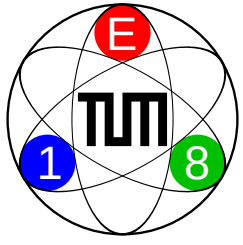
Meson Spectroscopy at COMPASS

F. Haas

for the COMPASS collaboration

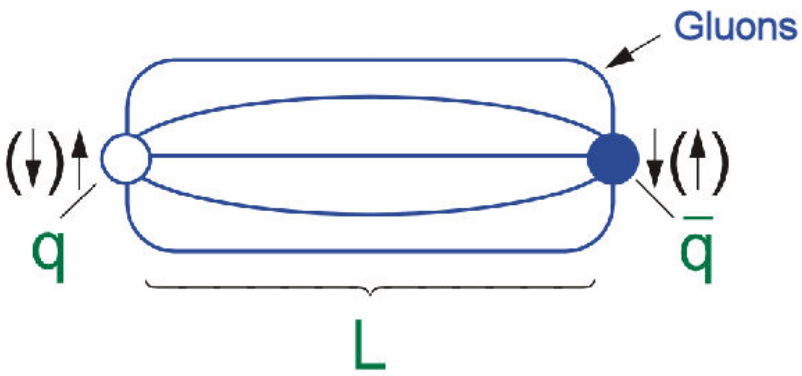
TU München, Physik Department E18

EPS HEP 2009, July 18th 2009



Overview

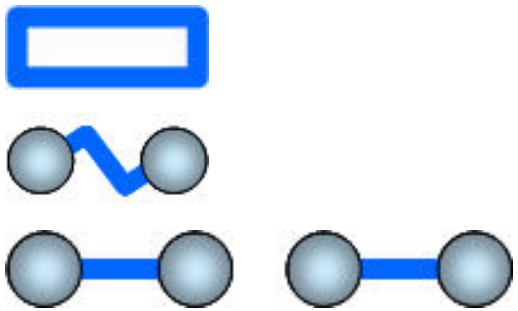
Quarkmodel and QCD



- $X(I^G J^{PC})$
- LS-Coupling:
  $J = \ell \oplus s = |\ell - s| ... \ell + s,$
  $(s = 0, 1)$
- Isospin and G-Parity conservation:
  $G = (-1)^{I+\ell+s}$
- Parity:
  $P = (-1)^{(\ell+1)}$
- Charge conjugation:
  $C = (-1)^{(\ell+s)}$

Quarkmodel and QCD

QCD allows states which are forbidden in the quarkmodel

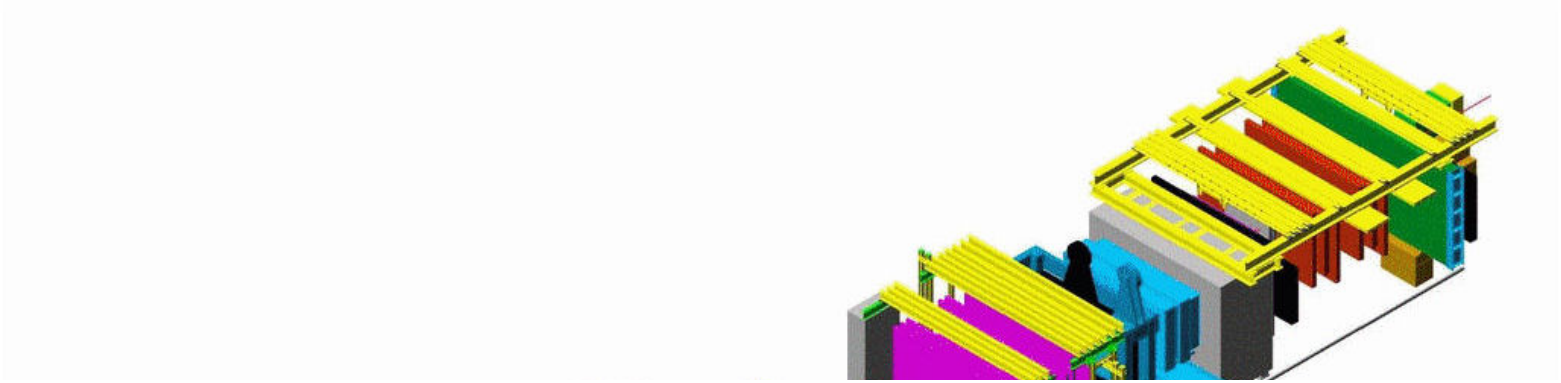


Glueballs: gg, ggg

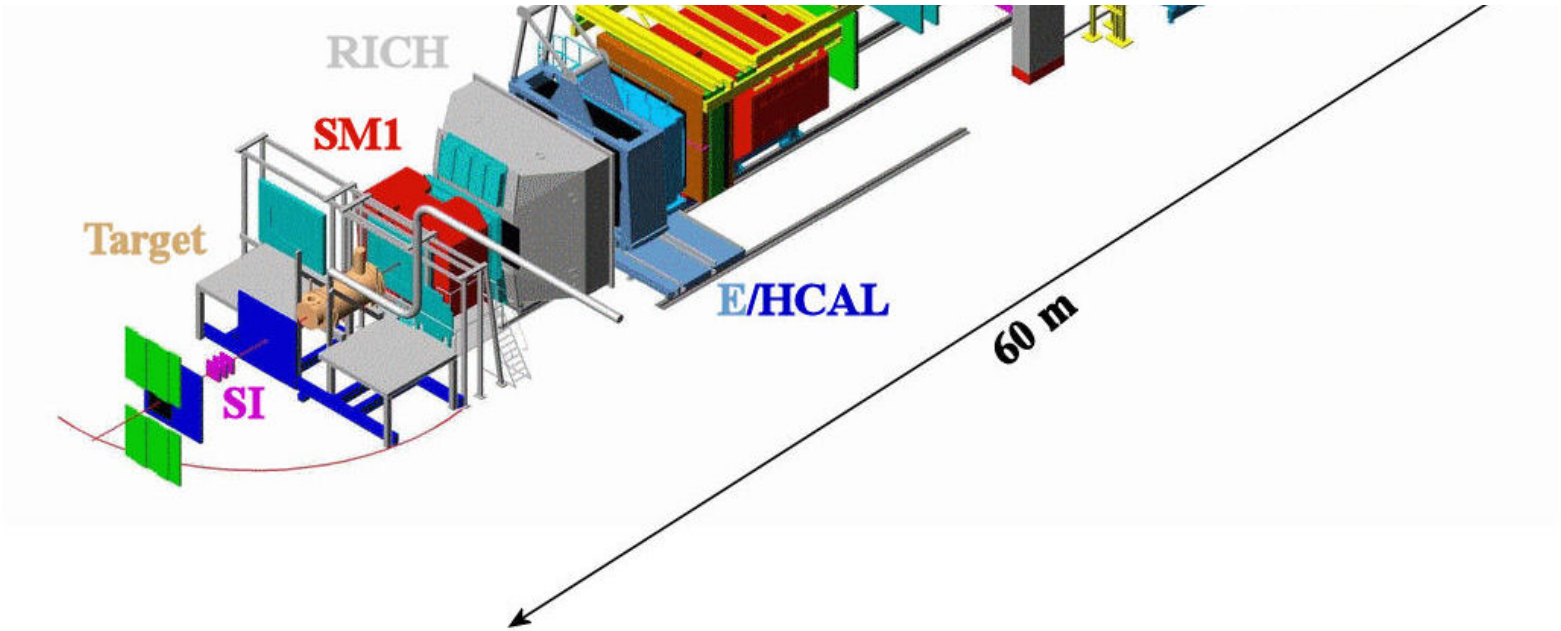
Hybrids: $qg\overline{q}$

Tetraquarks: $(q\overline{q})(q\overline{q})$

- Mixing of color neutral configurations with same quantum numbers
- leading $q\overline{q}$ term vanishes
  $\Rightarrow$ exotic $J^{PC}: 0^{--}, 0^{+-}, 1^{-+}, ...$

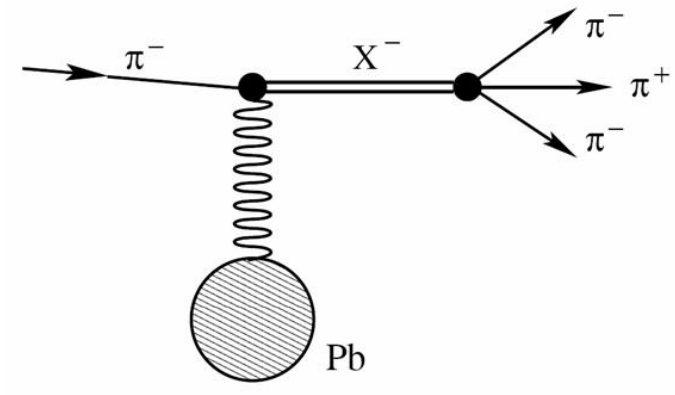


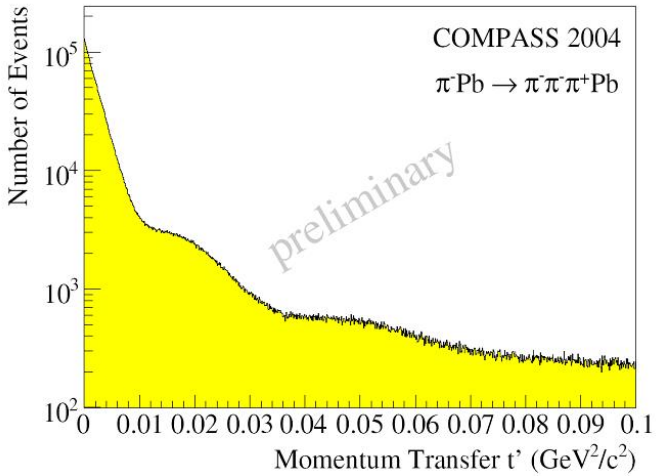
COMPASS can contribute significantly in the low mass region

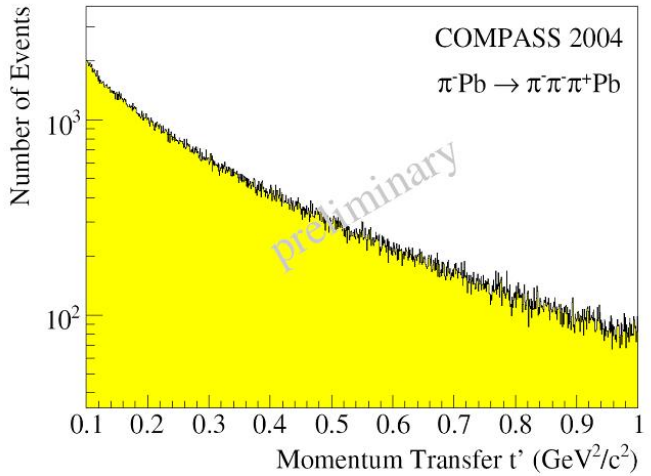


Diffractive Dissociation into 3π Final States

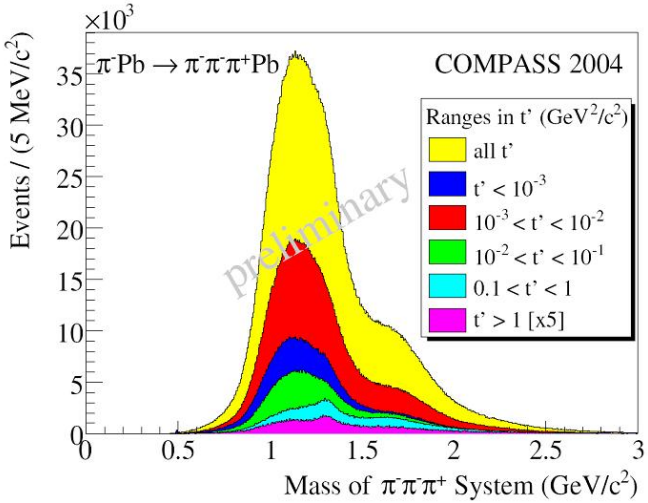
- $\pi^- + Pb \rightarrow \pi^-\pi^-\pi^+ + Pb$
- non-elastic but exclusive events
- target stays intact
- only momentum and angular momentum transfer to beam particle







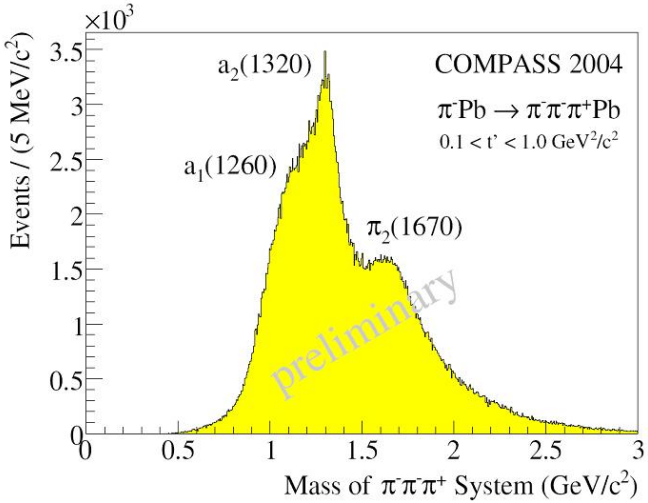
Invariant Mass of 3π System



COMPASS

- $p_\pi = 190 GeV/c$
- 4M events in 3 days (full t range)
- 450k events in $0.1 < \text{t'} < 1.0\ GeV^2/c^2$

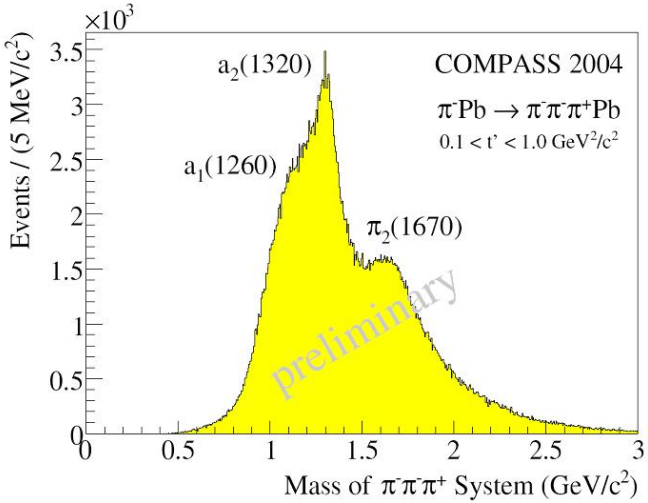
Invariant Mass of 3π System

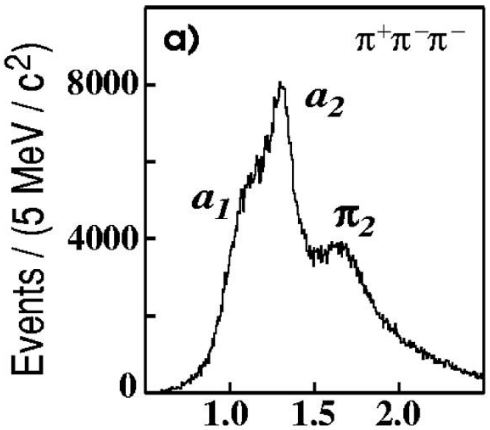


COMPASS

- $p_\pi = 190 GeV/c$
- 4M events in 3 days (full t range)
- 450k events in $0.1 < \text{t'} < 1.0\ GeV^2/c^2$

Invariant Mass of 3π System





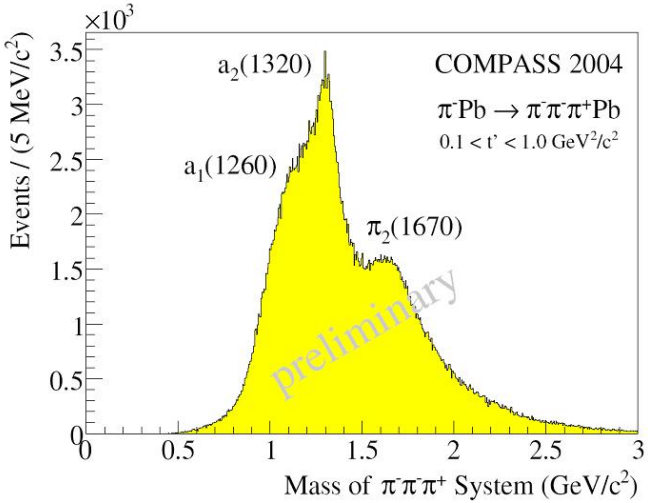
COMPASS

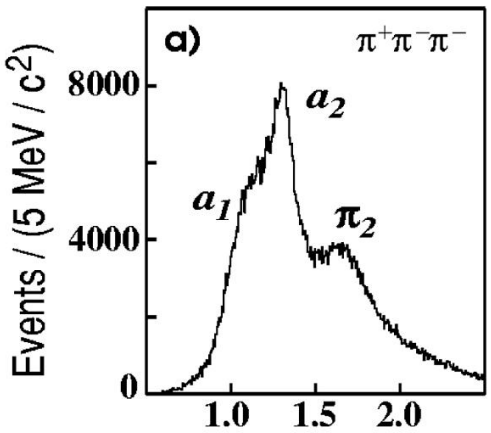
- $p_\pi = 190 GeV/c$
- 4M events in 3 days (full t range)
- 450k events in $0.1 < \text{t'} < 1.0\ GeV^2/c^2$

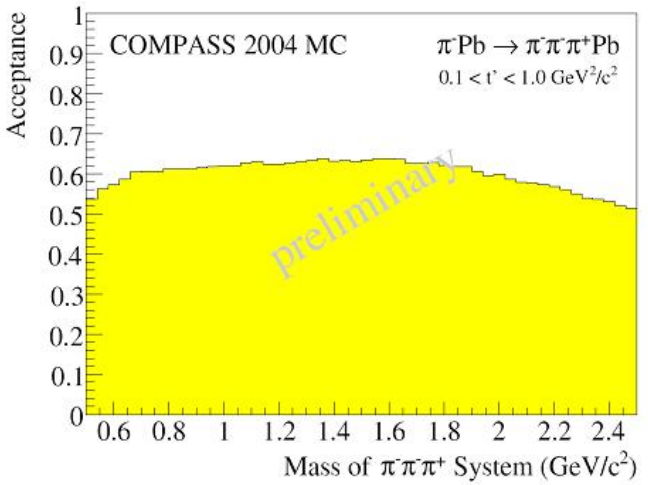
BNL E852

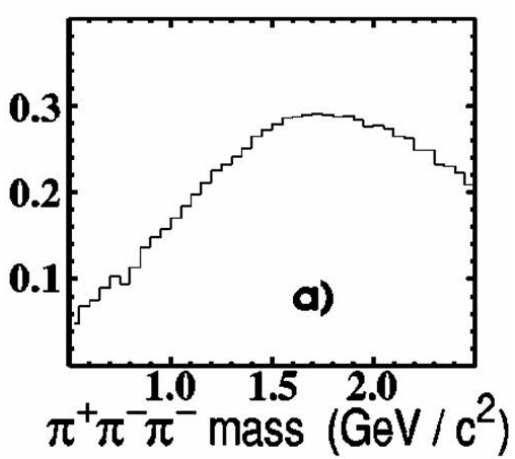
- $p_\pi = 18 GeV/c$
- 250k events in $0.08 < \text{t'} < 1.0\ GeV^2/c^2$

Invariant Mass of 3π System

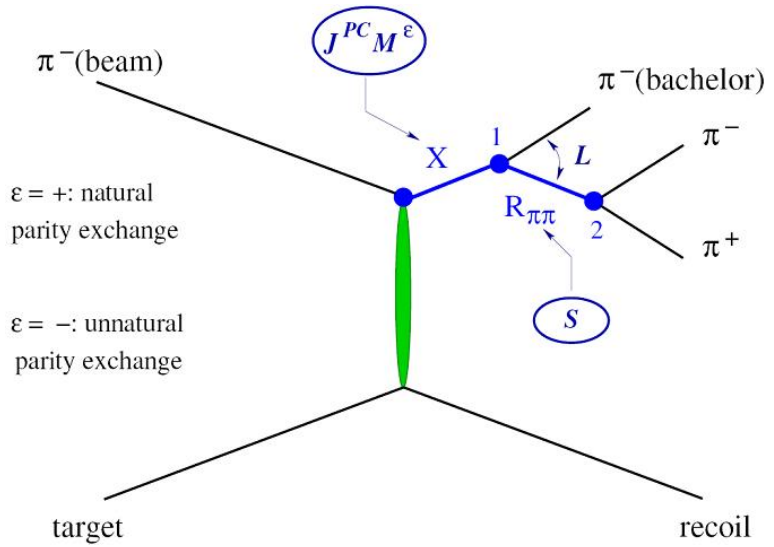


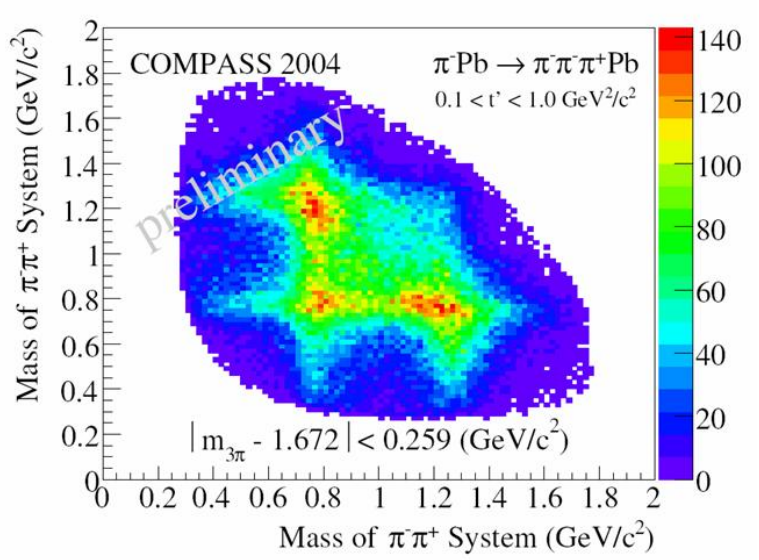






Partial Wave Analysis - Isobar Model





PWA: more detailed informations on quantum numbers of resonances

PWA Technique

Illinois/Protvino/Munich Program - BNL/Munich Program

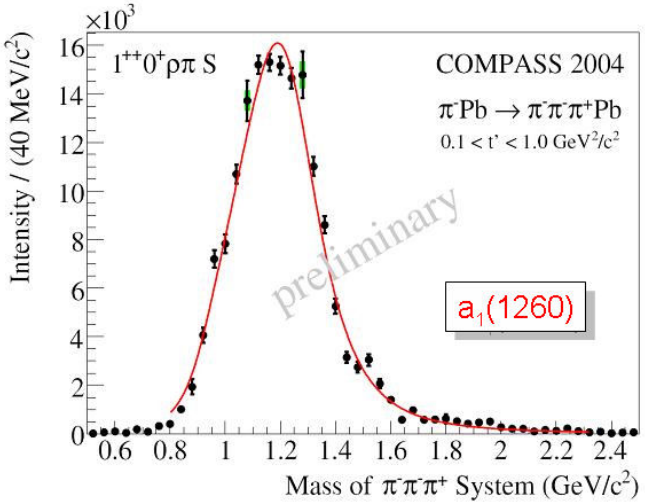
1. **Mass-Independent PWA**

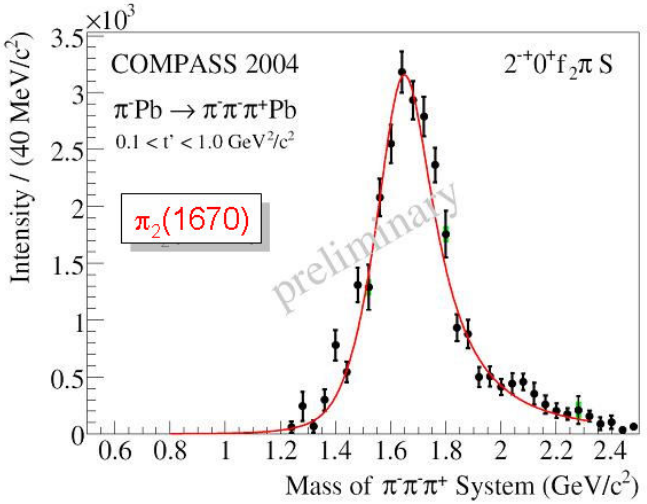
$$\sigma_{indep}(\tau, m, t') = \sum_{\epsilon=\pm 1} \sum_{r=1}^{N_r} \left| \sum_i T_{ir}^{\epsilon} f_i^{\epsilon}(t') \psi_i^{\epsilon}(\tau, m) / \sqrt{\int \left|\psi_i^{\epsilon}(\tau', m)\right|^2 d\tau'} \right|^2$$

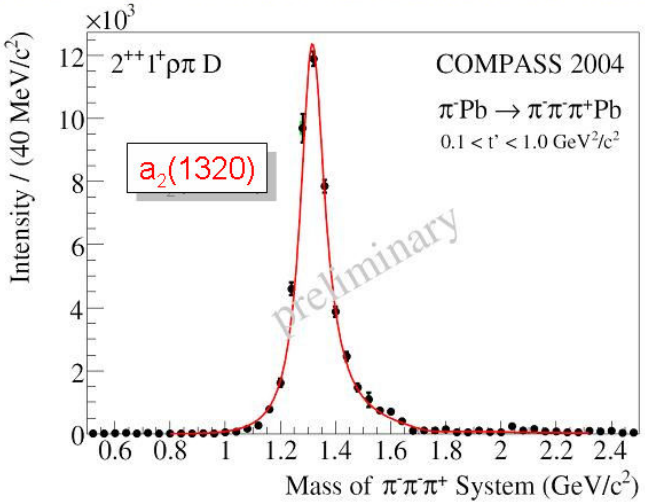
   - Production amplitudes $T_{ir}^{\epsilon} \rightarrow$ extended maximum likelihood fit
   - Decay amplitudes $\psi_i^{\epsilon}(\tau, m)$ (Zemach tensors, D functions)
   - 41 partial waves $i = J^{PC} M^{\epsilon} [Y] L$
     - with $[Y] = (\pi\pi)_S, \rho(770), f_0(980), f_2(1270), \rho_3(1690)$
   - Background wave

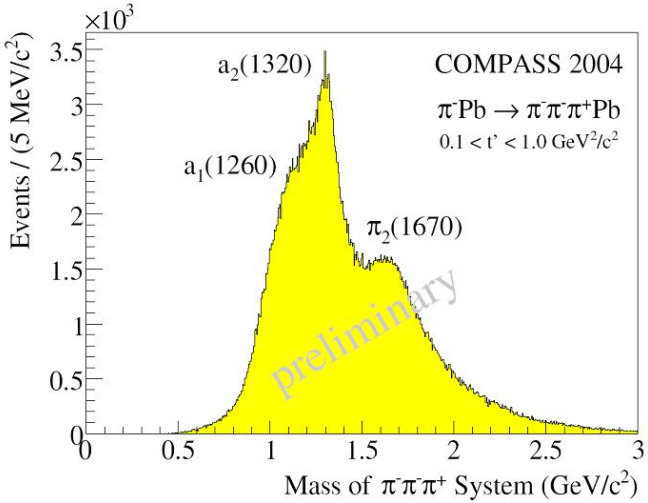
2. **Mass-Dependent χ^2 fit** to results of step 1
   - 6 waves
   - Parameterized by Breit-Wigner
   - Coherent background for some waves

Intensities of Major Waves

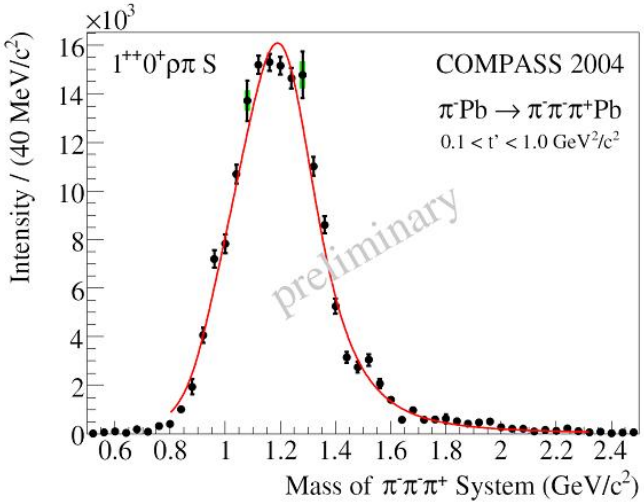


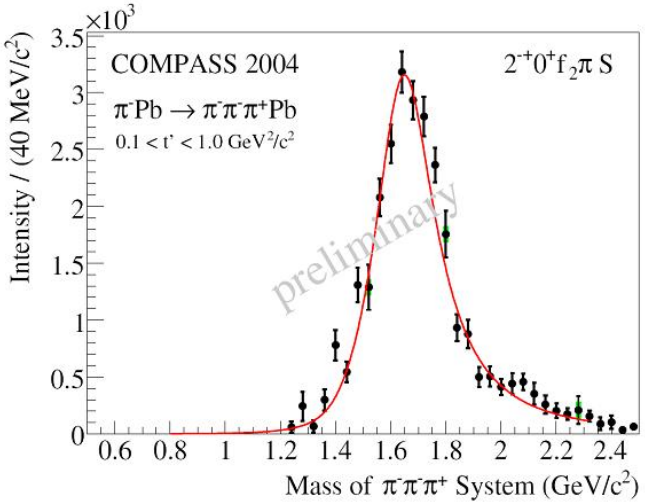


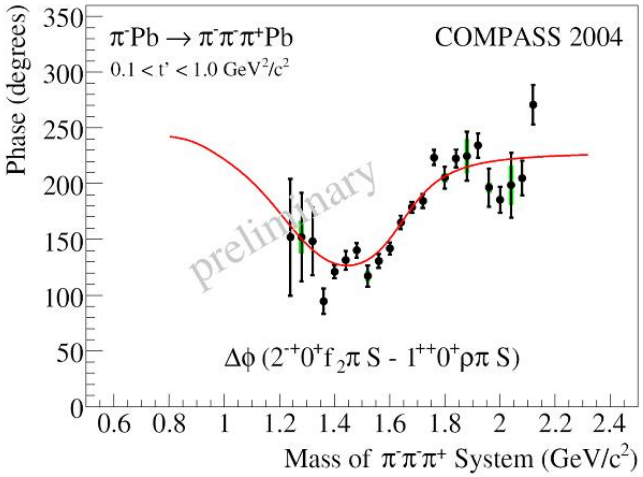




$a_1(1260)$ and $\pi_2(1670)$

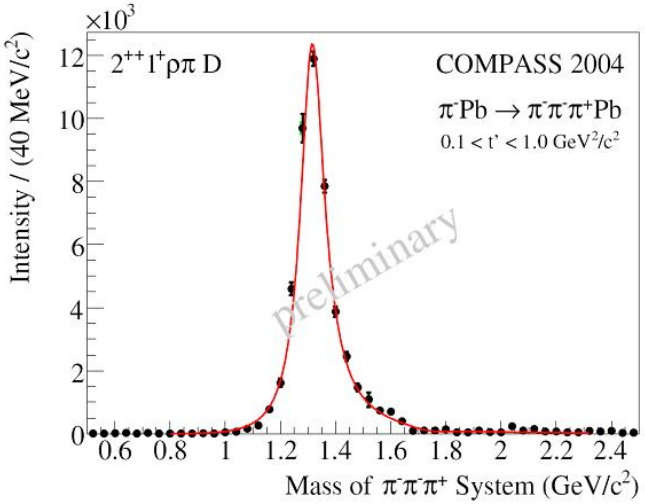


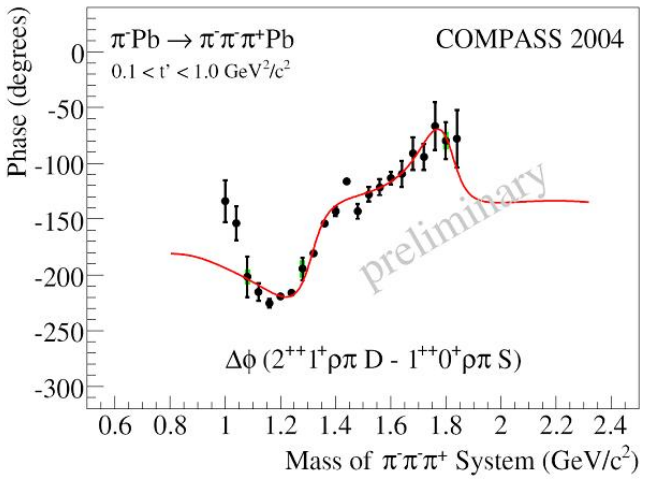




- BW for $a_1(1260)$ + bgr
  $M = \left(1255 \pm 6^{+7}_{-17}\right)\mathrm{MeV/c^2}$
  $\Gamma = \left(367 \pm 9^{+28}_{-25}\right)\mathrm{MeV/c^2}$
- BW for $\pi_2(1670)$
  $M = \left(1658 \pm 3^{+24}_{-8}\right)\mathrm{MeV/c^2}$
  $\Gamma = \left(271 \pm 9^{+22}_{-24}\right)\mathrm{MeV/c^2}$

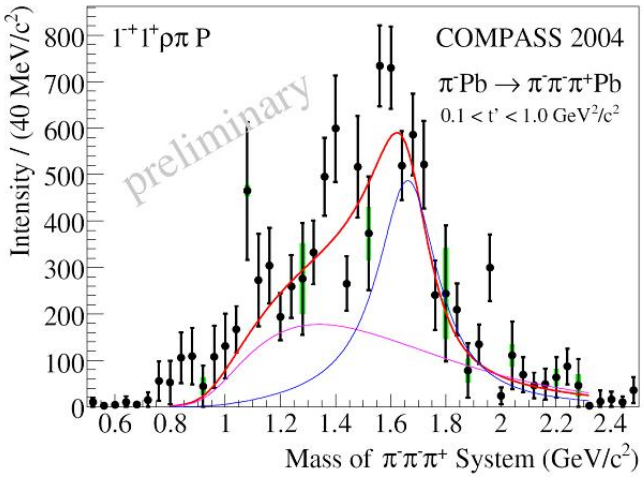
$a_2(1320)$

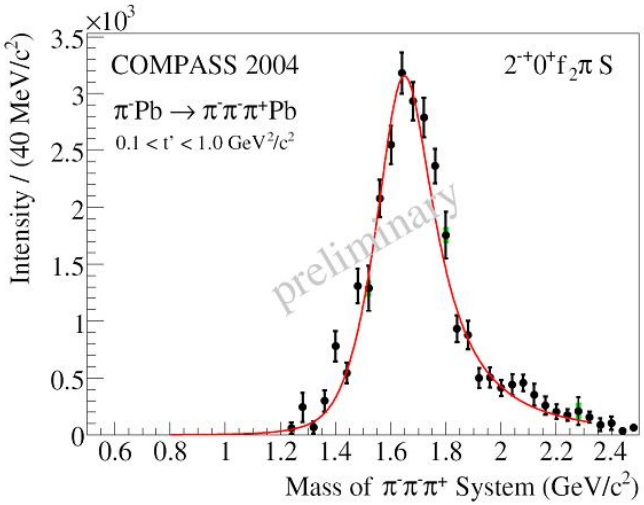


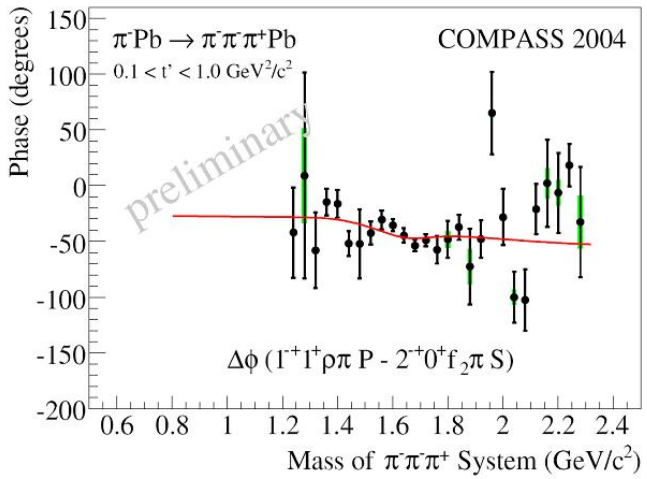


- Two Breit Wigner functions required to describe phase motion
- BW1 for $a_2(1320)$
  $M = \left(1321 \pm 1^{+0}_{-7}\right) \mathrm{MeV/c^2}$
  $\Gamma = \left(110 \pm 2^{+2}_{-25}\right) \mathrm{MeV/c^2}$
- BW2 for $a_2(1700)$: $M = 1732 MeV/c^2, \Gamma = 194 MeV/c^2$ (fixed PDG values)

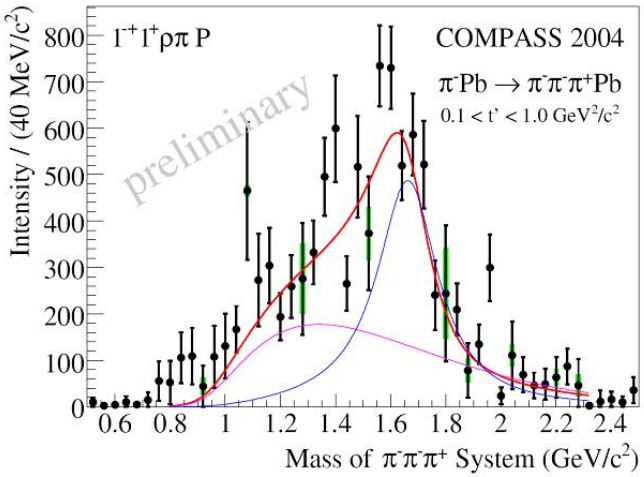
$J^{PC} = 1^{-+}$ Exotic Wave

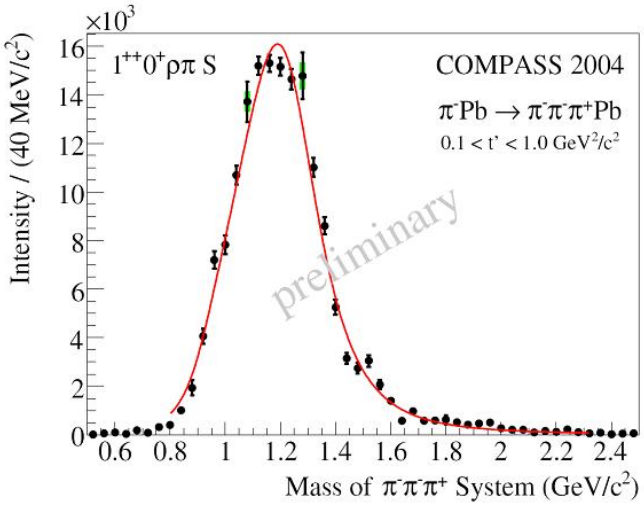




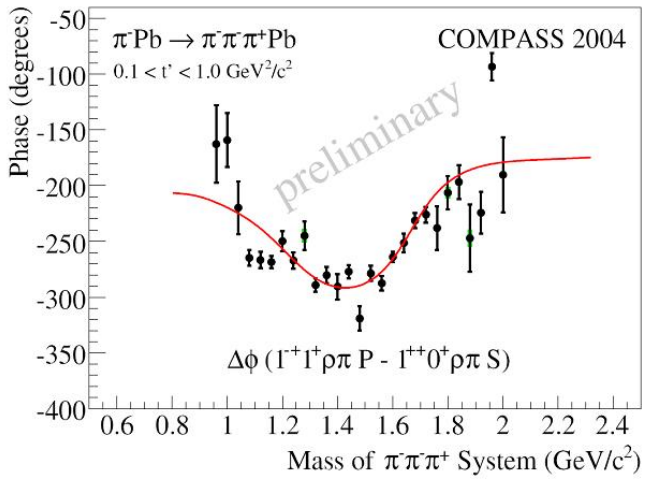


$J^{PC} = 1^{-+}$ Exotic Wave

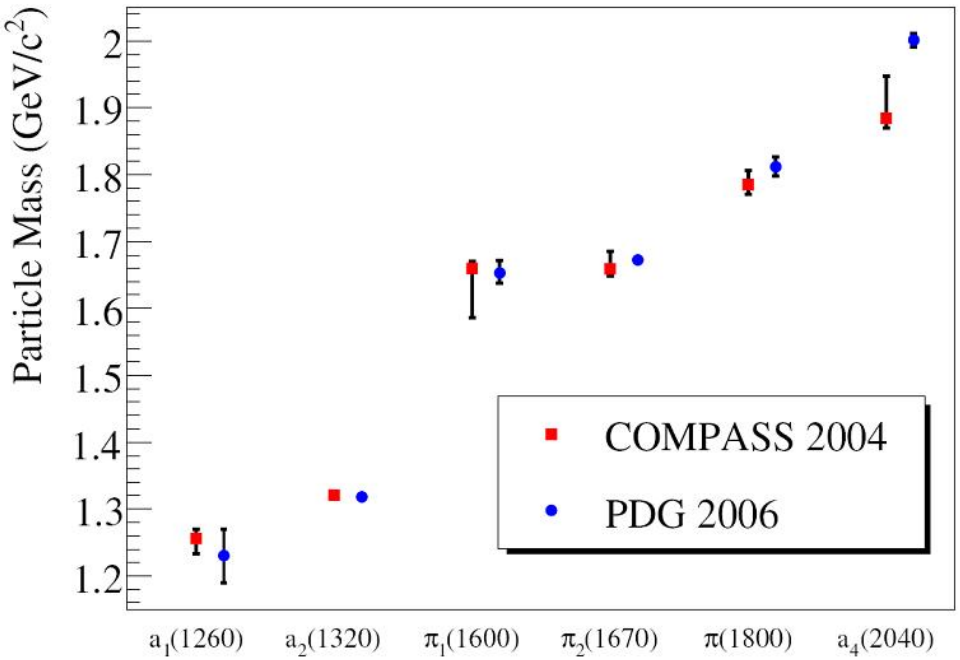




- BW parameters for $\pi_1(1600)$
  $M = \left(1660 \pm 10^{+0}_{-64}\right)\text{MeV/c}^2$
  $\Gamma = \left(269 \pm 21^{+42}_{-64}\right)\text{MeV/c}^2$
- Leakage negligible: $< 5\%$



Summary of Waves



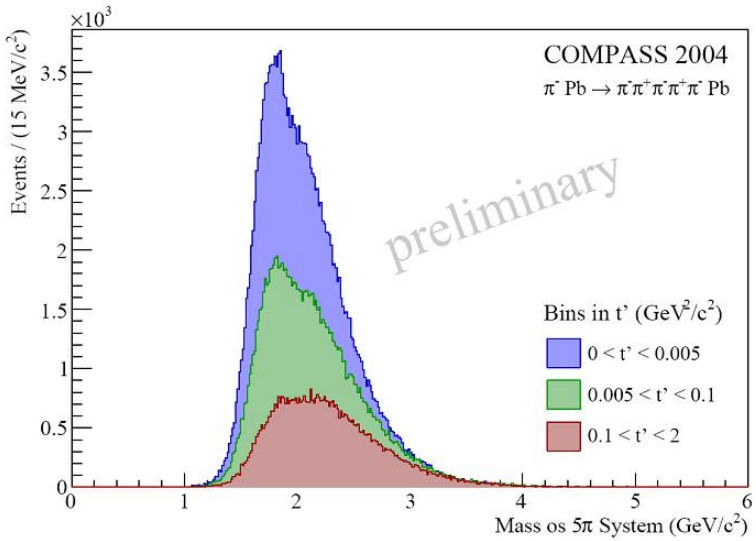
Resonance	Mass (MeV/c^2)	Width (MeV/c^2)	Intensity (%)	Channel $J^{PC}M^{\epsilon}[\mathrm{isobar}]L$
$a_1(1260)$	$1255 \pm 6^{+7}_{-17}$	$367 \pm 9^{+28}_{-25}$	$67 \pm 3^{+4}_{-20}$	$1^{++}0^{+}\,\rho\pi\,S$
$a_2(1320)$	$1321 \pm 1^{+0}_{-7}$	$110 \pm 2^{+2}_{-15}$	$19.2 \pm 0.6^{+0.3}_{-2.2}$	$2^{++}1^{+}\,\rho\pi\,D$
$\pi_1(1600)$	$1660 \pm 10^{+0}_{-64}$	$269 \pm 21^{+42}_{-64}$	$1.7 \pm 0.2^{+0.9}_{-0.1}$	$1^{-+}1^{+}\,\rho\pi\,P$
$\pi_2(1670)$	$1658 \pm 3^{+24}_{-8}$	$271 \pm 9^{+22}_{-24}$	$10.0 \pm 0.4^{+0.7}_{-0.7}$	$2^{-+}0^{+}\,f_2\pi\,S$
$\pi(1800)$	$1785 \pm 9^{+12}_{-6}$	$208 \pm 22^{+21}_{-37}$	$0.8 \pm 0.1^{+0.3}_{-0.1}$	$0^{-+}0^{+}\,f_0\pi\,S$
$a_4(2040)$	$1885 \pm 13^{+50}_{-2}$	$294 \pm 25^{+46}_{-19}$	$1.0 \pm 0.3^{+0.1}_{-0.1}$	$4^{++}1^{+}\,\rho\pi\,G$

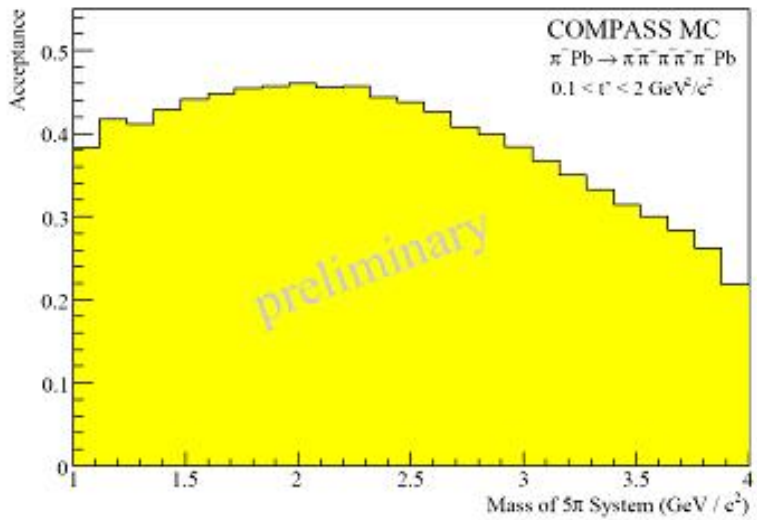
Diffractive Dissociation into 5π Final States

- Higher masses accessible
- many disputed states: $0^{-+}, 1^{++}, 2^{-+}, \ldots$
- flux tube model: $J^{PC} = 1^{-+}$ decay into $b_1(1235)\pi$ and $f_1(1285)\pi$

Invariant Mass of 5π System

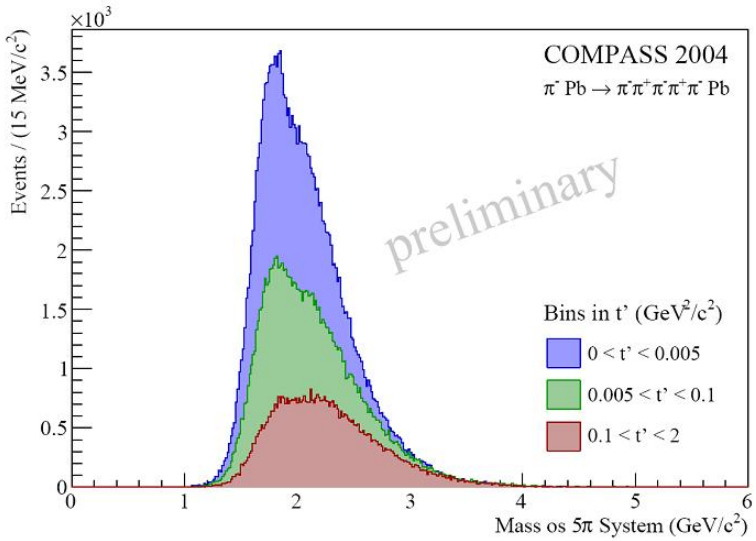
- $\pi^- Pb \longrightarrow \pi^-\pi^+\pi^-\pi^+\pi^- Pb$
- flux tube model: $J^{PC} = 1^{-+}$ decay into $f_1(1285)\pi$
- non-elastic but exclusive events
- target stays intact
- only momentum and angular momentum transfer to beam particle

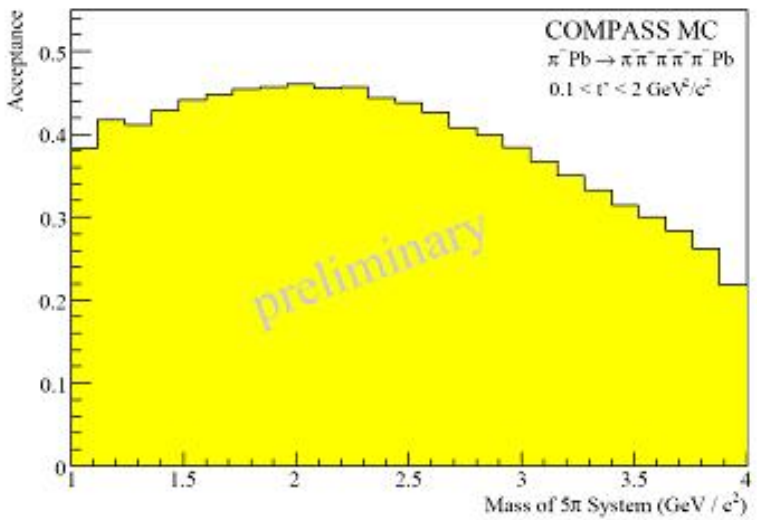




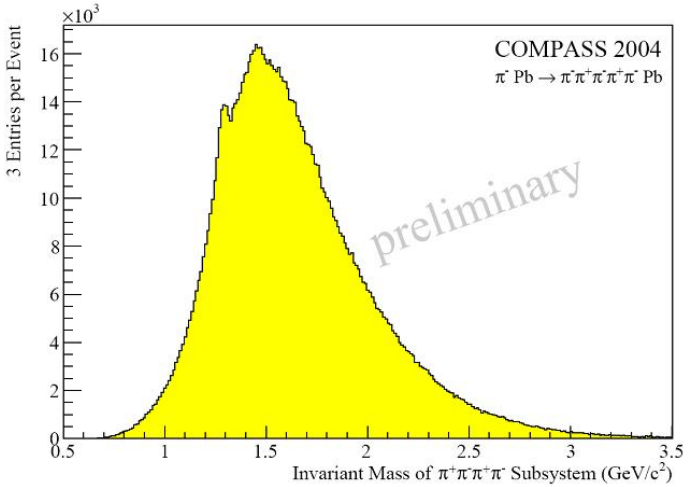
Invariant Mass of 5π System

Low t'	$t' \in [0, 0.005]\text{GeV}/c^2$	203k events
Medium t'	$t' \in [0.005, 0.1]\text{GeV}/c^2$	122k events
High t'	$t' \in [0.1, 2]\text{GeV}/c^2$	59k events



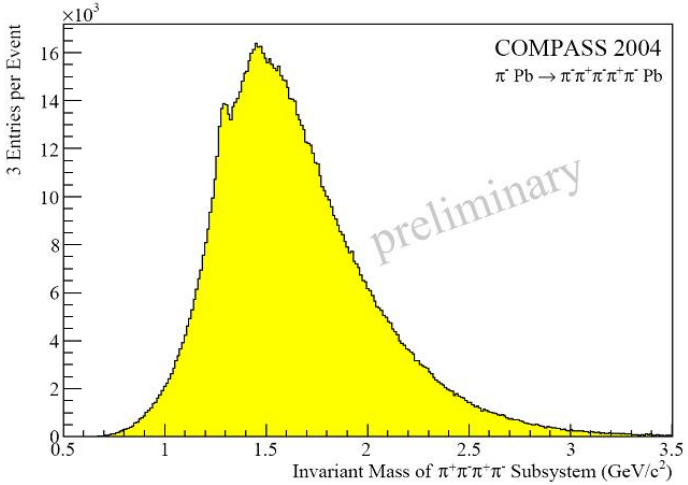


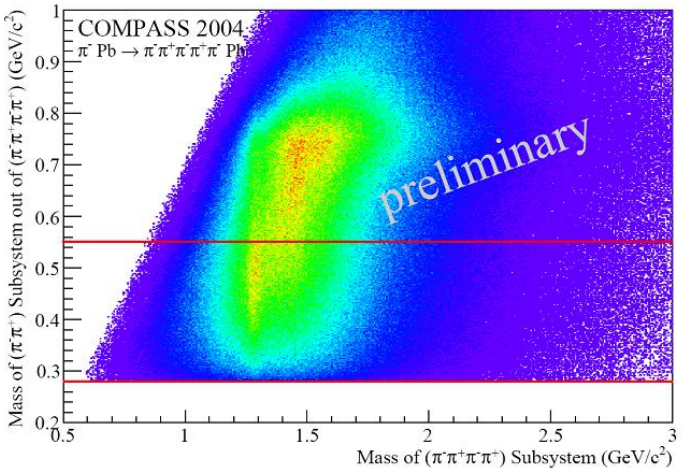
4π Subsystem



- neutral 4 π subsystem
- three entries per event
- exclusivity cut applied
- sharp peak at 1.3 Gev/c^2

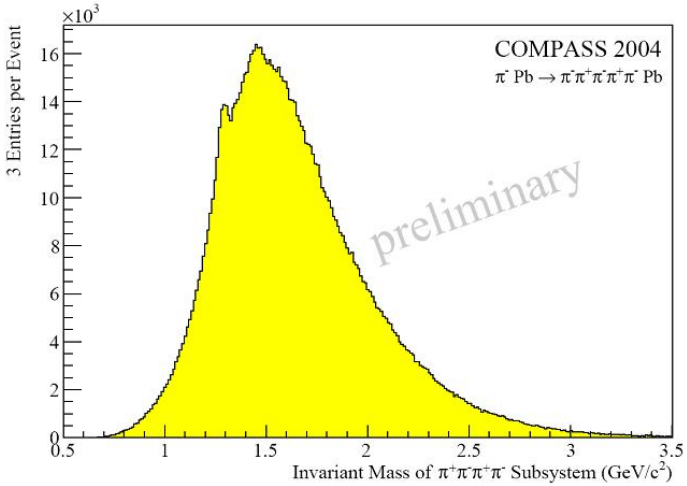
4π Subsystem

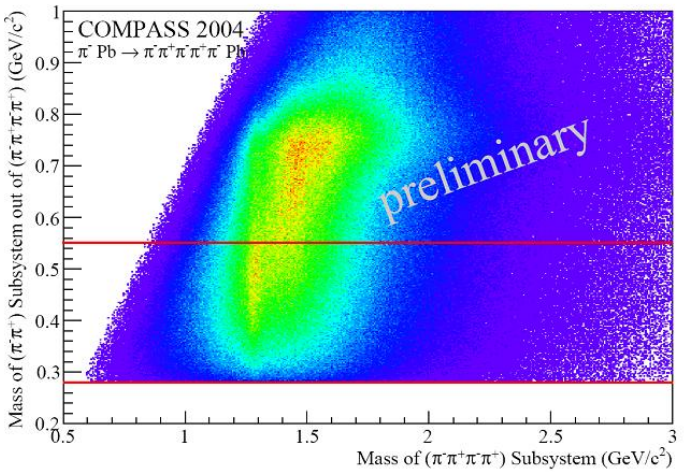




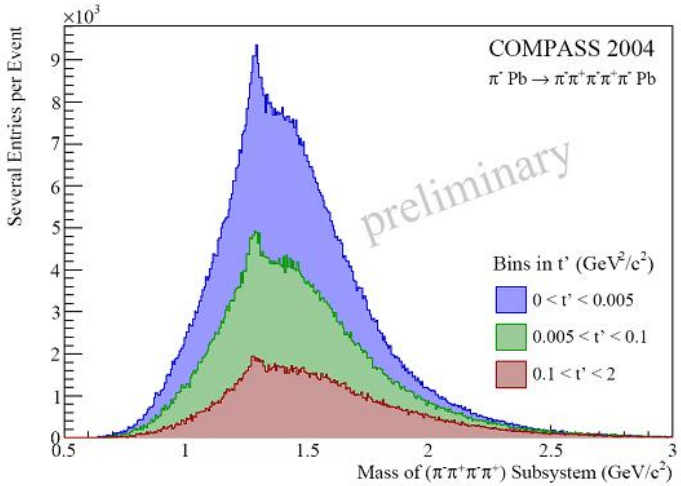
- PDG: branching ratio for $f_1(1285)$ into 4 charged π $\rightarrow$ (11$\pm$1)%
- 2π neutral susysystem vs. 4π neutral subsystem
- 12 entries per event

4π Subsystem

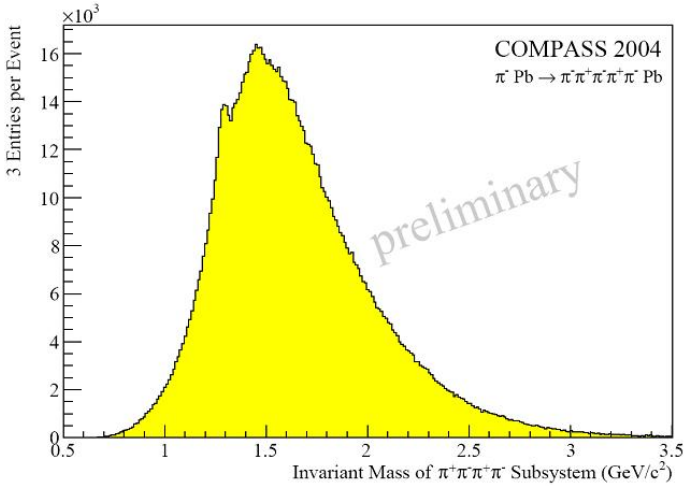




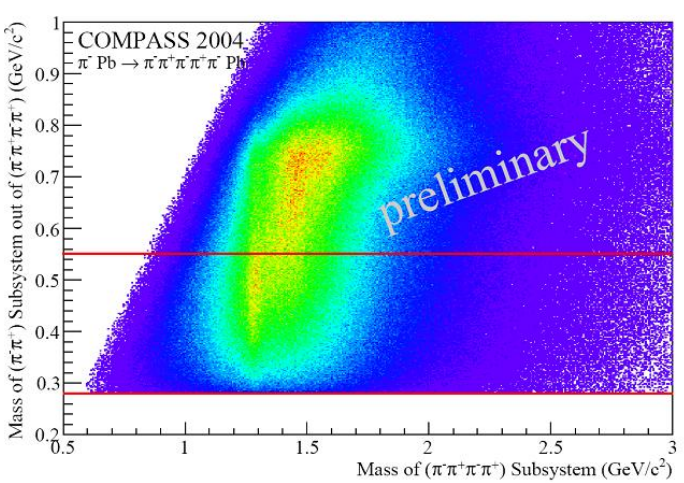
- invariant mass spectrum of the neutral 4π subsystem with cut on $\pi^-\pi^+$ subsystem (red lines)
- cut range: $0.28\text{GeV}/c^2 < m(2\pi) < 0.55\text{GeV}/c^2$

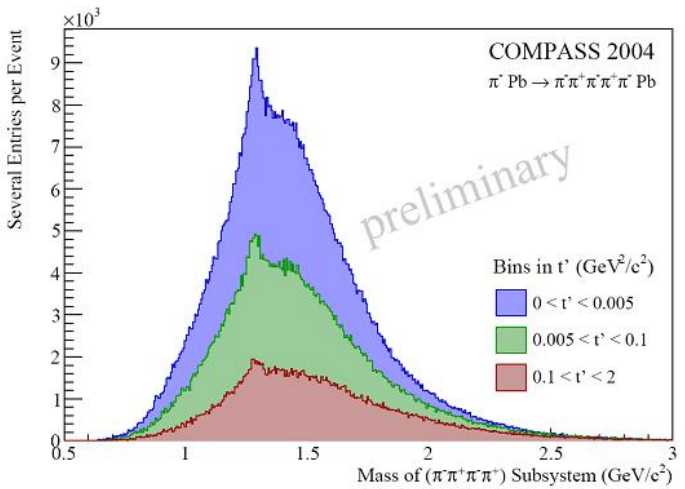


4π Subsystem

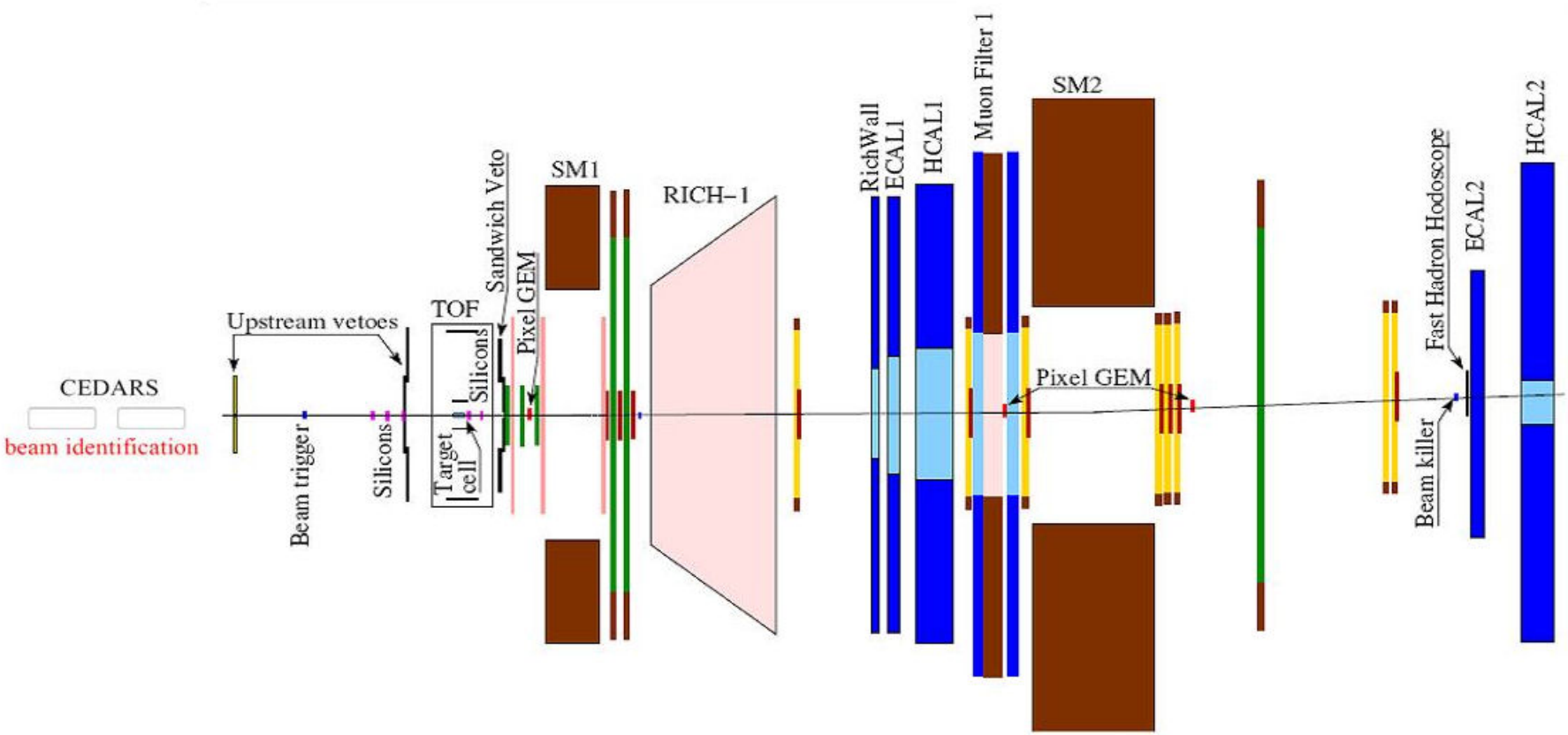


Name	Mass (GeV/c^2)	$I^G(J^{PC})$
f_0	1370 / 1700	$0^+(0^{++})$
η'	1403	$0^+(0^{-+})$
ρ'	1450	$1^+(1^{--})$
b_1	1235 / 1800	$1^+(1^{+-})$
f_1	1285 / 1450	$0^+(1^{++})$
η_2'	1645	$0^+(2^{-+})$
f_2	1565	$0^+(2^{++})$
ρ_3	1690	$1^+(3^{--})$

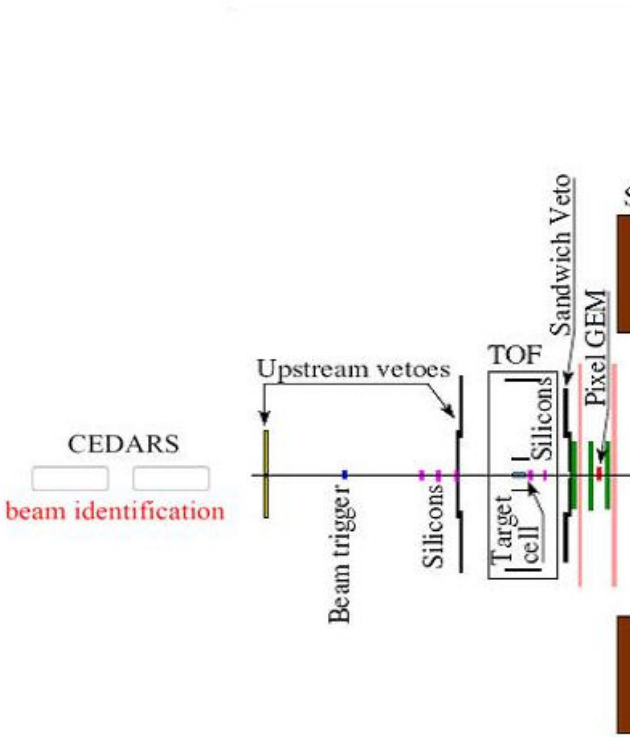




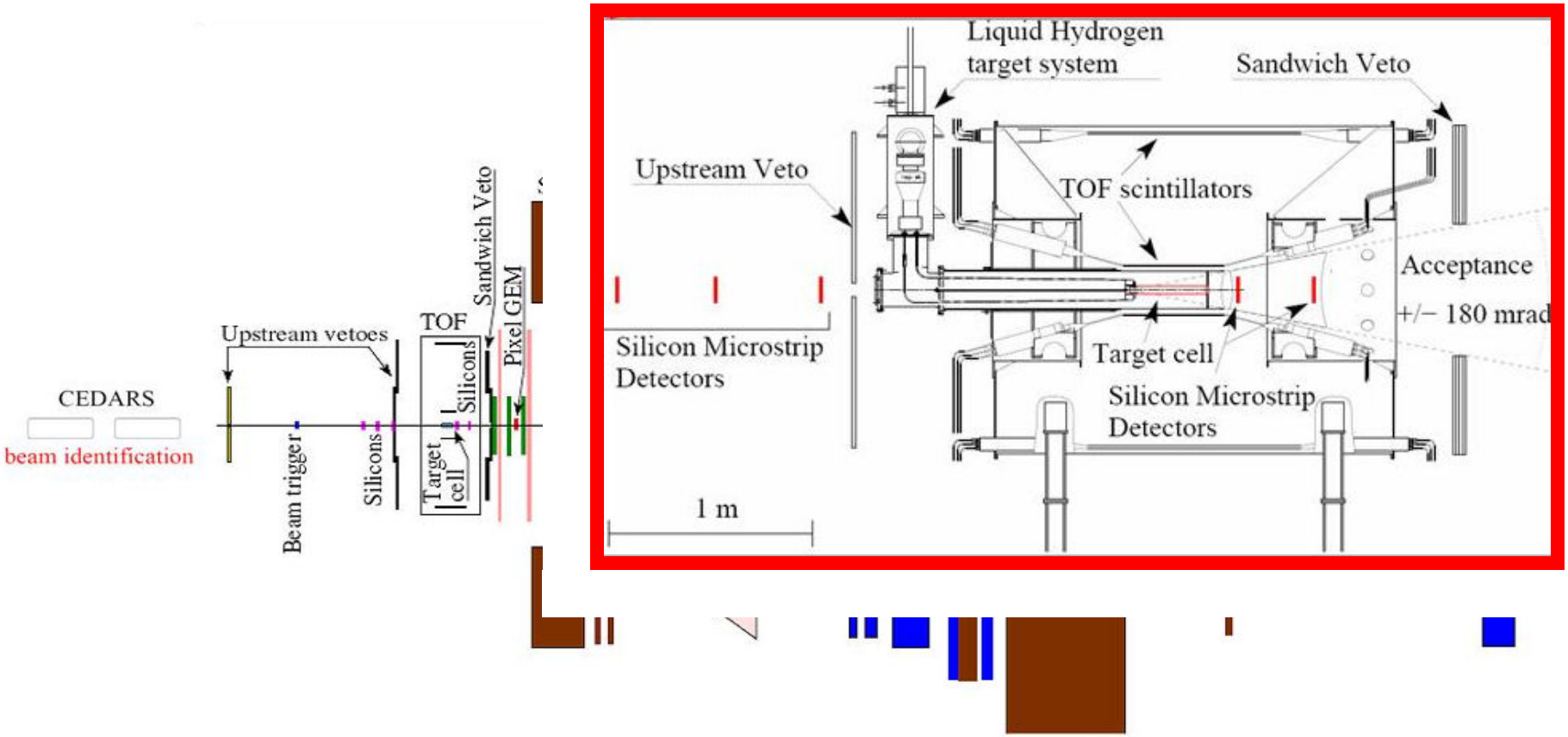
Spectrometer Upgrade 2008



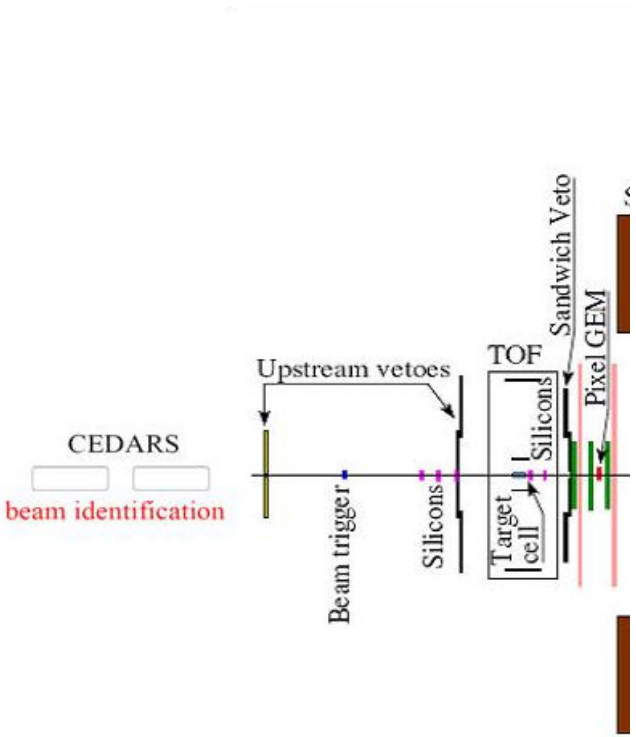
Spectrometer Upgrade 2008 - Beam Particle Identification

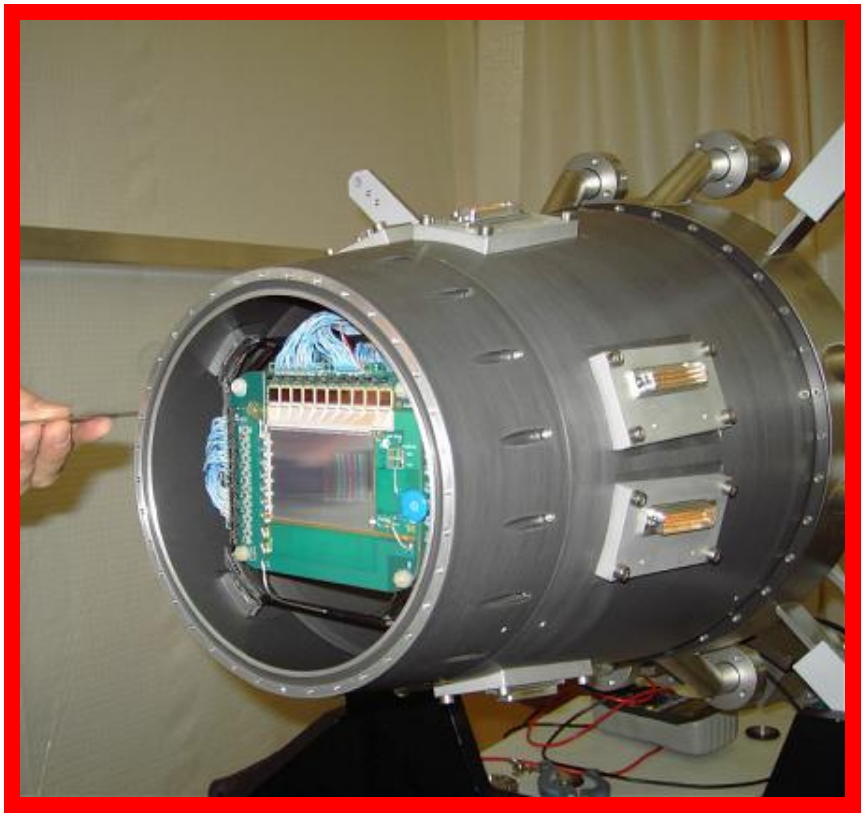


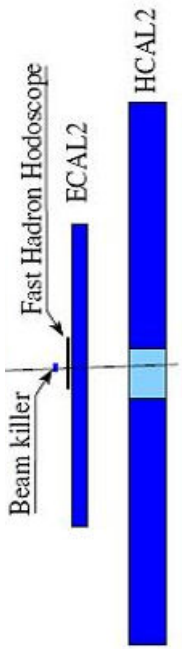
Spectrometer Upgrade 2008 - Liquid Hydrogen Target - Proton Recoil Detector



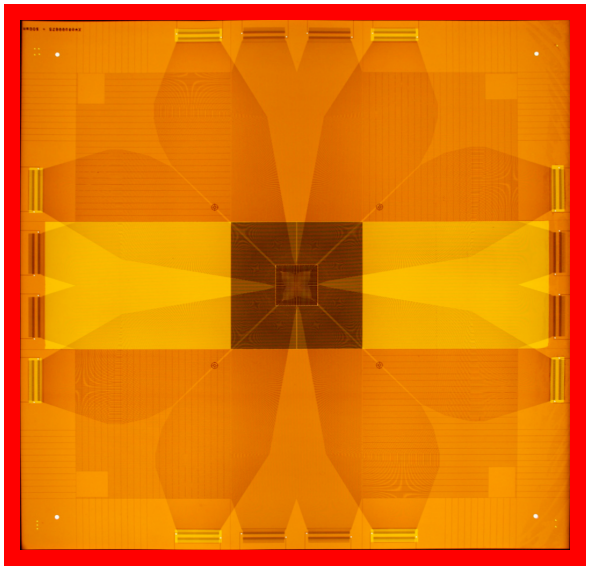
Spectrometer Upgrade 2008 - Target Region - Silicon Microstrip Detectors



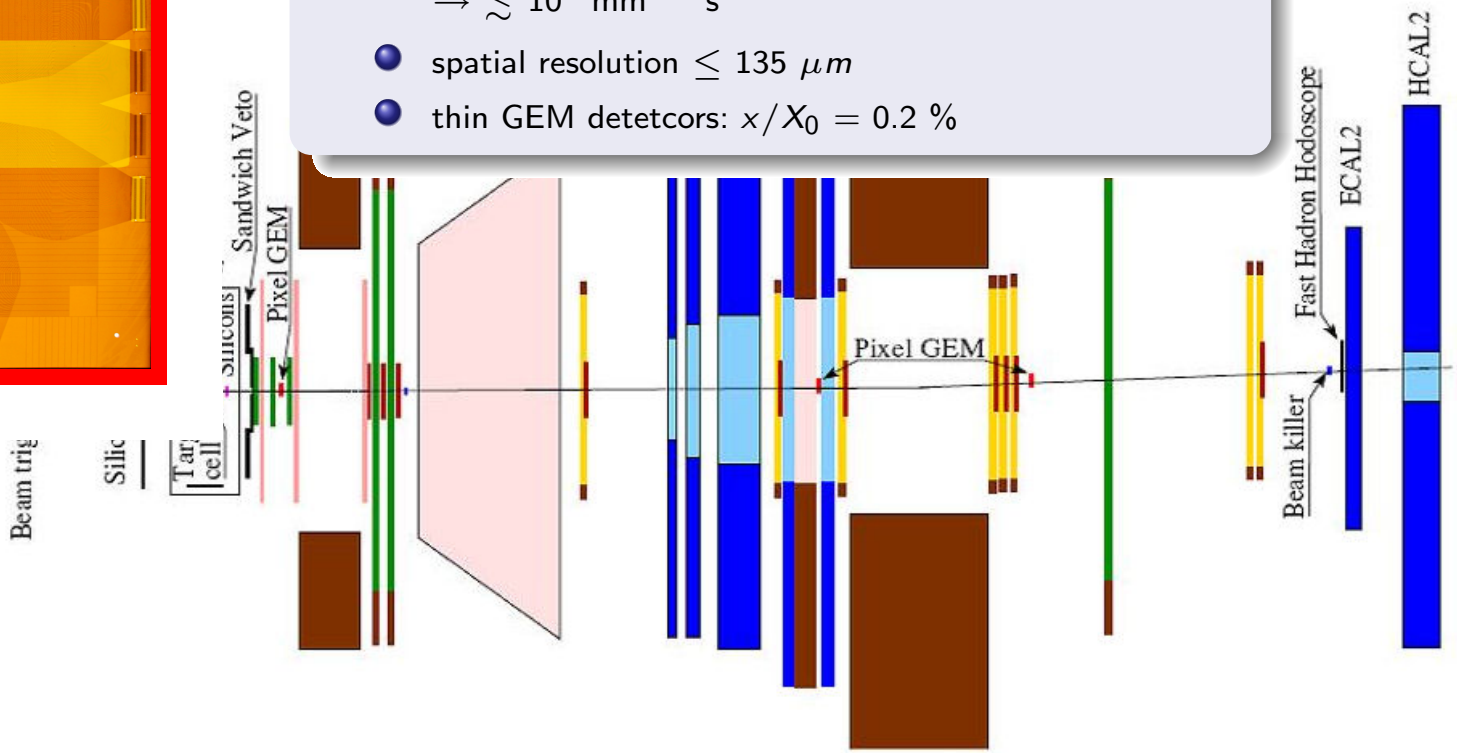




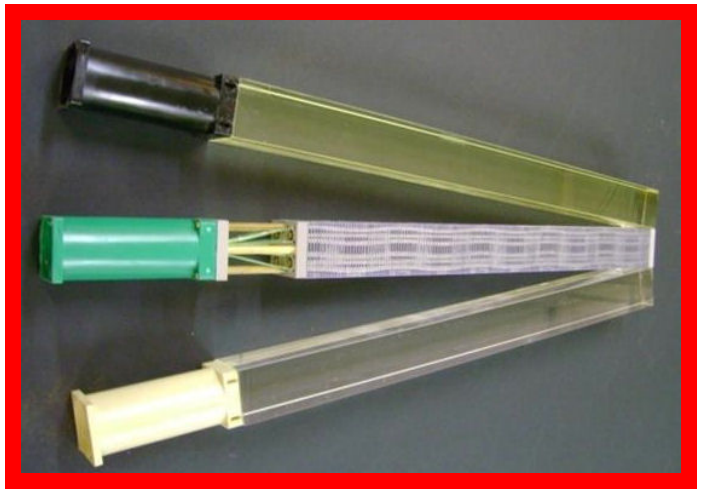
Spectrometer Upgrade 2008 - PixelGEM Detectors



- stable operation in high intensity muon/hadron beam $\rightarrow 4{\cdot}10^7 s^{-1}$
- Pixel readout allows tracking in a high rate beam $\rightarrow \lesssim 10^5$ mm^{-2} s^{-1}
- spatial resolution $\leq 135\ \mu m$
- thin GEM detetcors: $x/X_0 = 0.2$ %

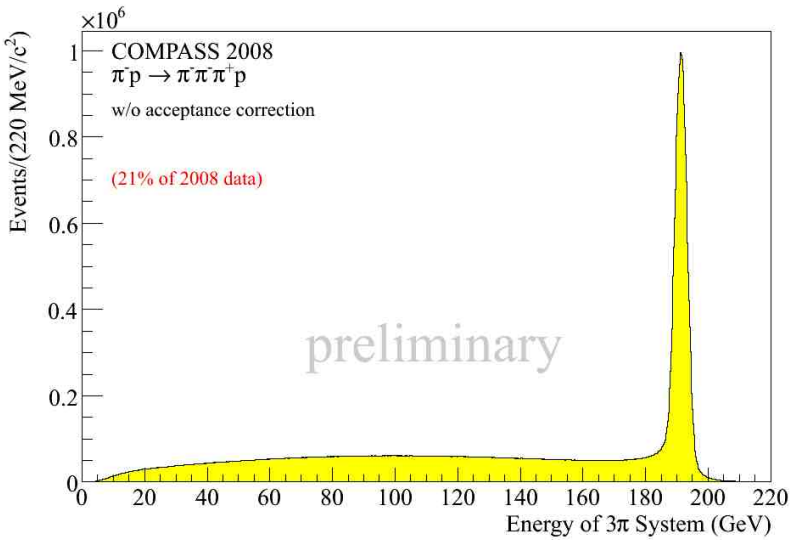


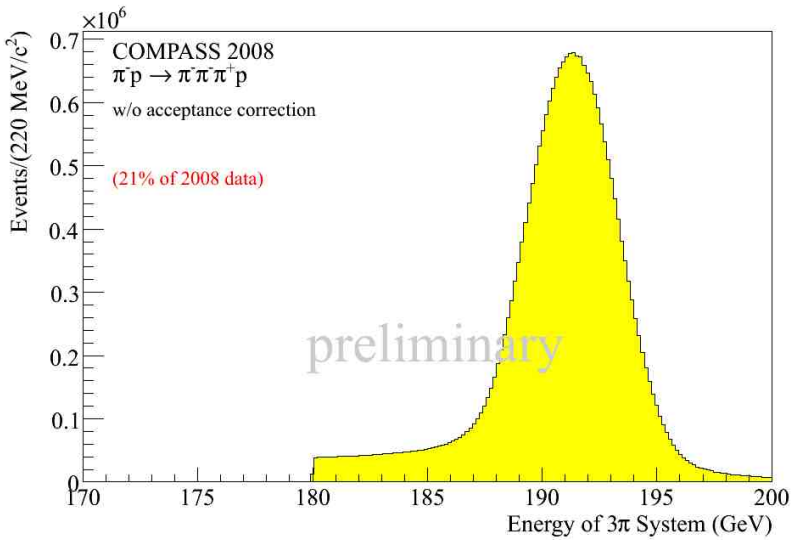
Spectrometer Upgrade 2008 - Electromagnetic Calorimeter



Diffractive Dissociation into 3π Final States

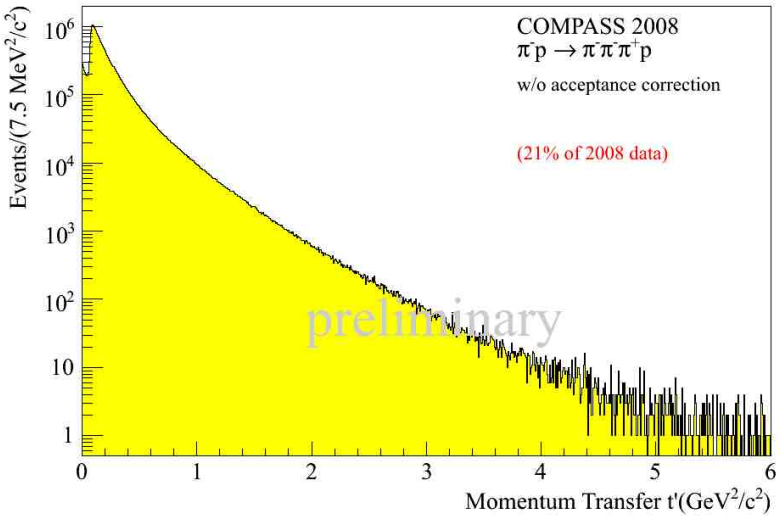
- 190 GeV/c hadron beam $\longrightarrow$ 96%π^-, 3.5%K^-, 0.5%$\overline{p}$
- 40cm liquid hydrogen target
- exclusivity

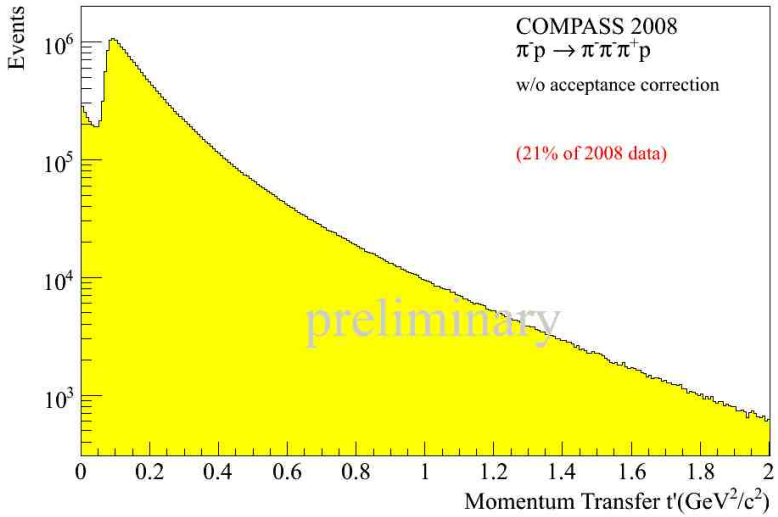




Diffractive Dissociation into 3π Final States

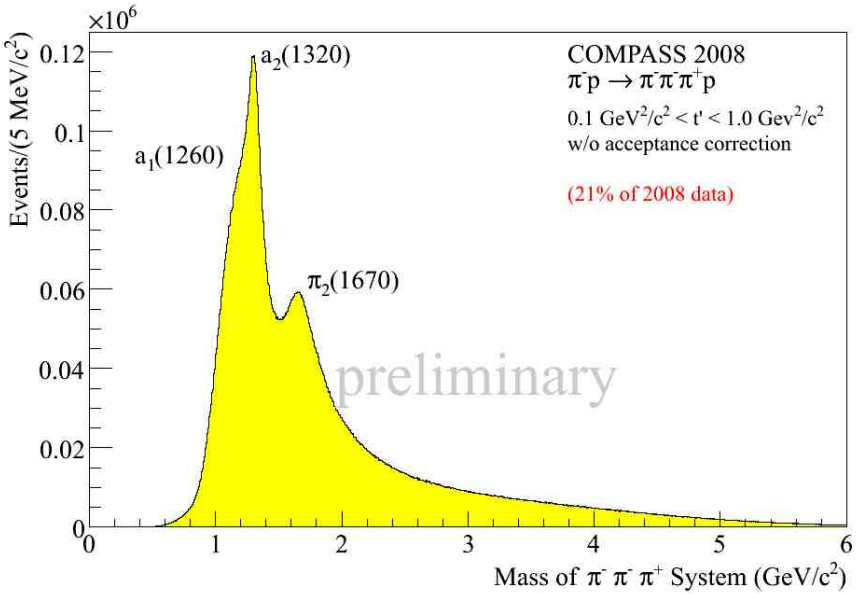
- 190 GeV/c hadron beam $\rightarrow$ 96%π^-, 3.5%K^-, 0.5%$\bar{p}$
- 40cm liquid hydrogen target
- exclusivity
- only high t' ($t' > 0.07\text{GeV}^2/c^2$) accessible in 2008

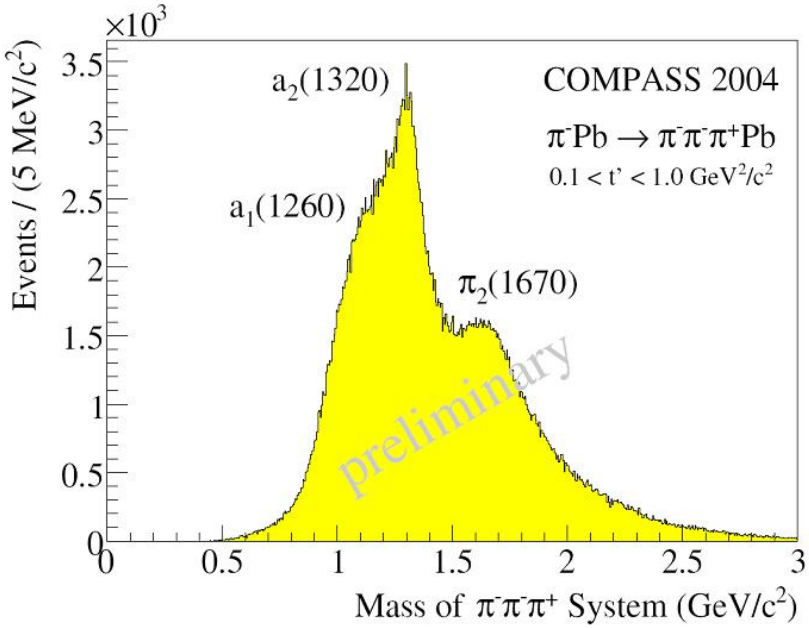




Ivariant Mass Spectrum of 3π Final States

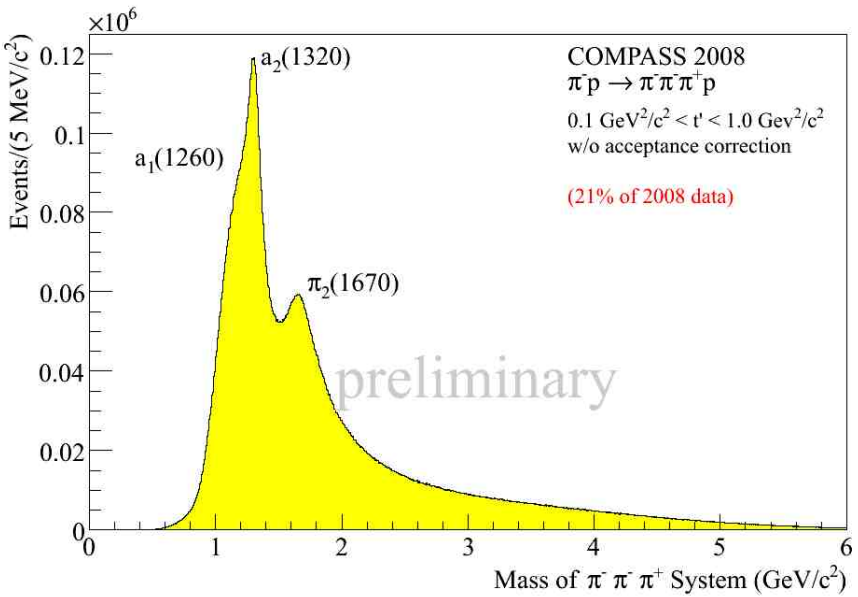
- 190 GeV/c hadron beam $\longrightarrow$ 96%π^-, 3.5%K^-, 0.5%$\overline{p}$
- 40cm liquid hydrogen target
- exclusivity
- $0.1\text{GeV}^2/c^2 < t' < 1.0\text{GeV}^2/c^2$

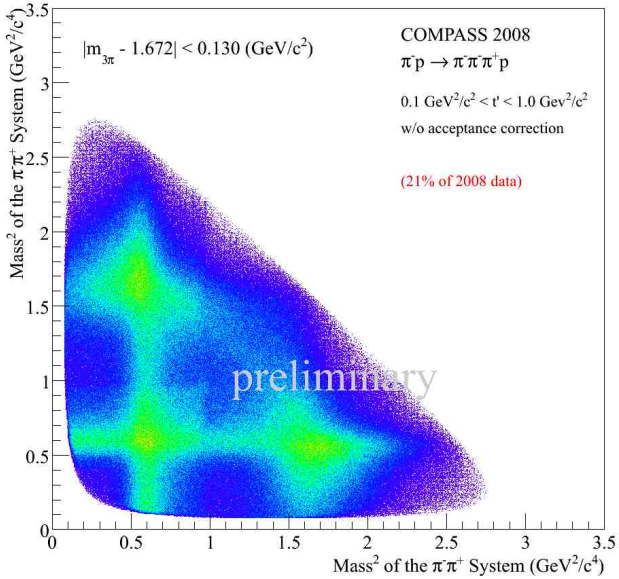




Diffractive Dissociation into 3π Final States

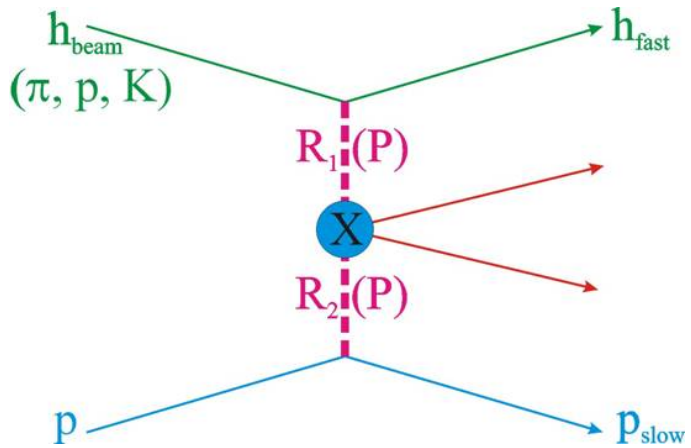
- 190 GeV/c hadron beam $\longrightarrow 96\%\pi^-, 3.5\%K^-, 0.5\%\overline{p}$
- 40cm liquid hydrogen target
- exclusivity
- $0.1\text{GeV}^2/c^2 < t' < 1.0\text{GeV}^2/c^2$
- 170k $\pi_1(1600)$ events expected

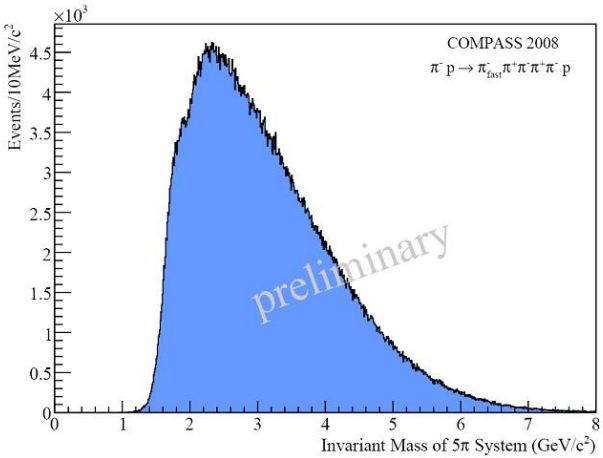


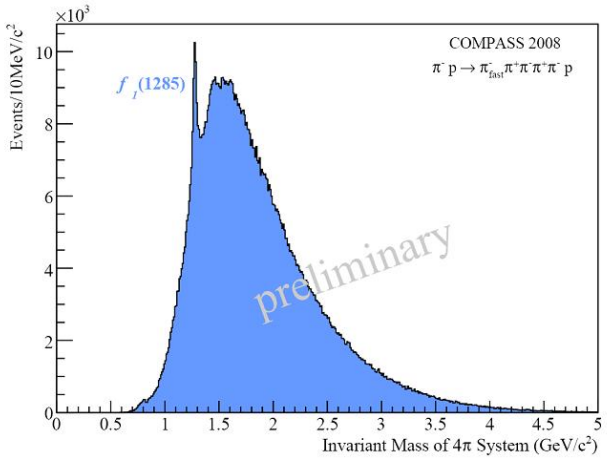


Central Production in COMPASS

- $\pi^- p \longrightarrow \pi^-_{fast} \pi^- \pi^+ \pi^- \pi^+ p$
- non-elastic but exclusive events
- target stays intact
- 1.06M events shown here







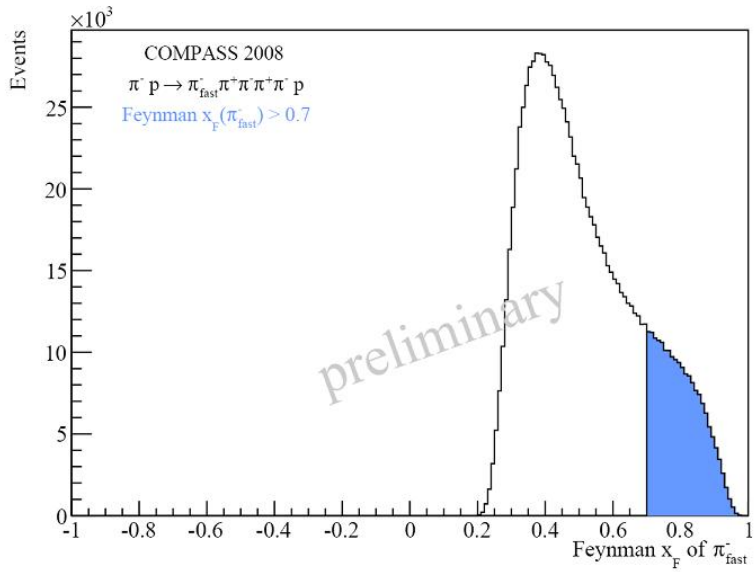
Central Production in COMPASS

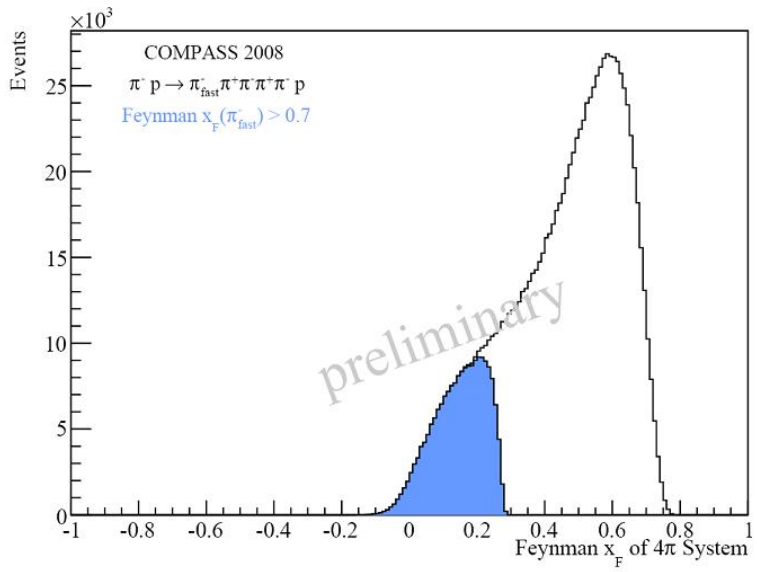
$$x_F = \frac{p_L}{p_L^{max}} \overset{CMS}{=} \frac{2p_{L,cms}}{\sqrt{s}}$$

Selection of centrally produced events:

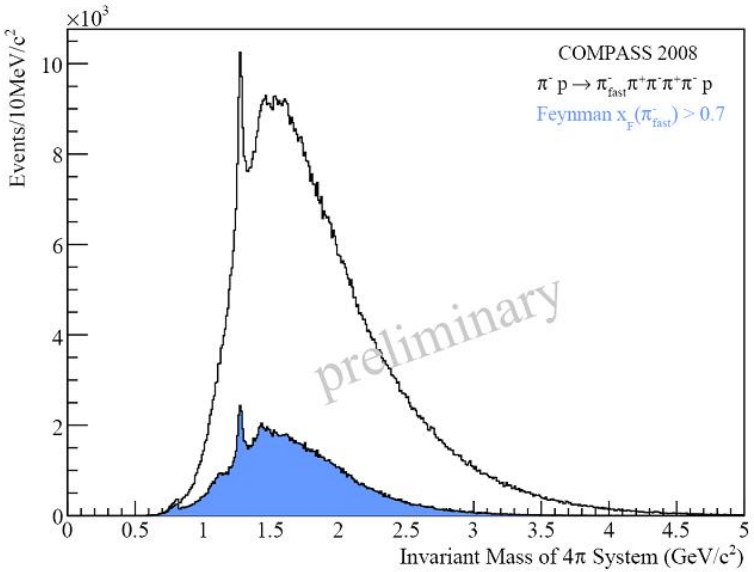
$\Rightarrow$ Cut on x_F of π^-_{fast}

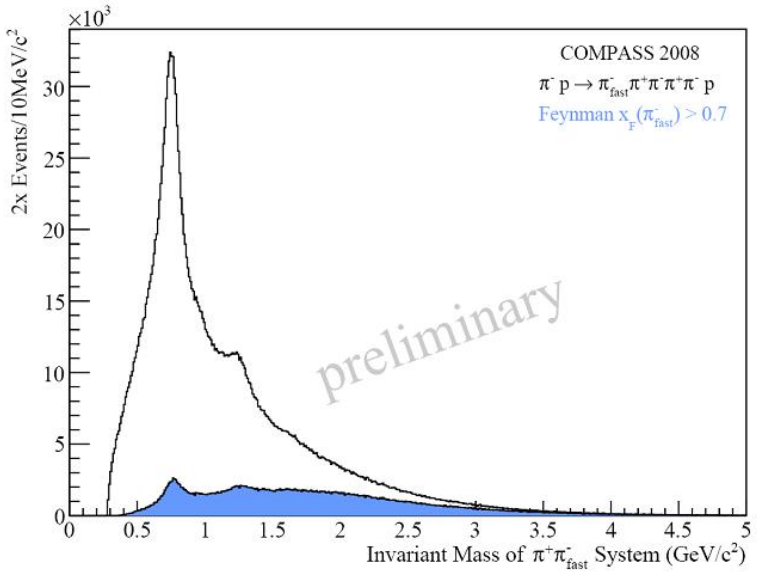
remaining events: 190k





Invariant Mass of Subsystems





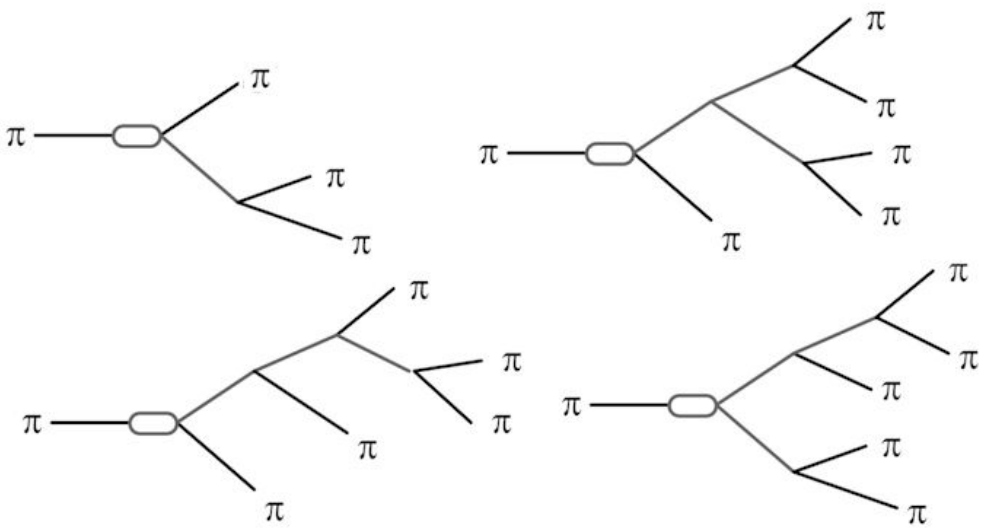
Further Analysis

- Diffractive Dissociation into $\pi^-\pi^0\pi^0$ Final States
- Central Production into $\pi^-\pi^0\pi^0$ and $\pi^-\eta\eta$ Final States
- Diffractive Dissociation of $K^-p \longrightarrow K^-\pi^-\pi^+p$ Final States
- $\pi^-p \longrightarrow \pi^-K^0_SK^0_Sp$ and $\pi^-p \longrightarrow \pi^-K^+K^-p$ Final States

- Pilot Run 2004
  - significant amount of data in few days of data taking
  - **strong signal in exotic wave 1^{-+} at 1.7 GeV/c**
- COMPASS 2008/2009
  - spectrometer upgrade:
    $\rightarrow$CEDARS, liquid hydrogen target, RPD, additional Silicons, PixelGEMs, ECALs
  - Diffractive reactions: 10x BNL E852 statistics
  - Central reactions: 10x WA102 statistics
  - analysis on charged, neutral and kaonic final states
- two independent PWA programs

Backup

Interesting Candidate



$\pi_1(1600)\ 1^-1^{-+}$

- $(2\pi)^0\pi^-$: $\rho\pi^-$, $f_2(1270)\pi^-$
- $(4\pi)^0\pi^-$: $b_1(1235)\pi^-$, $f_1(1285)\pi^-$
- $\eta'(958)\pi^-$

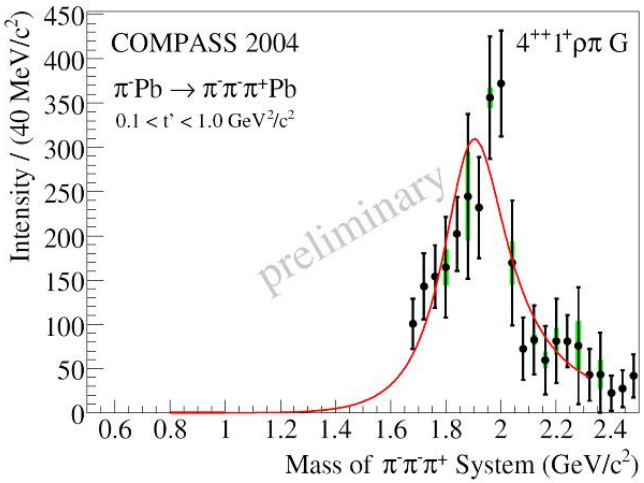
COMPASS has access to all of these decay modes

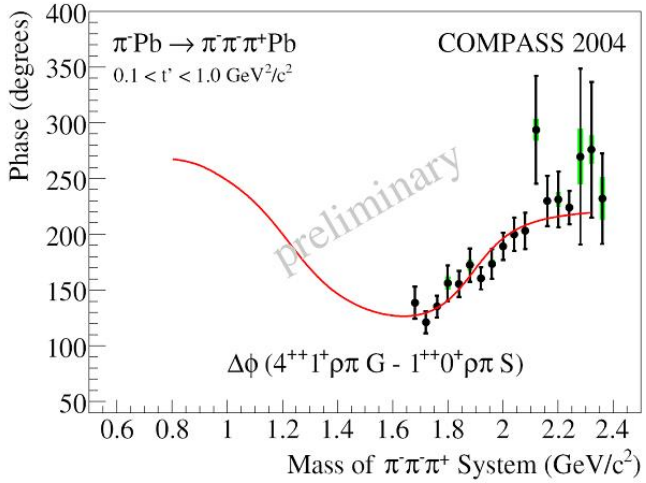
Wave Set of 2004 3π PWA

$J^{PC}M^{\epsilon}$	L	Isobar π	Thresh. [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	Thresh. [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			

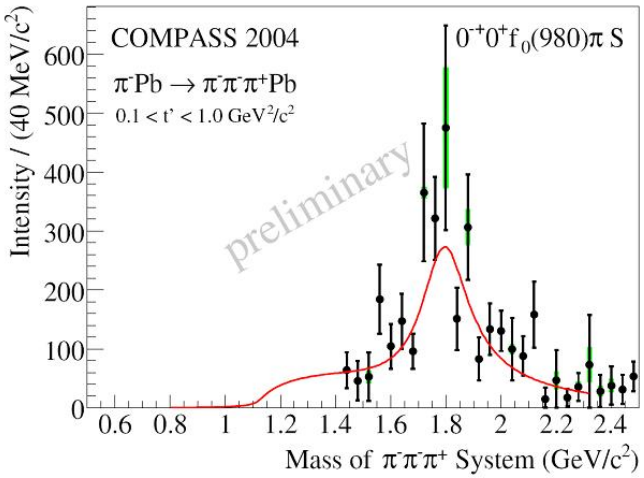
$a_4(2040)$

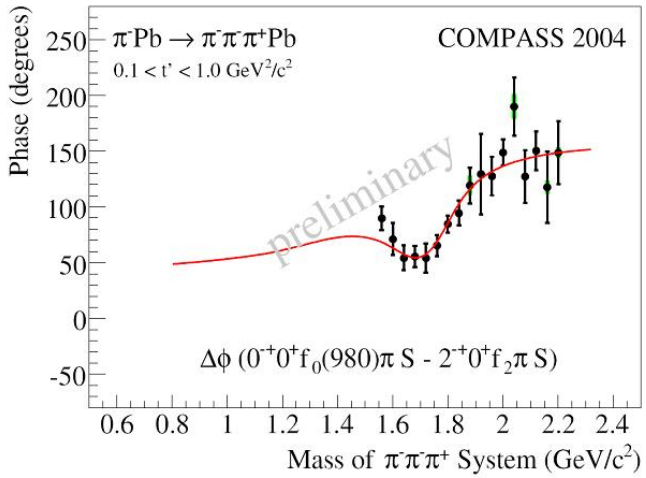




- Constant width BW used for $a_4(2040)$(branching ratios not known)
- BW parameters
  $M = \left(1885 \pm 13^{+50}_{-2}\right)\text{MeV}/c^2$
  $\Gamma = \left(294 \pm 25^{+46}_{-19}\right)\text{MeV}/c^2$

$\pi(1800)$





- Constant width BW used for $\pi(1800)$ and low-mass background
- BW parameters
  $M = \left(1785 \pm 9^{+12}_{-6}\right)\text{MeV}/c^2$
  $\Gamma = \left(208 \pm 22^{+21}_{-37}\right)\text{MeV}/c^2$