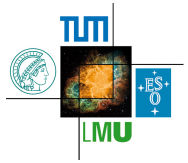
Recent Results from COMPASS

Hadron Spectroscopy

Sebastian Neubert

Technische Universität München

Bormio 2011



The Quark Model of (light) Mesons

Combining $q\bar{q}$ – there are some forbidden states!

Mesons:

- Color neutral objects,
- made from a fermion-antifermion ($q\bar{q}$) pair
- characterized by $I^G(J^{PC})$(mass)

Potential model:

$$V = H_{\text{conf}} + H_{\text{SS}} + H_{\text{LS}} + H_{\text{Annih}}$$

Godfrey, Isgur, Phys. Rev. D32(1985)189

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

The Quark Model of (light) Mesons

Combining $q\bar{q}$ – there are some forbidden states!

Technische Universität München

Mesons:

- Color neutral objects,
- made from a fermion-antifermion ($q\bar{q}$) pair
- characterized by $I^G(J^{PC})$(mass)

Potential model:

$$V = H_{\text{conf}} + H_{\text{SS}} + H_{\text{LS}} + H_{\text{Annih}}$$

Godfrey, Isgur, Phys. Rev. D32(1985)189

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

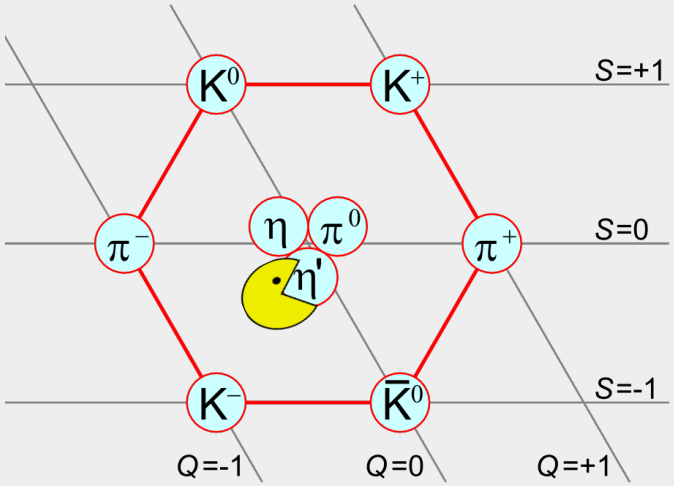
J^{PC} Multiplets

- $\ell = 0 \quad \Rightarrow \quad$ pseudoscalar 0^{-+}, vector 1^{--} states
- $\ell = 1 \quad \Rightarrow \quad$ scalar 0^{++}, axial vector 1^{+-}, 1^{++} and tensor 2^{++} states
- Same $J^{PC} \Rightarrow$ mixing!
- Forbidden: $0^{+-}, 1^{-+}, 2^{+-}, 3^{-+}, \ldots \rightarrow$ *spin exotic* states

Perspectives beyond the Quark Model

Chiral Symmetrie Breaking, Gluonic DoF ...

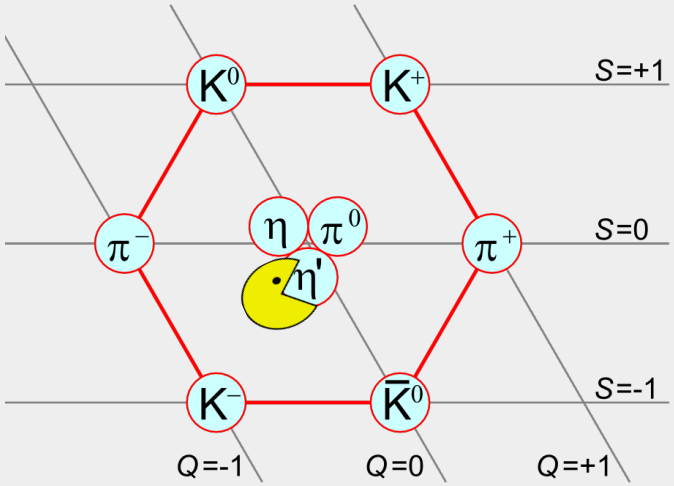
Octet: Goldstone-Bosons of Chiral Symmetrie Breaking



Perspectives beyond the Quark Model

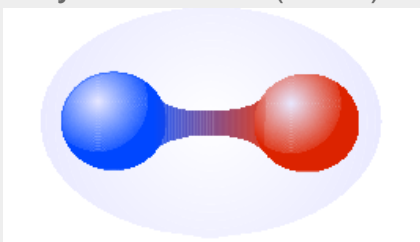
Chiral Symmetrie Breaking, Gluonic DoF ...

Octet: Goldstone-Bosons of Chiral Symmetrie Breaking



Exited States: Flux Tube Model

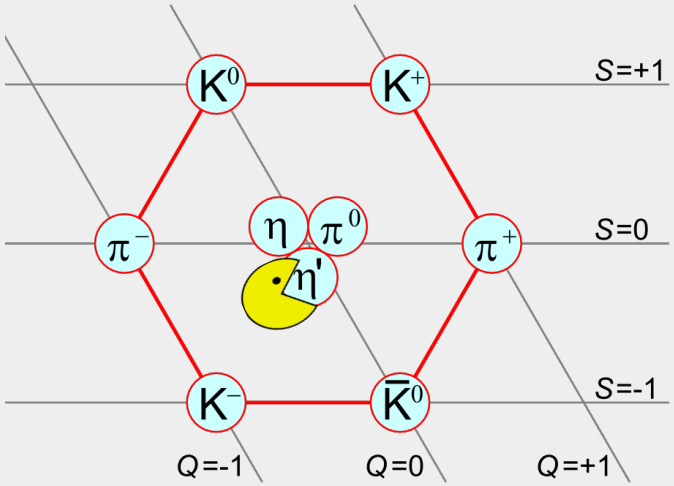
Isgur, Paton Phys. Rev. D31(1985)2910



Perspectives beyond the Quark Model

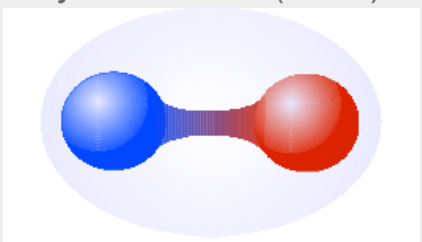
Chiral Symmetrie Breaking, Gluonic DoF ...

Octet: Goldstone-Bosons of Chiral Symmetrie Breaking

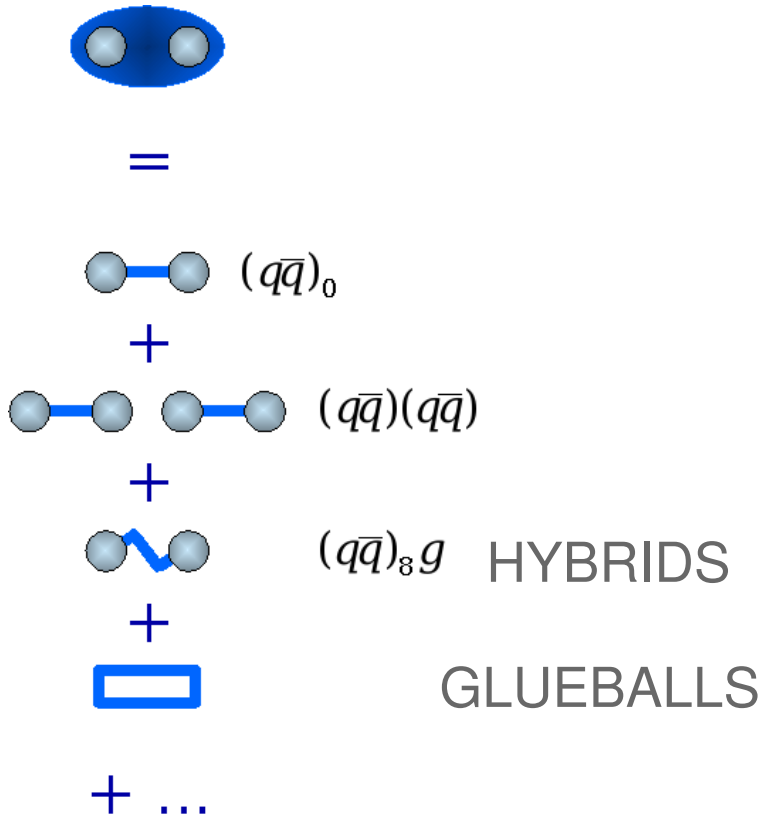


Exited States: Flux Tube Model

Isgur, Paton Phys. Rev. D31(1985)2910

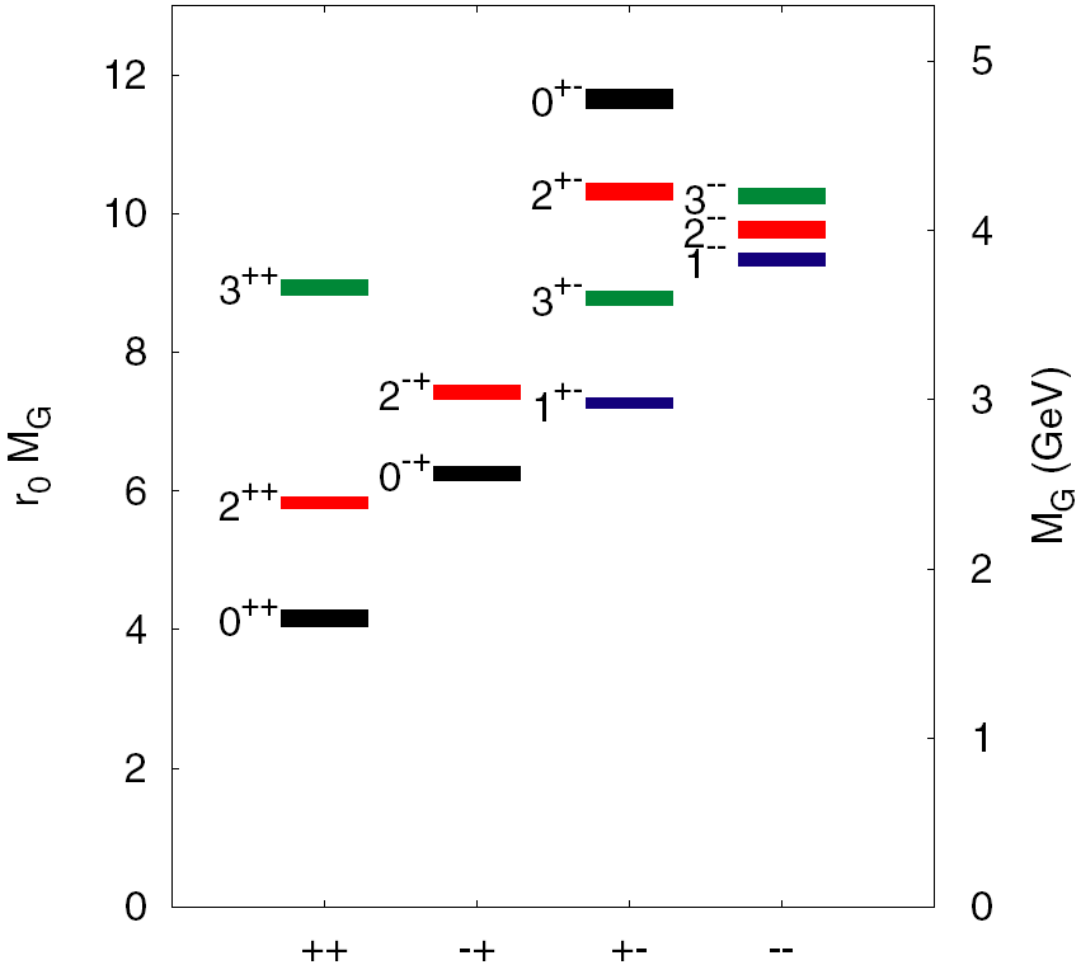


QCD allowed contributions to meson spectrum:



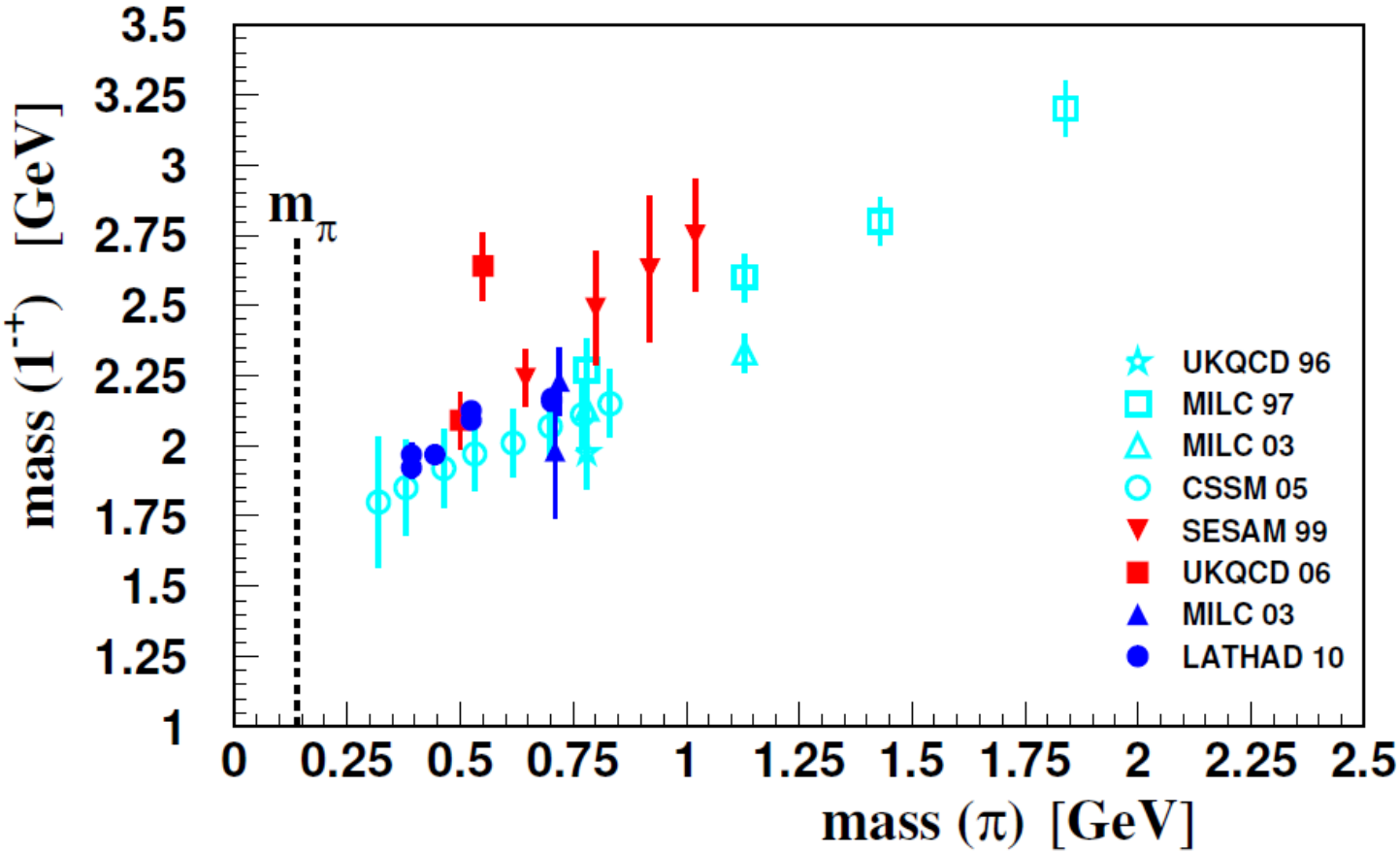
Guidance from the Lattice? - Glueballs

Y. Chen et al., Phys. Rev. D73(2006)014516



Guidance from the Lattice? - Hybrids

C. A. Meyer and Y. Van Haarlem, Phys. Rev. C 82, 025208 (2010) (arXiv:1004.5516v2)



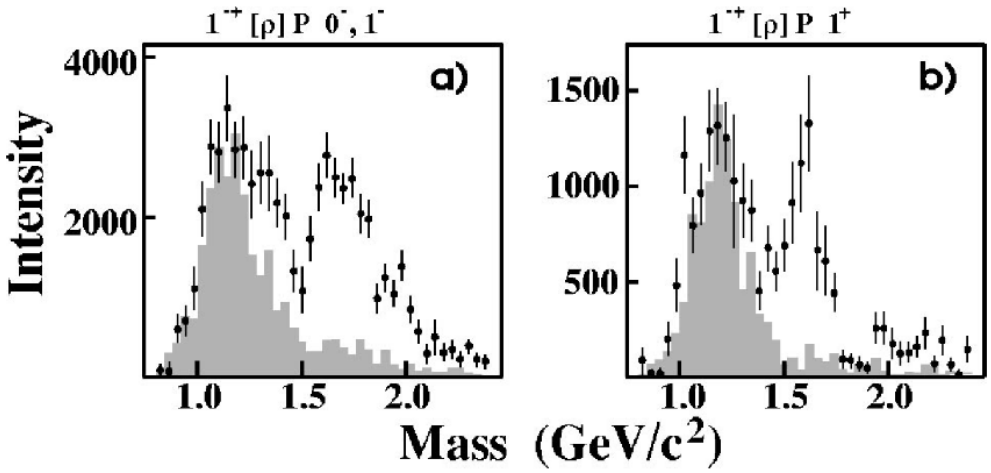
Search for States beyond the Quark Model

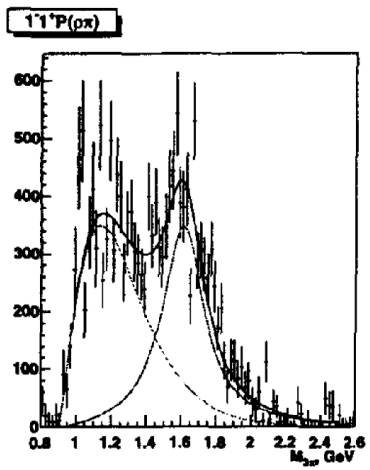
Exotic Signatures

- Over-filled Multiplets (too many states)
- Isospin exotics: “forbidden” decays
- Spin exotics: forbidden $J^{PC} = 0^{+-}, 1^{-+}, 2^{+-} \ldots$

- Evidences for $J^{PC} = 1^{-+}$ $\pi_1(1600)$ state with in $\rho\pi^- \to \pi^-\pi^+\pi^-$?

  [BNL-E852, Phys. Rev. **D65**, 072001, 2002], [VES, Nucl. Phys. **A663**, 596, 2000]

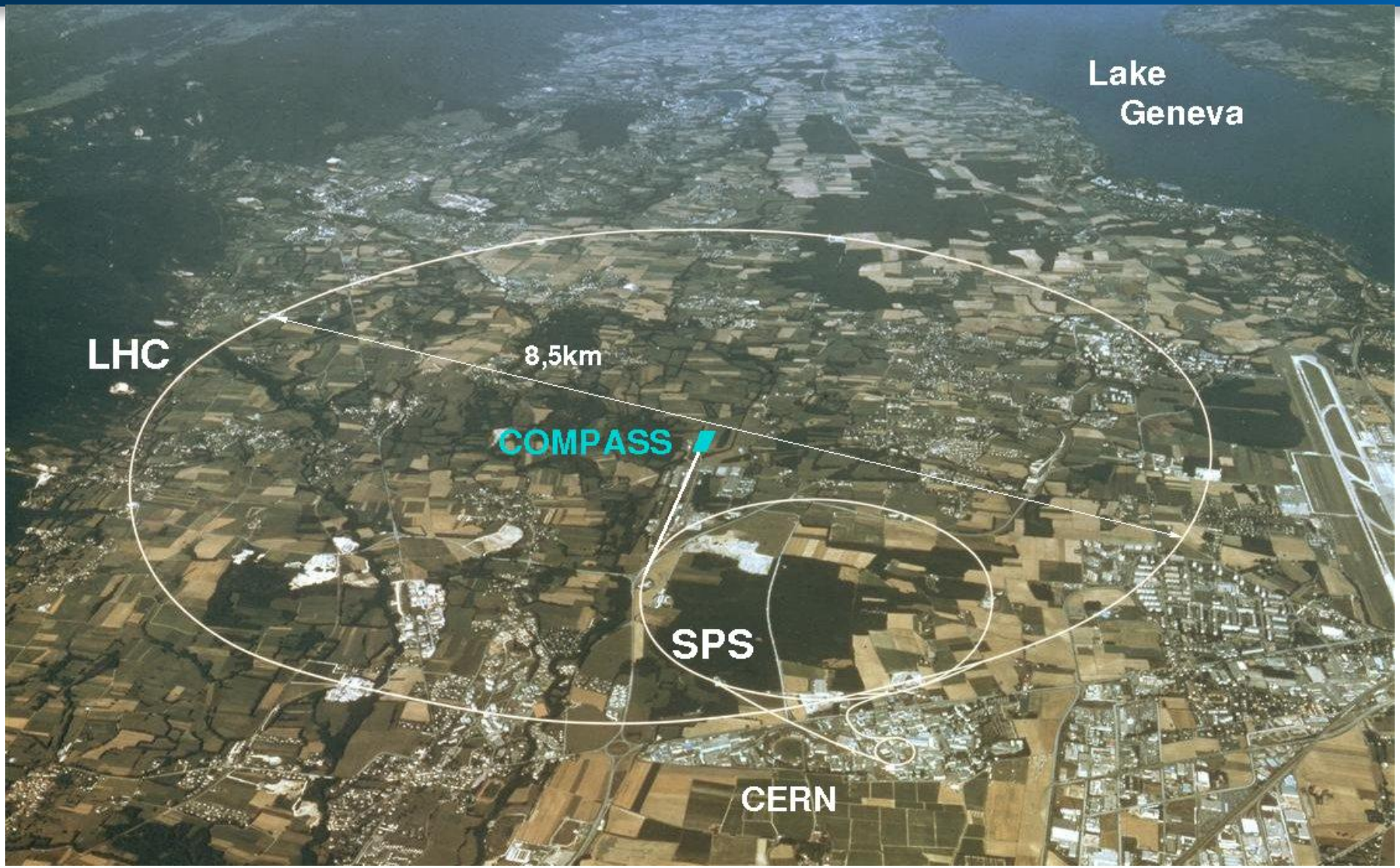




Reanalysis: Signal not confirmed!

COMPASS at the CERN SPS

Technische Universität München



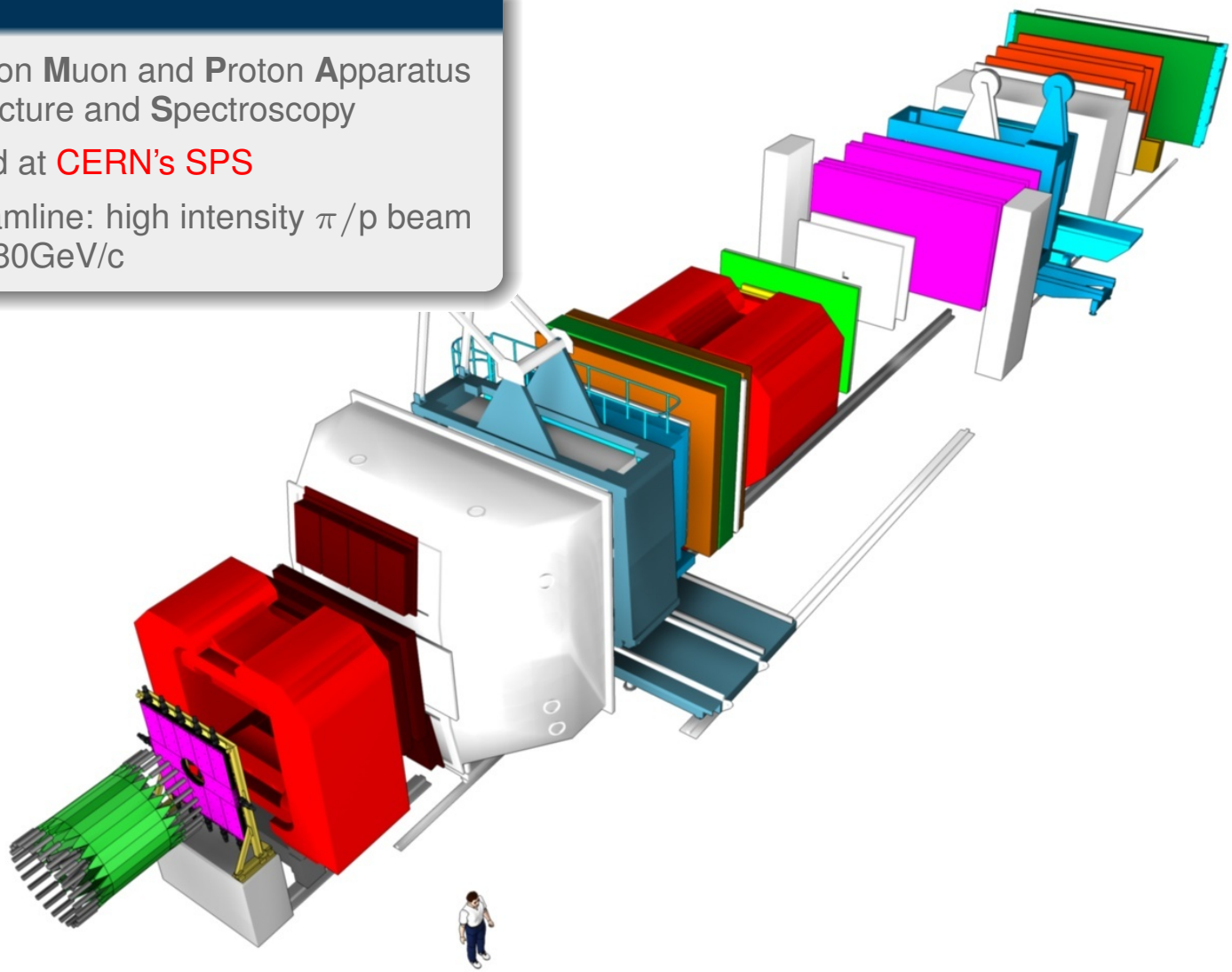
The COMPASS Experiment

Spectrometer and Hadron Beam

Technische Universität München

Overview

- **CO**mmon **M**uon and **P**roton **A**pparatus for **S**tructure and **S**pectroscopy
- Located at CERN's SPS
- M2-beamline: high intensity π/p beam up to 280GeV/c



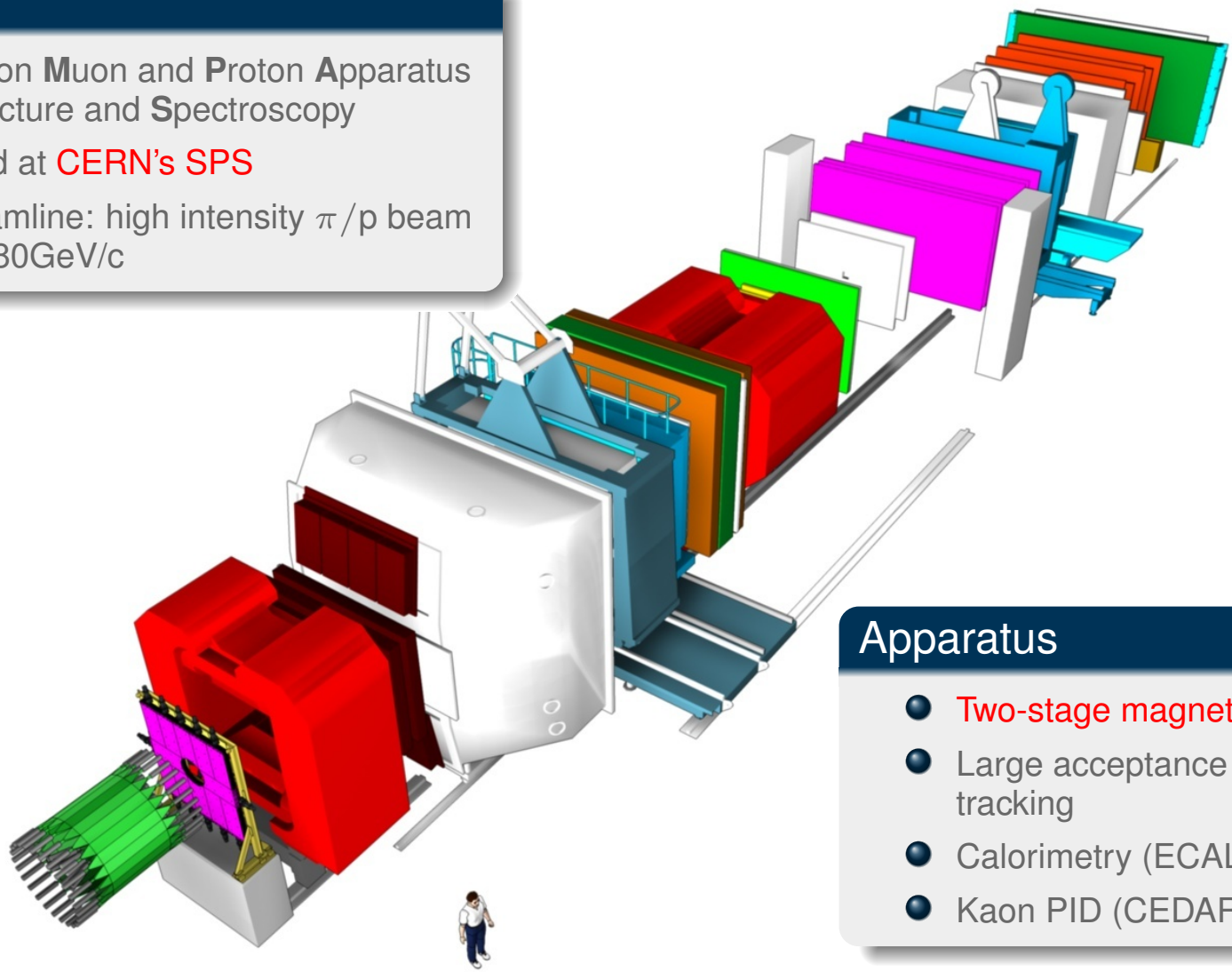
The COMPASS Experiment

Spectrometer and Hadron Beam

Technische Universität München

Overview

- **CO**mmon **M**uon and **P**roton **A**pparatus for **S**tructure and **S**pectroscopy
- Located at CERN's SPS
- M2-beamline: high intensity π/p beam up to 280GeV/c



Apparatus

- Two-stage magnetic spectrometer
- Large acceptance charged tracking
- Calorimetry (ECAL/HCAL)
- Kaon PID (CEDARs/RICH)

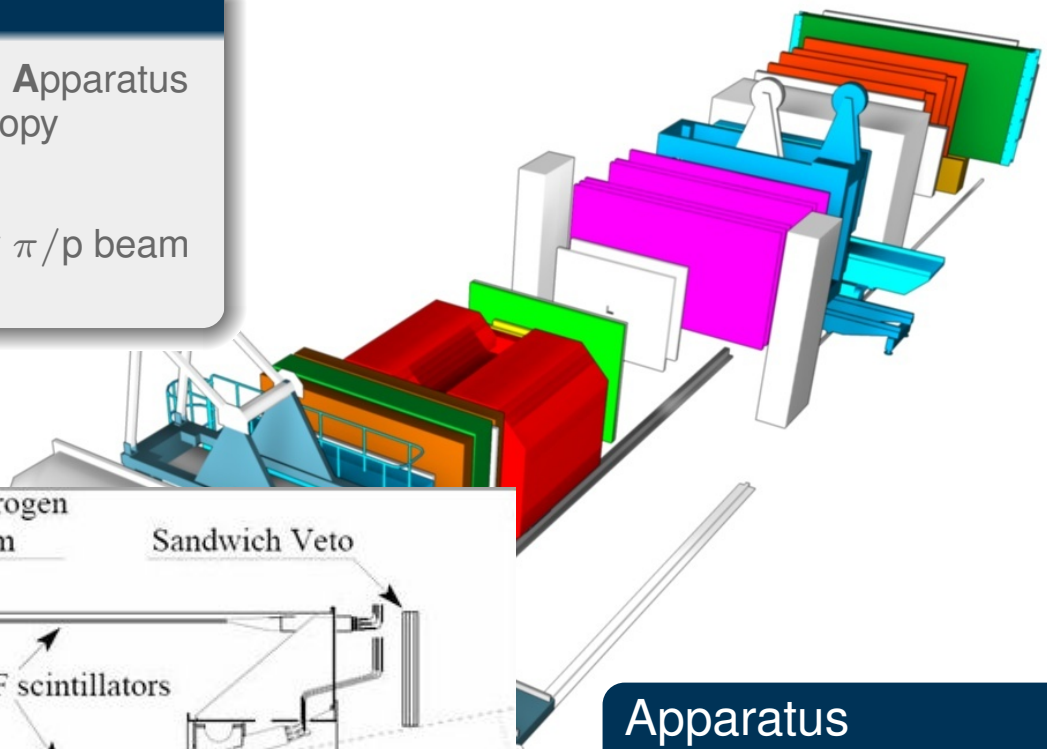
The COMPASS Experiment

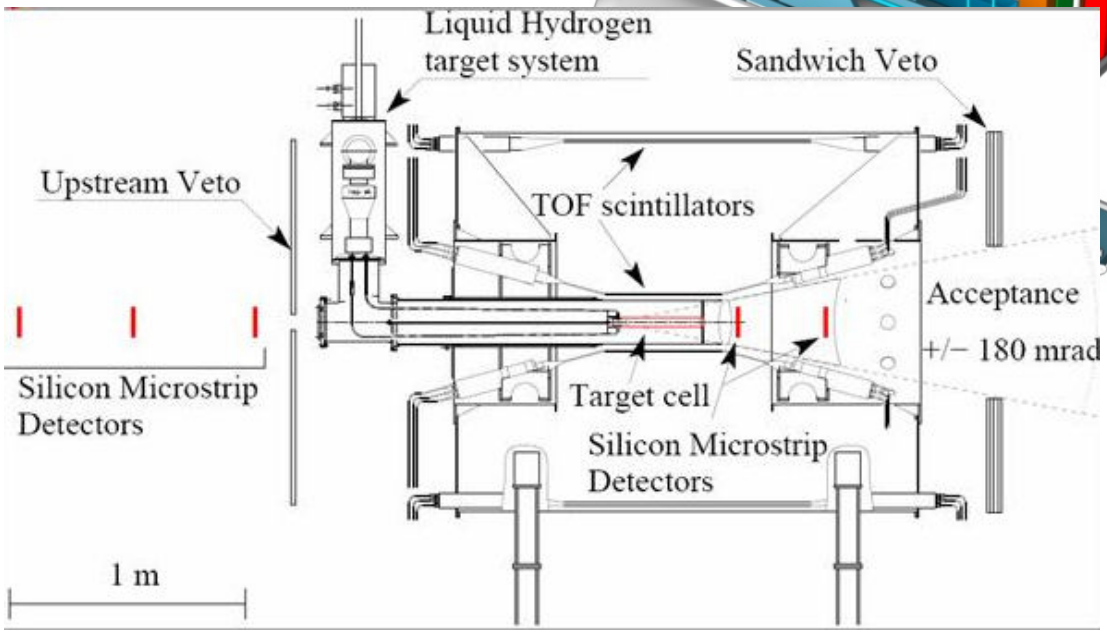
Spectrometer and Hadron Beam

Technische Universität München

Overview

- **CO**mmon **M**uon and **P**roton **A**pparatus for **S**tructure and **S**pectroscopy
- Located at CERN's SPS
- M2-beamline: high intensity π/p beam up to 280GeV/c





Apparatus

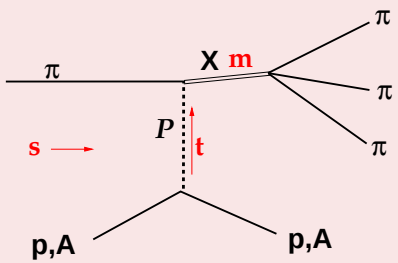
- Two-stage magnetic spectrometer
- Large acceptance charged tracking
- Calorimetry (ECAL/HCAL)
- Kaon PID (CEDARs/RICH)

Production Mechanisms at COMPASS

and most prominent Physics Motivations

Technische Universität München

Diffractive Dissociation → Search for Spin-Exotics



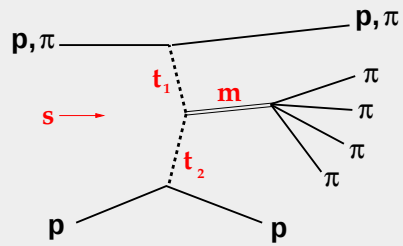
- Pomeron t-channel exchange

$$T \propto t^{\frac{1}{2}|\lambda_a - \lambda_x|} s^{\alpha(t)} t^{\frac{1}{2}|\lambda_b - \lambda_c|}$$

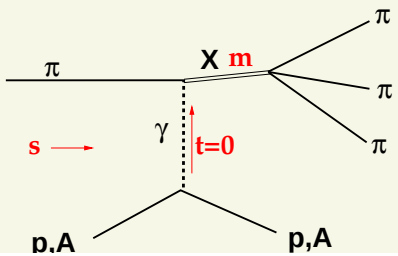
- Isospin Triplet States $I = 1$

Central Production → Glueball Search

- Pomeron-Pomeron fusion
- Isospin Singlet States $I = 0$



Primakoff Production → Radiative Widths



Photon exchange (Nucl.Field)

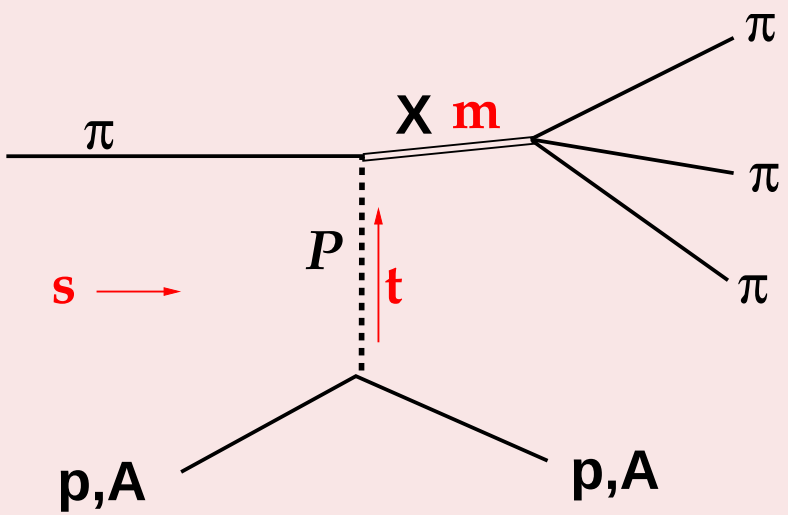
- $t \sim 0$
- Helicity $\lambda_x = 1$

Production Mechanisms at COMPASS

and most prominent Physics Motivations

Technische Universität München

Diffractive Dissociation $\rightarrow$ Search for Spin-Exotics



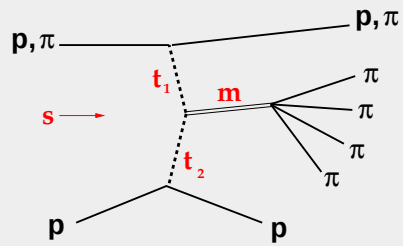
- Pomeron t-channel exchange

$$T \propto t^{\frac{1}{2}|\lambda_a - \lambda_x|} s^{\alpha(t)} t^{\frac{1}{2}|\lambda_b - \lambda_c|}$$

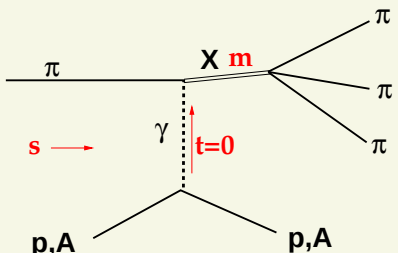
- Isospin Triplet States $I = 1$

[illegible]

- Isospin Singlet States $I = 0$



Primakoff Production $\rightarrow$ Radiative Widths



Photon exchange (Nucl.Field)

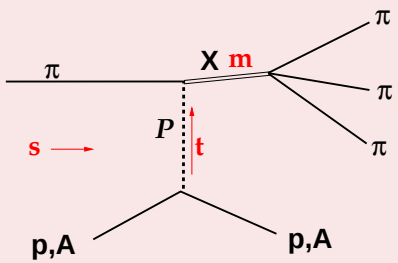
- $t \sim 0$
- Helicity $\lambda_x = 1$

Production Mechanisms at COMPASS

and most prominent Physics Motivations

Technische Universität München

Diffractive Dissociation → Search for Spin-Exotics



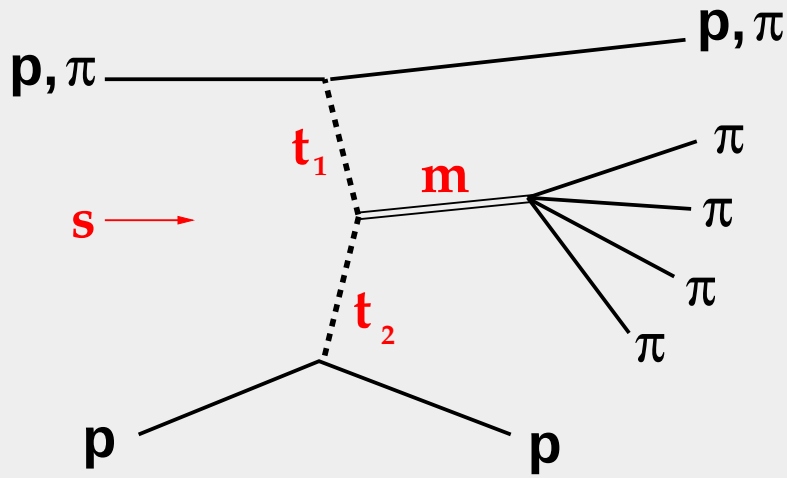
- Pomeron t-channel exchange

$$T \propto t^{\frac{1}{2}|\lambda_a - \lambda_x|} s^{\alpha(t)} t^{\frac{1}{2}|\lambda_b - \lambda_c|}$$

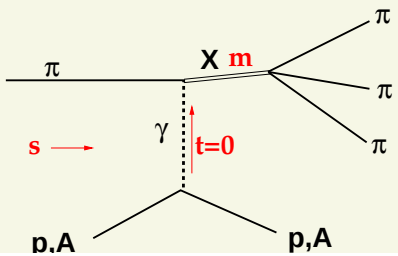
- Isospin Triplet States $I = 1$

Central Production → Glueball Search

- Pomeron-Pomeron fusion
- Isospin Singlet States $I = 0$



Primakoff Production → Radiative Widths



Pho

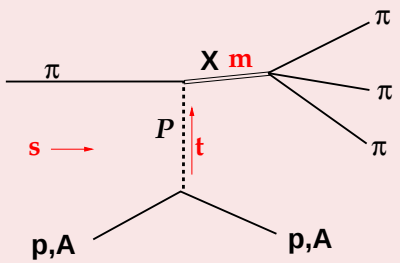
- $t \sim 0$
- Helicity $\lambda_X = 1$

Production Mechanisms at COMPASS

and most prominent Physics Motivations

Technische Universität München

Diffractive Dissociation $\rightarrow$ Search for Spin-Exotics



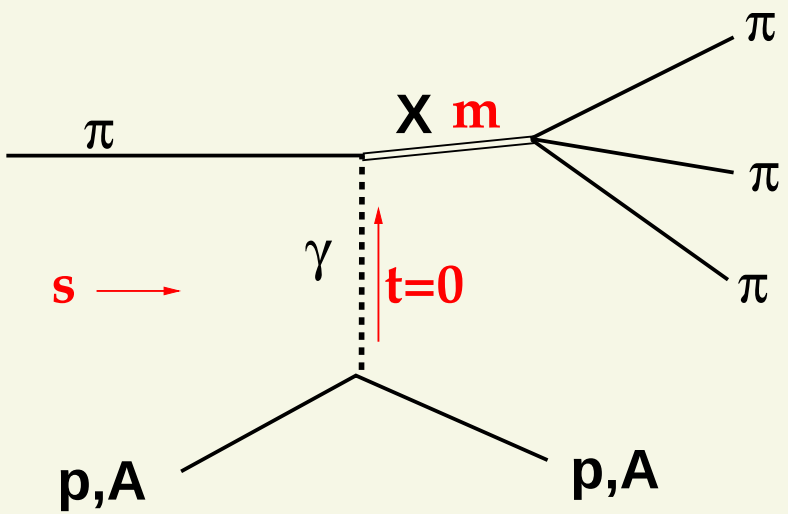
- Pomeron t-channel exchange

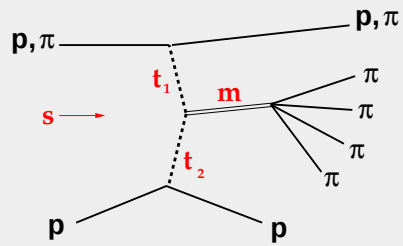
$$T \propto t^{\frac{1}{2}|\lambda_a - \lambda_x|} s^{\alpha(t)} t^{\frac{1}{2}|\lambda_b - \lambda_c|}$$

- Isospin Triplet States $I = 1$

Central Production $\rightarrow$ Glueball Search

Primakoff Production





dths

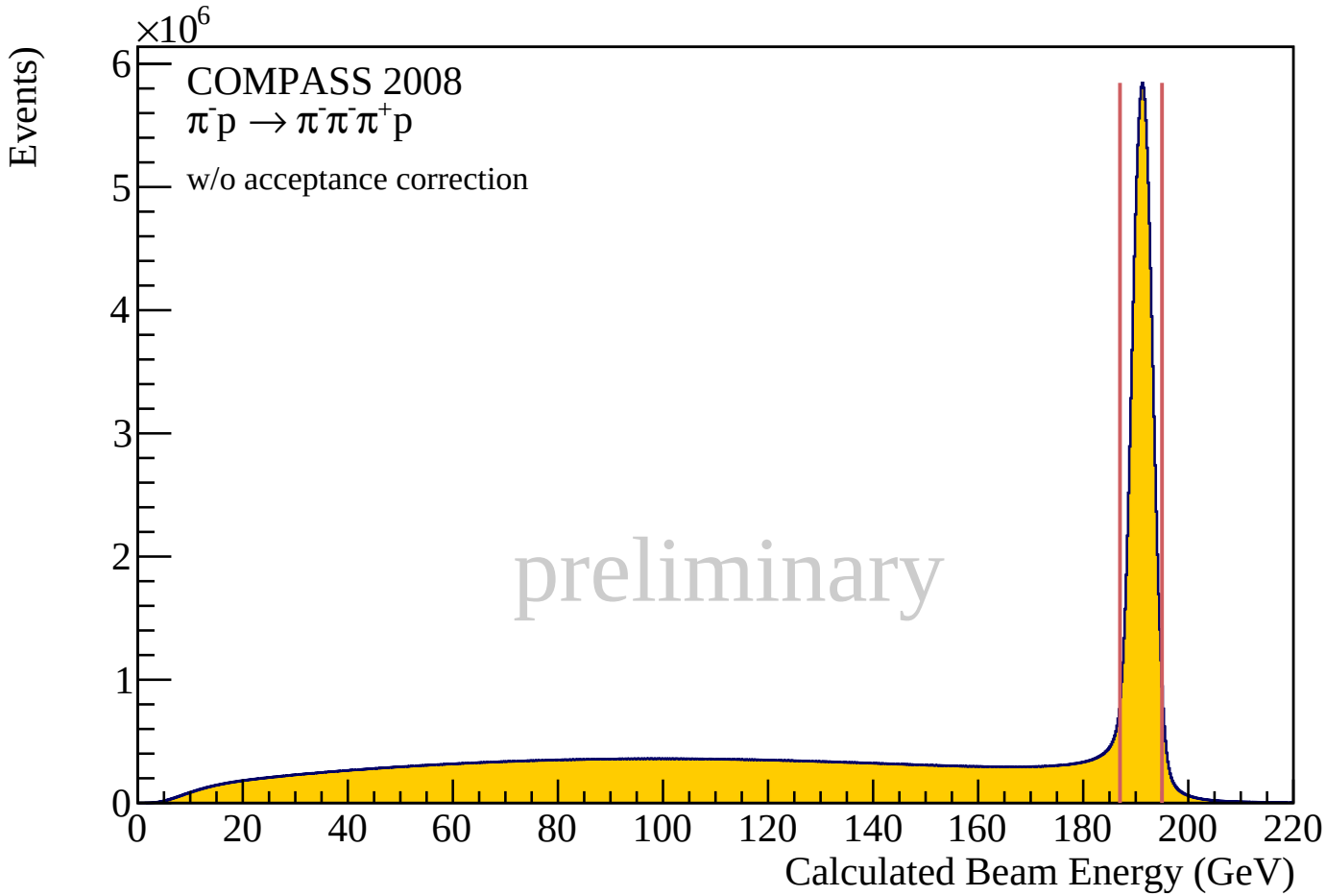
Photon exchange (Nucl.Field)

- $t \sim 0$
- Helicity $\lambda_x = 1$

Basic Event Selection - Exclusivity

E. g. $\pi^-\pi^-\pi^+$ similar for all analyses

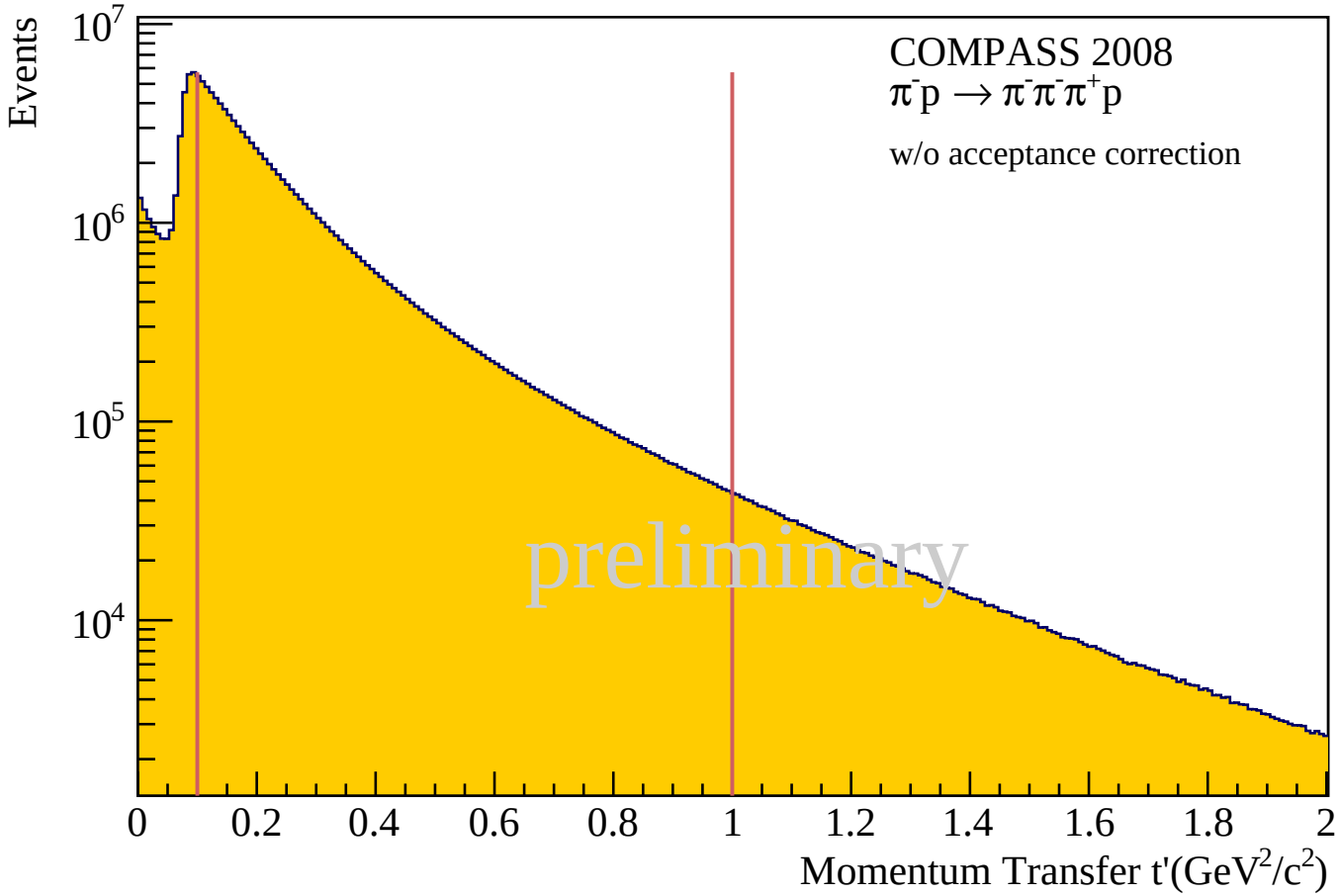
Technische Universität München



- Supplemented by recoil detector (see $\pi^-\pi^0\pi^0$ later in this talk)

Squared Momentum Transfer $t = -q^2$

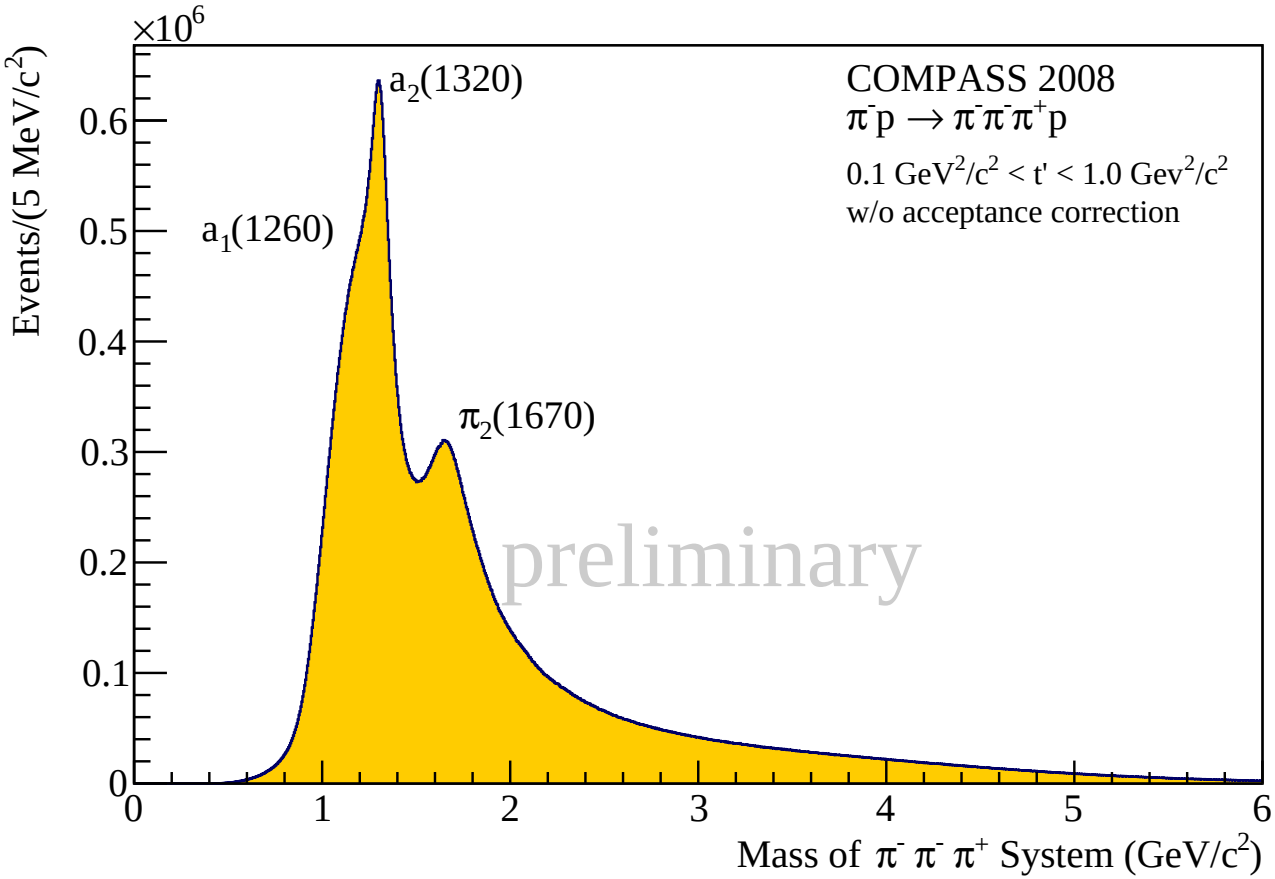
Diffractive Scattering



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

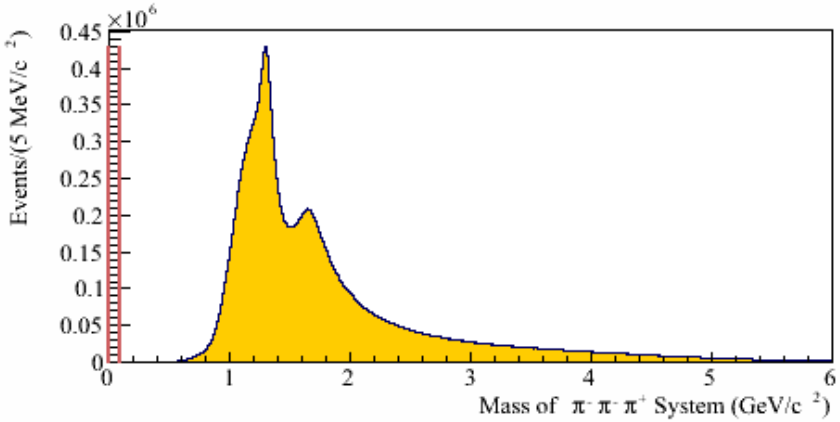
Invariant Mass Spectrum of $\pi^-\pi^-\pi^+$ (2008)

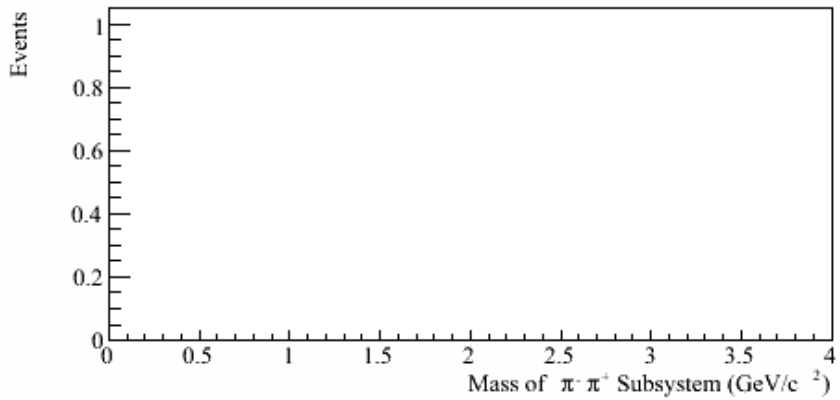
- 190 GeV/c hadron beam $\rightarrow$ $96\%\pi^-, 3.5\%K^-, 0.5\%\overline{p}$
- 40cm liquid hydrogen target
- $0.1\text{GeV}^2/c^2 < t' < 1.0\text{GeV}^2/c^2$
- $\sim$96M exclusive events (2008)

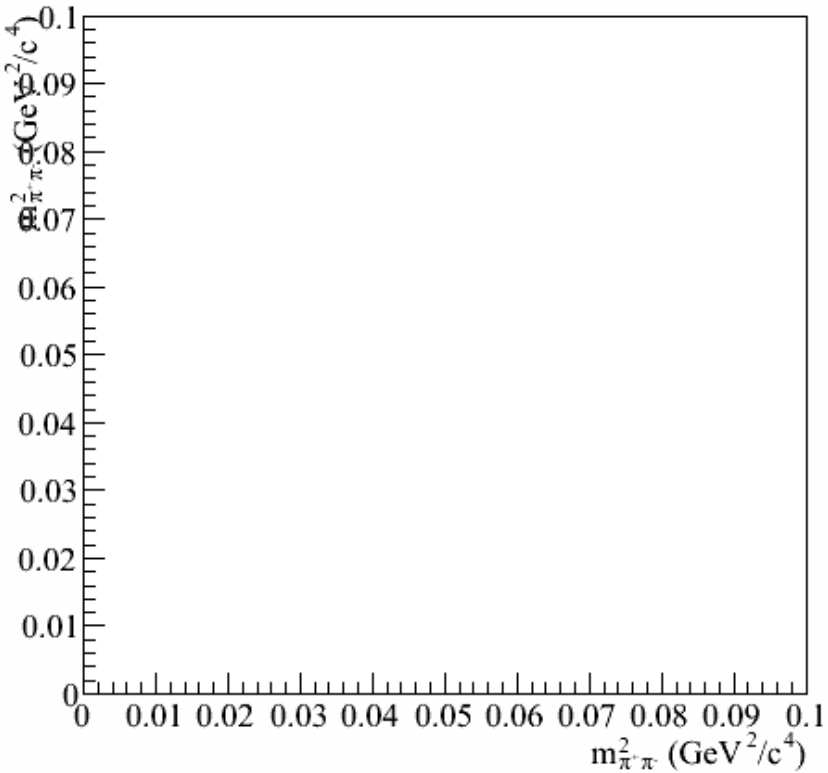


3π Dalitz Plots

Evolution with the 3π mass



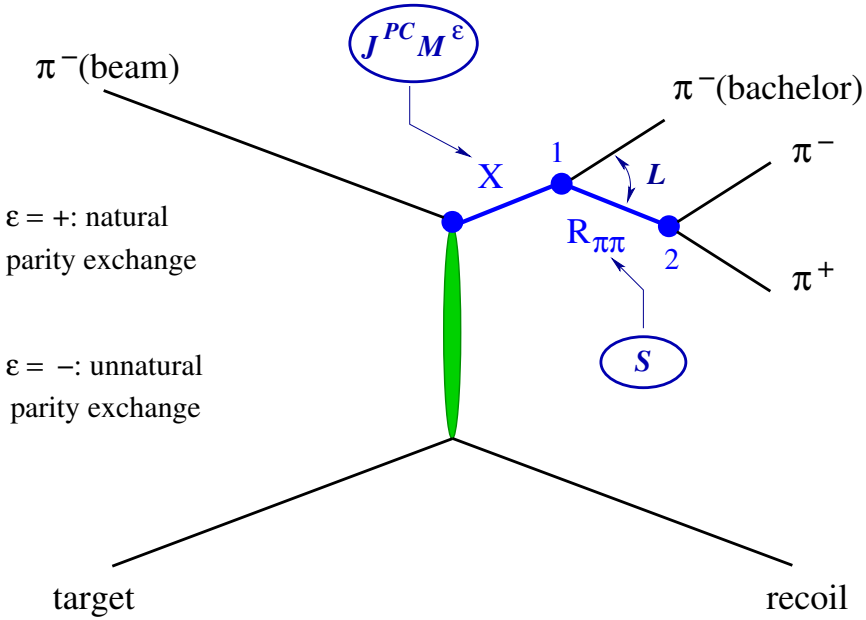




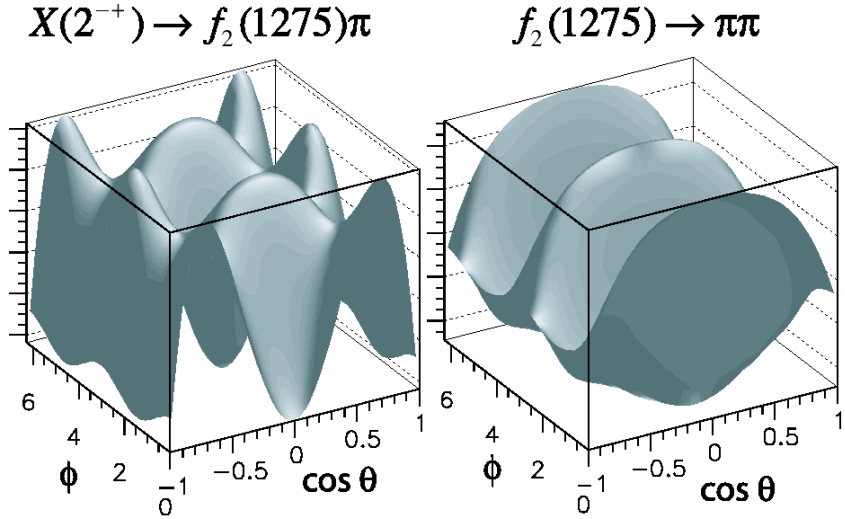
Decay Parameterization: The Isobar Model

Chain of successive 2-body decays

Model n-body decay by a chain of successive 2-body decays:



Example angular distributions:



- For fixed n-body mass m there are $3n - 4$ parameters (angles, intermediate state masses)
- Parameterization of isobar subsystems

PWA Formalism Redux

2Stage Isobar-Model Fit

Mass-Independent PWA

- Fit angular distributions + isobar systems in independent mass bins

$$\sigma(\tau, m) = \sum_{\epsilon=\pm 1} \sum_{r=1}^{N_r} \left| \sum_i T^{\epsilon}_{ir}(m) \, f^{\epsilon}_i(t') \, \psi^{\epsilon}_i(\tau, m) \right|^2$$

- Production amplitude
- t'-dependence (helicity "flip")
- Decay amplitude (Helicity formalism, reflectivity basis)

PWA Formalism Redux

2Stage Isobar-Model Fit

Mass-Independent PWA

- Fit angular distributions + isobar systems in independent mass bins

$$\sigma(\tau, m) = \sum_{\epsilon=\pm 1} \sum_{r=1}^{N_r} \left| \sum_{i} T_{ir}^{\epsilon}(m) \, f_i^{\epsilon}(t') \, \psi_i^{\epsilon}(\tau, m) \right|^2$$

- Production amplitude
- t'-dependence (helicity "flip")
- Decay amplitude (Helicity formalism, reflectivity basis)

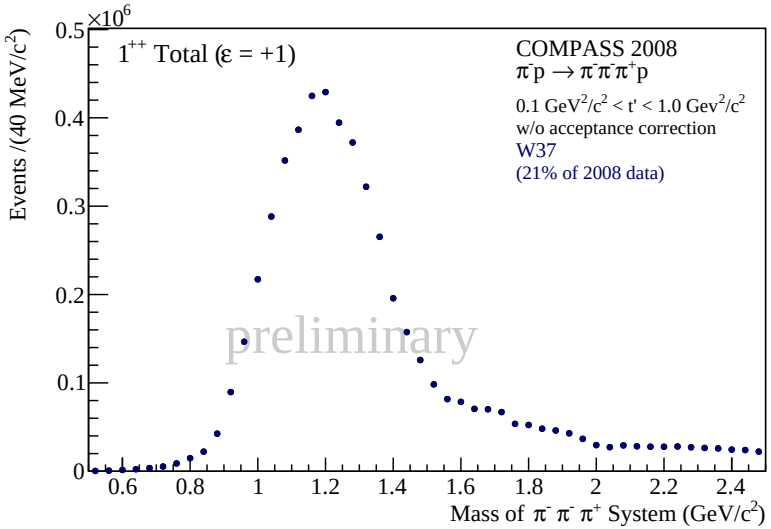
Mass-Dependent χ^2 fit $\rightarrow$ Extract Resonance Parameters

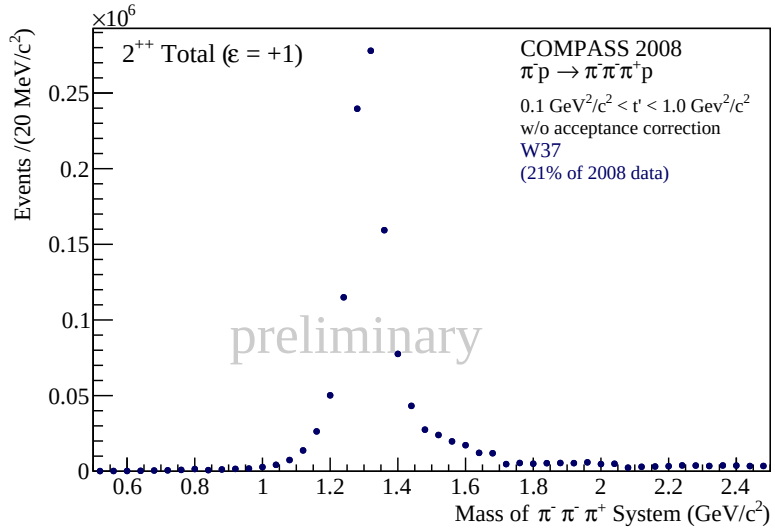
- Parameterization of spin-density matrix elements $\sum_r T_{ir}^{\epsilon} T_{jr}^{\epsilon *}(m_x)$
- Takes into account interference terms
- Coherent background for some waves

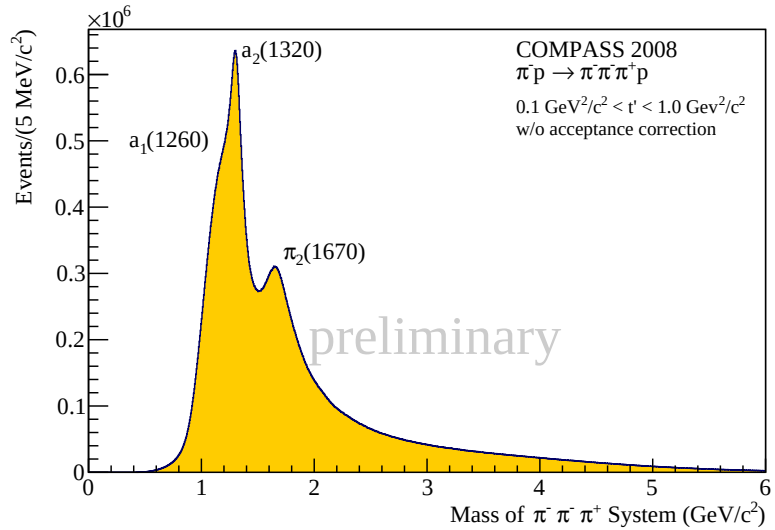
Intensities of dominant J^{PC} states

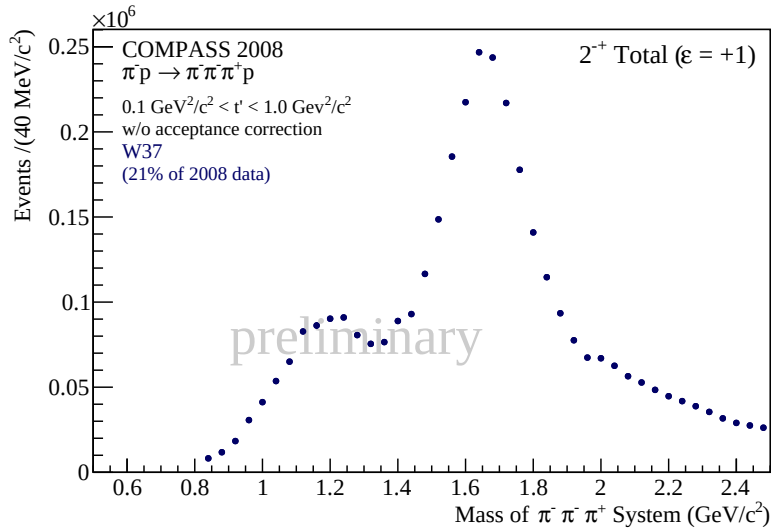
First results from mass independent PWA (2008)

Technische Universität München









First Publication on

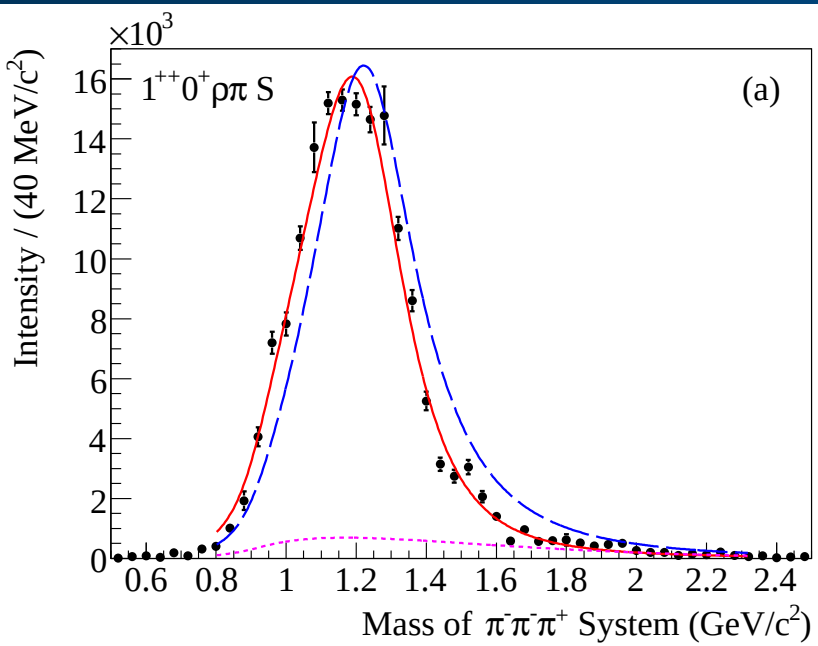
$$\pi^- + Pb \rightarrow \pi^-\pi^+\pi^- + Pb$$

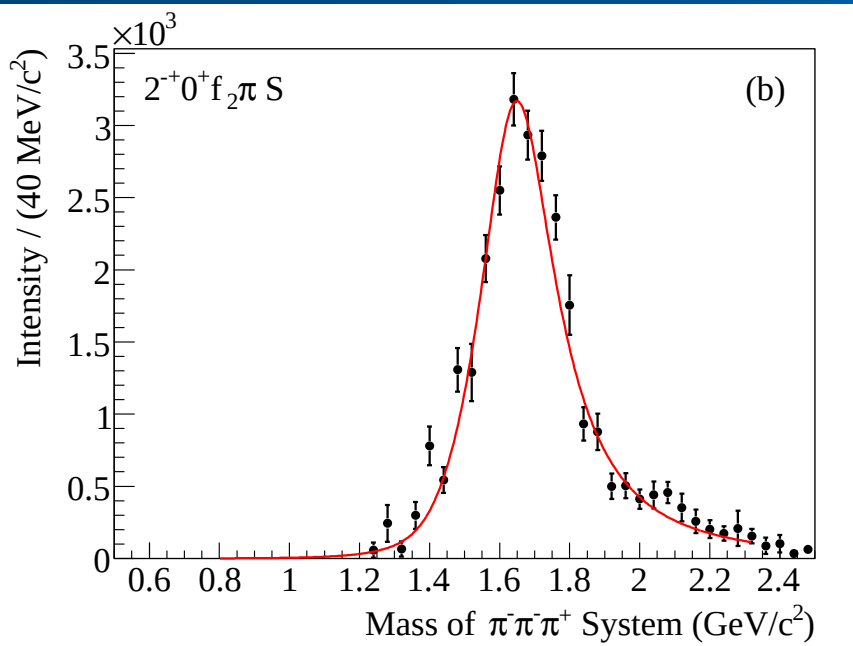
Phys. Rev. Lett. 104, 241803 (2010)

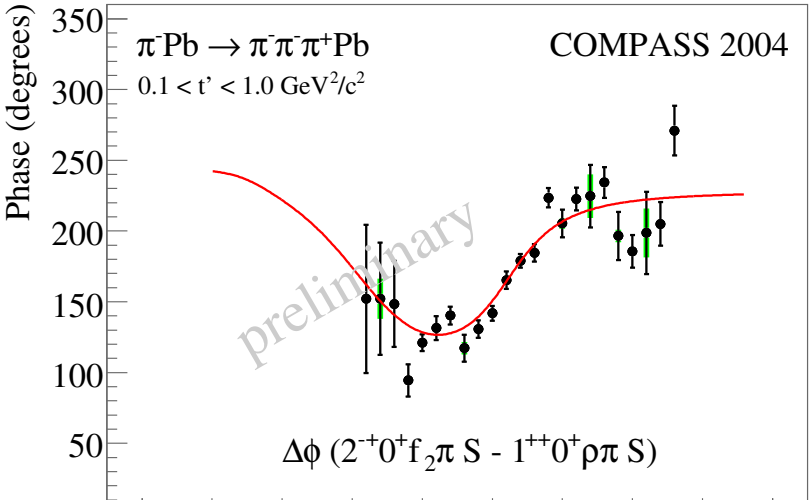
(2004 test-run data)

PWA Results for 2004 data

$1^{++}0^{+}\rho\pi S$ and $2^{-+}0^{+}f_2\pi S$



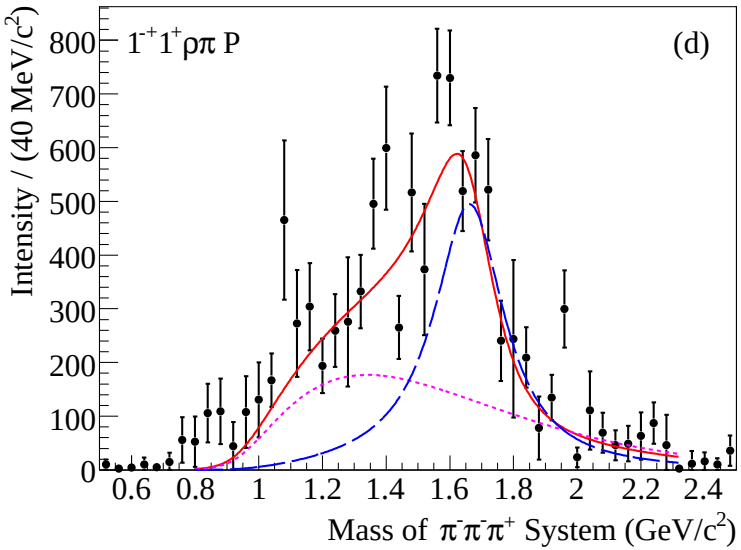


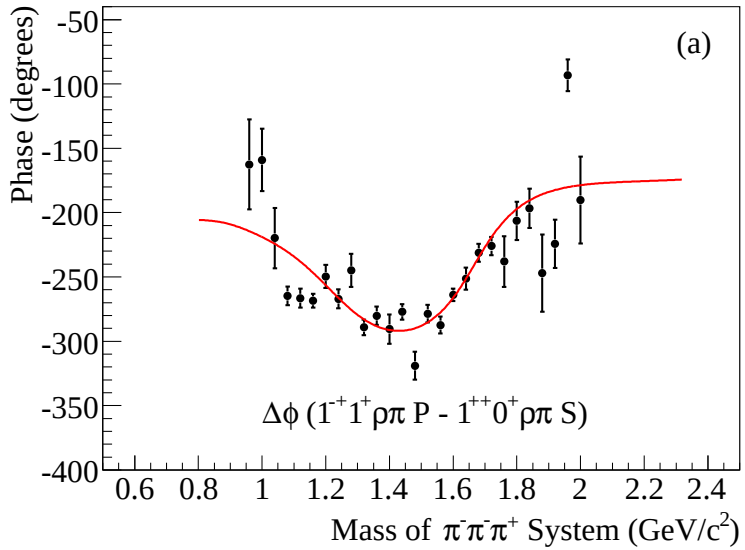


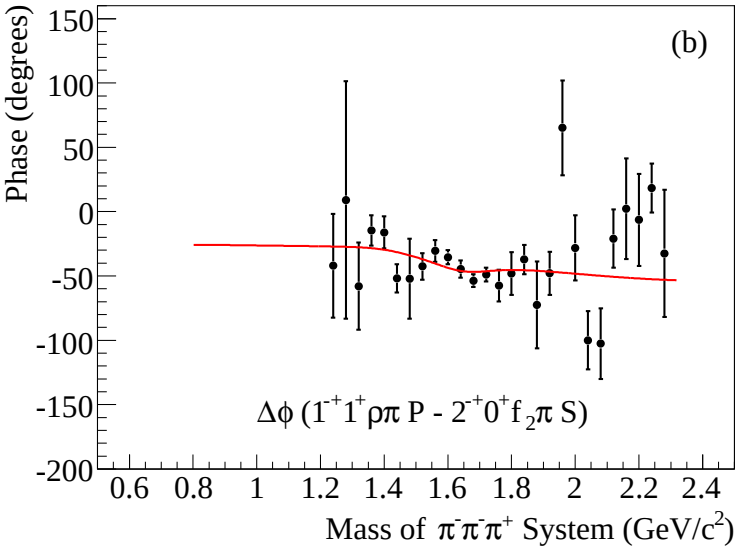
- BW for $a_1(1260)$ + background:
  $M = (1.255 \pm 0.006\ ^{+0.007}_{-0.017})\ \mathrm{GeV}/c^2$
  $\Gamma = (0.367 \pm 0.009\ ^{+0.028}_{-0.025})\ \mathrm{GeV}/c^2$
- BW for $\pi_2(1670)$:
  $M = (1.658 \pm 0.003\ ^{+0.024}_{-0.008})\ \mathrm{GeV}/c^2$
  $\Gamma = (0.271 \pm 0.009\ ^{+0.022}_{-0.024})\ \mathrm{GeV}/c^2$

Observation of a $J^{PC} = 1^{-+}$ Exotic

Phys. Rev. Lett. 104, 241803 (2010) $\pi^- + Pb \to \pi^-\pi^+\pi^- + Pb$ (2004 data)







- Significant 1^{-+} amplitude consistent with resonance at $\sim 1.7\,\mathrm{GeV}/c^2$
- No leakage observed ($< 5\%$)
- BW for $\pi_1(1600)$ + background:
  $M = (1.660 \pm 0.010\ ^{+0.000}_{-0.064})\,\mathrm{GeV}/c^2$
  $\Gamma = (0.269 \pm 0.021\ ^{+0.042}_{-0.064})\,\mathrm{GeV}/c^2$

Future Strategy on 1^{-+} Spin-Exotic

- Repeat analysis on 96M events π^- p$\rightarrow \pi^-\pi^-\pi^+$p
- Confirm Isospin $I = 1$ assignment in π^- p$\rightarrow \pi^-\pi^0\pi^0$p
- Look for state in further channels
  - $f_1\pi$, $b_1\pi$, $\eta\pi$, $\eta'\pi$...
  - Hybrid nature?
- Repeat measurement on nuclear targets (2009, improved acceptance)
- Study rescattering effects
- Search for Isospin $I = 0$ partner $\eta_1(1600)$

Spin Alignment Effect?
Helicity M
Comparison Pb/lH_2 Targets

A Spin Alignment Effect in 3π Production?

Comparison of fit results 2004/2008 data

- 2004 lead target, 2008 liquid hydrogen target
- Different statistcis
  - Normalisation to the integral of the $a_2(1320)$ in the mass region between 1.1 GeV/c^2 and 1.6 GeV/c^2
- Components with same Spin J but different Helicities $M = J_z$:

$$\left[\frac{Intensity(M=1)}{Intensity(M=0)}\right]_{Pb} > \left[\frac{Intensity(M=1)}{Intensity(M=0)}\right]_{H_2}$$

Total $J^{PC} = 1^{++}$ Intensity: Pb vs. H_2

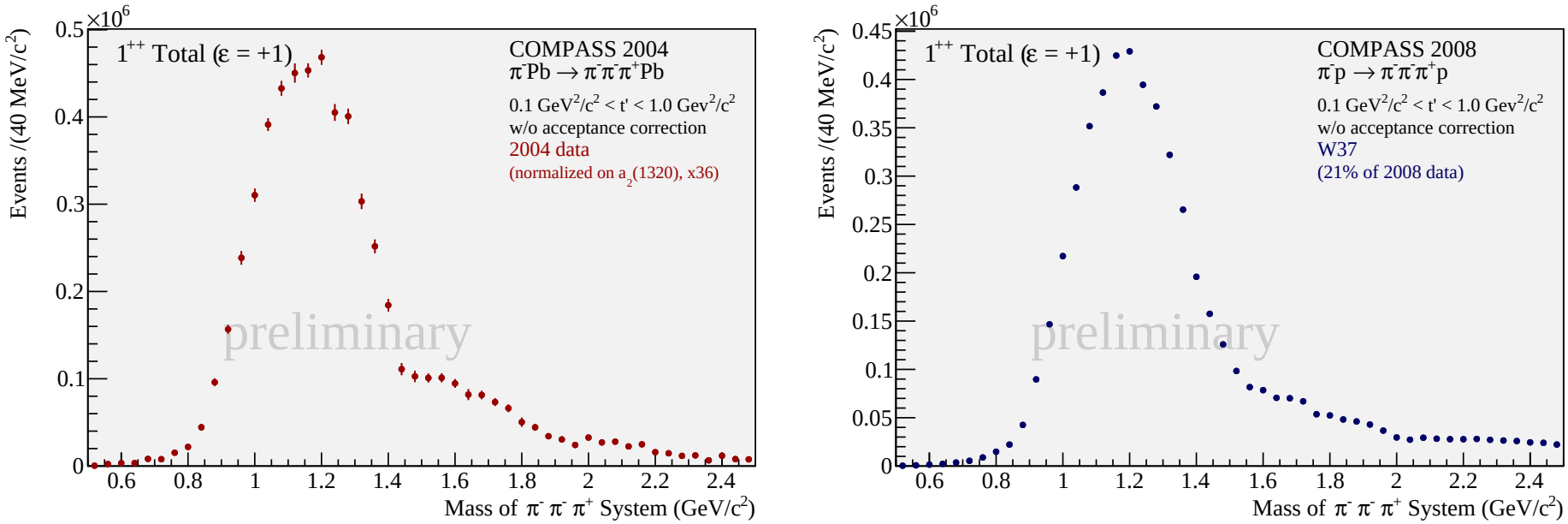


Figure: Total Intensities for $J^{PC} = 1^{++}$ (2004 red, 2008 blue)

$J^{PC} = 1^{++}$ with $M = 0$: Pb vs. H_2

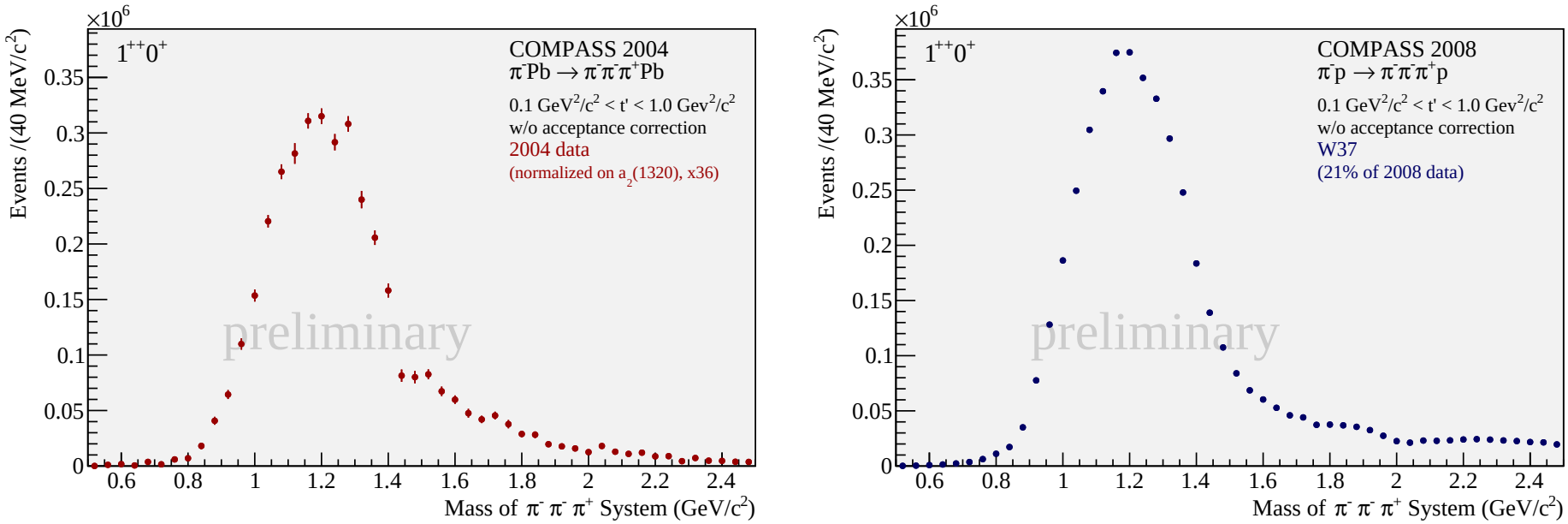


Figure: Total Intensities for $J^{PC} = 1^{++}$ with $M = 0$ (2004 red, 2008 blue)

$J^{PC} = 1^{++}$ with $M = 1$: Pb vs. H_2

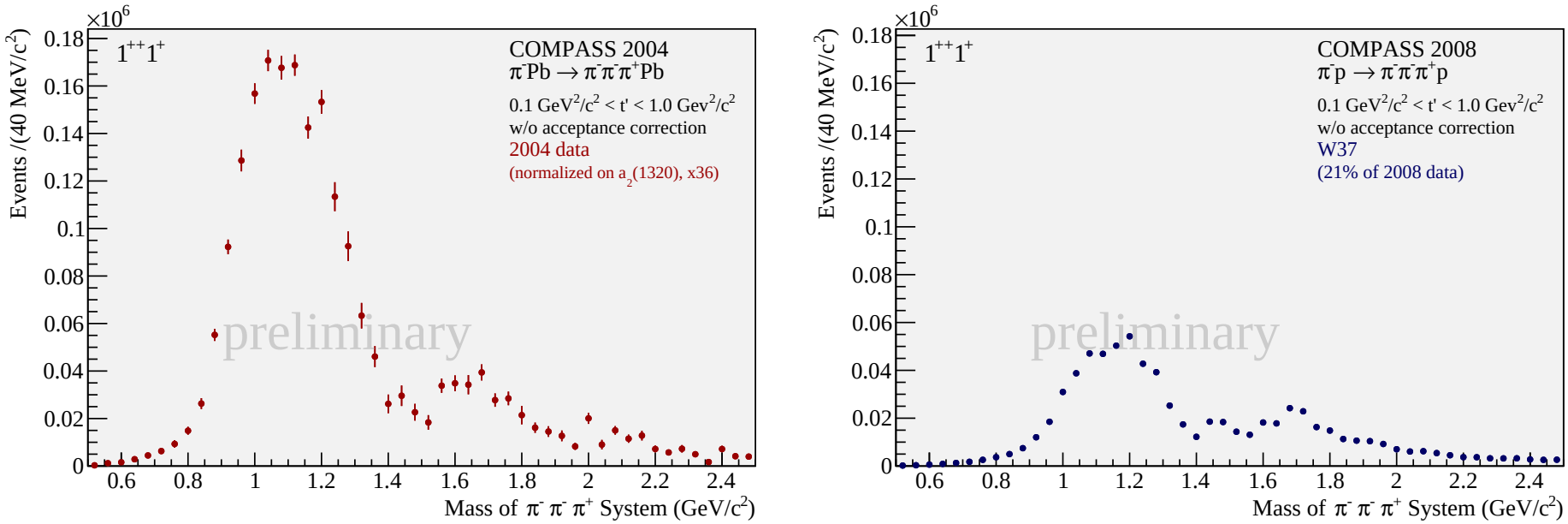


Figure: Total Intensities for $J^{PC} = 1^{++}$ with $M = 1$ (2004 red, 2008 blue)

Total $J^{PC} = 2^{-+}$ Intensity: Pb vs. H_2

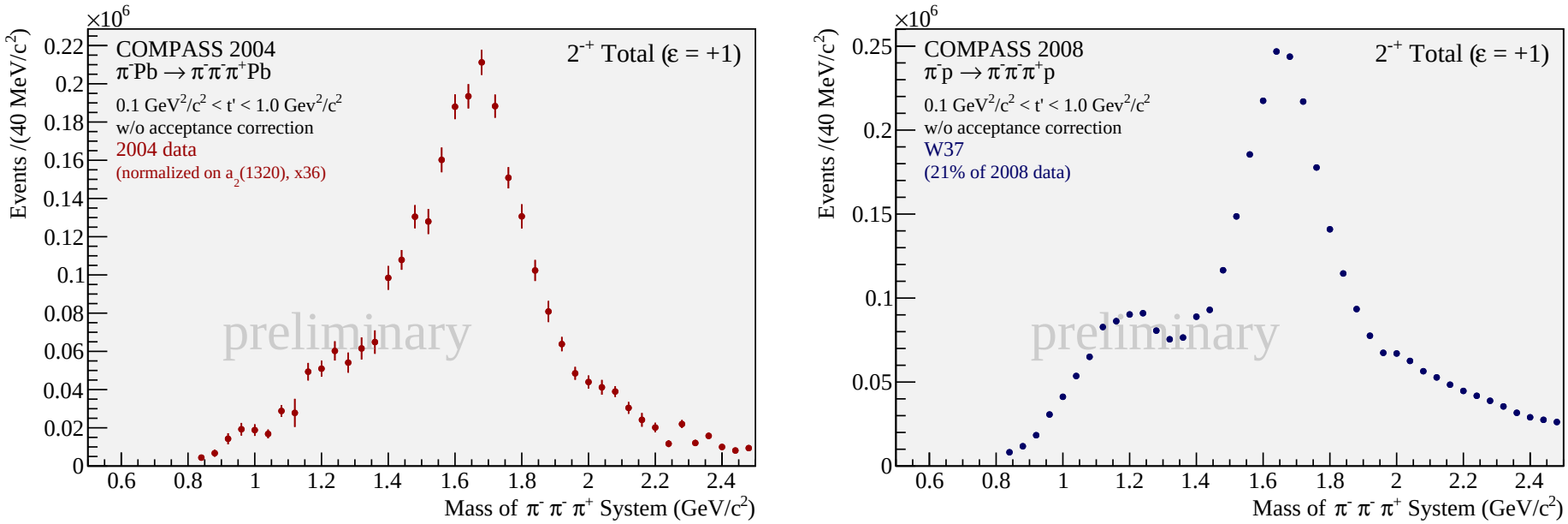


Figure: Total Intensities for $J^{PC} = 2^{-+}$ (2004 red, 2008 blue)

$J^{PC} = 2^{-+}$ with $M = 0$: Pb vs. H_2

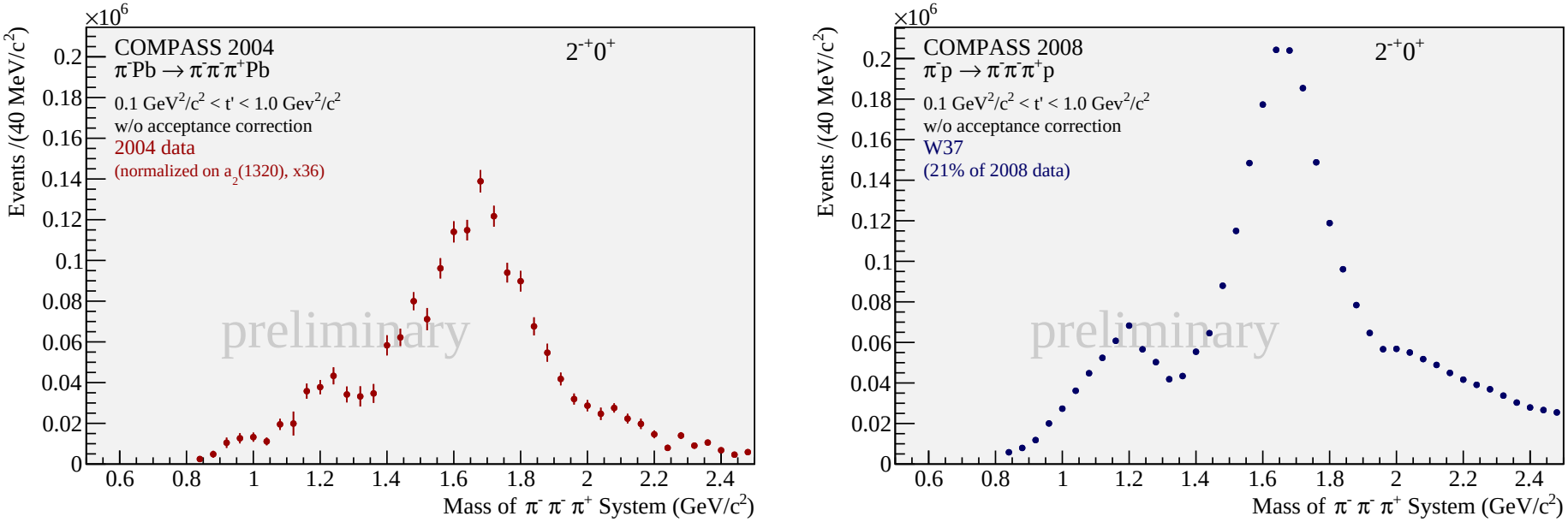


Figure: Total Intensities for $J^{PC} = 2^{-+}$ with $M = 0$ (2004 red, 2008 blue)

$J^{PC} = 2^{-+}$ with $M = 1$: Pb vs. H_2

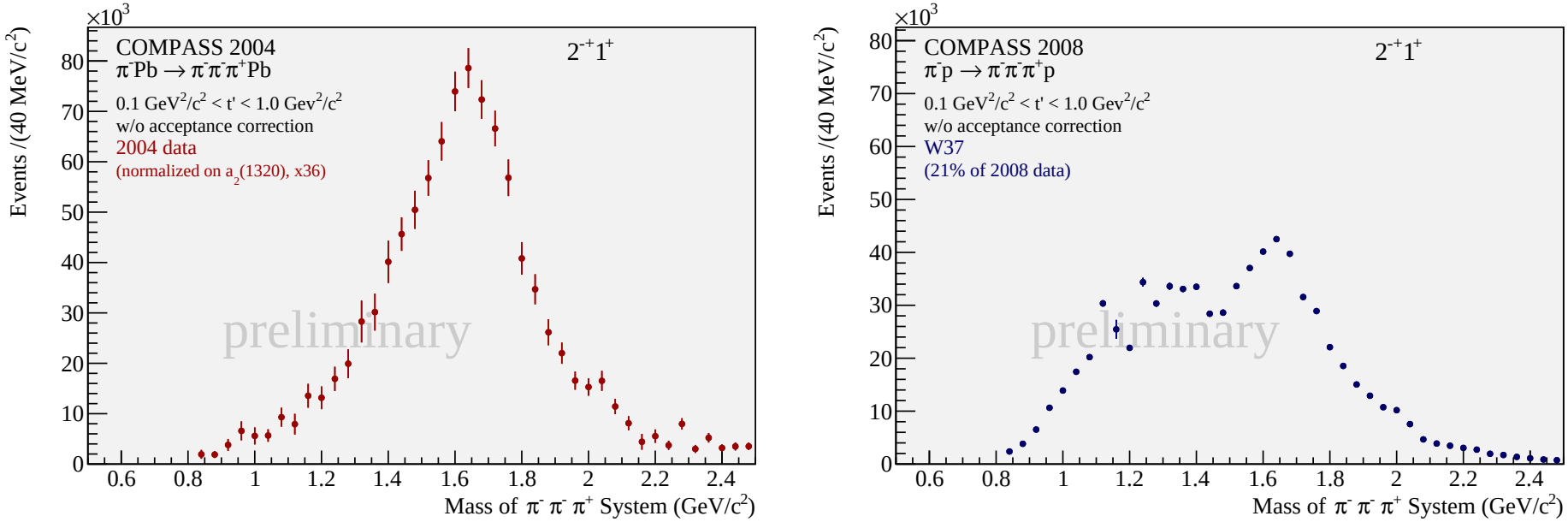
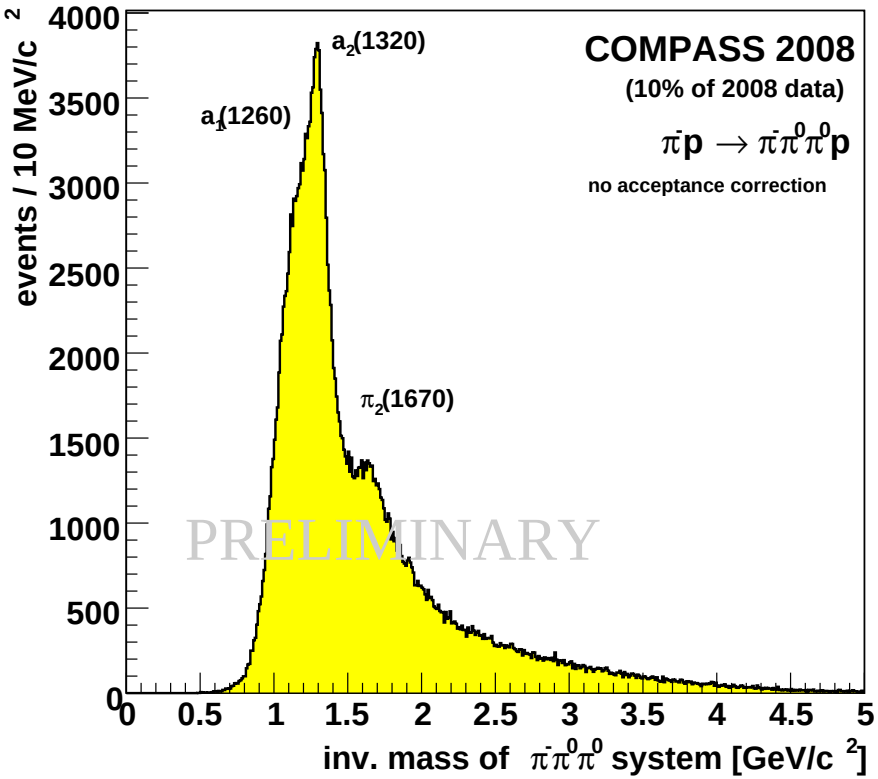


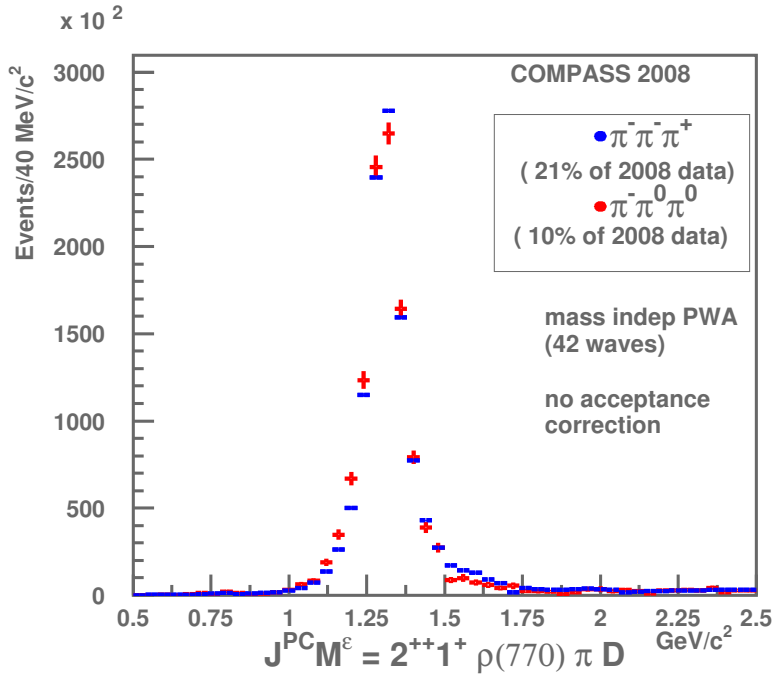
Figure: Total Intensities for $J^{PC} = 2^{-+}$ with $M = 1$ (2004 red, 2008 blue)

A Tour through Recent Data

$\pi^-\pi^0\pi^0$ Final State

Mass spectrum and first fit $\rightarrow$ a_2 peak

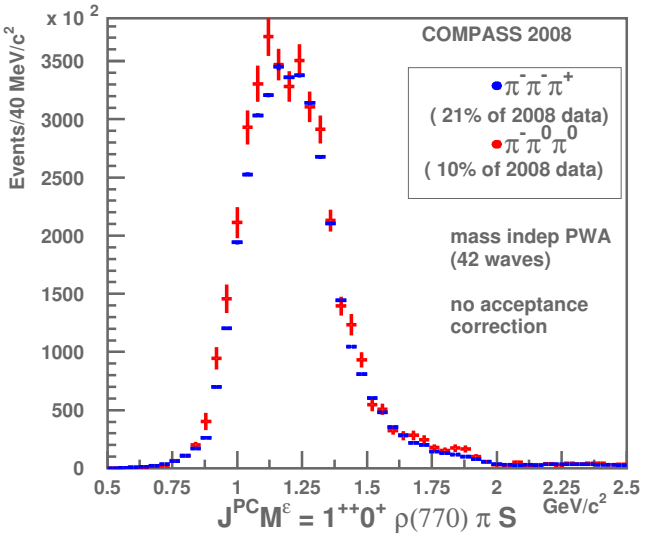


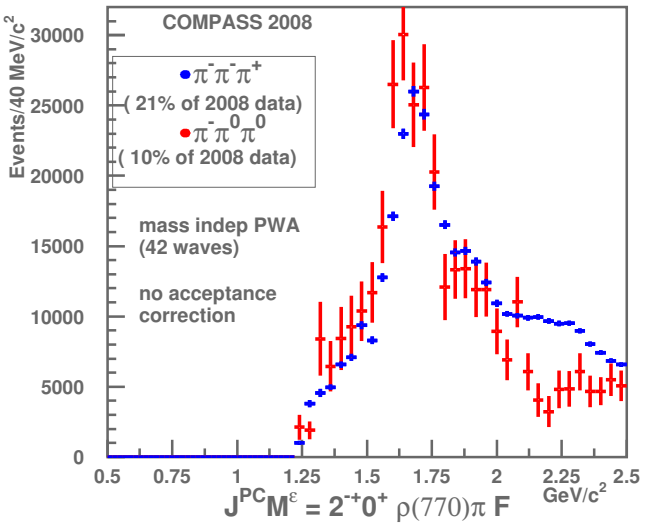


use $a_2(1320)$ for normalization

First results from 3π PWA (2008)

Comparison: $\pi^-\pi^+\pi^-$ vs. $\pi^-\pi^0\pi^0$ (normalized on $a2(1320)$ peak)

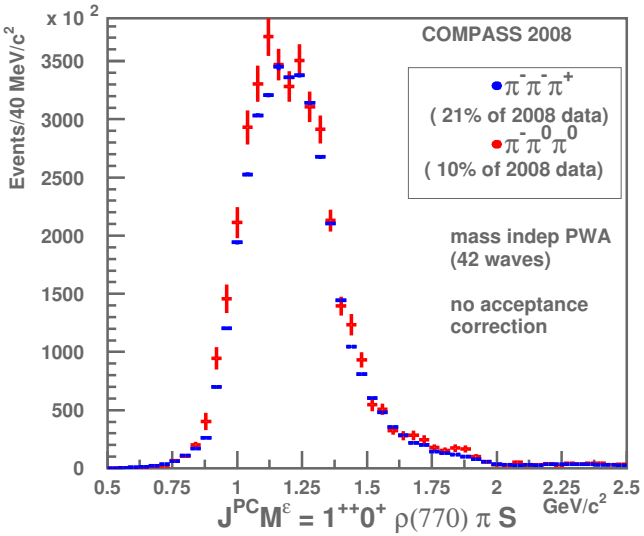


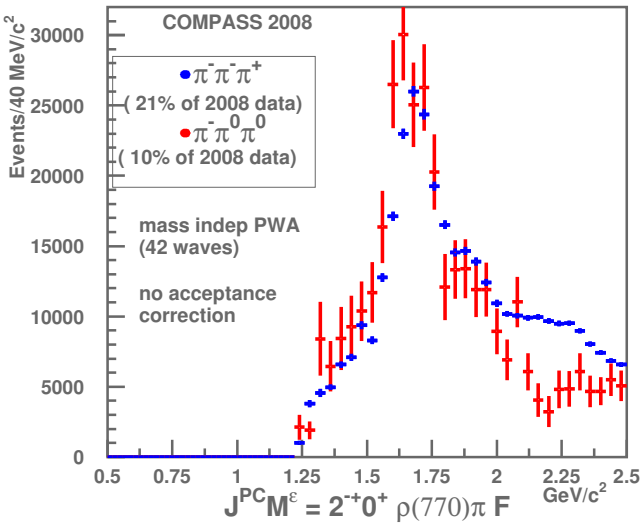


- Isospin symmetry
  $\pi^-\pi^+\pi^-$ vs. $\pi^-\pi^0\pi^0$
- $I = 0$ vs $I = 1$ $\pi\pi$ isobars
- $\Rightarrow$ factor 2 between
  $\pi^-\pi^+\pi^-$ and $\pi^-\pi^0\pi^0$ for $I_{\pi\pi} = 0$
  (Isospin Clebsch Gordan)

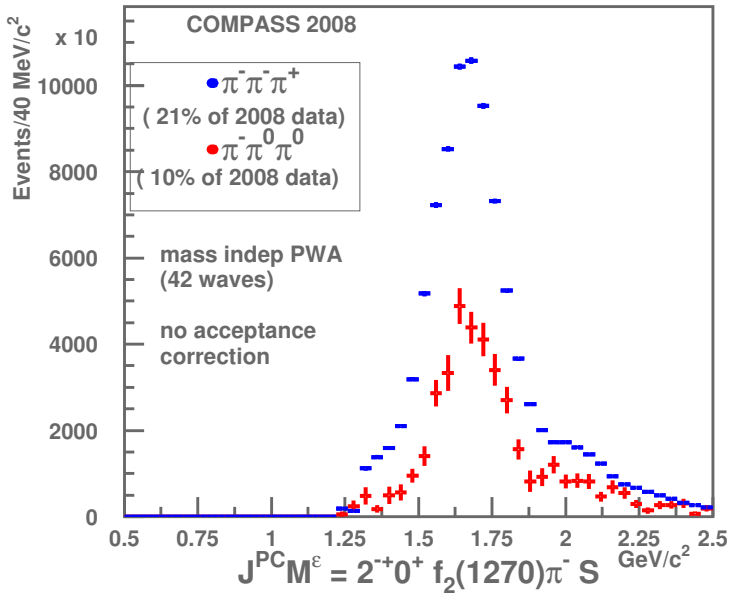
First results from 3π PWA (2008)

Comparison: $\pi^-\pi^+\pi^-$ vs. $\pi^-\pi^0\pi^0$ (normalized on $a2(1320)$ peak)



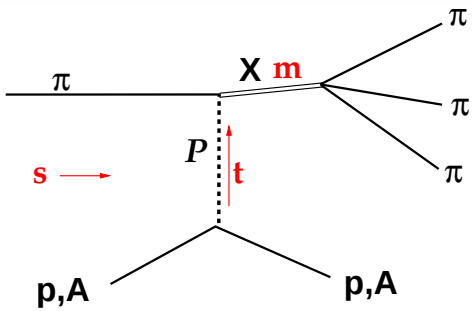


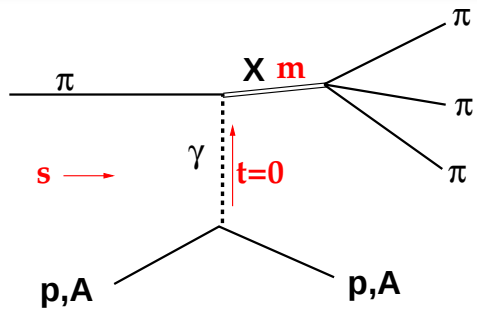
- Isospin symmetry
  $\pi^-\pi^+\pi^-$ vs. $\pi^-\pi^0\pi^0$
- $I = 0$ vs $I = 1$ $\pi\pi$ isobars
- $\Rightarrow$ factor 2 between
  $\pi^-\pi^+\pi^-$ and $\pi^-\pi^0\pi^0$ for $I_{\pi\pi} = 0$
  (Isospin Clebsch Gordan)



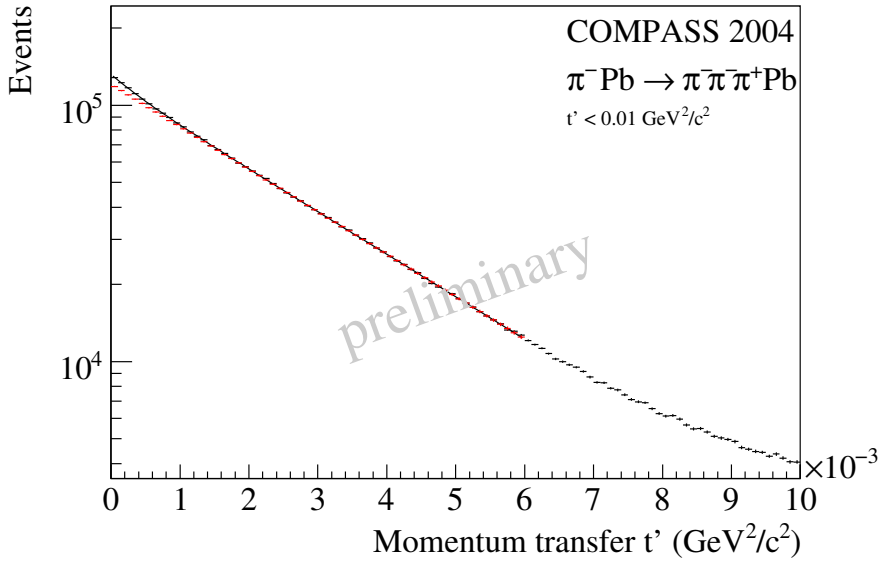
Primakoff Production of 3π States

Statistical Subtraction of Diffractive Component at low t'





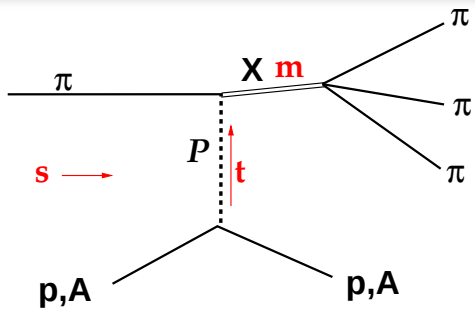
- Diffraction: Spinprojection $M_J^X = 1$ suppressed for $t \to 0$
- Primakoff photon: helicity 1 $\Rightarrow M = \pm 1$ expected

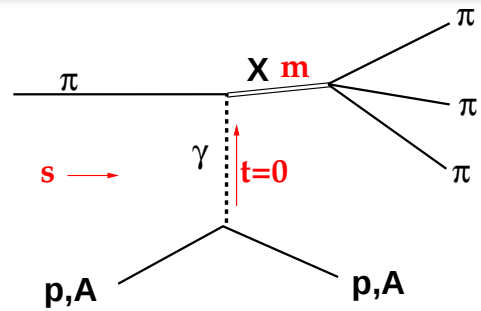


Primakoff Production of 3π States

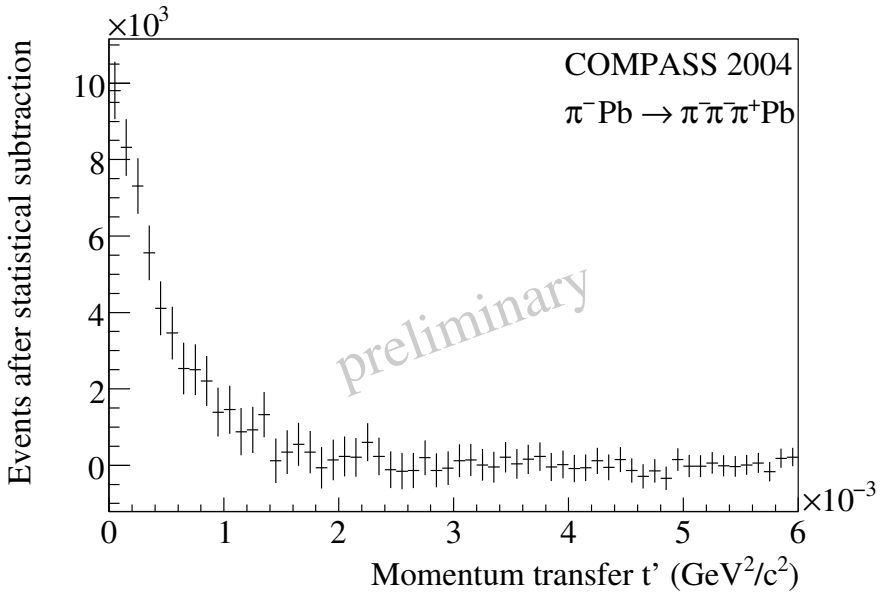
Statistical Subtraction of Diffractive Component at low t'

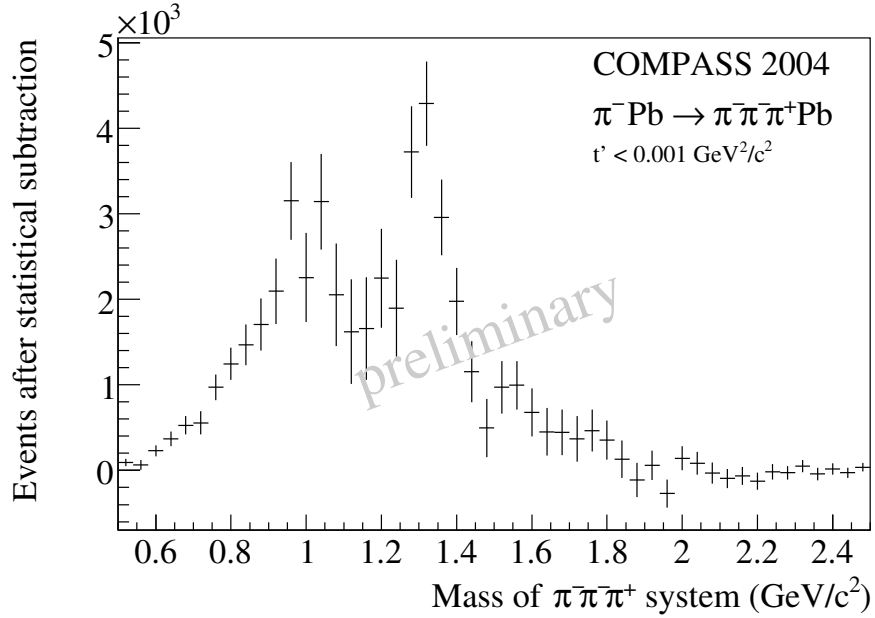
Technische Universität München





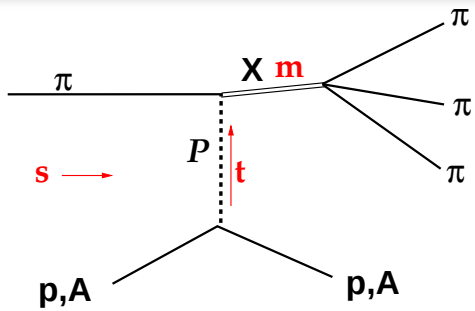
- Diffraction: Spinprojection $M_J^X = 1$ suppressed for $t \to 0$
- Primakoff photon: helicity 1 $\Rightarrow M = \pm 1$ expected

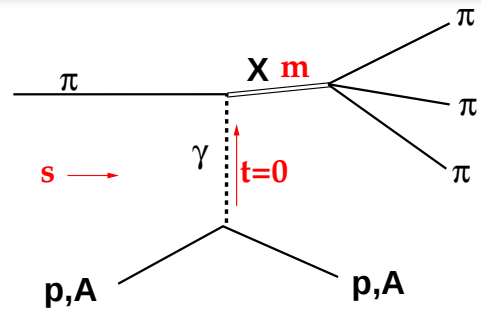




Primakoff Production of 3π States

Statistical Subtraction of Diffractive Component at low t'

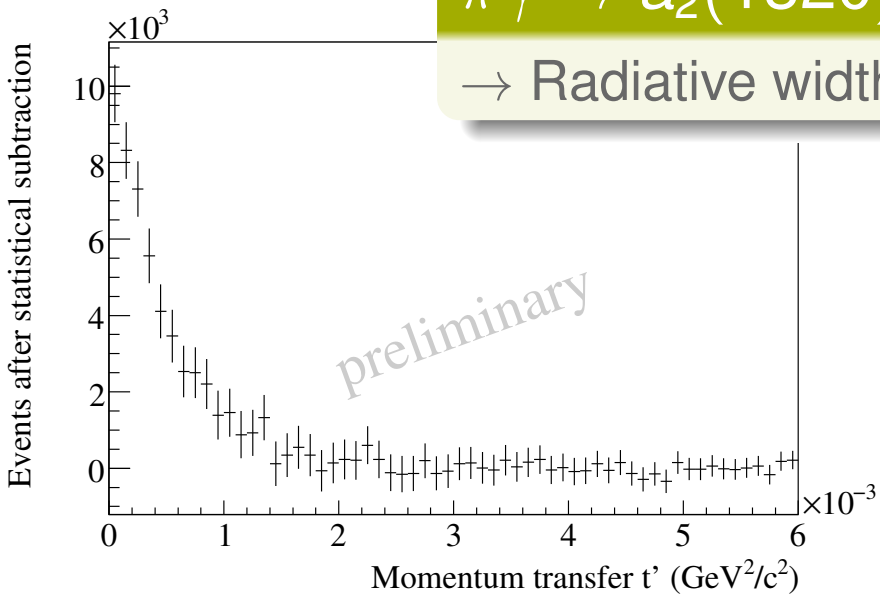


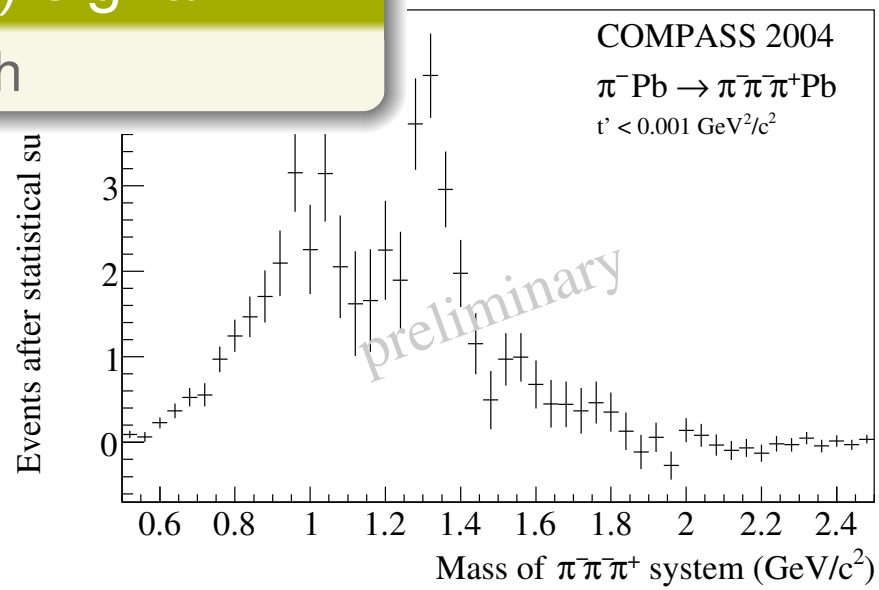


- Diffraction: Spinprojection $M_J^X = 1$ suppressed for $t \to 0$
- Primakoff photon: helicity 1 $\Rightarrow M = +1$ expected

$\pi\gamma \to a_2(1320)$ signal

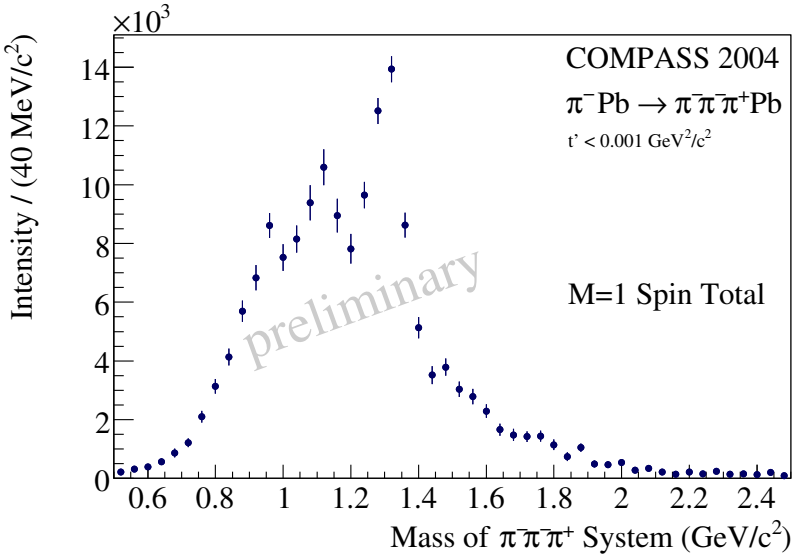
$\to$ Radiative width



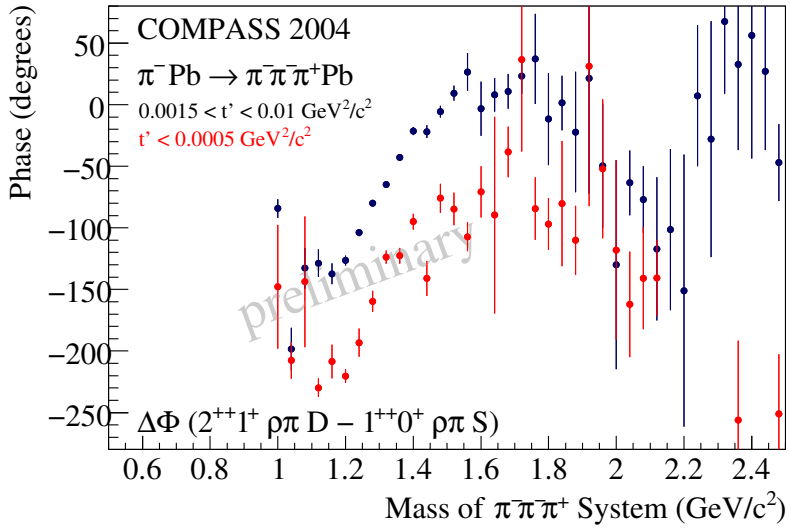


Extraction of a2(1320) Production Phase

- Partial wave fit $\Rightarrow 1^{++}$ and 2^{++} signals
- 2^{++} only produced with $M \geq 1$ (natural parity exchange)



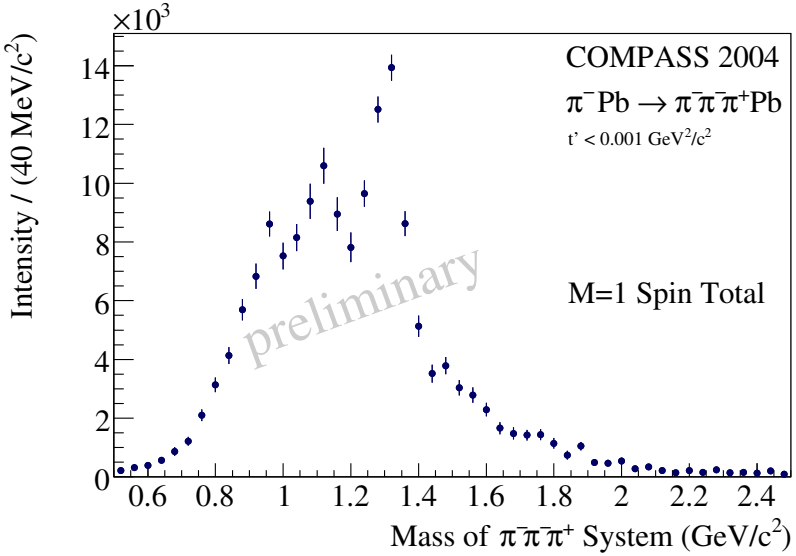
Total intensity with $M = 1$



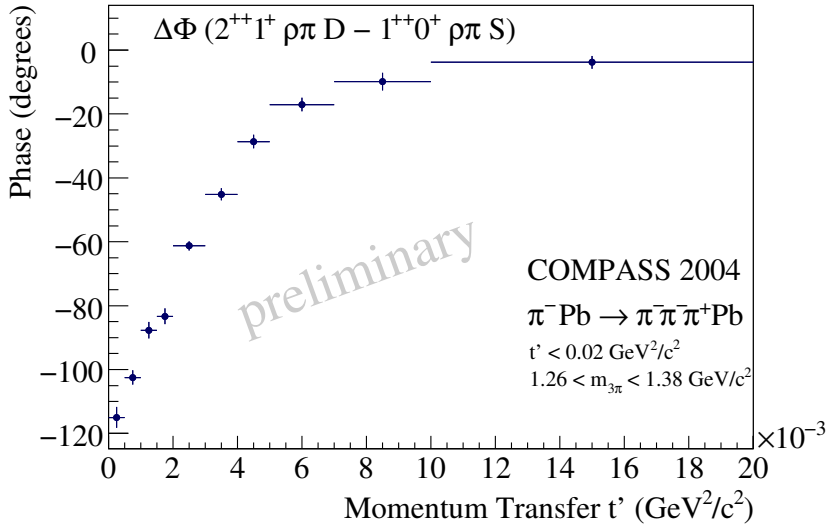
$a_2 - a_1$ phase difference

Extraction of a2(1320) Production Phase

- Partial wave fit $\Rightarrow 1^{++}$ and 2^{++} signals
- 2^{++} only produced with $M \geq 1$ (natural parity exchange)



Total intensity with $M = 1$



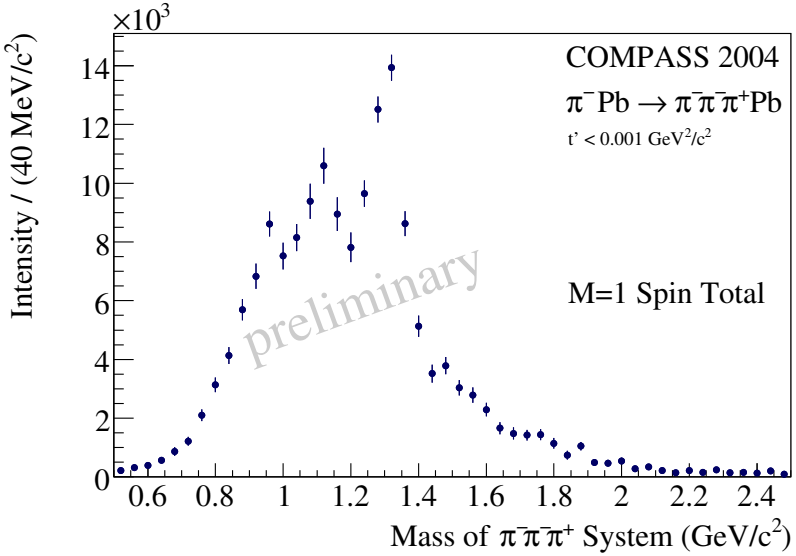
$a_2 - a_1$ phase difference

Extraction of a2(1320) Production Phase

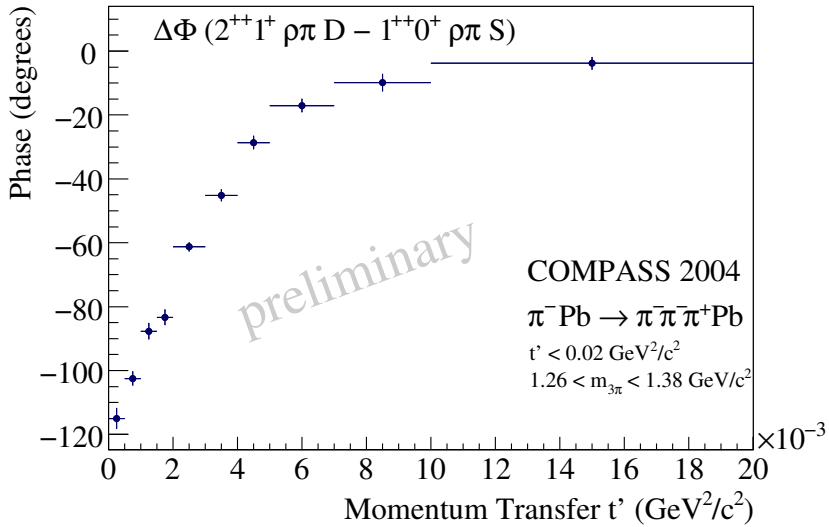
- Partial wave fit $\Rightarrow 1^{++}$ and 2^{++} signals
- 2^{++} only produced with $M \geq 1$ (natural

Interpretation

Transition from dominantly Primakoff to dominantly diffractive production



Total intensity with $M = 1$

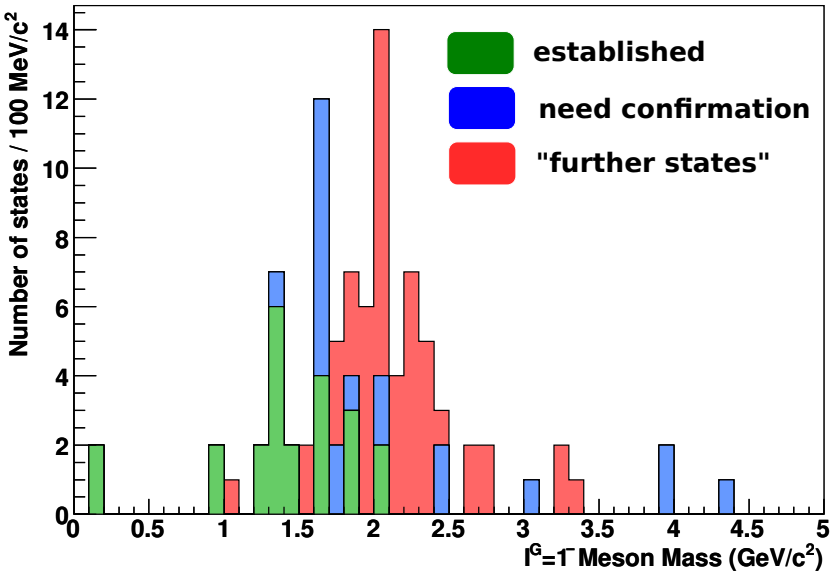


$a_2 - a_1$ phase difference

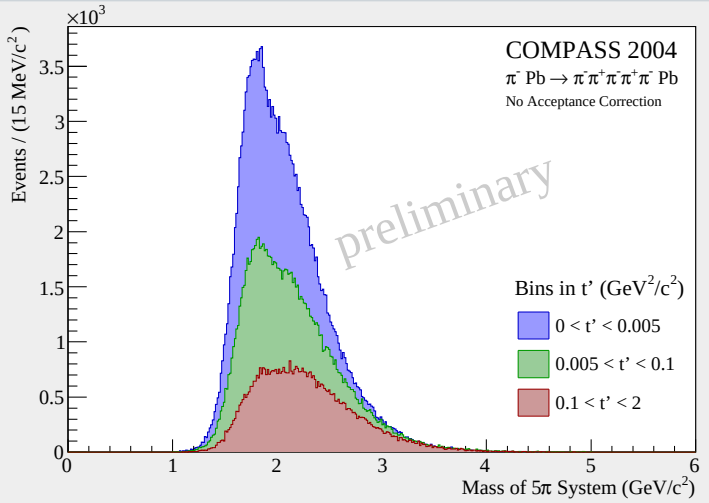
Multiparticle Final States: $\pi^-\pi^+\pi^-\pi^+\pi^-$

2004 Data Sample – Pb target

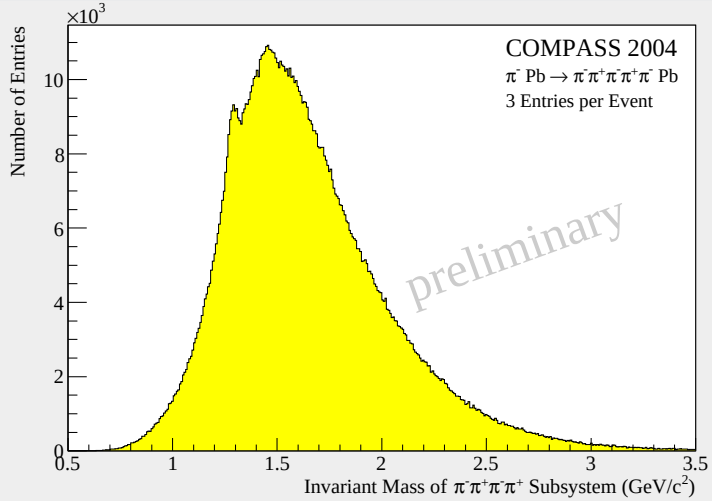
- Mass range $> 2\,\mathrm{GeV}/c^2$
- *Light meson frontier*:
  many disputed states in this region
  $(0^{-+})(1^{++})(1^{-+})(2^{-+})(4^{++})(4^{-+})$...
- Parity doublets?
  Effective restoration of classical QCD symmetries?



5π invariant mass



4π invariant mass $\rightarrow$ $f1(1285)$



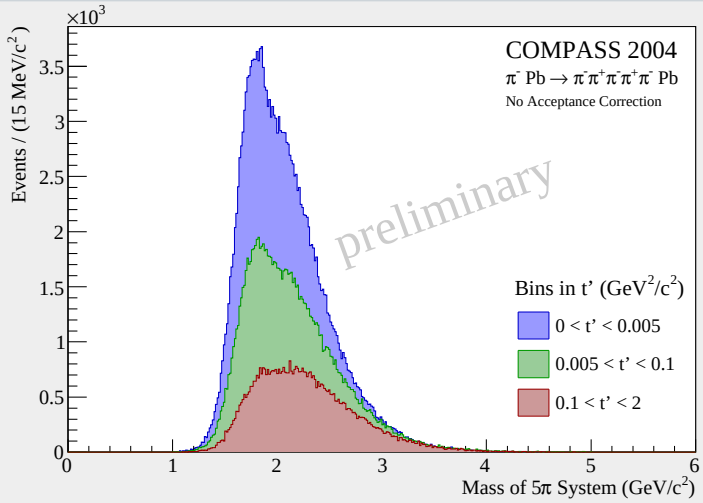
Multiparticle Final States: $\pi^-\pi^+\pi^-\pi^+\pi^-$

2004 Data Sample – Pb target

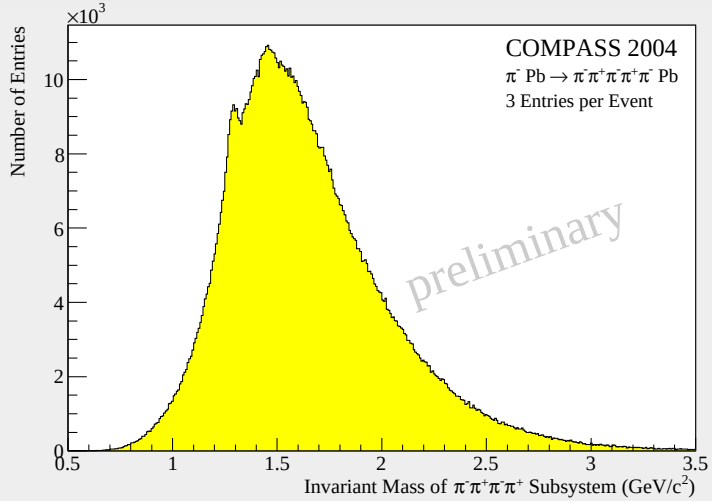
- Mass range $> 2\,\mathrm{GeV}/c^2$
- *Light meson frontier*:
  many disputed states in this region
  $(0^{-+})(1^{++})(1^{-+})(2^{-+})(4^{++})(4^{-+})$...
- Parity doublets?
  Effective restoration of classical QCD symmetries?

- Decay modes $b_1\pi$, $f_1\pi$, $\rho'\pi$
- Interesting 4π subsystem
- Complex isobar decays
- New algorithmic approaches
  $\rightarrow$ e. g. Genetic Optimization
  & Bayesian model evaluation

5π invariant mass

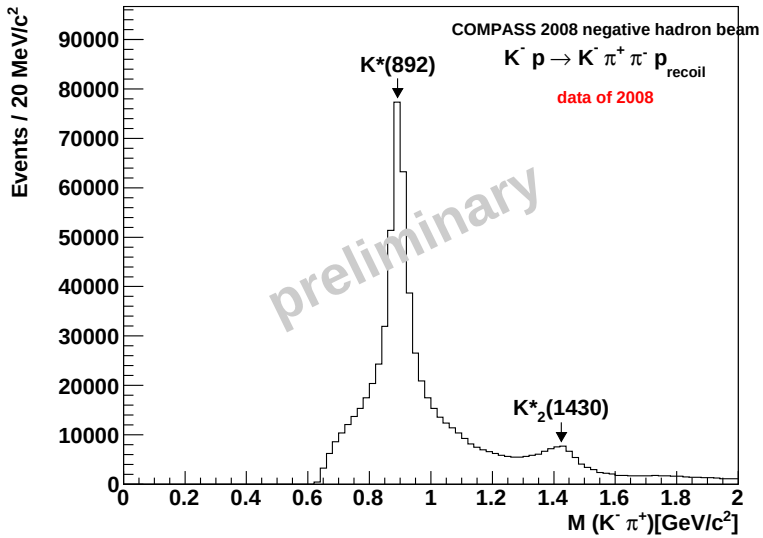


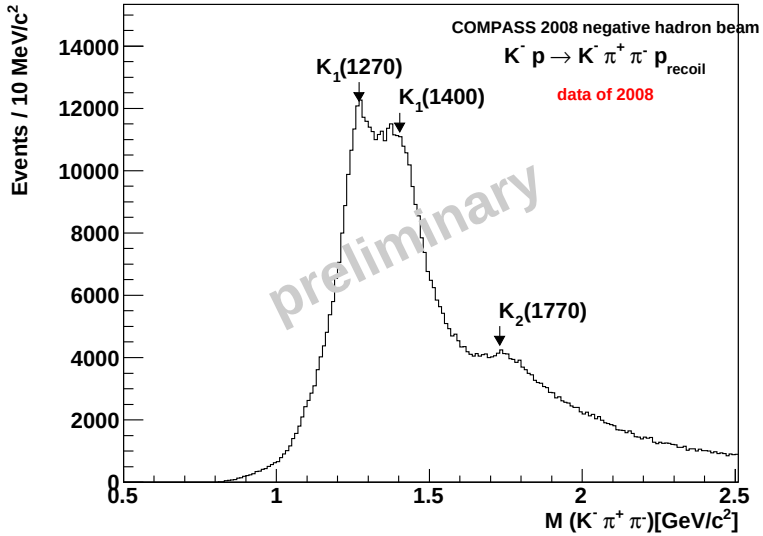
4π invariant mass $\rightarrow$ $f1(1285)$



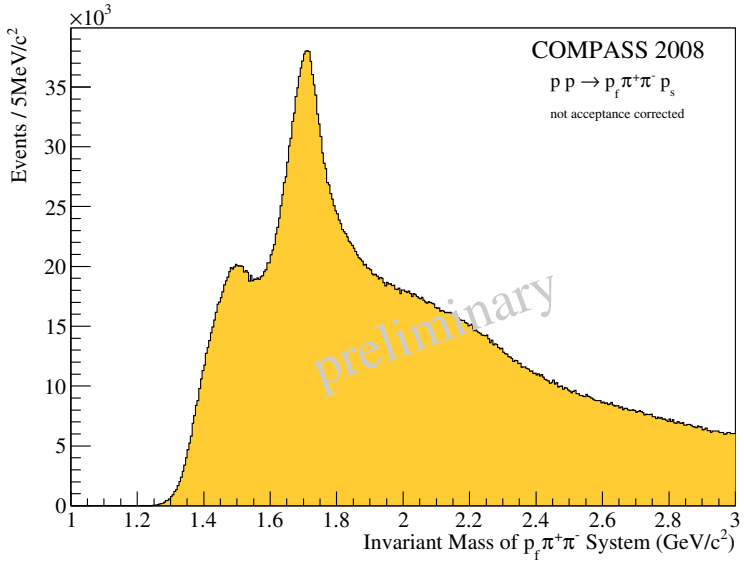
Kaon Diffraction $K^- p \to K^- \pi^+ \pi^- p$

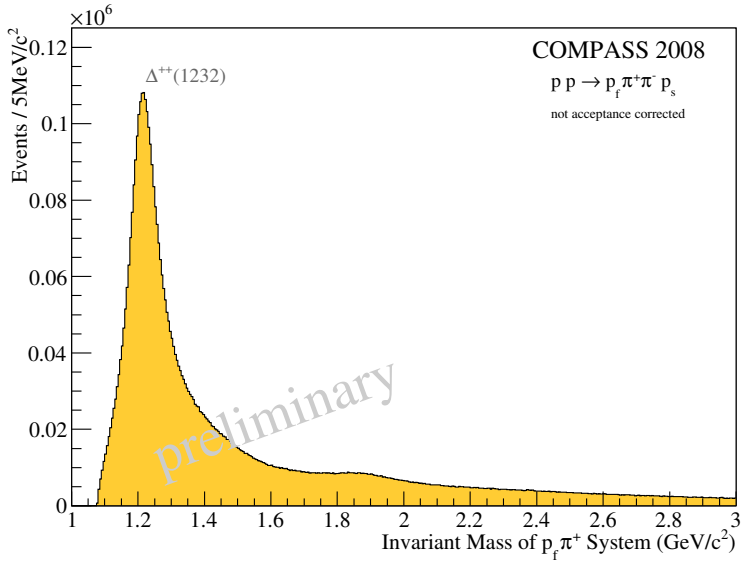
- Beam kaon tagging with Differential Cherenkov Counters (CEDAR)
- FS kaon ID with RICH
- $\sim$ 600 000 events on tape from 2008 (WA32: 200 000)

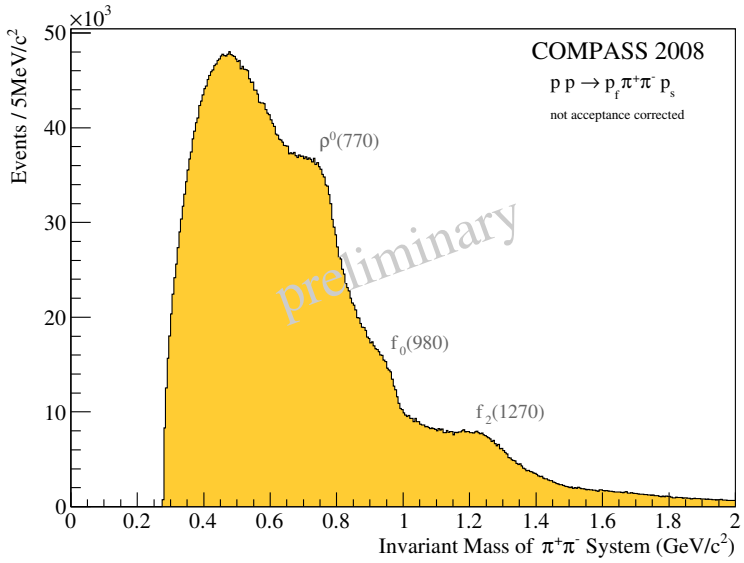


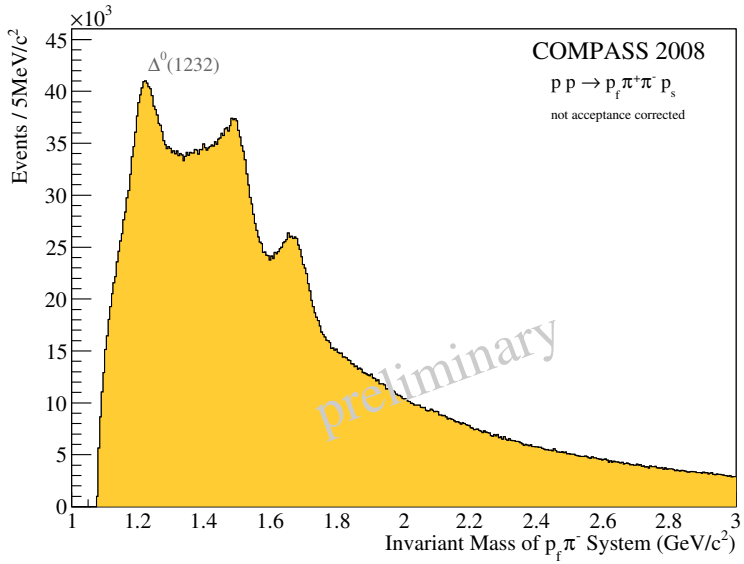


Proton Diffraction: $pp \to p\pi^+\pi^- p_{recoil}$

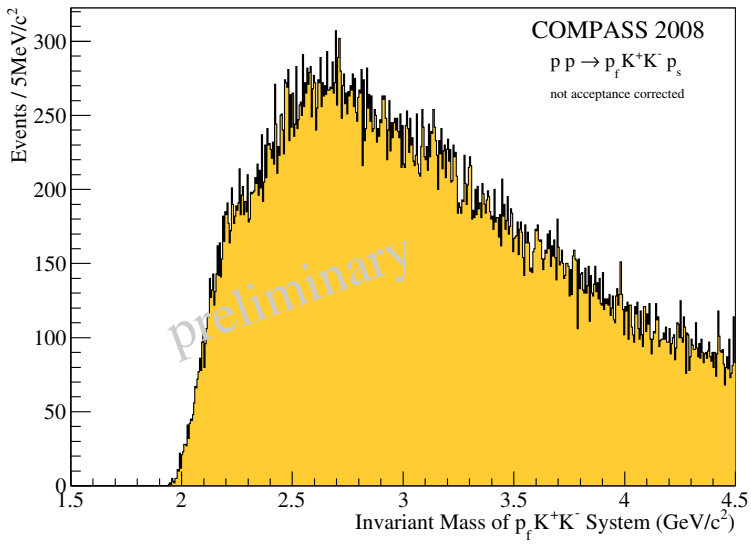


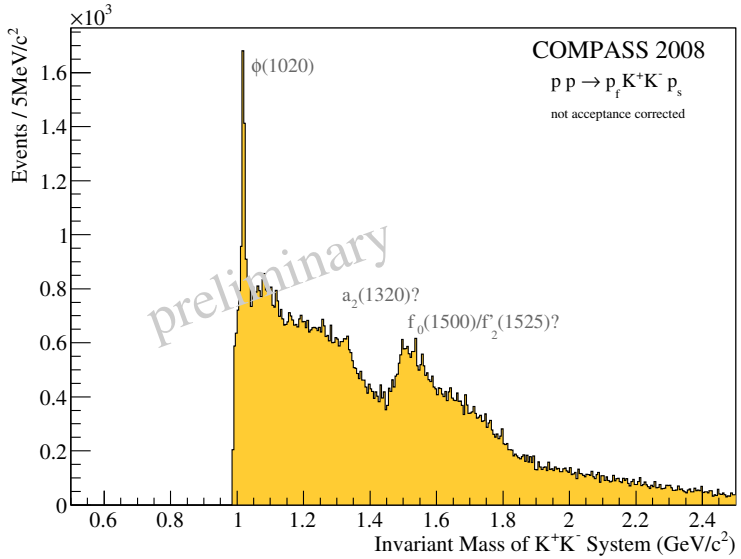


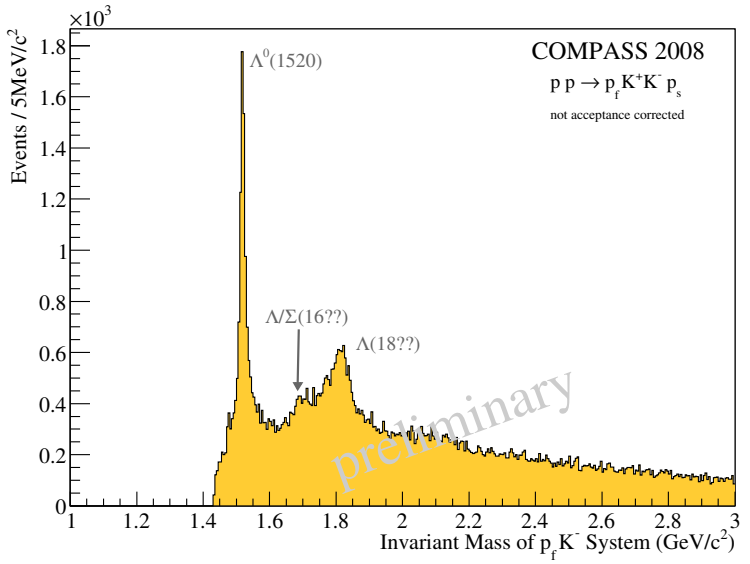


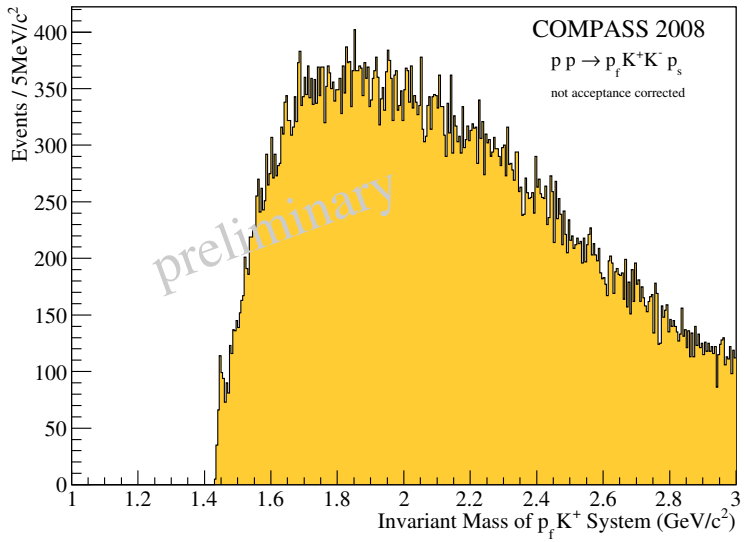


Proton Diffraction: $pp \to p_{fast} K^+ K^- p_{slow}$









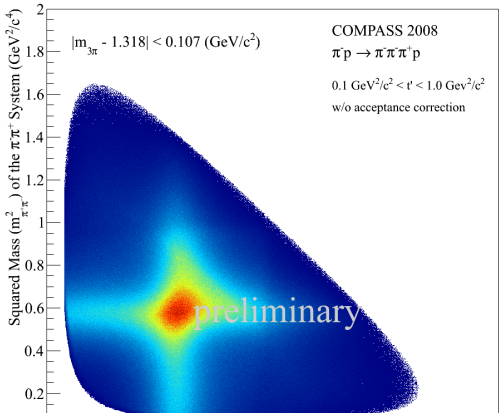
Summary and Outlook

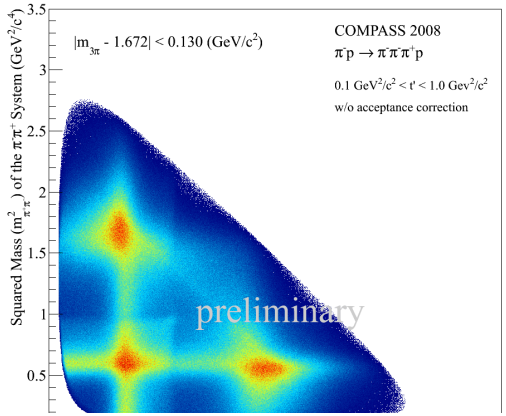
Hadron Spectroscopy at COMPASS

Technische Universität München

Summary:

- COMPASS has collected world record statistics in diffractive production
  - 96M $\pi^- p \to \pi^- \pi^+ \pi^- p$ events (2008)
- Observation of a spin exotic 1^{-+} resonance in $\rho\pi$
- Rich field of channels to analyse: 5π, 3π Primakoff, Kaon diffraction, 4π central production, $\pi^-\eta$, $KK\pi\pi$, K_sK_s central production
- Spin Alignment Effect: 2009 data Pb,Ni,H
- Baryon Spectroscopy from 2008/2009

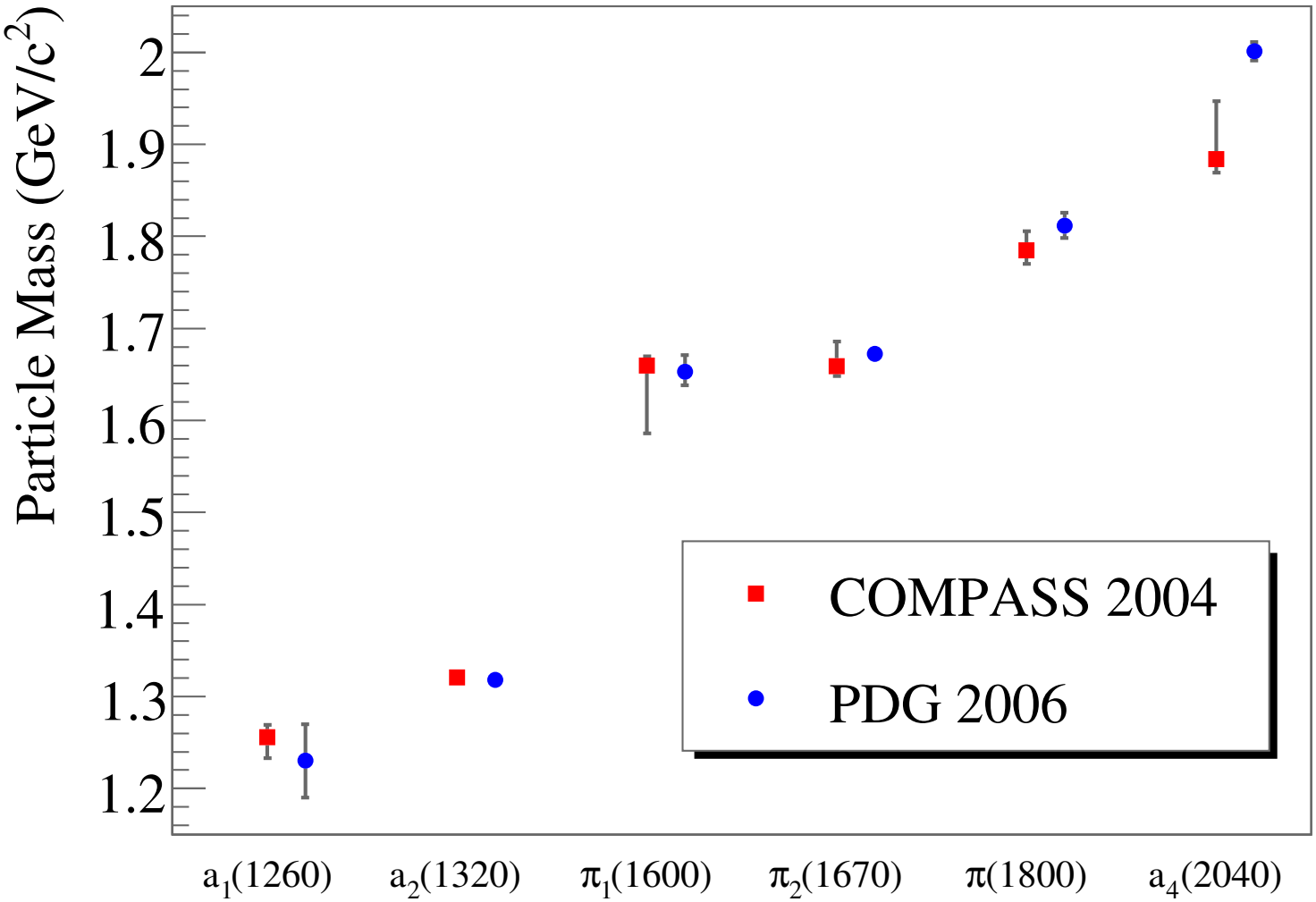




Summary of Extracted States

$\pi^- \mathrm{Pb} \to X^- \mathrm{Pb} \to \pi^-\pi^-\pi^+ \mathrm{Pb}$

Comparison with PDG values



Reflectivity Basis

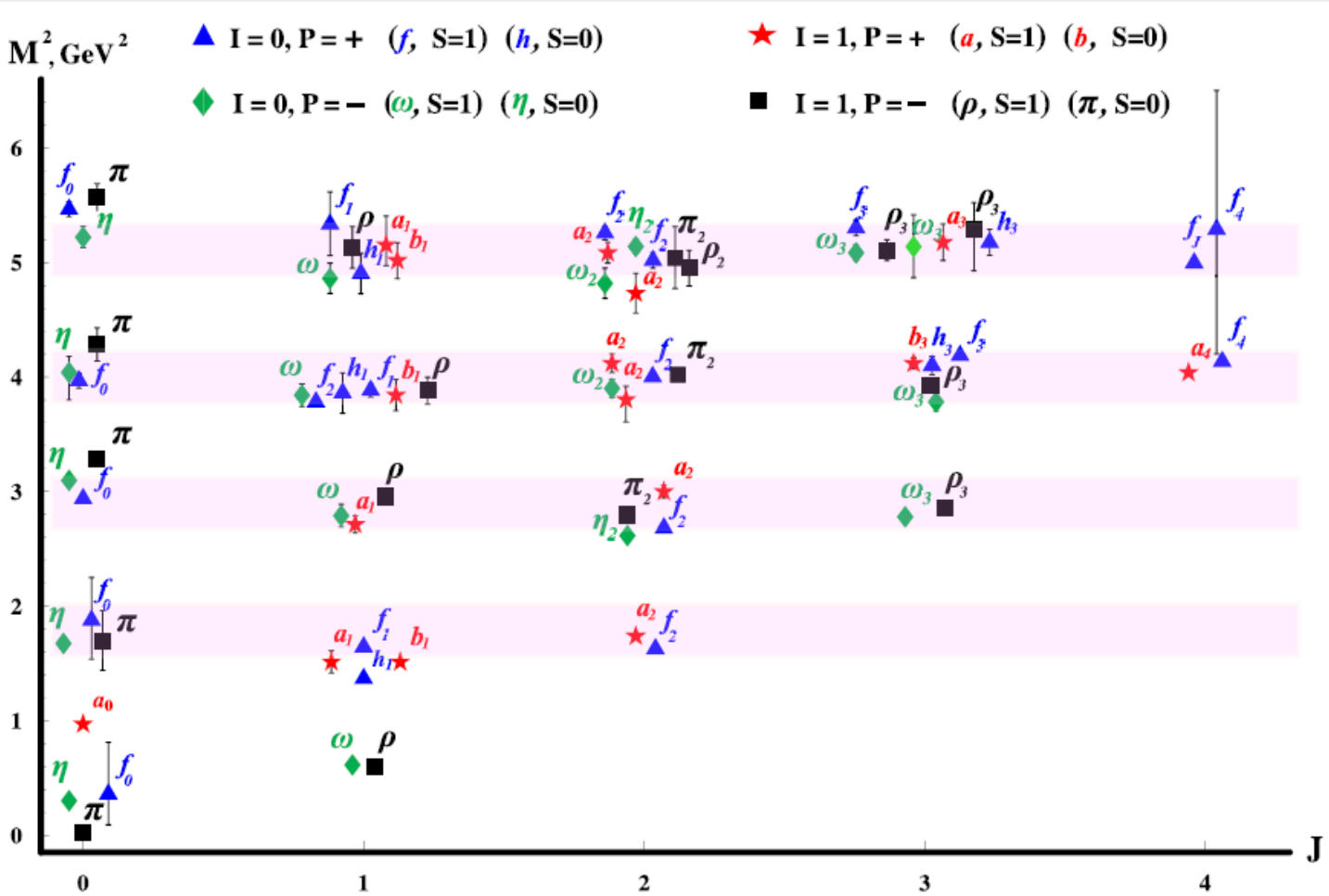
Implementing Parity Conservation

$$\psi^{\epsilon}_{JM} = c(M)\left[\psi_{JM}(\tau) - \epsilon P(-1)^{J-M}\psi_{J(-M)}(\tau)\right] \tag{1}$$

$$\epsilon = \pm 1 \qquad M \in [0, J] \qquad c(M > 0) = \frac{1}{\sqrt{2}} \qquad c(M = 0) = \frac{1}{2} \tag{2}$$

A Global Symmetry for Excited Mesons?

M. Shifman and A. Vainshtein Phys. Rev. D77 (2008) 034002

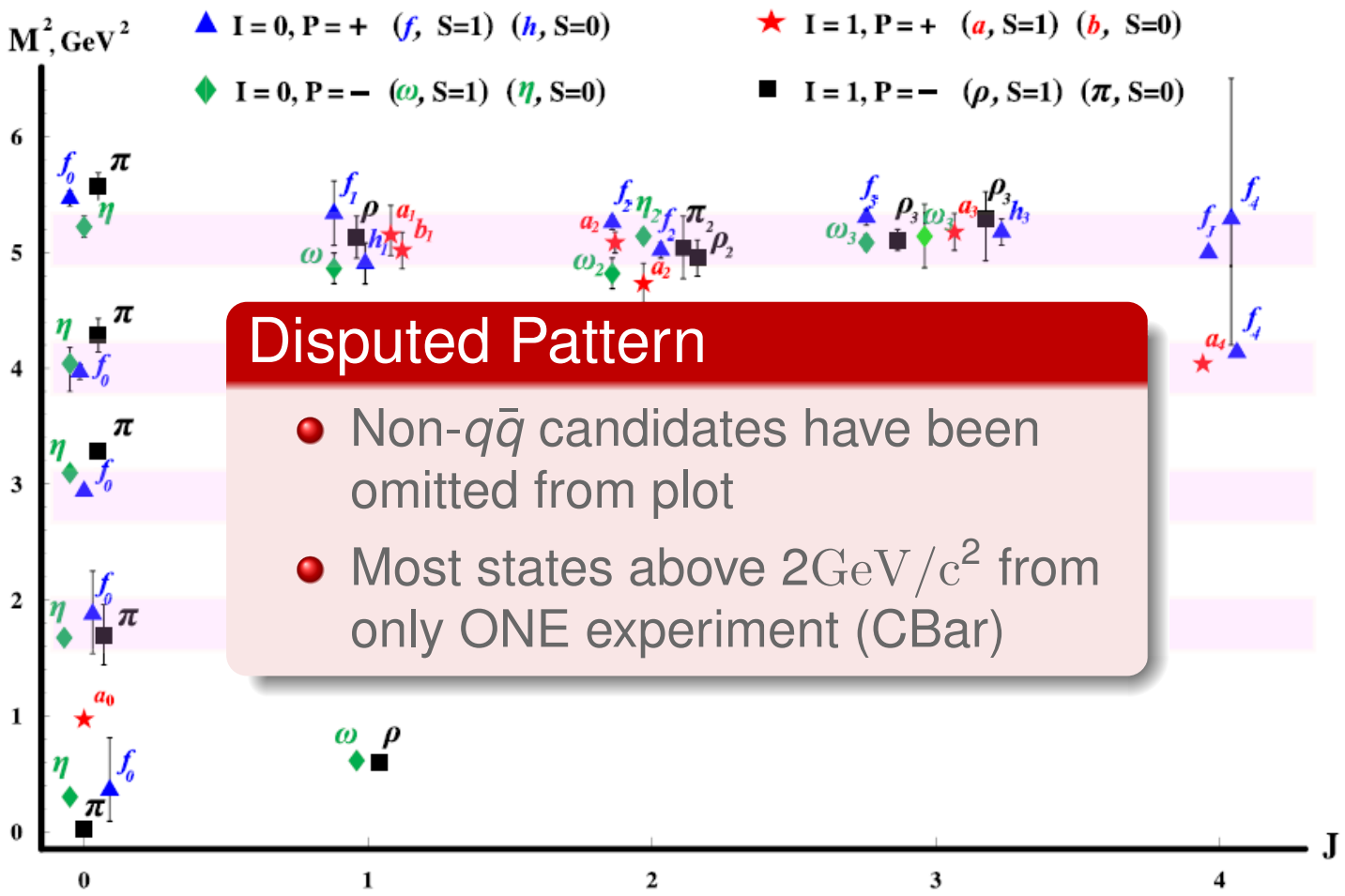


plot from M. Shifman and A. Vainshtein Phys. Rev. D77 (2008) 034002

See also: R. F. Wagenbrunn and L. Ya. Glozman Phys. Rev. D75 (2007) 036007 and references therein

A Global Symmetry for Excited Mesons?

M. Shifman and A. Vainshtein Phys. Rev. D77 (2008) 034002



Disputed Pattern

- Non-$q\bar{q}$ candidates have been omitted from plot
- Most states above $2\,\mathrm{GeV}/c^2$ from only ONE experiment (CBar)

plot from M. Shifman and A. Vainshtein Phys. Rev. D77 (2008) 034002

See also: R. F. Wagenbrunn and L. Ya. Glozman Phys. Rev. D75 (2007) 036007 and references therein

COMPASS Hadron Runs

2004, 2008, 2009

- CERN SPS M2-beamline:
  - neg. beam: 190GeV/c $\pi^-(96\%), K^-(3.5\%)$
  - pos. beam: 190GeV/c $p(71.5\%), \pi^+(25.5\%), K^+(3\%)$
- Pilotrun **2004** 190 GeV π^- beam on nuclear targets (mainly Pb)
  - $3\pi^\pm$ high-t' analysis $\sim$ 400 000 events ($\pi_1(1600)$ PRL 104, 241803 (2010))
  - $5\pi^\pm$ analysis
- **2008 Apparatus Upgrade**
  - Recoil Proton Detector (RPD), calorimetry, kaon PID
- **2008 Run** mainly 190 GeV π^- beam on lH_2 target
  - $3\pi^\pm$ diffractive on proton $\sim$ 100M events
- **2009 Run** pion / proton beams on lH_2 and nuclear targets