The Status of Exotic Meson Light and Heavy

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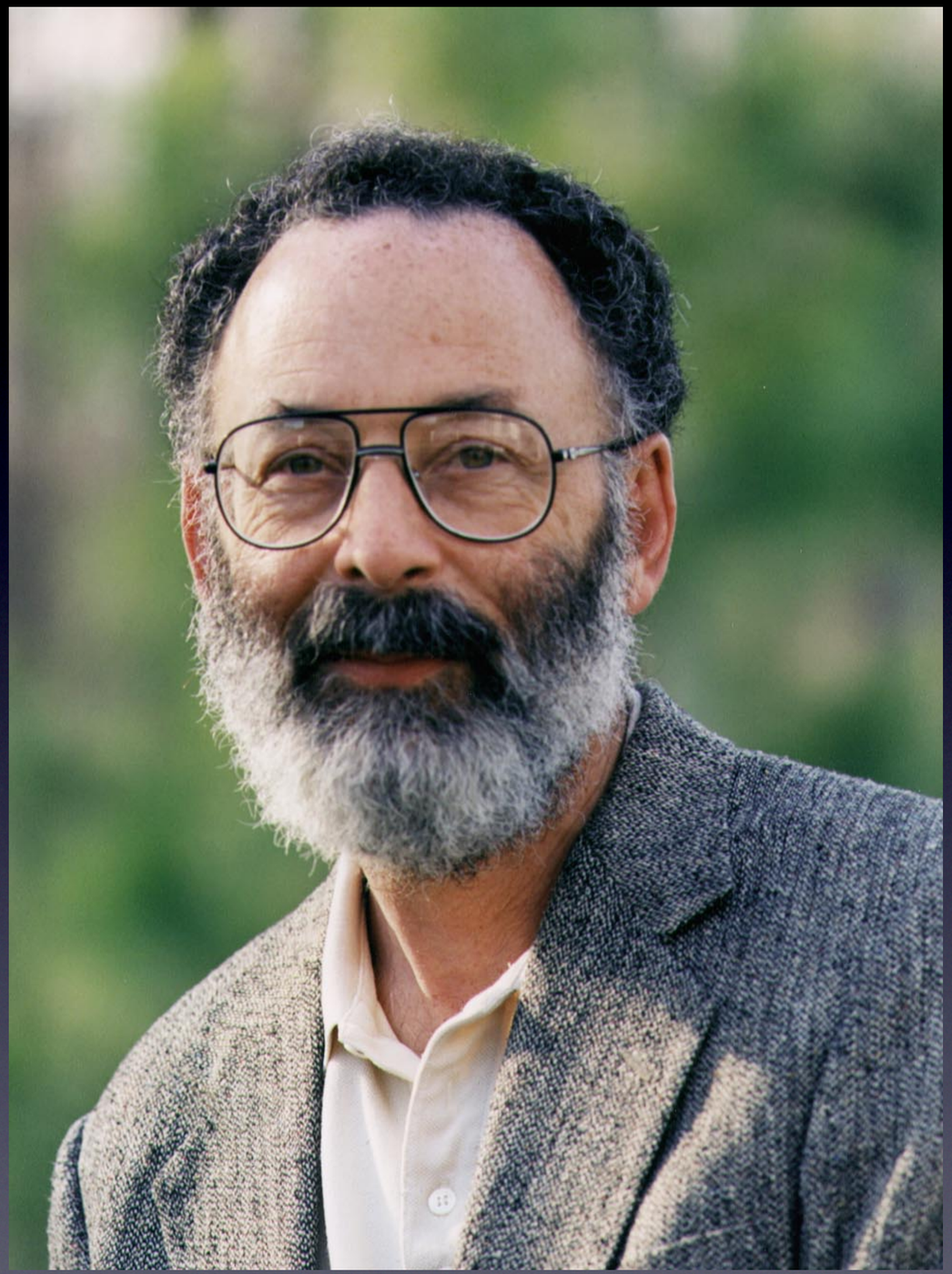
GLUE88 : BNL 1988

Nathan Isgur, b. 1947, d. 2001

I have been using the constituent quark model for many years now as a tool for understanding the spectrum and properties of the low-lying mesons and baryons. For most of this time I have been painfully aware of the difficulty of understanding from first principles (i.e., from QCD) why such a model should work. I have nevertheless had faith that we would eventually be able to justify the use of this model simply because it is such a good representation of the physics.

At the same time, the picture I will propose to rationalize the success of the quark model (which is related to the old string model) leads inevitably to a model for states beyond the quark model: hybrids, glueballs, and multiquark states.



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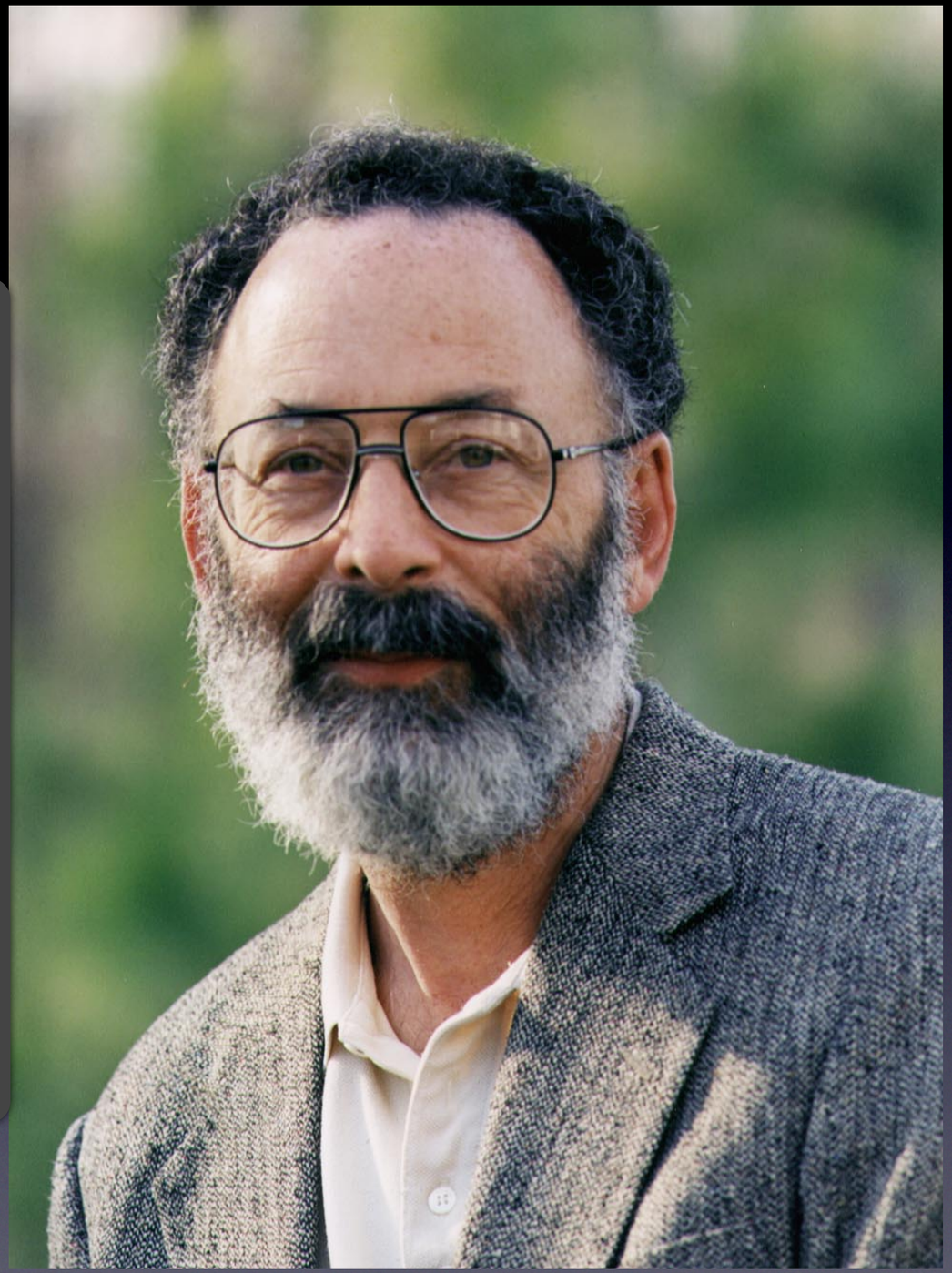
Questions:

Do exotic mesons exist in theory?

Do exotic mesons exist in experiment?



Experiment

The Partial Wave Analysis ‘Isobar’ Technique

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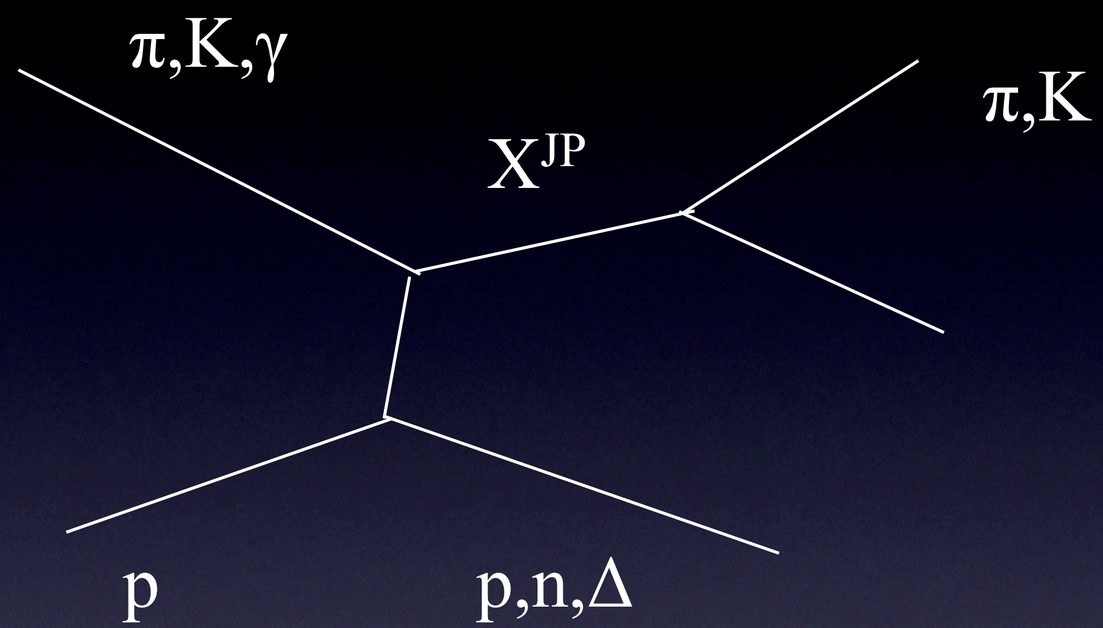

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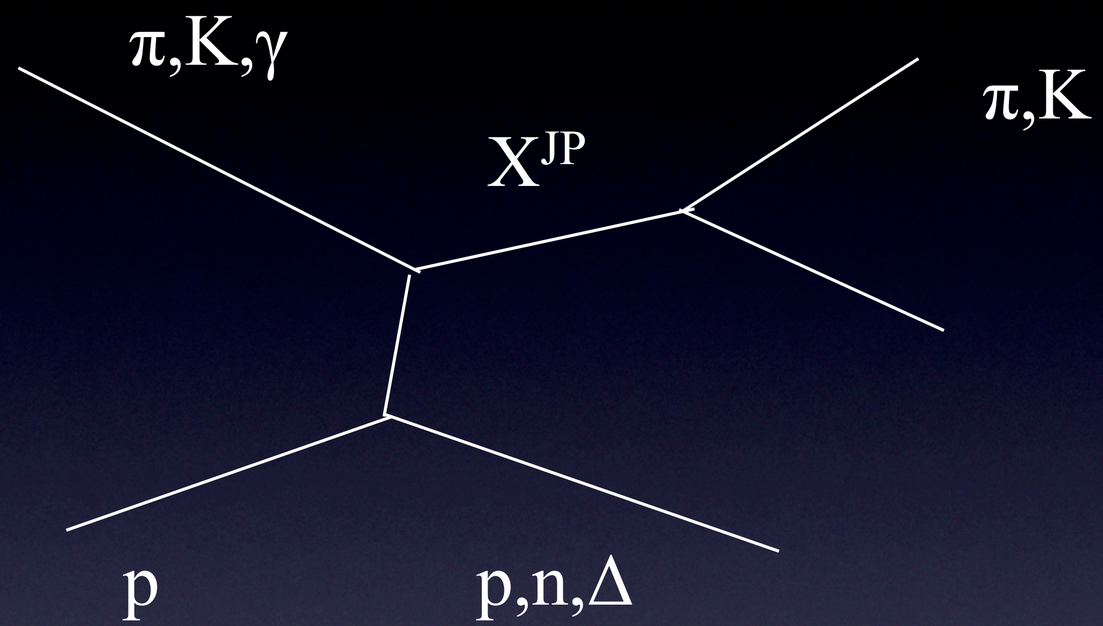

$$I(\tau) = \sum_{\epsilon,k} \left\{ \left| \sum_{\beta} {}^{\epsilon}V_{k\beta}\, {}^{\epsilon}A_{\beta}(\tau) \right|^2 \right.$$

Experiment

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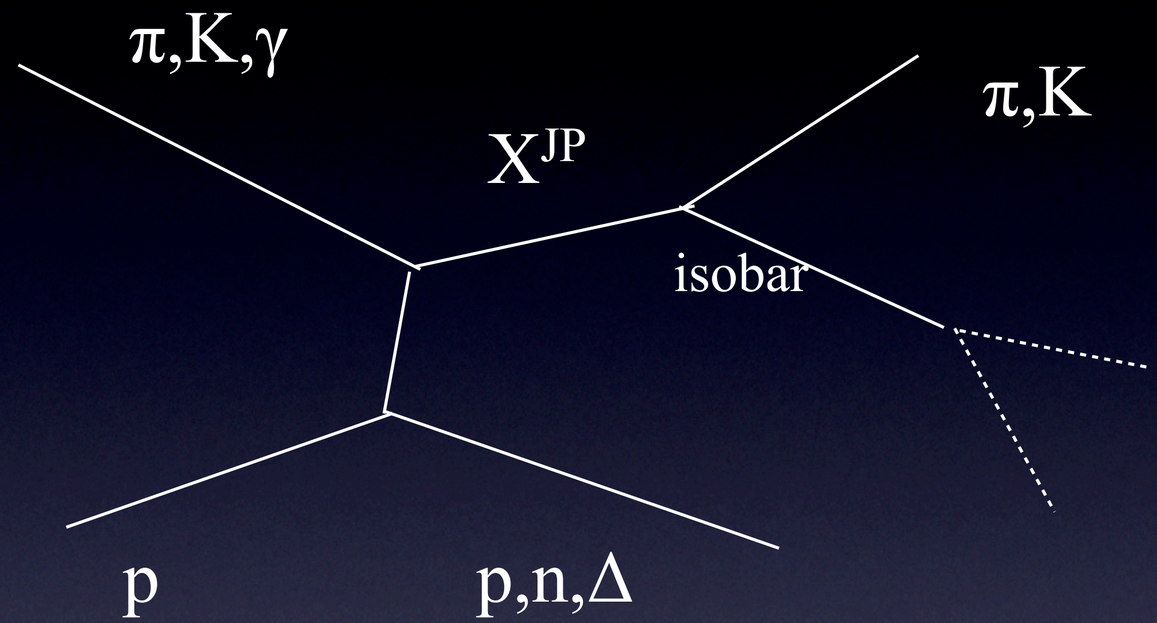

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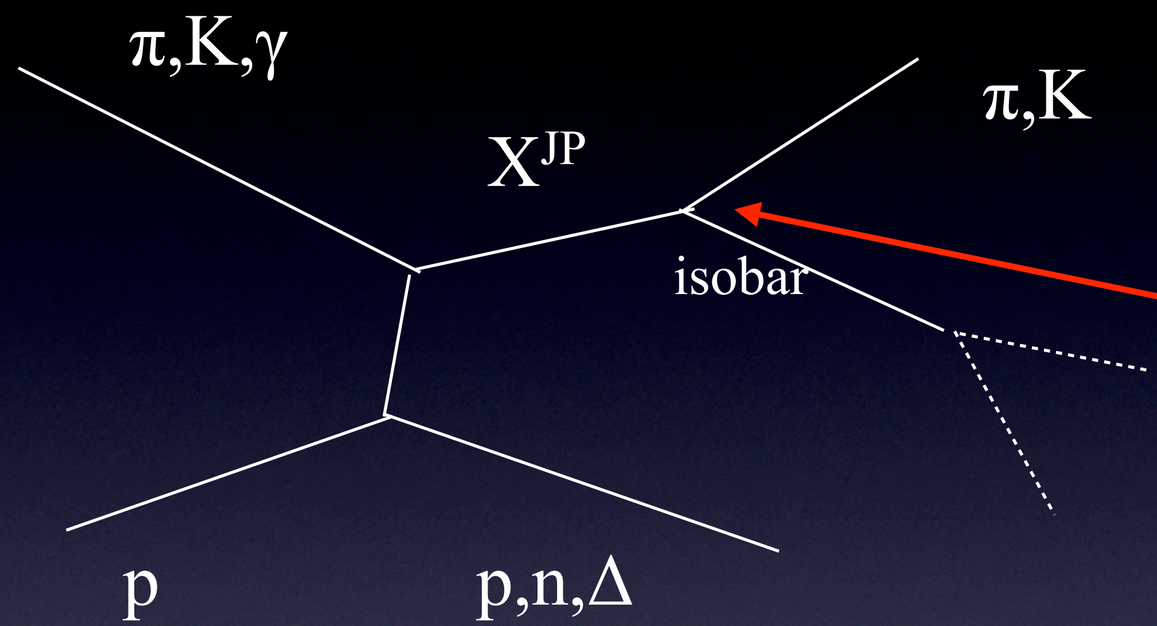

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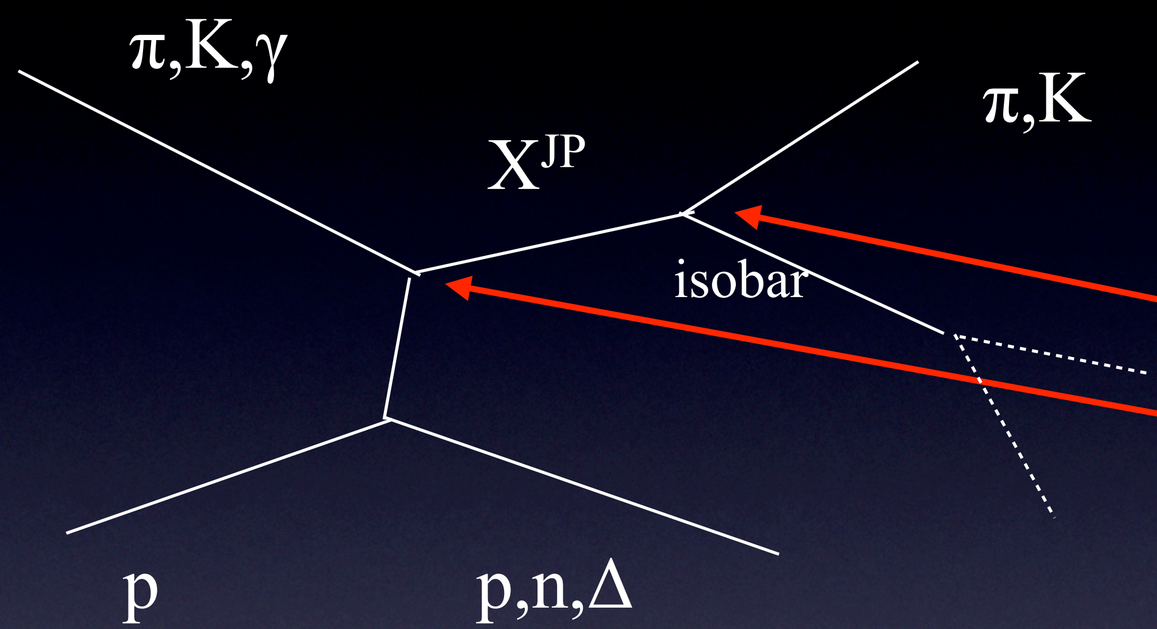

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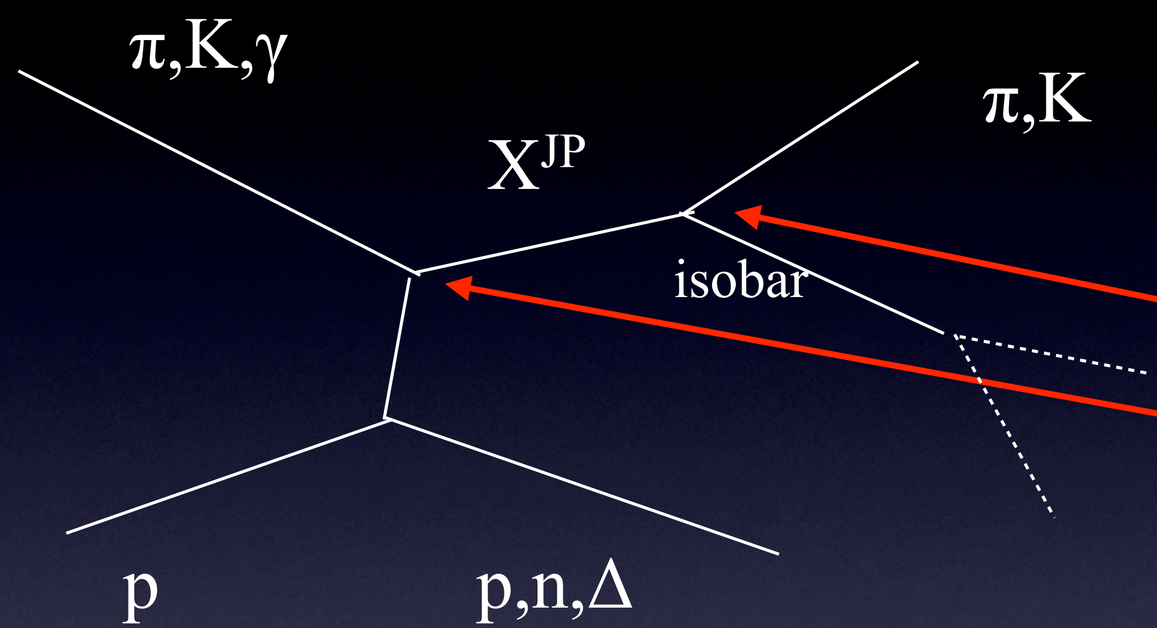
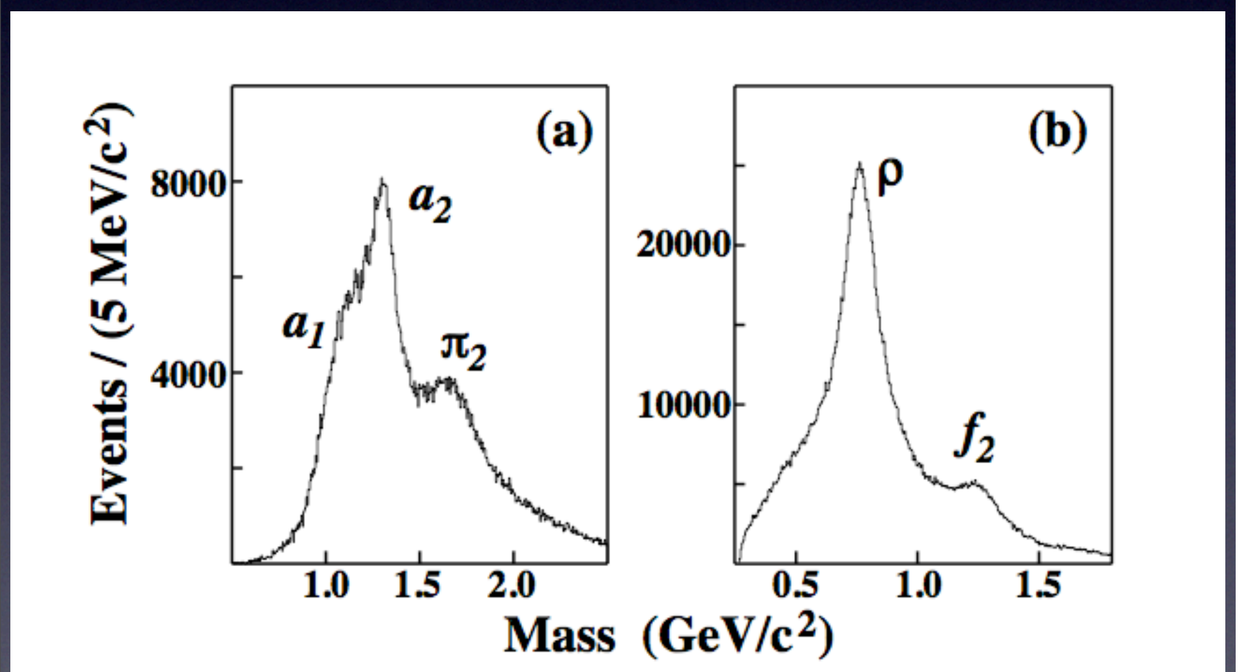


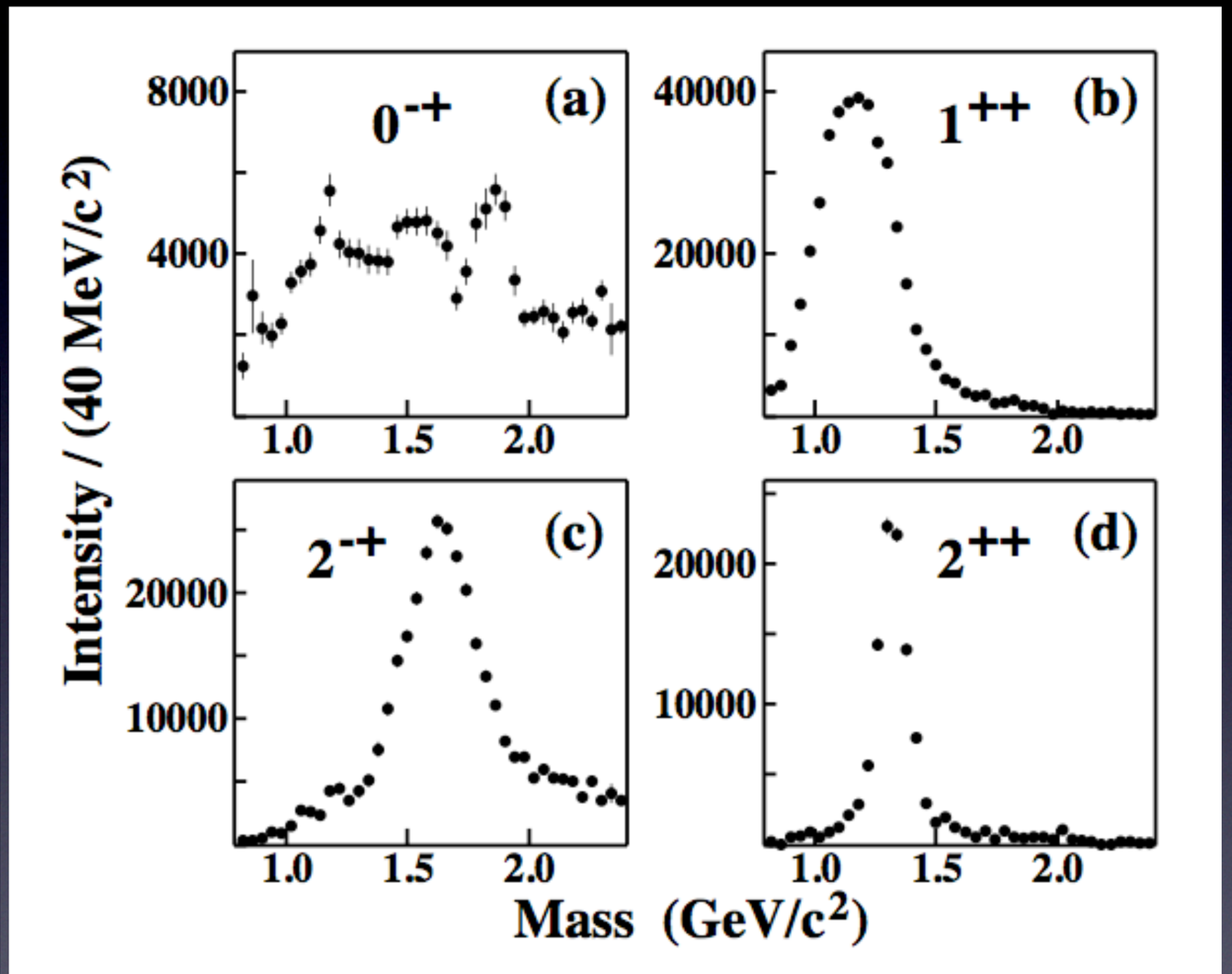
$$I(\tau) = \sum_{\epsilon,k} \left\{ \left| \sum_{\beta} {}^{\epsilon}V_{k\beta}\, {}^{\epsilon}A_{\beta}(\tau) \right|^2 \right.$$

$$\mathcal{L} = \left[\frac{\bar{n}}{n!} e^{-\bar{n}} \right] \prod_{i}^{n} \left[\frac{I(\tau_i)}{\int I(\tau)\eta(\tau)d\tau} \right]$$

E852 250000 events/1997

$\pi^- p \rightarrow \pi^- \pi^- \pi^+ p$





COMPASS

CERN-SPS fixed target

2004: 2 days, 190 GeVπ^- beam Pb target

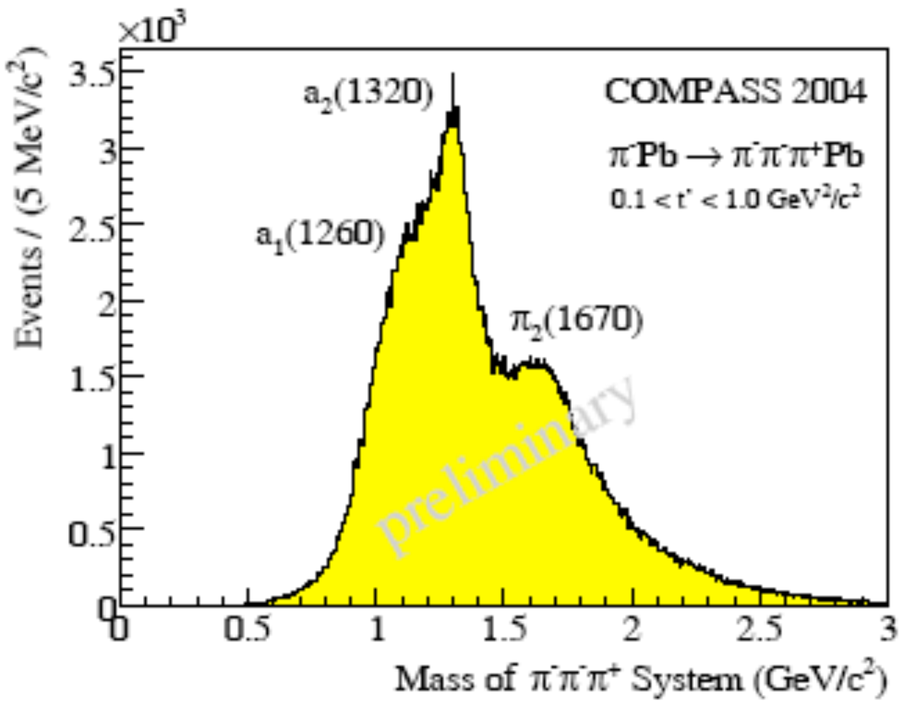


Fig. 1. Invariant mass of $\pi^-\pi^-\pi^+$ final states for $0.1 < t' < 1.0\,\mathrm{GeV}^2/c^2$.

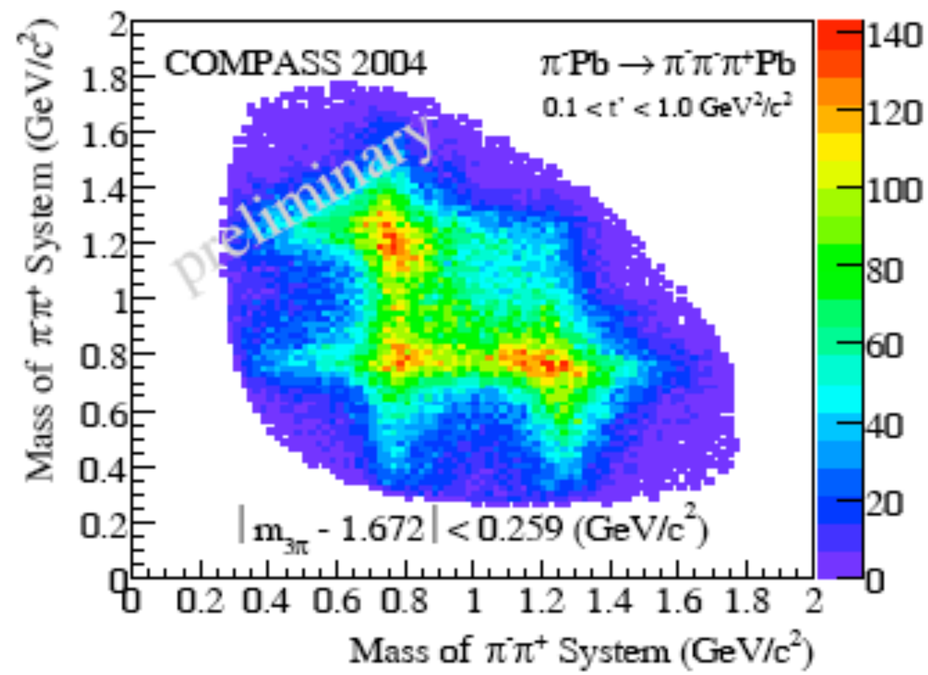


Fig. 2. Dalitz plot for $\pi_2(1670)$, selected by a $\pm 1\Gamma$ cut around its nominal mass.

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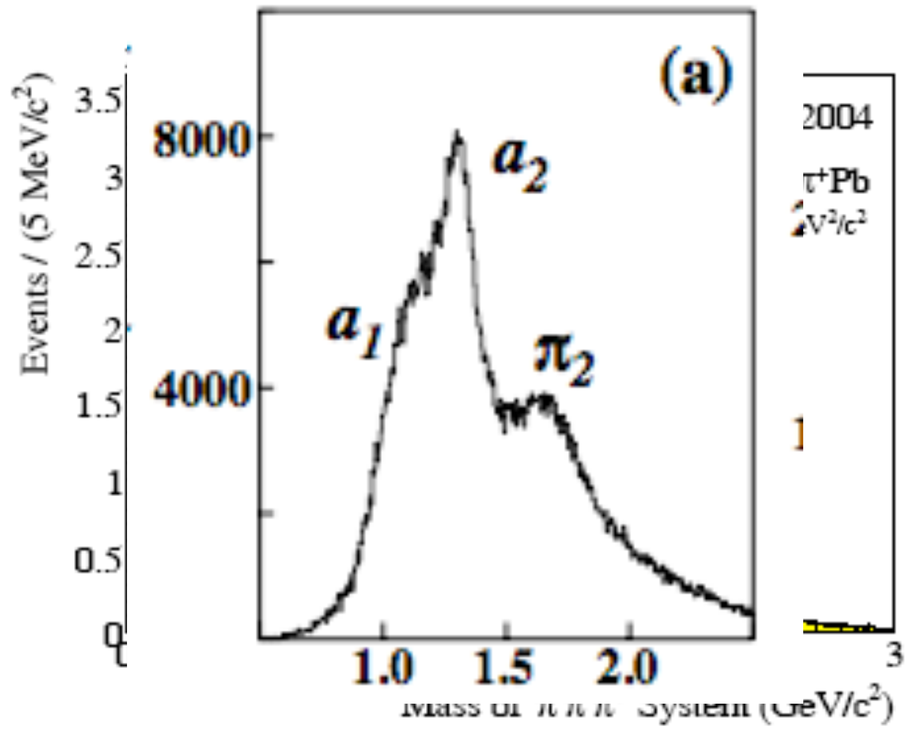

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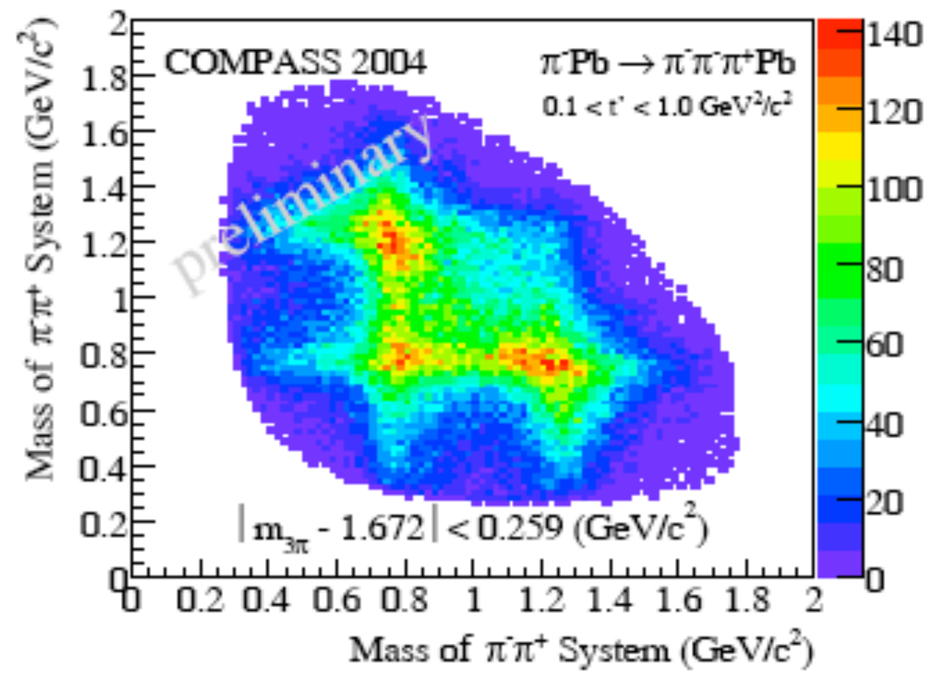

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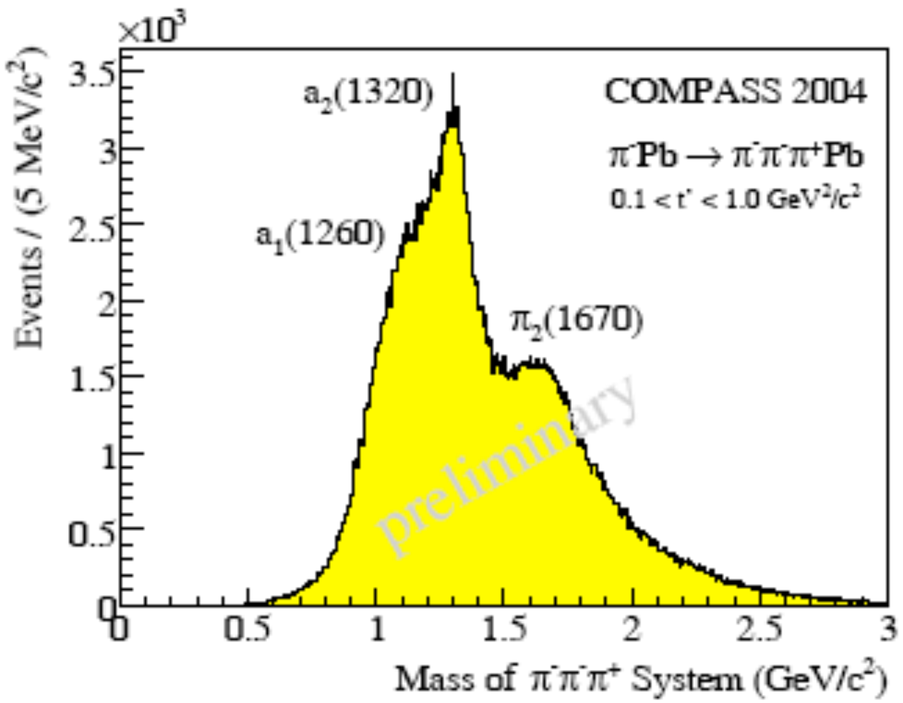

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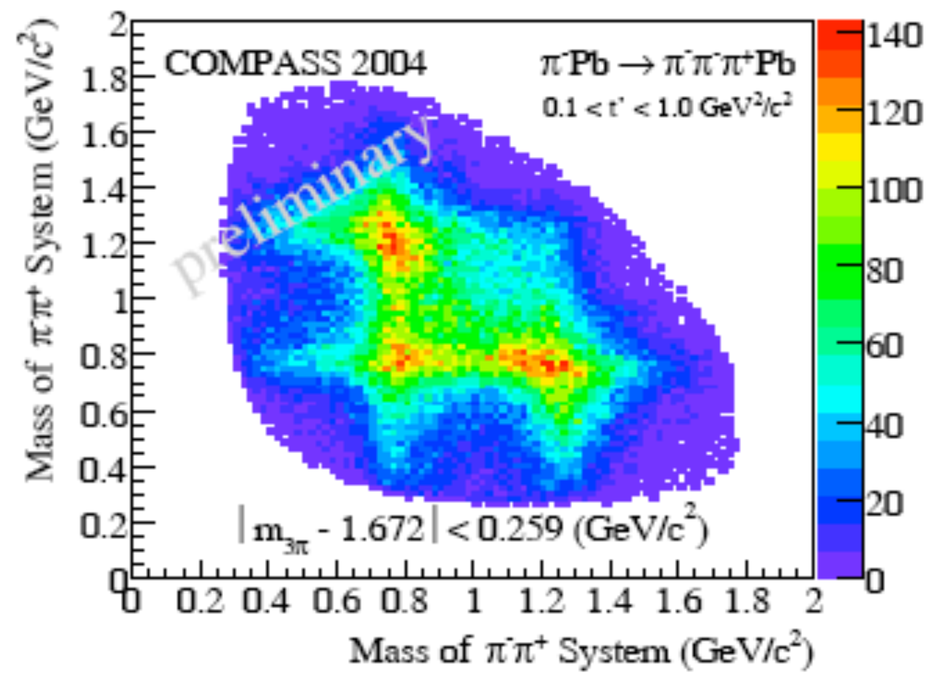

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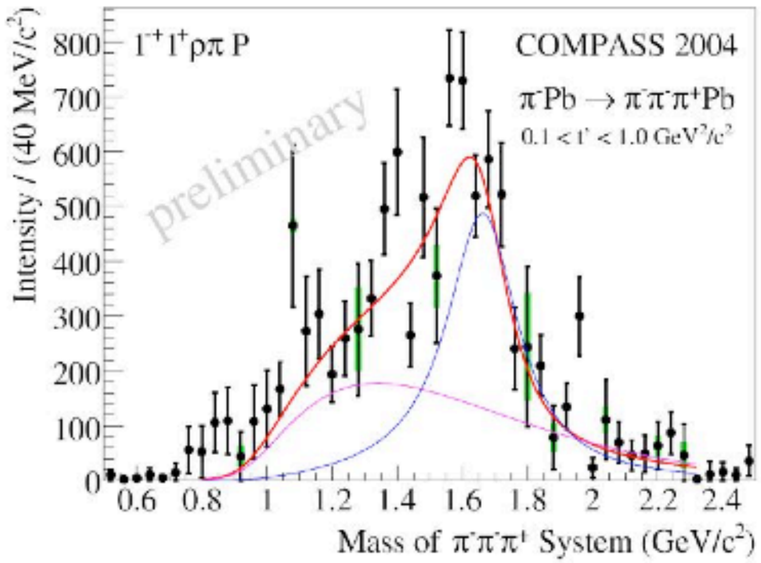
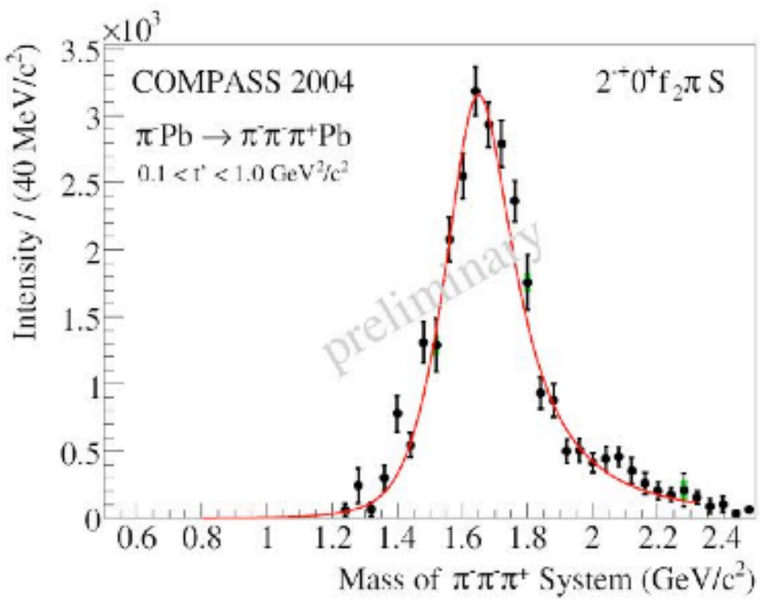
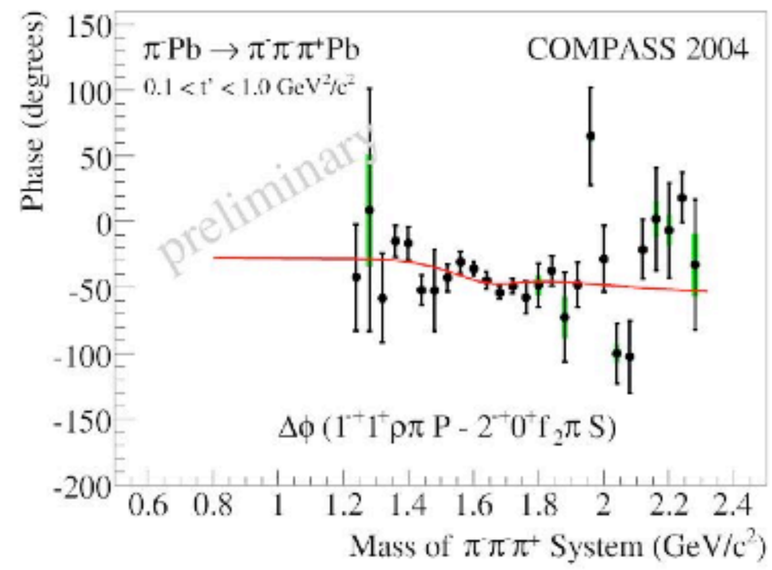
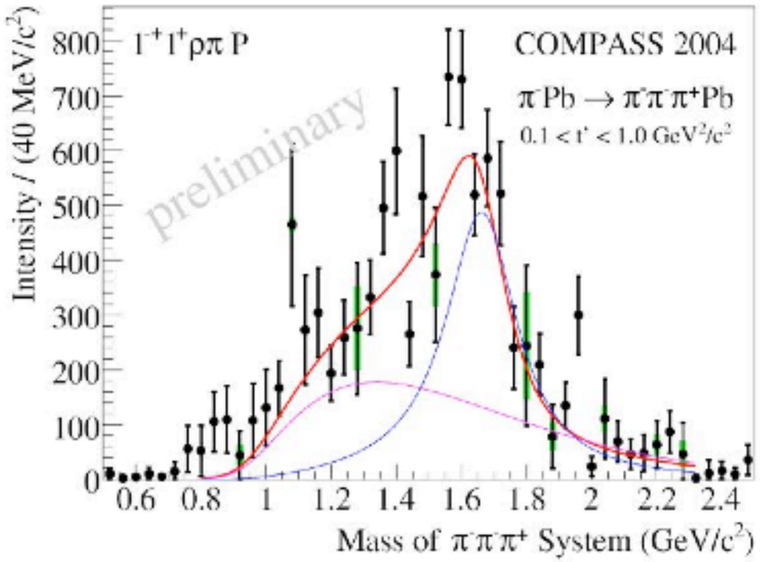

$1^{-+}1^{+}\rho\pi$ P
COMPASS 2004
$\pi^- Pb \to \pi^-\pi^-\pi^+ Pb$
$0.1 < t' < 1.0$ GeV^2/c^2
preliminary
Intensity / (40 MeV/c^2)
Mass of $\pi^-\pi^-\pi^+$ System (GeV/c^2)

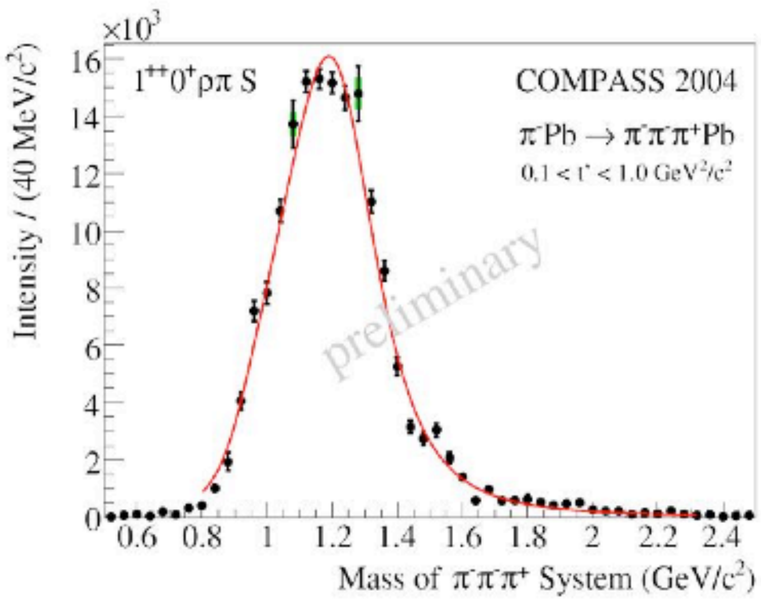
$J^{PC} = 1^{-+}$

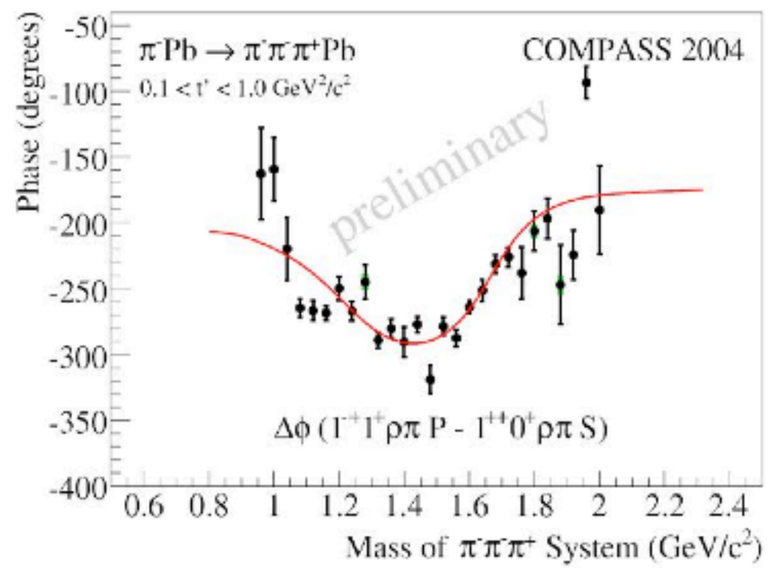

$\times 10^3$
COMPASS 2004
$2^{-+}0^{+}f_2\pi$ S
$\pi^- Pb \to \pi^-\pi^-\pi^+ Pb$
$0.1 < t' < 1.0$ GeV^2/c^2
preliminary
Intensity / (40 MeV/c^2)
Mass of $\pi^-\pi^-\pi^+$ System (GeV/c^2)


$\pi^- Pb \to \pi^-\pi^-\pi^+ Pb$
$0.1 < t' < 1.0$ GeV^2/c^2
COMPASS 2004
preliminary
$\Delta\phi$ ($1^{-+}1^{+}\rho\pi$ P - $2^{-+}0^{+}f_2\pi$ S)
Phase (degrees)
Mass of $\pi^-\pi^-\pi^+$ System (GeV/c^2)

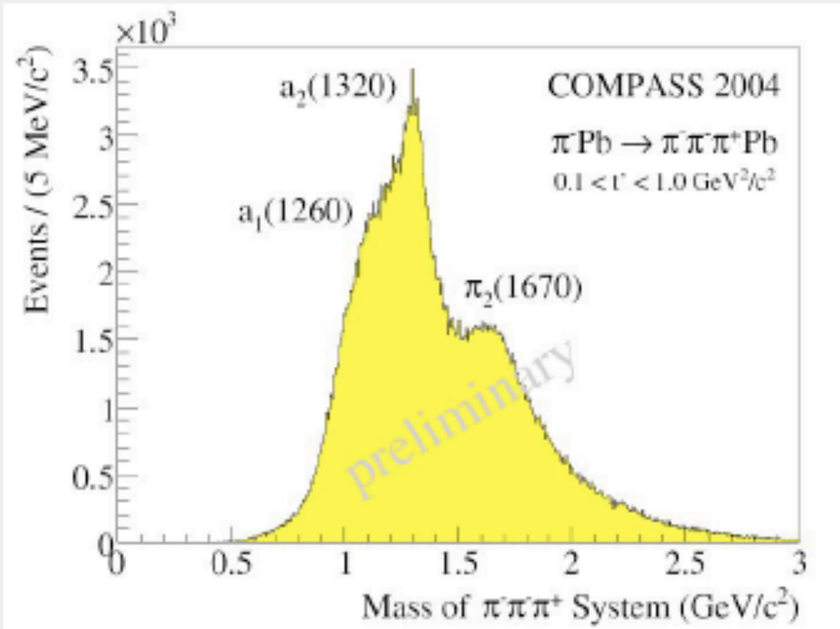


- BW parameters for $\pi_1(1600)$
  $M = (1660 \pm 10^{+0}_{-64})\,\mathrm{MeV/c^2}$
  $\Gamma = (269 \pm 21^{+42}_{-64})\,\mathrm{MeV/c^2}$
- Leakage negligible: $< 5\%$



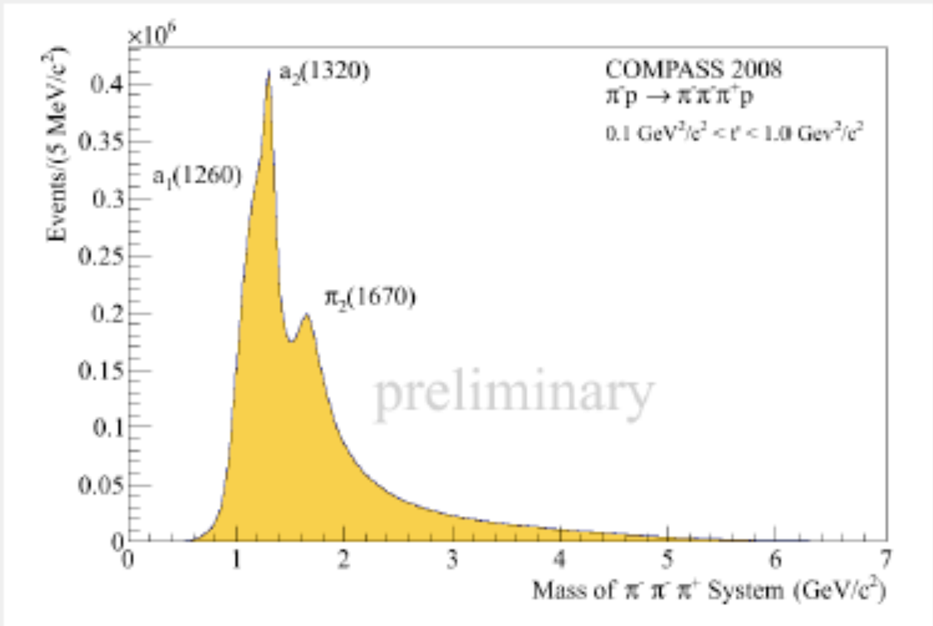


$\pi^- Pb \rightarrow \pi^-\pi^-\pi^+ Pb$ (2004)



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

$\pi^- p \rightarrow \pi^-\pi^-\pi^+ p$ (2008)



- $p_\pi = 190 GeV/c$
- $\sim$ 96M events in $0.1 < t' < 1.0\ GeV^2/c^2$

COMPASS

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

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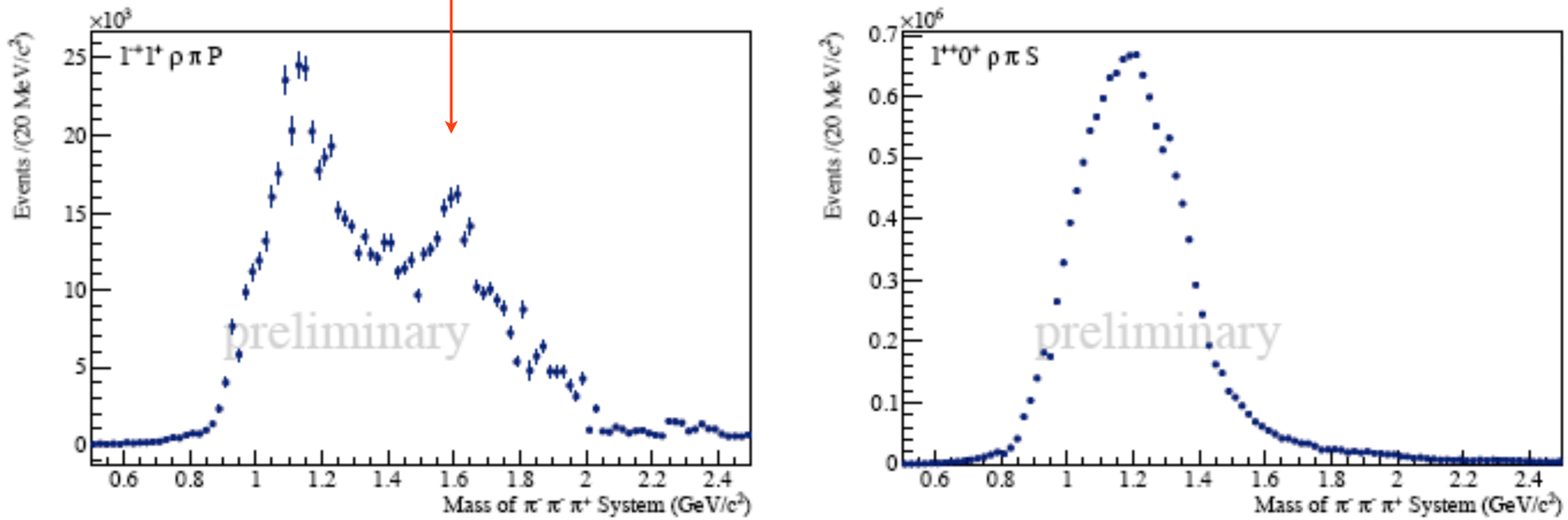
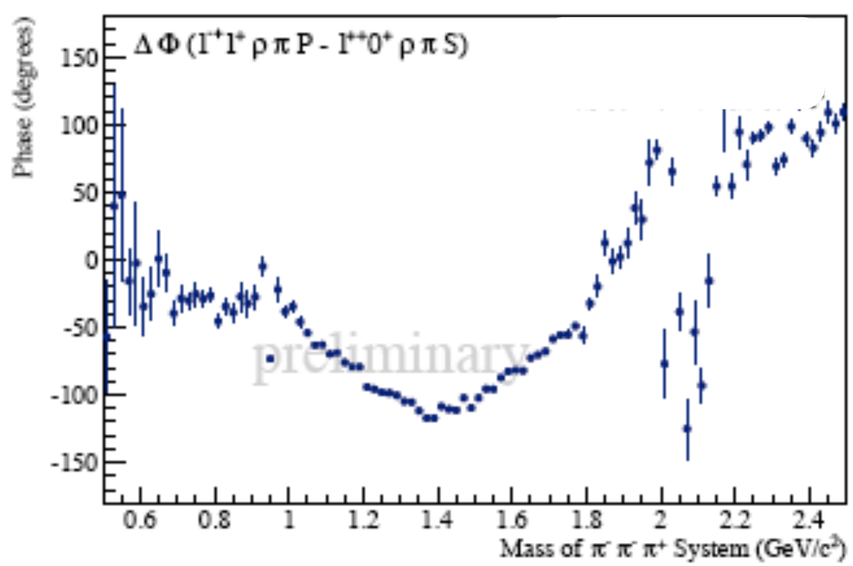


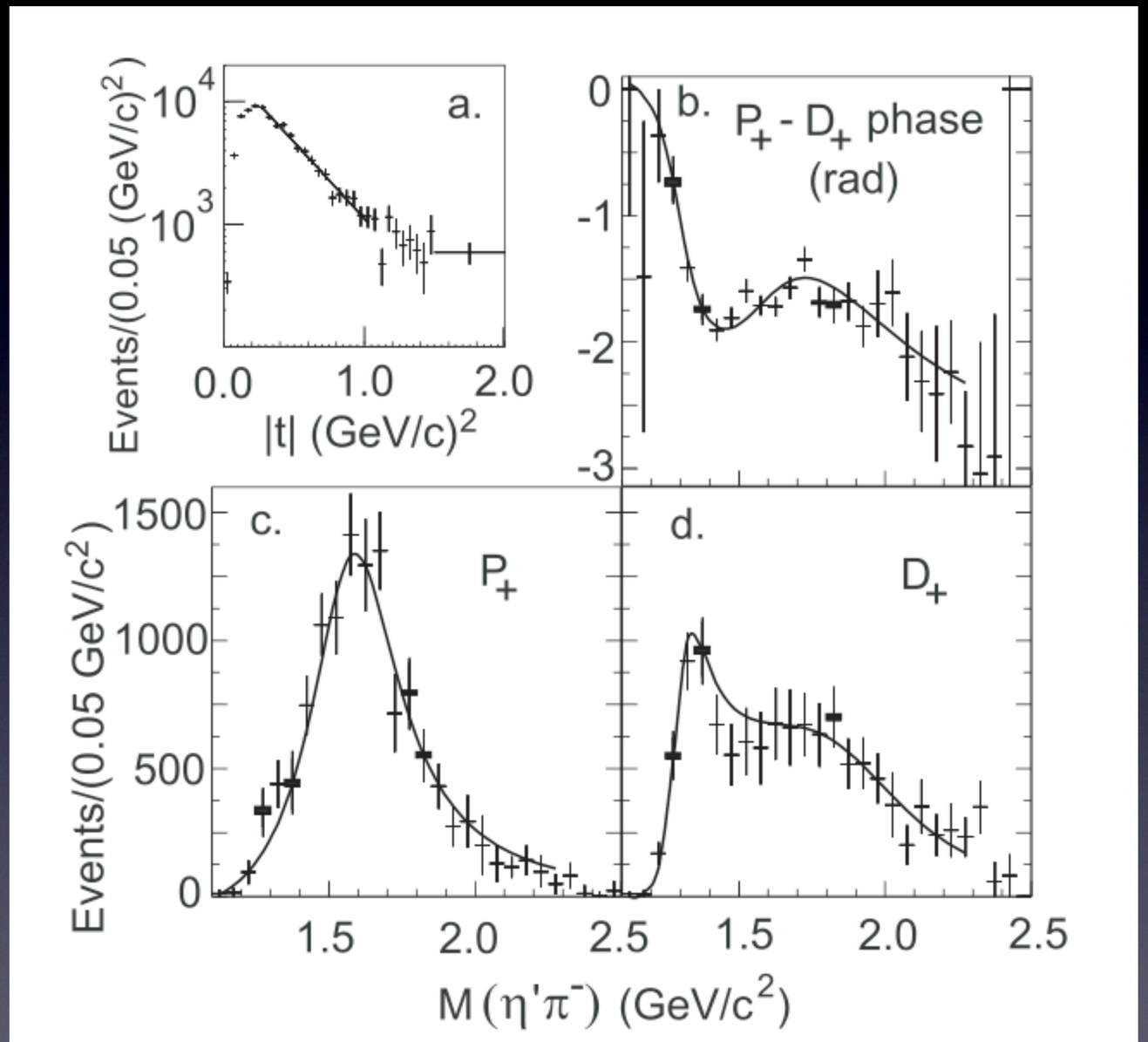
COMPASS 2008

$$\pi^- p \rightarrow \pi^- \pi^- \pi^+ p$$

$$0.1 \ \ GeV^2 < t' < 1.0 \ GeV^2$$



E852 $\pi^- p \rightarrow \eta' \pi^- p$



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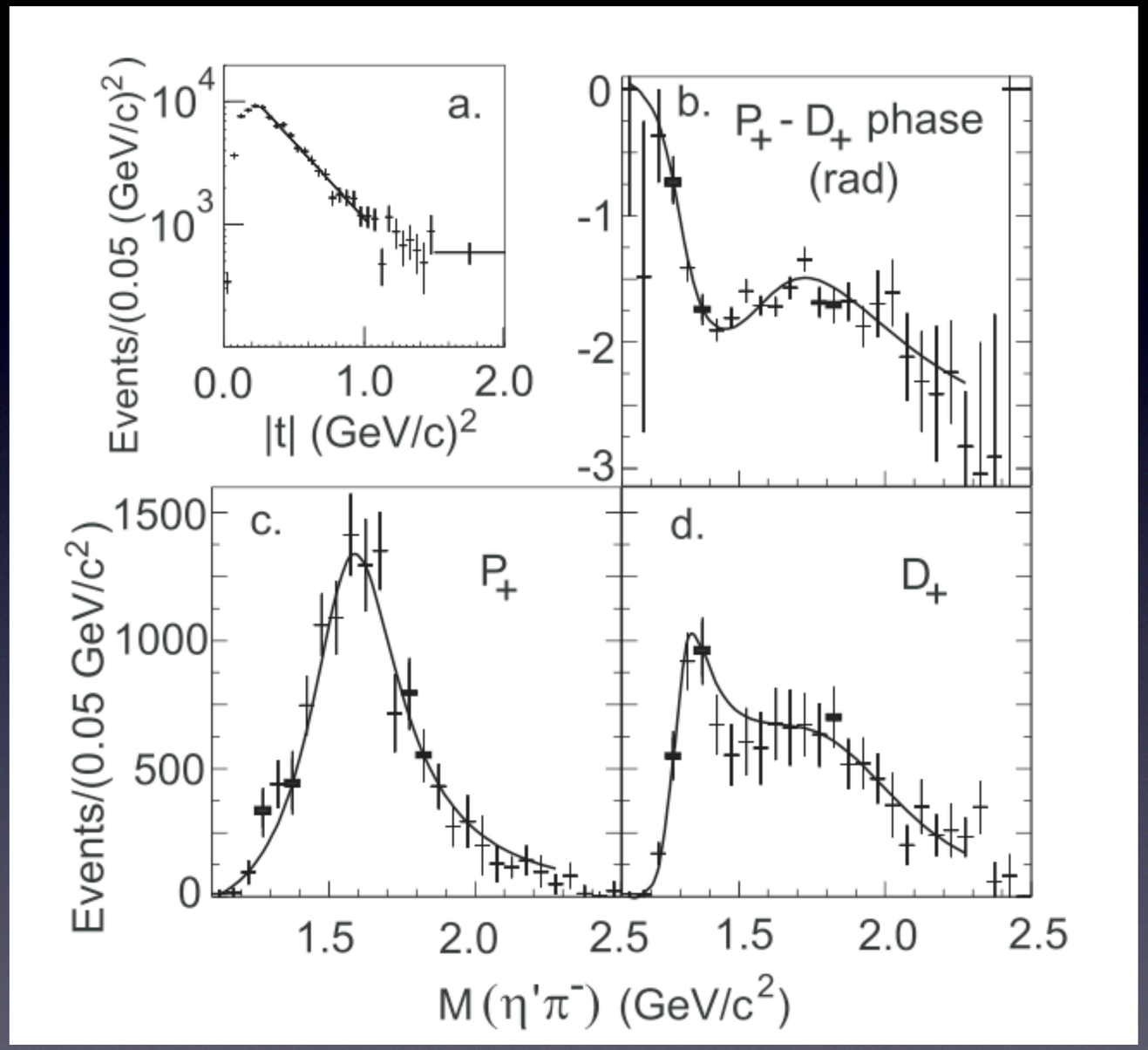

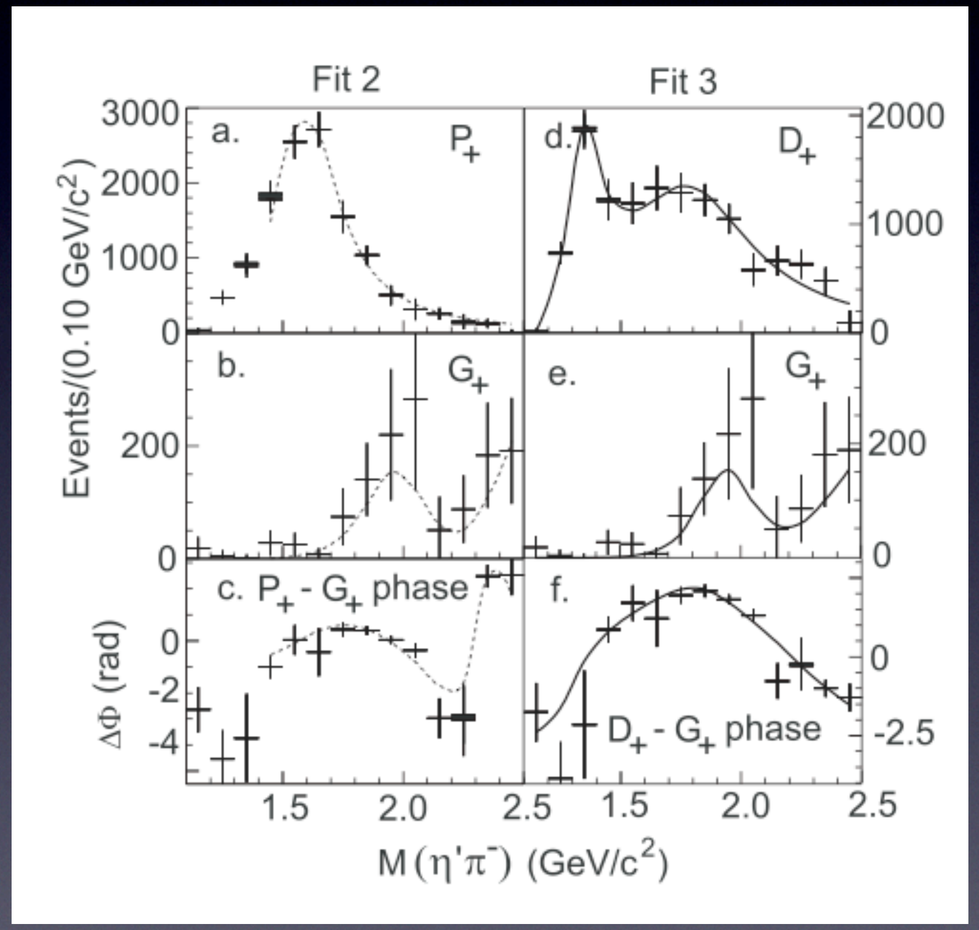

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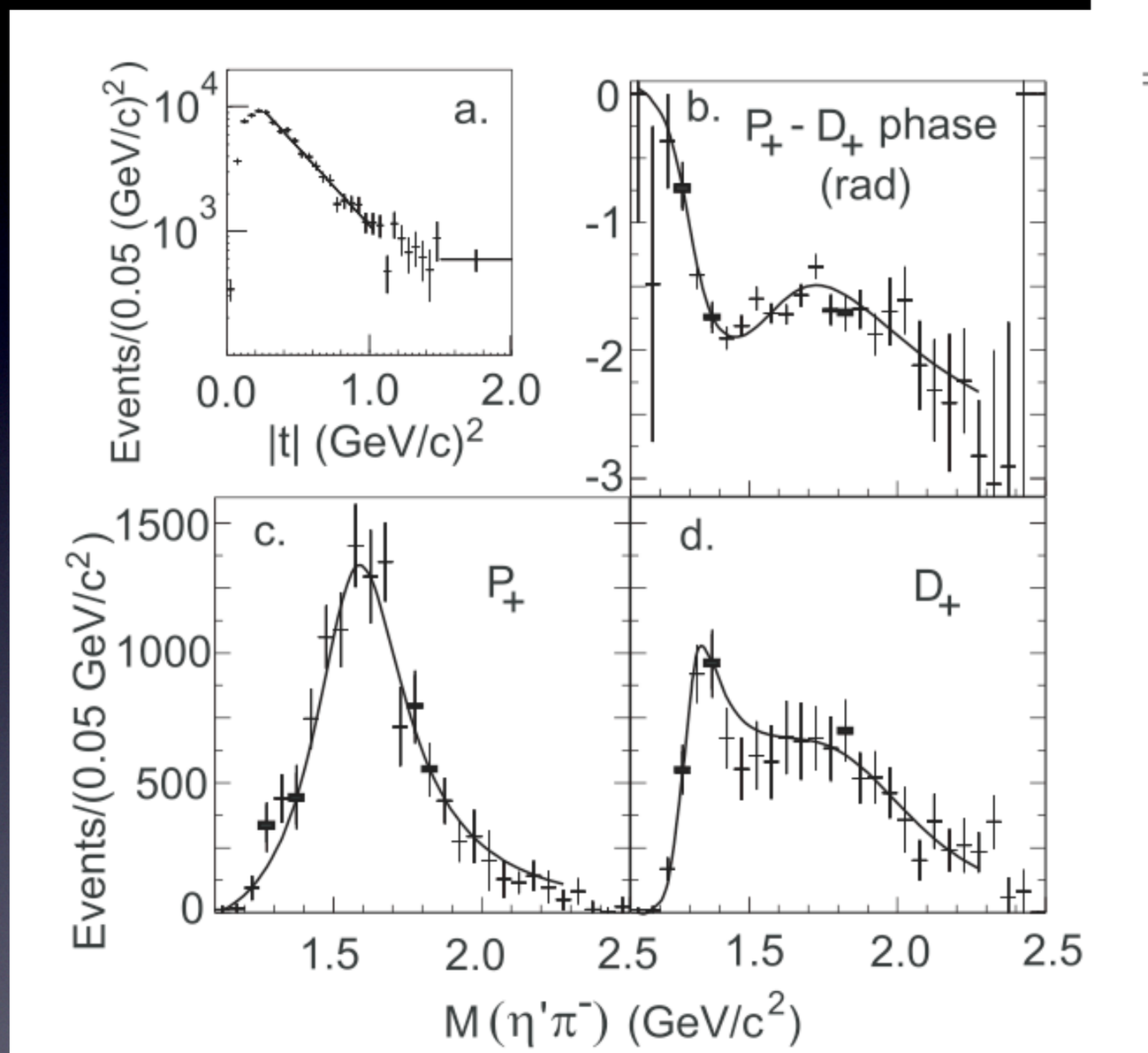
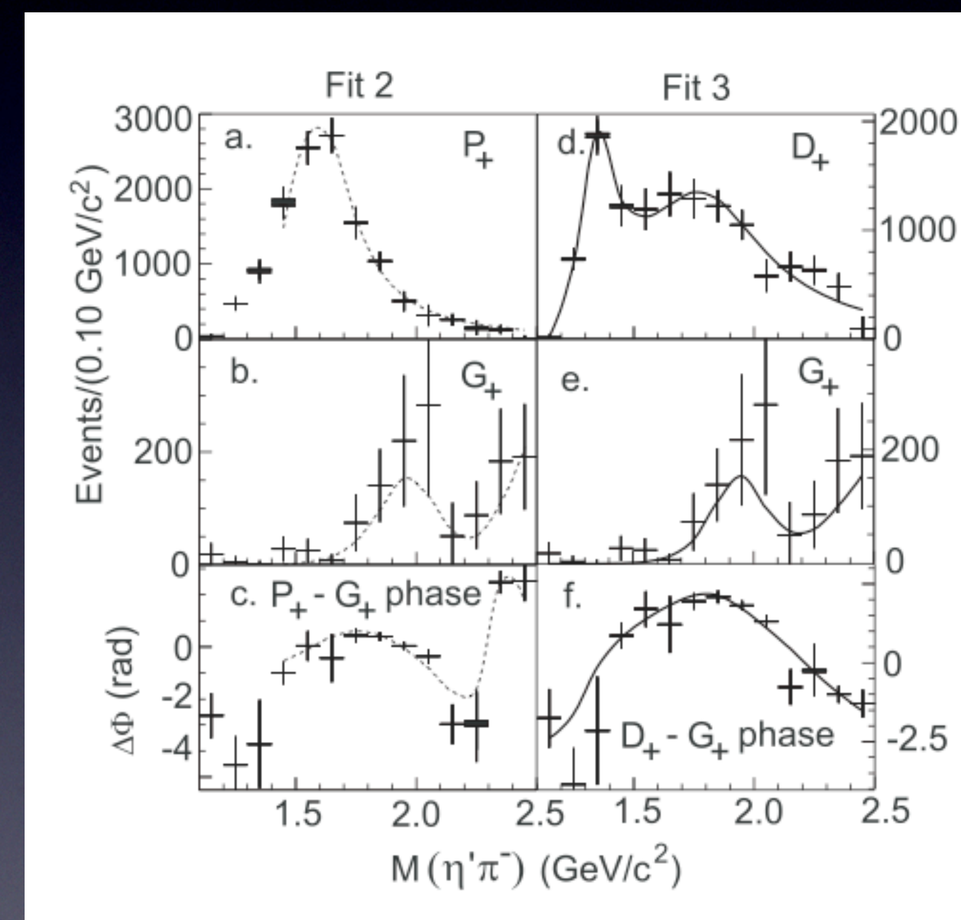


Partial Wave	Mass	Width
P_+	$1.597 \pm 0.010^{+0.045}_{-0.010}$	$0.340 \pm 0.040 \pm 0.050$
D_+	$1.318 \pm 0.008^{+0.003}_{-0.005}$	$0.140 \pm 0.035 \pm 0.020$
G_+	$2.000 \pm 0.040^{+0.060}_{-0.020}$	$0.350 \pm 0.100^{+0.070}_{-0.050}$



COMPASS

$\pi^- p \to \eta' \pi^- p$ @190 GeV/c

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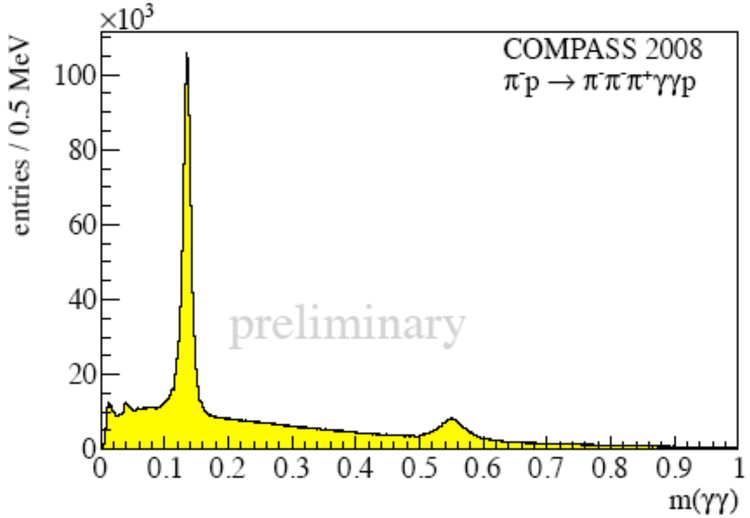
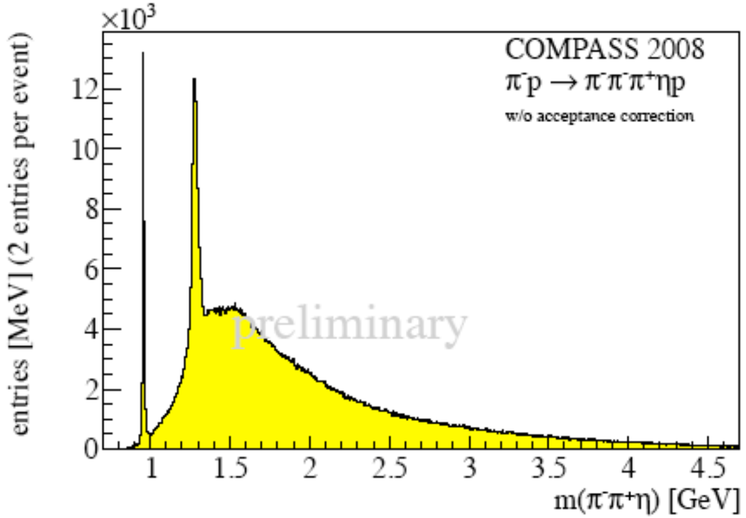
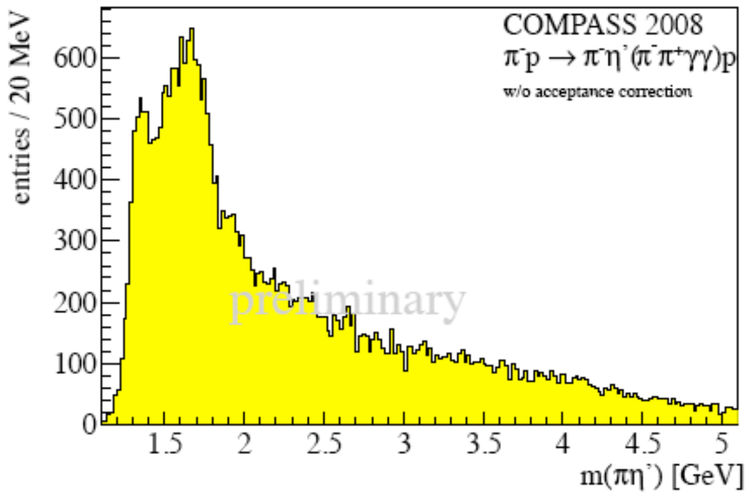
Final state selected: exclusive 3 tracks, 2 photons



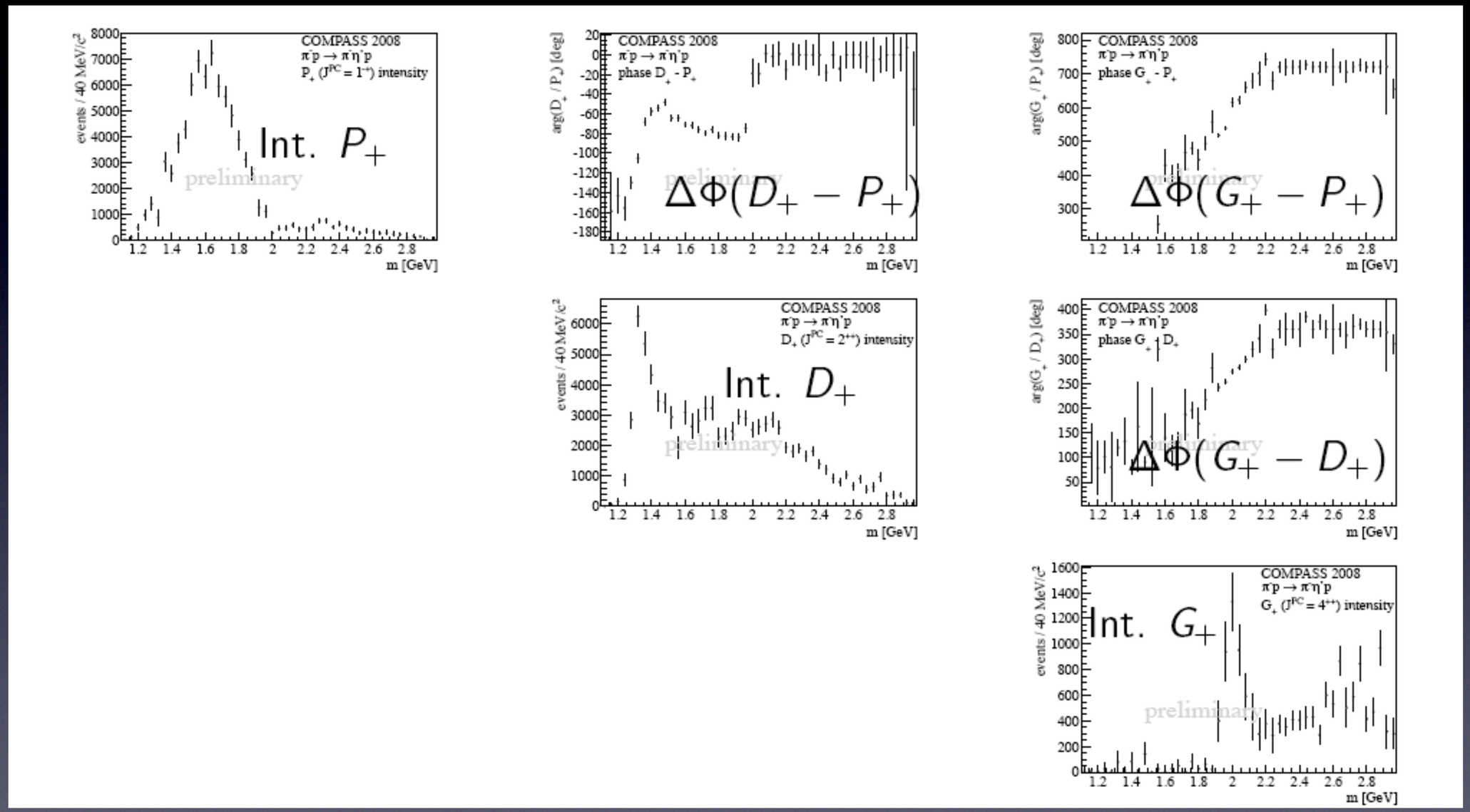




Result:

- 18 000 events with $m(\eta'\pi) < 2\,\mathrm{GeV}/c^2$, 35 000 total
- mass reach beyond $2\,\mathrm{GeV}/c^2$
- additionally, about 3 000 events in $\pi\eta'$, $\eta \to 3\pi$ channel

Partial Wave Analysis



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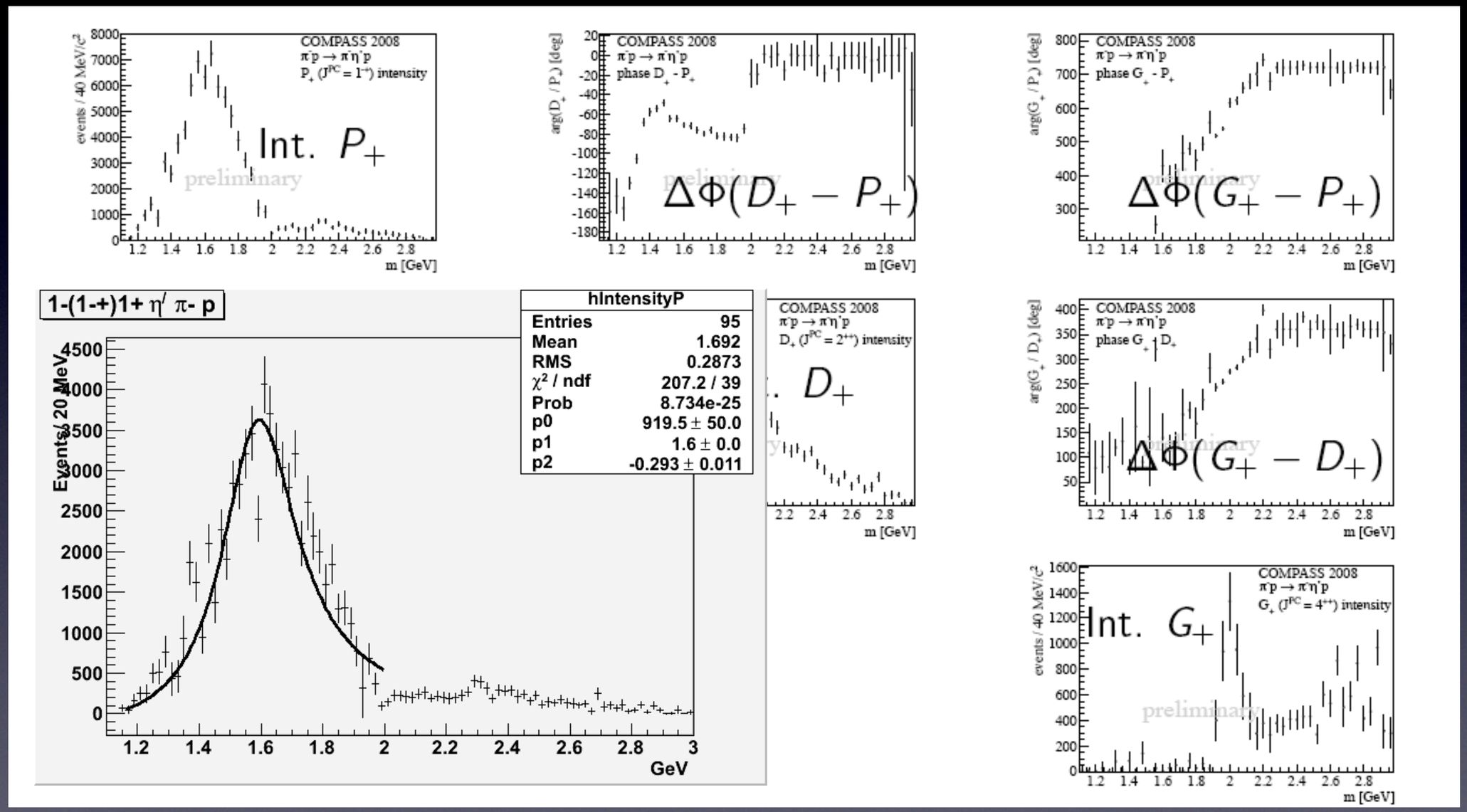


Study of the reaction π^-Be$\rightarrow \eta\pi^-\pi^-\pi^+$Be in the VES experiment

D. Ryabchikov

Institute for High Energy Physics, Protvino

parallel talk at HADRON2011

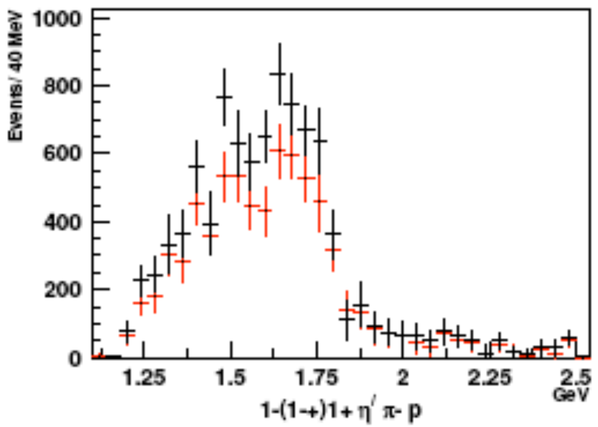
Motivation

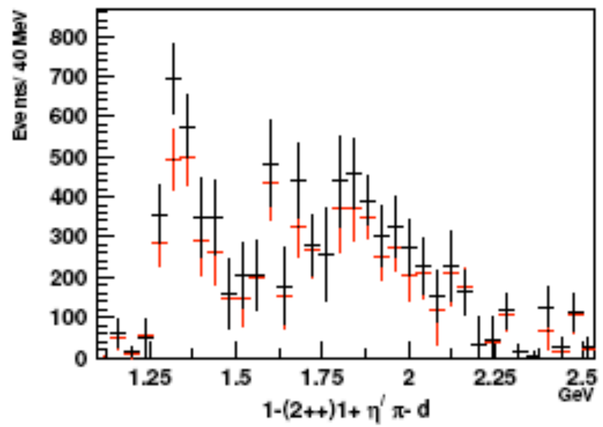
At VES beam energies ($p_{beam} = 28...36$ GeV) production of negative G-parity final states is dominated by diffraction.

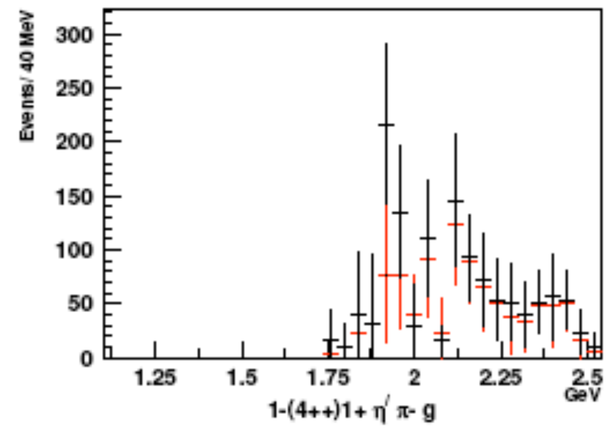
The reaction $\pi^- \mathrm{Be} \rightarrow \eta\pi^-\pi^-\pi^+\mathrm{Be}$, $\eta \rightarrow 2\gamma$ is especially interesting:

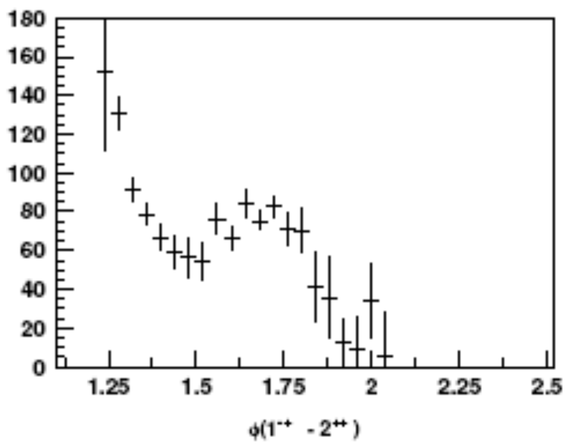
- try to study high-mass final states having $J^{PC} = 0^{-+}, 1^{++}, 2^{-+}, ...$
- try to understand nature of exotic 1^{-+} partial waves in $f_1(1285)\pi^-$ and $\eta'\pi^-$
- do we observe $\eta(1295)\pi^-$ channel ?
- known resonances: $\pi(1800)$, $\pi_2(1670)$, $a_2(1700) \rightarrow \eta 3\pi$?

$\eta'\pi^-$ results

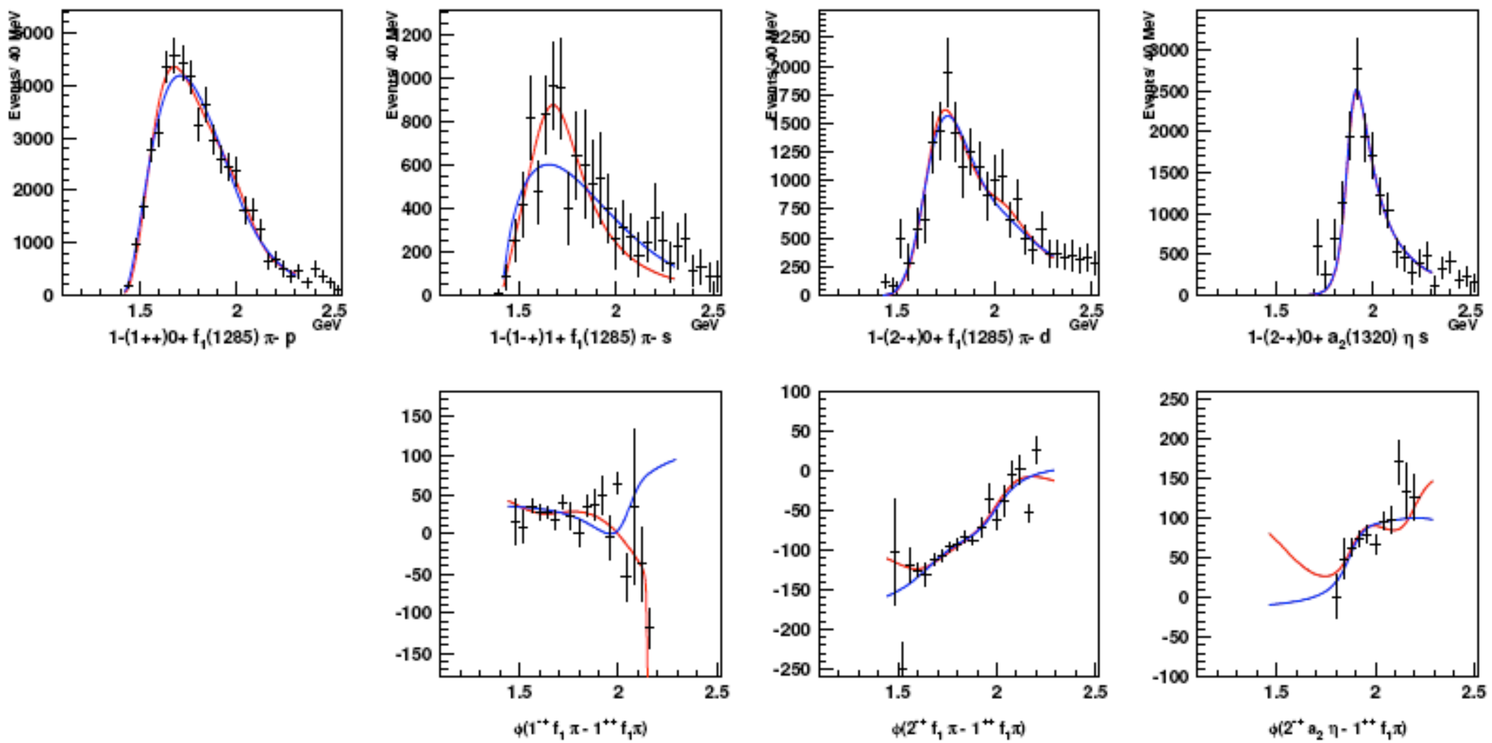








Mass-dependent fit



$$\rho^{\epsilon}_{ij} = \sum_{r=1}^{N_r} \left(\sum_k C^{\epsilon}_{ikr} \mathrm{BW}_k(m) \sqrt{\int |\psi^{\epsilon}_i(\tau)|^2 d\tau} \right) \left(\sum_l C^{\epsilon}_{jlr} \mathrm{BW}_l(m) \sqrt{\int |\psi^{\epsilon}_j(\tau)|^2 d\tau} \right)^*$$

Mass-dependent fit results

"Resonant model"

1^{-+}

M_1=1.640 ± 0.020, Γ_1=0.400± 0.050

1^{++}

M_1=1.530 ± 0.020, Γ_1=0.410± 0.040

M_2=2.050 ± 0.030, Γ_2=0.340± 0.080

2^{-+}

M_1=1.670 ± 0.024, Γ_1=0.330± 0.050

M_2=1.873 ± 0.011, Γ_2=0.167± 0.015

$a_2(1320)\eta S$

M_2=2.040 ± 0.026, Γ_2=0.290± 0.070

$f_1(1285)\pi^- D$

χ^2/NDF=300./(303-39)=1.14

Conclusions

- PWA in mass bins of $\eta 3\pi$-system demonstrates:
  - dominance of various NPE states
  - significant $f_1(1285)\pi^-$ and many other isobaric decay chains: $a_0(980)\rho$, $a_2(1320)\eta$, $a_1(1260)\eta$, $\rho(1450)(\rightarrow \rho\eta)\pi^-$, $a_2(1320)\rho$, ...
  - no $\eta(1295)\pi^-$
  - $\eta'\pi^-$ has $a_2(1320)$ + exotic wave, rather broad structure and no clear structures in high mass 2^{++}
  - very small 0^{-+}, no $\pi(1800) \rightarrow \eta 3\pi$
- Further mass-dependent analysis:
  - Can accomodate broad resonances in 1^{++} and 1^{-+} in 1.5-1.6 GeV region
  - $\pi_2(1670) \rightarrow f_1(1285)\pi^-$?? (not VERY clear yet)
  - $\pi_2(1880) \rightarrow a_2(1320)\eta$ values obtained: M_2=1.873 $\pm$ 0.011, Γ_2=0.167$\pm$ 0.015 Needed: systematic study + Branchings
  - Non-resonant model - a bit worse description. More natural to explain phase-lock between two very broad amplitudes.

Technische Universität München

Study of interference of Coulomb and strong diffractive production of $\pi^-\pi^-\pi^+$ systems produced off Pb target at COMPASS

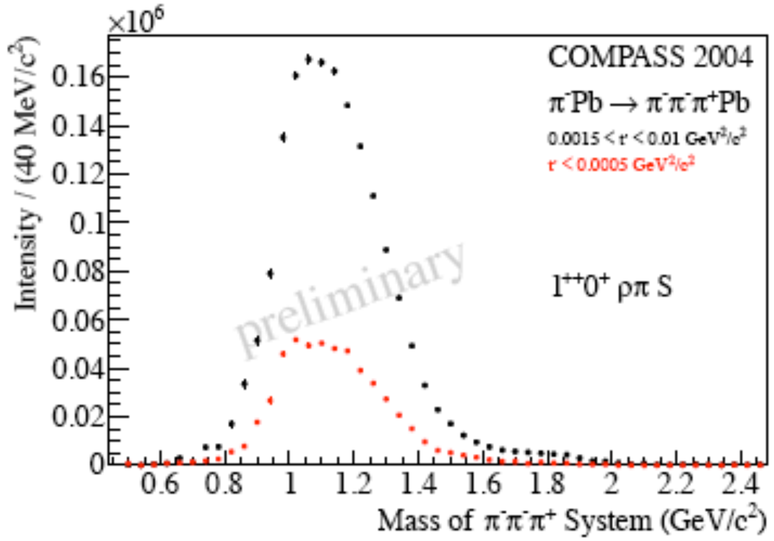
D. Ryabchikov, S. Grabmüller, J. Friedrich

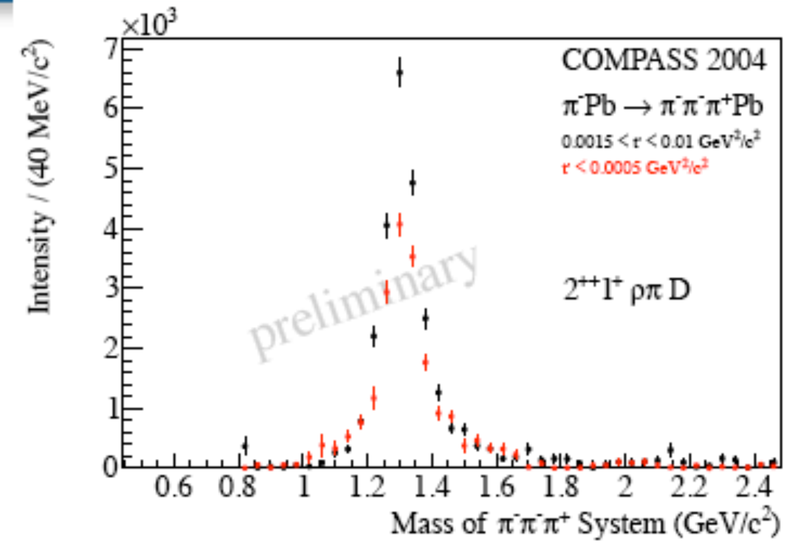
Institute for High Energy Physics, Protvino; Physik-Department, E18 Technische Universität München

HADRON2011 talk

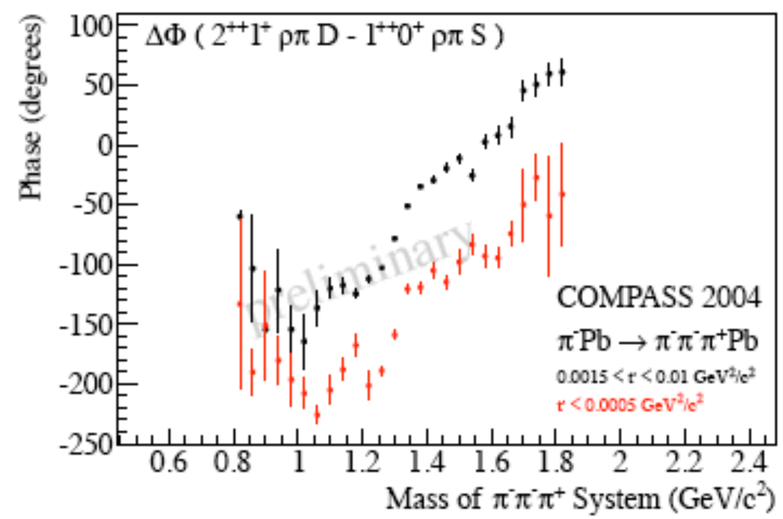
a1(1260) and a2(1320): fits in two regions of t′

Technische Universität München





$J^{PC} = 2^{++}$ amplitude shows resonant nature in two t' regions.
Phase is shifted by $\sim 90^0$ between those two fits.



D. Ryabchikov — Study of interference of Coulomb and strong diffractive production of $\pi^-\pi^-\pi^+$ systems produced off Pb target at COMPASS 7/18

Conclusions

Technische Universität München

- Primakoff contribution in π^-Pb$\rightarrow \pi^-\pi^-\pi^+$Pb in COMPASS 2004 Pilot run
  - Sharp Coulomb spike $t' \rightarrow 0$ already in raw data. Statistical substraction method reveals the specific Primakoff m(3π) spectrum (very different from dominating diffractive pattern).
  - Detailed study with special PWA:
    M=1 total mass spectrum found similar to stat. substr. result.
  - M=1 intensities with much narrower t' distribution than expected for strong production $\rightarrow$ Coulomb contribution
  - M=1 production phases of a_2 and π_2 (relative to M=0) show rapid increase as function of t'
- $a_2(1320)$ at $t' < 0.01$ predominantly Primakoff produced
- $\pi_2(1670)$ at $t' < 0.01$ shows both Primakoff and strong contributions
- Interference effects between electromagnetic and strong amplitudes visible

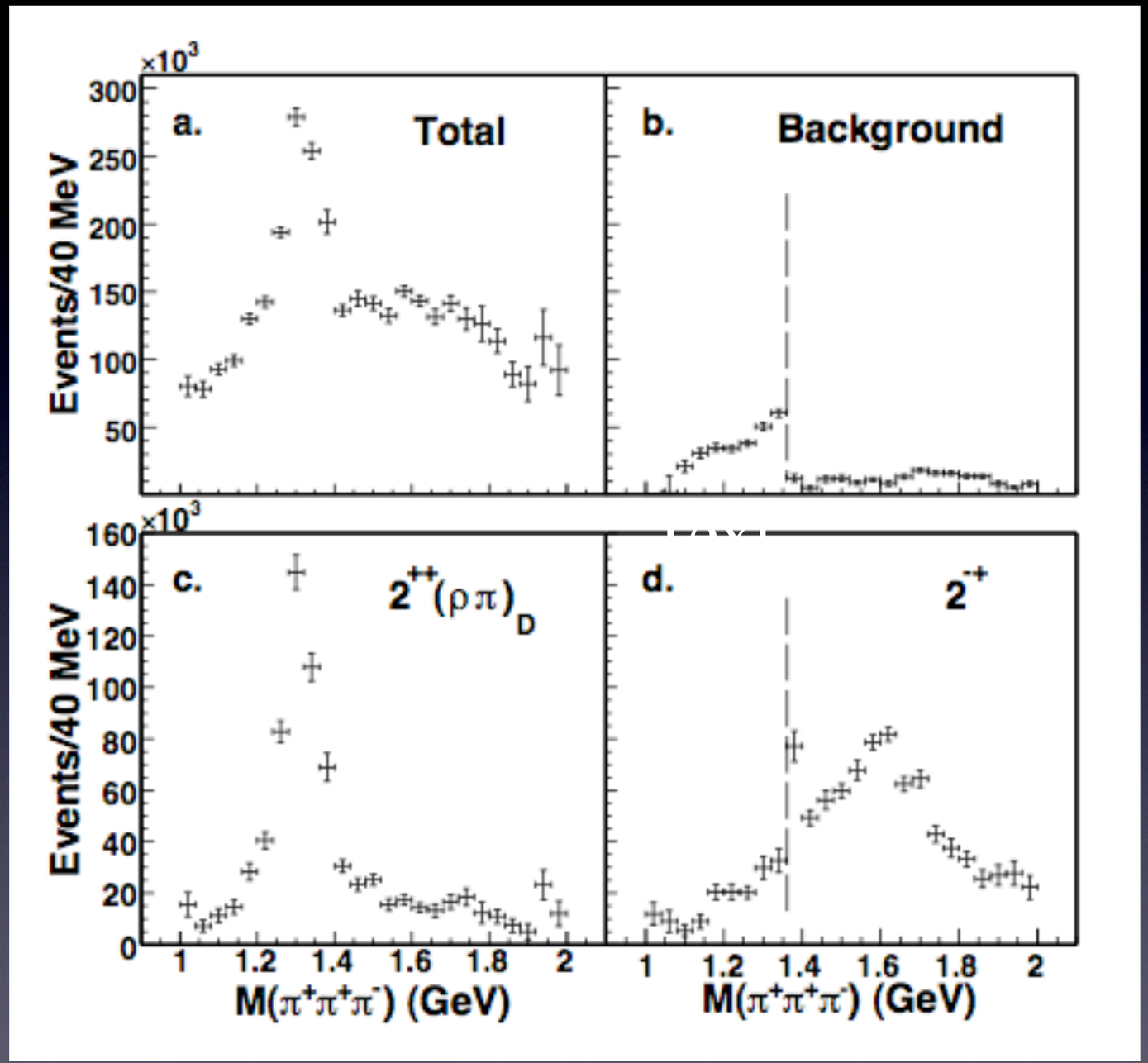
The Search for Exotic Mesons in $\gamma\, p \rightarrow \pi^+\pi^+\pi^- n$ with CLAS at Jefferson Lab

Craig Bookwalter
on behalf of the CLAS collaboration

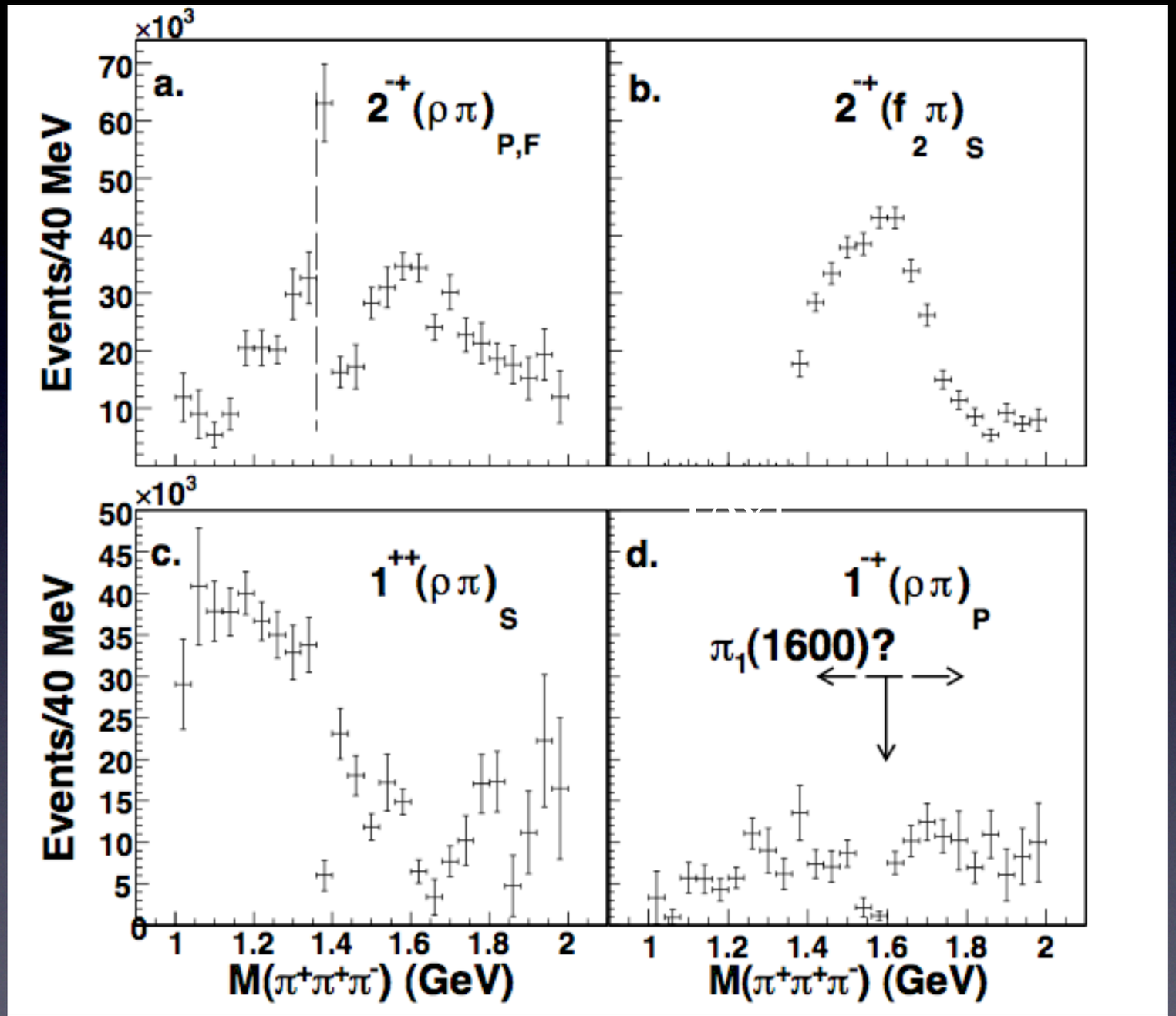
Florida State University
Tallahassee, FL USA

XIV International Conference on Hadron Spectroscopy (Hadron2011)
Munich, Germany
June 16, 2011

g6c: Major waves $\gamma p \rightarrow \pi^+\pi^+\pi^-(n)$ 2.3 pb^{-1}

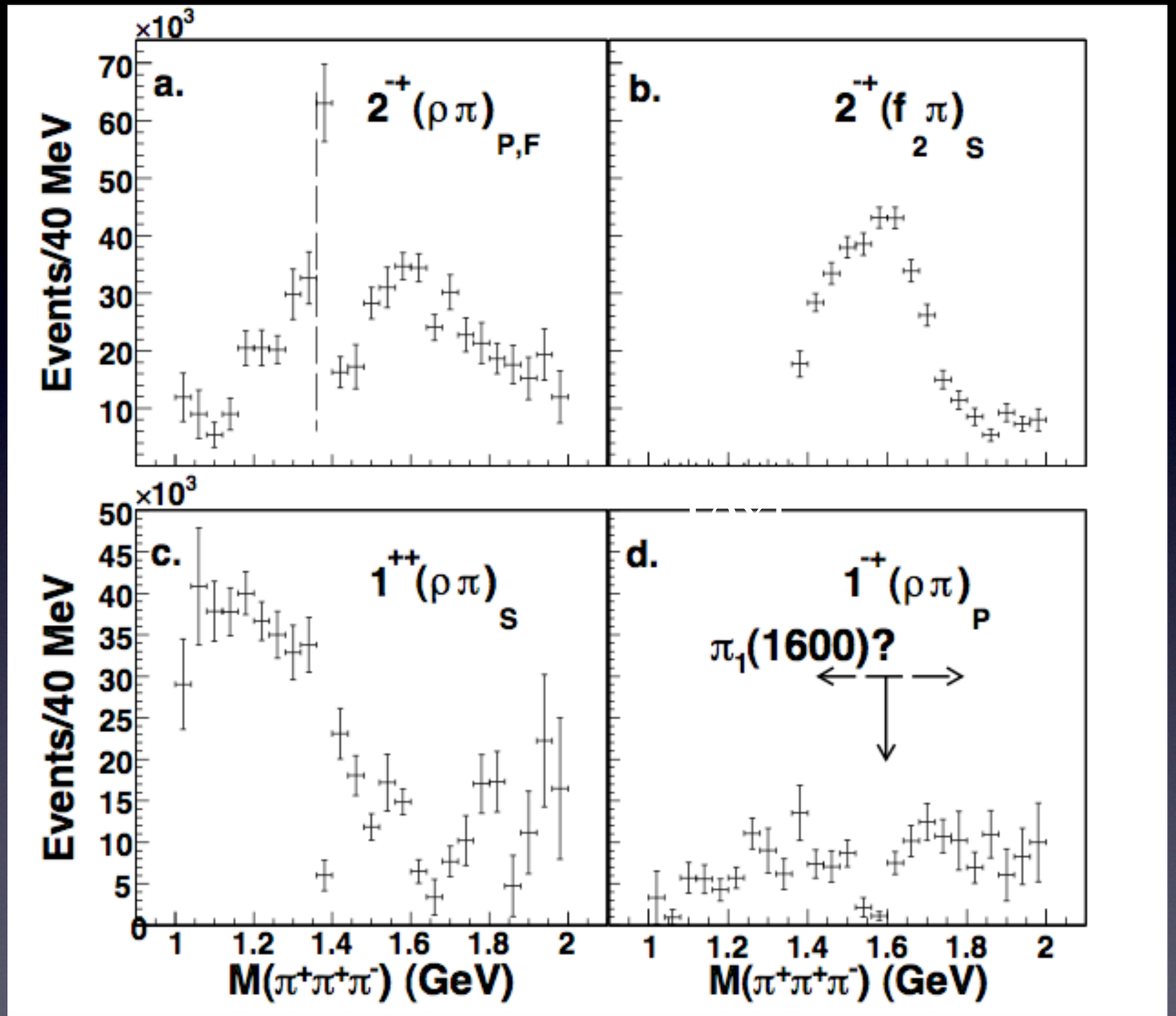


g6c: Major waves $\gamma p \rightarrow \pi^+\pi^+\pi^-(n)$ 2.3 pb^{-1}



g6c: Major waves $\gamma p \rightarrow \pi^+\pi^+\pi^-(n)$

2.3 pb^{-1}

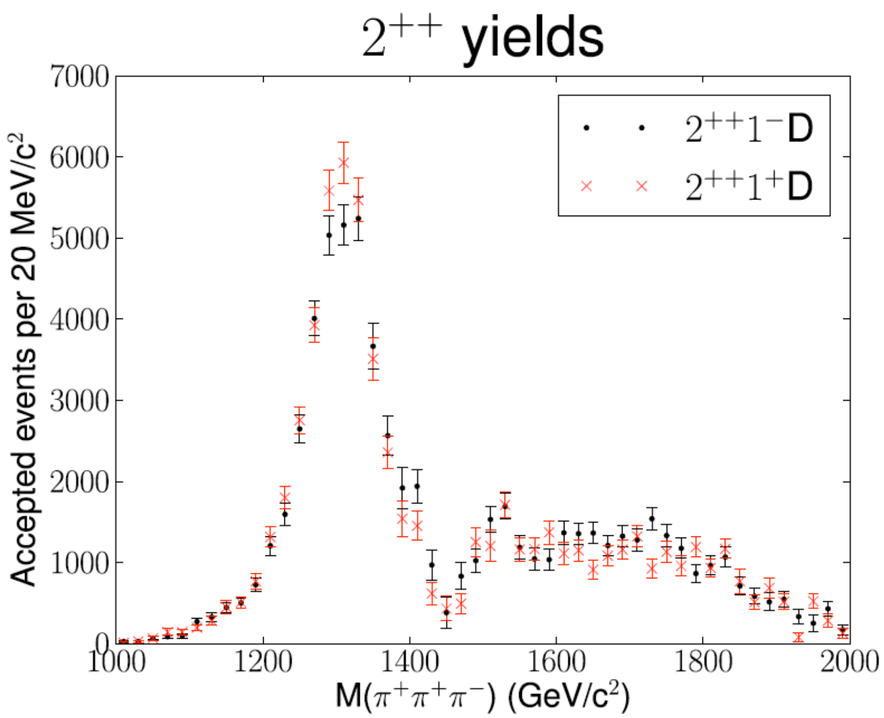


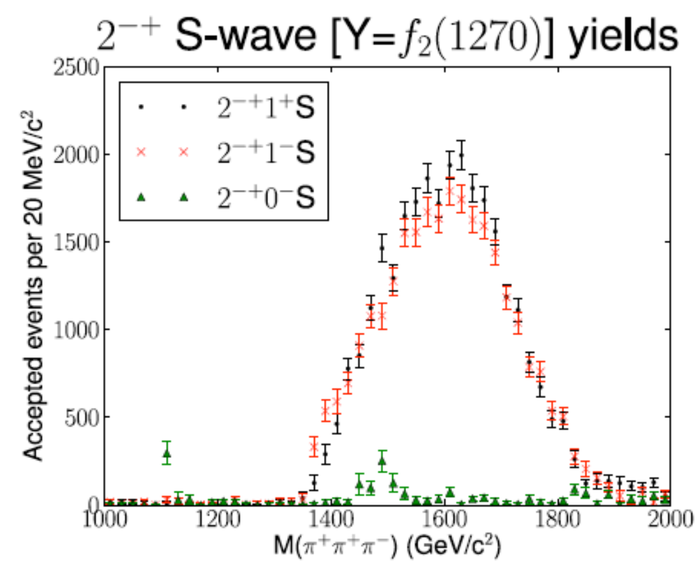
$\sigma_{\pi_1} < 13.5$ nb

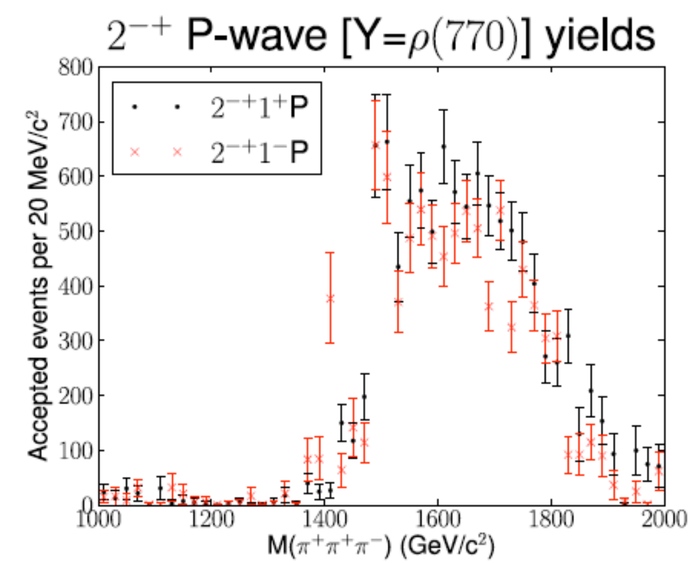
(<2% of a_2)

Nozar, et al Phys.Rev.Lett. 102:102002,2009. e-Print: **arXiv: 0805.4438** [hep-ex]

PWA: 2^{++} accepted yields







- Yield of $2^{-+} \rightarrow f_2(1270)\pi$: yield of $2^{-+} \rightarrow \rho(770)\pi \approx 3$

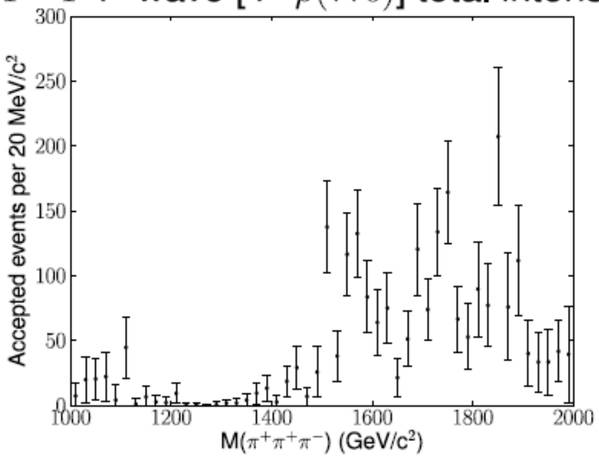
g_{12} High Energy (> 4.4 GeV) Luminosity:27 pb^{-1} ~10 X g_{6c} raw luminosity

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

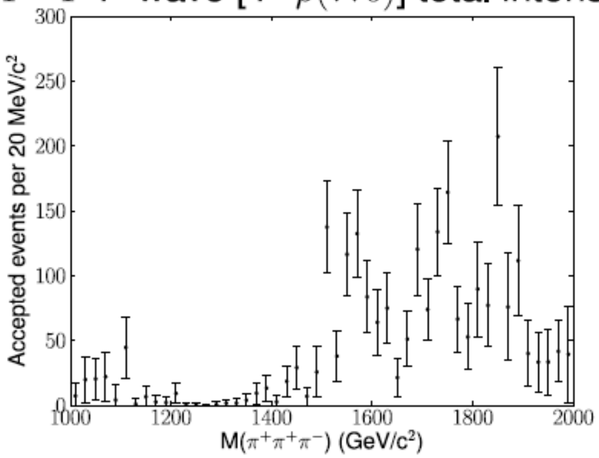
Craig Bookwalter, FSU

PWA: 1^{-+} accepted yields

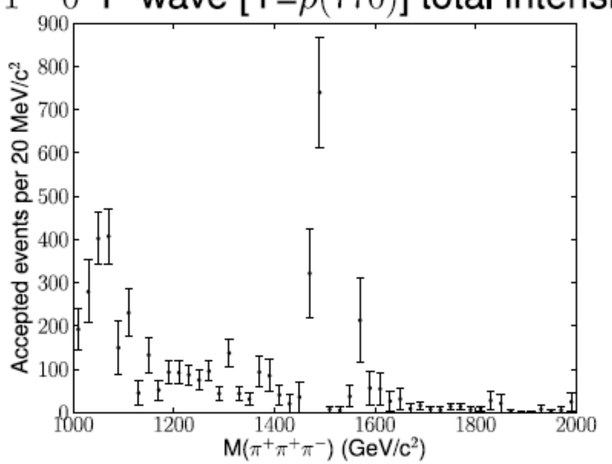
$1^{-+}1^{+}$P-wave [Y=$\rho(770)$] total intensity



$1^{-+}1^{-}$P-wave [Y=$\rho(770)$] total intensity



$1^{-+}0^{-}$P-wave [Y=$\rho(770)$] total intensity



- accounts for up to 2% of total intensity

Craig Bookwalter (FSU) | Exotics in $\gamma\ p \rightarrow \pi^+\pi^+\pi^- n$ | June 16, 2011 | 16 / 19

X(3872)

Discovered by Belle (2003) $B^+ \to J/\psi\, \pi^+\pi^- K^\pm$

S.-K. Choi et al. Belle Collaboration Phys. Rev. Lett. 91, 262001 (2003)

Confirmed by BaBar, CDF, D0

$J^{PC} = 1^{++}$ or 2^{-+}

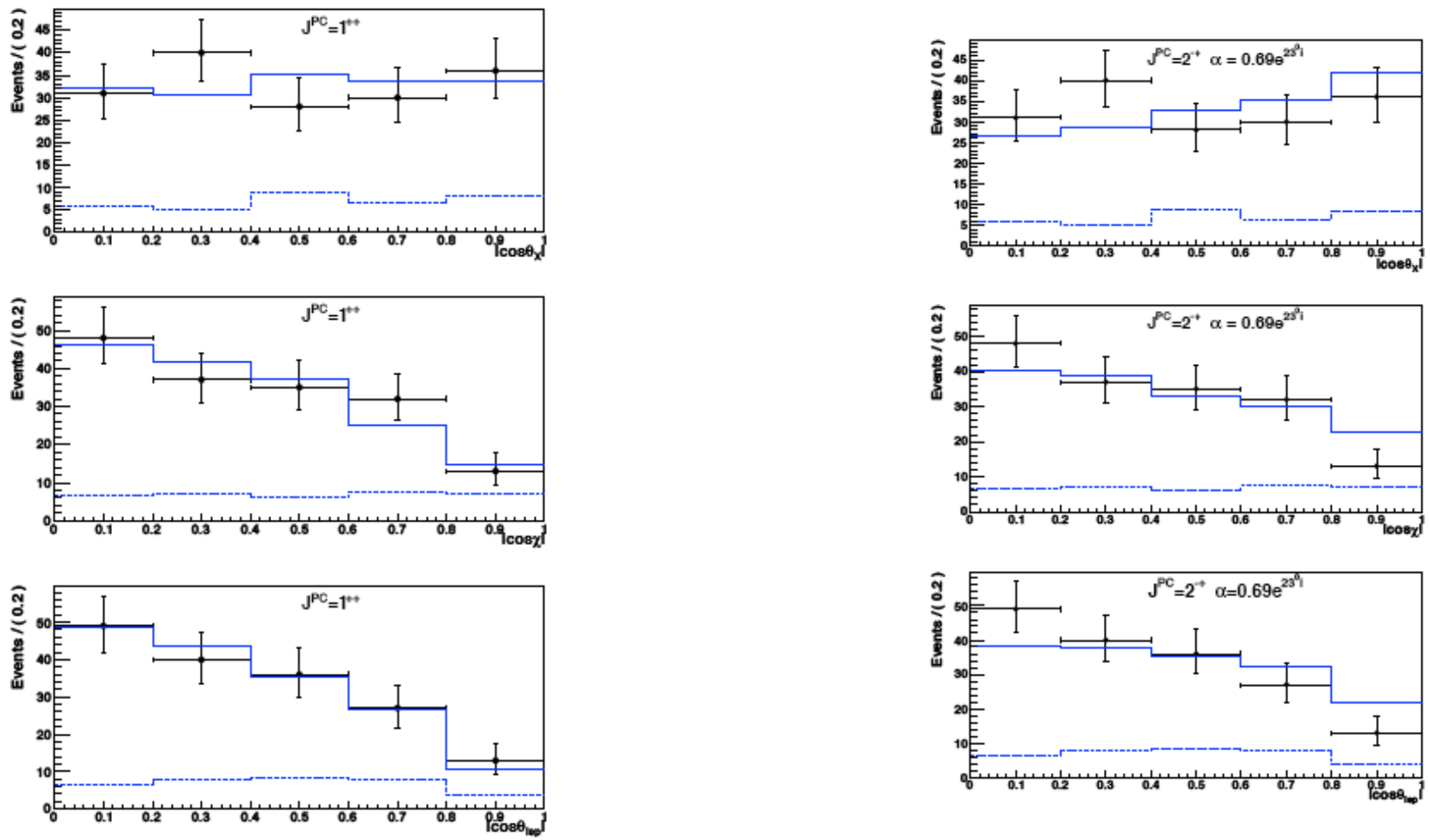
A. Abulencia et al. CDF Collaboration Phys. Rev. Lett. 98, 132002 (2007)

$$X(3872) \to J/\psi\, \pi^+\pi^-$$

$$X(3872) \to J/\psi\, \omega$$

favors 2^{-+}

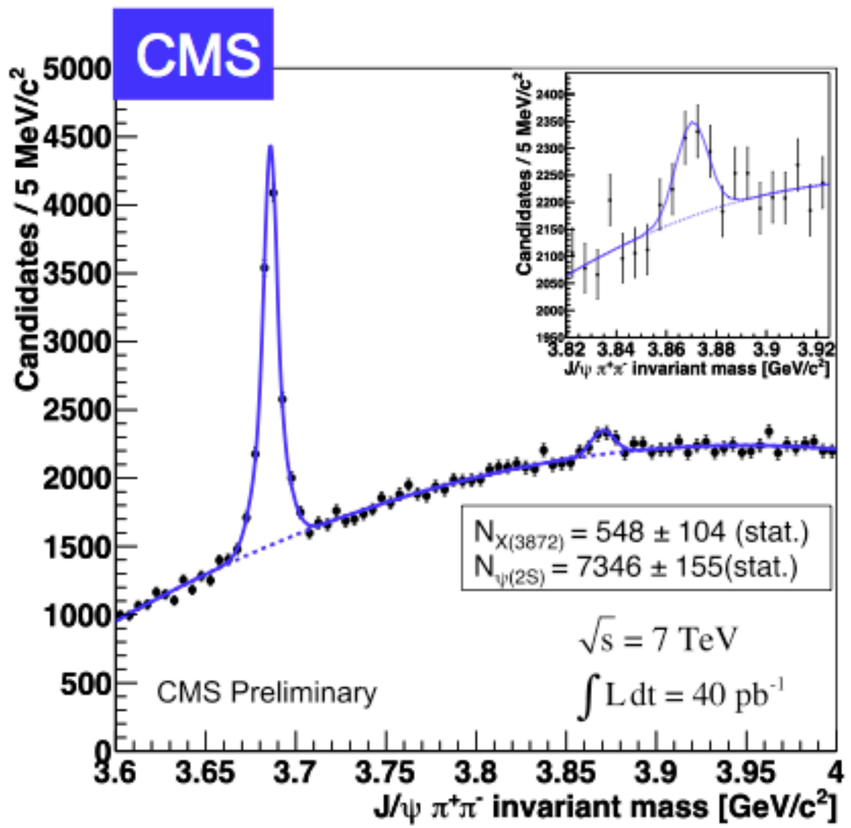
Study of $X(3872) \to \pi\pi J/\psi$ – III

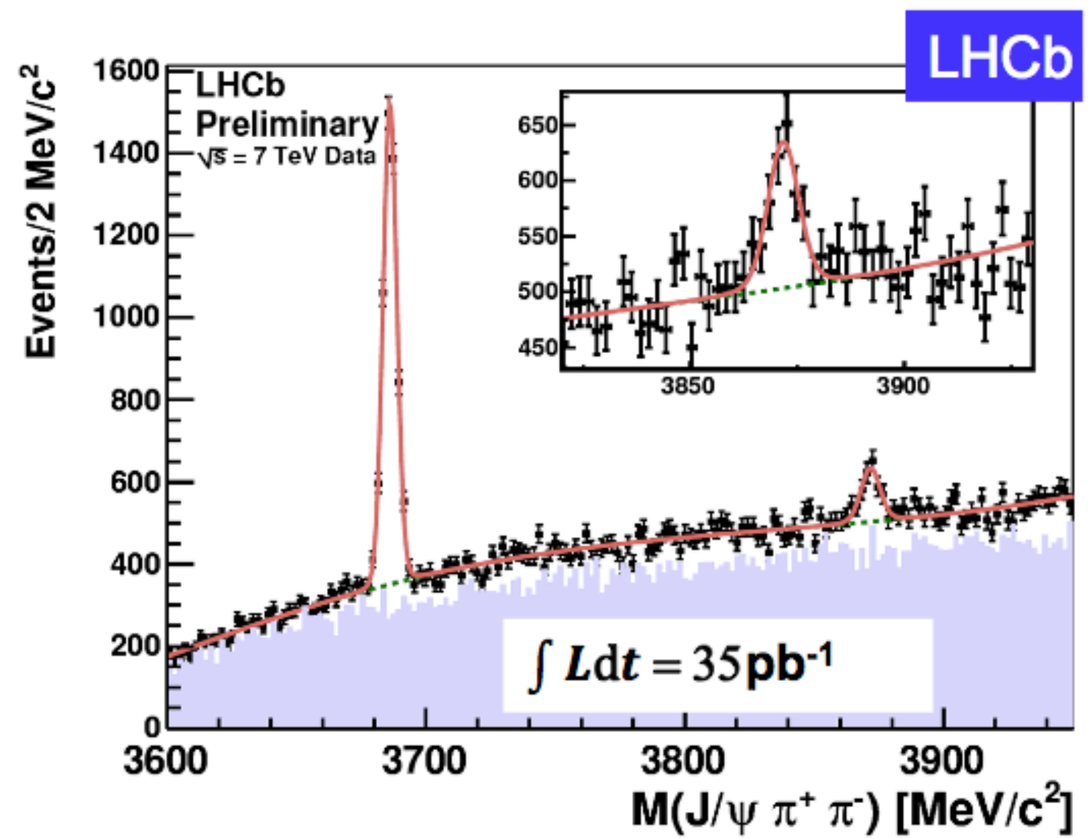


Both $J^{PC} = 1^{++}$ and 2^{-+} are possible

X(3872) at LHC Y. Gao at Hadron2011

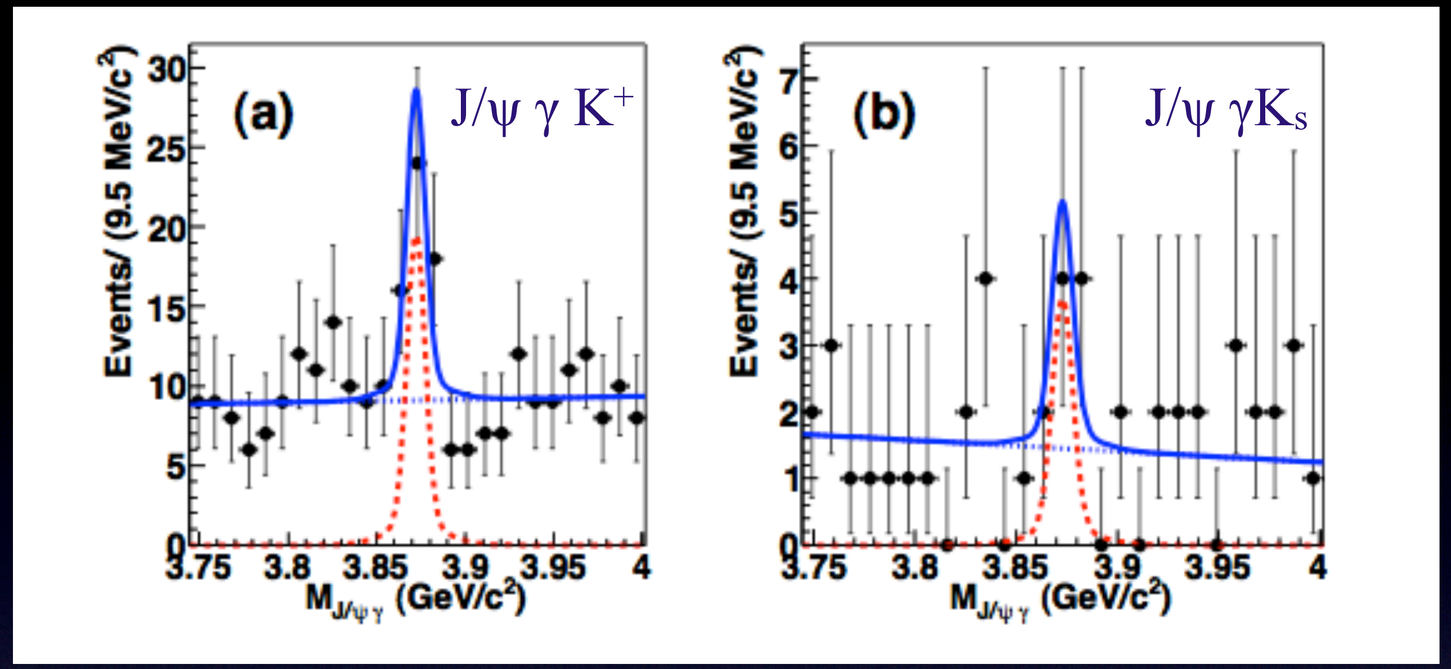
- At LHC, the first observations through X(3872)→J/ψππ

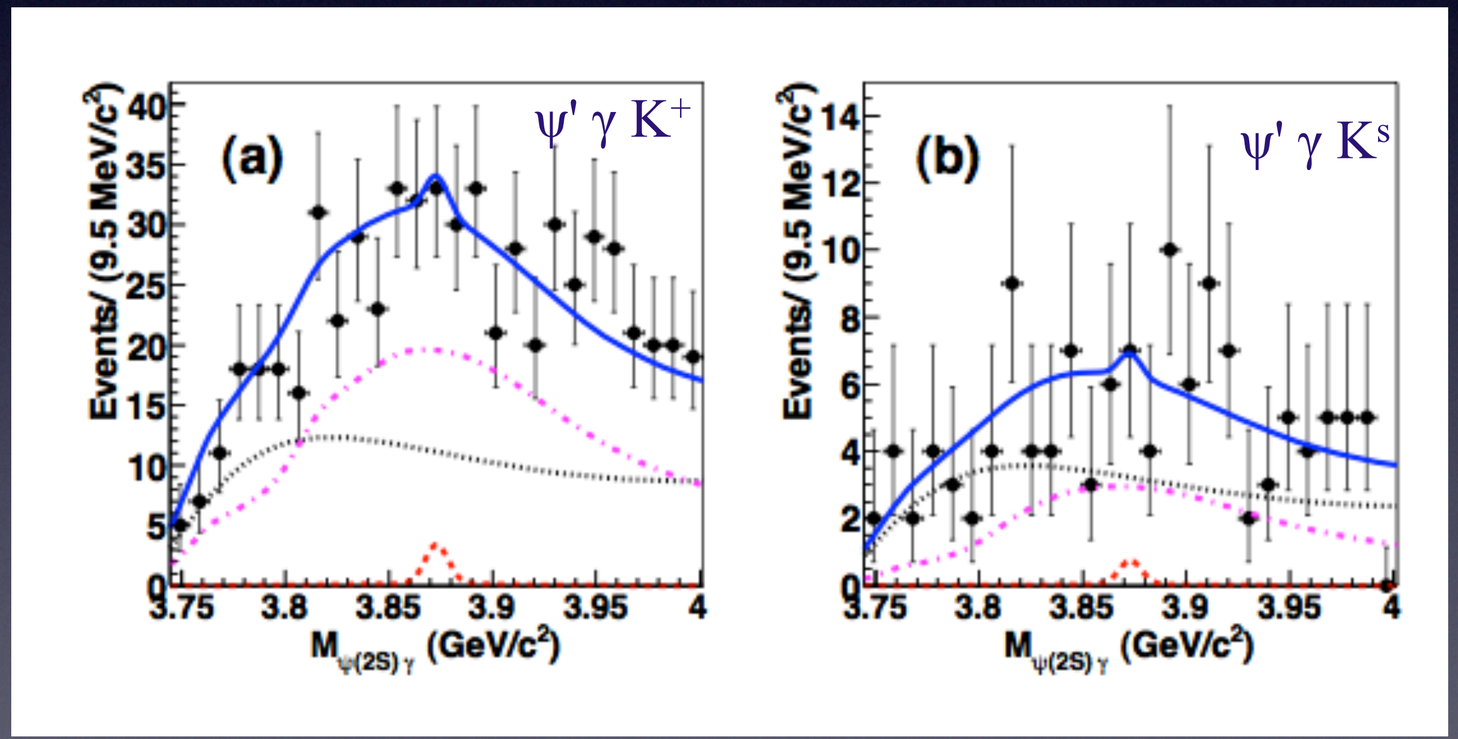




X(3872)

V. Bhardwaj, et al.
arXiv:1105.0177v1 [hep-ex] (2011)



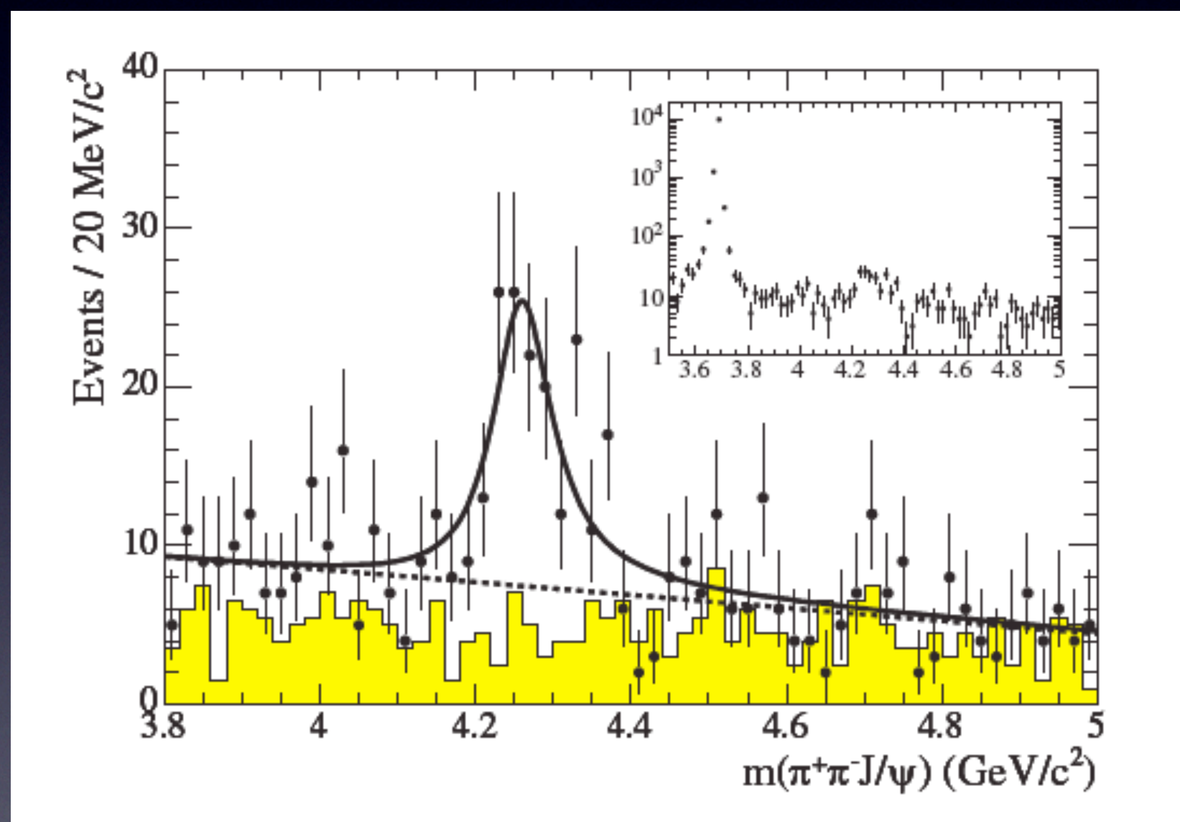


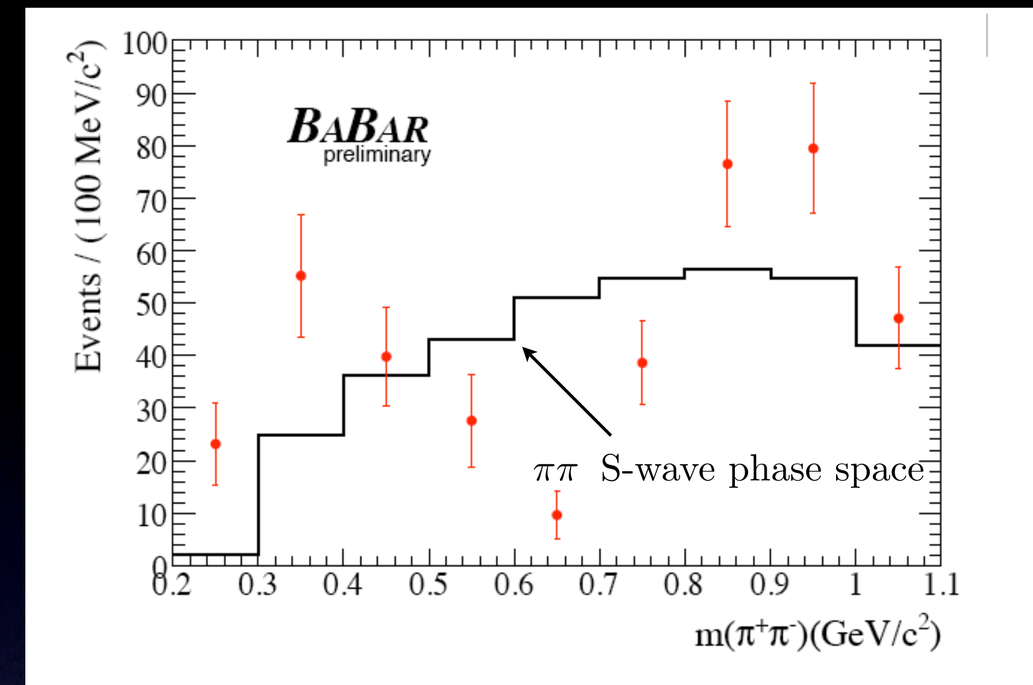
Y(4260)

B. Aubert *et al.* BABAR Collaboration

Phys. Rev. Lett. 95, 142001 (2005)

$$e^+e^- \to J/\psi\pi^+\pi^-\gamma \qquad J^{PC} = 1^{--}$$





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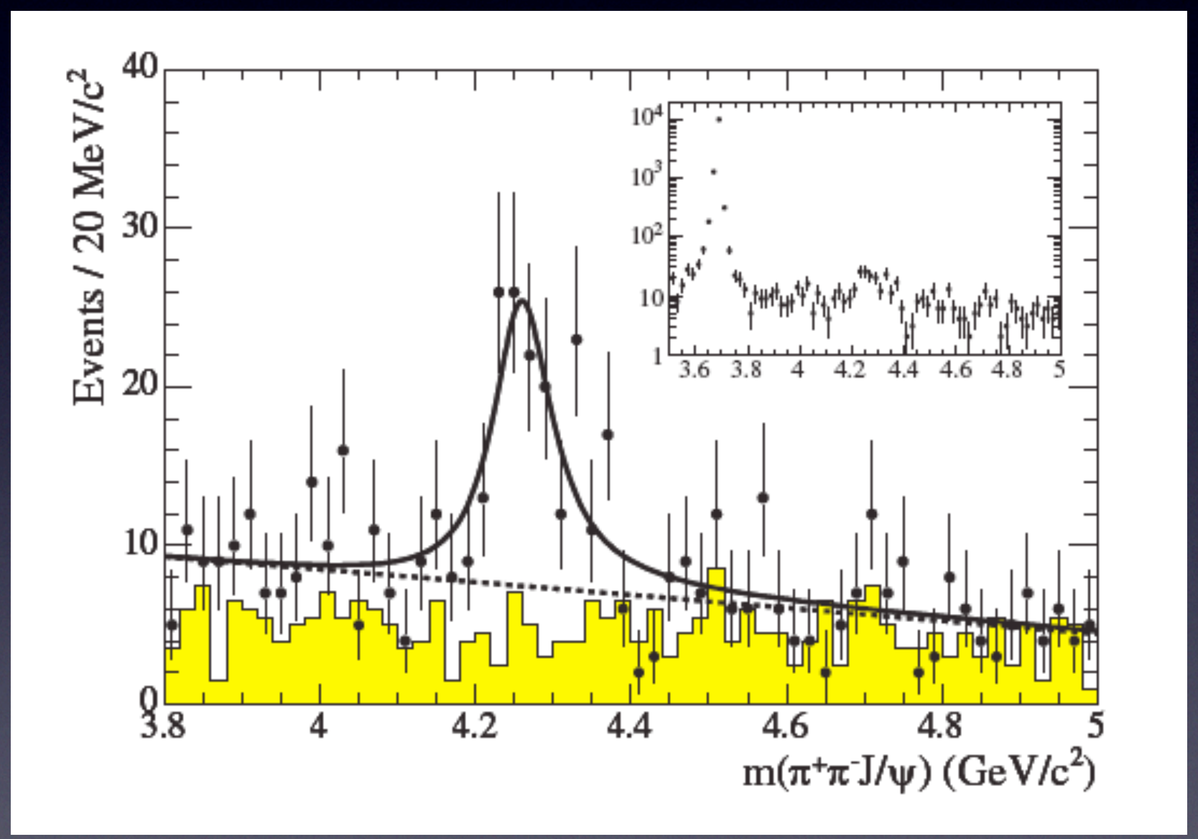
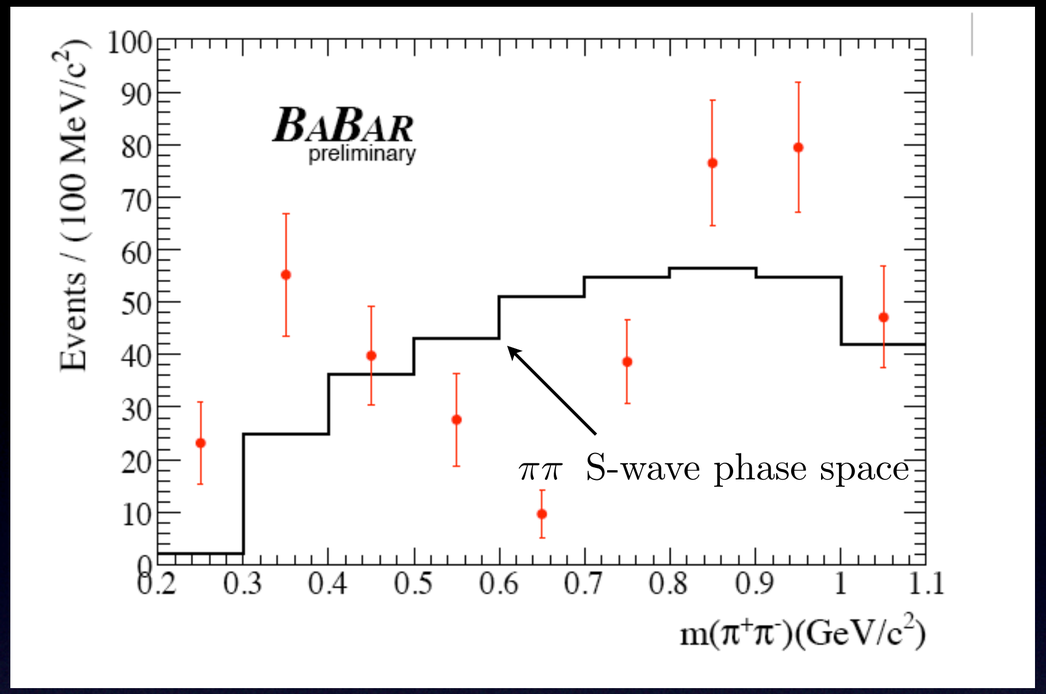
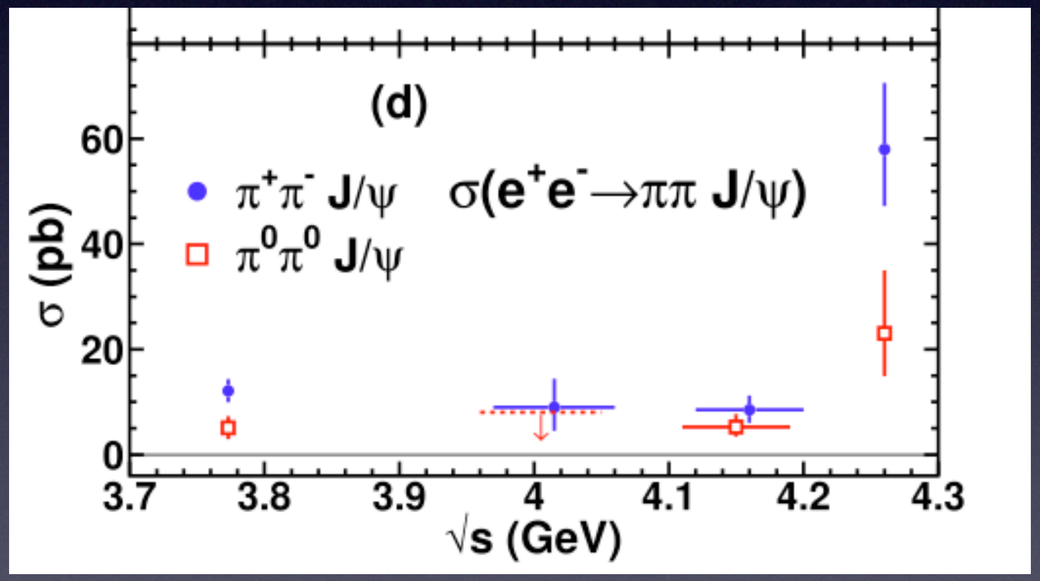






CLEO direct scan:
T.E. Coan et al. PRL96,162003 (2006)

Y(4260)

Charmonium gluonic hybrid
Lattice/NRQCD

Molecule/Bound State

Tetraquark

Hadrocharmonium
charmonium state embedded in light hadronic matter

S. Dubynskiy, M.B. Voloshin arXiv:0803.2224v2 [hep-ph]

$Z^+(4430)$

Discovered by Belle in 2007

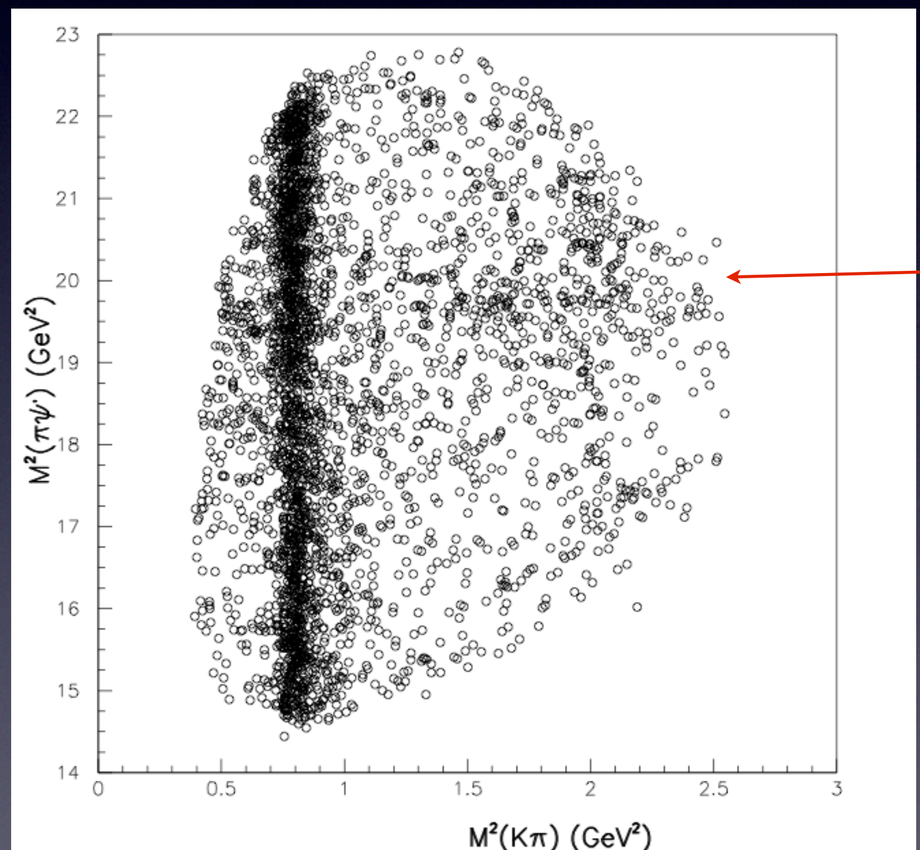
Confirmed 2010

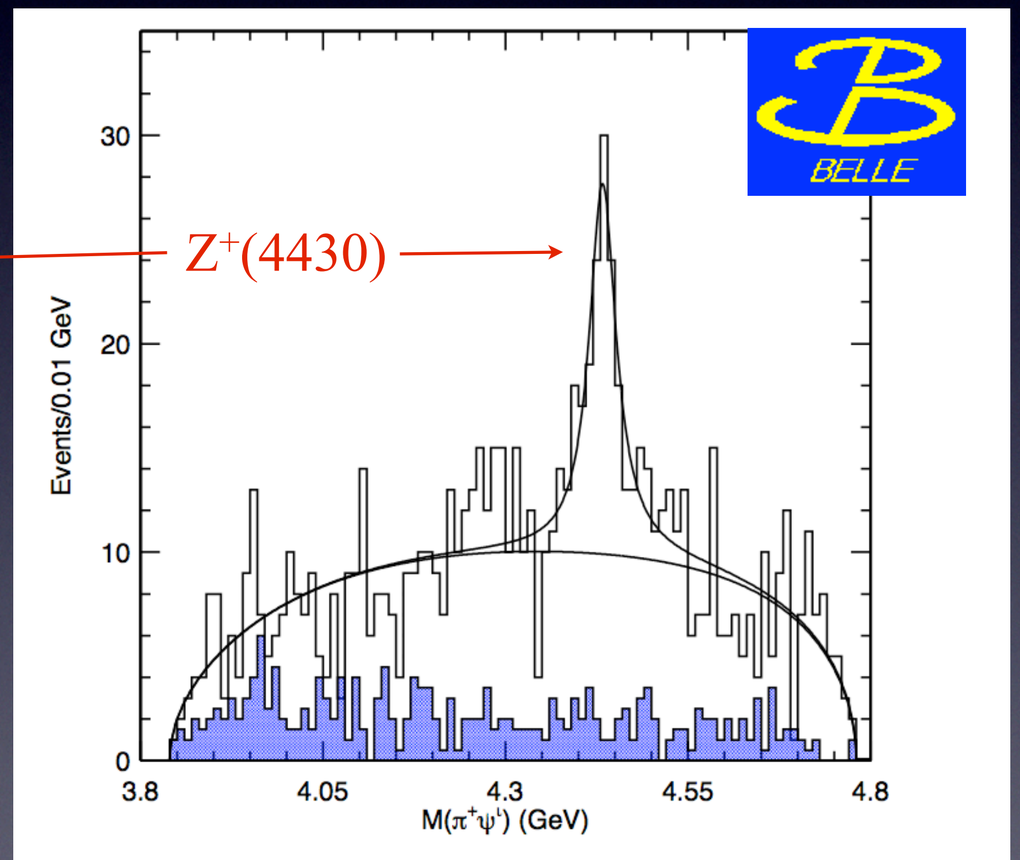
$$B \to K\pi\psi'$$
$$Z^+(4430) \to \pi^+\psi'$$

S.-K. Choi, S.L. Olsen et al. (Belle Collaboration), Phys. Rev. Lett. 100, 14200 (2008).

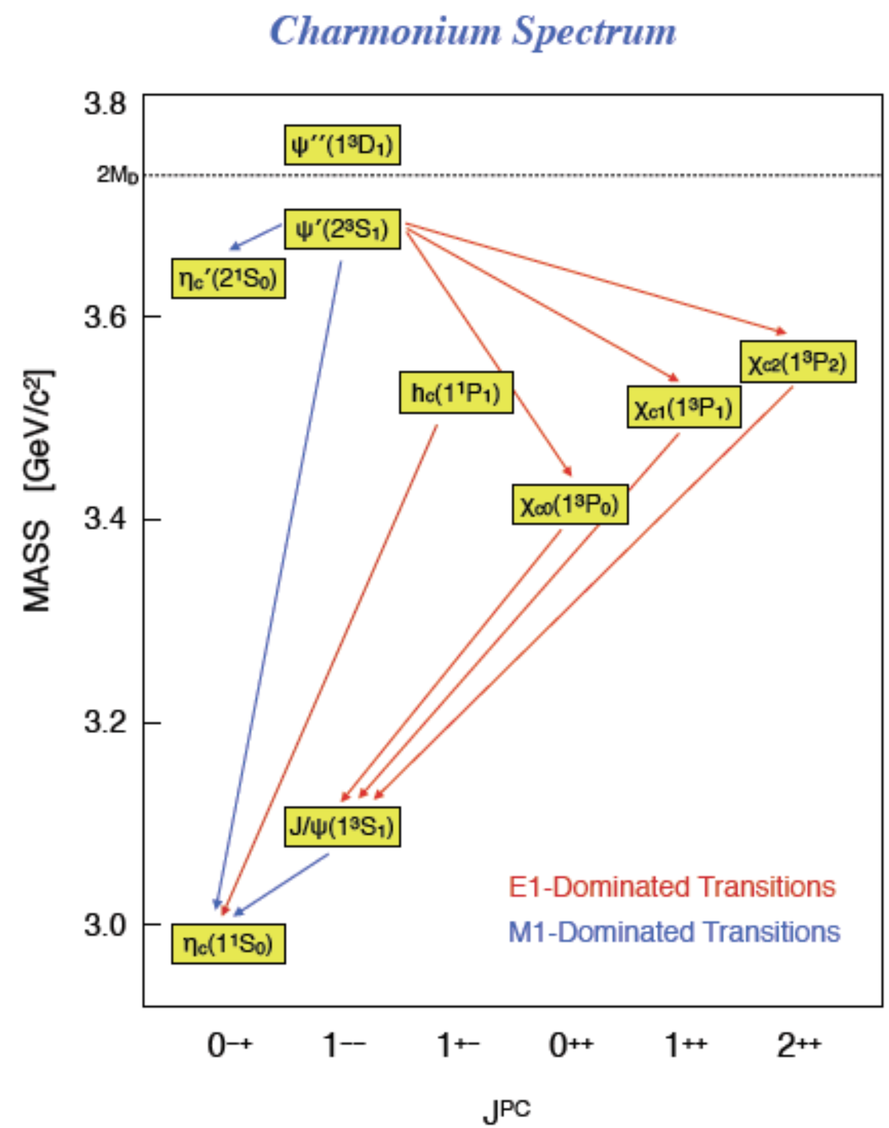
R. Mizuk et al.,Phys. Rev.D 80, 031104(R) (2010)

Not seen by BaBar (413 fb^{-1}), also in $J/\psi\ \pi^+$ Decay
B.Aubert et al., PRD 79, 112001 (2009)



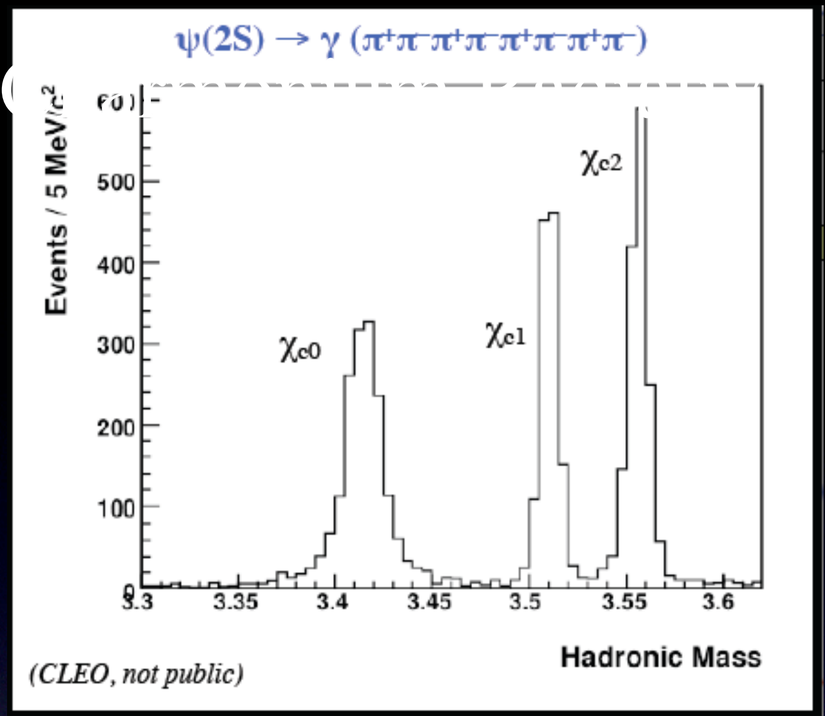


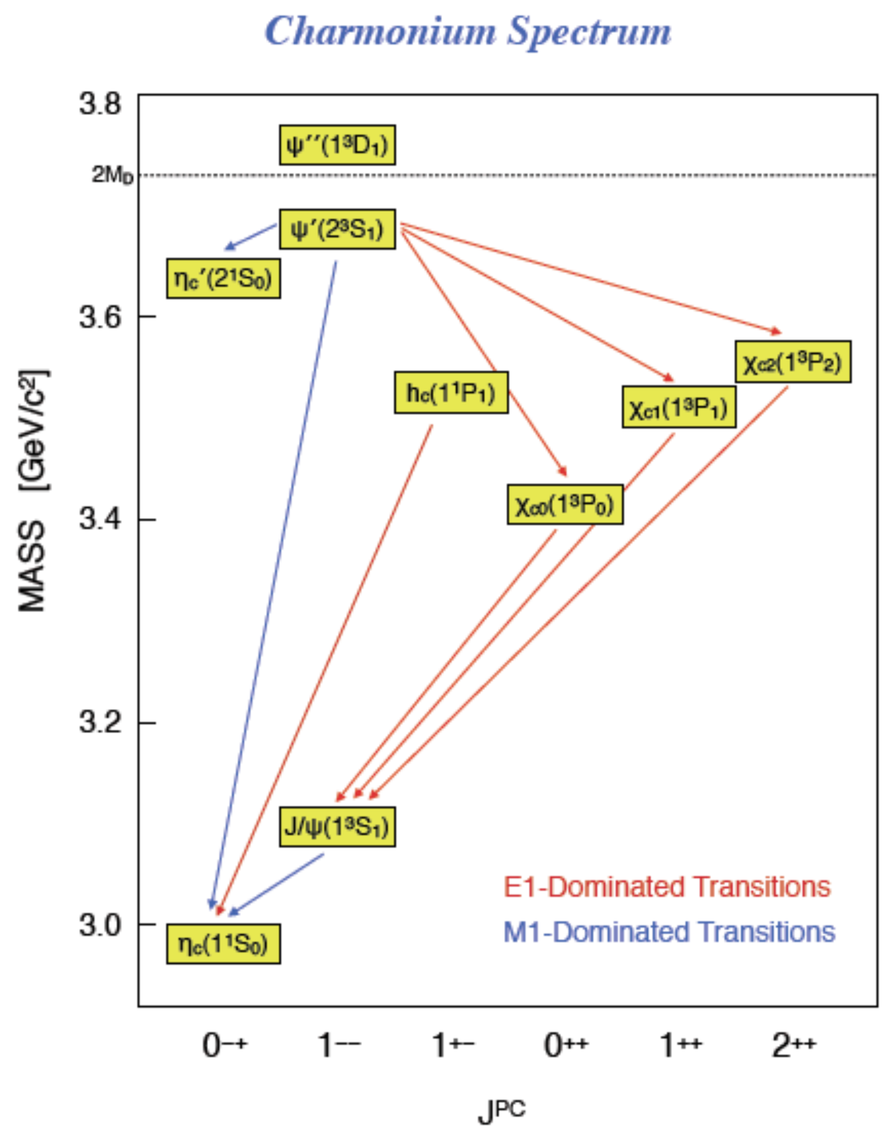
Charmonium Radiative Decays



other charmonium states are easily accessible from the ψ(2S) (and have many decay modes)

Decays





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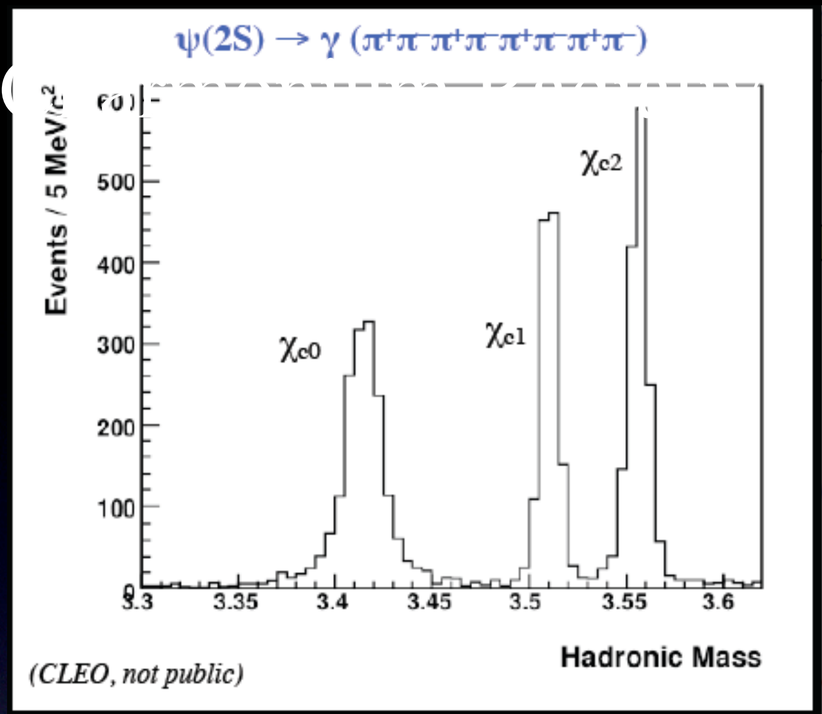

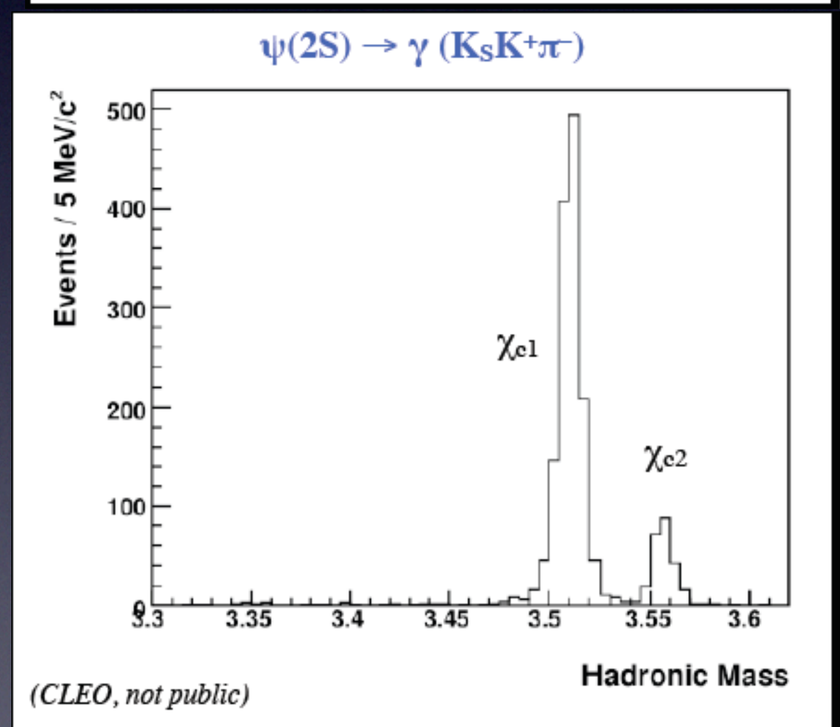

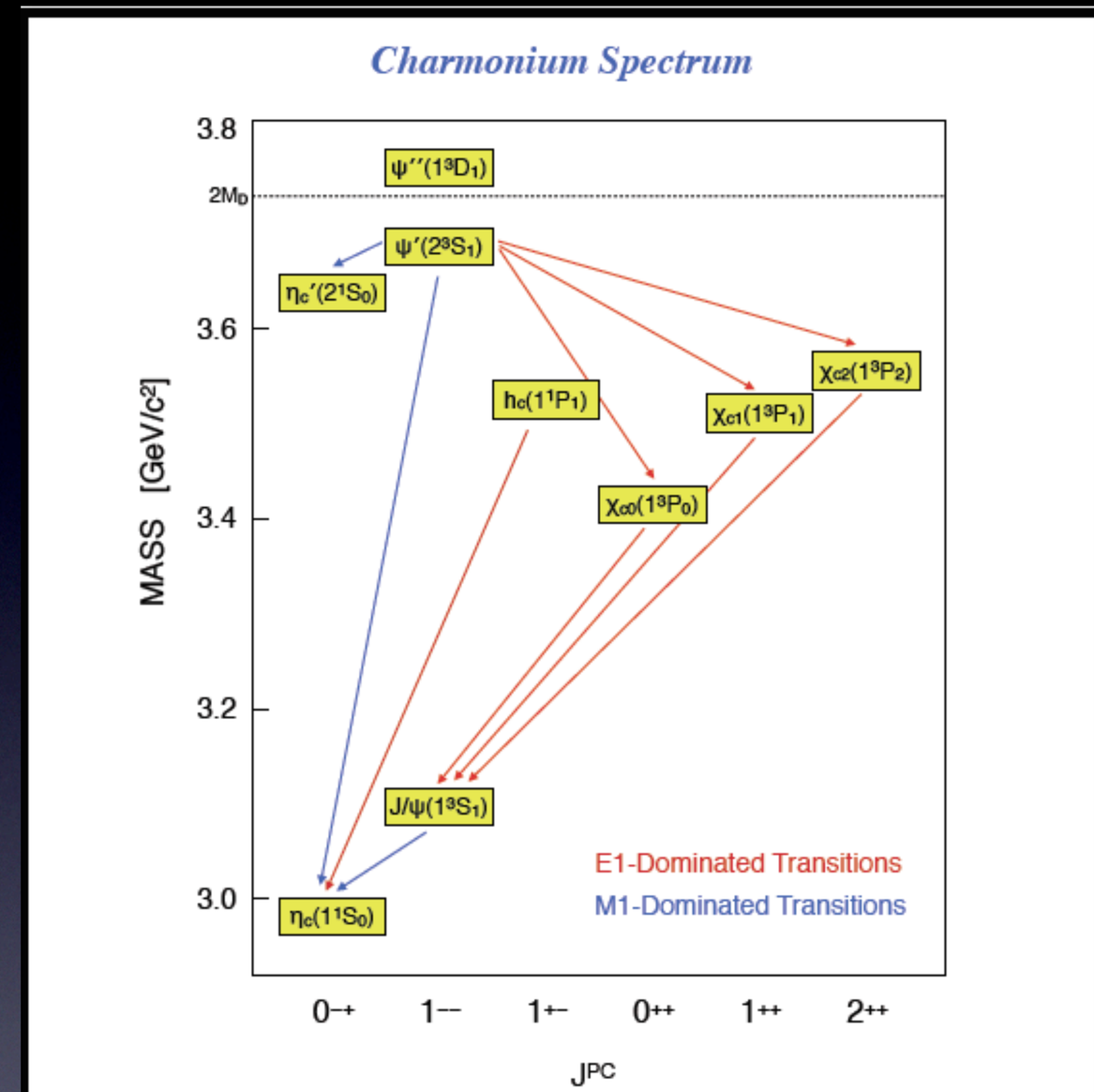

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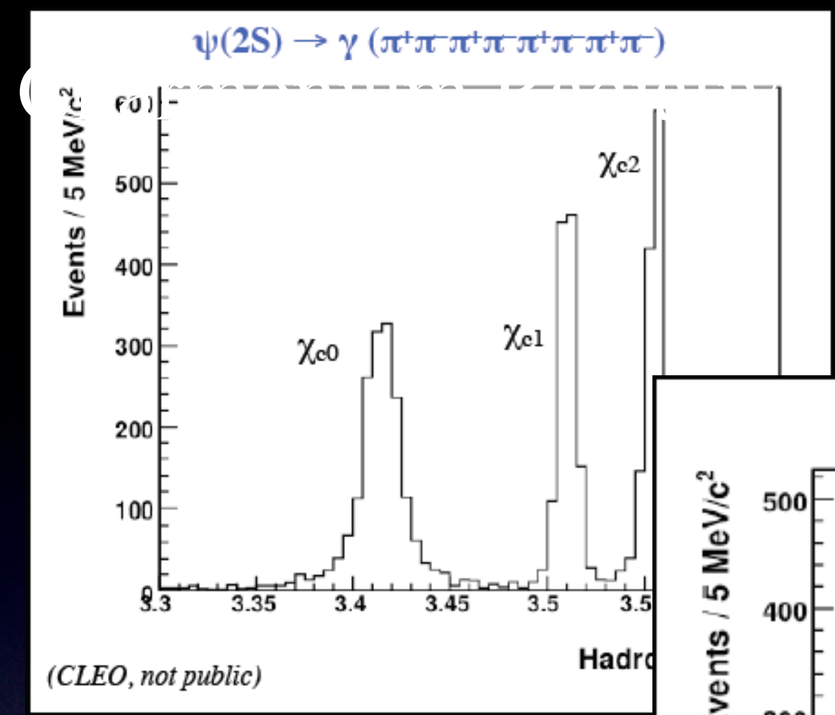
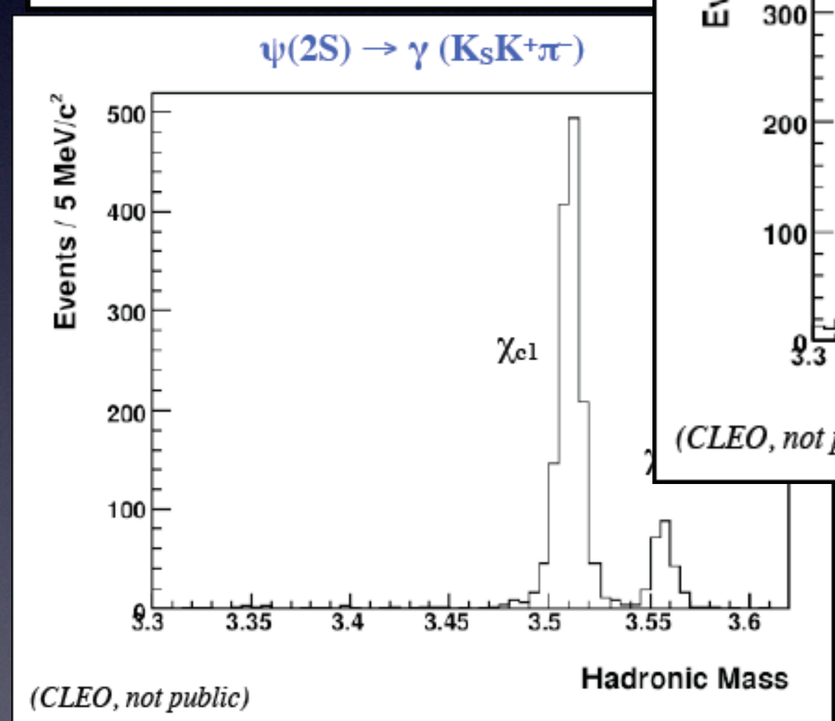
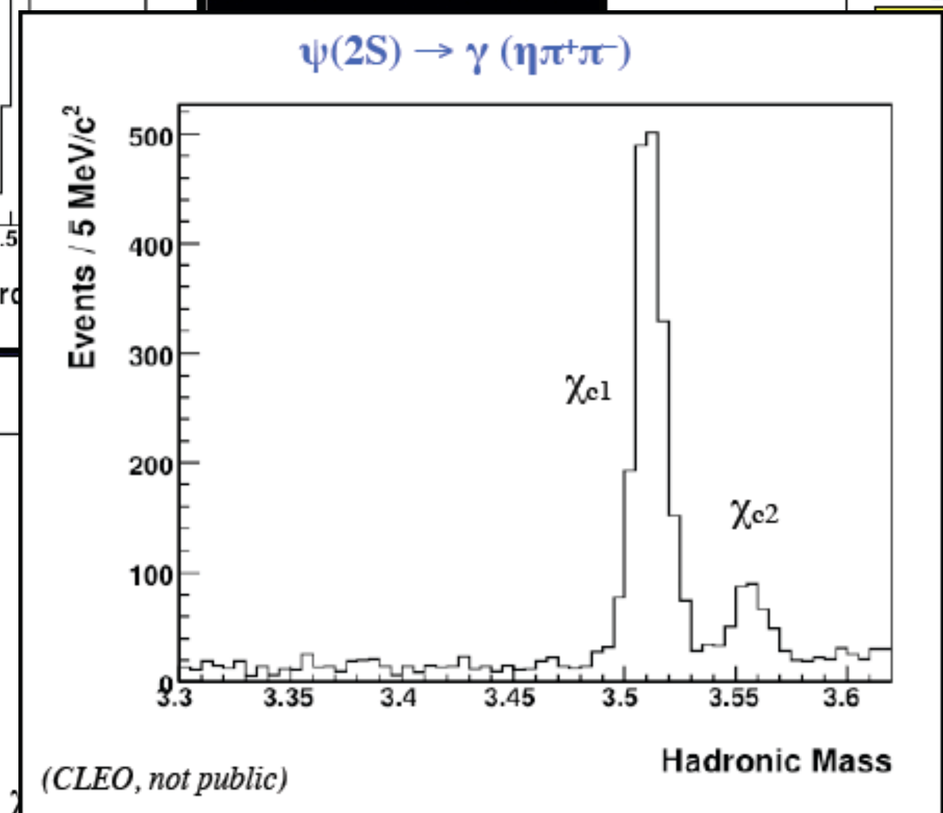
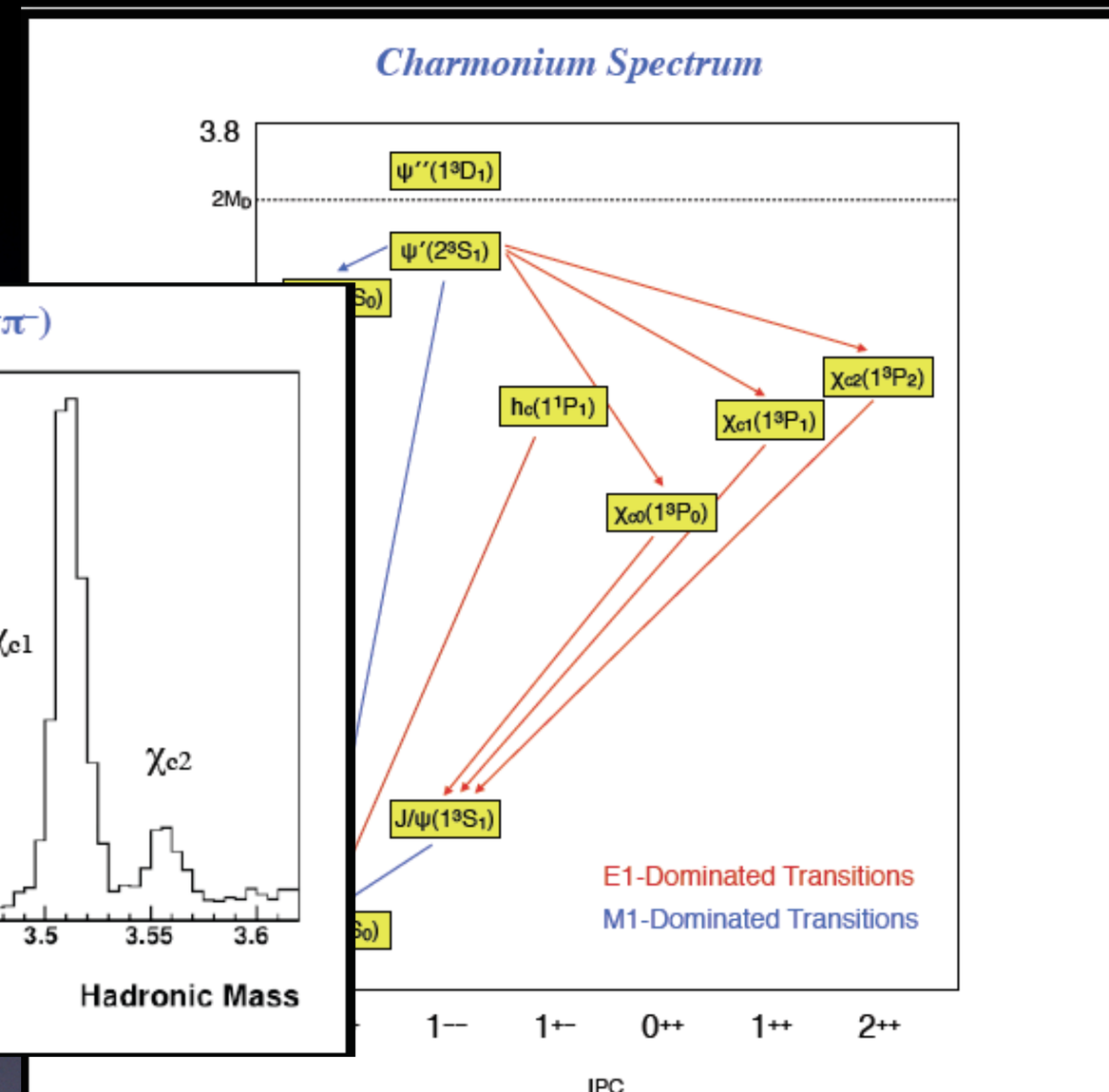


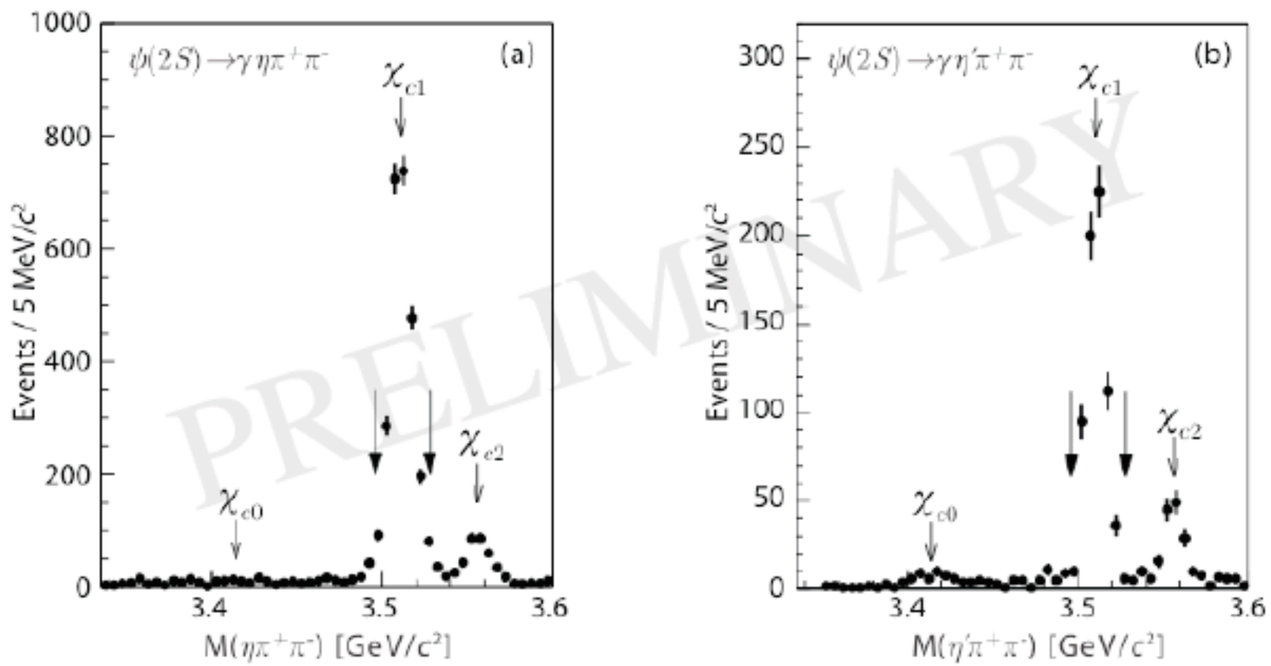






other charmonium states are easily accessible from the ψ(2S) (and have many decay modes)

Clean initial samples of $\chi_{c1} \to \eta^{(\prime)}\pi\pi$ decays



Search for π_1 exotic states:

⇒ **the only χ_{c1} S-wave decay allowed is**

$\chi_{c1} \to \pi_1\pi$ with $\pi_1 \to \eta^{(\prime)}\pi$

Study other dynamics:

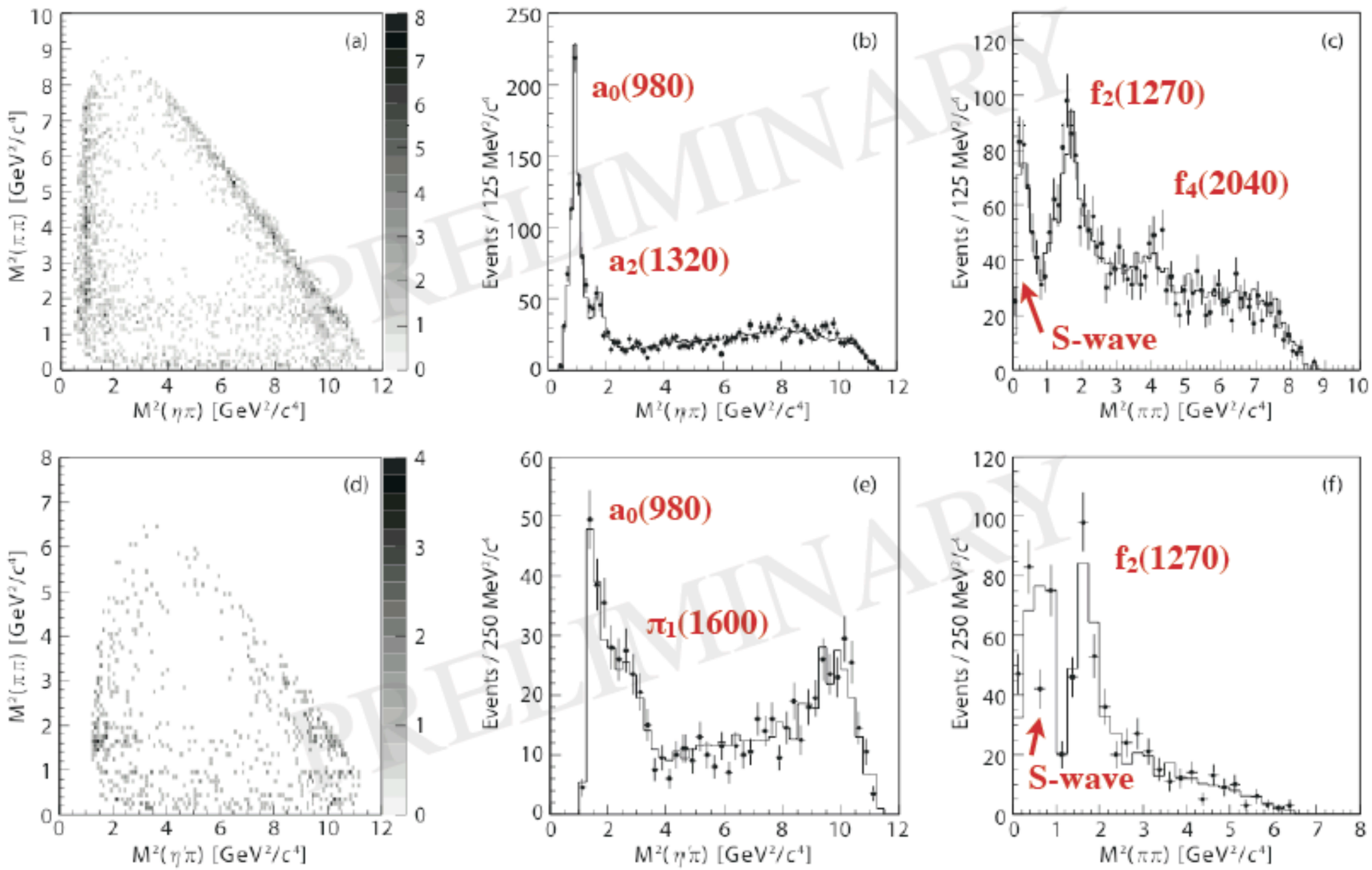
⇒ other decays include

χ_{c1} Decay Mode	L	Isobar J^{PC}
$a_0\pi;\ a_0 \to \eta^{(\prime)}\pi$	P	0^{++}
$\pi_1\pi;\ \pi_1 \to \eta^{(\prime)}\pi$	S, D	1^{-+}
$a_2\pi;\ a_2 \to \eta^{(\prime)}\pi$	P, F	2^{++}
$a_4\pi;\ a_4 \to \eta^{(\prime)}\pi$	F, H	4^{++}
→ $f_0\eta^{(\prime)};\ f_0 \to \pi\pi$	P	0^{++}
$f_2\eta^{(\prime)};\ f_2 \to \pi\pi$	P, F	2^{++}
$f_4\eta^{(\prime)};\ f_4 \to \pi\pi$	F, H	4^{++}

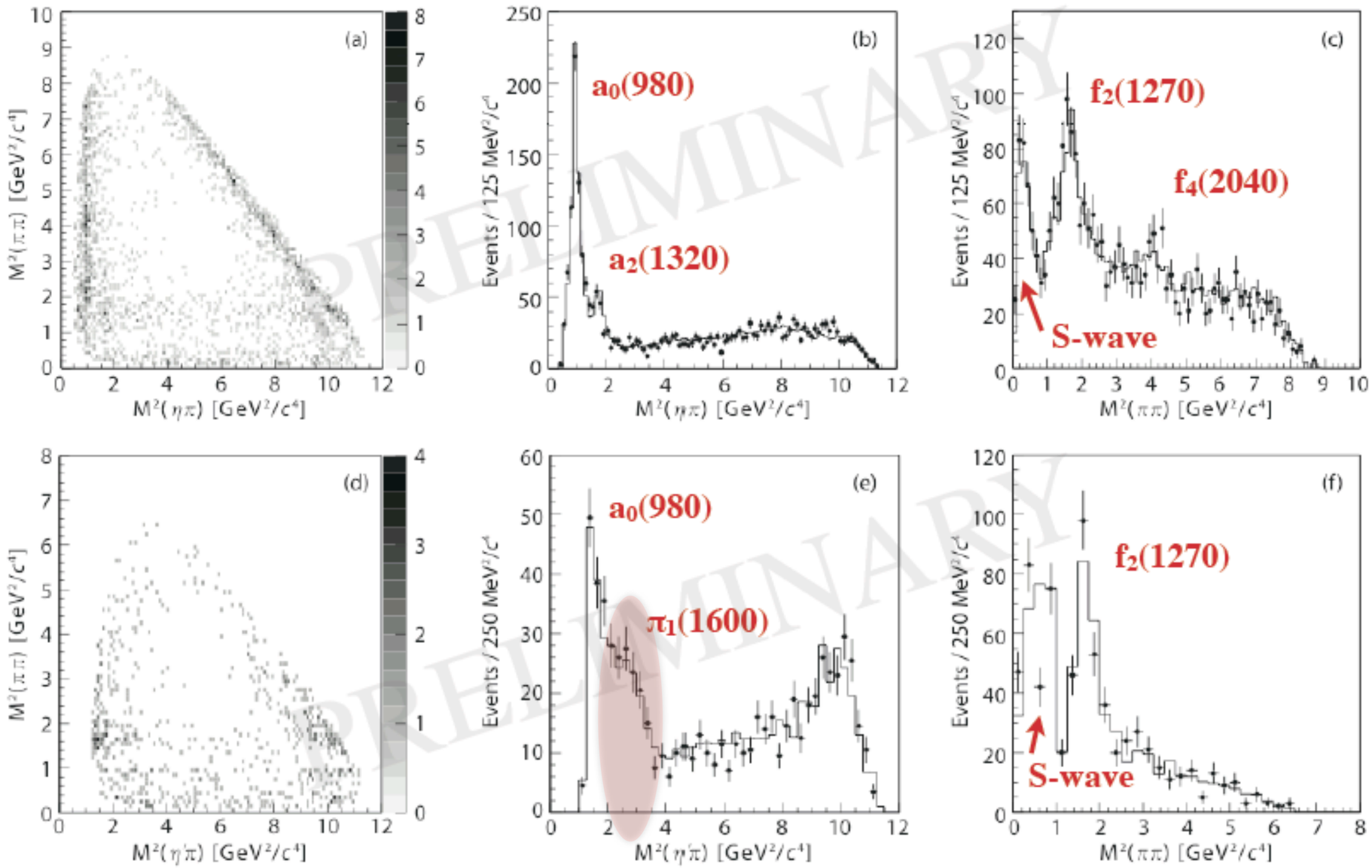
$\pi\pi$ S-wave

(work by Mihajlo Kornicer)

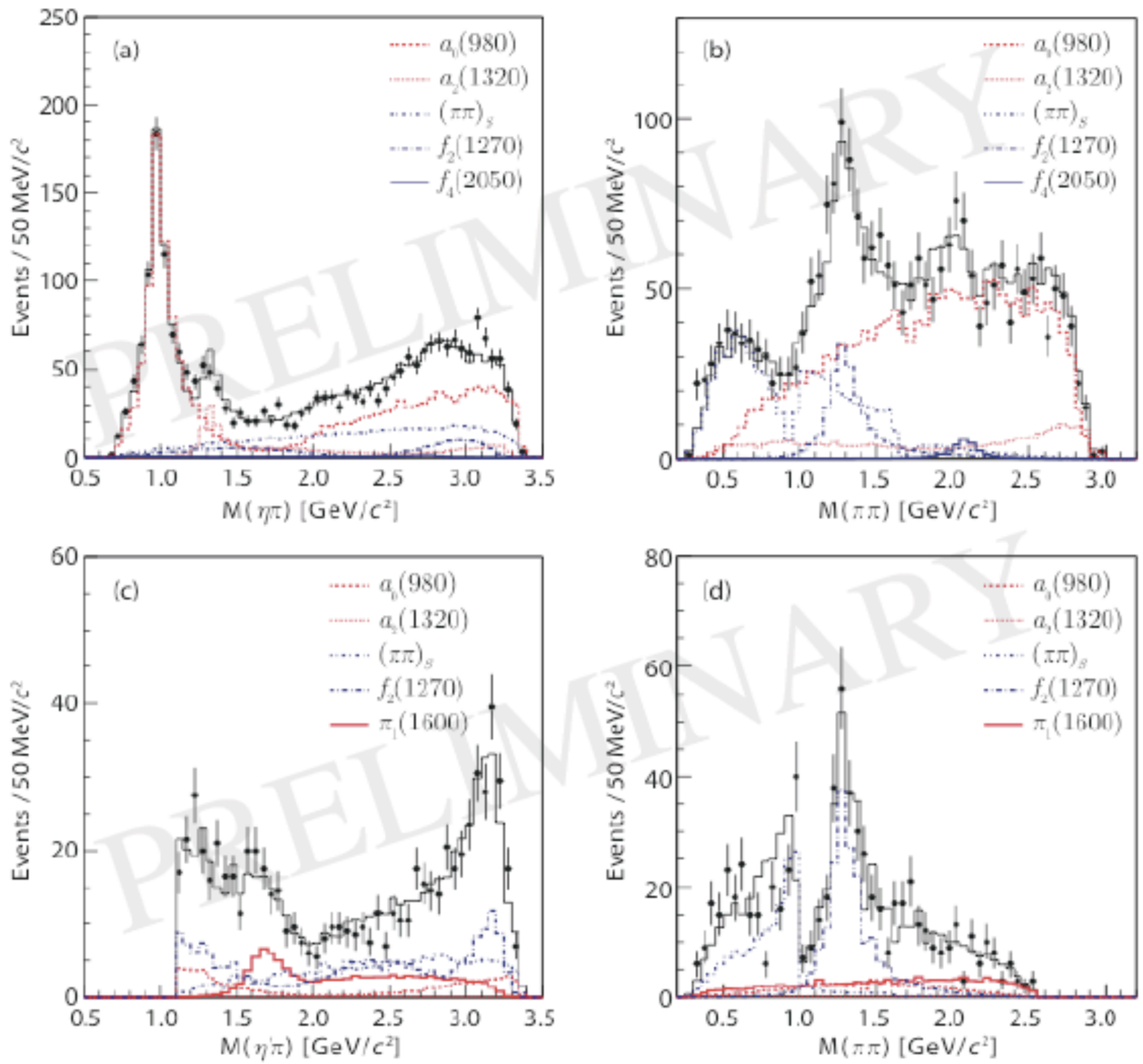
Rich substructure in $\chi_{c1} \to \eta^{(\prime)}\pi\pi$



Rich substructure in $\chi_{c1} \to \eta^{(\prime)}\pi\pi$



The Baseline Fit



Notes:

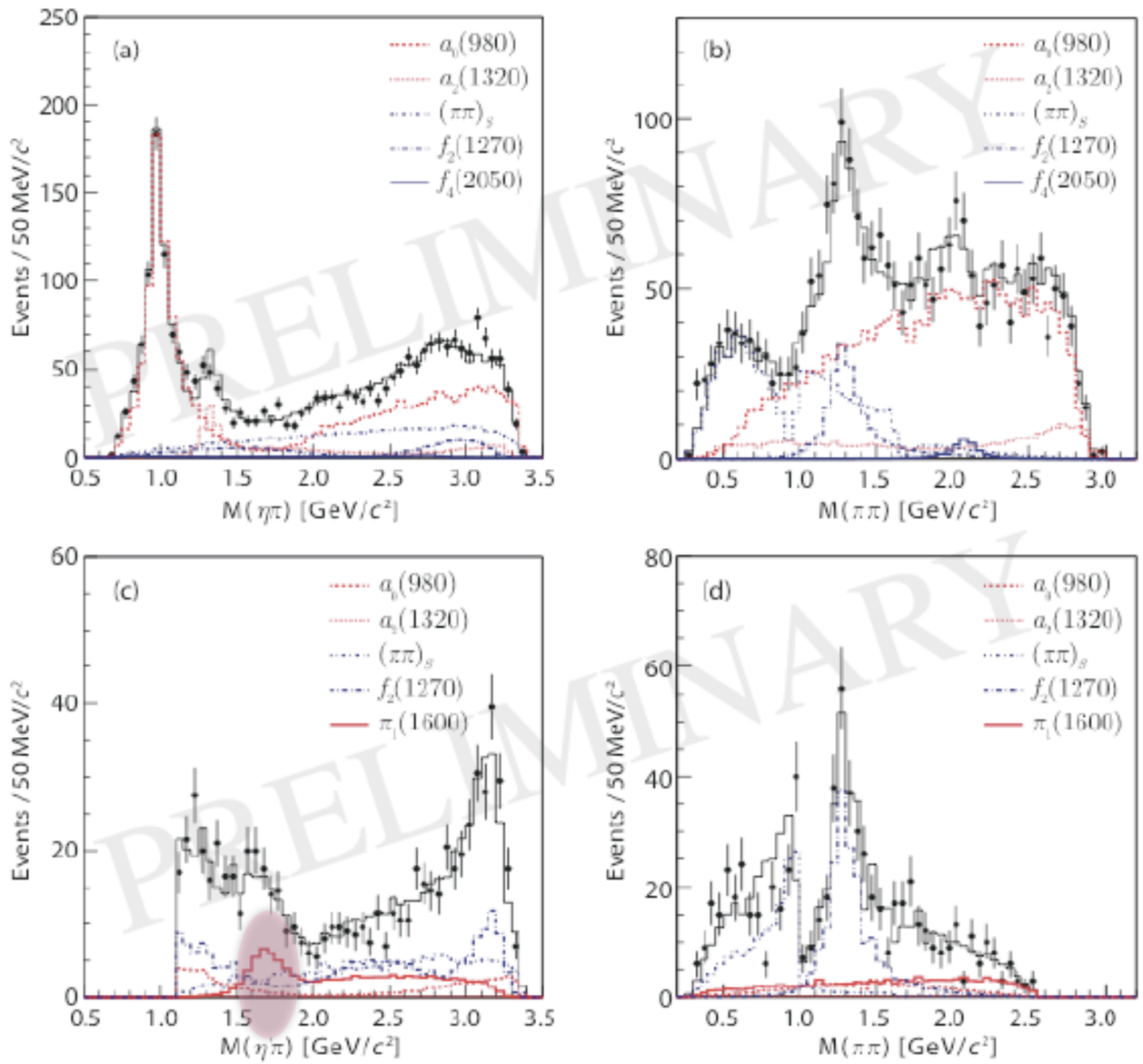
* the $\pi_1(1600)$ is preferred over all other fit variations by ~4σ

* the $\pi_1(1600)$ retains significance when M(ππ) > 1 GeV

* $a_0(980) \rightarrow \eta'\pi$ is a first observation

* the **ππ S-wave** does an "adequate" job describing data *(as good or better than a simple σ pole)*

The Baseline Fit



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Lattice QuantumChromodynamics

PRL **103,** 262001 (2009) PHYSICAL REVIEW LETTERS week ending 31 DECEMBER 2009

Highly Excited and Exotic Meson Spectrum from Dynamical Lattice QCD

Jozef J. Dudek,[1,2,*] Robert G. Edwards,[1] Michael J. Peardon,[3] David G. Richards,[1] and Christopher E. Thomas[1]

(for the Hadron Spectrum Collaboration)

[1]*Jefferson Laboratory, 12000 Jefferson Avenue, Newport News, Virginia 23606, USA*
[2]*Department of Physics, Old Dominion University, Norfolk, Virginia 23529, USA*
[3]*School of Mathematics, Trinity College, Dublin 2, Ireland*
(Received 13 October 2009; published 31 December 2009)

Using a new quark-field construction algorithm and a large variational basis of operators, we extract a highly excited isovector meson spectrum on dynamical anisotropic lattices. We show how carefully constructed operators can be used to reliably identify the continuum spin of extracted states, overcoming the reduced cubic symmetry of the lattice. Using this method we extract, with confidence, excited states, states with exotic quantum numbers (0^{+-}, 1^{-+}, and 2^{+-}), and states of high spin, including, for the first time in lattice QCD, spin-four states.

DOI: 10.1103/PhysRevLett.103.262001 PACS numbers: 12.38.Gc, 14.40.Cs

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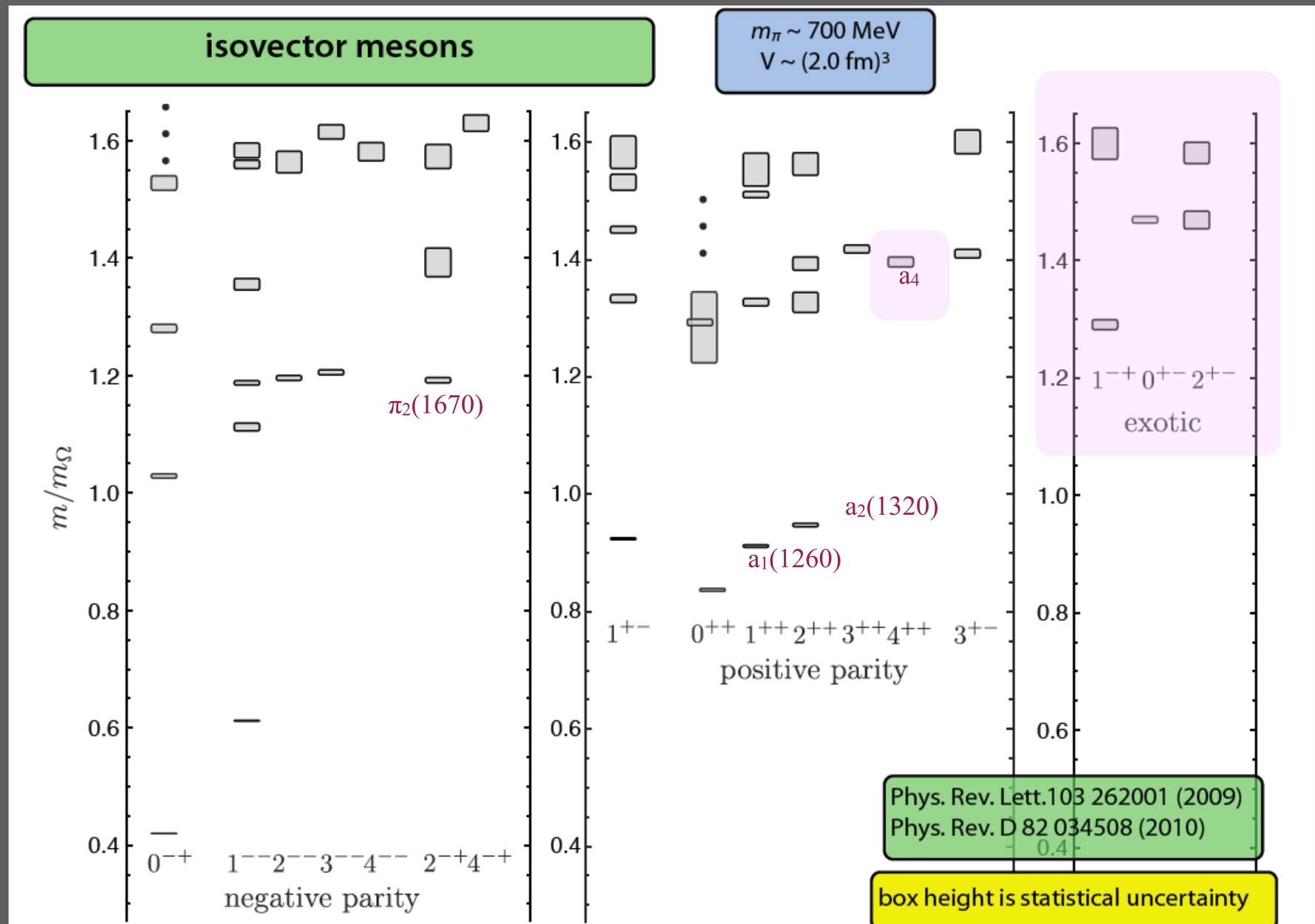
isovector mesons
m_π ~ 700 MeV
V ~ (2.0 fm)³
m/m_Ω
1.6
1.4
1.2
1.0
0.8
0.6
0.4
$\pi_2(1670)$
a_4
$a_2(1320)$
$a_1(1260)$
0^{-+} $1^{--}2^{--}3^{--}4^{--}$ $2^{-+}4^{-+}$
negative parity
1^{+-} 0^{++} $1^{++}2^{++}3^{++}4^{++}$ 3^{+-}
positive parity
1^{-+} 0^{+-} 2^{+-}
exotic
Phys. Rev. Lett.103 262001 (2009)
Phys. Rev. D 82 034508 (2010)
box height is statistical uncertainty

Conclusion and Outlook

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- Charmonium decays: valuable source of light mesons
- Clear evidence for spin-exotic $\pi_1(1600)$:
  - Diffraction vs. photoproduction ?
  - Where is the $I = 0$ partner $\eta_1(1600)$?

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- Improvement of Amplitude Analysis Models
- BES III, COMPASS continue data taking
- GluEx @ JLab Hall-D: Dedicated photoproduction experiment
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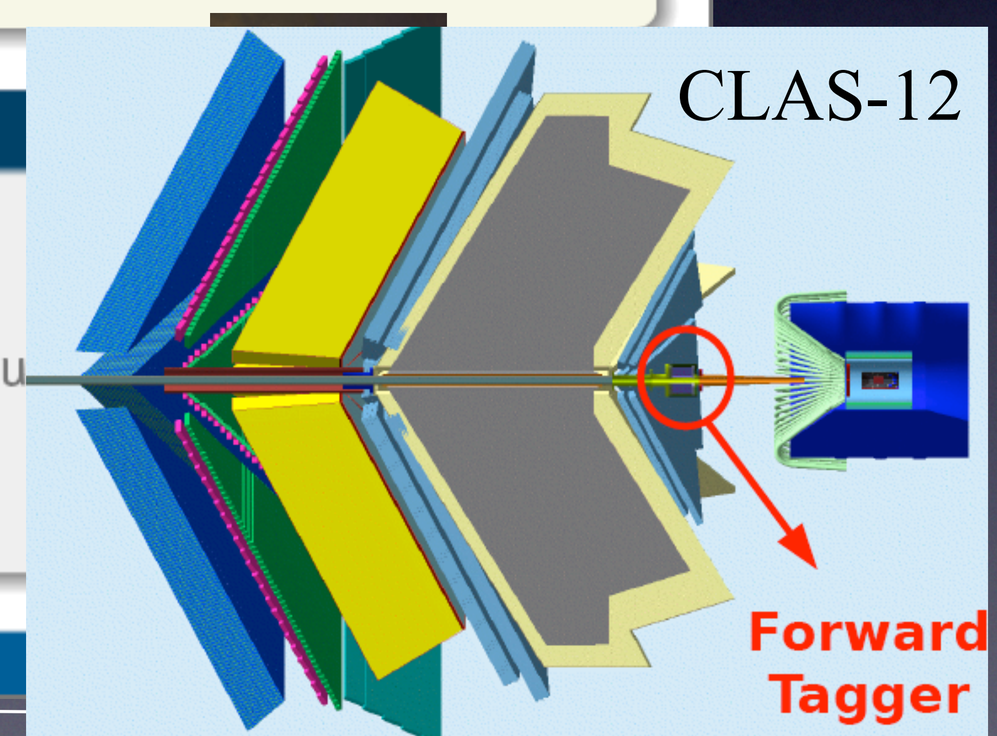

Thank you for inviting me to Providence