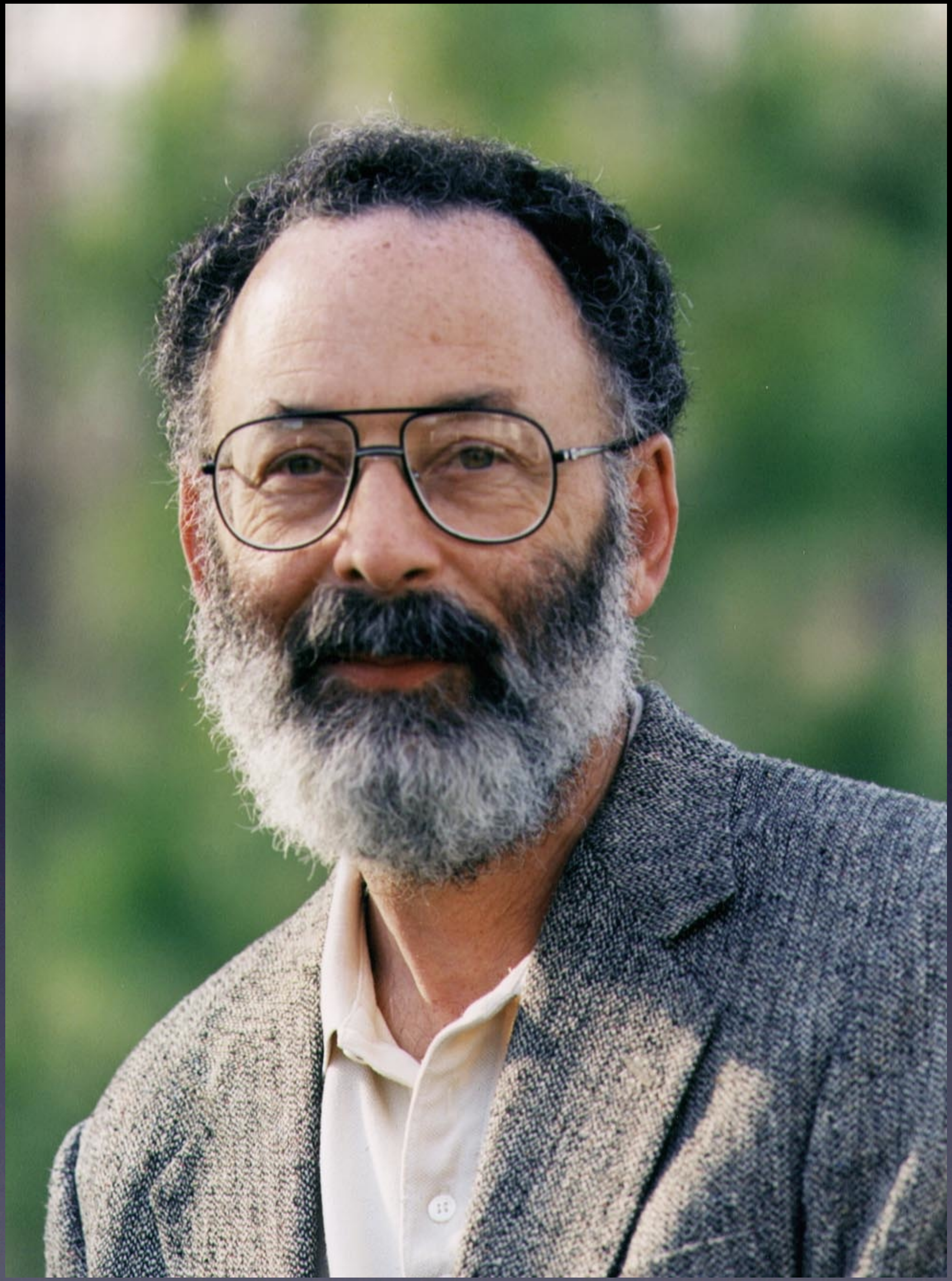
Exotic Mesons

D.P. Weygand
Jefferson Laboratory

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.

What exactly is an exotic meson?

Mesons outside of the Naive Quark Model (NQM)

- Glueballs
- Hybrids
- Multi-quark

‘Manifestly Exotic’

Mesons that *must* be outside of the NQM

Restrictions on fermion-anti fermion quantum numbers

$P = (-1)^{L+1}$
$C = (-1)^{L+S}$

$$C \mid f\bar{f}\rangle = (-1)^{L}(-1)^{S+1}(-1) \mid f\bar{f}\rangle = (-1)^{L+S} \mid f\bar{f}\rangle$$

Questions:

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Do exotics exist in theory?

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Do exotics exist in experiment?

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Do exotics exist in theory?

Do exotics exist in experiment?

Why photoproduction?

There are known knowns. These are things we know that we know. There are known unknowns. That is to say, there are things that we know we don't know. But there are also unknown unknowns. There are things we don't know we don't know.

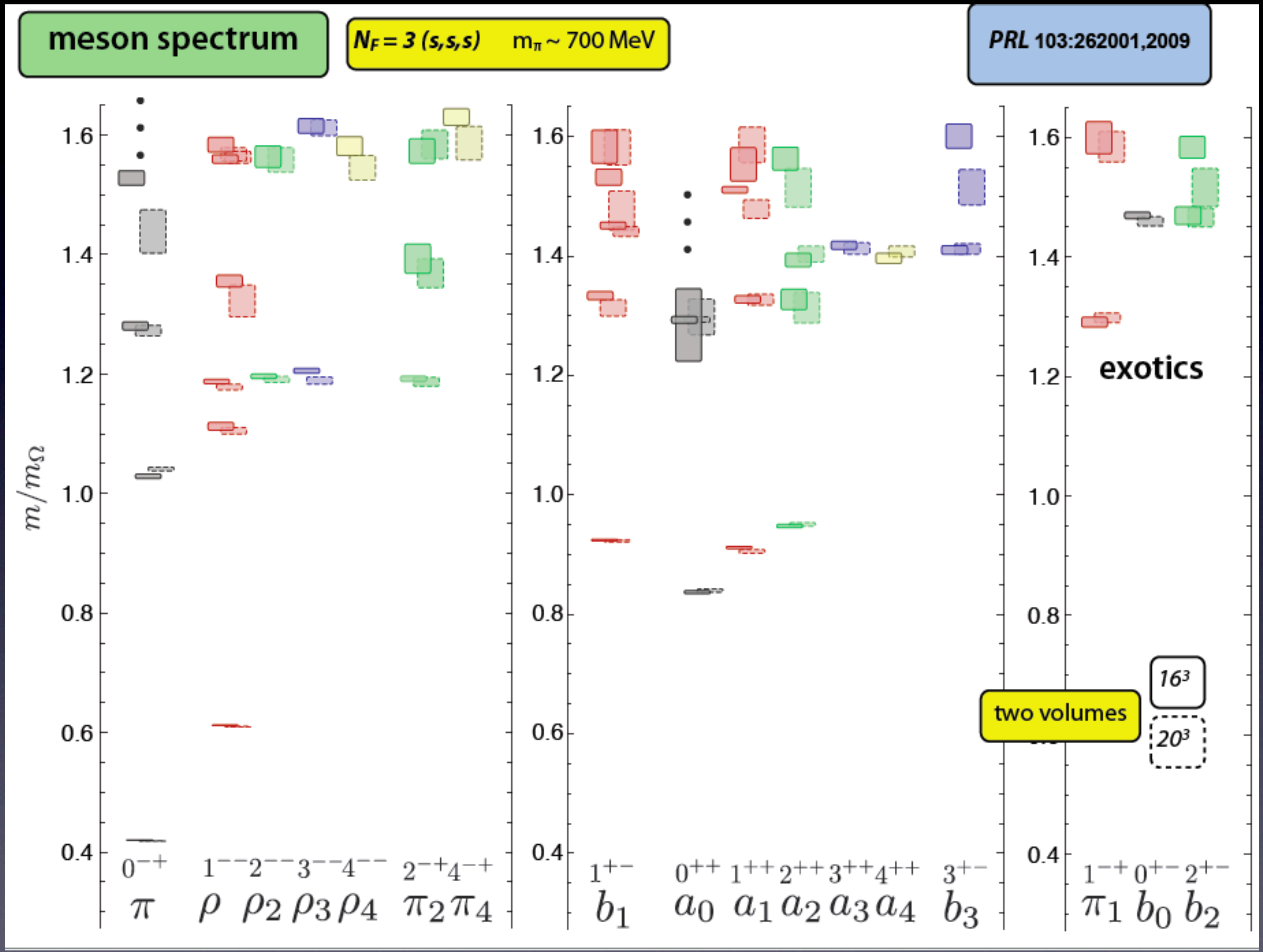
Donald Rumsfeld

Why photoproduction?

Isgur & Paton
Phys. Rev. Lett. 54, 869–872 (1985)

We would suggest that high-mass meson diffractive scattering will be particularly rich in hybrids. In the case where the beam flux tube is simply "plucked" by the target one will produce hybrids with the flavor and spin of the beam: A π beam would, for example, produce by this mechanism the nonexotic $I=1$, $J^{PC}=1^{++}$ and 1^{--} hybrids. More complicated spin-flip and quantum-number exchange mechanisms in which the hybrid is produced by quark scattering rather than pure glue scattering could produce the other hybrids, including the desirable exotic ones. Diffractive photoproduction, on the other hand, can produce "plucked" ρ, ω, and ϕ states and so could be a good source for all four of the desirable exotics y_2^{+-}, z_2^{+-}, x_1^{-+}, and y_0^{+-}. Traditional "gluon-rich" channels

From Dudek, et al.: Mesons on the Lattice



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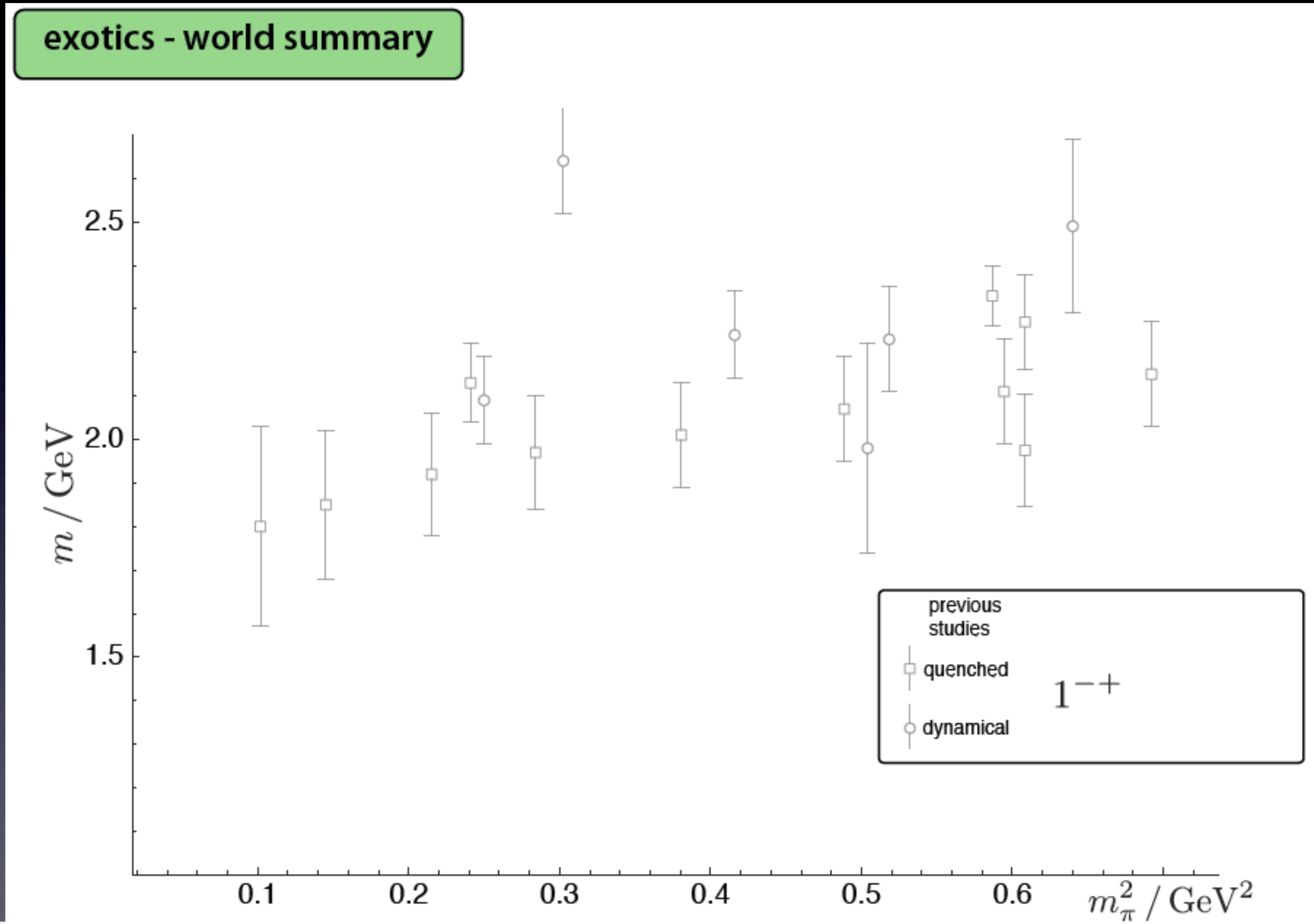

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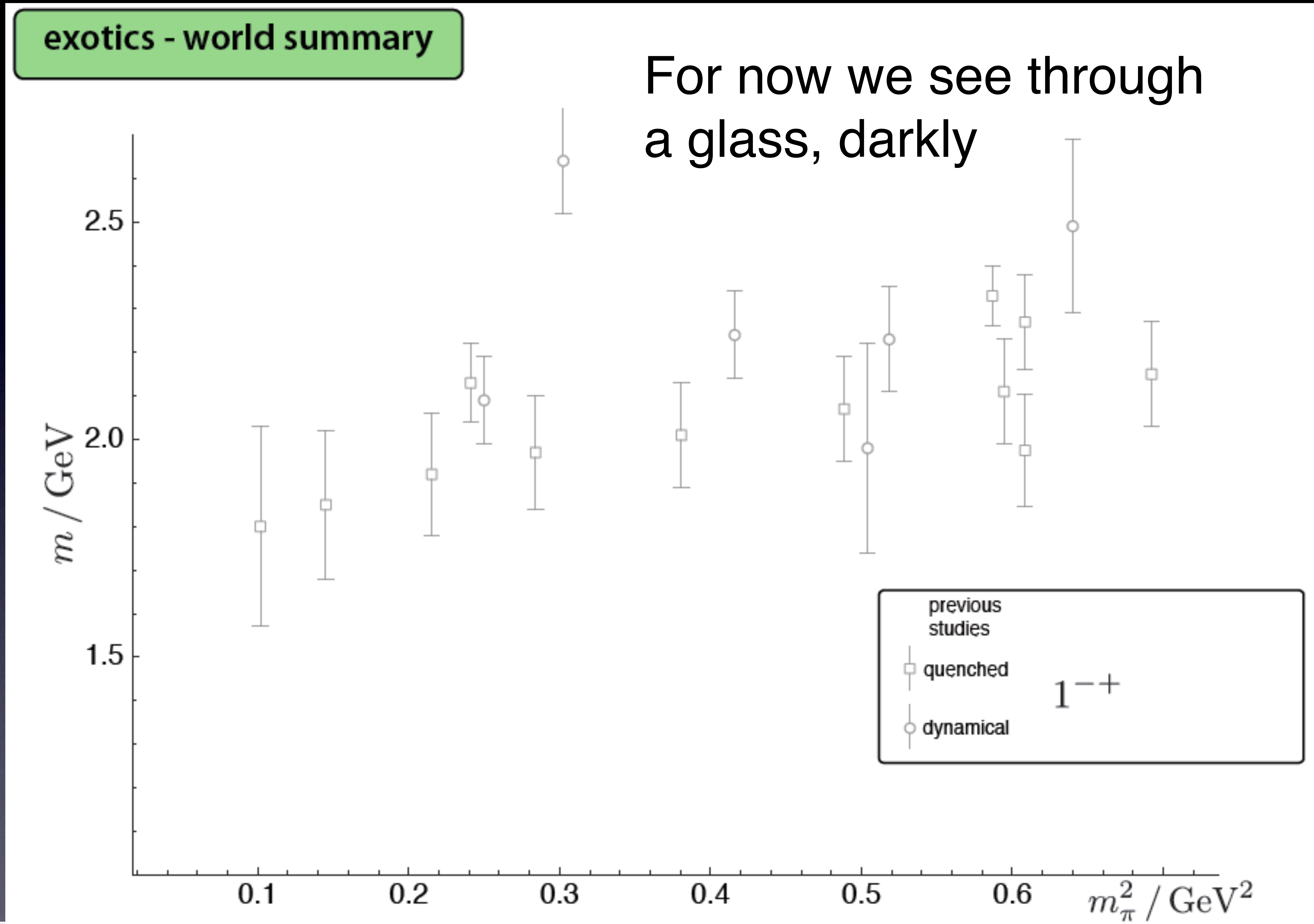

The Partial Wave Analysis 'Isobar' Technique

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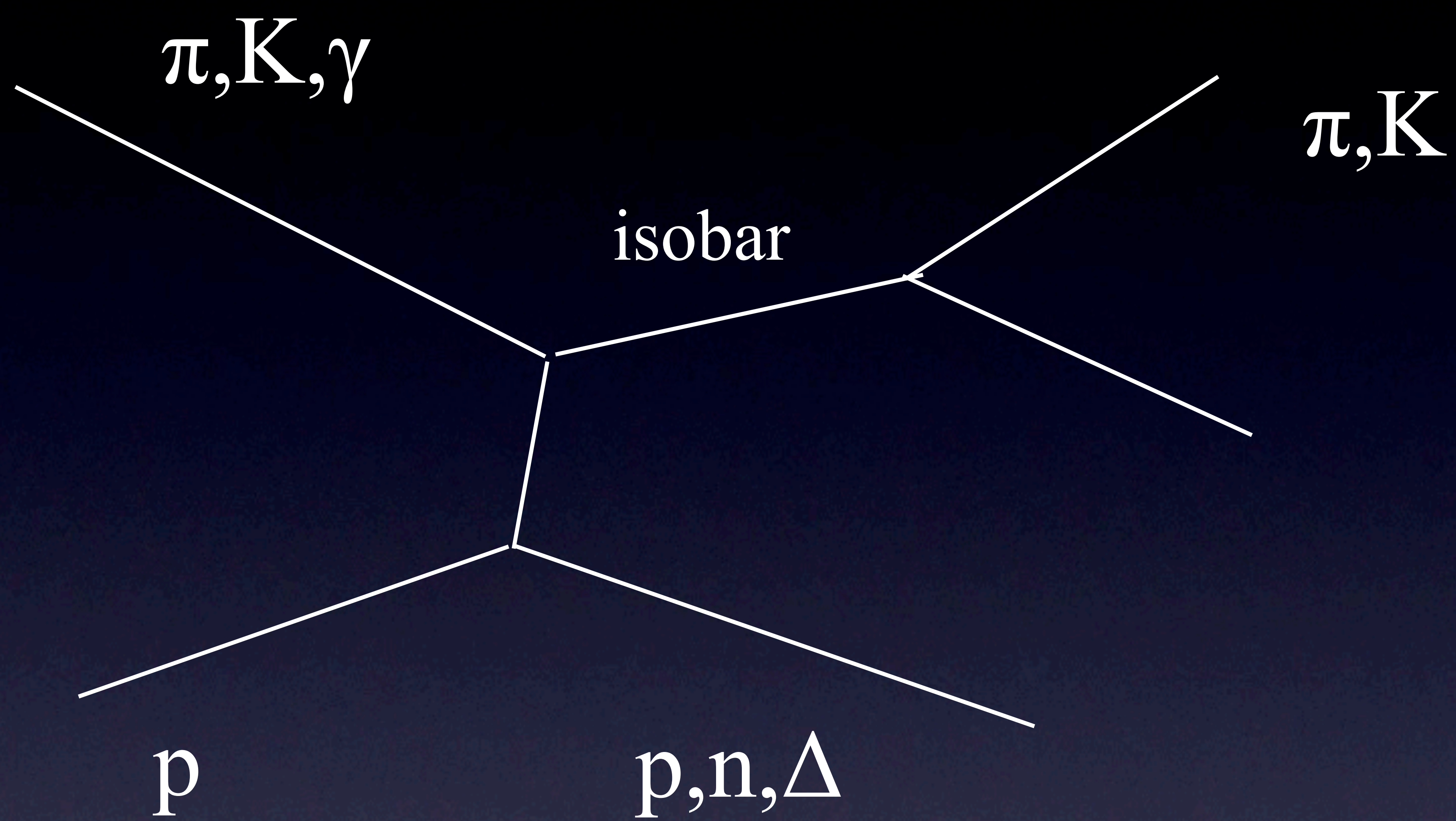
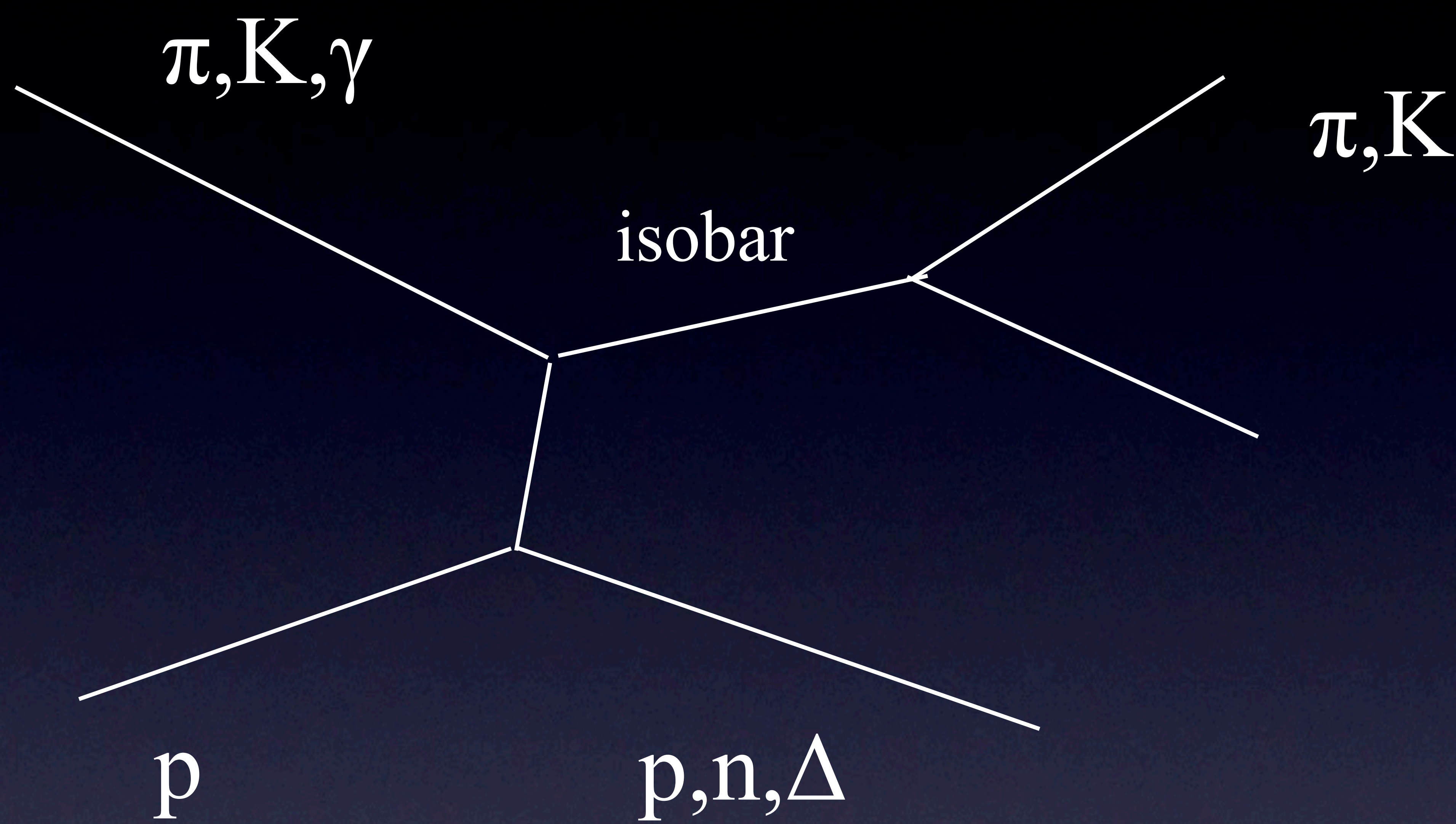
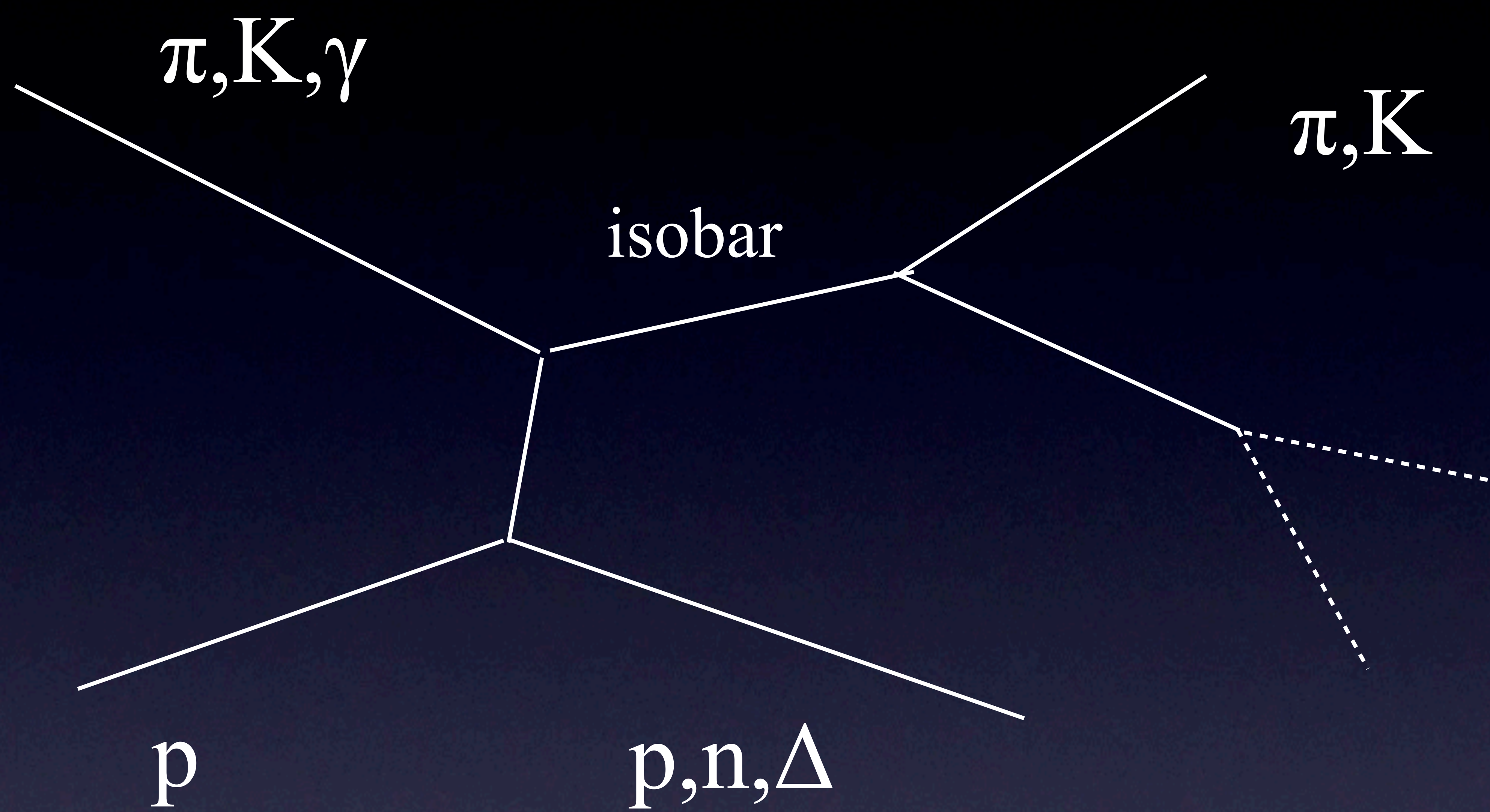


The Partial Wave Analysis ‘Isobar’ Technique



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

The Partial Wave Analysis 'Isobar' Technique



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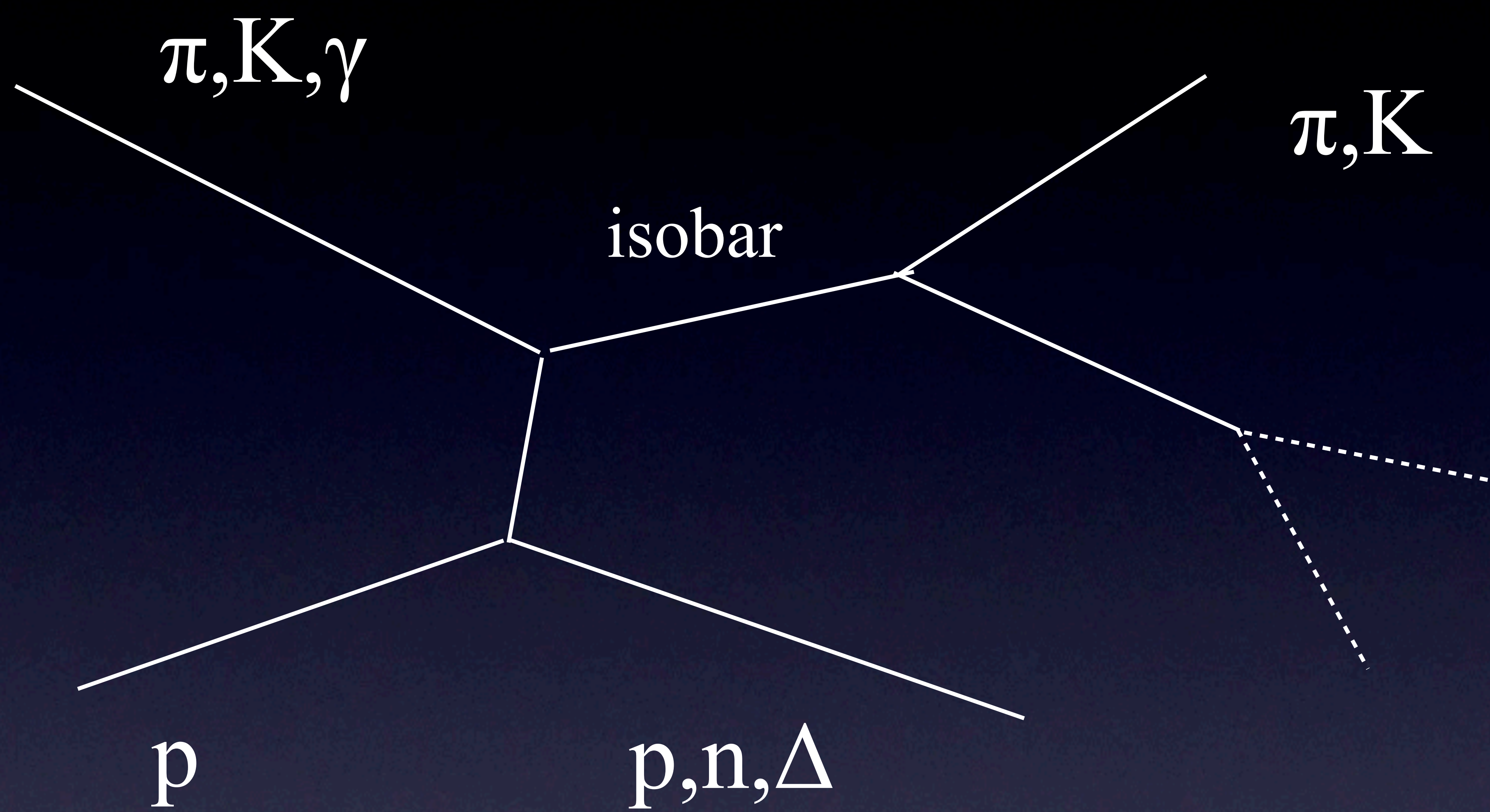


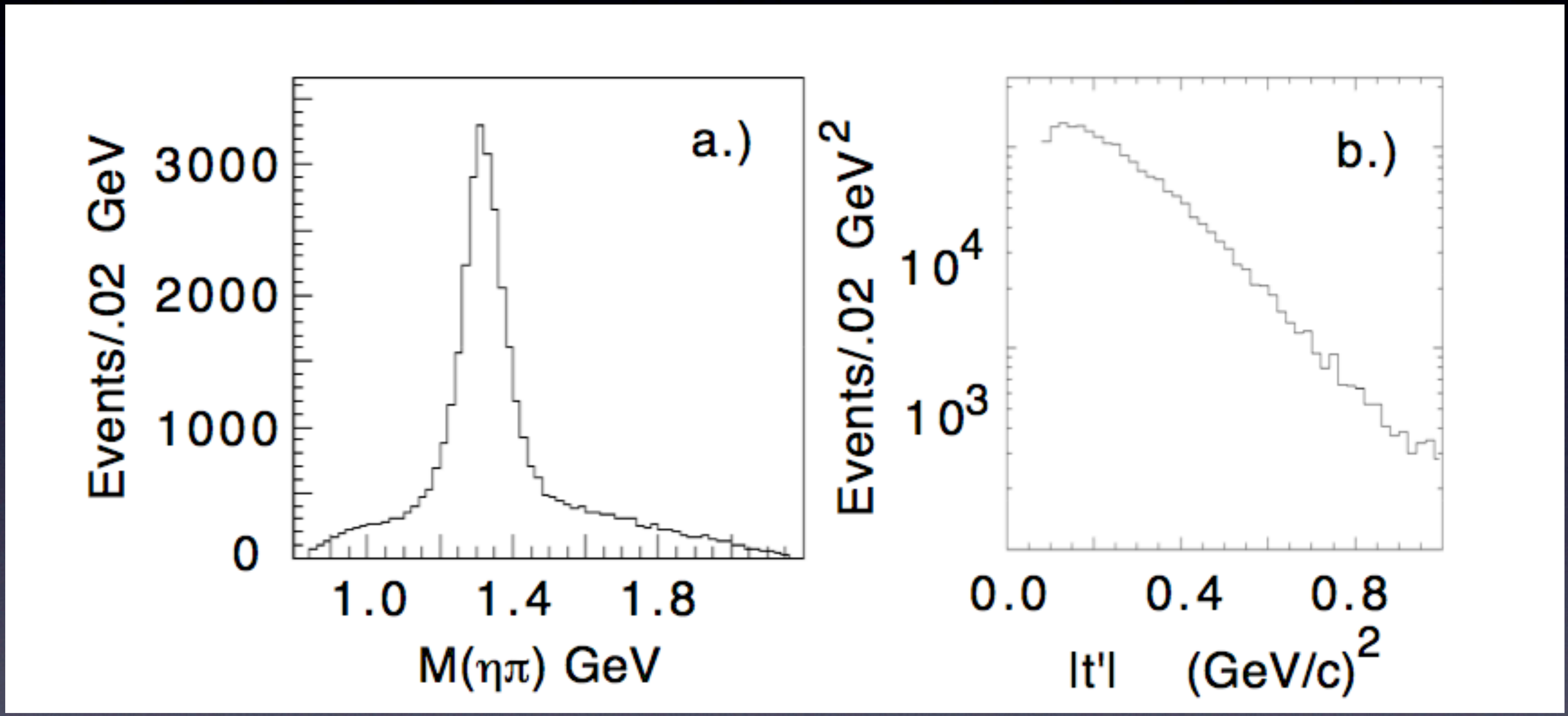
$$I(\tau) = \sum_{\epsilon,k} \left\{ \left| \sum_{\beta} {}^{\epsilon}V_{k\beta}\ {}^{\epsilon}A_{\beta}(\tau) \right|^2 \right.$$

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

The first exotic: BNL-E852

$$\pi^- p \to \eta \pi^- p$$

18 GeV/c



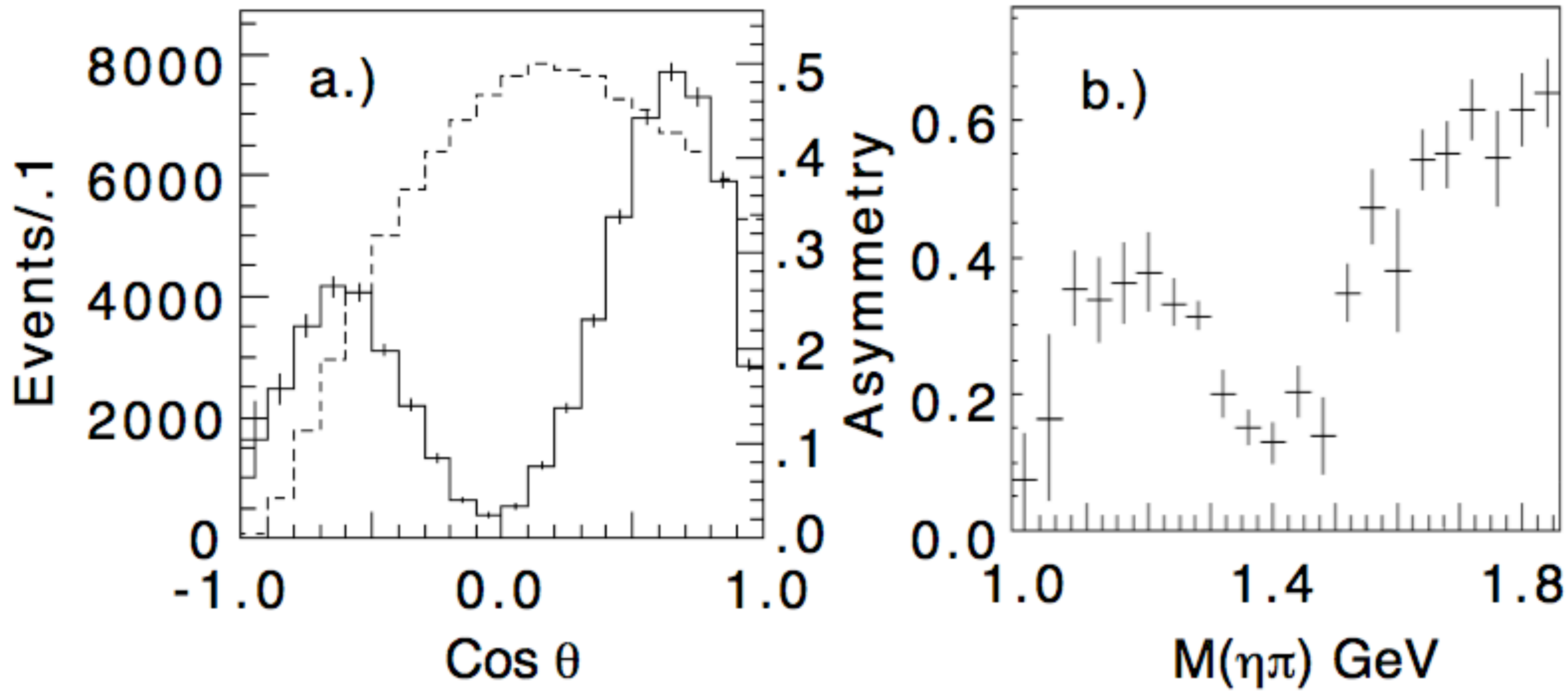
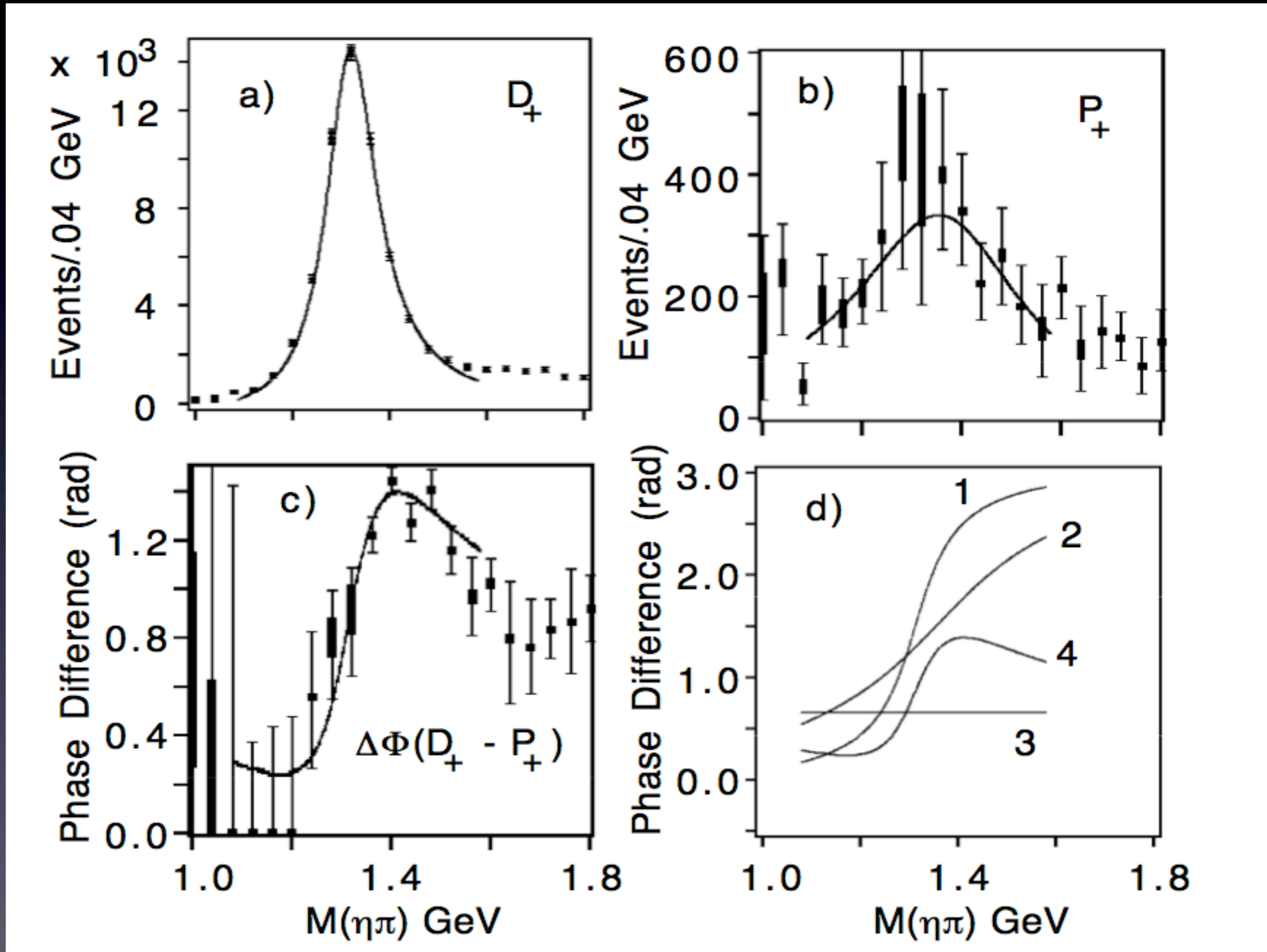


FIG. 2. Distributions of a.) the cosine of the decay angle in the Gottfried-Jackson frame for events with $1.22 < M(\eta\pi^-) < 1.42$ GeV/c^2, and b.) the forward-backward decay asymmetry as a function of $M(\eta\pi^-)$. The asymmetry $= (F - B)/(F + B)$ where F(B) is the number of events for which the η's momentum is forward (backward) in the Gottfried-Jackson frame. The dashed curve and the right-hand scale in a.) show the acceptance in this mass region.

$\eta\pi^-$ Partial Wave Analysis



Crystal Barrel

A. Abele *et al.*, **Phys.Lett.B423:175-184,1998**.

$$\bar{p}d \to \eta\pi^-\pi^0\eta(p)$$

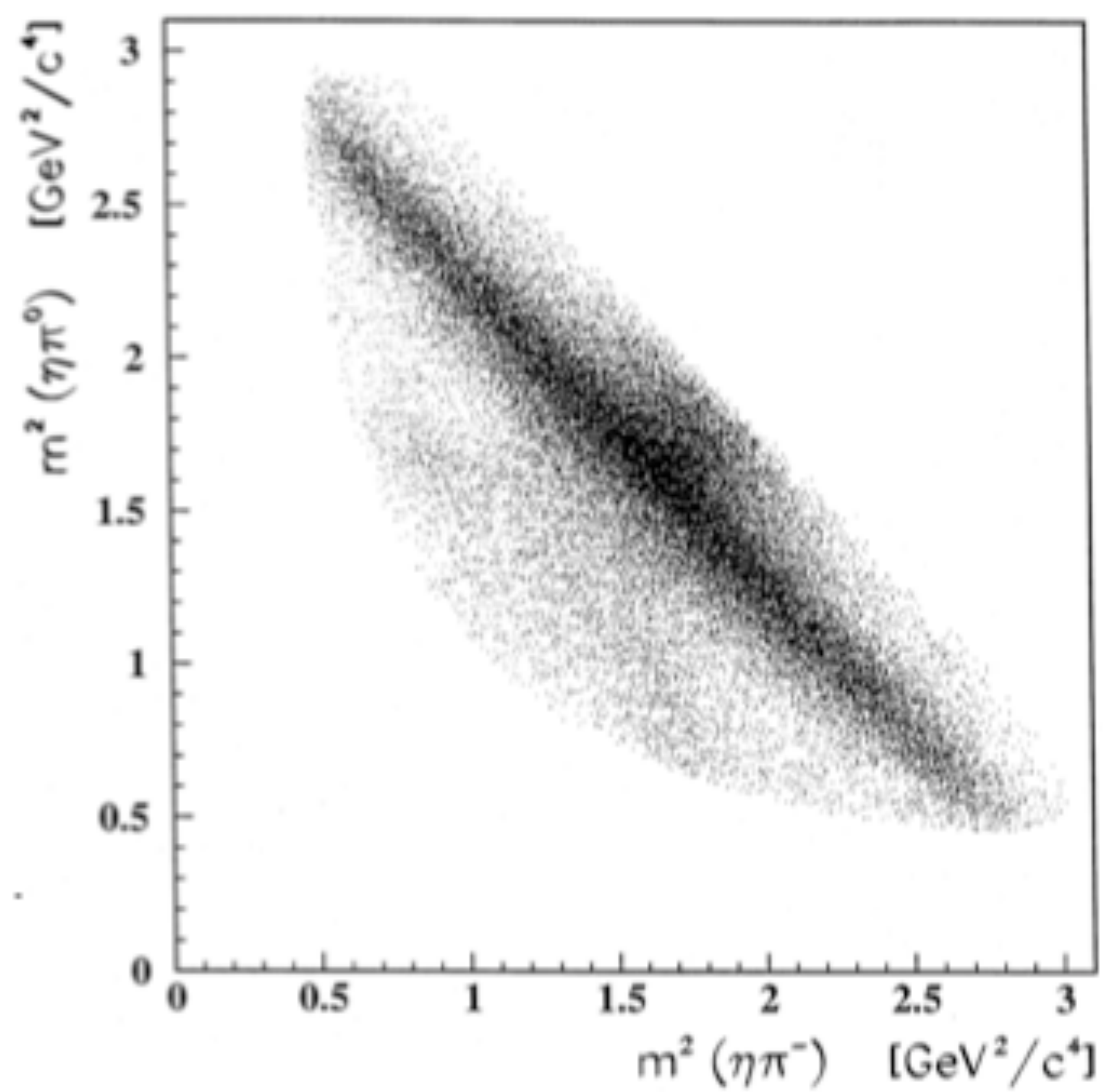


Fig. 1. Dalitz plot (not acceptance corrected) of the final sample of $\pi^-\pi^0\eta$ events from the annihilation reaction $\bar{p}d \to \pi^-\pi^0\eta p_{\text{spectator}}$ with $P(p_{\text{spectator}}) < 100$ MeV/c.

Crystal Barrel

A. Abele *et al.*, **Phys.Lett.B423:175-184,1998**.

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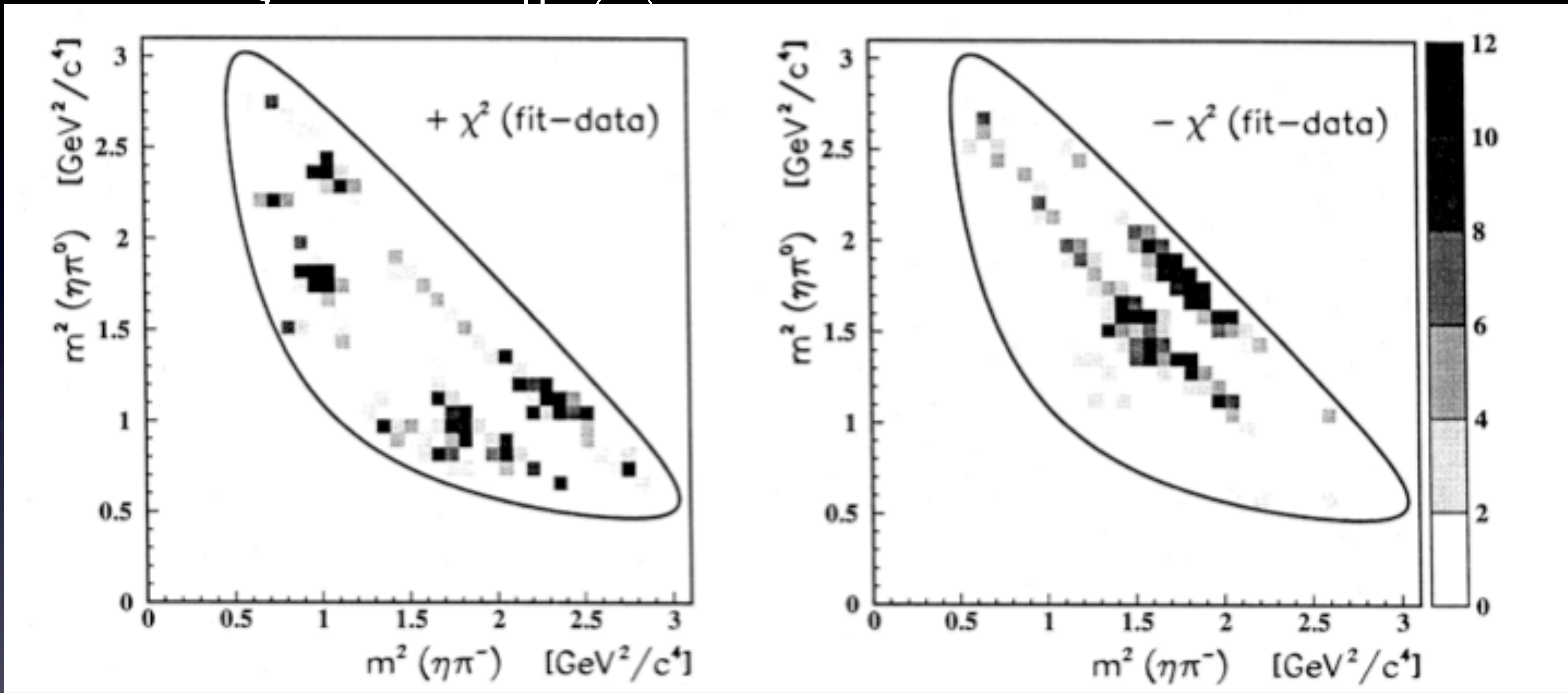

$\rho, a_2(1320), a_0(980), a_0(1450)$

Crystal Barrel

A. Abele *et al.*, **Phys.Lett.B423:175-184,1998**.

$$\bar{p}d \rightarrow \eta\pi^{-}\pi^{0}\eta(p)$$

Crystal Barrel

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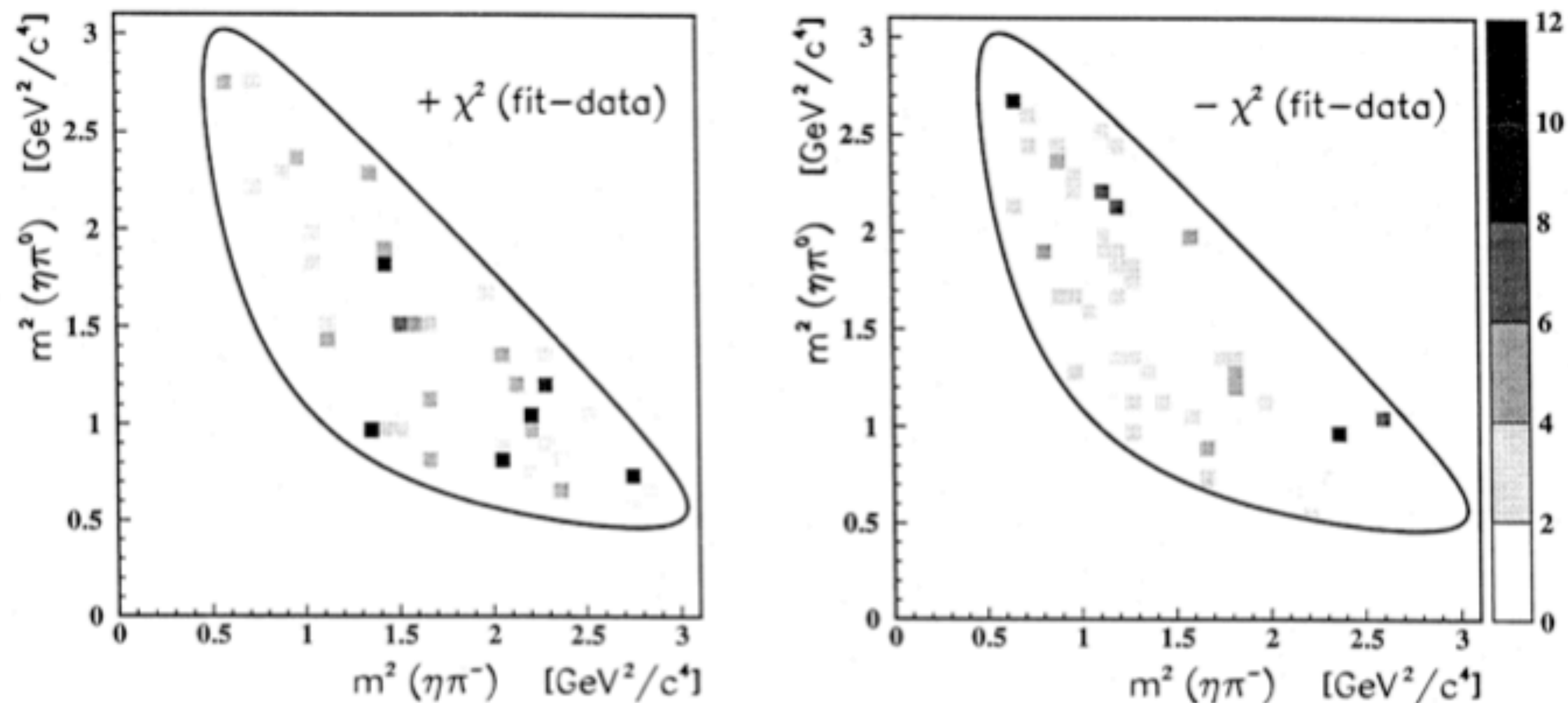
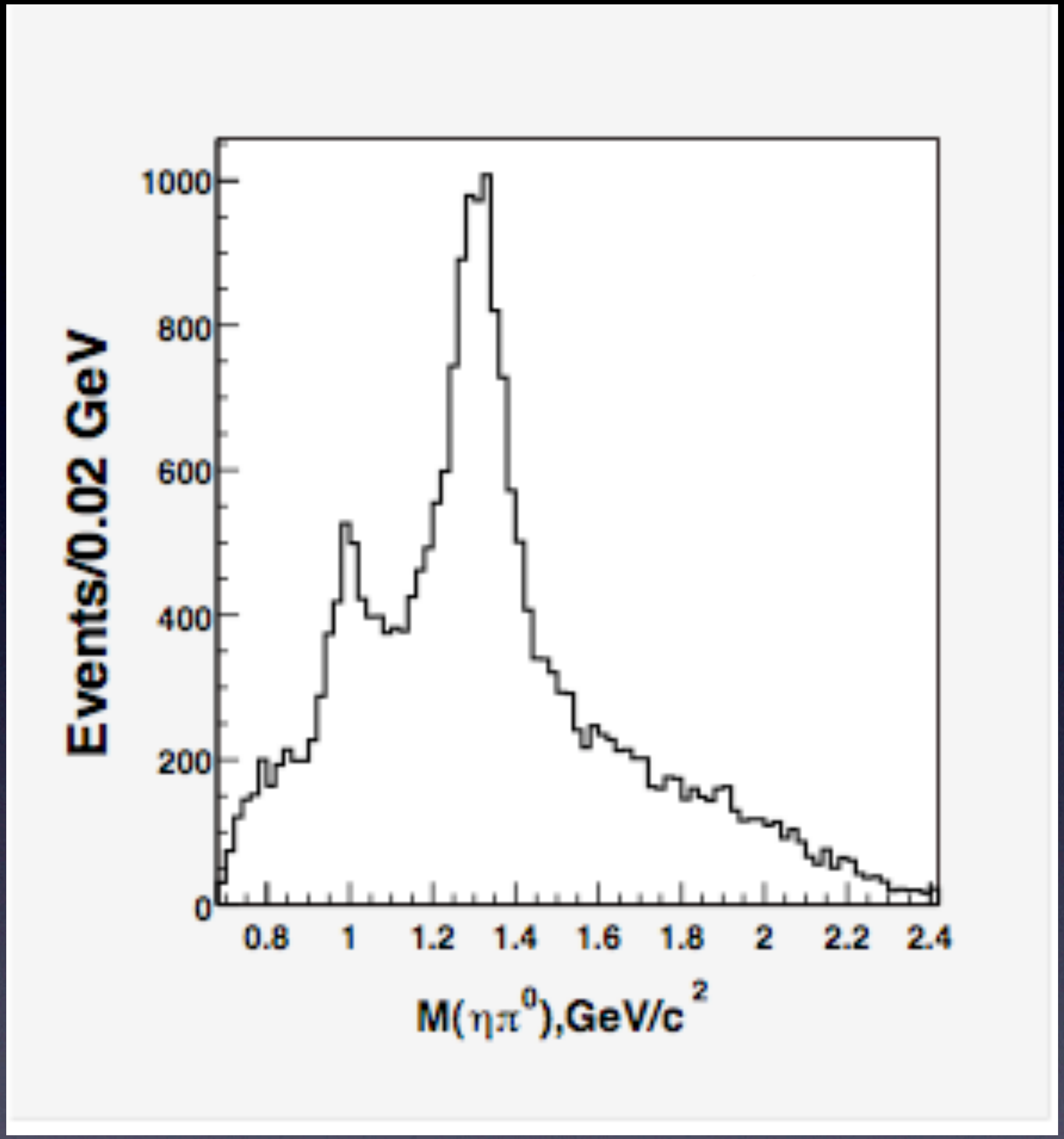
$$\bar{p}d \to \eta\pi^-\pi^0 p(n)$$

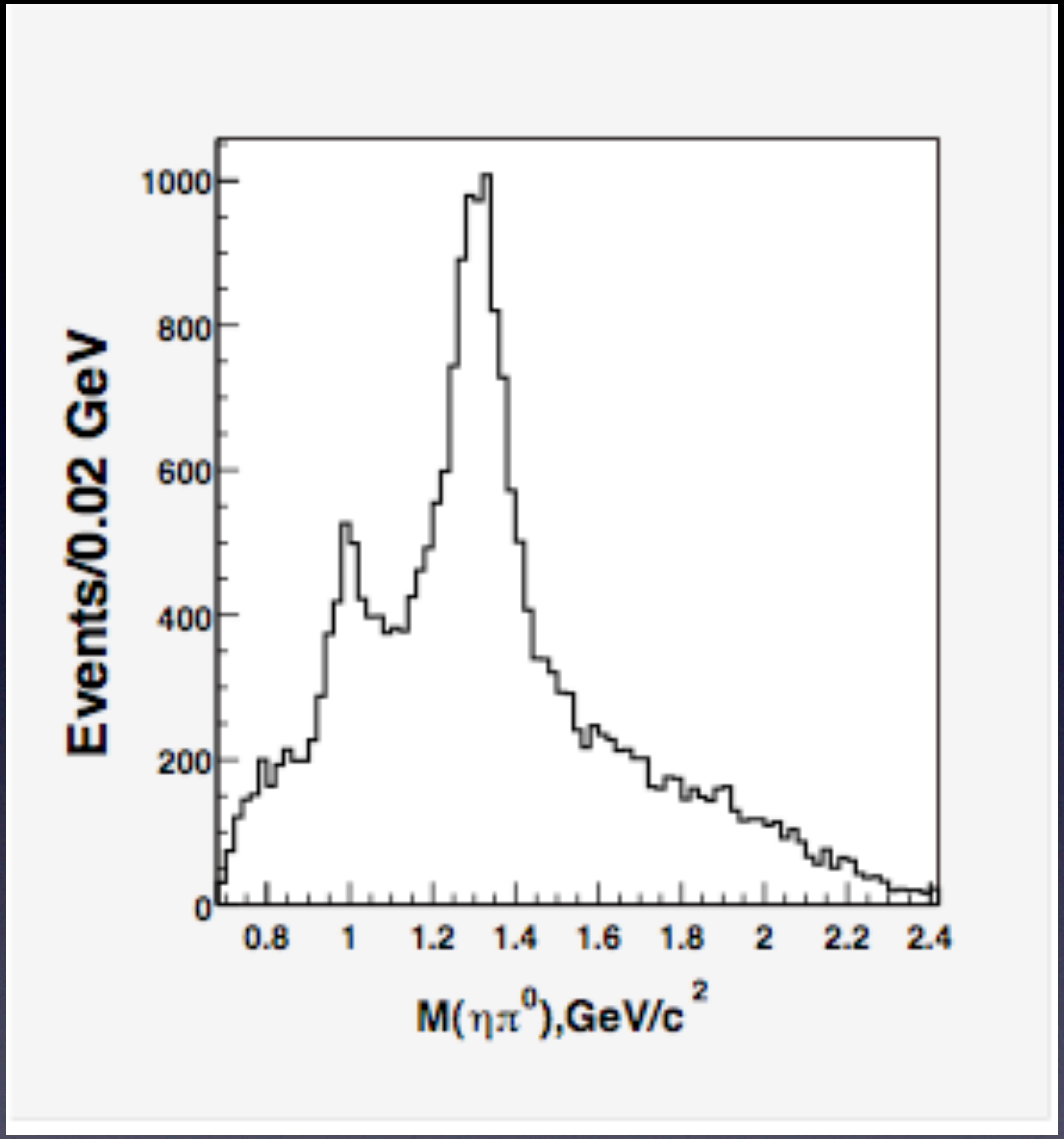


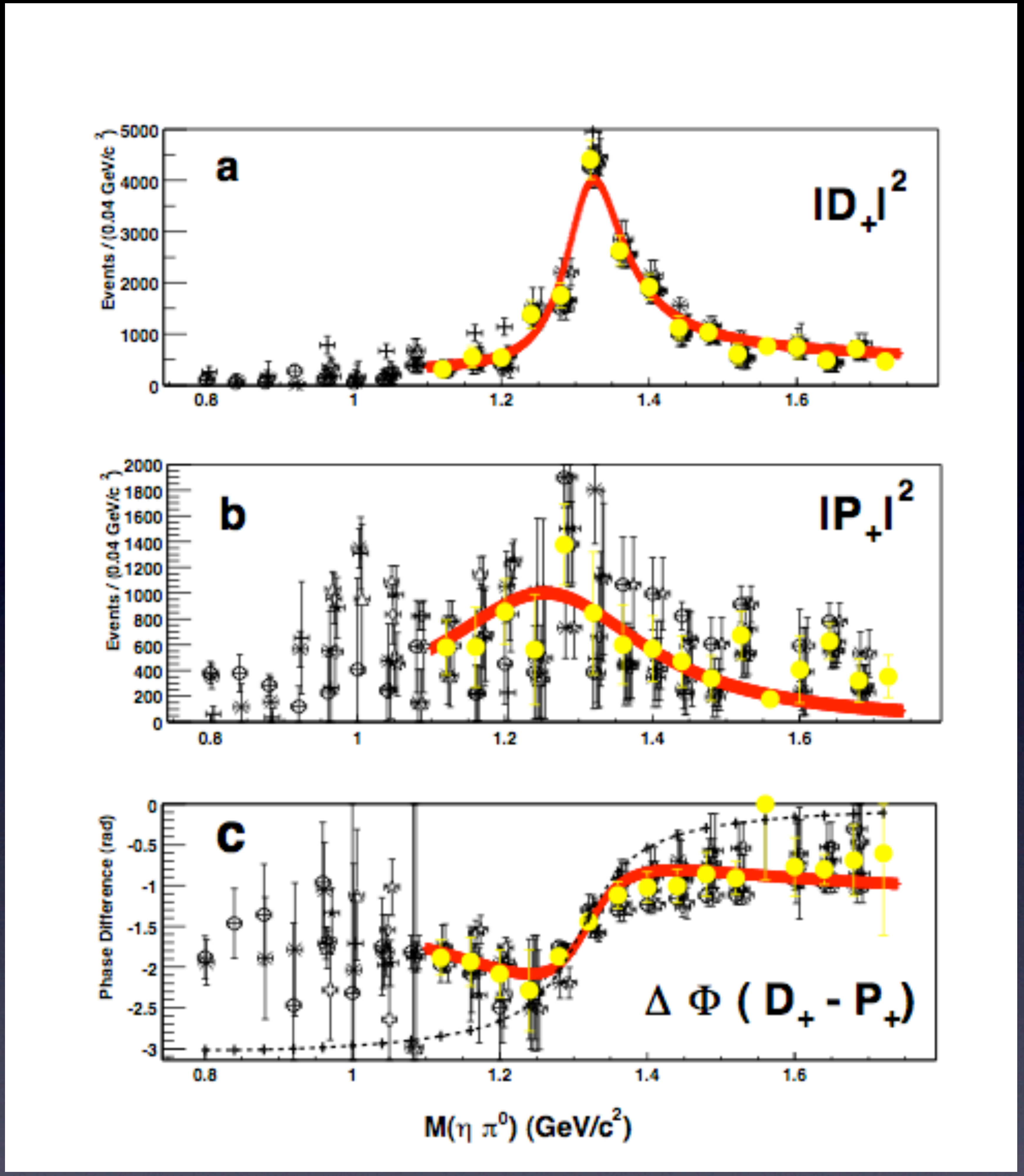
include $\pi_1(1405)$

$\eta\pi^0$ Partial Wave Analysis, BNL-E852

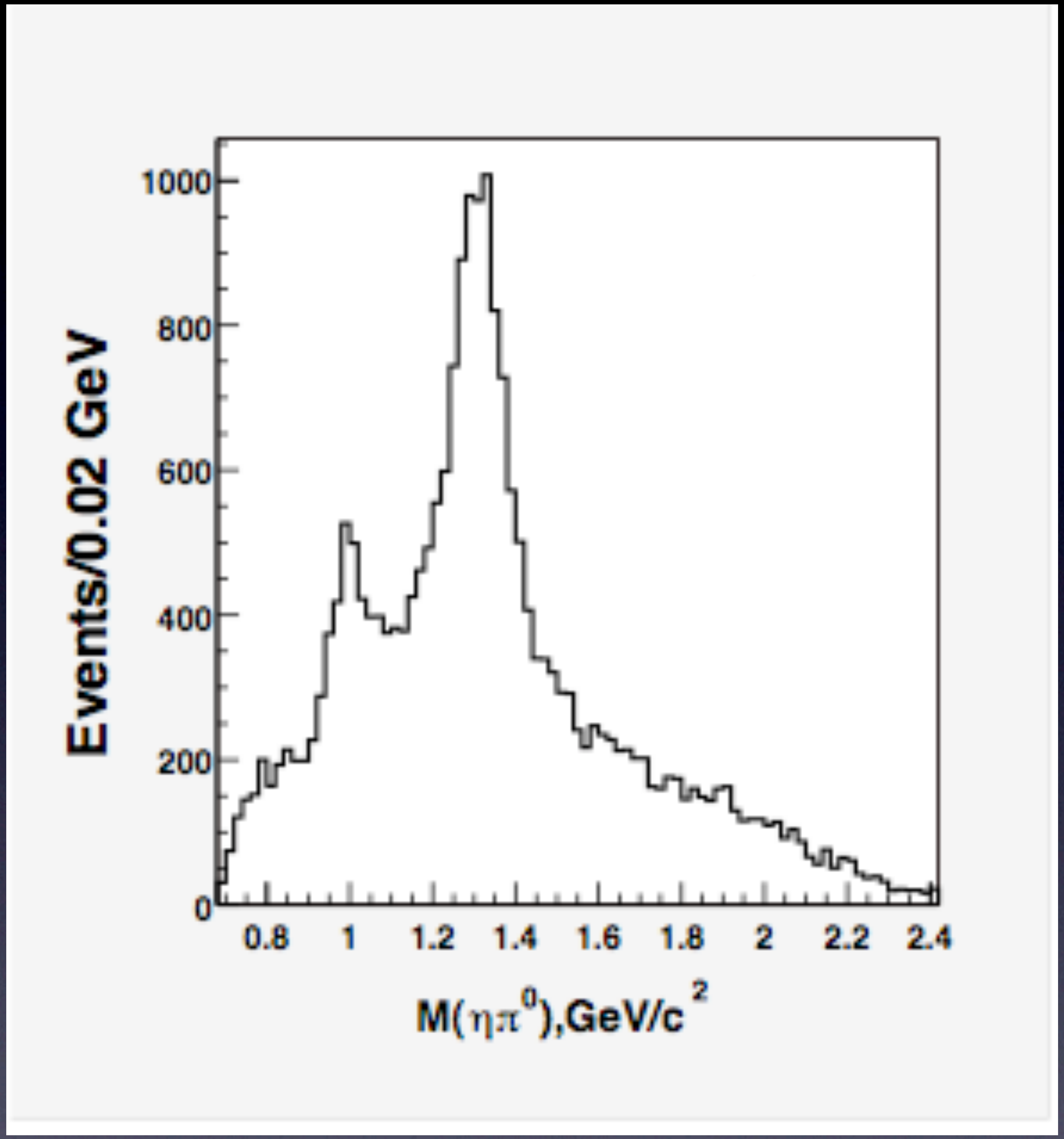


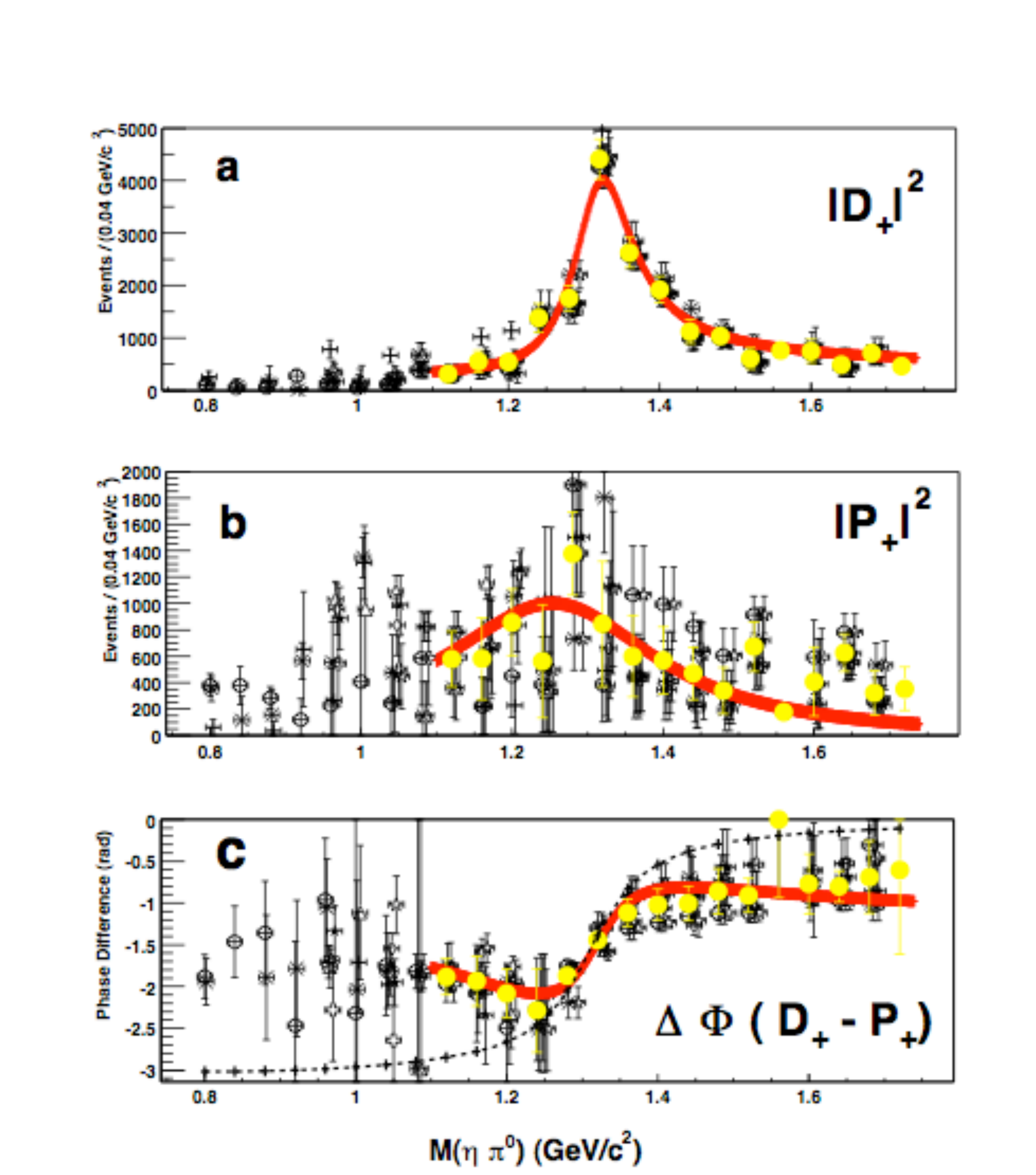
$\eta\pi^0$ Partial Wave Analysis, BNL-E852





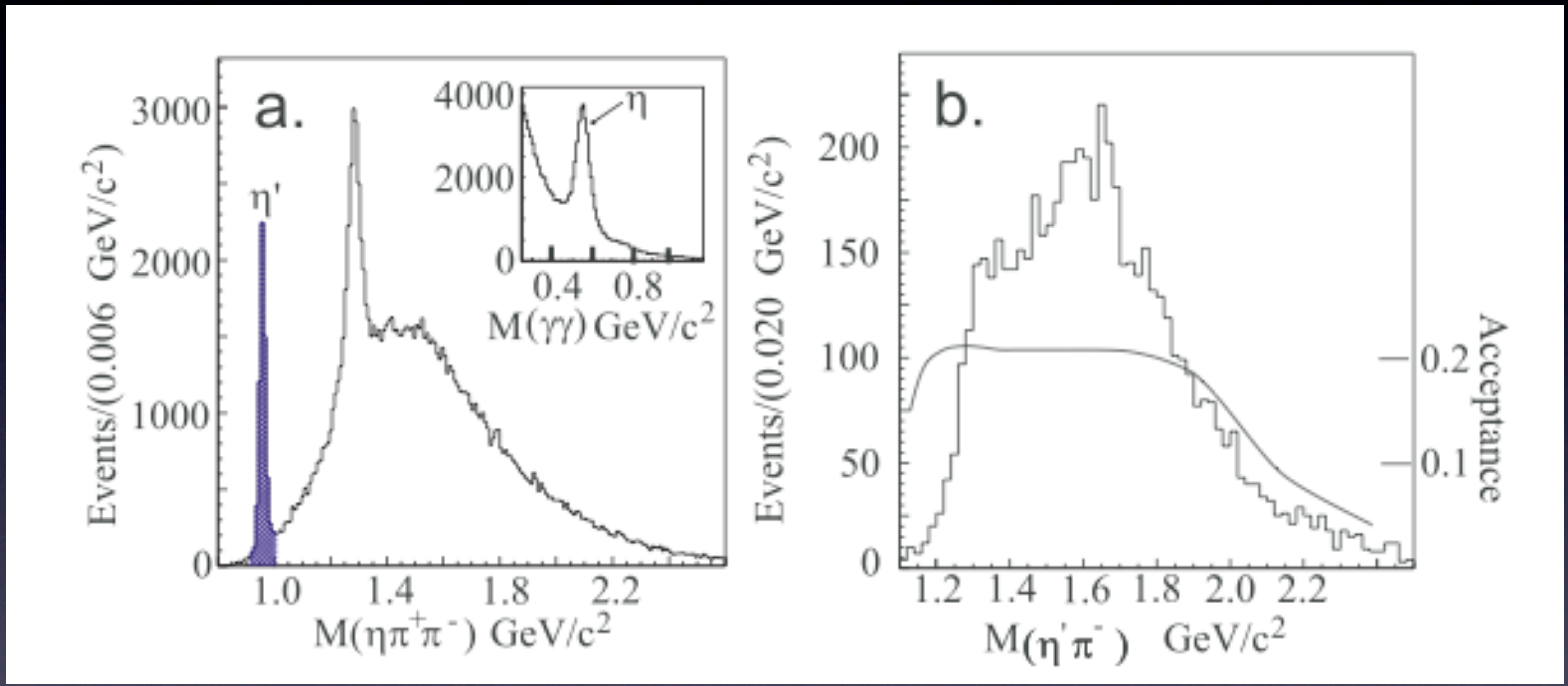
$\eta\pi^0$ Partial Wave Analysis, BNL-E852



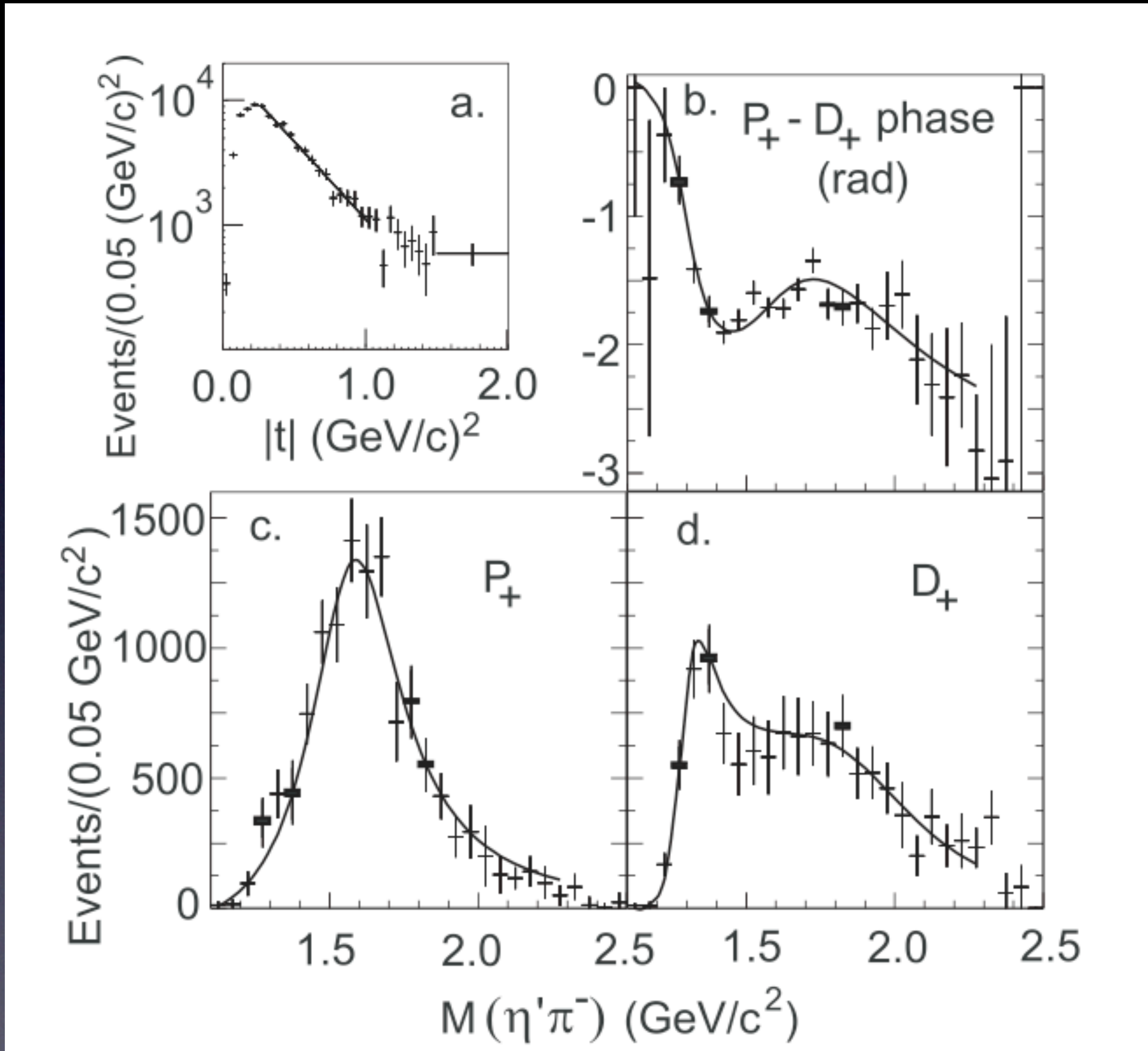


$$M = 1257 \pm 20\ \mathrm{MeV/c^2}\ \text{and}\ \Gamma = 354 \pm 64\ \mathrm{MeV/c^2}.$$

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



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



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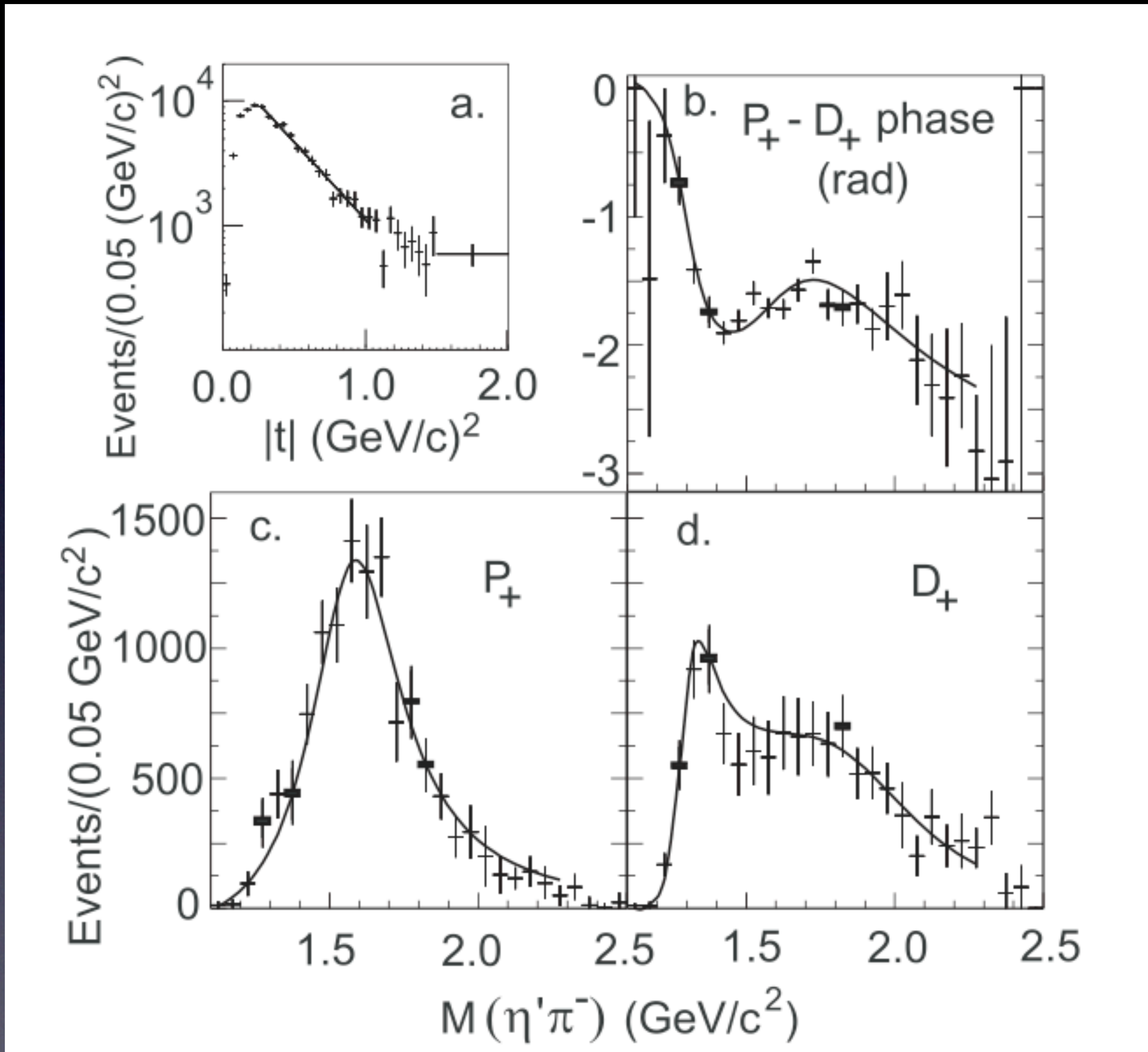

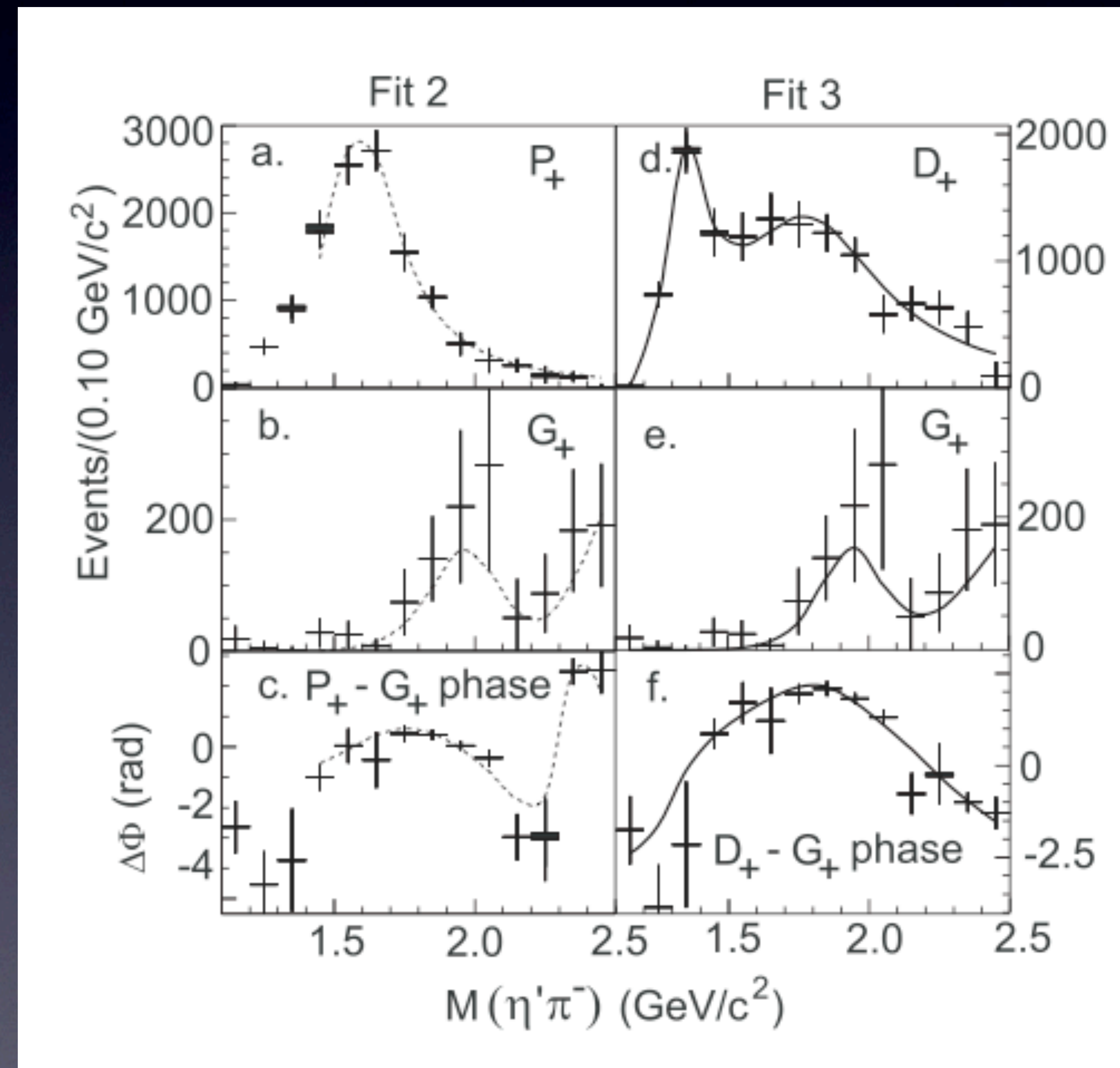

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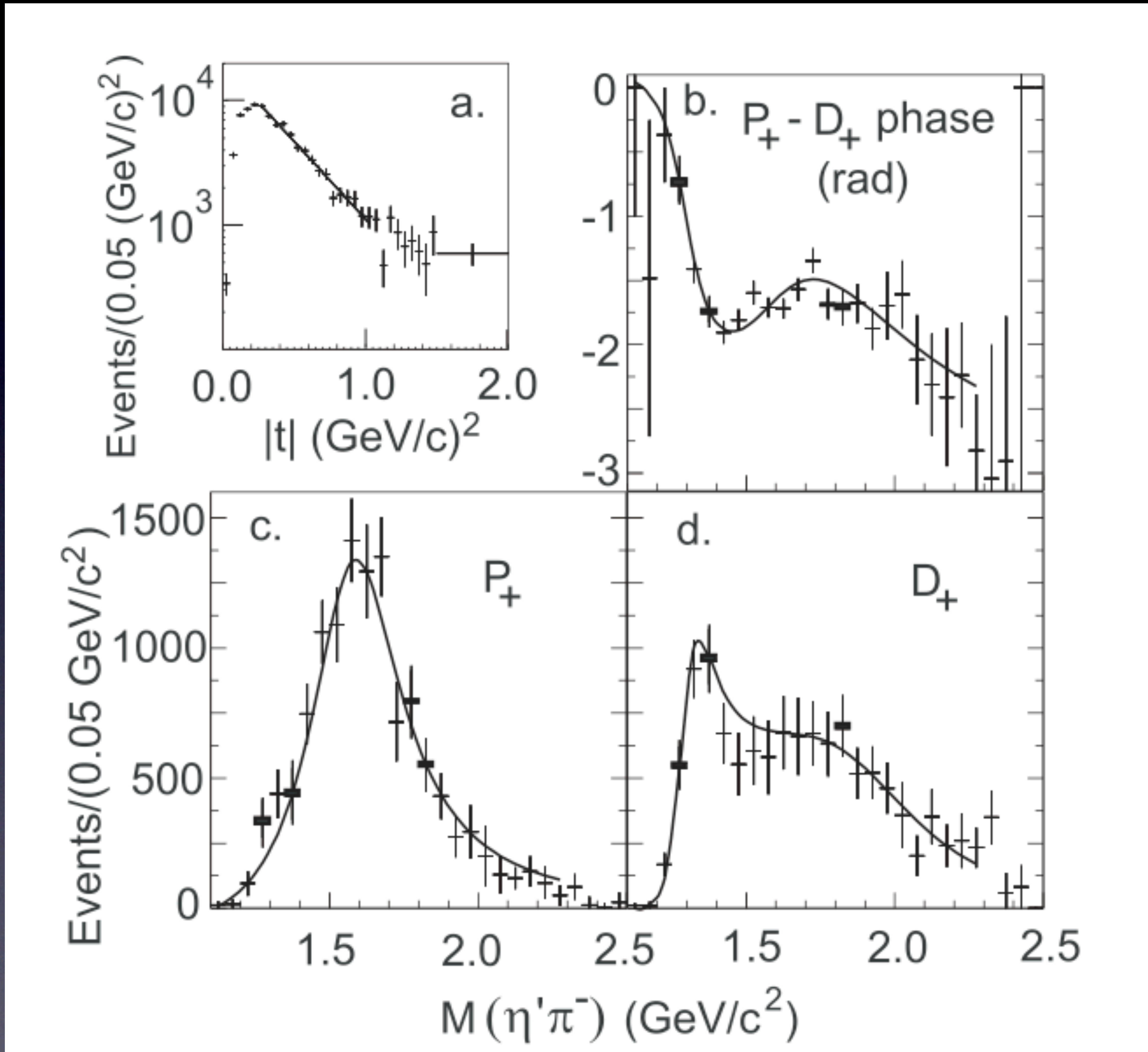
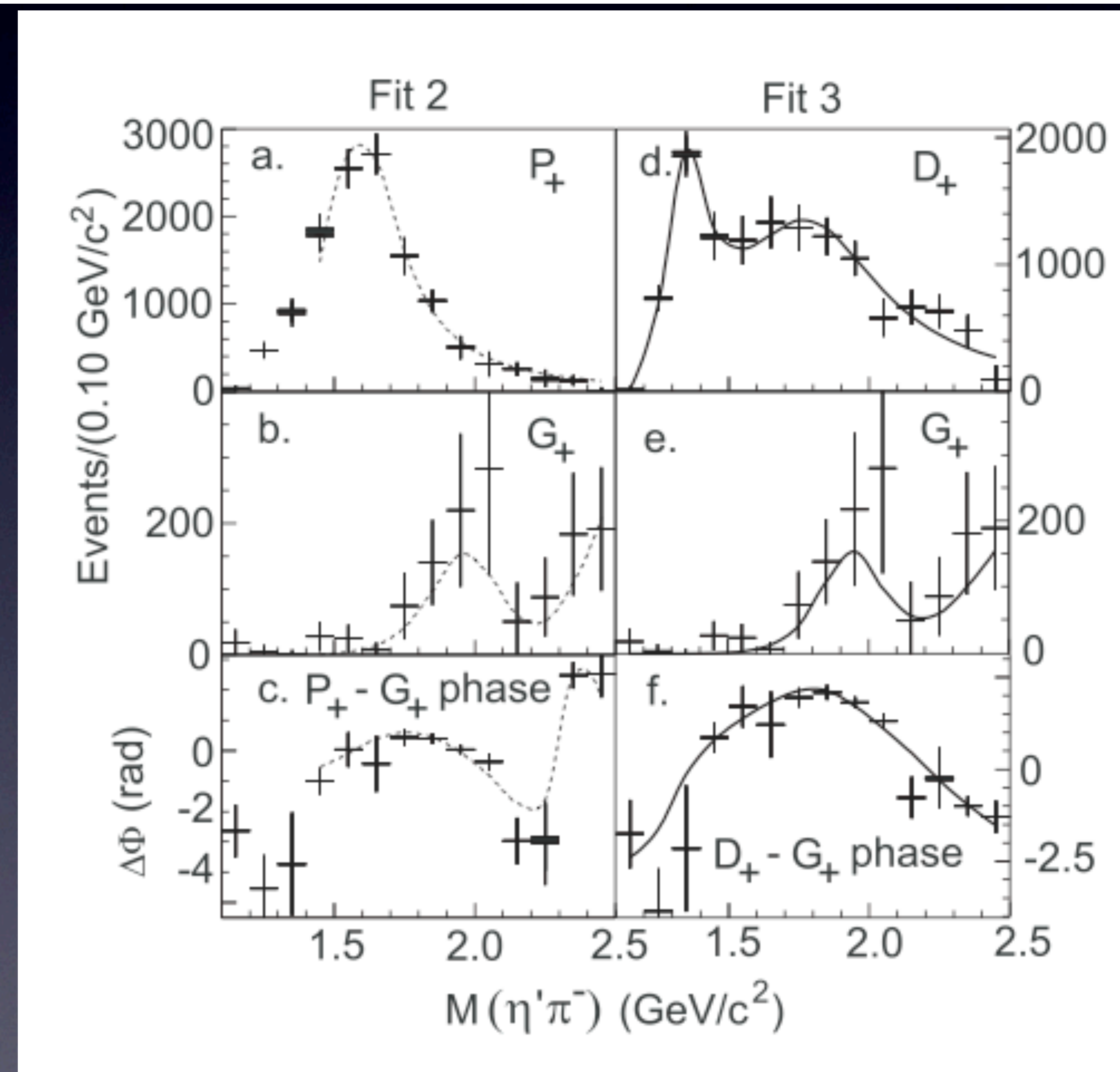
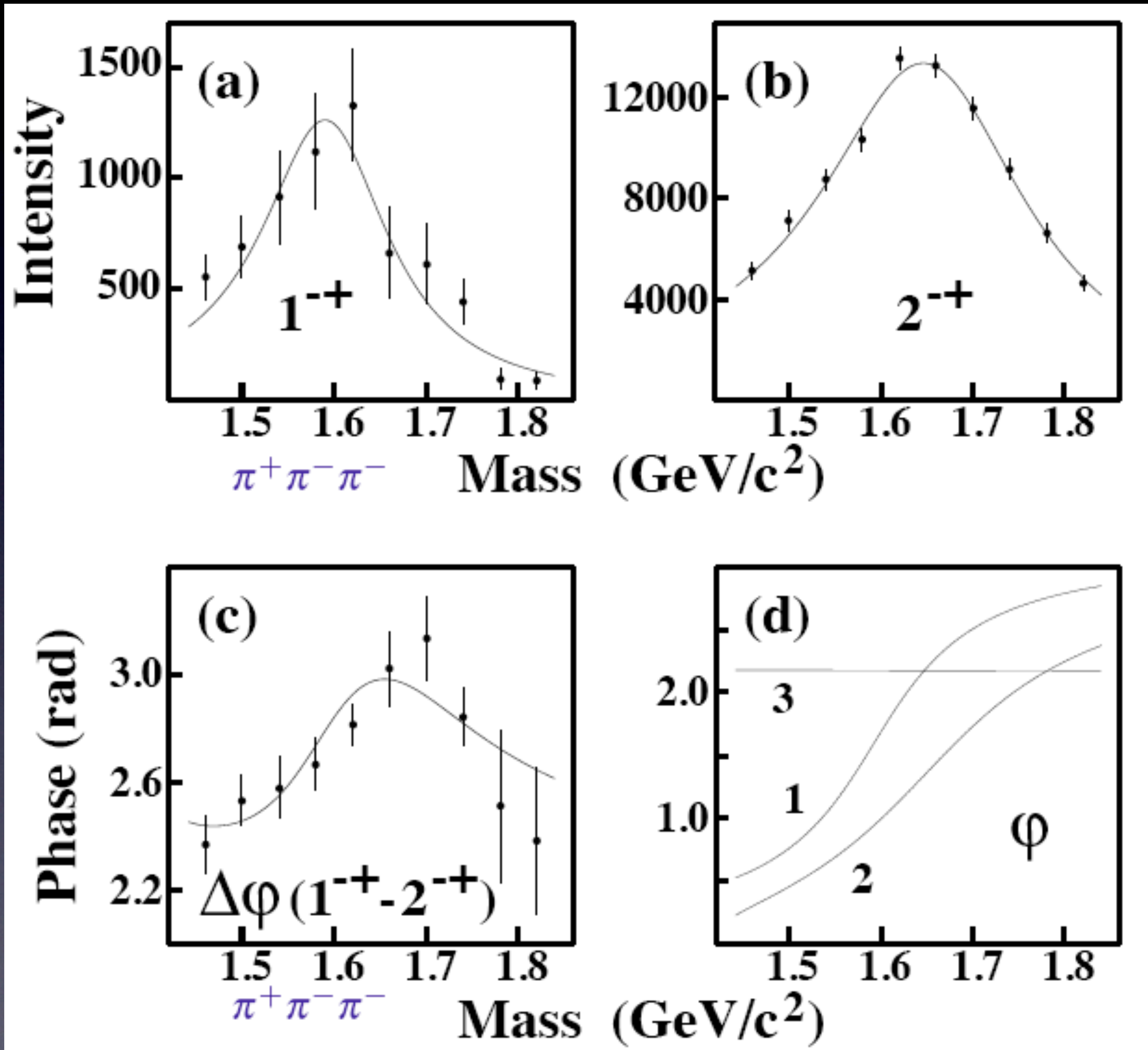


Partial Wave	Mass	Width
P_+	$1.597 \pm 0.010^{+0.045}_{-0.010}$	$0.340 \pm 0.040 \pm 0.050$
D_+	$1.318 \pm 0.008^{+0.003}_{-0.005}$	$0.140 \pm 0.035 \pm 0.020$
G_+	$2.000 \pm 0.040^{+0.060}_{-0.020}$	$0.350 \pm 0.100^{+0.070}_{-0.050}$



E852 250000 events/1997

$$\pi^- p \to \pi^- \pi^- \pi^+ p$$



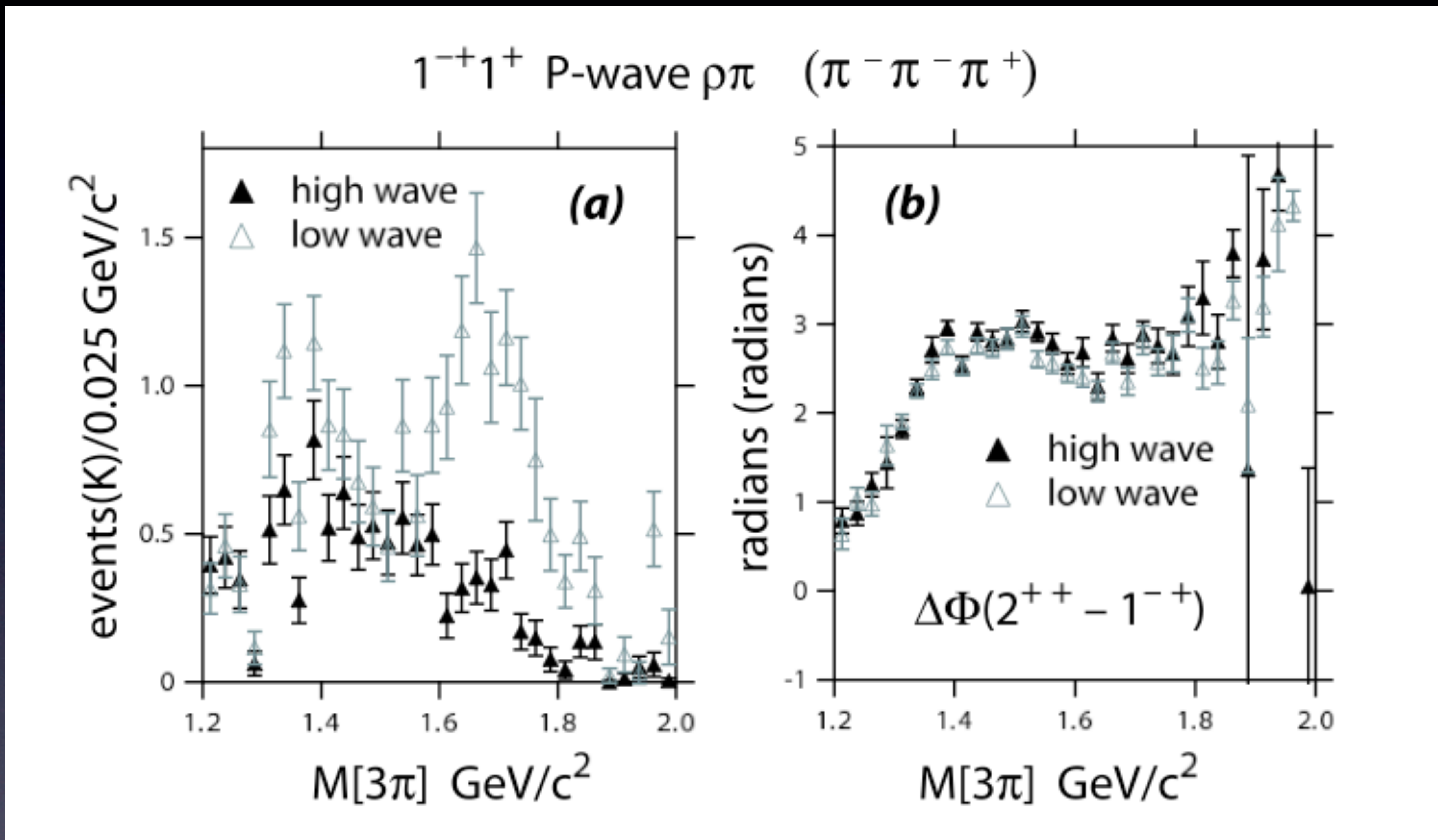
PRL <u>81</u>, 5760 (1998)
PRD <u>65</u>, 072001 (2002)

$$M = 1593 \pm 8^{+29}_{-47}\ \mathrm{MeV}$$

$$\Gamma = 168 \pm 20^{+150}_{-12}\ \mathrm{MeV}$$

Indiana University/E852

1995 $\pi^- p \rightarrow \pi^- \pi^- \pi^+ p$



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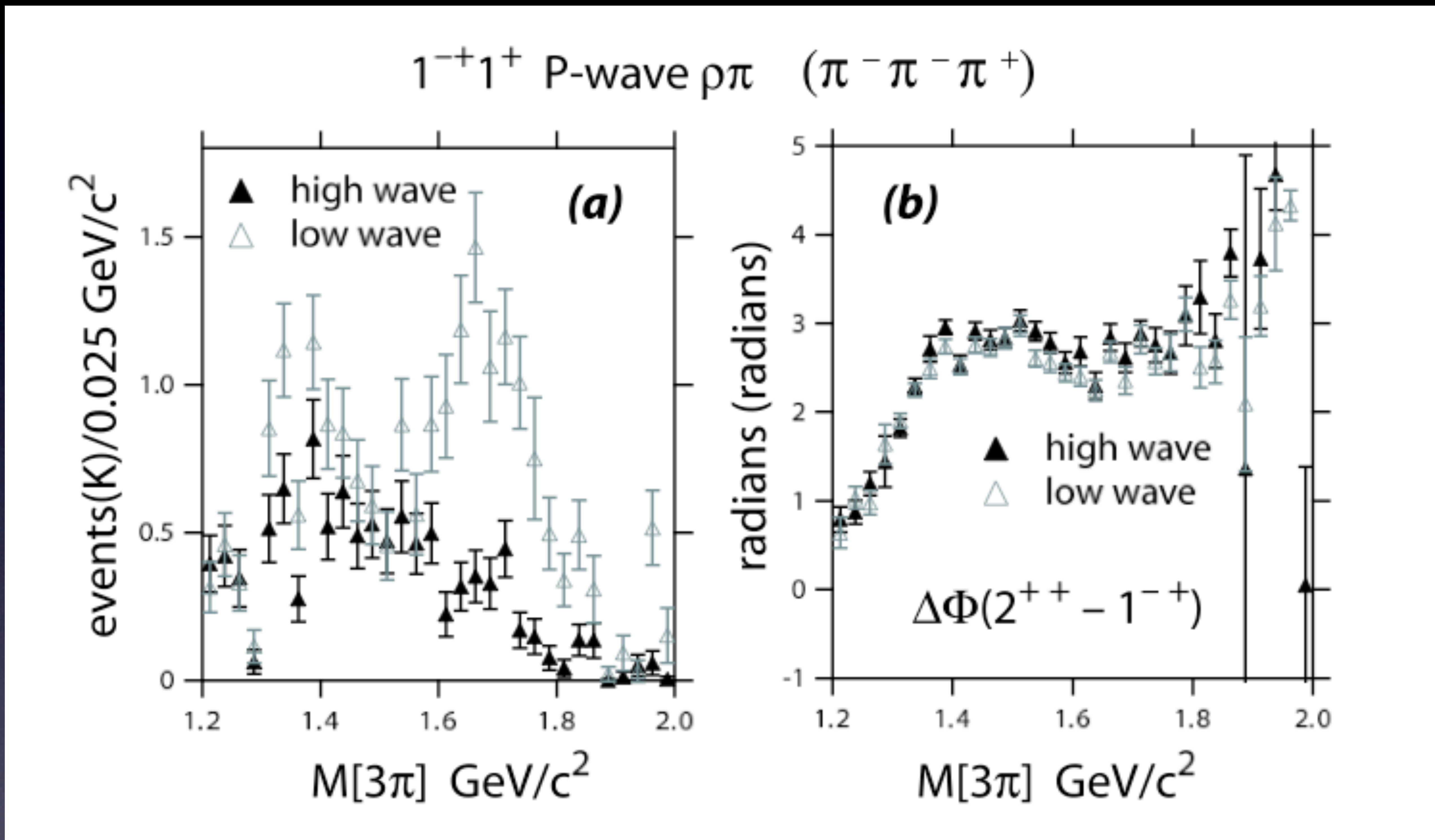

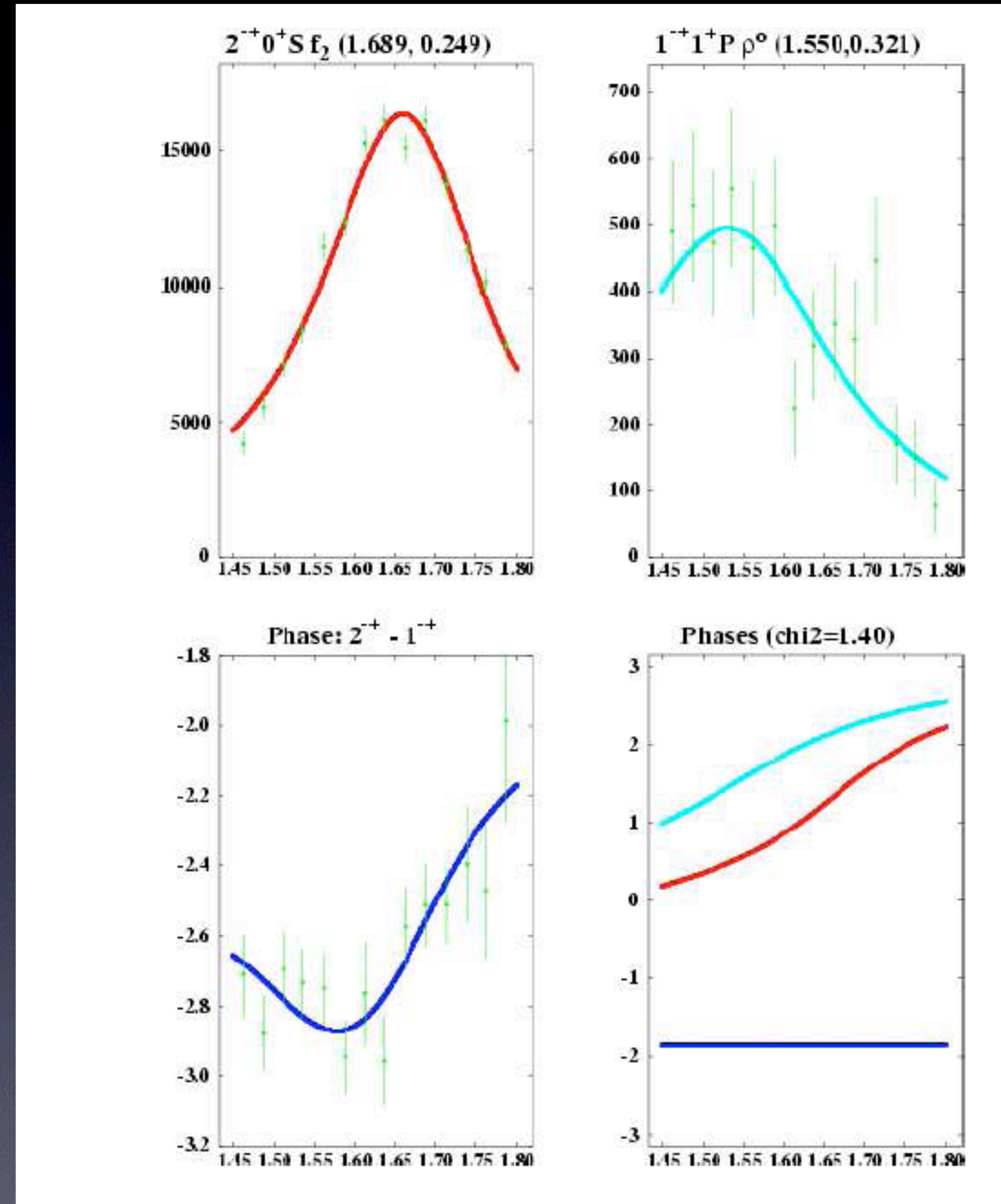

COMPASS

CERN-SPS fixed target

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

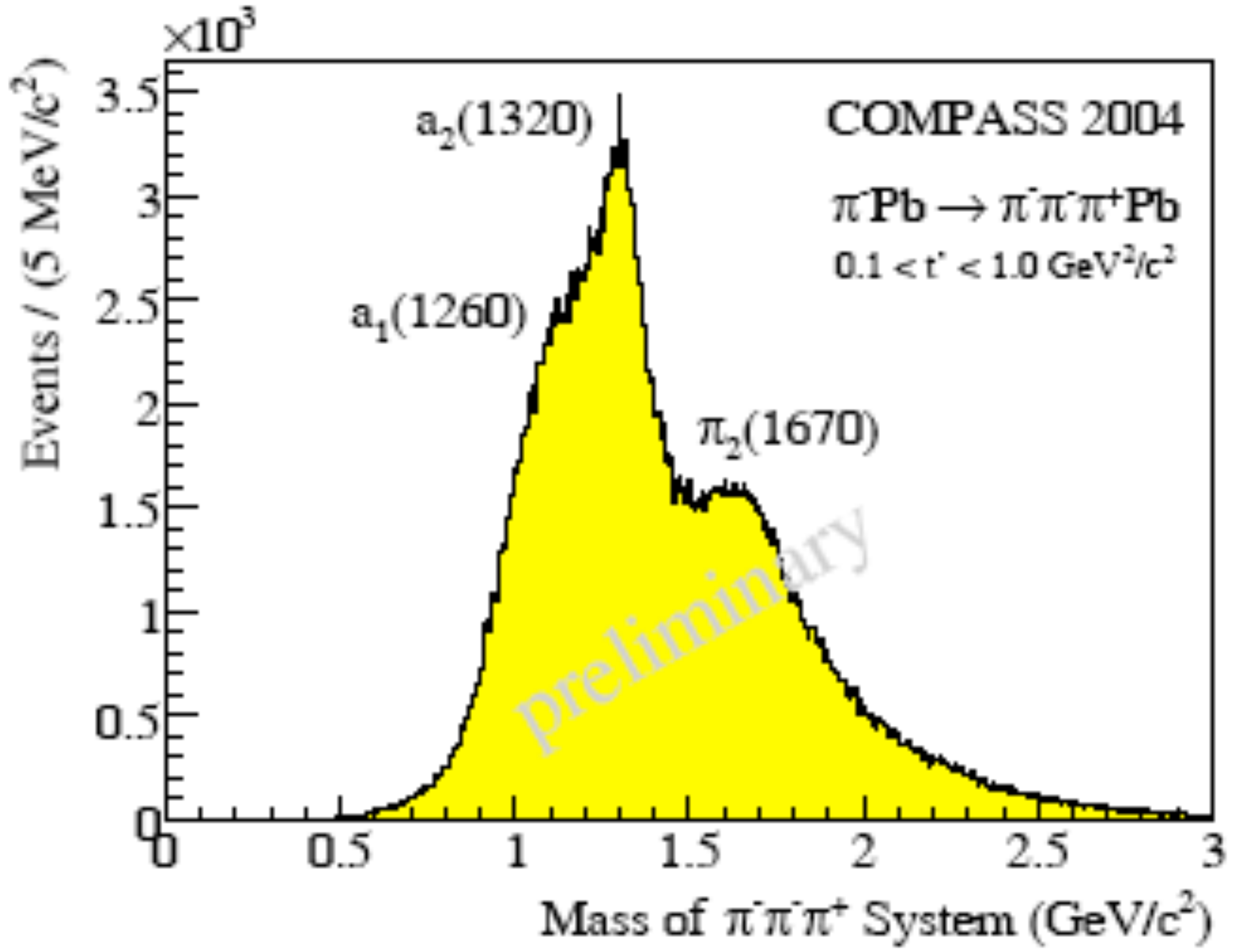

Fig. 1. Invariant mass of $\pi^-\pi^-\pi^+$ final states for $0.1 < t' < 1.0\,\mathrm{GeV}^2/c^2$.

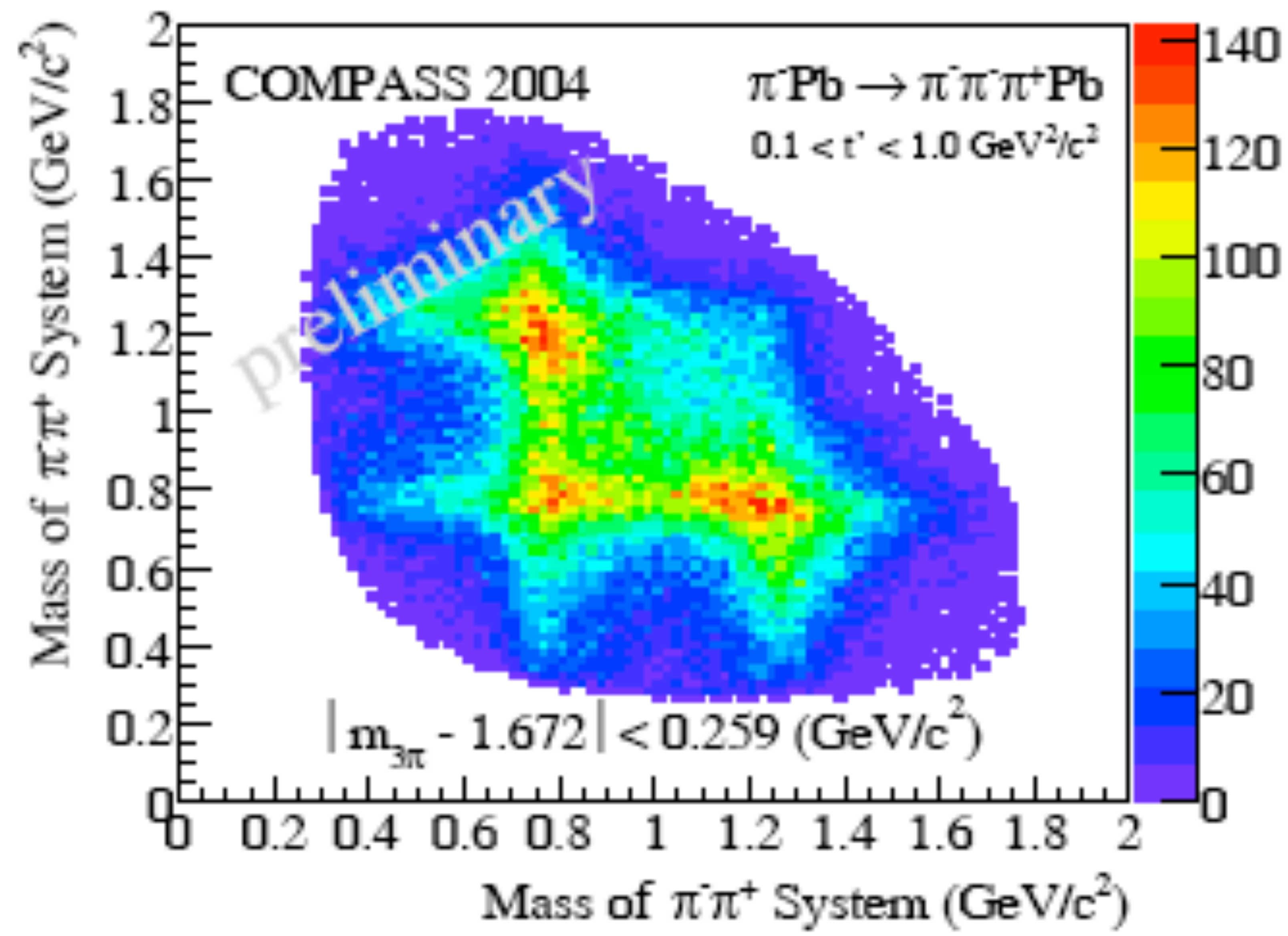

Fig. 2. Dalitz plot for $\pi_2(1670)$, selected by a $\pm 1\Gamma$ cut around its nominal mass.

COMPASS

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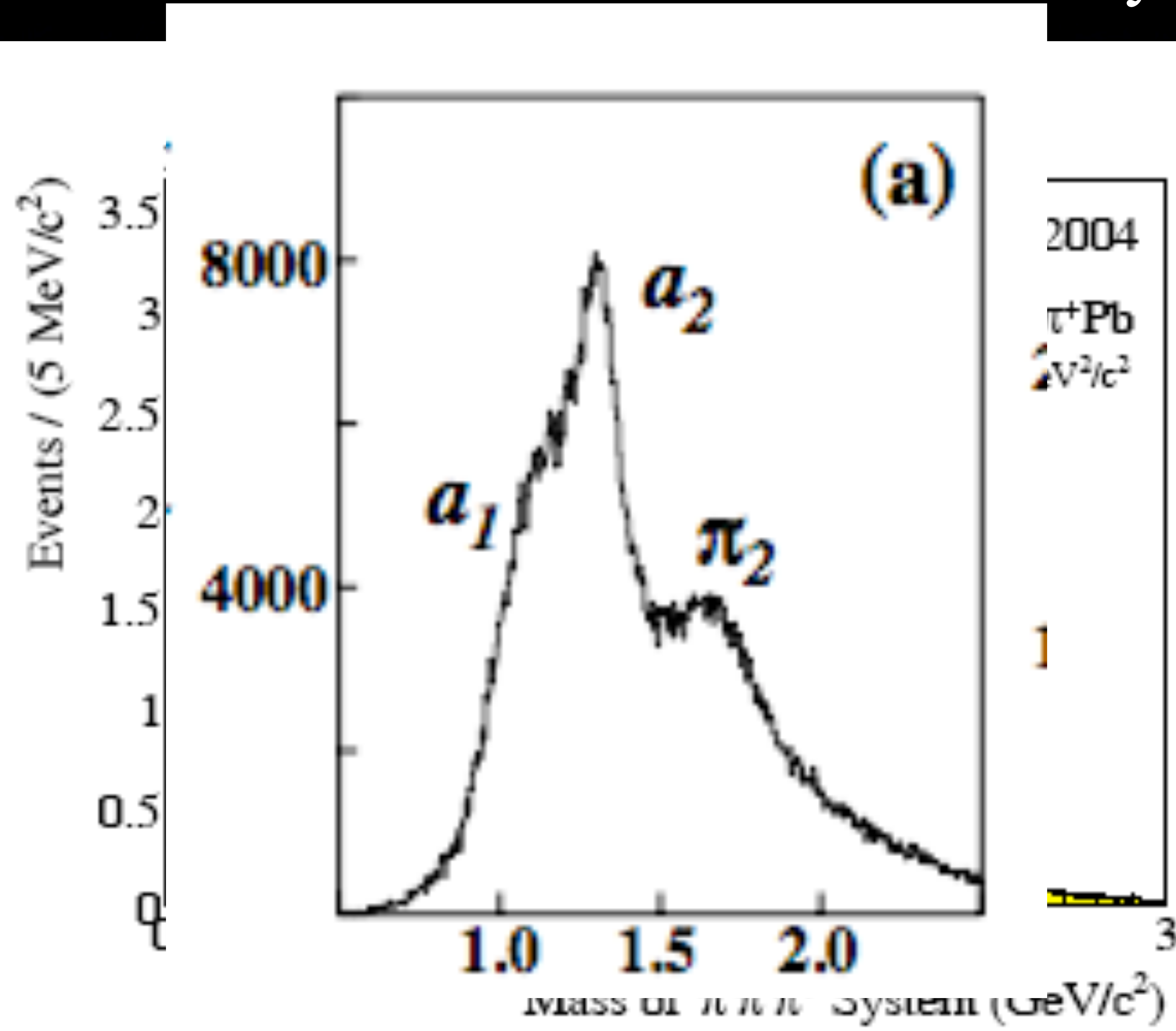

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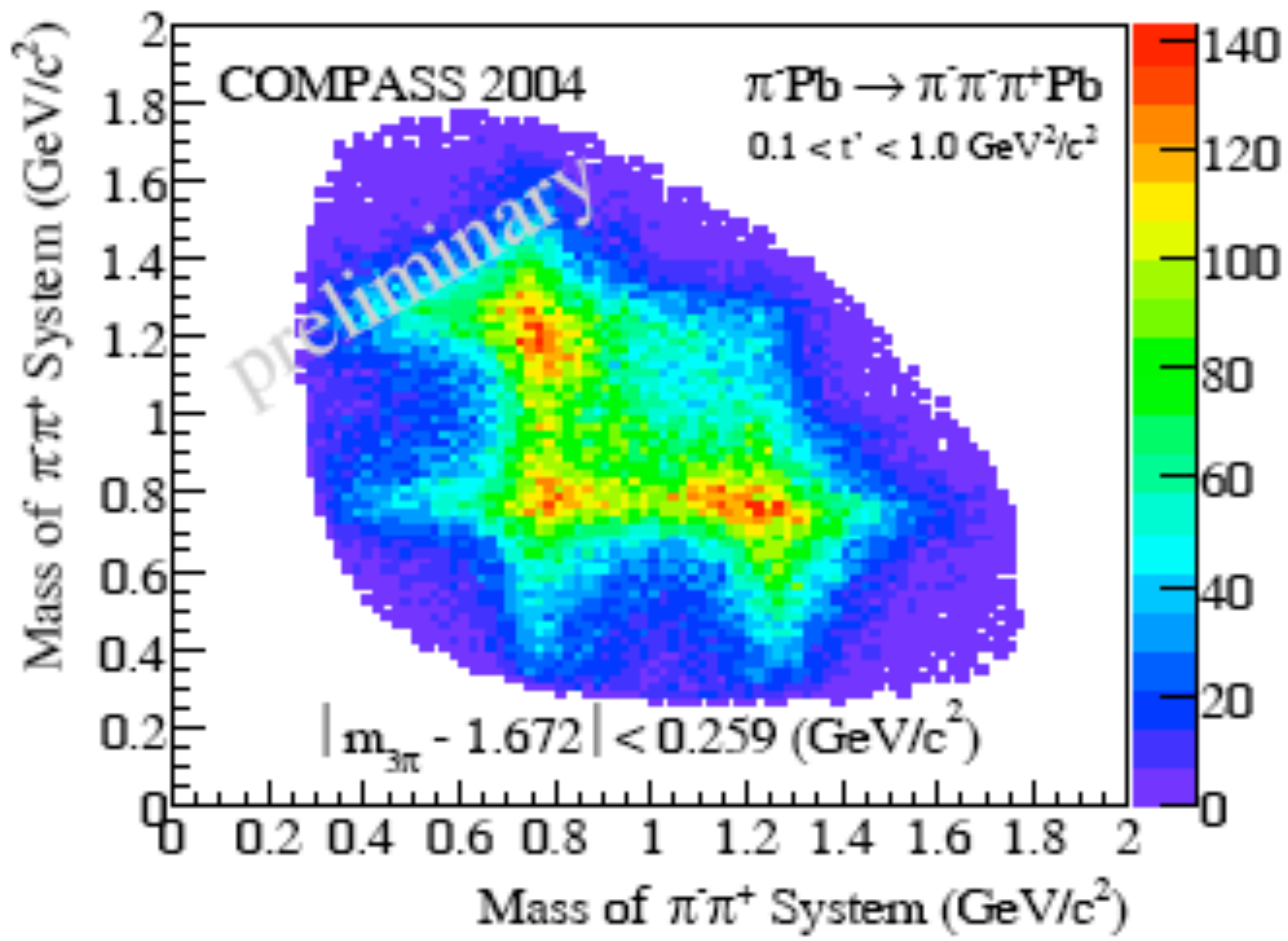

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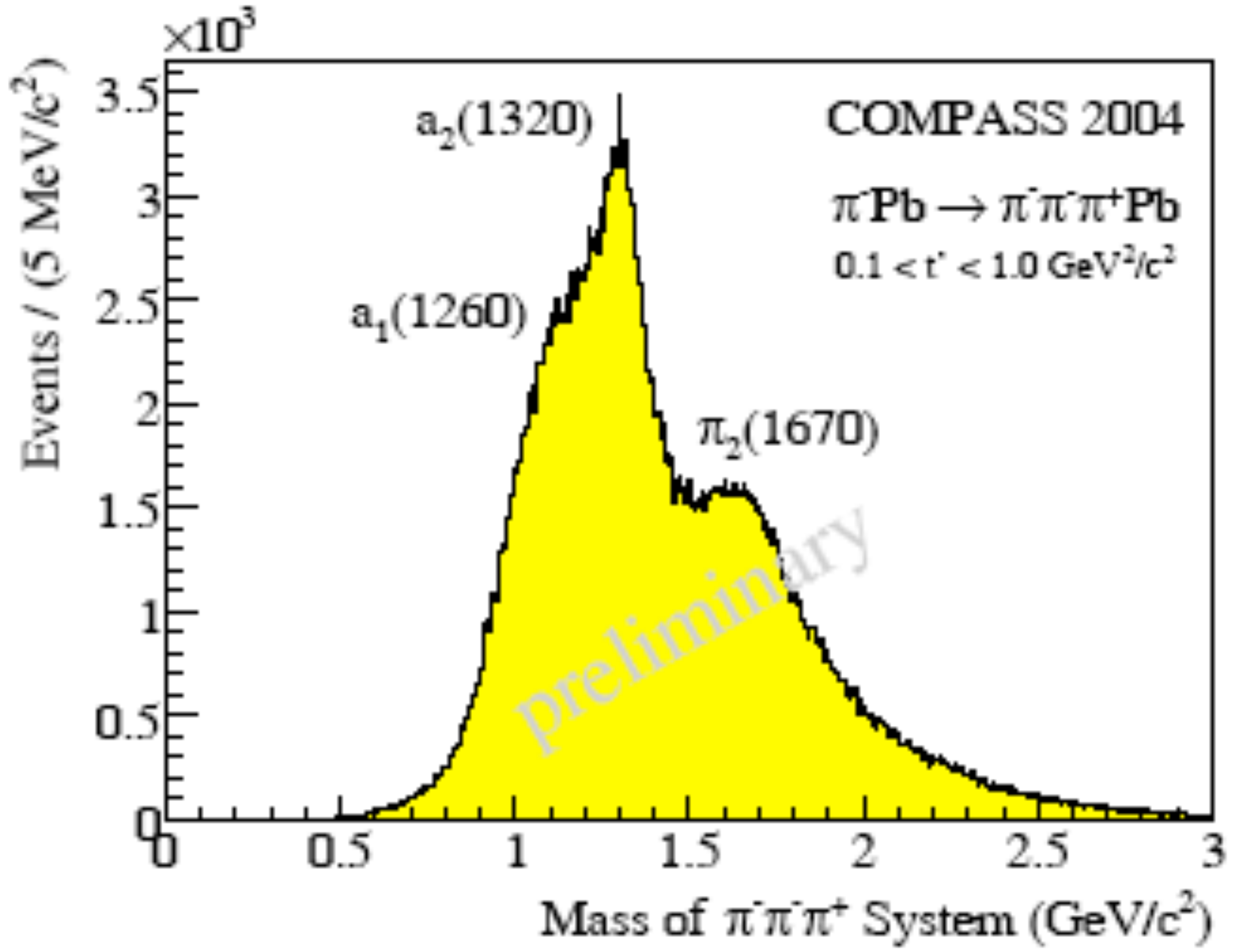

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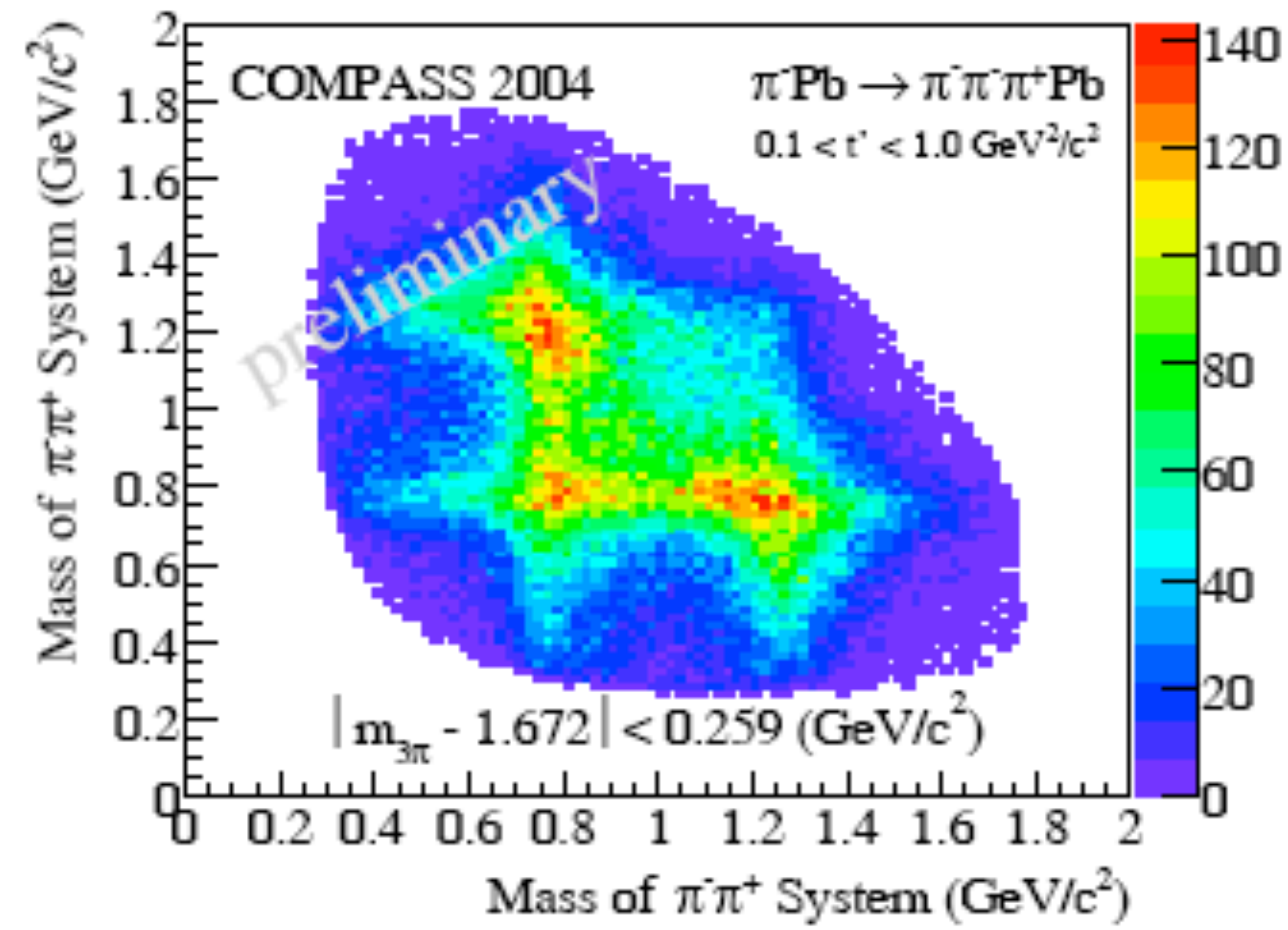

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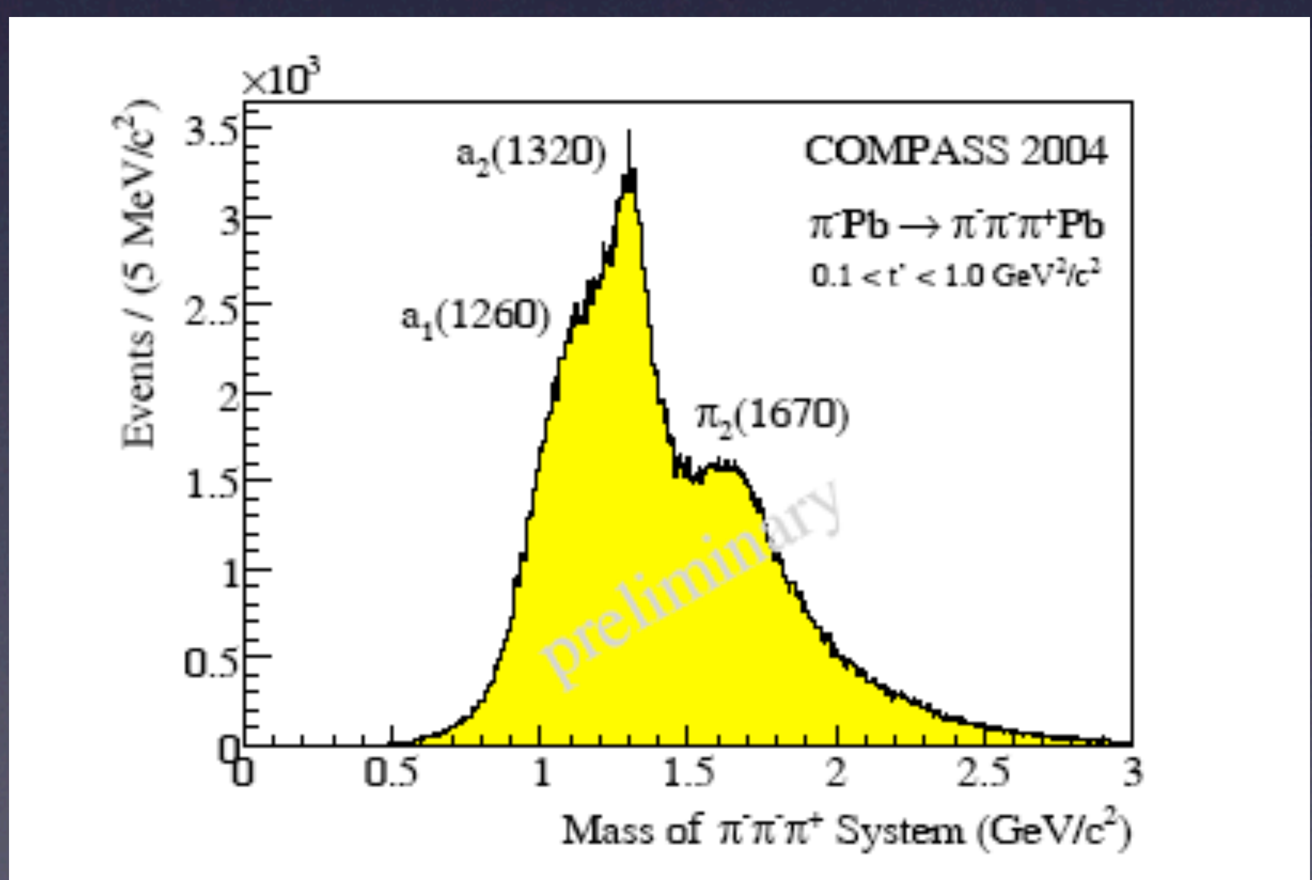
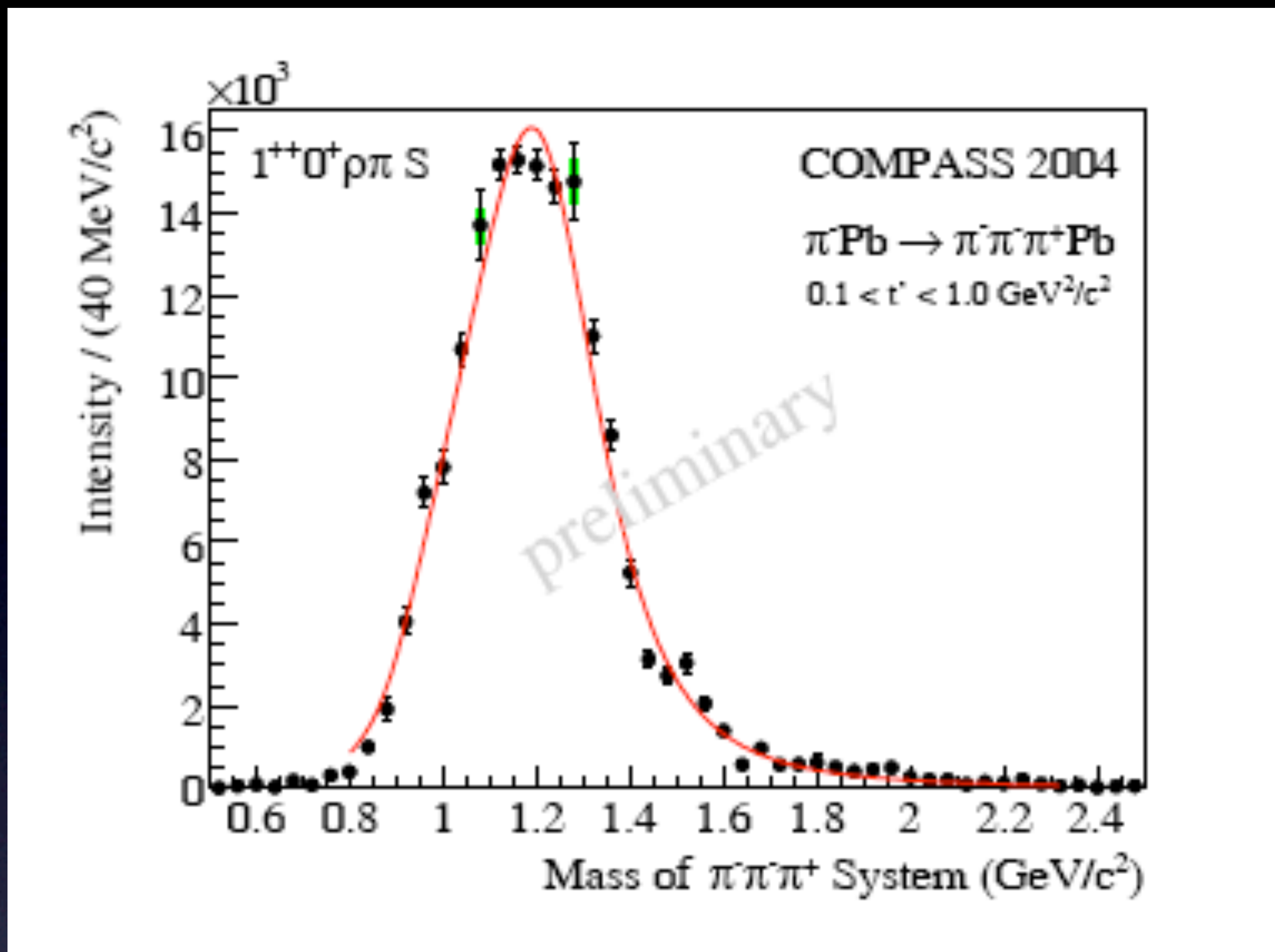
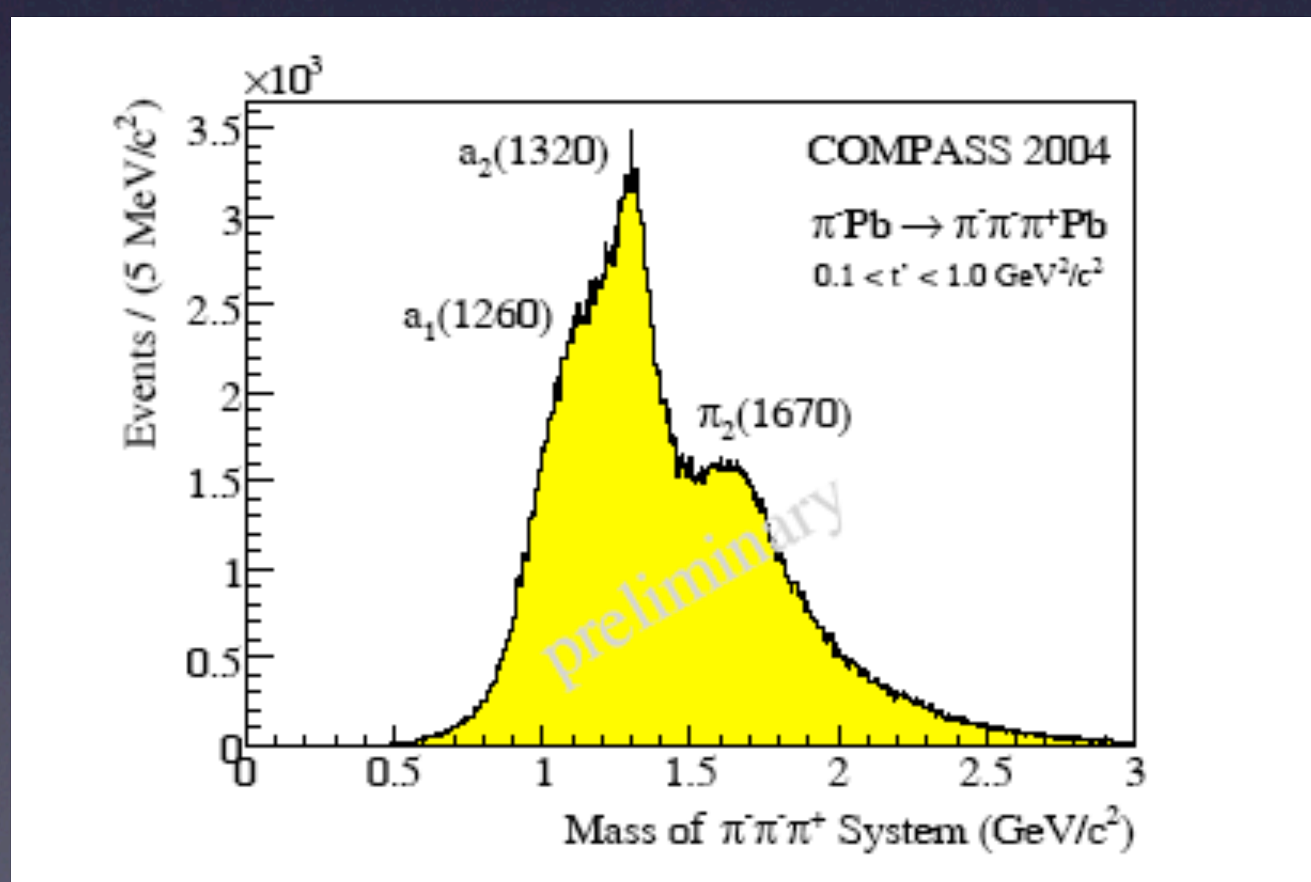
COMPASS: Major waves



COMPASS: Major waves





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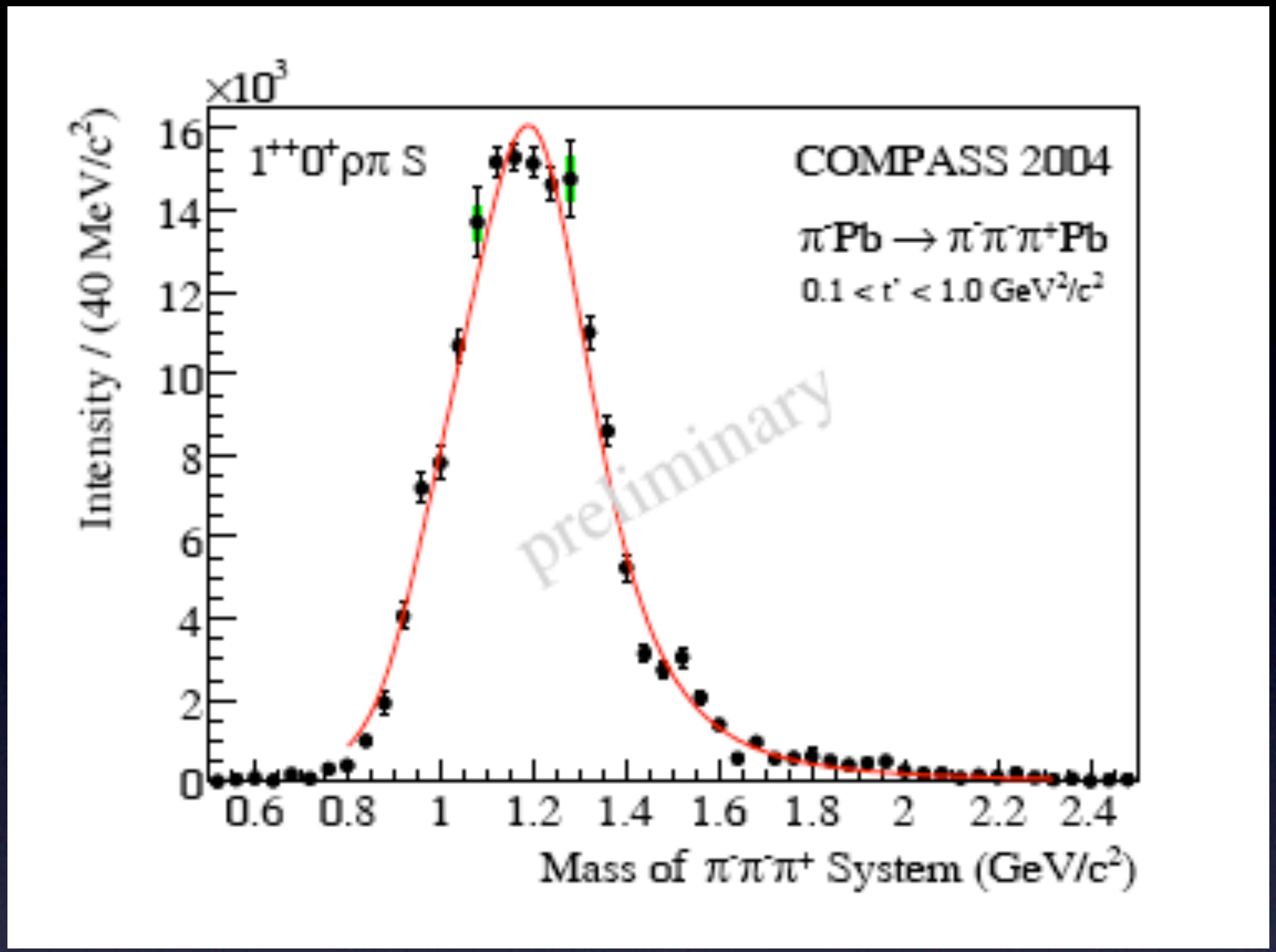
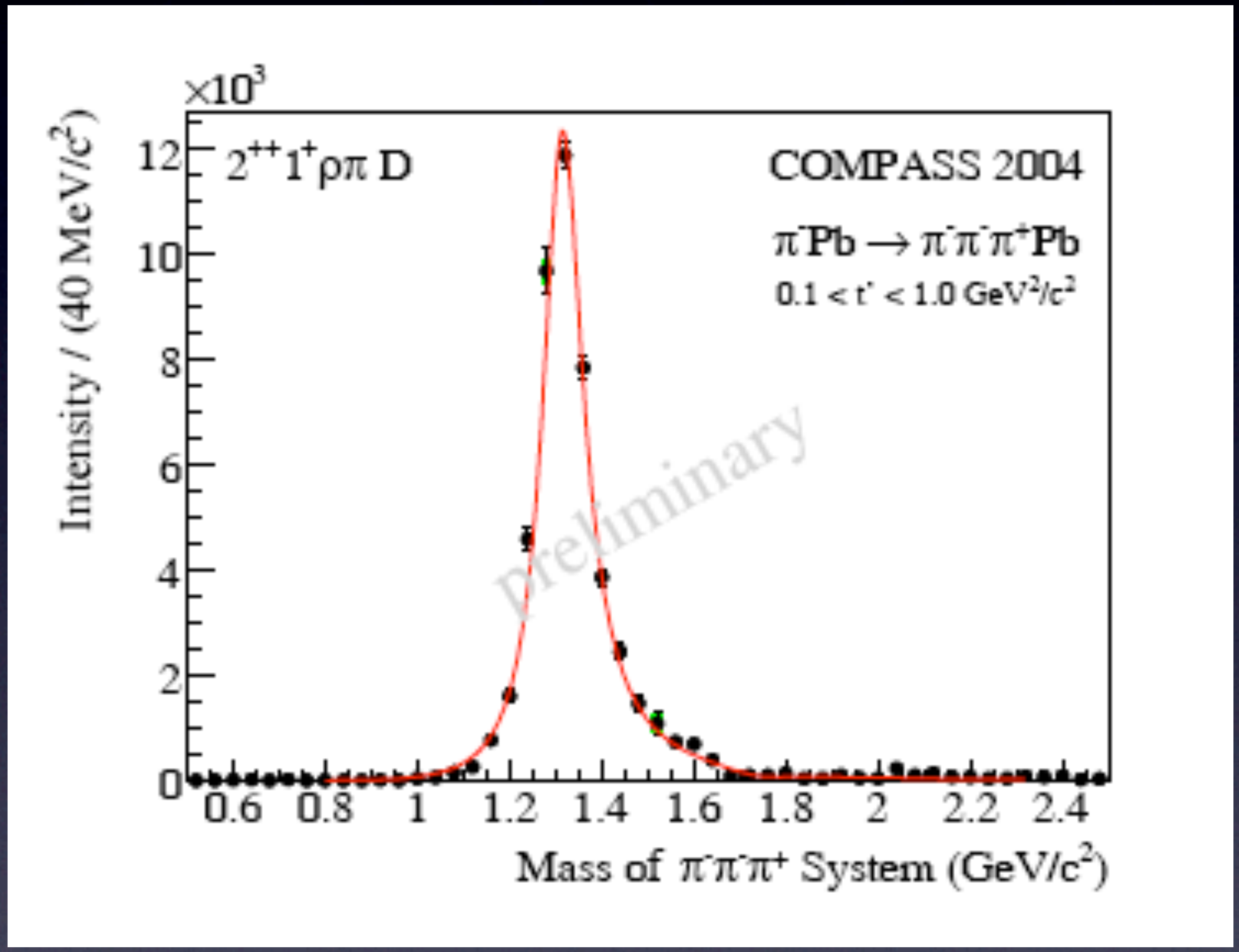
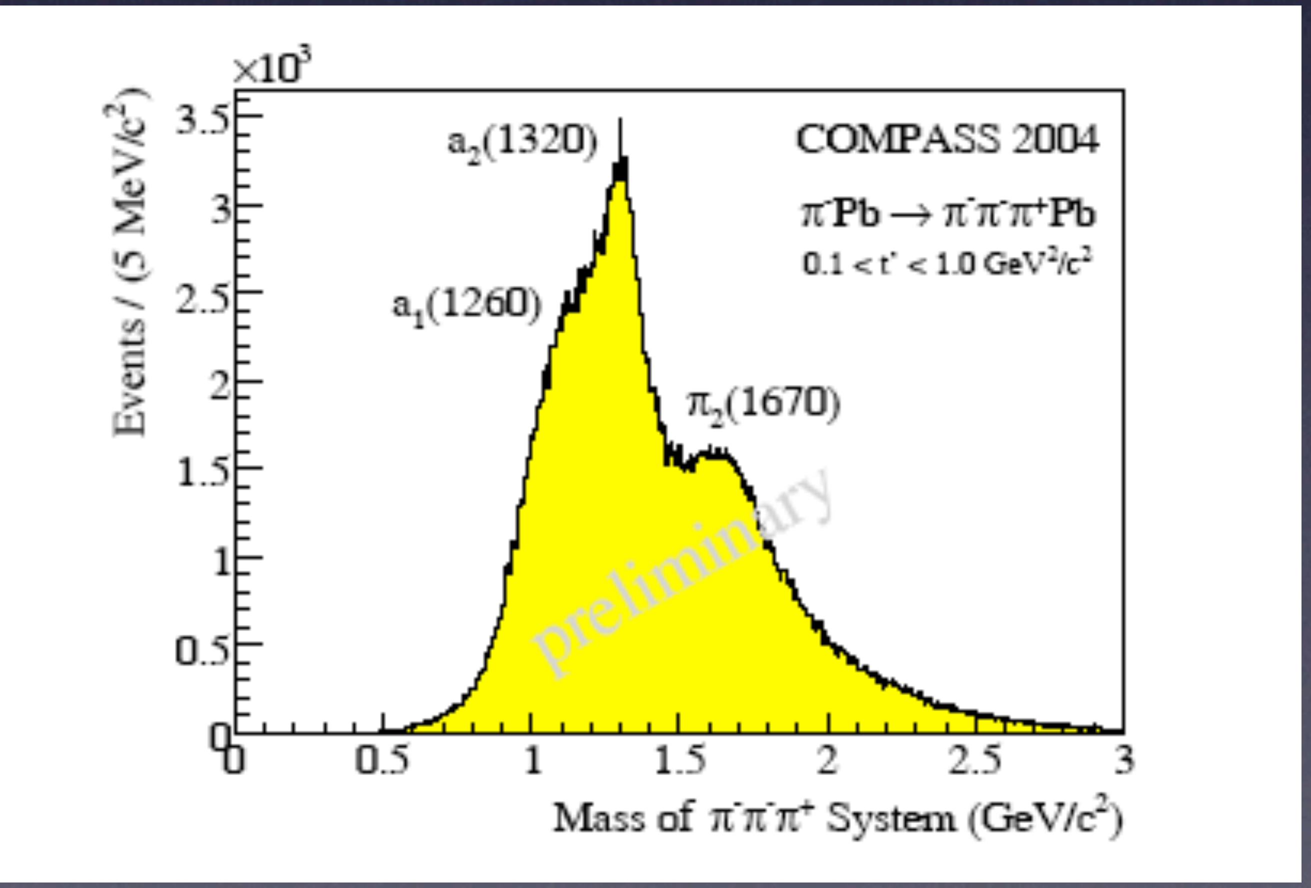
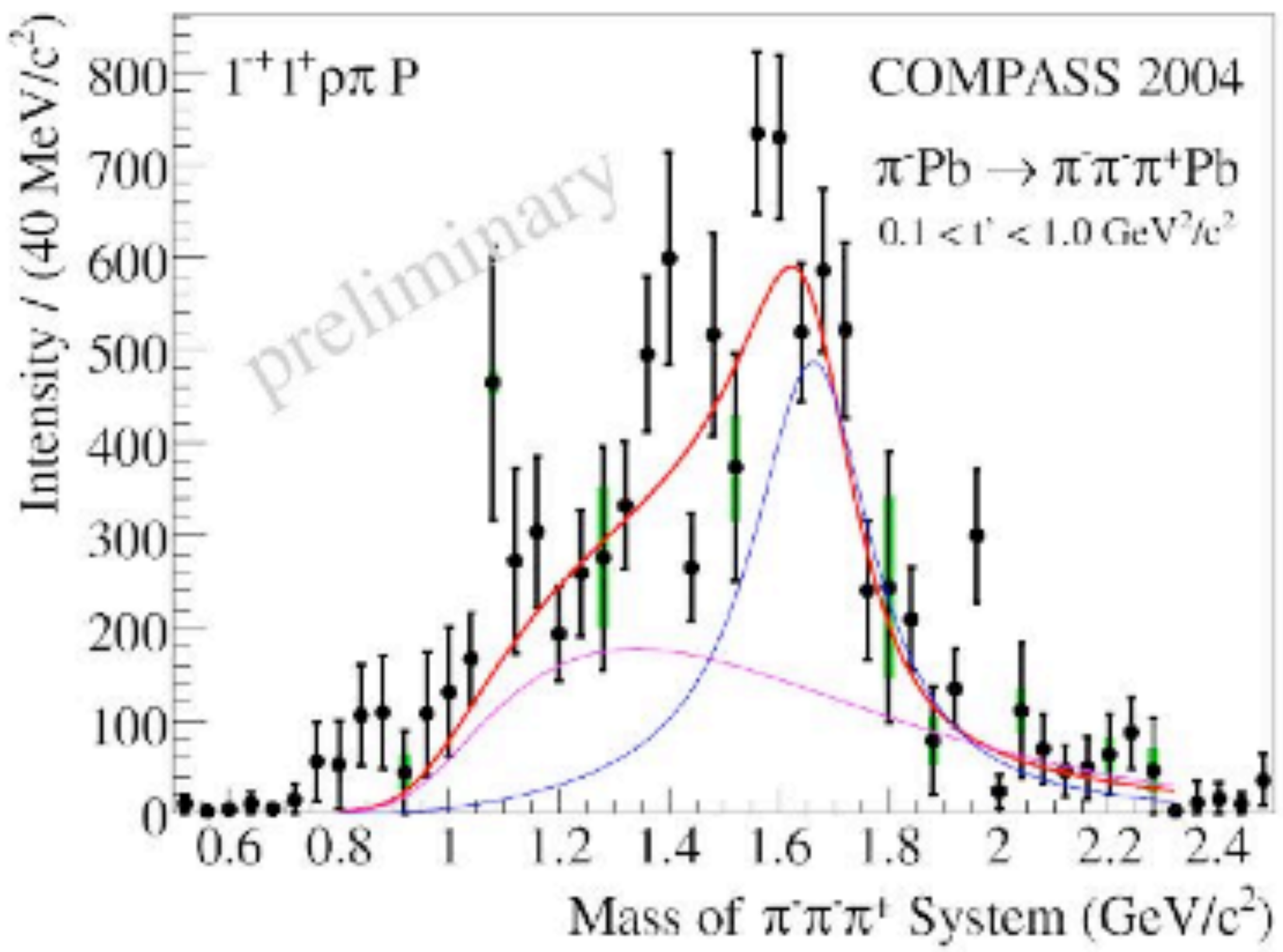
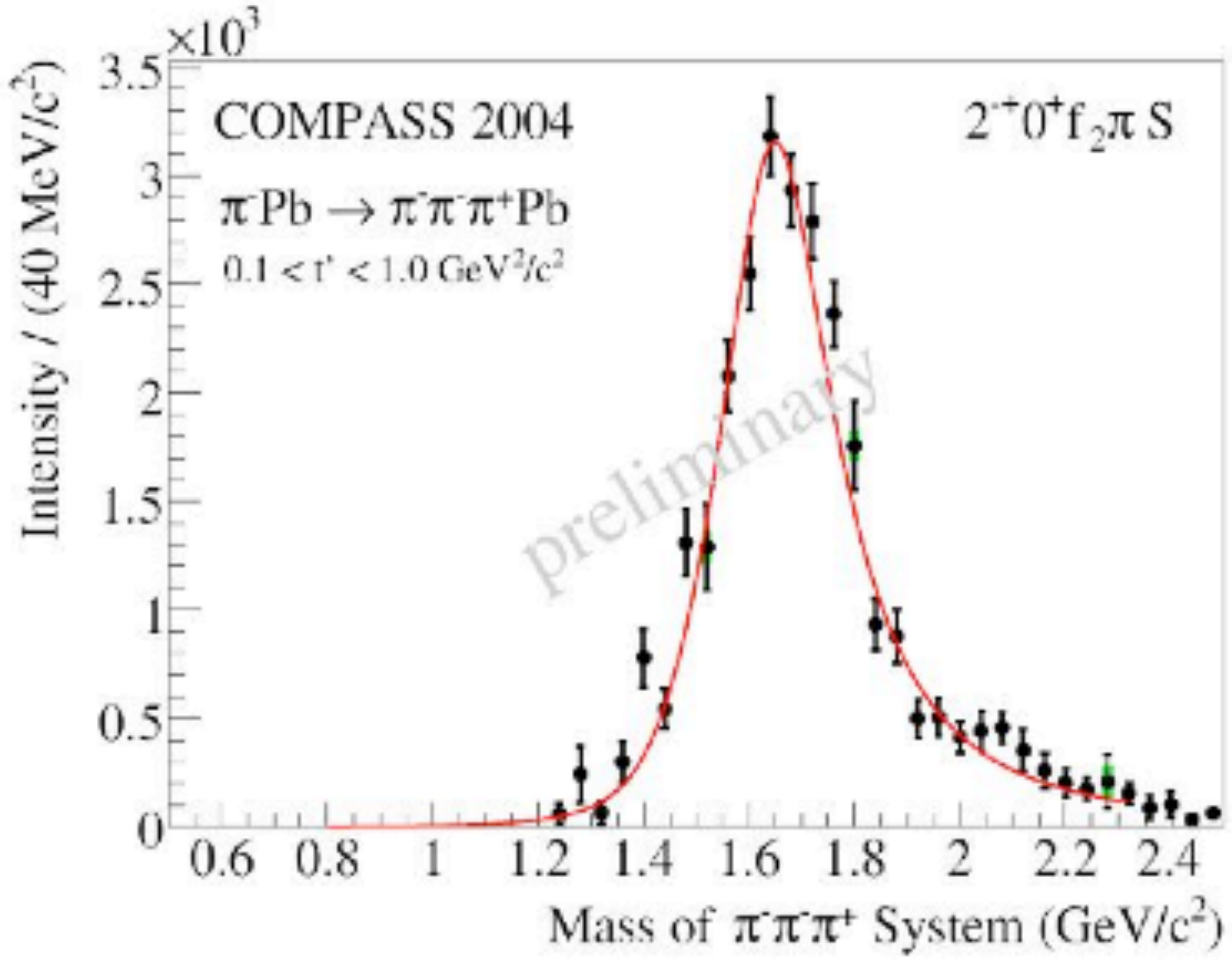


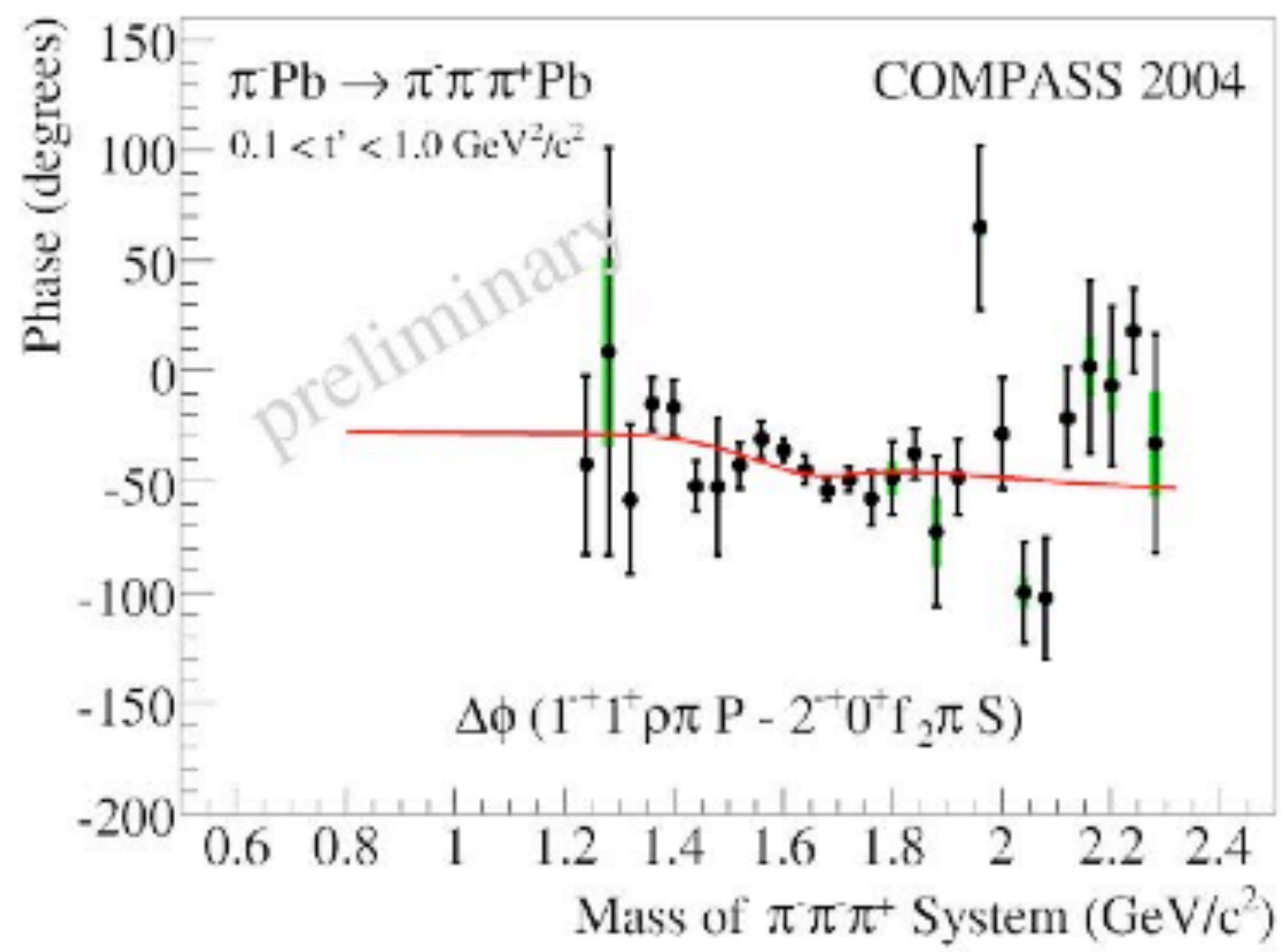


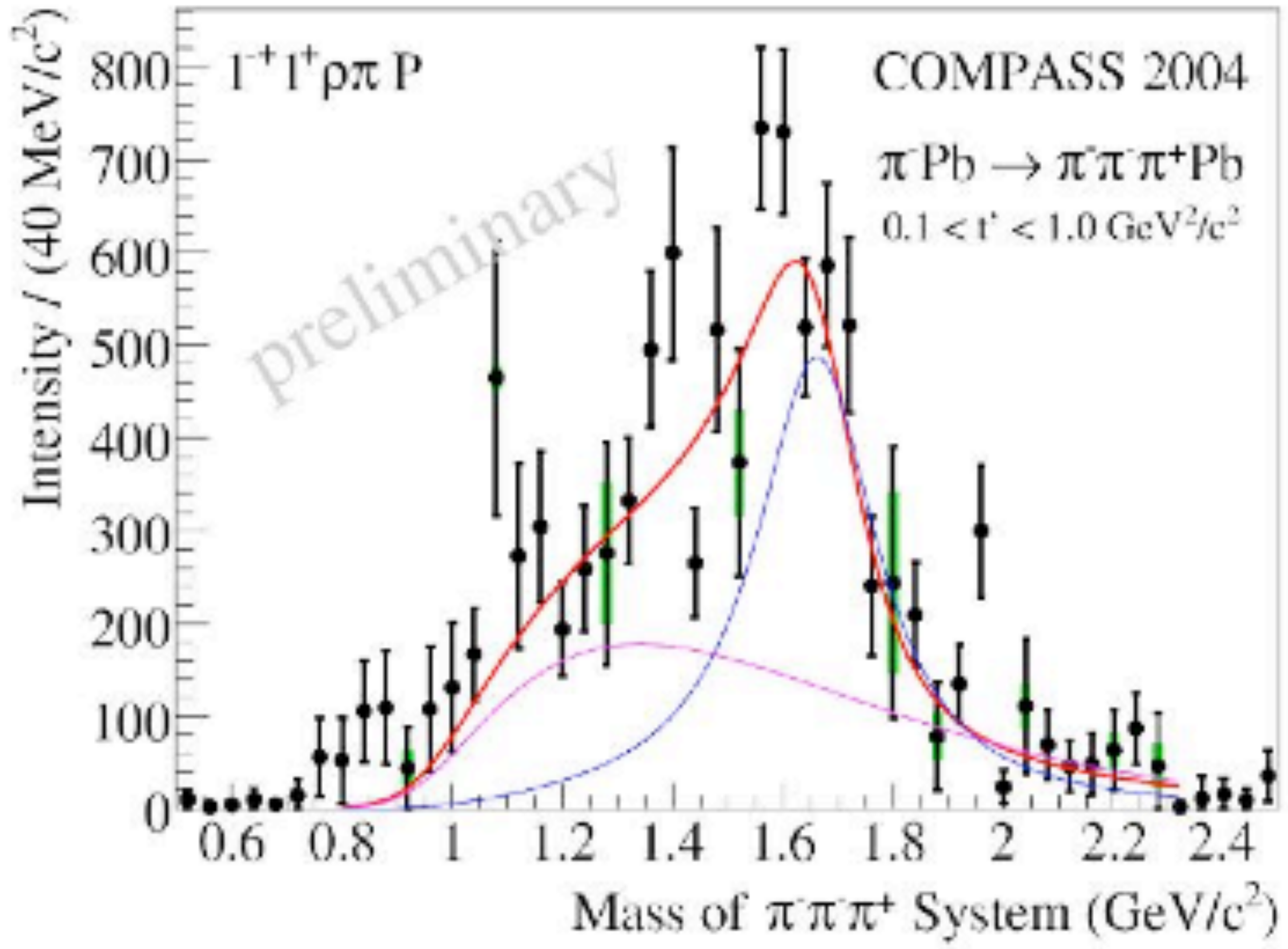



1⁺1⁺ρπ P
COMPASS 2004
π⁻Pb → π⁻π⁻π⁺Pb
0.1 < t' < 1.0 GeV²/c²
preliminary
Intensity / (40 MeV/c²)
Mass of π⁻π⁻π⁺ System (GeV/c²)

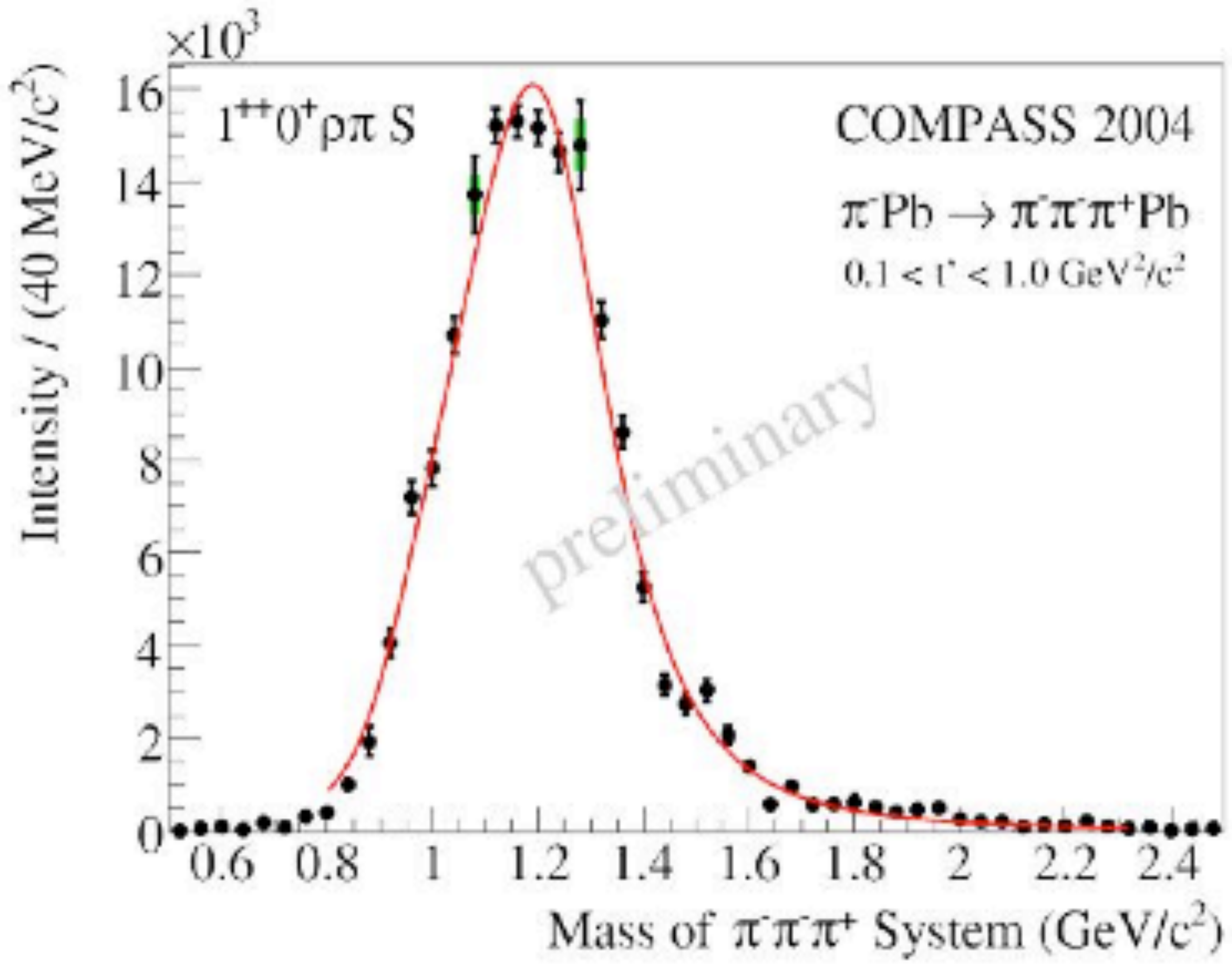
$J^{PC} = 1^{-+}$

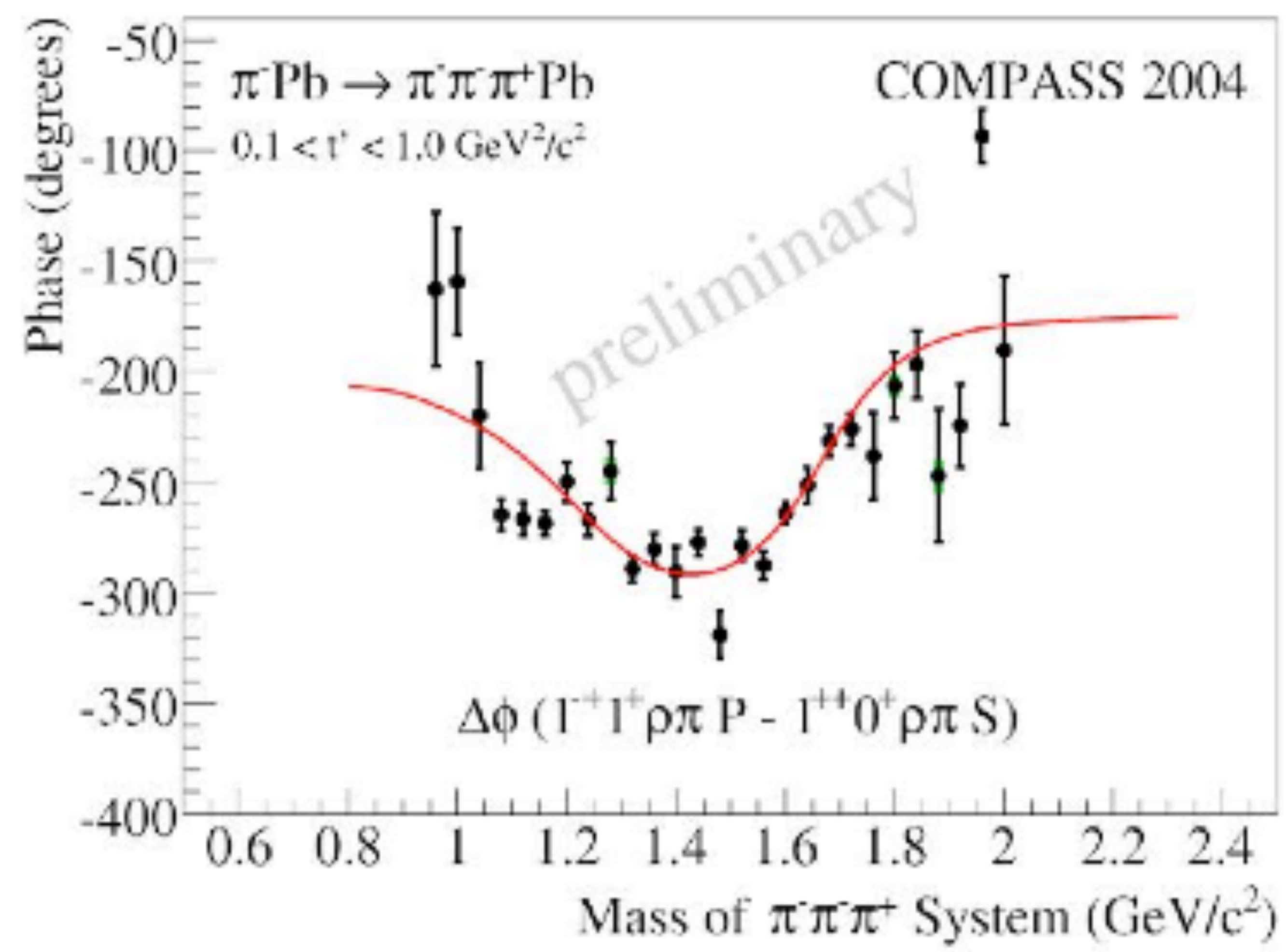

×10³
COMPASS 2004
2⁺0⁺f₂π S
π⁻Pb → π⁻π⁻π⁺Pb
0.1 < t' < 1.0 GeV²/c²
preliminary
Intensity / (40 MeV/c²)
Mass of π⁻π⁻π⁺ System (GeV/c²)


π⁻Pb → π⁻π⁻π⁺Pb
0.1 < t' < 1.0 GeV²/c²
COMPASS 2004
preliminary
Δφ (1⁺1⁺ρπ P - 2⁺0⁺f₂π S)
Phase (degrees)
Mass of π⁻π⁻π⁺ System (GeV/c²)

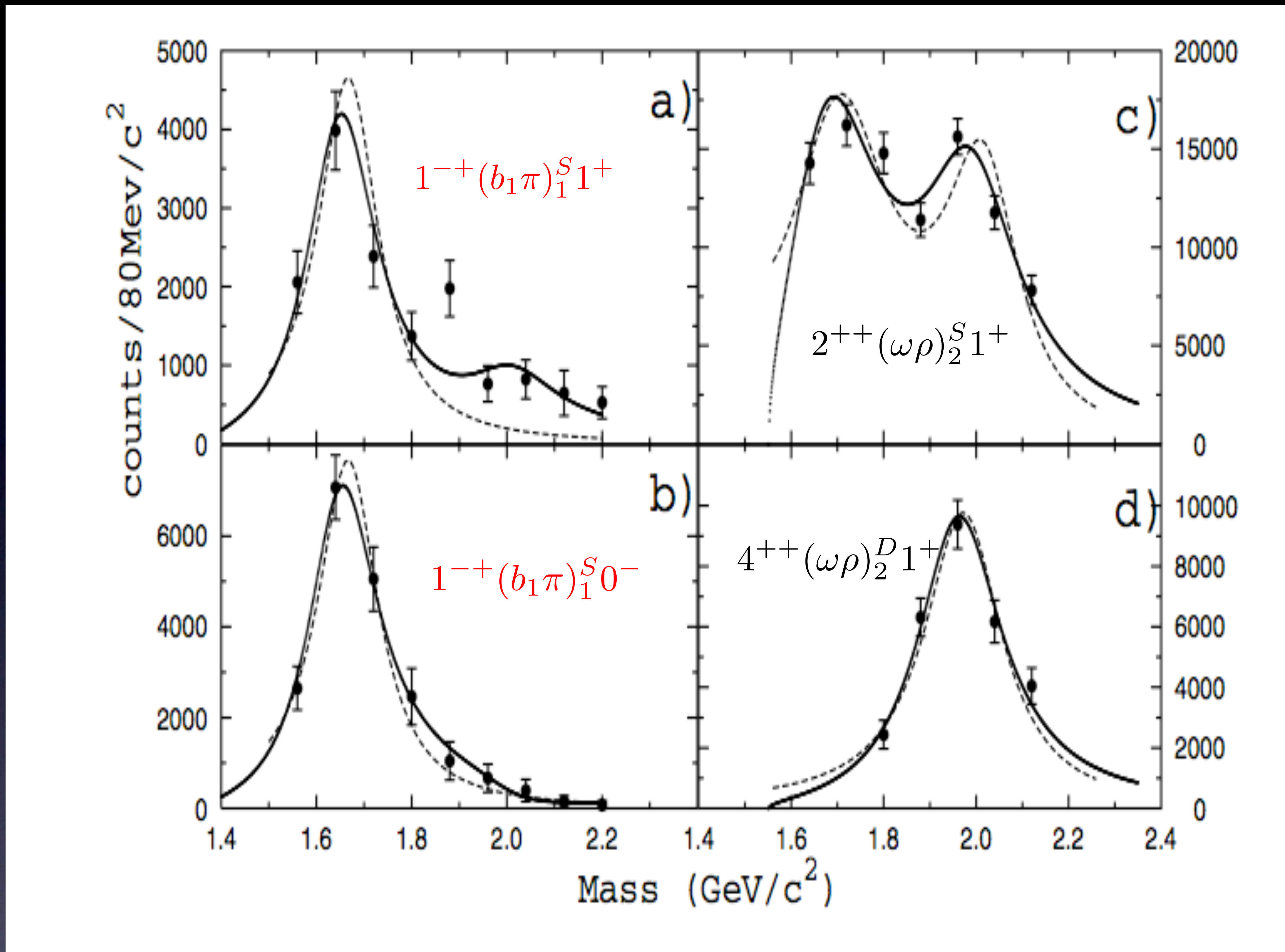


- BW parameters for $\pi_1(1600)$
  $M = \left(1660 \pm 10^{+0}_{-64}\right)\mathrm{MeV}/c^2$
  $\Gamma = \left(269 \pm 21^{+42}_{-64}\right)\mathrm{MeV}/c^2$
- Leakage negligible: $< 5\%$



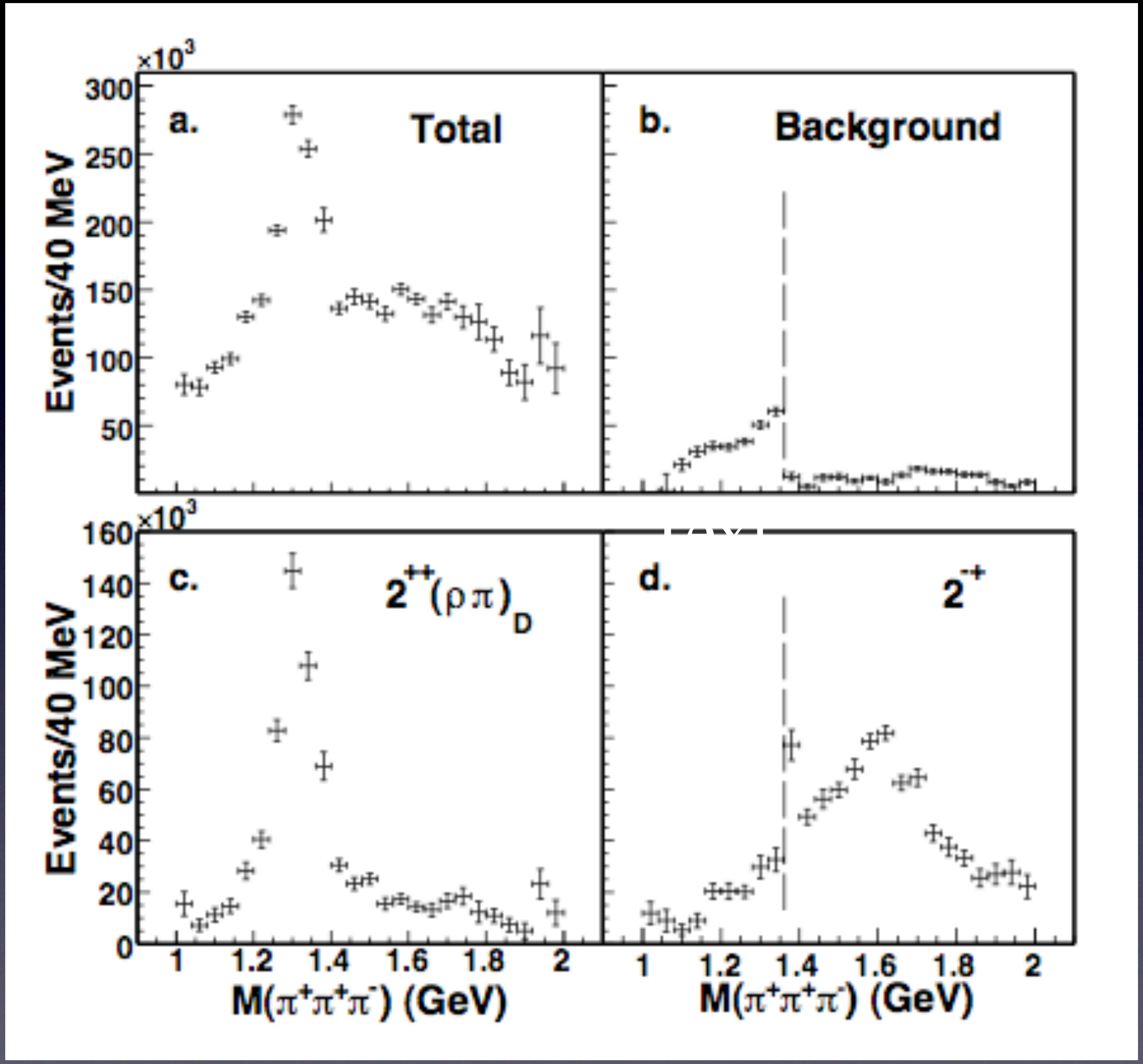


E852 $\pi^- p \to \omega\pi^-\pi^0 p$

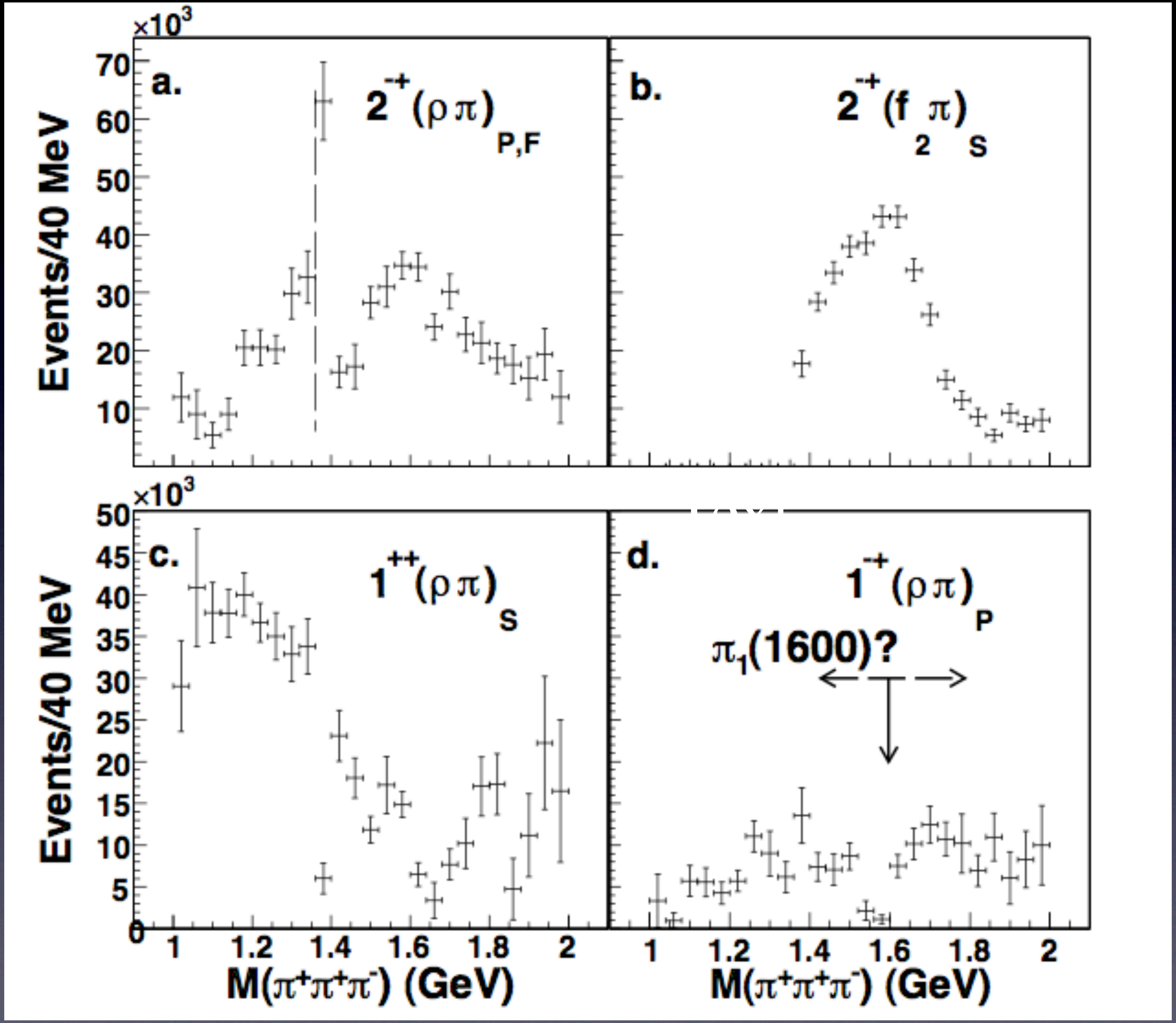


Resonance	Decay	Mass (MeV/c^2)	Width (MeV/c^2)
$a_4(2040)$	$(\omega\rho)_2^D$	$1985 \pm 10 \pm 13$	$231 \pm 30 \pm 46$
$a_2(1700)$	$(\omega\rho)_2^S$	$1721 \pm 13 \pm 44$	$279 \pm 49 \pm 66$
$a_2(2000)$	$(\omega\rho)_2^S$	$2003 \pm 10 \pm 19$	$249 \pm 23 \pm 32$
$\pi_1(1600)$	$(b_1\pi)_1^S$	$1664 \pm 8 \pm 10$	$185 \pm 25 \pm 28$
$\pi_1(2000)$	$(b_1\pi)_1^S$	$2014 \pm 20 \pm 16$	$230 \pm 32 \pm 73$
$\pi_2(1670)$	$(\omega\rho)_{1,2}^P$	$1749 \pm 10 \pm 100$	$408 \pm 60 \pm 250$
$\pi_2(1880)$	$(\omega\rho)_{1,2}^P$	$1876 \pm 11 \pm 67$	$146 \pm 17 \pm 62$
$\pi_2(1970)$	$(\omega\rho)_{1,2}^P$	$1974 \pm 14 \pm 83$	$341 \pm 61 \pm 139$

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



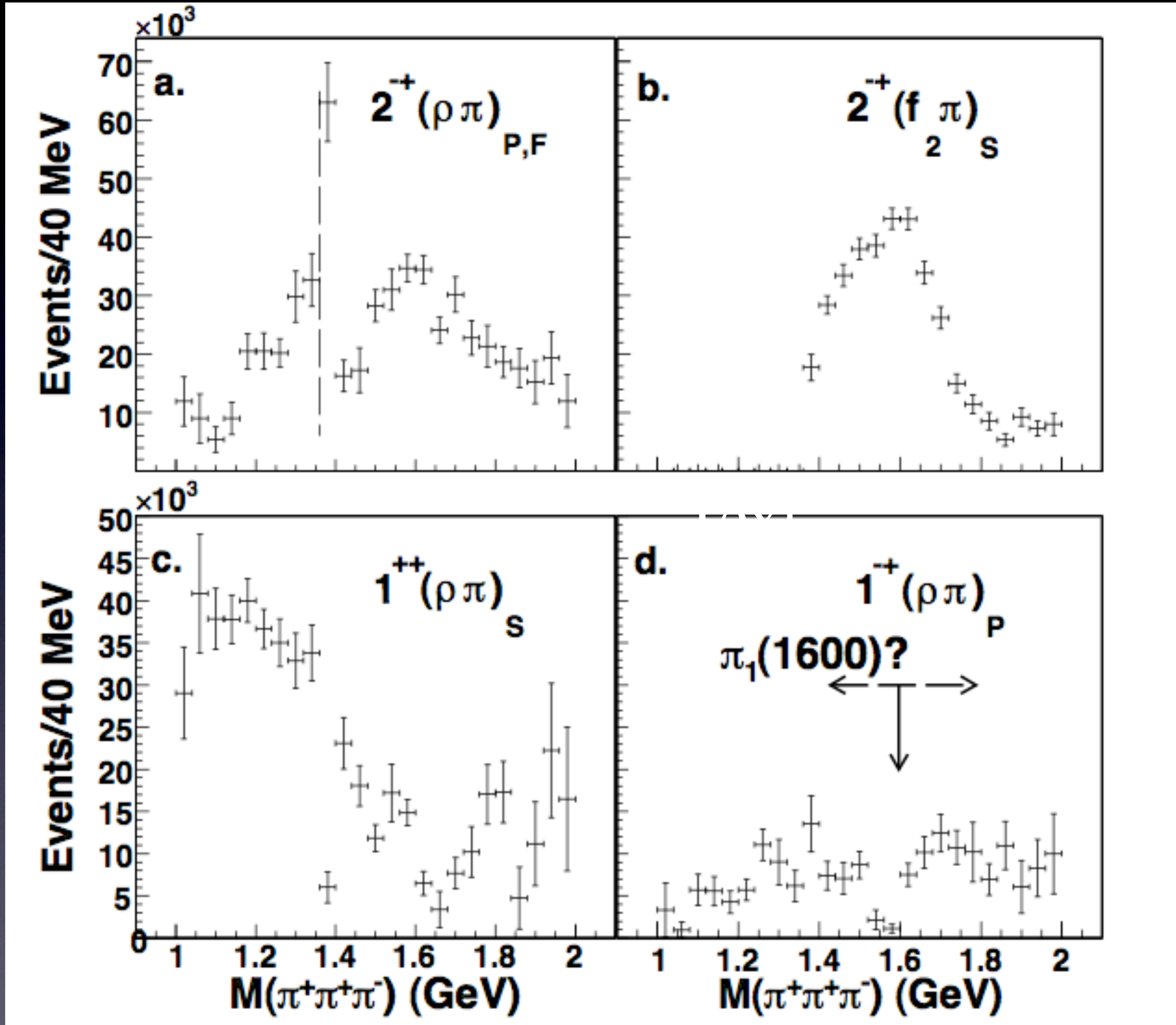
g6c: Major waves $\gamma p \to \pi^+\pi^+\pi^-(n)$



Monday, June 14, 2010

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

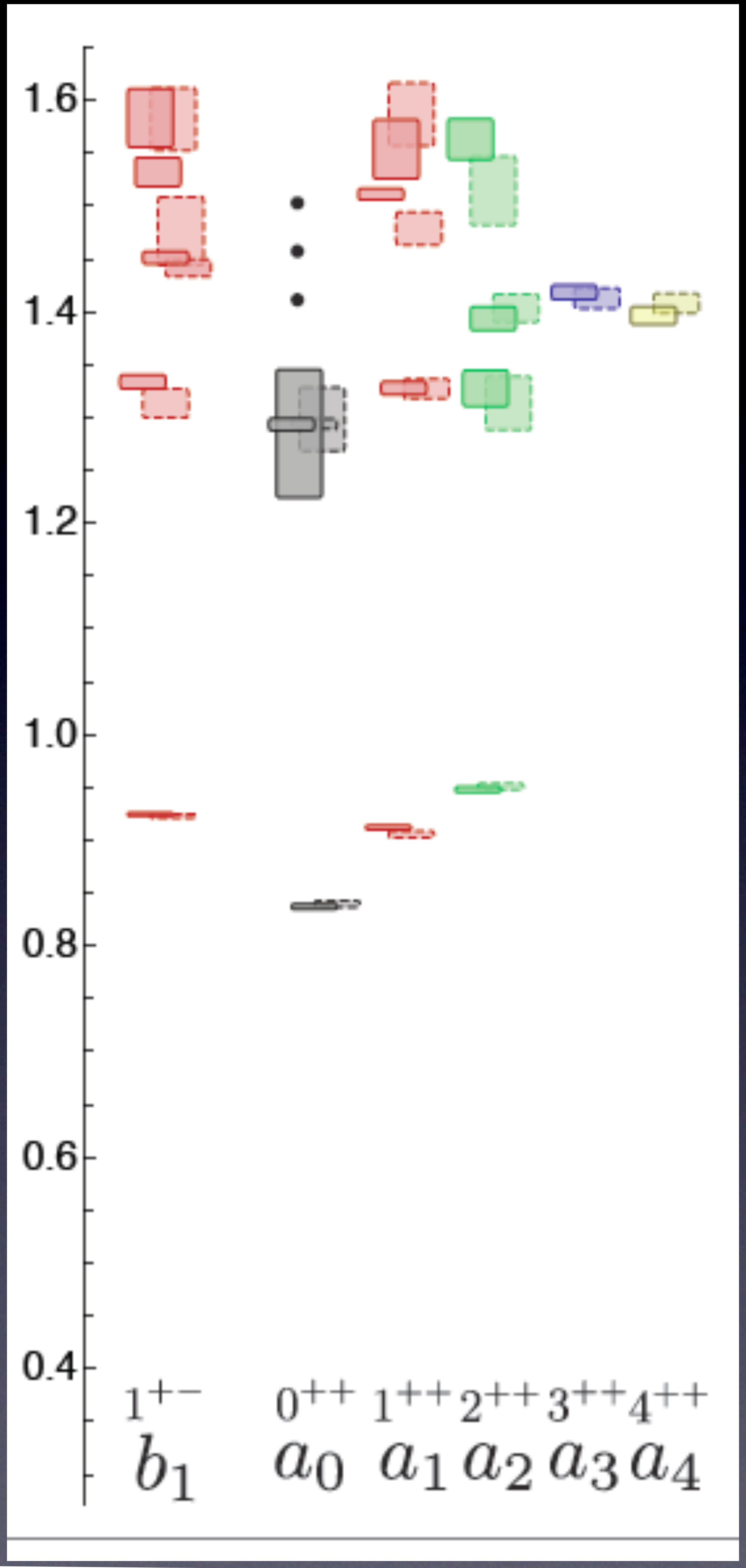
$\sigma_{\pi_1} < 13.5\ \text{nb}$



(<2% of a_2)

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

a4(2040)



$a_4(2040)$

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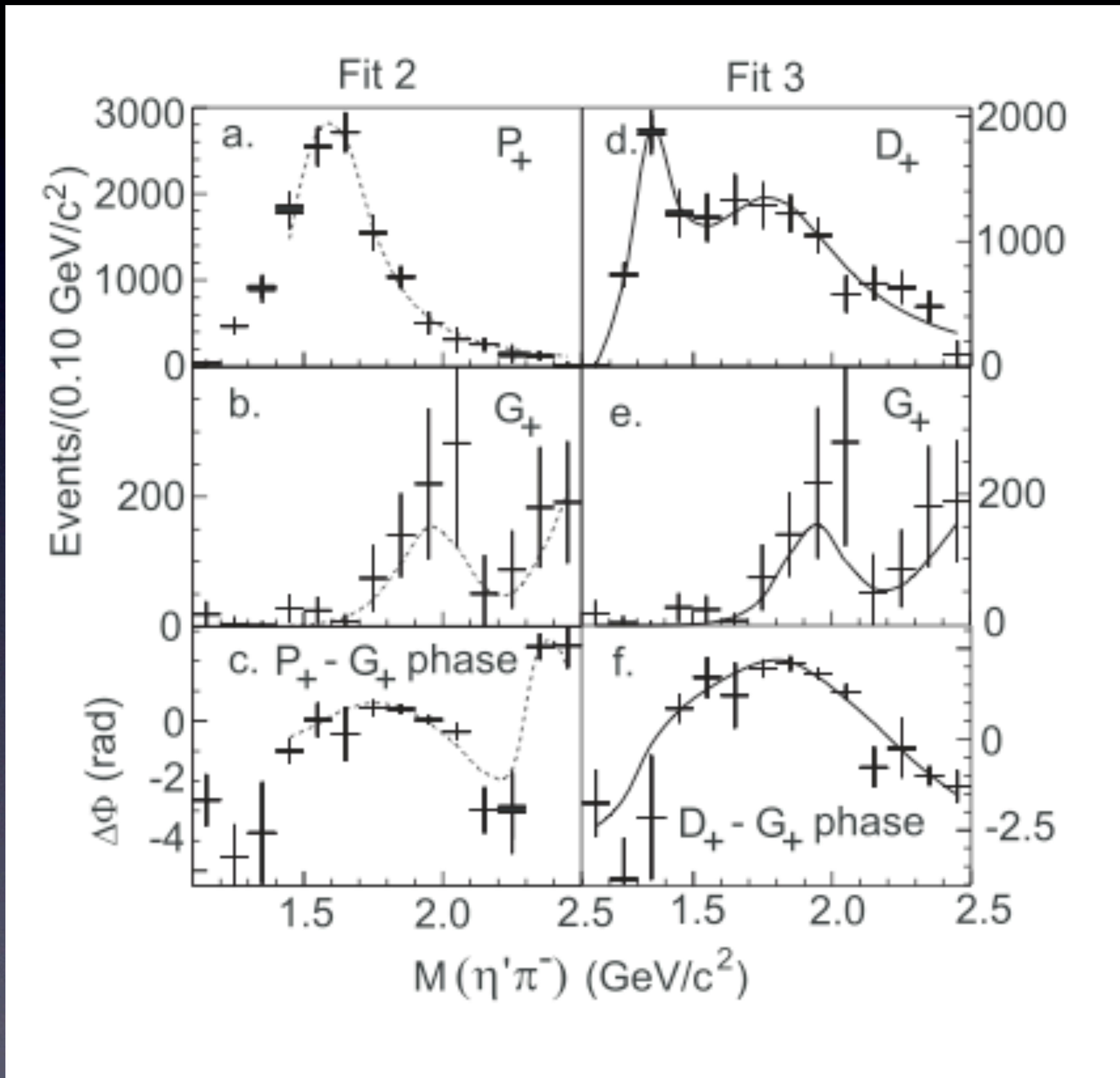
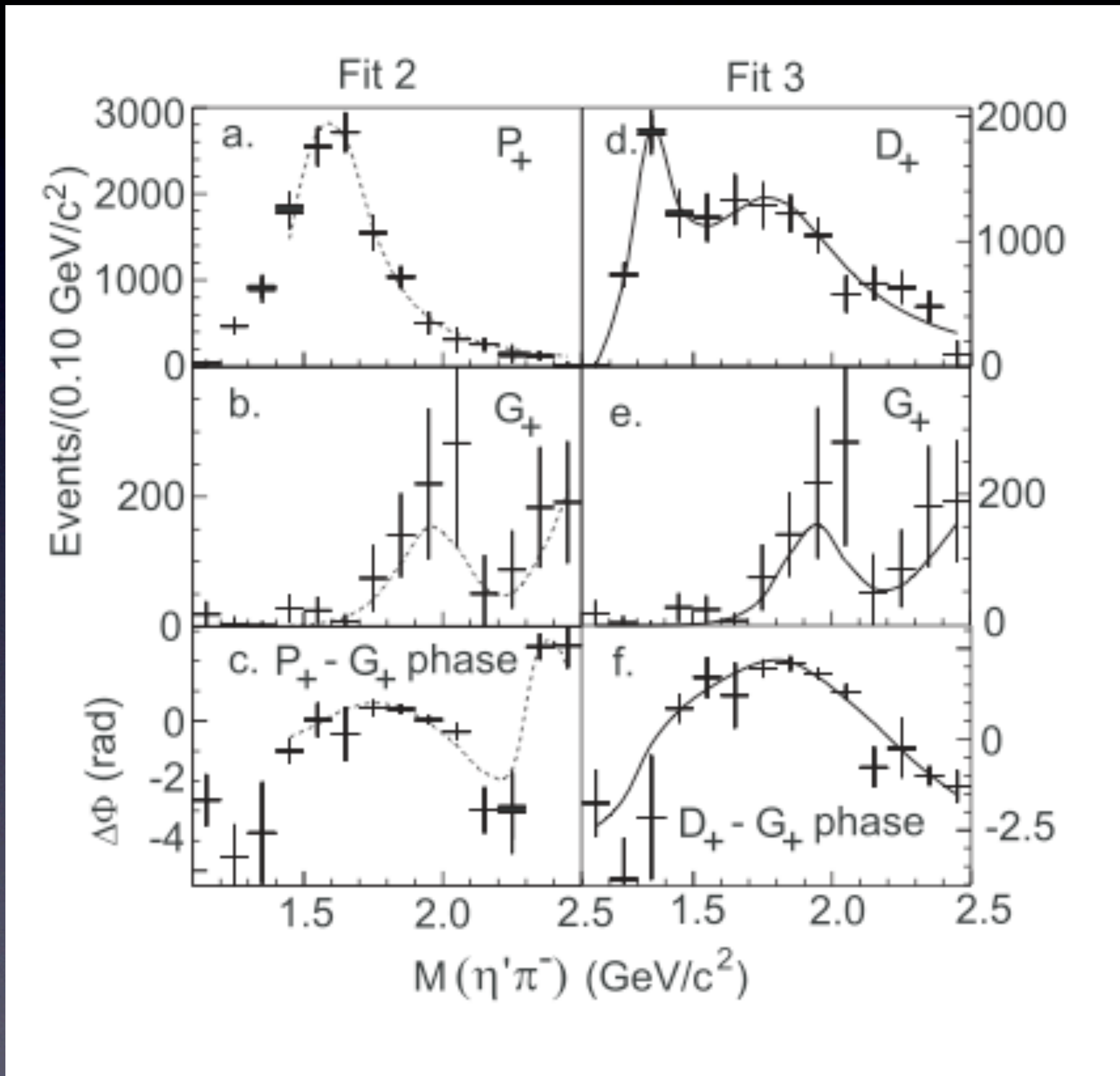
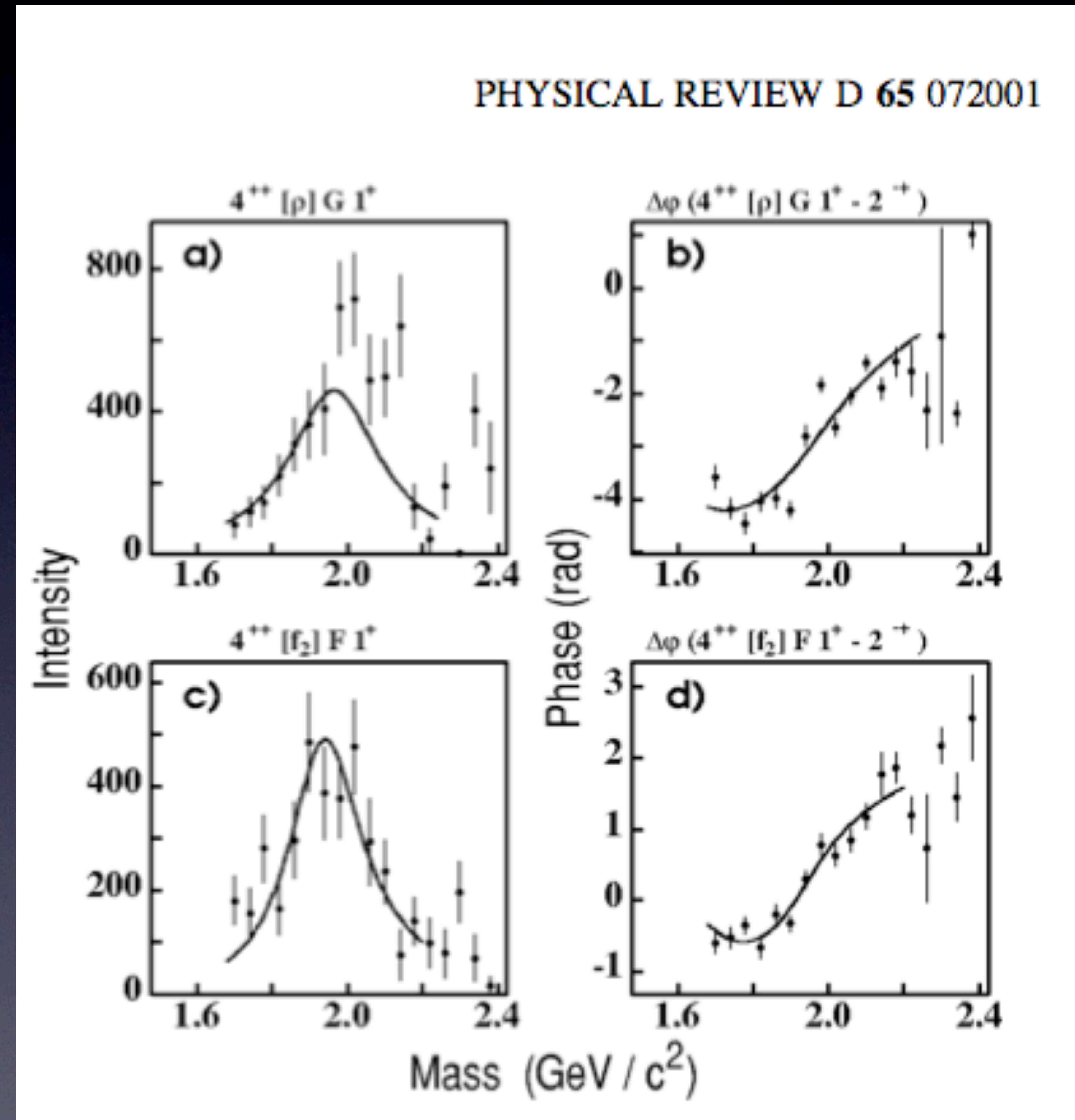


Fit 2
Fit 3
a.
P_+
d.
D_+
b.
G_+
e.
G_+
c. P_+ - G_+ phase
f.
D_+ - G_+ phase
Events/(0.10 GeV/c^2)
$\Delta\Phi$ (rad)
M ($\eta'\pi^-$) (GeV/c^2)

a₄(2040)



Fit 2
Fit 3
a.
P+
d.
D+
b.
G+
e.
G+
c. P+ - G+ phase
f.
D+ - G+ phase
Events/(0.10 GeV/c²)
ΔΦ (rad)
M (η'π⁻) (GeV/c²)



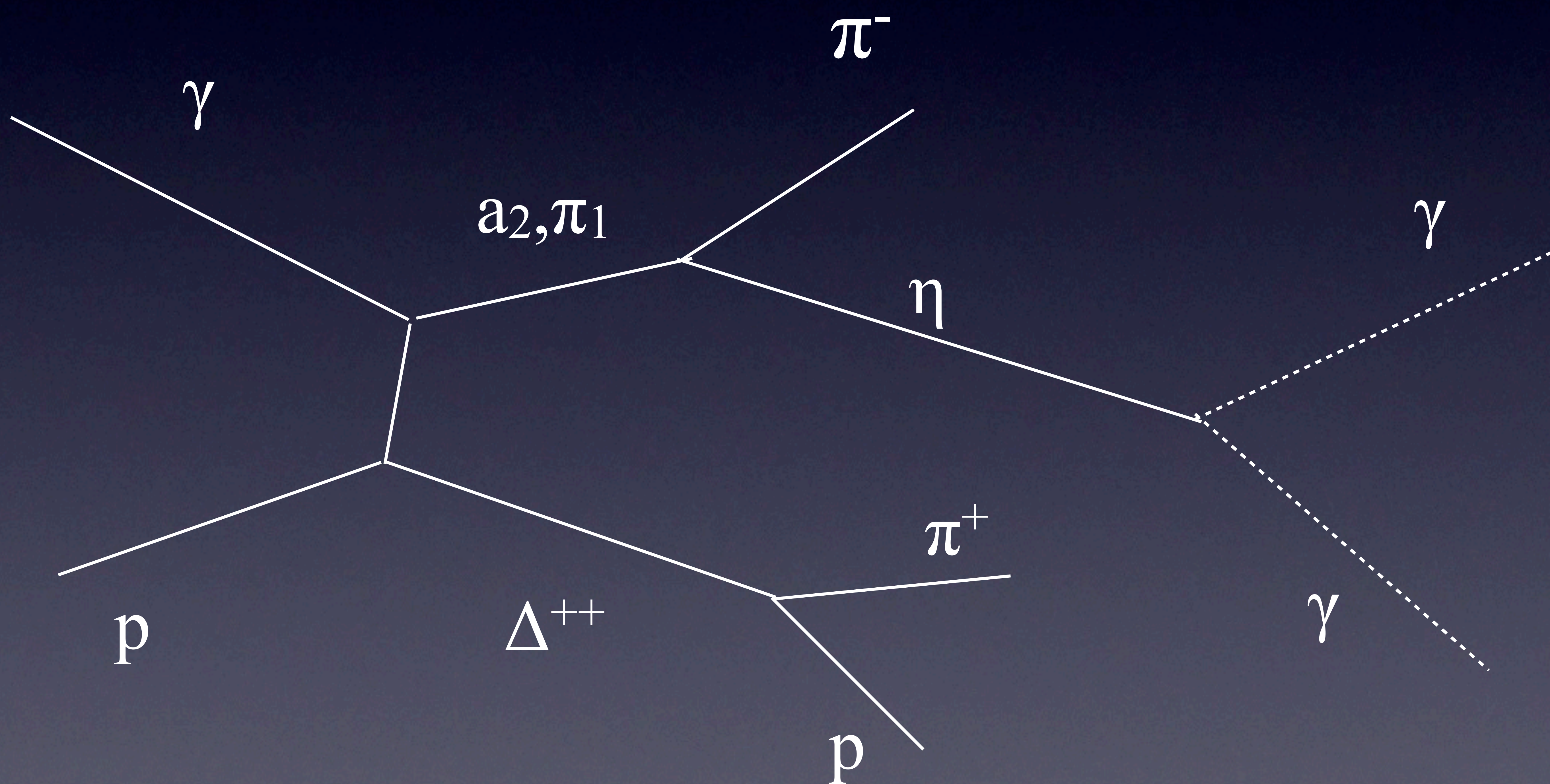
PHYSICAL REVIEW D 65 072001
a)
b)
c)
d)
Intensity
Phase (rad)
Mass (GeV / c²)

High Energy (> 4.4 GeV) Luminosity: 27 pb^{-1}

g12

$$\gamma p \rightarrow \eta\pi^-\Delta^{++}$$

~10 X g_{6c} raw luminosity



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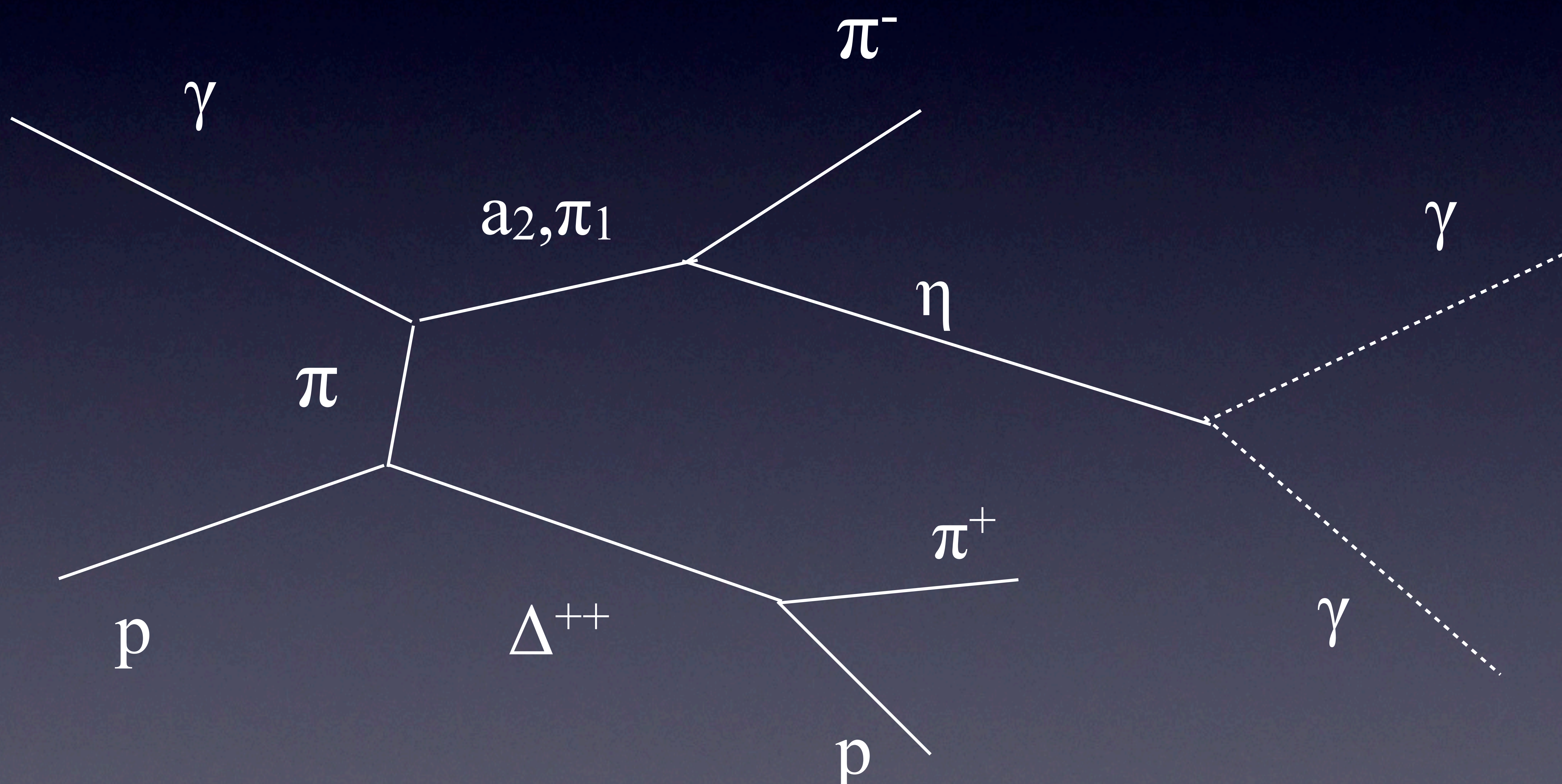
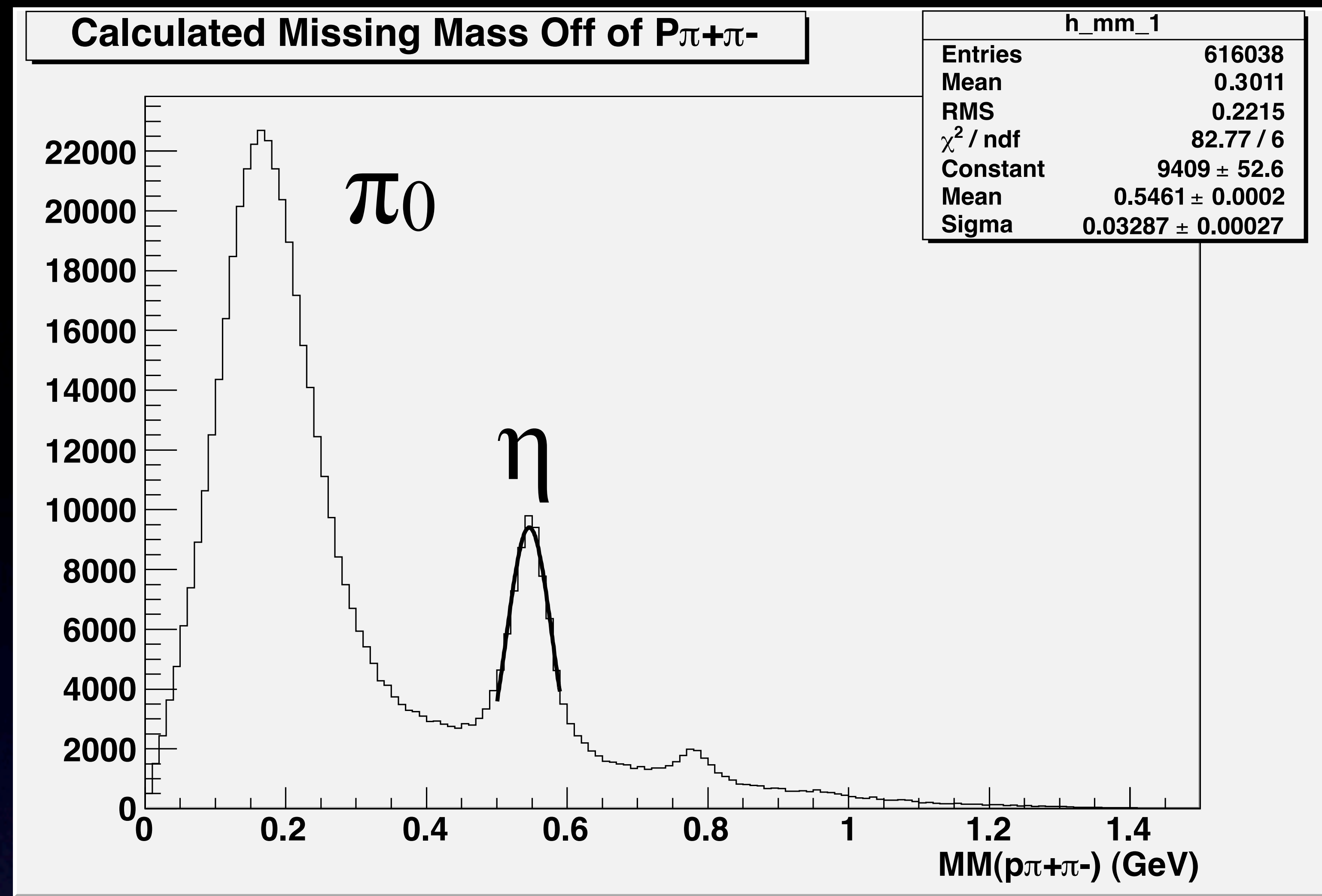
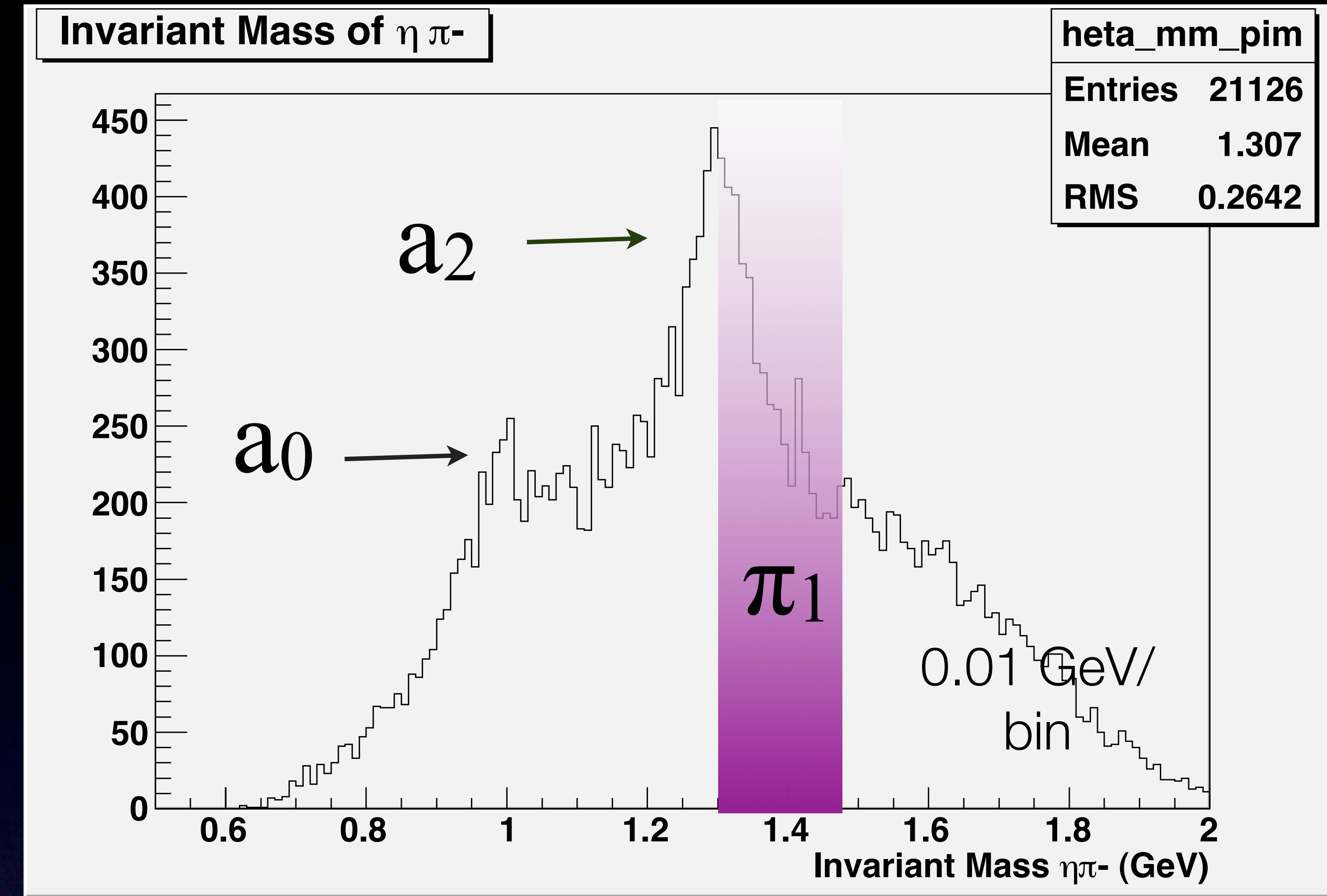


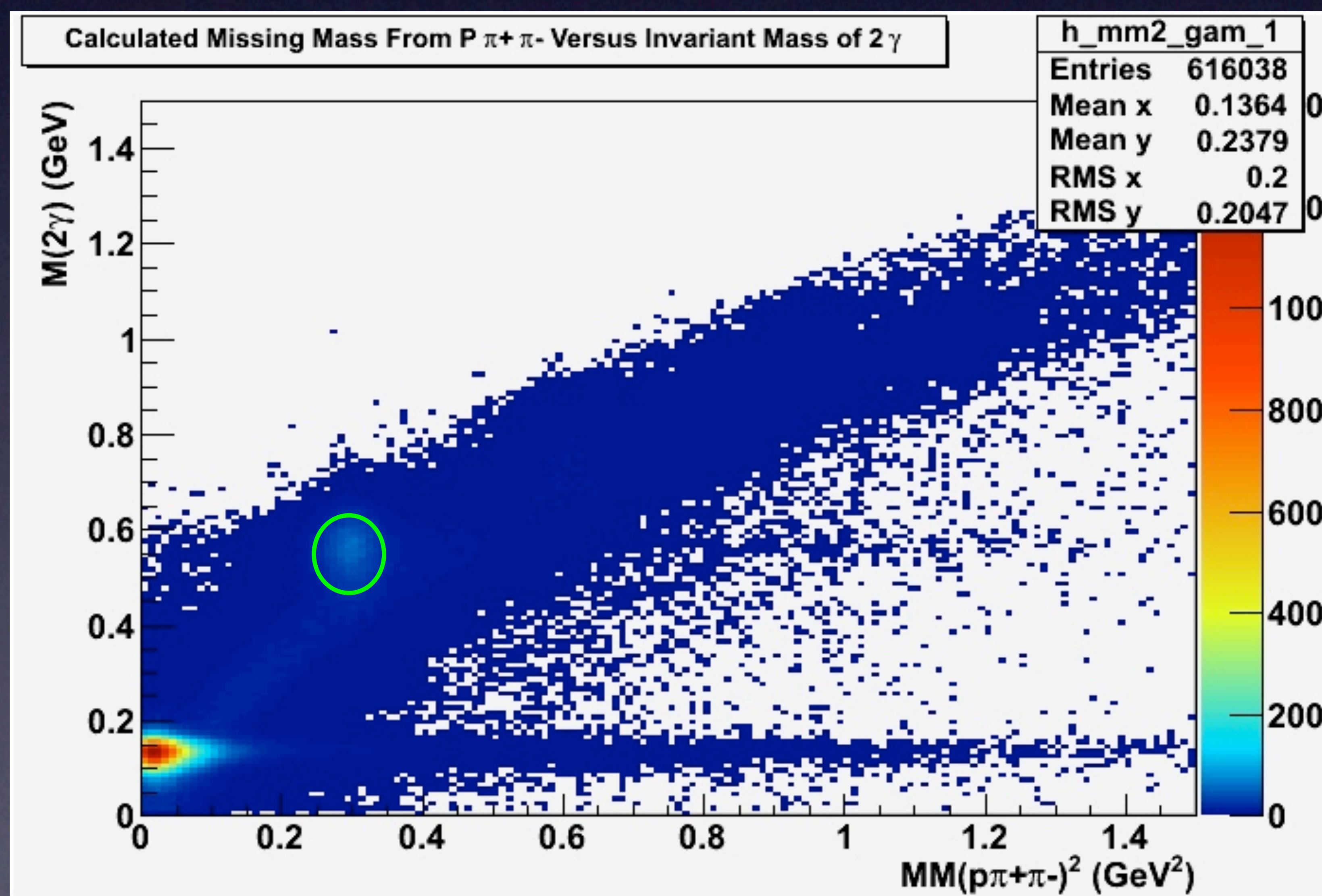
$\gamma p \to p\pi^+\eta\pi^-$

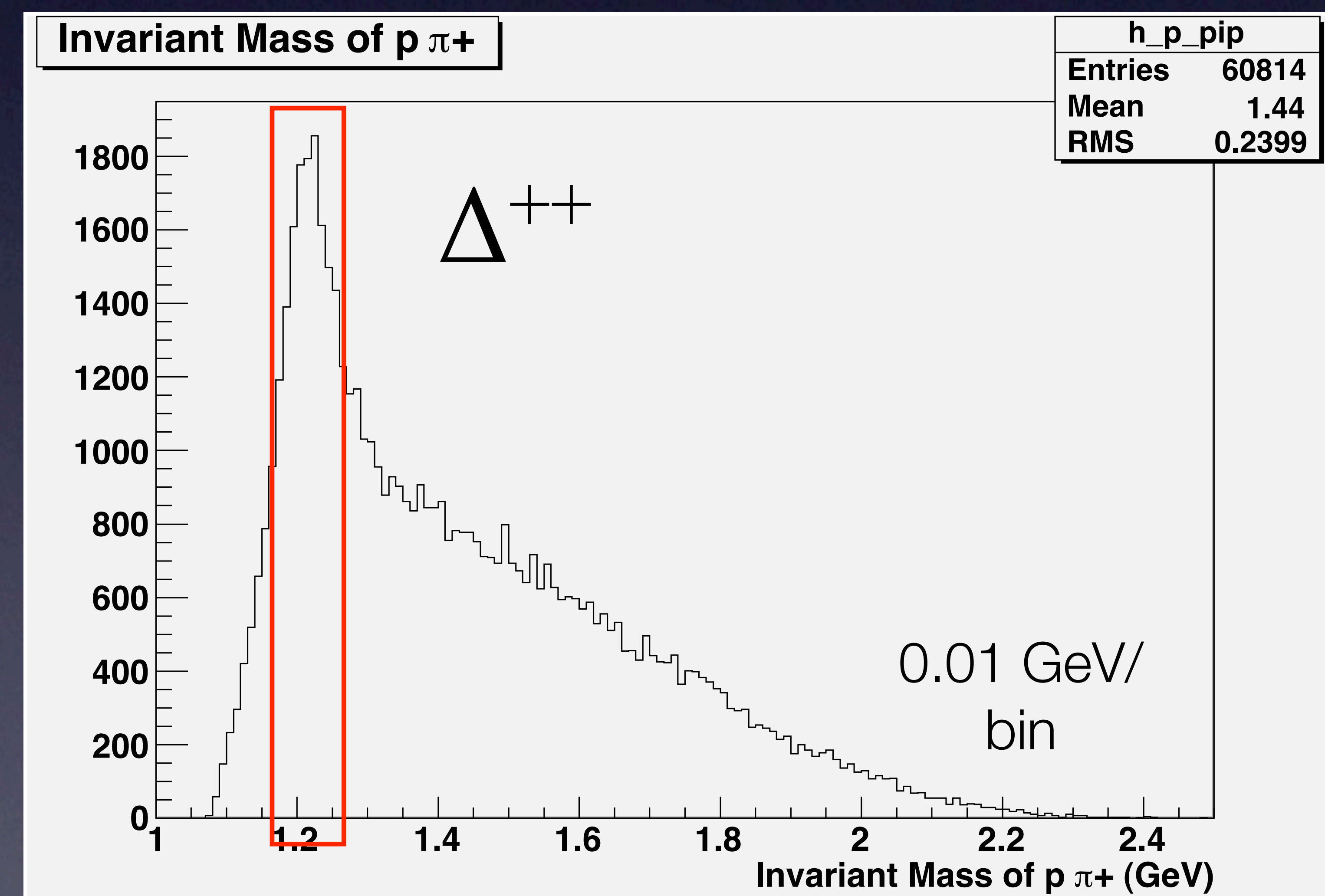
g_{12} CLAS photon run

Diane Schott, FIU









D.P. Weygand

Summary

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Do exotic mesons exist in QCD?

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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.

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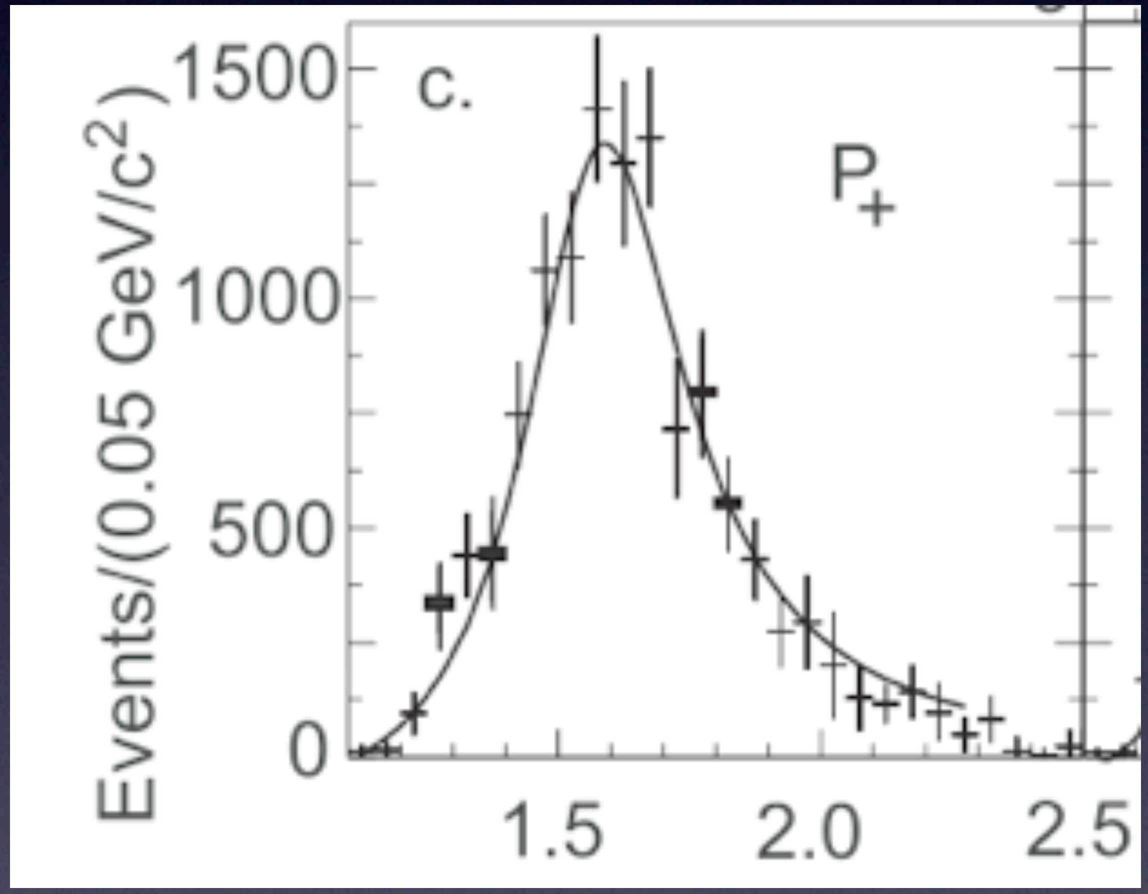

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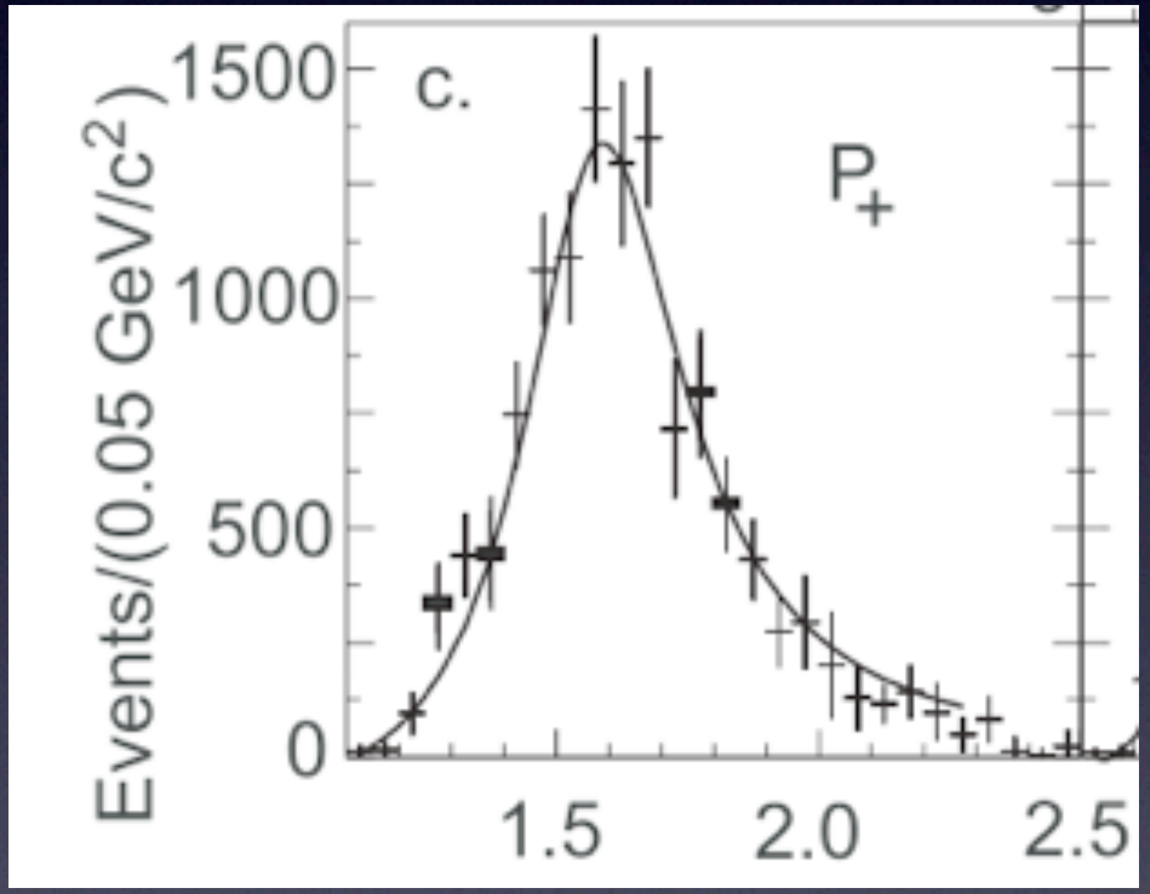

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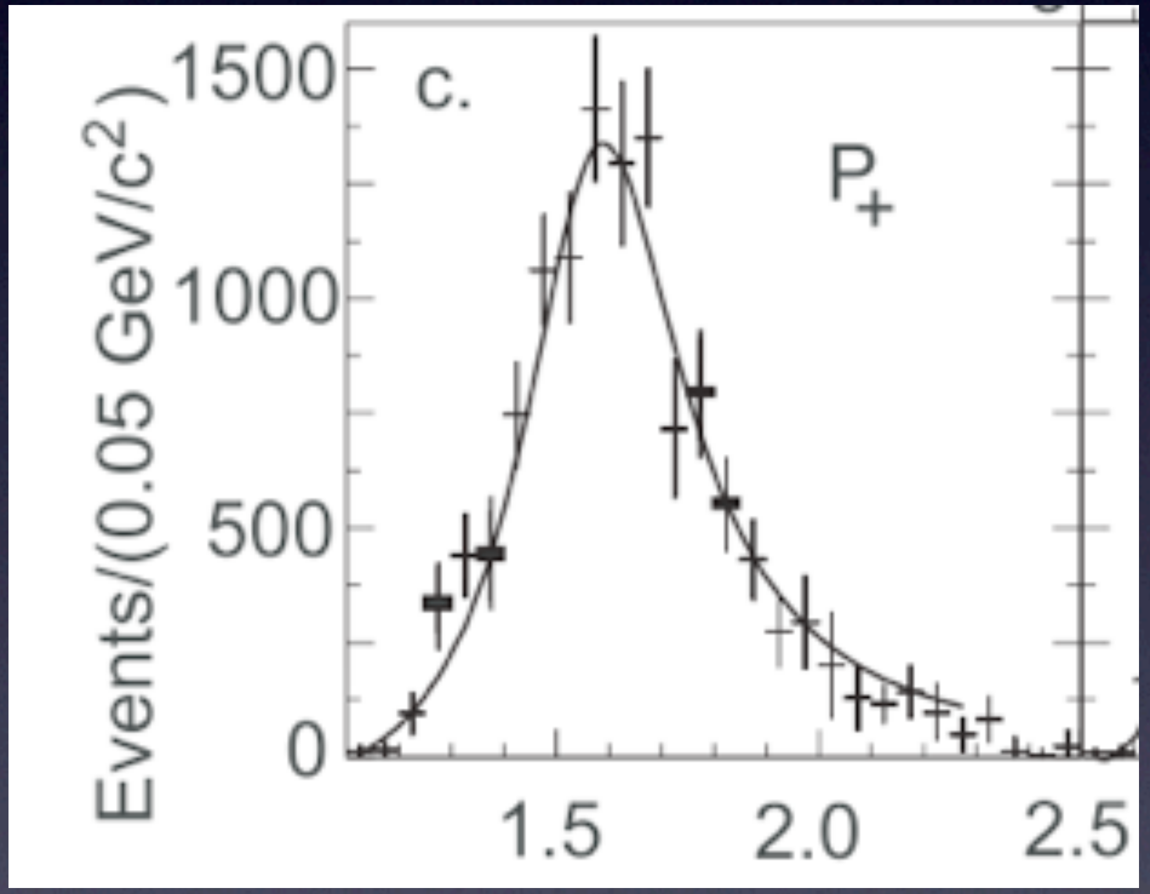

Is the question any longer interesting experimentally?

Is meson spectroscopy becoming 'hadro-chemistry'?

Thank you for your attention