FROM QUARKS TO NEUTRINOS

Adventures in Particle Physics

The scene in 1972

- Nuclear physics at various universities, CRNL
  - TRIUMF cyclotron under construction

- Just a few small university groups (+NRC) of particle physicists
  - Analysing bubble chamber film
  - Participating in a couple of experiments at US labs

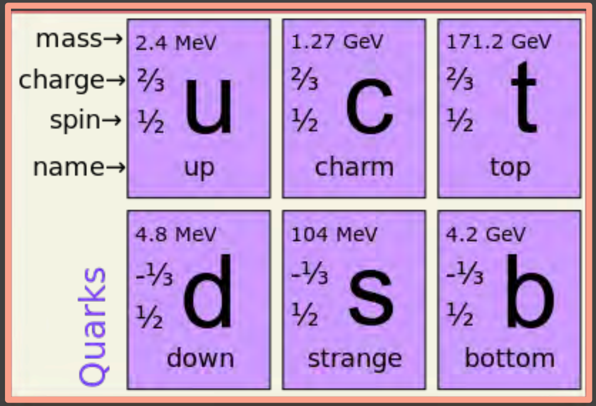
- Attempt to help fund/build Fermilab failed
  - Led to the formation of IPP (1971) to better coordinate particle physics in Canada

Particle physics at the time

- Still much exploration of new baryon and meson resonances – "particle explosion" of the 60s
- But, underlying "partons" had been found at SLAC

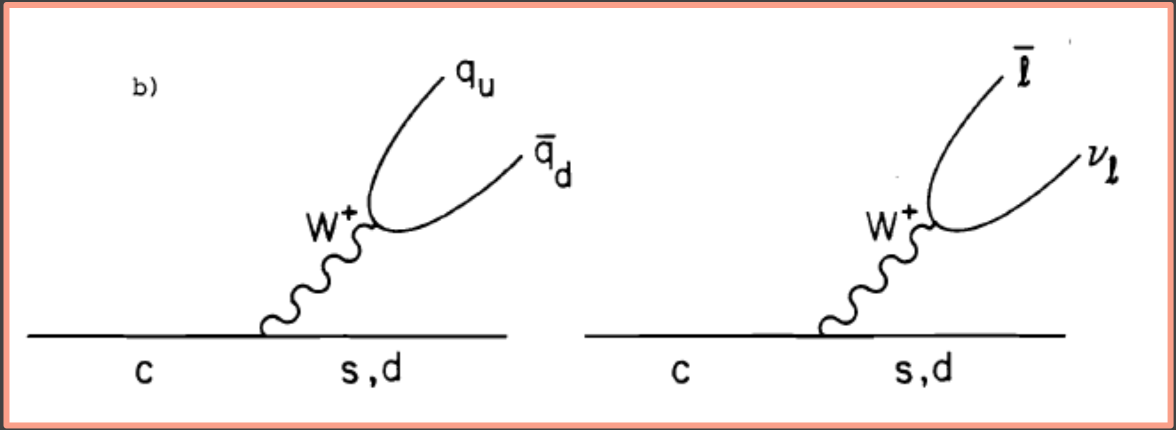
  Electroweak theory developed, QCD coming
- J/psi high mass narrow resonance – 1974
  - Bound state of $c\bar{c}$ - discovery of the 4th quark!!

  - A flurry of experiments at Fermilab racing to measure charm
    - Some more successful than others…!
    - My involvement: E531 and E516/691



Charm lifetimes

- Naively, all charmed particles would have the same lifetime (~ 10^{-13}s): "spectator" weak decay diagram

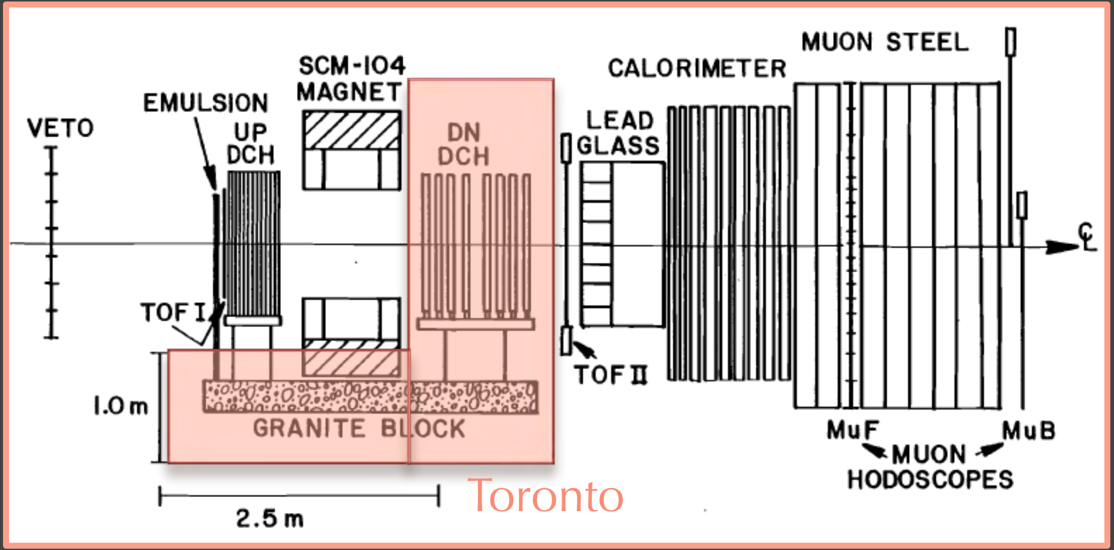


- Wrong! The other quark(s) in the particle and gluons from the strong interaction being exchanged mess things up
  - e.g., ratio of $D^+(c\bar{d})$ to $D^0(c\bar{u})$ lifetimes is ~3.

McGill, Ohio State, Ottawa, Toronto, Fermilab, Japan (Nagoya +), Korea

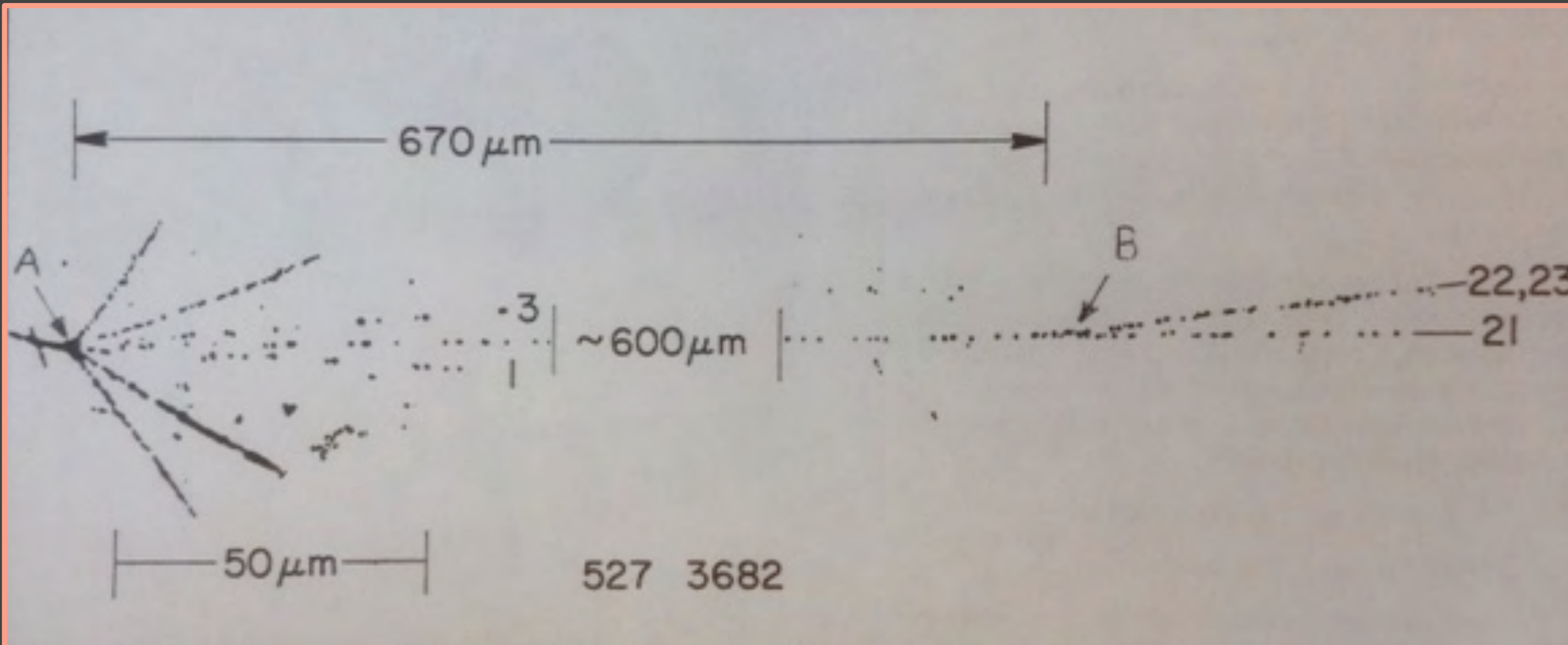
E531

$$\nu_\mu N \rightarrow (\mu^-)cX$$



- Emulsion target
  - Measure short (~10s of microns) decay lengths of charm
- First experiment with lifetime measurements
  - 1979 ~ 1986
- Keys to success:
  - Precision alignment system
  - Accurate tracking from spectrometer back to emulsion
    - Fiducial sheet of emulsion at downstream end of stack
    - Changed every 2 days: reduced track density, easier matching

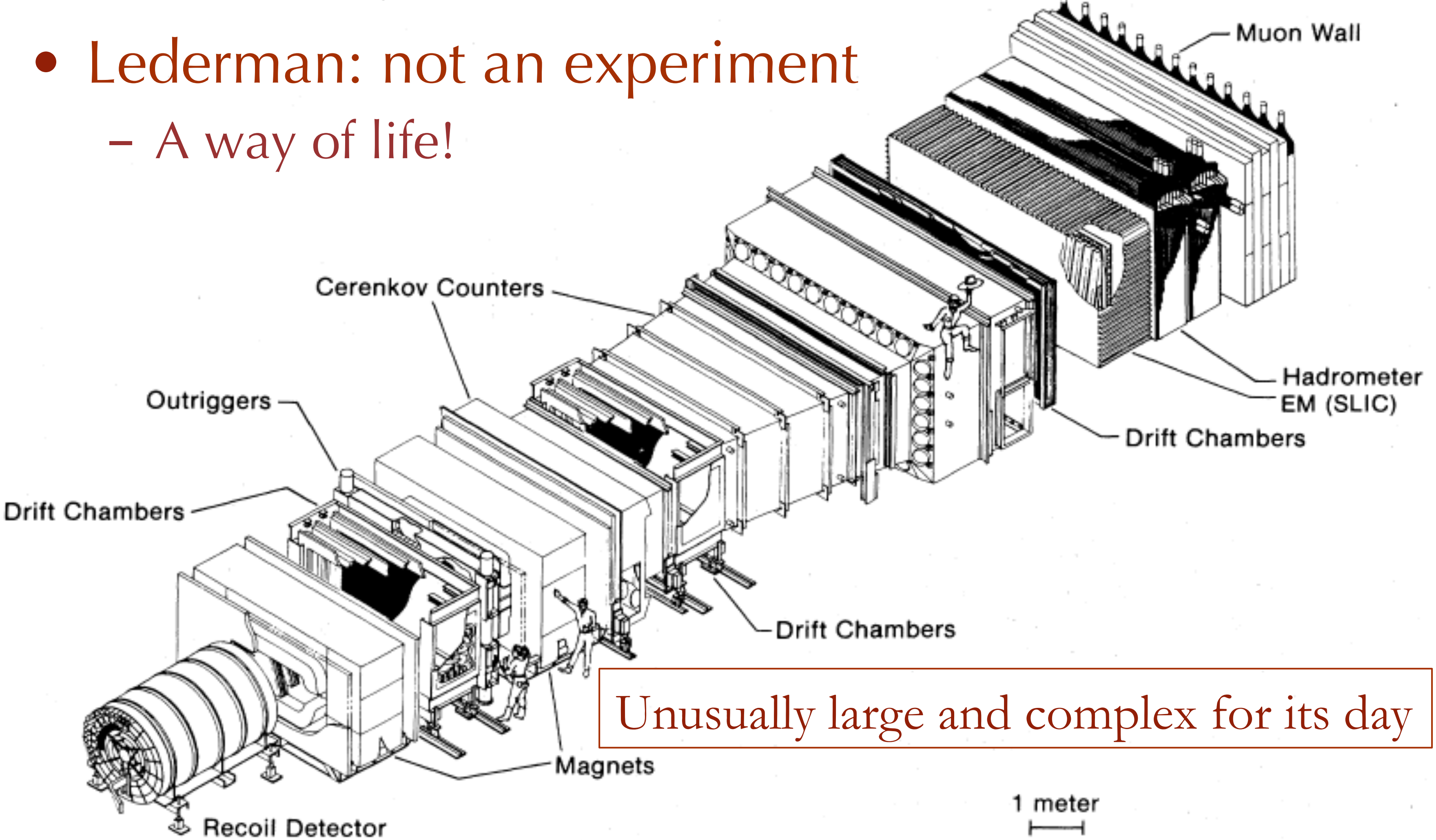
E531 charm decay event



Carleton, Toronto, Fermilab, Colorado, UC Santa Barbara

E516/691 photoproduction of charm

- Lederman: not an experiment
  - A way of life!

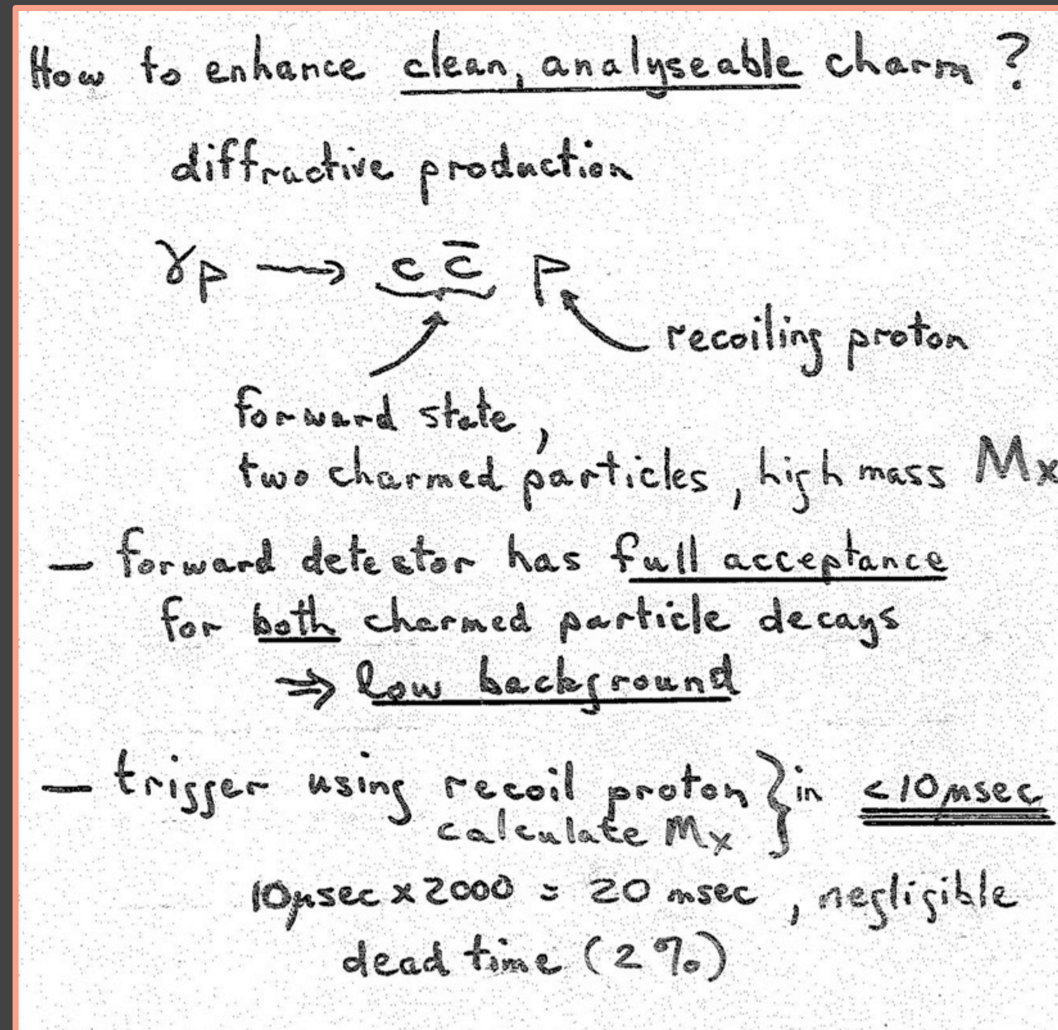


Unusually large and complex for its day

The trigger

- Our simple idea:

- Designed a fast (10μs) and powerful trigger processor system
  - Modular
  - Logic units
  - Programmable memory lookup units
  - Data driven



How to enhance clean, analyseable charm ?

diffractive production

$\gamma p \rightarrow c\bar{c}\ p$

forward state, two charmed particles, high mass M_x ; recoiling proton

— forward detector has full acceptance for both charmed particle decays

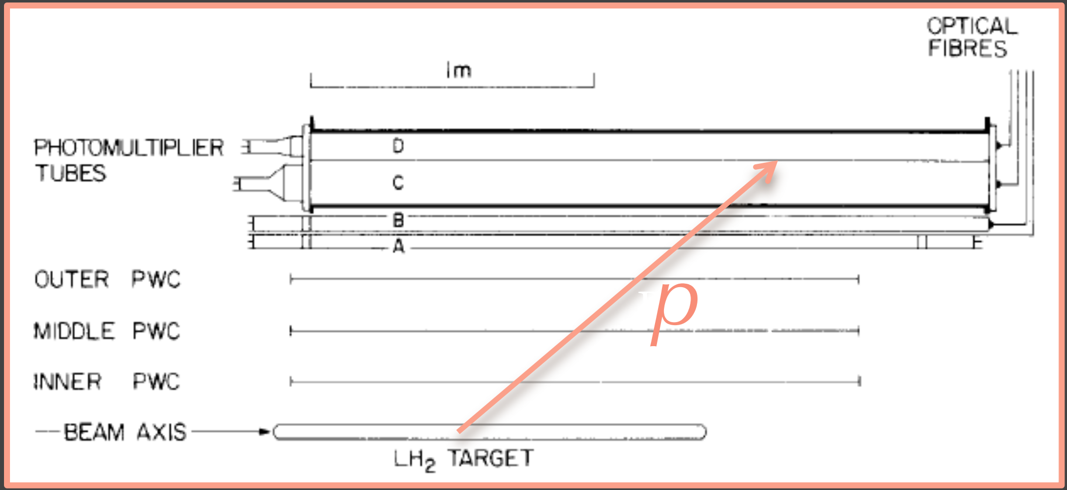
⇒ low background

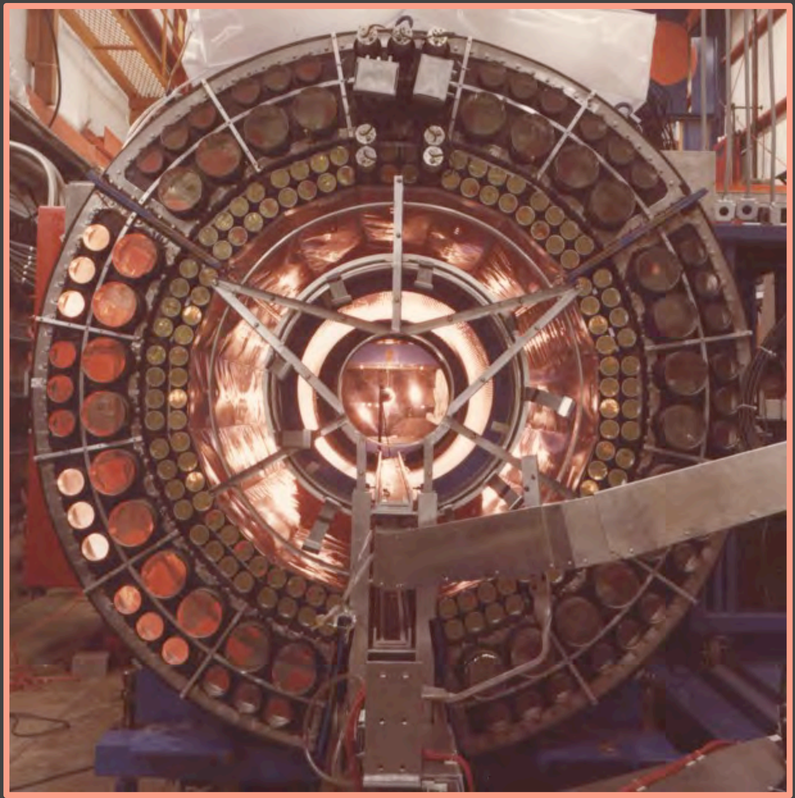
— trigger using recoil proton, calculate M_x } in ≤ 10μsec

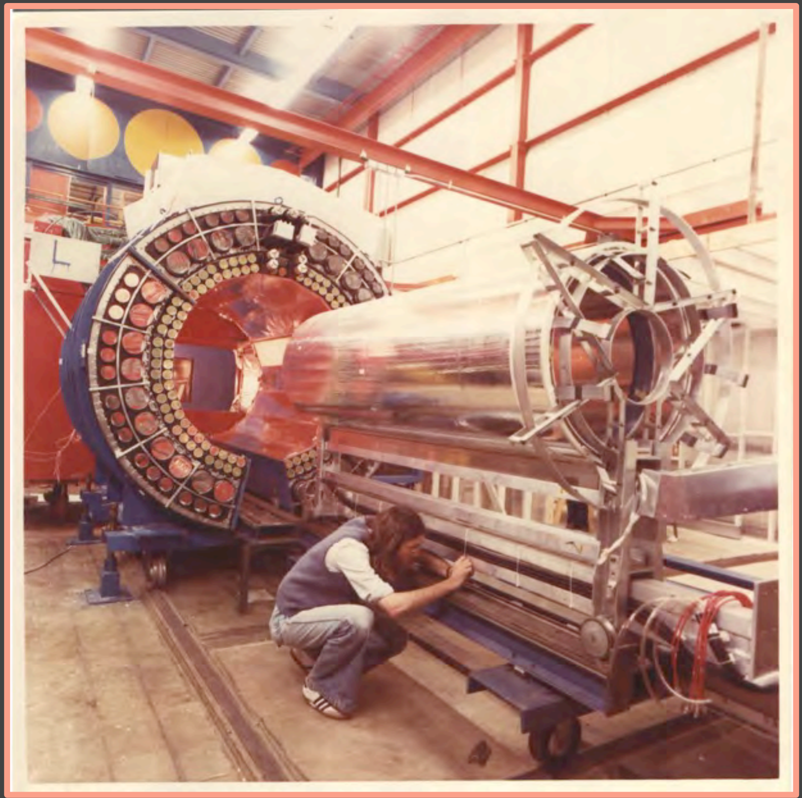
10μsec × 2000 = 20 msec, negligible dead time (2%)

Recoil detector

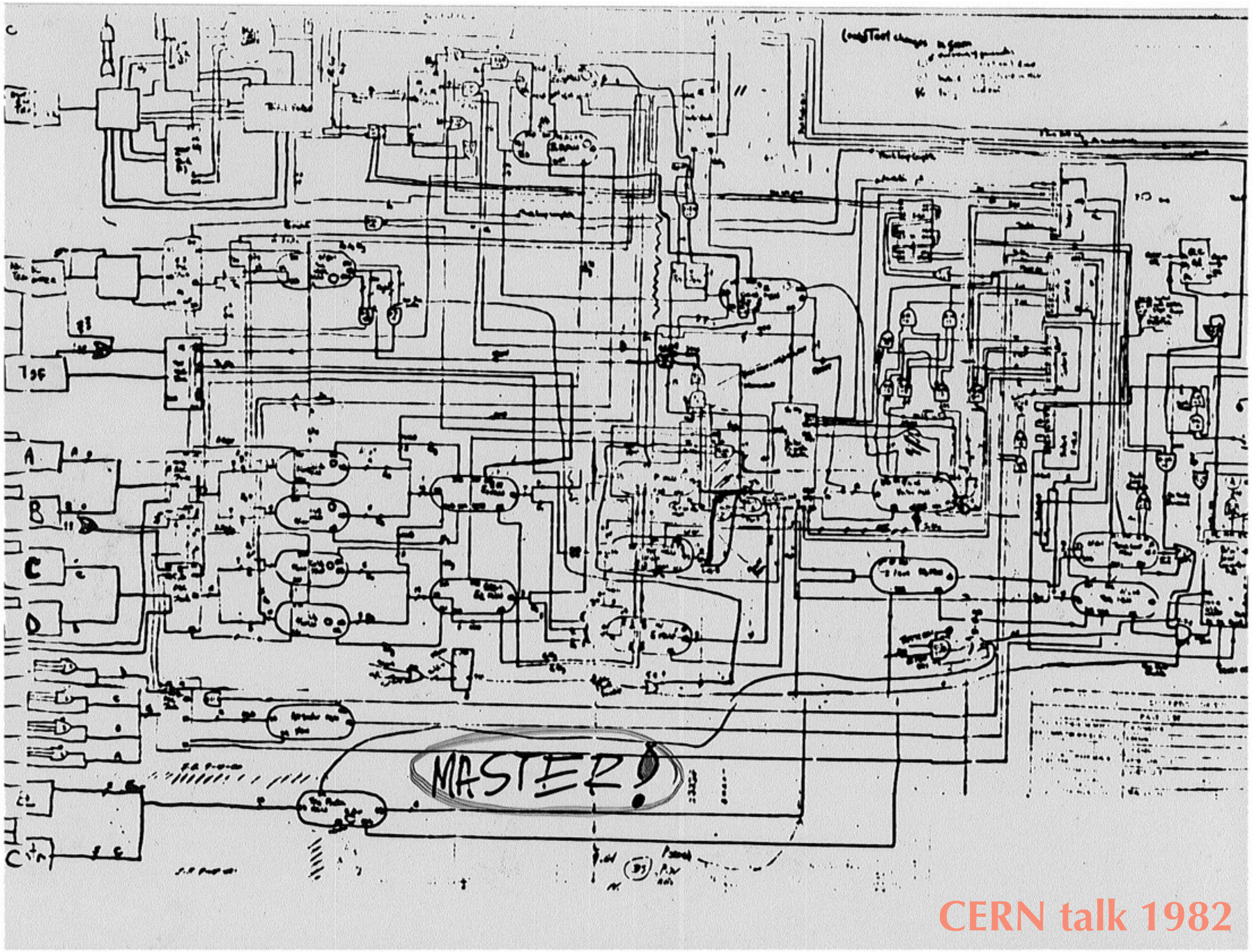
Built at Toronto, Carleton







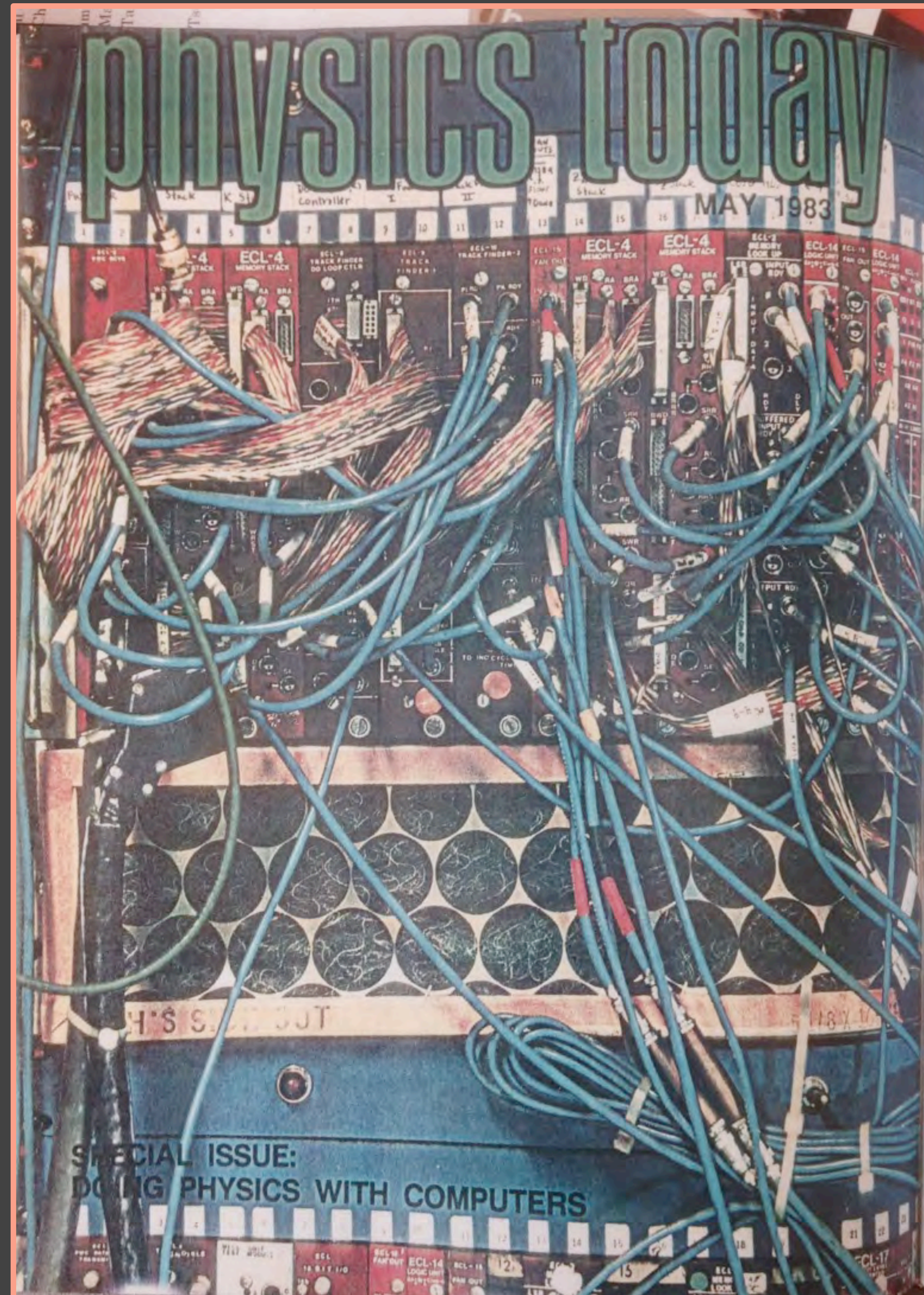
Trigger schematic (but it worked ...!)



CERN talk 1982

May 1983

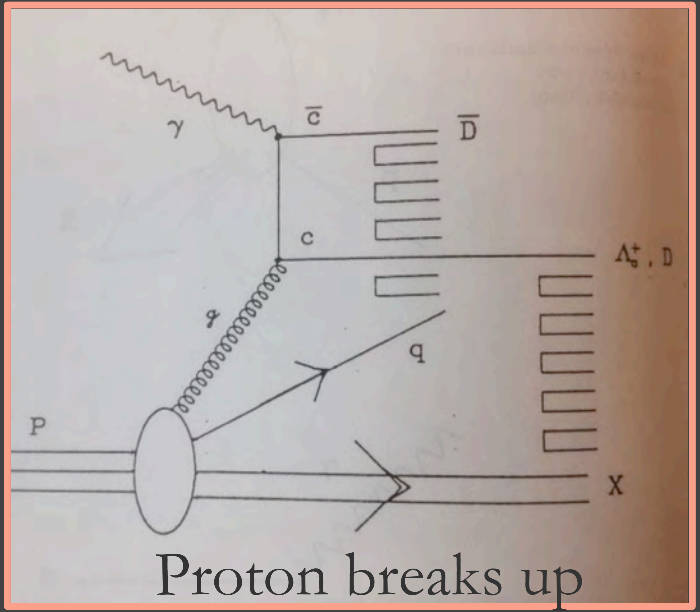
Featured on cover of Physics Today



Calamity (and almost ruin …)

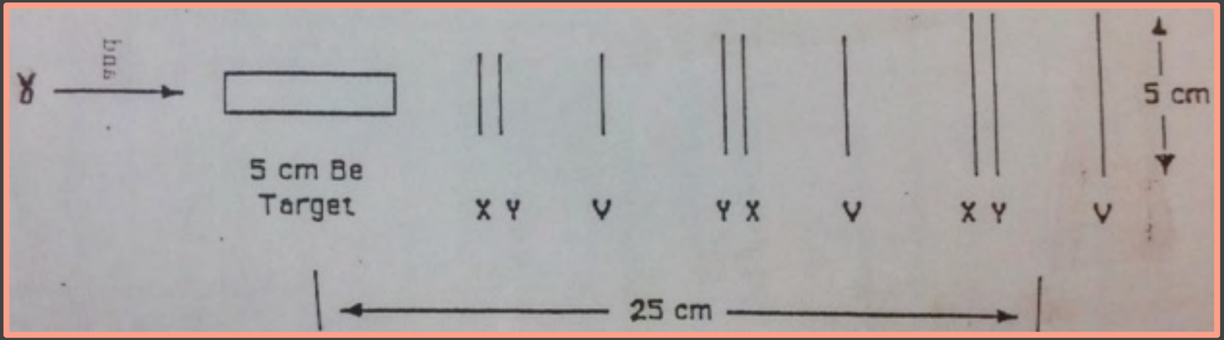
- Much less charm than expected was found in the data!
  - A tense time in our collaboration (1981~83)
  - Our understanding of QCD was naïve at the time
    - production mechanisms more complicated:

- But, we were saved (whew!)
  - Flexible trigger system
    - Rearrange to looser inclusive trigger based on high transverse mass
  - New environment (the Tevatron)
    - Still a small dead-time due to much better duty factor
  - New technology



Proton breaks up

- Silicon microstrip detector (SMD: “electronic emulsion”)
  - Shamelessly copied this new technology developed at CERN



10μm resolution

  - Recorded an unprecedented amount of data in 1985-6
- Parallel computing: developed the first “computer farms”
  - Cheap! based on commodity processors
  - data reconstruction otherwise impossible

Steve Bracker, George Luste involved from Toronto

- The first spectacularly successful experiment using SMDs
  - Found ~ 10,000 charmed particle decays
    - By far the most precise lifetime measurements
  - Later: x50 speed DAQ + hadron beam
    - Vast amounts more data into the 1990s
- Came to be known as one of the top 3 experimental programs in the history of Fermilab

The other race at Fermilab …

George Luste
1940-2015

fermi national accelerator laboratory

Operated by Universities Research Association Inc.
Under Contract with the Energy Research & Development Administration

Vol. 8 No. 38 October 8, 1976

CANADIANS WIN 1976 CANOE RACE

Three University of Toronto scientists were on the top two teams in the 1976 Main Ring Canoe Race held Saturday, October 2, at Fermilab. Their colleague, John Cumulat, the remaining team member, is from the University of California at Santa Barbara. The four are all collaborators on Experiment #25 in the Proton Area.

The Luste-Cumulat team came in first last Saturday, in 45 minutes, 19 seconds, bettering by eight minutes the record of 53:23 set in 1975 by the Prentice-Martin combination.

Prentice and Martin pushed the winners all the way, coming in second at 48:06.

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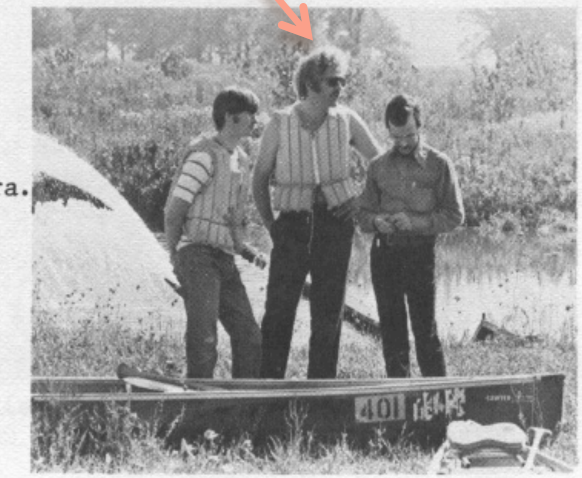


...(L-R) Winners J. Cumulat, George Luste and E-25 colleague Roland Egloff watch second place team approach finish line...

George's bowman in 1979

...Weary, wet and shoeless, a competitor climbs ashore at the finish line...

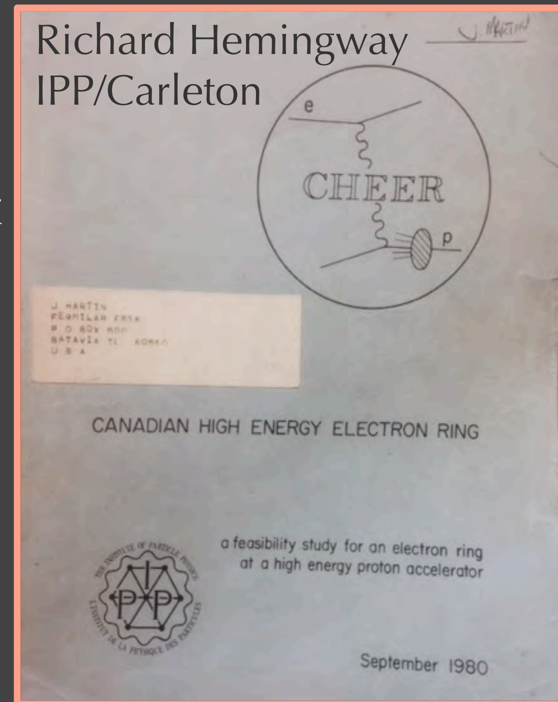
Report to NSERC on HEP (1982)

- HEP experimental community: still small
  - 5 IPP scientists, 13 university professors, 4 NRC scientists
  - \$2.7M from NSERC (82/83)

  – "It is to the credit of both the individual physicists and IPP that the quality of the Canadian experimental HEP program has improved significantly and attained recognition on an international scale and that the program has coalesced into a few highly visible experiments under the guidance of IPP."

1980s – dramatic new developments

- 1980 IPP CHEER proposal
  - *ep* collider at Fermilab – well reviewed but did not go forward – busy with $p\bar{p}$
- Led to invitations and proposals for:
  - HERA & ZEUS at DESY (*ep*)
  - OPAL at LEP (e^+e^-)
- Also, from the nuclear community:
  - SNO proposal for Sudbury (solar ν)



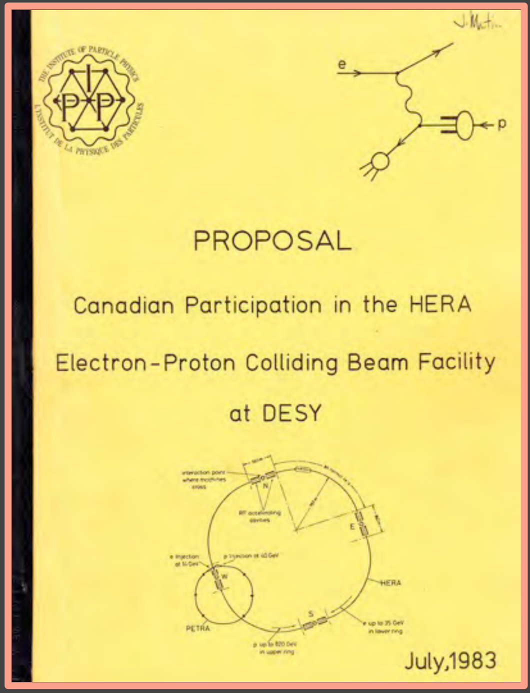
Richard Hemingway
IPP/Carleton

- Remarkably, all approved, big science, big new $$
  - The young NSERC had confidence in us!

HERA *ep* collider at DESY (Hamburg)

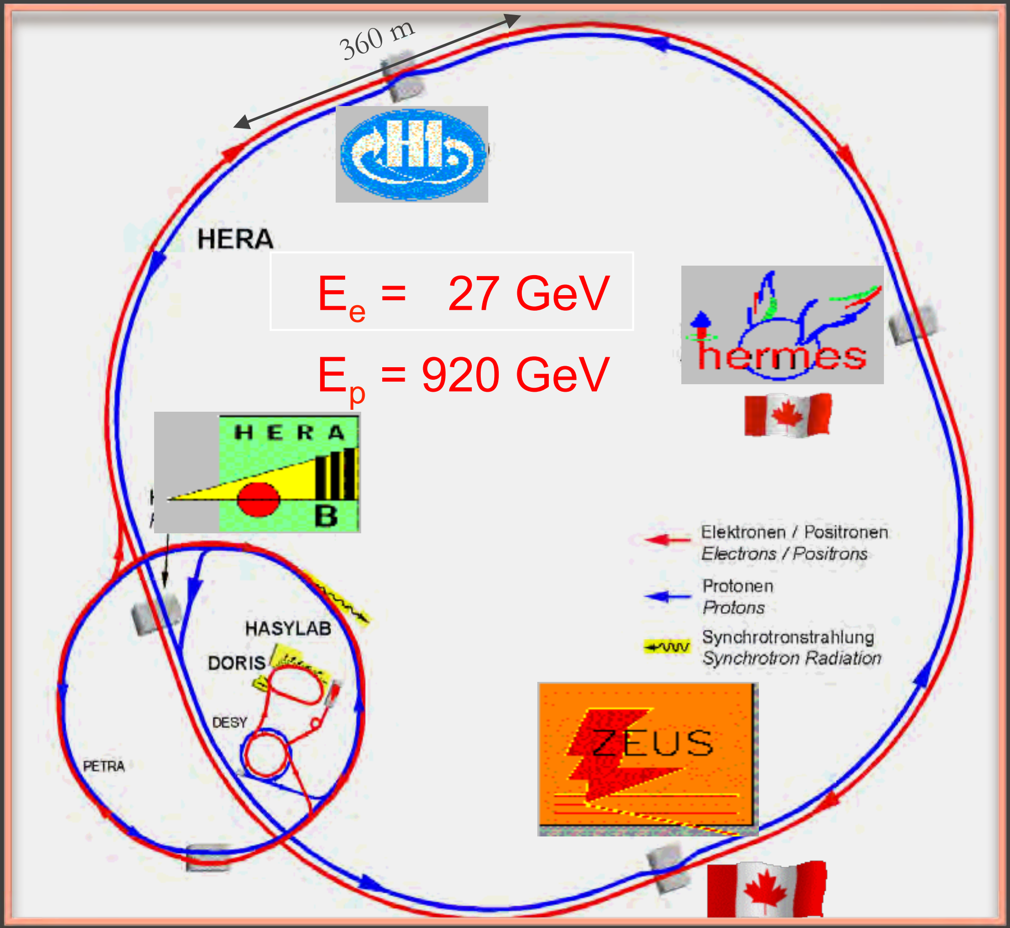
- Proposal to NSERC for RF (CRNL), magnets, transfer beam-line (TRIUMF)
    - Approval end of 1983 - relatively small ($5M) but significant!
        - **First country funded, led directly to approval in Germany**
        - **Eventually 11 countries**

- "HERA model":
  - contributions of accelerator components
  - human resources during construction
  - 1/3 cost from outside Germany

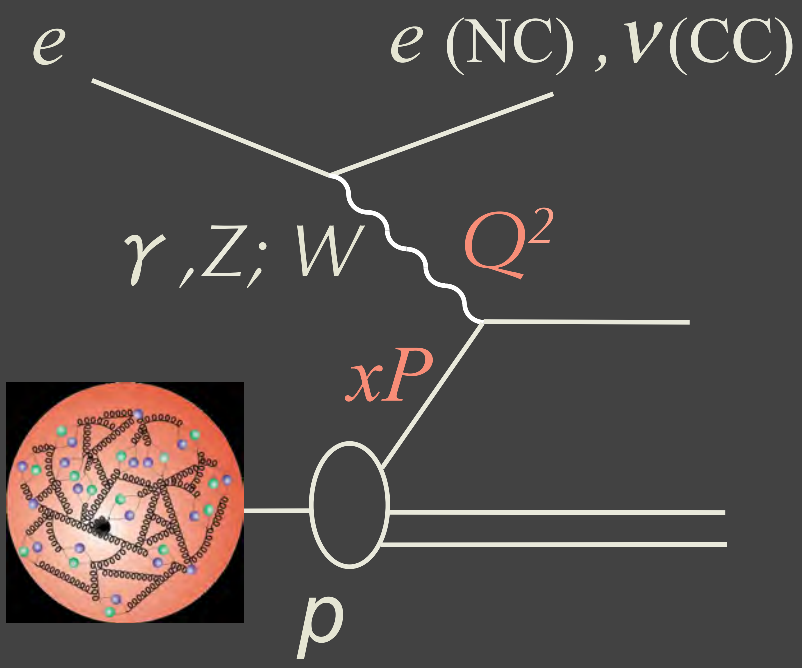


- Founding members of ZEUS experiment
- NSERC approval for calorimeter, trigger
    - MIG grants 1986-7 (~$11M)
        - Manitoba, McGill, Toronto, York

ZEUS at HERA



HERA 1992-2007

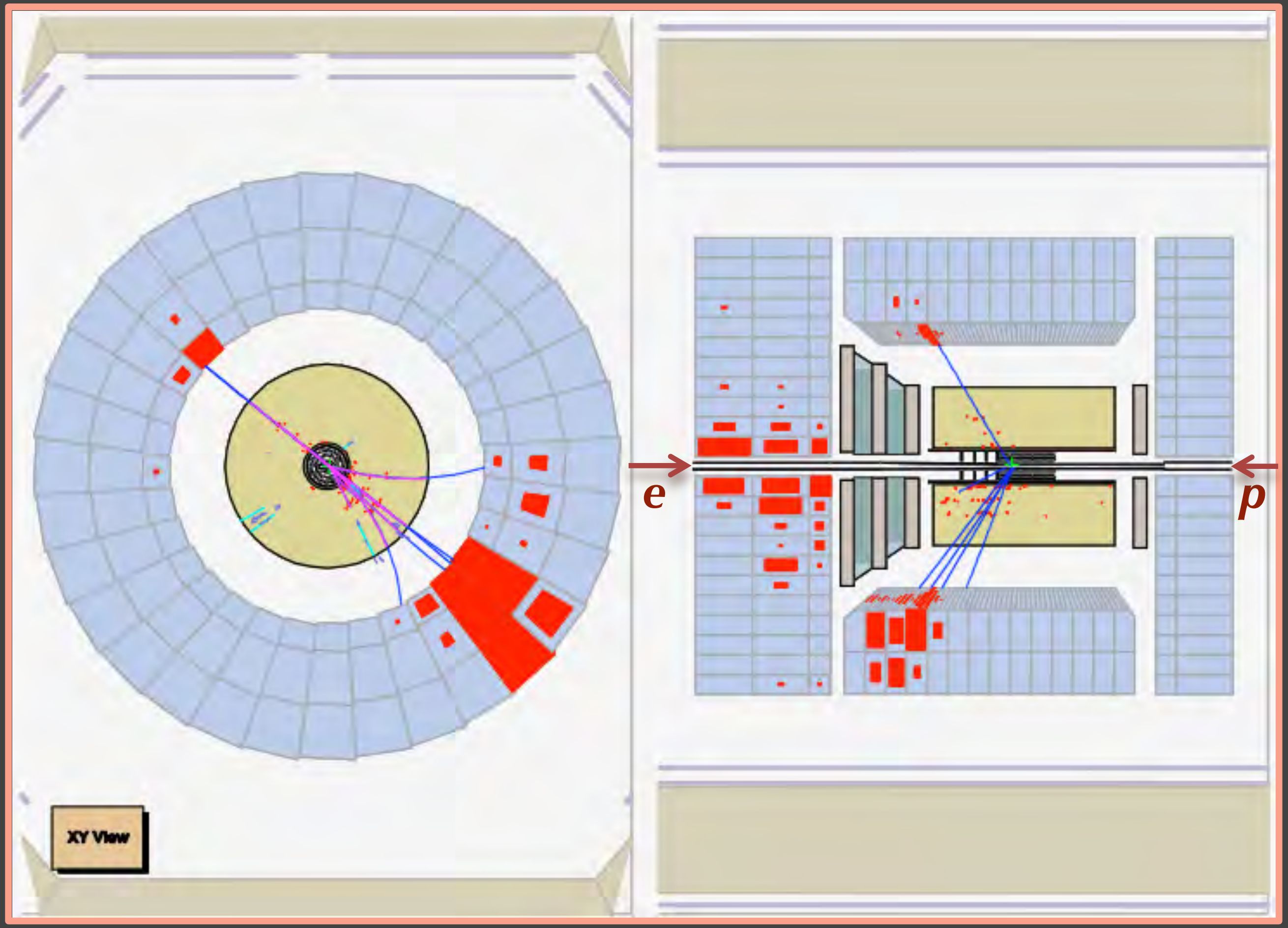


At HERA: largest Q > 200 GeV

from $\Delta p \Delta x \approx 0.2\,\text{GeV fermi}$,

probe to < 10^{-18} m

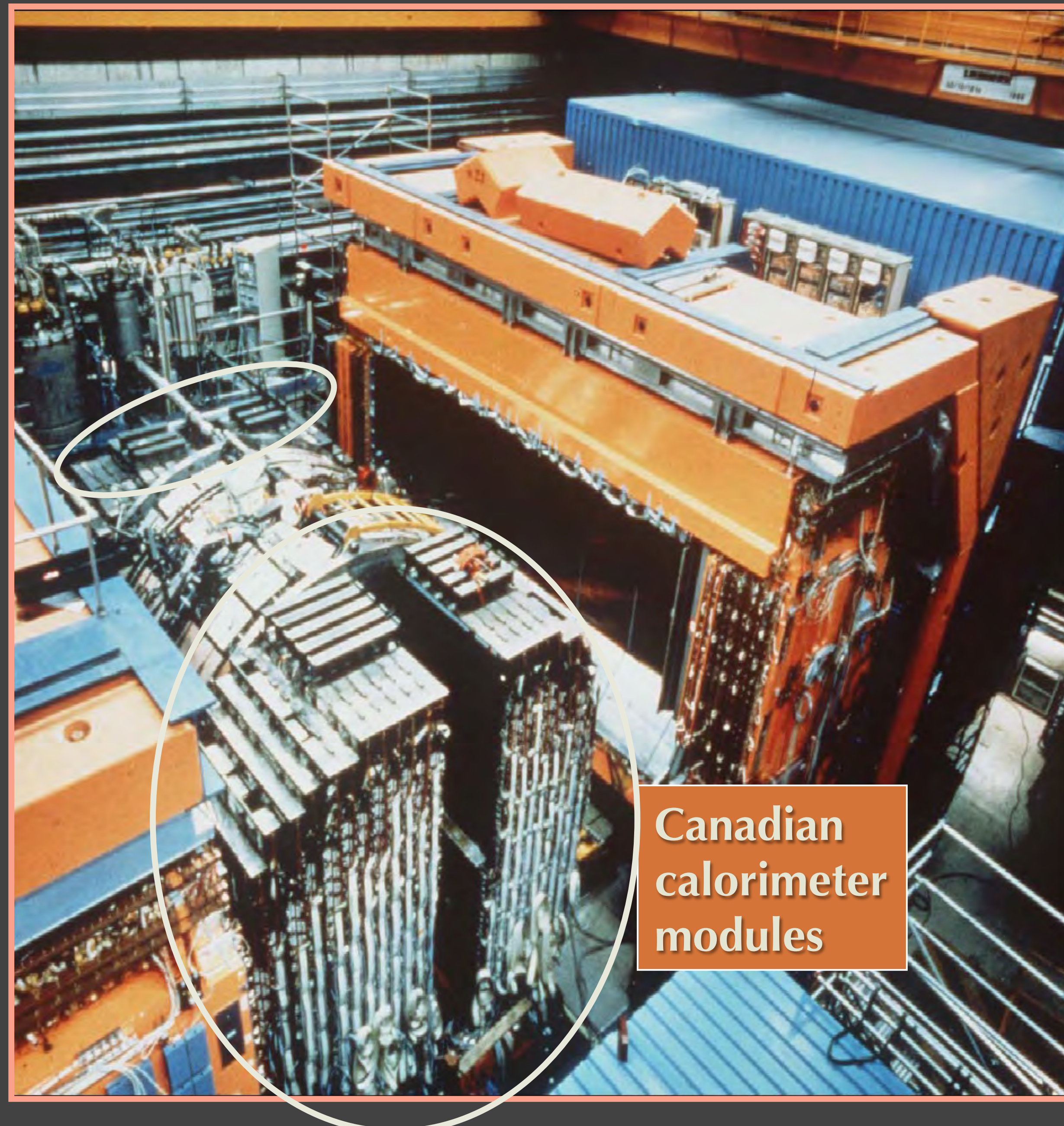
A high Q^2 "neutral current" event



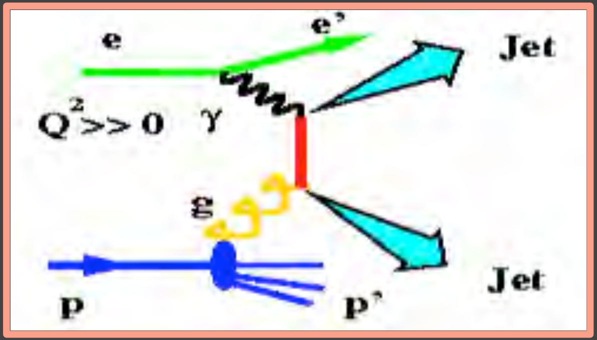
ep → e + jet + proton remnant

Calorimeter

- DU/scint "sampling" calorimeter
  - Alternating layers of absorber(DU) and detector (scintillator)
  - 10 tonne modules
  - 5 metres high



Why uranium?



- In hadronic showers, energy lost to breaking apart nuclei not sampled fluctuates event to event → poor energy resolution
  - $\sigma(E) = 60\%\sqrt{E}$ for a typical iron plate calorimeter
- Uranium seemed to do much better (60% → 35%) ??

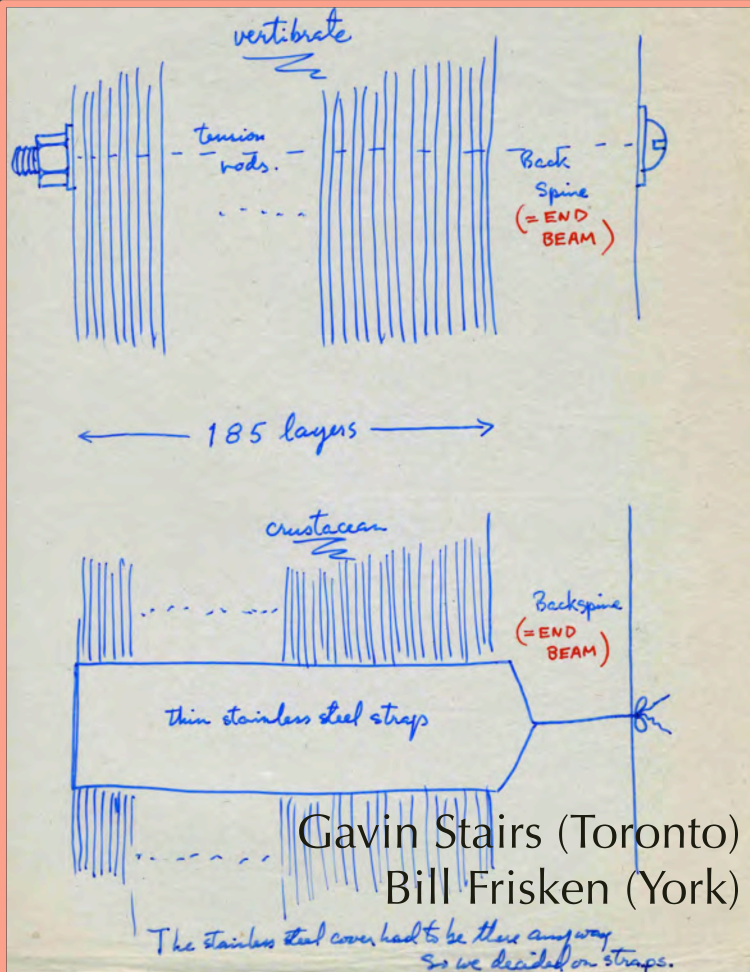
ZEUS: zero understanding of uranium scintillator

- Hanno Bruckmann (nuclear physicist, ZEUS) explained at the international calorimeter conference in California 1985:
  - Spallation neutrons from U breakup are proportional to binding energy lost
  - Neutrons "knock-on" protons in the hydrogen in scintillator – this gives a "compensating" signal (tune thickness of U to scintillator to get e/h =1)
- SLD (SLAC) planned DU-LAr calorimeter.
  - Bruckmann said no compensation: the neutrons just bounce off the big Ar nuclei, leaving no signal
  - **SLD abandoned DU that evening!!**

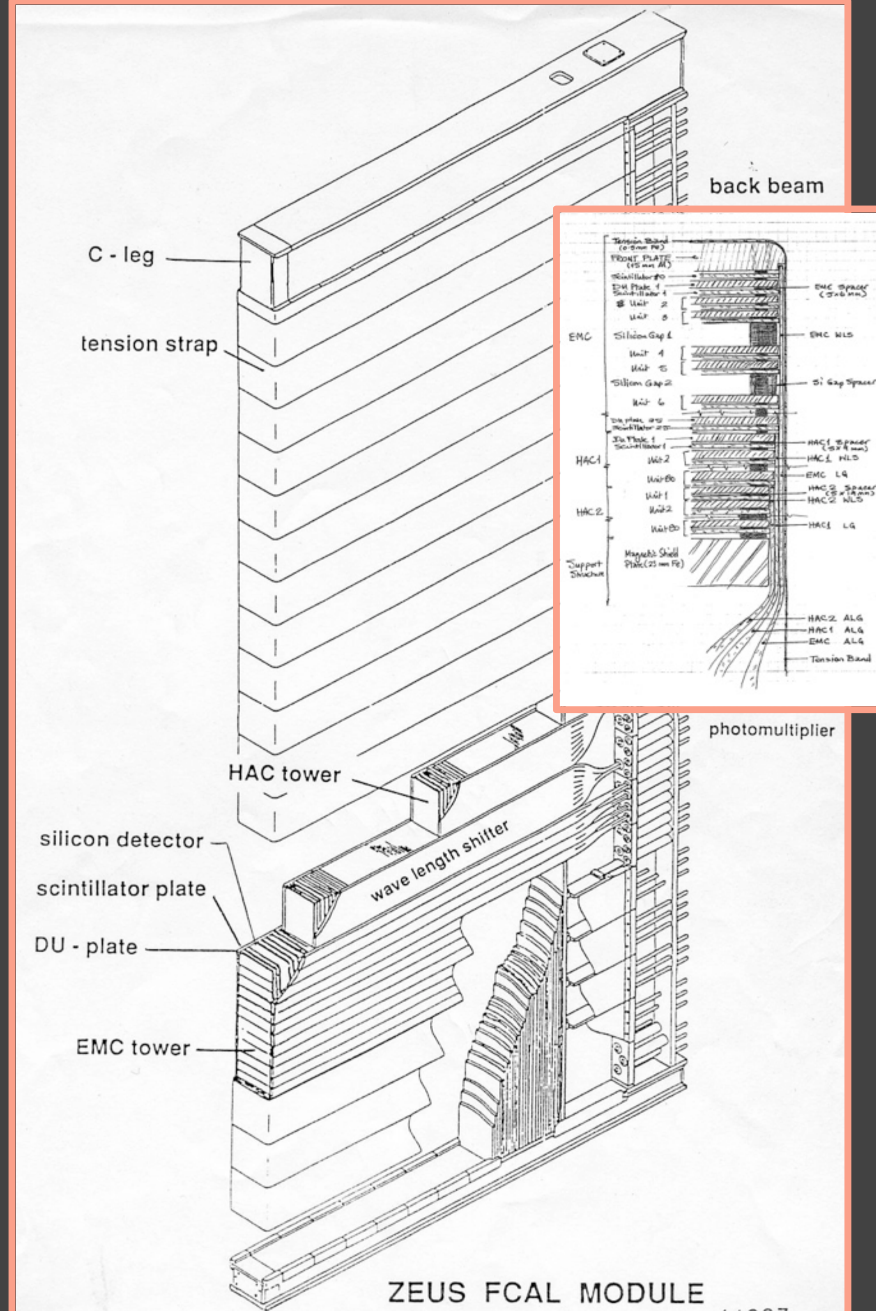
Aside: in 1995 we built a compensating Pb-scint. calorimeter to measure forward-going neutrons in ZEUS

Canadian design

A long saga to convince collaboration

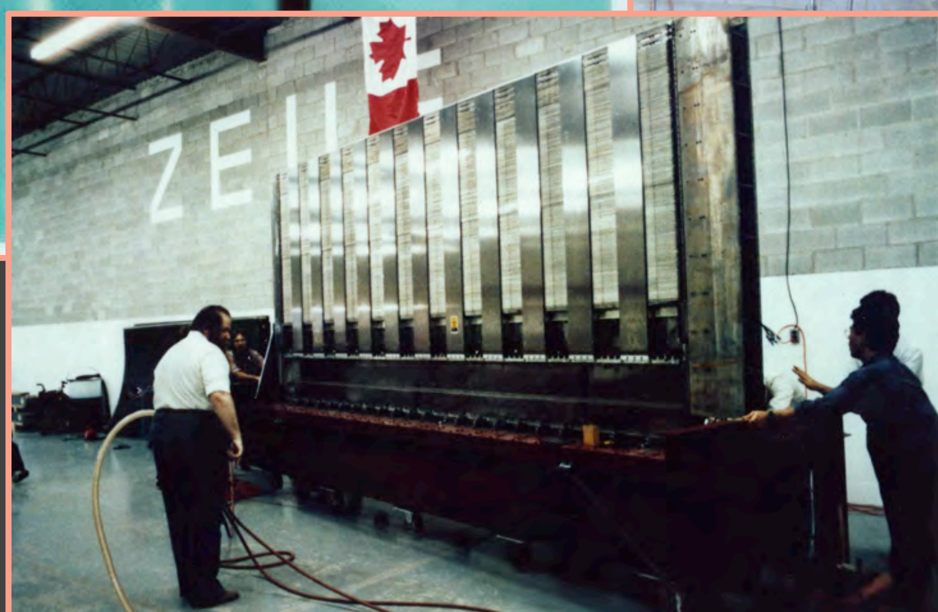


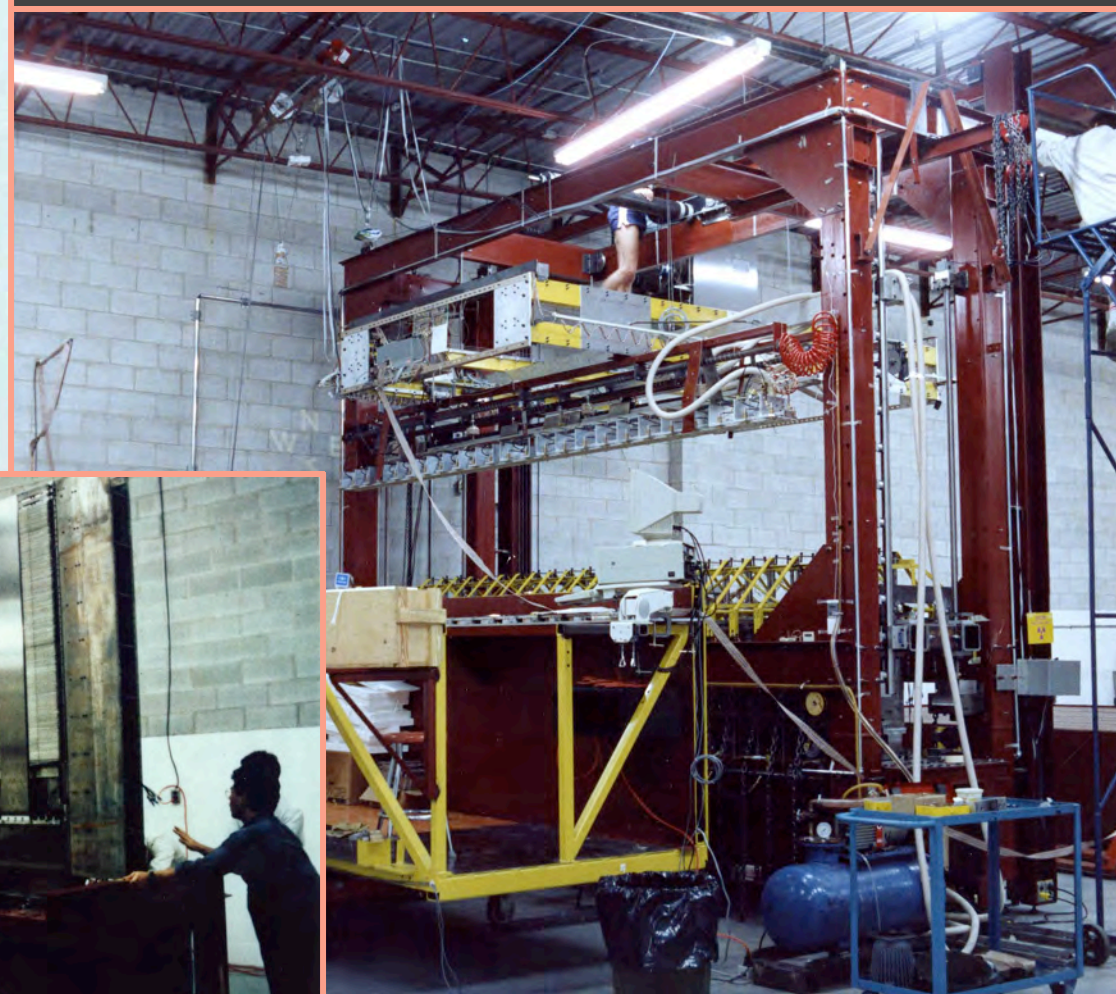
Gavin Stairs (Toronto)
Bill Frisken (York)



Were we crazy?

No space at universities
Built a lab in empty warehouse in Toronto suburb





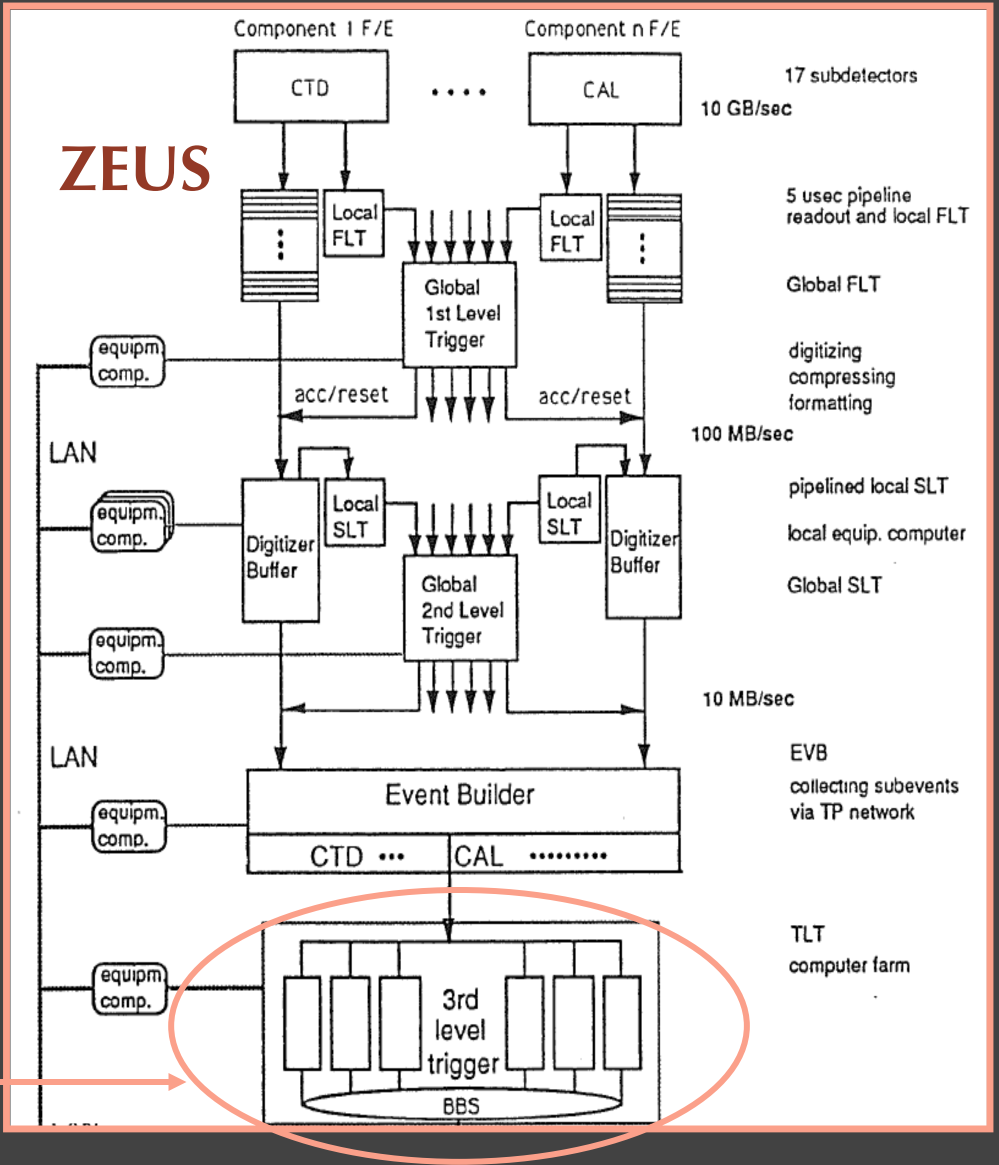
1986-90

The crew

Unique triggering

- First collider where parallel pipelines for data and trigger were developed
  - only 96 ns bunch separation
- LHC triggering heavily influenced by HERA experience

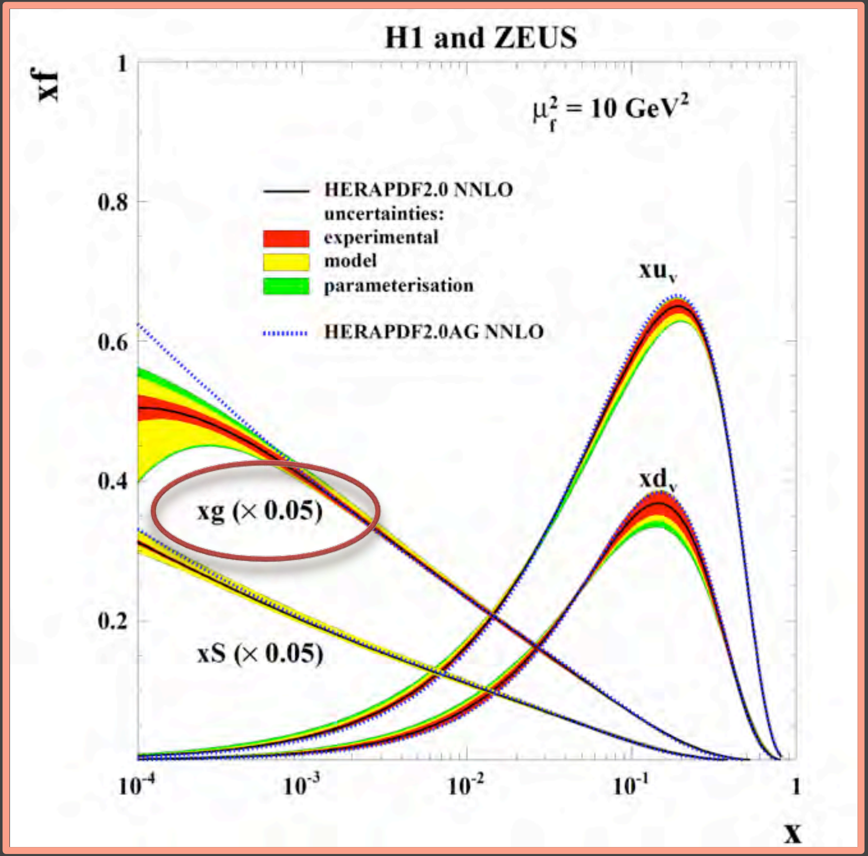
University of Toronto
(Bob Orr, Sampa Bhadra)



ZEUS/HERA physics

- Spectacular and wide-ranging results for electroweak tests and exploring the rich theory of QCD
  - sadly, no “beyond the Standard Model” discovery

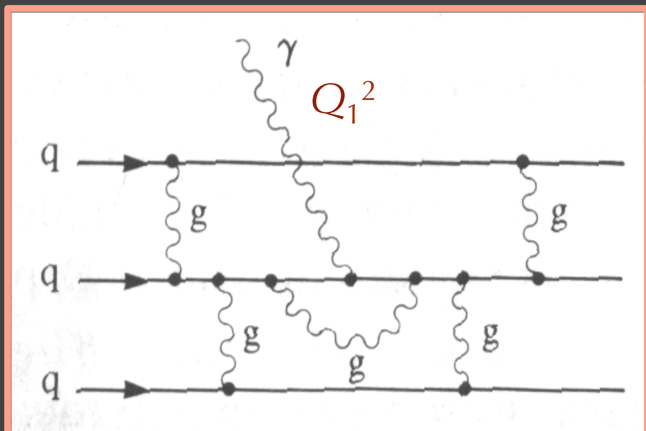
The proton in glorious detail →



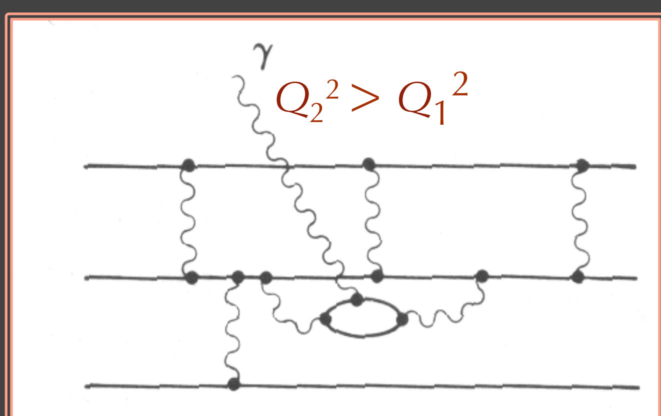
- A triumph of perturbative QCD!

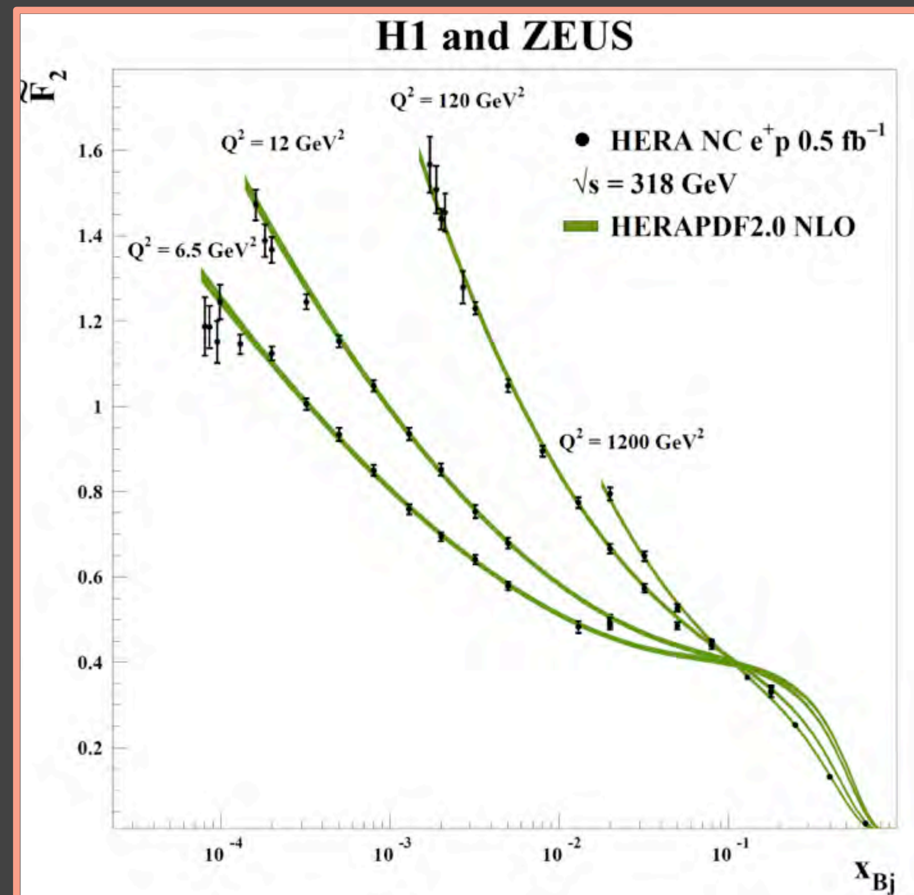
  Wilczek: the proton as soft glue “only clearly verified at HERA”

"Evolution" with Q^2



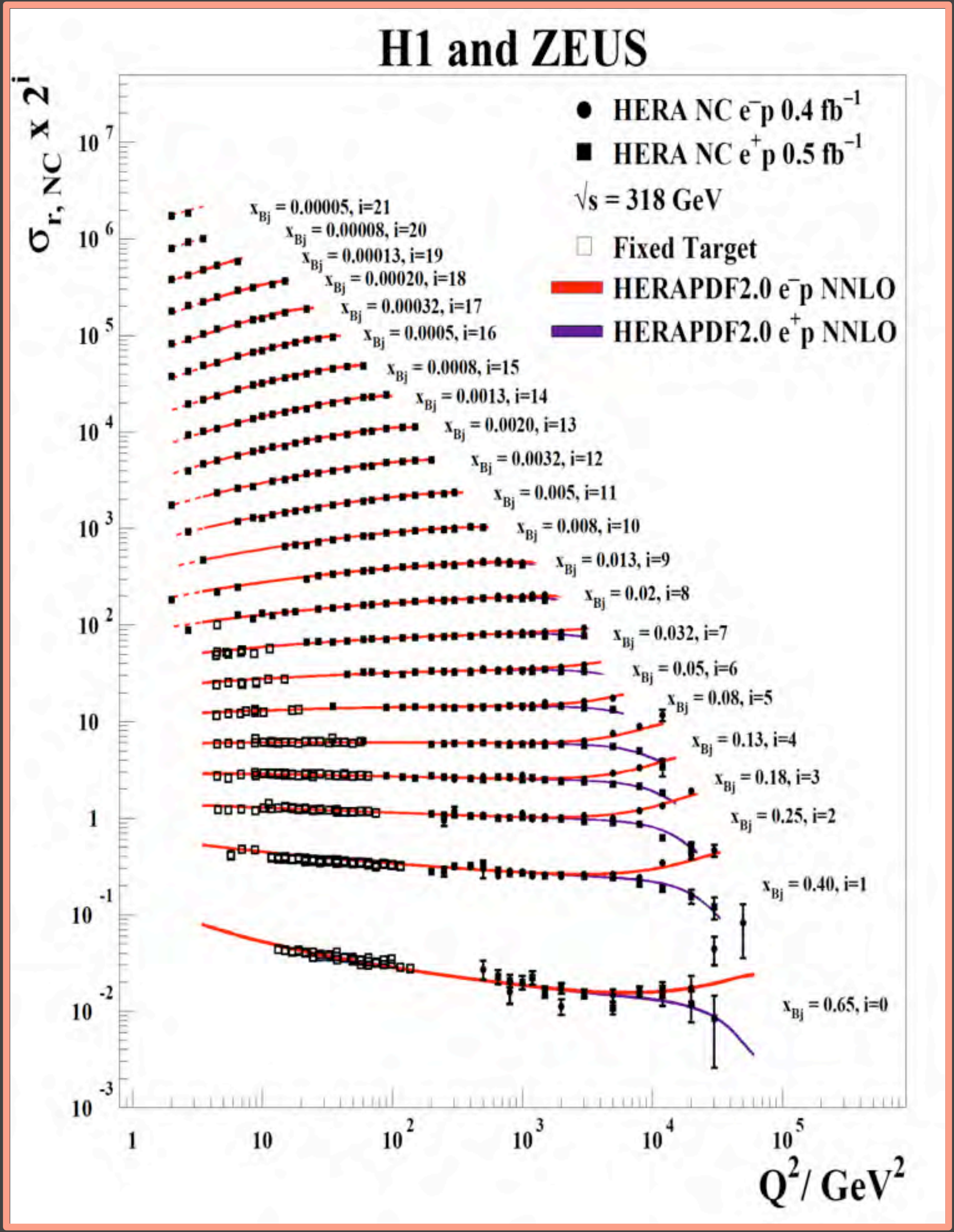
- As Q^2 increases, resolve more gluon splittings



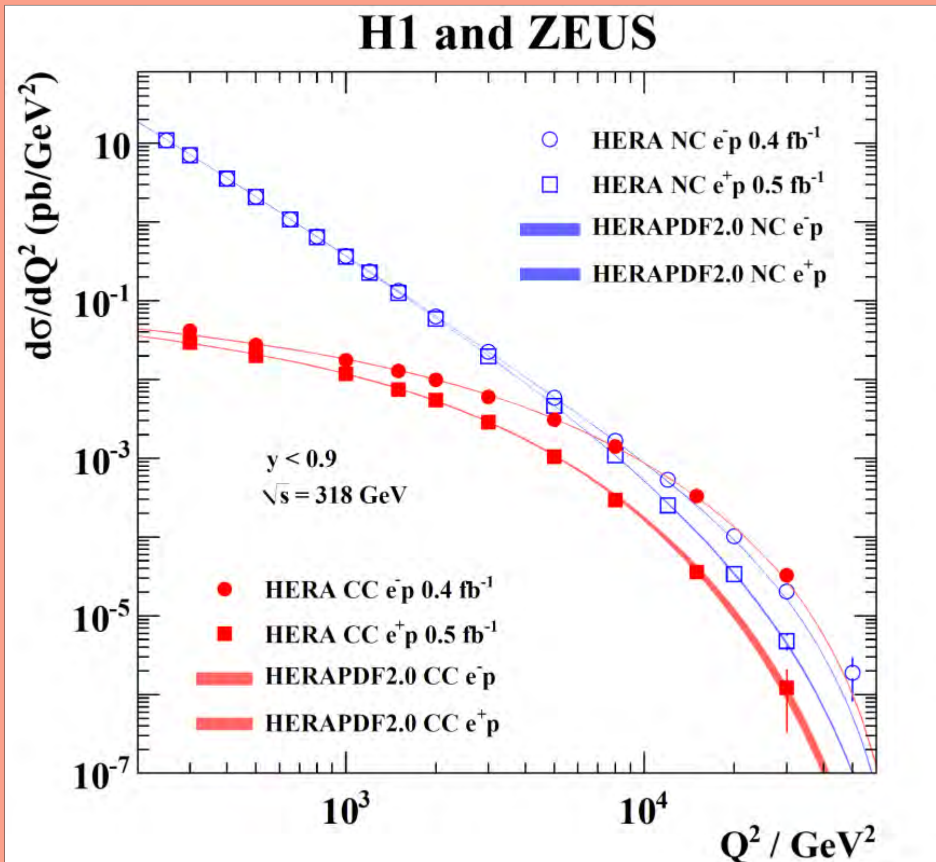


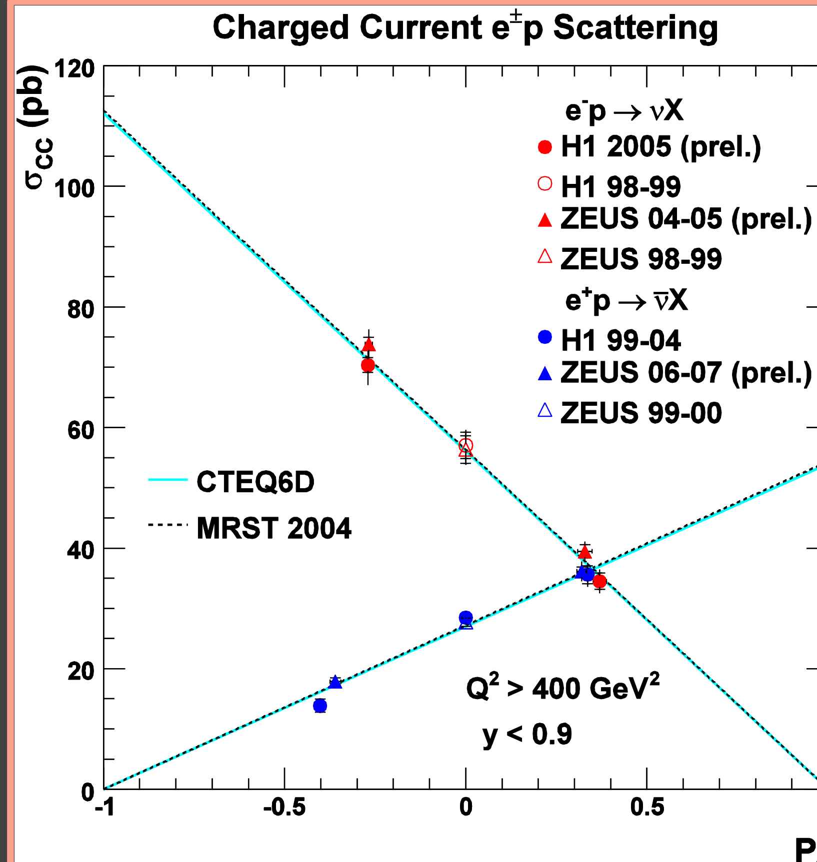
QCD verification

- Data described by NNLO QCD over range of 10^4 in x and Q^2
  - Released April 2015



Electroweak





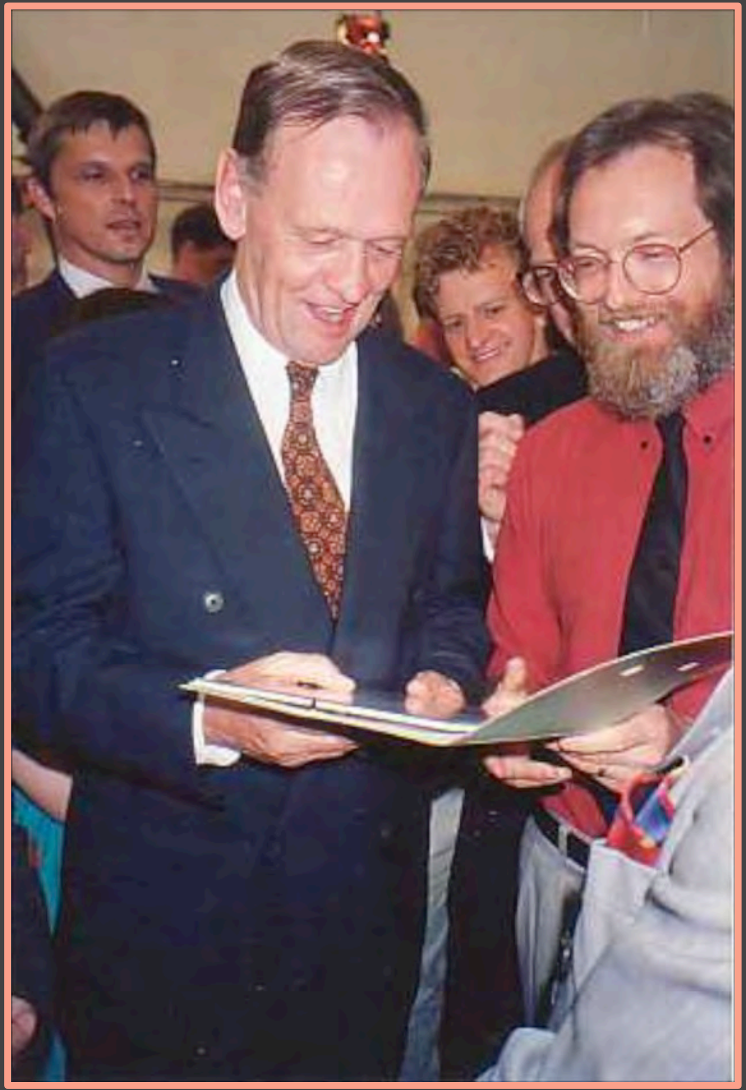
Unification !!

$\sigma_{CC} \approx \sigma_{NC}$ for $Q^2 \geq M_W^2, M_Z^2$

The weak interaction is still left-handed at high Q^2, no evidence of right-handed currents

My shortest ever physics lecture …

- 30 seconds explaining ep scattering to Prime Minister Chrétien at the Bonn Embassy, Canada Day 1994.



Colliders (smash the 2 stable particles, see what happens!)

- Canadians involved in all 3 possibilities 1990-2008:
  - e^+e^- OPAL at LEP, also SLD and BaBar at SLAC
  - ep ZEUS at HERA
  - $\bar{p}p$ CDF and D0 at Fermilab

    (younger Canadians returning to faculty positions)

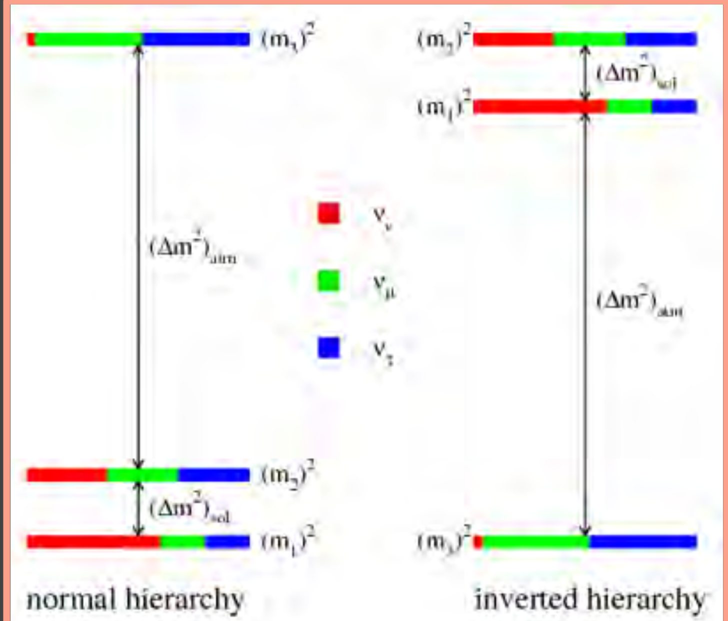
- No new physics → ATLAS at LHC now (pp)

- Meanwhile, dramatic news from Super-K and SNO:
  - Neutrinos oscillate and have mass, small but non-zero
    - the masses were zero in the Standard Model

Neutrinos

- Still mysterious 60 years after discovery
  - Why so much lighter than the charged fermions?
    - Connected with physics at a (much) higher mass scale? RH ν ?
  - Is the neutrino its own antiparticle?
  - Mass "hierarchy"?
  - CP violation?
  - 2 sets of eigenstates:
    - Mass (propagation)
    - Flavour (production, detection)

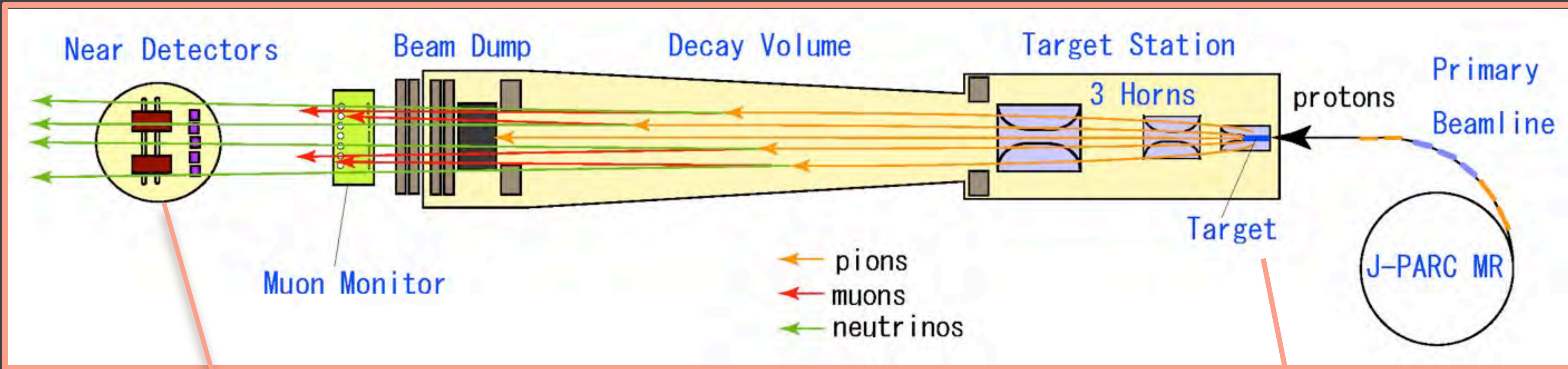
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

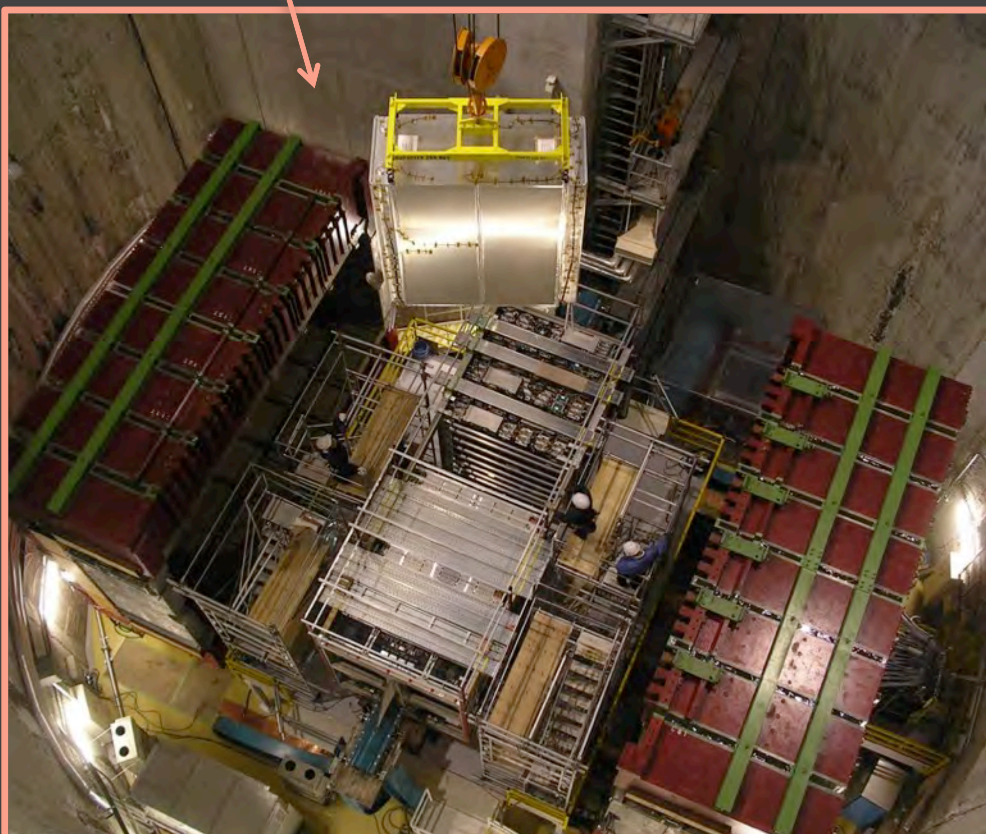


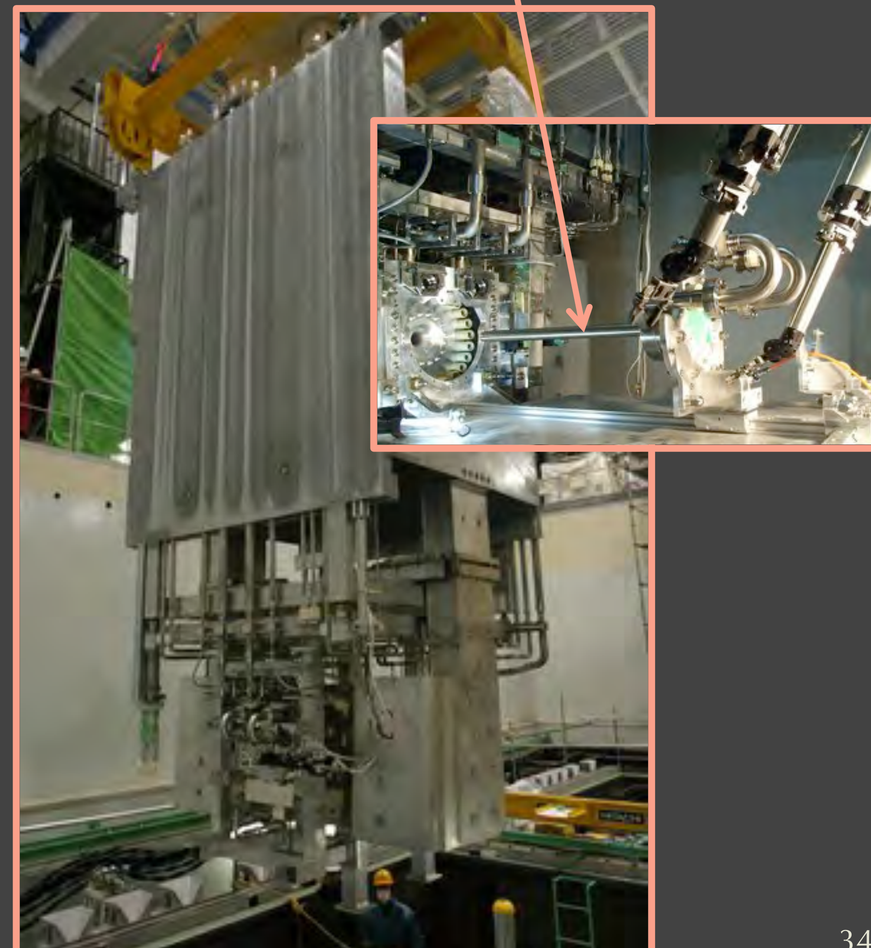
T2K

Japan, USA, England, France, Germany, Poland, Switzerland, Italy, Spain, Russia
+ Canada: Victoria, TRIUMF, UBC, Regina, Winnipeg, York, Toronto
very strong and influential group started by Akira Konaka (TRIUMF)

- Long baseline neutrino oscillation experiment (L/E)
  - Intense beam of ν_μ aimed at Super-K


Near Detectors
Beam Dump
Decay Volume
Target Station
Primary
Beamline
3 Horns
protons
Target
J-PARC MR
Muon Monitor
pions
muons
neutrinos





Discovery!

- First experiment to see a flavor "appear" in a neutrino beam different from the production flavor
  - $\nu_\mu \rightarrow \nu_e$ (2.5σ indication 2011, 7.5σ discovery 2013)
  - One of top 10 scientific breakthroughs 2011 (Physics World)

- Why so interesting?
  - Mixing angle (μ→e) uniquely multiplies a CPV parameter
  - Before T2K, only upper limit, could have been zero

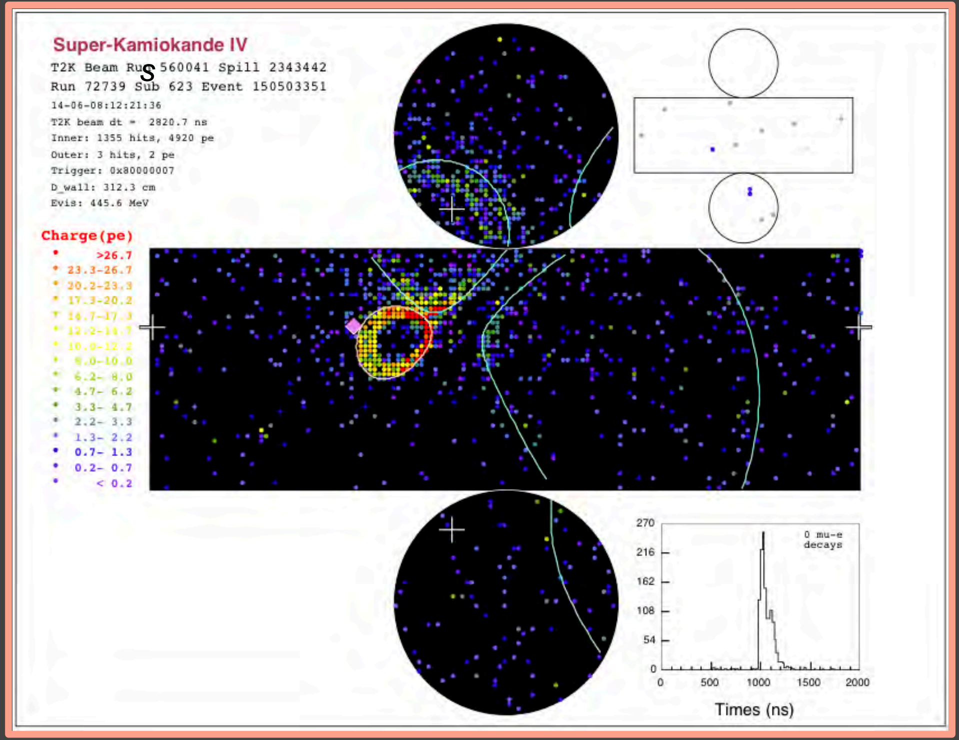
    → can now explore CP violation in the lepton sector
  - may be the clue to the matter-antimatter asymmetry of our universe

Antineutrinos

- Now running T2K with antineutrino beam
  - Compare ν with $\bar{\nu}$ results to measure CP violation parameter
    - X10 data to come

First T2K antineutrino event in Super-K →

First $\bar{\nu}$ oscillation results will be presented at EPS meeting in July



The future (for CDN PP) will be exciting!

- **In IPP ~ 90 faculty-level experimentalists (200 members)**
- ATLAS/LHC results soon, something new?
  - is our world supersymmetric? extra dimensions?...   need guidance
- SNOLAB: dark matter searches, neutrino properties
  - is the neutrino its own antiparticle?
- T2K, IceCube + proposal for huge new detector Hyper-K
  - neutrino mass hierarchy, CP violation
- Rare processes? Belle-II (e^+e^-), NA62 (K); Veritas (cosmic γs)

- TRIUMF: vibrant program   also experiments at Jlab, ANL
  - nuclear astrophysics, fundamental symmetries, UCN and much more
- Cosmology data will continue to pour in
  - Canada funded for a 30 metre telescope contribution
  - dark energy?
  - is our universe just a small patch of an infinite multiverse?