Experimental Challenges for Physics at the Terascale

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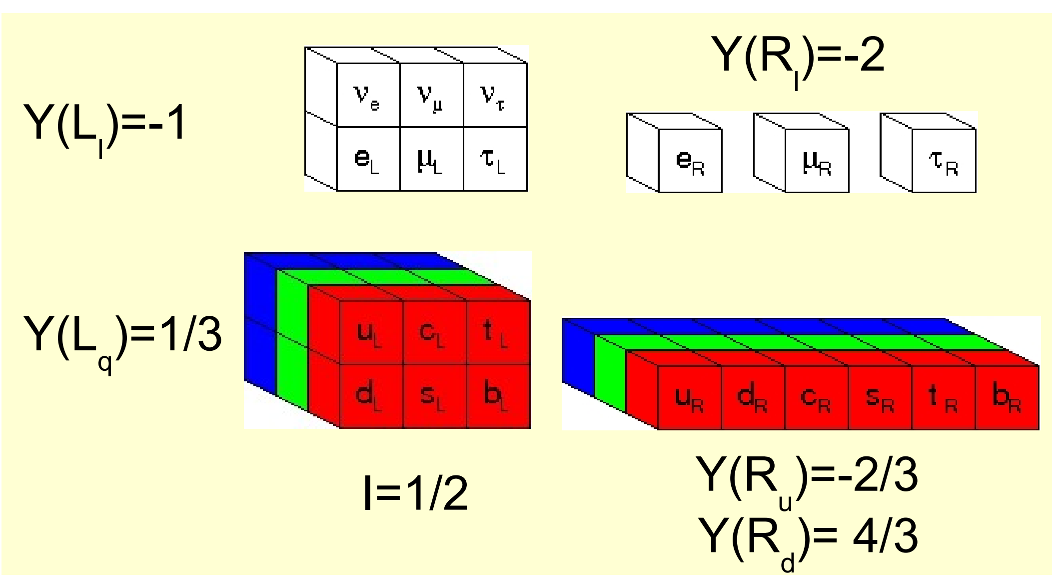
Outline

1. Introduction: Standard Model
2. Standard Model shortcomings
   - Theoretical
   - Experimental
3. Physics at the Terascale
4. Accelerators for physics at the Terascale:
   - The Large Hadron Collider (LHC)
   - The International Linear Collider (ILC)
   - LHC and ILC interplay:
     - Search of Standard Model Higgs
     - Supersymmetry Search
5. Detectors for ILC
   - Detector Concepts
   - Tracking
   - Calorimetry
6. Conclusions

INTRODUCTION: STANDARD MODEL

Standard Model: Summary

- Unified framework to describe elementary particle interctions:
  - Yang-Mills theory: based on Electroweak+Strong symmetry groups
    - $SU(2)_L \times U(1)_Y + SU(3)_c$
  - Gauge fields mediated by spin 1 bosons
    - Electroweak: Isovector + Isoscalar
    - Strong: 8 gluons
  - Matter fields: 3 generations (spin ½)
    - Left handed fermions are isodoublets in $SU(2)_L$
    - Right handed fermions are isosinglets in $SU(2)_L$
    - Quarks are triplets under $SU(3)_c$



Force	Symmetry Group	Fields	Coupling
Electromagnetic	$U(1)_Y$	W_μ^{123}	g_1
Weak	$SU(2)_L$	B_μ	g_2
Strong	$SU(3)_c$	$G_\mu^{1..8}$	g_s

$$Q = I_3 + \frac{1}{2} Y$$

Standard Model: Summary

$$L = L_{gauge} + L_{leptons} + L_{quarks}$$

$$L_{gauge} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{1}{4} f_{\mu\nu} f^{\mu\nu}$$

$$L_{leptons} = \overline{R}_l i \gamma^\mu \left(\partial_\mu + i \frac{g_1}{2} A_\mu Y \right) R_l + \overline{L}_l i \gamma^\mu \left(\partial_\mu + i \frac{g_1}{2} A_\mu Y + i \frac{g_2}{2} \tau \cdot W \right) L_l$$

$$L_{quarks} = \overline{R}_u^{(n)} i \gamma^\mu \left(\partial_\mu + i \frac{g_1}{2} A_\mu Y \right) R_u^{(n)} + \overline{R}_d^{(n)} i \gamma^\mu \left(\partial_\mu + i \frac{g_1}{2} A_\mu Y \right) R_d^{(n)} + \overline{L}_q^{(n)} i \gamma^\mu \left(\partial_\mu + i \frac{g_1}{2} A_\mu Y + i \frac{g_2}{2} \tau \cdot W \right) L_q^{(n)}$$

- All fermion and bosons are massless
  - Mass terms of type $m\phi^2$ or M^2W^2 violates local gauge invariance
  - Despite Electroweak symmetry, phenomenology of electromagnetic and weak interactions are quite different

Standard Model: Summary

FERMIONS
matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor	Mass GeV/c^2	Electric charge
ν_L lightest neutrino*	$(0-0.13)\times10^{-9}$	0
e electron	0.000511	–1
ν_M middle neutrino*	$(0.009-0.13)\times10^{-9}$	0
μ muon	0.106	–1
ν_H heaviest neutrino*	$(0.04-0.14)\times10^{-9}$	0
τ tau	1.777	–1

Quarks spin = 1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.002	2/3
d down	0.005	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	173	2/3
b bottom	4.2	–1/3

BOSONS
force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^- W bosons	80.39	–1
W^+ W bosons	80.39	+1
Z^0 Z boson	91.188	0

Strong (color) spin = 1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Properties of the Interactions

The strengths of the interactions (forces) are shown relative to the strength of the electromagnetic force for two u quarks separated by the specified distances.

Property	Gravitational Interaction	Weak Interaction (Electroweak)	Electromagnetic Interaction	Strong Interaction
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge
Particles experiencing:	All	Quarks, Leptons	Electrically Charged	Quarks, Gluons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons
Strength at 10^{-18} m	10^{-41}	0.8	1	25
Strength at 3×10^{-17} m	10^{-41}	10^{-4}	1	60

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- All fermion and bosons are massless
  - Mass terms of type $m\phi^2$ or M^2W^2 violates local gauge invariance
  - Despite Electroweak symmetry, phenomenology of electromagnetic and weak interactions are quite different
- To give masses to gauge bosons and fermions symmetry should be hidden (broken)

$$SU(2)_L \times U(1)_Y \rightarrow U(1)_Q$$

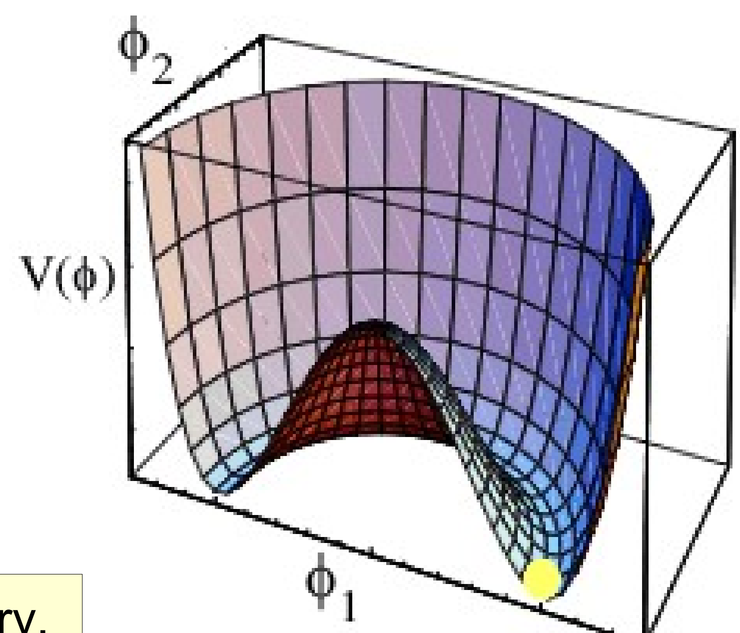
Higgs Mechanism

- Complex Scalar Field $\phi=\frac{1}{\sqrt{2}}(\phi_1+i\phi_2)$ $\quad L=\frac{1}{2}\partial_\mu\phi\,\partial^\mu\phi-V(\phi)$
- Define a Potential $V(\phi)=\frac{1}{2}\mu^2\phi^2+\frac{1}{4}\lambda^2\phi^4$ $\quad V(\phi)\rightarrow V(-\phi)$

  ϕ^3 *not included*

  - $\mu^2>0$ $\rightarrow$ S=0 m=μ $\quad \langle 0|\phi^2|0\rangle=0$
  - $\mu^2<0$ $\rightarrow$vev $\quad \langle 0|\phi^2|0\rangle=\frac{-\mu^2}{\lambda}=v^2$
- Expand about vacuum $\phi(x)=v+\eta(x)+i\xi(x)$
- Identify mass terms

$$L=\overbrace{\frac{1}{2}(\partial_\mu\xi)^2}^{m=0}+\overbrace{\frac{1}{2}(\partial_\mu\eta)^2+\mu^2\eta^2}^{m=\mu}$$
$$+\lambda v(\eta\xi^2+\eta^3)-\frac{\lambda}{2}\eta^2\xi^2-\frac{\lambda}{4}\eta^4-\frac{\lambda}{4}\xi^4+const$$



Goldstone Theorem:

For every spontaneously broken symmetry, the theory contains massless scalar

Higgs Mechanism in Standard Model

- $\phi \rightarrow$ SU(2) isodoublet

$$\Phi(x)=\begin{pmatrix}\phi^{+}\\ \phi^{0}\end{pmatrix}=\begin{pmatrix}\theta_2+i\theta_1\\ \frac{1}{\sqrt{2}}(v+H)-i\theta_3\end{pmatrix}=e^{i\theta_a(x)\tau^a(x)/v}\begin{pmatrix}0\\ \frac{1}{\sqrt{2}}(v+H(x))\end{pmatrix}$$

- Gauge bosons masses

$$V(\Phi)=\frac{1}{2}\mu^2\Phi^{+}\Phi+\frac{1}{4}\lambda^2(\Phi^{+}\Phi)^2$$

$$\langle\Phi\rangle=\langle 0|\Phi|0\rangle=\begin{pmatrix}0\\ \frac{v}{\sqrt{2}}\end{pmatrix}$$

$$M_{W^{\pm}}=\frac{1}{2}v\,g_2$$

$$M_Z=\frac{1}{2}v\sqrt{g_1^2+g_2^2}$$

$$M_{\gamma}=0$$

- 3 bosons absorbed by W and Z bosons
  - Longitudinal polarization
  - Acquire masses
- 1 massive boson "free" Higgs boson
  - Spin=0 $m^2=2\lambda v^2=-2\mu^2$

$$v=\frac{1}{(\sqrt{2}G_F)^{1/2}}\simeq 246\,GeV$$

- Fermion masses

$$\begin{aligned}L_F &= -\lambda_e\bar{L}\Phi e_R-\lambda_d\bar{Q}\Phi d_R-\lambda_u\bar{Q}\Phi u_R+h.c.\\ &= -\frac{1}{\sqrt{2}}\lambda_e(\bar{\nu}_e,\bar{e}_L)\begin{pmatrix}0\\ v+H\end{pmatrix}e_R+\cdots\\ &= -\frac{1}{\sqrt{2}}\lambda_e(v+H)\bar{e}_L e_R+\cdots\end{aligned}$$

$$m_e=\frac{\lambda_e v}{\sqrt{2}}\quad,\quad m_u=\frac{\lambda_u v}{\sqrt{2}}\quad,\quad m_d=\frac{\lambda_d v}{\sqrt{2}}$$

Standard Model: Experimental tests

- Impressive experimental confirmations (LEP/SLD/TeVatron)
- Tested at <1%
- Cosmological implications

... BUT ...

- Higgs boson still missing
  - Only unknown parameter in EW sector

LEP EWWG Dec 2006

Standard Model Higgs?

- Higgs and top masses enters into radiative corrections

$$M_W(GeV) = 80.3694 - 0.0579 \ln\left(\frac{M_H}{100GeV}\right) - 0.008 \ln^2\left(\frac{M_H}{100GeV}\right) - 0.5098\left(\Delta\alpha_{had}^{(5)}\frac{(M_Z)}{0.02761} - 1\right)$$
$$+0.525\left[\left(\frac{m_t}{172GeV}\right)^2 - 1\right] - 0.085\left(\frac{\alpha_s(M_Z)}{0.118} - 1\right)$$

July, 2006 — New top mass by CDF and D0

$$M_{top}^{Tev} = 171.4 \pm 1.2(stat) \pm 1.8(sys) GeV/c^2$$

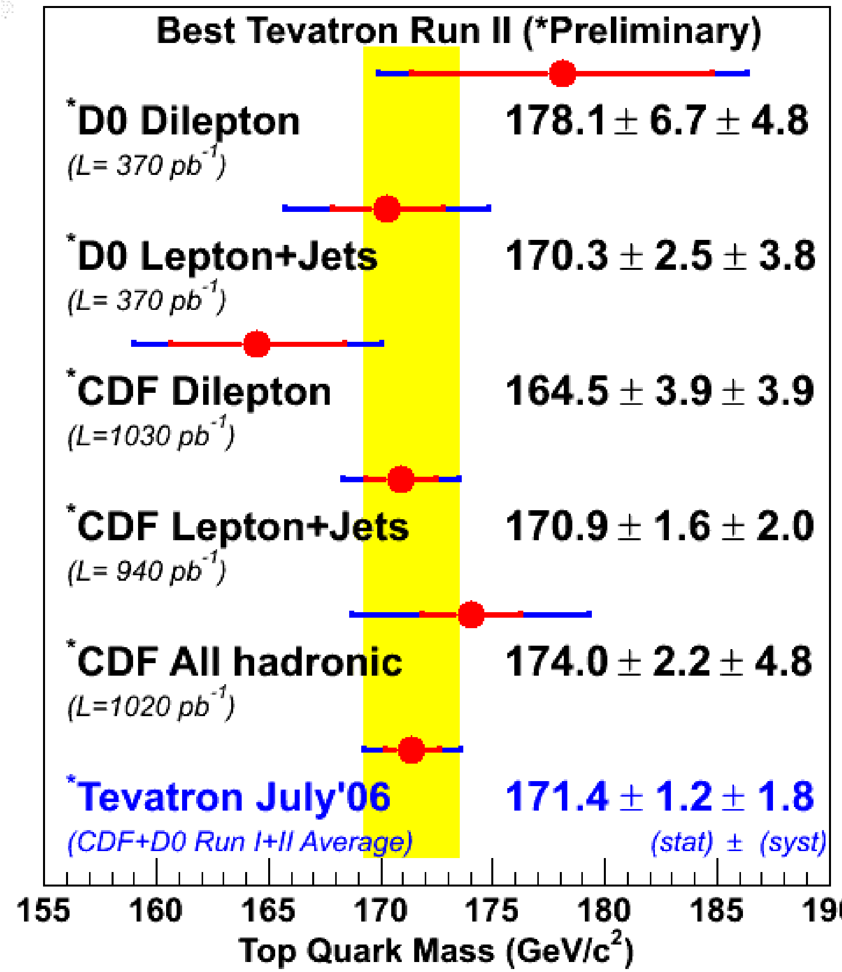
March, 2007 — $M_{top}^{Tev} = 170.9 \pm 1.1(stat) \pm 1.5(sys) GeV/c^2$

January, 2007 — New W mass by CDF

$$M_W^{CDF} = 80413 \pm 34(stat) \pm 34(sys) MeV/c^2$$

$$M_W^{old} = 80392 \pm 29 MeV/c^2 \rightarrow M_H = 85_{-28}^{+39} GeV/c^2$$

$$M_W^{new} = 80398 \pm 25 MeV/c^2 \rightarrow M_H = 80_{-26}^{+36} GeV/c^2$$



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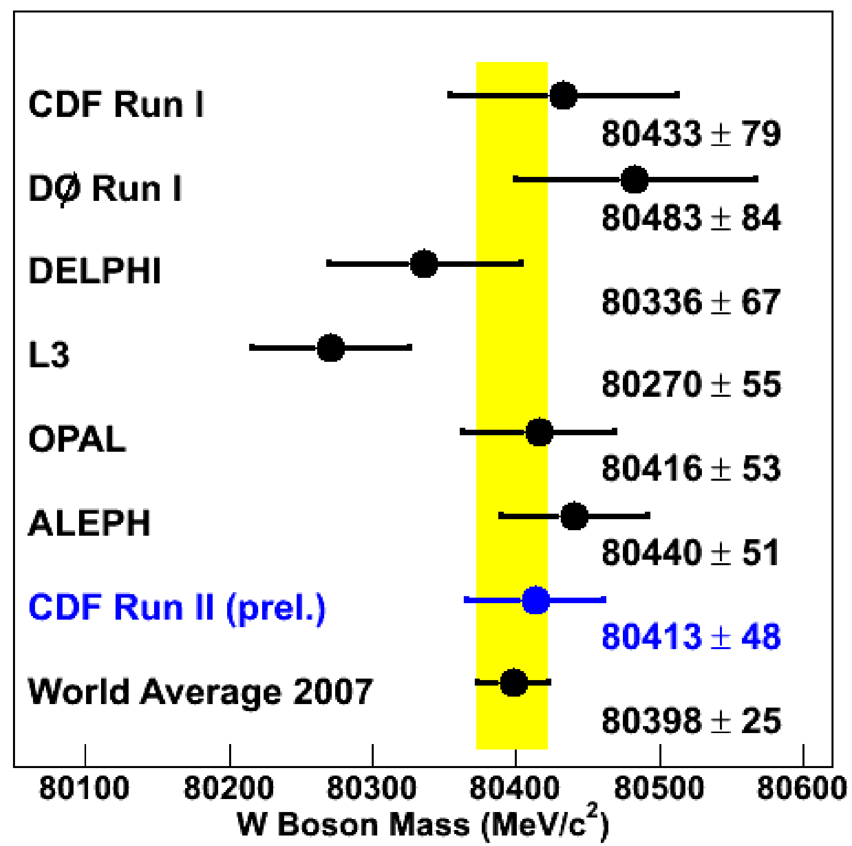
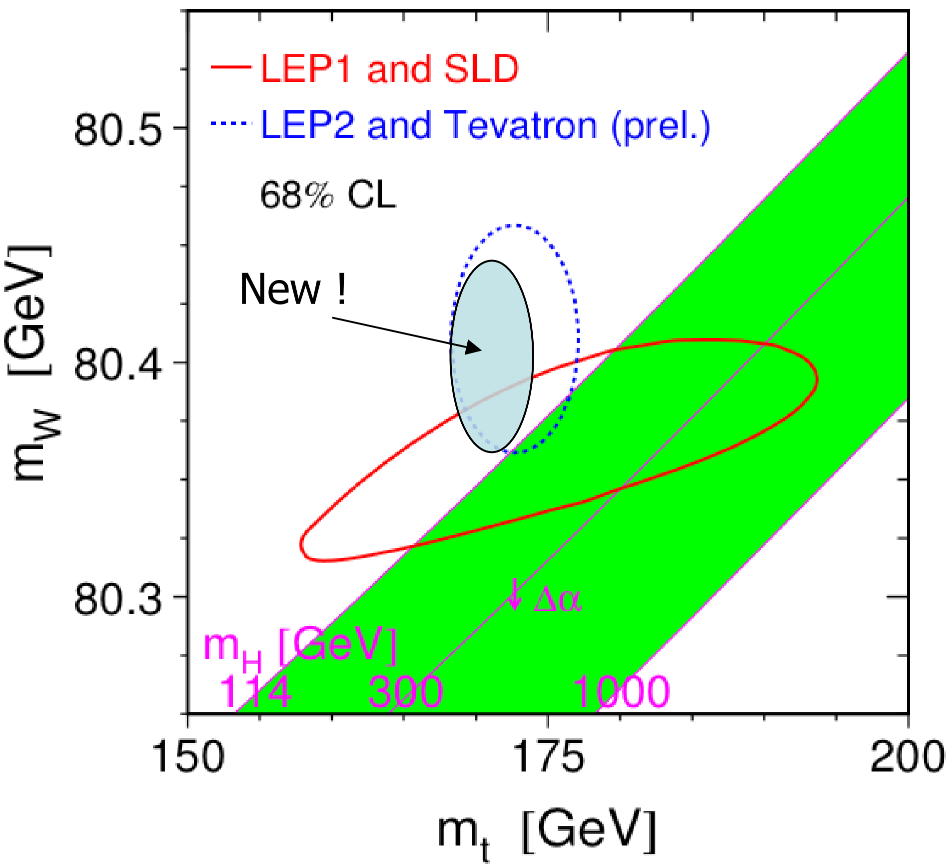
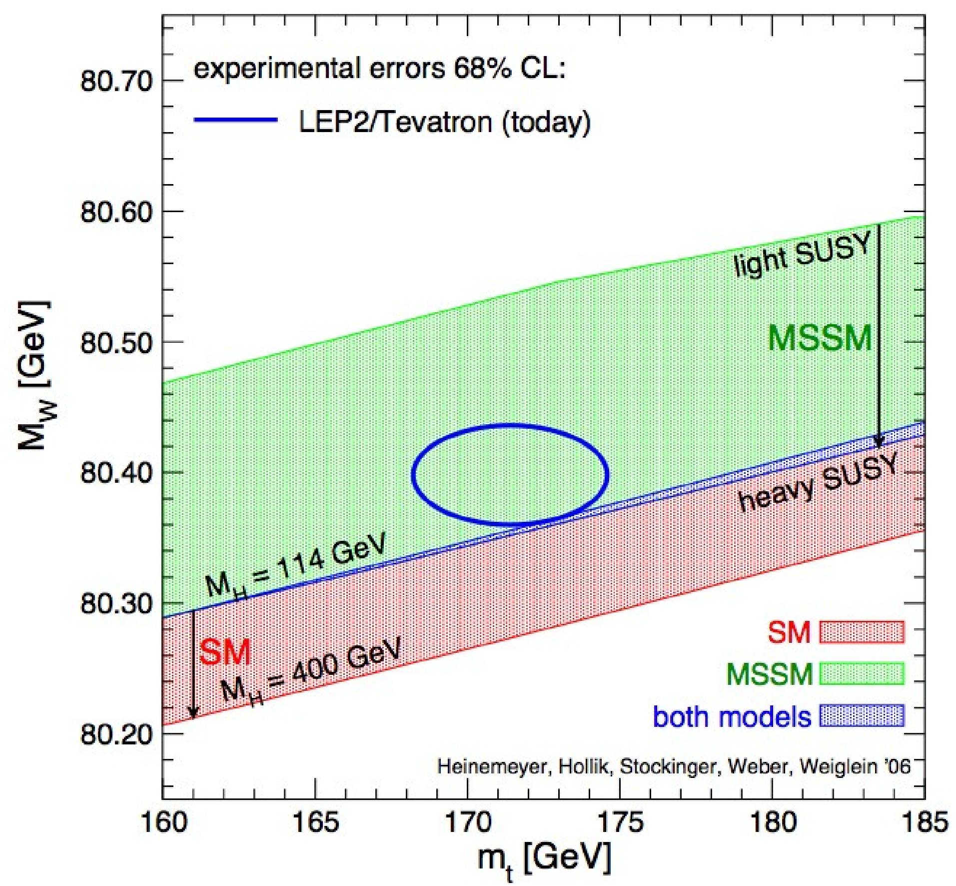


SM Higgs searches



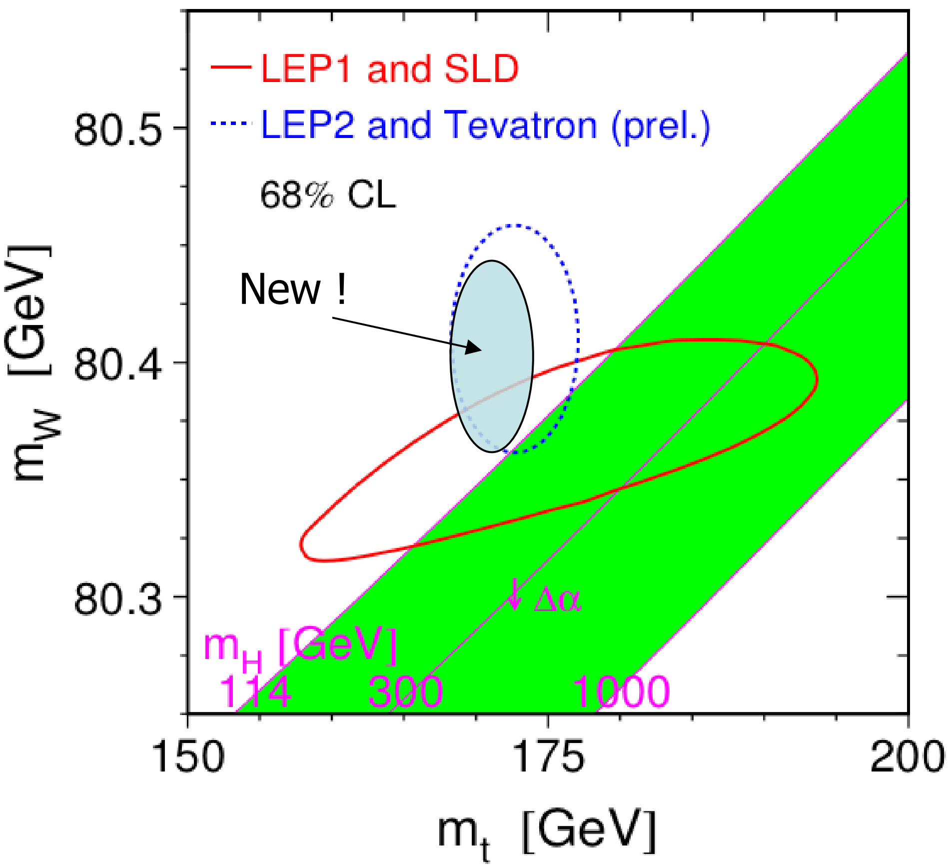
Data prefers a light Higgs

LEP direct searches
m_H>114 GeV



Data prefers a non SM Higgs

SM Higgs searches



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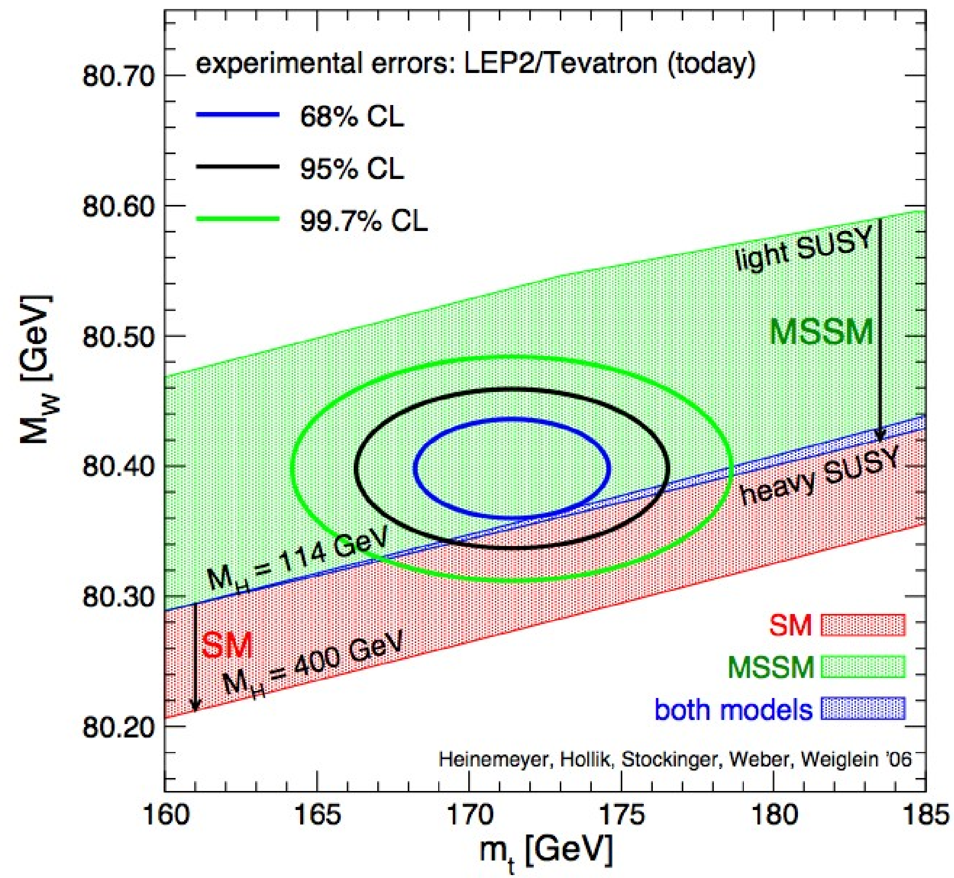


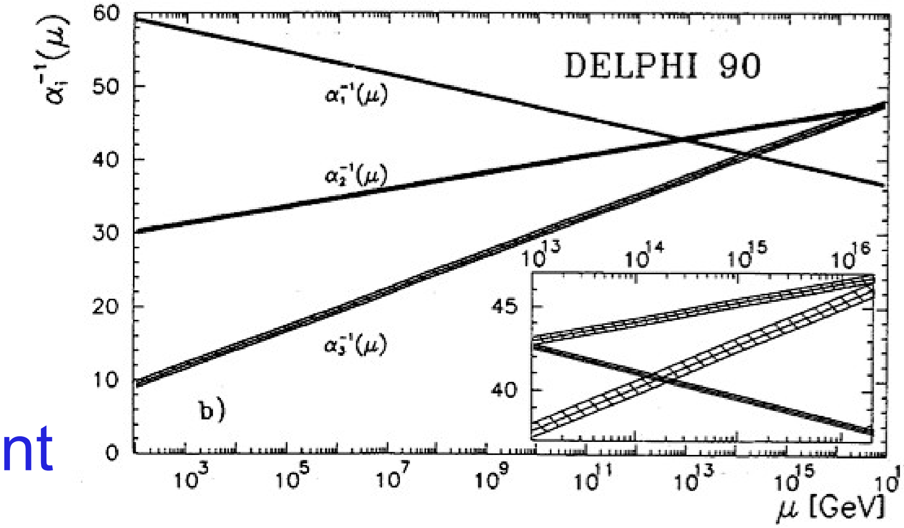
Data prefers a non SM Higgs

STANDARD MODEL SHORTCOMINGS

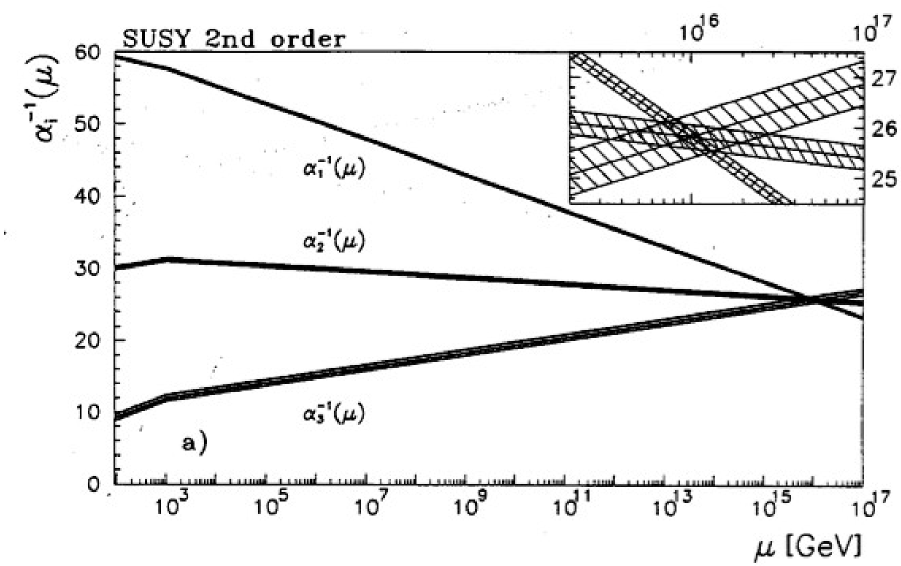
Theoretical shortcomings

- Gravity remains outside SM
- Effective theory with 19 free parameters
  - Why three families?
  - Why EW symmetry should be broken?
  - Why $m_\nu \sim 10^{-12} m_t$?

U. Amaldi, W. De Boer, H. Furstenau
Phys.Lett.B260:447-455,1991.



- Unification problem: evolution of gauge couplings fails to meet at a common point at GUT scale (10^{16} GeV)



- Hierarchy problem:
  - Un-natural fine-tuning constraint of parameters

$$M_H^2 = (M_H^0)^2 + \frac{3\Lambda^2}{8\pi^2 v^2}\left[M_H^2 + 2M_W^2 + M_Z^2 - 4m_t^2\right]$$

Experimental shortcomings: Neutrino masses

- Neutrino masses not accounted for
- First direct signal of physics BSM

$$P_{\alpha\to\beta}=\sin^2\theta_{\alpha\beta}\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

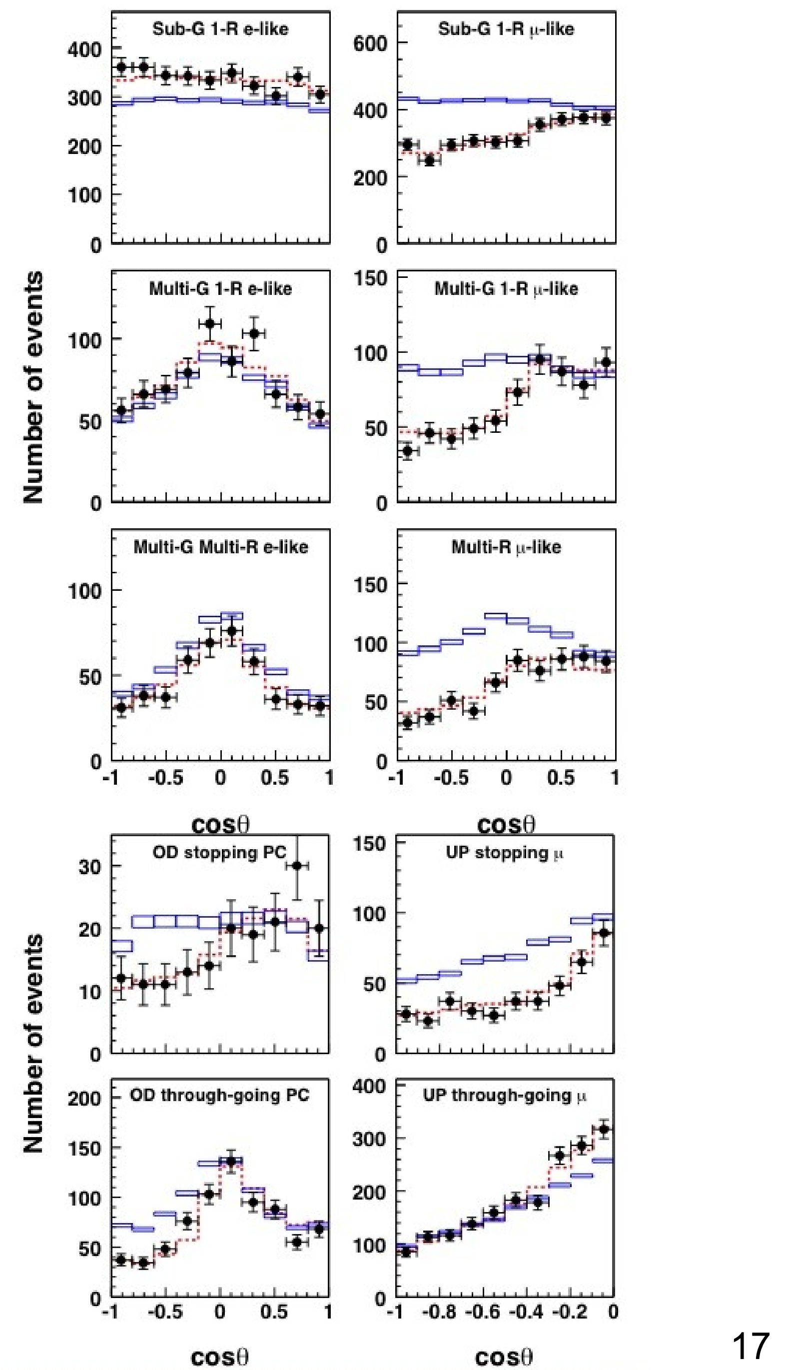
hep-ph/0405172

Parameter	Best Fit	3σ
$\Delta m^2_{21}[10^{-5}eV^2]$	7.9	7.1-8.9
$\Delta m^2_{31}[10^{-3}eV^2]$	2.6	2.0-3.2
$\sin^2\theta_{12}$	0.3	0.24-0.40
$\sin^2\theta_{23}$	0.5	0.34-0.68
$\sin^2\theta_{13}$	0.000	$\leq$0.040

Only WMAP $\Sigma m_\nu < 1.8\,eV$

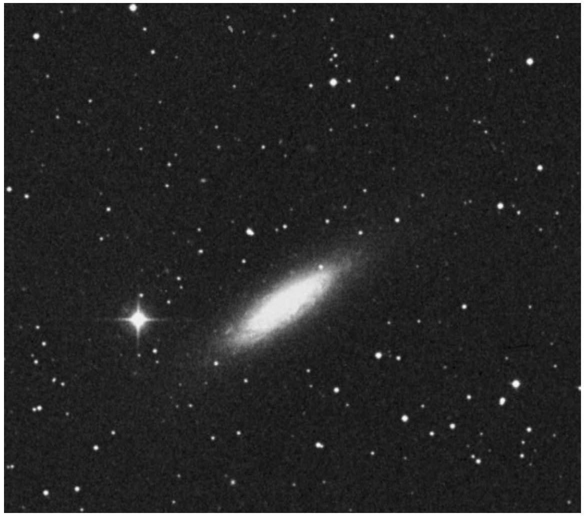
CMB+LSS+SN $\Sigma m_\nu < 0.66\,eV$

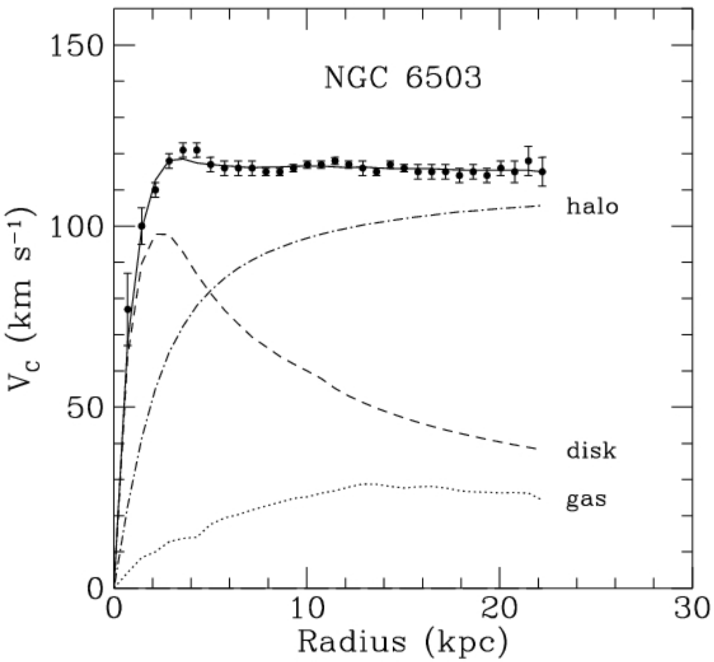
Phys.Rev.D74:032002,2006.



Experimental shortcomings: Dark Matter

Begeman et al, Mon.Not.R.Astr.Soc 259 (1991)523





- Existence of Dark Matter:
  - If all mass is visible

$$v_c \sim 1/\sqrt{r}$$

  - If an halo exists

$$\left.\begin{array}{c}\rho(r) \sim 1/r^2 \\ M(r) \sim r\end{array}\right\} \rightarrow v_c\, const$$

- No particle in SM can play the role of dark matter

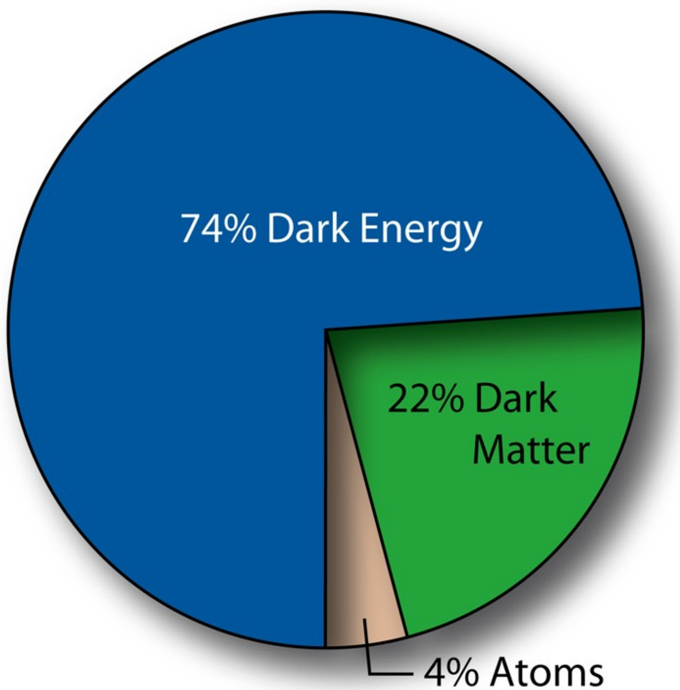
Experimental shortcomings: Dark Energy

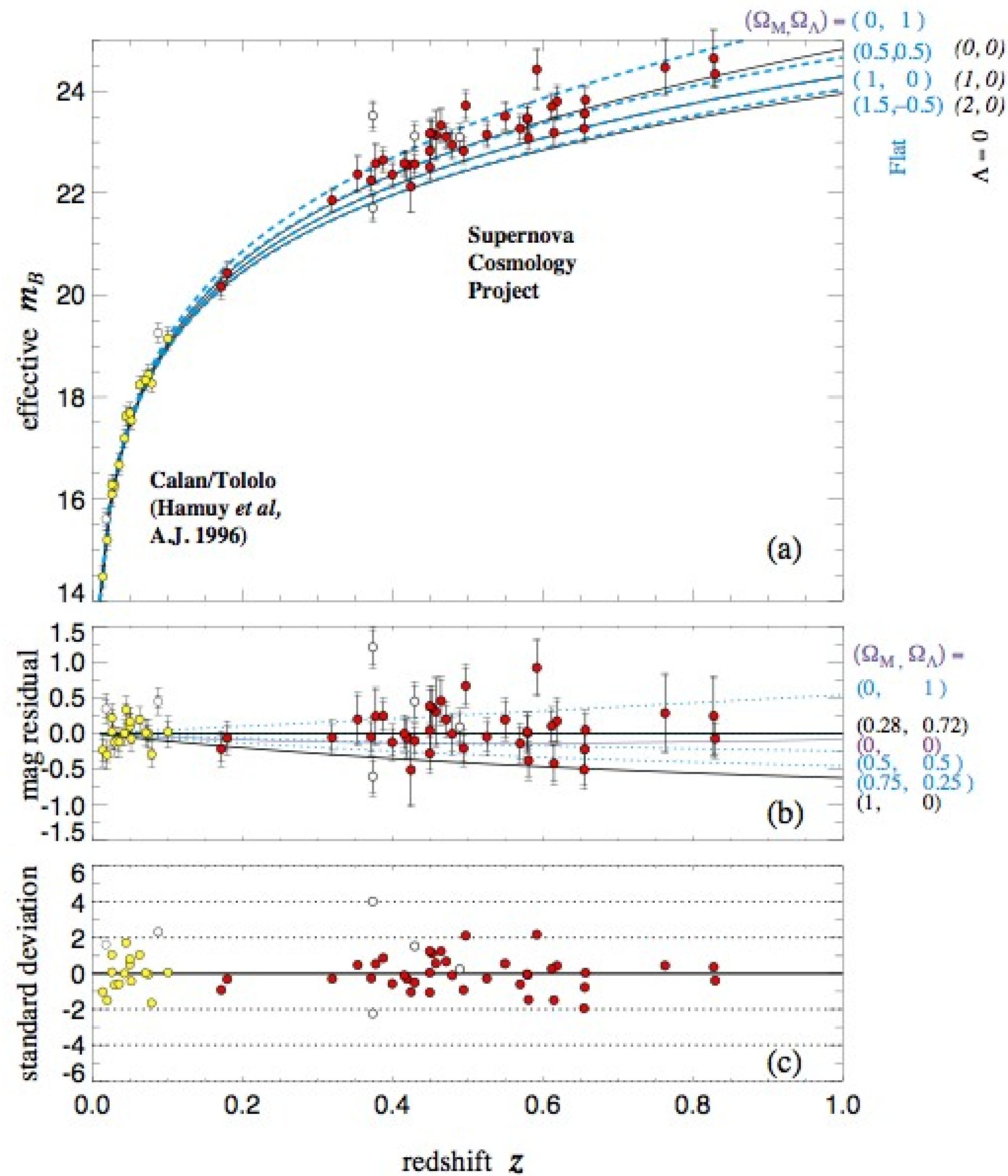
- Existence of Dark Energy:
  - (Re)discovered in 1998
  - Confirmed by CMB experiments
  - Inflation era

Riess et al,
Astron.J. 116:1009 (1998)

Perlmutter et al.
Astrophys.J.517:565-586,1999.

WMAP 2006 results
astro-ph/0603449





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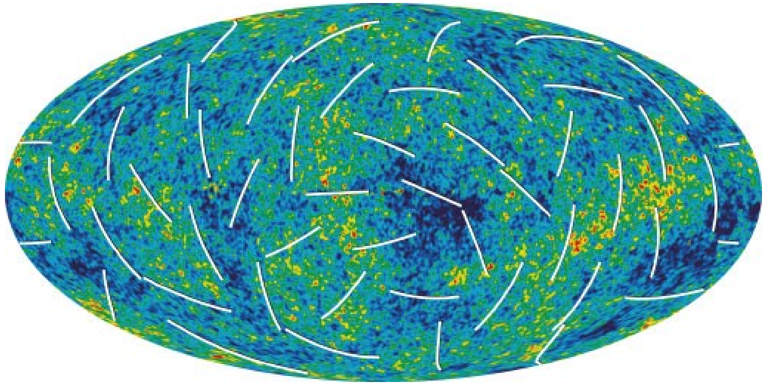
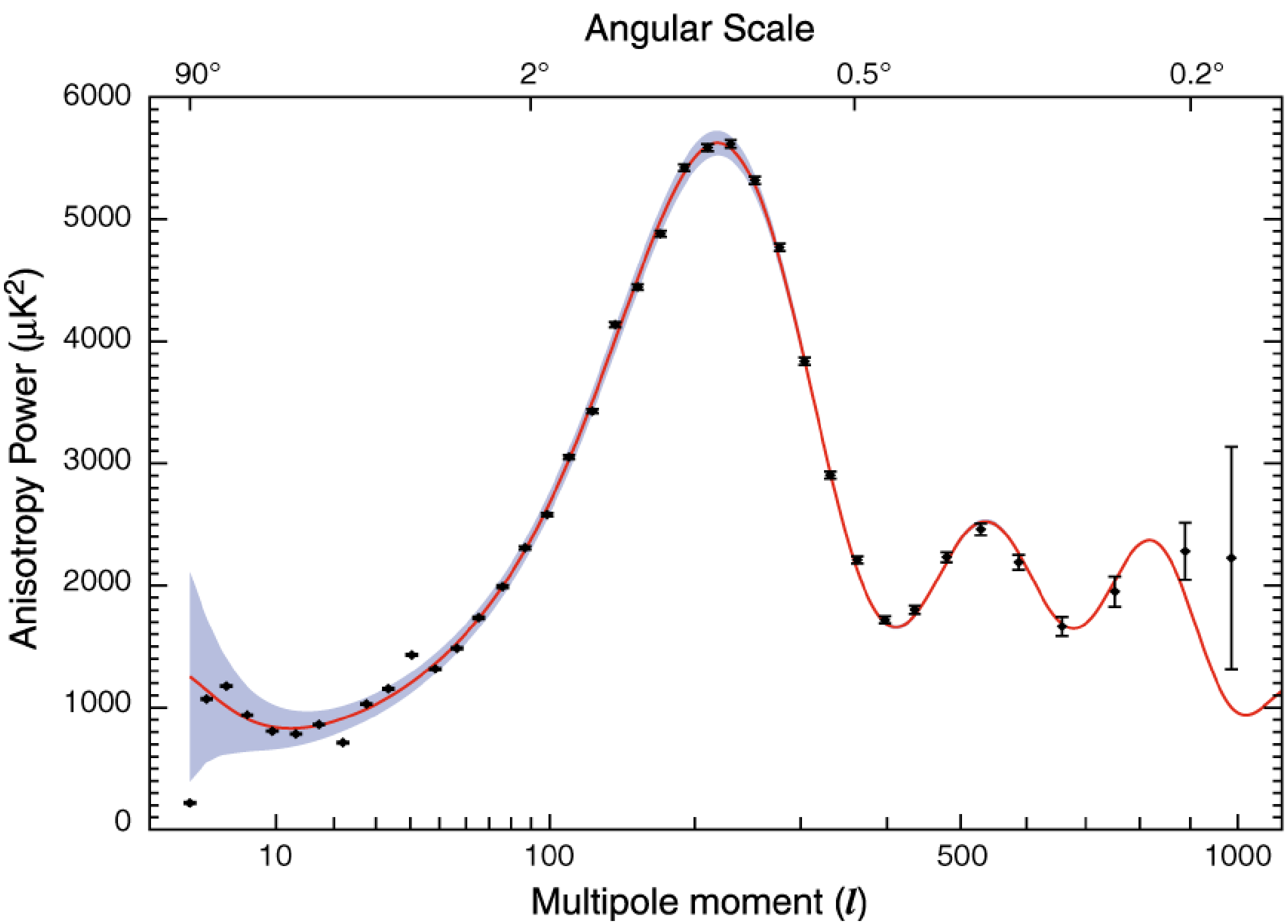
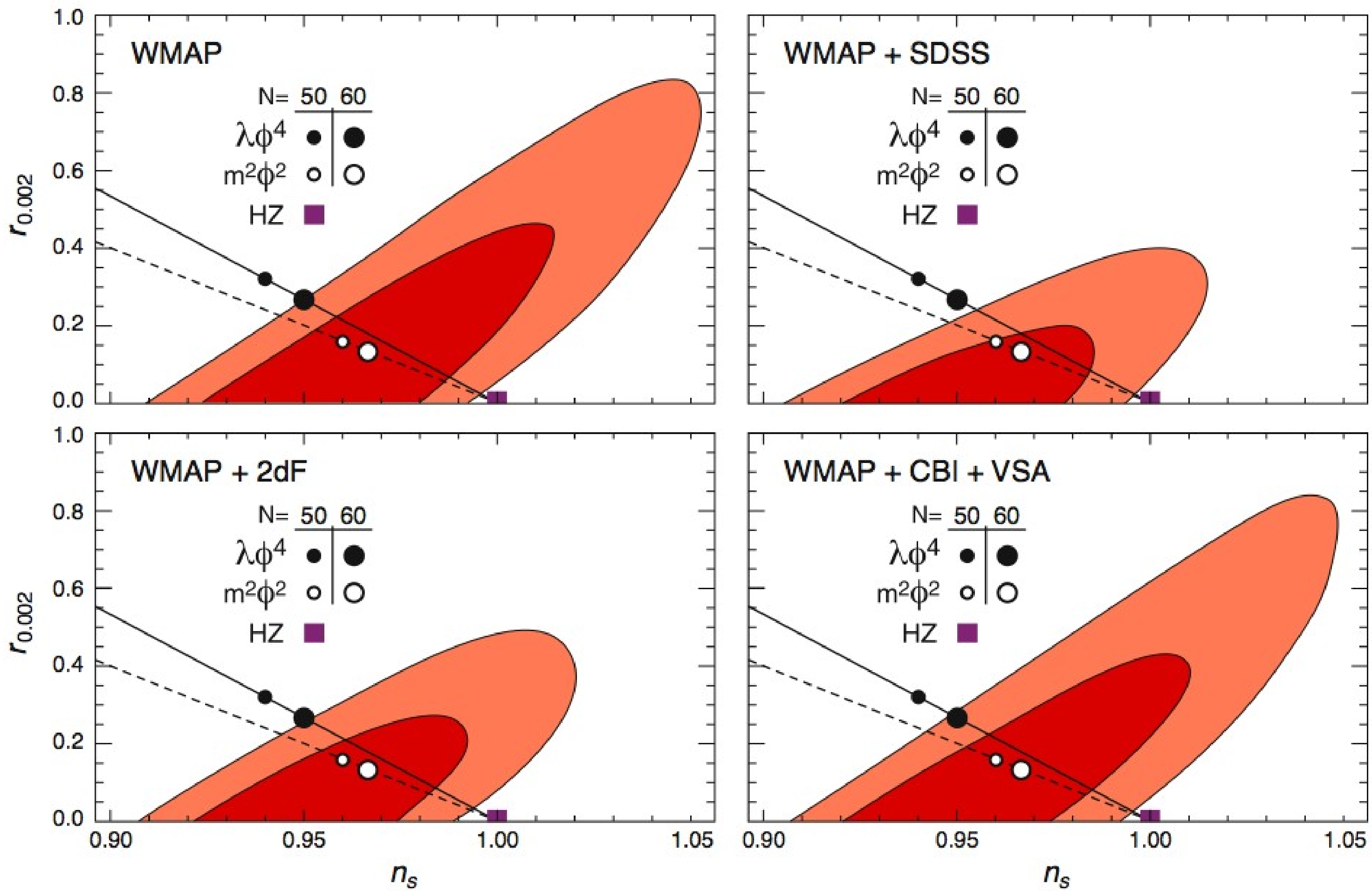




Experimental shortcomings: Dark Energy

- Existence of Dark Energy:
  - (Re)discovered in 1998
  - Confirmed by CMB experiments
  - Inflation era
  - ϕ^4 potential disfavoured by WMAP



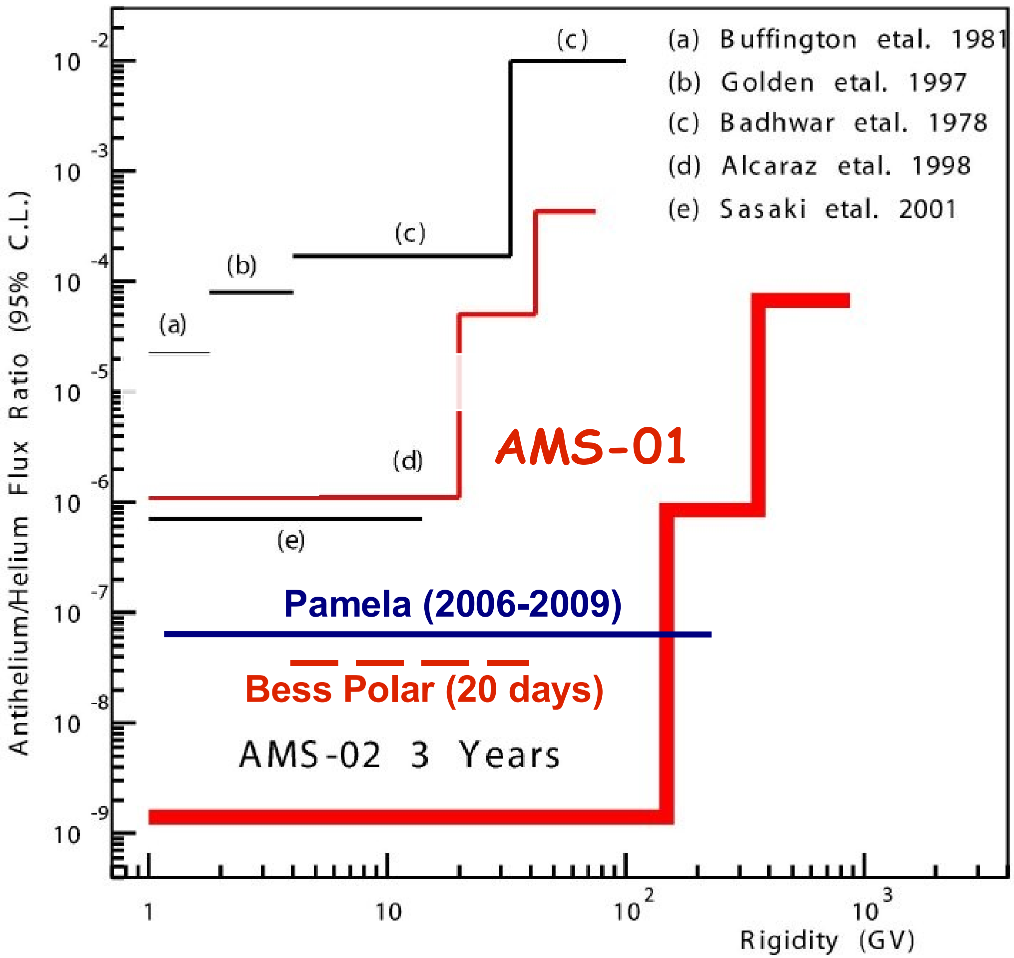
Experimental shortcomings: Baryon asymmetry

- CP violation can explain but fails quantitatively

- Weak experimental evidence
  - No annihilation radiation <20Mpc
  - No cosmic diffuse γ shoulder
  - No distorsion of CMB

    Cohen, De Rujula,Glashow
    Astrophys.J. 495:539-549(1998)

- New generation of satellites/balloons
  - PAMELA
  - AMS-II
  - BESS



If antihelium found → primordial antimatter
If anti-nuclei Z>2 found → anti-stars

Beyond SM: Supersymmetry

Supersymmetry (SUSY)

- Space-time symmetry relating fermions with bosons

$$Q|Fermion\rangle \Rightarrow |Boson\rangle$$
$$Q|Boson\rangle \Rightarrow |Fermion\rangle$$

- Every known particle is associated with a new particle (sparticles) differing by ½ spin.
  - Same masses and gauge structure if not broken
- R-parity $(-1)^{2S+3B+L}$
  - R_p = +1 ordinary particles
  - R_p = -1 sparticles
- SUSY must be broken:

$$m(\tilde{\chi}_1^{\pm}) > \sim 130\, GeV/c^2 \;\; CDF$$
$$m(\tilde{\chi}_1^{0}) > \sim 122\, GeV/c^2 \;\; CDF$$
$$m(\tilde{l}_R) > \sim 90\, GeV/c^2 \;\; LEP2$$
$$m(\tilde{g}) > \sim 195\, GeV/c^2 \;\; CDF$$
$$m(\tilde{q}) > \sim 380\, GeV/c^2 \;\; CDF$$

spin 1/2	
leptons	quarks
$[\nu_{e,\mu,\tau}]_L$	$[u,c,t]_{L,R}$
$[e,\mu,\tau]_{L,R}$	$[d,s,b]_{L,R}$

spin 0	
sleptons	squarks
$[\tilde{\nu}_{e,\mu,\tau}]_L$	$[\tilde{u},\tilde{c},\tilde{t}]_{L,R}$
$[\tilde{e},\tilde{\mu},\tilde{\tau}]_{L,R}$	$[\tilde{d},\tilde{s},\tilde{b}]_{L,R}$

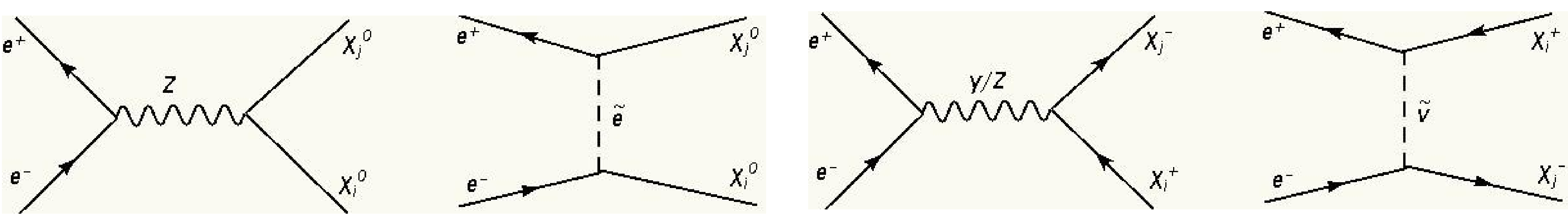
spin 1	spin 0
gauge bosons	higgs bosons
g	
$W^{\pm}$	$H^{\pm}$
γ, Z	h, H, A

spin 1/2		
gauginos	higgsinos	
$\tilde{g}$		
$\tilde{W}^{\pm}$	$\tilde{H}^{\pm}$	$\tilde{\chi}_i^{\pm}, i=1,2$
$\tilde{B}, \tilde{W}^0$	$\tilde{H}_1^0, \tilde{H}_2^0$	$\tilde{\chi}_i^0, i=1..4$

- Solve hierarchy problem
- Provides a candidate for DM
- New particles contribute to unification of gauge coplings
  - $M_{GUT} \sim 10^{16}$ GeV
- Local SUSY leads to quantum gravity

Supersymmetry (SUSY)

- Minimal Supersymmetric Standard Model (MSSM)
  - SM gauge group
  - Minimal particle content
  - R-parity conservation
  - Minimal set of soft SUSY-breaking terms
    - Mass terms for gluinos,winos, binos and scalar fermions
    - Mass and bilinear terms for Higgs bosons
    - Trilinear couplings between sfermions and Higgs bosons
- Unconstrained MSSM → 105 new parameters
- Constrained MSSM → 22 new parameters
  - SUSY breaking parameters real (no CP-violation)
  - sfermion and coupling constants diagonal (No FCNC)
  - First/Second mass parameters are equal



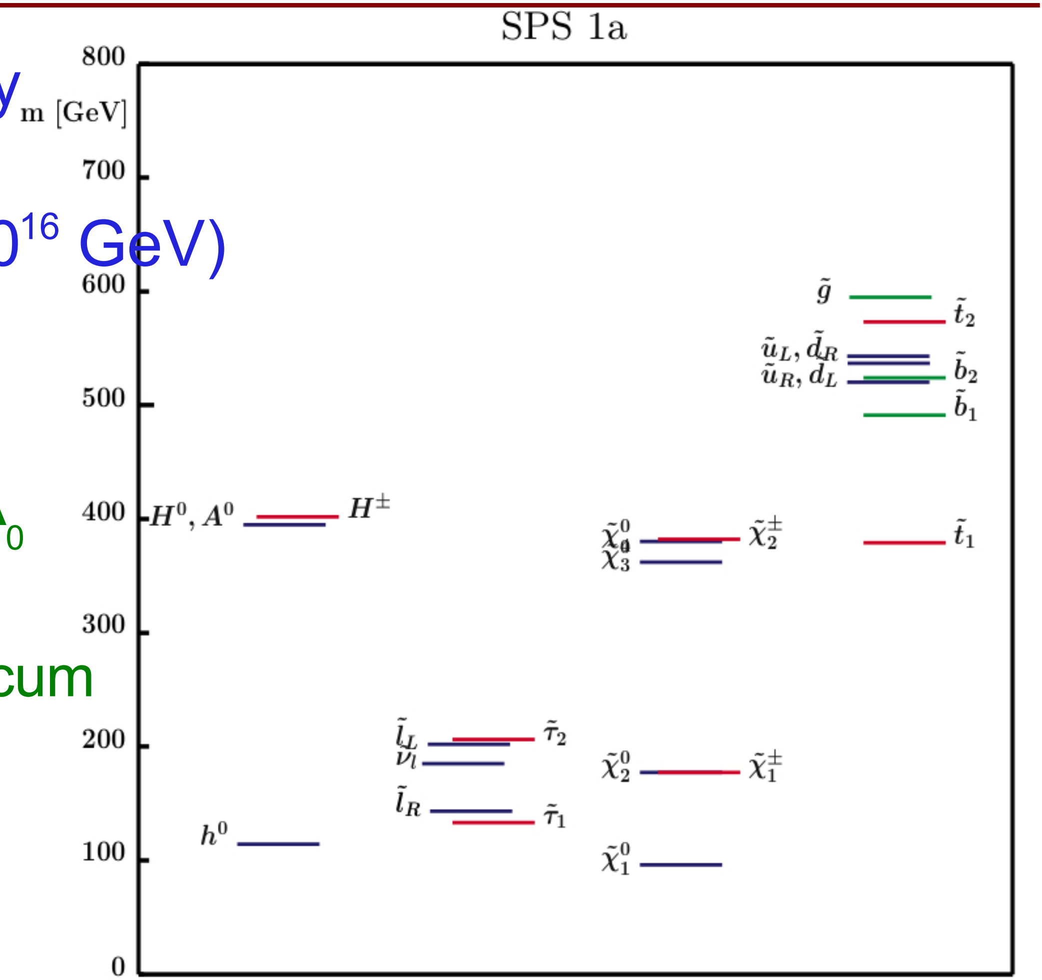
Supersymmetry (SUSY): mSUGRA

- SUSY symmetry broken by gravity
- Interactions are “flavor-blind”
- Unification at high energy (~2 x 10^{16} GeV)
  - Unification of gauginos → $m_{1/2}$
  - Unification of scalars → m_0
  - Universal trilinear couplings → A_0
- Two more free parameters
  - Ratio beetwen neutral Higgs vaccum expectation values

$$\langle H_1^0 \rangle = \frac{v_1}{\sqrt{2}} \qquad \tan\beta = \frac{v_2}{v_1} \qquad \langle H_2^0 \rangle = \frac{v_2}{\sqrt{2}}$$

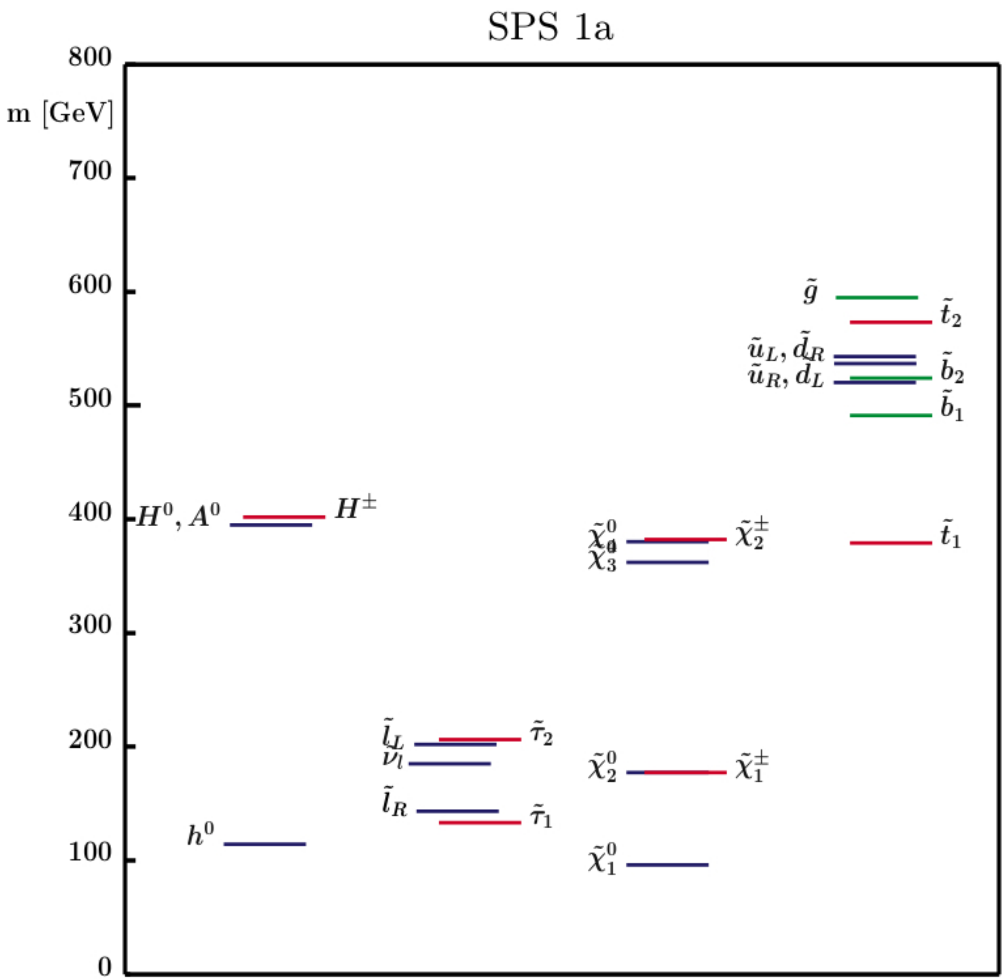
  - Sign (μ)

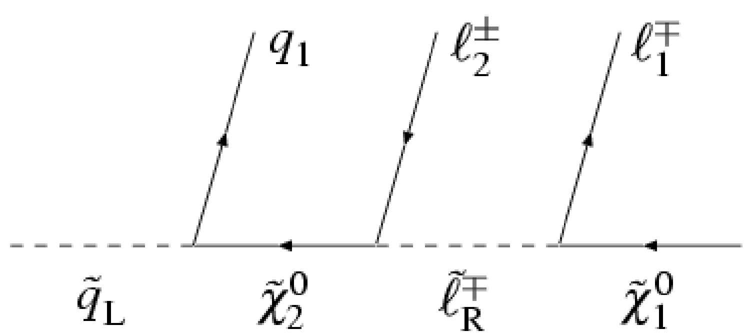
$$\mu^2 = \frac{m_{H_2}^2 \sin^2\beta - m_{H_1}^2 \cos^2\beta}{\cos 2\beta} - \frac{M_Z^2}{2}$$



$$m_0 = 250\,GeV$$
$$m_{1/2} = 100\,GeV$$
$$A_0 = -100\,GeV$$
$$\tan\beta = 10$$
$$sign(\mu) > 0$$

SUSY Decays





- Neutralinos $\tilde{\chi}_2^0 \rightarrow f \bar{f} \tilde{\chi}_1^0$
- Charginos $\tilde{\chi}_1^\pm \rightarrow f \bar{f}' \tilde{\chi}_1^0$
- sleptons $\tilde{l}^\pm \rightarrow \tilde{\chi}^0 l^\pm$ $\rightarrow \tilde{\chi}^\pm \nu_l$
- squarks $\tilde{u}_L \rightarrow d \tilde{\chi}_1^\pm$ $\rightarrow u \tilde{\chi}_1^0$
- Expected cascades with
  - Multiple leptons
  - Multiple jets
  - Missing Energy

Physics at the Terascale

Physics Landscape in 2007

- Impressive success of SM
  - Clear hints that some extension is needed
    - Neutrino masses
    - Hierarchy problem
- Higgs not discovered
  - direct search at LEP m_H>114 GeV/c^2
  - SM corrections m_H<160 GeV/c^2
- Extensions of SM
  - Up to know only exclusion limits.
  - Huge number of theories possible

LHC STARTS

Physics in the TeV range

- Reveal Electroweak Symmetry Breaking (EWSB)
  - Higgs Mechanism in SM and BSM
  - Experimentally signaled by one or more scalars
    - Discover new particles
    - Check its nature: mass, couplings, spin, parity, etc ...
  - If not found (no Higgs or Higgs too heavy)
    - Detailed study of WW,ZZ production
      - Four-gauge vertices highly suppressed in SM
      - Possible existence of strong interactions in the EW sector
- Decode SUSY sector
  - In case multiple particles found
    - Check its nature: mass, couplings, spin, parity, etc
    - Association with particles
- Search for Beyond SM signatures
  - Study of Extra Dimensions
  - Extended Gauge Structure
  - Little Higgs models

Physics in the TeV range

- Detailed study of gauge bosons couplings
  - Search for anomalous gauge couplings
  - Study of quartic couplings

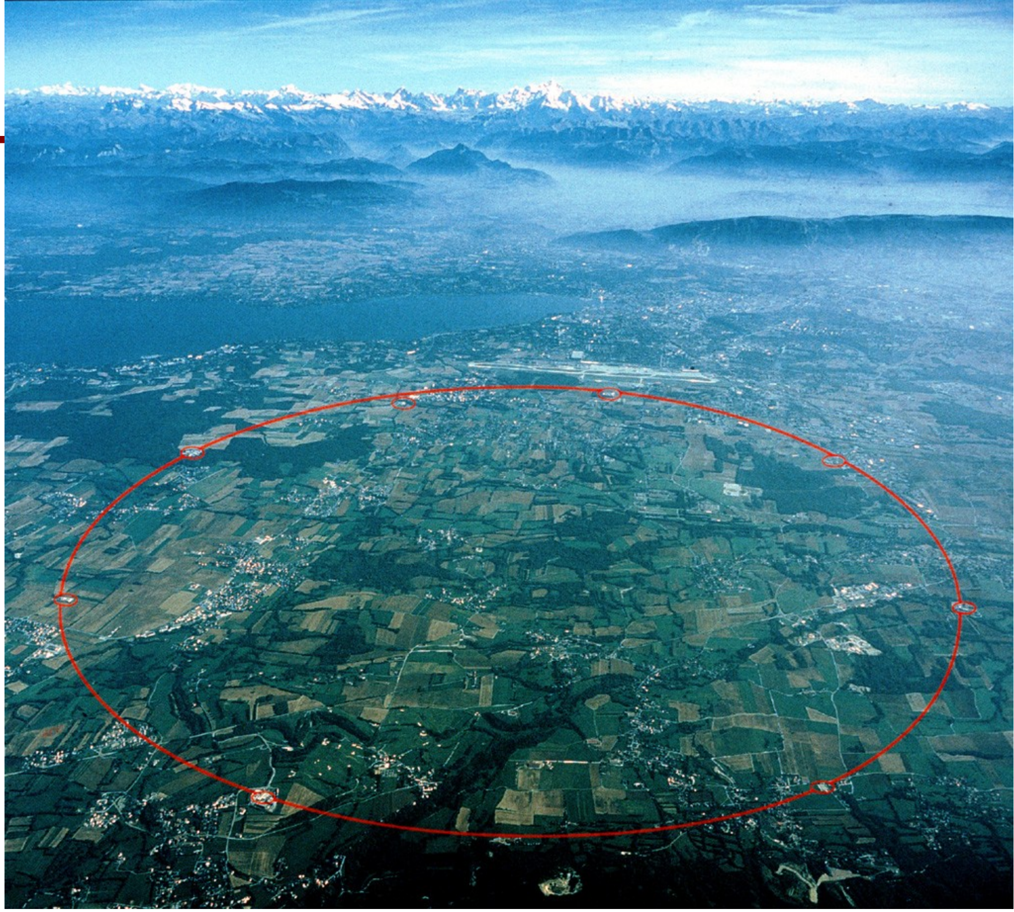
- Top quark physics
  - Mass and Width
  - Coupling with gauge bosons

What are the experimental conditions needed to cover all these topics?

hadron collider: LHC
e+e- collider: ILC

LARGE HADRON COLLIDER
LHC

Large Hadron Collider



- pp collider @ 14 TeV
- 4 Experiments
  - CMS,ATLAS
  - LHCb
  - ALICE
- Luminosity

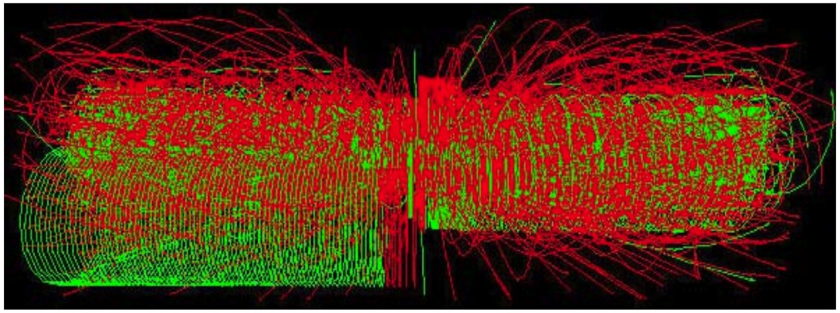
	2007	2008	2009-2010	2011-2015
Inst. ($cm^{-2}s^{-1}$)	$3x10^{29}$-$2x10^{31}$	10^{32}-$2x10^{33}$	$2x10^{33}$	10^{34}
Integral	10 pb^{-1}	<5 fb^{-1}	10 -30 fb^{-1}	100 -300 fb^{-1}

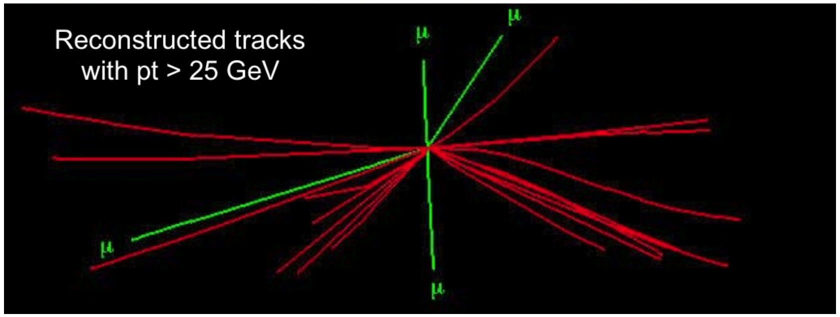
- Upgrade in luminosity in 2015? (sLHC)
- Upgrade in Energy???

LHC: Beam structure

	#bunches	Δt_{bunch}	Crossing angle	*p*/bunch	Peak Luminosity	
Pilot Run	43→156	-	0 μrad	$(1\text{-}5)\times10^{10}$	3×10^{29}-2×10^{31}	@900GeV
First Physics	936→2808	75→25 ns	0→250 μrad	5×10^{10}	10^{32}-2×10^{33}	
Low luminosity	2808	25 ns	285 μrad	5×10^{10}	2×10^{33}	
High Luminosity	2808	25 ns	285 μrad	1.15×10^{11}	10^{34}	

- Background
  - 20 interactions/BX (high lum)
    - ~700 charged particles/BX
    - 50 MHz/cm^2 → 10kHz/pixel (R= 5cm)
  - Integrated dose:
    - 840 kGy (R=5cm)
    - 0.2-1000 kGy (HCAL)



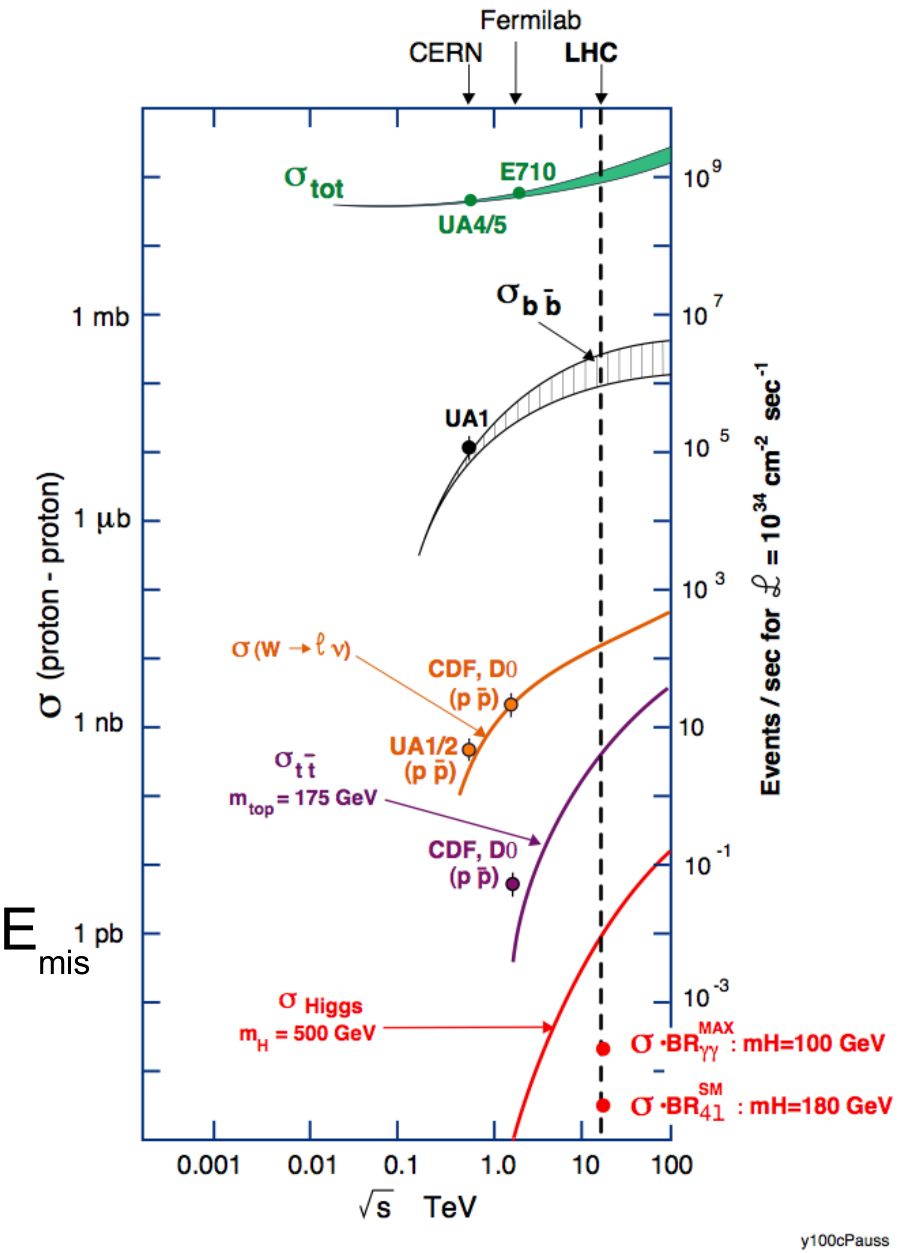


LHC: Trigger

- LHC total event rate ~ 10^9 Hz

inelastic pp scattering	: 10^9 Hz
single W → l ν	: 10^2 Hz
tt production	: 10 Hz
Higgs(m_H=100 GeV/c^2)	: 0.1 Hz
Higgs(m_H=600 GeV/c^2)	: 10^{-2} Hz

- decision to be taken every 25 ns
  - reduce rate 10^9 Hz →100 Hz
  - trigger decision taken in several trigger levels of increasing refinement
    - Level 1 (hardware)
      - Calorimeter trigger: γ,e,τ,jets,E_T,E_{mis}
      - Muon Trigger
    - High Level Trigger (software)
      - Regional event reconstruction



INTERNATIONAL LINEAR COLLIDER
ILC

International Linear Collider

- International proposal to build an electron-positron linear collider
  - International: world-wide effort
  - Linear: $\Delta E_{brems} \propto E^4/R$
- Main characteristics
  - E_{cm} tunable
    - Phase I : 200-500 GeV
    - Phase II: upgradable to 1 TeV
  - Luminosity
    - Peak: 2×10^{34} cm^{-2} s^{-1}
    - in 4 years: ~500 fb^{-1}
  - Energy stability <0.1%
  - Polarization
    - electrons: >80%
    - positrons: >60% (option)
  - option for e^--e^- and γ–γ collisions

http://www.linearcollider.org

- Proposal level
  - RDR issued Feb 2007
- No site chosen
  - America: FNAL
  - Asia: Japan
  - Europe: CERN
- Economical case

ILC – Economic Case

http://www.economist.com/science/displaystory.cfm?story_id=8810981

NOT content with spending around $10 billion on a shiny new collider at CERN, the European particle physics laboratory in Geneva, **physicists are now campaigning for its successor**. The International Linear Collider (**ILC**), as the machine is dubbed, **would cost** a mere **$8.2 billion**, according to its backers. Ray Orbach, the **head of America's Office of Science**, gave a warning last month that, although he supports the project, it is too expensive to build rapidly. The **first data to come** from such a collider would probably not emerge until the mid- to **late-2020s**

(...)

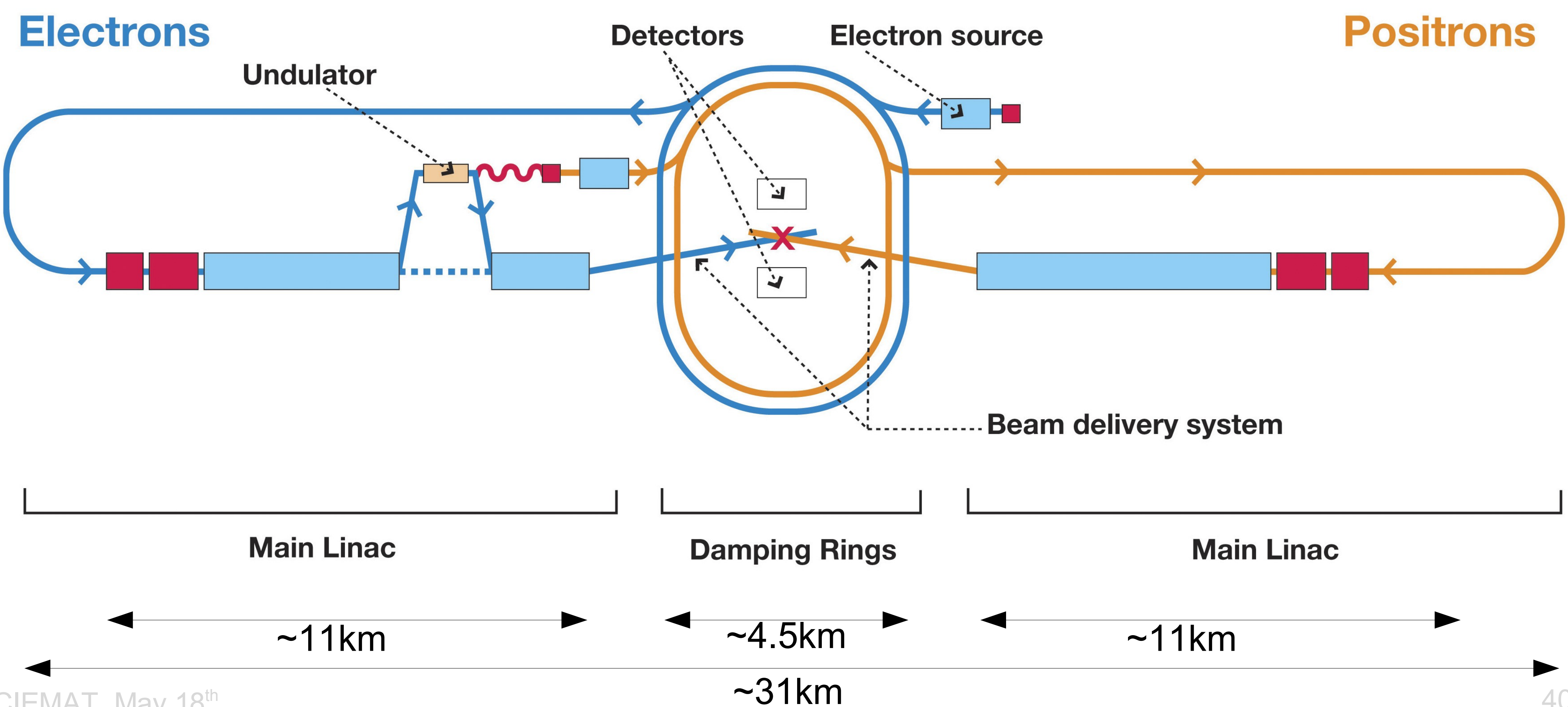
For diplomatic reasons, **three designs have been drafted**. One is tailored to geological conditions at Fermilab, near Chicago. The second is suitable for construction at CERN. A third would be appropriate for a mountainous area of granite in Japan. **The winner** will probably be **whoever has the biggest chequebook**.

Appeared in The Economist (March 2007)

ILC: Project overview

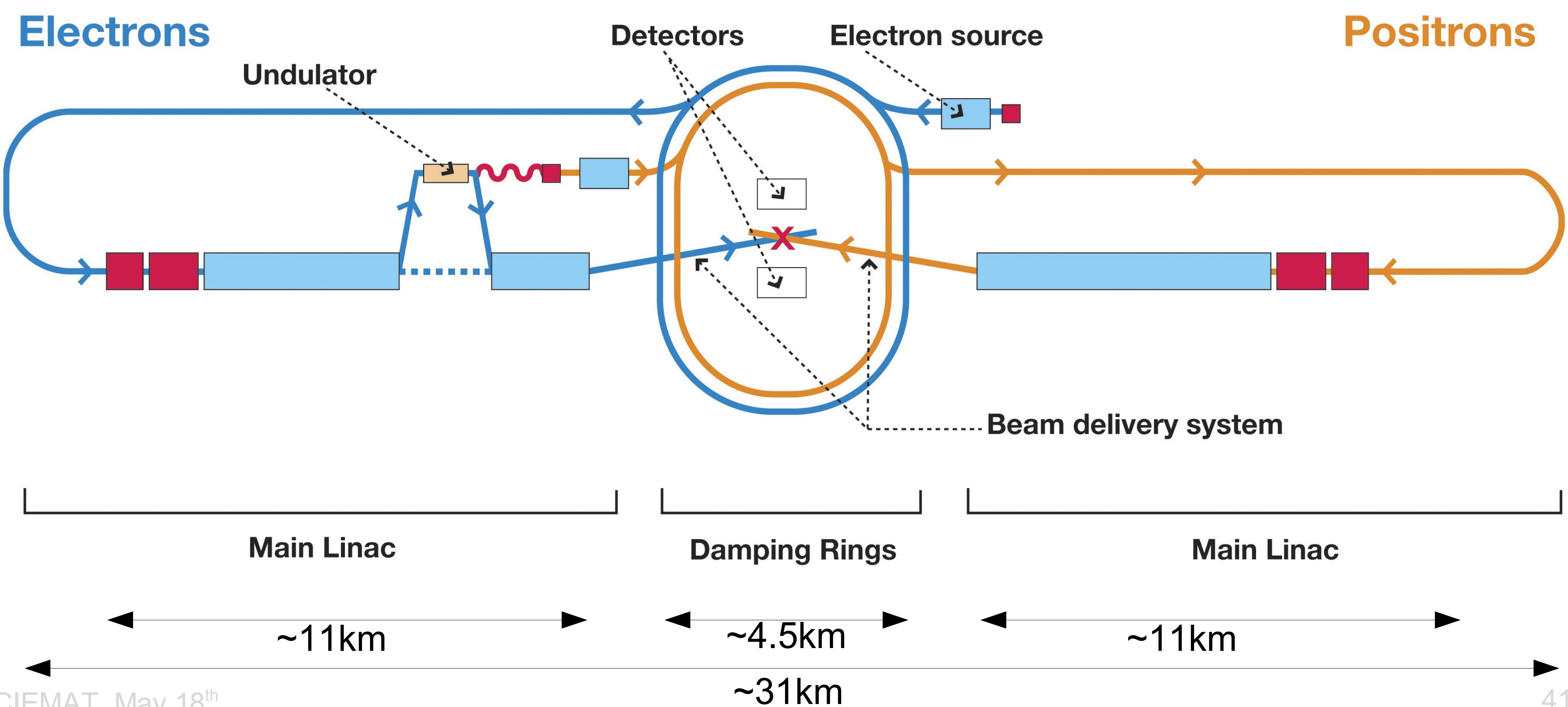
- 1 Interaction point
  - collisions at 7 mrad
  - 2 experiments (push-pull)

	ILC	CLIC
Accelerating Gradient	31.5 MV/m	150 MV/m
Accelerating RF	1.3 Ghz	30 Ghz
Length for 500 Gev	31 km	6.4 km
Lenght for 1 TeV	50 km	14.4 km
Length for 3 TeV	-	37 km



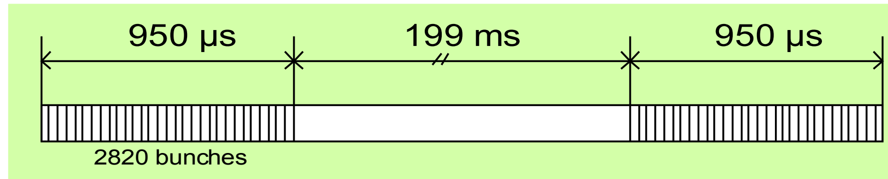
ILC: Schedule

- 1 Interaction point
  - collisions at 7 mrad
  - 2 experiments (push-pull)
    - Form collaborations ~2010
- Schedule (best case)
  - design ~2010
  - begin construction ~2012
  - end construction ~2019



ILC: Beam structure + Trigger

- 2820 (4500) bunches spaced by 337 (189) ns
- 199 ms between trains (5 Hz Bunch Trains)



- Background
  - Beamstrahlung
    - 140.000 e+e- pairs/BX (mostly within beam pipe)
      - 0.03(0.05) hits/mm^2/BX @ E=500(800) GeV, R=15mm, B=4T
      - Bunch train = 85 hits/mm^2/BT. 10% occupancy for 25 μm^2 pixel
  - Two photon events: $e^+e^- \rightarrow e^+e^-$+hadrons
    - 0.02/BX with visible tracks
      - ~400 hits/BX in vertex detectors
      - ~5 tracks/BX in central tracking
  - ~20 readout cycles/BT (47.5 μs) to keep occupancy low
  - 50 MHz (20 ns) readout @ detector level
- <u>NO ELECTRONIC TRIGGER</u>
  - All physics on tape is unbiased

Event Rates @ 500 GeV

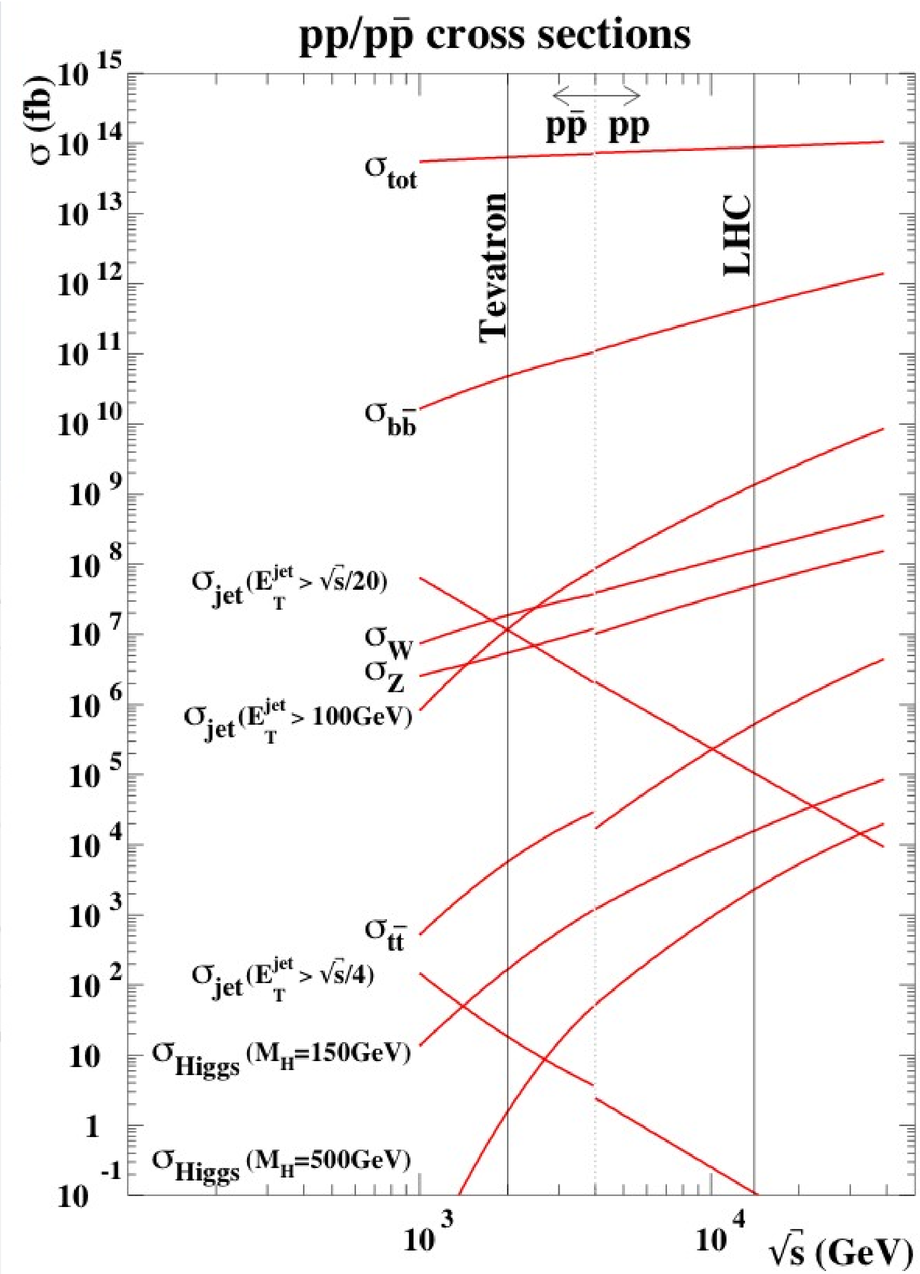
$e^+e^- \rightarrow e^+e^-$ (θ>20mrad)	210 s^{-1}
$e^+e^- \rightarrow$qq (q≠t)	960 h^{-1}
$e^+e^- \rightarrow W^+W^-$	560 h^{-1}
$e^+e^- \rightarrow$ tt	42 h^{-1}
$e^+e^- \rightarrow$ ZH (M_h=120GeV)	4 h^{-1}

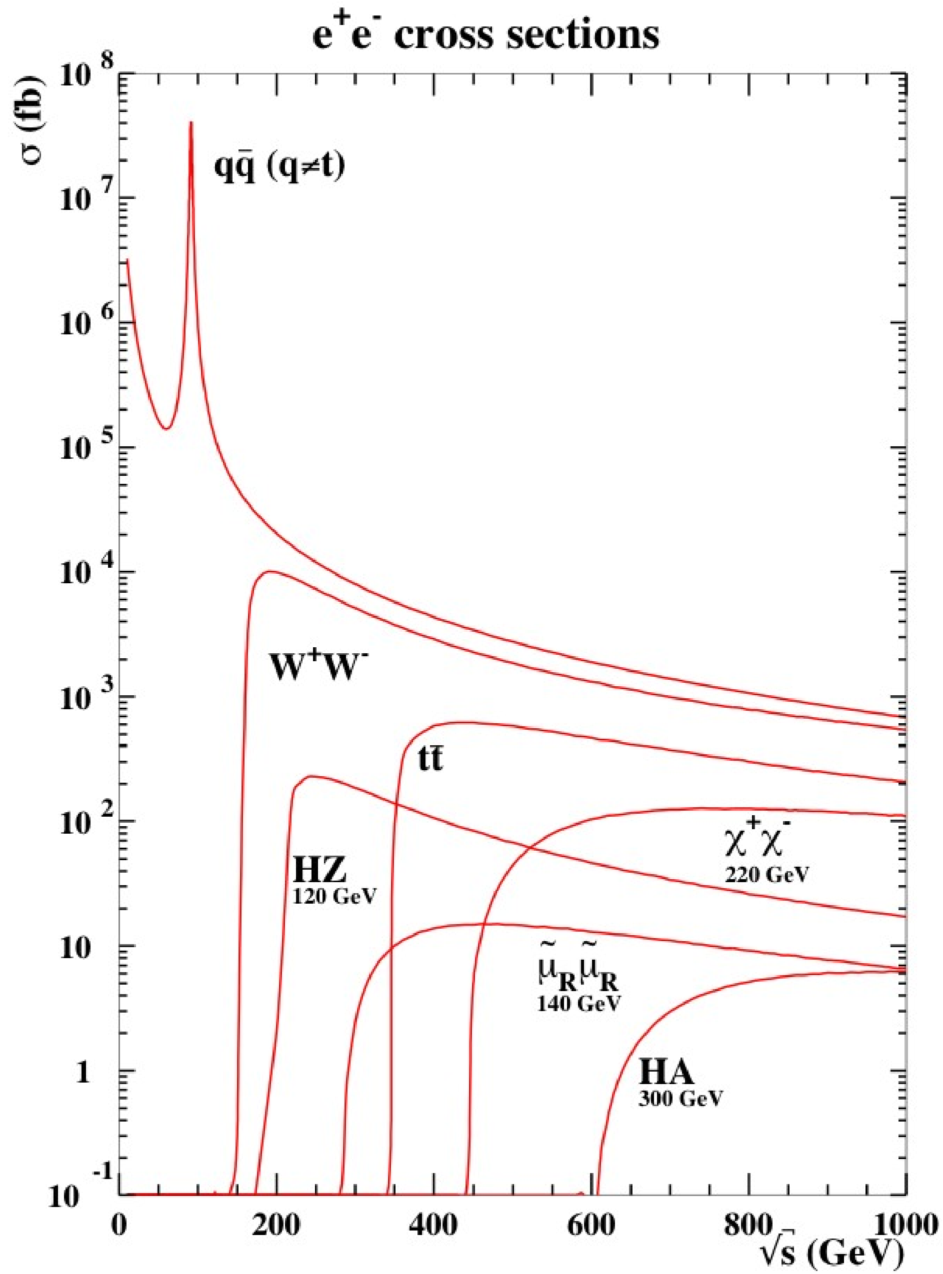
ILC: Operation Modes

- Maximum energy
  - $\sqrt{s} = 0.5/1$ TeV
  - Machine in "discovery" mode
- Threshold scan
  - To measure (selected) particles masses.
- Enhanced particle production
  - Produce maximum of particles in a channel.
- GigaZ mode
  - $\sqrt{s} = 91$ GeV $\rightarrow 10^9$ Z decays in < 1 year
    - ~4×10^6 Z/exp in LEPI
  - Go to this point from time to time for calibration
- MegaW mode
  - $\sqrt{s} = 2\ M_W$ GeV $\rightarrow 10^6$ W decays in < 1 year
    - ~10^4 W/exp in LEPII

LHC AND ILC INTERPLAY

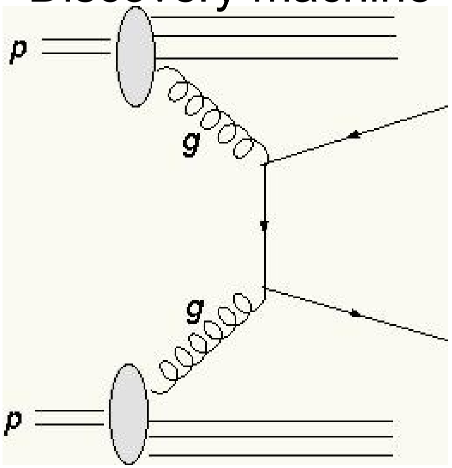
LHC vs ILC


pp/pp̄ cross sections
σ (fb)
pp̄ pp
Tevatron
LHC
σtot
σbb̄
σjet(ET jet > √s/20)
σW
σZ
σjet(ET jet > 100GeV)
σtt̄
σjet(ET jet > √s/4)
σHiggs (MH=150GeV)
σHiggs (MH=500GeV)
√s (GeV)


e+e- cross sections
σ (fb)
qq̄ (q≠t)
W+W-
tt̄
HZ
120 GeV
χ+χ-
220 GeV
μ̃R μ̃R
140 GeV
HA
300 GeV
√s (GeV)

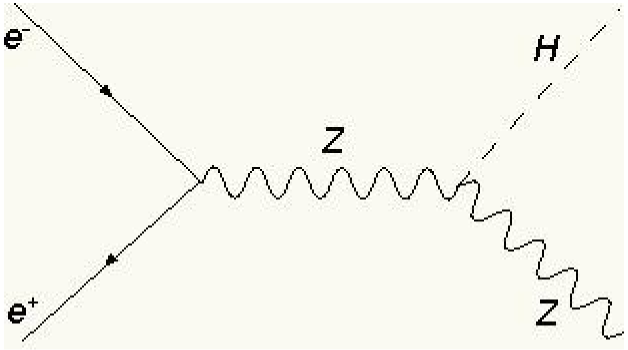
LHC vs ILC

LHC: pp @ 14 TeV
Discovery machine



- Parton scattering up to several TeV
  - CM energy not defined
  - Energy conservation in transverse plane
- Pile-up: 5-20 / bunch crossing
- Strong interactions
  - Huge QCD backgrounds
  - Underlying events
- Interaction rate 10^9
  - Trigger: 1 event in 10^7

ILC: e^+e^- @ 0.5-1 TeV
Precision machine

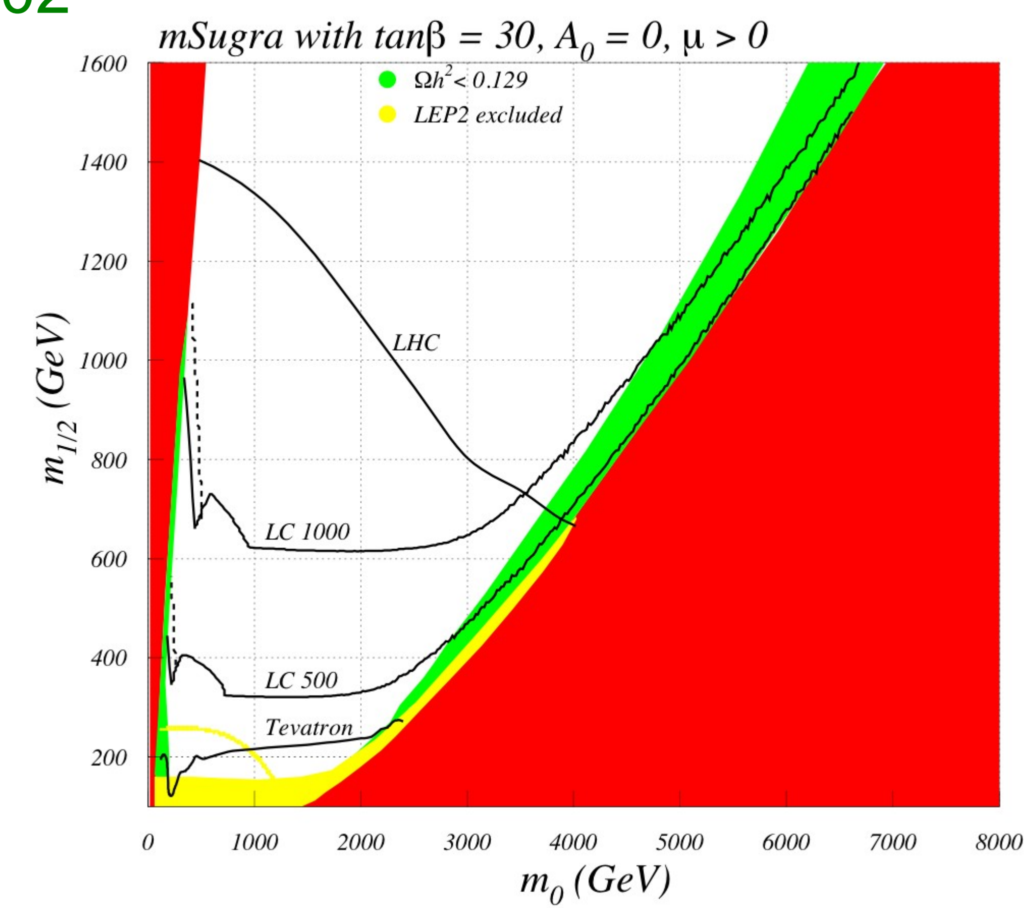


- Clean exp. Environment
  - 4-momentum conservation
- Well defined initial state
- Tunable CM energy
- Beam polarization possible
- $\gamma\gamma$, $e^-\gamma$, e^-e^- options
- Untriggered
  - Can find signal of unexpected new physics

LHC and ILC interplay

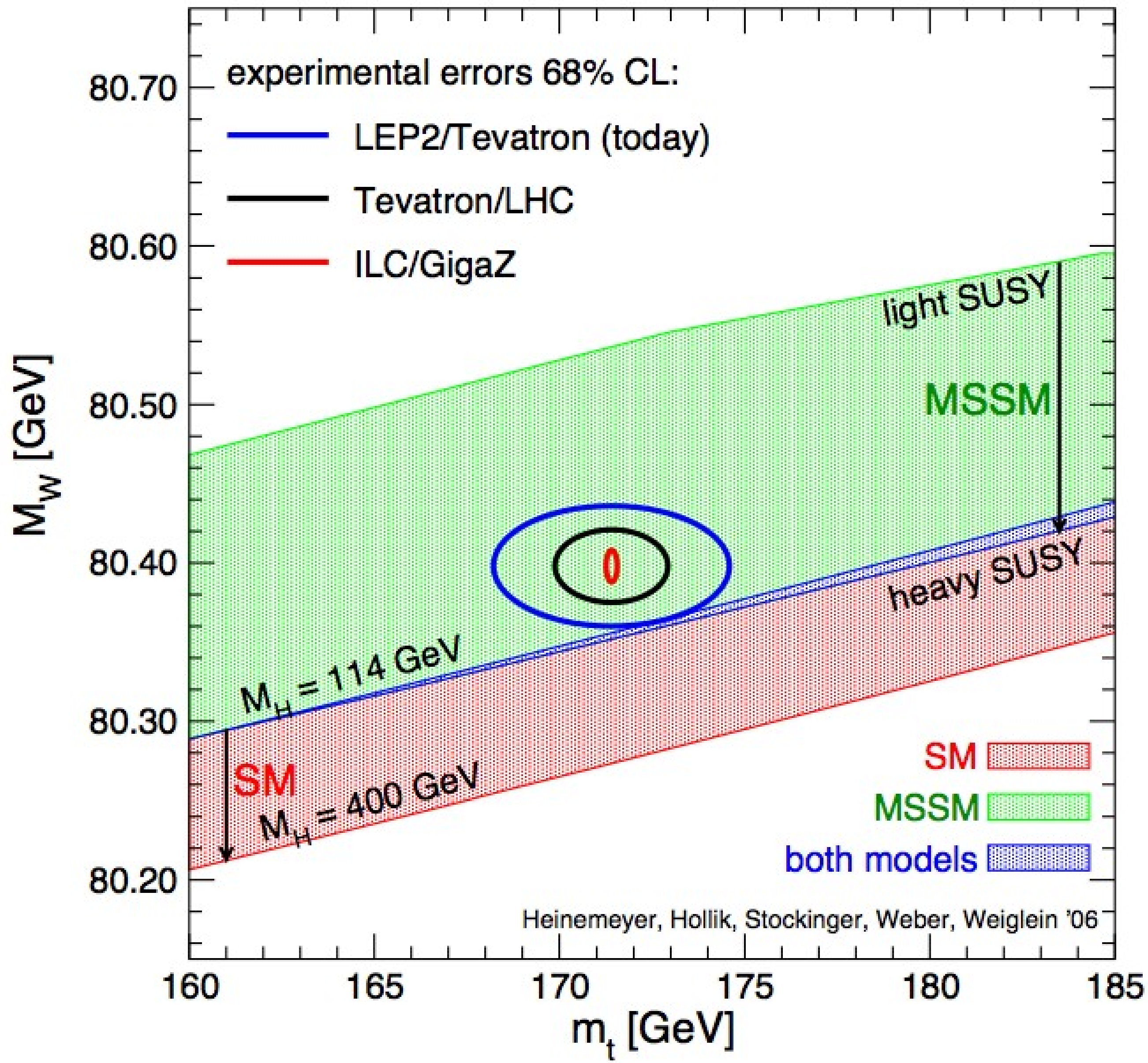
- Different situations
  - LHC (almost) ready
  - ILC still in design phase
- LHC analysis could profit from results obtained at ILC and vice-versa.
  - Working group stablished in 2002

hep-ph/0410364
Phys. Rep. 426 (2006) 47



- Complementarity
  - ILC will add precision, but ...
  - ILC can also make discoveries
- Synergy
- Concurrency
  - Not necessary but helps....

ILC precision



Synergy and Concurrency

- LHC/ILC interplay working group has provided various examples

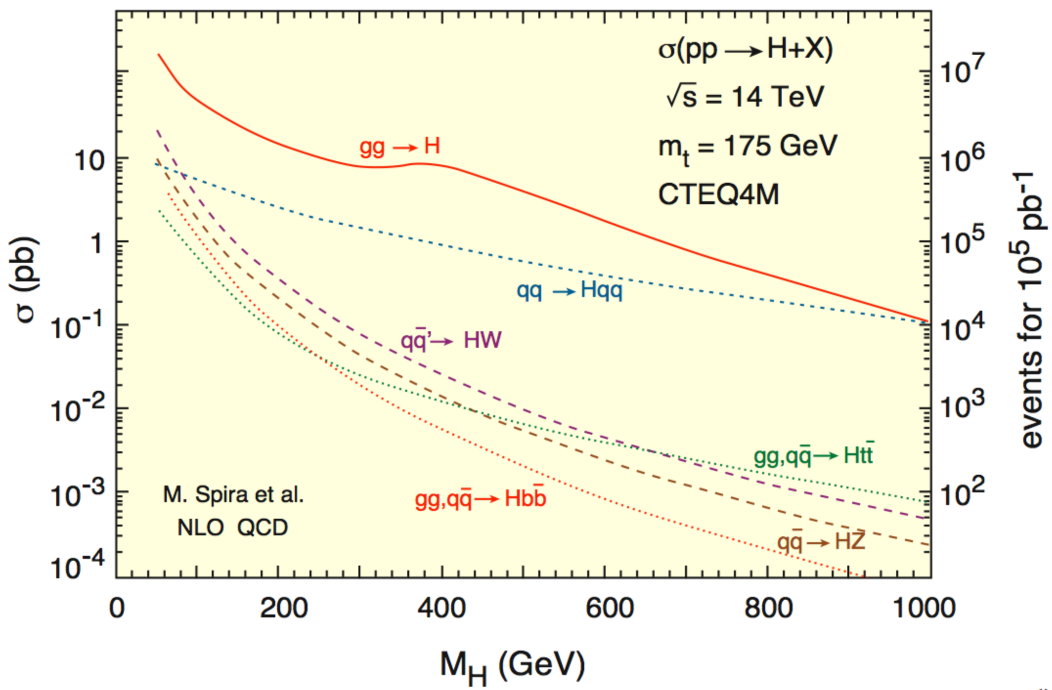
hep-ph/0410364
Phys. Rep. 426 (2006) 47

- Various scenarios
  - LHC + LC $\rightarrow$ No interaction
  - LHC $\oplus$ LC $\rightarrow$ Experiments will give inputs to each other
  - LHC $\otimes$ LC $\rightarrow$ Combined analysis: need “standard” data format

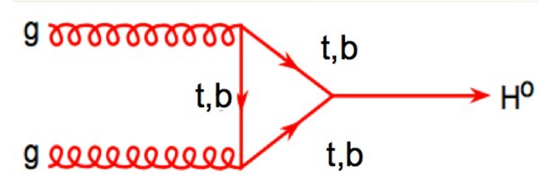
- Here presented just two examples:
  - Search of SM Higgs
  - Search of Supersymmetry

SEARCH OF
STANDARD MODEL HIGGS

SM Higgs production at LHC

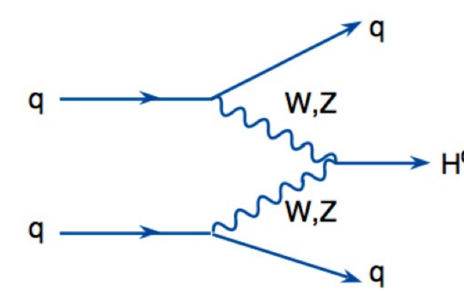


Gluon fusion(gg)

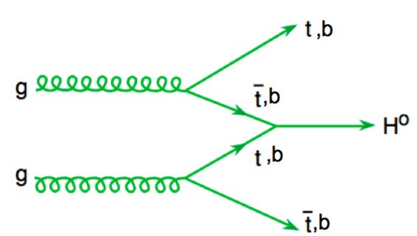


substantial QCD bkg
difficult signal - bkg separation

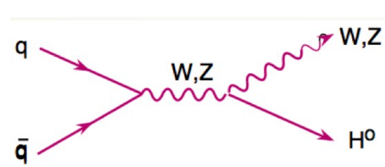
Weak Boson Fusion(WBF)



better signal / bkg ratio reached by
- double forward jet tagging
- Central Jet Vetoing techniques

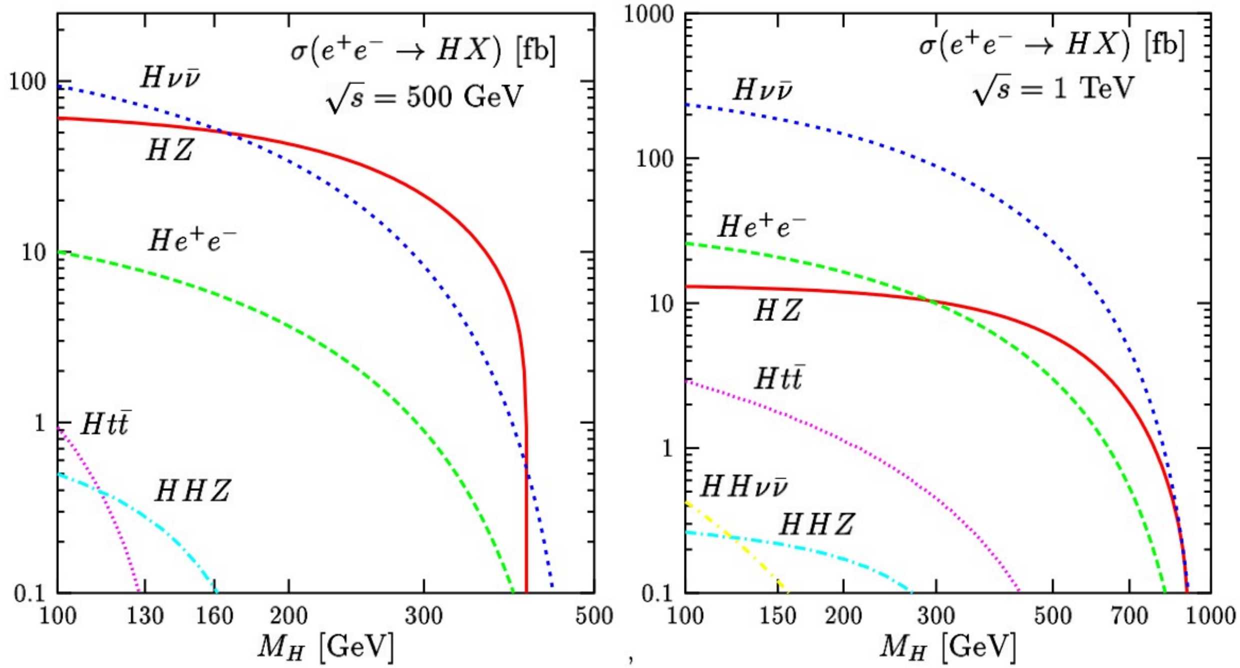


ttbar and bbbar fusion

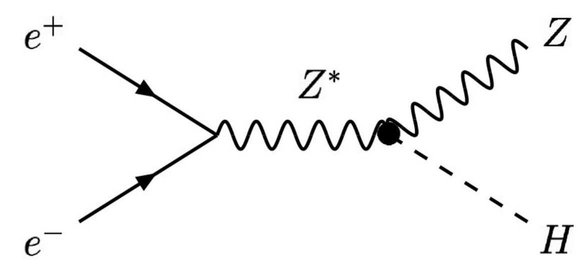


W/Z Higgs strahlung

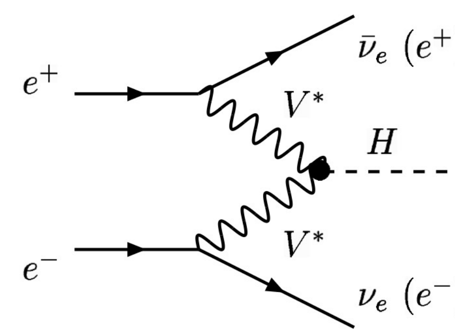
SM Higgs production at ILC



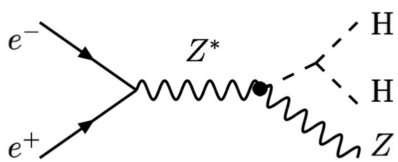
Higgs-strahlung

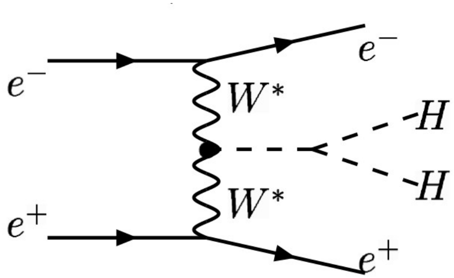


Weak boson fussion (WW,ZZ)

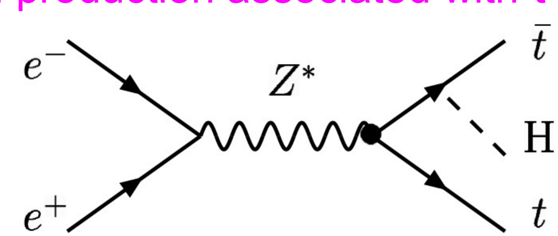


Double Higgs





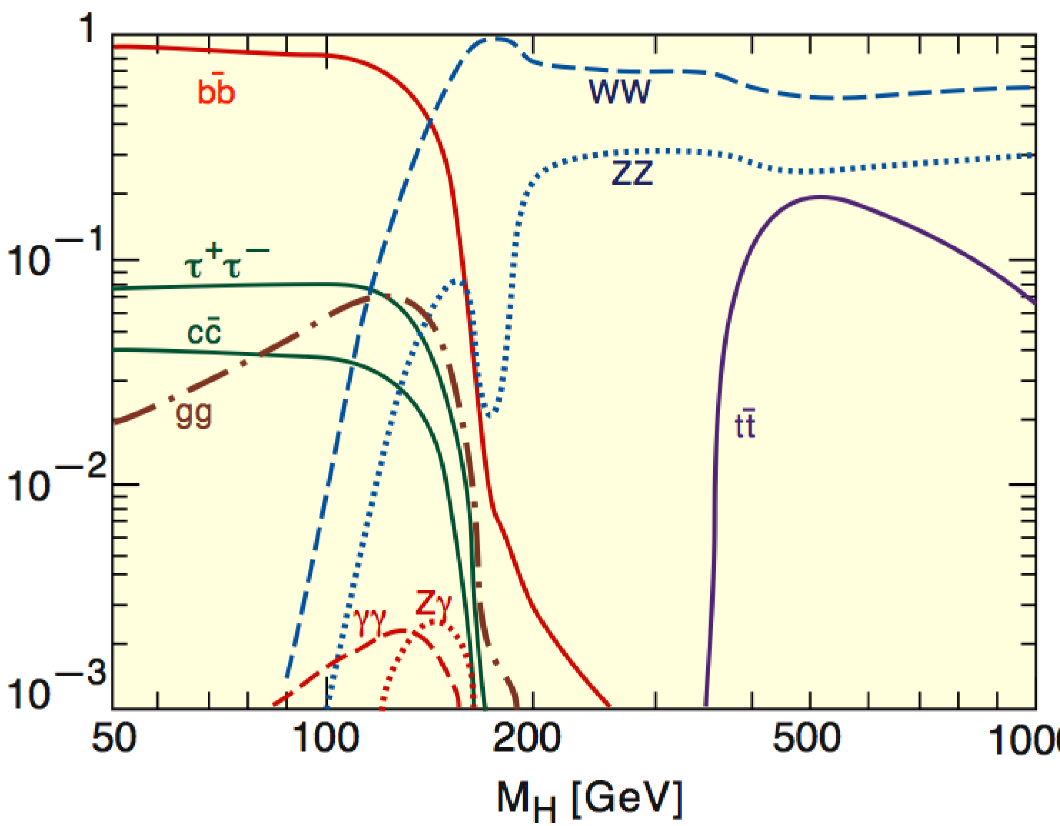
H production associated with t

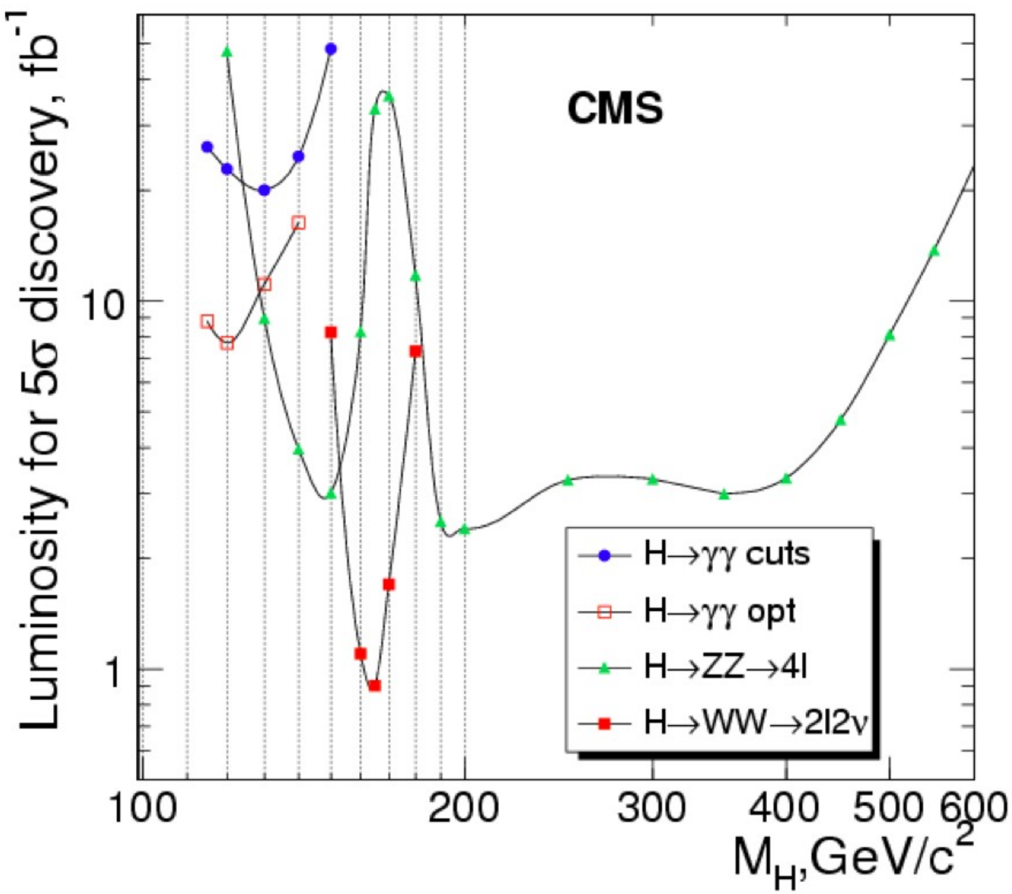


SM Higgs: Discovery and mass

	LHC	ILC
1. Find a new particle	✓	
2. Measure its mass	✓	
3. Measure coupling to gauge bosons		
4. Measure coupling to fermions		
5. Measure self-couplings		
6. Measure spin		

- LHC:
  - Search for selected channels
    - $H \to \gamma\gamma$ $m_H \in [114,130]$
    - $H \to ZZ^*$ $m_H \in [130,150]$, $m_H > 180$
    - $H \to WW^{(*)}$ $m_H \in [150,180]$





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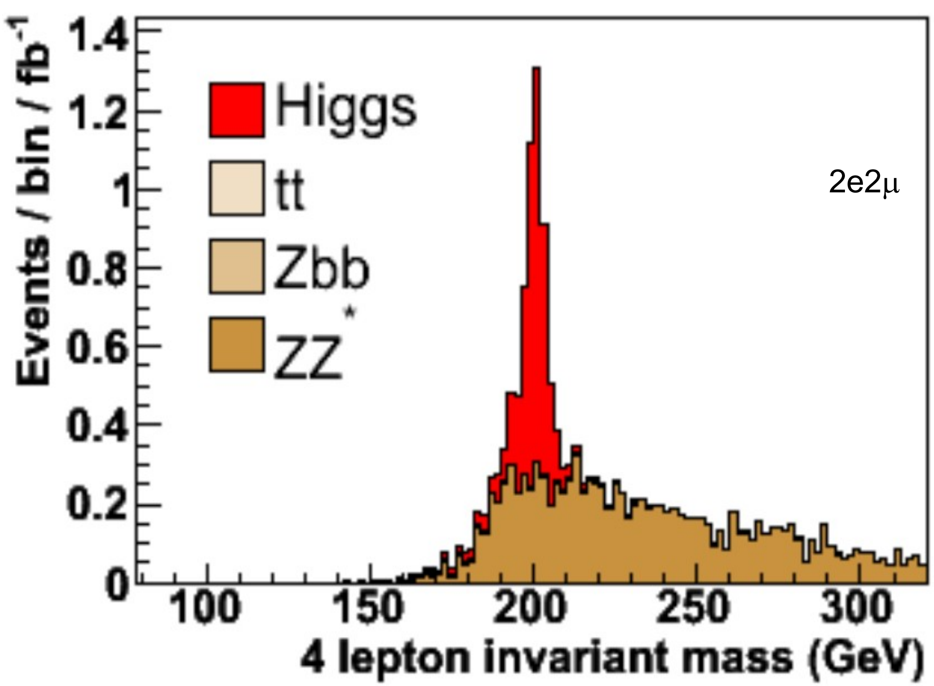

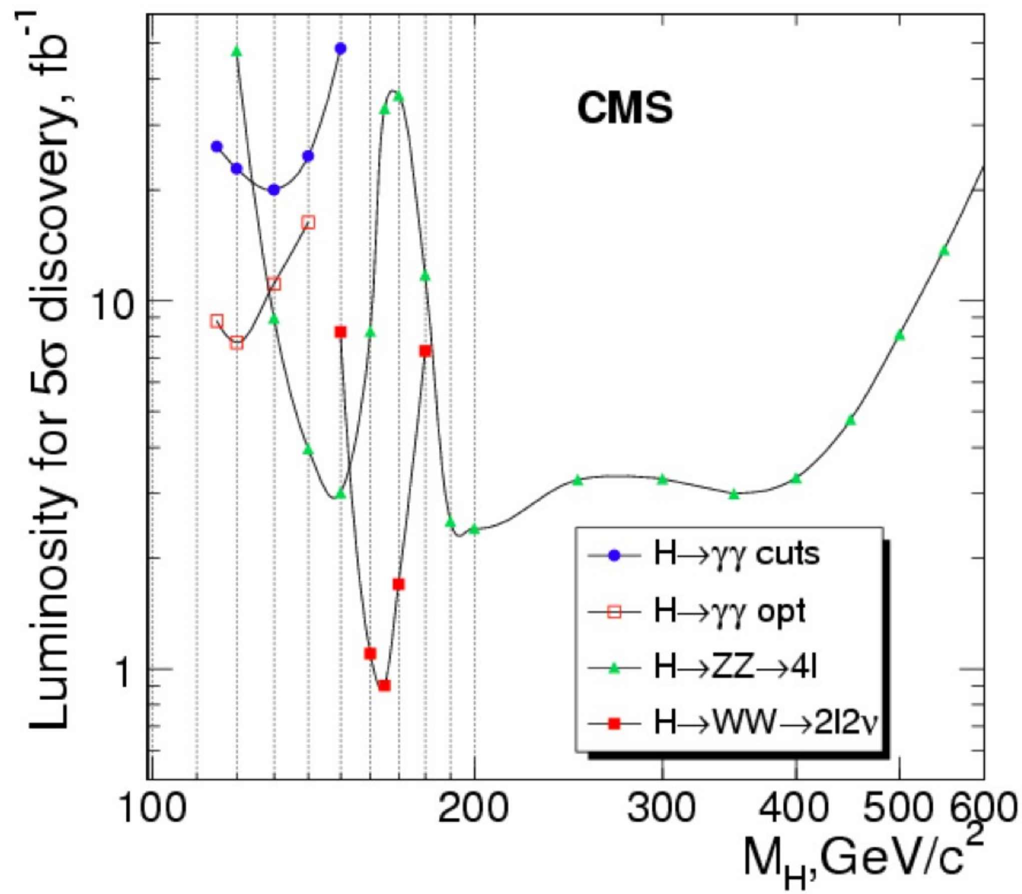

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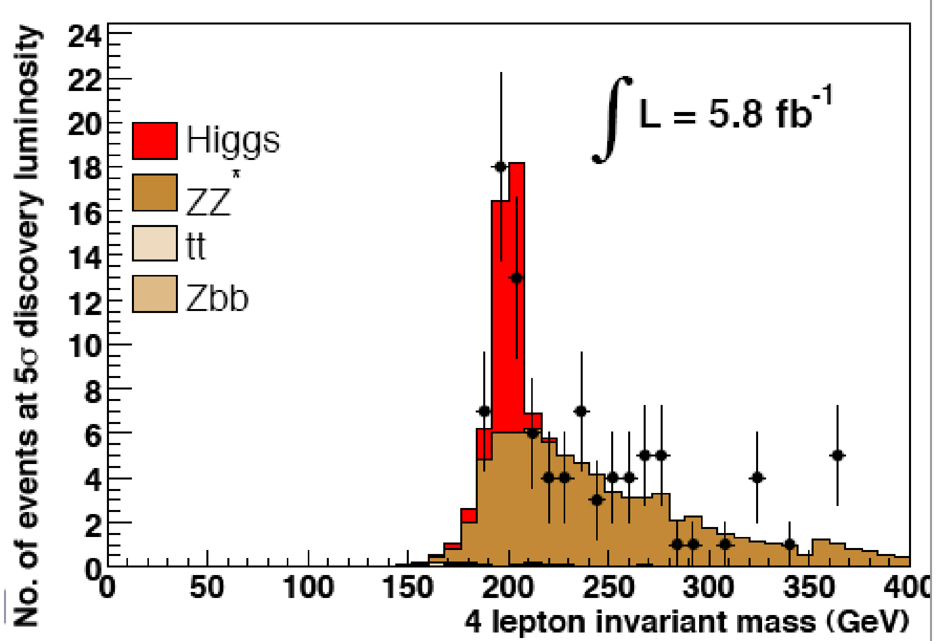
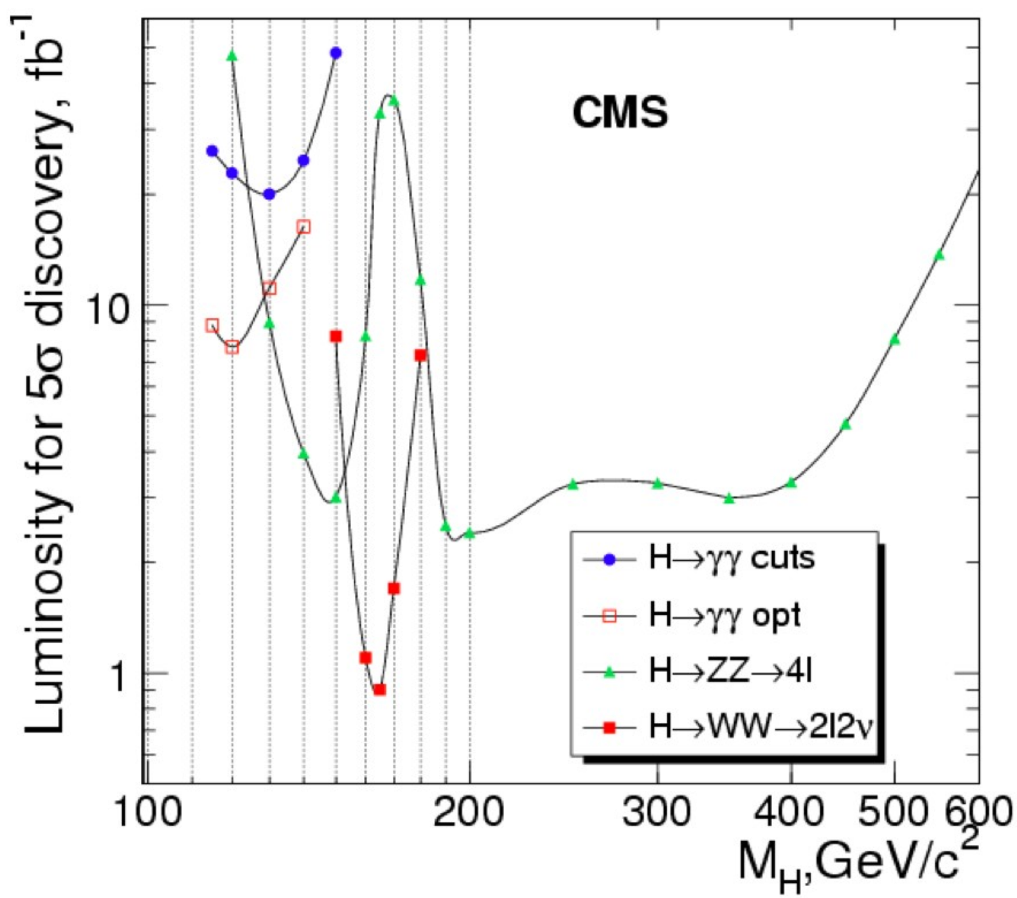
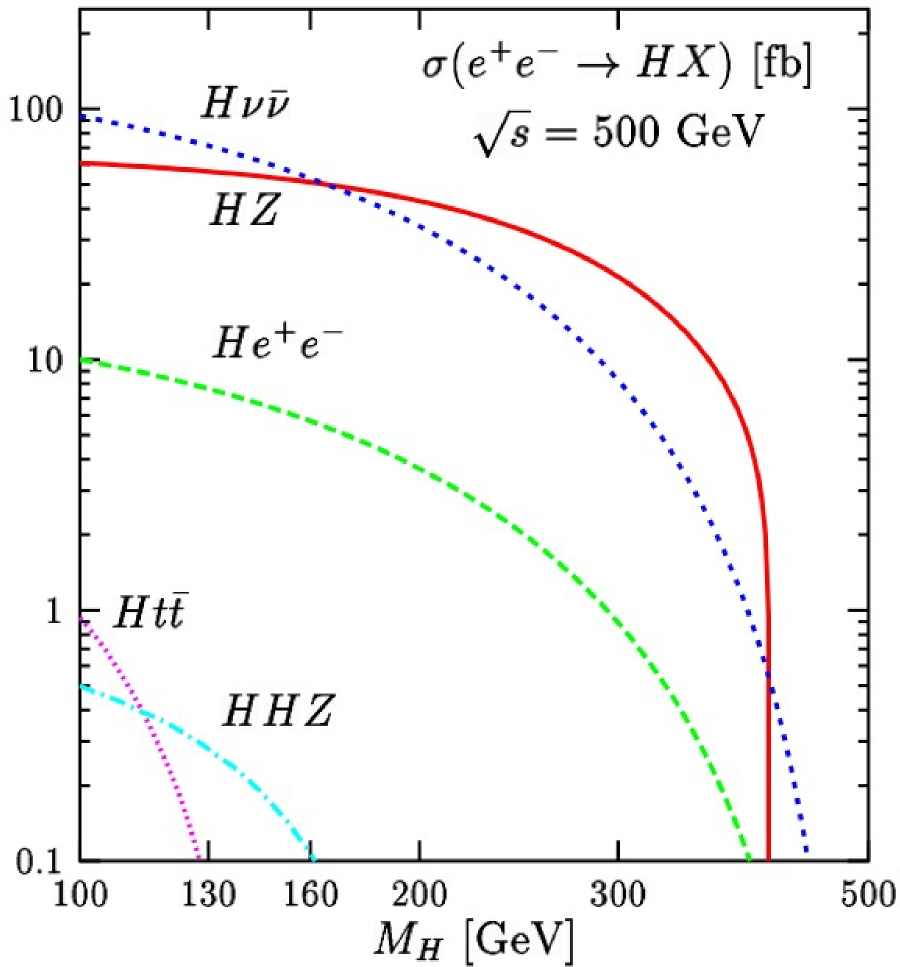


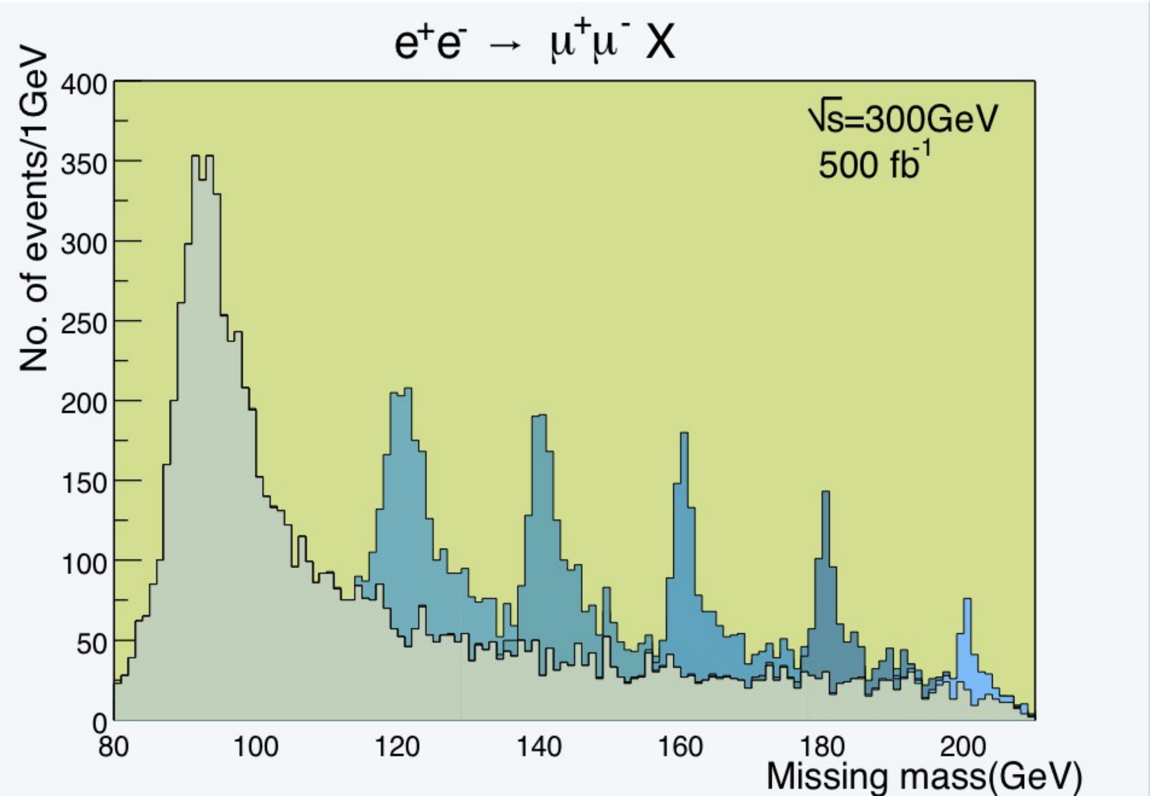


SM Higgs: Discovery and mass

	LHC	ILC
1. Find a new particle	✓	✓
2. Measure its mass	✓	✓
3. Measure coupling to gauge bosons		
4. Measure coupling to fermions		
5. Measure self-couplings		
6. Measure spin		

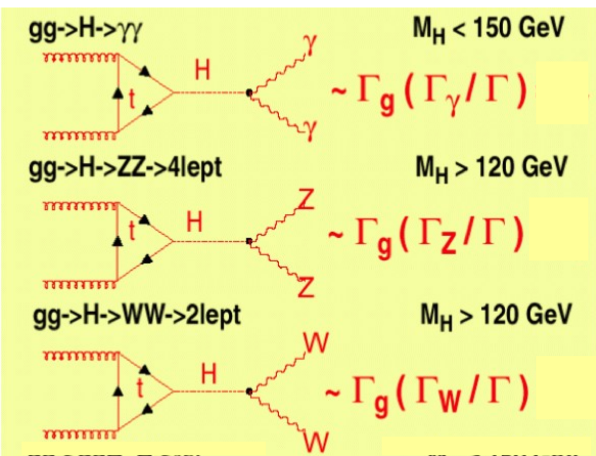
- ILC:
  - $e^+e^- \to HZ \to l^+l^-X$
  - $e^+e^- \to HX \quad H \to qq$
    - Possible if good quark id.
  - Few fb^{-1} needed for a 5σ signal
    - Expected ~80000 H in 500 fb^{-1}





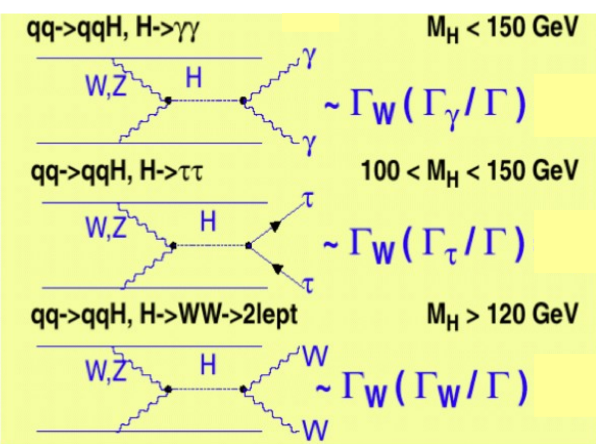
SM Higgs: Couplings

	LHC	ILC
1. Find a new particle	✓	✓
2. Measure its mass	✓	✓
3. Measure coupling to gauge bosons	✓	
4. Measure coupling to fermions	✓	
5. Measure self-couplings		
6. Measure spin		



$$\sigma(gg \rightarrow H) \propto \Gamma(H \rightarrow gg)$$

Theory syst. ~10%



$$\sigma(qq \rightarrow qqH) \propto \Gamma(H \rightarrow VV)$$

Theory syst. ~5-%

- LHC:
  - Total Higgs width and partial widths impossible without theoretical assumptions.
  - Not all final states observable
    - H→bb large exp uncertainities
    - H→ee,μμ non-obs. rate
    - H→qq,gg unidentifiable
  - Narrow width approx (M$_H$<200GeV)

$$\sigma(H) \times BR(H \rightarrow x) = \frac{\sigma(H)^{SM}}{\Gamma_p^{SM}} \times \frac{\Gamma_p \Gamma_x}{\Gamma_{tot}}$$

$$\begin{aligned}
&\Gamma(H \rightarrow ff) &&\propto g^2(H,f) \\
&\Gamma(H \rightarrow VV) &&\propto g^2(H,V) \\
&\Gamma(H \rightarrow gg) &&\propto g_{eff}^2(H,f) \propto g^2(H,t) \\
&\Gamma(H \rightarrow \gamma\gamma) &&\propto g_{eff}^2(H,\gamma) \propto g^2(H,t)
\end{aligned}$$

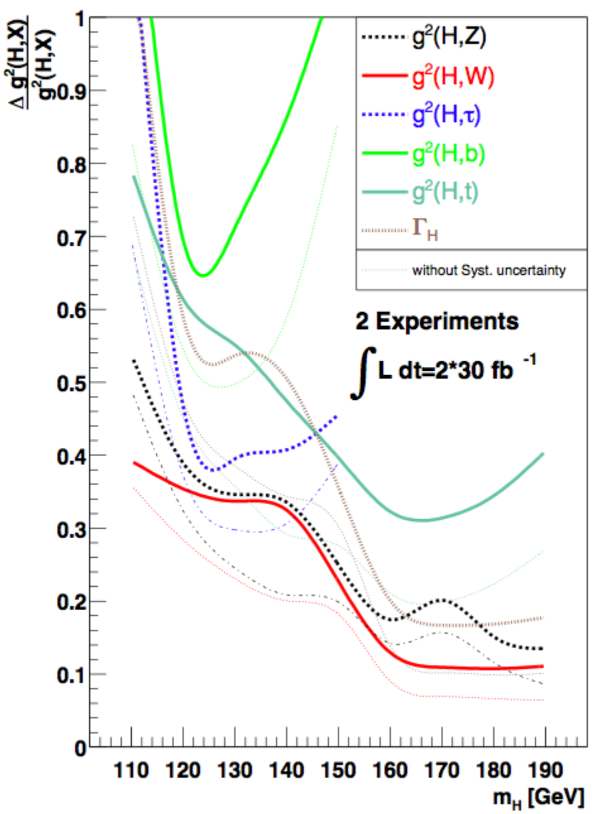
  - Determination using a global fit, under some assumptions

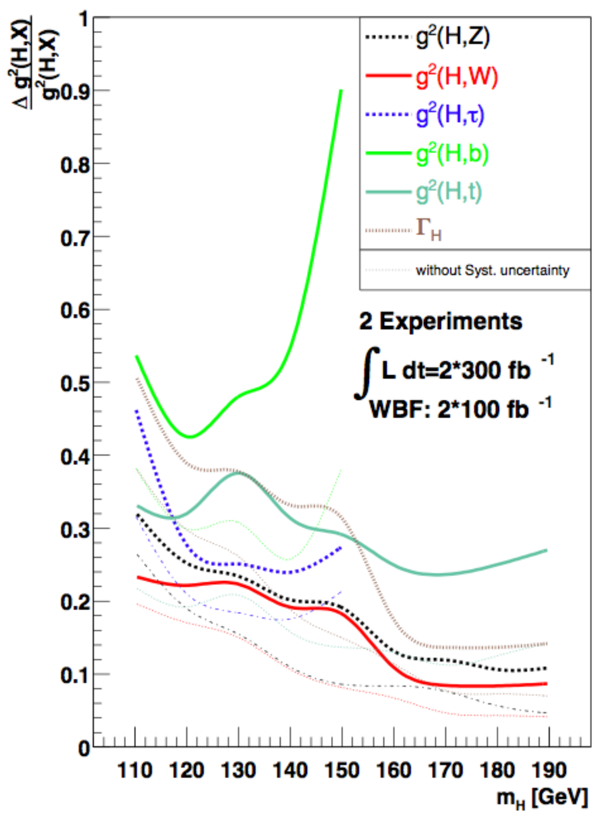
$$\Gamma_V \leq \Gamma_V^{SM} \qquad \textit{upper limit}$$

$$\Gamma_H < \Gamma_W + \Gamma_Z + \Gamma_t + \Gamma_\tau + \Gamma_b \qquad \textit{lower limit}$$

SM Higgs: Couplings

	LHC	ILC
1. Find a new particle	✓	✓
2. Measure its mass	✓	✓
3. Measure coupling to gauge bosons	✓	
4. Measure coupling to fermions	✓	
5. Measure self-couplings		
6. Measure spin		





- LHC:
  - Total Higgs width and partial widths impossible without theoretical assumptions.
  - Not all final states observable
    - $H\rightarrow bb$ large exp uncertainities
    - $H\rightarrow ee,\mu\mu$ non-obs. rate
    - $H\rightarrow qq,gg$ unidentifiable
  - Narrow width approx (M_H<200GeV)

$$\sigma(H)\times BR(H\rightarrow x)=\frac{\sigma(H)^{SM}}{\Gamma_p^{SM}}\times\frac{\Gamma_p\Gamma_x}{\Gamma_{tot}}$$

$$\begin{aligned}\Gamma(H\rightarrow ff) &\propto g^2(H,f)\\ \Gamma(H\rightarrow VV) &\propto g^2(H,V)\\ \Gamma(H\rightarrow gg) &\propto g^2_{eff}(H,f)\propto g^2(H,t)\\ \Gamma(H\rightarrow\gamma\gamma) &\propto g^2_{eff}(H,\gamma)\propto g^2(H,t)\end{aligned}$$

  - Determination using a global fit, under some assumptions

$$\Gamma_V\leq\Gamma_V^{SM}$$

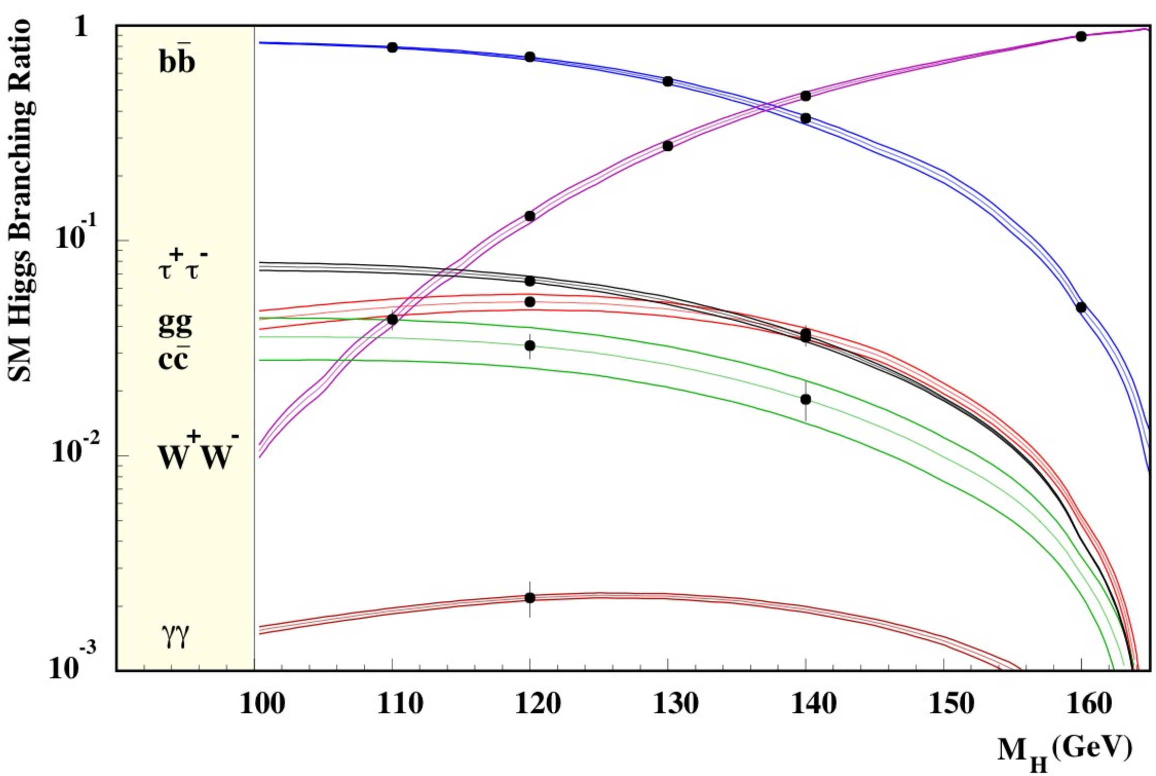
$$g^2(H,V)<1.05\,g^2_{SM}(H,V)$$

SM Higgs: Couplings

	LHC	ILC
1. Find a new particle	✓	✓
2. Measure its mass	✓	✓
3. Measure coupling to gauge bosons	✓	✓
4. Measure coupling to fermions	✓	✓
5. Measure self-couplings		
6. Measure spin		

- ILC:
  - Almost all couplings in a model independent way
  - High accuracy
    - BR < 5%
    - $\Delta g/g \sim$ 1-3%

Coupling	$M_H = 120\,\mathrm{GeV}$	$140\,\mathrm{GeV}$
g_{HWW}	$\pm\, 0.012$	$\pm\, 0.020$
g_{HZZ}	$\pm\, 0.012$	$\pm\, 0.013$
g_{Htt}	$\pm\, 0.030$	$\pm\, 0.061$
g_{Hbb}	$\pm\, 0.022$	$\pm\, 0.022$
g_{Hcc}	$\pm\, 0.037$	$\pm\, 0.102$
$g_{H\tau\tau}$	$\pm\, 0.033$	$\pm\, 0.048$



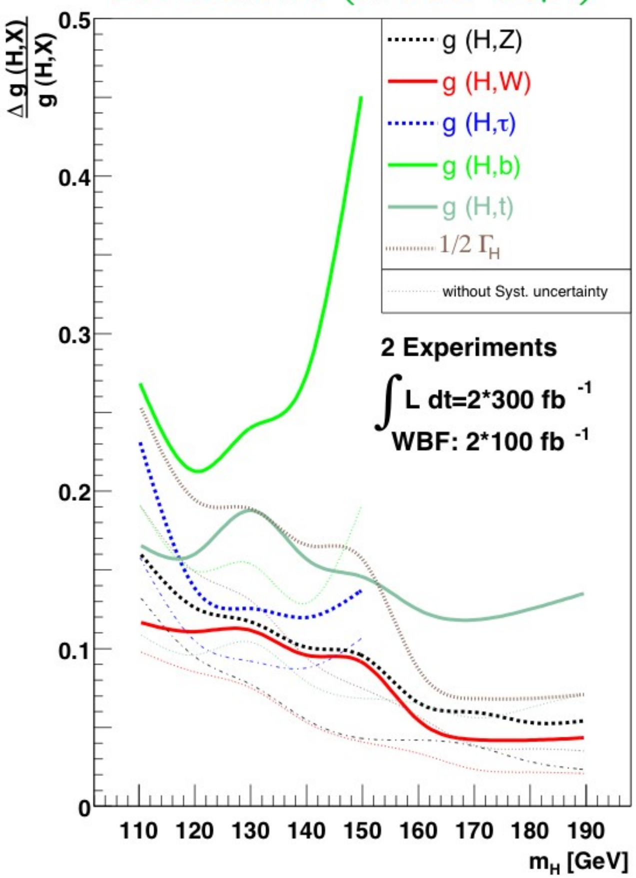
- g_{Htt} and $g_{H\gamma\gamma}$ bad measured at $\sqrt{s}$=500 GeV.
  - $\Delta g/g \sim$ 5-10%

SM Higgs: Couplings. LHC/ILC Interplay

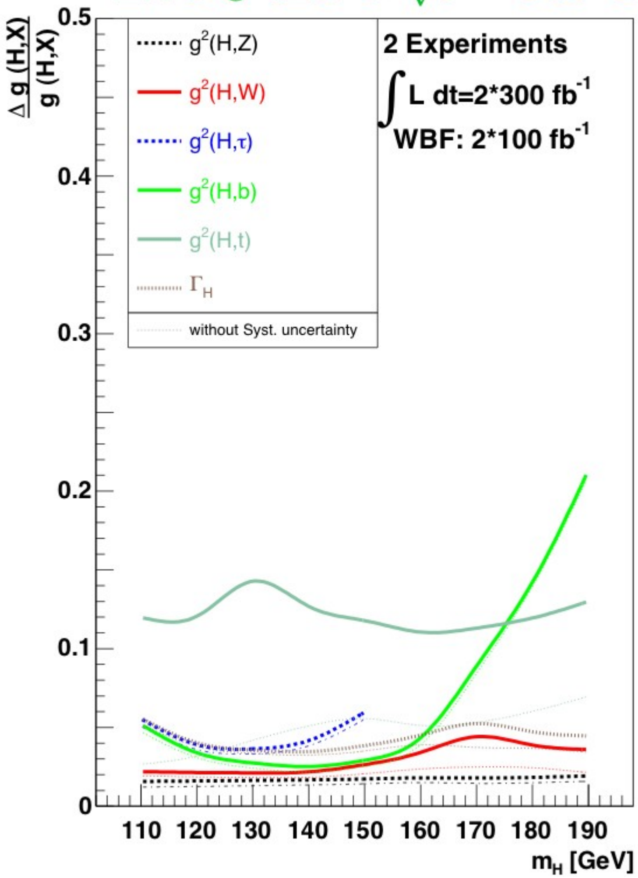
	LHC	ILC
1. Find a new particle	✓	✓
2. Measure its mass	✓	✓
3. Measure coupling to gauge bosons	✓	✓
4. Measure coupling to fermions	✓	✓
5. Measure self-couplings		
6. Measure spin		

- Give ILC inputs to LHC analysis
  - Harder constraints
  - Possible to measure absolute couplings
  - Independent analysis
  - Higher accuracy even in g_{Htt}

LHC alone (model dep.)

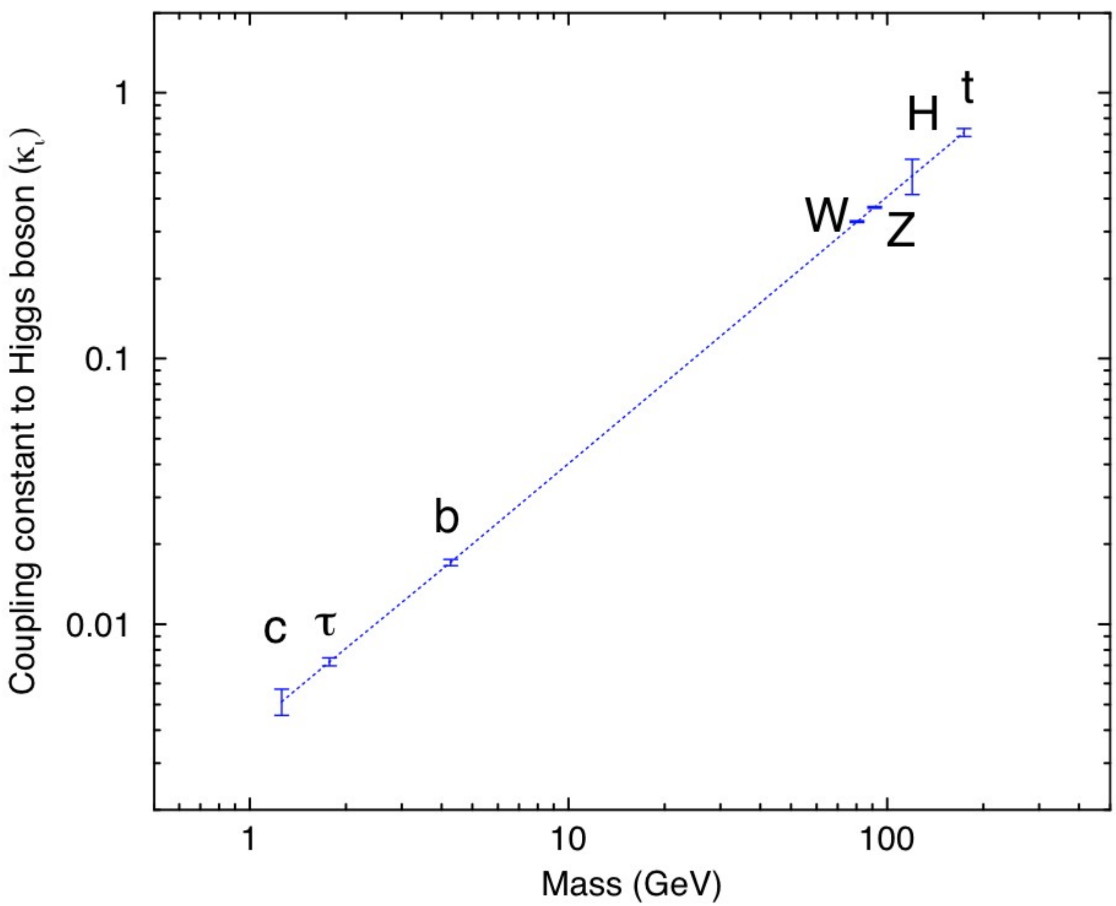


LHC ⊕ ILC @ $\sqrt{s} = 500$ GeV



SM Higgs: Self-couplings

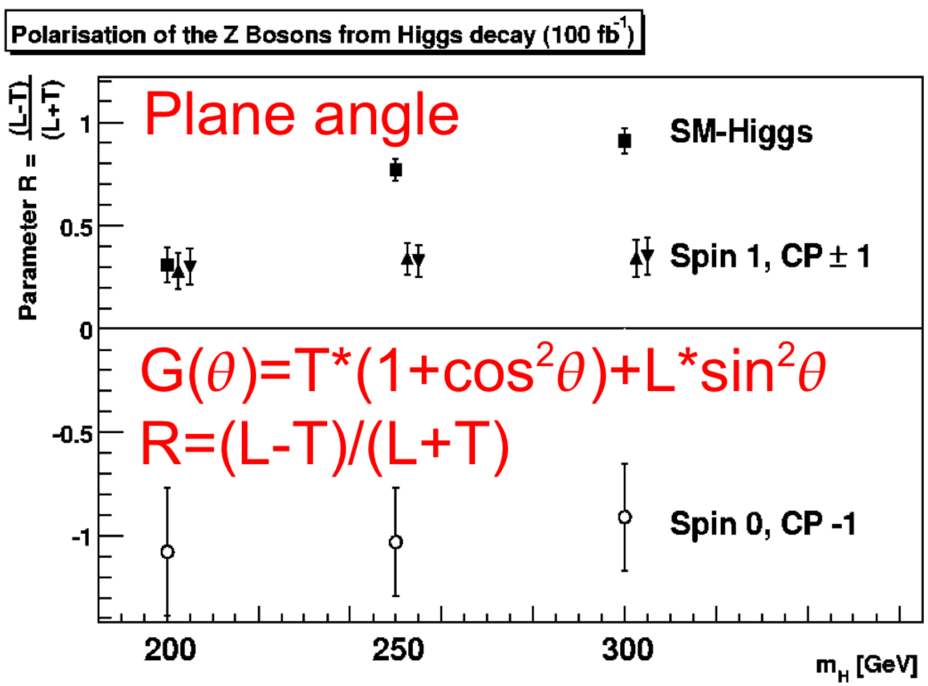
	LHC	ILC
1. Find a new particle	✓	✓
2. Measure its mass	✓	✓
3. Measure coupling to gauge bosons	✓	✓
4. Measure coupling to fermions	✓	✓
5. Measure self-couplings	✓	✓
6. Measure spin		



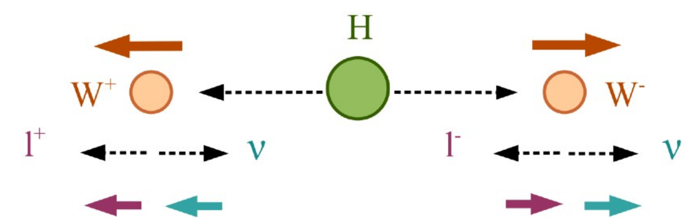
- LHC:
  - Extremely difficult
- ILC:
  - Small cross-sections ~0.1 fb
  - Large backgrounds expected
    - Excellent flavor tagging needed
    - Multijet+Multilepton events
  - Modest accuracies achieved
    - $\sqrt{s}$=500 GeV,L~1ab^{-1}, m_H<140
      - $\sigma(e^+e^- \rightarrow HHZ)$ ~ 20%
      - $\Delta\lambda_{HHH}$ ~ 22%
    - Increasing energy and using polarization
      - $\Delta\lambda_{HHH}$ ~ 12%

SM Higgs: Spin-Parity

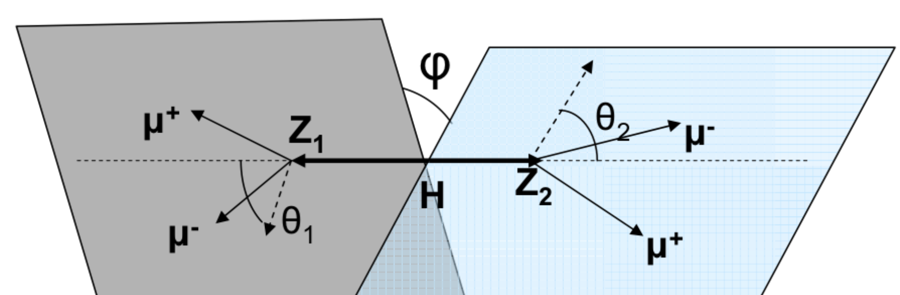
	LHC	ILC
1. Find a new particle	✓	✓
2. Measure its mass	✓	✓
3. Measure coupling to gauge bosons	✓	✓
4. Measure coupling to fermions	✓	✓
5. Measure self-couplings	✓	✓
6. Measure spin	✓	



- LHC:
  - Spin 1 ruled out if
    - Decays $H \to \gamma\gamma$ observed
    - Production in gluon fusion
  - WBF $H\to WW \to l\nu l\nu$
    - Spin 0: Exploit collinear leptons topology (spin correlations)



  - Angular correlations in gg $H\to ZZ\to 4l$
    - Measure J^{PC}
    - Some 10th fb^{-1} needed



SM Higgs: Spin-Parity

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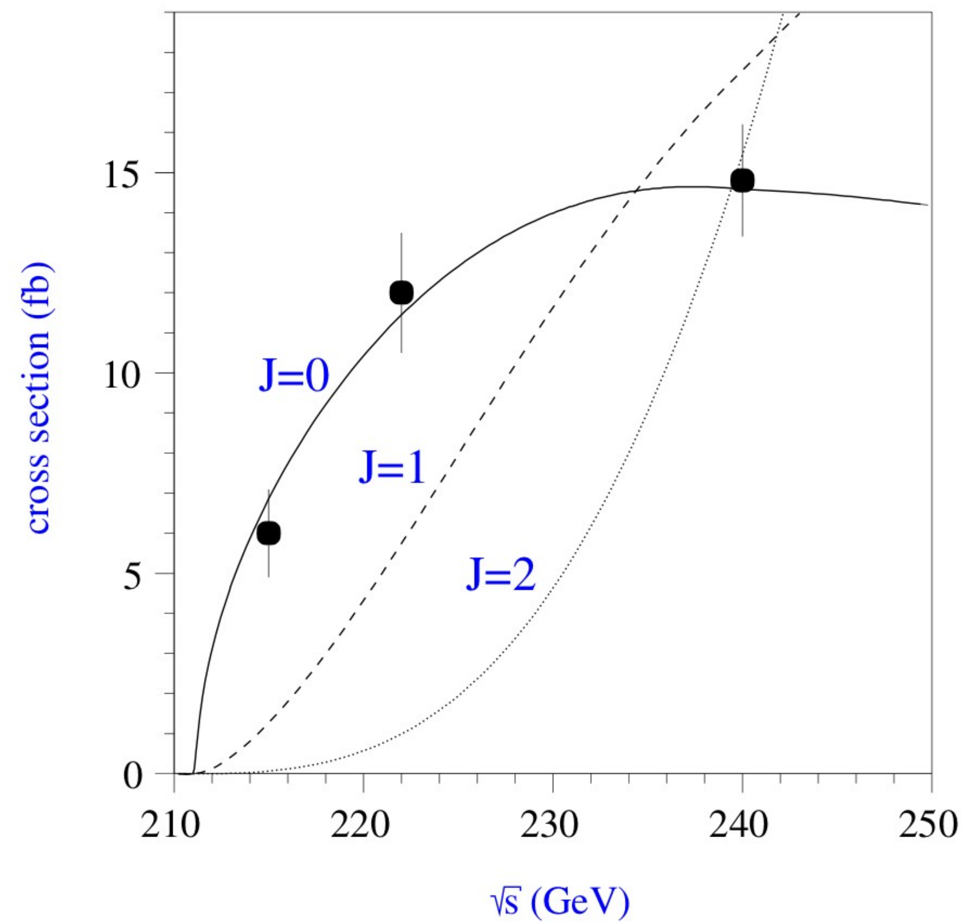
6. Measure spin	✓	✓



- ILC:
  - Spin can be measured with $e^+e^- \rightarrow ZH$ behaviour near threshold
    - Needed ~20 fb^{-1}
  - CP can be measured:
    - Angular distribution of Z/H in Higgs-strahlung
    - Correlations in $H\rightarrow\tau\tau$
    - Angular correlations in gg $H\rightarrow ZZ\rightarrow 4l$

SM Higgs: Spin-Parity

	LHC	ILC
1. Find a new particle	✓	✓
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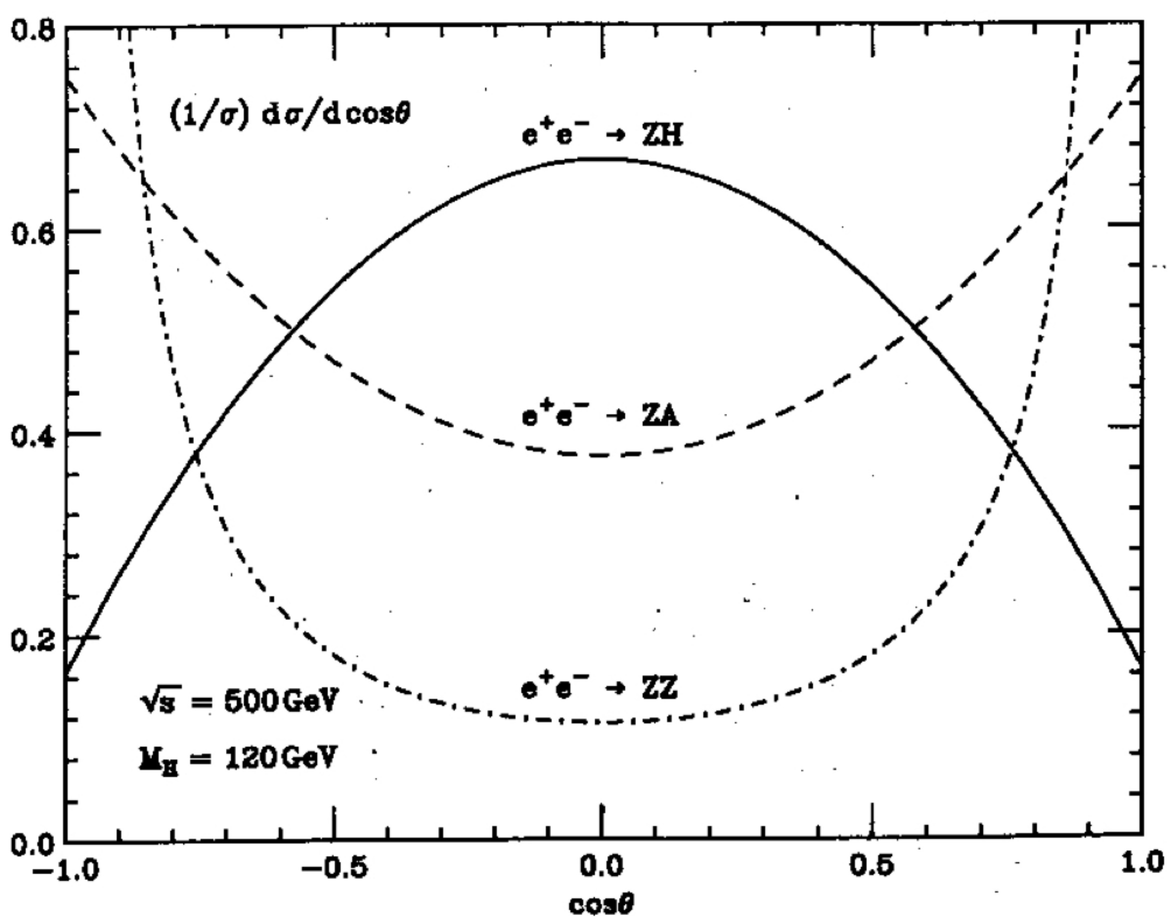

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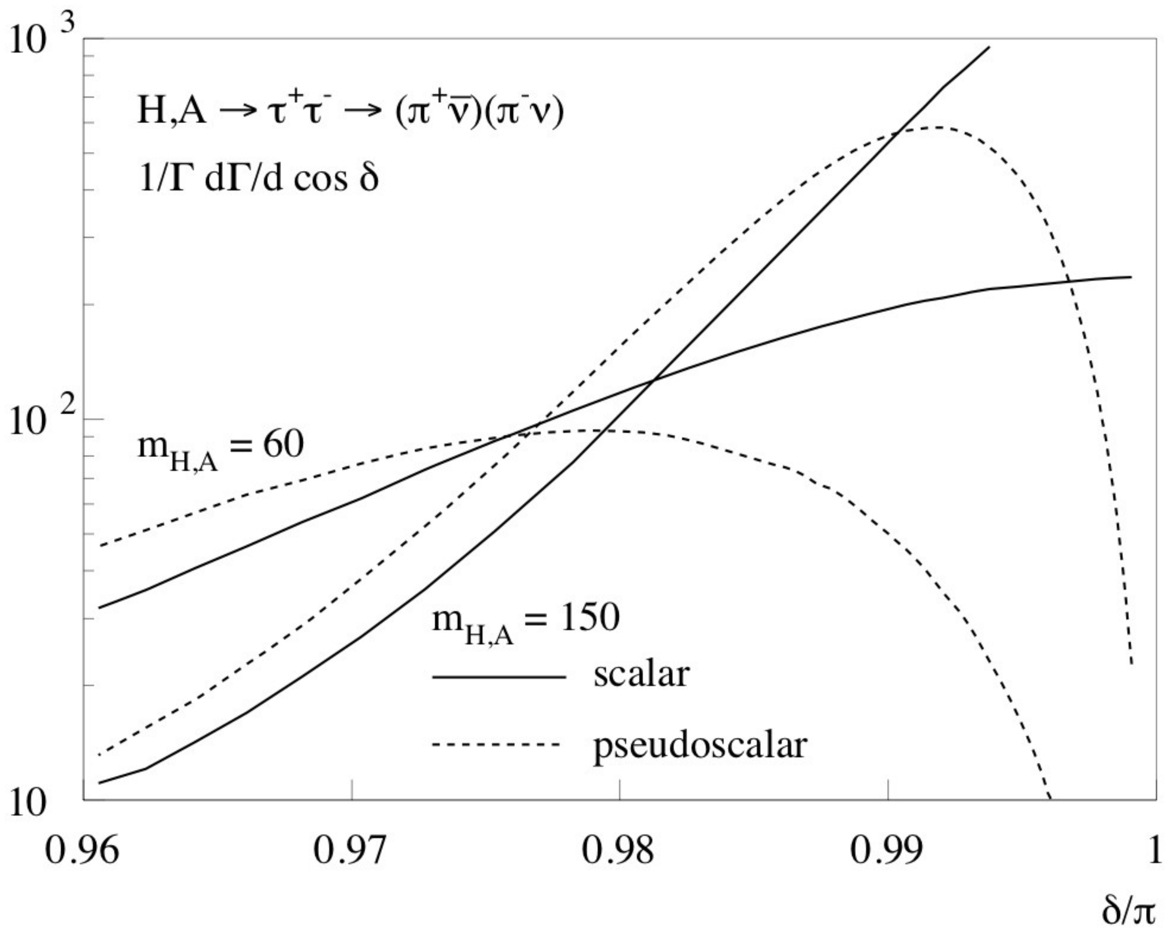
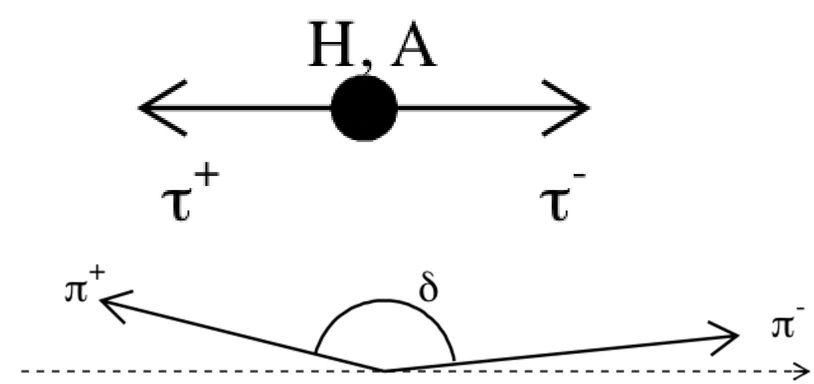




SEARCH OF SUPERSYMMETRY

Discovering Supersymmetry

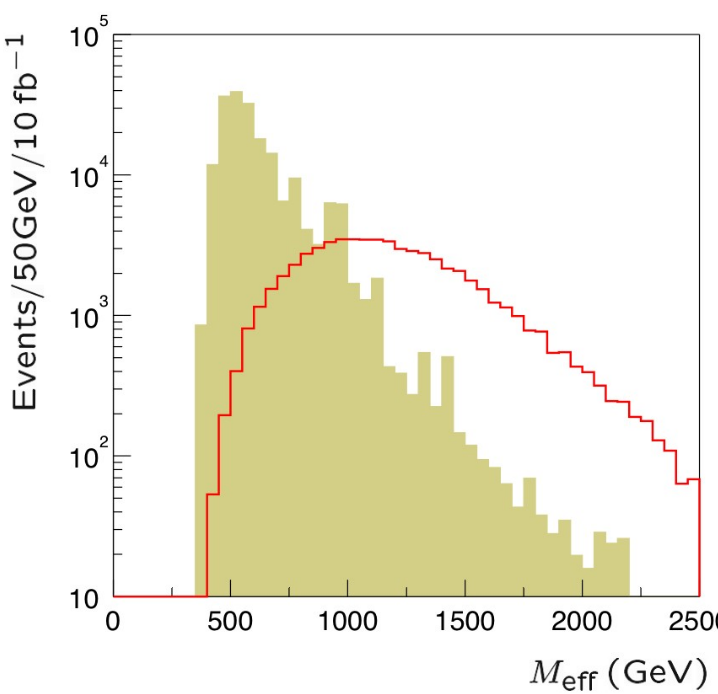
- Find (all) sparticles
  - Masses
  - Decay widths, BR, production cross sections
- Verify that all particles have a superpartner
  - Spins differ in 1/2
  - Gauge quantum numbers are the same
  - Couplings are identical
  - Mass relation holds
- Understand low-energy SUSY parameters
- Understand SUSY symmetry breaking mechanism (GUT)

- Here just discussed discovery and mass determination

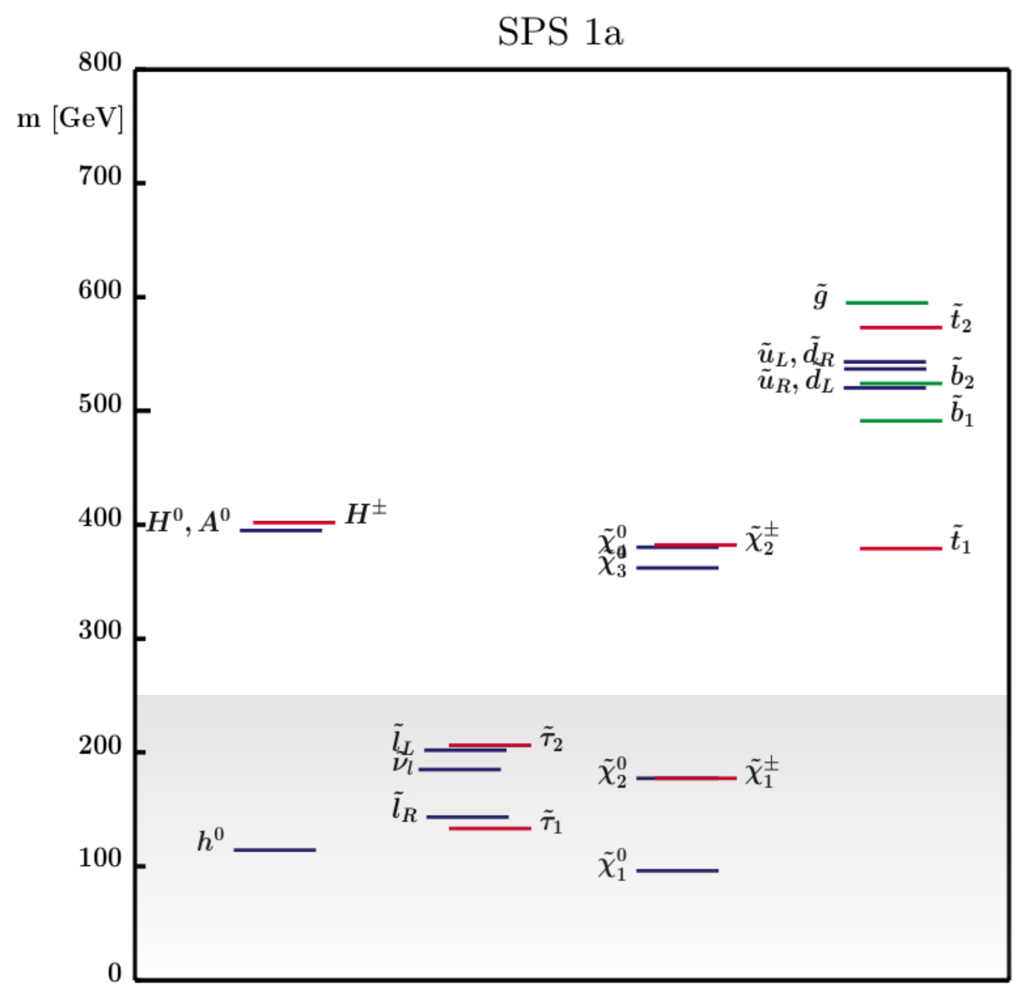
SUSY: Discovery

- LHC
- Up to few TeV
  - Gluino/squark
    - gg fusion
  - slepton/chargino/neutralino
    - Drell-Yan
    - Indirectly in Decays
- Inclusive discovery

$$M_{eff} = E_T^{mis} + \sum^{4} p_{T,i}$$



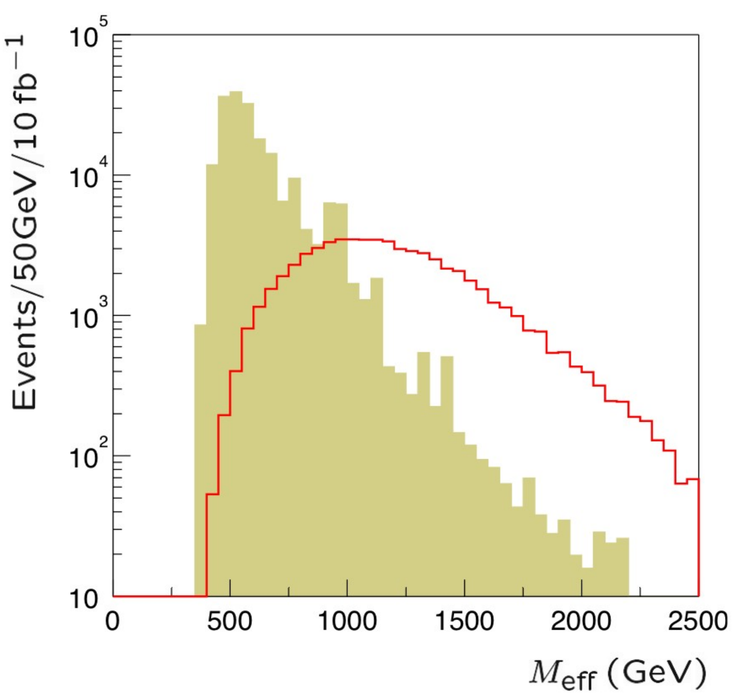
- ILC
- Up to m < √s/2
- Lepton distributions in the continuum
  - e+e- pol. Reduces bkg.



SUSY: Discovery

- LHC
- Up to few TeV
  - Gluino/squark
    - gg fusion
  - slepton/chargino/neutralino
    - Drell-Yan
    - Indirectly in Decays
- Inclusive discovery

$$M_{eff} = E_T^{mis} + \sum_{i=1}^{4} p_{T,i}$$



- ILC
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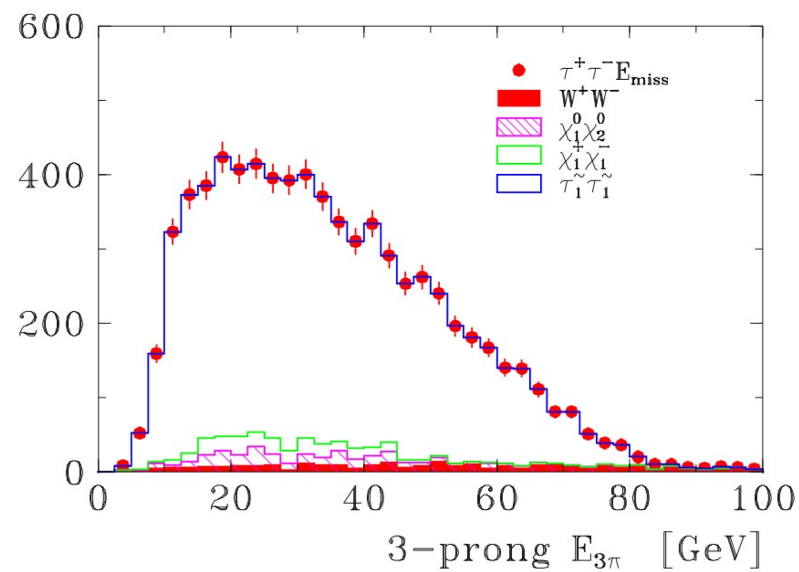
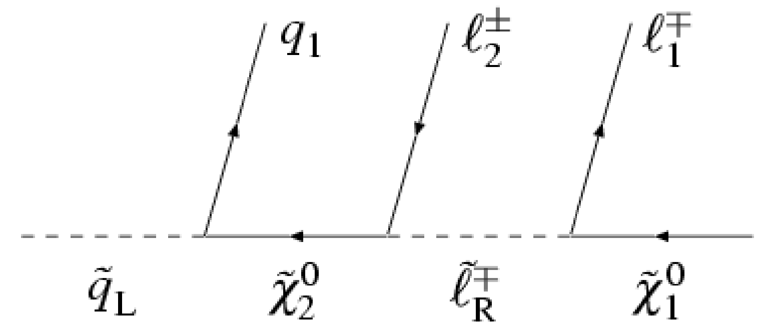
- Lepton distributions in the continuum
  - e+e- pol. Reduces bkg.



SUSY: Mass at LHC

- Challenging
  - Long decay chains
  - No kinematical constraints (boost)
  - LSP: no mass rec evt-by-evt
- Mass based in kinematical endpoints



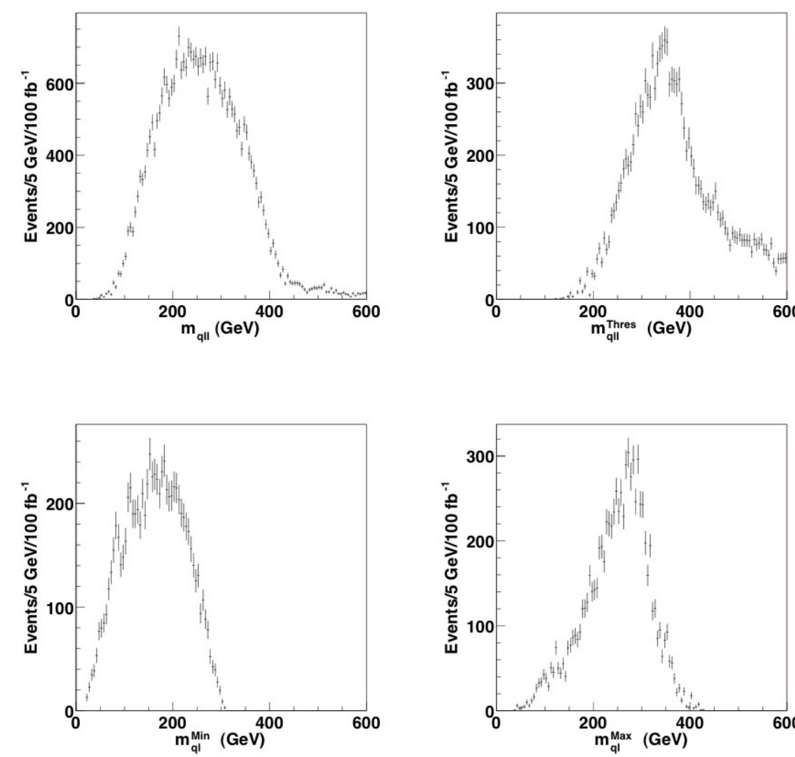
$$\left(m_{ll}^2\right)^{\text{edge}} = \frac{\left(m^2_{\tilde{\chi}_2^0} - m^2_{\tilde{l}_R}\right)\left(m^2_{\tilde{l}_R} - m^2_{\tilde{\chi}_1^0}\right)}{m^2_{\tilde{l}_R}}$$

$$\left(m_{qll}^2\right)^{\text{edge}} = \frac{\left(m^2_{\tilde{q}_L} - m^2_{\tilde{\chi}_2^0}\right)\left(m^2_{\tilde{\chi}_2^0} - m^2_{\tilde{\chi}_1^0}\right)}{m^2_{\tilde{\chi}_2^0}}$$

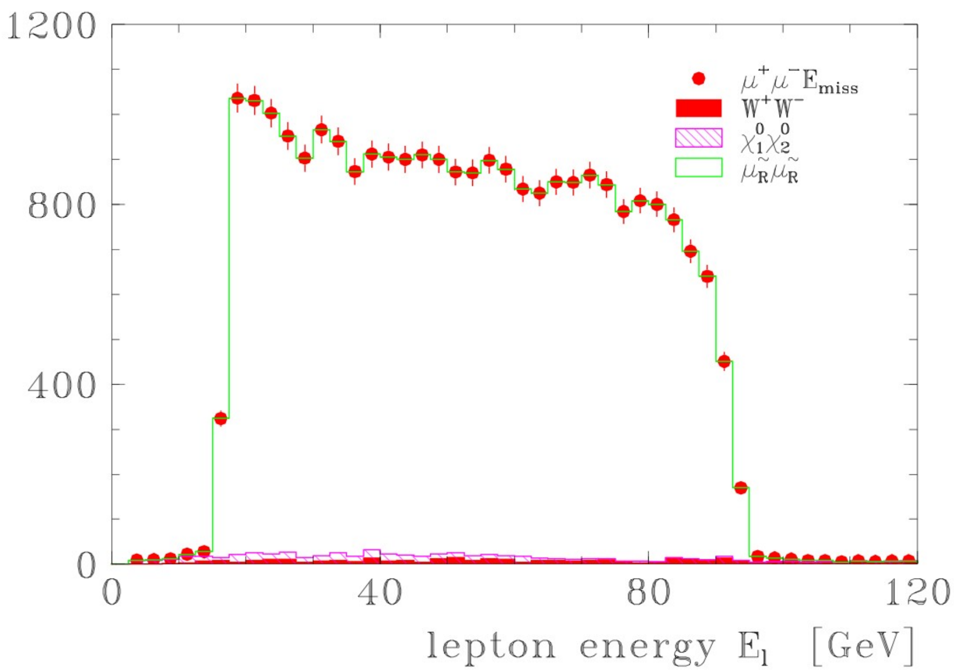
$$\left(m_{ql}^2\right)^{\text{edge}}_{\text{min}} = \frac{\left(m^2_{\tilde{q}_L} - m^2_{\tilde{\chi}_2^0}\right)\left(m^2_{\tilde{\chi}_2^0} - m^2_{\tilde{l}_R}\right)}{m^2_{\tilde{\chi}_2^0}}$$

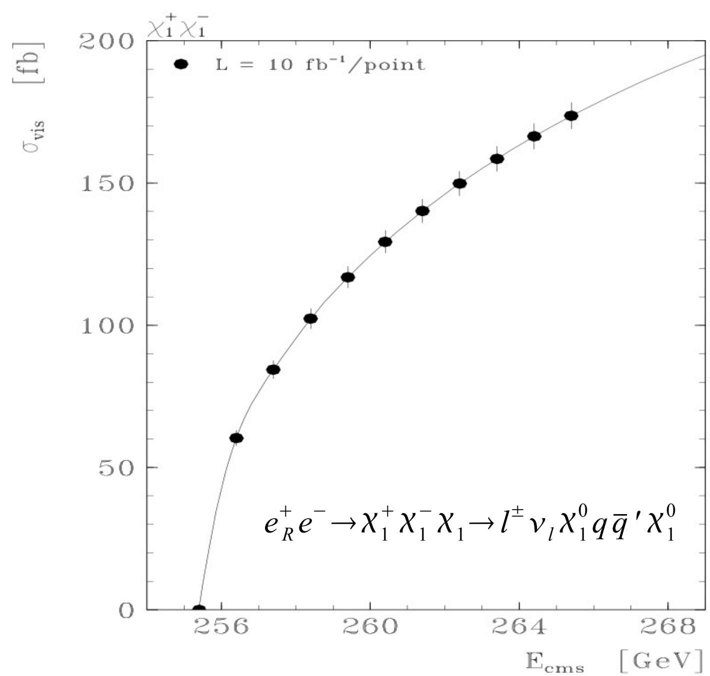
$$\left(m_{ql}^2\right)^{\text{edge}}_{\text{max}} = \frac{\left(m^2_{\tilde{q}_L} - m^2_{\tilde{\chi}_2^0}\right)\left(m^2_{\tilde{l}_R} - m^2_{\tilde{\chi}_1^0}\right)}{m^2_{\tilde{l}_R}}$$

$$\begin{aligned}\left(m_{qll}^2\right)^{\text{thres}} = {} & [(m^2_{\tilde{q}_L} + m^2_{\tilde{\chi}_2^0})(m^2_{\tilde{\chi}_2^0} - m^2_{\tilde{l}_R})(m^2_{\tilde{l}_R} - m^2_{\tilde{\chi}_1^0}) \\ & -(m^2_{\tilde{q}_L} - m^2_{\tilde{\chi}_2^0})\sqrt{(m^2_{\tilde{\chi}_2^0} + m^2_{\tilde{l}_R})^2(m^2_{\tilde{l}_R} + m^2_{\tilde{\chi}_1^0})^2 - 16m^2_{\tilde{\chi}_2^0}m^4_{\tilde{l}_R}m^2_{\tilde{\chi}_1^0}} \\ & +2m^2_{\tilde{l}_R}(m^2_{\tilde{q}_L} - m^2_{\tilde{\chi}_2^0})(m^2_{\tilde{\chi}_2^0} - m^2_{\tilde{\chi}_1^0})]/(4m^2_{\tilde{l}_R}m^2_{\tilde{\chi}_2^0})\end{aligned}$$



SUSY: Mass at ILC





- Continuum
  - Measure kinematical endpoints

$$e^+ e^+ \rightarrow \tilde{l}_i^+ \tilde{l}_j^-$$

$$m_{\tilde{l}^+} = \frac{\sqrt{s}}{E_- + E_+} \sqrt{E_- E_+}$$

$$m_{\tilde{\chi}_1^0} = m_{\tilde{l}} \sqrt{1 - \frac{E_- + E_+}{\sqrt{s}/2}}$$

- Threshold scan
  - ~10 fb^{-1} per point

- Precision on masses ~0.5-1%

SUSY: Mass - LHC/ILC

- Measure χ^0 from ILC
- Use kinematical endpoints analysis

- LHC: 300 fb-1

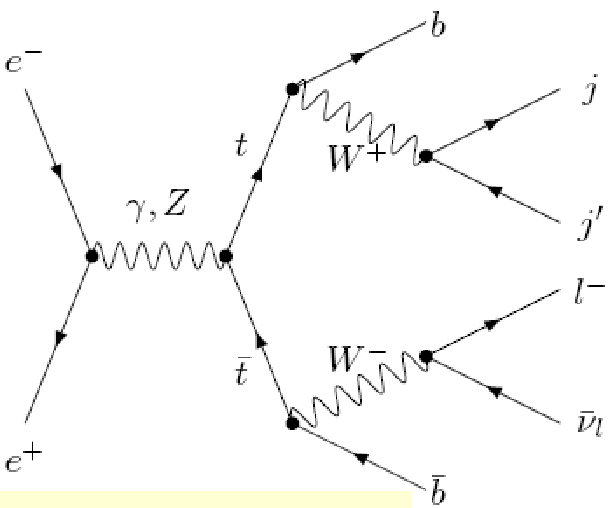
- Precision in masses
- Precision in SUSY parameters

	LHC	LHC + ILC
$\Delta m_{\tilde{\chi}_1^0}$	4.8	0.19
$\Delta m_{\tilde{l}_R}$	4.8	0.34
$\Delta m_{\tilde{\chi}_2^0}$	4.7	0.24
$\Delta m_{\tilde{q}_L}$	8.7	4.90
$\Delta m_{\tilde{b}_1}$	13.2	10.50
$\Delta m_{\tilde{g}}$	8.0	6.40
$\Delta m_{\tilde{q}_R}$	11.8	10.90
$\Delta m_{\tilde{b}_2}$	7.9	6.30
$\Delta m_{\tilde{l}_L}$	5.0	1.60
$\Delta m_{\tilde{\chi}_4^0}$	5.1	2.25

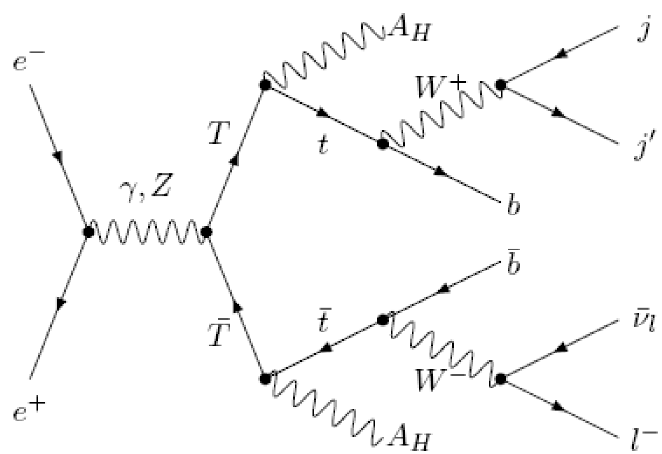
DETECTORS FOR ILC

ILC events

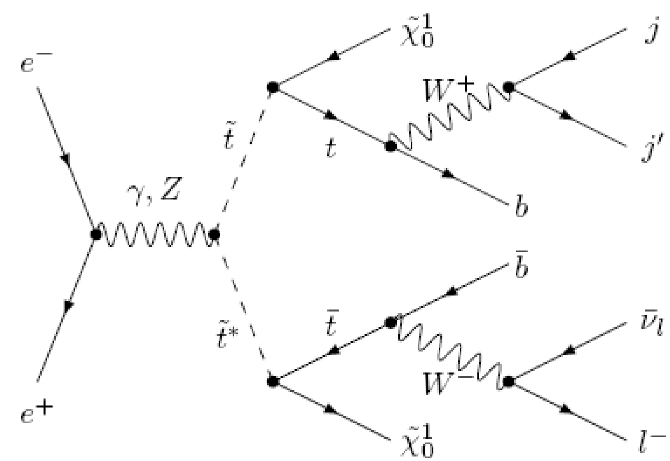
- What kind of events do we expect?
  - ILC can be seen as gauge boson factory
  - Final states will have
    - Multiple jets
    - Multiple leptons
    - Missing Energy
  - Same final state can be interpreted in many different way



SM top production
E_{mis} → neutrinos

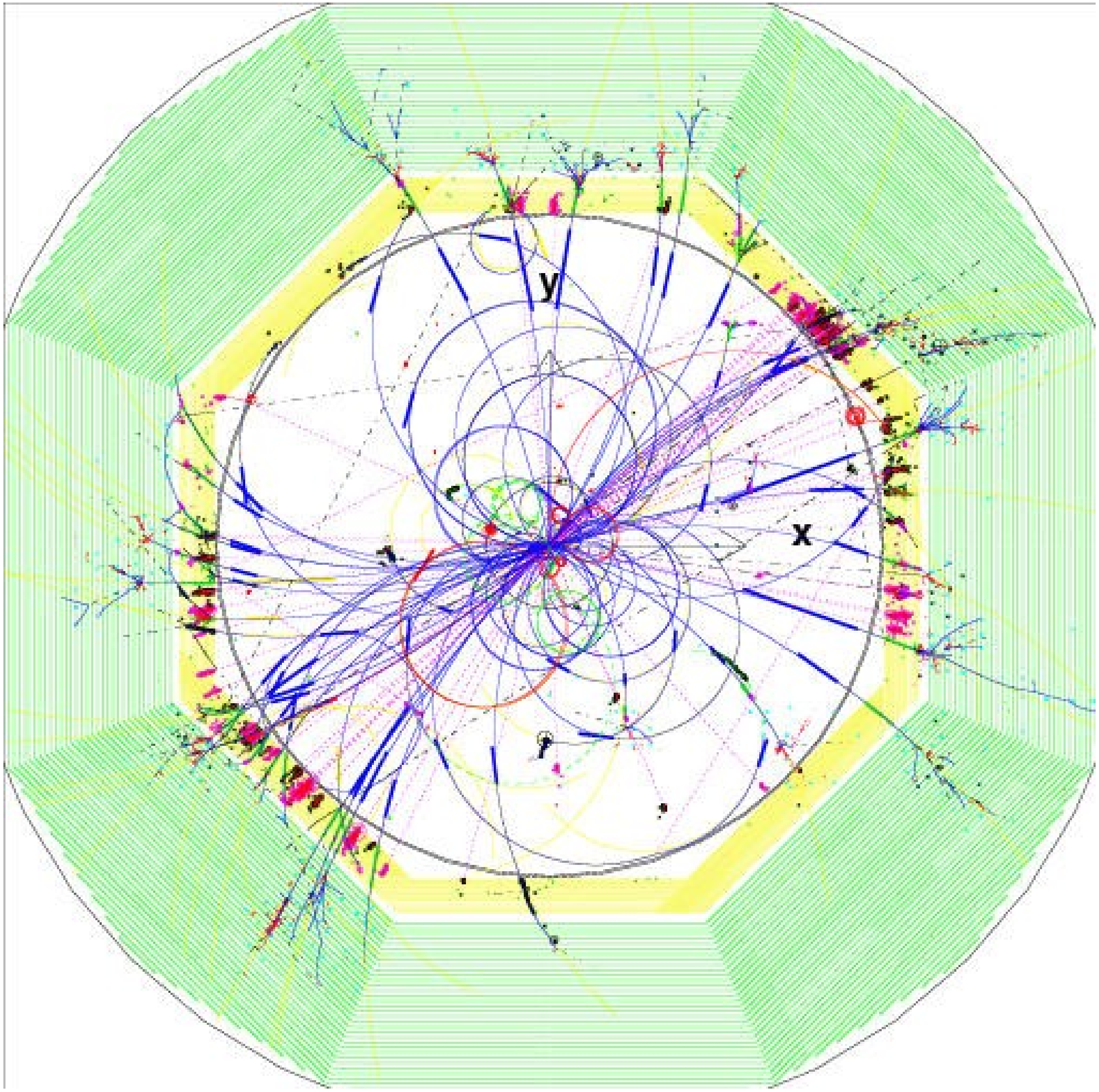


Little Higgs with T-parity
T-odd scalars production
E_{mis} → A_H (γ massive partner)



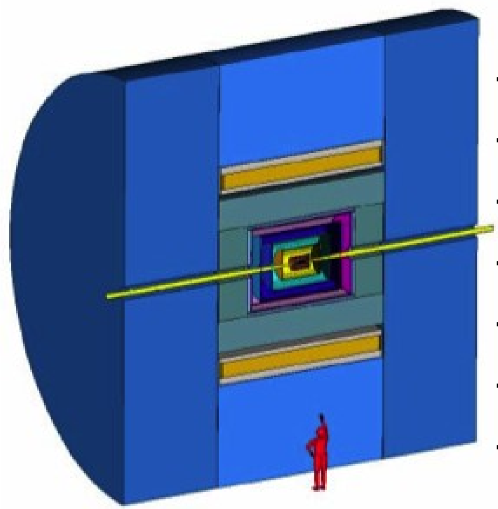
SUSY stop production
E_{mis} → neutrinos+neutralinos

ILC events



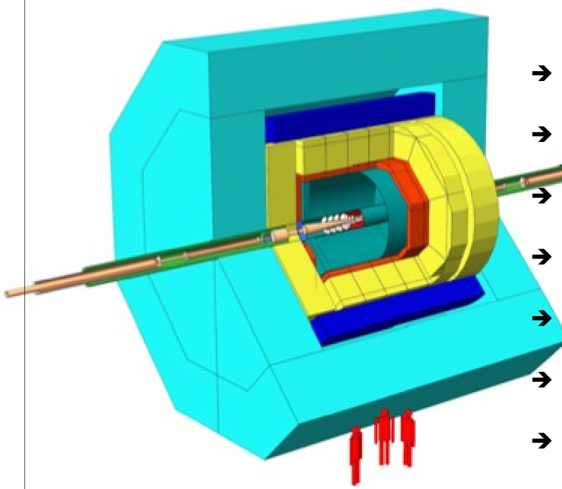
Detector Concepts

- 4 detector concepts proposed based on "conventional" cylindrical geometries



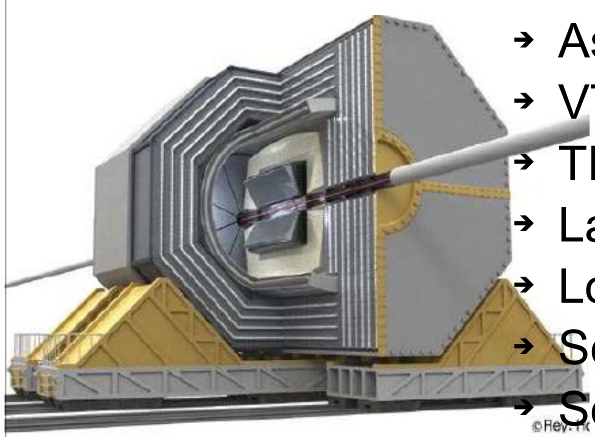
SiD

- American proposal
- VTX: rmin=1.4 cm
- Tracking: Silicon
- Small radius: 1.3 m
- High B field: 5T
- Si-W ECAL
- Steel/GAS HCAL



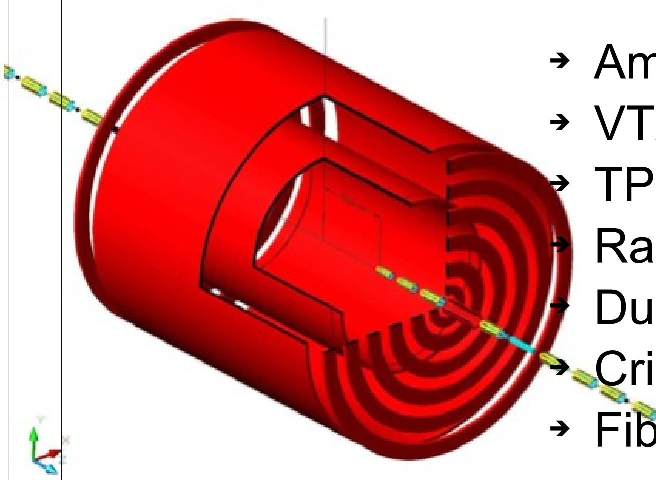
LDC

- European proposal
- VTX: rmin=1.5 cm
- TPC gaseous
- Med radius:1.6 m
- B field: 4T
- Si-W ECAL
- Steel/Scint HCAL



GLD

- Asian proposal
- VTX: rmin=2.0 cm
- TPC gaseous
- Large radius: 2.0 m
- Low B field: 3T
- Sci-W ECAL
- Sci-Pb HCAL



4th Concept

- American proposal
- VTX: rmin=1.5 cm
- TPC gaseous
- Radius:1.5 m
- Dual Sol.: 3.5T,-1.5T
- Cristal ECAL
- Fiber HCAL (Trip RO)

“My” typical detector

- ILC detectors will be “conventional”
  - VTX
  - Tracking device (TPC most likely)
  - (Sampling) Calorimeters
  - Magnet (3-5 T)
  - Muon system
- No big conceptual changes expected
  - More granularity
  - Use machine cycle for:
    - Collision in 1ms/200ms: Duty cycle 0.5%
    - Power saving
    - Avoid cooling systems
- “New” analysis paradigm: Particle Flow

Could a LEP-like detector do the work?

General Requirements

- ILC = precision measurements

- Reconstruction of all channels
  - Hermeticity
    - Expected channels with missing energy: neutrinos and neutralinos
    - Good angular coverage → forward regions
  - Particle/flavor identification → granularity
- High efficiency
  - Well establish detection techniques
- Lowest possible systematics
  - Stability with time
  - Radiation hardness
  - Minimum material
- Insensitive to machine related backgrounds
  - Fast electronics

Requirements from Physics: Tracking

- Measurement of recoil mass in

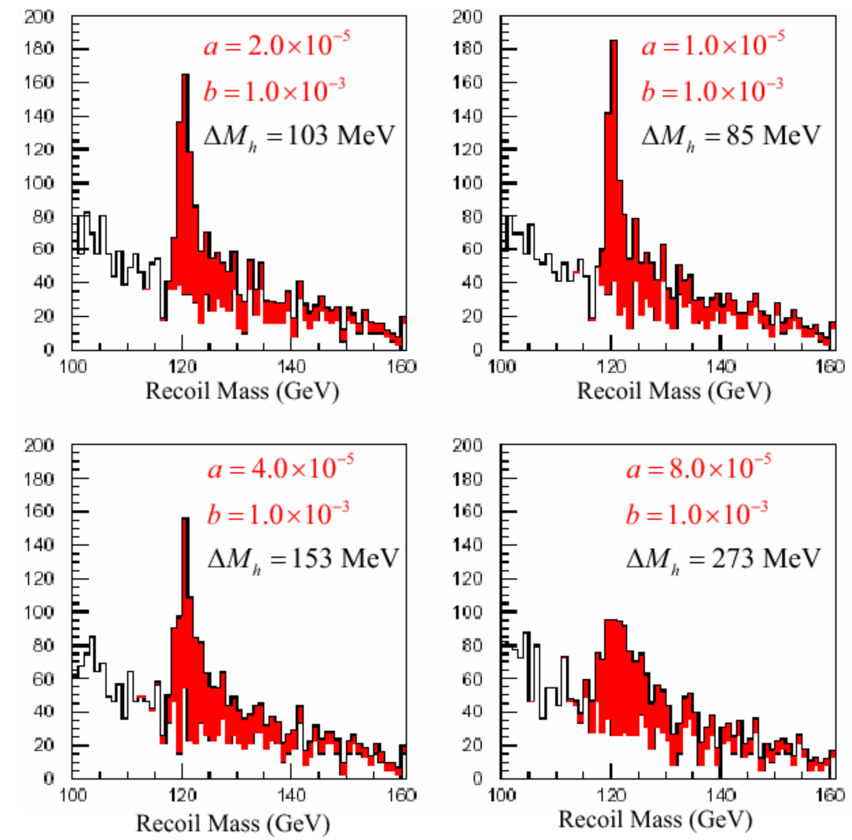
$$e^+e^- \to HZ \to \mu^+\mu^- X$$

- Kinematic endpoints in SUSY decays

$$\tilde{e}_L(203GeV) \to \tilde{\chi}_1^0(96GeV)e^-$$

$$E_- \sim 5\,GeV$$
$$E_+ \sim 225\,GeV$$

  - Upper limit depends strongly on tracking resolution



Momentum resolution

$$\frac{\Delta p}{p} = a \times p \oplus b$$

$$\Delta\frac{1}{p} = a \oplus \frac{b}{p}$$

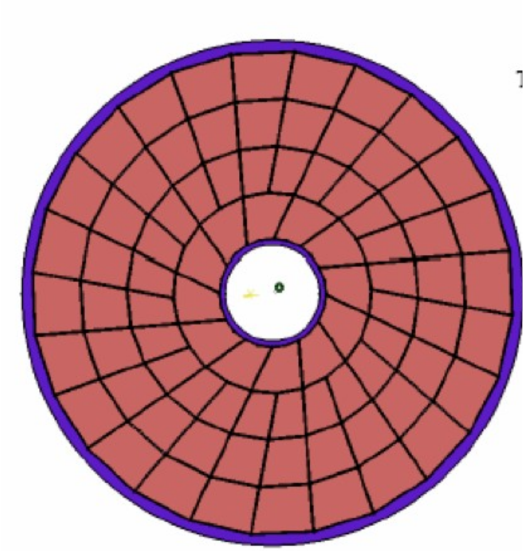
$$\Delta\frac{1}{p} \propto \frac{\delta}{R^2 B\sqrt{n}}$$

a = stochastic term
b = multiple scattering term

	DELPHI	CMS	ILC
a $(Gev/c)^{-1}$	$0.6 \cdot x \cdot 10^{-3}$	0.15×10^{-3}	5×10^{-5}
b	-	0.005	0.001

Central tracking

- Largest radius possible
- Absence of "pointing" cracks
-
- Extended tracking regions
  - $|\cos\theta| < 0.98$ $|\theta|>11°$
  - $|\cos\theta| < 0.87$ $|\theta|>29°$ in DELPHI



- Forward regions covered with silicon microstrips wheels

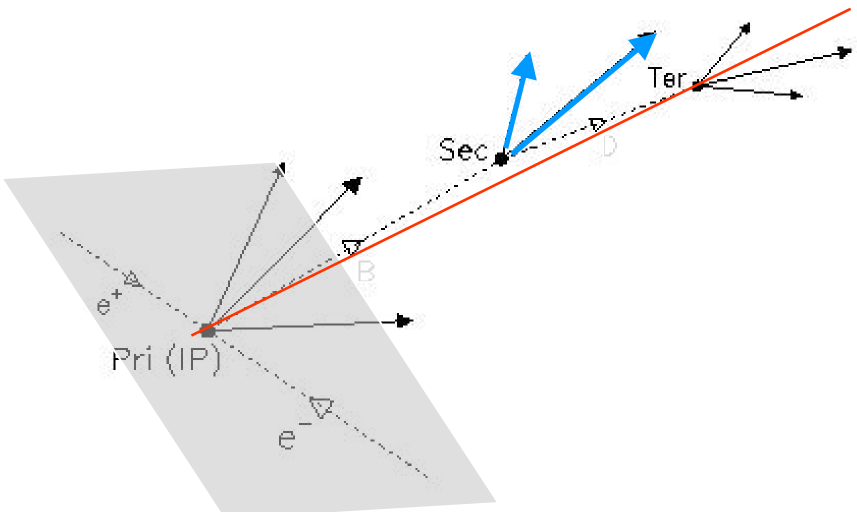
	ILC	DELPHI
Momentum resolution	$\delta(1/p_t) = 10^{-4}$ (GeV/c)	$\delta(1/p_t) = 10^{-3}$ (GeV/c)
Single point resolution (r-f)	100 μm	250 μm
Single point resolution (r-z)	0.5 mm	880 μm
2 track resolution (r-f)	<2 mm	<1 cm
2-track resolution (r-z)	<5 mm	<1 cm

Requirements from Physics: Flavor tagging

- Recoil mass in

$$e^+ e^- \rightarrow H Z \rightarrow q \bar{q} X$$

- Measure Higgs branching ratios
- Z/W reconstruction



- Full vertex reconstruction

Impact parameter

$$\sigma_{R\phi}^{IP} = \frac{\alpha_{MS}}{p \sin^{3/2}\theta} \oplus \sigma_{R\phi}^{0}$$

$$\sigma_{z}^{IP} = \frac{\alpha'_{MS}}{p \sin^{5/2}\theta} \oplus \sigma_{z}^{0}$$

$$\sigma^{IP} \propto \sqrt{X}\, r$$

	DELPHI	CMS	ILC
α_{MS} (μm GeV/c)	65	80	10
$\sigma_{R\Phi}$ (μm)	20	9	5
α'_{MS} (μm GeV/c)	71-151	200	
σ_z (μm)	39-96	10	

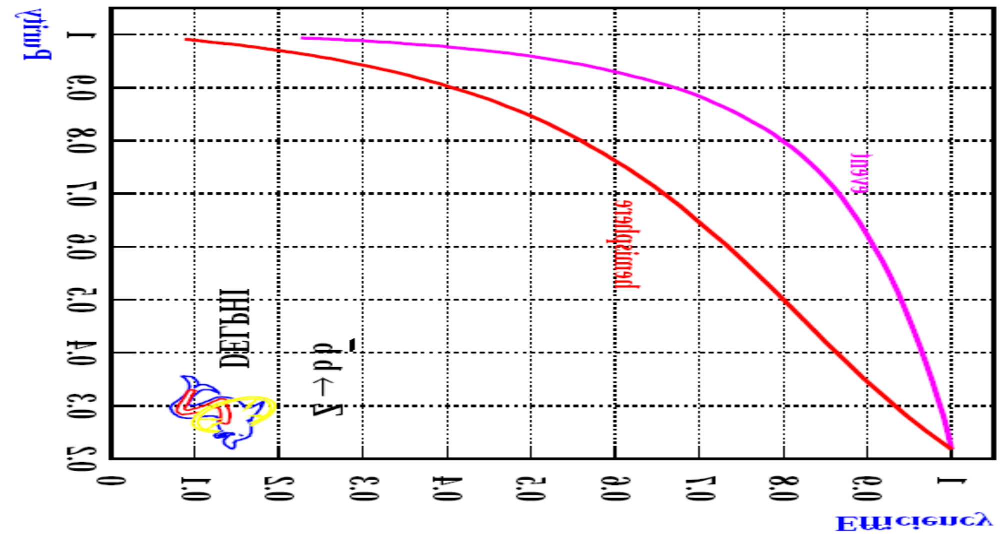
Requirements from Physics: Flavor tagging

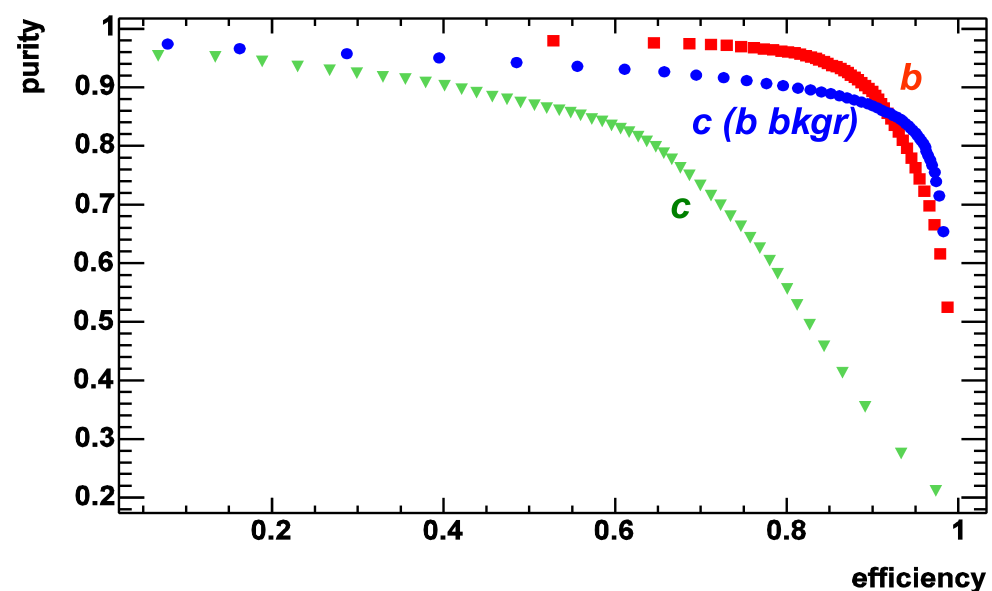
- Recoil mass in

$$e^+e^- \rightarrow HZ \rightarrow q\,\bar{q}\,X$$

- Measure Higgs branching ratios
- Z/W reconstruction

- Full vertex reconstruction





Impact parameter

$$\sigma^{IP}_{R\phi} = \frac{\alpha_{MS}}{p\sin^{3/2}\theta} \oplus \sigma^0_{R\phi}$$

$$\sigma^{IP}_{z} = \frac{\alpha'_{MS}}{p\sin^{5/2}\theta} \oplus \sigma^0_{z}$$

$$\sigma^{IP} \propto \sqrt{X}\,r$$

Requirements from Physics: Flavor tagging

- Recoil mass in

$$e^+ e^- \rightarrow H Z \rightarrow q \bar{q} X$$

- Measure Higgs branching ratios
- Z/W reconstruction

	DELPHI	CMS	ILC
Layer 1	63 mm	44 mm	15 mm
Layer 2	90 mm	73 mm	22 mm
Layer 3	109 mm	102 mm	35 mm
Layer 4	--	--	48 mm
Layer 5	--	--	61 mm

- Full vertex reconstruction

Impact parameter

$$\sigma^{IP}_{R\phi} = \frac{\alpha_{MS}}{p \sin^{3/2}\theta} \oplus \sigma^0_{R\phi}$$

$$\sigma^{IP}_{z} = \frac{\alpha'_{MS}}{p \sin^{5/2}\theta} \oplus \sigma^0_{z}$$

$$\sigma^{IP} \propto \sqrt{X}\, r$$

	DELPHI	CMS	ILC
α_{MS} (μm GeV/c)	65	80	10
$\sigma_{R\Phi}$ (μm)	20	9	5
α'_{MS} (μm GeV/c)	71-151	200	
σ_z (μm)	39-96	10	

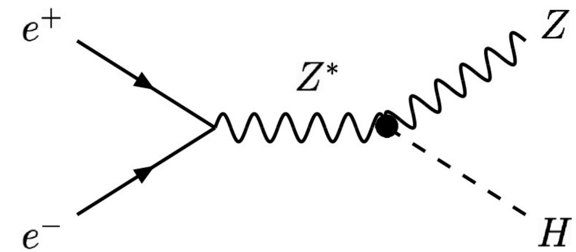
Requirements from Physics: Jet Energy resolution

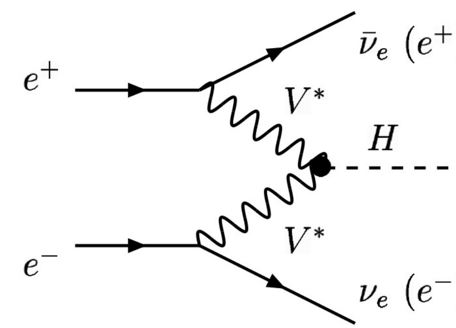
- Events at ILC will have several bosons and fermions.

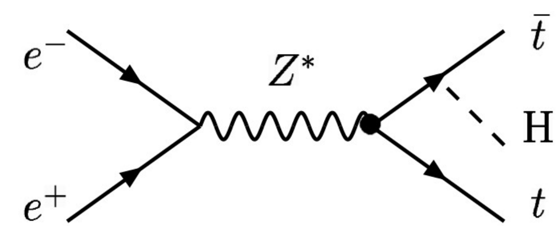
- Distinction of WW from ZZ

$$\frac{\Delta(E)}{E} = 0.3$$

- Study of $e^+e^- \rightarrow WW$
- Higgs BR to WW or ZZ
- Higgs self-coupling in HHZ events



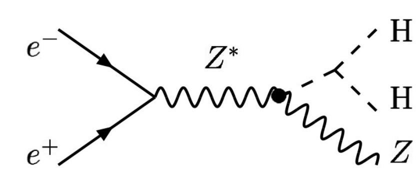




Z to	BR
$\ell^+\ell^-$	10 %
Qq (jets)	70 %

W to	BR
$\ell^\pm\nu$	32 %
qq' (jets)	68 %

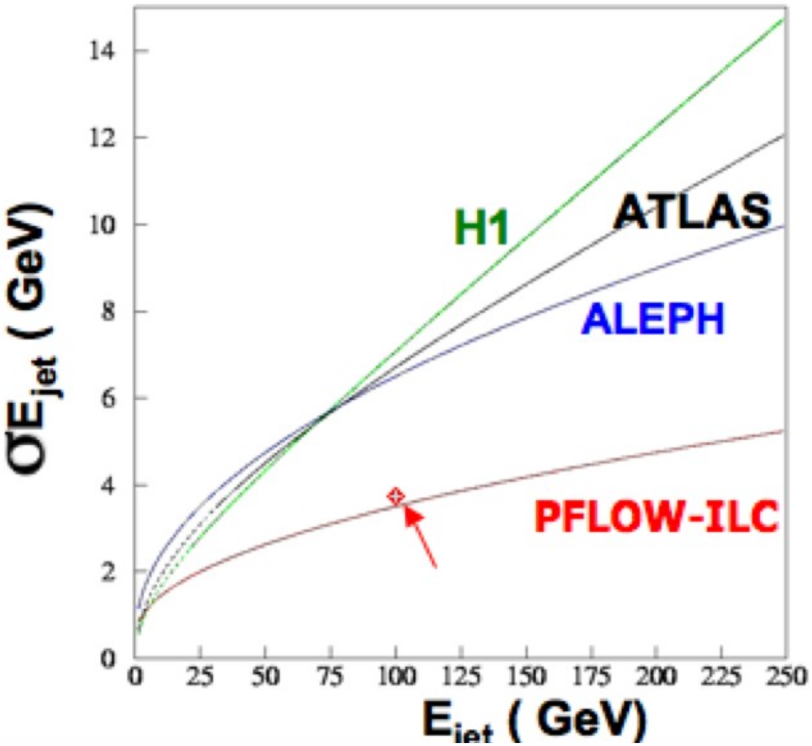
H(120,SM) to	BR
$\ell^+\ell^-$	<15 %
qq(jets),WW,ZZ	>85 %

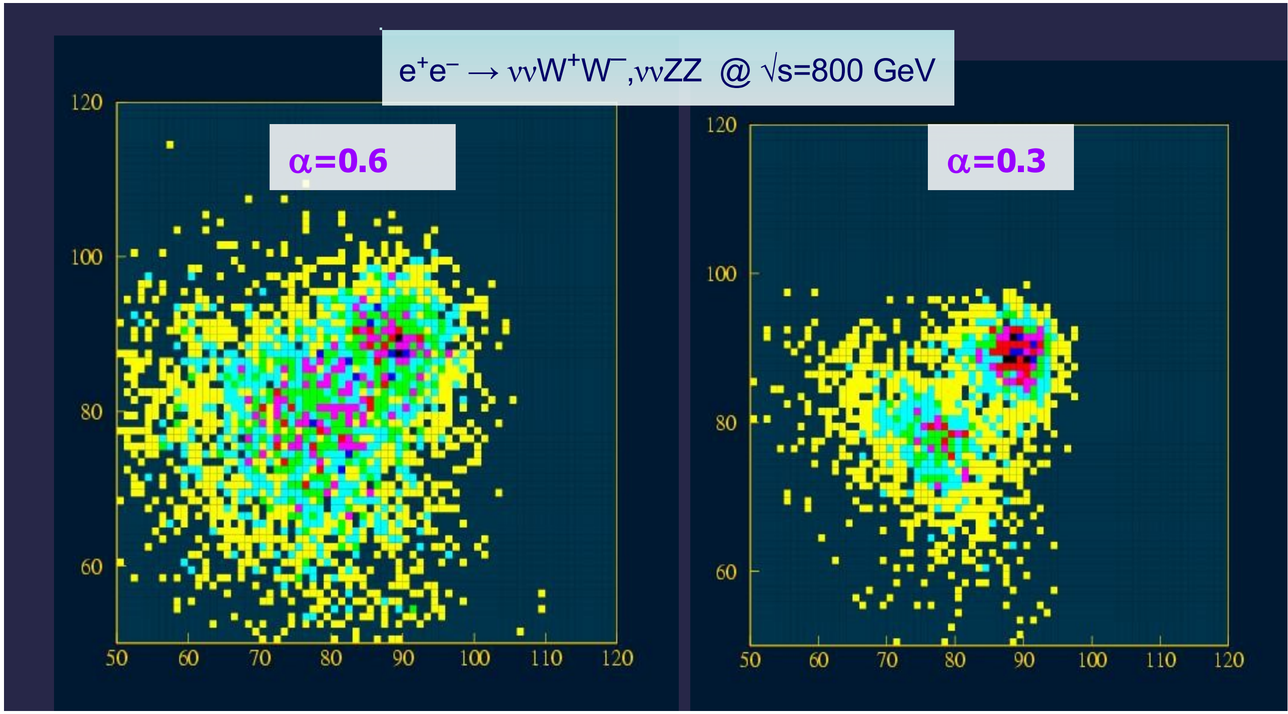


How much should calorimeters improve?

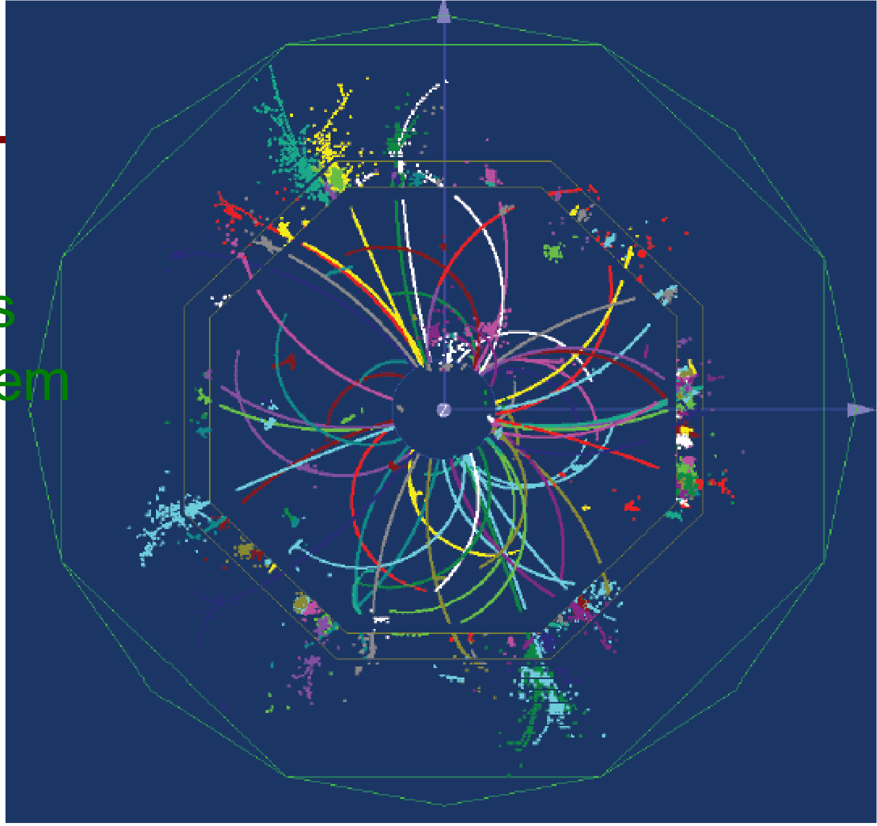
$\Delta E_J = a \times \sqrt{E_J} \oplus b \times E_J \oplus c$

	a	b	c
ALEPH	0.59	0	0.6
ATLAS	0.6	0.03	0
H1	0.5	0.05	0
ILC	0.3	0	0.5





How? .... Particle Flow



- Particle Flow needs
  1) Reconstruction of ALL final state particles
  2) Find charged particles in the tracker system
  3) Find photons in the ECAL
  4) Find neutral hadrons in ECAL and HCAL
     - 3) and 4) are only possible if there is no mixing between deposited energy from different particles
- Calorimeters should be then
  - far away from IP
  - dense (small lateral spread of showers)
  - high granularity
    - Detector readout in 3D
    - Small pixel size (< Moliere radius)
    - ECAL and HCAL inside the coil

E_{jet} =	$E_{charged\ tracks}$ +	E +	E_{h^0}
fraction	65%	26%	9%

Charged track(s) $\Delta p/p$ ~ qq 10^{-5}
Photon(s) $\Delta E/E$ ~ 12%
Neutral hadrons $\Delta E/E$ ~ 45%

Perfect Algorithm → $\sigma^2 jet = \sigma^2 ch + \sigma^2_\gamma + \sigma^2 h^0 \approx (0.14)^2 E_{jet}$

Real Life: Efficiency
Confusion → $\sigma^2 jet = (0.30)^2 E_{jet} + (0.50)^2$
Recons. Thres.

Conclusions

- Present understanding points out to an SM revision
  - Theoretical and experimental
  - “Something” should happens below 1 TeV
- Two main tools needed to explore this region
  - LHC: starts this year → main effort
  - ILC: still to be approved/constructed
  - Interplay needed to disentangle physics underneath
- Detector challenges: compulsory R+D now

“Delay always breeds danger and to protract a great design is often to ruin it”

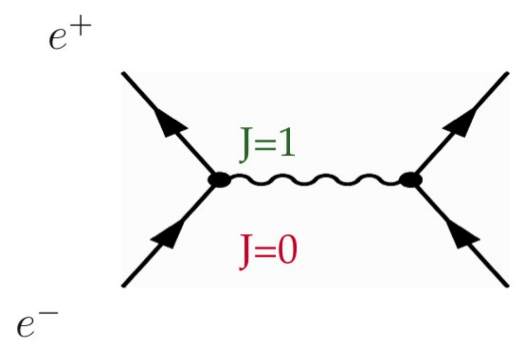
Barry Barish GDE/ILC Director
quoting Miguel de Cervantes in *Don Quixote*

Backup

ILC - Polarization

$$\sigma_{P_{e^-}P_{e^+}} = \frac{(1+P_{e^-})(1+P_{e^+})}{4}\sigma_{RR} + \frac{(1-P_{e^-})(1-P_{e^+})}{4}\sigma_{LL} + \frac{(1+P_{e^-})(1-P_{e^+})}{4}\sigma_{RL} + \frac{(1-P_{e^-})(1+P_{e^+})}{4}\sigma_{LR}$$

	e^-	e^+		
σ_{RR}	$\Rightarrow\!\!\rightarrow$	$\leftarrow\!\!\Leftarrow$	$\frac{1+P_{e^-}}{2}\cdot\frac{1+P_{e^+}}{2}$	$J_z = 0$
σ_{LL}	$\Leftarrow\!\!\rightarrow$	$\leftarrow\!\!\Rightarrow$	$\frac{1-P_{e^-}}{2}\cdot\frac{1-P_{e^+}}{2}$	
σ_{RL}	$\Rightarrow\!\!\rightarrow$	$\leftarrow\!\!\Rightarrow$	$\frac{1+P_{e^-}}{2}\cdot\frac{1-P_{e^+}}{2}$	$J_z = 1$
σ_{LR}	$\Leftarrow\!\!\rightarrow$	$\leftarrow\!\!\Leftarrow$	$\frac{1-P_{e^-}}{2}\cdot\frac{1+P_{e^+}}{2}$	



$\leftarrow$ only from RL, LR: γ, Z

$\leftarrow$ only from LL, RR

- Polarized beams can be used to suppress some bkg
  - SM couples with LR or RL
  - BSM can also with LL and RR

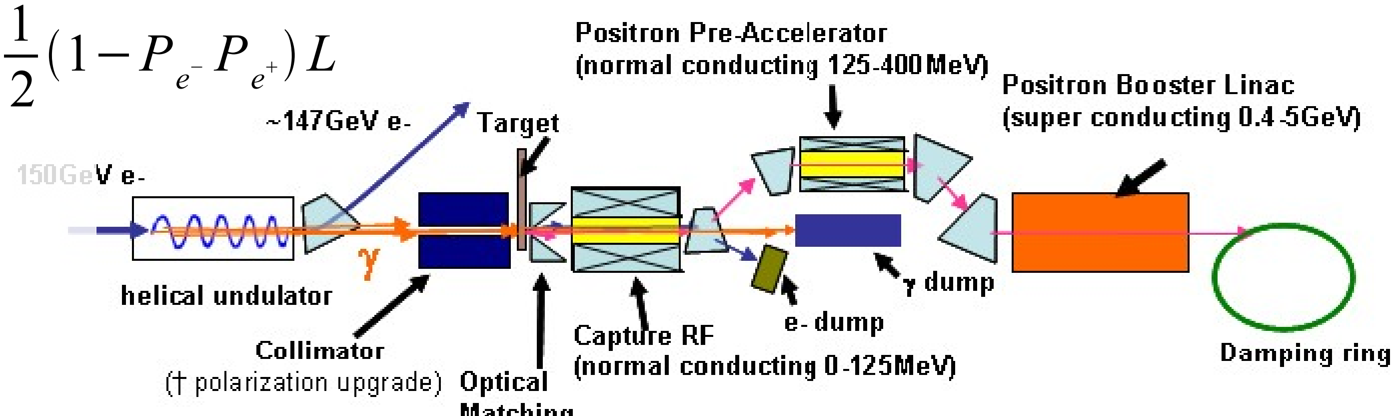
$$\sigma_{P_{e^-}P_{e^+}} = (1+P_{e^-}P_{e^+})\,\sigma_0[1-P_{eff}A_{LR}]$$

$\sigma_0 = \frac{\sigma_{RL}+\sigma_{LR}}{4}$ → Unpolarized Cross section

$A_{LR} = \frac{\sigma_{LR}-\sigma_{RL}}{\sigma_{LR}+\sigma_{RL}}$ → Left-right assymmetry

$P_{eff} = \frac{P_{e^-}-P_{e^+}}{1-P_{e^-}P_{e^+}}$ → Effective polarization

$$L_{eff} = \frac{1}{2}(1-P_{e^-}P_{e^+})L$$

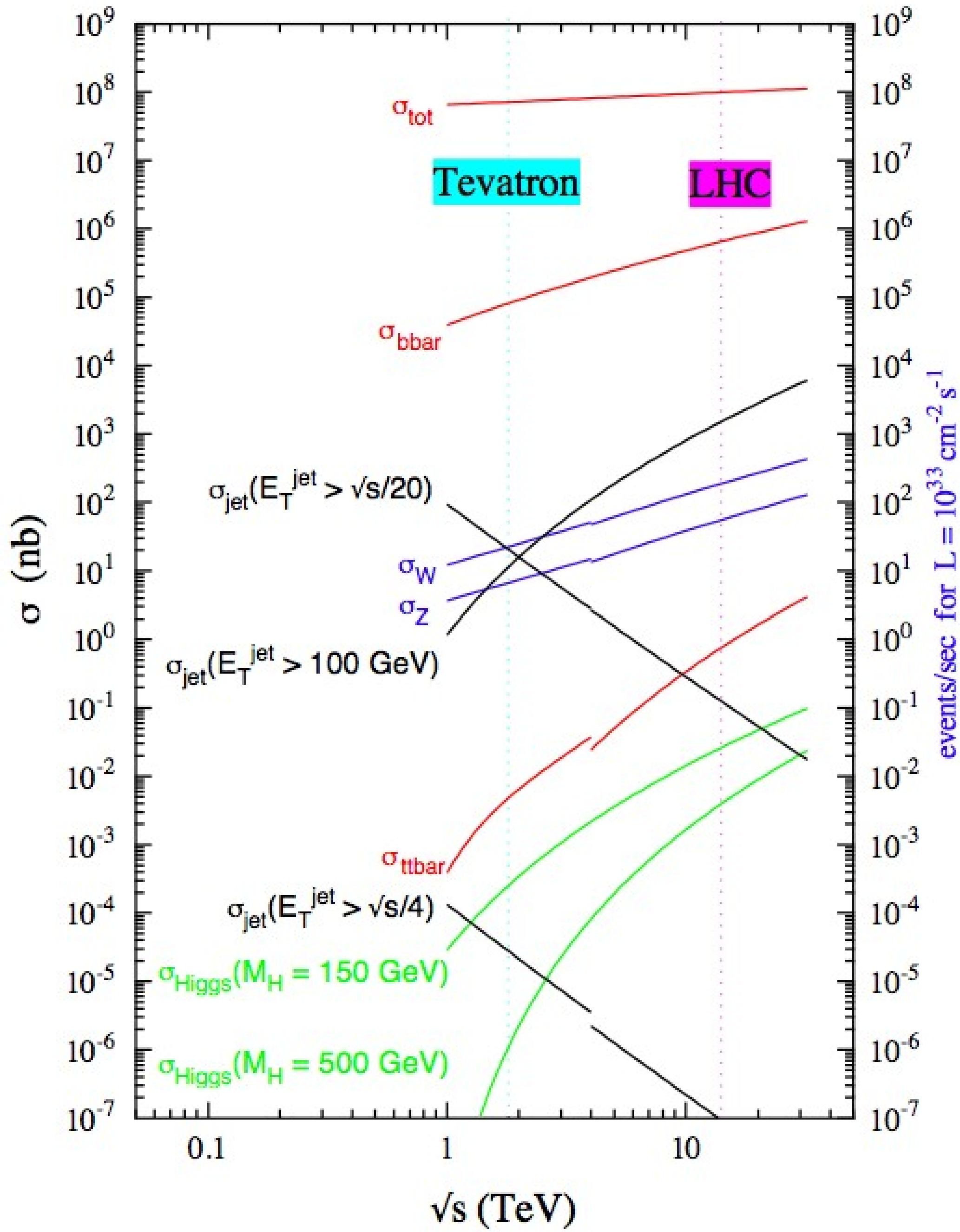


Accelerators Comparison

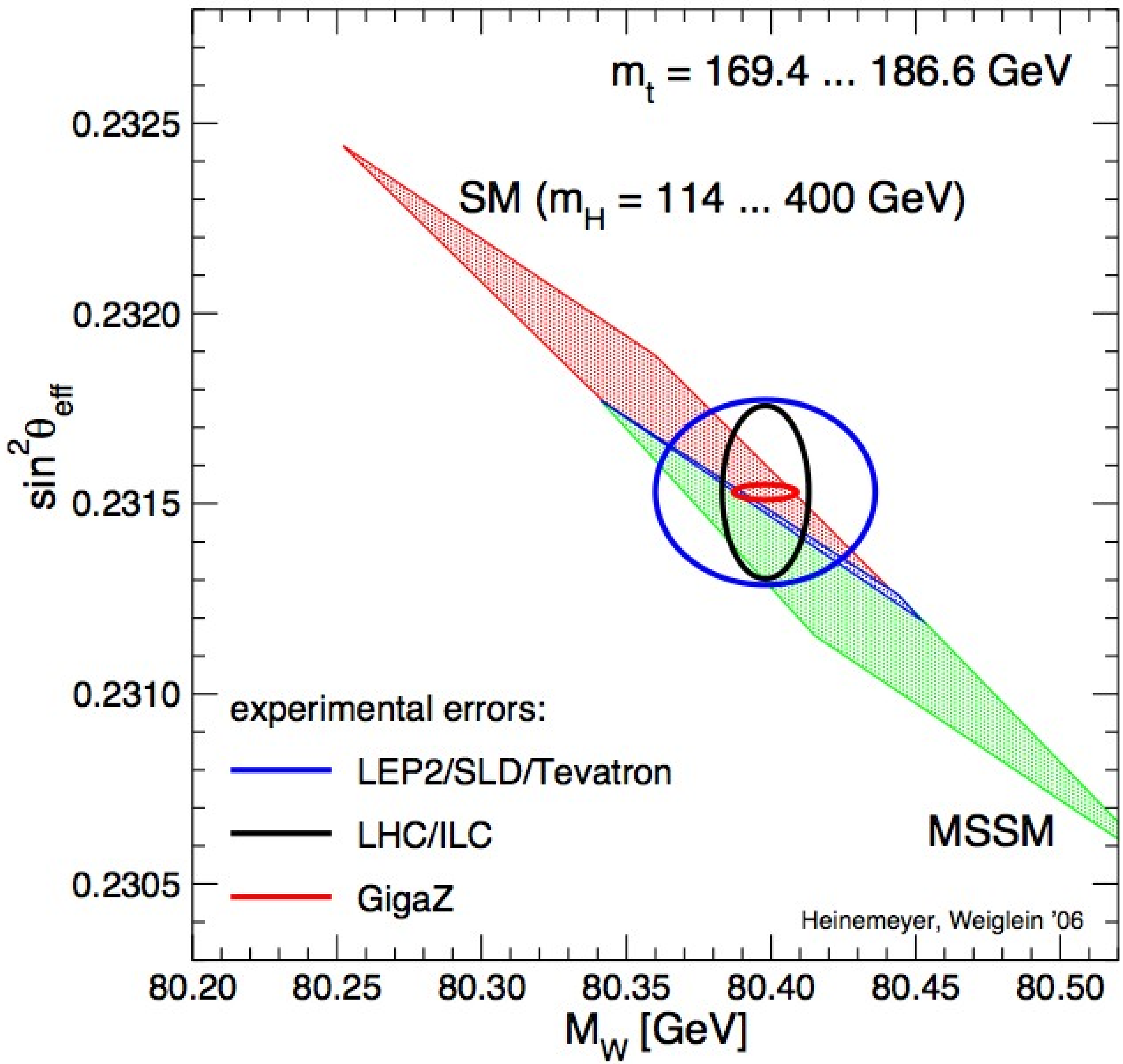
$$L \sim \frac{n_b N_e^2 f}{4\pi\sigma_x\sigma_y} H_D$$

	LEP	LHC	SLC	ILC
Energy (GeV)	45-100	7000	45	200-500
Time between collisions (μs)	22	0.025	8300	0.2-0.337
Beam dimensions	X: 200 μm	X: 16.7 μm	X: 1.4 μm	X: 543 nm
	Y: 2.5 μm	Y: 16.7 μm	Y: 0.7 μm	Y: 5.7 nm
	Z: 1.0 cm	Z: 7.7 cm		Z: 300 μm
Particles per bunch ($\times10^{10}$)	45	12	4	2
Bunches per ring	4 in trains <4	2808		2820-4000
Luminosity (10^{30} cm^{-2} s^{-1})	24-100	10000	3	20000
Radiation	-	~1 Grad/year	-	~20 krad/year

pp(bar) cross section

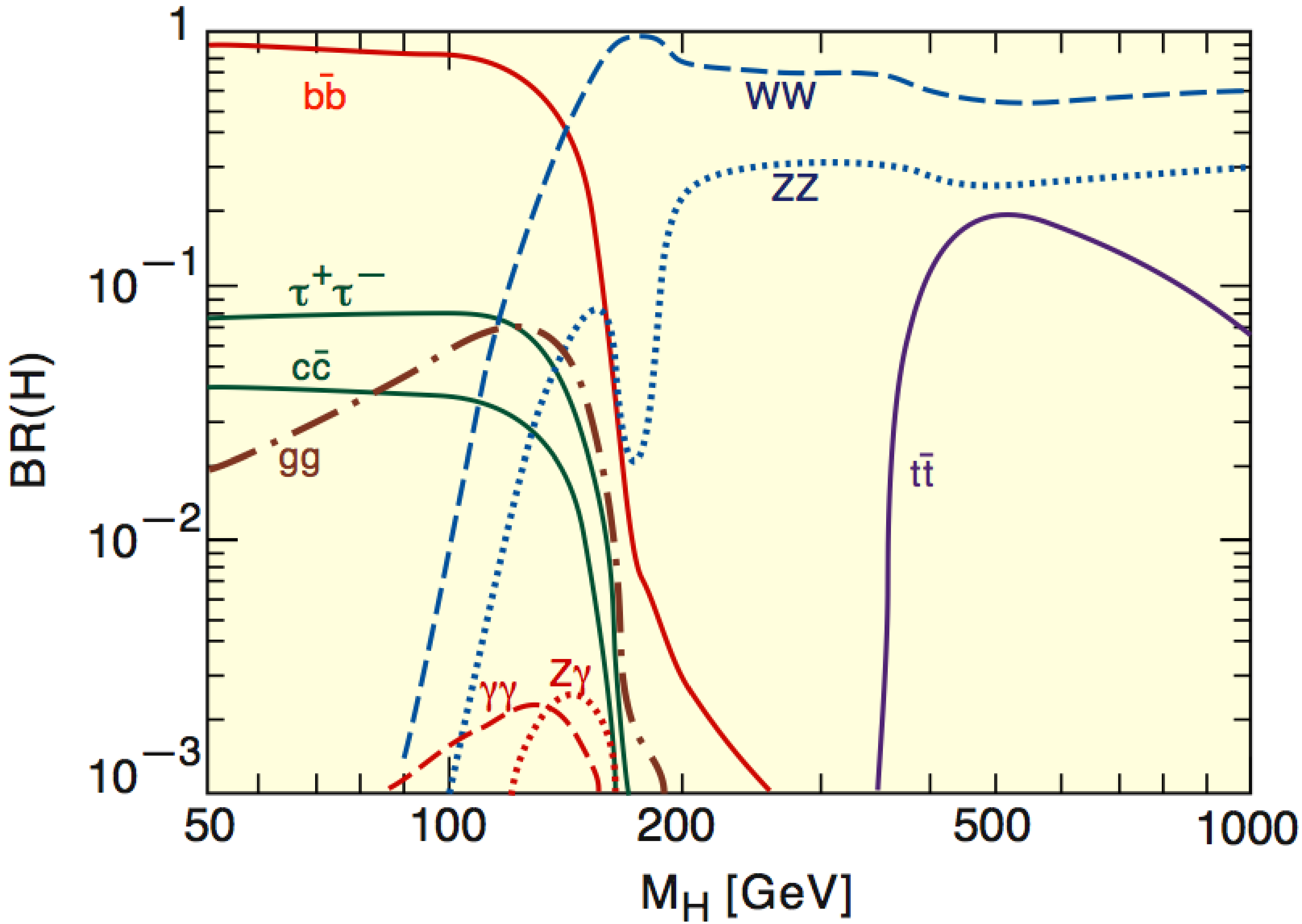


ILC precision

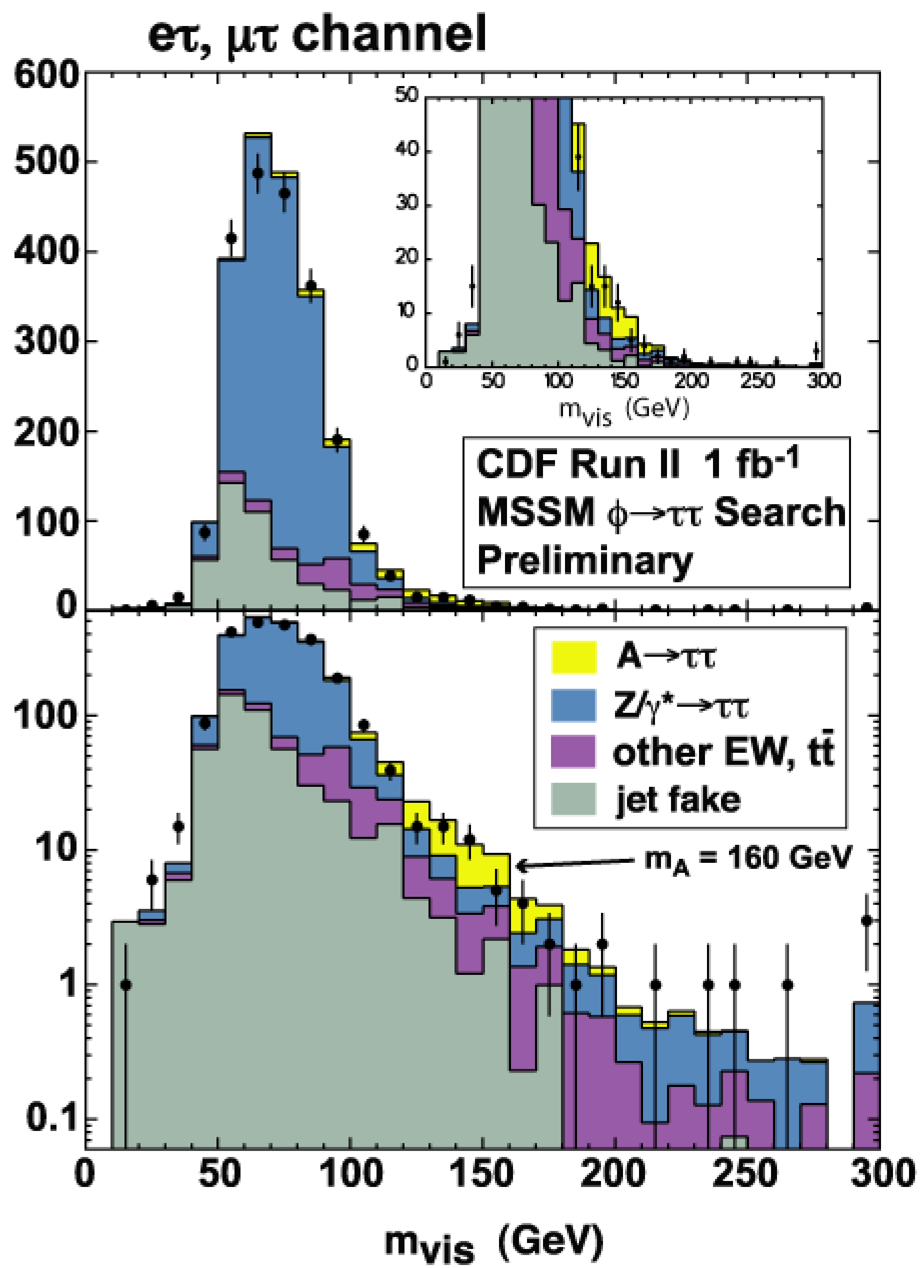


SM Higgs Decays

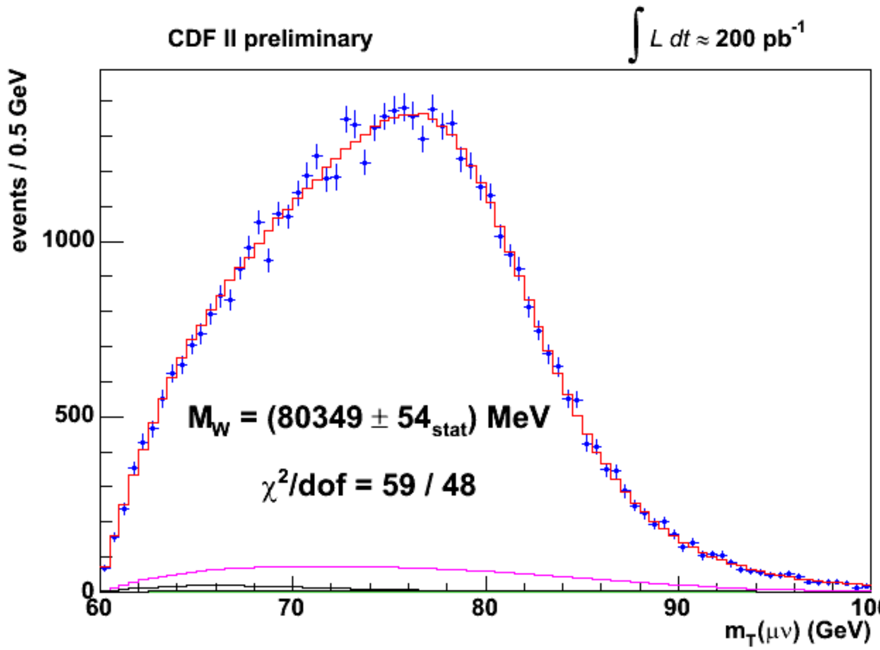
A.Djouadi, J.Kalinowski, M.Spira
(incl. all NLO-QCD corrections)

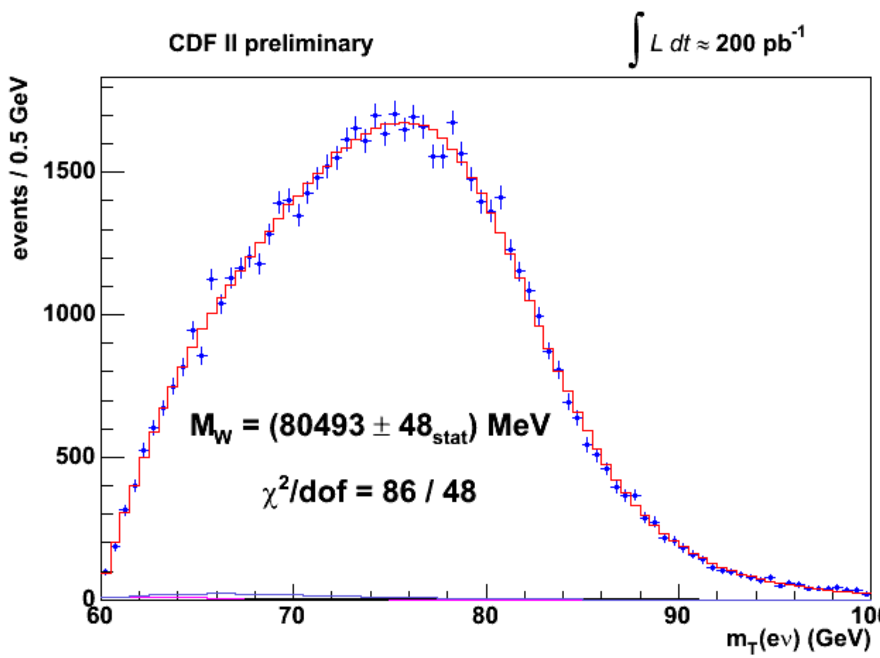


Higgs discovery at CDF?

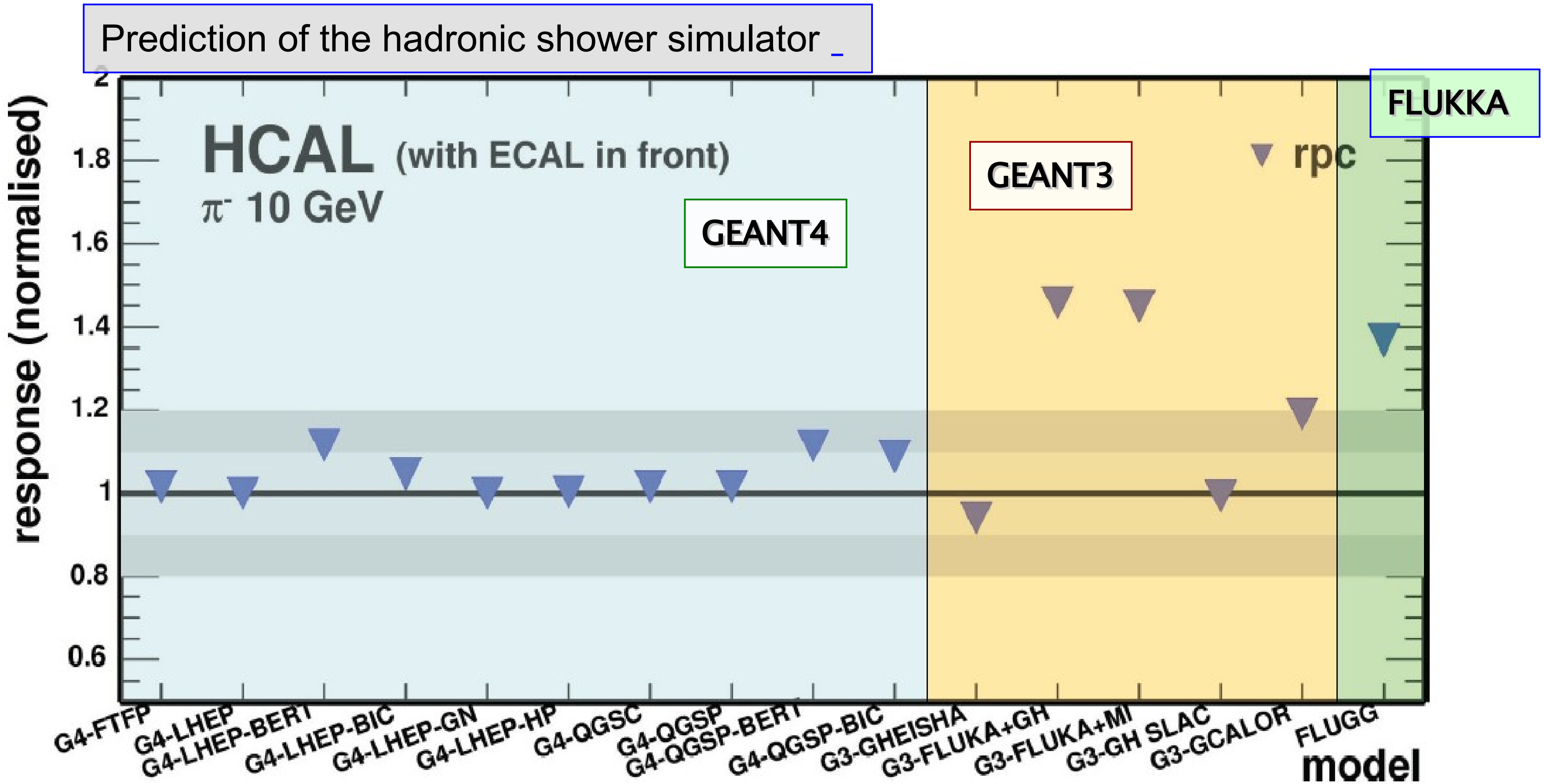


New W mass from CDF



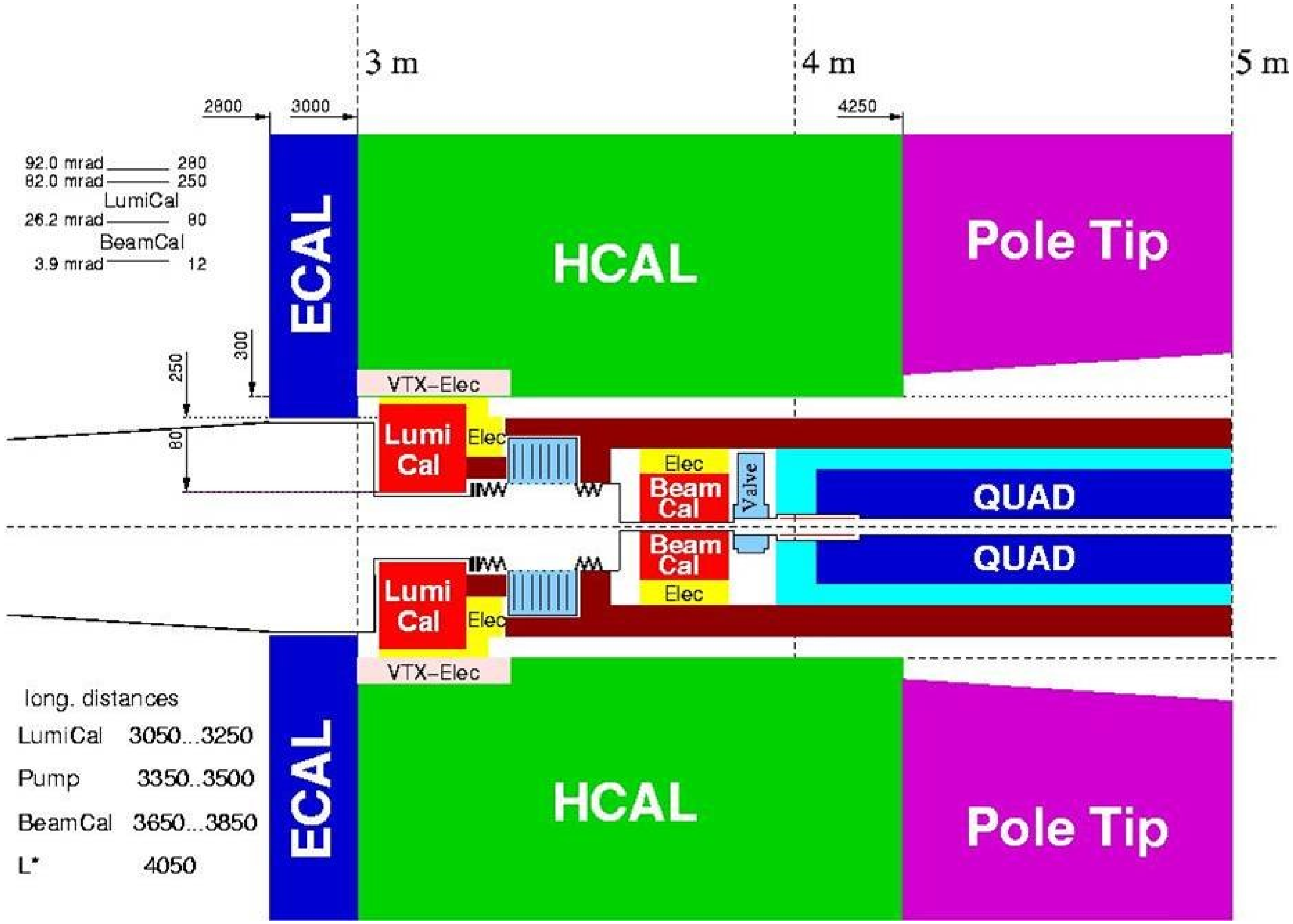


Hadronic showers simulation



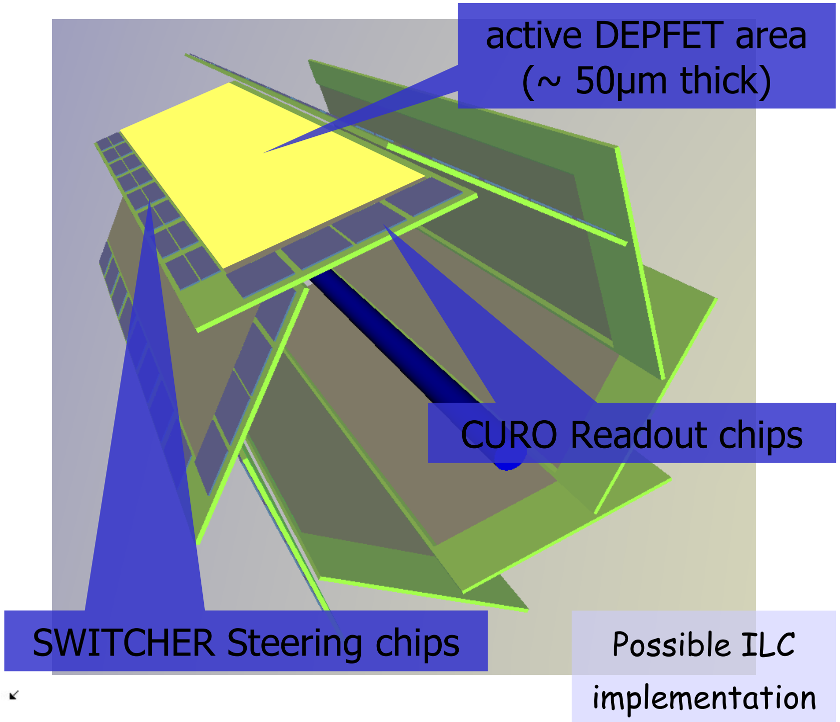
G.Mavromanolakis (Cambridge Univ.)

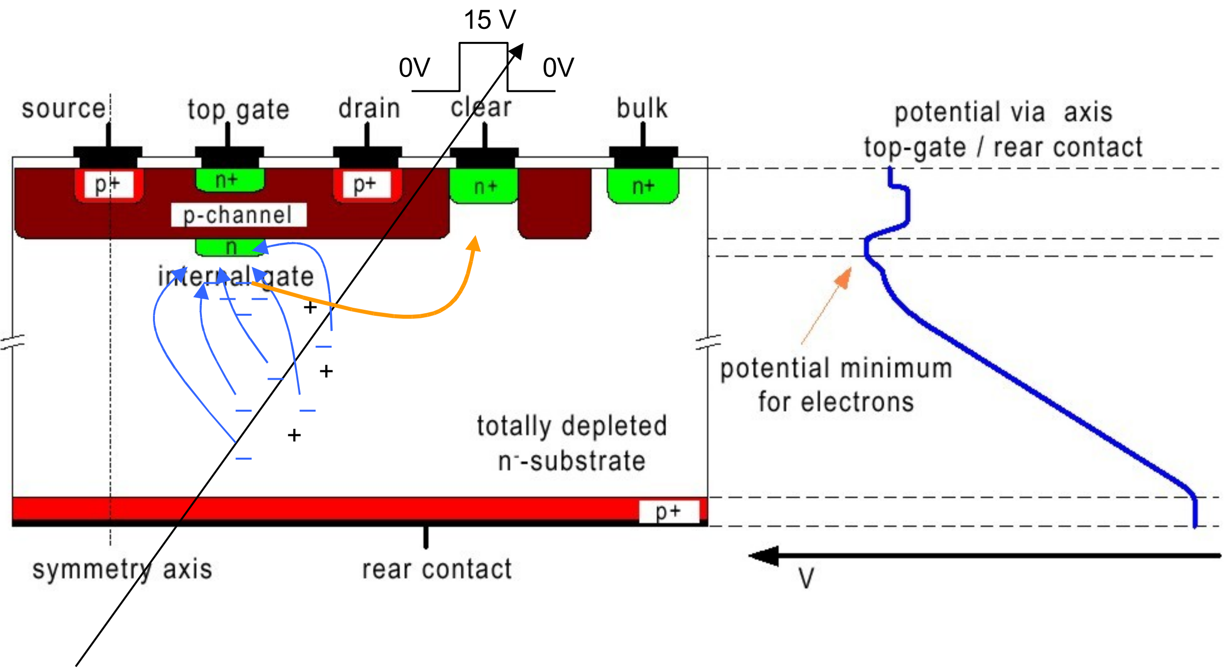
ILC Forward Region

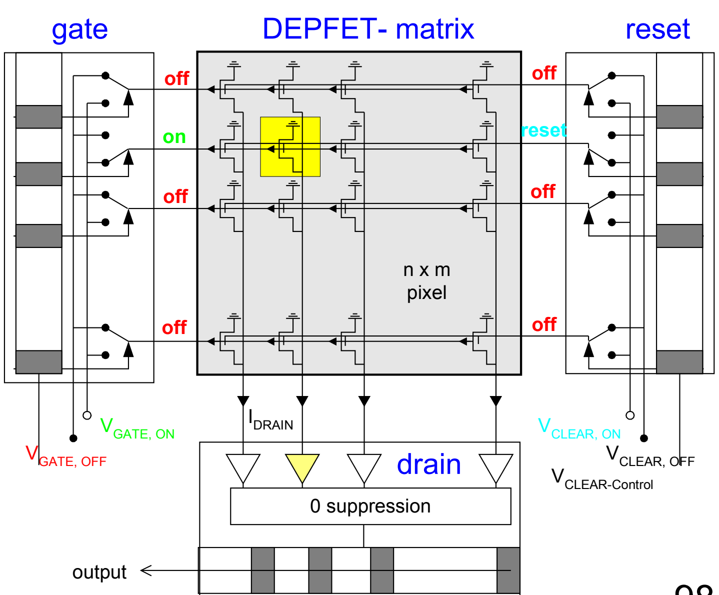


Vertex Detectors

- Based on pixel detectors (~15-25 μm)
  - DEPFET (Depleted Field Effect Transistor)
    - Combined function of sensor and amplifier
    - Low noise
    - Internal storage until reset
    - Readout at 50 MHz

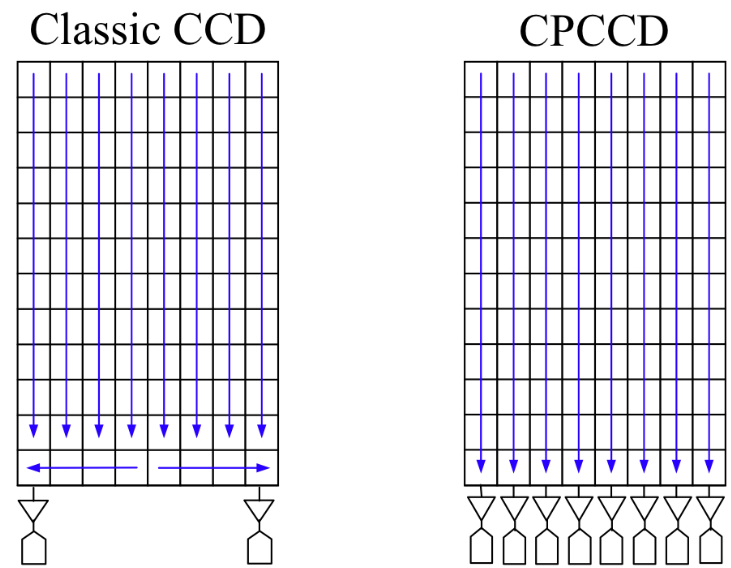


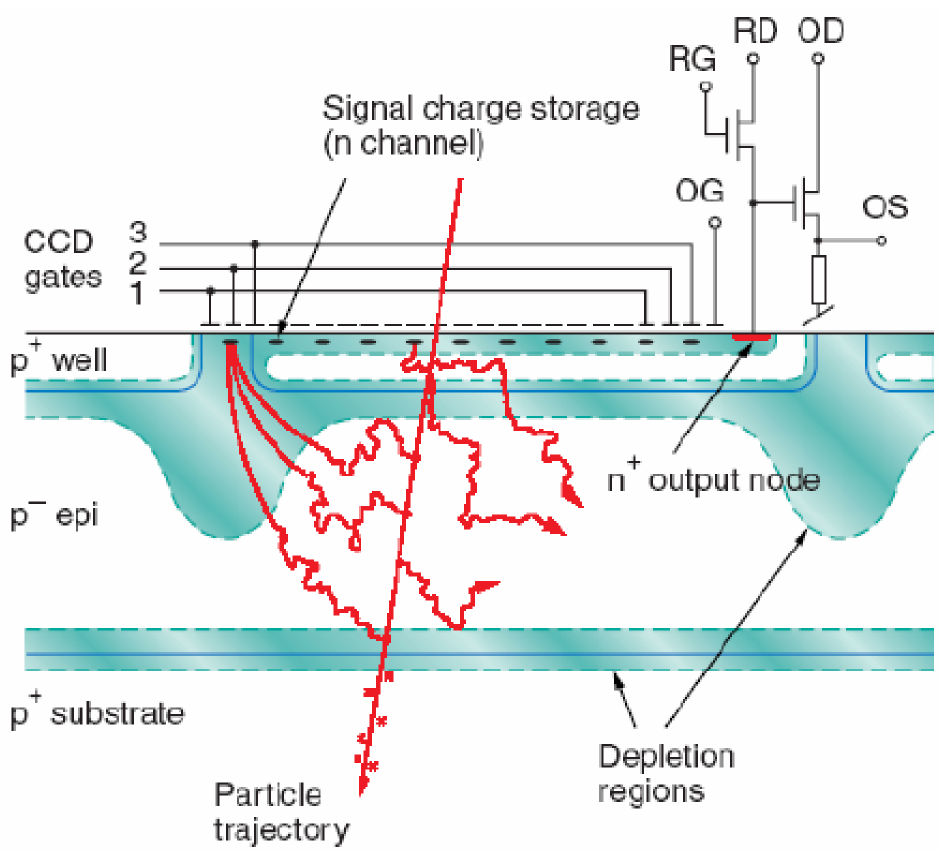




Vertex Detectors

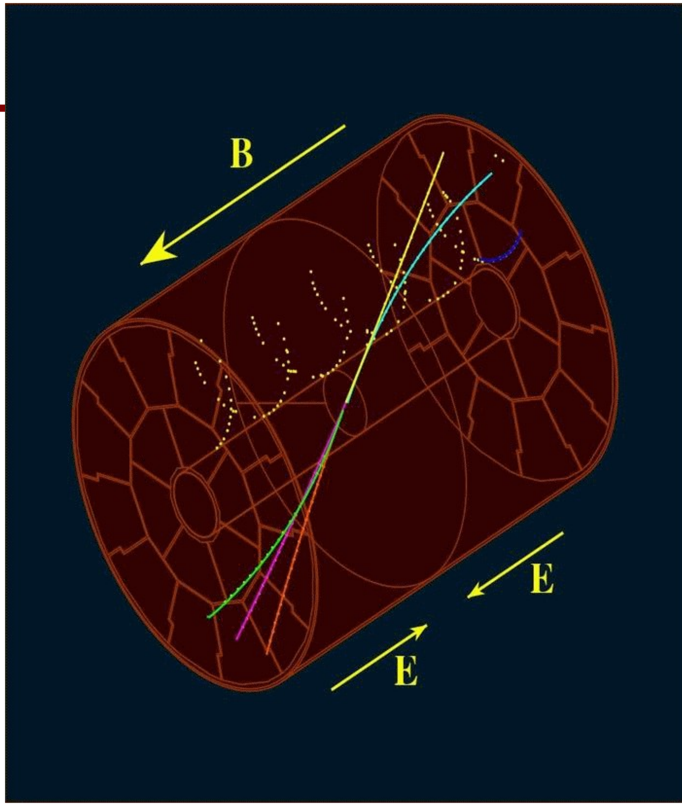
- Based on pixel detectors (~15-25 μm)
  - CPCCP (Column Parallel CCD)
    - Need to read @ 50 MHz
    - ~20 mm depletion layer
      - ~1000 e





- ISIS (In Situ Internal Storage)
  - Charge collected under a photogate
  - Charge transferred to 20 pixel in situ during bunches
    - Time tag
  - Conversion during beam quiet period
  - 1 Mhz readout enough

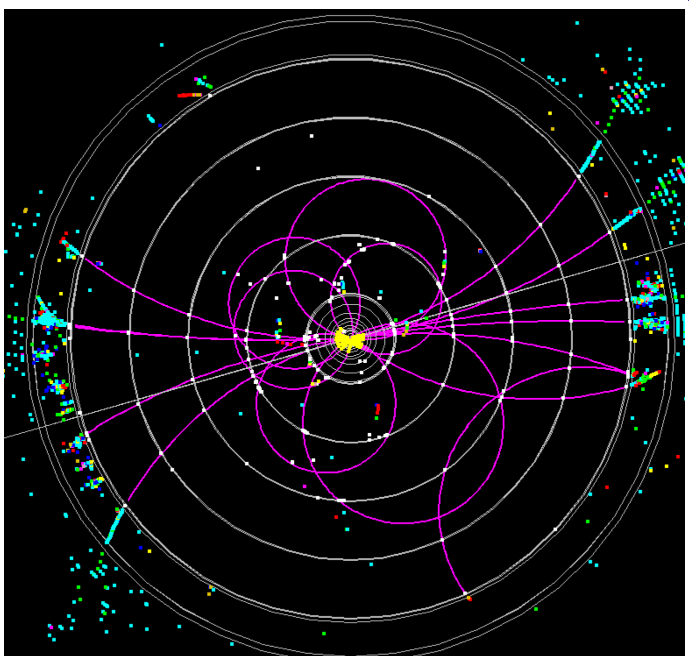
Central Tracker



Gaseous or silicon?

$$\Delta \frac{1}{p} \propto \frac{\delta}{R^2 B \sqrt{n}}$$

- Field Cage- homogeneous E field
- Mechanical Frame (< 3% X_0)
- Novel Gas Amplification System
- Gas Mixture
- Performance at High B –Field (100μm (Rϕ) Resolution)



- Track reconstruction efficiency
- Long Silicon Strip sensors (Barrel)
- Mechanical Support:<1% X_0/layer
- FE Electronics (low noise, digi)

$\sigma(1/p) = 6 \times 10^{-5}$ GeV^{-1}

CALICE

Calorimeter for ILC

http://polywww.in2p3.fr/flc/calice.html

- 200 physicist/engineers
- 38 institutes
- 12 countries

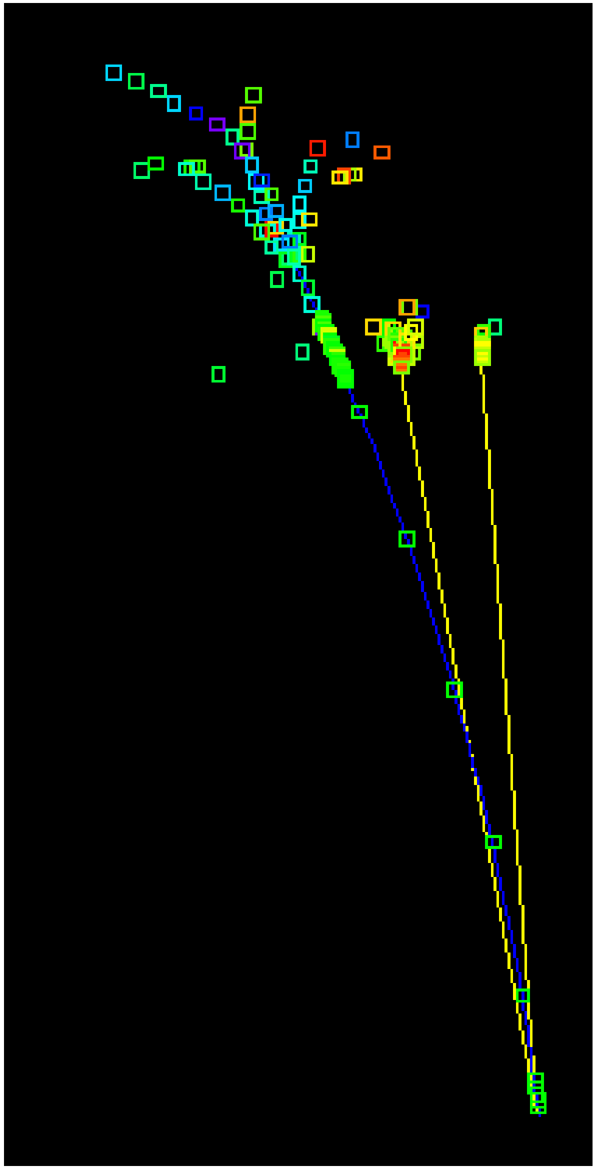
A high granularity calorimeter optimised for the Particle Flow measurement of multi-jets final state at the International Linear Collider running at a center-of-mass between 90 GeV and 1 TeV

	Material	Pixel Size	RO layers	Readout
ECAL	W+Si	1X1 cm^2	20-30	Si Pad
ECAL	W+Scin	3x3 cm^2	20-30	Si Pms
AHCAL	Steel+Scin	4x4 cm^2	~50	Si Pms
DHCAL	Steel+Gas	1X1 cm^2	~50	RPC/GEM/uMega

15-250 Millions channels for ECAL
~50 Millions channels for HCAL

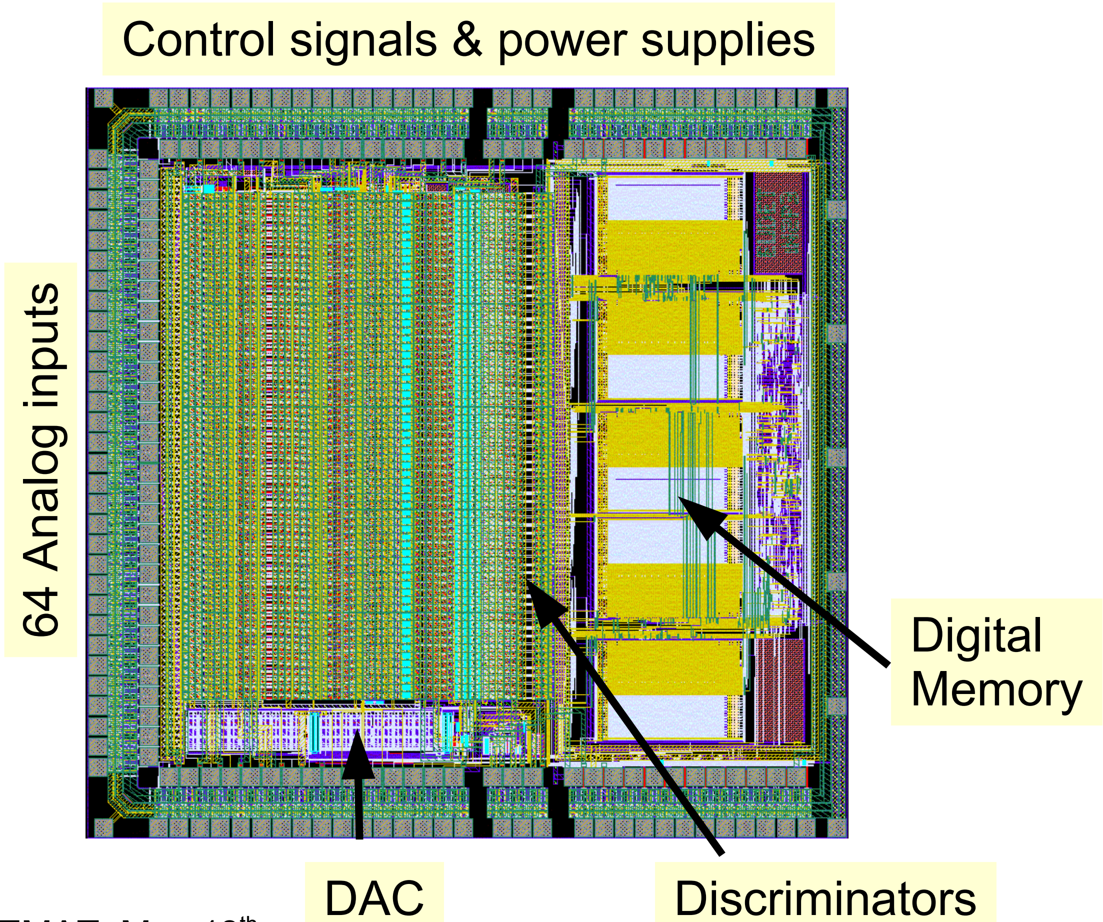
CALICE collaboration

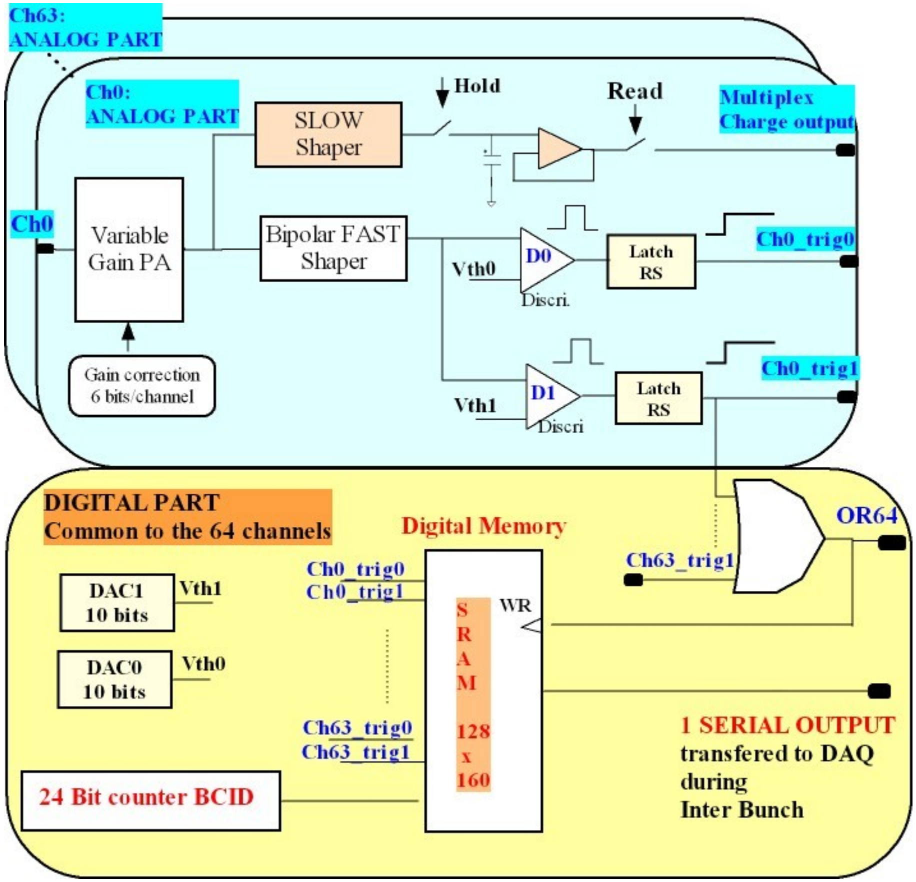
- Share major efforts
  - Front-End Chips (xxROC)
  - Common DAQ
  - Common Framework Analysis (Grid,Data Format)
  - Coordinate Test Beams
- MC Validation
  - Now data and MC compatible at 20%
- No "loosers" politics
  - Goal is to build the best calorimeter
- R&D motivated by physics analysis
  - Working groups in each channel
- Easy to join
  - Still lot of work needed to be done



Front-End electronics

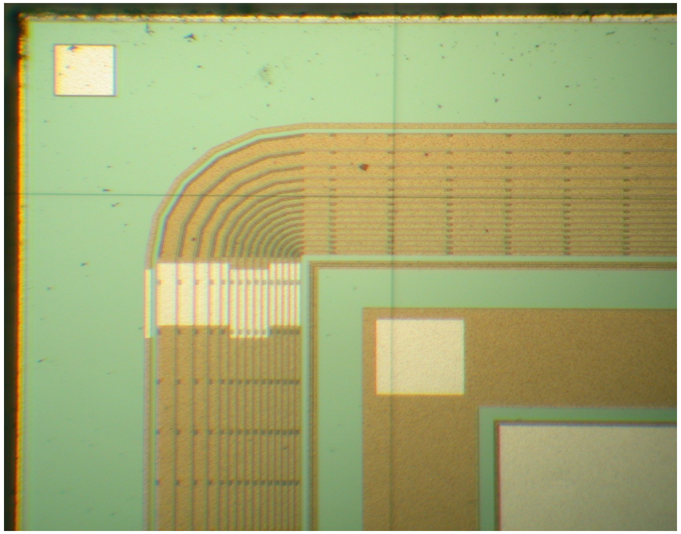
Ch. de la Taille (LAL)



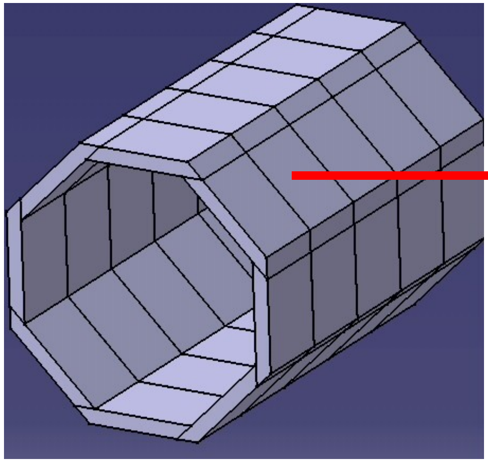


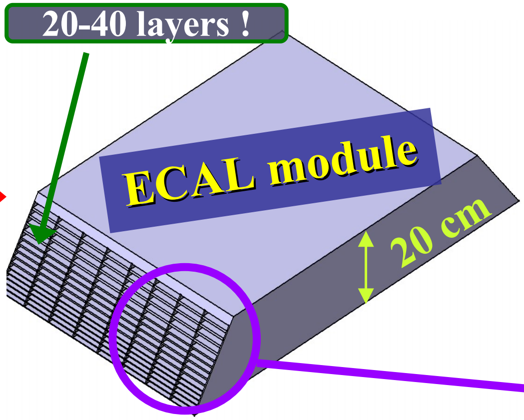
CALICE - ECAL

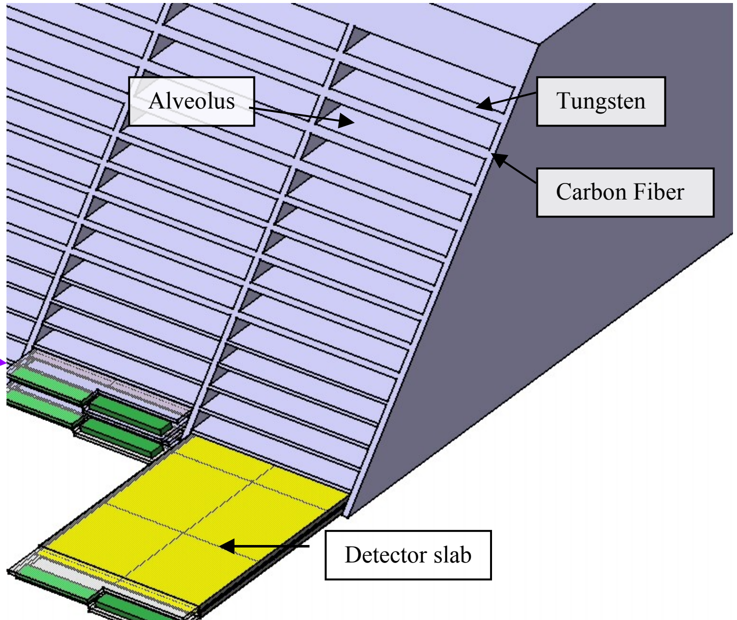
- Silicon Pads
  - 1x1 cm2 (~Molière Radius)
  - Analog Readout – 16 bits
    - Large Dynamic Range



- Prototype used at test beams
  - 30x30 cm^2 planes
  - 14 layers
  - Distinction of 2 close electrons (~3cm)







CALICE - ECAL

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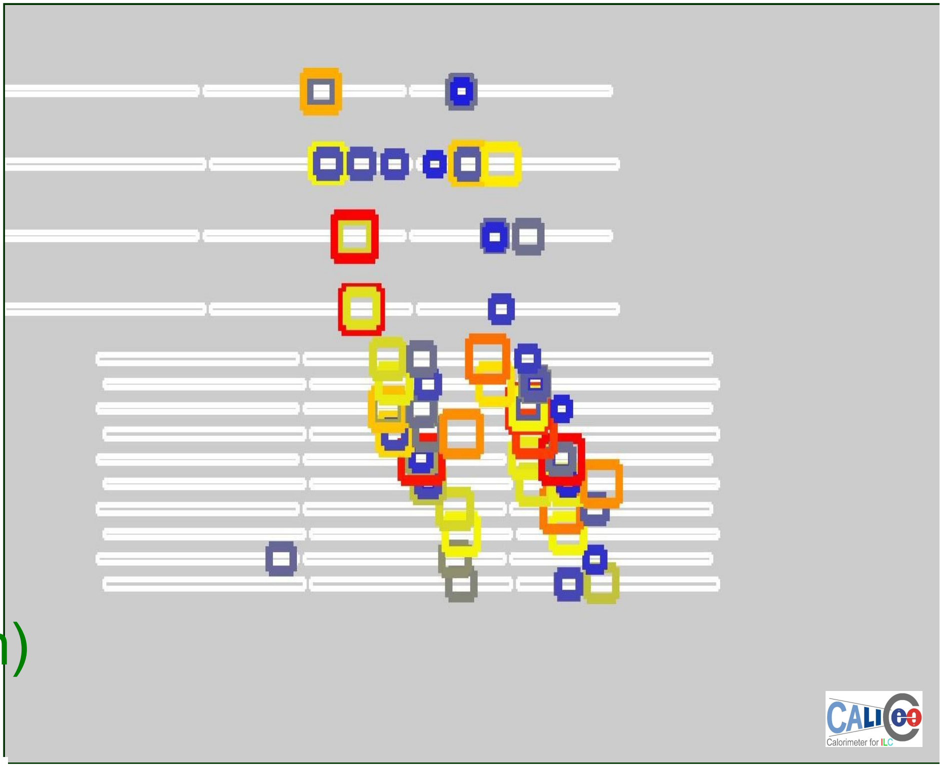
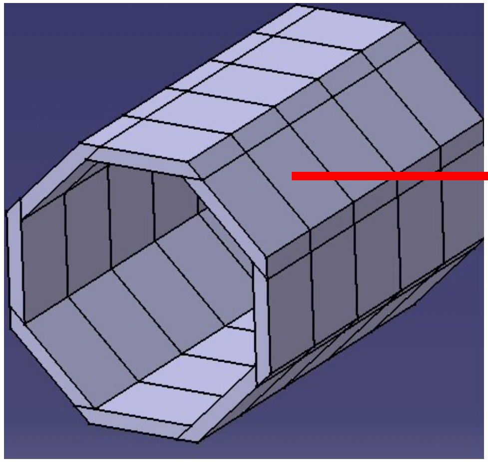
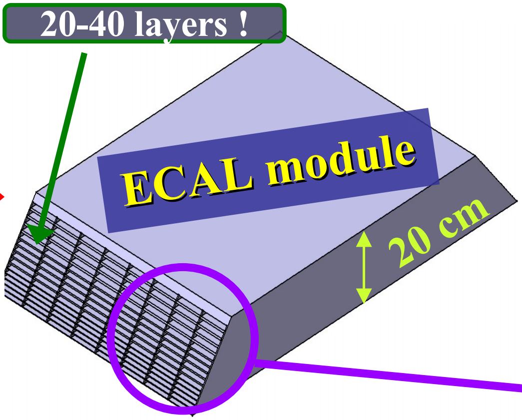
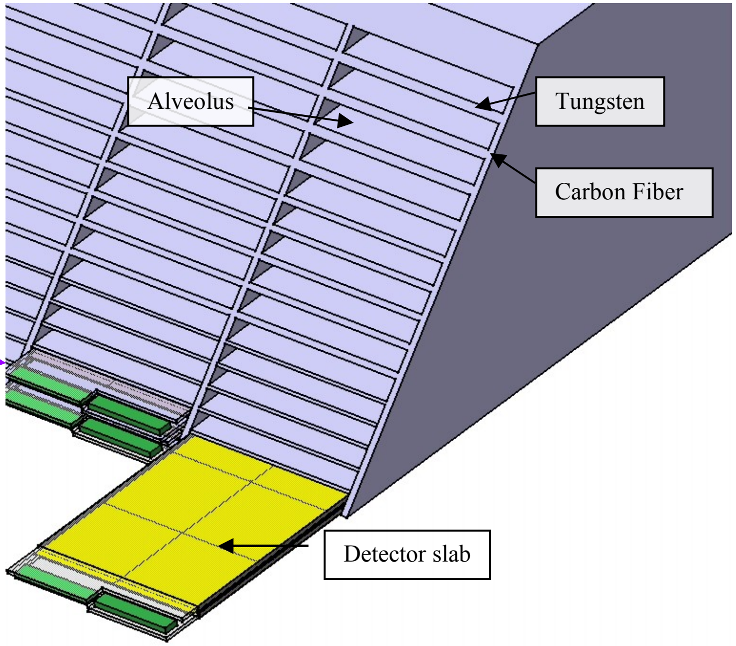


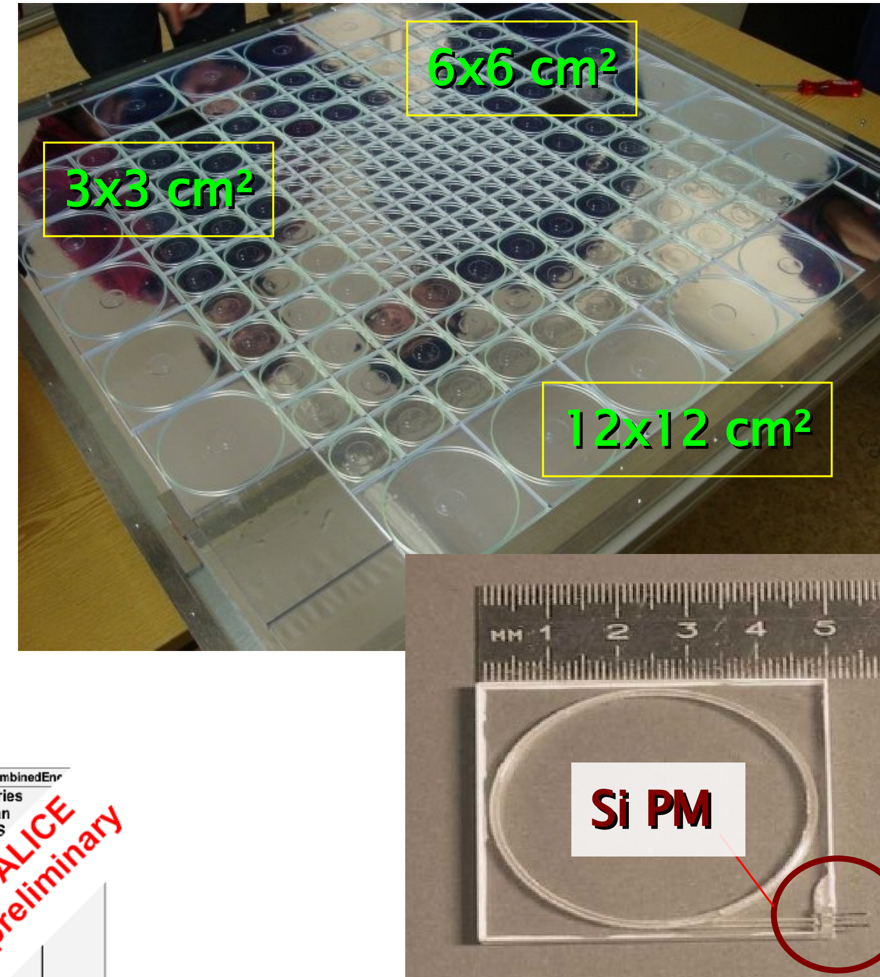






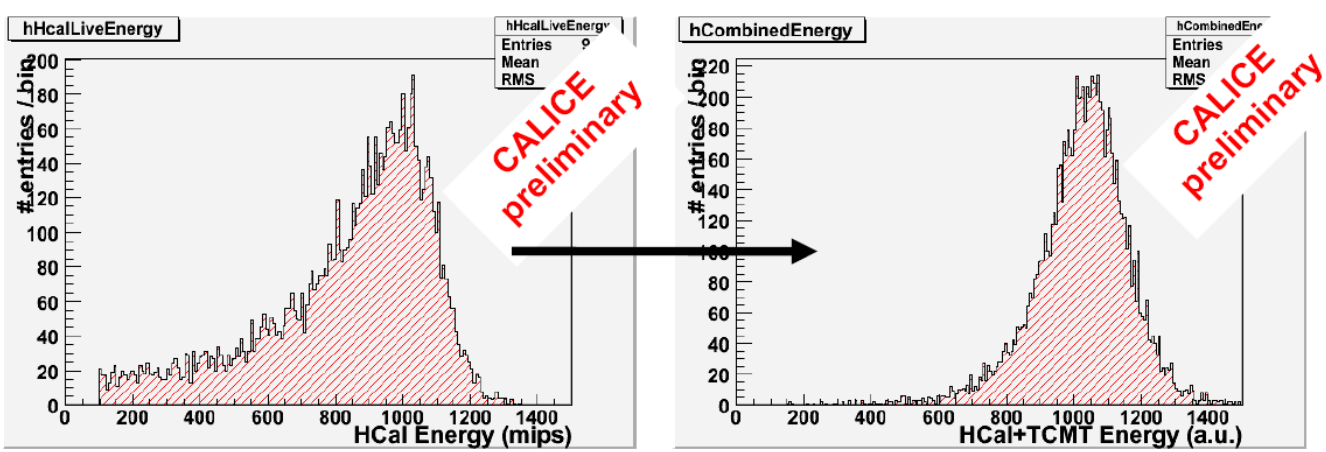
CALICE - AHCAL

- Scintillator tiles
  - $3x3 cm^2 \rightarrow 12x12 cm^2$
  - Wavelength shifter coupled to a SiPM
- 1 m^3 prototype (4.5λ)
  - 38 layers
  - ~8000 channels
  - Tail Catcher of 10λ

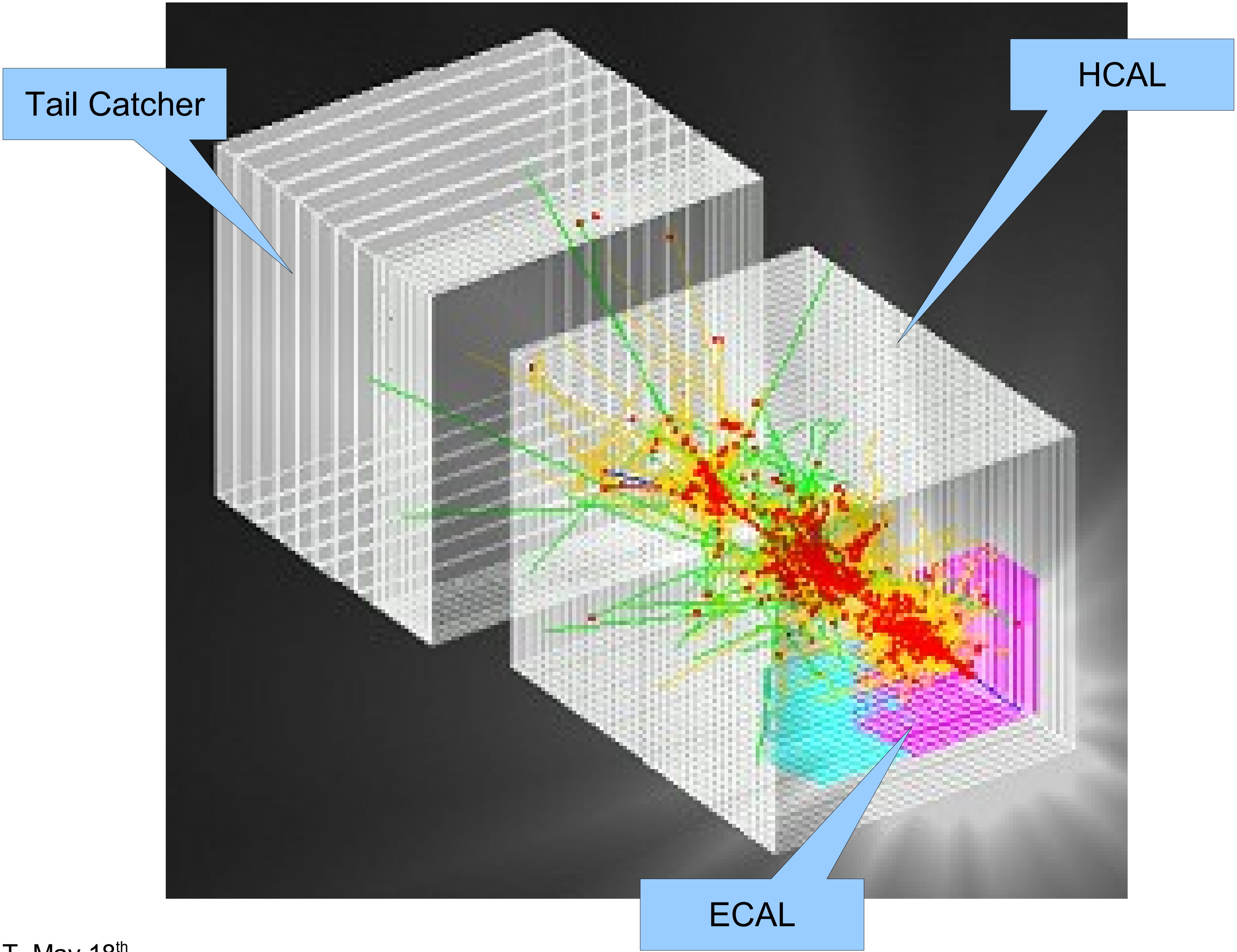


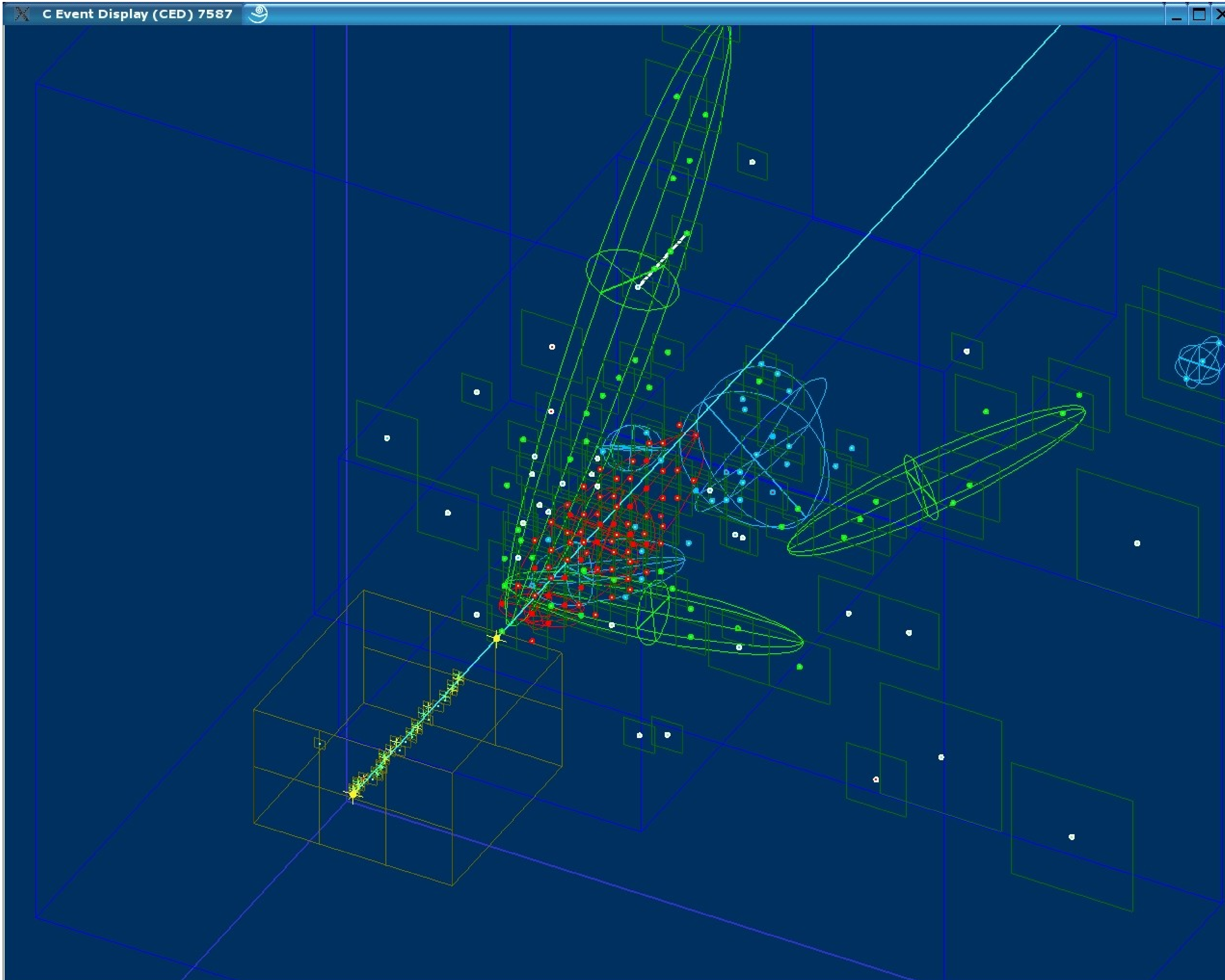
HCAL alone

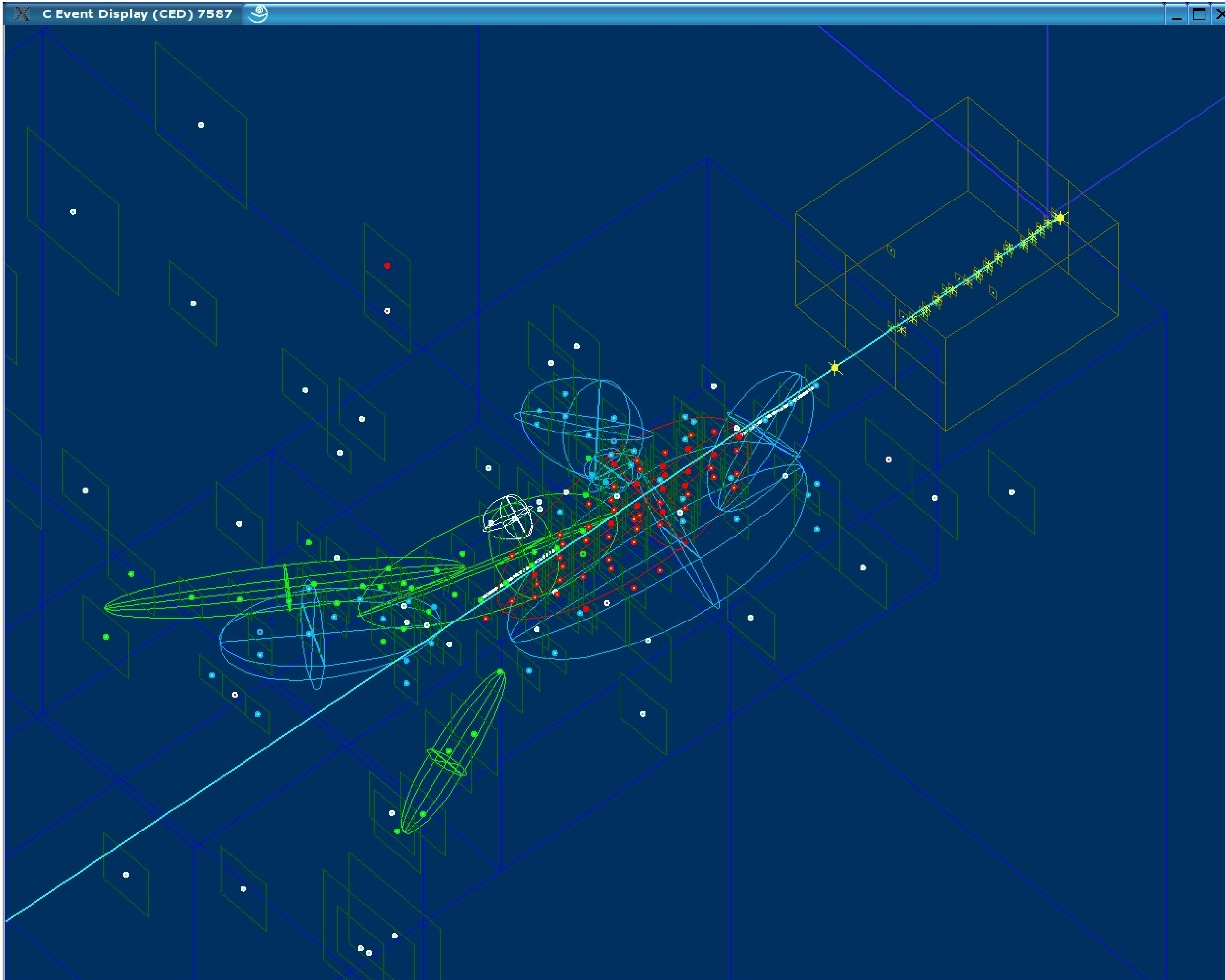
HCAL & TCMT

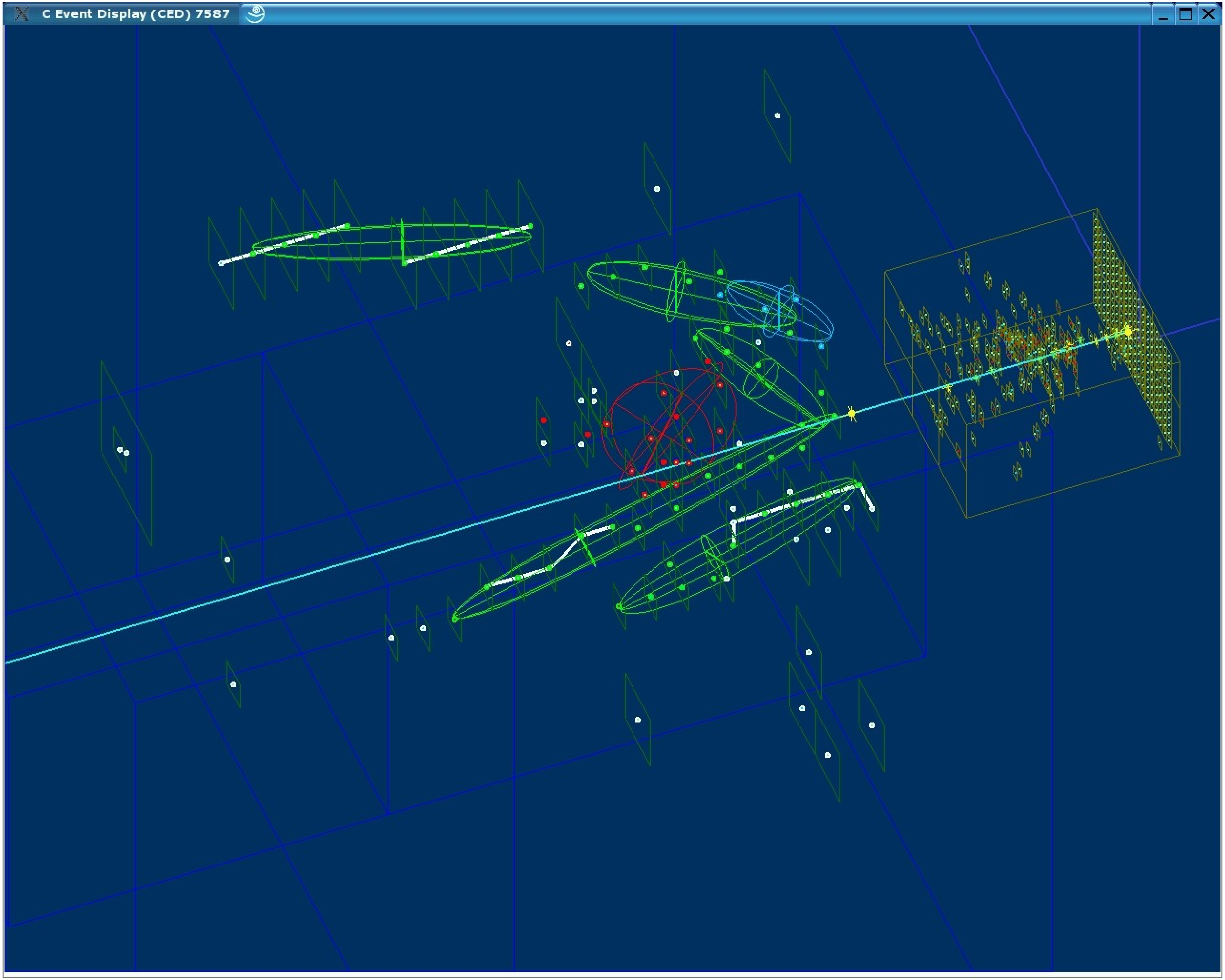


2006 Test Beams



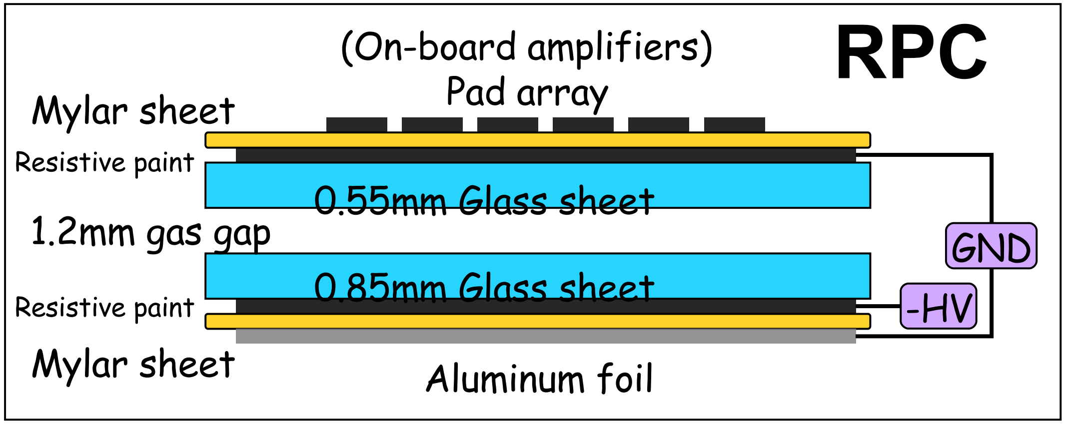

C Event Display (CED) 7587


C Event Display (CED) 7587

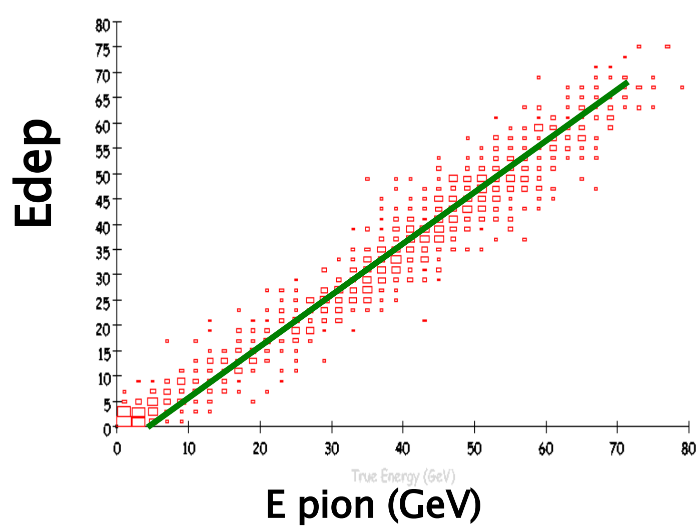

C Event Display (CED) 7587

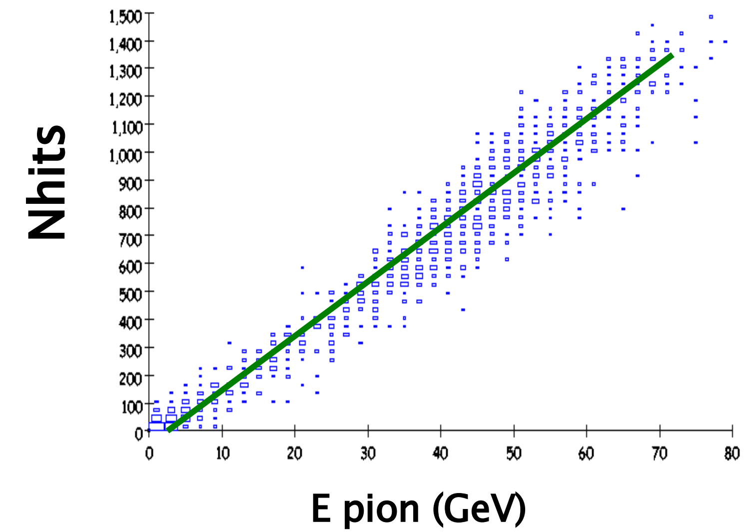
Digital Calorimetry

- Feasibility study started on digital hadronic calorimetry
- Use number of hits insted of deposited energy
  - Electronics simple per channel (just a comparator)
  - Price to pay: higher granularity
    - 1x1 cm^2
    - 40-50 sample planes
- It works on simulation



- Needed to be proved exp.
  - Construction of 1m^3 prototype
  - Test beams
- Two active groups in CALICE
  - American: 30x30x30 cm^3 prototype.
    - based on RPCs.
  - European: 1m^3 prototype to be build for 2009
    - based on gRPCs (baseline)
    - Micromegas readout also investigated

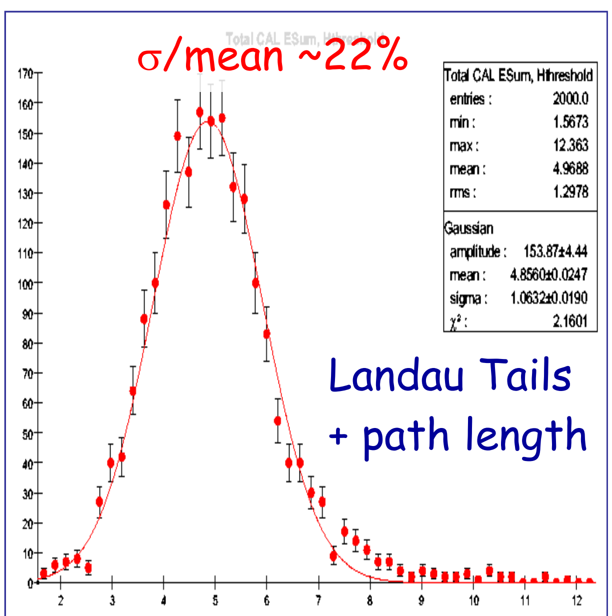




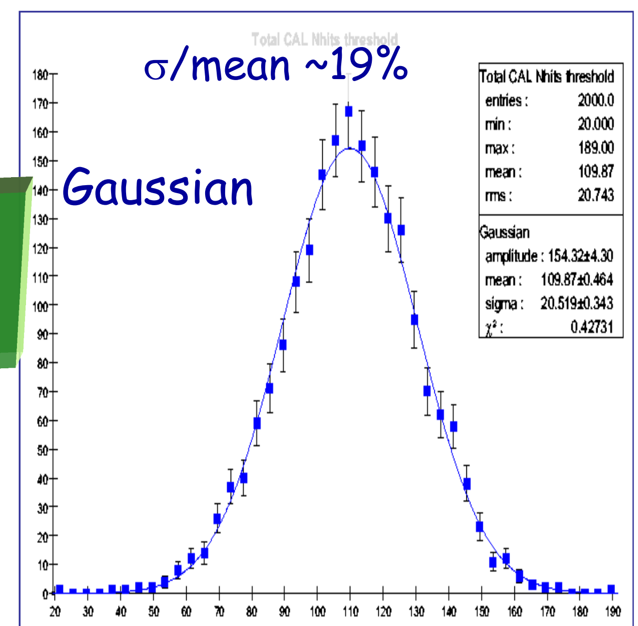
Analog

Digital

π^+ 5GeV



E (GeV)



Number of Hits