



# Light Meson Spectroscopy

## News and Recent Developments

Sebastian Neubert

Technische Universität München

Hadron 2011





## Search for Spin Exotic Resonances

Status of the  $\pi_1(1600)$

Diffractive Dissociation

Photoproduction

## Highly Excited Non-strange Mesons

Light Meson Resonances from Radiative  $J/\psi$  Decays

## News on Strange Mesons

$f_0(980)$ - $a_0(980)$  Mixing in Isospin Violating Decays

$f_0(980)$  and  $a_0(980)$  in Charmonium Decays

$f_1(1285) \rightarrow \pi^+ \pi^- \pi^0$

## Beyond Resonances



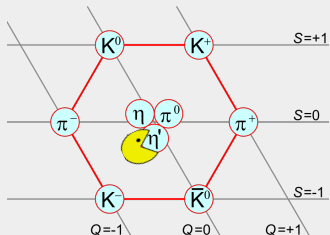
# Perspectives beyond the Quark Model

Chiral Symmetry Breaking, Gluonic DoF ...



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## Octet: Goldstone-Bosons of Chiral Symmetry breaking





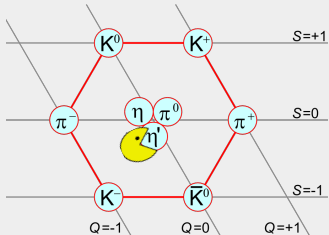
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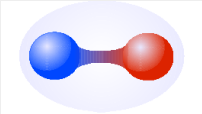
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## Octet: Goldstone-Bosons of Chiral Symmetry breaking



## Exited States: Flux Tube Model

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





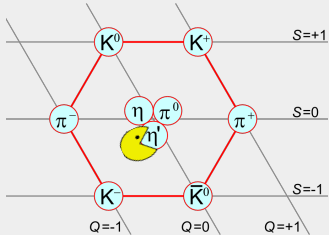
# Perspectives beyond the Quark Model

Chiral Symmetry Breaking, Gluonic DoF ...

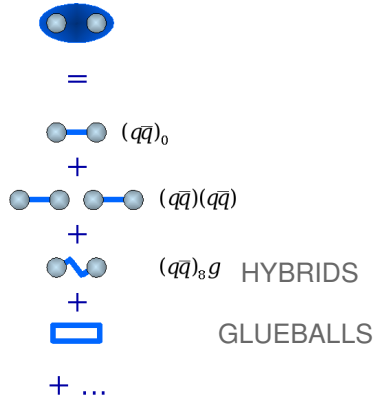


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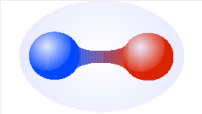


QCD-allowed contributions to meson spectrum:



## Exited States: Flux Tube Model

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





# Search for States beyond the Constituent Quark Model

## Status of the Spin Exotic $\pi_1(1600)$



# Search for States beyond the Quark Model

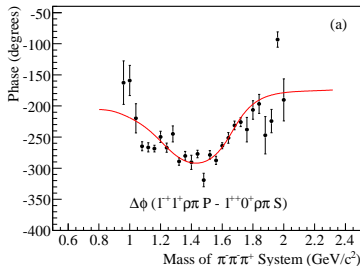
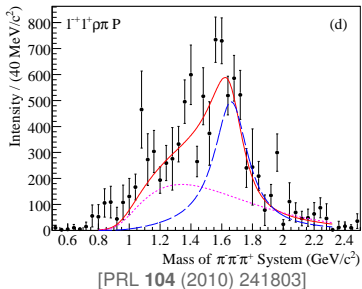


Status of the spin exotic  $\pi_1(1600)$

## Exotic Signatures

- Over-filled multiplets (too many states)
- Isospin exotics: “forbidden” decays
- **Spin exotics:**  $J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, 2^{+-} \dots$  forbidden in  $q\bar{q}$

COMPASS (2004):  $\pi^- \text{Pb} \rightarrow \pi^- \pi^+ \pi^- \text{Pb}$   $\sim 400\,000$  events





# Search for States beyond the Quark Model

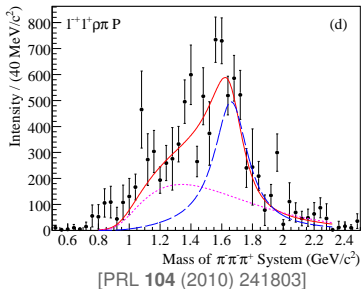


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## Spin Exotic $\pi_1(1600)$

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





# The COMPASS Experiment

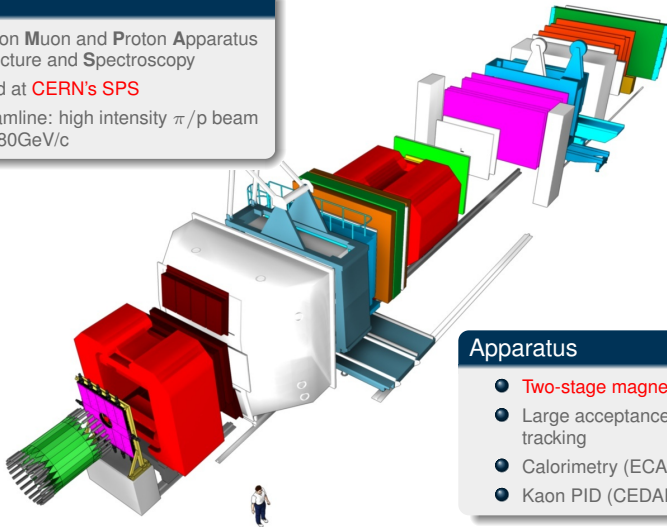
## Spectrometer and Hadron Beam



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### Overview

- **CO**mmun **MU**on and **P**roton **A**pparatus for **S**tructure and **S**pectroscopy
- Located at **CERN's SPS**
- M2-beamline: high intensity  $\pi/p$  beam up to 280GeV/c



### Apparatus

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



# Pion Diffraction at COMPASS

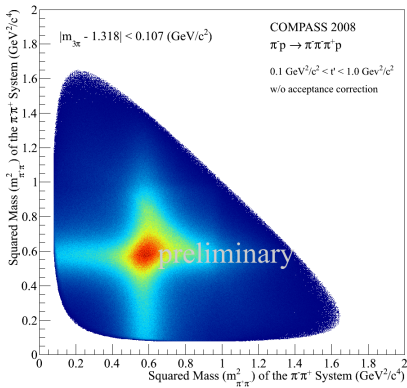


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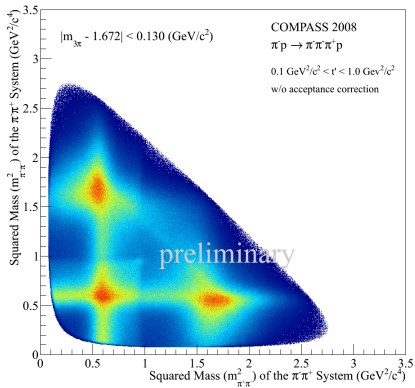
$$1^{-+} \text{ in } \pi^{-} \pi^{+} \pi^{-}$$

- 2008 run: 190 GeV  $\pi^{-}$  beam on  $\ell\text{H}_2$  target
- **100M events**  $\pi^{-} + p \rightarrow \pi^{-} \pi^{+} \pi^{-} + p$

$a_2(1320)$  mass region



$\pi_2(1670)$  mass region





# Pion Diffraction at COMPASS

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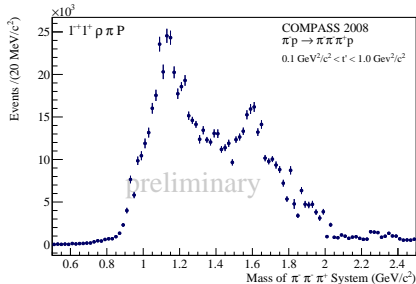


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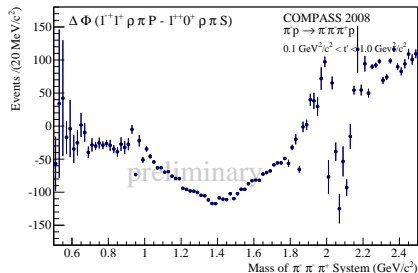
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The spin exotic  $J^{PC} = 1^{-+} \rho\pi$   $P$ -wave:

Intensity (statistical errors only)



Phase motion vs  $1^{++} \rho\pi$   $S$ -wave





# Pion Diffraction at COMPASS

$$1^{-+} \text{ in } \pi^- \pi^+ \pi^-$$



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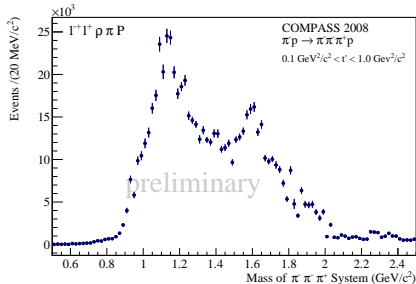
## Parallel Session

F. Haas, Fri. 17th, 9:20h,  
Light Mesons 6

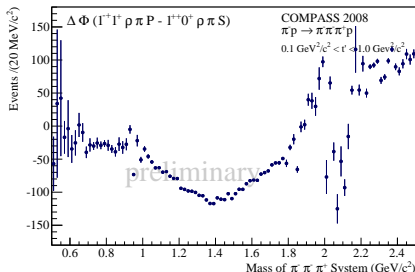
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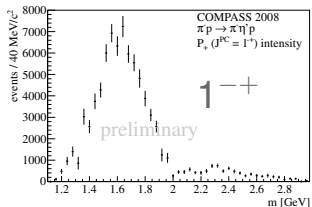
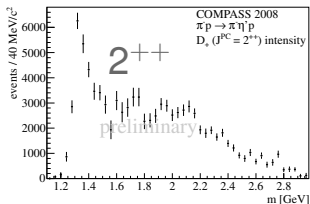




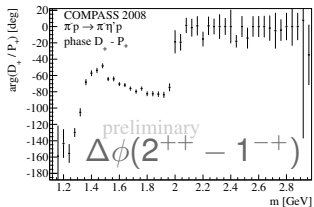
# COMPASS: $\pi^- + p \rightarrow \eta' \pi + p$

The spin exotic  $J^{PC} = 1^{-+} \eta' \pi$  P-wave

- Strong  $1^{-+} \eta' \pi$  P-wave reported by E852 and VES - resonant?



- Strong  $1^{-+}$  signal
- Similar to BNL / VES
- Extendend mass range
- No fit to spin-density matrix yet
- Production mechanism?





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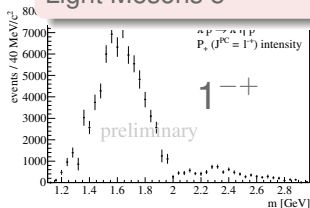
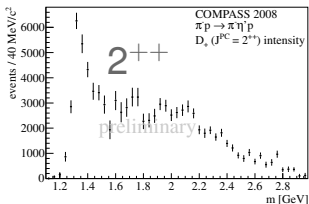


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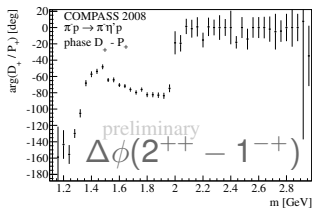
## Parallel Session

T. Schlüter, Thu. 16th, 17:10h,  
Light Mesons 5

- Strong  $1^{-+} \eta' \pi$  P-wave reported by E852



- Strong  $1^{-+}$  signal
- Similar to BNL / VES
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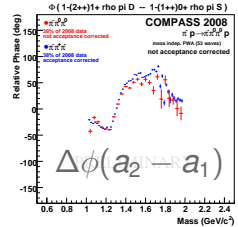
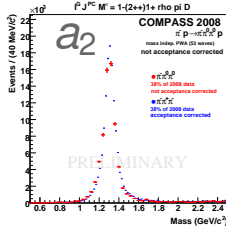
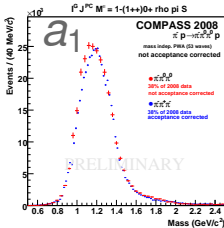
# COMPASS $\pi^- \pi^+ \pi^-$ vs $\pi^- \pi^0 \pi^0$

## Isospin Symmetry



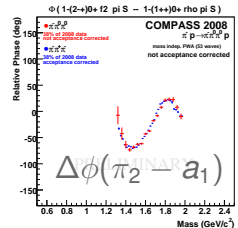
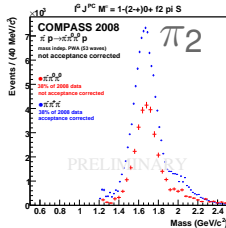
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Partial wave intensities/phases:  $\pi^- \pi^+ \pi^-$  vs  $\pi^- \pi^0 \pi^0$  (normalized to  $a_2$ )



## Comparison

- $\pi^- \pi^0 \pi^0$  not acceptance corrected yet
- Channels probe different parts of spectrometer
- Qualitative agreement





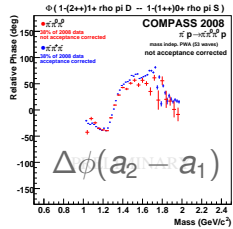
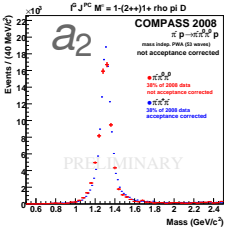
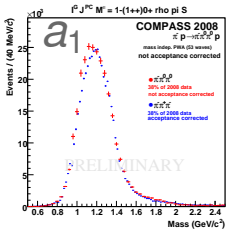
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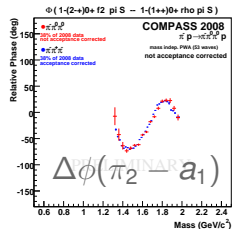
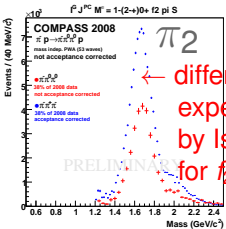
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## Isospin Symmetry

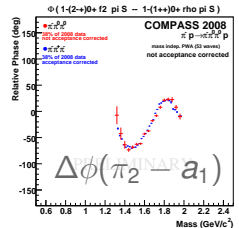
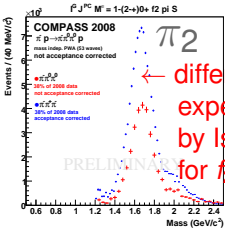
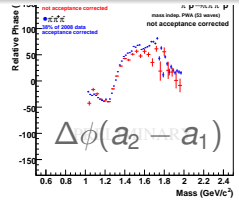
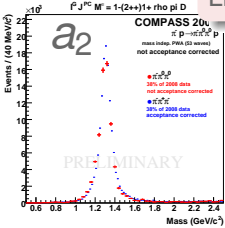
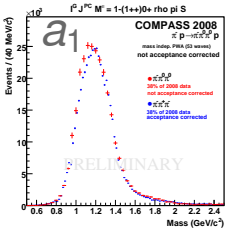


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### Parallel Session

F. Nerling, Fri. 17th, 9:40h  
Light Mesons 6

Partial wave intensities/phases:  $\pi^- \pi^+ \pi^-$  vs



### Comparison

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← difference expected by Isospin for  $f_2 \pi$



# CLAS Experiment at JLAB Hall B

## CEBAF Large Acceptance Spectrometer



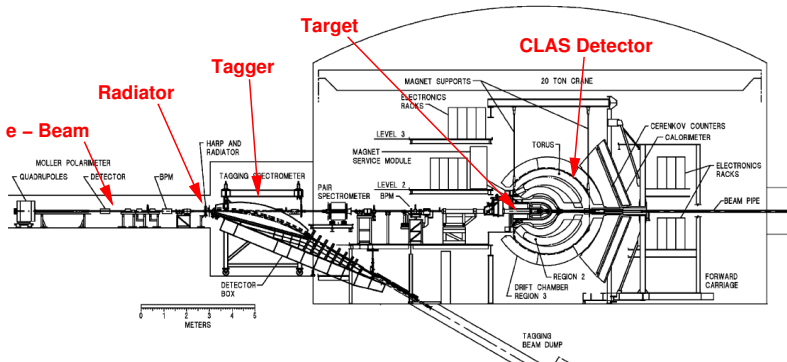
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### Tagged photon beam (2001)

- $E_{e^-} = 5.744 \text{ GeV}$
- $5 \times 10^7 \text{ photons / s}$
- Liquid  $\text{H}_2$  target (18cm cell)

### CLAS Detector

- Toroidal B-Field
- Large acceptance
- TOF and DIRC for PID





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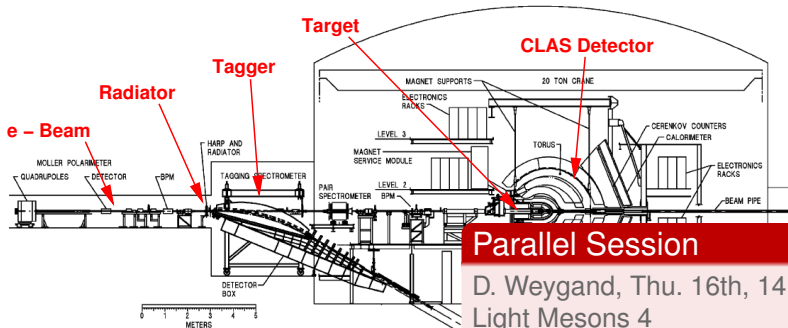
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**Parallel Session**

D. Weygand, Thu. 16th, 14:30h  
Light Mesons 4



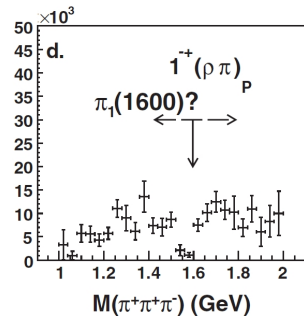
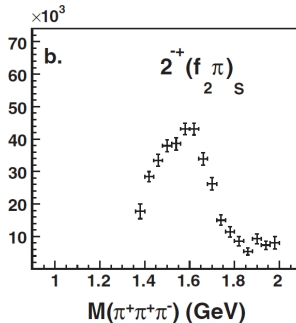
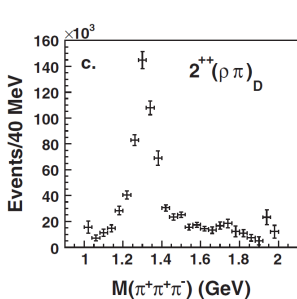
# Search for Photoproduction of $J^{PC} = 1^{-+}$



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$\gamma + p \rightarrow \pi^+ \pi^+ \pi^- + n$  at CLAS

- 83 000 events for PWA



- $a_2(1320)$  and  $\pi_2(1670)$  resonances clearly seen in photoproduction
- No exotic  $1^{-+}$  signal

[PRL 102 (2009) 102002]



# Search for Photoproduction of $J^{PC} = 1^{-+}$



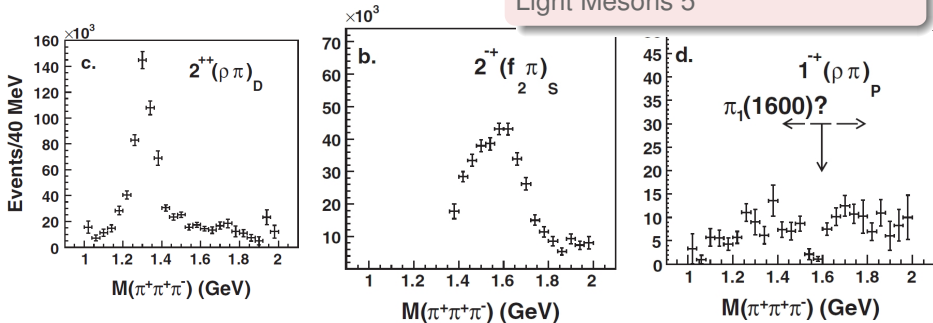
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## Parallel Session

C. Bookwalter, Thu. 16th, 16:30h,  
Light Mesons 5

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[PRL 102 (2009) 102002]



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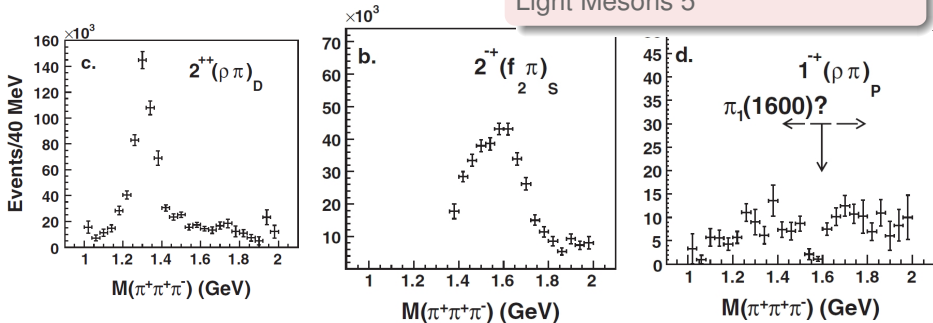
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→ confirmed by COMPASS Primakoff (preliminary)

[PRL 102 (2009) 102002]



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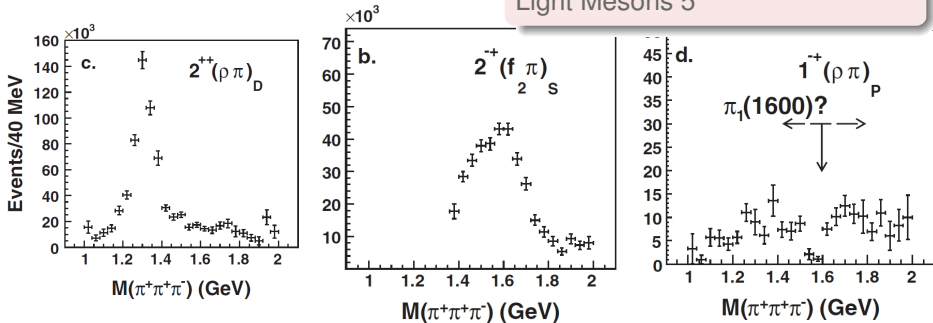
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## Parallel Session

D. Ryabchikov, Fri. 17th, 10:25h  
Low Energy Processes 2

[PRL 102 (2009) 102002]

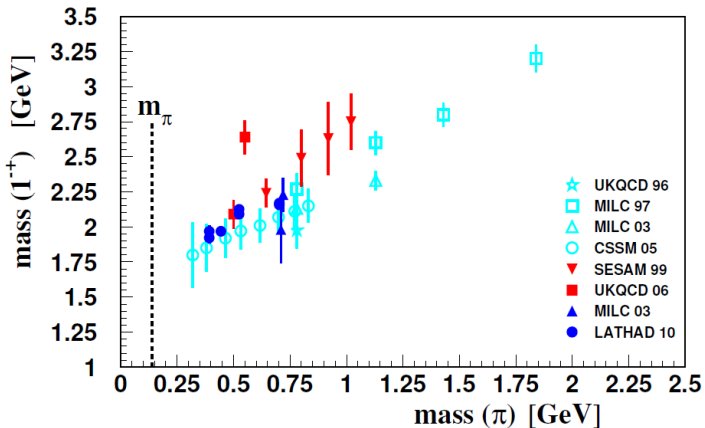


# The $1^{-+}$ Hybrid on the Lattice

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



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# Highly Excited Non-strange Mesons

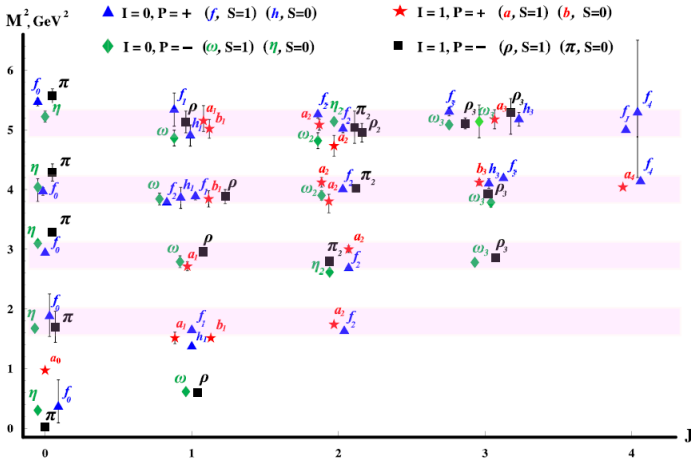


# Excited Mesons in Parity Doublets?

[PRD 77 (2008) 034002]



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plot from M. Shifman and A. Vainshtein [PRD 77 (2008) 034002]

See also: R. F. Wagenbrunn and L. Ya. Glozman [PRD 75 (2007) 036007] and references therein

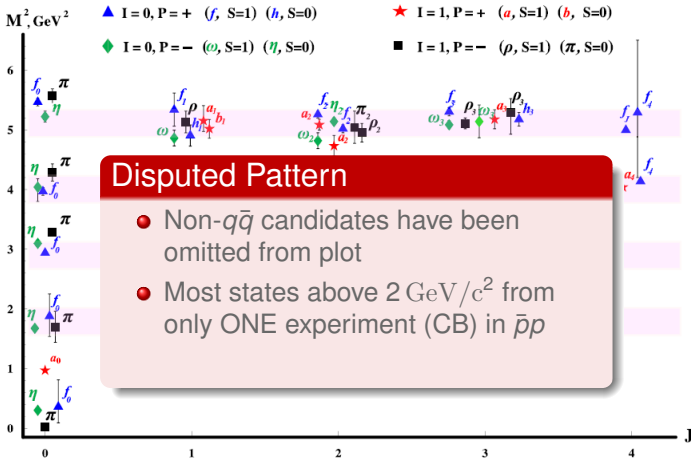


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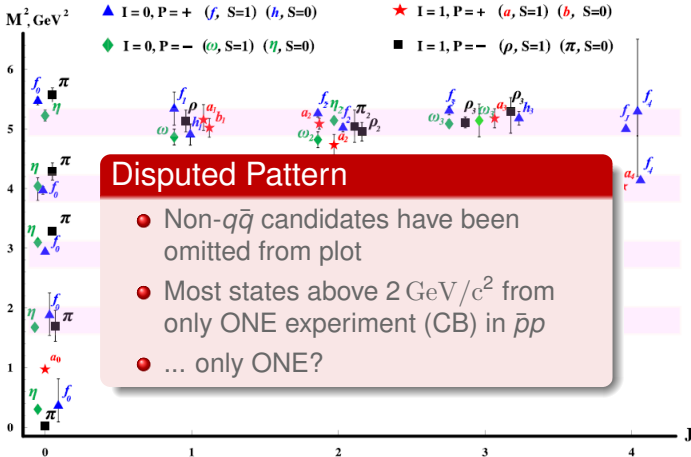


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# The BES III Experiment

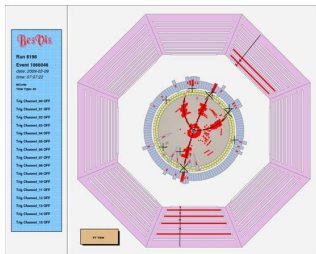
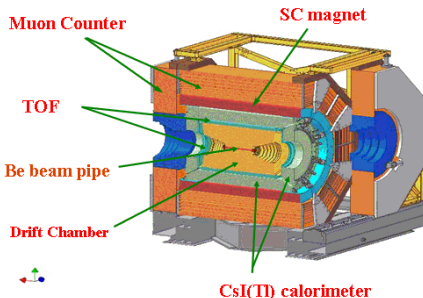
at the Beijing Electron Positron Collider



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## BES III @ BEPCII

- $e^+e^-$  Collider  $\sqrt{s} = 2 \dots 4.6$  GeV
- Design luminosity:  
 $\sim 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$  (@  $2 \times 1.89$  GeV)
- Charm-factory:
  - $2.25 \cdot 10^8 J/\psi$  events
  - $1.06 \cdot 10^8 \psi'$  events



## Plenary Talk

Li, Hai-Bo on Wed. 15th, 12:00h  
 “Highlights from BES III”

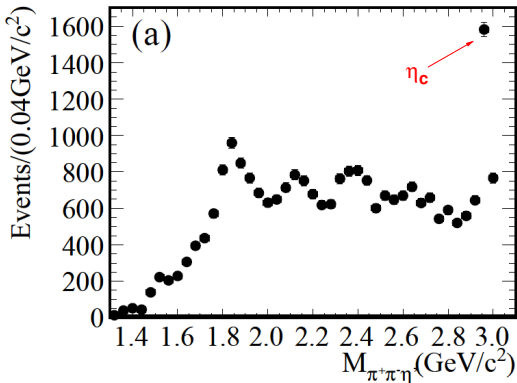


# $X(1835)$ & Co, in $J/\psi \rightarrow \gamma \eta' \pi^+ \pi^-$

at BES III [PRL 106 (2011) 072002]



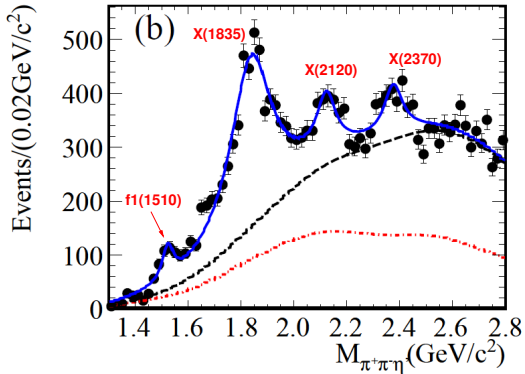
Technische Universität München





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at BES III [PRL 106 (2011) 072002]

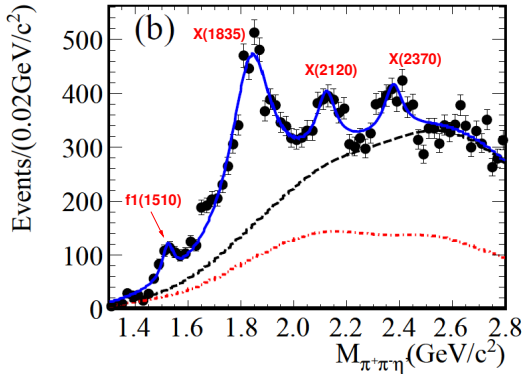


- Fitted mass spectrum: remarkably narrow peaks – interferences?
- No spin-parity assignments yet → amplitude analysis needed



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at BES III [PRL 106 (2011) 072002]

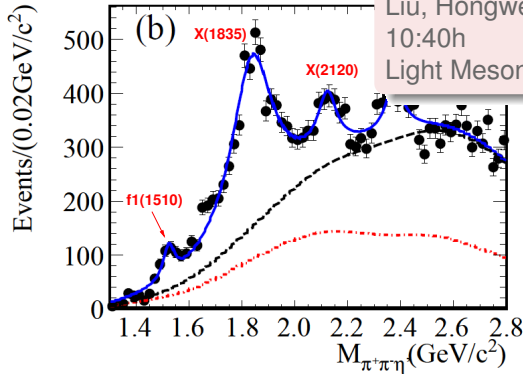


Technische Universität München

## Parallel Session

Liu, Hongwei Fri. 17th,  
10:40h

Light Mesons 6



- Fitted mass spectrum: remarkably narrow peaks – interferences?
- No spin-parity assignments yet → amplitude analysis needed

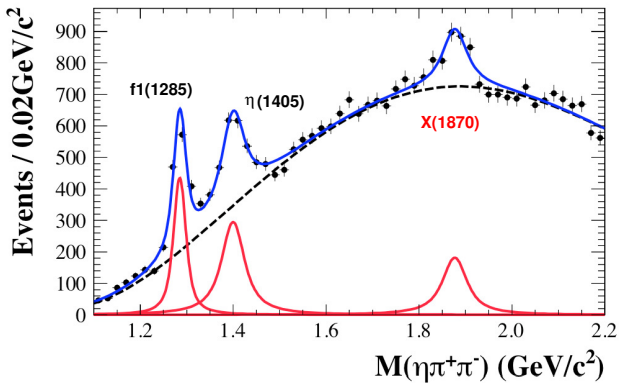


# $X(1870)$ in $J/\psi \rightarrow \omega\eta\pi^+\pi^-$ at BES III



Technische Universität München

$$J/\psi \rightarrow \omega a_0^\pm(980)\pi \rightarrow \omega\eta\pi^+\pi^-$$





# News on Strange Mesons



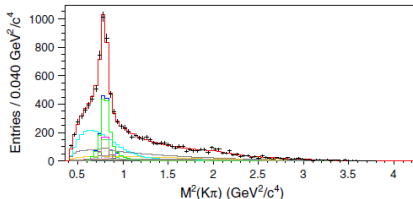
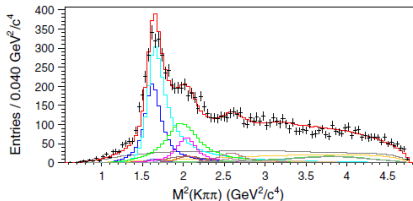
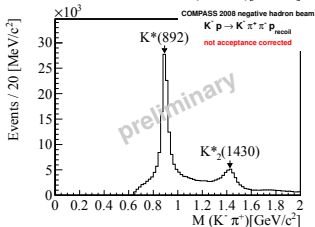
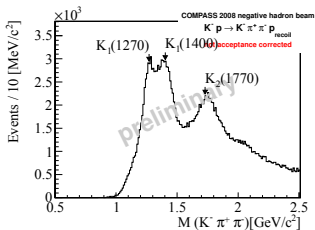
# Strangeness at COMPASS & BELLE



Technische Universität München

COMPASS:  $K^- + p \rightarrow K^- \pi^+ \pi^- + p$   
 $\sim 270\,000$  events

BELLE @  $\Upsilon(4s)$ :  $B^+ \rightarrow J/\psi K^+ \pi^+ \pi^-$   
 $\sim 10\,000$  events



[PRD 83 (2011) 032005]



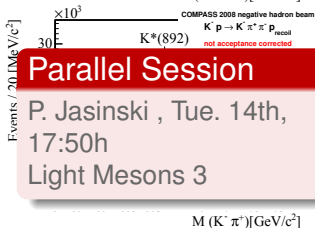
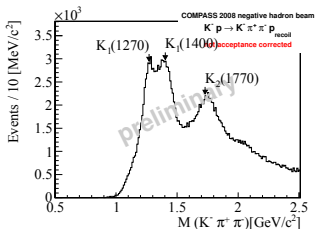
# Strangeness at COMPASS & BELLE



Technische Universität München

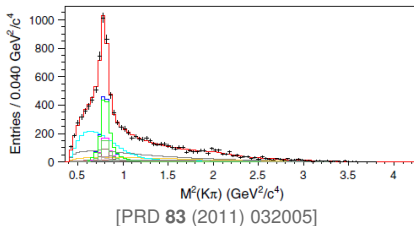
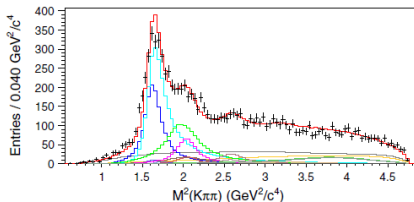
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## Parallel Session

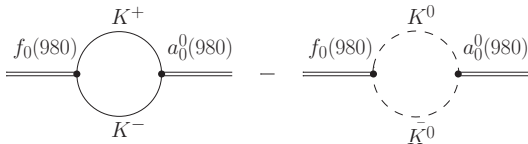
P. Jasinski, Tue. 14th,  
 17:50h  
 Light Mesons 3





# Isospin Violating Decays

## $f_0(980)$ - $a_0(980)$ Mixing



[PRD76 (2007) 074028]



# Sources of $f_0$ and $a_0 \rightarrow$ Charmonium Decays

Isospin Conserving  $J/\psi \rightarrow \phi(\pi\pi)$  and  $\chi_{c1} \rightarrow \pi\eta\pi$  Decays

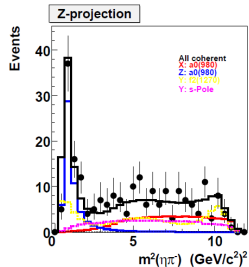
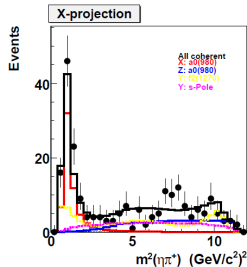
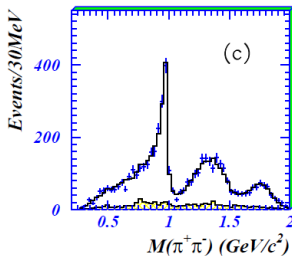
Technische Universität München

$$f_0(980) \rightarrow \pi\pi \quad I^G = 0^+$$

$$J/\psi \rightarrow \phi(\pi\pi) \text{ @ BES}$$

$$a_0(980) \rightarrow \eta\pi \quad I^G = 1^-$$

$$\psi' \rightarrow \gamma + \chi_{c1} \rightarrow \gamma + (\eta\pi^0)\pi^0 \text{ @ CLEO}$$

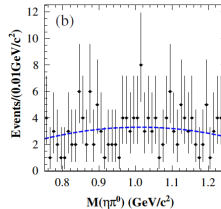
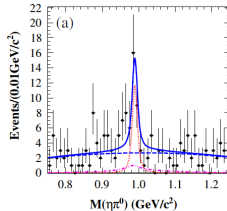
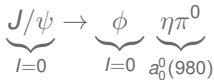




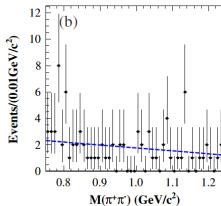
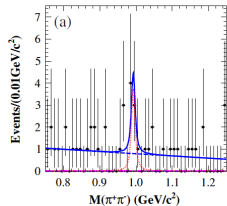
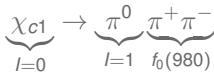
# $f_0(980) - a_0(980)$ Mixing Signals

Isospin Violating Decays  $J/\psi \rightarrow \phi \eta \pi^0$  and  $\psi' \rightarrow \gamma \pi^0 \pi^+ \pi^-$

$(a_0^0(980) \rightarrow \eta \pi)$  recoiling against  $\phi$  (and sideband)



$(f_0(980) \rightarrow \pi^+ \pi^-)$  in  $\chi_{c1}$  mass window (and sideband)



PRD 83 (2011) 032003





# $f_0(980)$ - $a_0(980)$ Mixing Intensities

BES III Charmonium Data  
Samples:

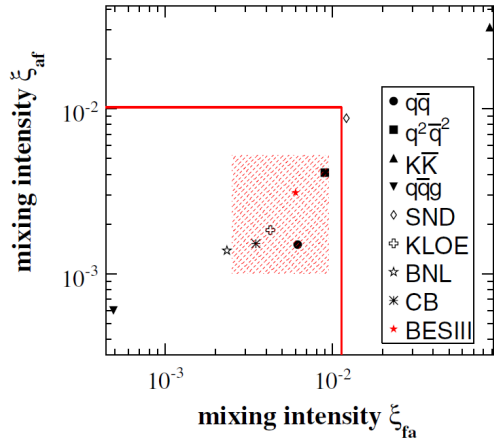
- $2.25 \cdot 10^8 J/\psi$  events
- $1.06 \cdot 10^8 \psi'$  events

$$\xi_{fa} = \frac{Br(J/\psi \rightarrow \phi a_0(980))}{Br(J/\psi \rightarrow \phi f_0(980))} = 0.60\%$$

$$\xi_{af} = \frac{Br(\chi_{c1} \rightarrow \gamma \pi^0 f_0(980))}{Br(\chi_{c1} \rightarrow \gamma \pi^0 a_0(980))} = 0.31\%$$

Errors given as red area

[PRD 83 (2011) 032003]





# $f_0(980)$ - $a_0(980)$ Mixing Intensities

Poster Session

Liu, Chuyan Tue. 14th,  
18:20h

BES III Charmonium Data  
Samples:

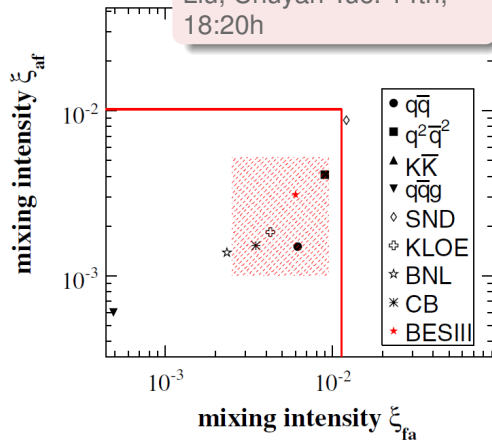
- $2.25 \cdot 10^8 J/\psi$  events
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Errors given as red area

[PRD 83 (2011) 032003]



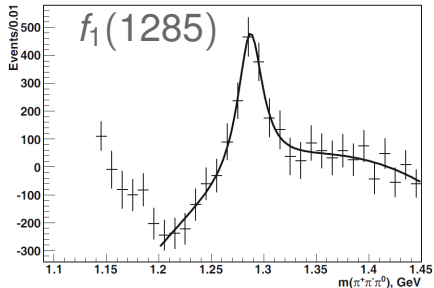


# Isospin Violating Decay $f_1(1285) \rightarrow \pi^+ \pi^- \pi^0$



VES:  $\pi^- + A \rightarrow f_1 \pi^- + A \rightarrow (\pi^0 \pi^+ \pi^-) \pi^- + A$

- Extracted  $f_1(1285) \rightarrow 3\pi$  signal:

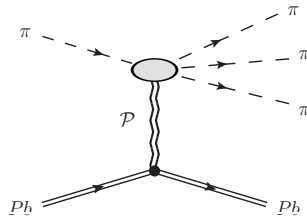
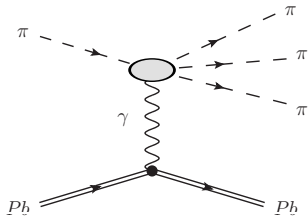


$$Br(a_0(980) \rightarrow \pi^- \pi^+) = 2.0 \pm 0.6 \pm 0.4\%$$

[EPJ A47 (2011) 68]



# Pion - Nucleus Scattering at Small Momentum Transfer @ COMPASS





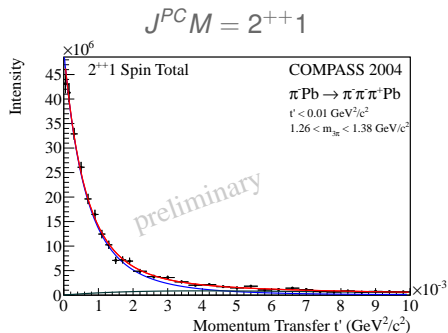
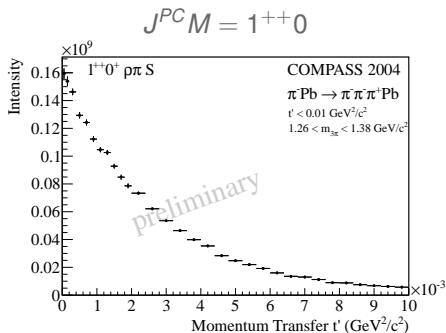
# Coulomb and Strong Interaction



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Disentangle both processes through

- Helicity structure (Partial wave analysis)
- Different  $t'$ -distributions (slope!)





# Coulomb and Strong Interaction



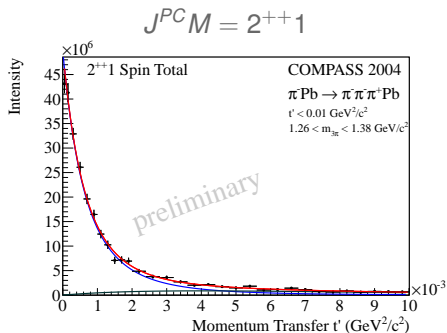
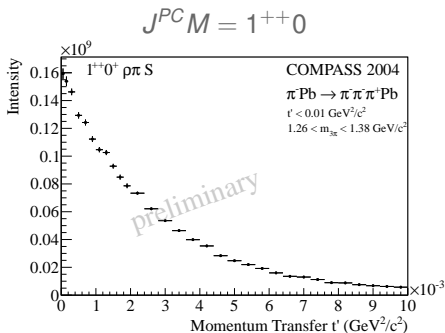
Technische Universität München

## Parallel Session

D. Ryabchikov , Fri. 17th, 10:25h  
Low Energy Processes 2

Disentangle both processes through

- Helicity structure (Partial wave analysis)
- Different  $t'$ -distributions (slope!)



- Allows to study interferences between both production mechanisms.

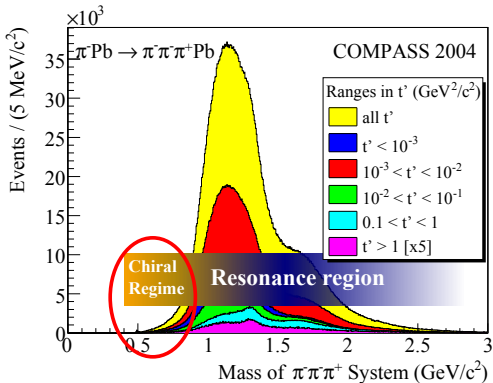
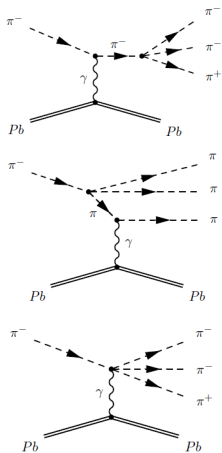


# Primakoff $3\pi$ Spectral Function from $\chi$ PT



Absolute Cross Section Measurement @ COMPASS

- Weizsäcker-Williams:  
heavy nucleus acts as a quasi-real photon source
- $\chi$ PT amplitude included in PWA
- $\Rightarrow \gamma\pi^- \rightarrow \pi^-\pi^+\pi^-$  absolute cross section



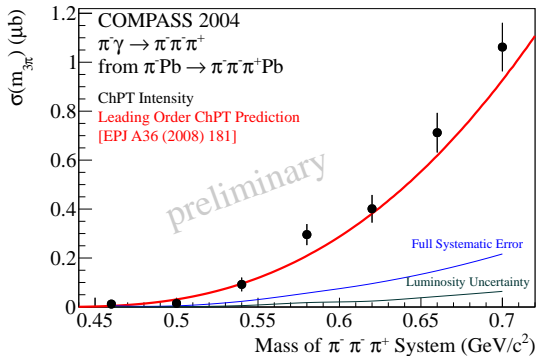
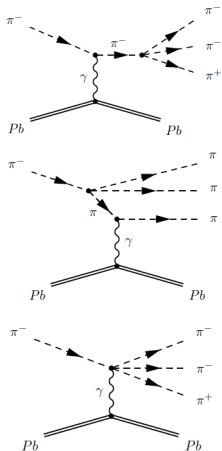


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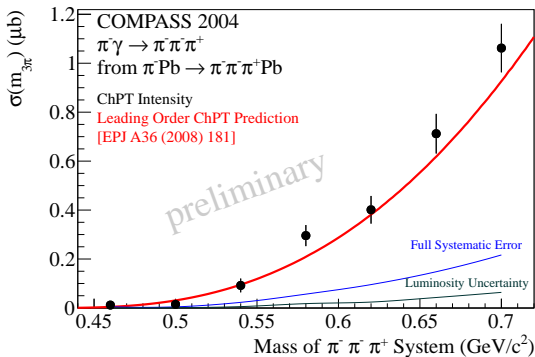
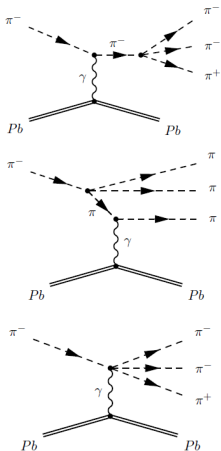
Technische Universität München

Absolute Cross Section Measurement @ COMPASS

Parallel Session

S. Grabmüller, Fri. 17th, 10:05h  
Low Energy Processes 2

- Weizsäcker-Williams heavy nucleus acts as source of virtual photons
- $\chi$ PT amplitude includes  $\pi^0$  exchange
- $\Rightarrow \gamma\pi^- \rightarrow \pi^-\pi^+\pi^-$  absolute cross section





## Conclusion

- COMPASS 2008/2009: **large data sets** in diffractive  $\pi^-/K^-/p$  dissociation (up to 2 orders of magnitude improvement)
- **Charmonium decays**: valuable source of light mesons
- Clear evidence for **spin-exotic  $\pi_1(1600)$** :
  - Diffraction vs. photoproduction ?
  - Where is the  $l = 0$  partner  $\eta_1(1600)$ ?

## Outlook

- **Improvement of Amplitude Analysis Models**
- BES III, COMPASS continue data taking
- GluEx @ JLab Hall-D: Dedicated photoproduction experiment
- Belle II: Charm/Beauty Factory
- PANDA:  $\bar{p}p$  annihilation