Why a muon collider?

What will we learn?

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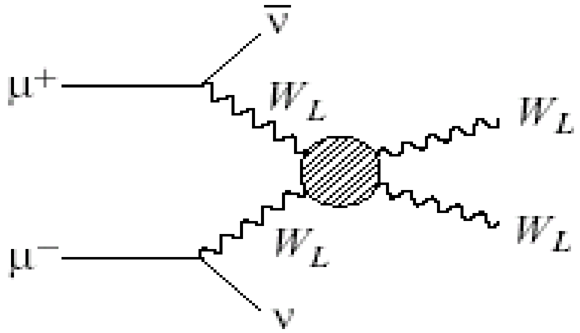
Why consider a Muon Collider?

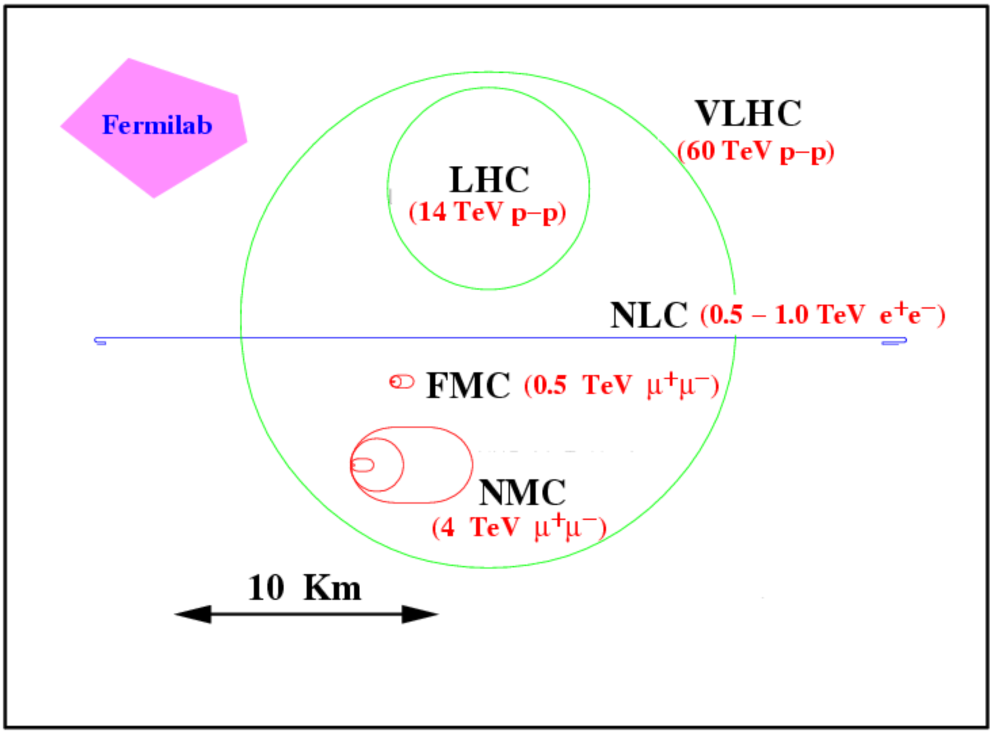
- The current story suggests that there “has” to be something at or approaching the TeV energy scale, but sooner or later we will want a multi-TeV lepton machine for precision measurements of SEWS (strongly interacting electroweak sector):



- The mass of the muon ($m_\mu/m_e = 207$) gives a μ collider some very desirable features:
  - ⇒ Less synchrotron ($\sim m^{-4}$), brem and init. state radiation => muons don’t radiate as readily as electrons:
    - ➢ much smaller beam energy spread ($\Delta p/p \sim 0.003\%$) ⟶ precise energy scans and hence precise mass and width measurements
    - ➢ easier to accelerate muons to higher energies ⟶ multi-TeV collider is possible.
  - ⇒ Larger couplings to Higgs-like particles ⟶ if $m_h < 2m_W$, possible to study Higgs boson production in the s-channel

A muon collider is compact…

- At least 2 generations of μ collider would fit on FNAL site =>> if feasible, could be significantly cheaper than other futuristic HEP colliders.
- Can be an upgrade to any other collider scheme.



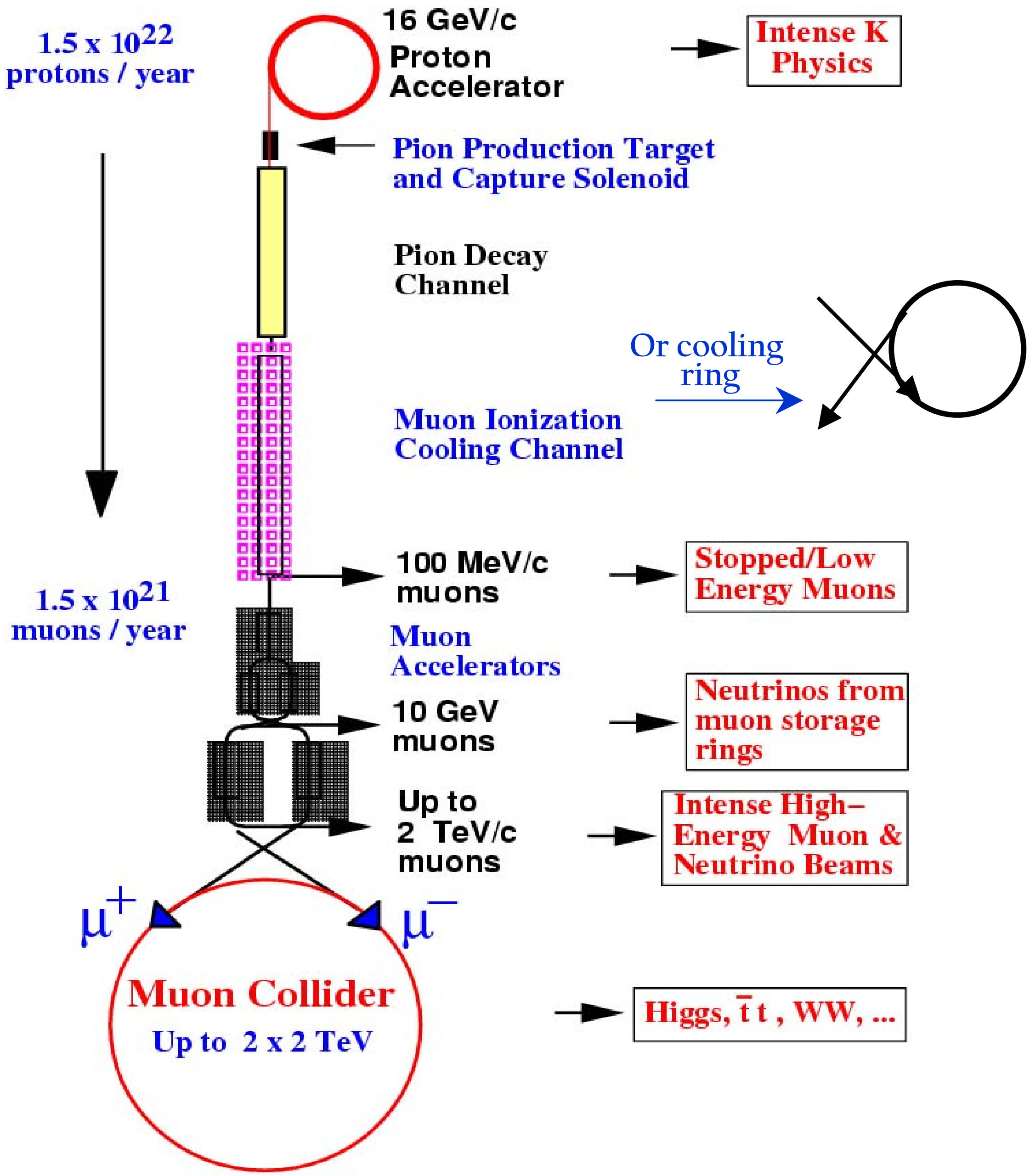
… and a challenge

- Short lifetime ⟶ need rapid acceleration
- Large PH init. μ beam ⟶ need rapid beam cooling
- Backgrounds:

  μ halo, $\mu^- \rightarrow e^- \nu_\mu \nu_e$, beamstrahlung, incoherent *e* production, μ pair production in EM showers (Bethe-Heitler)

Muon Collider Schematic

- Challenge: capture & cool μ's by ~ 10^5 in 6D PS
- Result: collider, proton driver, intense μ & ν beams



1.5×10^{22} protons / year

16 GeV/c Proton Accelerator

Intense K Physics

Pion Production Target and Capture Solenoid

Pion Decay Channel

Or cooling ring

Muon Ionization Cooling Channel

1.5×10^{21} muons / year

100 MeV/c muons

Stopped/Low Energy Muons

Muon Accelerators

10 GeV muons

Neutrinos from muon storage rings

Up to 2 TeV/c muons

Intense High–Energy Muon & Neutrino Beams

μ^+ μ^-

Muon Collider

Up to 2 x 2 TeV

Higgs, $\bar{t}t$, WW, ...

One possible muon collider…

500 GeV at Fermilab

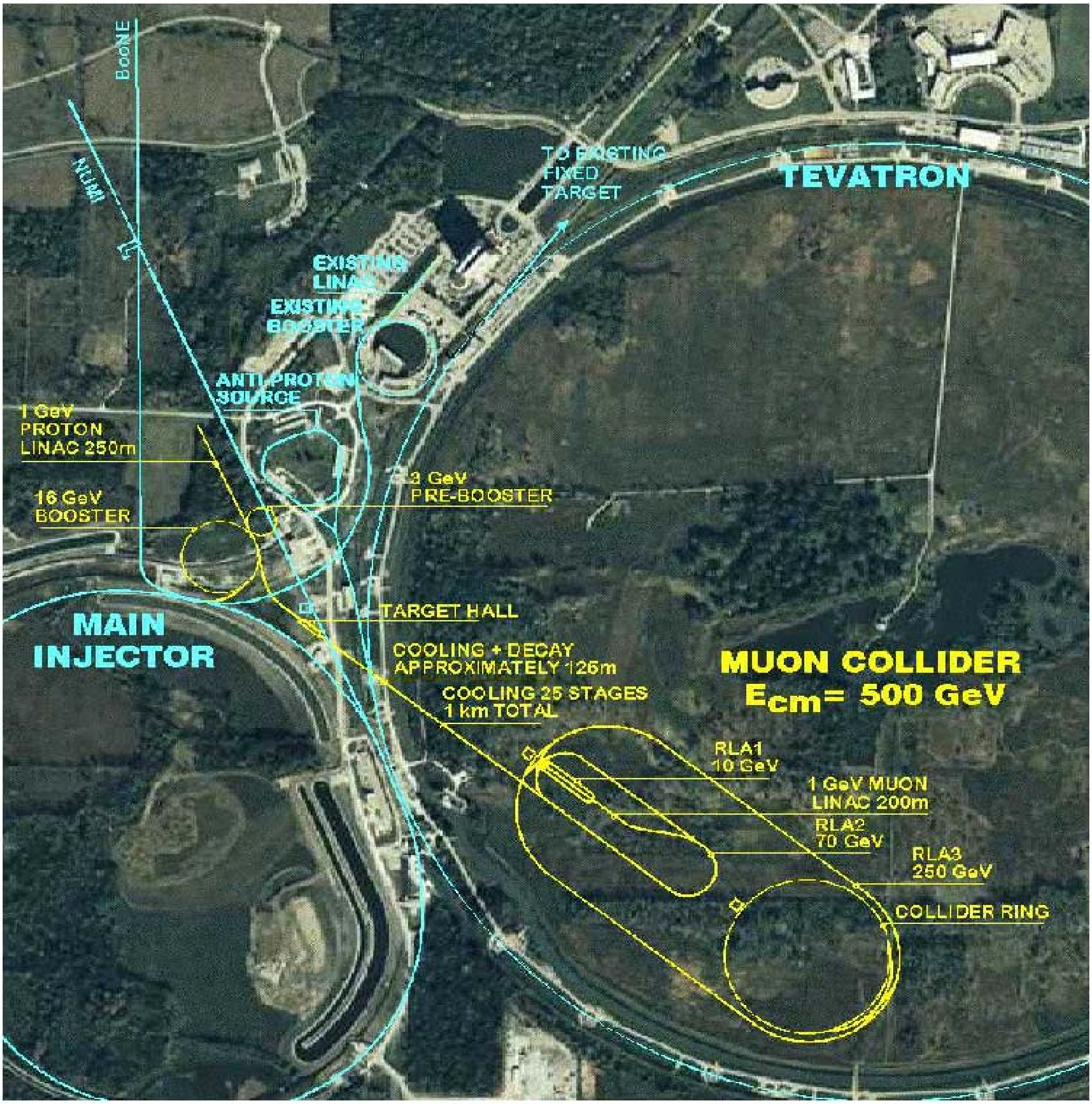


PHOTO DATE: OCTOBER 1997

Physics

- Falls into 3 categories:
  - **Front end** physics with a high intensity μ source
  - "First Muon Collider" (FMC) physics at c.o.m. energies 100-500 GeV
  - "Next Muon Collider" (NMC) physics at 3-4 TeV c.o.m.
- Front End:
  - ⇒ rare muon processes
  - ⇒ neutrino physics
  - ⇒ μp collider > leptoquarks, lepton flavor dep.
  - ⇒ stopped/slow intense μ beam physics
- First μC: s-channel resonance & $\Delta E/E \sim 10^{-6}$
  - ⇒ Higgs factory
  - ⇒ Technicolor
  - ⇒ Threshold cross sections:
    W^+W^-, tt, Zh, $\chi^+_1\chi^-_1$, $\chi^0_1\chi^0_1$ SS: l^+l^-, $\nu\nu$, ...
  - ⇒ Z^0 factory (using muon polarization)
- Next μC:
  - ⇒ High mass SS particles, Z' resonances
  - ⇒ If no Higgs < 1 TeV => Strong WW scattering

Other muon collider issues

- ***R***: Gaussian spread in beam energy can be made very small, but at cost of luminosity:

  Some "conservative" calculations:

  - $\mathcal{L} \sim (0.5,1,6) * 10^{31}\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ for $R = (0.003, 0.01, 0.1)\%$ and $\sqrt{s} \sim 100$ GeV
  - $\mathcal{L} \sim (1,3,7) * 10^{32}\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ for $\sqrt{s} = (200, 350, 400)$ GeV and $R \sim 0.1\%$

  So, μC best for: $h \longrightarrow \mu^+\mu^-$ $\Delta E_{beam}/E_{beam} = 0.01R$

  H0 and A0 peak separation, Higgs scan

  CP of Higgs bosons

  - Good measurement of $h \longrightarrow \tau^+\tau^-$ possible

- At FNAL unique opportunity for μ*p* collisions:

  200 GeV μ beams in collision with 1 TeV p beam:

  - $\mathcal{L} \sim 1.3 * 10^{23}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$, $\sqrt{s} = 894$ GeV

- Neutrino Factory a natural intermediate step!

- Luminosity can be improved by further R & D in emittance exchange, cooling, targetry.

  May be the best for extreme energies

  Can guarantee access to heavy SUSY particles, Z' and strong WW scattering if no Higgs Bosons and no SUSY

- If μ's and *e*'s are fundamentally different, a μC is necessary!

Front End Physics

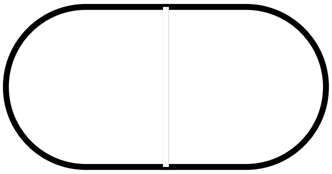
- Rare & stopped muon decays
  - $\mu \longrightarrow e\gamma$ branching fract. < $0.49 * 10^{-12}$
  - $\mu N \longrightarrow eN$ conversion
  - μ electric dipole moment
  - SUSY GUTS theories: these lepton violating or CP violating processes should occur via loops at "significant" rates:

    e.g. BF $(\mu \longrightarrow e\gamma) \sim 10^{-13}$

- μp collider
  - Probe lepto-quarks up to mass $M_{LQ} \sim 800$ GeV
  - Maximum $Q^2 \sim 8 * 10^4\ \text{GeV}^2$ (90 X HERA)
  - At FNAL: 200 GeV μ's on 1 TeV *p*'s
    - $\sqrt{s} = 894$ GeV, $L = 13\ \text{fb}^{-1}/\text{year}$

Neutrino Factory

- Neutrinos from a muon storage ring (μ decay)
  - ⇒ For ~ 10^{21} μ's/year could get $O(10^{20})$ ν's/year in the straight section.
  - ⇒ Point straight section to desired direction



Arc length = straight length
25% of decays could be pointed

Arc length ~ 50m for 10 GeV, 200m for 100 GeV
(lattice calculation by C. Johnstone)

- Precisely known flavour content

  $\mu^+ \longrightarrow e^+ \nu_e \bar{\nu}_\mu$, 50% ν_e ($\bar{\nu}_\mu$)
- Absolute flux (constrained kinematics, machine parameters)

oscillation	detect
$\nu_\mu \Rightarrow \nu_e$	e^-
$\nu_\mu \Rightarrow \nu_\tau$	τ^-
$\bar{\nu}_e \Rightarrow \bar{\nu}_\mu$	μ^+
$\bar{\nu}_e \Rightarrow \bar{\nu}_\tau$	τ^+

For example:

- $P(\nu_a \longrightarrow \nu_b) = \sin^2 2\theta \sin^2(1.27\,\delta m^2 L/E)$ **=>** $\delta m^2 \sim 10^{-5}$ eV^2/c^2 for $\sin^2 2\theta = 1$ with ~1000 events/yr
- CP violation studies, neutrino masses, rare decays

Higgs

- Away from the *s*-channel pole, *e* and μ colliders have similar capabilities for same $\sqrt{s}$ and $\mathcal{L}$
- Currently: L = 50 fb^{-1}/year for *e*
  L = 10 fb^{-1}/year for μ

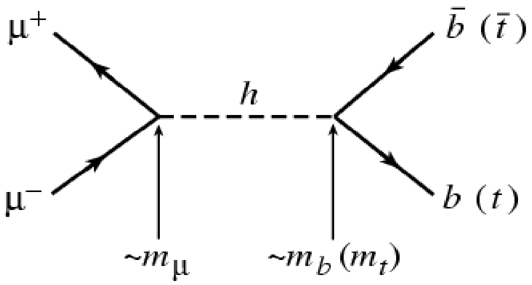


FIGURE 1. Feynman diagram for s-channel production of a Higgs boson.

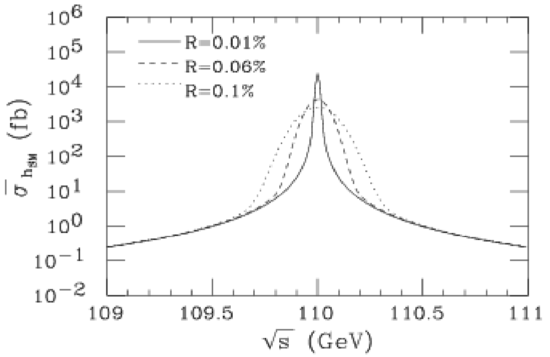
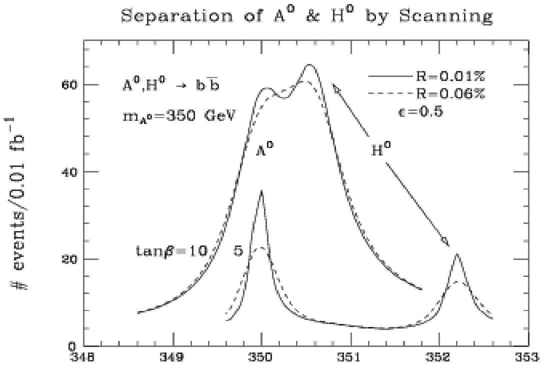


FIGURE 2. The effective cross section, $\bar{\sigma}_{h_{SM}}$, for $R = 0.01\%$, $R = 0.06\%$, and $R = 0.1\%$ vs. $\sqrt{s}$ for $m_{h_{SM}} = 110$ GeV.

- Very large cross section at s-channel pole for m collider
- Small R is crucial for peaking.
- $$\sigma \approx 2MeV \frac{R}{0.003\%} \frac{\sqrt{s}}{100GeV}$$ can be as small as width of SM-like Higgs

Scanning

Exploiting R to Separate H^0, A^0 :



R< 0.1

- H^0, A^0 discovery possibilities are limited at other machines, (constrained at various values of m_{A0} and tanβ)
- If available, H^0, $A0 \longrightarrow t\bar{t}$ and $H^+H^- \longrightarrow t\bar{c}, c\bar{t}$ for $\sqrt{s} <$ 2 TeV
- Some previous knowledge of m_{A0} can yield precise measurements of H^0 and A^0 for all tanβ > 1-2.

Precision measurement of m_W and m_t :

	Tevatron		LHC	*e*C	μC			
L_{tot} (fb^{-1})	2	10	10	50	1	3	10	50
Δm_W (MeV)/c^2	22-35	11-20	15	15-20	63	36	20	10
Δm_t (GeV)/c^2	4	2	2	0.12-0.2	0.63	.36	0.2	0.1

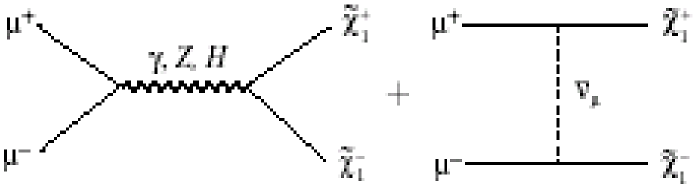
- At μC, small R => errors are always statistics dominated: accurracy is ~ 2X better than at *e*C
- L_{tot} > 50fb-1 is not useful for *e*C: errors are systematics dominated.

More threshold production..

tt, h thresholds:

- such measurements are valuable for determining as, $\Gamma^{tot}{}_{t}$, $|V_{tb}|^2$ as well as m_t
- Δm_h ~ 100MeV for m_h ~ 115 GeV

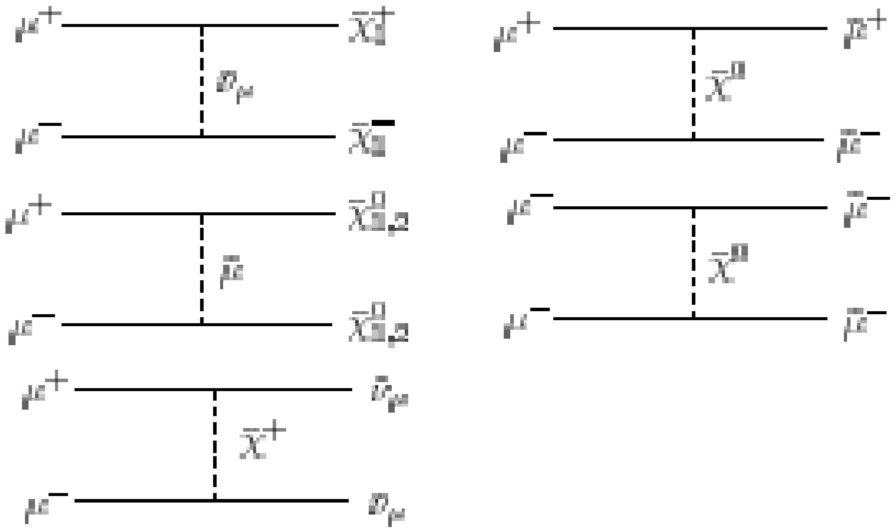
Two channels (s and t) for light chargino production:



For L = 50 fb^{-1}, R = 0.1%:

$\Delta m_{\tilde{\chi}_1^\pm}$ (MeV)	$m_{\tilde{\chi}_1^\pm}$ (GeV)	$m_{\tilde{\nu}_\mu}$ (GeV)
35	100	500
45	100	300
150	200	500
300	200	300

In the threshold regions, $\tilde{\chi}_1^+, \tilde{\nu}_\mu$ masses can be inferred from the shape of the cross sections



The ultimate SM probe

When all the noble dreams disappear…

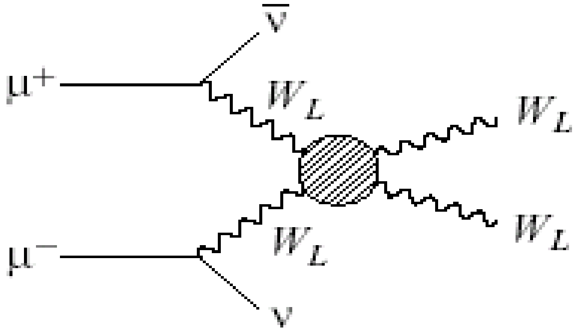


Figure 1. Symbolic diagram for strong VV scattering.

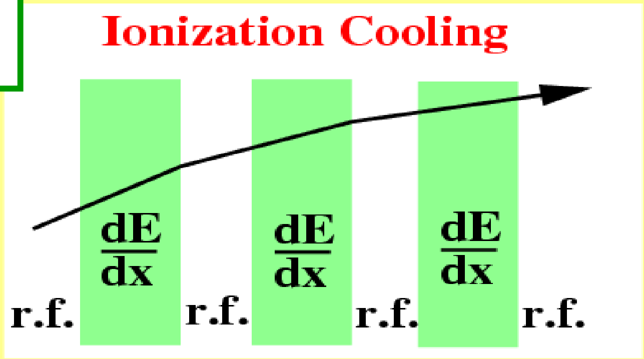
- LHC or LC may yield first evidence of SEWS, but for many models evidence may be of marginal statistical significance.

- Several Models:
  - SM with heavy Higgs boson $m_H = 1$ TeV
  - “scalar model with I=0, S=0 but non-SM width
  - “vector” model with I=1, s=1 vector resonance
  - SM Higgs of infinite mass

- Neither “light” Higgs nor SUSY exists!
  - $A \sim (W_L W_L \longrightarrow W_L W_L) \sim s_{WW}/v^2$ where $\sqrt{s_{WW}} \geq 1.5$ TeV
  - The nature of the dynamics here is unknown! We’ll need all information possible

New stuff: Ionization cooling

1



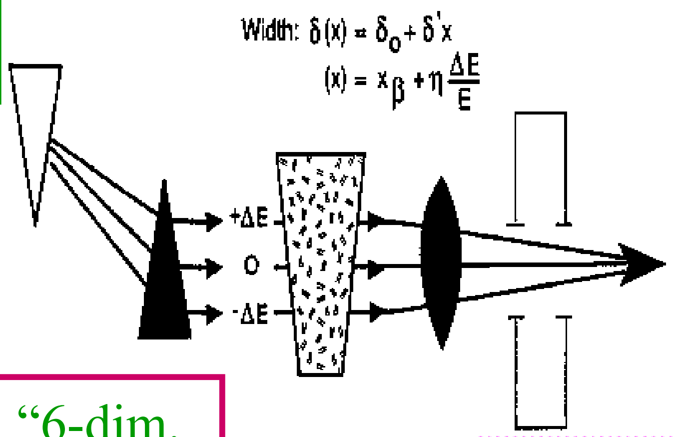
Transverse Cooling

Muons lose energy by dE/dx and longitudinal momentum replaced by r.f.

"4-dim. cooling"

- **To Minimize heating from Coulomb Scattering:**
  - **Small $\beta_\perp$ (strong focusing) : High–field solenoids or Lithium Lenses**
  - **Large L_R (low–Z absorber) : Liquid H_2**

2



Energy "Cooling"

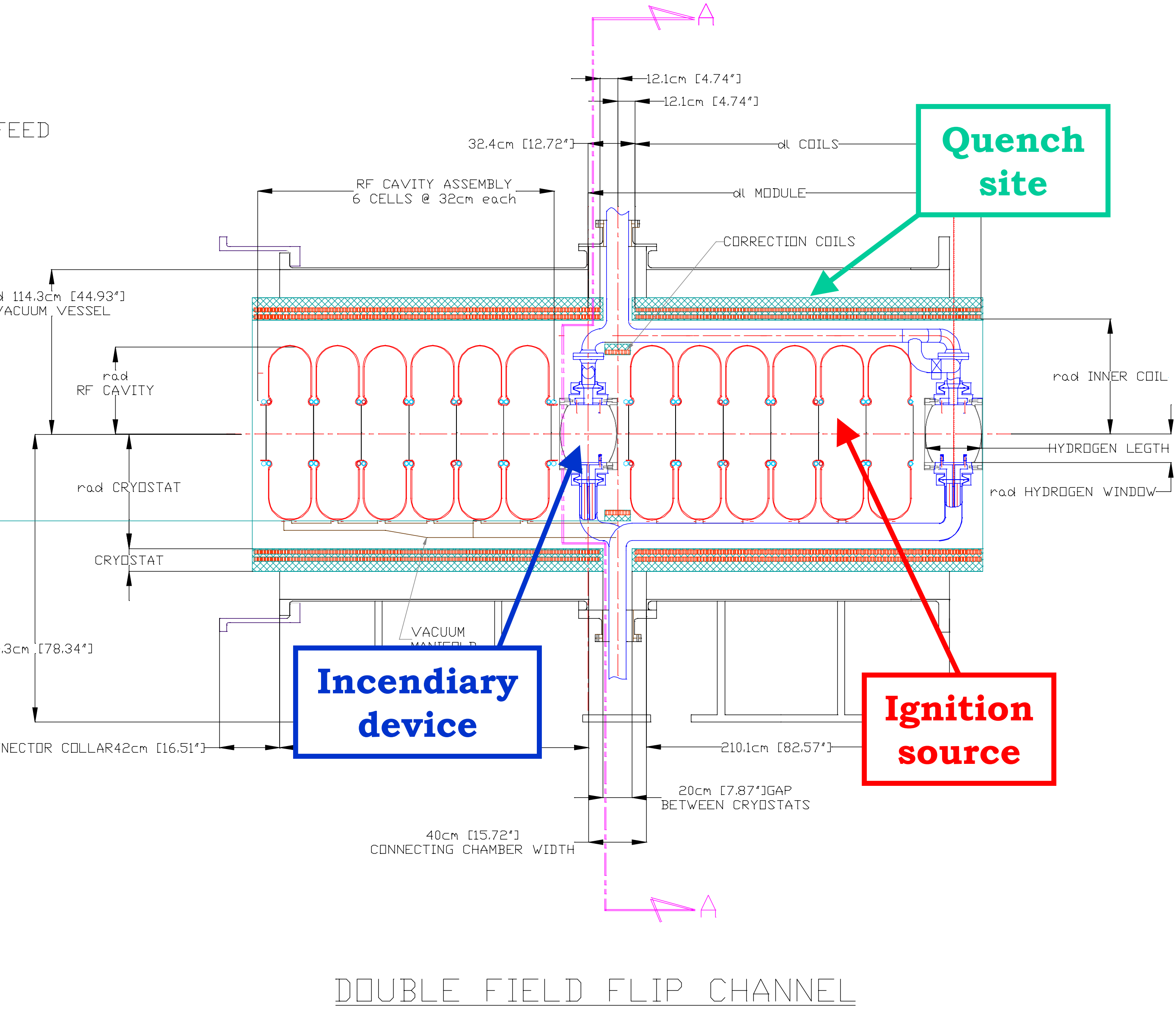
Ionization cooling using a wedge plus dispersion.

Exchanges emittance between transverse & longitudinal directions

"6-dim. cooling"

1) Sufficient for Neutrino Factory
2) Needed for Muon Collider

Risks: Cooling Channel Design



Quench site

Incendiary device

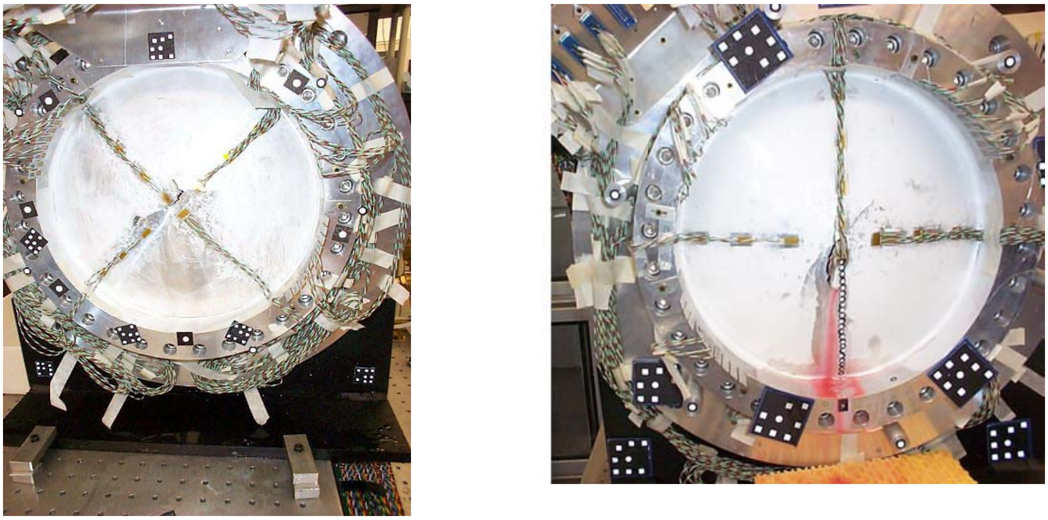
Ignition source

Shown here, a cooling cell with LH_2 Absorbers, RF cavities and Solenoid Magnet

Danger

- Testing the limits with new window design

Burst test for the LH2 absorber window:



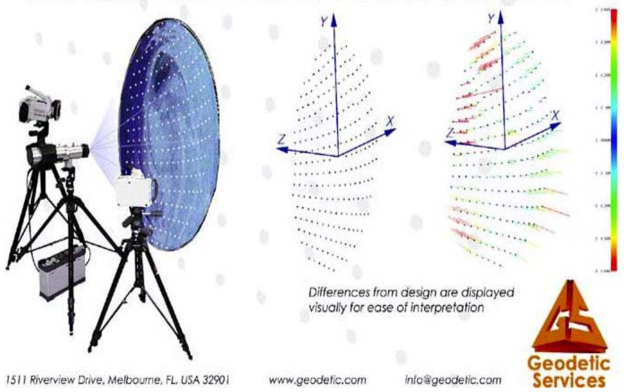
- Rediscovering solenoidal focussing!

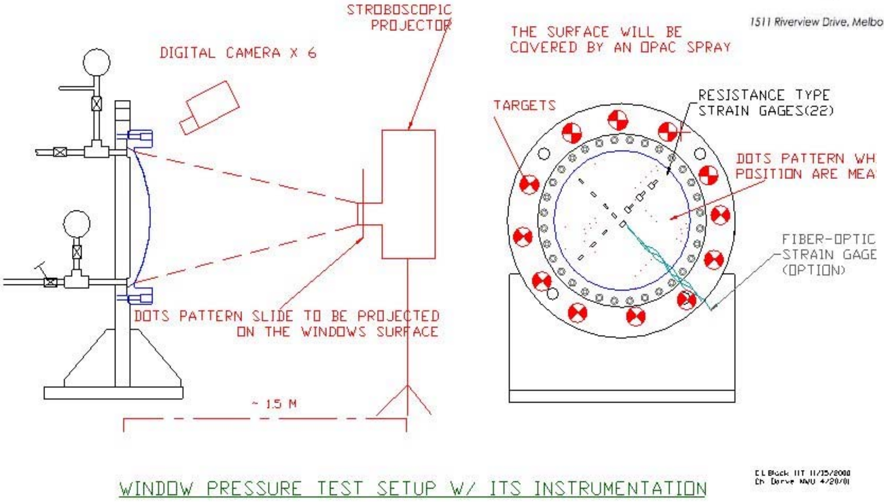
High gradient RF cavity within a solenoid – reducing dark current is essential: plexiglass windows demonstrate the destruction

Fun

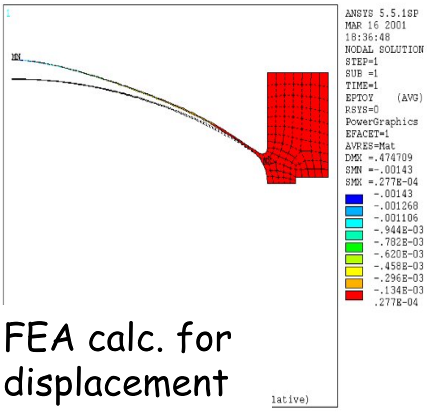
Pushing Technology:

Non-contact measurement of strain by calculating displacement



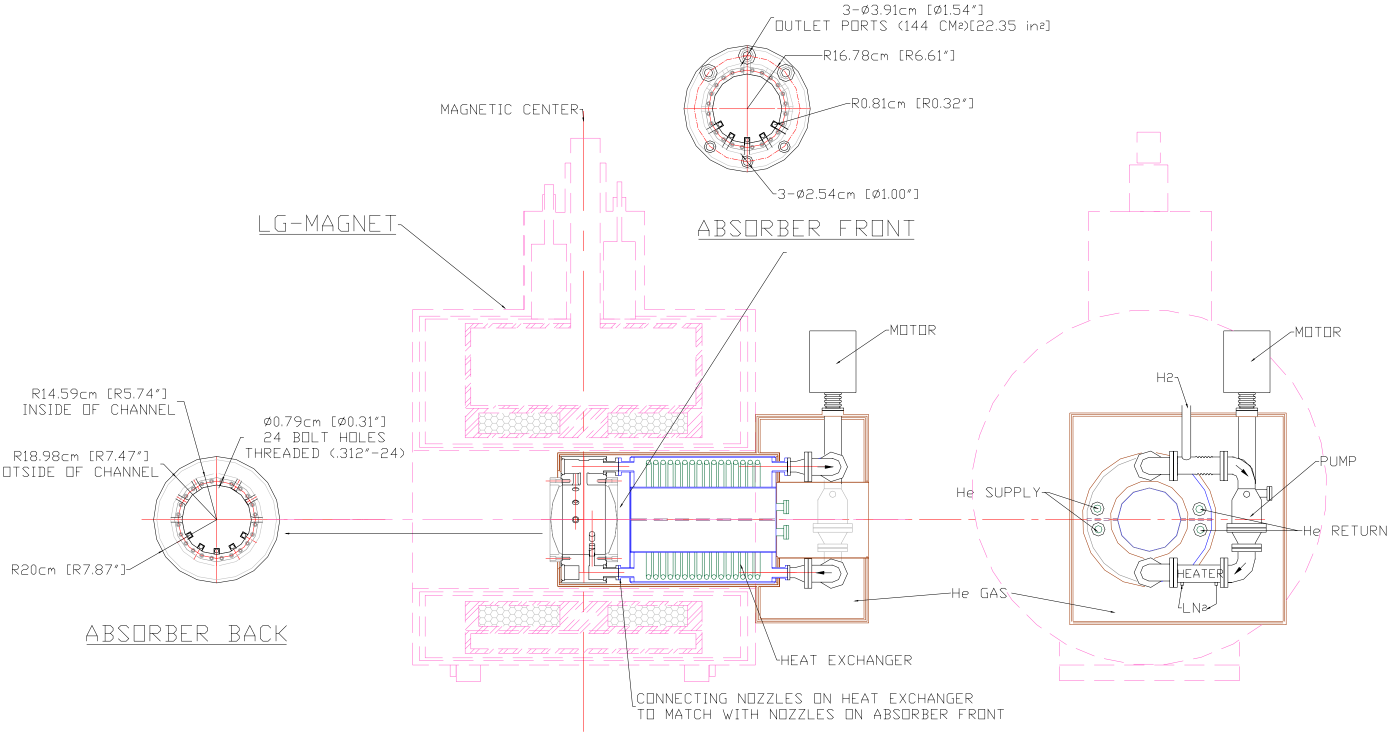


WINDOW PRESSURE TEST SETUP W/ ITS INSTRUMENTATION



FEA calc. for displacement

Design of LINAC LH2 Abs Beam Test



View from the FNAL LINAC access –
Test beam site for MuCool

Concluding remarks

- Hadron colliders have traditionally been the “discovery” machines, and the Tevatron and LHC at this time, may be no exception.
- We don’t have enough information to make a decision to commit to any ~ $10G machine at this time.
- We can’t build any proposed machine even if we got the ~ $10G at this time.
- Accelerator and detector R & D is needed for all major proposed machines, and breakthroughs in any of them help all of them.
- Muon colliders are the farthest reaching machines and furthest away from being built at this time: both statements support a strong R & D program.
- However, an early implementation of the μC, the ν factory, is a machine that technically and financially could be feasible ~ next 10 years.
- Aggressive accelerator and detector R & D is the only way we move from a “story” driven field to become a data driven field.
- Muon collaboration is a strong group of accelerator and particle physicists, reversing a > 40 year trend.