Meson production from diffractive pion dissociation at COMPASS

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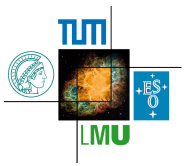
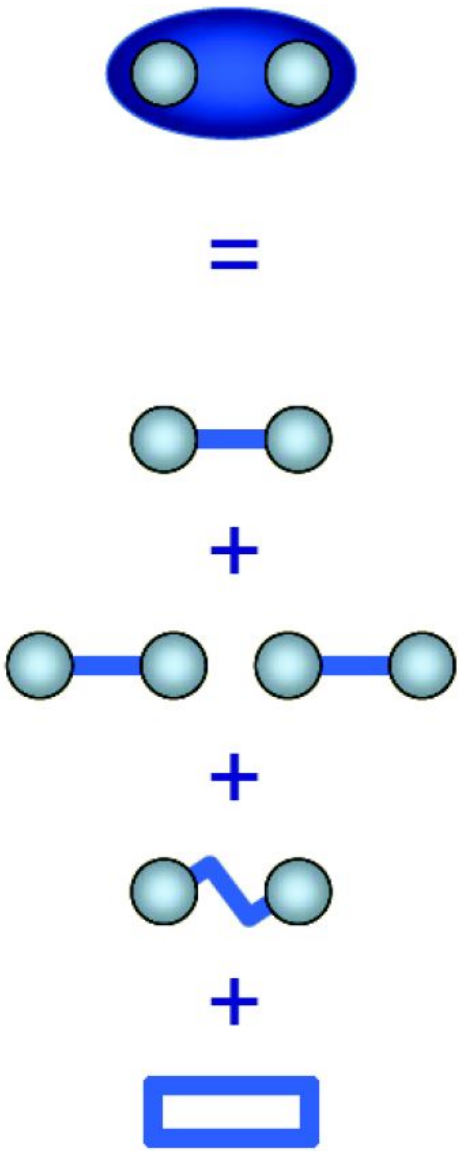


Outline



Constituent Quark Model

- Color-neutral $q\bar{q}$ systems
- Quantum numbers $I^G J^{PC}$
- $P = (-1)^{L+1}$ $C = (-1)^{L+S}$ $G = (-1)^{I+L+S}$
- J^{PC} Multiplets: $0^{++}, 0^{-+}, 1^{--}, 1^{+-}, 1^{++}, 2^{++}, \ldots$
- Forbidden: $0^{+-}, 1^{-+}, 2^{+-}, 3^{-+}, \ldots$

QCD: Additional color-neutral objects

- Tetraquarks $(q\bar{q})(q\bar{q})$
- Hybrids $(q\bar{q})g$
- Glueballs gg

Spin Exotic States

- J^{PC} forbidden $\Rightarrow$ cannot be a $q\bar{q}$ state
- No mixing with quark model states

Lightest Glueballs

- QCD predictions:

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

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

  $f_0(1500)$ $(J^{PC} = 0^{++})$

  (Crystal Barrel, WA102)

  $\longrightarrow$ mixing with isoscalar mesons!

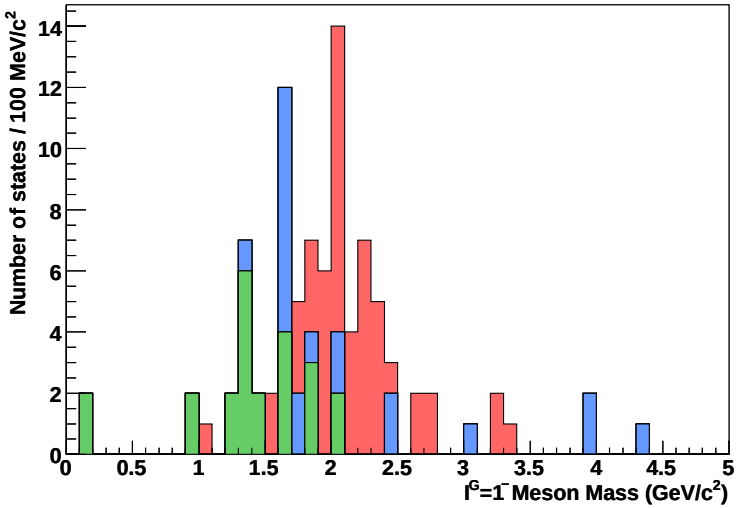
Hybrids

Light meson sector:

Spin-exotics $J^{PC} = 1^{-+}$

- $\pi 1(1400)$ (VES, E852, Crystal Barrel)
- $\pi 1(1600)$ (E852, VES)

Still controversial!



Meson states with $I^G = 1^-$ listed in the PDB.
Green = established,
blue = need confirmation,
red = “further states”.

The histogram is stacked.

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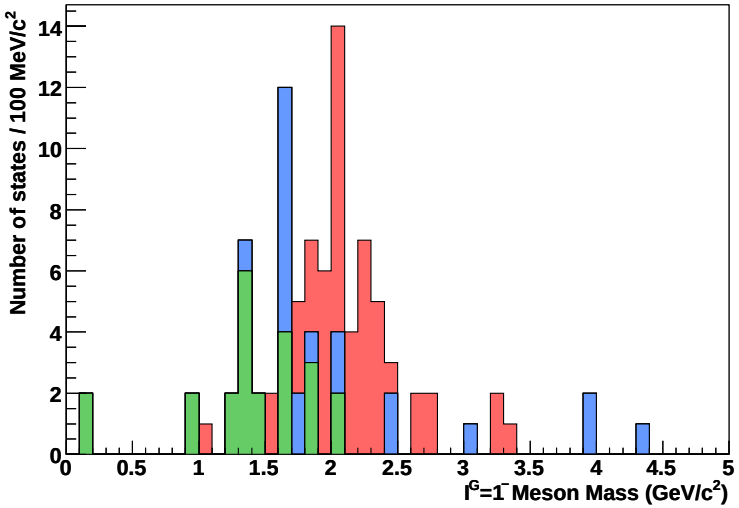

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Meson Spectroscopy and Search for **Spin-Exotic States** (non-$q\bar{q}$)

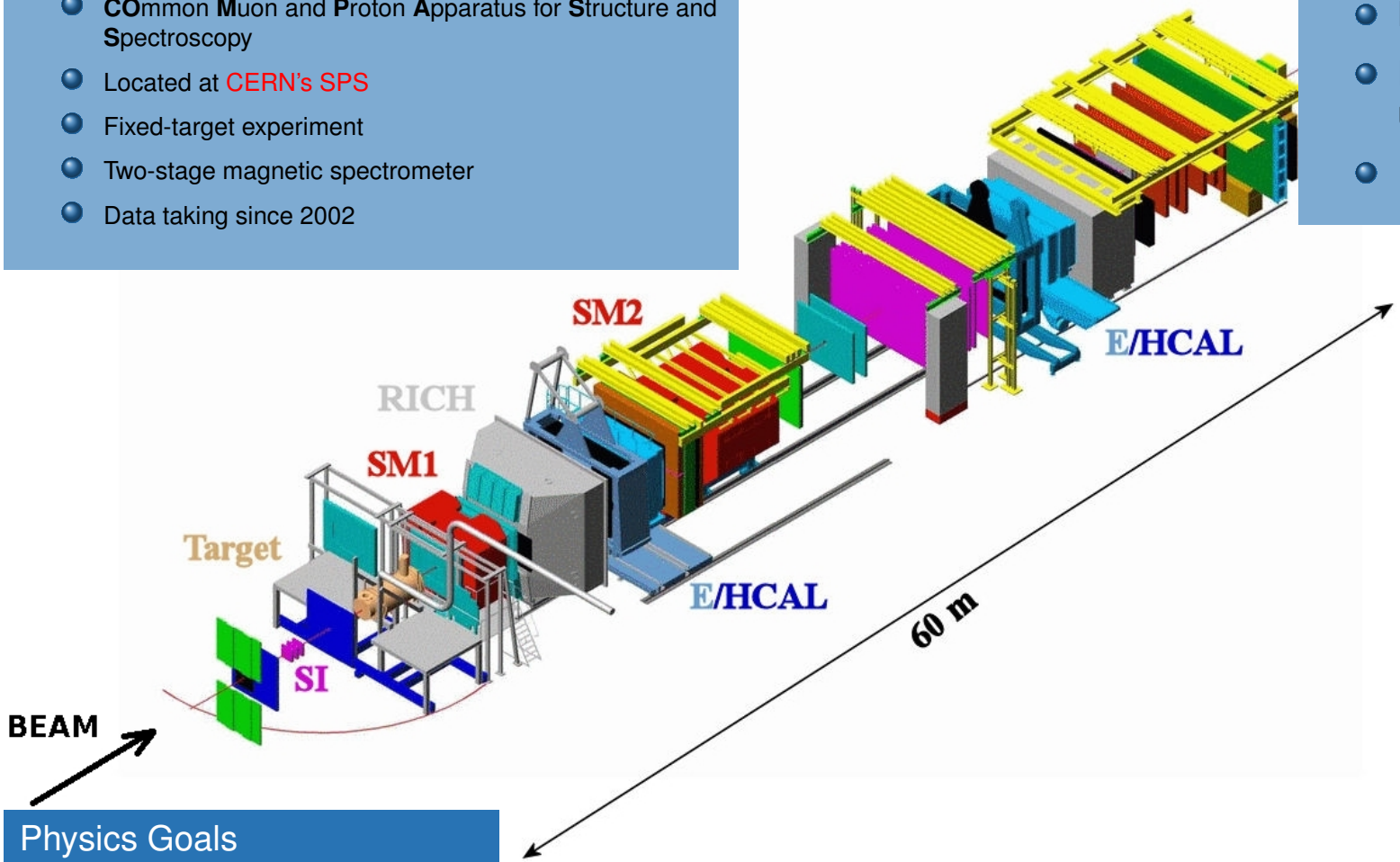
- **COMPASS can contribute significantly in the low mass region**

Overview

- **CO**mmon **M**uon and **P**roton **A**pparatus for **S**tructure and **S**pectroscopy
- Located at CERN's SPS
- Fixed-target experiment
- Two-stage magnetic spectrometer
- Data taking since 2002

Second./Tert. SPS Beams

- Muons: $4 \cdot 10^7 s^{-1}$
- Hadrons: up to $2 \cdot 10^7 s^{-1}$
- 100-250 GeV



Physics Goals

- Nucleon spin structure
- Hadron spectroscopy

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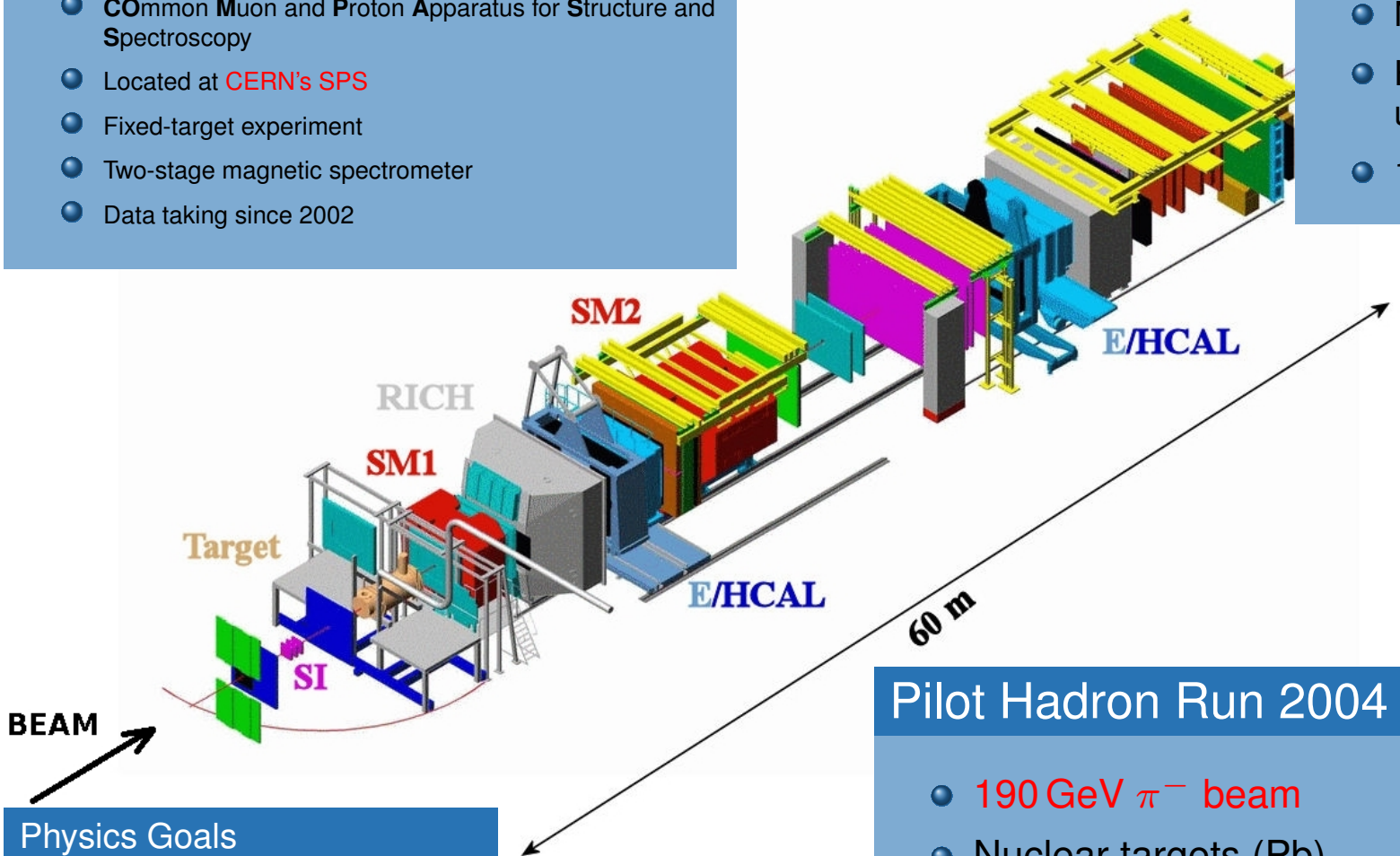


Pilot Hadron Run 2004

- 190 GeV π^- beam
- Nuclear targets (Pb)
- Tracking: Silicons for vertexing
- Trigger: Multiplicity trigger, ECAL trigger

Physics Goals

- Nucleon spin structure
- Hadron spectroscopy

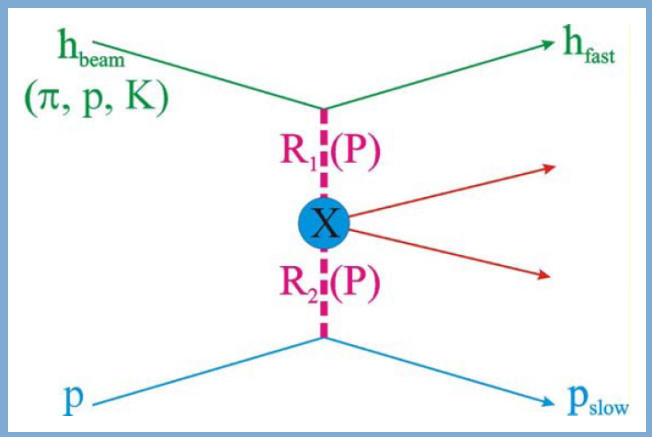
Challenges and Opportunities in the light (u,d) Quark Sector

- High density of states; broad, overlapping states
- Exploit interference effects $\rightarrow$ phase motion
- Requires high statistics, complete PS coverage $\rightarrow$ COMPASS

COMPASS

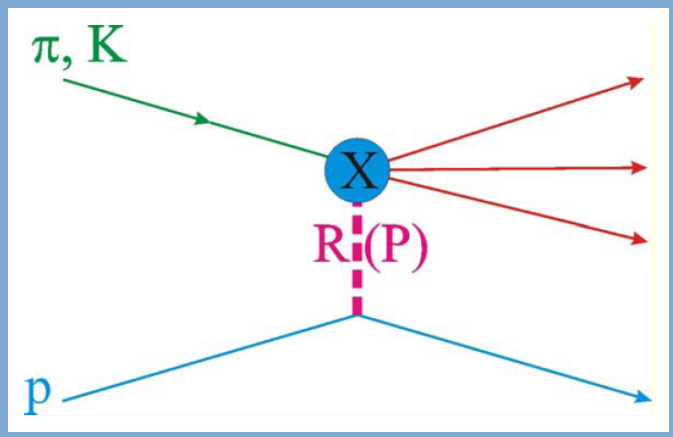
- Positive and negative beams (p, π, K) at variable energies
- Several decay modes accessible (neutral, kaonic, . . .)

Central production



(→ J. Bernhard)

Diffractive Dissociation



this talk!

Diffractive Production of Mesons

- Diffraction: target particle remains intact
  Reggeon t-channel exchange
  Assumptions: Factorization of meson and Pb vertex, no final state interaction

- Dissociation: beam pion is excited to a resonance X^-, which subsequently decays
  $\Rightarrow$ e. g. $\pi^- \mathrm{Pb} \rightarrow X^- \mathrm{Pb} \rightarrow \pi^-\pi^-\pi^+ \mathrm{Pb}$
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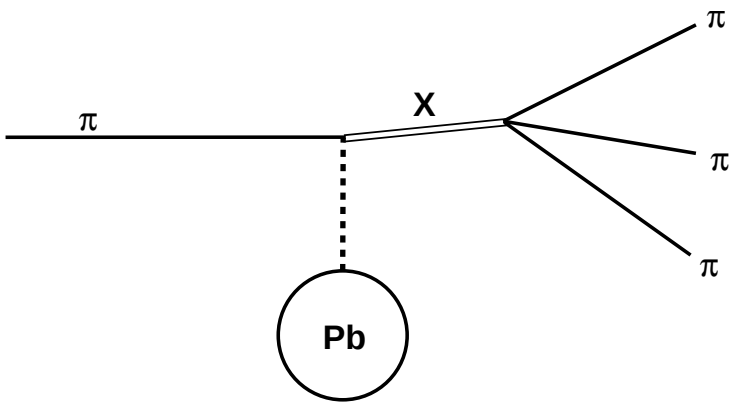
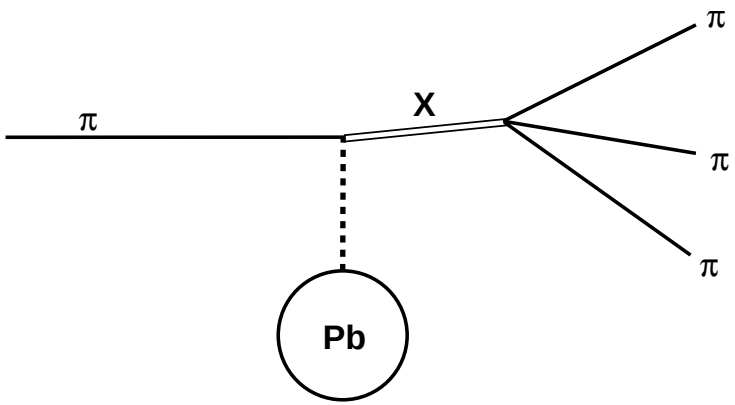


Diffractive Production of Mesons



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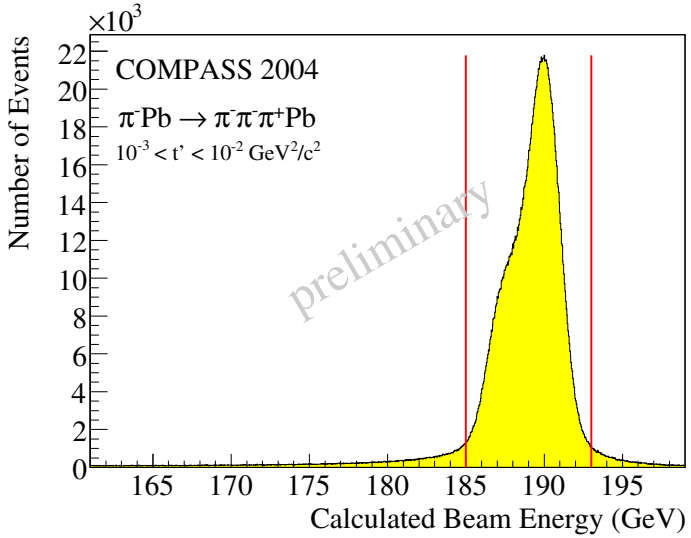
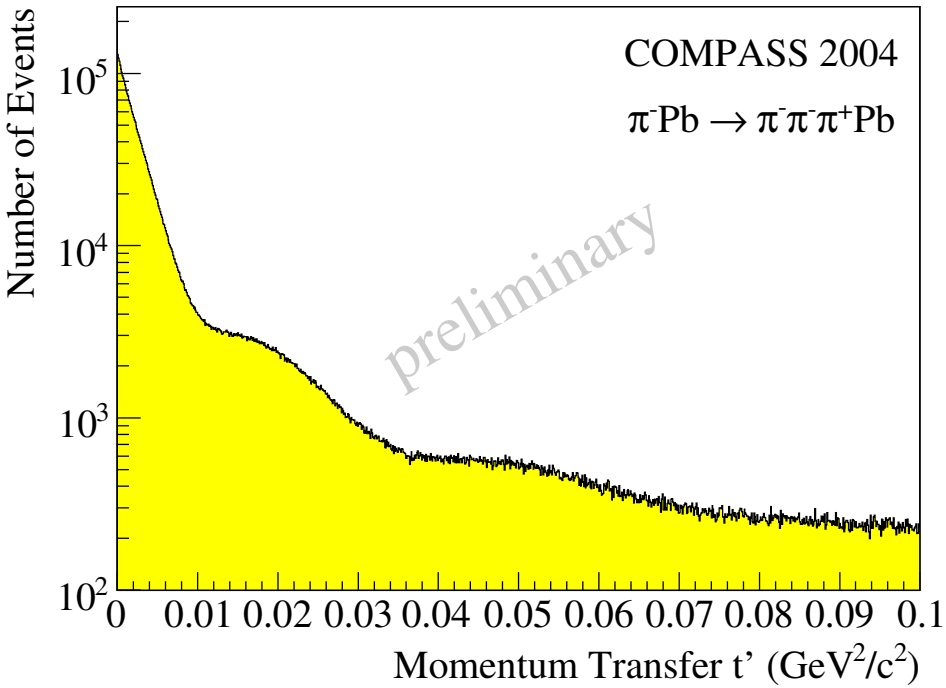
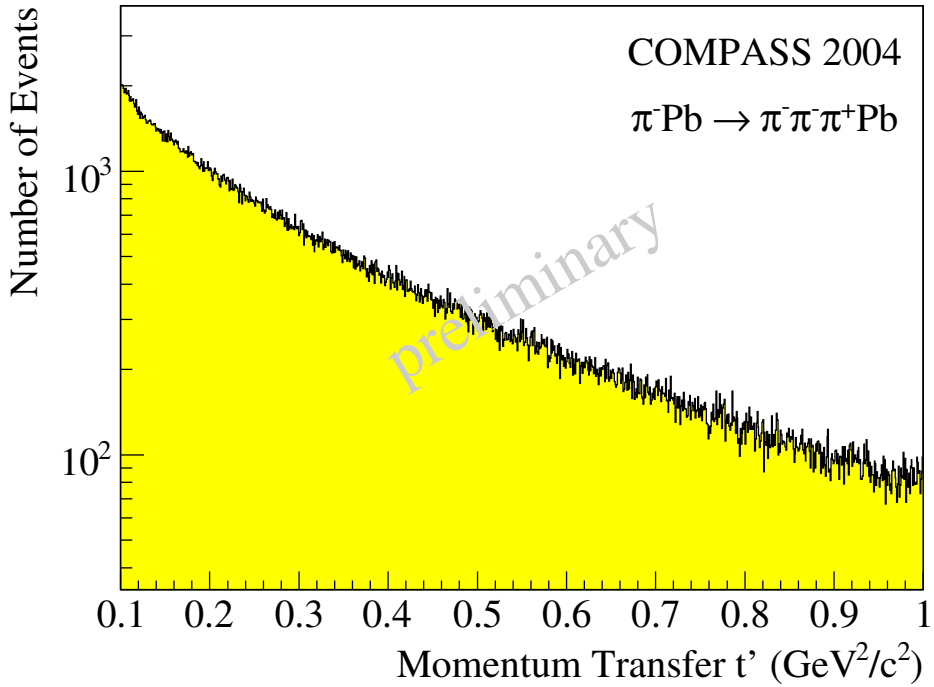
- Exclusive 3π or 5π final state events (pion hypothesis).
- COMPASS 2004 (few days of data taking):
  - $\sim$ 4 000 000 3π events
    $\sim$ 400 000 events enter analysis (BNL: 250 000)
  - $\sim$ 380 000 5π events



Momentum transfer from target: $-t = -(p_{\text{beam}} - p_{(\pi^-\pi^-\pi^+)})^2$

$\Rightarrow t' = |t| - |t|_{min}$

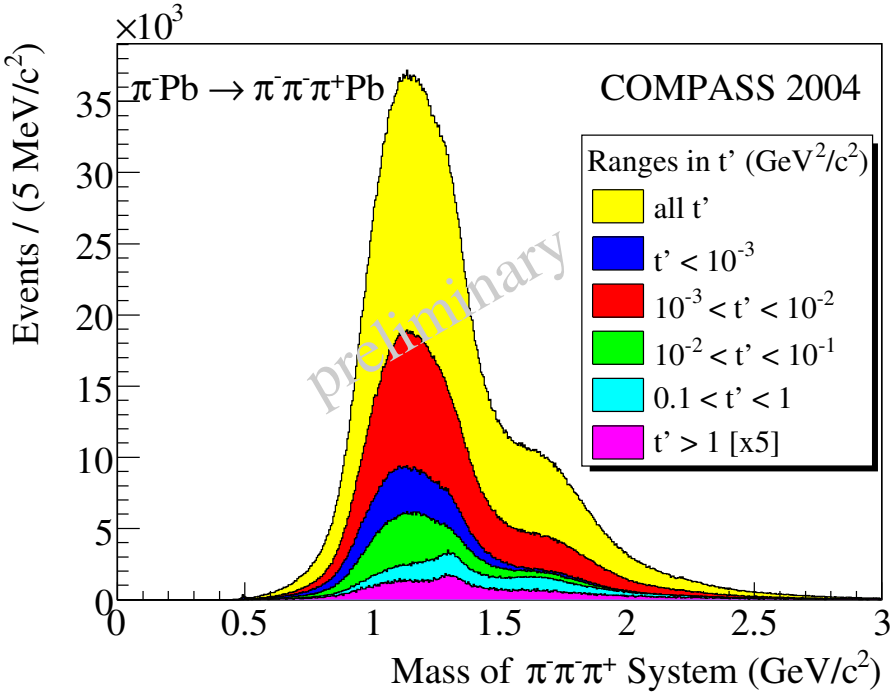




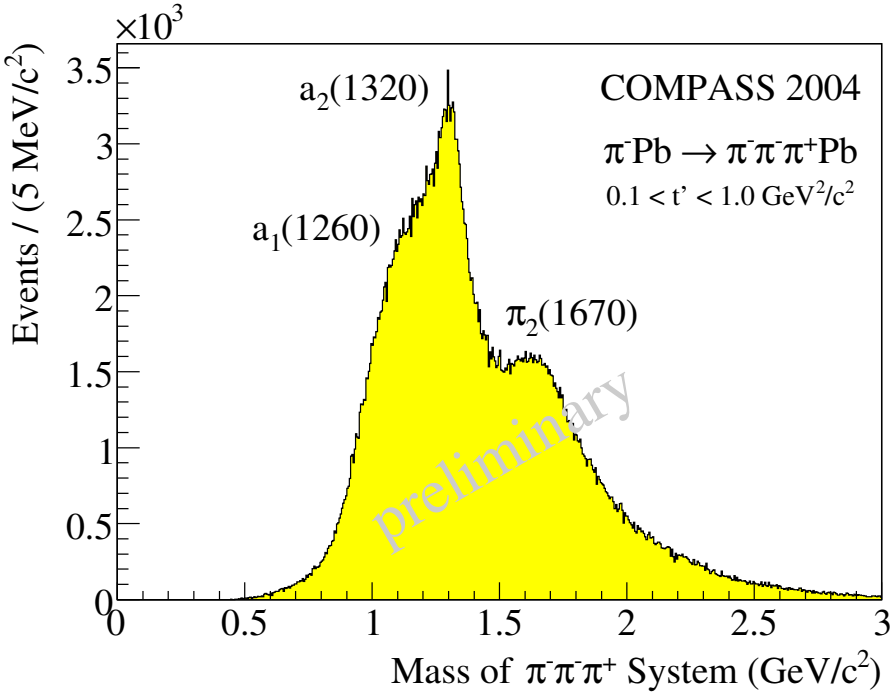
Diffraction pattern: Pb nucleus acts like "black disc" in optics

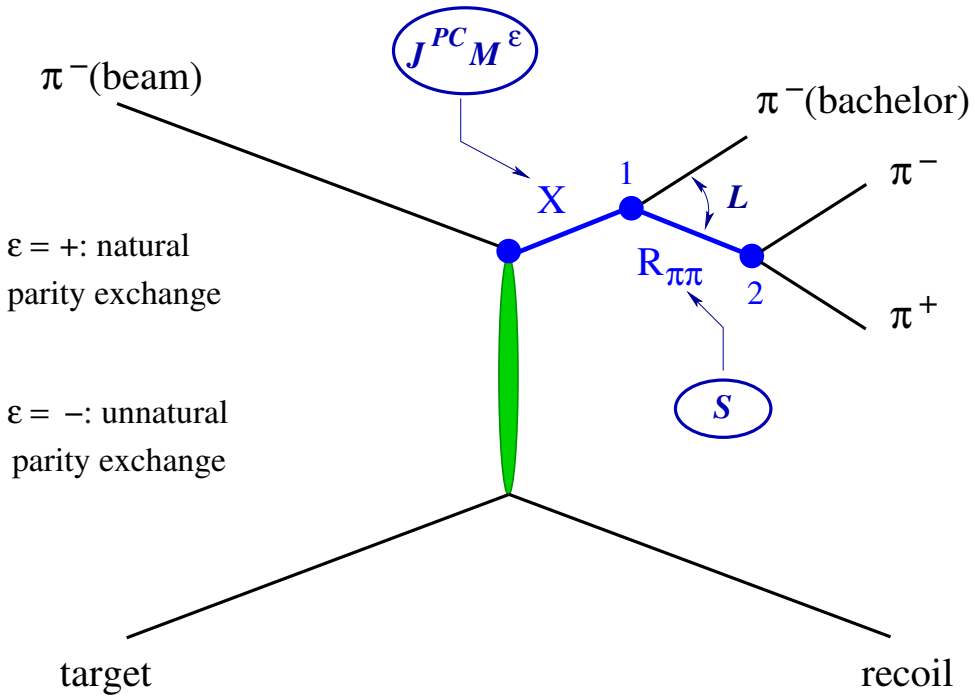
High-t': scattering on single nucleons inside Pb nucleus

Different t' Ranges



High-t' Spectrum





- Isobar model: Intermediate 2-particle decays
- Zemach / Helicity formalism, reflectivity basis
- Reggeon exchange
- Partial wave: $J^{PC}M^{\epsilon}[isobar]L$
- Nucleon target $\Rightarrow$ rank 2

- Mass-independent PWA (40 MeV/c^2 mass bins): 42 waves
  - Extended log-likelihood method
  - Acceptance corrections included
  - $\rho(770)$, $f_2(1270)$, $\rho_3(1690)$ from PDG, $(\pi\pi)_s$ with separated $f_0(980)$ from VES
- Mass-dependent χ^2-fit: 6 waves
  - X parameterized by Breit-Wigner (BW) functions
  - Coherent background added for some waves: $\exp(-\alpha p^2)$

Partial Wave Set for Mass-Independent Fit (42 Waves)

Description of possible Decay Amplitudes

$J^{PC}M^{\epsilon}$	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
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$3^{++}0^{+}$	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	$\rho\pi$	-
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FLAT			

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Waveset Features

- 41 Waves + Flat Background
- Isobars:
  - $(\pi\pi)_s$, $\rho(770)$, $f_0(980)$, $f_2(1270)$, ρ_3
- Larger waveset than all previous analyses

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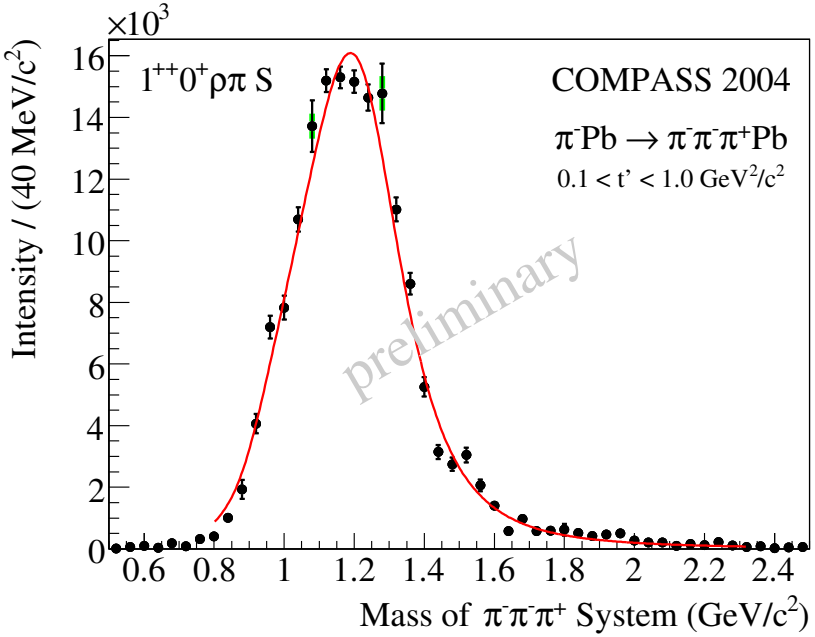
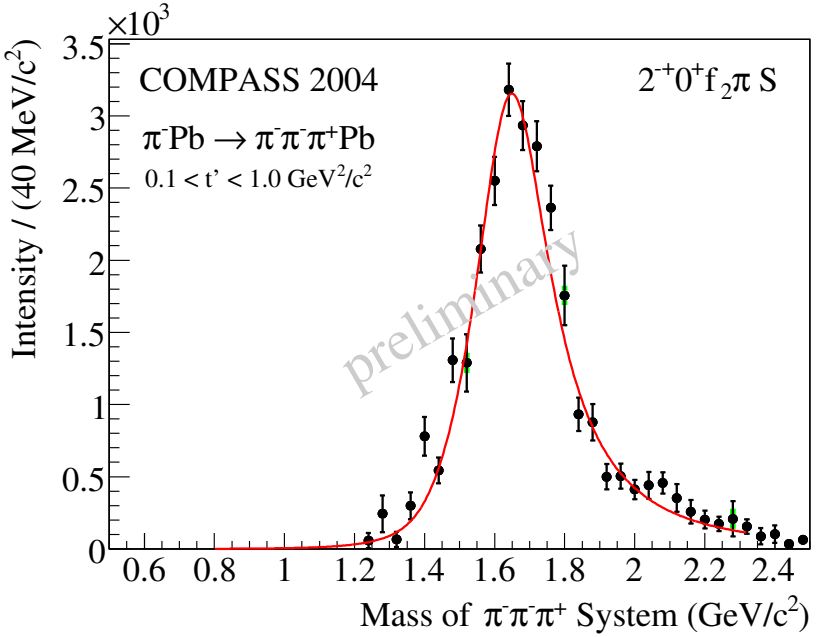
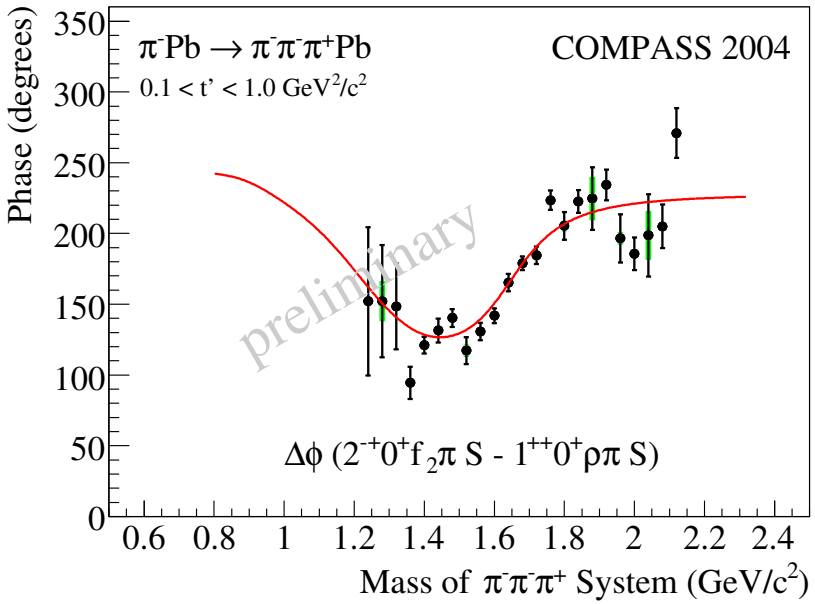






- BW for $a_1(1260)$ + background:

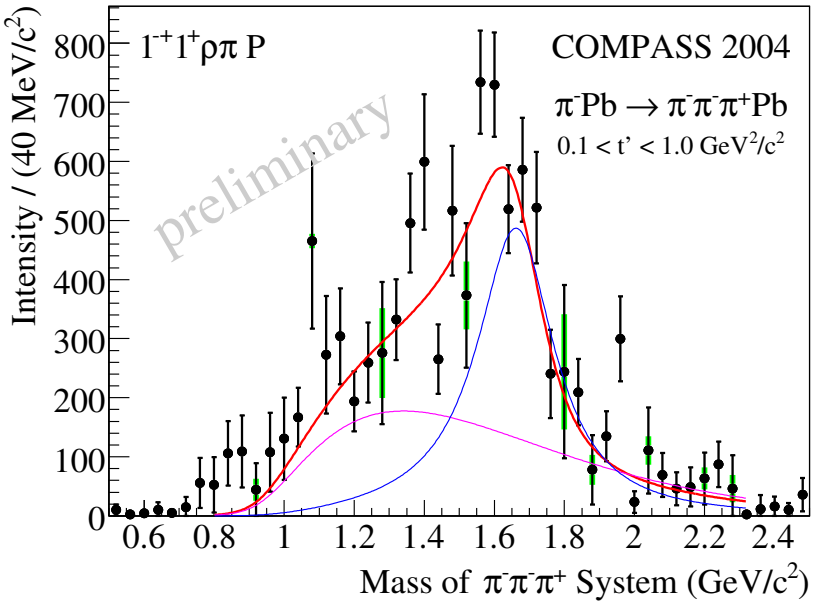
  $M = (1.255 \pm 0.006\ ^{+0.007}_{-0.017})\ \mathrm{GeV/c^2}$

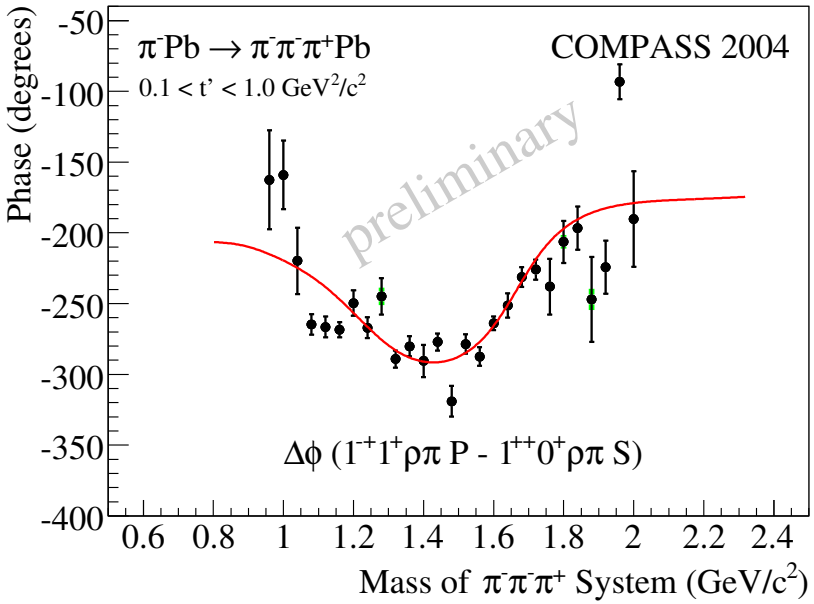
  $\Gamma = (0.367 \pm 0.009\ ^{+0.028}_{-0.025})\ \mathrm{GeV/c^2}$

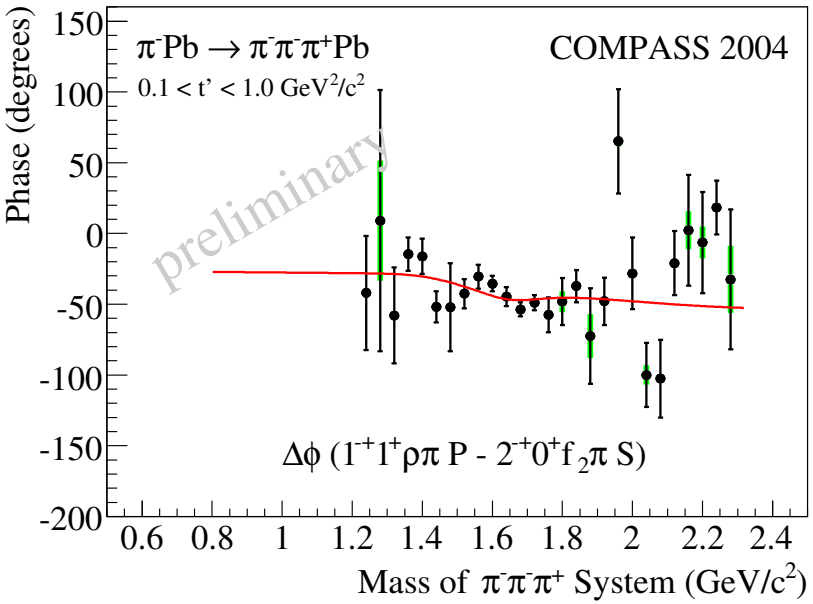
- BW for $\pi_2(1670)$:

  $M = (1.658 \pm 0.003\ ^{+0.024}_{-0.008})\ \mathrm{GeV/c^2}$

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







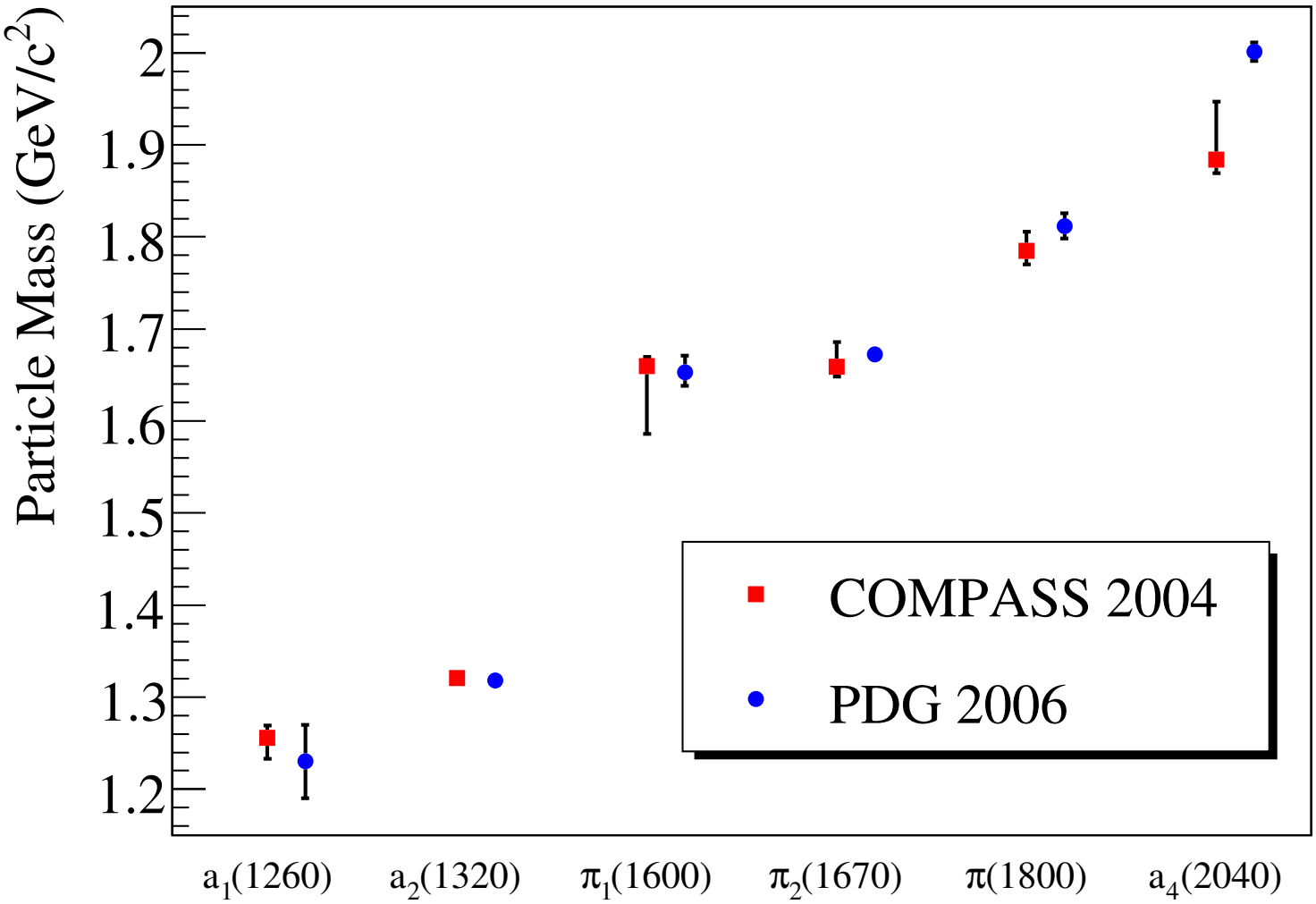
- Significant 1^{-+} amplitude consistent with resonance at $\sim 1.7\,\mathrm{GeV}/c^2$
- No leakage observed ($< 5\%$)
- BW for $\pi_1(1600)$ + background:

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

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

Summary of Extracted States from $\pi^- \mathrm{Pb} \to X^- \mathrm{Pb} \to \pi^-\pi^-\pi^+ \mathrm{Pb}$

Comparison with PDG values



Motivation:

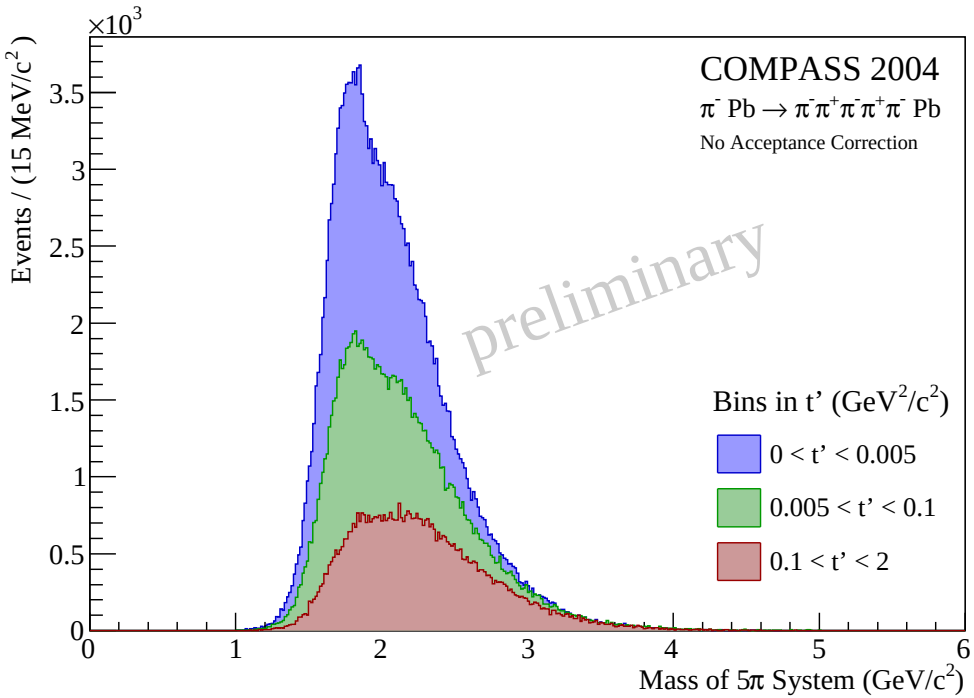
- Confirmation of hybrid with 1^{-+}
- Access to mass-range $> 2\,\mathrm{GeV}/c^2$
- Other interesting accessible quantum numbers:
  - $1^-(0^{++})$ not accessible in 3π!
  - $1^-(3^{-+})$ high J spin exotic?
- BNL: $\pi^- p \longrightarrow f_1\pi \longrightarrow \eta\pi^+\pi^-\pi^-$
  2 exotic 1^{-+} states

  (Kuhn et al., Phys. Lett. B, 595(2004)109)

$\pi_1(1^{-+})$ branching ratios

Flux-Tube model predictions:
(Page, Swanson, Szczepaniak, Phys. Rev. D59, 034016(1999))

m_{π_1}	$b_1\pi$	$f_1\pi$	$\eta'\pi$	$\rho(1450)\pi$
$1.6\,\mathrm{GeV}/c^2$	24:	5:	2	
$2.0\,\mathrm{GeV}/c^2$	43:	10:	27:	12



Motivation:

- Confirmation of hybrid with 1^{-+}
- Access to mass-range $> 2\,\mathrm{GeV}/c^2$
- Other interesting accessible quantum numbers:
  - $1^-(0^{++})$ not accessible in 3π!
  - $1^-(3^{-+})$ high J spin exotic?
- BNL: $\pi^- p \longrightarrow f_1\pi \longrightarrow \eta\pi^+\pi^-\pi^-$
  2 exotic 1^{-+} states

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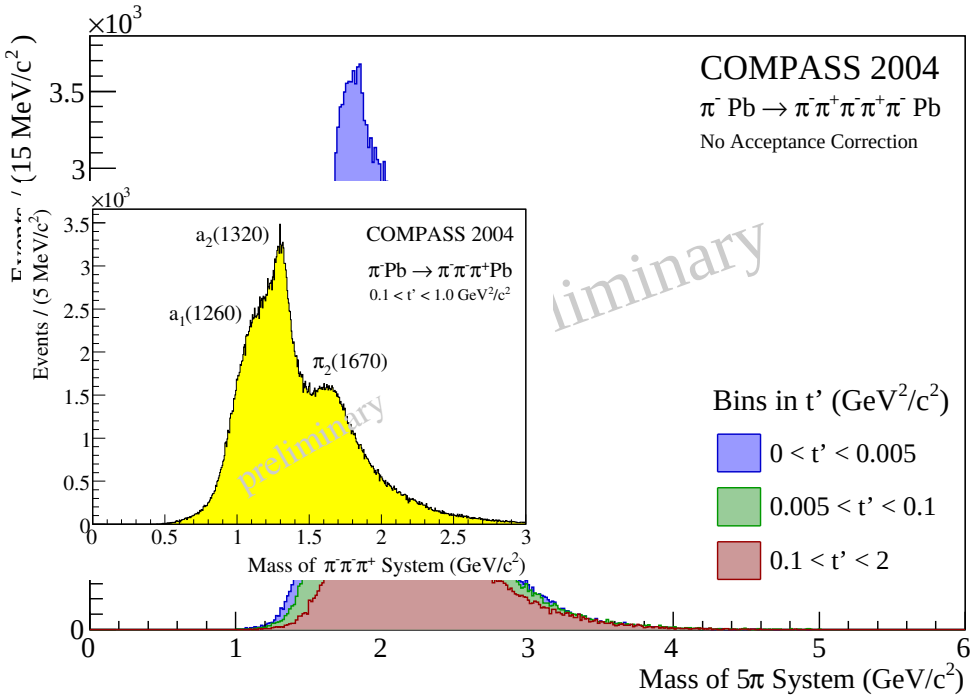
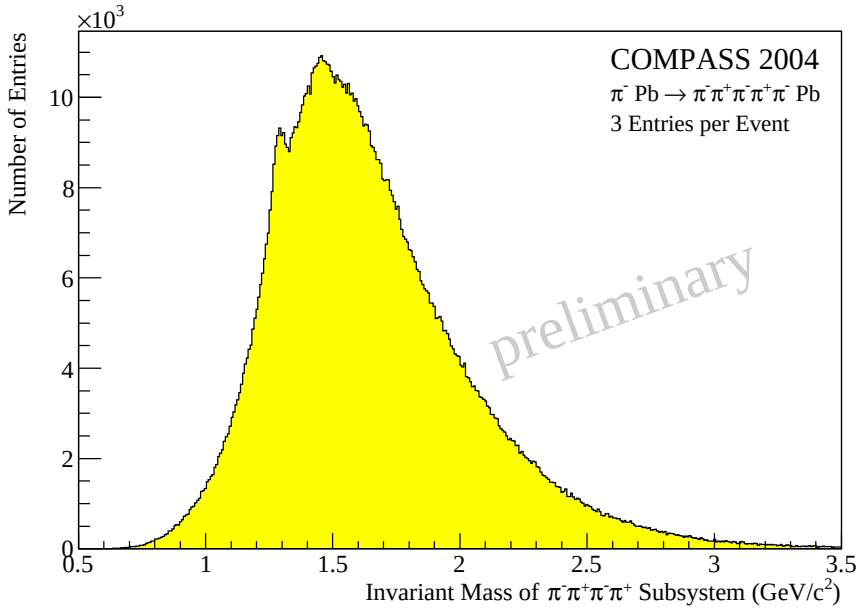
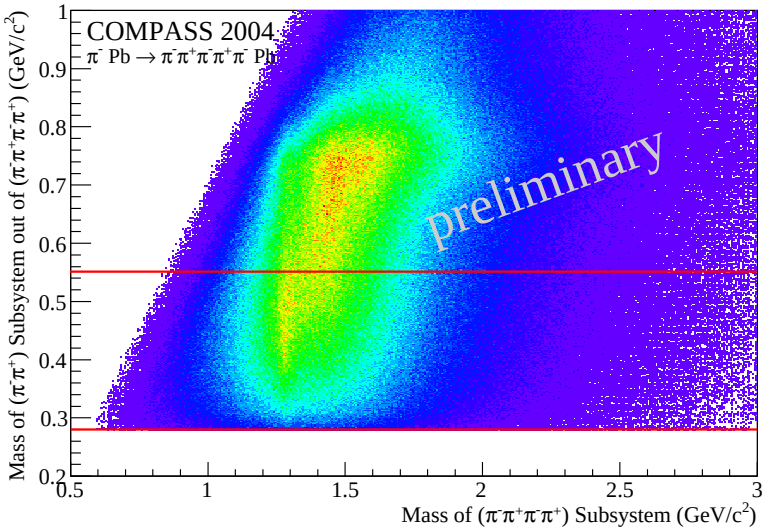


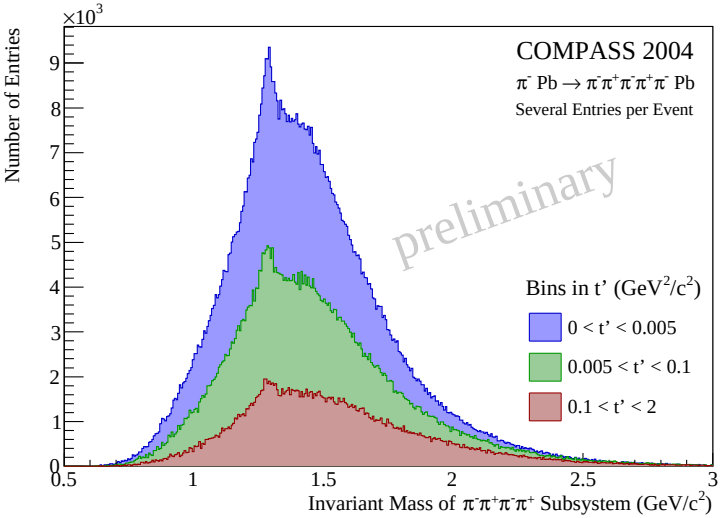
4π Subsystem – the f_1 and Friends

Isobar Candidates



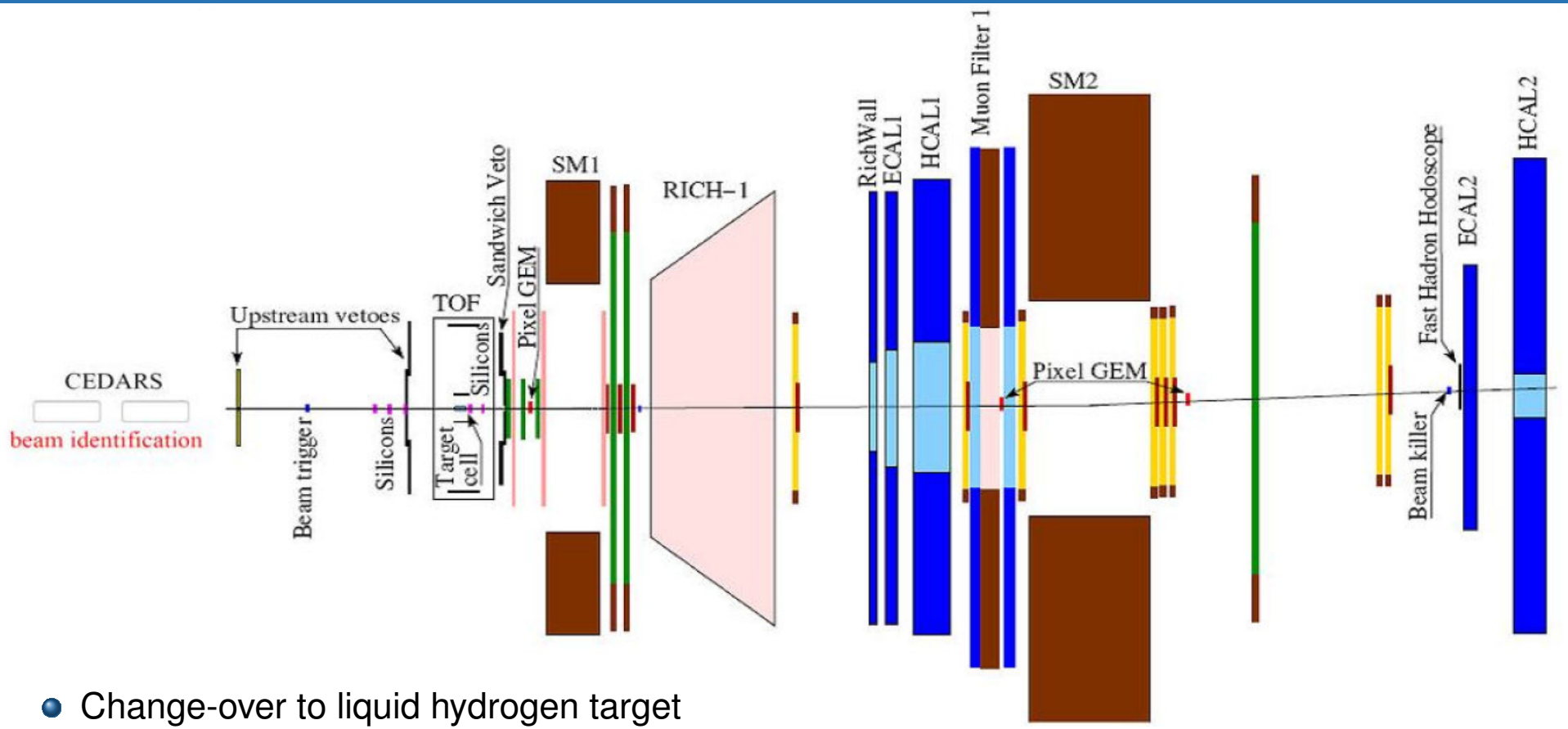


Cut 4π spectrum:

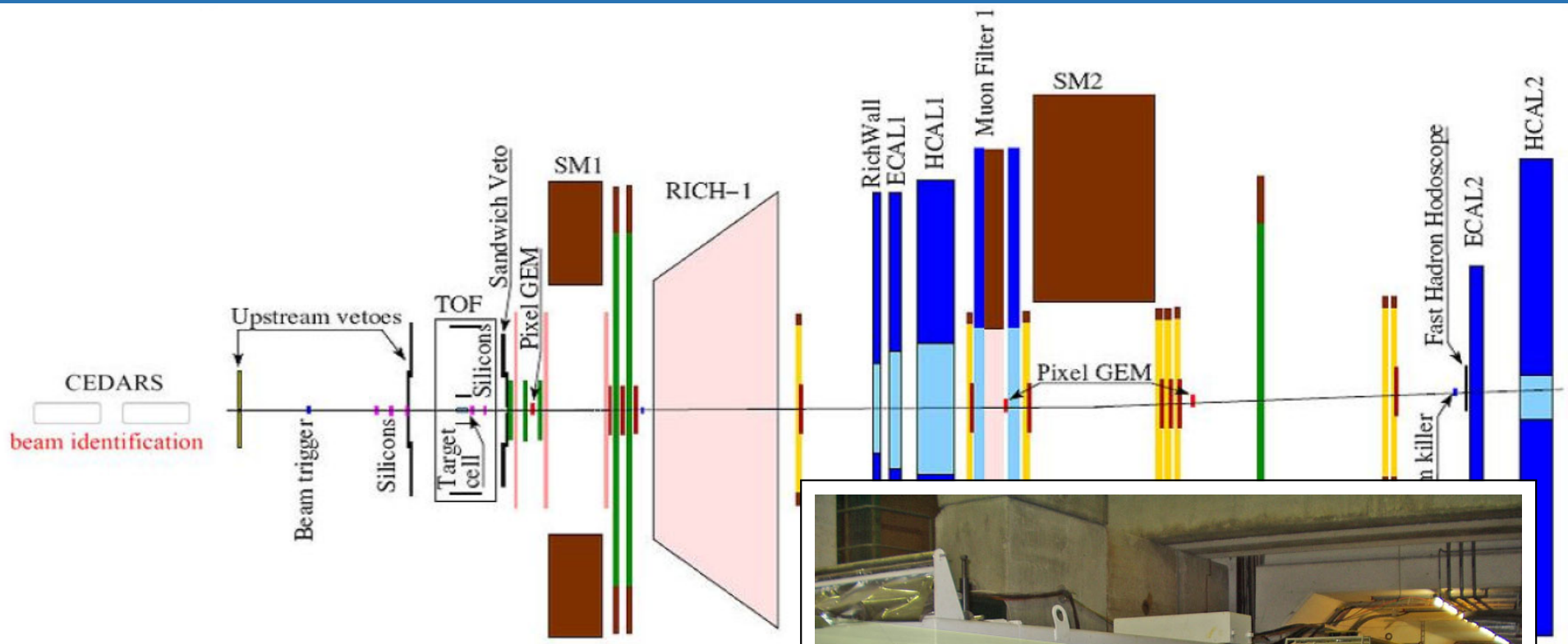


Isobar candidates:

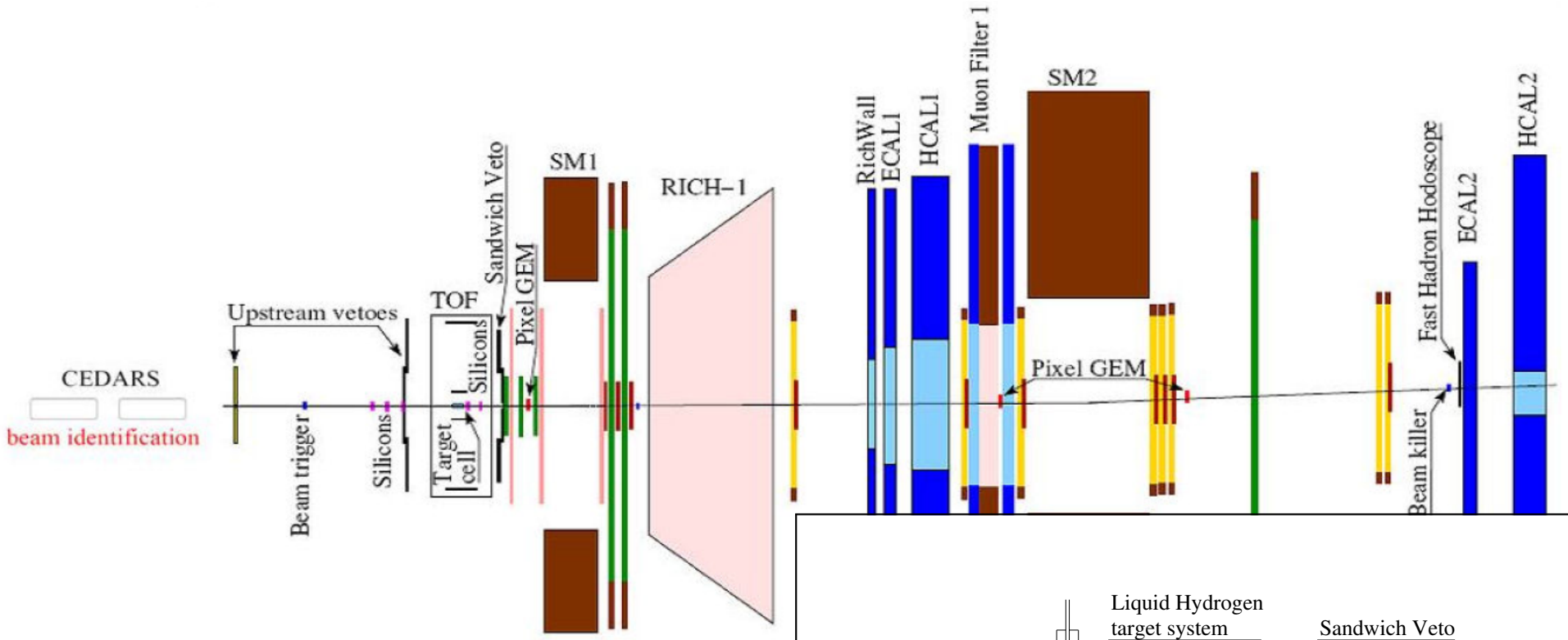
Name	Mass (GeV/c^2)	$I^G(J^{PC})$
f_0	1370 / 1700	$0^+(0^{++})$
η'	1403	$0^+(0^{-+})$
ρ'	1450	$1^+(1^{--})$
b_1	1235 / 1800	$1^+(1^{+-})$
f_1	1285 / 1450	$0^+(1^{++})$
η_2'	1645	$0^+(2^{-+})$
f_2	1565	$0^+(2^{++})$
ρ_3	1690	$1^+(3^{--})$



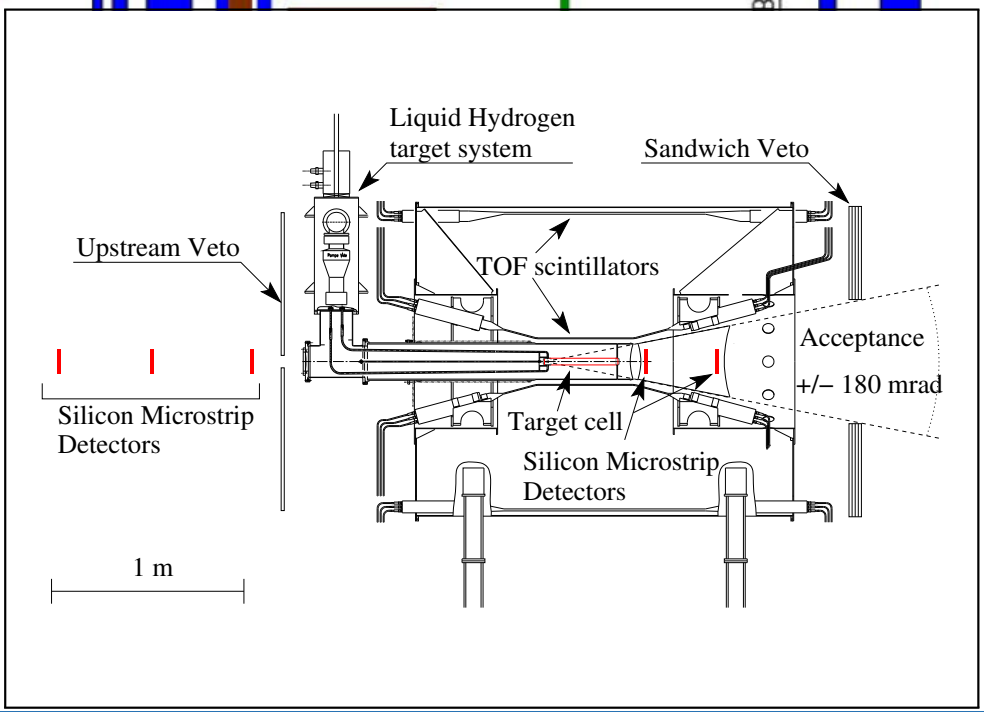
- Change-over to liquid hydrogen target
- Spectrometer upgrades:

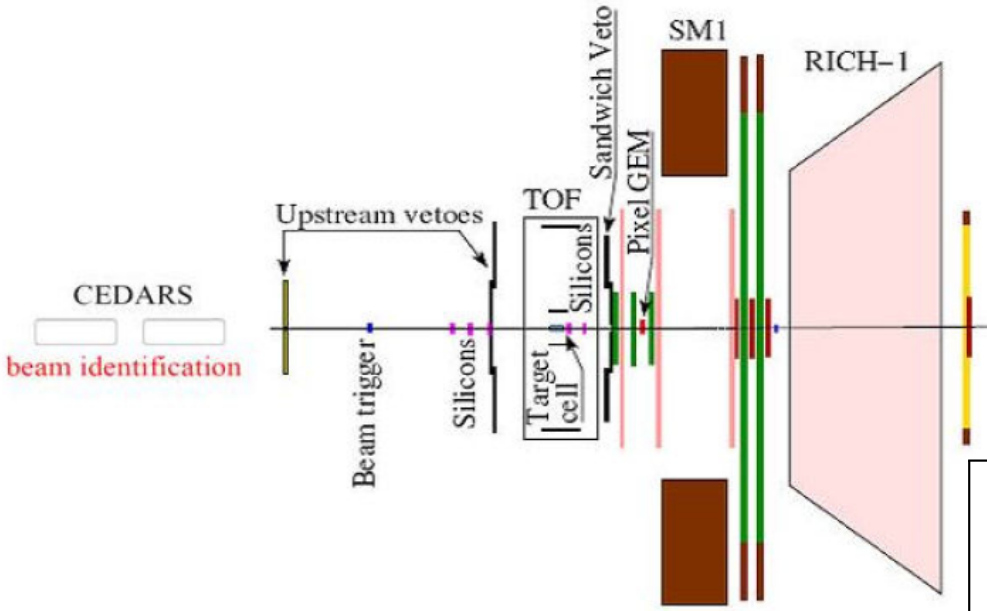


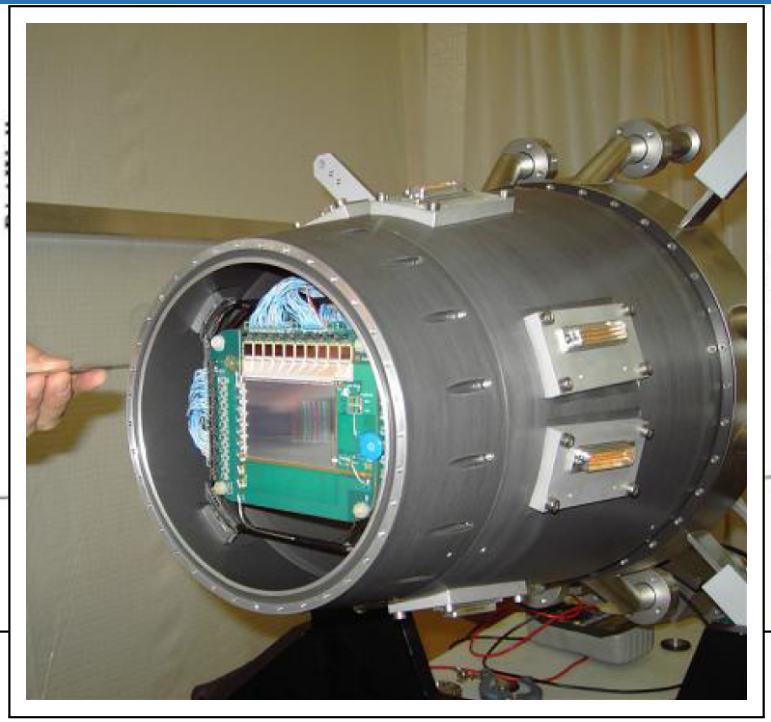
- Change-over to liquid hydrogen target
- Spectrometer upgrades:
  - CEDARs (→ P. Jasinski)



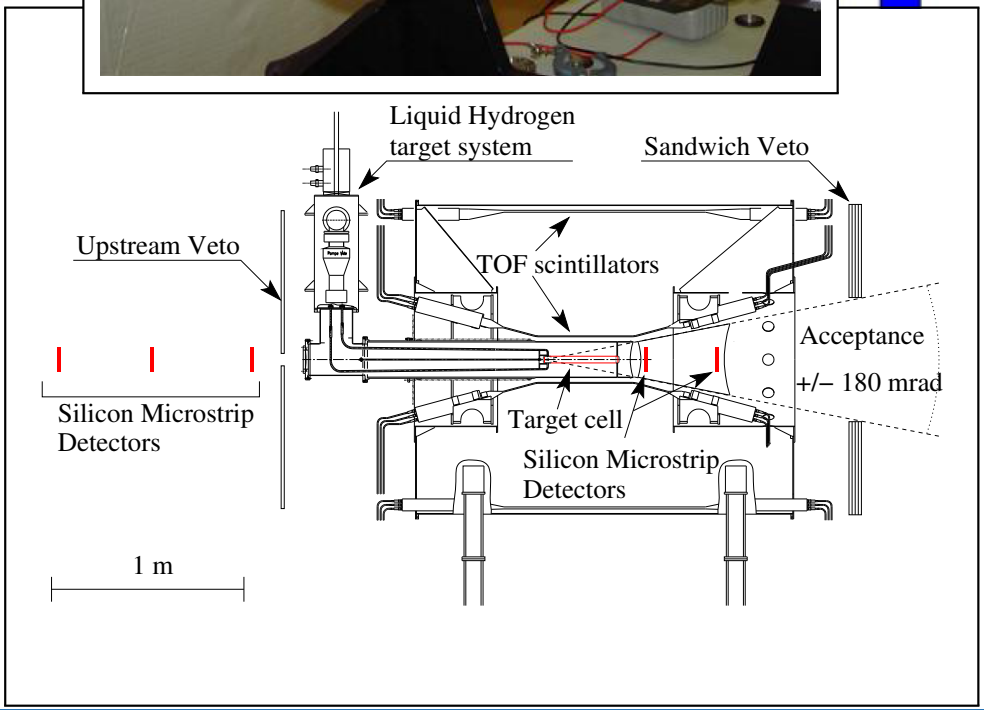
- Change-over to liquid hydrogen target
- Spectrometer upgrades:
  - CEDARs (→ P. Jasinski)
  - RPD (→ J. Bernhard)

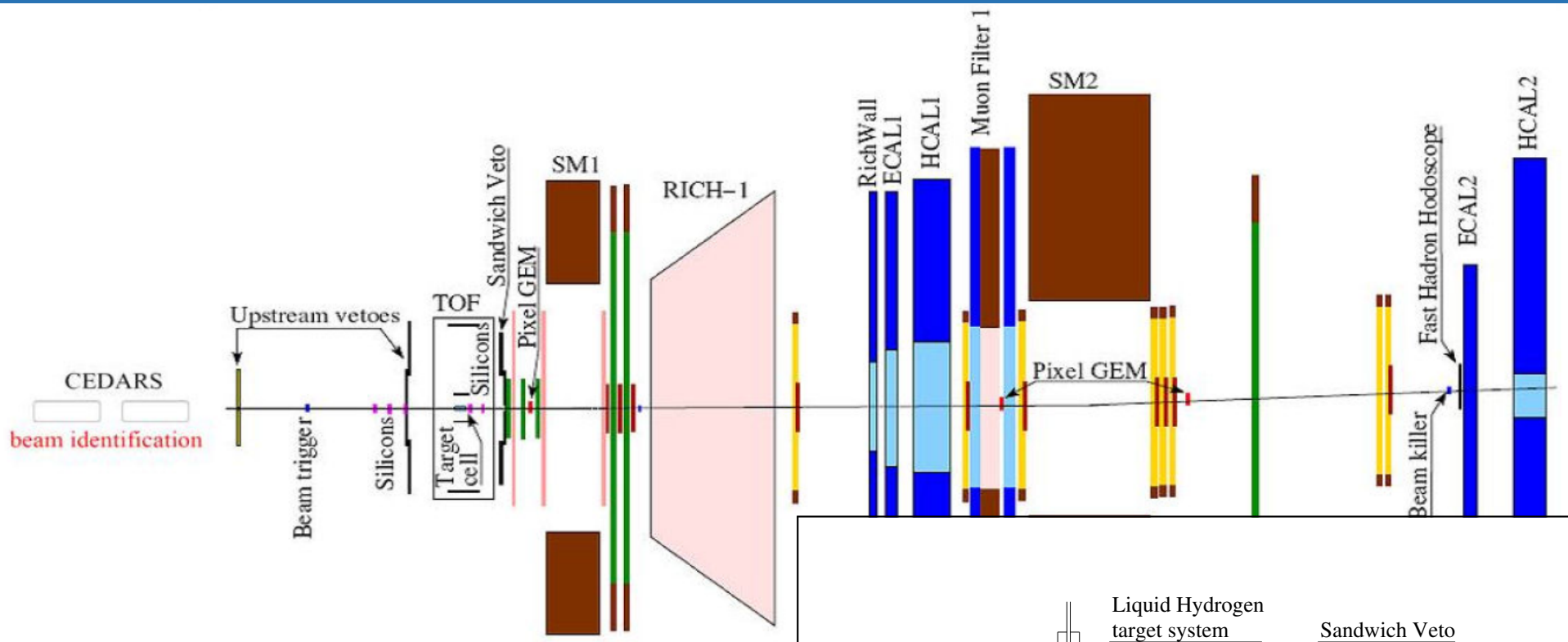




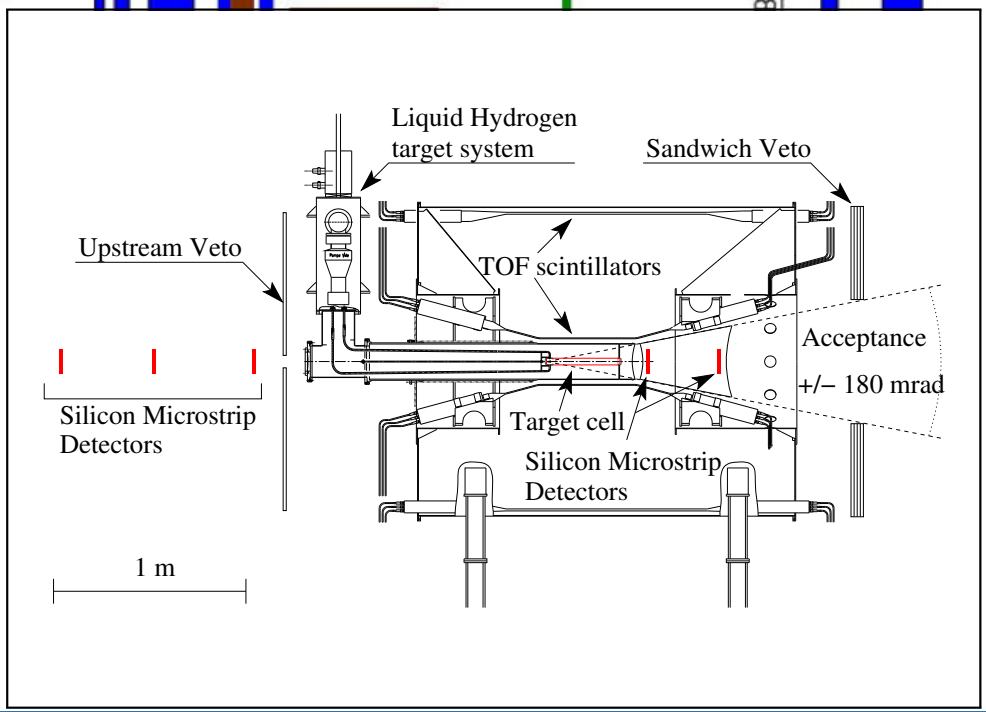


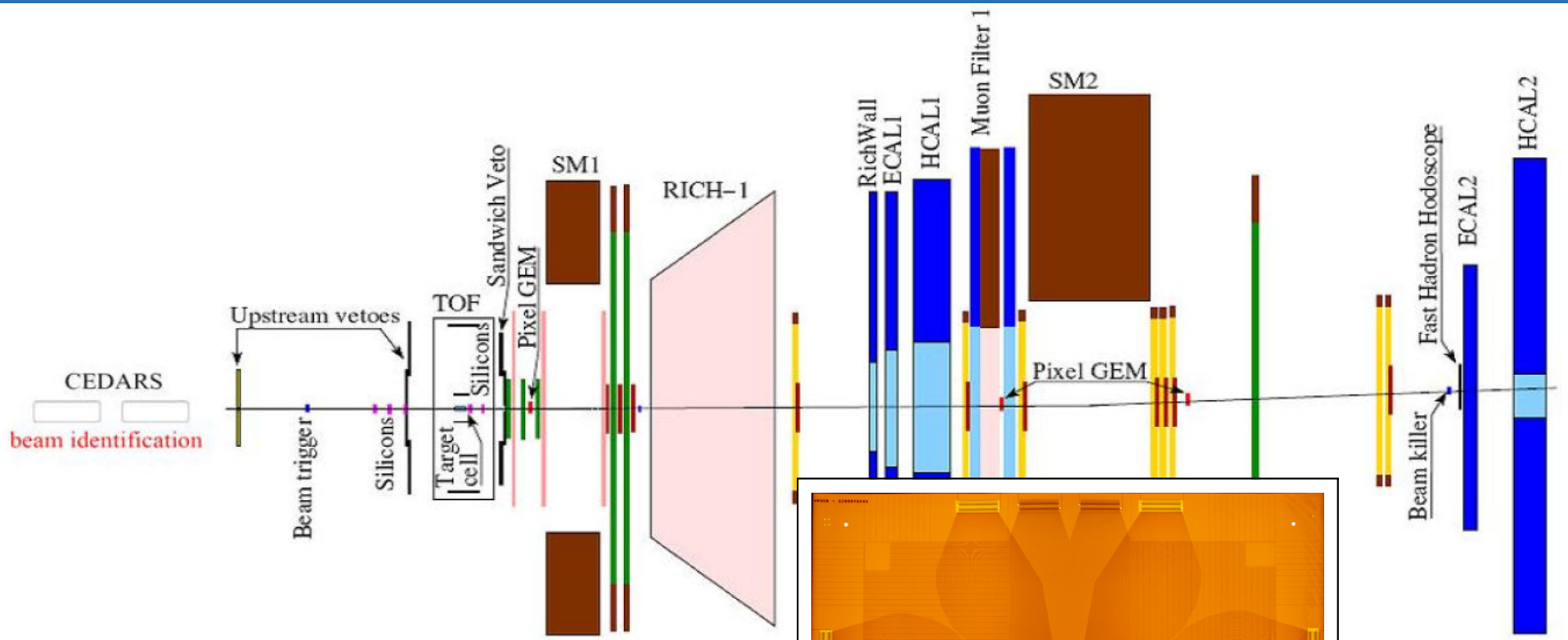
- Change-over to liquid hydrogen target
- Spectrometer upgrades:
  - CEDARs (→ P. Jasinski)
  - RPD (→ J. Bernhard)
  - Silicons

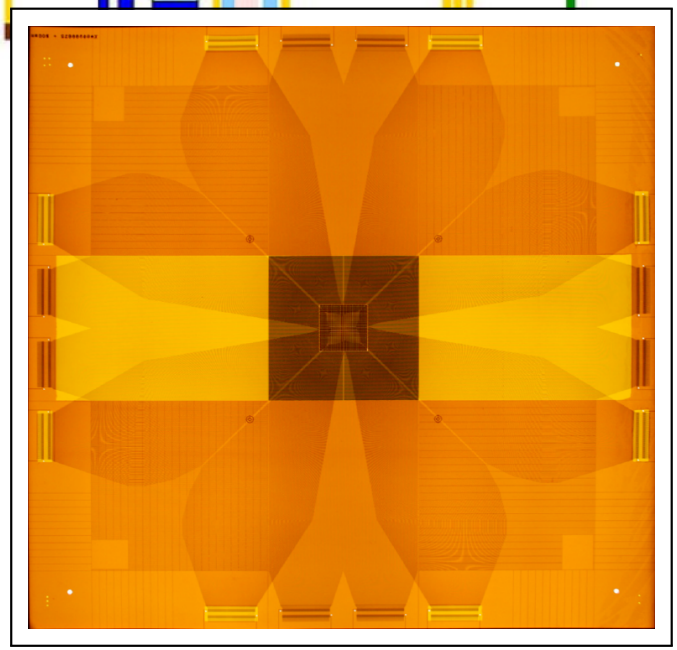




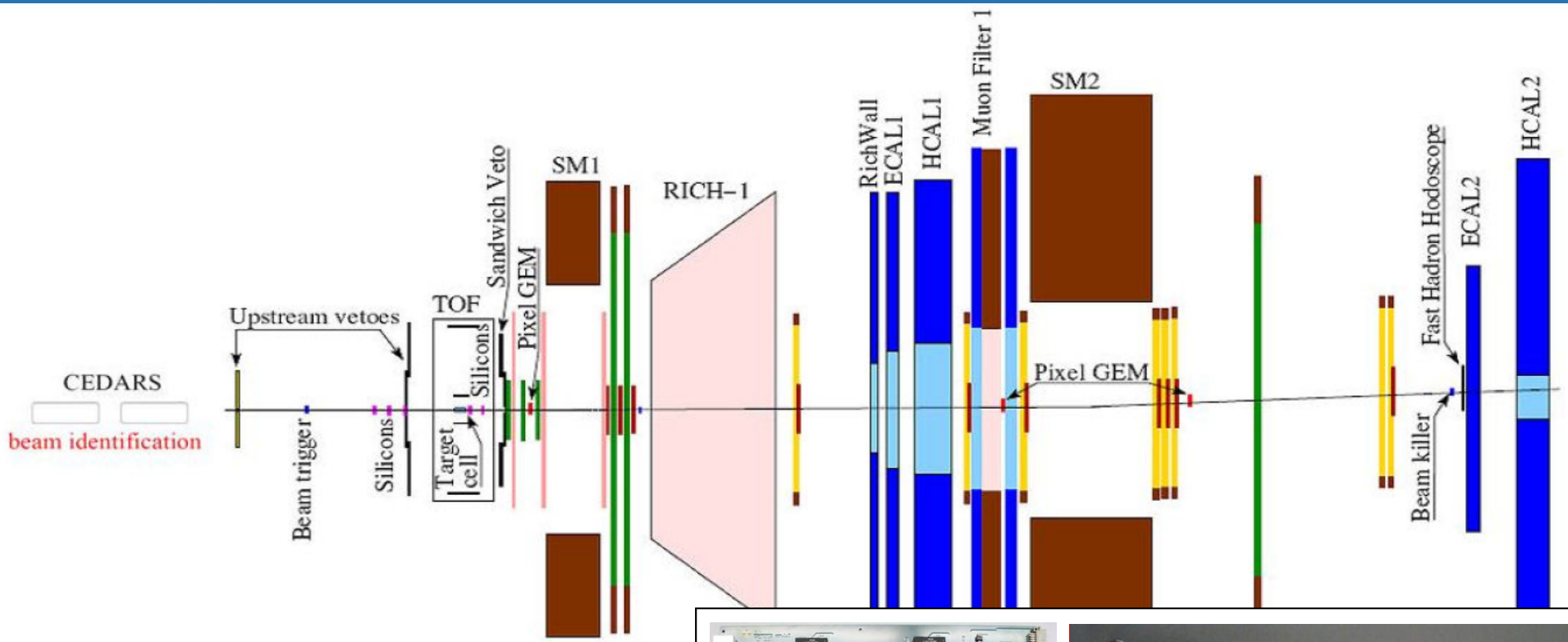
- Change-over to liquid hydrogen target
- Spectrometer upgrades:
  - CEDARs (→ P. Jasinski)
  - RPD (→ J. Bernhard)
  - Silicons
  - Sandwich Veto (→ T. Schlüter)



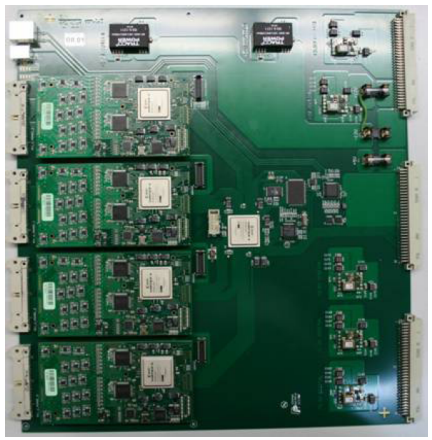


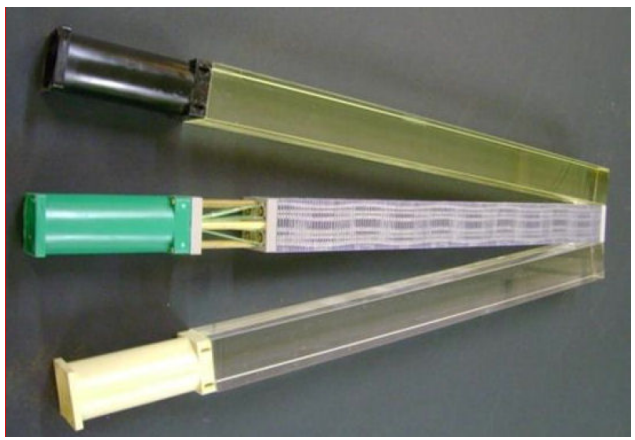


- Change-over to liquid hydrogen target
- Spectrometer upgrades:
  - CEDARs (→ P. Jasinski)
  - RPD (→ J. Bernhard)
  - Silicons
  - Sandwich Veto (→ T. Schlüter)
  - PixelGEMs

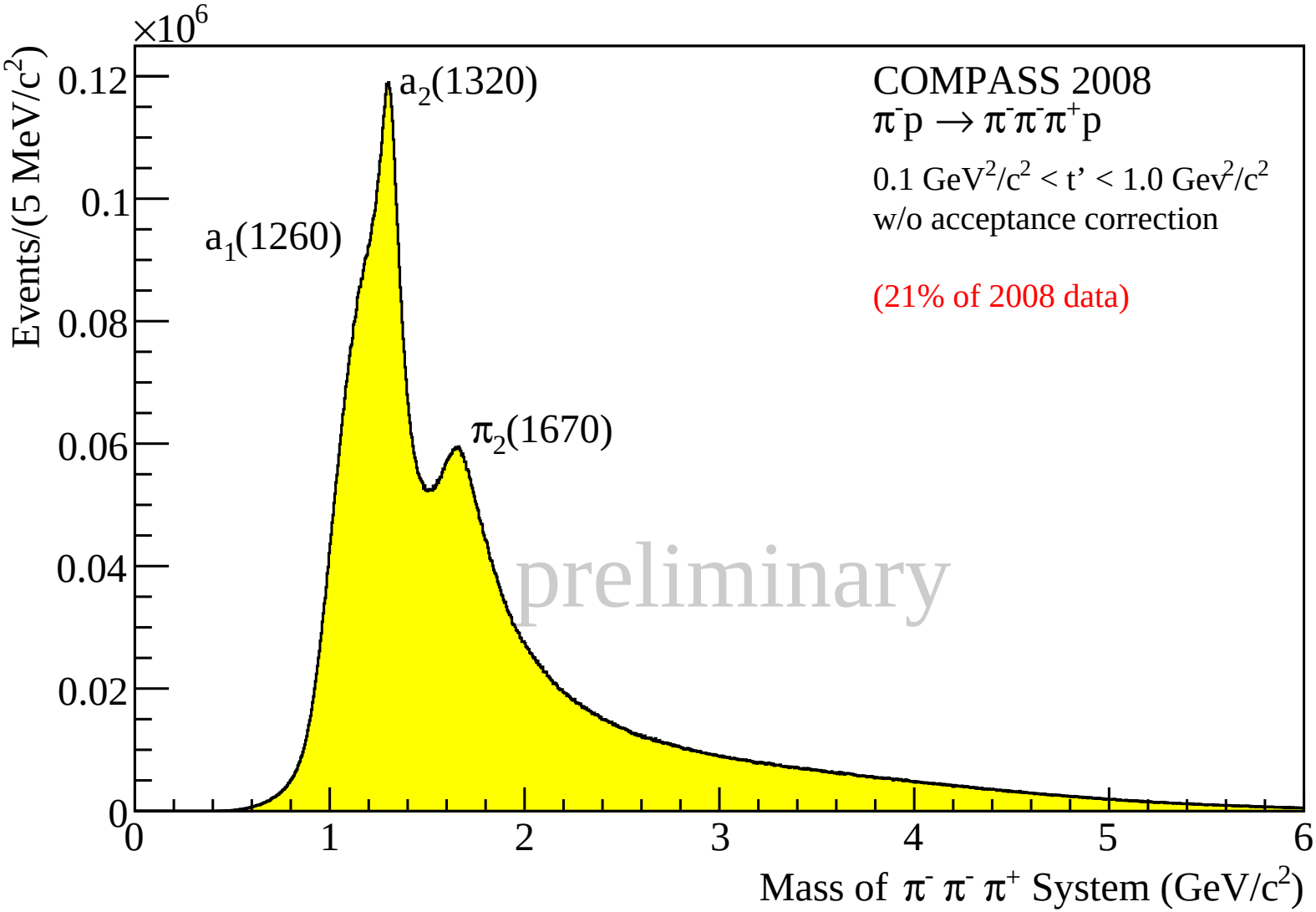


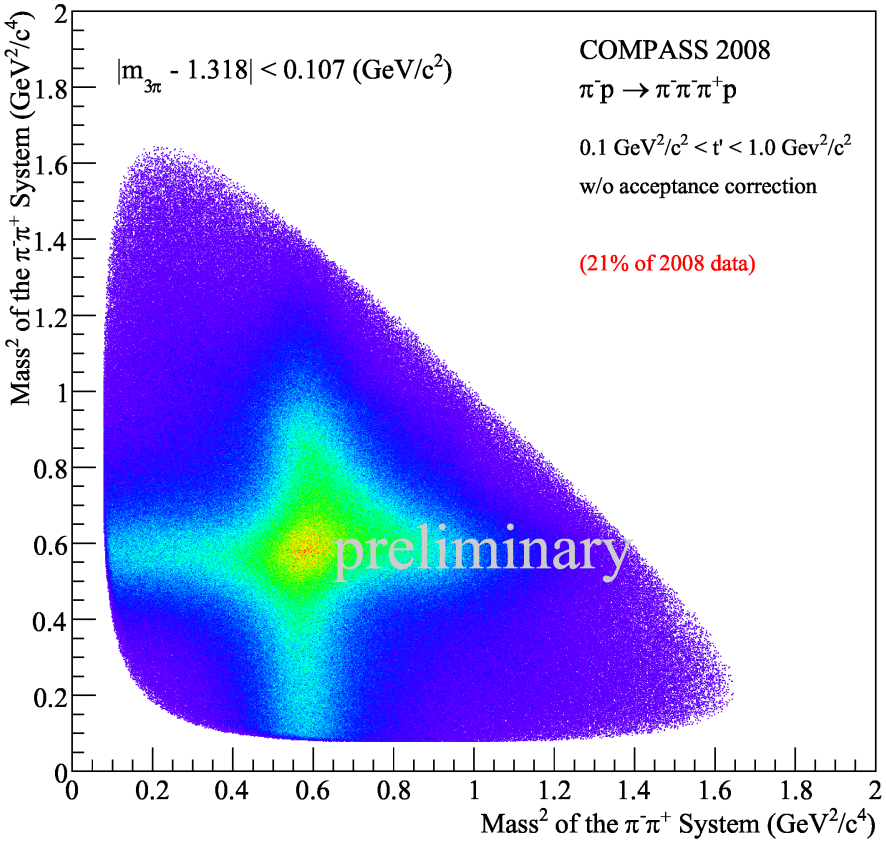
- Change-over to liquid hydrogen target
- Spectrometer upgrades:
  - CEDARs (→ P. Jasinski)
  - RPD (→ J. Bernhard)
  - Silicons
  - Sandwich Veto (→ T. Schlüter)
  - PixelGEMs
  - ECALs



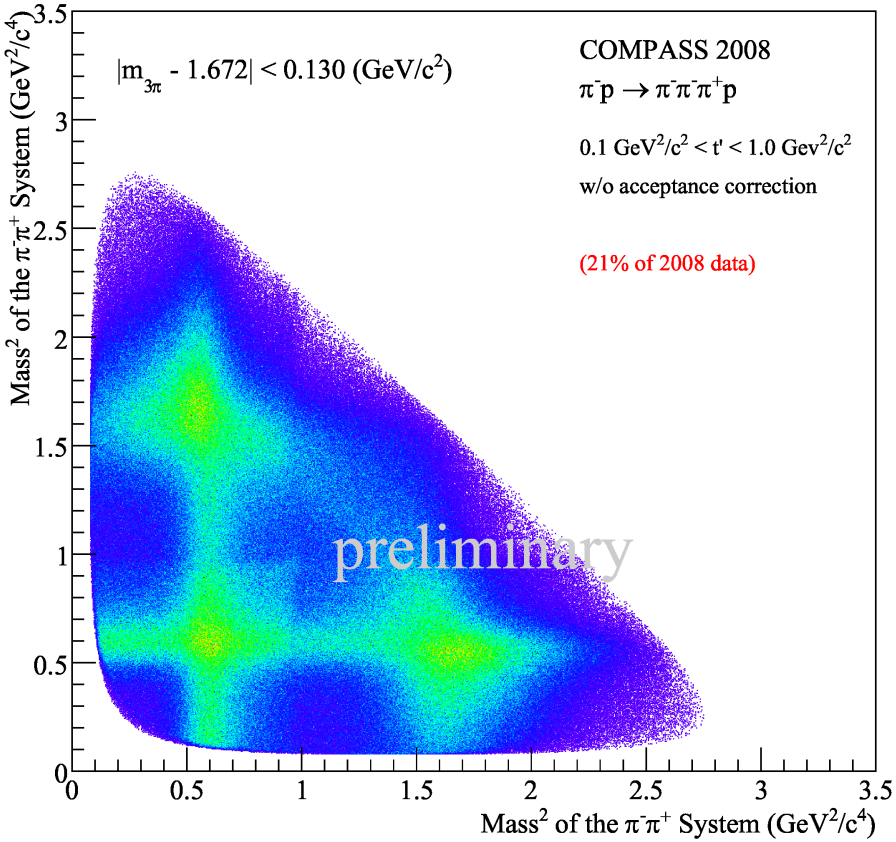


- $0.1\,\mathrm{GeV}^2/c^2 < t' < 1.0\,\mathrm{GeV}^2/c^2$





Dalitz Plot for $a_2(1320)$:
Events selected by $M_{a_2} \pm \Gamma_0$

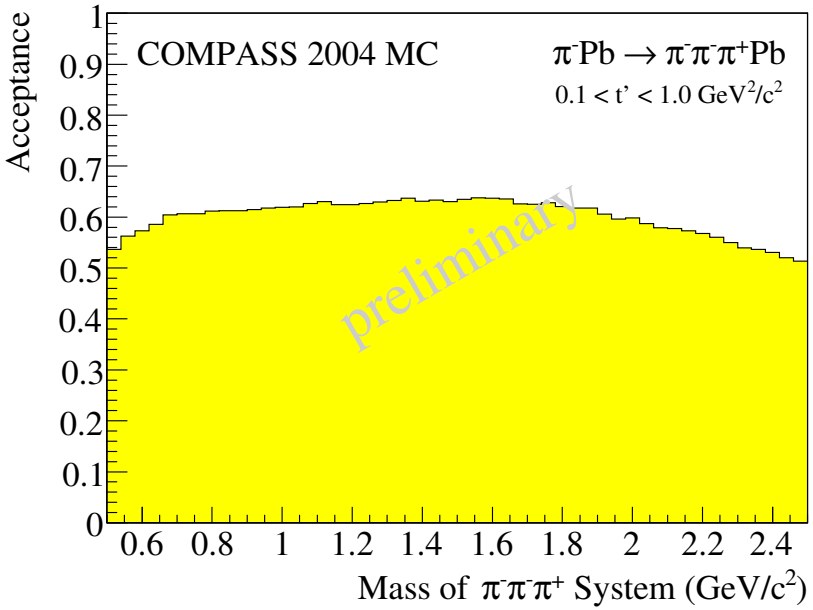


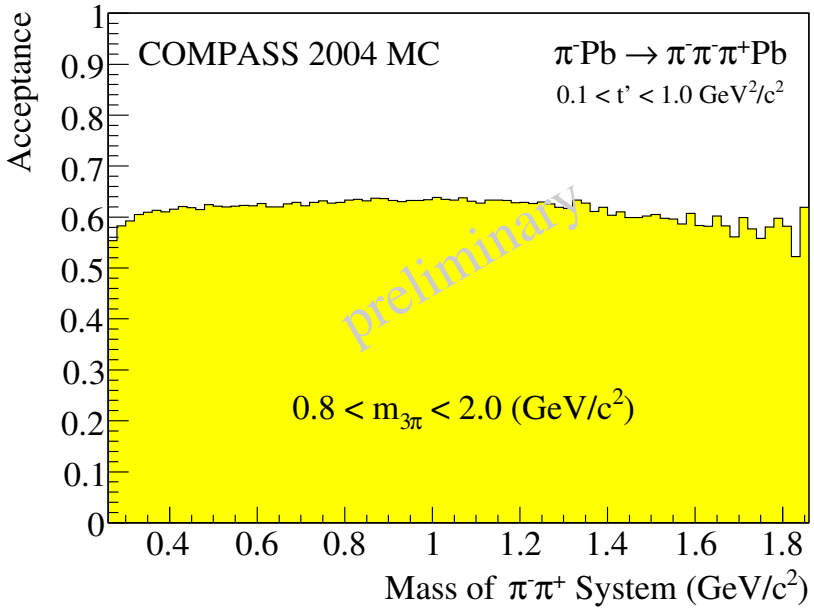
Dalitz Plot for $\pi_2(1670)$:
Events selected by $M_{\pi_2} \pm 0.5\Gamma_0$

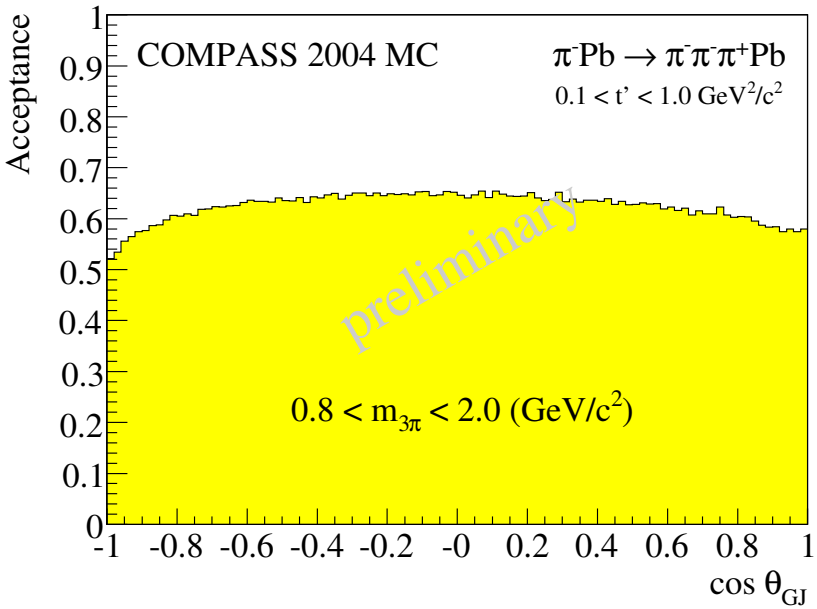
Summary and Outlook

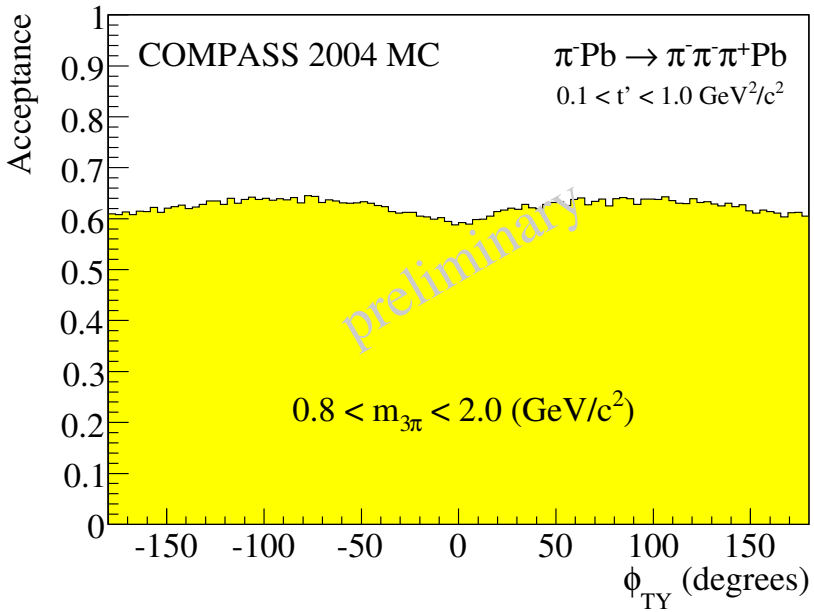
- COMPASS 2004 pilot run using a 190 GeV π^- beam
  - Partial wave analysis on $\sim$ 400 000 $\pi^-\pi^-\pi^+$ events
  - Strong evidence for spin-exotic 1^{-+} state in $\rho\pi$ decay
    $\Rightarrow$ consistent with $\pi_1(1600)$ resonance
  - Analysis of $5\pi^{\pm}$ final state in progress
- Two independent PWA Programs
  - Illinois / Protvino / Munich Program (D. Ryabtschikov)
  - New software BNL / Munich (S. Neubert): `http://ospdev.org/projects/rootpwa`
- COMPASS Hadron Run 2008/2009
  - Change-over to liquid hydrogen target
  - Spectrometer upgrade (Recoil Detector, PID, ECAL ...)
  - $\sim$ 2 orders of magnitude more high-t' statistics (2008)
  - Analysis in progress
- Further Analyses of COMPASS Hadron Data
  - low-t' $\pi^-\pi^-\pi^+$ and Primakoff
  - Central Production: $\pi^- p \longrightarrow \pi^-_{fast}\pi^-\pi^-\pi^+\pi^+ p$ ($\longrightarrow$ J. Bernhard)
  - Central Production / Diffractive Dissociation: Neutral channels
  - Central Production / Diffractive Dissociation: Kaonic final states ($\longrightarrow$ T. Schlüter)
  - Diffractive Dissociation of Kaons ($\longrightarrow$ P. Jasinski)
  - ...

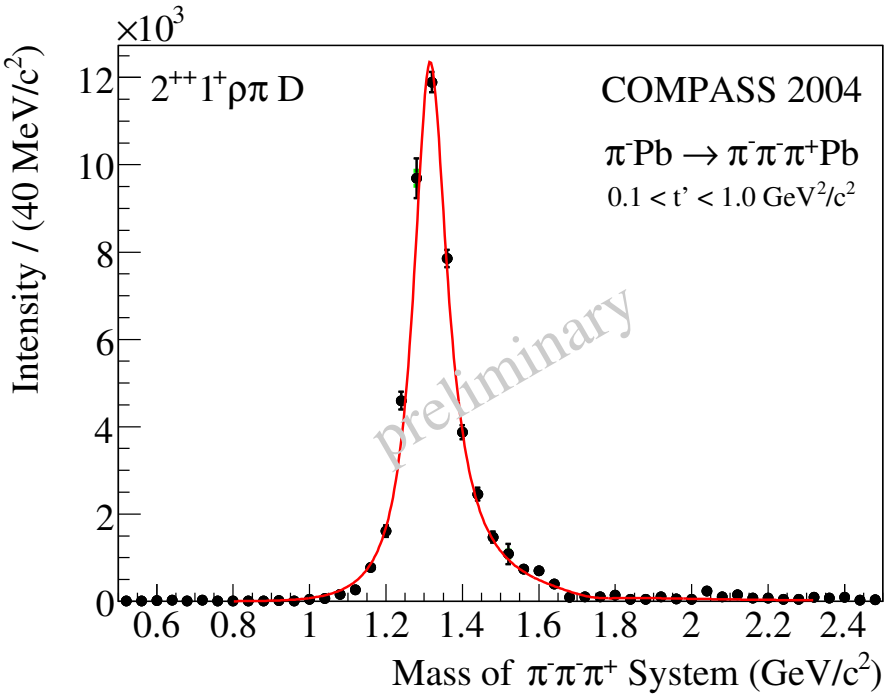
Backup Slides: COMPASS Acceptance for $\pi^-\pi^-\pi^+$ Events

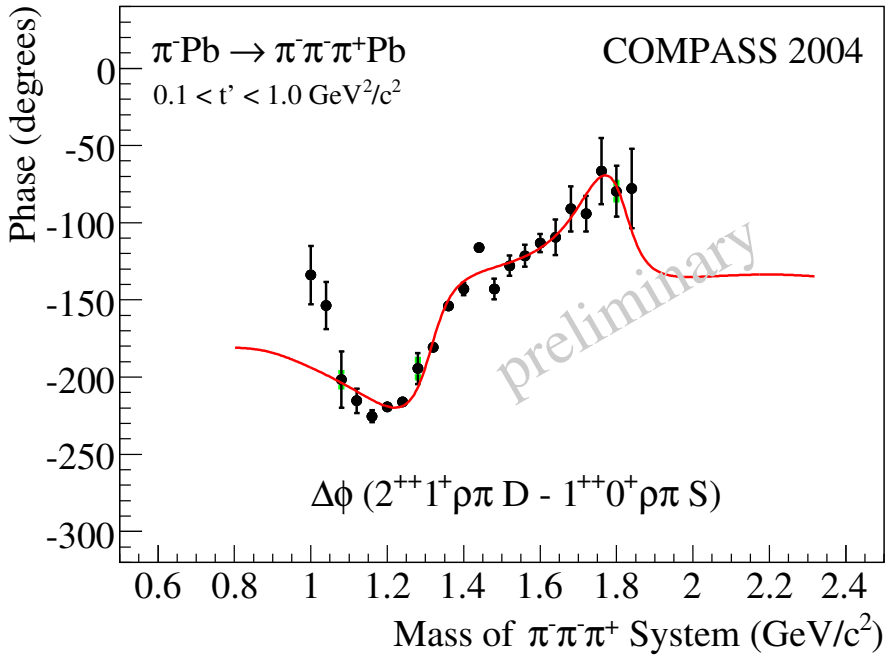












- Two Breit-Wigners needed to describe $2^{++}1^{+}\rho\pi D$ phase motion:
  BW1 for $a_2(1320)$ + BW2 for $a_2(1700)$
- $M = (1.321 \pm 0.001\ ^{+0.000}_{-0.007})$ GeV, $\Gamma = (0.110 \pm 0.002\ ^{+0.002}_{-0.015})$ GeV
- $a_2(1700)$ parameters fixed to PDG values: $M = 1.732$ GeV, $\Gamma = 0.194$ GeV

Mass-Independent Cross-Section and Spin Density Matrix

$$\sigma_{\text{indep}}(\tau) = \sum_{\epsilon} \sum_{r} \left| \sum_{i} T^{\epsilon}_{ir} \psi^{\epsilon}_{i}(\tau) \Big/ \sqrt{\int |\psi^{\epsilon}_{i}(\tau')|^2 \mathrm{d}\tau'} \right|^2 \quad , \quad \rho^{\epsilon}_{ij} = \sum_{r} T^{\epsilon}_{ir} T^{\epsilon *}_{jr}$$

- ϵ: reflectivity, r: rank of density matrix, i: different partial waves
- T: complex production amplitudes (fit parameters!)
- ψ: complex decay amplitudes
- τ: phase space coordinates (5 parameters for 3-body decay)

Likelihood Function

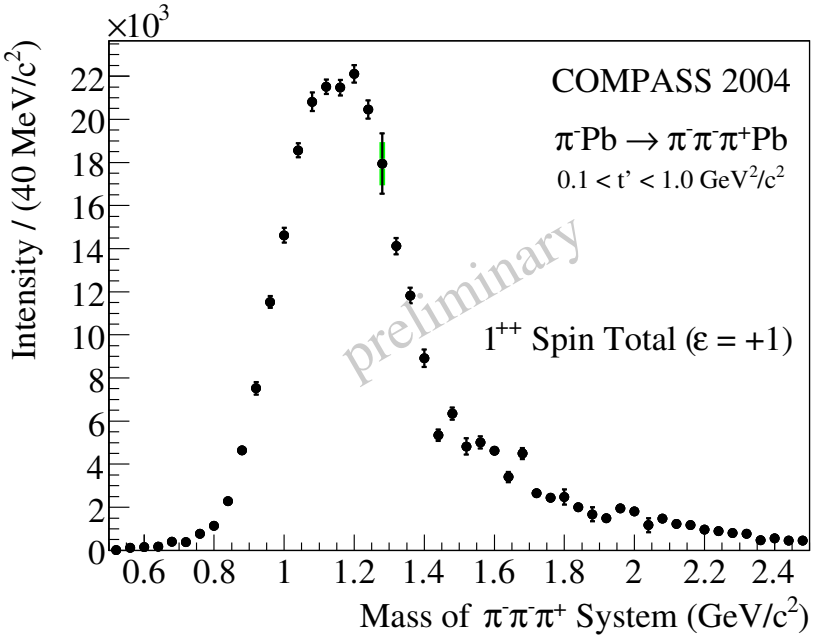
$$\ln L = \sum_{n} \ln \sigma_{\text{indep}}(\tau_n) - \int \sigma_{\text{indep}}(\tau') \text{Acc}(\tau') \mathrm{d}\tau'$$

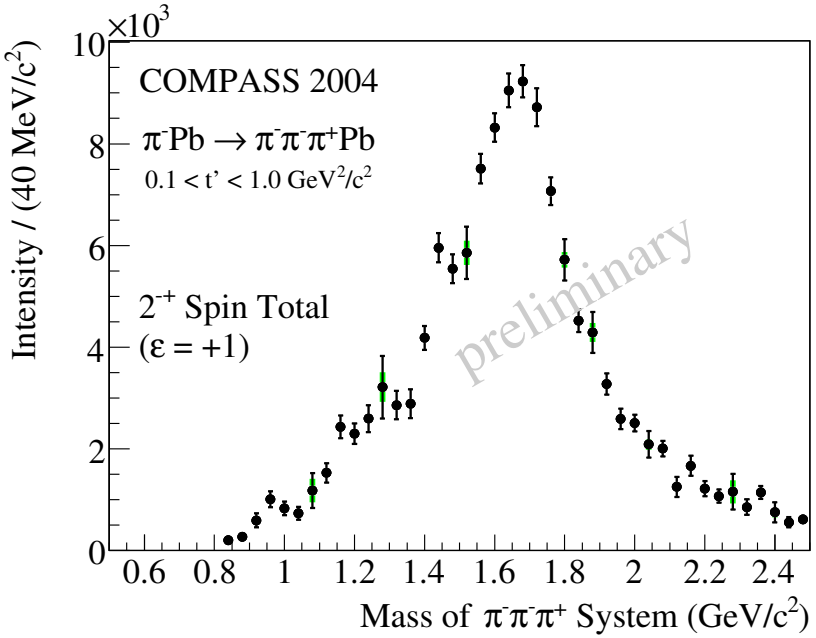
- n: analyzed events, Acc: Acceptance

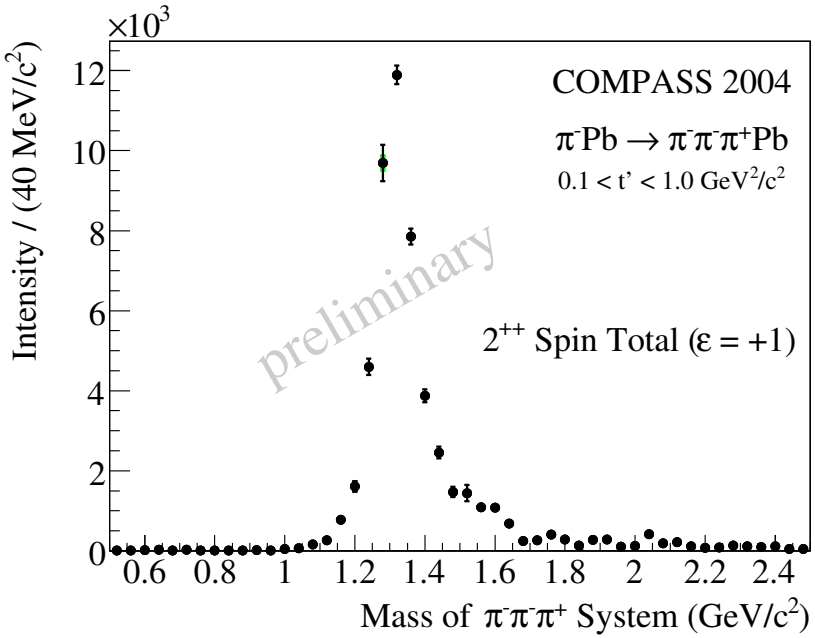
Mass-Dependent Fit

$$\rho^{\epsilon}_{ij} = \sum_{r} \left(\sum_{k} C^{\epsilon}_{ikr} \text{BW}_k(m) \sqrt{\int |\psi^{\epsilon}_{i}(\tau)|^2 \mathrm{d}\tau} \right) \left(\sum_{l} C^{\epsilon}_{jlr} \text{BW}_l(m) \sqrt{\int |\psi^{\epsilon}_{j}(\tau)|^2 \mathrm{d}\tau} \right)^*$$

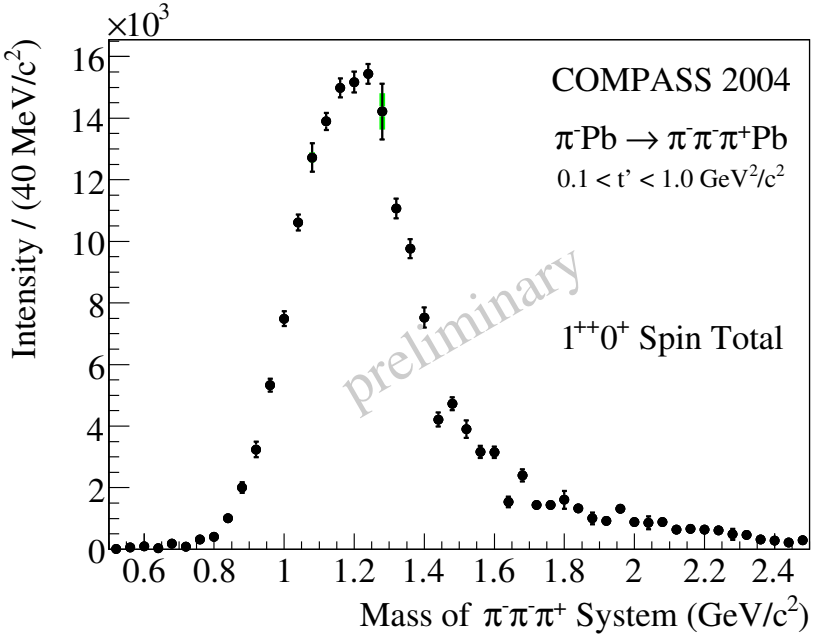
Backup Slides: Spin Totals

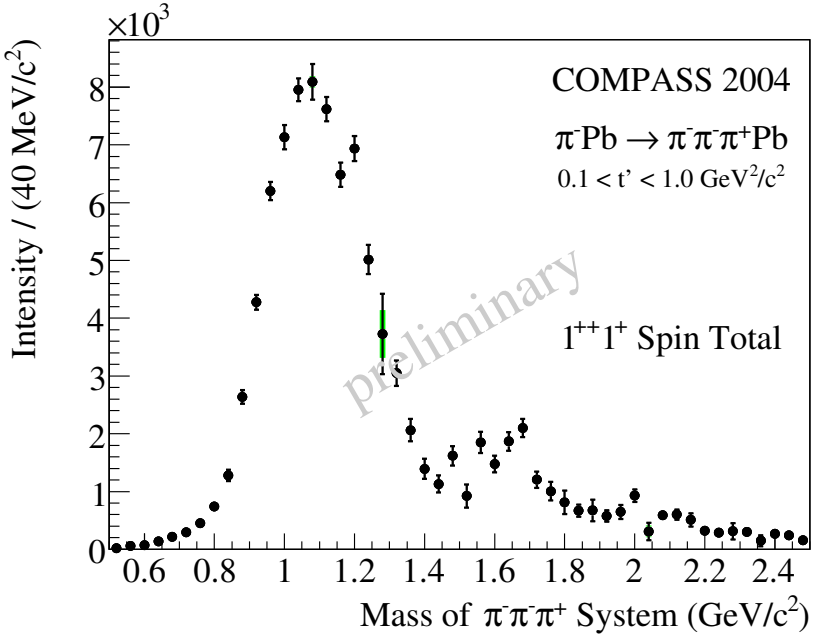


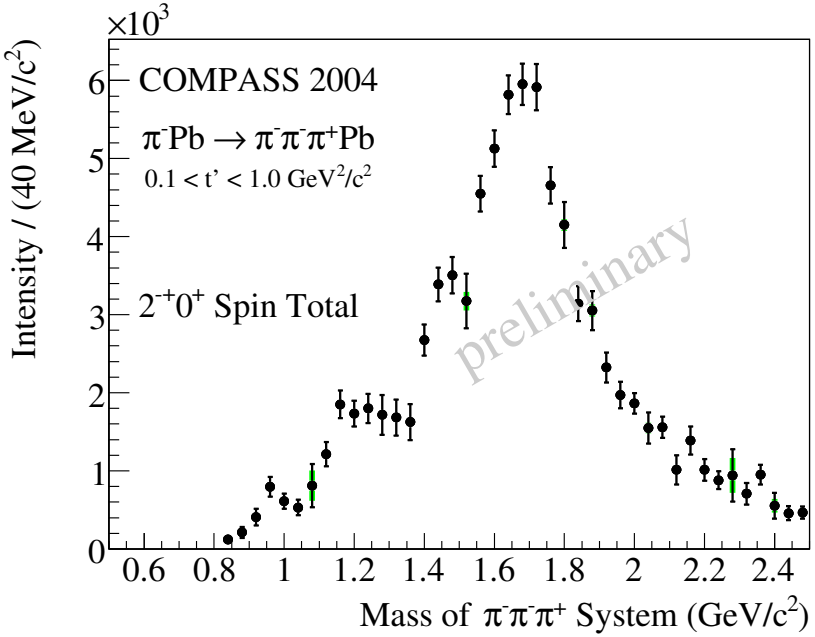


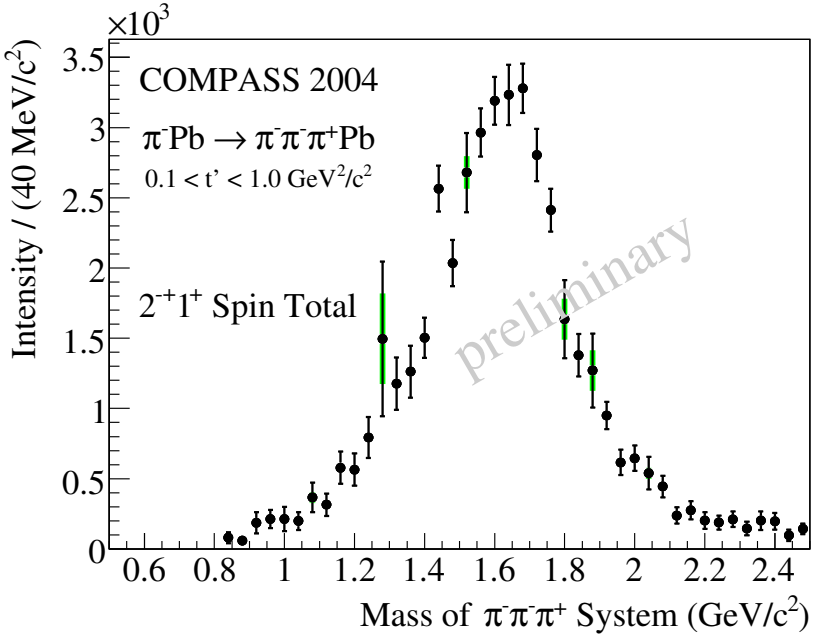


Backup Slides: $M = 0$ and $M = 1$ Spin Totals





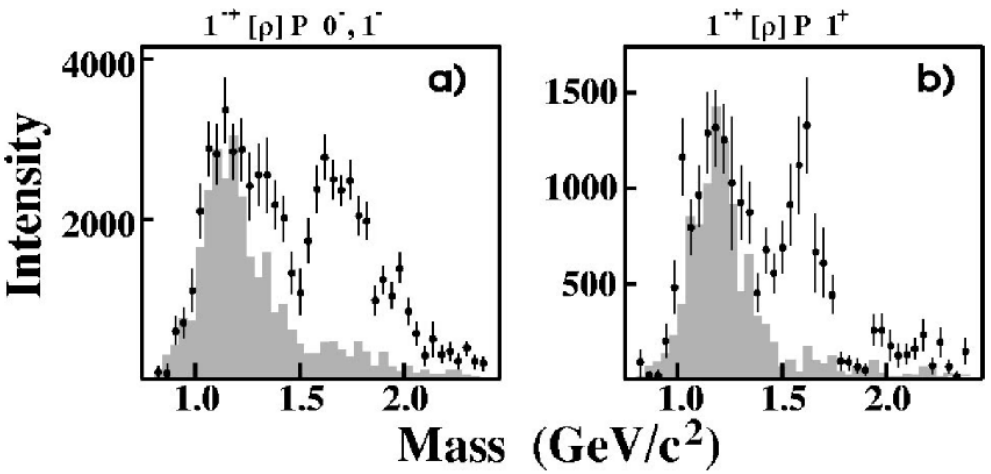




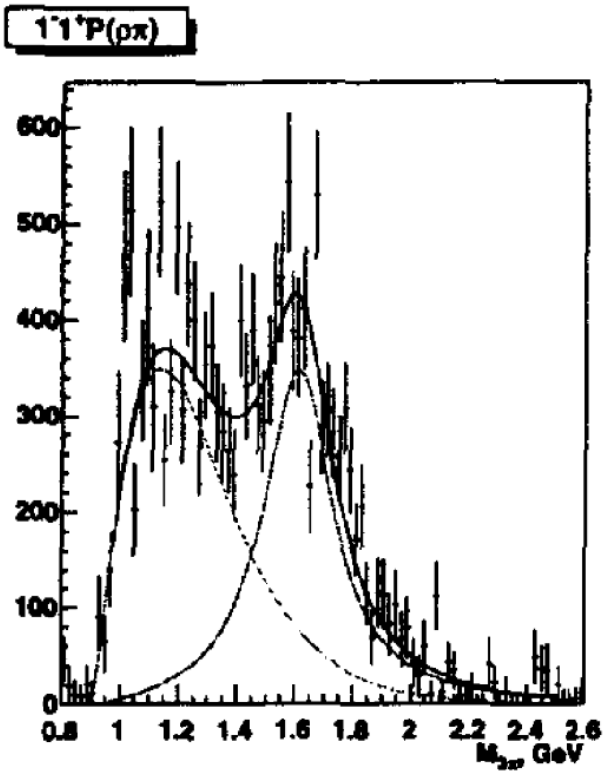
Summary of Results and Comparison to PDG (2006)

State	(GeV)	COMPASS $\pm$ stat $\pm$ 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

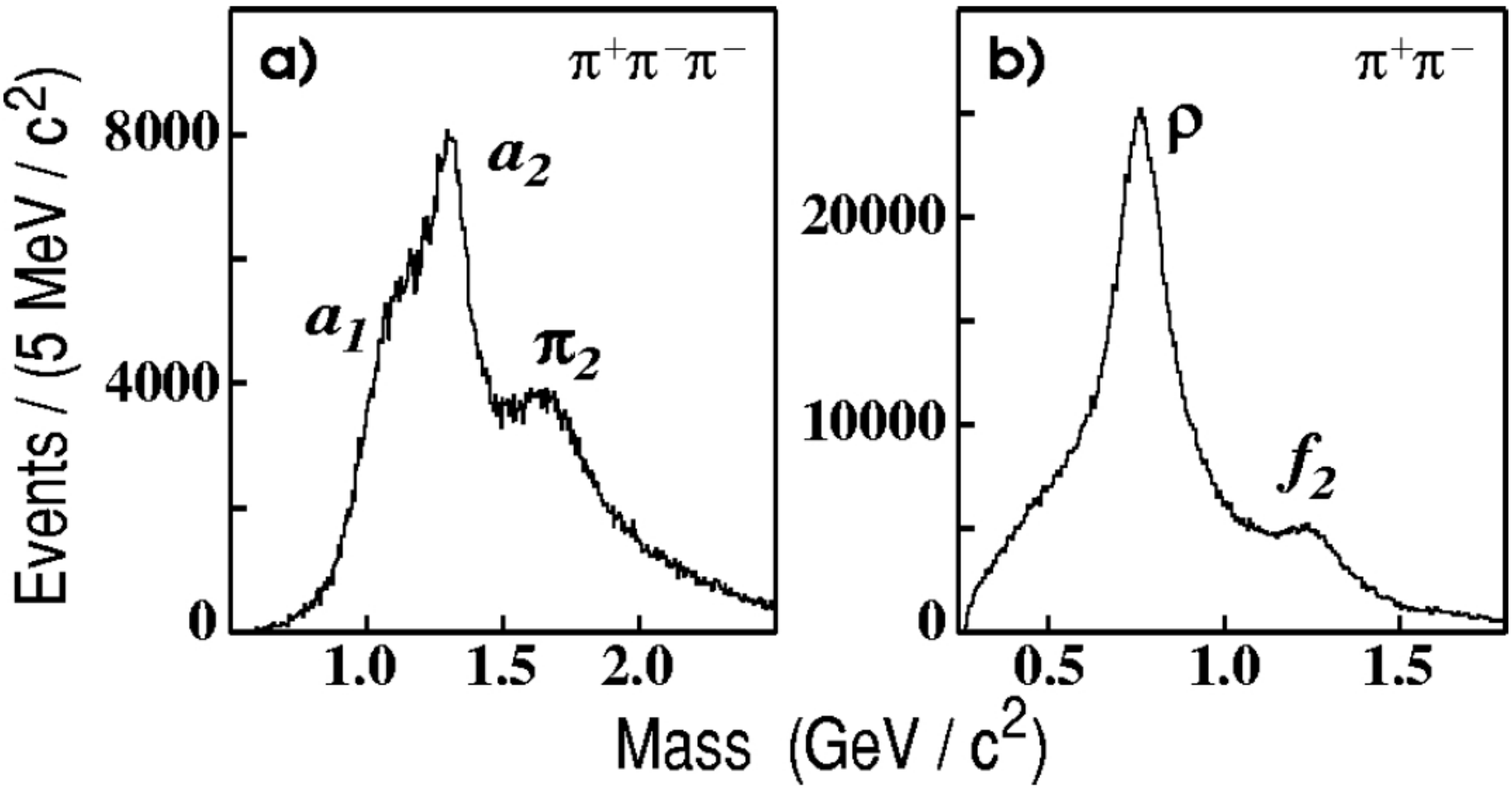
Backup Slides: BNL-E852 and VES 1^{-+} Signal



BNL-E852, Phys. Rev. **D65**, 072001, 2002

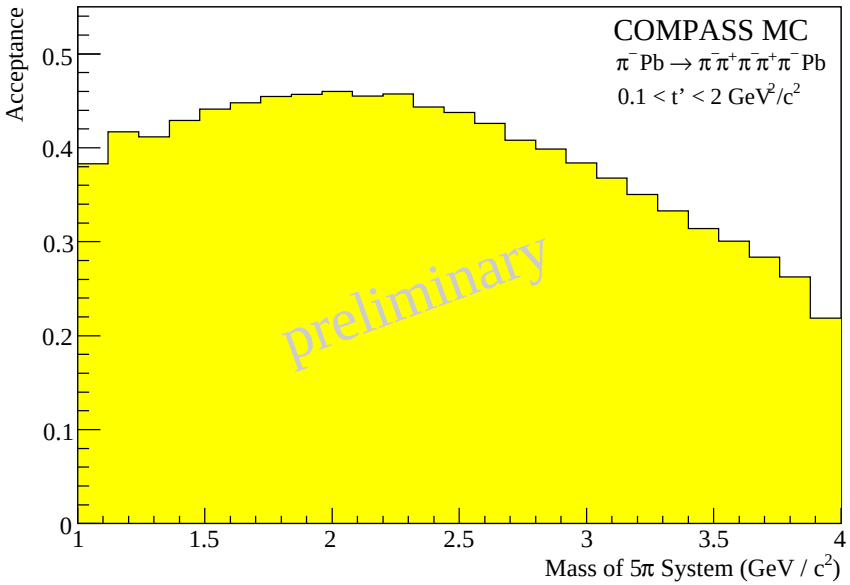


VES, Nucl. Phys. **A663**, 596, 2000

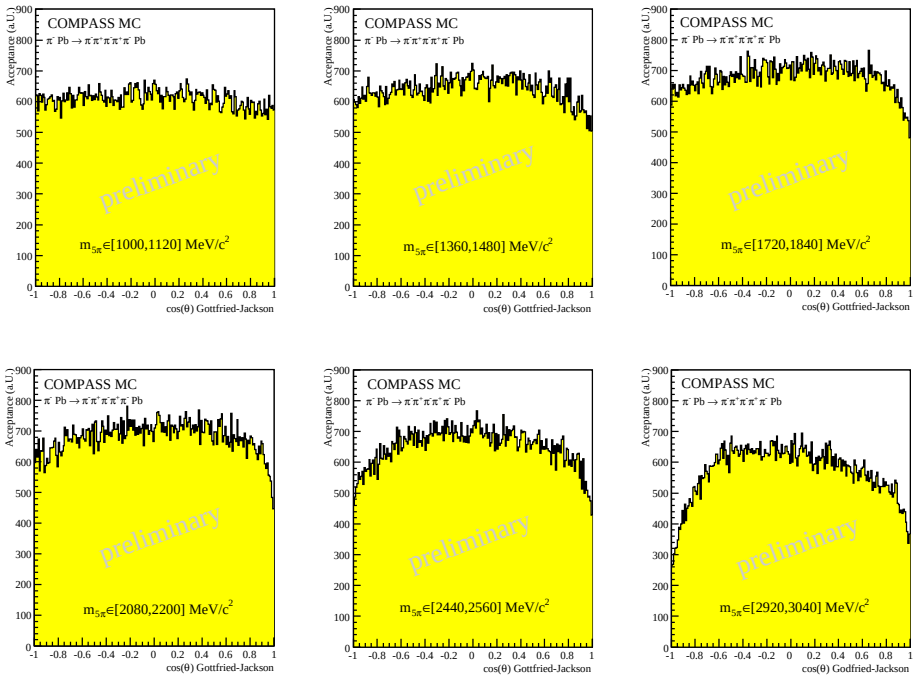


Phys. Rev. **D65**, 072001, 2002

Backup Slides: 5π Acceptance from Monte Carlo Simulation



Single pion decay angle in X^- rest frame (Gottfried-Jackson frame).



Backup Slides: 3 and 2π Subsystems