Hadron Hose: Continuous Toroidal Focusing for Conventional Neutrino Beams

J. Hylen, R. Ducar, C. Jensen, A. Marchionni, M. May, W. Smart, J. Walton,
Fermi National Accelerator Laboratory

M. Messier, *Harvard University*

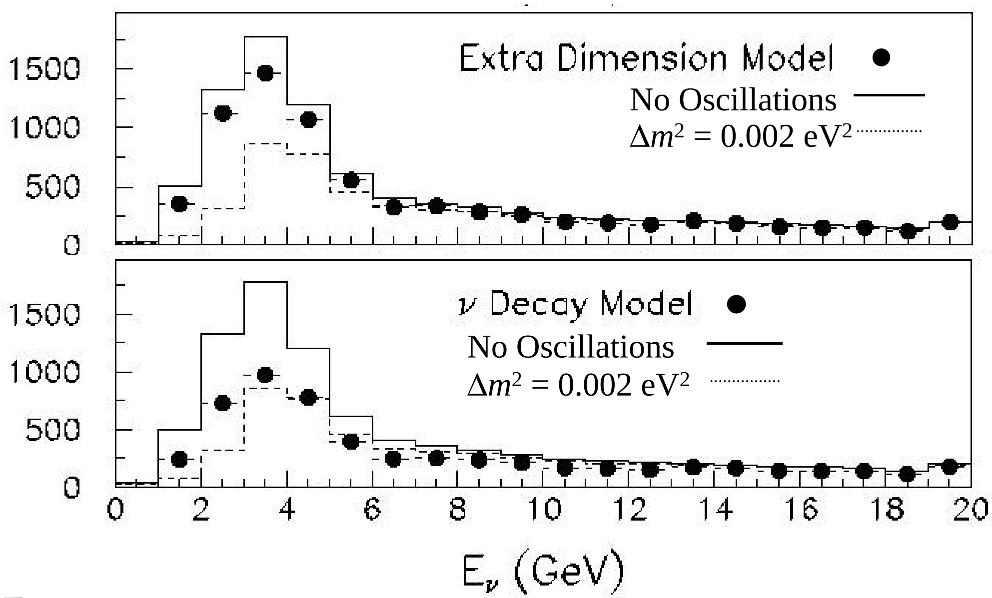
V. Garkusha, F. Novoskoltsev, V. Zarucheisky, *IHEP, Protvino*

J. Hall, S. Kopp, M. Kostin, A. Lyukov, R. Zwaska *University of Texas – Austin*

R. Milburne, *Tufts University*

‘Precision Neutrino Physics’

- Make best *a priori* measurement of E_ν spectrum.
- Many alternative models exist, more to come
- Demonstrate oscillations (or not) ⇒ comparison with alternatives

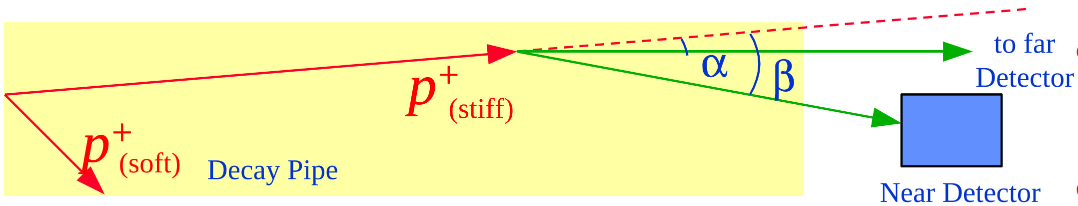


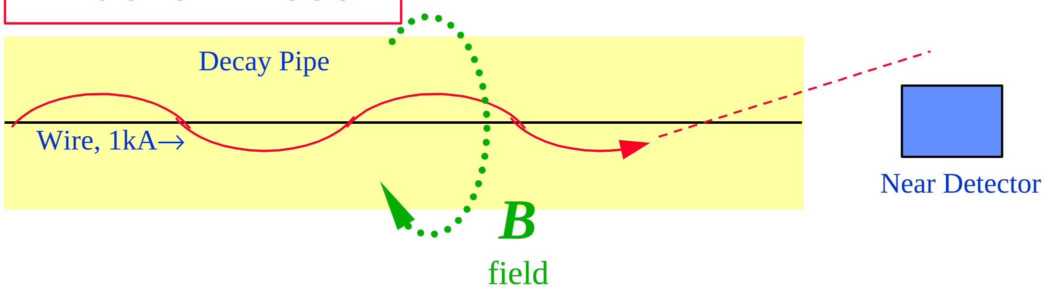
- Need ‘control sample’ (no depletion observed)
- Need control over systematics over entire energy range.

Systematics from ν Beam

- Two detector experiment helps.
  - »Cross sections σ(νN) cancel out
  - »Constraints on ν flux
- Acceptance problems for beam:
  - »Far detector sees ~ "point source"
  - »Near sees extended source
- Acceptances ⇒ modeling ⇒ uncertainties
  - »See yesterday's talk by M. Messier
- Can solve by
  - »Moving 'near' detector far away
  - »Making acceptance cut-offs small (huge decay pipe)
  - »Hadron Hose

What is Hadron Hose?





$$E_u = \frac{0.43E_p}{1+g^2q^2} \qquad Flux \propto \frac{1}{L^2}\left(\frac{1}{1+g^2q^2}\right)^2$$

- Hadrons oscillate as travel down pipe.
- Fewer *p*'s interact in wall before decay

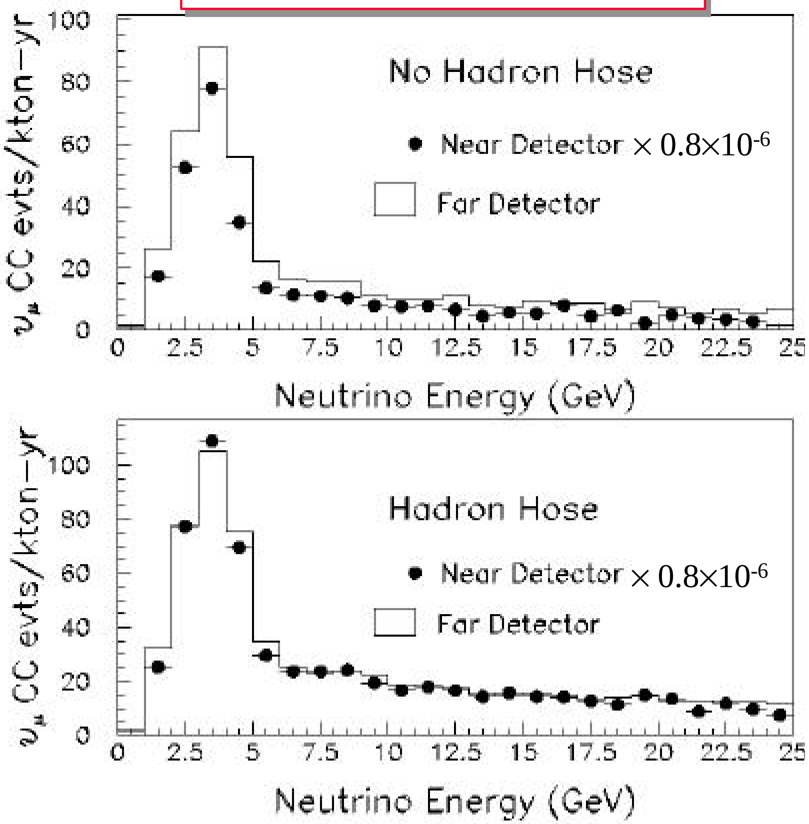
Þ MORE n_m FLUX

- Reduce correlation between decay θ and detection.

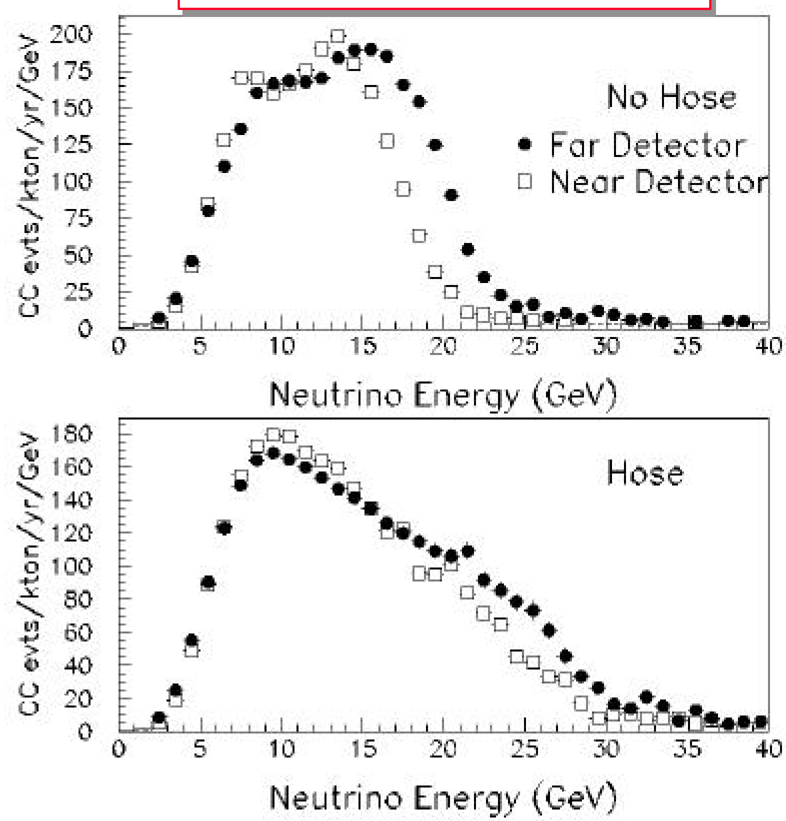
Þ Reduced Systematics

Neutrino Energy Spectra

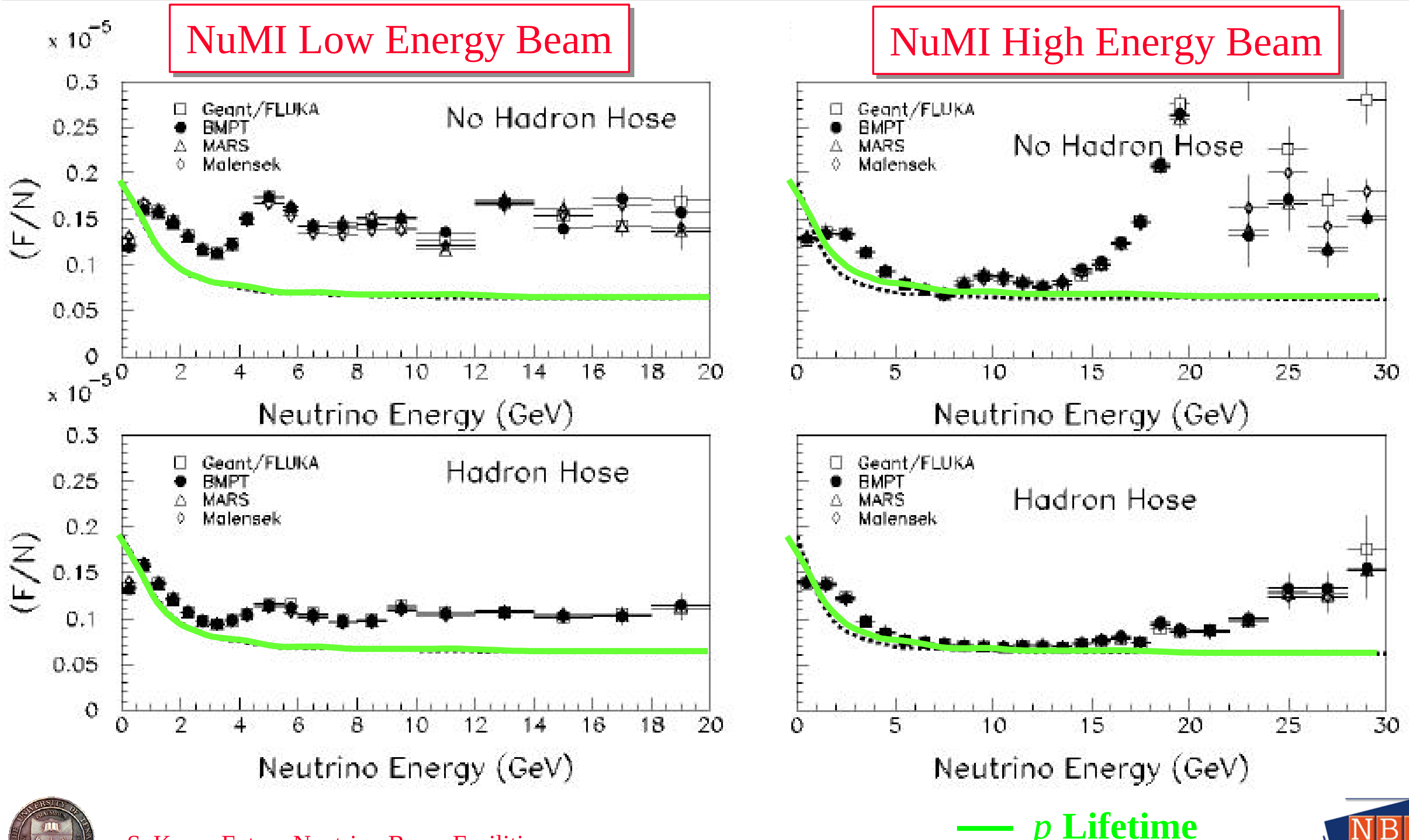
NuMI Low Energy Beam



NuMI High Energy Beam



Extrapolating to the Far Detector



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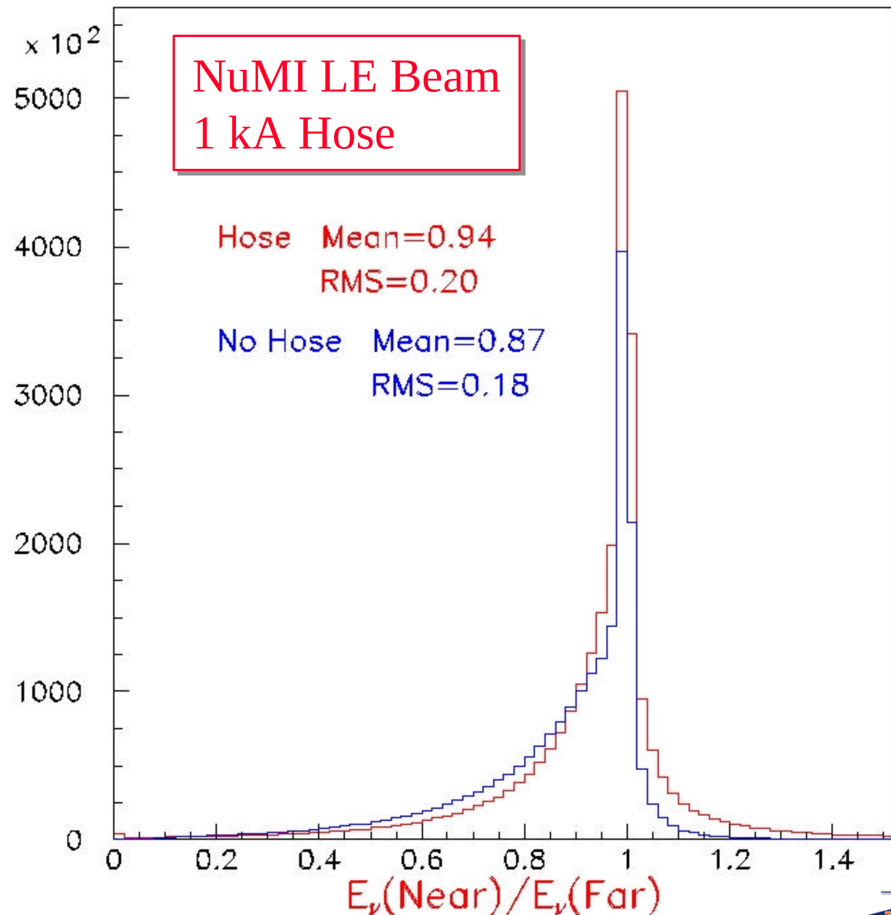
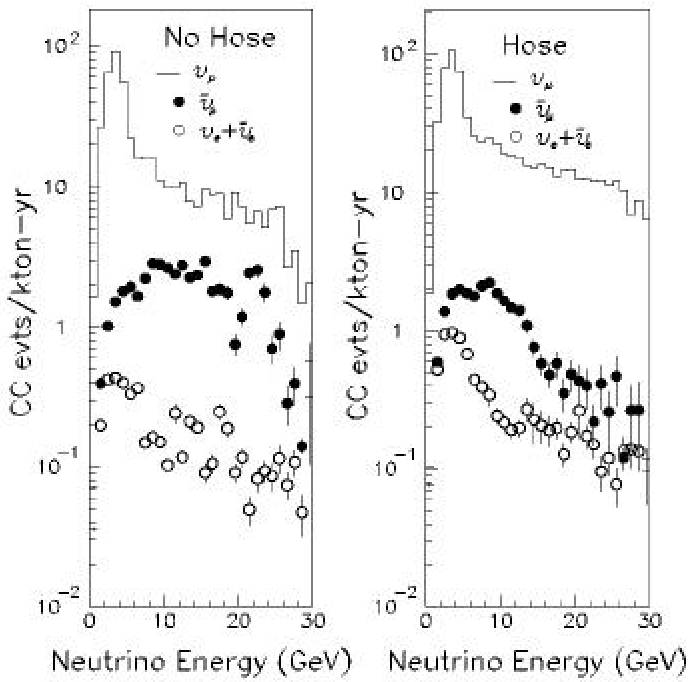
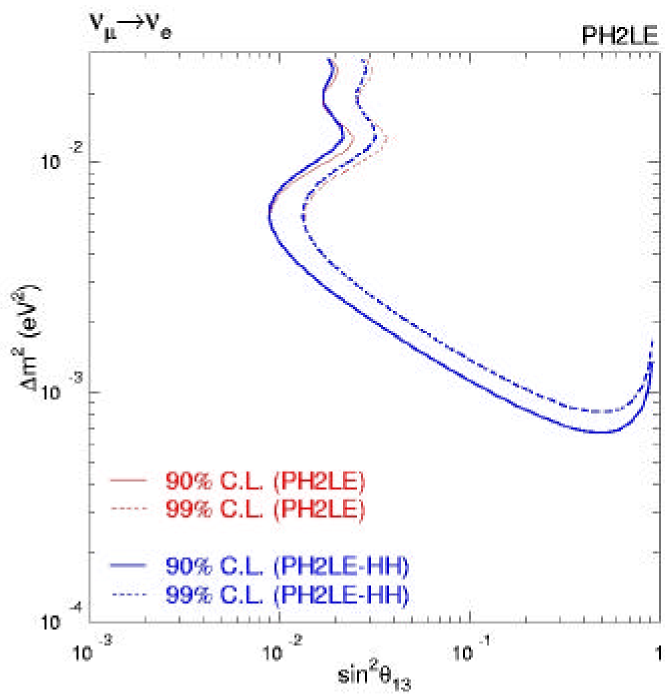
Near-Far Comparison (cont'd)

- Propagate pions through horns
- Allow to decay in decay tube
- Plot E_ν if decay to near *vs* E_ν if decay to far detector (weighted)
- Would like ~1.0



ν_μ - ν_e Oscillations





- Hose also focuses K^+, μ^+ (particularly for NuMI – long DV)
- Increase in ν_e, $\overline{\nu}_e$ backgrounds
- Still dominated by NC events, and $S/\sqrt{B}$ unchanged
- Irrelevant for off-axis beams

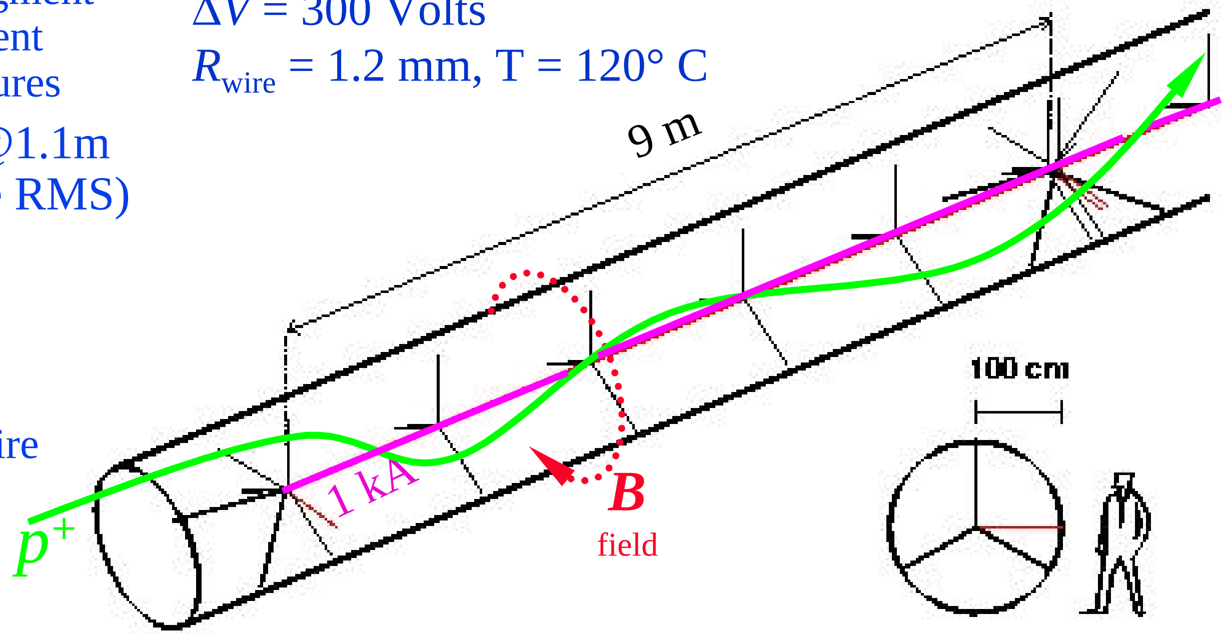
R&D Effort

- Full-scale prototype
  - »Wire support, alignment, tensioning
  - »Installation procedures
  - »Wire vibration when pulsed
  - »Long-term pulsing behavior
- We chose anodized aluminum wire as best choice
  - »Low *Z* so fewer pion interactions
  - »Diameter 2.38 mm Ø – also constrained by pion interactions
  - »Conductivity ~80% of copper (Al 1350, ECH18) reduces i^2r heating & voltage drop along wire
  - »Have to live with aluminum creep (could consider alloys)
- Measure Aluminum creep
- Wire Heating Studies
  - »Measure cooling from radiation + residual gas cooling
  - »Calculate wire heating due to i^2r and beam heating
- Measure Voltage breakdown in vacuum

Hadronic Hose Construction

- Wire in 72 sections, limit:
  - »Voltage on each segment
  - »Expansion of segment
  - »Damage due to failures
- "Spider" supports @1.1m (require <2mm wire RMS)
- Tensioning springs
  - »Limit sag
  - »Take up thermal expansion
  - »Take up creep of wire
- Move connections to outer radii, lower beam heating
- Wire anodized ⇒ improves emissivity.

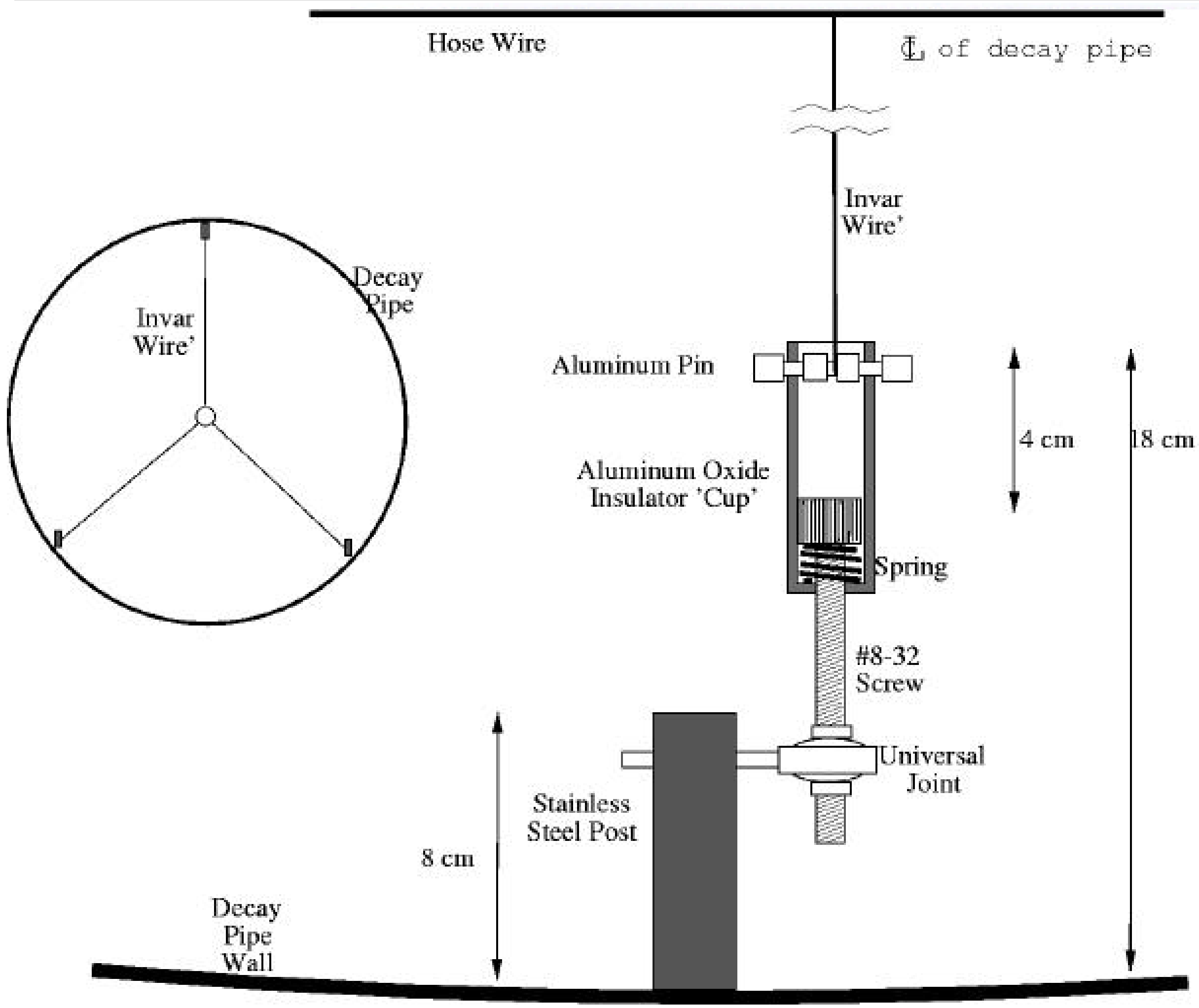
I = 1 kA, B = 0.02 kG @ r=10 cm
ΔV = 300 Volts
R_{wire} = 1.2 mm, T = 120° C



Hadron Hose Prototype

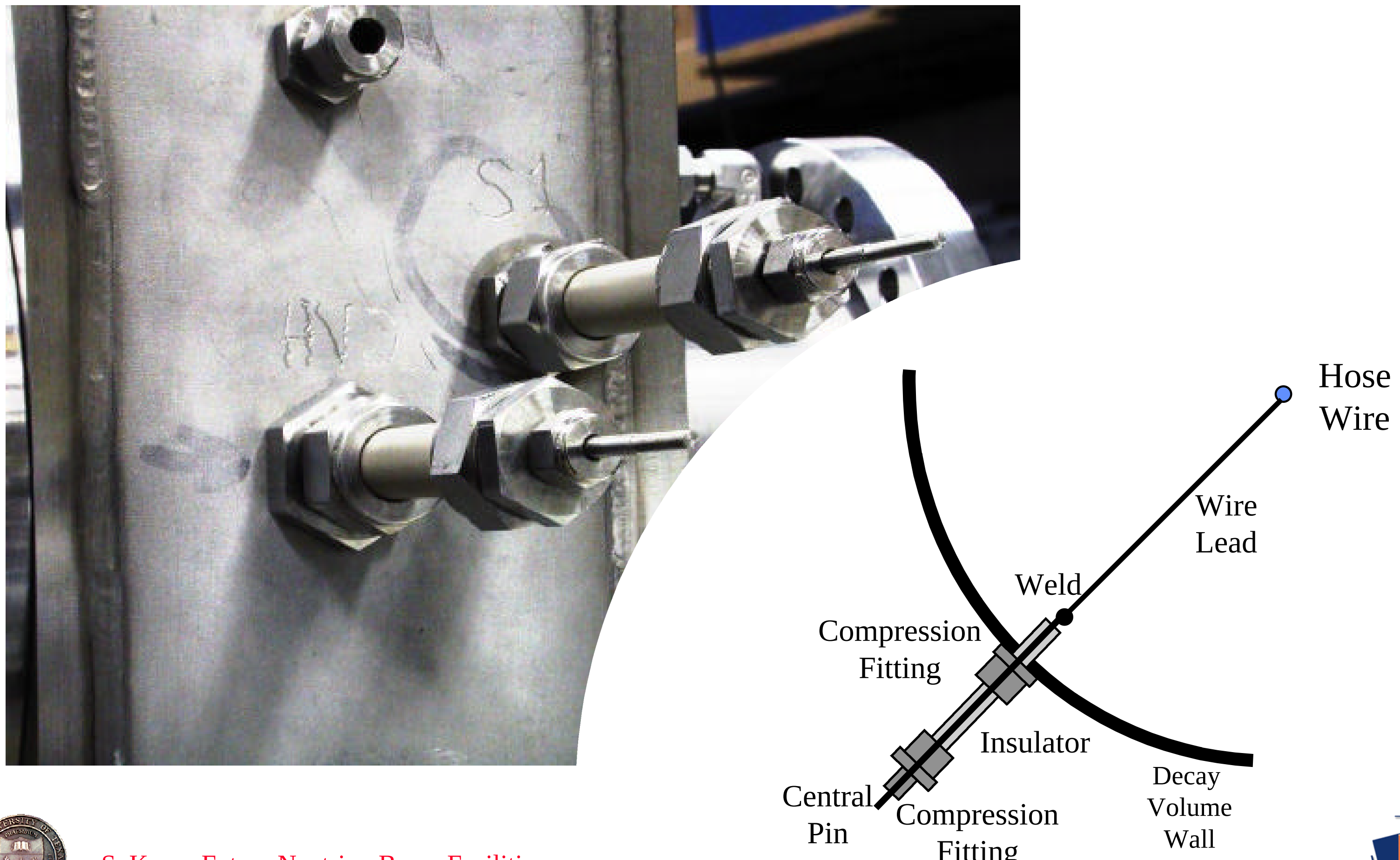
- Demonstration of parts, installation
- Pulsed with 1000A
- Tests performed:
  - »Creep
  - »Long-term stability
  - »Vibration
  - »Installation
  - »Survey

Spider Supports



Older design

Feedthroughs

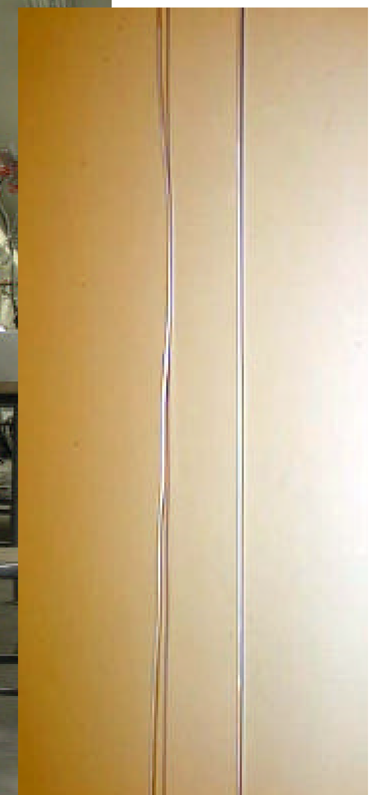


Hadron Hose Survey

- "Laser tracker" system.
- Coordinate system every ~30m, overlap
- Observed 1.7mm sag between spiders & spider rms ~0.5mm
- Posts also survey pipe.
- Also could have established coordinate system in exterior tunnel through feedthroughs.

Measuring Creep

- Also used to straighten wire!



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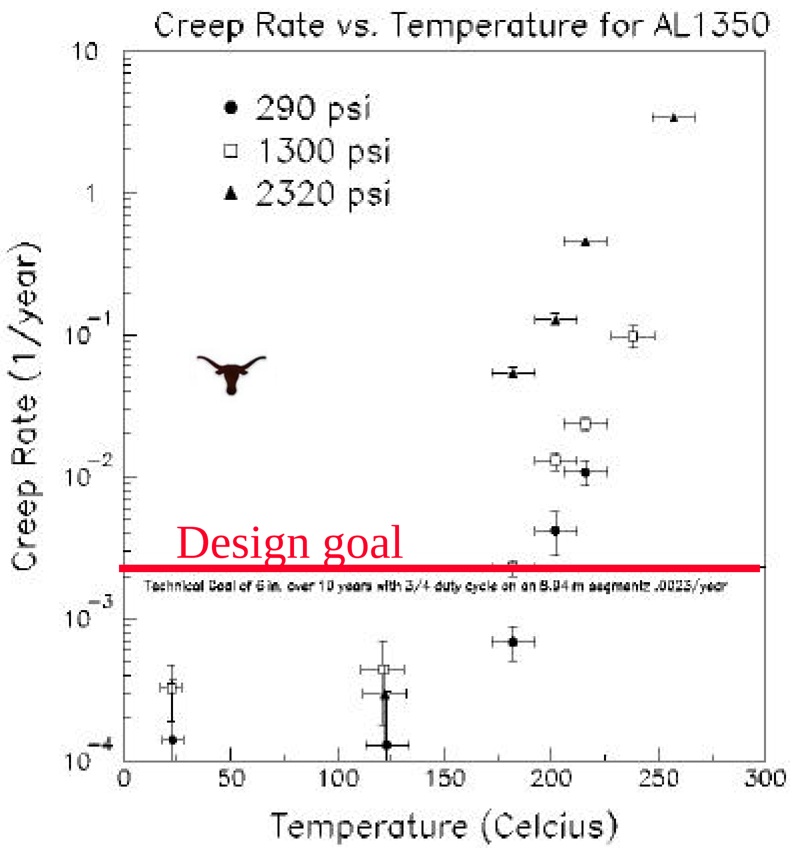
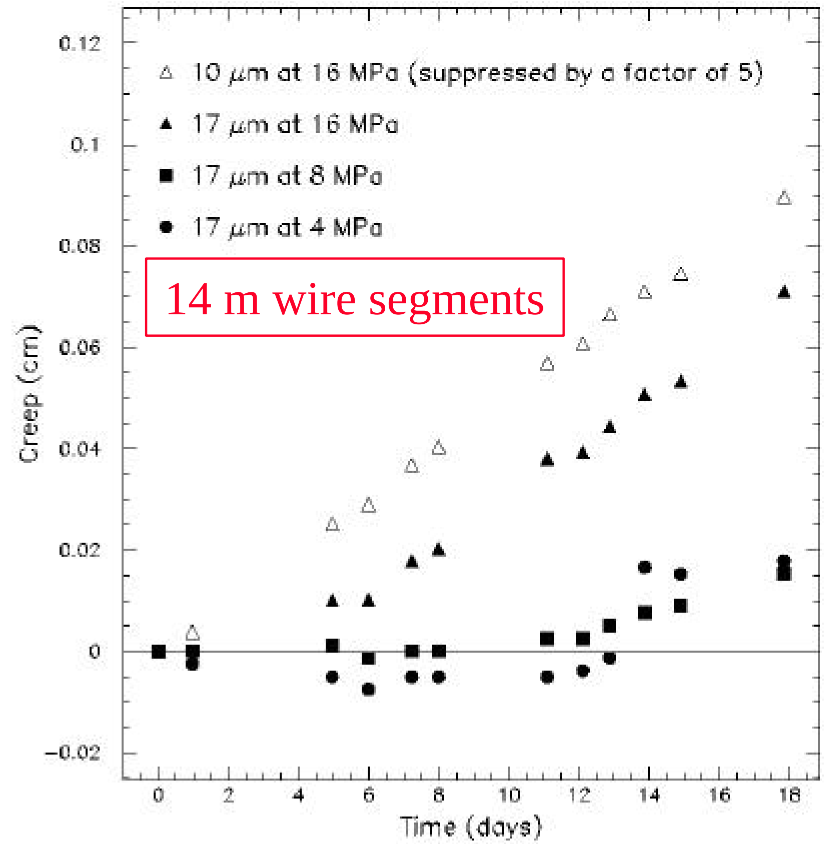
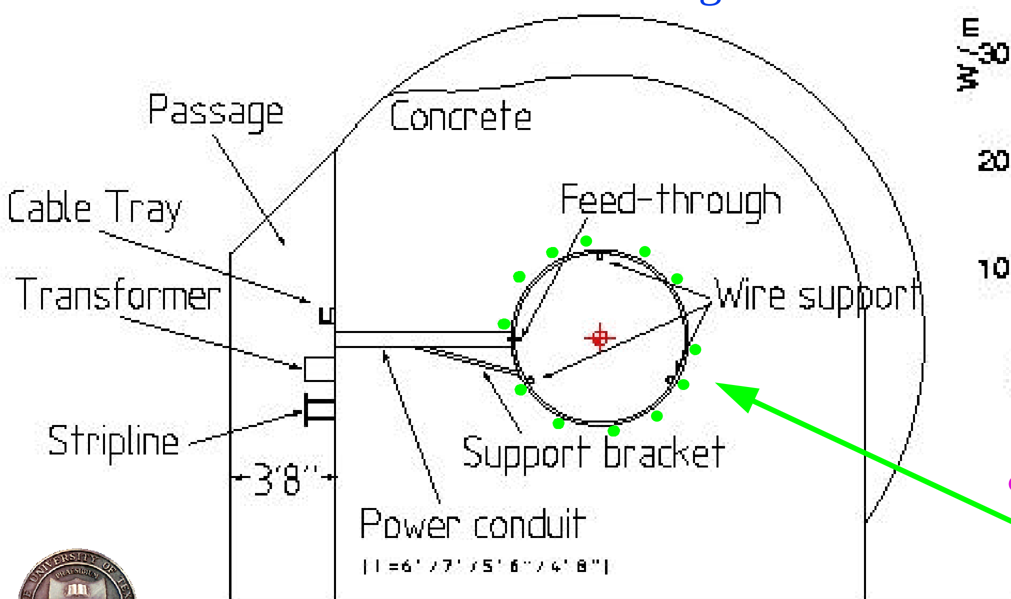
Aluminum Creep

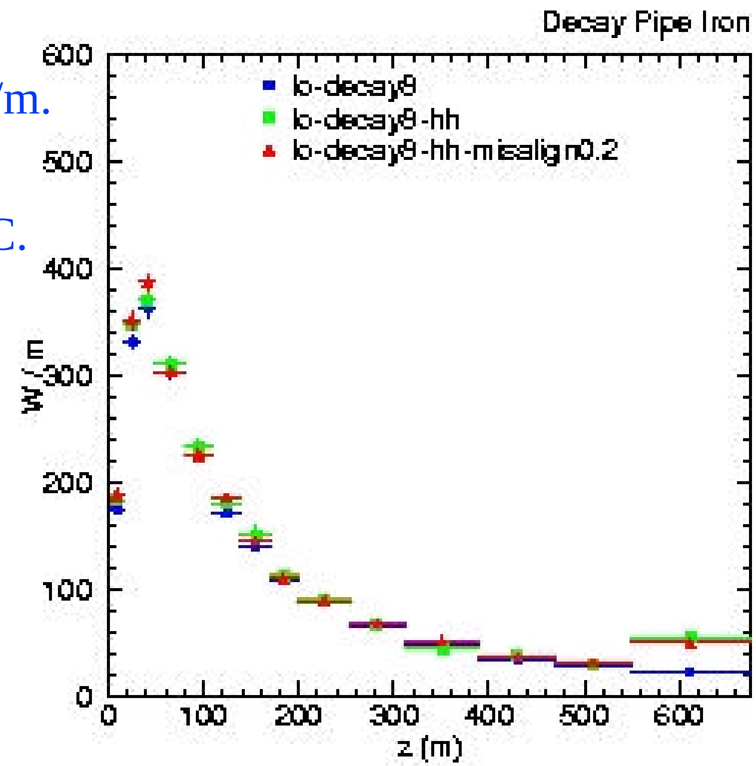




Decay Pipe Cooling

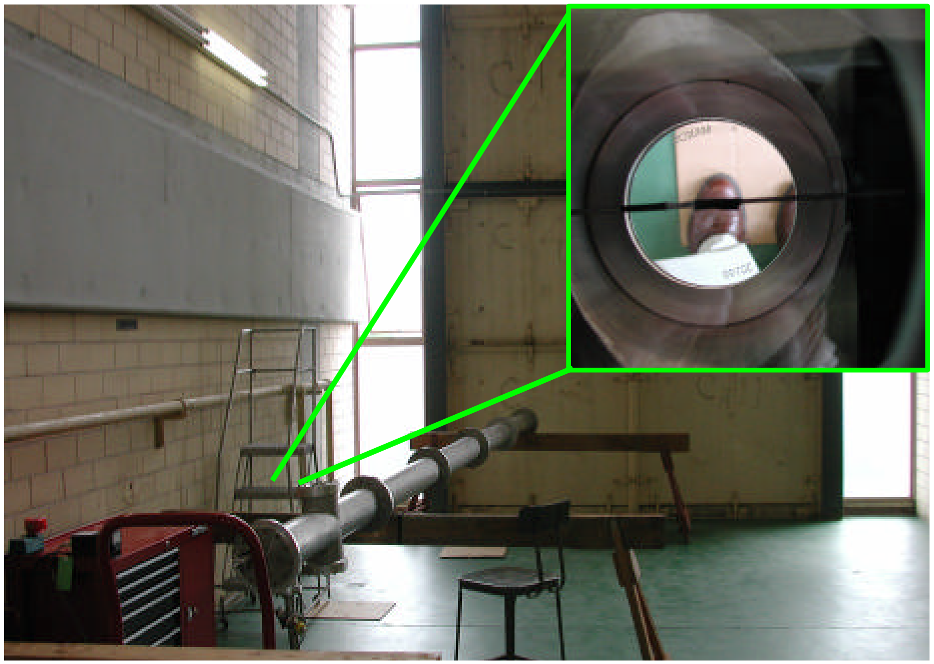
- Largest energy deposition in walls ~ 400 W/m.
- Decay pipe surrounded by 2.3 m concrete.
- Temperature drop through concrete ~ 150° C.
- Thermal motion affects hose alignment?

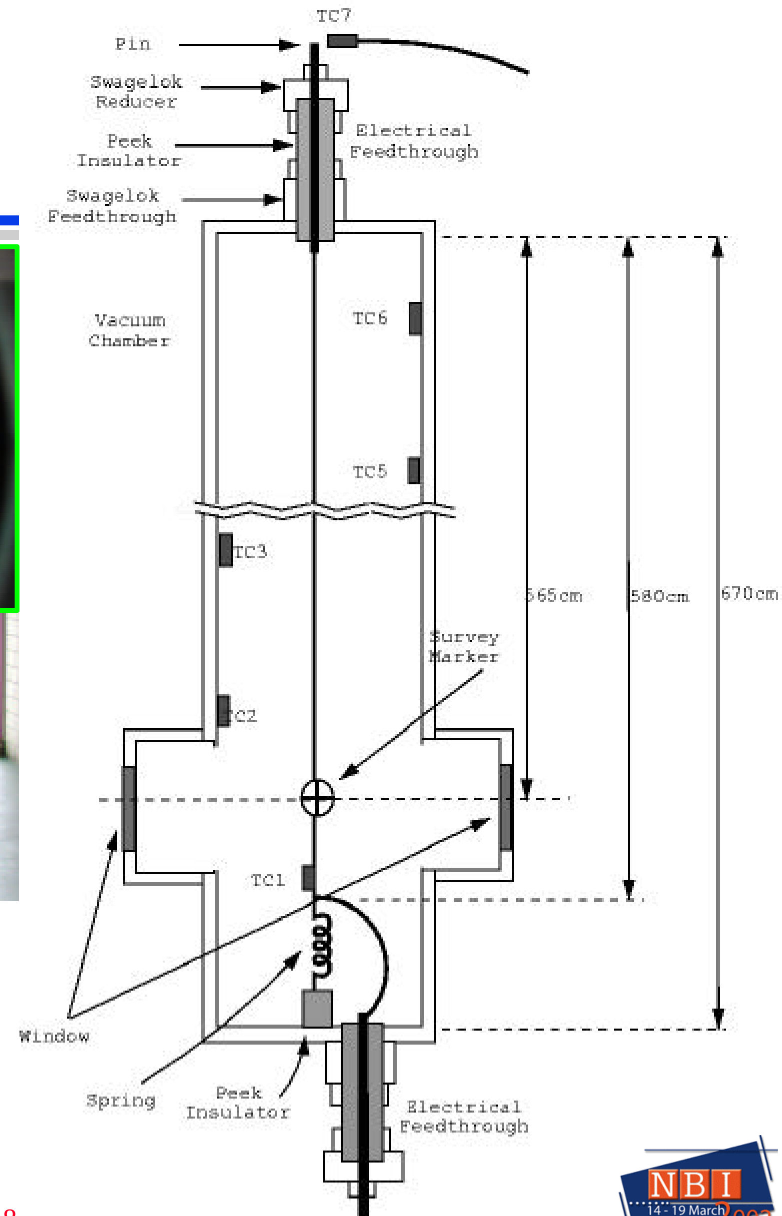




- We will add 12 1” Ø copper lines (2.2 ft./sec. H_2O flow)

Wire Emissivity



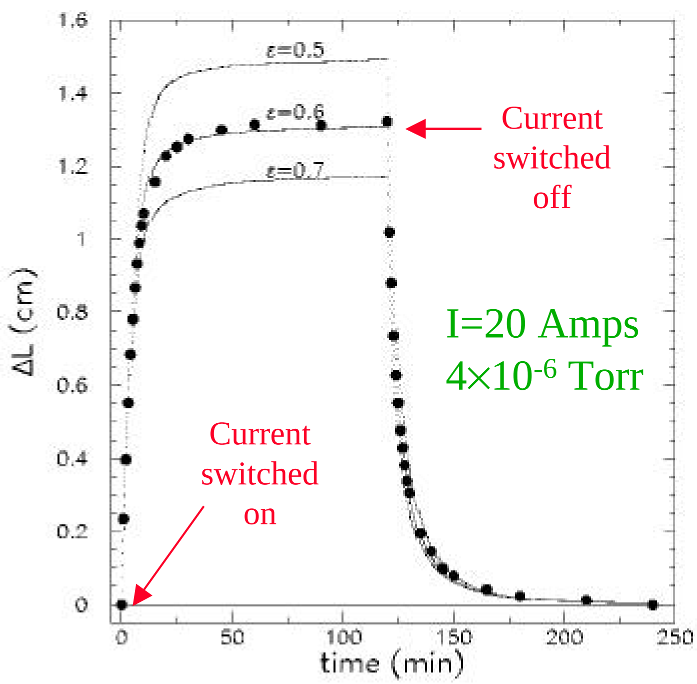


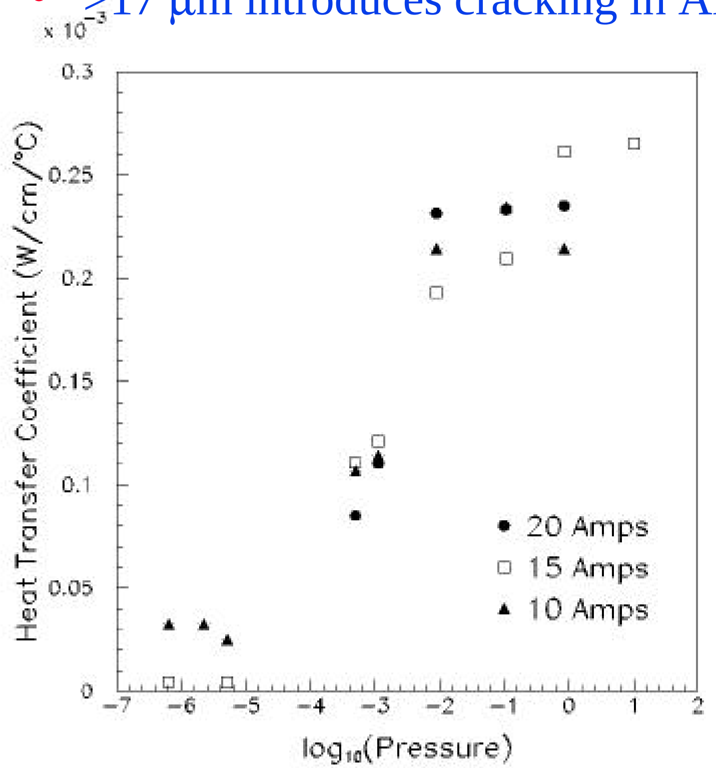
- Simulate what wire will see beam
  - Variable vacuum chamber pressure
  - Flow known i^2r power through wire.
  - Observe wire elongation through window $\Rightarrow$ measures temperature

Observations

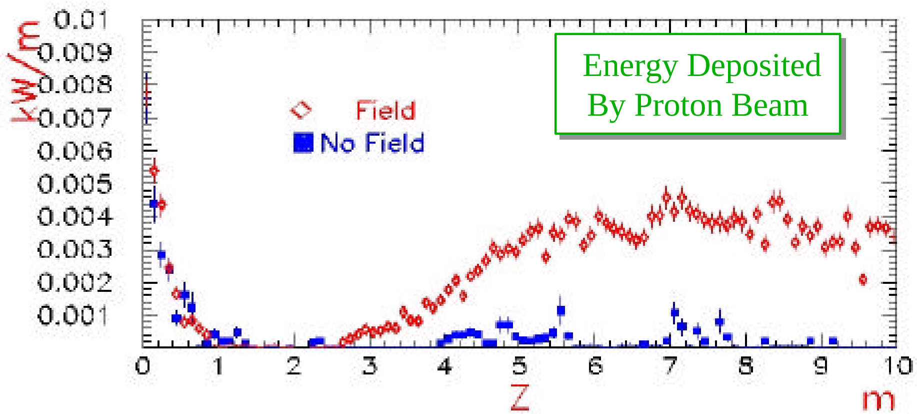
- e ~ 0.2 (bare wire)
- e ~ 0.5 (10 μm anodization)
- e ~ 0.6-0.7 (17 μm anodization)

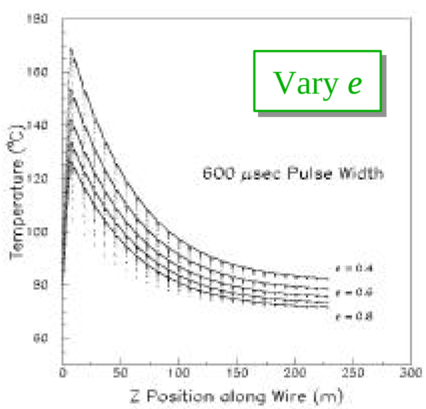
- Anodization is Type II, Class 1 (also tried Class 2)
- ≥17 μm introduces cracking in Al.

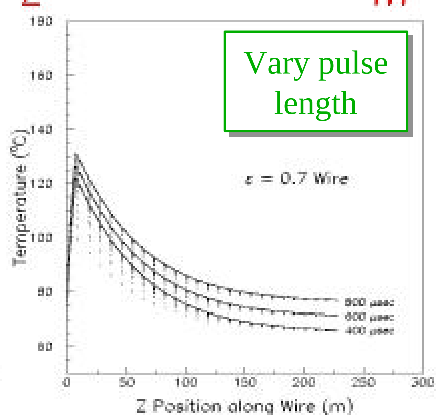




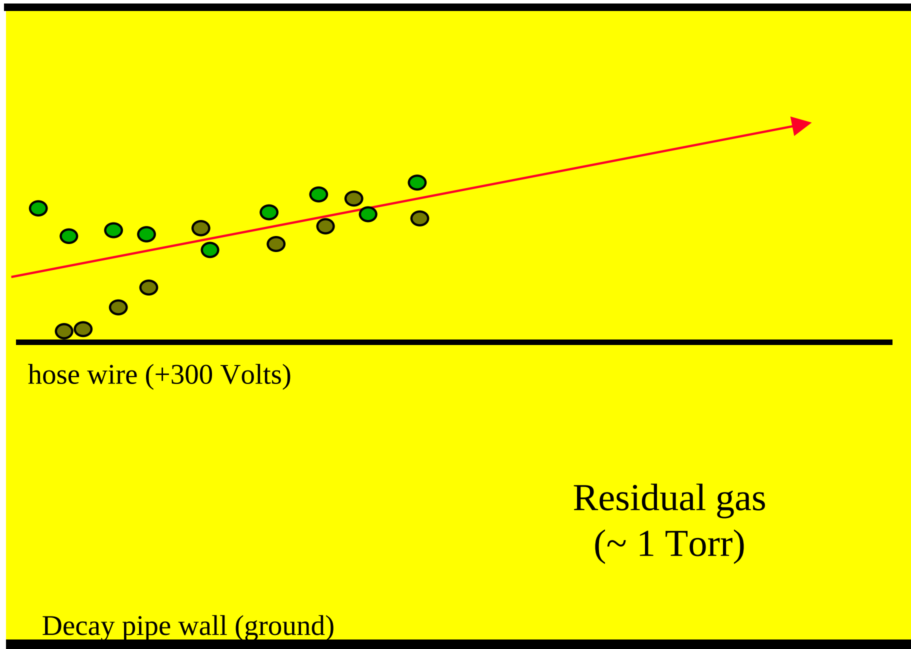
Thermal Modeling







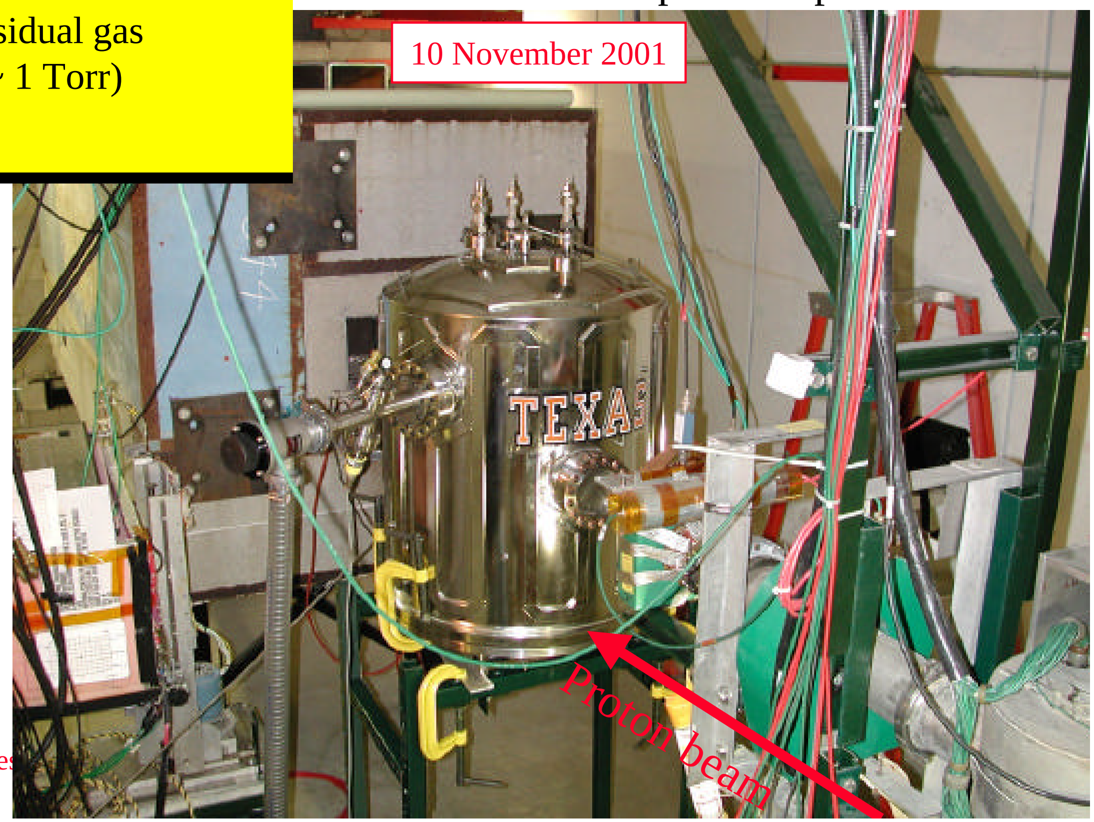
- Hose wire gets hot in vacuum
  - »i^2r from current
  - »Protons hitting wire
- Wire gets rid of heat via
  - »Radiation ~ $e s_B T^4$
  - »Gas conduction
- Thermal balance < 160°C with
  - 600 *ms* pulse width
  - emissivity *e* ~ 0.7 - 0.8



Radiation Effects

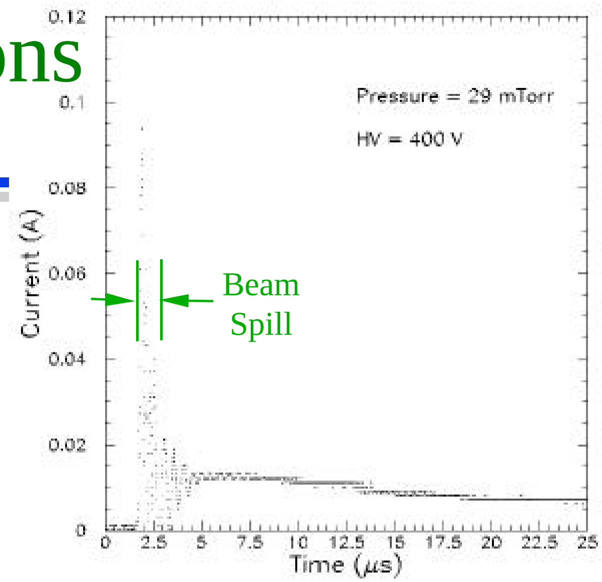
Fermilab Booster Accelerator

8 GeV proton beam
5×10^9 - 5×10^{12} protons/spill

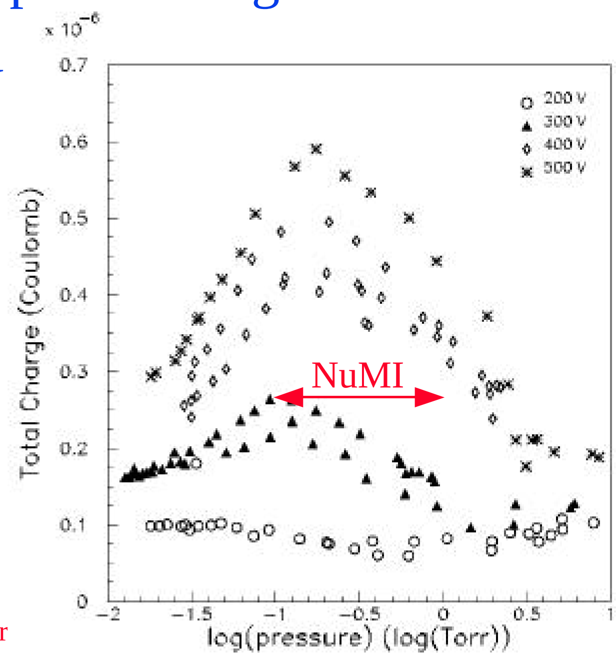


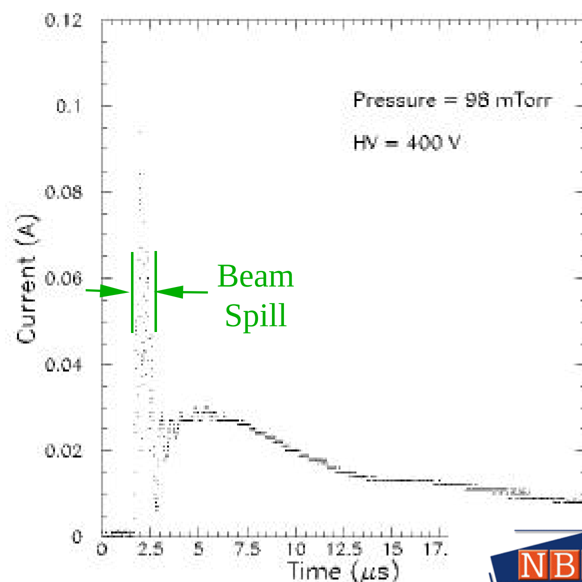
- Lots of ionizing radiation in decay pipe
- Residual Gas ~1Torr
- Electrical breakdown?

Beam Test Observations



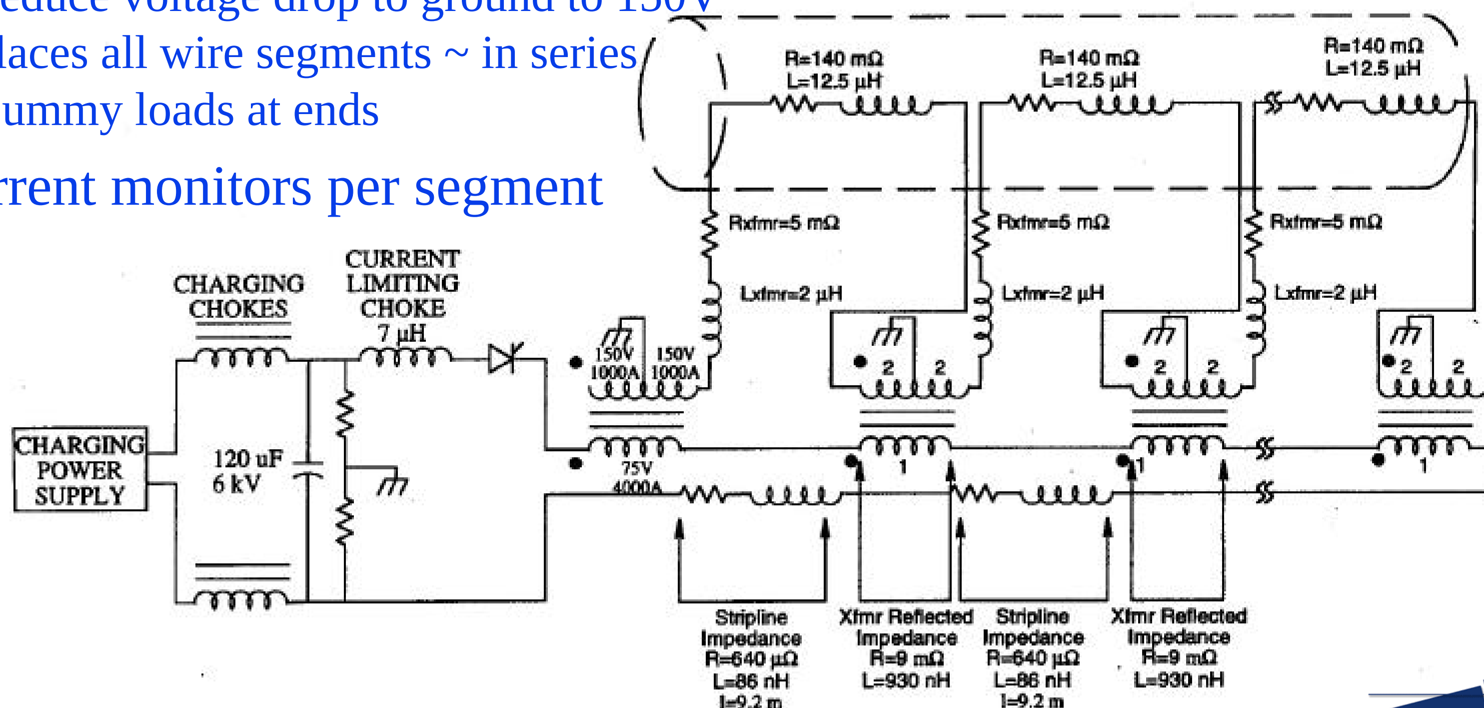
- See fast arrival of charge on wires during beam spill, followed by slow drift over many μsec.
- Total charge collected is function of pressure, applied voltage
- Data follow trend expected from Paschen curve



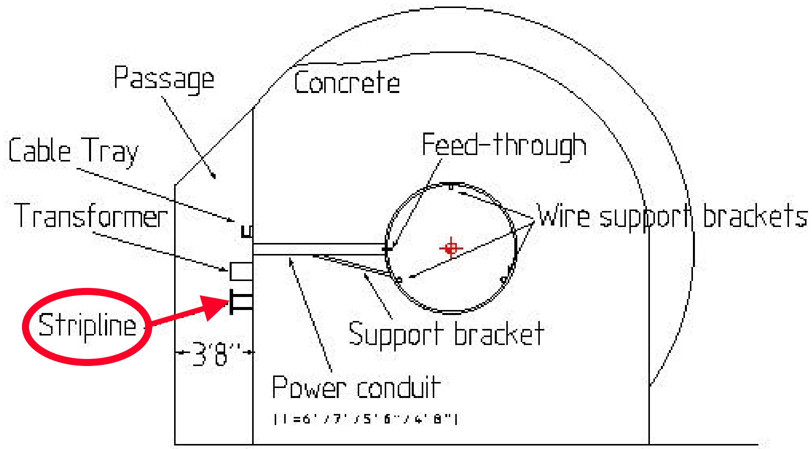


The Hose Circuit

- Transmission line @ 5000V
- Wire segments 'center-tapped' to transformers.
  - »Reduce voltage drop to ground to 150V
  - »Places all wire segments ~ in series
  - »Dummy loads at ends
- Current monitors per segment



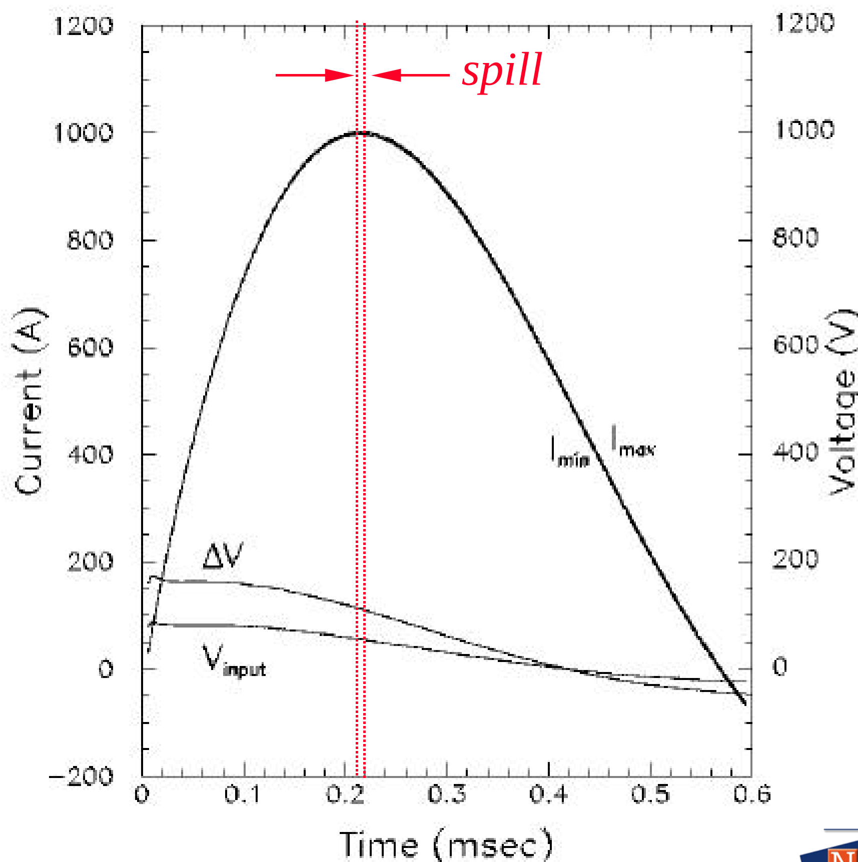
Stripline



- Sits in NuMI decay tunnel passageway
  - »humidity!
  - »10^6 Rad/year
- Energized to 5000 V
- 9mΩ, 900 nH / 9 m segment (measurements: welds important)
- Schedule 'K' Cu water tubing
- Peek Spacers

Current Pulse

- L_{vac} ~ 13 *m*H,
  ΔV = 100-200 V (inductance)
- R ~ 83-110 mΩ
  ΔV = 80 V (resistance)
- Need ~ 200V to drive 1 kA at 600 μsec pulse width
- Current variation during beam spill <0.1%
- Variation amongst wires <1A (despite ~ 80°C variation)



Summary

- Hose increase flux by ~25%, cheaper than
  - »More detector mass
  - » More running time
  - »Larger diameter decay pipe

- 'Simple' extensions to make 50%+ flux in future beamlines:
  - »Run 2-4 kA (parallel wires)
  - »Move horns + target closer to decay tube (NuMI separation ~30m)

- Hadron Hose reduces near/far differences to < 2%
  - »Enhances credibility of future MINOS results
  - »Extends MINOS sensitivity to $\nu_\mu \leftrightarrow \nu_\tau$ oscillations
  - »Allows discrimination between $\nu_\mu \leftrightarrow \nu_\tau$ and *new physics*
  - »Easier than near detector that's semi-far?

- Thanks to Jim Hylen

- Thanks to Konrad and all for a great workshop!

BACKUP SLIDES

Predicting the Far Detector Flux

- If beam were a point source, could say

$$N_{\text{far}} = R_{FN} N_{\text{near}}$$

where $R_{FN} = (Z_{\text{near}}/Z_{\text{far}})^2$ is ratio of solid angles

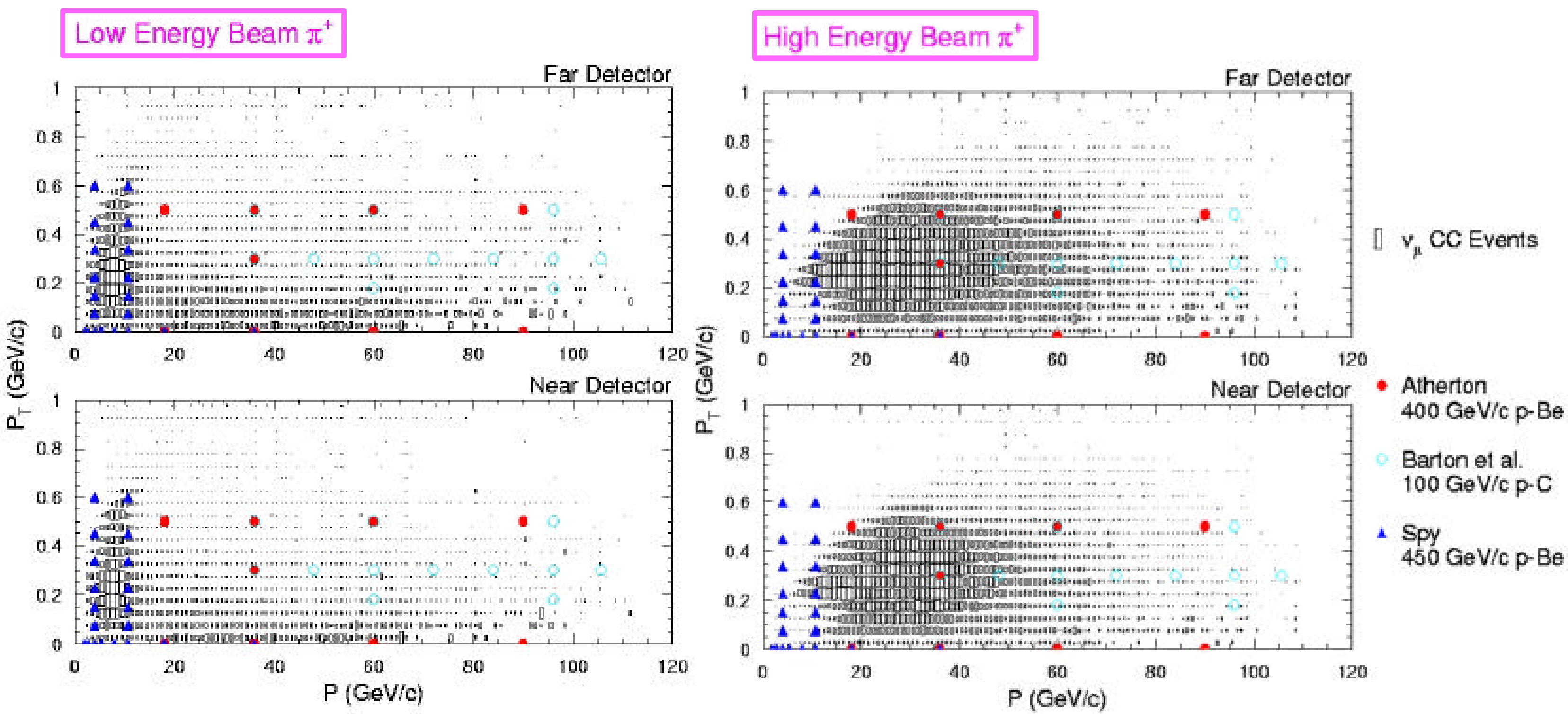
- Accounting for extended length:

$$R_{FN} = \frac{\int_{0m}^{720m} \frac{1}{(Z_F - z)^2} e^{-0.43 m_p z / E_n c t} \, dz}{\int_{0m}^{720m} \frac{1}{(Z_N - z)^2} e^{-0.43 m_p z / E_u c t} \, dz}$$

where E_n » 0.43 E_p.

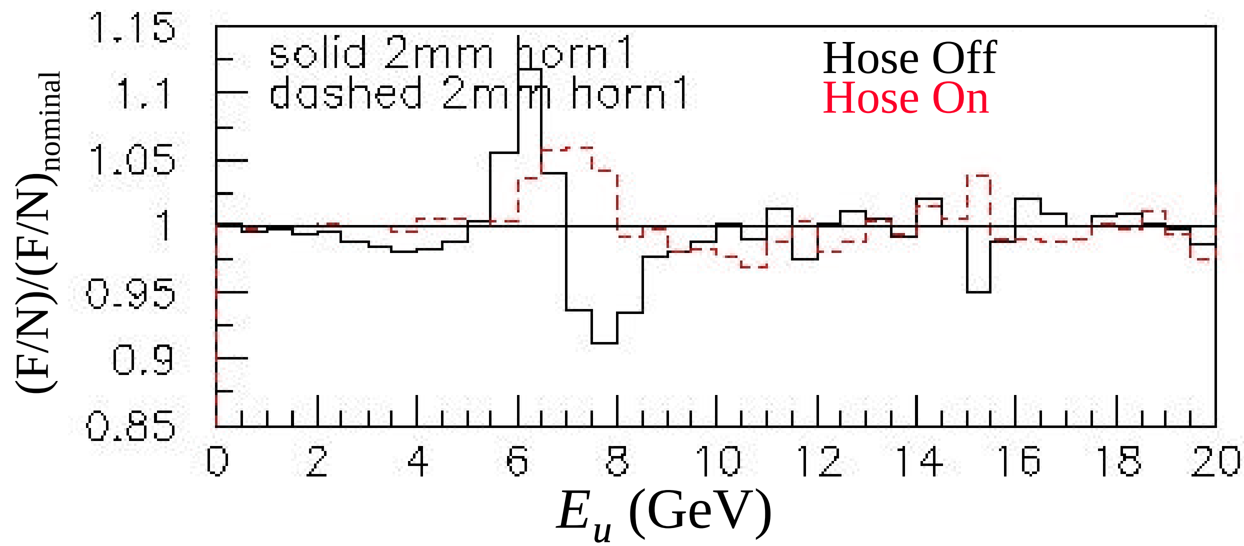
- Better than this need a MC to evaluate R_{FN}.
  - »Pions that interact before decaying
  - »Angular correlations in decay kinematics $E_u = \frac{0.43 E_p}{1 + g^2 q^2}$

Systematics of Extrapolation



Relaxes Other Tolerances

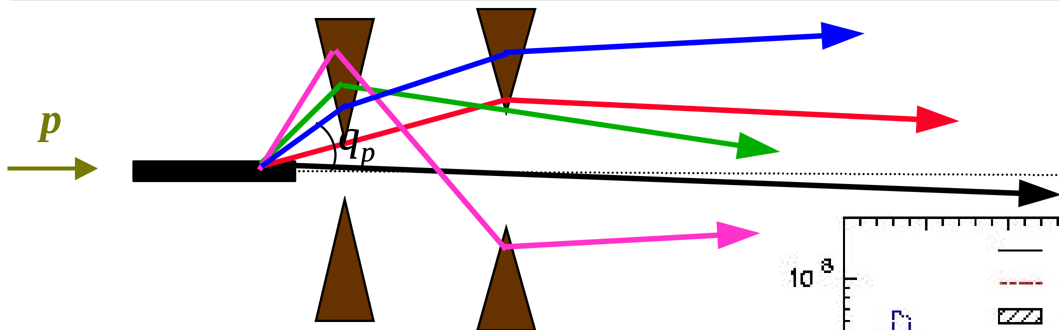
- Increased focusing of hose means hose tolerances less stringent:



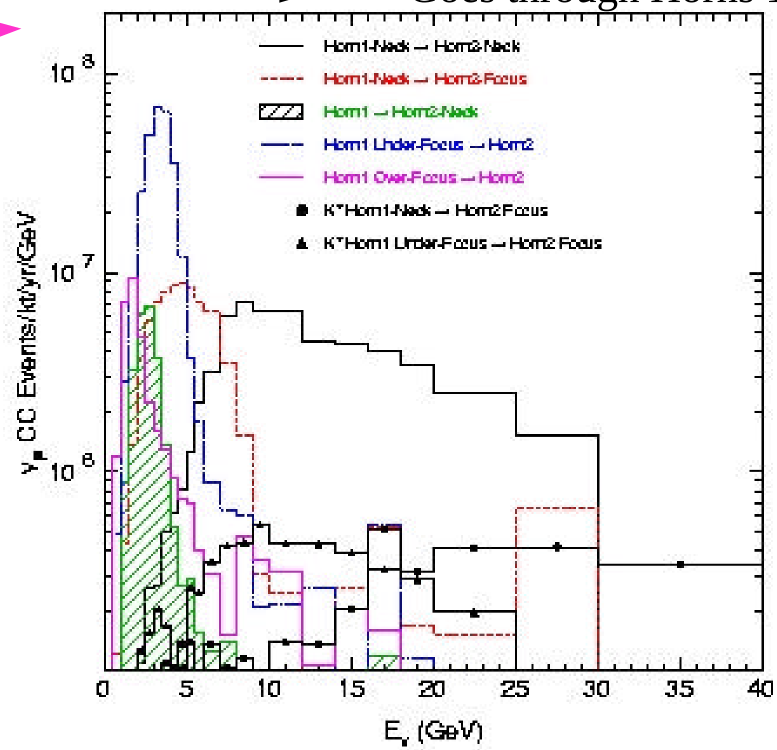
  - Horn Current variation: ±1.0% → ±1.5%;

    Eccentricity Horn 1 in. conductor: 0.08 mm → 0.10 mm

What are all those edges?



- p_T ~ 300 MeV/c for all p^+.
- $q_p = p_T/p \sim 1/g$.
- Can pretty much predict components of spectra just from apertures of horns.
- Leads to correlation between pion (ν_μ) energy and detector acceptances.
- Component through both horns just like 'bare' target.



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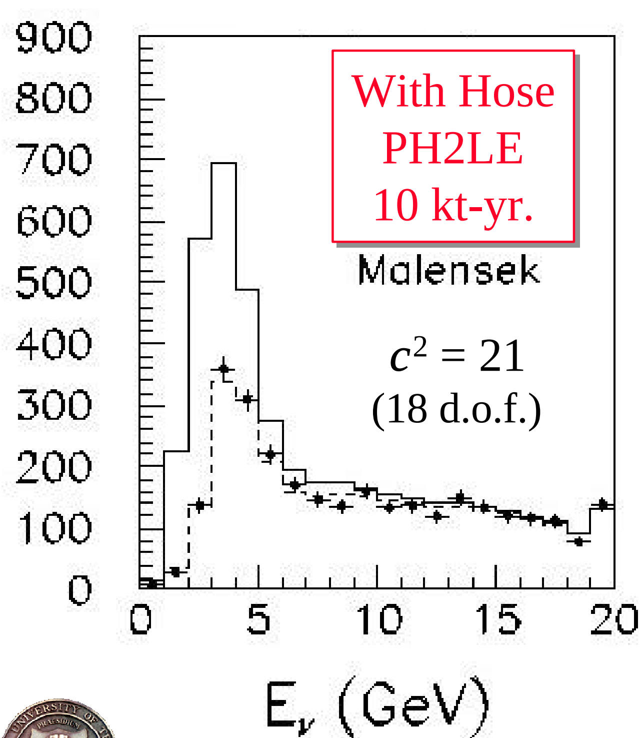
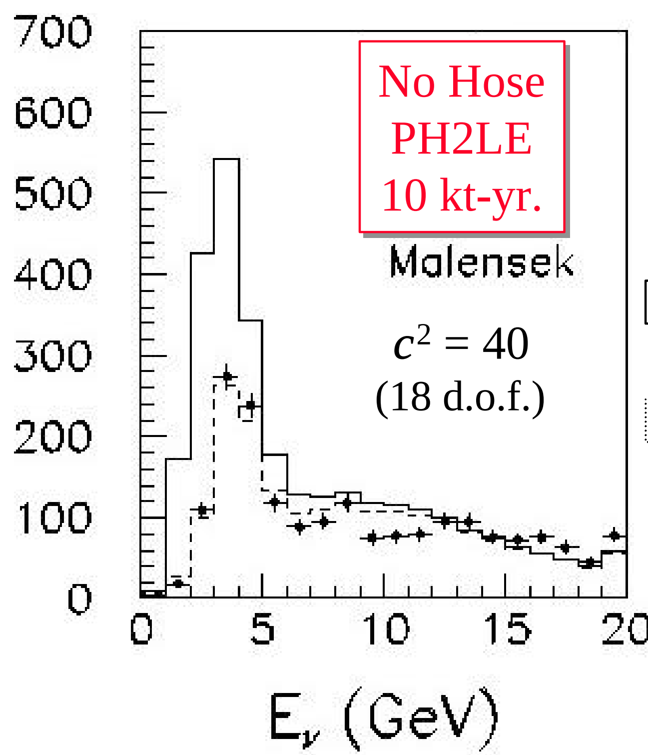
How Bad Could it Be?

- For most Δm^2, distortions won't produce oscillation-like signals.
- Accurate spectrum prediction for best parameter determination.

- Agreement across entire E_u important for credibility of measurement in oscillation region.





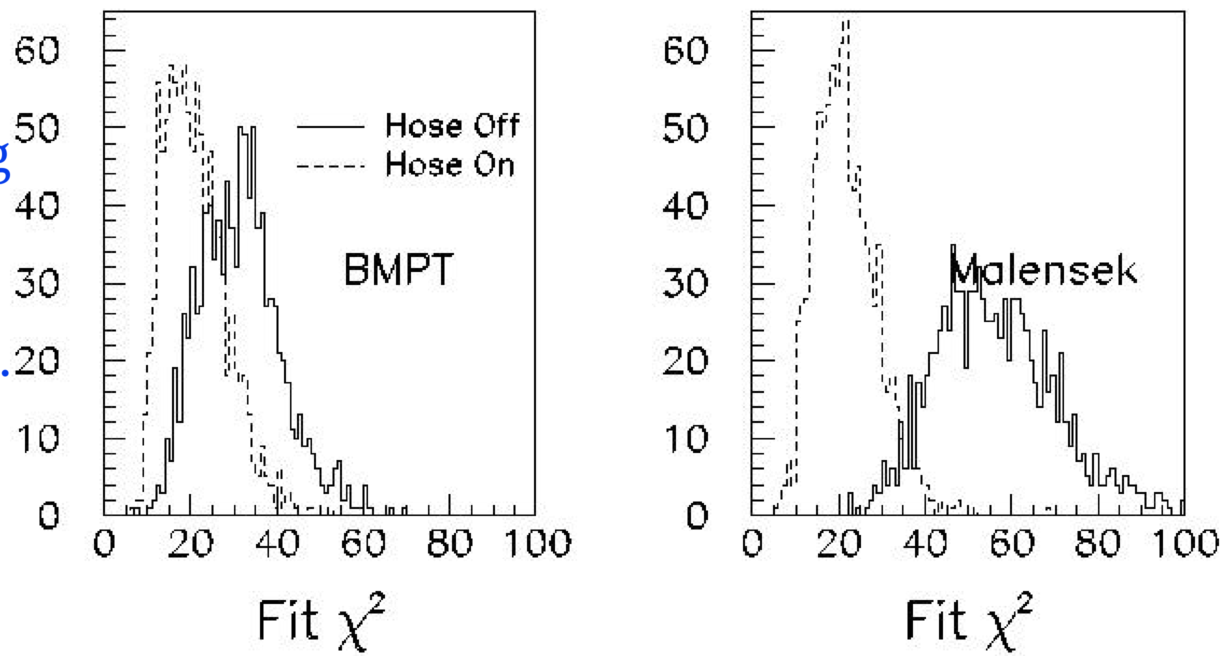
Expectation (no oscillations)

Expectation (Δm^2=0.002 eV^2)

● Far Detector Observed Events

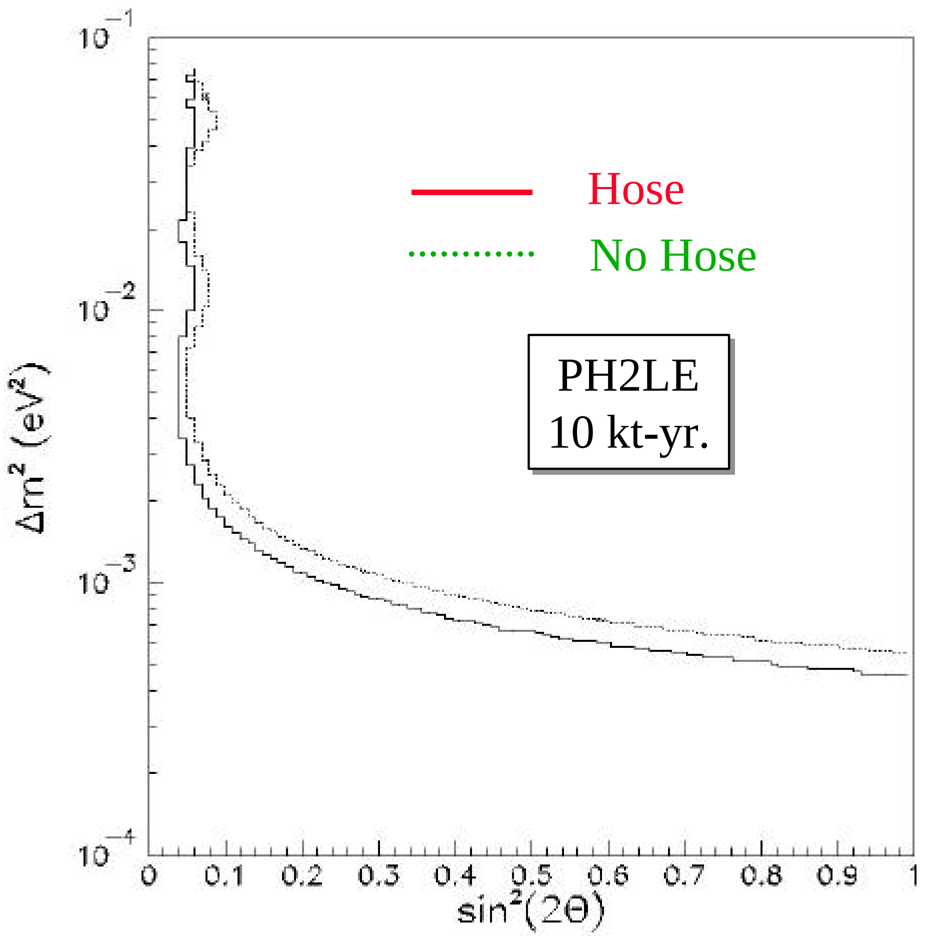
Look at Many "Experiments"

- Simulate MINOS experiments with 10 kt-yr. exposure.
- Generate using different hadron production models.
- Always extrapolate near→far using R_{FN} calculated with Geant/FLUKA.



Sensitivity Curves

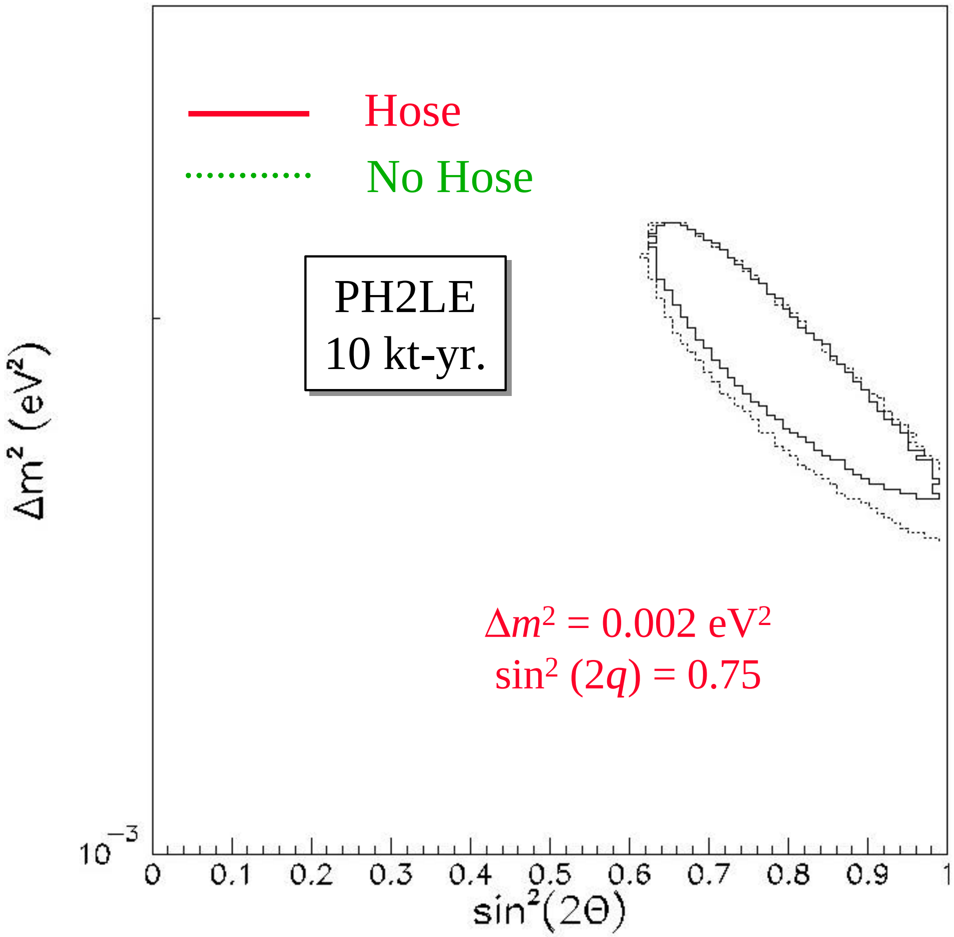
- Assumed spread of hadron production models as $s_{syst.}$
- At low Δm^2, benefit from increased statistics of hose
- At high Δm^2, benefit from lower systematic uncertainties with hose.



Improved Oscillation Fits

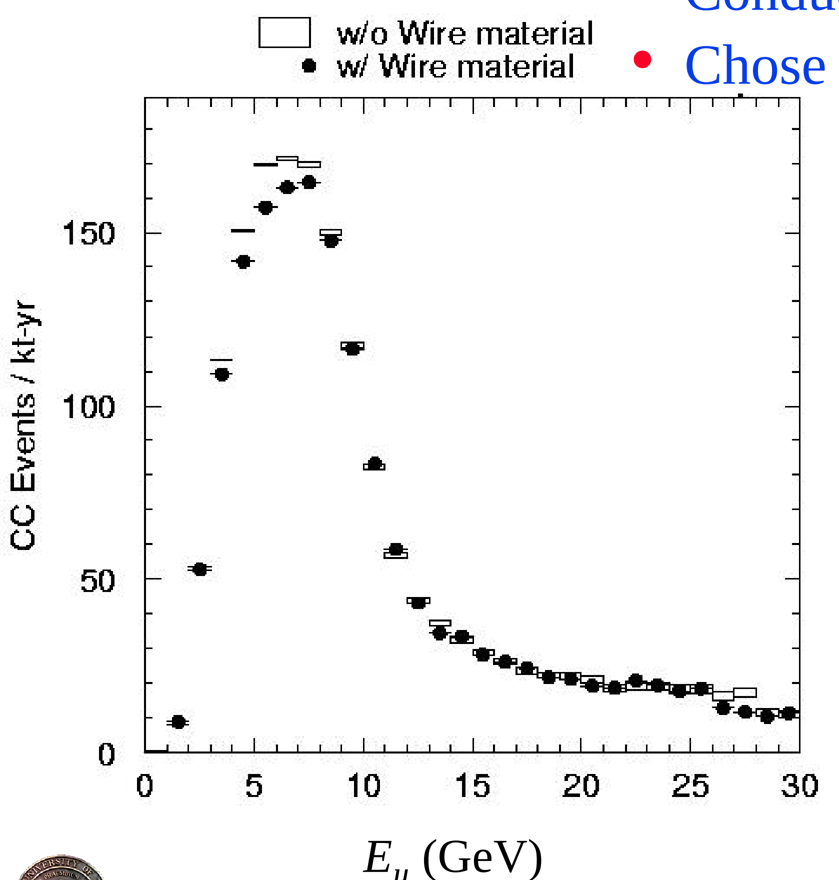
- At all Δm^2, resolution improves either due to statistics or due to systematics.

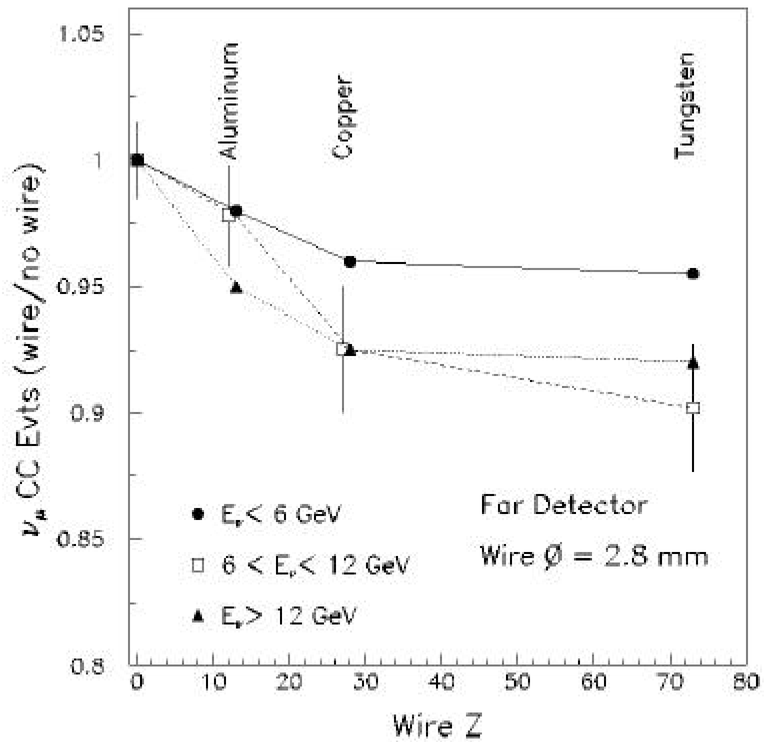
Δm^2input (eV^2)	Resolution (hose off)	Resolution (hose on)
.002	0.00023	0.00020
.003	0.00015	0.00012
.005	0.00016	0.00013
.007	0.00017	0.00013



Low Mass Wire

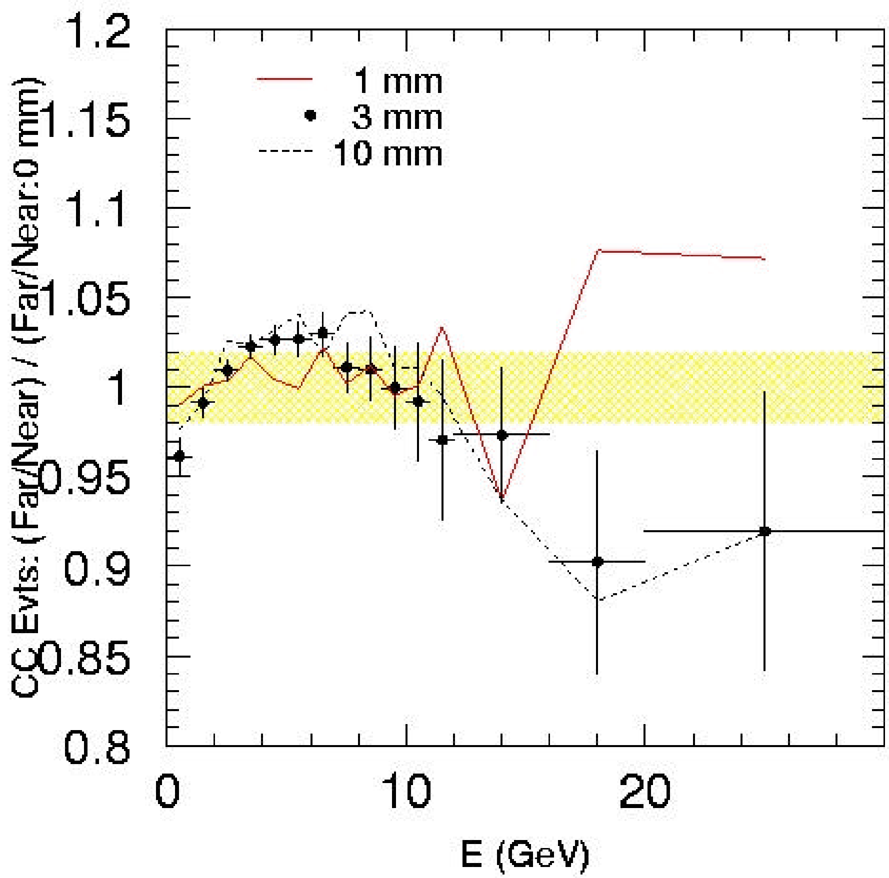
- Conductivity high ⇒ voltage drop low
- Chose Aluminum 1350, ECH 18





Wire Alignment

- MC indicates 2 mm is limit for wire sag.
- Practicality of ~1 m between wire spider supports.
- Must have ~ 300 psi wire tension.
- Only way to keep creep down is to keep temperature low.



Segment Failure

- Could run with as much as 10% of segment failures.
- Want to keep below 2% distortions.
- Here would *know* about the failure.
- Worst case: first two segments fail.
- Most likely case: upstream segments fail!