Precision Higgs Measurements! Future Facilities

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Energy frontier: Future Facilities

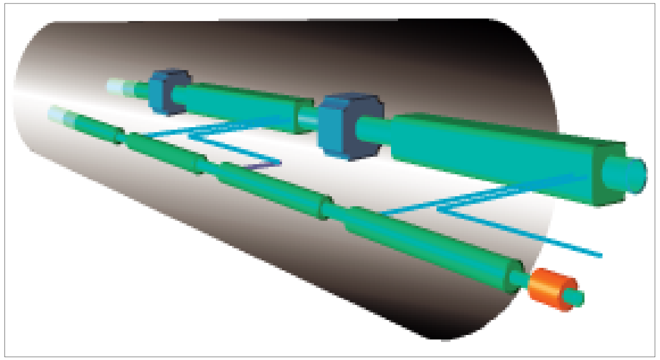
European Strategy for Particle Physics

Open Symposium - European Strategy Preparatory Group

10-12 September 2012 *Krakow, Poland*

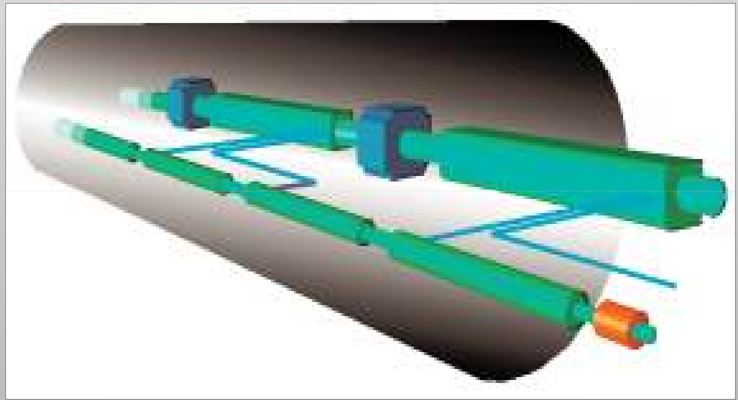
Europe/Zurich timezone

- Hadron colliders and ep machines
  - Emmanuel Tsesmelis
- Electron-positron colliders
- ILC
  - Karsten Buesser
- CLIC
- LEP3
- Muon colliders
  - Far future



1. CLIC two- beam acceleration

Compact
LInear
Collider

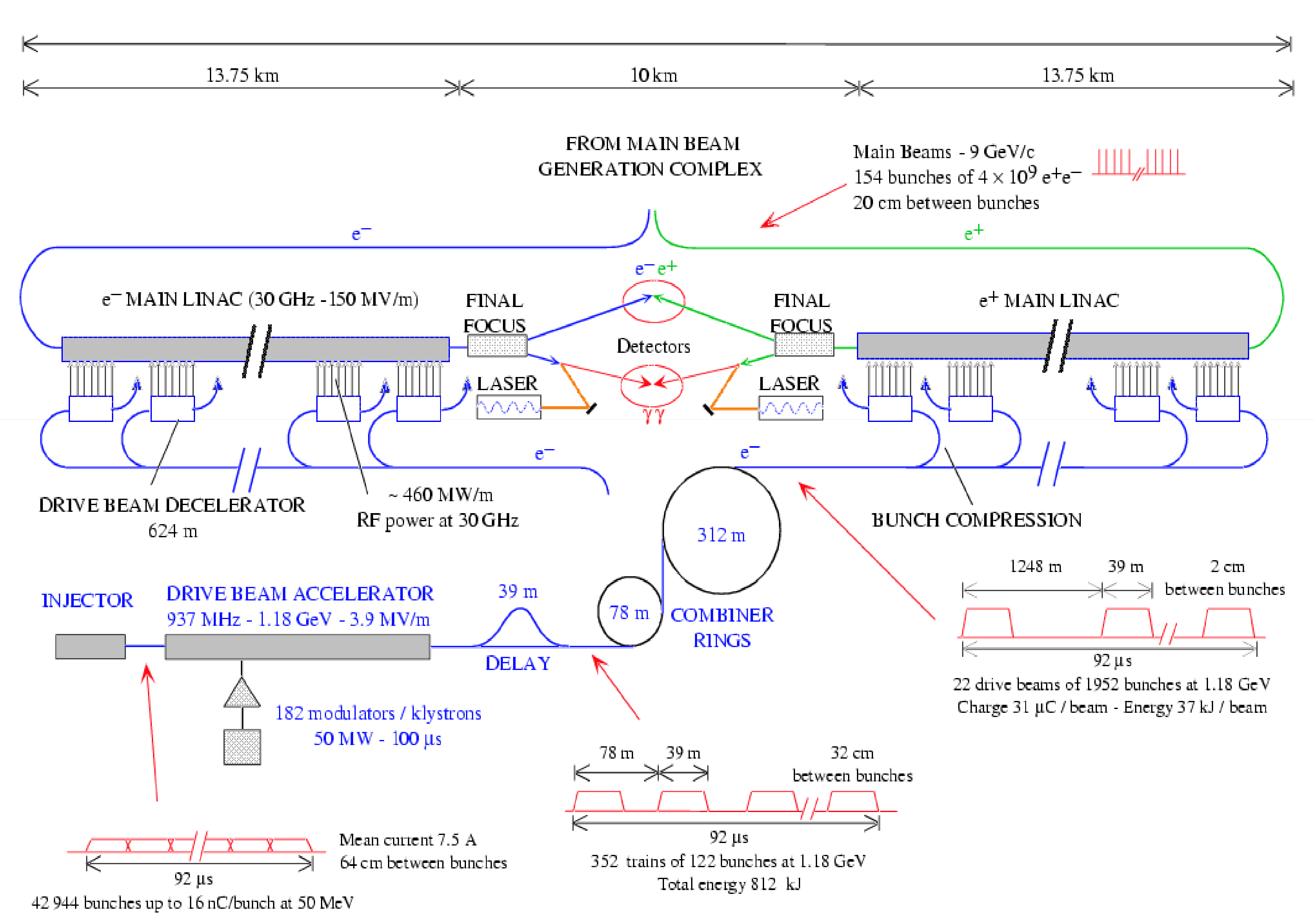


Drive beam

Main LINAC

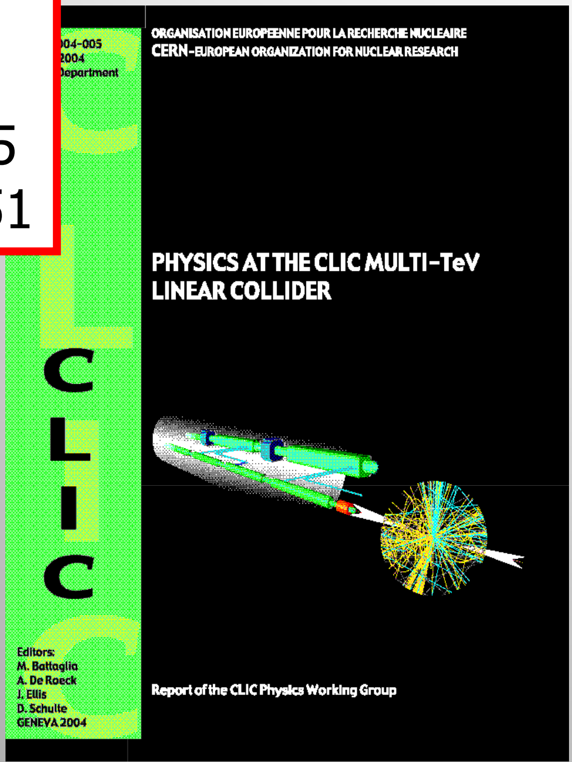
- A drive beam and a main linear accelerator
- Gradient: ~100 MV/m. Aim: reach multi-TeV e+e- collisions
- Studied since the 90's at CERN (and SLAC) with collaborating institutes -- about 20 institutes at present

CLIC: The Machine (2004 Layout)

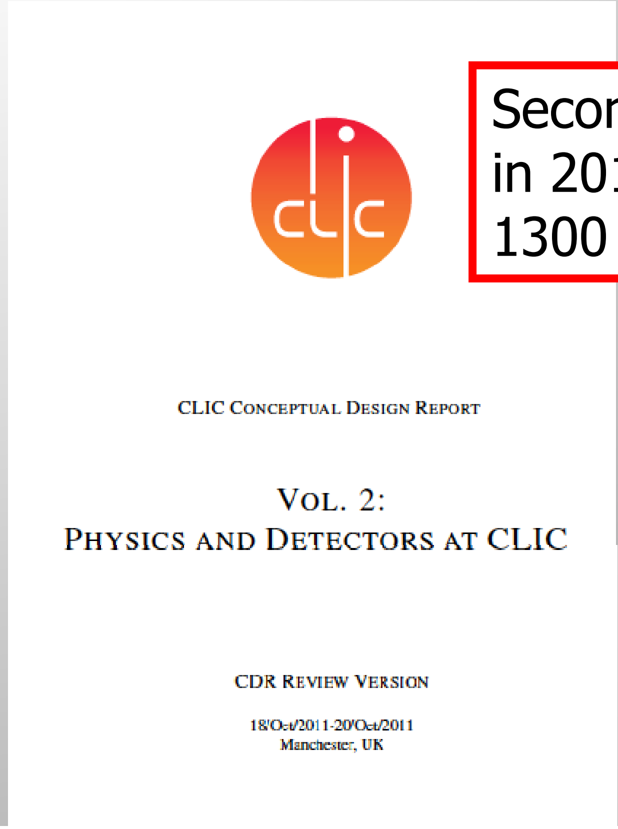


Studies on CLIC Physics Potential

First report
in 2004
CERN-2004-005
hep-ph/0412251



Many of the results are still used, eg for the 2012 ESG reports



Second report
in 2011
1300 authors

- There was always a good collaboration between ILC and CLIC machine groups
- Since 2008 there is close collaboration between the ILC and CLIC on detectors and physics groups
- ESG common document submitted

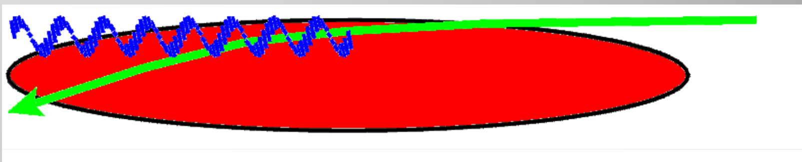
I personally was directly involved from 2000-2008

CLIC Parameters and Issues (2004)

CLIC 3 TeV e+e- collider with a luminosity ~ $10^{35}cm^{-2}s^{-1}$ (1 ab^{-1}/year)

E_{cm}	[TeV]	0.5	3	3
$\mathcal{L}$	$[10^{34}cm^{-2}s^{-1}]$	2.1	10.0	8.0
$\mathcal{L}_{0.99}$	$[10^{34}cm^{-2}s^{-1}]$	1.5	3.0	3.1
f_r	[Hz]	200	100	100
N_b		154	154	154
Δ_b	[ns]	0.67	0.67	0.67
N	$[10^{10}]$	0.4	0.4	0.4
σ_z	[μm]	35	30	35
ϵ_x	[μm]	2	0.68	0.68
ϵ_y	[μm]	0.01	0.02	0.01
σ_x^*	[nm]	202	43	≈ 60
σ_y^*	[nm]	≈ 1.2	1	≈ 0.7
δ	[%]	4.4	31	21
n_γ		0.7	2.3	1.5
$N_\perp$		7.2	60	43
N_{Hadr}		0.07	4.05	2.3
N_{MJ}		0.003	3.40	1.5

To reach this high luminosity: CLIC has to operate in a regime of high beamstrahlung



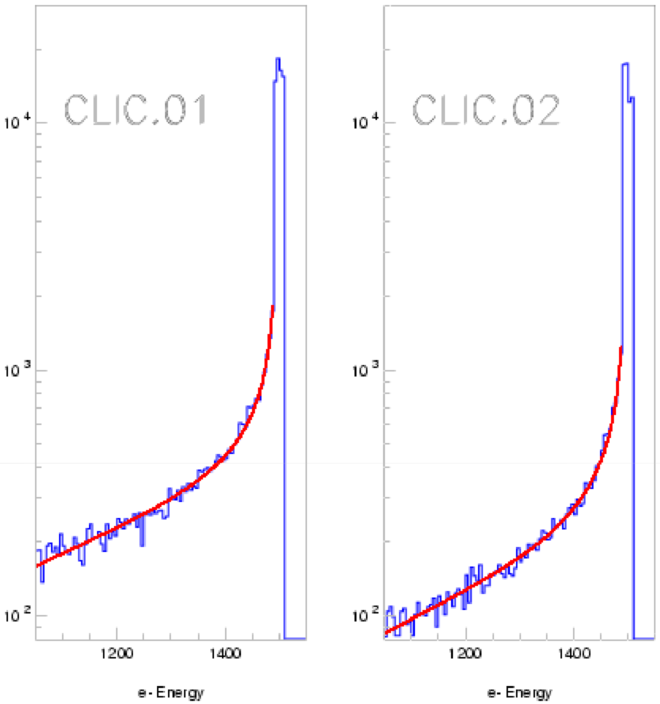
Expect large backgrounds
# of photons/beam particle

- e+e- pair production
- γ γ events
- Muon backgrounds
- Neutrons
- Synchrotron radiation

Expect distorted lumi spectrum

Luminosity Spectrum (2004)

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



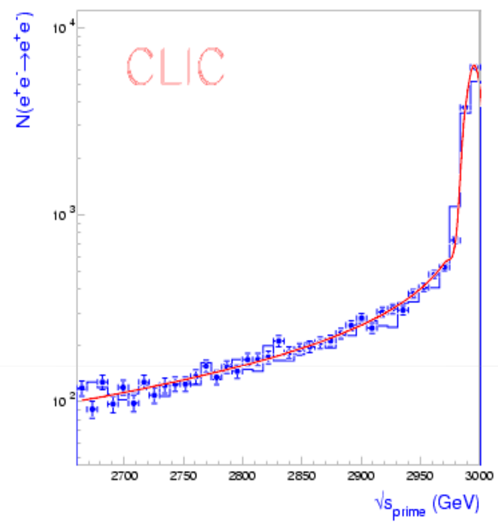
CLIC.01: $\mathcal{L} = 1.05 \times 10^{35}$ CLIC.02: $\mathcal{L} = 0.40 \times 10^{35}$

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%

Reconstructed $\sqrt{s'}$ Spectrum from Bhabha Angles



Preliminary Results: expect accuracy $\frac{\delta\sqrt{s'}}{\sqrt{s}} \simeq 10^{-4}$ for 100 fb^{-1}

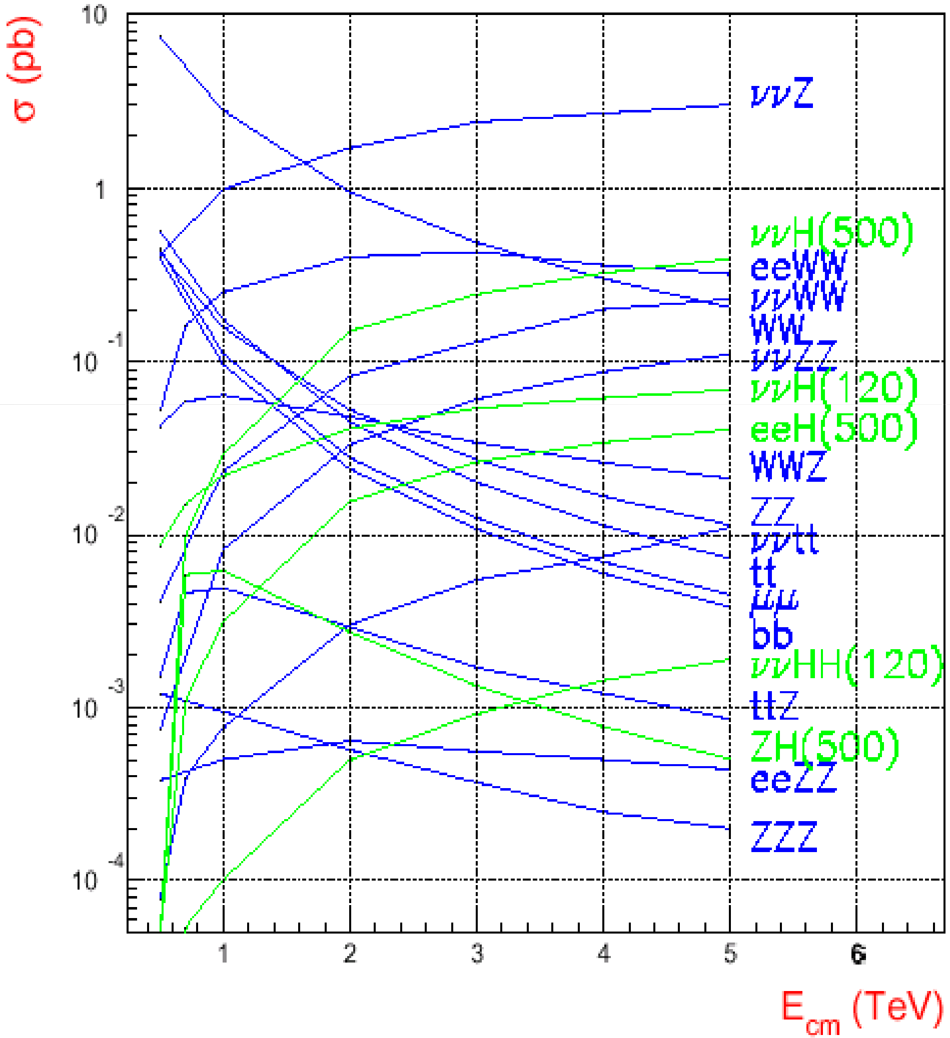
Luminosity spectrum not as sharply peaked as e.g. at LEP

Physics Menu at CLIC

- Higgs sector: properties of the 125 GeV particle, Higgs potential, searches for heavy Higgs particles.
- Supersymmetry: if exists, should be discovered at the LHC. Role of CLIC: completing the particle spectra with precision measurements (masses < $\sqrt{s}/2$)
- Particle Factory: if new particles have been detected/anticipated at the LHC (or lower energy LC) in the range of 1-3 TeV (New Gauge bosons, Kaluza-Klein resonances, resonances in WW scattering…): CLIC can produce them directly, provide an accurate determination of their couplings and establish their nature. Also exotic decays can be detected.
- If NO new particles are observed directly, probe scales up to the O(100-400) TeV indirectly via precision measurements
- QCD measurements: BFKL, photon structure, α_s,…
- The unexpected???

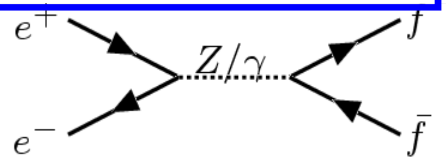
e+e- at $\sqrt{s} \approx 3$ TeV: Expect to break new grounds

Cross Sections at CLIC



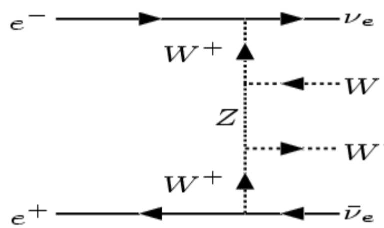
Event Rates/Year (1000 fb^{-1})	3 TeV 10^3 events	5 TeV 10^3 events
$e^+e^- \to t\bar{t}$	20	7.3
$e^+e^- \to b\bar{b}$	11	3.8
$e^+e^- \to ZZ$	27	11
$e^+e^- \to WW$	490	205
$e^+e^- \to hZ/h\nu\nu$ (120 GeV)	1.4/530	0.5/690
$e^+e^- \to H^+H^-$(1 TeV)	1.5	0.95
$e^+e^- \to \tilde{\mu}^+\tilde{\mu}^-$ (1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

s-Channel Production



$\sigma \propto 1/s$

t-Channel Production

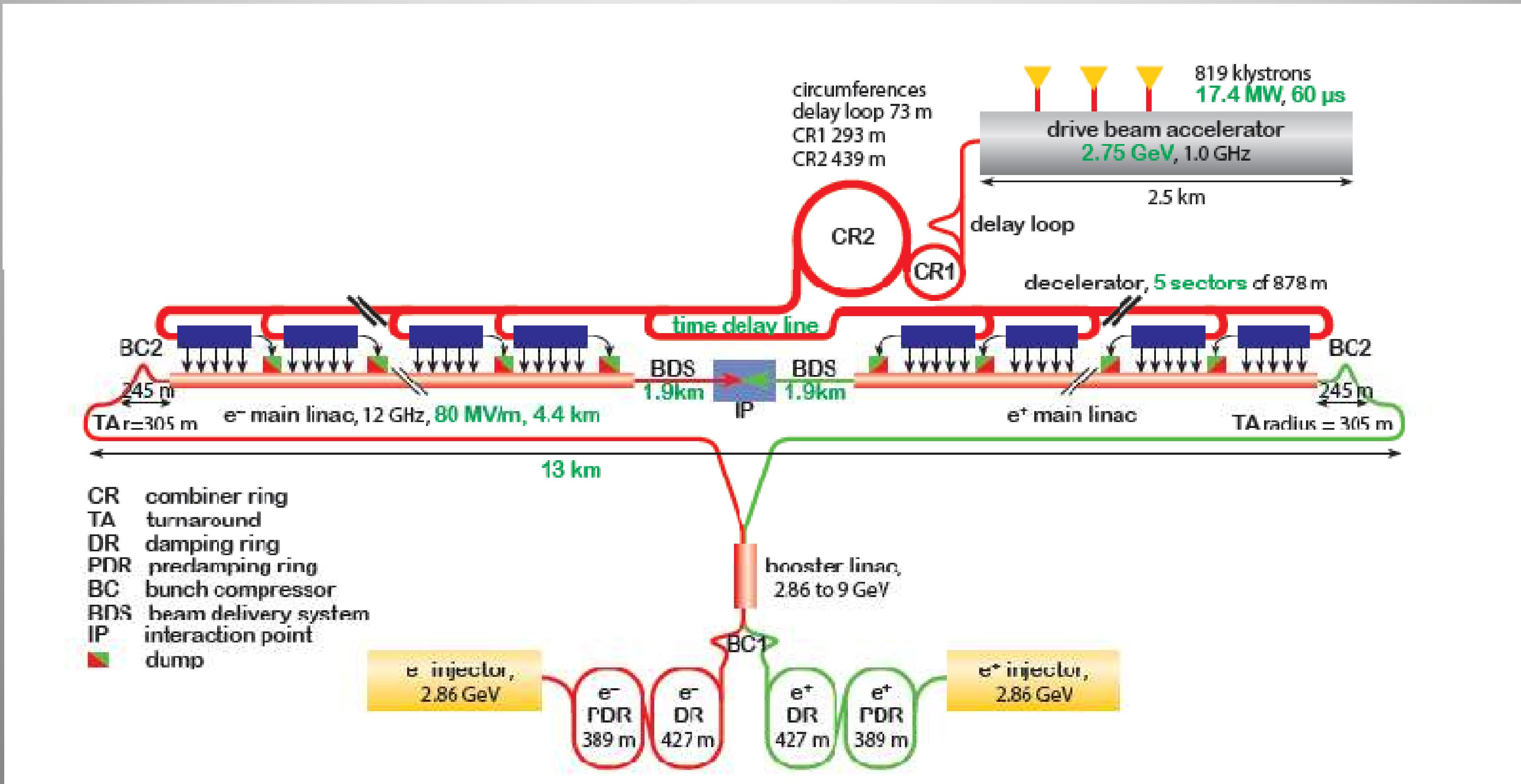


$\sigma \propto log(s)$

CLIC 2012: Staged Proposal

First phase: up to 500 GeV
Second Phase: up to 1400/1500 GeV

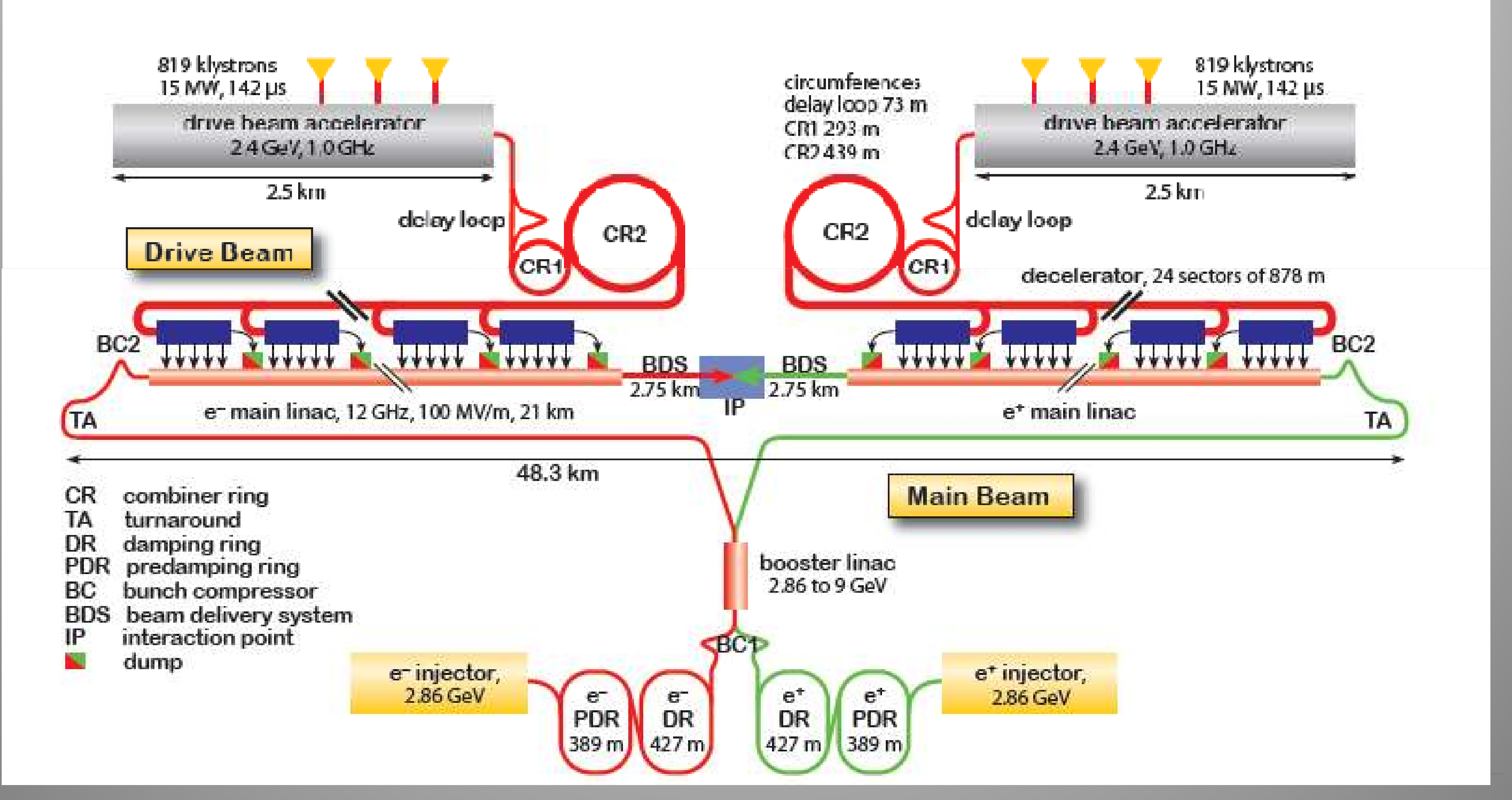
1 drive beam



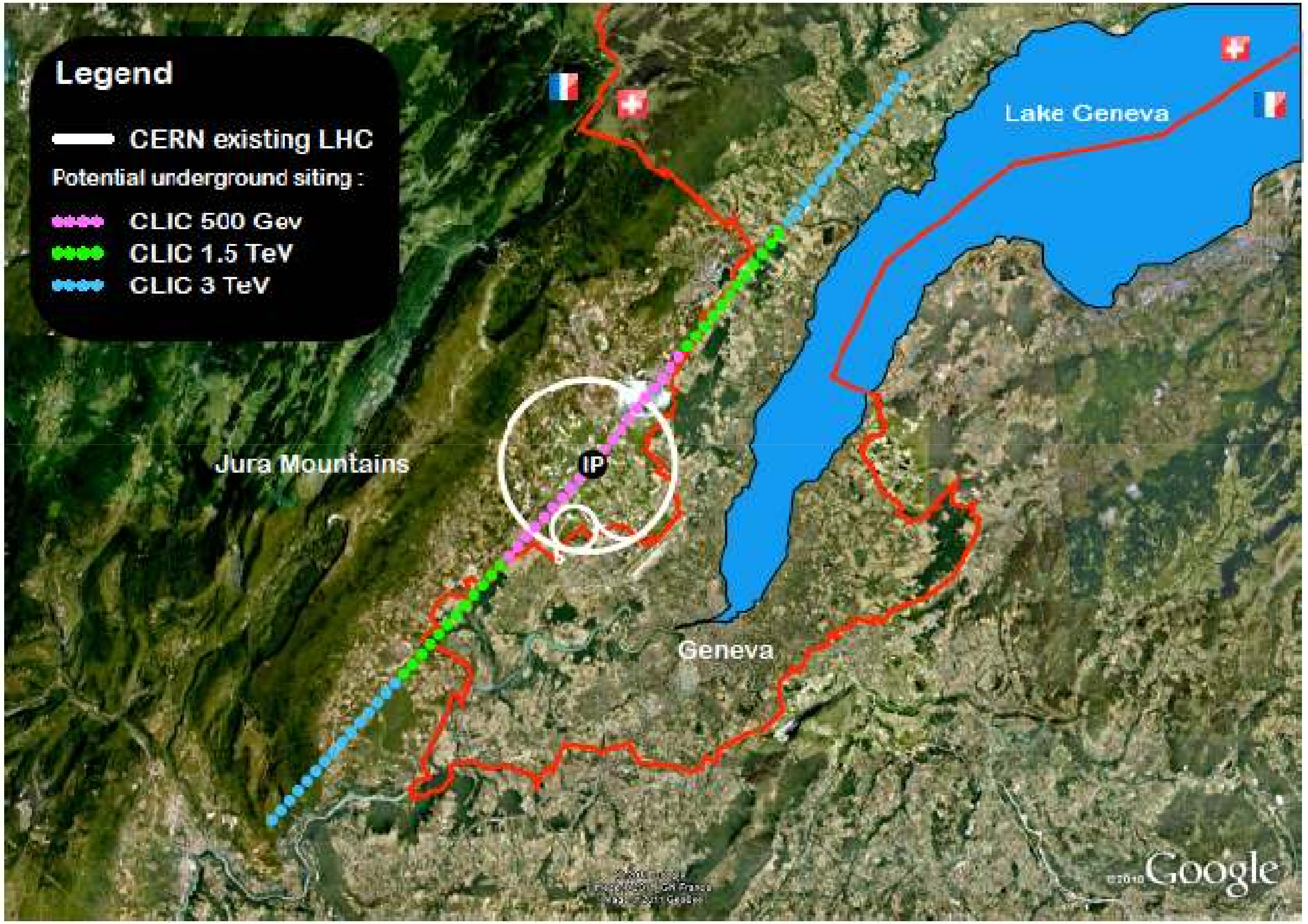
CLIC 2012: Staged Proposal

Third phase: up to 3 TeV

2 drive beams



CLIC @ CERN?



It is possible can build CLIC at CERN, but CLIC is a site independent study

CLIC 2012 Parameters

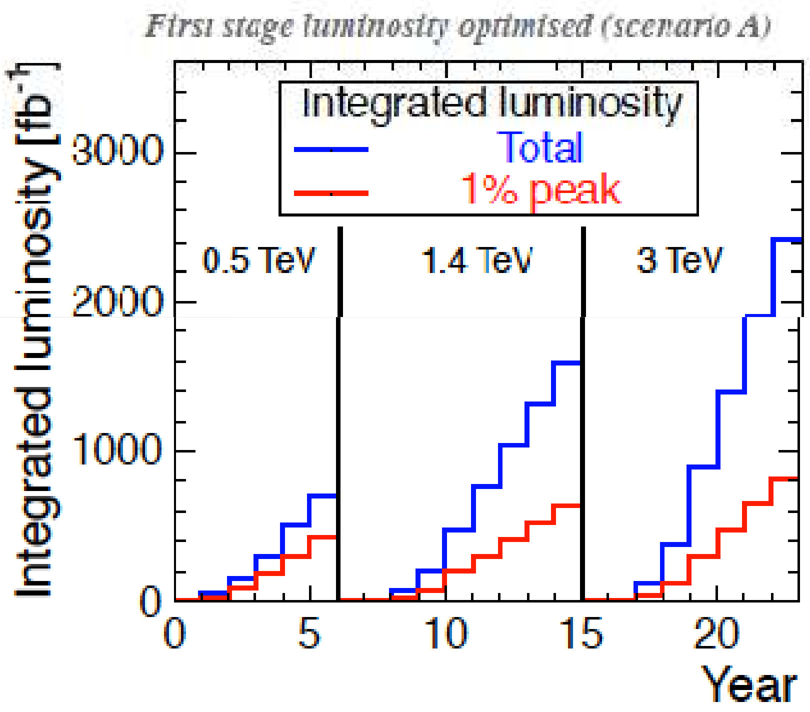
Table 1: Parameters for the CLIC energy stages of scenario A.

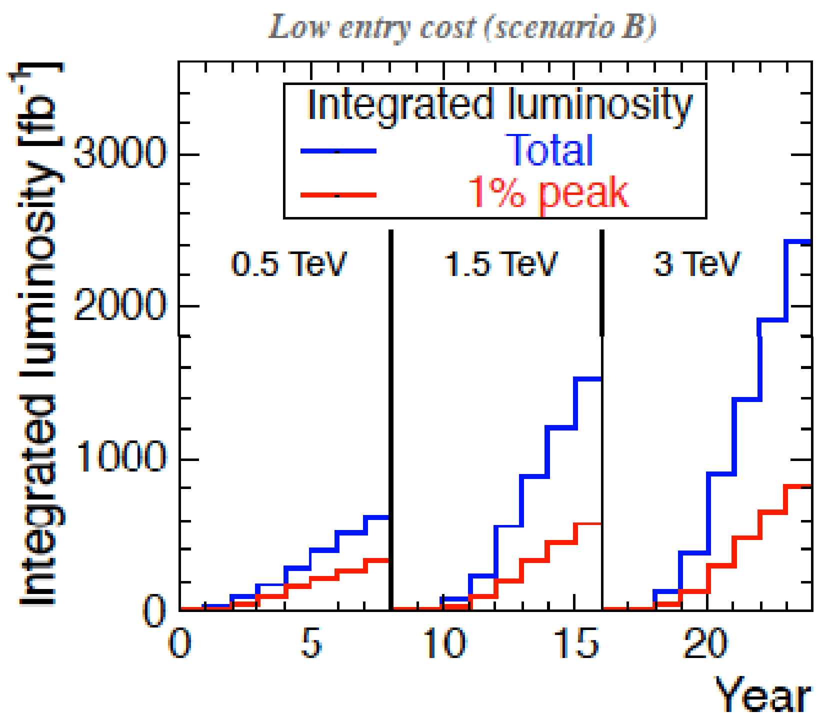
Parameter	Symbol	Unit	Stage 1	Stage 2	Stage 3
Centre-of-mass energy	$\sqrt{s}$	GeV	500	1400	3000
Repetition frequency	f_{rep}	Hz	50	50	50
Number of bunches per train	n_b		354	312	312
Bunch separation	Δt	ns	0.5	0.5	0.5
Accelerating gradient	G	MV/m	80	80/100	100
Total luminosity	$\mathscr{L}$	10^{34} cm^{-2}s^{-1}	2.3	3.2	5.9
Luminosity above 99% of $\sqrt{s}$	$\mathscr{L}_{0.01}$	10^{34} cm^{-2}s^{-1}	1.4	1.3	2
Main tunnel length		km	13.2	27.2	48.3
Charge per bunch	N	10^9	6.8	3.7	3.7
Bunch length	σ_z	μm	72	44	44
IP beam size	σ_x/σ_y	nm	200/2.6	$\sim$ 60/1.5	$\sim$ 40/1
Normalised emittance (end of linac)	$\varepsilon_x/\varepsilon_y$	nm	2350/20	660/20	660/20
Normalised emittance (IP)	$\varepsilon_x/\varepsilon_y$	nm	2400/25	—	—
Estimated power consumption	P_{wall}	MW	272	364	589

- Challenging: collisions every 0.5 nano-seconds; trains of 312 bunch-X
- Read out all 312 bunch crossings without trigger

Running Scenarios

Assume 3 phases: Integrated luminosity per phase
Two scenarios: A= low energy optimized - B= cost effective for TeV CLIC

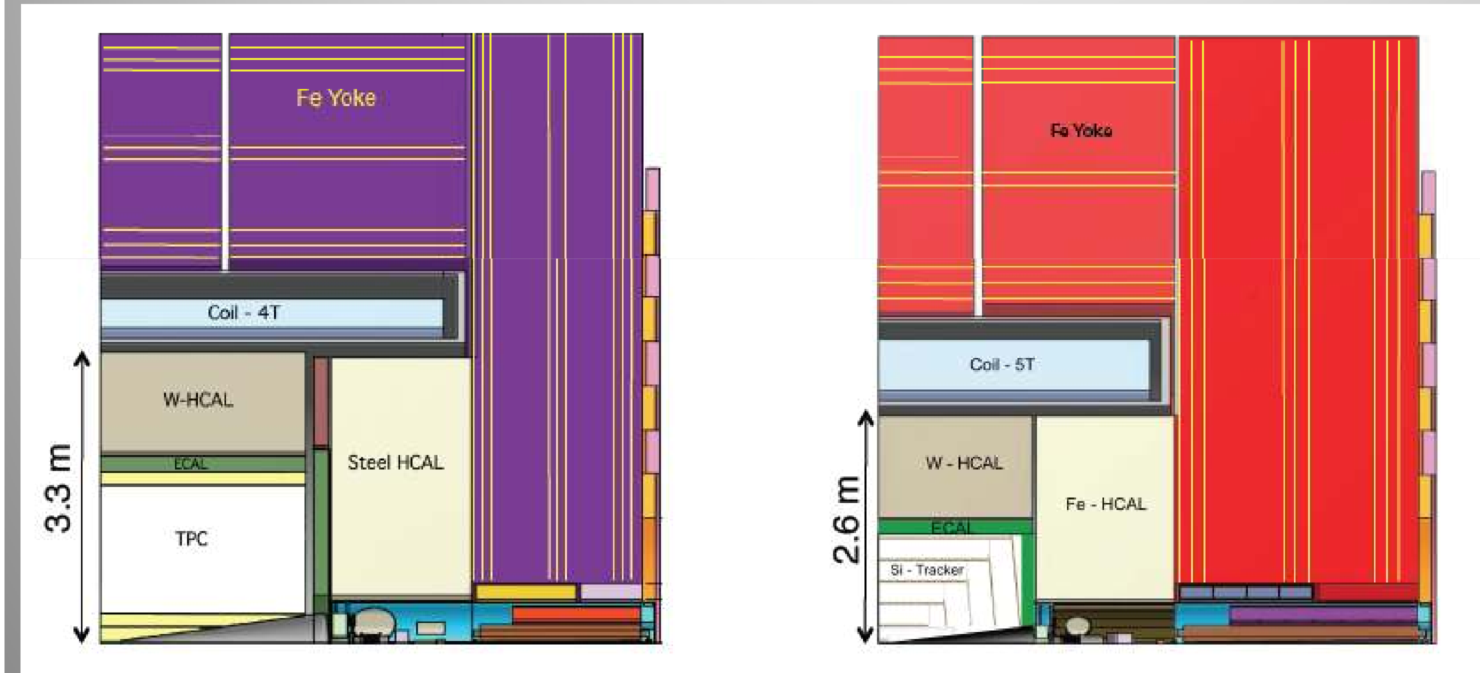




When would be year "zero"?
Construction time ~ 7 years. Start of construction earliest by 2023

Detectors for CLIC

Extended versions of the ILD can SiD detectors of the ILC
•Interaction lengths for the hadronic calorimeter extended to 8.5 λ
use of tungsten in the barrel.



3-5% energy resolution for jets at 1 TeV

Tracking:
$\sigma_{p_T} / p_T^2 \sim 2 \times 10^{-5} \mathrm{GeV}^{-1}$

Magnetic fields are 4 & 5 Tesla for these detectors

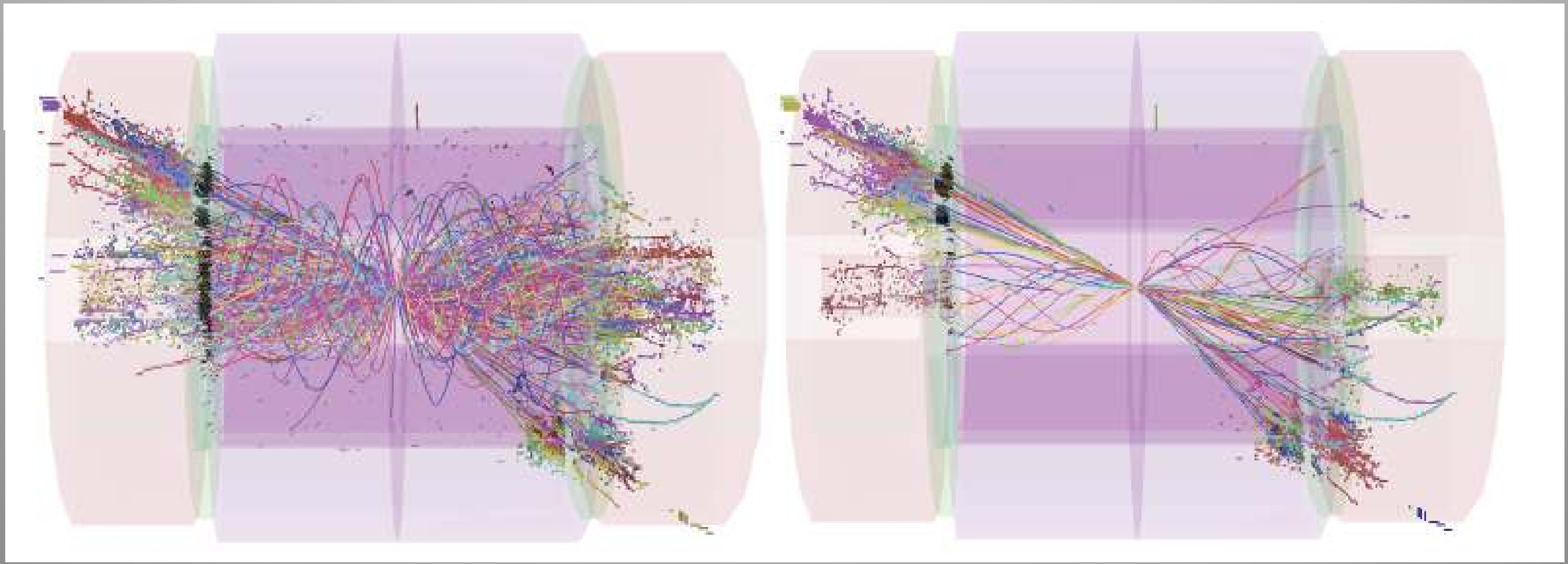
These detectors are used for the 2012 physics studies

CLIC Detectors

Effect of using timing in the detectors
10 ns for silicon/1 ns for calorimeter

Full bunch train

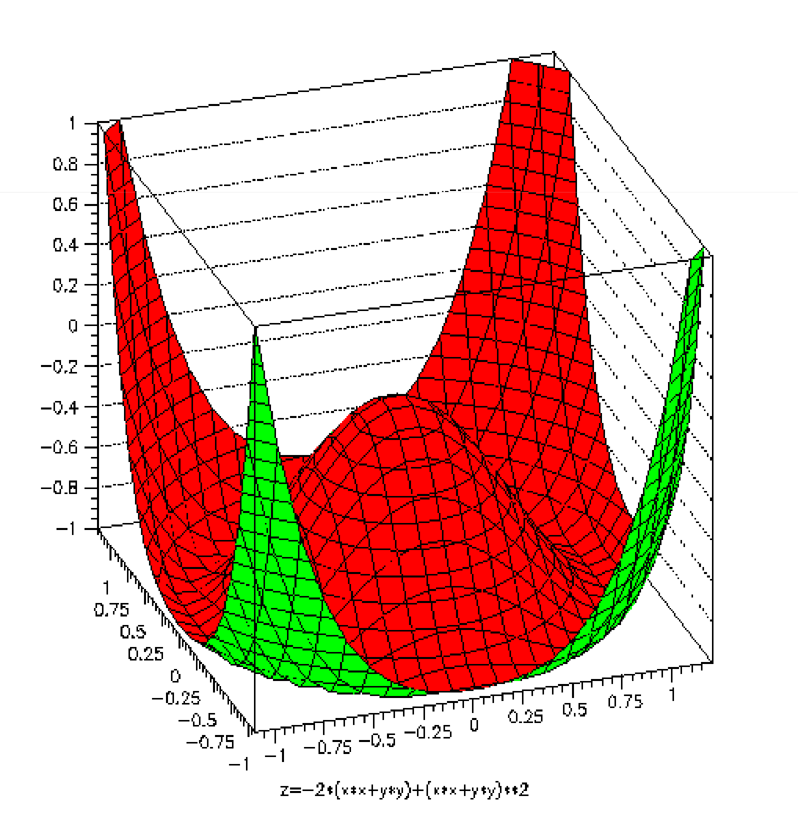
Time selected information



~ 20 TeV in the detector

~ 100 GeV in the detector

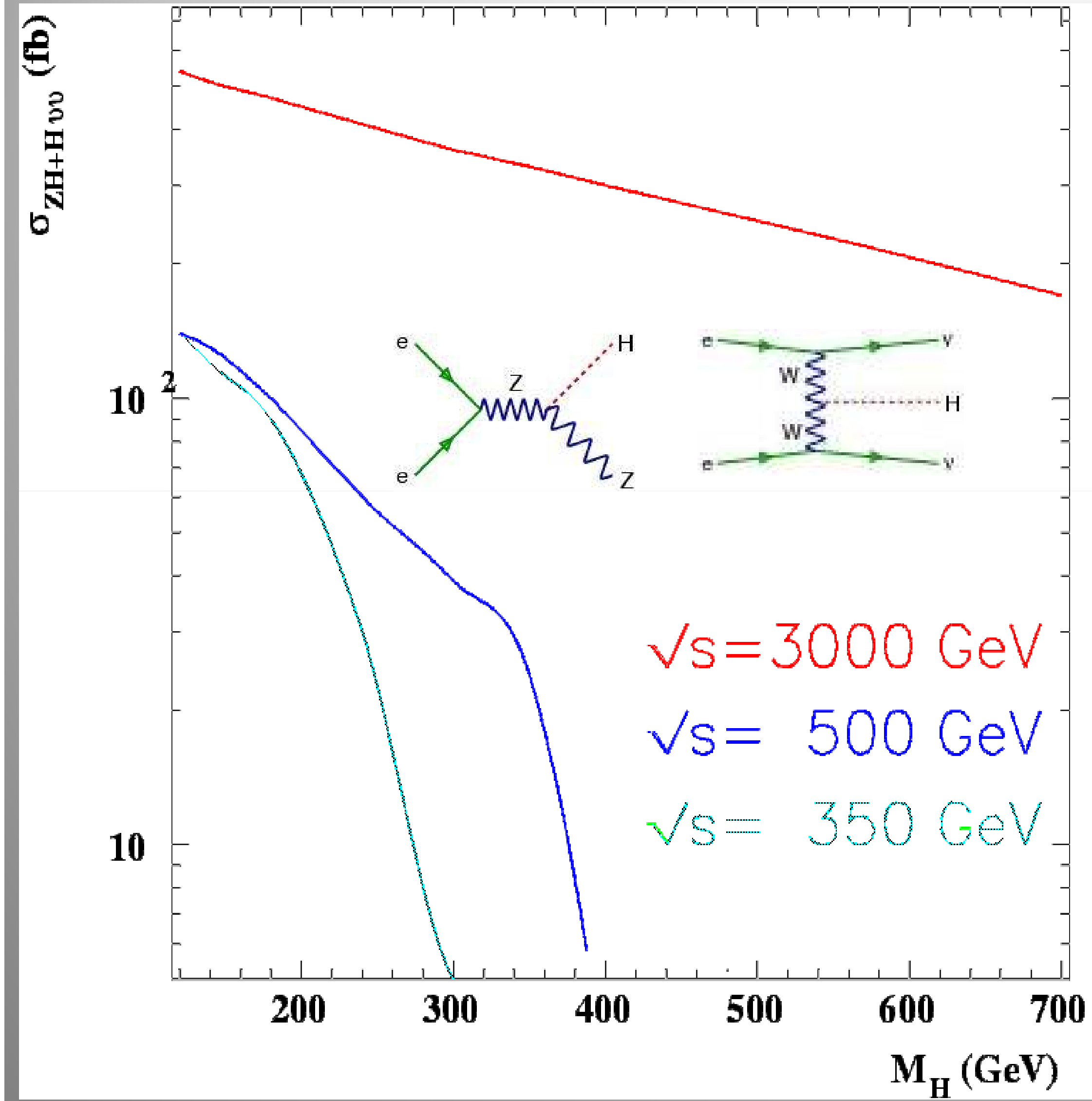
2. Higgs Physics



Study properties of the Higgs particles with high precision

Reconstruct the Higgs potential

Higgs Production



Cross section at 3 TeV:

- Large cross section at low masses
- Large CLIC luminosity

→Large events statistics

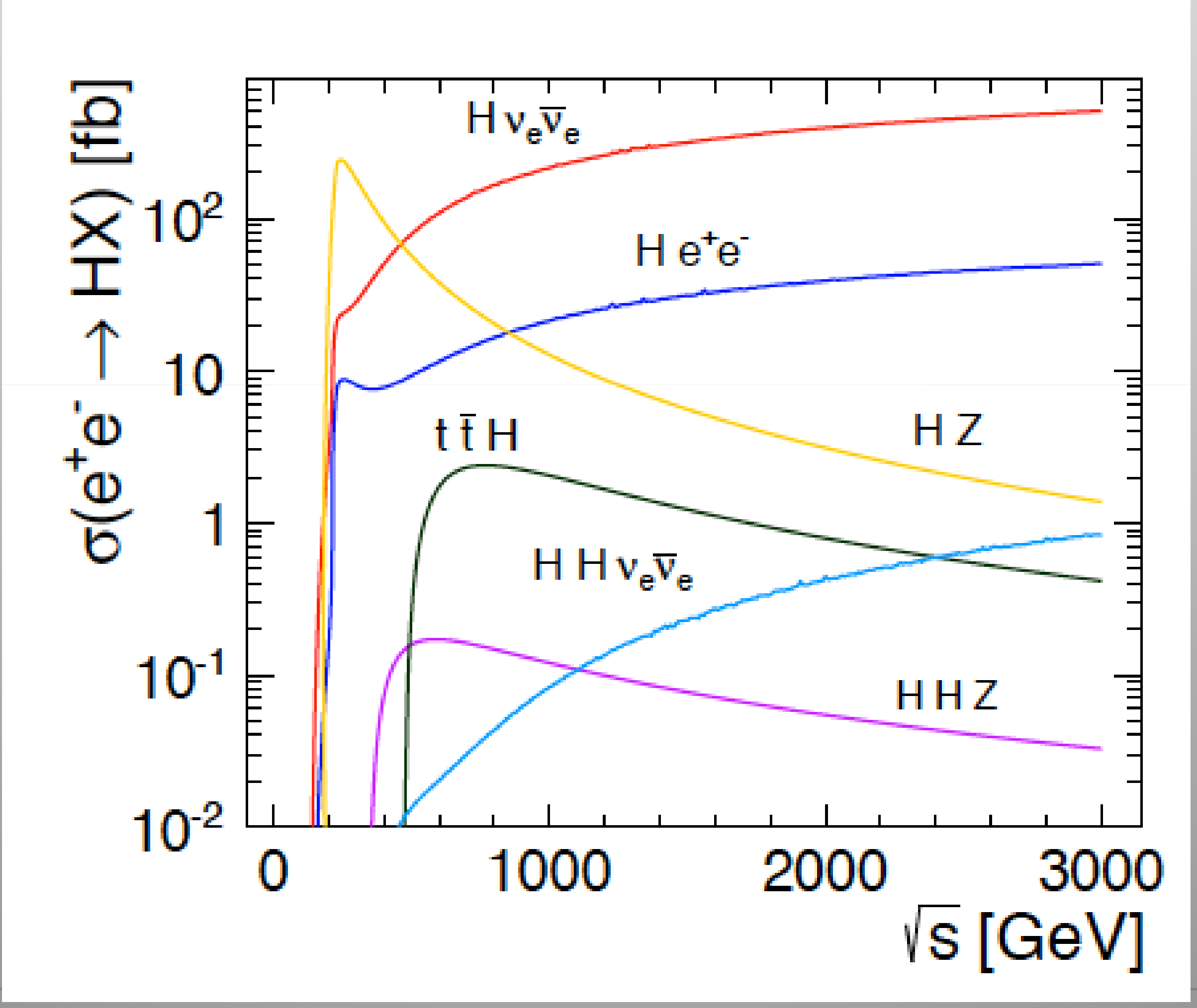
- Keep large statistics also for highest Higgs masses

Higgs @ 125 GeV
>400 000 Higgs particles/ab^{-1}

Higgs Boson Production

M_H= 125 GeV

At high energy VBF dominant



Higgs Studies Projections: Examples

350/500 GeV @ 500 fb^{-1} and 1.4 (3.0) TeV at 1.5 (2) ab^{-1}

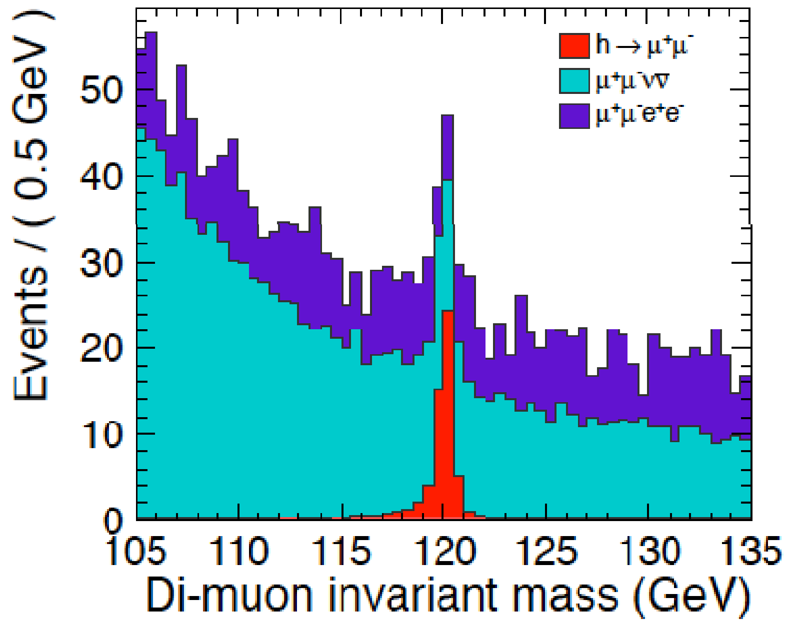
Higgs studies for m_H =120 GeV

$\sqrt{s}$ (GeV)	Process	Decay mode	Measured quantity	Unit	Generator value	Stat. error	Comment
350	SM Higgs production	$ZH \to \mu^+\mu^- X$	σ	fb	4.9	4.9%	Model independent, using Z-recoil
			Mass	GeV	120	0.131	
500		$ZH \to q\bar{q}q\bar{q}$	$\sigma \times$ BR	fb	34.4	1.6%	$ZH \to q\bar{q}q\bar{q}$ mass reconstruction
			Mass	GeV	120	0.100	
500		$ZH, H\nu\bar{\nu} \to \nu\bar{\nu}q\bar{q}$	$\sigma \times$ BR	fb	80.7	1.0%	Inclusive sample
			Mass	GeV	120	0.100	
1400	WW fusion	$H \to \tau^+\tau^-$	$\sigma \times$ BR	fb	19.8	<3.7%	
3000		$H \to b\bar{b}$			285	0.22%	
		$H \to c\bar{c}$			13	3.2%	
		$H \to \mu^+\mu^-$			0.12	15.7%	
1400 3000	WW fusion		Higgs tri-linear coupling g_{HHH}			~20% ~20%	

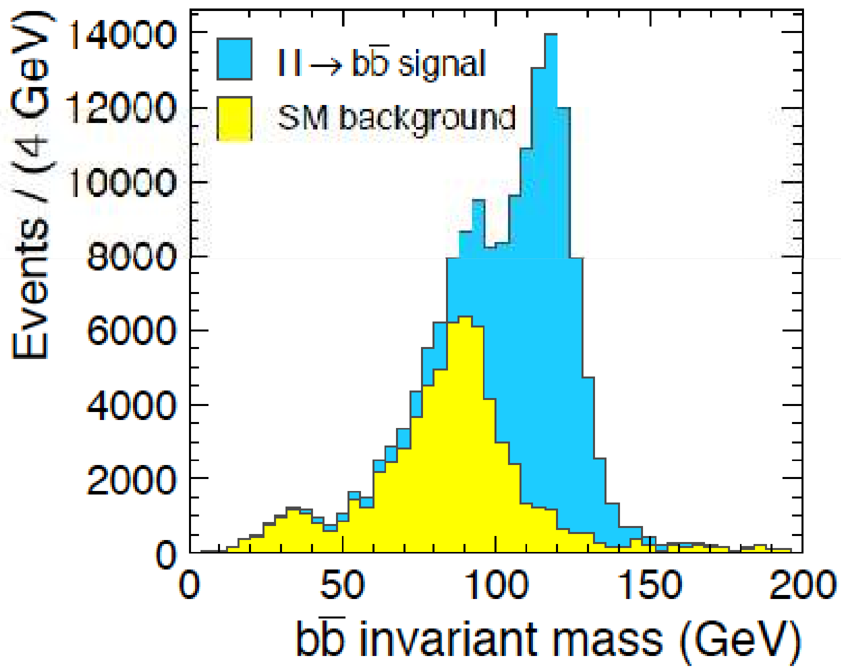
Rare Higgs Decays

120 GeV H-> μμ
60 events for 3 TeV 2 ab^{-1}

150 GeV H-> bb
for 3 TeV 2 ab^{-1}



(a) $e^+e^- \to H\nu\bar{\nu}, H \to \mu^+\mu^-$

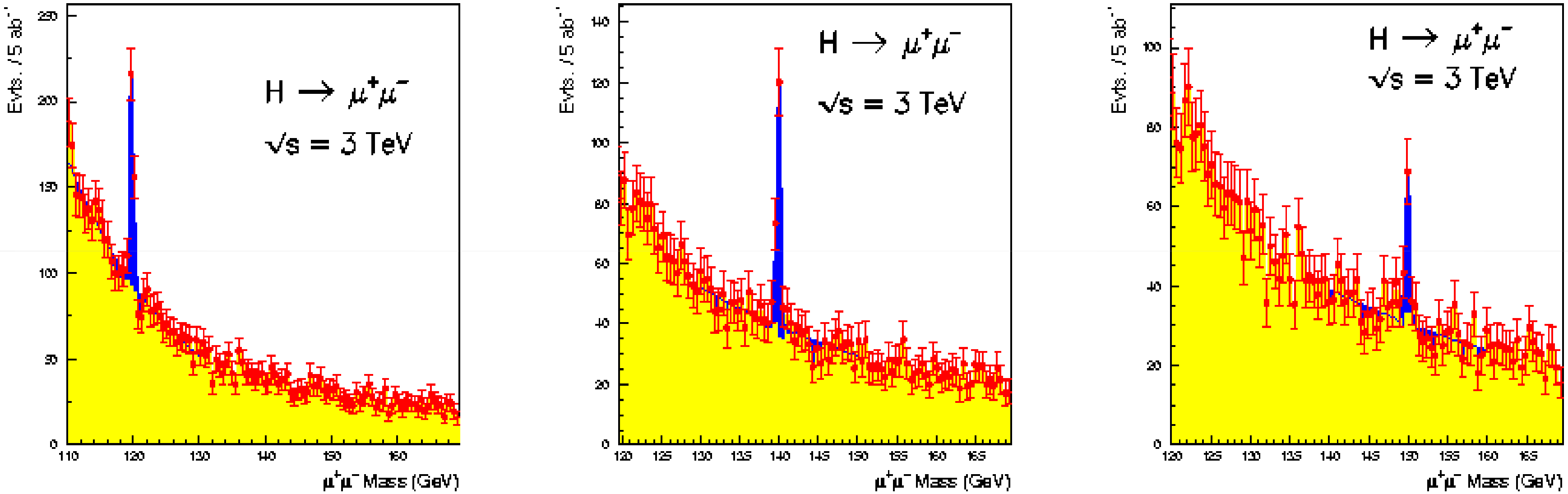


(b) $e^+e^- \to H\nu\bar{\nu}, H \to b\bar{b}$

Rare Higgs Decays: H→μμ

$H \to \mu^+\mu^-$: Branching Ratio $\sim 10^{-4}$

2004 study



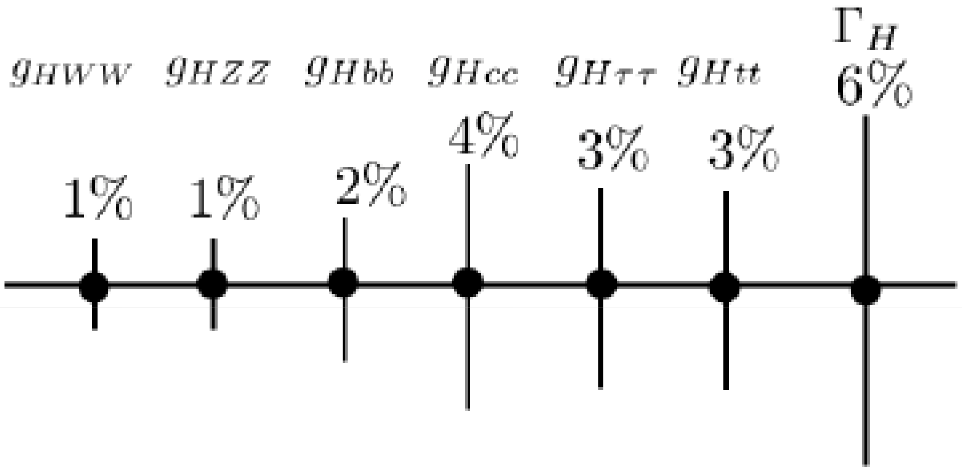
Result for $\sqrt{s} = 3.0$ TeV with $\int \mathcal{L} = 5$ ab^{-1}

M_H	120 GeV	140 GeV	150 GeV
$\delta BR/BR$	0.072	0.121	0.210

⇒ Precision on $g_{H\mu\mu}$: 3.5% → 10%

Projected Relative Precision

$m_H = 120$ GeV



500 GeV 500 fb^{-1}

	Stat. Acc.(%)
g_{Hbb}	0.22

3 TeV 2 ab^{-1}

Reconstruct the Higgs Potential

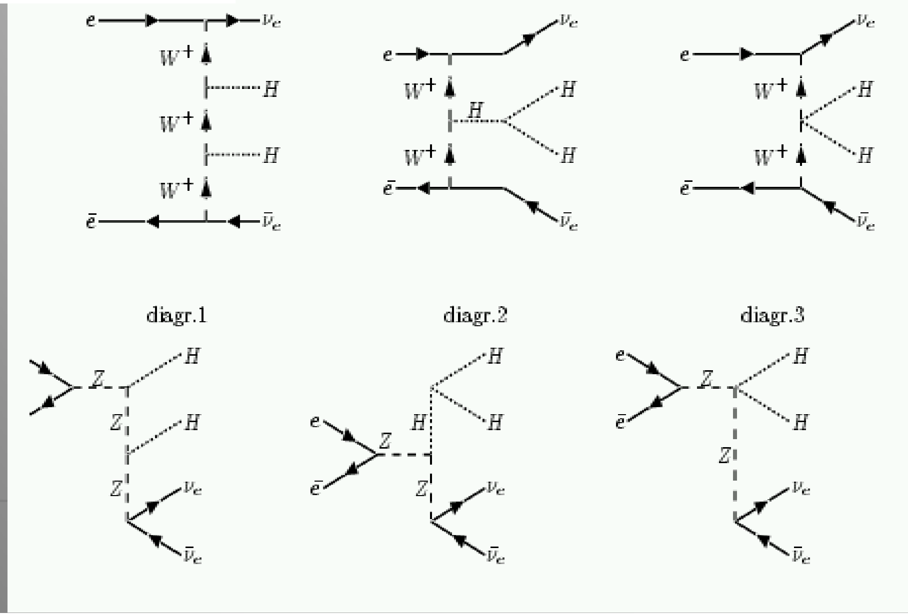
Reconstruct shape of the Higgs potential to complete the study of the Higgs profile and to obtain a direct proof of the EW symmetry breaking mechanism

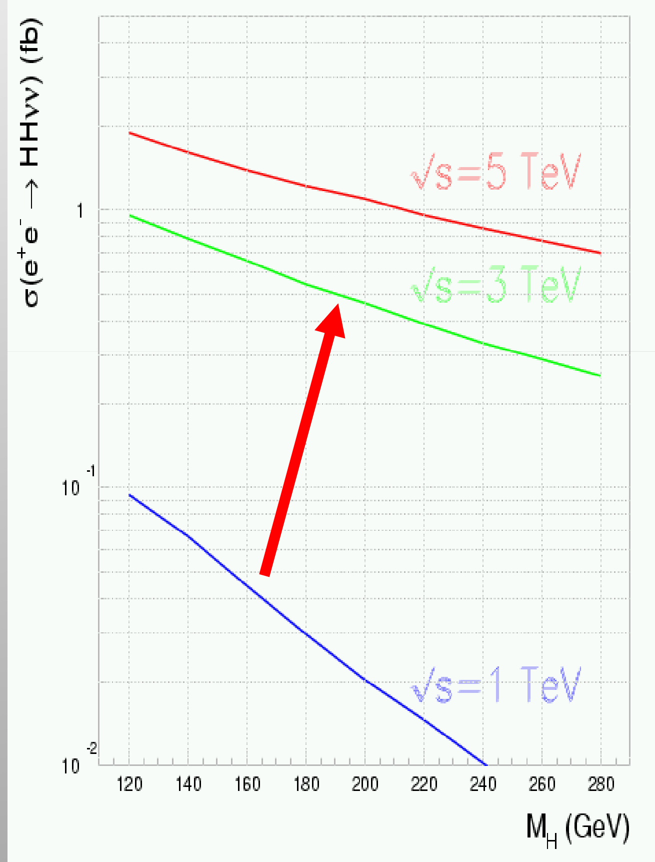
⇒ Measure the triple (quartic) couplings

$$V_H = \frac{m_H^2}{2} H^2 + \frac{m_H^2}{2v} H^3 + \frac{m_H^4}{8v^2} H^4$$

$$\lambda_{HHH} = 3m_H^2/v$$

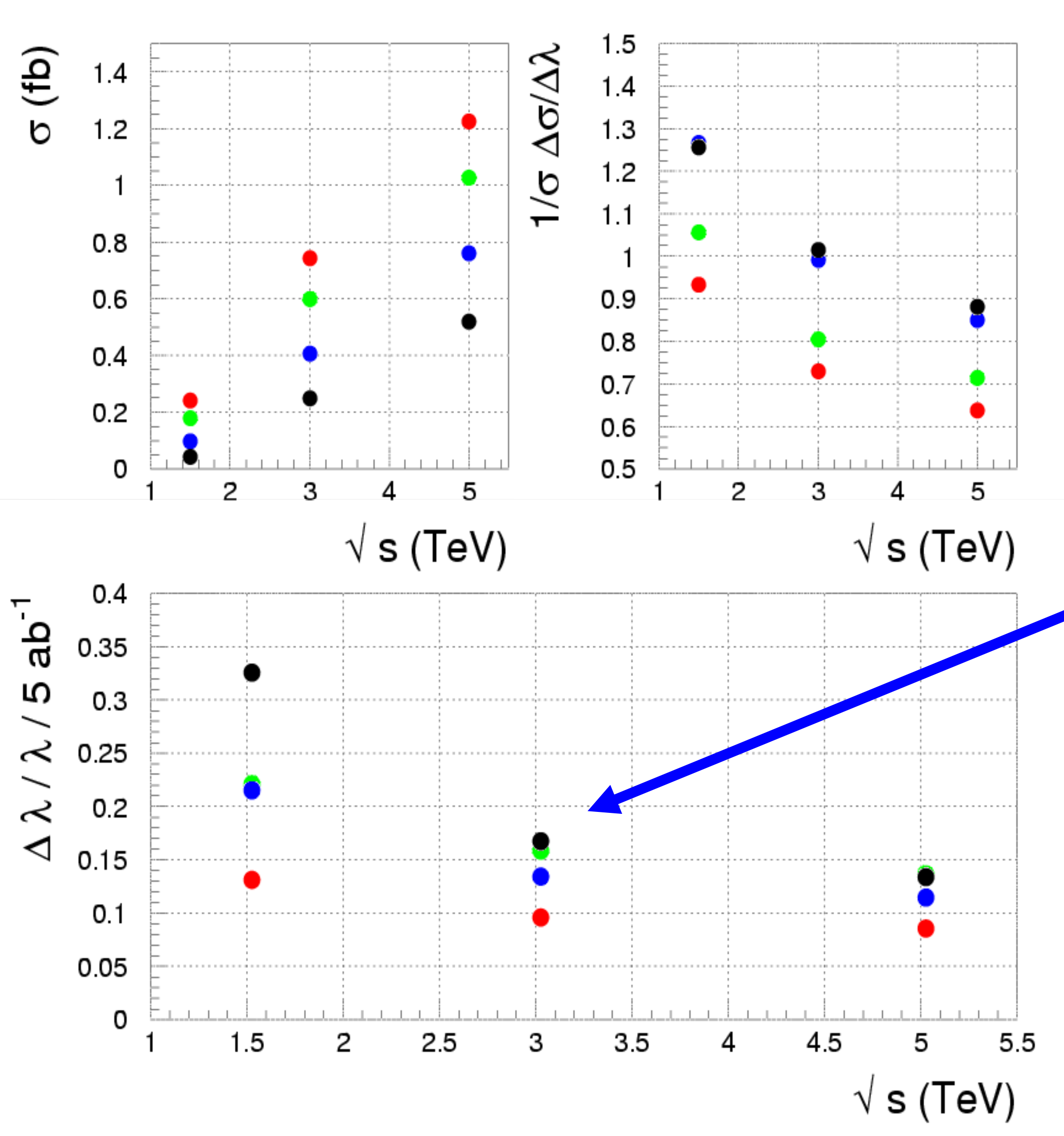
process $e^+e^- \to (WW)\nu\bar{\nu} \to hh\nu\bar{\nu}$





$$HH \to b\bar{b}b\bar{b},\ W^+W^-W^+W^-$$

Results: e+e- →HHνν (2004)



Precision on λ_{HHH} for 5 ab^{-1} for Higgs masses in the range

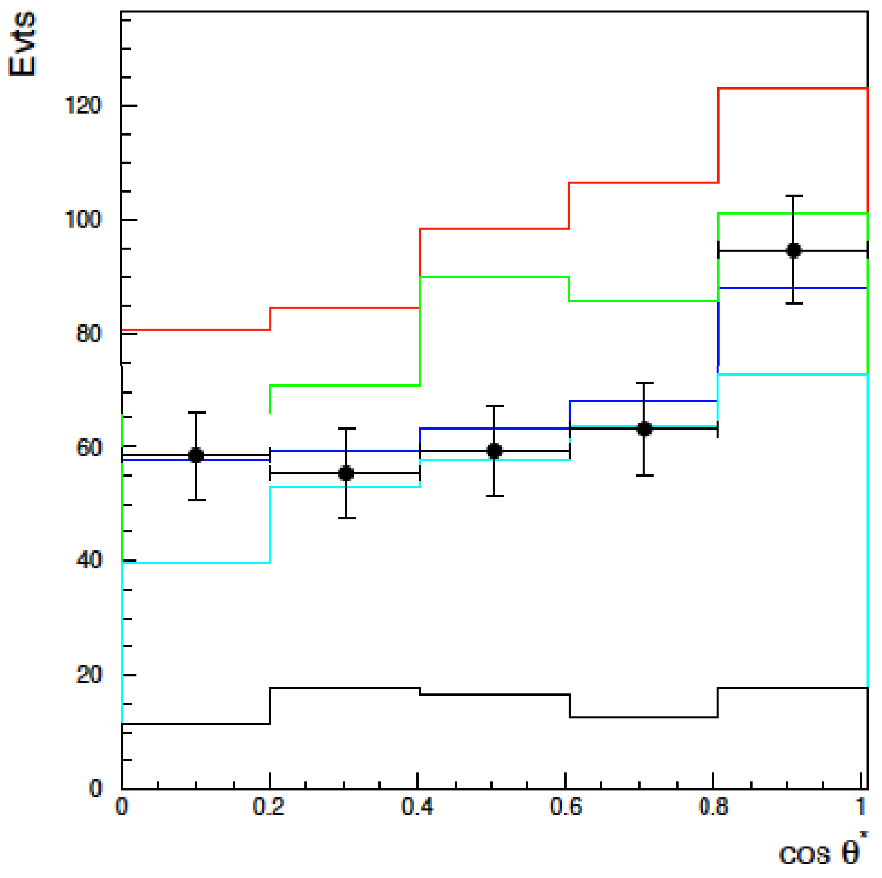
- m_H = 120 GeV
- m_H = 140 GeV
- m_H = 180 GeV
- m_H = 240 GeV

3 TeV

M_H (GeV)	$\sigma_{HH\nu\bar{\nu}}$ Only	$\lvert\cos\theta^*\rvert$ Fit
120	± 0.094 (stat)	± 0.070 (stat)
180	± 0.140 (stat)	± 0.080 (stat)

Can improve by factor 1.7 if both beams are polarized

Triple Higgs Coupling: 2012



(c) $|\cos\theta^*|$ distribution

Two Higgs events

120 GeV Higgs

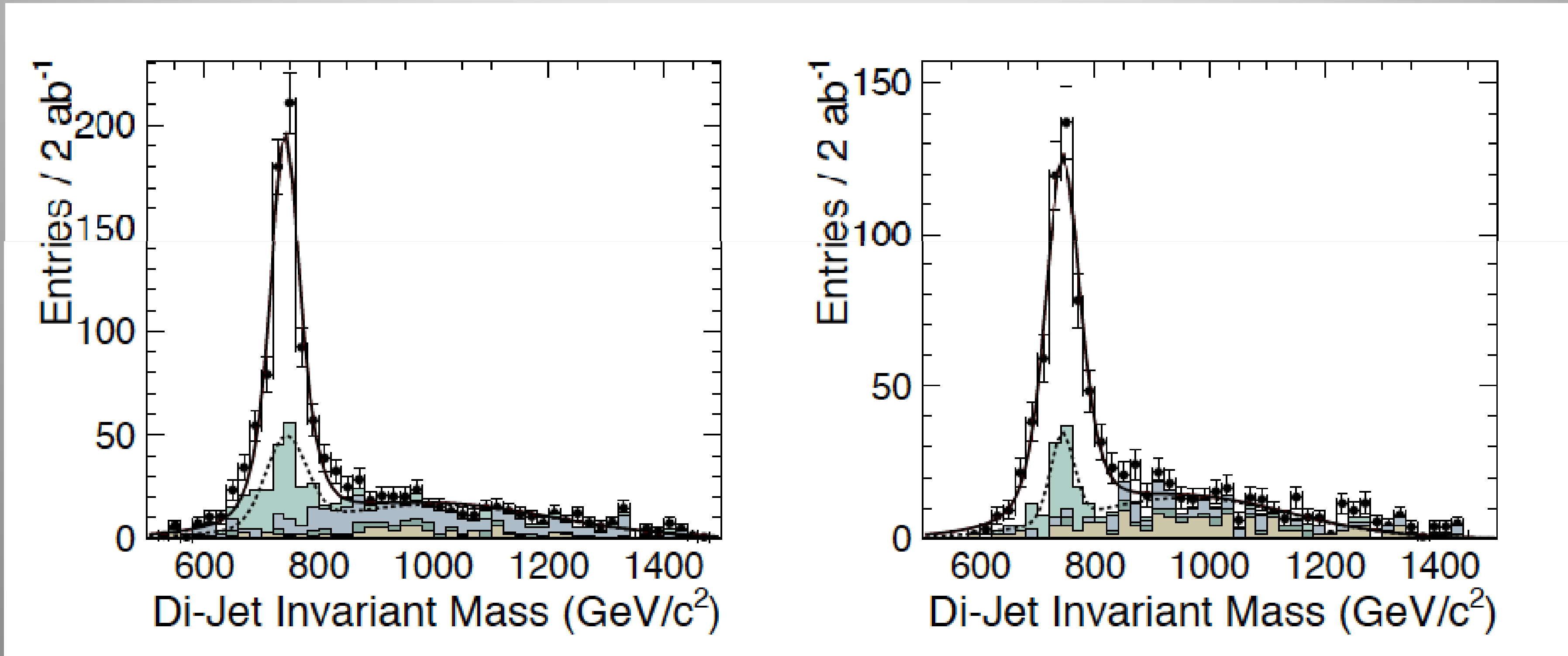
$$\lambda_{HHH}/\lambda_{HHH}^{SM} = 1.25, 1.0, 0.75 \text{ and } 0.5$$

CLIC can differentiate at the 10-20% level

Not all tricks used yet…

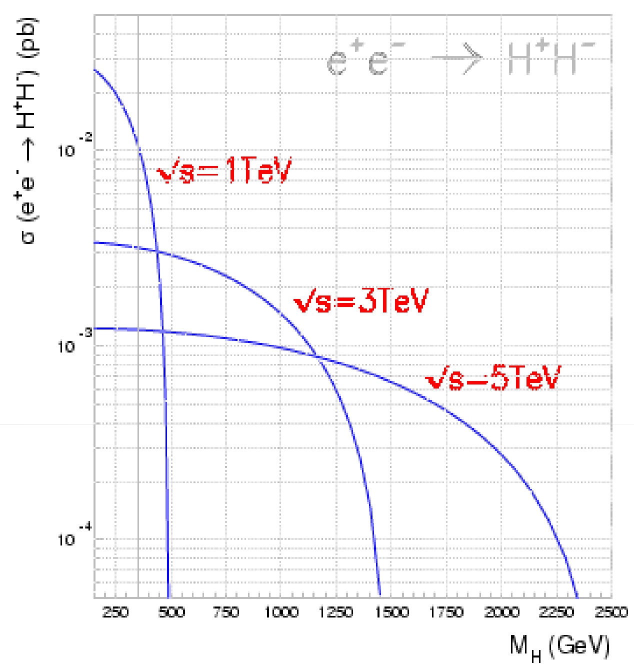
(Very) Heavy Higgs Searches

ee-> HA and ee-> H+H- Higgs mass reconstruction for Higgs' around 800 GeV, decaying into di-jets

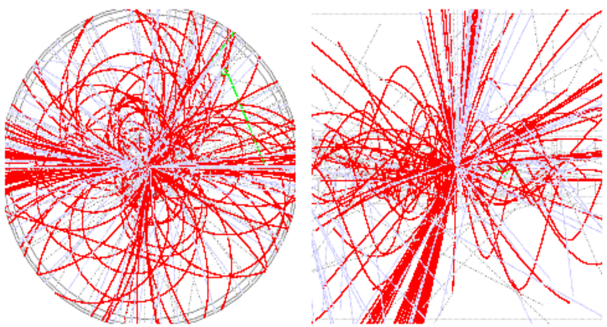


Heavy Higgs in MSSM (2004)

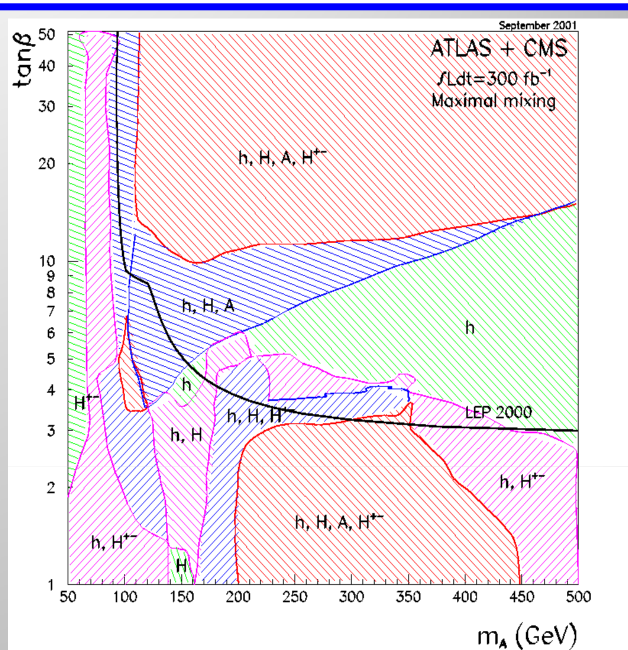
Cross section as function of Higgs mass



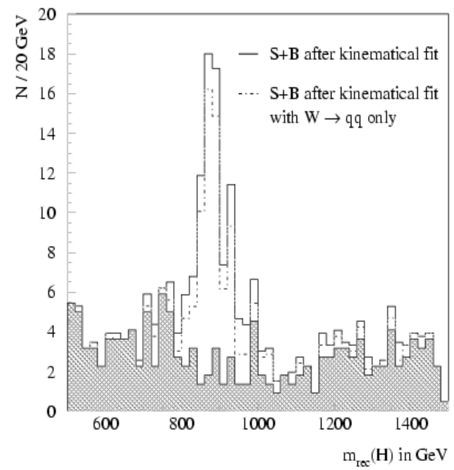
$e^+e^- \to H^+H^-\ M_H = 900$ GeV



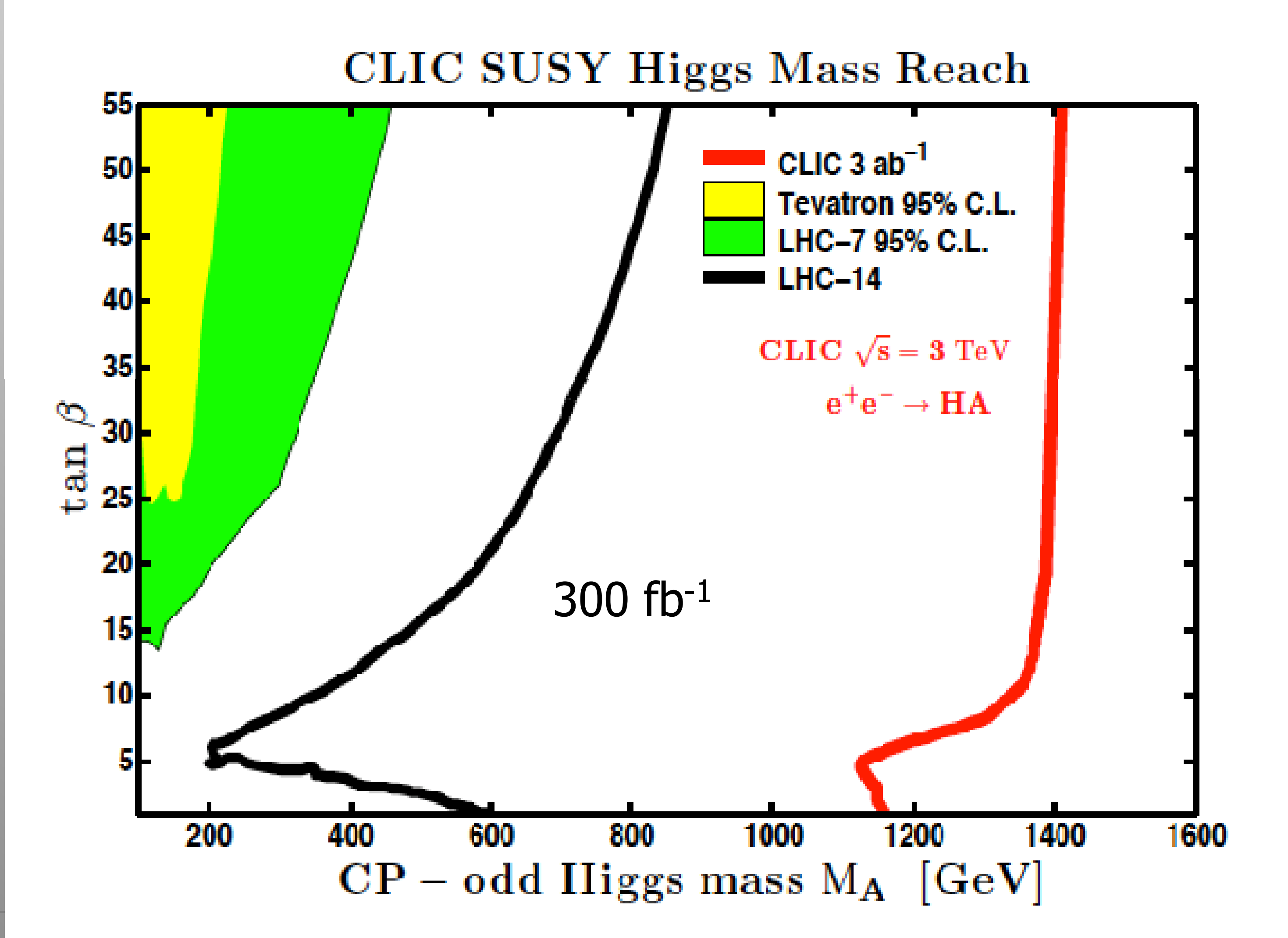
LHC: Plot for 5 σ discovery



3 TeV CLIC
$\Rightarrow$ H, A
detectable
up to ~ 1.2 TeV



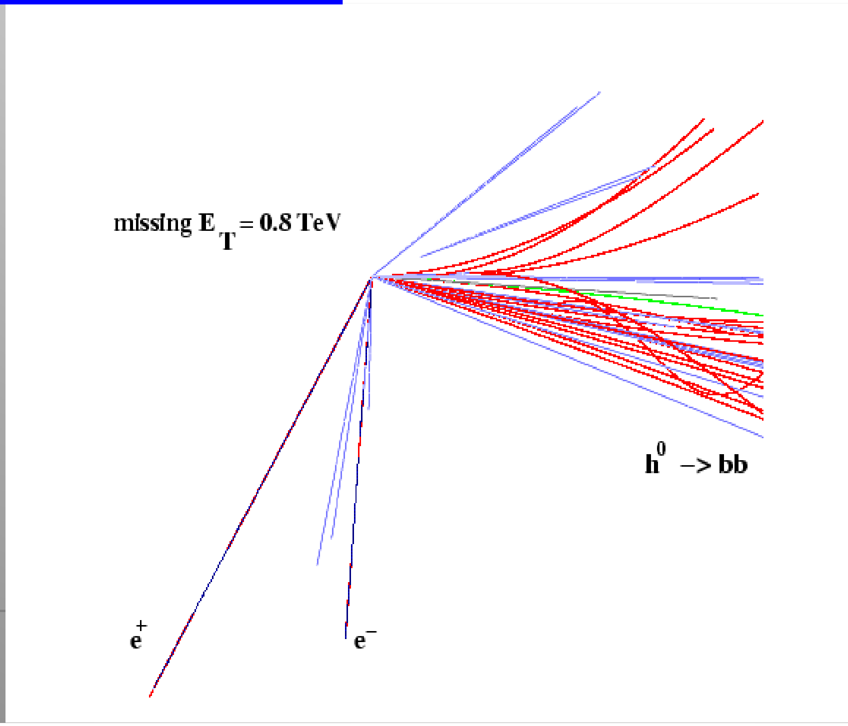
M_A-tanβ Coverage (2012)



3. Supersymmetry

CLIC 3 TeV

$e^+e^- \to \tilde{e}_L\tilde{e}_R$



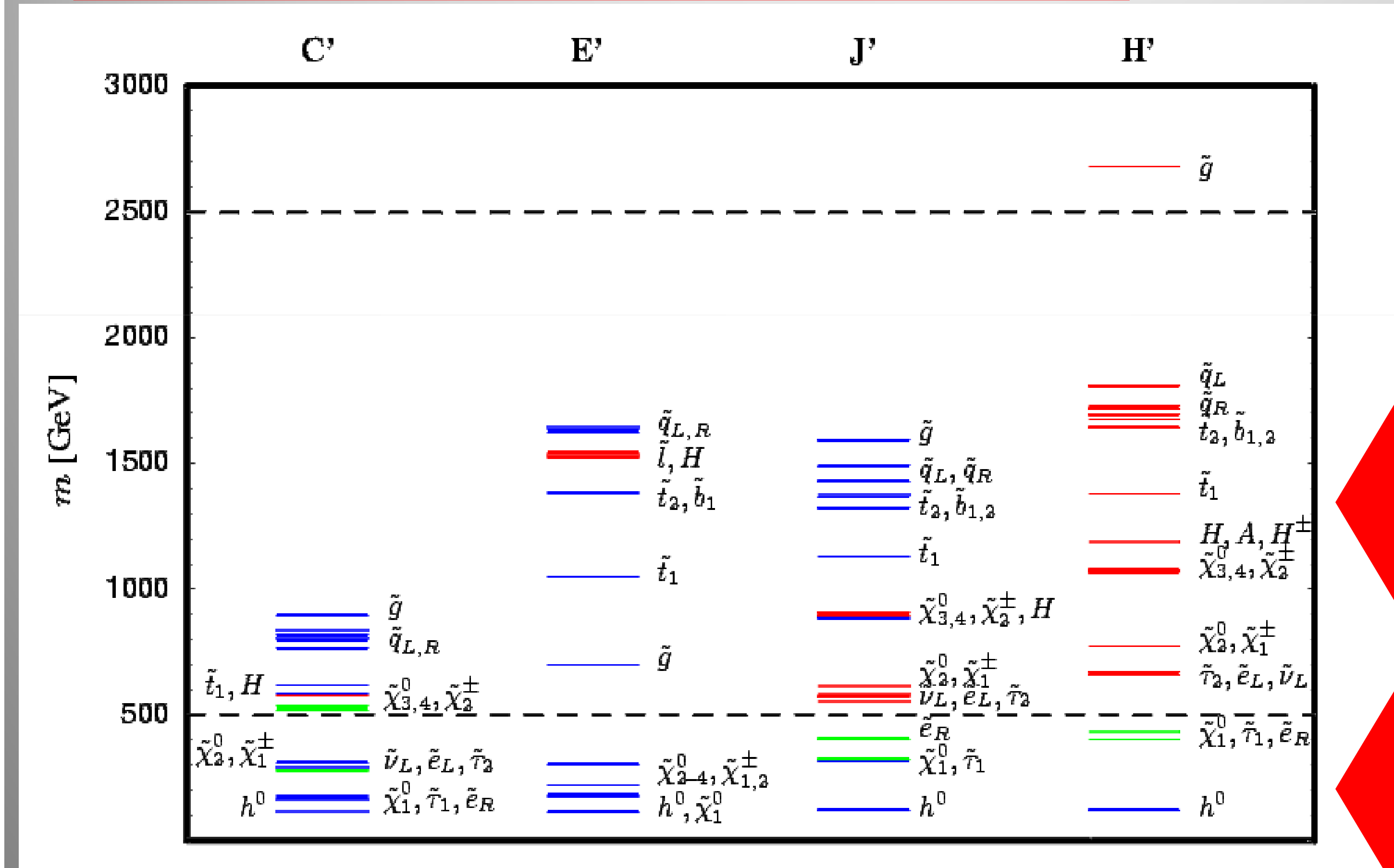
Completing the SUSY spectrum

Masses of Sparticles

Depend on SUSY parameters, SUSY breaking mechanism…

We don't really know…

Examples: Scenarios in Constrained MSSM



Multi-TeV LC

TeV LC

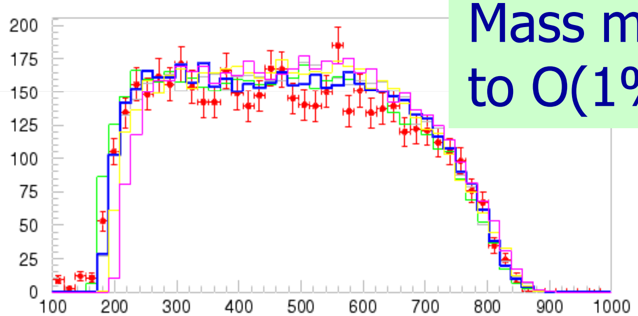
SUSY Mass Measurements (2004)

E.G. $m_{1/2} = 1500$ GeV, $m_0 = 420$ GeV, $\tan\beta = 20$, $A = 0$ GeV, $sign(\mu) > 0$ (mSUGRA) (point H)

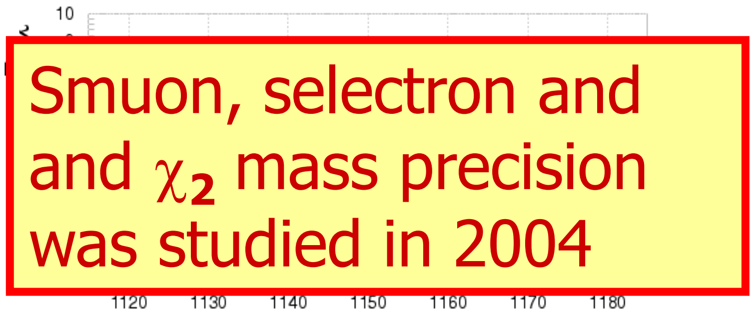
$\Rightarrow M_{\tilde{\mu}} = 1150$ GeV

Measure inclusive muon spectrum in $\tilde{\mu} \to \mu\chi^0$

$$\Rightarrow E_{max/min} = \frac{E_{beam}}{2}\left(1 - \frac{M^2_{\chi^0}}{M^2_{tilde\mu}}\right) \times \left(1 \pm \sqrt{1 - \frac{M^2_{\tilde{\mu}}}{E^2_{beam}}}\right)$$

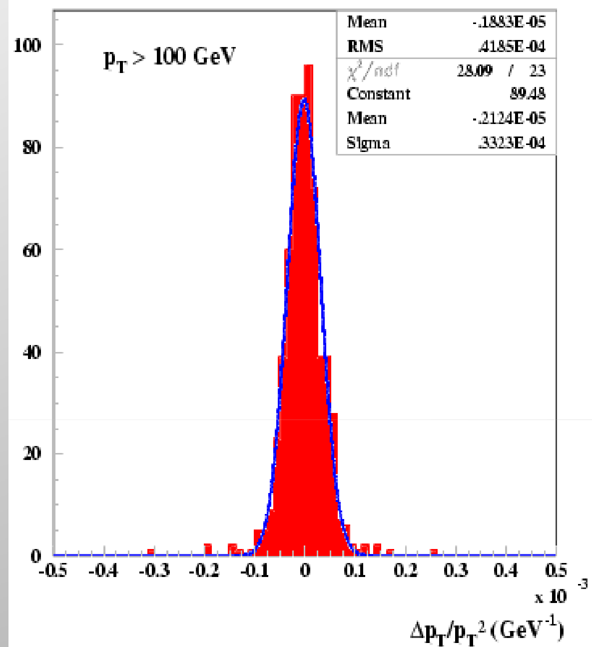


Mass measurements to O(1%)



Smuon, selectron and and χ_2 mass precision was studied in 2004

Momentum resolution



Momentum resolution $\delta p_t/p_t^2 \sim 10^{-4}$ GeV^{-1} adequate for this measurement

Smuon Mass Precision (2004)

Point E: m_μ = ~1500 GeV
Point H: m_μ =~1000 GeV

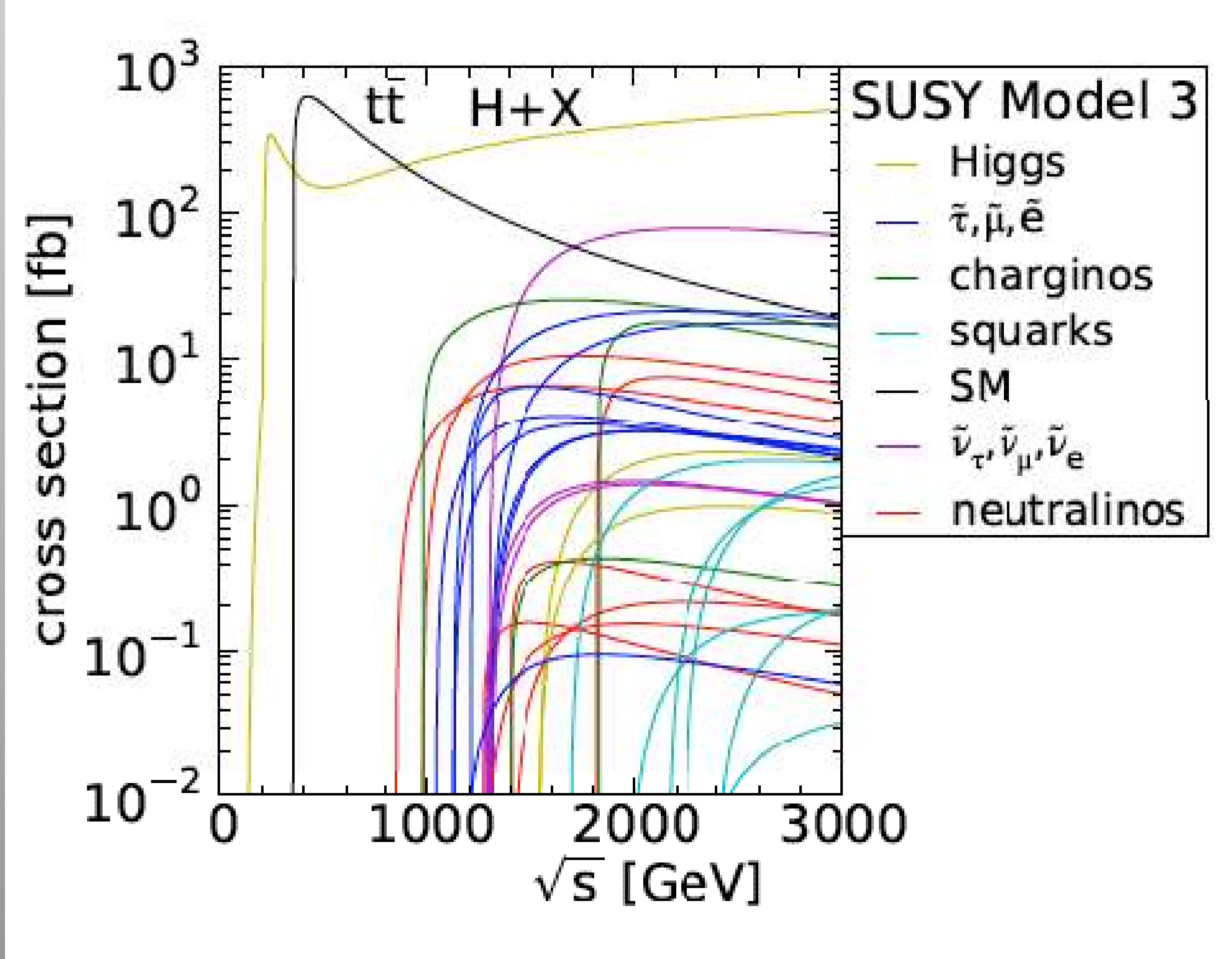
Battaglia et al. benchmarks
hep-ph/0106204

Point		Beam-strahlung	Pol.	$\sqrt{s}$ (TeV)	$\int \mathcal{L}$ (ab^{-1})	δM (GeV)
H	$\tilde{\mu}_L$	none	0/0	3.0-3.5	1	± 11
H	$\tilde{\mu}_L$	Std.	0/0	3.0-3.5	1	± 15
E	$\tilde{\mu}_L$	none	0/0	3.8-4.2	1	± 29
E	$\tilde{\mu}_L$	Std.	0/0	3.8-4.2	1	± 36
E	$\tilde{\mu}_L$	none	80/60	3.8-4.2	1	± 17
E	$\tilde{\mu}_L$	Std.	80/60	3.8-4.2	1	± 22

Mass measurements to O(1%) possible

Example SUSY Spectrum (2012)

Benchmark: Used for studies at CLIC



Warning: LHC is cleaning out these scenarios soon…

SUSY Benchmark Studies

Full detector simulation with 2 ab^{-1} each point

Particle	Mass	Stat. acc.
$\tilde{\chi}_1^0$	340.3	± 3.3
$\tilde{\chi}_2^0$	643.1	± 9.9
$\tilde{\chi}_3^0$	905.5	$\pm 19.0^*$
$\tilde{\chi}_4^0$	916.7	$\pm 20.0^*$
$\tilde{\chi}_1^\pm$	643.2	± 3.7
$\tilde{\chi}_2^\pm$	916.7	$\pm 7.0^*$
$\tilde{e}_R^\pm$	1010.8	± 2.8
$\tilde{\mu}_R^\pm$	1010.8	± 5.6
$\tilde{\nu}_1$	1097.2	± 3.9

Particle	Mass	Stat. acc.
h	118.5	$\pm 0.1^*$
A^0	742.0	± 1.7
H^0	742.0	± 1.7
$H^\pm$	747.6	± 2.1

Quantity	Value	Stat. acc.
$\Gamma(A^0)$	22.2	± 3.8
$\Gamma(H^\pm)$	21.4	± 4.9

Particle	Mass
$\tilde{\tau}_1$	670
$\tilde{\tau}_2$	974
$\tilde{t}_1$	1393
$\tilde{t}_2$	1598
$\tilde{b}_1$	1544
$\tilde{b}_2$	1610
$\tilde{u}_R$	1818
$\tilde{u}_L$	1870
$\tilde{g}$	1812

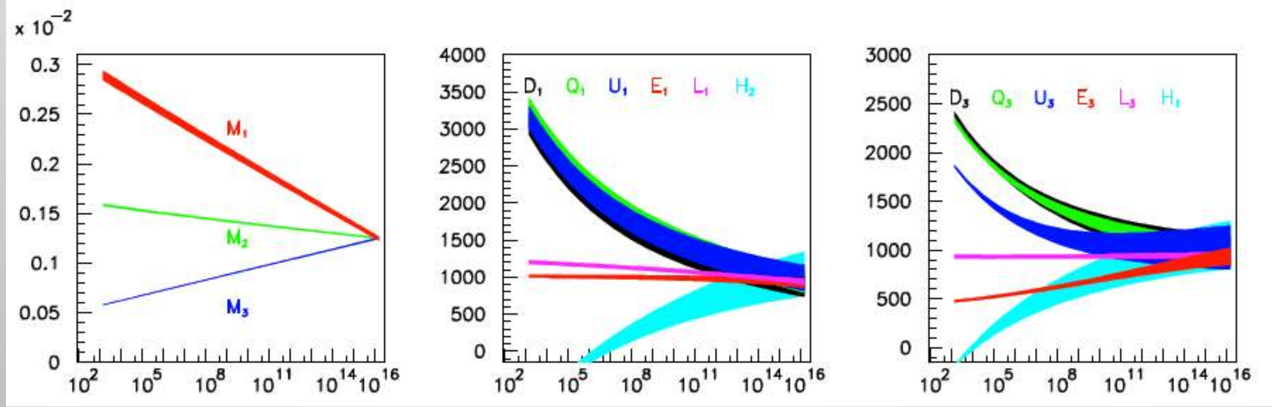
Fitted parameters for the chargino-neutralino sector

M_1	342.1 ± 4.1	-341.9 ± 4.1	341.9 ± 4.1	-342.2 ± 1.0
M_2	655.3 ± 6.5	655.3 ± 6.5	654.2 ± 6.5	654.2 ± 6.5
μ	924.8 ± 6.2	924.8 ± 6.2	-925.5 ± 6.2	-925.5 ± 6.2

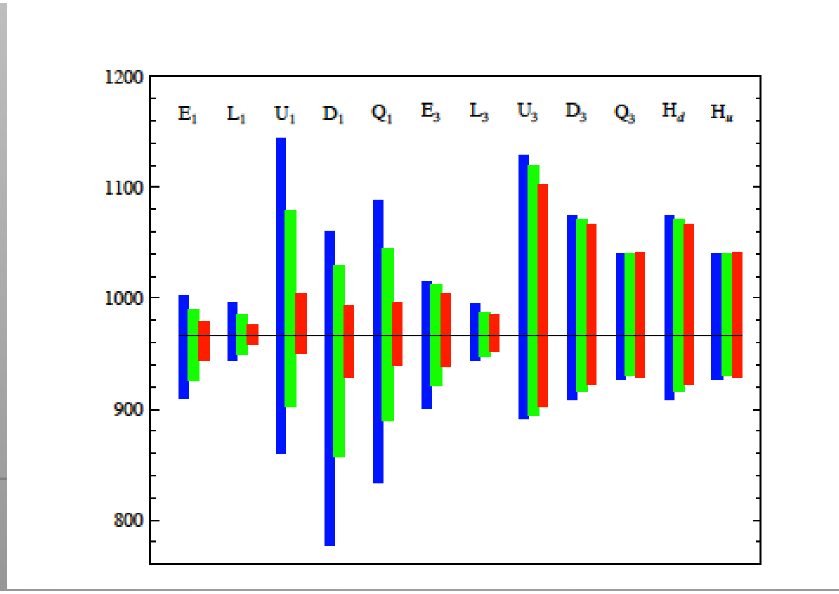
Four-fold sign ambiguity
Needs polarization

Supersymmetry: Precision

Extrapolation of the SUSY breaking parameters to the GUT scale

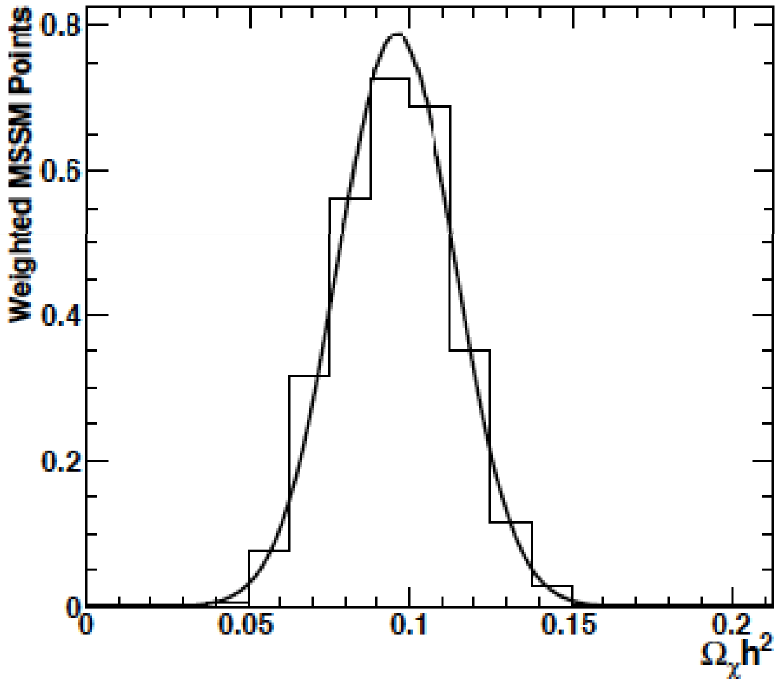


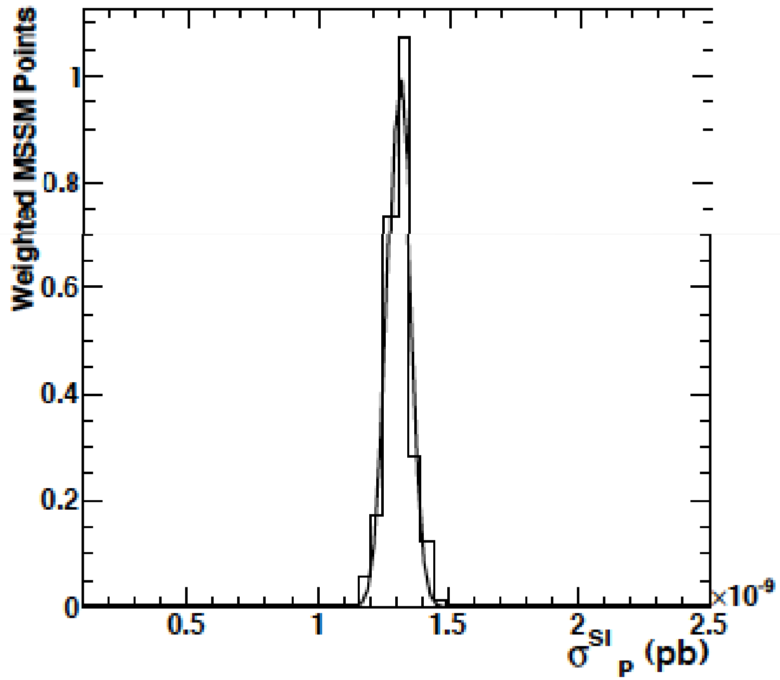
1σ uncertainties on the mass parameters on the GUT scale for different sfermion mass precision assumption (5%, 3% and 1%)



Dark Matter Connection

Reconstructed relic density and predicted dark matter cross section from the measurements of the sparticles





~20% precision
(for this benchmark point)

~5% precision
(for this benchmark point)

Different Scenarios

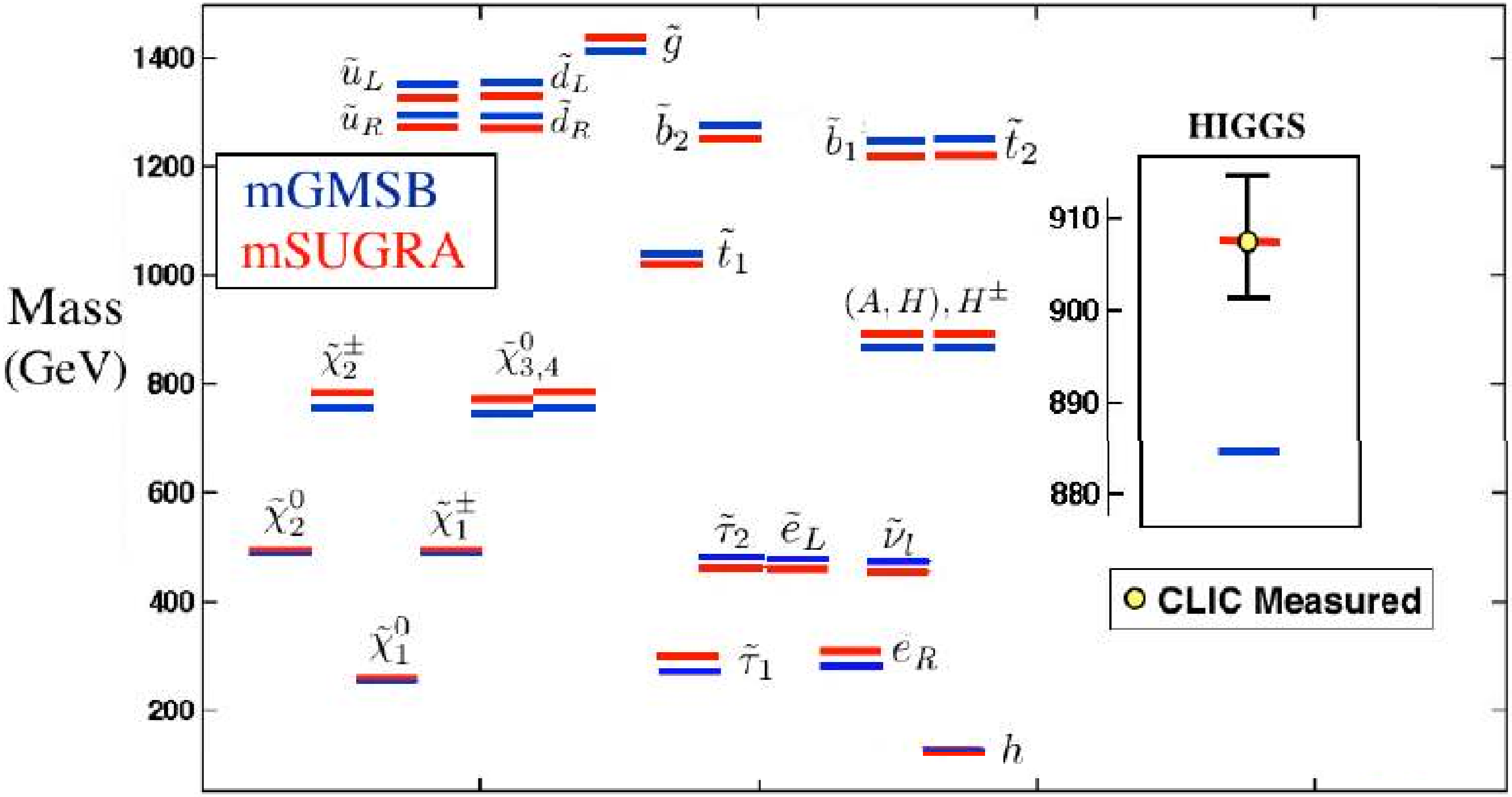
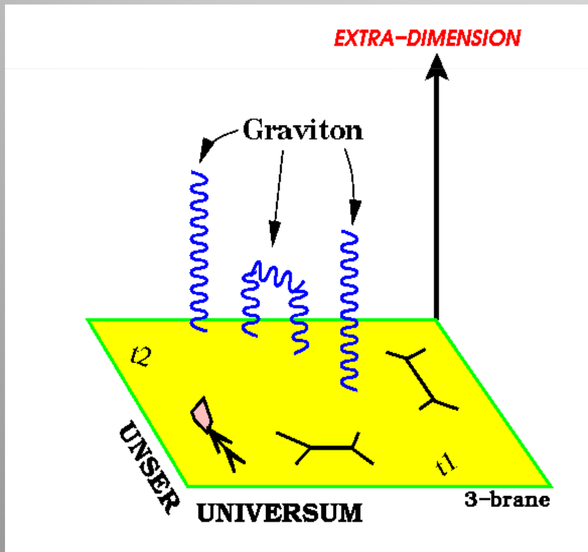


Fig. 1.19: Resolving SUSY breaking models and masses with CLIC: Shown are the nearly degenerate spectra of a mSUGRA model and a mGMSB model. Assuming some of the SUSY particles masses are measured, with a spectrum of the type above predicted by the different models of Supersymmetry breaking, CLIC would be able to discern not only some of the slepton masses and the heavier charginos within the two models, but also the SUSY Higgs masses. For mSUGRA the soft masses are $m_0 =$ 175 GeV, $m_{1/2} = 645$ GeV, $A_0 = 0$, with $\tan\beta = 10$ and $\mu > 0$. For mGMSB the number of messengers are $n_l = n_q = 5$, and $\Lambda_{SUSY} = 4 \cdot 10^4$ GeV, $M_{Mess} = 10^{12}$ GeV, with $\tan\beta = 10$.

4. Large Extra Dimensions

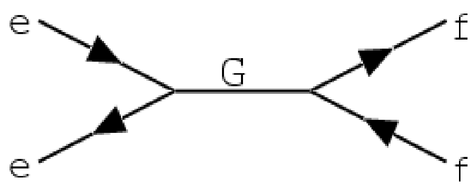


Move the Planck scale closer to the EW scale, eg. in the TeV region (ADD)

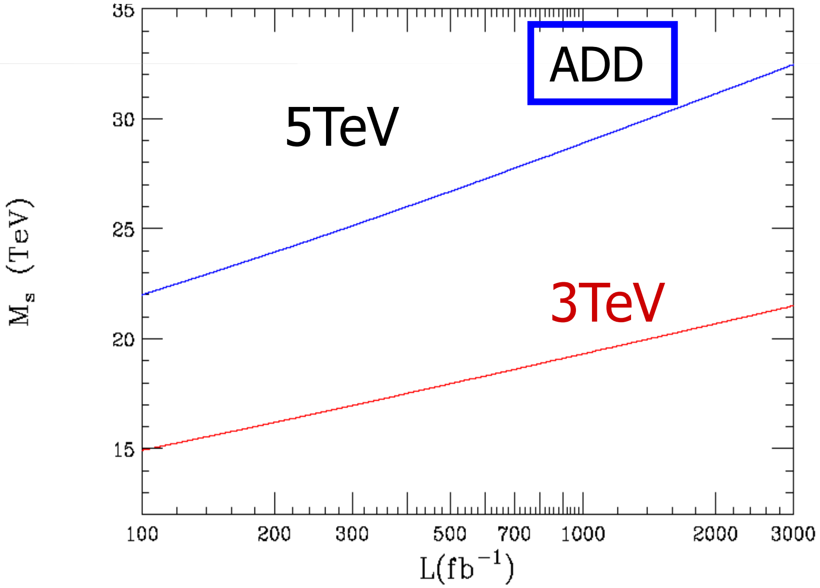
Extra Dimension Reach

Example: Deviations from SM due to virtual Kaluza Klein Graviton effects

2004 Study



Discovery reach (T. Rizzo)



Benakli, Antoniadis, Accomando

Scale of extra longitudinal dimension

TeV scale EDs

Collider	$\mathcal{L}$ (fb^{-1})	Gluon	$W^{\pm}$	$\gamma + Z$
LC500	1000	-	-	15
LC1000	1000	-	-	22
LC3000	1000	-	-	42
LHC	10	15	8.2	6.7
LHC	100	20	14	12

Scales in TeV

T. Han, T. Rizzo et al. (Moriond '00/debated...)

Collider	$\mathcal{L}$ (fb^{-1})	Reaction	Limit
LC	100	$e^+e^- \to f\bar{f}$	$6.5\sqrt{s}$
$\gamma\gamma$ Collider	100	$\gamma\gamma \to WW$	$11\sqrt{s}$
LHC	100	$p\bar{p} \to t\bar{t}$	6.0

KK Towers

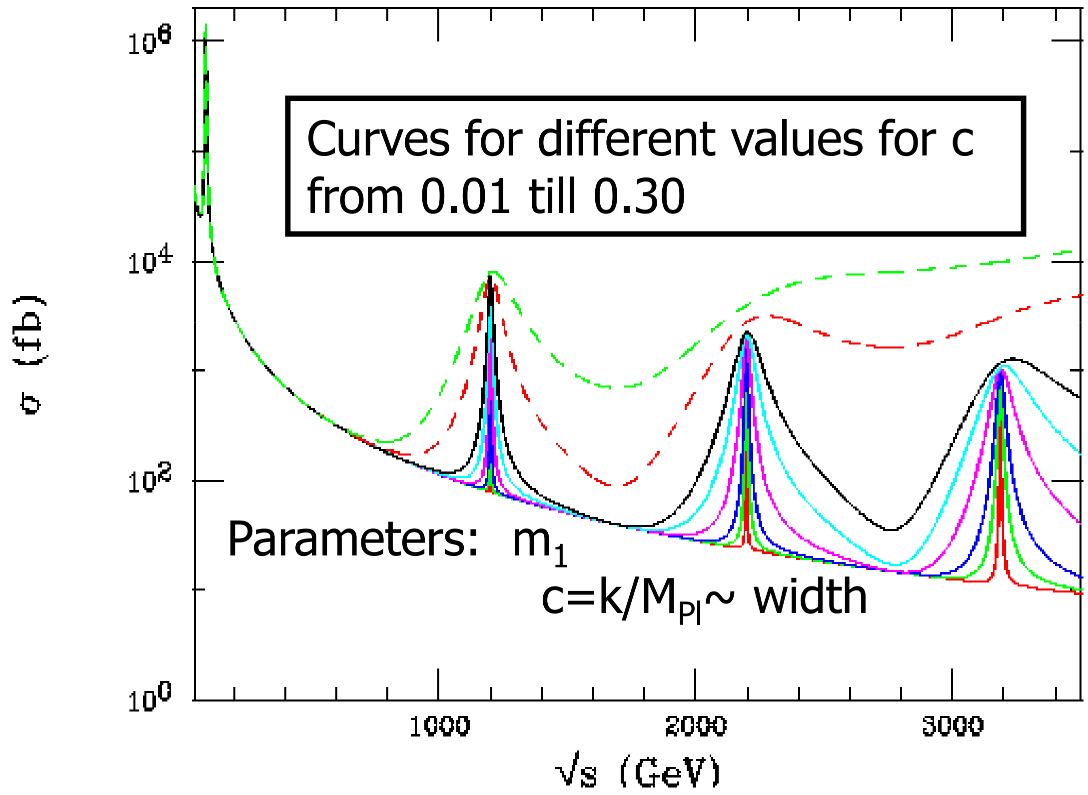
Extra Dimensions Randall-Sundrum phenomenology (curves by T. Rizzo)

SM fields on brane
and graviton in bulk

Observe KK resonances
in e.g. e+e- $\rightarrow \mu\mu$
cross sections

LC is like a KK
factory

Allows to measure
properties of KKs
(spin, BRs…)



But would need to see these at the LHC first!!

Can determine parameters c up to 0.2%, M to O(0.1%)

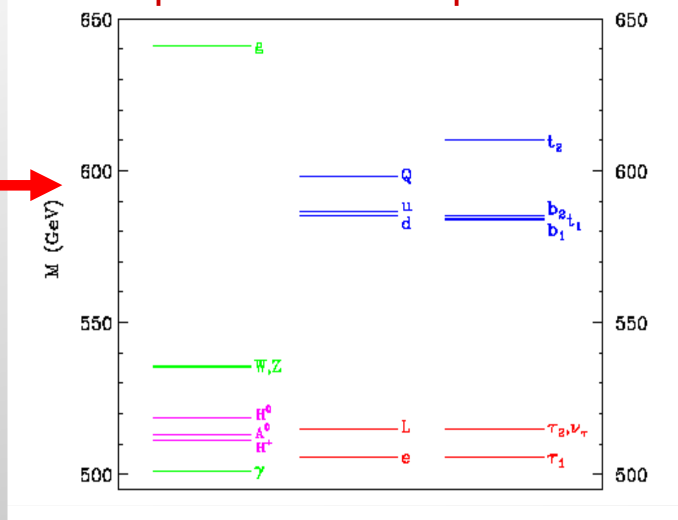
Universal Extra Dimensions UED

- All particles can go into the bulk
  KK-partners for all particles!
- Resulting spectrum looks very similar to a SUSY spectrum (there are subtle differences)

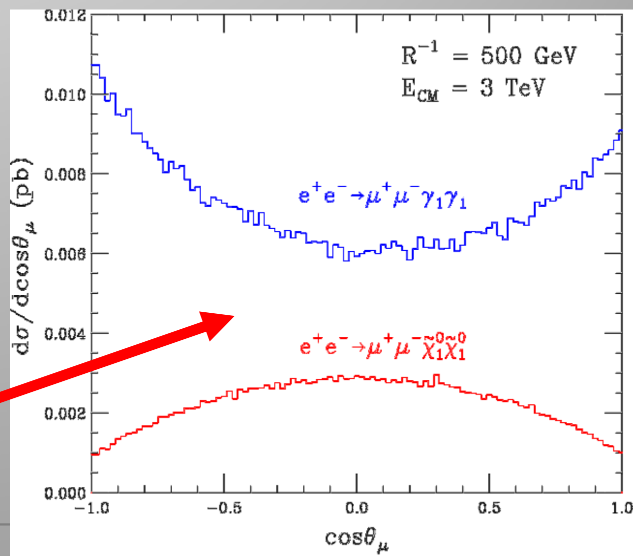
  ⇒ Did we discover SUSY or UEDs?
- Important difference: spin of the KK same as SM partner, while it differs by ½ from SUSY sparticles → measure spin
- Not easy at the LHC but doable at a LC
- Compare SUSY/UED for 500 GeV (s)muons

$$e^+e^- \rightarrow \mu_1^+\mu_1^- \quad \Leftrightarrow \quad e^+e^- \rightarrow \tilde{\mu}^+\tilde{\mu}^-$$

KK partners mass spectrum

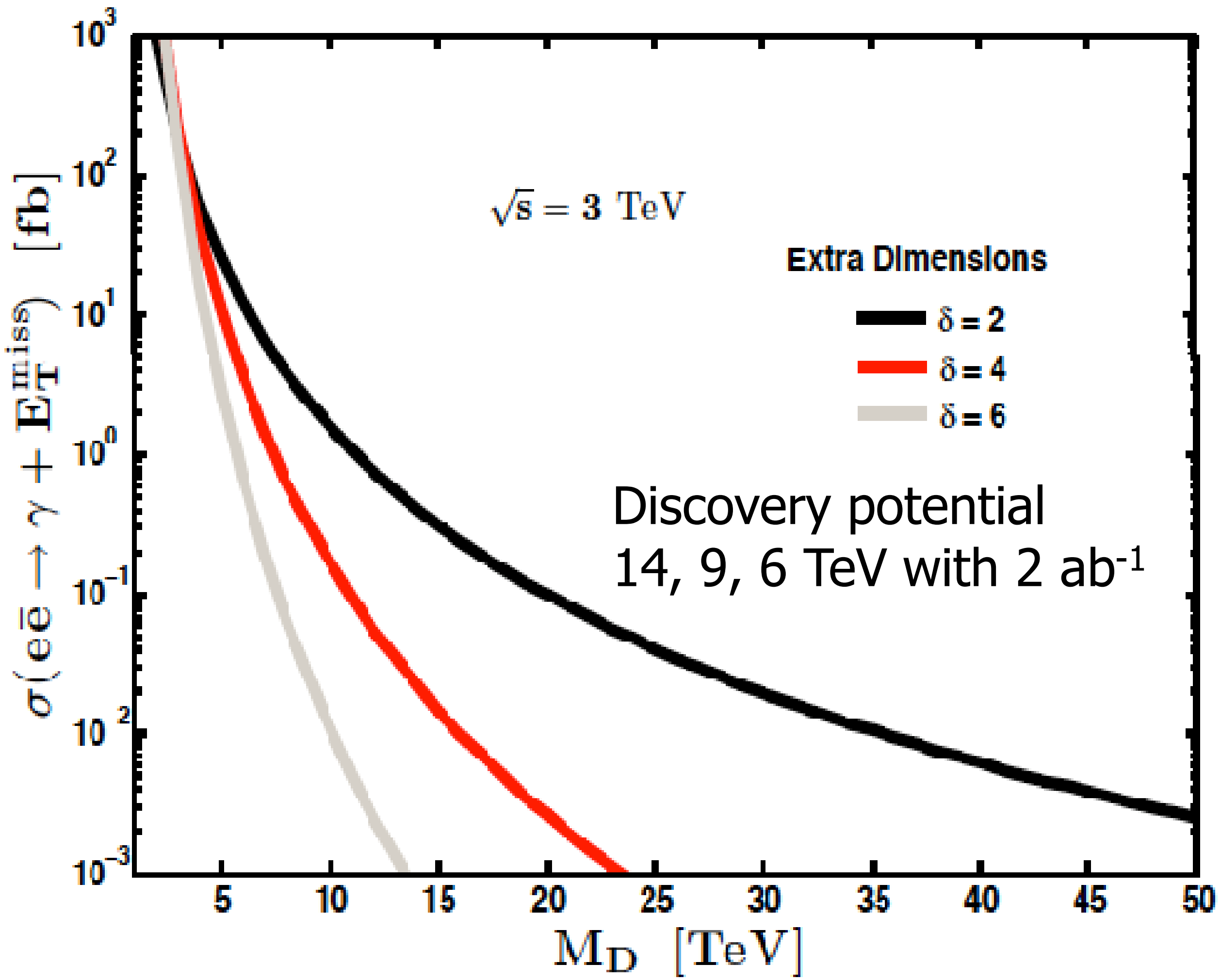


Production polar angle θ of the decay muons



Extra Dimensions

Cross sections for the e+e- -> photon + MET channel

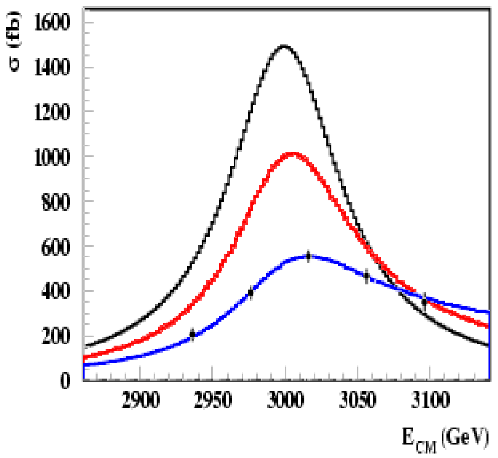


Discovery potential
14, 9, 6 TeV with 2 ab^{-1}

ADD type of EDs

5. New Gauge Theories Contact Interactions etc.

Assume $M_{Z'} = 3.0$ TeV and
$\Gamma(Z')/M_{Z'} \simeq \Gamma(Z^0)/M_{Z^0}$



$\Rightarrow$ FIT ACCURACY ($1\,\mathrm{AB}^{-1}$)
$\delta M'_Z/M'_Z \sim 10^{-4}$; $\delta\Gamma'_Z/\Gamma'_Z \sim 3 \cdot 10^{-3}$

- New Z′ resonances in the TeV range
- WW scattering at high energy
- Little Higgs models
- Triple Gauge couplings
- Contact interactions
- Excited lepton production
- non-commutative interactions
- Transplanckian effects
- Lepton size measurements

Some of these being ruled out by the LHC

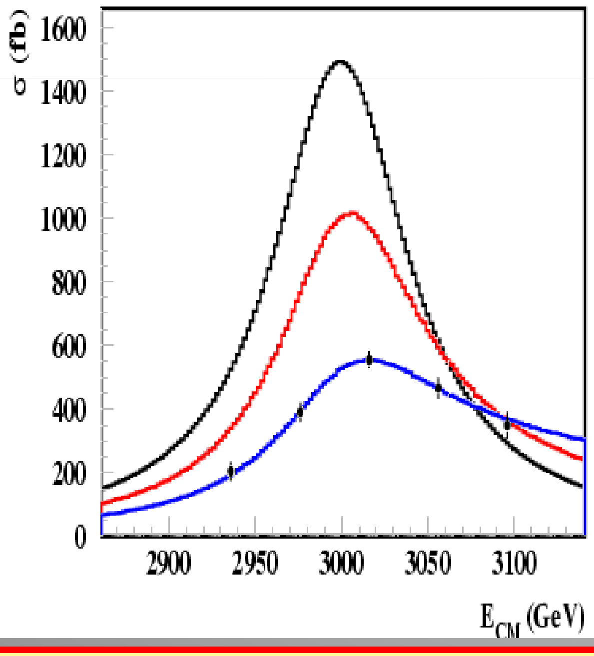
Resonance Production

✦ $\sqrt{s}$ Scan (Z^0-like Lineshape Scan) $e^+e^- \to Z' \to f\bar{f}$

✦ Assume $M_{Z'} = 3.0$ TeV and $\Gamma(Z')/M_{Z'} \simeq \Gamma(Z^0)/M_{Z^0}$ (Γ_{SM});

✦ Compute $\sigma(e^+e^- \to Z')$ vs. $\sqrt{s}$ including ISR and beamstrahlung for a range of mass and $\Gamma(Z')/\Gamma_{SM}$ values;

✦ Assume $\int L = 1000$ fb^{-1} (CLIC.01) or 400 fb^{-1} (CLIC.02) shared in 3-7 points scan and extract $M_{Z'}$, $\Gamma(Z')/\Gamma_{SM}$ and σ_{peak} from χ^2 fit:

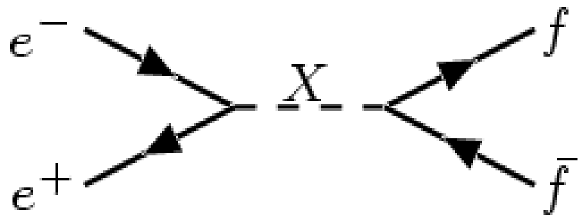


FIT ACCURACY — Calibrated

Observable	Breit Wigner	CLIC.01	CLIC.02
$M_{Z'}$ (GeV)	$3000 \pm .12$	$\pm .15$	$\pm .21$
$\Gamma(Z')/\Gamma_{SM}$	$1. \pm .001$	$\pm .003$	$\pm .004$
σ_{peak}^{eff} (fb)	1493 ± 2.0	564 ± 1.7	669 ± 2.9

Absolute energy calibration ~10^{-3}, Relative energy calibration ~10^{-4}

Precision Measurements



Measure $\sigma_{b\bar{b}}$, $A_{FB}^{\mu^+\mu^-}$ and $A_{FB}^{b\bar{b}}$

Examples: $\frac{\delta\sigma_{b\bar{b}}}{\sigma_{b\bar{b}}} = 0.012/\ 1\ \text{ab}^{-1}$

$$\frac{\delta A_{FB}^{\mu^+\mu^-}}{A_{FB}^{\mu^+\mu^-}} = 0.018/\ 1\ \text{ab}^{-1}$$

Observable	Relative Stat. Accuracy $\delta\mathcal{O}/\mathcal{O}$ for 1 ab^{-1}
$\sigma_{\mu^+\mu^-}$	± 0.010
$\sigma_{b\bar{b}}$	± 0.012
$\sigma_{t\bar{t}}$	± 0.014
$A_{FB}^{\mu\mu}$	± 0.018
A_{FB}^{bb}	± 0.055
A_{FB}^{tt}	± 0.040

Contact Interactions

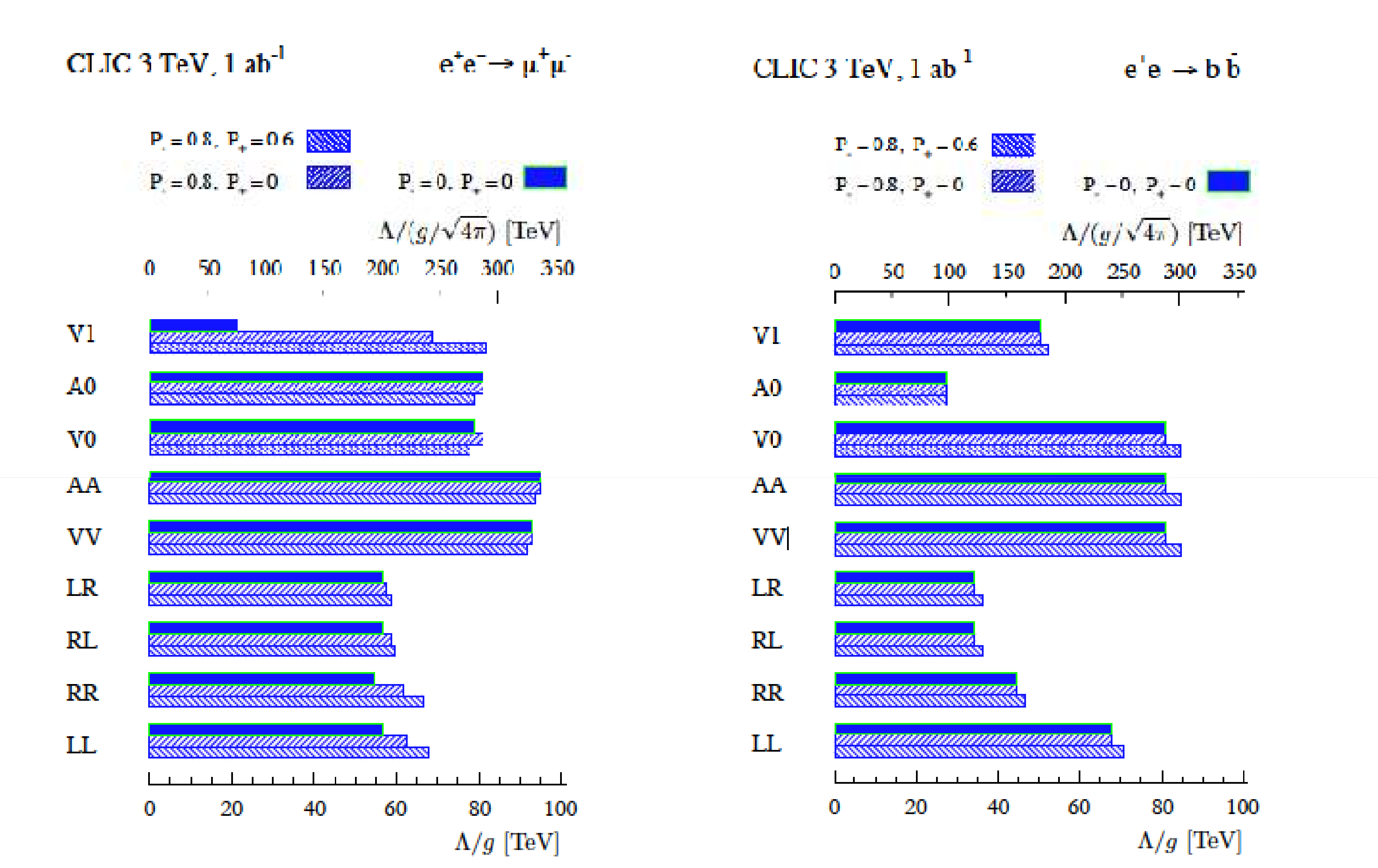
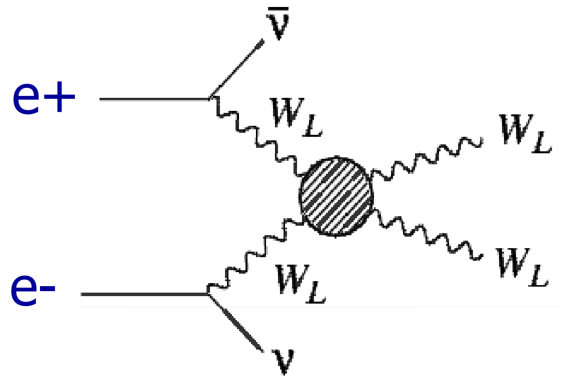
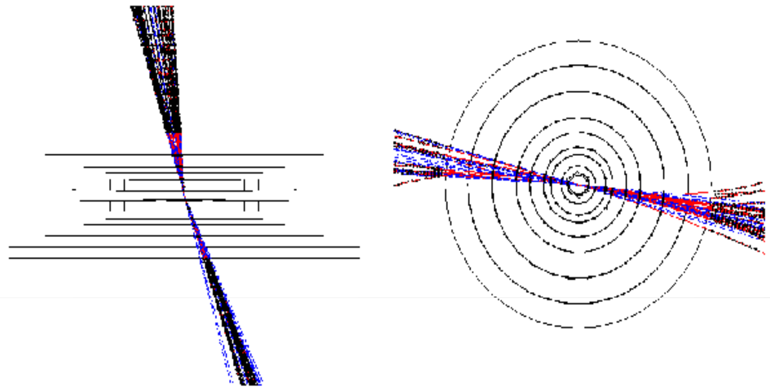


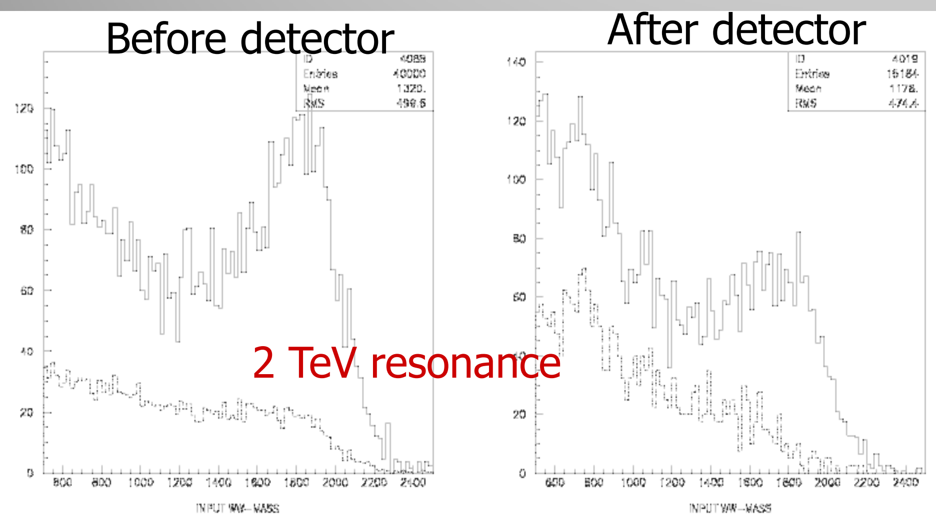
Fig. 1.14: Limits on the scale of contact interactions (Λ/g) that can be set by CLIC in the $\mu^+\mu^-$ (left) and $b\bar{b}$ (right) channels with $\sqrt{s} = 3$ TeV and $\mathscr{L} = 1$ ab^{-1}. A degree of polarisation $P_- = 0, 0.8$ ($P_+ = 0, 0.6$) has been assumed for the electrons (positrons). The various models are defined in Table 6.6 of [20], except the model V1 which is defined as $\{\eta_{LL} = \pm, \eta_{RR} = \mp, \eta_{LR} = 0, \eta_{RL} = 0\}$.

WW Scattering

In case that there is no Higgs:
WW scattering will show effects of strong dynamics in the TeV region
⇒ Study WW→WW scattering







Resonances can form in the TeV range that can be observed directly
These measurements are difficult at the LHC.

Summary Table

Taken from ESG document but based on Ellis, Ganotti & ADR 2001

Particle / parameter	Collider: $\mathscr{L}$:	LHC14 100 fb^{-1}	SLHC 1 ab^{-1}	LC800 500 fb^{-1}	CLIC3 1 ab^{-1}
Squarks [TeV]		2.5	3	0.4	1.5
Sleptons [TeV]		0.3	-	0.4	1.5
Z' (SM couplings) [TeV]		5	7	8	20
2 extra dims M_D [TeV]		9	12	5-8.5	20-30
TGC (95%) (λ_γ coupling)		0.001	0.0006	0.0004	0.0001
μ contact scale [TeV]		15	-	20	60
Higgs compos. scale [TeV]		5-7	9-12	45	60

CLIC Timescale Projection

2012-16 Development Phase

Develop a Project Plan for a staged implementation in agreement with LHC findings; further technical developments with industry, performance studies for accelerator parts and systems, as well as for detectors.

2017-22 Preparation Phase

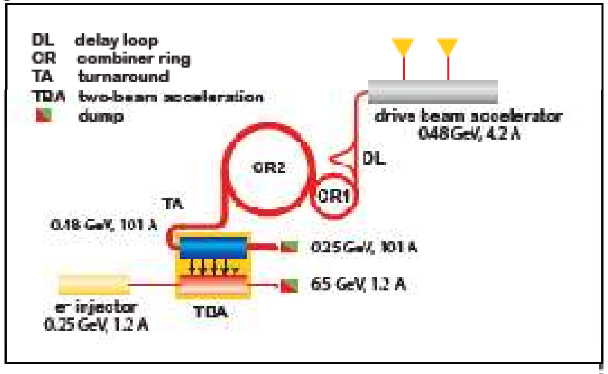
Finalise implementation parameters, Drive Beam Facility and other system verifications, site authorisation and preparation for industrial procurement.

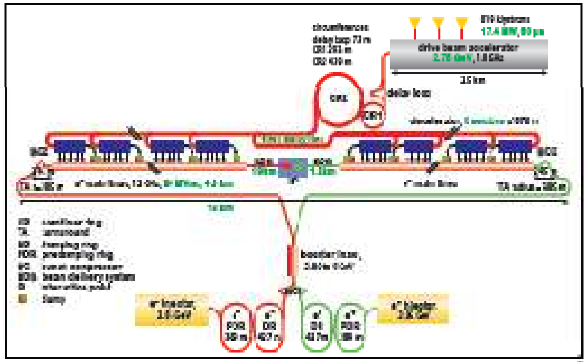
Prepare detailed Technical Proposals for the detector-systems.

2023-2030 Construction Phase

Stage 1 construction of a 500 GeV CLIC, in parallel with detector construction.

Preparation for implementation of further stages.





2016-17 Decisions

On the basis of LHC data and Project Plans (for CLIC and other potential projects), take decisions about next project(s) at the Energy Frontier.

2022-23 Construction Start

Ready for full construction and main tunnel excavation.

2030 Commissioning

From 2030, becoming ready for data-taking as the LHC programme reaches completion.

Finally: Price Estimate

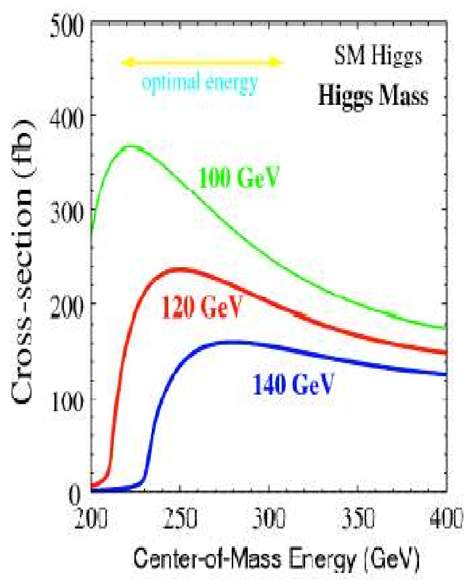
Table 4: Value and labour estimates of CLIC 500 GeV.

Staging scenario	Value [MCHF]	Labour [FTE years]
A	8300^{+1900}_{-1400}	15700
B	7400^{+1700}_{-1300}	14100

Will need very broad consensus in the field for such a project…

LEP3: a Circular e+e- Collider?

LEP3?



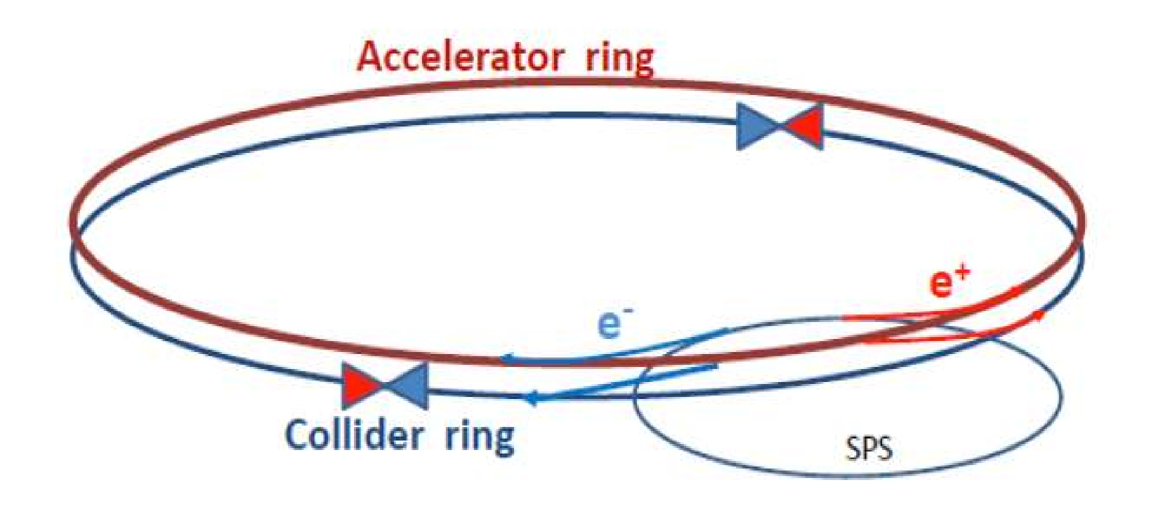
What if the Higgs is 120-125 GeV?
Do we need a Linear Collider for a Higgs factory?

A. Blondel and F. Zimmerman: LEP3? arXiv:1112.2518v1
Proposal: Reinstall an e+e- collider in the LHC tunnel
With LC RF to make up for the energy loss of 7 GeV for a 120 GeV/beam

Note: beam lifetime ~ 15-30 minutes. Needs top-up ring

RF power Max 100MW

Gain lumi by having 2 or 4 experiments on the ring



ESG contributions this week

Prospective Studies for LEP3
with the CMS Detector

submitted to the European Strategy Preparatory Group

Patrizia Azzi[3], Colin Bernet[1], Cristina Botta[1], Patrick Janot[1], [0]
Markus Klute[2], Piergiulio Lenzi[1], Luca Malgeri[1], and Marco Zanetti[2]

[1] CERN, Geneva
[2] Massachusetts Institute of Technology
[3] INFN, Sezione di Padova

Initial Studies

CERN-ATS-NOTE-2012-062 TECH

**LEP3: A HIGH LUMINOSITY E+E- COLLIDER
TO STUDY THE HIGGS BOSON**

Submitted to the European Strategy Preparatory Group

A. Blondel, U. Geneva, Switzerland;

M. Koratzinos, Geneva, Switzerland;

R. W. Assmann, A. Butterworth, P. Janot, J. M. Jimenez, C. Grojean, A. Milanese, M. Modena, J.A. Osborne, F. Zimmermann, CERN, Geneva, Switzerland;

H. Piekarz, FNAL, U.S.A.; K. Oide, K. Yokoya, KEK Japan;

J. Ellis, King's College London and CERN, Geneva, Switzerland;

M. Klute, M. Zanetti, MIT, Cambridge, Massachusetts, USA;

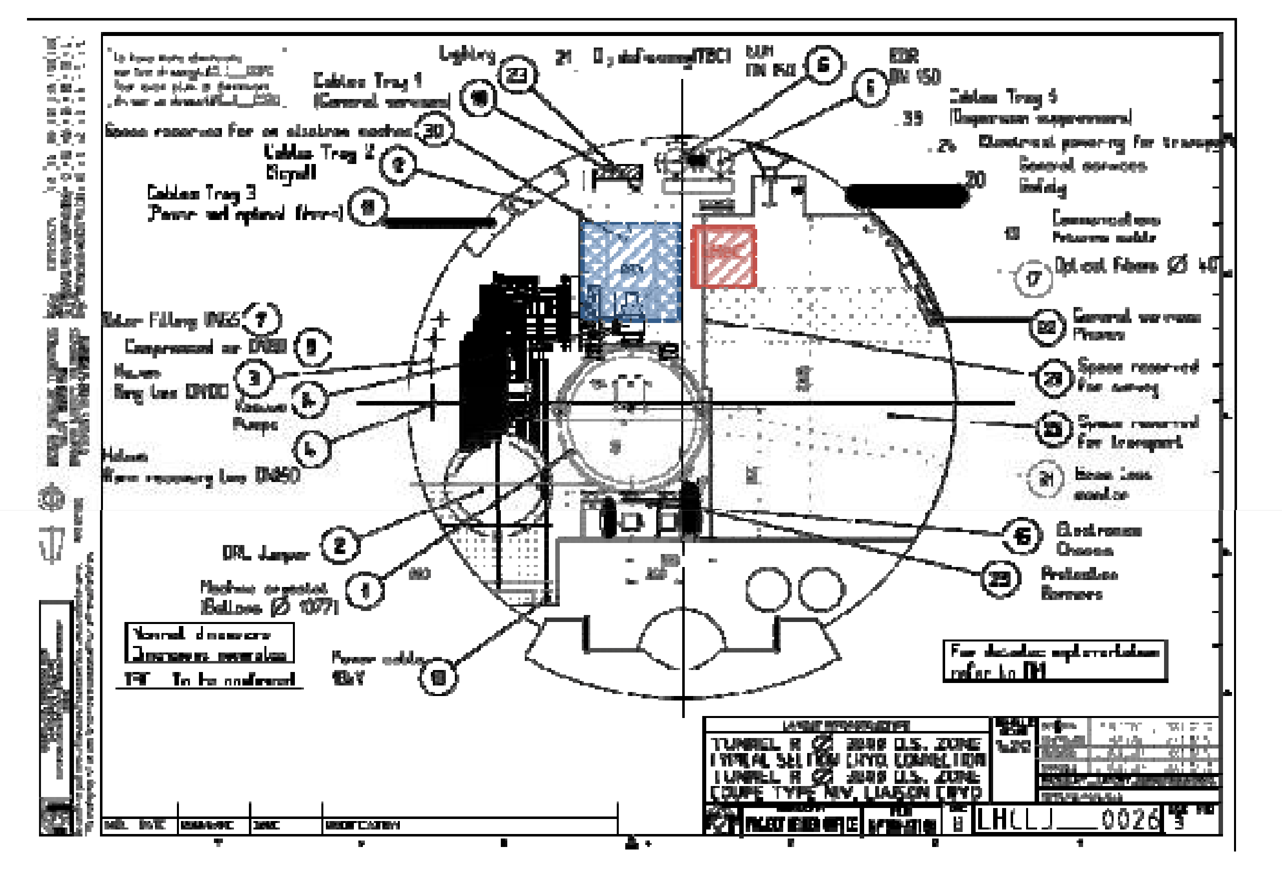
M. Velasco, Northwestern U., U.S.A.;

V. Telnov, Budker INP, Novosibirsk, Russia;

L. Rivkin, PSI, Villigen, Switzerland;

Y. Cai, SLAC National Accelerator Laboratory, Stanford, U.S.A.

LEP3 in the LHC Tunnel?

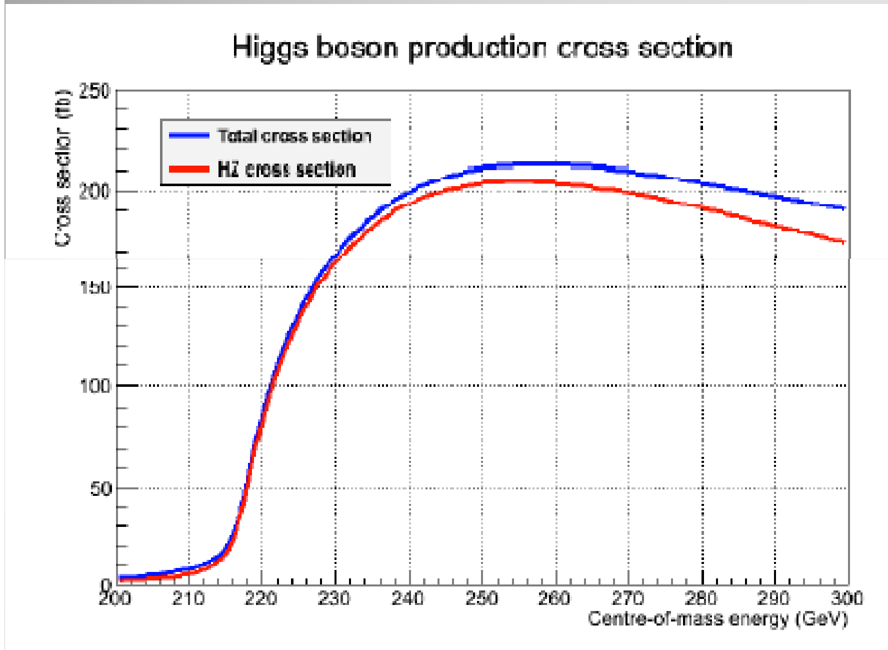


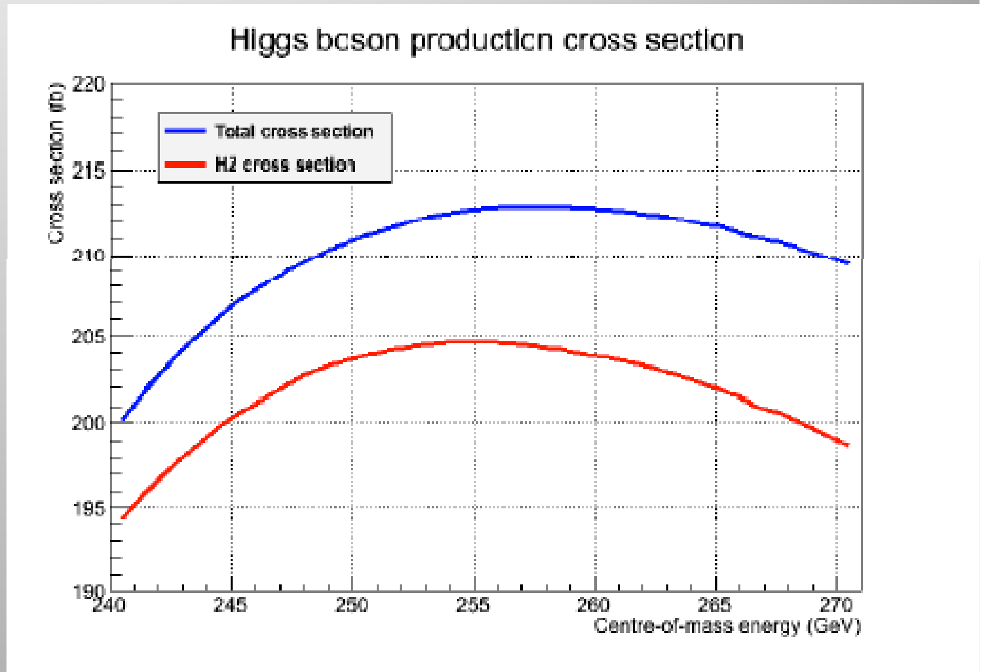
There are other ideas: 53 km tunnel, 80 km tunnel, SSC tunnel….?

Timeline for LEP3: 5-7 years preparation. Decision around 2018?
Installation? LEP was installed in 18 months but this is more complicated
Cost? Likely much cheaper that other Higgs machine proposals…

Beam Energy

For LHC/LEP tunnel: 120 GeV/beam





This is within 6% of the cross section maximum

LEP3 Parameters

	LEP2	LHeC	LEP3	DLEP	TLEP
beam energy E_b [GeV]	104.5	60	120	120	175
circumference [km]	26.7	26.7	26.7	53.4	80
beam current [mA]	4	100	7.2	14.4	5.4
#bunches/beam	4	2808	4	60	12
#e^-/beam [10^{12}]	2.3	56	4.0	16.0	9.0
horiz. emit. [nm]	48	5	25	10	20
vert. emit. [nm]	0.25	2.5	0.10	0.05	0.1
bending radius [km]	3.1	2.6	2.6	5.2	9.0
partition number J_ϵ	1.1	1.5	1.5	1.5	1.0
momentum compaction α_c [10^{-5}]	18.5	8.1	8.1	2.0	1.0
SR power/beam [MW]	11	44	50	50	50
β^*_x [m]	1.5	0.18	0.2	0.2	0.2
β^*_y [cm]	5	10	0.1	0.1	0.1
σ^*_x [μm]	270	30	71	45	63
σ^*_y [μm]	3.5	16	0.32	0.22	0.32
hourglass F_{hg}	0.98	0.99	0.67	0.75	0.65
E^{SR}_{loss}/turn [GeV]	3.41	0.44	6.99	3.5	9.3
V_{RF},tot [GV]	3.64	0.5	12.0	4.6	12.0
$\delta_{max,RF}$ [%]	0.77	0.66	4.2	5.0	4.9
ξ_x/IP	0.025	N/A	0.09	0.05	0.05
ξ_y/IP	0.065	N/A	0.08	0.05	0.05
f_s [kHz]	1.6	0.65	3.91	0.91	0.43
E_{acc} [MV/m]	7.5	11.9	20	18	20
eff. RF length [m]	485	42	606	376	600
f_{RF} [MHz]	352	721	1300	1300	700
δ^{SR}_{rms} [%]	0.22	0.12	0.23	0.16	0.22
$\sigma^{SR}_{z,rms}$ [cm]	1.61	0.69	0.23	0.17	0.25
L/IP[10^{32}cm^{-2}s^{-1}]	1.25	N/A	107	142	65
number of IPs	4	1	2	2	2
beam lifetime [min]	360	N/A	16	22	54
Υ_{BS} [10^{-4}]	0.2	0.05	10	8	15
n_γ/collision	0.08	0.16	0.60	0.25	0.51
ΔE^{BS}/col. [MeV]	0.1	0.02	33	12	61
ΔE^{BS}_{rms}/col. [MeV]	0.3	0.07	48	26	95

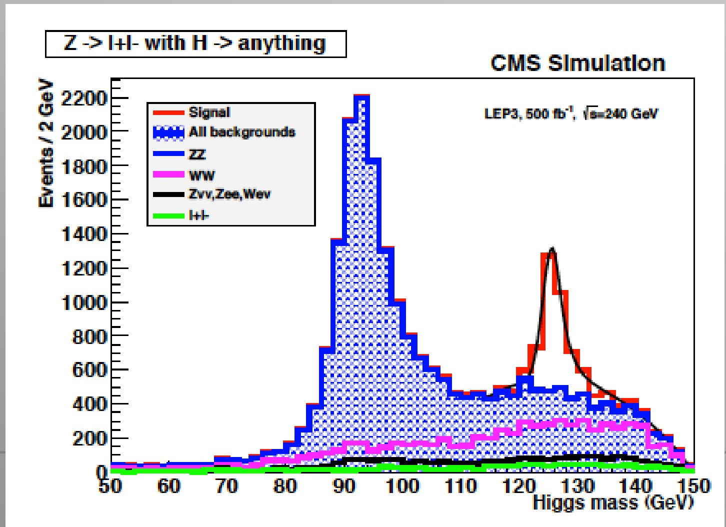
Number of Higgs events

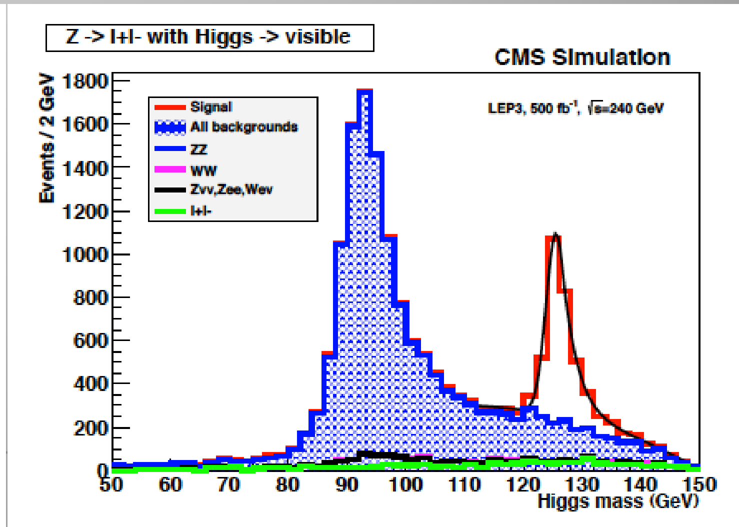
500 fb^{-1}

Total over a period of 5 years

Signal	BR (%)	Events	Background	σ (pb)	Events	Rate (Hz)
$H \to b\bar{b}$	57.9	57,870	$e^+e^- \to Z^*/\gamma^* \to q\bar{q}$	50	25,000,000	0.50
$H \to W^+W^-$	21.6	21,630	$e^+e^- \to Z^*/\gamma^* \to \ell^+\ell^-$	12.5	6,250,000	0.12
$H \to gg$	8.19	8,200	$e^+e^- \to W^+W^-$	16	8,000,000	0.16
$H \to \tau^+\tau^-$	6.40	6,400	$e^+e^- \to ZZ$	1.3	650,000	0.01
$H \to c\bar{c}$	2.83	2,820	$e^+e^- \to We\nu$	1.35	700,000	0.01
$H \to ZZ$	2.62	2,620	$e^+e^- \to Ze^+e^-$	3.8	1,900,000	0.04
$H \to \gamma\gamma$	0.27	266	$e^+e^- \to Z\nu\bar{\nu}$	0.032	16,000	–
$H \to Z\gamma$	0.16	160	$e^+e^- \to e^+e^-$ (Bhabha)	5,000	$2.5\,10^9$	50
$H \to \mu^+\mu^-$	0.02	22	$\gamma\gamma \to \ell^+\ell^-, q\bar{q}$	15,000	$7.5\,10^9$	150

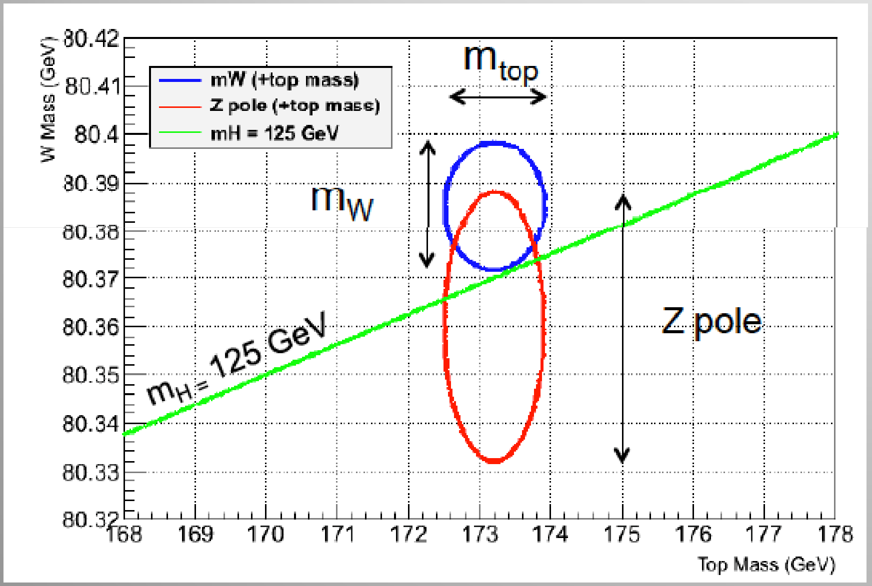
(Re)-using the CMS detector

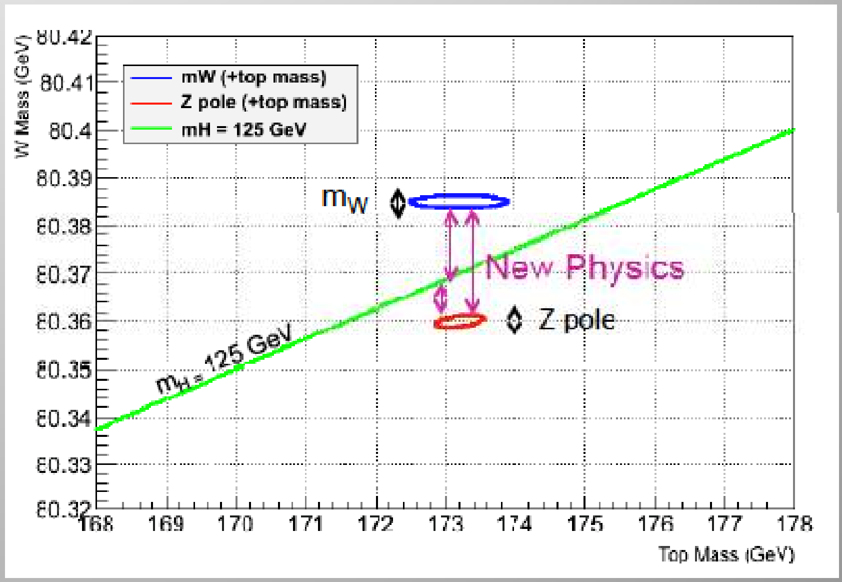




Precision Measurements

Tera-Z factory! With ~5.10^{35} cm^{-2}s^{-1} one can collect 10^{12} Zs
Mega-W factory! With 10^{35} cm^{-2}s^{-1} one can collect a few times 10^{6} Ws





Mass of W to O(1) MeV; EWK variables improved by factor 25-100 @ Z-pole

Precise W and Z measurements. Do the whole LEP program in 10 minutes!

Comparison of Facilities

From the ESG note: slightly provocative…

	ILC	LEP3 (2)	LEP3 (4)	LHC
σ_{HZ}	3%	2.7%	1.9%	–
$\sigma_{HZ} \times BR(H \to b\bar{b})$	1%	1.2%	0.8%	–
$\sigma_{HZ} \times BR(H \to \tau^+\tau^-)$	6%	3.1%	2.2%	–
$\sigma_{HZ} \times BR(H \to \text{invisible})$	?	1%	0.7%	–
g_{HZZ}	1.5%	1.3%	1%	13%
g_{Hbb}	1.6%	1.5%	1%	21%
$g_{H\tau\tau}$	3%	2.0%	1.5%	13%
g_{Hcc}	4%	?	?	?
g_{HWW}	4%	?	?	11%

Take away as indicative…

Summary

- CLIC: the path to multi-TeV e+e- collisions!
- Will be important if the LHC sees a signal for new physics
- Potential to go beyond the LHC in physics reach in a number of channels
- Precision measurements of the Higgs; information on the the Higgs potential & rare decays, heavy Higgs' up to a TeV

- LEP3: may be a fast and not so expensive path to a Higgs factory. Cohabitation with the LHC? Installation?
- Precise measurements of a number of Higgs properties
- Precise measurements at the Z and of the W mass
- But limited energy & scope of the physics program