The combined sensitivity of current long-baseline experiments

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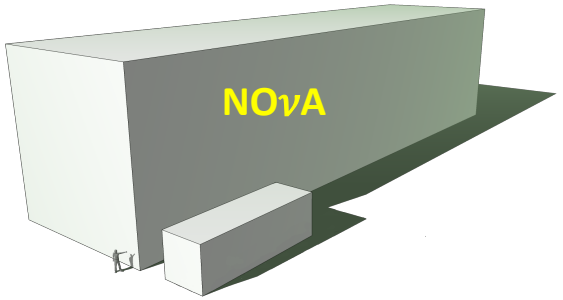
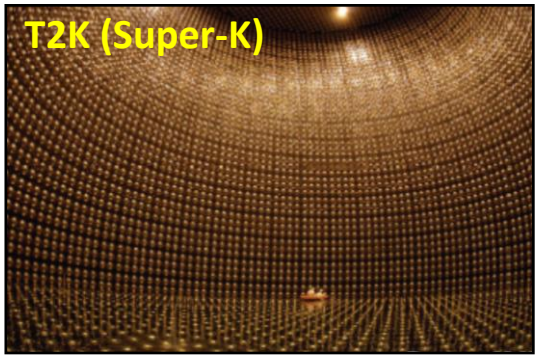
Current long-baseline experiments

- **Mass hierarchy, CP violation, ν_3 flavor mixing:**
  NOνA, T2K
  (Impact of MINOS discussed in backup slides)
- ***Also included in these experiments' goals:***
  - **precision measurements of dominant atmospheric parameters $|\Delta m^2_{atm}|$, $\sin^2(2\theta_{23})$**
  - **comparisons of ν, $\bar{\nu}$ disappearance (BSM physics)**
  - **sterile searches, supernovae, cross sections, …**
- **Will discuss separate and combined reaches**
- **Other current LBL experiments are somewhat orthogonal in scope. I won't talk about them:**
  OPERA (ν_τ appearance, ToF, …)
  ICARUS (LAr R&D, ν_τ appearance, steriles, …)

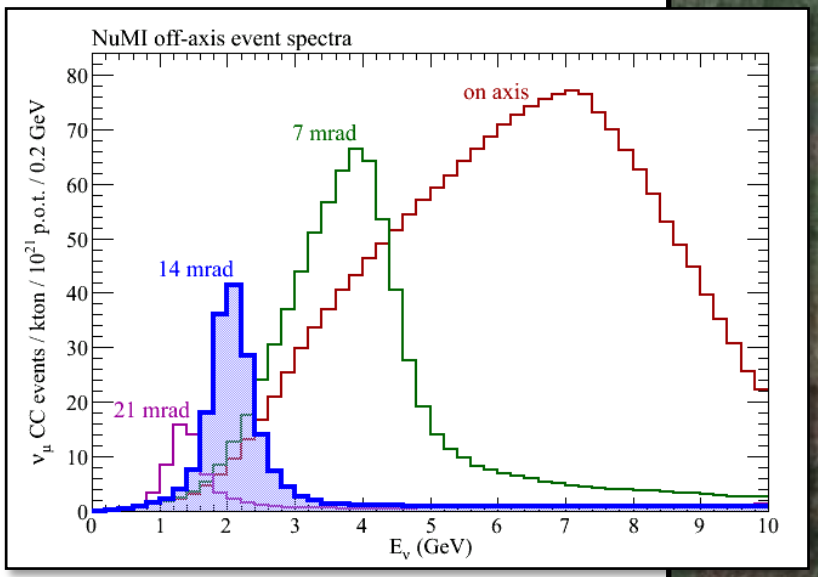


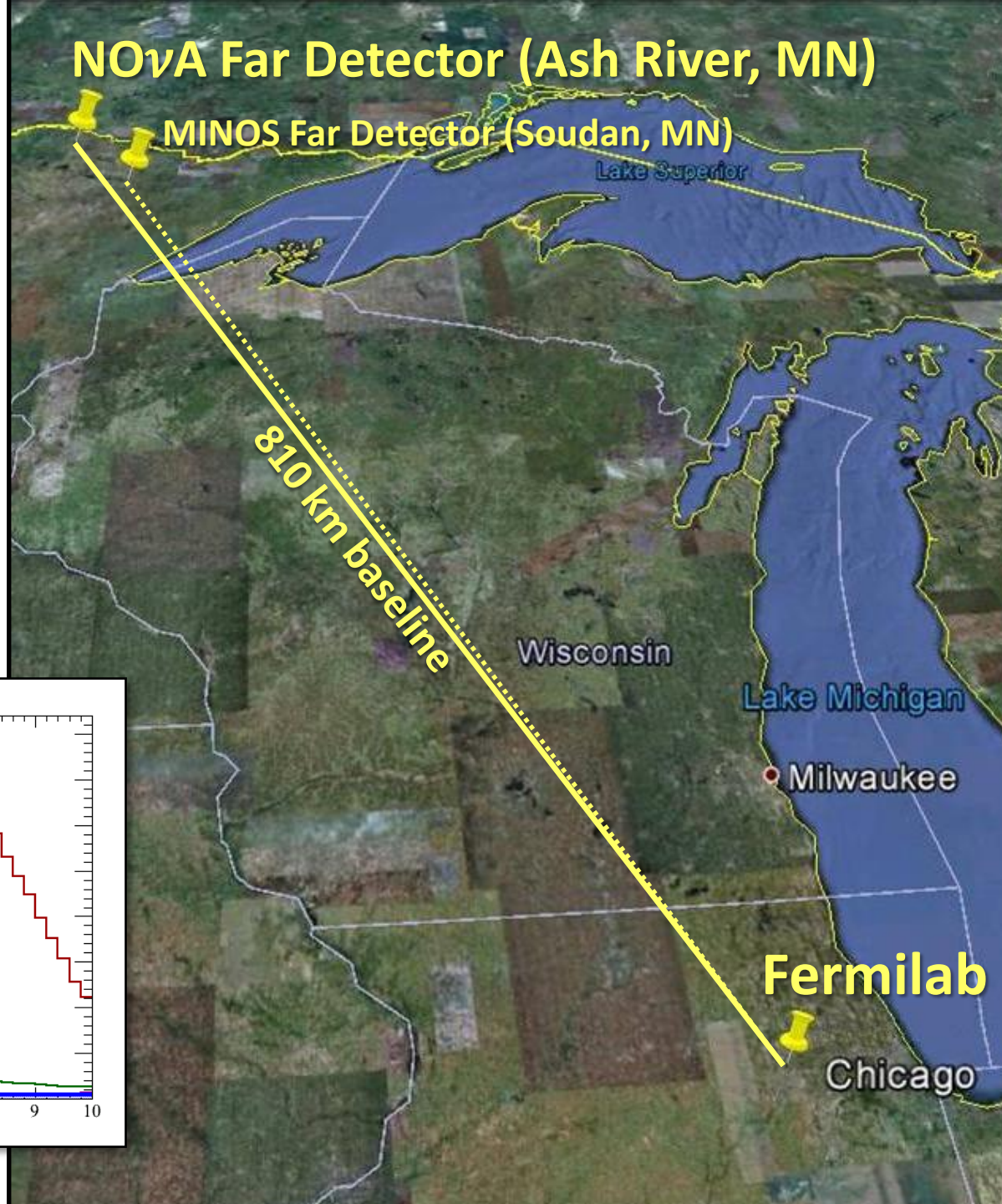


NOνA

In comparison to MINOS:

- Similarly long baseline, NuMI to Ash River (810 km)
- Better-matched energy for oscillation max. (2 GeV)
- Narrow-band spectrum
- Larger exposure
- Much better detector for ν_e CC identification





NOνA ν_e appearance

Nominal run plan: 3 yr (ν) + 3 yr ($\bar{\nu}$) (with 6×10^{20} p.o.t./year)

- **Using NOνA's *earlier analysis methods*, but including new θ_{13} knowledge**
- **Representative event counts**
  - ⇨ *These depend greatly on the specific osc. parameters*

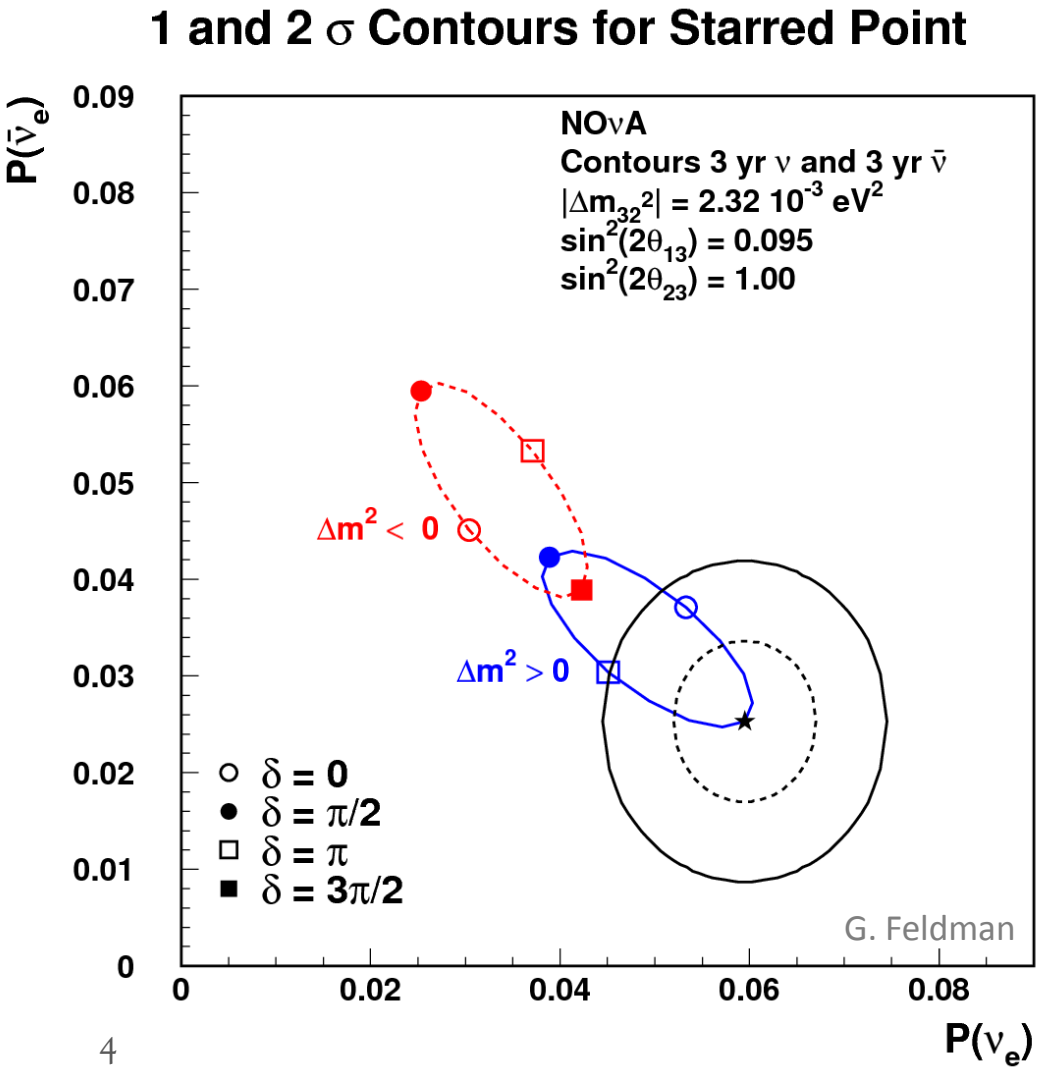
3 yr + 3 yr

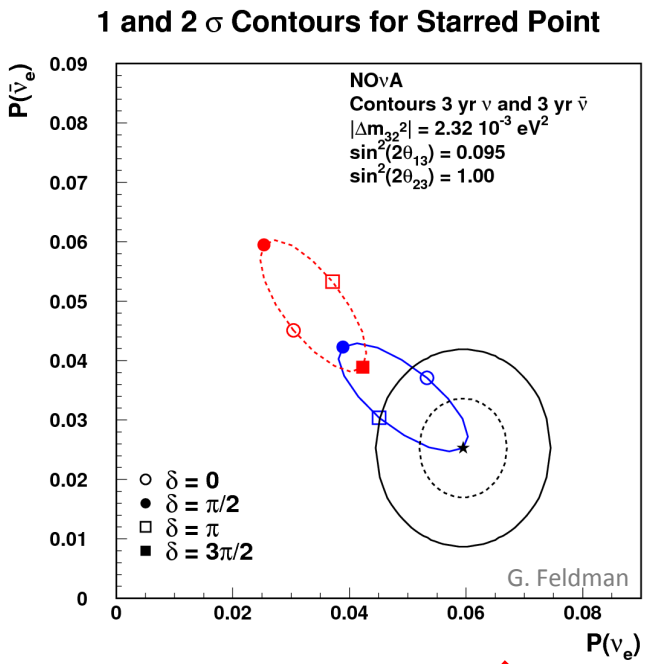
beam =	ν	$\bar{\nu}$
NC	19	10
ν_μ CC	5	<1
ν_e CC	8	5
tot. BG	32	15
$\nu_\mu \rightarrow \nu_e$	68	32

Example NOνA result →

…in terms of allowed regions in $P(\bar{\nu}_e)$ vs. $P(\nu_e)$ space

Here, all inverted hierarchy scenarios are excluded at >2σ.

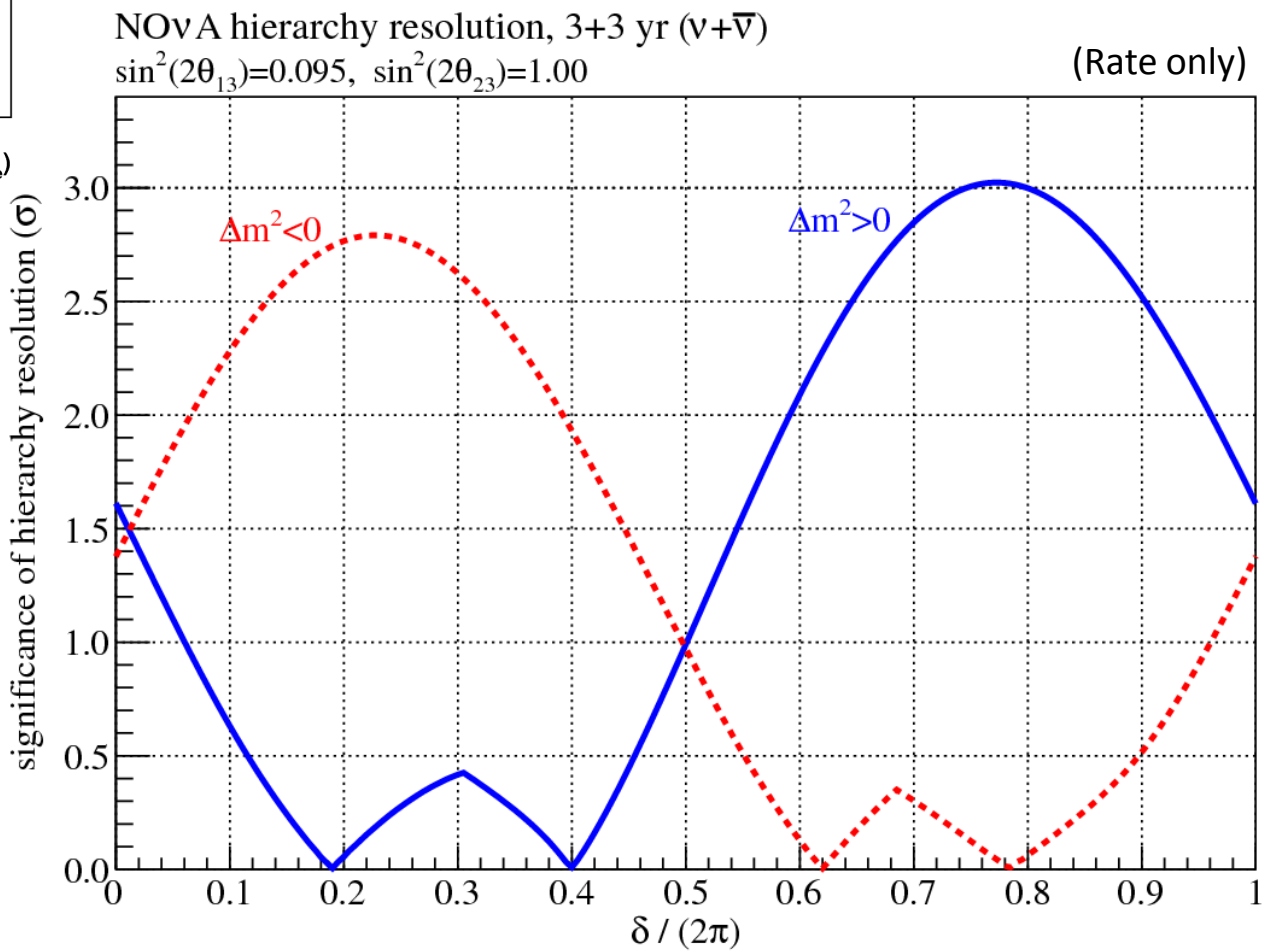




NOνA hierarchy determination in a more general form

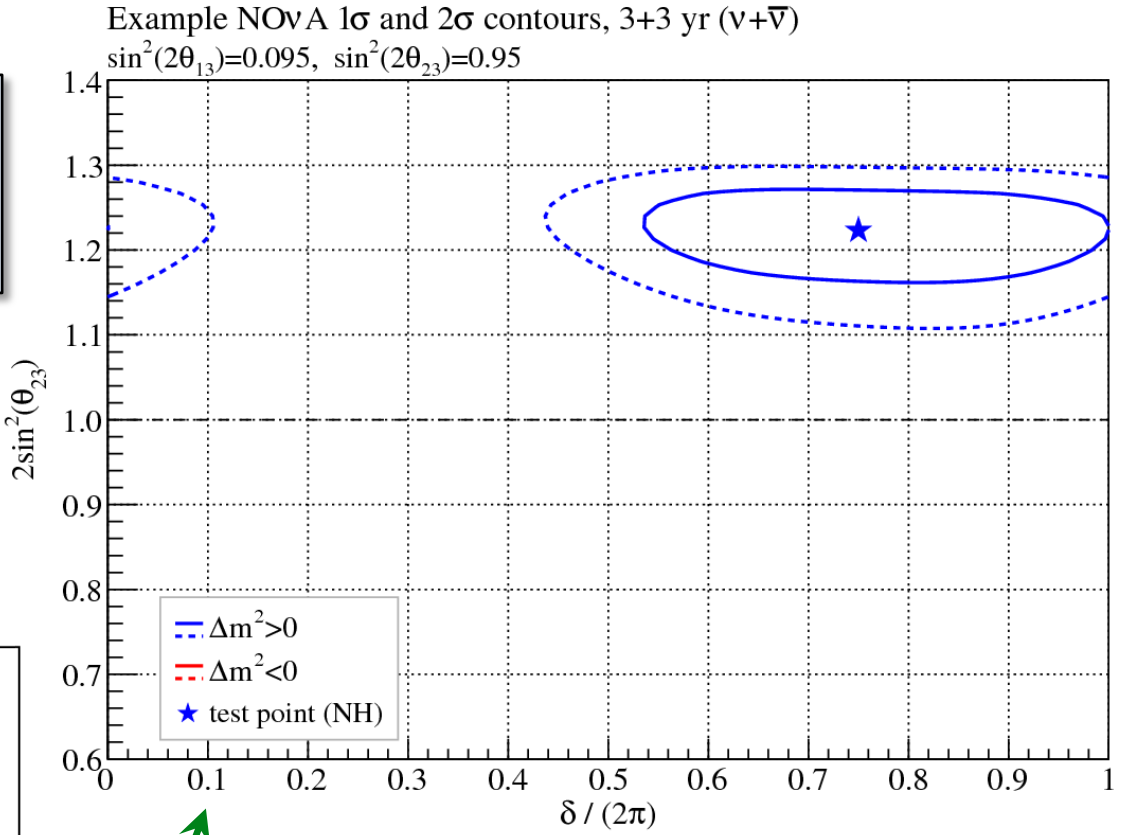
[for $\sin^2(2\theta_{13})=0.095$, $\sin^2(2\theta_{23})=1$]

(will combine with T2K later)

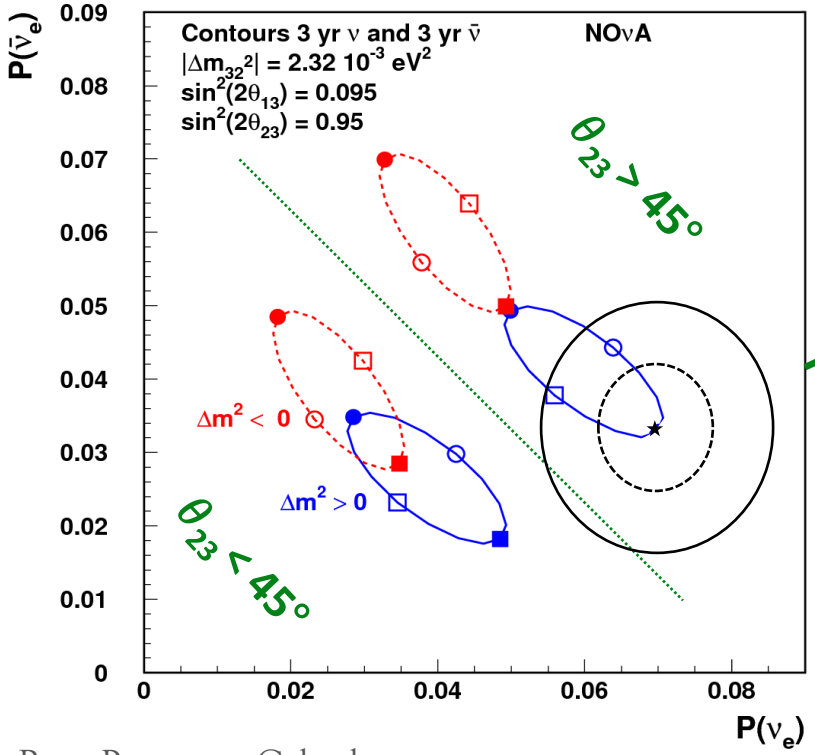


$P(\nu_e) \propto \sin^2(\theta_{23})\sin^2(2\theta_{13})$

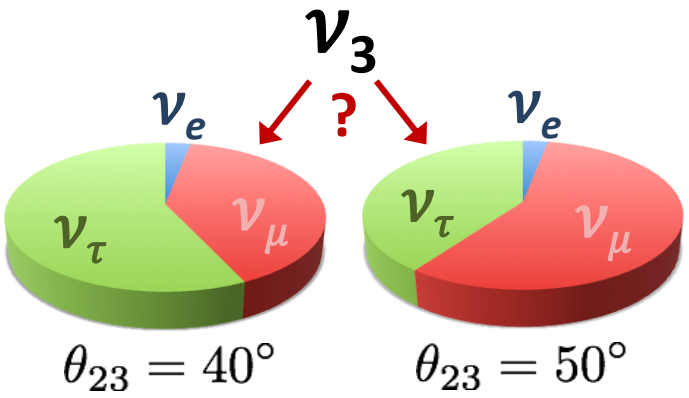
⇨ θ_{23} *octant sensitivity*



Expected NOνA contours for one example scenario at 3 yr + 3 yr

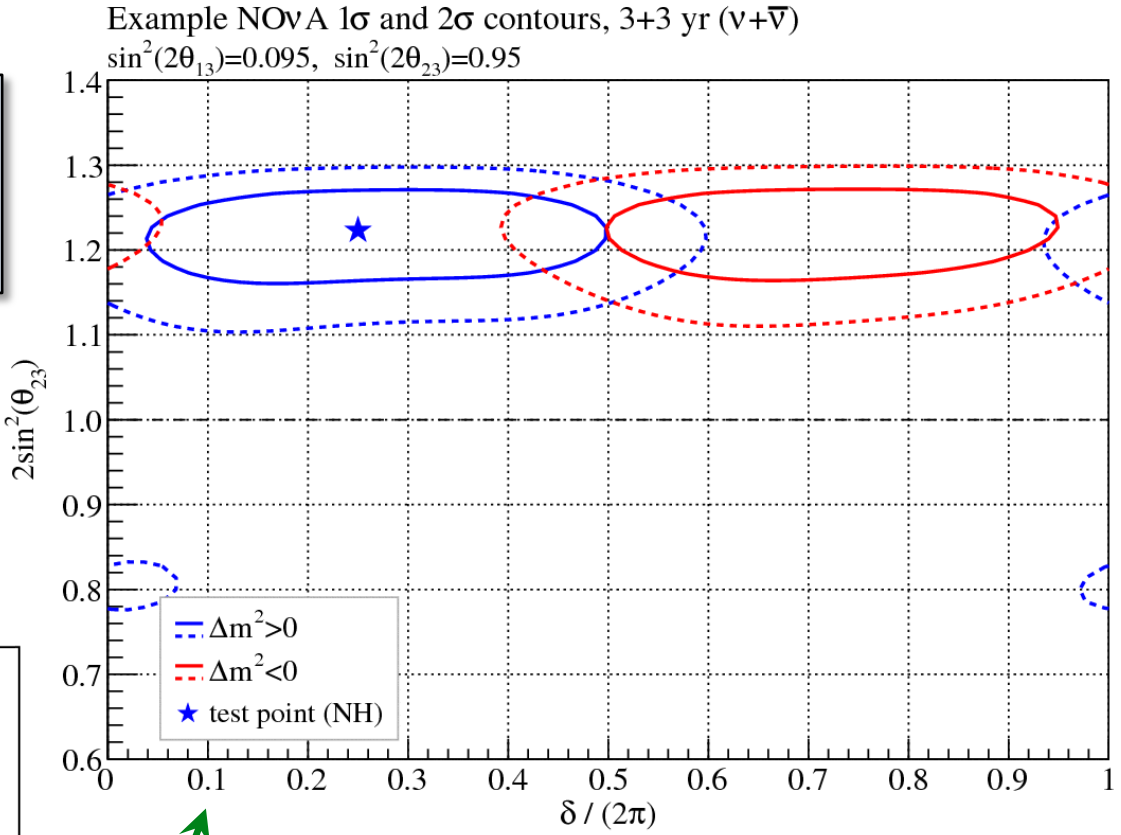


Simultaneous hierarchy, CP phase, and θ_{23} octant information



$P(\nu_e) \propto \sin^2(\theta_{23})\sin^2(2\theta_{13})$

⇨ θ_{23} *octant sensitivity*



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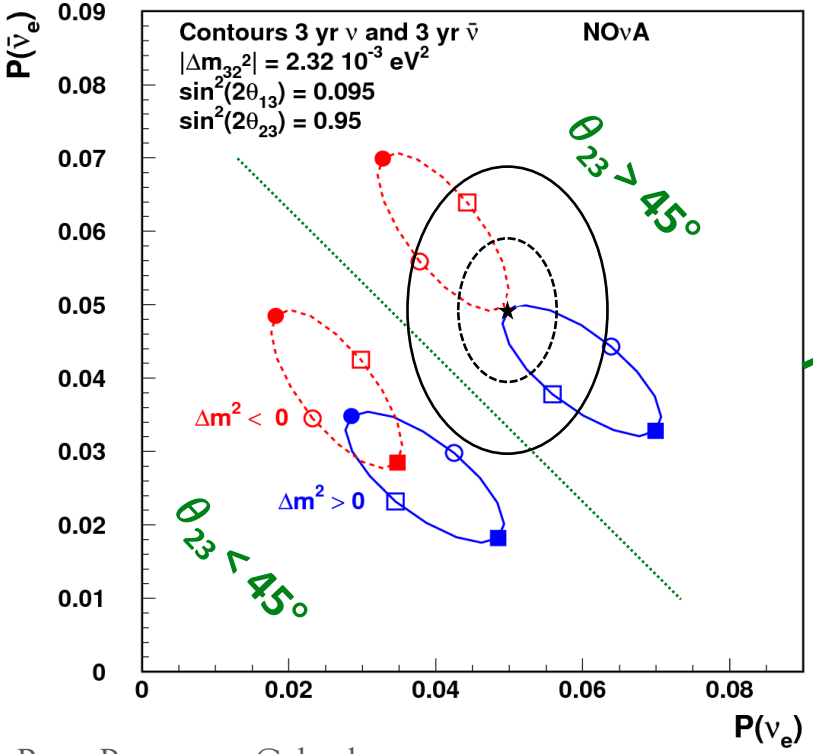
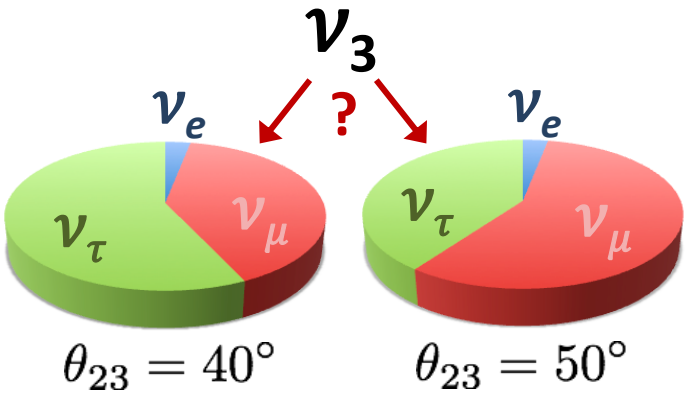
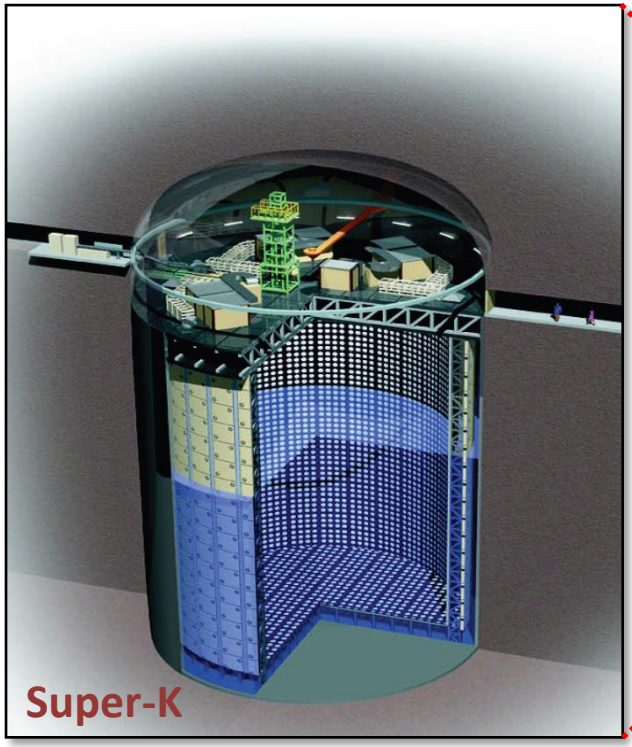


In "degenerate" cases, hierarchy and δ information is coupled. θ_{23} octant information is not.



T2K

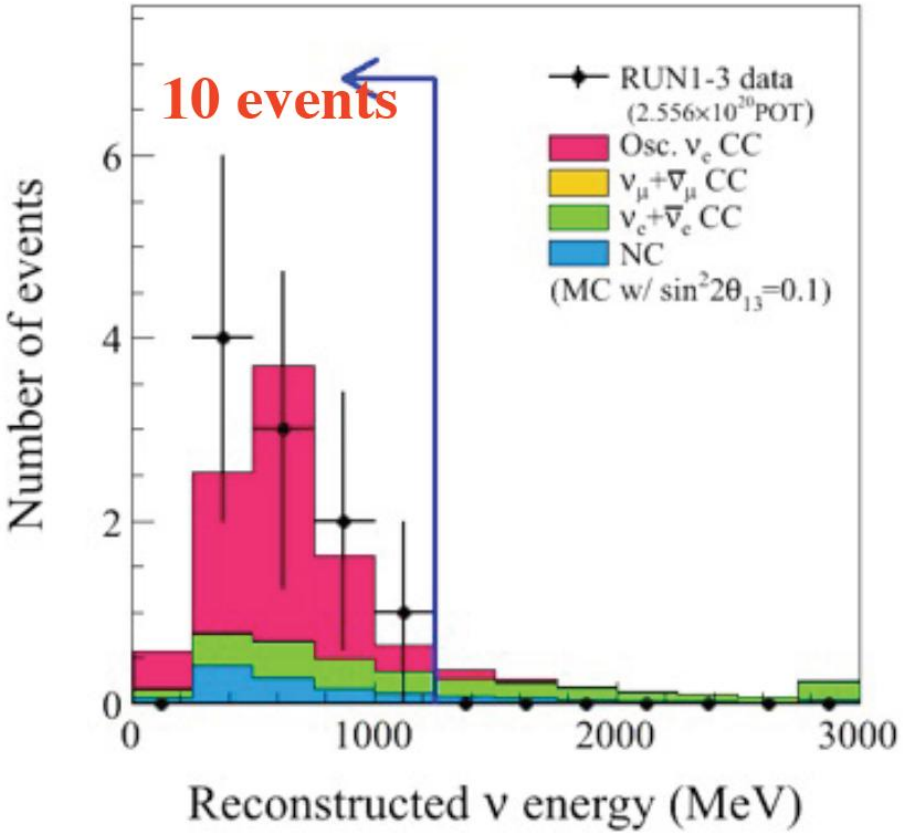
- Tokai to Kamioka (295 km)
- New neutrino beam from J-PARC
- Existing far detector: Super-K
  - *well understood detector!*
  - *existing analysis tools!*
- INGRID and ND280 near detectors



Latest T2K ν_e appearance result

- **From Neutrino 2012** *(T. Nakaya)*
- **3.2σ evidence of ν_e appearance, with 2.56×10^{20} p.o.t.**
  (When beam gets to full power, this exposure takes only 2 months!)

10 events in signal region



Representative predictions, errors

	$\sin^2 2\theta_{13}=0.1$
Total	**9.07±0.93**
ν_e signal	6.60
ν_e background (beam org.)	1.32
ν_μ background (~NCπ^0)	1.02
anti-ν background	0.13

	$\sin^2 2\theta_{13}=0.1$
Flux+Xsec in T2K fit	5.7%
Xsec (from other exp.)	7.5%
SK + FSI	3.9%
Total	**10.3%**

Looking beyond this result

- **Figures that follow are not official from T2K but rather my own calculations**
- **Assuming the exposure profile official from T2K as of the LBNE re-configuration workshop** *(taken from Y.-K. Kim's intro talk)* ⟶
- **Normalizing to event counts just shown in T2K prediction table**
- **Assuming systematic errors will go down (10.3%→8%, arbitrarily), and performing counting expt.**
- **For anti-ν running, assuming:**
  - *same selection efficiencies*
  - *same energy spectrum*
  - *3.8x reduction in rate (15% from flux, the rest from cross sections)*

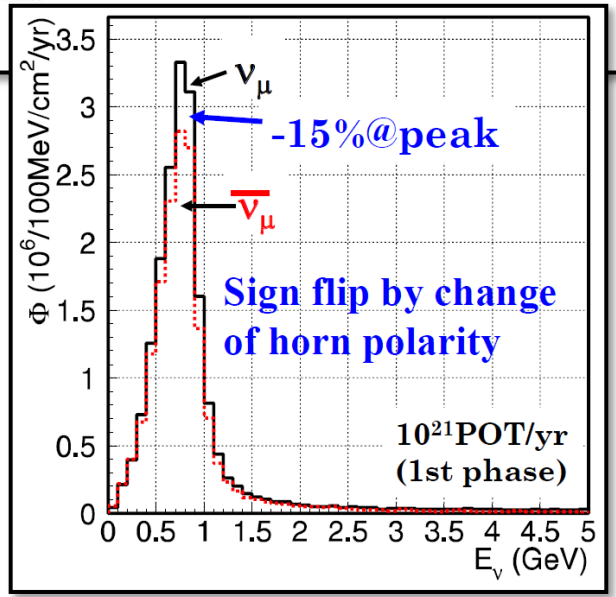
Period	Integ. No. of Proton on Target	Beam Power (kW)	
-Jun.2012	3.1E+20	170	
-Jun.2013	7.8E+20	200	
-Jun.2014	1.2E+21	250	*2
-Jun.2015	1.8E+21	250	
-Jun.2016	2.5E+21	300	
-Jun.2017	3.2E+21	300	
-Jun.2018	3.9E+21	300	
-Jun.2019	5.5E+21	700	*1
-Jun.2020	7.1E+21	700	
-Jun.2021	8.8E+21	700	

*1 Completion time of MR upgrade (assumed to be 2018) is suject to change, depending on economical situation, readiness and so on.

*2 LINAC upgrade completed

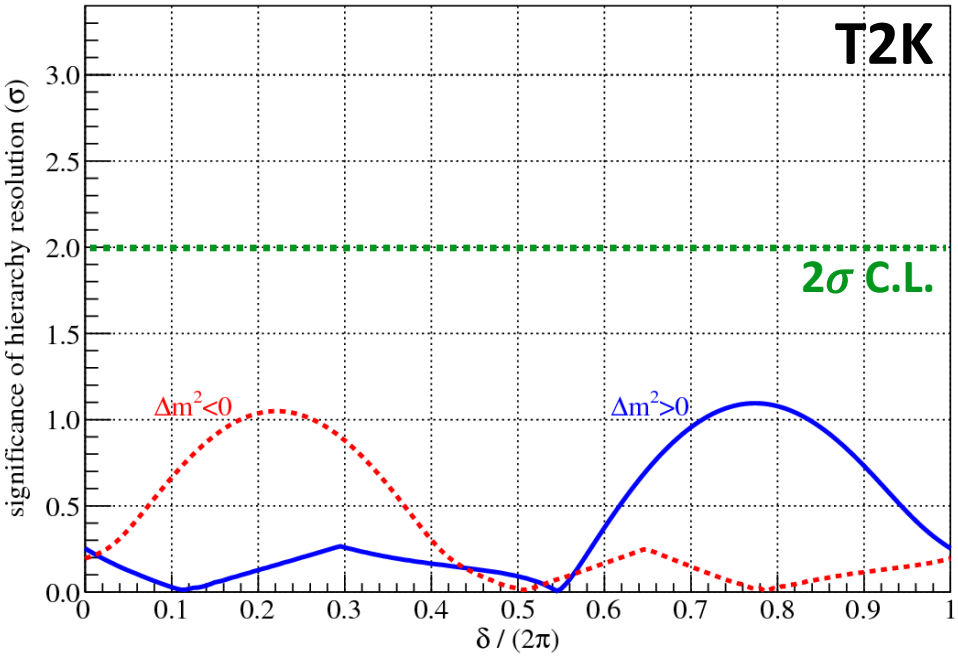
* Beam Energy 30GeV

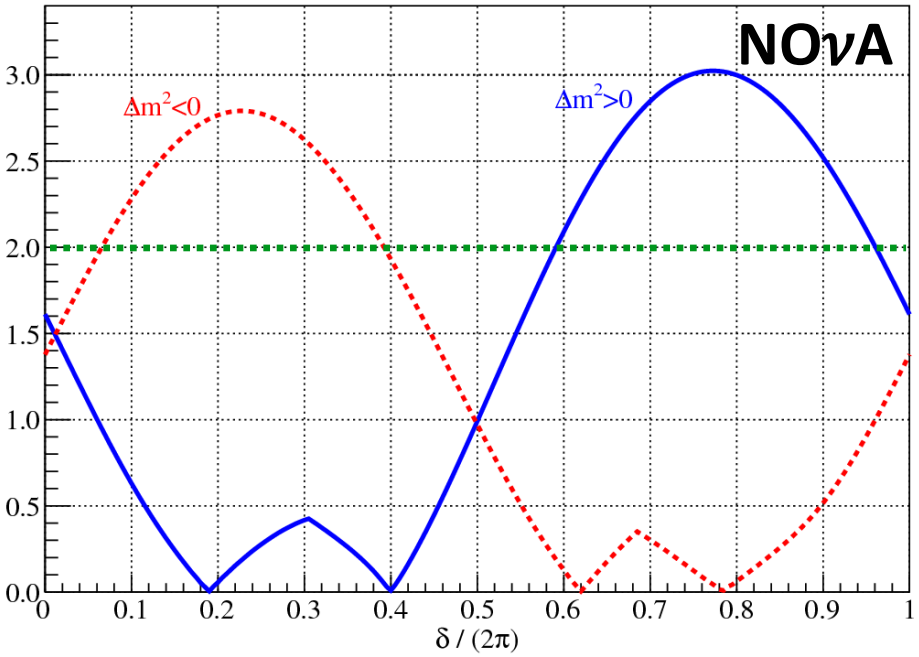
Antineutrino flux from an old T2K talk (at 2° off axis)

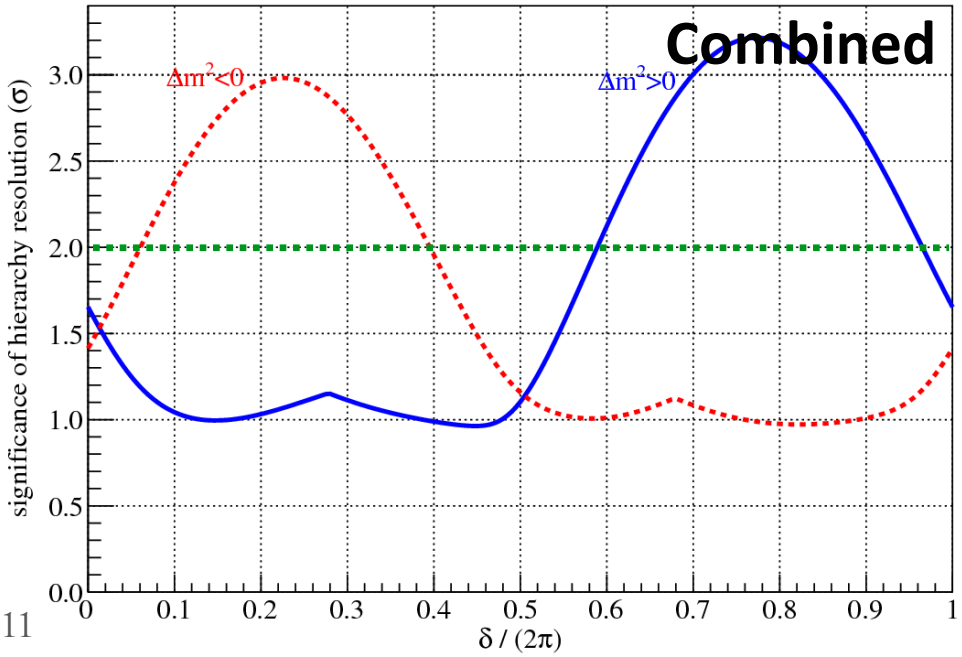


Hierarchy resolution at the end of 2019. Even split of ν and $\bar{\nu}$ running at both expts.

For test scenario of $\sin^2(2\theta_{13})=0.095$, $\sin^2(2\theta_{23})=1$



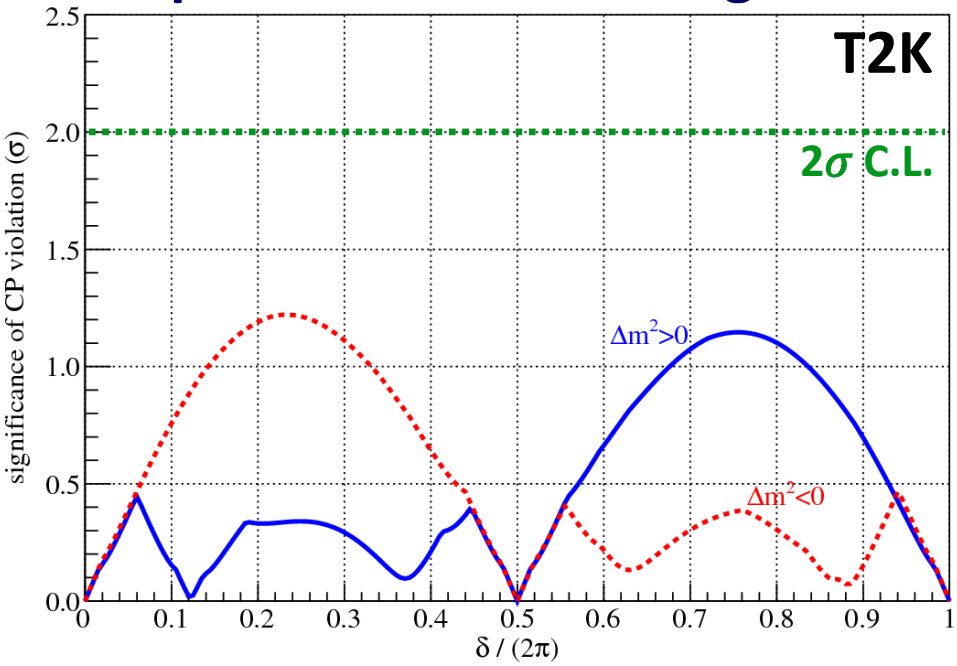


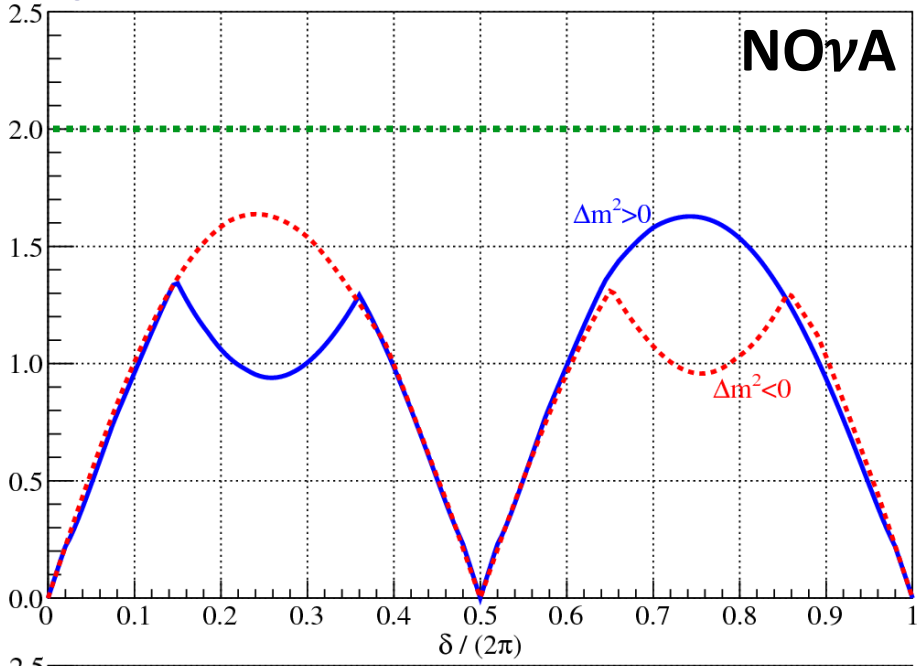


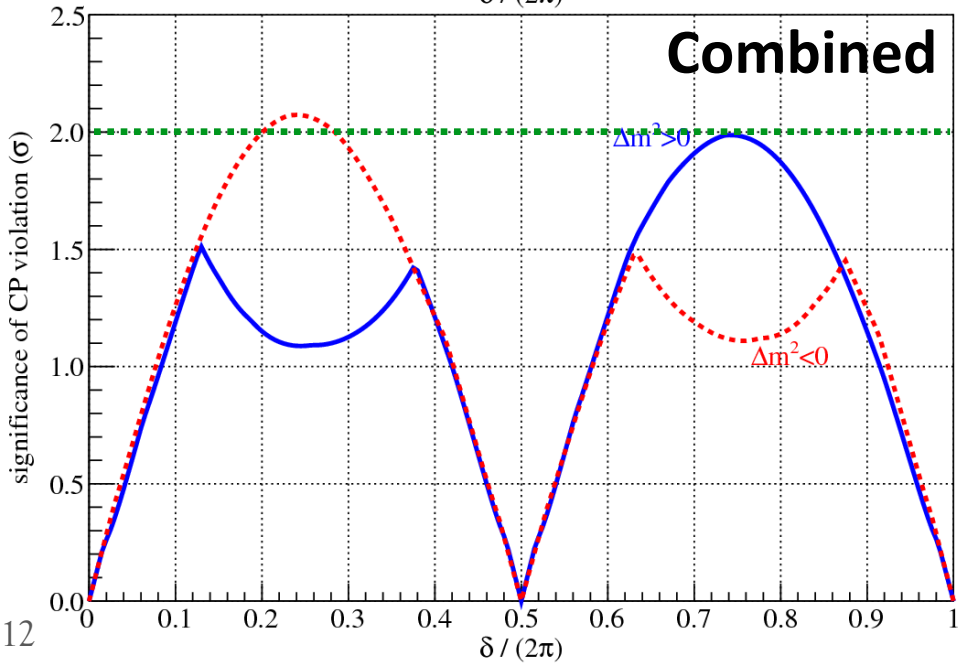
- **2σ C.L. (~95% C.L.) marked in green**
- **T2K baseline** too short for hierarchy
- **<u>NOνA alone:</u>** 37% of δ range covered
- **<u>NOνA+T2K:</u>** 38% of δ range covered
- *But:* note that the **combination is greater than the sum of its parts** in the "degenerate" region (reaching a modest 1σ everywhere)

CP violation determination at the end of 2019. Even split of ν and $\bar{\nu}$ running at both expts.

For test scenario of $\sin^2(2\theta_{13})=0.095$, $\sin^2(2\theta_{23})=1$



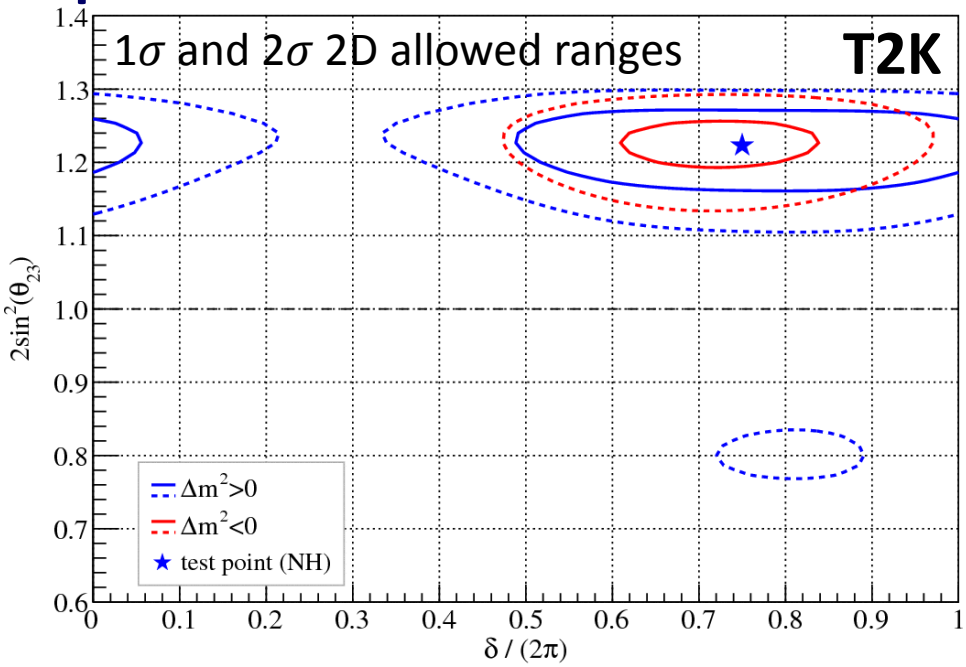


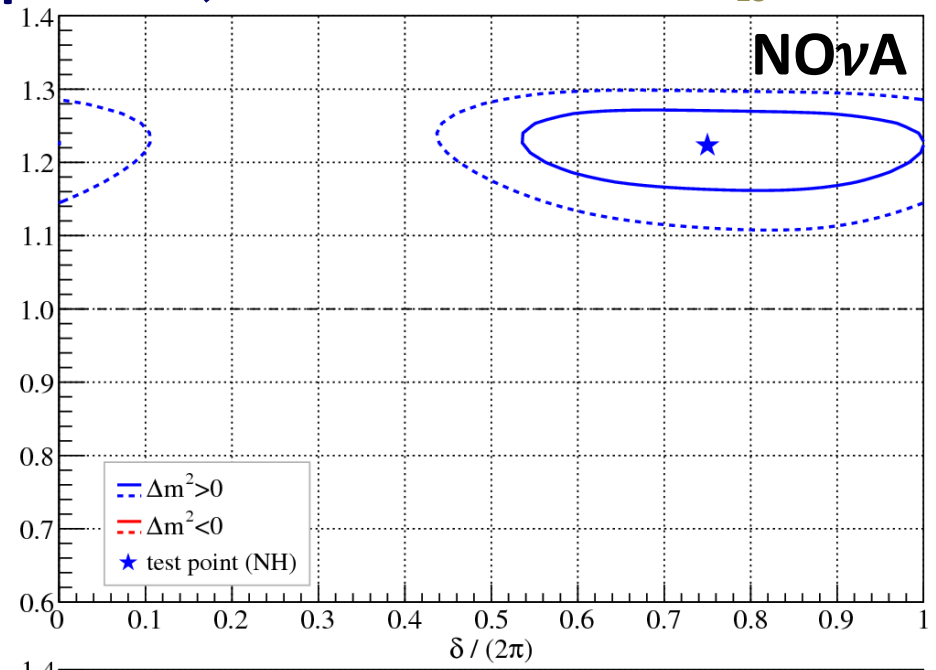


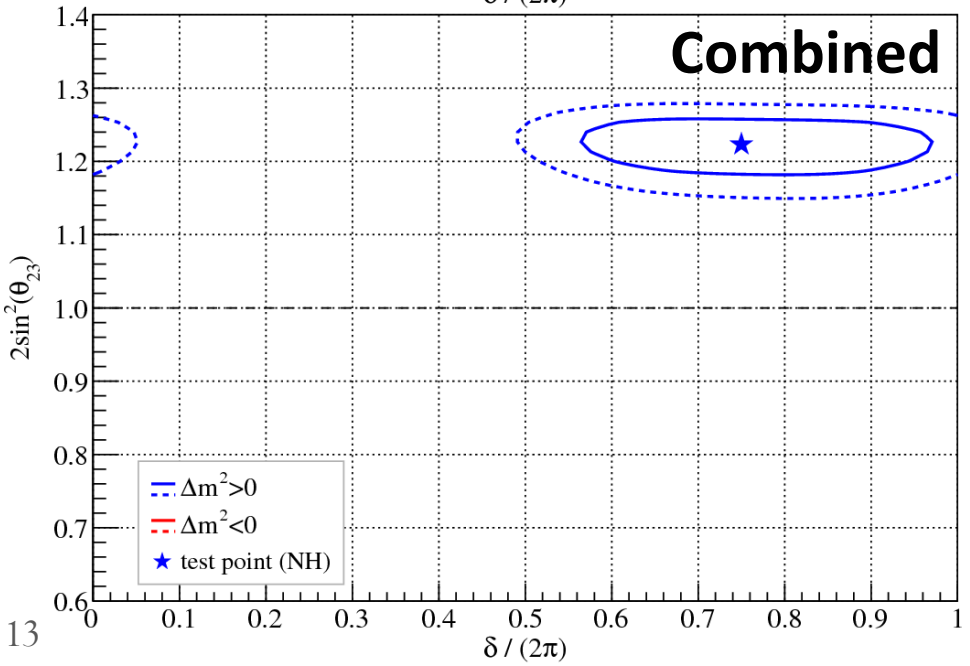
- **CPv tough all around!**
- Essentially **no coverage at 2σ**, but a good start over much of δ
- <u>Note:</u> unlike the hierarchy reach, this **can be arbitrarily hard**, depending on the true answer

Simultaneous δ, θ_{23}, and hierarchy information expected at the end of 2019. Even split of ν, $\overline{\nu}$.

For starred point shown and $\sin^2(2\theta_{13})=0.095$



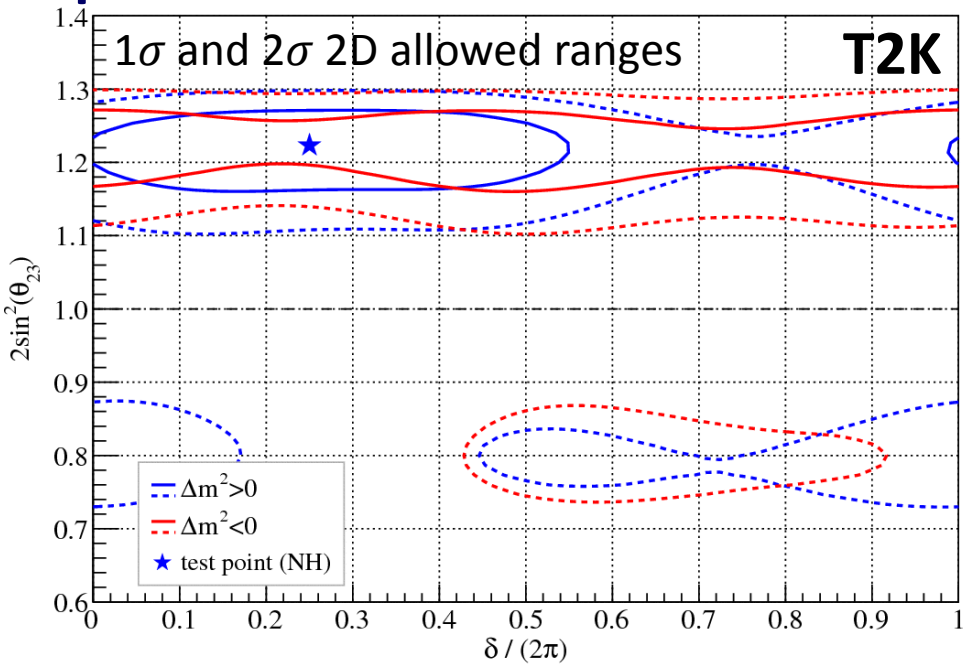


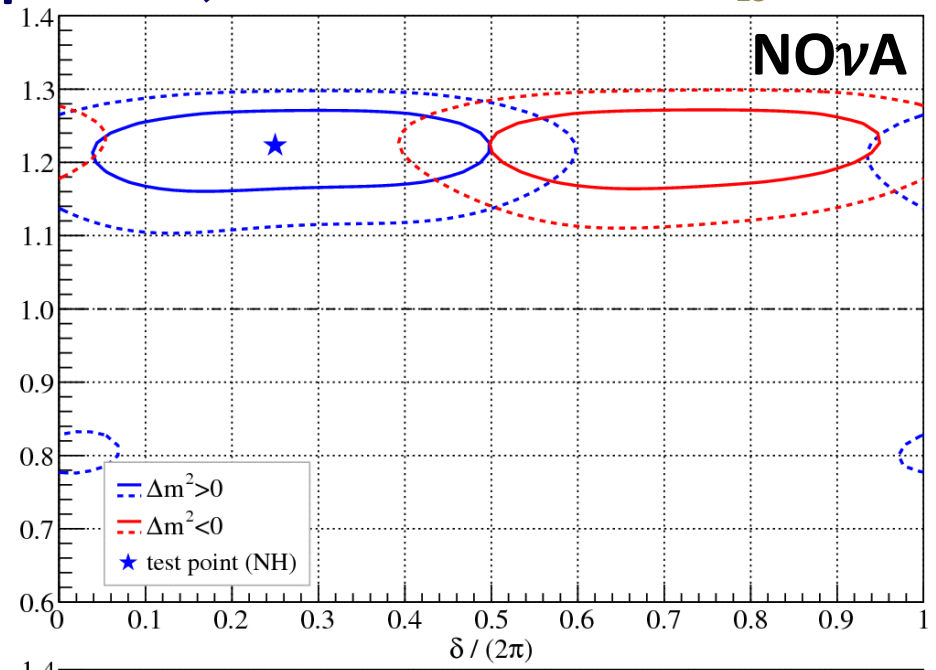


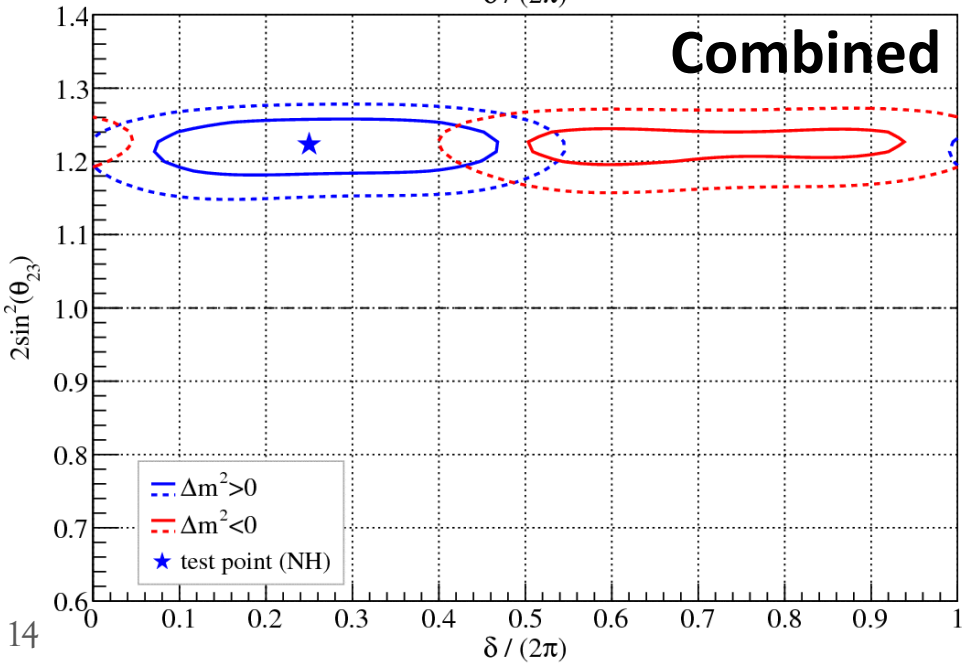
- **Non-maximal mixing scenario: $\sin^2(2\theta_{23})=0.95$, $\theta_{23}>\pi/4$**
- **Octant resolved** in NOνA and combined cases at >2σ.
- **Note:** this includes the ν_μ disappearance constraints on θ_{23}

Simultaneous δ, θ_{23}, and hierarchy information expected at the end of 2019. Even split of ν, $\bar{\nu}$.

For starred point shown and $\sin^2(2\theta_{13})=0.095$







- **Non-maximal mixing scenario: $\sin^2(2\theta_{23})=0.95$, $\theta_{23}>\pi/4$**
- **…with unfavorable δ this time**
- **Octant still resolved** at >2σ, despite "degeneracy"
- ***This is a general point:*** *octant determination is largely insensitive to hierarchy and δ*

Longer-term, "ultimate" reach

- **The preceding slides considered a nominal run of NOνA and T2K, through 2019.**
- **Relevance goes well beyond 2019, given the timescale for 3rd generation experiments**
- **So, let's consider this scenario:**
  - **NOνA continues running at 14 kton × 700 kW for another 6 years (to 2025)**
  - **T2K continues running at 22.5 kton × 700 kW for another 6 years (to 2025)**
  - **NOνA achieves a further 20% sensitivity gain through analysis improvements** *(analysis development currently underway)*
  - **T2K achieves a further 10% sensitivity gain through analysis improvements** *(analysis well developed already)*

- **The scenario**
  - **NOνA continues running at 14 kton × 700 kW for another 6 years (to 2025)**
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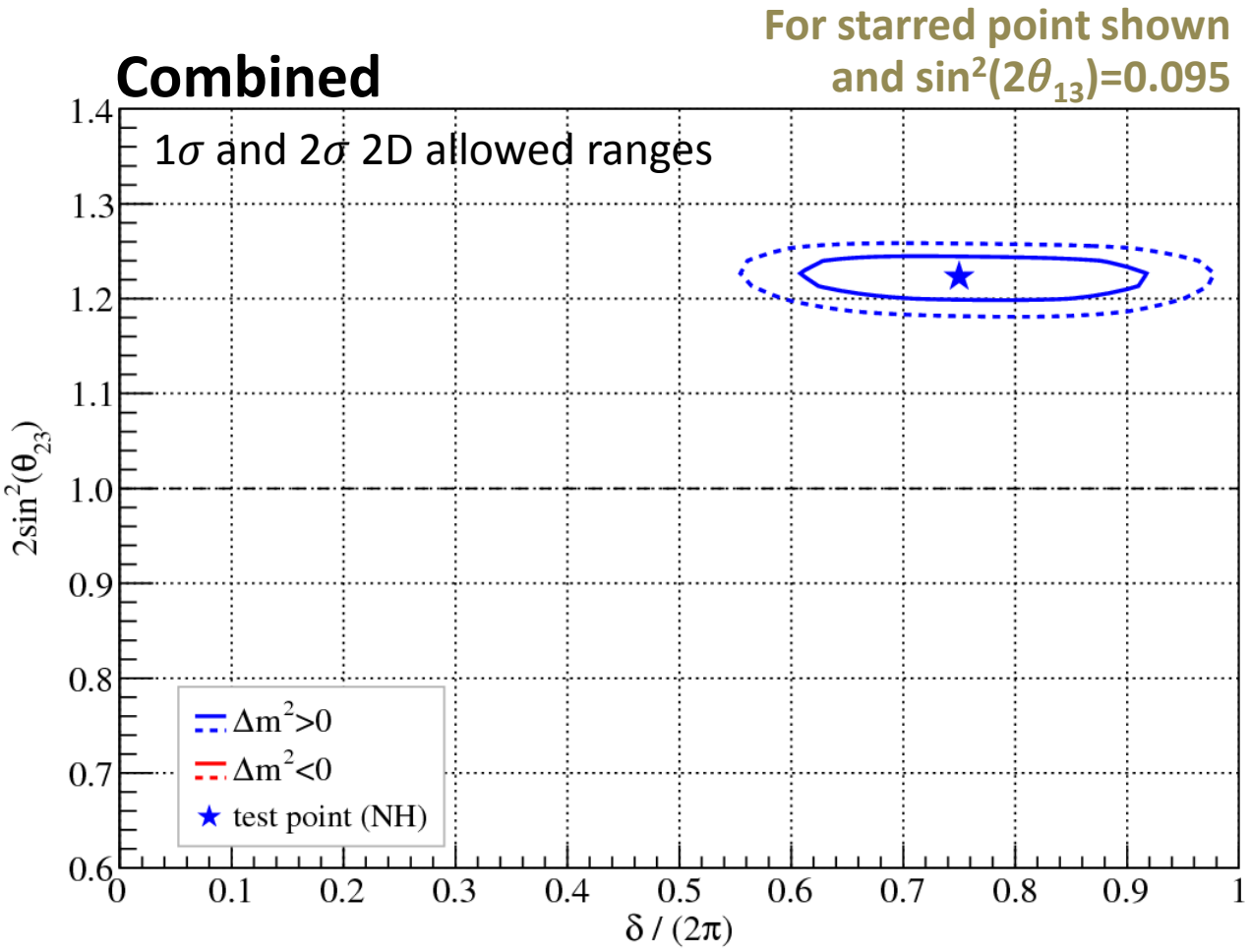
Expected contours for:

$\sin^2(2\theta_{23}) = 0.95$

$\theta_{23} > \pi/4$

δ favorable

All targets determined at >2σ (much greater for some)



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Expected contours for:

$\sin^2(2\theta_{23}) = 0.95$

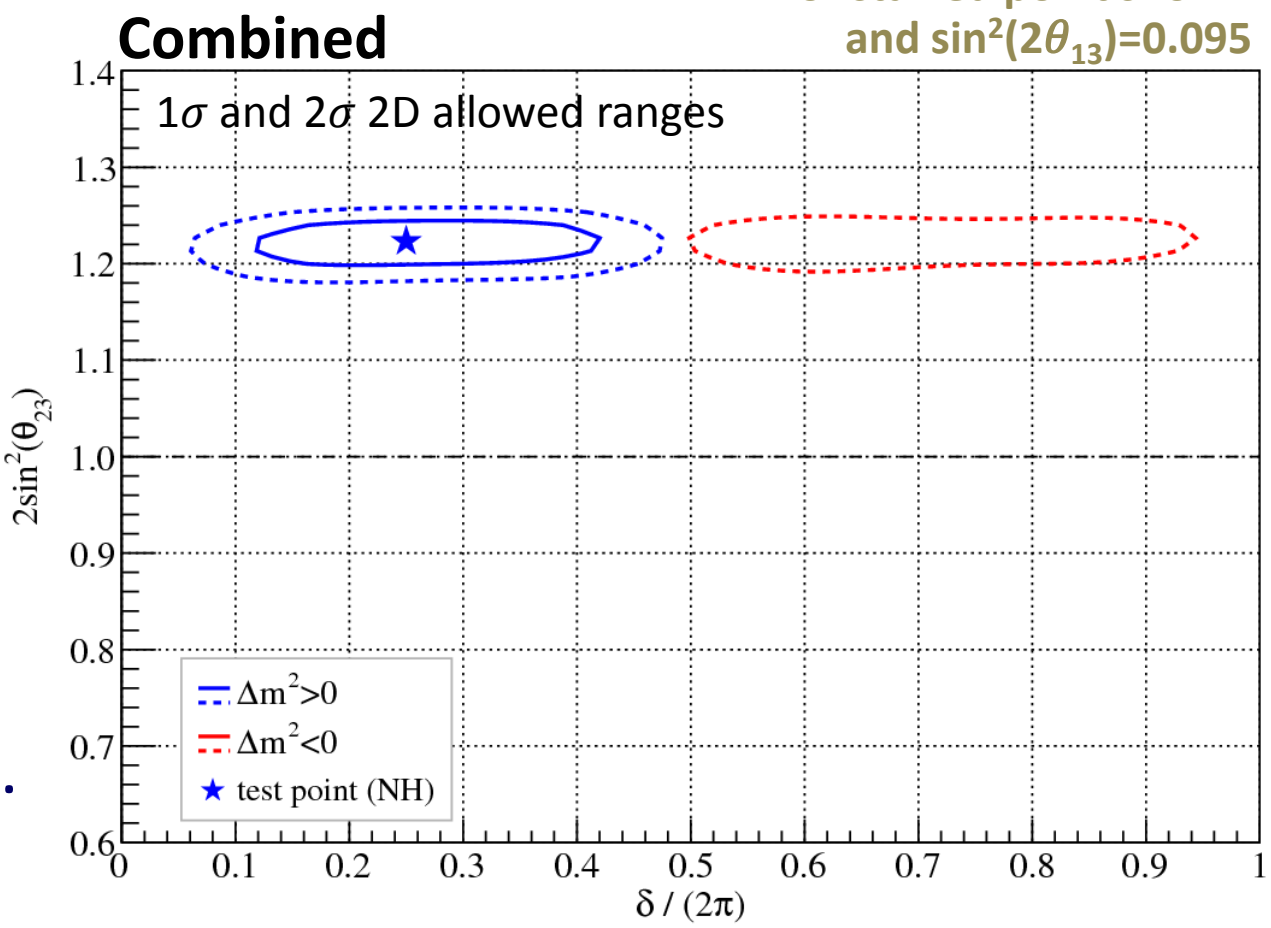
$\theta_{23} > \pi/4$

δ unfavorable

Not bad:

CP conserving points and wrong octant ~excluded; wrong hierarchy still allowed.

For starred point shown and $\sin^2(2\theta_{13})=0.095$



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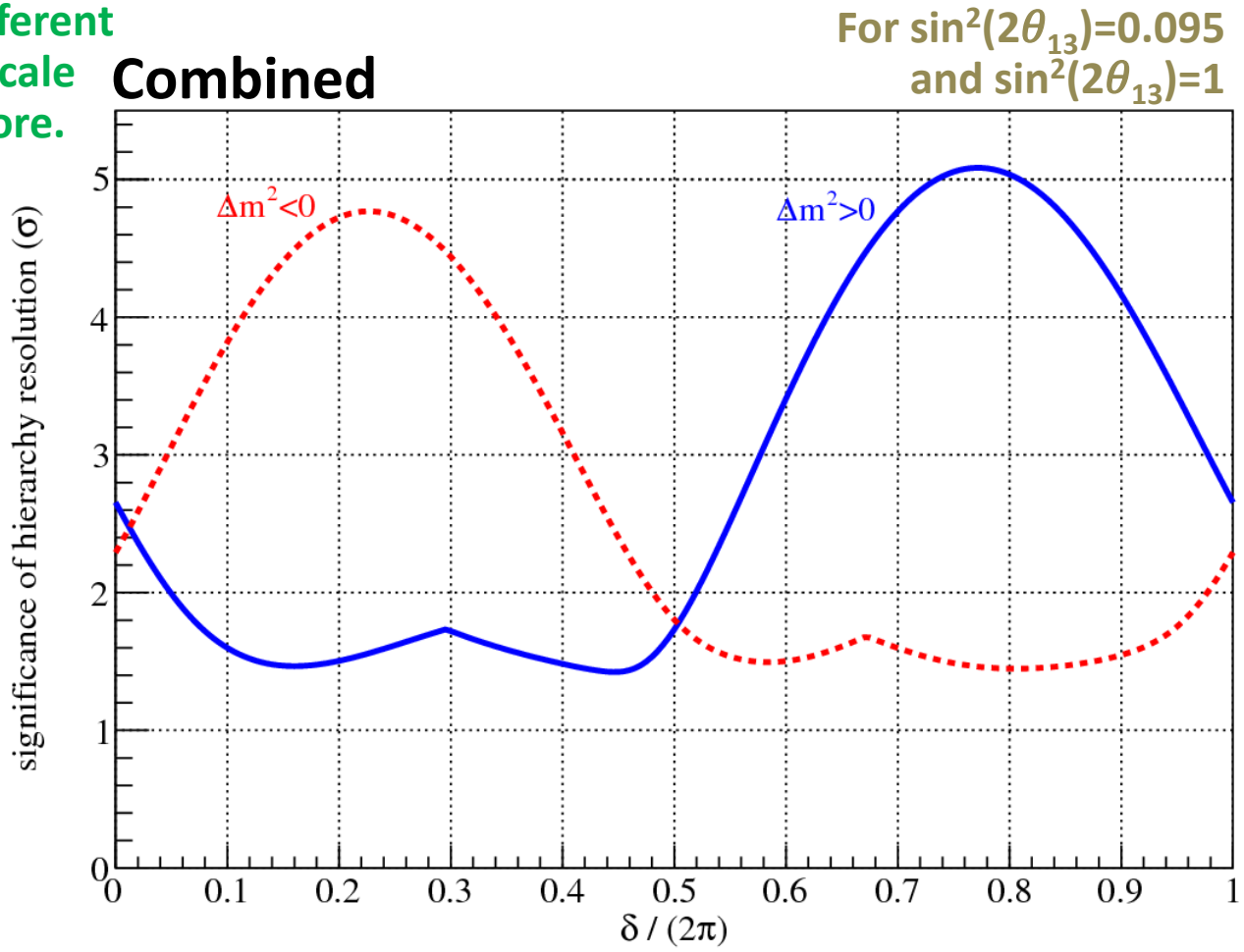
Raw hierarchy sensitivity
maximal mixing scenario

Best: 5.1σ

53% of δ range: >2σ
40% of δ range: >3σ

Everything >1.4σ: a good start.

Note: different vertical scale than before.



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  - **NOνA continues running at 14 kton × 700 kW for another 6 years (to 2025)**
  - **T2K continues running at 22.5 kton × 700 kW for another 6 years (to 2025)**
  - **NOνA achieves a further 20% sensitivity gain through analysis improvements**
  - **T2K achieves a further 10% sensitivity gain through analysis improvements**

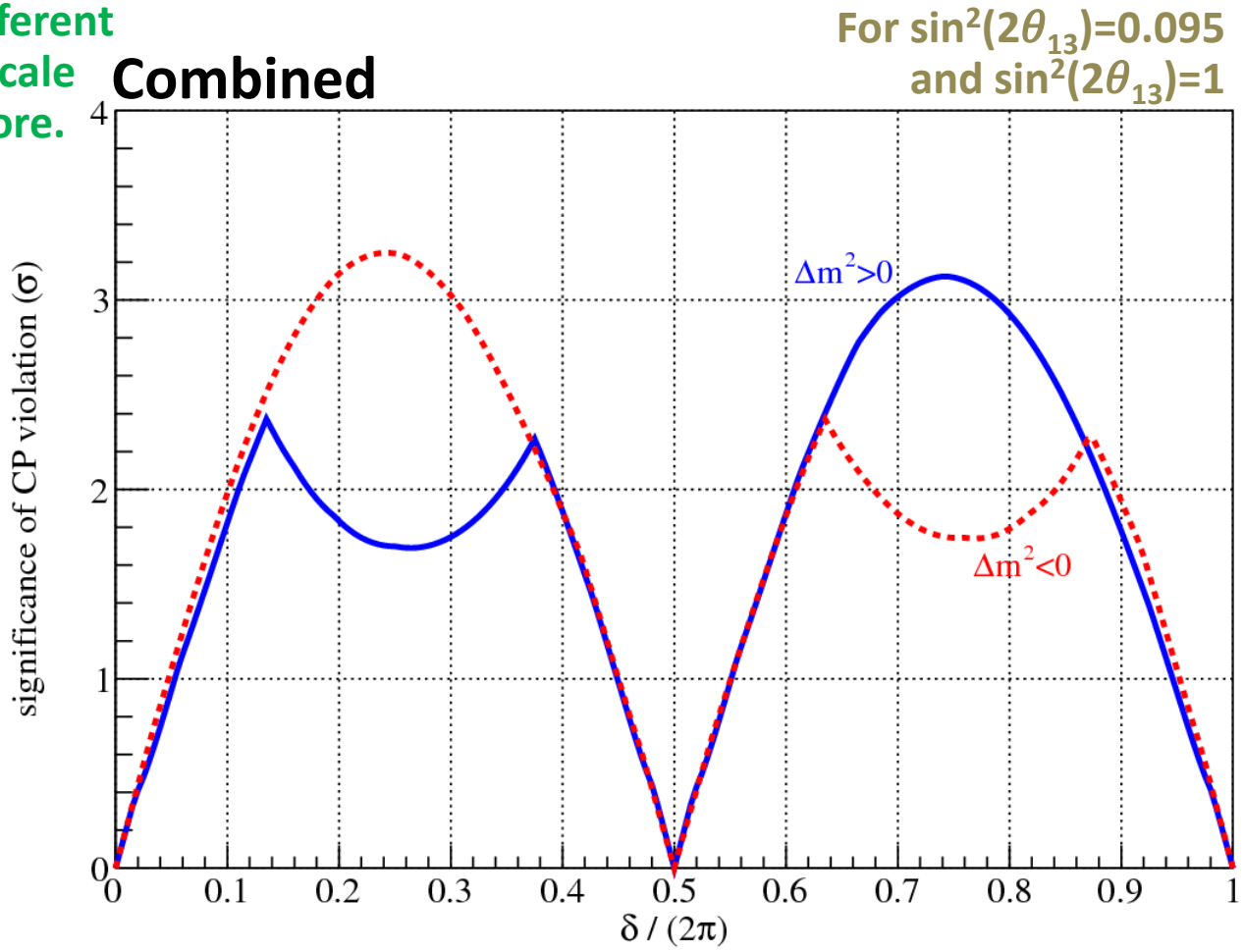
Raw CPv sensitivity
maximal mixing scenario

Best: 3.2σ

40% of δ range: >2σ
10% of δ range: >3σ

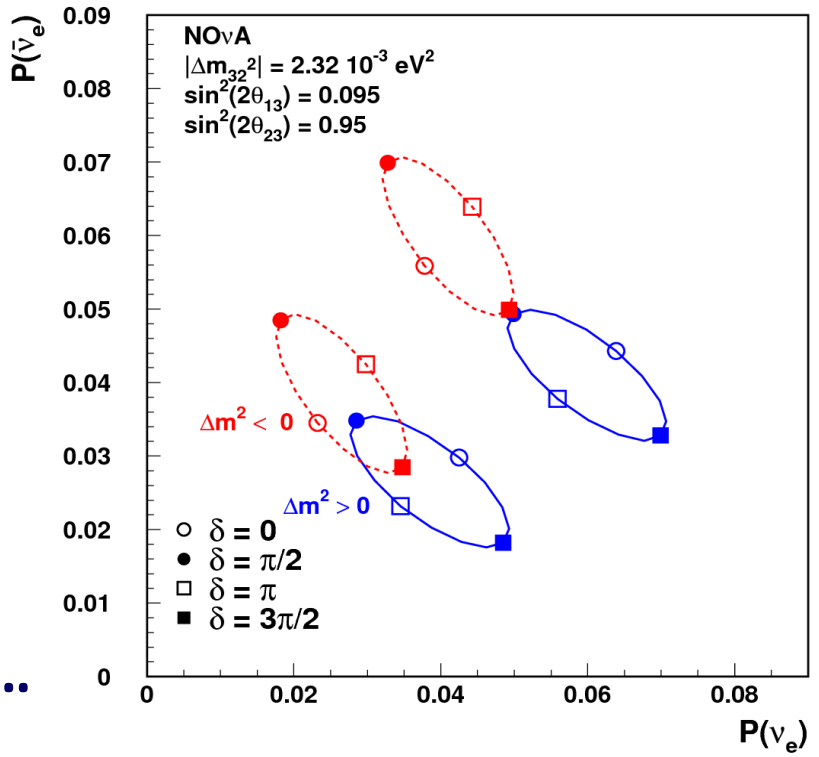
No mininum.
(Can be arbitrarily hard! A future experiment can't have too much CP sensitivity.)

Note: different vertical scale than before.



A few words on run plans

- **Too many scnearios to enumerate, so some rules of thumb…**
  - **If you knew that $\sin^2(2\theta_{23})=1$, then ν running is generally best**
    But, you don't – and won't – know that…
  - **If $\sin^2(2\theta_{23})<1$** (*even slightly, say: 0.98*), **some $\overline{\nu}$ running is needed** ⟶
    (A few outlier cases prefer only $\overline{\nu}$ or ν, but not most)
  - **A mixed run plan is generally better for each of T2K and NOνA, but the T2K choice is not critical if NOνA runs mixed**
    (Biggest influence of T2K in the combined reach is in hierarchy degeneracy breaking, which can be done with ν-only running)



- **There are other reasons to run mixed…**
  - **ν+$\overline{\nu}$ over-constrains the atmospheric sector**
  - **Standard 3ν formalism okay? CPTv (effective or otherwise)?**
- **Run plan decisions are temporally coarse by their nature**
  - **Start with a slug of ν data**
  - ***Note:* data-driven run plan changes make future statistical analysis trickier**

Closing thoughts

- End of 2019: **NOνA can get hierarchy** at 95% C.L. for **~37% of δ range**
  (exact fraction depends on θ_{23})
- In combination with T2K, **this metric doesn't change.**
  But: the other ~63% of δ values get a head start of ~1σ for future combined fits
- **In super scenario** (2025 + analysis gains), the combination reaches:

Hierarchy:
40% of δ range: >3σ
53% of δ range: >2σ
100% of δ range: >1.4σ

CP violation:
10% of δ range: >3σ
40% of δ range: >2σ

(Exact fractions depend on θ_{23})

- An unambiguous **demonstration of CP violation**…
  - *…**can be arbitrarily hard**, depending on what Nature has chosen*
  - *…requires **considerably more confidence** than the hierarchy determination (which is not a "discovery" result)*
  - *…is **tough for T2K+NOνA***
- Future experiments should **emphasize CPv reach.**
  *As long as we've got LBL+atm. expts., we'll get the hierarchy **(if we aren't already there in a few years!).** Also, **future scenarios should be shown as combined fits**: recall the "non-linear" benefits in T2K+NOνA combination*

Extras

MINOS ν_e appearance

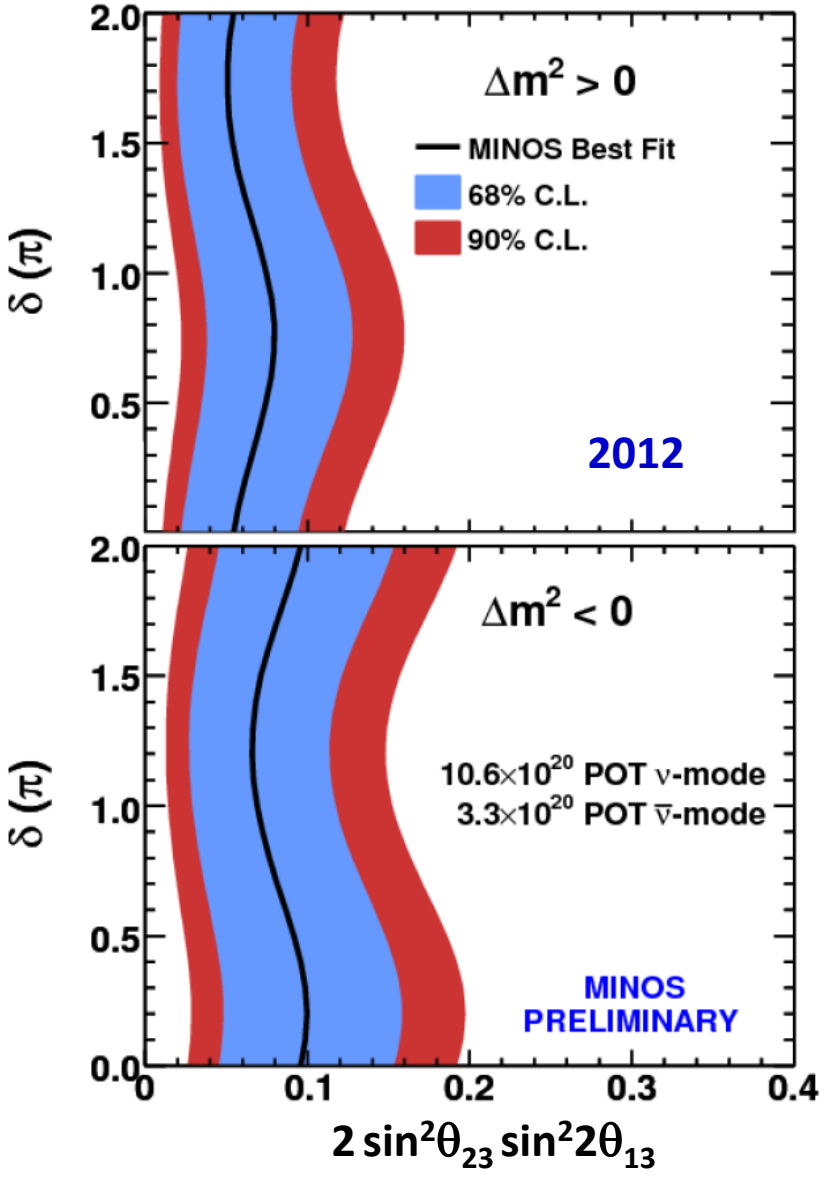
- **Result will probably not improve competitively in MINOS+ era. (MINOS+ spectrum not very favorable for ν_e appearance measurement.)**
- **ν_e appearance significance: 96% C.L.**
  1st-generation, iron-based, broadband-spectrum experiment: remarkable that this can be done!

MINOS (at δ=0, θ_{23}=45°)

$\sin^2 2\theta_{13} = 0.05^{+0.04}_{-0.04}$ (normal hier.)

$\sin^2 2\theta_{13} = 0.09^{+0.06}_{-0.06}$ (inverted hier.)

- **δ and hierarchy dependence visible in contours at right. What does the MINOS result tell us about the mass hierarchy?**
  (Getting a little ahead of myself, but…)

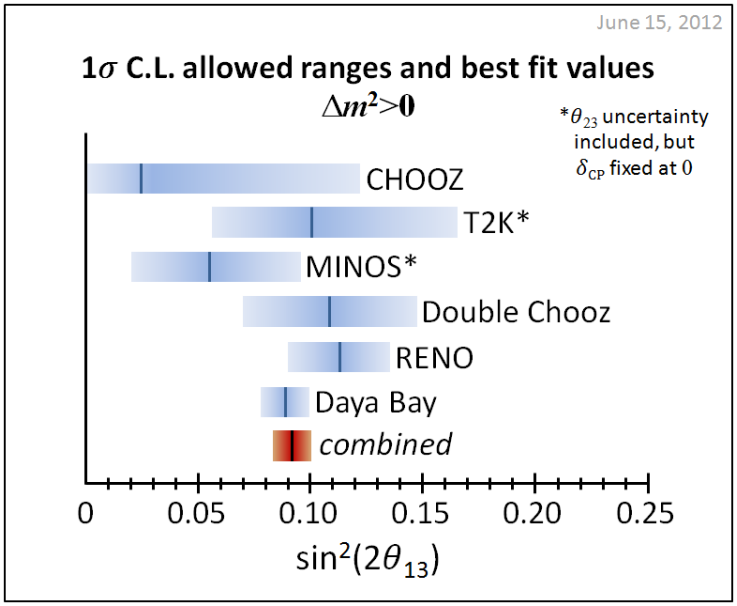


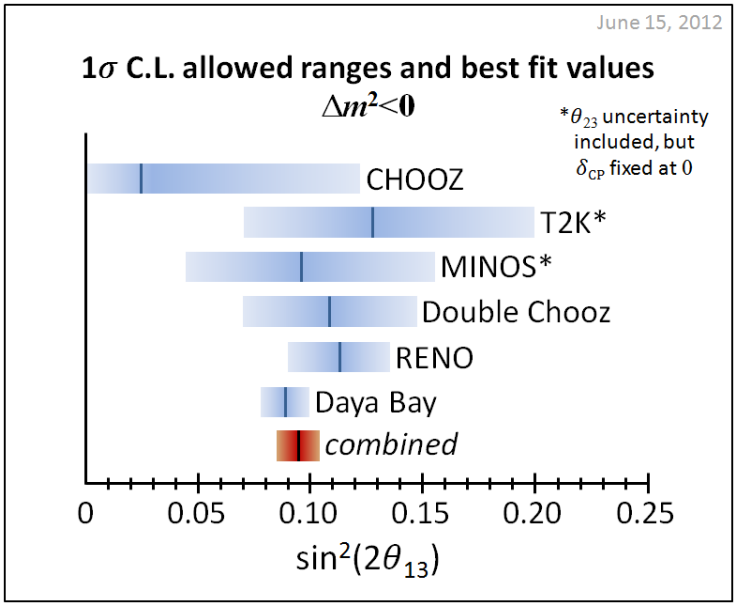
MINOS ν_e appearance – hierarchy?

Qualitative idea is evident here:

(MINOS ranges vs. combined range)

Quantitatively?





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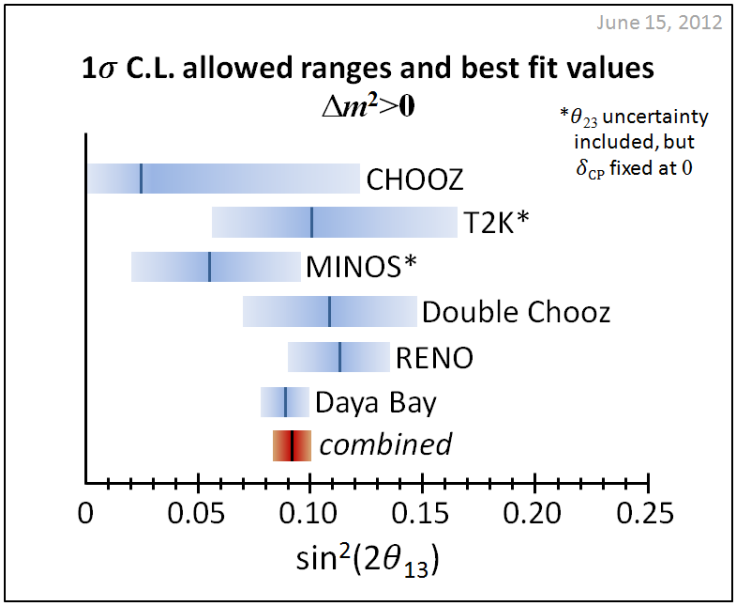

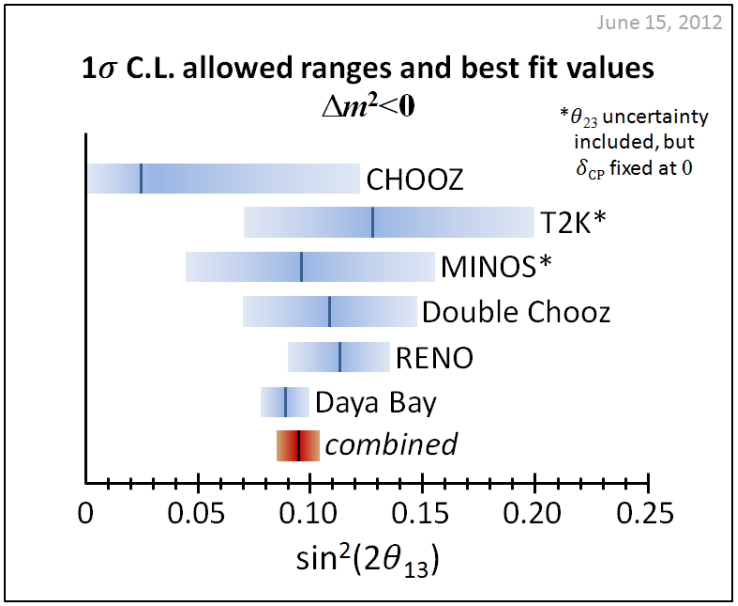

Quantitatively?

- **Today: must marginalize over θ_{13}, θ_{23}, & δ; pull terms on θ_{13}, θ_{23} w/ current errors:**
  The MINOS data prefer inverted hierarchy at 0.20σ
  (so, not much preference)

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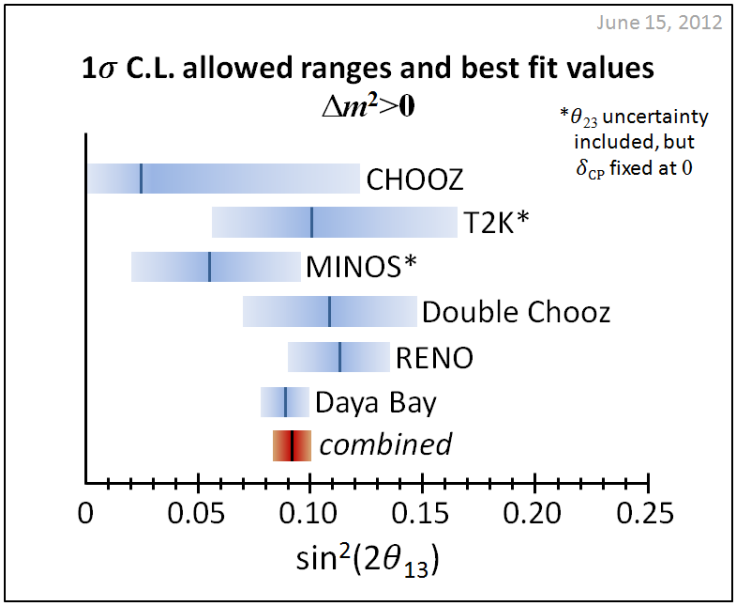

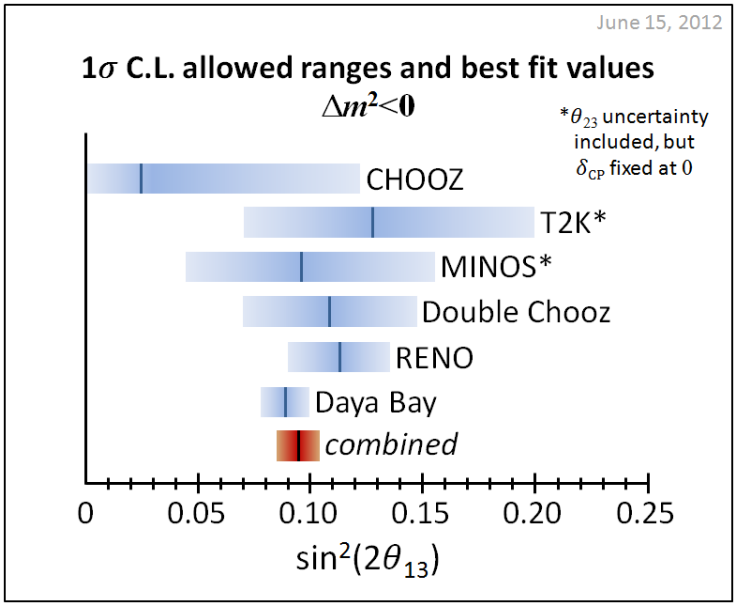

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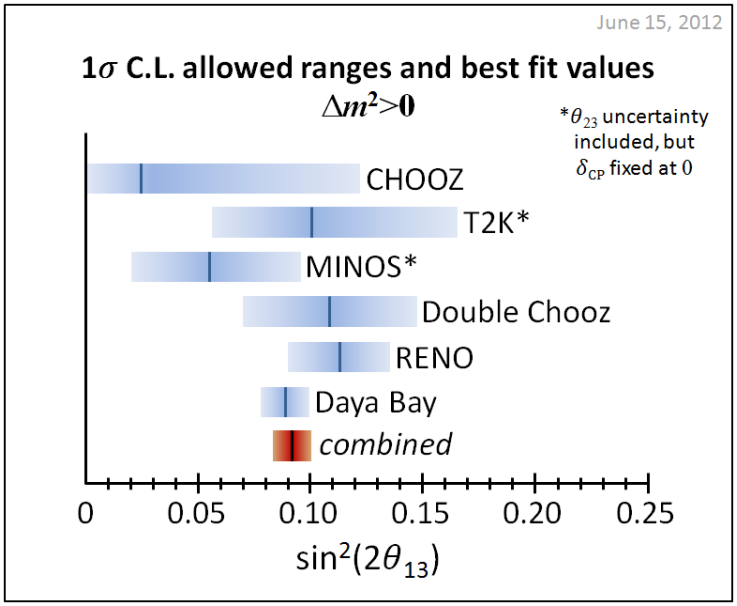
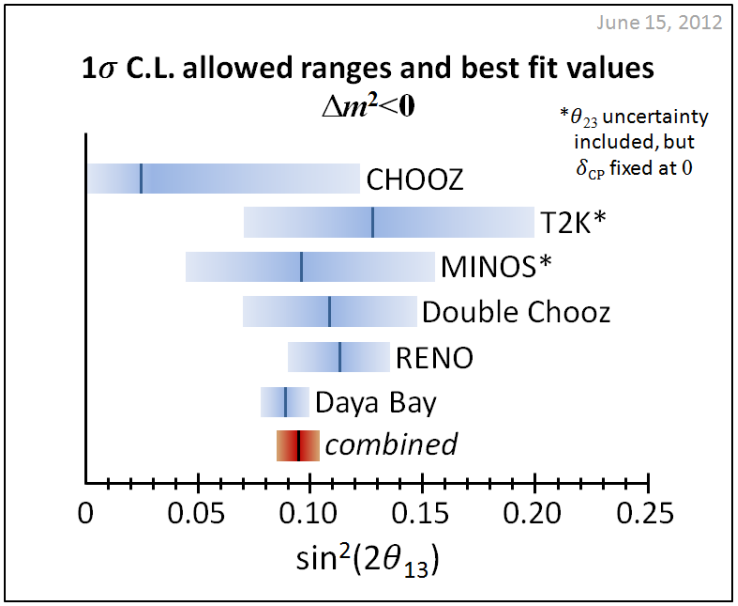
  (so, not much preference)
- **Future: Will soon enough know θ_{13} and θ_{23} very well. Assume $\sin^2(2\theta_{23})=1$ and $\sin^2(2\theta_{13})=0.095$, and marginalize over δ:**
  The MINOS data would prefer inverted hierarchy at 0.24σ
  (This is the approximate impact at the time of full T2K and NOvA exposures.)

MINOS ν_e appearance – hierarchy?

Qualitative idea is evident here:

(MINOS ranges vs. combined range)





Quantitatively?

- **Today:** must marginalize over θ_{13}, θ_{23}, & δ; pull terms on θ_{13}, θ_{23} w/ current errors:
  The MINOS data prefer inverted hierarchy at 0.20σ
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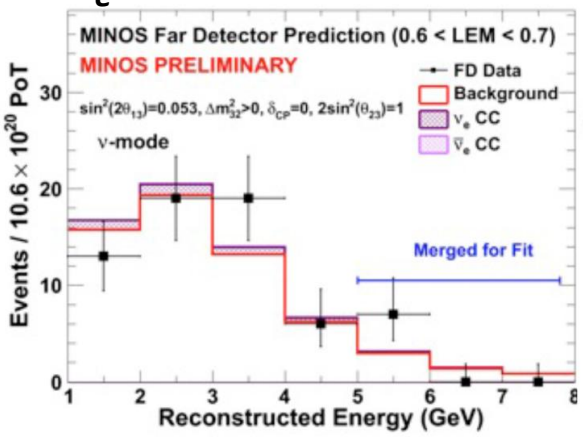
- **Future:** Will soon enough know θ_{13} and θ_{23} very well. Assume $\sin^2(2\theta_{23})=1$ and $\sin^2(2\theta_{13})=0.095$, and marginalize over δ:
  The MINOS data would prefer inverted hierarchy at 0.24σ
  (This is the approximate impact at the time of full T2K and NOvA exposures.)
- **Dream world:** Know θ_{13}, θ_{23}, and δ perfectly. If $\sin^2(2\theta_{23})=1$, $\sin^2(2\theta_{13})=0.095$, $\delta=0$:
  The MINOS data would prefer inverted hierarchy at 0.94σ
  (This is the approximate impact in the fullness of time.)

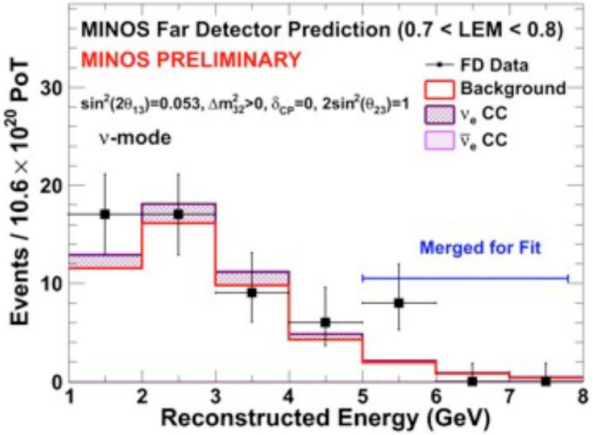
MINOS ν_e appearance

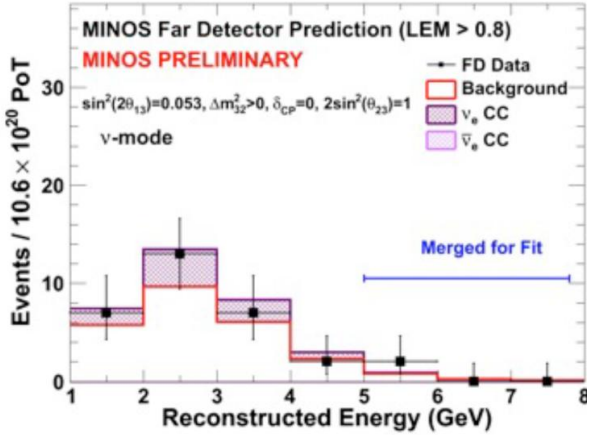
From MINOS talk at 2012

Full neutrino and antineutrino data sets combined

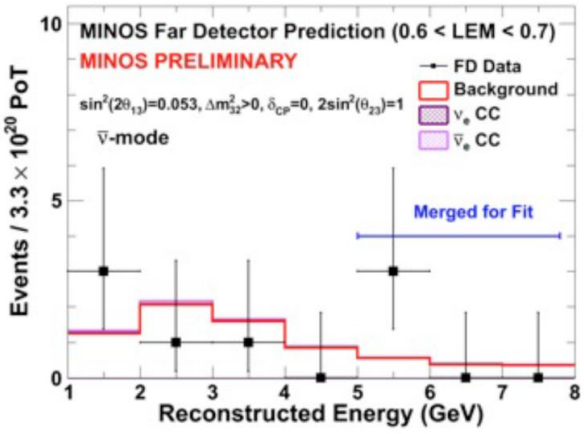
ν_e candidates in neutrino data

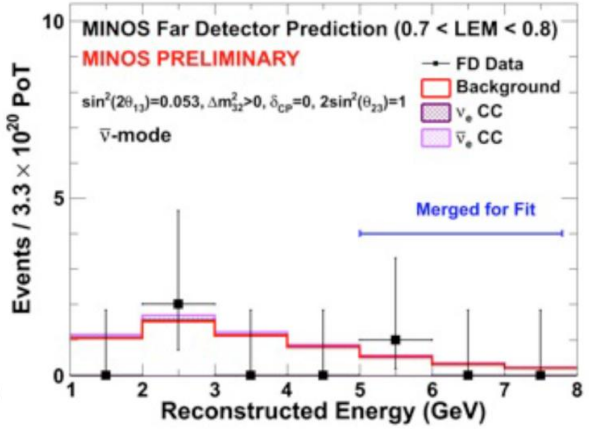


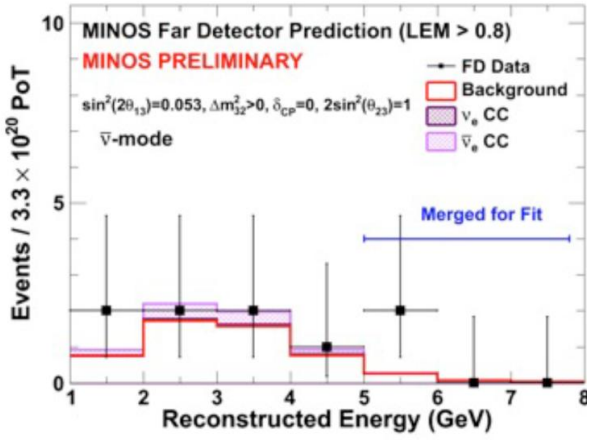




$\bar{\nu}_e$ candidates in antineutrino data

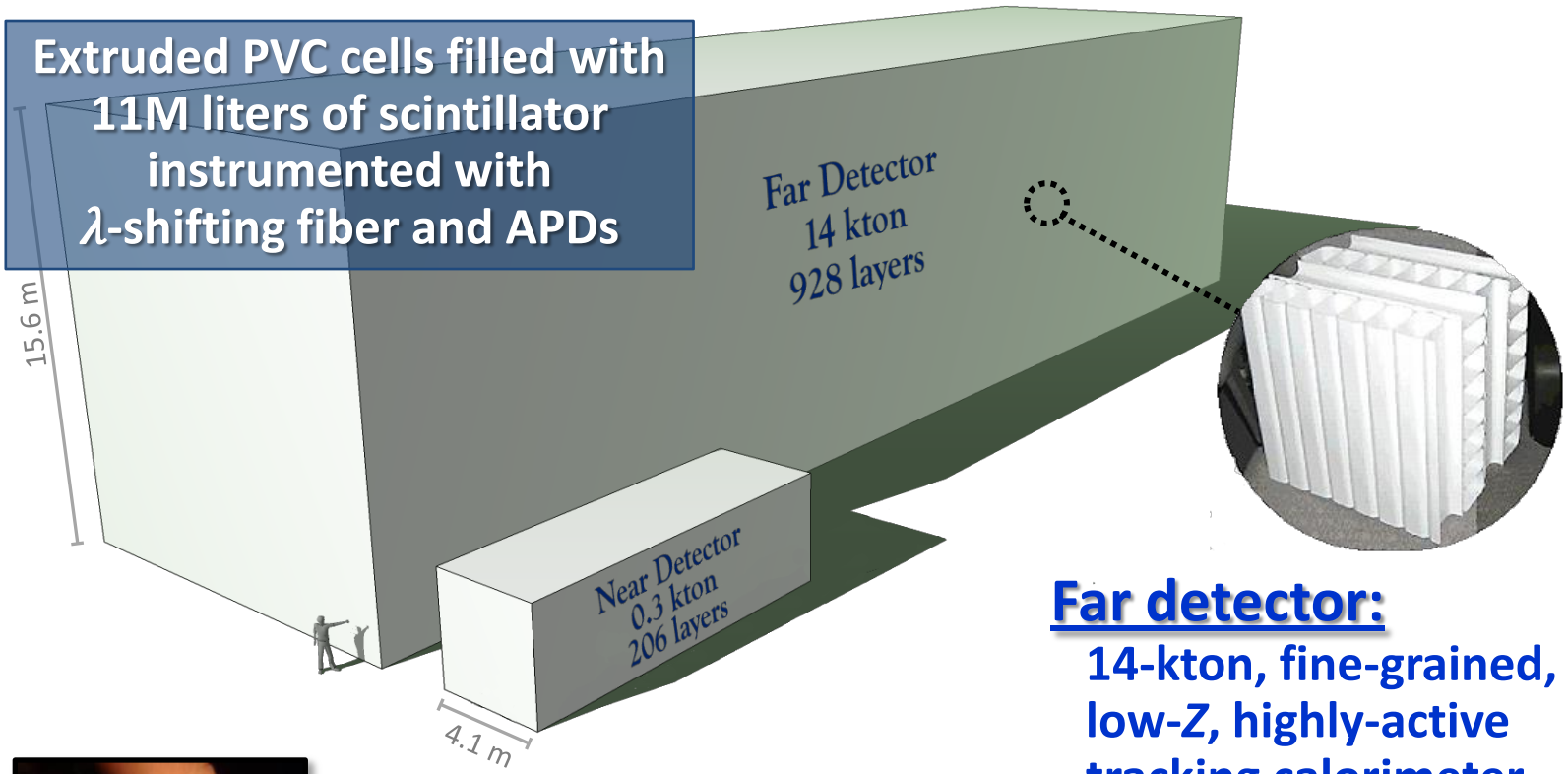




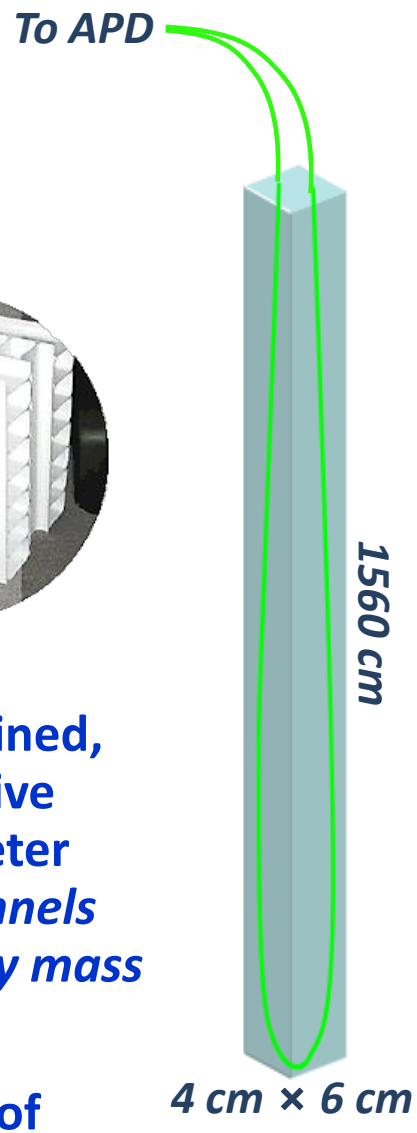


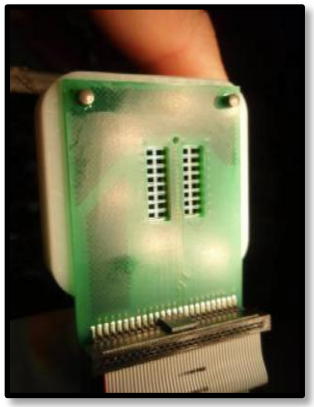
NOνA Detectors

Extruded PVC cells filled with 11M liters of scintillator instrumented with λ-shifting fiber and APDs



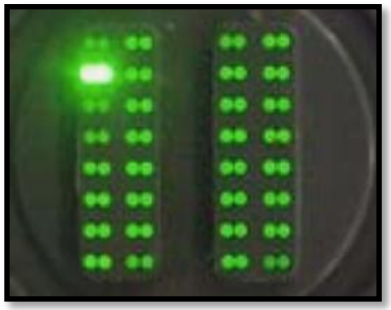
A NOνA cell





32-pixel APD ←

Fiber pairs from 32 cells →



Far detector:

14-kton, fine-grained, low-*Z*, highly-active tracking calorimeter

→ *360,000 channels*

→ *77% active by mass*

Near detector:

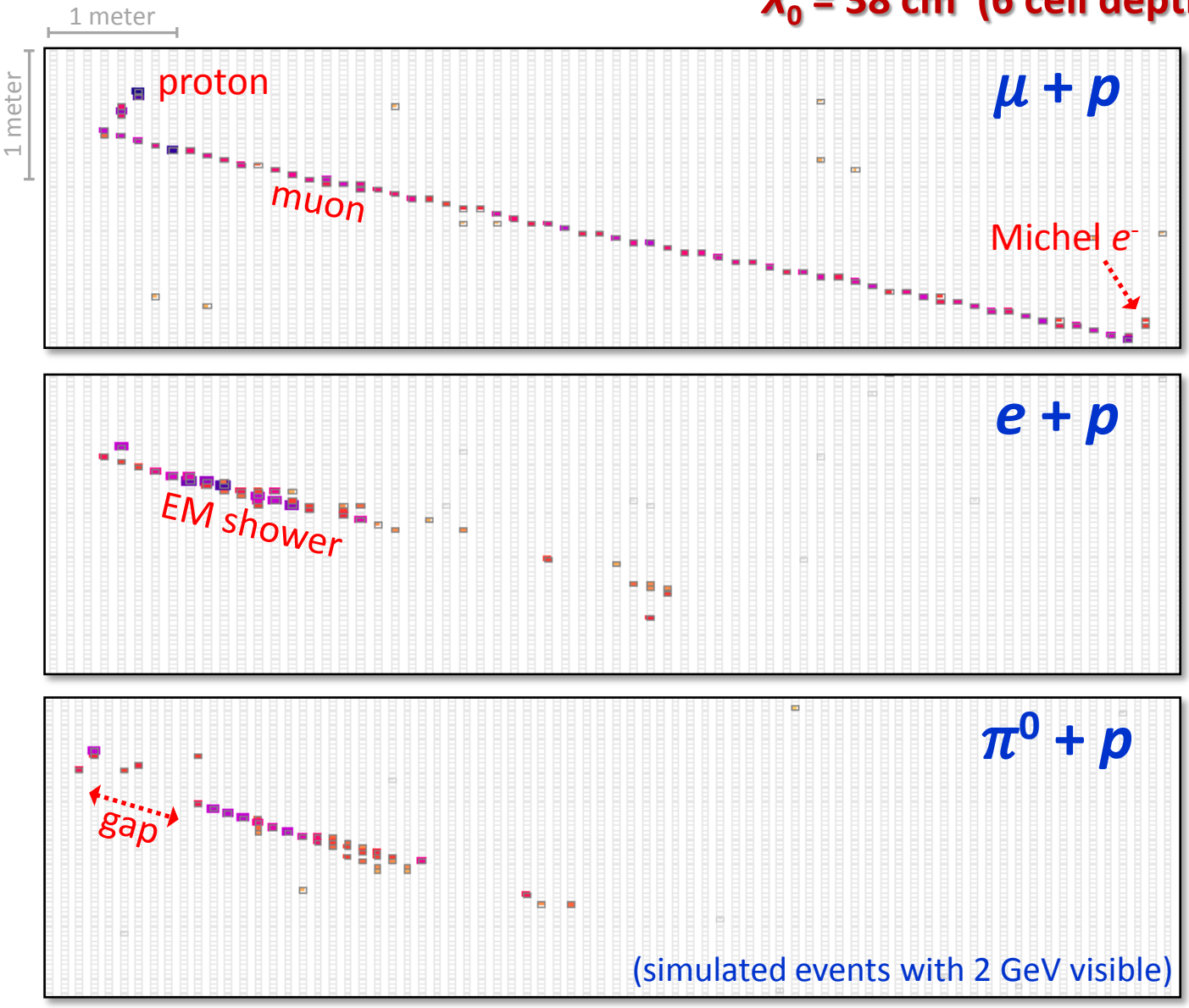
0.3-kton version of the same

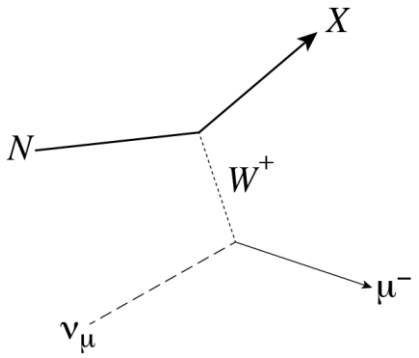
→ *18,000 channels*

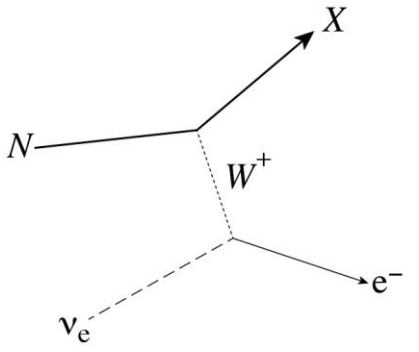
Events in NOνA

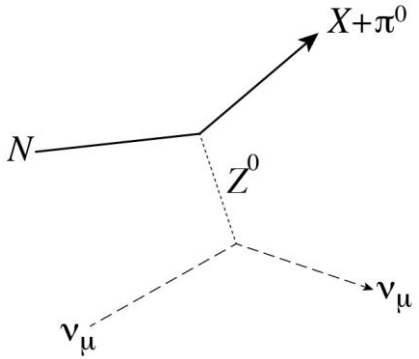
Superb spatial granularity for a detector of this scale

X_0 = 38 cm (6 cell depths, 10 cell widths)



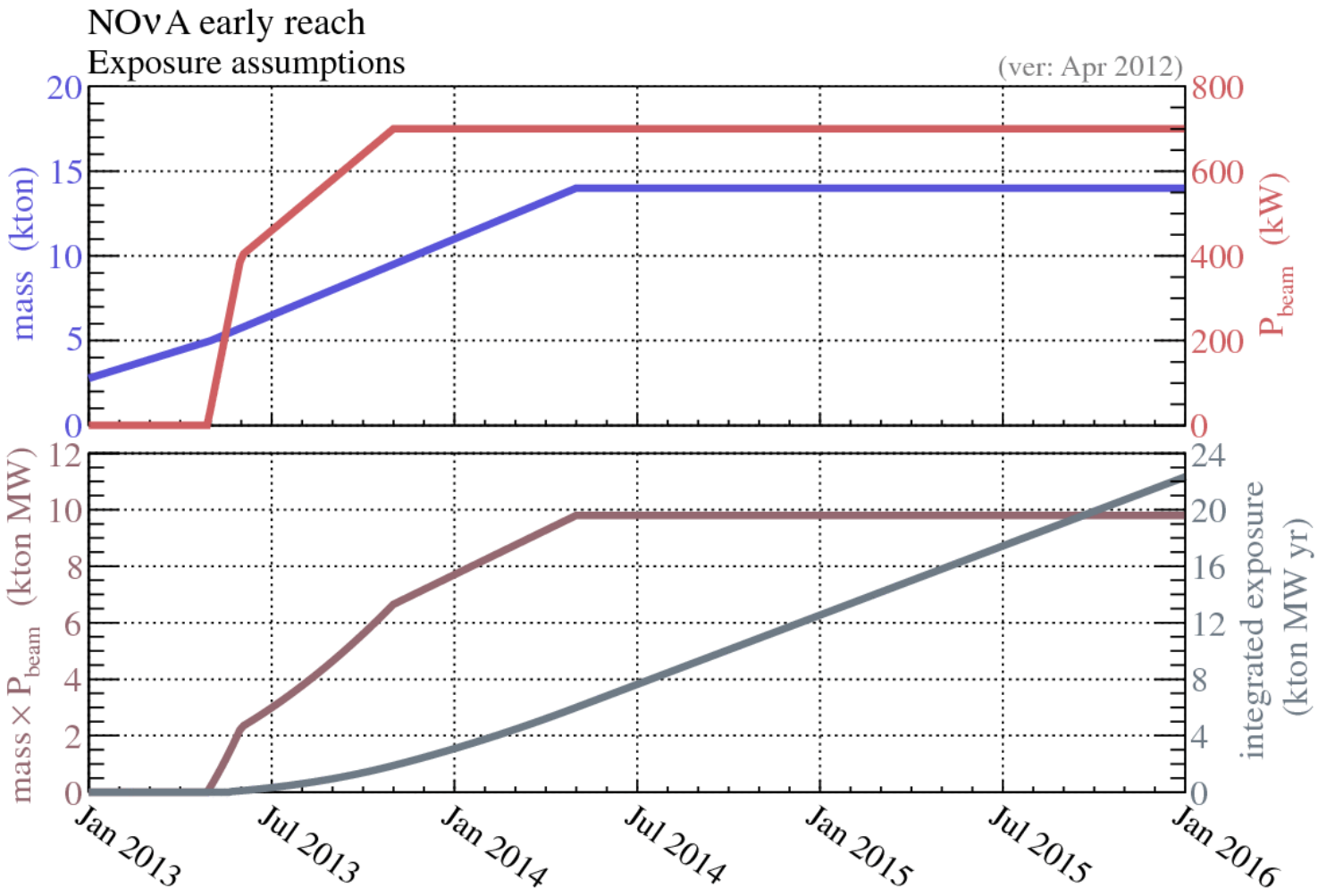






NOνA Exposure in Early Running

Evolution of detector mass and beam power…



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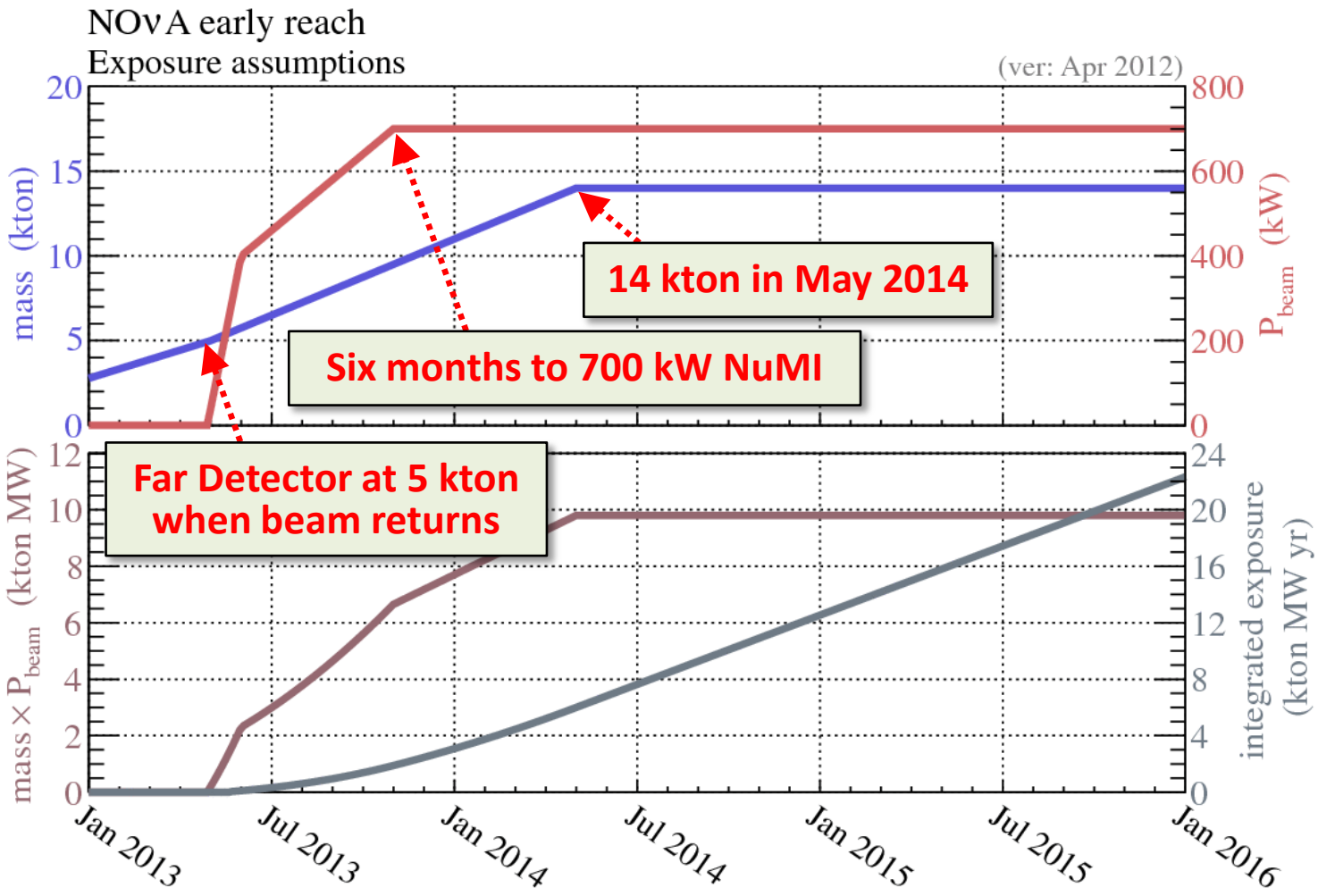
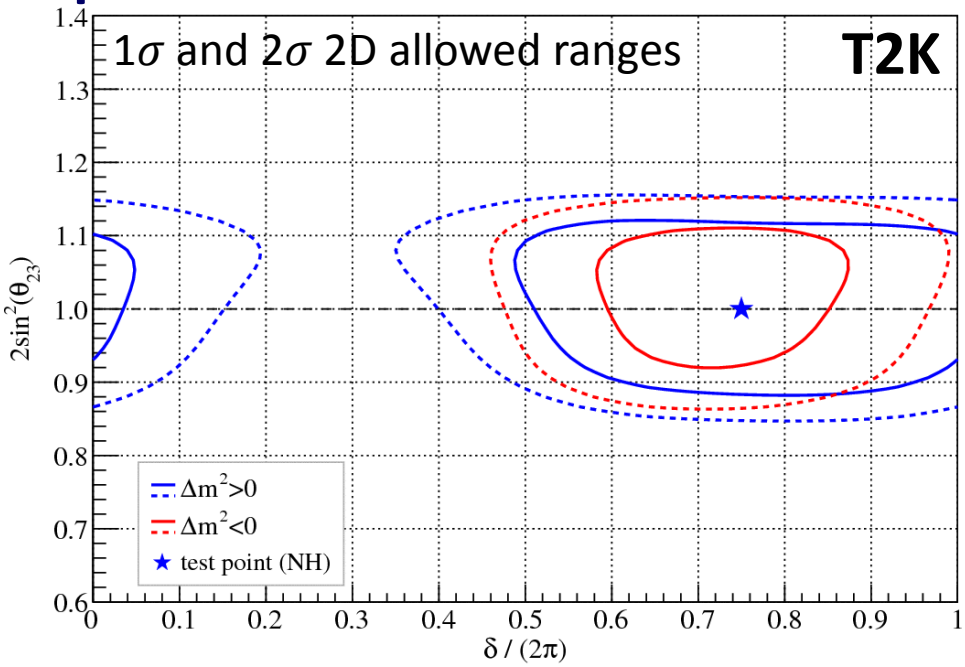
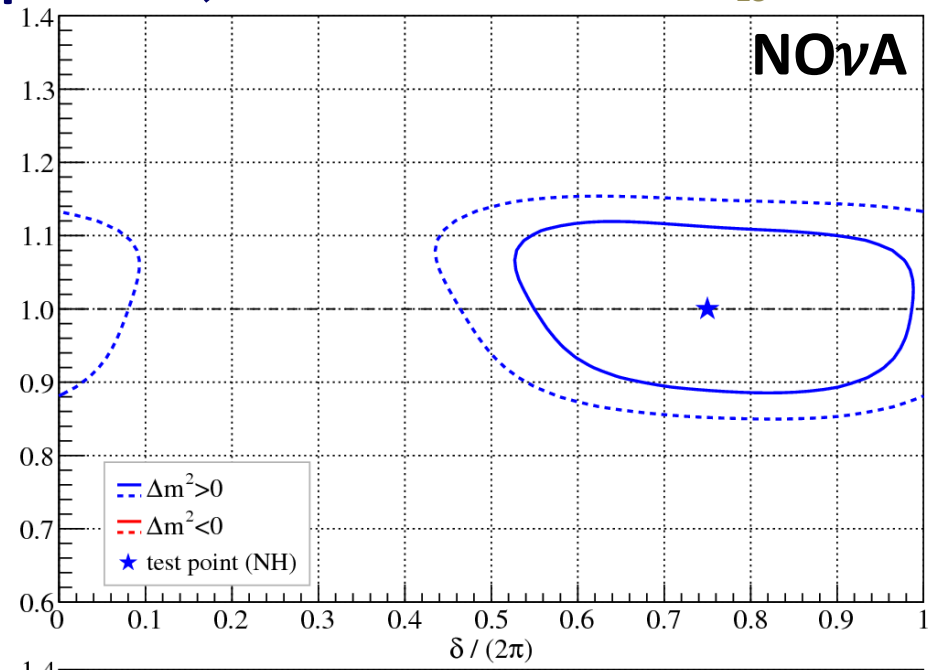


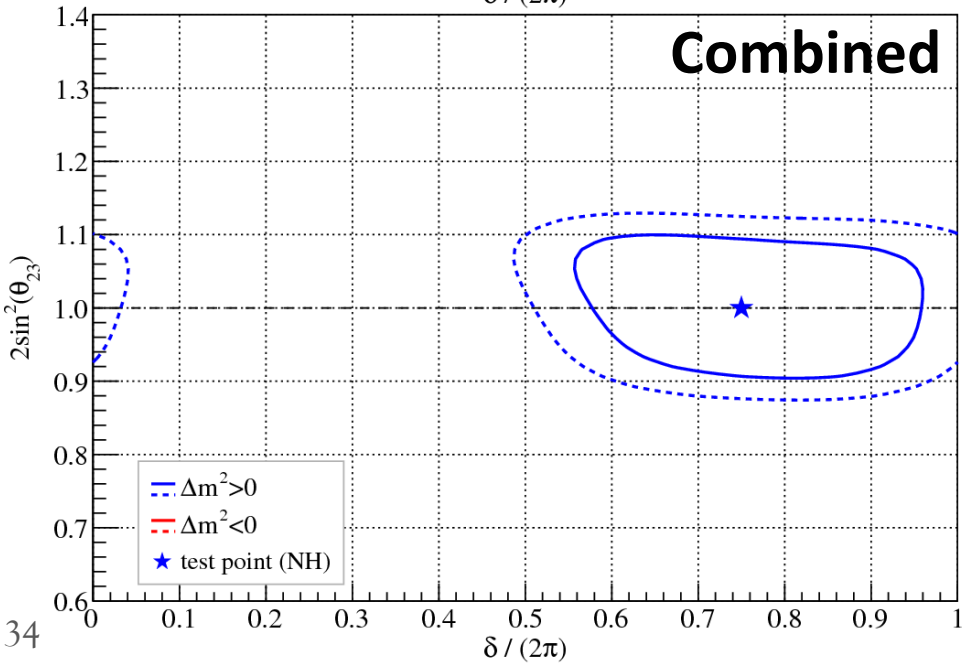
Simultaneous δ, θ_{23}, and hierarchy information expected at the end of 2019. Even split of ν, $\overline{\nu}$.

For starred point shown and $\sin^2(2\theta_{13})$=0.095



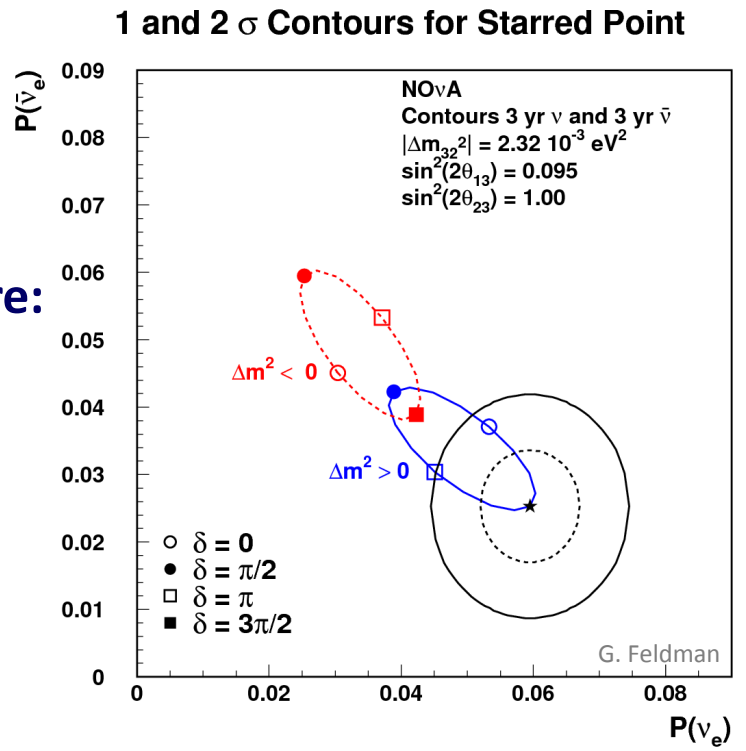


- **Maximal mixing scenario**
- These plots show the combined influence of ν_e **appearance** and ν_μ **disappearance** data
- A particularly favorable test point
- **Hierarchy resolved at >2σ** (no red contours remaining)
  (Actually >2.5σ, since $\Delta\chi^2$=6.18 sets the 2σ contours drawn in this 2D space.)



Bi-probability comments

- **These plots are great for *qualitative* intuition about LBL sensitivities**
- **Good for *quantitative* intuition, too, but take care:**
  - The 2D space shown is not dense with possible answers; 2D contours aren't very interesting
  - So, 1D contours are drawn. Really, this just shows $\Delta\chi^2$ values between points, in "sigma" units
  - *For example:* the best inverted hierarchy point is apparently >2σ ($\Delta\chi^2$>4) worse than the expected best fit

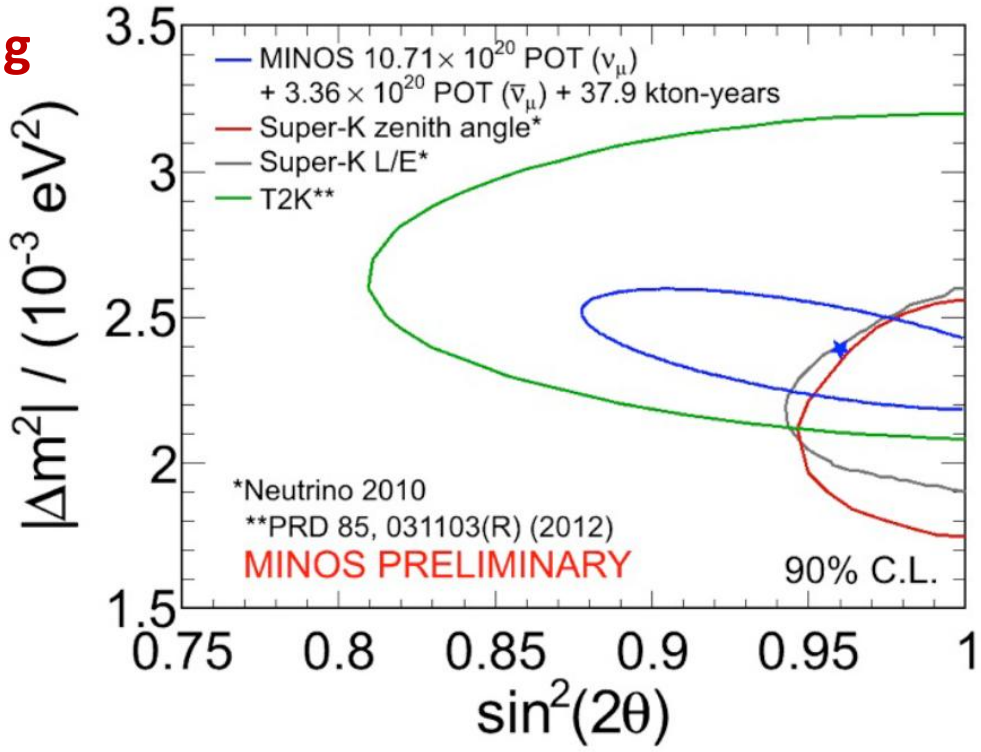


- **Also: we're making measurements of discrete quantities (hierarchy; octant of θ_{23})**
  - An experiment with <u>arbitrarily little hierarchy sensitivity</u> will "exclude" the wrong hierarchy at 50% C.L. (not 0% C.L.) for any number of sensible constructions of frequentist or Bayesian intervals.
  - Someone instead talking about "number of sigma" based on $\Delta\chi^2$, would, in contrast, show 0σ (often interpreted at 0% C.L.)
- **While we're picking through the seedling sensitivity over the next couple of years, we'll have to pay more attention to statistics than perhaps we'd rather.**

MINOS ν_μ disappearance

- **~4% error on squared-mass splitting**
  (Note: $|\Delta m^2_{21} / \Delta m^2_{32}| \approx 3\%$
  ⇨ precision, 3-flavor era)

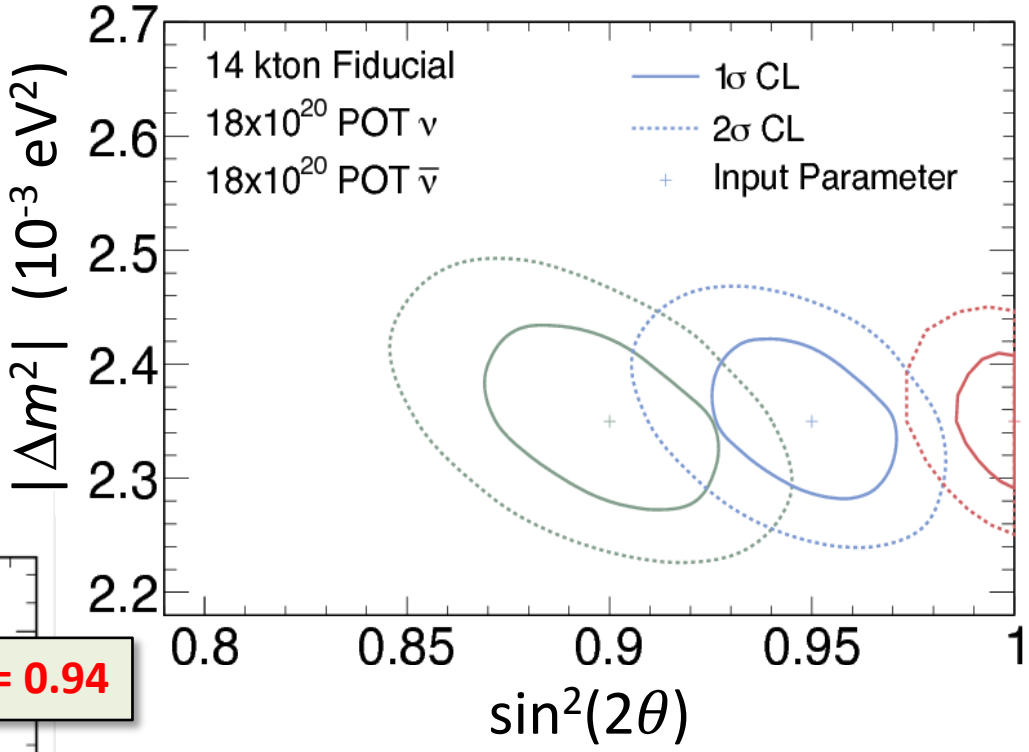
- ***Best-fit:* non-maximal mixing**
  - ***Only at 1σ, but relevant for discussion later***
  - ***New Super-K atmospheric result at Neutrino 2012 also prefers non-maximal mixing***

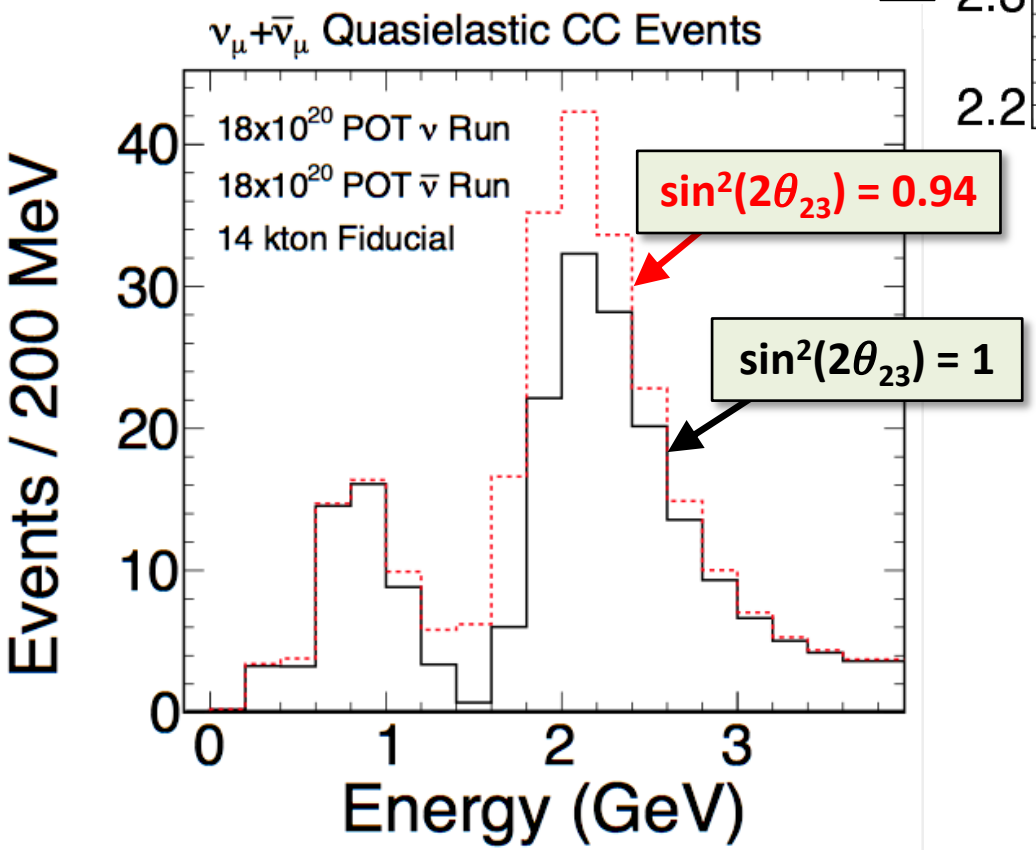


$$|\Delta m^2_{atm}| = (2.39^{+0.09}_{-0.10}) \times 10^{-3}\ eV^2$$
$$\sin^2(2\theta_{23}) = 0.96 \pm 0.04$$
$$\sin^2(2\theta_{23}) > 0.90\ (90\%\ C.L.)$$

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

Example NOνA contours for three test points →



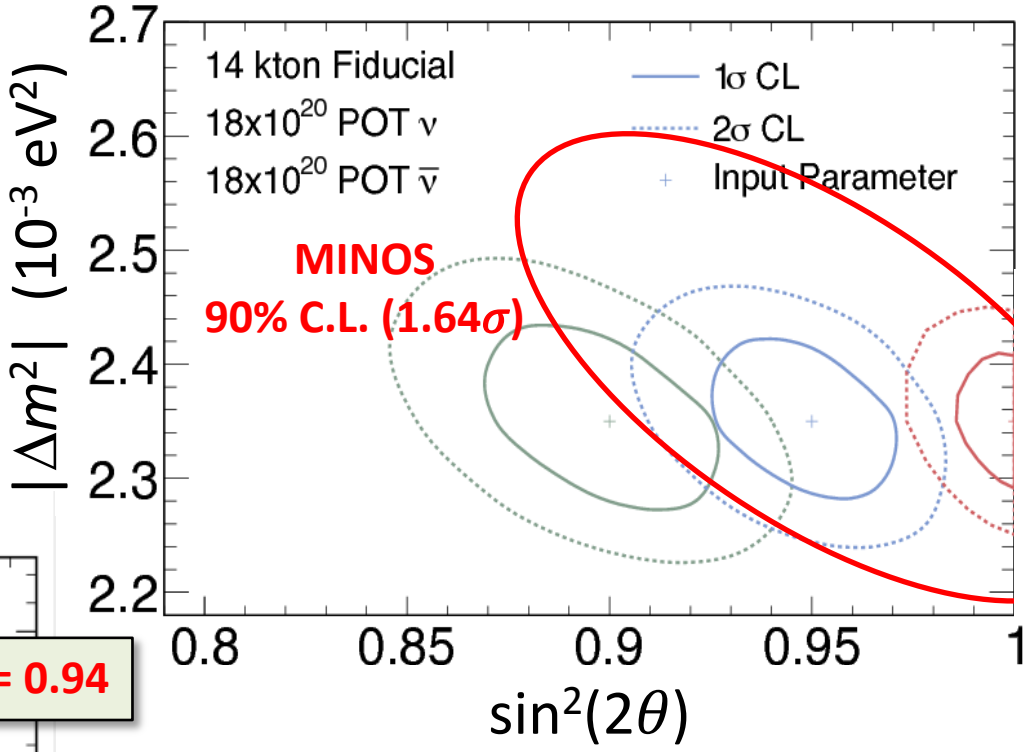


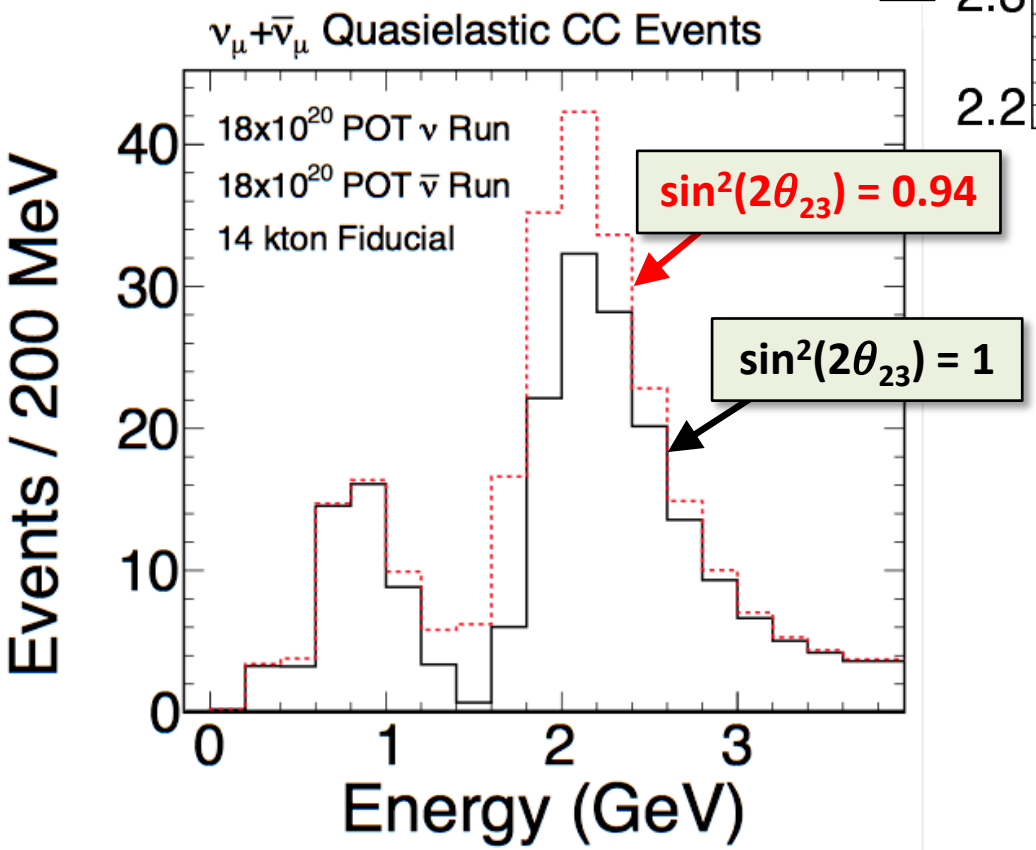
4% energy resolution for the QE sample.

Inclusive ν_μ CC sample should be background-free

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

Example NOνA contours for three test points →



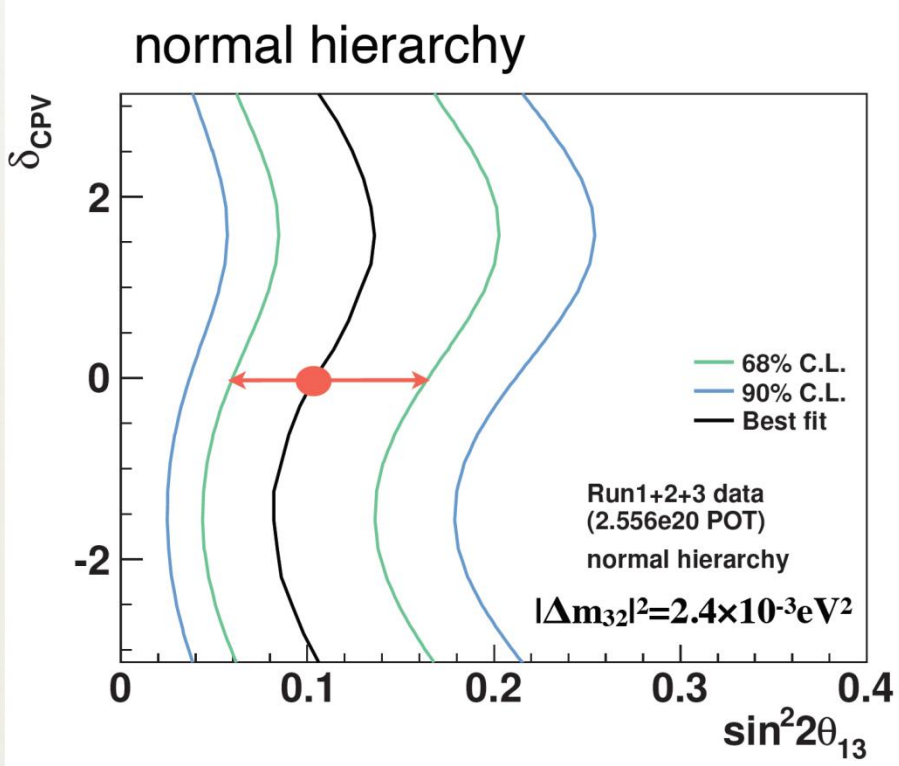


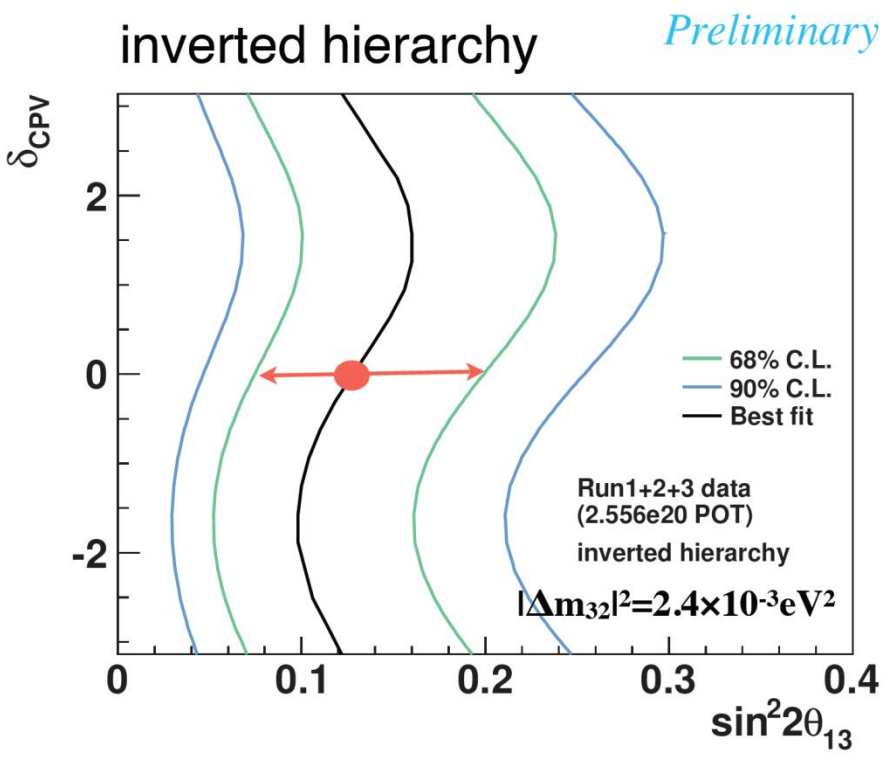
4% energy resolution for the QE sample.

Inclusive ν_μ CC sample should be background-free

Latest T2K ν_e appearance result

T. Nakaya, for T2K





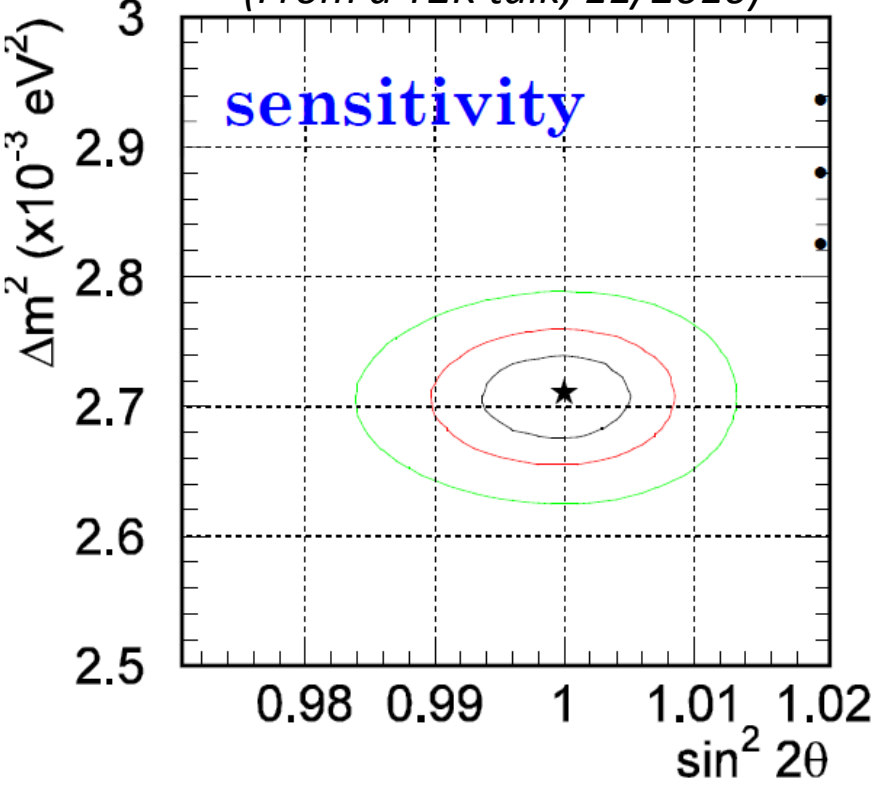
$\sin^2 2\theta_{13}=0.104\ ^{+0.060}_{-0.045}\ @\ \delta_{CP}=0$

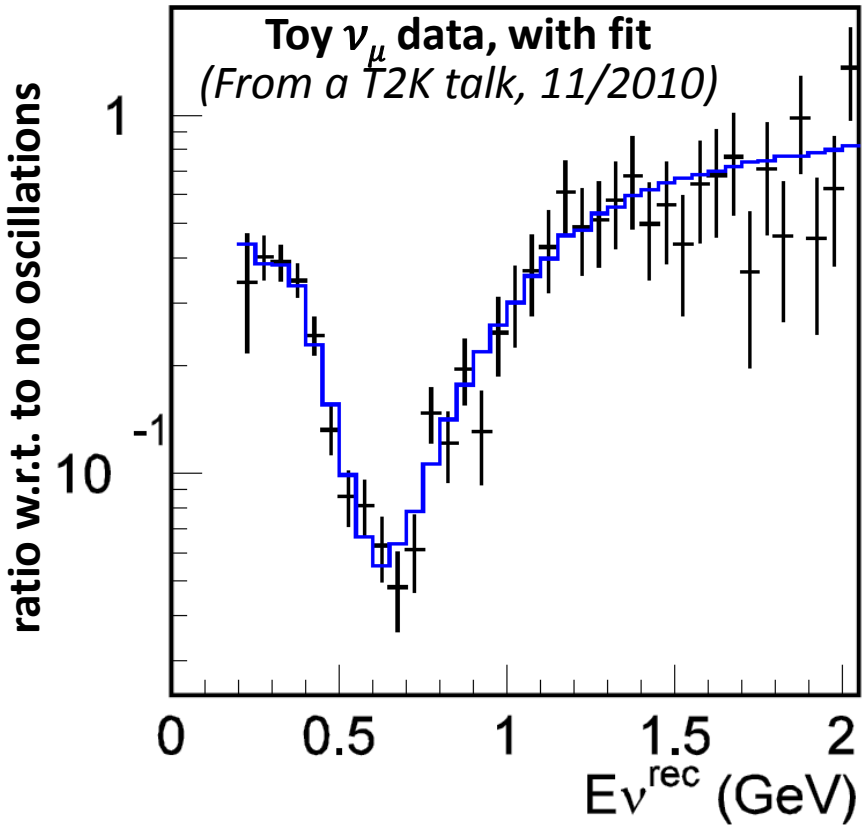
$\sin^2 2\theta_{13}=0.128\ ^{+0.070}_{-0.055}\ @\ \delta_{CP}=0$

For ν_μ disappearance

- **Assuming ν_μ CC disappearance sensitivity to $\sin^2(2\theta_{23})$ is equal to NOνA**

Atmos. parameter sensitivity at full 5-yr, 750 kW (?) exposure with no systematic errors
(From a T2K talk, 11/2010)

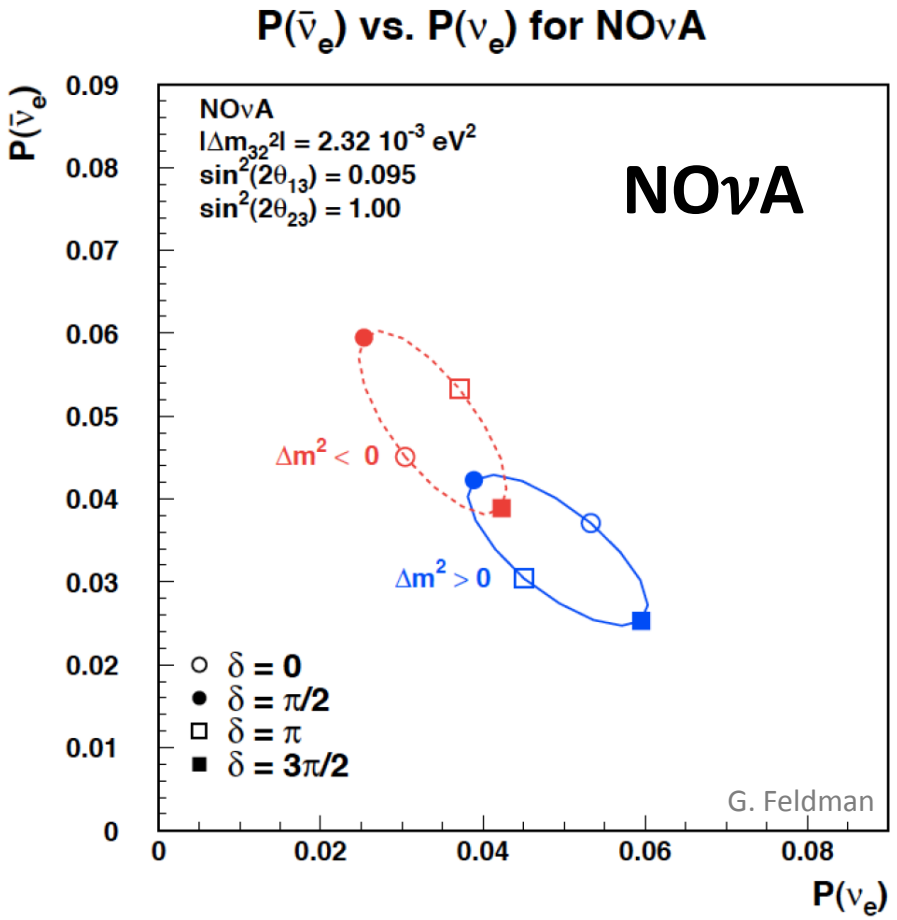


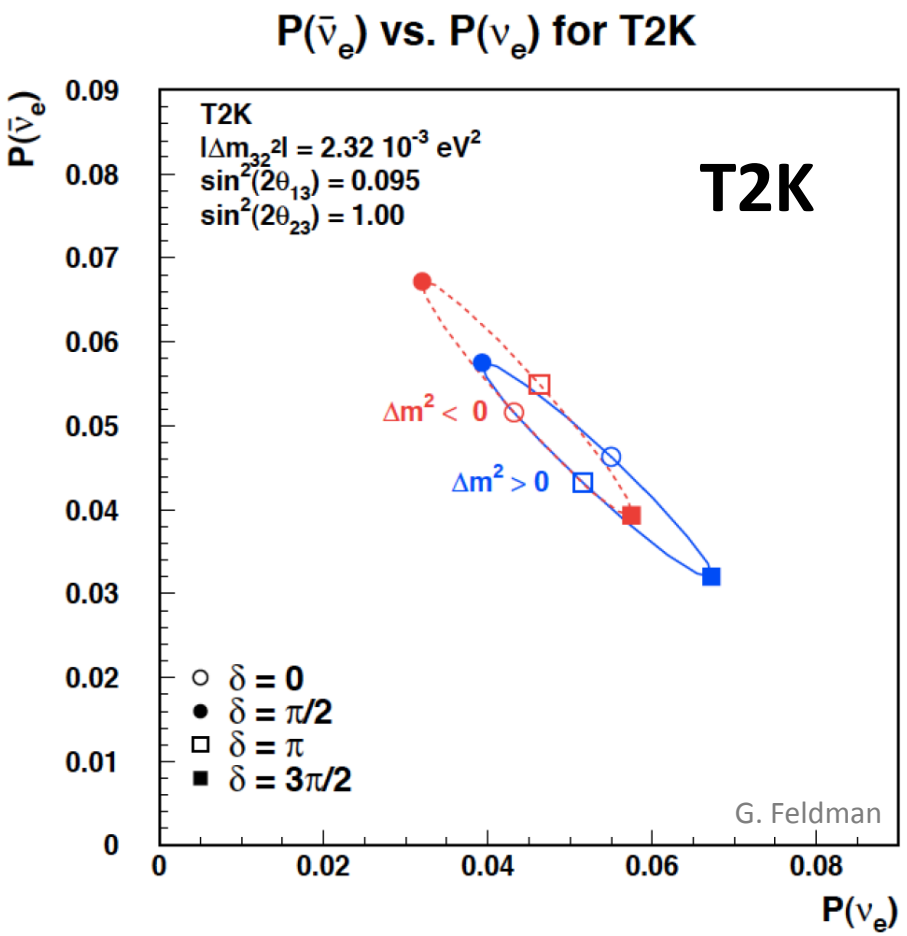


- **Systematic errors take $\sin^2(2\theta_{23})$ error to <u>1%</u>** *(from same T. Nakaya talk)*
- **Reduction of exposure to forecast levels for 2019 plus possible antineutrino running would reduce this a bit further, but ignoring these losses (1%→1.5%)**

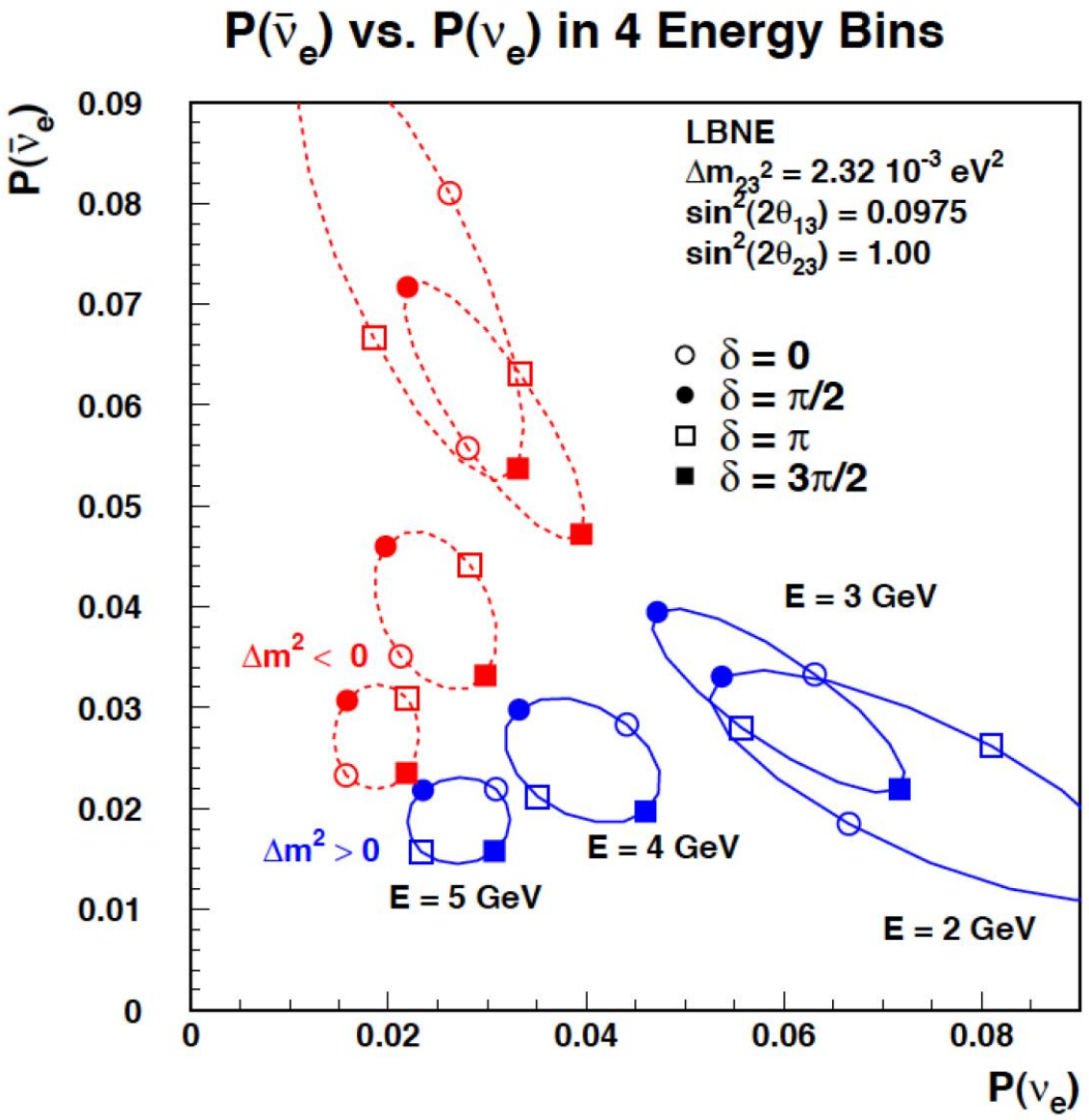
Qualitative expectations?

- **hierarchy sensitivity ⇔ separation of ellipses**
- **CPv sensitivity ⇔ δ=0 and δ=π points displaced from other points**
- *(Note: expected NOνA and T2K errors on these probabilities are similar, 10%–30%)*





Bi-probability plots for LBNEthree values of $\sin^2(2\theta_{23})$



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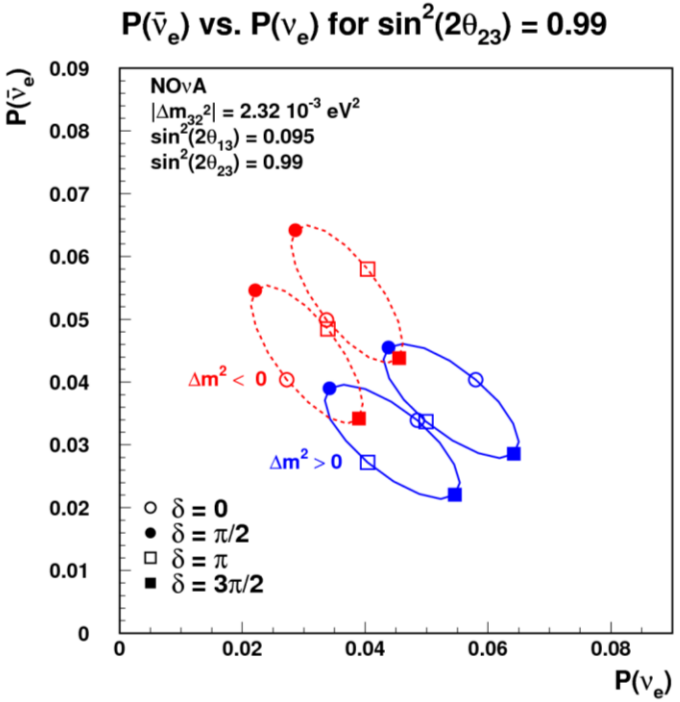
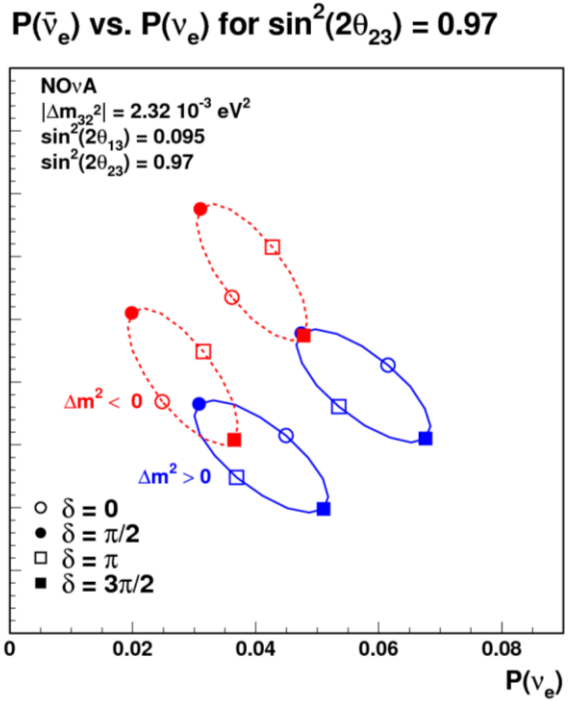
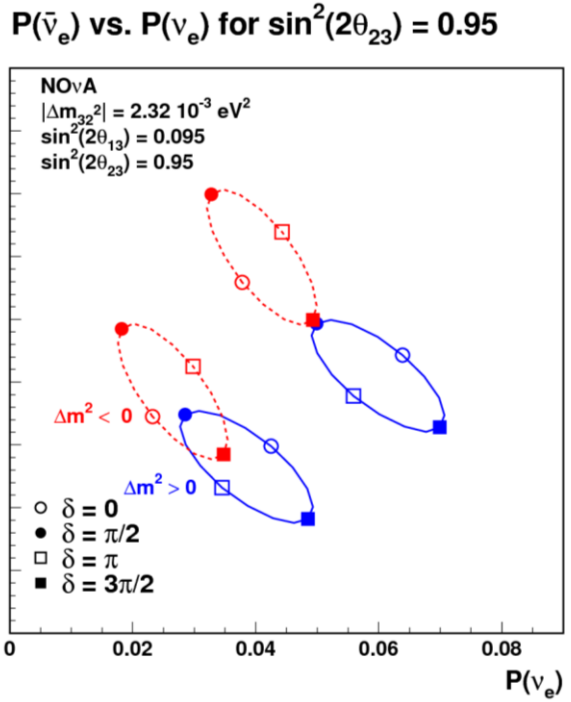
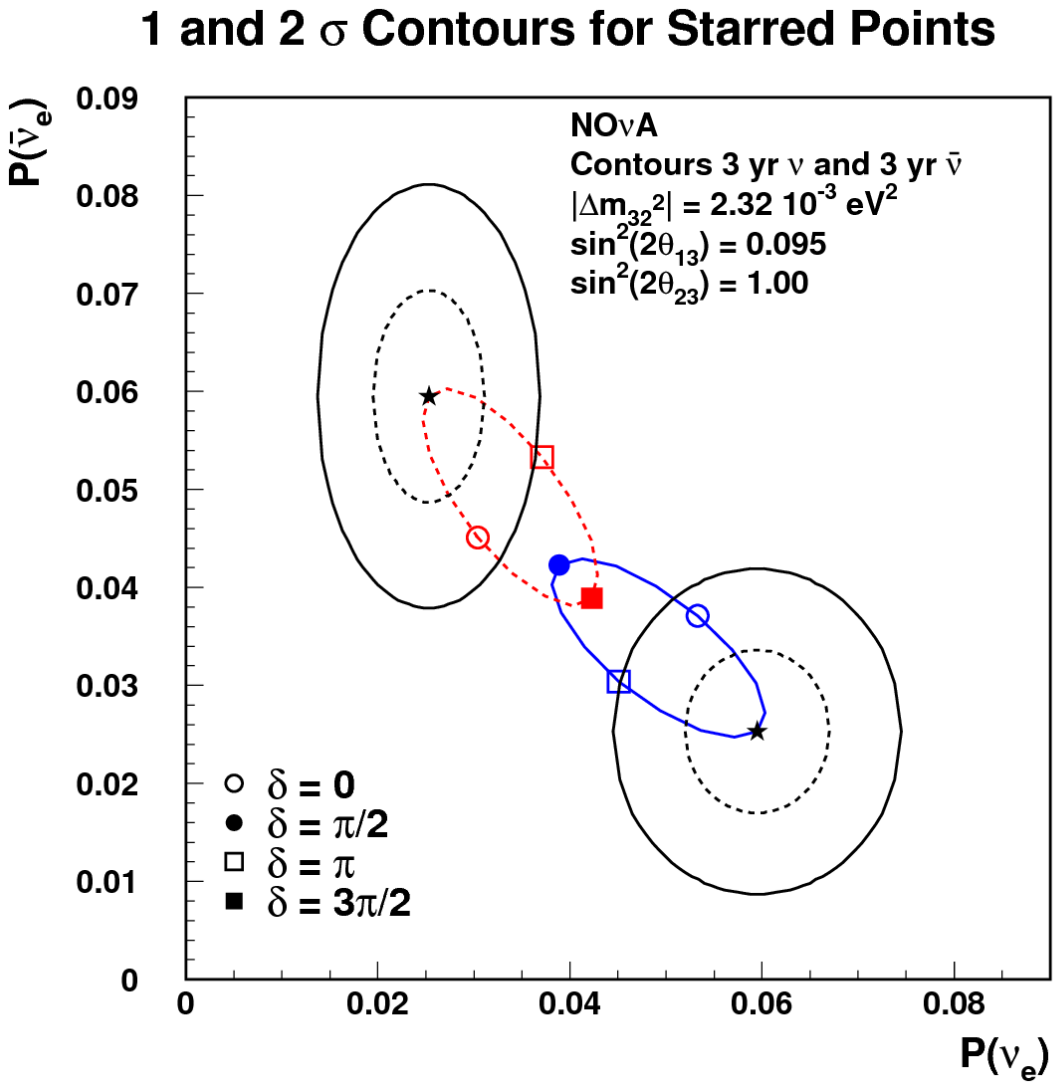






Example bi-probability plot, with contours



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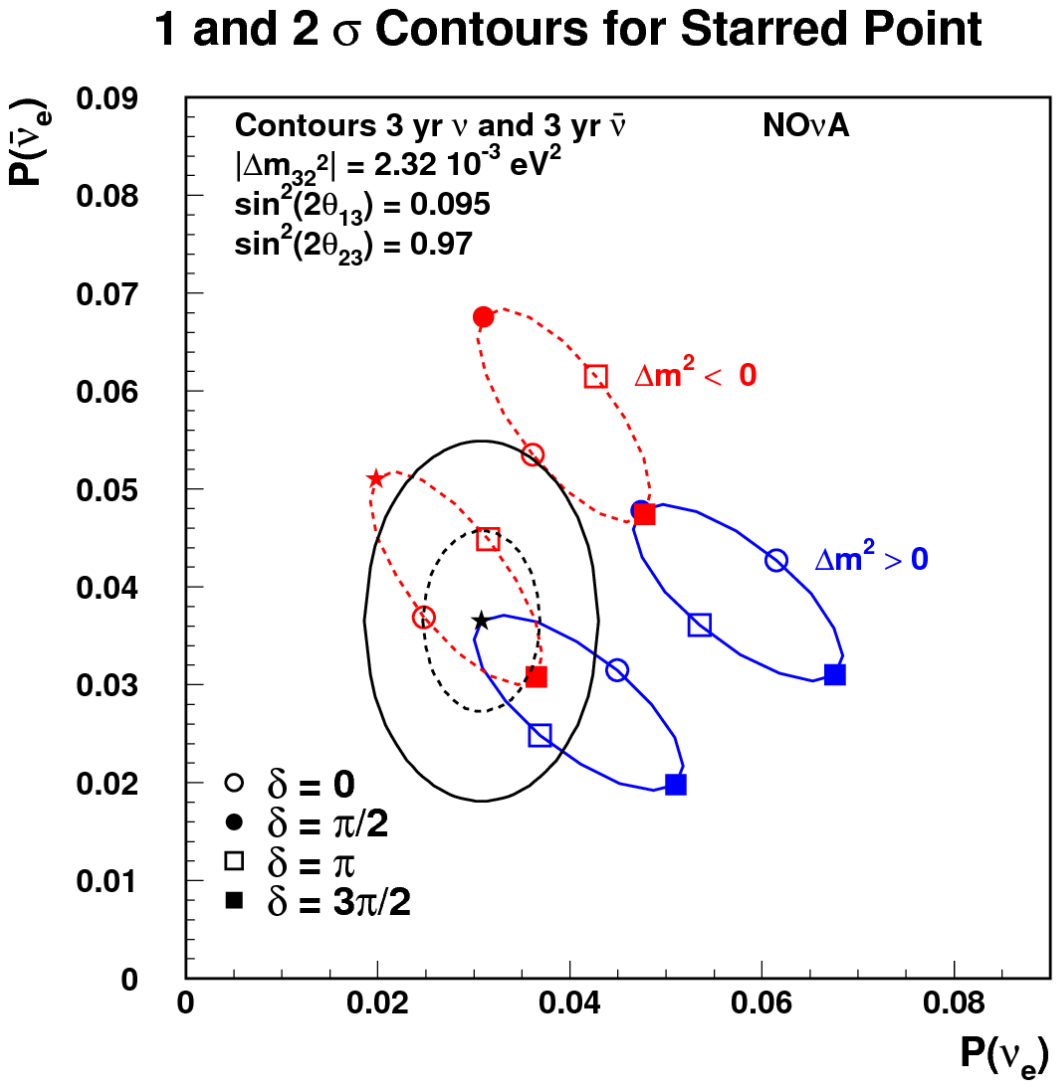
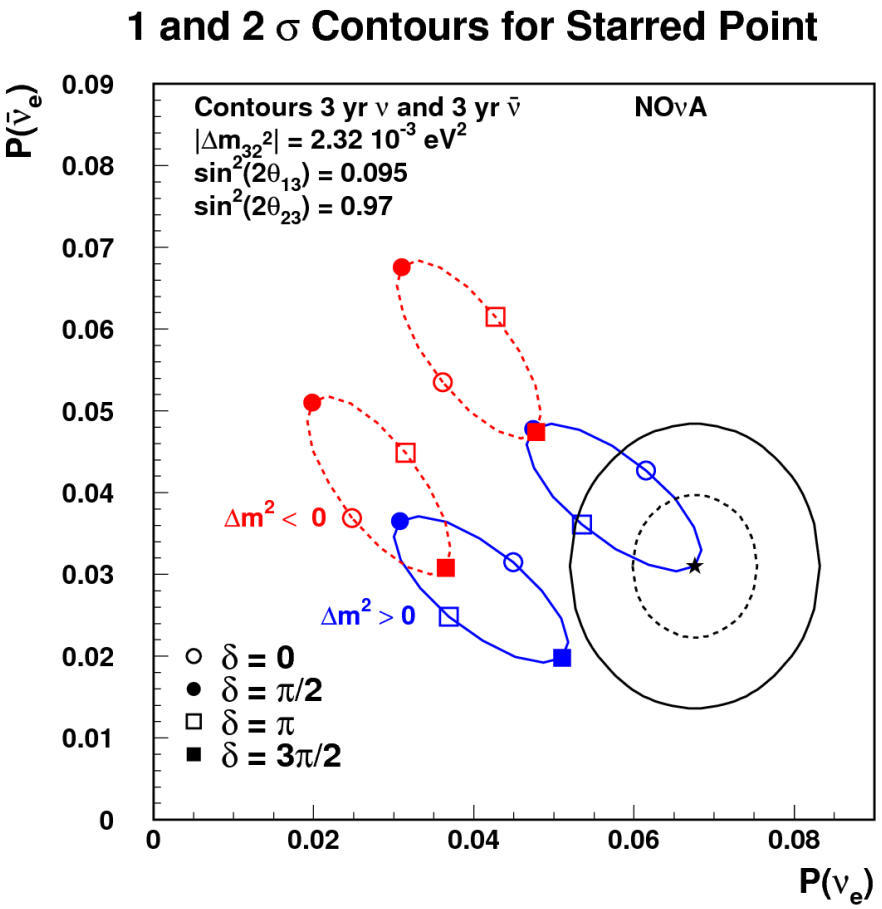
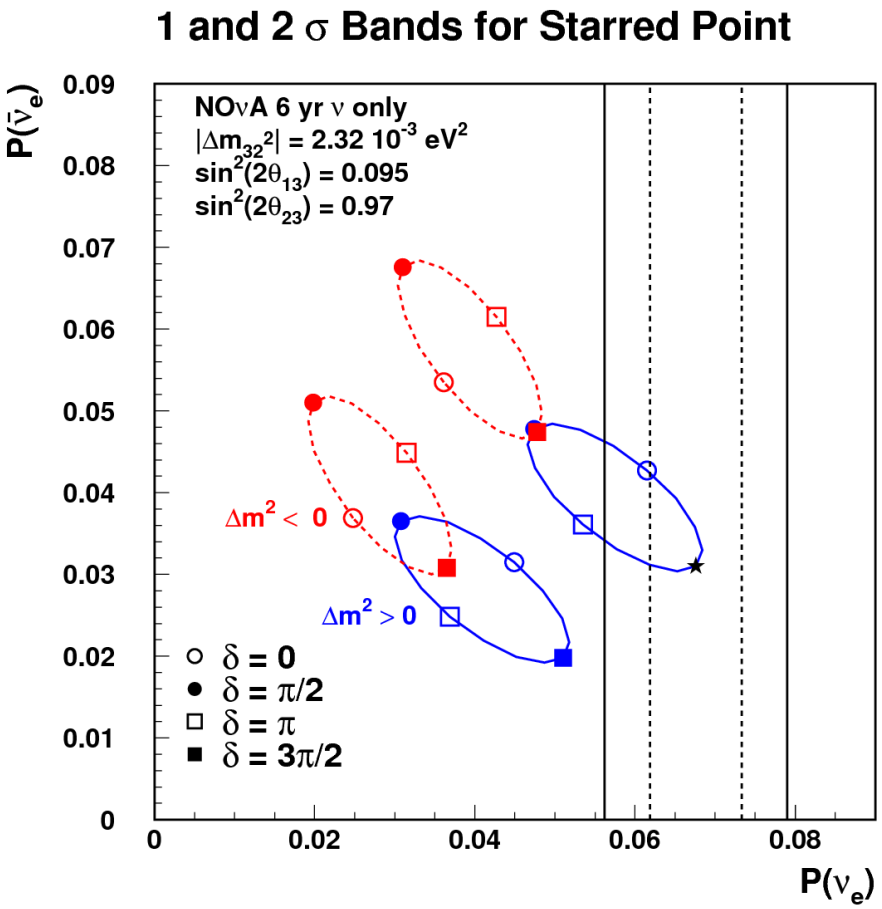


Example bi-probability plots, with contours for two possible run plans





Example bi-probability plots, with contours for two possible run plans