Search for Exotic Mesons

with STAR/BNL and COMPASS/CERN

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http://www.phy.bnl.gov/˜e852/reviews.html

Plan of Talk

- Introduction:
  A brief overview of exotic mesons

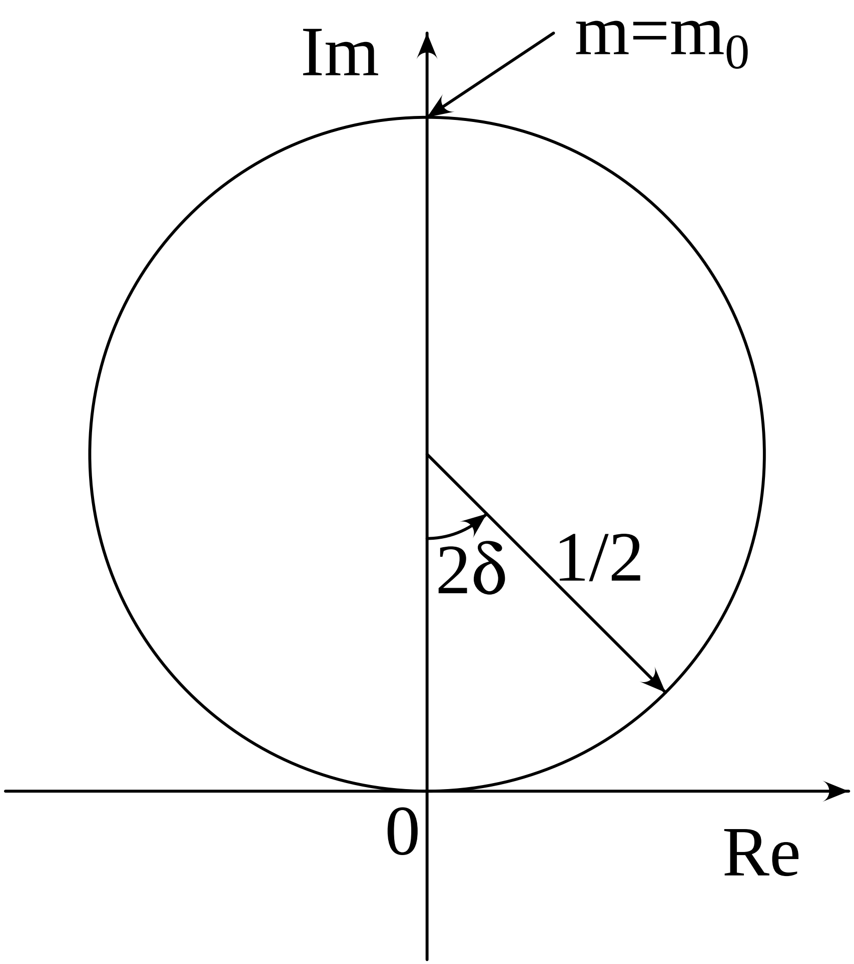
- Three Exotic Mesons from BNL-E852:
  $\pi_1(1400)$, $\pi_1(1600)$, $\pi_1(2000)$

- STAR and COMPASS

- Search for $SU(3)$ Partners of the $\pi_1(1400,\ 1600,\ 2000)$

- Conclusions and Future Prospects

Phase motion of a Breit-Wigner form



$$\Delta(m) = \frac{m_0\,\Gamma_0}{m_0^2 - m^2 - i\,m_0\,\Gamma_0}$$
$$= e^{i\,\delta(m)}\ \sin\delta(m)$$

$$\cot\delta(m) = \frac{m_0^2 - m^2}{m_0\,\Gamma_0}$$

Interference effect:

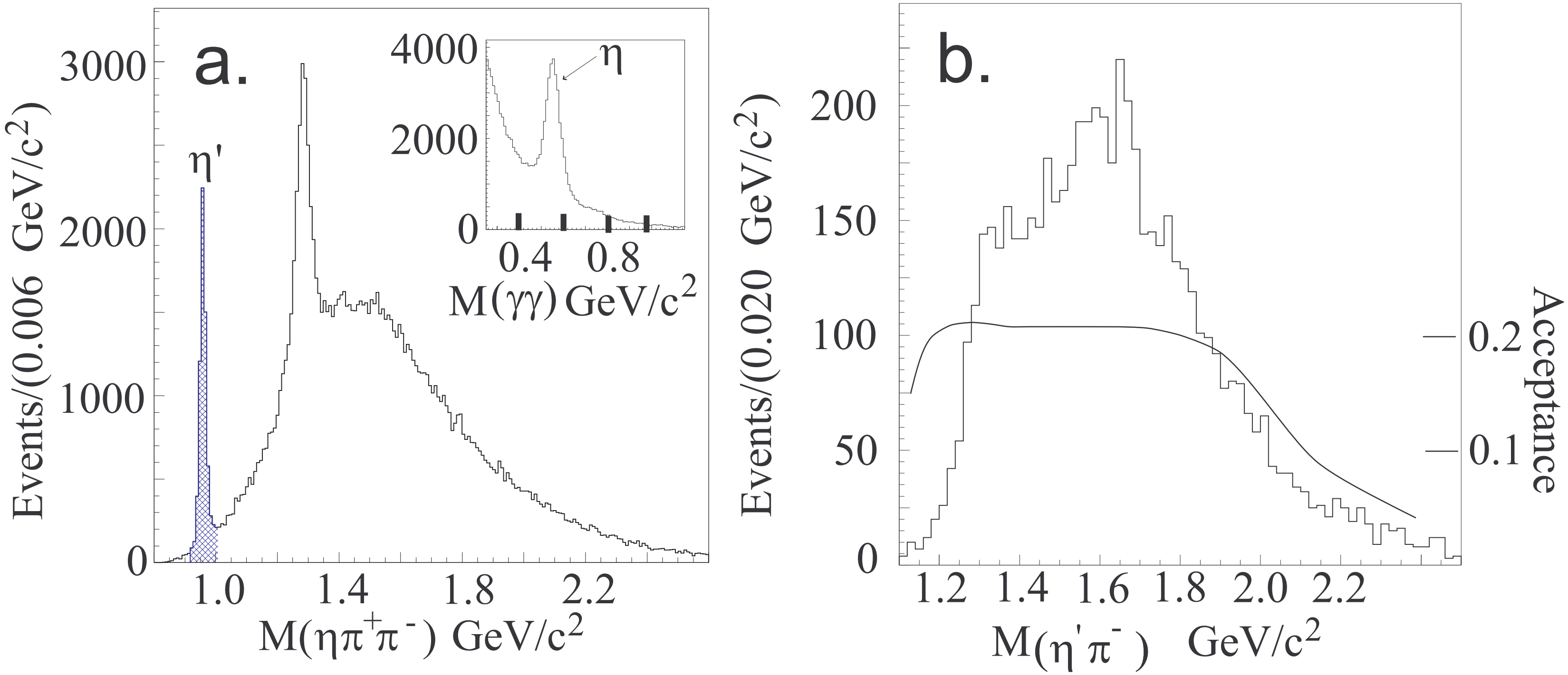
$$A = 1 + \alpha, \quad \alpha \sim 0.1$$
$$|A|^2 = 1 + 2\alpha + \alpha^2$$

Exotic Meson: $\pi_1^-(1600) \to \eta'\pi^-$ BNL-E852

Reaction: $\pi^- p \to \eta'\pi^- p$ at 18 GeV/c

$\eta' \to \eta\pi^+\pi^-$, $\eta \to \gamma\gamma$, $\sigma(\eta' \to \eta\pi^+\pi^-) \sim 9$ MeV

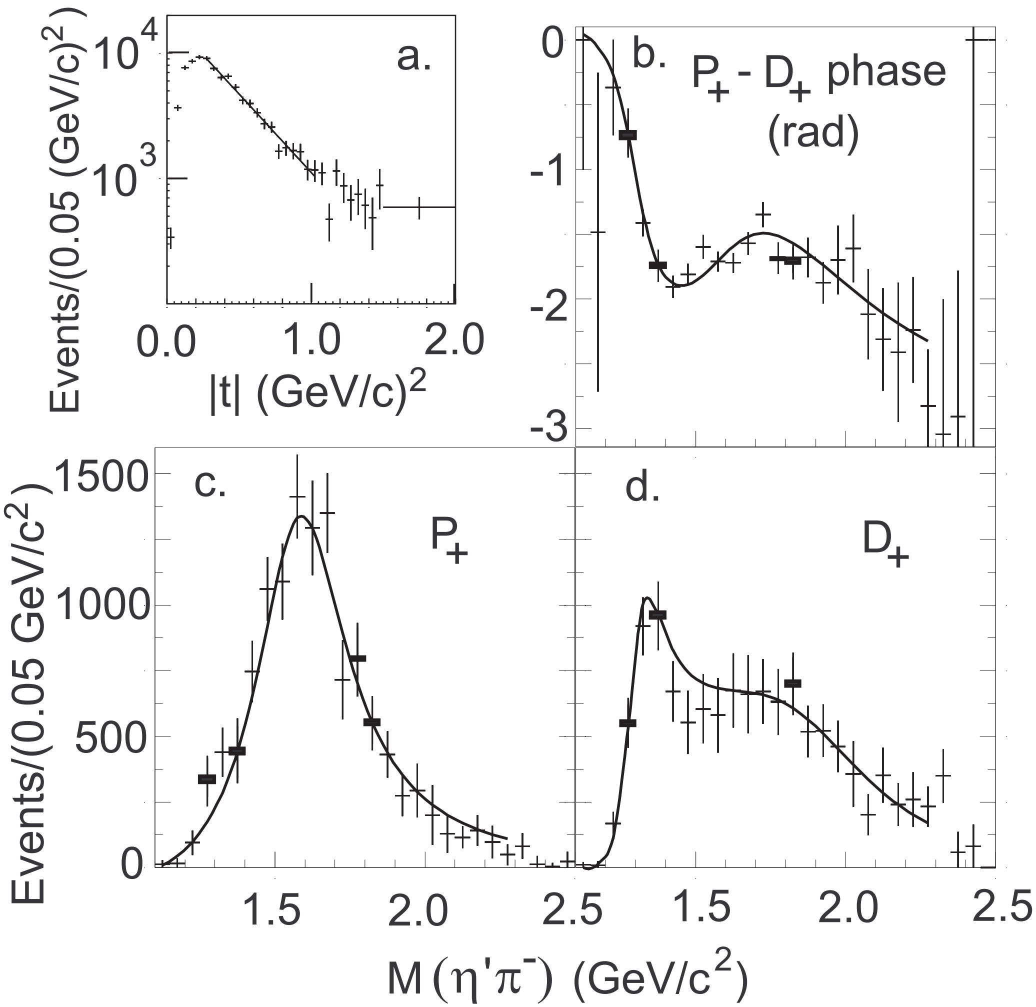
$\sim 6\,000$ events



Exotic Meson: $\pi_1^-(1600) \to \eta'\pi^-$ BNL-E852

Reaction: $\pi^- p \to \eta'\pi^- p$ at 18 GeV/c, $\eta' \to \eta\pi^+\pi^-$, $\eta \to \gamma\gamma$

$\sim 6\,000$ events



$1^{-+}1^+\ \eta'\left[{P \atop 0}\right]\pi \to P_+$

$2^{++}1^+\ \eta'\left[{D \atop 0}\right]\pi \to D_+$

$$\begin{cases} M(P_+) = 1597 \pm 10 {+45 \atop -10} \\ \Gamma(P_+) = 340 \pm 40 \pm 50 \end{cases}$$

PRL 86, 3977 (2001)

Exotic Meson: $\pi_1(1600)$

Experiments	M (MeV)	Γ (MeV)	Decay
BNL ($\pi^- p$ at 18 GeV/c) [a]	$1593 \pm 8 {}^{+20}_{-47}$	$168 \pm 20 {}^{+150}_{-12}$	$\rho\pi$
BNL ($\pi^- p$ at 18 GeV/c) [b]	$1596 \pm 10 {}^{+45}_{-10}$	$340 \pm 40 \pm 50$	$\eta'\pi$
BNL ($\pi^- p$ at 18 GeV/c) [c]	$1709 \pm 24 \pm 41$	$403 \pm 80 \pm 115$	$f_1(1285)\pi$
BNL ($\pi^- p$ at 18 GeV/c) [d]	$1664 \pm 8 \pm 4$	$185 \pm 25 \pm 12$	$b_1(1235)\pi$
VES ($\pi^- N$ at 37 GeV/c) [e]	1560 ± 6	340 ± 5	$\rho\pi$
			$\eta'\pi$
			$b_1(1235)\pi$
CB ($\bar{p}p$ at rest) [f]	$1596 {}^{+25}_{-14} {}^{+50}_{-50}$	$312 {}^{+64}_{-24} {}^{+75}_{-75}$	$b_1(1235)\pi$

[a] PRD 65, 072001 (2002)

[b] PRL 86, 3977 (2001)

[c] PL B595, 109 (2004)

[d] PRL 94, 032002 (2005)

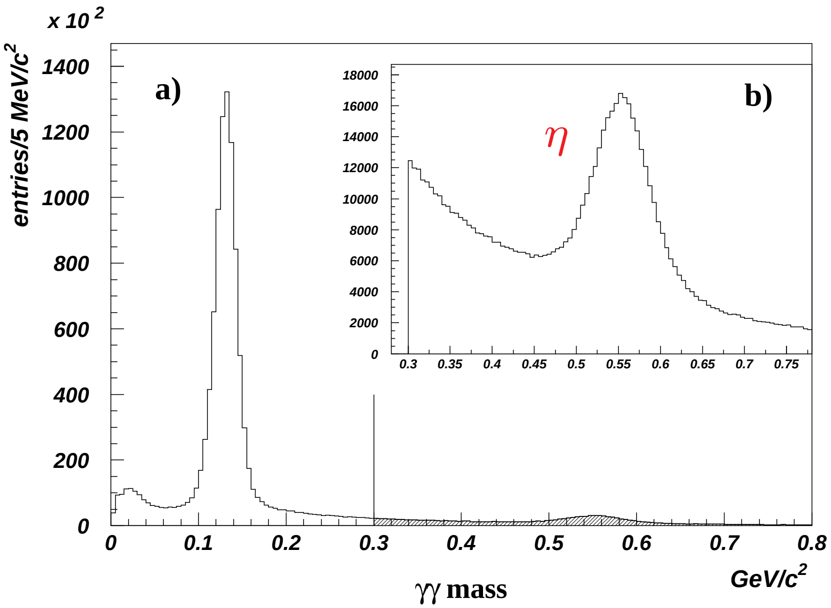
[e] V. Dorofeev, Proc. Workshop on Hadron Spectroscopy, Frascati, Italy (1999), p. 3.

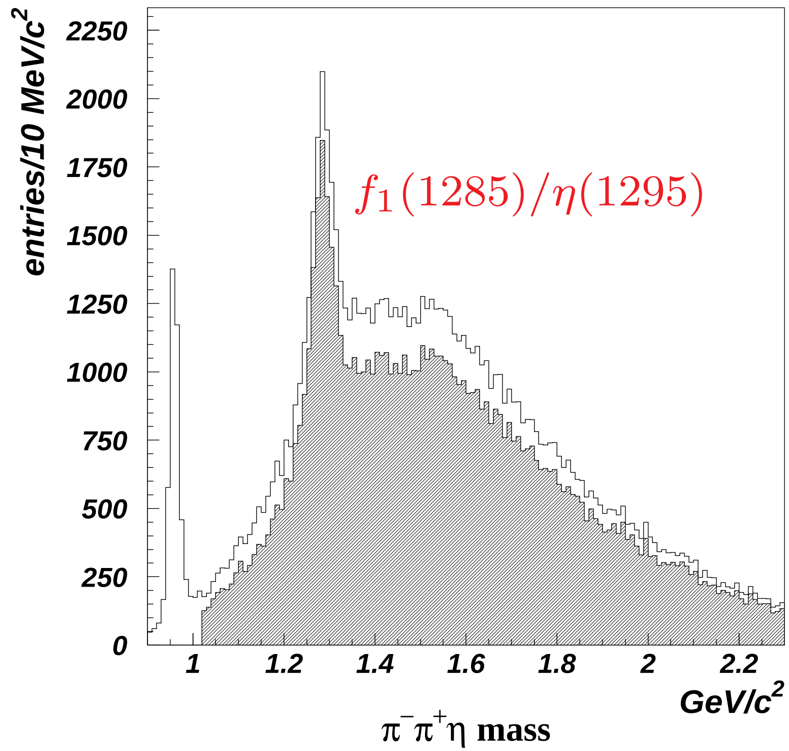
[f] PL B563, 140 (2003)—Mass and Width fixed to PDG values

Results on $f_1(1285)\pi$ BNL-E852

Reaction: $\pi^- p \to \eta\pi^+\pi^-\pi^- p$, $\sim 69\,000$ events

$$\pi^- p \to f_1(1285)\pi^- p,\ f_1(1285) \to \eta\pi^+\pi^-,\ \eta \to \gamma\gamma$$

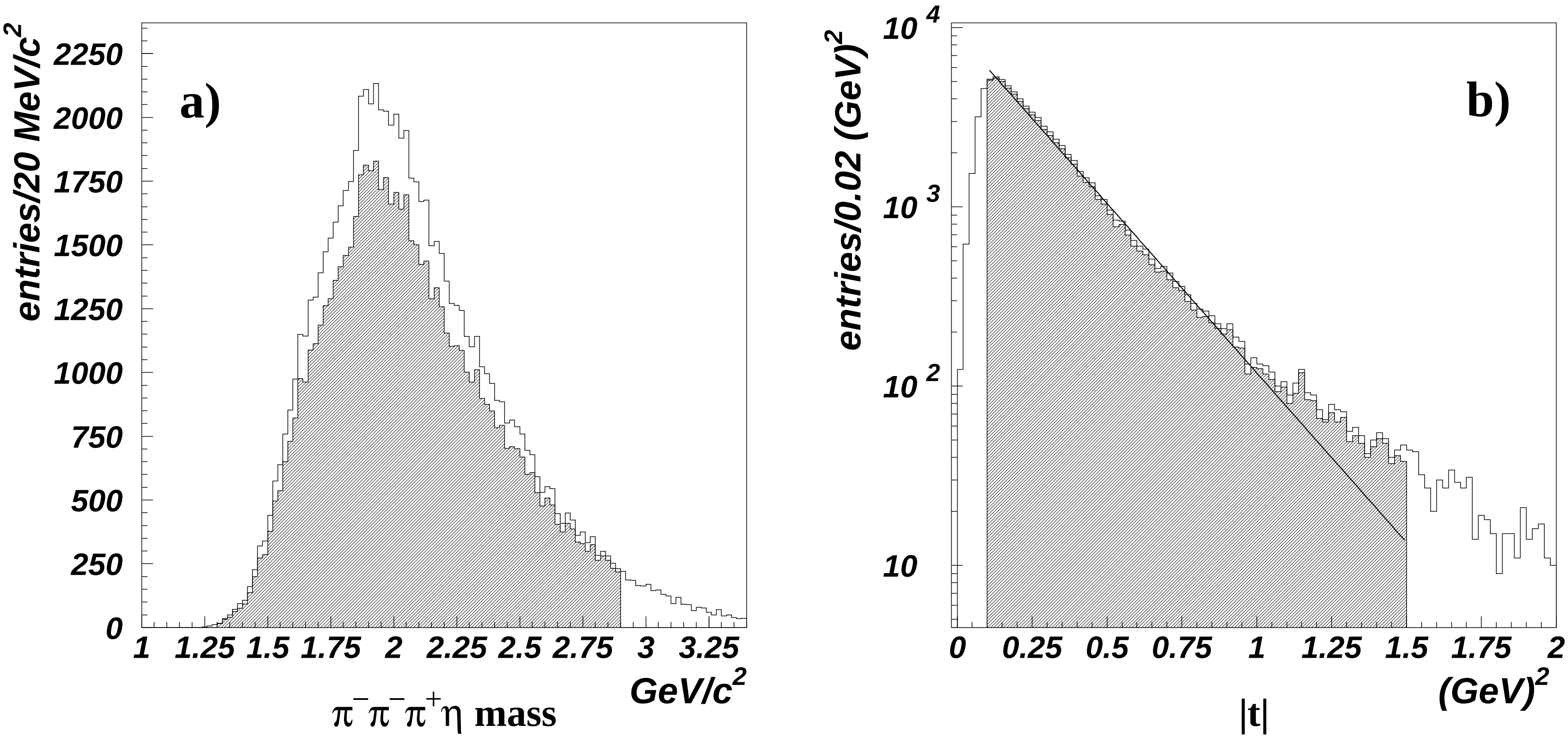




Results on $f_1(1285)\pi$ BNL-E852

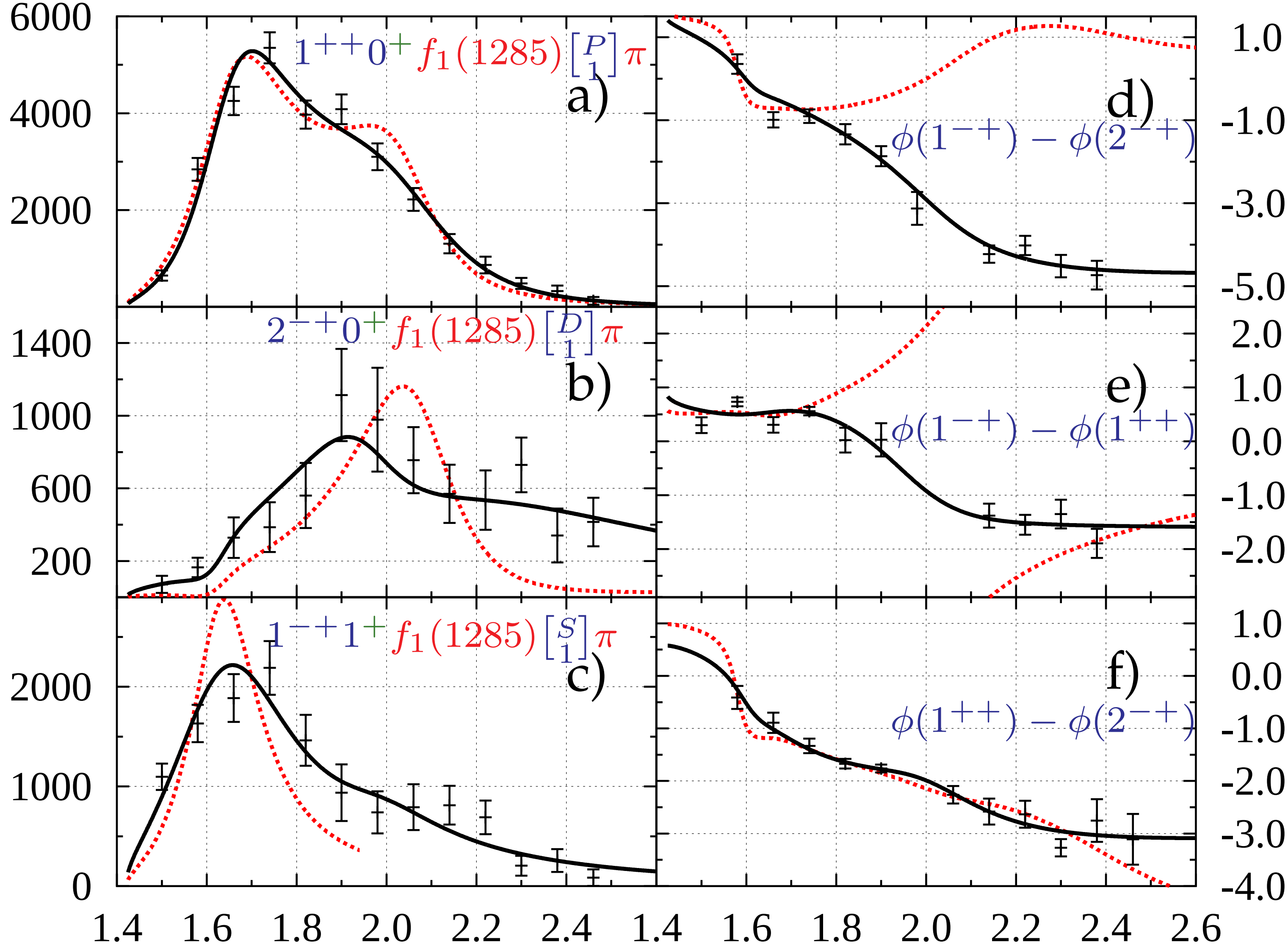
Reaction: $\pi^- p \to \eta\pi^+\pi^-\pi^- p$, $\sim 69\,000$ events

$\pi^- p \to f_1(1285)\pi^- p$, $f_1(1285) \to \eta\pi^+\pi^-$, $\eta \to \gamma\gamma$



Results of Partial-wave Analysis **BNL-E852**

Intensity and phase difference for selected $f_1(1285)\pi^-$ waves: $J^{PC} M^{\varepsilon}\ f_1(1285) \left[{L \atop 1}\right] \pi$



$\pi_1(1600)$ and $\pi_1(2000)$

Exotic Meson: $\pi_1(2000)$

Experiments	M (MeV)	Γ (MeV)	Decay
BNL ($\pi^- p$ at 18 GeV/c) [a]	$2001 \pm 30 \pm 92$	$333 \pm 52 \pm 49$	$f_1(1285)\pi$
BNL ($\pi^- p$ at 18 GeV/c) [b]	$2014 \pm 20 \pm 10$	$230 \pm 32 \pm 15$	$b_1(1235)\pi$

[a] PL B595, 109 (2004)

[b] PRL 94, 032002 (2005)

Exotic Meson: $\pi_1^-(1400) \to \eta\pi^-$

Experiments	M (MeV)	Γ (MeV)
BNL ($\pi^- p$ at 18 GeV/c) '94 data	$1370 \pm 16 {}^{+50}_{-30}$	$385 \pm 40 {}^{+65}_{-105}$
BNL ($\pi^- p$ at 18 GeV/c) '95 data	$1359 {}^{+16}_{-14} {}^{+50}_{-30}$	$385 {}^{+31}_{-29} {}^{+9}_{-66}$
CB ($\bar{p}n \to \pi^-\pi^0\eta$ at rest) [a]	$1400 \pm 20 \pm 20$	$310 \pm 50 {}^{+50}_{-30}$
	$\chi^2/\mathrm{dof} = 3.1 \to 1.3$	
CB ($\bar{p}p \to \pi^0\pi^0\eta$ at rest) [b]	1360 ± 25	220 ± 90
KEK ($\pi^- p$ at 6.3 GeV/c) [c]	1323.1 ± 4.6	143.2 ± 12.5
VES ($\pi^-\mathrm{Be}$ at 28 GeV/c) [d]	1316 ± 12	287 ± 25

[a] PL B423, 175 (1998).

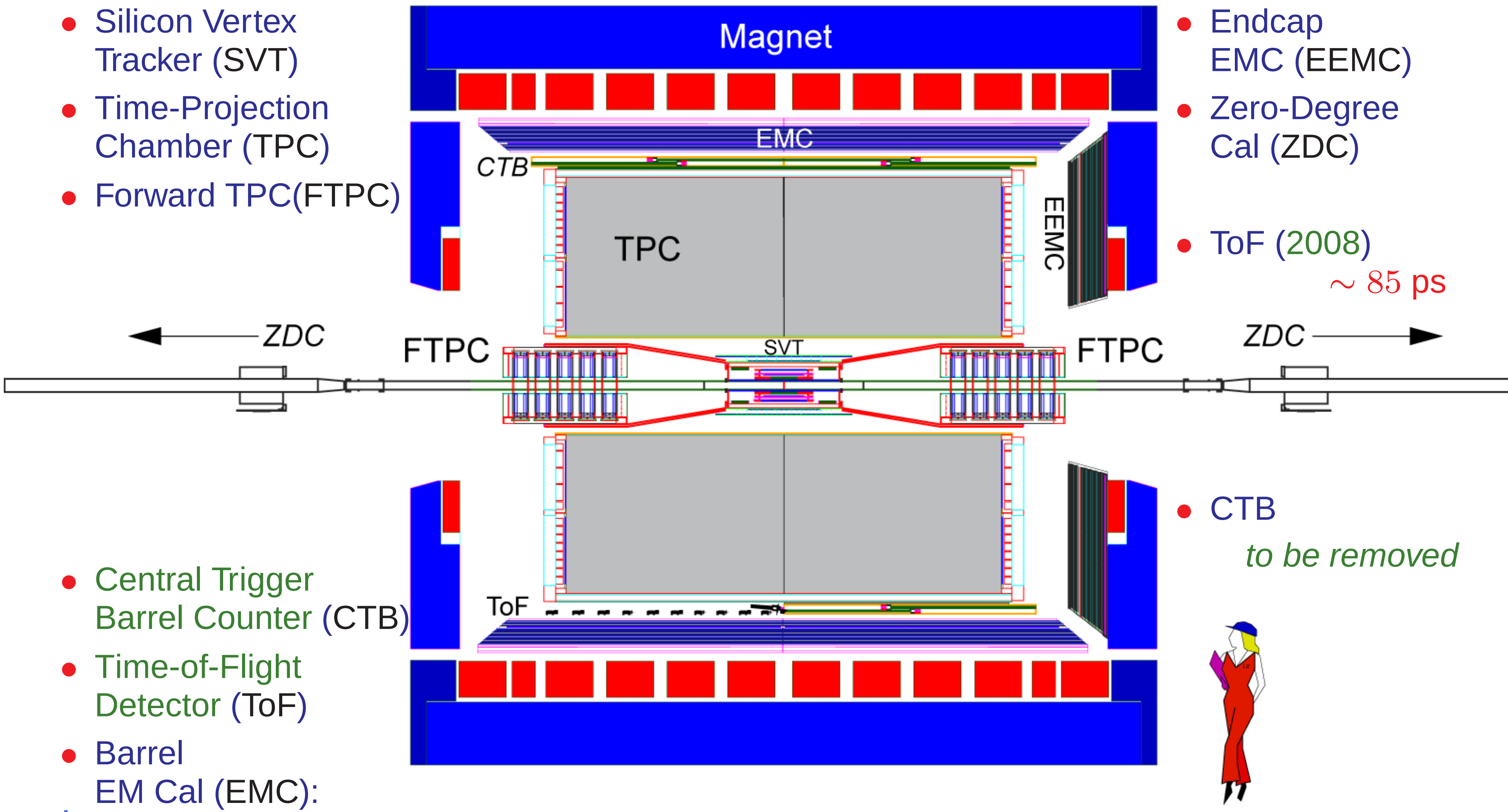
[b] PL B446, 349 (1999).

[c] PL B314, 246 (1993).

[d] V. Dorofeev (VES), Proc. Hadron2001, p.143.

Magnetic Field : 0.5 T

- Silicon Vertex Tracker (SVT)
- Time-Projection Chamber (TPC)
- Forward TPC(FTPC)



- Endcap EMC (EEMC)
- Zero-Degree Cal (ZDC)
- ToF (2008)
  ~ 85 ps
- CTB
  to be removed

- Central Trigger Barrel Counter (CTB)
- Time-of-Flight Detector (ToF)
- Barrel EM Cal (EMC):
  4,800 Towers

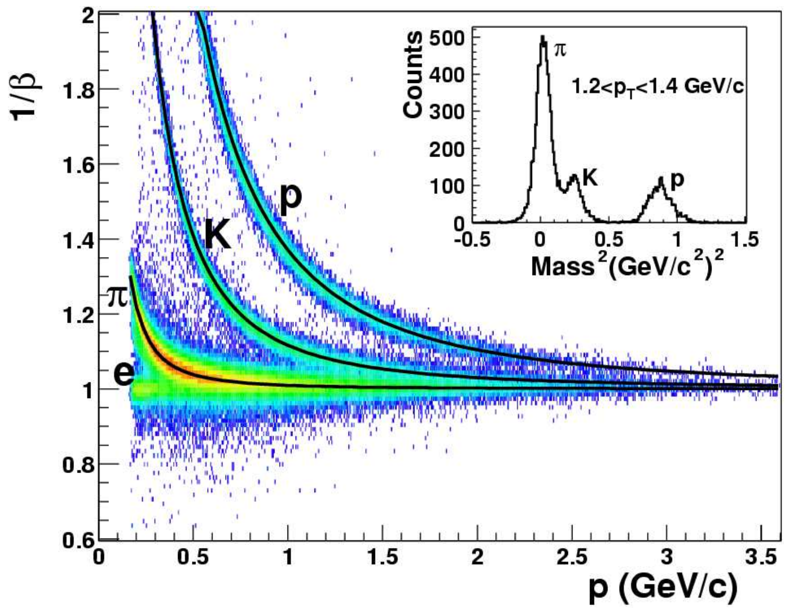
"The First Few Microseconds"

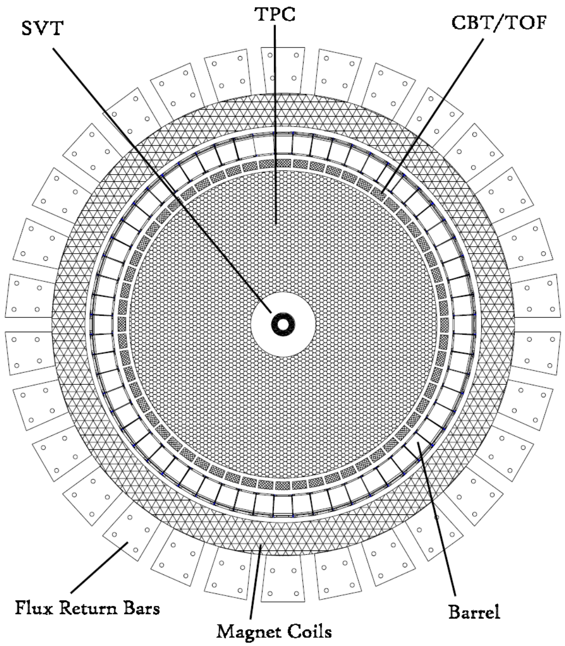
—Michael Riordan and William A. Zajc

Scientific American
Volume 294 Number 5 Page 34A
May 2006

ToF Detector

- MRPC(Multi-gap Resistive Plate Chamber) Detector
- 6 Channels $\times$ 32 Plates $\times$ 120 Trays = 23,040 Channels
- Full ToF coverage($|\eta| < 1$) and 2π coverage in azimuth
- Intrinsic Timing Resolution $\sim$ 85 ps
- By combining measurements from TPC and ToF Detector:
  p/π (K/π) separation up to $p_T = 10$ GeV/c ($p_T = 3$ GeV/c)





Hadron Spectroscopy Program of STAR

within the Ultra-Peripheral Collisions (UPC) Group

- $\mathrm{Au} + \mathrm{Au} \rightarrow \mathrm{Au}^{(*)} + \mathrm{Au}^{(*)} + \rho$
  Photon+Pomeron$\rightarrow \rho \rightarrow \pi^+\pi^-$
  Trigger on events with two charged particles in CTB
  with or without ZDC

- $\mathrm{Au} + \mathrm{Au} \rightarrow \mathrm{Au}^{(*)} + \mathrm{Au}^{(*)} + \rho'$
  Photon+Pomeron$\rightarrow \rho' \rightarrow \pi^+\pi^-\pi^+\pi^-$
  Pilot run in 2004
  Trigger on events with four or more charged particles in CTB and ZDC

- Future Runs with a Ultra-Peripheral Detector (UPD) systems
  An example: $p + p \rightarrow p + (\pi^+\pi^+\pi^-\pi^-) + p$
  Pomeron+Pomeron$\rightarrow f_0(1500) \rightarrow \pi^+\pi^-\pi^+\pi^-$

  Central production of exotic mesons

Possible Decay Modes and Final States

★ Characteristics of a $J^{PC} = 0^{+-},\ 2^{+-}$ State [$b_{0,2}(2000?),\ h_{0,2}(2000?)$]:

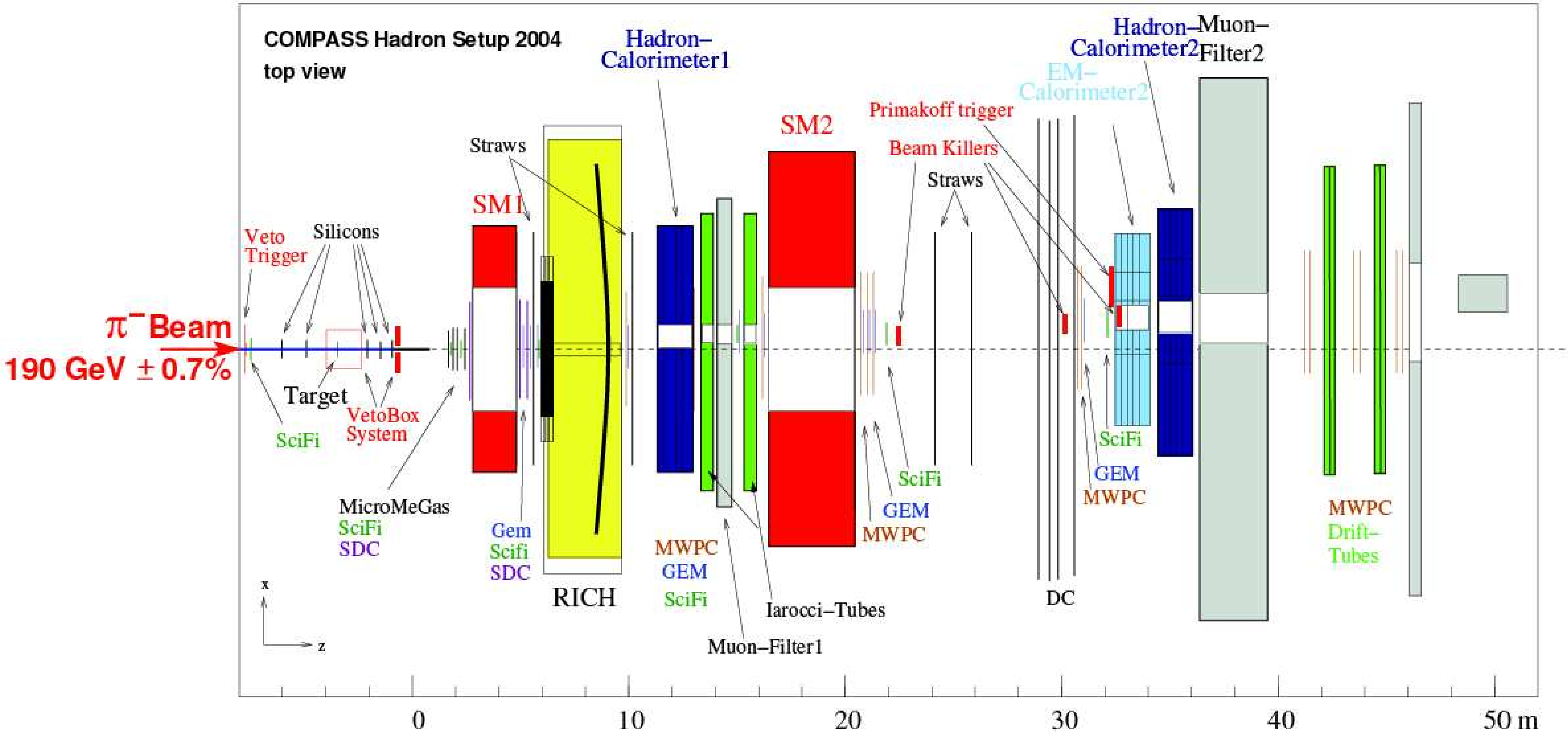
I^G	Intermediate States	Final States
1^+	$[\rho^0\,(770) f_0(600)]_P$	$\pi^+\pi^-\pi^+\pi^-$
1^+	$f_0(980)\,\rho^0(770)$, $f_2'(1525)\,\rho^0(770)$	$K^+K^-\pi^+\pi^-$
0^-	$a_0^0(980)\,\rho^0(770)$, $a_2^0(1320)\,\rho^0(770)$	$K^+K^-\pi^+\pi^-$

★ Characteristics of a $J^{PC} = 0^{--}$ State [$\rho_0(3000?),\ \omega_0(3000?)$]:

I^G	Intermediate States	Final States
1^+	$[a_2^{\pm}(1320)\,\pi^{\mp}]_D$, $[\rho^0\,(770) f_2(1270)]_D$,	$\pi^+\pi^-\pi^+\pi^-$
1^+	$f_2'(1525)\,\rho^0(770)$	$K^+K^-\pi^+\pi^-$
1^+	$K^*(890)\,\bar{K}$, $K_2^*(1420)\,\bar{K}$, $a_2^{\pm}(1320)\,\pi^{\mp}$	$K_S K^{\pm}\pi^{\mp}$
0^-	$K^*(890)\,\bar{K}$, $K_2^*(1420)\,\bar{K}$	$K_S K^{\pm}\pi^{\mp}$
0^-	$a_2^0(1320)\,\rho^0(770)$	$K_S K^{\pm}\pi^{\mp}$

Layout of COMPASS Experiment

for Hadron Runs



Possible Decay Modes and Final States

★ Characteristics of a $J^{PC} = 1^{-+},\ 3^{-+}$ State [$\eta_{1,3}(2000?)$]:

I^G	Intermediate States	Final States
0^+	$[\rho^0\,(770)\ \rho^0\,(770)]_P,\ S = 1$	$\pi^+\pi^-\pi^+\pi^-$
0^+	$[f_0(980)\ f_0(600)]_P,\ [f_2'(1525)\ f_0(600)]_P$	$K^+K^-\pi^+\pi^-$
0^+	$[K^*(890)\ \bar{K}]_P,\ [K_2^*(1420)\ \bar{K}]_D$	$K_S K^\pm\pi^\mp$

$SU(3)$ Partners to the Exotic Mesons

- Consider three species of quarks, i.e. $q = \{u,\ d,\ s\}$:

  Then there must exist
  $K(J^P = 0^-,\ 1^+,\ 2^-)$'s and $K^*(J^P = 0^+,\ 1^-,\ 2^+)$'s,

  $SU(3)$ Partners to
  $\pi_1(1400)$, $\pi_1(1600)$, $\pi_1(2000)$ ($J^{PC} = 1^{-+}$)

- Strangeonium $=$ Any hadrons containing an $s\bar{s}$ pair.
  Exotic Strangeonia: $s\bar{s} + g$, $s\bar{s} + n\bar{n}$, $n = \{u,\ d\}$
  $SU(3)$ Partners to the π_1's

Diffractive Dissociation from K^-p interactions

Consider a process

$$\begin{aligned} &K^- + p \to K^-(X) + p, \\ &\quad K^-(X) \to K^- + (n\,\pi)^0, \quad n = 1,\ 2,\ 3,\ 4\ldots \\ &\quad K^-(X) \to \overline{K}^{\,0} + (n\,\pi)^-, \quad n = 1,\ 2,\ 3,\ 4\ldots \end{aligned} \tag{1}$$

where π stands for both charged and neutral pions. Here $K^-(X)$ stands for some excited state with the flavor content of an s quark, which has been transmitted from that of the $K^-(s\ \bar{u}\ )$ beam.

In the limit of a *pure* Pomeron exchange, dominant spin-parity series for $K^-(X)$ are $J^P = 0^-,\ 1^+,\ 2^-$, etc., assuming the Pomeron acts as a $J^{PC} = 0^{++}$ state. However, at some level, the Pomeron may act as a $J^{PC} = 1^{-+}$ state, which is an *exotic state* and which is forbidden by the constraint of the signature factor.

$$J^P = 0^-,\ 1^\pm,\ 2^\pm,\ 3^\pm \tag{2}$$

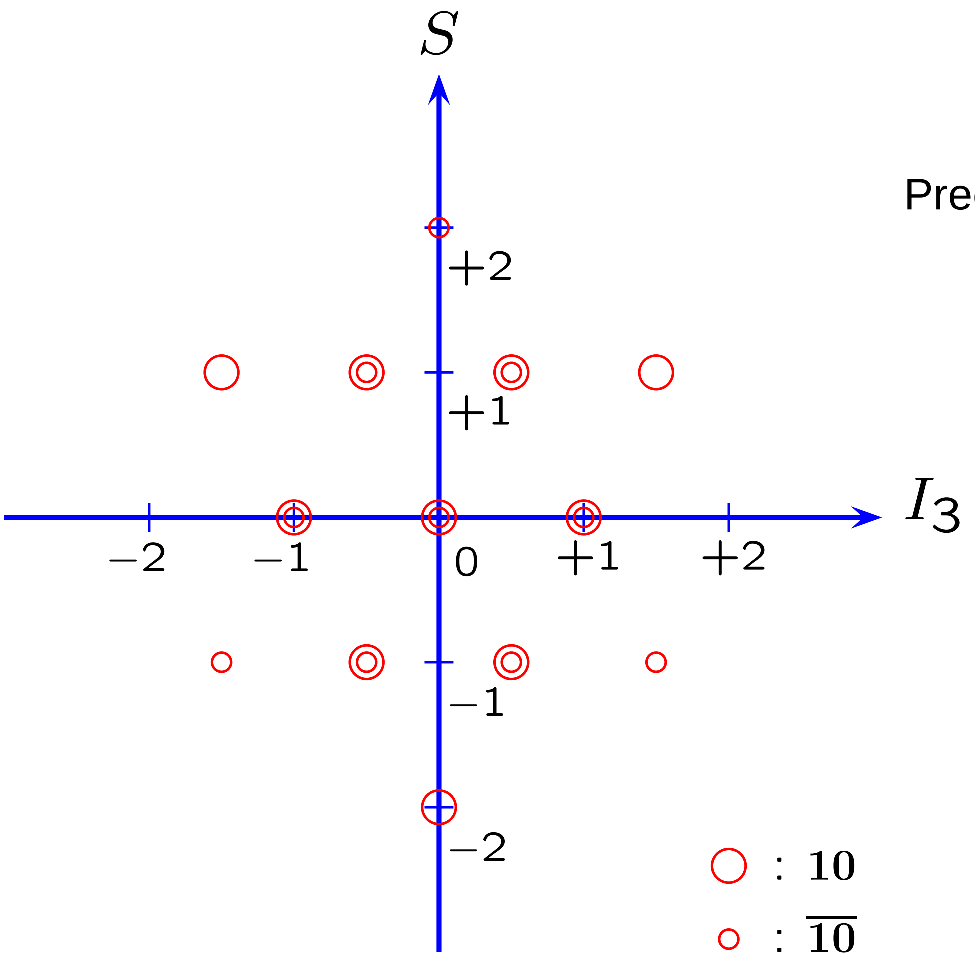
Diffractive Dissociation

Recall that the strange partners of the pseudovectors $a_1(1260)$ and $b_1(1235)$ mix to produce two physical $J^P = 1^+$ K_1 states

$$K_1/a_1(1260) \oplus K_1/b_1(1235) \Longrightarrow K_1(1270) \oplus K_1(1400) \tag{3}$$

where $K_1(1270)$ decays predominantly to $K\rho$, whereas the $K_1(1400)$ has a dominant decay mode *only* into $K^*\pi$.

A P-Wave $\pi\eta$ State: Mesons in flavor $10 \oplus \overline{10}$



Predict: no $\eta_1(1400)$
one $\rho(1400)$

○ : $\mathbf{10}$
∘ : $\overline{\mathbf{10}}$

Single circles have just one member of the multiplet,

while the double circles indicate two occupancies by the members of the multiplet.

Diffractive Dissociation

It should be pointed out that the scenario above is overly simplistic. The K^*'s belonging to the decuplet family of $SU(3)$ are more complex

$$
\begin{aligned}
& K^*(892)/\rho(770) \\
& \qquad \oplus K^*(\mathbf{10})/\pi_1(1400)\Big|_{I=1/2} \oplus K^*(\overline{\mathbf{10}})/\pi_1(1400)\Big|_{I=3/2} \\
& \qquad\qquad \oplus K^*/\pi_1(1600) \\
& \Longrightarrow K^*(1) \oplus K^*(2) \oplus K^*(3) \oplus K^*(4)
\end{aligned} \tag{4}
$$

The PDG Book lists three $J^P = 1^-$ K^*'s, e.g. $K^*(892)$, $K^*(1400)$ and $K^*(1680)$. It is thought that the $K^*(1680)$ is a radial excitation of the $K^*(892)$. If so, then we have *two* missing in the spectra of the experimentally found K^*'s. It is for this reason, among others, that a further experimental search for the K^*'s and their decay modes is required. In particular, we expect existence of a flavor-exotic $I = 3/2$ K^* states.

Search for Flavor-Exotic $K^*(\overline{\mathbf{10}})$'s

- Consider mesons containing $\{u,\ d,\ s\}$ and $\{\bar{u},\ \bar{d},\ \bar{s}\}$ [Flavor $SU(3)$]. Then $Q = S/2 + I_3$, where $S =$ strangeness, i.e. $S = -1$ for an s quark.

$I = 1/2\ K^*(\mathbf{10})$'s

I_3	$+1/2$	$-1/2$
Q	0	-1

$I = 3/2\ K^*(\overline{\mathbf{10}})$'s

I_3	$+3/2$	$+1/2$	$-1/2$	$-3/2$
Q	$+1$	0	-1	-2

- An example for the production of a $I = 3/2\ K^*(\overline{\mathbf{10}})$:

$$\begin{aligned} K^- p &\rightarrow K^{*\,+} + N^{*\,-} \\ K^{*\,+} &\rightarrow K^- + \pi^+ + \pi^+ \\ N^{*\,-} &\rightarrow p + \pi^- + \pi^- \end{aligned} \tag{5}$$

Or

$$\begin{aligned} K^- p &\rightarrow K^{*\,--} + \Delta^{++} \\ K^{*\,--} &\rightarrow K^- + \pi^- \\ \Delta^{++} &\rightarrow p + \pi^+ \end{aligned} \tag{6}$$

Strangeonium Excitations

Consider the process

$$K^- + p \to H^0(X) + \Lambda \quad \text{or} \quad H^-(X) + \Sigma^+,$$
$$H(X) \to (K\ \overline{K}\ ) + (n\,\pi), \quad n = 1,\ 2\ldots$$
$$H(X) \to (K\ \overline{K}^{\,*}\ ) + (n\,\pi), \quad n = 1,\ 2\ldots \tag{7}$$
$$H(X) \to (K^*\ \overline{K}\ ) + (n\,\pi), \quad n = 1,\ 2\ldots$$
$$H(X) \to (K^*\ \overline{K}^{\,*}\ ) + (n\,\pi), \quad n = 1,\ 2\ldots$$

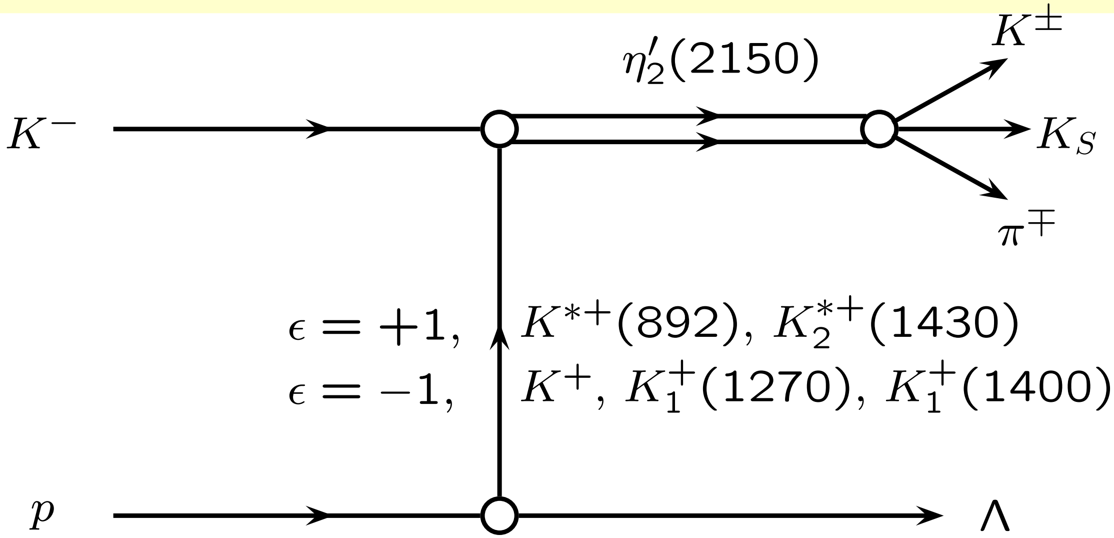
Here $H(X)$ is a non-strange meson system, which carries a flavor content of an $s\,\bar{s}$-quark pair. For this production to occur, we need to invoke Reggeon exchanges, corresponding to K or K^*. All quantum numbers are allowed

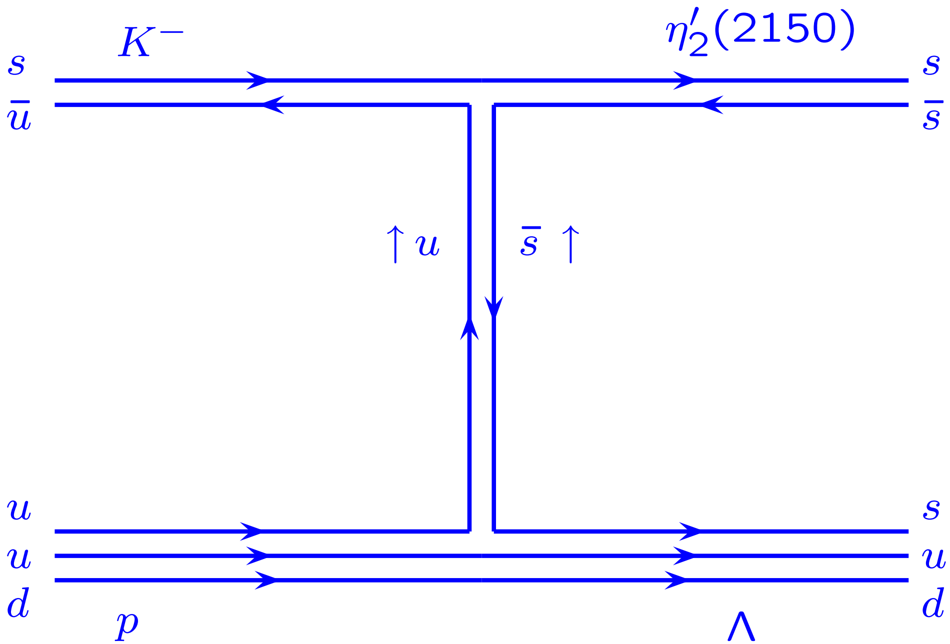
$$J^{PC} = 0^{\pm\pm},\ 1^{\pm\pm},\ 2^{\pm\pm},\ 3^{\pm\pm} \tag{8}$$

Note that the states $H(X)$ with $J^{PC} = 0^{+-},\ 1^{-+},\ 2^{+-},\ 3^{-+}$, etc. are *exotic*.
It must be pointed out that a state with $J^{PC} = 0^{--}$ is *hyper-exotic*,

Its mass must be much greater than those of the other exotic mesons.

Strangeonium Excitations





Strangeonium Excitations

Consider scalar and tensor states, i.e. $J^{PC} = 0^{++}$ or $J^{PC} = 2^{++}$. There must be four different constituents contributing

$$(s\,\bar{s}\,) \oplus (s\,\bar{s}\, + g) \oplus (g + g) \oplus (s\,\bar{s}\, + n\bar{n}), \quad n = \{u,\ d\} \tag{9}$$

Chanowitz has recently pointed out that the scalar glueball G_0 should decay preferentially into K^+K^- over $\pi^+\pi^-$. Specifically, he states that, with $n = \{u, d\}$,

$$\frac{\Gamma(G_0 \to s\bar{s})}{\Gamma(G_0 \to n\bar{n})} = 20 \text{---} 100 \tag{10}$$

He states, in addition, that the scalar glueballs G_0 should mix strongly with $s\bar{s}$ mesons. If so, the K^-p interactions may provide an excellent production mechanism for the production of the scalar glueballs G_0.

Michael Chanowitz, "Chiral Suppression of Scalar-Glueball Decay,"
PRL **95**, 172001 (2005)

Conclusions and Future Prospects

- Three Exotic Mesons from BNL-E852:

1. $\pi_1(1400)$: $M \sim 1370$ MeV, $\Gamma \sim 400$ MeV:
   $\rightarrow \eta\pi$
   $\not\rightarrow \eta'\pi,\ \rho\pi,\ f_1(1285)\pi,\ b_1(1235)\pi$

   $\Rightarrow$ If $10 \oplus \overline{10}$, then predict <u>no</u> $\eta_1(1400)$ partner but $\rho(1400)$

   ◇ Constituents: $(n\bar{n}) + (n\bar{n})$?

2. $\pi_1(1600)$: $M \sim 1590$ MeV, $\Gamma \sim 300$ MeV:
   $\not\rightarrow \eta\pi$
   $\rightarrow \eta'\pi,\ \rho\pi,\ f_1(1285)\pi,\ b_1(1235)\pi$

   ◇ Constituents: $(n\bar{n}) + (n\bar{n})$? $\oplus$ $(n\bar{n}) + \text{gluon}$?

3. $\pi_1(2000)$: $M \sim 2000$ MeV, $\Gamma \sim 300$ MeV
   $\rightarrow f_1(1285)\pi,\ b_1(1235)\pi$:

   ◇ Constituents: $(n\bar{n}) + \text{gluon}$?

Conclusions and Future Prospects

- Future Prospects beyond

  BNL-E852, VES/IHEP/Protvino/Russia, FOCUS/Fermilab:

1. Beijing Spectrometer/China and BaBar/SLAC and Belle/KEK)
2. CLEO-C (CESR/Cornell)
3. PANDA (GSI/Darmstadt/Germany)

   $\bar{p}$'s from 1.5–15 GeV/c
4. GLUE-X (Hall D/JLAB)

   Photons with a maximum energy of 9 GeV
5. GSI/Darmstadt/Germany, J-Parc/Japan and COMPASS/CERN:

   ⋆ Use separated K^- beam to search for

   exotic strangeonia ($s\bar{s} + n\bar{n}$ and $s\bar{s} + g$)

   ⋆ Search for exotic strange mesons,

   $SU(3)$ partners of the nonstrange exotic mesons