Tevatron 2014 Impact on NOνA
Fermilab PAC
August 27, 2010
Impact Summary

Impact of Tevatron 2014 on NOνA:

- Reduce the NOνA data set by roughly a factor of 2 in the 2015-2016 time period.
- Delay first results on νμ antineutrino oscillations by 2 years.
- Delay first results on mass ordering and the CP-violating phase by 2 years.
- Delay the final results by 1.5 years.
- Add an additional 3.7 M$ to the cost of the project.
### Scenarios

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Far detector</strong></td>
<td>detector construction</td>
<td></td>
<td>10 kton complete</td>
<td>14 kton complete</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Near detector</strong></td>
<td></td>
<td>cavern construction</td>
<td>near detector complete</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Baseline accelerator plan</strong></td>
<td>320 kW</td>
<td></td>
<td>NuMI, RR, &amp; MI work</td>
<td>ramp</td>
<td>700 kW</td>
<td></td>
</tr>
<tr>
<td><strong>Impacted accelerator plan</strong></td>
<td>320 kW</td>
<td></td>
<td>NuMI</td>
<td>400 kW</td>
<td>RR</td>
<td>ramp</td>
</tr>
</tbody>
</table>
Why 400 kW?

- This is consistent with the present limit of 320 kW and consistent with the 700 kW NOvA baseline.
- 320 kW → 400 kW is due mainly to two ~10% effects: a decrease in the cycle time from 2.2 to 2.0 s and interleaving cycles so that NOvA gets an average of 10 Booster batches instead of 9.
- 400 kW → 700 kW is also due to two effects: a decrease in the cycle time from 2.0 s to 1.33 s and an increase in the number of Booster batches from 10 to 12.
### Detailed Power Assumptions

<table>
<thead>
<tr>
<th></th>
<th>Baseline</th>
<th>Run IIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Booster batch Intensity (e12)</td>
<td>4.3</td>
<td>4.3</td>
</tr>
<tr>
<td>Average number of NO\textnu\textalpha batches</td>
<td>12</td>
<td>10</td>
</tr>
<tr>
<td>MI efficiency</td>
<td>0.95</td>
<td>0.95</td>
</tr>
<tr>
<td>Average NO\textnu\textalpha Intensity (e12)</td>
<td>49</td>
<td>41</td>
</tr>
<tr>
<td>Fill period (s)</td>
<td>0</td>
<td>0.67</td>
</tr>
<tr>
<td>Base cycle time (s)</td>
<td>1.33</td>
<td>1.33</td>
</tr>
<tr>
<td>Total cycle time (s)</td>
<td>1.33</td>
<td>2.00</td>
</tr>
<tr>
<td>NO\textnu\textalpha Power (kW)</td>
<td>706</td>
<td>392</td>
</tr>
</tbody>
</table>
Integrated POT & Detector Mass

![Graph showing integrated POT and detector mass over calendar years from 2010 to 2022. The graph includes lines for Baseline POT, Impacted, Impacted w/o RR, and Detector Mass (kt).]
Integrated (POT × Detector Mass)
Ratio Impacted / Baseline

[Graph showing the ratio impacted compared to baseline from 2012 to 2021]
90% CL Sensitivity to $\sin^2(2\theta_{13})$

- $\sin^2(2\theta_{13})$ vs CY
- Two curves: baseline and impacted
- Y-axis: $\sin^2(2\theta_{13})$ from 0 to 0.05
- X-axis: CY from 2013 to 2019
Other Experiments: Reactors

- Reactors: Three reactor experiments will report results in the 2014 time frame (or sooner): Double Chooz, RENO, and Daya Bay.
  - Reactors do not measure the same thing as accelerator experiments.
    - Reactors measure $\sin^2(2\theta_{13})$.
    - Accelerators measure a complex combination of $\sin^2(2\theta_{13})$, $\sin^2(\theta_{23})$, the CP-violating phase $\delta$, and the mass ordering. If all these effects go in the same direction, the oscillation rate in reactors and accelerator experiments can differ by a factor of 2.5.
  - Thus, a comparison of reactor and accelerator results is informative.
Other Experiments: T2K

- T2K is the only other accelerator experiment in this time frame. It should measure the identical oscillations as NO$\nu$A except for matter effects, which are used to determine the mass ordering. These effects are 2.7 times larger in NO$\nu$A than in T2K.

- T2K is running now, but at low power. They are projecting a slow ramp-up of power (next slide).
T2K Power Projections

AN EXPECTED BEAM POWER CURVES
FOR RCS AND MR FAST BEAM EXTRACTION

\[ P_{MR} (8\text{-bunch@30\text{GeV}}) = 1.6 \times P_{RCS} / MRCYCLE \]

( ): Beam transfer ratio from RSC to MR

- 6sec (2.7%)
- 3.62sec (+.5%)
- 3.25sec (5.0%)
- 2.47sec (6.5%)
- 2.23sec (7.2%)
- (maximum cycle with existing power supply)

- 0.72MW
- 1.7MW

MR CYCLE [sec] vs BEAM POWER [MW]

JFY:
- 2008 H20
- 2009 H21
- 2010 H22
- 2011 H23
- 2012 H24
- 2013 H25
- 2014 H26
- 2015 H27
- 2016 H28

2010 February
Status of T2K
Akira Komatsu (TRIUMF)

Gary Feldman
PAC Meeting
27 August 2010
Estimated Sensitivities
90% CL for $\sin^2(2\theta_{13})$ at the end of CY 2014

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Double Chooz</td>
<td>0.03</td>
</tr>
<tr>
<td>RENO</td>
<td>0.02</td>
</tr>
<tr>
<td>Daya Bay</td>
<td>0.009</td>
</tr>
<tr>
<td>T2K</td>
<td>0.02 0.01</td>
</tr>
<tr>
<td>NOvA baseline</td>
<td>0.011 0.012</td>
</tr>
<tr>
<td>NOvA impacted</td>
<td>0.015 0.016</td>
</tr>
</tbody>
</table>

Warning: 90% CL Gaussian calculation at the sensitivity level does not mean much for NOvA and T2K. Both would have only a handful of events, e.g. 2.8 signal on a background of 2.5 for NOvA.
Antineutrinos

- The major rationale for the NOνA experiment is not to measure sin^2(2\theta_{13}), but to compare neutrino and antineutrino oscillations to gain information on the mass ordering of neutrinos and CP violation.

- A difference in neutrino and antineutrino ν_μ disappearance oscillations would be a sign of beyond-the-standard-model physics.
  - There is currently an about 2-σ effect seen by the MINOS experiment. If this persists into the NOνA era, NOνA will be able to easily confirm or rebut the effect.
NOvA Sensitivity to the MINOS Effect

1 year each $\nu$ and $\bar{\nu}$

3 years each $\nu$ and $\bar{\nu}$

\[
\Delta m^2_{23} \left( 10^{-3} \text{ eV}^2 \right)
\]

\[
\sin^2(2\theta_{23}) - \sin^2(2\theta_{23})
\]
Impact on Antineutrino Running

- NO\(\nu\)A would normally start running antineutrinos after one year of neutrino running, provided it had seen a believable \(\nu_\mu \rightarrow \nu_e\) signal by then. In the baseline scenario, this would be in June 2014.

- In the impacted scenario, this point would come at the end of 2015, just as we were finishing commissioning the 700 kW beam. We would then want to delay switching to antineutrinos for six months to assure ourselves that the 400 kW and the 700 kW configurations gave the same results. Thus, we would not start antineutrino running until mid 2016, a two year delay.
95% CL Determination of the Mass Ordering at the Most Favorable $\delta$

\[
\sin^2(2\theta_{13})
\]
There would be at least a 1-year delay in reaching CD-4. We estimate the additional cost to be 3.7 M$:

- 1.1 M$ for escalation on the delayed modifications to the Main Injector and Recycler.
- 2.6 M$ for continued, but reduced, project management.
Conclusion

- NOνA is the flagship US accelerator experiment for the 2010-2020 decade. It is also the first step in the future US intensity frontier program.

- It was already delayed a year due to the disastrous omnibus funding bill in December 2007. However, it is still competitive with the other second-generation experiments in the field due to slips in their schedules.

- Delaying it further would
  - Make it less relevant in the time period when all experiments will be reporting significant results.
  - Reinforce the impression abroad that the US is not a reliable partner.
Horn and Target Tunes

Unoscillated $\nu_\mu$

$\nu_\mu \rightarrow \nu_e$, $\sin^2(2\theta_{13}) = 0.01$
Parameters Consistent with a $2\% \ \nu_\mu \rightarrow \nu_e$ Oscillation Probability

$\sin^2(2\theta_{13})$ vs. $P(\bar{\nu}_e)$ for $P(\nu_e) = 0.02$

$L = 810$ km, 12 km off-axis
$\Delta m^2 = 2.4 \times 10^{-3}$ eV$^2$
$\sin^2(2\theta_{23}) = 1$
95% CL Resolution of the Mass Ordering
NOvA Alone

Normal Ordering

2 sin^2(θ_{23}) sin^2(2θ_{13})

Inverted Ordering

sin^2(2θ_{23}) = 1

L = 810 km, 15 kT

Δm^2 > 0

3 years for each ν and ν̅
NOvA at 700 kW,
1.2 MW, and 2.3 MW

Δm^2 = 2.4 × 10^{-3} eV^2

NOvA

Gary Feldman

PAC Meeting

27 August 2010

23
$\delta$ vs. $\theta_{13}$ Contours: Best Possible $\delta$

1 and 2 $\sigma$ Contours for Starred Point for NOvA

$\Delta m_{32}^2 = 2.4 \times 10^{-3} \text{ eV}^2$
$\sin^2(2\theta_{32}) = 1$

NOvA 3 years at 700 kW for each $\nu$ and $\bar{\nu}$

Gary Feldman
PAC Meeting
27 August 2010
$\delta$ vs. $\theta_{13}$ Contours: Worst Possible $\delta$

T2K and NO$\nu$A Alone

1 and 2 $\sigma$ Contours for Starred Point for T2K

1 and 2 $\sigma$ Contours for Starred Point for NO$\nu$A

Contours, not limits

$\Delta m^2 = 2.4 \times 10^{-3} \text{eV}^2$

$\sin^2(2\theta_{23}) = 1$

T2K 6 years at 700 kW, $\nu$ only

NO$\nu$A 3 years at 700 kW for each $\nu$ and $\bar{\nu}$
δ vs. $\theta_{13}$ Contours: Worst Possible δ
T2K and NOvA Combined

1 and 2 $\sigma$ Contours for Starred Point for NOvA + T2K

NOvA

$\Delta m_{32}^2 = 2.4 \times 10^{-3} \text{ eV}^2$  
$\sin^2(2\theta_{23}) = 1$

NOvA 3 years  
at 700 kW  
for each ν and $\bar{\nu}$  
+ T2K 6 years  

$\Delta m^2 > 0$  
$\Delta m^2 < 0$

NOvA

$\Delta m_{32}^2 = 2.4 \times 10^{-3} \text{ eV}^2$  
$\sin^2(2\theta_{23}) = 1$

NOvA 3 years  
at 2.3 MW  
for each ν and $\bar{\nu}$  
+ T2K 6 years  
at 3x power

$\Delta m^2 > 0$  
$\Delta m^2 < 0$