Lectures on Phenomenology

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Lecture 1:

- The Higgs boson of the electroweak Standard Model

- Brief tour of collider physics

- Higgs search at present and future colliders

- Quark mixing and $\mathcal{CP}$-violation

Further reading

Standard Model phenomenology:

- D.H. Perkins
  Introduction to High Energy Physics (Addison-Wesley, 2000)

- M. Böhm, A. Denner and H. Joos
  Gauge theories of the strong and electroweak interaction (Teubner, 2001)

- D. Bardin and G. Passarino
  The Standard Model in the Making : Precision Study of the Electroweak Interactions (Oxford University Press, 1999)

Higgs physics:

- J.F. Gunion, H.E. Haber, G. Kane, S. Dawson
  The Higgs Hunter's Guide (Perseus Books, 2000)

Supersymmetry:

- JMR's lecture

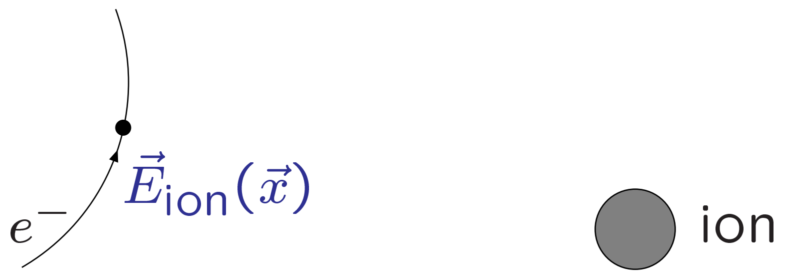
- S.P. Martin
  A Supersymmetry Primer (In: Perspectives on Supersymmetry, ed. G. Kane, World Sci., 1998)

The Standard Model (SM) of the electroweak and strong interactions

Standard Model: quantum field theory

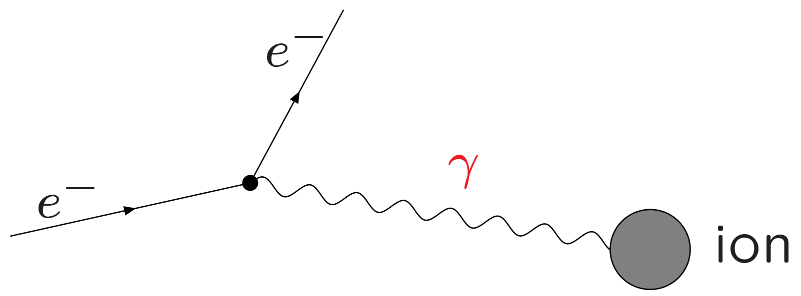
Classical field theory:

Classical Electrodynamics (Maxwell theory, unification of electrostatics and magnetism)



Quantum field theory:

QED; field is quantized, field quantum: photon



Interaction: exchange of field quanta

Electroweak interaction:

Fermion fields:

$$\text{quarks: } \begin{pmatrix} u_L \\ d_L \end{pmatrix}, u_R, d_R, \quad \text{leptons: } \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}, e_R$$

3 generations:

$$\begin{array}{lll} u, d, & s, c & t, b \\ \nu_e, e & \nu_\mu, \mu & \nu_\tau, \tau \end{array}$$

gauge bosons: γ, Z, W^+, W^-

Gauge group: $\mathrm{SU}(2)_\mathrm{I} \times \mathrm{U}(1)_\mathrm{Y} \supset \mathrm{U}(1)_\mathrm{em}$

Strong interaction: QCD

quarks: q_r, q_g, q_b

gauge bosons: $g_1, \ldots g_8$: gluons, $\mathrm{SU}(3)_\mathrm{C}$

All postulated fermions and gauge bosons experimentally verified

Construction principle of SM: gauge invariance

Example: Quantum electrodynamics (QED)

free electron field: $\mathcal{L}_{\text{Dirac}} = i\overline{\Psi}\gamma_\mu\partial^\mu\Psi - m\overline{\Psi}\Psi$

invariant under global gauge transform.: $\Psi \to e^{i\theta}\Psi$

Requirement of local gauge invariance:

gauge field A_μ introduced, $\partial_\mu \to D_\mu = \partial_\mu - ieA_\mu$

gauge transform.: $\Psi \to e^{ie\lambda(x)}\Psi$, $A_\mu \to A_\mu + \partial_\mu\lambda(x)$

$\Rightarrow$ Lagrangian with interaction term:

$$\mathcal{L}_{\text{QED}} = \underbrace{-\frac{1}{4}F_{\mu\nu}F^{\mu\nu}}_{\text{free photon field}} + \underbrace{\overline{\Psi}(i\gamma_\mu\partial^\mu - m)\Psi}_{\text{free electron field}} + \underbrace{e\overline{\Psi}\gamma_\mu\Psi A^\mu}_{\text{interaction}}$$

invariant under local gauge transformation

mass term, $m^2 A^\mu A_\mu$: not gauge-invariant

$\Rightarrow$ A_μ: massless gauge field

Problem:

gauge fields Z, W^+, W^- are massive

explicit mass terms $\Leftrightarrow$ gauge invariance broken

$\Rightarrow$ **Higgs mechanism**

scalar field postulated, gauge-invariant
mass terms from coupling to Higgs field

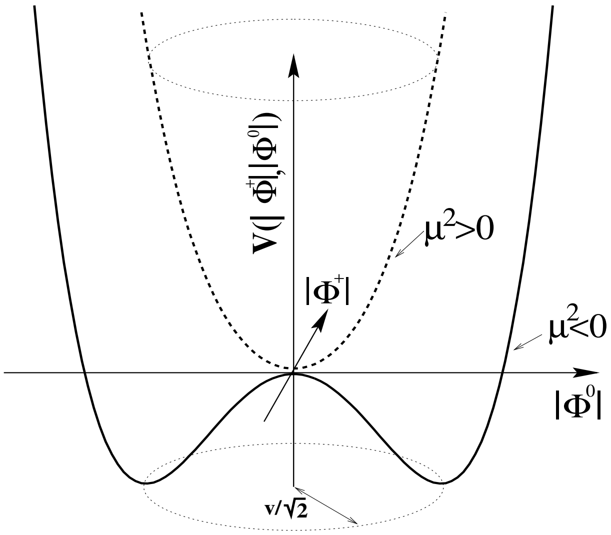
Higgs sector of the Standard Model:

$$\text{scalar SU(2) doublet:} \quad \Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

Higgs potential:

$$V(\phi) = \mu^2 \left|\Phi^\dagger \Phi\right| + \lambda \left|\Phi^\dagger \Phi\right|^2, \quad \lambda > 0$$

$\mu^2 < 0$: spontaneous symmetry breaking



minimum of the potential at $\langle \Phi \rangle = \frac{1}{\sqrt{2}}\sqrt{\frac{-\mu^2}{\lambda}} \equiv \frac{v}{\sqrt{2}}$

Gauge-invariant interaction with gauge fields:

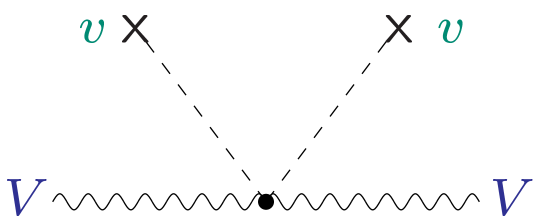
$$\mathcal{L}_{\mathsf{Higgs}} = (D_\mu \Phi)^\dagger (D^\mu \Phi) - V(\Phi)$$

$\Rightarrow$ mass terms

Unitary gauge:

$$\Phi = \begin{pmatrix} 0 \\ v + H \end{pmatrix}$$

$VV\Phi\Phi$ coupling:



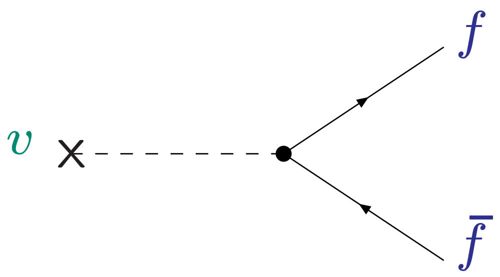
$\Rightarrow$ VV mass terms

$$\frac{1}{2} g_2^2 v^2 \equiv M_{\mathsf{W}}^2, \quad \frac{1}{2}(g_1^2 + g_2^2) v^2 \equiv M_{\mathsf{Z}}^2$$

3 components of Higgs doublet $\longrightarrow$ longitudinal components of $W^\pm$, Z

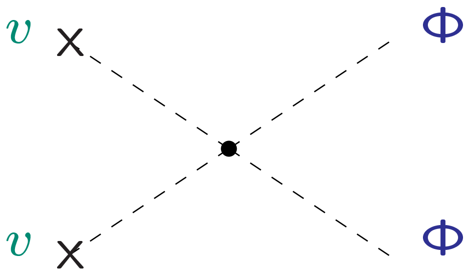
H: elementary scalar field, Higgs boson

Fermion mass terms: Yukawa couplings



$m_f = v\, g_f$ free parameters

Mass of the Higgs boson: self-interaction



$M_{\mathsf{H}} = v\sqrt{\lambda}$ free parameter

$\Rightarrow$ Higgs couplings proportional to masses of the particles

Gauge-invariant Lagrangian:

$$\mathcal{L}_{\mathrm{EW}}(\underbrace{g_2, g_1, v}_{M_{\mathrm{W}},\, M_{\mathrm{Z}},\, \alpha}, \underbrace{\lambda}_{M_{\mathrm{H}}}, \underbrace{g_f}_{m_f}) + \mathcal{L}_{\mathrm{QCD}}(\alpha_{\mathrm{s}})$$

gauge invariance $\Rightarrow$ **theory is renormalizable**

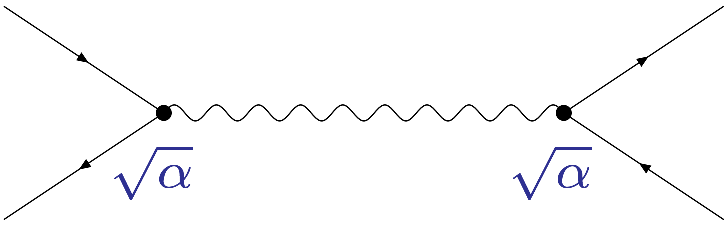
[*G. 't Hooft '71*] *Nobel price '99*

[*G. 't Hooft, M. Veltman '72*]

$\Rightarrow$ quantum field theory: quantum effects calculable

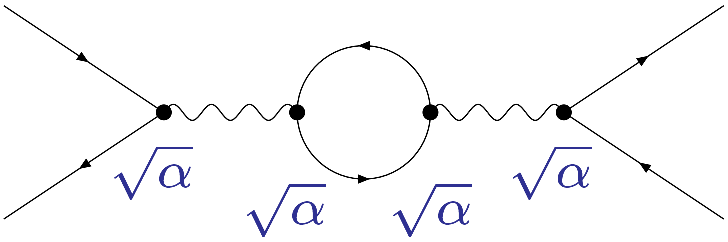
expansion in coupling constant:

lowest order, classical limit



$\alpha \approx \frac{1}{137}$

quantum corrections: loop diagrams



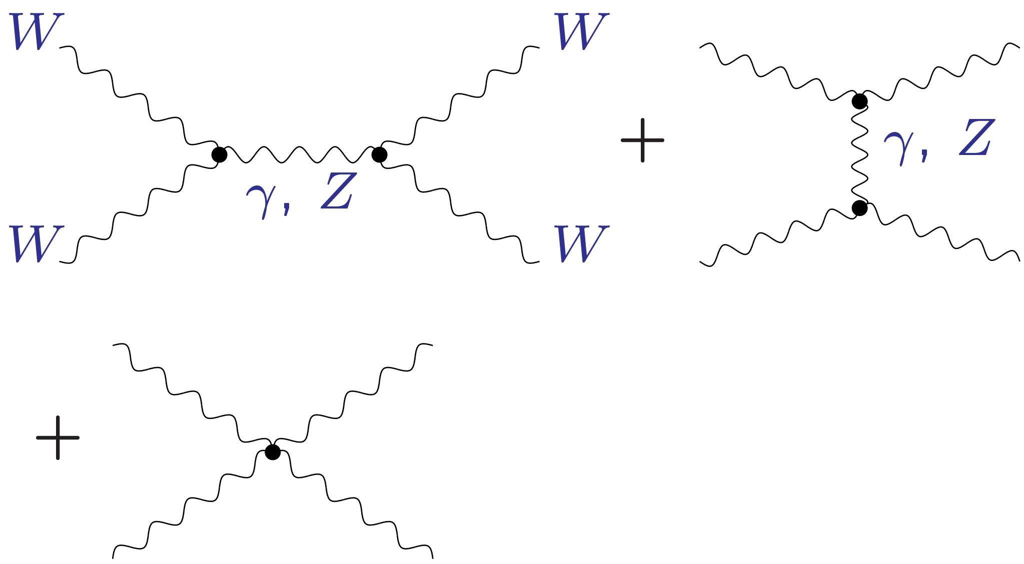
via loop corrections: all particles of the model enter

Further effect of the Higgs field:

scattering of longitudinally polarized W bosons:

$$W_L W_L \to W_L W_L$$

$\mathcal{M}_V =$

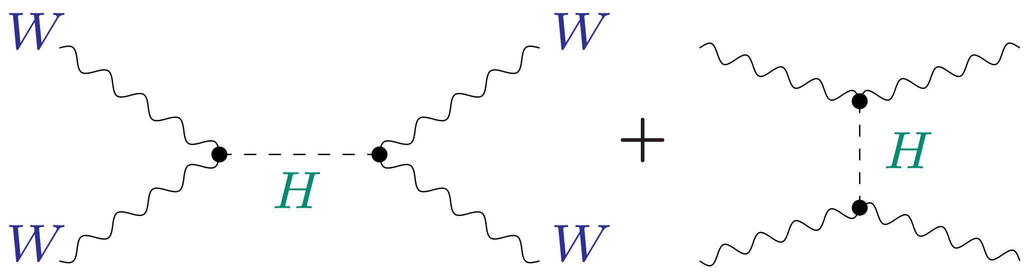


$$= -g^2 \frac{E^2}{M_\mathrm{W}^2} + \mathcal{O}(1) \qquad \text{for } E \to \infty$$

$\Rightarrow$ violation of probability conservation

Extra contribution from scalar particle:

$\mathcal{M}_S =$



$$= g_{WWH}^2 \frac{E^2}{M_\mathrm{W}^4} + \mathcal{O}(1) \qquad \text{for } E \to \infty$$

$$\mathcal{M}_\mathrm{tot} = \mathcal{M}_V + \mathcal{M}_S$$

$\Rightarrow$ terms with bad high-energy behavior cancel for

$$g_{WWH} = g\, M_\mathrm{W}$$

$\Rightarrow$ Upper limit on M_H: $M_\mathrm{H} \lesssim 1$ TeV

If no fundamental Higgs field exists:

strong interaction in gauge-boson sector for $E \gtrsim 1$ TeV

probability conservation via non-perturbative effects:

dynamical symmetry breaking, “Technicolor”, . . .
[*S. Weinberg ’79*] [*L. Susskind ’79*]

$\Rightarrow$ Higgs boson is last missing ingredient of ew SM

M_H: free parameter of SM

Theoretical arguments (unitarity, . . .): $M_H \lesssim 1$ TeV

$\Rightarrow$ Higgs search (& Higgs physics) is one of the main goals of collider physics

$\leq$ 2000:	LEP:
	e^+e^- collider, $E_{CM} \lesssim 206$ GeV
$\geq$ 2001:	Tevatron, Run II:
	$p\bar{p}$ collider, $E_{CM} \approx 2$ TeV
$\gtrsim$ 2007:	LHC:
	pp collider, $E_{CM} \approx 14$ TeV
$\gtrsim$ 2012: ?	LC:
	e^+e^- collider, $E_{CM} \approx 500$–1000 GeV

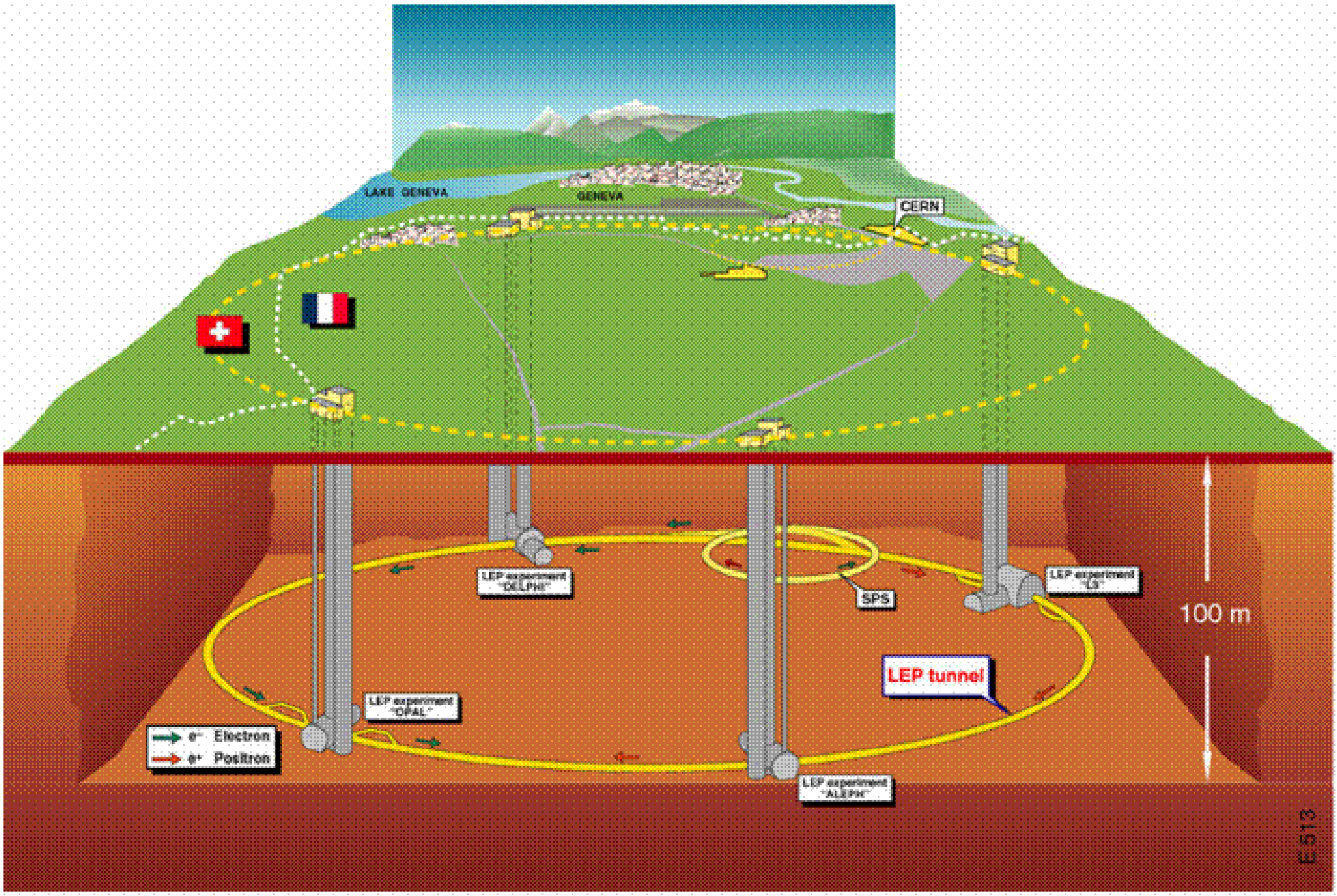
LEP: circular accelerator, ≈ 28 km long

Energy loss due to synchrotron radiation:

$$\Delta E \sim \frac{E^4}{m^4\, r}$$

$\Rightarrow$ High energy e^+e^- collider can only be realized as Linear Collider (LC)

Synchrotron radiation loss smaller for proton by factor $(m_\mathrm{e}/m_\mathrm{p}) \approx 10^{-13}$


LAKE GENEVA
GENEVA
CERN
LEP experiment "DELPHI"
SPS
LEP experiment "L3"
100 m
LEP tunnel
LEP experiment "OPAL"
e⁻ Electron
e⁺ Positron
LEP experiment "ALEPH"
E 513

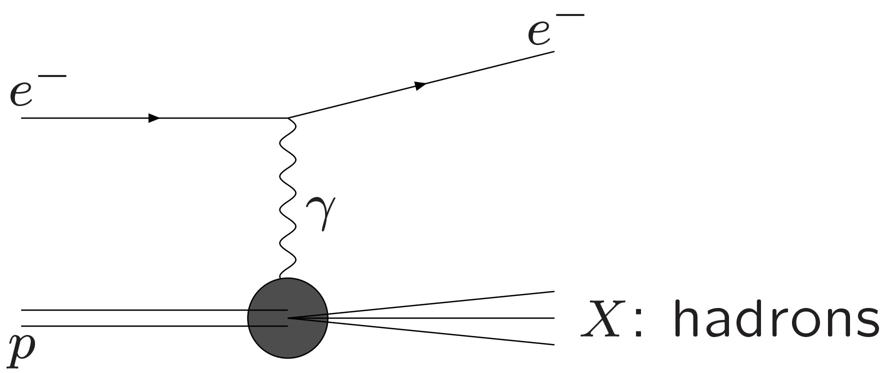
Higgs, Supersymmetry, . . . :
weakly interacting phenomena

$\Rightarrow$ e^+e^- collider provides “clean” experimental environment

hadron colliders: very large QCD backgrounds

ep collider (HERA): use e beam to probe structure of the proton

$ep \to eX$: “deep inelastic scattering”

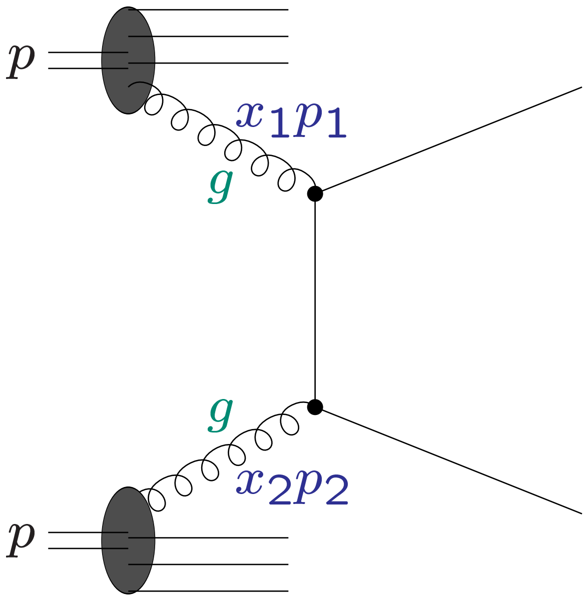


Relation between ep scattering cross section and eq “partonic” sub-process:

$$\sigma(ep) = \sum_{q,\bar{q} \text{ in proton}} \underbrace{f_{q|p}(x, Q^2)}_{\text{parton density function}} \sigma(eq)$$

Proton – proton scattering:

pp scattering contains "hard" collision process of partons q, $\bar{q}$, g, e.g.:



Available (energy)^2 for partonic sub-process:

$$\hat{s} = x_1 x_2 s$$

LHC: $\sqrt{s} = 14$ TeV; $\sqrt{\hat{s}}$ up to several TeV

most of available energy lost in beam pipe as proton remnant

Lepton collider kinematics: momentum conservation can be used to analyze decay products

Hadron collider kinematics: can in general only use conservation of transverse momentum p_T

Traces of produced particles in collider detectors:

$e^{\pm}$: charged $\Rightarrow$ leaves track in inner tracking chambers, energy deposit in calorimeter

$\mu^{\pm}$: track similar to $e^{\pm}$, but leads to signal in muon chambers

γ: calorimeter signal as for $e^{\pm}$, but no charged track

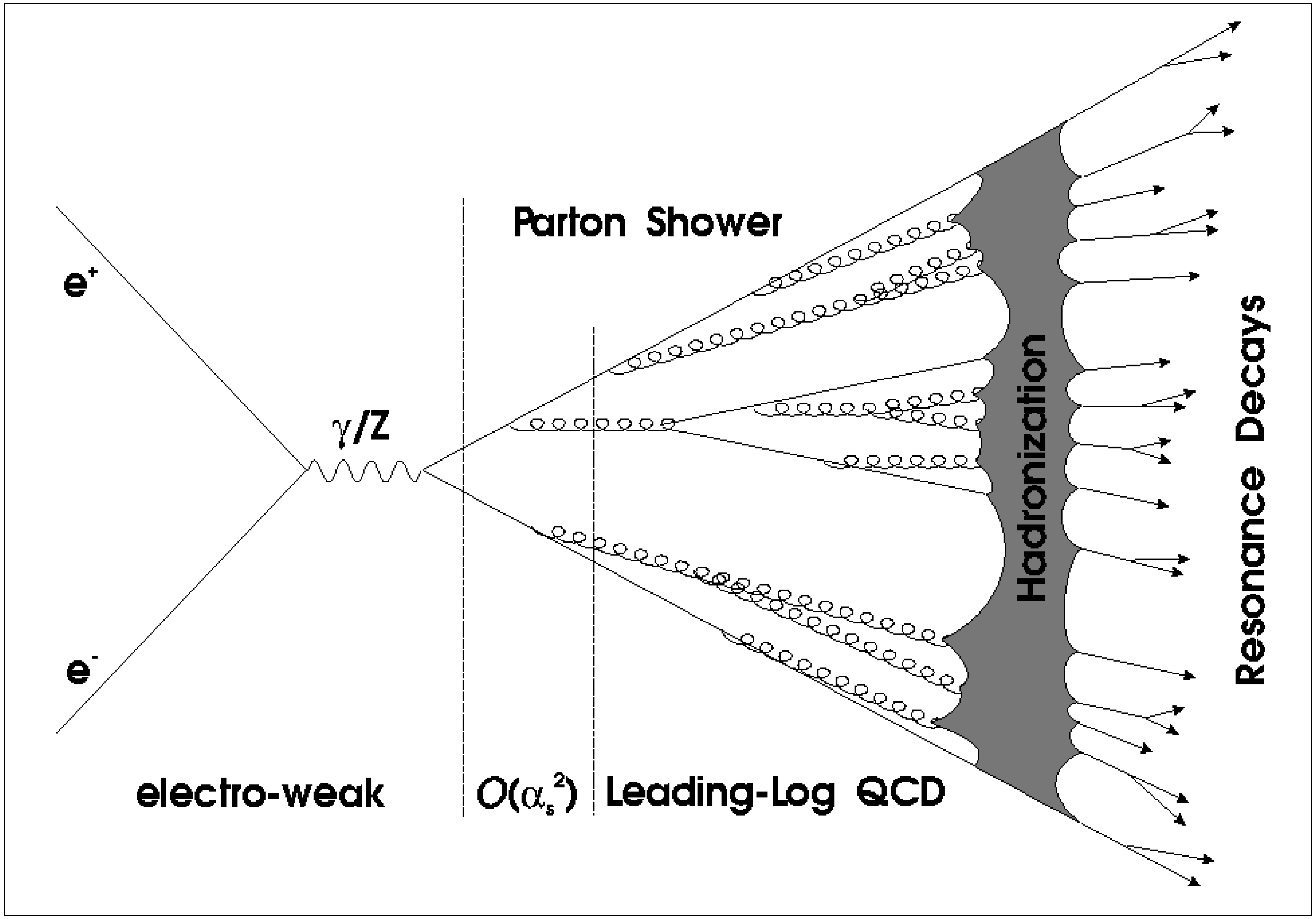
neutrinos, other weakly interacting particles: do not interact inside detector $\Rightarrow$ "missing momentum"

quarks: hadronization $\Rightarrow$ "jets"; direction of high-energetic jets related to parton momentum

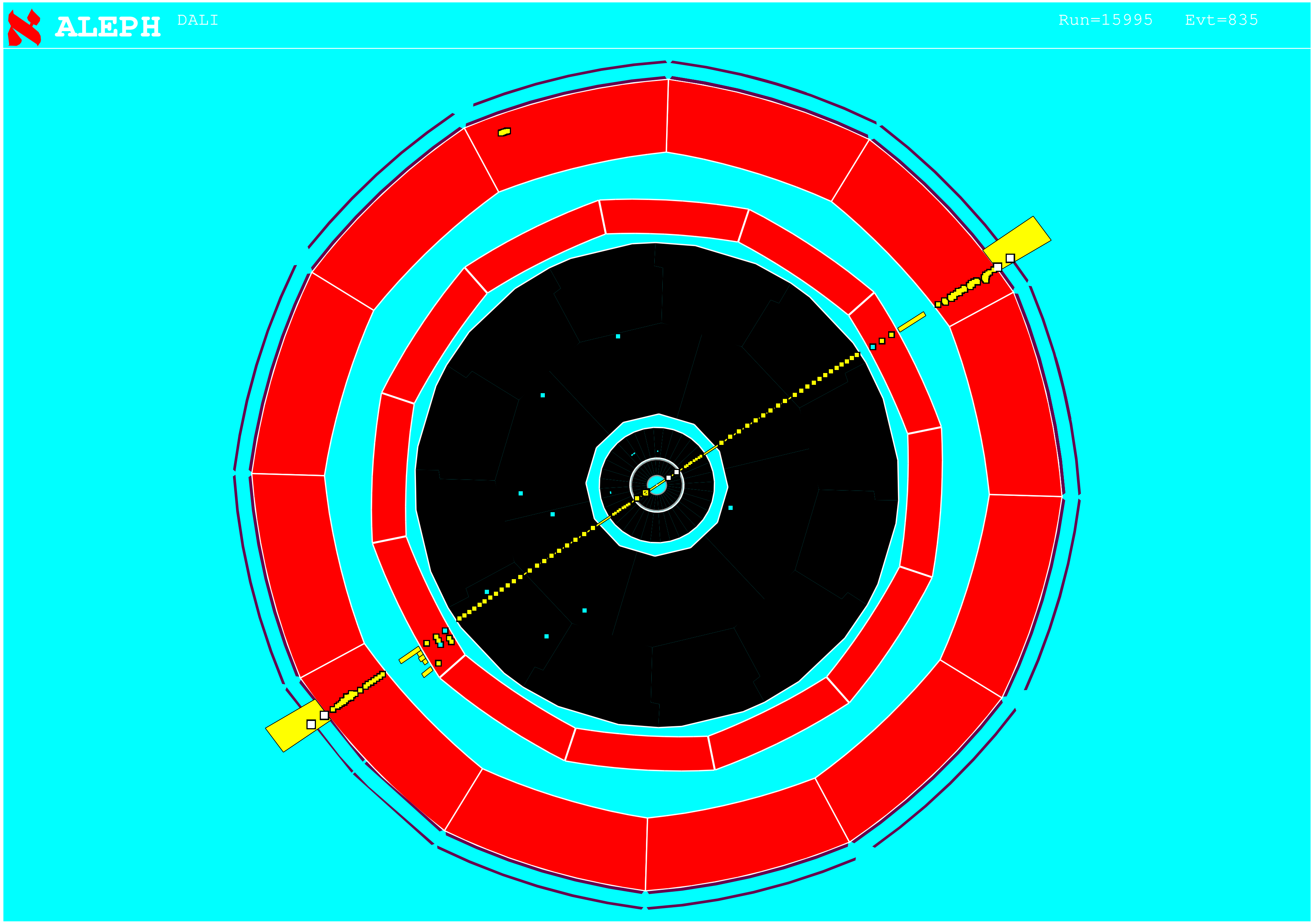
heavy quarks or leptons: reconstruction of decay vertex in micro vertex detector;
"b tagging" with displaced vertices, etc.

"Cuts" $\Rightarrow$ improve signal over background ratio

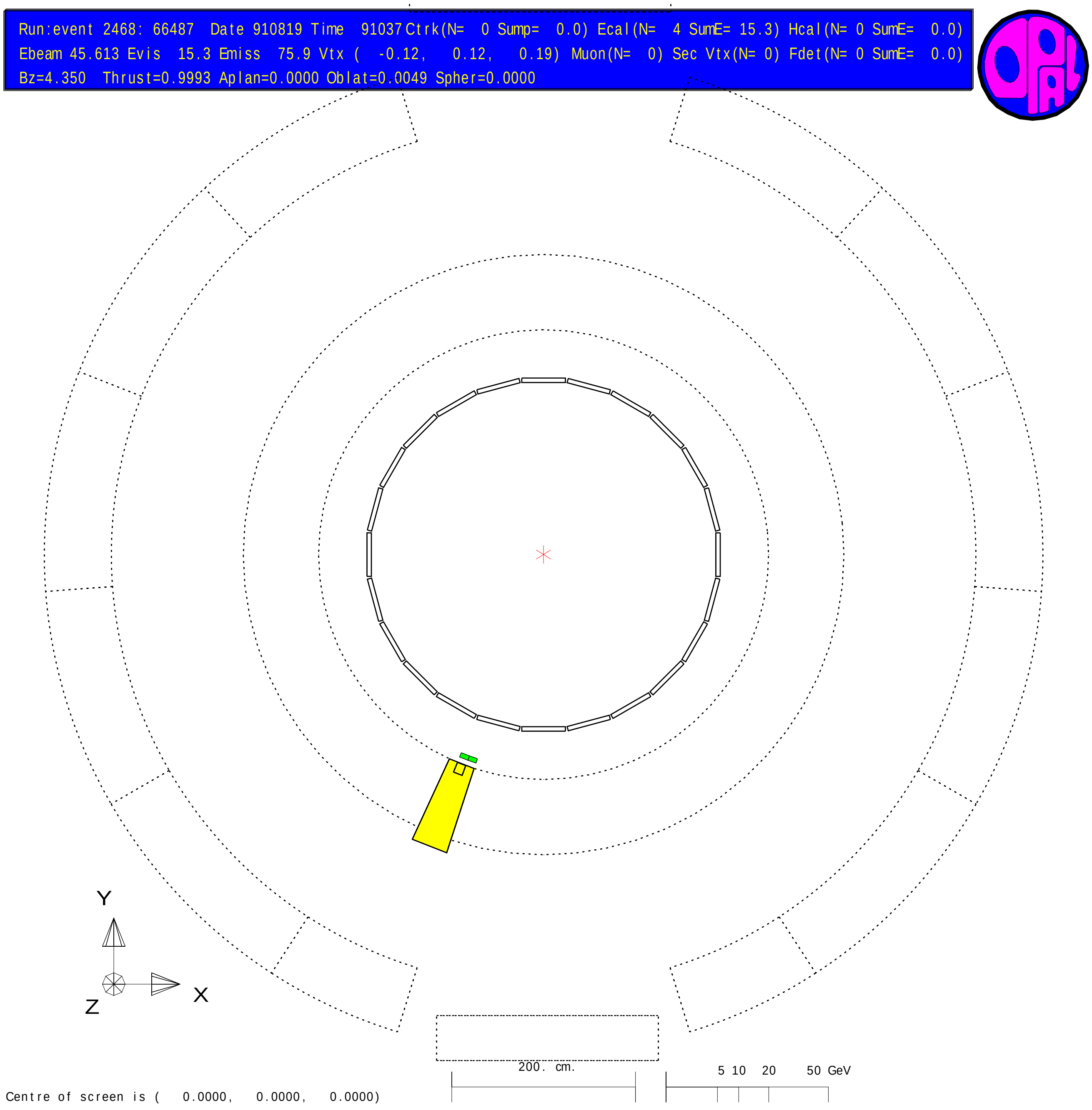
important to have good understanding of backgrounds

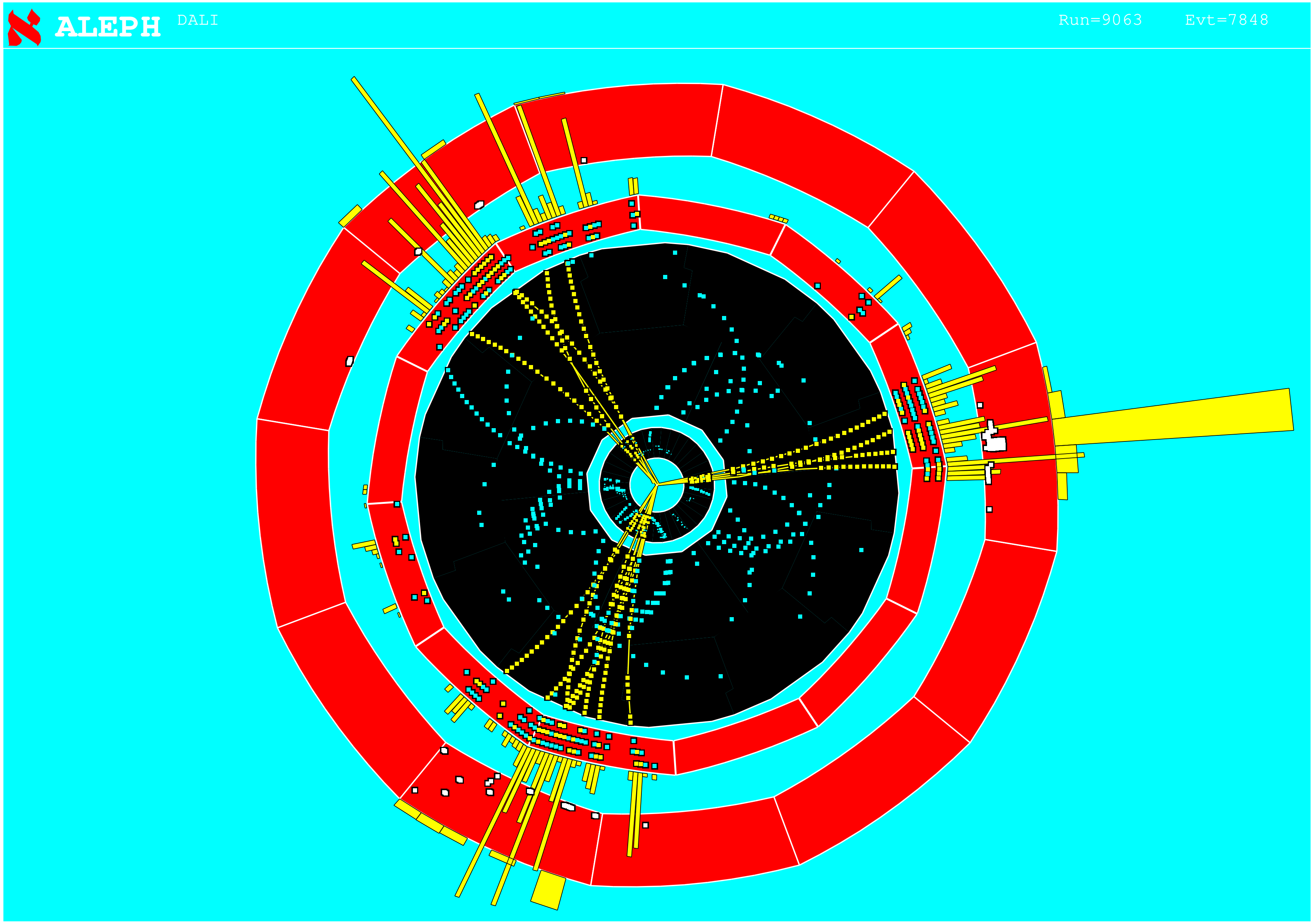


e+
e-
γ/Z
Parton Shower
Hadronization
Resonance Decays
electro-weak
$O(\alpha_s^2)$
Leading-Log QCD


ALEPH
DALI
Run=15995
Evt=835

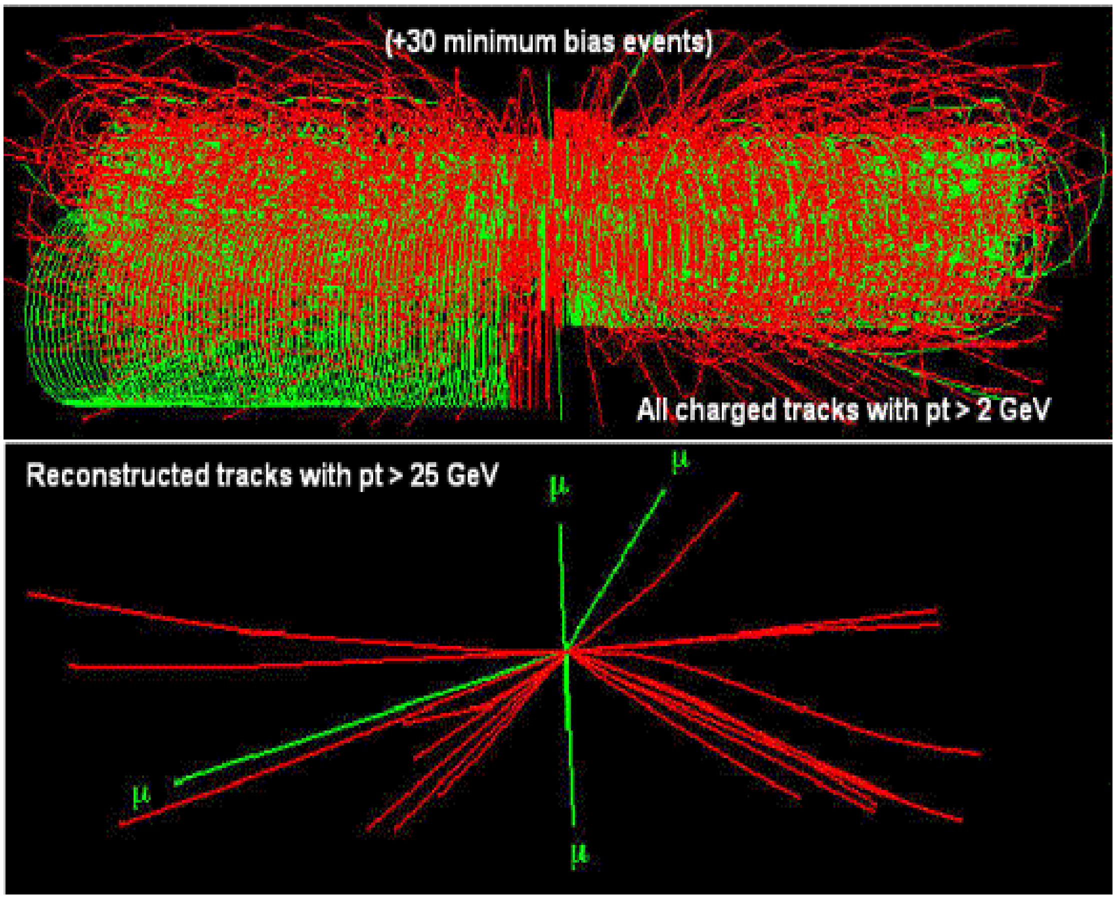
$e^+e^- \to \nu\bar{\nu}\gamma$:




ALEPH
DALI
Run=9063
Evt=7848

Simulation of an LHC event:

Computing in LHC experiments

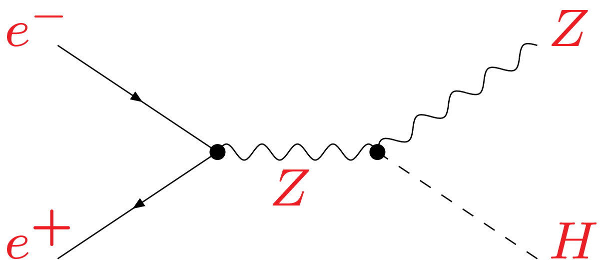


1 Higgs decay in 4 muons in 10^{13} events

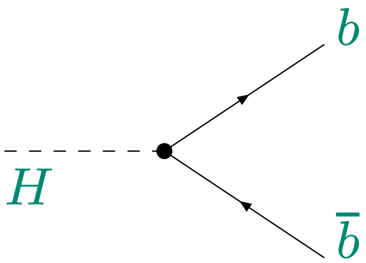
1000 charged tracks/event, most of them p<0.5 GeV

Search for the Standard Model Higgs at LEP

Dominant production process: $e^+e^- \to ZH$



Dominant decay process: $H \to b\bar{b}$



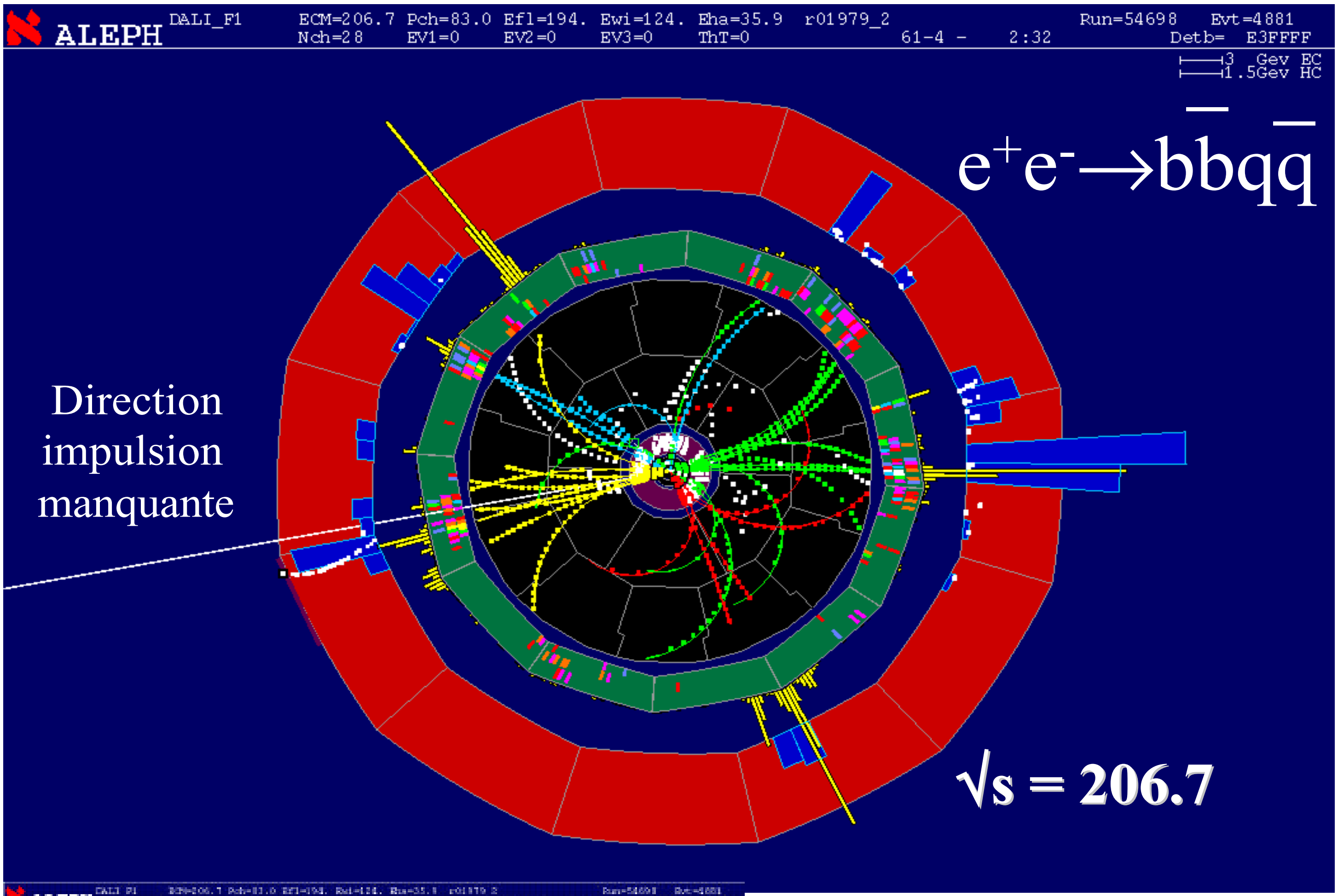
Highest energy: $E_{\mathrm{CM}} \approx 206$ GeV

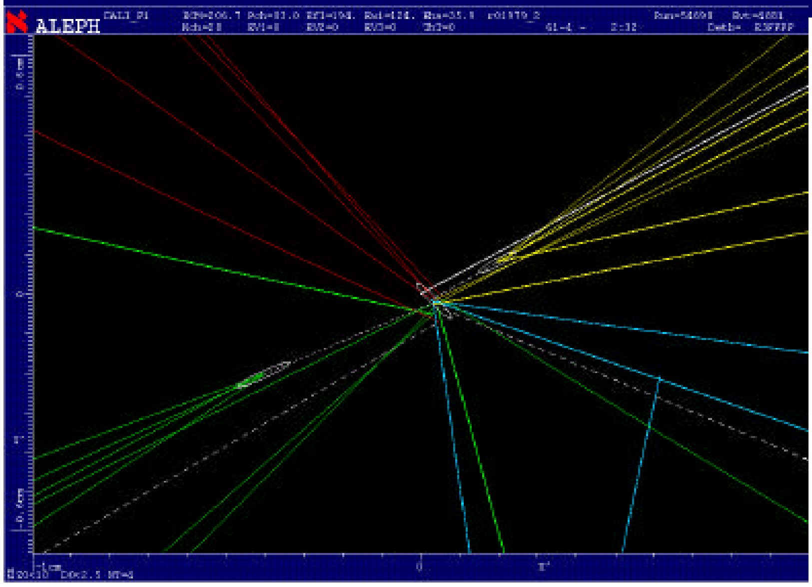
Exclusion limit, 95% C.L.:

$M_{\mathrm{H}} > 114.4\,\mathrm{GeV}$ (expected: $115.3\,\mathrm{GeV}$)

Higgs candidate event from LEP: $e^+e^- \to b\bar{b}q\bar{q}$

Candidate -d- (14/06/2000)

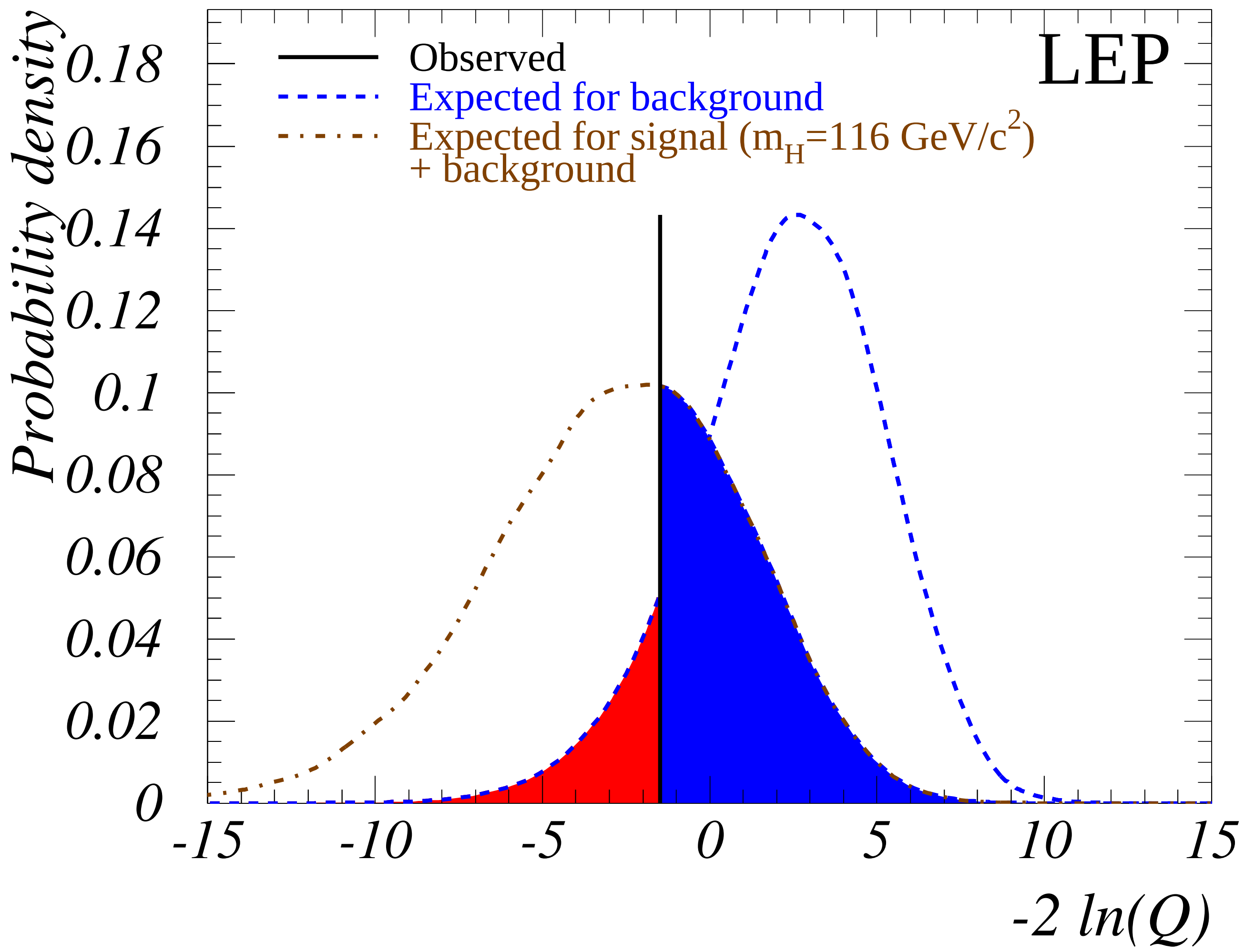




$\boxed{M_{rec}=114 \pm 3\ \mathrm{GeV}/c^2}$

Two well b-tagged jets with two reconstructed displaced vertices

Comparison of observed data with expected background and expected signal + background for $M_{\mathsf{H}} = 116$ GeV:
[*LEP Higgs Working Group '02*]



$\Rightarrow$ 1.7σ excess over background expectation

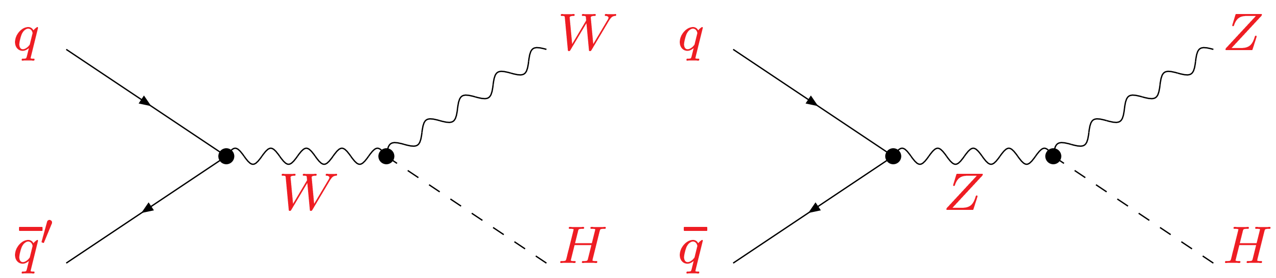
compatible with production of SM Higgs
with $M_{\mathsf{H}} \approx 116$ GeV

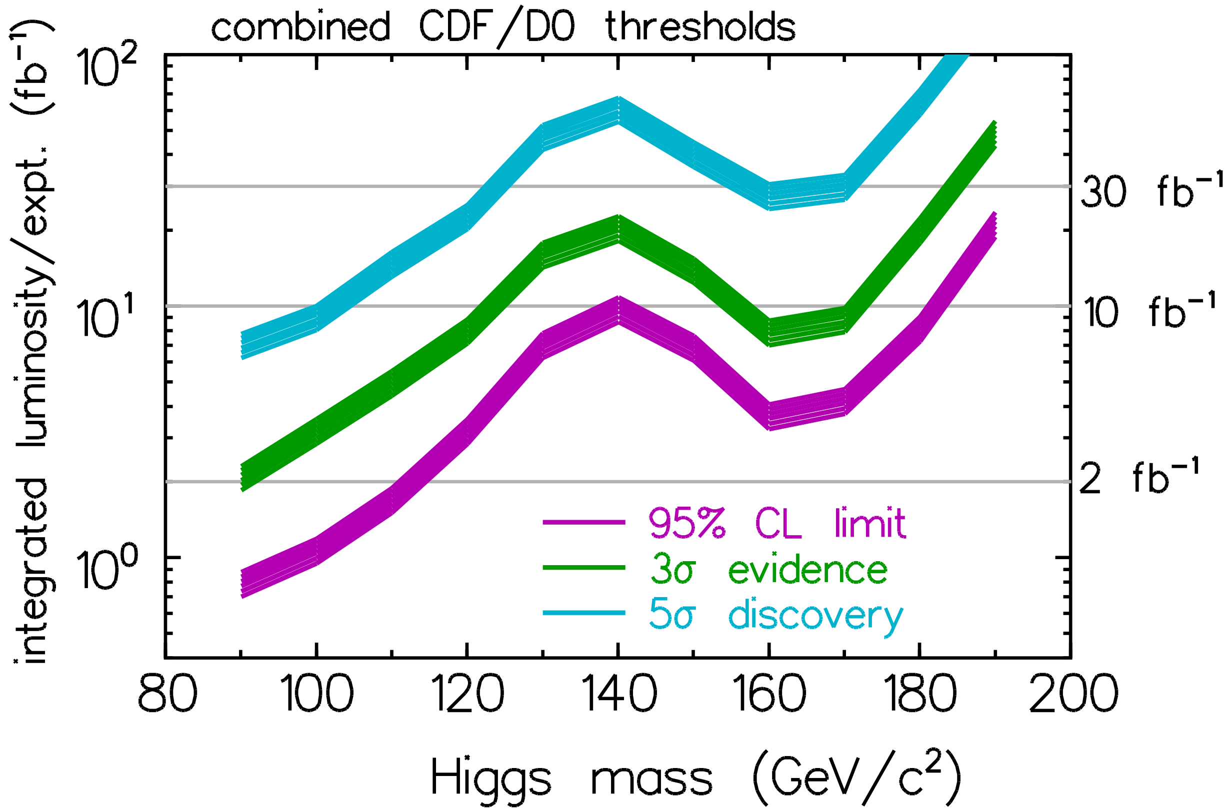
probability of background fluctuation: 8%

Search for SM Higgs at Tevatron, Run II:

$p\bar{p}$ collider with $E_{\text{CM}} \approx 2$ TeV

Dominant production processes:





For SM Higgs with $M_{\text{H}} \lesssim 120$ GeV:

$\approx$ 2004: sensitivity for 95% C.L. exclusion

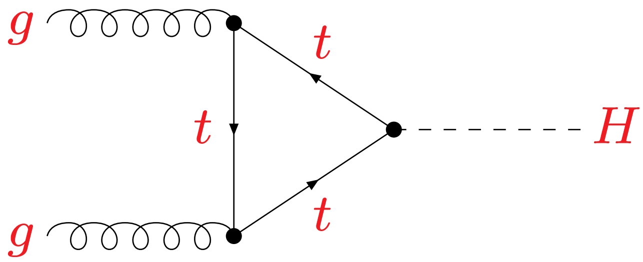
$\approx$ 2008: sensitivity for 5σ discovery

Search for the SM Higgs at the LHC:

pp collider with $E_{\text{CM}} \approx 14$ TeV

covers whole range $M_{\text{H}} \lesssim 1$ TeV

Dominant production process:



For SM Higgs:

$\approx$ 2008: sensitivity for 5σ discovery

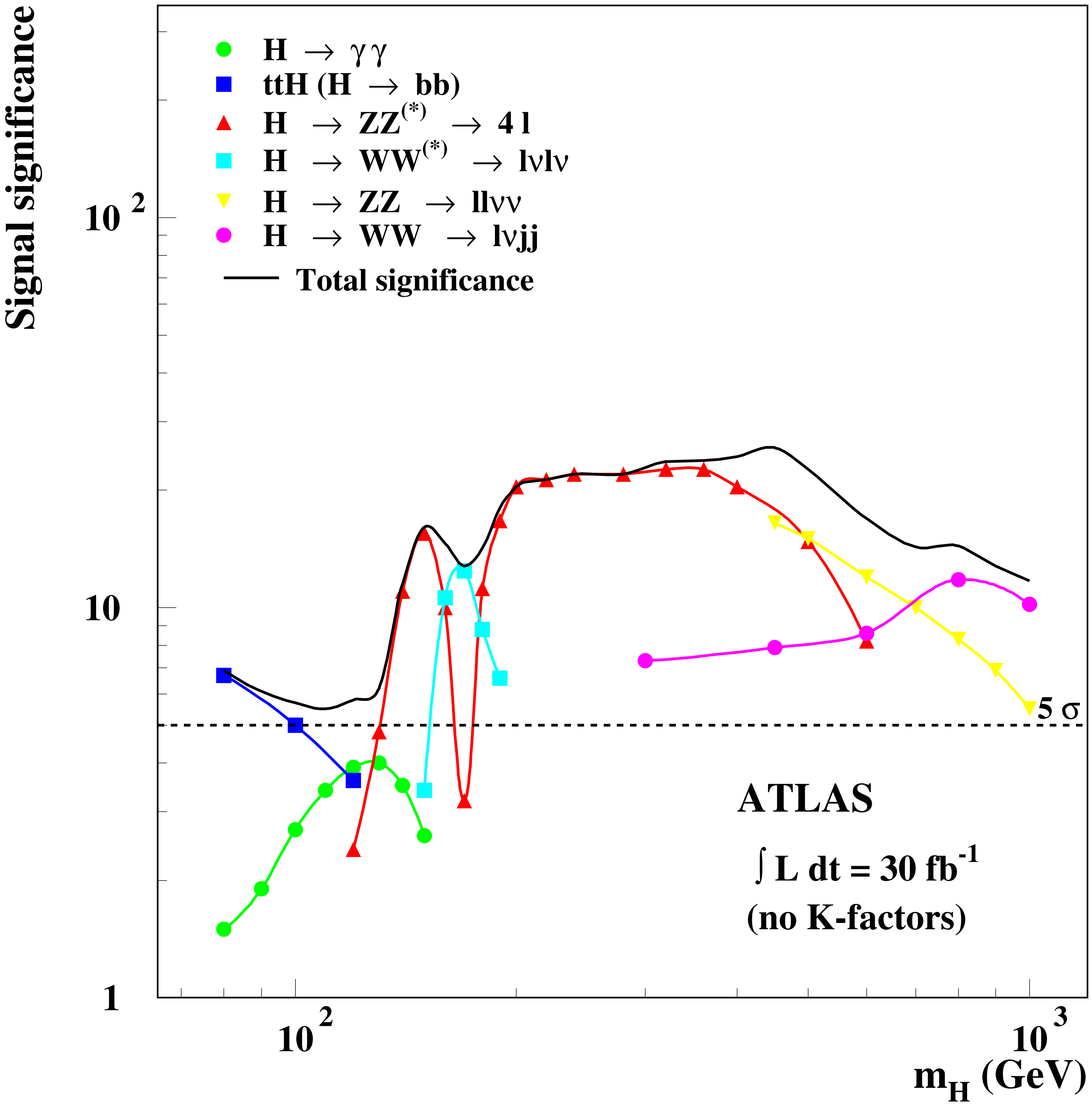
For light SM-like Higgs:

$\Rightarrow$ first precision measurement in Higgs sector:

$$\delta M_{\text{H}}^{\text{exp}} \approx 0.2 \text{ GeV}$$

Significance of signal for SM Higgs:

[*ATLAS TDR '99*]



Higgs physics at an e^+e^- LC

LC with $E_{\mathrm{CM}} \approx 500$–$1000$ GeV

Precise measurement of Higgs mass ($\approx 4 \times 10^{-4}$) and couplings, determination of Higgs spin and quantum numbers, . . .

$\Rightarrow$ Verification of Higgs mechanism

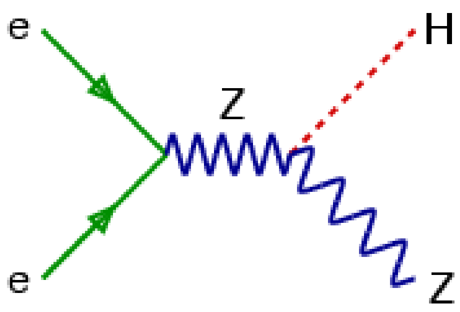
Precision measurements at

Z resonance / WW threshold (GigaZ), tt threshold:

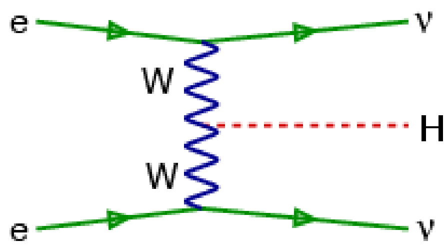
$\delta M_{\mathrm{W}} \approx 6$ MeV, $\delta \sin^2\theta_{\mathrm{eff}} \approx 1 \times 10^{-5}$, $\delta m_{\mathrm{t}} \approx 0.2$ GeV

The Profile of the Higgs Boson

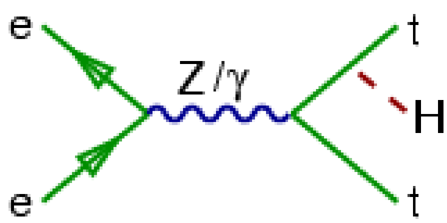
Production Processes



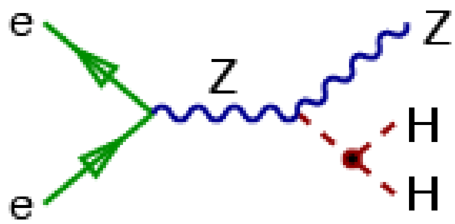
	500 fb^{-1}	500 fb^{-1}	1000 fb^{-1}
	350 GeV	500 GeV	800 GeV
m_H = 120	74000	35000	27000
m_H = 160	52000	29000	24000
m_H = 250	5500	16500	19000



	500 fb^{-1}	500 fb^{-1}	1000 fb^{-1}
	350 GeV	500 GeV	800 GeV
m_H = 120	15500	37500	158000
m_H = 160	7500	25000	126000
m_H = 250	6500	8000	71000



	500 fb^{-1}	500 fb^{-1}	1000 fb^{-1}
	350 GeV	500 GeV	800 GeV
m_H = 120	–	90	2600
m_H = 160	–	–	1500
m_H = 250	–	–	390

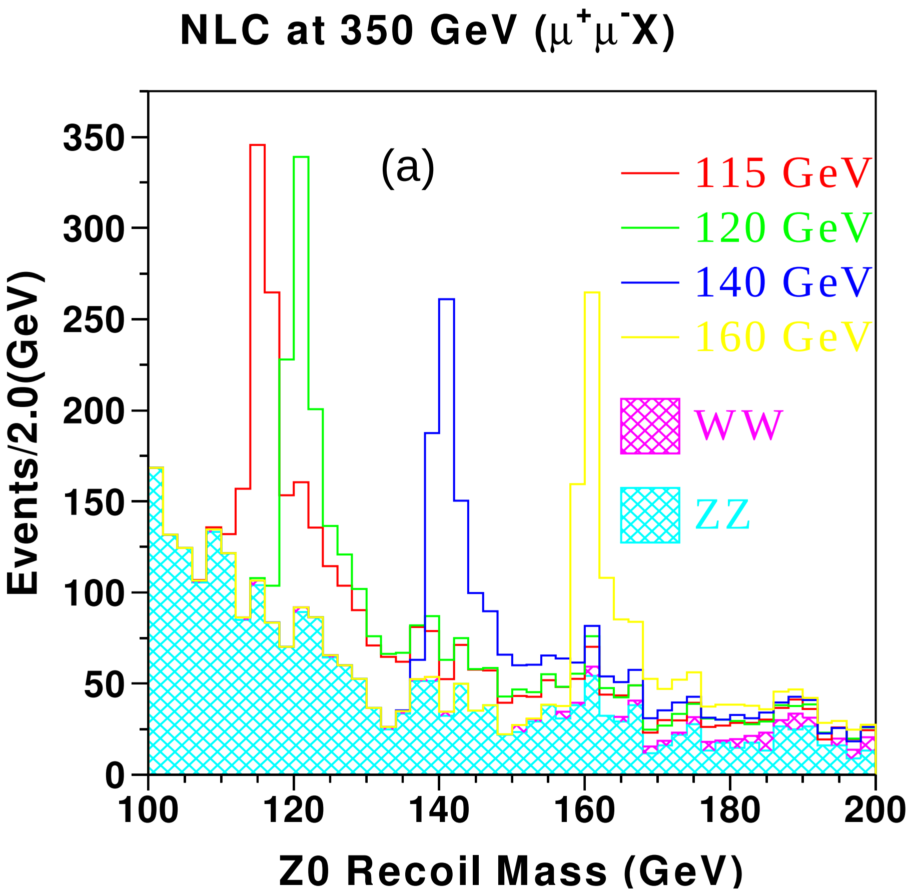


	500 fb^{-1}	500 fb^{-1}	1000 fb^{-1}
	350 GeV	500 GeV	800 GeV
m_H = 120	–	80	160
m_H = 160	–	20	120
m_H = 250	–	–	30

Observation

Gold plated channel:

$e^+e^- \to ZH$ **with** $Z \to e^+e^-, \mu^+\mu^-$



Use recoil mass against $\ell^+\ell^-$ pair:

$\Rightarrow$ **independent of Higgs decay**

$\Rightarrow$ **direct probe of Higgs coupliung to the Z**

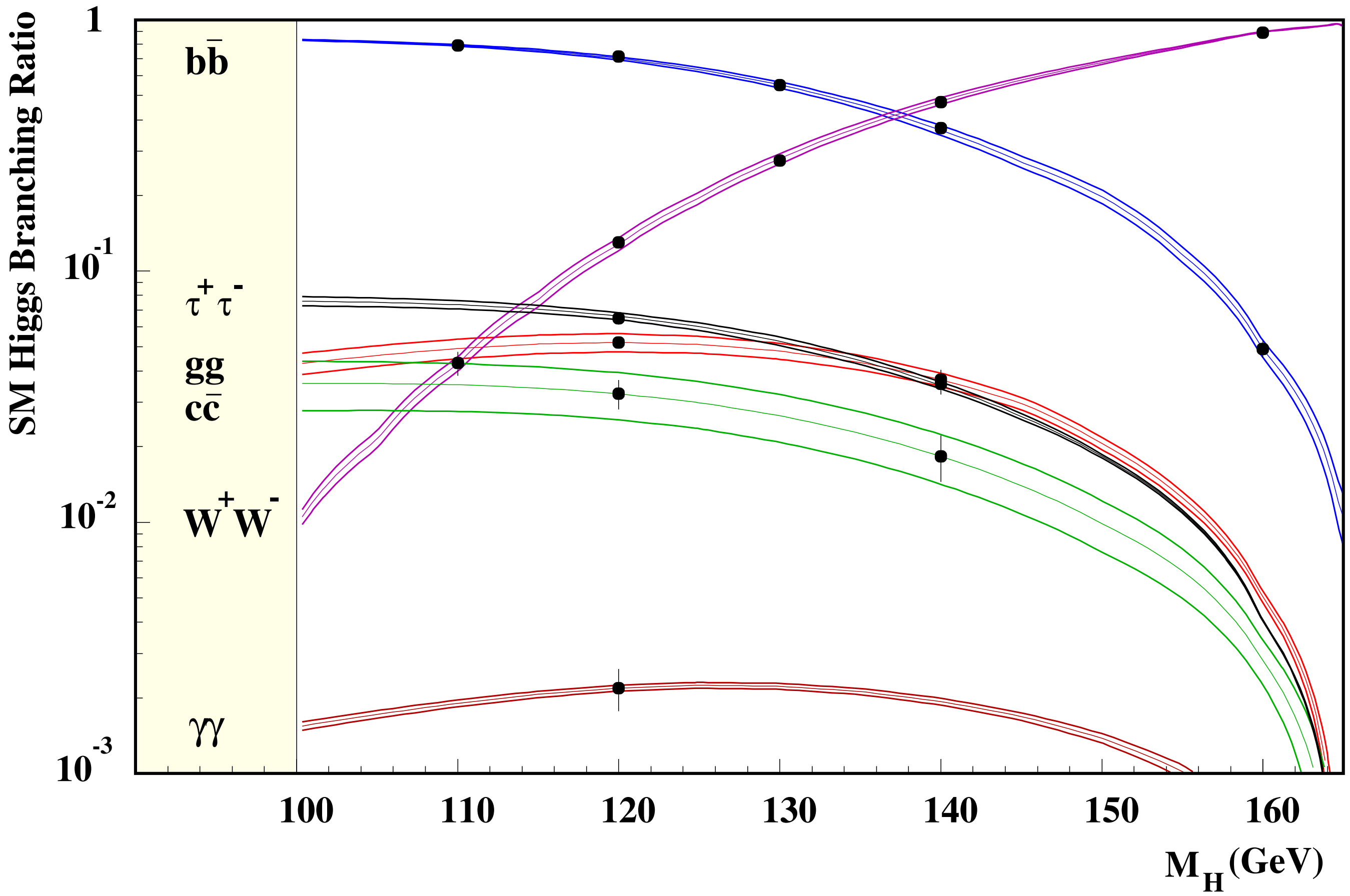
$\Delta\sigma_{HZ}/\sigma_{HZ} \approx 2\%$

(350 GeV/ 500 fb^{-1})

Very precise measurement of

Higgs mass: $\Delta M_{\mathsf{H}}/M_{\mathsf{H}} \approx 3 - 5 \times 10^{-4}$

Higgs branching ratios, $H \to f\bar{f}, VV$: % level
[*TESLA TDR '01*]



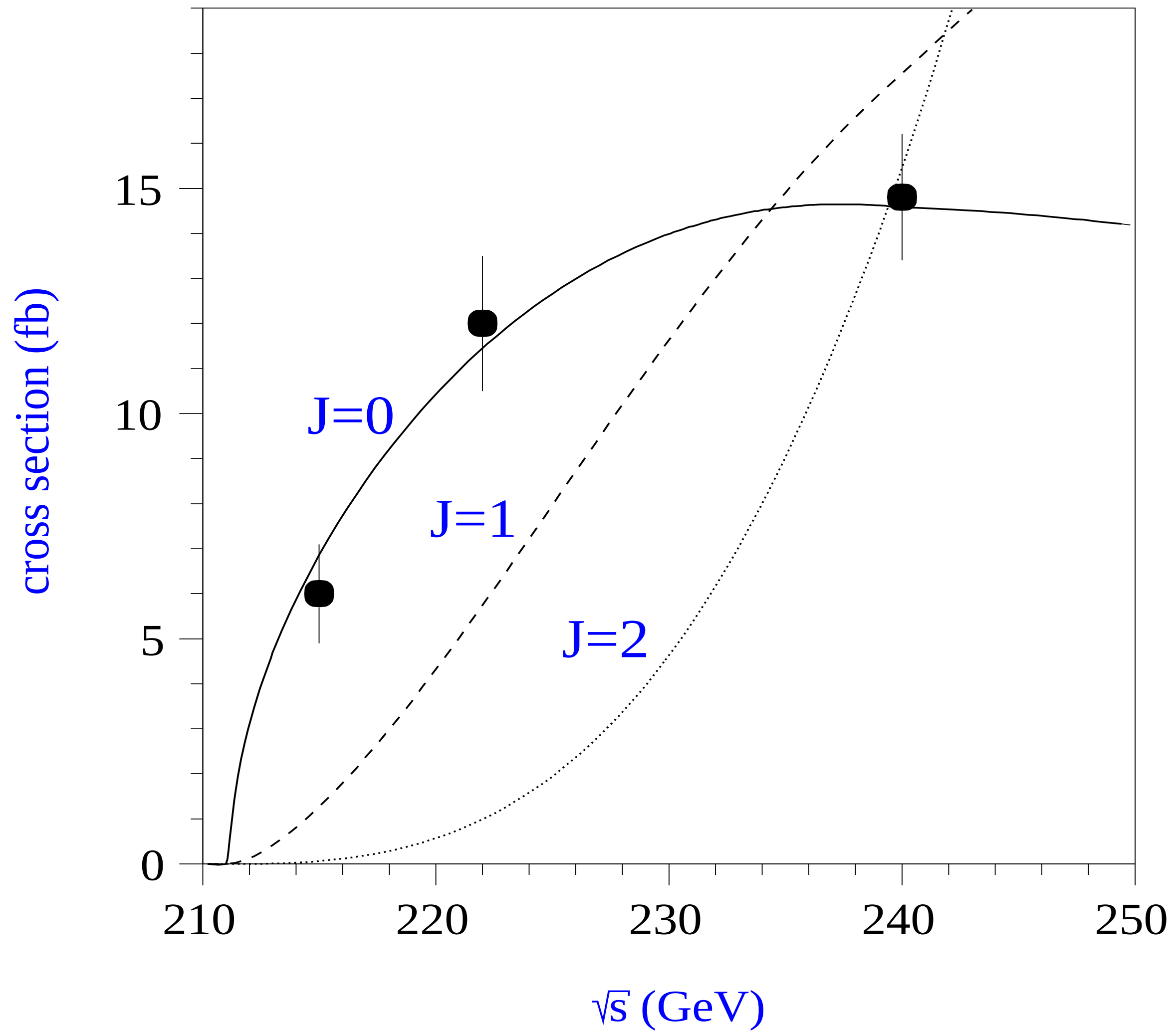
Coupling to gauge bosons: % level

Higgs width: % level

. . .

Determination of spin and $\mathcal{CP}$ quantum numbers:

Energy dependence of σ_{HZ} near threshold:
[*TESLA TDR '01*]



$\Rightarrow$ Spin

Angular distributions of fermions in $ZH \to f\bar{f}H$

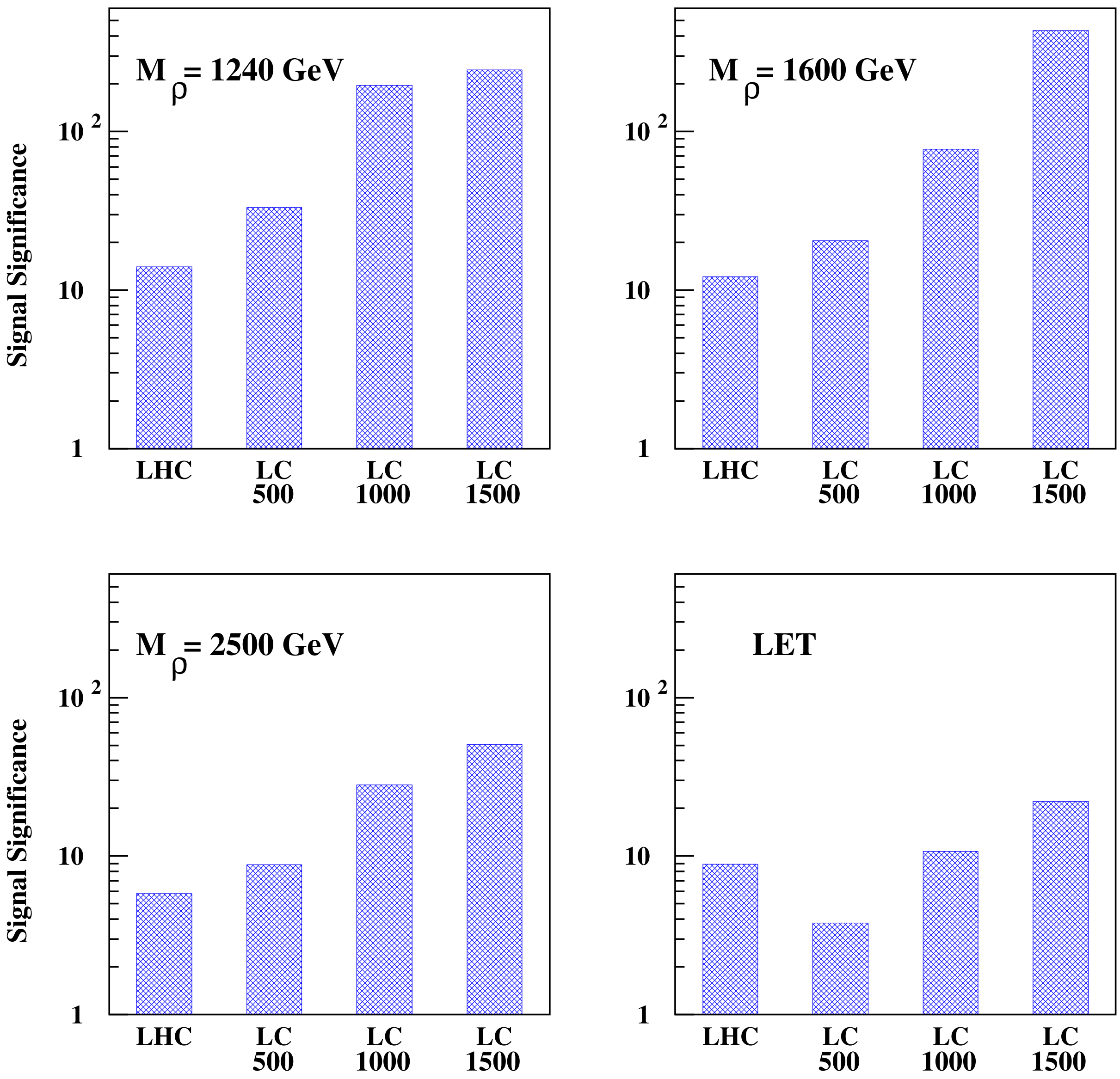
$\Rightarrow$ $\mathcal{CP}$ quantum numbers

Higgs self coupling: $\Delta\lambda_{HHH}/\lambda_{HHH} \approx 20\%$

$\Rightarrow$ Reconstruction of Higgs potential

Sensitivity of LHC and LC measurements to signals of strong electroweak symmetry breaking:

Signal significance in σ for various masses M_ρ of vector resonance in $W_L W_L$ scattering
[*American LC Working Group '01*]



⇒ Strong electroweak symmetry breaking scenarios can be probed in detail

Quark mixing and $\mathcal{CP}$-violation

The weak eigenstates (d', s', b') of quarks differ from the mass eigenstates d, s, b:

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} \equiv V_{\mathrm{CKM}} \begin{pmatrix} d \\ s \\ b \end{pmatrix}.$$

V_{CKM}: unitary transformation, Cabibbo-Kobayashi-Maskawa (CKM) matrix

GIM Mechanism:

unitarity of CKM-matrix $\Rightarrow$ no flavor changing neutral current transitions at tree level

$b \to s\gamma$, ... are loop-induced in SM $\Rightarrow$ high sensitivity to new physics effects

$V^{\dagger}_{\mathrm{CKM}} V_{\mathrm{CKM}} = 1$

$\Rightarrow$ parameterized by 3 angles $\underbrace{+\ 1\ \text{phase}}_{\text{gives rise to } \mathcal{CP}\text{-violation in SM}}$

$\Rightarrow$ weak interaction violates $\mathcal{C}$, $\mathcal{P}$ and $\mathcal{CP}$

SM: CKM phase is only source of $\mathcal{CP}$-violation

almost all models of new physics give new sources of $\mathcal{CP}$-violation

cosmology: baryogenesis ($\longrightarrow$ matter − antimatter imbalance in universe) requires further sources of $\mathcal{CP}$-violation beyond CKM phase

$\mathcal{CP}$-violation discovered in neutral kaon system (1964)

Recently ("b factories") also established in B-meson decays

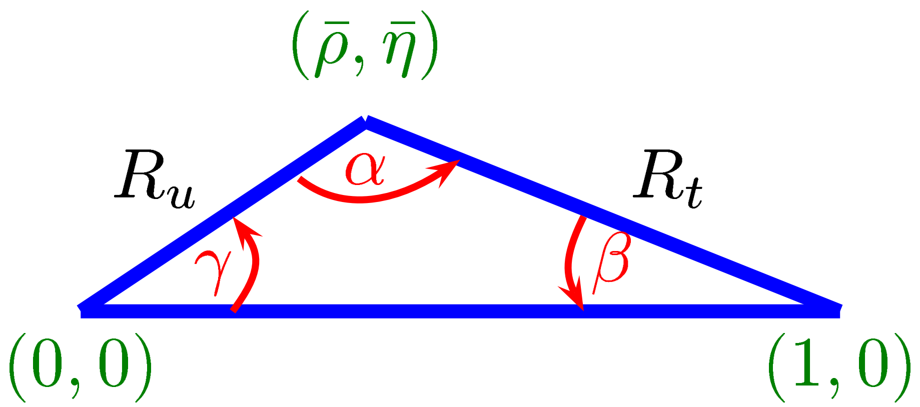
<u>Unitarity triangles:</u>

$V^{\dagger}_{\text{CKM}} V_{\text{CKM}} = 1$

$\Rightarrow V_{ud} V^*_{ub} + V_{cd} V^*_{cb} + V_{td} V^*_{tb} = 0$, etc.

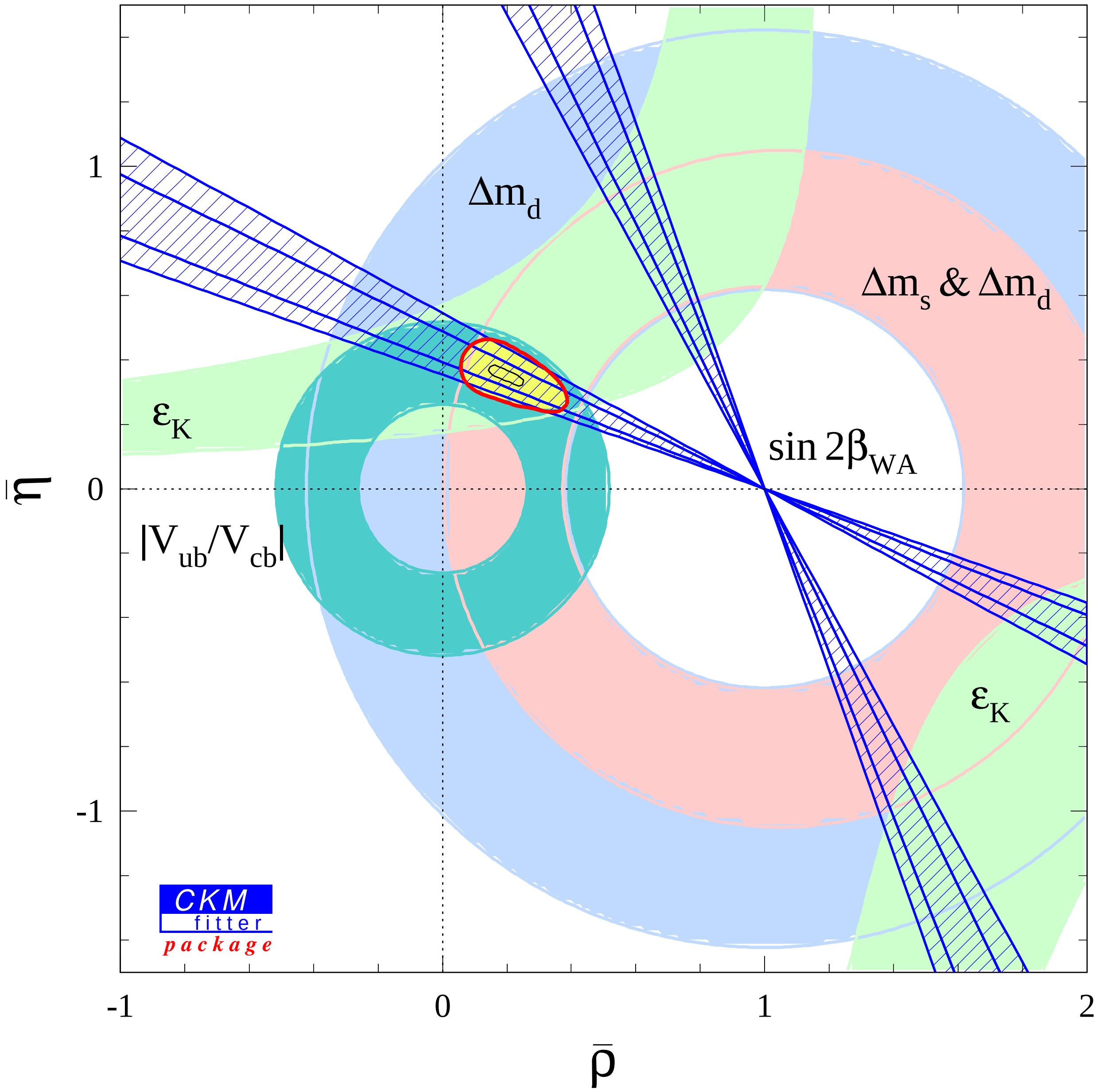
$\Rightarrow$ triangle relation in complex plane

after reparameterization:



Constraints on the parameters of the unitarity triangle from all observables ($\mathcal{CP}$-violating and $\mathcal{CP}$-conserving): [*ICHEP '02*]

$\Rightarrow$ first precision test of CKM picture



$\Rightarrow$ CKM matrix provides consistent description of all flavor and $\mathcal{CP}$-violating processes

large ($\gtrsim$ 20%) new physics contributions to $\mathcal{CP}$-violation in flavor changing processes disfavored

$\mathcal{CP}$-violation in B-meson decays:

$\mathcal{A}_{\text{CP}}(B \to \psi K_S) \Rightarrow \sin 2\beta = 0.734 \pm 0.054$
[*BaBar, Belle, CDF, ALEPH, OPAL '02*]

$\Rightarrow$ "approximate $\mathcal{CP}$" scenario (all $\mathcal{CP}$-violating phases small, $\sin \phi_i \ll 1$) disfavored

$\Rightarrow$ sensitive constraints on new physics scenarios

Lepton sector:

SM: no mixing in the lepton sector, since neutrinos in the SM are massless

Summary of Lecture 1:

- Higgs boson is last missing ingredient of the Standard Model

  $\Rightarrow$ implies gauge invariance, renormalizability, unitarity

  M_H is free parameter of the SM

  Unitarity arguments: $M_\mathrm{H} \lesssim 1$ TeV

- Search for the Standard Model Higgs at LEP

  $\Rightarrow$ $M_\mathrm{H} > 114.4$ GeV, 95% C.L.

  $\approx 2\sigma$ excess at $M_\mathrm{H} \approx 116$ GeV

- A SM-like Higgs boson will be discovered at the Tevatron or the LHC

  LC: precision physics in the Higgs sector

  LHC and LC also provide high sensitivity for probing alternative scenarios of electroweak symmetry breaking

- $\mathcal{CP}$-violation now also established in B decays

  Experimental results in agreement with CKM description

  $\Rightarrow$ Sensitive constraints on new physics scenarios