Muon Collider

- Unique: s-channel Higgs Factory

Std Model and Multi-Higgs, L → few x 10^{31}

- Ultra Fine DE/E → few x 10-5

- Upward evolution to 3 – 6… TeV cms

L → few x 10^{34} → Recapture Energy Frontier

- HEF → SUSY, NSD, W-fusion, "W-collider"
  Z' narrow resonance would allow low luminosity 10^{30} HEF program (little or no cooling)

- Staged program
  that builds upon Intensity Frontier

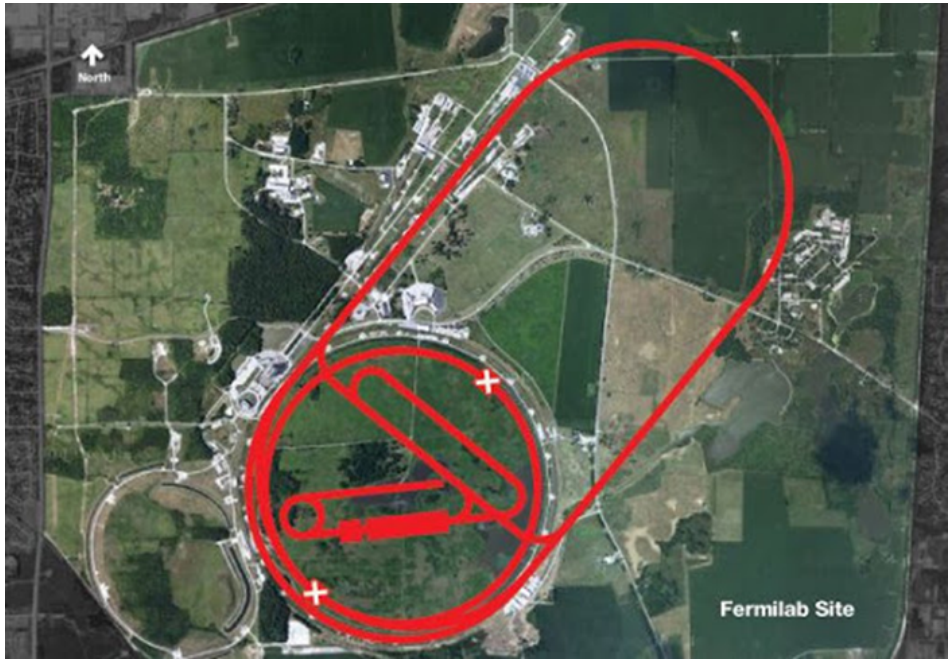
→ Project-X

→ Muon Storage Ring
  advanced Neutrino program

→ S-channel Higgs Factory

→ High Energy Frontier Machine

- Compact footprint stages + synchrotron



Energy Frontier: 3 TeV cms (3.6 km circumference, 2 detectors)
L > 10^{34} (350 fb^{-1} /year)

Muon Collider

- Unique: s-channel Higgs Factory

Std Model and Multi-Higgs, L → few x 10^{31}

- Ultra Fine DE/E → few x 10-5

- Upward evolution to 3 – 6… TeV cms

L → few x 10^{34} → Recapture Energy Frontier

- HEF → SUSY, NSD, W-fusion, "W-collider"
  Z' narrow resonance would allow
  low luminosity 10^{30} HEF program
  (little or no cooling)

- Staged program
  that builds upon Intensity Frontier

→ Project-X

→ Muon Storage Ring
  advanced Neutrino program

→ S-channel Higgs Factory

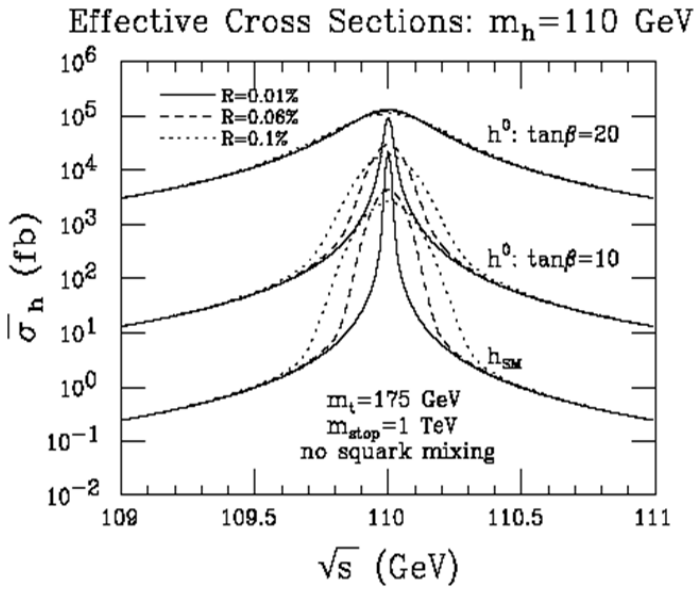
→ High Energy Frontier Machine

- Compact footprint stages + synchrotron

Higgs Factory: 125 GeV cms
(350 m circum, 1-2 detector?)
L > 10^{31} (2 fb^{-1} /year)

S-Channel Higgs Production

Barger, Gunion, Han



$$\sigma_h = \frac{4\pi\Gamma(h \to \mu\bar{\mu})\ \Gamma(h \to b\bar{b})}{(s - m_h^2)^2 + m_h^2\Gamma_h^2}$$

$h(125)$	$\longrightarrow$	$b\bar{b}$	5.78×10^{-1}	W^+W^-	2.16×10^{-1}
		$\tau\bar{\tau}$	6.37×10^{-2}	Z^0Z^0	2.67×10^{-2}
		$c\bar{c}$	2.68×10^{-2}	gg	8.56×10^{-2}
		$s\bar{s}$	4.40×10^{-4}	$\gamma\gamma$	2.30×10^{-3}
		$\mu^+\mu^-$	2.21×10^{-4}	$Z^0\gamma$	1.55×10^{-3}

$$\Gamma(h(125)) = 4.03\ \text{MeV}$$

m_H = 125 GeV:

- Higgs couples to mass so rate enhanced by $\left[\frac{m_\mu}{m_e}\right]^2 = 4.28 \times 10^4$ so the cross section is $\sigma(\mu^+\mu^- \to h) = 49.2$ pb
- The excellent energy resolution of a muon collider makes the process observable.
- To obtain the same sensitivity to Higgs decay modes in a electron collider via Zh process as s-channel production at a MC requires more than 1000 times the integrated luminosity.

Collider parameter	Small δE 125 GeV Collider
Energy/beam	62.5 GeV
Luminosity	10^{31}
Proton Energy, Power	8GeV, 4MW
N_p/bunch, frequency	5×10^{13}, 60 Hz
N_μ/ bunch	1.5×10^{12}
ε_L, ε_T	0.002, 0.0005m
β^*	0.1m
σ_{IR}	0.3mm
Collider circumference C	350m
δE	2 MeV
σ_{bunch}	10cm
$\delta\nu_{beam\text{-}beam}$	0.0003

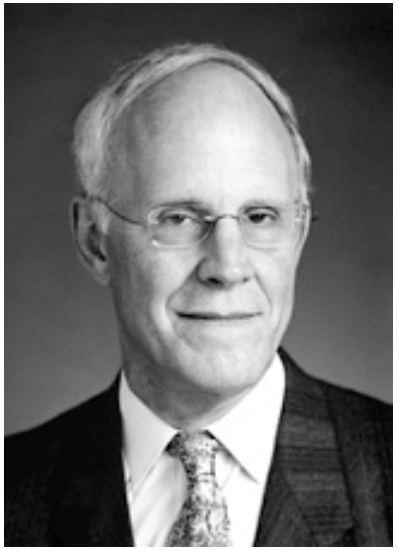
D. Neuffer, 15th Advanced Accelerator Concepts Workshop, Austin, TX (June 10-15, 2012)

Carlo Rubbia thinks the next big experiment in particle physics should be a muon collider.

"With a Higgs of 125 GeV we need only a modest machine, perhaps not a large linear collider." Rubbia points out that muons colliding at a combined energy of roughly 125 GeV would suffice – just over half the energy of LEP and requiring a machine with a much smaller radius.

One physicist who shares Rubbia's vision is David Gross …

"A muon collider is a great idea," …
"and one that the US should take the lead on."



physicsworld.com/cws/article/news/50159

A Muon Collider provides a Staged Pathway from the Intensity Frontier to the Energy frontier via a Unique Higgs Factory

- The observation of a new state at 125 GeV by both ATLAS and CMS revitalizes consideration of a Higgs factory as part of a staged multi-Tev muon collider. This is particularly attractive if there is an enlarged scalar sector (eg. THDM, SUSY)
- A multiTeV lepton collider will be required for full coverage of Terascale physics.
- The physics potential for a muon collider at $\sqrt{s} \sim 3$ TeV and integrated luminosity of 1 ab^{-1} is outstanding. Particularly strong case for SUSY and new strong dynamics.
- Narrow s-channel states played an important role in past lepton colliders. If such states exist in the multi-TeV region, they will play a similar role in precision studies for new physics. Sets the minimum luminosity scale.
- A staged Muon Collider can also provide a Neutrino Factory to fully disentangle neutrino physics.

- Only a Low energy Muon Collider can directly measure full width of h(125)
  $\sigma_{peak} \times 10^{31} \times (1\ SMyr) = 10k$ Higgs

- Given LHC discovery, it is imperative that a full feasibility study be done for Higgs Factory option with staged Muon Collider scenario

Physics and detector studies have begun and initial studies indicate backgrounds can be handled with fast timing pixelated detectors. More work (and help) is needed for a convincing demonstration.

Meet at UCLA, Spring 2013, https://hepconf.physics.ucla.edu/higgs2012/index.html

Backup

Evolution in Energy of Muon Collider

For $\sqrt{s} < 500$ GeV

- SM thresholds: Z^0h ,W^+W^-, top pairs
- Higgs factory ($\sqrt{s} \approx 126$ GeV) ✔

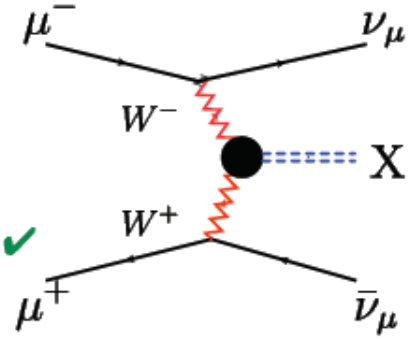
For $\sqrt{s} > 500$ GeV

- Sensitive to possible Beyond SM physics.
- High luminosity required. ✔
  - Cross sections for central ($|\theta| > 10°$) pair production ~ R × 86.8 fb/s(in TeV^2) (R ≈ 1)
  - At $\sqrt{s}$ = 3 TeV for 100 fb^{-1} ~ 1000 events/(unit of R)

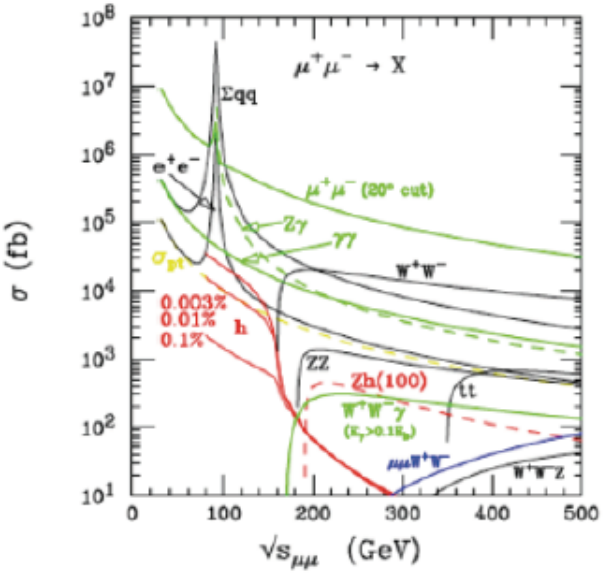
For $\sqrt{s} > 1$ TeV

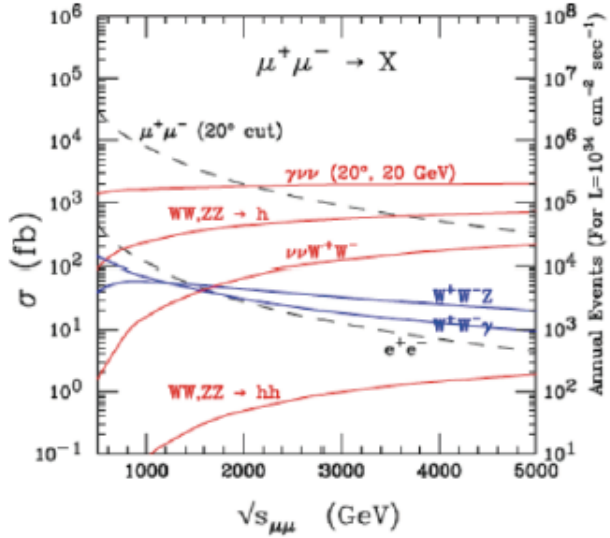
- Fusion processes important at multi-TeV MC

$$\sigma(s) = C \ln\left(\frac{s}{M_X^2}\right) + \ldots$$



- An Electroweak Boson Collider ✔





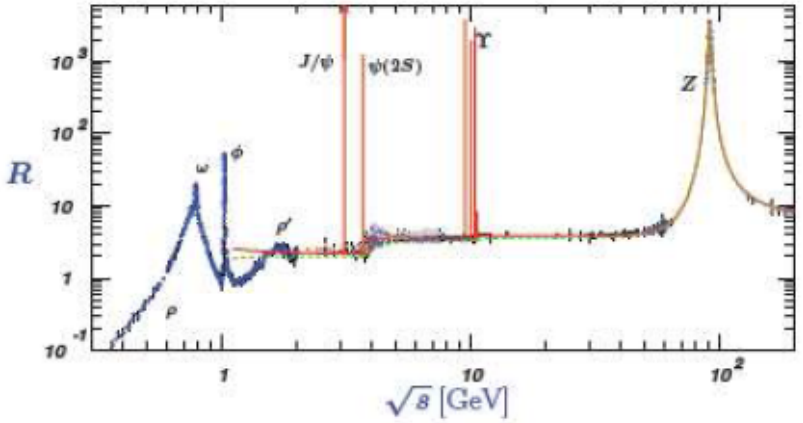
Example: S Channel Resonances

- Universal behavior for s-channel resonance

$$\sigma(E) = \frac{2J+1}{(2S_1+1)(2S_2+1)}\frac{4\pi}{k^2}\left[\frac{\Gamma^2/4}{(E-E_0)^2+\Gamma^2/4}\right]B_{in}B_{out}$$

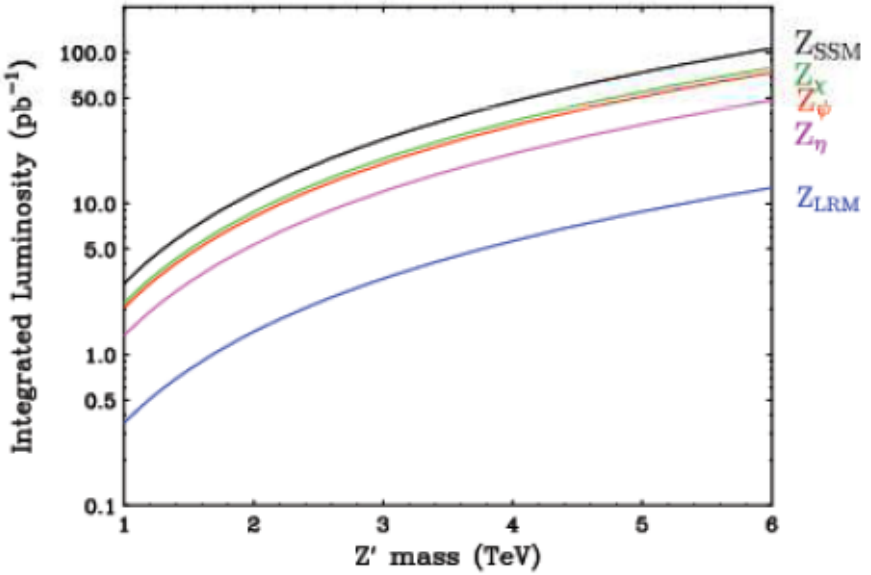
Convolute with beam resolution ΔE.
If ΔE≪ Γ

$$R_{\text{peak}} = (2J+1)3\frac{B(\mu^+\mu^-)B(visible)}{\alpha^2_{\text{EM}}}$$

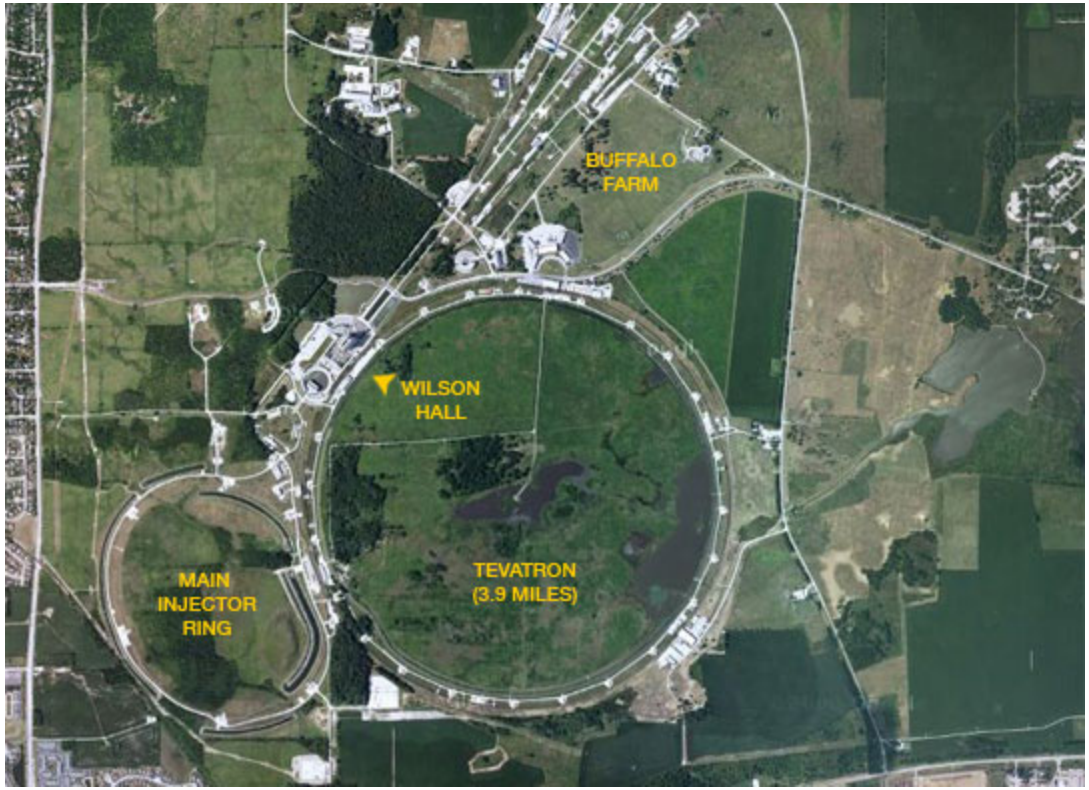


- Can use to set minimum required luminosity for a muon colider:
  - Likely new physics candidates:
    - scalars: h, H^0, A^0,...
    - gauge bosons: Z′
    - new dynamics: bound states
    - ED: KK modes
  - Example - new gauge boson: Z′
    - SSM, E6, LRM
    - 5σ discovery limits: 4-5 TeV at LHC (@ 300 fb^{-1})

Minimum luminosity at Z′ peak:
$\mathcal{L} = 0.5\text{-}5.0 \times 10^{30}$ cm^{-2} sec^{-1}
for M(Z′) -> 1.5-5.0 TeV



The integrated luminosity required to produce 1000 $\mu^+\mu^-$ -> Z′ events on the peak


BUFFALO
FARM
WILSON
HALL
MAIN
INJECTOR
RING
TEVATRON
(3.9 MILES)

Rich High Energy Program Potential at Muon Collider

The Telluride 2011 Top Five Benchmark Studies

Process	Observables	Experimental considerations	Theoretical considerations	Strategy
Z'	M, Γ couplings final states	energy scale = M ? beam energy resolution initial state polarization ? cone size	coupling strength L – R chiral compelling models	first priority if confirmed at LHC; may enable low-L machine
WW fusion	M couplings states?	beam energy initial state polarization cone size !	coupling strength strong dynamics (broad TeV scale Higgs)	High priority if no low mass Higgs at LHC
SUSY	many states decay chains m's, Br's, σ's	beam energy resolution initial state polarization missing ET cone size	Mainstream theory perturbative dynamics MSSM or else?	Simply depends upon confirmation at LHC
Dark Matter	γ or Z + missing ET	cms frame is known initial state polarization? missing ET cone size	Very interesting how powerful are limits? Need the paper asap !	High priority appears easy to dc
Contact Term				

The SM Higgs:

- All properties are determined for given mass.
- Any deviations signal new physics.

Theoretical questions:

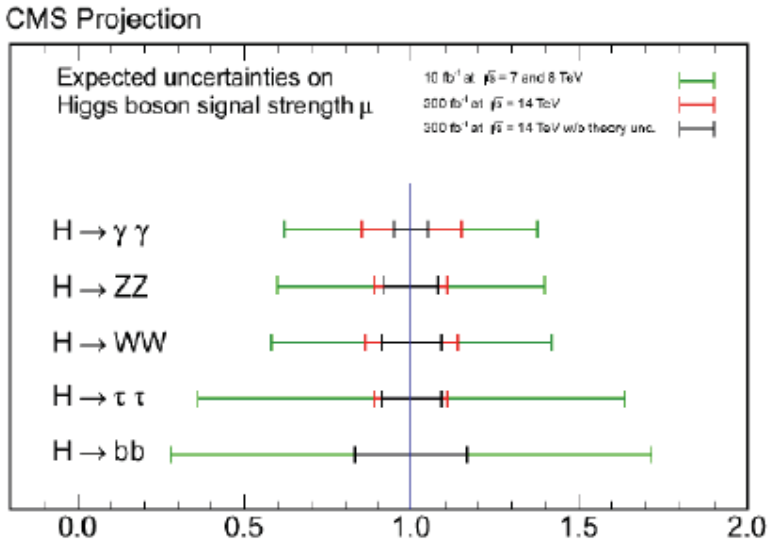
- Couplings and width SM?
- Scalar self-coupling SM?
- Any additional scalars? EW doublets, triplets or singlets? (e.g. SUSY requires two Higgs doublets)
- Any invisible decay modes?

What can be done at the LHC?

- New projections from ATLAS and CMS:
- With 3000 fb^{-1} at 14 TeV:
  - Further error reduction by factor of 3 (stat)
  - Observe H->$\mu^+\mu^-$ to 6 σ. (ATLAS)
  - Measure the Higgs self-coupling to 30% (ATLAS)

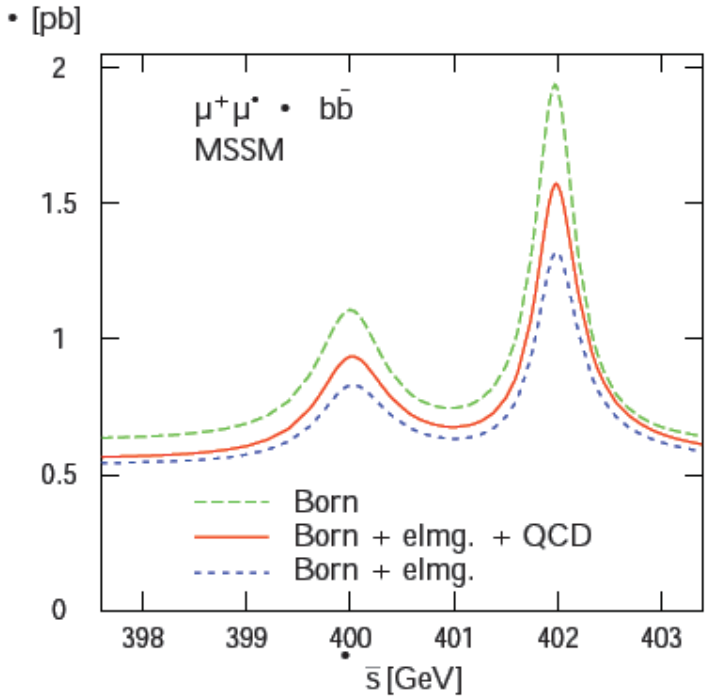
$$
\begin{array}{llllll}
h(125) & \longrightarrow & b\bar{b} & 5.78\times10^{-1} & W^+W^- & 2.16\times10^{-1} \\
 & & \tau\bar{\tau} & 6.37\times10^{-2} & Z^0Z^0 & 2.67\times10^{-2} \\
 & & c\bar{c} & 2.68\times10^{-2} & gg & 8.56\times10^{-2} \\
 & & s\bar{s} & 4.40\times10^{-4} & \gamma\gamma & 2.30\times10^{-3} \\
 & & \mu^+\mu^- & 2.21\times10^{-4} & Z^0\gamma & 1.55\times10^{-3}
\end{array}
$$

$$\Gamma(h(125)) = 4.03 \text{ MeV}$$



- Good energy resolution is needed for H^0 and A^0 studies:
  - for s-channel production of H^0 : $\Gamma/M \approx 1\%$ at $\tan\beta = 20$.
  - nearby in mass need good energy resolution to separate H and A.
  - can use bremsstrahlung tail to see states using bb decay mode.

good benchmark process for MC



Dittmaier and Kaiser [hep-ph/0203120]

- Strong case for a Muon Collider

Rich High Energy Program Potential at Muon Collider

Telluride, June, 2011 Discussion Points

(1) Supersymmetry full model simulations

(2) Extra Dimensions: KK Modes (Moose models)

(3) Contact Interactions

(4) Z' Narrow Resonances

(5) WW, WZ , ZZ fusion processes

(6) Higgs and Multi-Higgs (H^0 A^0 Resonances)

(7) Dark Matter (gamma + missing E)

(8) New Strong Dynamics

(9) Standard Model Physics

Discussion:
Physics Benchmarks for Lepton Colliders

Purpose of Benchmarks:

Probe efficacy of Muon Collider (cone angle, bkgnds, pol., L , dE/E , E)

Compare and contrast e+e- and $\mu+\mu-$ machines:
- Energy reach?
- Luminosity?
- polarization?
- dE/E ?

Test physics discovery potential against background and geometry issues

Benchmarks should be robust as the new physics emerges at LHC

Provide useful issues for detector simulation studies
- e.g., how is forward WW fusion impacted by cone blockout?
- how is reconstruction affected by polarization, dE/E?

For $\sqrt{s}$ < 500 GeV

- SM thresholds: Z^0h ,W^+W^-, top pairs
- Higgs factory ($\sqrt{s} \approx$ 126 GeV) ✔

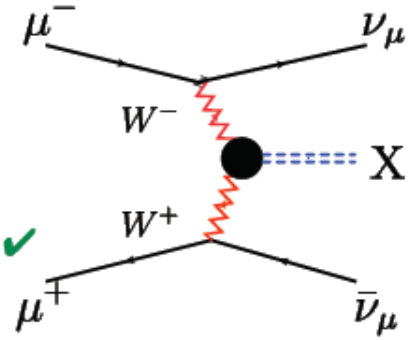
For $\sqrt{s}$ > 500 GeV

- Sensitive to possible Beyond SM physics.
- High luminosity required. ✔
  - Cross sections for central ($|\theta|$ > 10°) pair production ~ R × 86.8 fb/s(in TeV^2) (R ≈ 1)
  - At $\sqrt{s}$ = 3 TeV for 100 fb^{-1} ~ 1000 events/(unit of R)

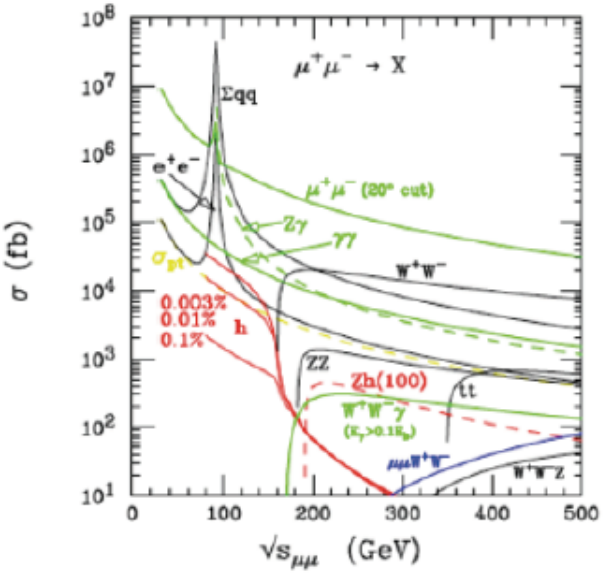
For $\sqrt{s}$ > 1 TeV

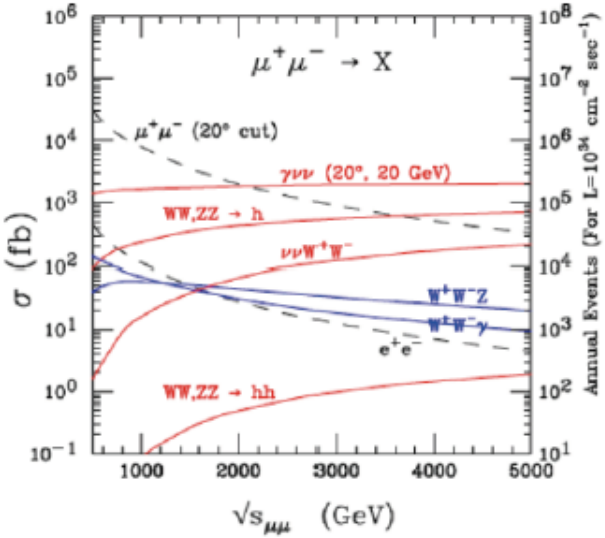
- Fusion processes important at multi-TeV MC

$$\sigma(s) = C \ln(\frac{s}{M_X^2}) + \ldots$$



- An Electroweak Boson Collider ✔





Two Higgs doublets expected in MSSM

- Five scalar particles: h^0, H^0, A^0, $H^{\pm}$
- The LHC has difficulty observing the H, A especially for masses > 500 GeV. Even at $\sqrt{s}$ = 14 TeV and 300 fb^{-1}
- Pair produced easily at a multi-TeV lepton collider.

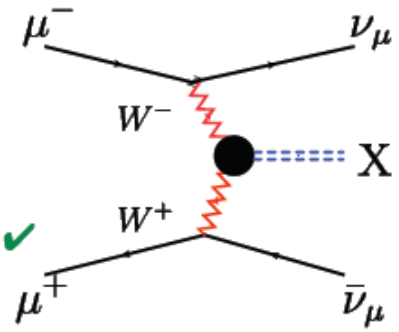
Decoupling limit $m_{A^0} >> m_{Z^0}$:

- h^0 couplings close to SM values
- H^0, $H^{\pm}$ and A^0 nearly degenerate in mass
- H^0 small couplings to VV, large couplings to ZA^0
- For large $\tan\beta$, H^0 and A^0 couplings to charged leptons and bottom quarks enhanced by $\tan\beta$. Couplings to top quarks suppressed by $1/\tan\beta$ factor

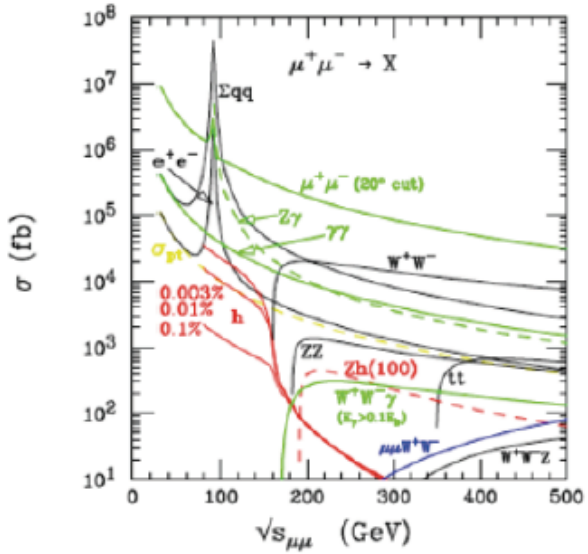
Basics of a Muon Collider

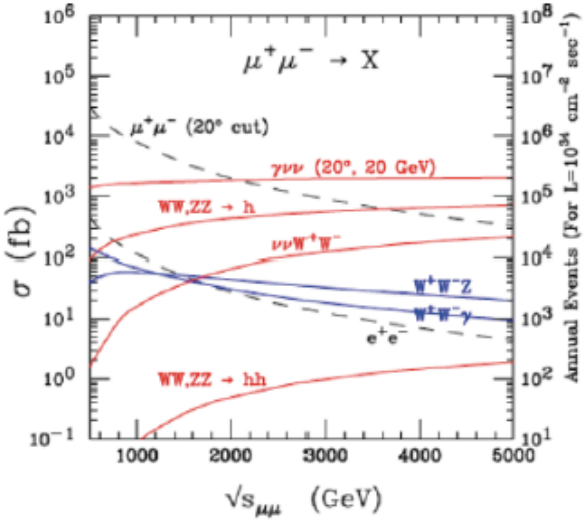
- For $\sqrt{s}$ < 500 GeV
  - SM thresholds: Z^0h ,W^+W^-, top pairs
  - Higgs factory ($\sqrt{s}\approx$ 126 GeV) ✔
- For $\sqrt{s}$ > 500 GeV
  - Sensitive to possible Beyond SM physics.
  - High luminosity required. ✔
    - Cross sections for central ($|\theta|$ > 10°) pair production ~ R × 86.8 fb/s(in TeV^2) (R ≈ 1)
    - At $\sqrt{s}$ = 3 TeV for 100 fb^{-1} ~ 1000 events/(unit of R)
- For $\sqrt{s}$ > 1 TeV
  - Fusion processes important at multi-TeV MC

$$\sigma(s) = C\ln(\frac{s}{M_X^2}) + \ldots$$



  - An Electroweak Boson Collider ✔



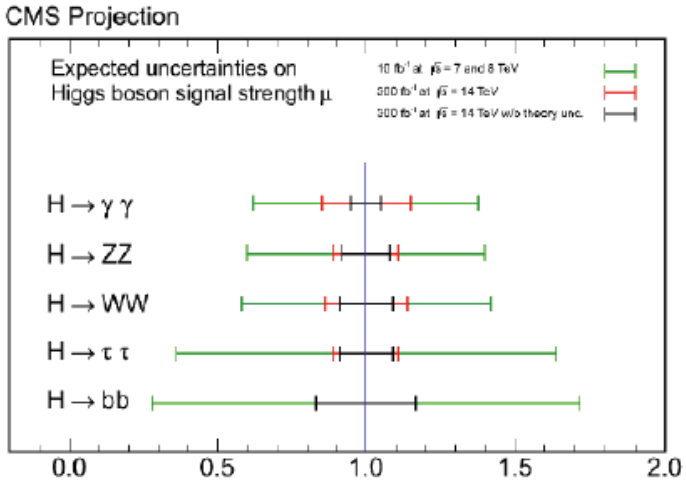


The Scalar Sector

- The SM Higgs:
  - All properties are determined for given mass.
  - Any deviations signal new physics.
- Theoretical questions:
  - Couplings and width SM?
  - Scalar self-coupling SM?
  - Any additional scalars? EW doublets, triplets or singlets? (e.g. SUSY requires two Higgs doublets)
  - Any invisible decay modes?
- What can be done at the LHC?
  - New projections from ATLAS and CMS:
  - With 3000 fb^{-1} at 14 TeV:
    - Further error reduction by factor of 3 (stat)
    - Observe H->$\mu^+\mu^-$ to 6 σ. (ATLAS)
    - Measure the Higgs self-coupling to 30% (ATLAS)

$h(125)$	$\longrightarrow$	$b\bar{b}$	5.78×10^{-1}	W^+W^-	2.16×10^{-1}
		$\tau\bar{\tau}$	6.37×10^{-2}	Z^0Z^0	2.67×10^{-2}
		$c\bar{c}$	2.68×10^{-2}	gg	8.56×10^{-2}
		$s\bar{s}$	4.40×10^{-4}	$\gamma\gamma$	2.30×10^{-3}
		$\mu^+\mu^-$	2.21×10^{-4}	$Z^0\gamma$	1.55×10^{-3}

$$\Gamma(h(125)) = 4.03 \text{ MeV}$$



The Scalar Sector

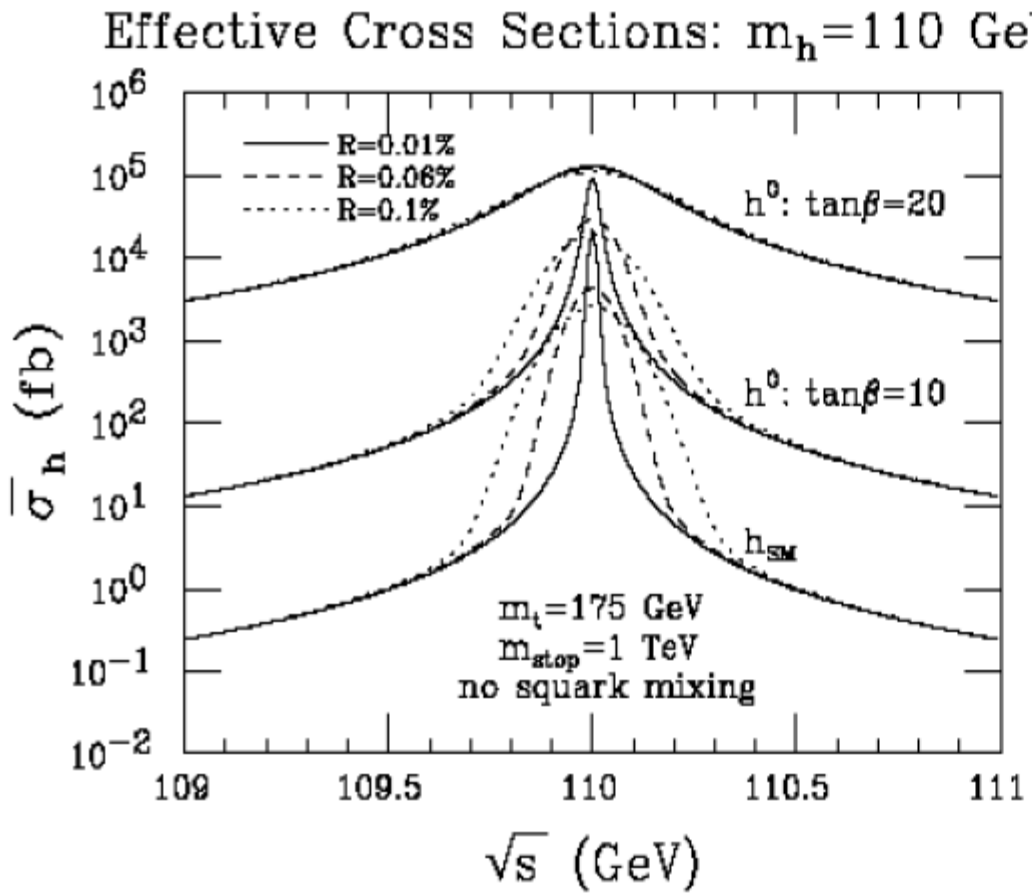
- The Role for Lepton Colliders
  - Only lepton collider can measure the h -> cc and h -> gg decays directly.
  - Precise measurements of the h -> W^+W^-, Z^0Z^0 probe if the higgs is composite or if there is any other mechanism contributing to EWSB.
  - Electron colliders (linear or circular) do detailed studies of Higgs decays using the associated production process:
    $\sigma(e^+e^- \to Zh \to l^+l^- h) = 19.1$ fb

Table 5: Summary of results obtained in the Higgs studies for $m_H = 120$ GeV. All analyses at centre-of-mass energies of 350 GeV and 500 GeV assume an integrated luminosity of 500 fb^{-1}, while the analyses at 1.4 TeV (3 TeV) assume 1.5 ab^{-1}(2 ab^{-1}).

Higgs studies for $m_H = 120$ GeV							
$\sqrt{s}$ (GeV)	Process	Decay mode	Measured quantity	Unit	Generator value	Stat. error	Comment
350	SM Higgs production	$ZH \to \mu^+\mu^- X$	σ	fb	4.9	4.9%	Model independent, using Z-recoil
			Mass	GeV	120	0.131	
500		$ZH \to q\bar{q}q\bar{q}$	$\sigma \times$ BR	fb	34.4	1.6%	$ZH \to qqqq$ mass reconstruction
			Mass	GeV	120	0.100	
500		$ZH, H\nu\bar{\nu}$ $\to \nu\bar{\nu}q\bar{q}$	$\sigma \times$ BR	fb	80.7	1.0%	Inclusive sample
			Mass	GeV	120	0.100	
1400	WW fusion	$H \to \tau^+\tau^-$	$\sigma \times$ BR	fb	19.8	<3.7%	
3000		$H \to b\bar{b}$			285	0.22%	
		$H \to c\bar{c}$			13	3.2%	
		$H \to \mu^+\mu^-$			0.12	15.7%	
1400 3000	WW fusion		Higgs tri-linear coupling g_{HHH}			~20% ~20%	

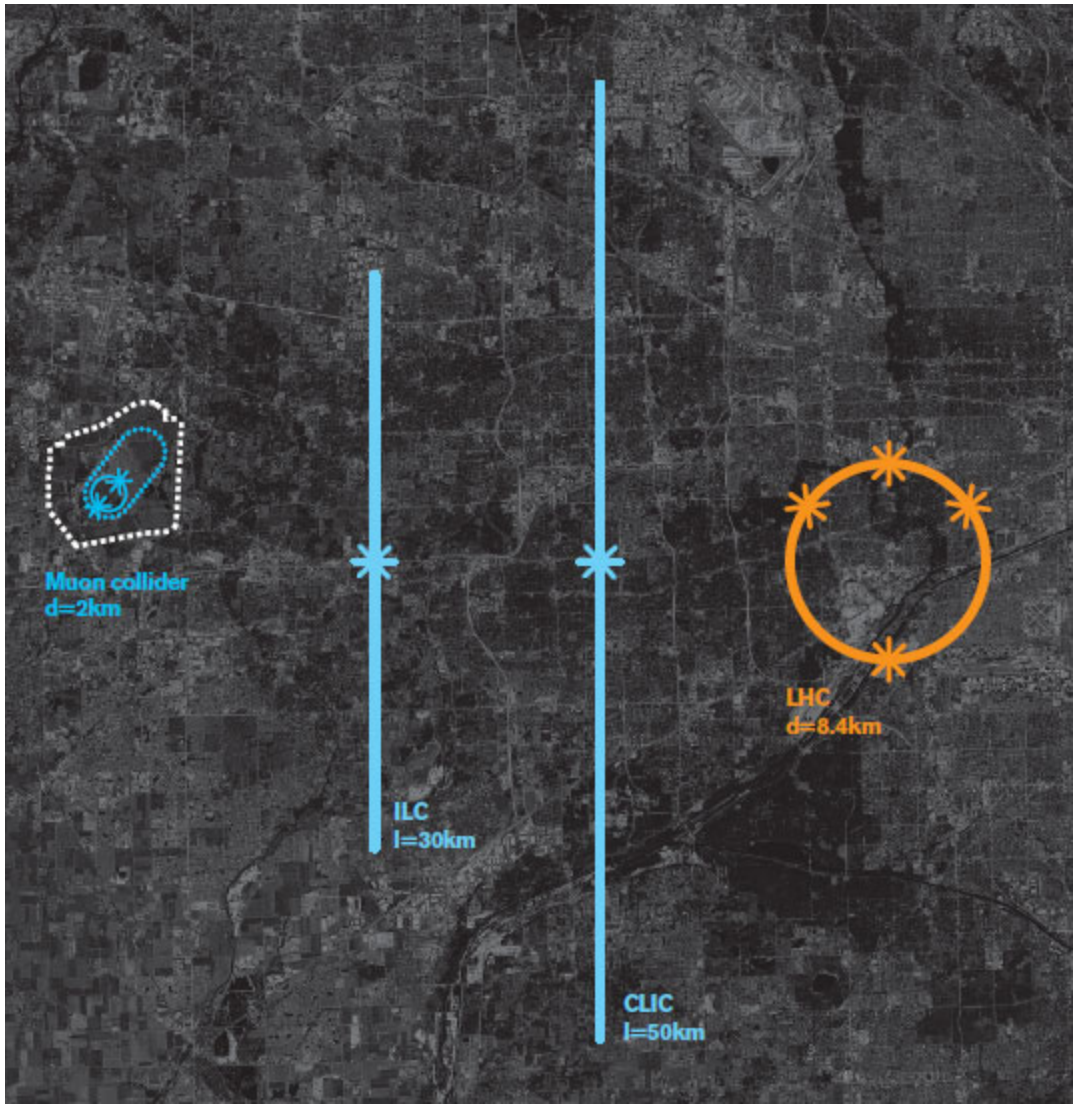
- A muon collider can directly produce the Higgs as an s-channel resonance.
  - Higgs couples to mass so rate enhanced by $\left[\frac{m_\mu}{m_e}\right]^2 = 4.28 \times 10^4$ so the cross section is $\sigma(\mu^+\mu^- \to h) = 49.2$ pb
  - The excellent energy resolution of a muon collider makes the process observable.
  - To obtain the same sensitivity to Higgs decay modes in a electron collider via Zh process as s-channel production at a MC requires more than 1000 times the integrated luminosity.

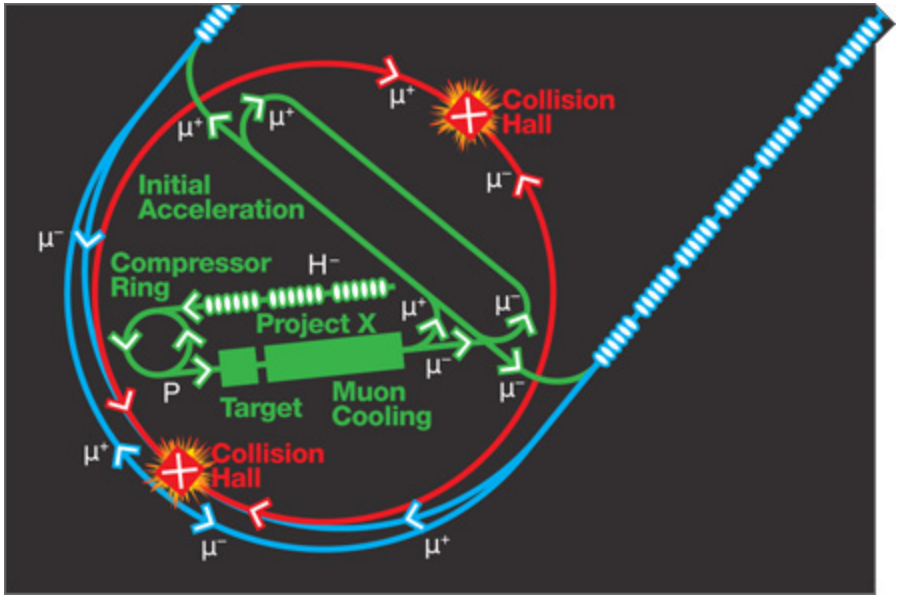
S – Channel Higgs Physics

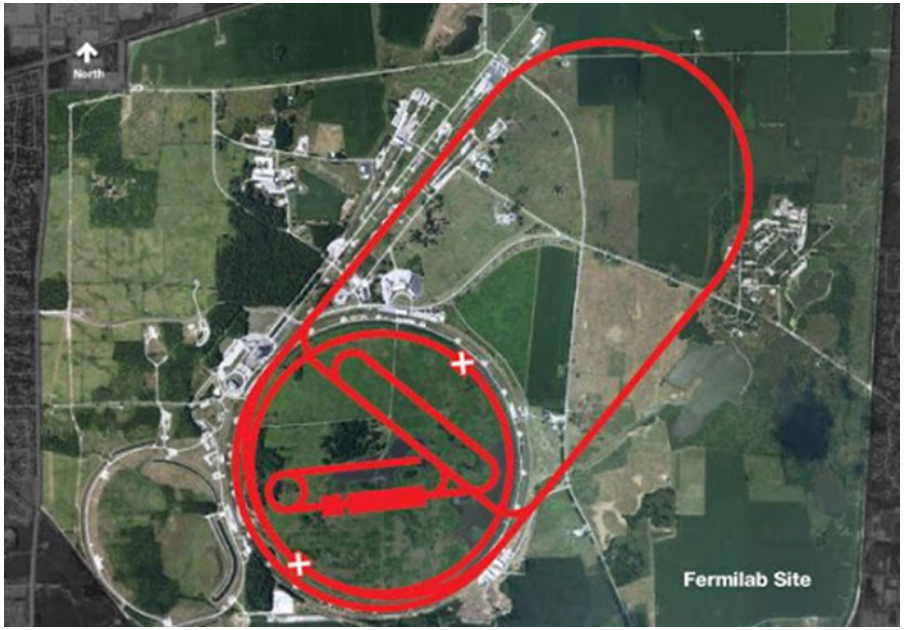


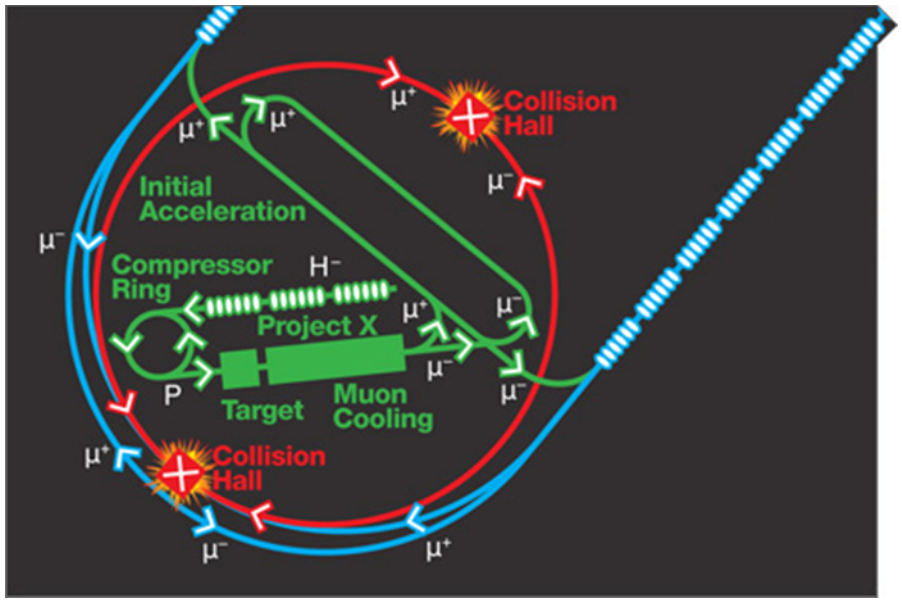
$$\sigma_h = \frac{4\pi\Gamma(h \to \mu\bar{\mu})\ \Gamma(h \to b\bar{b})}{(s - m_h^2)^2 + m_h^2\Gamma_h^2}$$

Barger, Gunion, et.al.


Muon collider
d=2km
ILC
l=30km
CLIC
l=50km
LHC
d=8.4km


Collision Hall
Initial Acceleration
Compressor Ring
H⁻
Project X
P
Target
Muon Cooling
Collision Hall
μ⁺
μ⁻


North
Fermilab Site


Collision Hall
Initial Acceleration
Compressor Ring
H⁻
Project X
P
Target
Muon Cooling
Collision Hall
μ⁺
μ⁻