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• General Remarks
• The SM Higgs?
• Finding the Higgs
• Measuring the Higgs Couplings
• Beyond the Standard Model
• Summary

Higgs Factory Muon Collider Workshop @ UCLA
March 21-23, 2012
Basics of a Muon Collider

- **$\mu^+\mu^-$ Collider:**
  - Center of Mass energy: 1.5 - 6 TeV (3 TeV)
  - Luminosity > $10^{34}$ cm$^{-2}$ sec$^{-1}$ (440 fb$^{-1}$/yr)
  - Compact facility
    - 3 TeV - ring circumference 3.8 km
    - 2 Detectors
  - Superb Energy Resolution
    - MC: 95% luminosity in dE/E ~ 0.1%
    - CLIC: 35% luminosity in dE/E ~ 1%
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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 ($|\theta| > 10^\circ$) pair production $\sim R \times 86.8$ fb/s (in TeV$^2$) (R $\approx 1$)
    - At $\sqrt{s} = 3$ TeV for 100 fb$^{-1} \sim 1000$ events/(unit of R)

- For $\sqrt{s} > 1$ TeV
  - Fusion processes important at multi-TeV MC
  - An Electroweak Boson Collider ✔

\[
\sigma(s) = C \ln\left(\frac{s}{M_X^2}\right) + ... \]
Basics of a Muon Collider

- Provides a flexible staging scenario with physics at each stage.
  - Neutrino Factory
  - Higgs Factory

- But muons decay:
  - The muon beams must be accelerated and cooled in phase space (factor \( \approx 10^6 \)) rapidly
    -> ionization cooling
  - Requires a complex cooling scheme
  - The decay products \( (\mu^- \rightarrow \nu_\mu \bar{\nu_e} e^-) \)
    have high energies.
    - Detector background issues
    - Serious neutrino beam issue for \( E_{cm} \geq 4 \text{ TeV} \)
Staging Steps:

- **Higgs factory $\sqrt{s} = m_H \approx 126$ GeV**
  - Some initial running on Z peak for calibration.
  - Nominal Luminosity $1.7 \times 10^{31} \sim 170$ pb$^{-1}$/yr; beam energy spread 0.003%
  - Upgraded Luminosity: $8 \times 10^{31} \sim 800$ pb$^{-1}$/yr; beam energy spread 0.004%

- **High Energy Muon Collider:**
  - The choice of the high energy muon collider design energy will depend on the scale of BSM physics discovered at the LHC with $\sqrt{s} \approx 14$ TeV after 300 fb$^{-1}$
  - $\sqrt{s} = 1.5$ TeV; luminosity $1.25 \times 10^{34} \sim 125$ fb$^{-1}$/yr; beam energy spread 0.1%
    (present detector and machine detector interface studies)
  - $\sqrt{s} = 3.0$ TeV; luminosity $4.4 \times 10^{34} \sim 440$ fb$^{-1}$/yr; (beginning studies)
  - $\sqrt{s} = 6.0$ TeV; luminosity $1.6 \times 10^{35} \sim 1.6$ ab$^{-1}$/yr (Palmer's scaling)
Muon Physics Staging Scenerio

- Parameters of various stages (MAP review J-P Delahaye’s talk)

### Difference Between Higgs Factory and Muon Collider

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Higgs Factory</th>
<th>Multi-TeV Baselines</th>
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<tr>
<td></td>
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<td>Initial Cooling</td>
<td>Upgraded Cooling / Combiner</td>
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<tr>
<td>CoM Energy</td>
<td>TeV</td>
<td>0.126</td>
<td>0.126</td>
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<tr>
<td>Avg. Luminosity</td>
<td>$10^{34}$cm$^{-2}$s$^{-1}$</td>
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<td>0.008</td>
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<tr>
<td>Beam Energy Spread</td>
<td>%</td>
<td>0.003</td>
<td>0.004</td>
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<tr>
<td>Circumference</td>
<td>km</td>
<td>0.3</td>
<td>0.3</td>
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<tr>
<td>No. of IPs</td>
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<tr>
<td>Repetition Rate</td>
<td>Hz</td>
<td>30</td>
<td>15</td>
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<tr>
<td>$\beta^*$</td>
<td>cm</td>
<td>3.3</td>
<td>1.7</td>
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<tr>
<td>No. muons/bunch</td>
<td>$10^{12}$</td>
<td>2</td>
<td>4</td>
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<tr>
<td>No. bunches/beam</td>
<td></td>
<td>1</td>
<td>1</td>
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<tr>
<td>Norm. Trans. Emittance, $\varepsilon_{\text{T}}$</td>
<td>mm-rad</td>
<td>0.4</td>
<td>0.2</td>
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<tr>
<td>Norm. Long. Emittance, $\varepsilon_{\text{L}}$</td>
<td>mm-rad</td>
<td>1</td>
<td>1.5</td>
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<tr>
<td>Bunch Length, $\sigma_z$</td>
<td>cm</td>
<td>5.6</td>
<td>6.3</td>
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<td>Beam Size @ IP</td>
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<td>75</td>
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<tr>
<td>Beam-beam Parameter / IP</td>
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<td>0.005</td>
<td>0.02</td>
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<tr>
<td>Proton Driver Power</td>
<td>MW</td>
<td>4&quot;</td>
<td>4</td>
</tr>
</tbody>
</table>

*Could begin operation at lower beam power (e.g., with Project X Phase 2 beam)*
The Standard Model Higgs

- **The SM Higgs:**
  - All properties are determined for given mass.
  - Any deviations signal new physics.

\[ m(H) = 126 \text{ GeV} \quad \Gamma(H) = 4.21 \pm 0.16 \text{ MeV} \]

branching fractions:

- \( b\bar{b} = 0.561 \quad (3.4\%) \)
- \( \tau\bar{\tau} = 6.15 \times 10^{-2} \quad (5.8\%) \)
- \( c\bar{c} = 2.83 \times 10^{-2} \quad (12.2\%) \)
- \( \mu^+\mu^- = 2.14 \times 10^{-4} \quad (5.8\%) \)
- \( WW^* = 0.231 \quad (4.1\%) \)
- \( ZZ^* = 2.89 \times 10^{-2} \quad (4.1\%) \)
- \( gg = 8.48 \times 10^{-2} \quad (10.0\%) \)
- \( \gamma\gamma = 2.28 \times 10^{-3} \quad (4.9\%) \)
- \( Z^0\gamma = 1.62 \times 10^{-3} \quad (8.8\%) \)

- **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?
Indirect measurements are all consistent with a 126 GeV Higgs.

For a 126 GeV Higgs the SM is consistent to the Planck scale; but the vacuum is only metastable above $10^{10}$ GeV.

Jean Elias-Miro et. al. [arXiv:1112.3022]

To theorists: “When life gives you lemons, make lemonade”
The Standard Model Higgs?

- Moriond results:
  
  • ATLAS (Tim Adye)
    
    • $m_H = 125.5 \pm 0.2 \text{ (stat)} \pm 0.5 \text{ (sys)} \text{ GeV}$
    
    • $\mu = 1.30 \pm 0.13 \text{ (stat)} \pm 0.14 \text{ (sys)}$
    
    • $\mu_{\text{VBF}+\nu_H} / \mu_{\text{ggF}+ttH} = 1.2^{+0.7}_{-0.5}$
    
    • $3.1\sigma$ evidence for VBF production
  
  • CMS (Andrew Whitbeck)
    
    **m_H = 125.8 +/- 0.4 (stat) +/- 0.4 (syst) GeV**
    
    **$\sigma / \sigma_{\text{SM}} = .88 +/- 0.21$**
    
    • Data consistent with
      
      – Custodial symmetry
      
      – Fermion universality tests
      
      – Fermionic and bosonic couplings expected from SM Higgs
- **Pseudoscalar versus Scalar**
  - Light pseudoscalars often appear in dynamical EWSB models
  - However they don’t couple to WW/ZZ in lowest order.
  - Assuming spin zero - a pure pseudoscalar is experimentally disfavored.

- **Measure couplings to distinguish SM Higgs from BSM scalars**

  ![Graph](image)

  - Within large present errors, ATLAS and CMS results consistent with SM Higgs couplings.
• List of issues for MC Higgs Factory
  
  - Requires precise energy resolution: \( \Delta E/E \sim few \times 10^{-5} \)
    • Can such a resolution be achieved?
    • What error on the Higgs width would be possible?
    • Integrated luminosity?
    • Beam energy stability - store-to-store?

  - What branching ratios could be measured?
    • \( W^+W^-, ZZ \) (very small backgrounds)
    • \( bb \) (\( S/B \sim 1 \))
    • \( \Delta (\text{BR}(\mu^-\mu^+)\times\text{BR}(WW)) \) [2%]. Will provide the most accurate measure a Yukawa coupling. (Grinstein)
    • Detector backgrounds from muon decays in beams
    • \( S/B \) studies?

• Preliminary studies:
  
  - \( \Delta E = 4 \text{ MeV and } \mathcal{L} > 10^{31} \text{ cm}^{-2}\text{sec}^{-1} \)
  - Can use nearby Z pole to tune machine.
  - Use spin precession to measure beam energy.
  - Initial studies of decay modes with backgrounds
Finding the Higgs

• The Higgs mass will be known to 100 MeV from the LHC (or ILC). But we need to find $m_H$ to ~4 MeV then sit on the resonance at a muon collider.

• Alex Conway and E.E. have studied the question of what integrated luminosity is required to discover the Higgs to $5\sigma$ ($3\sigma$) as a function of beam energy spread

• b-bbar channel.
  - $\sigma = \Gamma_H$ best
  - p-value < 0.0027 => 400 pb$^{-1}$
Finding the Higgs

- **W W* channel.**
  - Very small backgrounds WW*
  - Use the lν + 2jets final state
  - Expect backgrounds to this channel with appropriate cuts approximately 0.1 pb⁻¹
  - p-value < 0.0027 => 170 pb⁻¹

- Can improve results by using both channels
Finding the Higgs

- **Combining the two channels:**
  
  - needed luminosity for a (5$\sigma$) Higgs signal
    
    p-value = 2.6×10$^{-3}$ (3$\sigma$):
    
    \[
    \text{bin} = 4.2 \text{ MeV} \quad \text{int } L = 48 \text{ pb}^{-1}
    \]
  
  - needed luminosity for a (3$\sigma$) Higgs signal
    
    \[
    \text{int } L \approx 26 \text{ pb}^{-1}
    \]

Finding the Higgs requires a few months running at $1.7 \times 10^{31}$ luminosity.
• Measurements for a Higgs factory

  - partial decay widths into $W W^*$ and $Z Z^*$:
    • Establishes whether the Higgs is the sole agent of EWSB.
    • If additional contributors to EWSB are all $SU_L(2)$ doublets then $\Gamma / \Gamma_{SM} < 1$
    • The relative couplings of the Higgs to $W W$ and $Z Z$ is fixed by EW symmetry.

  - mass, total width and self coupling $\lambda$:
    • $\langle \Phi^+ \Phi \rangle = v^2/2 = m_h^2/2\lambda$ \[v = (G_F\sqrt{2})^{1/2} \approx 247 \text{ GeV}\]
    • look for invisible decays associated with BSM particles

  - Branching fractions into fermions:
    • Establishes whether the Higgs is the sole agent of fermion masses.
    • N.B. The original technicolor model provided for EWSB but not fermion masses.
    • Measure coupling to (top, bottom, tau) 3rd gen. and (charm, muon) 2nd gen. (2HDM)

  - Branching fractions into gauge bosons ($Z\gamma, gg, \gamma\gamma$)
    • Sensitive to BSM particles contributing in loops.
What can be done at the LHC?

- New projections from ATLAS and CMS for European Strategy Studies

- With 3 ab\(^{-1}\) HL-LHC may well:
  - Observe $H \rightarrow \mu^+ \mu^-$ to 6 $\sigma$. (ATLAS)
  - Measure the Higgs self-coupling to 30% (ATLAS)
What to measure and how well?

- Linear Colliders compared to LHC results for various decay channels

- Awaiting updates on LHC capabilities based on the 2012 run experience.
- Missing comparisons: $A=\mu$ [20%], $\Delta m(h)$ [100 MeV], $\Delta \Gamma(h)$ [5-10%] for both HL-LHC and ILC TeV
- The lepton collider results are limited by statistics.

M. Klute et.al. [arXiv:1301.1322]
A Muon Collider Higgs Factory

- Distinguish background processes: $\mu^+\mu^- \rightarrow \gamma \gamma + Z$ (ISR) (71%)
  from $\mu^+\mu^- \rightarrow Z^*$ (29%) [A. Conway, H. Wenzel]

- Jet momenta, opening angles, event shape.
- $WW^*/ZZ^*$ decay modes has very small background
- $b$-$b$ decay mode has $S/B = 1.47$

- $c$-$cbar$ decay mode more difficult. (see M. Purohit's talk)

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<tr>
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<th>Background (pb)</th>
<th>Higgs signal at peak (pb)</th>
<th>s/b</th>
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<tbody>
<tr>
<td>Basic counting</td>
<td>376</td>
<td>42.5</td>
<td>0.11</td>
</tr>
<tr>
<td>Z/gamma* tag</td>
<td>113</td>
<td>42.5</td>
<td>0.38</td>
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<tr>
<td>b-tagging</td>
<td>56.4</td>
<td>24.8</td>
<td>0.44</td>
</tr>
<tr>
<td>Combined</td>
<td>16.9</td>
<td>24.8</td>
<td>1.47</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>(in pb)</th>
<th>Background ($Z^<em>/\gamma^</em>$)</th>
<th>Signal (H)</th>
<th>s/b</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c$-$cbar$</td>
<td>19.4</td>
<td>1.2</td>
<td>0.062</td>
</tr>
<tr>
<td>$\tau^+\tau^-$</td>
<td>9.5</td>
<td>2.9</td>
<td>0.31</td>
</tr>
<tr>
<td>light quarks/gluons</td>
<td>46</td>
<td>3.6</td>
<td>0.078</td>
</tr>
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</table>
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
  $\sigma(\mu^+ \mu^- \rightarrow h) = 49.2 \text{ pb}$ (\(\Delta = \Gamma\))

- The excellent energy resolution \(\Delta\) of a muon collider makes the process observable.

Tao Han and Zhen Liu [arXiv:1210.7803]

To obtain the same sensitivity to Higgs decay modes in an electron collider via Zh process as s-channel production at a MC requires more than 100 times the integrated luminosity.
The strong case for a Tev scale hadron collider rested on two arguments:

1. Unitarity required that a mechanism for EWSB was manifest at or below the TeV scale.

2. The SM is unnatural (‘t Hooft conditions) and incomplete (dark matter, insufficient CP violation for the observed baryon excess, gauge unification, gravity and strings).

If after the analysis of the 2012 CMS/ATLAS data, the 126 GeV state is found to be a 0+ state with couplings consistent with the SM Higgs, the first argument is satisfied.

- The second argument remains strong, but is less strongly tied to the TeV scale.
- Scales already probed at the LHC suggest that any new collider (of LHC level costs) should be able the probe the BSM physics in the multi-TeV range.
No evidence for new physics beyond the Standard Model (BSM) to date:

- ATLAS limits
- CMS limits

Scales already probed at the LHC suggest that the energy of a MC should be in the multi-TeV range to study BSM new physics.

However there must be new physics!!! WHY? Let me list the reasons.
1. The Standard Model is incomplete:
   - dark matter; neutrino masses and mixing -> new fields or interactions;
   - baryon asymmetry in the universe -> more CP violation
   - gauge unification -> new interactions;
   - gravity: strings and extra dimensions

2. Experimental hints of new physics: \((g-2)_\mu\), top \(A_{fb}\), ...

3. Theoretical problems with the SM:
   - Scalar sector problematic:
     \[ \mu^2 (\Phi^+ \Phi) + \lambda (\Phi^+ \Phi)^2 + \Gamma_{ij} \psi_i^L \psi_j^R \Phi + h.c. \]
     
     - \(m_H^2/M_{\text{planck}}^2 \approx 10^{-34}\)
     - Hierarchy problem
     - vacuum stability
     - large range of fermion masses
   - The SM Higgs boson is unnatural. \((m_H^2/\mu^2)\)
   - Solutions: SUSY, New Strong Dynamics, ...

---

muon \((g-2)\)

- Davier, Hoecker, Malaescu, Zhang
- Jegerlehner, Szafron
- Hagiwara, Liao, Martin, Nomura, Teubner

<table>
<thead>
<tr>
<th>Experiment</th>
<th>BNL</th>
<th>BNL (new from shift in (\lambda))</th>
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<td>JN (09)</td>
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<td>Davier et al, (\tau) (10)</td>
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<td>Davier et al, (\sigma) ((\sigma \sigma) (10)</td>
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<td>JS (11)</td>
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<td>HLMNT (10)</td>
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</tr>
<tr>
<td>HLMNT (11)</td>
<td></td>
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</tr>
</tbody>
</table>

There remains a persistent discrepancy of 3.3-3.6 \(\sigma\)
Dilaton - (B. Grinstein’s talk)
- couplings proportional to mass
- loops can vary from SM because of new particles in the loops.

NMSSM - possibility of nearly degenerate (h,S) scalars:
- Models exist with very nearly degenerate pair of scalars
- The various decay rates could be disentangled at a muon collider.
Two Higgs doublets (MSSM):

- Five scalar particles: \( h^0, H^0, A^0, H^\pm \)

- Decay amplitudes depend on two parameters: \((\alpha, \beta)\)

\[
\begin{align*}
\mu^+\mu^-, b\bar{b} & & t\bar{t} & & ZZ, W^+W^- & & ZA^0 \\
h^0 & - \sin\alpha/\cos\beta & \cos\alpha/\sin\beta & \sin(\beta - \alpha) & \cos(\beta - \alpha) \\
H^0 & \cos\alpha/\cos\beta & \sin\alpha/\sin\beta & \cos(\beta - \alpha) & -\sin(\beta - \alpha) \\
A^0 & -i\gamma_5\tan\beta & -i\gamma_5/\tan\beta & 0 & 0 \\
\end{align*}
\]

\[
\tan 2\alpha = \frac{M_A^2 + M_Z^2}{M_A^2 - M_Z^2} \tan 2\beta.
\]

- decoupling limit \( m_A^0 \gg m_z^0 \): 
  - \( h^0 \) 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.
Beyond the Standard Model

- 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 with easy at a multi-TeV lepton collider.
- Good energy resolution is needed for $H^0$ and $A^0$ studies:

- At a $\mu C$ the states can be separated for $m_A < 900$ GeV

Dittmaier and Kaiser
[hep-ph/0203120]
Supersymmetry

- Symmetry charges $Q_{\text{susy}}$ have spin 1/2. Not a purely internal symmetry
  
  \[ \{Q_{\text{susy}}, Q_{\text{susy}}\} = 2 \gamma \mu P_{\mu}; \quad Q_{\text{susy}} H|\text{state}\rangle = H Q_{\text{susy}}|\text{state}\rangle \]

- $Q_{\text{susy}} |\text{boson}\rangle = |\text{fermion}\rangle$: gluon -> gluino,...; W boson -> wino; higgs -> higgino, ...
  
  $Q_{\text{susy}} |\text{fermion}\rangle = |\text{boson}\rangle$: top quark (L,R) -> top squark (L,R), ...

- Supersymmetry dictates the couplings between particles and sparticles
- Dark matter candidates, GUT unification
- No superpartner has yet been observed => Supersymmetry is broken $M_{\text{sparticle}} 
eq 27$

- What is the spectrum of superpartner masses?
- Dark matter candidates?
- Are all the couplings correct?
- What is the structure of flavor mixing interactions?
- Are there additional CP violating interactions?
- Is R parity violated?
- What is the mass scale at which SUSY is restored?
- What is the mechanism of SUSY breaking?
• LHC limits on SUSY sparticles in various cMSSM scenarios:
  
  - Gluino and light squark masses limits ~ 1 TeV
  
  - Stop (3rd generation) ~ 600 GeV (except very near top mass)
  
  - The detailed study of SUSY will require a multiTeravolt lepton collider
Supersymmetry

- **cMSSM** - simple model with only 5 parameters \((m_0, m_{1/2}, \tan \beta, A/m_0, \text{sign}(\mu))\)

- LHC limits on SUSY sparticles in various cMSSM scenarios:
  - Gluino and light squark masses limits ~ 1 TeV
  - The detailed study of SUSY will require a multiTev lepton collider

- As mass scales increase \((\mu^2\text{ increases})\) more fine tuning
  \[
m_Z^2 = 2 \frac{M_H^2 \tan^2 \beta M_{H_u}^2}{\tan^2 \beta - 1} - 2\mu^2 \quad + \text{loop corrections: logs}(m_t/m_t)
\]

- Are various constrained models consistent with a Higgs mass of 126 GeV?
  - Parameters varied in wide range.
    Upper bound - \(m_h\) in top 1%
  - **GMSB, AMSB** ✗
  - **mSUGRA** ✓
    - **NUHM**: non universal \(m_0\)
    - **VCMSSM**: \(m_0 \approx -A_0\)
    - **NMSSM**: \(m_0 = 0\) \(A_0 \approx -1/4m_{1/2}\)
    - no scale: \(m_0 \approx A_0 \approx 0\)

[A. Atbey, et. al.: arXiV:1112.3028]
Supersymmetry

- pMSSM - minimal assumptions on SUSY breaking parameters
  - 22 parameters varied
    \[ 1 \leq \tan \beta \leq 60, \ 50 \text{ GeV} \leq M_A \leq 3 \text{ TeV}, \ -9 \text{ TeV} \leq A_t \leq 9 \text{ TeV}, \ 50 \text{ GeV} \leq m_{\tilde{f}_L}, m_{\tilde{f}_R}, M_3 \leq 3 \text{ TeV}, \ 50 \text{ GeV} \leq M_1, M_2, |\mu| \leq 1.5 \text{ TeV}. \]
  - stop mixing parameter \( X_t = A_t - \mu \cot \beta; \quad M_S = \sqrt{m_{t\bar{t}} - m_{t\bar{t}}^2} \)

- Consistence requires: \( M_A \gg M_h; \quad \tan \beta > 10; \quad M_S \text{ large}; \quad \text{maximal mixing} \sim \sqrt{6} M_S \)
- Sleptons, charginos and neutralinos still remain easily assessible at a multi-TeV lepton collider.
- Supersymmetry provides a very strong case for a multi-TeV muon collider.

[A. Atbey, et. al.: arXiV:1112.3028]
New Dynamics

- **Electroweak Symmetry Breaking is generated dynamically at nearby scale**
  - Technicolor, ETC, walking TC, topcolor, Two Scale TC, composite Higgs models, ...
  - **New strong interaction around 1 TeV:**
    - What is the spectrum of low-lying states? s-channel production $\pi_T$ (technipion) ($0^-$), $\rho_T$, $\omega_T$ (technirho, techniomega) nearly degenerate - needs good energy resolution
    - What is the ultraviolet completion? Gauge group? Fermion representations?
    - What is the energy scale of the new dynamics?
    - Any new insight into quark and/or lepton flavor mixing and CP violation?

- **Contact interactions**
  - e.g. Compositeness, broken flavor symmetries, ...
  - Present LHC bounds (~ 10 TeV) 
    $$\mathcal{L} = \frac{g^2}{\Lambda^2} (\bar{\Psi} \Gamma \Psi) (\bar{\Psi'} \Gamma' \Psi)$$
  - Muon collider sensitive to scales > 200 TeV
    - Forward cone cut not important
    - Polarization useful in determining chiral character of the interaction.
In Summary

• The unique measurements of the Muon Higgs factory (1 fb⁻¹)
  - Most precise measurement of Higgs mass: \( \Delta m_H = 0.1 \text{ MeV} \)
  - Direct Higgs width measurement: \( \Delta \Gamma_H = 0.17 \text{ MeV} \).
  - Measurement of \( \text{BR}(\mu^+\mu^-) \text{BR}(WW^*) \) to 2\%. Other channels: bb, ZZ, \(\tau\tau\), cc under investigation.
  - Disentangle nearly degenerate scalar resonances.

• Issues to address for MC Higgs factory:
  - Can the shot to shot energy of the beams be controlled to a few \( \times 10^{-5} \) accuracy
  - Detailed studies of S/B required for physics reach.
  - High backgrounds in the detectors from muon decays upstream.
  - Studies should combine information available from LHC results to determine the added benefit of any future lepton collider.

• The high energy Muon Collider is the only lepton machine capable of reaching \( \geq 3\text{TeV} \) energy scales in an affordable way.
BACKUP SLIDES
1. The LHC is the Higgs Accelerator - Continue -> HL-LHC

2. Continue research and development of lepton colliders. In particular the muon collider needs a convincing proof of 6D cooling.

3. Push neutrino physics - Lepton sector

4. After 300 fb$^{-1}$ of ~14 TeV running OR the discovery of BSM physics, chose the next accelerator for Higgs physics.

Is a Muon Collider Feasible?

New physics below $\sqrt{s} = 1$ TeV?

- YES
  - e+e- linear collider extendable to $\sqrt{s} = 1$ TeV

- NO
  - $\mu$on higgs factory --> muon collider with $\sqrt{s} \geq 3$ TeV
  - $e^+e^-$ circular collider in large tunnel --> hadron collider with $\sqrt{s} \geq 100$ TeV
• Excess in the 126 GeV region: Is it the SM higgs?
  
  - spin and parity: 0\(^+\) or 0\(^-\) (or 2\(^\pm\))

  - use ZZ* \(\rightarrow\) 4 leptons, WW* \(\rightarrow\) lepton + E\(_T\) (missing) + 2jets angular correlations

  [Z\(^0\)Z\(^0\)] P.S. Bhupal Dev, et. al. [arXiv:0707.2878]; Yanyan Gao et. al. [arXiv:1001.3396]
  [W\(^+\)W\(^-\)] J. Ellis and D.S. Hwang [arXiv:1202.6660]

S. Bolognesi [ICHEP 2012]
More S-channel Resonances

- New $Z'$, $W'$
  - S-channel resonances - factories for lepton colliders
  - Set minimum luminosity for MC.

Minimum luminosity at $Z'$ peak:
$\mathcal{L} = 1.0 - 5.0 \times 10^{30}$ cm$^{-2}$ sec$^{-1}$
for $M(Z') \rightarrow 2.5 - 5.0$ TeV

- A muon collider can be built to operate well above 4 TeV:
  - Keeping the same limits on neutrino radiation.
  - The luminosity will scale as:
    \[ \frac{L(E_{cm})}{L(4 \text{ TeV})} = \left( \frac{E_{cm}}{4 \text{ TeV}} \right)^{-2} \]
  - If the emittance can be reduced as the energy is increased, up to one power of energy ratio can be recovered.

- Hence an s-channel resonance well in excess of 10 TeV could be studied in detail at such a muon collider.
Example study of slepton pair production:

\[ \mu^+ \mu^- \rightarrow \tilde{e}_1^+ \tilde{e}_1^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 e^+ e^- \]

- Mass measurements of neutrino using edge method:

\[ E_{\text{max/min}} = \frac{1}{2} M_{\tilde{e}} \left[ 1 - \frac{M_{\tilde{\chi}_1^0}^2}{M_{\tilde{e}}^2} \right] \gamma(1 \pm \beta) \]

- Inherently better at MC. No beamstrahlung. CLIC does well for slepton pair production near threshold.

N. Alster and M. Battaglia [arXiv:1104.0523]
Detailed study for muon collider

- large backgrounds

- suitable cuts reduce backgrounds but limit sensitivity to small mass difference between smuon and its decay products.

\[ \sqrt{s} = 3 \text{ TeV}, \ m_{R_R} = 1 \text{ TeV}, \ m_{\tilde{\chi}_1^0} = 0.6 \text{ TeV} \]

for 6° shielding cone: \( \delta m_{\tilde{\mu}_R}^{\text{fit}} = +\frac{32}{40} \text{ GeV}, \)

for 20° shielding cone: \( \delta m_{\tilde{\mu}_R}^{\text{fit}} = +\frac{40}{40} \text{ GeV}, \)

- Shows the advantage of instrumenting the shielding cone.

[A. Freitas: arXiV:1107.3853]
New Dynamics

- Electroweak Symmetry Breaking is generated dynamically at a nearby scale.
  - What is the spectrum of low-lying states?
  - What is the ultraviolet completion? Gauge group? Fermion representations?
  - What is the energy scale of the new dynamics?
  - Any new insight into quark and/or lepton flavor mixing and CP violation?
  - ...

- State observed at 125 GeV would more naturally be a pseudoscalar (0−)

Technicolor, ETC, Walking TC, Topcolor, ...

For example with a new strong interaction at TeV scale expect:
- Technipions - s channel production (Higgs like)
- Technihros - Nearby resonances (ρT,ωT)- need fine energy resolution of muon collider.

Eichten, Lane, Womersley PRL 80, 5489 (1998)
M(ρT) = 210 GeV M(ωT) = 211, 209 GeV
MC 40 steps (total 1 fb⁻¹)

good benchmark processes

CLIC - D-BESS model (resolution 13 GeV)
Contact Interactions

- The SM is only an effective theory valid below the compositeness scale.
  - New interactions (at scales not directly accessible) give rise to contact interactions.
    \[ \mathcal{L} = \frac{g^2}{\Lambda^2}(\bar{\psi} \Gamma \psi)(\bar{\psi} \Gamma' \psi) \]
  - Present LHC Limits (CMS table)
  - Muon collider is sensitive to contact interaction scales over 200 TeV as is CLIC.
  - Cuts on forward angles for a muon collider not an issue.
    Muon Collider Study
  - Polarization useful to disentangle the chiral structure of the interaction.
    (CLIC) good benchmark process
A few words about Detector Issues

- ILC-like detector requirements for efficient heavy quark tags, muon and electron id, and jet energy scale calibration.

- The high backgrounds events entering the detector from muon decays in the beam upstream requires a detector employing a traveling time gate to reduce out of time hits.