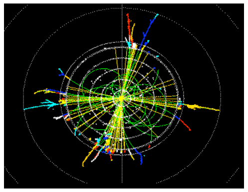
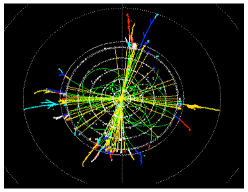


Physics and Detectors of the International Linear Collider

Jim Brau

Univ. of Oregon

Lecture presented at the Second International Accelerator School for Linear Colliders, Erice, Italy October 9, 2007



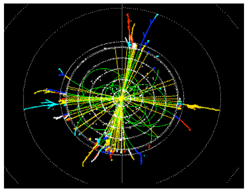
Physics and Detectors of the International Linear Collider

- **LHC will open exploration of Terascale physics**
  - Deep significance to fundamental physics
  - What is nature of ElectroWeak Symmetry Breaking?
  - Are there new symmetries of space and time?
  - Are there hidden extra dimensions?
  - Dark matter particles might explain astrophysical observations

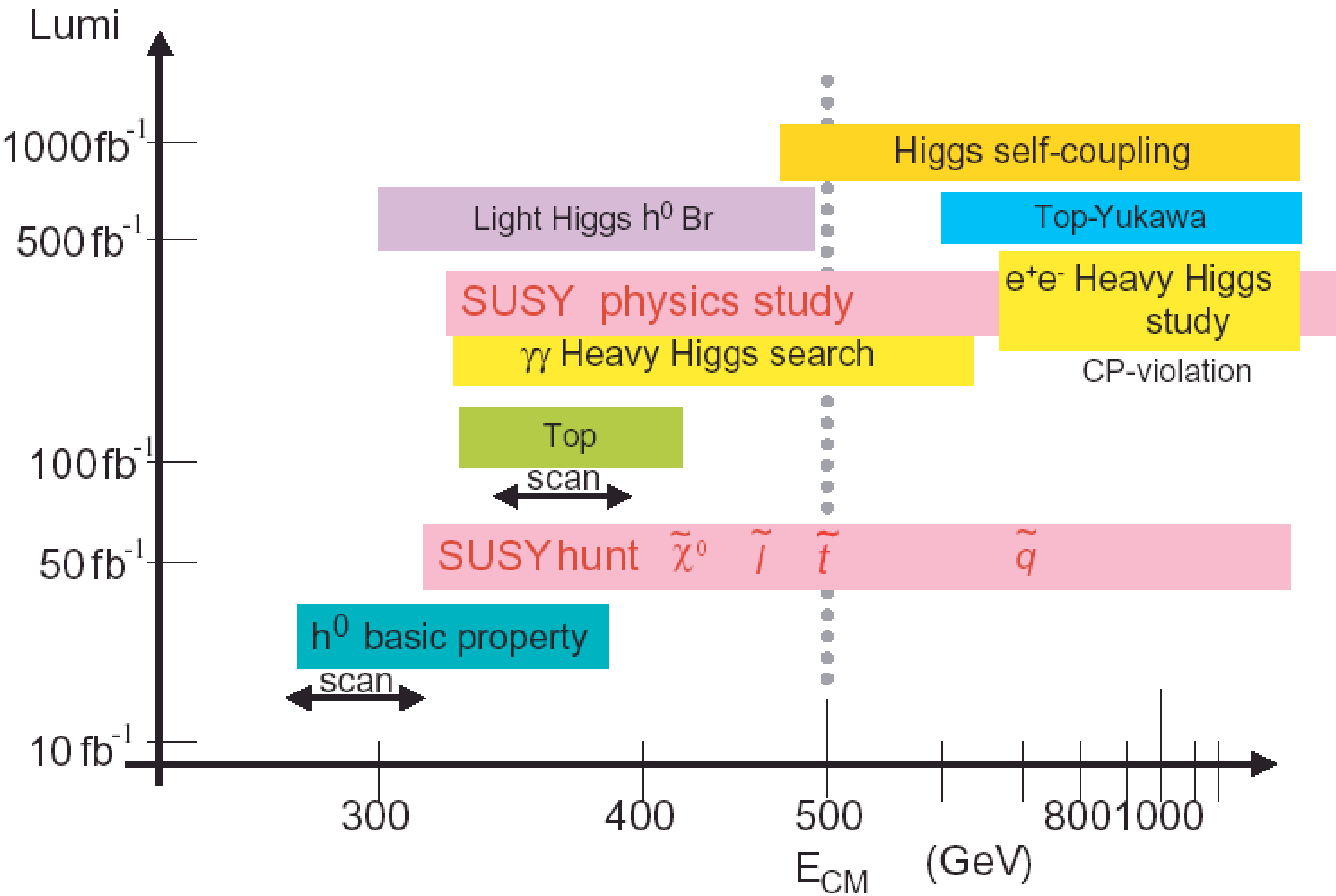
- **ILC is needed to explore and elucidate nature of Terascale**
  - Deeper look into Terascale questions
  - Precision exploration of new physics

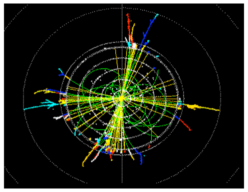
- **Sophisticated, precise detectors are required to exploit the scientific opportunity of the ILC**

ENORMOUS EFFORTS ON MANY ASPECTS
THIS TALK IS NECESSARILY SELECTIVE DUE TO BREADTH OF SUBJECT



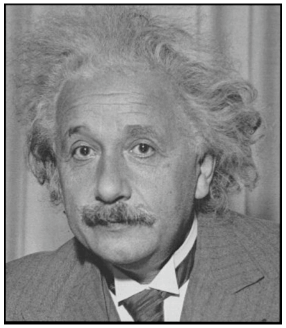
ILC Physics

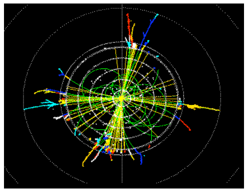

Lumi
1000fb-1
500 fb-1
100 fb-1
50 fb-1
10 fb-1
Higgs self-coupling
Light Higgs h0 Br
Top-Yukawa
SUSY physics study
e+e- Heavy Higgs study
γγ Heavy Higgs search
CP-violation
Top
scan
SUSY hunt χ̃0 l̃ t̃ q̃
h0 basic property
scan
300
400
500
800
1000
ECM (GeV)



Electroweak Symmetry Breaking

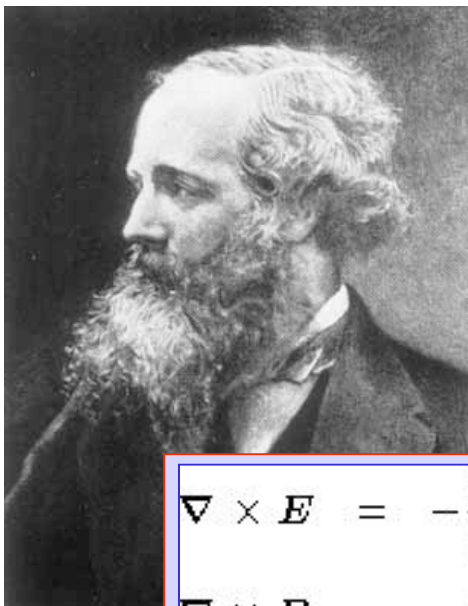
- **A central focus of particle physics research today is the origin of Electroweak Symmetry Breaking**
  - **The weak nuclear force and the electromagnetic force have been unified into a single description SU(2) x U(1)$_Y$**
  - **Why is this symmetry hidden?**
  - **The answer to this appears to promise deep understanding of fundamental physics**
    - the origin of mass
    - supersymmetry and possibly the elements of dark matter
    - additional unification (strong force, gravity) and possibly hidden space-time dimensions





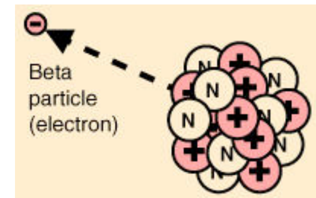
Electromagnetism and Radioactivity

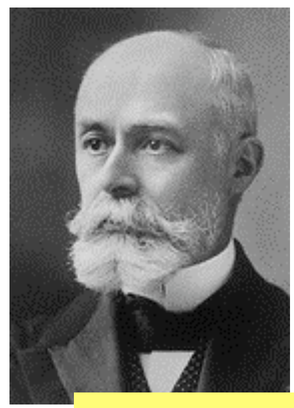
- Maxwell unified Electricity and Magnetism with his famous equations (1873)

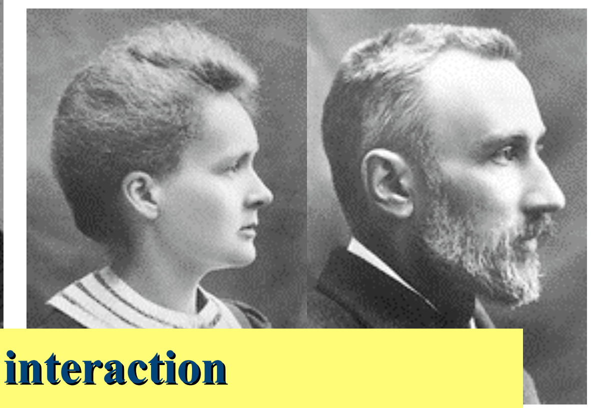


$$\nabla \times E = -\frac{\partial B}{\partial t}$$
$$\nabla \times B = \mu_0 J + \frac{1}{c^2}\frac{\partial E}{\partial t}$$
$$\nabla \cdot E = \rho / \epsilon_0$$
$$\nabla \cdot B = 0$$

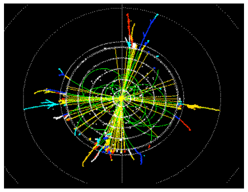
- Matter spontaneously emits penetrating radiation
  - Becquerel uranium emissions in 1896
  - The Curies find radium emissions by 1898





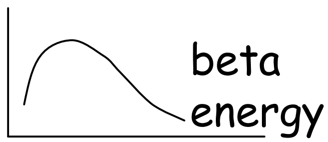


This new interaction
(the weak force)
is related to E&M



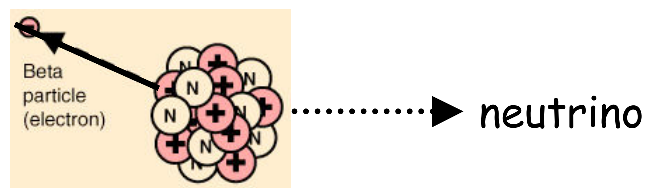
Advancing understanding of Beta Decay

- Pauli realizes there must be a neutral invisible particle accompanying the beta particle:
  - the neutrino



- Fermi develops a theory of beta decay (1934)

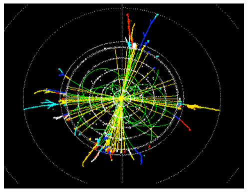
  $$n \rightarrow p\, e^- \bar{\nu}_e$$



- 1956 - Neutrino discovered

  Reines and Cowan

  - Savannah River Reactor, SC



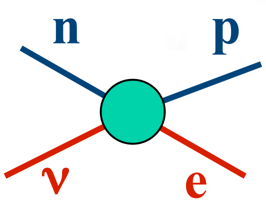
EM and Weak Theory in 1960

Weak Interaction Theory

- Fermi's 1934 pointlike, four-fermion interaction theory

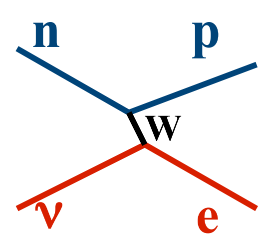
V-A

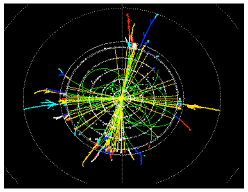
$$M = G J^{\text{weak}}_{\text{baryon}} J^{\text{weak}}_{\text{lepton}} = G(\bar{\psi}_p O \psi_n)(\bar{\psi}_e O \psi_\nu)$$



$$W = \frac{2\pi}{\hbar} G^2 |M|^2 \frac{dN}{dE_0}$$

- Theory <u>fails at higher energy</u>, since rate increases with energy, and therefore will violate the "unitarity limit"
  - Speculation on <u>heavy mediating bosons</u> but no theoretical guidance on what to expect





EM and Weak Theory in 1960

Quantum Electrodynamics (QED)

- **Dirac introduced theory of electron - 1928**
- **Through the pioneering theoretical work of Feynman, Schwinger, Tomonga, and others, a theory of electrons and photons was worked out with precise predictive power**
- **example: magnetic dipole of the electron**

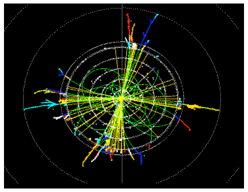
[(g-2)/2] $\mu = g \; (e\hbar/2mc) \; S$

- **current values of electron (g-2)/2**

theory: $0.5\,(\alpha/\pi) - 0.32848\,(\alpha/\pi)^2 + 1.19\,(\alpha/\pi)^3 + ..$

$= (115965230 \pm 10) \times 10^{-11}$

experiment $= (115965218.6 \pm 0.4) \times 10^{-11}$



The New Symmetry Emerges

VOLUME 19, NUMBER 21 PHYSICAL REVIEW LETTERS 20 NOVEMBER 1967

[11] In obtaining the expression (11) the mass difference between the charged and neutral has been ignored.

[12] M. Ademollo and R. Gatto, Nuovo Cimento 44A, 282 (1966); see also J. Pasupathy and R. E. Marshak, Phys. Rev. Letters 17, 888 (1966).

bra is slightly larger than that (0.23%) obtained from the ρ-dominance model of Ref. 2. This seems to be true also in the other case of the ratio $\Gamma(\eta\to\pi^+\pi^-\gamma)/\Gamma(\gamma\gamma)$ calculated in Refs. 12 and 14.

[14] L. M. Brown and P. Singer, Phys. Rev. Letters 8, ...2).

A MODEL OF LEPTONS*

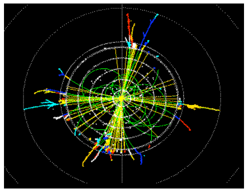
Steven Weinberg†

Laboratory for Nuclear Science and Physics Department, Massachusetts Institute of Technology, Cambridge, Massachusetts

Leptons interact only with photons, and with the intermediate bosons that presumably mediate weak interactions. What could be more natural than to unite[1] these spin-one bosons into a multiplet of gauge fields? Standing in the way of this synthesis are the obvious differences in the masses of the photon and intermediate meson, and in their couplings. We might hope to understand these differences

... a right-handed singlet

$$R = [\tfrac{1}{2}(1-\gamma_5)]e.$$



Enter Electroweak Unification

- Weinberg realized that the vector field responsible for the EM force
  - the photon

  and the vector fields responsible for the Weak force
  - yet undiscovered W^+ and W^-

  could be unified if another vector field,

  mediated by a heavy neutral boson (Z^0), were to exist

- This same notion occurred to Salam

$$L = g\mathbf{J}_\mu \cdot \mathbf{W}_\mu + g' J^Y_\mu B_\mu$$

$g'/g \equiv \tan\theta_W$

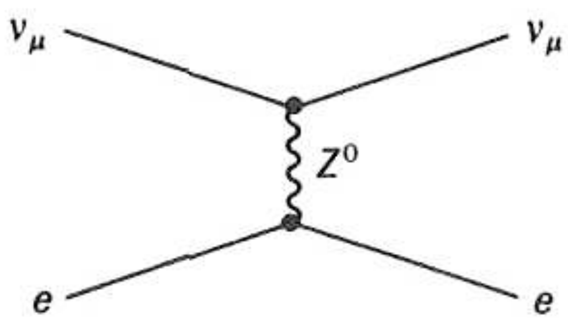
$\sin^2\theta_W = g'^2/(g'^2+g^2)$

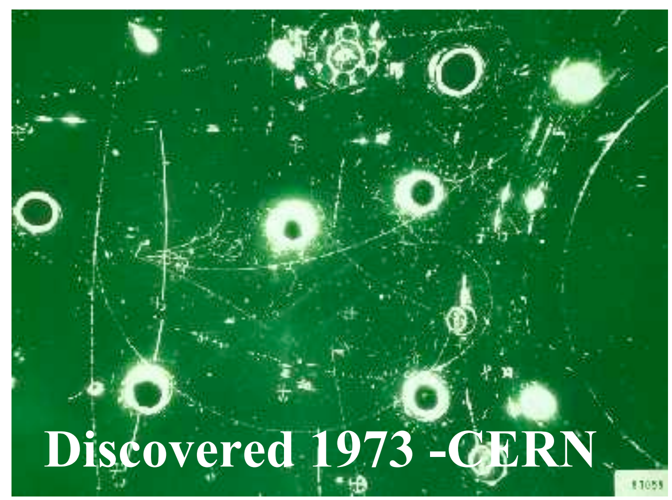
$$W^{(3)}_\mu = \frac{gZ_\mu + g'A_\mu}{\sqrt{g^2+g'^2}} \qquad B_\mu = \frac{-g'Z_\mu + gA_\mu}{\sqrt{g^2+g'^2}} \rightarrow e\, J_\mu^{(em)} A_\mu$$

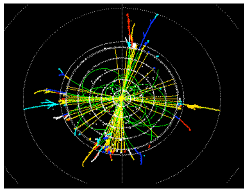
$e = g \sin\theta_W = g' \cos\theta_W$

Electroweak Unification

- There remained a phenomenological problem:
  - where were the effects of the Z^0
- These do not appear so clearly in Nature
  - they are small effects in the atomic electron energy level
- One has to look for them in high energy experiments

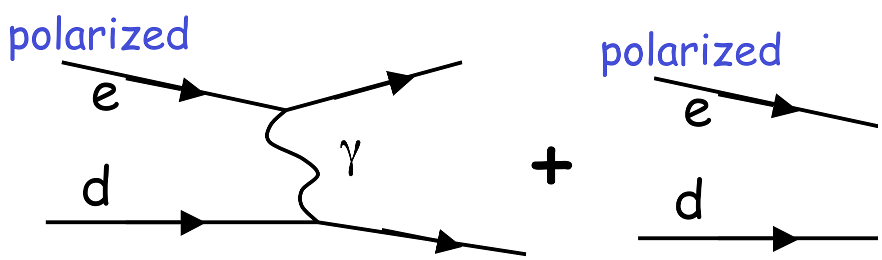






Confirmation of Neutral Currents

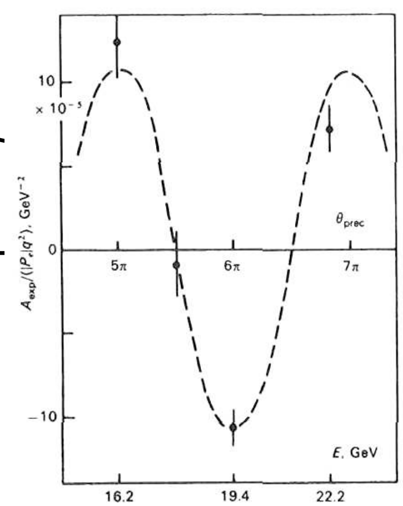
- **Weinberg-Salam Model predicts there should be some parity violation in polarized electron scattering**
  - **The dominant exchange is the photon (L/R symmetric)**
  - **A small addition of the weak neutral current exchange leads to an expected asymmetry of ~ 10^{-4} between the scattering of left and right-handed electrons**



nge violates parity

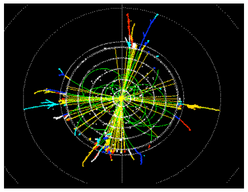
$g_R \neq g_L$

ymmetry of 10^{-4}



- **Prescott et al. (SLAC) 1978**
- **confirms theory**
- **first accurate measurement of weak mixing angle**

$\sin^2\theta_W = 0.22 \pm 0.02$



W and Z Masses

- Knowing $\sin^2\theta_W$ allows one to predict the W and Z boson masses in the Weinberg-Salam Model

$$M_{W^\pm} = \left(\frac{e^2\sqrt{2}}{8G\sin^2\theta_W} \right)^{1/2} = \frac{37.4}{\sin\theta_W}\ \mathrm{GeV}$$

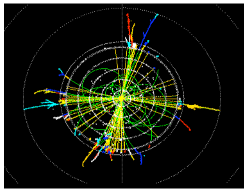
~ 80 GeV/c^2

$$M_{Z^0} = \frac{M_{W^\pm}}{\cos\theta_W} = \frac{75}{\sin 2\theta_W}\ \mathrm{GeV}$$

~ 90 GeV/c^2

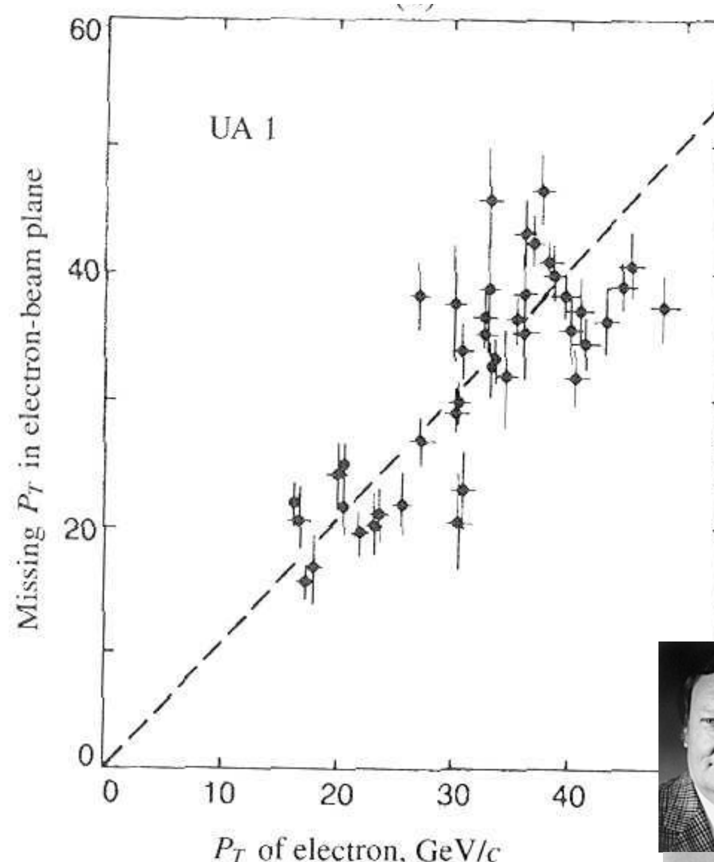
TREE LEVEL EXPRESSIONS

- Motivated by these predictions, experiments at CERN were mounted to find the W and Z

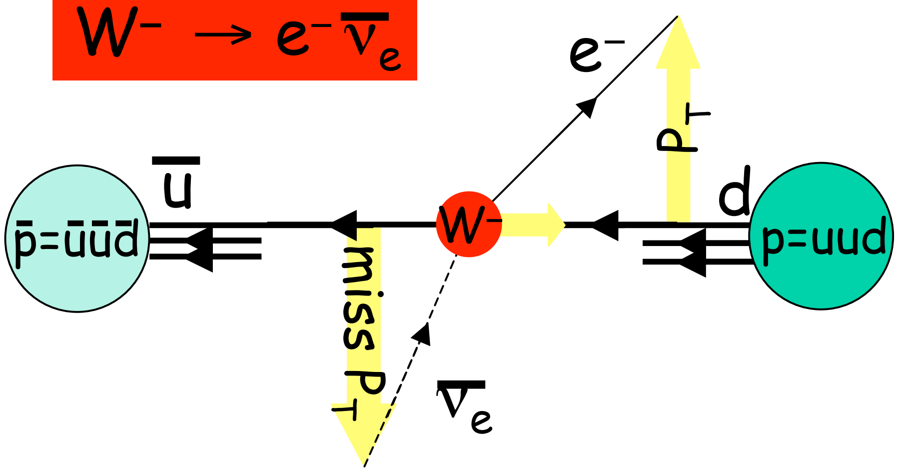


Discovery of the W and Z

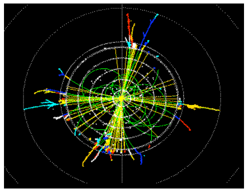
Antiprotons stored at CERN in 1981



$W^- \rightarrow e^- \overline{\nu}_e$



UA1 and UA2 discovered the W and the Z bosons



Discovery of the W and Z

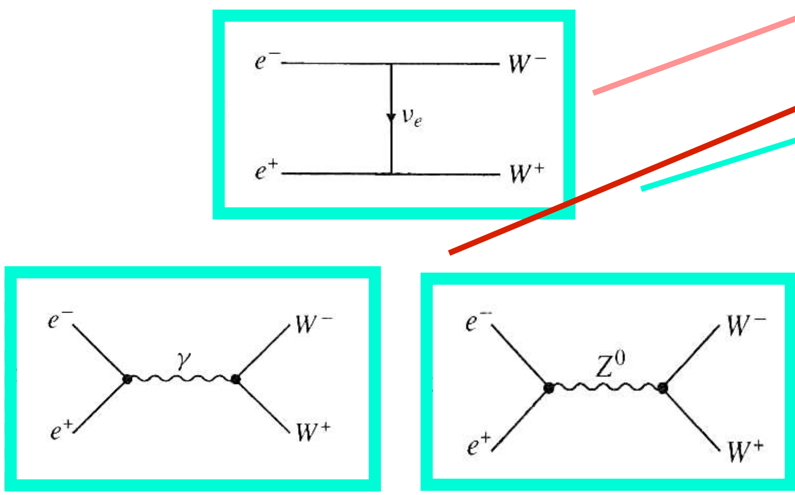
- **That was over 20 years ago**
- **Since then:**
  - **<u>precision</u> studies at Z^0 Factories**
    - LEP and SLC
  - **<u>precision</u> W measurements at colliders**
    - LEP2 and TeVatron

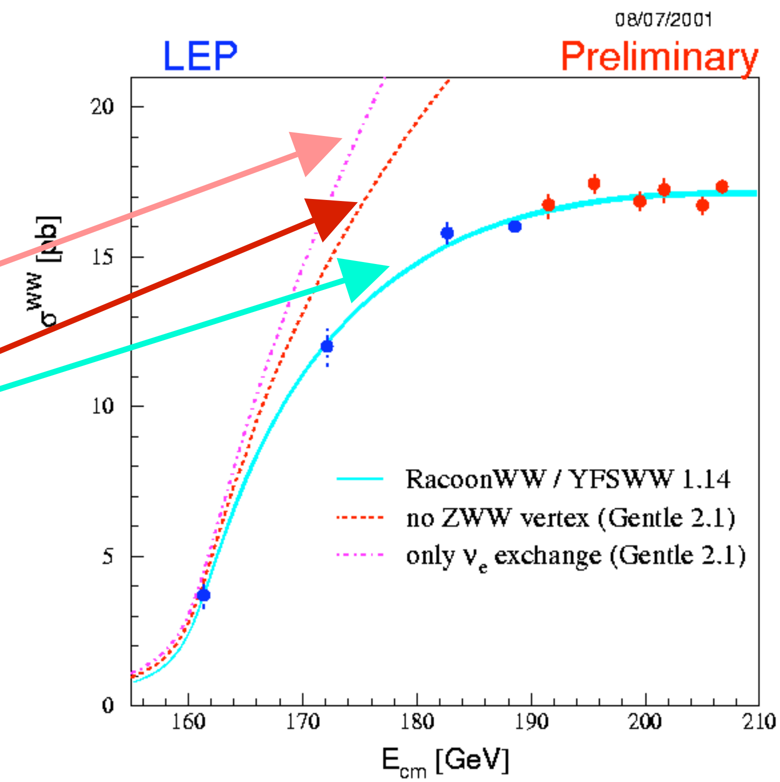
M_Z = 91187.5 ± 2.1 MeV M_W = 80398 ± 25 MeV/c^2

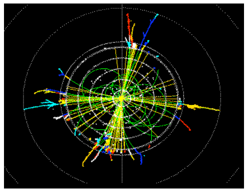
- **These <u>precise</u> measurements (along with other <u>precision</u> measurements) test the Standard Model with keen sensitivity**
  - **eg. are all observables consistent with the same value of $\sin^2\theta_W$**

Confirmation of the completeness of the Standard Model

$e^+e^- \rightarrow W^+W^-$ **(LEP2)**







The Higgs Boson

- Why is the underlying SU(2)xU(1) symmetry

$$L = g\mathbf{J}_\mu \cdot \mathbf{W}_\mu + g' J^Y_\mu B_\mu$$

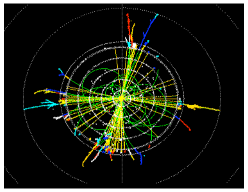
broken

$$= -\frac{g}{2\sqrt{2}} \sum_i \overline{\psi}_i \, \gamma^\mu \, (1-\gamma^5)(T^+ \, W^+_\mu + T^- \, W^-_\mu) \, \psi_i$$

$$- e \sum_i q_i \, \overline{\psi}_i \, \gamma^\mu \, \psi_i \, A_\mu$$

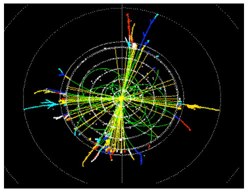
$$- \frac{g}{2\cos\theta_W} \sum_i \overline{\psi}_i \, \gamma^\mu (g^i_V - g^i_A \gamma^5) \, \psi_i \, Z_\mu \, .$$

- Theoretical conjecture is the Higgs Mechanism: a non-zero vacuum expectation value of a scalar field, gives mass to W and Z and leaves photon massless

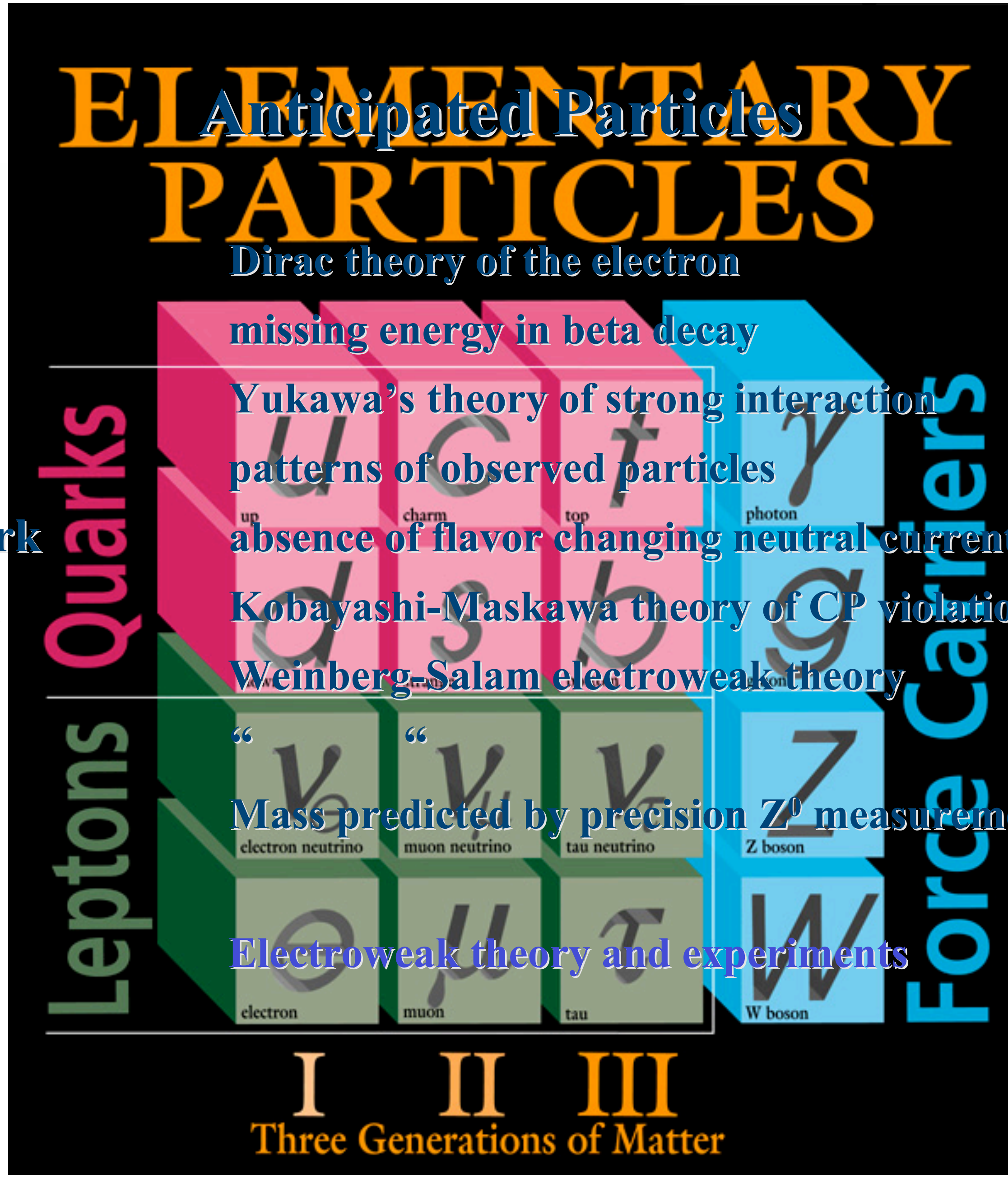


The Higgs Boson

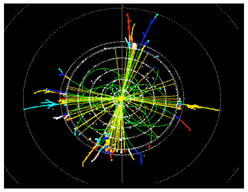
- This scalar field, like any field, has quanta, the Higgs Boson or Bosons
  - Minimal model - one complex doublet $\Rightarrow$ 4 fields
    - — 3 “eaten” by W^+, W^-, Z to give mass
    - — 1 left as physical Higgs
- This spontaneously broken local gauge theory is renormalizable - t’Hooft (1971)
- The Higgs boson properties
  - Mass < ~ 800 GeV/c^2 (unitarity arguments)
    - but hierarchy problem
  - Strength of Higgs coupling increases with mass
    - fermions: $g_{ffh} = m_f / v$ $\quad$ $v = 246$ GeV
    - gauge boson: $g_{wwh} = 2\, m_Z^2/v$



Anticipated Particles

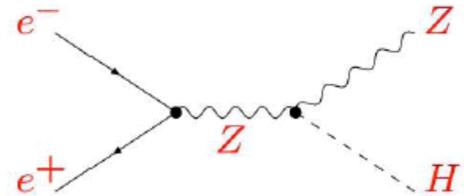


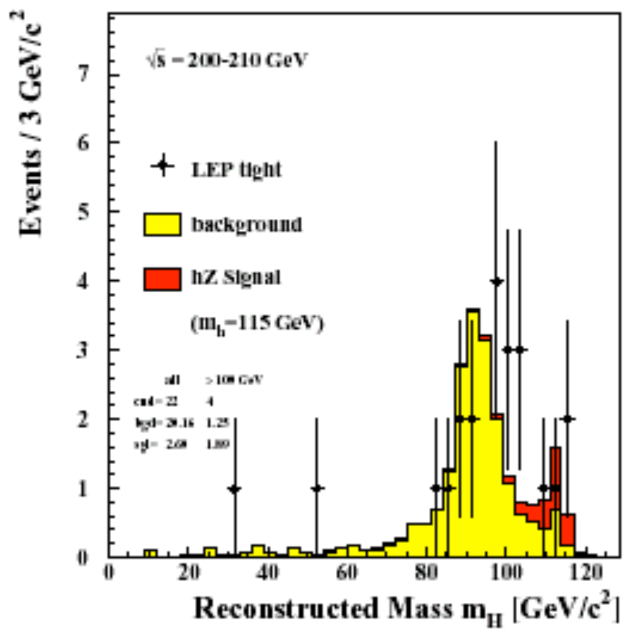
Positron	Dirac theory of the electron
Neutrino	missing energy in beta decay
Pi meson	Yukawa's theory of strong interaction
Quark	patterns of observed particles
Charmed quark	absence of flavor changing neutral currents
Bottom quark	Kobayashi-Maskawa theory of CP violation
W boson	Weinberg-Salam electroweak theory
Z boson	“ “
Top quark	Mass predicted by precision Z^0 measurements
Higgs boson	Electroweak theory and experiments



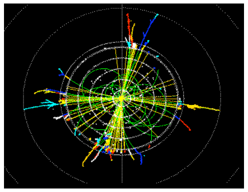
The Search for the Higgs Boson

- LEP II (1996-2000)

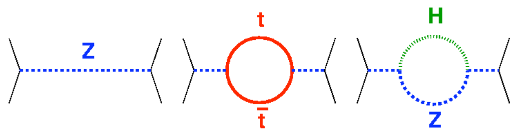




M_H > 114 GeV/c^2 (95% conf.)

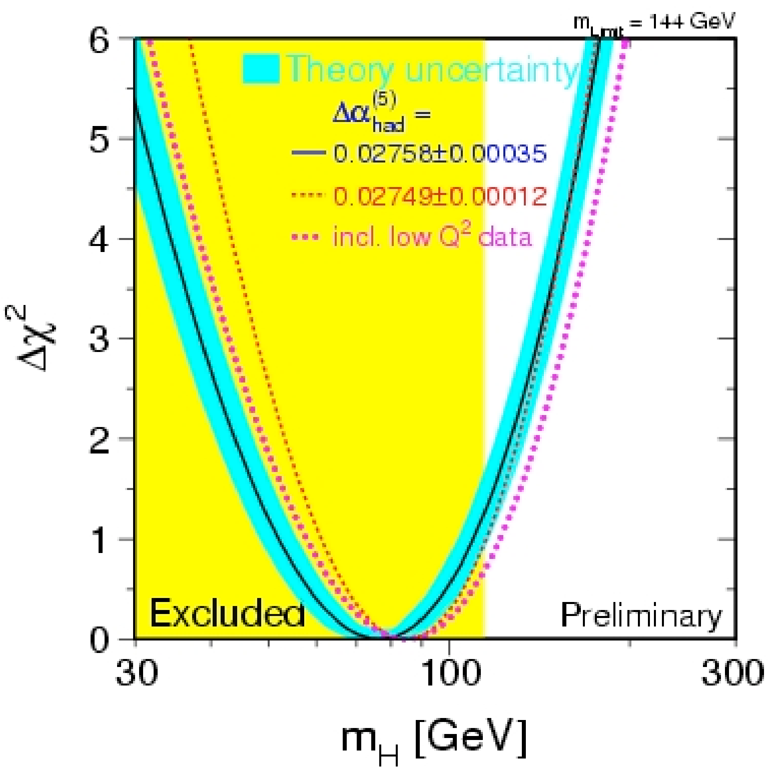


Standard Model Fit

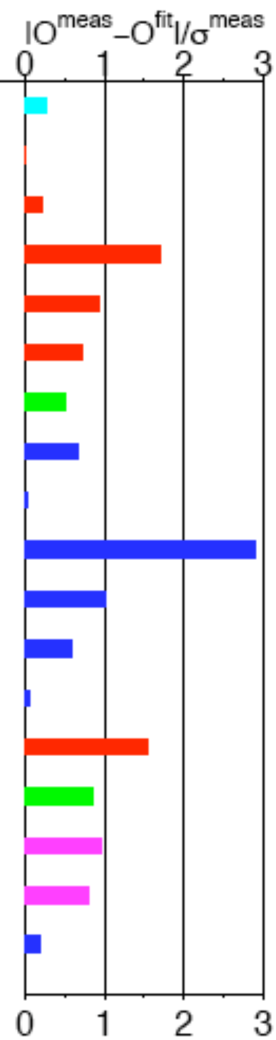


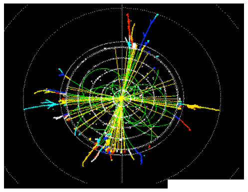
JULY 2007

- $M_H = 76\ ^{+33}_{-24}$ GeV/c²



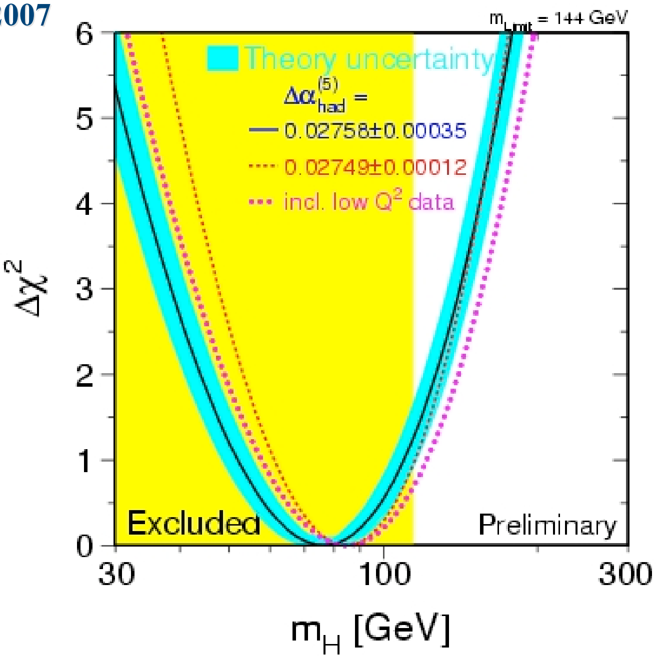
	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758 ± 0.00035	0.02768
m_Z [GeV]	91.1875 ± 0.0021	91.1875
Γ_Z [GeV]	2.4952 ± 0.0023	2.4957
σ^0_{had} [nb]	41.540 ± 0.037	41.477
R_l	20.767 ± 0.025	20.744
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21586
R_c	0.1721 ± 0.0030	0.1722
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1038
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.398 ± 0.025	80.374
Γ_W [GeV]	2.140 ± 0.060	2.091
m_t [GeV]	170.9 ± 1.8	171.3

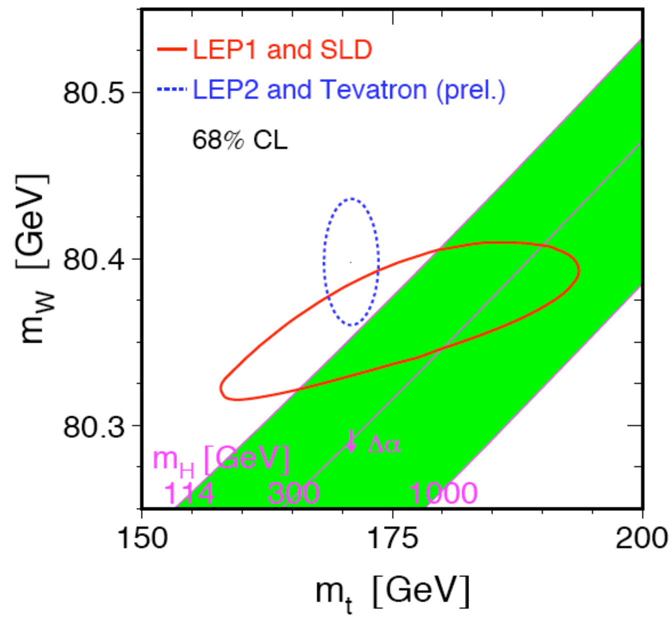




Light Standard Model-like Higgs

JULY 2007

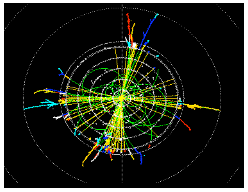




(SM) M_{higgs} < 144 GeV at 95% CL.
LEP2 direct limit M_{higgs} > 114.4 GeV.

W mass (± 25 MeV)
and top mass (± 2 GeV)
consistent with precision measures
and indicate low SM Higgs mass

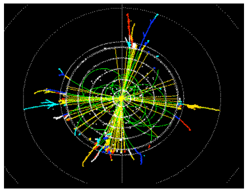
LEP Higgs search – Maximum Likelihood for Higgs signal at m_H = 115.6 GeV with overall significance (4 experiments) ~ 2σ



The Search for the Higgs Boson

- **Tevatron at Fermilab**
  - **Proton/anti-proton collisions at E_{cm}= 2000 GeV**
  - **through 2009 (perhaps 2010)**

- **LHC at CERN**
  - **Proton/proton collisions at E_{cm}=14,000 GeV**
  - **First collisions in 2008**



Models of Electroweak Symmetry Breaking

Standard Model Higgs

excellent agreement with EW precision measurements
implies $M_H < 175$ GeV (but theoretically ugly - h'archy prob.- M_h unstable)

MSSM Higgs

expect $M_h <\sim 135$ GeV
light Higgs boson (h) may be very "SM Higgs-like"
(de-coupling limit)

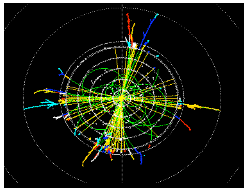
Non-exotic extended Higgs sector

eg. 2HDM

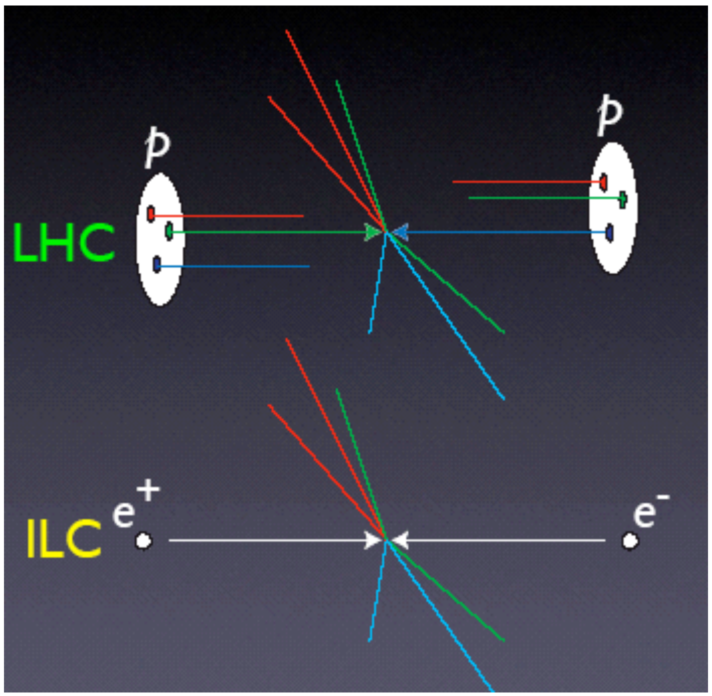
Strong Coupling Models

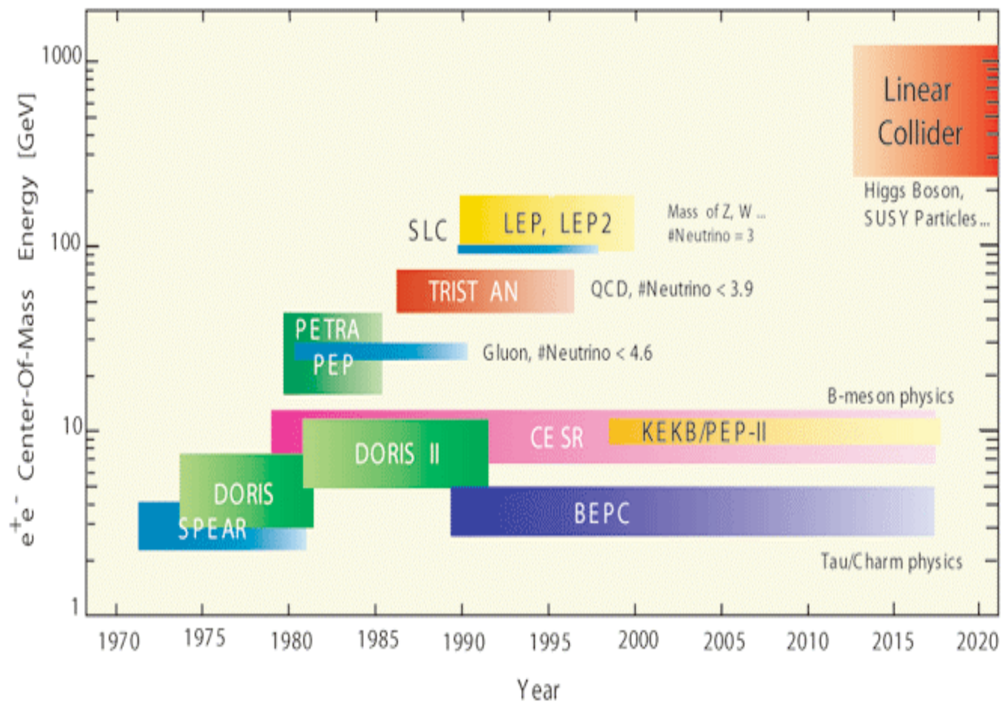
New strong interaction

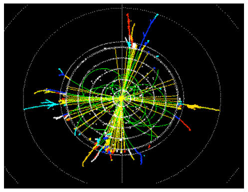
The ILC will provide critical data to assess these possibilities



Complementarity of Electron Colliders





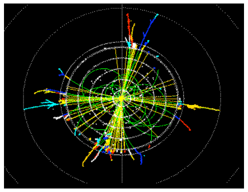


The Large Hadron Collider and the ILC

- LHC at CERN, colliding protons
  first collisions – next year
- History demonstrates the complementarity of hadron and electron experiments

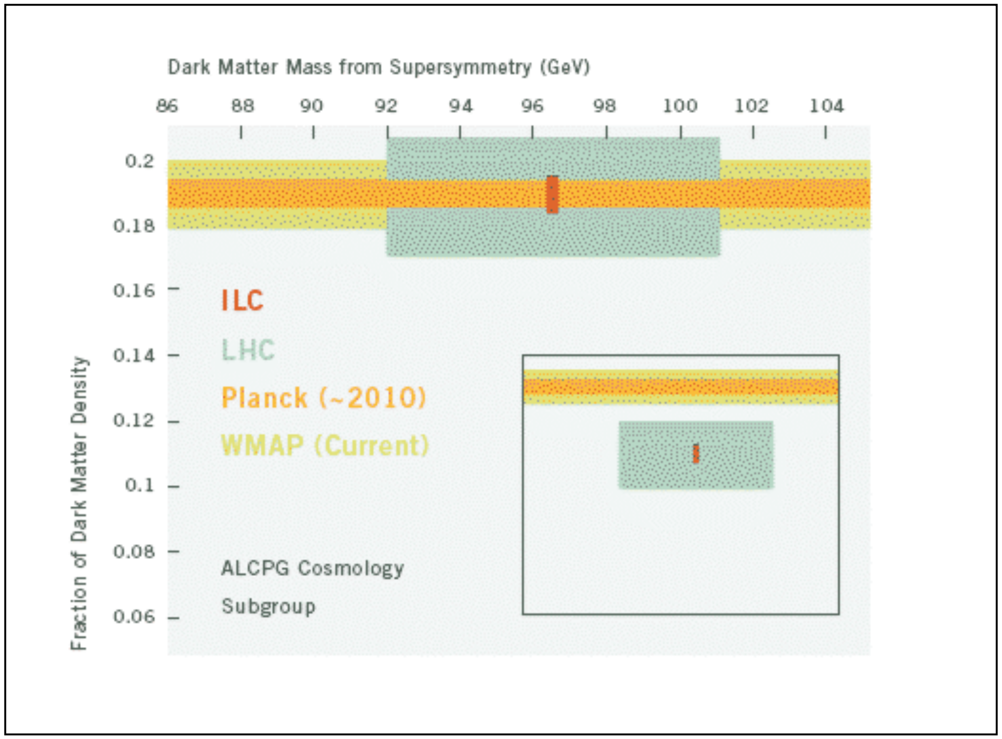
discovery	facility of discovery	facility of detailed study
charm	BNL + SPEAR	SPEAR at SLAC
tau	SPEAR	SPEAR at SLAC
bottom	Fermilab	Cornell/DESY ⇒ B Factories
Z^0	SPPS/CERN	LEP and SLC

- Electron experiments have frequently provided most precision

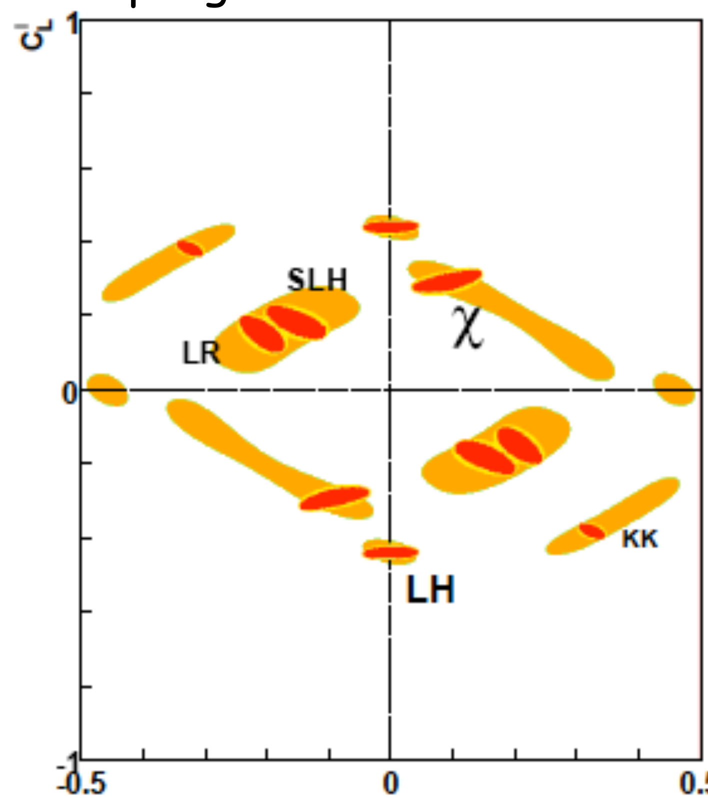


Complementarity with LHC

SUSY mass and coupling measurements
=> Identification of dark matter

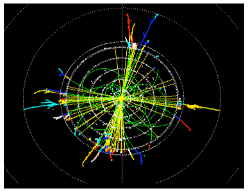


Z′ discovered at LHC
Couplings determined at ILC



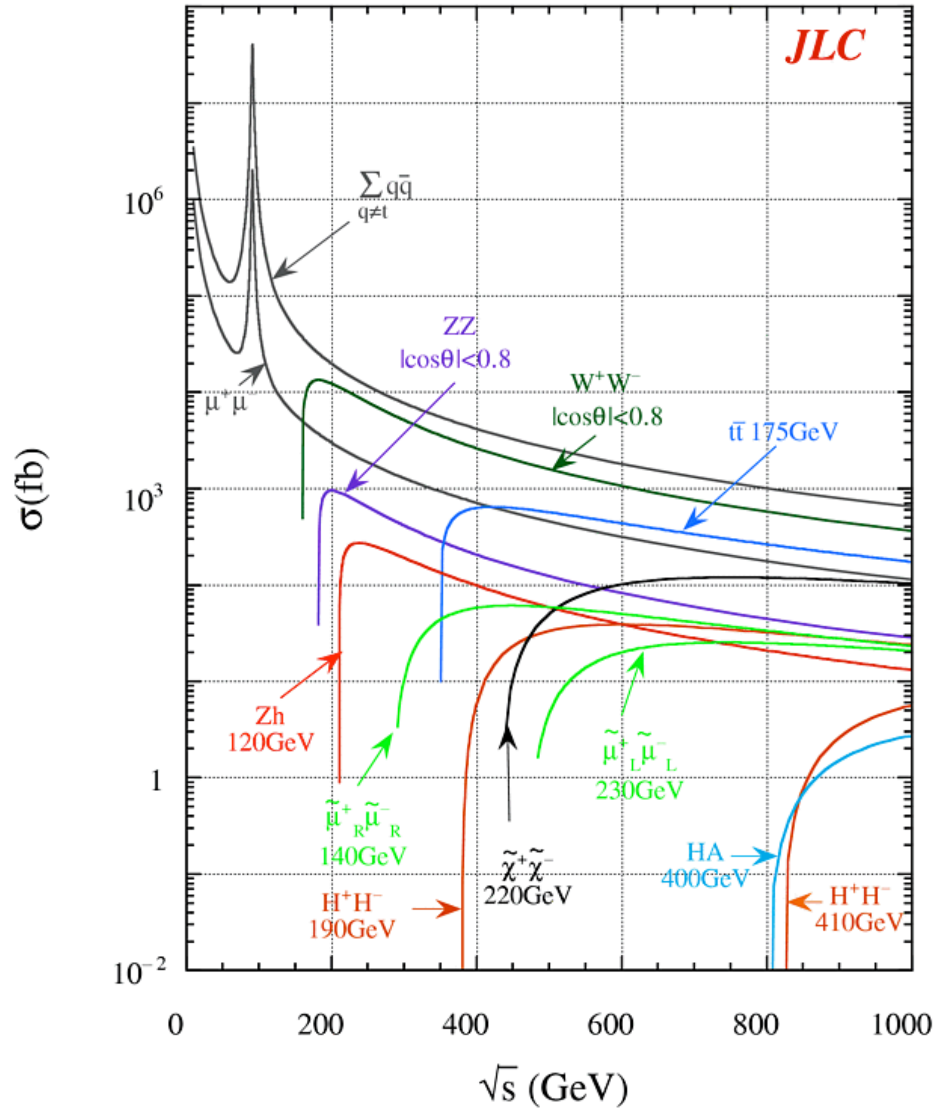
$m_{Z'}$ =2TeV,Ecm=500 GeV, L=1ab^{-1}
with and w/o beam polarization

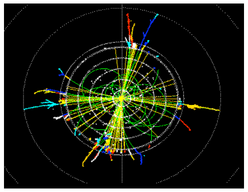
S.Godfrey, P.Kalyniak, A.Tomkins



ILC Physics Program

- Higgs Mechanism
- Supersymmetry
- Strong Electroweak Symmetry Breaking
- Precision Measurements at lower energies



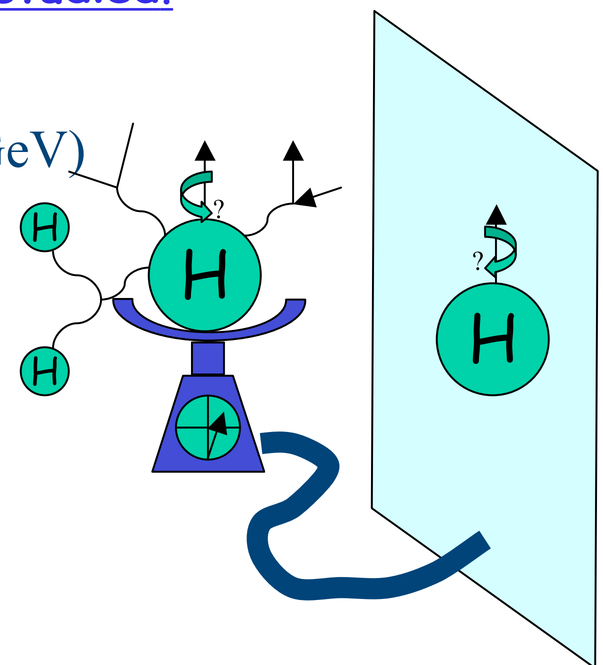


Higgs Physics Program of the ILC

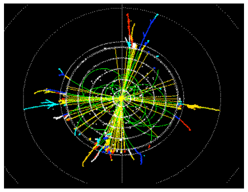
Electroweak precision measurements suggest there should be a relatively light Higgs boson:

When it's discovered, its nature must be studied.
The ILC is essential to this program.

- **Mass Measurement** (~50 MeV at 120 GeV)
- **Total width**
- **Particle couplings**
  - **vector bosons**
  - **fermions (including top)**
- **Spin-parity-charge conjugation**
- **Self-coupling**

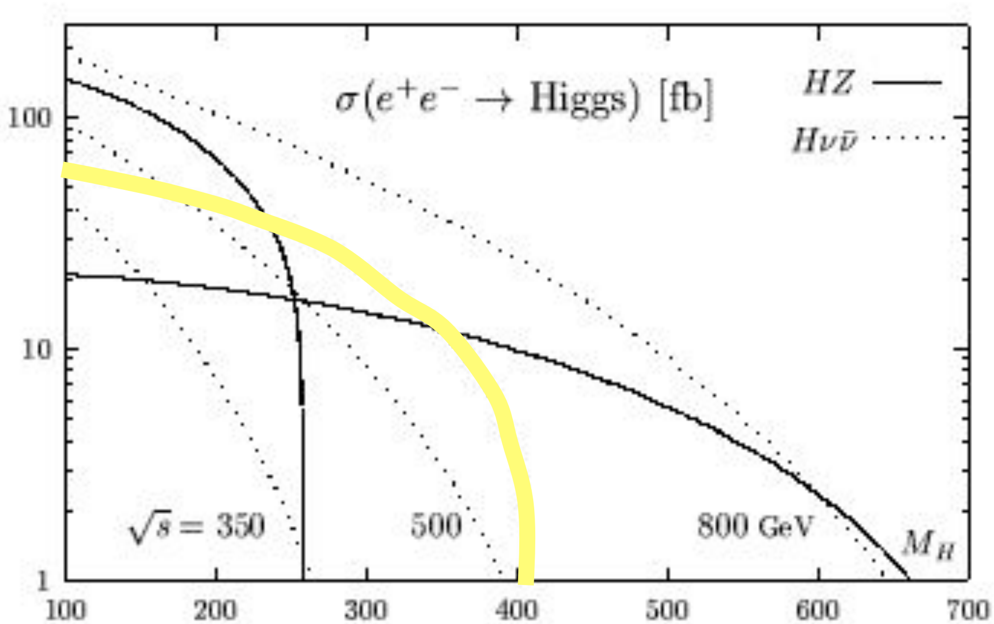


The ILC makes precise measurements

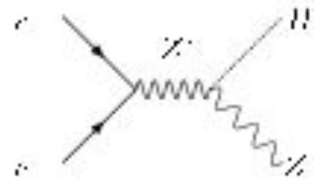


Higgs Production Cross-section

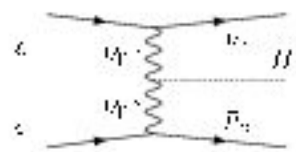
ILC program ~ 500 events / fb



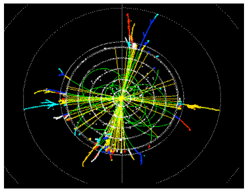
Higgs-strahlung



WW fusion



σ_{PT} = **87** nb / $(E_{cm})^2$ ~ **350** fb @ 500 GeV

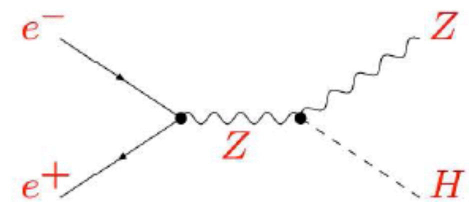


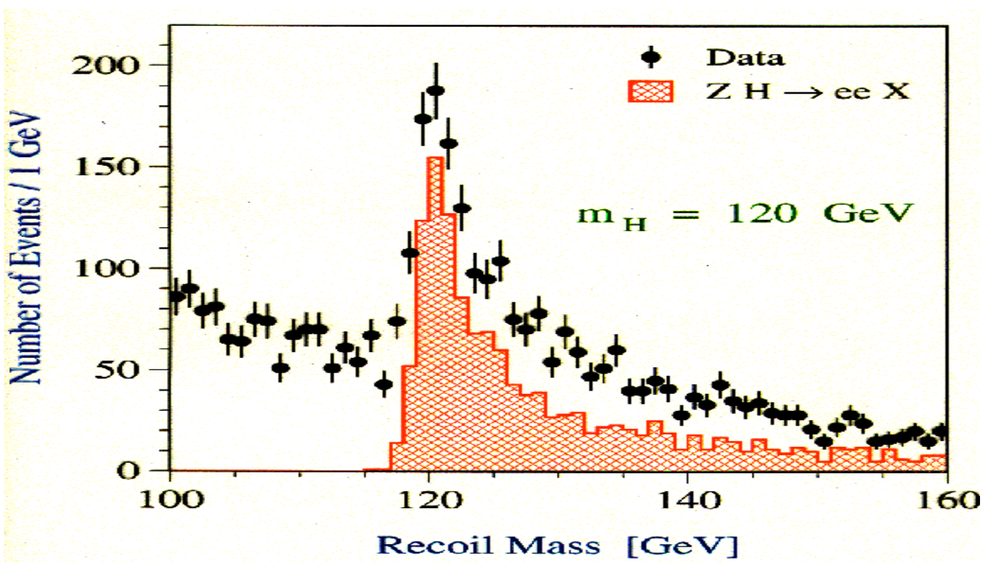
Higgs Studies - the Power of Simple Interactions

ILC observes Higgs recoiling from a Z, with known CM energy⇓
- powerful channel for unbiassed tagging of Higgs events
- measurement of even invisible decays

(⇓ - some beamstrahlung)

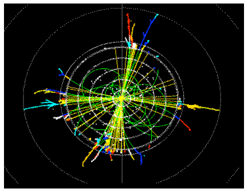
- Tag $Z \rightarrow l^+ l^-$
- Select $M_{recoil} = M_{Higgs}$





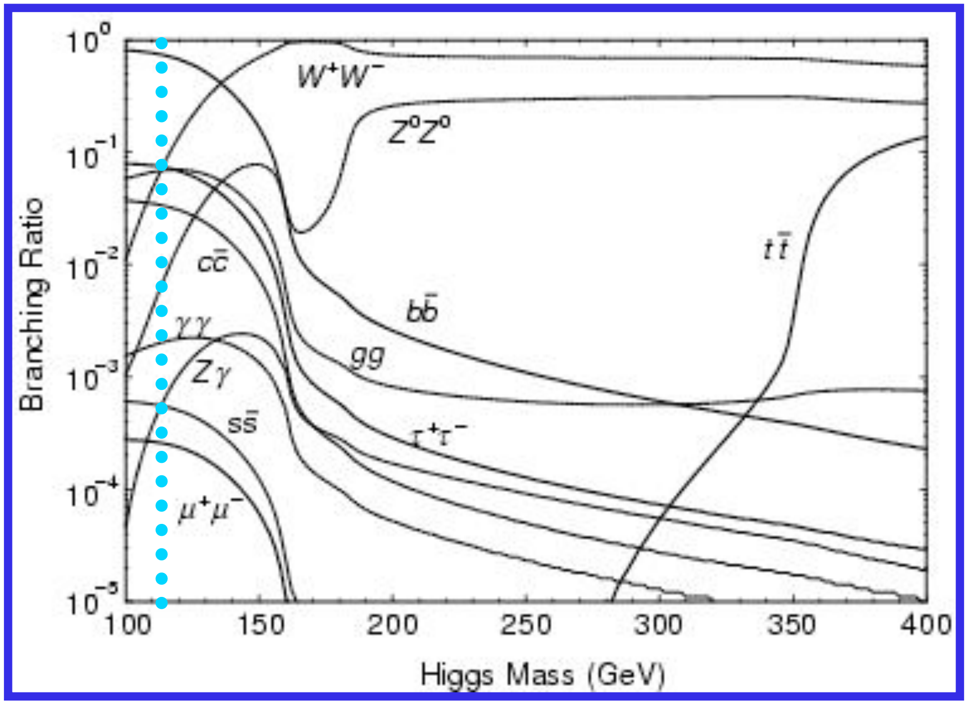
Invisible decays are included

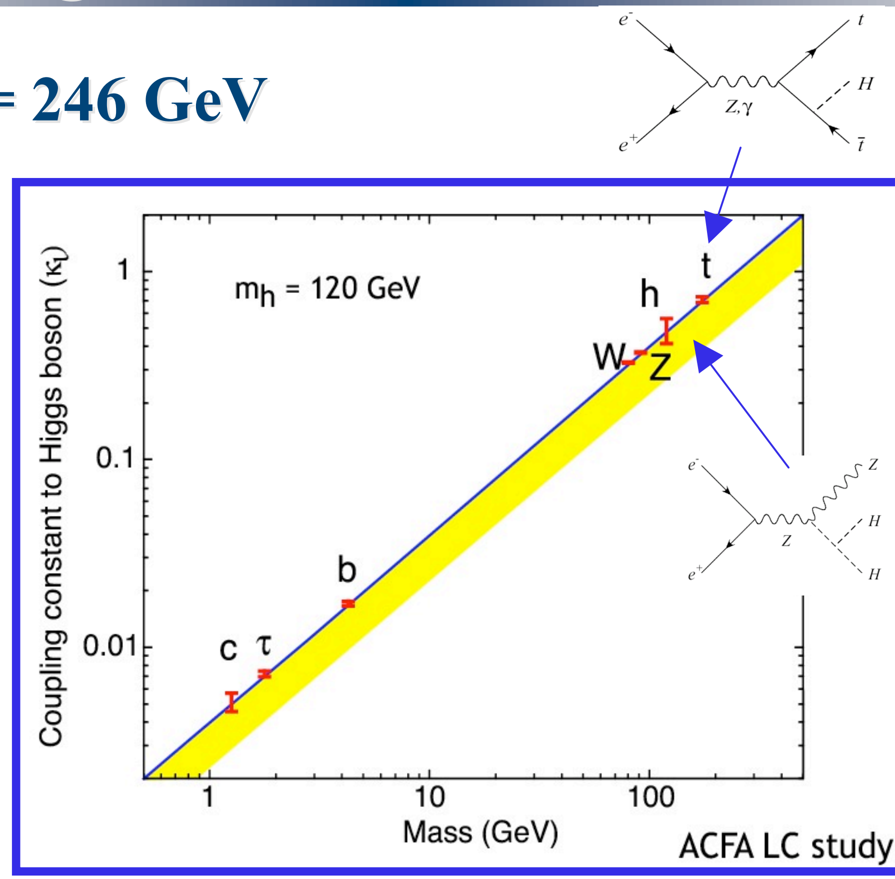
500 fb^{-1} @ 500 GeV, TESLA TDR, Fig 2.1.4



Higgs Couplings the Branching Ratios

$g_{ffh} = m_f / v$ $\qquad$ $v = 246$ GeV

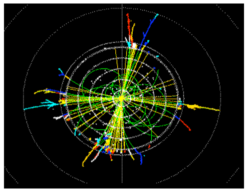




Measurement of BR's is powerful indicator of new physics

e.g. in MSSM, these differ from the SM in a characteristic way.

Higgs BR must agree with MSSM parameters from many other measurements.



Is This the Standard Model Higgs?

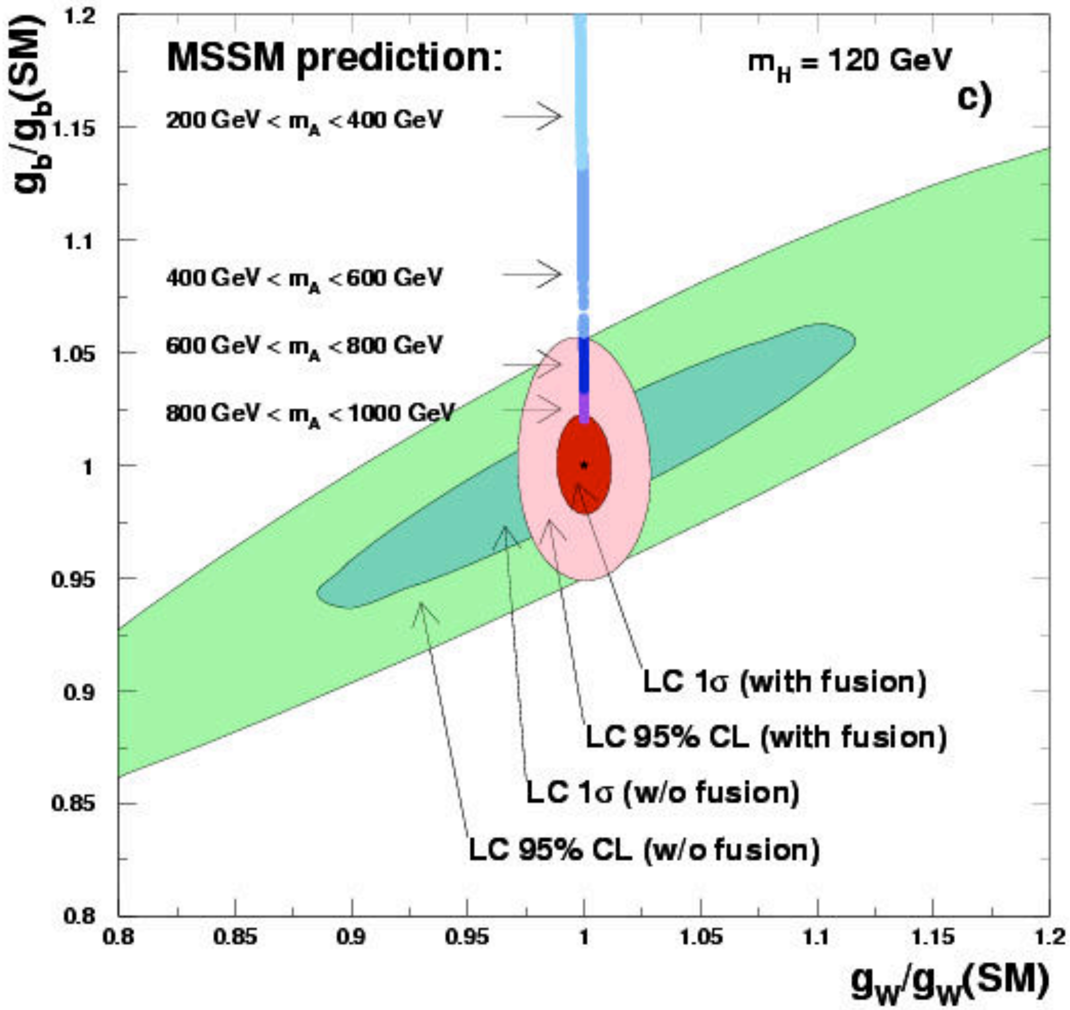
b vs. W

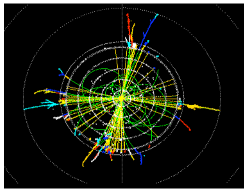
TESLA TDR, Fig 2.2.6

Arrows at:
- M_A = 200-400
- M_A = 400-600
- M_A = 600-800
- M_A = 800-1000

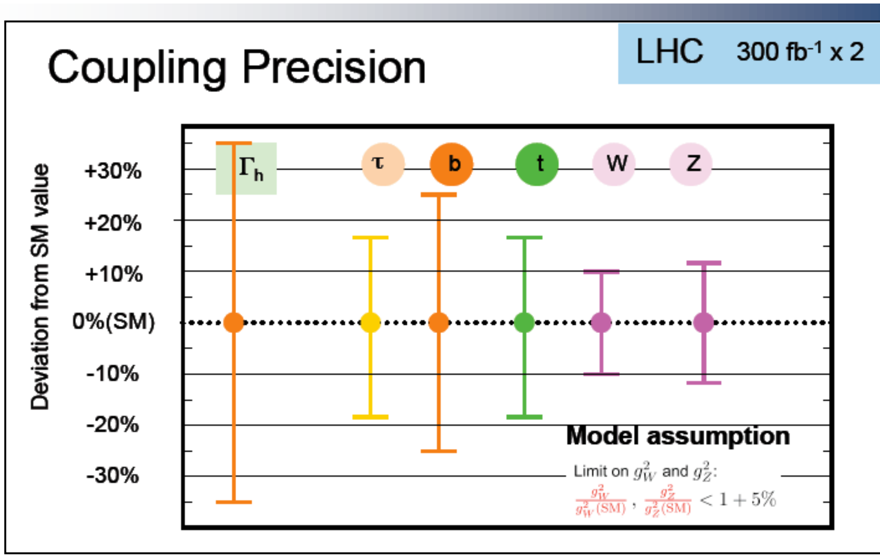
HFITTER output

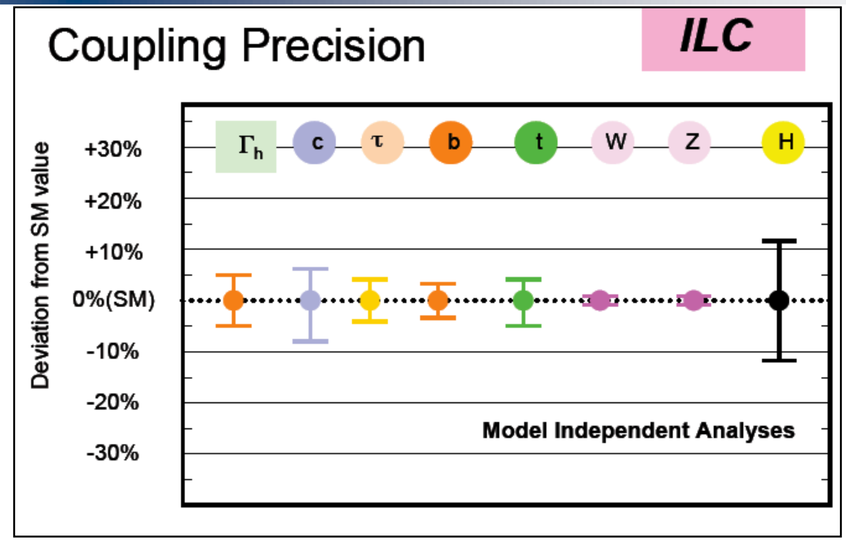
conclusion:
for M_A < 600,
likely to distinguish

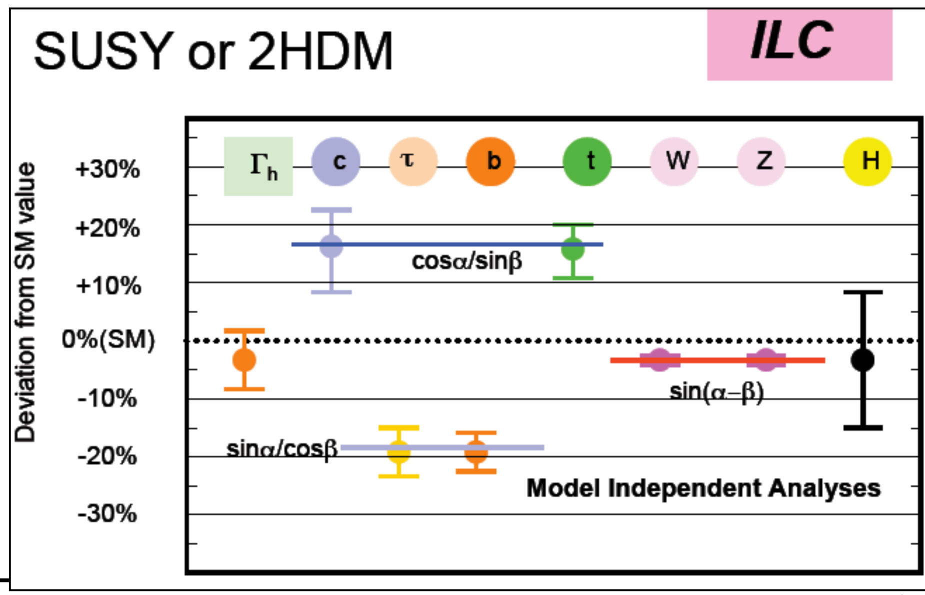




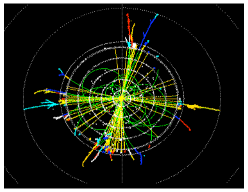
Is This the Standard Model Higgs? Precision tells us!



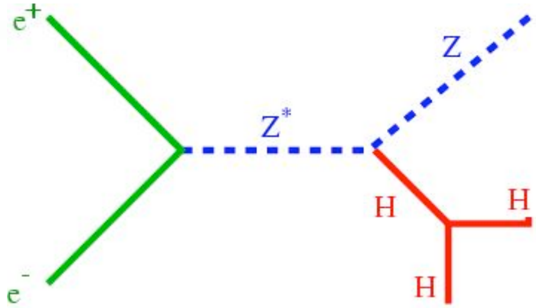




Yamashita

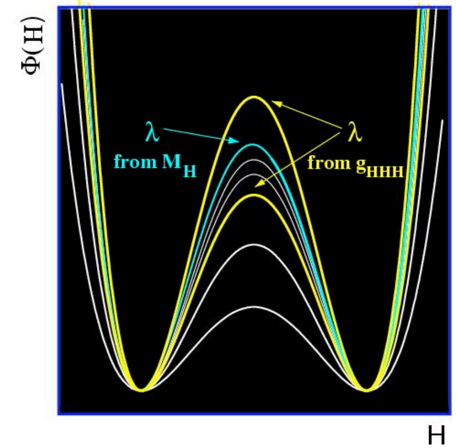


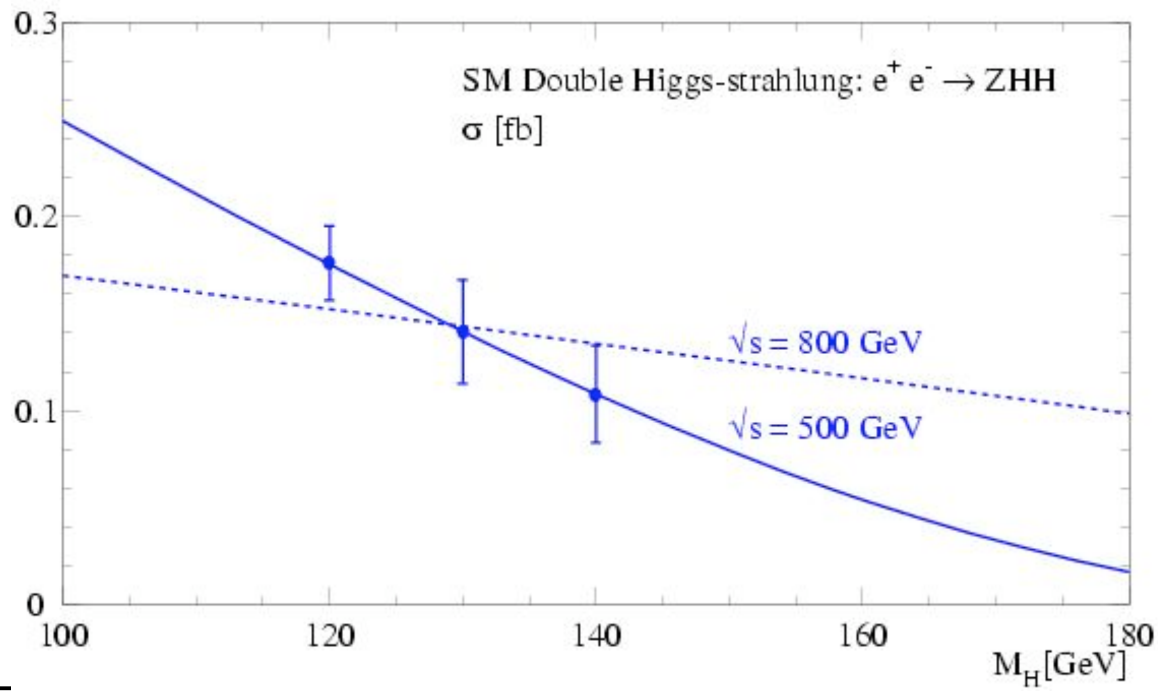
Higgs Self Coupling



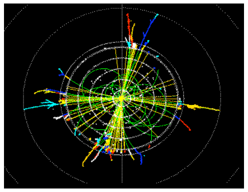
$\Phi(H) = \lambda v^2 H^2 + \lambda v H^3 + 1/4 \lambda H^4$

SM: $g_{HHH} = 6\lambda v$, fixed by M_H



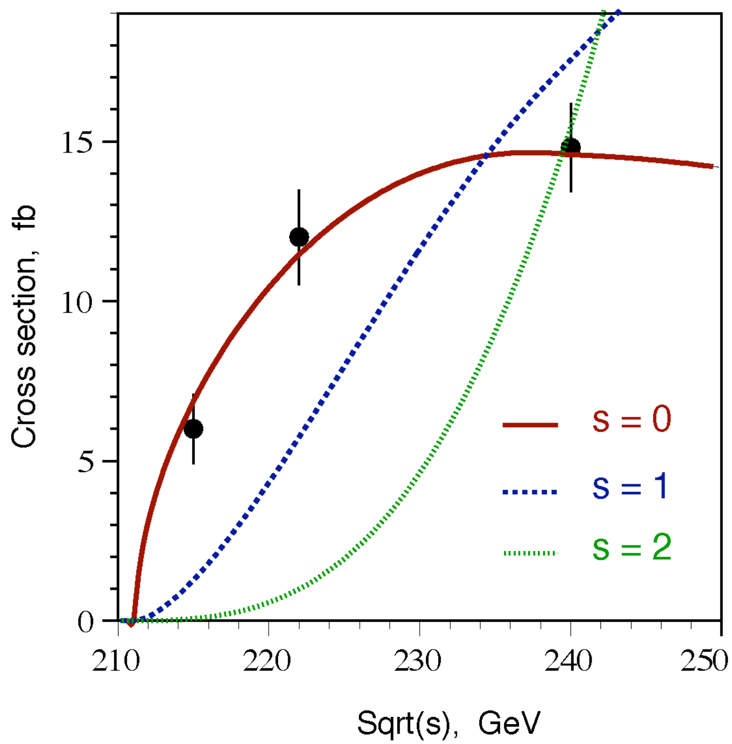


$\Delta\lambda/\lambda \sim$ 10-20 %
for 1 ab^{-1}



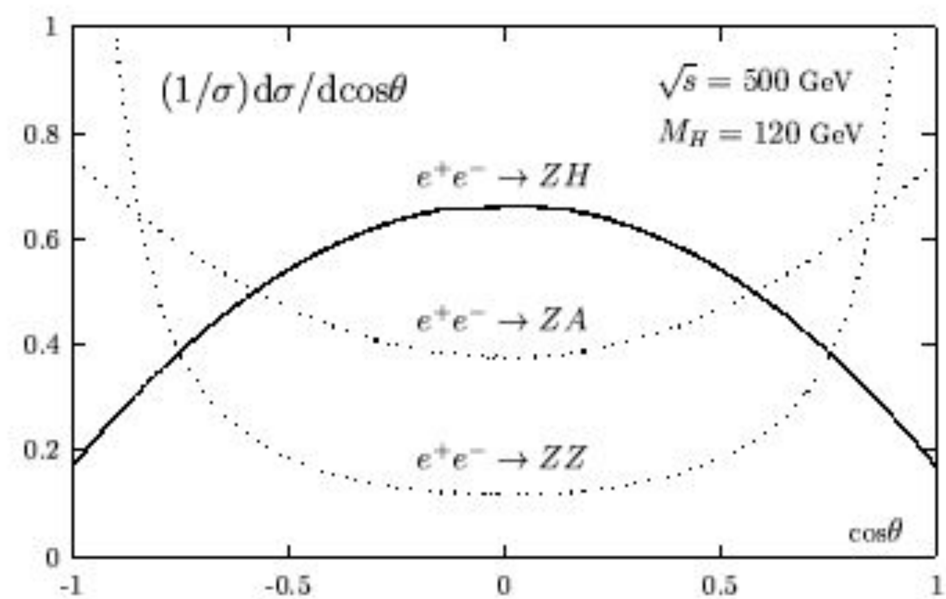
Higgs Spin Parity and Charge Conjugation (J^{PC})

$H \rightarrow \gamma\gamma$ or $\gamma\gamma \rightarrow H$
rules out J=1 and indicates C=+1

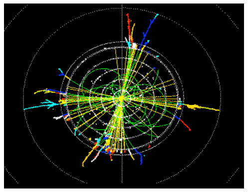


LC Physics Resource Book,
Fig 3.23(a)

Production angle (θ) and Z decay angle in Higgs-strahlung reveals J^P ($e^+ e^- \rightarrow Z H \rightarrow f\bar{f}H$)



TESLA TDR, Fig 2.2.8



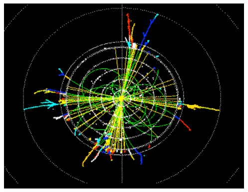
New Physics Beyond the Higgs

- Motivated by Hierarchy Problem
  - Gigantic Mismatched between electroweak scale (100 GeV) and the Planck Scale (10^{19} GeV)

- **Supersymmetry**
  - new space-time symmetry with new particles

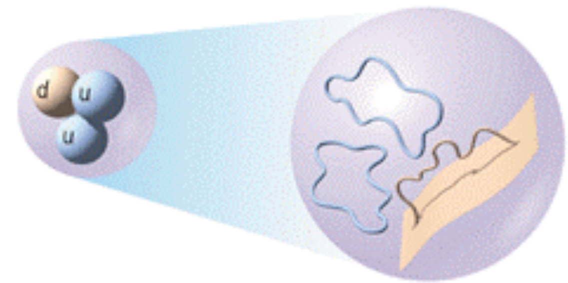
- **New Strong Interactions**

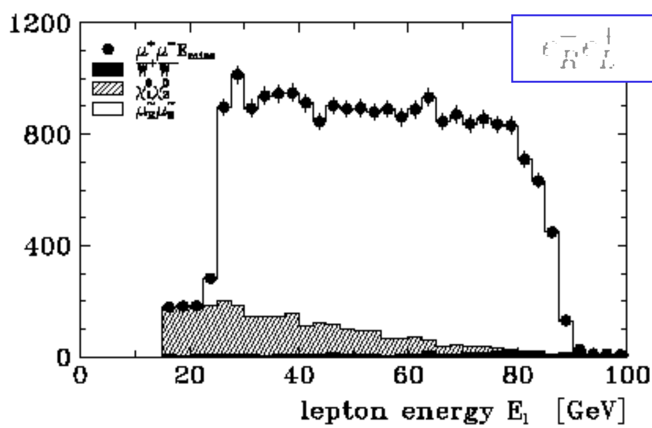
- **Hidden Dimensions**



Supersymmetry

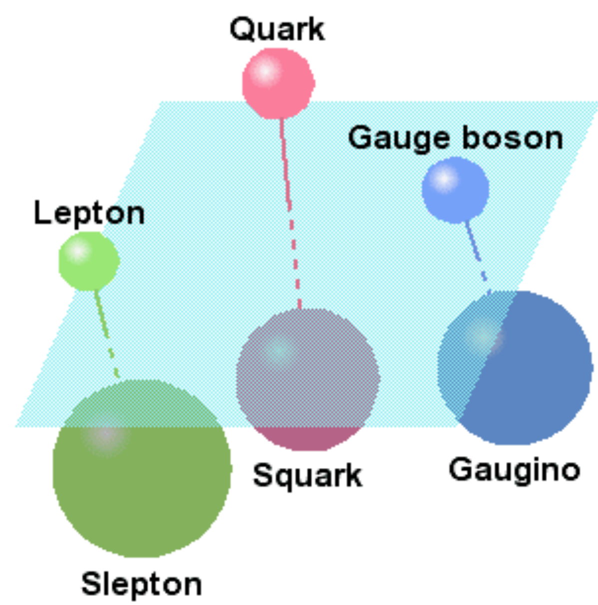
- **Supersymmetry**
  - **particles matched by super-partners**
    - super-partners of fermions are bosons
    - super-partners of bosons are fermions
  - **inspired by string theory**
  - **cancellation of divergences**
    - Solves "hierarchy problem"
  - **dark matter?**
  - **many new particles**
    - ILC could detail properties

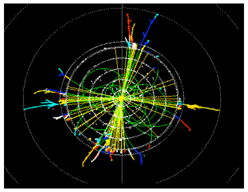




$e_R^- e_L^+ \to \tilde{\mu}_R \tilde{\mu}_R \to \mu^- \tilde{\chi}_1^0 \mu^+ \tilde{\chi}_1^0$

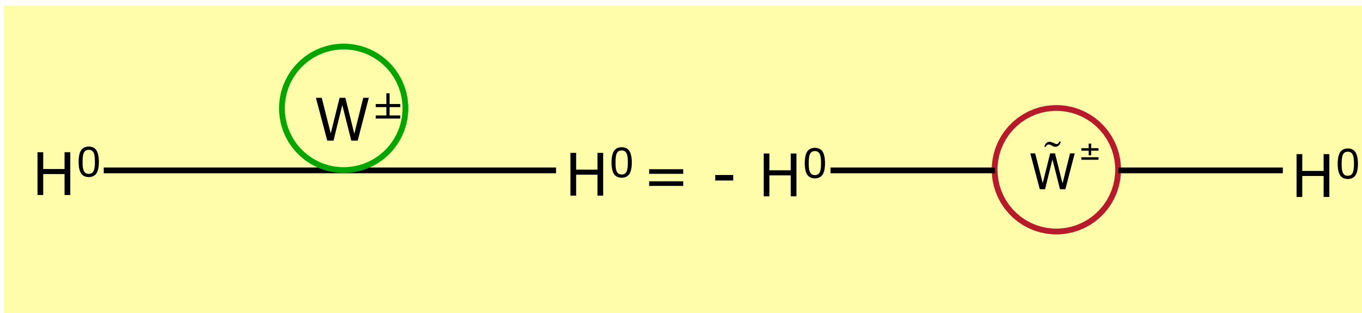
$\delta m_{\tilde{\mu}_R} < 0.1\,\mathrm{GeV}$





Why Supersymmetry #1

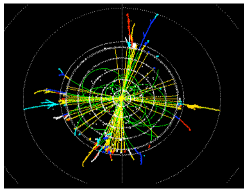
It solves the hierarchy problem



The Higgs mass naturally diverges in Standard Model.

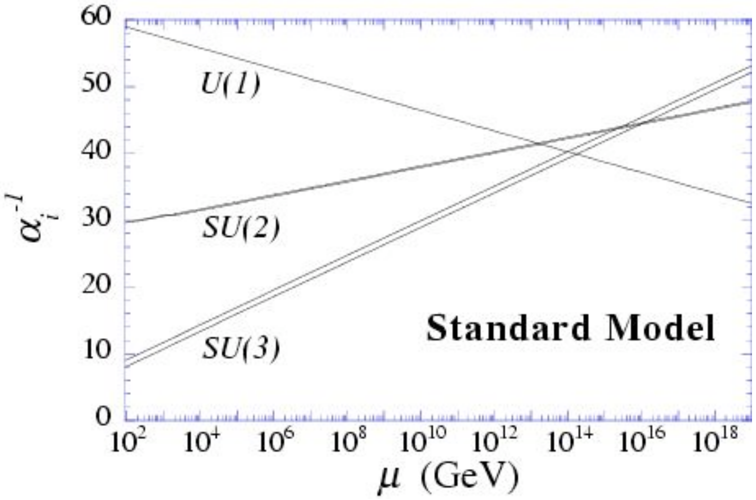
SUSY cancels diverges exactly for unbroken SUSY.

Weak breaking (that is ~1 TeV) solves this problem.

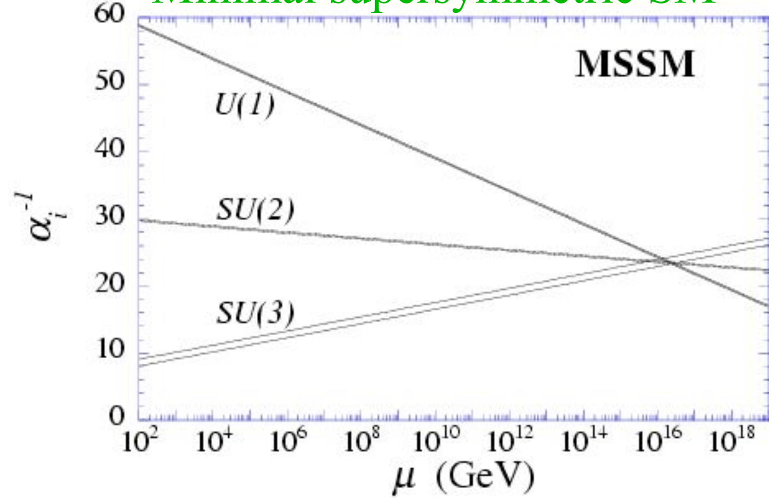


Why Supersymmetry #2

Gauge coupling constants unify



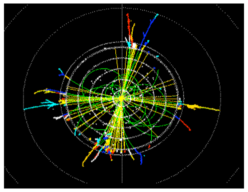
Minimal supersymmetric SM



(Requires light (< TeV) partners of EW gauge bosons)

This is achieved for $\sin^2\theta_W{}^{SUSY} = 0.2335(17)$

Experiment: $\sin^2\theta_W{}^{exp} = 0.2314(2)$



Why Supersymmetry #3, #4, #5

#3: Provides cold dark matter candidate

If lightest SUSY particle is stable, it is an excellent dark matter candidate.

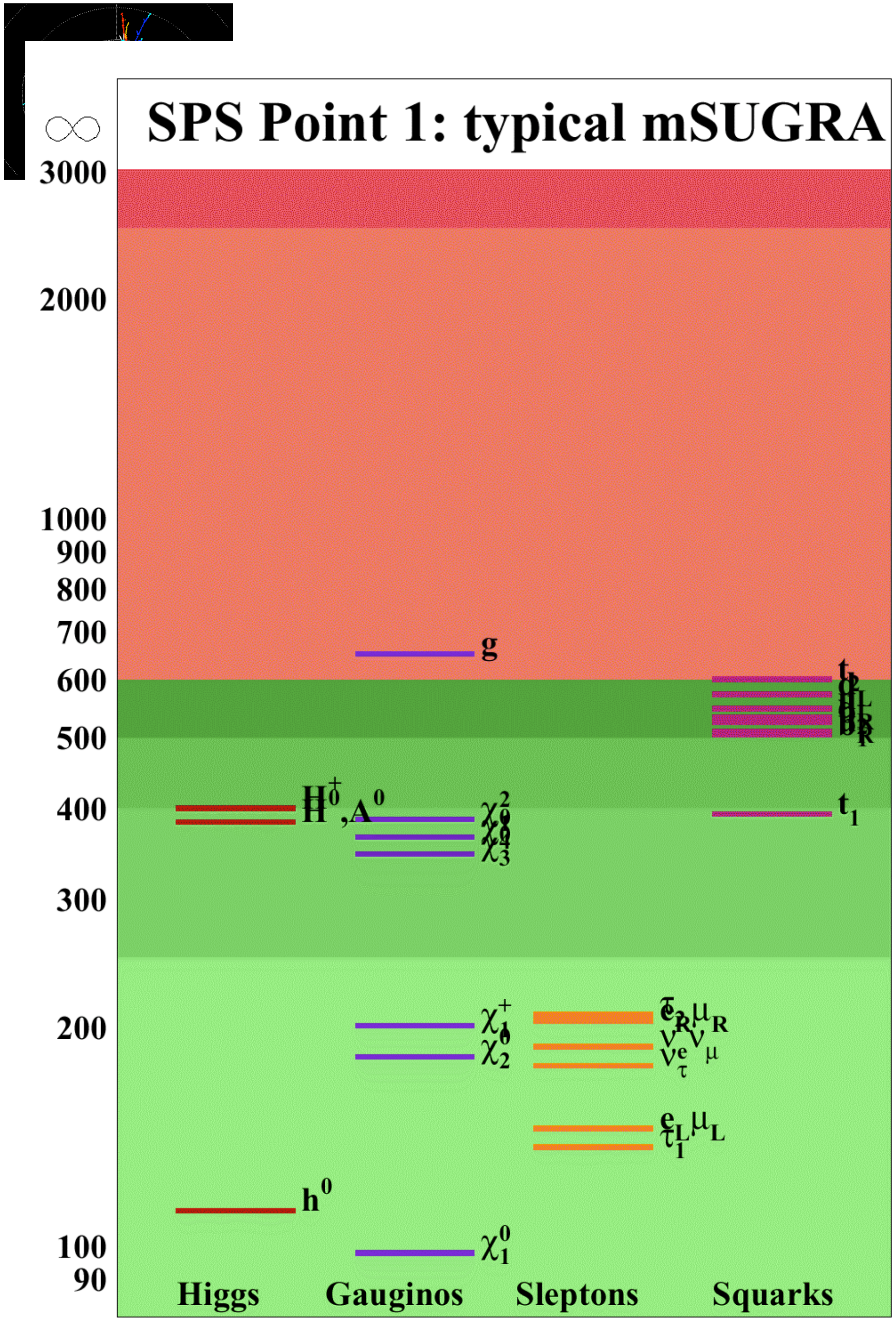
#4: Link to gravity

SUSY offers the theoretical link to incorporate gravity. Most string models are supersymmetric.

#5: Predicts light Higgs boson

SUSY predicts a light (< 135 GeV) Higgs boson as favored by EW precision data.

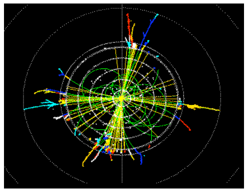
Supersymmetry



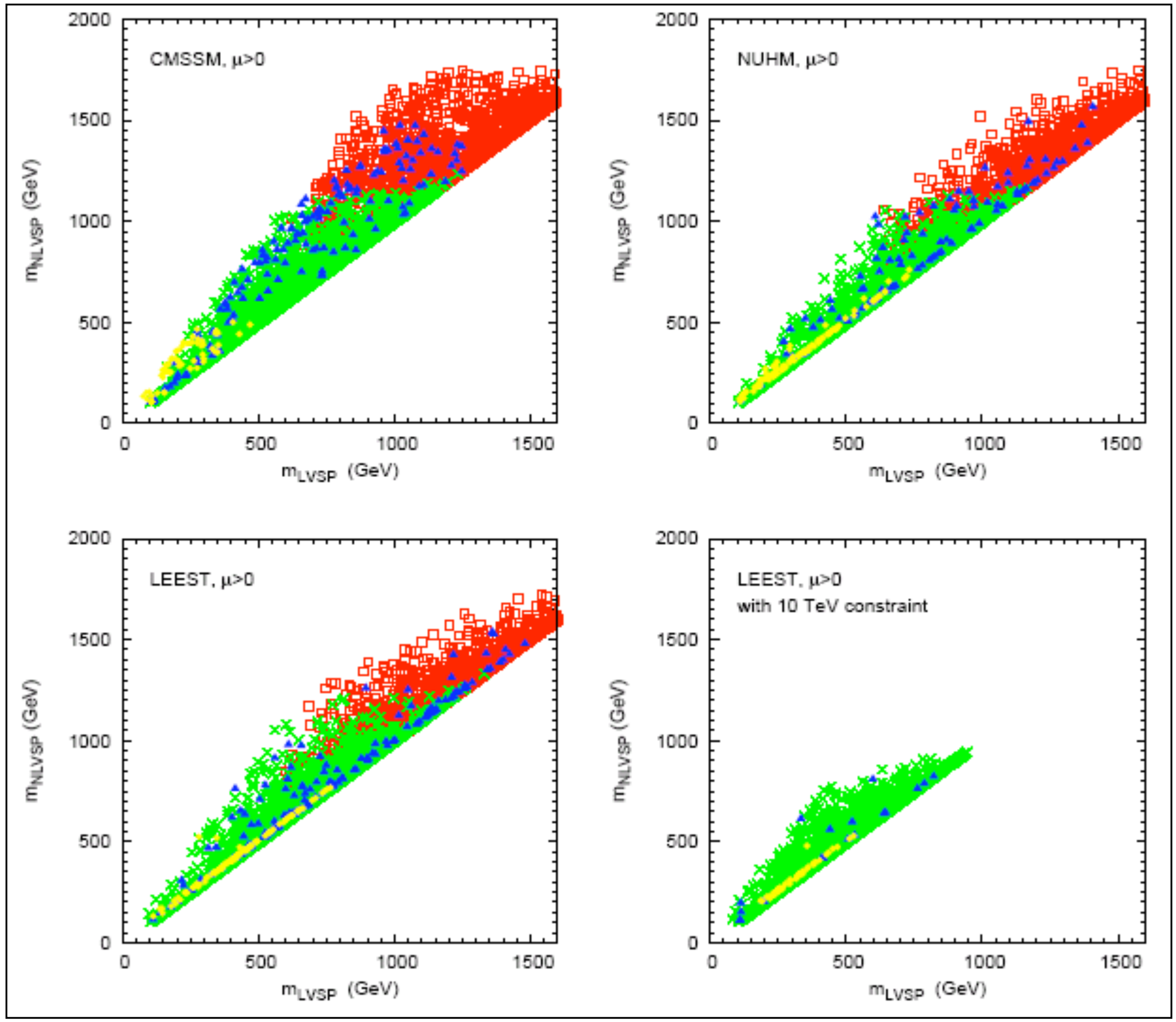
Mass spectrum is model dependent

Squarks are well measured at LHC

Sleptons/Neutralinos may benefit from precise spectroscopy at the Linear Collider



Sparticle Mass Models



Next to lightest

<u>Visible Sparticle</u>

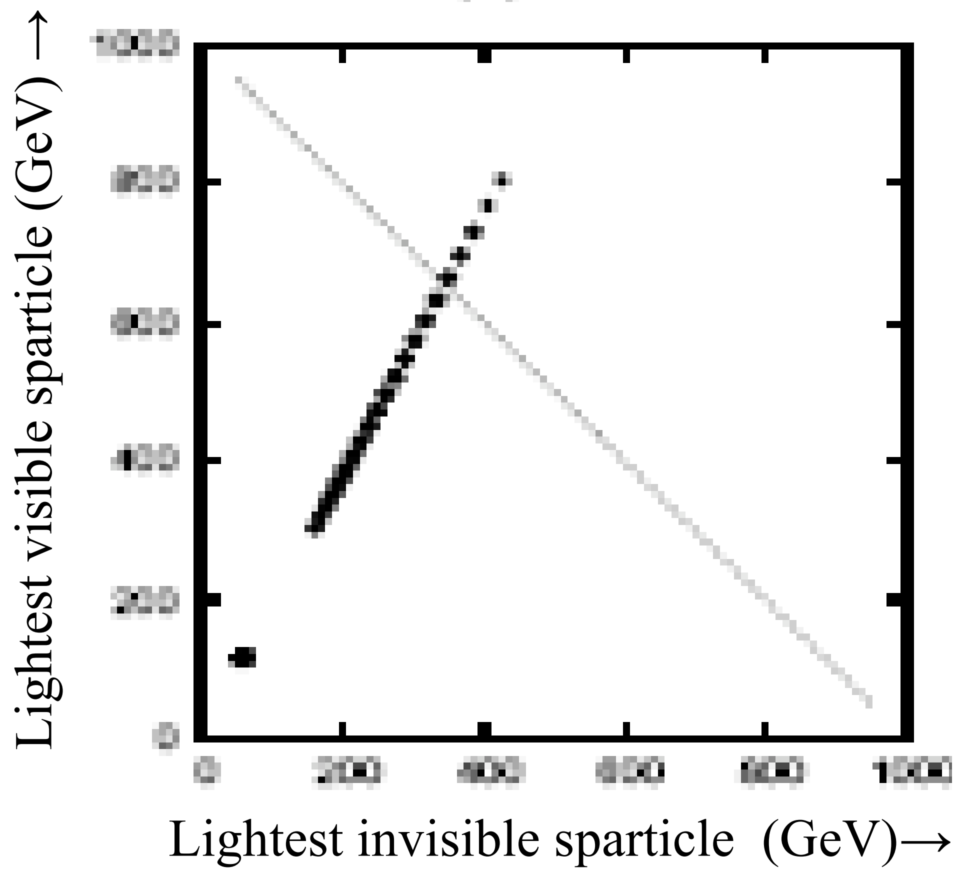
vs.

Lightest

<u>Visible Sparticle</u>

Ellis, Olive,
Santoso, & Spanos

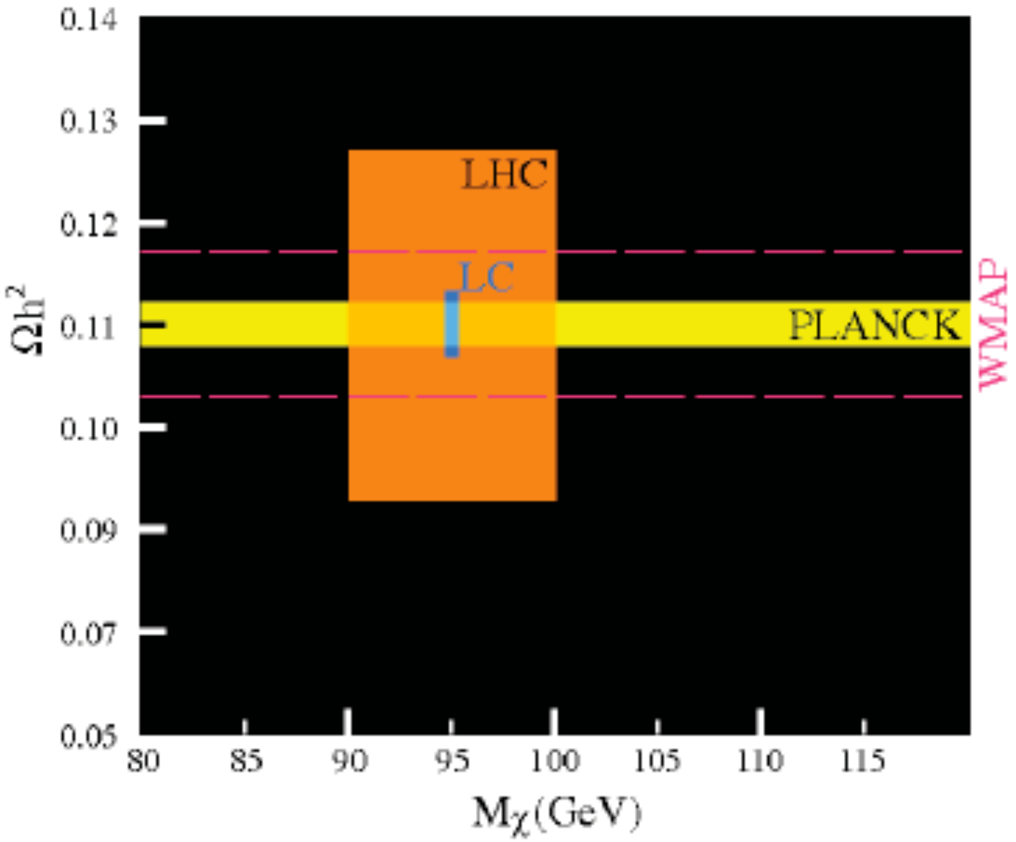
LSP Usually Light



Kalinowski

e+e- → $\chi_1\chi_2$

Is Dark Matter SUSY?

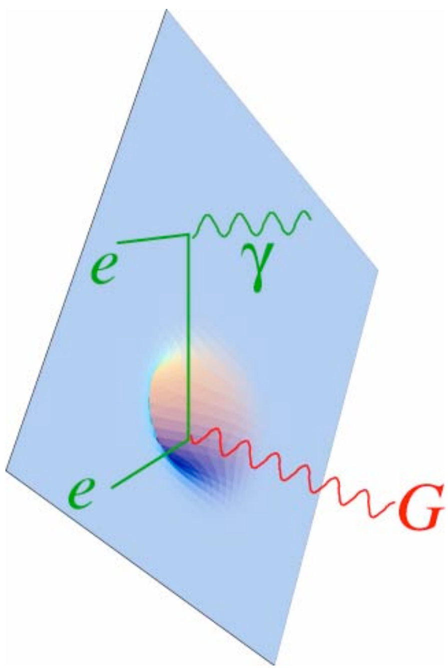


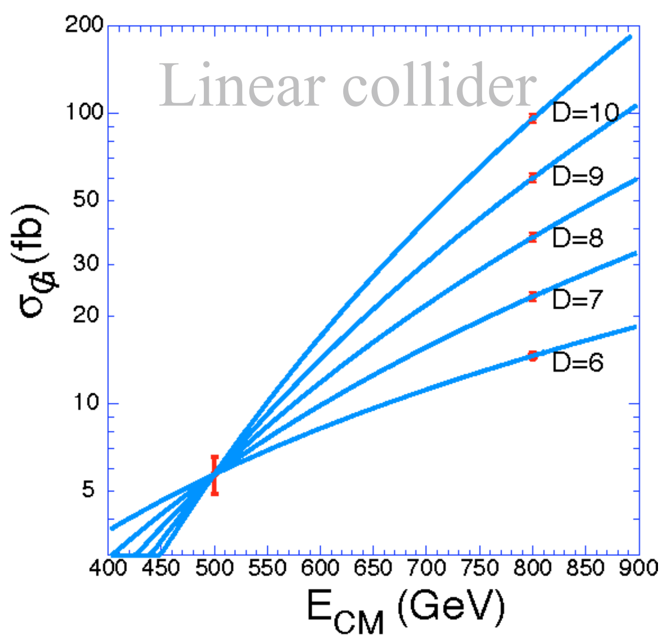
'WMAP'	7 %
LHC	~15 %
'Planck'	~2 %
ILC	~3 %

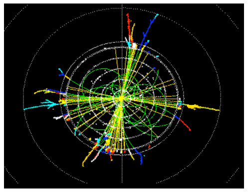
Precise measurement of couplings by the ILC critical to this understanding

Extra Dimensions

- Extra Dimensions
  - string theory inspired
  - solves hierarchy problem ($M_{planck} >> M_{EW}$)
    - if extra dimensions are large
  - large extra dimensions observable at ILC

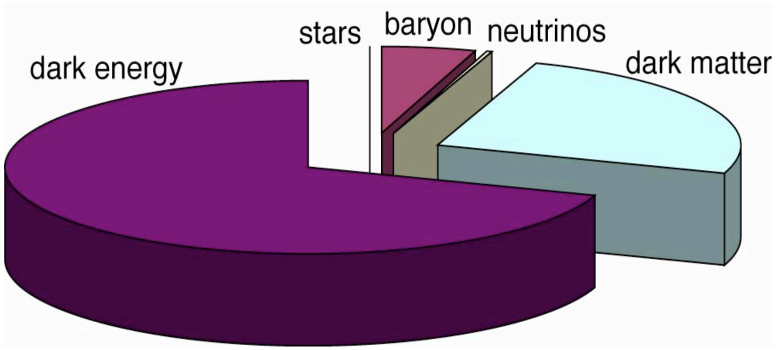


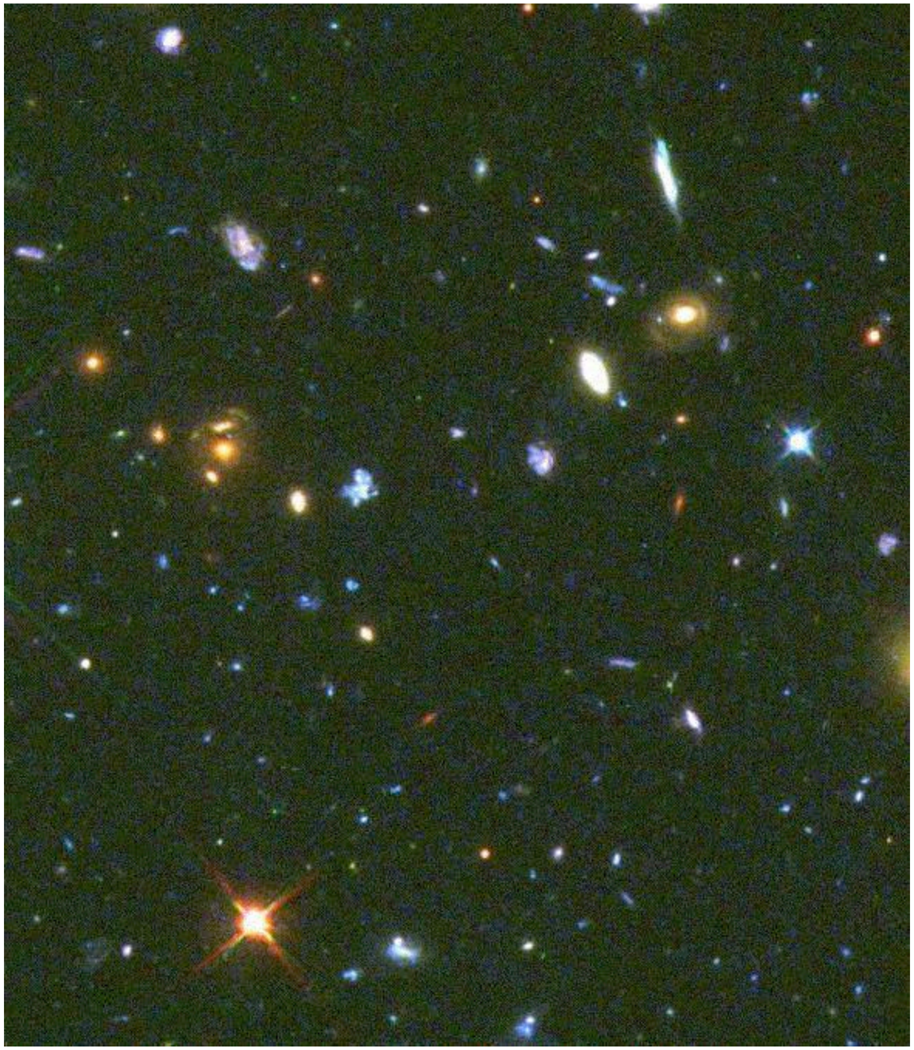


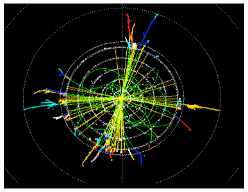


Cosmic connections

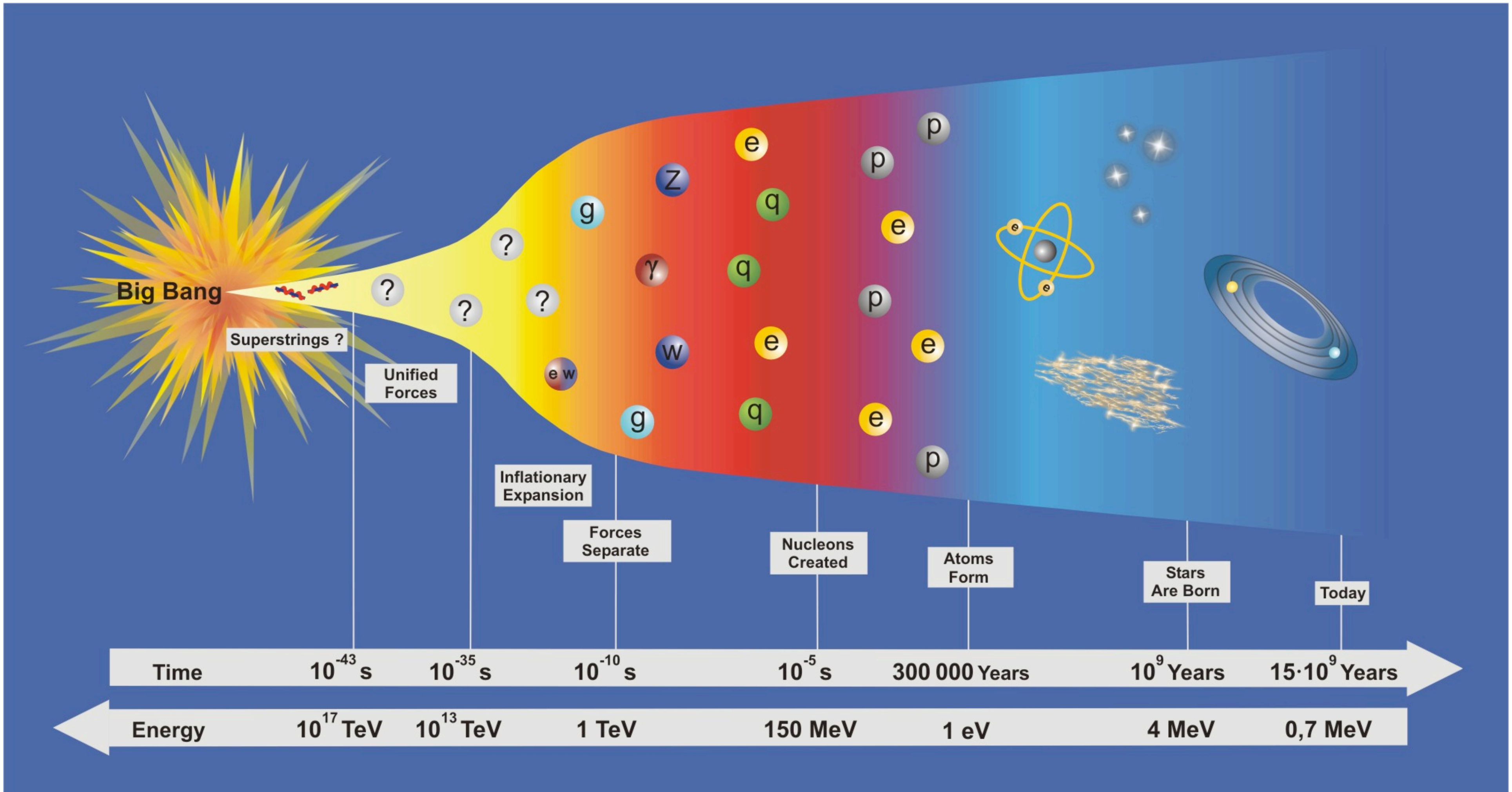
- Early universe
- GUT motivated inflation
- Dark matter
- Accelerating universe
- Dark energy
- What happened to the anti-matter?





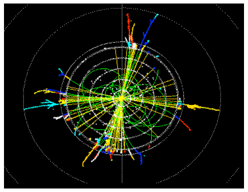


History of the Universe



extrapolation via
precision measurement

LHC, ILC
RHIC,HERA

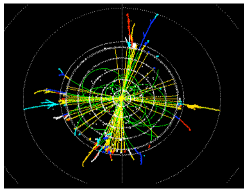


Detector Requirements are defined by
- **ILC machine parameters**
- **physics goals**

ILC creates new challenges and opportunities,
different in many respects from the challenges and opportunities of the LHC detectors

Physics motivates
- Triggerless event collection (software event selection)
- Extremely precise vertexing
- Synergistic design of detectors components:
  - vertex detector, tracker, calorimeters integrated for optimal jet reconstruction
- Advanced technologies based on recent detector innovations

Detector R&D to optimize ILC opportunity is critically needed



ILC Experimental Advantages

Elementary interactions at known E_{cm}*

eg. $e^+e^- \rightarrow$ Z H * beamstrahlung manageable

Democratic Cross sections

eg. $\sigma(e^+e^- \rightarrow ZH) \sim 1/2\ \sigma(e^+e^- \rightarrow d\,\bar{d})$

Inclusive Trigger

total cross-section

Highly Polarized Electron Beam

~ 80% (positron polarization? – R&D)

Exquisite vertex detection

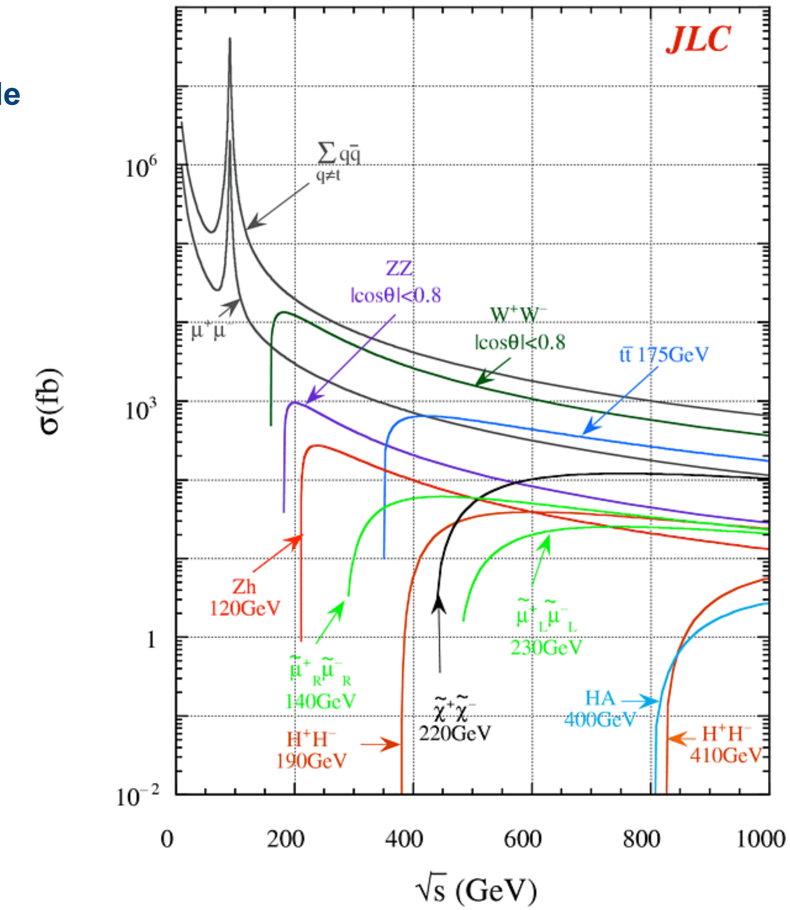
eg. $R_{beampipe} \sim 1$ cm and $\sigma_{hit} \sim 3\ \mu m$

Calorimetry with Particle Flow Precision

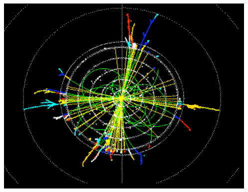
$\sigma_E/E_{jet} \sim 3\%$ for $E_{jet} > 100$ GeV

Advantage over hadron collider on precision meas.

eg. $H \rightarrow c\,\bar{c}$

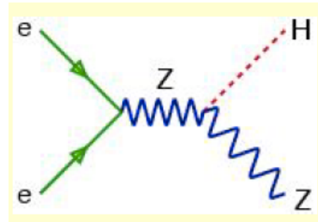


Detector performance translates directly into effective luminosity

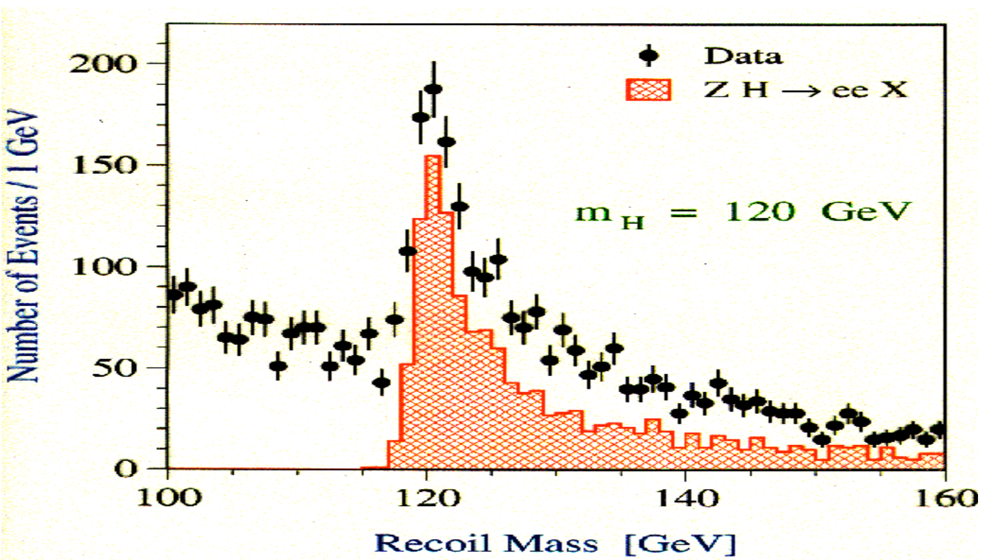


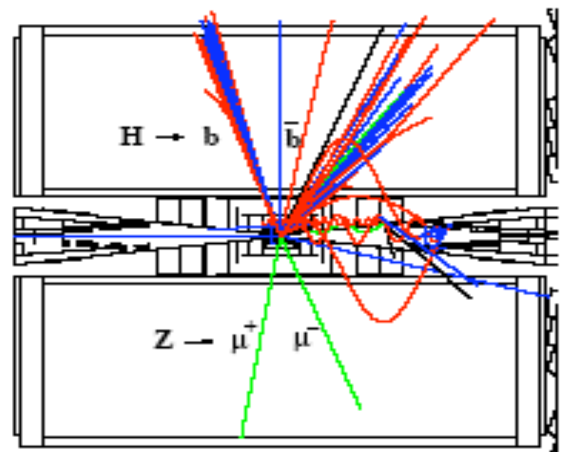
Power of Constrained Initial State + Simple Reactions

- •Well defined initial state
- •Democratic interactions



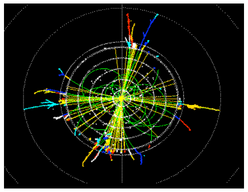
Higgs recoiling from a Z, with known CM energy⇓, provides a powerful channel for unbiassed tagging of Higgs events, allowing measurement of <u>even invisible decays</u> (⇓ - some beamstrahlung)





Demands Precise Tracking

500 fb^{-1} @ 500 GeV, TESLA TDR, Fig 2.1.4

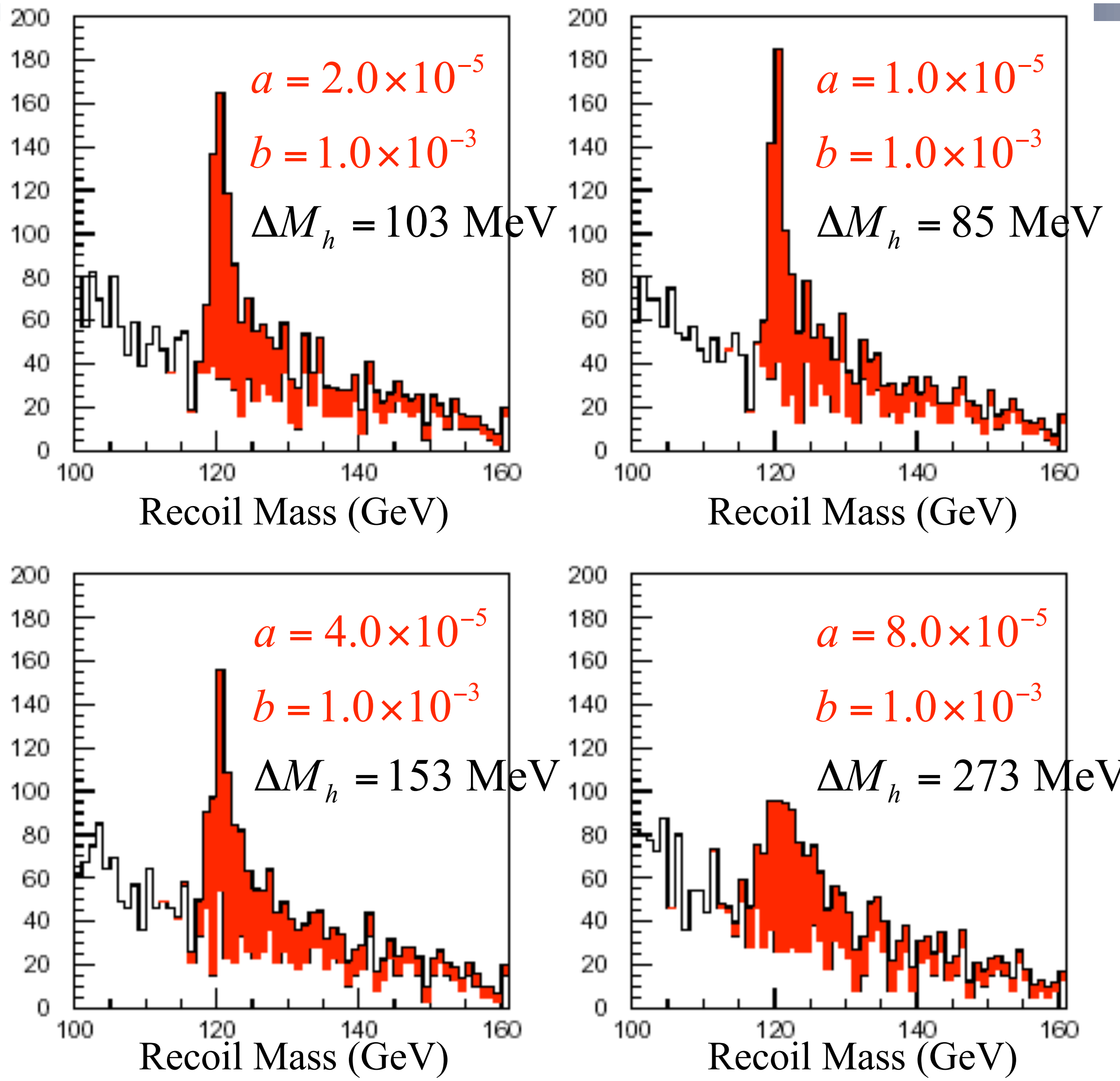


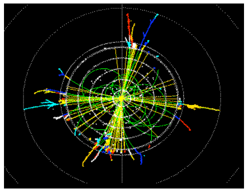
Effect of Tracking Resolution

$$e^+e^- \rightarrow ZH$$
$$\rightarrow \mu^+\mu^- X$$

$$\sqrt{s} = 350\ GeV$$
$$L = 500\ fb^{-1}$$

$$\frac{\delta p_t}{p_t^2} = a \oplus \frac{b}{p_t \sin\theta}$$





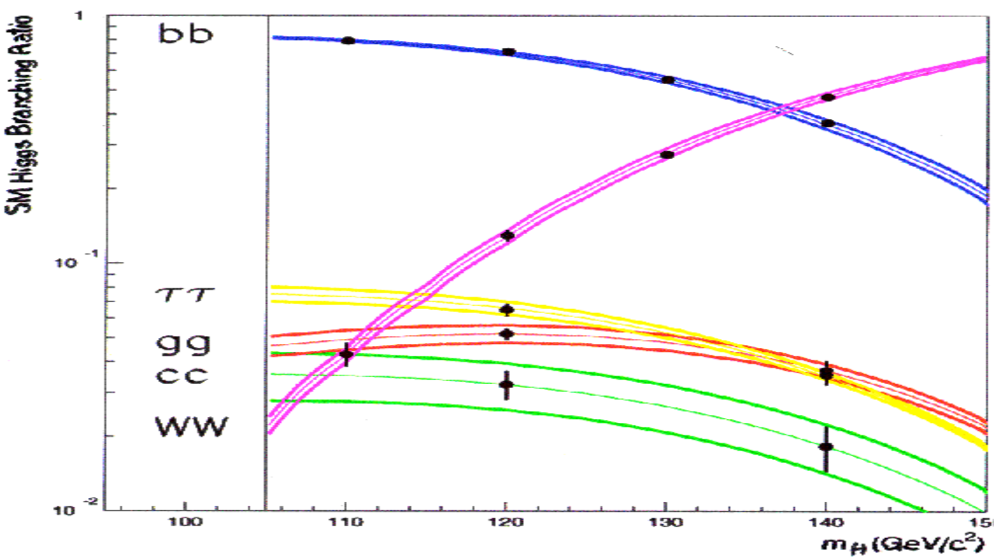
The Electroweak Precision Measurements Anticipate a Light Higgs – Then What?

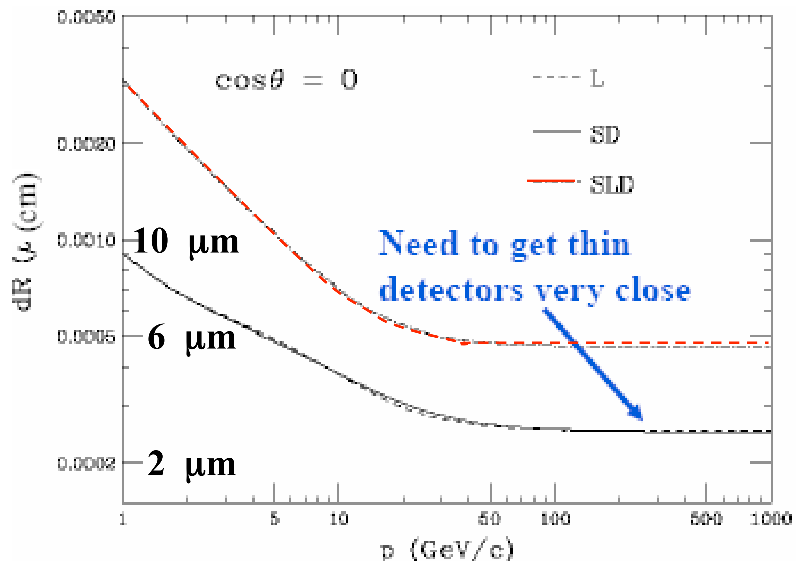
- Measurement of BR's is powerful indicator of new physics

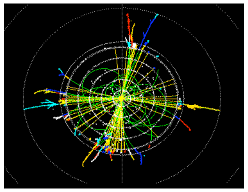
  e.g. in MSSM, these differ from the SM in a characteristic way.

- Higgs BR must agree with MSSM parameters from many other measurements.

Vertex Detector Impact Parameter Resolution







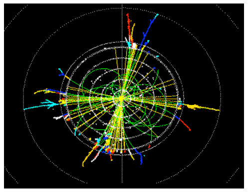
Detector R&D Required

- Performance requirements for ILC Detector exceed state-of-the-art
  - Calorimeters with ~100 million cells being developed for PFA
    - Jet resolution goal ~ 3-4% for Ejet > 100 GeV
  - Pixel Vertex Detector with ~10^9 ≤20 μm pixels
    - Impact parameter resolution 5 μm $\oplus$ 10μm/(p $\sin^{3/2}\theta$)
    - Sensitivity to full 1 msec bunchtrain
  - Tracking resolution $\sigma(1/p) \leq 5\times10^{-5}$ /GeV
    - TPC with silicon
    - Silicon microstrips
  - High Field Solenoid up to 5 Tesla
  - High quality forward tracking systems
  - Triggerless readout

- R&D Essential

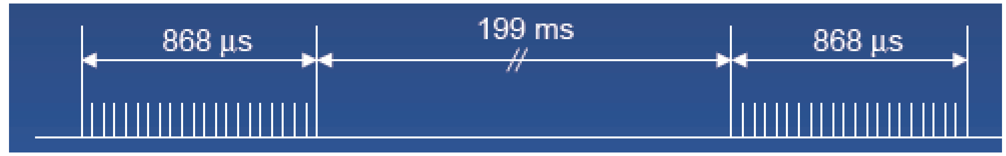
DISCOVERY OPPORTUNITY IS GREAT

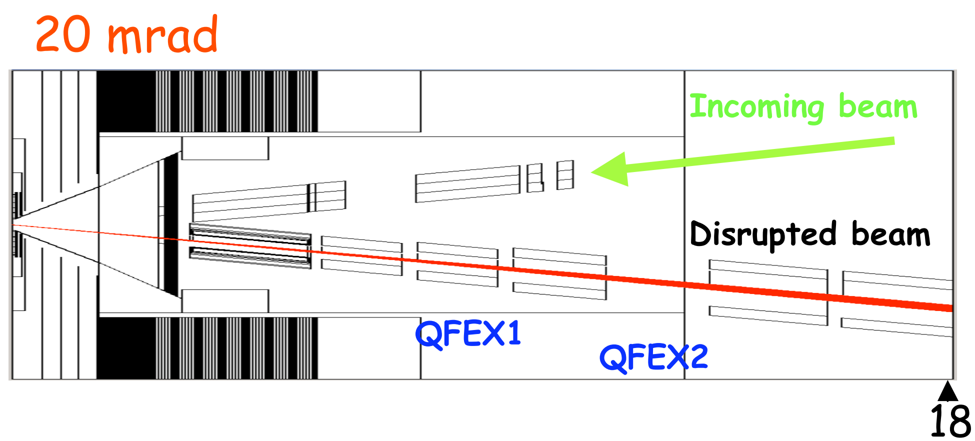
- limited by detector performance
  small cross sections/significant backgrounds
- advances different from LHC required

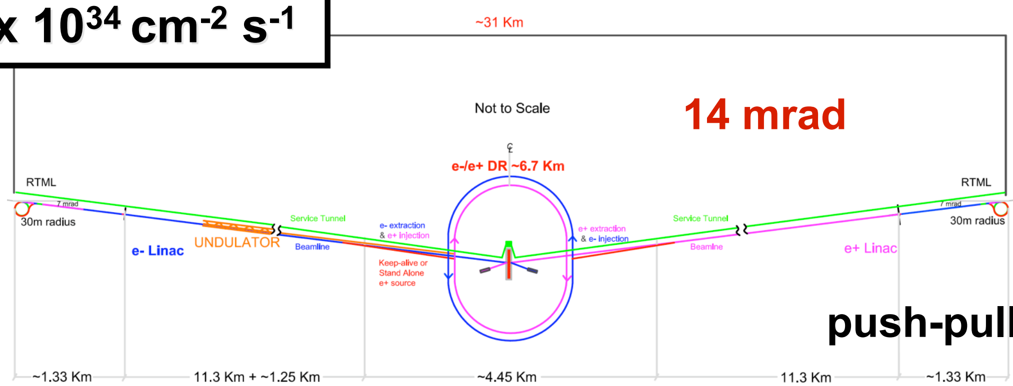


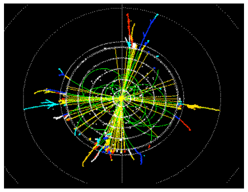
Collider Parameters

Machine parameter	Value (approx.)
#bunches/train	2820
#trains/sec	5
bunch spacing	308 nsec
bunches/sec	14100
length of train	868 μsec
train spacing	199 msec
crossing angle	14 mrad
Luminosity	2 x 10^{34} cm^{-2} s^{-1}









Background Sources

IP Backgrounds

- Beam-beam Interactions
  - Disrupted primary beam
    - Extraction line losses
  - Beamstrahlung photons
  - e+e- pairs
- Radiative Bhabhas
- $\gamma\gamma \rightarrow$ hadrons/μ+μ-

Somewhat manageable -

- Scale with luminosity
- Transport them away from IP
- Shield sensitive detectors
- Exploit detector timing

- Reliable simulations.

Machine backgrounds

- Muon production at collimators
- Collimator edge scattering
- Beam-gas
- Synchrotron radiations
- Neutrons from dumps/extr. line

Harder to handle -

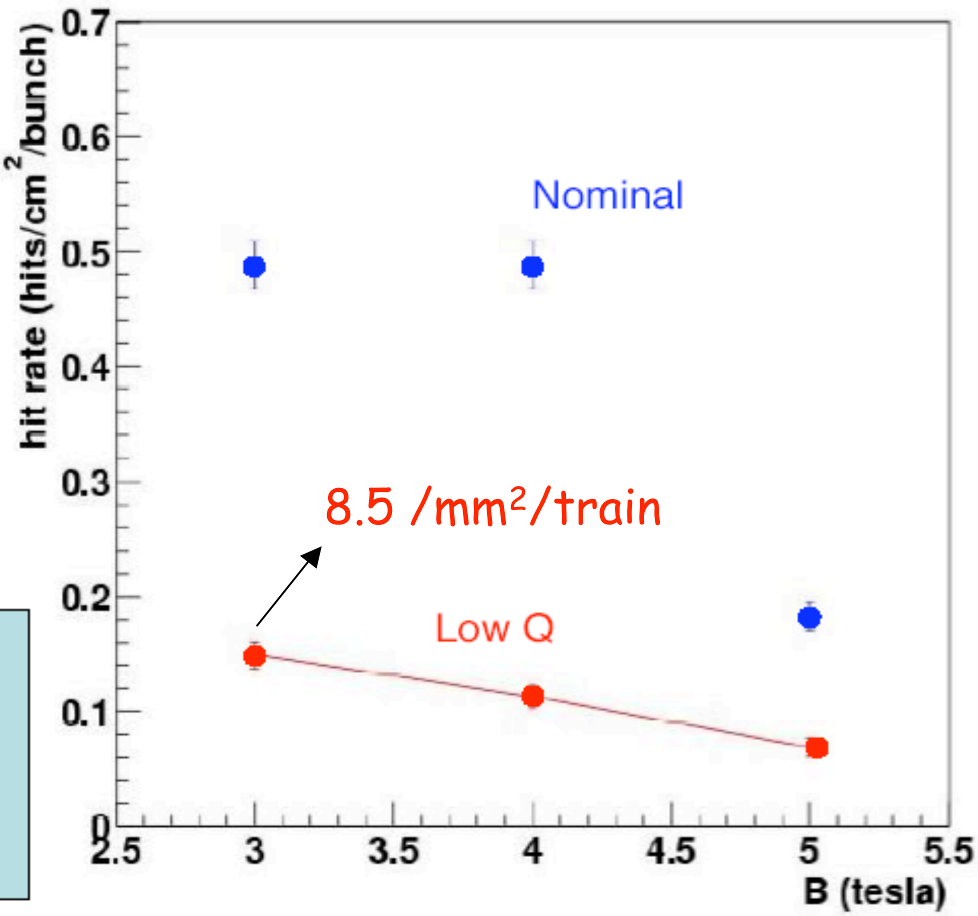
- Don't make them
- Keep them from IP if you do

- Dominated by beam halo
- Dependent on assumptions

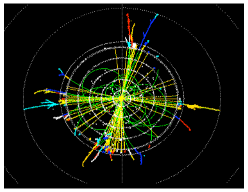
VXD background hits

- Pair background hit rate on the 1st layer of the Vertex Detector (R=24mm)
- Simulation using CAIN and JUPITER
- Hit rate of the Low Q option is ~1/3 of the nominal option, as expected

Pair B.G. hit rate (/cm^2/bunch)		
B(tesla)	Nominal	LowQ
3	0.488	0.149
4	0.48	0.113
5	0.183	0.069

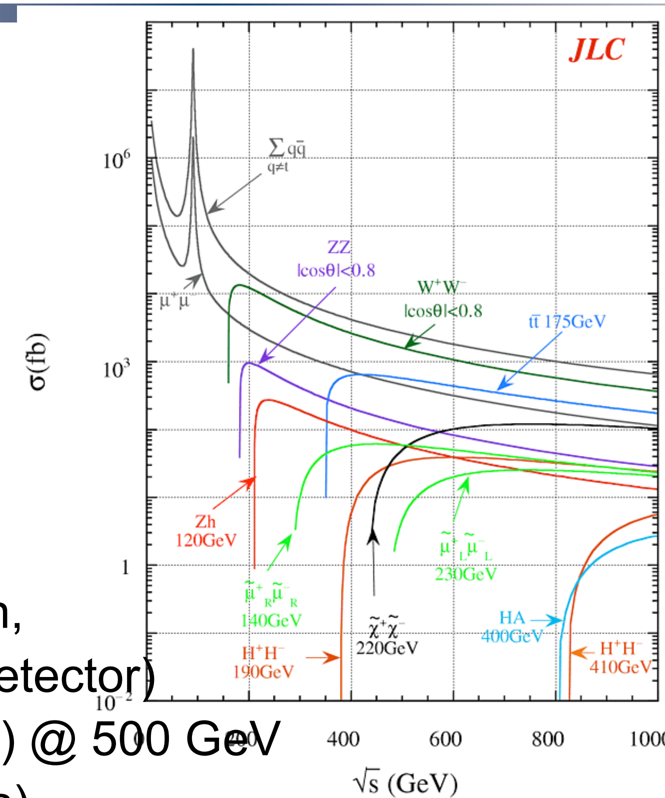


GLD study



Event Rates and Backgrounds

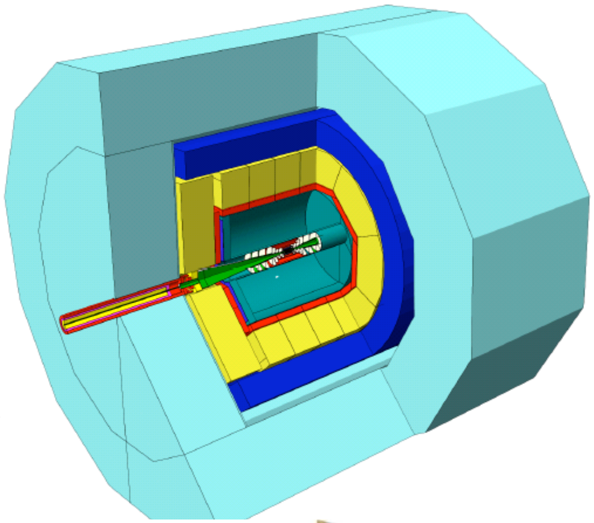
- **Event rates (Luminosity = 2 x 10^{34})**
  - $e^+e^- \rightarrow$ qq, WW, tt, HX
    - **~ 0.1 event / train**
  - $e^+e^- \rightarrow e^+e^- \gamma\gamma \rightarrow e^+e^-$ X
    - **~ 200 /train**



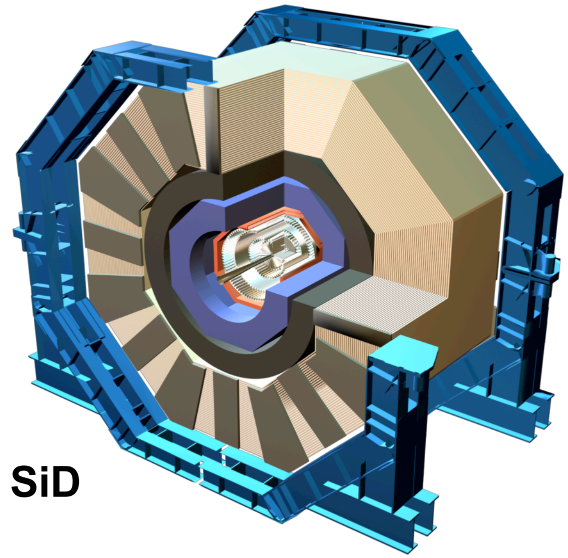
- **Background**
  - 6 x 10^{10} γ / BX (from synchrotron radiation, scatters into central detector)
  - 40,000-250,000 e^+e^- / BX (90-1000 TeV) @ 500 GeV
  - Muons: < 1 Hz/cm^2 (w/ beamline spoilers)
  - Neutrons: ~3 x 10^8 /cm^2/ yr @ 500 GeV

Ref: Maruyama, Snowmass 2005

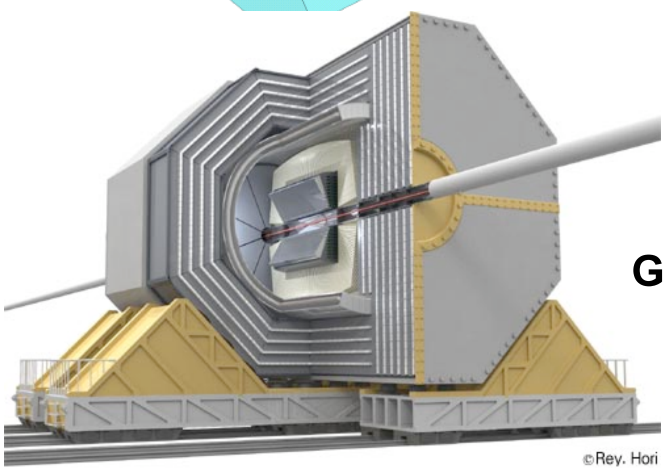
The Concepts



LDC

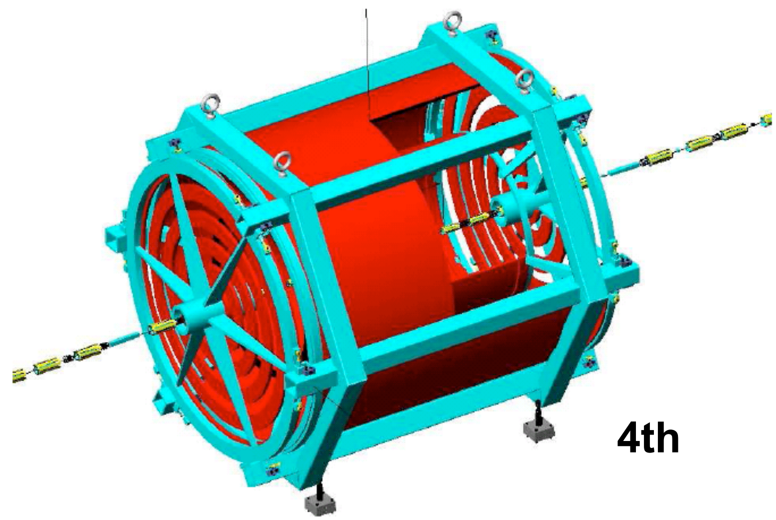


SiD

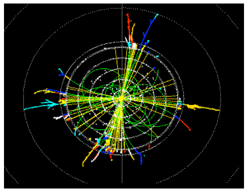


GLD

Teams working on LDC and GLD are in the process of merging → ILD

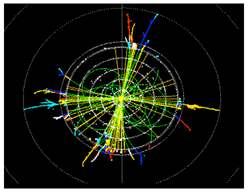


4th



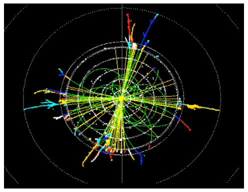
ILC Detector Requirements

- Two-jet mass resolution comparable to the natural widths of W and Z for an unambiguous identification of the final states.
- Excellent flavor-tagging efficiency and purity (for both b- and c-quarks, and hopefully also for s-quarks).
- Momentum resolution capable of reconstructing the recoil-mass to di-muons in Higgs-strahlung with resolution better than beam-energy spread.
- Hermeticity (both crack-less and coverage to very forward angles) to precisely determine the missing momentum.
- Timing resolution capable of separating bunch-crossings to suppress overlapping of events .



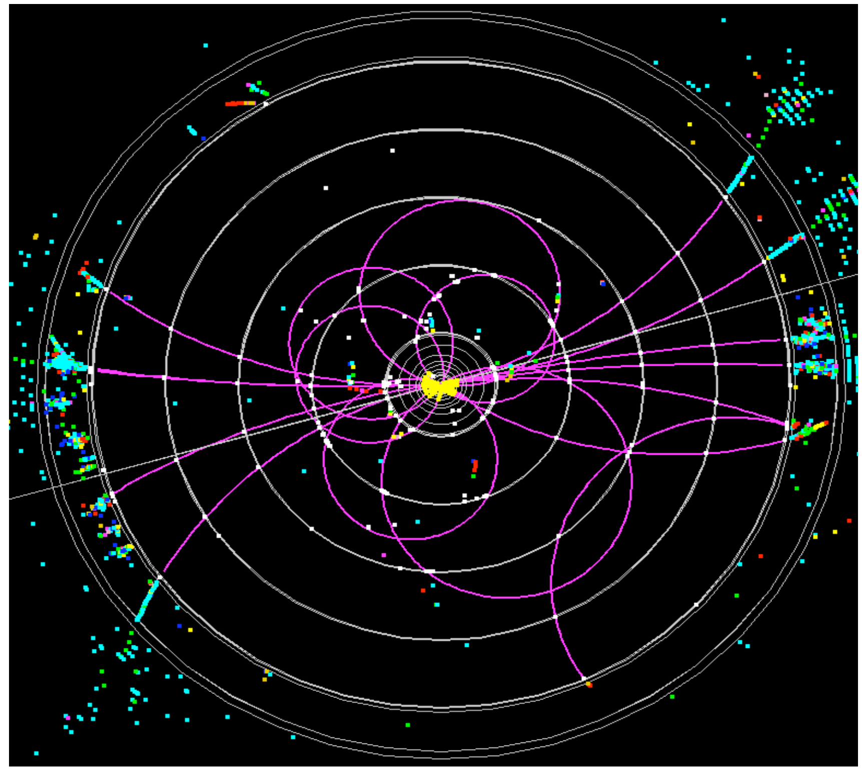
The Concepts

		Tracking	ECal Inner Radius	Solenoid	EM Cal	Hadron Cal	Other
	SiD	silicon	1.27 m	5 Tesla	Si/W	Digital (RPC..)	Had cal inside coil
ILD	LCD	TPC gaseous	1.58 m	4 Tesla	Si/W	Digital or Analog	Had cal inside coil
ILD	GLD	TPC gaseous	2.1 m	3 Tesla	W/ Scin.	Pb/ Scin.	Had cal inside coil
	4th	TPC gaseous	1.5 m	3.5 Tesla	crystal	Dual readout fiber	Double Solenoid (open mu)

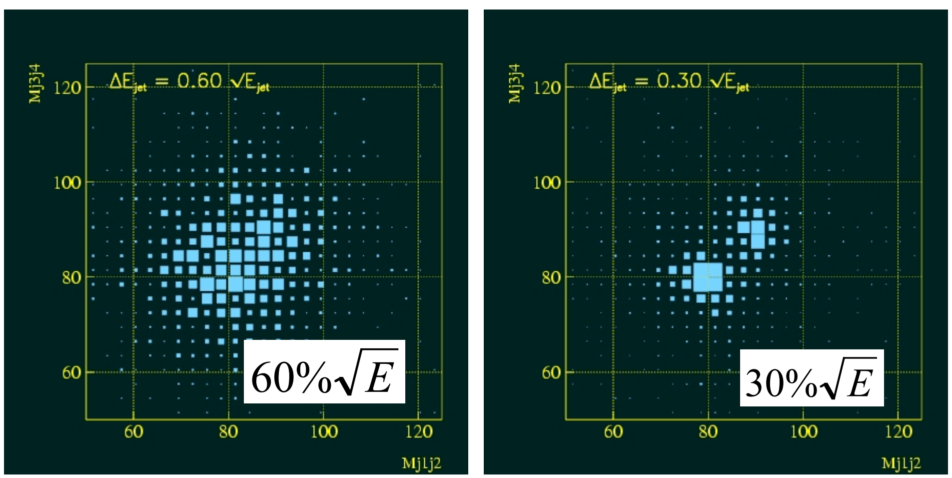


Linear Collider Events

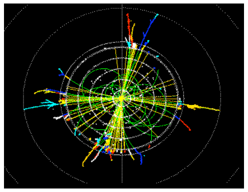
- Simple events (relative to Hadron collider) make particle level reconstruction feasible
- Heavy boson mass resolution requirement sets jet energy resolution goal



$e^+e^- \rightarrow WW\nu\bar{\nu}$, $e^+e^- \rightarrow ZZ\nu\bar{\nu}$



This event shows single bunch crossing in tracker, 150 bunches in the vertex detector

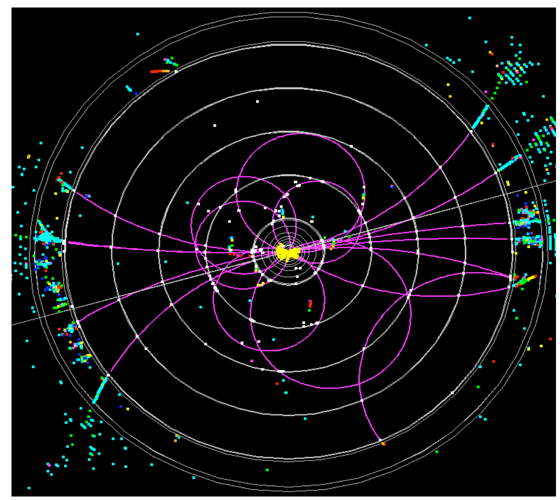


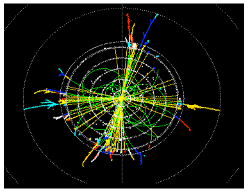
Example Concept - SiD (the Silicon Detector)

CALORIMETRY IS THE STARTING POINT IN THE SiD DESIGN

<u>assumptions</u>

- Particle Flow Calorimetry will result in the best possible performance
- Silicon/tungsten is the best approach for the EM calorimeter
- Silicon tracking delivers excellent resolution in smaller volume
- Large B field (5 Tesla) desirable to contain electron-positron pairs in beamline
- Cost is constrained

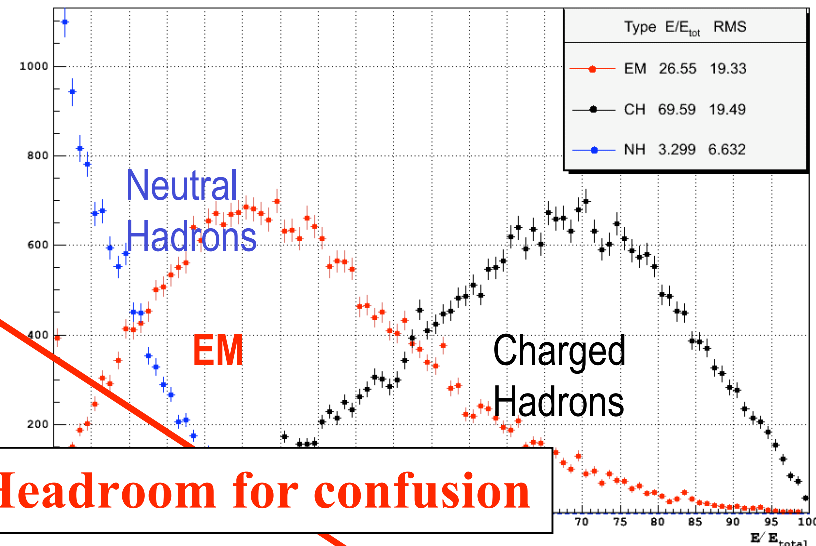




Calorimetry

Current paradigm: Particle Flow

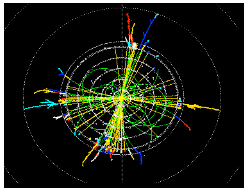
- Jet resolution goal is 30%/√E
- In jet measurements, use the excellent resolution of tracker, which measures bulk of the energy in a jet



Headroom for confusion

Particles in Jet	Fraction of Visible Energy	Detector	Resolution
Charged	~65%	Tracker	< 0.005% p_T negligible
Photons	~25%	ECAL	~ 15% / √E
Neutral Hadrons	~10%	ECAL + HCAL	~ 60% / √E

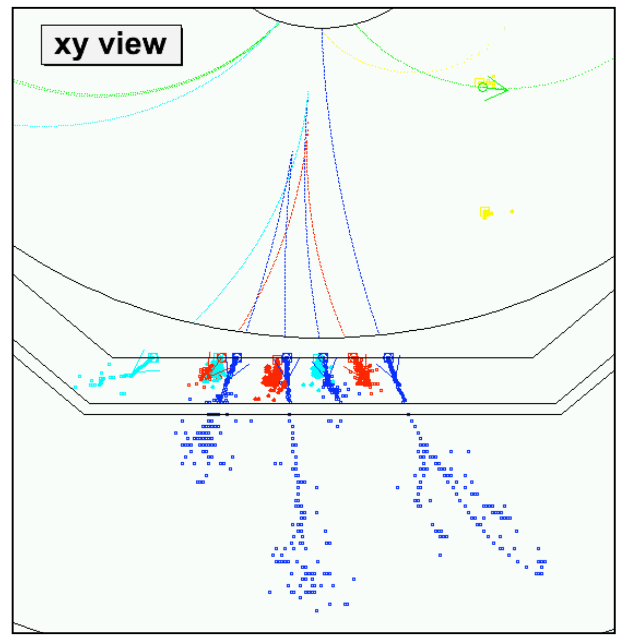
< 20% / √E

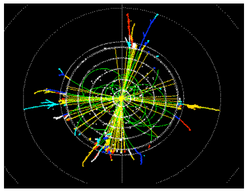


EM Calorimetry

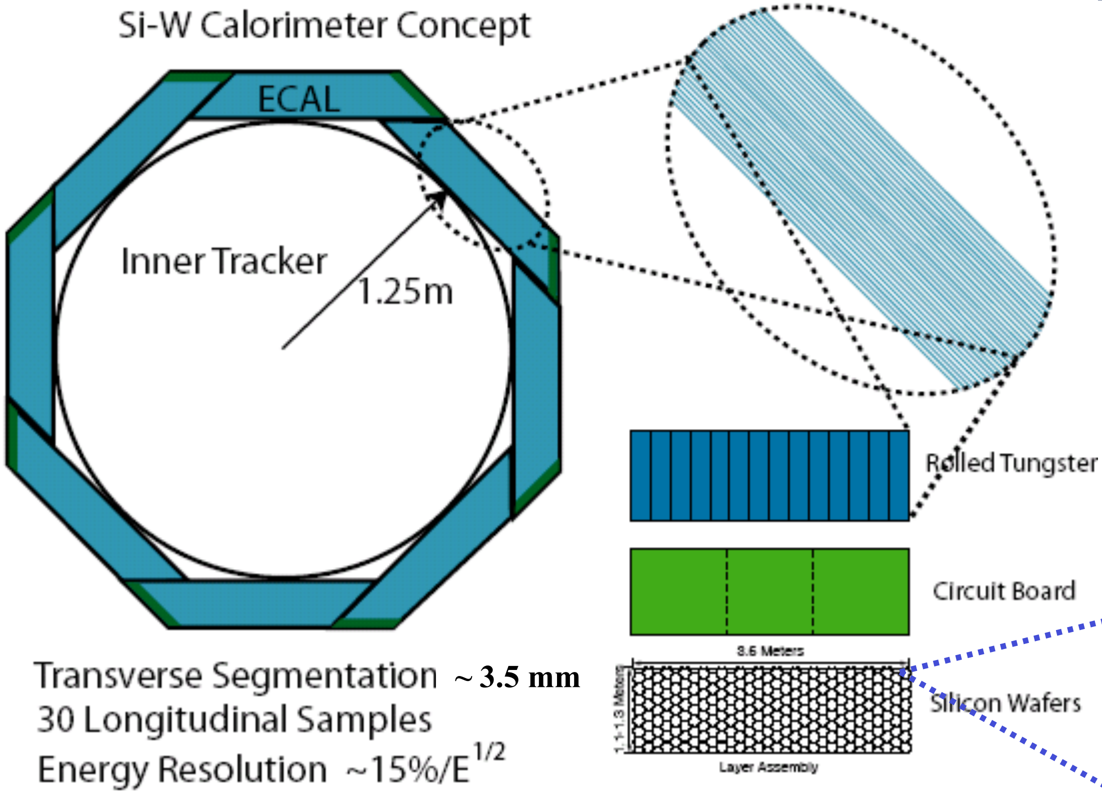
- Physics with isolated electron and gamma energy measurements require ~10-15% / $\sqrt{E} \oplus$ 1%
- Particle Flow Calorimetry requires fine grained EM calorimeter to separate neutral EM clusters from charged tracks entering the calorimeter
  - **Small Moliere radius**
    - Tungsten
  - **Small sampling gaps – so not to spoil R_M**
  - **Separation of charged tracks from jet core helps**
    - Maximize BR^2
  - **One technology choice – Si/W calorimeter**
    - Good success using Si/W for Luminosity monitors at SLD, DELPHI, OPAL, ALEPH
    - Oregon/SLAC/BNL/Davis/Annecy
    - CALICE Si/W
  - **Another choice - Scintillator sampling**

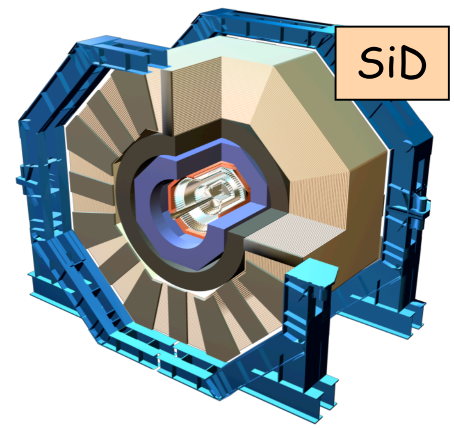
material	R_M
Iron	18.4 mm
Lead	16.5 mm
Tungsten	9.5 mm
Uranium	10.2 mm

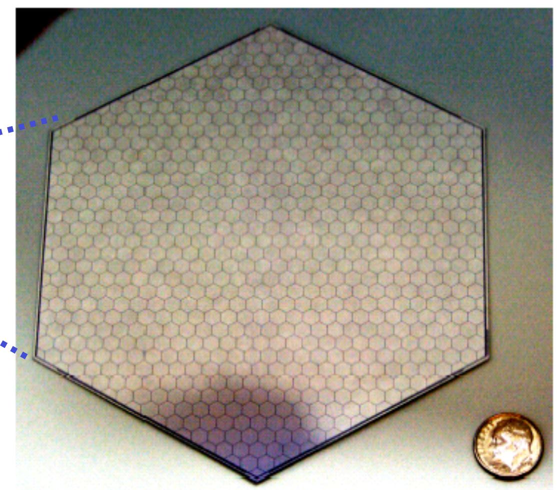




Silicon/Tungsten EM Calorimeter



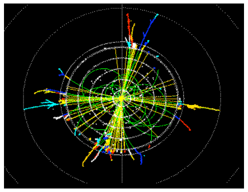




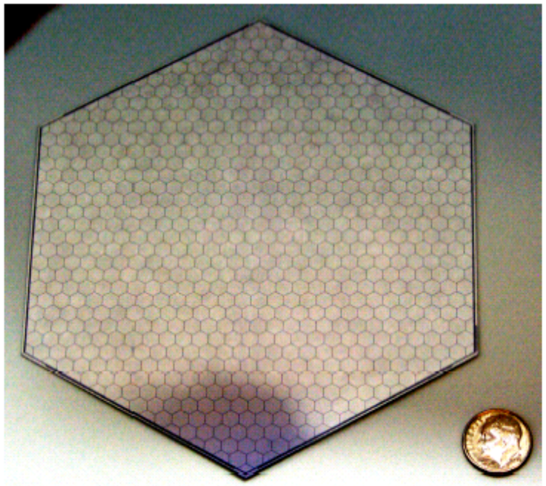
SLAC/Oregon/BNL/Davis/Annecy

(proposed at Snowmass 1996 - JB, A. Arodzero, D. Strom: Proceedings - 1996 DPF/DPB Summer Study, pg. 437 (1997))

Si/W also being developed by CALICE Collaboration



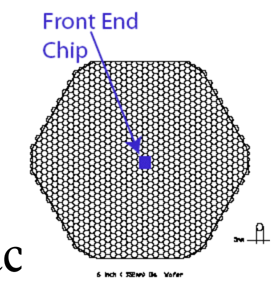
Silicon/Tungsten EM Calorimetry for ILC



SLAC/Oregon/BNL/Davis/Annecy

Dense, fine grained silicon tungsten calorimeter (builds on SLC/LEP experience)

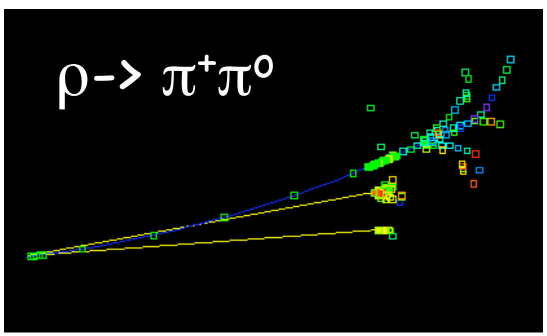
- Pads: 12 mm^2 to match Moliere radius ($\sim R_m/4$)
- Each six inch wafer read out by one chip
- < 1% crosstalk

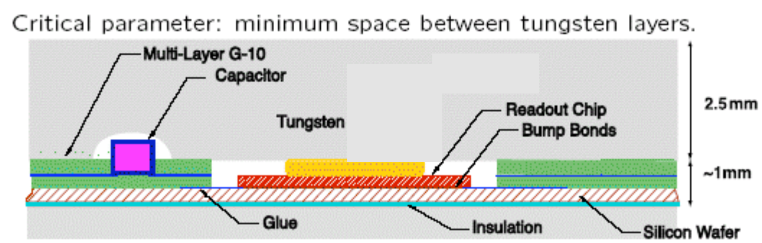


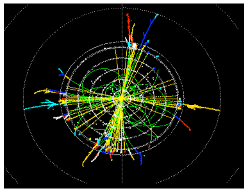
Electronics design

- Noise < 2000 electrons
- Single MIP tagging (S/N ~ 7)
- Dynamically switchable feedback capac scheme achieves required dynamic range: 0.1-2500 MIPs – 4 deep storage/bunch train

Passive cooling – conduction in W to edge

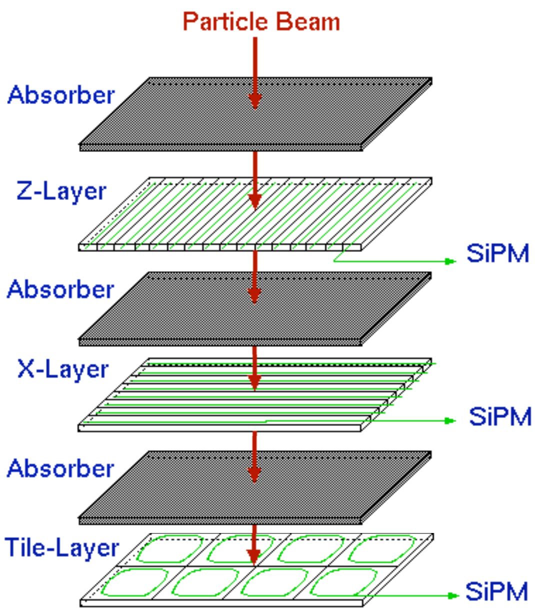




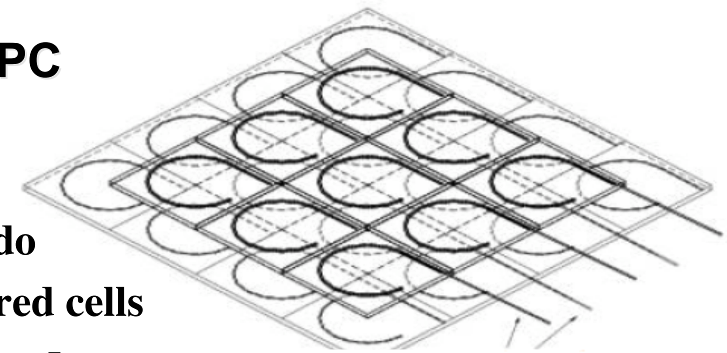


Scintillator/Tungsten ECAL

- Cheaper and larger granularity (3x3 - 5x5cm^2)
- Scintillator strips may be cost-effective way for granularity
  - (1cm x Ycm)
- Read out by fibre + PMT or SiPM/MPPC



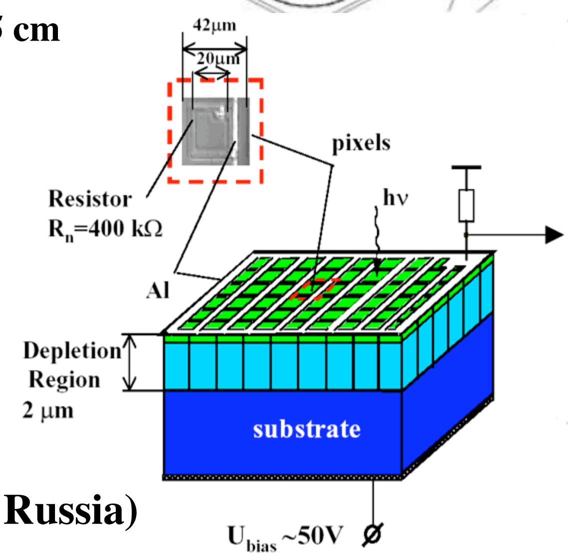
Japan/Korea/Russia



Colorado

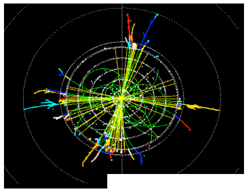
-staggered cells

5 cm x 5 cm



SiPMs

(invented in Russia)



Hadron Calorimeter

Again Highly Segmented – for Particle Flow

M. Thomson

- Longitudinal: ~40 samples
- 4 – 5 λ (limited by cost - coil radius)
- Would like fine (1 cm^2 ?) lateral segmentation
- For 10000 m^2 of 1 cm^2 HCAL = 10^8 channels – cost !

Two Main Options:

★ Tile HCAL (Analogue readout)

Steel/Scintillator sandwich

Lower lateral segmentation

~ 3x3 cm^2 (motivated by cost)

★ Digital HCAL

High lateral segmentation

~ 1x1 cm^2

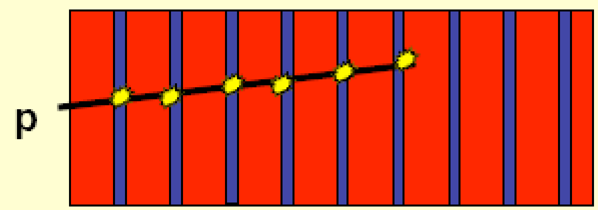
digital readout (granularity)

RPCs, wire chambers, GEMS…

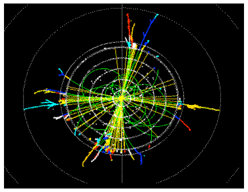
OPEN QUESTION

The Digital HCAL Paradigm

- Sampling Calorimeter:
  Only sample small fraction of the total energy deposition



- Energy depositions in active region follow highly asymmetric Landau distribution

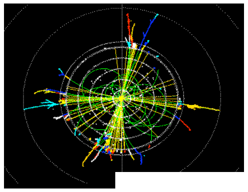


Hadron Calorimetry (~4λ)

Options for Digital HCal: SS or Tungsten / 3 readout technologies

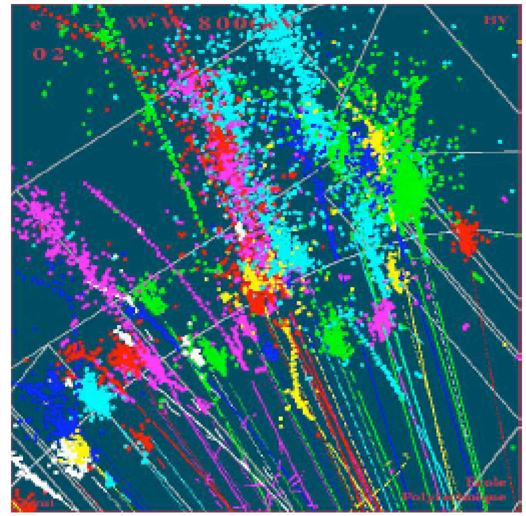
	Scintillator	GEMs	RPCs
Technology	**Proven (SiPM?)**	**Relatively new**	**Relatively old**
Electronic readout	**Analog (multi-bit) or Semi-digital (few-bit)**	**Digital (single-bit)**	**Digital (single-bit)**
Thickness (total)	**~ 8mm**	**~8 mm**	**~ 8 mm**
Segmentation	**3 x 3 cm^2**	**1 x 1 cm^2**	**1 x 1 cm^2**
Pad multiplicity for MIPs	**Small cross talk**	**Measured at 1.27**	**Measured at 1.6**
Sensitivity to neutrons (low energy)	**Yes**	**Negligible**	**Negligible**
Recharging time	**Fast**	**Fast?**	**Slow (20 ms/cm^2)**
Reliability	**Proven**	**Sensitive**	**Proven (glass)**
Calibration	**Challenge**	**Depends on efficiency**	**Not a concern (high efficiency)**
Assembly	**Labor intensive**	**Relatively straight forward**	**Simple**
Cost	**Not cheap (SiPM?)**	**Expensive foils**	**Cheap**

J. Repond



Calorimeter Reconstruction

- ★ High granularity calorimeters – **very different** to previous detectors (except LEP lumi. calorimeters)
- ★ "Tracking calorimeter" – requires a new approach to ECAL/HCAL reconstruction



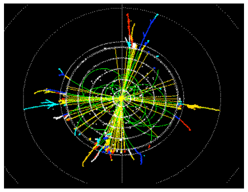
+PARTICLE FLOW

- ★ ILC calorimetric performance = HARDWARE + SOFTWARE
- ★ Performance will depend on the software algorithm

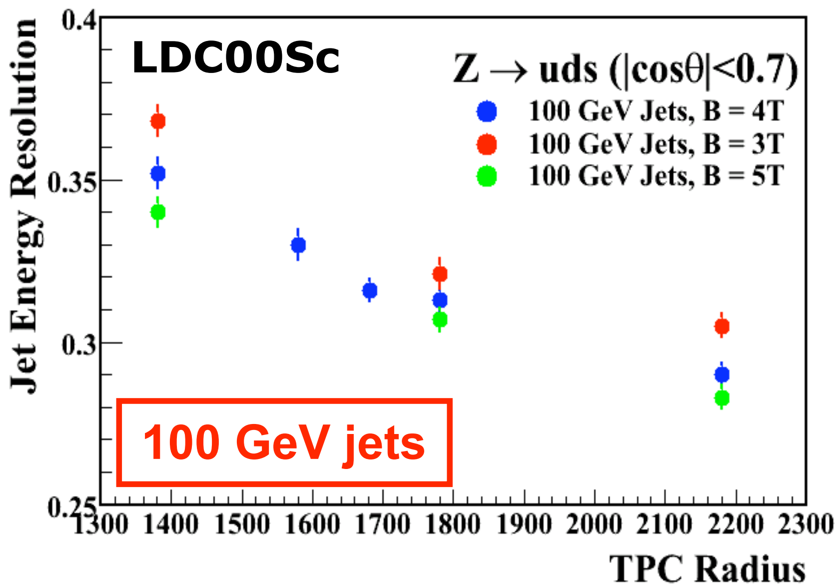
➡ Nightmare from point of view of detector optimisation

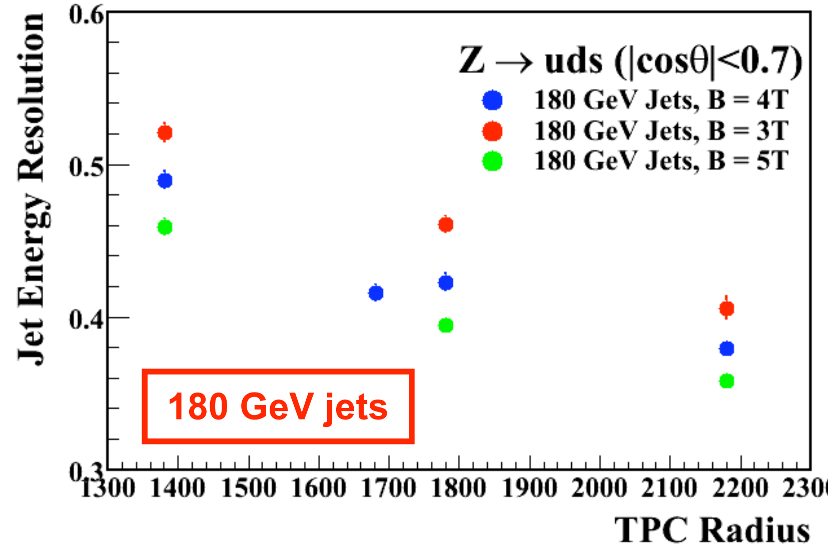
- ★ *a priori* not clear what aspects of hadronic showers are important (i.e. need to be well simulated)

M. Thomson



Radius vs. Field





★ LDC Jet energy performance found to depend mainly on:
- HCAL thickness
- TPC Radius
- B-field

100 GeV Jets

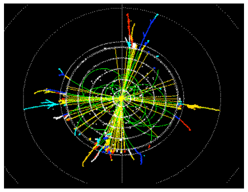
$$\alpha = 0.315 \left(\frac{B}{4}\right)^{-0.19} \left(\frac{R}{1.68}\right)^{-0.49} (1 + 6.3e^{-\frac{N}{8.0}})$$

180 GeV Jets

$$\alpha = 0.42 \left(\frac{B}{4}\right)^{-0.31} \left(\frac{R}{1.78}\right)^{-0.61} (1 + 21.6e^{-\frac{N}{7.1}})$$

← **Empirical Parametrizations**

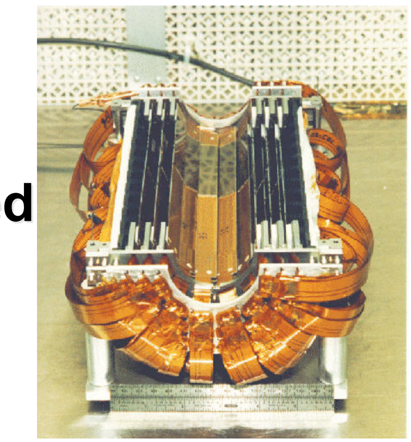
M. Thomson



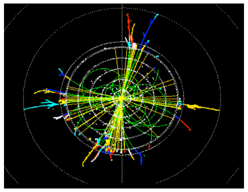
Tracking

- Tracking for any modern experiment should be conceived as an integrated system, combined optimization of:
  - the inner tracking (vertex detection)
  - the central tracking
  - the forward tracking
  - the integration of the high granularity EM Calorimeter

- Pixelated vertex detectors are capable of track reconstruction on their own, as was demonstrated by the 307 Mpixel CCD vertex detector of SLD, and is being planned for the ILC



- Track reconstruction in the vertex detector impacts the role of the central and forward tracking system



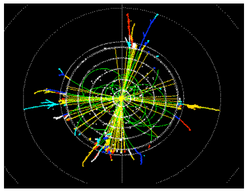
Inner Tracking/Vertex Detection for the ILC

Detector Requirements

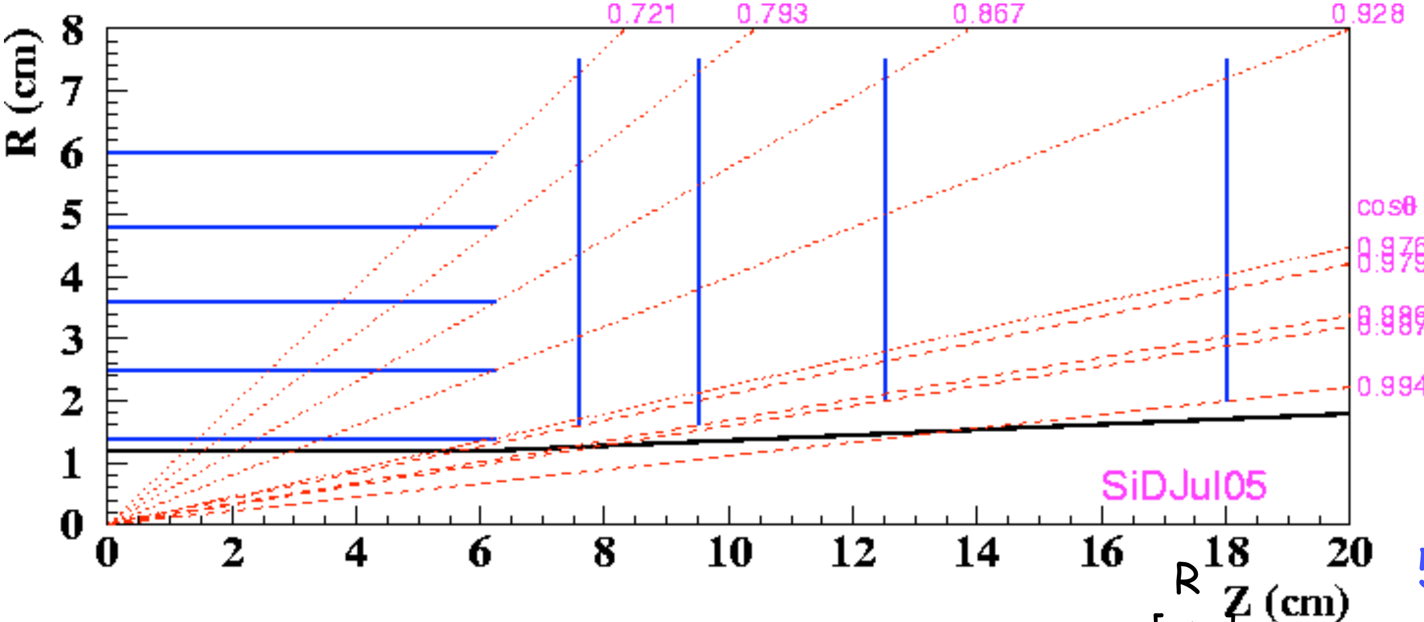
- Excellent spacepoint precision (**< 4 microns**)
- Superb impact parameter resolution (**$5\mu m \oplus 10\mu m/(p \sin^{3/2}\theta)$**)
- Transparency **(~0.1% X_0 per layer**)
- Track reconstruction (**find tracks in VXD alone**)
- Sensitive to acceptable number of bunch crossings (**<150 = 45 μsec**)
- EMI immunity
- Power Constraint **(< 100 Watts**)

Concepts under Development for International Linear Collider

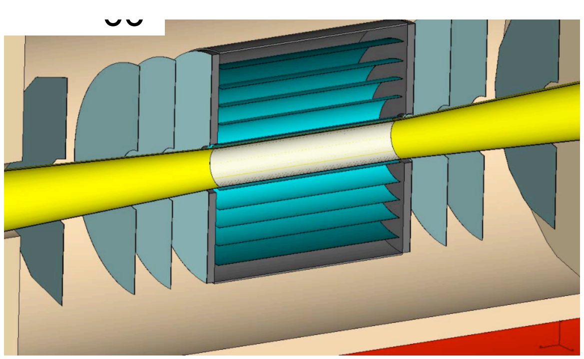
- Charge-Coupled Devices (CCDs)
  - demonstrated in large system (307Mpx) at SLD, but slow ⇒ Column Parallel CCDs, FPCCD
- Monolithic Active Pixels – CMOS
  - MAPs, FAPs, Chronopixels, 3D-Fermilab
- DEpleted P-channel Field Effect Transistor (DEPFET)
- Silicon on Insulator (SoI)
- Image Sensor with In-Situ Storage (ISIS)
- HAPS (Hybrid Pixel Sensors)



SiD Vertex Layout

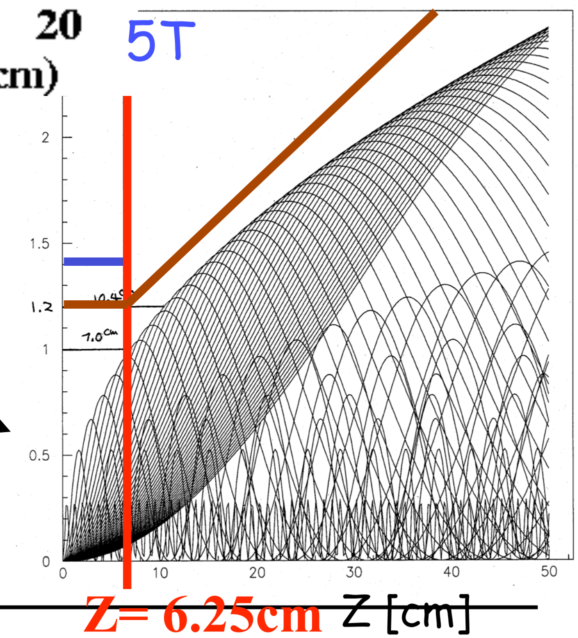


5 barrel layers
4 end disks

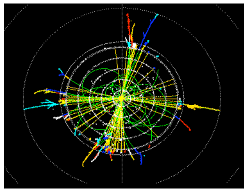


Design drivers:

Smallest radius possible
Clear pair background



Role:
Seed tracks & vertexing
Improve forward region



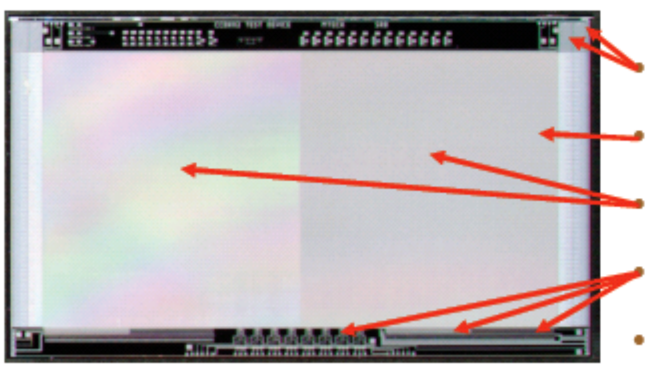
Column Parallel CCD for ILC

SLD Vertex Detector designed to read out
  800 kpixels/channel at 10 MHz, operated at
  5 MHz => readout time = 200 msec/ch

ILC requires faster readout for 300 nsec bunch spacing
  << 1 msec

Possible Solution: Column Parallel Readout

LCFI (Bristol,Glasgow,Lancaster,Liverpool,Nijmegen,Oxford,RAL)

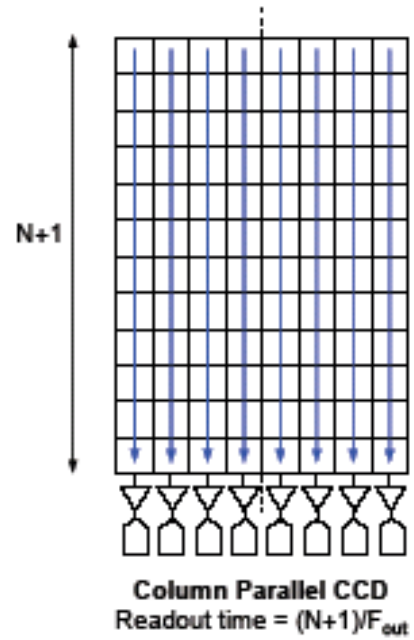


CPC1 produced by E2V

- Two phase operation
- Metal strapping for clock
- 2 different gate shapes
- 3 different types of output
- 2 different implant levels

➢ *Clock with highest frequency at lowest voltage*

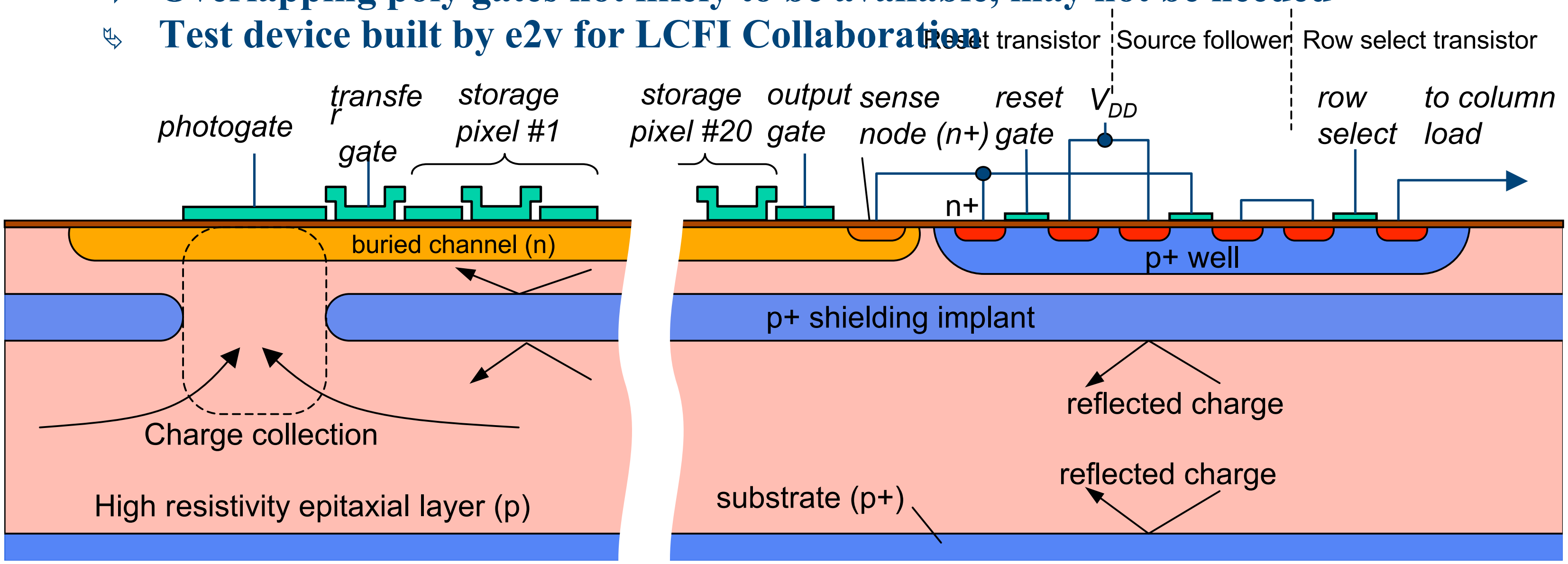
- **Separate amplifier and readout for each column**



(Whereas SLD used one readout channel for each 400 columns)

Image Sensor with In-situ Storage (ISIS)

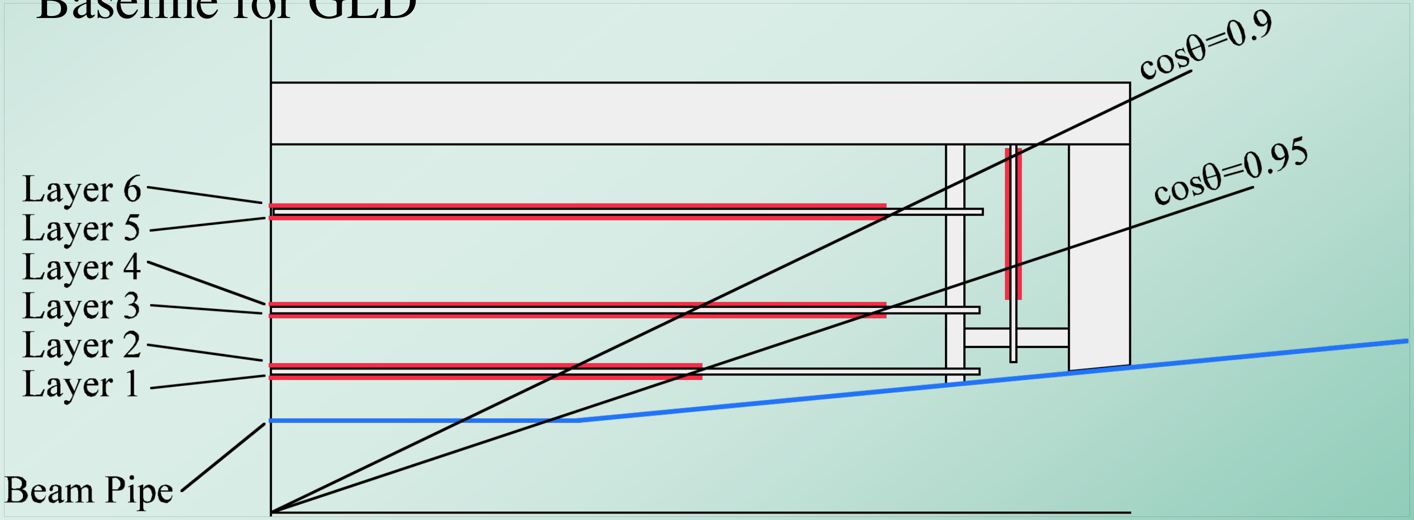
- EMI concern (SLC experience) motivates delayed operation during beam
- Robust storage of charge in buried channel during beam passage
  - Pioneered by W F Kosonocky et al IEEE SSCC 1996, Digest of Technical Papers, 182
  - T Goji Etoh et al, IEEE ED 50 (2003) 144; runs up to 1 Mfps.
- ISIS Sensor details:
  - CCD-like charge storage cells in CMOS or CCD technology
  - Processed on sensitive epi layer
  - p+ shielding implant forms reflective barrier (deep implant)
  - Overlapping poly gates not likely to be available, may not be needed
  - Test device built by e2v for LCFI Collaboration

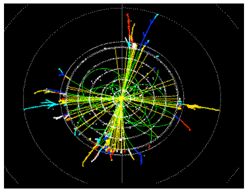


FPCCD (KEK)

- Fine-pixel CCD
  - $(5\mu m)^2$ pixel
  - Fully-depleted to suppress diffusion
  - Immune to EMI
  - CCD is an established technology
  - Baseline for GLD

- Fully-depleted CCD exists (Hamamatsu : astrophys.)
- Background hits can be further reduced by hit pattern (~1/20)
- No known problems now
- Prototyping





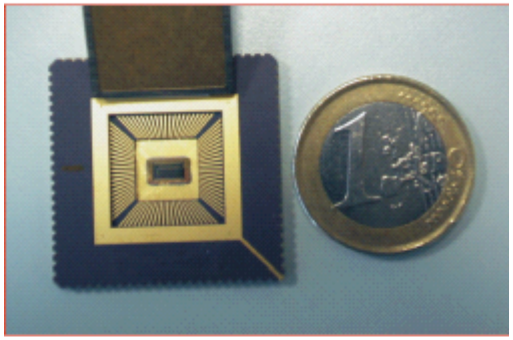
Monolithic CMOS for Pixel Detector

Concept

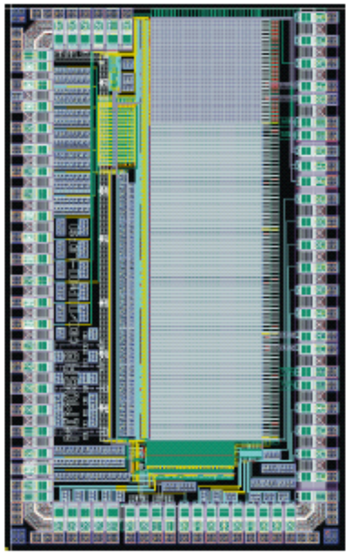
- **Standard VLSI chip, with thin, un-doped silicon sensitive layer, operated undepleted**

Advantages

- **decoupled charge sensing and signal transfer (improved radiation tolerance, random access, etc.)**
- **small pitch (high tracking precision)**
- **Thin, fast readout, moderate price**



MIMOSA VIII

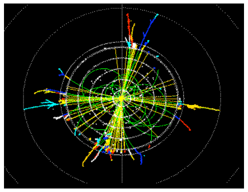


R&D

- Strasbourg IReS has been working on development of monolithic active pixels since 1989; others (RAL, Yale/Or., etc.)
- IReS prototype arrays of few thousands pixels demonstrated viability.
- Large prototypes now fabricated/tested.
- Attention on readout strategies adapted to specific experimental conditions, and transfer to AMS 0.35 OPTO from TSMC 0.25
  - ~< 12 um epi vs. < 7 um
- Application to STAR

Parallel R&D:

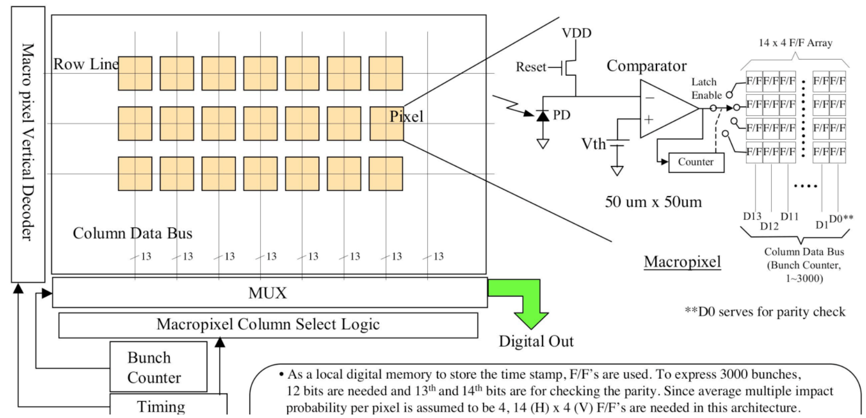
- FAPS (RAL): 10-20 storage caps/pixel

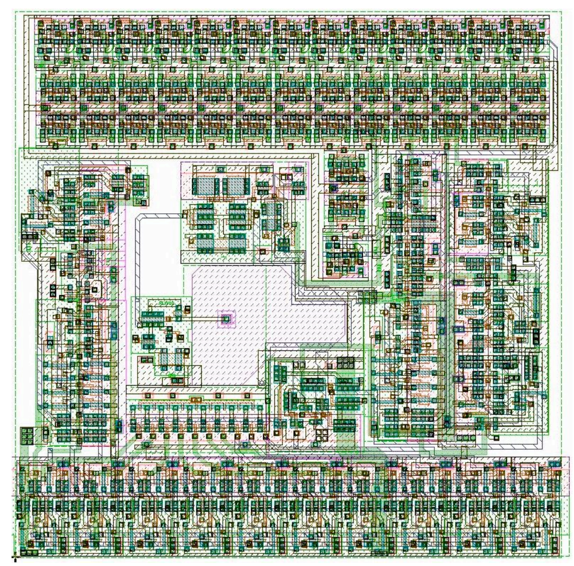


Chronopixel (CMOS)

Yale/Oregon/Sarnoff

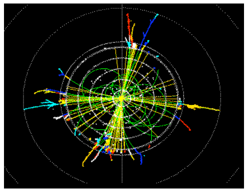
- **Completed Macropixel design last year**
  - ⇒ **Key feature – stored hit times (4 deep)**
  - **645 transistors**
  - **Spice simulation verified design**
  - **TSMC 0.18 μm ⇒ ~50 μm pixel**
    - Epi-layer only 7 μm
    - Talking to JAZZ (15 μm epi-layer)
  - **90 nm ⇒ 20-25 μm pixel**
- **January, 2007**
  - **Completed design - Chronopixel**
  - **Deliverable – tape for foundry**
- **Near Future (dependent on funding)**
  - **Fab 50 μm Chronopixel array**
    - Demonstrate performance
  - **Then, 10-15 μm pixel**





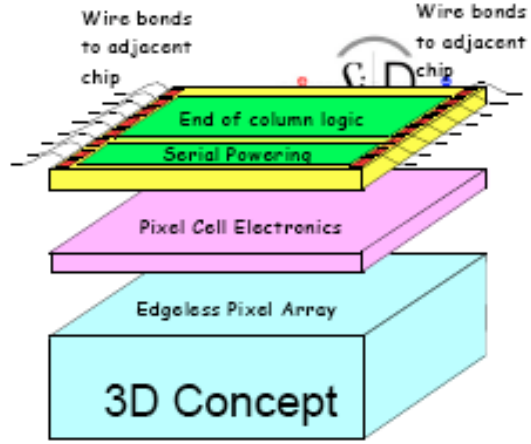
563 Transistors

50 um

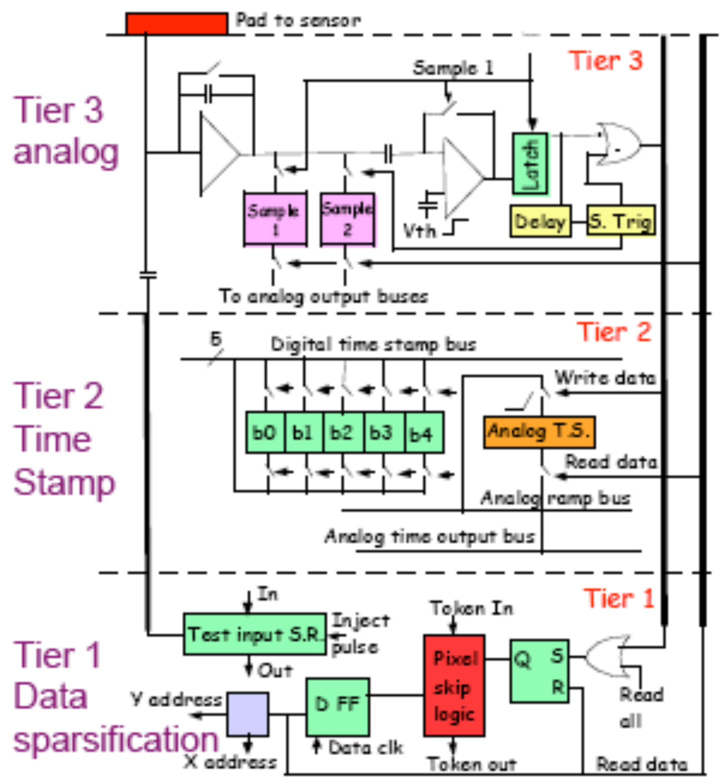


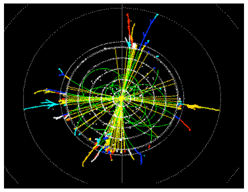
3D/SOI

Fermilab



- Designs based on newly available technologies, separate circuit, detector layers
  - SOI - thin circuit layer on oxide on fully depleted substrate (OKI, ASI(Cypress))
    - 12 bit 26 micron x-ray counting chip OKI/KEK (due soon)
    - ILC pixel readout chip (designed)
  - 3D - multi-layered circuit assembly based on thinned, bonded silicon
    - Full time stamp/double correlated sample in 20 micron pixel, low power
    - Due back in August
  - Thinned sensors - MIT-LL
    - 50, 100 microns thick, 4-side abuttable
  - S/N ~100:1 in SOI/3D
  - Demonstrated laser annealing of backside
  - Demonstrated FPIX chip thinning to 15 microns

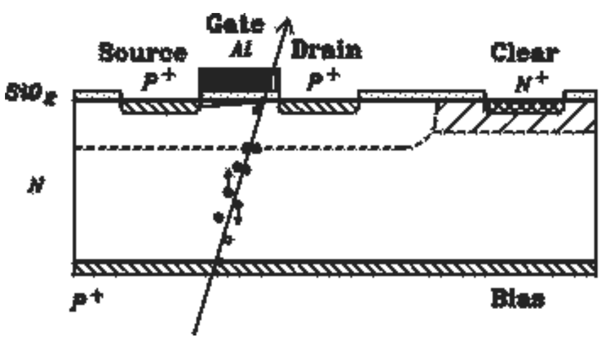




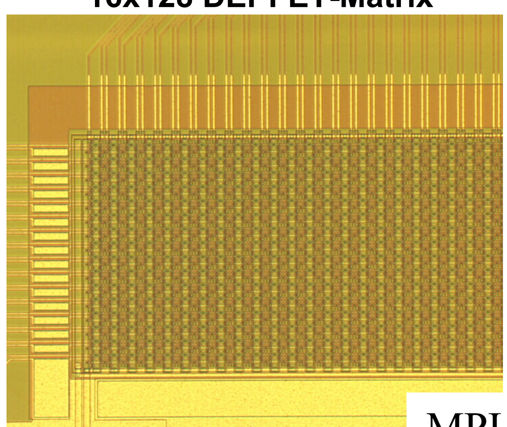
Inner Tracking/Vertex Detection (DEPFET)

Concept

- Field effect transistor on top of fully depleted bulk
- All charge generated in fully depleted bulk; assembles underneath the transistor channel; steers the transistor current
- Clearing by positive pulse on clear electrode
- Combined function of sensor and amplifier



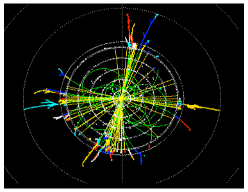
16x128 DEPFET-Matrix



Properties

- low capacitance ▸ low noise
- Signal charge remains undisturbed by readout ▸ repeated readout
- Complete clearing of signal charge ▸ no reset noise
- Full sensitivity over whole bulk ▸ large signal for m.i.p.; X-ray sens.
- Thin radiation entrance window on backside ▸ X-ray sensitivity
- Charge collection also in turned off mode ▸ low power consumption
- Measurement at place of generation ▸ no charge transfer (loss)
- Operation over very large temperature range ▸ no cooling needed

MPI Munich, MPI Halle, U. Bonn, U. Mannheim

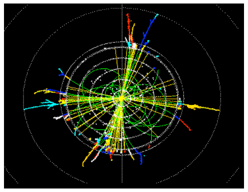


Central Tracking

- **Two general approaches being developed for the ILC**

  <u>TPC</u> (GLD, LDC, 4th)
  - **Builds on successful experience of PEP-4, ALEPH, ALICE, DELPHI, STAR, …..**
  - **Large number of space points, making reconstruction straight-forward**
  - **dE/dx ⇒ particle ID, bonus**
  - **Minimal material, valuable for calorimetry**
  - **Tracking up to large radii**

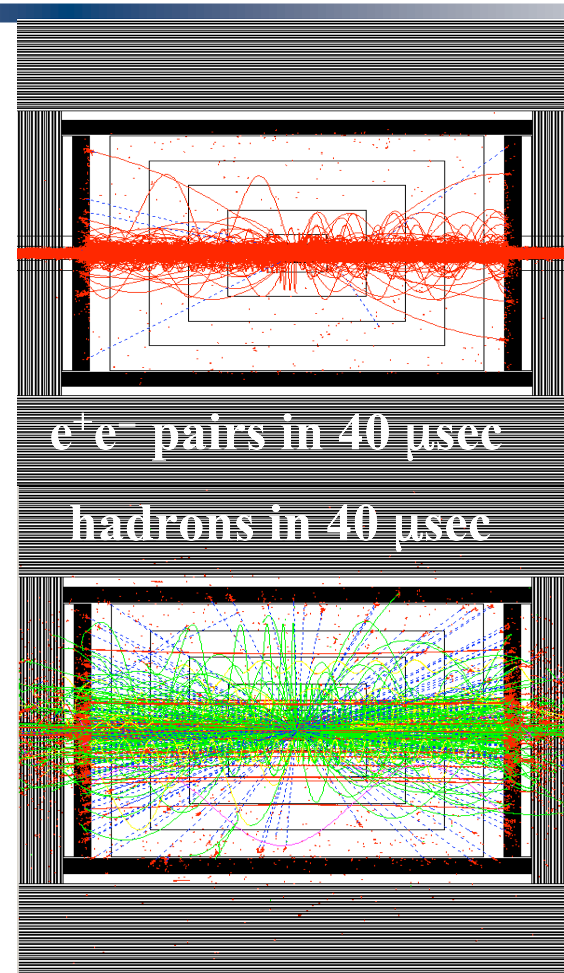
  <u>Silicon</u> (SiD)
  - **Superb spacepoint precision allows tracking measurement goals to be achieved in a compact tracking volume**
  - **Robust to spurious, intermittent backgrounds**
    - ILC is not a storage ring

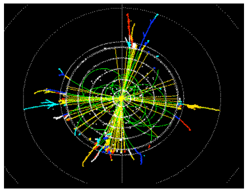


Central Tracking with TPC

Issues for an ILC TPC

- **Optimize novel gas amplification systems**
  - **Conventional TPC readout based on MWPC and pads**
    - limited by positive ion feedback and MWPC response
  - **Improvement by replacing MWPC readout with micropattern gas chambers (eg. GEMs, Micromegas, Medipix)**
    - Small structures (no E×B effects)
    - 2-D structures
    - Only fast electron signal
    - Intrinsic ion feedback suppression
- **Neutron and gamma backgrounds (~130 bunch crossings)**
- **Optimize single point and double track resolution**
- **Performance in high magnetic fields**
- **Demonstrate large system performance with control of systematics**
- **Minimize impact of endplate**





Central Tracking with Silicon

Expecting the machine backgrounds (esp. beam loss occurrences) of the ILC to be erratic (based on SLC experience),

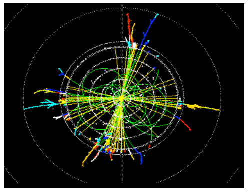
- robustness of silicon is very attractive.
- single bunch timing

The SiD barrel tracking is baselined as 5 layers of pixellated vertex detector and 5 layers of Si strip detectors (in ~10 cm segments) going out to 1.25 meters

With superb position resolution, compact tracker which achieves the linear collider tracking resolution goals is possible

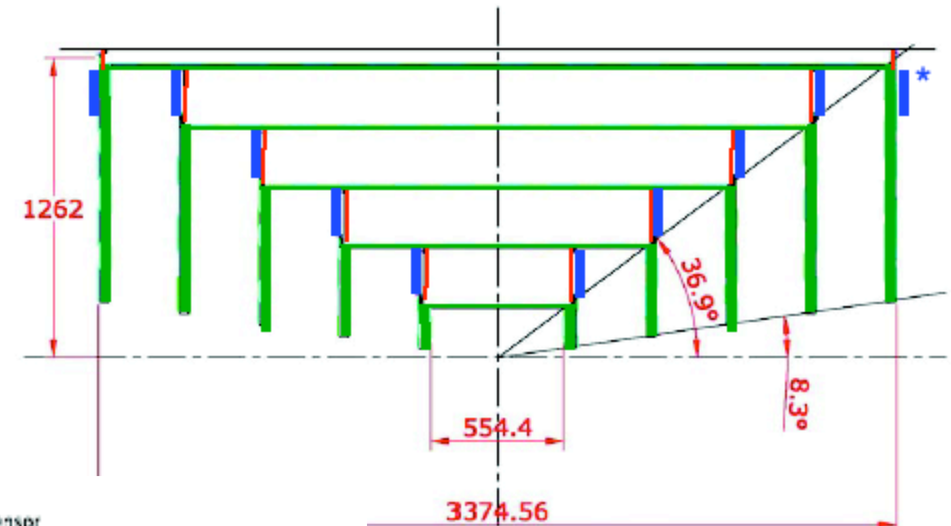
Compact tracker makes the calorimeter smaller and therefore cheaper, permitting more aggressive technical choices (assuming cost constraint)

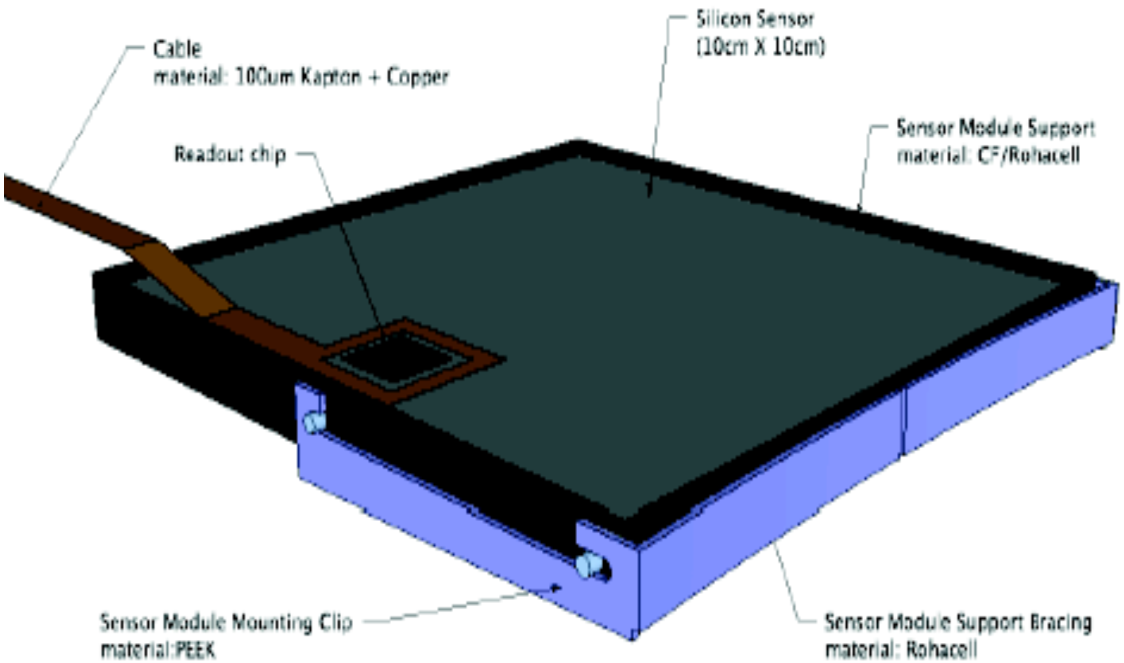
Silicon tracking layer thickness determines low momentum performance



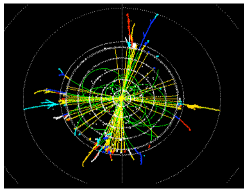
SID$_{00}$ Tracking

- Closed CF/Rohacell cylinders
- Nested support via annular rings
- Power/readout motherboard mounted on support rings



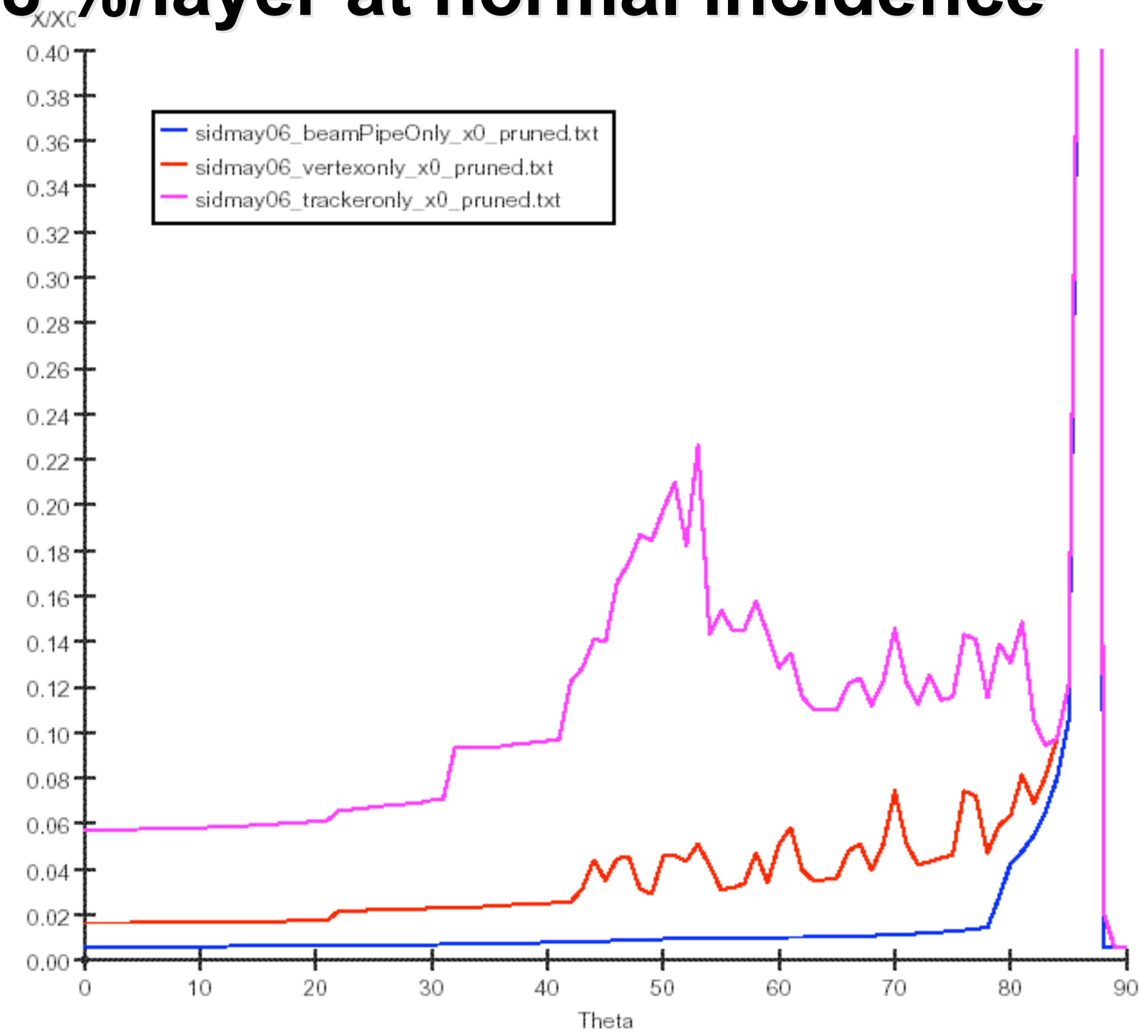


- Cylinders tiled with 10x10cm sensors with readout chip
- Single sided (ϕ) in barrel
- R, ϕ in disks
- Modules mainly silicon with minimal support (0.8% X_0)
- Overlap in *phi* and *z*



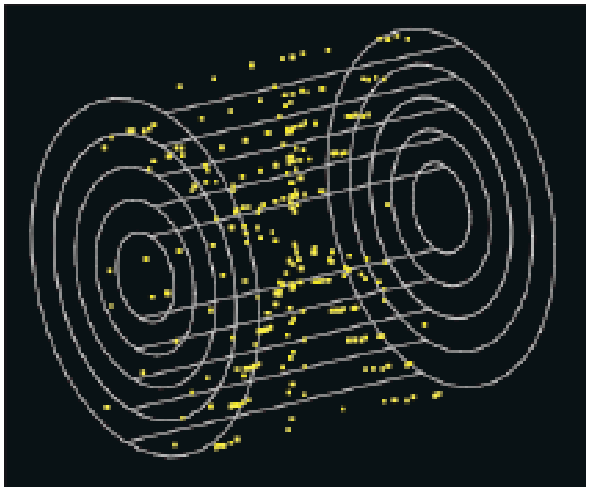
Material Budget of Silicon Tracker

~ 0.8 %/layer at normal incidence

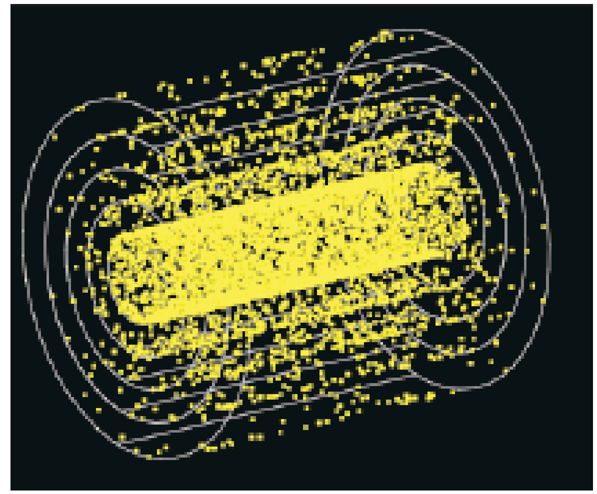


Robust Pattern Recognition with Silicon

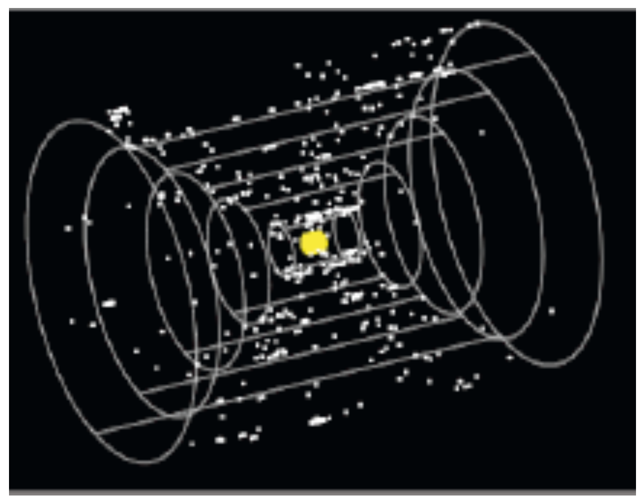
- t tbar event in VXD

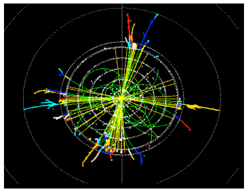


w/ backgrounds from 150 bunch crossings
- BUT 1 billion pixels!

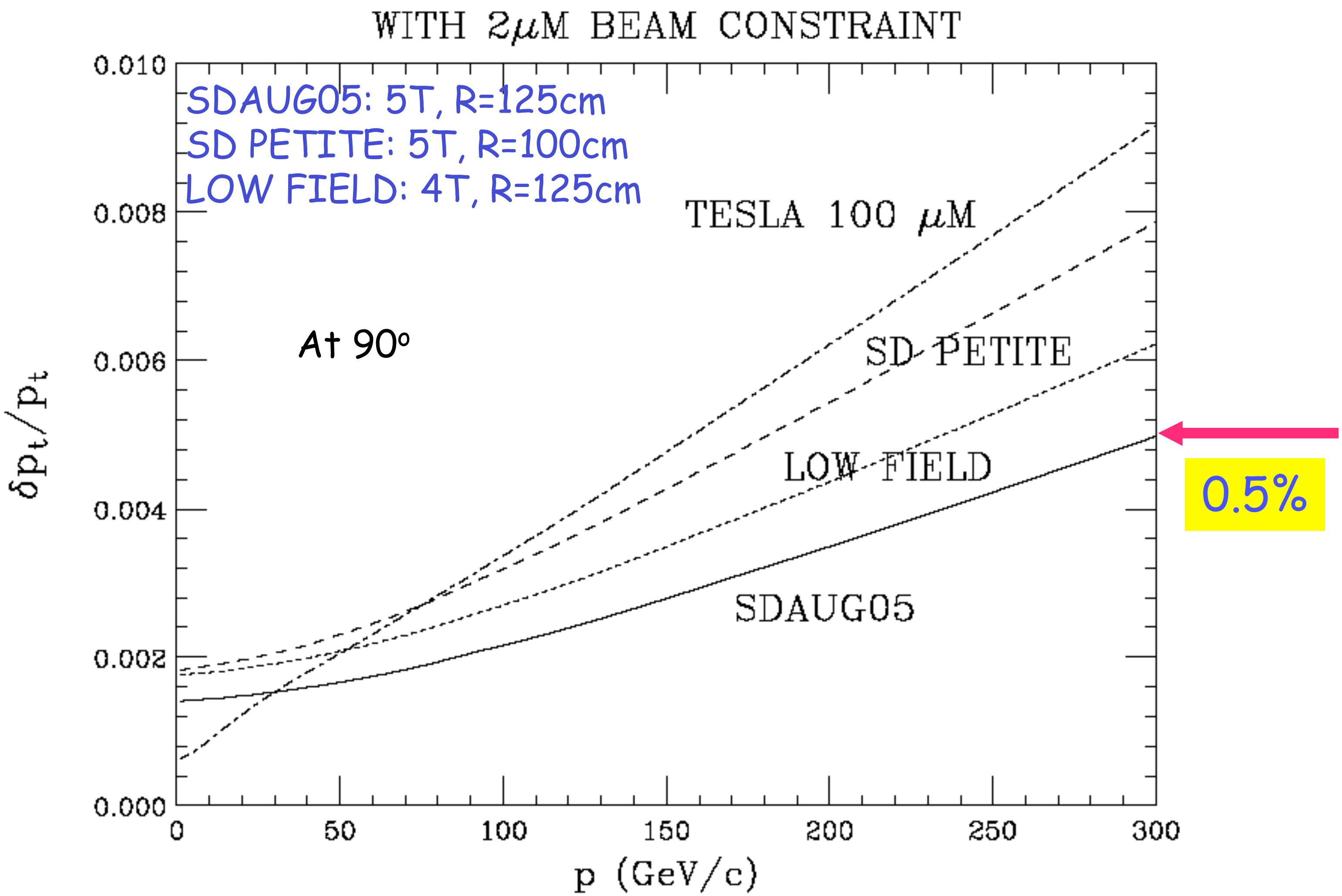


clean detection with
time stamping



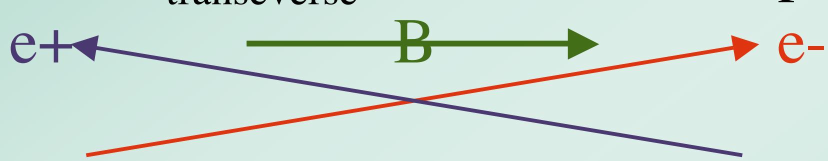


Excellent momentum resolution with Silicon

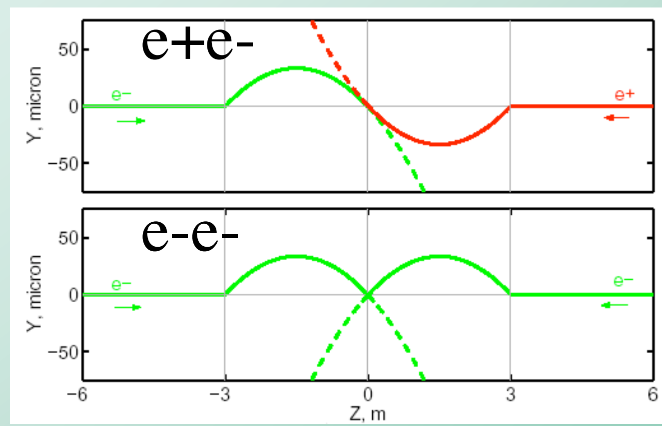


DID (Detector-Integrated Dipole)

- Xing angle (w/o correction)
  - beam sees $B_{transeverse}$ of solenoid → spiral



  - Still head-on (mod xing angle) ?
    - Yes for e+e-.
    - No for e-e-.

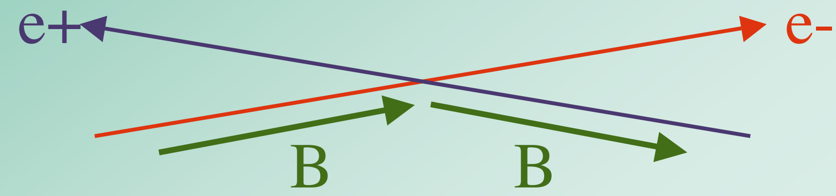


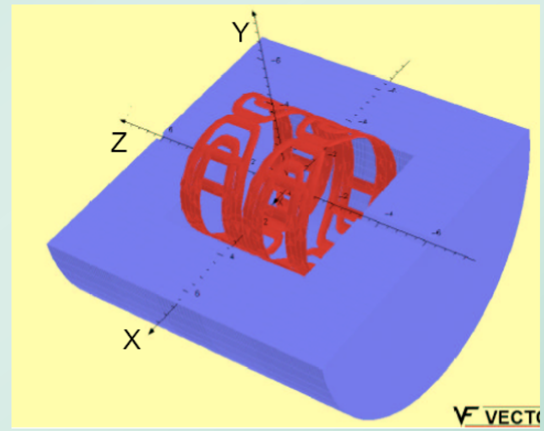
Problems still for e+e- :

- SR emittance growth (significant in some cases)
- Polarization vector rotation (minor problem?)

DID and anti-DID

Align B with <u>incoming</u> e+/e- beams (on av.) - **DID**

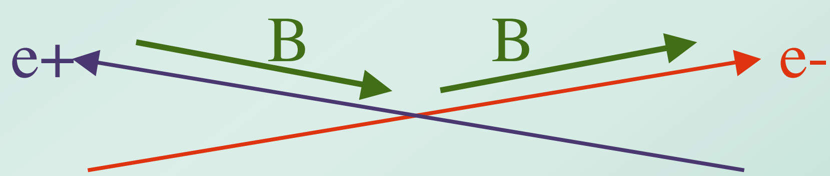




- Solves SR emittance growth
- ×2Bt for outgoing beams

  → worse pair background

Align B with <u>outgoing</u> e+/e- beams (on av.) - **anti DID**

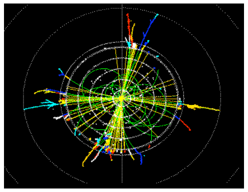


- Pair background ~ 0 mrad xing angle
- ×2Bt for incoming beams

  → worse for SR emittance growth

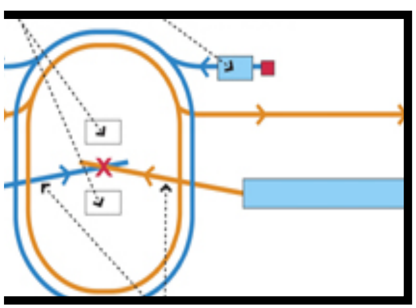
  ~OK for 14 mrad

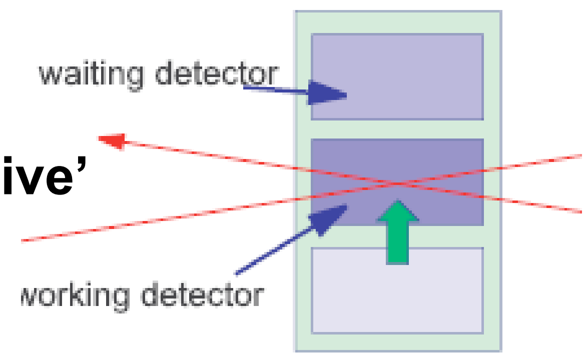
DID or antiDID,
not both simultaneouly

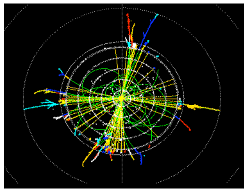


Single IR with Push-Pull Detectors

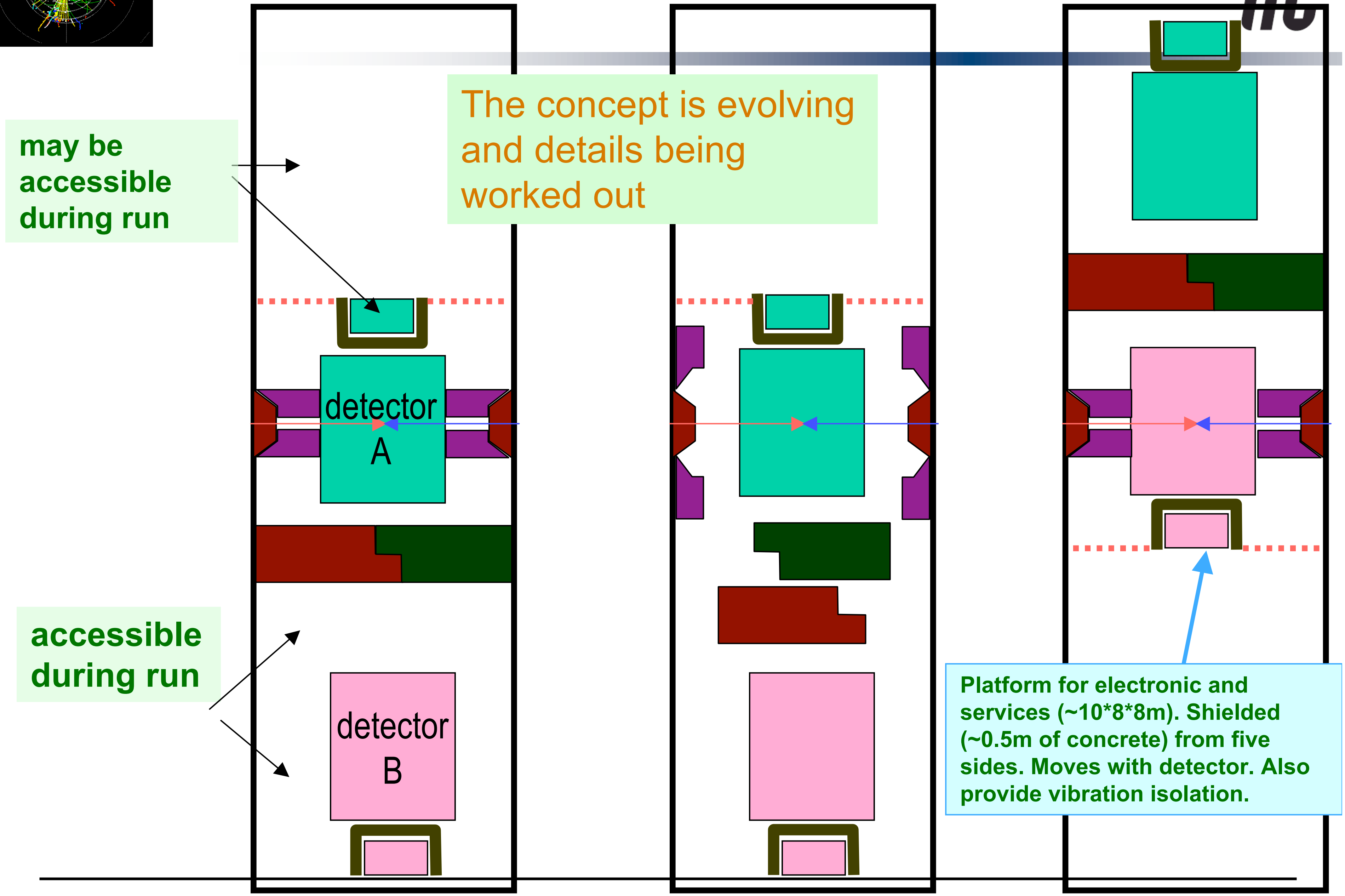
- Large cost saving compared with 2 IR
  - ~200 M$ compared with 2 IR with crossing angles 14/14 mrad
- Push-pull detectors
  - Task force of WWS and GDE studied issues
  - Initial conclusion:
    - **No show-stopper**
    - **But need careful design and R&D**
      - **For example, need quick switch-over**
    - **2 IR should be kept as an 'Alternative'**





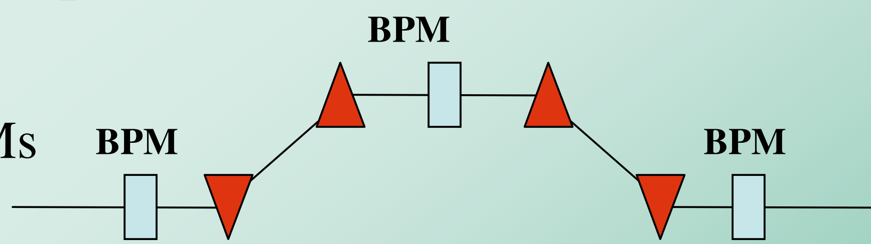


Concept of IR hall with two detectors

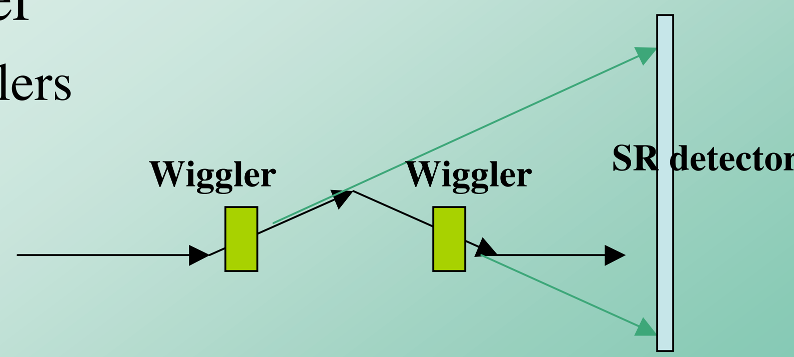


Energy Measurement

- Goal:
  - 100ppm (10^{-4}) absolute energy measurement
- Baseline:
  - 1 upstream + 1 downstream spectrometers / beam
  - Upstream spectrometer
    - 4-magnet chicane + RF BPMs
    - 1mm offset + σ=100nm:10^{-4}



  - Downstream spectrometer
    - 3-magnet chicane w/wigglers + SR photon detectors

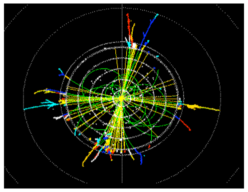


Polarization Measurement

- Goal :
  - 0.25% accuracy (particularly on Z)
- Baseline :
  - 1 upstream + 1 downstrem polarimeters / beam
  - Compton polarimeter
    - Shoot circularly-polarized photon at the electron beam at a focus.
    - Measure the compton-scattered electron.
    - Polarization vector at IP = that at the polarimeter
      → beam direction at IP parallel to that at the polarimeter
    - 4-magnet chicane

Luminosity Measurement

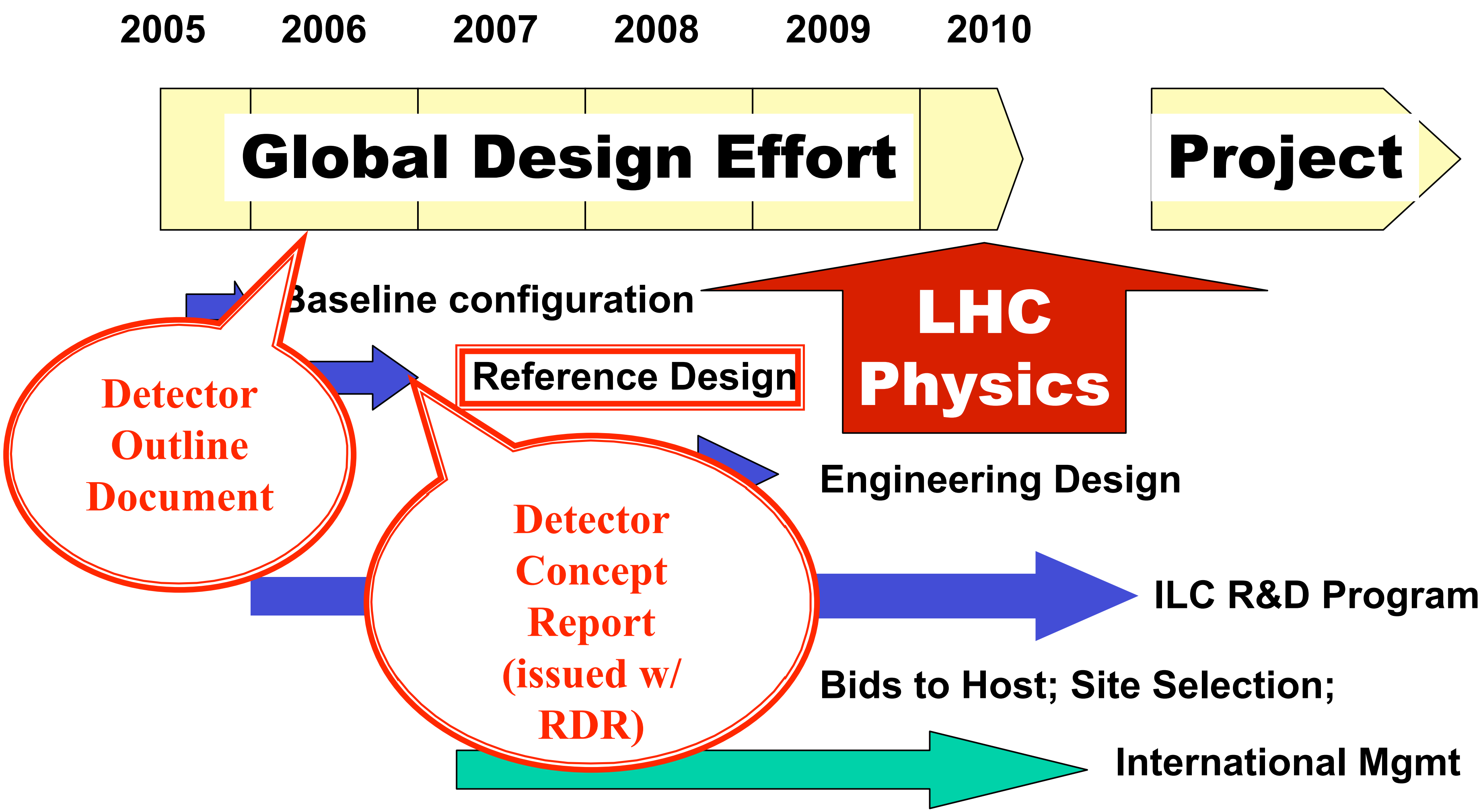
- Accuracy goal : 10^{-3} or better absolute
- Detector : LUMCAL(LUMMON/FCAL)
  - ~30-90 mrad
  - ~10 Bhabhas / bunch train
  - Default: Si-W calorimeter
- R&D required
  - The precision achievable for different xing angles? Careful systematics studies.
  - 10^{-4} desirable for Giga-Z, larger polar angles?
  - Backgrounds from pairs etc.?
- 'Physics' events (central detector) :
  - Acollinear Bhabha → Luminosity spectrum, etc.



Organization

- World Wide Study (WWS) - http://physics.uoregon.edu/~lc/wwstudy
  - Formed in 1998 (Vancouver ICHEP)
  - 18 member organizing committee - 6/region
  - Co-chairs
    - S. Komamiya → H. Yamamoto
    - D. Miller → F. Richard
    - C. Baltay → J. Brau
  - Tasks
    - Recognize and coordinate detector concept studies
    - Register and coordinate detector R&Ds
    - Interface with GDE
    - Organize LCWS (International Linear Collider Workshop, 1 per year now)
- Research Director
  - S. Yamada appointed by ILCSC - fall 2007
  - WWS co-chairs advising
  - Forming International Detector Advisory Group
  - Coordinating with GDE Directorate

The GDE Plan and Schedule



Detector Roadmap

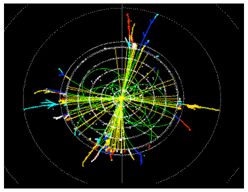
(not yet fully implemented)

- 2007 – Writing of Physics and Detector volumes (2 vol. of RDR) ✓
  Call for Letters of Intent from Detector groups
  ILCSC, Research Director

- 2008 – Letters of Intent received by ILCSC, RD
  International Detector Advisory Group reviews LOIs
  Guides community to the definition of two detectors for
  EDR preparation
  Collaborations formed to develop EDRs

- 2009-2011 – Development of two engineered designs,
  produce first engineering design reports (EDRs) for the two overall detectors,

NOTE - THESE EFFORTS NEED NOT REPRESENT THE FINAL SELECTION OF DETECTORS FOR THE ILC EXPERIMENTAL PROGRAM



Conclusion

- **Current status of Electroweak Precision measurements indicates the physics at the LHC and ILC will be rich**

- **The International Linear Collider will be a powerful tool**
  - **Electroweak Symmetry Breaking**
  - **origin of mass**
  - **other fundamental physics**
  - **advance understanding of LHC discoveries**

- **DISCOVERY OPPORTUNITIES at the ILC will be limited by detector performance**
  - **advances different from LHC required**
  - **program of ILC Detector R&D is developing these capabilities**