Le futur collisionneur linéaire : où en est on ?

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OUTLINE

- Introduction

- Machine(s)
- Detector(s)
- Physic(s)

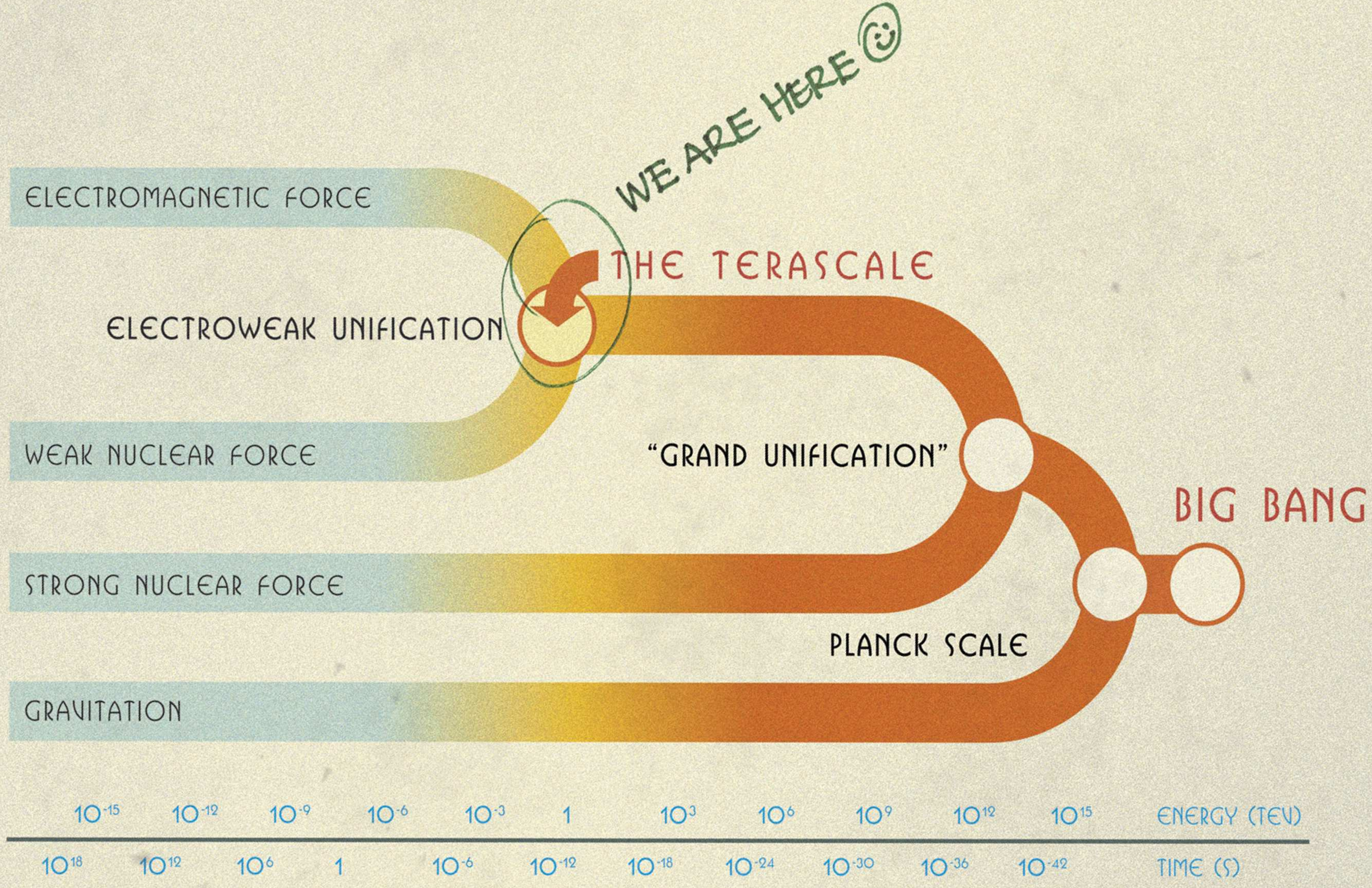
- Conclusion(s)

Introduction

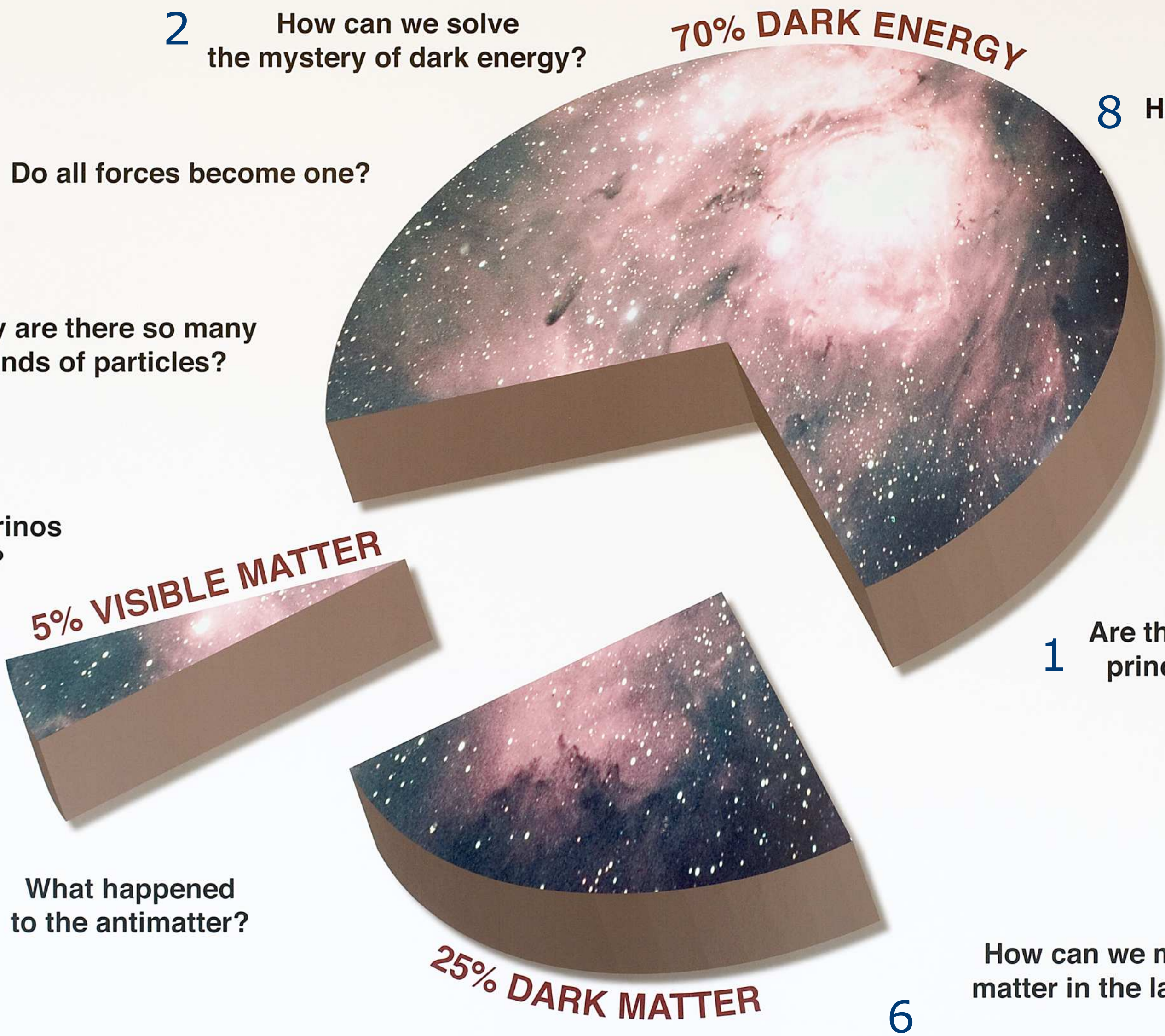
- No historical recall !

- Today situation, and (far?) future
- Probably optimistic ! (biased ?)

- Today, physics is SM like, but SM is incomplete for sure. Thus QUESTIONS


WE ARE HERE ☺
ELECTROMAGNETIC FORCE
THE TERASCALE
ELECTROWEAK UNIFICATION
WEAK NUCLEAR FORCE
"GRAND UNIFICATION"
BIG BANG
STRONG NUCLEAR FORCE
PLANCK SCALE
GRAVITATION
10^{-15} 10^{-12} 10^{-9} 10^{-6} 10^{-3} 1 10^{3} 10^{6} 10^{9} 10^{12} 10^{15} ENERGY (TEV)
10^{18} 10^{12} 10^{6} 1 10^{-6} 10^{-12} 10^{-18} 10^{-24} 10^{-30} 10^{-36} 10^{-42} TIME (S)

QUANTUM QUESTIONS



2 How can we solve the mystery of dark energy?

8 How did the universe come to be?

4 Do all forces become one?

5 Why are there so many kinds of particles?

3 Are there extra dimensions of space?

7 What are neutrinos telling us?

1 Are there undiscovered principles of nature?

9 What happened to the antimatter?

How can we make dark matter in the laboratory?

6

What is dark matter?

Discoveries, discoveries !

Imagine : we are in 2013 ! Whatever the scenario at LHC, the Physics case for a LC is rich.

	If LHC discovers :	What a LC could do :
1	Higgs particle	Discover why the Higgs exists and who its cousins are. Discover effects of extra dim. or a new source of matter-antimatter asymmetry

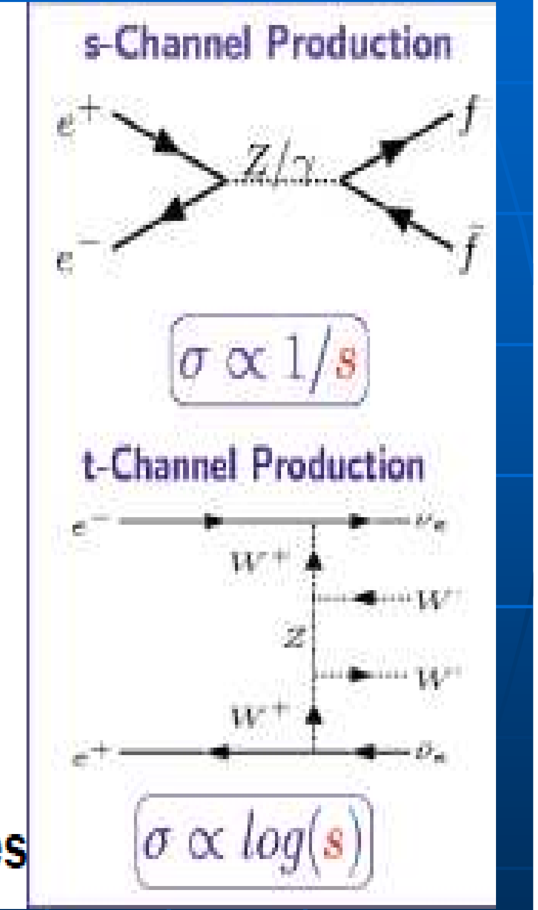
	If LHC discovers :	What a LC could do :
2	Superpartner particles	Detect the symmetry of supersymmetry. Reveal the supersymmetric nature of dark matter. Discover force unification and matter unification at ultra-high energies.
3	Evidence for extra dimensions	Discover the number and shape of the extra dimensions. Discover which particles are travelers in extra dimensions, and determine their locations.
4	Missing energy from a WIMP	Discover its identity as dark matter. Determine what fraction of the total dark matter it accounts for.
5	Heavy charged particles appearing as stable.	Discover that these eventually decay into very weakly interacting particles. Identify these « super WIMPs » as dark matter.
6	A Z-prime particle, representing a previously unknown force of nature	Discover the origin of this Z'. Connect this new force to the unification of quarks with neutrinos, of quarks with the Higgs, or with extra dimensions.

Machines

ILC and CLIC

Basics of e^+e^- colliders

- e^+e^- collision is a very simple reaction:
  - Well defined initial state
  - Rather simple topologies in the final state
  - Favorable signal to background ratio
- Very clean experimental environment which allows to
  - easily search for new phenomena
  - perform very high–precision measurements and studies


s-Channel Production

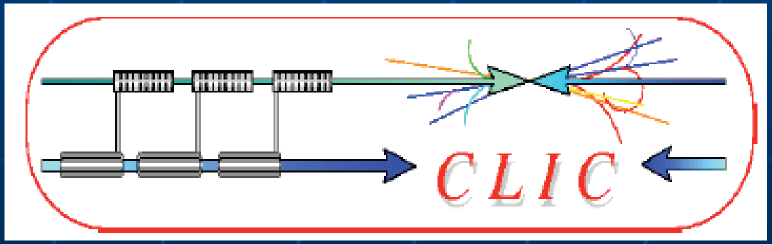
$\sigma \propto 1/s$

t-Channel Production

$\sigma \propto log(s)$

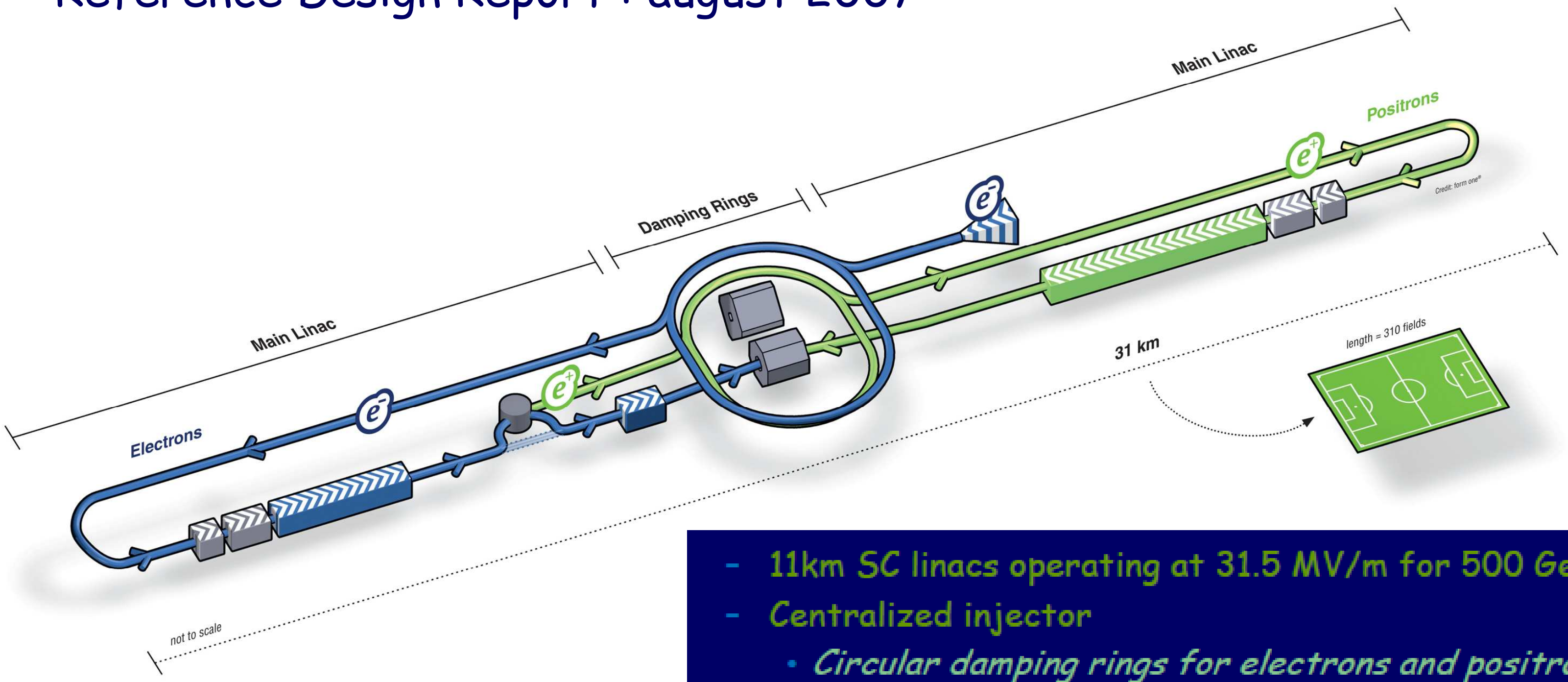
Collider(s)

- There is a world-wide consensus for a machine with superconducting acc. cavities (2004)
- Since long, CERN is looking into a new accelerating technique : the 2 beam scheme.



ILC : today's design

Reference Design Report : august 2007



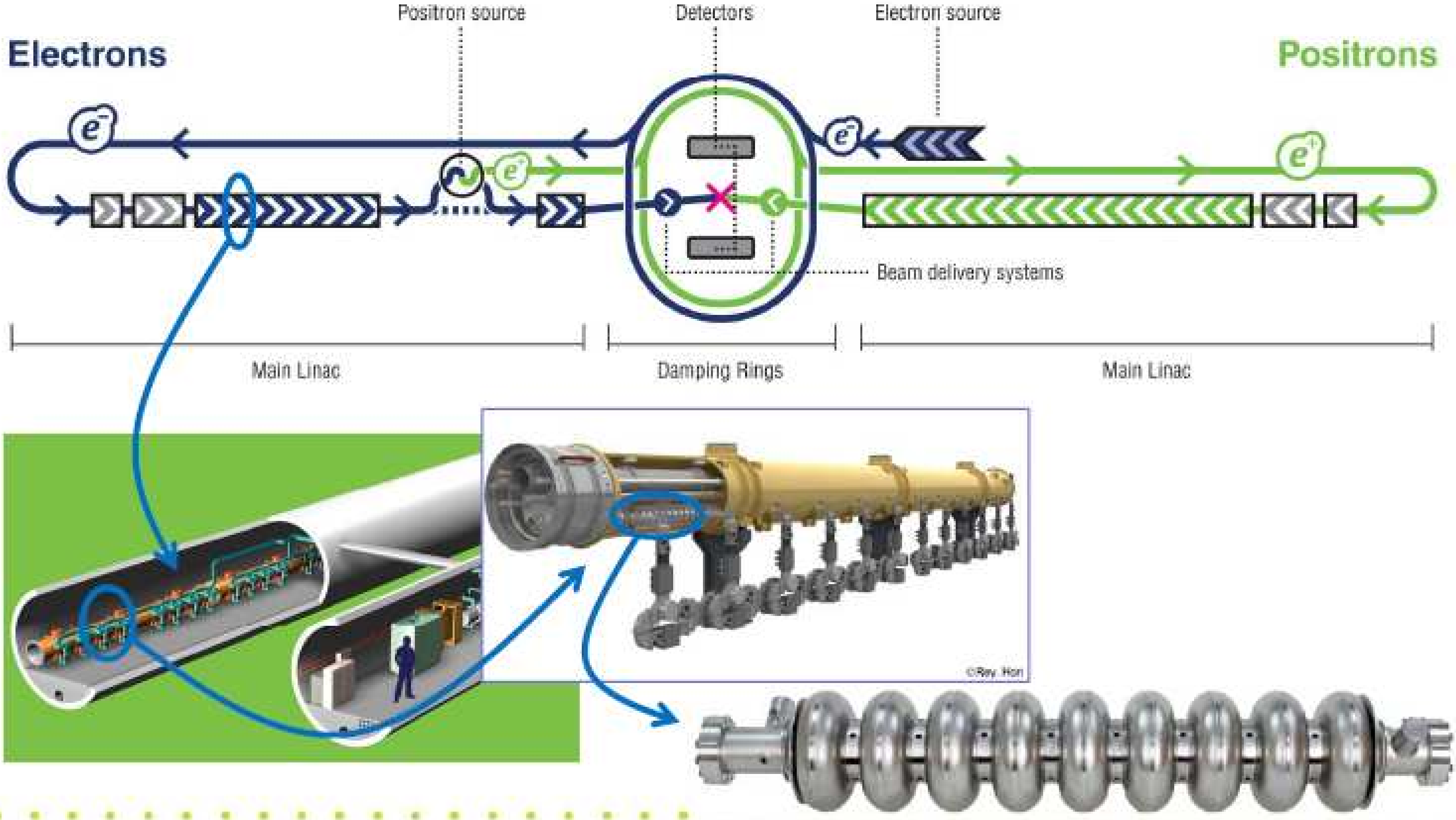
- 11km SC linacs operating at 31.5 MV/m for 500 GeV
- Centralized injector
  - *Circular damping rings for electrons and positrons*
  - *Undulator-based positron source*
- Single IR with 14 mrad crossing angle
- Dual tunnel configuration for safety and availability

ILC parameters (at 500 GeV)

- E_{cm} adjustable from 200 to 500 GeV
- Luminosity 500 fb^{-1} in 4 years
- Energy stability and precision below 0.1%
- Electron polarization of at least 80%
- Machine upgradable to 1 TeV

Center-of-mass energy	500	GeV
Peak Luminosity	~2×10^{34}	$1/cm^2s$
Beam Current	9.0	mA
Repetition rate	5	Hz
Average accelerating gradient	31.5	MV/m
Beam pulse length	0.87	ms
Total Site Length	31	km
Total AC Power Consumption	~230	MW

ILC Reference Design



Accelerating cavities

- Advantages of supercond. techno.
  - weaker wake field
  - power transmission eff.
- Cavities
  - Niobium at 2K
  - Frequency 1.3 GHz
  - Gradient = 31.5 MV/m (same as for XFEL)

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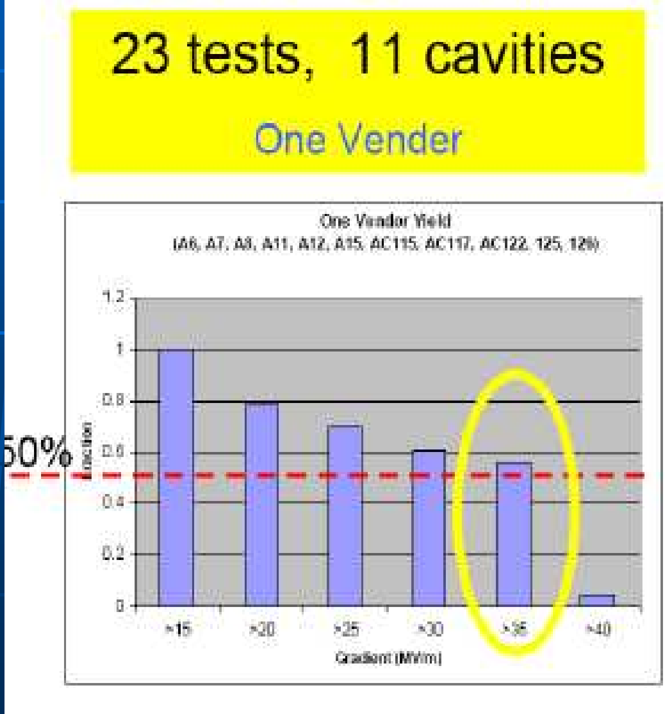


the two beam scheme

Two Beam Scheme:

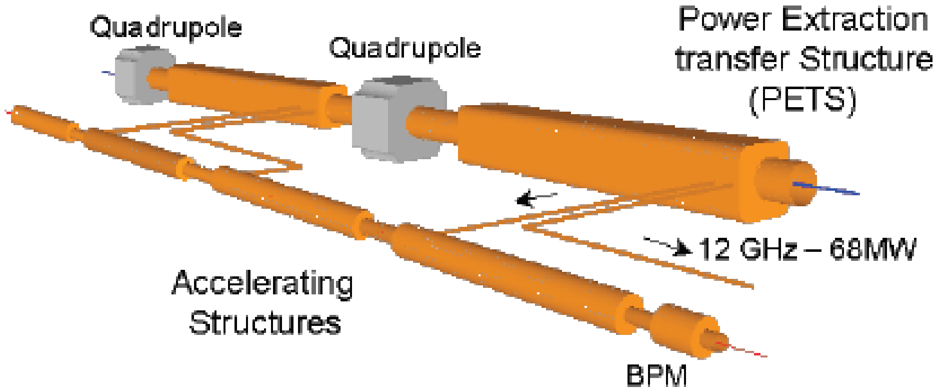
Drive Beam supplies RF power

- 12 GHz bunch structure
- low energy (2.4 GeV - 240 MeV)
- high current (100A)

Main beam for physics

- high energy (9 GeV – 1.5 TeV)
- current 1.2 A

Drive beam – 100 A, 240 ns
from 2.4 GeV to 240 MeV



Main beam – 1.2 A, 156 ns
from 9 GeV to 1.5 TeV

No individual RF power sources

- **CLIC website**
- http://clic-study.web.cern.ch/CLIC-Study/

- **CLIC physics/detector web**
- http://clic-meeting.web.cern.ch/clic-meeting/CLIC_Phy_Study_Website/default.html

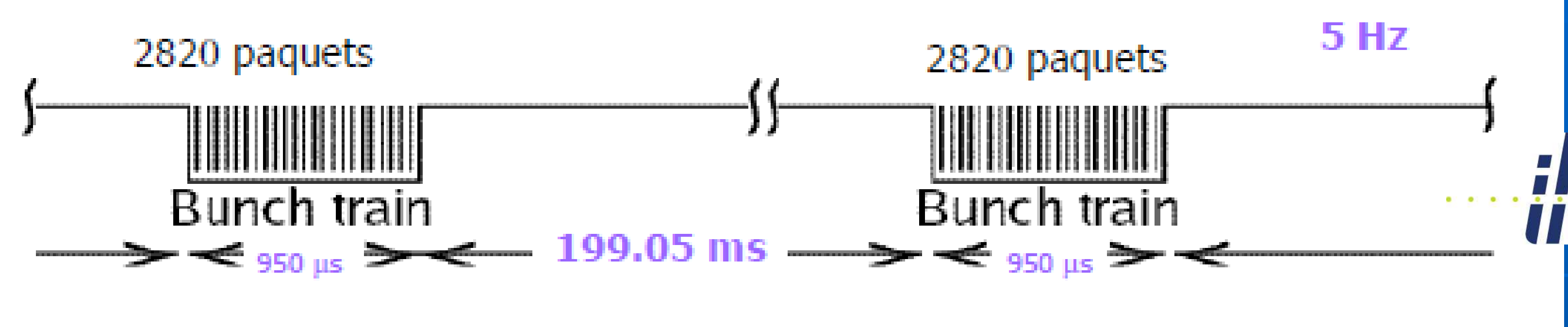
CLIC parameters

Center-of-mass energy	3 TeV	
Peak Luminosity	$6 \cdot 10^{34}$ cm^{-2} s^{-1}	←
Peak luminosity (in 1% of energy)	$2 \cdot 10^{34}$ cm^{-2} s^{-1}	←
Repetition rate	50 Hz	←
Loaded accelerating gradient	100 MV/m	
Main linac RF frequency	12 GHz	
Overall two-linac length	42 km	
Bunch charge	$3.72 \cdot 10^{9}$	
Bunch separation	0.5 ns	←
Beam pulse duration	156 ns	←
Beam power/beam	14 MWatts	
Hor./vert. normalized emittance	660 / 20 nm rad	
Hor./vert. IP beam size bef. pinch	40 / ~1 nm	←
Total site length	48 km	
Total power consumption	415 MW	

ILC vs CLIC : differences

- Timeline
  ILC TDR in 2 phases : 2010 and 2012
  CLIC TDR foreseen for 2015
- Energy
  first phase at 500 GeV for both
  max energy : 1TeV (ILC), 3 TeV (CLIC)
- Time structure
- Beam-induced background

Time structure



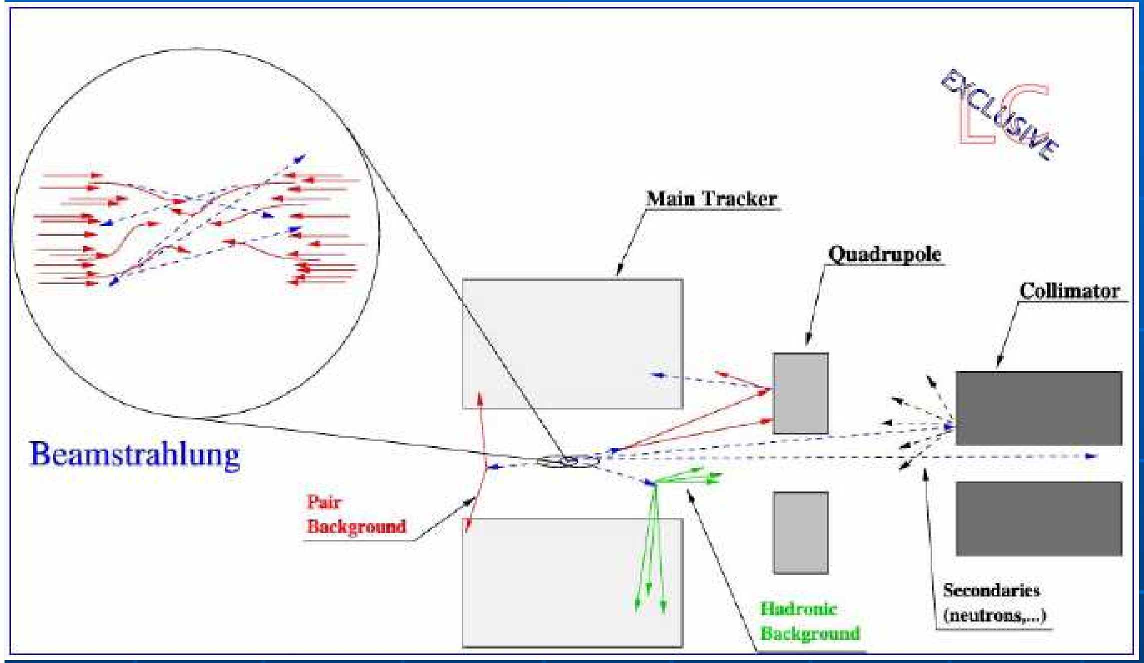
CLIC:	1 train = 312 bunches	0.5 ns apart	50 Hz
ILC:	1 train = 2820 bunches	337 ns apart	5 Hz

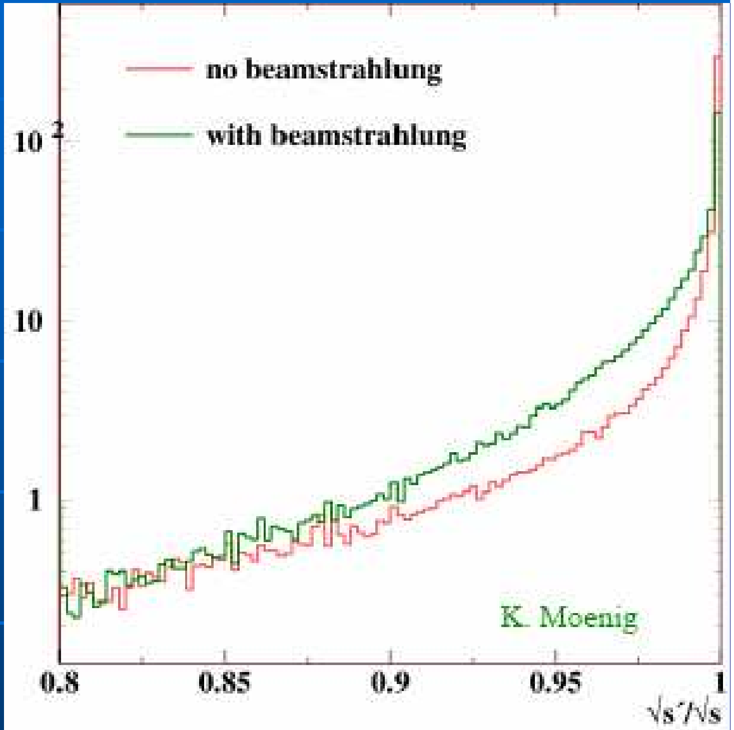
ILC : no hardware trigger !!!

Consequences for CLIC detector:

- Assess need for detection layers with time-stamping
  - Innermost tracker layer with sub-ns resolution
  - Additional time-stamping layers for photons and for neutrons
- Readout electronics will be different from ILC
- Power pulsing at 50 Hz, instead of 5 Hz

The price of high lumi : beamstrahlung





ILC 500

Electrons radiate against the coherent field of the other bunch, generating beam-beam interactions : it reduces the effective c.m.s

Beam-induced background

Background sources: CLIC and ILC similar

Due to the higher beam energy and small bunch sizes they are significantly more severe at CLIC.

- CLIC 3TeV beamstrahlung ΔE/E = 29% $(10\times\mathrm{ILC}_{\mathrm{value}})$

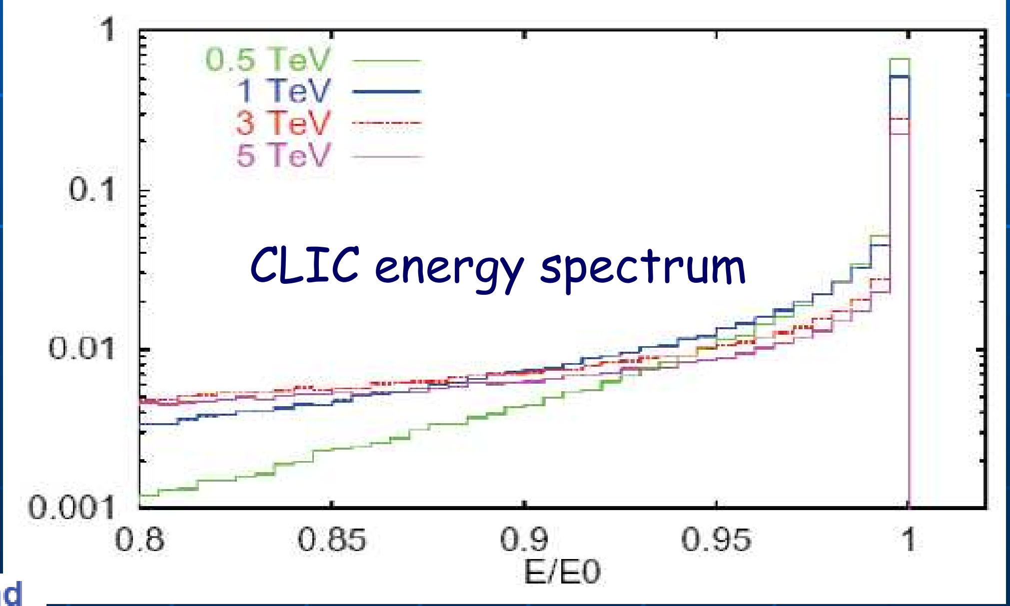
But also :

Muon background from upstream linac

Synchrotron radiation

Beam tails from linac

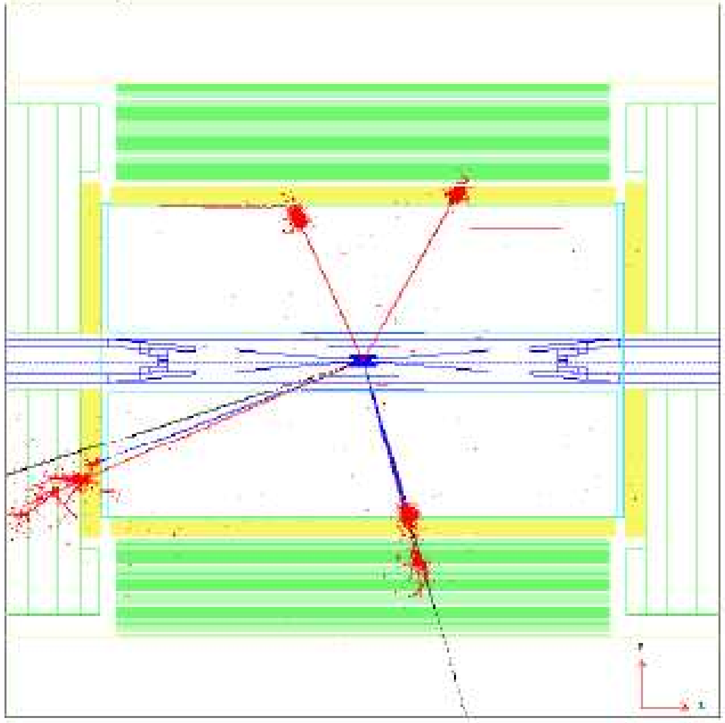
Backscattered particles



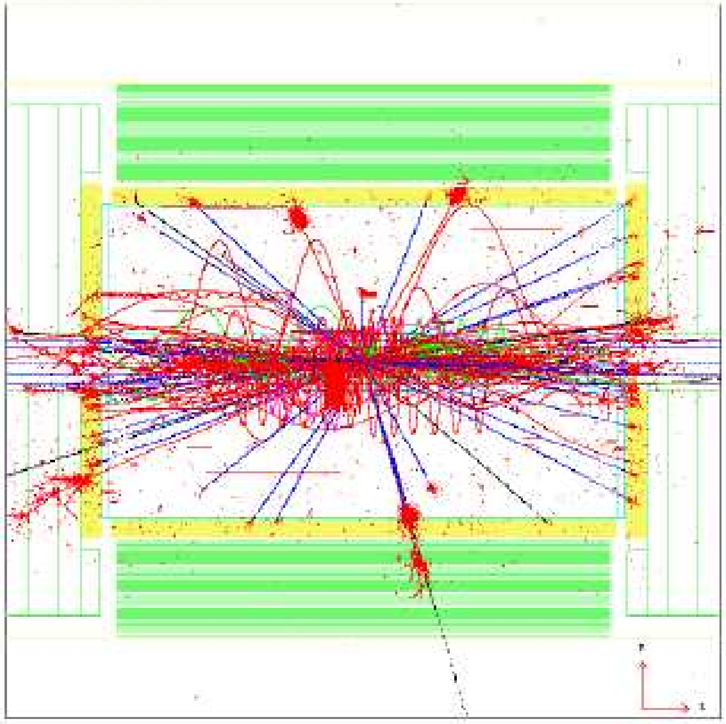
→
- CLIC VTX: O(10) times more background
- CLIC TPC: O(30) times more background

HZ → ττee event

Without soft hadronic events overlaid (=ILC)



With 32 BX (=16 ns) „CLIC nominal 500" overlaid

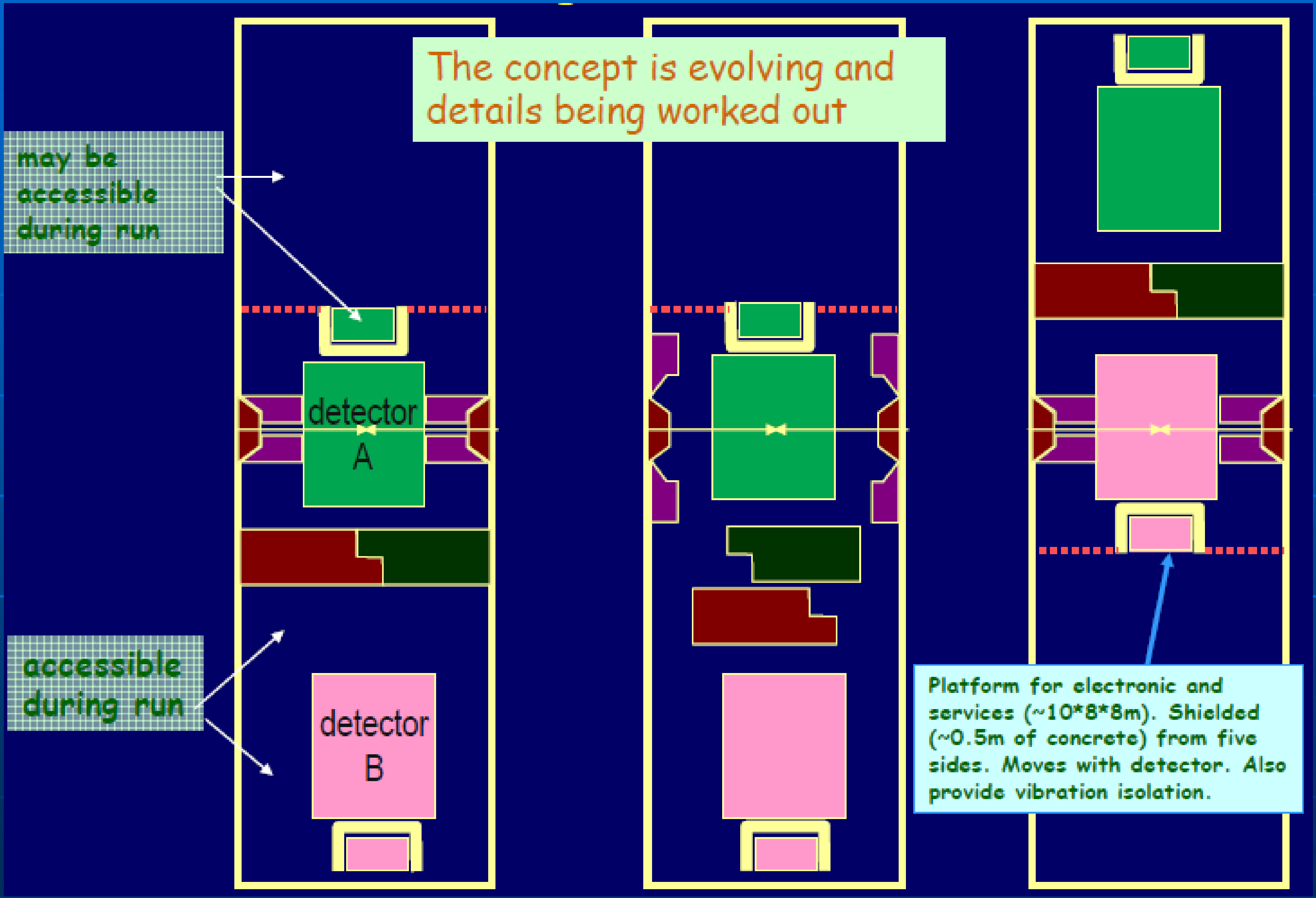


note: CLIC 3000 nominal has 14 times CLIC500 overlaid

Detectors

Two , in push-pull mode

Detector configuration : TWO for ONE IP



The concept is evolving and details being worked out

may be accessible during run

accessible during run

Platform for electronic and services (~10*8*8m). Shielded (~0.5m of concrete) from five sides. Moves with detector. Also provide vibration isolation.

Some detector design criteria

Requirement for ILC	Compared to best performance to date
Impact parameter resolution	Need factor 3 better than SLD
$\sigma_{r\phi} \approx \sigma_{rz} \approx 5 \oplus 10/(p\sin^{3/2}\vartheta)$	$\sigma_{r\phi} = 7.7 \oplus 33/(p\sin^{3/2}\vartheta)$
Momentum resolution	Need factor 10 (3) better than LEP (CMS)
$\sigma\left(\frac{1}{p_T}\right) = 5\times10^{-5}\ (GeV^{-1})$	
Jet energy resolution goal	Need factor 2 better than ZEUS
$\cancel{\frac{\sigma_E}{E} = \frac{30\%}{\sqrt{E}}}$ $\quad \frac{\sigma_E}{E} = 3-4\%$	$\frac{\sigma_E}{E} = \frac{60\%}{\sqrt{E}}$
Detector implications:	Detector implications:
– Calorimeter granularity	– Need factor ~200 better than LHC
– Pixel size	– Need factor ~20 smaller than LHC
– Material budget, central	– Need factor ~10 less than LHC
– Material budget, forward	– Need factor ~ >100 less than LHC

Observation: LHC: staggering increase in scale, but modest extrapolation of performance
ILC: modest increase in scale, but significant push in performance

b and c tagging

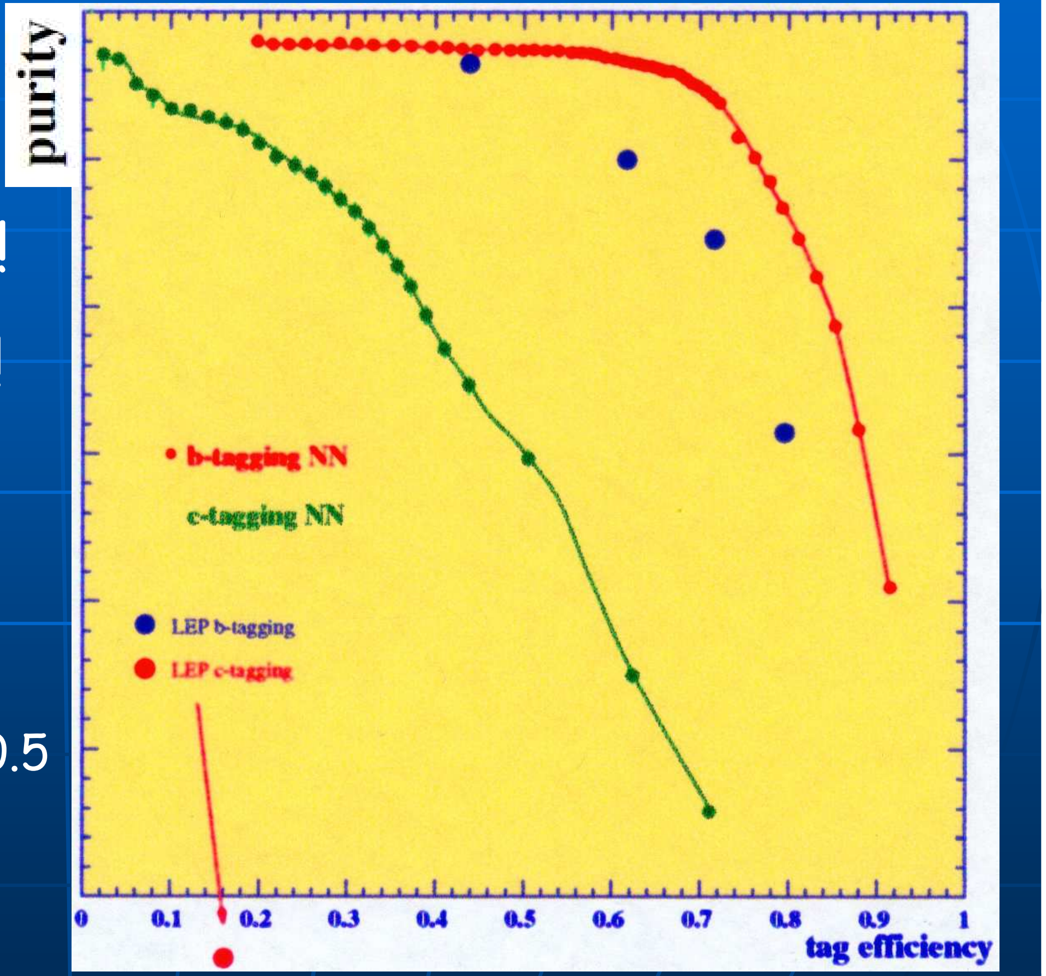
Want to measure BR(H→cc) !

Have to tag 4-b final states !

We do not know how to built such a VDET !

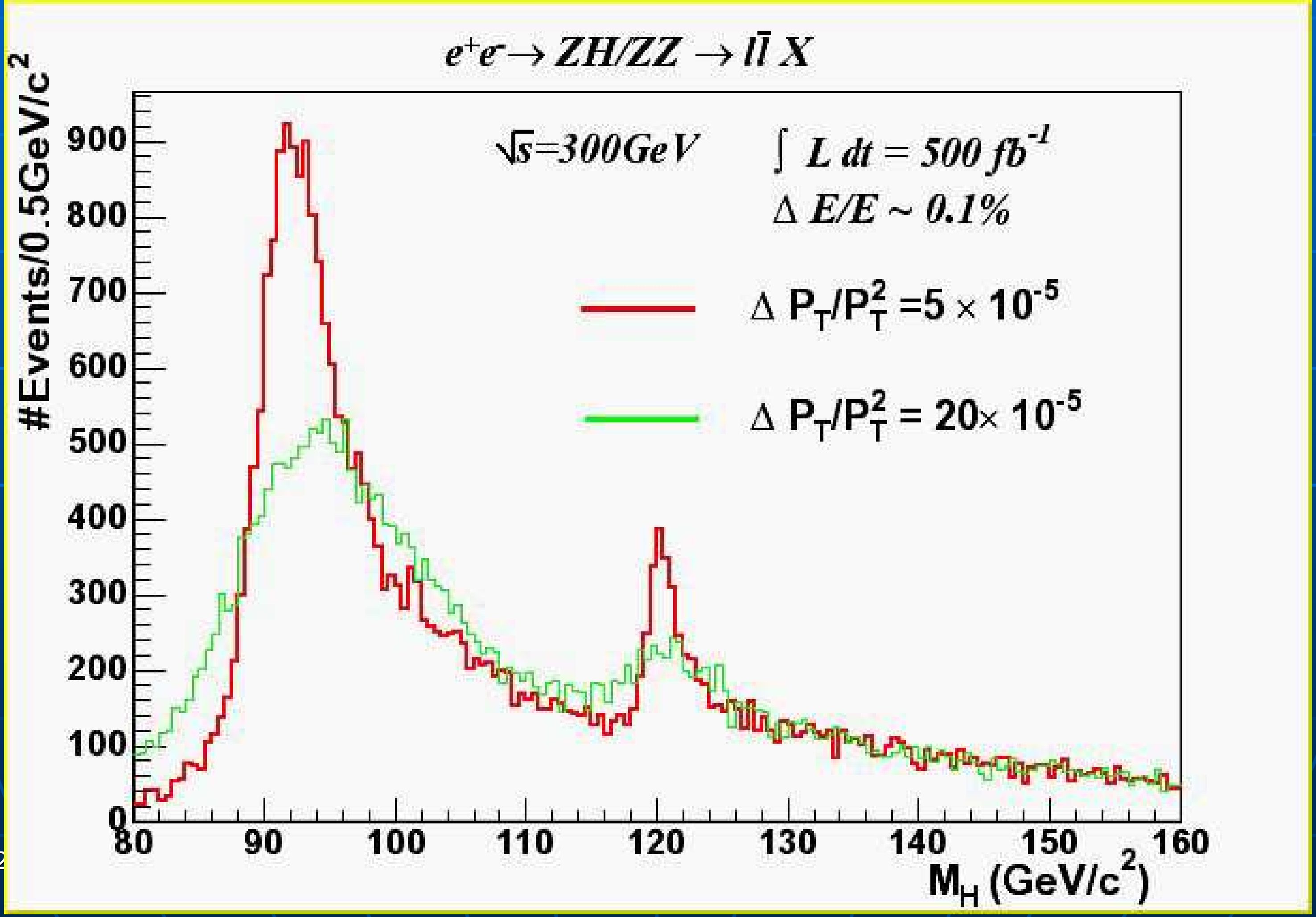
Many R&D on various technologies :

CCD, MAPS, Depfet, 3D



Momentum resolution

Recoil mass to a Z seen in 2 leptons



Design driver for 2 detector concepts : PFA

To be able to achieve the jet resolution can NOT simply use calorimeters as sampling devices.

$\cancel{\frac{\sigma_E}{E} \cong 0.30\frac{1}{\sqrt{E(GeV)}}}$ $\frac{\sigma_E}{E} = 3 - 4\%$

Have to use "energy/particle flow (PFA)". Technique has been used to improve jet resolution of existing calorimeters.

Algorithm:

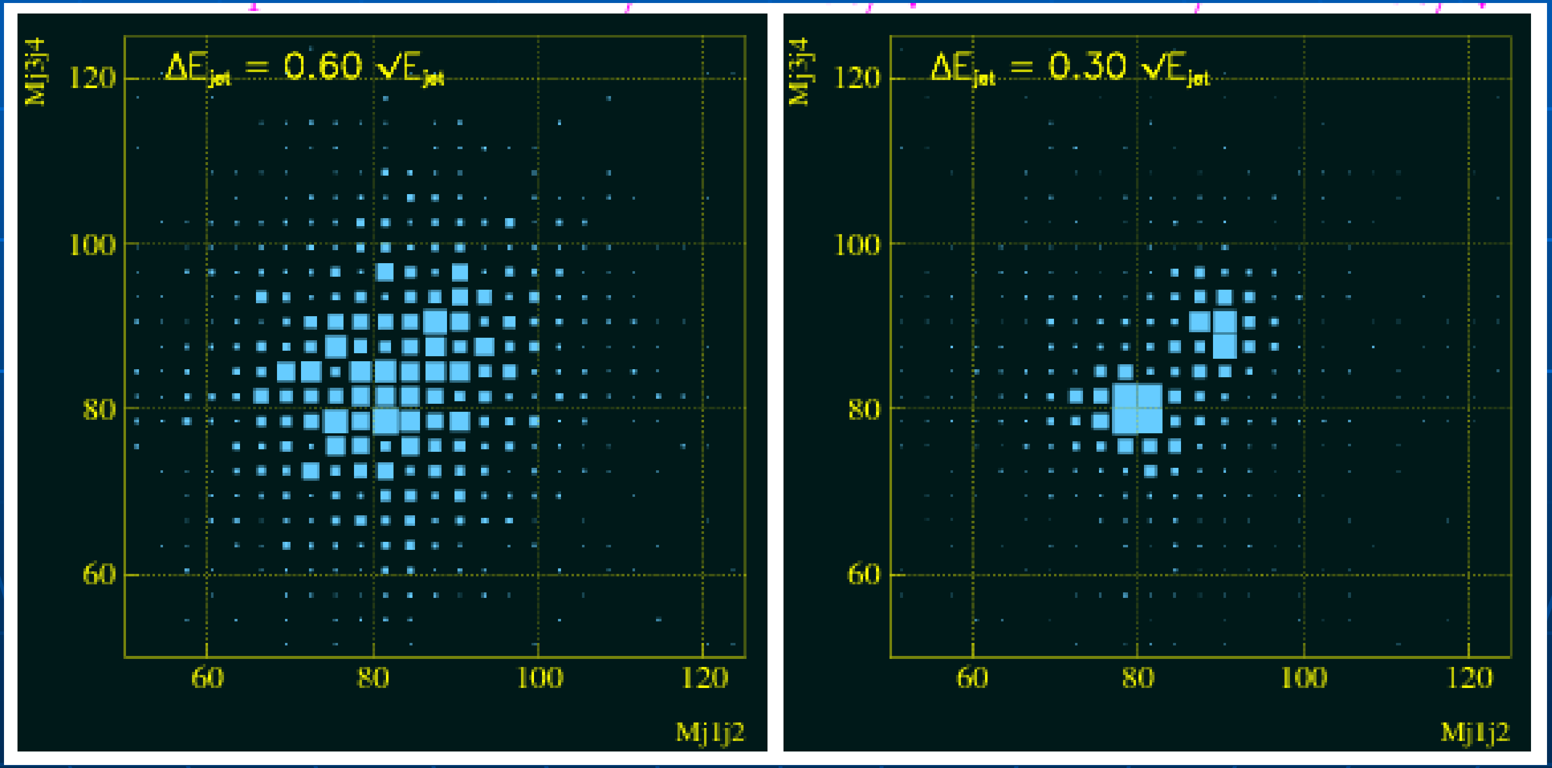
- use EM calorimeter (EMCAL) to measure photons and electrons;
- track charged hadrons from tracker through EMCAL,
- identify energy deposition in hadron calorimeter (HCAL) with charged hadrons & replace deposition with measured momentum (very good)
- When completed only E of neutral hadrons (K's, Lambda's) is left in HCAL. Use HCAL as sampling cal for that.

Require:

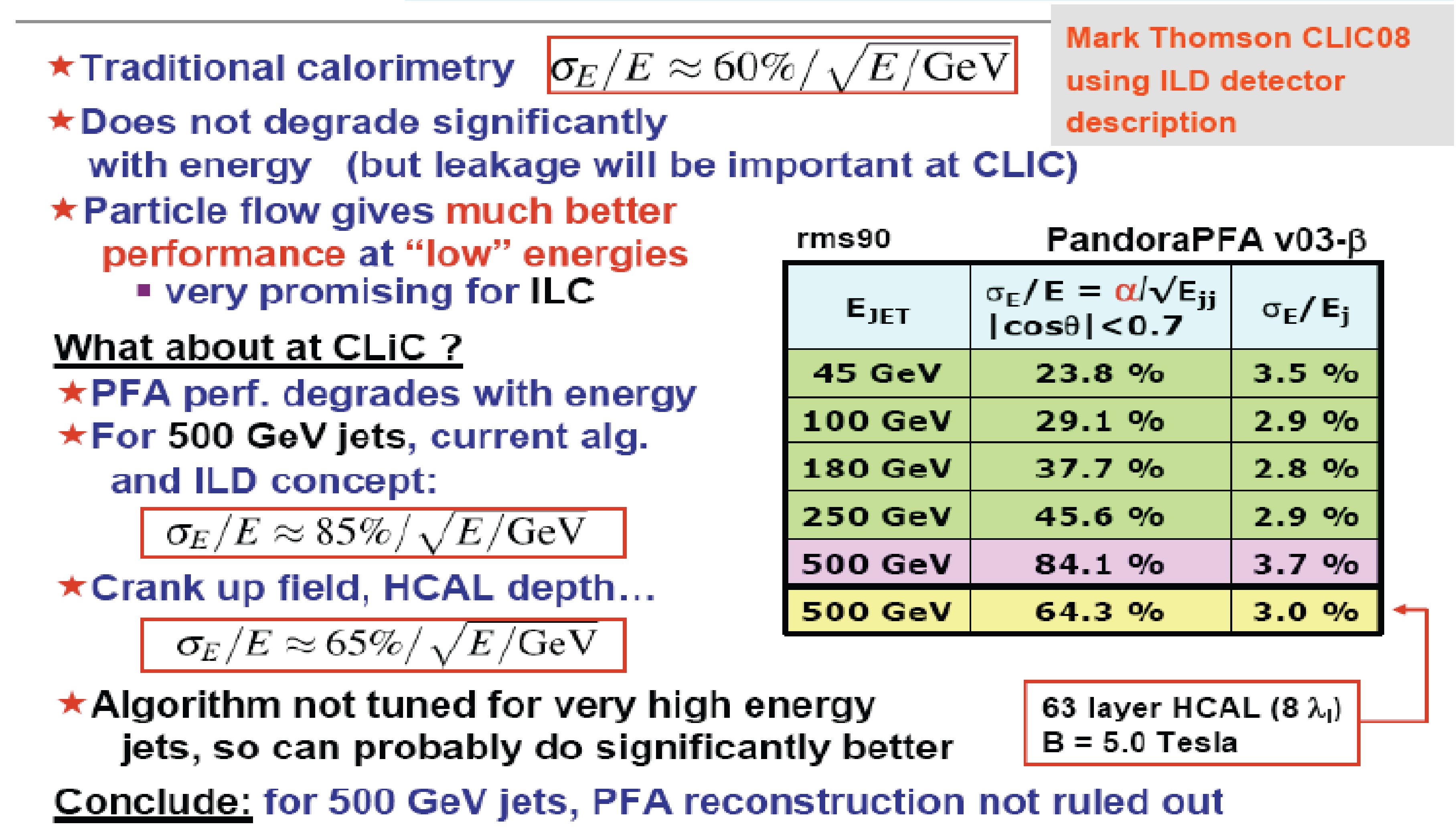
Imaging cal (use as tracker = like bubble chamber),
➔ very fine transverse & longitudinal segmentation
Large dynamic range: MIP…. to …..shower
Excellent EM resolution

Challenge in calorimetry

The W/Z separation, in processes like WWνν or ZZνν needs an unprecedented energy resolution (jet energy)



Does PFA work for high-energy jets?



Mark Thomson CLIC08 using ILD detector description

- ★ Traditional calorimetry $\boxed{\sigma_E/E \approx 60\%/\sqrt{E/\mathrm{GeV}}}$
- ★ Does not degrade significantly with energy (but leakage will be important at CLIC)
- ★ Particle flow gives much better performance at "low" energies
  - very promising for ILC

What about at CLiC ?

- ★ PFA perf. degrades with energy
- ★ For 500 GeV jets, current alg. and ILD concept:

$$\boxed{\sigma_E/E \approx 85\%/\sqrt{E/\mathrm{GeV}}}$$

- ★ Crank up field, HCAL depth…

$$\boxed{\sigma_E/E \approx 65\%/\sqrt{E/\mathrm{GeV}}}$$

- ★ Algorithm not tuned for very high energy jets, so can probably do significantly better

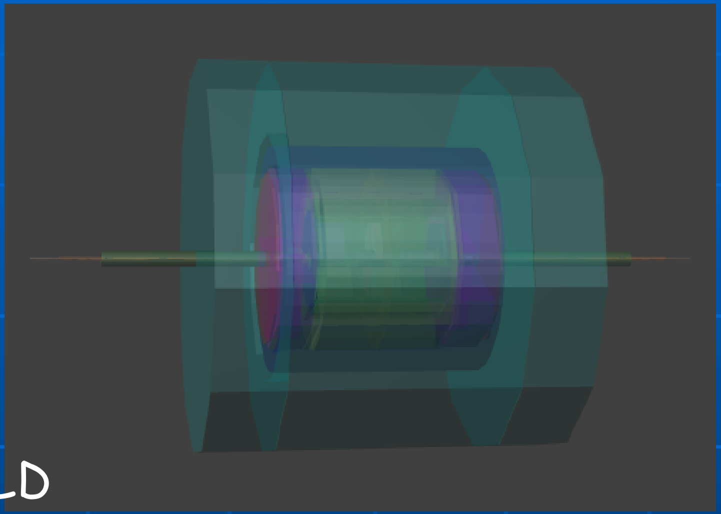
rms90 PandoraPFA v03-β

E_{JET}	$\sigma_E/E = \alpha/\sqrt{E_{jj}}$ $\lvert\cos\theta\rvert<0.7$	σ_E/E_j
45 GeV	23.8 %	3.5 %
100 GeV	29.1 %	2.9 %
180 GeV	37.7 %	2.8 %
250 GeV	45.6 %	2.9 %
500 GeV	84.1 %	3.7 %
500 GeV	64.3 %	3.0 %

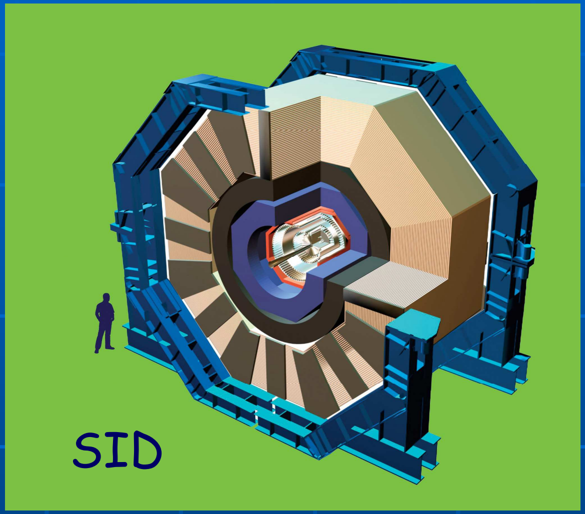
63 layer HCAL (8 λ_I)
B = 5.0 Tesla

Conclude: for 500 GeV jets, PFA reconstruction not ruled out

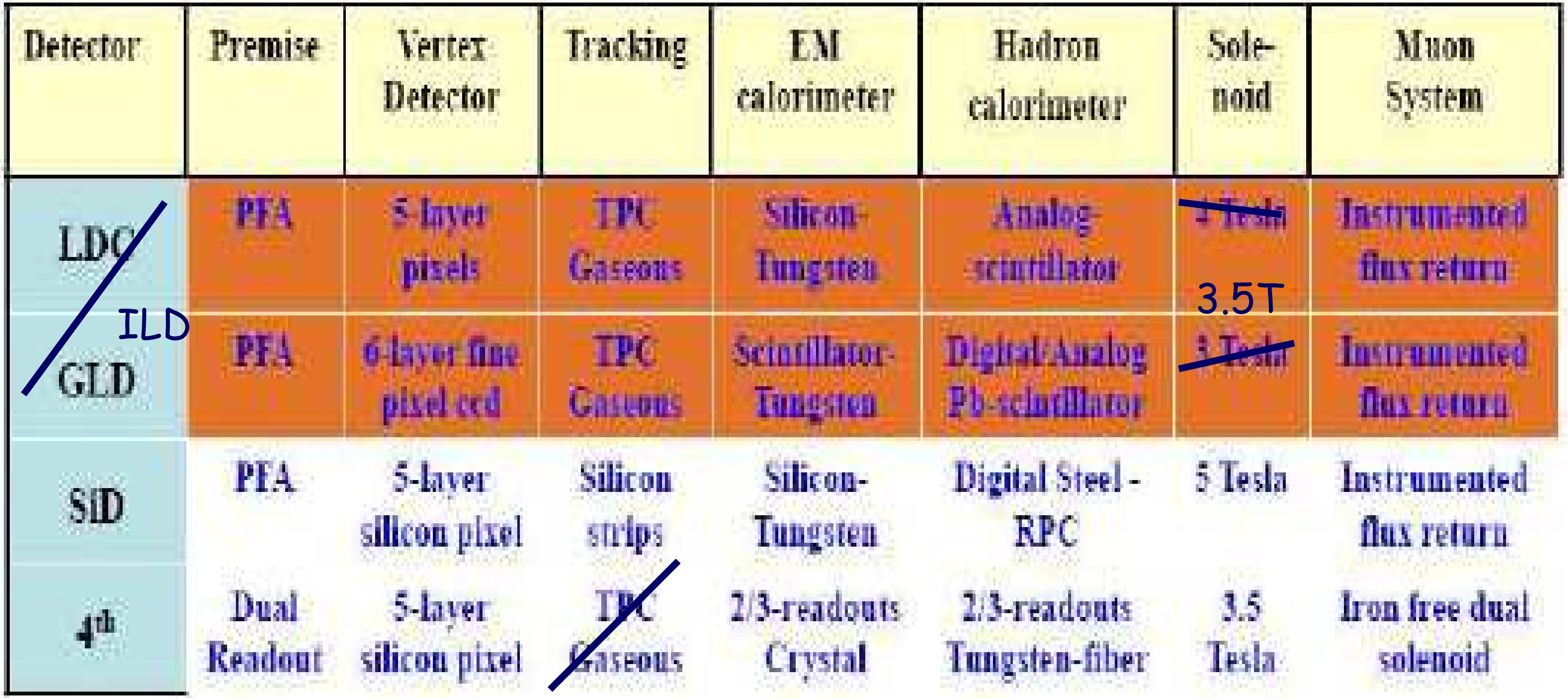
The three Concepts



ILD



ILD is a « merge » of LDC and GLD



Detector	Premise	Vertex Detector	Tracking	EM calorimeter	Hadron calorimeter	Sole-noid	Muon System
LDC	PFA	5-layer pixels	TPC Gaseous	Silicon-Tungsten	Analog-scintillator	~~4 Tesla~~ 3.5T	Instrumented flux return
ILD GLD	PFA	6-layer fine pixel ccd	TPC Gaseous	Scintillator-Tungsten	Digital/Analog Pb-scintillator	~~3 Tesla~~	Instrumented flux return
SiD	PFA	5-layer silicon pixel	Silicon strips	Silicon-Tungsten	Digital Steel - RPC	5 Tesla	Instrumented flux return
4th	Dual Readout	5-layer silicon pixel	~~TPC Gaseous~~	2/3-readouts Crystal	2/3-readouts Tungsten-fiber	3.5 Tesla	Iron free dual solenoid

DC with
cluster
counting

Physics

1) A SM scenario
2) Hints towards darkness

A Higgs boson analyser

- ILC is not meant as a Higgs hunter

- ILC will not be a Higgs boson factory (like a muon collider) despite a high rate. at ECM = 500 GeV, ILC will produce
  > 30k Higgs (120 GeV) every 300 fb^{-1}

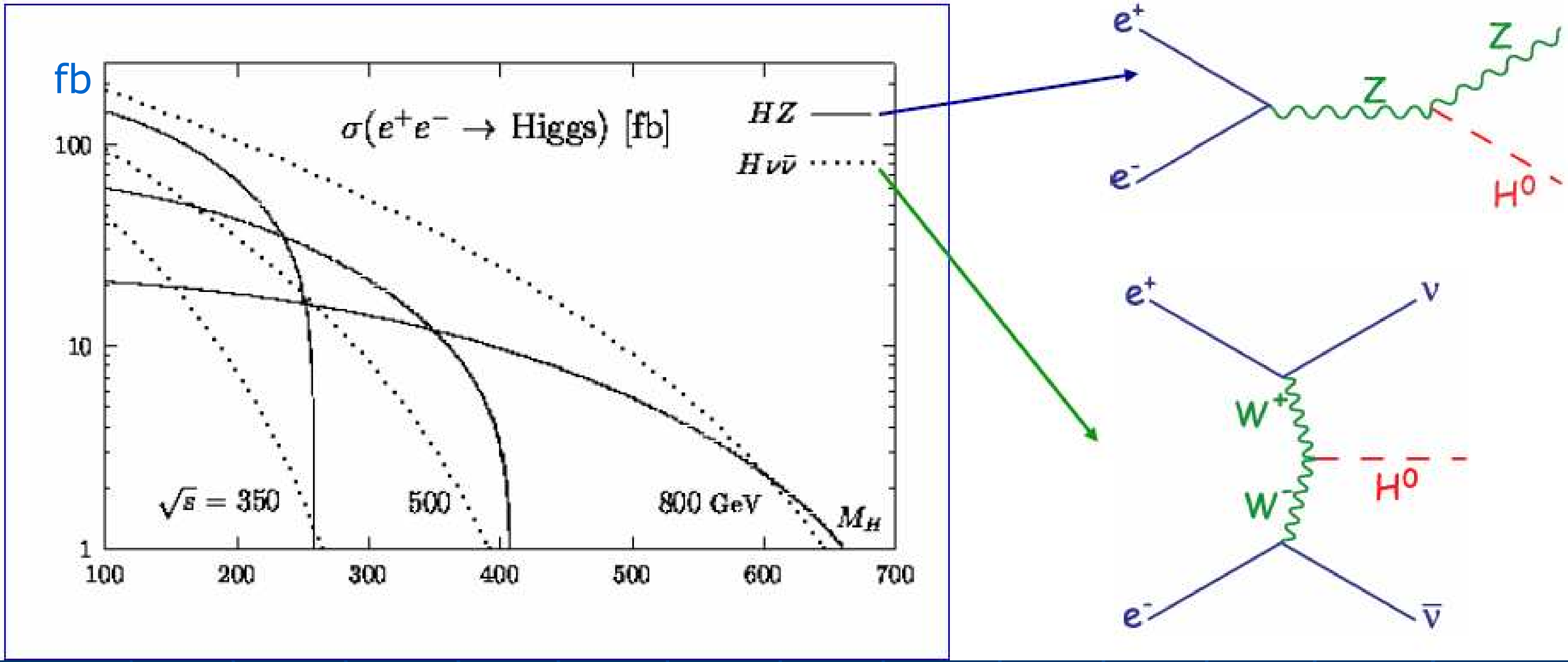
- ILC is meant to be a Higgs analyser

Which analyses ?

- The Higgs boson is a particle, it has a mass, a width, a spin, …
- It generates all masses in nature by its coupling to the particles, fermions and bosons
- The Higgs boson couples to itself

ILC goal is to measure all the above

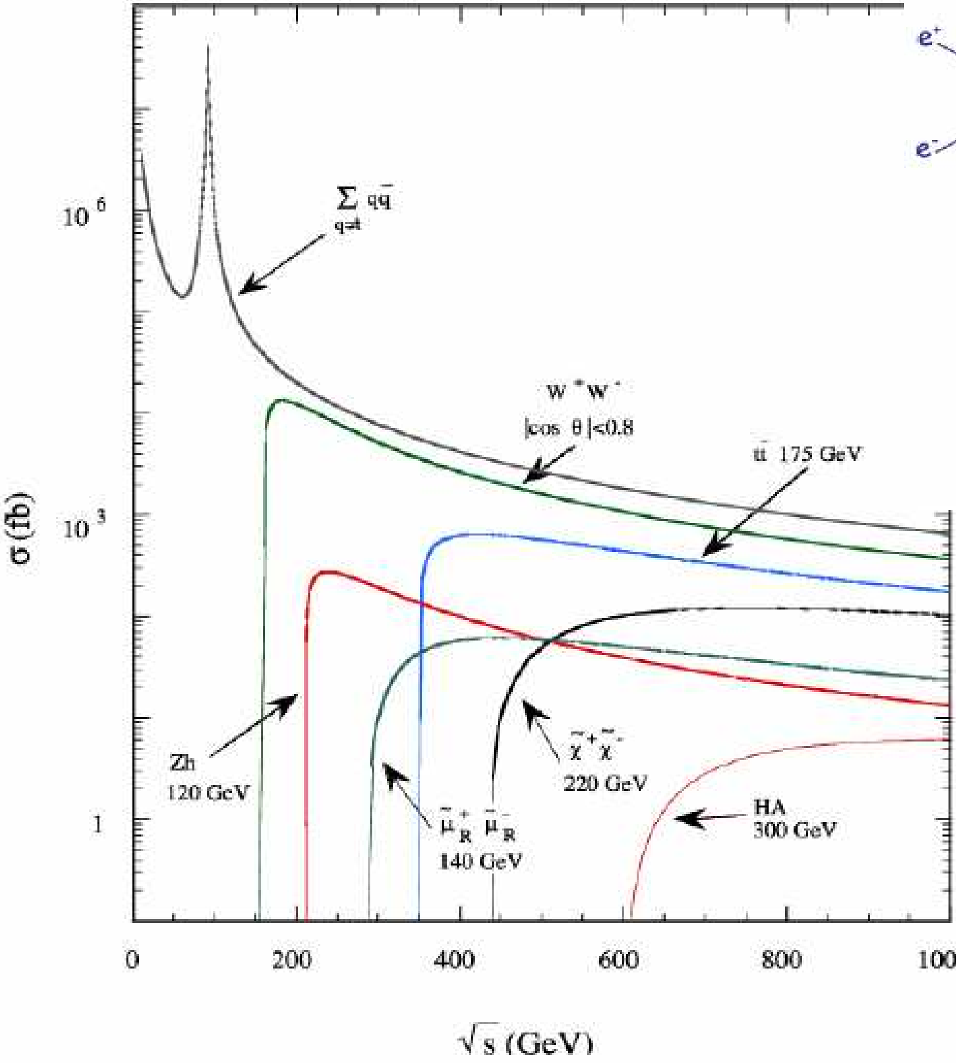
Higgs production at the ILC

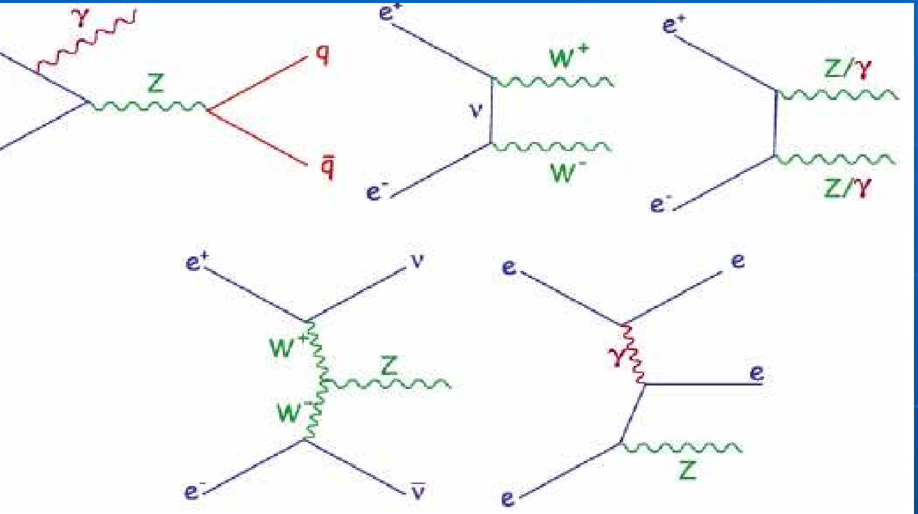


Copious production : each 10 fb^{-1} will deliver > 1000 Higgs bosons

The higher the energy, the higher x-section, but more and more from fusion process.

Background sources

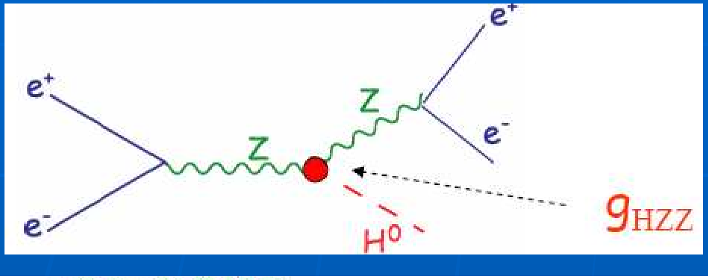


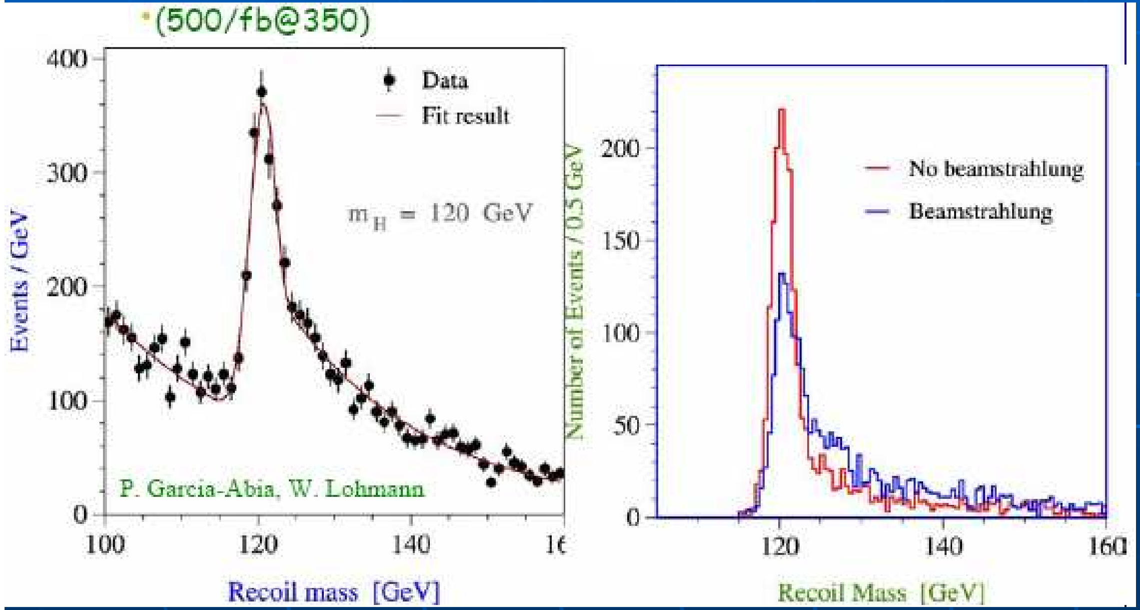


- •Most background sources are well known from LEP (exception of top-pair and other top related)

- •But the H bosons themselves (or new physics like SUSY) can be a source of background : Higgstrahlung to fusion

Measuring the Higgstrahlung x-section





- Reconstruct the di-lepton as a Z boson
- The recoil mass

$$m_R^2 = s - 2\sqrt{s}E_Z + m_Z^2$$

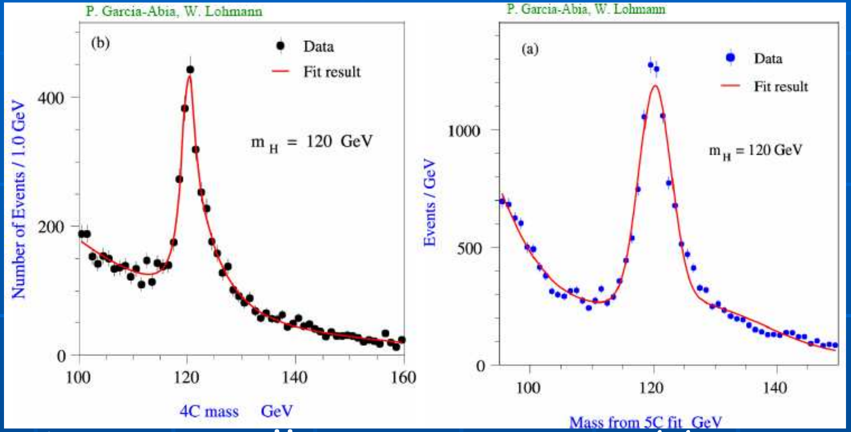
spectrum is used to select the Higgs boson events.

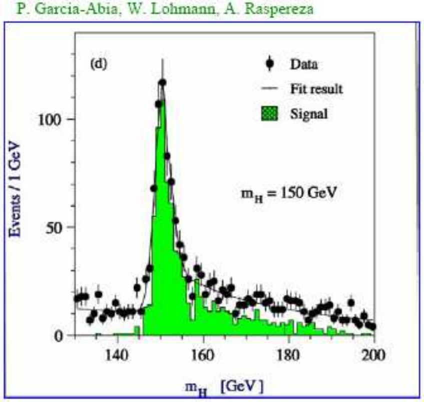
- Simple counting, independent of the Higgs decay modes (INCLUDING INVISIBLE)
- BG is mainly from ZZ

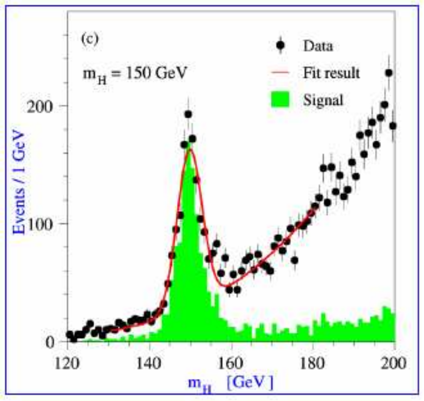
$$\begin{aligned}\Delta\sigma(ee \to HZ)/\sigma = 2.6\%\ (m_H = 120\ GeV)\\ 3.8\%\ (m_H = 180\ GeV)\end{aligned}$$

($500fb^{-1}$@350)

Measuring the Higgs boson mass





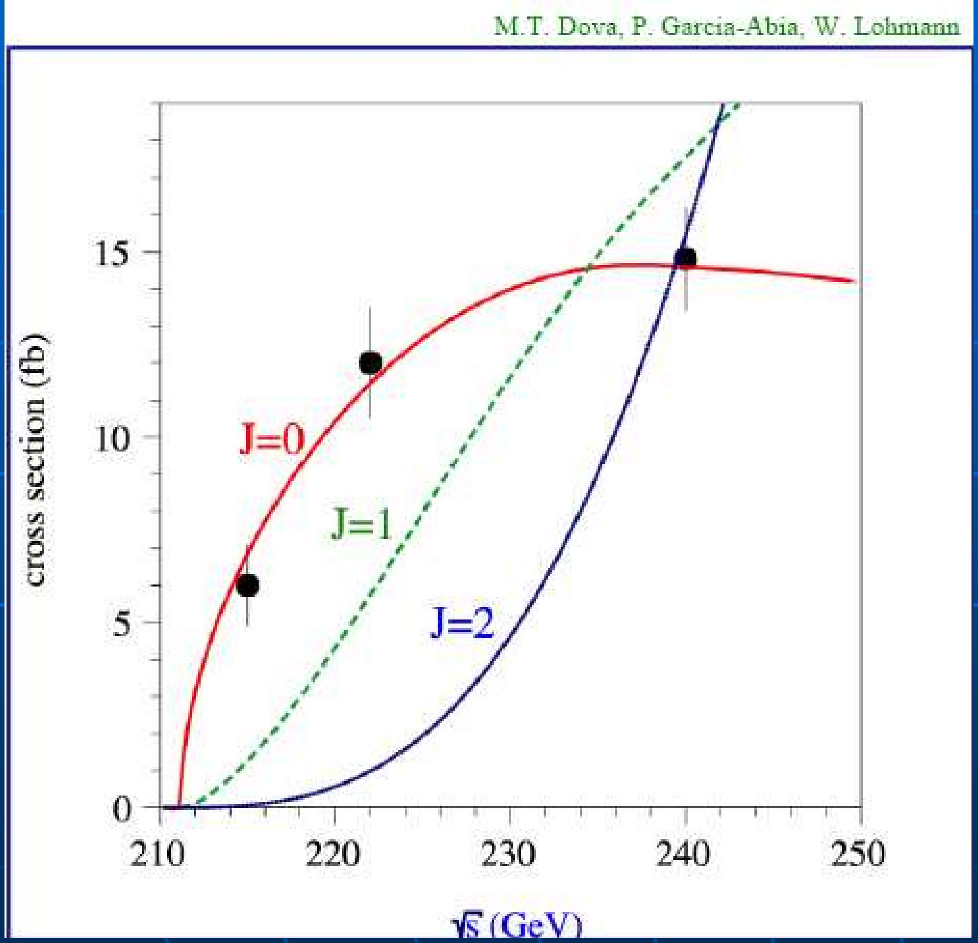


Signature :	llqq	qqbb	llWW	qqWW
Kin. fit	4C	5C	4C	5C

m_H (GeV)	llqq (MeV)	qqbb(MeV)	llWW (MeV)	qqWW(MeV)	Comb (MeV)
120	70	45			40
150	90	170	100	130	70
180			100	150	80

(500 fb^{-1} @ 350)

A scalar Higgs boson

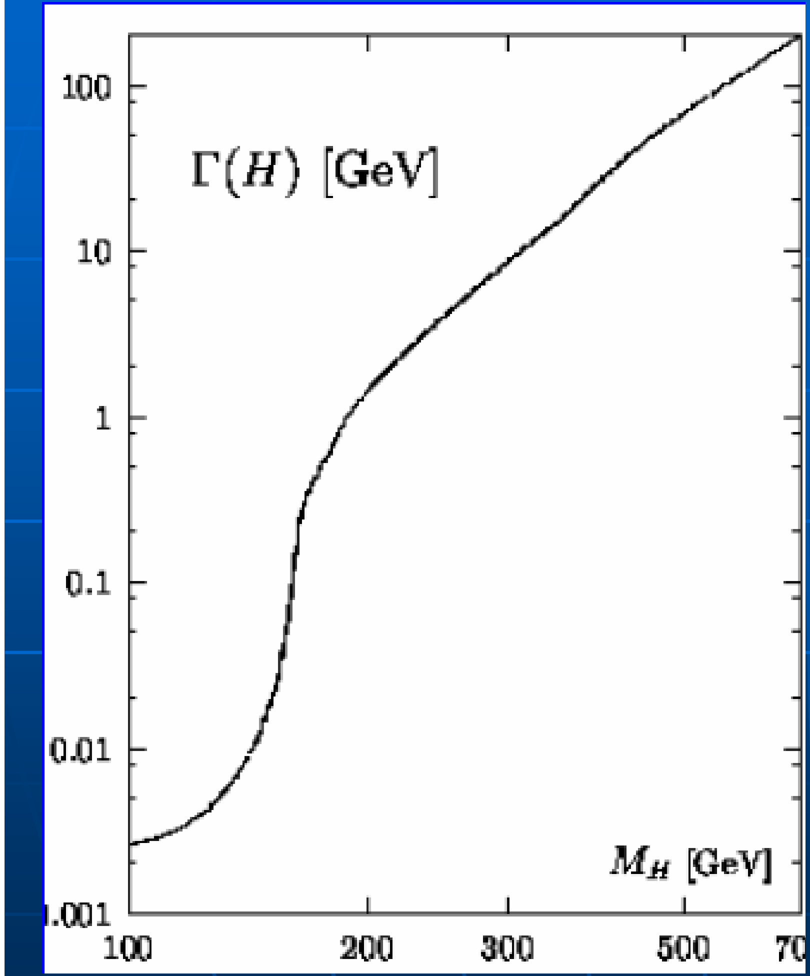


$$\sigma(ee \to HZ) \sim \beta_{ZH} \sim \sqrt{s-(m_H+m_Z)^2}$$

near threshold

- For J = 0 , $\sigma \sim \beta$
  J = 1 , $\sigma \sim \beta^3$
  J = 2 , $\sigma \sim \beta^5$
- Threshold scan with 20 fb^{-1} per point is sufficient to have the answer
- ECM = 215, 222 and 240 GeV
- signal ZH → llqq

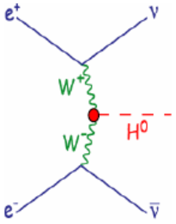
Higgs boson total width Γ_H

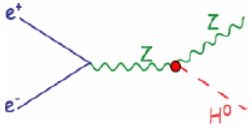


- Above the ZZ threshold the width can be measured directly via a line shape
- For m_H<160 GeV the best accuracy is obtained from

$$\boxed{\Gamma_H^{Total} = \frac{\Gamma(H \to WW)}{BR(H \to WW)}}$$

- The partial width $\Gamma_{H \to WW}$ can be obtained directly from the Higgs fusion production or making a plausible assumption $g_{HWW}=g_{HZZ}\cos\theta_W$ and use the Higgstrahlung process to measure g_{Hzz}





m_H	$\delta\Gamma_{TOT}/\Gamma_{TOT}$ g_{HWW}	$\delta\Gamma_{TOT}/\Gamma_{TOT}$ $g_{HWW}=g_{HZZ}\cos\theta_W$
120 GeV	6.1%	5.6%
160 GeV	13.4%	3.6%

(500/fb)

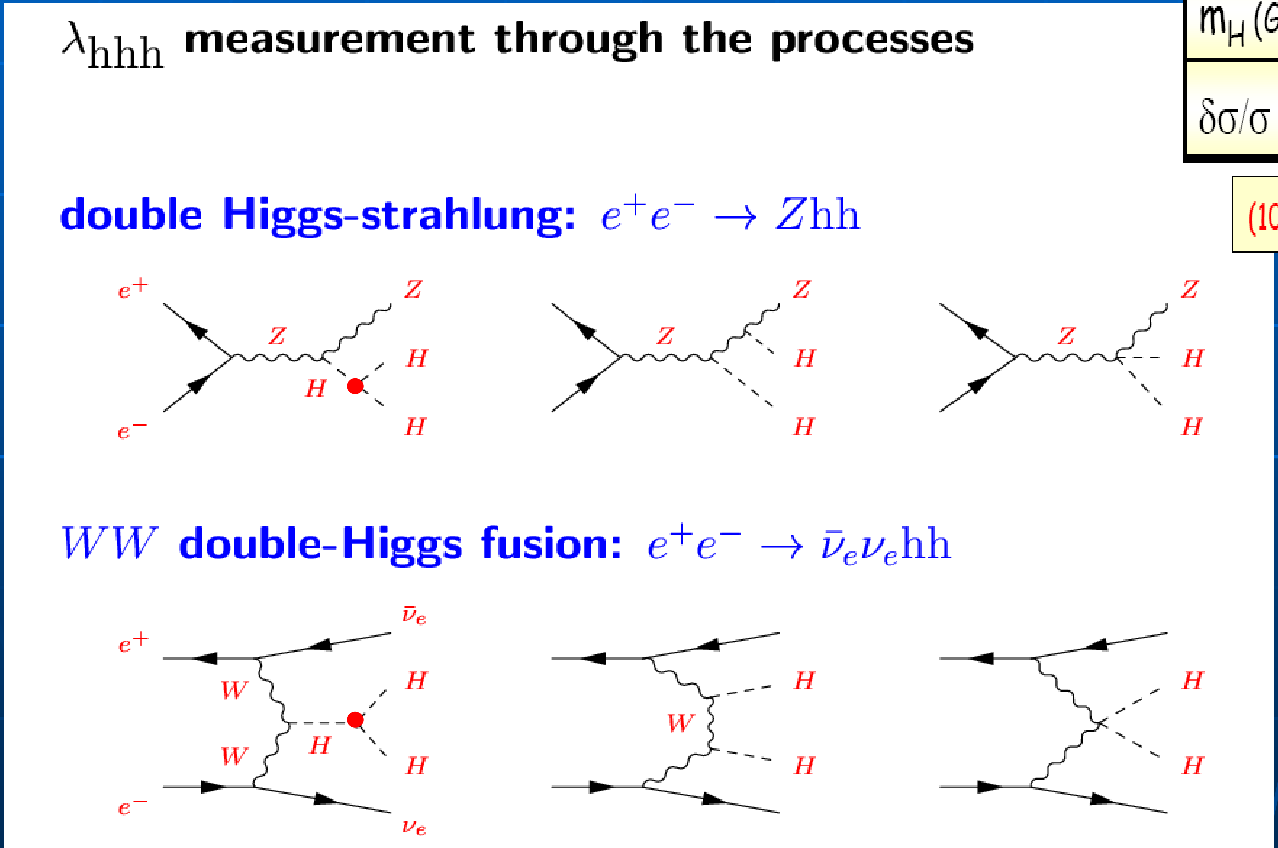
Higgs self-couplings

$$V = \lambda v^2 H^2 + \lambda v H^3 + \frac{1}{4}\lambda H^4$$

very low x-sec. : 2*0.15 fb for 130 GeV H

m_H (GeV)	120	130	140
$\delta\sigma/\sigma$	17%	19%	23%

(1000/fb@500 GeV)

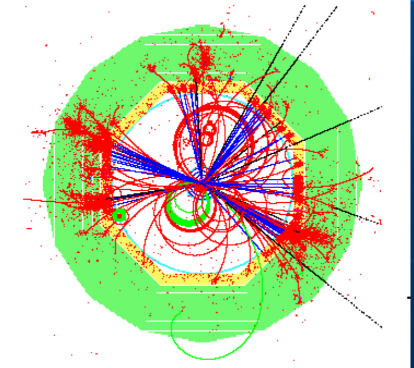


λ_{hhh} **measurement through the processes**

double Higgs-strahlung: $e^+e^- \to Z\mathrm{hh}$

WW **double-Higgs fusion:** $e^+e^- \to \bar{\nu}_e\nu_e\mathrm{hh}$

$\delta\lambda/\lambda \sim 22\%$



Higgs decay rates

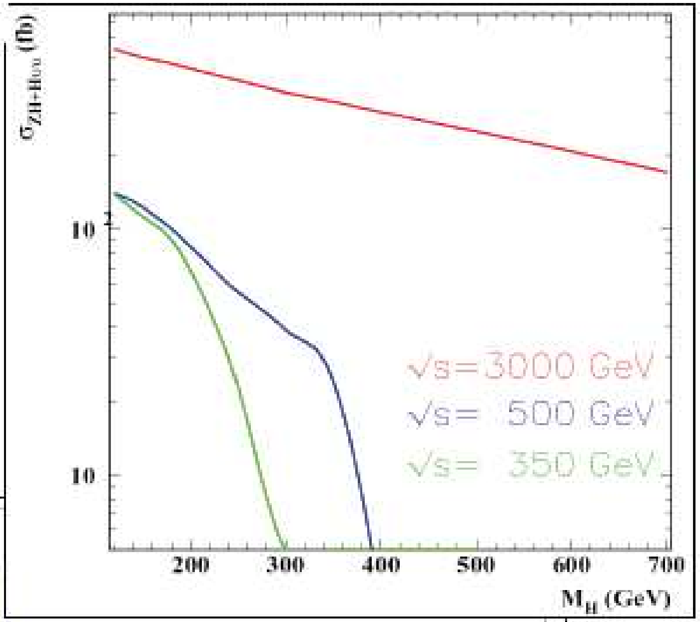
- The Higgs boson generates the fermion masses ("the God particle" :)
- one needs a precise determination of the coupling constants (including b/c discrimination, in order to tell a SUSY Higgs from a SM Higgs
- That is the power of the LC

Needs an excellent vertex detector

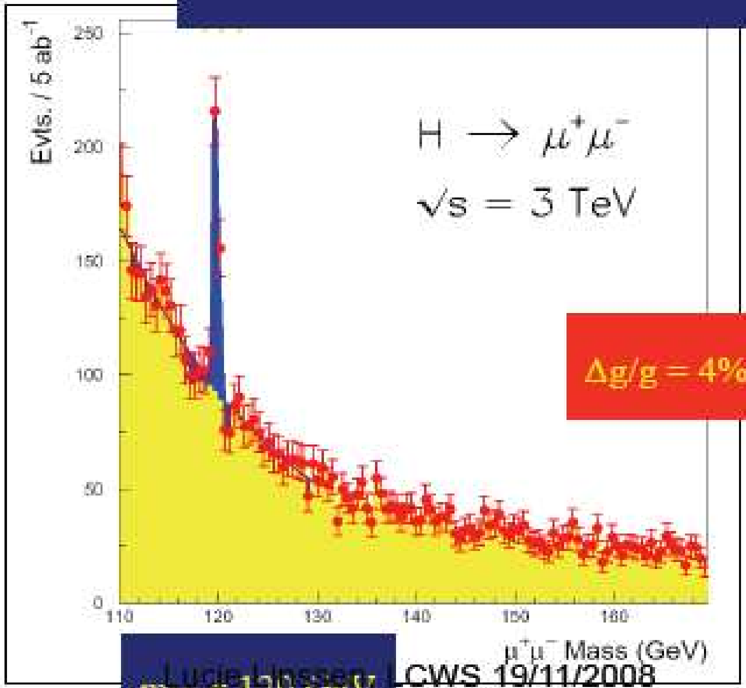
Channel	δBR/BR	δBR/BR
	m_H=120	m_H=140
bb	2.4%	2.6%
cc	8.3	19.0
gg	5.5	14.0
ττ	5.0	8.0
WW	5.1	2.5
γγ	26	

John Ellis, CLIC07

Large Cross Section
@ CLIC

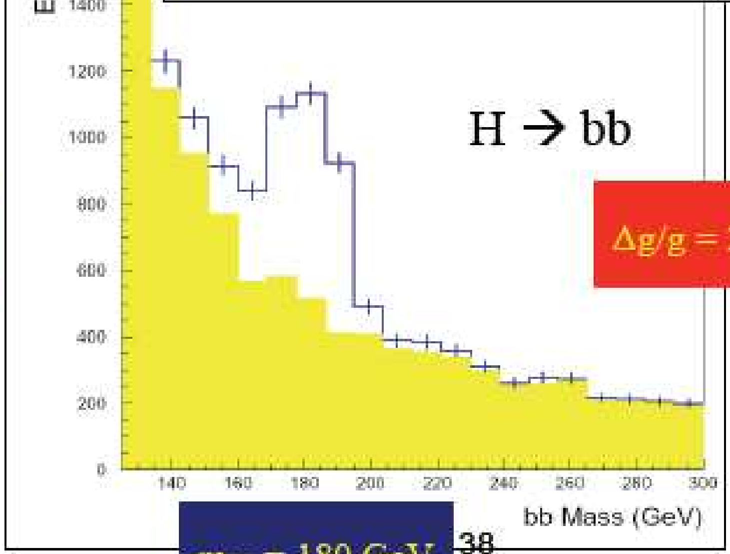


Can measure rare decay modes



$\Delta g/g = 4\%$

$m_H = 120$ GeV



$\Delta g/g = 2\%$

$m_H = 180$ GeV

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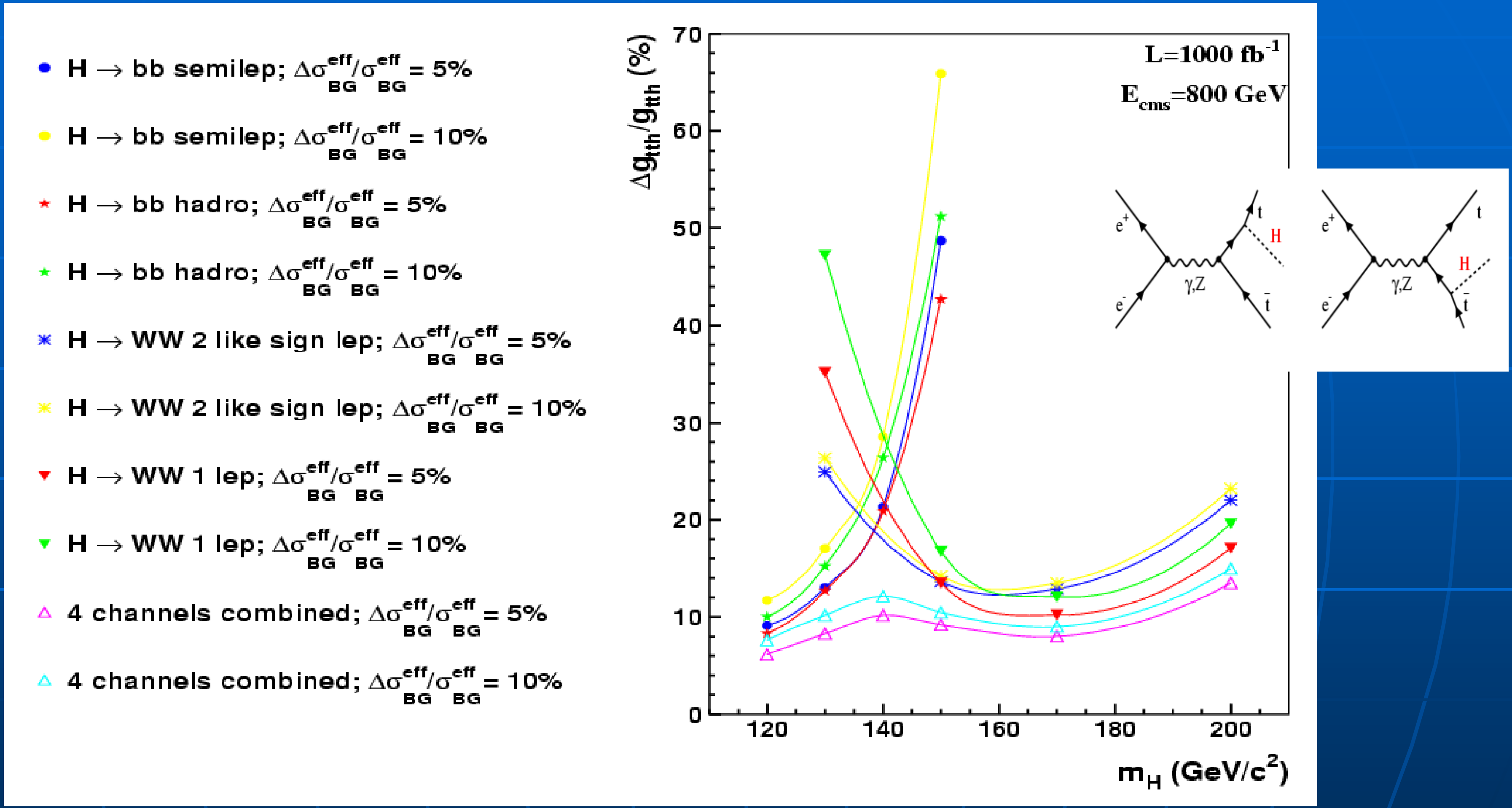
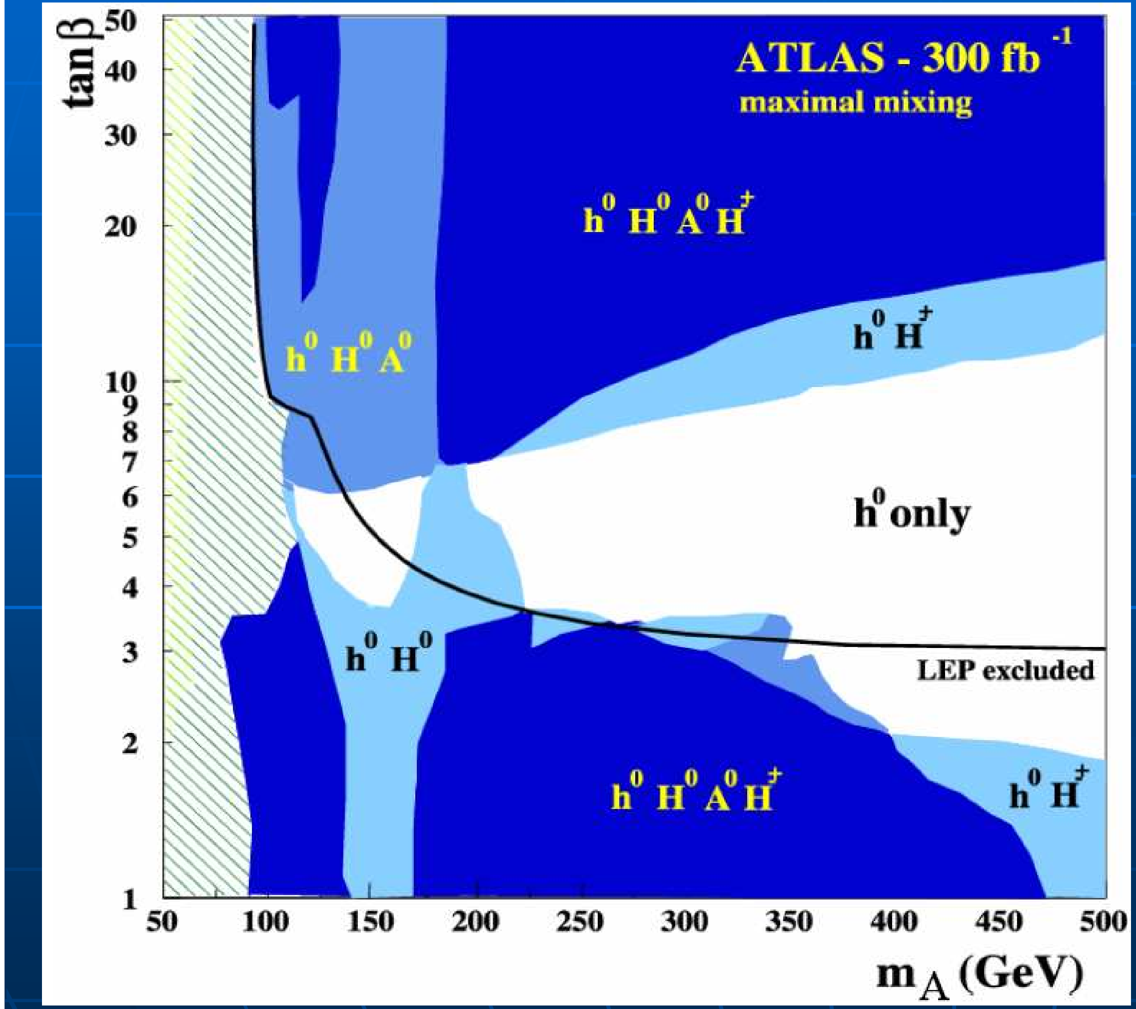
Light Higgs off top quark



One obtains $\delta g_{Htt}/g_{Htt}$ = 5.5% for m_H = 120 GeV @ E_{cm} = 800 GeV

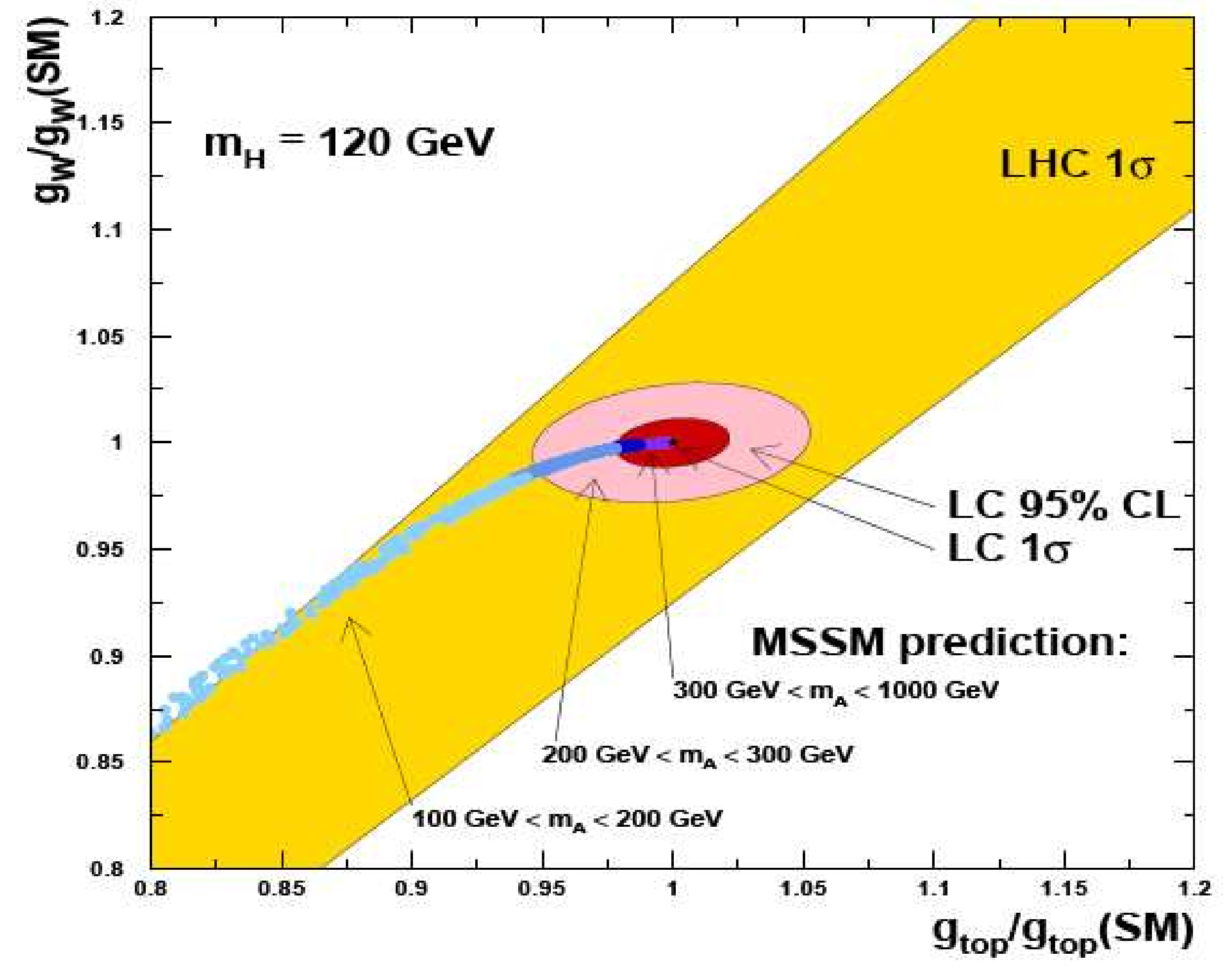
SM versus MSSM



ILC running at 500 GeV with an integrated lumi. of 500 fb^{-1} has the sensitivity to probe indirectly the tgβ ~ 5 region and tell a SM from a MSSM Higgs.

The Higgs sector of the MSSM

The Higgs profile can be entirely determined, even close to the decoupling regime

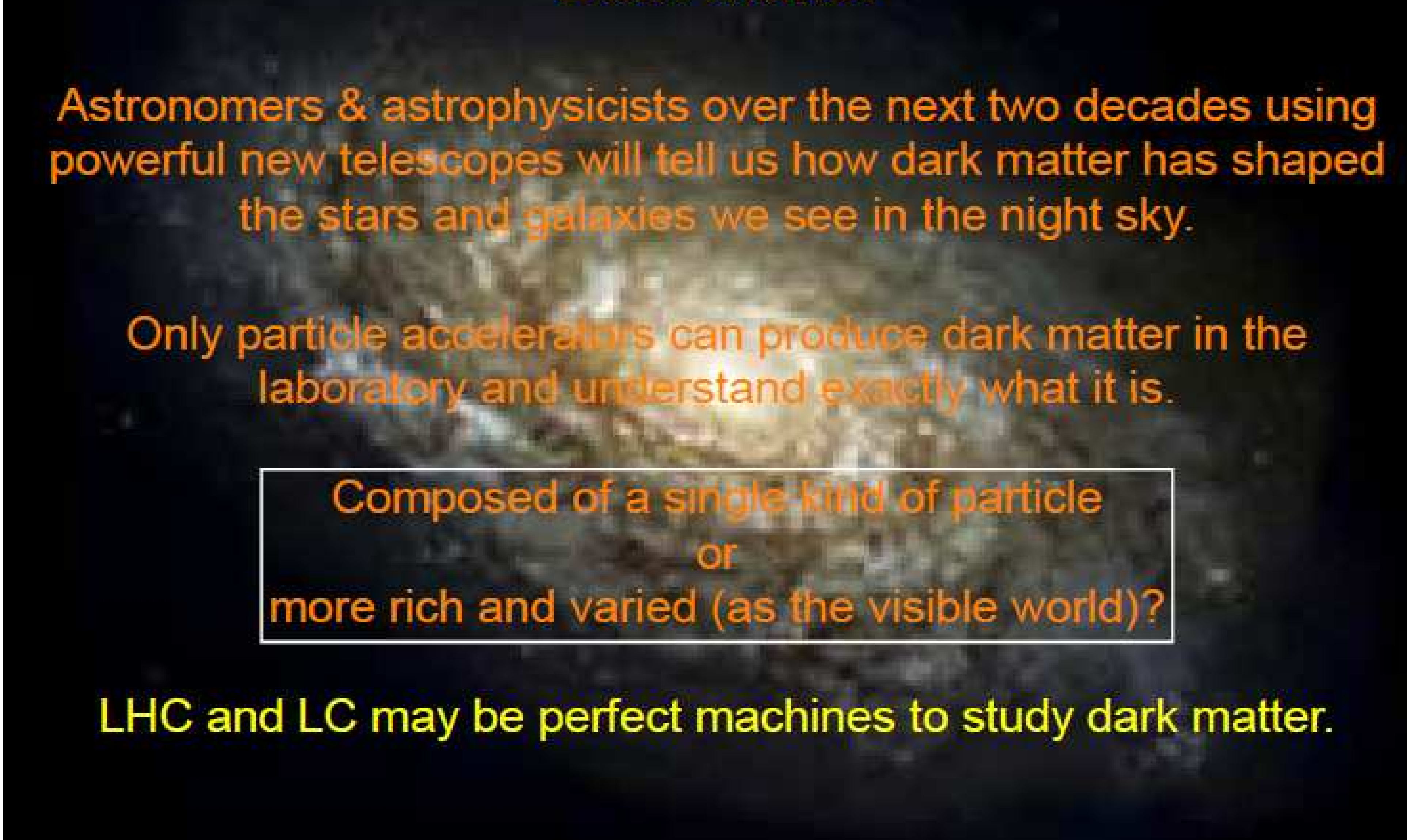


Deviations of the couplings of the h from the SM predictions : 95% of all MSSM solutions can be distinguished

from the SM case if

M_A < 600 GeV

Dark Matter



Astronomers & astrophysicists over the next two decades using powerful new telescopes will tell us how dark matter has shaped the stars and galaxies we see in the night sky.

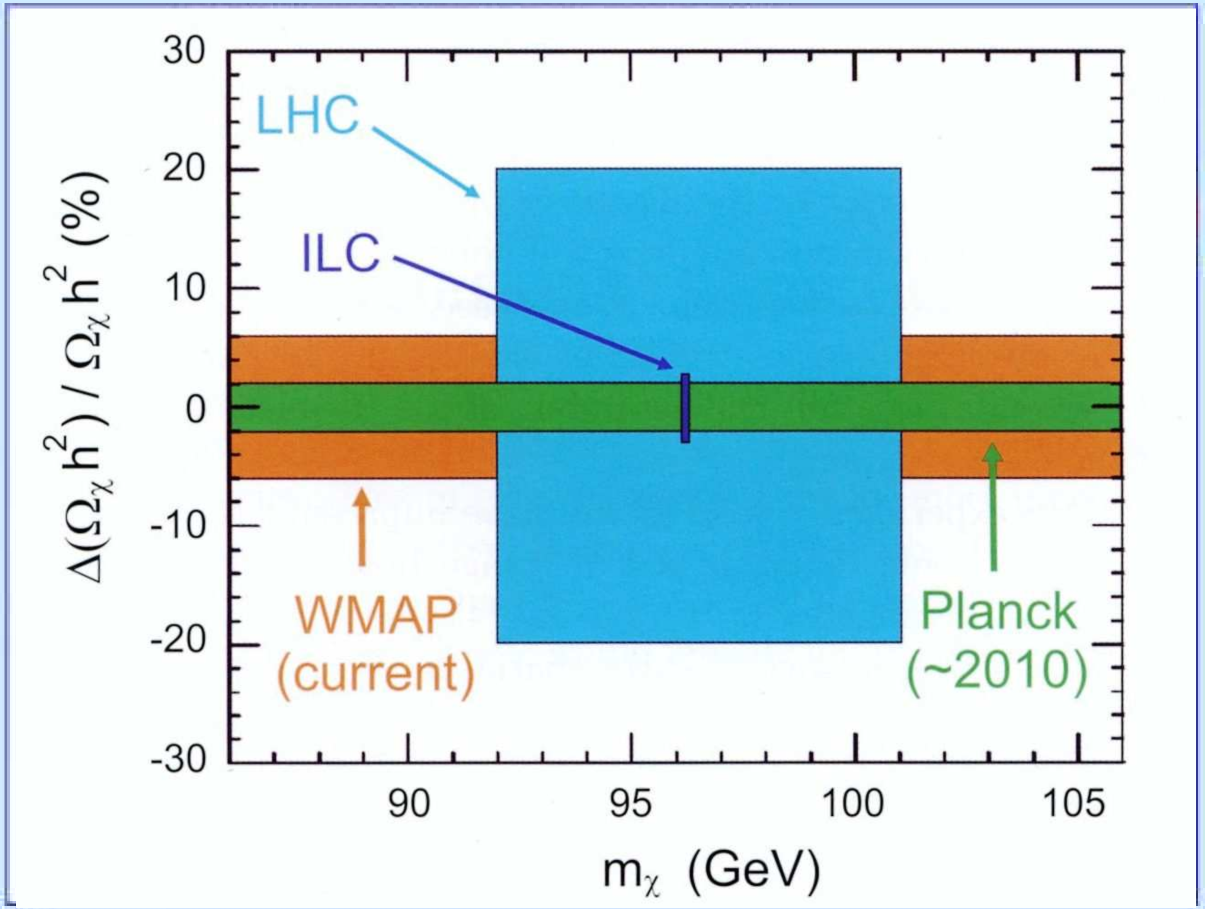
Only particle accelerators can produce dark matter in the laboratory and understand exactly what it is.

Composed of a single kind of particle
or
more rich and varied (as the visible world)?

LHC and LC may be perfect machines to study dark matter.

Dark Matter and SUSY

- Is dark matter linked to the Lightest Supersymmetric Particle?



LC and satellite data (WMAP and Planck):

complementary views of dark matter.

LC: identify DM particle, measures its mass;

WMAP/Planck: sensitive to total density of dark matter.

Together with LHC they establish the nature of dark matter.

The Higgs is Different!

All the matter particles are spin-1/2 fermions.
All the force carriers are spin-1 bosons.

Higgs particles are spin-0 bosons.
The Higgs is neither matter nor force;
The Higgs is just different.
This would be the first fundamental scalar ever discovered.

The Higgs field is thought to fill the entire universe.
Could give some handle of dark energy (scalar field)?

Many modern theories predict other scalar particles like the Higgs.
Why, after all, should the Higgs be the only one of its kind?

LHC and LC can search for new scalars with precision.

LHC and LC results will allow
to study the Higgs mechanism in detail and
to reveal the character of the Higgs boson

This would be the first investigation
of a scalar field

This could be the very first step to
understanding dark energy

Summary

As we look to the future, we anticipate that LHC results will establish the scientific case for a linear collider.

If the science warrants a 0.5 to 1.0-TeV ILC, the agreement for joint ILC/CLIC work will be helpful towards our primary GDE goal of being ready to propose a solid project at that time.

If the LHC results indicate the need for a higher-energy lepton collider, we will be prepared as a community to aggressively continue to develop the CLIC concept on a longer timescale.

Barry Barish

Pour en savoir plus

- From the LHC to a Future Collider, workshop at CERN (9 au 27 février) http://indico.cern.ch/conferenceDisplay.py?confId=40437
- En particulier :

  Brian Foster : Technology progress report of the ILC

  Klaus Desch : ILC Physics case