Muon Collider Physics at 10-100 TeV

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What are the possible physics signals at 10-100 TeV energies of a future muon collider?

Muon colliders reign supreme at $\sqrt{s} > 10$ TeV. It is hard to imagine an e^+e^- collider at those energies.

A new collider might be necessary, but it is impossible to motivate a specific energy.

We can only speculate, but the LHC, NLC, or muon colliders might give us a clue.

Muon Colliders
The next "generation" of Lepton Collider?

The original motivation for a muon collider is the possibility of multi-TeV energies.

A very large hadron collider ($E_{cm} \sim 50 - 100$ TeV would require a cost reduction of at least an order of magnitude, and a luminosity of 10^{35} cm^{-2}s^{-1} giving radiation and detector difficulties.

Neutrino-induced radiation hazard.

What is the profile of the muon beam at 10-100 TeV? Is R=0.1% still reasonable? Can reduced spread in E_{cm} be utilized at these energies?

Large violations of flavor symmetries?

Source of SUSY breaking? Physics beyond the SUSY spectrum, or just a desert?

What physics could exist in the 10 - 100 TeV energy range?

- The Usual Suspects

  a) Vector Bosons

  b) New Matter (Fermions)

  c) SUSY particles

  d) Excited Quarks

  e) Leptoquarks

  f) New Contact Interactions

  g) Extra Dimensions

- Electroweak symmetry breaking
- Fermion mass generation (Appelquist-Chanowitz bound)
- Running of Couplings

  a) gauge b) Yukawa

- Flavor Tagging
- Photon-photon collider(?)

Luminosity Requirements

Figure of merit:

$$\sigma_{QED} = \frac{100 \text{ fb}}{s \ (\text{TeV}^2)} \left(\frac{\alpha(s)}{\alpha(M_Z^2)} \right)^2$$

Integrated luminosity needed:

$$\left(\int \mathcal{L} dt \right) \sigma_{QED} \gtrsim 1000 \text{ events}$$

One year's running, the luminosity requirement is

$$\mathcal{L} \gtrsim 10^{33} \cdot s \ (\text{cm})^{-2} \, (\text{sec})^{-1}$$

- $\sqrt{s} \simeq 10$ TeV, requiring

$$\int \mathcal{L} dt \gtrsim 1 \ (\text{fb})^{-1}, \quad \mathcal{L} \gtrsim 10^{35} \ (\text{cm})^{-2} \, (\text{sec})^{-1}$$

- $\sqrt{s} \simeq 100$ TeV, requiring

$$\int \mathcal{L} dt \gtrsim 100 \ (\text{fb})^{-1}, \quad \mathcal{L} \gtrsim 10^{37} \ (\text{cm})^{-2} \, (\text{sec})^{-1}$$

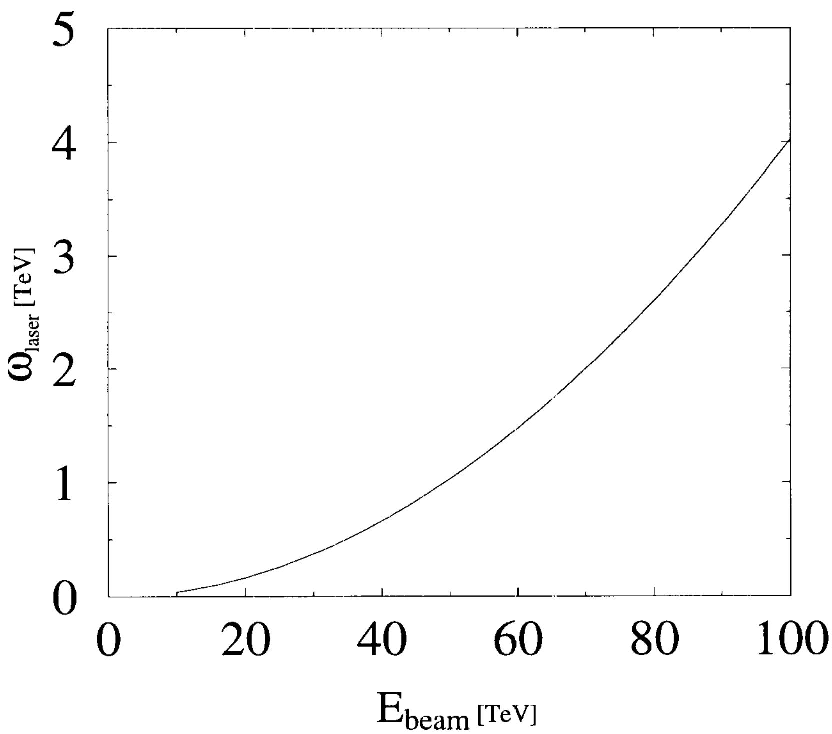
Can we really handle these luminosities?

Compton Backscattering

At what muon beam energy does kinematics allow useful backscattered photons?

$$x = \frac{4E_{\text{beam}}\omega_{\text{laser}}}{m_\mu^2}$$

$$\omega_m = \frac{x}{1+x}E_{\text{beam}}$$



Interactions of the laser photon with backscattered photon $\gamma\gamma \to e^+e^-$: $\omega_m\omega_{\text{laser}} > m_e^2$

Extra dimensions

The rise in cross section for some processes when there are extra space-time dimensions can be dramatic, amplifying the need for a small energy spread.

$$\frac{d^2\sigma}{dx_\gamma d\cos\theta}(\mu^+\mu^- \to \gamma G) = \frac{\alpha\pi^{\delta/2}}{32\Gamma(\delta/2)}\left(\frac{\sqrt{s}}{M_D}\right)^{\delta+2}\frac{1}{s}f(x_\gamma,\cos\theta)$$

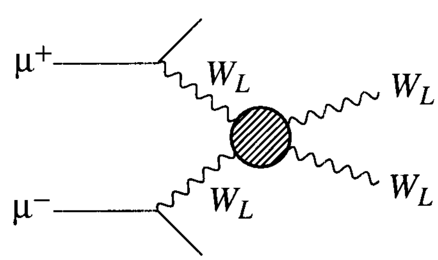
$$f(x,y) = \frac{2(1-x)^{\delta/2-1}}{x(1-y^2)}\left[(2-x)^2(1-x+x^2) - 3y^2x^2(1-x) - y^4x^4\right]$$

- Rapid rise of cross section with $\sqrt{s}$
- Very precise beam energy resolution could be useful in measuring the rise of the cross section.
- KK graviton behaves like massive, noninteracting stable particle

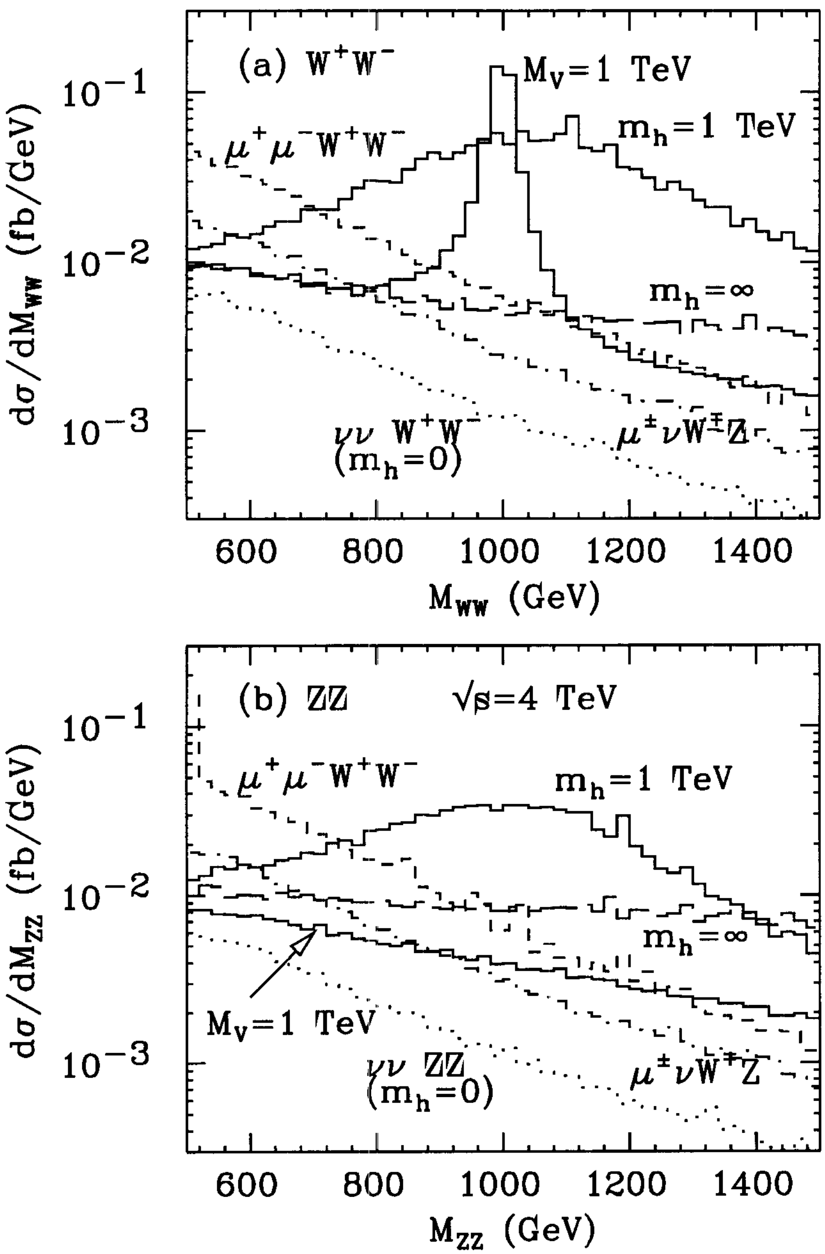
Strong electroweak symmetry breaking

- Explore the physics responsible for electroweak symmetry breaking
- Strong interactions, resonances, etc. (lots of spectroscopy, but can we really study it considering the backgrounds?)
- If Higgs bosons with $m_H < \mathcal{O}(800)$ GeV do not exist then interactions of longitudinally polarized weak bosons (W_L, Z_L) become strong. Therefore, new physics must be present at the TeV energy scale.

Study strong $W_L W_L$ scattering at LHC, NLC, $\mu^+\mu^-$



- Higher energy $\mu^+\mu^-$ colliders: possibly study spectroscopy of the strongly interacting sector(s)
- Some strongly interacting Higgs sectors have narrow resonances for which a small energy spread might be helpful.



Level 0 determination of the electroweak symmetry breaking mechanism.

Fermion mass generation

Appelquist-Chanowitz unitarity bound

$$f\bar{f} \to V_L V_L$$

$$\Lambda_f < \frac{8\pi v^2}{\sqrt{3N_c}\, m_f} \qquad v^2 = (\sqrt{2}G_F)^{-1}$$

For top quark, $\Lambda_t \approx 3$ TeV.
For muon, $\Lambda_\mu \approx 8,000$ TeV.

$$V_L V_L \to V_L V_L$$
$$\Lambda^2_{EWSB} = 8\pi v^2 \approx (1.2 \text{ TeV})^2$$

The source of fermion mass generation need not be the same as the source of the electroweak symmetry breaking (c.f. technicolor). Whatever physics unitarizes $V_L V_L \to V_L V_L$ need not unitarize $f\bar{f} \to V_L V_L$.

Look at the process $\mu^+\mu^- \to \nu\bar{\nu}t\bar{t}$.

Heavy supersymmetric particles

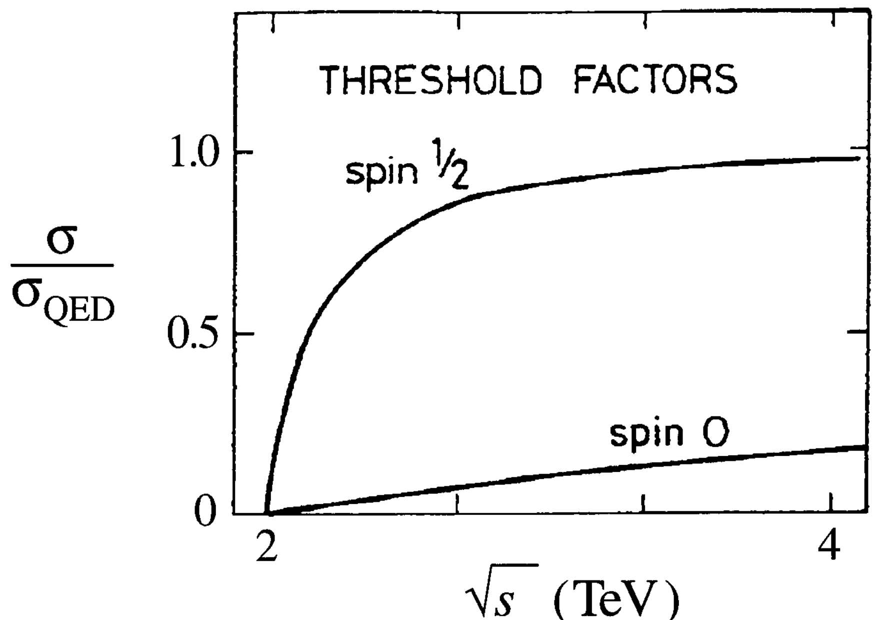
- Detection and study of the plethora of SUSY scalars could be the main contribution of a high energy lepton collider.
- Pair production of scalar particles (at a lepton collider) is p-wave suppressed, so energies well above threshold may be needed to get beyond the angular momentum suppression.
- Naturalness arguments can be avoided, and there could be matter content beyond the MSSM to study.
- Need high luminosities to have sufficient event rates to study the complex decay chains of these particles.
- One can contemplate threshold studies of these particles, especially new fermions. Here the energy spread of the beam may be a critical issue. How does the beam spread scale with energy?
- Threshold structures might be investigated (CERN study looked at chargino production for $m_{\chi^\pm} \approx 1$ TeV, and $\Lambda_{\chi^\pm} = 4.7$ MeV).

  Issue: What are the expected widths of particles in the 10-100 TeV range?

Threshold Production

Production of particles near the threshold energy is sensitive to

1) mass
2) spin



3) decay width

These studies can be and have been done at a lepton collider.

Cases Studied (at reasonable energies):

$$\mu^+\mu^- \rightarrow \begin{cases} t\bar{t} \\ W^+W^- \\ Zh \\ \tilde{\chi}^+\tilde{\chi}^- \end{cases}$$

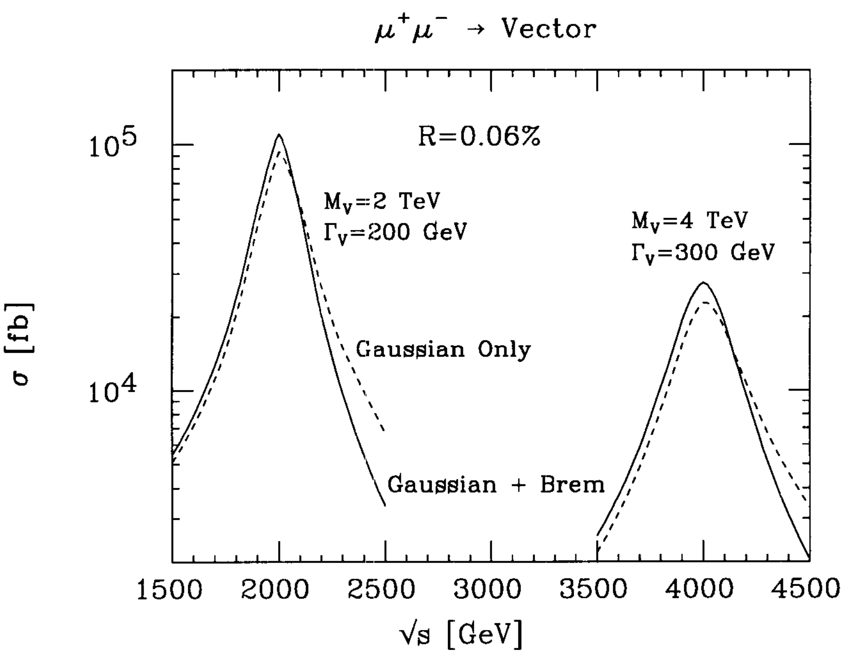
Precision Measurements

- Muon colliders are ideal: excellent beam energy resolution (precise knowledge of the energy), flexibility in adjusting the beam energy, small initial state radiation (ISR)
- Precision measurements of particle production cross sections (both at the threshold and above) gives us indirect information about heavy new particles.
- Measurements at NLC, earlier muon colliders

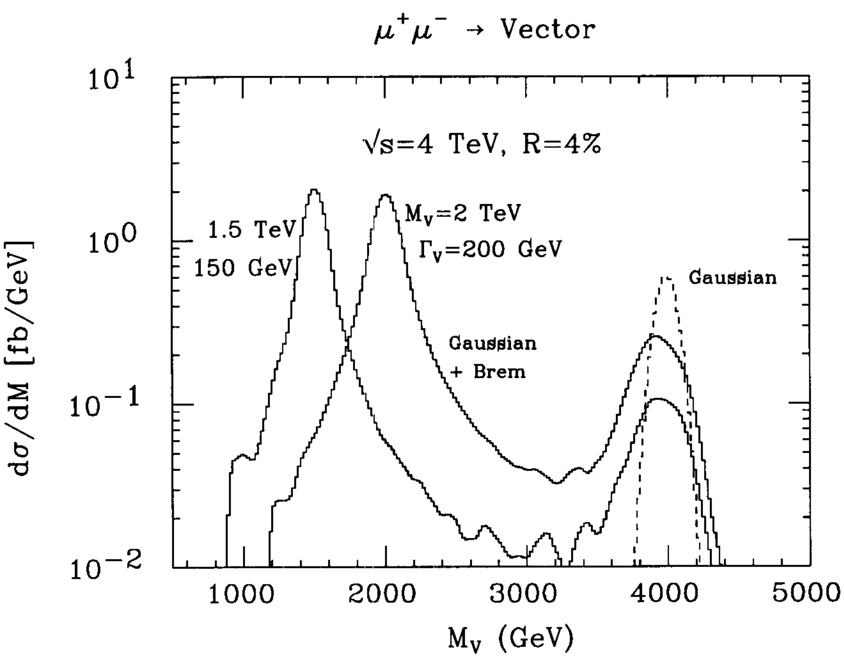
New Gauge Bosons

- New neutral gauge bosons could be found by the bremstrahlung tail method. How effective this would be could be studied.

- Information on the likely masses and couplings of these particles could be gleaned from data from earlier colliders.



$\mu^+\mu^- \to$ Vector
R=0.06%
M_V=2 TeV
Γ_V=200 GeV
M_V=4 TeV
Γ_V=300 GeV
Gaussian Only
Gaussian + Brem
σ [fb]
10^5
10^4
1500
2000
2500
3000
3500
4000
4500
$\sqrt{s}$ [GeV]



$\mu^+\mu^- \to$ Vector
$\sqrt{s}$=4 TeV, R=4%
1.5 TeV
150 GeV
M_V=2 TeV
Γ_V=200 GeV
Gaussian
Gaussian
+ Brem
$d\sigma/dM$ [fb/GeV]
10^1
10^0
10^{-1}
10^{-2}
1000
2000
3000
4000
5000
M_V (GeV)

μp Collider

- Very high Q^2, new domain for lepton-proton collisions
- Bremsstrahlung is practically absent
- Flavor effects (μ instead of e) are more likely to be evident at higher energies
- Neutral Current deep inelastic scattering (DIS) events
- Probe leptoquark and contact interactions (likely to be larger for muons than for electrons)

Like-sign colliders

Should not be thought of a competing with a conventional “opposite sign” collider.

Rather it can be a complement, provided there is a physics signal to see:
At lower energies: double charged Higgs, like sign strong W scattering ($I = 2$ channel);
At higher energies: what?

s-wave production of sleptons

small backgrounds

Physics Potential

Who knows what physics (if any) lurks in the energy regime of 10-100 TeV?

Information from the LHC, NLC, earlier muon colliders should provide the direction.

The original and ultimate goal of muon colliders is to go to the very highest energies. Muon colliders are (at the moment) the only option that might go to 10-100 TeV at a reasonable cost.