e^+e^- Physics Above 500 GeV - Quantifying the Advantage of High Energy

Jan 29, 2002

Tim Barklow

Upcoming LC technology discussions will include energy expandibility beyond $\sqrt{s} = 0.5$ TeV

$\Rightarrow$ Physics gains from higher energy running should be fully explored and understood.

To that end it would seem appropriate for this group to undertake a study with the following two objectives:

1. **For several physics scenarios, perform a detailed comparison of the physics programs at $\sqrt{s} = 0.8$, 1.0, 1.2, and 1.5 TeV.**
2. **Determine if there is a natural energy scale above $\sqrt{s} = 0.5$ TeV which the next LC should be capable of attaining through energy expansion.**

Physics Scenarios:

a. SM w/ 120 GeV Higgs Boson

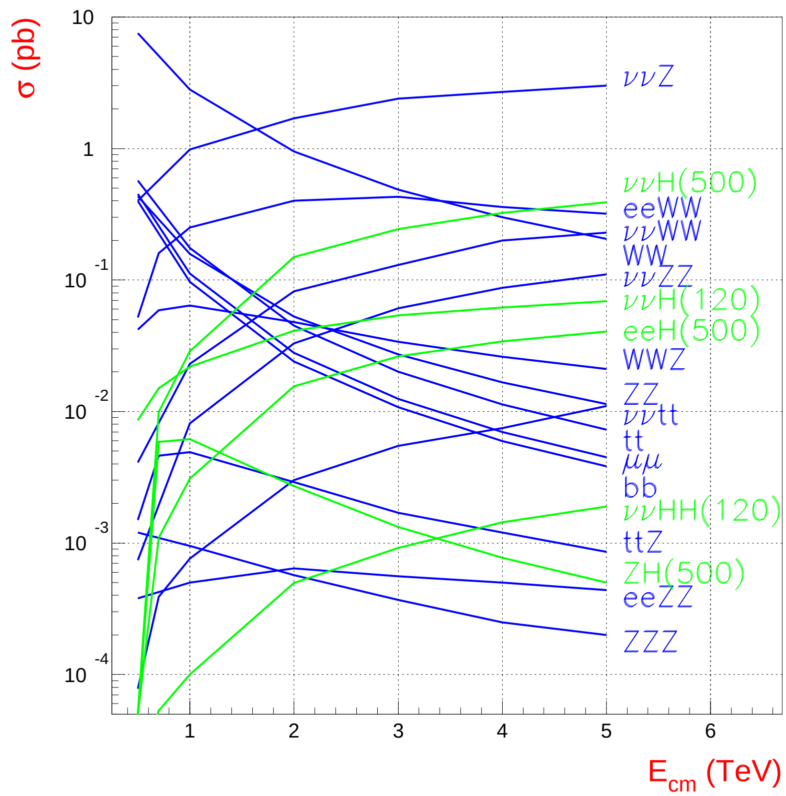
b. SM w/o Higgs Boson

c. SUSY Models X,Y,Z

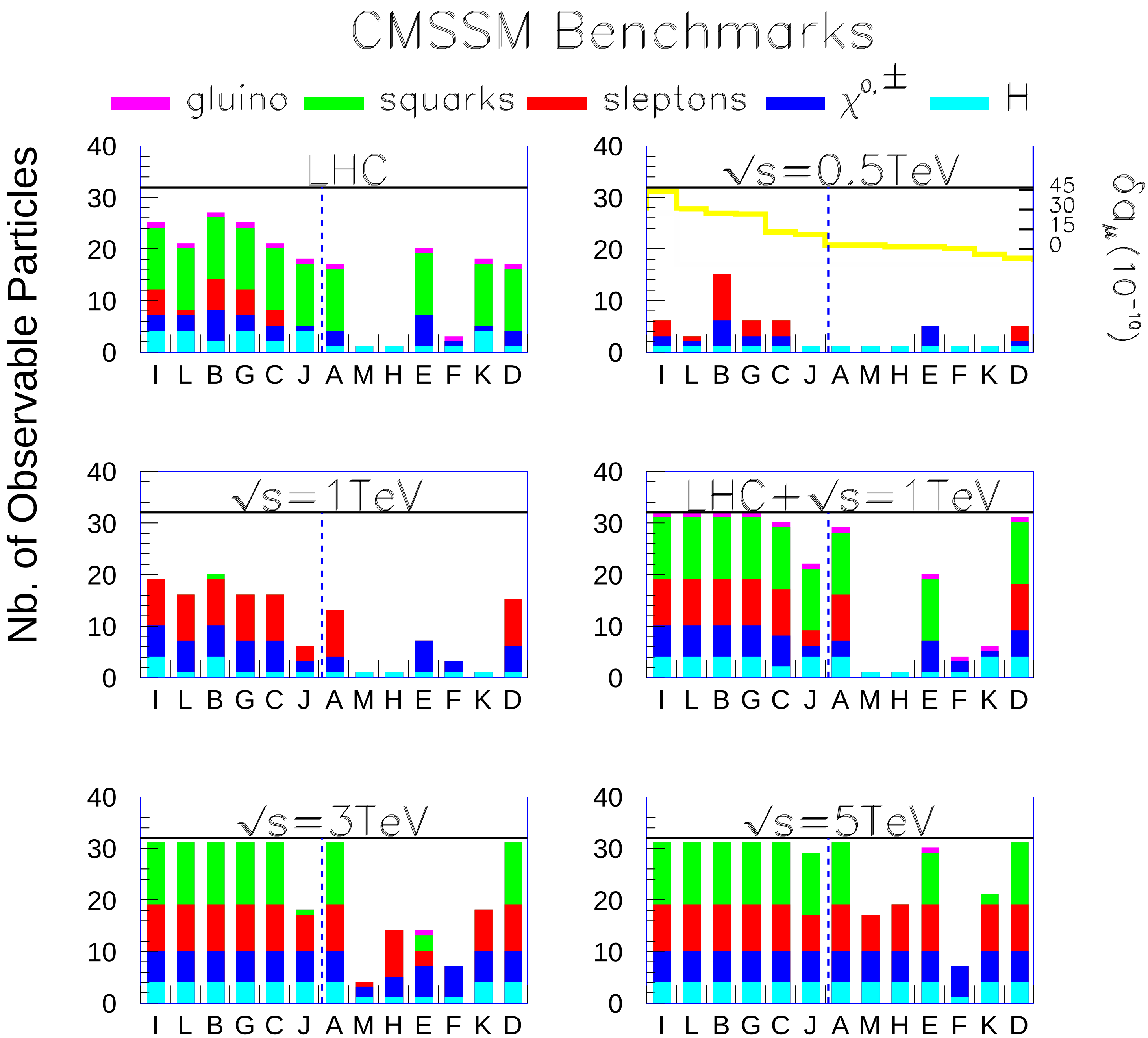
Suggestion is to ignore Z' resonance production, extra dimensions and other possibilities for now in order to avoid proliferation of physics scenarios.

Limits **on Z' bosons, fermion compositeness, etc. can always be included as these are independent of physics scenarios.**

Cross Sections



Event Rates/Year (1000 fb^{-1})	3 TeV 10^3 events	5 TeV 10^3 events
$e^+e^- \to t\bar{t}$	20	7.3
$e^+e^- \to b\bar{b}$	11	3.8
$e^+e^- \to ZZ$	27	11
$e^+e^- \to WW$	490	205
$e^+e^- \to hZ/h\nu\nu$ (120 GeV)	1.4/530	0.5/690
$e^+e^- \to H^+H^-$(1 TeV)	1.5	0.95
$e^+e^- \to \tilde{\mu}^+\tilde{\mu}^-$ (1 TeV)	1.3	1.0



CMSSM Benchmarks
gluino
squarks
sleptons
$\chi^{0,\pm}$
H
Nb. of Observable Particles
LHC
$\sqrt{s}$=0.5TeV
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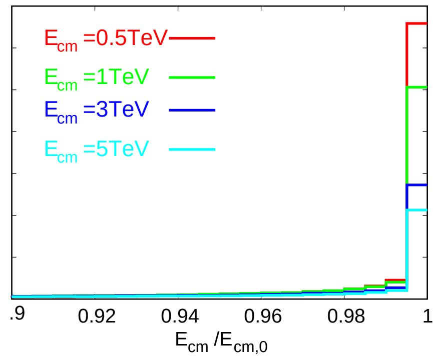
$\sqrt{s}$=3TeV
$\sqrt{s}$=5TeV
I L B G C J A M H E F K D
0
10
20
30
40

Luminosity Spectra

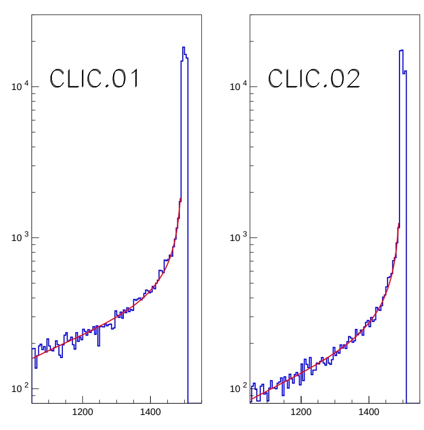
Energy loss due to beam-beam interactions



Luminosity within 1% & 5% of c.m. energy

Energy (TeV)	0.5	1	3	5
$\mathcal{L}$ in 1% $\sqrt{s}$	71%	56 %	30%	25%
$\mathcal{L}$ in 5% $\sqrt{s}$	87%	71 %	42%	34%

Spectra for CLIC studies (sharper $\leftrightarrow$ high lumi)



CLIC.01: $\mathcal{L} = 1.05 \times 10^{35}$ CLIC.02: $\mathcal{L} = 0.40 \times 10^{35}$

Experimenting at CLIC

Machine parameters lead to challenges for experimenting at CLIC

Beam-Beam effects lead to considerable backgrounds and distortion of the luminosity spectrum (beam strahlung)

For 3 TeV and $\mathcal{L} = 10^{35} cm^{-2} s^{-1}$ (D. Schulte)

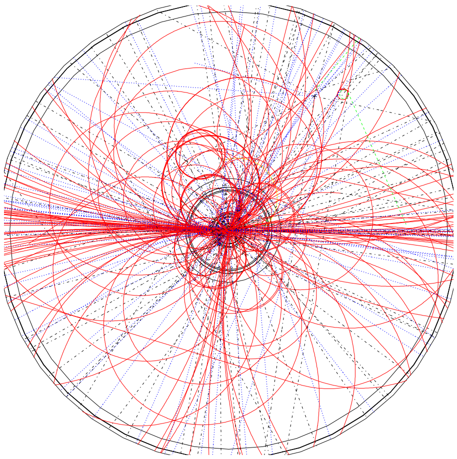
Luminosity/bunch	10^{-2} nb^{-1}
Beam energy spread	1%(FWHM)
Time between bunches	0.67 ns
Average energy loss	31%
photons/beam particle	2.3
Number/energy incoh. pairs	$4.6 \cdot 10^5 / 3.9 \cdot 10^4$ TeV
Number/energy coh. pairs	$1.4 \cdot 10^9 / 4.4 \cdot 10^8$ TeV
Hadronic ($\gamma\gamma$) events, $W_{\gamma\gamma} > 5$ GeV	4

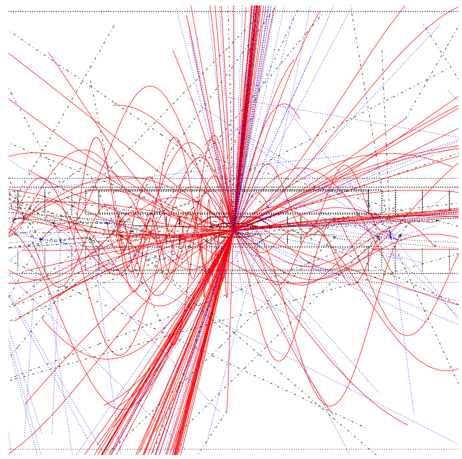
- ✦ Coherent pairs disappear in beampipe (backscattering!)
- ✦ Incoherent pairs: suppressed by strong magnetic field of detector

Further backgrounds to consider: neutrons, muons, synchrotron radiation...

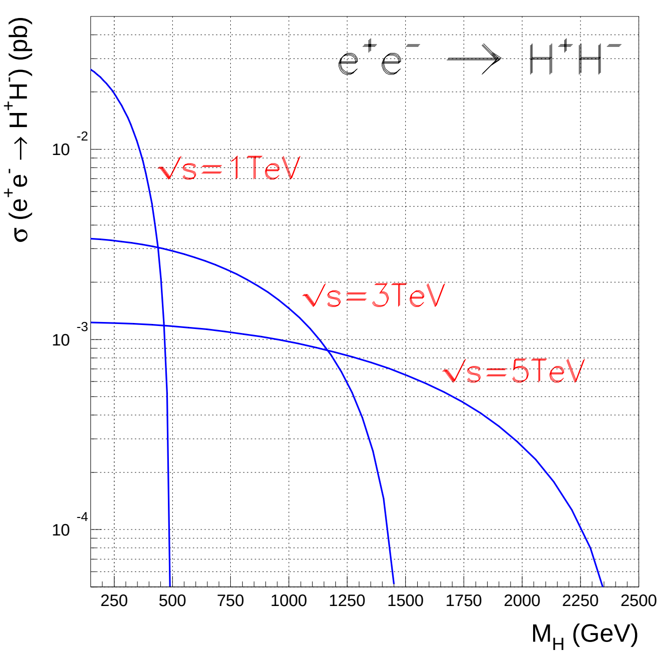
$$\sqrt{s} = 3 \text{ TeV}$$

$e^+e^- \to H^+H^-$ $M_H = 900$ GeV





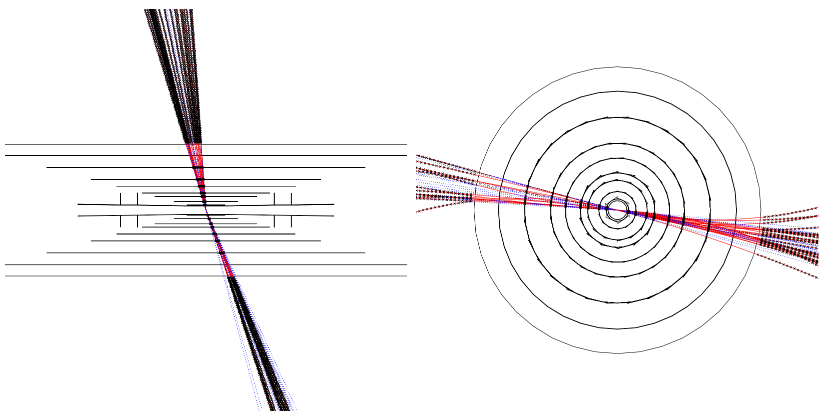
Cross section as function of mass



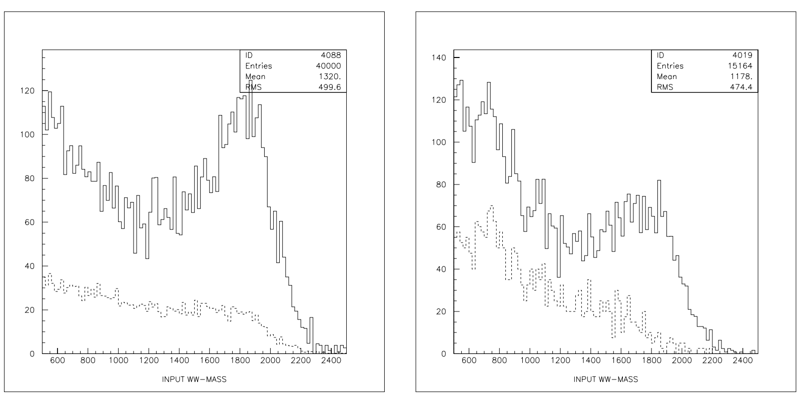
WW Scattering at CLIC

ADR

- ✦ Longitudinal W scattering $W_L W_L \to W_L W_L, (t\bar{t})$
- ✦ Analysis of WW spectrum: excess of events w.r.t. SM and possible resonance structure
- ✦ Study of vector model $M_{WW} \sim 2$ TeV

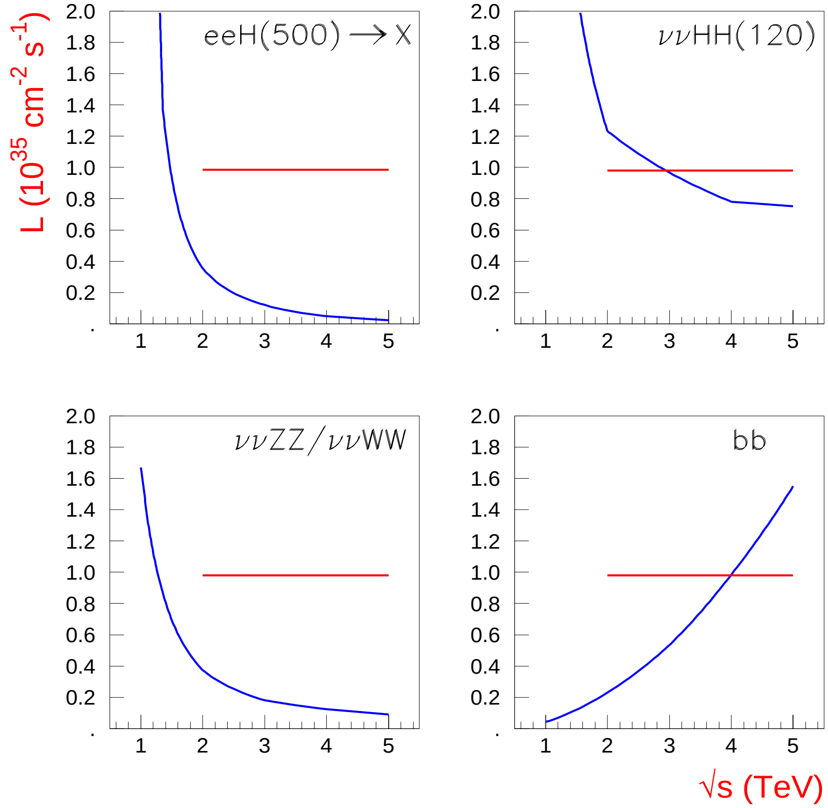


EWChL Langrangian form. $(a_5 = -0.002, a_4 = 0)$
1500 fb^{-1}



Before detector After detector

Luminosity needed for discovery/ precision measurements

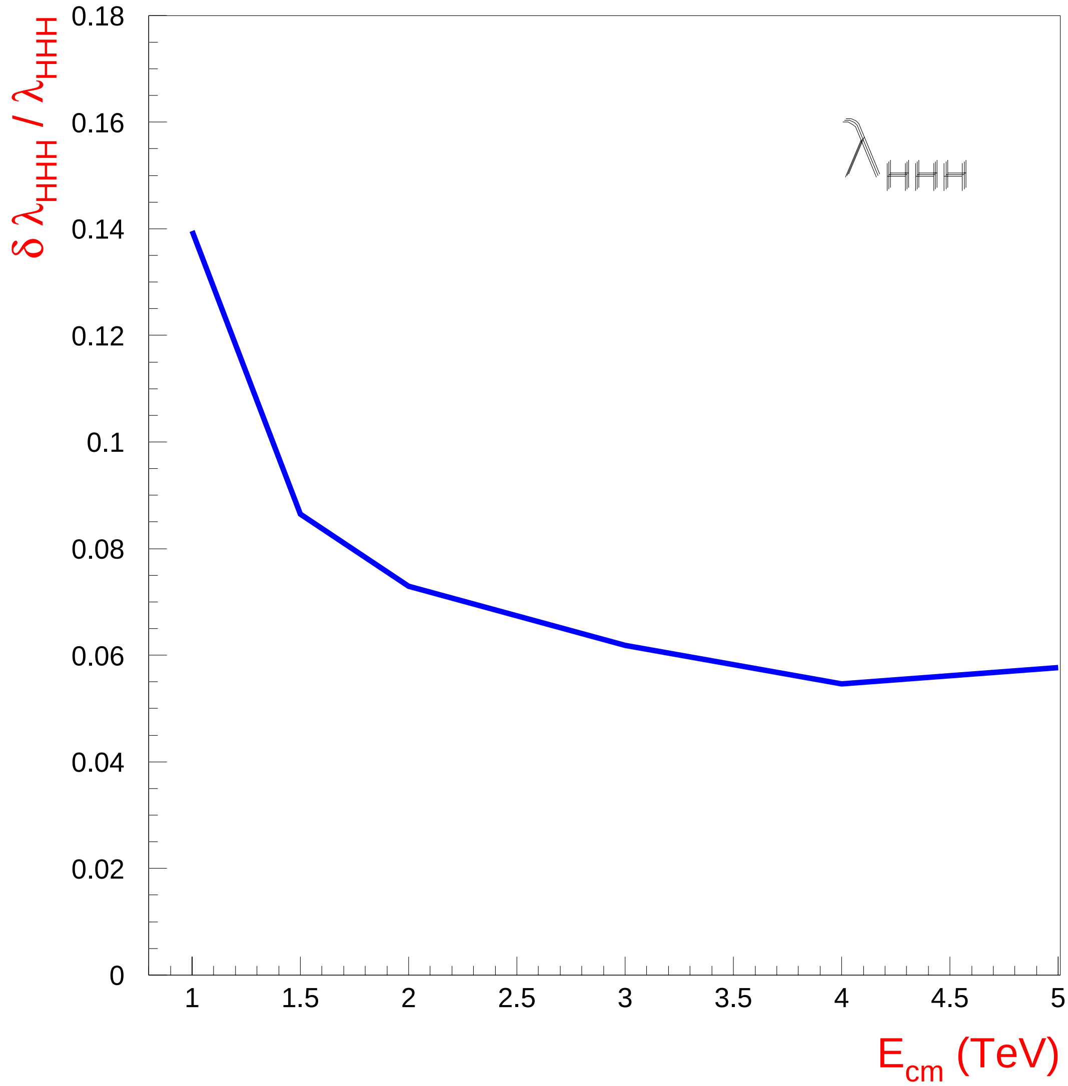


Based on statistical errors, including background

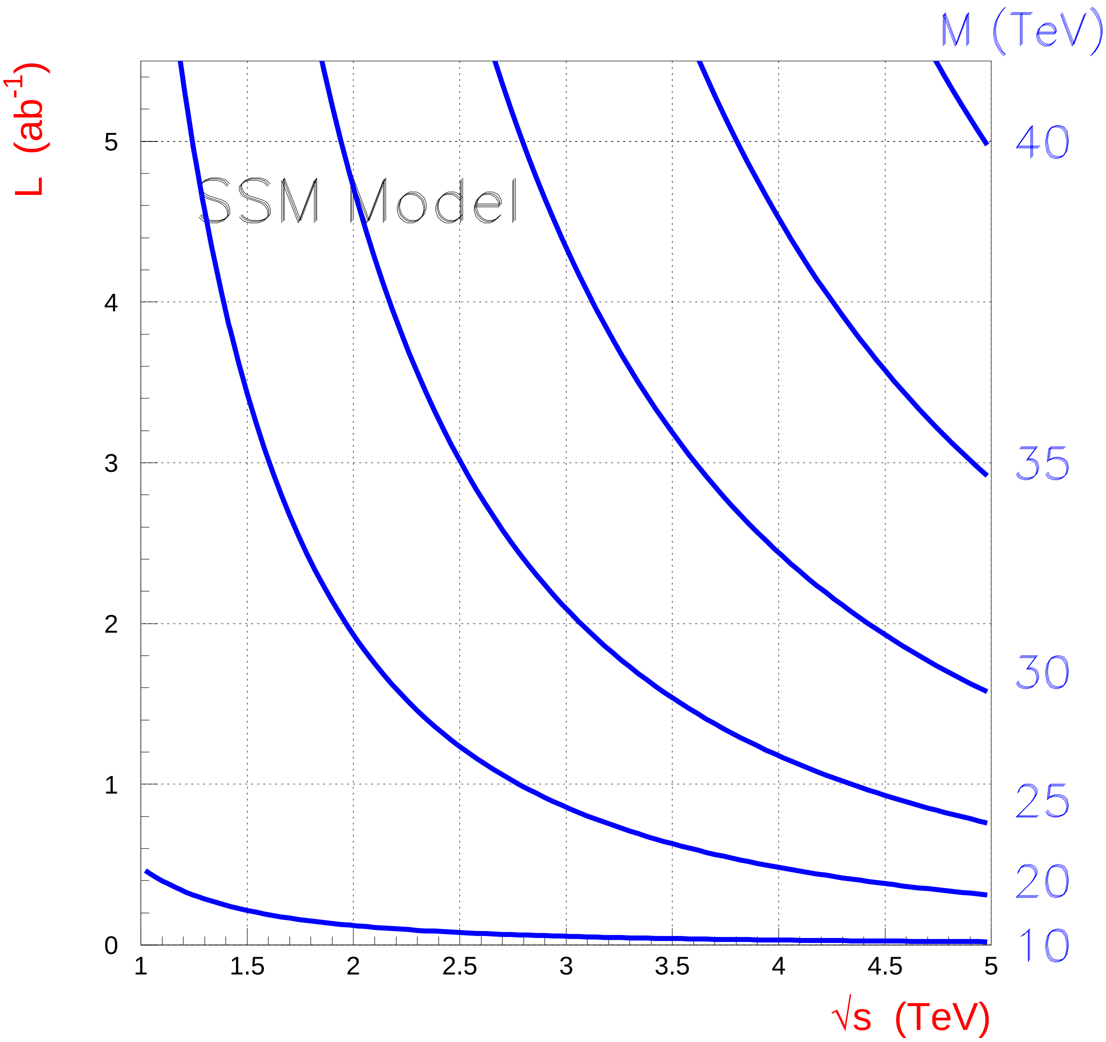
- $e^+e^- \longrightarrow H(500\text{GeV, invisible})X$: 5$\sigma$ discovery
- $e^+e^- \longrightarrow \nu\nu HH(120)$: $\delta\lambda_{HHH}/\lambda_{HHH} < 15\%$
- $e^+e^- \longrightarrow \nu\nu ZZ/\nu\nu WW$: $\delta\sigma/\sigma < 1\%$
- $e^+e^- \longrightarrow b\bar{b}$: $\delta\sigma/\sigma < 1\%$

CLIC Study by A. De Roeck et al.

Precision on λ_{HHH} (5000 fb^{-1})



Study by M. Battaglia et al.



95% CL Contours for SSM Z'
(M. Battaglia)

Sum Rule I

$$\sum_i g^2_{H_iWW} = g^2 M_W^2$$

In MSSM

$$\begin{aligned} g_{hWW} &= gM_W \sin(\beta - \alpha) \\ g_{HWW} &= gM_W \cos(\beta - \alpha) \end{aligned}$$

$\cos(\beta - \alpha) \to 0$ in decoupling limit of $M_A, M_H \to \infty$

Can measure $\Delta \sin^2(\beta - \alpha)/\sin^2(\beta - \alpha) \simeq 3\%$ using $e^+e^- \to Zh$ and $e^+e^- \to \nu\overline{\nu}W^+W^- \to \nu\overline{\nu}h$ at $\sqrt{s} = 350$ GeV assuming $M_h = 120$ GeV

(R. Van Kooten)

Sum Rule I (cont.)

Consider $W_L W_L \to Z_L Z_L$ as studied in $e^+e^- \to \nu\bar{\nu}ZZ$

Amplitude $\mathcal{A}$ for $W_L W_L \to Z_L Z_L$ in MSSM :

$$\mathcal{A} = \frac{-s^2(M_h^2 \sin^2(\beta-\alpha) + M_H^2 \cos^2(\beta-\alpha)) + sM_h^2 M_H^2}{v^2(s-M_h^2)(s-M_H^2)}$$

For $s \gg M_h^2, M_H^2$:

$$\mathcal{A} = -\frac{1}{v^2}(M_h^2 \sin^2(\beta-\alpha) + M_H^2 \cos^2(\beta-\alpha))$$

For $s \gg M_h^2, \quad s \ll M_H^2$:

$$\mathcal{A} = -\frac{M_h^2}{v^2}\left(1 - \frac{s}{M_H^2}\sin^2(\beta-\alpha) - \frac{s}{M_h^2}\cos^2(\beta-\alpha)\right)$$

For $s \gg M_h^2, \quad s \ll M_H^2, \quad cos^2(\beta-\alpha) \to 0$:

$$\mathcal{A} = -\frac{M_h^2}{v^2}\left(1 - \frac{s}{M_H^2}\right)$$

For $s \gg M_h^2, \quad s \ll M_H^2, \quad cos^2(\beta-\alpha) \gg M_h^2/s$:

$$\mathcal{A} = \frac{s}{v^2}\cos^2(\beta-\alpha)$$

Sum Rule II : Closure of the Neutralino System

$$\sum_{i,j=1}^{4} \mathcal{Z}_{ij}\mathcal{Z}^*_{ij} = \frac{1}{2} \qquad \sum_{i,j=1}^{4} g_{Lij}g^*_{Lij} = \frac{1}{16c_W^4 s_W^4}$$

$$\sum_{i,j=1}^{4} \mathcal{Z}_{ij}g^*_{Lij} = 0 \qquad \sum_{i,j=1}^{4} g_{Lij}g^*_{Rij} = \frac{1}{4c_W^4}$$

$$\sum_{i,j=1}^{4} \mathcal{Z}_{ij}g^*_{Rij} = 0 \qquad \sum_{i,j=1}^{4} g_{Rij}g^*_{Rij} = \frac{1}{c_W^4}$$

$$\mathcal{A}\left(e^+e^- \to \tilde{\chi}^0_i\tilde{\chi}^0_j\right) = \frac{e^2}{s} Q_{\alpha\beta}\left[\overline{v}(e^+)\gamma_\mu P_\alpha u(e^-)\right]\left[\overline{u}(\tilde{\chi}^0_i)\gamma^\mu P_\beta v(\tilde{\chi}^0_j)\right]$$

$$Q_{LL} = +\frac{D_Z}{s_W^2 c_W^2}(s_W^2 - \tfrac{1}{2})\mathcal{Z}_{ij} - D_{uL}g_{Lij} \qquad Q_{RL} = +\frac{D_Z}{c_W^2}\mathcal{Z}_{ij} + D_{tR}g_{Rij}$$

$$Q_{LR} = -\frac{D_Z}{s_W^2 c_W^2}(s_W^2 - \tfrac{1}{2})\mathcal{Z}^*_{ij} + D_{tL}g^*_{Lij} \qquad Q_{RR} = -\frac{D_Z}{c_W^2}\mathcal{Z}^*_{ij} - D_{uR}g^*_{Rij}$$

(Choi, Kalinowski, Moortgat-Pick, Zerwas, hep-ph/0108117)

Sum Rule II (cont.)

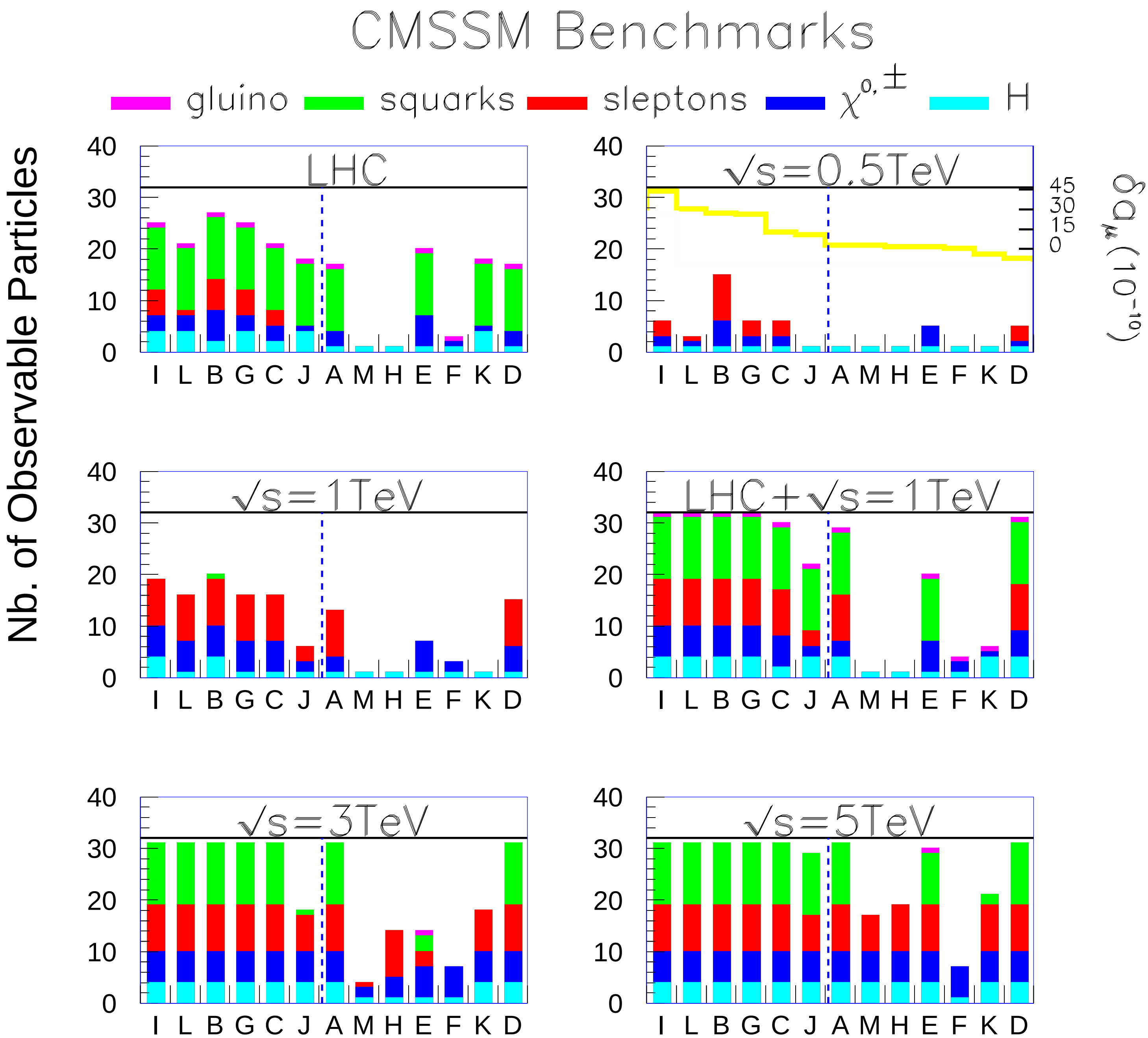
Neutralino Mass Matrix in $(\tilde{B}, \tilde{W}^3, \tilde{H}_1^0, \tilde{H}_2^0)$ basis:

$$\mathcal{M} = \begin{pmatrix} M_1 & 0 & -m_Z c_\beta s_W & m_Z s_\beta s_W \\ 0 & M_2 & m_Z c_\beta c_W & -m_Z s_\beta c_W \\ -m_Z c_\beta s_W & m_Z c_\beta c_W & 0 & -\mu \\ m_Z s_\beta s_W & -m_Z s_\beta c_W & -\mu & 0 \end{pmatrix}$$

Do the MSSM neutral gauginos and Higgsinos $(\tilde{B}, \tilde{W}^3, \tilde{H}_1^0, \tilde{H}_2^0)$ saturate the Neutralino System ?

Chargino Mass Matrix:

$$\mathcal{M}_C = \begin{pmatrix} M_2 & \sqrt{2} m_W \, c_\beta \\ \sqrt{2} m_W \, s_\beta & |\mu| \, \mathrm{e}^{i\Phi_\mu} \end{pmatrix}$$



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I L B G C J A M H E F K D

Post-LEP CMSSM Benchmarks of J. Ellis et al.

Model	A	B	C	D	E	F	G	H	I	J	K	L	M
$m_{1/2}$	600	250	400	525	300	1000	375	1500	350	750	1150	450	1900
m_0	140	100	90	125	1500	3450	120	419	180	300	1000	350	1500
$\tan\beta$	5	10	10	10	10	10	20	20	35	35	35	50	50
sign(μ)	+	+	+	−	+	+	+	+	+	+	−	+	+
$\alpha_s(m_Z)$	120	123	121	121	123	120	122	117	122	119	117	121	116
m_t	175	175	175	175	171	171	175	175	175	175	175	175	175
Masses													
$\lvert\mu(m_Z)\rvert$	739	332	501	633	239	522	468	1517	437	837	1185	537	1793
h^0	114	112	115	115	112	115	116	121	116	120	118	118	123
H^0	884	382	577	737	1509	3495	520	1794	449	876	1071	491	1732
A^0	883	381	576	736	1509	3495	520	1794	449	876	1071	491	1732
$\mathrm{H}^\pm$	887	389	582	741	1511	3496	526	1796	457	880	1075	499	1734
χ_1^0	252	98	164	221	119	434	153	664	143	321	506	188	855
χ_2^0	482	182	310	425	199	546	291	1274	271	617	976	360	1648
χ_3^0	759	345	517	654	255	548	486	1585	462	890	1270	585	2032
χ_4^0	774	364	533	661	318	887	501	1595	476	900	1278	597	2036
$\chi_1^\pm$	482	181	310	425	194	537	291	1274	271	617	976	360	1648
$\chi_2^\pm$	774	365	533	663	318	888	502	1596	478	901	1279	598	2036
$\tilde{g}$	1299	582	893	1148	697	2108	843	3026	792	1593	2363	994	3768
e_L, μ_L	431	204	290	379	1514	3512	286	1077	302	587	1257	466	1949
e_R, μ_R	271	145	182	239	1505	3471	192	705	228	415	1091	392	1661
ν_e, ν_μ	424	188	279	371	1512	3511	275	1074	292	582	1255	459	1947
τ_1	269	137	175	233	1492	3443	166	664	159	334	951	242	1198
τ_2	431	208	292	380	1508	3498	292	1067	313	579	1206	447	1778
ν_τ	424	187	279	370	1506	3497	271	1062	280	561	1199	417	1772
u_L, c_L	1199	547	828	1061	1615	3906	787	2771	752	1486	2360	978	3703
u_R, c_R	1148	528	797	1019	1606	3864	757	2637	724	1422	2267	943	3544
d_L, s_L	1202	553	832	1064	1617	3906	791	2772	756	1488	2361	981	3704
d_R, s_R	1141	527	793	1014	1606	3858	754	2617	721	1413	2254	939	3521
t_1	893	392	612	804	1029	2574	582	2117	550	1122	1739	714	2742
t_2	1141	571	813	1010	1363	3326	771	2545	728	1363	2017	894	3196
b_1	1098	501	759	973	1354	3319	711	2522	656	1316	1960	821	3156
b_2	1141	528	792	1009	1594	3832	750	2580	708	1368	2026	887	3216

General Higgs potential with one Higgs doublet:

$$V_{\mathcal{SSB}} = \lambda \left\{ \left[\Phi^\dagger \Phi - \frac{v^2}{2} \right]^2 + \sum_{n \geq 3} \frac{g^{2(n-2)}}{\Lambda^{2(n-2)}} \frac{a_n}{(n-1)^2} \left[\Phi^\dagger \Phi - \frac{v^2}{2} \right]^n \right\}$$

To leading order in $1/\Lambda$ the potential is:

$$\begin{aligned} V_{\mathcal{SSB}} &= \frac{1}{2} M_H^2 \left\{ H^2 + \frac{g}{M_W} H (\varphi^+ \varphi^- + \frac{\varphi_3^2}{2}) + \frac{g}{2M_W} h_3 H^3 \right. \\ & \left. + h_4 \left(\frac{g}{4M_W} \right)^2 H^4 + h'_4 \left(\frac{g}{2M_W} \right)^2 H^2 (\varphi^+ \varphi^- + \frac{\varphi_3^2}{2}) ..... \right\} \end{aligned}$$

Non-SM part parameterized by δh_3:

$$\begin{aligned} h_3 &= 1 + a_3 \frac{M_W^2}{\Lambda^2} = 1 + \delta h_3 \\ h_4 &= 1 + 6 \delta h_3 \\ h'_4 &= 1 + 3 \delta h_3 \end{aligned}$$

(F. Boudjema and E. Chopin, hep-ph/9507396)

In MSSM the trilinear coupling of the lightest Higgs:

$$\begin{aligned}\lambda_{hhh} &= -\frac{1}{2v^2} s_{\beta-\alpha}\, M_h^2 + \\ &\frac{c_{\beta-\alpha}^2}{s_\beta c_\beta}\left(s_{\beta-\alpha}\lambda_a + c_{\beta-\alpha}\lambda_b + \frac{(M_A^2 - M_h^2)}{2v^2}(s_{2\beta} s_{\beta-\alpha} + c_{2\beta} c_{\beta-\alpha})\right)\end{aligned}$$

Non-MSSM part parameterized by λ_a, λ_b

For $cos^2(\beta - \alpha) \rightarrow 0$ the trilinear coupling is not sensitive to beyond-MSSM parameters:

$$\lambda_{hhh} = -\frac{1}{2v^2} s_{\beta-\alpha}\, M_h^2$$

(F. Boudjema and A. Semenov, hep-ph/0201219)

Summary

- **Clear understanding of e^+e^- physics case beyond $\sqrt{s} = 0.5$ TeV would help LC technology comparison.**
- **Analyze specific physics processes at energies of $\sqrt{s} = 0.8$, 1.0, 1.2 and 1.5 TeV.**
- **Attempt to identify the energy scale beyond $\sqrt{s} = 500$ GeV which the next LC should reach through energy expansion.**