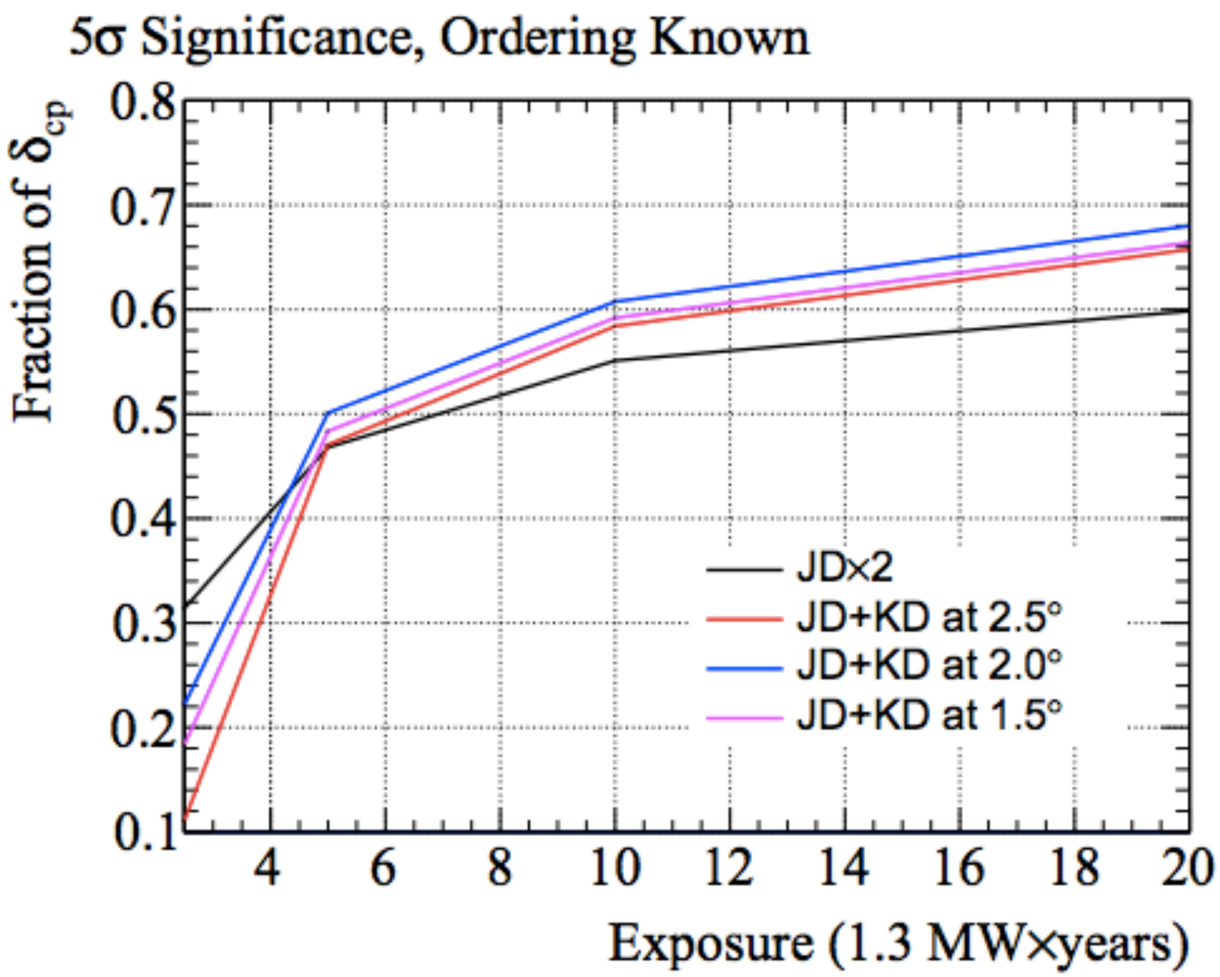
CONSIDERATIONS FOR SYSTEMATIC ERRORS IN T2HKK

MARK HARTZ

KAVLI IPMU, UNIVERSITY OF TOKYO/TRIUMF

SYSTEMATIC ERRORS IN THE 2 DETECTOR CONFIGURATION

- The inclusion of a second detector in Korea has the potential to overcome systematic limitations that a single detector in Japan my encounter in <10 years

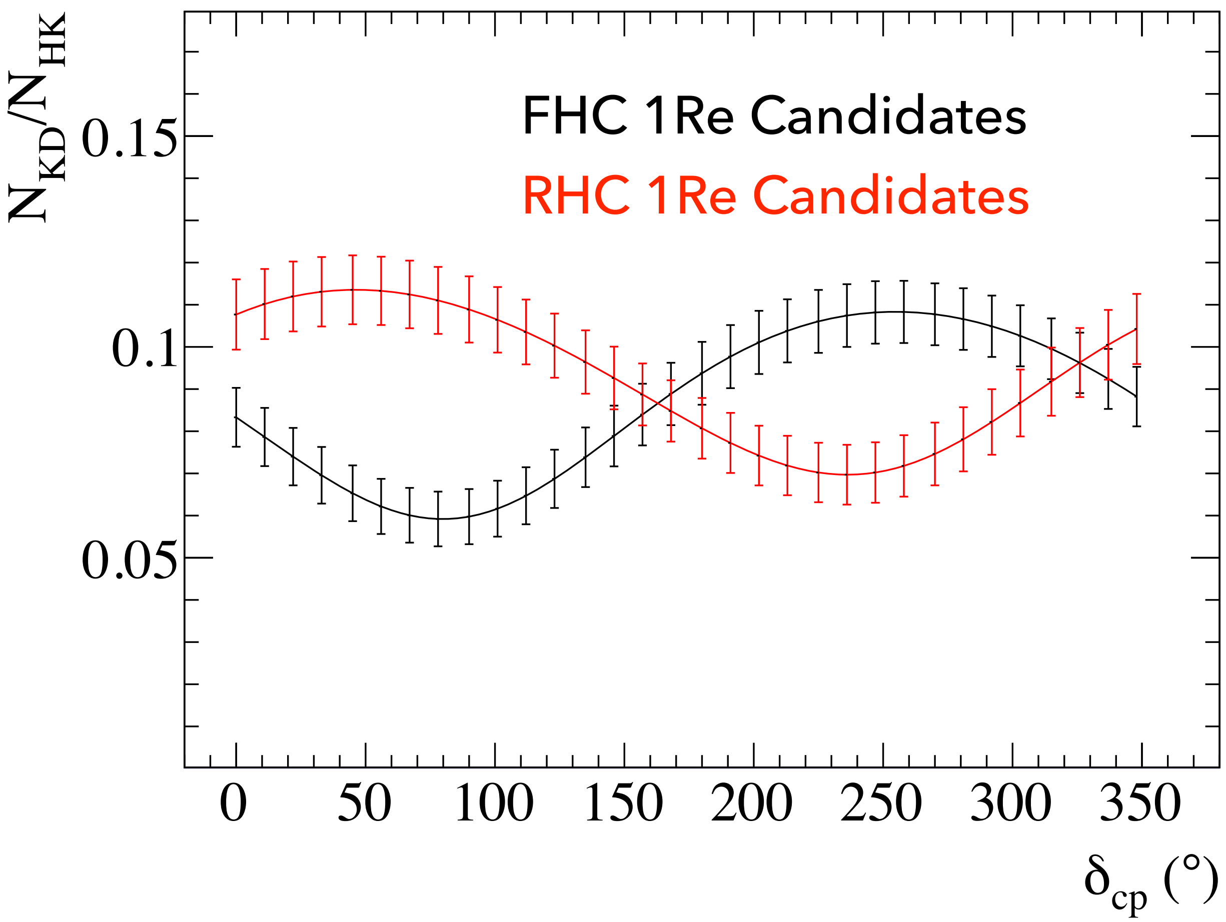


Sensitivity increasing faster with exposure when a Korean detector is included

- The obvious improvement: Korean detector has a larger CP effect, but fewer statistics. Becomes systematics limited much later

FIRST VS SECOND OSCILLATION MAXIMUM

- A detector in Korea measures the oscillation probability at the second oscillation maximum, while the Japanese detector measures at the first oscillation maximum
- The relative magnitude of oscillations at the second and first oscillation maxima depend on sin(δ_{cp})



Ratio of the observed event rates in Korea (2nd oscillation maximum) relative to Japan (1st oscillation maximum)

3:1 Antineutrino:Neutrino mode running

2.0 degree off-axis for Korean detector

Error bars are statistical

MEASURING CP ODD EFFECT

- Two ways to measure $\sin(\delta_{cp})$:
  - Compare neutrinos and antineutrinos at the same baseline
    - Sensitive to systematic errors on the neutrino/antineutrino interaction ratio
  - Compare (anti)neutrinos to (anti)neutrinos at two different baselines
    - Not sensitive to uncertainty on neutrino/antineutrino interaction ratio
- Keep in the mind that the second approach is measuring $\sin(\delta_{cp})$ in the framework of 3 neutrino mixing, not by comparing neutrinos and antineutrinos

ELECTRON (ANTI)NEUTRINO UNCERTAINTY (1)

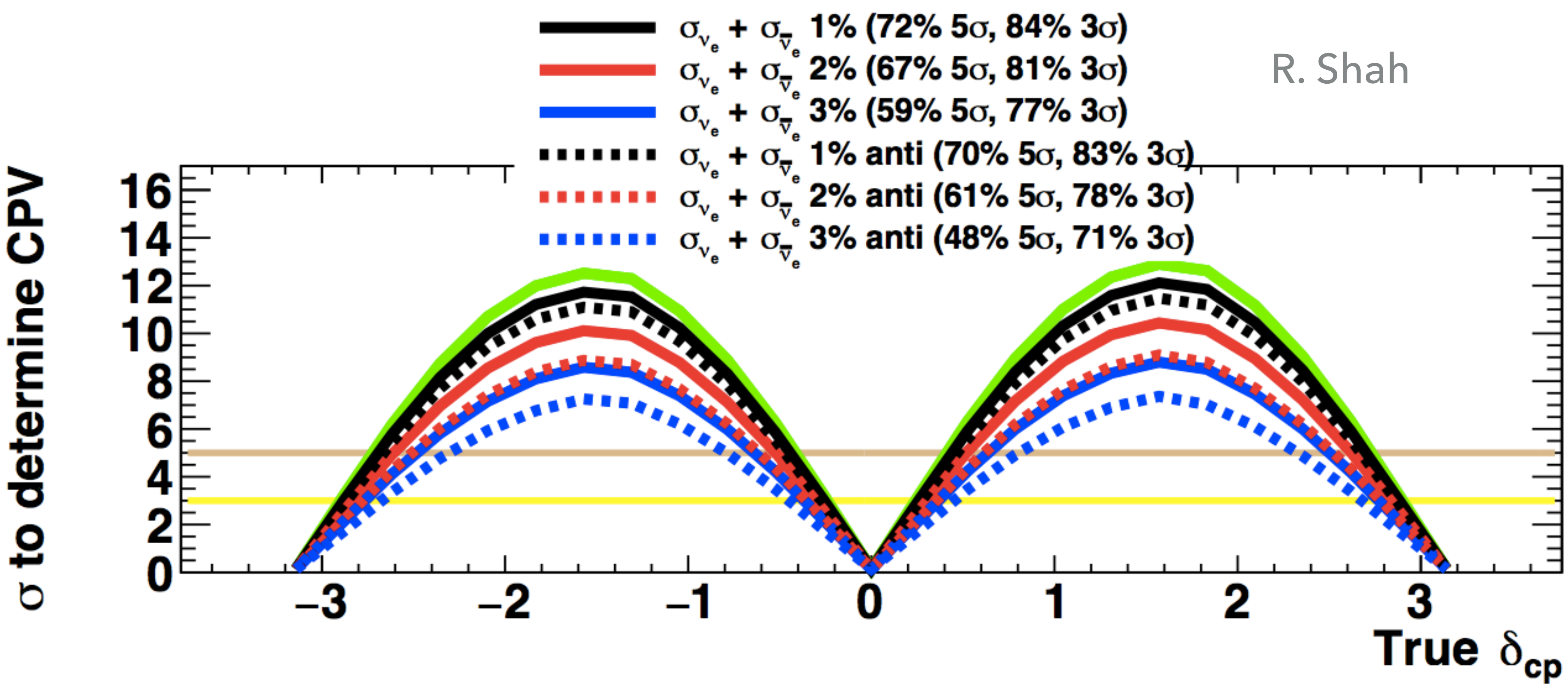
arXiv:1609.04111

	$\delta_{N_{SK}}/N_{SK}$ (%)				
	1-Ring μ		1-Ring e		
Error Type	ν mode	$\bar{\nu}$ mode	ν mode	$\bar{\nu}$ mode	$\nu/\bar{\nu}$
SK Detector	3.9	3.3	2.5	3.1	1.6
SK Final State & Secondary Interactions	1.5	2.1	2.5	2.5	3.5
ND280 Constrained Flux & Cross-section	2.8	3.3	3.0	3.3	2.2
$\sigma_{\nu_e}/\sigma_{\nu_\mu}$, $\sigma_{\bar{\nu}_e}/\sigma_{\bar{\nu}_\mu}$	0.0	0.0	2.6	1.5	3.1
NC 1γ Cross-section	0.0	0.0	1.5	3.0	1.5
NC Other Cross-section	0.8	0.8	0.2	0.3	0.2
Total Systematic Error	5.1	5.2	5.5	6.8	5.9
External Constraint on θ_{12}, θ_{13}, Δm^2_{21}	0.0	0.0	4.1	4.0	0.8

- For the measurement of sin(δ_{cp}), systematic errors on the relative rate of electron neutrinos and electron antineutrinos are critical
- In T2K, there error on the normalization of the electron (anti)neutrino cross sections has been set to 3% based on theoretical considerations
  - 50% anti-correlation applied

ELECTRON (ANTI)NEUTRINO UNCERTAINTY (2)

R. Shah



- This uncertainty is potentially dominant for Hyper-K
- But when we compare first and second oscillation maxima, we are comparing neutrinos to neutrinos or antineutrinos to antineutrinos
  - Not sensitive to relative errors between neutrino and antineutrino rates
- The following studies will focus on a simple toy with an uncertainty on the neutrino/antineutrino rate

SIMPLE TOY STUDY

- We can use a simple toy to try to understand the sensitivity to $\sin(\delta_{cp})$ from comparing neutrinos and antineutrinos vs. comparing first and second oscillation maxima
- Consider a simple toy experiment where the CP effect is modeled as a perturbation parameterized by α (CP odd term):

$$N_{JD}^{\nu(\bar{\nu})}(\alpha)=N_{JD0}^{\nu(\bar{\nu})}(1+(-)\alpha)$$

$$N_{KD}^{\nu(\bar{\nu})}(\alpha)=N_{KD0}^{\nu(\bar{\nu})}(1+(-)3\alpha)$$

- Here, the CP effect is three times larger in the Korean detector (KD) than it is in the Japanese detector (JD)

RATIO OBSERVABLES

- We can construct ratio observables that probe neutrinos vs. antineutrino and first vs. second oscillation maxima

$$R_{JD}^{\nu,\bar{\nu}}(\alpha)=\frac{N_{JD0}^{\nu}(1+\alpha)}{N_{JD0}^{\bar{\nu}}(1-\alpha)}\approx\frac{N_{JD0}^{\nu}}{N_{JD0}^{\bar{\nu}}}(1+2\alpha)$$

$$R_{JD,KD}^{\nu}(\alpha)=\frac{N_{JD0}^{\nu}(1+\alpha)}{N_{KD0}^{\nu}(1+3\alpha)}$$

$$R_{KD}^{\nu,\bar{\nu}}(\alpha)=\frac{N_{KD0}^{\nu}(1+3\alpha)}{N_{KD0}^{\bar{\nu}}(1-3\alpha)}\approx\frac{N_{KD0}^{\nu}}{N_{KD0}^{\bar{\nu}}}(1+6\alpha)$$

$$R_{JD,KD}^{\bar{\nu}}(\alpha)=\frac{N_{JD0}^{\bar{\nu}}(1-\alpha)}{N_{KD0}^{\bar{\nu}}(1-3\alpha)}$$

- Assume 1800 events at the Japanese detector in each polarity and 1/9 statistics at the Korean detector
- Significance of non-zero α with only statistical errors:
  - JD neutrino vs. antineutrino: 60*α
  - KD neutrino vs. antineutrino: 60*α
  - 1st vs. 2nd oscillation max (neutrino): 27*α
  - 1st vs. 2nd oscillation max (antineutrino): 27*α

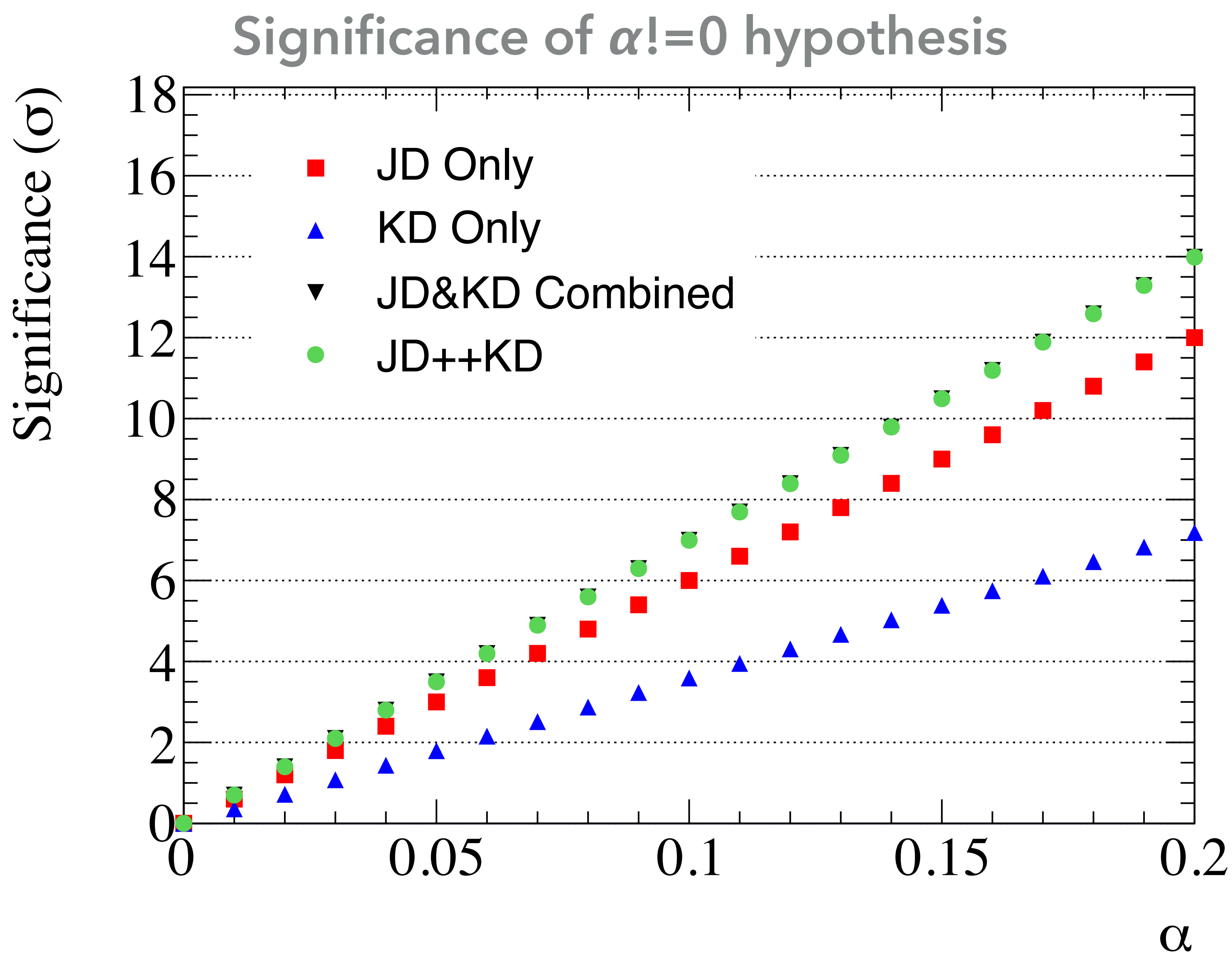
COMMENT ON SIMPLE TOY

- For a given exposure, the sensitivities from comparing the first and second oscillation maxima are smaller
  - The sensitivity is even smaller than the neutrino vs. antineutrino sensitivity in the Korean detector alone: 38*α vs. 60*α
- The combination of the two detectors should only give an advantage for systematic error cancellation **after** the Korean detector becomes systematics limited

SIMPLE TOY WITH SYSTEMATICS

- Update the simple toy experiment:
- Add a systematic error on the neutrino and antineutrino interaction rates of 3% each
  - -0.5 correlation between the neutrino and antineutrino systematic error parameters
- Use more realistic statistics reduction at Korean detector of 1/13.5 (from baseline ratio)
- Assume CP effect is only 2.2 times larger at Korean detector
  - Chosen to give similar sensitivity at detectors when 1800 events at JD
- Show dependence on exposure in following slides

NO SYSTEMATIC ERROR



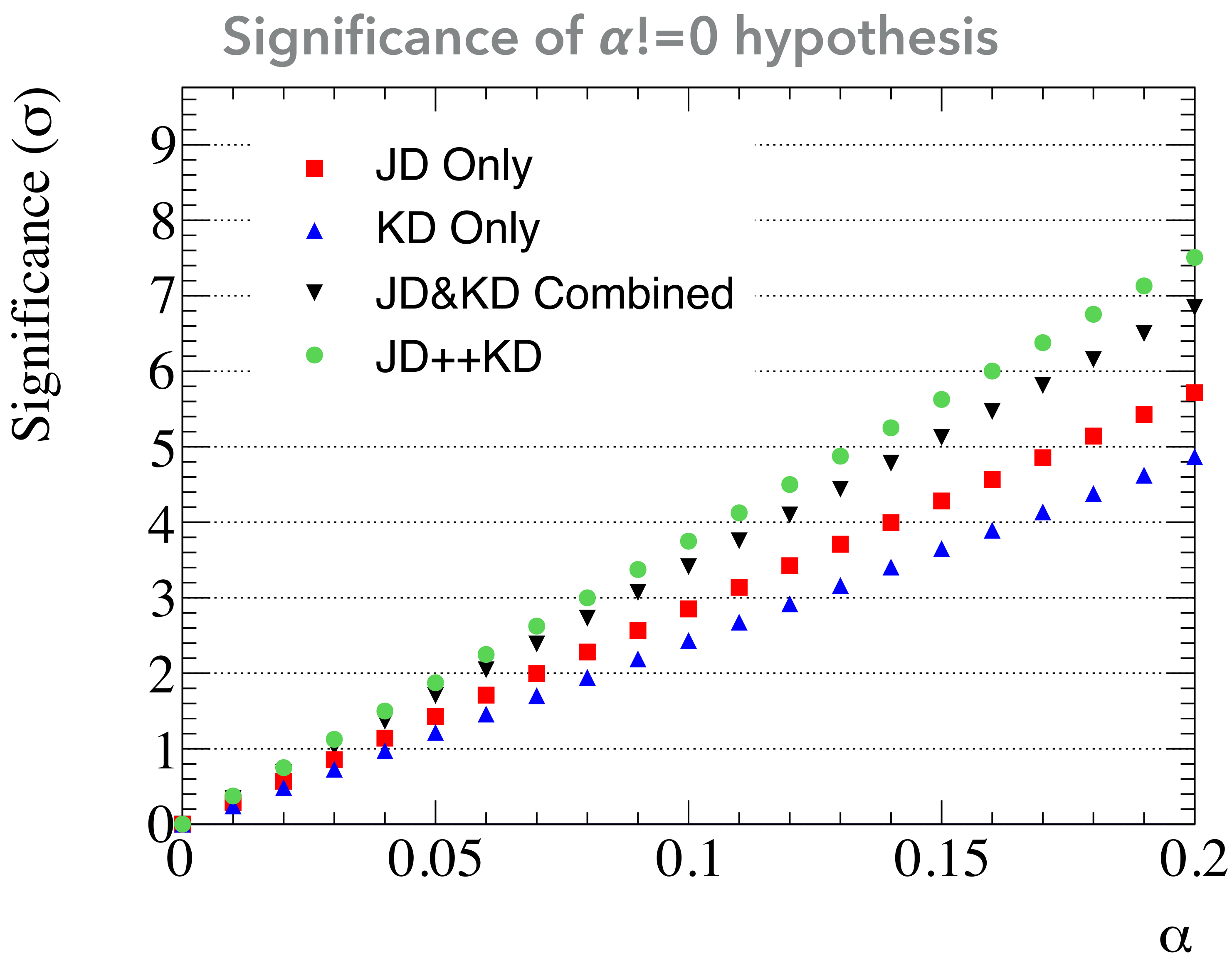
JD Statistical error = 2.4%

KD Statistical error = 8.7%

With no systematic error, the combined measurement significance is equivalent to the separate measurements' significances added in quadrature

Less significance at Korean detector due to 2.2 times larger CP effect vs. factor of 13.5 reduction in statistics due to baseline (similar to actual situation)

1/2 STATISTICS, SYSTEMATIC ERROR



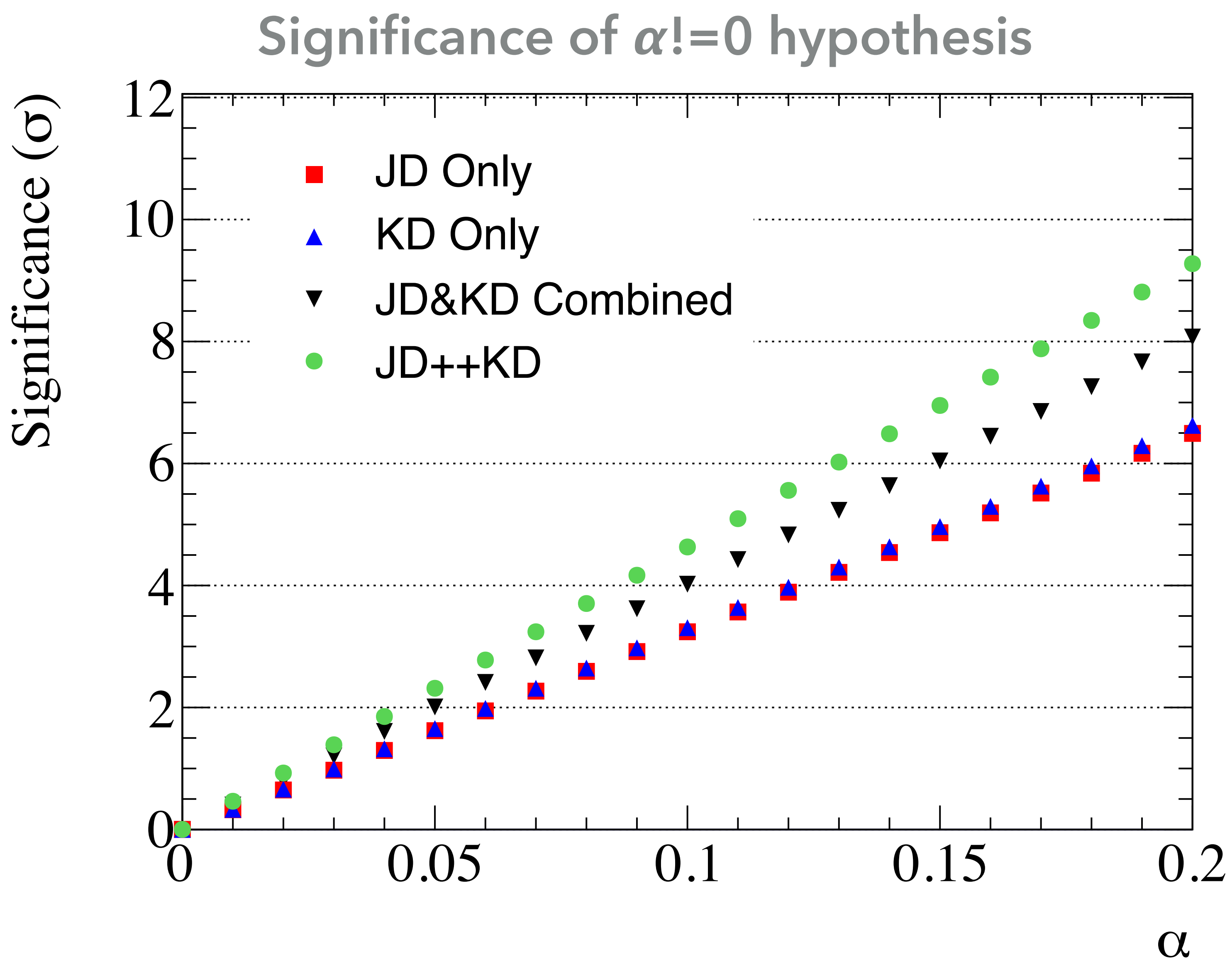
JD Statistical error = 3.3%

KD Statistical error = 12.2%

At 1/2 exposure, there is an impact of the systematic errors on the JD measurement

There is also some impact of the systematic errors on the combined fit since the black points are below the green

FULL STATISTICS, SYSTEMATIC ERROR

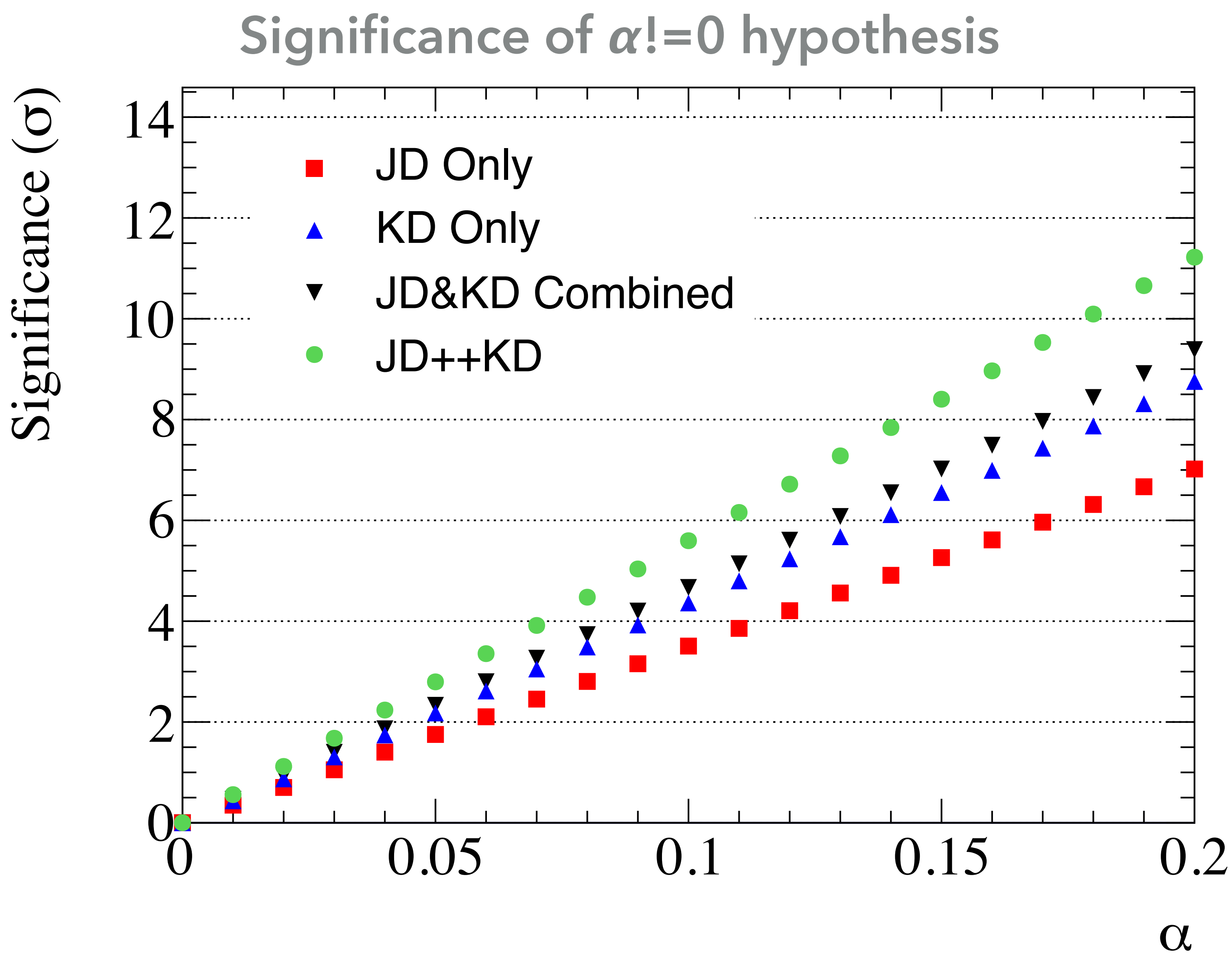


JD Statistical error = 2.4%

KD Statistical error = 8.7%

At “full” exposure, there is an impact of the systematic errors have reduced the JD sensitivity to be similar to the KD sensitivity

2X STATISTICS, SYSTEMATIC ERROR



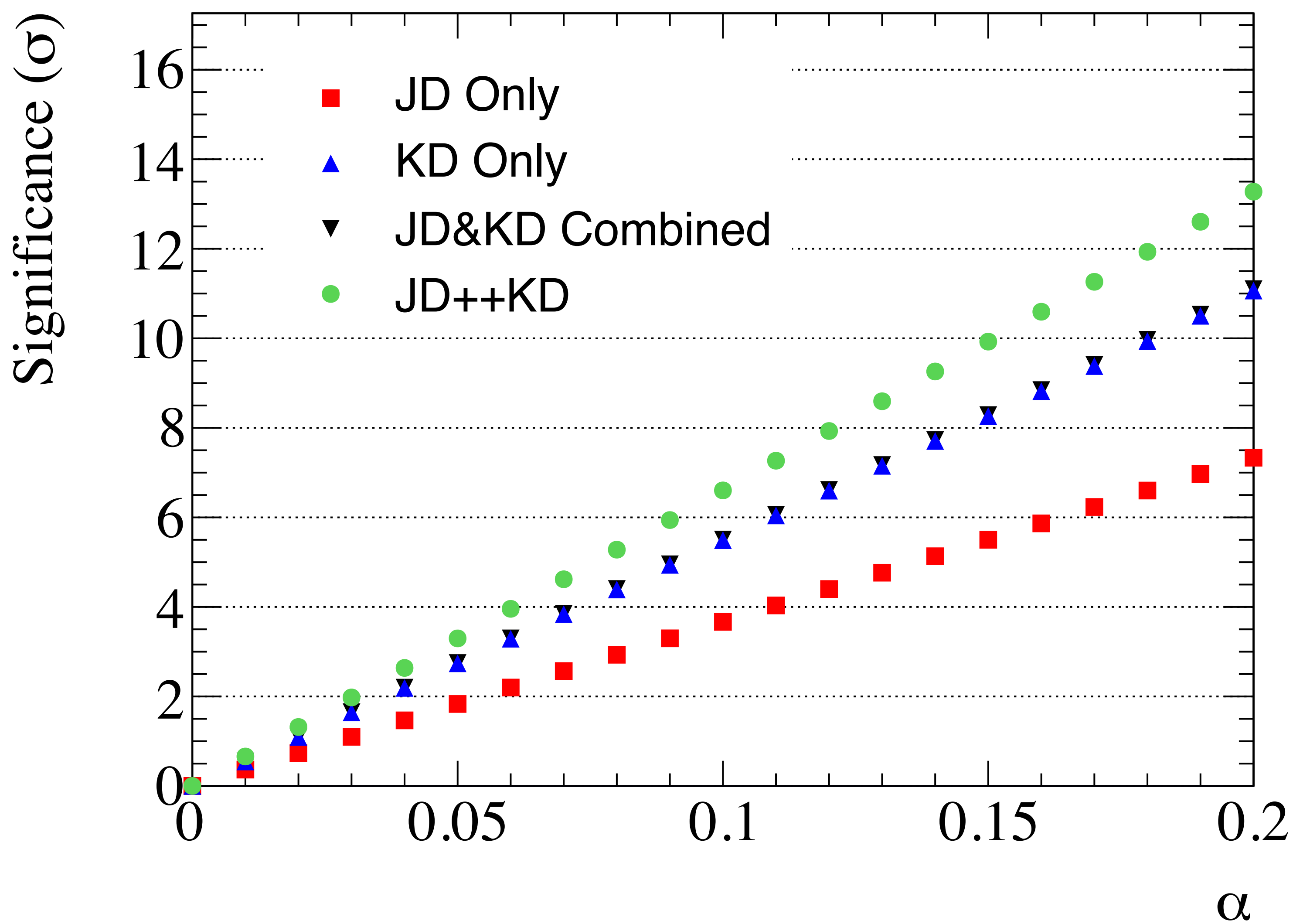
JD Statistical error = 1.7%

KD Statistical error = 6.1%

Once the JD measurement becomes systematics limited, it contributes little to the total sensitivity

4X STATISTICS, SYSTEMATIC ERROR

Significance of α!=0 hypothesis



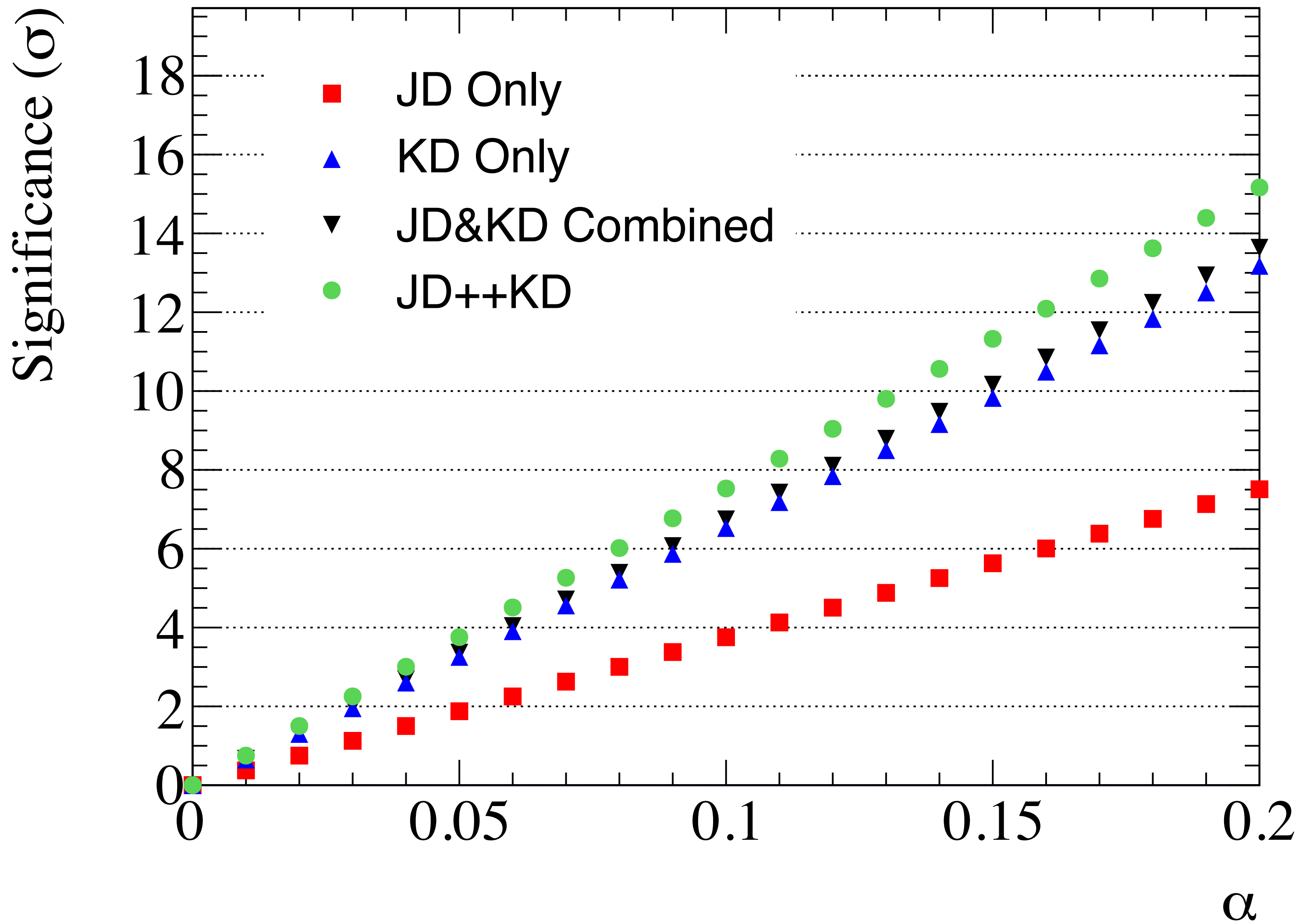
JD Statistical error = 1.2%

KD Statistical error = 4.3%

At 4x statistics, the KD measurement is still largely statistics limited, and the JD doesn't improve the total sensitivity

8X STATISTICS, SYSTEMATIC ERROR

Significance of α!=0 hypothesis



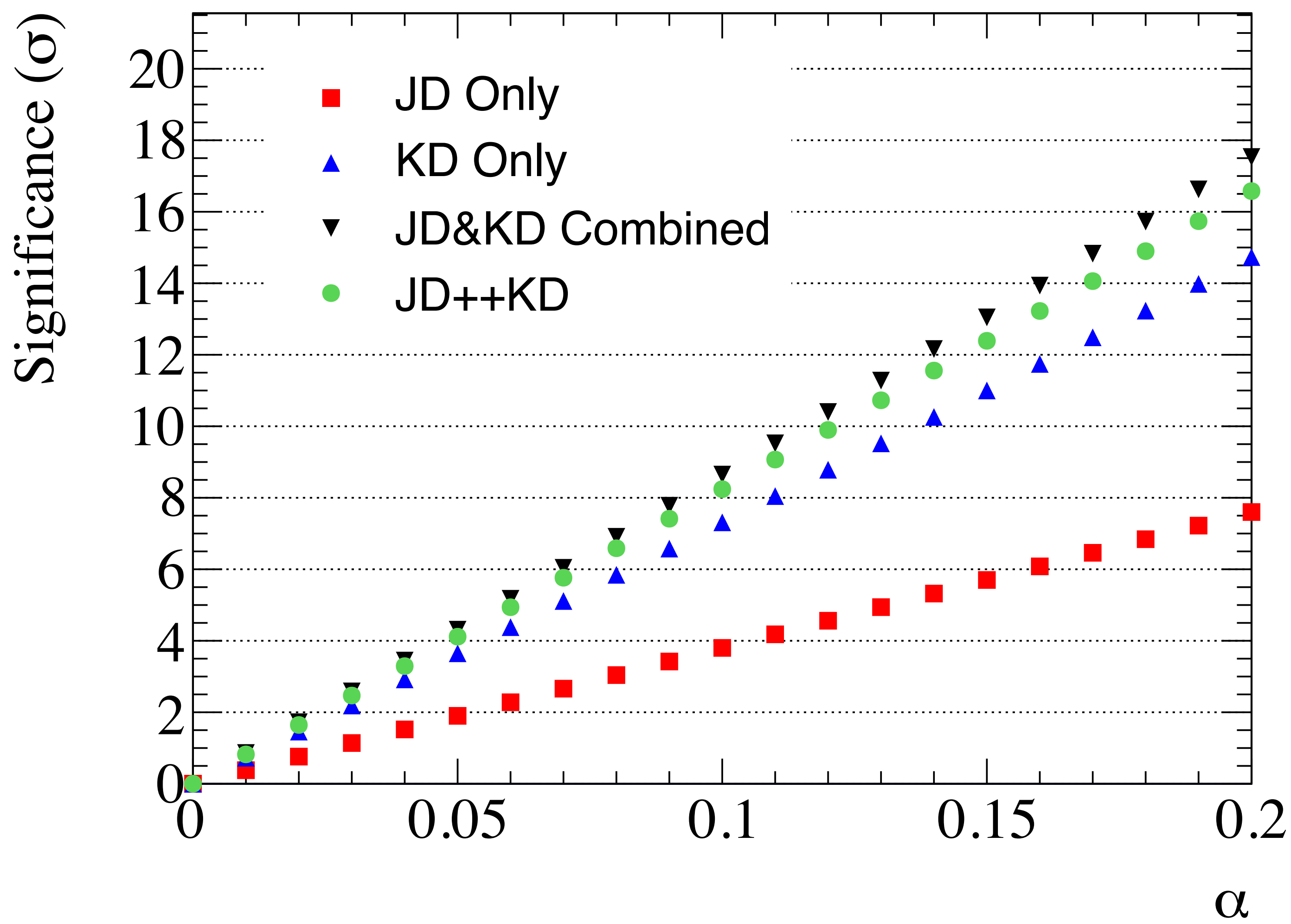
JD Statistical error = 0.8%

KD Statistical error = 3.1%

At 8x statistics, the Korean detector starts to become systematics limited. The Japanese detector starts to increase the sensitivity again

16X STATISTICS, SYSTEMATIC ERROR

Significance of α!=0 hypothesis



JD Statistical error = 0.6%

KD Statistical error = 2.1%

Once the Korean detector is systematics limited, the total sensitivity starts to benefit from two detectors again

COMMENTS ON TOY WITH SYSTEMATIC ERRORS

- There are 3 regimes of statistical vs. systematic error (on neutrino/antineutrino ratio) as a function of exposure
  - Both detectors are making statistics limited measurements
    - Can be largely treated as two independent measurements
  - The Japanese detector is systematics limited while the Korean detector is statistics limited
    - The measurement in the Korean detector provides all of the sensitivity
  - Both detectors are making systematics limited measurements
    - The first vs. second oscillation maxima comparison contributes to the total sensitivity

MOVING FORWARD

- We should confirm the behavior observed in the toy study with the full T2HKK sensitivity framework
- Increase the exposures for the T2HKK study to observe when:
    - Total sensitivity to $\sin(\delta_{cp})$ becomes dominated by the Korean detector
    - Measurement at Korean detector becomes systematics limited
- Carefully consider the systematic error correlations between neutrinos and antineutrinos or between detectors
- Evaluate the relative systematic errors between neutrinos and antineutrinos or between detectors