INSPIRING PRECISION

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SSI, 5 August 2024

CONSTRUCTIVE DECONSTRUCTION

- In considering the title I was given, “Inspiring Precision”, I’ve chosen to take it as a description of my topic rather than of my talk.
    - So my choice is that “Inspiring” refers to “Precision”. (If it also, by chance, describes my talk, then so much the better, but we’ll consider that a stretch goal.)
- When I asked our hosts about what they had in mind for this talk and why me, one part of the answer was,
    - *“As our field evolved into more compartmentalized enclaves in the last couple of decades, with more and more specialized conferences and workshops indulging such evolution, it is increasingly more difficult to find speakers to do such a broad lecture, especially among experimentalists.”*
    - I’ll take that as license to talk about things that I’ve done, or seen, as examples.
    - Each of you may find parallels in things you have done, are doing, or want to do.

ELEMENTS

- What do we mean by “precision”?
- What are the goals of precision measurements?
- What do we actually learn from precision measurements?
  - And, along the way maybe we learn a little about what it means, scientifically and sociologically, to work in a field that makes precision measurements.

WHAT DO I THINK "PRECISION" IS?

- For the purposes of this lecture – and the program suggests the school organizers mostly agree – I am going to characterize precision measurements as those that are not the first observation of some quantity.
  - But they may be the first non-zero observation of some symmetry-forbidden quantity against a competing symmetry-allowed process.
  - Precision measurements are also those of quantities with some clear interpretation in a fundamental theory.

- My definition evidently leaves out many measurements which can be achingly precise in other senses of the word.
  - E.g., the LIGO observation of gravitational waves, the mean distance of the sun to the earth, the number of Presidential votes cast in the state of Georgia, etc.

GOALS OF PRECISION

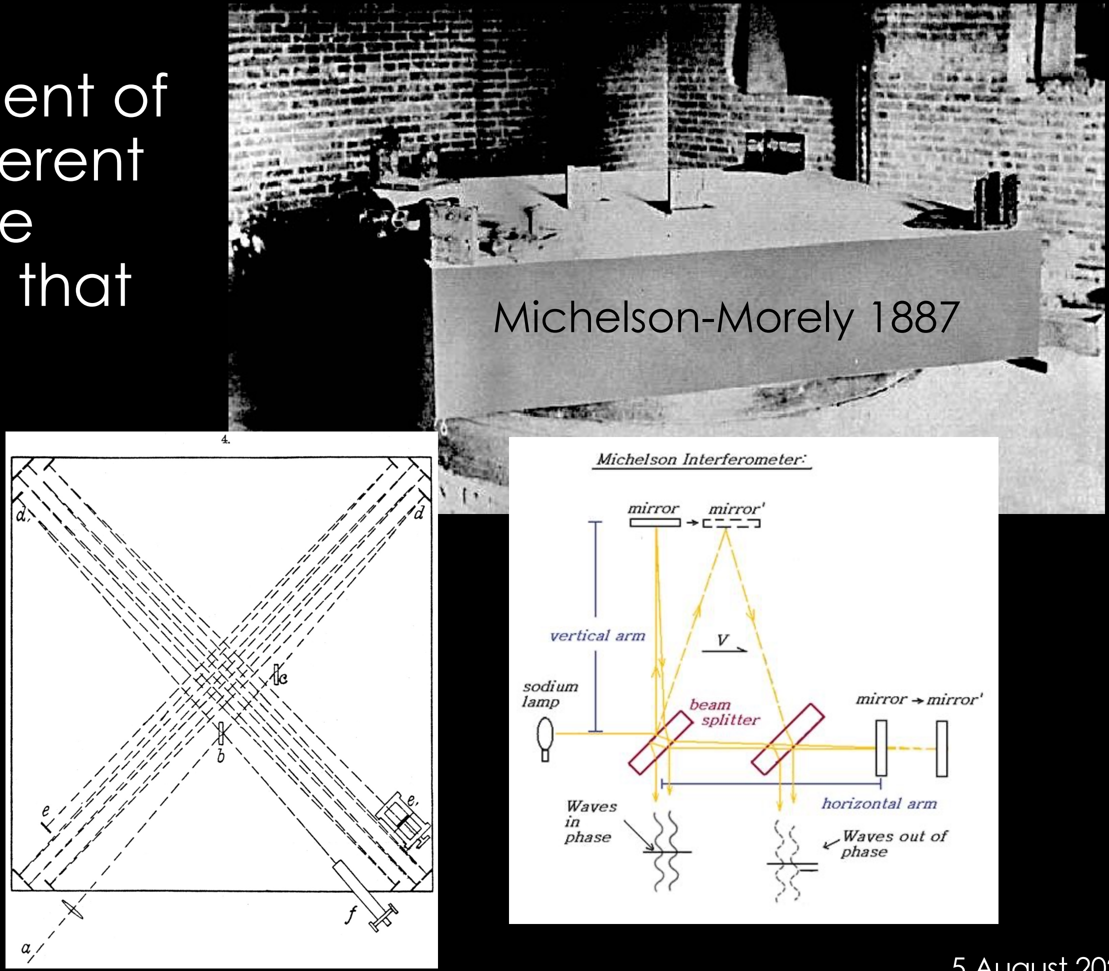
- Precision measurements that succeed can alter the way we construct our understanding of physical phenomena.
- This happens in (at least) two different ways:

    1. Precision measurements reveal a new symmetry/conservation law, or a violation thereof.
    2. Precision measurements can be translated into a measure of a quantum correction, potentially involving a first measurement of a new particle or its interactions.

- I'll illustrate these with two distant historical examples from textbook physics, to keep these at arm's length from any topic in this school.

EXAMPLE OF #1: MICHELSON-MORLEY EXPERIMENT

- In brief, an interferometric measurement of the speed of light propagating in different directions relative to the motion of the earth through the medium ("æther") that carries light waves.
- "Precision", in that it is not the first measurement of a finite speed of light, and that it meant to discover the æther and verify the preferred frame required by Maxwell's Eqns.
    - Effect is ∝ $v_{\ae ther}^2/c^2 \sim 10^{-9}$.


Michelson-Morely 1887

M-M BACKGROUND

- Galilean relativity applied to light predicts a frame-dependent speed of light.

$$\vec{x}' = \vec{x} - \vec{v}t$$
$$t' = t$$

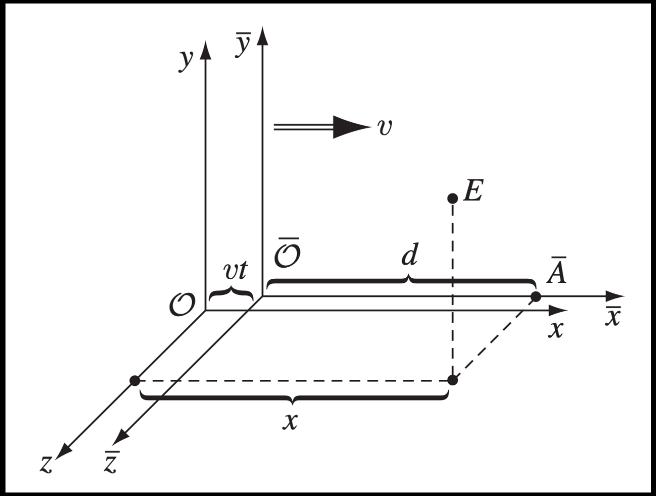
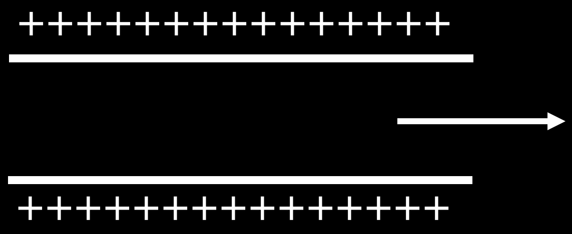
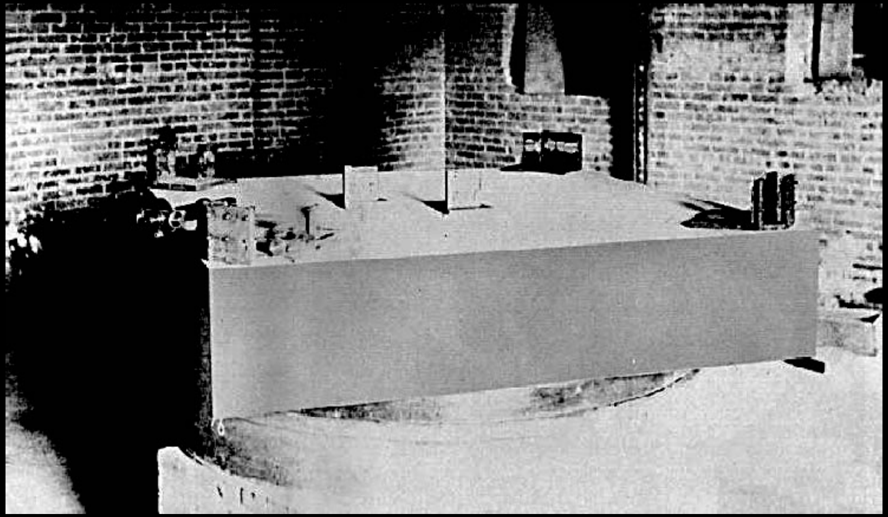


Figure from "Introduction to Electrodynamics" by David Griffiths (who prefers $\bar{x}$ to x').

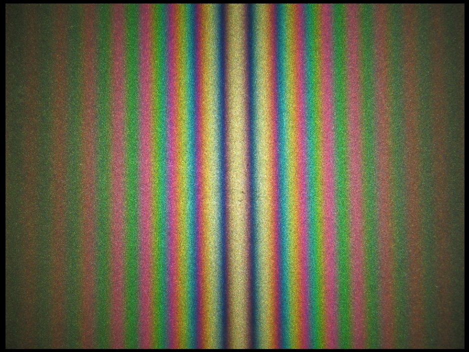
- However, Maxwell's Equations, which predicted electromagnetic radiation and passed every possible precision test, are inconsistent with Galilean relativity.
  - Consider, for example, the force between two line charges in motion. The moving charges create a frame-dependent magnetic force from one which acts on the current of the other and changes the force between them.



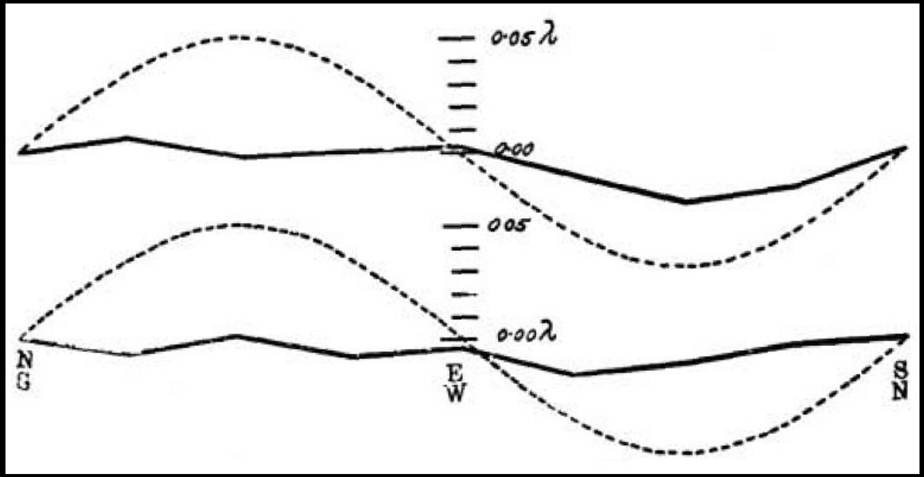
M-M TECHNOLOGY



- This was an amazingly careful experiment.
- The apparatus included the massive sandstone block floating on a bed of mercury to make it relatively free of vibrations and ease to rotated to see the directional effect of travel through the æther.
- Monochromatic light was useful for alignment, but difficult to work with because an observer would get ”lost” without a reference if a transient vibration destroyed the fringe pattern.
- White light was used, since the central fringe was white or black. But then the coherence length was very short, so alignment was excruciating.



M-M CONCLUSIONS



- We all know the textbook scientific outcome.
  - The æther was not found at the expected level.
  - There were epicycle-like attempts to "fix" the result to not rule out the æther. As David Griffiths says, we are now taught to "snicker" at this.
  - Einstein built on work of others, including FitzGerald and Lorentz who had found fixes to Maxwell's Equations, to build a correct and consistent theory, special relativity.
- This was the signal outcome, but not the only outcome of these experiments. What else happened?

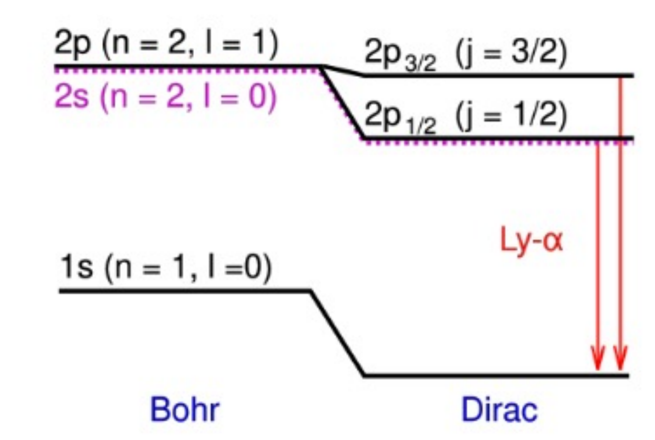
$$\vec{x}' = \gamma(\vec{x} - \vec{\beta}ct)$$
$$ct' = \gamma(ct - \vec{\beta} \cdot \vec{x})$$

LESSER KNOWN M-M OUTCOMES

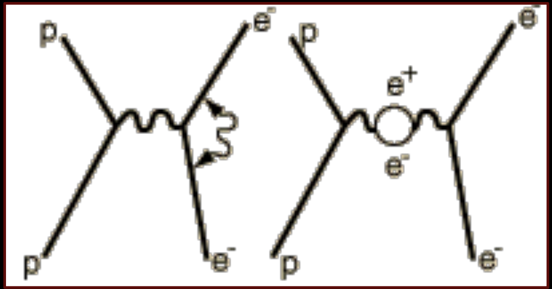
- The field of repeating this measurement with very similar apparatus continued well into the 1920s.
    - They used larger interferometers, better environmental control and light sources.
    - Some tested (in retrospect) crazy ideas, such as the (in)famous 1921 Miller experiment which used a similar apparatus on top of Mt. Wilson without walls surrounding the interferometer. Why? Well in case the walls were confining the æther in the room and ruining the experiment.
- Similar experiments, with different goals, have since been repeated with coherent light sources (~1960s) and (~2000s) cryogenic optical resonators.
    - FYI, the gap between those two was due to taste, not a leap in technology.
    - Each of those technologies allowed for increases of several orders of magnitude in sensitivity to an anomalous velocity which… has never been seen.
- What inspiration does this history offer you?

EXAMPLE OF #2: LAMB SHIFT

- In brief, a measurement of the small energy difference between the $^2S_{1/2}$ and $^2P_{1/2}$ states of the hydrogen atom made by exciting a low energy transition $^2S_{1/2}$ to $^2P_{3/2}$.
- The single-body quantum theory of the atom does not predict this shift. Rather it requires self-energy quantum field theory corrections.
- “Precision”, in that is was measuring expected transitions but sensitive to this small shift which was the first visible signature of a quantum field correction and helped to stimulate the development of QED.



Fine structure corrections in the Dirac model, with the Lamb shift shown, but barely visible.



LAMB TECHNOLOGY

- Thermal Doppler broadening was a foundational problem in precision atomic spectroscopy. Working in microwaves (small energy transition) suppressed this.
- An important element of the experiment was to detect several transitions due to Zeeman splitting in an external magnetic field.
- This gave confidence that the shift being observed was real, since transitions with different Zeeman splittings all converged to the same (shifted) value.

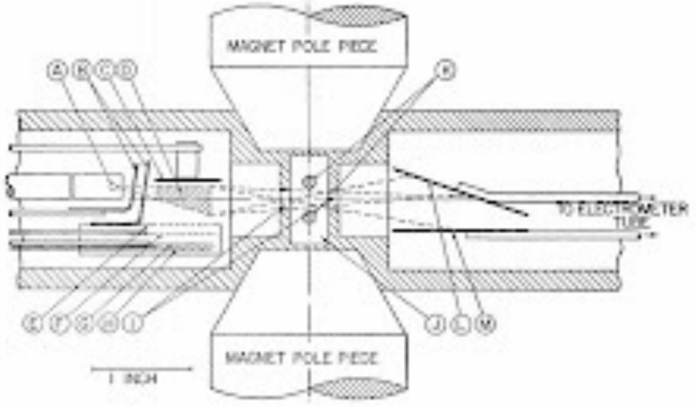
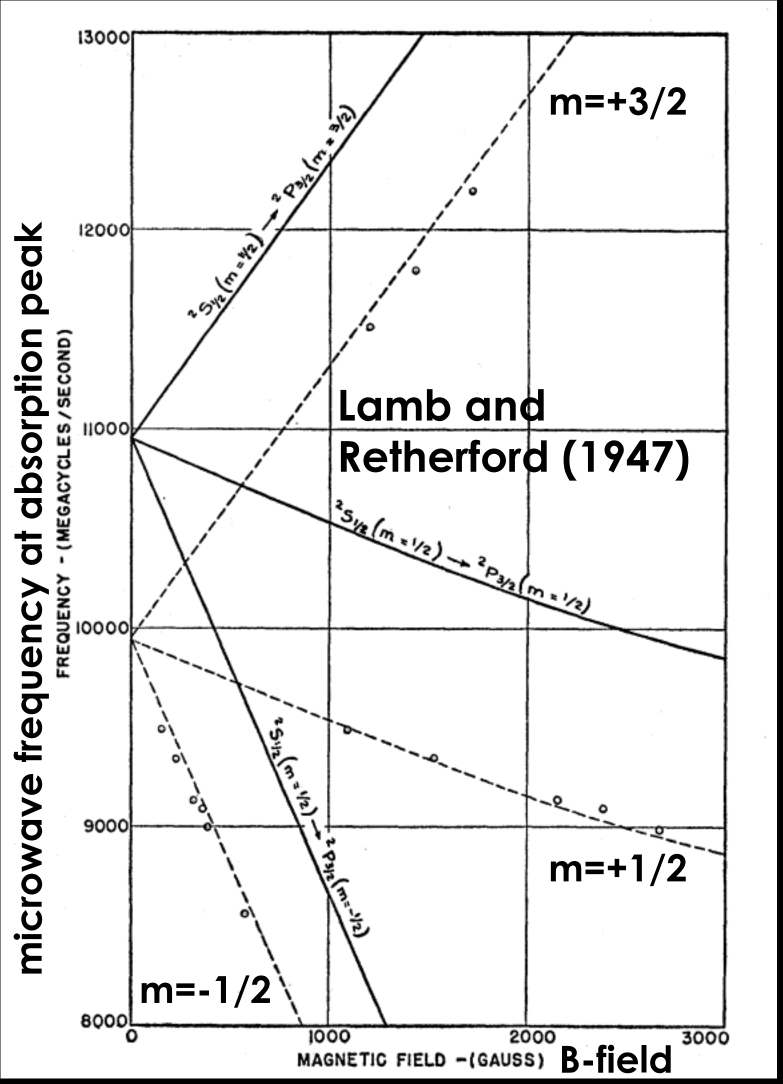


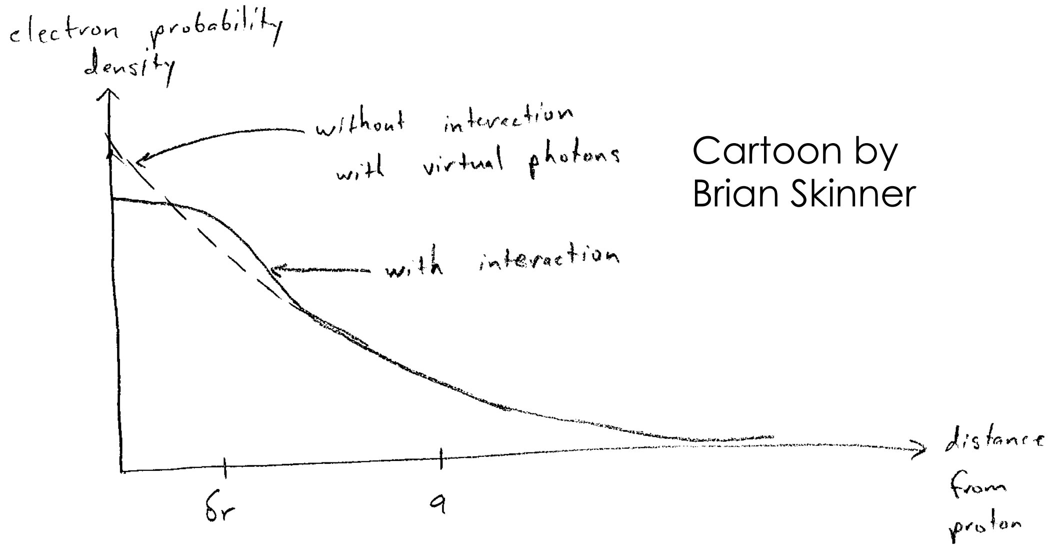
Fig. 19. Cross section of apparatus. A. Tungsten oven of hydrogen dissociator. B. Shields. C. Anode of electron bombarder. D. Bombardment region. E. Accelerator grid of electron bombarder. F. Control grid. G. Cathode of electron bombarder. H. Heater for cathode. I. Slits. J. Wave guide. K. Quenching wires and transmission lines. L. Metastable detector target. M. Electron collector.



Lamb and Retherford (1947)

LAMB OUTCOME

- QED like calculations weren’t seen as reliable because of the inherent infinities.
- Lamb did this measurement, in part, because of awareness of earlier measurements that suggested this, and an understanding of that it was sensitive to high field effects (“coupling of the electron to the radiation field”).
- A report of the Lamb shift inspired Hans Bethe to work out proto-QED calculations of the self-energy effect (on the train home from a Shelter Island conference).



Cartoon by Brian Skinner

- In words, near the proton where the field is very high, there are many e^+e^- pairs created which, on average, have the effect of pushing the electrons away from the proton and thus (slightly) increase the energy of the S-wave state which has significant wave-function at zero radius, as opposed to the P-wave state where the wave-function vanishes at zero radius.
- This helped to motivate further development of QED.

INSPIRATION?

- We’ve seen two examples of classic precision experiments that significantly changed our understanding of the physical world.
- Both made significant technological developments.
- Both had clear ways to interpret their result that, with some luck, happened to be particularly meaningful.
- For both results to be impactful, there was significant collaboration with theory to bring the result into full focus.
  - Only with Einstein’s special relativity was the interpretation of the Michelson-Morley null result clear.
  - Only with quick work of Bethe, followed by many others, was the Lamb shift understood as a validation of renormalization of infinities in QFTs.
- Not all precision measurements (e.g., the dramatic 1921 M-M repeat) succeed in these senses.

MY CAREER IN PRECISION MEASUREMENTS

- ϵ' in the neutral kaon system.
- Precision couplings of the *W* and *Z* in neutrino scattering.
    - Followed by precision couplings of the heaviest particles (top, *W, and* Z) in hadron collider physics.
- Precision neutrino oscillation physics.

    - Again, my purpose is not to illustrate these as great examples of impactful science, but rather to dissect them against a background of interpretation and context in the field of particle physics.
    - Your mileage may vary. And probably should vary.

ϵ' IN THE NEUTRAL KAON SYSTEM

- While doing my Ph.D., I worked at University of Chicago and Fermilab from 1989-1993, in a group that work in rare and precision neutral kaon physics.
  - I was the black sheep of the group. My thesis was the first measurement (first at the correct branching ratio of several$\times 10^{-8}$, anyway) of $\pi^0 \rightarrow e^+e^-$.
  - I used π^0 from neutral kaon decays to $\pi^0\ \pi^0\ \pi^0$, so now you know that our experiment reconstructed billions of kaon decays for its measurements.
- Why the neutral kaon system?

$$\begin{pmatrix} K^+ \\ K^0 \end{pmatrix} \qquad \begin{pmatrix} K^- \\ \bar{K}^0 \end{pmatrix} \qquad \begin{matrix} u \text{ or } \bar{u} \\ d \text{ or } \bar{d} \end{matrix}$$

$$\bar{s} \qquad\qquad s$$

K^+ decays into $\pi^+\ \pi^0$ and also $\pi^+\pi^0\pi^0$ (states of different parity).

Weak interactions violate parity, so K^+ can have parity, P=-1, but still decay into different parity states

Isospin rotation suggests that the decays $K^0 \rightarrow \pi^0\pi^0$ and $K^0 \rightarrow \pi^0\pi^0\pi^0$ both can happen.

NEUTRAL KAON SYSTEM

- Why the neutral kaon system?

$$\underset{\bar{s}}{\begin{pmatrix} K^+ \\ K^0 \end{pmatrix}} \qquad \underset{s}{\begin{pmatrix} K^- \\ \bar{K}^0 \end{pmatrix}} \qquad \begin{matrix} u \text{ or } \bar{u} \\ d \text{ or } \bar{d} \end{matrix}$$

Isospin rotation suggests that the decays $K^0 \to \pi^0\pi^0$ and $K^0 \to \pi^0\pi^0\pi^0$ both can happen.

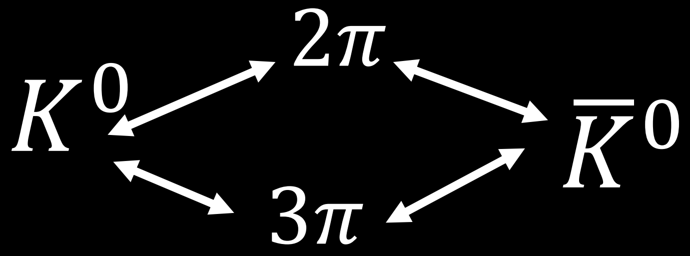
Similarly, $K^- \to \pi^-\pi^0$ and $K^- \to \pi^-\pi^0\pi^0$ both happen, and by the same isospin argument, $\bar{K}^0 \to \pi^0\, \pi^0$ and $\bar{K}^0 \to \pi^0\pi^0\pi^0$ both can happen.

And similarly for $\pi^+\pi^-$ and $\pi^+\pi^-\pi^0$ final states, again by isospin symmetry arguments.

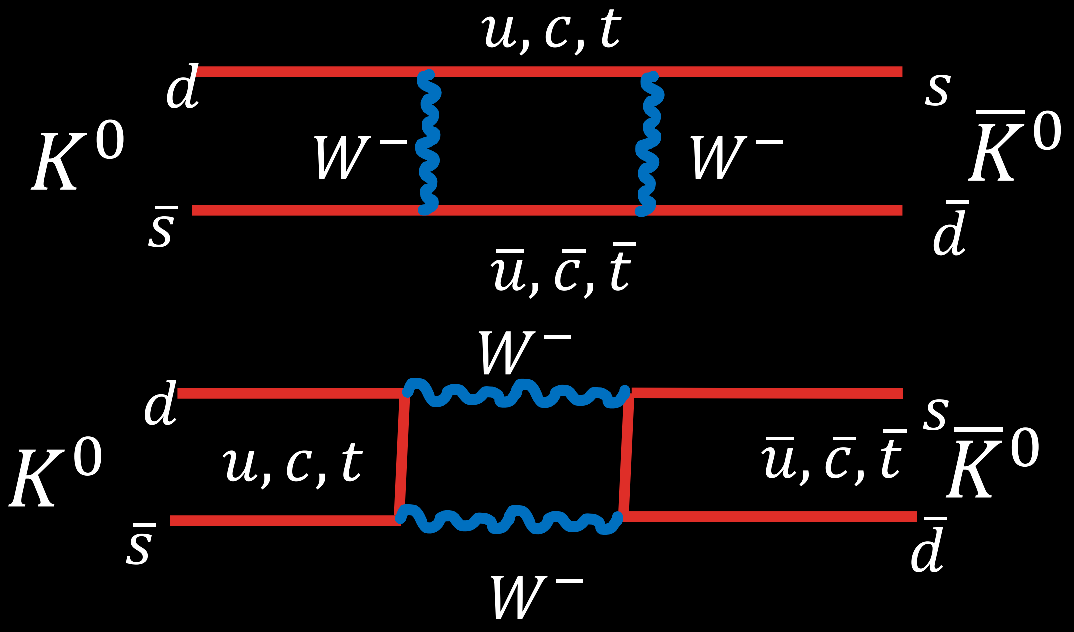
So in neutral kaons, a particle and its antiparticle mostly decay into the same final states! 😮

NEUTRAL KAON DECAYS INTO PIONS

If a K^0 propagates, it can virtually turn into a 2π or a 3π state, but so can a $\bar{K}^0$. So in free space,



Quark model version:



Like the π^0, K^0 and $\bar{K}^0$ both are eigenstates of P with eigenvalue -1.

$$\therefore\ CP|K^0\rangle = -|\bar{K}^0\rangle$$

$$CP|\bar{K}^0\rangle = -|K^0\rangle$$

Consider the states $|K^0\rangle - |\bar{K}^0\rangle$ and $|K^0\rangle + |\bar{K}^0\rangle$

$$\mathrm{CP}(|K^0\rangle - |\bar{K}^0\rangle) = -|\bar{K}^0\rangle + |K^0\rangle = |K^0\rangle - |\bar{K}^0\rangle$$

$$\mathrm{CP}(|K^0\rangle + |\bar{K}^0\rangle) = -|\bar{K}^0\rangle - |K^0\rangle = -1\times(|K^0\rangle + |\bar{K}^0\rangle)$$

∴ *equal* mixtures of K^0 and $\bar{K}^0$ are CP eigenstates.

IF CP WERE CONSERVED IN WEAK INTERACTIONS…

Denote the normalized CP eigenstates the following way:

$|K_1\rangle = \frac{1}{\sqrt{2}}(|K^0\rangle - |\bar{K}^0\rangle)$ CP = +1 (“even”)

$|K_2\rangle = \frac{1}{\sqrt{2}}(|K^0\rangle + |\bar{K}^0\rangle)$ CP=-1 (“odd”)

If CP is conserved in weak interactions,
then K_1 → CP -even states and K_2 → CP -odd states

- Two pion states from kaon decays have CP +1.
- Three pion states from kaon decays have CP -1.

So K_1 → 2π and K_2 → 3π

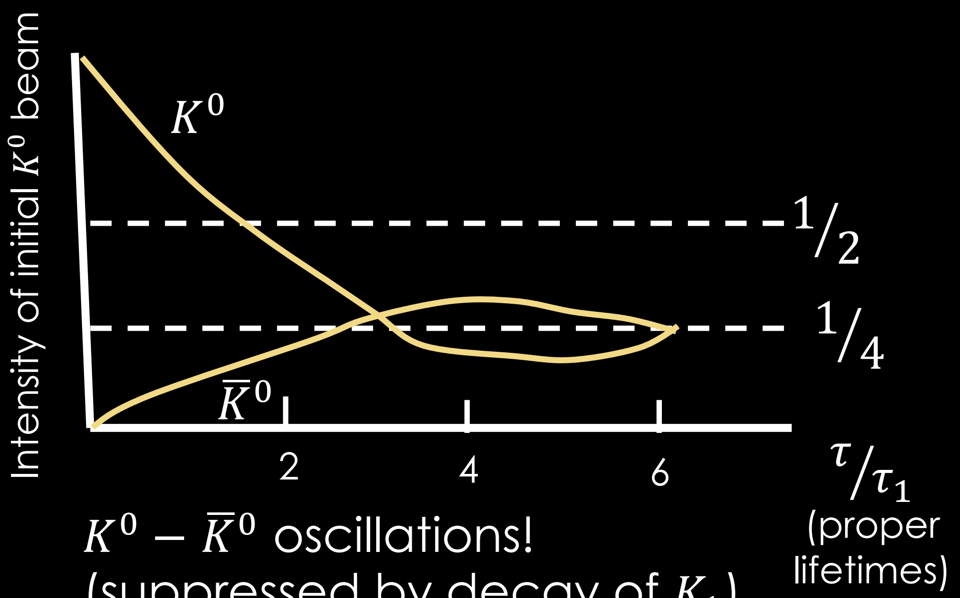
K_1 will decay more quickly because of increased phase space.

TIME EVOLUTION OF NEUTRAL KAONS

- If we start with a pure K^0 state and let it evolve,

$$N(K^0) = \frac{1}{4}\left[e^{-\Gamma_1 t/\hbar} + e^{-\Gamma_2 t/\hbar} + 2e^{-\frac{\Gamma_1+\Gamma_2}{2}t/\hbar}\cos\Delta m t\right]$$

$$N(\overline{K}^0) = \frac{1}{4}\left[e^{-\Gamma_1 t/\hbar} + e^{-\Gamma_2 t/\hbar} - 2e^{-\frac{\Gamma_1+\Gamma_2}{2}t/\hbar}\cos\Delta m t\right]$$



$K^0 - \overline{K}^0$ oscillations!
(suppressed by decay of K_1)

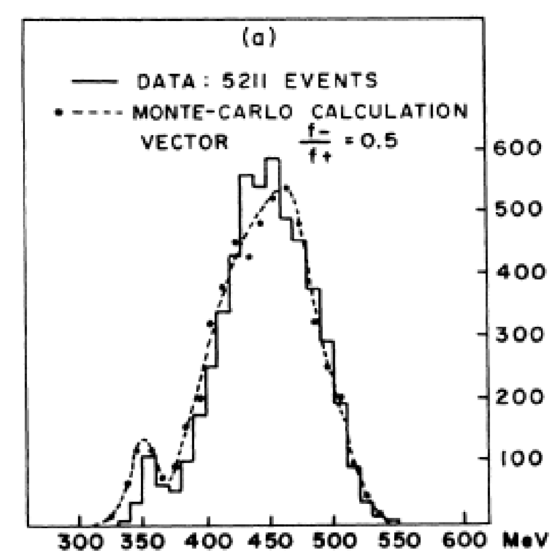
$$\tau_{K_1} = {}^{\hbar}/_{\Gamma_1} \approx 9.0\times10^{-11}\text{ sec}$$

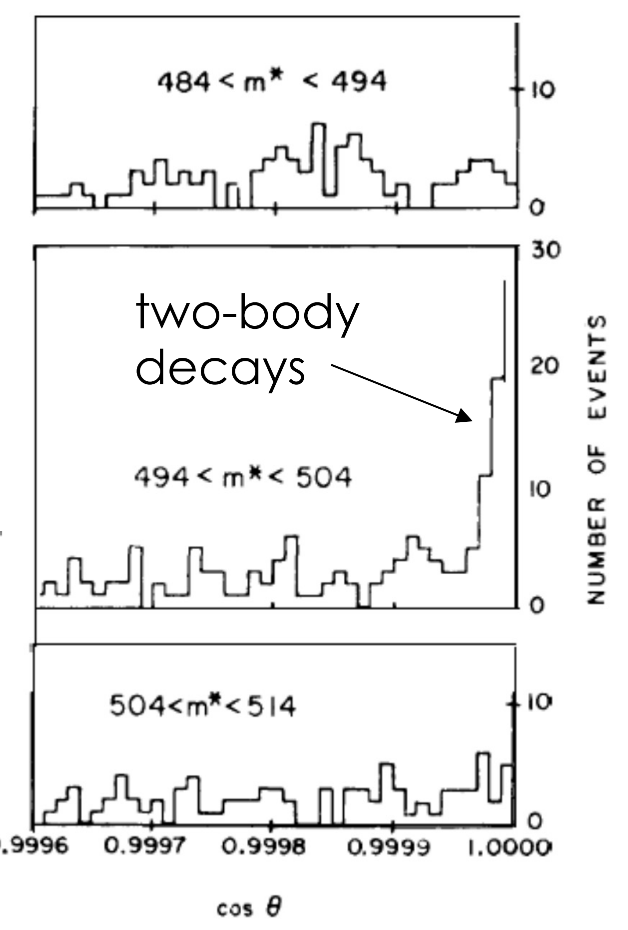
$$\tau_{K_2} = {}^{\hbar}/_{\Gamma_2} \approx 5.1\times10^{-8}\text{ sec}$$

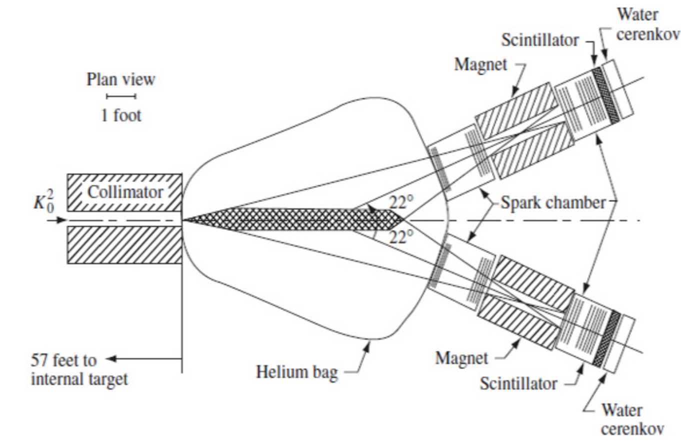
$$\Delta m\tau_{K_1} \approx 0.56\hbar \Longrightarrow \Delta m \approx 0.56\Gamma_1 \approx 3\times10^{-6}eV$$

DISCOVERY OF CP VIOLATION

- Of course, this isn't the whole story because we know that (small) CP violation occurs in weak interactions of quarks.
- Christenson-Cronin-Fitch-Turlay in 1964 showed that a small number of long lived kaons decay into two pion final states.
- This was a sort of precision experiment of Type #1, although arguably this result was not (mostly) what they were looking for.







DECAY OF KAONS AND CP VIOLATION

- If it is CP violation only in mixing (the short-lived state is not only K_1), the phenomenology is simple. Define ϵ_K so that

$$|K_S\rangle = |K_1\rangle \text{-} \epsilon_K|K_2\rangle \qquad |K_L\rangle = |K_2\rangle + \epsilon_K|K_1\rangle$$

where K_S is the short-lived state and K_L is the long-lived state.

- The real part of ϵ_K (seen in propagation) is $\approx +1.6\times10^{-3}$.
- If this mixing is the only source of CP violation, what does it mean?
- $K_S \rightarrow \pi^+\pi^-$ and $K_S \rightarrow \pi^0\pi^0$, a lot, but Christenson-Cronin-Fitch-Turlay showed $K_L \rightarrow \pi^+\pi^-$ and $K_L \rightarrow \pi^0\pi^0$ occasionally.

Define η_{+-} and η_{00} as ratios of amplitudes (complex)

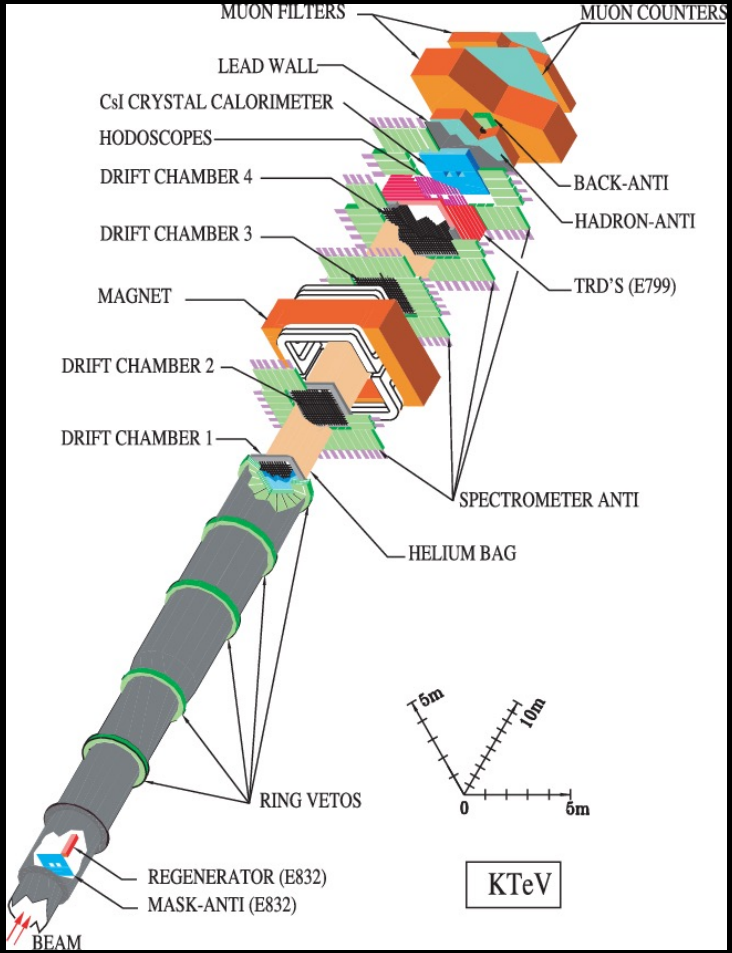
$\eta_{+-} = \frac{A(K_L\rightarrow\pi^+\pi^-)}{A(K_S\rightarrow\pi^+\pi^-)}$ and similarly η_{00} for decays into $\pi^0\pi^0$

If mixing is the only source of CP violation, then $\eta_{+-} = \eta_{00} = \epsilon_K$.

MIXING VS DECAYS

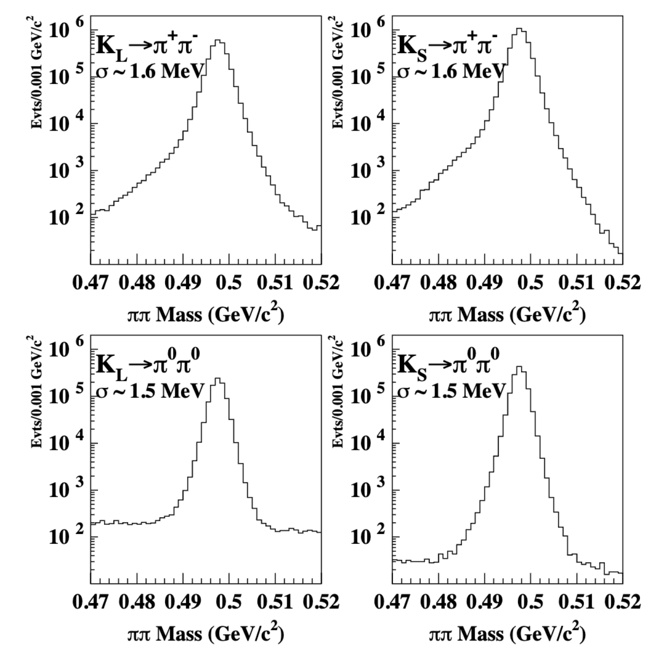
- As it turns out, the quark mixing (CKM) model for CP violation predicts both mixing and decay contributions. However, experimentally and by prediction, the mixing effect is much larger.
- Experimentally, $\eta_{+-} = \epsilon_K(1 + \mathcal{O}(10^{-3}))$ and $\eta_{00} = \epsilon_K(1 - \mathcal{O}(10^{-3}))$, so measuring this effect, parameterized as ϵ_K', is very difficult and took nearly 40 years of successor experiments.
- KTeV is shown here, and NA48 at CERN was a competing experiment.

Pure CsI crystal calorimeter

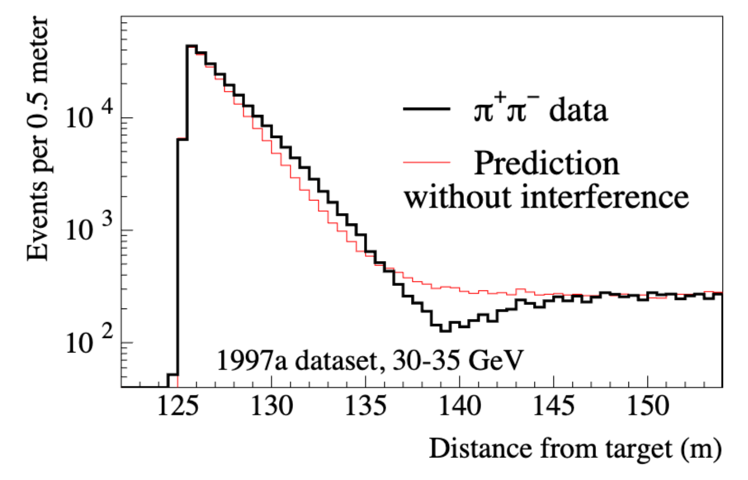


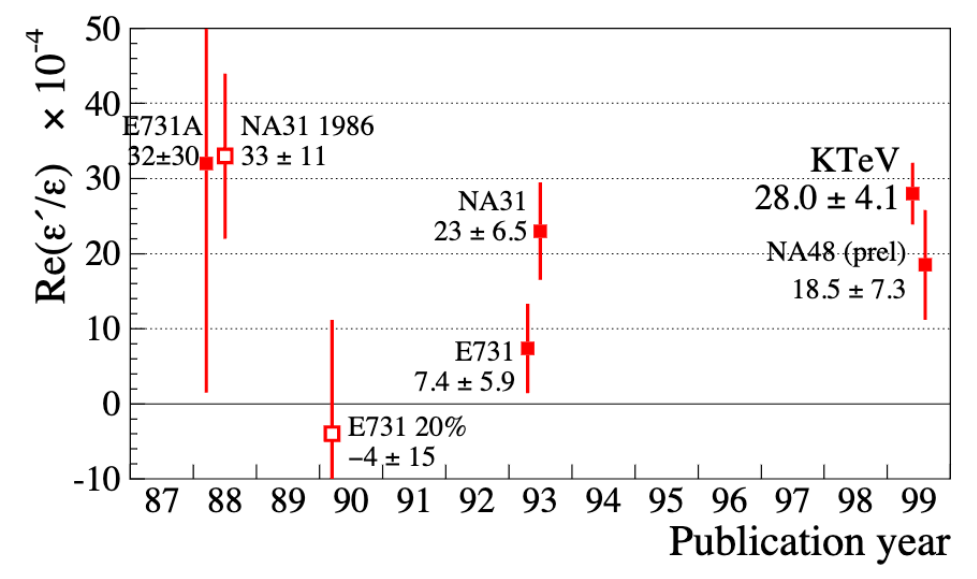
ϵ' IN THE NEUTRAL KAON SYSTEM

- These experiments were high statistics and massive undertakings which ultimately found something consistent with the (imprecise) CKM prediction.



figures from E. Blucher seminar, 2000





- But unfortunately, ϵ' got to this point in the decade when the asymmetric B factories were also measuring time-dependent mixing, with sensitivity to larger, better predicted decay processes.

QUARK MIXING RESULTS: CKM MATRIX

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Weak eigenstates Mass eigenstates

Magnitudes of $V_{CKM} \cong \begin{pmatrix} 0.974 & 0.225 & 0.0036 \\ 0.224 & 0.974 & 0.042 \\ 0.0090 & 0.041 & 0.999 \end{pmatrix}$

Wolfenstein Parameterization:

$$V_{CKM} \cong \begin{pmatrix} 1 - {}^{\lambda^2}\!/_2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - {}^{\lambda^2}\!/_2 & -A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

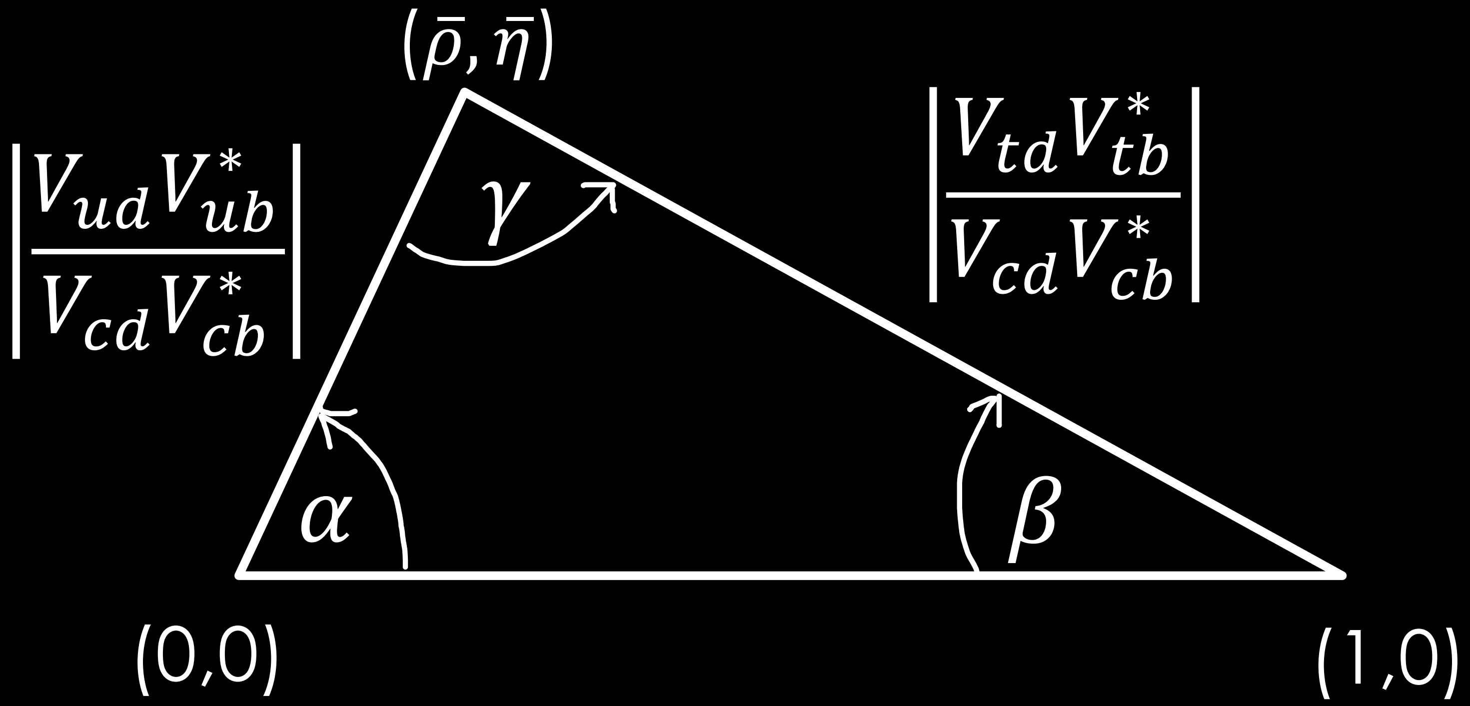
$\times\lambda$ $\times\lambda^2$

CP violation from the imaginary phases.

$$\lambda \approx 0.225, A \approx 0.84, |\rho + i\eta| \sim 1$$

UNITARITY TRIANGLES OF CKM MATRIX

- Unitarity says $V_{ud}V_{ub}^{*} + V_{cd}V_{cb}^{*} + V_{td}V_{tb}^{*} = 0$



Where

$\bar{\rho} \approx \rho\left(1 - \frac{\lambda^2}{2} + \cdots\right)$

etc.

UNITARITY OF CKM MATRIX

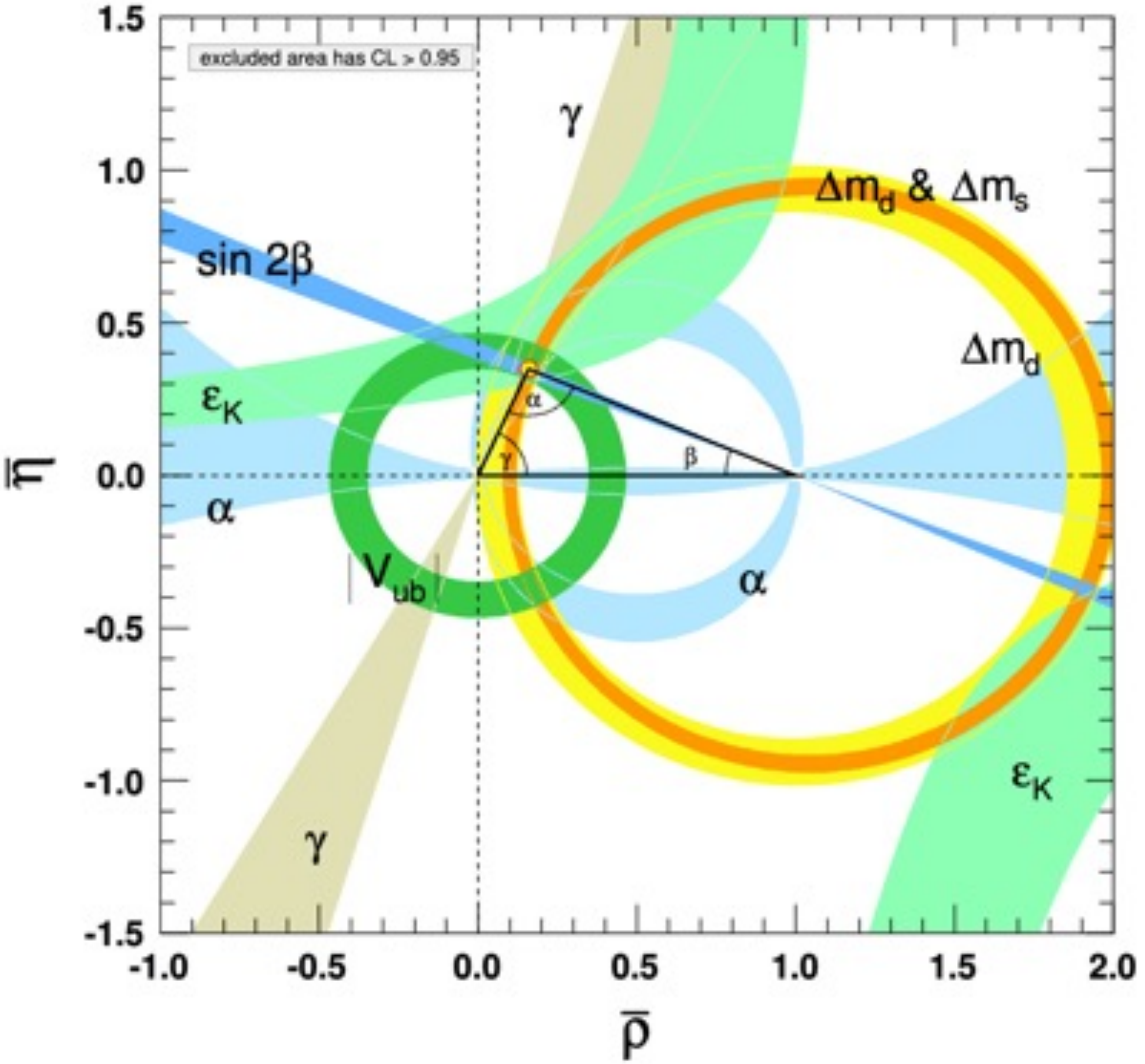


Figure 12.2: Constraints on the $\bar{\rho}, \bar{\eta}$ plane. The shaded areas have 95% CL.

Particle Data Group (PDG), 2022 Review of Particle Properties,
CKM Quark-mixing Matrix

UNITARITY TRIANGLES AND KAONS

- So, where are the kaons?
- ϵ_K, the part from the mixing original observed in the 1960s, can be fairly precisely in terms of CKM matrix elements.
- But the decay contributions are predicted very imprecisely, because they are small and rely on details of quarks inside mesons, so they don't even appear here.
    - Conclusion of ϵ_K' experiments is that no non-standard decay amplitude was seen.
    - Whereas ϵ_K will always be a textbook measurement because it first showed η was non-zero.
- And anyway, in this framework, all the kaon work has been obliterated by measurements of B mesons, at SLAC and elsewhere, that you'll hear about later.

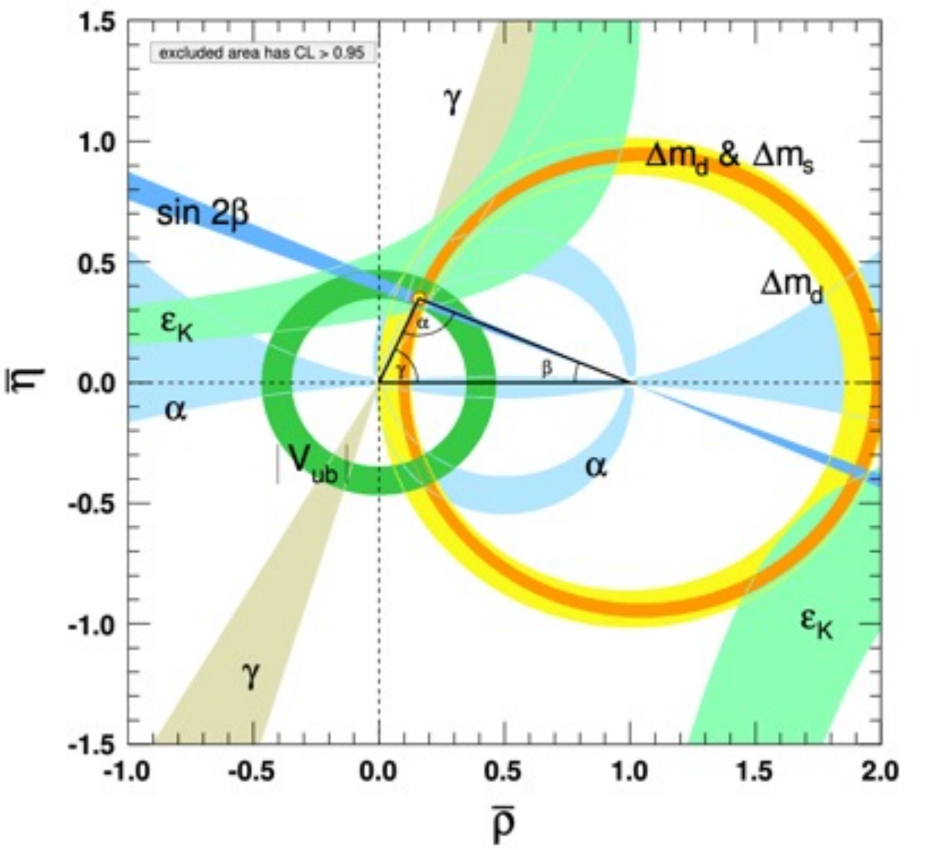


Figure 12.2: Constraints on the $\bar{\rho}, \bar{\eta}$ plane. The shaded areas have 95% CL.

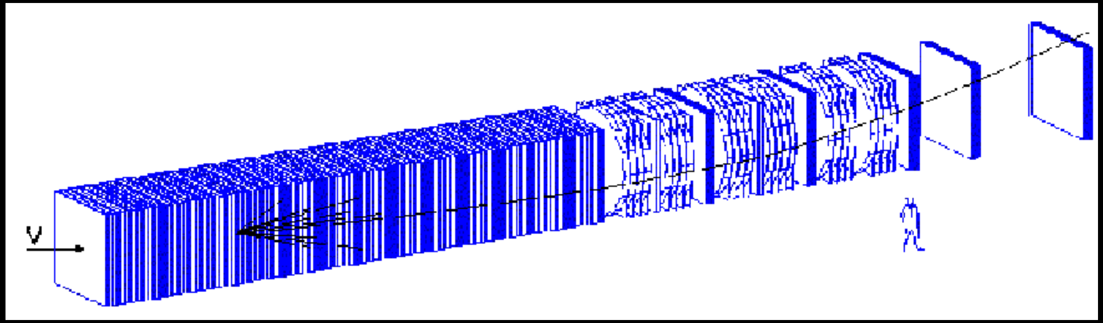
PRECISION W/Z PHYSICS

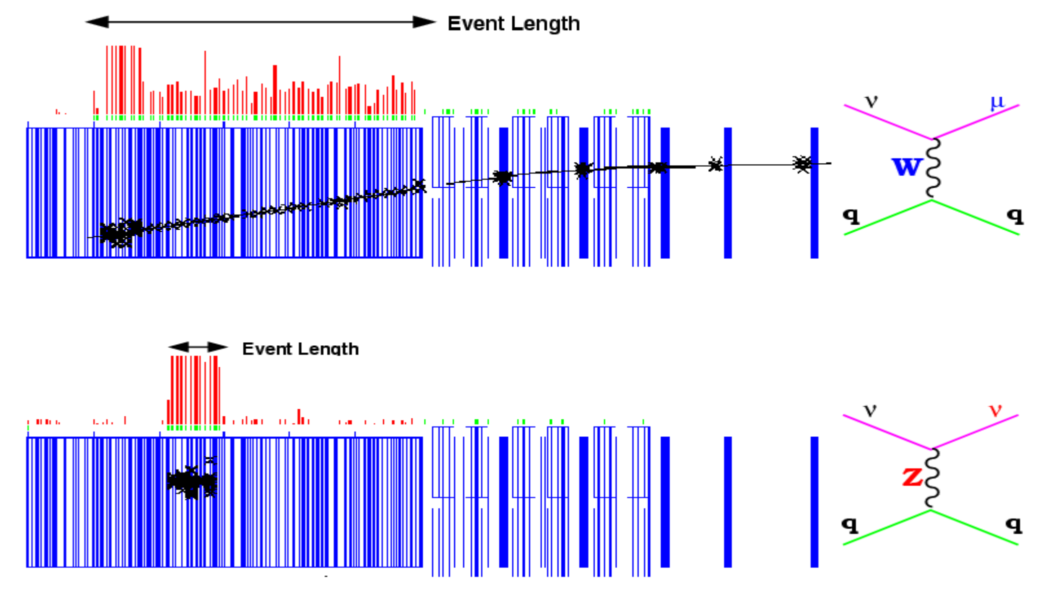
- I was a postdoc at Fermilab from 1994-1997 working on high energy neutrino scattering (NuTeV), and then as an assistant professor (mostly) at Rochester, I joined CDF at the Tevatron to do similar physics in a hadron colliders.
  - I'll speak about NuTeV, since you'll hear much more about precision hadron collider electroweak physics later at the school.
- Both experimental programs had as a goal (primary in the case of NuTeV) to make precision measurements couplings of fermions to the weak bosons as a way to test and look for new, expected or not, physics.

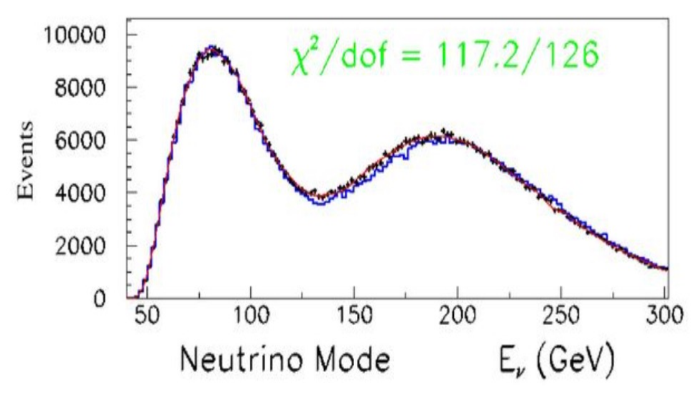
  - *As an aside, I was very heavily involved in all the details of the NuTeV measurement, and revisiting it for this talk gave me a little PTSD.*
  - *I recall saying to anyone who would listen afterward that I would never do a measurement with more than a thousand events again. (Which was a lie.)*

NuTeV

- NuTeV was a high energy (~100 GeV), high statistics neutrino measurement of neutrino deep inelastic scattering.
- The idea was to compare the neutral to charged current to compare against the (precise) prediction.

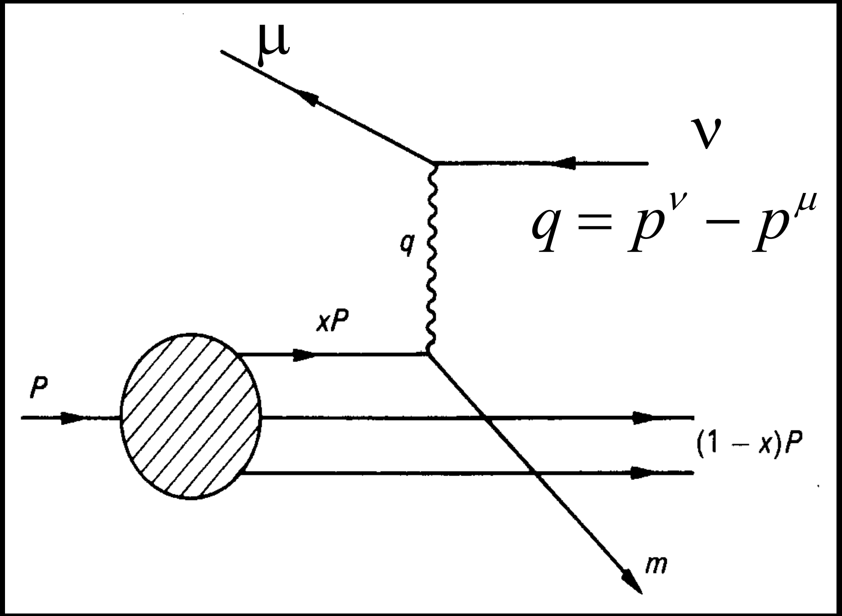






QUARK-PARTON MODEL OF NEUTRINO DEEP INELASTIC SCATTERING

In "infinite momentum frame", *xP* is four momentum of partons inside the nucleon



Neutrino scatters off a parton (quark) inside the nucleon.

$$m_q{}^2 = x^2 P^2 = x^2 M_T^2$$

Effective mass of target quark is large, so cross-section is large, by neutrino standards.

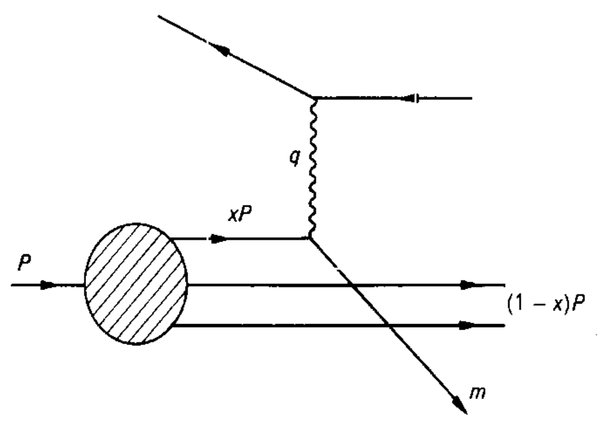
Can measure final state lepton (muon) energy and direction, and recoil energy, "ν" or E_{had}.

$$x = \frac{Q^2}{2P \cdot q} = \frac{Q^2}{2M_T \nu}$$

FACTORIZATION AND PARTONS

- Factorization Theorem of QCD allows cross-sections for hadronic processes to be written as:

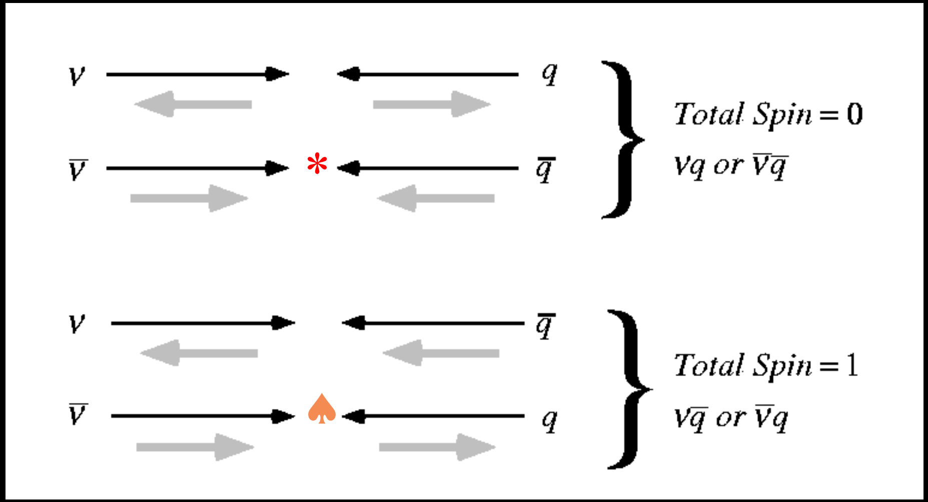
$$\sigma(l+h\rightarrow l+X)$$
$$=\sum_{q}\int dx\sigma(l+q(x)\rightarrow l+X)q_{h}(x)$$



  - $q_h(x)$ is the probability of finding a parton, *q*, with momentum fraction x inside the hadron, *h*. It is called a parton distribution function (PDF).
  - PDFs are universal
  - PDFs are not calculable from first principles in QCD
- "Scaling": parton distributions are largely independent of Q^2 scale, and depend on fractional momentum, x.

HELICITY, CHARGE IN CC ν-Q INTERACTION

- Massless limit for simplicity
- Total spin determines inelasticity distribution
    - spin-1 favors forward scattering, or less inelastic events.



Flat in $y=1-E_{lep}/E_{\nu}$

$1/4(1+\cos\theta^*)^2 = (1-y)^2$

$\int(1-y)^2 dy=1/3$

$$\frac{d\sigma^{\nu p}}{dxdy} = \frac{G_F^2 s}{\pi}\left(x\overset{*}{d}(x) + x\overset{\spadesuit}{\bar{u}}(x)(1-y)^2 \right)$$

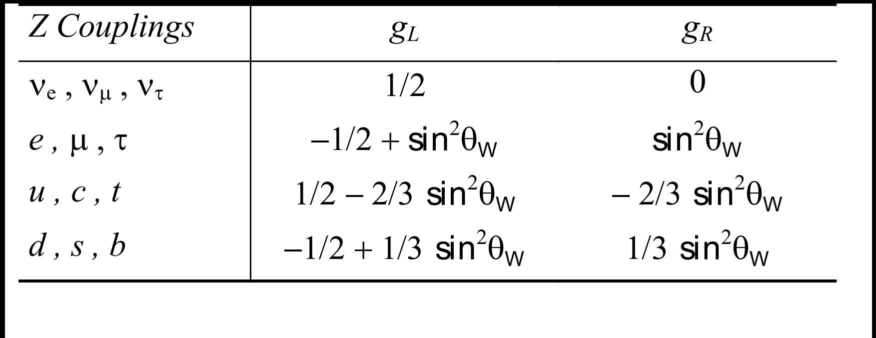
$$\frac{d\sigma^{\bar{\nu} p}}{dxdy} = \frac{G_F^2 s}{\pi}\left(x\overset{*}{\bar{d}}(x) + x\overset{\spadesuit}{u}(x)(1-y)^2 \right)$$

- Neutrino/Anti-neutrino CC each produce particular Δq in scattering

$$\nu d \rightarrow \mu^- u$$
$$\bar{\nu} u \rightarrow \mu^+ d$$

CHARGED AND NEUTRAL CURRENT

- In charged current, couplings to Fermions are all left-handed.
  - But in neutral current, right handed current couples to target (but not neutrino)
  - Complicated couplings
  - For neutral current case, scattering from all flavors of quarks because there is no charge carried by boson.
  - Looks like a difficult comparison.



Z Couplings	g_L	g_R
ν_e , ν_μ , ν_τ	1/2	0
e , μ , τ	$-1/2+\sin^2\theta_W$	$\sin^2\theta_W$
u , c , t	$1/2-2/3\ \sin^2\theta_W$	$-\,2/3\ \sin^2\theta_W$
d , s , b	$-1/2+1/3\ \sin^2\theta_W$	$1/3\ \sin^2\theta_W$

$$\frac{d\sigma^{\nu p,CC}}{dxdy}=\frac{G_F^2 s}{\pi}x\left(d(x)+\bar{u}(x)(1-y)^2\right)$$

$$\frac{d\sigma^{\nu p,NC}}{dxdy}=\frac{G_F^2 s}{\pi}\left(\begin{array}{l}xd_L^2d(x)+d_R^2\bar{d}(x)+u_L^2u(x)+u_R^2\bar{u}(x)\\+(1-y)^2\left(d_R^2d(x)+d_L^2\bar{d}(x)+u_R^2u(x)+u_L^2\bar{u}(x)\right)\end{array}\right)$$

ISOSCALAR TARGETS

- Heavy nuclei are roughly neutron-proton isoscalar
  - OK, more neutrons than protons, but it's closer to 1:1 than 2:1 or 0:1
- Isospin symmetry implies

$$u_p = d_n, d_p = u_n$$

$$\frac{d\sigma^{\nu N,CC}}{dxdy} = \frac{G_F^2 s}{\pi} x\left(u(x) + d(x) + \left(\bar{u}(x) + \bar{d}(x)\right)(1-y)^2\right)$$
$$= \frac{G_F^2 s}{\pi} x\left(q(x) + \bar{q}(x)(1-y)^2\right)$$

$$\frac{d\sigma^{\bar{\nu} N,CC}}{dxdy} = \frac{G_F^2 s}{\pi} x\left(\bar{u}(x) + \bar{d}(x) + \left(u(x) + d(x)\right)(1-y)^2\right)$$
$$= \frac{G_F^2 s}{\pi} x\left(\bar{q}(x) + q(x)(1-y)^2\right)$$

Llewellyn Smith Formulae

$$R^{\nu(\bar{\nu})} = \frac{\sigma_{NC}^{\nu(\bar{\nu})}}{\sigma_{CC}^{\nu(\bar{\nu})}} = \left(\left(u_L^2 + d_L^2\right) + \frac{\sigma_{CC}^{\bar{\nu}(\nu)}}{\sigma_{CC}^{\nu(\bar{\nu})}}\left(u_R^2 + d_R^2\right)\right)$$

- Holds for isoscalar targets of u and d quarks only
  - Heavy quarks, differences between u and d quark distributions are corrections
- Isospin symmetry causes PDFs to drop out, even outside of naïve quark-parton model

PASCHOS-WOLFENSTEIN RELATION

- NuTeV employed very pure ($\sim 10^{-4}$ contamination) neutrino and anti-neutrino separated beams to measure…

Paschos - Wolfenstein Relation

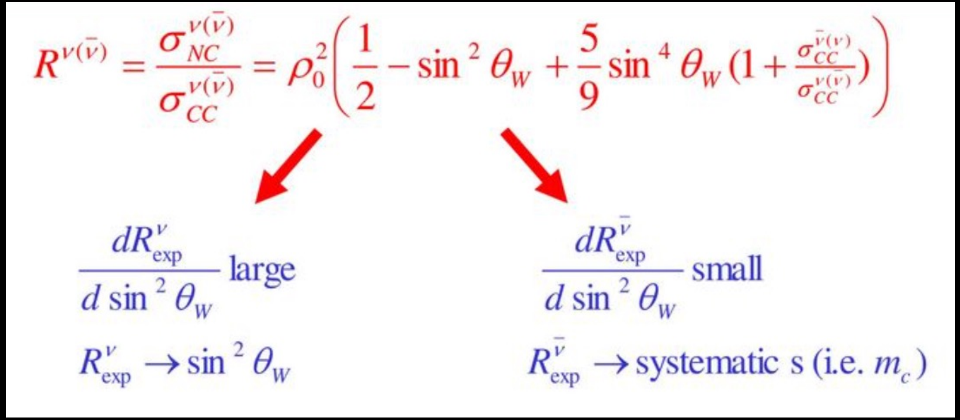
$$R^{-} = \frac{\sigma_{NC}^{\nu} - \sigma_{NC}^{\bar{\nu}}}{\sigma_{CC}^{\nu} - \sigma_{CC}^{\bar{\nu}}} = \rho^{2}\left(\tfrac{1}{2} - \sin^{2}\theta_{W}\right)$$

So any quark-antiquark symmetric part is not in difference, e.g., heavy quark seas.

$$\sigma(\nu q) = \sigma(\bar{\nu}\bar{q})$$
$$\sigma(\nu\bar{q}) = \sigma(\bar{\nu} q)$$

$$\therefore \sigma(\nu q) - \sigma(\bar{\nu}\bar{q}) = 0$$

- Detail: actual measurement was NC/CC in each beam



$$R^{\nu(\bar{\nu})} = \frac{\sigma_{NC}^{\nu(\bar{\nu})}}{\sigma_{CC}^{\nu(\bar{\nu})}} = \rho_{0}^{2}\left(\frac{1}{2} - \sin^{2}\theta_{W} + \frac{5}{9}\sin^{4}\theta_{W}\left(1 + \frac{\sigma_{CC}^{\bar{\nu}(\nu)}}{\sigma_{CC}^{\nu(\bar{\nu})}}\right)\right)$$

$$\frac{dR_{\exp}^{\nu}}{d\sin^{2}\theta_{W}} \text{ large}$$

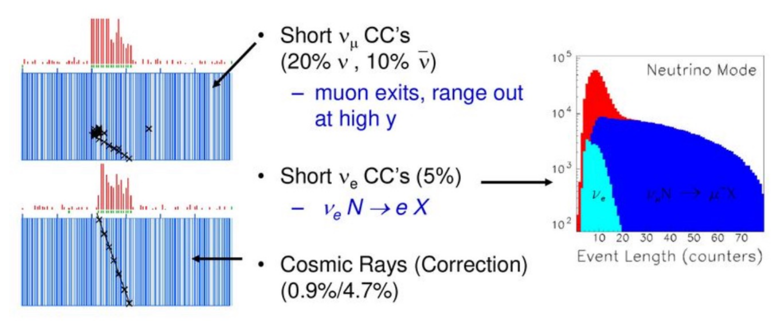
$$R_{\exp}^{\nu} \rightarrow \sin^{2}\theta_{W}$$

$$\frac{dR_{\exp}^{\bar{\nu}}}{d\sin^{2}\theta_{W}} \text{ small}$$

$$R_{\exp}^{\bar{\nu}} \rightarrow \text{systematic s (i.e. } m_{c}\text{)}$$

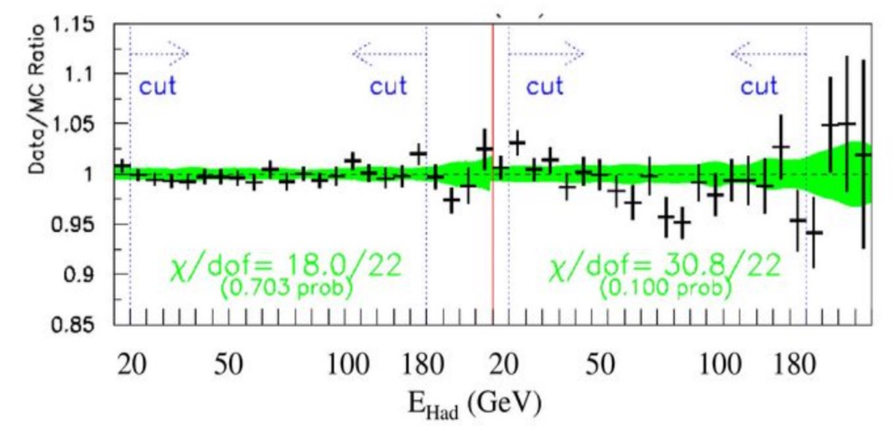
“TECHNOLOGY” OF NuTeV

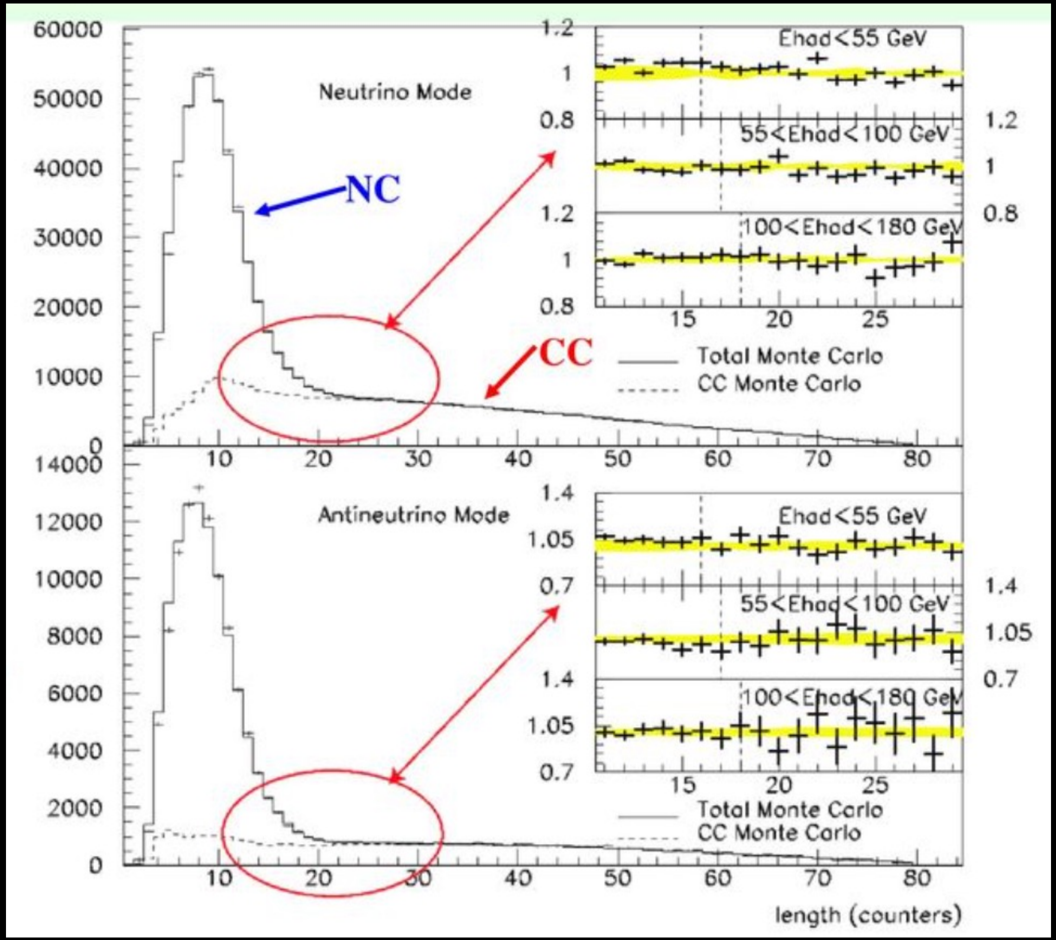
- It was mostly (a the lie always goes), “a counting experiment”.
  - Control samples for NC/CC confusion.



- Short ν_μ CC’s (20% ν , 10% $\bar{\nu}$)
  - muon exits, range out at high y
- Short ν_e CC’s (5%)
  - $\nu_e N \rightarrow e X$
- Cosmic Rays (Correction) (0.9%/4.7%)

- Copious checks against nuisance distributions, etc.





NuTeV FIT TO R^{ν} AND $R^{\nu BAR}$

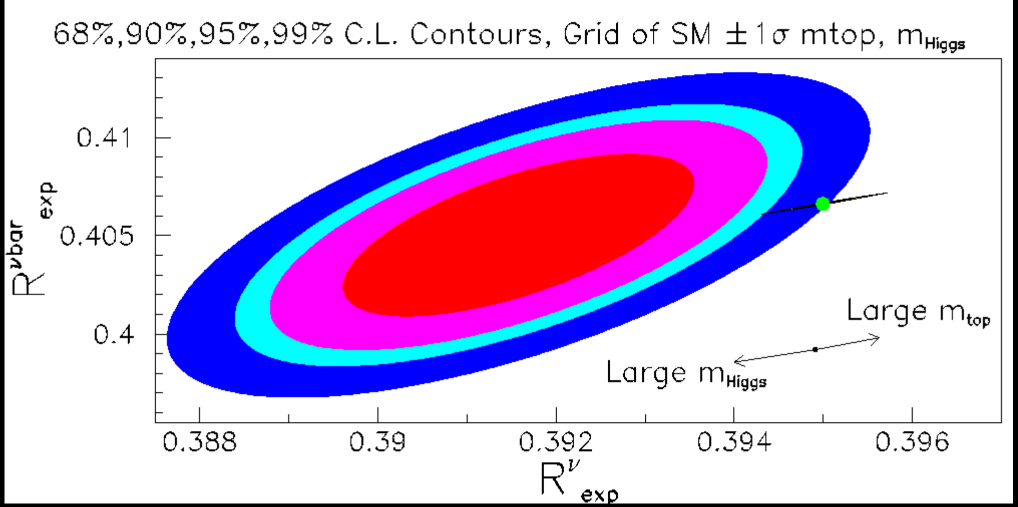
- NuTeV result:

$$\sin^2\theta_W^{(on-shell)} = 0.2277 \pm \pm 0.0013(stat.) \pm 0.0009(syst.)$$
$$= 0.2277 \pm 0.0016$$

(Previous neutrino measurements gave 0.2277 ± 0.0036)

- But Standard model fit predicted 0.2227 ± 0.0004.

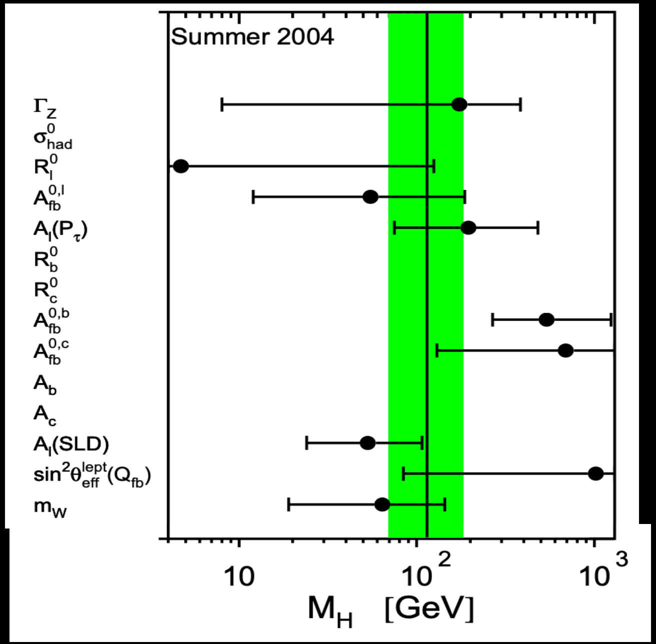
$$R^{\nu}_{\exp} = 0.3916 \pm 0.0013$$
$$(SM : 0.3950) \quad \Leftarrow 3\sigma\ difference$$
$$R^{\bar{\nu}}_{\exp} = 0.4050 \pm 0.0027$$
$$(SM : 0.4066) \quad \Leftarrow Good\ agreement$$

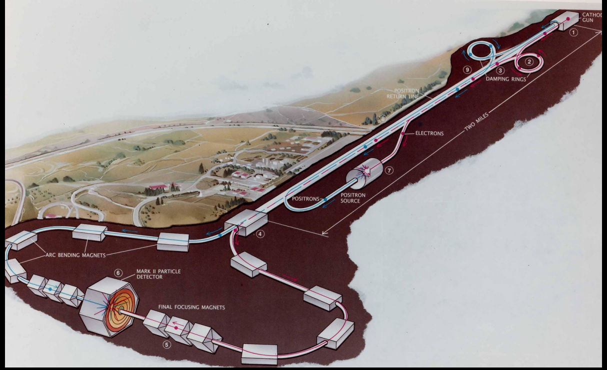


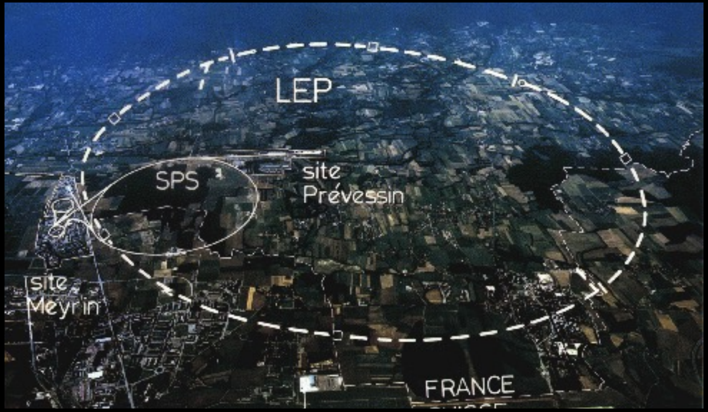
THE CONTEXT IN WHICH NuTeV MADE ITS MEASUREMENT

- This was 1996-2000, from data taking through analysis, when LEP and SLC running $e^+e^- \to Z^0$ were in their most productive phase.
- Hadron collider (CDF and D0) W mass were becoming precise also.

- Every conference had a long, incremental talk from electroweak fitting groups and multi-hundred page papers with bland titles like, “A Combination of Preliminary Electroweak Measurements and Constraints on the Standard Model”.

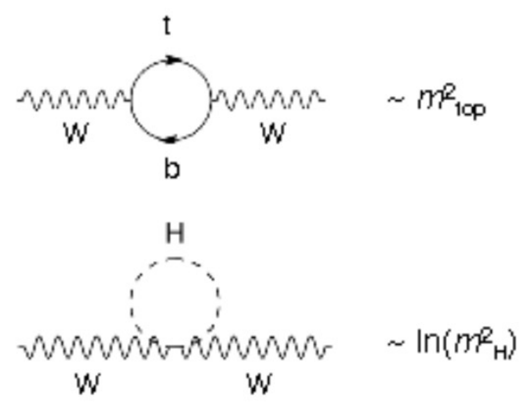


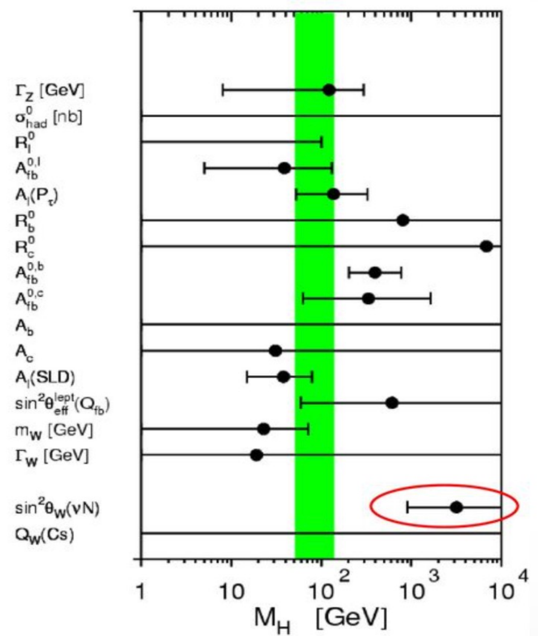




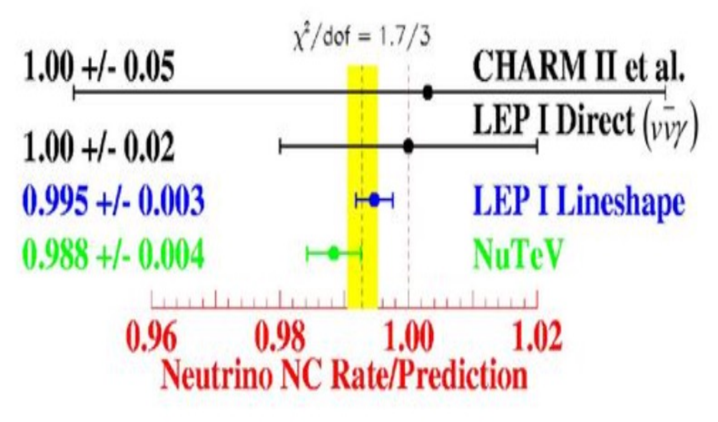
THE CONTEXT IN WHICH NuTeV MADE ITS MEASUREMENT (cont'd)

- These were important and "inspiring" precision measurements of Type II (Quantum Corrections).
- We knew, for example, the Higgs boson mass to decent precision before it was observed.





- NuTeV arguably had particular sensitivity to neutrino couplings, along with the LEP measurement of the invisible Z width. But how does that fit?



You'll note I didn't refer to SLD as ゴジラ in deference to our hosts.

SO WHAT DID NuTeV FIND??

- The favorite community explanation is a so-called “Altarelli Cocktail” of small effects.
  - Asymmetry of the strange quark sea, NLO QCD corrections, nucleon or nuclear isospin violation, small shifts in subsequent predictions and inputs, etc.

ALTARELLI COCKTAILS

- The favorite community explanation is a so-called "Altarelli Cocktail" of small effects.
    - Asymmetry of the strange quark sea, NLO QCD corrections, nucleon or nuclear isospin violation, small shifts in subsequent predictions and inputs, etc.

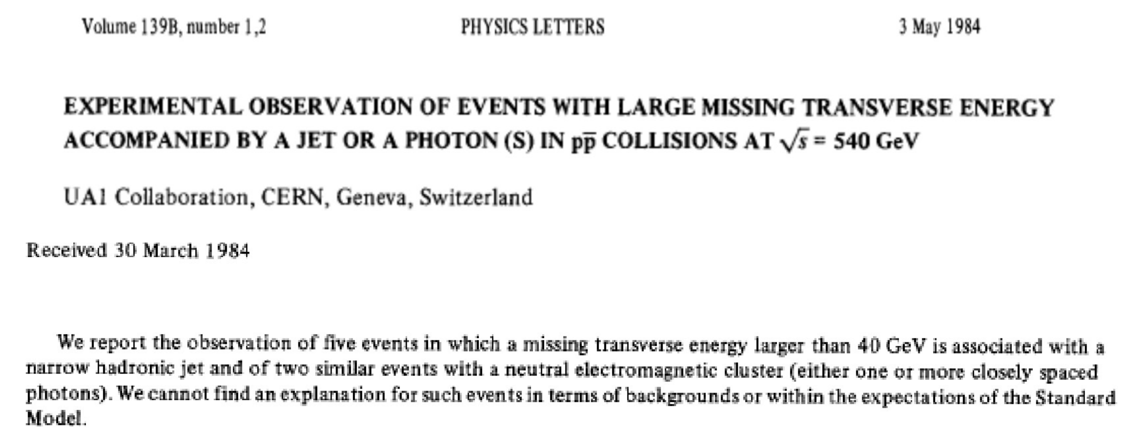
- But why is it called an Altarelli Cocktail?

from J. Kopp, NuINT 2024

Image: ChatGPT
(who refused to draw an Italian physicist w/o a beard)

ALTARELLI COCKTAILS

- What is an Altarelli Cocktail?



Volume 139B, number 1,2 PHYSICS LETTERS 3 May 1984

EXPERIMENTAL OBSERVATION OF EVENTS WITH LARGE MISSING TRANSVERSE ENERGY ACCOMPANIED BY A JET OR A PHOTON (S) IN $p\bar{p}$ COLLISIONS AT $\sqrt{s}$ = 540 GeV

UA1 Collaboration, CERN, Geneva, Switzerland

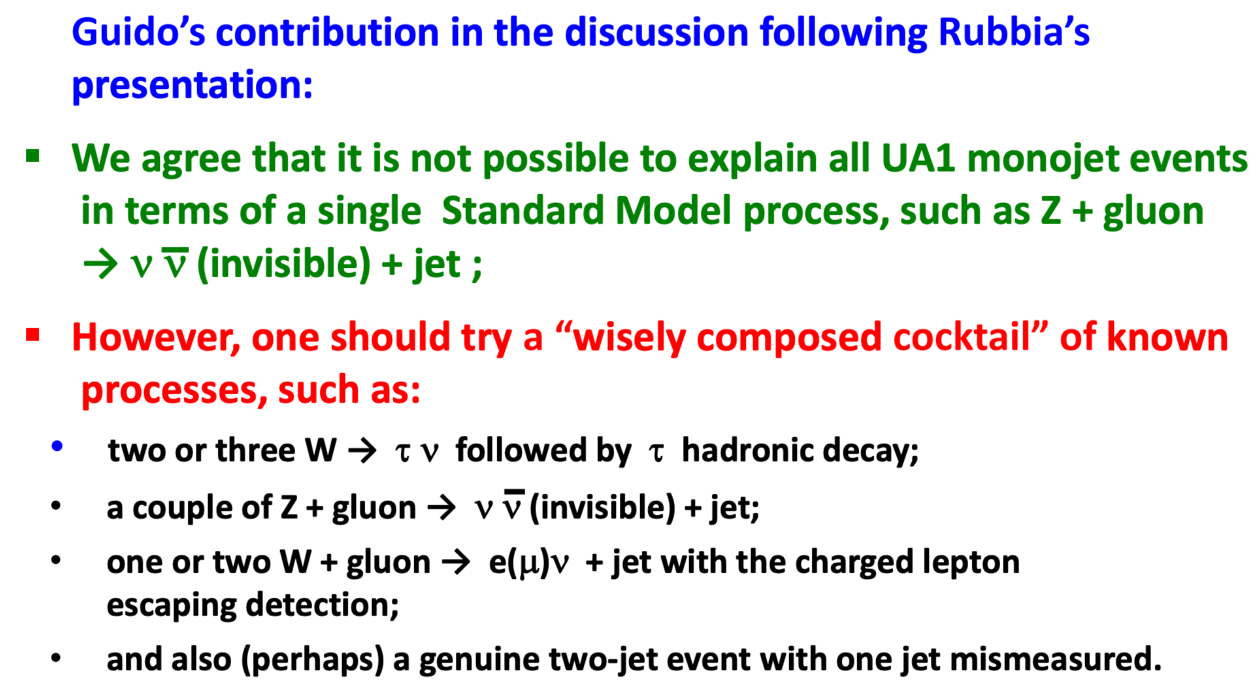
Received 30 March 1984

We report the observation of five events in which a missing transverse energy larger than 40 GeV is associated with a narrow hadronic jet and of two similar events with a neutral electromagnetic cluster (either one or more closely spaced photons). We cannot find an explanation for such events in terms of backgrounds or within the expectations of the Standard Model.

UA2 (with sketchy calorimetry) and then UA1 (with better calorimetry) reported an excess of "monojet" like events in the mid-80s.

Must be Supersymmetry!

From a lovely (and loving) summary by Luigi Di Lella at a memorial symposium for Altarelli in 2016…



Guido's contribution in the discussion following Rubbia's presentation:

- **We agree that it is not possible to explain all UA1 monojet events in terms of a single Standard Model process, such as Z + gluon → $\nu\bar{\nu}$ (invisible) + jet ;**
- **However, one should try a "wisely composed cocktail" of known processes, such as:**
  - **two or three W → $\tau\nu$ followed by τ hadronic decay;**
  - **a couple of Z + gluon → $\nu\bar{\nu}$ (invisible) + jet;**
  - **one or two W + gluon → e(μ)ν + jet with the charged lepton escaping detection;**
  - **and also (perhaps) a genuine two-jet event with one jet mismeasured.**

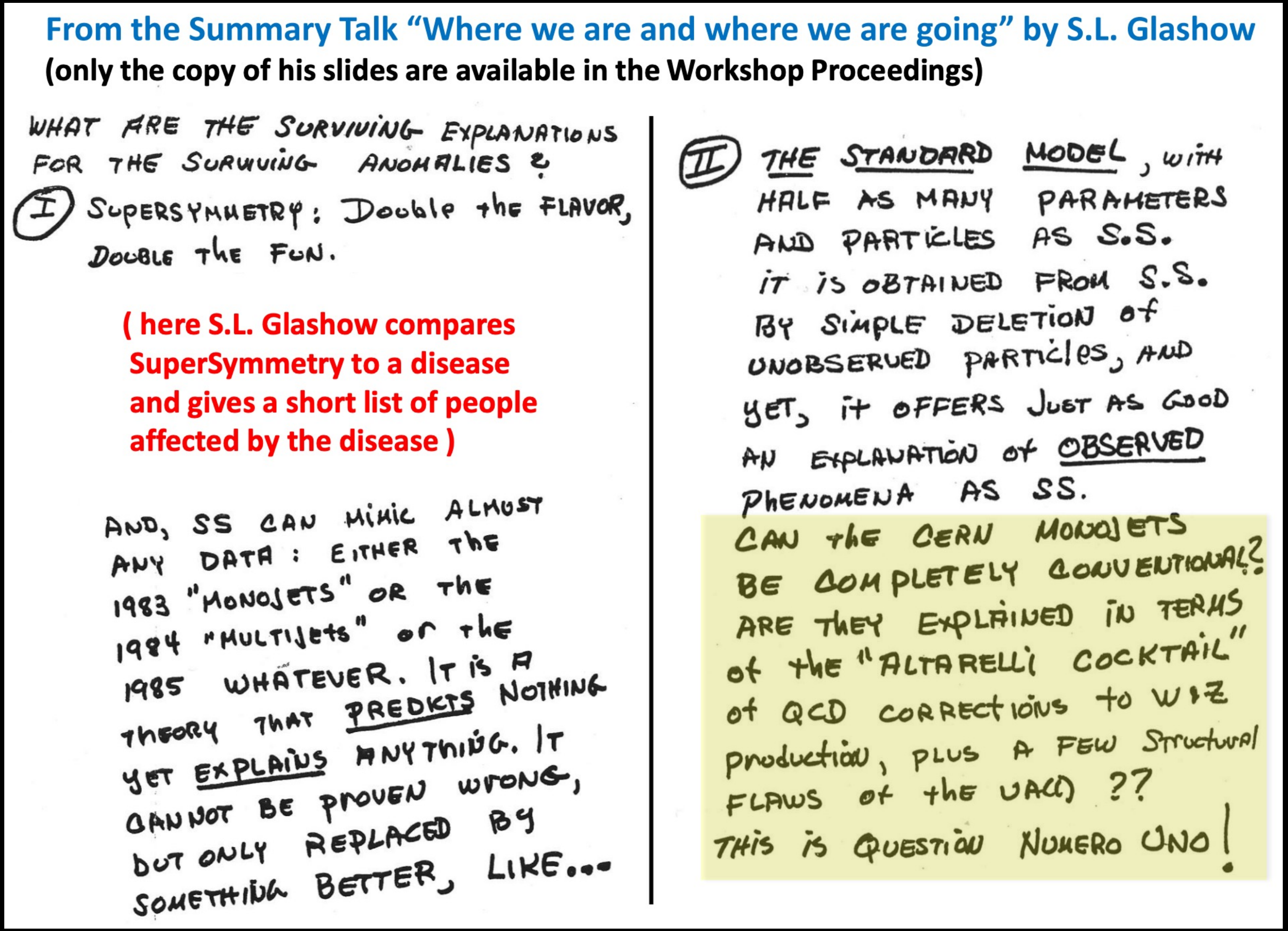
ALTARELLI COCKTAILS

Continuing from the summary by Luigi Di Lella at a memorial symposium for Altarelli in 2016…

- In this case, Altarelli was correct, and by the end of the meeting had won over his colleagues, including Sheldon Glashow in his workshop summary.

(Ouch! Free career advice: don't put stuff like the redacted bit on your slides until after your Nobel Prize.

And even then don't do it.)



From the Summary Talk "Where we are and where we are going" by S.L. Glashow

(only the copy of his slides are available in the Workshop Proceedings)

WHAT ARE THE SURVIVING EXPLANATIONS
FOR THE SURVIVING ANOMALIES ?
(I) SUPERSYMMETRY: Double the FLAVOR,
DOUBLE THE FUN.

(here S.L. Glashow compares SuperSymmetry to a disease and gives a short list of people affected by the disease)

AND, SS CAN MIMIC ALMOST
ANY DATA : EITHER THE
1983 "MONOJETS" OR THE
1984 "MULTIJets" or the
1985 WHATEVER. IT IS A
THEORY THAT PREDICTS NOTHING
YET EXPLAINS ANYTHING. IT
CANNOT BE PROVEN WRONG,
BUT ONLY REPLACED BY
SOMETHING BETTER, LIKE...

(II) THE STANDARD MODEL, with
HALF AS MANY PARAMETERS
AND PARTICLES AS S.S.
IT IS OBTAINED FROM S.S.
BY SIMPLE DELETION of
UNOBSERVED PARTICLES, AND
YET, it OFFERS JUST AS GOOD
AN EXPLANATION of OBSERVED
PHENOMENA AS SS.
CAN THE CERN MONOJETS
BE COMPLETELY CONVENTIONAL?
ARE THEY EXPLAINED IN TERMS
of the "ALTARELLI COCKTAIL"
of QCD CORRECTIONS to W+Z
production, PLUS A FEW Structural
FLAWS of the UA(1) ??
THIS IS QUESTION NUMERO UNO!

SO WHAT DID NuTeV FIND??

- The favorite community explanation is a so-called "Altarelli Cocktail" of small effects.
  - Asymmetry of the strange quark sea, NLO QCD corrections, nucleon or nuclear isospin violation, small shifts in subsequent predictions and inputs, etc.
- I'm more an Occam's Razor kind of guy, so my bet is very large isospin violation in nuclei.
  - if $d_p(x) \neq u_n(x)$ at the 5% level… it would shift charge current (normalizing) cross-sections enough to reproduce NuTeV.
  - there is no data to forbid it.
- NuTeV may have been let down by its inputs.

- As a final editorial comment in this section…
- In this school, you will hear several talks about the muon *g*-2 theory situation, which may have some similarities to my Occam's Razor hypothesis at left.
- That said, muon *g*-2 is clearly a Type II precision measurement, whereas NuTeV's place in the lesser pantheon is unclear.

PRECISION NEUTRINO OSCILLATIONS

- At the 2001 Snowmass meeting, I started talking with a fellow graduate student from the KTeV precursor experiments, then working at Kyoto University on the K2K experiment, and he told me about the developing plans for what become T2K.

- I got interested in the science goals, but also, perhaps chastened by my NuTeV experience, got interested in some of the shaky experimental inputs to precision neutrino oscillation physics.
  - You'll have three detailed talks on this subject, so I will be relatively brief.

NEUTRINO INTERFEROMETRY

- A neutrino wavefunction has a time-varying phase in its rest frame,

$$H|\psi(t)\rangle = i\hbar\frac{\partial}{\partial t}|\psi(t)\rangle$$

- Now, imagine you produce a neutrino of definite momentum which is a mixture of two masses, m_1, m_2

$$E_1 = \sqrt{p^2+m_1^2} \approx p\left(1+\frac{m_1^2}{2p^2}\right)$$

$$E_2 = \sqrt{p^2+m_2^2} \approx p\left(1+\frac{m_2^2}{2p^2}\right)$$

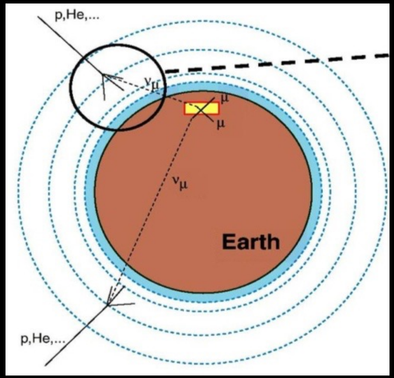
$$i(E_1-E_2)\frac{\tau}{h} \approx i(m_1^2-m_2^2)\frac{Lc}{2ph}$$

- they pick up a phase difference in lab frame.
- With time evolution, this interference can become visible as neutrino flavor oscillation.

LUCKY NEUTRINOS!

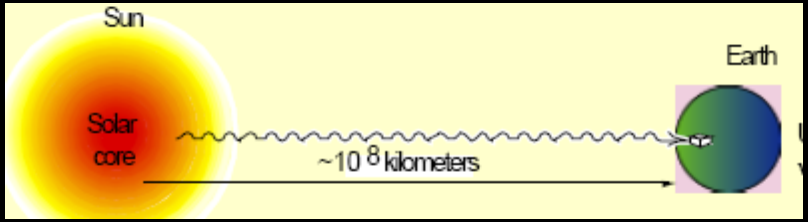
“We live in the best of all possible worlds”

– Alvaro deRujula, Neutrino 2000



By which he meant that it required $E_{atm\ \nu}/R_{earth} < \Delta m_{atm}^2 < E_{atm\ \nu}/h_{atm}$

and a solar density profile matching Δm_{sol}^2



To make two interferometric discoveries of ν flavor oscillations from the sun and from cosmic ray neutrinos!

Art McDonald and Takaaki Kajita, 2015 Nobel Laureates in Physics & Lucky People ?

TWO INTERFERENCE SIGNATURES AND THREE NEUTRINOS

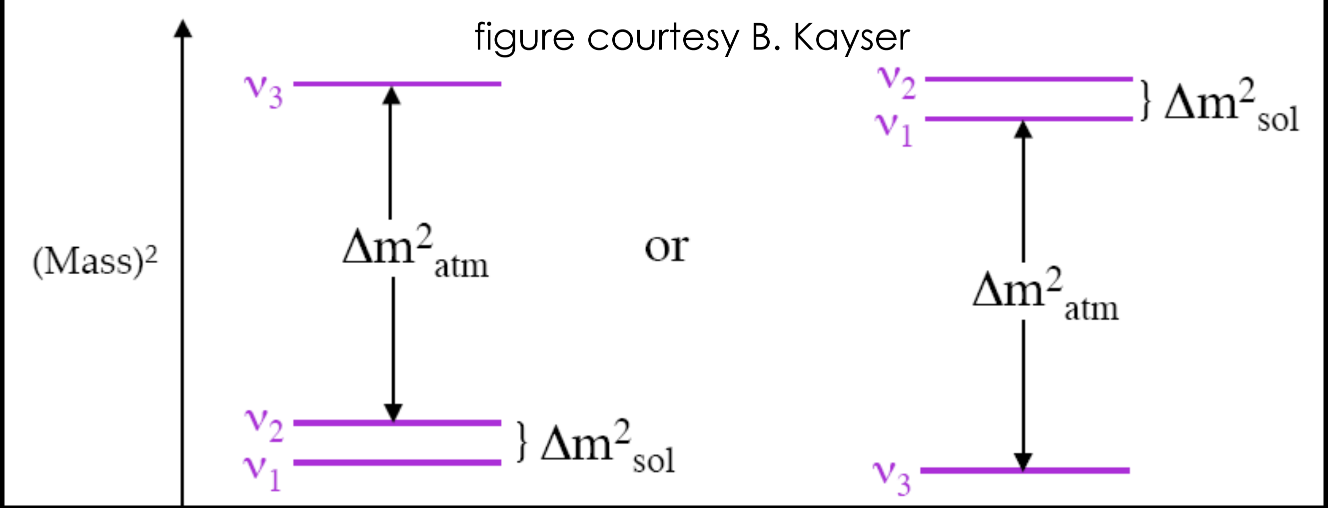


figure courtesy B. Kayser

$\Delta m_{sol}{}^2 \rightarrow \Delta m_{12}{}^2 \approx 8x10^{-5} eV^2$

$\Delta m_{atm}{}^2 \rightarrow \Delta m_{23}{}^2 \approx 2.5x10^{-3} eV^2$

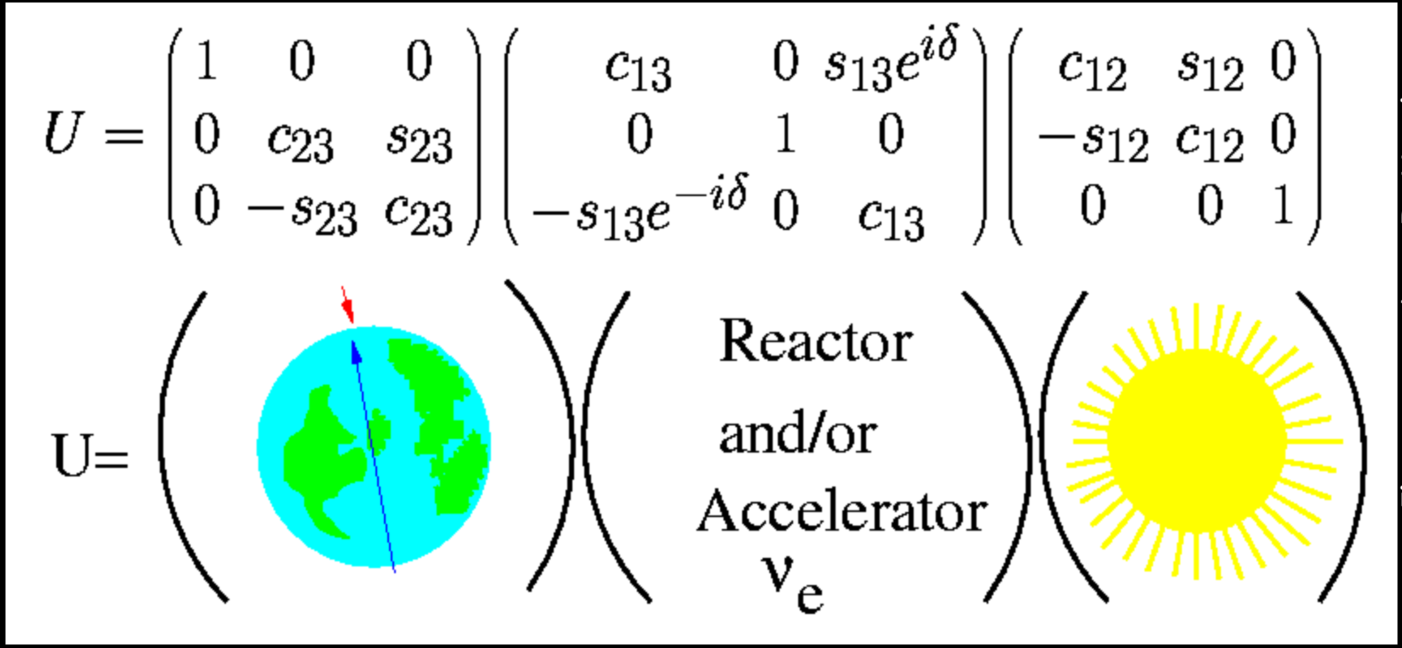
- Interferometry has told us the differences in m^2, but nothing about the ordering of masses of the third state relative to the other two.
- The electron neutrino potential as neutrinos pass through electron containing material (“*matter effects*”) can resolve the ordering.
  - *That happens in the sun, and that is how we know the 1-2 ordering.*

THREE GENERATION MIXING

- As noted by Kobayashi and Maskawa in the quarks, a third generation of mixing admits the possibility of a complex phase → CP violation

$$\begin{pmatrix} \upsilon_e \\ \upsilon_\mu \\ \upsilon_\tau \end{pmatrix} = \mathrm{U} \begin{pmatrix} \upsilon_1 \\ \upsilon_2 \\ \upsilon_3 \end{pmatrix}$$

$$c_{ij} = cos\theta_{ij}$$
$$s_{ij} = sin\theta_{ij}$$



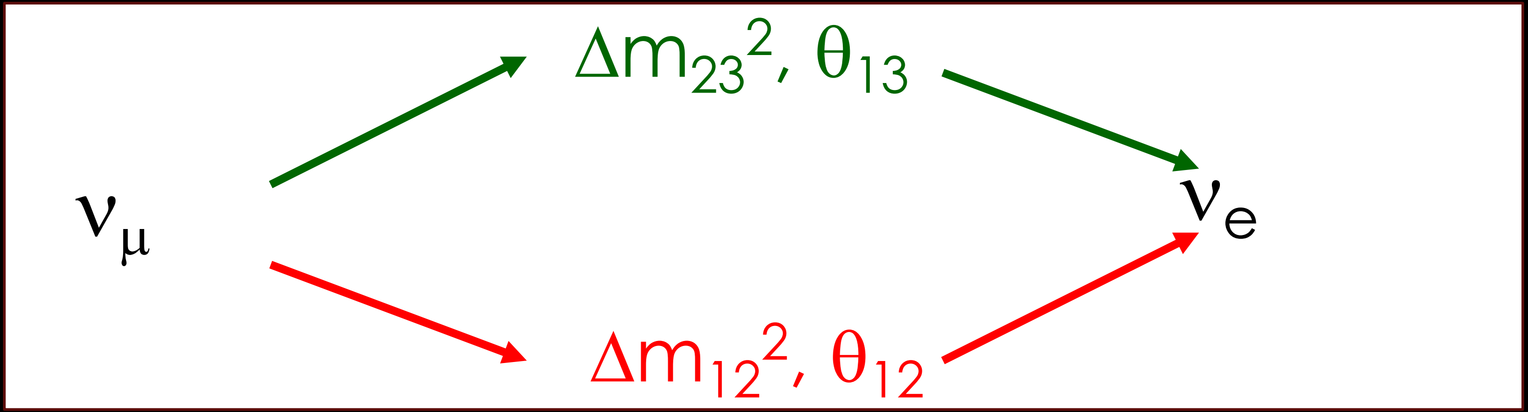
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Figure courtesy D. Harris

- Note the new mixing in middle, and the phase, δ

ARE TWO PATHS OPEN TO US?

- We knew, pre-T2K, Daya Bay, and RENO, that if the “reactor” mixing, θ_{13}, were small, but not too small, there is an interesting possibility

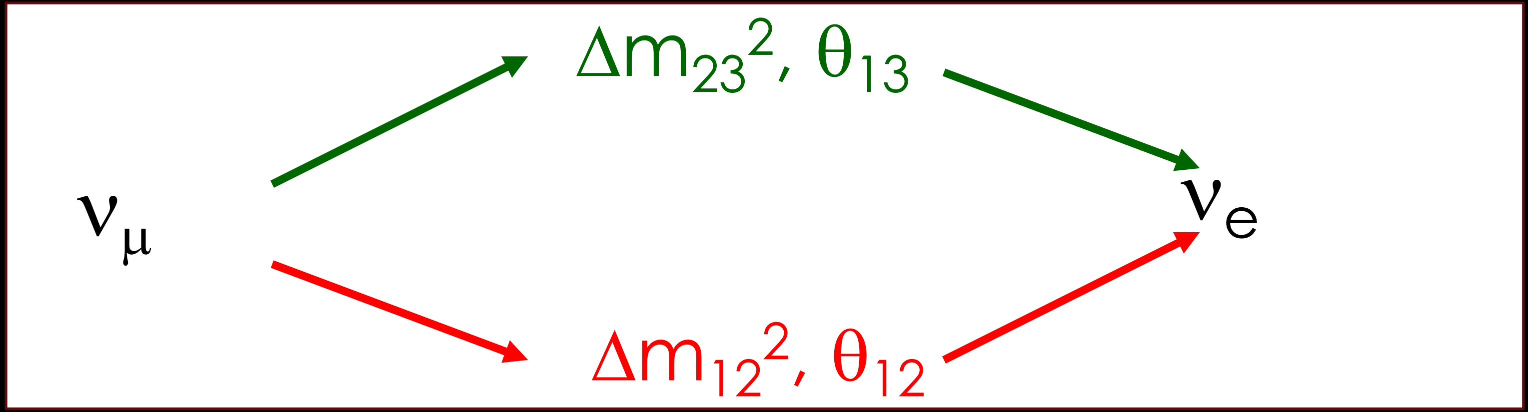


- At atmospheric L/E,

$$P(\nu_\mu \to \nu_e) = \underset{\text{LARGE}}{\overset{\text{SMALL}}{\sin^2 2\theta}} \sin^2\left(\frac{\overset{\text{LARGE}}{(m_2^2 - m_1^2)}L}{4\underset{\text{SMALL}}{E}}\right)$$

IMPLICATION OF TWO PATHS

- Two amplitudes

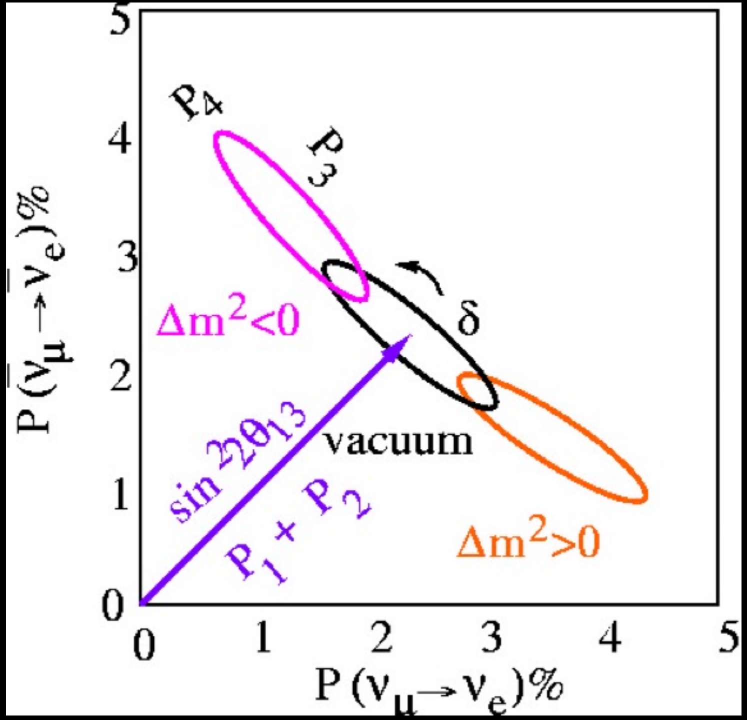


- Since T2K, Daya Bay, and RENO have now told us that both are small, but not too small, both can contribute ~ equally
- Relative phase, δ, between the paths can lead to observable CP violation (neutrinos and anti-neutrinos differ) in flavor oscillations!

OBSERVABLE EFFECTS DUE TO THIS INTERFERENCE

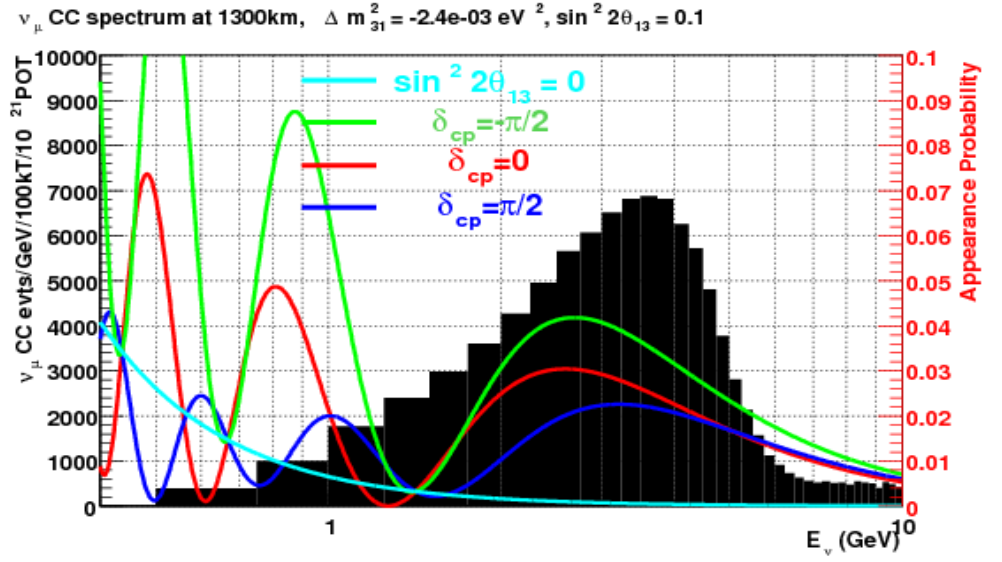
- “CP violation” (interference term) and matter effects lead to a complicated mix…
- Simplest case at right:
  first interference maximum,
  neutrinos and anti-neutrinos
- CP violation gives ellipse but matter effects shif the ellipse in a *precision* long-baseline accelerator experiment.
  - Either a broadband beam (DUNE) or a low energy beam (Hyper-K) can disentangle this.

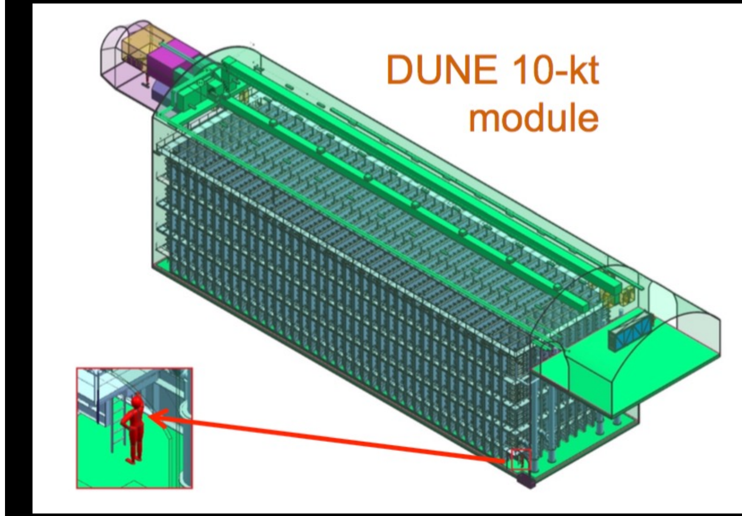
Minakata & Nunokawa
JHEP 2001



PRECISION NEUTRINO OSCILLATION TECHNOLOGY

- The future experiments, DUNE and Hyper-K require enormous beam power and capable massive detectors to get the statistics required for sub-percent measurements of these flavor transitions.

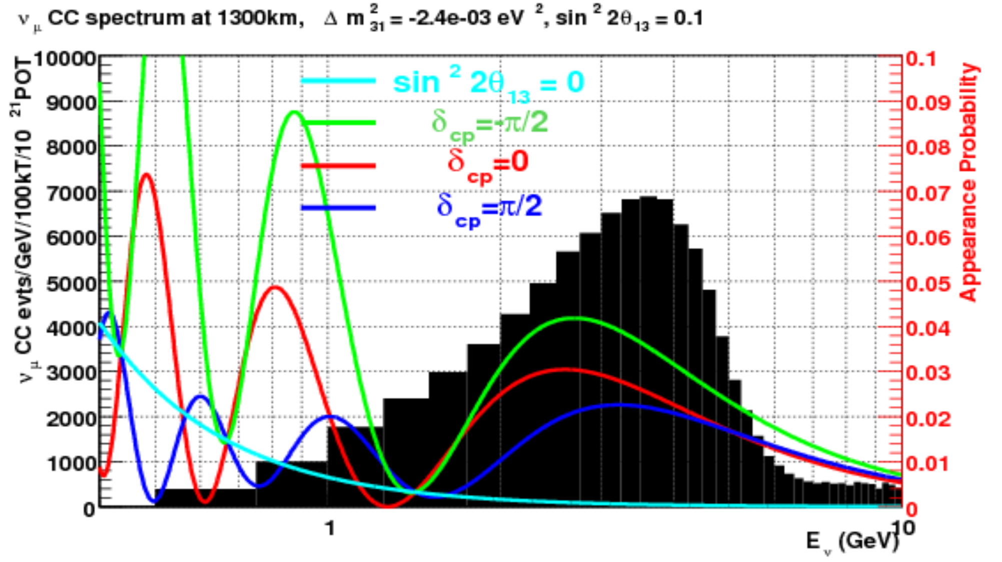




NEUTRINO INTERFEROMETRY MEASUREMENTS

- You have to measure two things for precision interferometry: the flavor of the neutrino and the energy of the neutrino.

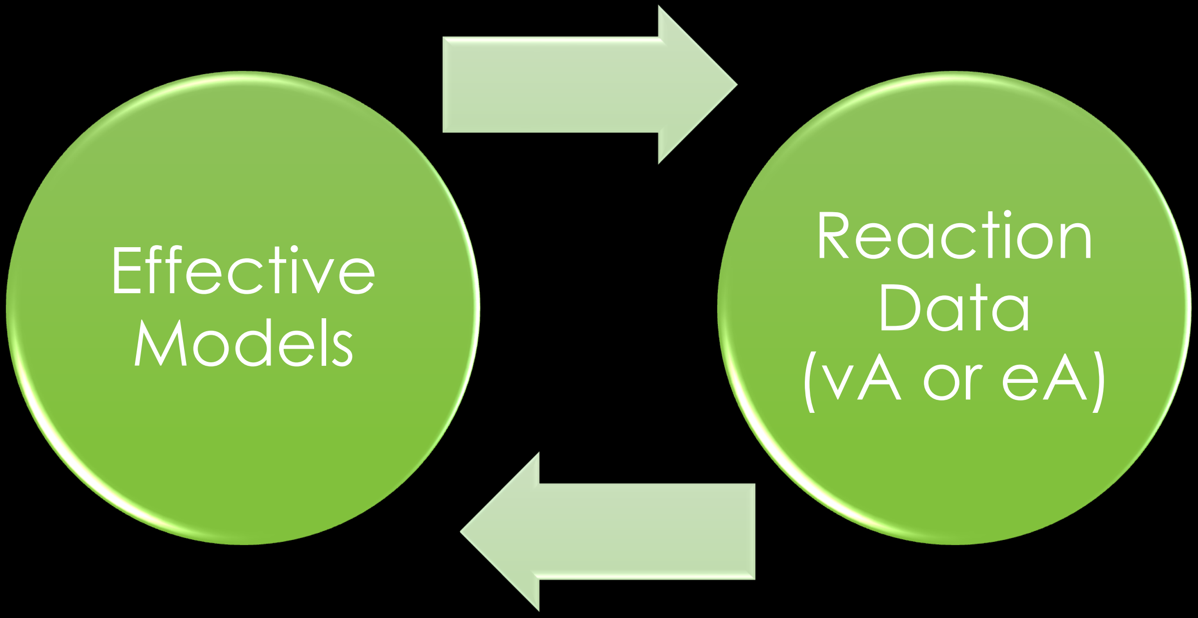
$$
\begin{aligned}
P(\nu_\mu \to \nu_e) \;\simeq\;& \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{32}L}{4E}\right)\left(1+\frac{4\sqrt{2}G_F n_e E}{\Delta m^2_{31}}(1-2\sin^2\theta_{13})\right) \quad \leftarrow \text{Leading term}\\
&- \sin 2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13}\cos\theta_{13}\sin\delta\,\sin\left(\frac{\Delta m^2_{32}L}{4E}\right)\sin\left(\frac{\Delta m^2_{31}L}{4E}\right)\sin\left(\frac{\Delta m^2_{21}L}{4E}\right)\\
&\hspace{20em}\nwarrow \text{CP violating term}
\end{aligned}
$$



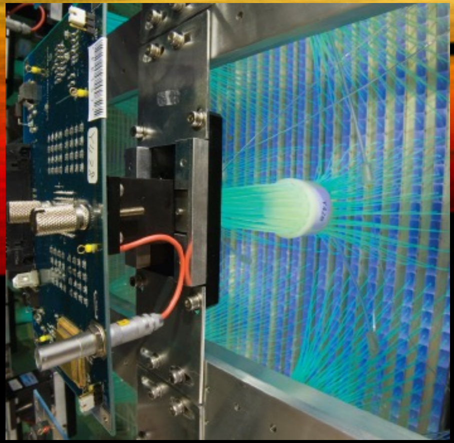
- The flavor is measured well from the type of lepton visible in a charged-current interaction.
- But the energy, particularly in a broad band experiment like DUNE, comes from the final state.
- *Requires a detailed understanding of a large number of neutrino interaction mechanisms, and how they may obscure energy and flavor.*

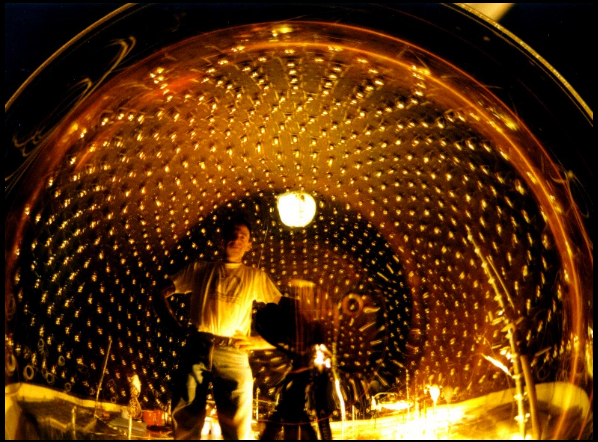
INTERACTIONS: THEORY AND EXPERIMENT

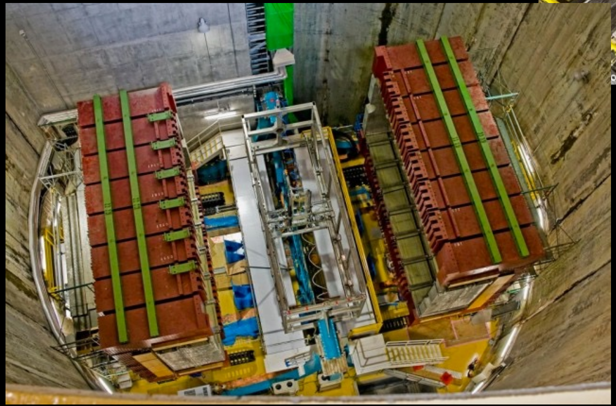
- Both are critical, but both are limited in what they can offer.
- Theory uses necessary approximations, is limited in phase space, or calculates overly inclusive reactions ill-suited to describing the full final state.
- Data are good at pointing out modeling deficiencies, but often poor at pinpointing the problem.



INTERACTION EXPERIMENTS





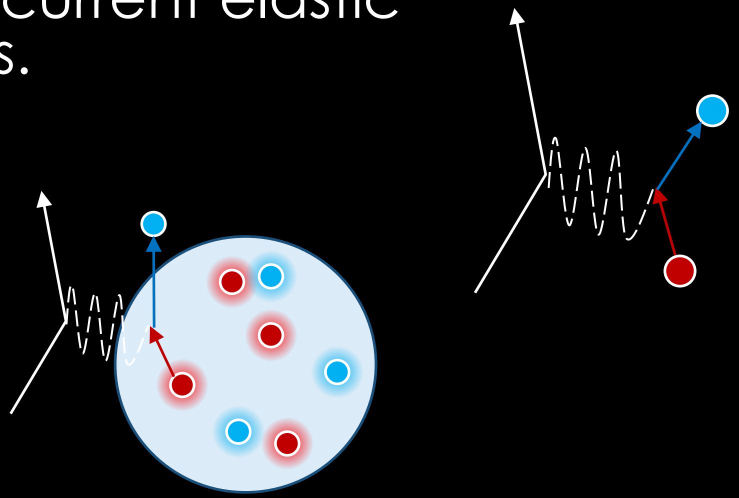

- Short baseline oscillation experiments have enough rate to also measure neutrino interactions: LSND, MiniBooNE, MicroBooNE.
- Oscillation experiments have near detectors which measure interactions with varying degrees of effort: K2K, MINOS, T2K, NOvA, SBN.
- A few dedicated experiments: SciBooNE, MINERvA, ANNIE.

DONE, PUBLISHING, SOON

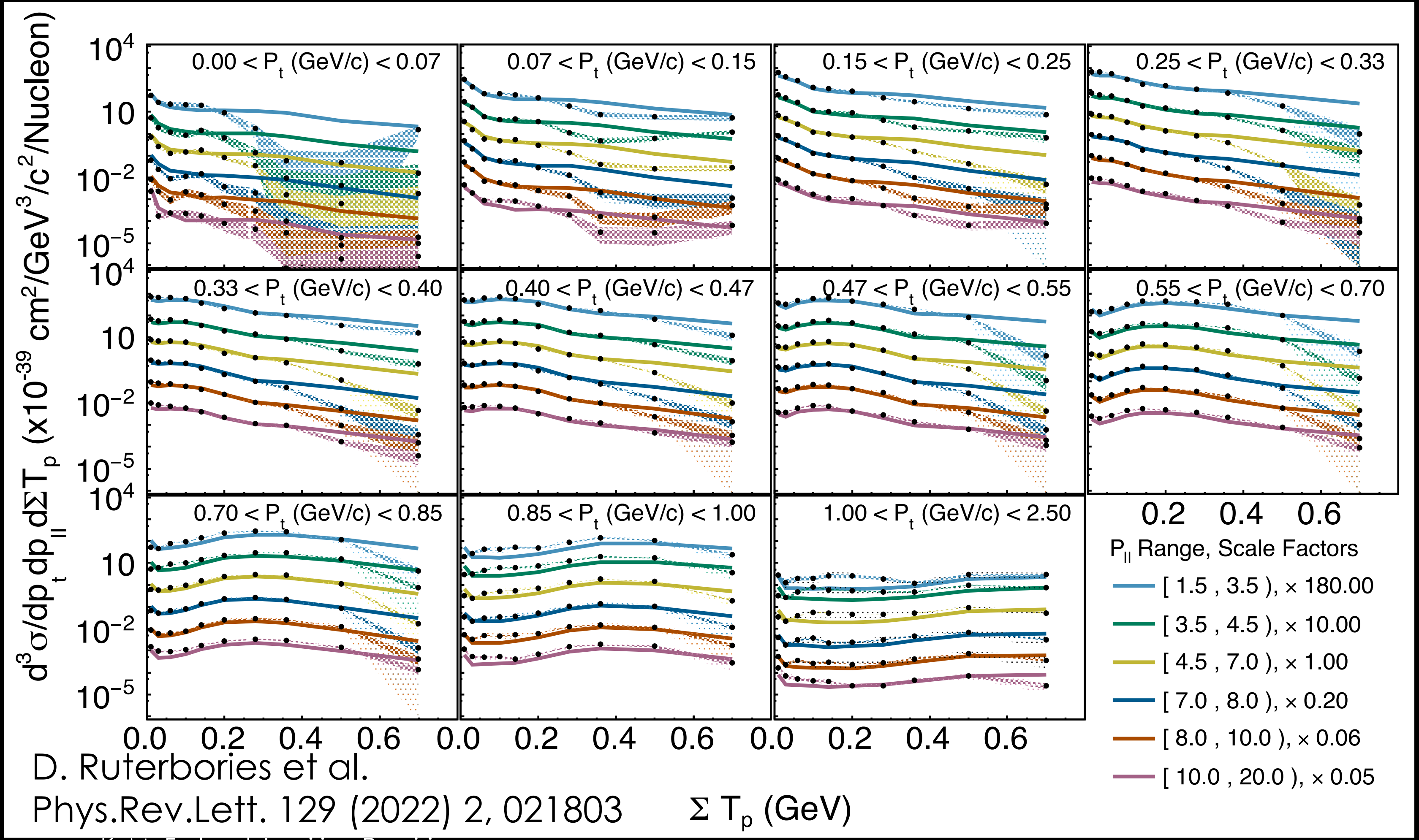
A QUICK ZOOM INTO ONE INTERACTION MEASUREMENT

- MINERvA's targets are primarily nuclei, and the main active target is polystyrene scintillator (CH).
- Most of the "least inelastic" reactions from this target that are quasielastic scattering, , or CC0$\boldsymbol{\pi}$ events, meaning the "charged current elastic scattering" but from a target embedded in a nucleus.
- So charged current elastic is,
  $\bar{\nu}_\mu p \to \mu^+ n$, a.k.a. $p(\bar{\nu}_\mu, \mu^+)n$,

  but quasielastic means we look at $A(\bar{\nu}_\mu, \mu^+ n \ldots)A'$.
- These measurements convolve nucleon structure with nuclear effects.
- We mostly focus on nuclear effects and how they change the visible content.



MINERVA RESULTS: CC0$\boldsymbol{\pi}$ ΣT_p, p_T, $p_\parallel$



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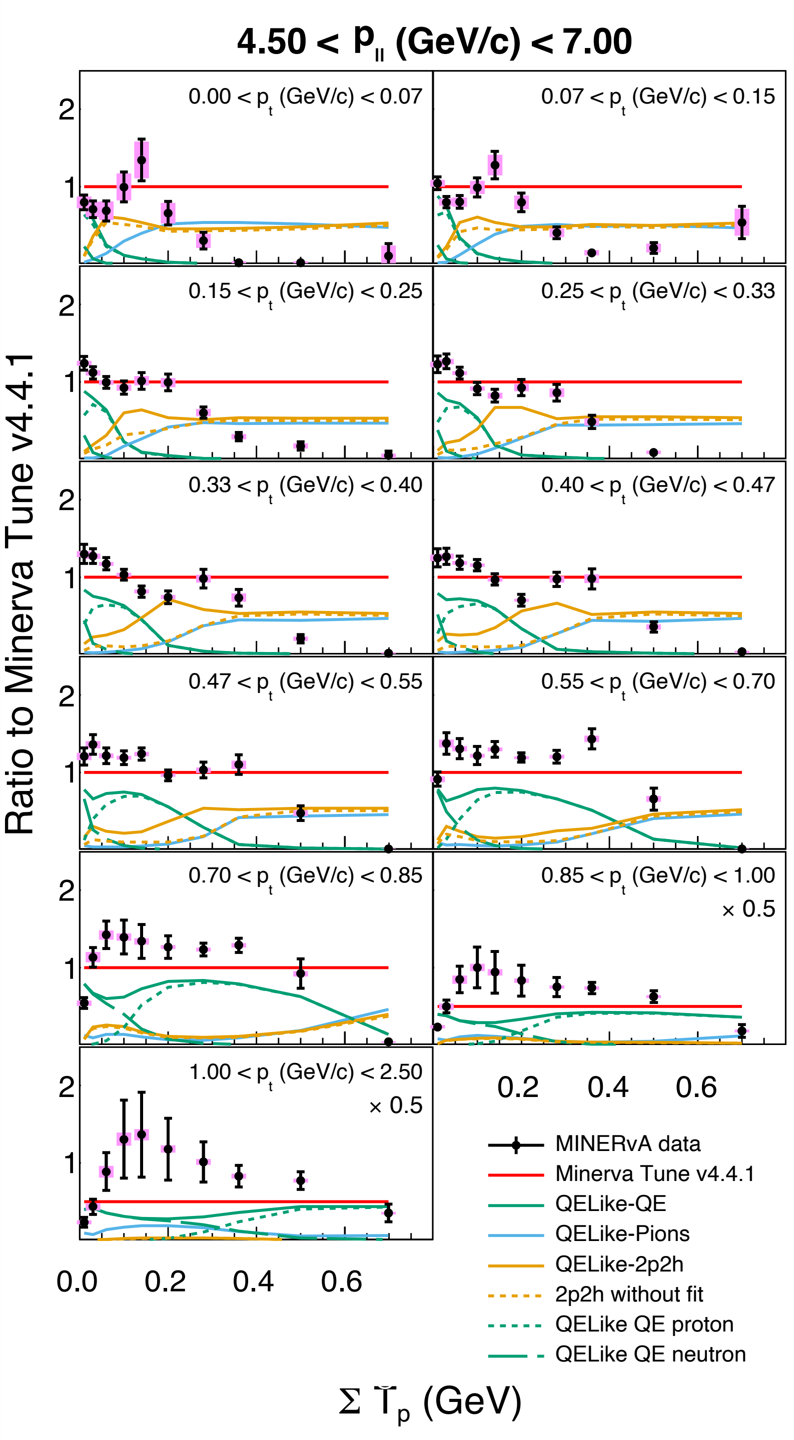
- Lots to see here.
- The trends we see are independent of $p_\parallel$, suggesting they are not strongly energy dependent.
- Easier to break it down in a single bin of $p_\parallel$



RESULTS: CC0π ΣT_p, p_T, $p_{\|}$

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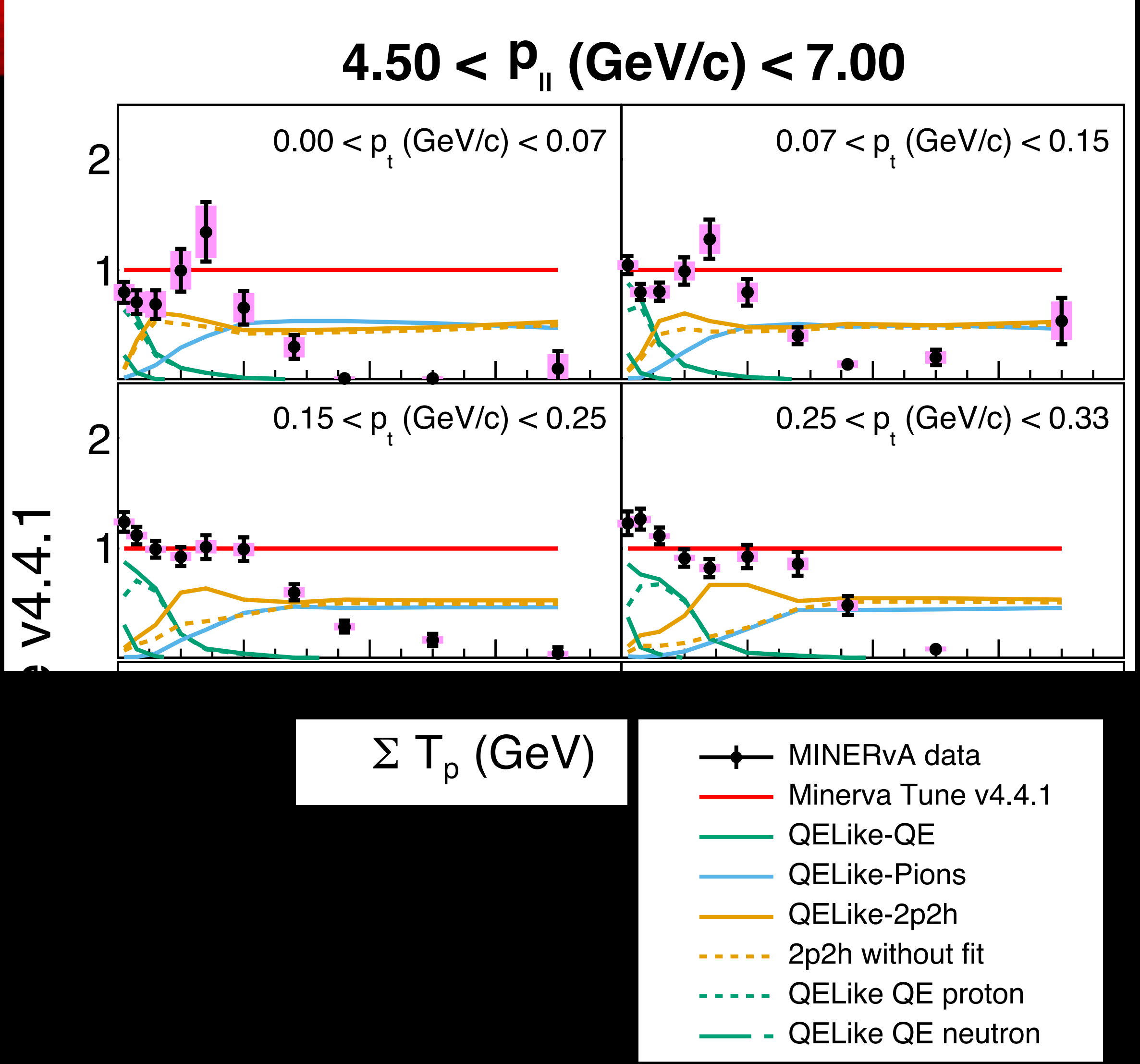
- The biggest change in cross-section, though not in the ratio, are the small deviations just above the QE peak.
- Low p_T high ΣT_p events predicted by the model as 2p2h and stopped pions are almost completely absent in the data.
- Highest p_T low ΣT_p events, events where the leading proton's energy ends up as neutrons through final state interactions, are also very overpredicted.

RESULTS: CC0π ΣT_p, p_T, $p_{\|}$



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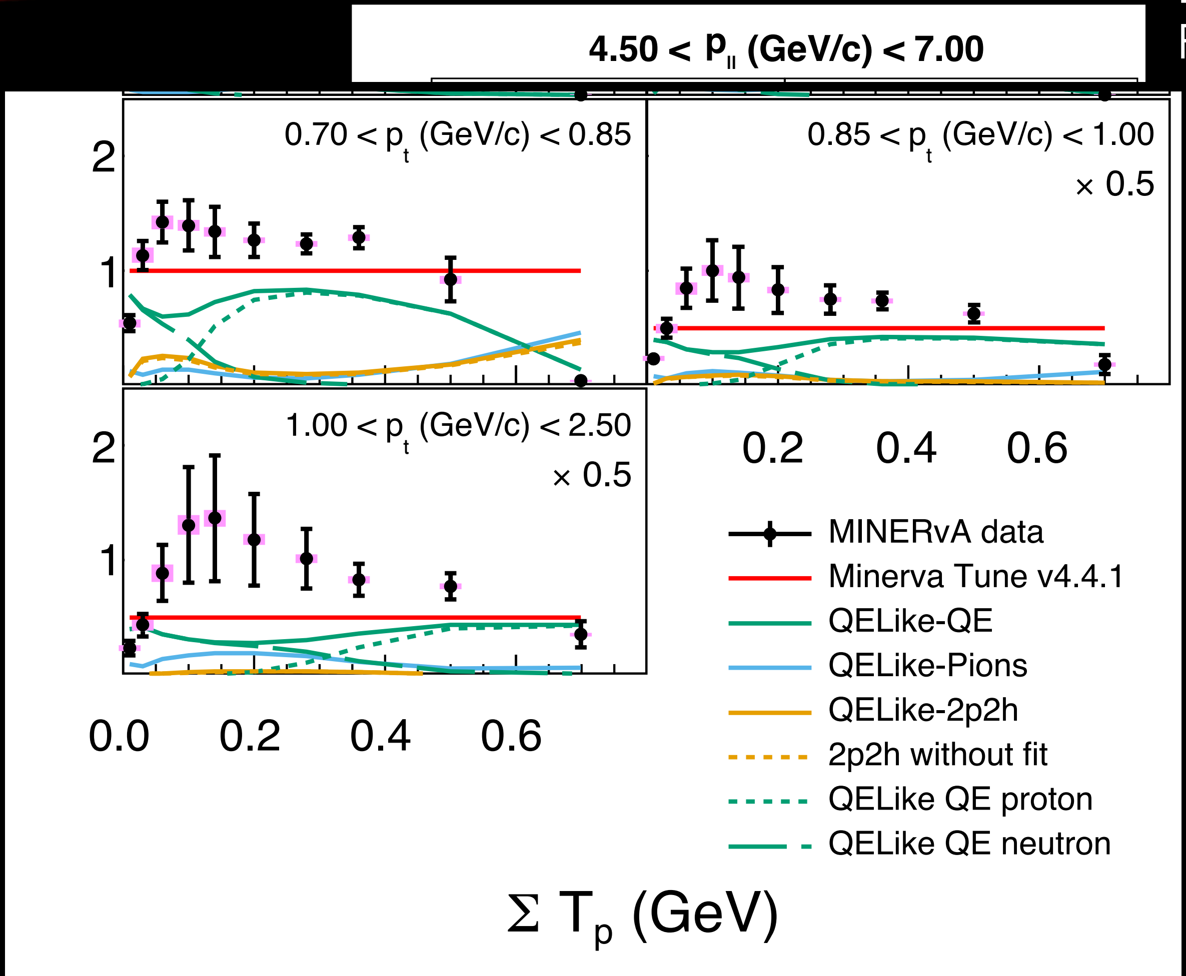

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ANOTHER VISUALIZATION OF CC0π ΣT_p, p_T, $p_{||}$

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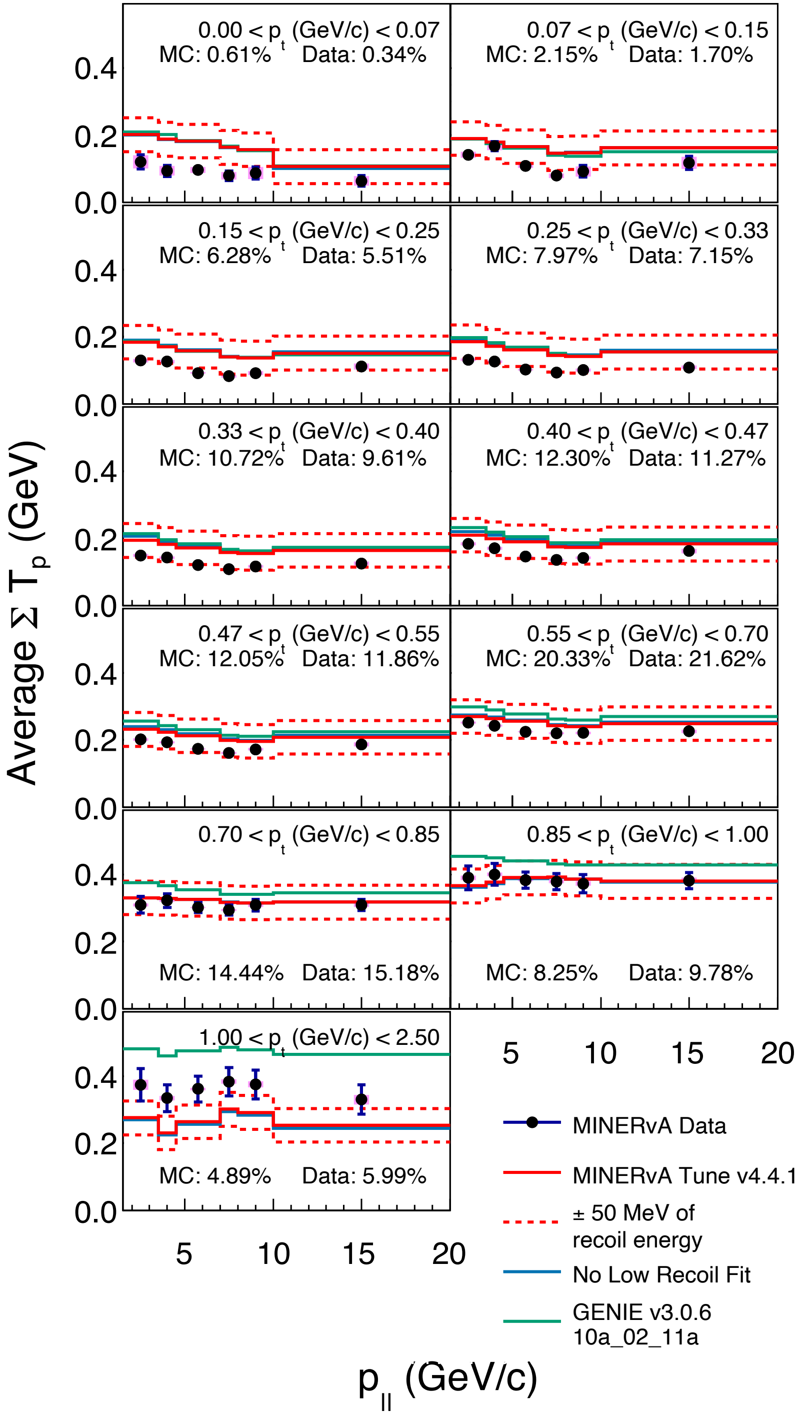
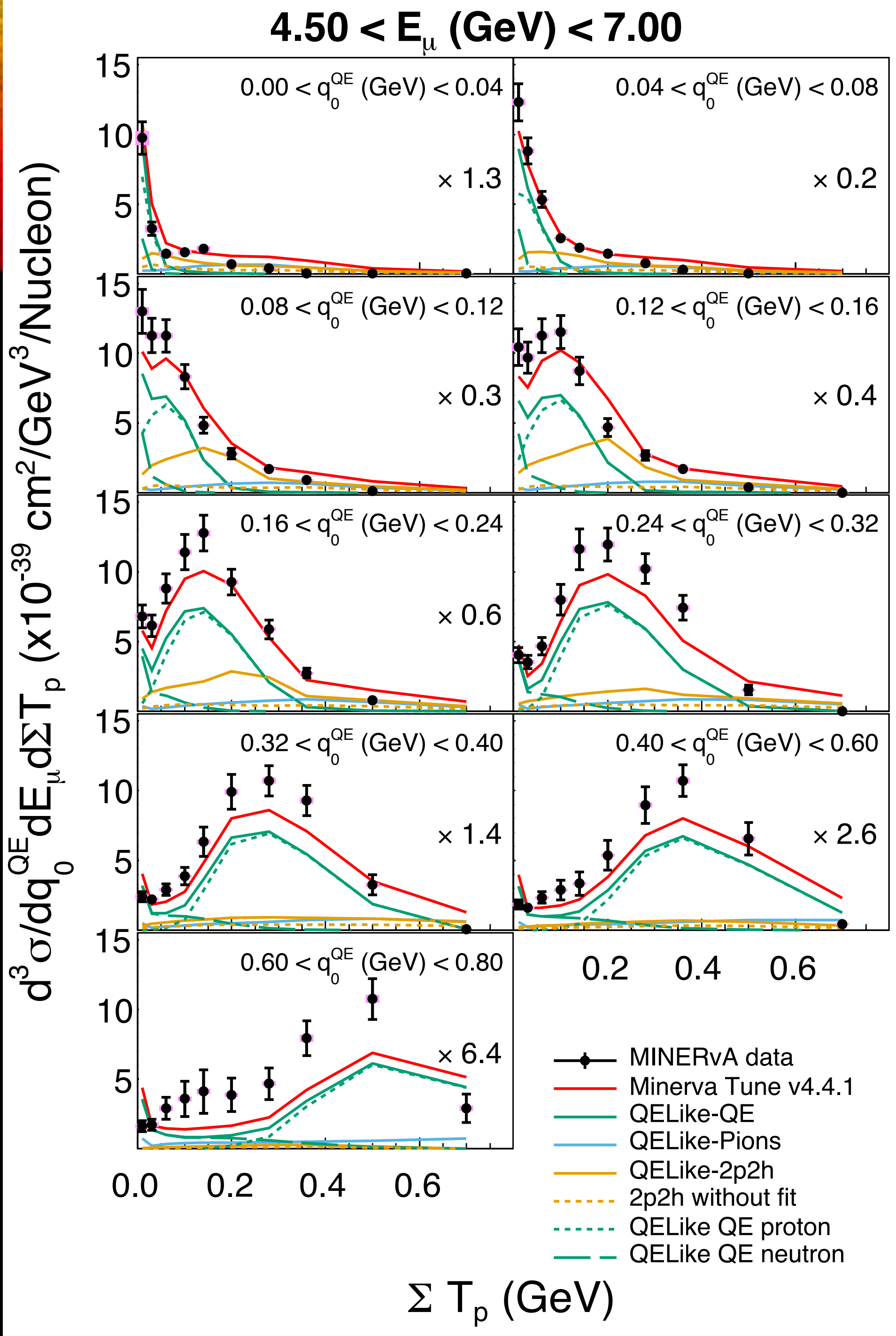


- The first and second discrepancies are the biggest and potentially most important effects in cross-sections: large parts of the rate shows up at a given p_T with a different recoil than expected.
- Problem for interferometry experiments?
  - In T2K (and future Hyper-K) p_T is used to measure the recoiling energy by two body quasielastic kinematics.
  - In NOvA and DUNE, the visible recoil is measured. And SBN can do both.
  - Apparently, these two won't agree.
- Recoil is 50 MeV too high, until high Q^2. No model we checked sees anything like this discrepancy.

ANOTHER VISUALIZATION OF CC0$\boldsymbol{\pi}$ ΣT_p, p_T, $p_{\|}$



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- Problem for oscillation experiments?
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  - In NOvA and DUNE, the visible recoil is measured. And SBN can do both.
  - Apparently, these two won’t agree.
- We can actually directly compare the two types of energy measures: recoil in bins of q_0^{QE}.
- Agreement with the model is, as expected, poor.
  - Peaks are missed at low p_T.
  - High side tail is overestimated and low side is underestimated.

NEUTRINO INTERACTIONS FOR PRECISION OSCILLATION

- This, as I hope my one of many example convinced you, is a lot of detailed work.
- As noted, it’s insufficient to make the measurements, but the theory interpretation is also critical.
- Here the goal is not fundamental physics, but building of an accurate nuclear model…

  … to support the fundamental oscillation physics we want to do.

- Perhaps I’ve been overcompensating from my NuTeV experience?
- You’ll have three lectures next week to help you decide.

CONCLUDING THOUGHTS

- I hope I've given you some framework for thinking about what we mean by "precision" measurements and why we pursue them.
- Some of the experiments I've described here have illustrated the sometimes stark differences between goals and results in these measurements.
  - There may be some cautionary tales.
  - Then again, if we knew the answers when we started, why do the experiment?
- Precision measurements will continue to provide some of the most important inputs to our understanding of fundamental particles and fields and how they influence our Universe.

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- Precision measurements will continue to provide some of the most important inputs to our understanding of fundamental particles and fields and how they influence our Universe.
    - All you have to do is to pick the right ones in your future careers. ☺