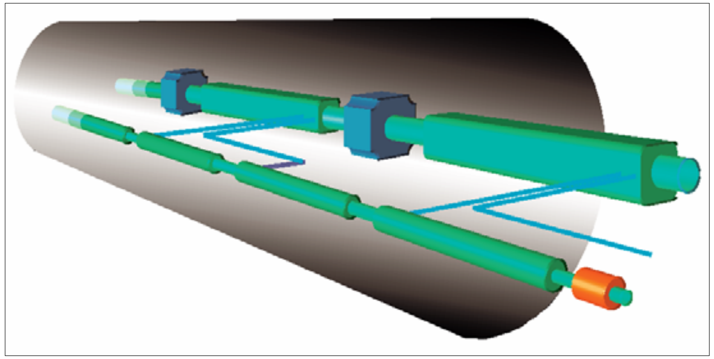
Physics @ CLIC
A Multi-TeV Linear Collider

Albert De Roeck CERN



Introduction
Experimenting at a Multi-TeV e+e- Collider
Physics Studies and Physics Potential
Outlook

Web Site http://clicphysics.web.cern.ch/CLICphysics/

Linear e+e- Colliders

Since end of 2001 there seems to be a worldwide consensus (ECFA/HEPAP/Snowmass 2001…)

↓

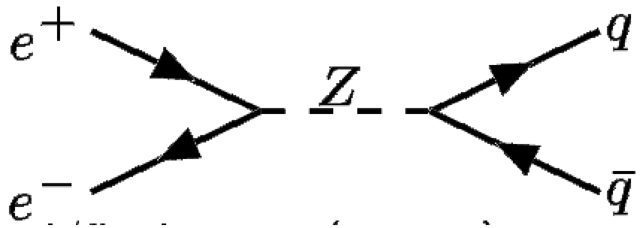
The machine which will complement and extend the LHC best, and is closest to be realized is a Linear e+e- Collider with a collision energy of at least 500 GeV

PROJECTS:

⇒ TeV Colliders (cms energy up to 1 TeV) → Technology ~ready
August'04 ITRP: NLC/GLC/TESLA → ILC superconducting cavities

⇒ Multi-TeV Collider (cms energies in multi-TeV range) → R&D
CLIC (CERN + collaborators) → Two Beam Acceleration

Linear e+e- Colliders



- To reach high energies with electron beams in future, linear accelerators are the only possibility (due to the sync. radiation)
- Advantages w.r.t. hadron machines
  - Electron are pointlike particles: all beam energy used in the collision i.e. beam energy in the collision is very monochromatic and tunable
  - Beams can be polarised to a high degree (e-: 80/90%; e+ 60%)
  - Beams are used once, so can be converted e.g. via Compton scattering (photon collider)
- Disadavantages:
  - Lower energy reach than proton machines
  - Beams are used only once: more effort to make enough luminosity

An e+e- linear collider will be a precision machine!

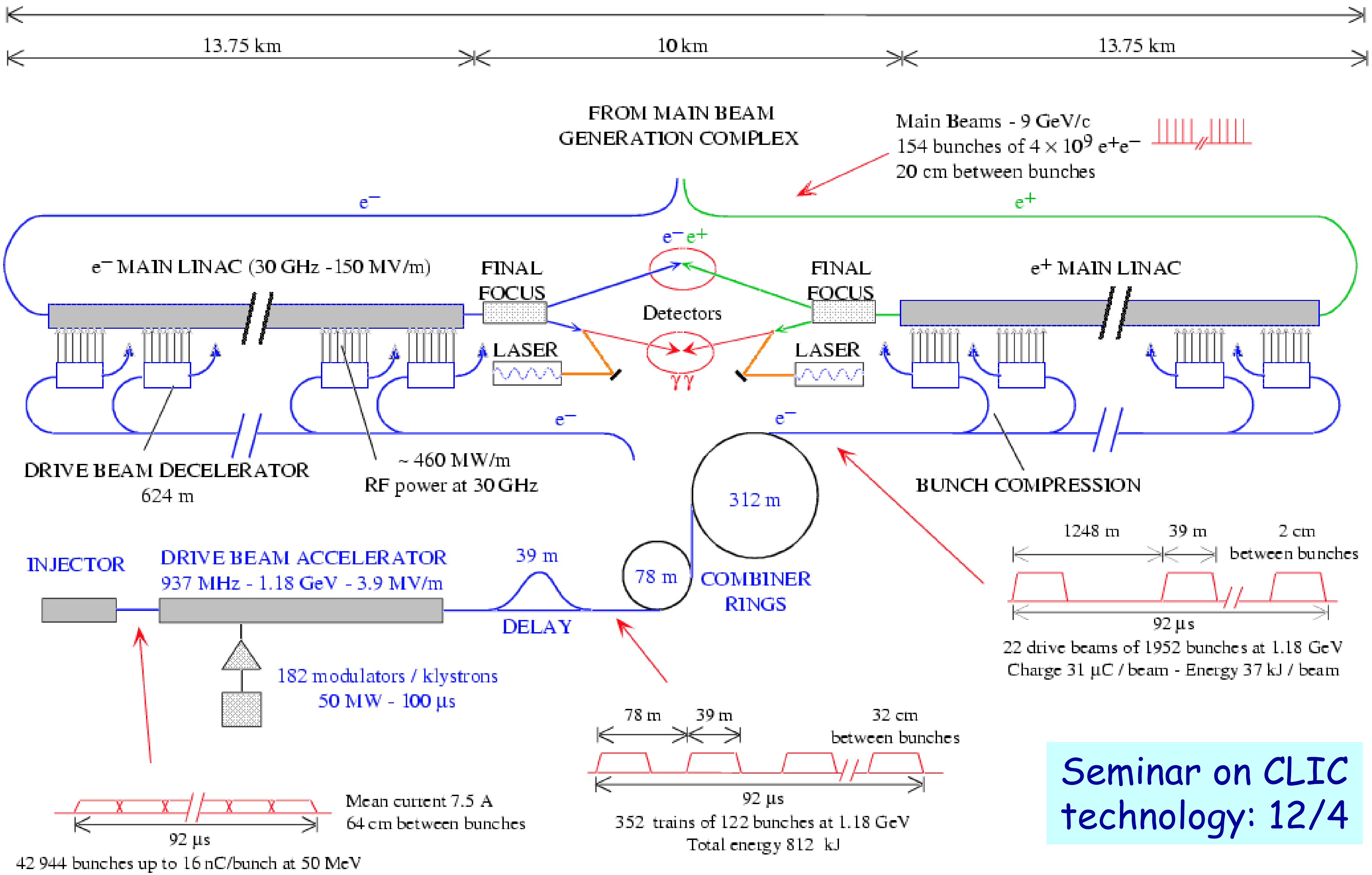
LC R&D at CERN: CLIC

- An e+e- linear collider optimized for a cms energy of 3 TeV with a luminosity of ≅ 10^{35} $cm^{-2}s^{-1}$
- Aim: 3 TeV complementing LHC/TeV class LC and breaking new ground, with a final stage up to 5 TeV
- To achieve this with reasonable cost (less than ~35 km) and not to many active elements
  - →High accelerating gradient: ~ 150 MV/m
    two beam acceleration (TBA)
  - → High beamstrahlungs regime to reach high luminosity
  - →Challenging beam parameters and machine requirements (nm stability, strong final focus, 30GHz accelerating structures)
    - ⇒ CLIC TBA to date the only known way to reach multi-TeV

Comparison with ILC

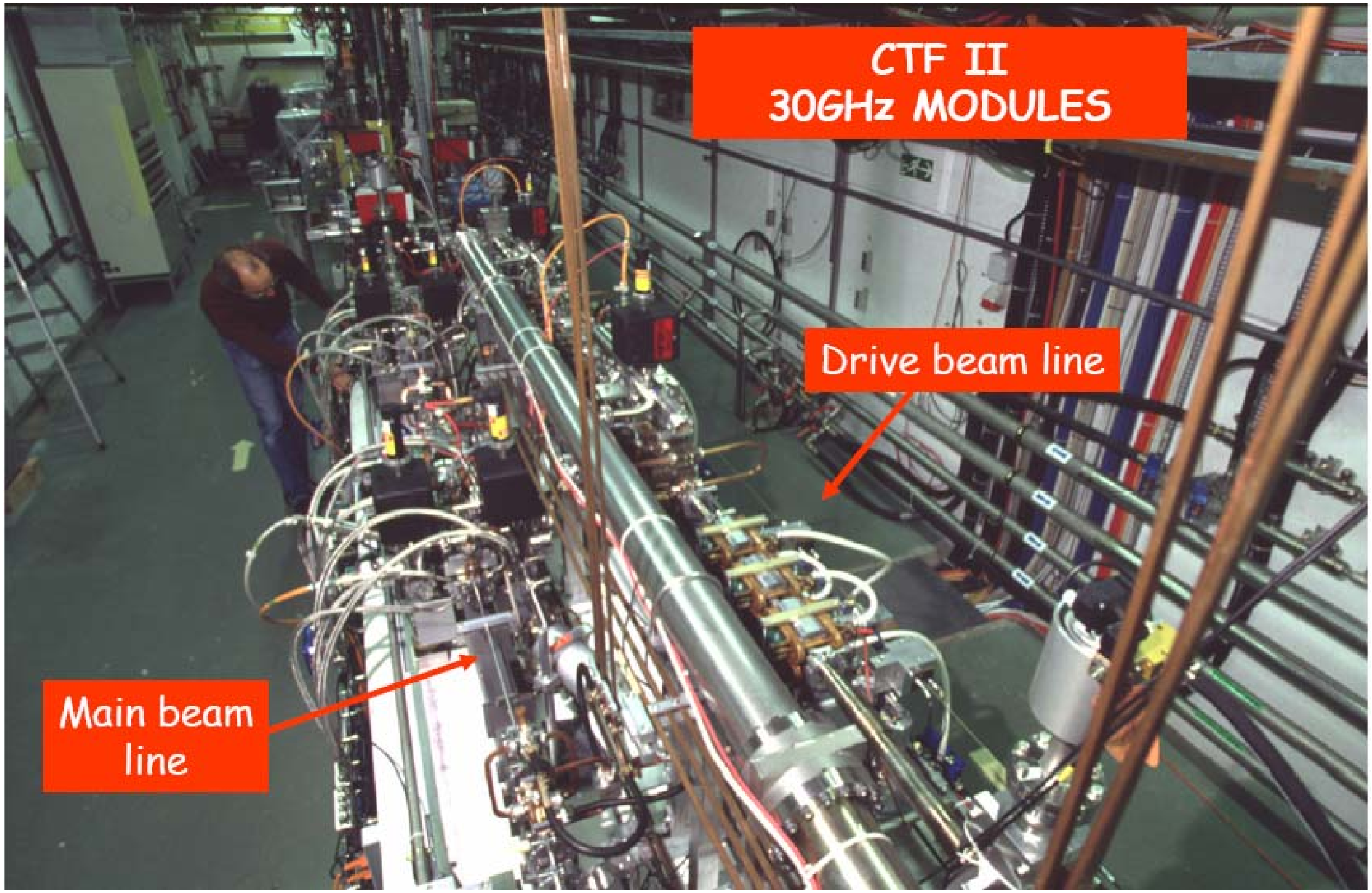
- TESLA 500 GeV 25MV/m
  800 GeV 35MV/m
- Future ILC study?: 44MV/m

- Test facilities CTF2 ('96-'02): 150-193 MV/m in TBA (16 ns pulses)
  CTF3 ('02-'09): Test of drive beam, R1's/ R2's of TRC (2003)

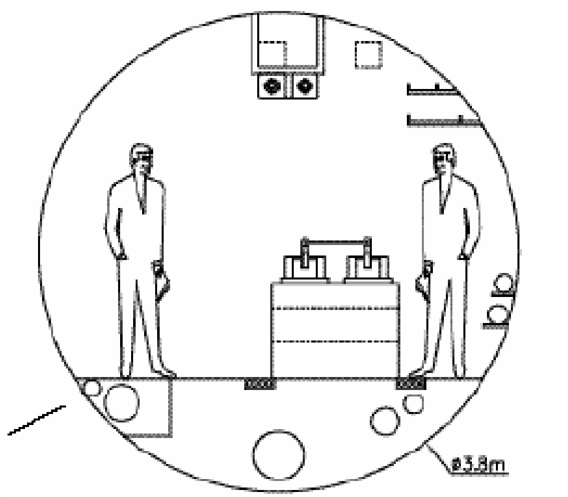


Seminar on CLIC technology: 12/4

CTF2: CLIC Test Facility 2



CLIC TUNNEL CROSS-SECTION



FAQs (frequently asked questions)

- Q: CLIC still in R&D state. How far is CLIC behind w.r.t. a TeV collider?
- A: ~5 years

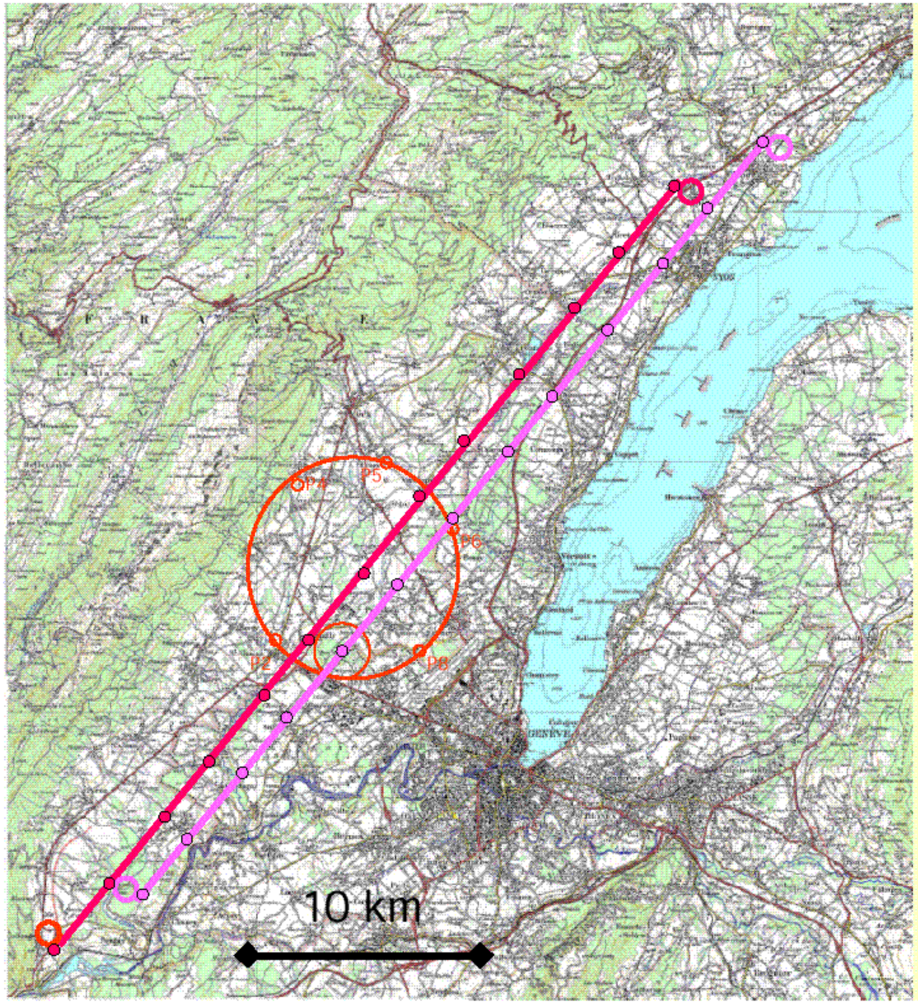
- Q: When will CLIC demonstrate its readiness as a technology for a LC?
- A: By ~2009 (if additional funding will be in place)

- Q: Can CLIC run at lower energies?
- A: Yes you can run in the energy range from 90 GeV-3TeV
- More on this at the end of the talk

- Q: Can CLIC be built at CERN?
- A: See next slide

- Q: Can you perform precision physics at CLIC? What can we gain in
- physics reach with CLIC?
- A: → This talk

Building CLIC at CERN?



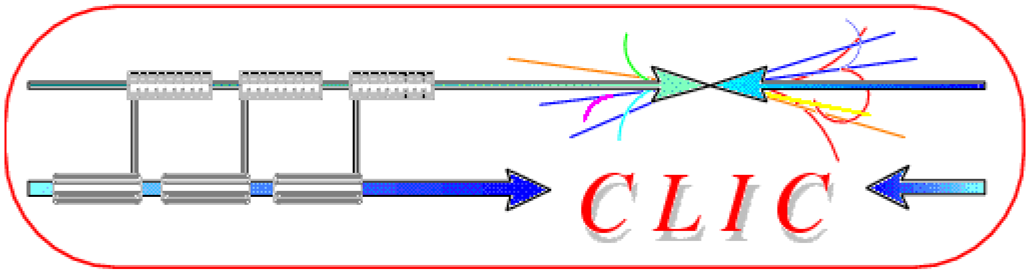
It is possible!

Geological analyses show that there is a contineous stretch of 40 km parallel to the Jura and the lake, with good geological conditions.

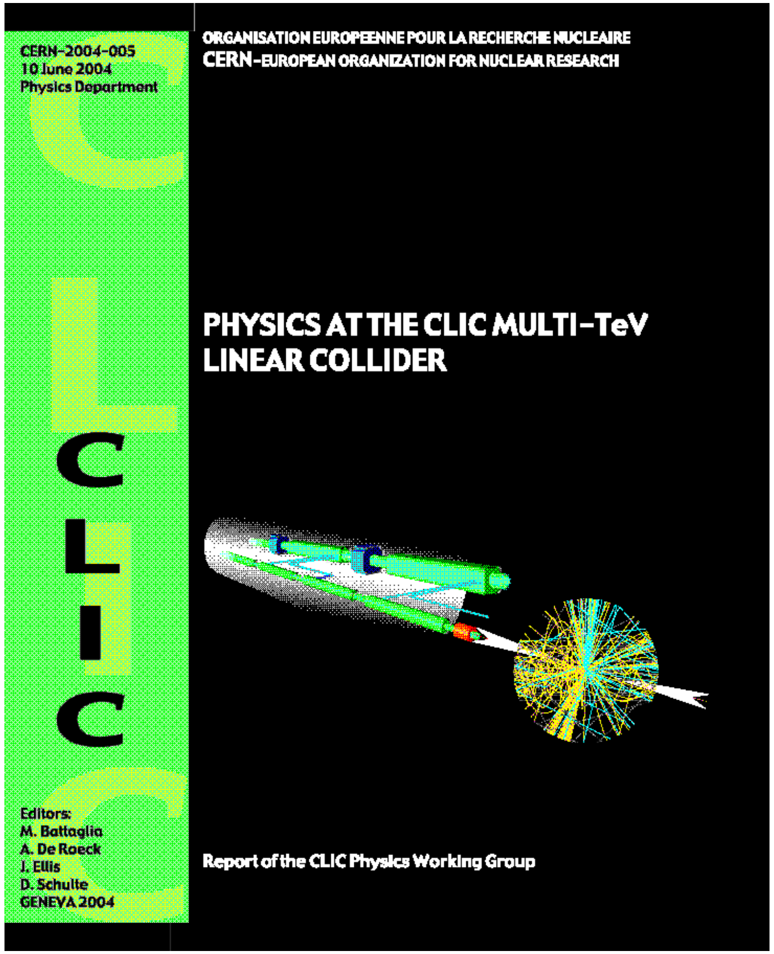
Reminder

The CLIC study is a site independent feasibility study aiming at the development of a realistic technology at an affordable cost for an e± Linear Collider in the post-LHC era for Physics in the multi-TeV center of mass colliding beam energy range.

1. Experimenting at CLIC



CLIC Physics Report



PHYSICS AT THE
CLIC MULTI-TeV LINEAR COLLIDER

Report of the CLIC Physics Working Group

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Physics case for CLIC documented in
a CERN yellow report CERN-2004-005 and hep-ph/0412251

CLIC Parameters & Backgrounds

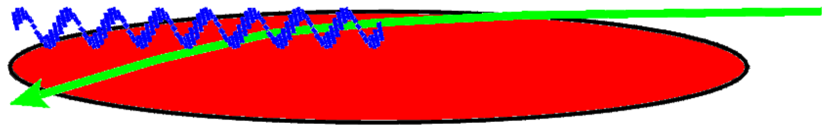
CLIC 3 TeV e+e- collider with a luminosity ~ $10^{35}cm^{-2}s^{-1}$ (1 ab^{-1}/year)

CLIC parameters

			old	new
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

CLIC

CLIC operates in a regime of high beamstrahlung



Time between 2 bunches = 0.67ns

Expect large backgrounds

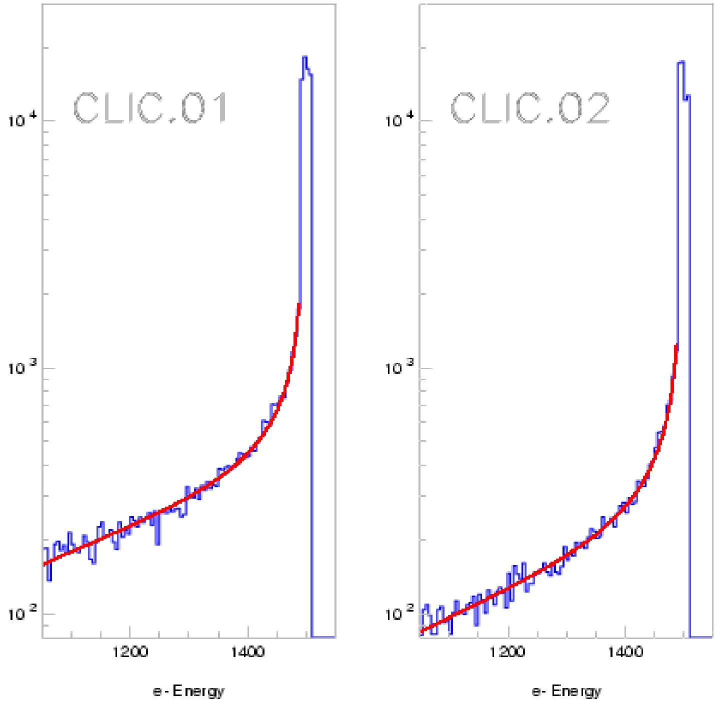
# of photons/beam particle

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

Expect distorted lumi spectrum

Luminosity Spectrum

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



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

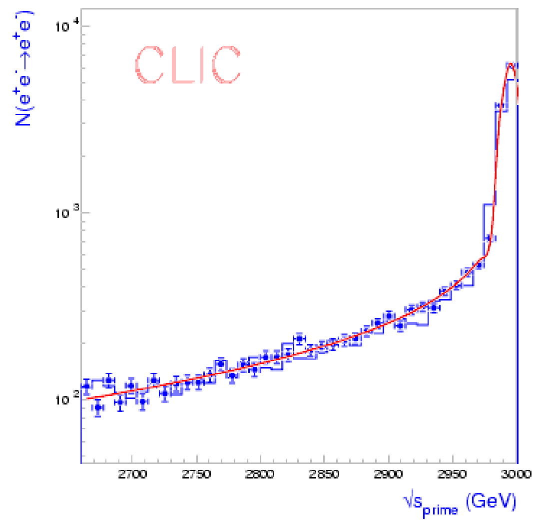
Energy loss due to beam-beam interactions

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%

CLIC

RECONSTRUCTED $\sqrt{s'}$ SPECTRUM FROM BHABHA ANGLES

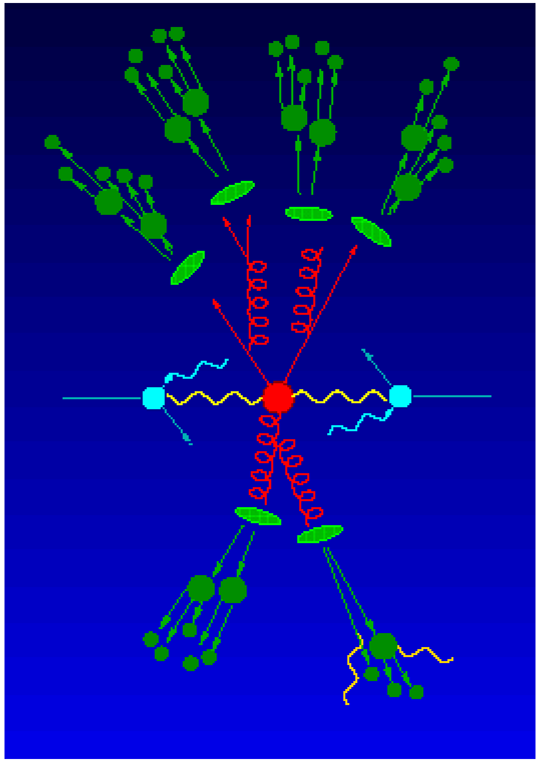


Preliminary Results: expect accuracy $\frac{\delta\sqrt{s'}}{\sqrt{s}} \simeq 10^{-4}$ for 100 fb^{-1}

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

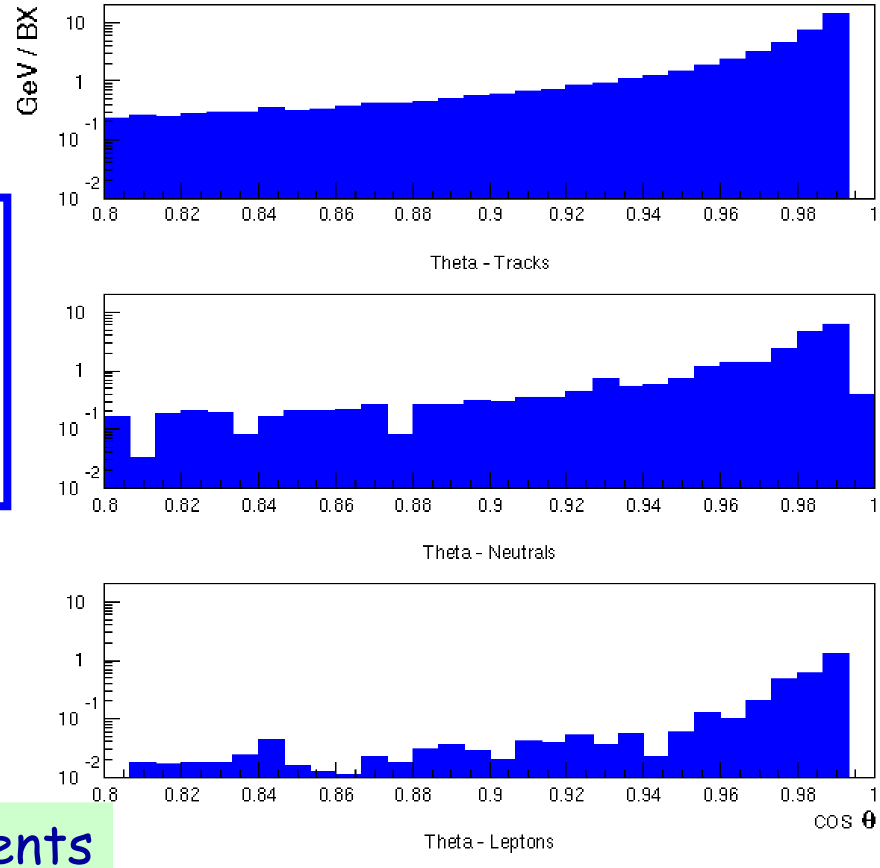
$\gamma\gamma$ Background

$\gamma\gamma \rightarrow$ hadrons: 4 interactions/bx with W_{HAD}>5 GeV



Particles accepted within θ > 120mrad

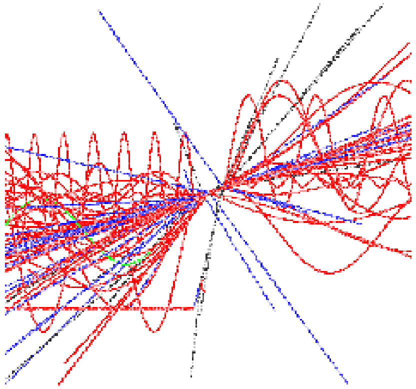
Neutral and charged energy as function of cosθ per bx

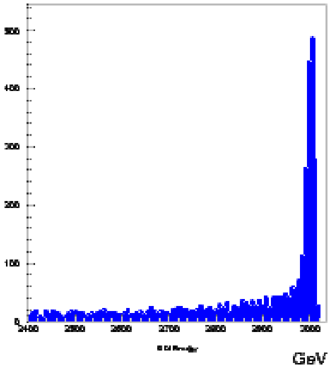


For studies: take 20 bx and overlay events

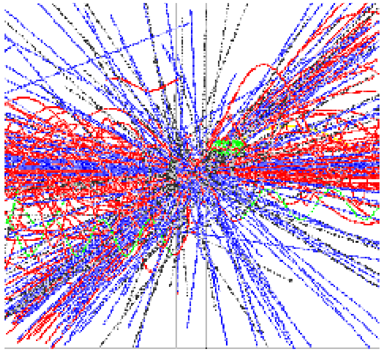
Most activity at small angles

CLIC Tools for Background/Detector

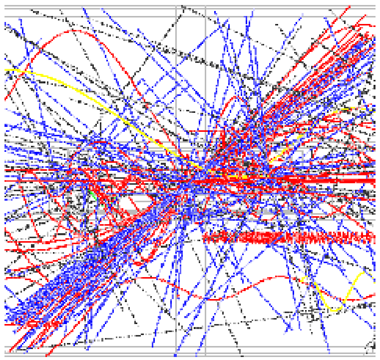




Physics generators (COMPHEP PYTHIA6,…)
+ CLIC lumi spectrum (CALYPSO)



+ $\gamma\gamma \rightarrow$ hadrons background
e.g. overlay 20 bunch crossings
(+ e+e- pair background files…)

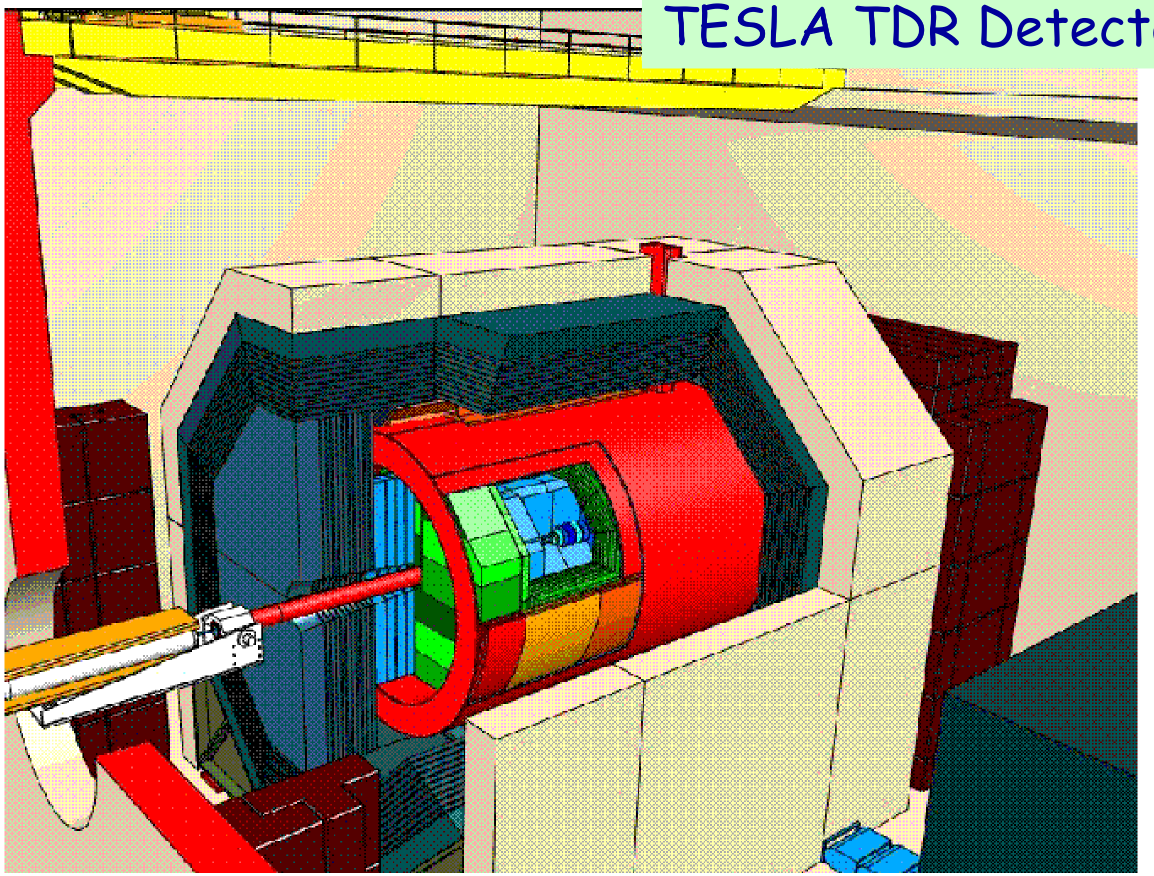


Detector simulation
- SIMDET (fast simulation)
- GEANT3 based program

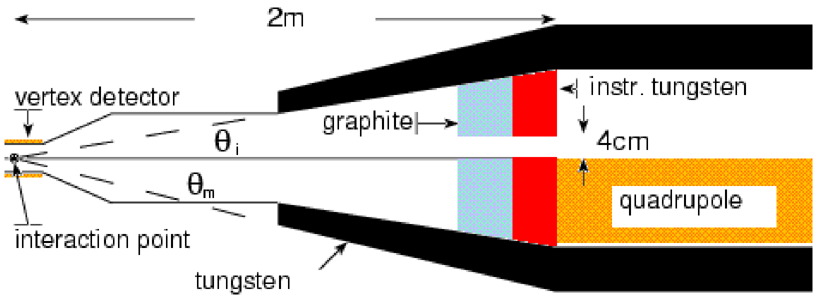
$\Rightarrow$Study benchmark processes

A Detector for a LC

TESLA TDR Detector



Background at the IP enforces use of a mask



CLIC: Mask covers region up to 120 mrad
Energy flow measurement possible down to 40 mrad

~TESLA/NLC detector qualities: good tracking resolution, jet flavour tagging, energy flow, hermeticity,…

Detector Parameters

Detector	CLIC
Vertexing	$15\mu m \oplus \frac{35\mu m GeV/c}{p \sin^{3/2}\theta}$ $15\mu m \oplus \frac{35\mu m GeV/c}{p \sin^{5/2}\theta}$
Solenoidal Field	$B = 4\ T$
Tracking	$\frac{\delta p_t}{{p_t}^2} = 5. \times 10^{-5}$
E.m. Calorimeter	$\frac{\delta E}{E(GeV)} = 0.10\frac{1}{\sqrt{E}} \oplus 0.01$
Had. Calorimeter	$\frac{\delta E}{E\ (GeV)} = 0.40\frac{1}{\sqrt{E}} \oplus 0.04$
μ Detector	Instrumented Fe yoke $\frac{\delta p}{p} \simeq 30\%$ at 100 GeV/c
Energy Flow	$\frac{\delta E}{E\ (GeV)} \simeq 0.3\frac{1}{\sqrt{E}}$
Acceptance mask beampipe small angle tagger	$\lvert\cos\theta\rvert < 0.98$ 120 mrad 3 cm $\theta_{min} = 40$ mrad

Starting point: the TESLA TDR detector
Adapted to CLIC environment

First ideas:

3–15 cm	VDET
15–80 cm	Silicon/forward disks
80–240 cm	TPC
240–280 cm	ECAL (30 X_0)
280–400 cm	HCAL (6λ)
400–450 cm	Coil (4T)
450–800 cm	Fe/muon

Needs more detailed study

Tracking Technologies

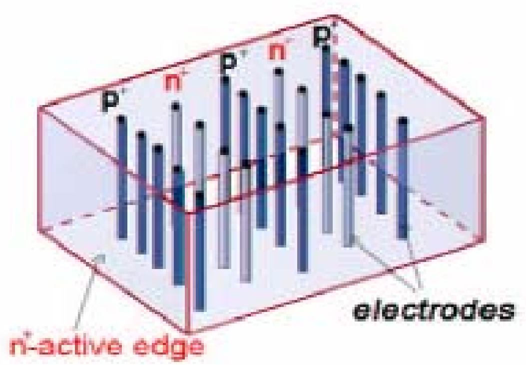
Properties	Standard planar crystal silicon	3D- silicon	Monolithic CMOS pixel detector	a-Si:H pixel detector
Collection speed Electron transient t Holes transient t	10ns 20ns	Short drift $<$ 1ns 1ns	Thermal drift 100ns 200ns	Short drift, high field 2ns 150ns
Thickness	300μm	100μm -200μm	2μm - 8μm	30μm - 50μm
MIP charge signal	24 000 e-	10 000e-20 000e-	100 e- 500 e-	1000 e- 2000 e-
Radiation hardness Fluence n/cm^2	3 10^{14} at -20^{0}C	At least 10^{15} at +20^{0}C	$<$ 10^{13}, strong surface effects	$>$ 510^{15}, limit not known, self-annealing by mobile H
Operating temperature	-20^{0}C, cryogenic T	Room T	Room T	Room T to 60^{0}C
Manufacturing Cost	High	High	Low	Low
Field of applications	Microvertex detector tracker	Small detector area, fast timing, high radiation level	Microvertex detector, low radiation level, slow readout	Large area detector, macropad and microvertex, high radiation environment

- Time stamping will be important O(ns)
- Macro-pixels?
- Radiation however not a big issue
  ~ 5 10^{10} neutrons/cm^{-2}/year

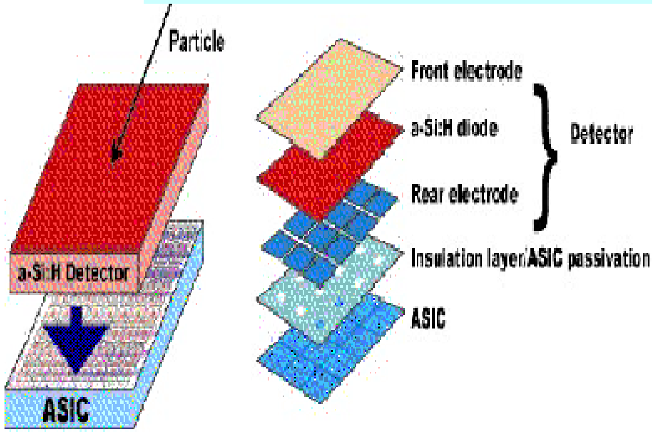
⇒R&D will be required!!

⇒In context of SLHC R&D or
Follow up on the former NLC R&D program

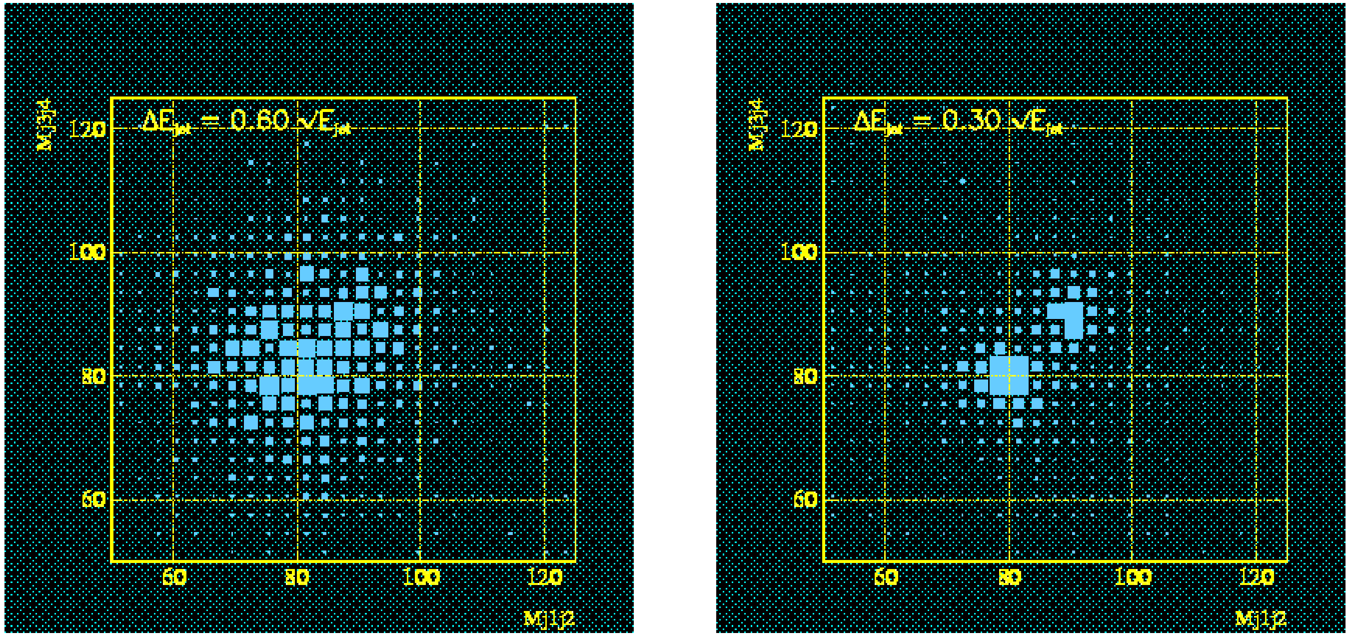
3D Silicon



Amorphous Silicon



Calorimetry



$$e^+e^- \rightarrow \nu\bar{\nu}W^+W^-, \nu\bar{\nu}ZZ, \quad W, Z \rightarrow 2\text{jets}$$

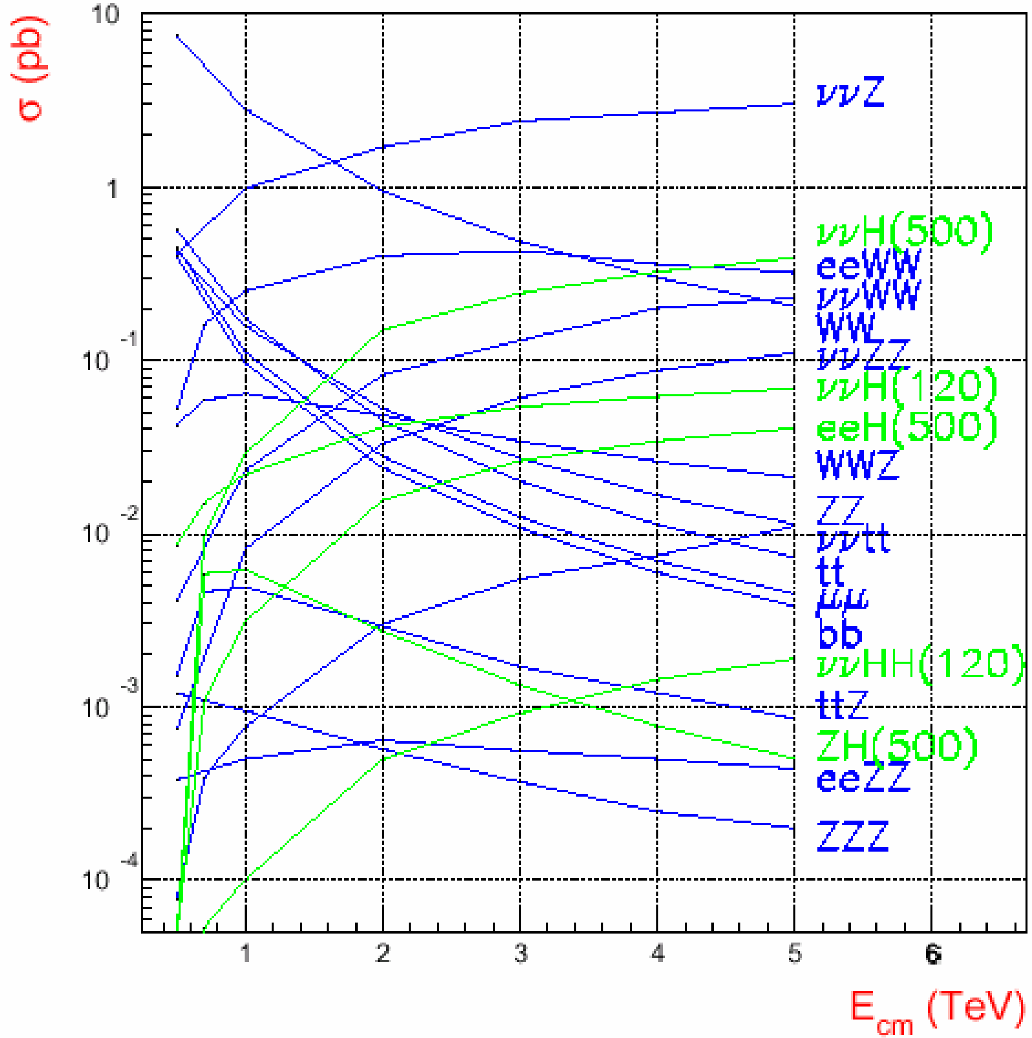
Importance of good energy resolution (e.g via energy flow)
Interesting developments in TeV-class LC working groups
e.g. compact 3D EM calorimeters, or "digital" hadronic calorimeters
⇒Detailed simulation studies of key processes required
⇒R&D accordingly afterwards/Join ILC detector efforts?

Physics Menu at CLIC

- Higgs sector: light and heavy Higgses, Higgs potential
- Supersymmetry: if exists, will be discovered at a hadron collider
  Role of CLIC: completing the particle spectra with precision measurements (masses < $\sqrt{s}/2$)
- Particle Factory: if new particles have been detected/predicted at the LHC/LC-500 in the range of 1-5 TeV (New Gauge bosons, Kaluza-Klein resonances, resonances in WW scattering…): CLIC will produce them directly, provide an accurate determination of their couplings and establish their nature. Also exotic decays (such as $Z' \rightarrow$ heavy Majorana Neutrinos) can be detected.
- If NO new particles are observed directly, probe scales up to the O(100-800) TeV indirectly via precision measurements
- QCD measurements: BFKL, photon structure, α_s,…
- The unexpected???

e+e- at $\sqrt{s} \approx$ 3-5 TeV: Expect to break new grounds

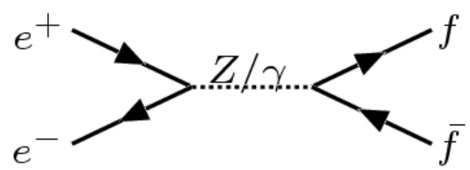
Cross Sections at CLIC



CLIC

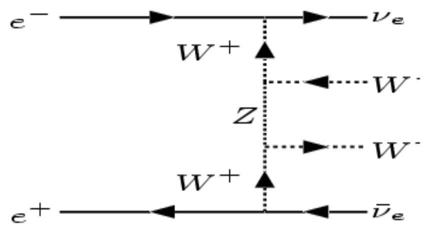
Event Rates/Year (1000 fb^{-1})	3 TeV 10^3 events	5 TeV 10^3 events
$e^+e^- \to t\bar{t}$	20	7.3
$e^+e^- \to b\bar{b}$	11	3.8
$e^+e^- \to ZZ$	27	11
$e^+e^- \to WW$	490	205
$e^+e^- \to hZ/h\nu\nu$ (120 GeV)	1.4/530	0.5/690
$e^+e^- \to H^+H^-$(1 TeV)	1.5	0.95
$e^+e^- \to \tilde{\mu}^+\tilde{\mu}^-$ (1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

s-Channel Production



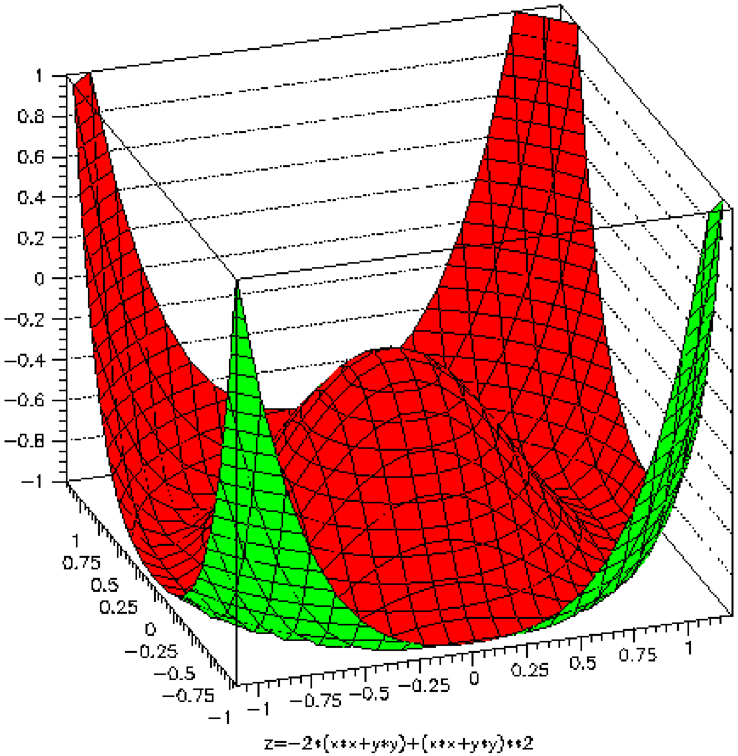
$\sigma \propto 1/s$

t-Channel Production



$\sigma \propto log(s)$

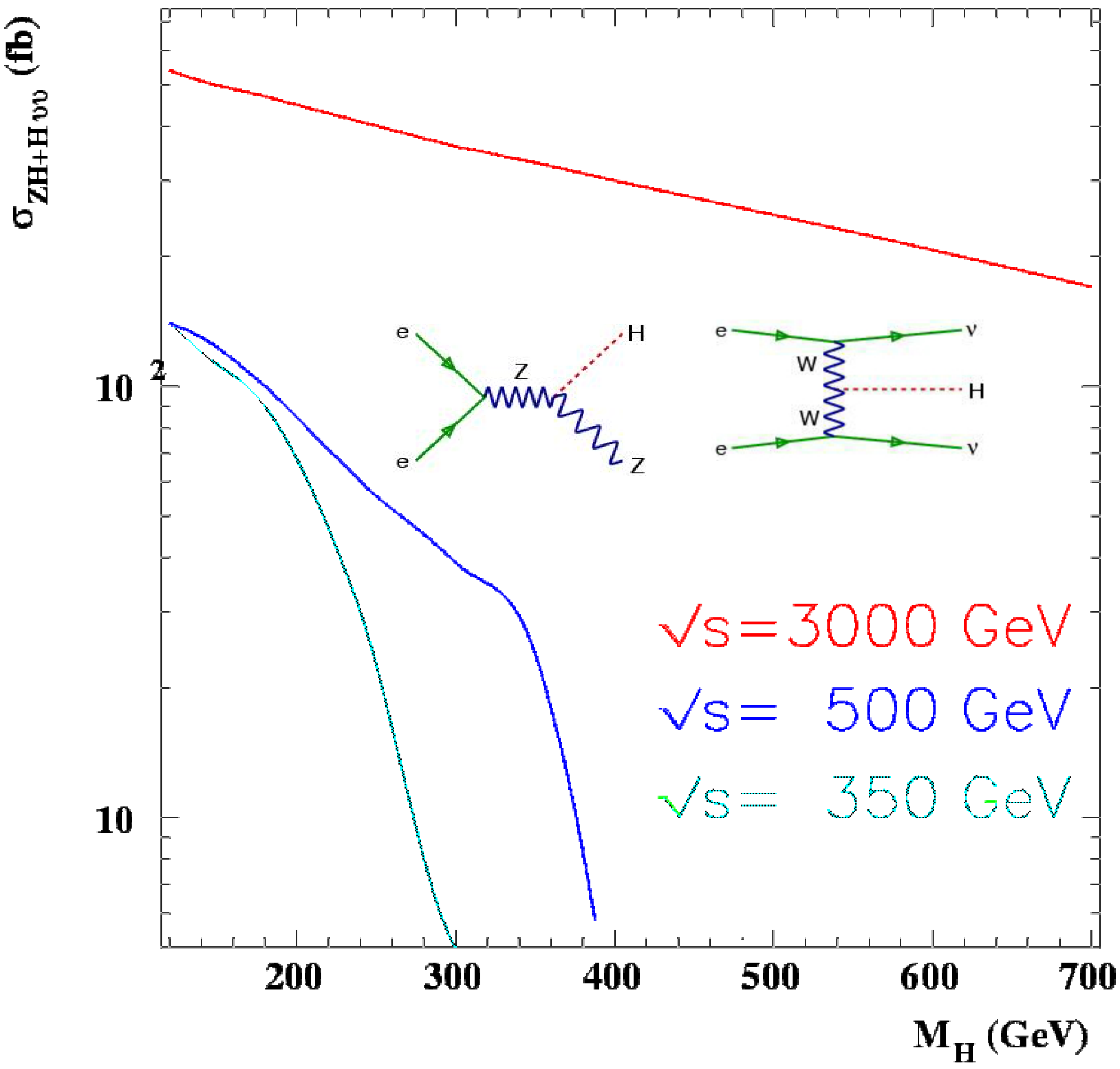
2. Higgs Physics



Study properties of the Higgs particles in detail (couplings, spin, CP structure,…)

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

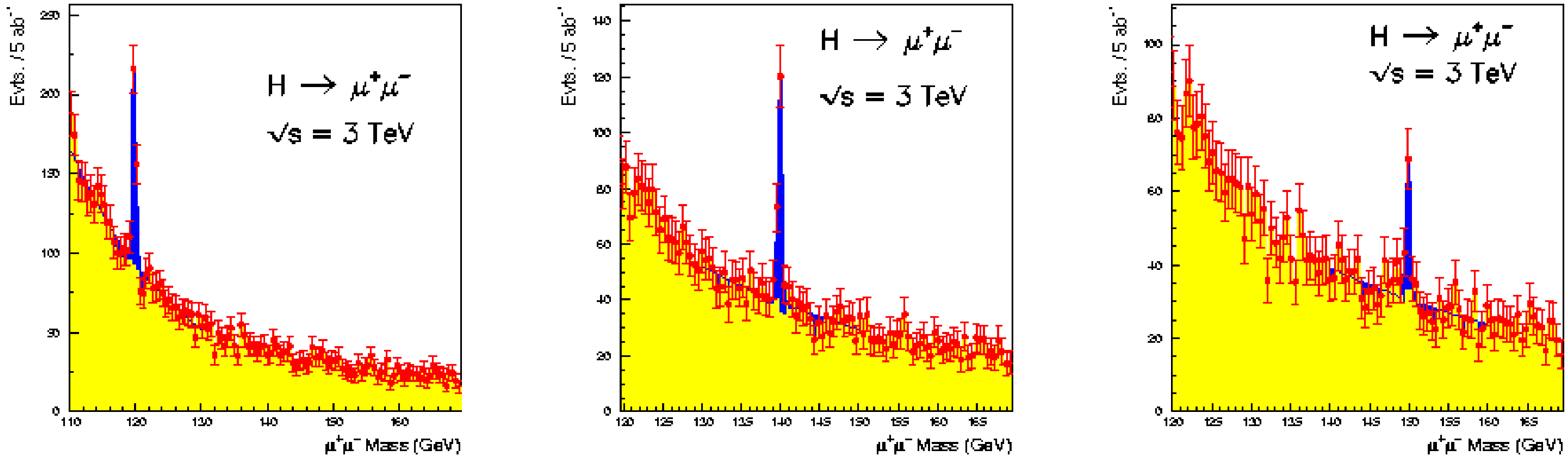
Low mass Higgs:
400 000 Higgses/year

45K/100K for 0.5/1 TeV LC

Rare Higgs Decays: H→μμ

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

Not easy to access at a 500 GeV collider



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%

Also H→bb for masses up to 220 GeV

CLIC

Higgs Potential

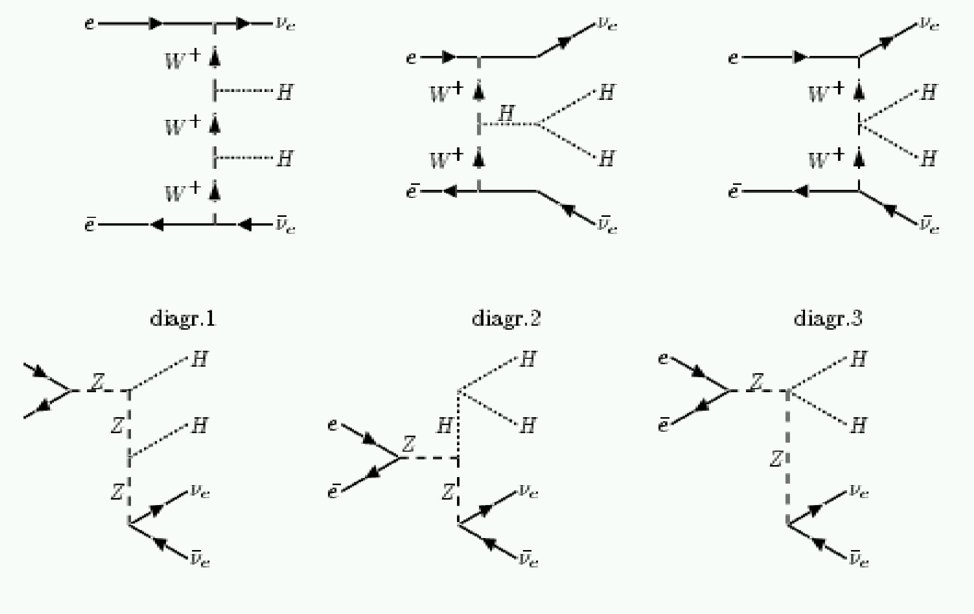
Reconstruct shape of the Higgs potential to complete the study of the Higgs profile and to obtain a direct proof of the EW symmetry breaking mechanism

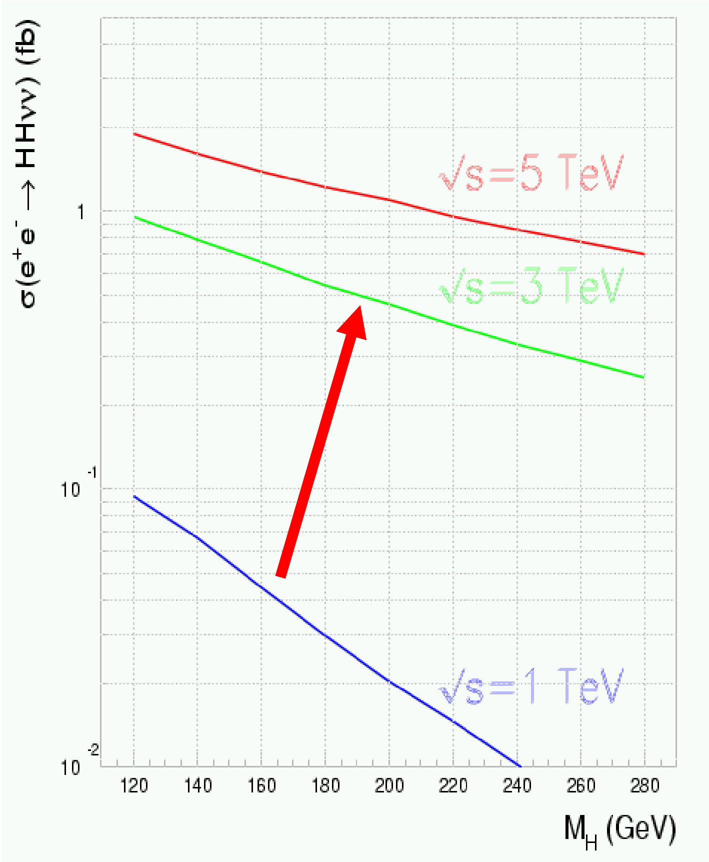
⇒ Measure the triple (quartic) couplings

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

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

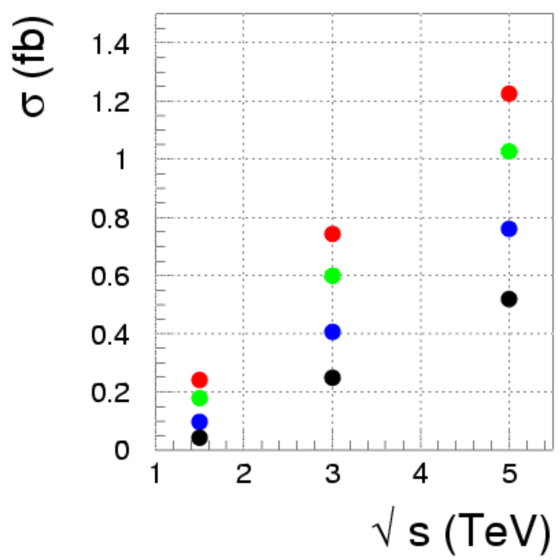
process $e^+e^- \rightarrow (WW)\nu\bar{\nu} \rightarrow hh\nu\bar{\nu}$

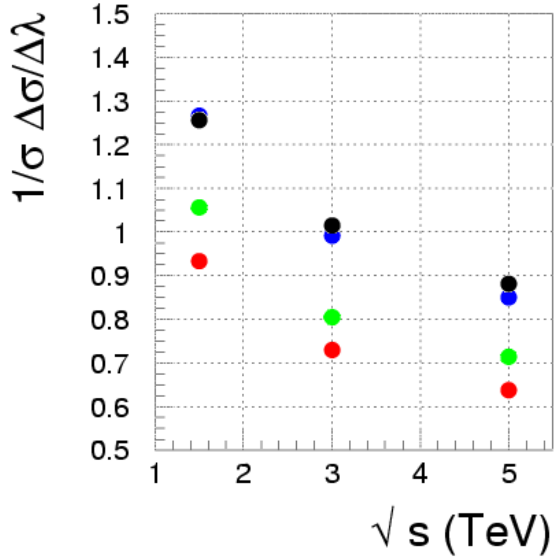


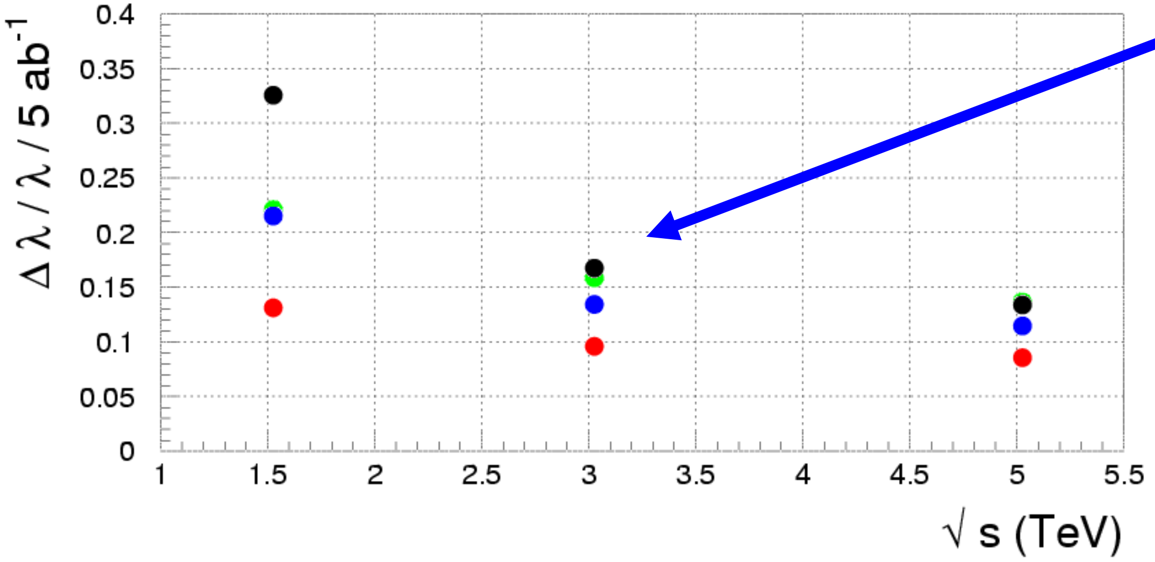


$$HH \rightarrow b\bar{b}b\bar{b},\ W^+W^-W^+W^-$$

Results: e+e- →HHνν







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

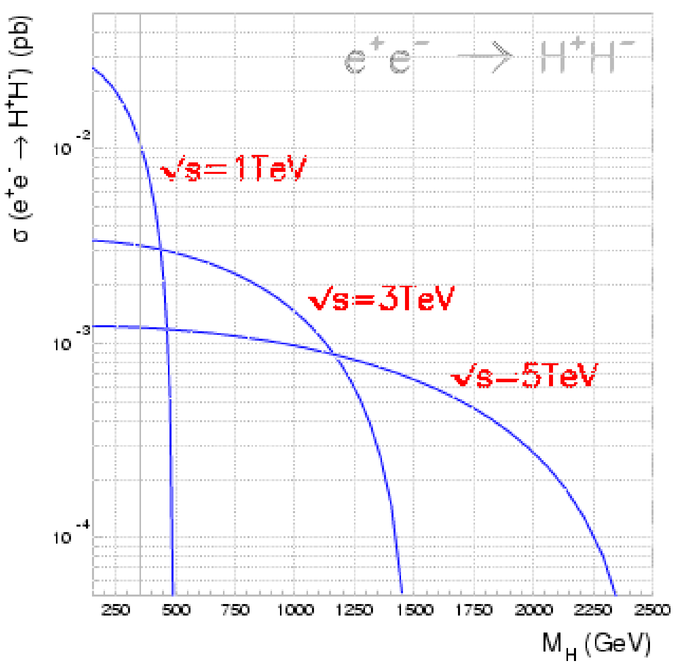
3 TeV

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

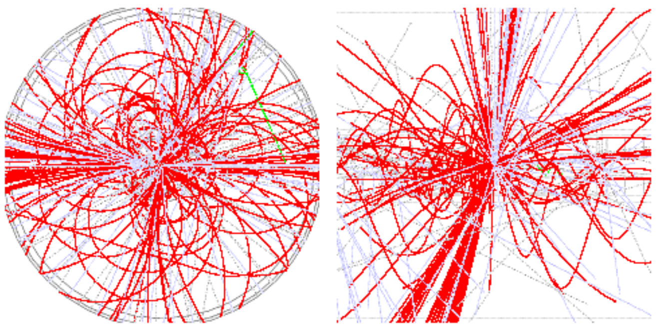
Can improve by factor 1.7 if both beams are polarized

Heavy Higgs (MSSM)

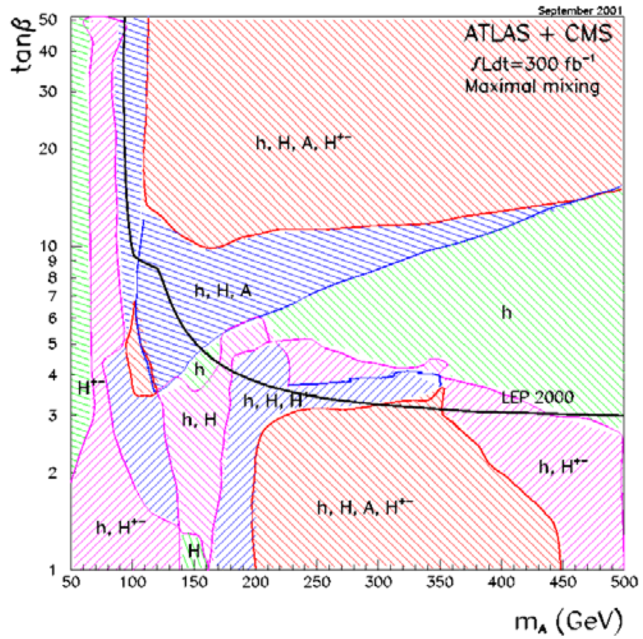
Cross section as function of Higgs mass



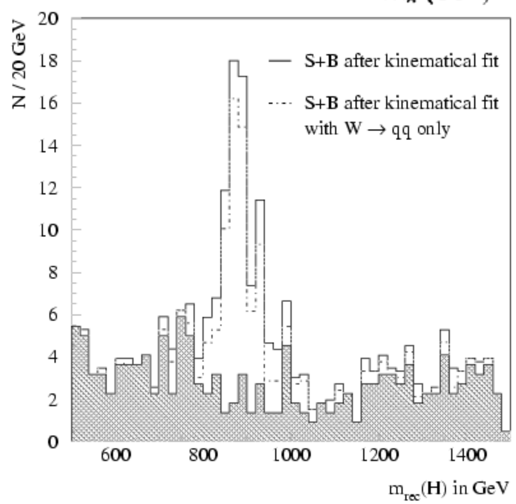
$e^+e^- \to H^+H^-$ $M_H = 900$ GeV



LHC: Plot for 5 σ discovery



3 TeV CLIC
⇒ H, A
detectable
up to ~ 1.2 TeV



.IC

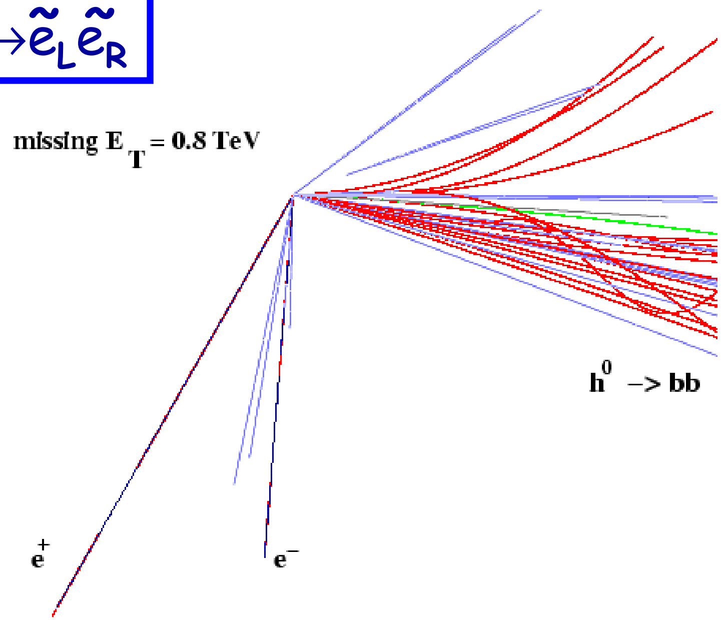
Higgs: Strength of a multi-TeV collider

- Precision measurements of the quantum numbers and properties of Higgs particles, for large Higgs mass range
- Study of Heavy Higgses (e.g. MSSM H,A,$H^{\pm}$)
- Rare Higgs decays, even for light Higgs
- Higgs self coupling over a wide range of Higgs masses
- Study of the CP properties of the Higgs…

Parameter	M_H (GeV)	$\delta X/X$
$\delta g_{Htt}/g_{Htt}$	120–180	0.05–0.10
$\delta g_{Hbb}/g_{Hbb}$	180–220	0.01–0.03
$\delta g_{H\mu\mu}/g_{H\mu\mu}$	120–150	0.03–0.10
$\delta g_{HHH}/g_{HHH}$	120–180	0.07–0.09
g_{HHHH}	120	$\neq 0$ (?)

3. Supersymmetry

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



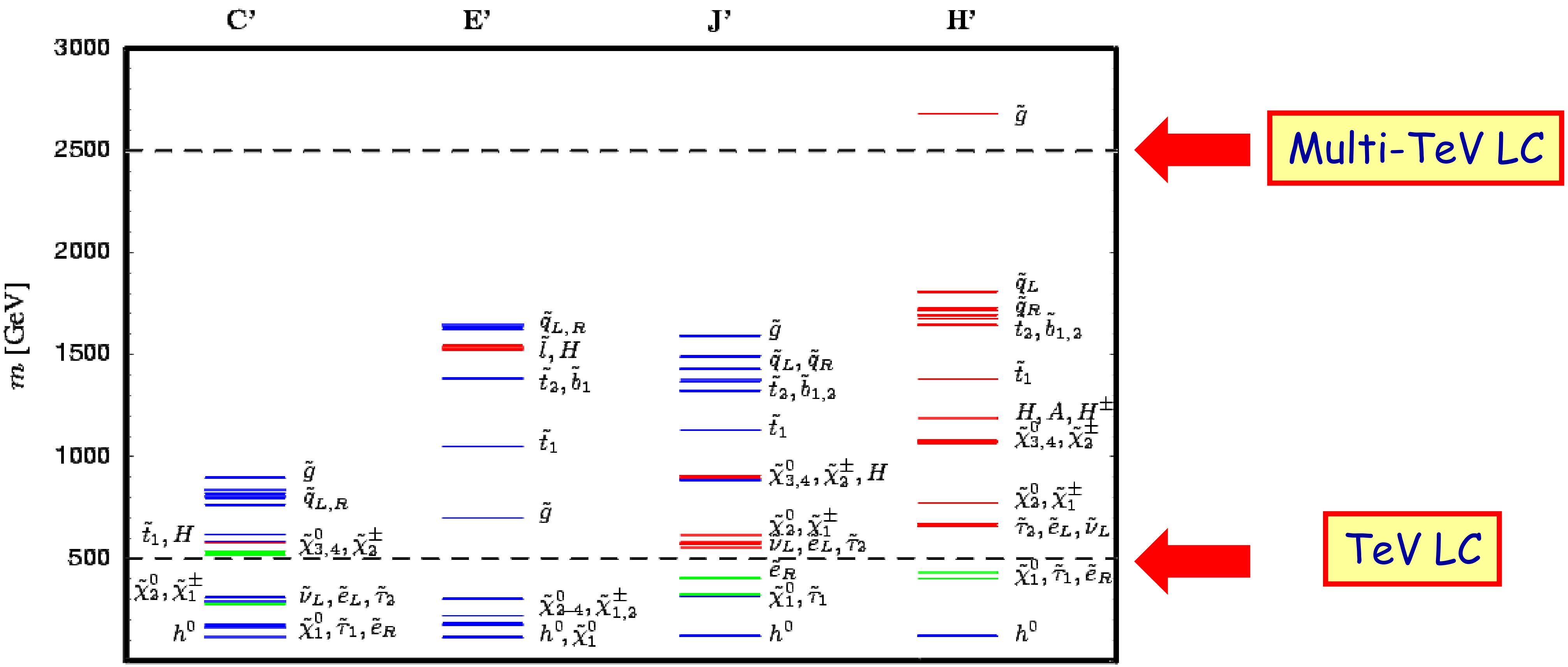
Completing the SUSY spectrum

Masses of Sparticles

Depend on SUSY parameters, SUSY breaking mechanisme...

We don't really know...

Examples: Scenarios in Constrained MSSM



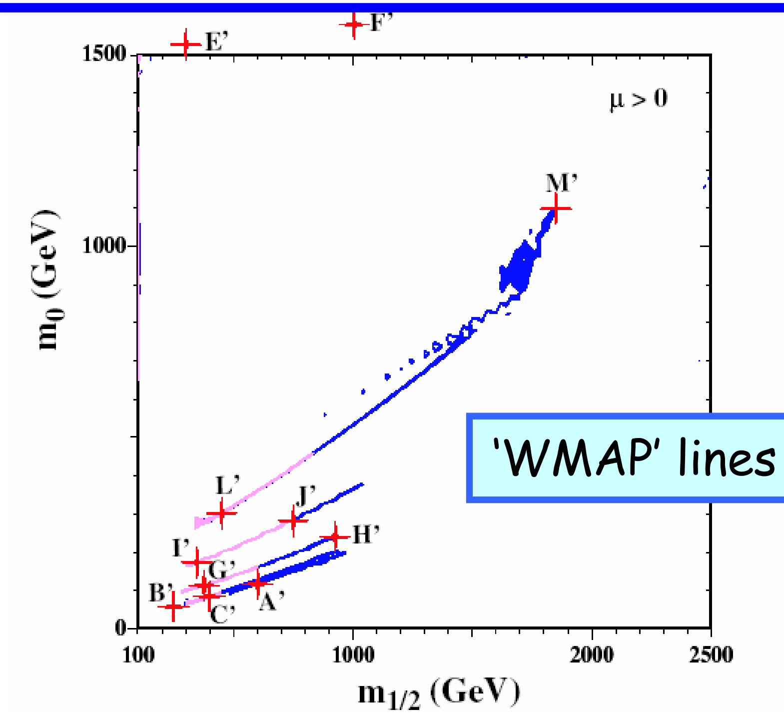
Sparticle Discoveries

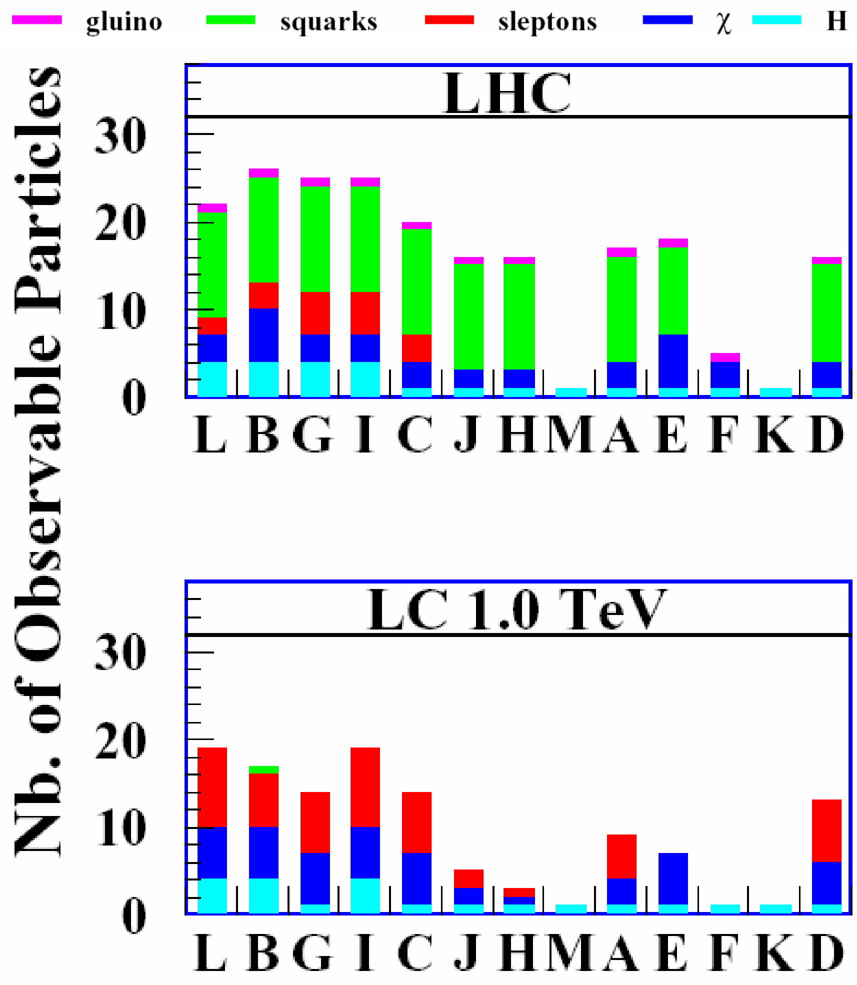
- A number of SUSY (mSUGRA) benchmark points to study LHC/LC sensitivity

(Battaglia at al hep-ph/0306219)

- Take into account direct searches at LEP and Tevatron, BR ($b \to s\gamma$), g_μ-2 (E821), Cosmology: $0.09 \leq \Omega_\chi h^2 \leq 0.13$

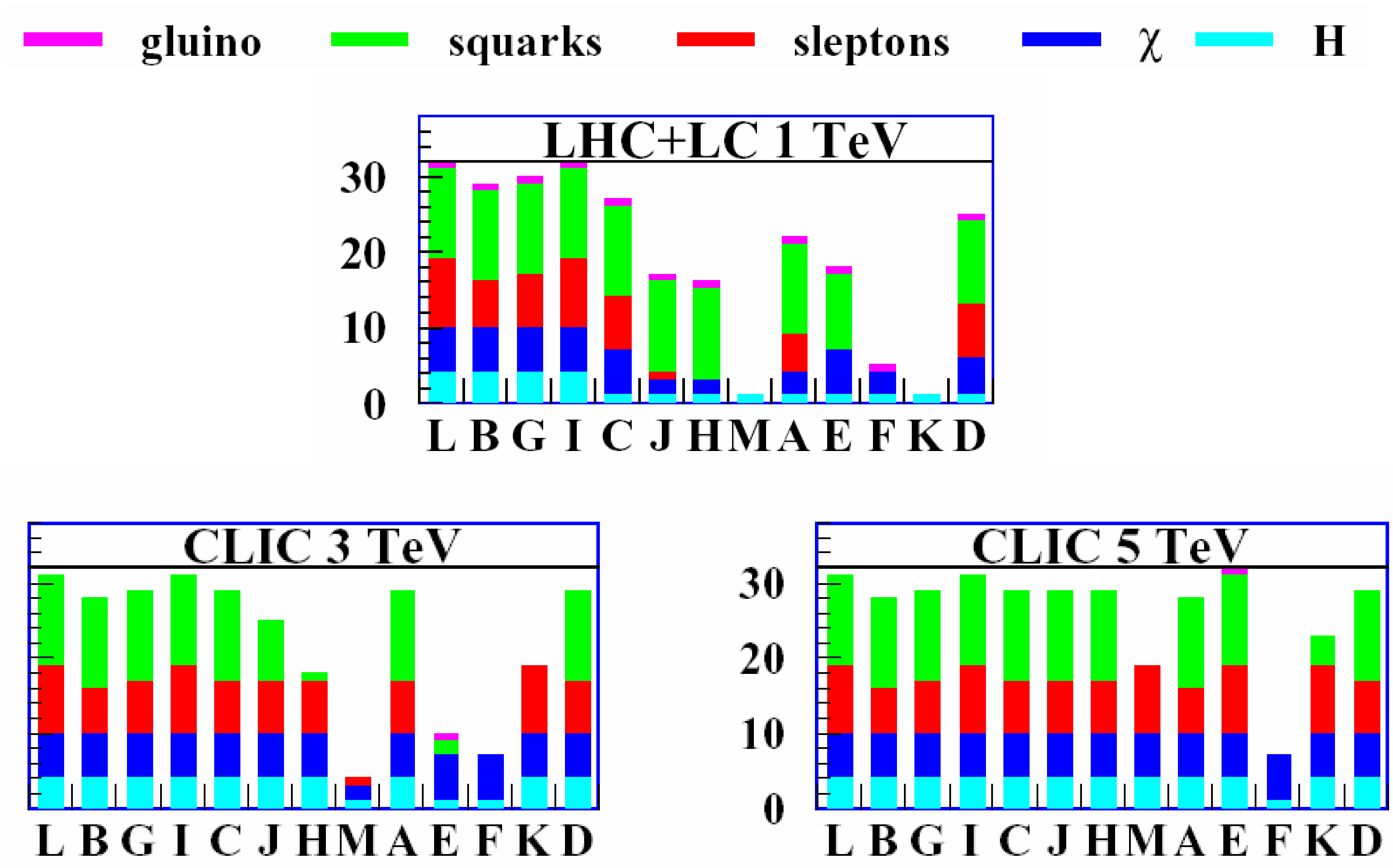
Allowed regions in the M_0-$M_{1/2}$ plane





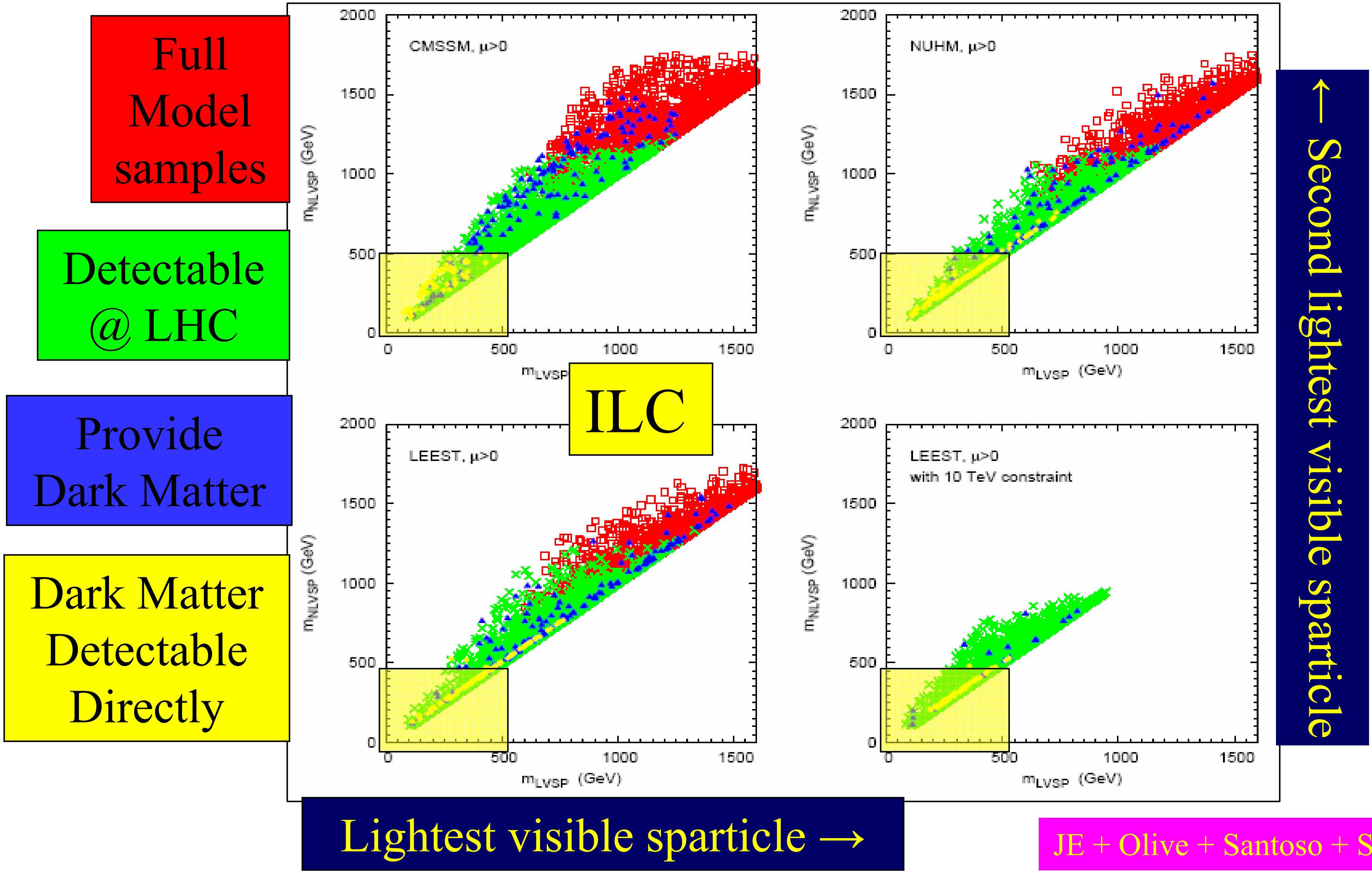
sleptons and gauginos often difficult to detect at a LHC

Sparticle Discoveries



CLIC can help to complete the sparticle spectra

Sparticle Detection

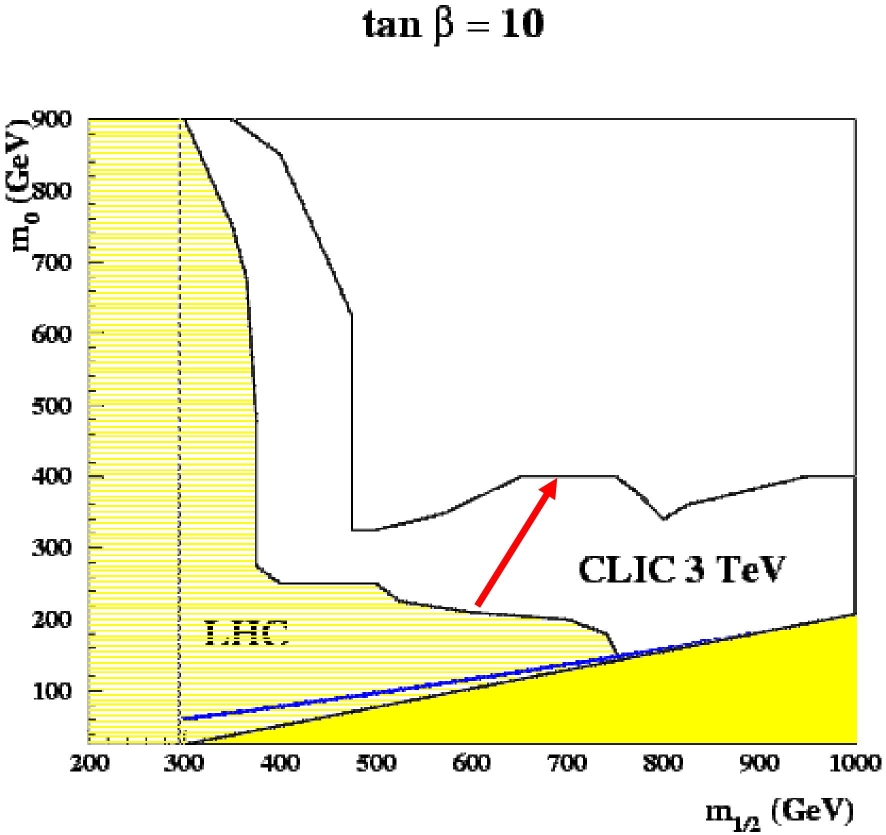


JE + Olive + Santoso + Spanos

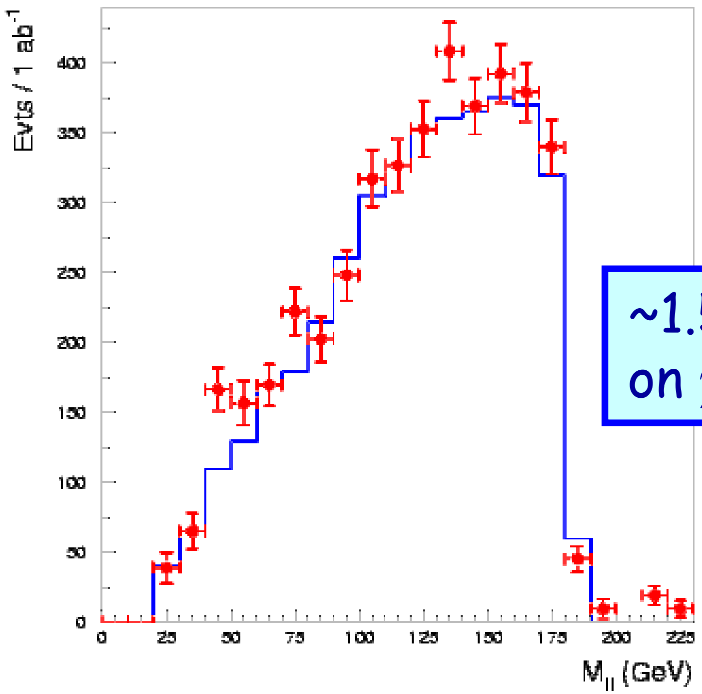
Sensitivity to $\chi_2 \rightarrow \chi_1$+2 leptons

Case study: χ_2

Sensitivity (5σ) for LHC and LC



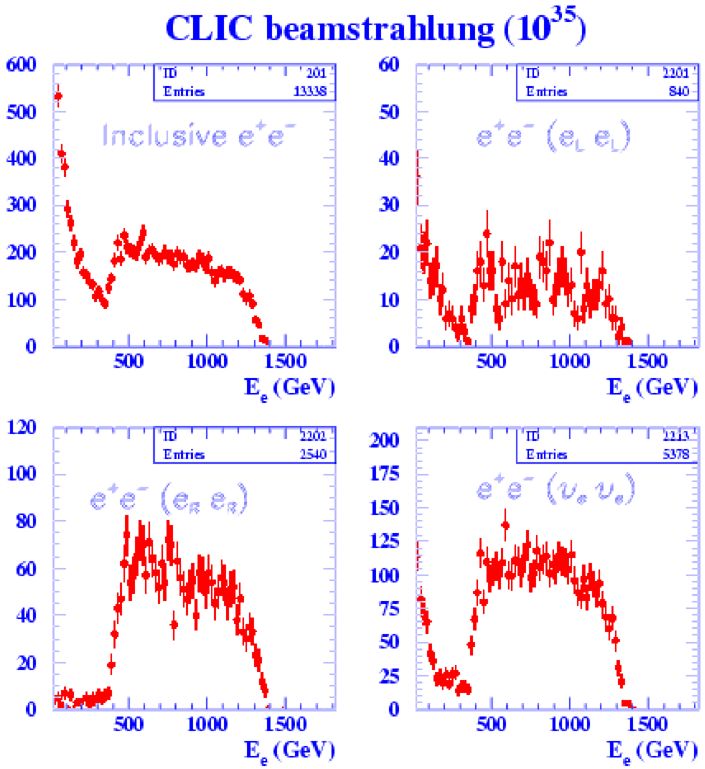
Mass measurement precision
$m\chi_2$= 540 GeV, $m\chi_1$=290 GeV



~1.5% precision on χ_2 mass

Selectron and Smuon Measurements

E.G. $m_{1/2} = 300$ GeV, $m_0 = 1450$ GeV, $\tan\beta = 10$, $A = 0$ GeV, $sign(\mu) > 0$ (mSUGRA) (point E)



Signal $\tilde{\nu}_e \tilde{\nu}_e \to e^+ \tilde{\chi}_1^- e^- \chi_1^+ (180)$

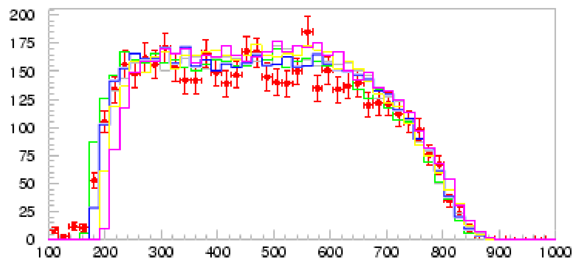
Typical 'box' shape of the signal preserved in CLIC environement

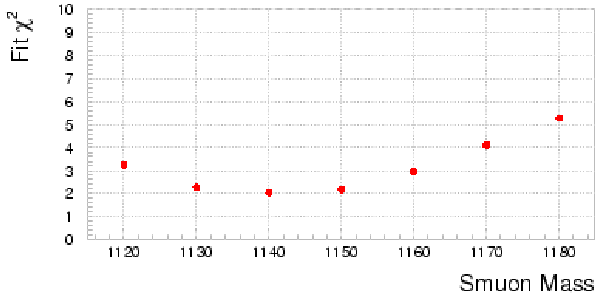
E.G. $m_{1/2} = 1500$ GeV, $m_0 = 420$ GeV, $\tan\beta = 20$, $A = 0$ GeV, $sign(\mu) > 0$ (mSUGRA) (point H)

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

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

$$\Rightarrow \quad E_{\text{max/min}} = \frac{M_{\tilde{\mu}}}{2}\left(1 - \frac{M^2_{\tilde{\chi}^0_1}}{M^2_{\tilde{\mu}}}\right) \times \left(1 \pm \sqrt{1 - \frac{M^2_{\tilde{\mu}}}{E^2_{\text{beam}}}}\right)$$





Typical 'box' shape of the signal preserved in CLIC environement (1 ab^{-1})

Smuon Mass Precision

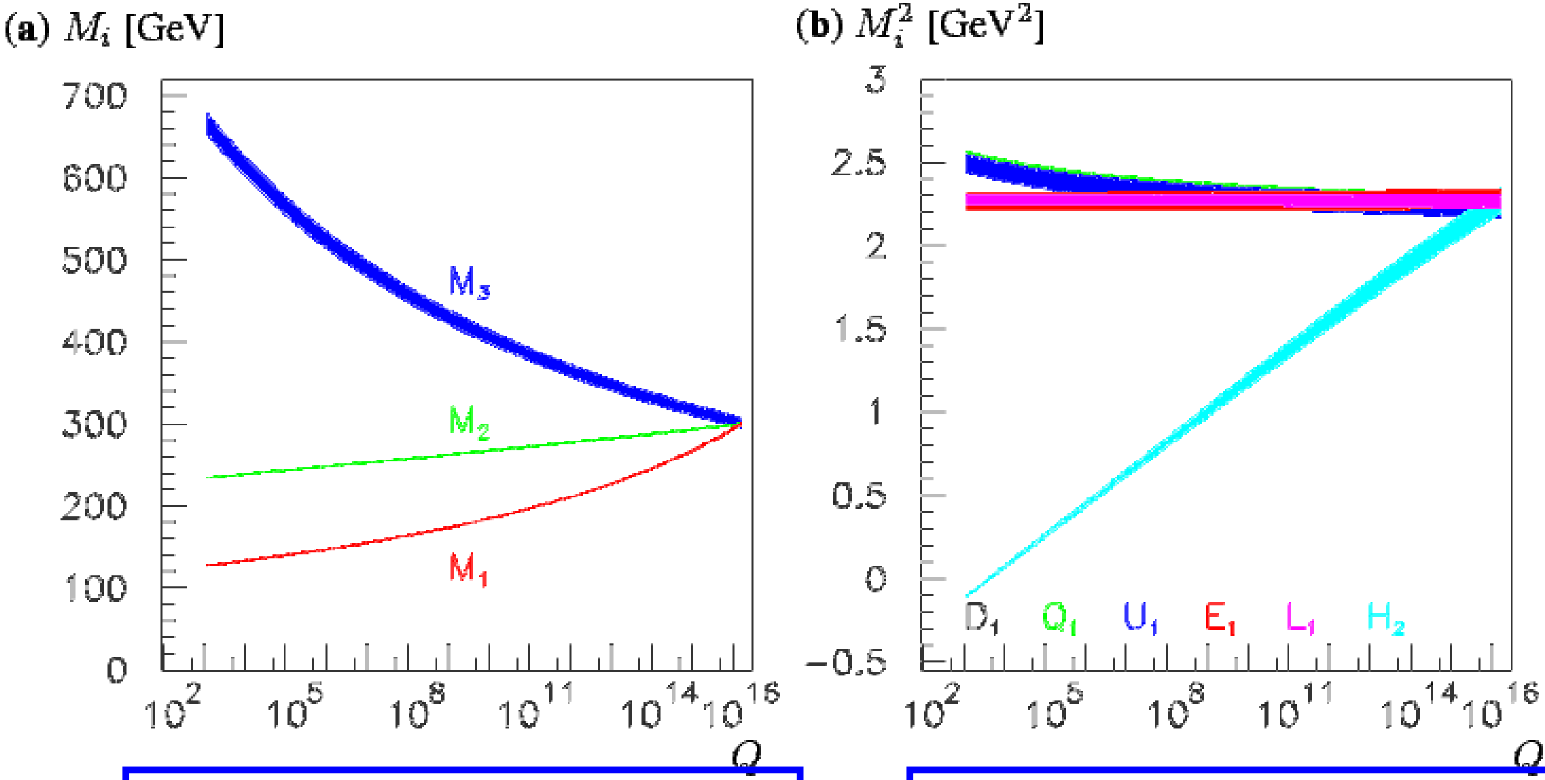
Point E: m_μ = ~1500 GeV
Point H: m_μ =~1000 GeV

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	$\pm$ 11
H	$\tilde{\mu}_L$	Std.	0/0	3.0-3.5	1	$\pm$ 15
E	$\tilde{\mu}_L$	none	0/0	3.8-4.2	1	$\pm$ 29
E	$\tilde{\mu}_L$	Std.	0/0	3.8-4.2	1	$\pm$ 36
E	$\tilde{\mu}_L$	none	80/60	3.8-4.2	1	$\pm$ 17
E	$\tilde{\mu}_L$	Std.	80/60	3.8-4.2	1	$\pm$ 22

→ Mass measurements to O(1%) possible

Importance of Precision Measurements

Reconstruct the theory at the high scale from measured masses and cross sections, evolve with Renormalization Group Equations.
Do the masses unify at a higher GUT scale?
⇒ Precision measurements are crucial!



1σ bands for 1% mass errors

GeV

Gaugino mass parameters

1st generation sfermion parameters

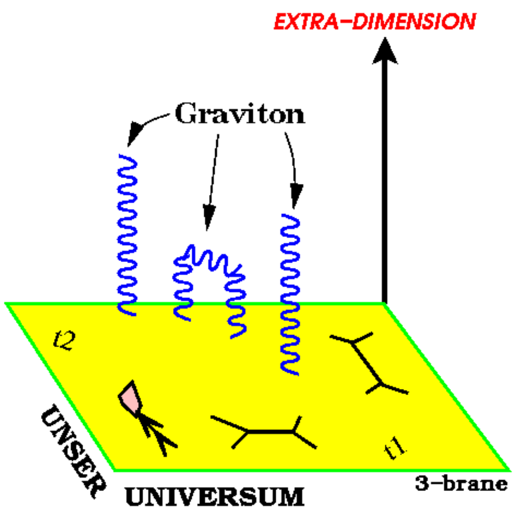
SUSY: Strength of a Multi-TeV Collider

- Complete the SUSY spectrum further (extended reach w.r.t. LC and LHC)
- Measure properties of sparticles with linear collider type of precisions in the high mass range (e.g. masses up to 1%, spin, mixing angles, tanβ, gaugino couplings, slepton quantum numbers…) → see CLIC Report for details

Smuon mass, 1 ab^{-1}

$\delta p/p^2$	Beamstrahlung	Fit Result (GeV)
0.	none	1150 ± 10
3.0×10^{-5}	none	1150 ± 12
4.5×10^{-5}	none	1151 ± 12
4.5×10^{-5}	Std.	1143 ± 18

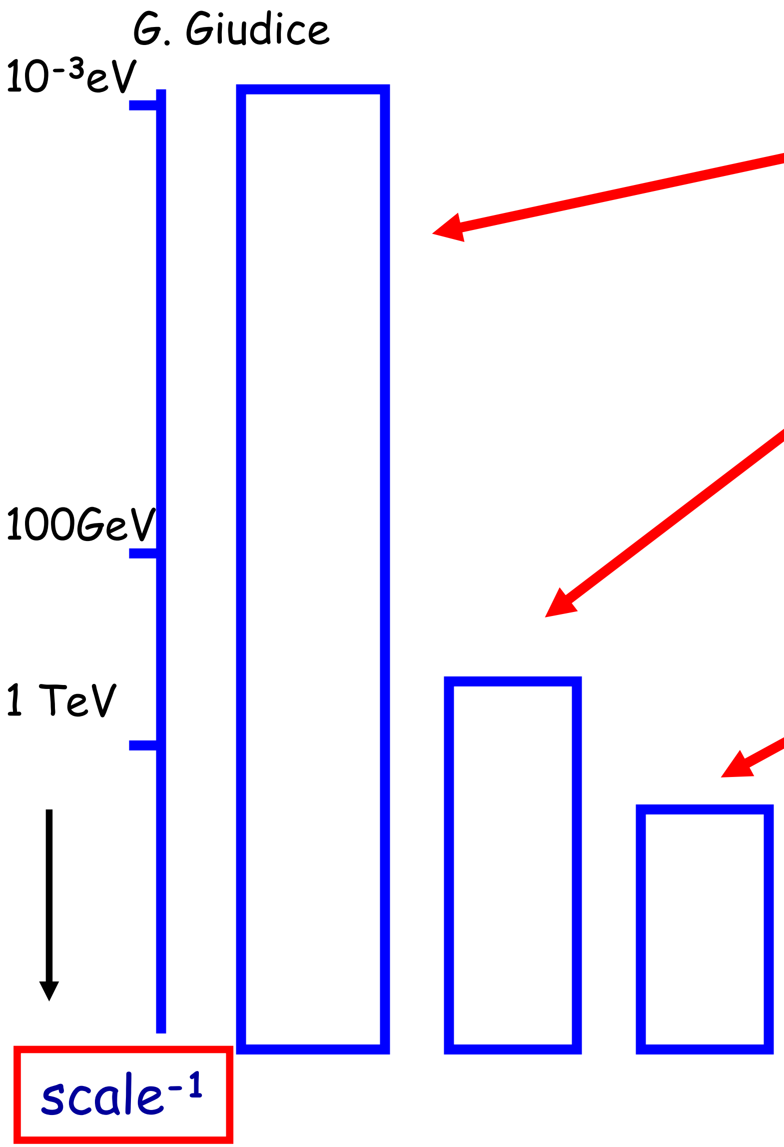
4. Large Extra Dimensions



Idea of from String Theory:
Assumes a total of ~11 space-time dimensions

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

Large Extra Dimensions



Large Extra dimensions (ADD)
Gravity in bulk / flat space
Missing energy/interference/black holes

$$ds^2 = G_{IJ}dx^I dx^J = \eta_{\mu\nu}dx^\mu dx^\nu + h_{ij}(y)dy^i dy^j \ ,$$

Warped Extra Dimensions (Randal-Sundrum)
Gravity in bulk / curved space
Spin 2 resonances > TeV range

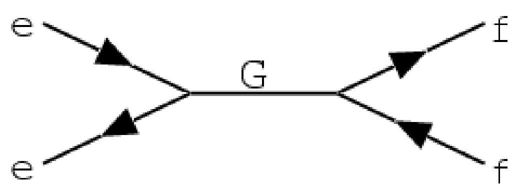
$ds^2 = e^{-2ky}\eta_{\mu\nu}dx^\mu dx^\nu - dy^2 \,,$ k = warp factor

TeV Scale Extra Dimensions (Antoniadis et al.)
Gauge bosons/Higgs in the bulk
Spin 1 resonances > TeV range
Interference with Drell-Yan

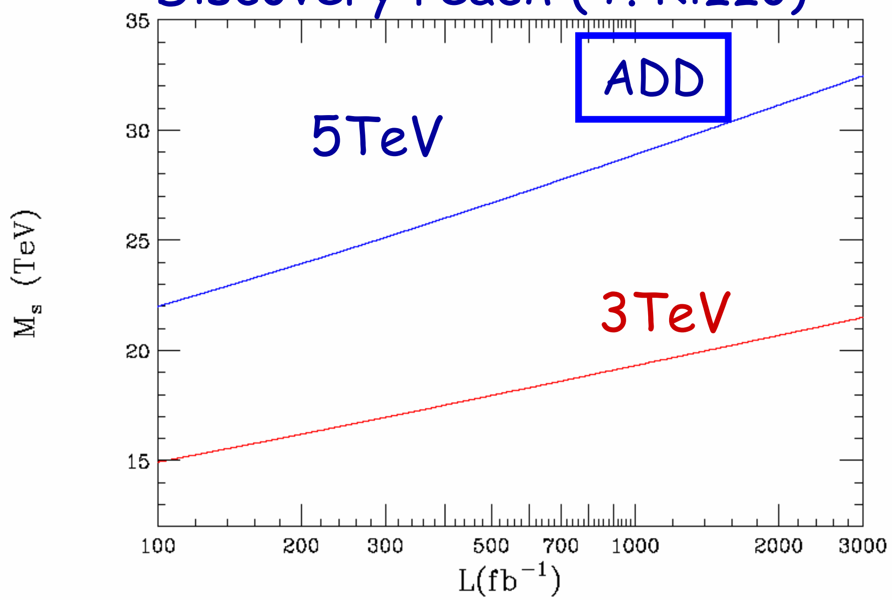
Universal Extra Dimensions (Appelquist et al.)
Everybody in the bulk!
Fake SUSY spectrum of KK states
+ many combinations/variations

Extra Dimension Reach

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



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	$e^+e^- \rightarrow f\bar{f}$	$6.5\sqrt{s}$
$\gamma\gamma$ Collider	100	$\gamma\gamma \rightarrow WW$	$11\sqrt{s}$
LHC	100	$p\bar{p} \rightarrow t\bar{t}$	6.0

CLI

KK Towers

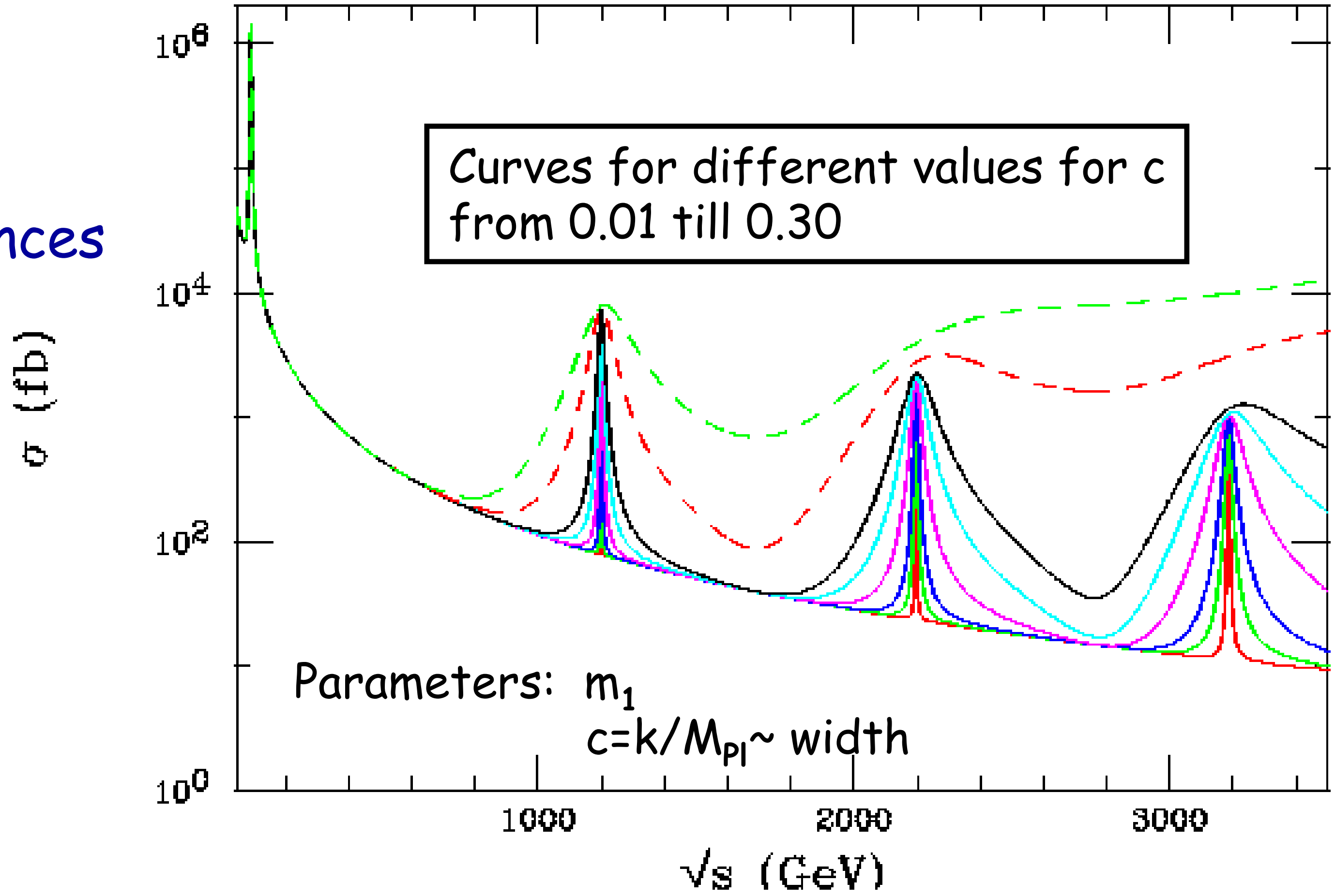
Extra Dimensions Randall-Sundrum phenomenology (curves by T. Rizzo)

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…)



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

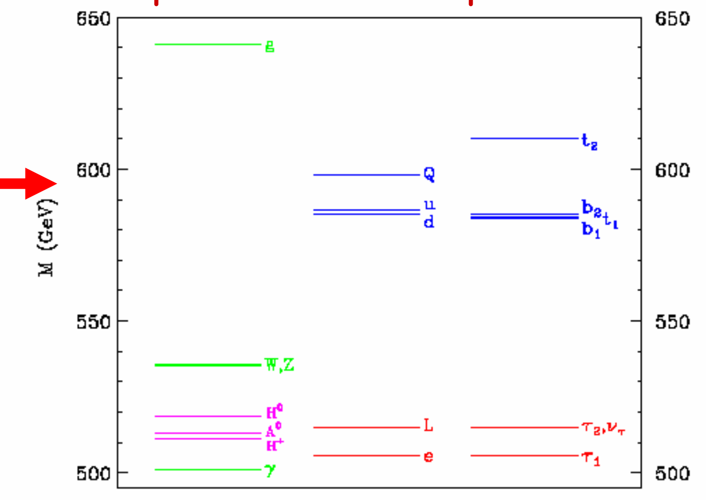
Universal Extra Dimensions UED

- 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)

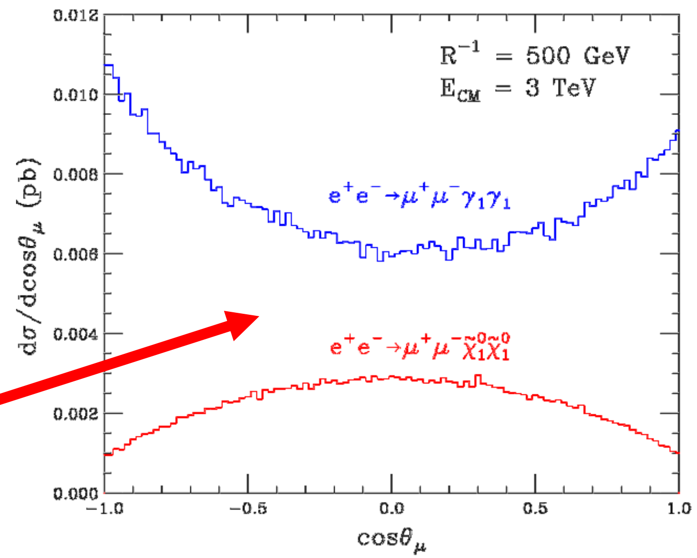
  ⇒ ? Did we discover SUSY or UEDs?
- Important difference: spin of the KK same as SM partner, while it differs by ½ from SUSY sparticles
  → measure spin
- Not easy at the LHC but doable at a LC
- Compare SUSY/UED for 500 GeV (s)muons

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

KK partners mass spectrum



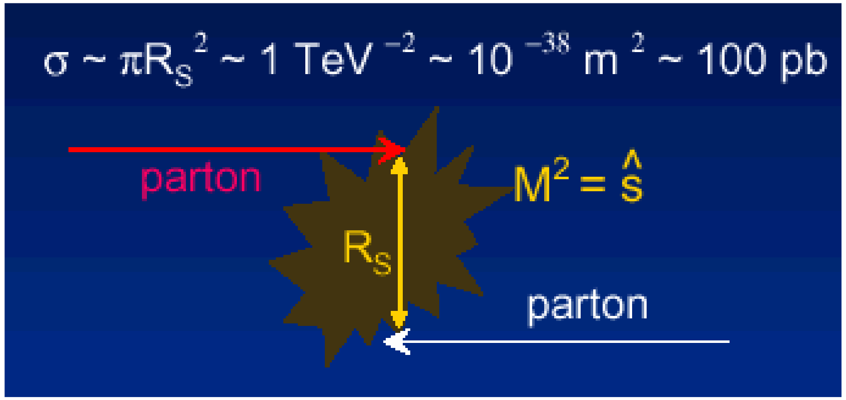
Production polar angle θ of the decay muons



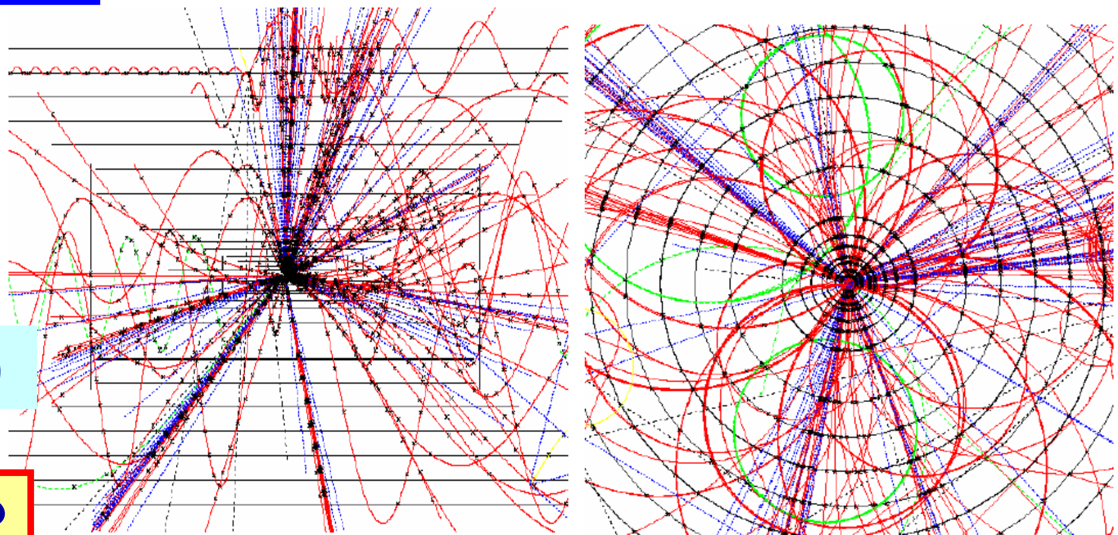
Black Holes

If M_{planck} ~ O(1 TeV) ⇒ Black Hole production at Multi-TeV Scale

- $\sigma = \pi R_s^2 \sim 1\ TeV^{-2} \sim O(100)$ pb
  R_s = Schwarzschild Radius
- If $\sqrt{s}_{e+e-} > M_{BH} > M_{planck} \rightarrow$ BH factory
- BH lifetime ~ 10^{-25}-10^{-27} sec
- Decay via 'Democratic' Hawking Radiation



Many jets, 2% hard photons leptons, 10% leptons



Large cross sections O(100-1000 pb)

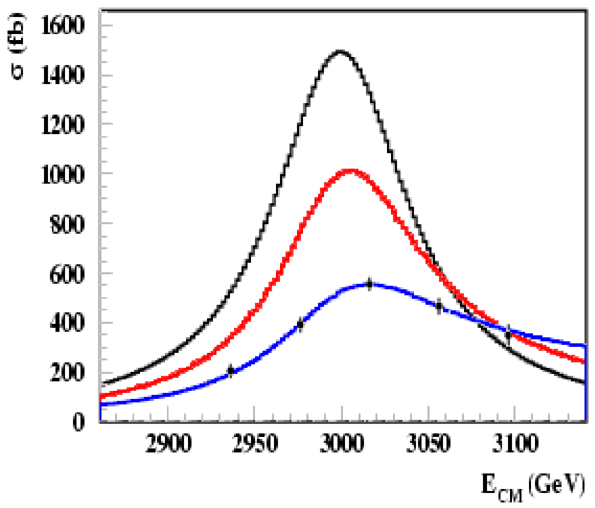
Study Quantum Gravity in the lab?

EDs: Strength of a multi-TeV collider

- Extended sensitivity to Extra Dimensions into several tens of TeV range
- Can observe directly/study KK resonances in the few TeV range. Measure quantum numbers and properties precisely. Distinguish between models.
- Large lever arm in energy to study more complicated ED scenarios such as soft branes
- If the Planck scale is O(1 TeV) $\rightarrow$ micro black hole production. Study quantum gravity in the lab

ED (ADD)	30 TeV (e^+e^-)
	55 TeV ($\gamma\gamma$)
ED (RS)	18 TeV (c=0.2)
ED (TeV^{-1})	80 TeV
Black Holes	5 TeV

5. New Gauge Theories Contact Interactions etc.



- New Z' resonances in the TeV range
- WW scattering (Higgsless models)
- Little Higgs models
- Triple Gauge couplings
- Contact interactions
- Excited lepton production
- Production of 4th family quarks and leptons
- Leptoquarks
- non-commutative interactions
- Transplanckian effects
- Lepton size measurements

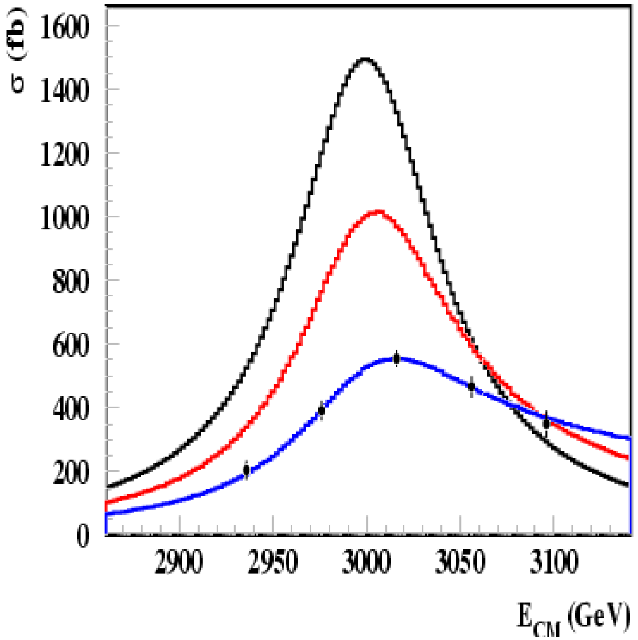
Z' with mass < 3 (5) TeV

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

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

✦ Compute $\sigma(e^+e^- \rightarrow Z')$ 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:

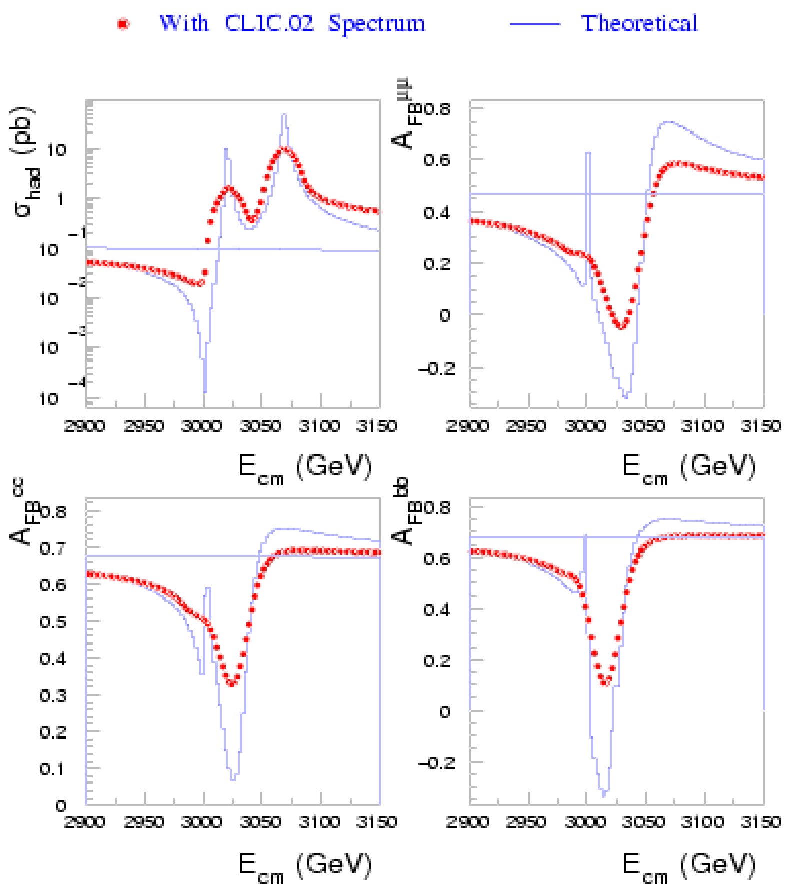


FIT ACCURACY Calibrated

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^{eff}_{peak} (fb)	1493 ± 2.0	564 ± 1.7	669 ± 2.9

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

Degenerate Resonances



Smearing due to the lumi spectrum of CLIC

E.G. Degenerate BESS Model (Strong EWSB)

D. Dominici, De Curtis, M. Battaglia

Two (almost) degenerate Triples $L_3, L_3^{\pm}, R_3, R_3^{\pm}$

Sensitivity to L_3 and R_3 with M =3 TeV for L =500 fb^{-1} at LHC and L =1000 fb^{-1} at CLIC

g/g''	M (GeV)	Γ_{L_3} / Γ_{R_3} (GeV)	$S/\sqrt{S+B}$ LHC $(e+\mu)$	$S/\sqrt{S+B}$ CLIC (had.)	ΔM CLIC
0.1	3000	2.0 / 0.3	(3.4)	62	23.20 ± .06
0.2	3000	8.2 / 1.2	(6.6)	152	83.50 ± .02

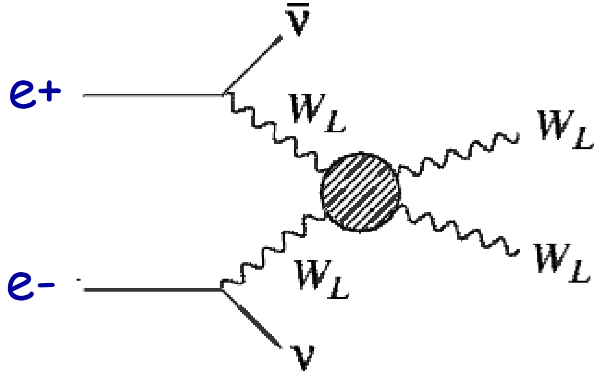
Energy Scan of Narrow Resonances $(g/g'' = 0.15)$

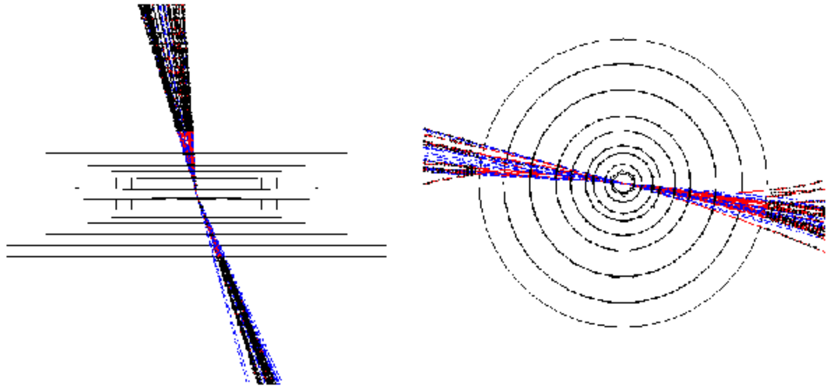
CLIC: can measure ΔM down to 13 GeV $(g/g'' > 0.08)$

CLIC can disentangle two nearby resonances

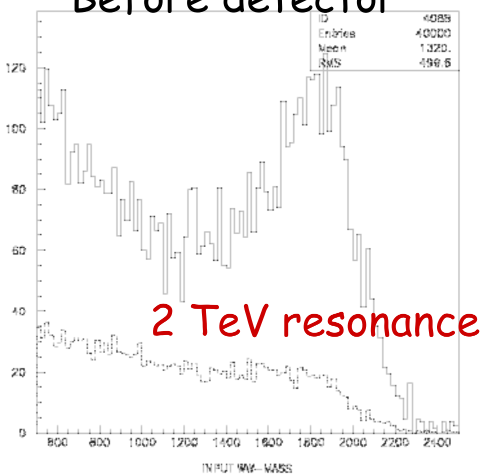
WW Scattering

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

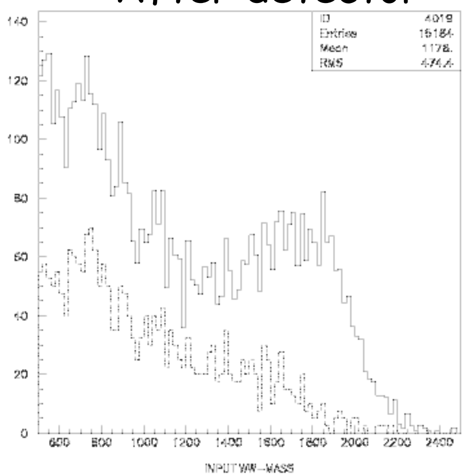




Before detector

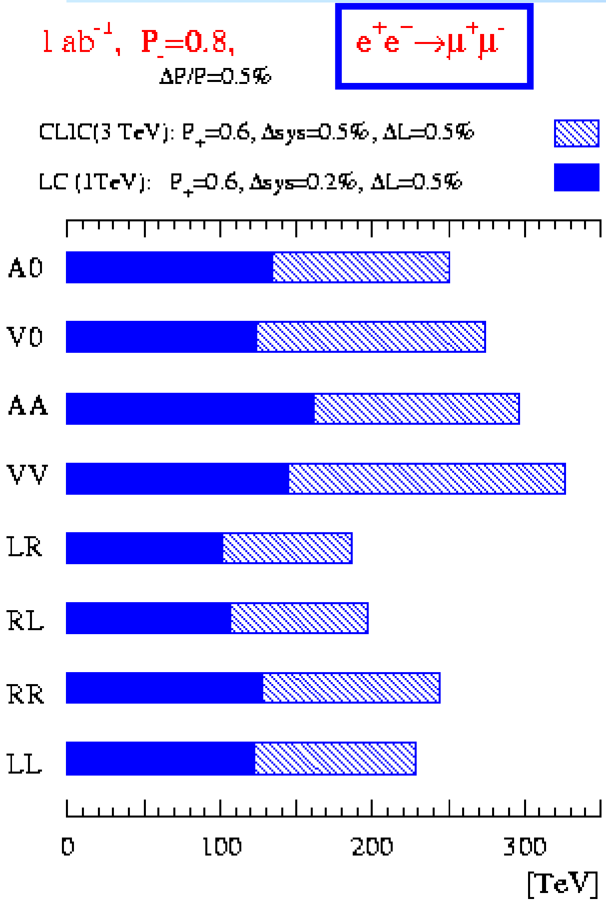


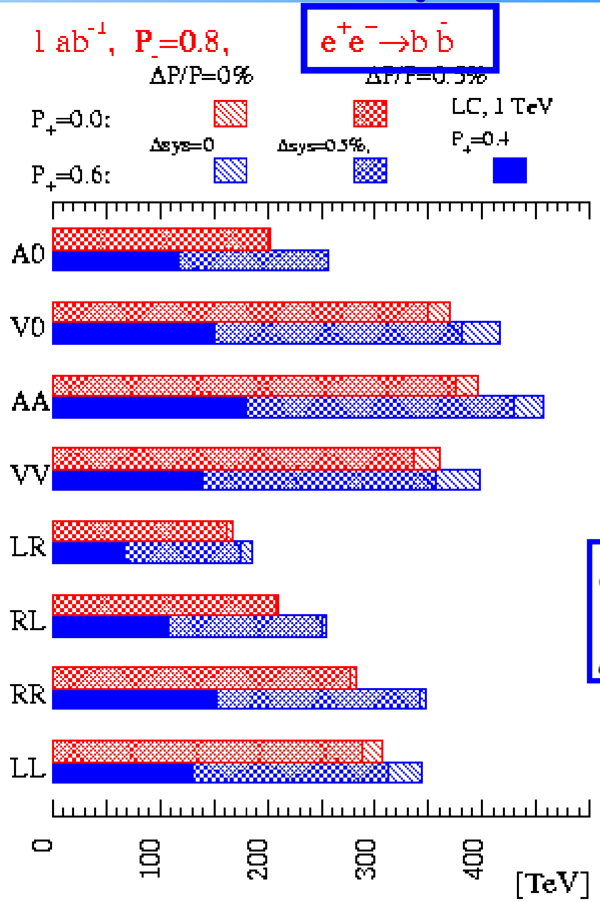
After detector

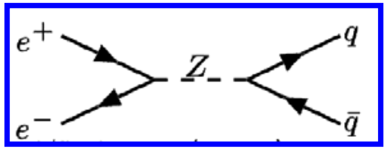


Resonances can form in the TeV range that can be observed directly (difficult at the LHC)

Reach to Probe New Physics







⇒ Contact Interactions: sensitivity to scales up to 100-400 TeV

Ultimate: 5 ab^{-1} at 5 (10) TeV → 400-800 (500-1000) TeV

Note If Higgs light → something new must happen before 1000 TeV

Summary: CLIC vs Hadron Colliders

ADR, F. Gianotti, J. Ellis hep-ph/0112004 + updates
U. Bauer et al. hep-ph/0201227

Process	LHC 14 TeV 100 fb^{-1}	SLHC 14 TeV 1000 fb^{-1}	VLHC* 200 TeV 100 fb^{-1}	CLIC 3-5 TeV 1000 fb^{-1}
squarks (TeV)	2.5	3	20.	1.5-2.5
sleptons (TeV)	0.34			1.5-2.5
Z' (TeV)	5.4	6.5	30-40	20-30
q^* (TeV)	6.5	7.5	70-75	3-5
l^* (TeV)	3.4			3-5
ED (ADD/2D/TeV)	9	12	65	30-55
$W_L W_L$	3.4 σ	$>$ 4.0 σ	30 σ	70-90 σ
TGC (95%)	0.0014	0.0006	0.0003	0.00013- 0.00008
Λ Compos (TeV)	30	40	100	300-400

CLIC Comparable to VLHC

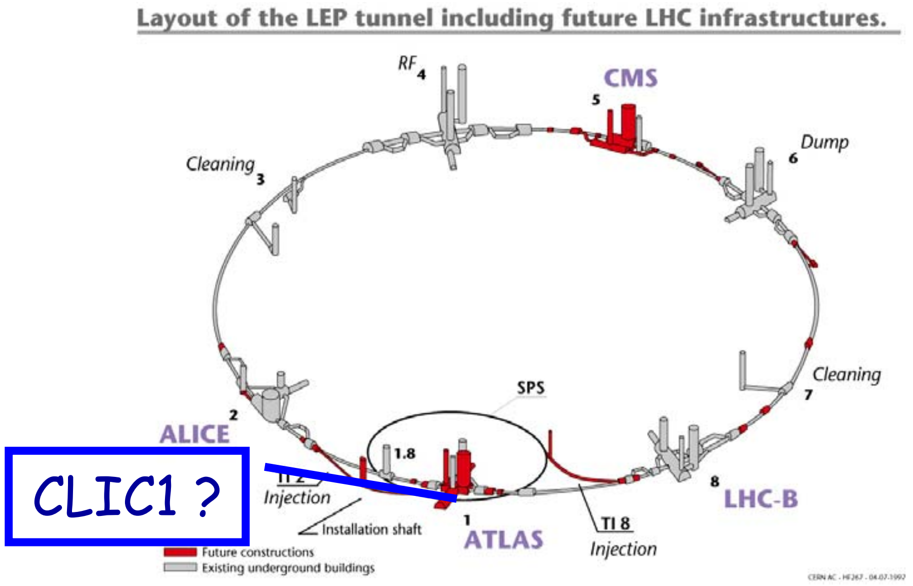
* Very Large Hadron Collider: 233 km Circumference

CLIC physics studies: The next phase

$\Rightarrow$ Start in 2005

- New & more detailed studies on physics processes
  - Some processes have been just touched upon, others are new
  - Some new backgrounds identified (muons)
- Detector optimization
  - Study so far uses a somewhat adapted TESLA detector
- Initiate/link with real detector R&D
  - If (tracker, calorimeter, timestamping)
- Study options based on CLIC ? I.e. lower energy 'start up' options
  - ep option (γp,γA options)
  - CLICHE ($\gamma\gamma$ collider Higgs factory)
  - Z/WW factory
  - e+e- Higgs factory
  - Compare with TeV class collider (0.5-1 TeV)
  - Full energy $\gamma\gamma$ and $e\gamma$ option for CLIC

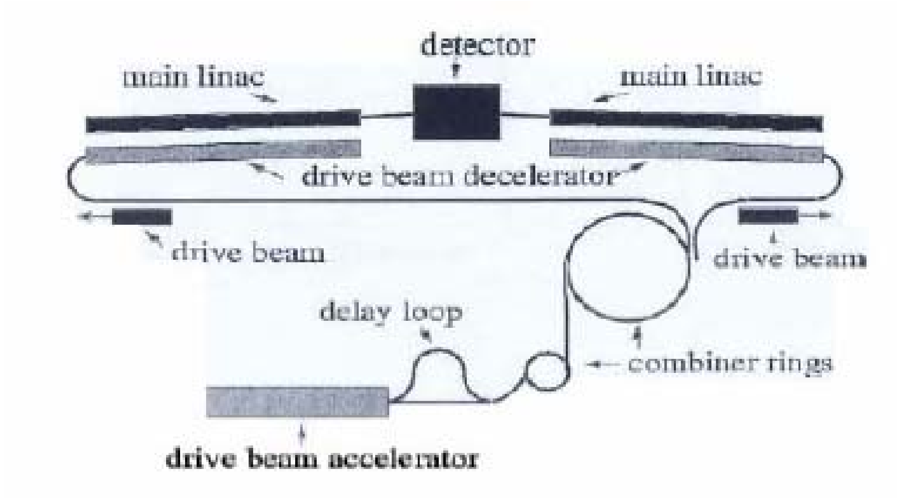
Possible Low Energy (Startup) Facilities



A CLIC sections⇒
length = 624 m
maximum E_{BEAM}= 68 GeV

CLIC⊗LHC

- 1 CLIC module
- 70 GeV ⊗ 7 TeV ep collisions
- $\sqrt{s} \sim 4 \sqrt{s_{HERA}}$
- L= 10^{28} to 10^{30}-10^{31} $cm^{-2}s^{-1}$ (see CLIC Note 589)



Z or WW factory

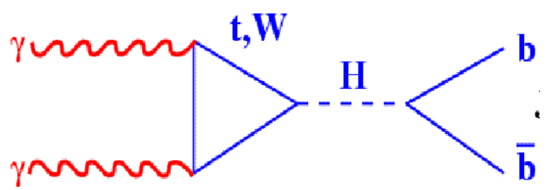
- 2 modules
- Luminosity 8•10^{33} ⇒ > 2•10^9 Z/year
- Needs both e+e- beams
- Optimal with polarization of both beams

CLICHE

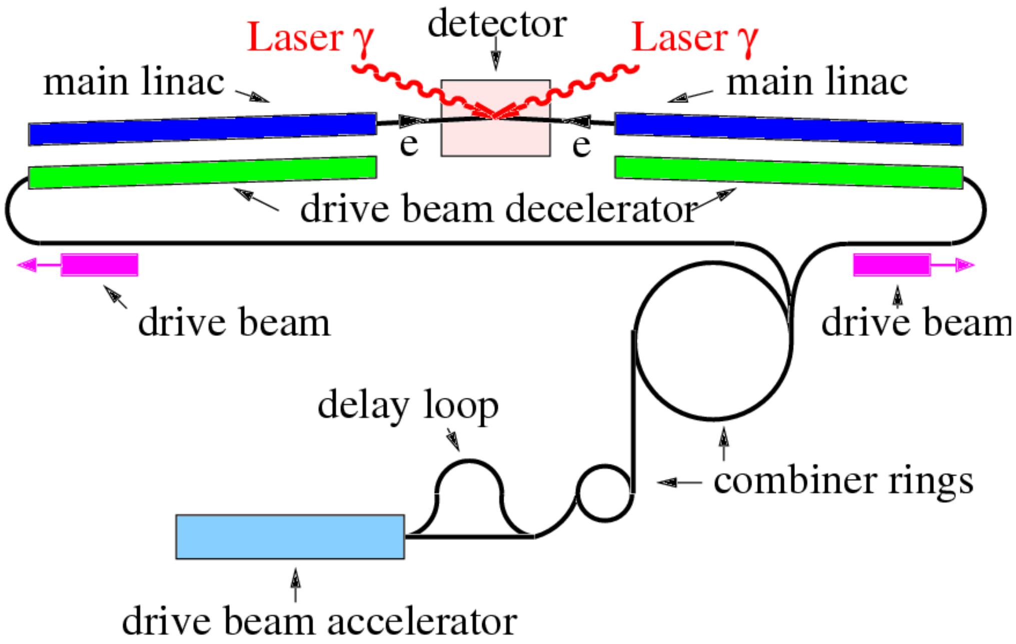
D. Asner et al., hep-ex/0111056

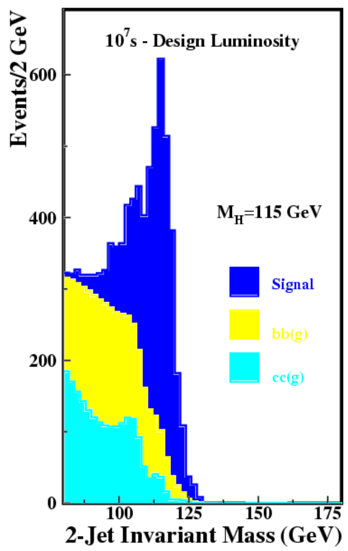
CLICHÉ: CLIC Higgs Experiment
- Photon collider mode (R&D phase)
- 2 CLIC sections + lasers
- Higgs factory & more

Production Mechanism for Neutral Higgs Bosons



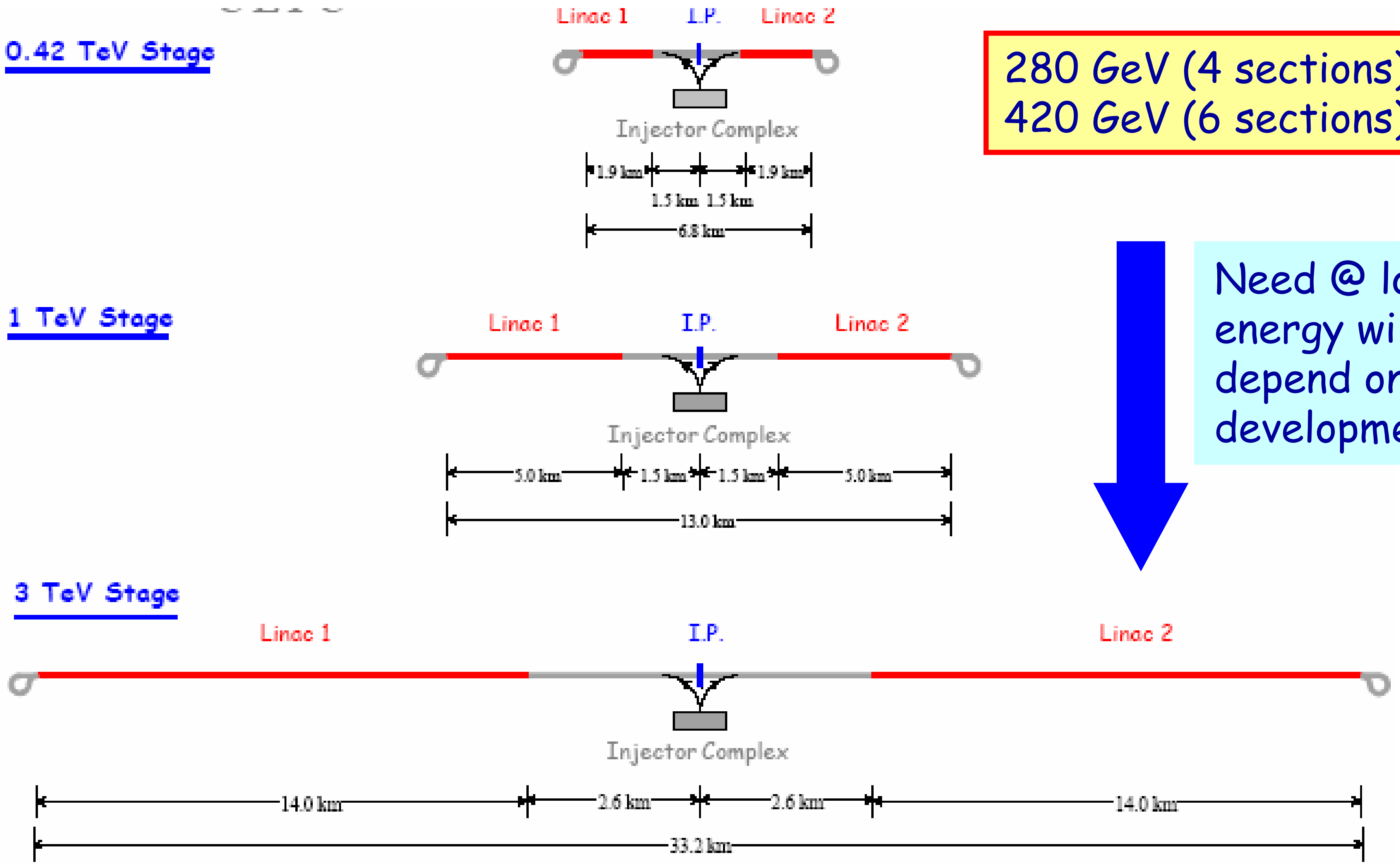
70-75 GeV beams
Convert electron into photon beams





Approx 16,000 Higgs/year

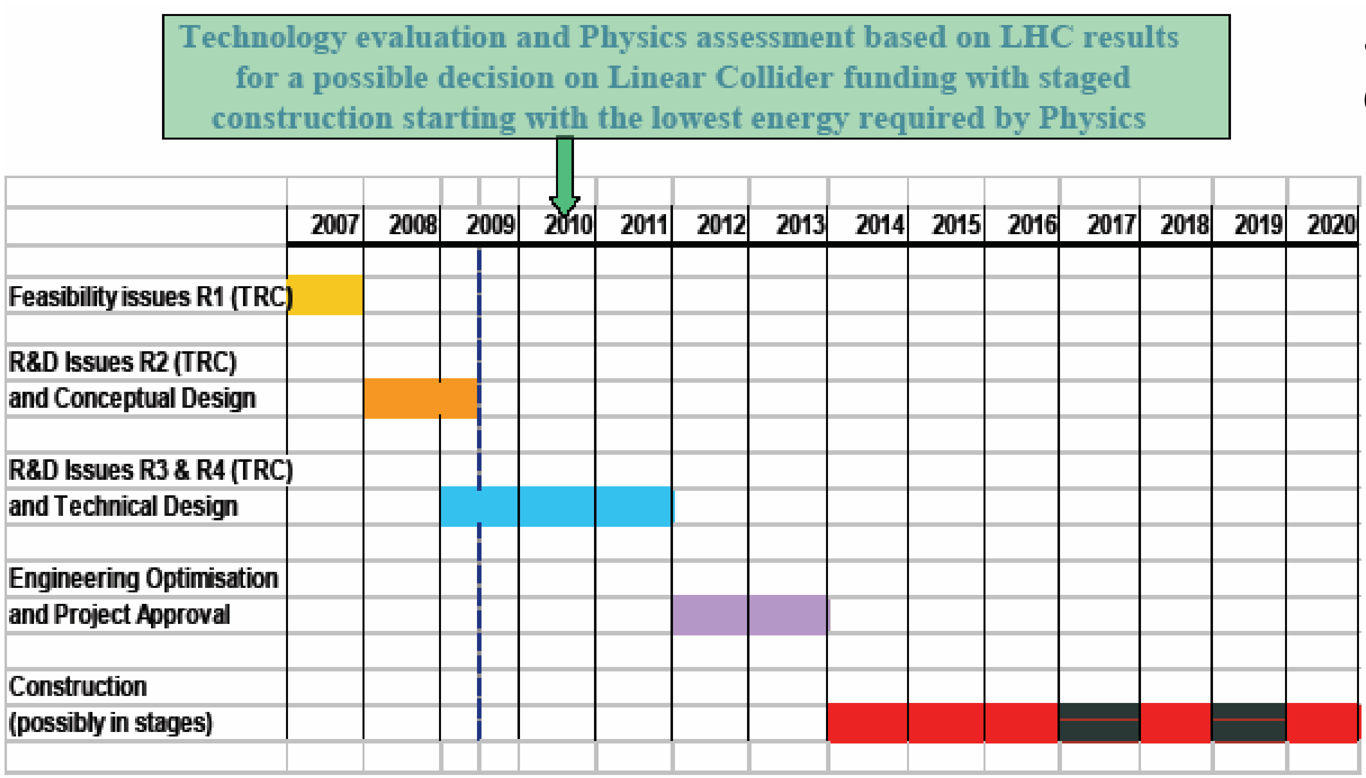
Staged e+e- Collider



280 GeV (4 sections) or
420 GeV (6 sections)

Need @ lower energy will depend on ILC developments

CLIC: shortest and technically limited schedule



J.P. Delahaye
Gif 2004

Assumes extra resources via CLIC collaboration

CLIC is working together with ILC on common issues
CARE, EuroTeV

Comparison ILC schedule
- CDR 2005 (GDI context)
- TDR 2007
- Site selection 2008?
- Ground breaking 2009-2010? (if budget in place)

Decision on what machine to built will depend on
- Proof of feasibility at the time
- Physics landscape: LHC results

⇒ Expect debate ~2009/2010

Summary: Physics at CLIC

Measurements at CLIC (5 TeV / 1 ab^{-1})

Higgs (Light)	λ_{HHH} to $\sim 5-10\%$ (5 ab^{-1})
Higgs (Light)	$g_{H\mu\mu}$ to $\sim 3.5-10\%$ (5 ab^{-1})
Higgs (Heavy)	2.0 TeV (e^+e^-) 3.5 TeV ($\gamma\gamma$)
squarks	2.5 TeV
sleptons	2.5 TeV
Z' (direct)	5 TeV
Z' (indirect)	30 TeV
l^*, q^*	5 TeV
TGC (95%)	0.00008
Λ compos.	400 TeV
$W_L W_L$	>5 TeV
ED (ADD)	30 TeV (e^+e^-)
	55 TeV ($\gamma\gamma$)
ED (RS)	18 TeV (c=0.2)
ED (TeV^{-1})	80 TeV
Resonances	$\delta M/M, \delta\Gamma/\Gamma \sim 10^{-3}$
Black Holes	5 TeV

Experimental conditions at CLIC are more challenging than at LEP, or ILC

Physics studies for CLIC have included the effects of the detector, and backgrounds e.g e+e- pairs and $\gamma\gamma$ events.

Benchmark studies show that CLIC will allow for precision measurements in the TeV range

CLIC has a very large physics potential, reach beyond that of the LHC.

Urgent: Detector R&D will be needed: Tracking with good time stamping, improved calorimetry, mask area,...