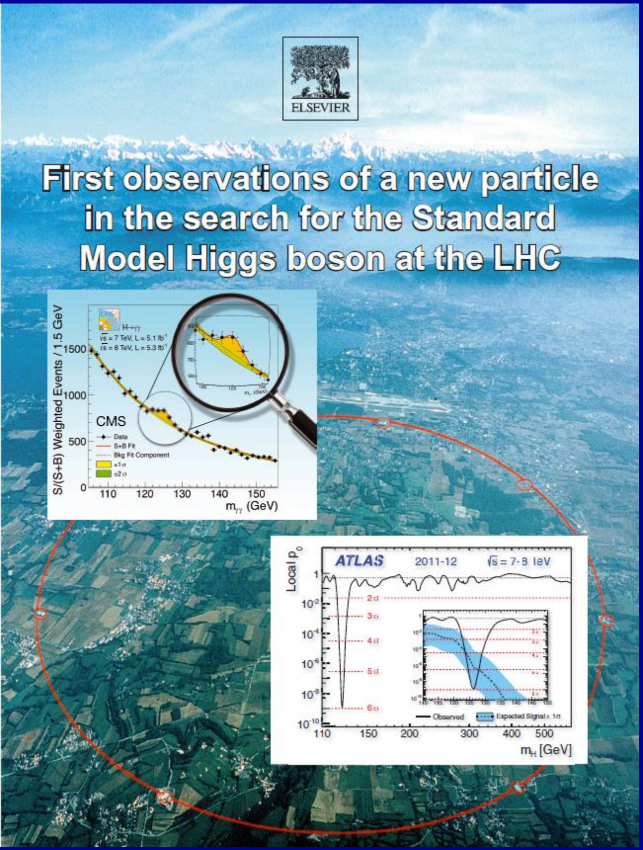
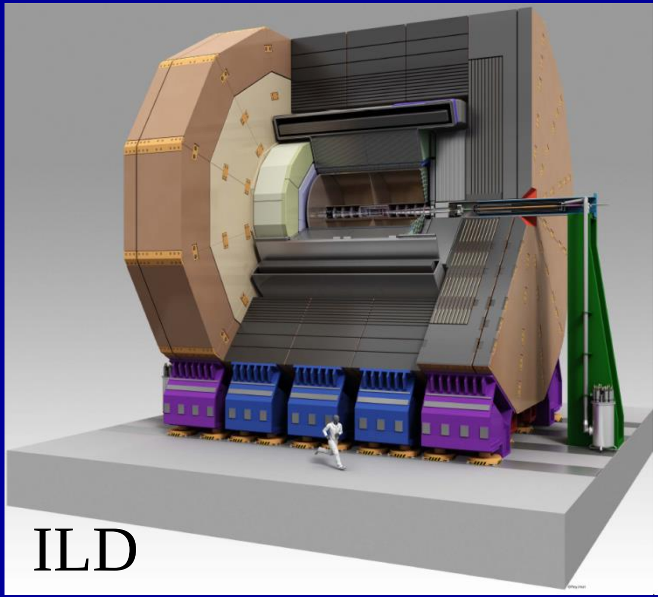
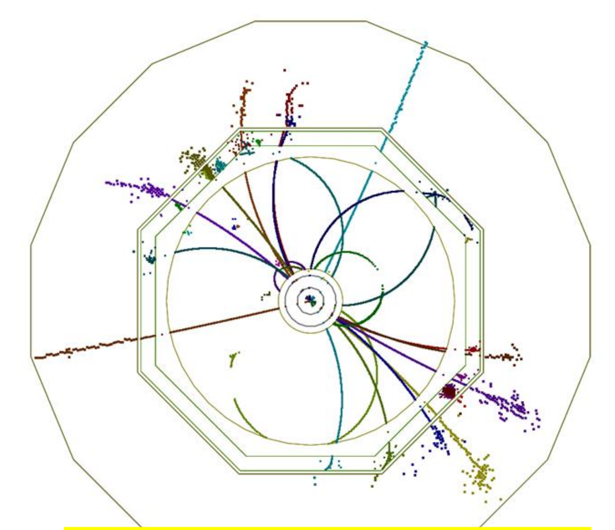
Precisely Exploring Higgs-Scale Physics with the ILC



First observations of a new particle in the search for the Standard Model Higgs boson at the LHC



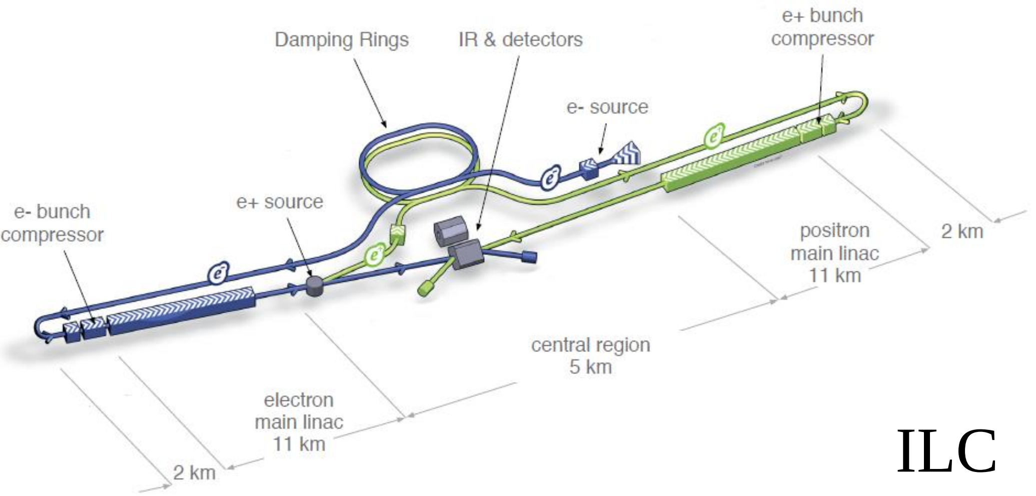
ILD



$\sqrt{s}$=250 GeV, $e^+e^- \to \mu^+ \mu^- H$

Graham W. Wilson

University of Kansas



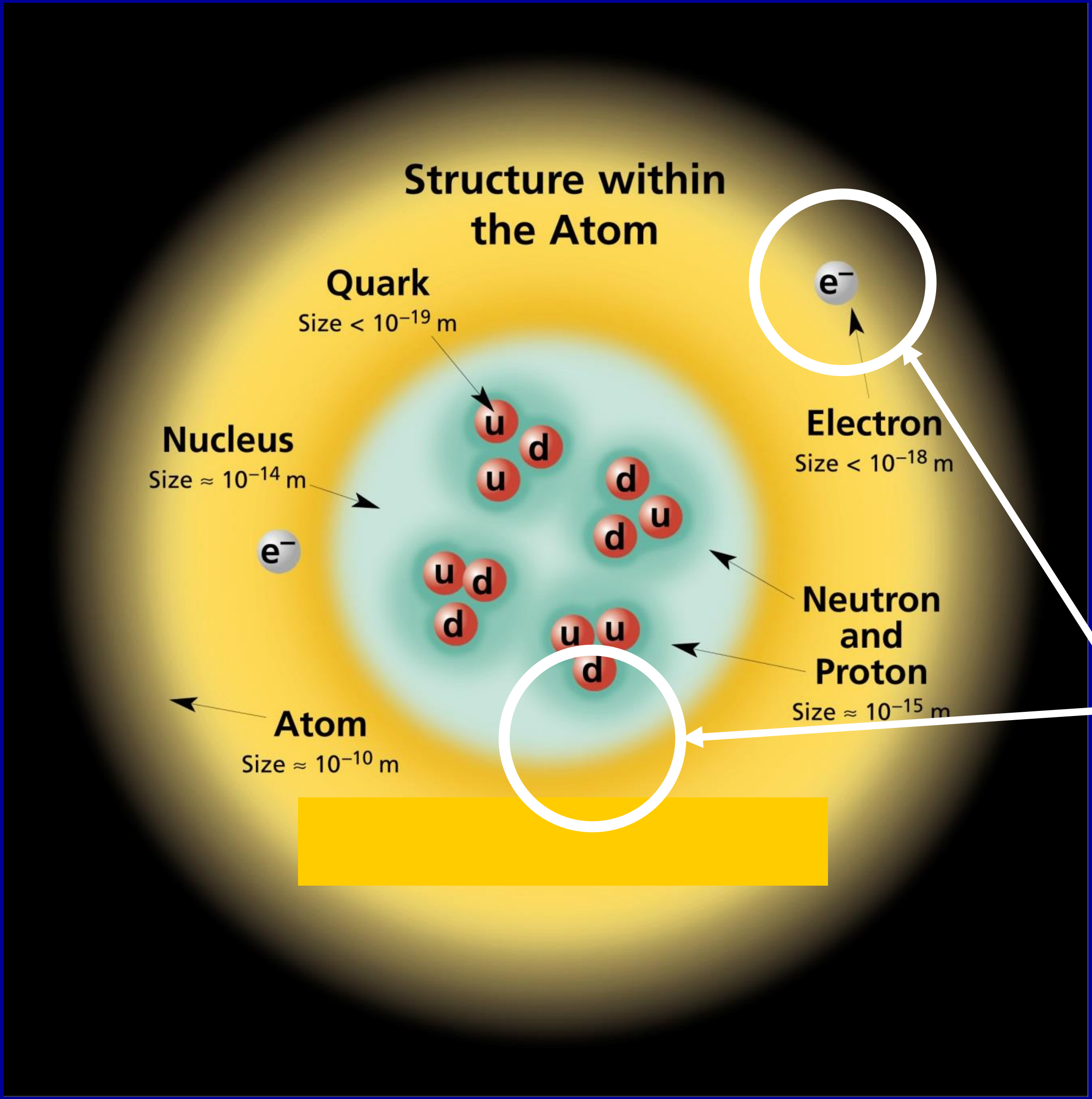
ILC

Plan

- 1. Brief Particle Physics Initiation
- 2. What is the proposed ILC accelerator ?
- 3. What is the proposed ILD detector concept ?
- 4. Particle Physics: Particles, Higgs, Interactions

- 5. Brief ILC Physics Overview
- 6. Experimental Methods which Broaden the ILC Science Scope

Particle Physics

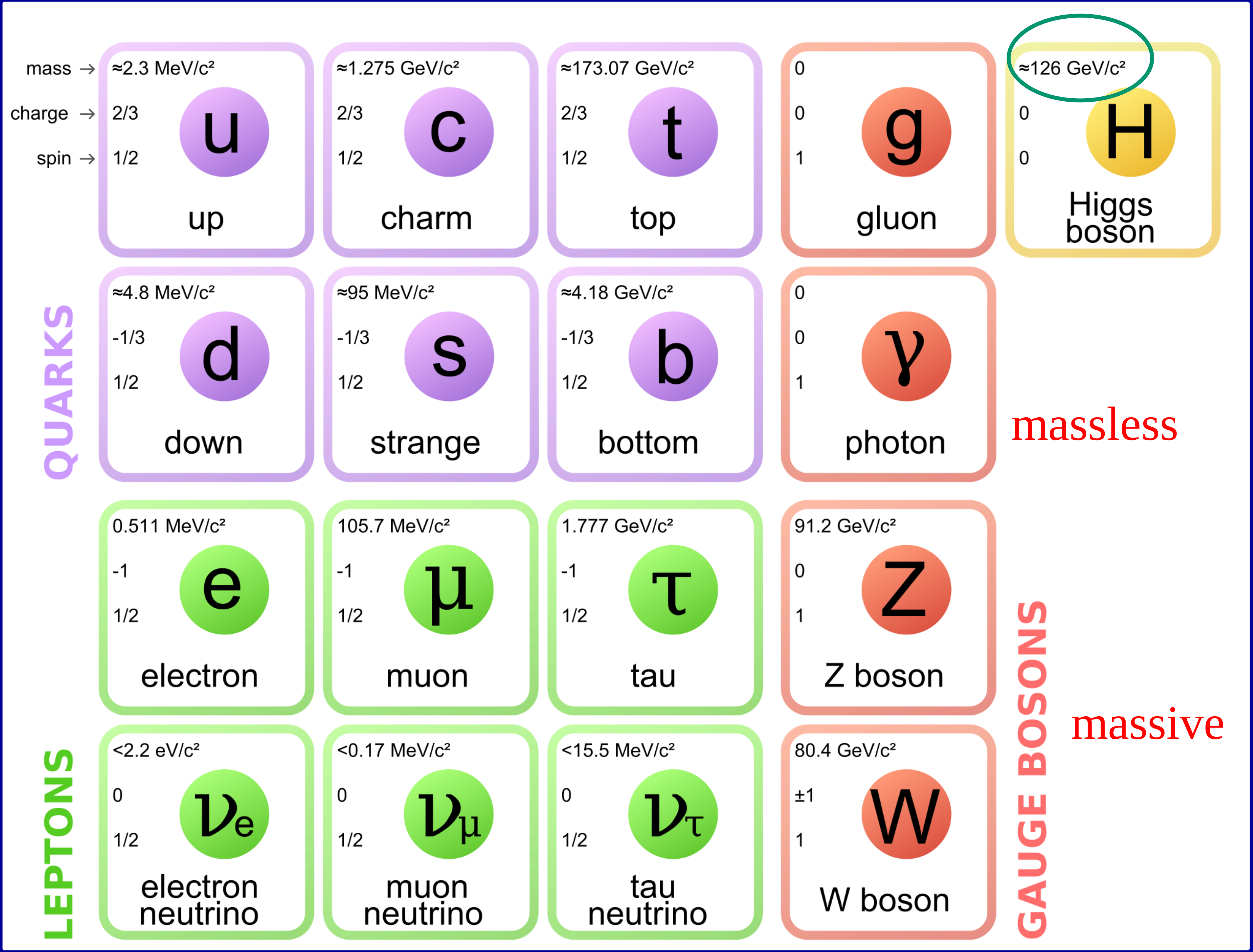


Elementary Particle Physics seeks to understand the fundamental building blocks of matter and their interactions.

The point-like particles (leptons, quarks) and the particles that mediate their interactions.

A bit like a board game – find all the pieces and figure out the rules of the game.

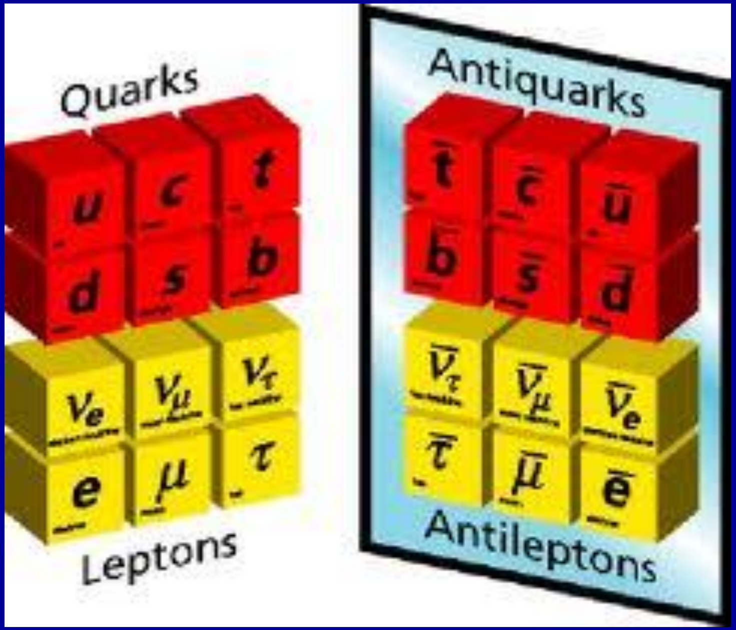
Standard Model Particle Content



mass → charge → spin →	≈2.3 MeV/c^2 2/3 1/2 u up	≈1.275 GeV/c^2 2/3 1/2 c charm	≈173.07 GeV/c^2 2/3 1/2 t top	0 0 1 g gluon	≈126 GeV/c^2 0 0 H Higgs boson
QUARKS	≈4.8 MeV/c^2 -1/3 1/2 d down	≈95 MeV/c^2 -1/3 1/2 s strange	≈4.18 GeV/c^2 -1/3 1/2 b bottom	0 0 1 γ photon	massless
	0.511 MeV/c^2 -1 1/2 e electron	105.7 MeV/c^2 -1 1/2 μ muon	1.777 GeV/c^2 -1 1/2 τ tau	91.2 GeV/c^2 0 1 Z Z boson	
LEPTONS	<2.2 eV/c^2 0 1/2 ν_e electron neutrino	<0.17 MeV/c^2 0 1/2 ν_μ muon neutrino	<15.5 MeV/c^2 0 1/2 ν_τ tau neutrino	80.4 GeV/c^2 ±1 1 W W boson	GAUGE BOSONS massive

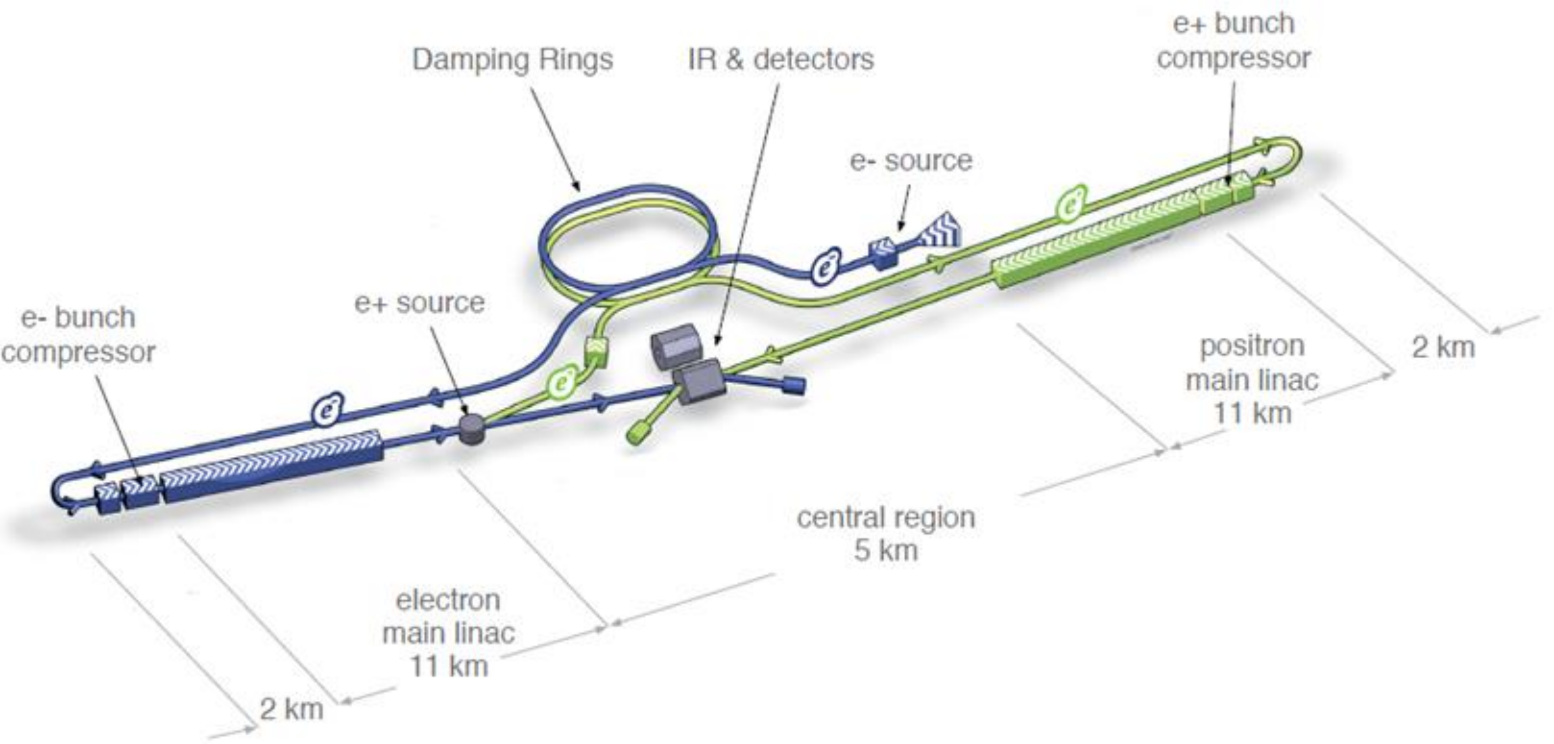
The Fermions

- Quarks and Charged Leptons behave like Dirac Fermions
  - Particles with 2 spin states
  - Anti-Particles with 2 spin states
- In practice, there are 4 kinds of electron.



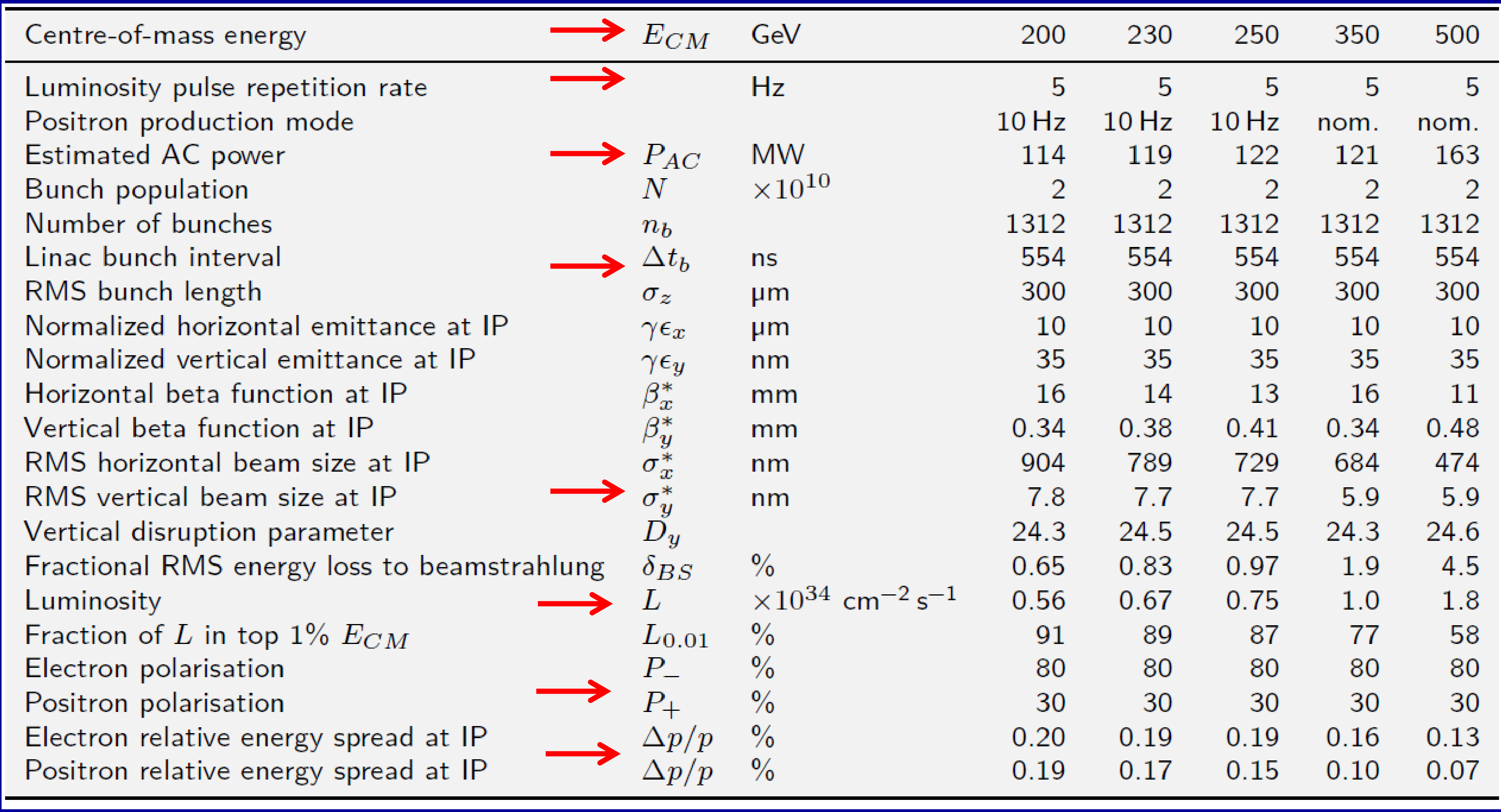
- The ILC is an accelerator where one can experiment with all 4 varieties (longitudinally polarized electrons and longitudinally polarized electron anti-particles: positrons)

What is the International Linear Collider (ILC) ?



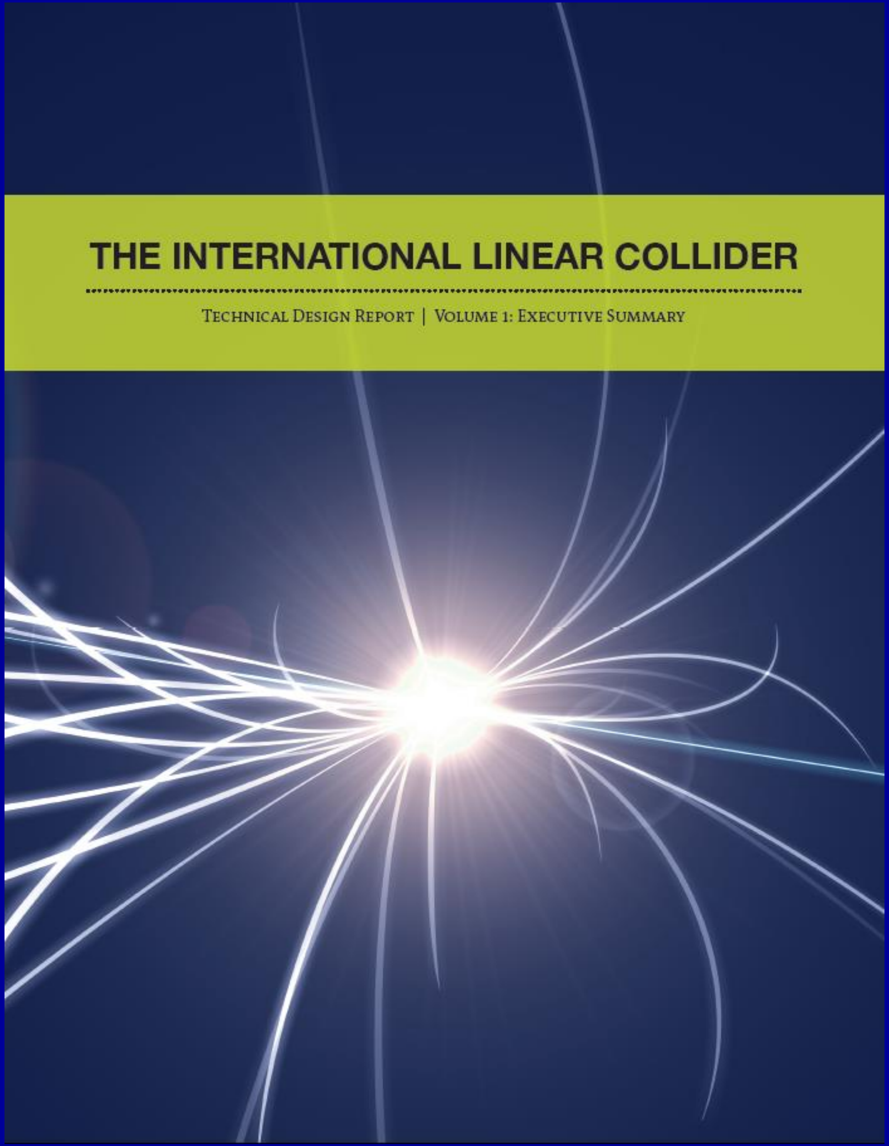
YouTube Video

ILC Baseline Parameters



Centre-of-mass energy	E_{CM}	GeV	200	230	250	350	500
Luminosity pulse repetition rate		Hz	5	5	5	5	5
Positron production mode			10 Hz	10 Hz	10 Hz	nom.	nom.
Estimated AC power	P_{AC}	MW	114	119	122	121	163
Bunch population	N	$\times 10^{10}$	2	2	2	2	2
Number of bunches	n_b		1312	1312	1312	1312	1312
Linac bunch interval	Δt_b	ns	554	554	554	554	554
RMS bunch length	σ_z	µm	300	300	300	300	300
Normalized horizontal emittance at IP	$\gamma\epsilon_x$	µm	10	10	10	10	10
Normalized vertical emittance at IP	$\gamma\epsilon_y$	nm	35	35	35	35	35
Horizontal beta function at IP	β_x^*	mm	16	14	13	16	11
Vertical beta function at IP	β_y^*	mm	0.34	0.38	0.41	0.34	0.48
RMS horizontal beam size at IP	σ_x^*	nm	904	789	729	684	474
RMS vertical beam size at IP	σ_y^*	nm	7.8	7.7	7.7	5.9	5.9
Vertical disruption parameter	D_y		24.3	24.5	24.5	24.3	24.6
Fractional RMS energy loss to beamstrahlung	δ_{BS}	%	0.65	0.83	0.97	1.9	4.5
Luminosity	L	$\times 10^{34}$ cm^{-2} s^{-1}	0.56	0.67	0.75	1.0	1.8
Fraction of L in top 1% E_{CM}	$L_{0.01}$	%	91	89	87	77	58
Electron polarisation	P_-	%	80	80	80	80	80
Positron polarisation	P_+	%	30	30	30	30	30
Electron relative energy spread at IP	$\Delta p/p$	%	0.20	0.19	0.19	0.16	0.13
Positron relative energy spread at IP	$\Delta p/p$	%	0.19	0.17	0.15	0.10	0.07

25-years of Development



THE INTERNATIONAL LINEAR COLLIDER

TECHNICAL DESIGN REPORT | VOLUME 1: EXECUTIVE SUMMARY

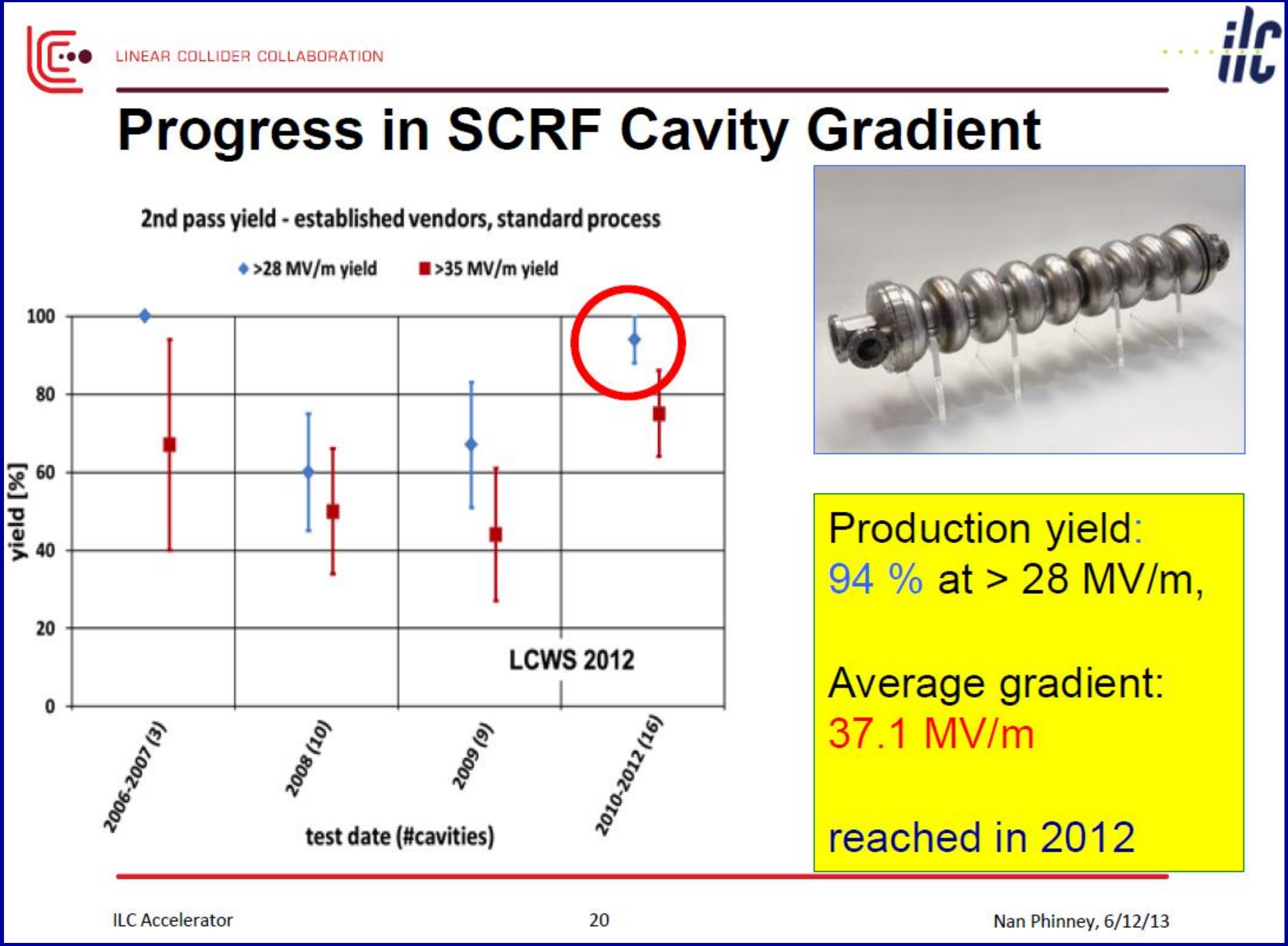
The International Linear Collider
– A Worldwide Event
From Design to Reality

12 June 2013
Tokyo, Geneva, Chicago

www.linearcollider.org/worldwideevent

Enabling Technology Now Ready

Superconducting RF accelerating cavities. 5 MV/m → 37 MV/m



LINEAR COLLIDER COLLABORATION

Progress in SCRF Cavity Gradient

Production yield:
94 % at > 28 MV/m,

Average gradient:
37.1 MV/m

reached in 2012

ILC Accelerator 20 Nan Phinney, 6/12/13

Also starting to be used on a large scale in light sources.

ILC Where ?

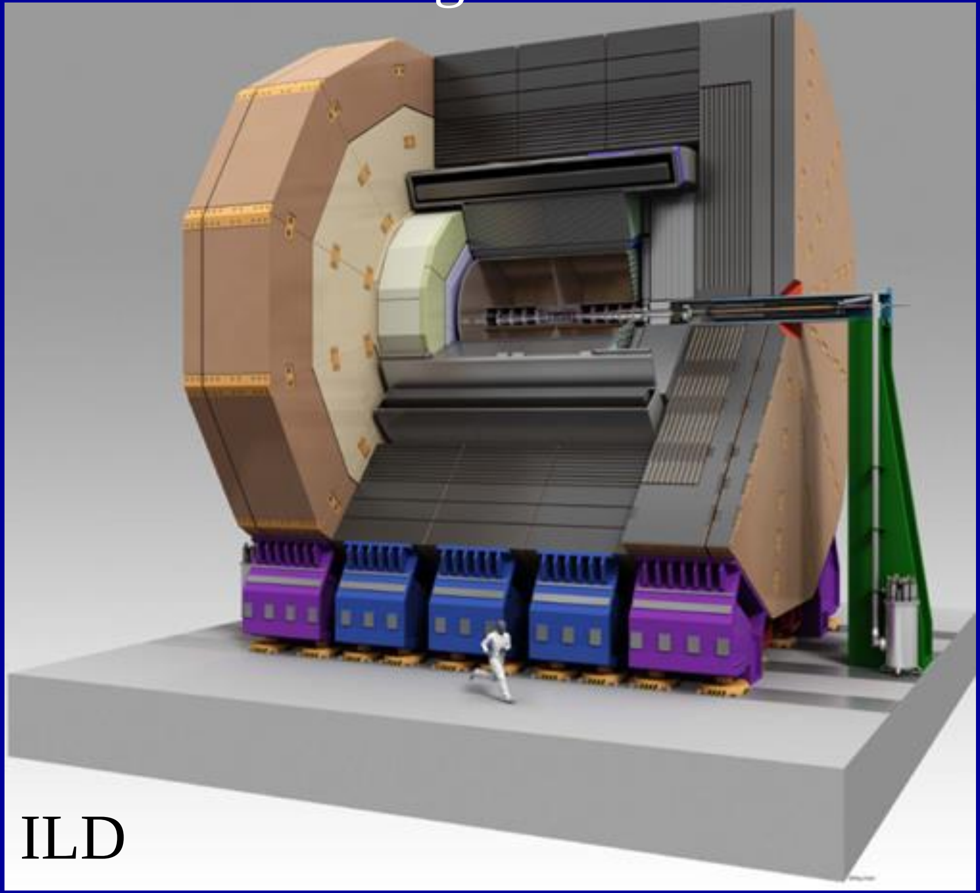
Candidate sites in Chicago, Geneva, Russia, Japan.

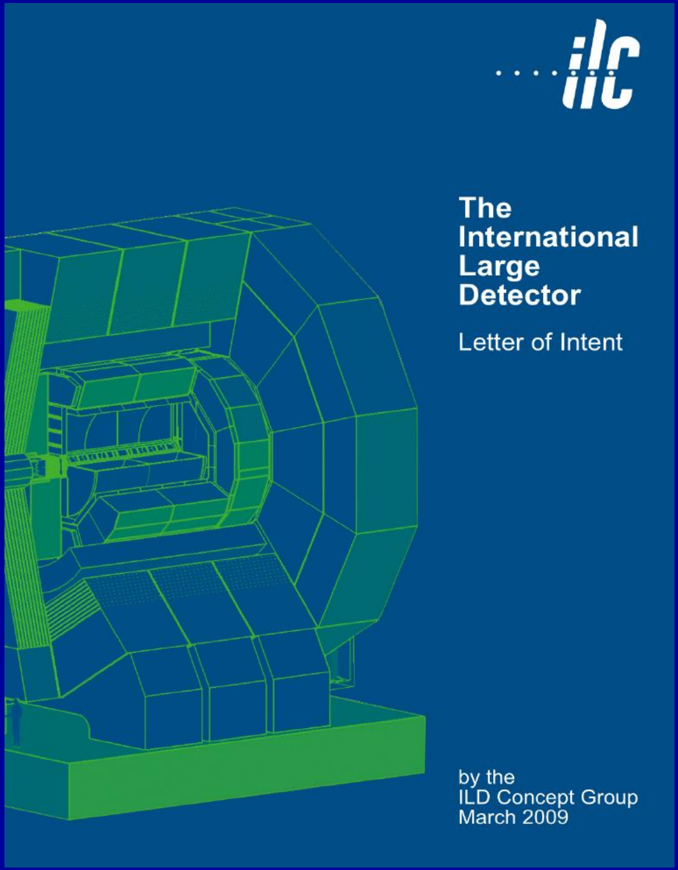
Japan is currently seen as most likely.

(Chicago was a fair bet 7 years ago)

What is ILD ?

International Large Detector





The International Large Detector

Letter of Intent

by the
ILD Concept Group
March 2009

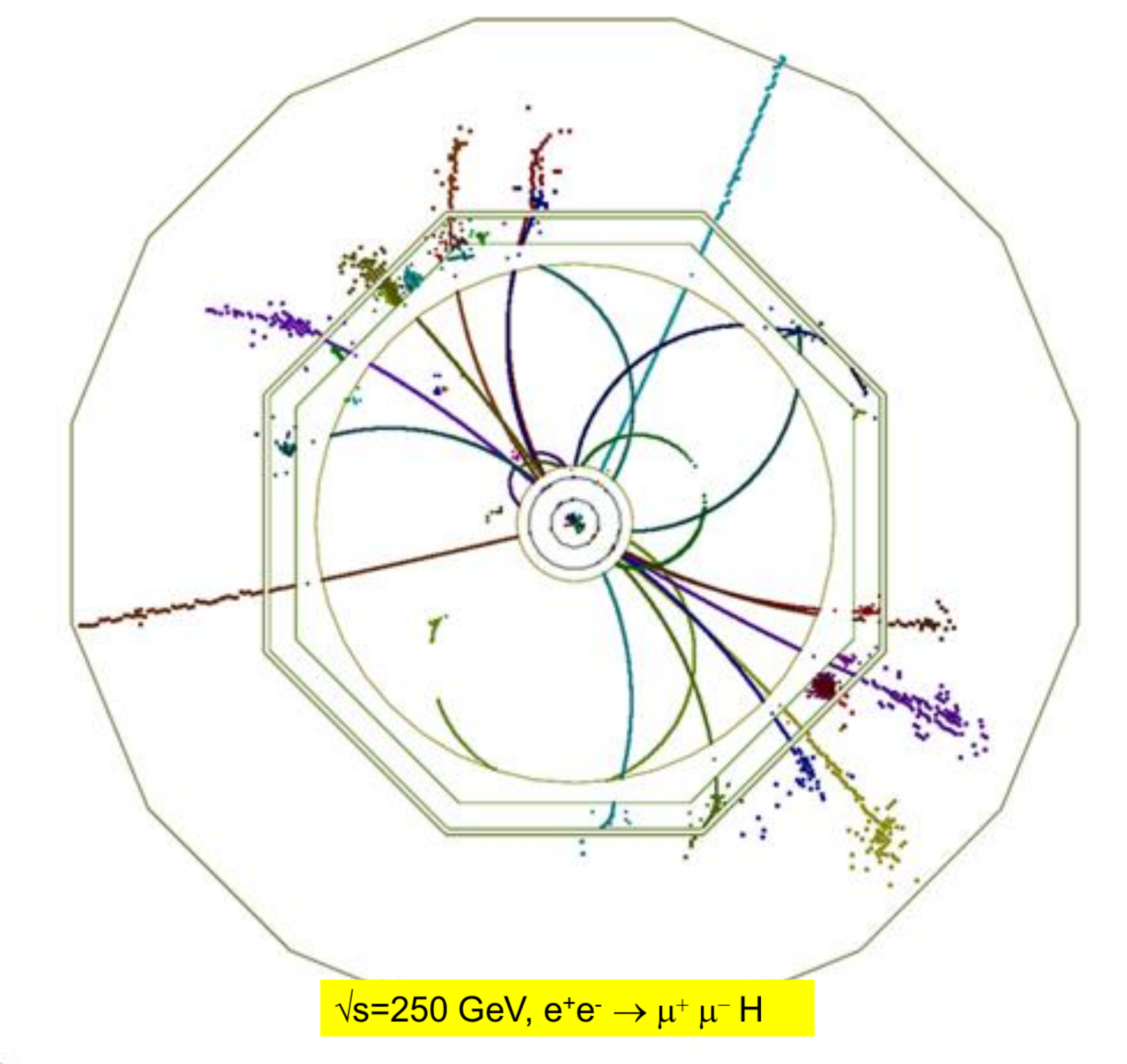
A modern detector designed for ILC. Similar size to CMS.
I have been involved in the big picture design of this since 1995.
ILC: higher energy (x 5), higher luminosity (x 500), much better detector.

Detector Design Philosophy

Designed based on the **particle-flow** approach to complete reconstruction of the event.

Major emphasis on granularity so that individual particles are separated and unambiguously reconstructed.

Requires hardware and software in the design process.



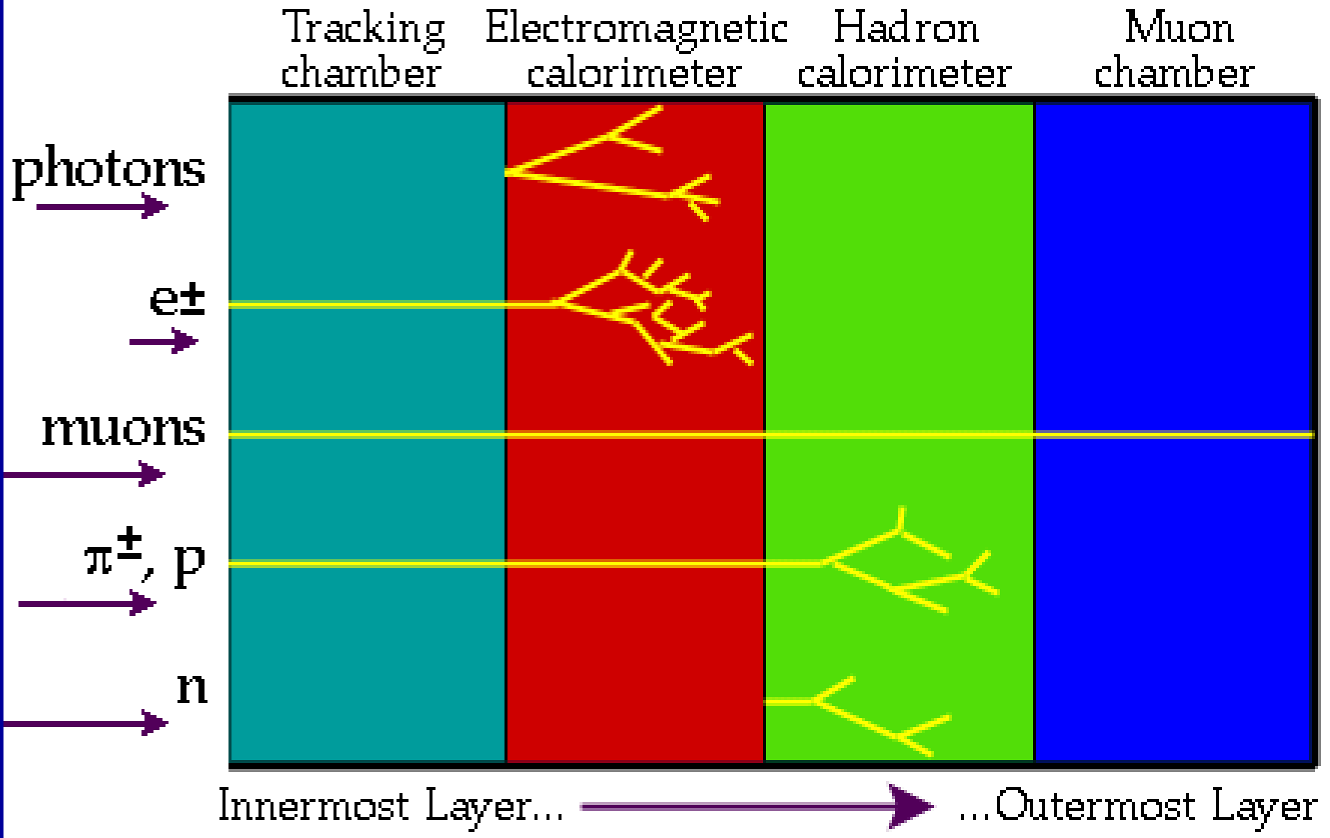
$\sqrt{s}$=250 GeV, $e^+e^- \to \mu^+ \mu^- H$

Detectors

Photons

Charged particles

Neutral Hadrons



Often, hadronic interactions do start in the electromagnetic calorimeter

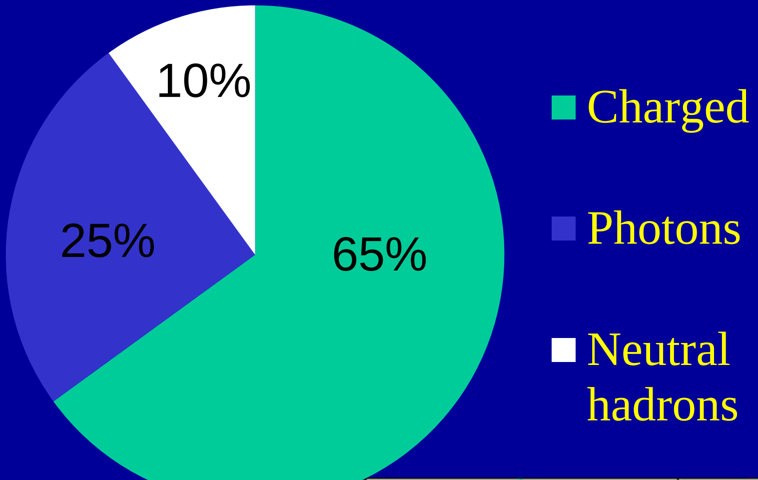
Particle-Flow in a Nut-Shell

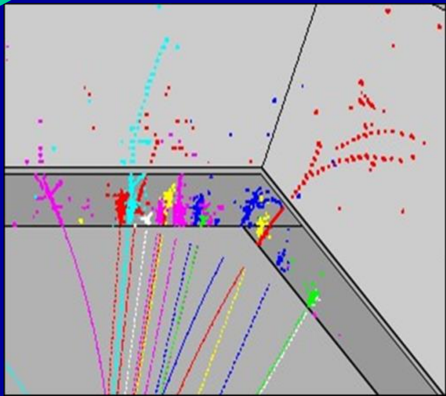
E(jet) = E(charged) + E(photons) + E(neutral hadrons)

- Outsource **65%** of the event-energy measurement responsibility from the calorimeter to the tracker
  - Emphasize particle separability (large R) and tracking
  - Leading to better jet energy precision
- Reduce importance of hadronic leakage
  - Now only 10% instead of 75% of the average jet energy is susceptible
  - Detector designs suited to wide energy range
- Maximize event information
  - Aim for full reconstruction of each particle including V^0s, kinks, π^0 etc.
  - Understand energy response and resolution event-by-event.

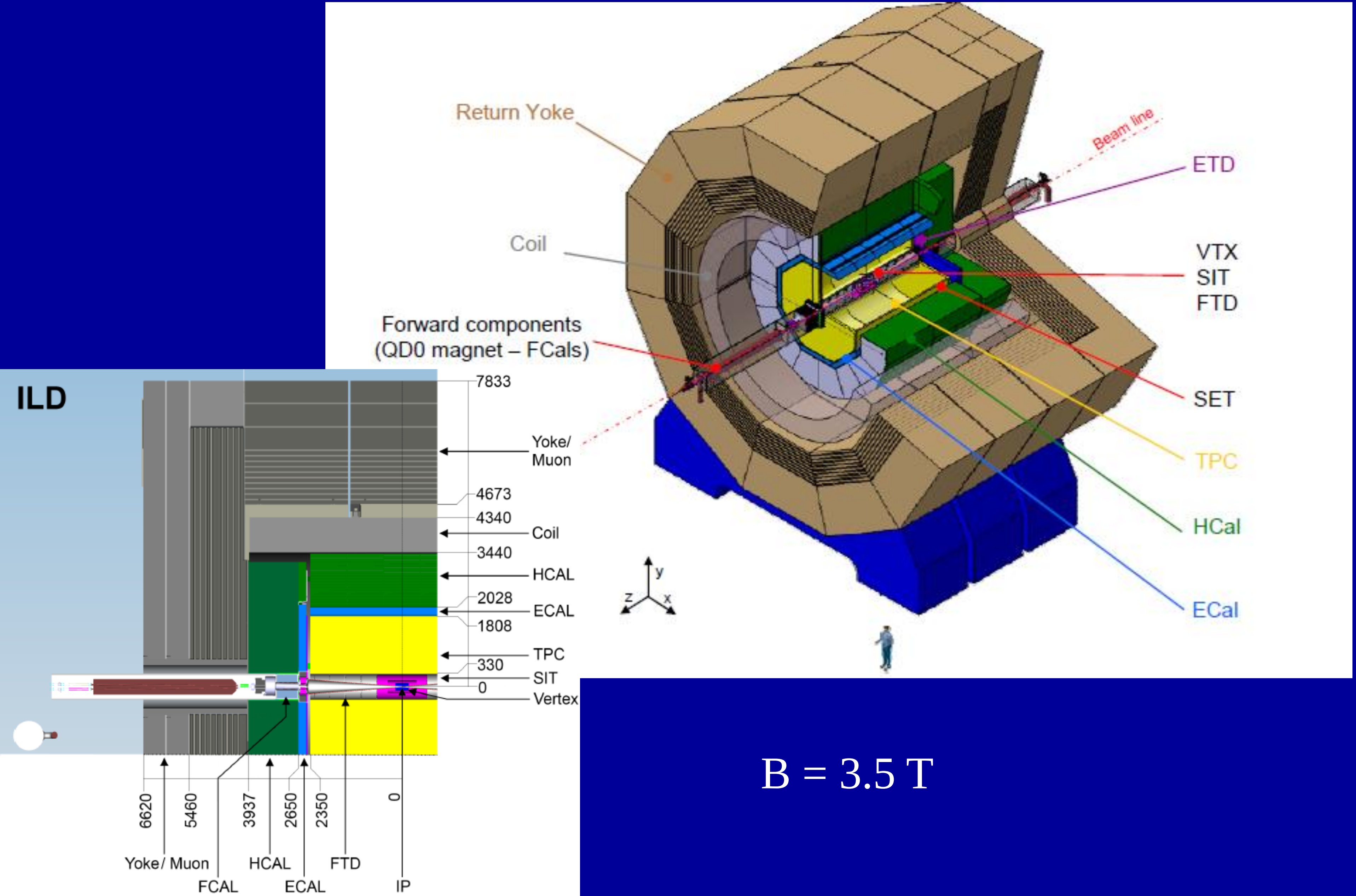
← Emphasis of recent work

Particle AVERAGEs



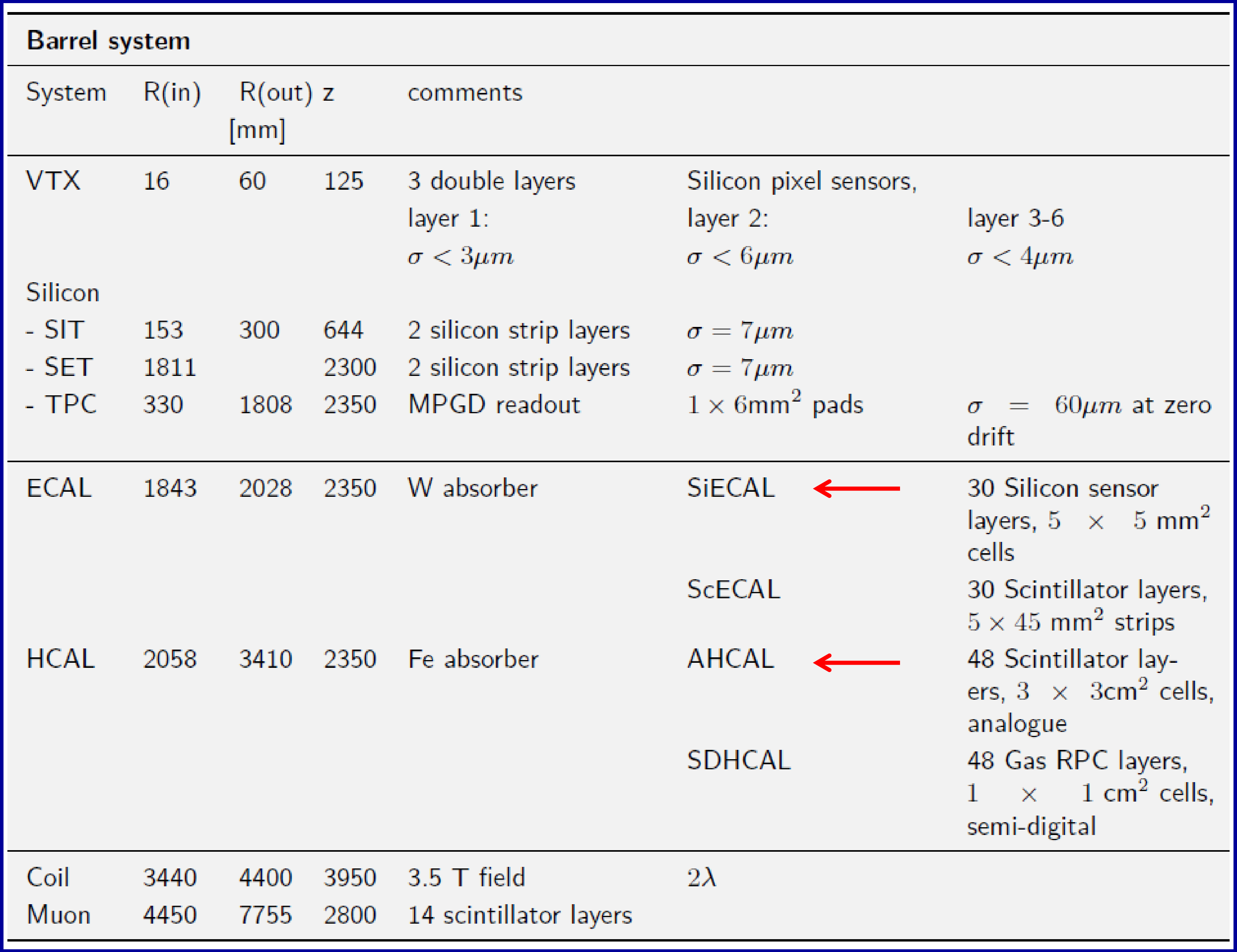


ILD Detector Sub-systems



B = 3.5 T

Barrel Detector Parameters



Barrel system

System	R(in)	R(out) z [mm]		comments		
VTX	16	60	125	3 double layers layer 1: $\sigma < 3\mu m$	Silicon pixel sensors, layer 2: $\sigma < 6\mu m$	layer 3-6 $\sigma < 4\mu m$
Silicon						
- SIT	153	300	644	2 silicon strip layers	$\sigma = 7\mu m$	
- SET	1811		2300	2 silicon strip layers	$\sigma = 7\mu m$	
- TPC	330	1808	2350	MPGD readout	1×6mm^2 pads	$\sigma = 60\mu m$ at zero drift
ECAL	1843	2028	2350	W absorber	SiECAL	30 Silicon sensor layers, 5×5 mm^2 cells
					ScECAL	30 Scintillator layers, 5×45 mm^2 strips
HCAL	2058	3410	2350	Fe absorber	AHCAL	48 Scintillator layers, 3×3cm^2 cells, analogue
					SDHCAL	48 Gas RPC layers, 1×1 cm^2 cells, semi-digital
Coil	3440	4400	3950	3.5 T field	2λ	
Muon	4450	7755	2800	14 scintillator layers		

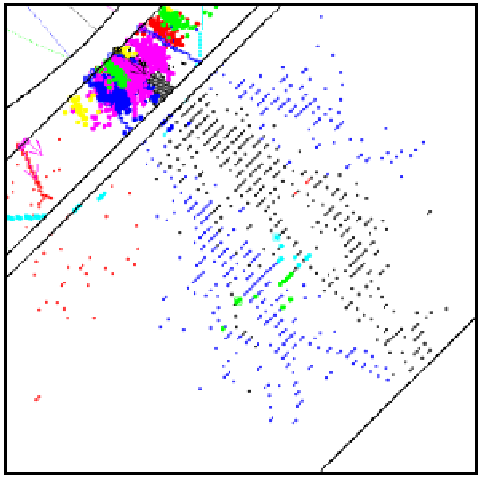
Particle Flow Performance

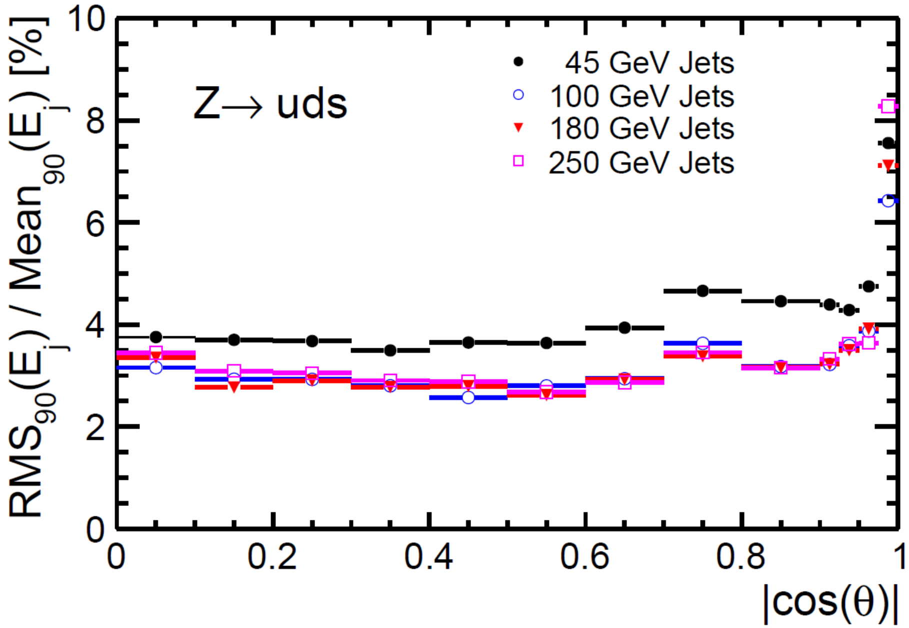
★ **Benchmarked using:**

- $Z \to u\bar{u}, d\bar{d}, s\bar{s}$ decays at rest
- |cosθ|<0.7

Jet Energy	rms_{90}	$\mathrm{rms}_{90}/\sqrt{E_{jj}/\mathrm{GeV}}$	σ_{E_j}/E_j
45 GeV	2.4 GeV	24.7 %	(3.66 ± 0.05) %
100 GeV	4.0 GeV	28.3 %	(2.83 ± 0.04) %
180 GeV	7.3 GeV	38.5 %	(2.86 ± 0.04) %
250 GeV	10.4 GeV	46.6 %	(2.95 ± 0.04) %

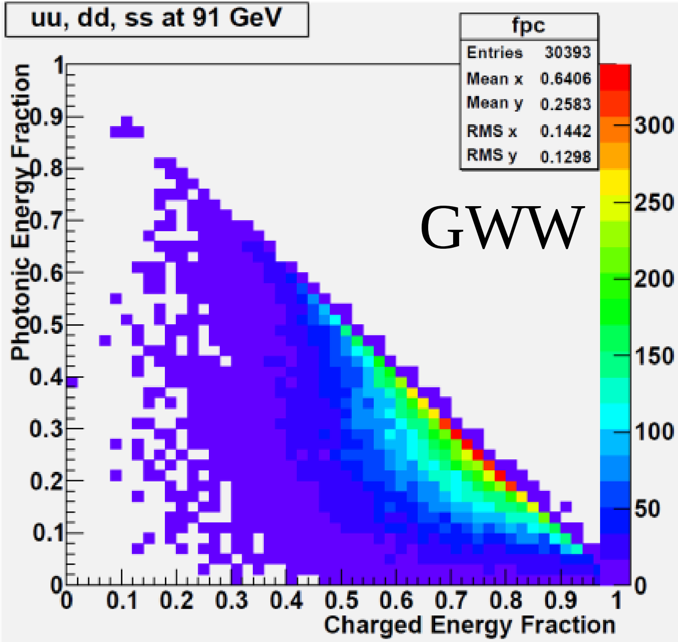
$\underbrace{\mathrm{rms}_{90}\quad \mathrm{rms}_{90}/\sqrt{E_{jj}/\mathrm{GeV}}}_{\text{di-jet}} \quad \underbrace{\sigma_{E_j}/E_j}_{\text{jet}}$

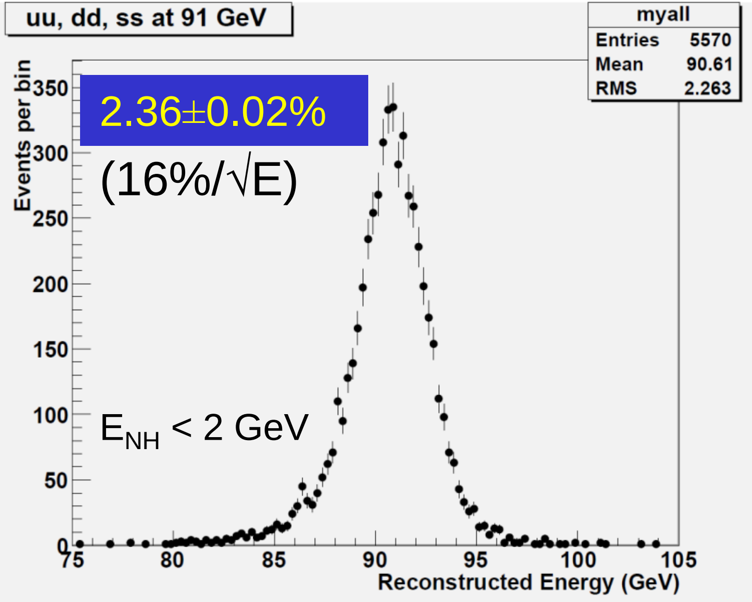


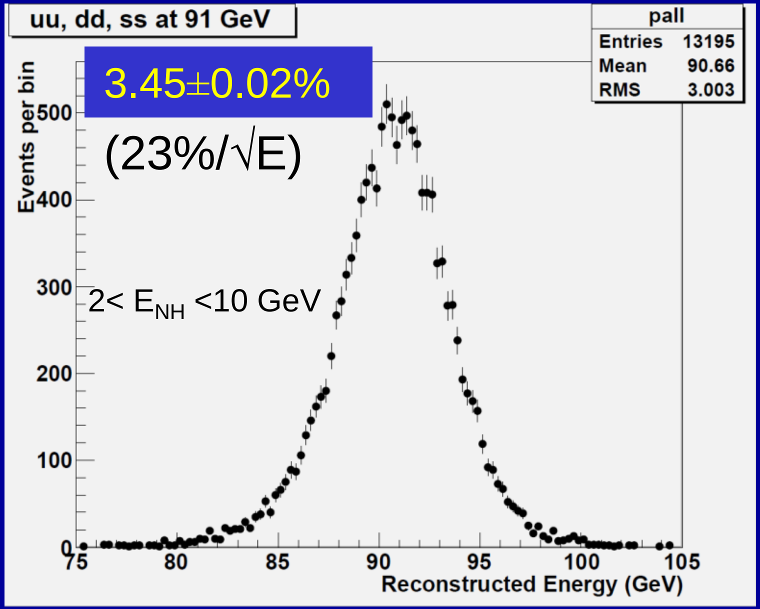


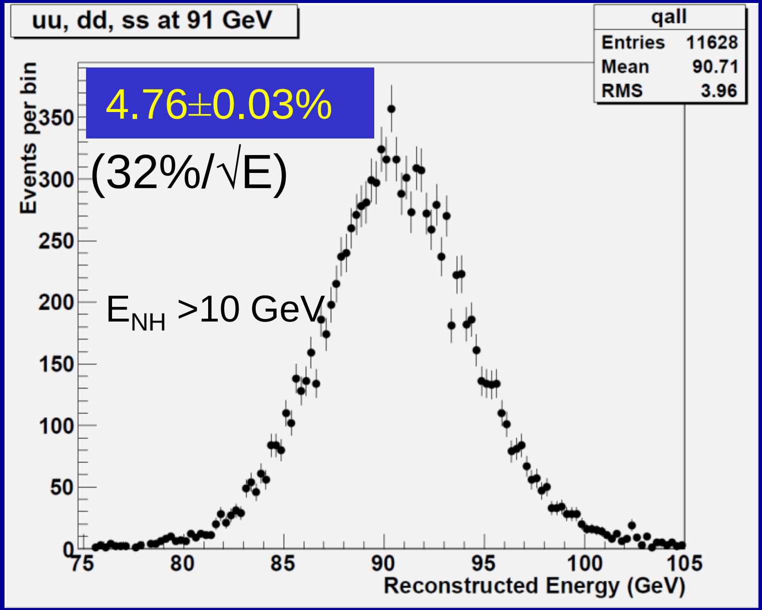
Very good jet energy resolution essential for resolving W, Z decaying hadronically.

Event-Specific Resolution

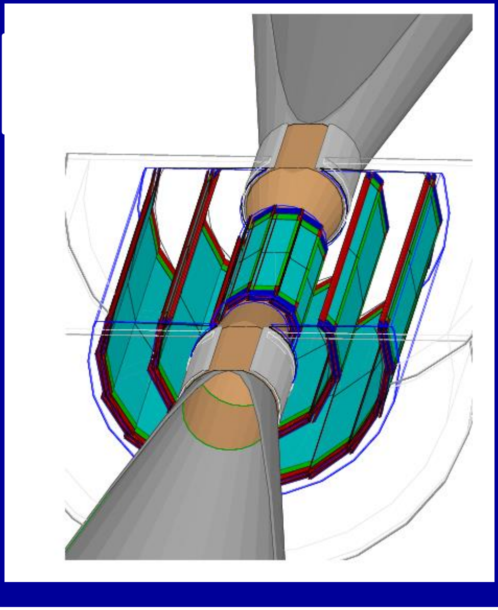








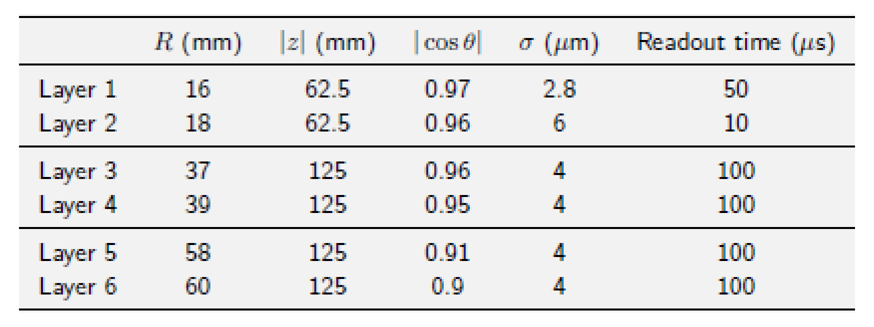
Vertex Detector



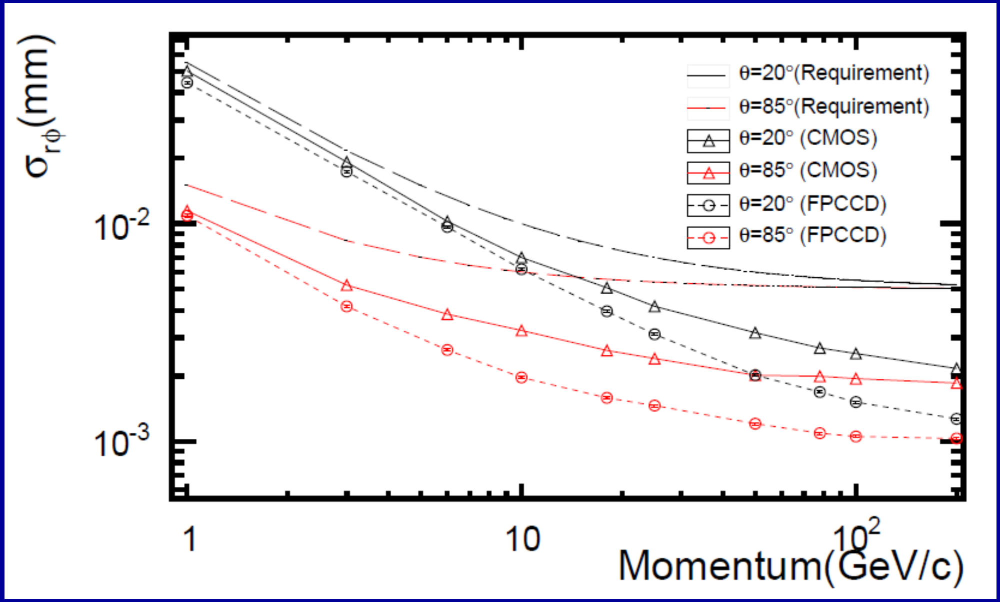
Several different technologies: pixel sensors, readout scheme, material budget. CMOS, FPCCD, DEPFET.

Pairs background => Inner radius ~ 1/√B

Baseline geometry: 3 double-layers.



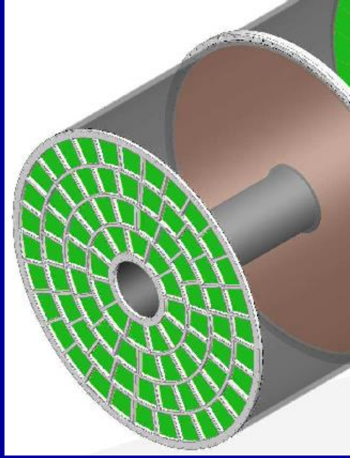
	R (mm)	$\|z\|$ (mm)	$\|\cos\theta\|$	σ (μm)	Readout time (μs)
Layer 1	16	62.5	0.97	2.8	50
Layer 2	18	62.5	0.96	6	10
Layer 3	37	125	0.96	4	100
Layer 4	39	125	0.95	4	100
Layer 5	58	125	0.91	4	100
Layer 6	60	125	0.9	4	100



CMOS and FPCCD solutions meet the design requirement of

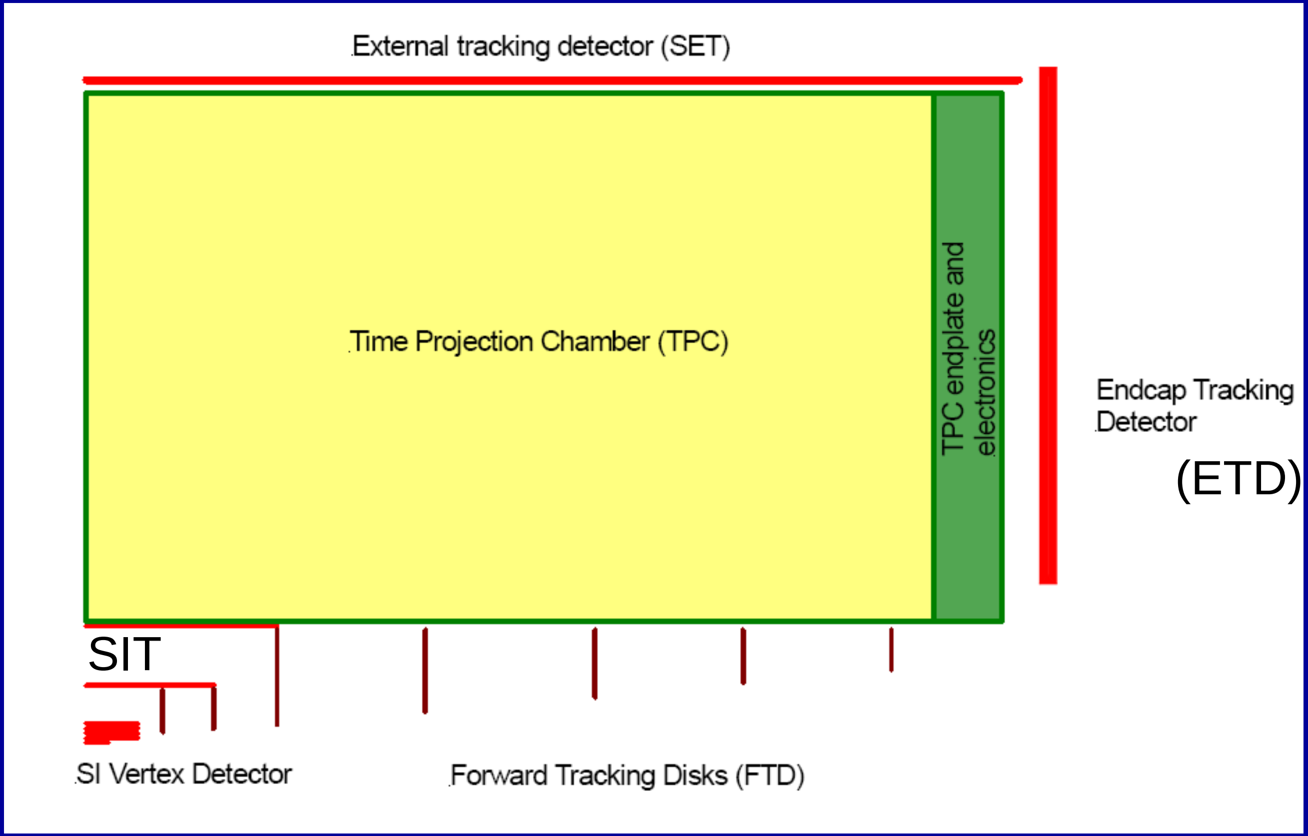
$$\sigma_b=5 \oplus 10/(\ p\ \beta\ \sin^{3/2}\theta)\ \mu\mathrm{m}$$

Main Tracker: Time Projection Chamber



Supplemented by stand-alone VTX tracking, SIT + Forward tracking disks.

SET and ETD provide precise external space-point.



3 10^9 volume pixels.

224 points per track.

Single-point resolution

50 - 100 μm r-φ,

400 μm r-z

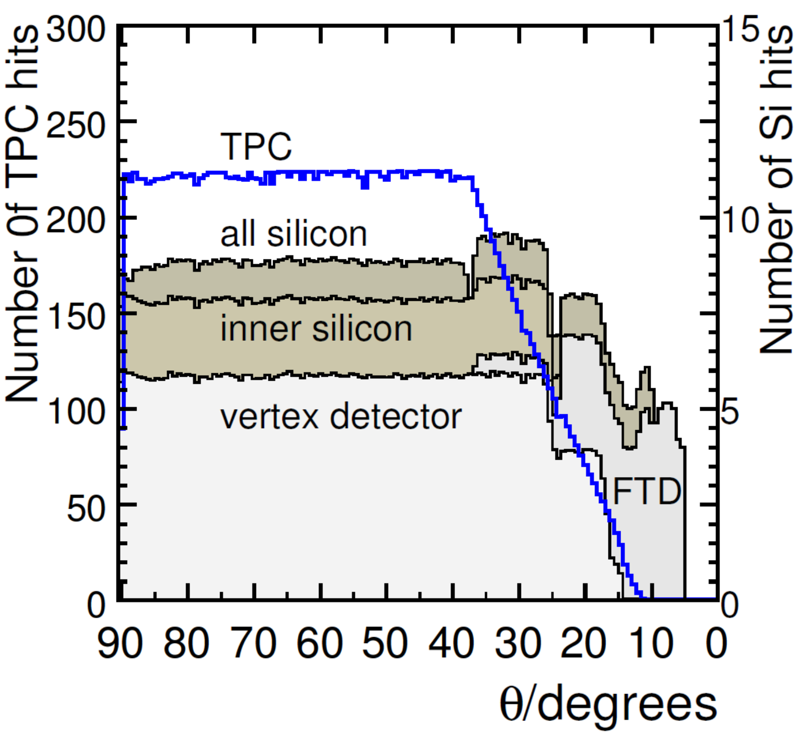
|cosθ| < 0.985 (TPC)

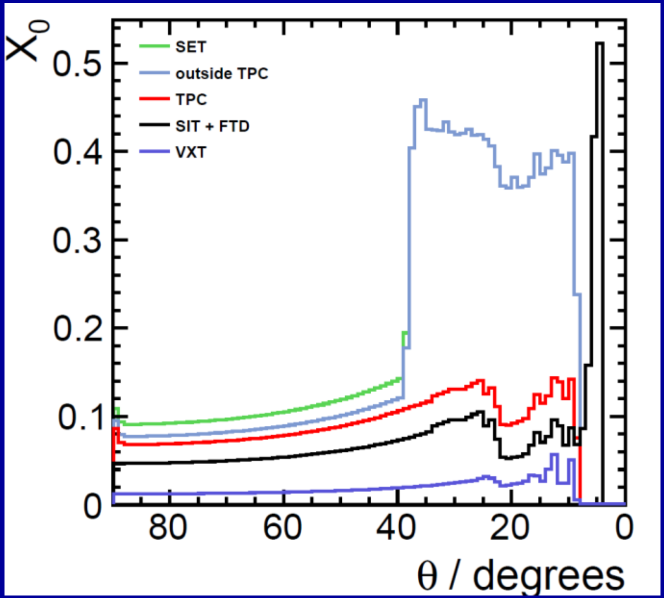
|cosθ| < 0.996 (FTD)

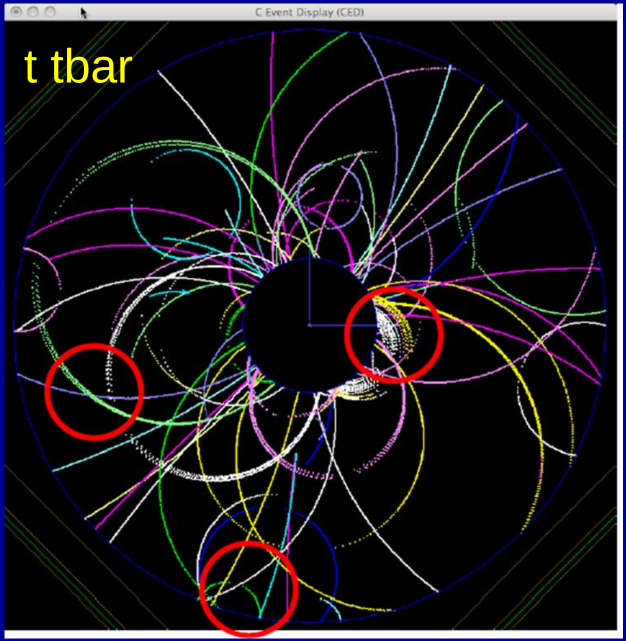
Readout options: GEM, Micromegas. Alternative: Si Pixel

SIT and FTD are essential elements of an integrated design.

Tracking System

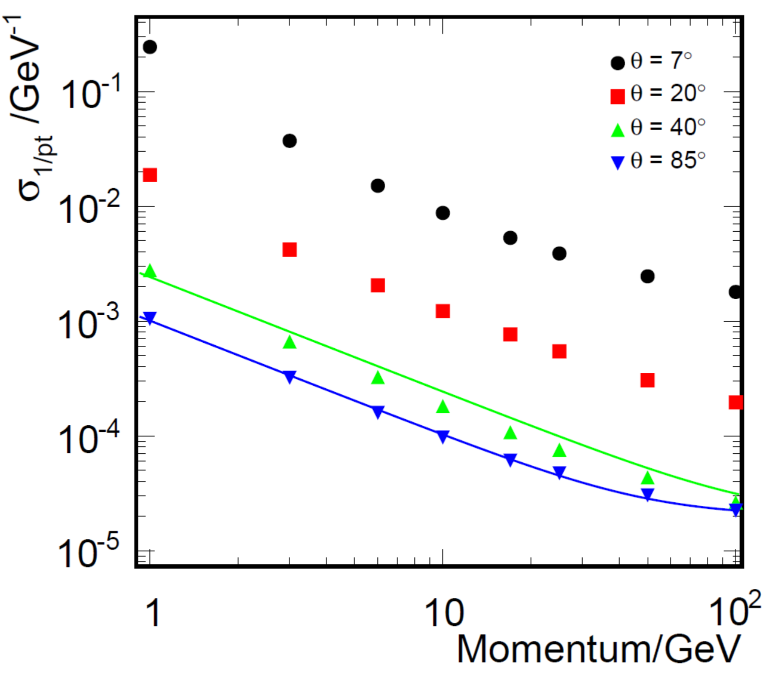






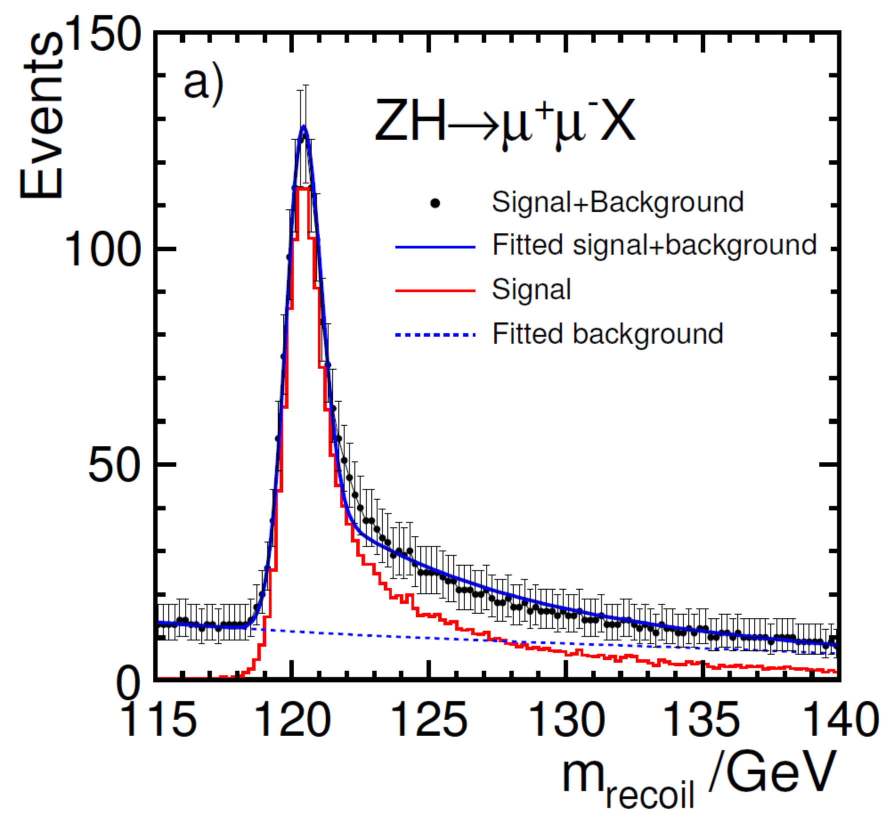
Complete TPC coverage to 37°
VTX + SIT + FTD + SET + ETD =>
precision, redundancy and coverage to
|cosθ| = 0.996.

Momentum Resolution



$$\sigma_{1/p_T} = a \oplus b/(p_T \sin\theta)$$

$$a = 2 \times 10^{-5}\,\mathrm{GeV}^{-1} \quad \text{and} \quad b = 1 \times 10^{-3}$$



$$M_X^2 = \left(p_{CM} - (p_{\mu^+} + p_{\mu^-})\right)^2$$

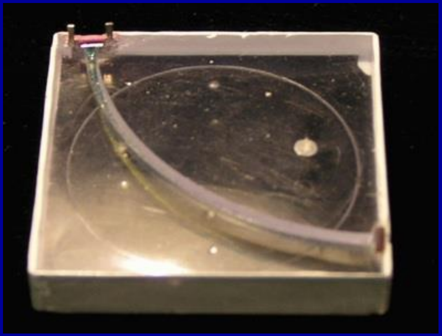
Matches well requirements from Higgs recoil measurement.

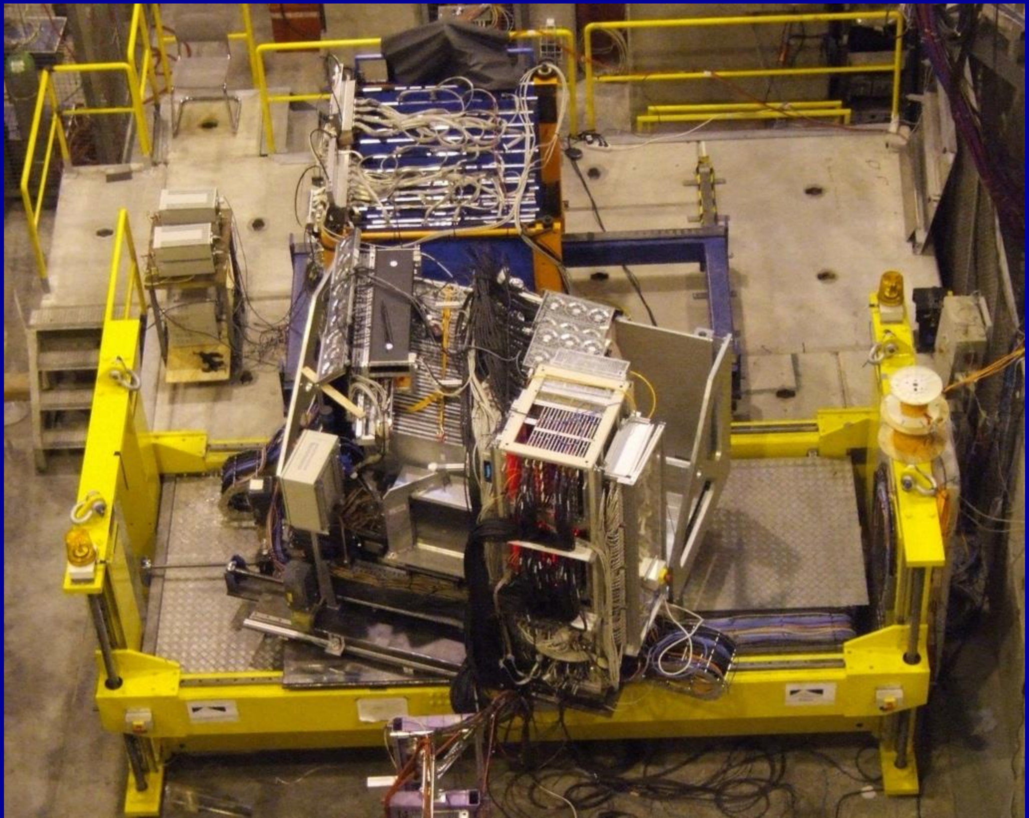
CALICE Collaboration

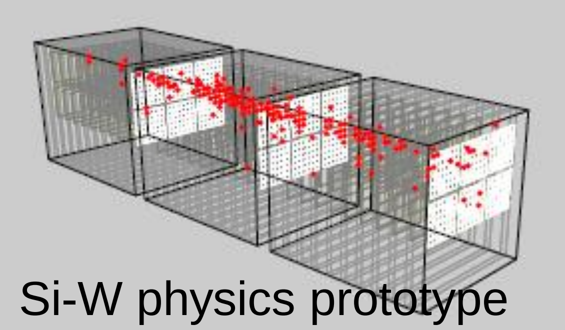
281 members, 12 countries, 47 institutes (including Argonne, Boston, Iowa, Kansas, NIU)

Framework for integrated testing of calorimeter technologies suited to a Particle-Flow collider detector

Major test-beam runs: CERN 06, 07, Fermilab 08, 09.





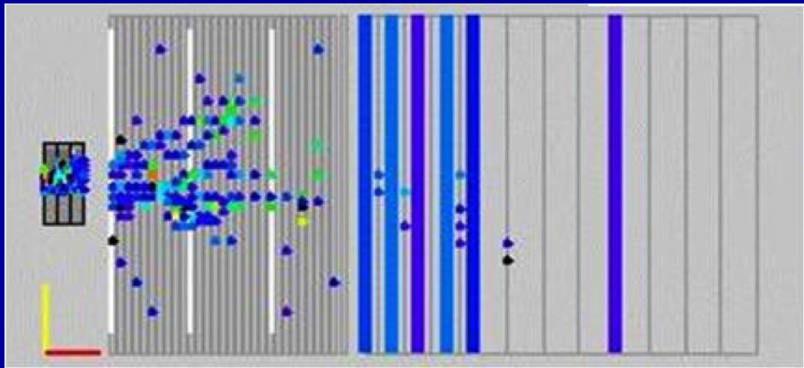


Si-W physics prototype

Si-W ECAL

Analog HCAL

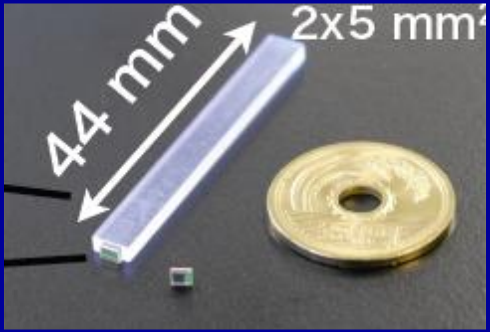
Tail-catcher / muon tracker

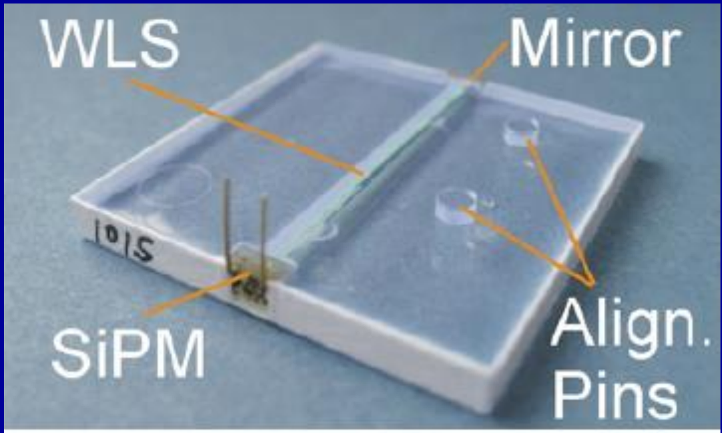


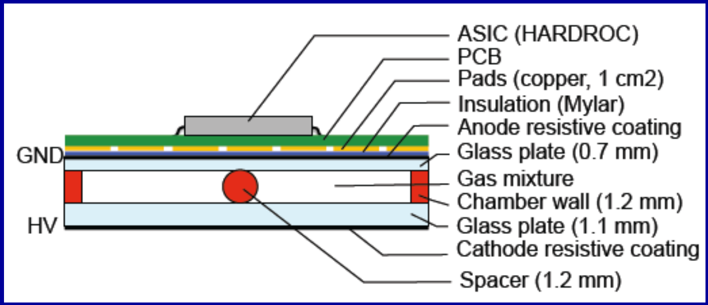
Calorimetry Technologies

All are studied by the CALICE collaboration

- ECAL (23 X_0 : 20 x 0.6 X_0 + 9 x 1.2 X_0)
  - Silicon-W
    - transverse cell-size 5mm X 5mm
  - Scintillator-W with MPPC readout
    - 5mm X 45 mm X 2mm strips
  - (Digital: MAPS)
- HCAL
  - Analog : Scintillator + Stainless Steel.
    - Tiles with Si-PM readout
    - 3mm Sc, 3cm X 3cm.
  - Digital/Semi-Digital : Gas + Stainless Steel.
    - Glass RPCs or MPGDs, 1cm X 1cm





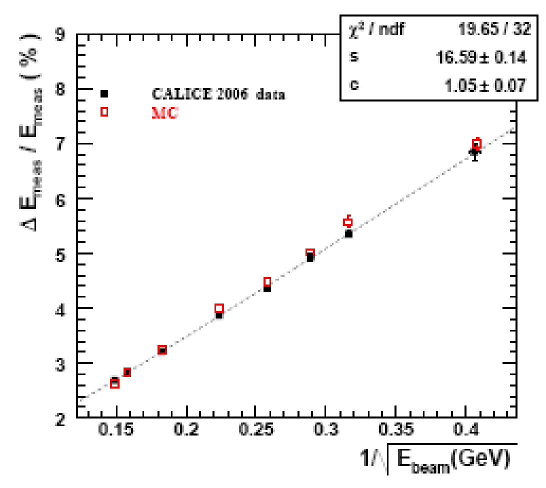


CALICE Results from Physics Prototypes

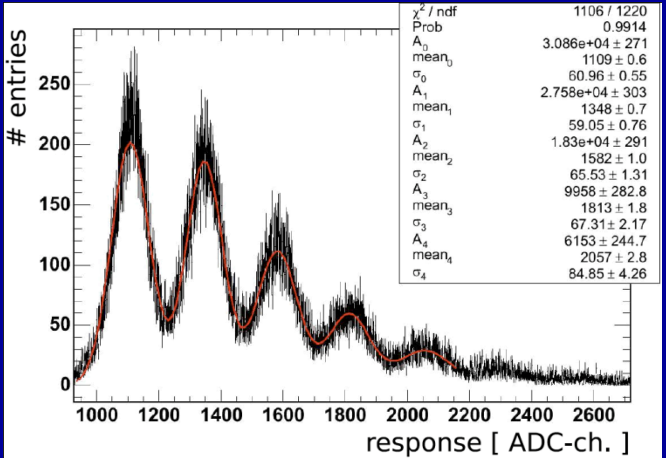
Si-W ECAL

1cm × 1cm

(6480 channels)



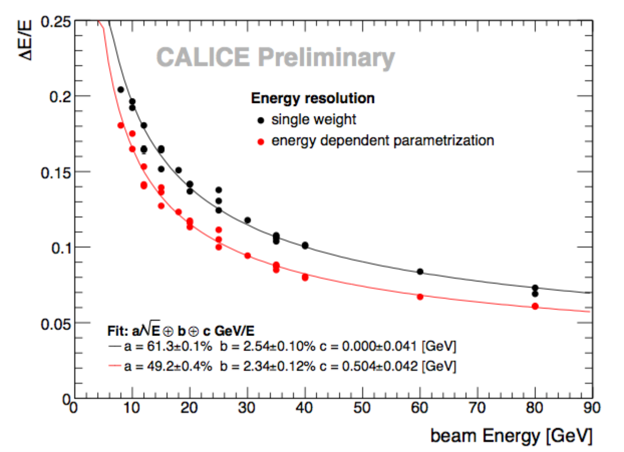
AHCAL: 7680 Si-PMs

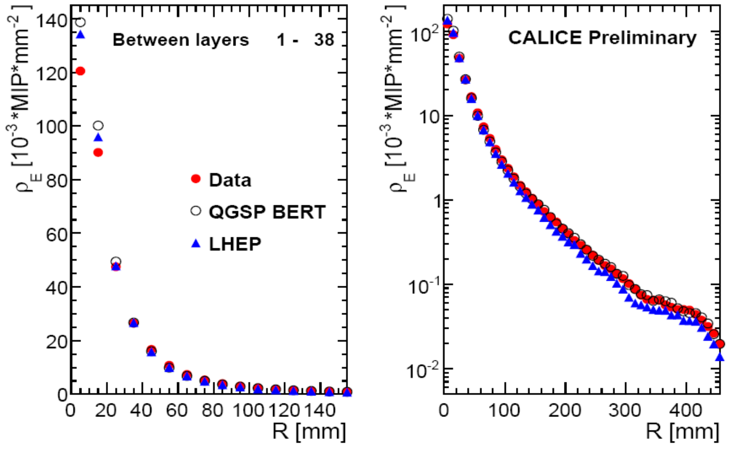


Analog (steel-scintillator) HCAL

38-layers

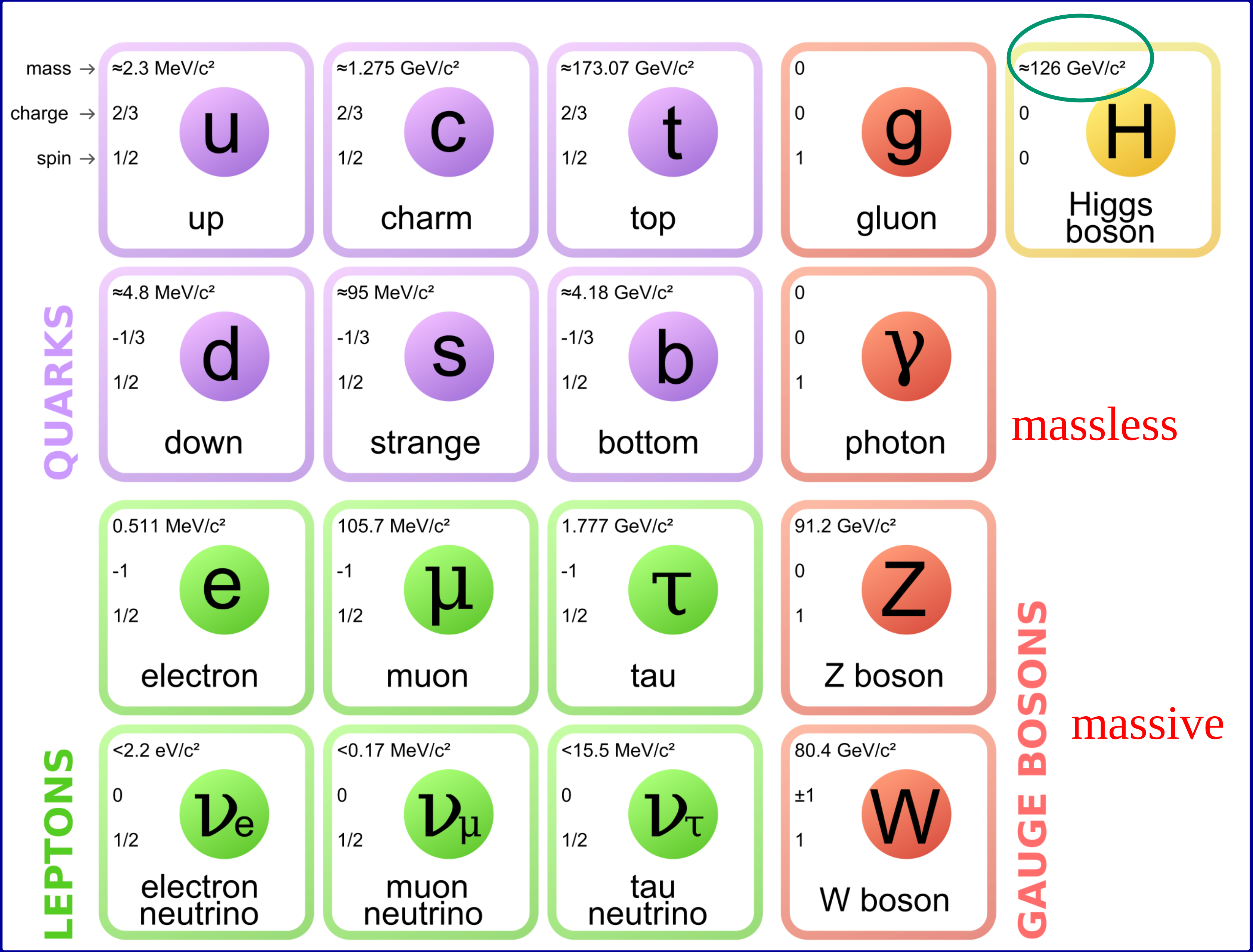
1m^3





Strong support for predicted Particle Flow performance from first-ready technologies.

Standard Model Particle Content



mass → charge → spin →	≈2.3 MeV/c^2 2/3 1/2 u up	≈1.275 GeV/c^2 2/3 1/2 c charm	≈173.07 GeV/c^2 2/3 1/2 t top	0 0 1 g gluon	≈126 GeV/c^2 0 0 H Higgs boson
QUARKS	≈4.8 MeV/c^2 -1/3 1/2 d down	≈95 MeV/c^2 -1/3 1/2 s strange	≈4.18 GeV/c^2 -1/3 1/2 b bottom	0 0 1 γ photon	massless
	0.511 MeV/c^2 -1 1/2 e electron	105.7 MeV/c^2 -1 1/2 μ muon	1.777 GeV/c^2 -1 1/2 τ tau	91.2 GeV/c^2 0 1 Z Z boson	**GAUGE BOSONS**
LEPTONS	<2.2 eV/c^2 0 1/2 ν_e electron neutrino	<0.17 MeV/c^2 0 1/2 ν_μ muon neutrino	<15.5 MeV/c^2 0 1/2 ν_τ tau neutrino	80.4 GeV/c^2 ±1 1 W W boson	massive

Electro-weak Symmetry Breaking

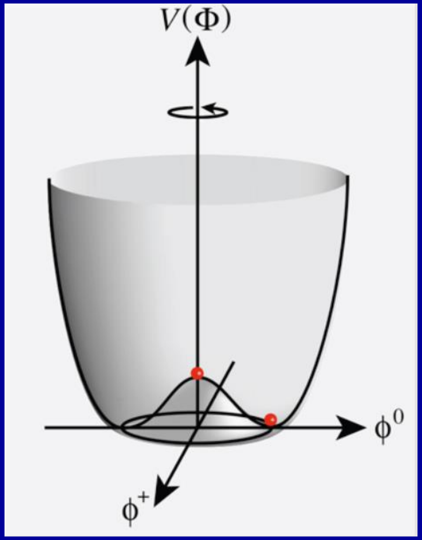
- Gauge theories are formulated with massless particles – in particular massless W and Z.
- But need massive W and Z …. while keeping the photon massless.
- Hypothesize a complex scalar doublet field. (4 degrees of freedom).
- 3 are used to give mass to the W^+, W^- and Z.
- 1 remnant dof is the scalar particle of the SM commonly called the SM Higgs boson

Higgs Concepts

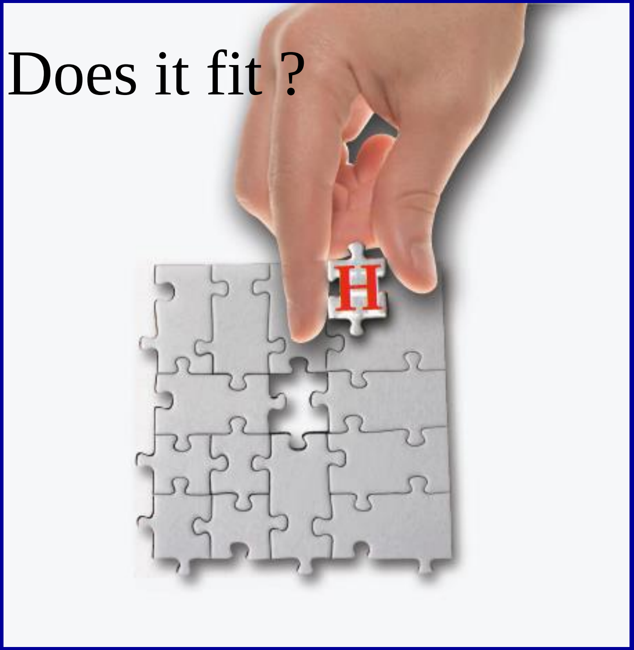
Anderson, Brout, Englert, Higgs, Guralnik, Hagen, Kibble, Weinberg...

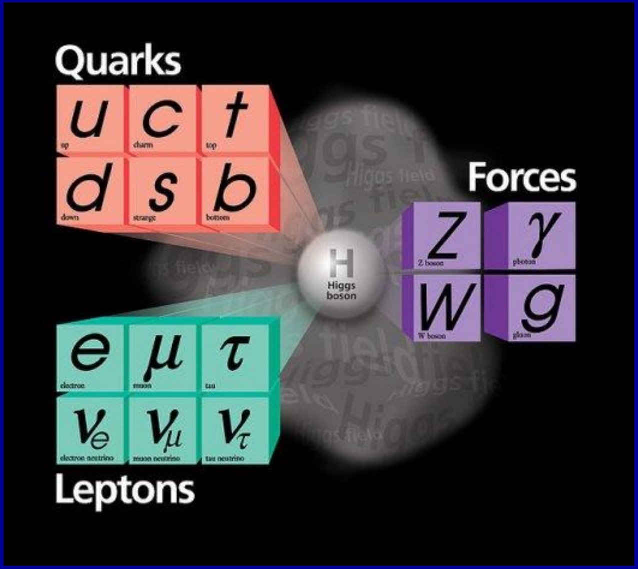
1960’s …

- Higgs Mechanism
  - The spontaneous symmetry breaking mechanism in which the W and Z become massive
- Higgs Particle
  - The most obvious initially testable consequence
- Higgs Field
  - A new universal scalar field thought to be present throughout the universe posited to endow all elementary particles with their mass



Higgs Puzzle


Does it fit ?



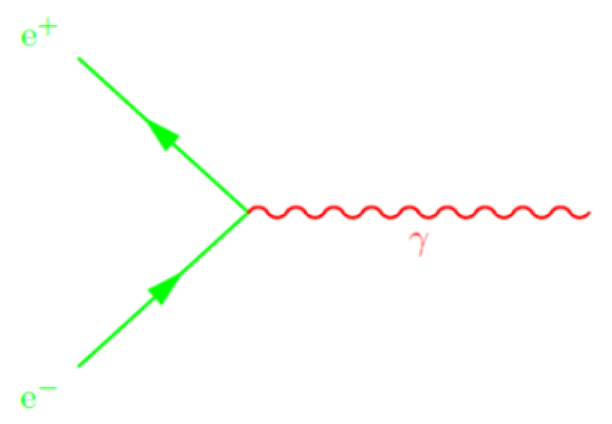
“Energy frontier” main themes are:

- 1. Measure properties of the Higgs boson
- 2. Measure properties of the t, W and Z
- 3. Direct search for new particles

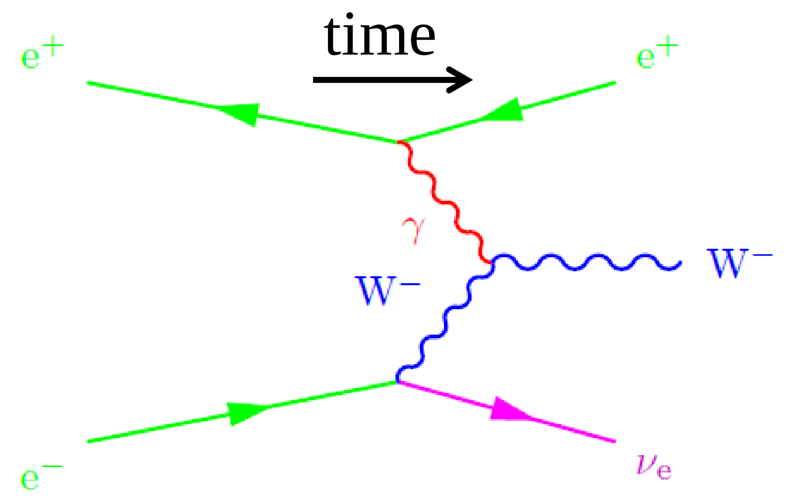
- All will be advanced by the LHC.
- Particularly 1, 2 will be advanced much further with ILC

Standard Model of Particle Physics

$SU(3)_C \times SU(2)_L \times U(1)_Y$

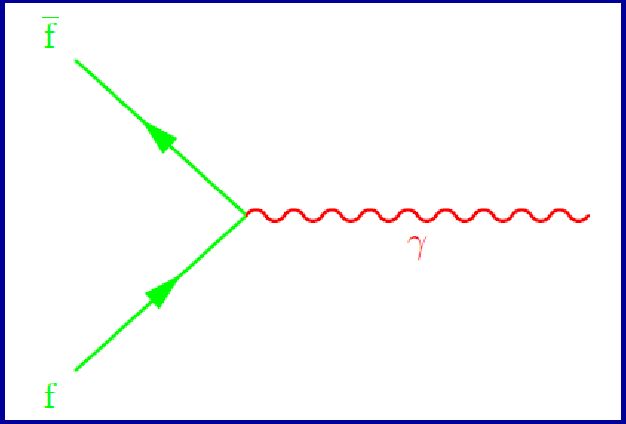


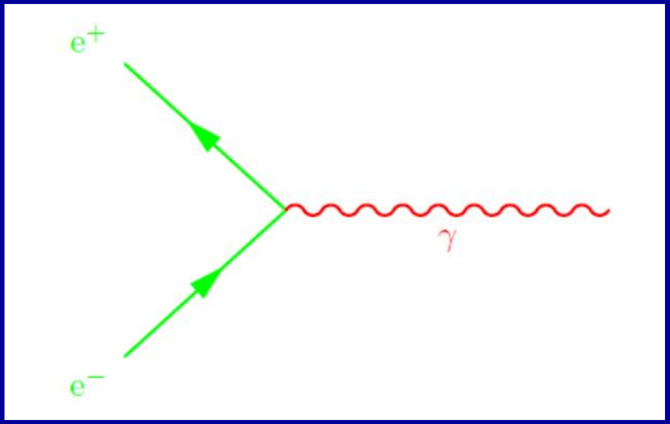
- The fermions interact via gauge bosons.
- The allowed vertices encapsulate the essence of the physics.
- Feynman diagrams for allowed process can be constructed from the allowed vertices.
- Can calculate interaction rates etc
- Example $e^+e^- \rightarrow e^+ W^- \nu_e$



Standard Model of Particle Physics

$SU(3)_C$ x $SU(2)_L$ x $\mathbf{U(1)_Y}$



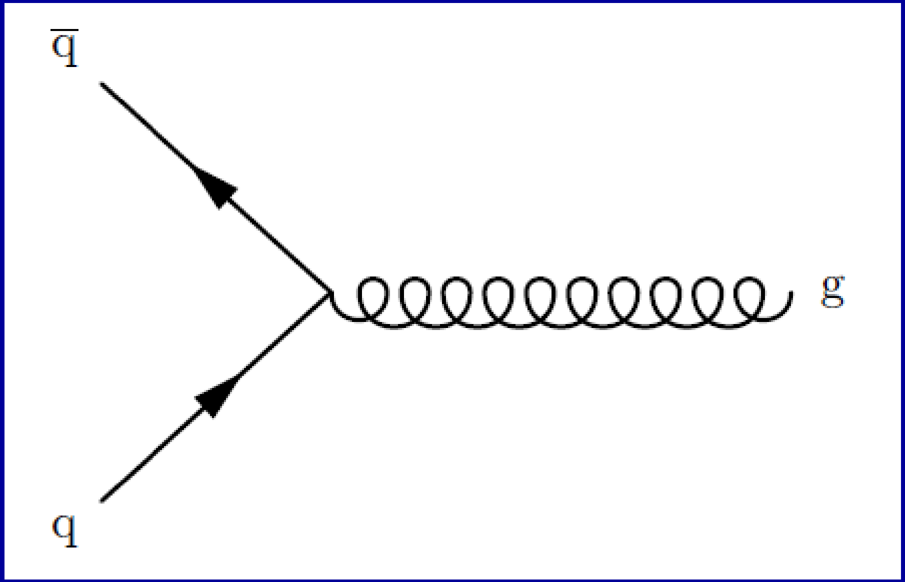


Charged fermions couple to photons: Quantum Electrodynamics (QED).

Not just for the electron, but for f = e, μ, τ, u, d, c, s, b, t, with coupling proportional to Q_f

Standard Model of Particle Physics

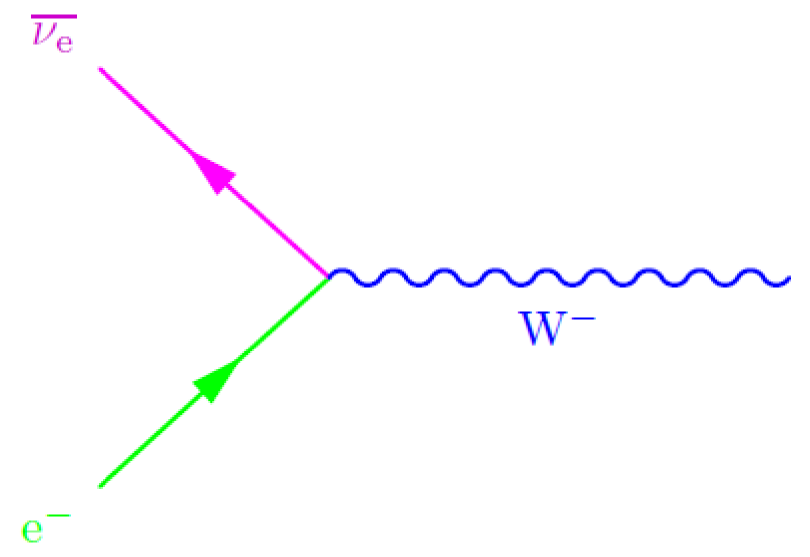
$\mathbf{SU(3)_C}$ x $SU(2)_L$ x $U(1)_Y$

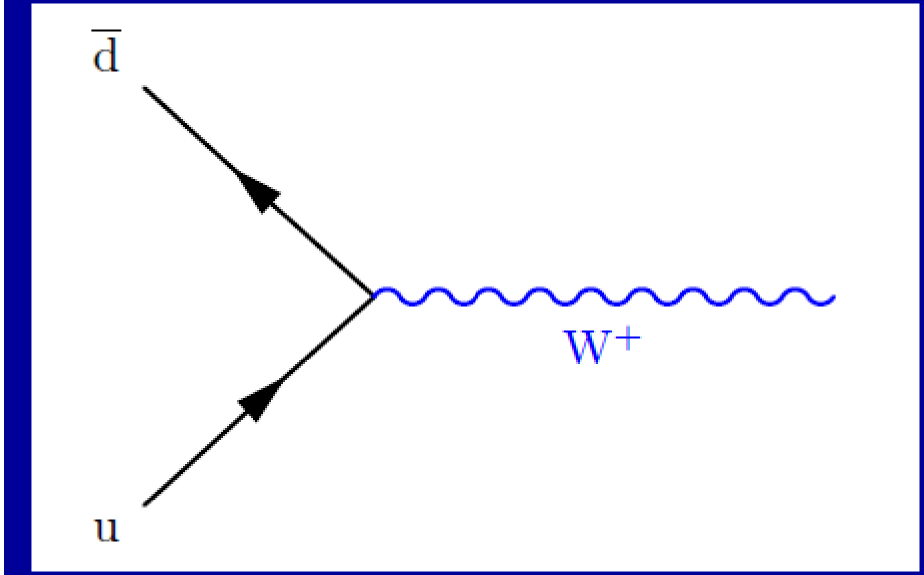


Quarks couple to gluons:
Quantum Chromo-Dynamics (QCD).
For q = u, d, c, s, b, t

Standard Model of Particle Physics

$\mathrm{SU}(3)_C$ x $\mathbf{SU(2)}_L$ x $\mathrm{U}(1)_Y$

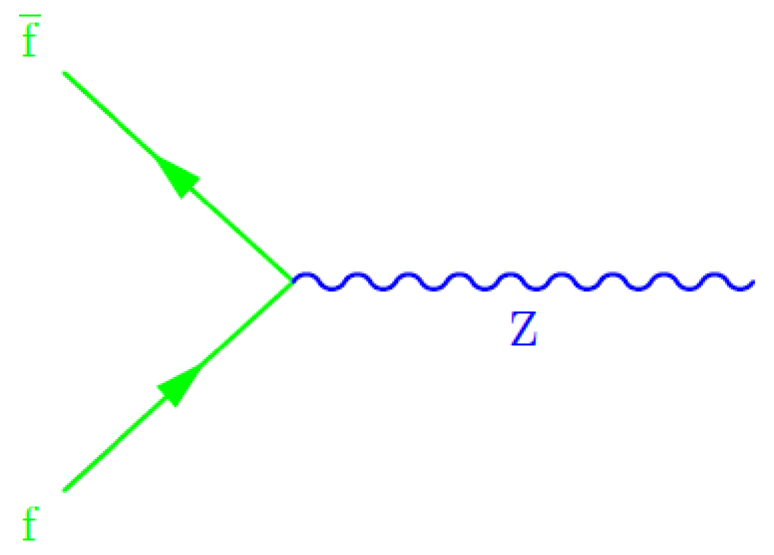


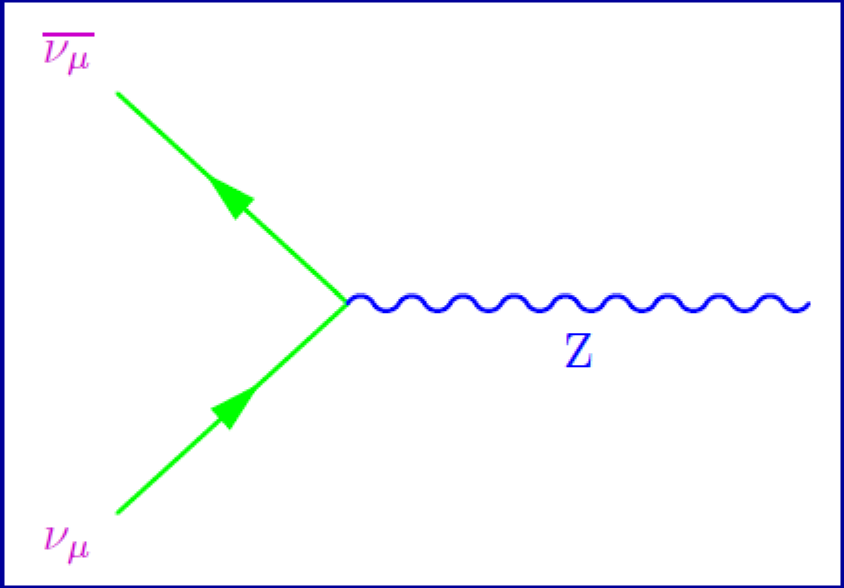


Fermions couple to the charged W bosons (Electro-weak).
The weak nuclear force as in β-decay.

Standard Model of Particle Physics

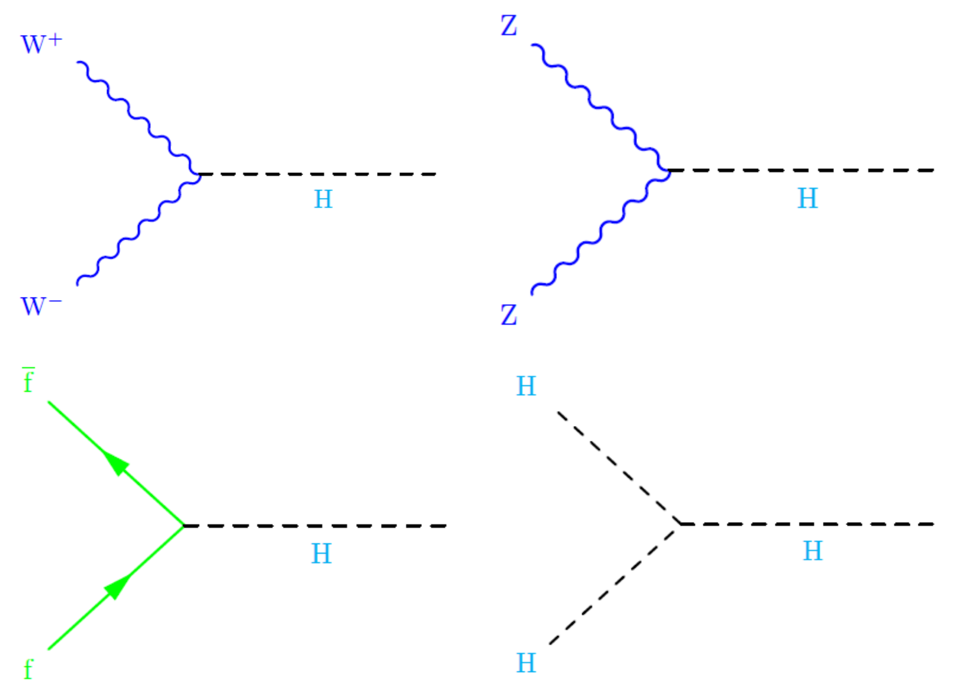
$SU(3)_C$ x **$SU(2)_L$ x $U(1)_Y$**

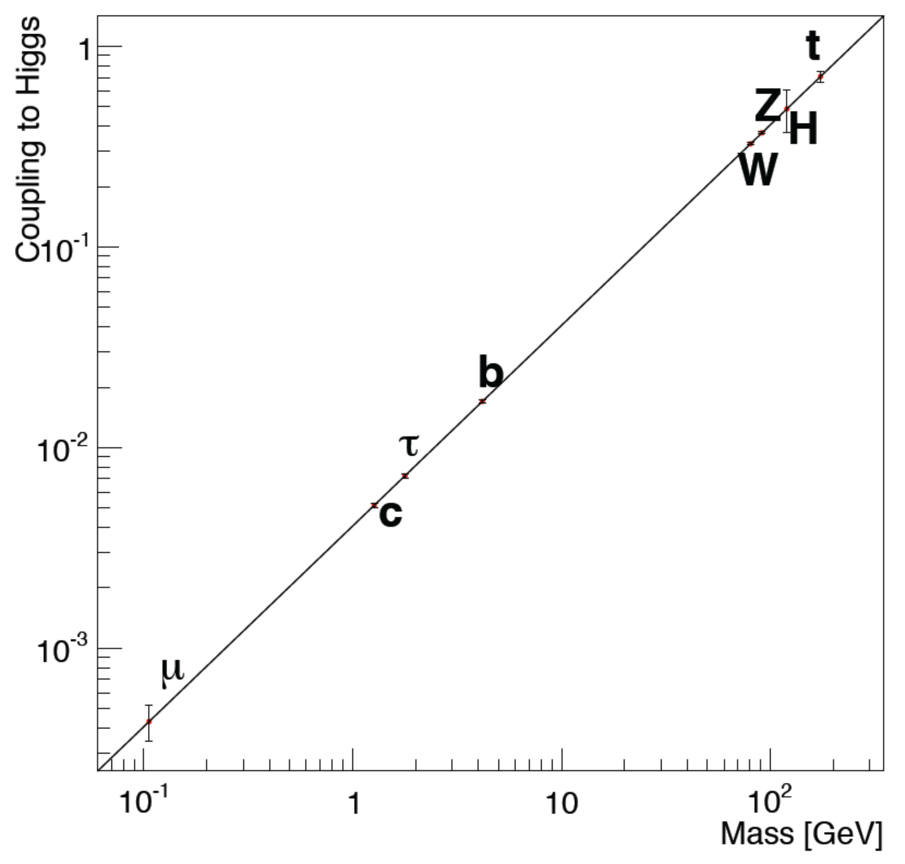




Fermions couple to Z bosons (Electro-weak).
“Heavy-photon”.
The allowed ffZ vertices include the same ones as for ffγ, but with the addition of ννZ.

Higgs Interactions

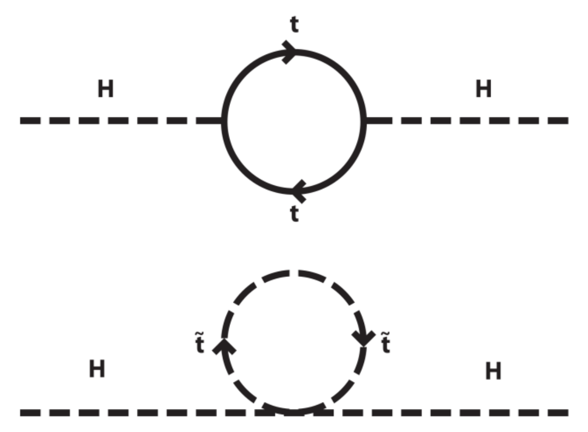




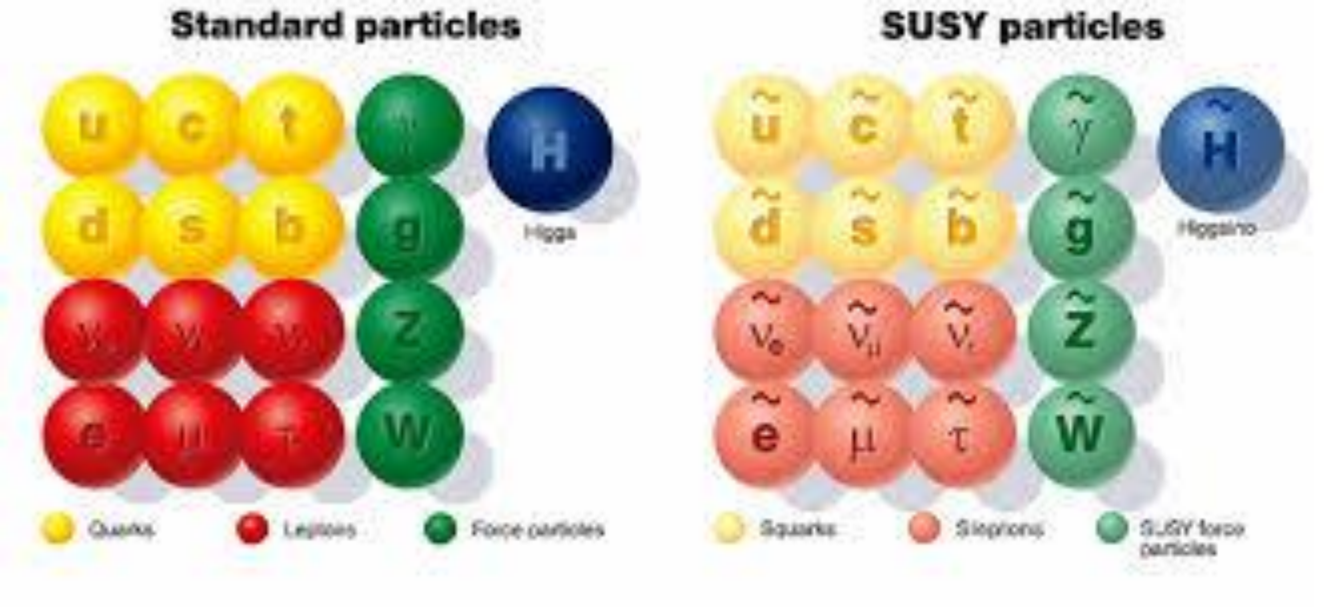
Couplings depend on mass of the particle.
Higgs also couples to itself with a coupling depending on its mass.

Beyond the Standard Model ?

Quantum corrections to the Higgs mass likely drive it close to the Planck mass (10^{19} GeV). To naturally explain a 126 GeV Higgs – need some new physics at or below the TeV scale to cancel these divergent corrections.

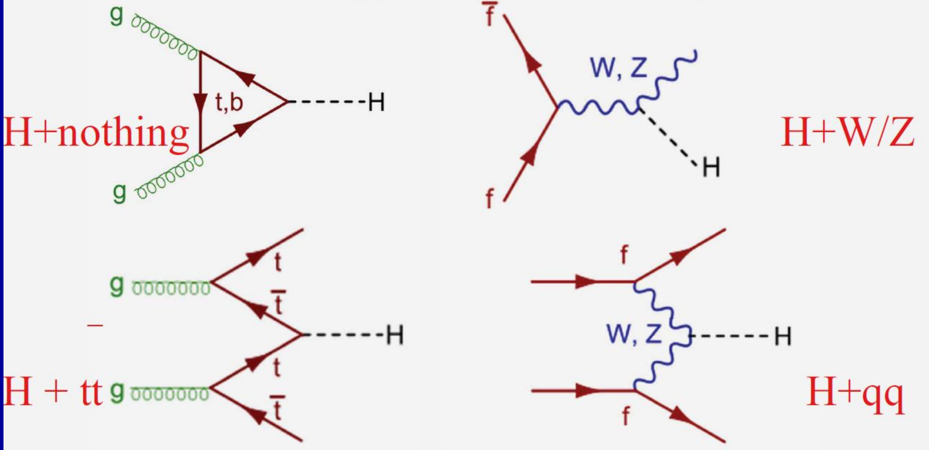


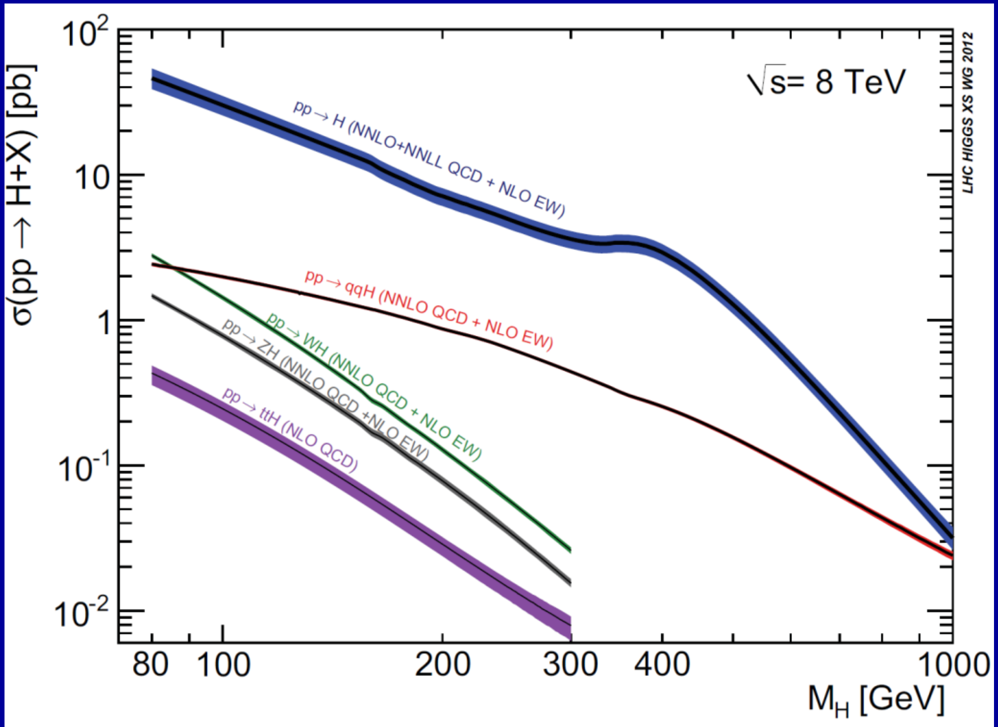
The leading framework is supersymmetry (SUSY) which posits a whole new set of particles including a particle physics candidate for dark matter.

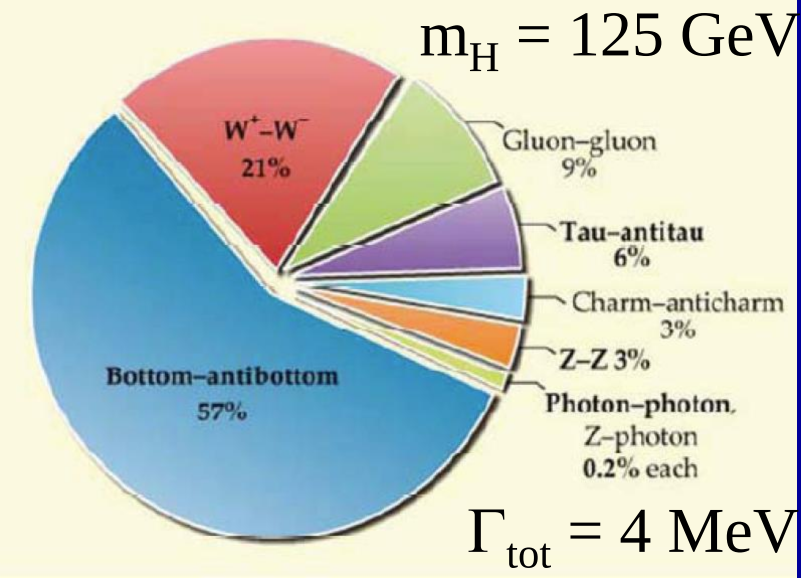


1. Higgs exists
2. But no evidence so far for sparticles.

SM Higgs Production and Decay







$m_H = 125$ GeV

$\Gamma_{tot} = 4$ MeV

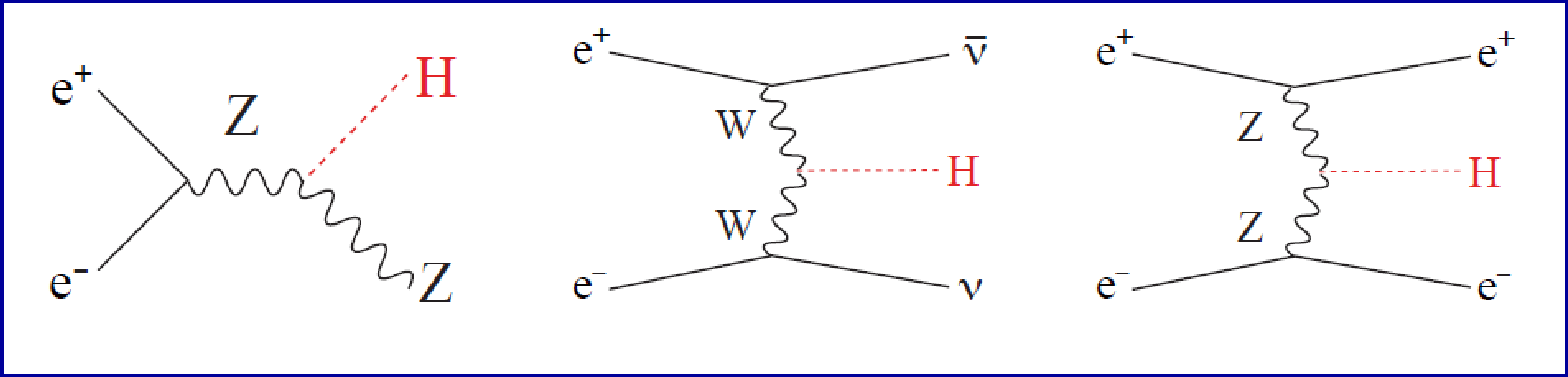
Best options at LHC are gluon-gluon fusion production of H (can reconstruct the mass)

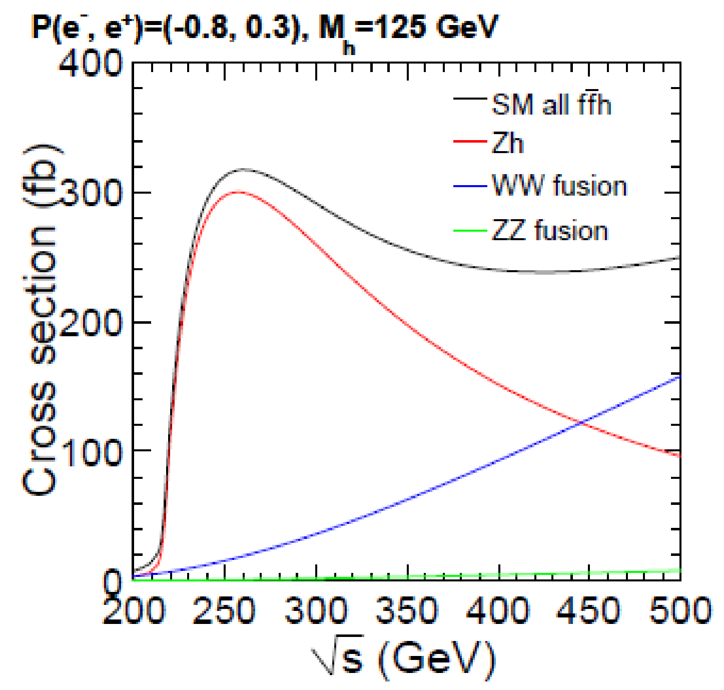
i) $H \to \gamma\,\gamma$ (0.2%)

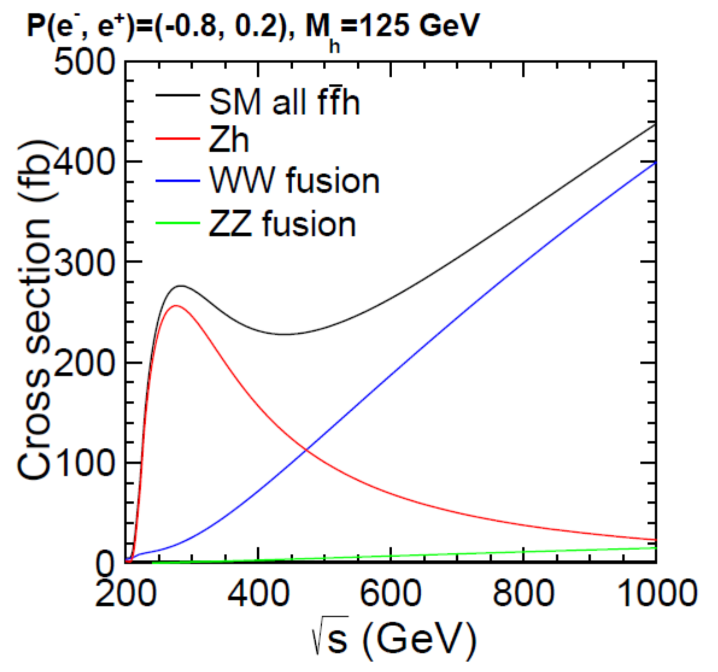
ii) $H \to Z\,Z^* \to 4$ leptons (0.013% !)

(Many more obvious channels are not experimentally viable)

SM Higgs Production at ILC



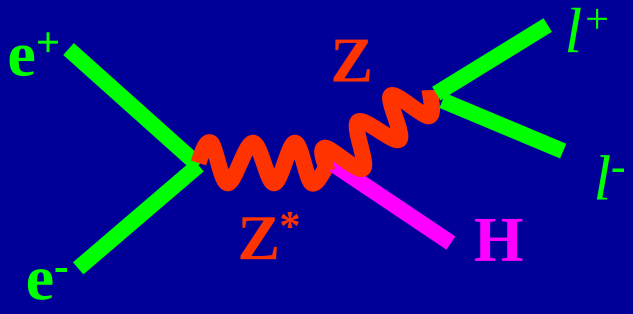




Sensitive to all production and decay modes including hadronic decays of Z and H

Higgs Measurements

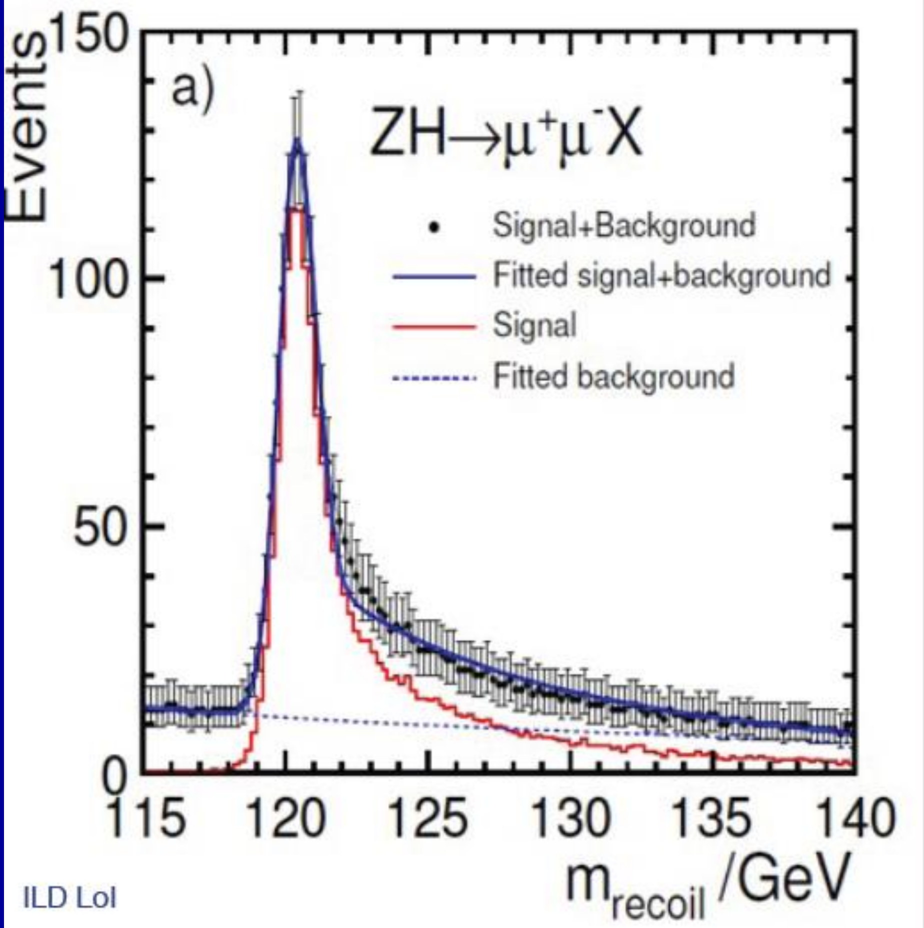
At ILC : (6% of Z decays)



Higgs mass measured from di-lepton recoil mass :

Linear collider can find Higgs events no matter how the Higgs decays. **Even invisibly !**

Can measure ZH cross-section directly



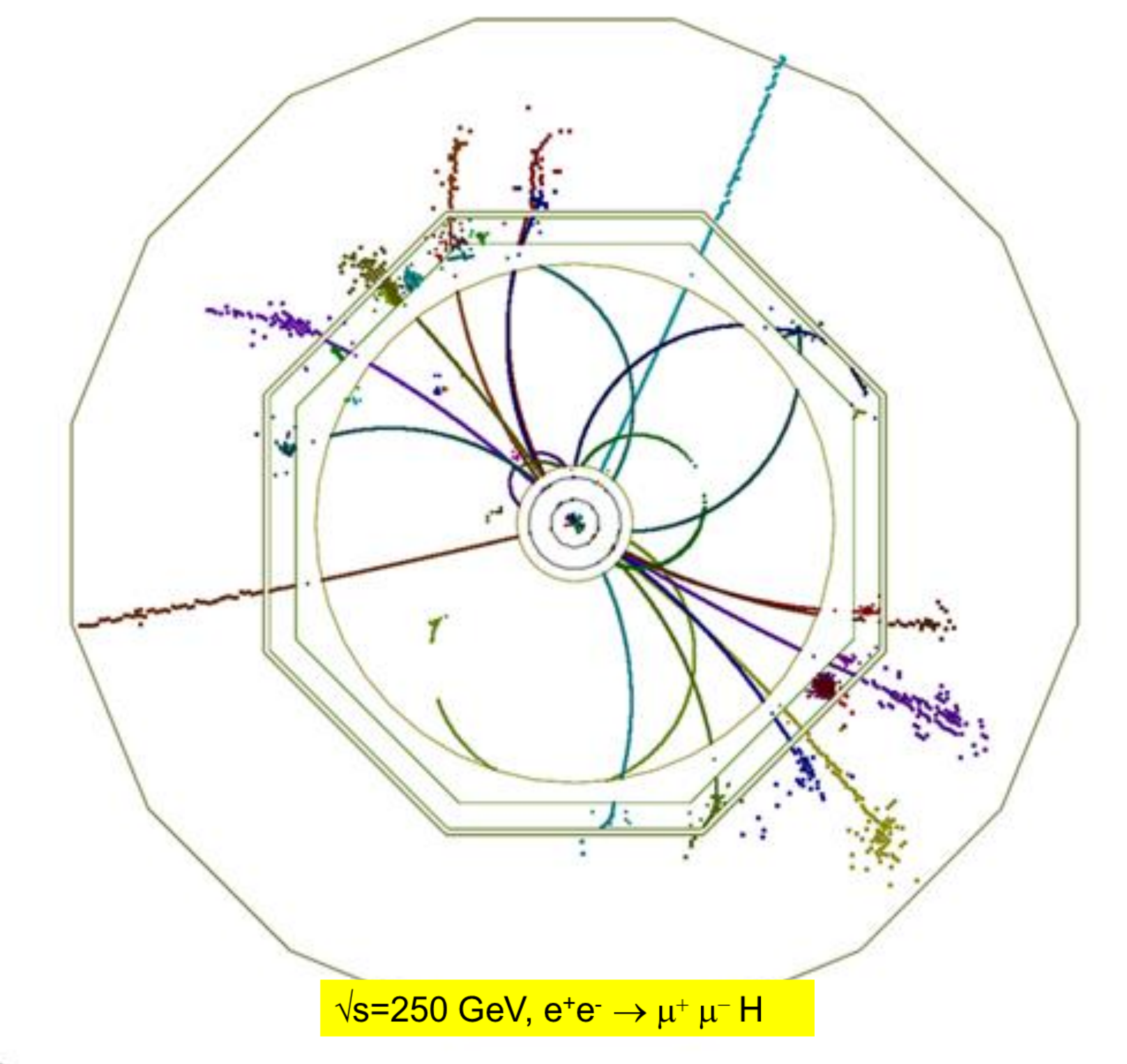
$$M_X^2 = (p_{CM} - (p_{\mu^+} + p_{\mu^-}))^2$$

Branching ratio measurements follow: does Higgs couple to mass ?

This Event Again

Spot the muons ?

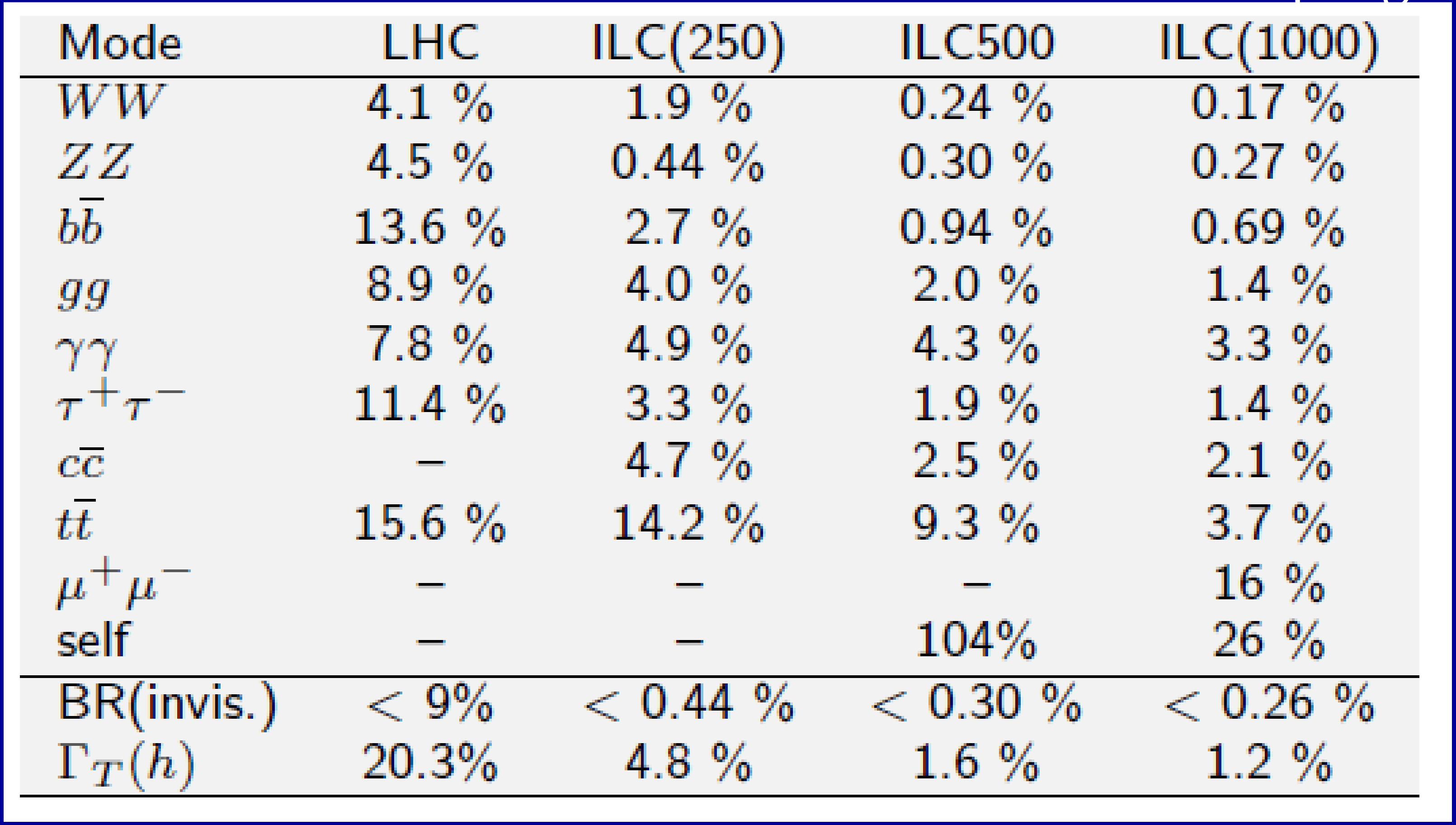
Recoil – mass.



$\sqrt{s}$=250 GeV, $e^+e^- \rightarrow \mu^+ \mu^- H$

Higgs Measurement Prospects

couplings



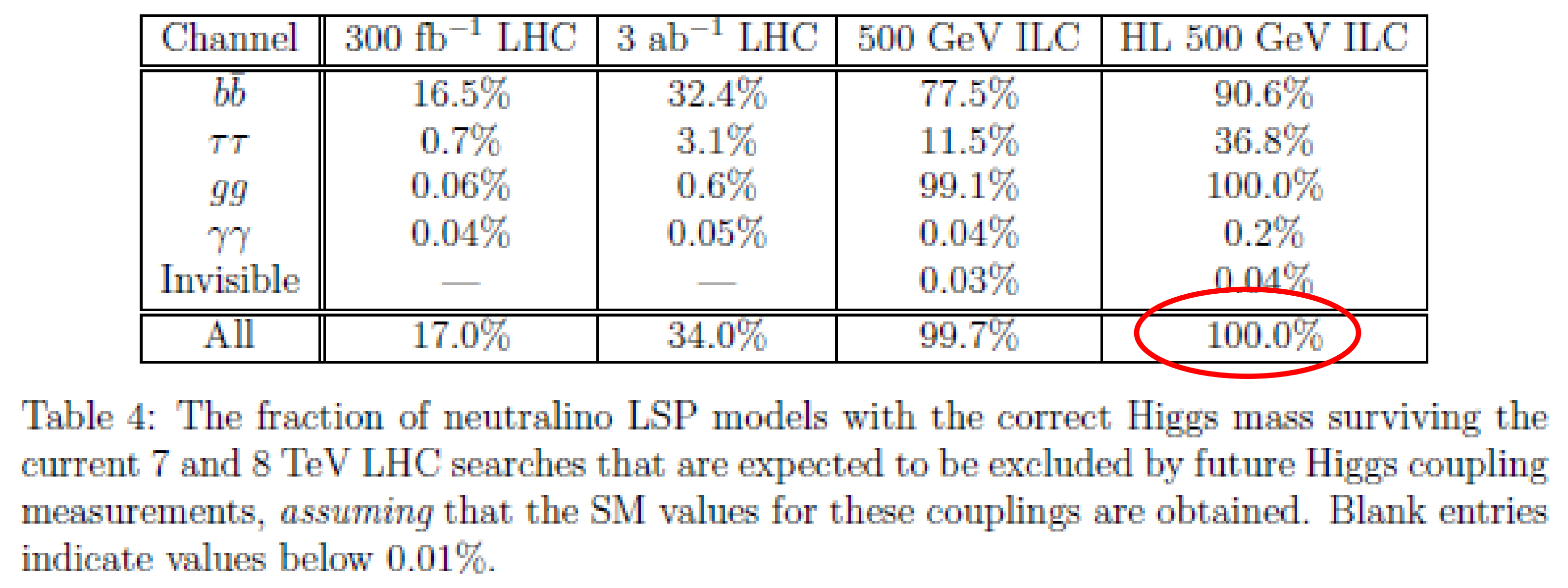
Mode	LHC	ILC(250)	ILC500	ILC(1000)
WW	4.1 %	1.9 %	0.24 %	0.17 %
ZZ	4.5 %	0.44 %	0.30 %	0.27 %
$b\bar{b}$	13.6 %	2.7 %	0.94 %	0.69 %
gg	8.9 %	4.0 %	2.0 %	1.4 %
$\gamma\gamma$	7.8 %	4.9 %	4.3 %	3.3 %
$\tau^+\tau^-$	11.4 %	3.3 %	1.9 %	1.4 %
$c\bar{c}$	–	4.7 %	2.5 %	2.1 %
$t\bar{t}$	15.6 %	14.2 %	9.3 %	3.7 %
$\mu^+\mu^-$	–	–	–	16 %
self	–	–	104%	26 %
BR(invis.)	$< 9\%$	$< 0.44\ \%$	$< 0.30\ \%$	$< 0.26\ \%$
$\Gamma_T(h)$	20.3%	4.8 %	1.6 %	1.2 %

ILC quantitatively and qualitatively can probe Higgs couplings at the few % level where deviations from the SM may be expected.

Is that precision and uniqueness really useful ?

The phenomenological MSSM (pMSSM) has 19 parameters.

Cahill-Rowley et al, 1308.0297



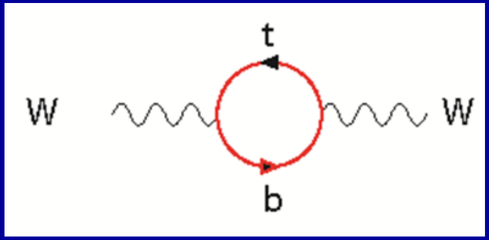
Channel	300 fb^{-1} LHC	3 ab^{-1} LHC	500 GeV ILC	HL 500 GeV ILC
$b\bar{b}$	16.5%	32.4%	77.5%	90.6%
$\tau\tau$	0.7%	3.1%	11.5%	36.8%
gg	0.06%	0.6%	99.1%	100.0%
$\gamma\gamma$	0.04%	0.05%	0.04%	0.2%
Invisible	—	—	0.03%	0.04%
All	17.0%	34.0%	99.7%	100.0%

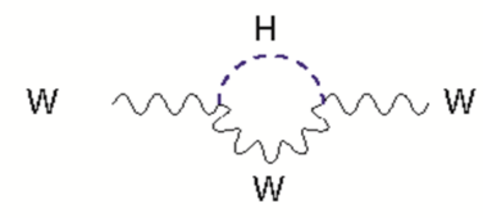
Table 4: The fraction of neutralino LSP models with the correct Higgs mass surviving the current 7 and 8 TeV LHC searches that are expected to be excluded by future Higgs coupling measurements, *assuming* that the SM values for these couplings are obtained. Blank entries indicate values below 0.01%.

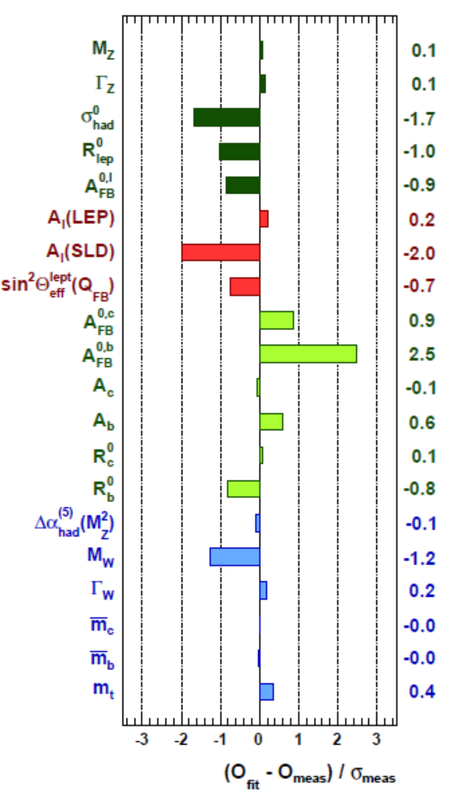
Lessons: 1. H to b bbar important channel at LHC

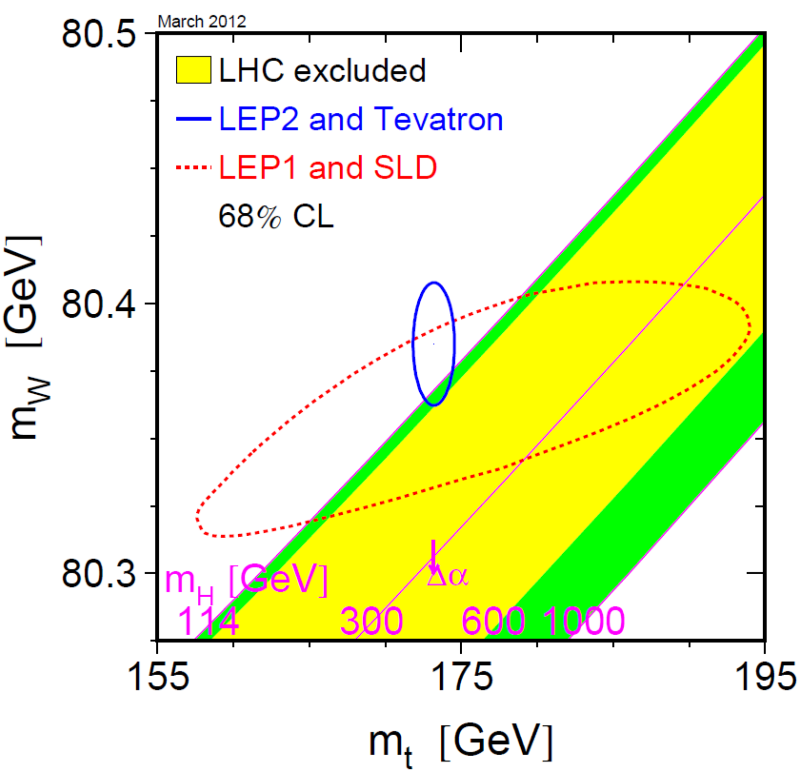
2. ILC Higgs measurements can exclude ALL SUSY model points. (prior has masses below 4 TeV)

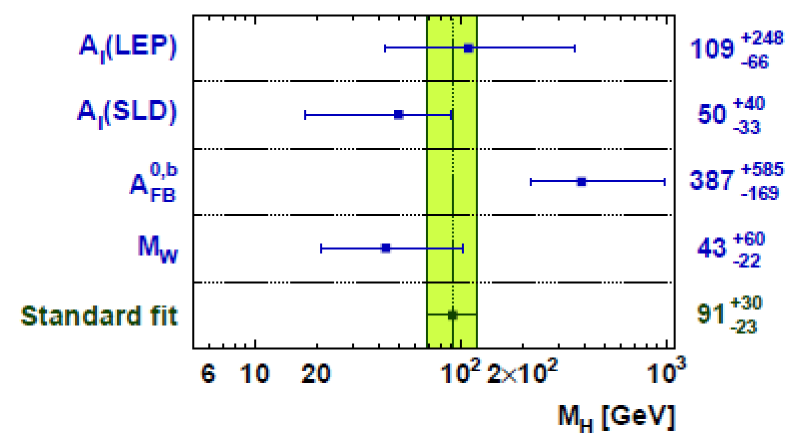
Precision Electroweak - 2011







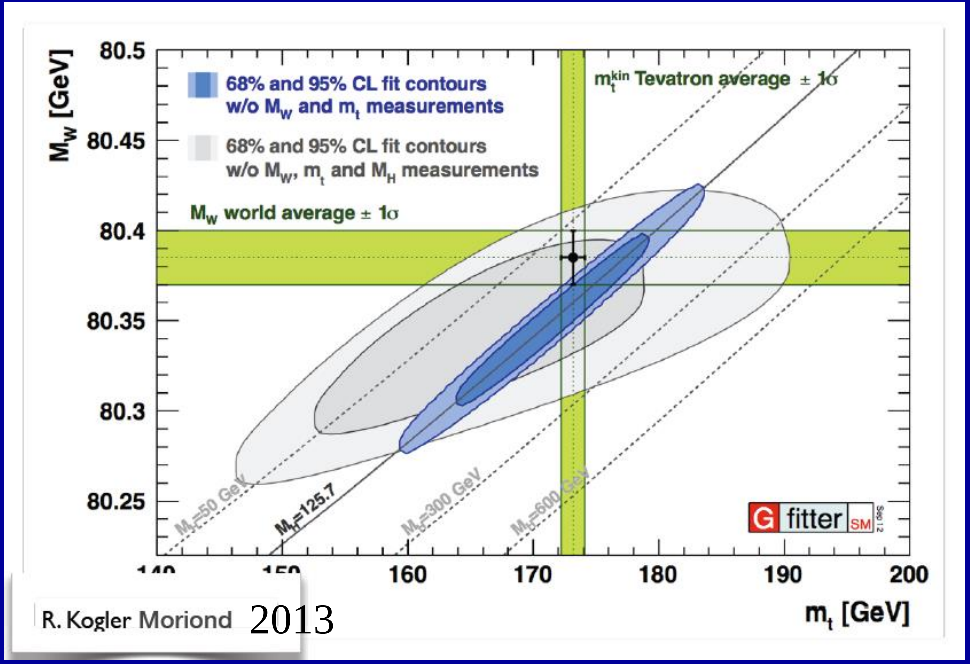




Data have been indicating a light Higgs for quite some time.

Precision Measurements

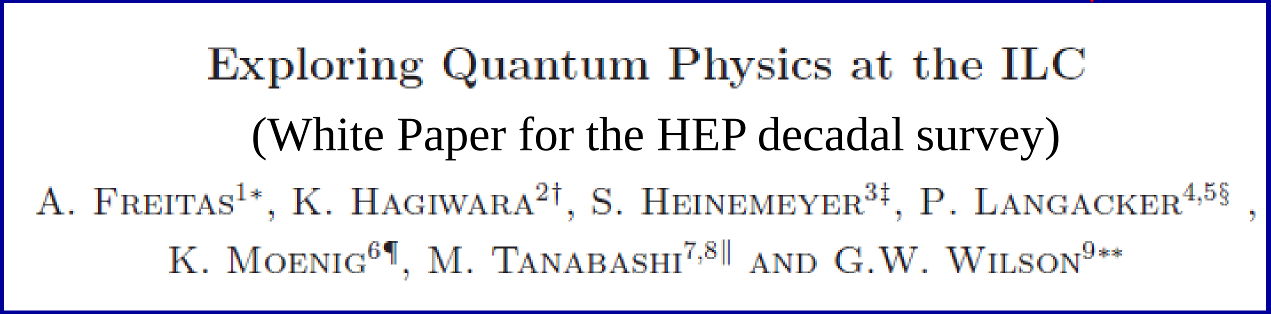
Testing Nature at ILC.
Can measure mW, mt, mH, ALR. mZ? with unprecedented precision.



R. Kogler Moriond 2013

Experimental reach depends on ability to control systematics such as those associated with the beam energy measurement and detector energy scales. I've been working on these aspects.

arXiv: 1307.3962

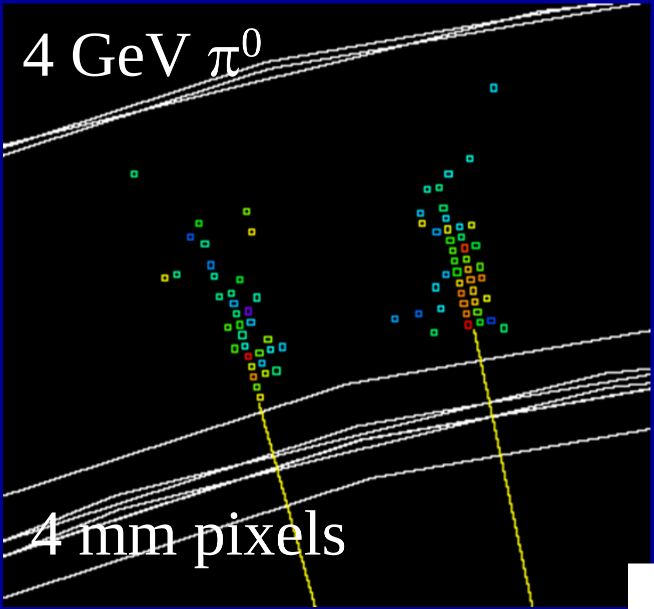


Exploring Quantum Physics at the ILC

(White Paper for the HEP decadal survey)

A. Freitas[1*], K. Hagiwara[2†], S. Heinemeyer[3‡], P. Langacker[4,5§] , K. Moenig[6¶], M. Tanabashi[7,8‖] and G.W. Wilson[9**]

Pi0 Fitting



GWW and Brian van Doren

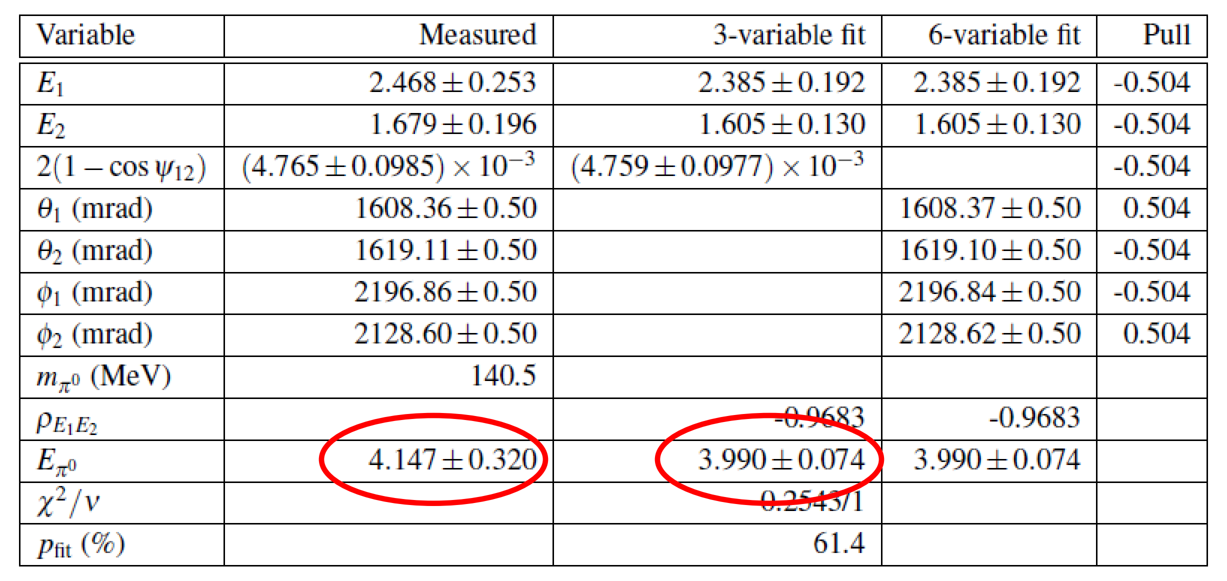
$$\pi^0 \rightarrow \gamma_1\gamma_2 \ (98.8\%)$$

$$m^2 = 2E_1E_2(1-\cos\psi_{12})$$

We know m=134.9766 ± 0.0006 MeV

$$\chi^2(\mathbf{x}) = f(\mathbf{x}) = (\mathbf{x}-\mathbf{x}_M)^T\,\mathbf{V}_M^{-1}\,(\mathbf{x}-\mathbf{x}_M)$$

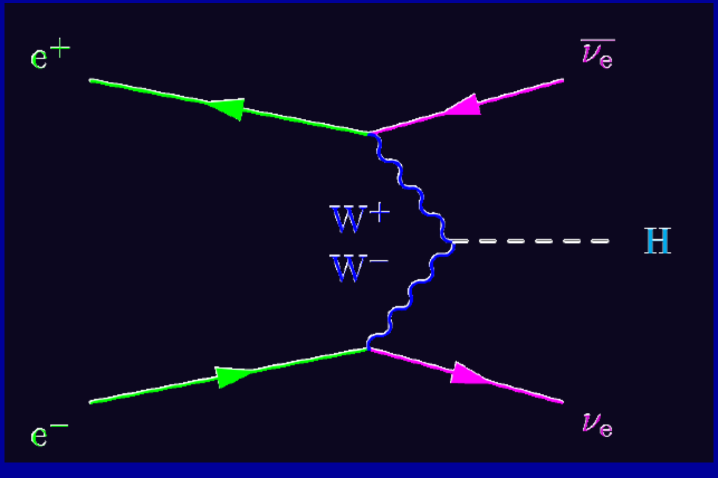
We can fit, minimizing the χ^2 between the measurement vector ($\mathbf{x}_M$) and the fit vector ($\mathbf{x}$) subject to the mass constraint.

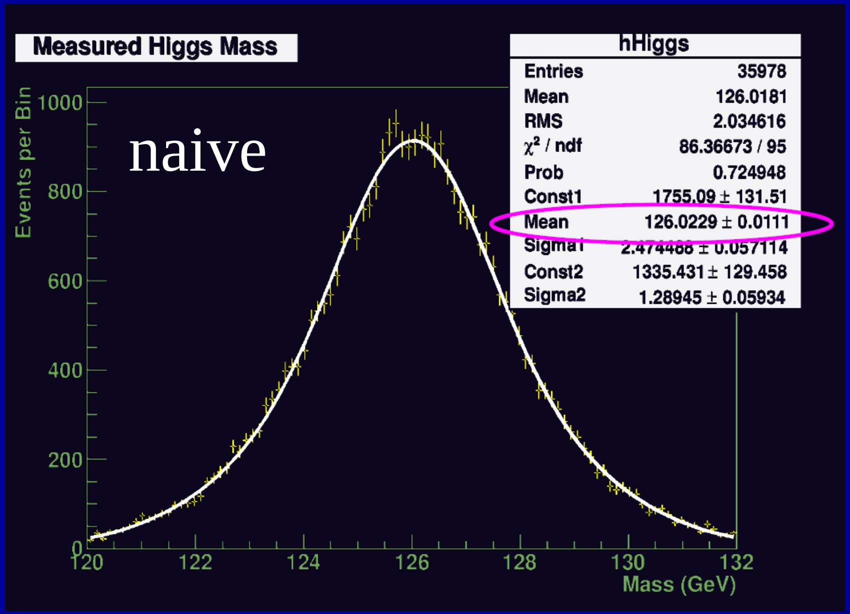


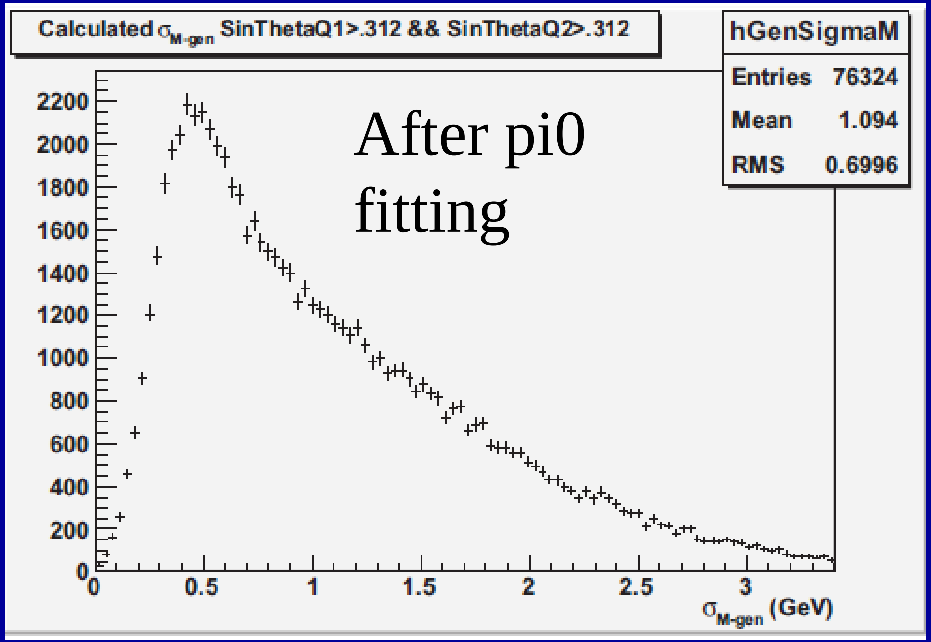
Variable	Measured	3-variable fit	6-variable fit	Pull
E_1	2.468 ± 0.253	2.385 ± 0.192	2.385 ± 0.192	-0.504
E_2	1.679 ± 0.196	1.605 ± 0.130	1.605 ± 0.130	-0.504
$2(1-\cos\psi_{12})$	$(4.765 \pm 0.0985) \times 10^{-3}$	$(4.759 \pm 0.0977) \times 10^{-3}$		-0.504
θ_1 (mrad)	1608.36 ± 0.50		1608.37 ± 0.50	0.504
θ_2 (mrad)	1619.11 ± 0.50		1619.10 ± 0.50	-0.504
ϕ_1 (mrad)	2196.86 ± 0.50		2196.84 ± 0.50	-0.504
ϕ_2 (mrad)	2128.60 ± 0.50		2128.62 ± 0.50	0.504
m_{π^0} (MeV)	140.5			
$\rho_{E_1E_2}$		-0.9683	-0.9683	
E_{π^0}	4.147 ± 0.320	3.990 ± 0.074	3.990 ± 0.074	
χ^2/ν		0.2543/1		
p_{fit} (%)		61.4		

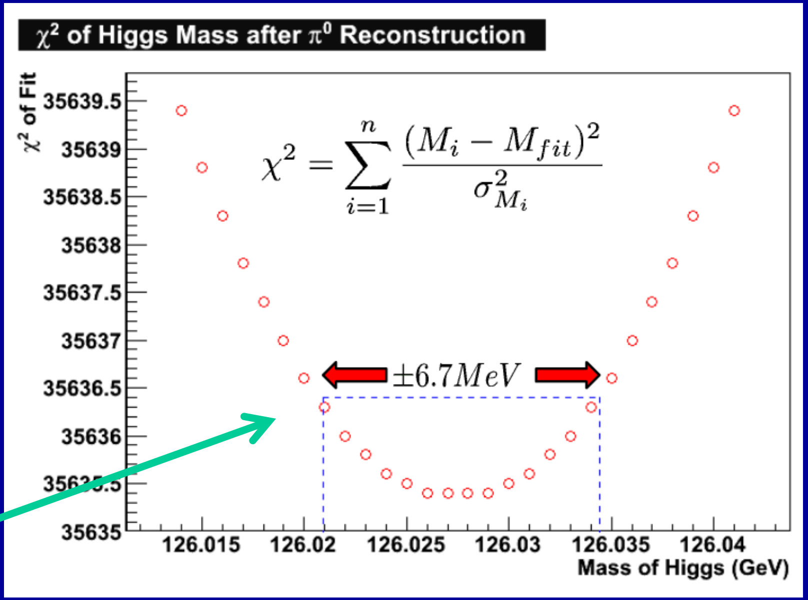
Can greatly improve E measurement error

Applying to Physics (H → hadrons)




naive


After pi0 fitting



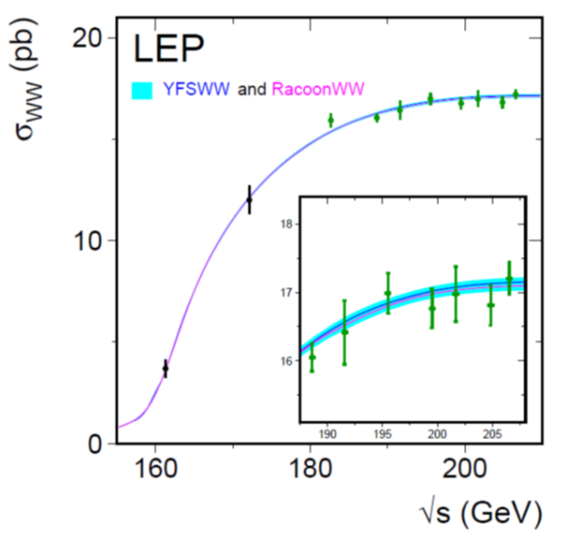
$$\chi^2 = \sum_{i=1}^{n} \frac{(M_i - M_{fit})^2}{\sigma^2_{M_i}}$$

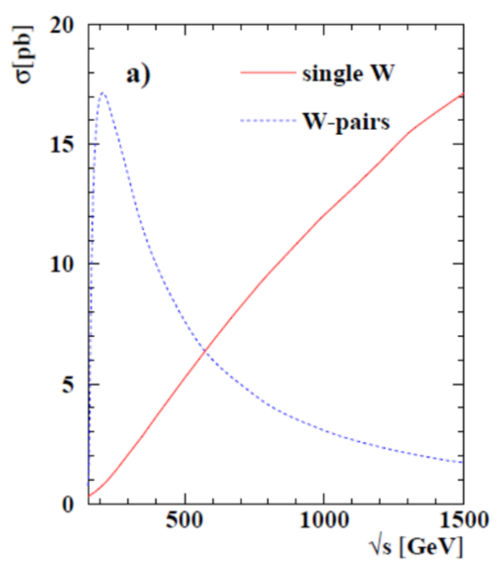
$\pm 6.7 MeV$

Using event-to-event error knowledge

ILC W Mass Measurement Strategies

- W^+W^-
  - 1. Threshold Scan ($\sigma \sim \beta/s$)
    - Can use all WW decay modes
  - 2. Kinematic Reconstruction (qq e nu and qq mu nu)
    - Apply kinematic constraints
- W e ν (+ WW) - proposed by me – same issues as $\nu\nu$H discussed above
  - 3. Directly measure the hadronic mass in W $\rightarrow$ q q' decays.
    - Can use WW -> q q tau nu too

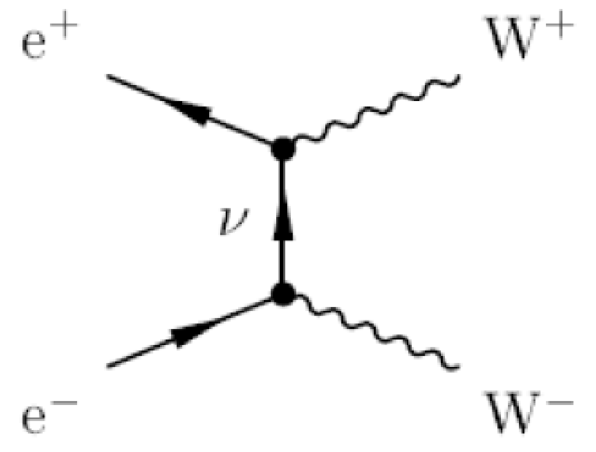




Methods 1 and 2 were used at LEP2. Both require good knowledge of the absolute beam energy.

Method 3 is novel (and challenging), very complementary systematics to 1 and 2 if the experimental challenges can be met.

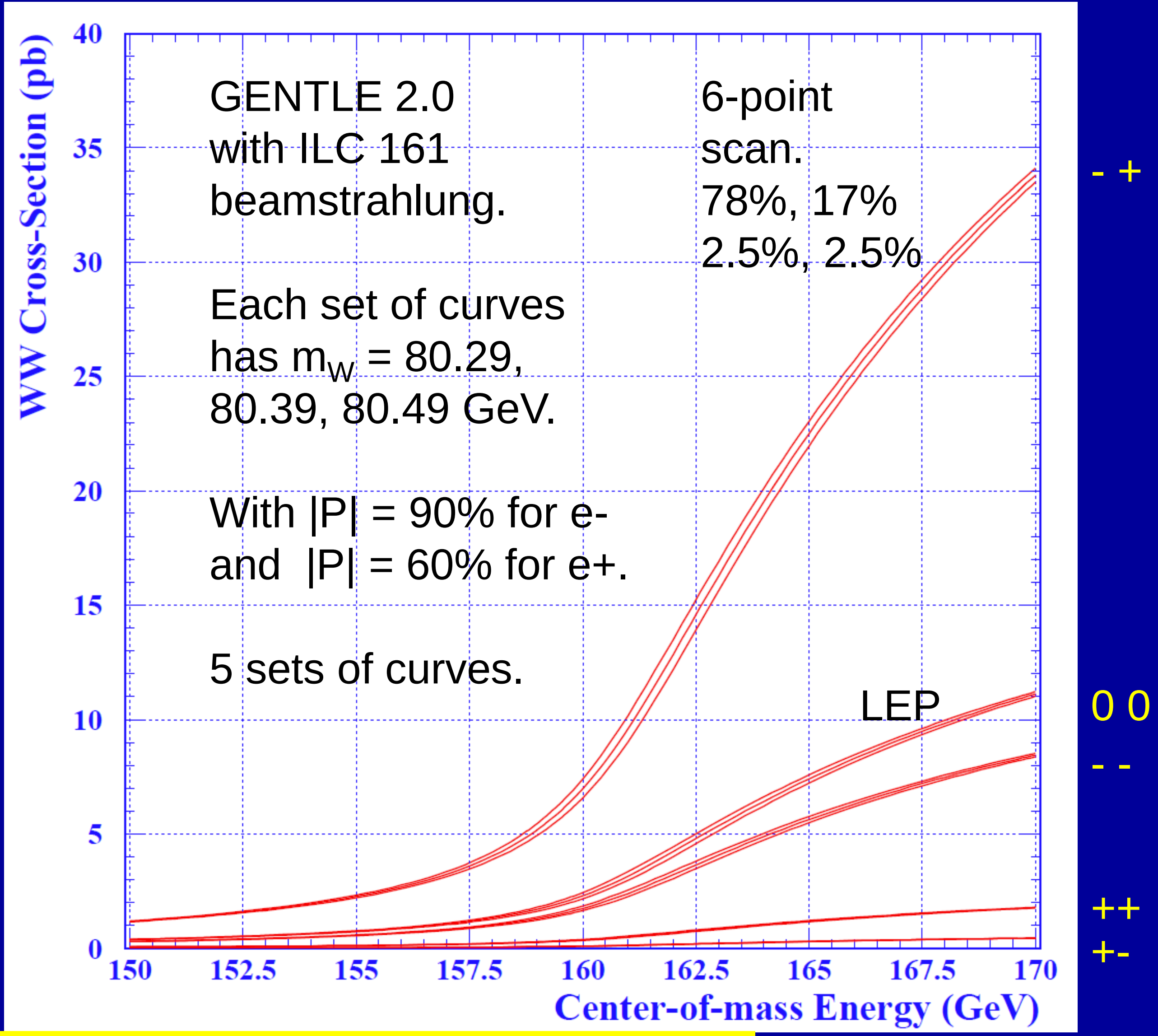
Polarized Threshold Scan (GWW)



Use (-+) helicity combination of e- and e+ to enhance WW.

Use (+-) helicity to suppress WW and measure background.

Use (--) and (++) to control polarization (also use 150 pb qq events)



GENTLE 2.0
with ILC 161
beamstrahlung.

6-point
scan.
78%, 17%
2.5%, 2.5%

Each set of curves has m_W = 80.29, 80.39, 80.49 GeV.

With |P| = 90% for e- and |P| = 60% for e+.

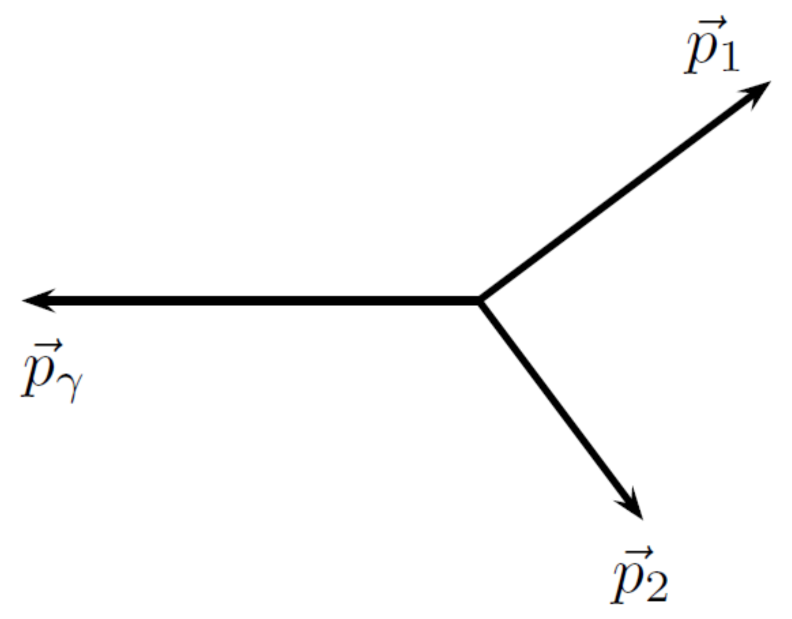
5 sets of curves.

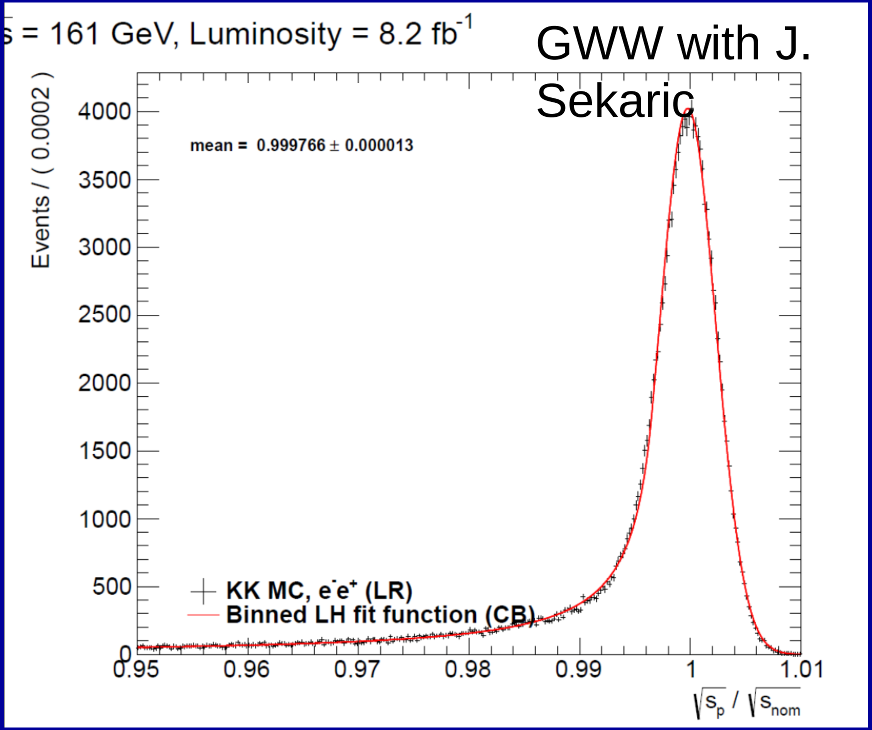
Experimentally very robust. Fit for eff, pol, bkg, lumi

“New” In-Situ Beam Energy Method

GWW

$e^+e^- \rightarrow \mu^+\mu^-(\gamma)$





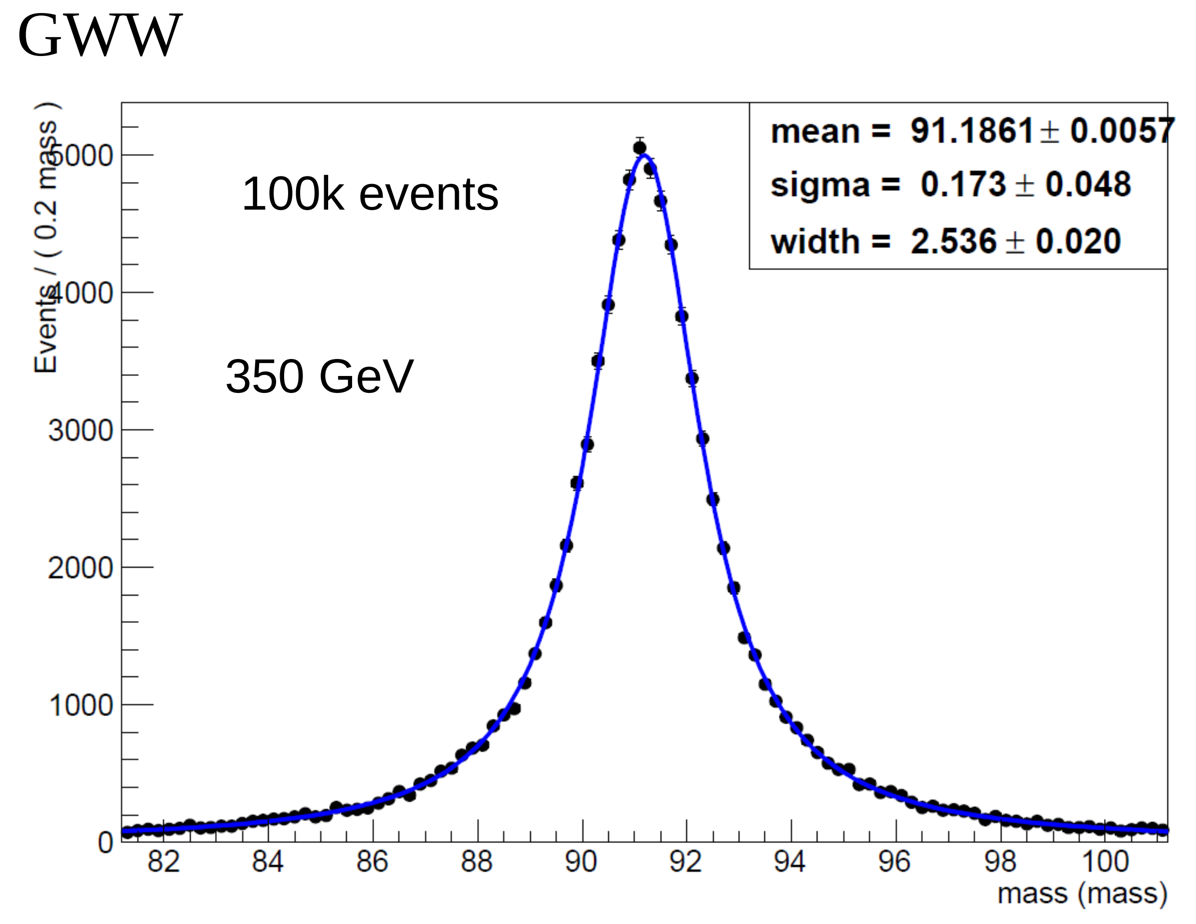
GWW with J. Sekaric

Use muon momenta. Measure $E_1 + E_2 + |p_{12}|$ as an estimator of √s

ILC detector momentum resolution (0.15%), gives beam energy to better than 5 ppm statistical. Momentum scale to 10 ppm => 0.8 MeV beam energy error projected on mW. (J/psi)

Beam Energy Uncertainty should be controlled for √s <= 500 GeV

Can control momentum scale using measured di-lepton mass



This is about 100 fb^{-1} at ECM=350 GeV.

Statistical sensitivity if one turns this into a Z mass measurement (if p-scale is determined by other means) is

1.8 MeV / √N

With N in millions.

Alignment ?
B-field ?
Push-pull ?
Etc …
Note Z mass only known to 23 ppm

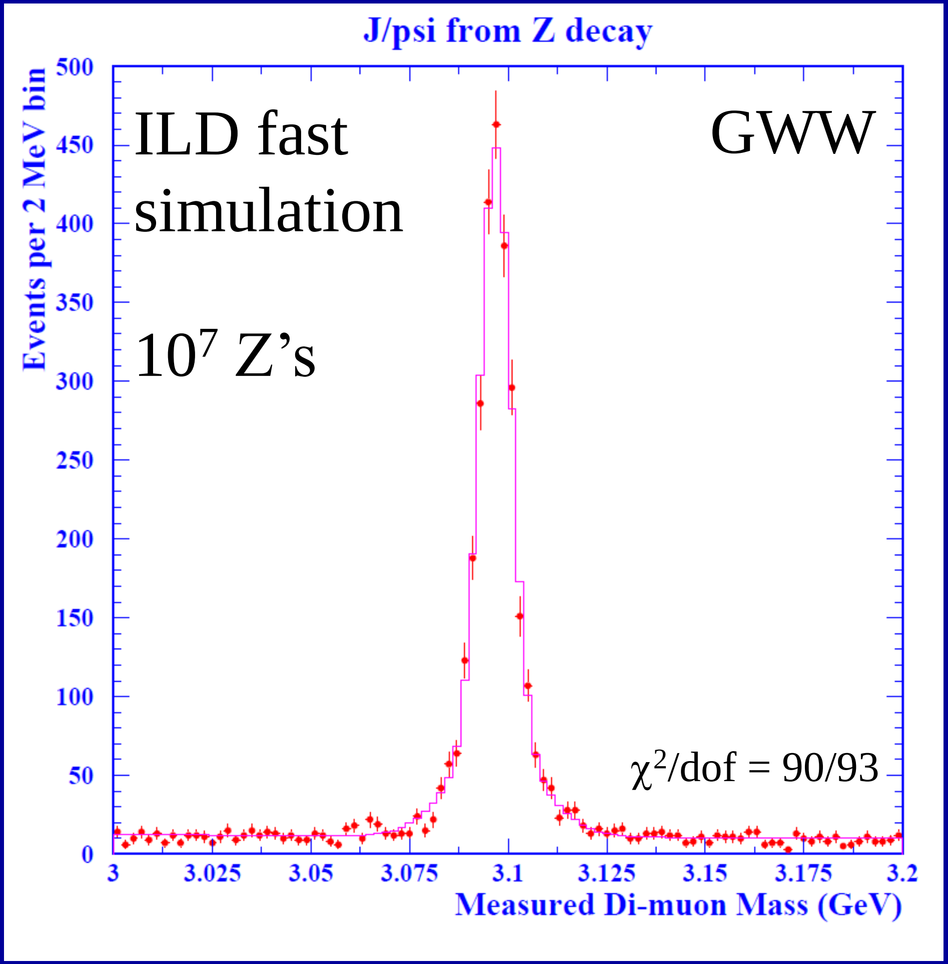
Momentum Scale with J/psi

With 10^9 Z's expect statistical error on mass scale of < 3.4 ppm given ILD momentum resolution.

Most of the J/psi's are from B decays.

J/psi mass is known to 3.6 ppm.

Can envisage also improving on the measurement of the Z mass (23 ppm error)

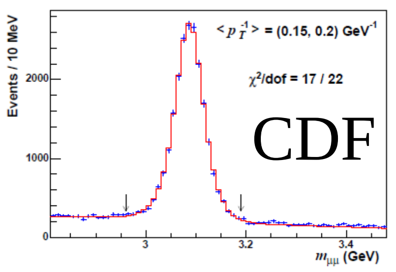


ILD fast simulation

10^7 Z's

GWW

$\chi^2/\text{dof} = 90/93$



CDF

Double-Gaussian + Linear Fit

W Mass Measurements

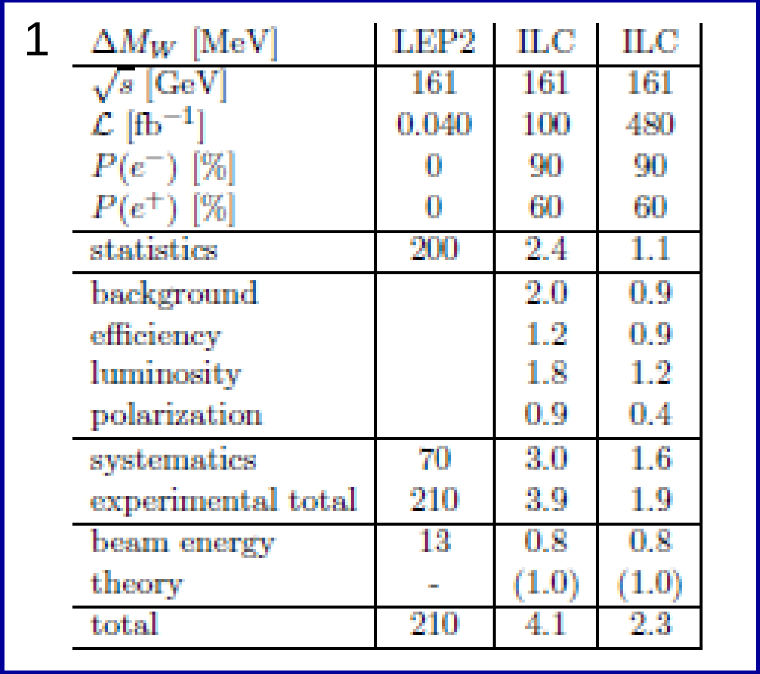
GWW

1. Polarized Threshold Scan
2. Kinematic Reconstruction
3. Hadronic Mass

Method 1: Statistics limited.

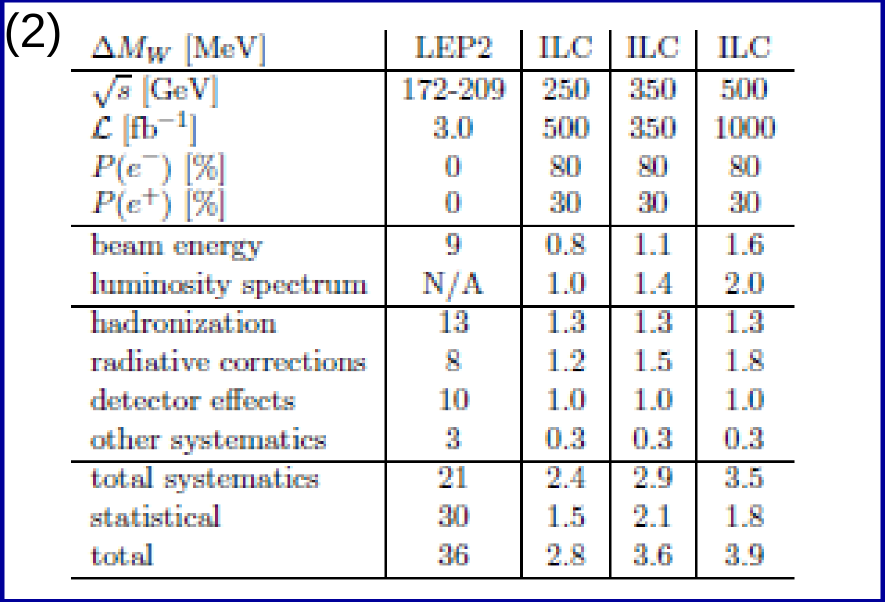
Method 2: With up to 1000 the LEP statistics and much better detectors. Can target factor of 10 reduction in systematics.

Method 3: Depends on di-jet mass scale. Plenty Z’s for 3 MeV.



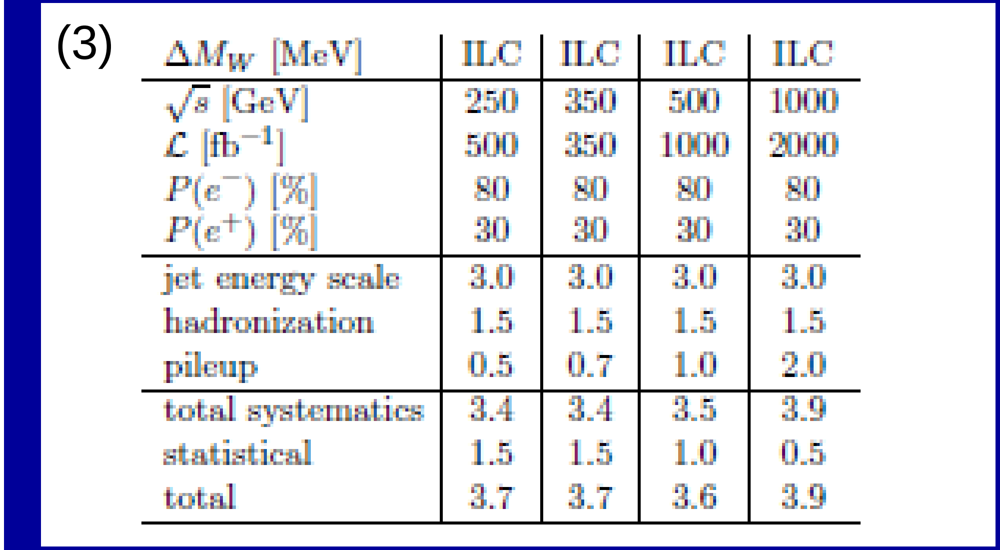
1

ΔM_W [MeV]	LEP2	ILC	ILC
$\sqrt{s}$ [GeV]	161	161	161
$\mathcal{L}$ [fb^{-1}]	0.040	100	480
$P(e^-)$ [%]	0	90	90
$P(e^+)$ [%]	0	60	60
statistics	200	2.4	1.1
background		2.0	0.9
efficiency		1.2	0.9
luminosity		1.8	1.2
polarization		0.9	0.4
systematics	70	3.0	1.6
experimental total	210	3.9	1.9
beam energy	13	0.8	0.8
theory	-	(1.0)	(1.0)
total	210	4.1	2.3



(2)

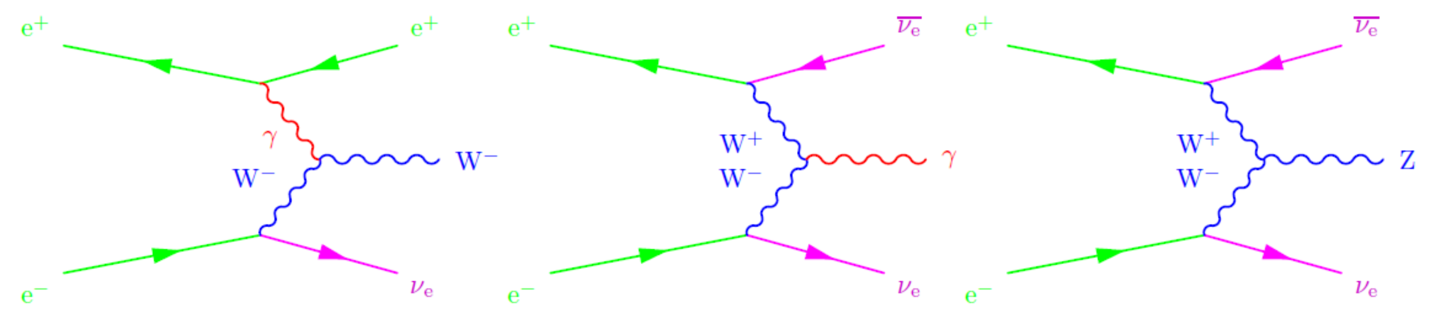
ΔM_W [MeV]	LEP2	ILC	ILC	ILC
$\sqrt{s}$ [GeV]	172-209	250	350	500
$\mathcal{L}$ [fb^{-1}]	3.0	500	350	1000
$P(e^-)$ [%]	0	80	80	80
$P(e^+)$ [%]	0	30	30	30
beam energy	9	0.8	1.1	1.6
luminosity spectrum	N/A	1.0	1.4	2.0
hadronization	13	1.3	1.3	1.3
radiative corrections	8	1.2	1.5	1.8
detector effects	10	1.0	1.0	1.0
other systematics	3	0.3	0.3	0.3
total systematics	21	2.4	2.9	3.5
statistical	30	1.5	2.1	1.8
total	36	2.8	3.6	3.9



(3)

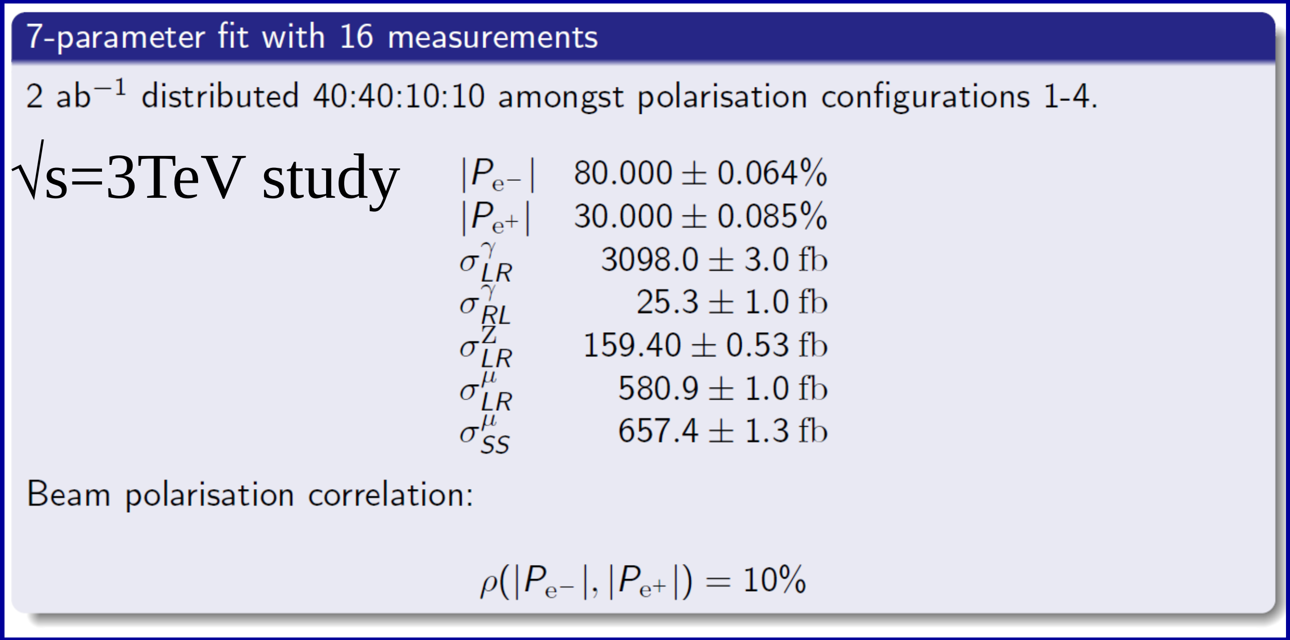
ΔM_W [MeV]	ILC	ILC	ILC	ILC
$\sqrt{s}$ [GeV]	250	350	500	1000
$\mathcal{L}$ [fb^{-1}]	500	350	1000	2000
$P(e^-)$ [%]	80	80	80	80
$P(e^+)$ [%]	30	30	30	30
jet energy scale	3.0	3.0	3.0	3.0
hadronization	1.5	1.5	1.5	1.5
pileup	0.5	0.7	1.0	2.0
total systematics	3.4	3.4	3.5	3.9
statistical	1.5	1.5	1.0	0.5
total	3.7	3.7	3.6	3.9

New Beam Polarization Measurement Method (GWW)



Use final states with photon or muon(s) with missing energy

Collect data with all 4 pairings.
(-+) (+-) (--) (++)
Count events in each of the 4 channels.



7-parameter fit with 16 measurements

2 ab^{-1} distributed 40:40:10:10 amongst polarisation configurations 1-4.

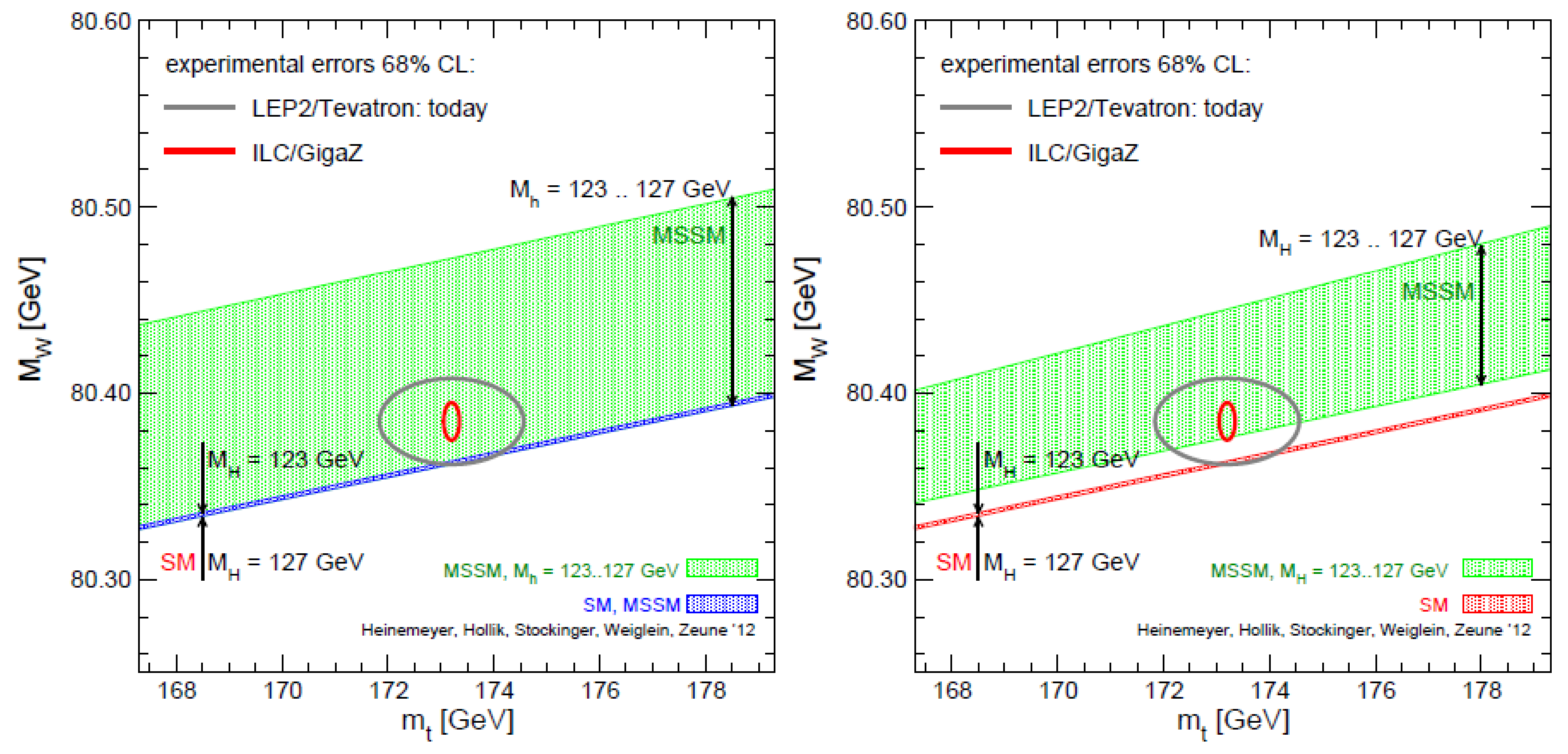
√s=3TeV study

$\|P_{e^-}\|$	$80.000 \pm 0.064\%$
$\|P_{e^+}\|$	$30.000 \pm 0.085\%$
σ^{γ}_{LR}	3098.0 ± 3.0 fb
σ^{γ}_{RL}	25.3 ± 1.0 fb
σ^{Z}_{LR}	159.40 ± 0.53 fb
σ^{μ}_{LR}	580.9 ± 1.0 fb
σ^{μ}_{SS}	657.4 ± 1.3 fb

Beam polarisation correlation:

$$\rho(|P_{e^-}|, |P_{e^+}|) = 10\%$$

Would mW to 2 MeV be interesting ?



Can test whether W and top masses are consistent with the SM Higgs mass or MSSM with either the 126 GeV object being the light (left plot) or heavy (right plot) CP even Higgs

Conclusions

- Driving theme for the field is to follow up on the Higgs discovery.
- The ILC accelerator is the machine we know we can build today that can explore much further.
- There is much to do at the “Higgs-scale”
  - Important to plan the best experimental strategies for precision measurements.
  - Personal contributions to several areas impacting on the scientific scope.