Benchmarks for the Muon Collider

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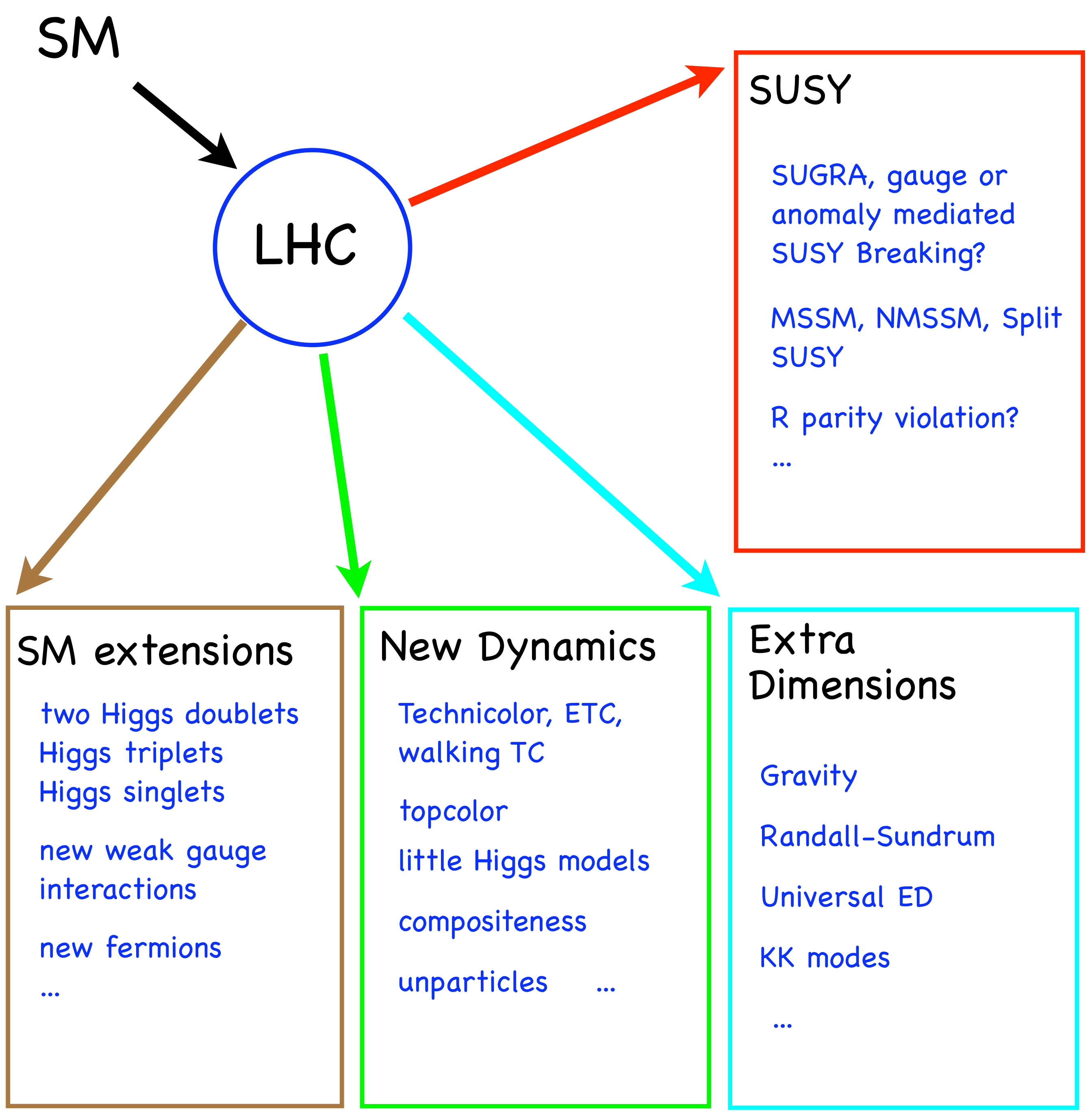
- Physics basics
- Initial benchmarks
- General Questions

Crossroad In Theoretical Physics

- Existing facilities in 2020:
  - LHC with luminosity or energy upgrade
- Options:
  - low energy lepton collider:
    ILC (500 GeV) (upgradable) or
    muon collider - Higgs Factory
  - lepton collider in the multi-TeV range:
    CLIC or muon collider
  - hadron collider in hundred TeV range:
    VLHC
- High energy lepton collider likely required for full study of Tevascale physics.



A Muon Collider

- $\mu^+\mu^-$ Collider:
  - Center of Mass energy: 1.5 - 5 TeV (focus 3 TeV)
  - Luminosity > 10^{34} cm^{-2} sec^{-1} (focus 400 fb^{-1} per year)

Abridged Parameter List

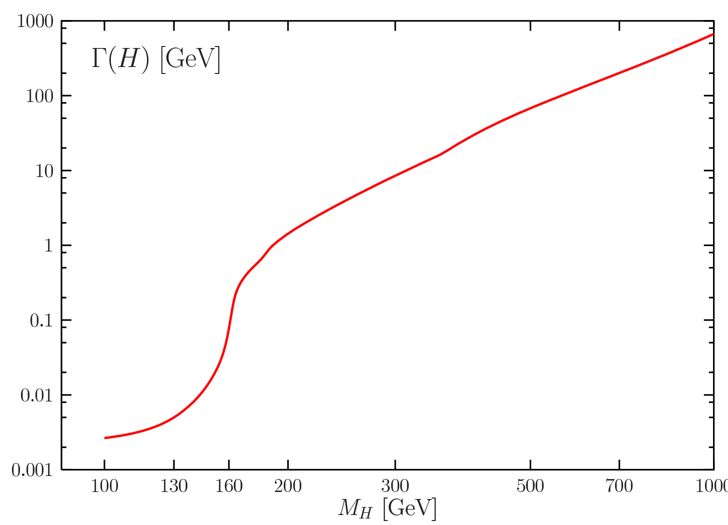
Machine	1.5-TeV $\mu^+\mu^-$	3.0-TeV $\mu^+\mu^-$	CLIC 3 TeV
$\mathcal{L}_{\text{peak}}$ [cm^{-2} s^{-1}]	7×10^{34}	8.2×10^{34}	8×10^{34} tot
$\mathcal{L}_{\text{avg}}$ [cm^{-2} s^{-1}]	3.0×10^{34}	3.5×10^{34}	3.1×10^{34} 99%
$\Delta p/p$ [%]	1	1	0.35
$\beta^\star$	0.5 cm	0.5 cm	35 μm
Turns / lifetime	2000	2400	
Rep. rate [Hz]	65	32	
Mean dipole field	10 T	10 T	
Circumference [m]	2272	3842	33.2 km site
Bunch spacing	0.75 μs	1.28 μs	0.67 ns

Low Energy Muon Collider Basics

- For $\sqrt{s}$ < 500 GeV lepton collider
  - SM threshold regions: top pairs; W^+W^-; Z^0Z^0; Z^0h production
- For low energy muon collider
  - s-channel Higgs production
    - Coupling ∝ lepton mass

$$\left[\frac{m_\mu}{m_e}\right]^2 = 4.28 \times 10^{4}$$

    - Narrow width

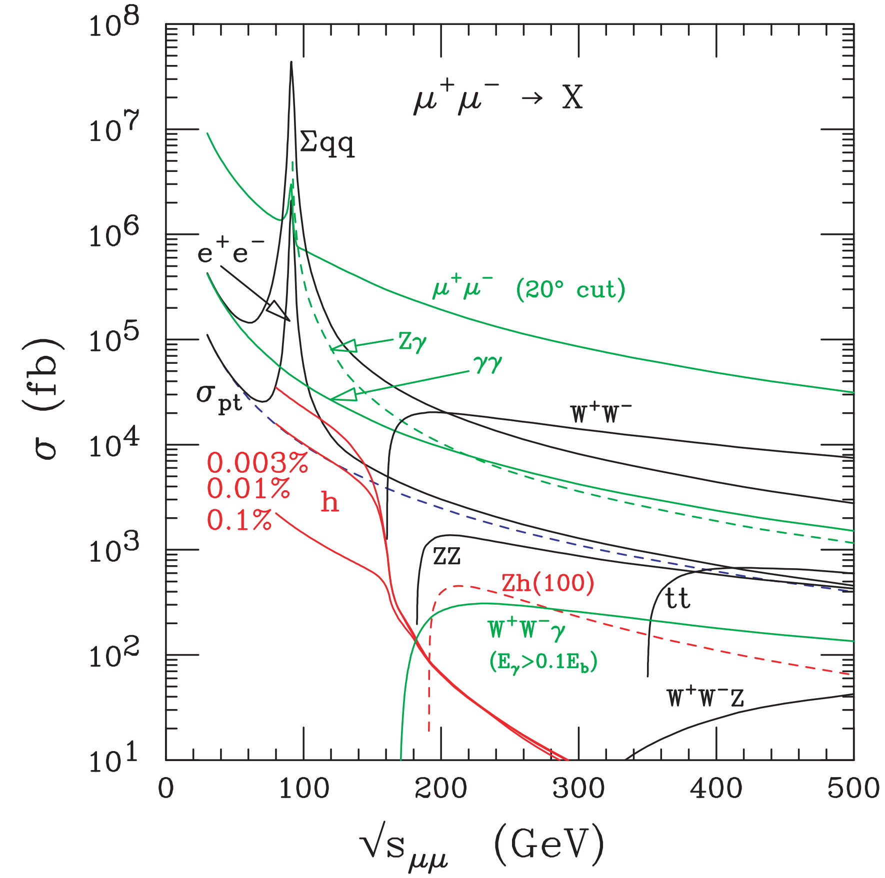


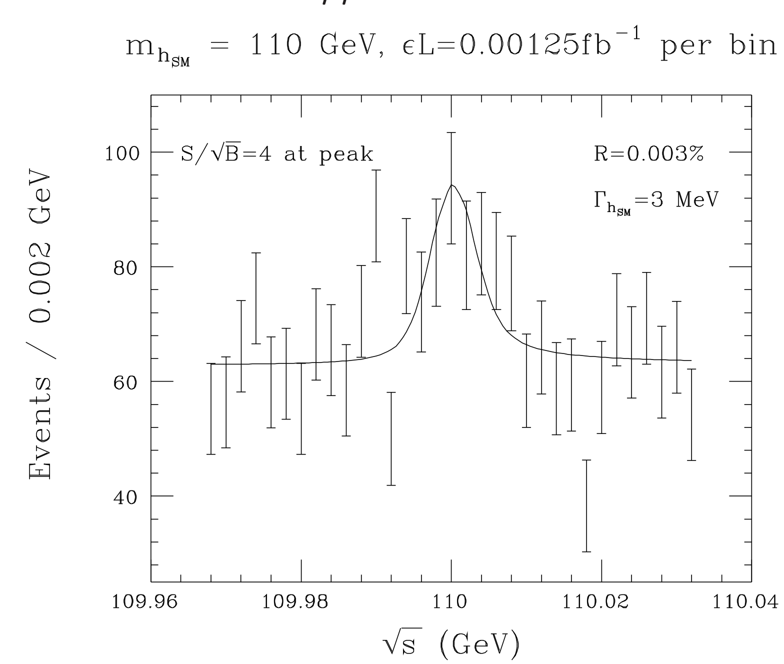
$$\begin{aligned}\Gamma &= 3.6 \text{ MeV} \\ (m_h &= 120 \text{ GeV})\end{aligned}$$

    - Direct width measurement

$$\Delta E/E \approx 0.003\% \quad \text{and } 100\ pb^{-1}$$

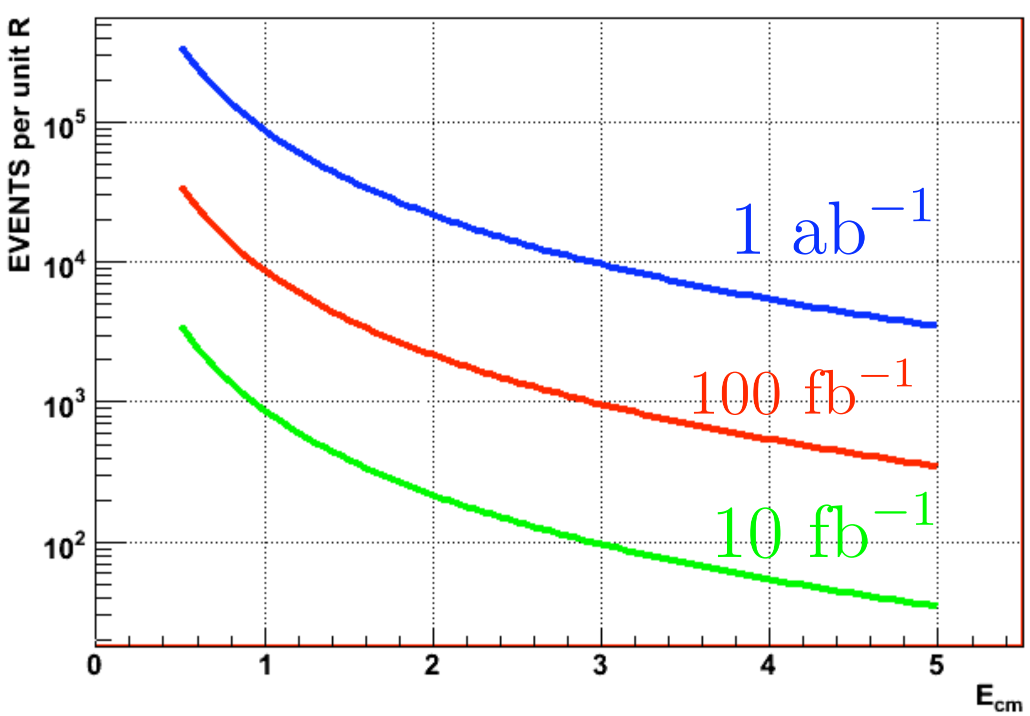
Standard Model Cross Sections





Multi-TeV Muon Collider Basics

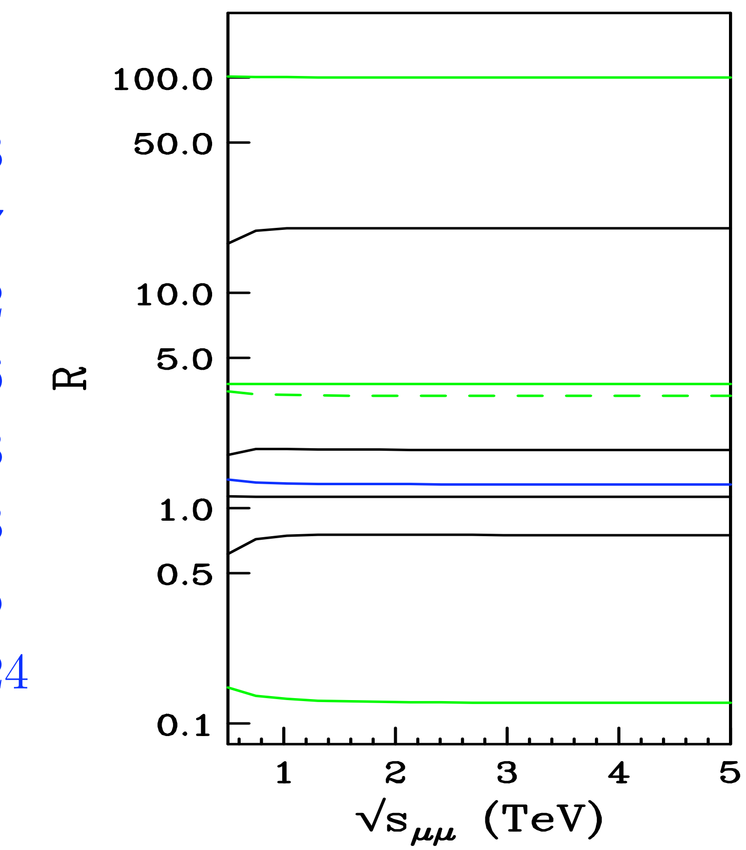
- For $\sqrt{s}$ > 500 GeV
  - Above SM pair production thresholds: $R \equiv \sigma/\sigma_{QED}\,(\mu^+\mu^- \to e^+e^-)$ flat
- Luminosity Requirements



R at $\sqrt{s}$ = 3 TeV

$O(\alpha_{em}^2)$ $O(\alpha_s^0)$

$$\begin{aligned}
\mu^+\mu^-(20^\circ\ \mathrm{cut}) &= 100\\
W^+W^- &= 19.8\\
\gamma\gamma &= 3.77\\
Z\gamma &= 3.32\\
t\bar{t} &= 1.86\\
b\bar{b} &= 1.28\\
e^+e^- &= 1.13\\
ZZ &= 0.75\\
Zh(120) &= 0.124
\end{aligned}$$



(one unit of R)

$$\sigma_{\mathrm{QED}}(\mu^+\mu^- \to e^+e^-) = \frac{4\pi\alpha^2}{3s} = \frac{86.8\ \mathrm{fb}}{s(\mathrm{TeV}^2)}$$

For example: $\sqrt{s} = 3.0\ \mathrm{TeV}$ $\Rightarrow$ 965 events/unit of R

$$\mathcal{L} = 10^{34}\ \mathrm{cm}^{-2}\mathrm{sec}^{-1} \rightarrow 100\ \mathrm{fb}^{-1}\mathrm{year}^{-1}$$

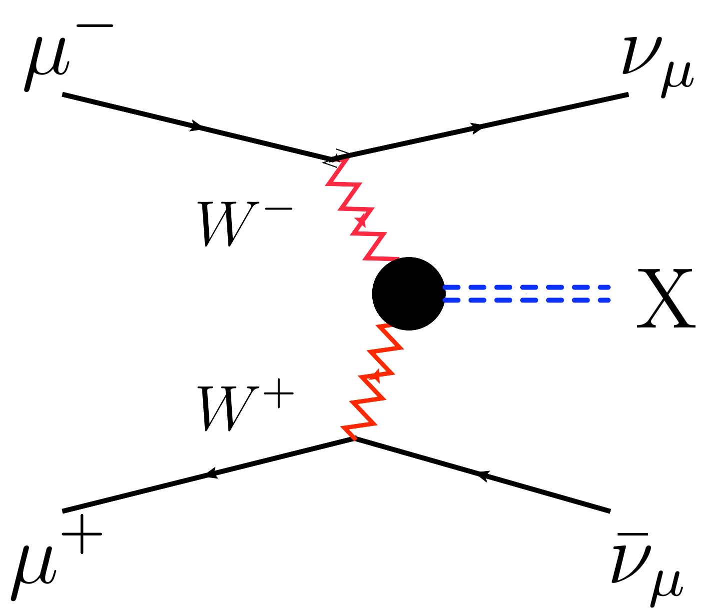
Processes with R ≥ 0.1 can be studied

Total - 128 K SM events per year

Fusion Processes

- Large cross sections
- Increase with s.
- Important at multi-Tev energies
- $M_X^2 < s$

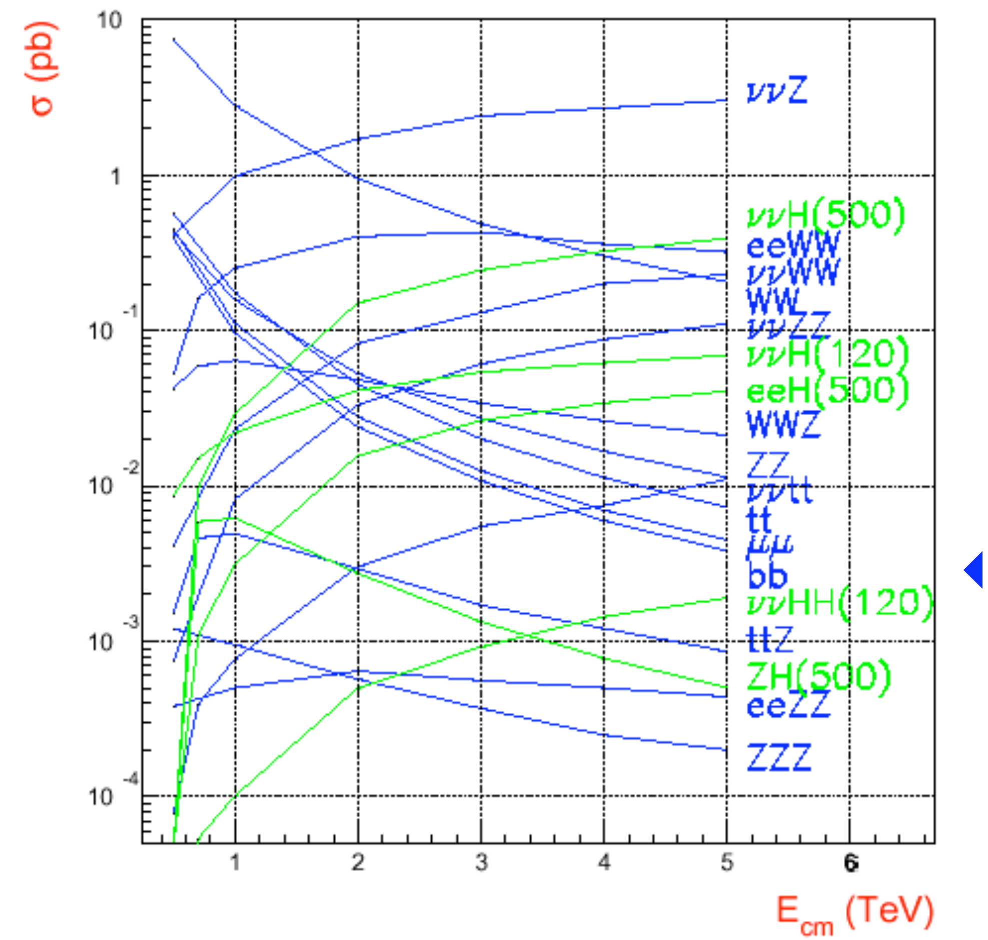
- Backgrounds for SUSY processes
- t-channel processes sensitive to angular cu



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

☐ An Electroweak Boson Collider

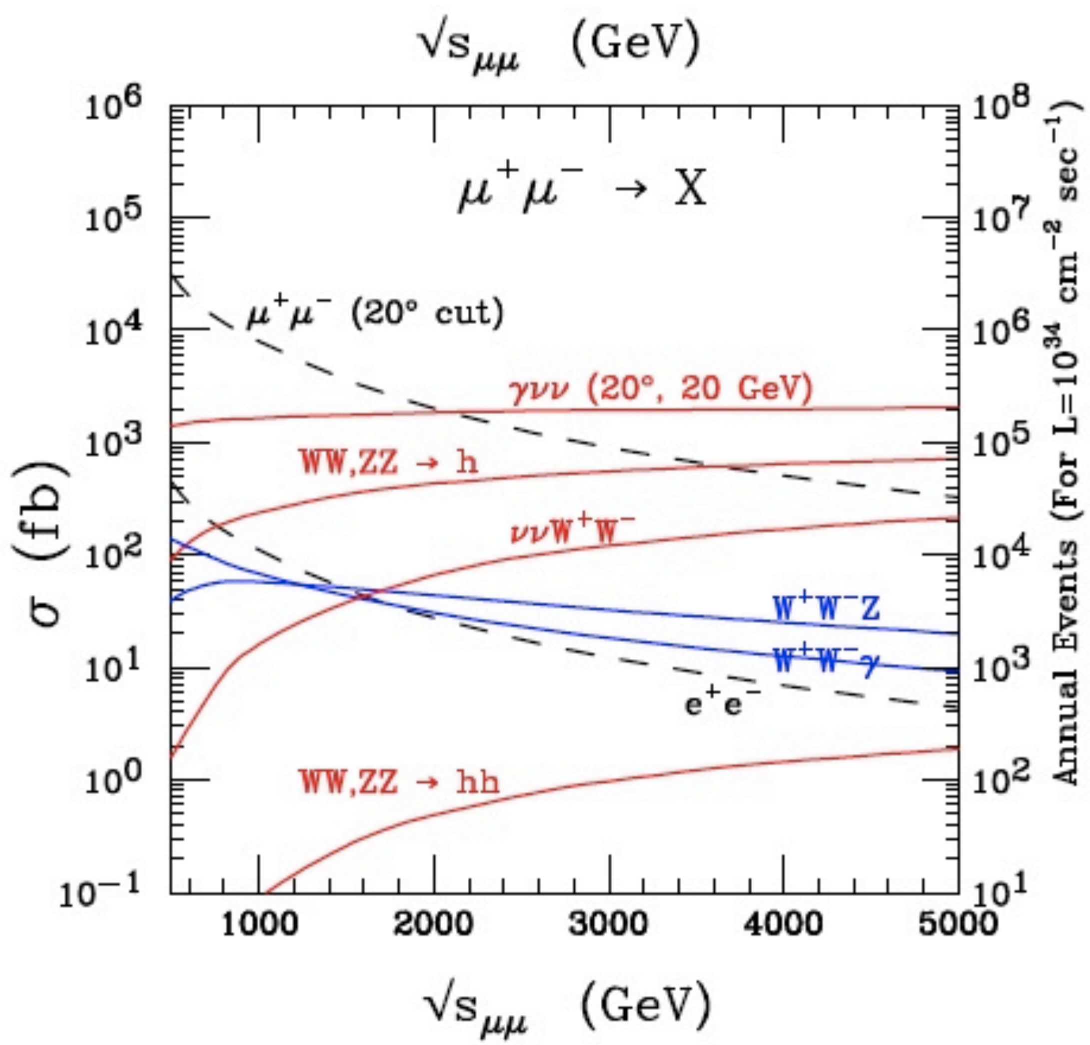
CLIC (or MC e<->μ)



X	R (@ 3 TeV)
Z^0	230
$h^0(500)$	25
W^+W^-	19.8
Z^0Z^0	5.8
$h^0(120)$	5.5
$t\bar{t}$	0.6
$h^0h^0(120)$	0.1

Muon Collider Benchmarks

- Physics processes similar CLIC/MC for 3TeV energy



Jets from W, Z decays
-> Must resolve W/Z

Many events have large missing energy
-> What is impact for SUSY?

No penalty for heavy flavors
-> Need excellent b and t tagging

Initial Benchmarks

- Ayres Freitas, Tao Han, E.E.: A first pass at benchmarks

Final states	Exp. considerations	Theo. considerations
$\ell^+\ell^-, \quad \ell = e,\ \mu,\ \tau$	Ecal, μ-chamber; τ-tagging at HE	Contact interaction
$q\bar{q}, \quad q = u,\ c,\ s,\ b$	Hcal, b-tagging at HE	Contact interaction
$\gamma\gamma$	Ecal	QED
$\gamma + \not{E}$	Ecal, missing energy	missing mass/dark matter
$W^+W^- \to q\bar{q}', q\bar{q}'$	Hcal: M_W-reconstruct	New resonances
$W^+W^- \to \ell\bar{\nu}, q\bar{q}'$	$\not{E}$, M_W-reconstruct	New resonances
$ZZ \to q\bar{q}, q\bar{q}$	Hcal: M_Z-reconstruct	New resonances
$ZZ \to \ell^+\ell^-, \nu\bar{\nu}$	Ecal; $\not{E}$	New resonances
$t\bar{t} \to bW^+\ \bar{b}W^+$	E,Hcal, b-tagging, mass reconstruct	New heavy quarks
ZHH	multiple $b\bar{b}$	Higgs self coupling
$W^+W^- \to HH$	multiple $b\bar{b}$	Higgs self coupling
$\nu\bar{\nu}W^+W^- \to 4j + \not{E}$	Hcal: M_W-reconstruct	WW scattering
$\nu\bar{\nu}ZZ \to 4j + \not{E}$	Hcal: M_Z-reconstruct	WW scattering
$\nu\bar{\nu}t\bar{t}$	Hcal: m_t-reconstruct	$WW \to t\bar{t}$
$\tilde{\chi}_i\tilde{\chi}_j$	leptons, jets+$\not{E}$	SUSY
$\tilde{\ell}_i\tilde{\ell}_j$	leptons+$\not{E}$	SUSY
$\tilde{q}_i\tilde{q}_j$	jets+$\not{E}$	SUSY

Z'

KK mode

Strong Dynamics

4th Generation,
Little Higgs Models

Strong Dynamics

SUSY

General Questions

- Should we adopt the ILC benchmarks for a multiTeV lepton collider?

Benchmarks for ILC Physics Study 2009-2010 (1 TeV) from Michael Peskin

1. $e^+e^- \to \nu\overline{\nu}h^0$ at $E_{CM} = 1$ TeV, where h^0 is a Standard Model Higgs boson of mass 200 GeV, in the final states $h^0 \to b\overline{b}$ and $h^0 \to \mu^+\mu^-$. The goal is to measure the cross section times branching ratio for these reaction.
2. $e^+e^- \to t\overline{t}h^0$ at $E_{CM} = 1$ TeV, where h^0 is a Standard Model Higgs boson of mass 200 GeV, in the final state $h^0 \to WW, ZZ$, in the 10 jet mode. The goal is to measure the Higgs boson coupling to $t\overline{t}$.
3. $e^+e^- \to \tau^+\tau^-$ at $E_{CM} = 1$ TeV. The goal is to measure the forward-backward asymmetry and the final-state τ polarization.
4. $e^+e^- \to b\overline{b}, c\overline{c}$ at $E_{CM} = 1$ TeV. The goal is to measure the cross section and the forward-backward asymmetry of each reaction.
5. $e^+e^- \to \nu\overline{\nu} + WW, ZZ$ at $\sqrt{s} = 1$ TeV. The goal is to measure the effective Lagrangian parameters α_4 amd α_5 in strongly interacting models of the Higgs sector.

- If a s-channel resonance is observed at LHC, how do CLIC/MC studies compare?
- What is the best way to determine the SUSY spectrum and couplings at a few TeV lepton collider?
- If the LHC results suggest a new strong dynamics, can we reach the scale?
- What if the LHC finds the SM Higgs (with possibly more scalars)?

A Start

Toward Benchmark Processes for 3 TeV Muon Collider:

The SM with h(120) as reference point. Generate samples for 1 ab^{-1} total luminosity.

- $\mu^+\mu^-$ SM: reference process. BSM: contact term sensitivity versus angular cuts.
- $(W^+W^-,\ ZZ,\ ZW^-\mu^+)\ +X$. Here X is anything not visible in detector (i.e. ν's, particles outside the detectors angular acceptance, ...).
  SM: W/Z resolution in jets. $W^+ \to c\bar{s}$, $Z \to b\bar{b}$, resolution in WW pair invariant mass.
  BSM: new strong dynamics (eg. ρ_T)
- $b\bar{b}$ + X. SM: resolve h from Z. BSM: Two Higgs doublet model - resolve H, A. (Use SUSY parameters with $m(H) = 400$ GeV.)
- $\tilde{\mu}^+\tilde{\mu}^-$ SUSY: Study decays. Find neutralino mass using edge effect