Physics @ CLIC

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:

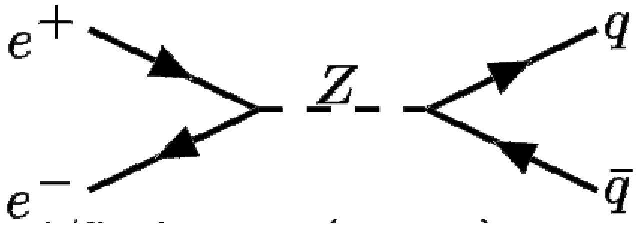
⇒TeV Colliders (cms energy up to 1 TeV) → ~Technology ready

NLC (US)	Warm technology (X band)
GLC (Japan)	Warm technology (X and C band)
TESLA (DESY/Europe)	Superconducting technology

⇒Multi-TeV Collider (cms energy up to 1 TeV) → R&D

CLIC (CERN/Europe)	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%; e+ 60%)
  - Beams are used once, so can be converted e.g. via Compton scattering (photon collider)
- Disadavantages:
  - Lower energy reach than pp (ppbar) machines
  - Beams are used only once: more effort to make enough luminosity

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

R&D at CERN: CLIC

- An e^+e^- linear collider optimized for a c.m. energy of 3 TeV with $\mathcal{L} \cong 10^{35} cm^{-2} s^{-1}$

- Construction can be staged without major modifications, starting an experimental program at lower energies, if useful.

- Aim: 3 TeV collisions, complementing LHC/TeV class LC and breaking new ground, with a final stage up to 5 (10?)TeV

To achieve this within reasonable cost (length ~ 35-40 km), and not too many active elements:

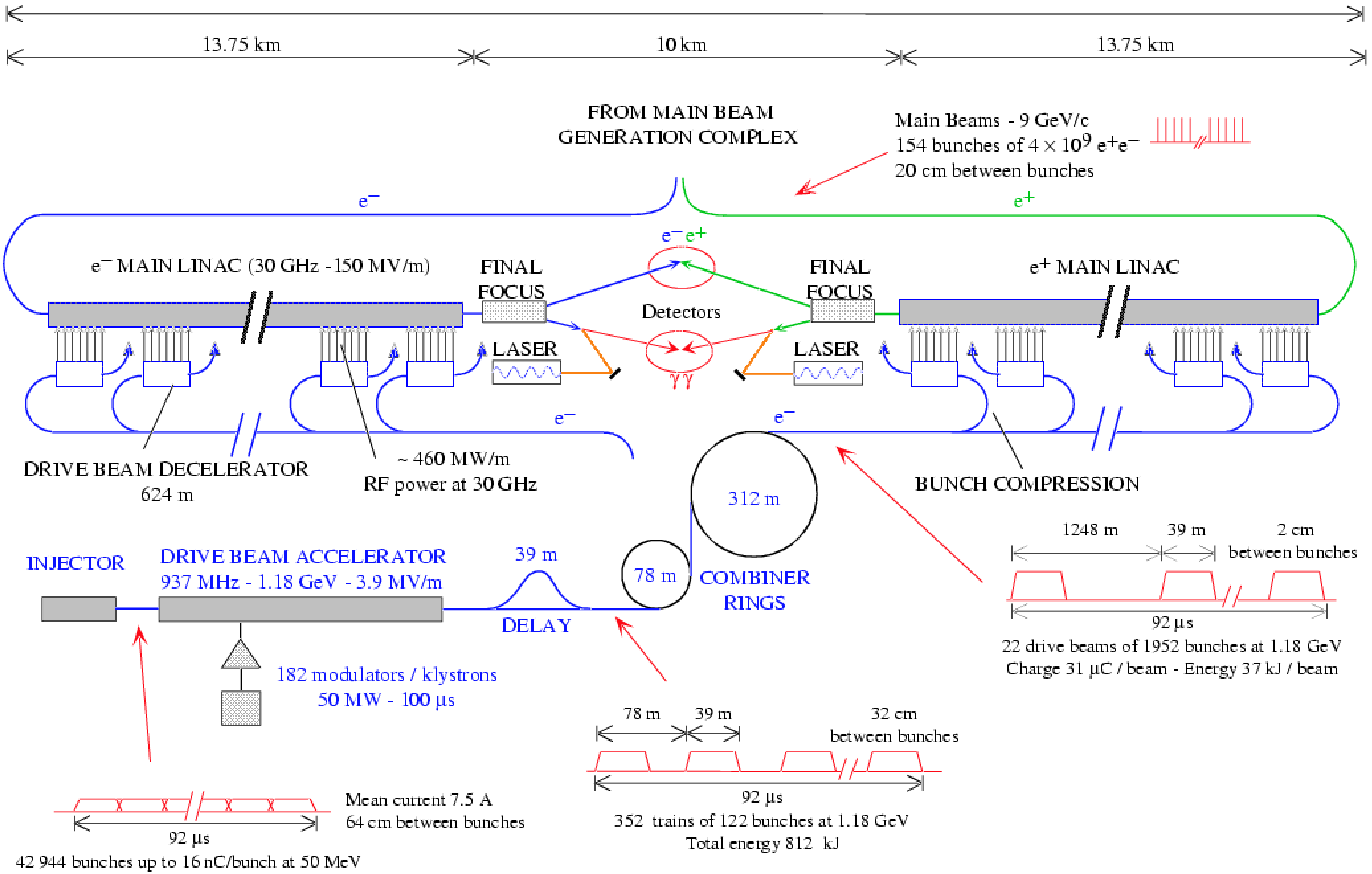
→ Accelerating gradient ~ 150 MV/m: Two Beam Acceleration (TBA)

→ High beamstrahlungs regime to reach luminosity

→ Challenging beam parameters and machine requirements (nm stability, strong final focus, 30 GHz accelerating structures,...)

⇒J.P Delahaye

- Status CTF2: 150-193 MV/m (15 ns pulses)
  CTF3: Under construction: 2002-2006 (drive beam test)



Main Beams - 9 GeV/c
154 bunches of 4×10^9 e^+e^-
20 cm between bunches

22 drive beams of 1952 bunches at 1.18 GeV
Charge 31 μC / beam - Energy 37 kJ / beam

Mean current 7.5 A
64 cm between bunches

42 944 bunches up to 16 nC/bunch at 50 MeV

352 trains of 122 bunches at 1.18 GeV
Total energy 812 kJ

FAQs (frequently asked questions)

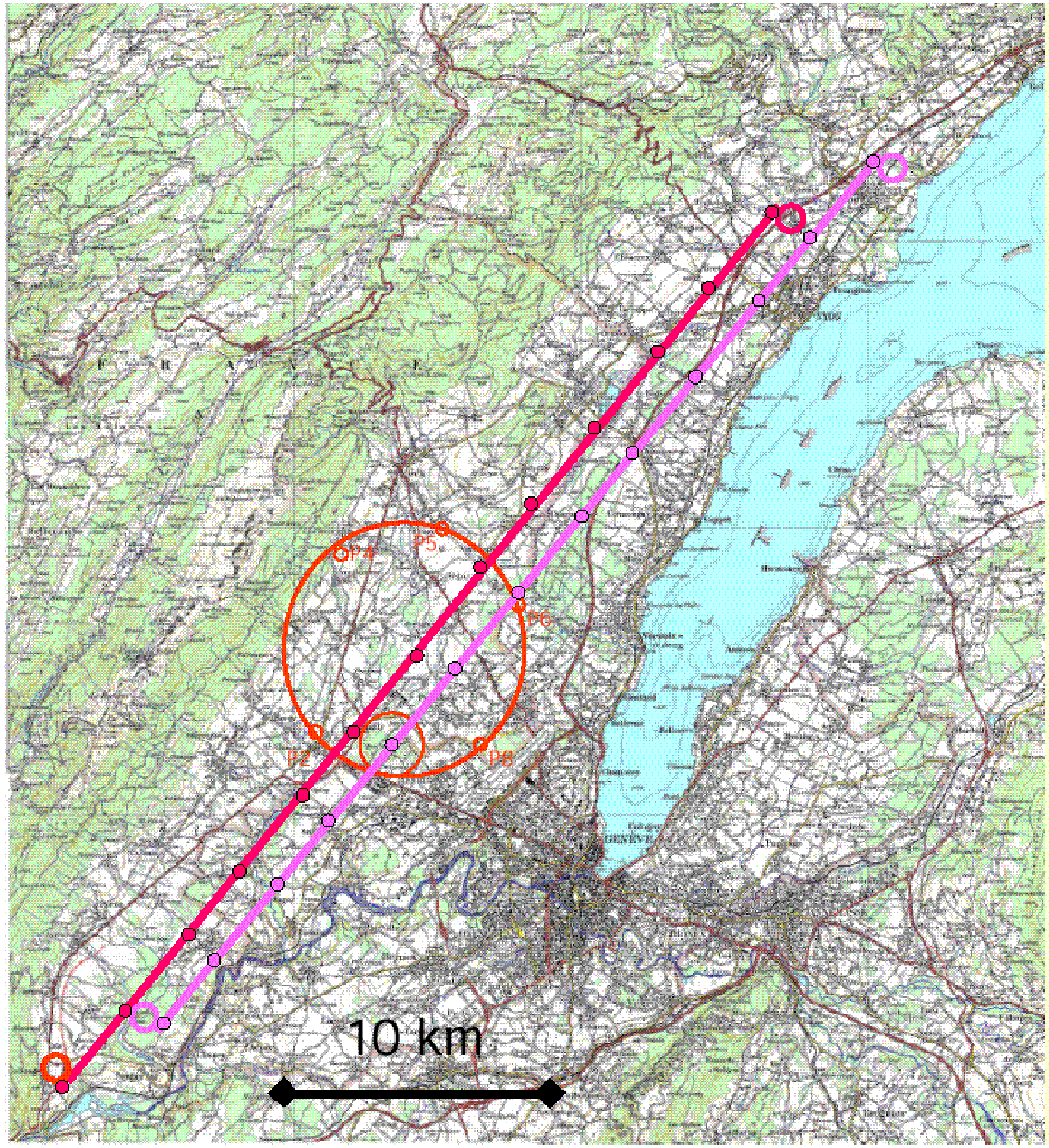
- Q: CLIC still in R&D state. How far is CLIC behind w.r.t. a TeV collider?
- A: O(5 years)

- Q: When will CLIC demonstrate its readiness as a technology for a LC?
- A: By 2009/2010 (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

- Q: What can we gain on physics reach with CLIC?
- A: → This lecture

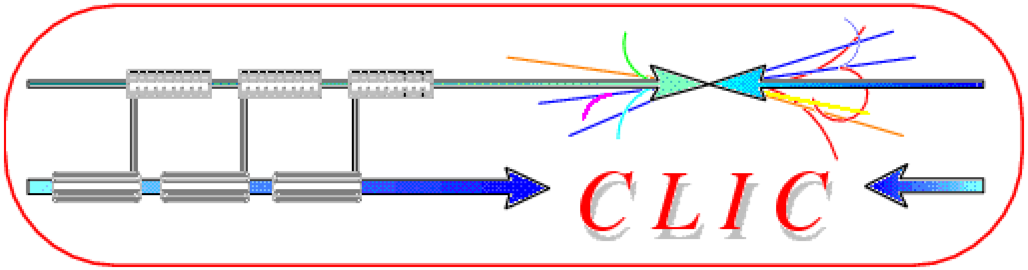
Building CLIC at CERN?



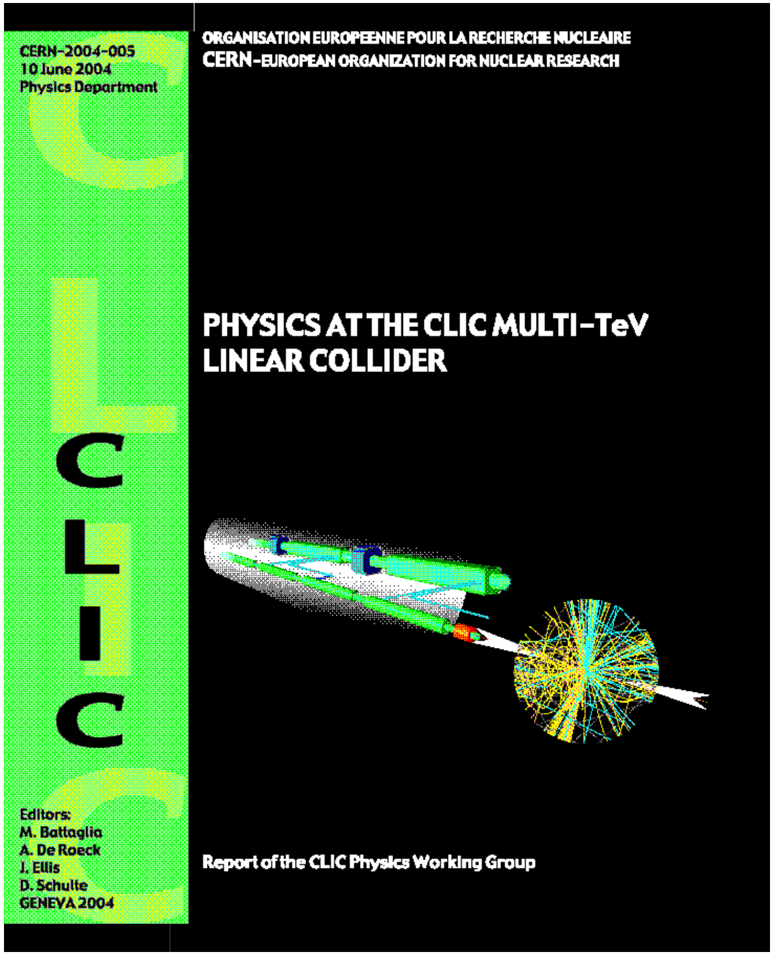
It is possible!

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

1. Experimenting at CLIC



CLIC Physics Report



CERN-2004-005
10 June 2004
Physics Department

ORGANISATION EUROPEENNE POUR LA RECHERCHE NUCLEAIRE
CERN-EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

PHYSICS AT THE CLIC MULTI-TeV LINEAR COLLIDER

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GENEVA 2004

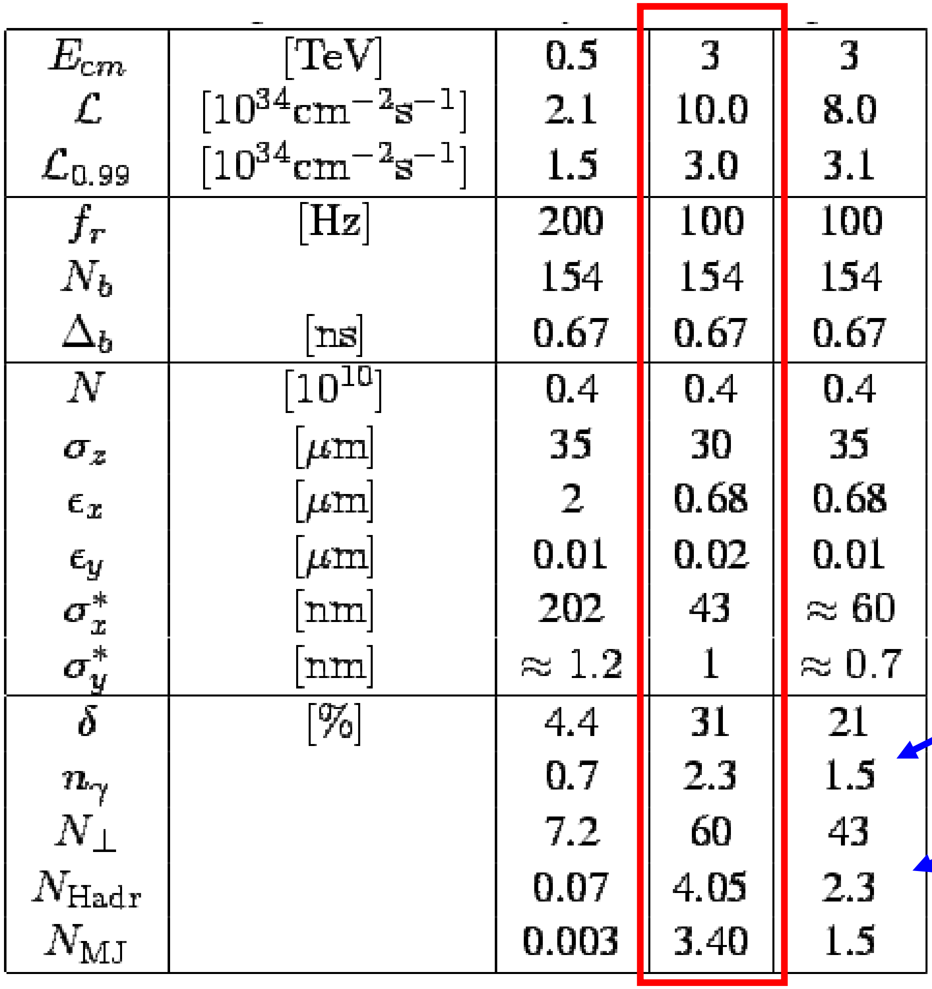
Report of the CLIC Physics Working Group

83 authors

Physics case for CLIC documented in
a new CERN yellow report CERN-2004-005

CLIC Backgrounds

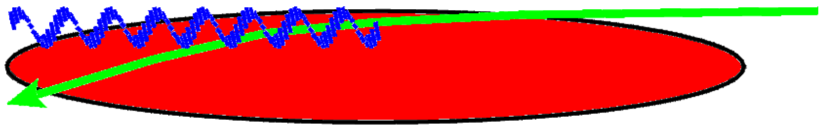
CLIC 3 TeV e+e- collider with a luminosity ~ $10^{35}\text{cm}^{-2}\text{s}^{-1}$ (1 ab^{-1}/year)



E_{cm}	[TeV]	0.5	3	3
$\mathcal{L}$	$[10^{34}\text{cm}^{-2}\text{s}^{-1}]$	2.1	10.0	8.0
$\mathcal{L}_{0.99}$	$[10^{34}\text{cm}^{-2}\text{s}^{-1}]$	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

old **new**

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



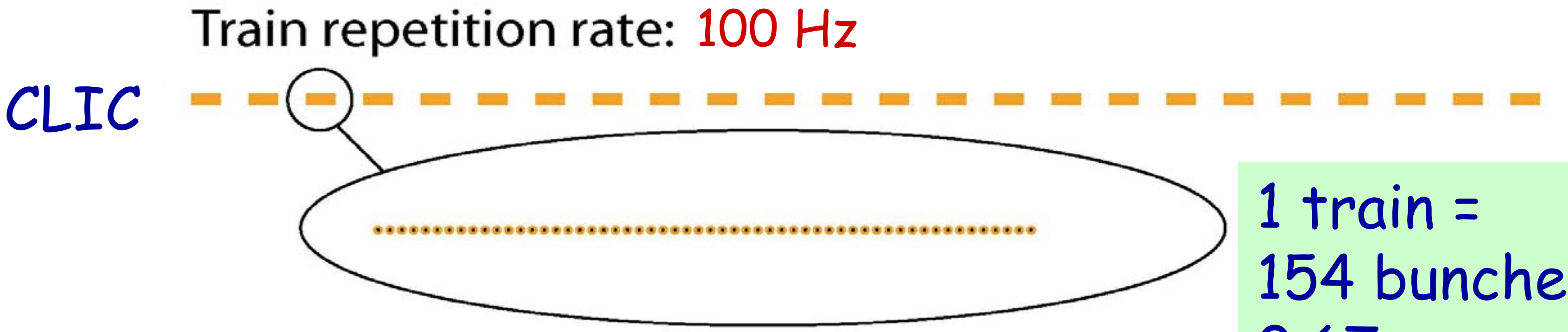
Expect large backgrounds

# of photons/beam particle

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

Expect distorted lumi spectrum

Time Structure of the Beams



1 train =
154 bunches
0.67 nsec apart
~ 20 cm

Sub-TeV colliders

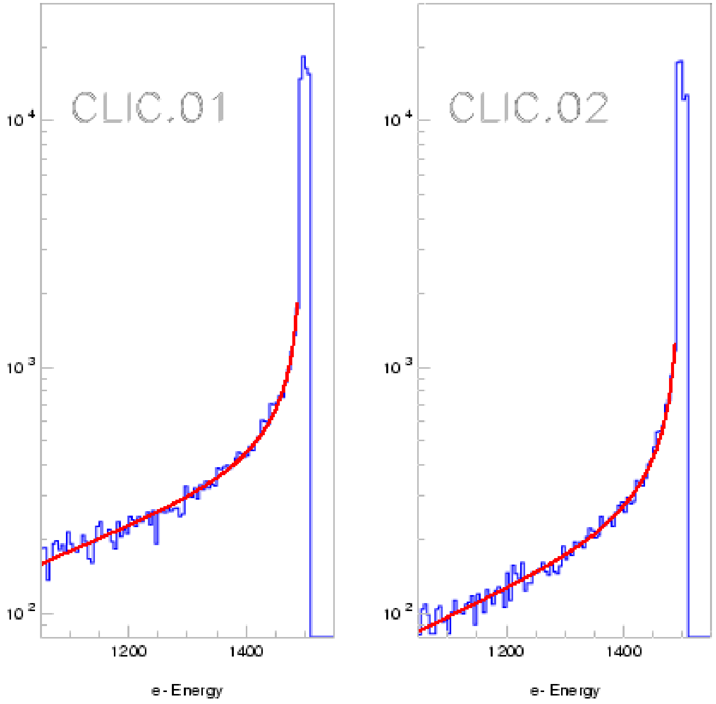
Warm technology
⇒ 120 Hz 1 train = 192 bunches 1.4 nsec apart

Cold technology
⇒ 5 Hz 1 train = 2820 bunches 336 ns apart

Experimenting at CLIC similar to the NLC

Luminosity Spectrum

Spectra for CLIC studies (sharper ↔ high lumi)



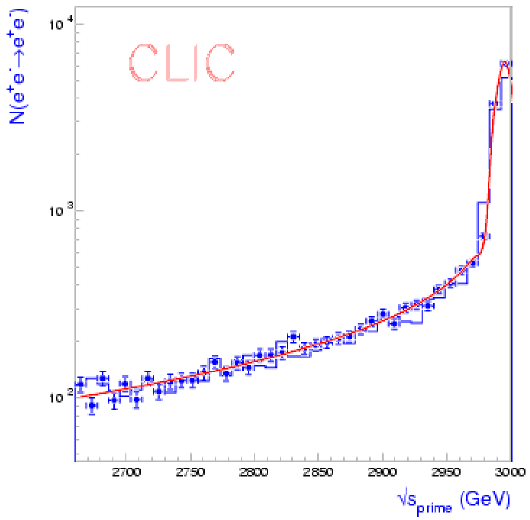
CLIC.01: $\mathcal{L} = 1.05 \times 10^{35}$ CLIC.02: $\mathcal{L} = 0.40 \times 10^{35}$

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

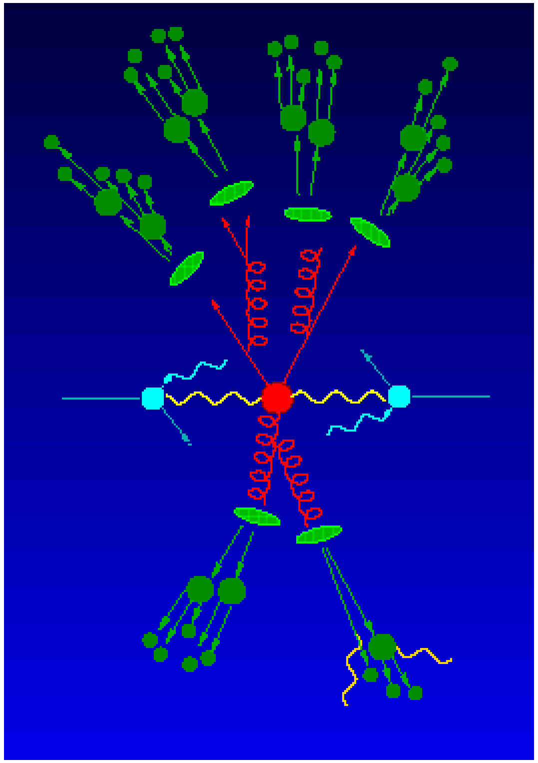


Preliminary Results: expect accuracy $\frac{\delta\sqrt{s'}}{\sqrt{s}} \simeq 10^{-4}$ for 100 fb^{-1}

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

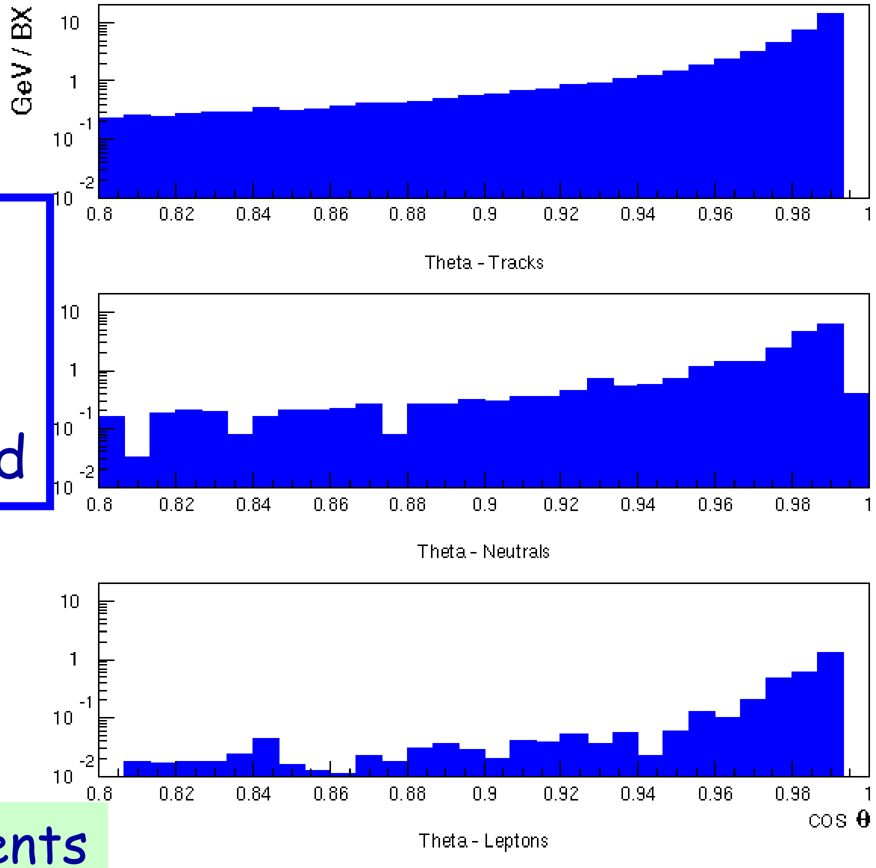
$\gamma\gamma$ Background

$\gamma\gamma \rightarrow$ hadrons: 4 interactions/bx with W>5 GeV



Neutral and charged energy as function of cosθ per bx

Particles accepted within θ > 120mrad

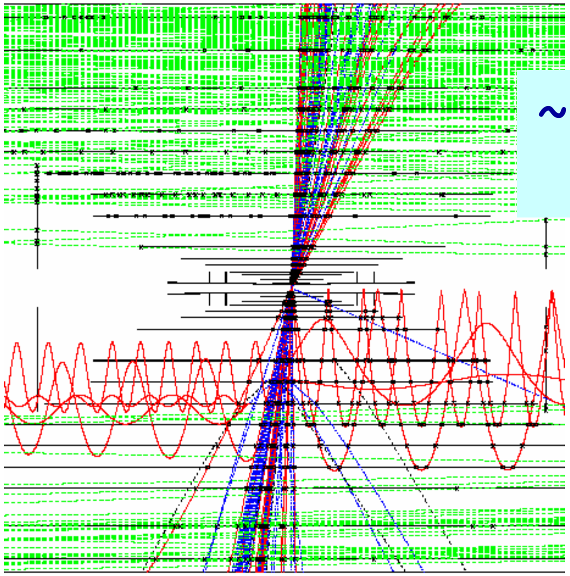


For studies: take 20 bx and overlay events

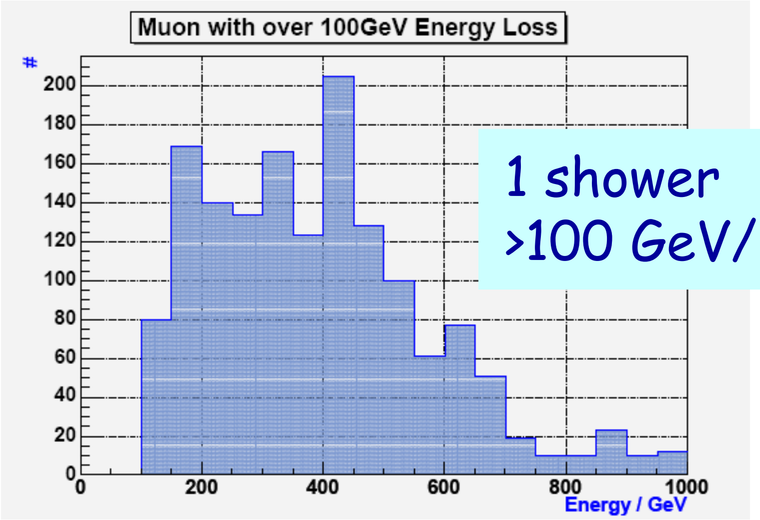
Most activity at small angles

Muon Background

$e^+e^- \rightarrow t\bar{t}$ AT $\sqrt{s} = 3$ TEV
+ MUON BACKGROUND (10 BX)



~20 muons per bx



1 shower >100 GeV/5 bx

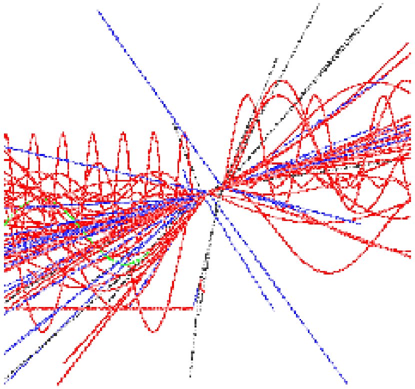
Muon pairs produced in electromagnetic interactions upstream of the IP e.g beam halo scraping on the collimators

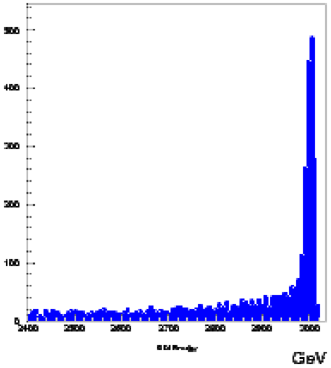
GEANT3 simulation, taking into account the full CLIC beam delivery system

# of muons expected in the detector ~ few thousand/bunch train (150 bunches/100ns)

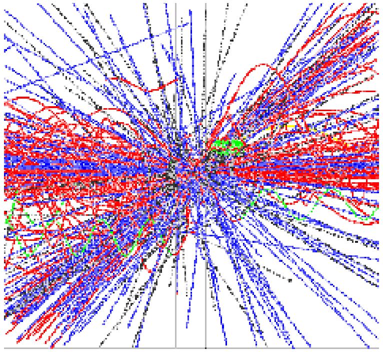
⇒ OK for (silicon like) tracker
⇒ Calorimeter?

CLIC Tools for Background/Detector

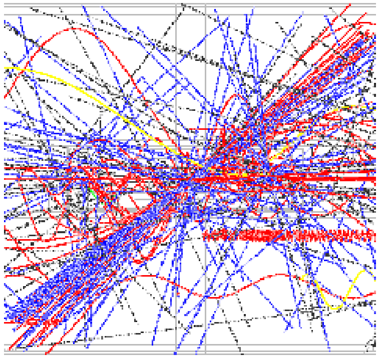




Physics generators (COMPHEP PYTHIA6,…)
+ CLIC lumi spectrum (CALYPSO)



+ γ γ→ hadrons background
e.g. overlay 20 bunch crossings
(+ e+e- pair background files…)

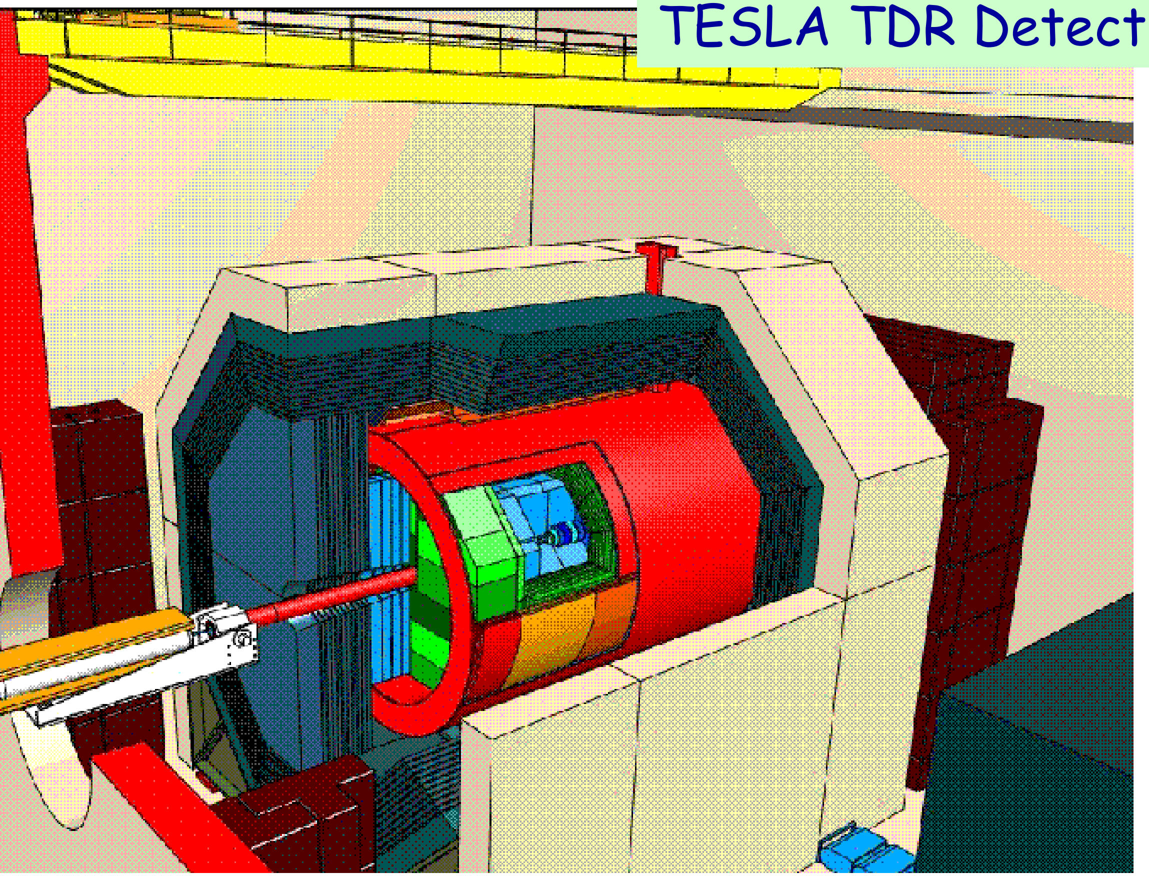


Detector simulation
- SIMDET (fast simulation)
- GEANT3 based program

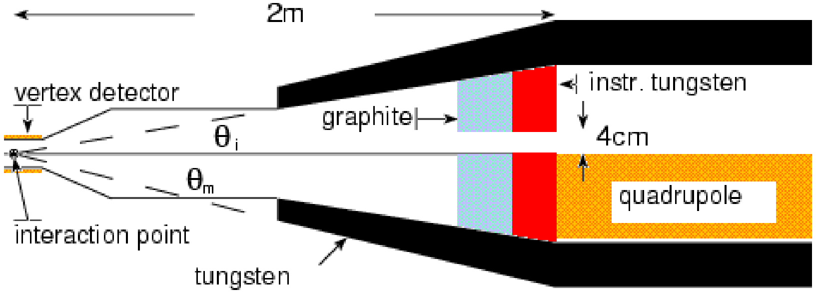
⇒Study benchmark processes

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	$\|\cos\theta\| < 0.98$
mask	120 mrad
beampipe	3 cm
small angle tagger	$\theta_{min} = 40$ mrad

Starting point: the TESLA TDR detector
Adapted to CLIC environment

First ideas:

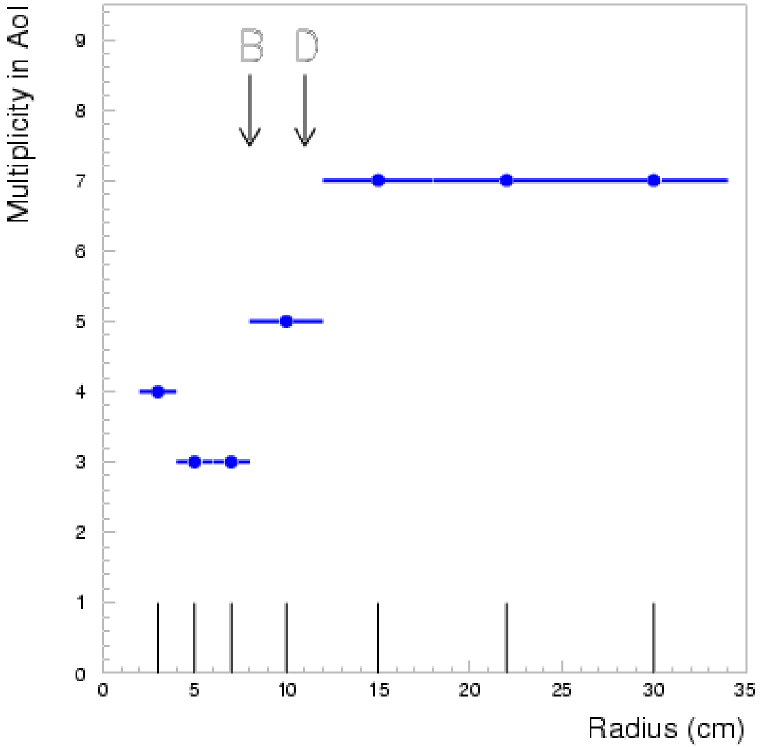
3–15 cm	VDET
15–80 cm	Silicon/forward disks
80–240 cm	TPC
240–280 cm	ECAL (30 X_0)
280–400 cm	HCAL (6λ)
400–450 cm	Coil (4T)
450–800 cm	Fe/muon

..or all silicon (15-120 cm)
more compact…

Example B-tagging

$B \to X$ DECAY LENGTH

$\sqrt{s}$ (TeV)	0.09	0.2	0.35	0.5	**3.0**	
	Z^0	HZ	HZ	HZ	H^+H^-	$b\bar{b}$
d_{space} (cm)	0.3	0.3	0.7	0.85	**2.5**	**9.0**



B-Decay length is long!

- Define Area of Interest by ± 0.04 rad cone around the jet axis
- Count hit multiplicity (or pulse height) in Vertex Track layers
- Tag heavy hadron decay by step in detected multiplicity
- Can reach 50% eff./~80% purity

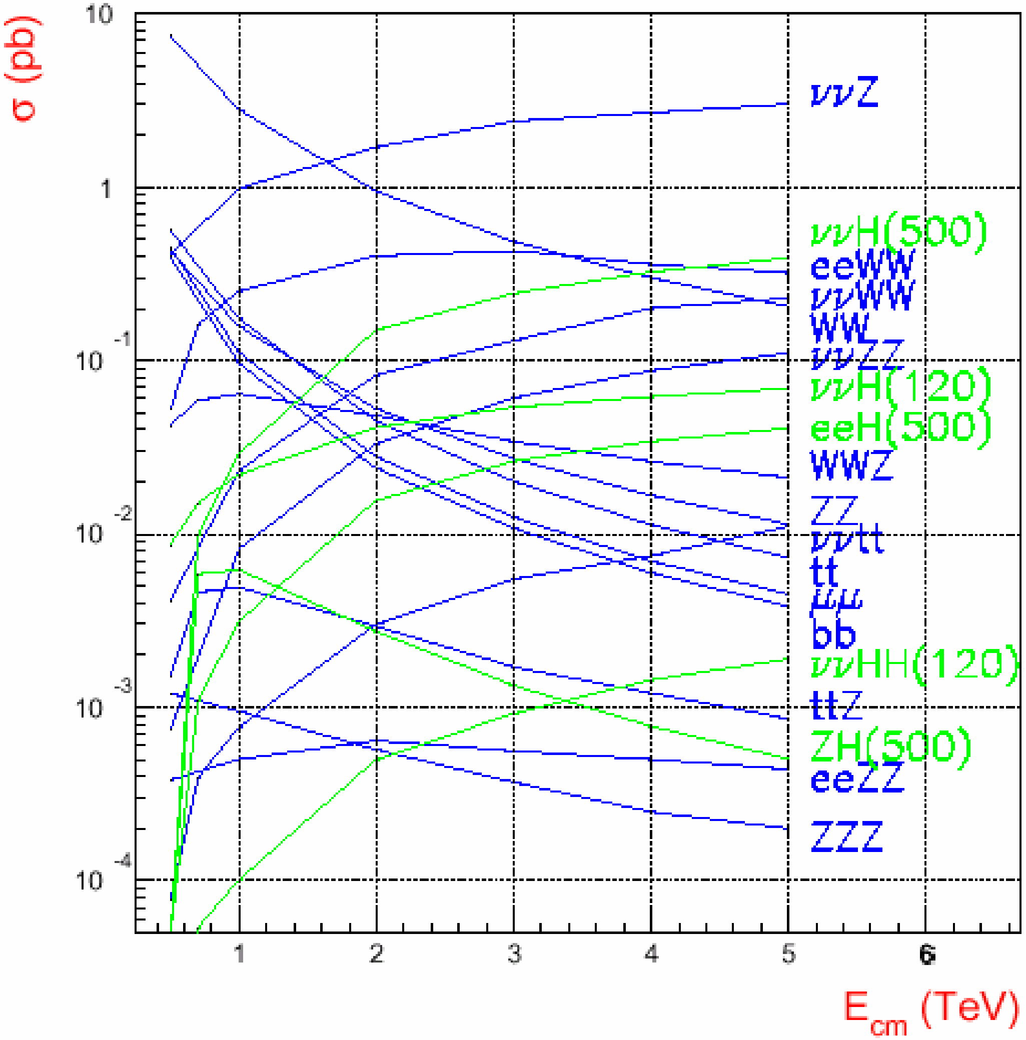
Physics Menu at CLIC

- 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 < √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′→ 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 √s ≈ 3-5 TeV: Expect to break new grounds

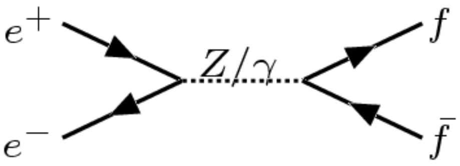
Cross Sections at CLIC



CLIC

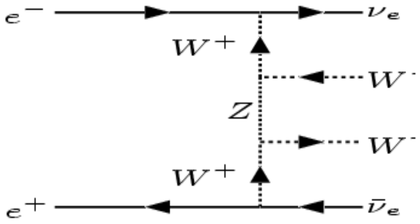
Event Rates/Year (1000 fb^{-1})	3 TeV 10^3 events	5 TeV 10^3 events
$e^+e^- \to t\bar{t}$	20	7.3
$e^+e^- \to b\bar{b}$	11	3.8
$e^+e^- \to ZZ$	27	11
$e^+e^- \to WW$	490	205
$e^+e^- \to hZ/h\nu\nu$ (120 GeV)	1.4/530	0.5/690
$e^+e^- \to H^+H^-$(1 TeV)	1.5	0.95
$e^+e^- \to \tilde{\mu}^+\tilde{\mu}^-$ (1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

s-Channel Production



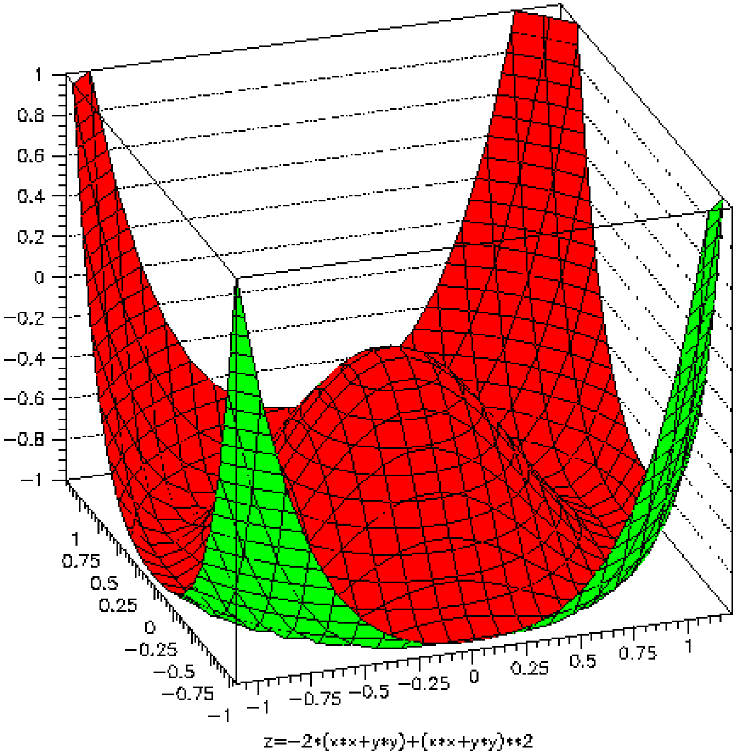
$$\sigma \propto 1/s$$

t-Channel Production



$$\sigma \propto log(s)$$

2. Higgs Physics

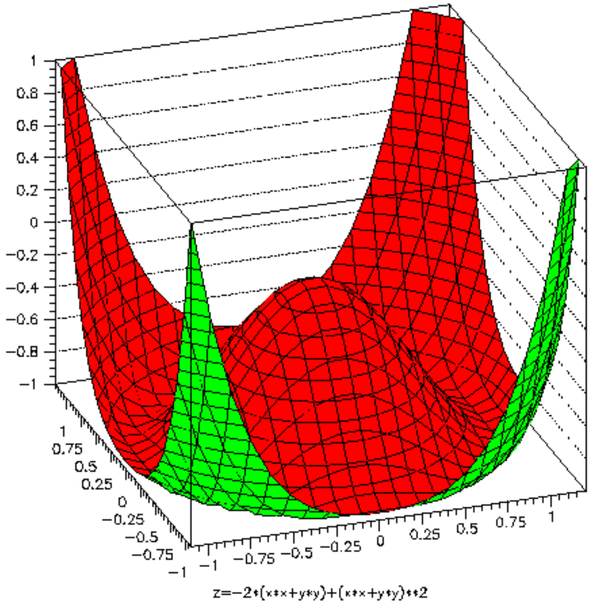


The Higgs Mechanism

The Higgs Field

$$\mathcal{V}(\phi) = \mu^2 \mid \phi(x) \mid^2 + \lambda \mid \phi(x) \mid^4$$

Particles acquire mass trough interaction with the Higgs field



At least one scalar Higgs boson should be discovered
We do not know its mass!!!
Except → Theory M_H < ~ 1 TeV

The Higgs coupling to particles is proportional to their mass
⇒Needs to be checked

Reconstruct the Higgs potential (depends on the new physics)

Potential energy density of the Higgs field: lowest value is not at zero!

$$g_{HVV} = 2M_V^2/v$$

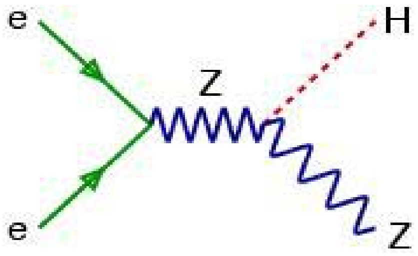
$$g_{Hff} = m_f/v$$

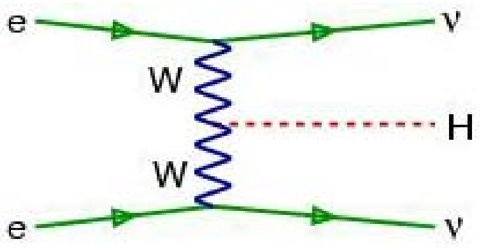
$$(\sqrt{2}G_F)^{-1/2} \approx 246 \text{ GeV}$$

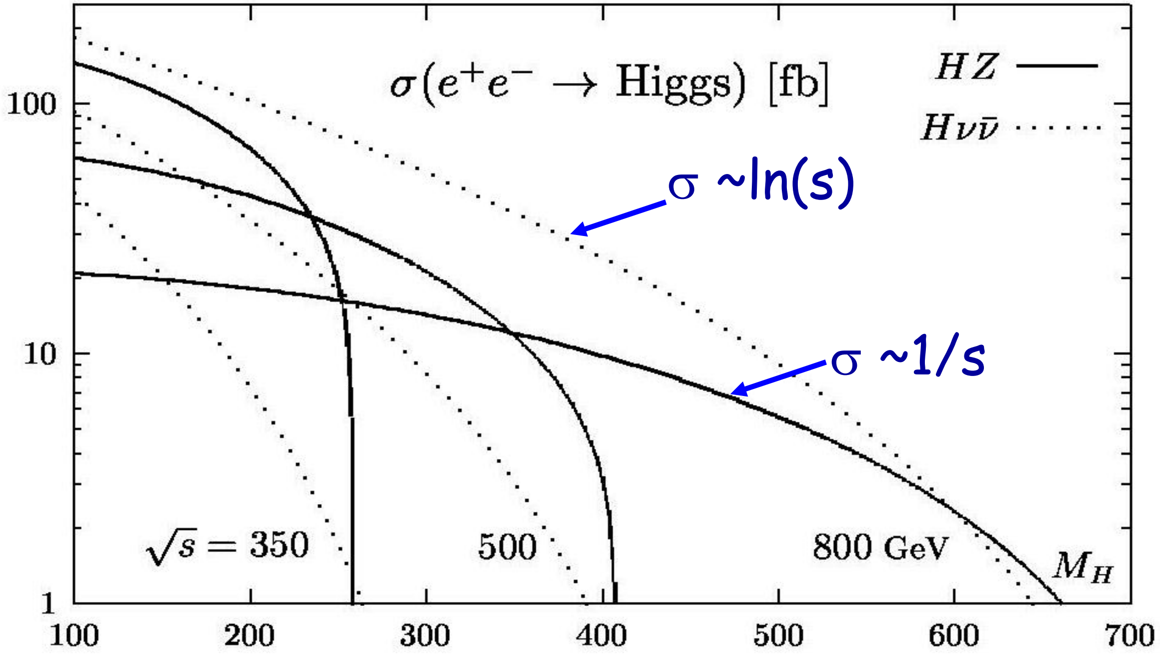
Vacuum expectation value of the Higgs field

Higgs Production at a e+e- Linear Collider

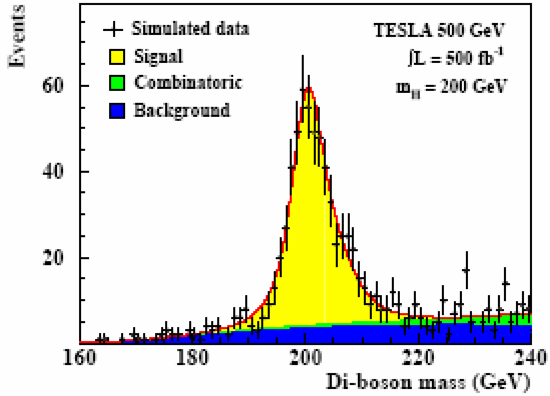
Dominant production processes at LC:

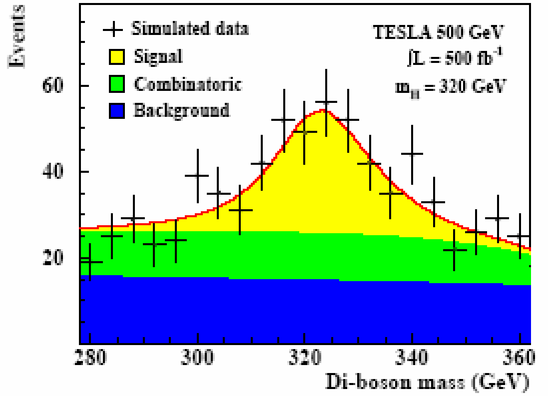






Heavy Higgs

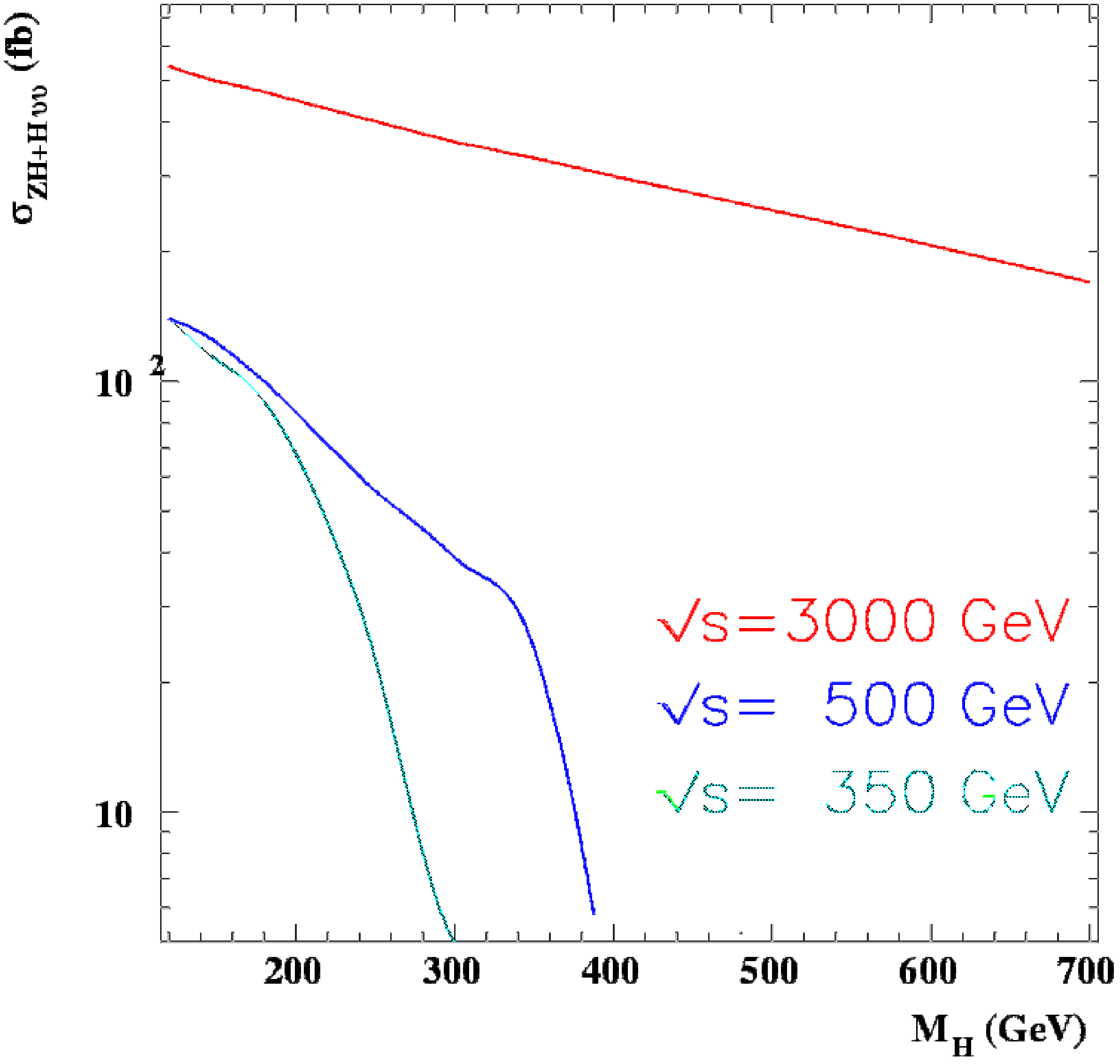




500 GeV, 500 fb^{-1}

TeV LC: statistics drop for high masses

Higgs Production

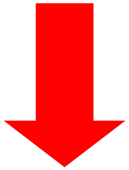


Cross section at 3 TeV:

- Large cross section at low masses
- Large CLIC luminosity

→Large events statistics

- Keep large statistics also for highest Higgs masses



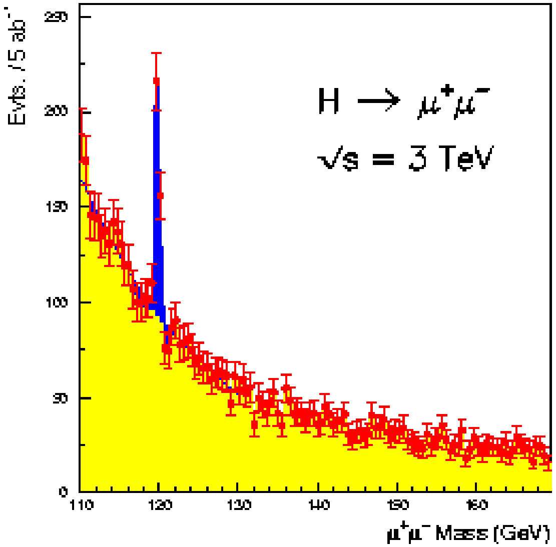
Low mass Higgs:
400 000 Higgses/year

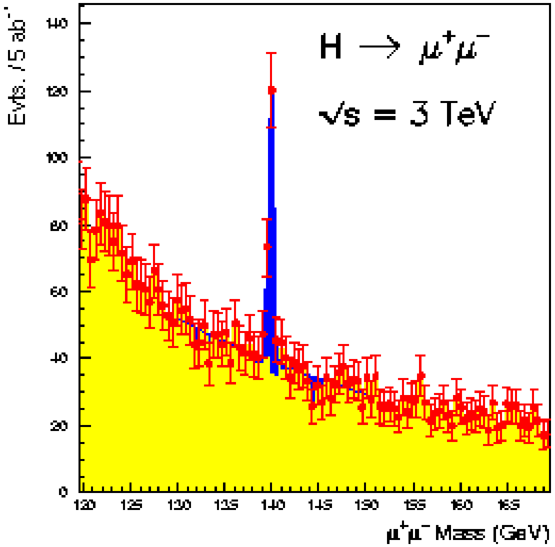
45K/100K for 0.5/1 TeV LC

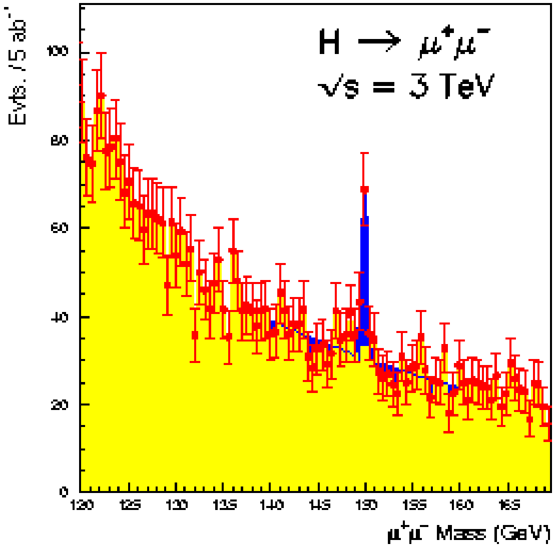
Rare Higgs Decays: H→μμ

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

Not easy to access at a 500 GeV collider







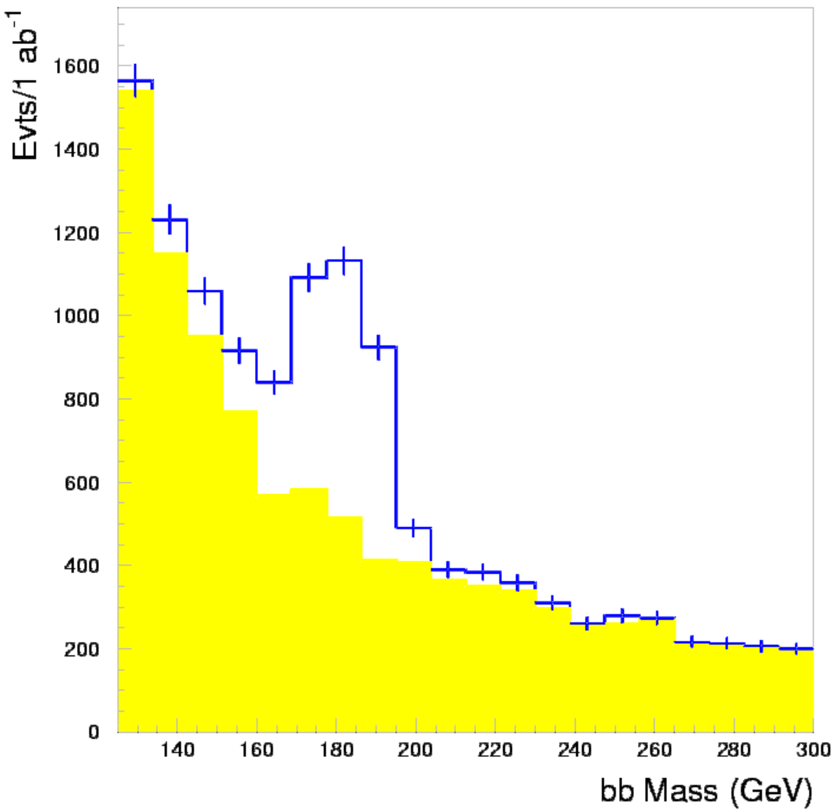
Result for $\sqrt{s} = 3.0$ TeV with $\int \mathcal{L} = 5$ ab^{-1}

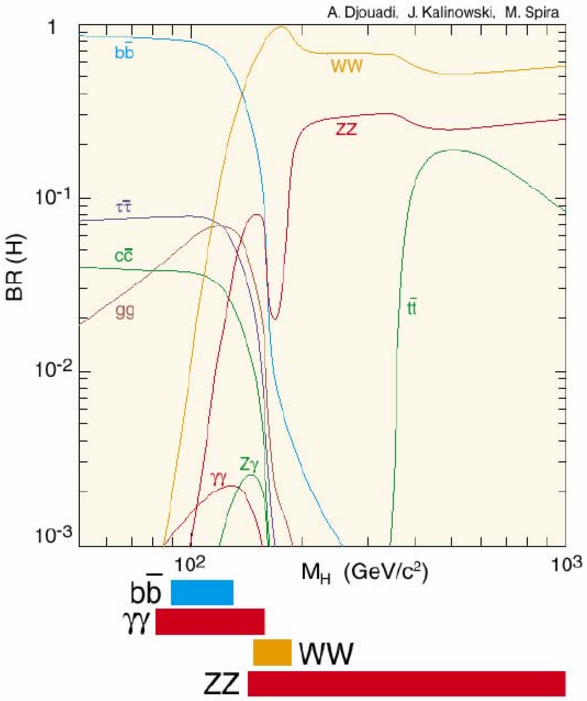
M_H	120 GeV	140 GeV	150 GeV
δBR/BR	0.072	0.121	0.210

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

Rare Higgs Decays

Higgs→ BB decays for higher Higgs masses, e.g. 180 GeV





M_H (GeV)	$S/\sqrt{B}$	$\delta\, g_{Hbb}\, /\, g_{Hbb}$
180	40.5	0.016
200	25.0	0.025
220	18.0	0.034

Higgs Potential

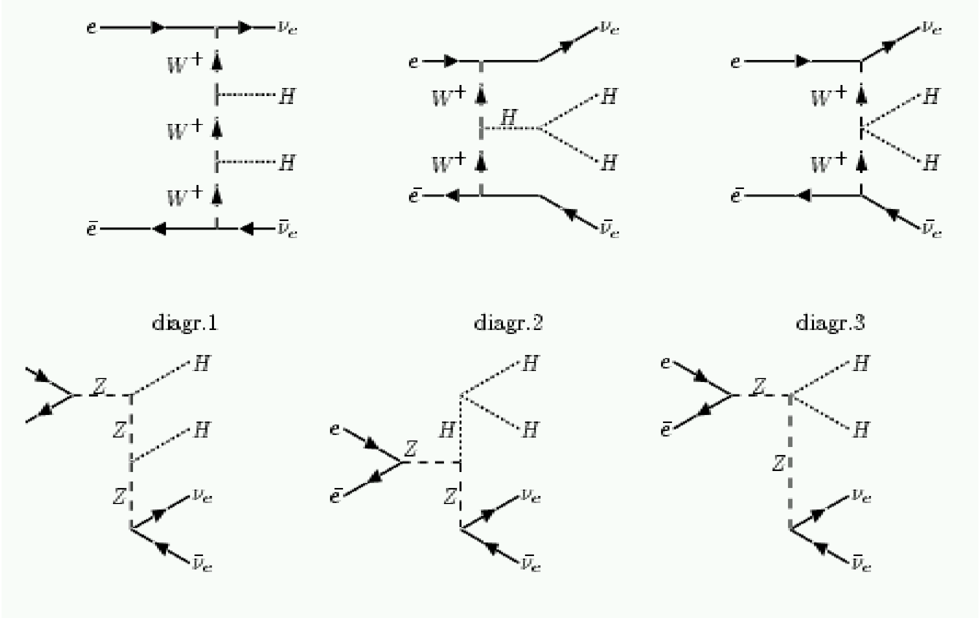
Reconstruct shape of the Higgs potential to complete the study of the Higgs profile and to obtain a direct proof of the EW symmetry breaking mechanism

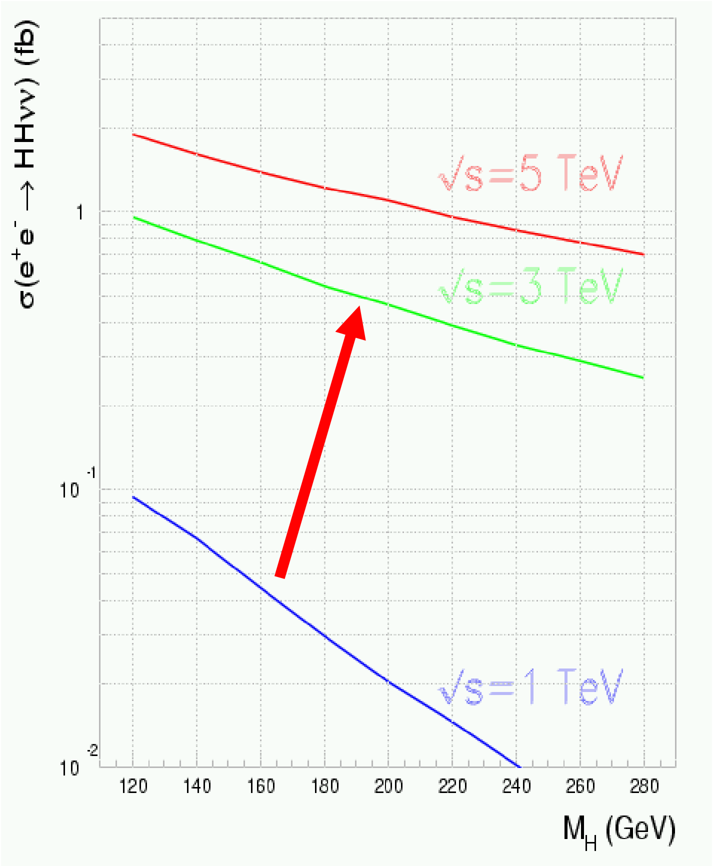
⇒ Measure the triple (quartic) couplings

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

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

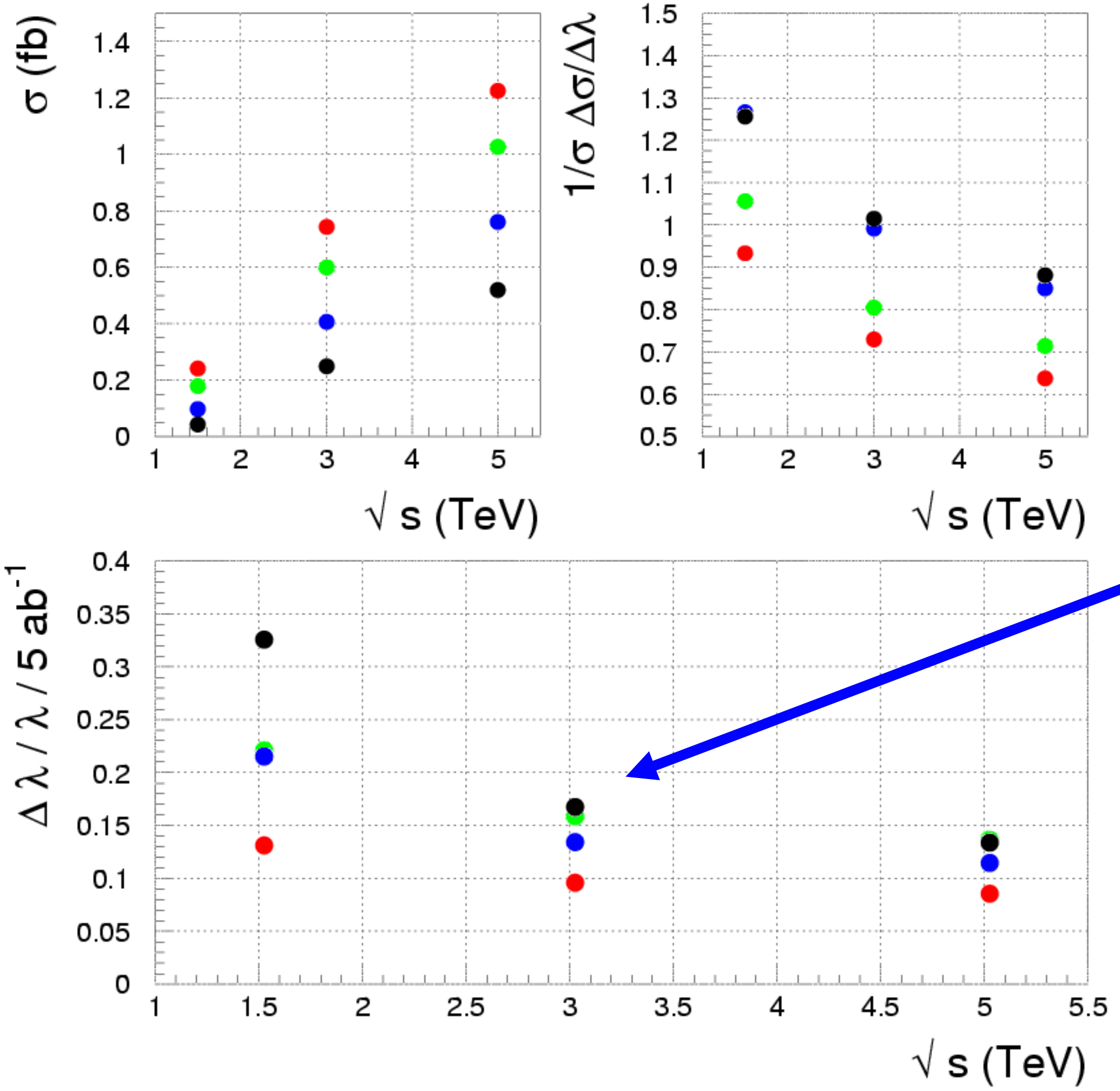
process $e^+e^- \to (WW)\nu\bar{\nu} \to hh\nu\bar{\nu}$





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

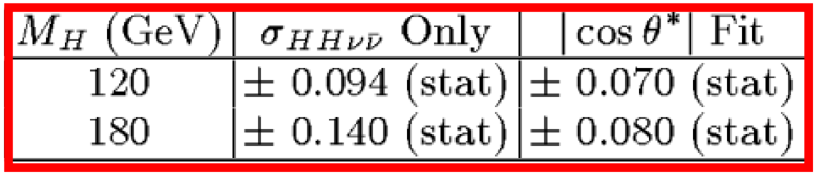
Results: e+e- $\rightarrow HH\nu\nu$



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

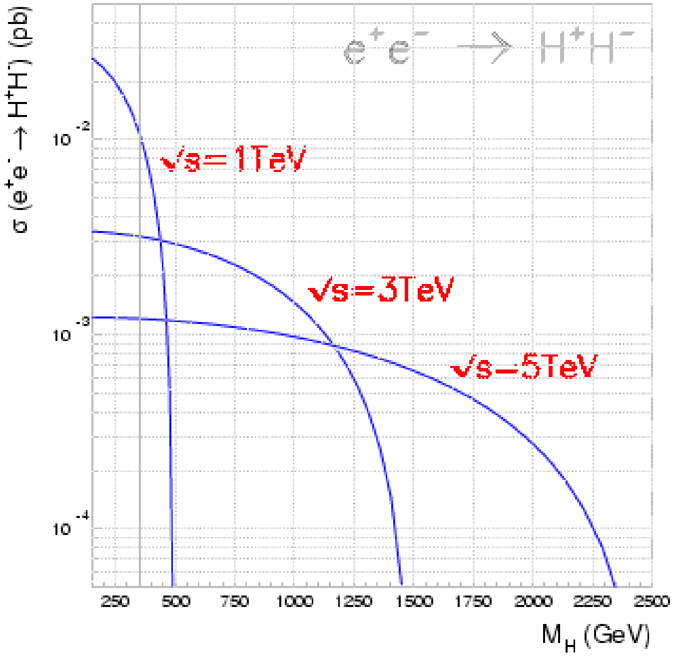


M_H (GeV)	$\sigma_{HH\nu\bar{\nu}}$ Only	$\lvert\cos\theta^*\rvert$ Fit
120	± 0.094 (stat)	± 0.070 (stat)
180	± 0.140 (stat)	± 0.080 (stat)

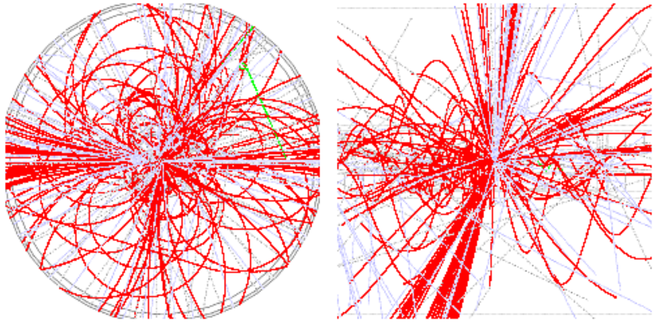
Can improve by factor 1.7 if both beams are polarized

Heavy Higgs (MSSM)

Cross section as function of Higgs mass



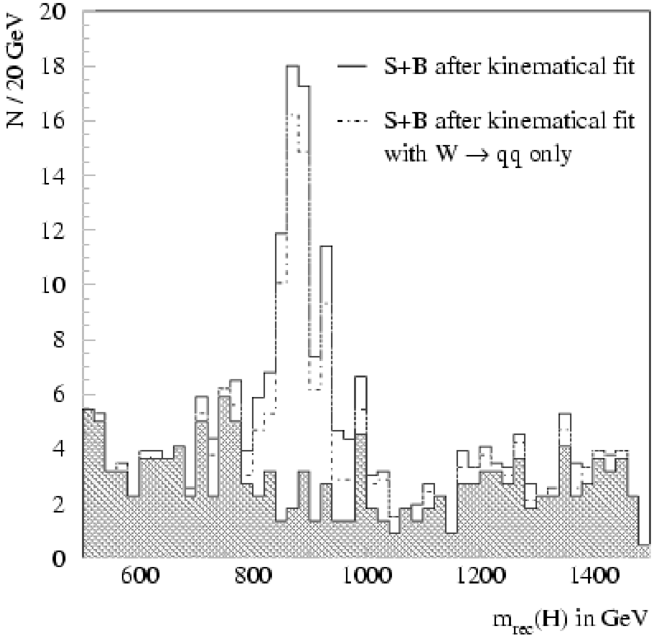
$e^+e^- \to H^+H^-$ $M_H = 900$ GeV



Study the channel $H^{\pm} \to tb \to Wbb \to qqbb$

Example for $M_H = 880$ GeV (15 BC background)

Tag 4 b jets / reconstruct W's from 4 'light' jets / reconstruct t jet $\longrightarrow$ events with 8 jets



$O(20)$ events/ ab^{-1}, with negligable background

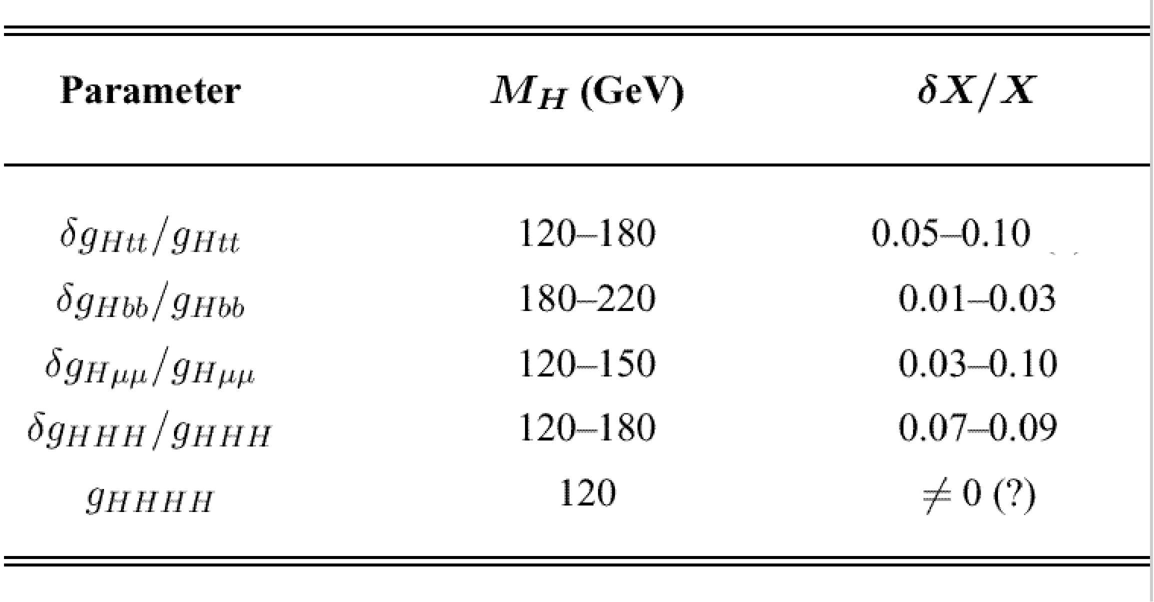
Increase statistics by factor 10 for 'single' H tags

Mass measurement $\Delta m/m \sim 1\%$ (3 ab^{-1})

Discovery potential $M_H < 1.2$ TeV (3TeV/3 ab^{-1})

Higgs: Strength of a multi-TeV collider

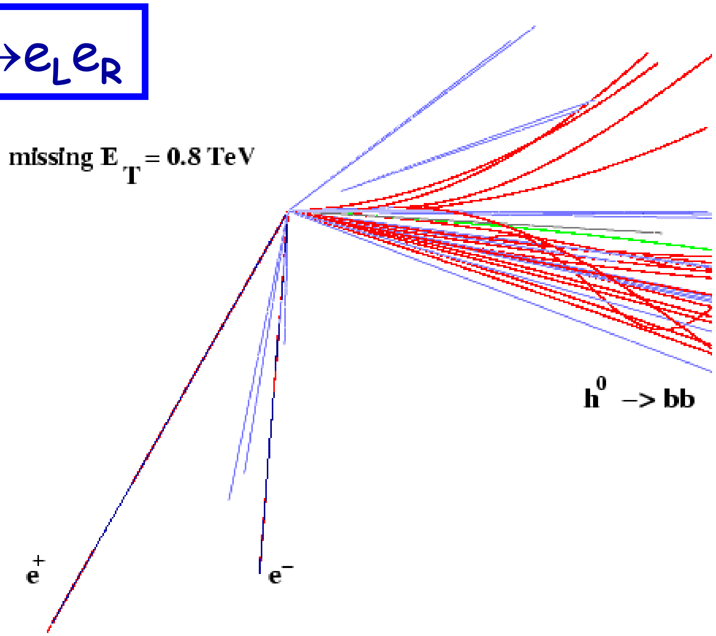
- Precision measurements of the quantum numbers and properties of Higgs particles, for large Higgs mass range
- Study of Heavy Higgses (e.g. MSSM H,A,$H^{\pm}$)
- Rare Higgs decays
- Higgs self coupling over a wide range of Higgs masses
- Study of the CP properties of the Higgs…



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

$e^+e^- \to e_L e_R$

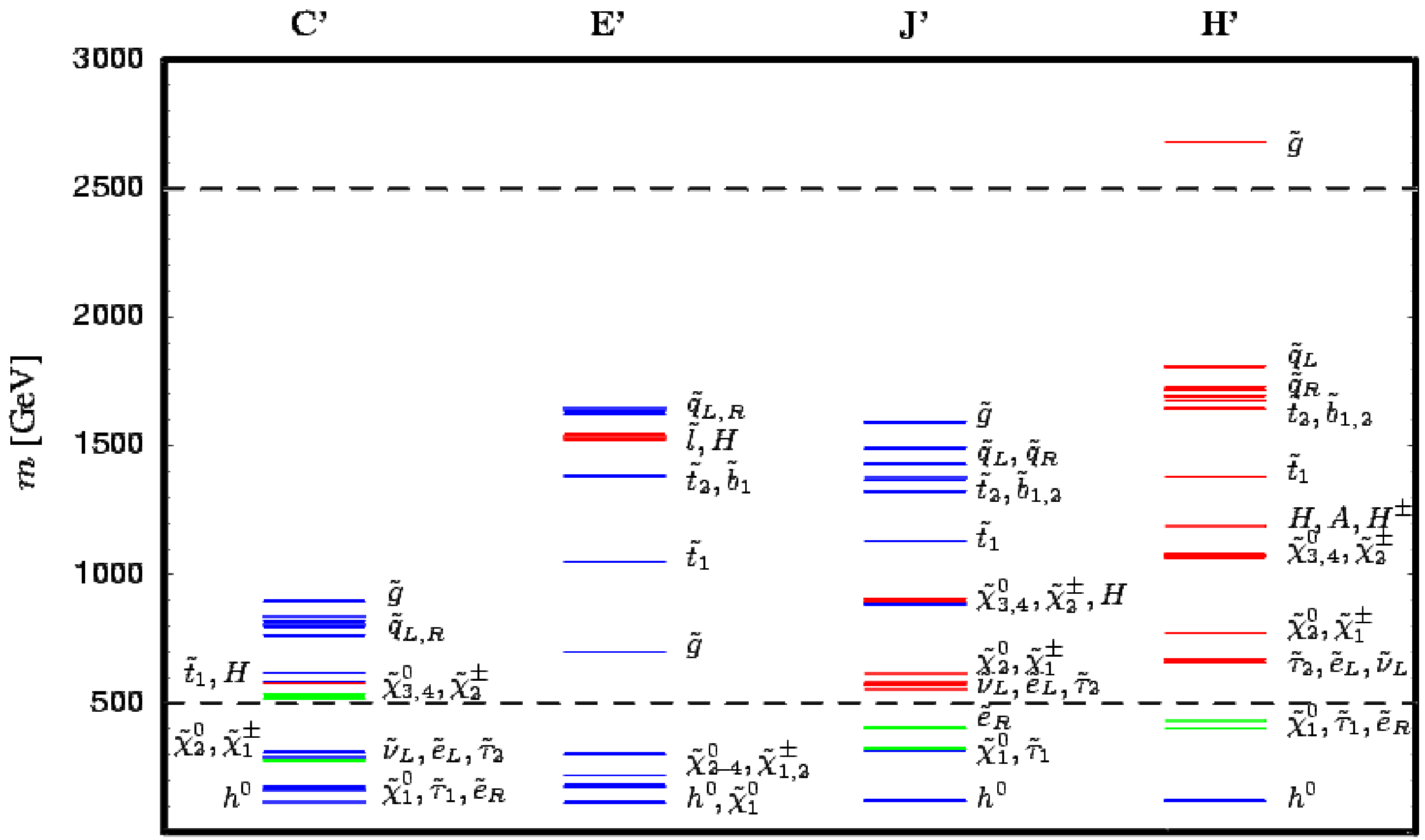


Masses of Sparticles

Depend on SUSY parameters, SUSY breaking mechansme…

We don’t really know…

Examples: Scenarios in Constrained MSSM



Multi-TeV LC

TeV LC

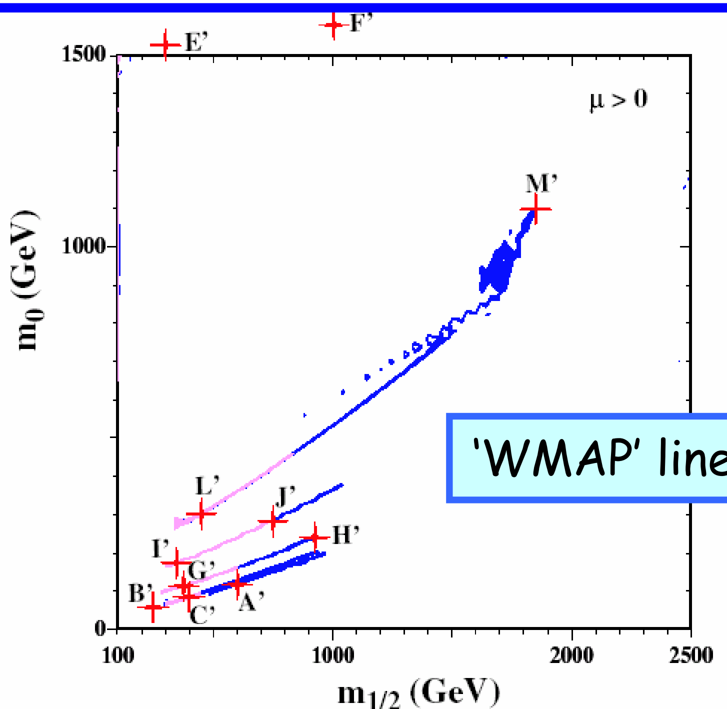
Sparticle Discoveries

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

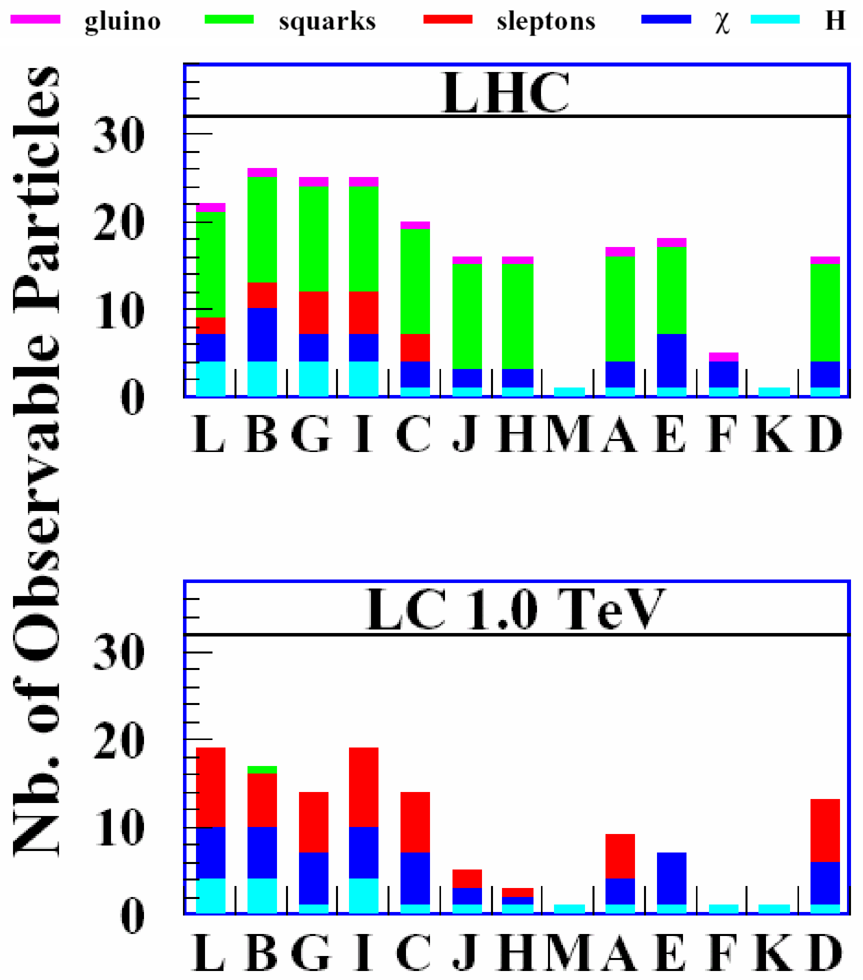
(Battaglia at al hep-ph/0306219)

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

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

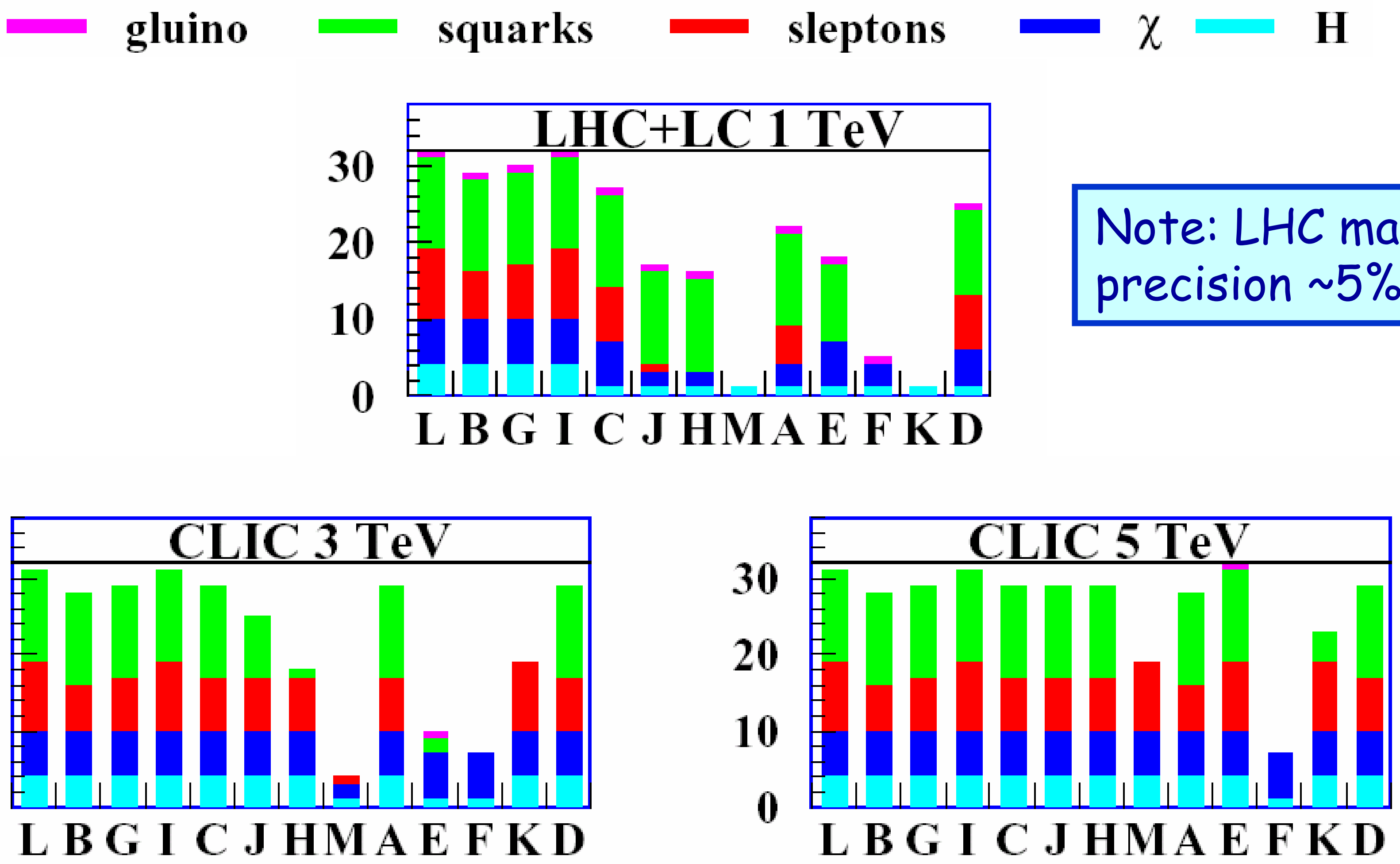


'WMAP' lines



sleptons and gauginos often difficult to detect at a LHC

Sparticle Discoveries

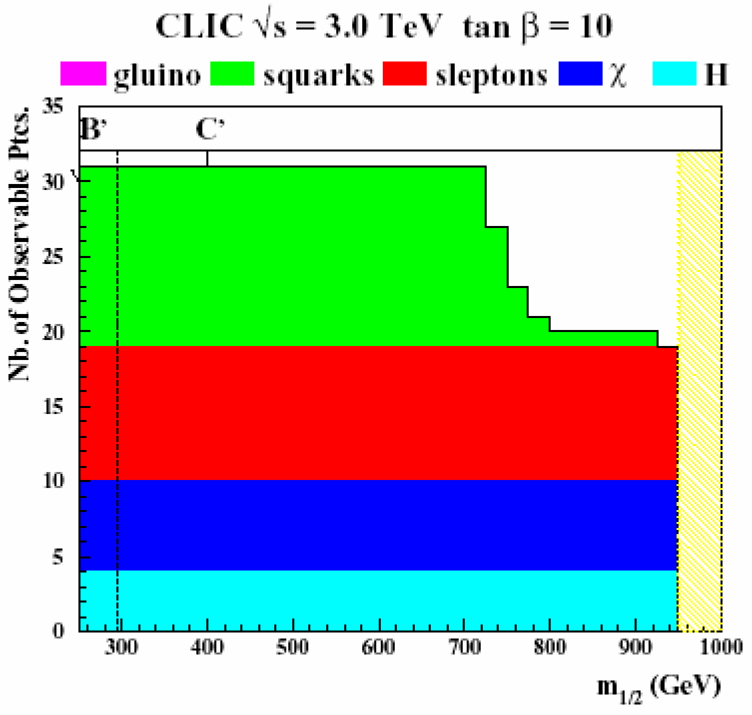


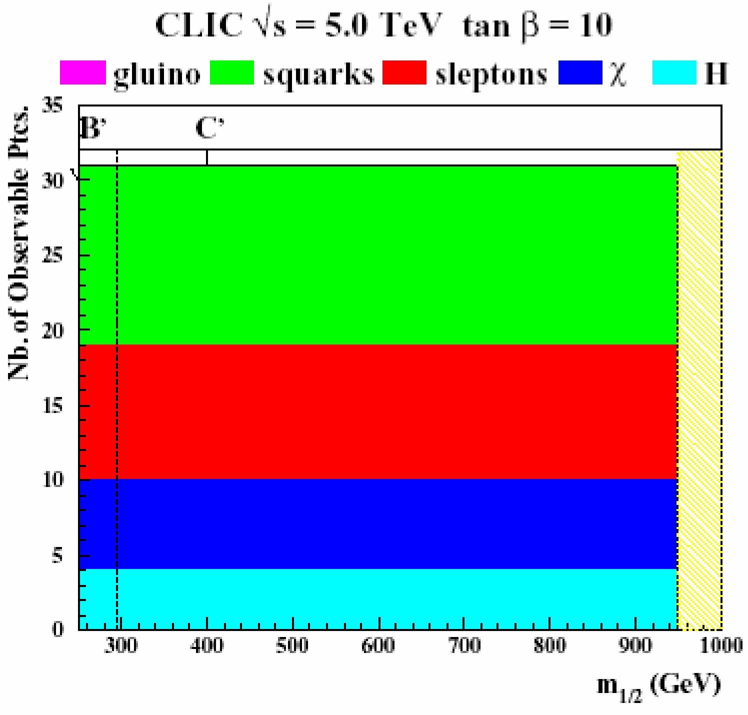
Note: LHC mass precision ~5%

CLIC can help to complete the sparticle spectra

Sparticle Discoveries

Particle discovery scan along a WMAP line

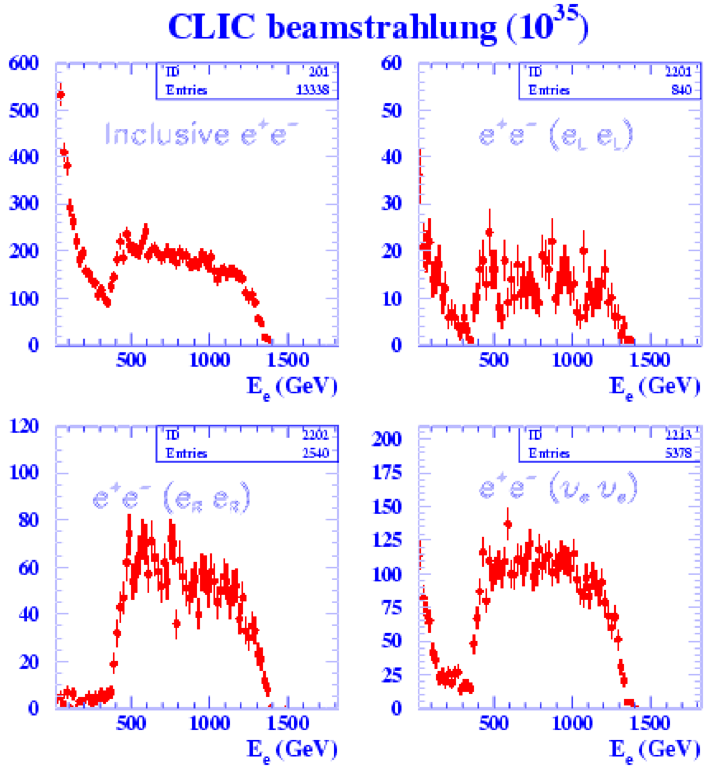




Observe all sparticles & measure properties more precisely than at LHC

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

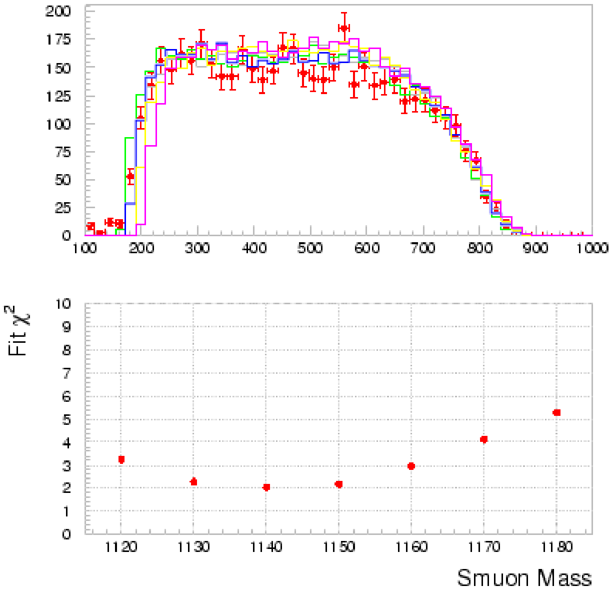
Typical 'box' shape of the signal preserved in CLIC environement

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 $\tilde{\mu} \to \mu\chi^0$

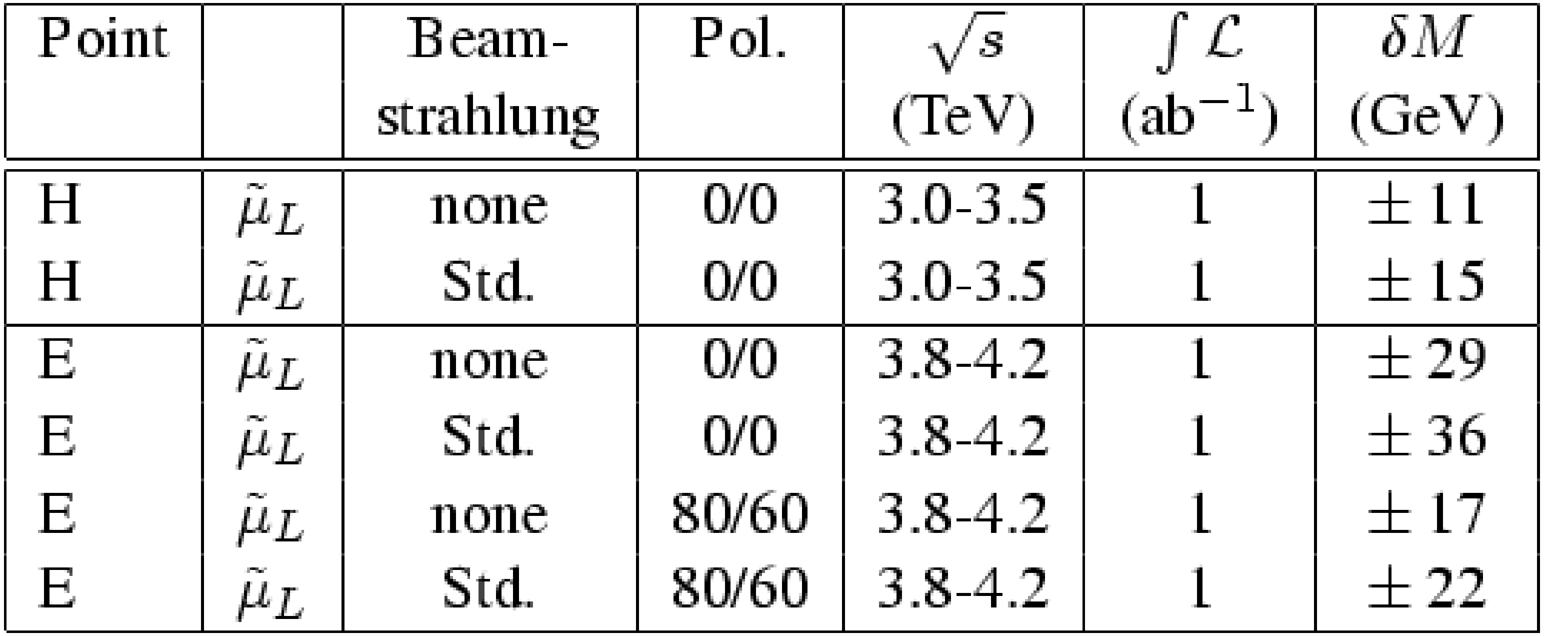
$$\Rightarrow E_{max/min} = \frac{M_{\tilde{\mu}}}{2}\left(1 - \frac{M^2_{\chi^0}}{M^2_{tilde\mu}}\right) \times \left(1 \pm \sqrt{1 - \frac{M^2_{\tilde{\mu}}}{E^2_{beam}}}\right)$$



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

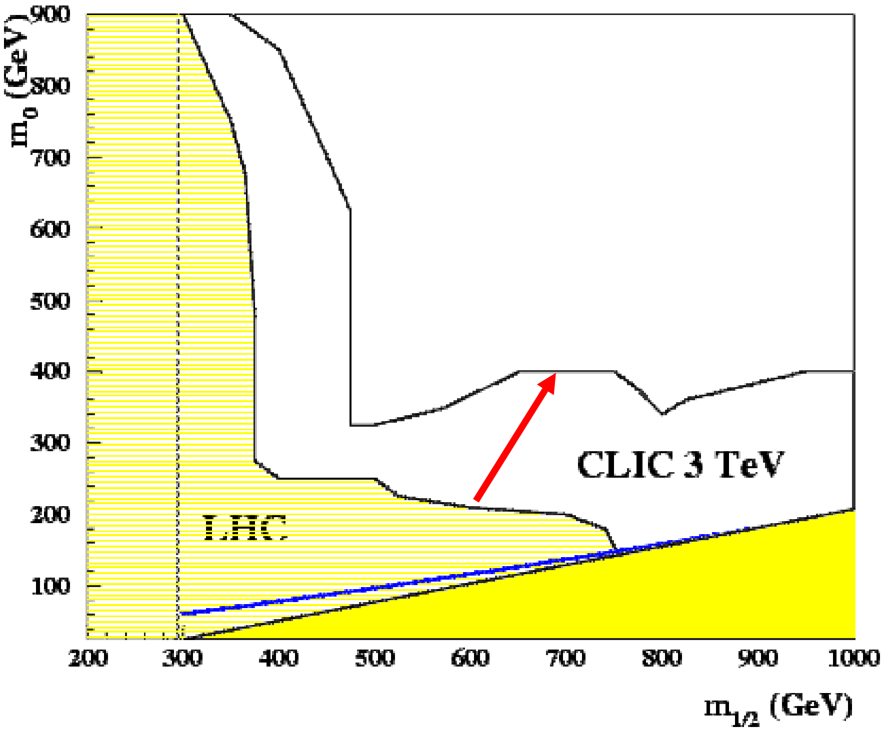
→ Mass measurements to O(1%) possible

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

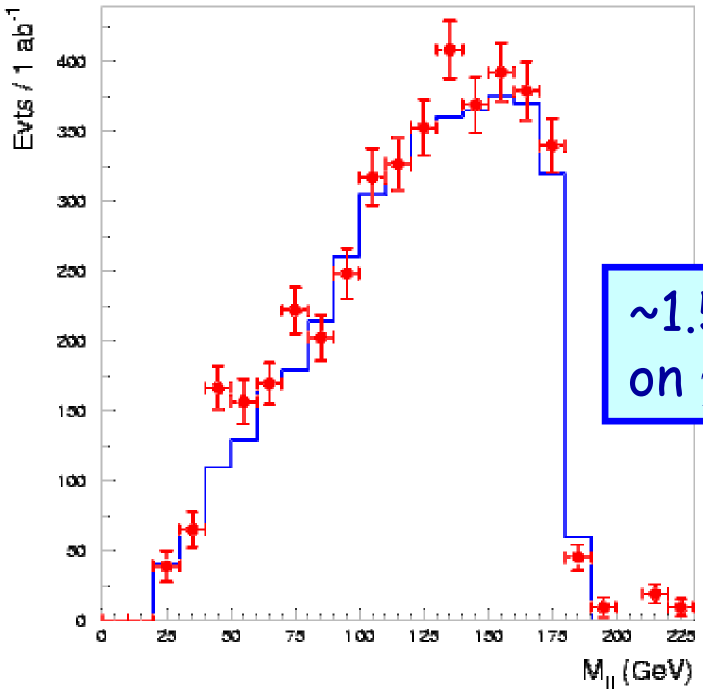
Case study: χ_2

Sensitivity (5σ) for LHC and LC

tan β = 10



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

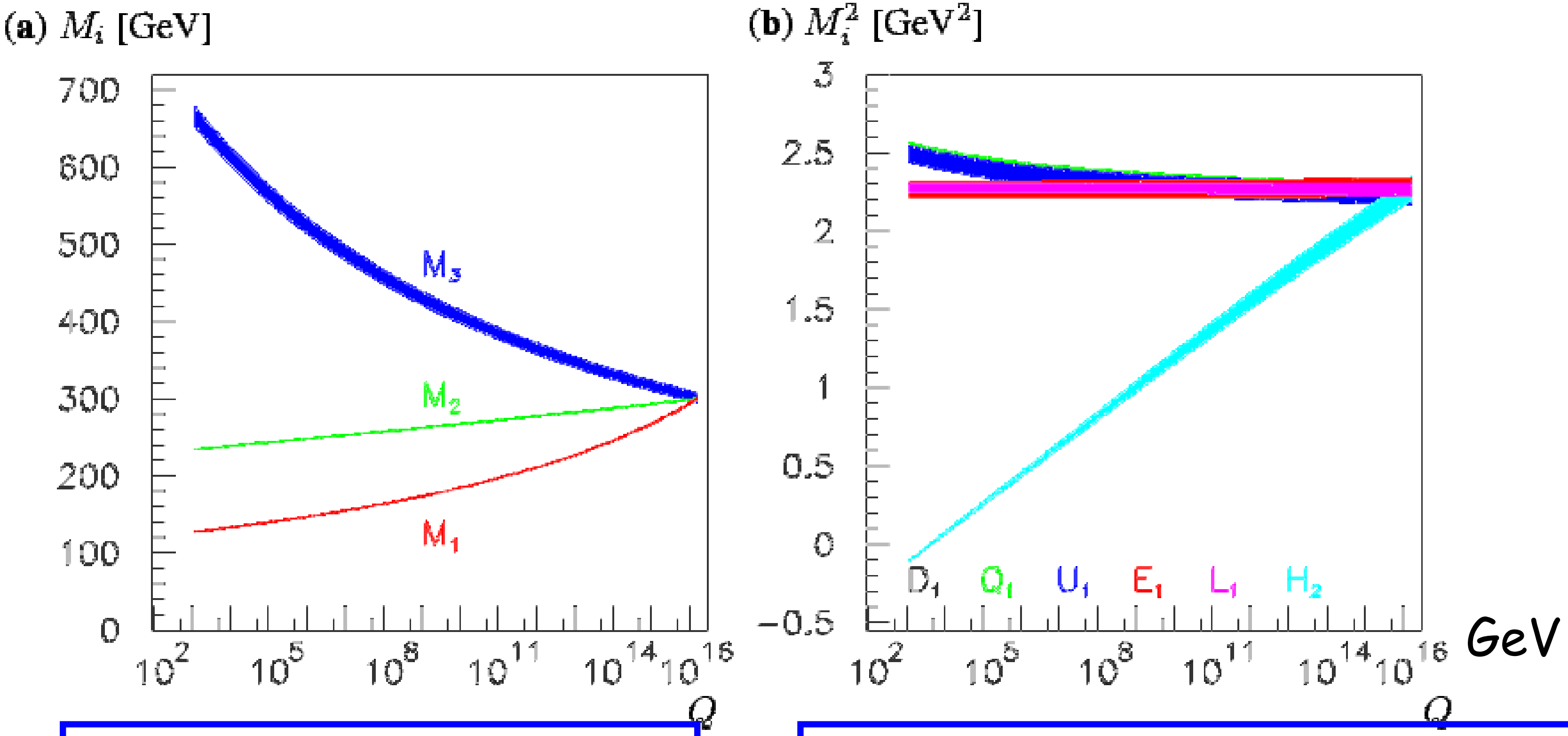


~1.5% precision on χ_2 mass

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!



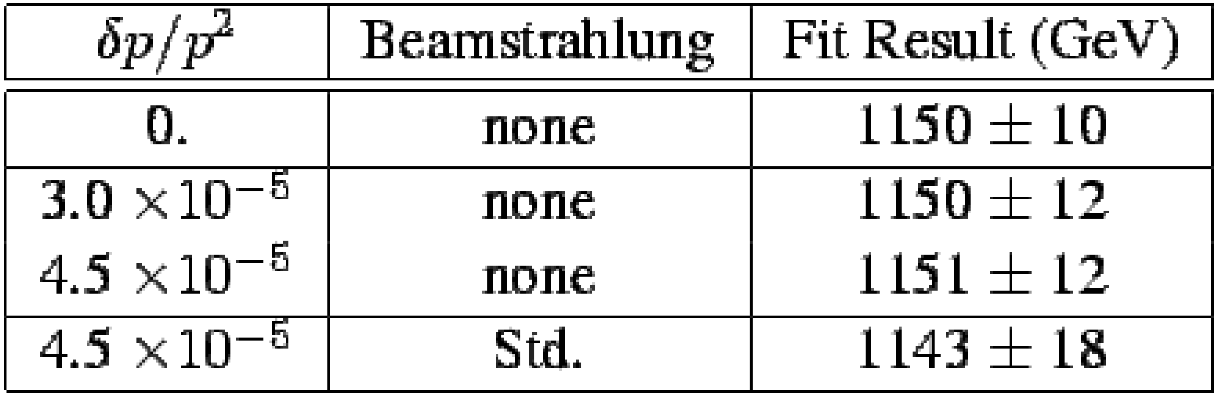
Gaugino mass parameters

1st generation sfermion parameters

SUSY: Strength of a Multi-TeV Collider

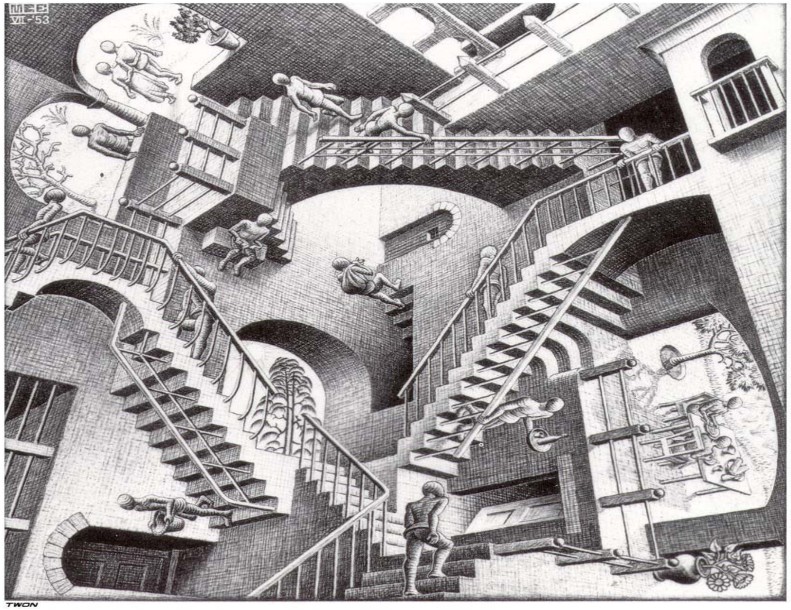
- Complete the SUSY spectrum further (extended reach w.r.t. LC and LHC)
- Measure properties of sparticles with linear collider type of precisions in the high mass range (e.g. masses up to 1%, spin, mixing angles, tanβ, gaugino couplings, slepton quantum numbers…) → see CLIC Report for details

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. Extra Dimensions

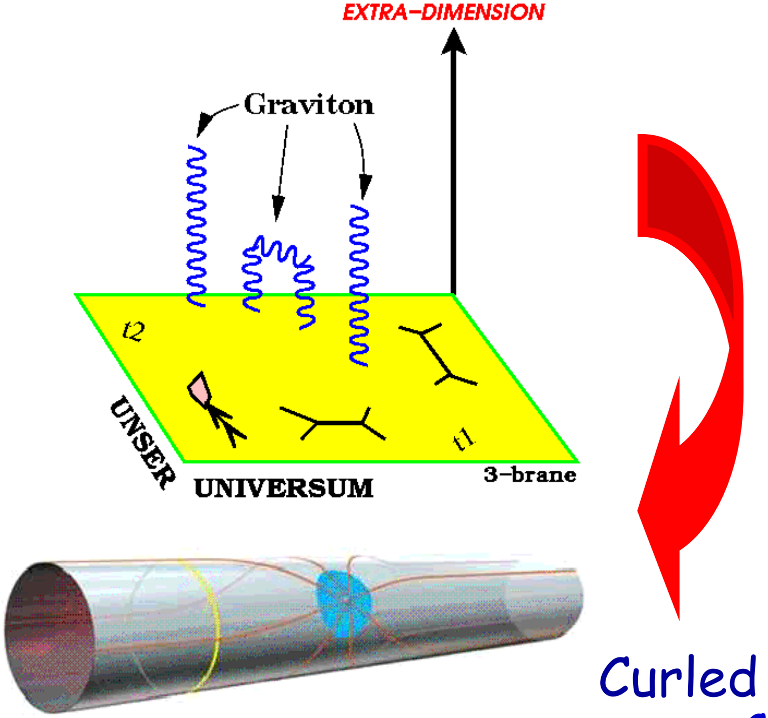


Large Extra Dimensions

ADD: Arkani –Ahmed, Dimopolous, Dvali

Problem: $m_{EW} = \frac{1}{(G_F \cdot \sqrt{2})^{\frac{1}{2}}} = 246\ \text{GeV}$ ⟷ $M_{Pl} = \frac{1}{\sqrt{G_N}} = 1.2 \cdot 10^{19}\ \text{GeV}$

Idea of from String Theory (assumes 11 space-time dimensions)
Assume the world we see is in 4 dimensions but that gravity can expand in 4+δ dimensions. Extra dimensions have size R (mm to fm)



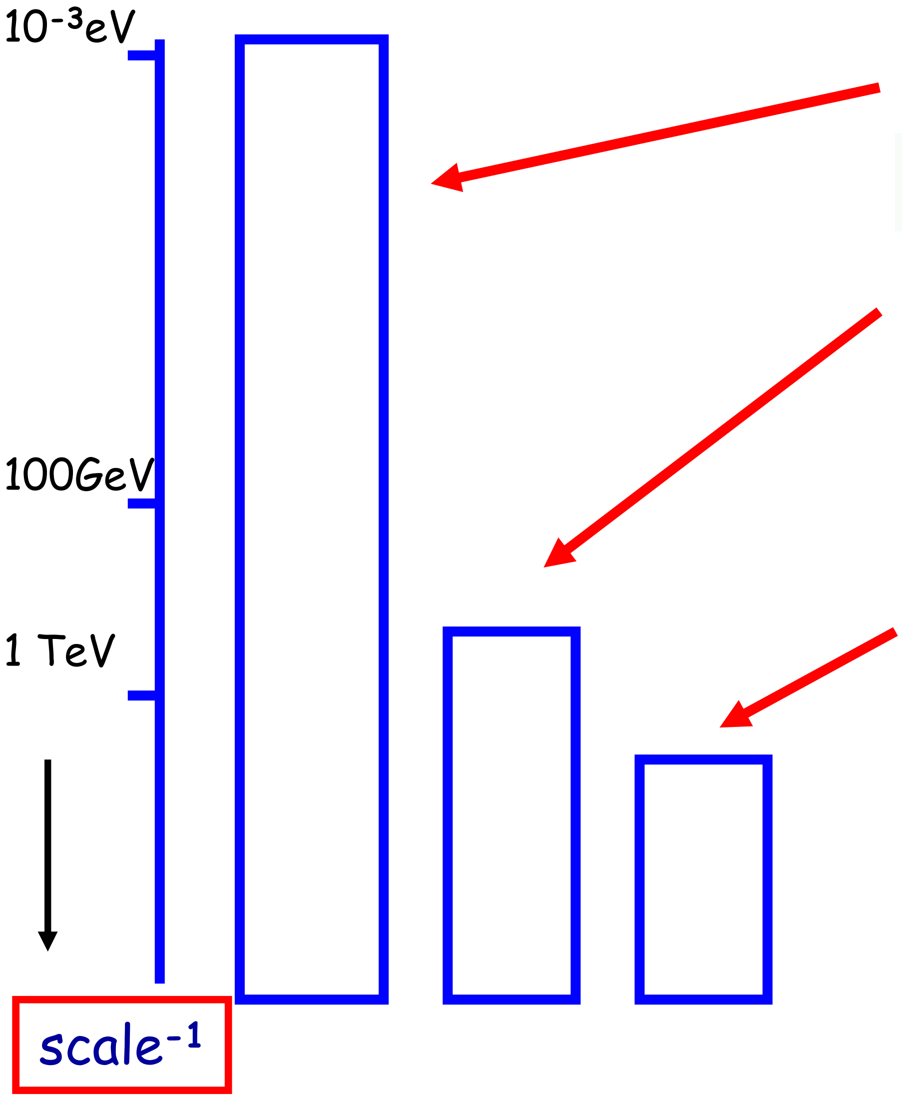
Curled up…

$$V(r) \sim \frac{m_1 m_2}{M_{Pl}^2}\frac{1}{r}$$

$$V(r) \sim \frac{m_1 m_2}{M_D^{\delta+2}}\frac{1}{r^{\delta+1}}, \quad (r \ll R)$$

$$V(r) \sim \frac{m_1 m_2}{M_D^{\delta+2} R^{\delta}}\frac{1}{r}, \quad (r \gg R)$$

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

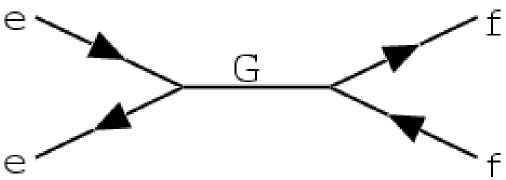
$$ds^2 = e^{-2ky}\eta_{\mu\nu}dx^\mu dx^\nu - dy^2 \, ,$$ k = warp factor

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

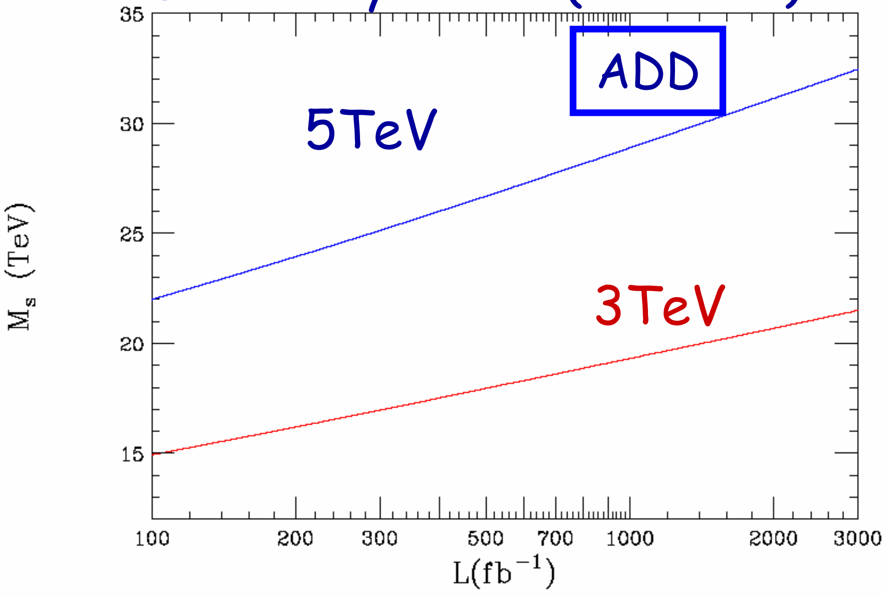
Universal Extra Dimensions (Appelquist et al.)
Everybody in the bulk!
Fake SUSY spectrum of KK states
+ many combinations/variations

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

CLI

KK Towers

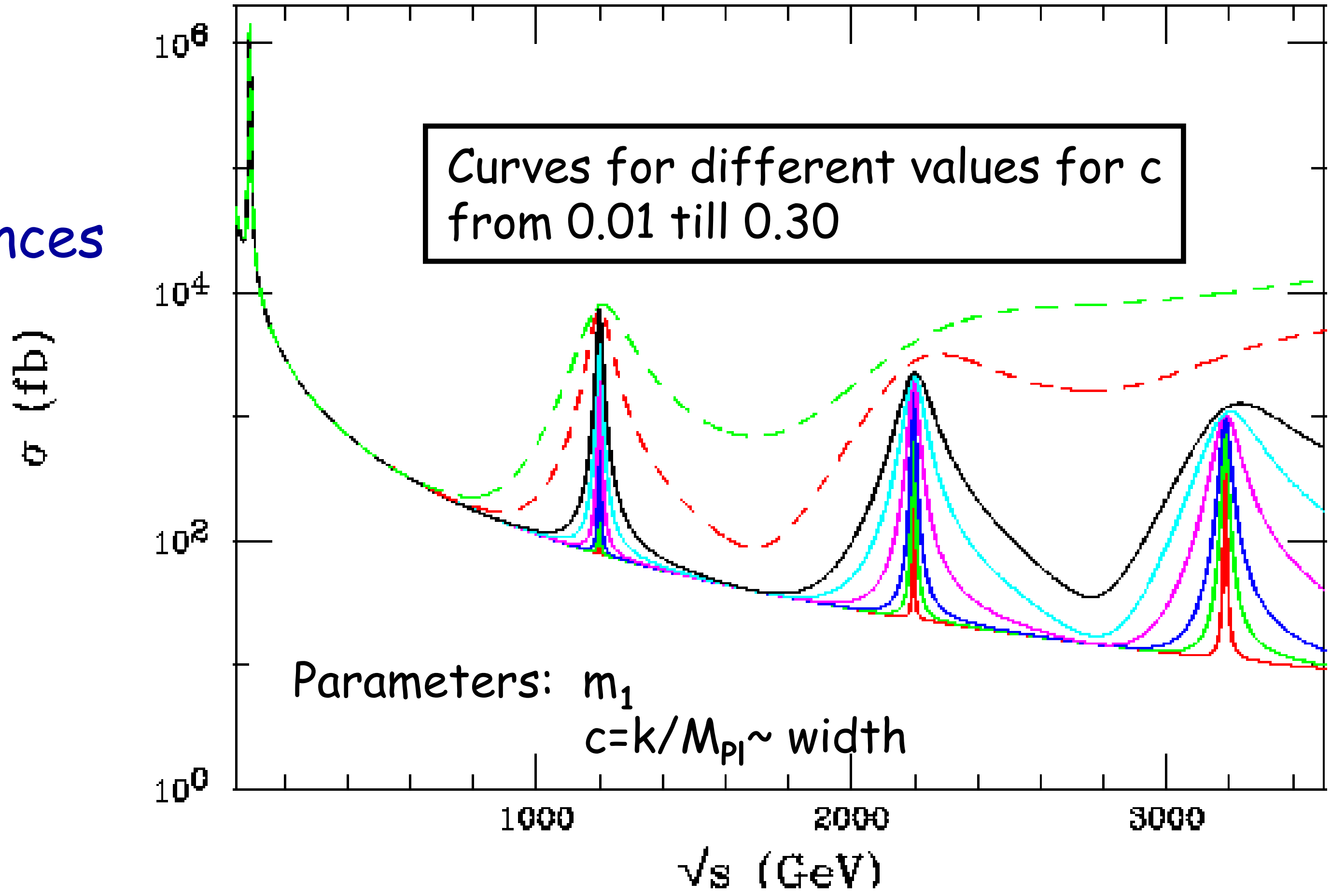
Extra Dimensions Randall-Sundrum phenomenology (curves by T. Rizzo)

SM fields on brane and graviton in bulk

Observe KK resonances in e.g. e+e- →μμ cross sections

LC is like a KK factory

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



Curves for different values for c from 0.01 till 0.30

Parameters: m_1
$c=k/M_{Pl} \sim$ width

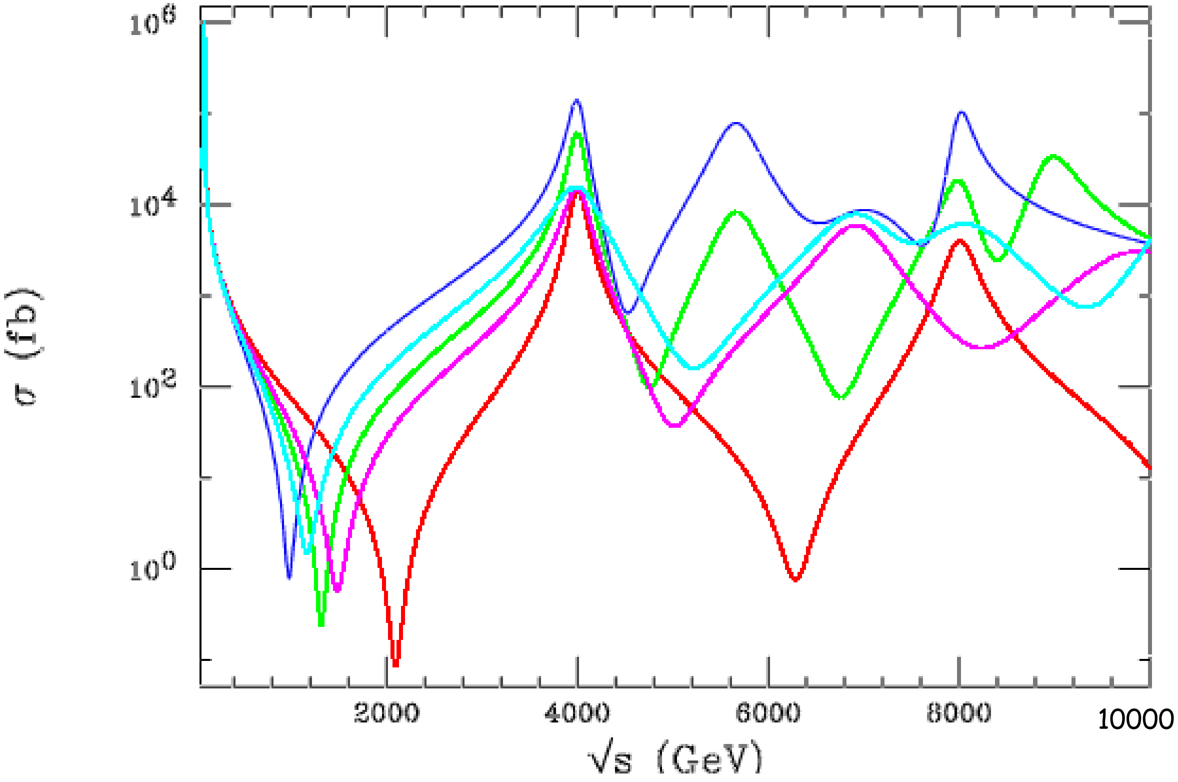
Can determine parameters c up to 0.2%, M better than 0.1%

Extra Dimensions

TeV scale extra dimensions

⇒ SM gauge field in the bulk

⇒ May lead to complicated spectra in e.g. e+e- →μμ (interference effects/spin-1 states)



Different models

Rigid/Soft Branes

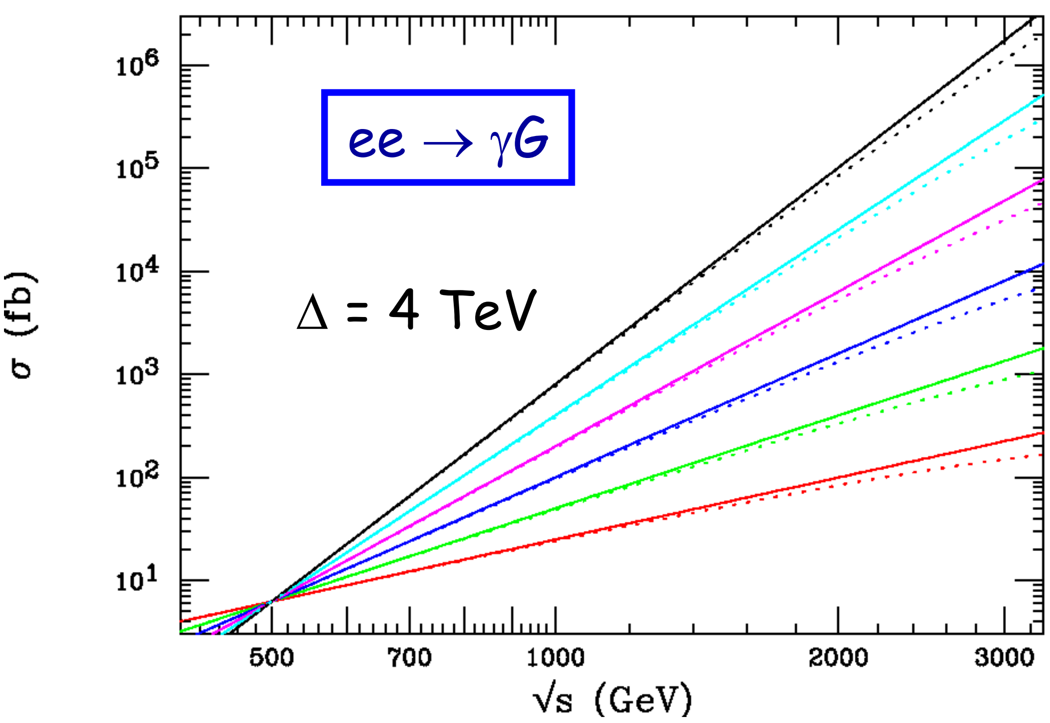
ADD Models

Rigid brane: Coupling of massive KK towers is exactly the same for less massive towers

Soft branes: Coupling of higher mass KK towers reduced

$g_n^2 \to g_n^2\, e^{-(m/\Delta)^2}$ Δ = wall tension

could have any value but expected ~ O(TeV)



δ = 7

δ = 2

M_D's fixed
to agree with
M_D=5 TeV, n=2

Discover deviations ⇒
Energy lever arm important!!

CLIC

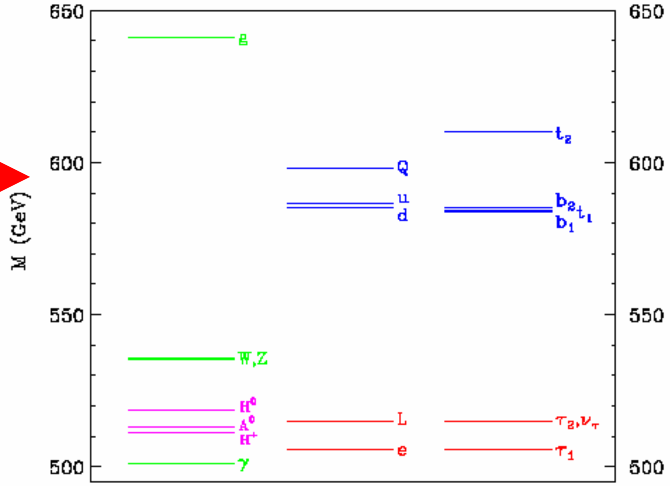
Universal Extra Dimensions UED

- 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)

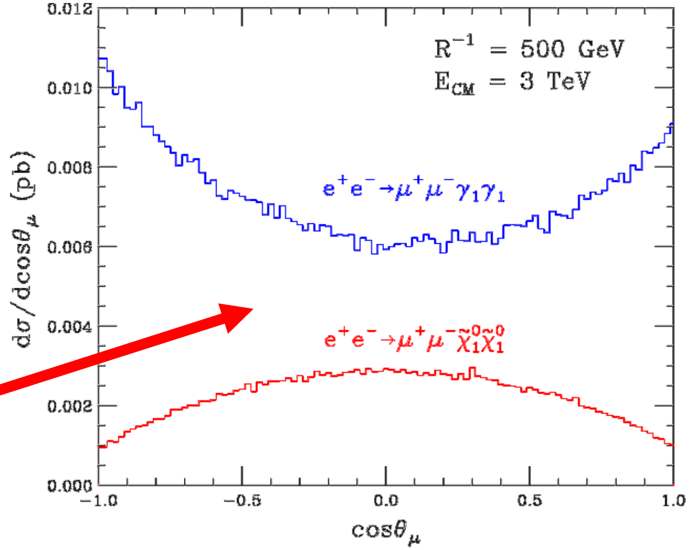
$\Rightarrow$? Did we discover SUSY or UEDs?

- 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

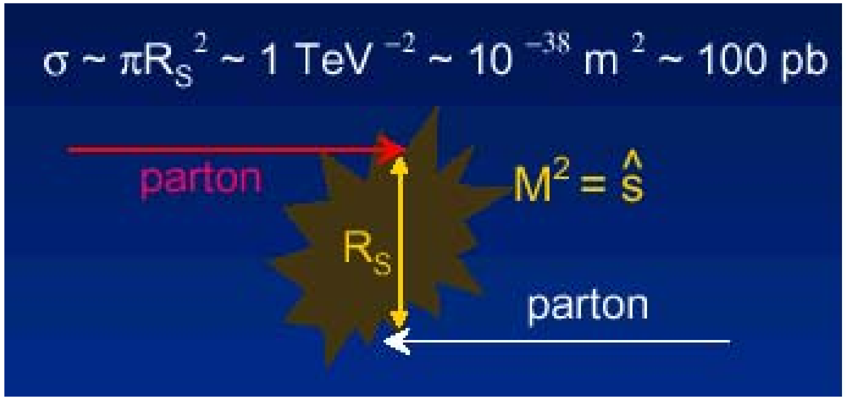


Production polar angle θ of the decay muons

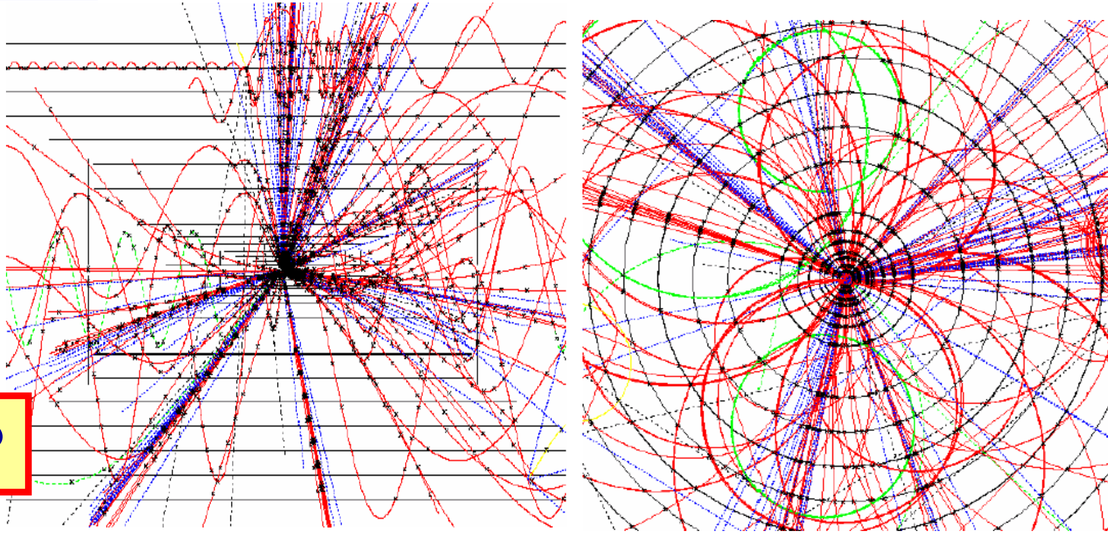
Black Holes

If $M_{planck} \sim O(1\ \mathrm{TeV}) \Rightarrow$ Black Hole production at Multi-TeV Scale

- $\sigma = \pi R_s^2 \sim 1\ \mathrm{TeV}^{-2} \sim O(100)$ 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

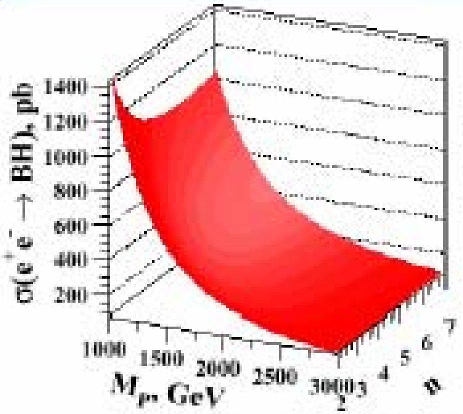


Study Quantum Gravity in the lab?

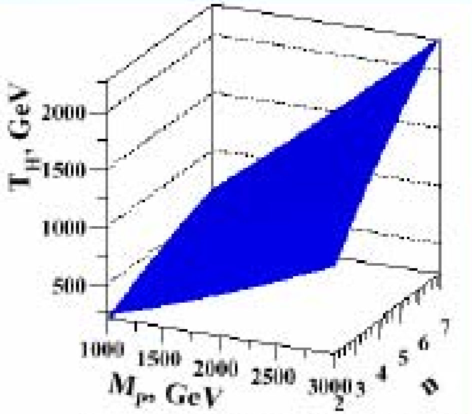
BH Production at CLIC

3 TeV

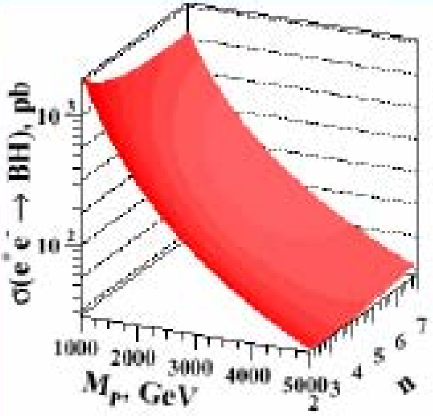
5 TeV



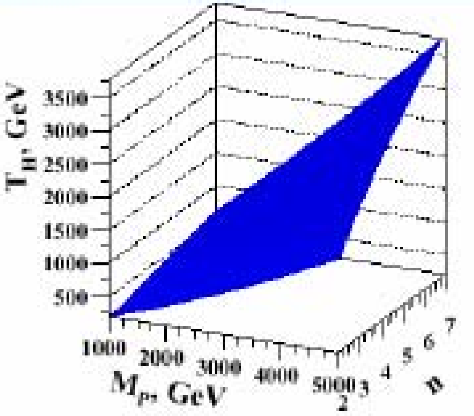
σ vs. M_P and n, 3 TeV CLIC



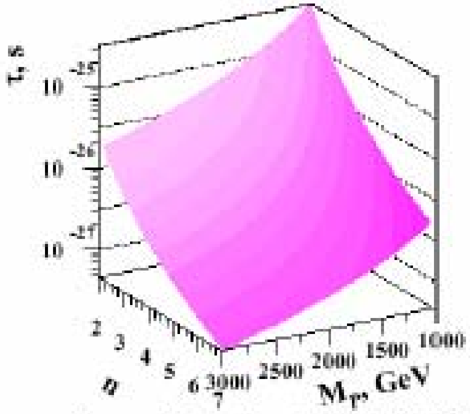
T_H vs. M_P and n, 3 TeV CLIC



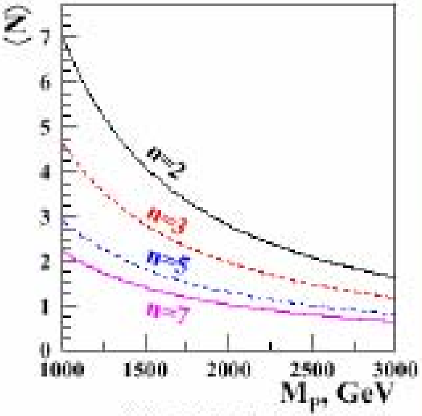
σ vs. M_P and n, 5 TeV CLIC



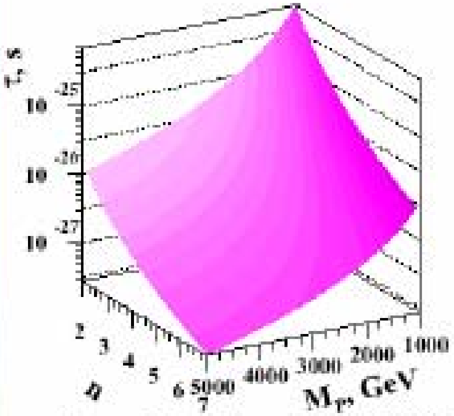
T_H vs. M_P and n, 5 TeV CLIC



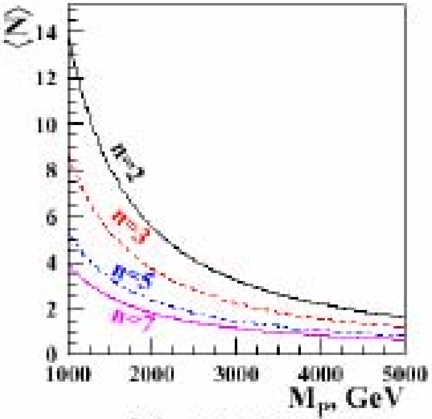
T_H vs. M_P and n, 3 TeV CLIC



⟨N⟩, 3 TeV CLIC



T_H vs. M_P and n, 5 TeV CLIC

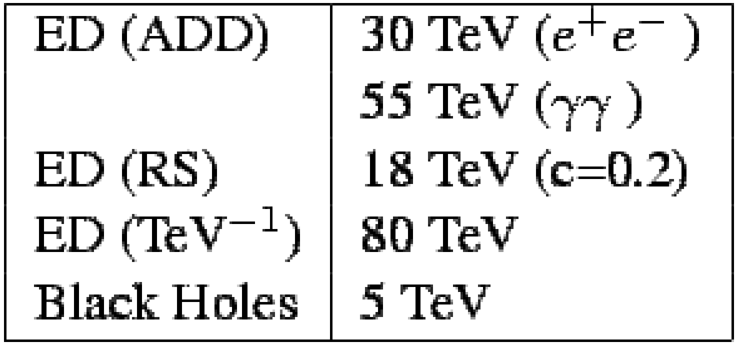


⟨N⟩, 5 TeV CLIC

Large cross sections!

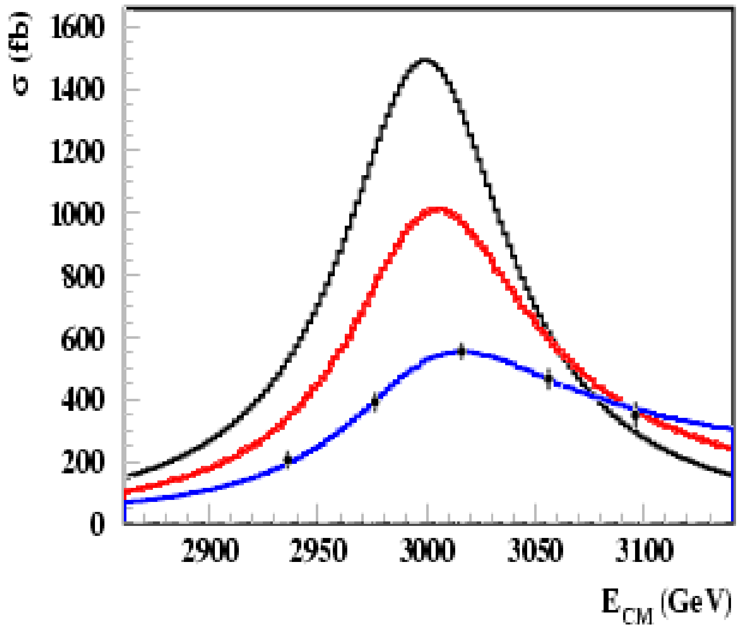
EDs: Strength of a multi-TeV collider

- 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) → 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

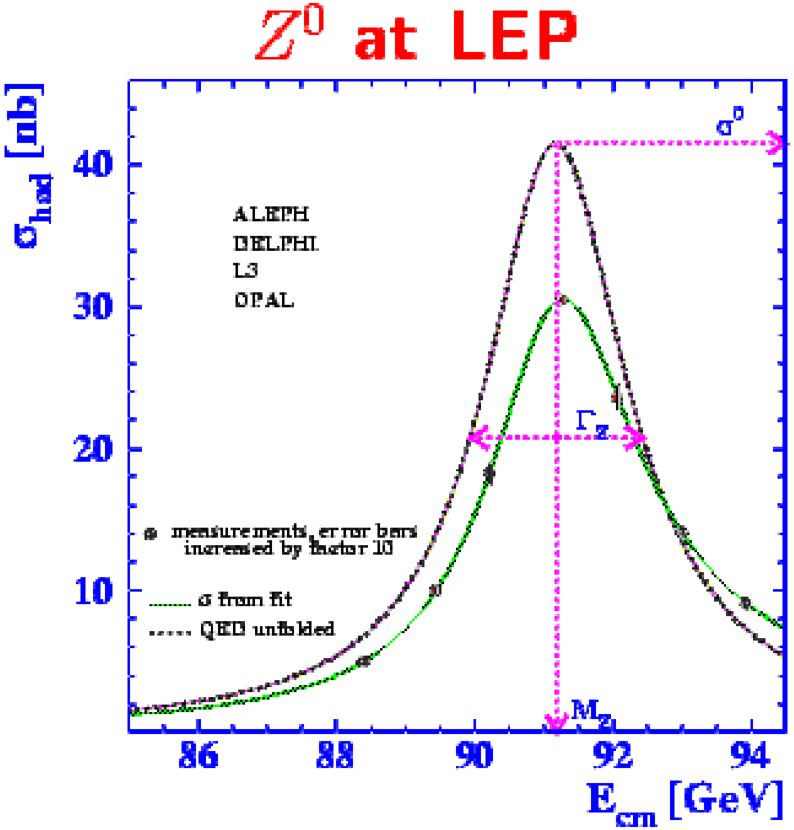
5. New Gauge Theories
Contact Interactions etc.



Z Profile Measured at LEP

One of the most important measurements at LEP

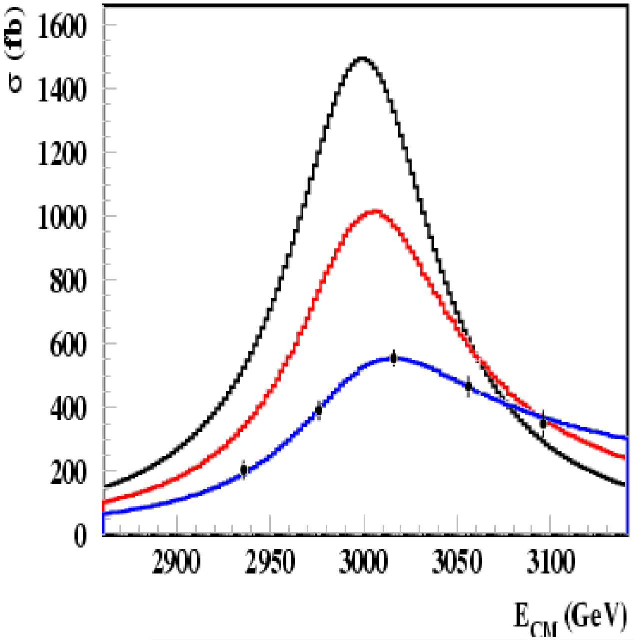
Uncanny precision!



$$\delta M_Z/M_Z \sim 2.5 \cdot 10^{-5};\ \delta\Gamma_Z/\Gamma_Z \sim 1 \cdot 10^{-3}$$

Z' with mass < 3 (5) TeV

- ✦ $\sqrt{s}$ 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:

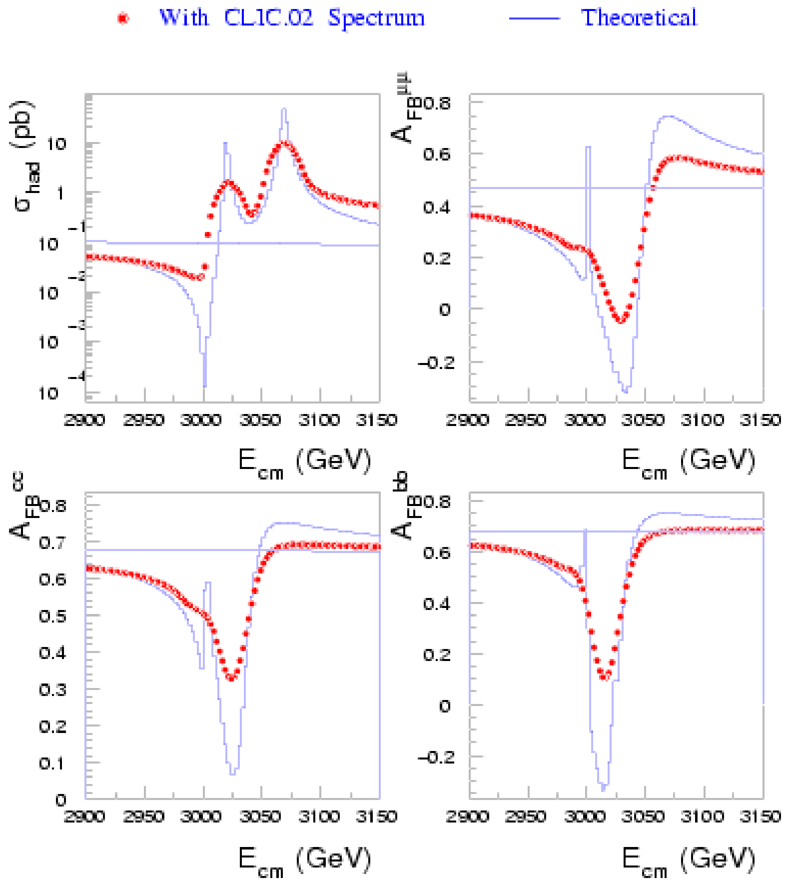


FIT ACCURACY

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

Precision will be comparable to LEP (factor 2-3 worse)

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

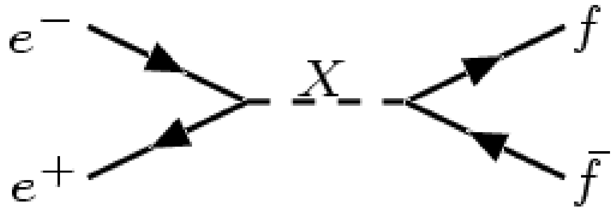
g/g''	M (GeV)	Γ_{L_3} / Γ_{R_3} (GeV)	$S/\sqrt{S+B}$ LHC ($e+\mu$)	$S/\sqrt{S+B}$ CLIC (had.)	ΔM CLIC
0.1	3000	2.0 / 0.3	(3.4)	62	23.20 ± .06
0.2	3000	8.2 / 1.2	(6.6)	152	83.50 ± .02

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

CLIC can disentangle two nearby resonances

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

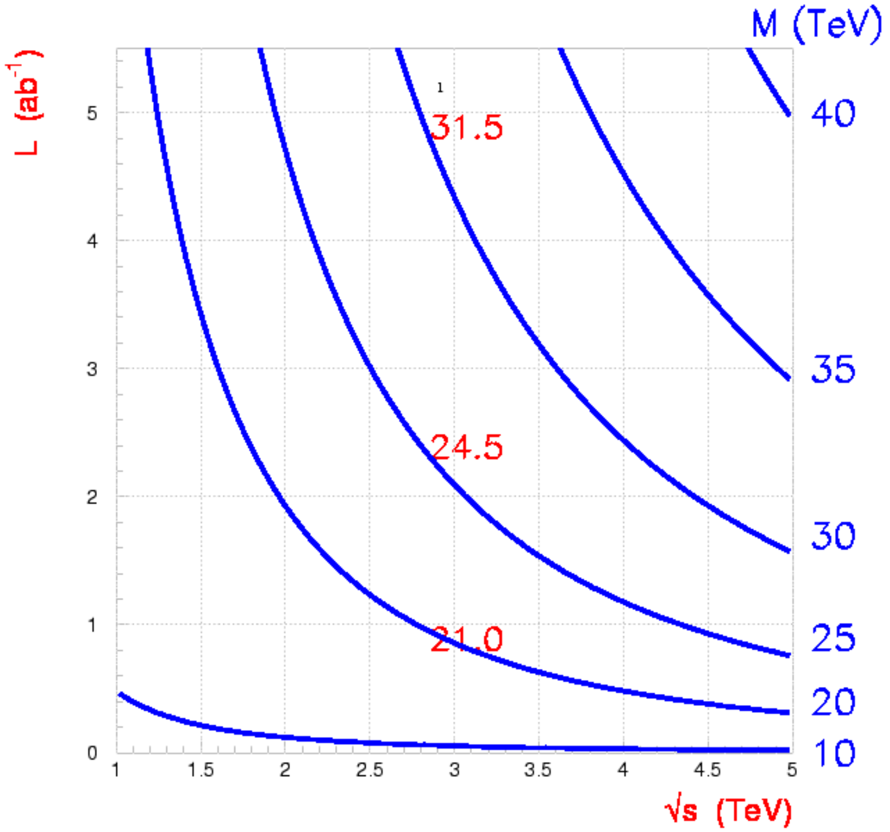
Precision Measurements



Indirect searches

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

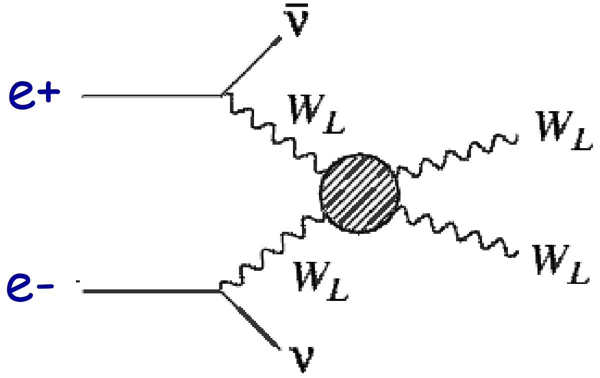
Observable	Relative Stat. Accuracy $\delta\mathcal{O}/\mathcal{O}$ for 1 ab^{-1}
$\sigma_{\mu^+\mu^-}$	± 0.010
$\sigma_{b\bar{b}}$	± 0.012
$\sigma_{t\bar{t}}$	± 0.014
$A_{FB}^{\mu\mu}$	± 0.018
A_{FB}^{bb}	± 0.055
A_{FB}^{tt}	± 0.040

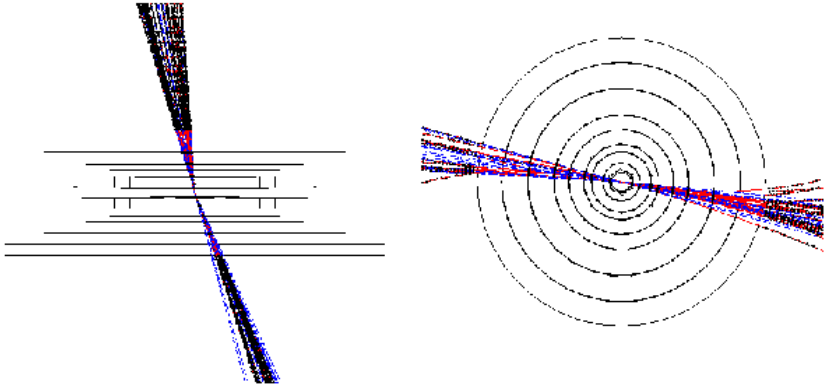


⇒ Sensitivity to $M_{Z'}$ to 30-40 TeV

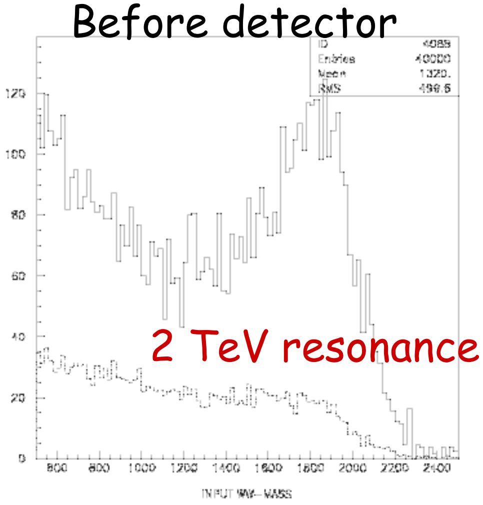
WW Scattering

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



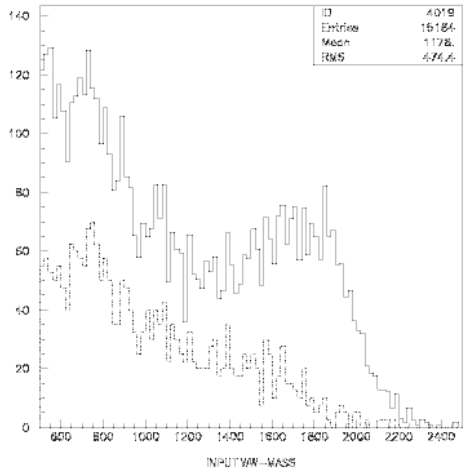


Before detector



2 TeV resonance

After detector



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

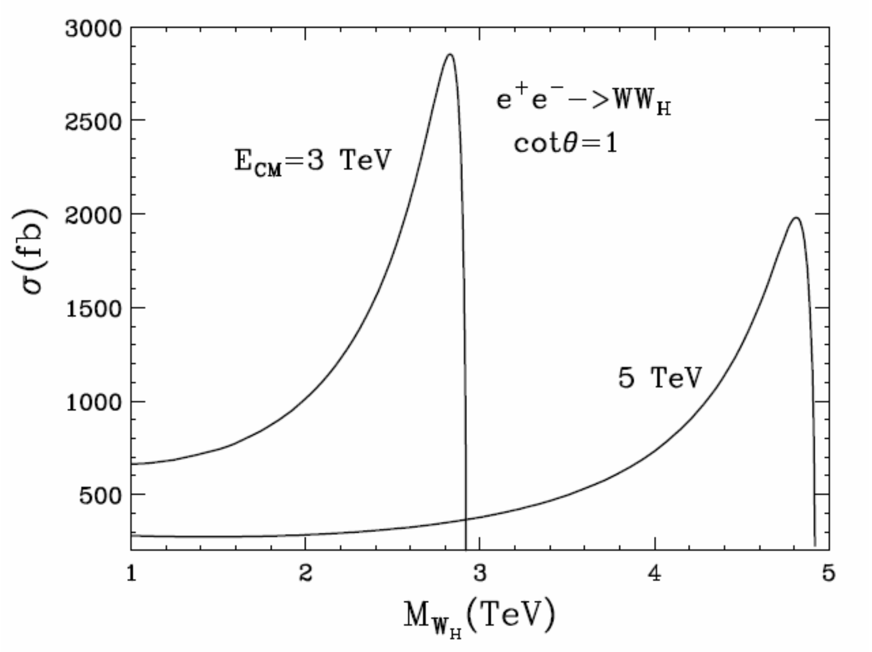
Little Higgs Models

- Stabelizing the Higgs with new weakly coupled fermions and Gauge bosons

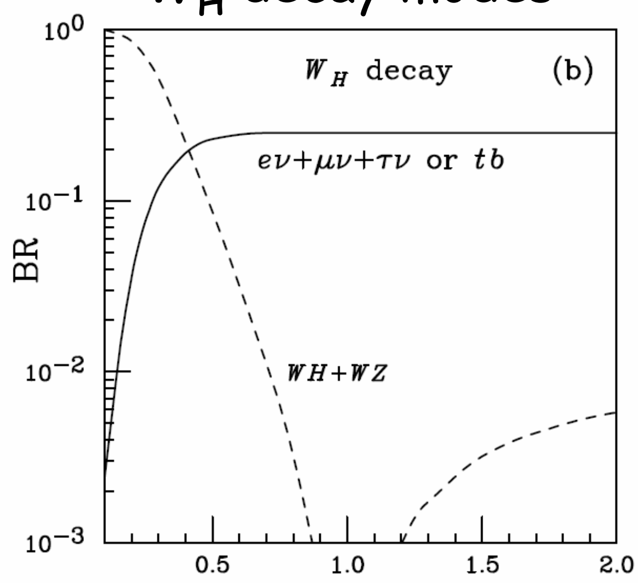
$\Rightarrow$ Expect 'new top' quark and new W_H,Z_H around 1 TeV.

$\Rightarrow$ Expect the new gauge bosons to be copiously be produced at a LC, e.g. via the associated production $e+e- \rightarrow WW_H$

Cross section: Large!



W_H decay modes

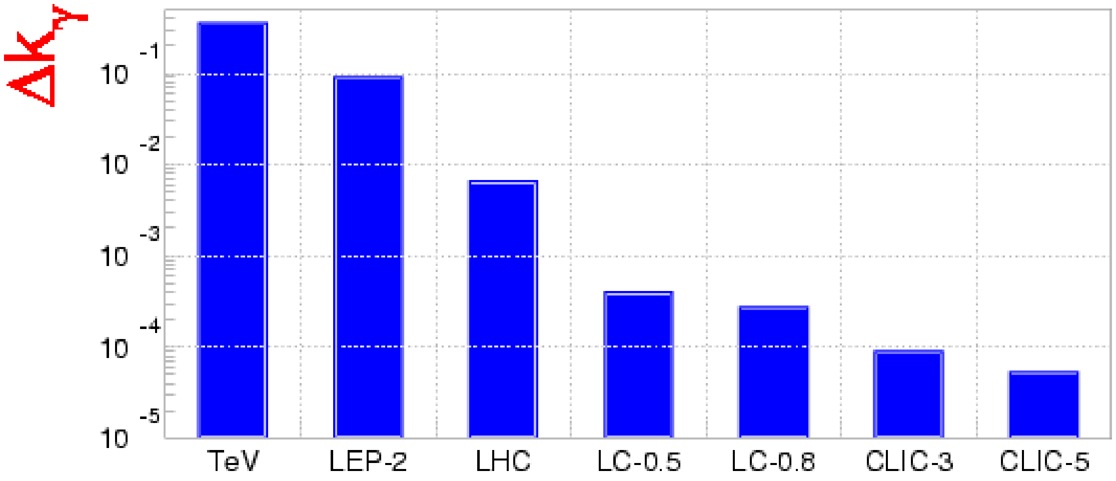


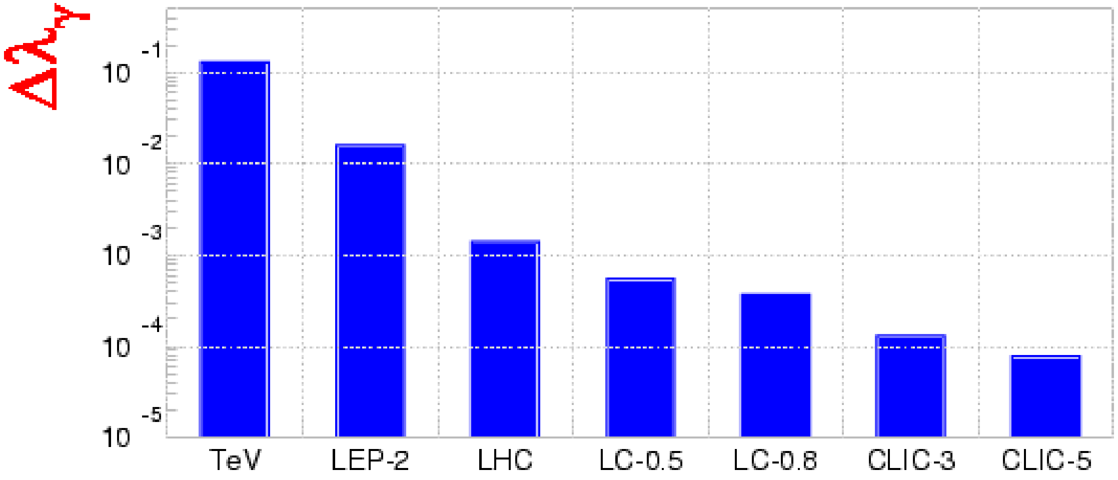
cotθ =Gauge coupling mixing parameter

Allow for detailed studies of W_H (and other new particles) properties

Triple Gauge Couplings

High precision analysis of the self coupling of the EW gauge bosons

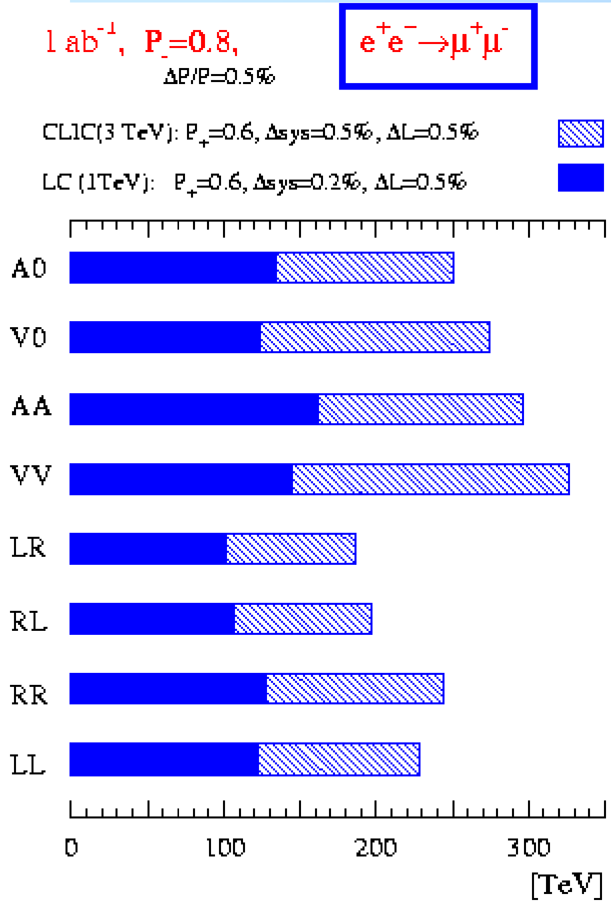


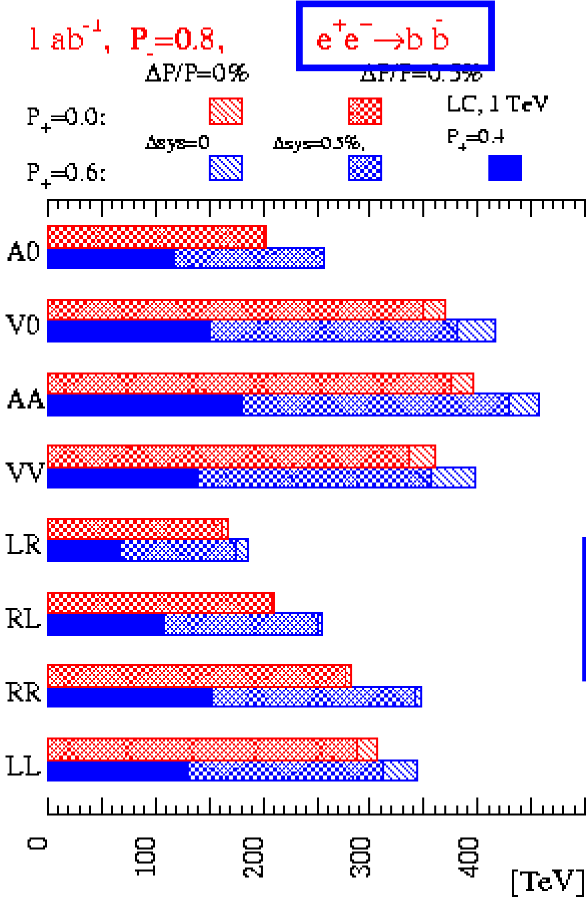


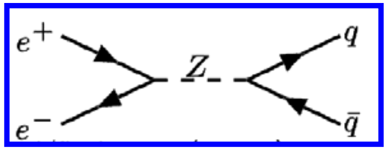
Expectation of the precision for $\Delta\lambda_\gamma$ and $\Delta\kappa_\gamma \sim 10^{-4}$

Measurements for one year of high luminosity for the future colliders

Reach to Probe New Physics







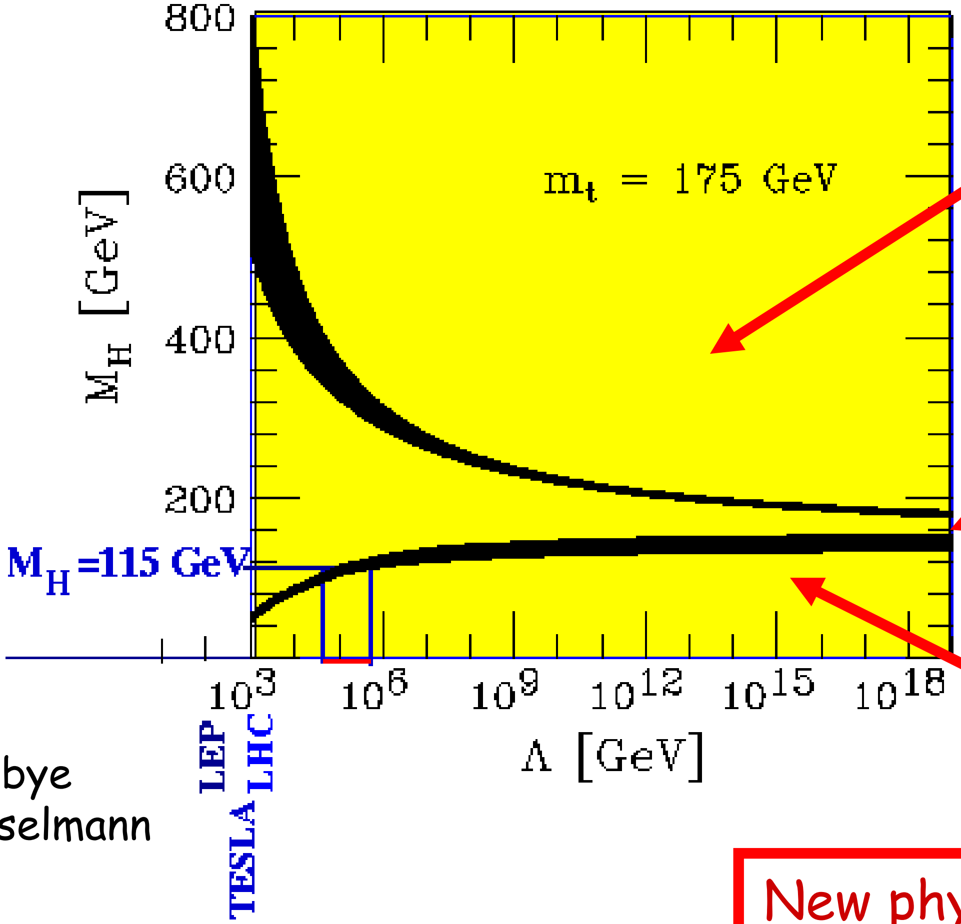
⇒ Contact Interactions: sensitivity to scales up to 100-400 TeV

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

Remember: If Higgs light ⟶ something new must happen before 1000 TeV

A light Higgs…important consequences

A light Higgs implies that the Standard Model cannot be stable up to the GUT or Planck scale (10^{19} GeV)



Hambye
Riesselmann

The effective potential blows up, due to heavy top quark mass

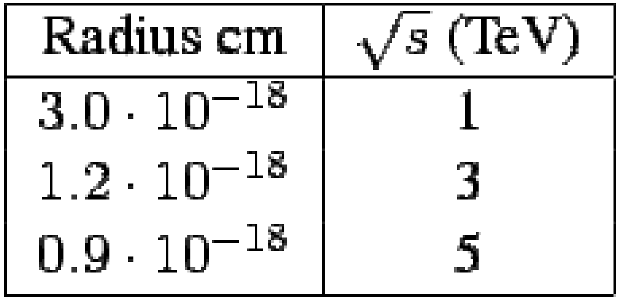
Allowed corridor but needs strong fine-tuning…

The electroweak vacuum is unstable to corrections from scales $\Lambda \gg v$= 246 GeV

New physics expected in TeV range

Alternative Theories

- Excited lepton production
- Production of 4th family quarks and leptons
- Leptoquarks
- Effects of non-commutative interactions on physical observables
- Transplanckian effects when the centre of mass system energy is above the fundamental gravity mass scale
- Lepton size measurements



Radius cm	$\sqrt{s}$ (TeV)
$3.0 \cdot 10^{-18}$	1
$1.2 \cdot 10^{-18}$	3
$0.9 \cdot 10^{-18}$	5

Summary: CLIC vs Hadron Colliders

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

+ updates

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

Summary: CLIC Physics Potential

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 e.g. at LEP, or even a TeV collider.

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

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

Very large physics potential, reach beyond that of the LHC.