Muon Collider Physics

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OUTLINE

- Landscape - 2020
- Beyond the Standard Model
- Narrow States
- Outlook and Opportunities

Landscape for 2020
Energy Frontier Facilities

Existing facilities:

- LHC with luminosity or energy upgrade
- ILC - with potential upgrades

Options:

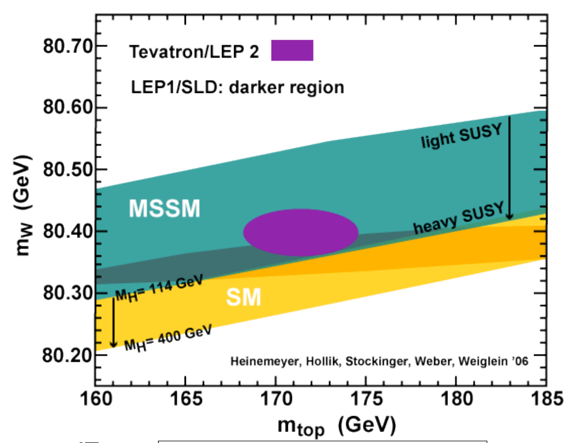
- lepton collider in multi Tev range.
  CLIC or Muon collider
  - Energy, Luminosity, Polarization?
- hadron collider in hundred TeV range
  VLHC

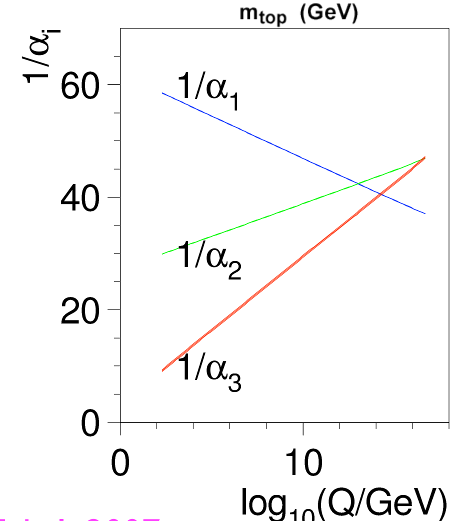
Comparison of Muon Collider and CLIC (same $\sqrt{s}$ and $\mathcal{L}$)

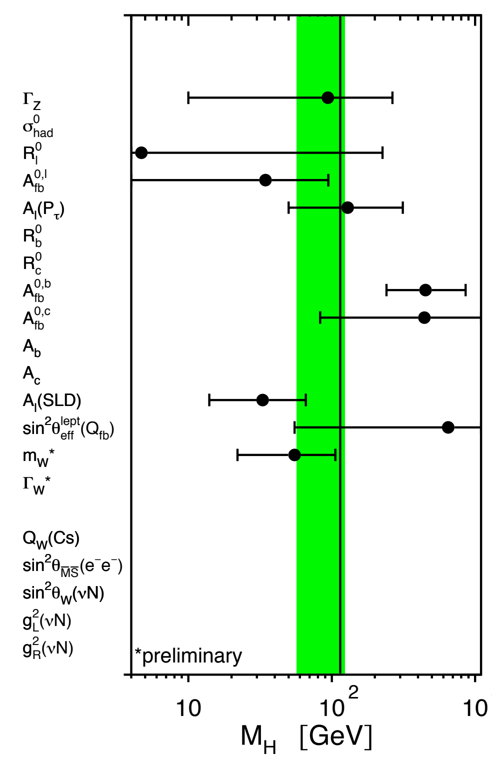
- Present theoretical studies of physics potential of multi-TeV muon colliders are inadequate.
- For many processes the cross sections are essentially the same as for CLIC.
- For scalars (eg h, A, H) with fermion mass dependent couplings, the muon collider has advantage of s-channel single production.
- Especially for SUSY options, lepton beam polarization is useful.
- For muon collider, the effects of muon decay backgrounds and required angular cuts needs detailed study.

Today

- All data consistent with Standard Model - but:
- incomplete
  - dark matter
  - neutrino masses and mixing
    - new fields ν_R or new interactions $\frac{1}{\Lambda}\nu^c H^\dagger H \nu$ (seesaw)
  - baryon asymmetry
    - more CP violation
- experimental hints
  - higgs mass
  - muon (g-2)
- theoretical questions
  - origin of mass:
    - naturalness and higgs
  - gauge unification:
    - new interactions
  - gravity: strings and ED





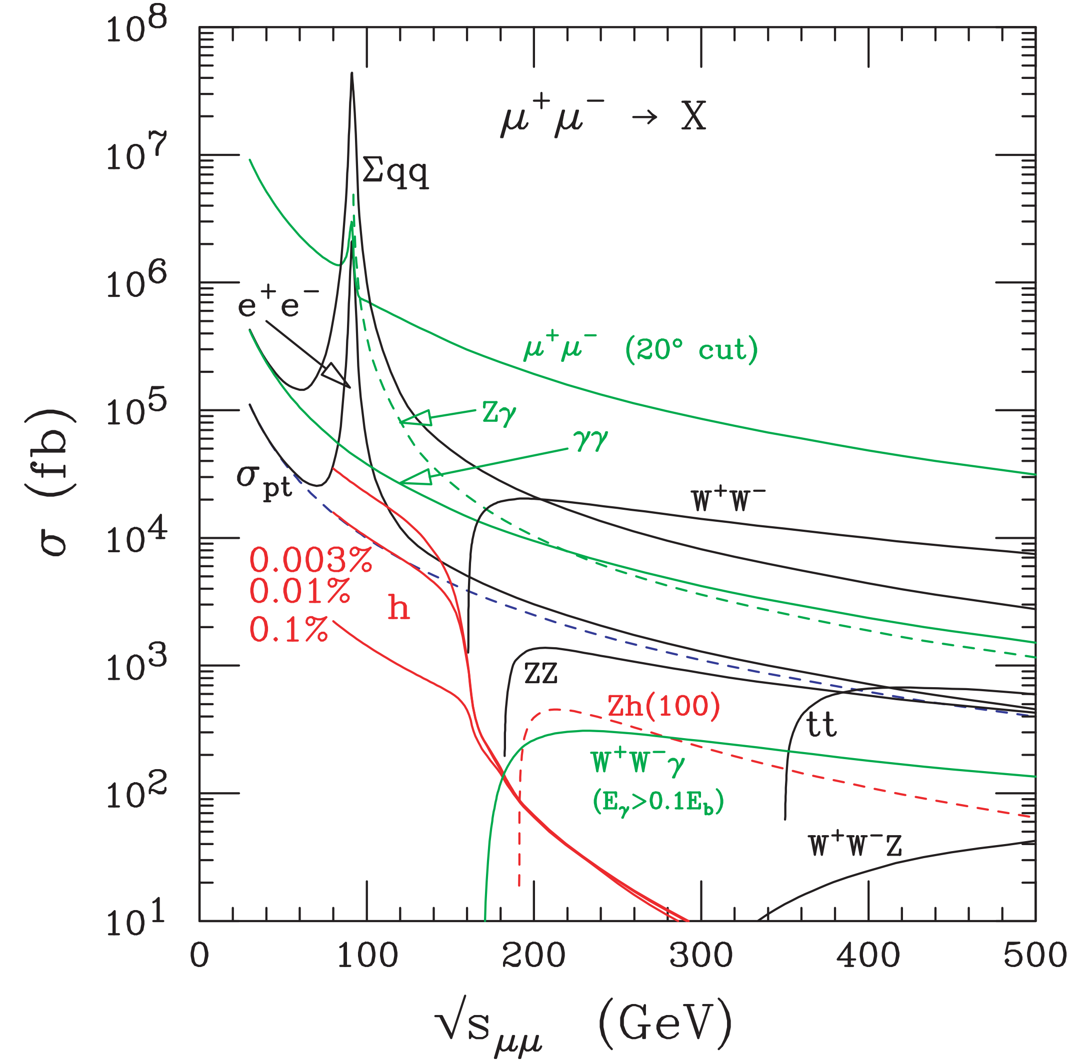


Standard Model Cross Sections

- For √s < 500 GeV muon collider
  - threshold regions:
    - top pairs
    - electroweak boson pairs
    - Zh production
  - s-channel Higgs production:
    - coupling ∝ mass

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

$m(h) = 110$ GeV : $\Gamma = 2.8$ MeV
$m(h) = 120$ GeV : $\Gamma = 3.6$ MeV
$m(h) = 130$ GeV : $\Gamma = 5.0$ MeV
$m(h) = 140$ GeV : $\Gamma = 8.1$ MeV
$m(h) = 150$ GeV : $\Gamma = 17$ MeV
$m(h) = 160$ GeV : $\Gamma = 72$ MeV



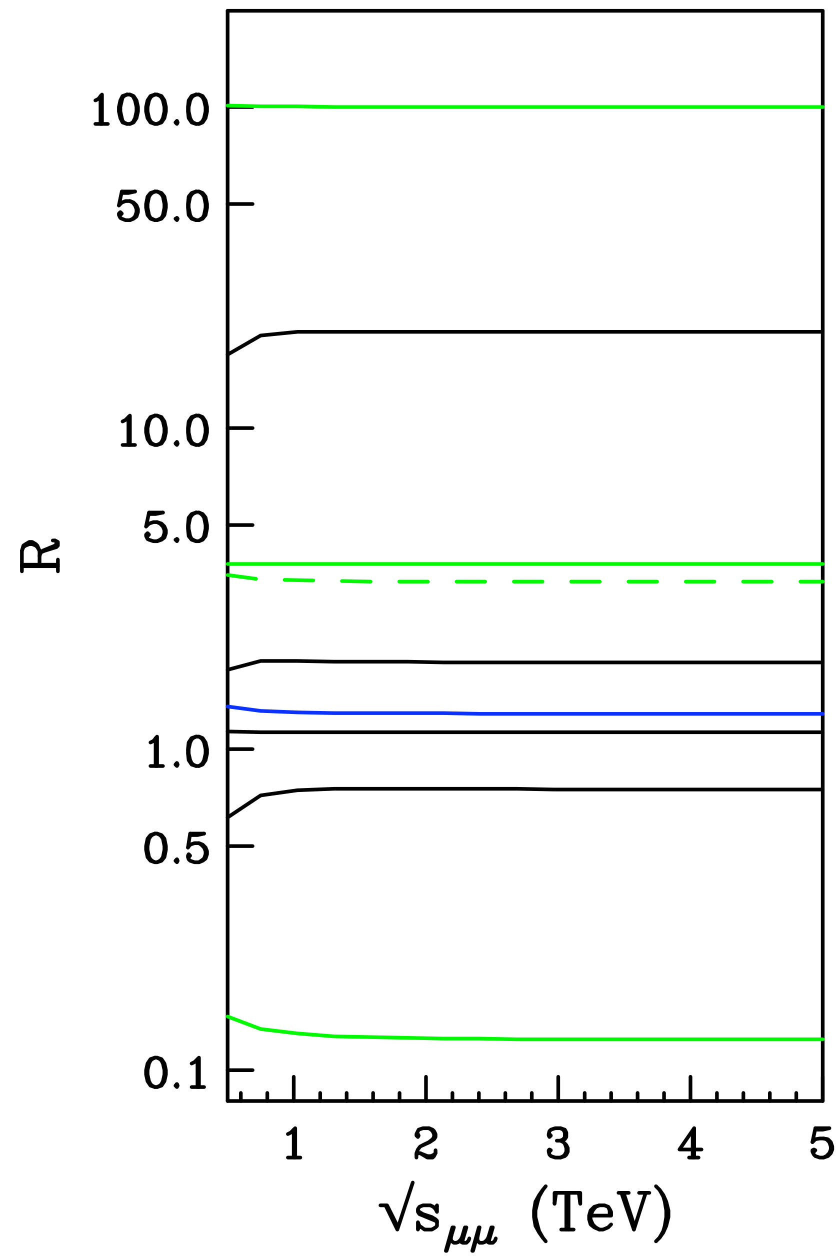
For $\sqrt{s}$ > 500 GeV muon collider

- Above SM thresholds:
- R essentially flat:

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

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

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



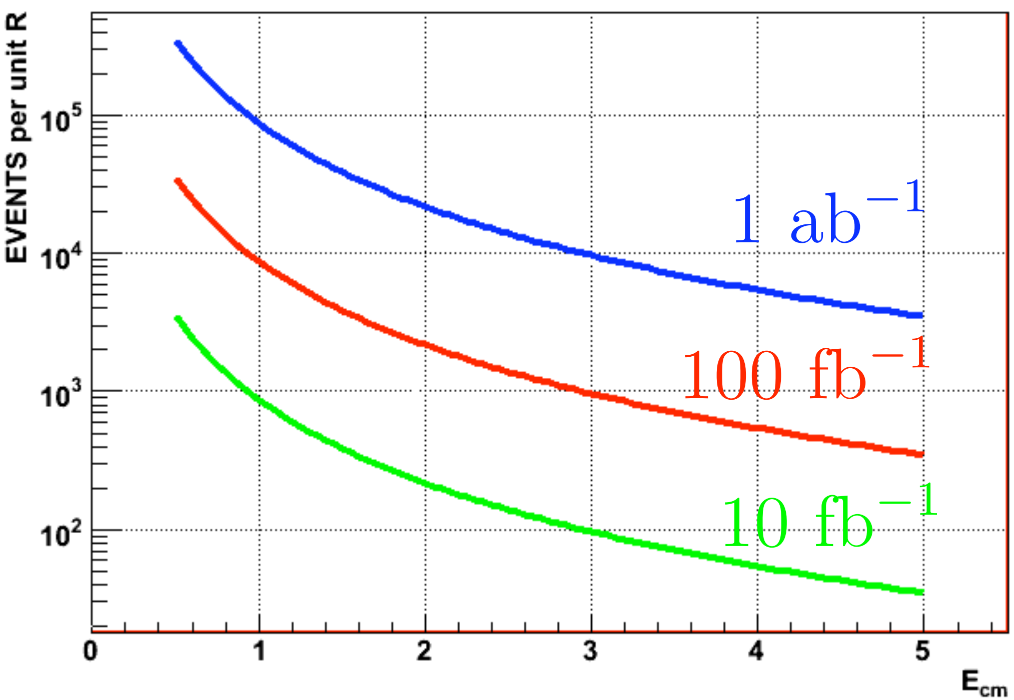
Luminosity requirements:

one unit of R: $\sigma_{\text{QED}}(\mu^+\mu^- \to e^+e^-) = \frac{4\pi\alpha^2}{3s} = \frac{86.8 \text{ fb}}{s(\text{TeV}^2)}$

$\sqrt{s} = 1.5 \text{ TeV}$

Luminosity per year

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

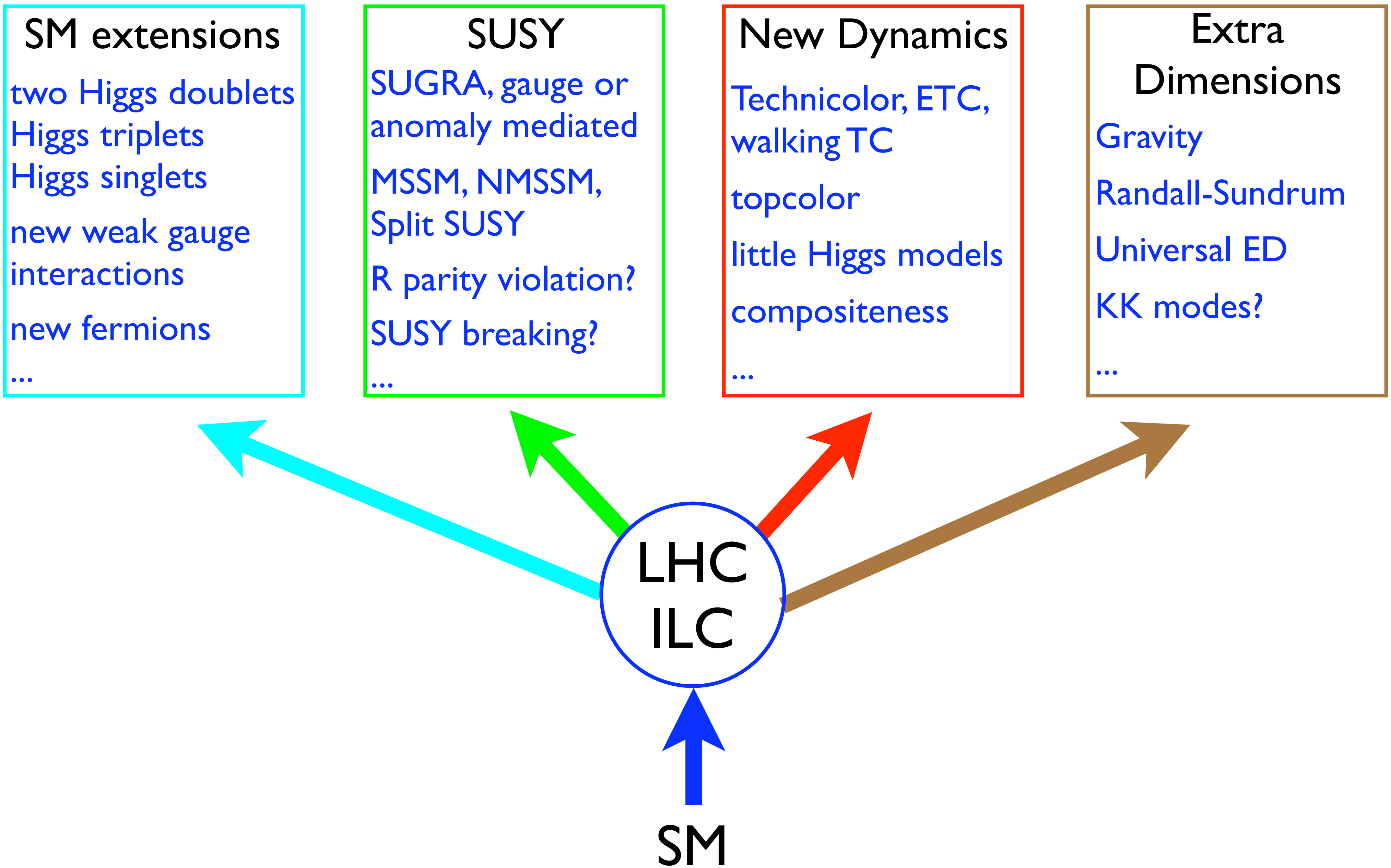


3860 events/unit of R

Processes with R ≥ 0.01 can be studied

510 K events per year

Landscape for 2020 Theoretical Physics



SM and Extensions

Theoretical issues

- Higgs boson couplings SM?
- Scalar interaction coupling SM?
- Any additional scalars?   EW doublets, triplets or singlets ?
- More fermions?
- Addition gauge interactions ?
- Where's the next scale? GUT?

Studying the SM Higgs boson:

- Higgs coupling proportional to fermion mass
- Various processes available:
  - s-channel direct production: h ($\sqrt{s} = m_h$)
  - associated production: Zh (see figure)
    - R ~ 0.12
    - search for invisible h decays
  - Higgsstrahlung: $t\bar{t}h$
    - R ~ 0.01
    - measure top coupling
  - W*W* fusion : $\nu_\mu \bar{\nu}_\mu h$ (see figure)
    - R ~ 1.1 s ln(s) (s in TeV^2) (m_h =120 GeV)
    - study some rare decay modes
    - measure Higgs self coupling

Fine energy resolution ($\Delta E/E$) is possible for muon colliders

h

$$\sigma_h(\sqrt{\hat{s}}) = \frac{4\pi\Gamma(h\to\mu\mu)\,\Gamma(h\to X)}{(\hat{s}-m_h^2)^2 + m_h^2[\Gamma_h^{\rm tot}]^2}\,,$$

$$\sigma_{\sqrt{s}} = (7\ \mathrm{MeV})\left(\frac{R}{0.01\%}\right)\left(\frac{\sqrt{s}}{100\ \mathrm{GeV}}\right)\,.$$

$$\overline{\sigma}_h = \frac{2\pi^2\Gamma(h\to\mu\mu)\,BF(h\to X)}{m_h^2}\times\frac{1}{\sigma_{\sqrt{s}}\sqrt{2\pi}} \qquad (\Gamma_h^{\rm tot}\ll\sigma_{\sqrt{s}})\,.$$

$$\overline{\sigma}_h = \frac{4\pi BF(h\to\mu\mu)BF(h\to X)}{m_h^2} \qquad (\Gamma_h^{\rm tot}\gg\sigma_{\sqrt{s}})$$

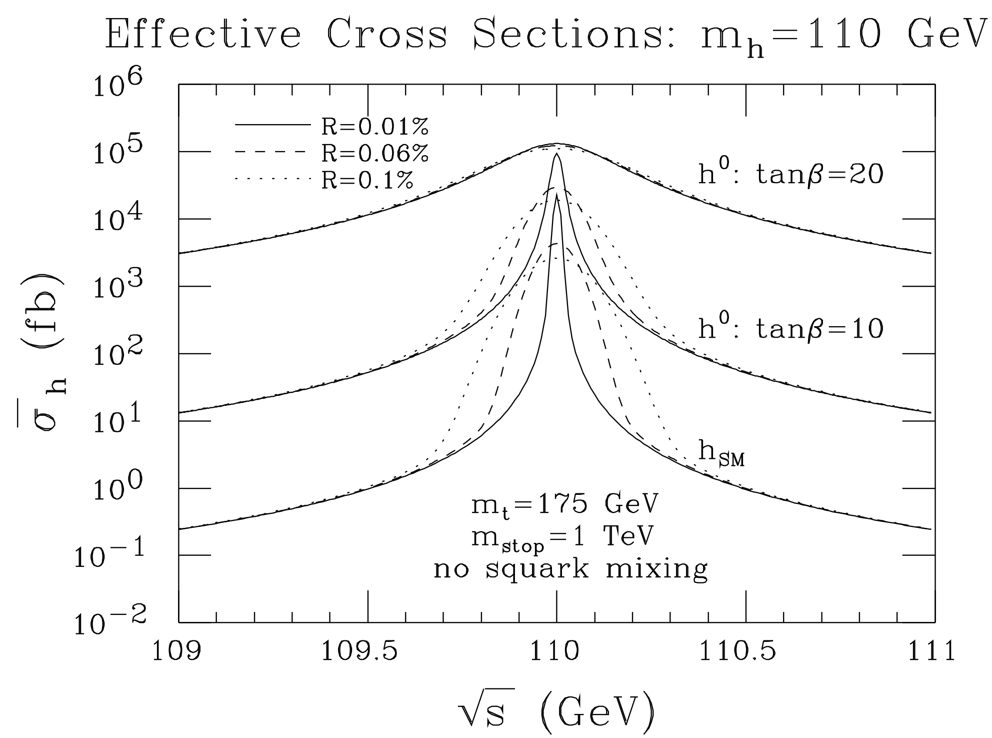
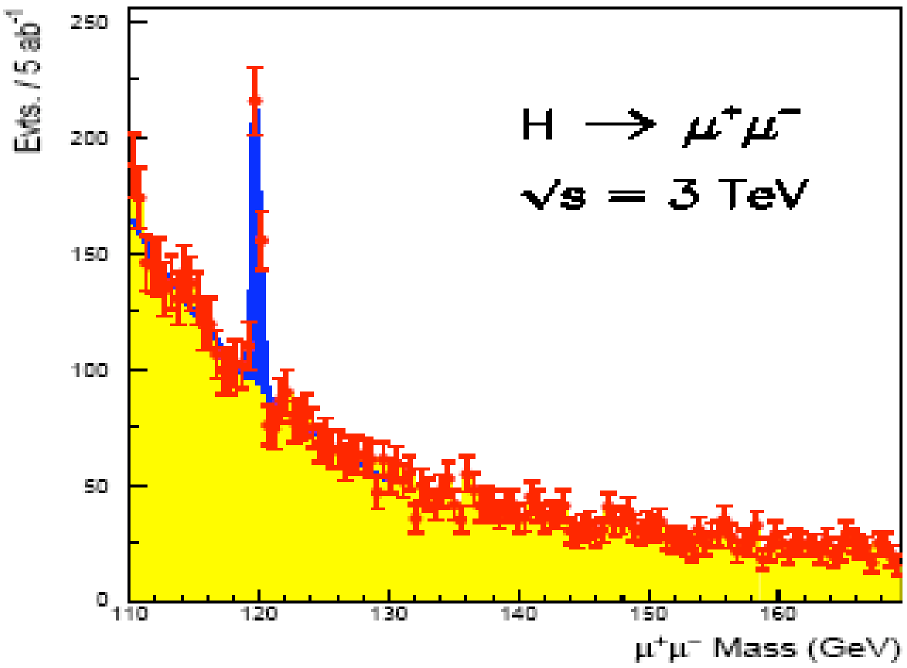
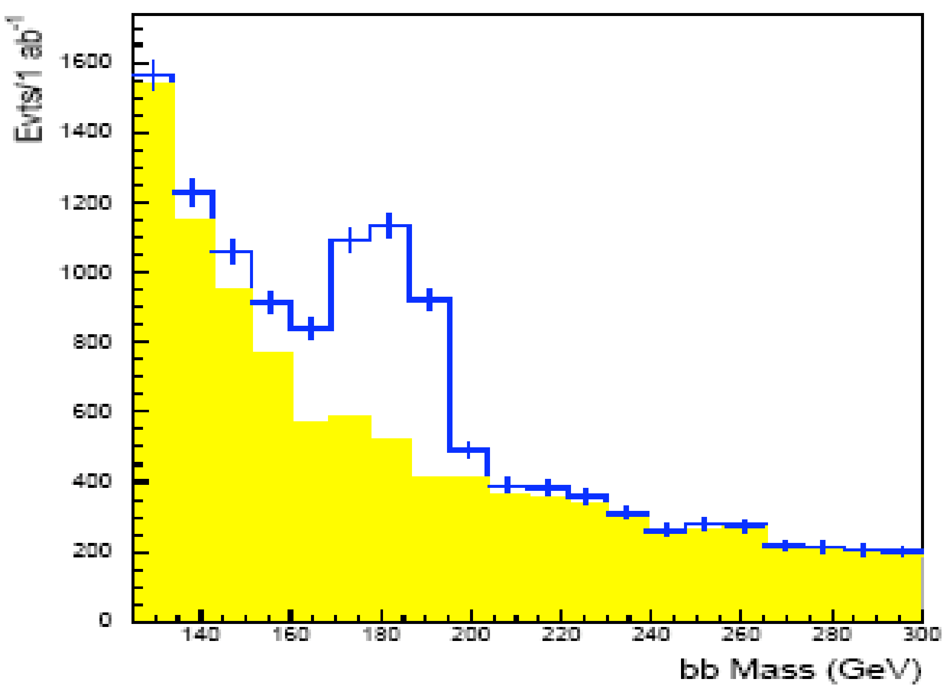


Figure 7: The effective cross section, $\overline{\sigma}_h$, obtained after convoluting σ_h with the Gaussian distributions for $R = 0.01\%$, $R = 0.06\%$, and $R = 0.1\%$, is plotted as a function of $\sqrt{s}$ taking $m_h = 110$ GeV. Results are displayed in the cases: h_{SM}, h^0 with $\tan\beta = 10$, and h^0 with $\tan\beta = 20$. In the MSSM h^0 cases, two-loop/RGE-improved radiative corrections have been included for Higgs masses, mixing angles, and self-couplings assuming $m_{\widetilde{t}} = 1$ TeV and neglecting squark mixing. The effects of bremsstrahlung are not included in this figure.

Measuring SM Higgs width directly requires: $\Delta E/E < 0.002\%$ with an integrated lumonisity > 2 pb^{-1}

Higgs reconstruction - ZH (CLIC)





m(h) = 120 GeV

m(h) = 200 GeV

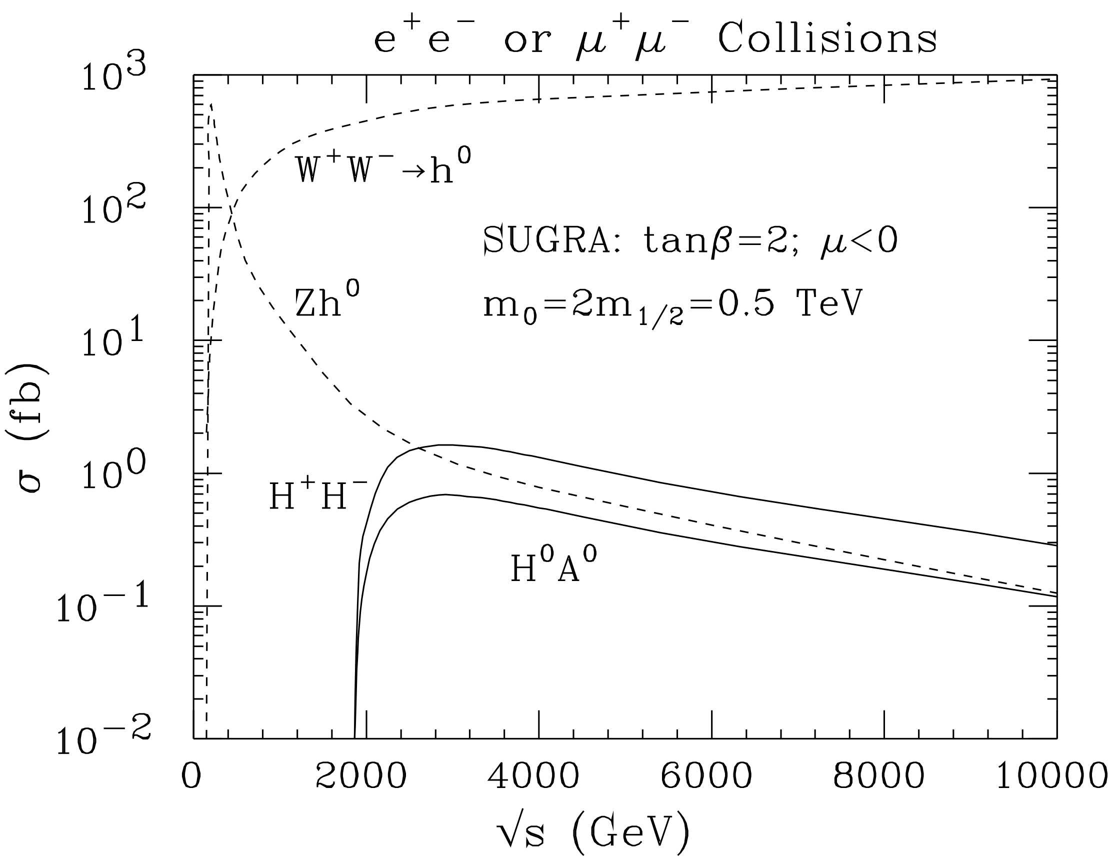


FIGURE 6. Pair production of heavy Higgs bosons at a high energy lepton collider. For comparison, cross sections for the lightest Higgs boson production via the Bjorken process $\mu^+\mu^- \to Z^* \to Zh^0$ and via the WW fusion process are also presented.

Two Higgs doublets (MSSM)

	$\mu^+\mu^-, b\bar{b}$	$t\bar{t}$	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

- decoupling limit $m_{A^0} >> m_{Z^0}$:
  - h 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 tanβ, H^0 and A^0 couplings to charged leptons and bottom quarks enhanced by tanβ. Couplings to top quarks suppressed by 1/tanβ factor.

- 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

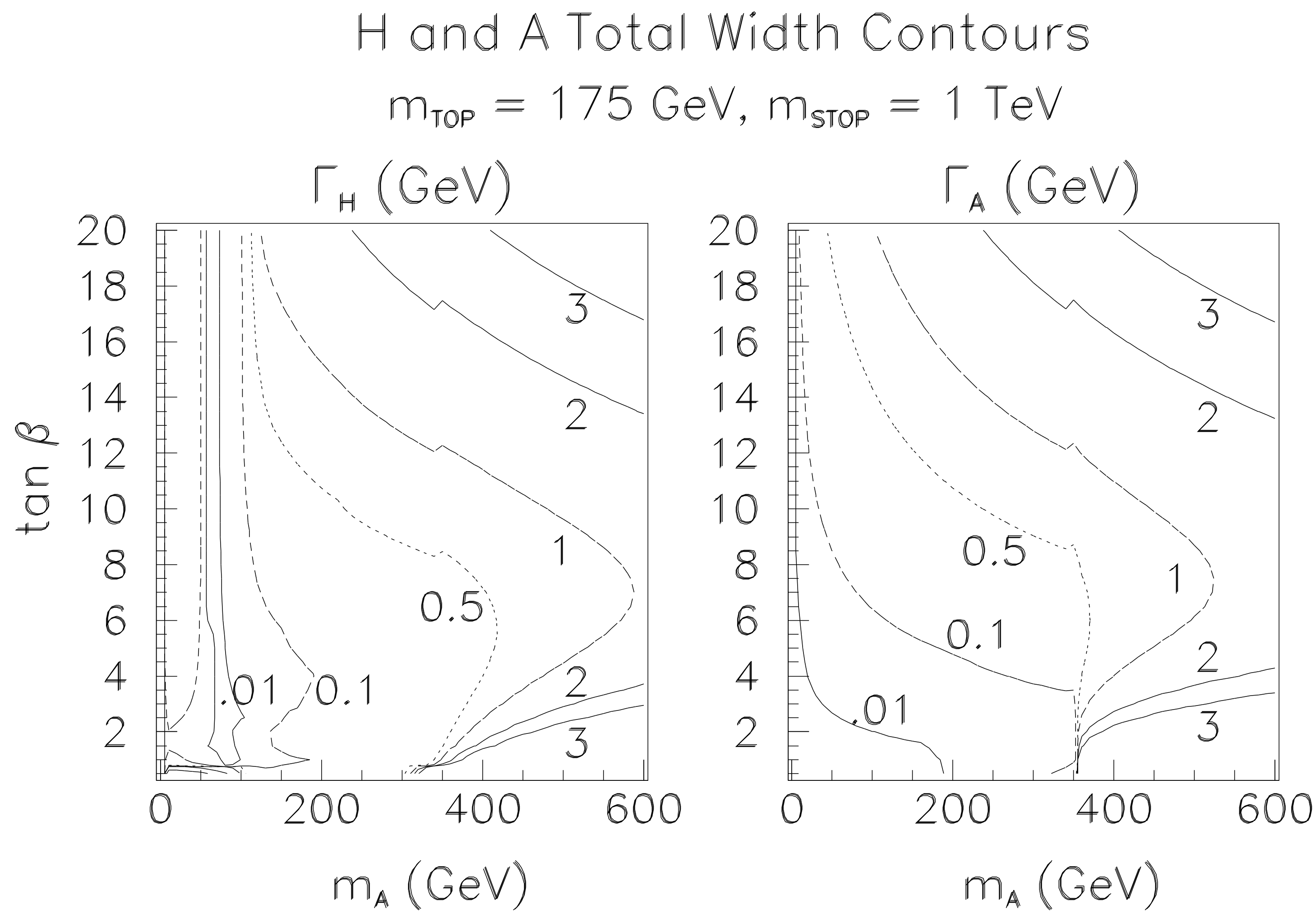


Figure 20: Contours of H^0 and A^0 total widths (in GeV) in the $(m_{A^0}, \tan\beta)$ parameter space. We have taken $m_t = 175$ GeV and included two-loop/RGE-improved radiative corrections using $m_{\tilde{t}} = 1$ TeV and neglecting squark mixing. SUSY decay channels are assumed to be absent.

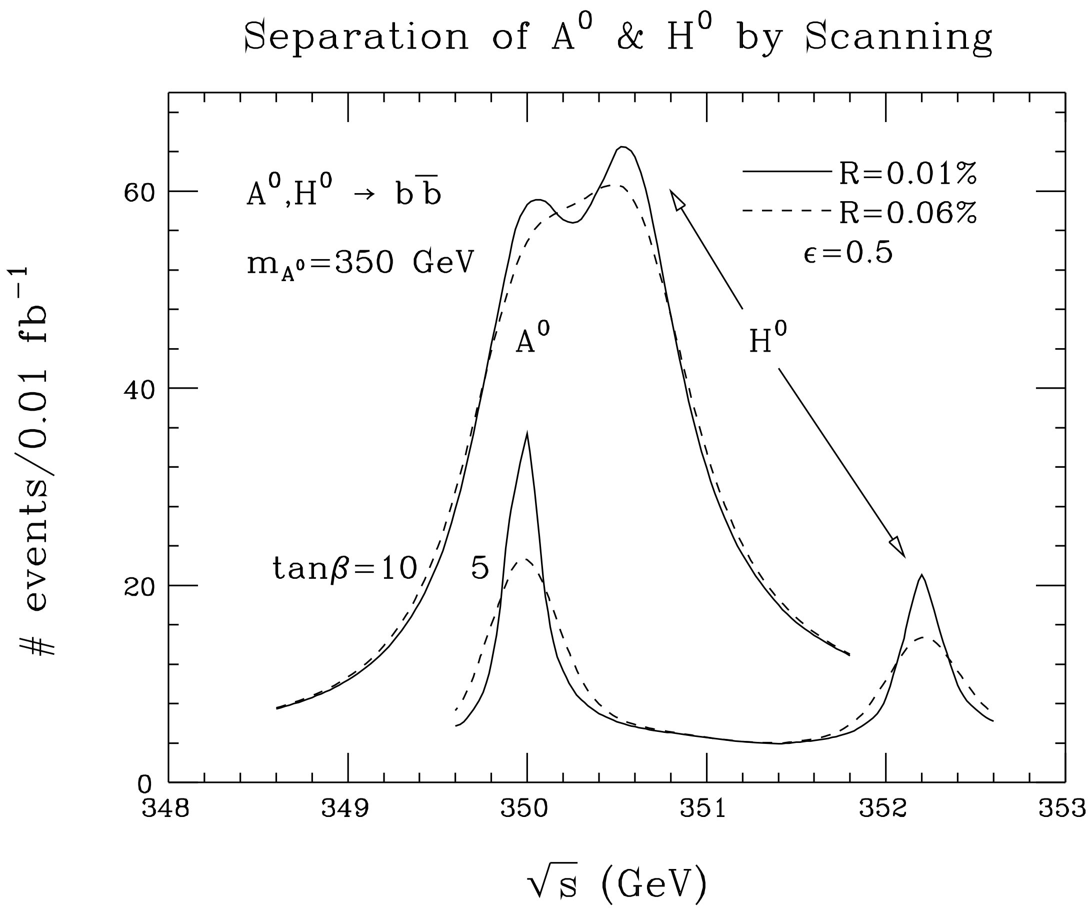


FIGURE 4. Plot of $b\bar{b}$ final state event rate as a function of $\sqrt{s}$ for $m_{A^0} = 350$ GeV, in the cases $\tan\beta = 5$ and 10, resulting from the H^0, A^0 resonances and the $b\bar{b}$ continuum background. We have taken $L = 0.01\ \mathrm{fb}^{-1}$ (at any given $\sqrt{s}$), efficiency $\epsilon = 0.5$, $m_t = 175$ GeV, and included two-loop/RGE-improved radiative corrections to Higgs masses, mixing angles and self-couplings using $m_{\tilde{t}} = 1$ TeV and neglecting squark mixing. SUSY decays are assumed to be absent. Curves are given for two resolution choices: $R = 0.01\%$ and $R = 0.06\%$

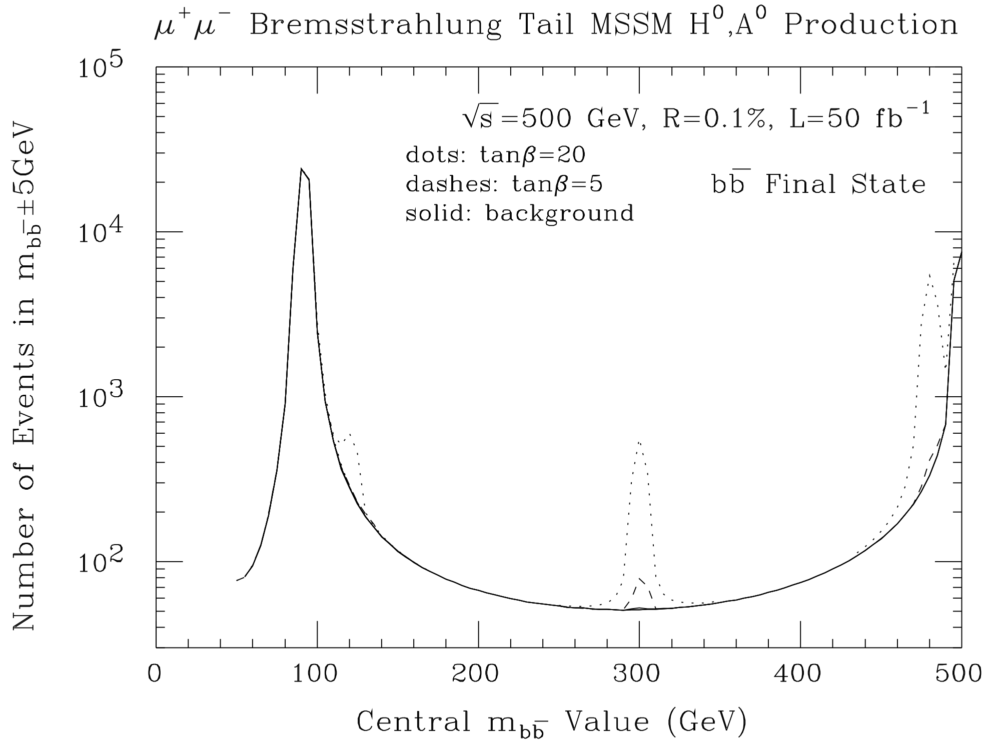


FIGURE 5. Taking $\sqrt{s} = 500$ GeV, integrated luminosity $L = 50\ \text{fb}^{-1}$, and $R = 0.1\%$, we consider the $b\bar{b}$ final state and plot the number of events in the interval $[m_{b\bar{b}} - 5\ \text{GeV}, m_{b\bar{b}} + 5\ \text{GeV}]$, as a function of the location of the central $m_{b\bar{b}}$ value, resulting from the low $\sqrt{\hat{s}}$ bremsstrahlung tail of the luminosity distribution. MSSM Higgs boson H^0 and A^0 resonances are present for the parameter choices of $m_{A^0} = 120$, 300 and 480 GeV, with $\tan\beta = 5$ and 20 in each case. Enhancements for $m_{A^0} = 120$, 300 and 480 GeV are visible for $\tan\beta = 20$; $\tan\beta = 5$ yields visible enhancements only for $m_{A^0} = 300$ and 480 GeV. Two-loop/RGE-improved radiative corrections are included, taking $m_t = 175$ GeV, $m_{\widetilde{t}} = 1$ TeV and neglecting squark mixing. SUSY decay channels are assumed to be absent.

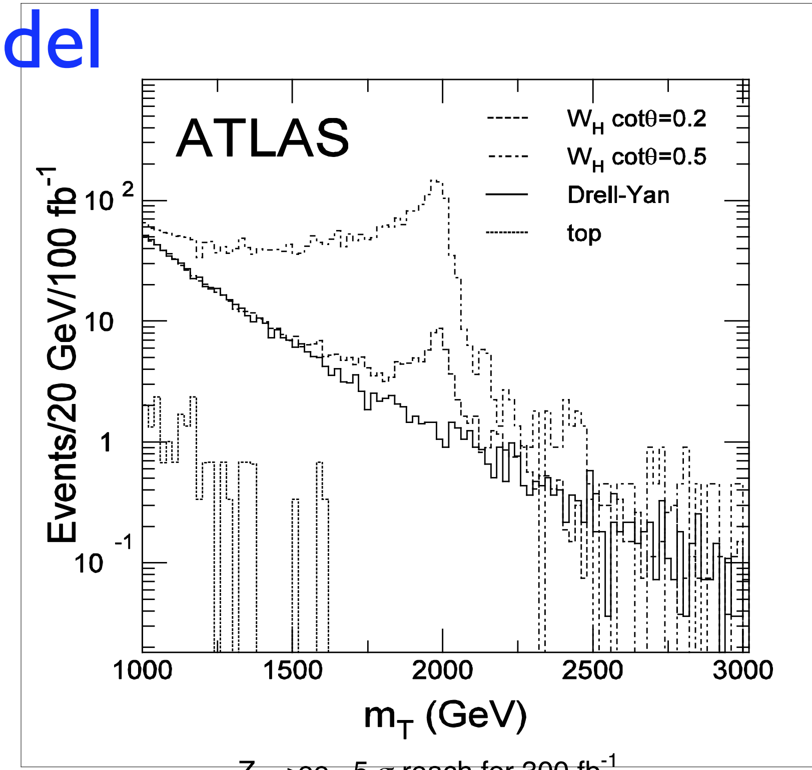
Other extensions of the standard model
New fermions and gauge bosons

Littlest Higgs model -
charge (2/3) quark T (EW singlet),
new W, Z, and A gauge bosons,
Higgs triplet

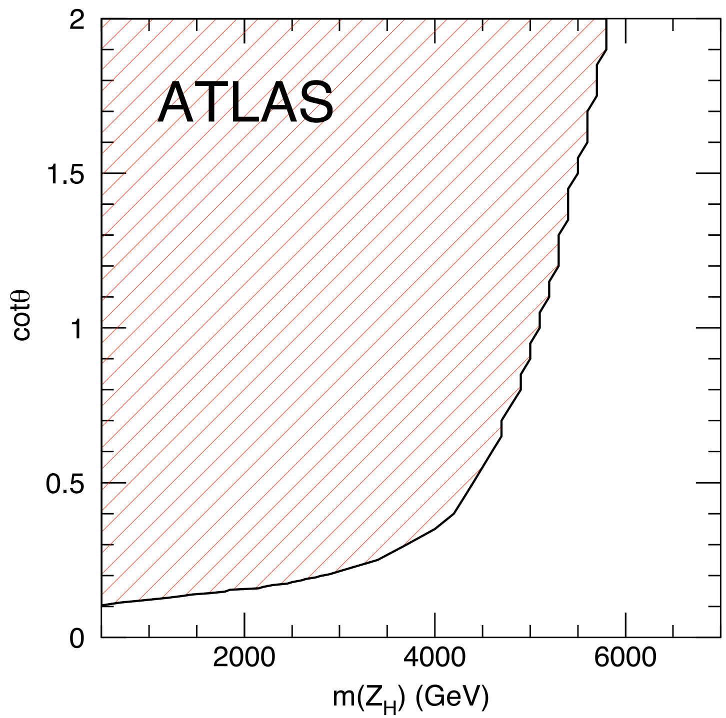
ATLAS study LHC [hep-ph/0402037]

T observable for m(T) < 2.5 TeV
For W, Z, and A dependent on mixing parameters --> see figures

Muon collider will allow detailed study.
high luminosity



$Z_H \rightarrow ee$ 5 σ reach for 300 fb^{-1}



Supersymmetry

Theoretical issues

- 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 mechanism of SUSY breaking?
- What is the mass scale at which SUSY is restored?
- ...

CLIC detailed study - CERN report 2004

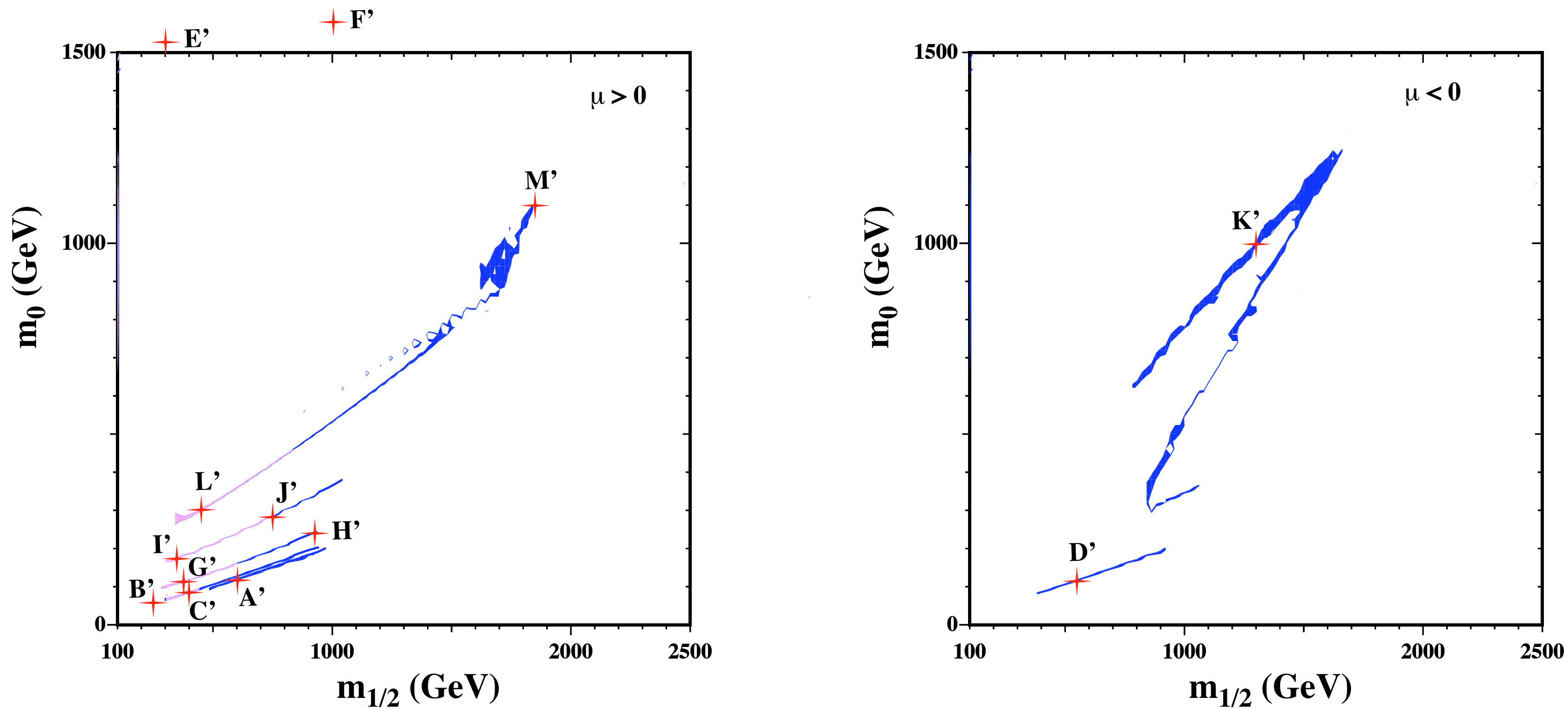


Fig. 5.2: Overview of the updated proposed CMSSM benchmark points in the $(m_0, m_{1/2})$ planes, superposed on the strips allowed by laboratory limits and the relic density constraint, for $\mu > 0$ and $\tan\beta$ = 5, 10, 20, 35, 50, and for $\mu < 0$ and $\tan\beta$ = 10, 35 [8]

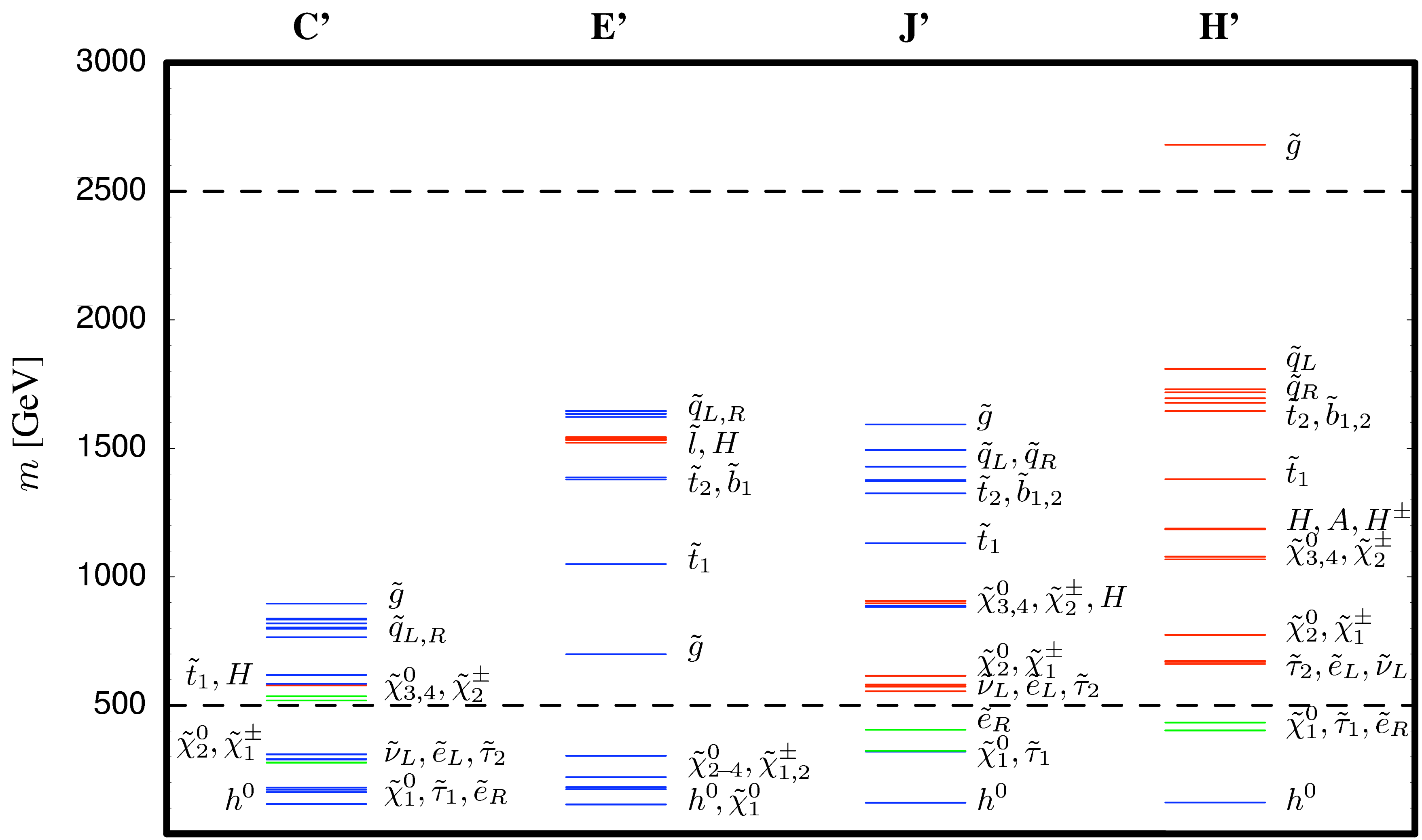


Fig. 5.1: Examples of mass spectra of updated post-LEP benchmark points [8]. Sparticles that would be discovered at the LHC, a 1-TeV LC and CLIC are shown as blue, green and red lines, respectively. The kinematic reaches of a 1-TeV LC and CLIC at 5 TeV are shown as dashed lines.

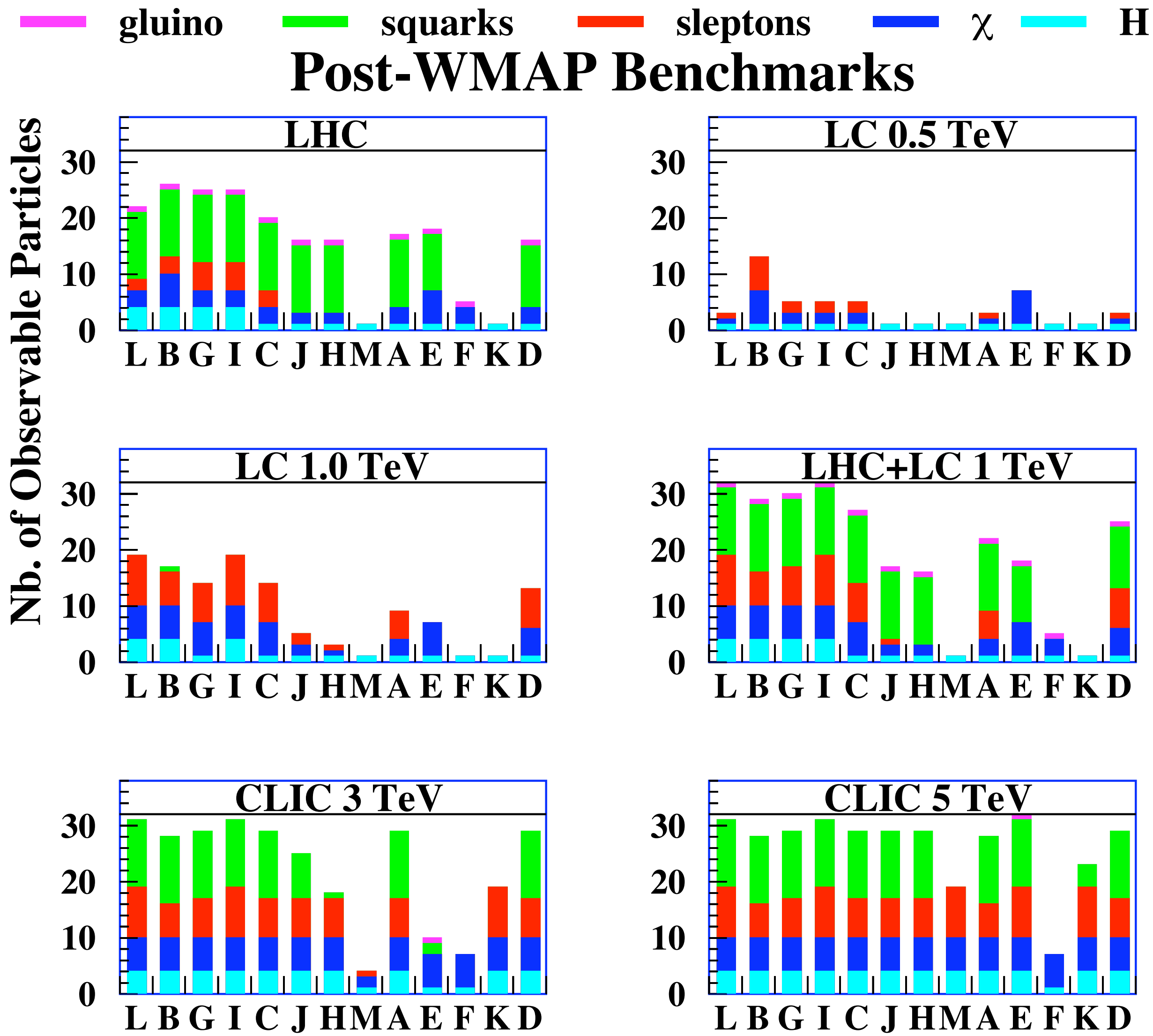


Fig. 1.1: Bar charts of the numbers of different sparticle species observable in a number of benchmark supersymmetric scenarios at different colliders, including the LHC and linear e^+e^- colliders with various centre-of-mass energies. The benchmark scenarios are ordered by their consistency with the most recent BNL measurement of $g_\mu - 2$ and are compatible with the WMAP data on cold dark matter density. We see that there are some scenarios where the LHC discovers only the lightest neutral supersymmetric Higgs boson. Lower-energy linear e^+e^- colliders largely complement the LHC by discovering or measuring better the lighter electroweakly-interacting sparticles. Detailed measurements of the squarks would, in many cases, be possible only at CLIC.

- Point C has very low masses, and is representative also of points A, B, D, G, I, L. In these cases, the LHC would have discovered the $H^{\pm}$, as well as seen the h^0, and also the gauginos $\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^{\pm}$, the charged sleptons, the squarks and the gluino. A 1-TeV linear collider would enable the detailed study of the h^0 and of the same gauginos and sleptons, and it might discover the missing gauginos in some of the scenarios. However, one would require CLIC, perhaps running around 2 TeV, to complete the particle spectrum by discovering and studying the heavy Higgses and the missing gauginos. CLIC could also measure more precisely the squarks and in particular disentangle the left- and right-handed states and, to some extent, the different light squark flavours.
- Point J features intermediate masses, much like point K. Here, the LHC would have discovered all the Higgs bosons, the squarks and the gluino, but no gauginos or sleptons. The 1-TeV e^+e^- linear collider would study in detail the h^0 and could discover the $\tilde{e}_R$, $\tilde{\mu}_R$ and $\tilde{\tau}_1$, but other sparticles would remain beyond its kinematic reach. CLIC3000 could then study in detail the heavy Higgses, as discussed in the previous chapter. It would also discover and study the gauginos and the missing sleptons, and even observe in more detail a few of the lighter squarks that had already been discovered at the LHC. However, to see the remaining squarks at a linear collider would require CLIC to reach slightly more than 3 TeV.
- Point E has quite distinctive decay characteristics, due to the existence of heavy sleptons and squarks. In this situation, the LHC would have discovered the h^0, all squarks and the gluino. The gauginos are in principle accessible, but their discovery may be made more difficult by their predominant decays into jets, contrary to the previous benchmark points, and sleptons would remain unobserved. At a 1-TeV e^+e^- linear collider, the detailed study of the h^0 and of the gauginos could be undertaken. The discovery of the first slepton, actually a $\tilde{\nu}_e$, could be made at CLIC3000, which could also study the three lightest squarks. The discovery and analysis of the heavy Higgses would then require the CLIC energy to reach about 3.5 TeV, which would also allow the discovery of all sleptons and the observation of all squarks. A detailed analysis of the accuracy in the determination of the smuon mass at $\sqrt{s}$ = 3.8–4.2 TeV is presented later in this chapter.

- Point H has quite heavy states, as does scenario M. The LHC would only discover the h^0, all other states being beyond its reach, so the LHC might leave the existence of supersymmetry as an open question! At point H, a 1-TeV linear collider would discover the lighter $\tilde{\tau}$ and the LSP χ, but no other sparticles. A 1-TeV linear collider would discover no sparticles at point M. However, CLIC at 3 TeV would be able to discover most of the gauginos and sleptons. The CLIC sensitivity to the smuon mass, using both a muon energy technique and a threshold scan, is discussed later. On the other hand, to discover all the squarks, $\ell^+\ell^-$ collisions in excess of 5 TeV would be needed. There is currently no e^+e^- project aiming at such energies, and we recall that neutrino radiation would become a hazard for a $\mu^+\mu^-$ collider at such a high energy.
- Along the lines defined by the WMAP constraints, the reach in supersymmetric particles for a given collider and the phenomenology of their decays change significantly. As we discuss later, the CLIC reach for the dilepton decay signature of a heavier neutralino, $\chi_2 \rightarrow \ell^+\ell^-\chi$ is significantly greater than that of the LHC or a 1-TeV linear collider. Additionally, we have chosen a point at $m_{1/2}$ = 750 GeV and $\tan\beta$ = 10 to study the potential accuracy in the determination of the mass of the sleptons and of the $\tilde{\chi}_2^0$. This point is located at the limit of the sensitivity of the LHC and of a 1-TeV linear collider for probing the heavy neutralinos and the slepton sectors, and represents the limit of the coverage of the full supersymmetric spectrum at CLIC at 3 TeV.
- As in the case of a 1-TeV e^+e^- linear collider, a photon collider option for CLIC would extend the discovery range for heavy Higgs bosons. Additionally, it would allow one to discover all four Higgs bosons in scenarios E, H and M, for a 3-TeV collider, and also in F, for a 5-TeV collider. The detection of heavier MSSM Higgs bosons at a CLIC-based $\gamma\gamma$ collider is discussed in more detail in the previous section.

SUSY is a strong case for a lepton collider in the TeV range.

New Strong Dynamics

Theoretical issues

- 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?
- ...

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

Technipions:

$$\frac{d\sigma(\mu^+\mu^- \to \pi_T^0 \,\mathrm{or}\, \pi_T^{0\prime} \to \bar{f} f)}{dz} =$$
$$\frac{N_f}{2\pi}\left(\frac{C_\mu C_f m_\mu m_f}{F_T^2}\right)^2 \frac{s}{(s - M_{\pi_T}^2)^2 + s\,\Gamma_{\pi_T}^2}\,,$$

$$\frac{d\sigma(\mu^+\mu^- \to \pi_T^{0\prime} \to gg)}{dz} =$$
$$\frac{C_{\pi_T}}{32\pi^3}\left(\frac{C_\mu m_\mu \alpha_S N_{TC}}{F_T^2}\right)^2 \frac{s^2}{(s - M_{\pi_T}^2)^2 + s\,\Gamma_{\pi_T}^2}\,.$$

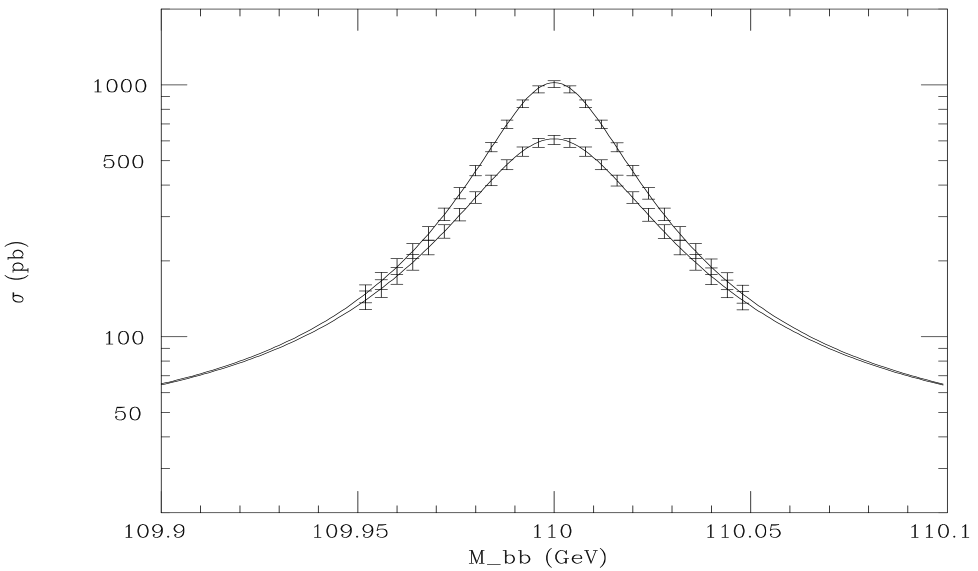


Figure 1: Cross sections for $\mu^+\mu^- \to \pi_T^0 \to \bar{b}b$ (upper curve) and $\pi_T^{0\prime} \to \bar{b}b$. Statistical errors only are shown for a luminosity of $1\,\mathrm{pb}^{-1}$ per point. Cuts and efficiencies are described in the text. The solid lines are the theoretical cross sections (perfect resolution).

Technirhos:

Can have nearby vector resonances that interfere:

Would need the fine resolution to disentangle states

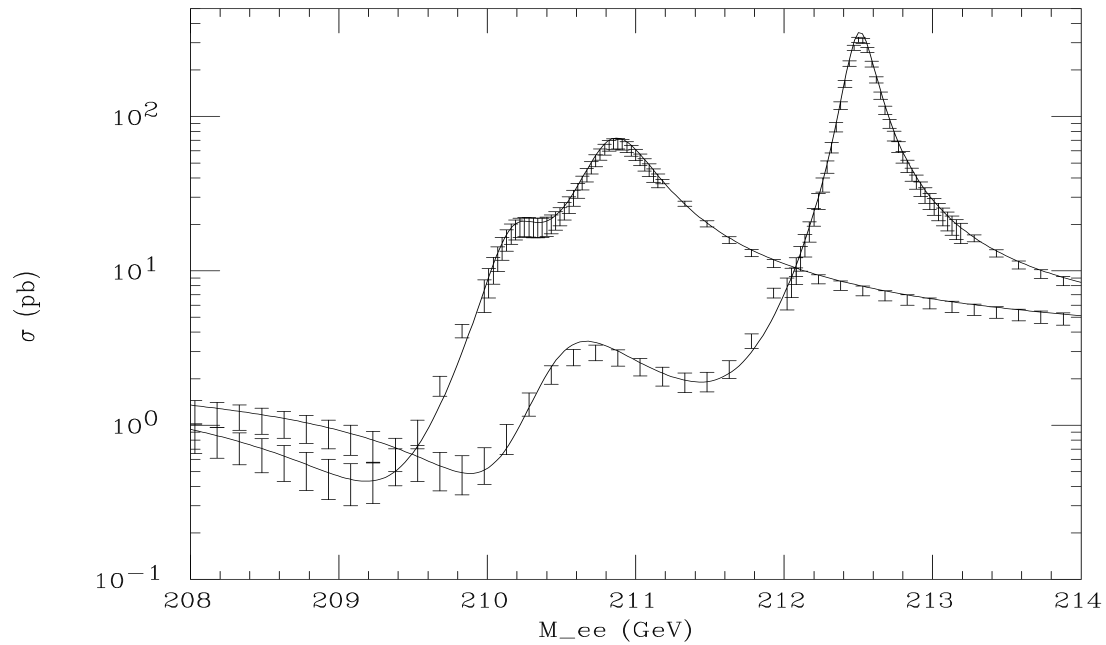


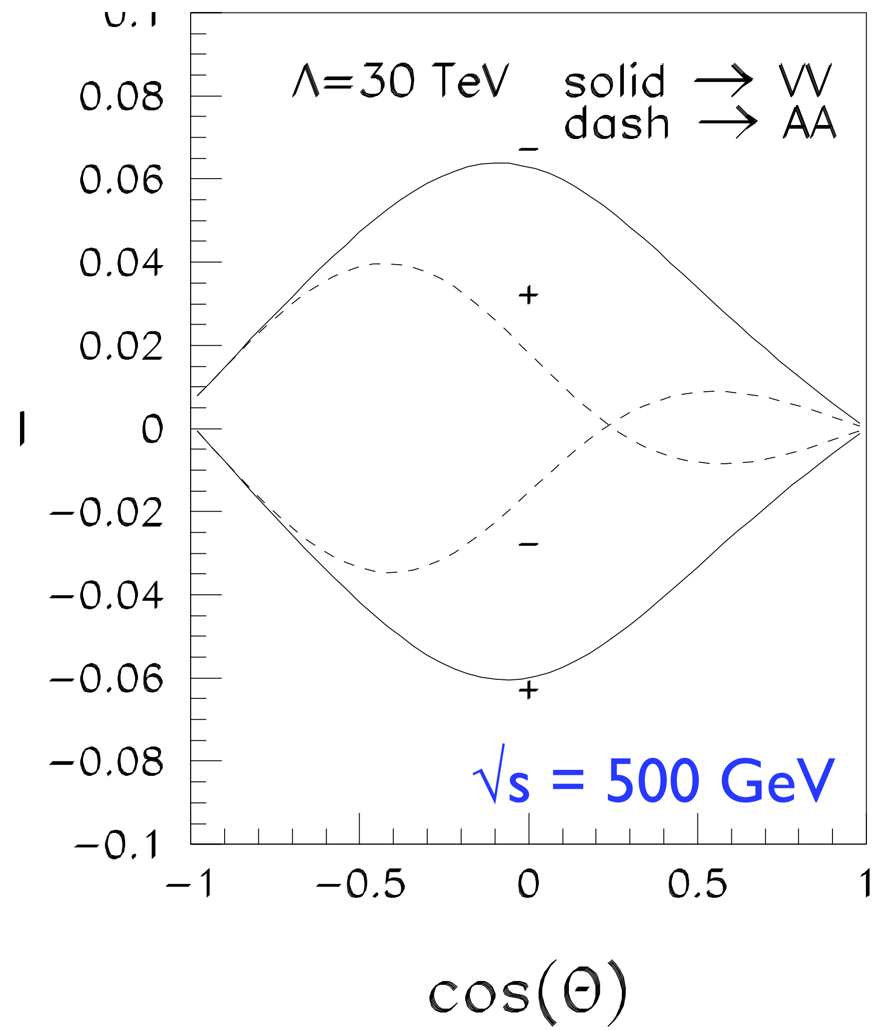
Figure 2: Cross sections for $\mu^+\mu^- \to \rho_T, \omega_T \to e^+e^-$ for $M_{\rho_T} = 210\,\mathrm{GeV}$ and $M_{\omega_T} = 211\,\mathrm{GeV}$ (higher-peaked curve) and $209\,\mathrm{GeV}$. Statistical errors only are shown for resolutions and luminosities described in the text. The solid lines are the theoretical cross sections (perfect resolution).

Common case with new strong dynamics

Contact Interaction

$$\mathcal{L} = \frac{g^2}{2\Lambda^2}[\eta_{LL} j_L j_L + \eta_{RR} j_R j_R + \eta_{LR} j_L j_R]$$

$$\Delta = \frac{\left(\frac{d\sigma}{dcos\theta}\right)_{EW+\Lambda} - \left(\frac{d\sigma}{dcos\theta}\right)_{EW}}{\left(\frac{d\sigma}{dcos\theta}\right)_{EW}}$$



Angular cut not an issue

TABLE 2. 95% CL limits (in TeV) for different on the scattering angle θ cuts ($\sqrt{s} = 500$ GeV, $\mathcal{L} = 7fb^{-1}$).

$\lvert\cos\theta\rvert <$	.6	.8	.9	.95
LL	26	29	31	32
RR	24	28	30	30
VV	50	54	56	57
AA	28	32	34	35

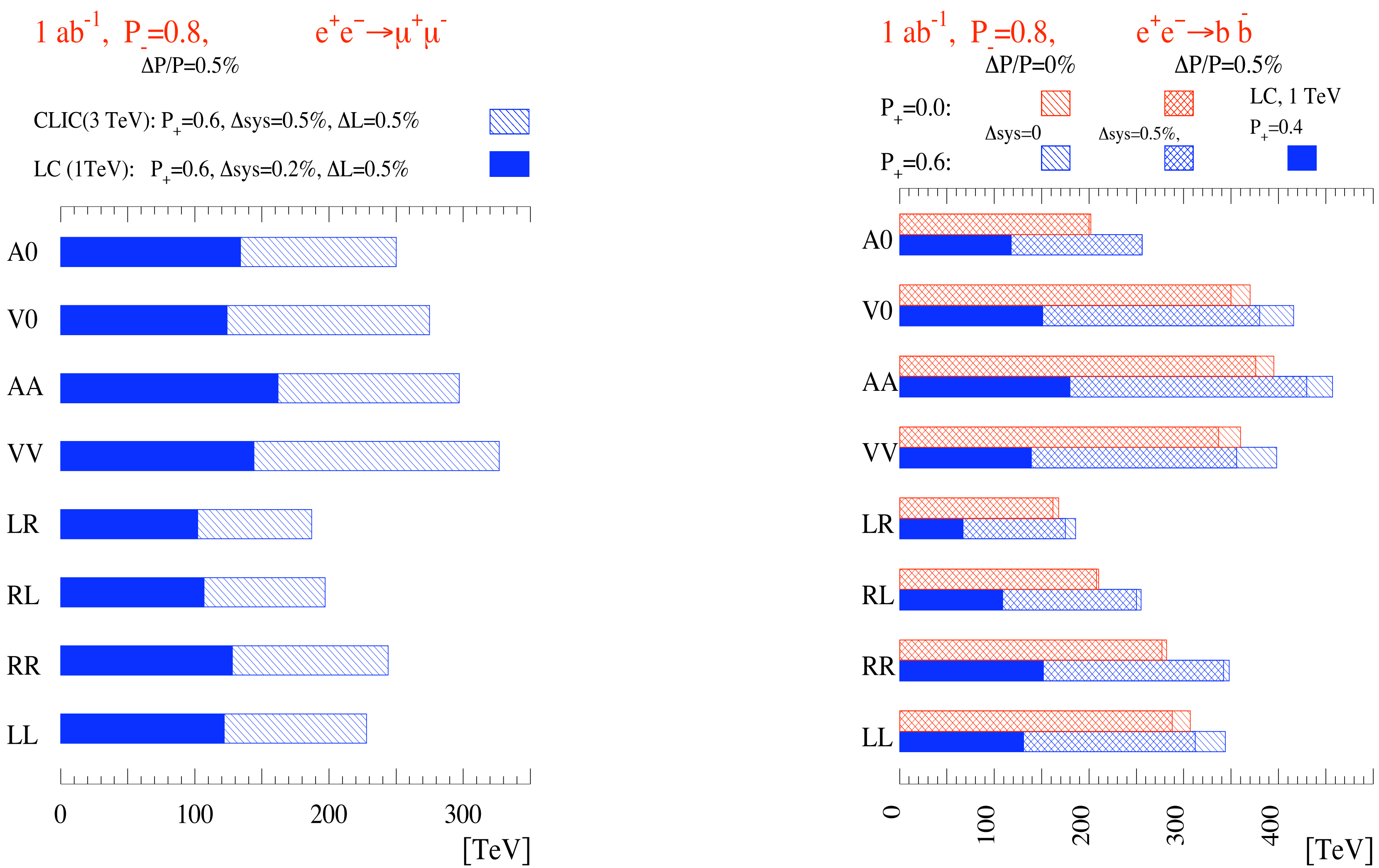


Fig. 6.22: Limits on the scale Λ of contact interactions for CLIC operating at 3 TeV (dashed histogram) compared with a 1 TeV LC (filled histogram) for different models and the $\mu^+\mu^-$ (left) and $b\bar{b}$ (right) channels. The polarization of electrons $\mathcal{P}_-$ is taken to be 0.8 and that of positrons $\mathcal{P}_+ = 0.6$. For comparison, the upper bars in the right plot show the sensitivity achieved without positron polarization. The influence of systematic uncertainties is also shown.

Extra Dimensions

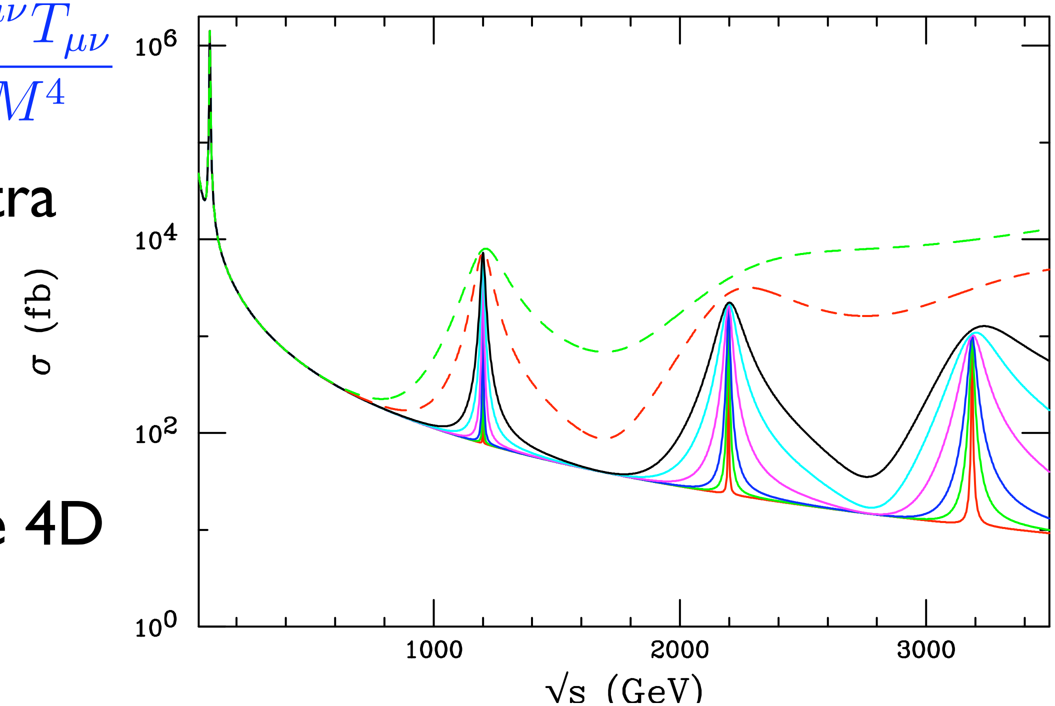
Theoretical issues

- How many dimensions?
- Which interactions (other than gravity) extend into the extra dimensions?
- At what scale does gravity become a strong interaction?
- What happens above that scale?
- ...

LHC discovery - Detailed study at muon collider

- A variety of models - nonrenormalizable effective theories at low energies.
- Arkani-Hamed, Dimopoulos, Dvali model:
  - effective contact interaction $\propto \lambda \frac{T^{\mu\nu}T_{\mu\nu}}{M^4}$
- Randall-Sundrum model: warped extra dimensions
  - two parameters:
    - mass scale ∝ first KK mode;
    - width ∝ 5D curvature / effective 4D Planck scale.

$\mu^+\mu^- \to e^+e^-$



Narrow States

Narrow resonances in lepton colliders: vital role in precision studies

	State	$\mathrm{BR}(\mu^+\mu^-)$	Γ/M	
	$\phi(1.019)$	2.9×10^{-4}	3.98×10^{-3}	Kaons CPV
	$J/\psi(3.097)$	5.9×10^{-2}	3.02×10^{-5}	1D- $D^{\pm,0}$ 3S - D, D*; 2D - D_s
	$\Upsilon(9.460)$	2.5×10^{-2}	5.71×10^{-6}	4S - B factory, tau, charm
	$Z^0(91.19)$	3.4×10^{-2}	2.74×10^{-2}	precision tests - SM
IF	$h^0(115)$	2.5×10^{-4}	2.78×10^{-5}	Higgs couplings - EW

Universal behavior

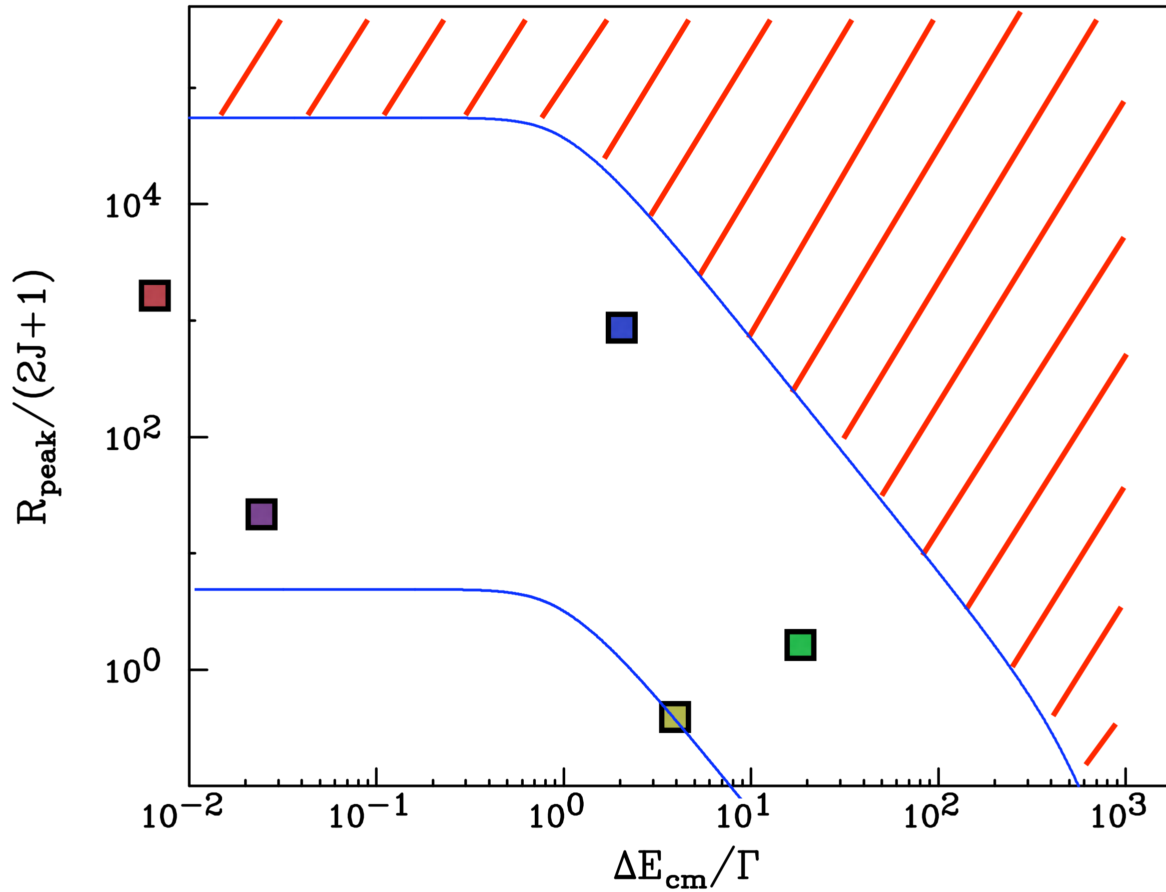
$$\sigma(E) = \frac{2J+1}{(2S_1+1)(2S_2+1)} \frac{4\pi}{k^2} \left[\frac{\Gamma^2/4}{(E-E_0)^2 + \Gamma^2/4} \right] B_{in} B_{out}$$

$$\to R_{\mathrm{peak}} = (2J+1) 3 \frac{B(\mu^+\mu^-) B(visible)}{\alpha_{\mathrm{EM}}^2}$$

beam spread $\frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\frac{(E-E_0)^2}{2\sigma^2}\right)$

$$\to \Delta E_{\mathrm{cm}}/E_{\mathrm{cm}} = 2\ln(2)\sigma$$

- Likely candidates:
  - scalars: h, H^0, A^0,...
  - gauge bosons: Z'
  - new dynamics: bound states
  - ED: KK modes



Assuming $\Delta E_{cm}/E_{cm}$= 0.01%

Outlook and Opportunities

- The physics potential for a lepton collider at $\sqrt{s} \sim 3$ TeV and integrated luminosity ~1 ab^{-1}/yr is outstanding.
- 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.
- A detailed study of physics case for multi-TeV lepton colliders is needed:
  - Must be able to withstand the real physics environment after ten years of running at the LHC.
  - Dependence on initial beam [electron/muon, polarization and beam energy spread] as well as luminosity should be considered.

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