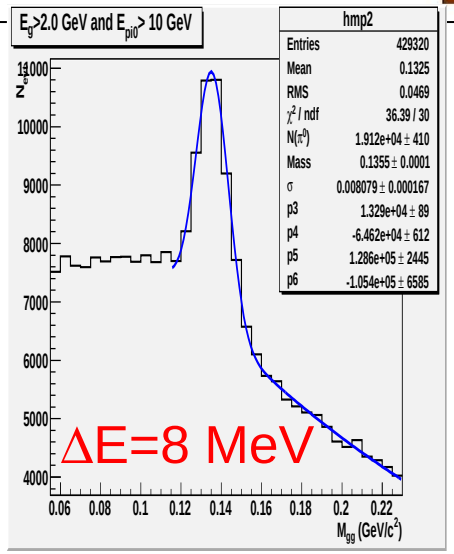
- very low mass: 0.2% X_0
- high rates: ~10^5 $mm^{-2}s^{-1}$
- resolution: ~120 μm

COMPASS in 2008

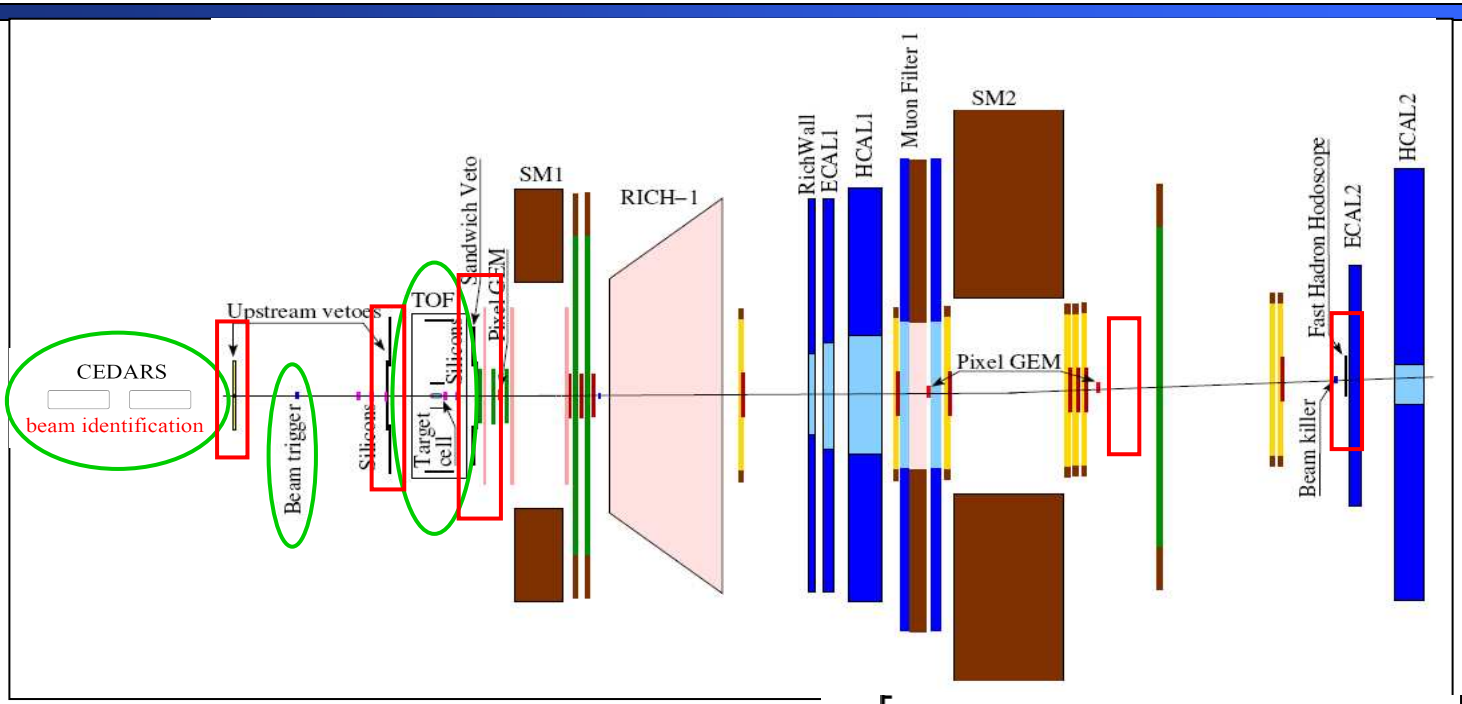


ECAL:

- ~800 Shashlik modules
- rad. hard: dose >1k rad
- 80 MHz sampling ADC



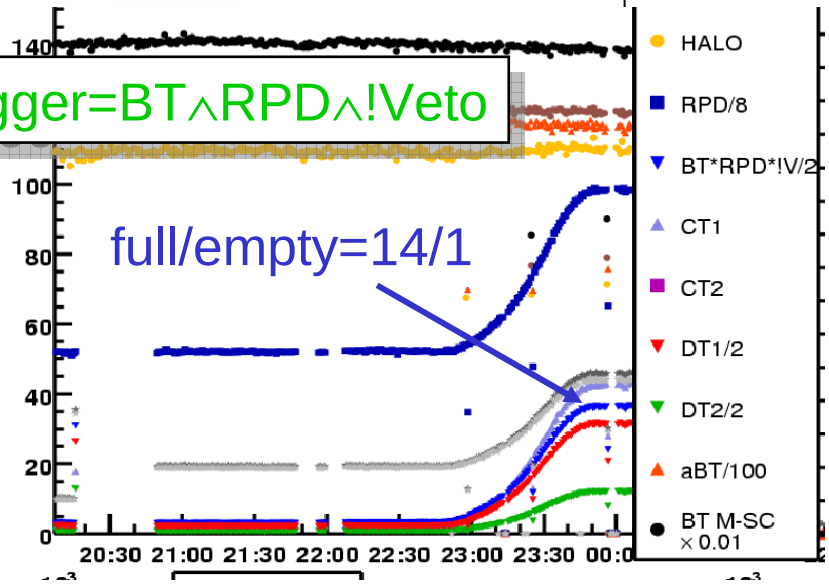
COMPASS in 2008



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.** $\approx$✓

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

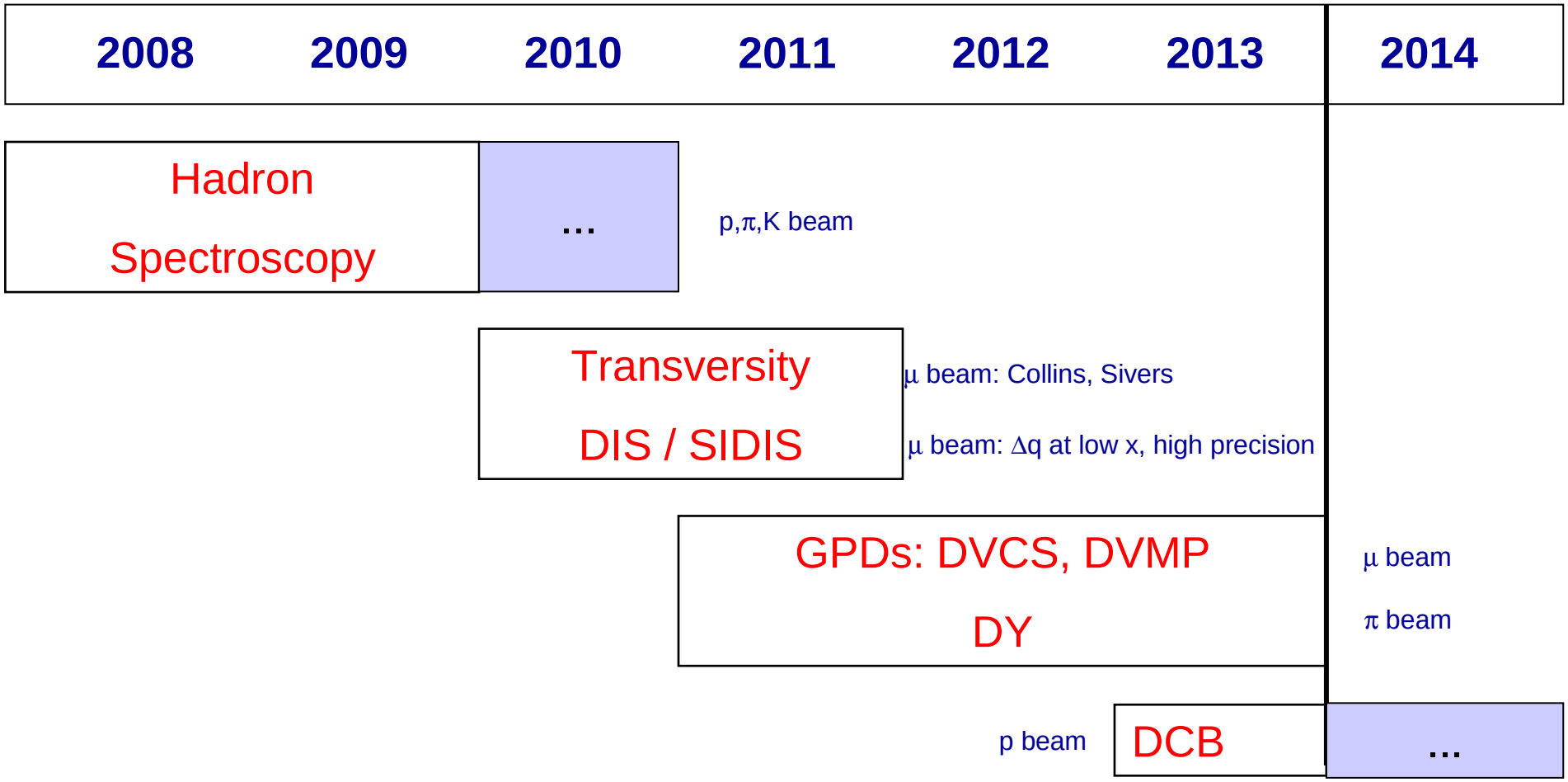
Early North Area stop due to LHC problems

only a few days of testing...

Summary and Outlook

- **COMPASS** has started with light meson spectroscopy
  - High angular resolution for charged particles
    - Final states with neutral and charged particles
    - High statistics
- Physics results from 2004 **pilot run with incoming π**
  - PWA for $\pi^+\pi^-\pi^-$ (high t'): signal in exotic 1^{-+} wave at 1.6 GeV/c^2
  - PWA for low t' and for $\pi^+\pi^+\pi^-\pi^-\pi^-$ started
- Data from muoproduction $\mu A \rightarrow \mu' X A'$, $X \rightarrow 4\pi$ being analyzed
- **Hadron beam** running 2008 with LH_2 target
  - Experiment upgrade, diffractive running with π^- beam
  - Diffractive reactions: 10× world statistics in ~35 days
- **Hadron beam** running 2009 with LH_2 target
  - Mainly central production: 10× world statistics in ~50 days
  - Some more diffractive excitation and Primakoff

COMPASS Future Plans



COMPASS submitted LoI, **common proposal** to follow

Strong wish to involve **new groups**