BABAR Update and Plans

David B. MacFarlane
SLAC Annual Program Review
June 14, 2005
The BABAR Collaboration
11 Countries
80 Institutions
623 Physicists

USA [38/311]
California Institute of Technology
UC, Irvine
UC, Los Angeles
UC, Riverside
UC, San Diego
UC, Santa Barbara
UC, Santa Cruz
U of Cincinnati
U of Colorado
Colorado State
Harvard U
U of Iowa
Iowa State U
LBNL
LLNL
U of Louisville
U of Maryland
U of Massachusetts, Amherst
MIT
U of Mississippi
Mount Holyoke College
SUNY, Albany
U of Notre Dame
Ohio State U
U of Oregon
U of Pennsylvania
Prairie View A&M U
Princeton U
SLAC
U of South Carolina
Stanford U
U of Tennessee
U of Texas at Austin
U of Texas at Dallas
Vanderbilt
U of Wisconsin
Yale

Canada [4/24]
U of British Columbia
McGill U
U de Montréal
U of Victoria

China [1/5]
Inst. of High Energy Physics, Beijing

France [5/53]
LAPP, Annecy
LAL Orsay

Germany [5/24]
Ruhr U Bochum
U Dortmund
Technische U Dresden
U Heidelberg
U Rostock

Italy [12/99]
INFN, Bari
INFN, Ferrara
Lab. Nazionali di Frascati dell’ INFN
INFN, Genova & Univ
INFN, Milano & Univ
INFN, Napoli & Univ
INFN, Padova & Univ
INFN, Pisa & Univ & Scuola Normale Superiore

The Netherlands [1/4]
NIKHEF, Amsterdam

Norway [1/3]
U of Bergen

Russia [1/13]
Budker Institute, Novosibirsk

Spain [2/3]
IFIC-Valencia
IFIC-Valencia

United Kingdom [11/75]
U of Birmingham
U of Bristol
Brunel U
U of Edinburgh
U of Liverpool
Imperial College
Queen Mary, U of London
U of London, Royal Holloway
U of Manchester
Rutherford Appleton Laboratory
U of Warwick

INFN, Perugia & Univ
INFN, Roma & Univ "La Sapienza"
INFN, Torino & Univ
INFN, Trieste & Univ
BABAR Detector

1.5T solenoid

DIRC (PID)
144 quartz bars
11000 PMs

EMC
6580 CsI(Tl) crystals

Instrumented Flux Return
iron / RPCs or LSTs (muon / neutral hadrons)

Silicon Vertex Tracker
5 layers, double sided strips

Collaboration founded in 1993
Detector commissioned in 1999
DCH electronics upgrade

- **Motivation:**
  - Reduce deadtime due to serialization and shipping of data from DIOM to ROM

- **Upgrade in two steps:**
  - Phase 1 (summer 2004)
    - Ship only 1/2 waveform information (32 → 16 bytes) from frontends
    - No change observed with data
  - Phase 2 (Oct 2005)
    - Larger FPGA for feature extraction before transmission → hardware change
    - New boards in production
IFR upgrade with LSTs

Bottom & top sextants installed summer 2004
Remaining sextants delayed until summer 2006
LST installation summer 2004

Bottom sextant: Aug 15-Sep 4
Top sextant: Sep 16-29
LSTs are fully operational

Efficiency curves from Run 5 data

LST sextants

wire holders

RPC sextants
Weak Interaction in Standard Model

**Unitarity Triangle as a summary of Standard Model $b$ physics**

$$V = \begin{pmatrix}
  v_{ud} & v_{us} & v_{ub} \\
  v_{cd} & v_{cs} & v_{cb} \\
  v_{td} & v_{ts} & v_{tb}
\end{pmatrix}$$

$+ \text{ phases}$

$\Gamma(b \to u \ell \nu)$

$\alpha = \phi_2$

$\gamma = \phi_3$

$\beta = \phi_1$

$t_B \text{ and } \Gamma(b \to c \ell \nu)$

$\eta$

$\bar{\rho}$

(0,0)

(1,0)

Apex at $(\bar{\rho}, \eta)$
\textbf{CP violation in B decays}

- CPV through interference of decay amplitudes

\[ \Gamma(B \to f) = |A_1 + A_2 e^{i\varphi_{wk}} e^{i\delta_{st}}|^2 \]

\[ \Gamma(\bar{B} \to \bar{f}) = |A_1 + A_2 e^{-i\varphi_{wk}} e^{i\delta_{st}}|^2 \]

\( \Gamma(B \to f) \neq \Gamma(\bar{B} \to \bar{f}) \) for \( \varphi_{wk} \neq 0 \) and \( \delta_{st} \neq 0 \)
**CPV in charmonium modes**

\[ \Gamma(b \rightarrow u \ell \nu) \]

\[ (\rho, \eta) \]

\[ \alpha = \phi_2 \]

\[ \beta = \phi_1 \]

\[ \gamma = \phi_3 \]

\[ (0,0) \rightarrow (1,0) \]

\[ \tau_B \text{ and } \Gamma(b \rightarrow c \ell \nu) \]

**Interference of \( b \rightarrow c \) tree decay with mixing**

**CPV in \( B^0 \rightarrow J/\psi K^0 \)**

**B^0 - \( \bar{B}^0 \) mixing**
Measuring time-dependent CP asymmetries

$\beta_{\gamma(4S)} = 0.56$

$\Delta t \approx \Delta z \frac{1}{\langle \beta \gamma \rangle c}$

$\Delta t$ is a signed quantity

$\sigma_{\Delta t} \sim 1 \text{ ps} \Leftrightarrow 170 \mu\text{m}$

$\tau_B \sim 1.6 \text{ ps} \Leftrightarrow 250 \mu\text{m}$

Exclusive $B$ meson and vertex reconstruction

Start the clock

Tag vertex reconstruction

Start the clock

Flavor Tagging

Tagging performance: $Q = 30.5\%$

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$\sin 2\beta$ results from charmonium modes

$(c\bar{c})K^0_S$ (CP odd) modes

$(c\bar{c})K^0_L$ (CP even) modes

$\sin 2\beta = +0.722 \pm 0.040 \pm 0.023$

$|\lambda| = |\bar{A}/A| = 0.950 \pm 0.031 \pm 0.013$

Limit on direct CPV

205 fb$^{-1}$ on peak or 227 $M$ $B\bar{B}$ pairs

7730 CP events (tagged signal)
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<th>Journal Papers</th>
<th>BABAR</th>
<th>Belle</th>
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<table>
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<th>Conference Contributions</th>
<th>BABAR</th>
<th>Belle</th>
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<td>Papers submitted to ICHEP04</td>
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<td>63</td>
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<tr>
<td>Abstracts submitted to LP05</td>
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BABAR publication history
Even our backgrounds yield physics!

Inner detector tomography with pK_s vertices from electro- and hadro-production events
Searches for the $\theta(1540)$ pentaquark

Object lesson: with data in hand, clever analysis ideas will emerge

HERMES: possible acceptance loss at low mass (PID on proton > 4.1 GeV/c)

BABAR is also a tau, charm, ISR, and $\gamma\gamma$ Factory
Progress on b quark couplings

\[ \Gamma(b \rightarrow u \ell \nu) \]

\[ \alpha = \phi_2 \]

\[ \gamma = \phi_3 \]

\[ \beta = \phi_1 \]

\[ V_{td} / V_{ts} \]

\[ V_{ub} / V_{cb} \]

\[ V_{cb} \]

\[ B^0 - \bar{B}^0 \text{ mixing} \]

\[ \tau_B \text{ and } \Gamma(b \rightarrow c \ell \nu) \]
Search for $B \rightarrow \rho \gamma, \omega \gamma$

**BABAR-PUB-04/035**

**211M $B\bar{B}$ pairs**

Simultaneous fit to $B \rightarrow \rho^+ \gamma, \rho^0 \gamma, \omega \gamma$

$BF < 1.2 \times 10^{-6}$ (90% CL)

Penguins are starting to provide meaningful CKM constraint

$\rho \gamma$ 95% CL BABAR allowed region (inside the blue arc)

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Inclusive $|V_{ub}|$ measurements

Different approaches available to extract partial rates

$$\frac{\Gamma(b \rightarrow u \ell \bar{\nu})}{\Gamma(b \rightarrow c \ell \bar{\nu})} \approx \left| \frac{V_{ub}}{V_{ub}} \right|^2 \approx \frac{1}{50}$$

- hep-ex/0408075
- hep-ex/0408045
- hep-ex/0408068

$82 \text{ fb}^{-1}$
$V_{ub}$ from $B_{reco}$-tagged $M_x$-$q^2$ analysis

Inclusive methods now: $\sigma(V_{ub}) = 11.5\%$

Imagine what this will look like with 10x data in 2008!
CPV in charmless modes

\[ \Gamma(b \rightarrow u \ell \nu) \]

\[ \alpha = \phi_2 \]
\[ \beta = \phi_1 \]
\[ \gamma = \phi_3 \]

CPV in \( B^0 \rightarrow \pi \pi, \rho \pi, \rho \rho, \ldots \)

\[ B^0 - \bar{B}^0 \] mixing

\[ \Gamma \rightarrow A \]

3rd component: sizable Penguin diagram

Interference of suppressed \( b \rightarrow u \) tree decay with mixing
**Very promising: \( B \rightarrow \rho\rho \) decays**

Extraction of \( \alpha \) similar to \( \pi\pi \), but with advantage of smaller Penguin pollution:

\[
\frac{|A^{00}|}{|A^{+0}|} = \frac{|A^{00}|}{|A^{-+}|} \] found small: \( \Delta \alpha_{peng} \) small

\[|\alpha - \alpha_{eff}| < 11^0 \text{ (90\% CL)}\]

Potentially \( \rho^+ \rho^- \) could be mixed \( CP \), but is found to be almost pure \( CP = +1 \)

\[B^0 \rightarrow \rho^+ \rho^- \text{ (232M } BB \text{ pairs)}\]

Signal: \( 617 \pm 52 \) events

\[f_{long} = 0.978 \pm 0.014 \pm 0.021 \]

\[S_{long} = -0.33 \pm 0.24 \pm 0.08 \pm 0.14 \]

\[C_{long} = -0.03 \pm 0.18 \pm 0.09 \]
Summary of constraints on $\alpha$

**BABAR only**

Mirror solutions disfavored

From combined $\pi\pi, \rho\pi, \rho\rho$ results:

$$\alpha = \left[ 100 \pm 9 \right]^\circ$$

**CKM indirect constraint fit:** $\alpha = 98 \pm 16^\circ$

Object lesson: with data in hand, clever analysis ideas will emerge
Unexpectedly good progress on gamma!

\[ \Gamma(b \rightarrow u \ell \nu) \]

\[ \alpha = \phi_2 \]

\[ \gamma = \phi_3 \]

\[ \beta = \phi_1 \]

\[ B^0 - \bar{B}^0 \text{ mixing} \]

\[ \tau_B \text{ and } \Gamma(b \rightarrow c \ell \nu) \]

Interference of color-allowed and color-suppressed tree decays

\[ \gamma : \text{CPV in } B^0 \rightarrow D_{CP}K, D_{DCS}K, \ldots \]

Effect depends on ratio of two diagrams
Dalitz plot analysis for gamma

Idea: Increase $B$ decay interference through $D$ decay Dalitz plot

From Dalitz analysis:
$$\gamma = \left[ 63^{+34}_{-26} \right]^\circ$$

Indirect constraint:
$$\gamma = \left[ 58^{+8}_{-7} \right]^\circ$$

Object lesson: with data in hand, clever analysis ideas will emerge
UT from $\sin 2\beta$ & indirect constraints
UT from CP violation measurements alone

New B Factory milestone: Comparable UT precision from CPV alone
Global CKM fit: 2005

Paradigm change!

Now: looking for New Physics as correction to CKM
CPV in Penguin Modes

\( \Gamma(b \rightarrow u\ell\nu) \)

\( \rho, \eta \) (0,0)

\( \alpha = \phi_2 \)

\( \beta = \phi_1 \)

\( \gamma = \phi_3 \)

\( \tau_B \) and \( \Gamma(b \rightarrow c\ell\nu) \)

Interference of suppressed \( b \rightarrow s \) Penguin decay with mixing

CPV in \( B^0 \rightarrow \phi K_s^0, \eta' K_s^0, \ldots \)
Potential New Physics contributions

\[ B^0 \rightarrow \phi K^0 \]

\[ B^0 \rightarrow \eta' K^0 \]

New physics in loops?

SUSY contribution with new phases
CPV in charmonium & s-penguin modes

Good consistency between B Factory experiments

3.7σ between CP violation in s-penguin vs sin2β (cc)

No sign of Direct CP

June 14, 2005  BABAR Update and Plans 31
New three-body mode: \( B \to K_S K_S K_S \)

88\( \pm 10 \) signal events

\[ -\eta_{CP} \cdot S_{3K_S} = +0.71^{+0.38}_{-0.32} \pm 0.04 \]

\[ C_{3K_S} = -0.34^{+0.28}_{-0.25} \pm 0.05 \]
How good are Standard Model predictions?

Charmonium
0.726 ± 0.037

Present SM uncertainty "3 sigma"

Beneke, CKM05

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BABAR Update and Plans
PEP-II/BABAR run plan for 2005-2008

- **Run 5: Apr 2005 to July 31, 2006**
  - Down for month of October for PPS certification, Linac & PEP-II safety issues, DCH readout phase 2, LST preparations
  - Run through holidays in Dec 2005

- **LST installation down: Aug 1 to Nov 30, 2006**
  - Installation of remaining 4 barrel sextants of the IFR
  - Installation of PEP-II vacuum upgrades and rf-station
  - LCLS construction and installation

- **Run 6: Dec 1, 2006 to Aug 31, 2007**
  - Down for Sep-Nov 2007 for LCLS construction & installation
  - Run through holidays in Dec 2006

- **Run 7: Dec 1, 2007 to Sep 30, 2008**
  - Run through holidays in Dec 2007
Projections of data sample growth

1 month
PPS down

4 month
LST down

Double data by summer 2006

Double again by Sep 2008
**Snapshot I: Summer 2006**

**Penguin Sum Comparison**

**Penguin Significance**

*Sum of all modes reaches ~5 sigma level*
Snapshot II: Summer 2008

- Golden modes reach 5 sigma level
- Luminosity expectations:
  - 2004 = 240 fb^{-1}
  - 2008 = 1.1 ab^{-1}
- Projections are statistical errors only; but systematic errors at few percent level
- 5 sigma discovery region if non-SM physics is 0.30 effect
- \( \sigma(S) = 0.30 \)
**Global CKM fit: 2008**

![Graph showing 95% contours and CKM parameters](image)

- $\sigma(V_{ub}) = 7\%$
- $\sigma(\Delta m_s) = 5\%$
- $\sigma(\sin 2\beta) = 0.019$
- $\sigma(\alpha) = 6^\circ$
- $\sigma(\gamma) = 10^\circ$

**June 14, 2005**

**BABAR Update and Plans**
Snapshot III: Fall 2010?

Present SM uncertainty “1 sigma”

\[ B^0 \rightarrow X K_S^0 \]

NP in Z-Penguins

NP in gluonic-Penguins

NP in chromomagnetic operator

Projected errors

Present SM uncertainty “1 sigma”

SM + various New Physics

Buchalla, Hiller, Nir, Raz
hep-ph/0503151
**UT constraints with ~no NP assumptions**

- Assumption: no NP in trees [almost any NP model]

- Assumption: NP only in $|\Delta F|=2$ and $b \rightarrow s$ [not too strong]

- $\sigma(V_{ub}) = 11.5\%$

- 68% contours
UT constraints in 2008

- Assumption: no NP in trees [almost any NP model]

- Assumption: NP only in $|\Delta F|=2$ and $b\to s$ [not too strong]

Significant constraint on all New Physics models in LHC era

$\sigma(V_{ub}) = 7\%$
Summary: Physics reach of BABAR

_goal for 2005-2006: double current data set_
- Delay in Run 5 can be overcome by summer 2006 with extended running period, with substantial reduction in errors on CP violation asymmetries in rare decay modes
- Error on average of Penguin modes should reach 0.06

_goal for 2007-2008: double again to ~1 ab⁻¹_
- Individual Penguin modes with errors in range 0.06-0.12
- Suite of fundamental Standard Model measurements with substantially improved levels of precision

- Sensitivity to New Physics through rare decays, CP violation, & large data sample with a significant discovery potential
- Full program of flavor physics/CP violation measurements provide fundamental constraints on future New Physics discoveries

_beyond 2008 might offer exciting opportunities if New Physics has been seen by B Factories & LHC_
Backup Slides
BABAR line organization
### BABAR training matrix

<table>
<thead>
<tr>
<th>Category</th>
<th>Training Requirement</th>
<th>Recommended Supervisor</th>
<th>Documentation Requirements</th>
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<tbody>
<tr>
<td>a. Short-term visitor</td>
<td>None. Category (b) or higher recommended for BABAR users.</td>
<td>None</td>
<td>None</td>
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<tr>
<td>b. Office worker</td>
<td>EOESH, GERT, ES&amp;H 239</td>
<td>Member of BABAR Management team or SLAC Group Leader</td>
<td>Office JHAM, Office Building AHA</td>
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<td>c. Shift-taker</td>
<td>(b) above plus Shift Training</td>
<td>Run Coordinator</td>
<td>(b) above plus Shifter JHAM, IR-2 AHA</td>
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<tr>
<td>d. System worker</td>
<td>(b) above plus BABAR Orientation, job specific training</td>
<td>System Manager</td>
<td>(b),(c) above plus System JHAM(s)</td>
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<tr>
<td>e. R&amp;D worker</td>
<td>(b) above plus job specific training</td>
<td>R&amp;D Manager</td>
<td>(b) above plus job specific JHAM, job site AHA</td>
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BABAR work categories

Short-term visitor
Attends no more than one collaboration meeting per year or equivalent

Office worker
Only works in the ROB or one of the other office areas but not IR-2 or other laboratory space

Shift-taker
Stands shifts on BABAR in IR-2

System worker
Does maintenance work on a detector system in IR-2 or in a system laboratory space

R&D worker
Does development or testing work in a lab setting or temporary system space
### Operational & physics manpower

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<td>125.4</td>
<td>125.4</td>
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**Detector operations, online & offline data processing, MC production**
BABAR Detector
$B^0 \rightarrow J/\psi K_S^0$
Recoil B

Flavor tag: $b \rightarrow ce^- \nu_e$

$\nu_e$ vertex separation = time difference

Recoil B

The PEP-II/BaBar B-Factory
Run: 43532
Date Taken: Wed Jan 7 22:44:38.421915000 2004 PST
HER: 8.994 GeV, LER: 3.110 GeV
Summer 2004 results for $B \rightarrow \pi\pi$

>3σ discrepancy between BABAR & Belle

Belle 3.2σ evidence for Direct $CP$ violation not supported by BABAR measurements

Caution averaging!
Winter 2005 results for $B \rightarrow \pi\pi$

Belle 4.0$\sigma$ evidence for Direct $CP$ violation not supported by BABAR measurements

~2.2$\sigma$ discrepancy between BABAR & Belle
**Combined GLW and ADS constraint on $\gamma$**

**BABAR & Belle combined**

From combined GLW and ADS fit:

$\gamma = \left[ 51^{+20}_{-34} \right]^{\circ}$

*CKM indirect constraint fit: $\gamma = \left[ 58^{+8}_{-7} \right]^{\circ}$*
## Competition: Better physics performance

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<th>stat err</th>
<th>lumi</th>
<th>Untag sample</th>
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<td>-0.100</td>
<td>0.140</td>
<td>192</td>
<td>1184</td>
<td>2.721</td>
<td>1.940</td>
<td>1.403</td>
<td>1.968</td>
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<td>rhopi A-</td>
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<td>0.160</td>
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<td>1184</td>
<td>3.431</td>
<td>1.940</td>
<td>1.769</td>
<td>3.129</td>
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<td>1.432</td>
<td>2.153</td>
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</tr>
</tbody>
</table>

Typically better errors for BABAR despite larger Belle dataset

Bottom line: BABAR is getting the equivalent of a factor of 2 in luminosity through better analysis/detector performance
\[ \Gamma(B^0 \rightarrow \pi^-\ell\nu) = 2 \Gamma(B^+ \rightarrow \pi^0\ell\nu) \]

### $m_{ES}$ and $\Delta E$ fit for $B \rightarrow \pi\ell\nu$

<table>
<thead>
<tr>
<th>$q^2$ range</th>
<th>$m_{ES}$ Candidates / 0.01 GeV</th>
<th>$\Delta E$ Candidates / 0.1 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 &lt; $q^2$ &lt; 5 GeV$^2$</td>
<td><img src="image1.png" alt="Graph" /></td>
<td><img src="image2.png" alt="Graph" /></td>
</tr>
<tr>
<td>5 &lt; $q^2$ &lt; 10 GeV$^2$</td>
<td><img src="image3.png" alt="Graph" /></td>
<td><img src="image4.png" alt="Graph" /></td>
</tr>
<tr>
<td>10 &lt; $q^2$ &lt; 15 GeV$^2$</td>
<td><img src="image5.png" alt="Graph" /></td>
<td><img src="image6.png" alt="Graph" /></td>
</tr>
<tr>
<td>15 &lt; $q^2$ &lt; 20 GeV$^2$</td>
<td><img src="image7.png" alt="Graph" /></td>
<td><img src="image8.png" alt="Graph" /></td>
</tr>
<tr>
<td>20 &lt; $q^2$ &lt; 25 GeV$^2$</td>
<td><img src="image9.png" alt="Graph" /></td>
<td><img src="image10.png" alt="Graph" /></td>
</tr>
</tbody>
</table>

- **Data**
- **Signal MC**
- **Comb. Sig.**
- **Crossfeed**
- **b\rightarrow\text{cl}\nu**
- **qq**

- **5 $q^2$ bins**
  - $427 \pm 68 \, \pi^-\ell\nu$
  - $147 \pm 23 \, \pi^0\ell\nu$
$m_{ES}$ and $\Delta E$ fit for $B \rightarrow \rho \ell \nu$

$$\Gamma(B^0 \rightarrow \rho^- \ell \nu) = 2 \Gamma(B^+ \rightarrow \rho^0 \ell \nu)$$

Data

- $82 \text{ fb}^{-1}$

Signal MC

Comb. Sig.

Crossfeed

$b \rightarrow c \ell \nu$

$qq$

$m_{ES}$

3 $q^2$ bins

$101 \pm 17 \rho^- \ell \nu$

$104 \pm 18 \rho^0 \ell \nu$