The Standard Model

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wanted

- a unified theory to explain
  - the fundamental constituents of matter
    - quarks & leptons
  - their interactions
    - gravity
    - electromagnetism
    - weak interaction
    - strong interaction

Outline

- the standard model
- experimental confirmation
- precision measurements
- does it fit?
- future prospects
- are we done?
- summary

internal symmetries

- all particles have three internal symmetries
  - U(1) invariance
    - weak hypercharge $Y=2(Q-T_3)$
    - → gauge boson B^μ - coupling = g_1
  - SU(2) invariance
    - weak isospin T_3
    - → gauge bosons W^+ W^0 W^- - coupling = g_2
  - SU(3) invariance
    - color
    - → gauge bosons $G^\mu{}_{1\ldots8}$ (gluons) - coupling = g_3

principle of local gauge invariance

- global gauge transformations
  - observables can only depend on $|\Psi|^2$
  - theory is invariant under $\Psi \rightarrow \Psi' = e^{-i\alpha}\Psi \rightarrow$ U(1)
  - Ψ and Ψ' satisfy the Schrödinger equation

$$-\frac{1}{2m}\nabla^2\Psi = i\frac{\partial\Psi}{\partial t}$$

- local gauge transformations
  - to get invariance under $\Psi(x,t) \rightarrow \Psi^{\sim}(x,t) = e^{-i\alpha(x,t)}\Psi(x,t)$
  - replace $\nabla \rightarrow \nabla + ie\vec{A} \quad \frac{\partial}{\partial t} \rightarrow \frac{\partial}{\partial t} - ieV$
- electromagnetic interaction
  - spin 1 particle → photon (gauge boson)

electroweak mixing

- neutrinos have no electromagnetic interactions
  - U(1) cannot be the electromagnetic U(1)
  - define electromagnetic field $A_\mu \propto g_2 B_\mu + g_1 W^0{}_\mu$
  - the orthogonal combination is $Z^0{}_\mu \propto -g_1 B_\mu + g_2 W^0{}_\mu$
  - or with $g_1 \propto \sin\theta_w$ and $g_2 \propto \cos\theta_w$

$$\begin{pmatrix} A_\mu \\ Z^0_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta_w & \sin\theta_w \\ -\sin\theta_w & \cos\theta_w \end{pmatrix} \begin{pmatrix} B_\mu \\ W^0_\mu \end{pmatrix}$$

$$\sqrt{4\pi\alpha} = g_e = g_1 \cos\theta_w = g_2 \sin\theta_w$$

- there must be a neutral current interaction mediated by the Z^0 boson

particle masses

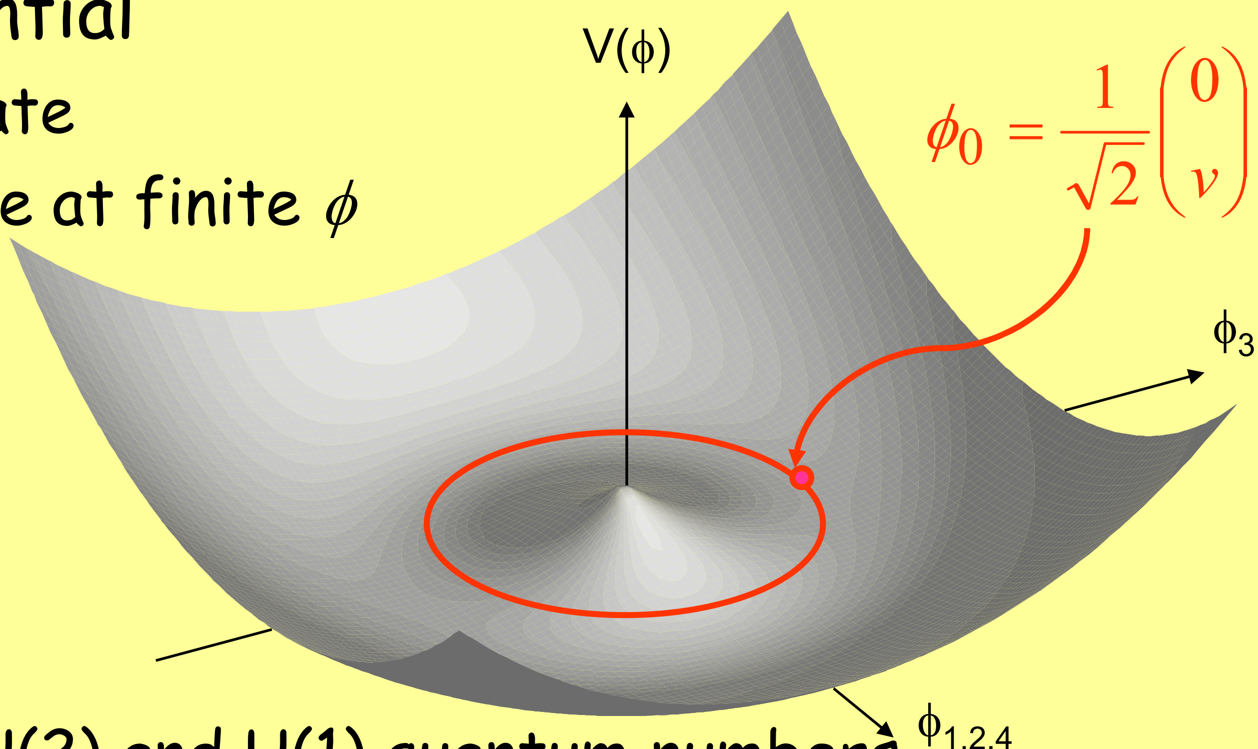
- explicit mass terms break SU(2) symmetry
- Higgs mechanism
  - add complex scalar field

$$\phi = \begin{pmatrix} \phi^{+} \\ \phi^{0} \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix}$$

  - SU(2) doublet, SU(3) singlet
- 3 components absorbed by $W^{\pm}$ and Z^{0}
- 1 physical particle → Higgs boson H^{0}
- couplings to fermions → fermion masses

spontaneous symmetry breaking

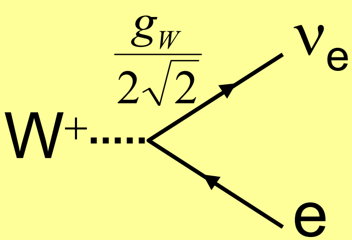
- Higgs potential
  - ground state
  - degenerate at finite ϕ

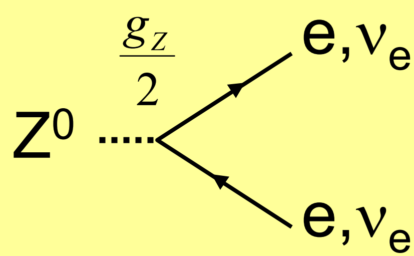


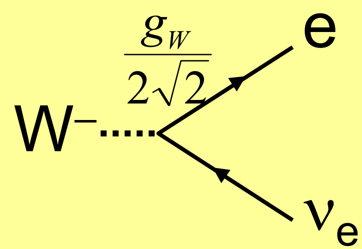
  - carries SU(2) and U(1) quantum numbers
  - SU(2) and U(1) symmetries spontaneously broken
  - invariant under $U(1)_{EM}$ → photon massless

Glashow-Weinberg-Salam model

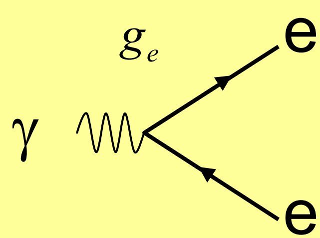
- three massive bosons: W^+, Z^0, W^-







- one massless boson: γ

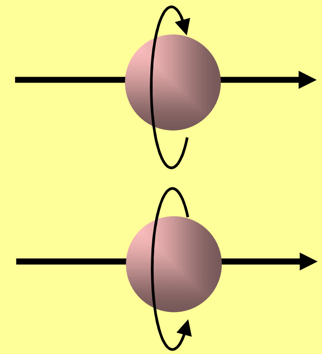


- unifies weak and electromagnetic forces

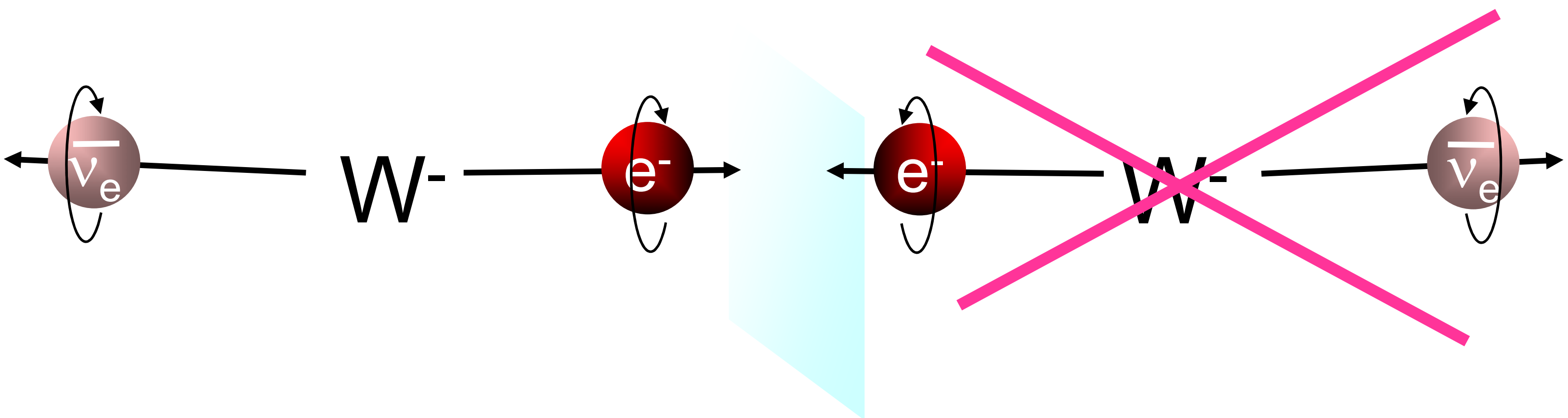
$$g_W \sin\theta_w = g_Z \sin\theta_w \cos\theta_w = g_e = \sqrt{4\pi\alpha} \qquad M_W^2 = M_Z^2 \cos^2\theta_w$$

parity violation in weak interactions

➲ handedness



⇨ W couples only to lefthanded particles



Glashow-Weinberg-Salam model

- W couples only to lefthanded fermion doublets

$$\begin{pmatrix} u \\ d \end{pmatrix}_L \begin{pmatrix} c \\ s \end{pmatrix}_L \begin{pmatrix} t \\ b \end{pmatrix}_L \quad \begin{pmatrix} e \\ \nu_e \end{pmatrix}_L \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}_L \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}_L$$

all left-handed fermions are SU(2) doublets
all right-handed fermions are SU(2) singlets

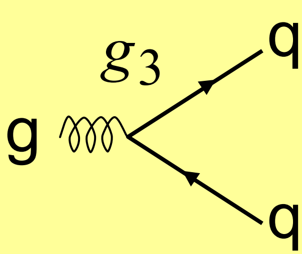
- Z couples differently to left/righthanded fermions

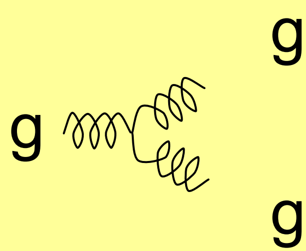
$$\begin{array}{lll} \nu & c_L = 1 & c_R = 0 \\ \ell & c_L = -1 + 2\sin^2\theta_w & c_R = 2\sin^2\theta_w \\ u & c_L = 1 - \frac{4}{3}\sin^2\theta_w & c_R = -\frac{4}{3}\sin^2\theta_w \\ d & c_L = 1 + \frac{2}{3}\sin^2\theta_w & c_R = \frac{2}{3}\sin^2\theta_w \end{array}$$

- γ couples equally to left/righthanded fermions

Quantum Chromo Dynamics

- gauge theory of the strong interactions
  - 8 massless gauge bosons (gluons)





all leptons are SU(3) singlets
all quarks are SU(3) triplets

standard model

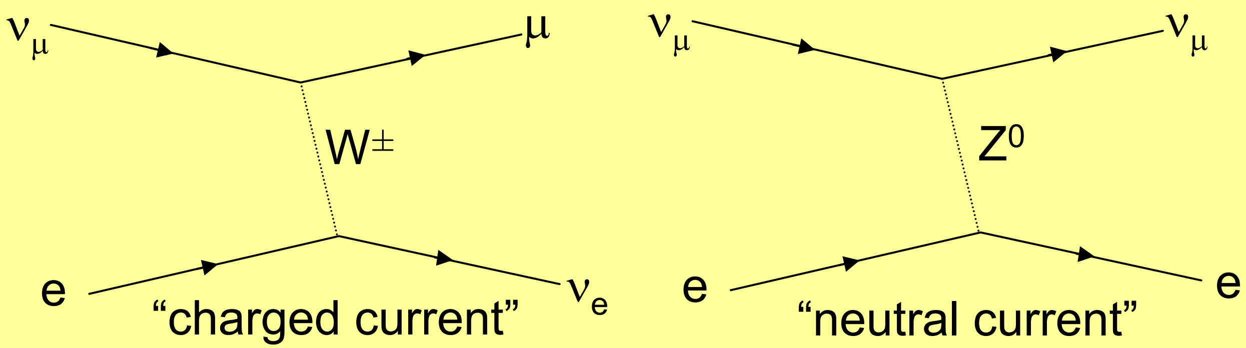
- input parameters of the standard model
  - 3 gauge couplings: $g_{U(1)}\ g_{SU(2)}\ g_{SU(3)}$
  - 1 Higgs vev: v or M_Z or M_W
  - 9 fermion masses: $m_e\ m_\mu\ m_\tau\ m_u\ m_d\ m_s\ m_c\ m_b\ m_t$
  - 4 CKM parameters: $\theta_1\ \theta_2\ \theta_3\ \delta$
  - 1 Higgs mass: M_H or λ
- 18 free parameters
- neutrino masses and mixing parameters

Outline

- the standard model
- experimental confirmation
- precision measurements
- does it fit?
- future prospects
- are we done?
- summary

experimental confirmation

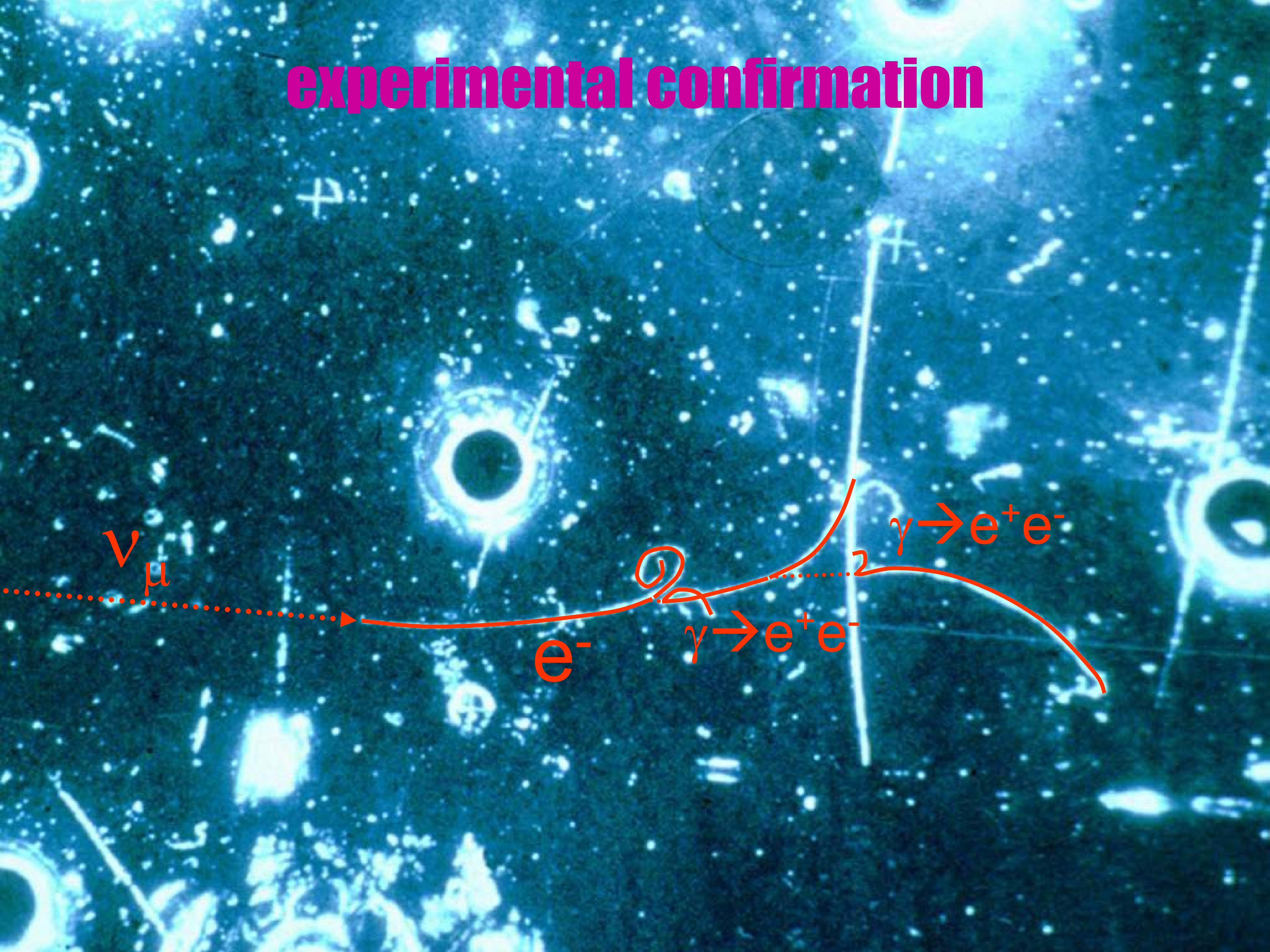
- weak neutral currents
  - observed at CERN in 1973



  - ratio of rates depends on $\dfrac{g_Z}{g_W} = \cos\theta_w$

$$\Rightarrow \sin^2\theta_w \approx 0.4$$

experimental confirmation



experimental confirmation

- vector boson masses
  - prediction

$$\left.\begin{aligned} G_F &= \frac{\sqrt{2}g_W^2}{8M_W^2} \\ g_W \sin\theta_w &= \sqrt{4\pi\alpha} \end{aligned}\right\} \Rightarrow M_W = \left(\frac{\pi\alpha}{\sqrt{2}G_F}\right)^{\frac{1}{2}} \frac{1}{\sin^2\theta_w} \approx 93\,\text{GeV}$$

  - observed at CERN in 1983

$$M_W = 80 \pm 5\,\text{GeV}$$

$$M_Z = 90 \pm 5\,\text{GeV}$$

Outline

- the standard model
- experimental confirmation
- precision measurements
  - properties of the Z boson (→ e^+e^- colliders)
  - properties of the W boson (→ $p\bar{p}$ colliders)
  - the top quark
  - neutrino couplings (→ fixed target experiment)
- does it fit?
- future prospects
- are we done?
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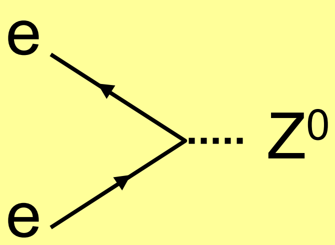
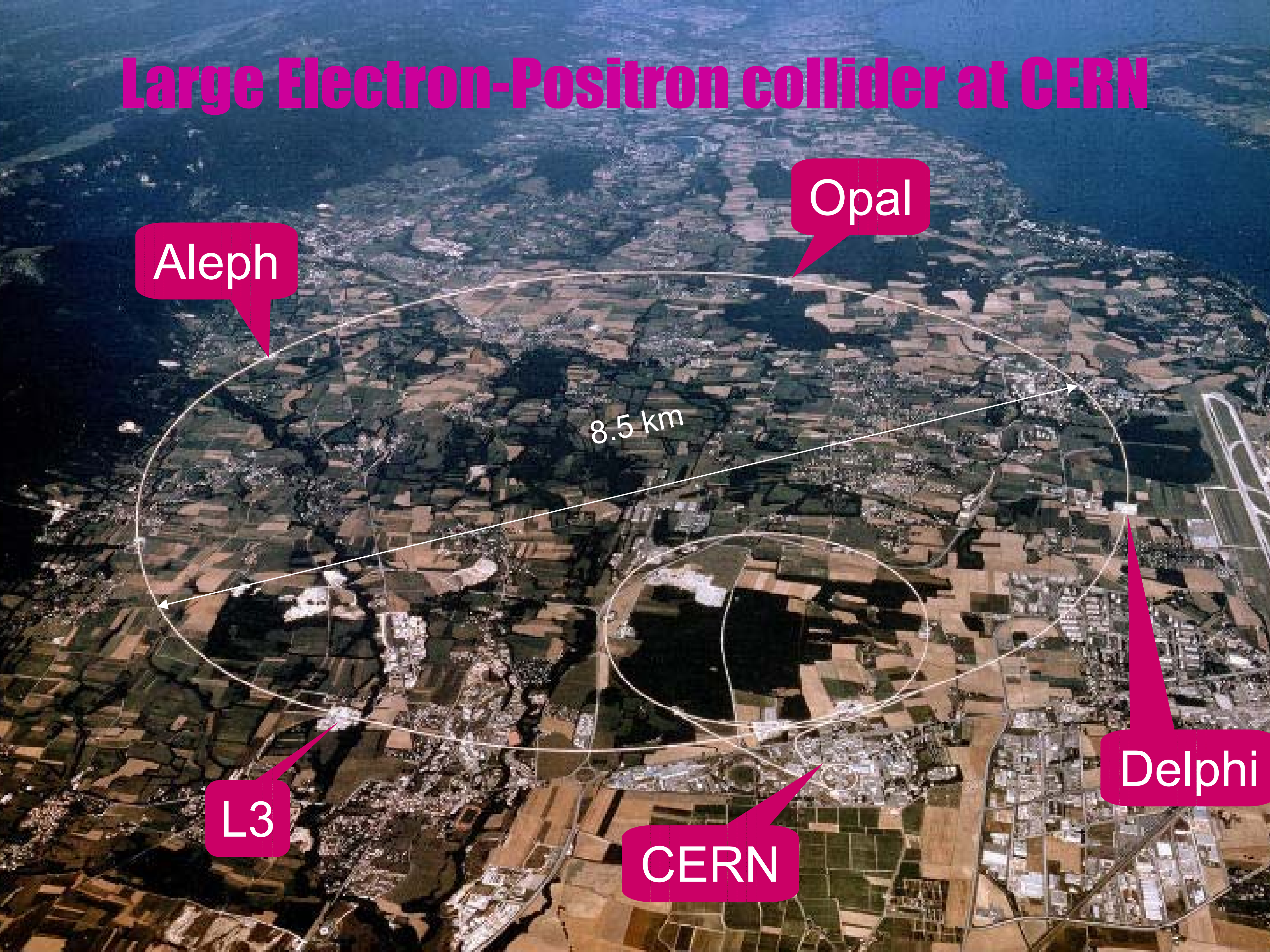
LEP/SLD

- colliding e^+ and e^- beams
- beam energy $\approx$ 46 GeV
- produce Z^0 bosons

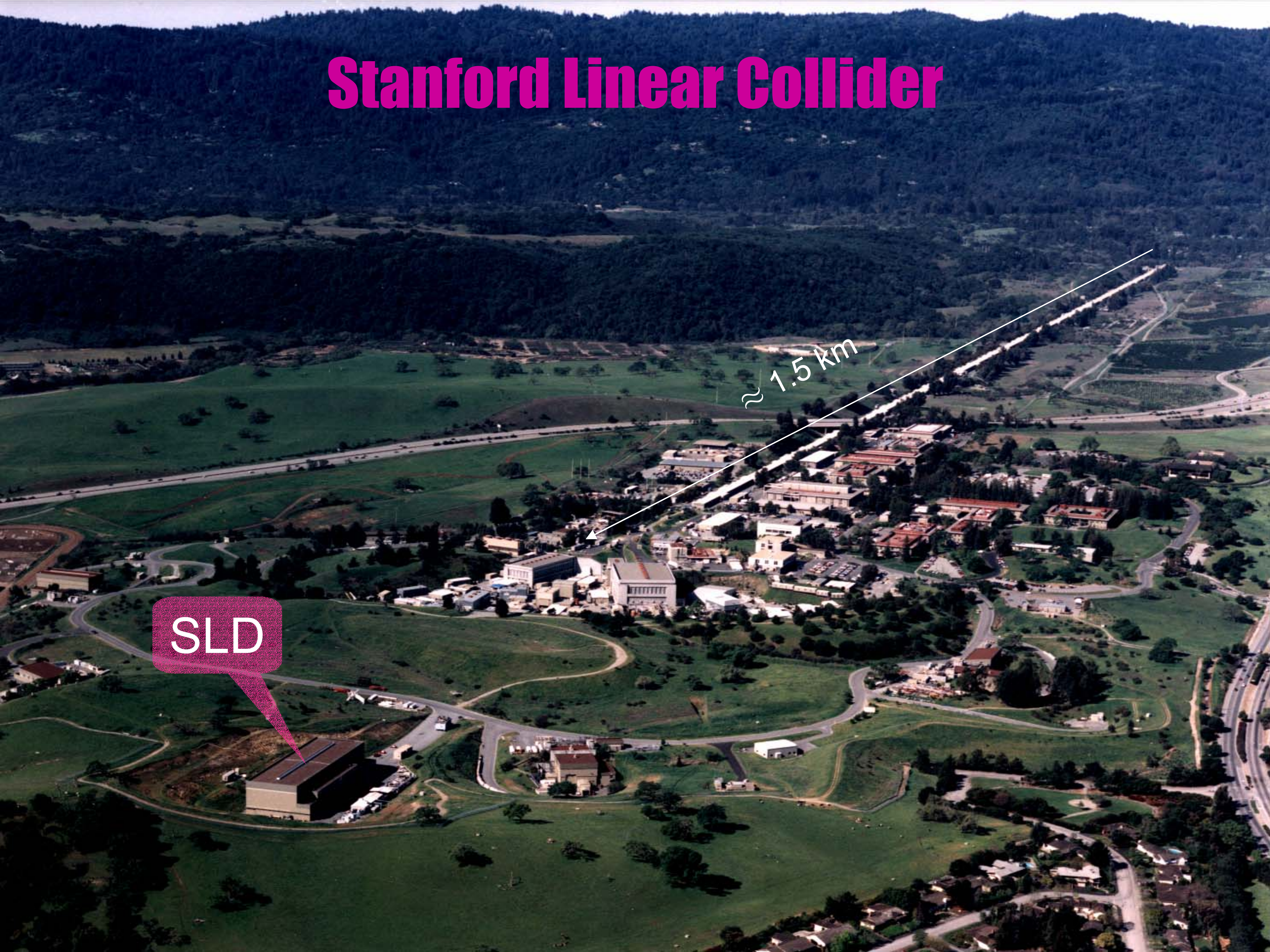


- LEP
  - 4 detectors: ALEPH, DELPHI, L3, OPAL
  - recorded 17×10^6 Z^0 decays (1990 – 1995)
- SLC
  - SLD detector
  - recorded 550,000 Z^0 decays (1993 – 1998)

Large Electron-Positron collider at CERN

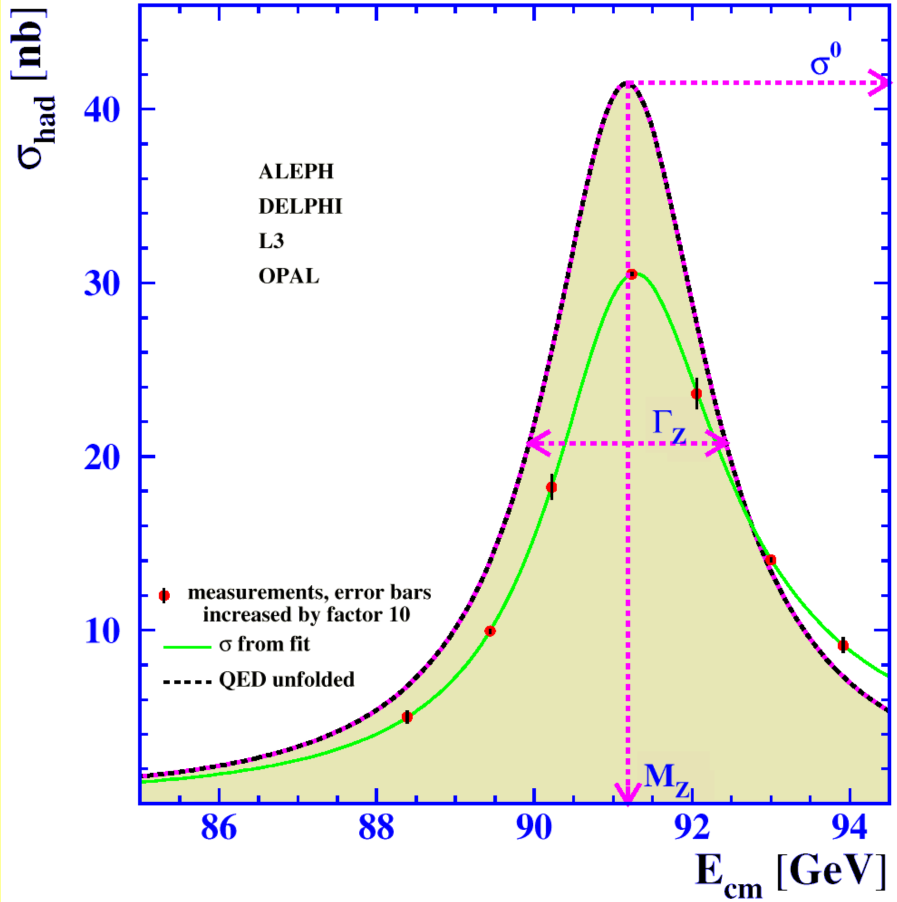


Stanford Linear Collider



Z^0 lineshape measurements

- Z^0 lineshape
  - M_Z=91.1876±0.0021 GeV
  - Γ_Z = 2.4952±0.0023 GeV
  - σ_h = 41.541±0.037 nb
  - $R_e=\Gamma_{had}/\Gamma_{ee}$=20.804±0.050
  - $R_\mu=\Gamma_{had}/\Gamma_{\mu\mu}$=20.785±0.033
  - $R_\tau=\Gamma_{had}/\Gamma_{\tau\tau}$=20.764±0.045
- consistent with lepton universality

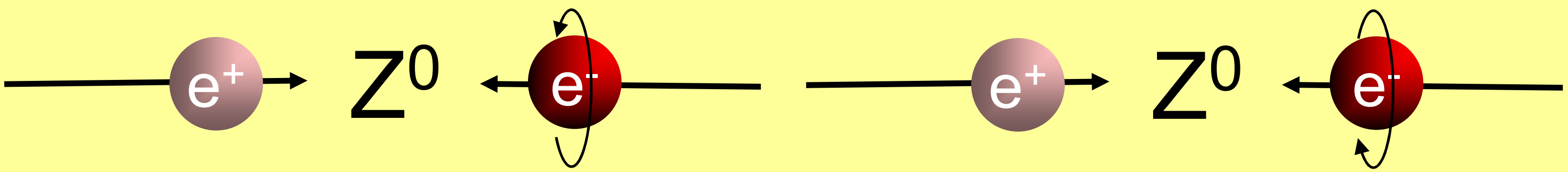


partial widths of Z^0

- visible decay modes
  - Γ_{had} = 1744.4±2.0 MeV
  - $\Gamma_{\ell\ell}$ = 83.984±0.086 MeV
- invisible width
  - $\Gamma_{inv} = \Gamma_Z - \Gamma_{had} - 3\times\Gamma_{\ell\ell}$ = 499.0±1.5 MeV
  - $\Gamma_{inv}/\Gamma_{\ell\ell}$ = 5.942±0.016
- standard model prediction
  - $\Gamma_{\nu\nu}/\Gamma_{\ell\ell}$ = 1.9912±0.0012
- 3 light neutrinos

many ways to measure $\sin^2\theta_W$

- left/right asymmetry A_{LR}
  - Z couples differently to left/right handed fermions
  - expect parity violating asymmetry



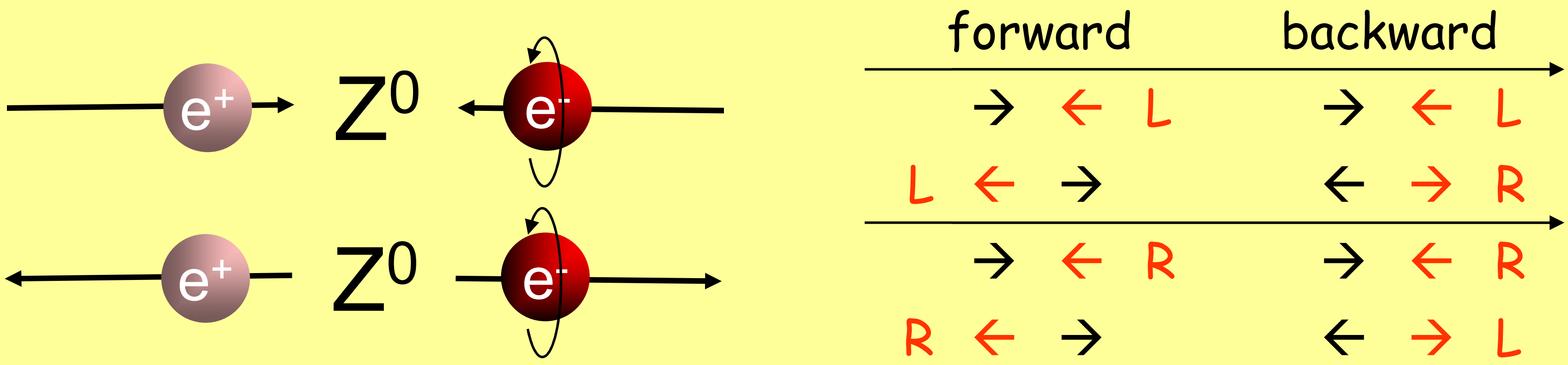
$$\sigma_L \neq \sigma_R$$

$$A_{LR} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} \neq 0$$

  - couplings depend on $\sin^2\theta_w$ ➔ A_{LR} depends on $\sin^2\theta_w$
  - only possible at SLC (e^- polarization ≈ 75%)

many ways to measure $\sin^2\theta_W$

- forward/backward asymmetries



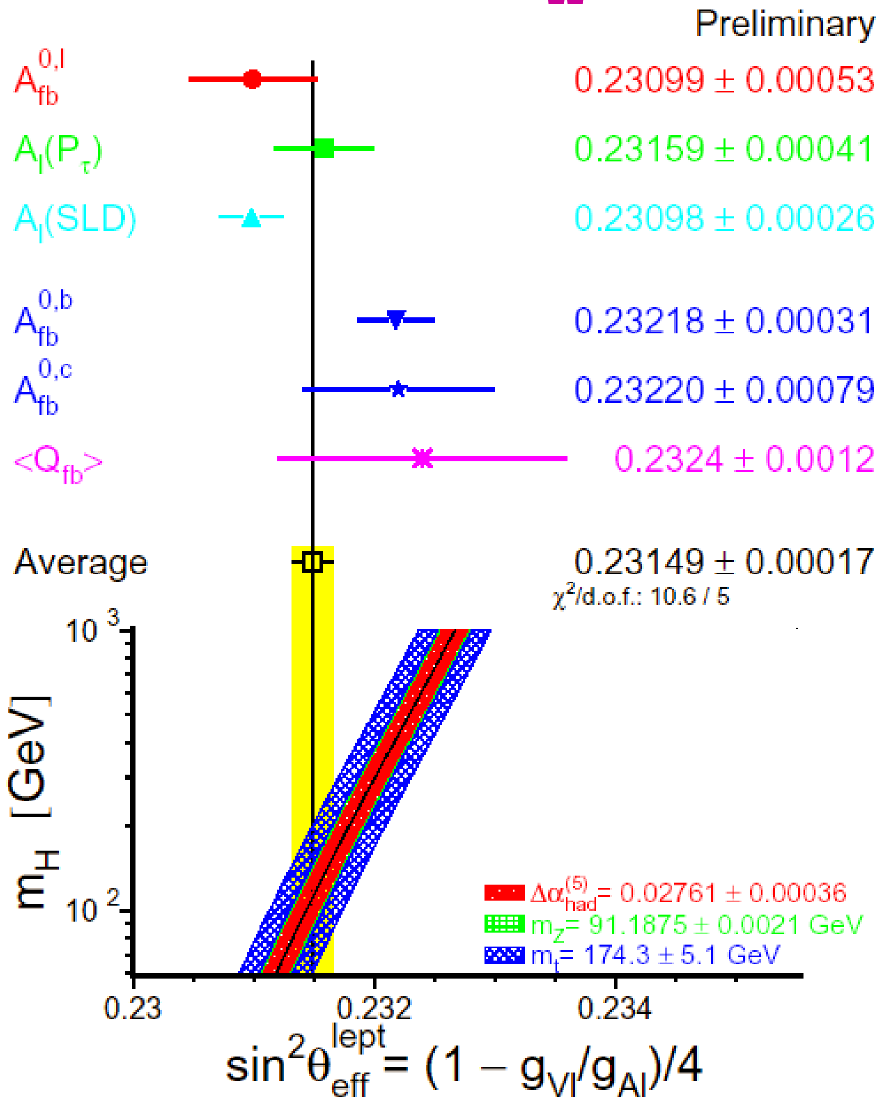
$$\sigma_F \neq \sigma_B$$

- requires no beam polarization

- $$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$ depends on $\sin^2\theta_W$

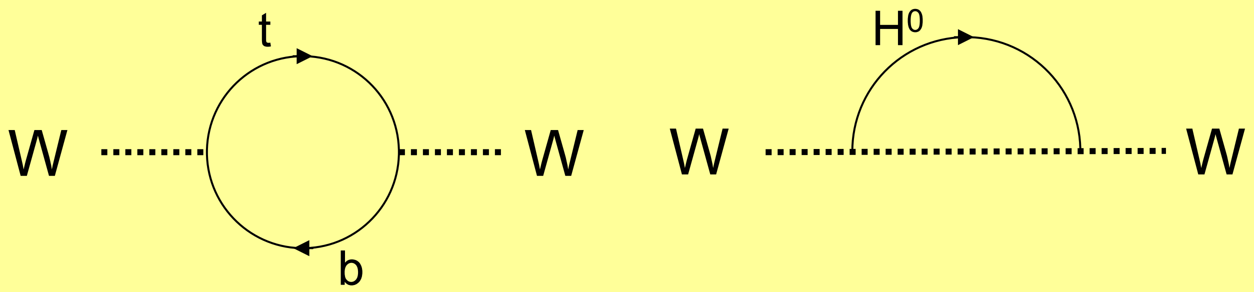
many ways to measure $\sin^2\theta_W$

- $\sin^2\theta_{eff}$
  - differs from $\sin^2\theta_W$ by radiative corrections
- agreement between all measurements



radiative corrections

- the gauge sector of the standard model is determined (at tree level) by
  - $\sin^2\theta_w$, M_Z, $\alpha \Rightarrow g_W, g_Z, M_W, A_{FB},\ldots$
- loops introduce additional dependencies



- $M_W = M_W^{tree}(1 + \mathcal{O}(m_t^2) + \mathcal{O}(\log m_H))$
- similarly for other quantities

precision measurements

- global electroweak fit
  - are all measurements consistent with one set of parameters?
  - all Z-pole data:

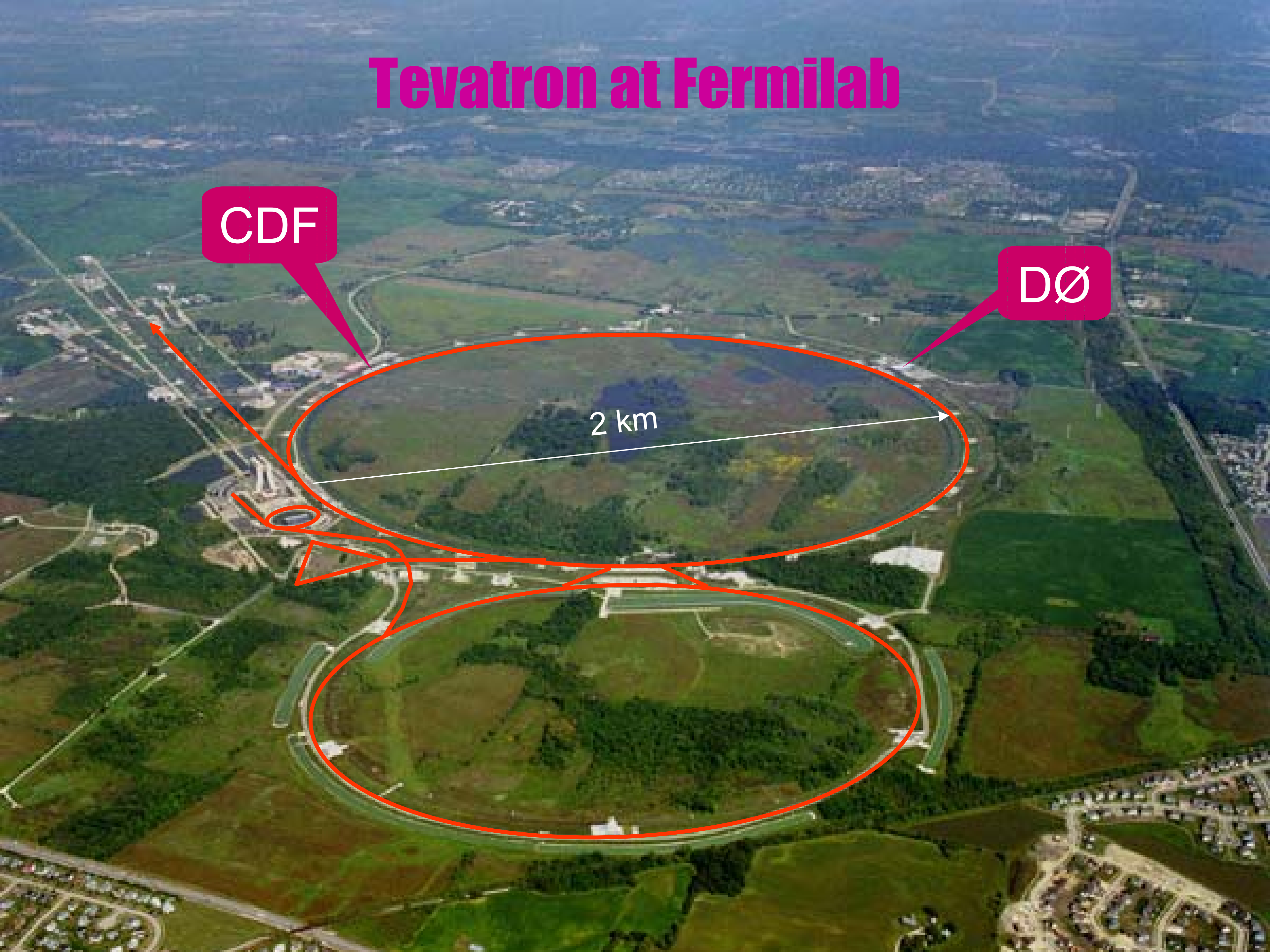
$$\left.\begin{aligned} m_t &= 171 \pm 10\,\text{GeV} \\ m_H &= 82^{+109}_{-41}\,\text{GeV} \\ \sin^2\theta_w &= 0.22315 \pm 0.00063 \\ M_W &= 80.372 \pm 0.033\,\text{GeV} \end{aligned}\right\} \chi^2 = 15.3/10\ dof \quad (12\%)$$

what about the W?

- $W^{\pm}$ is charged
  - cannot produce (singly) in $e^+ e^-$ collisions
  - need beam energy > M_W for $e^+e^- \rightarrow W^+W^-$
  - hadron colliders…

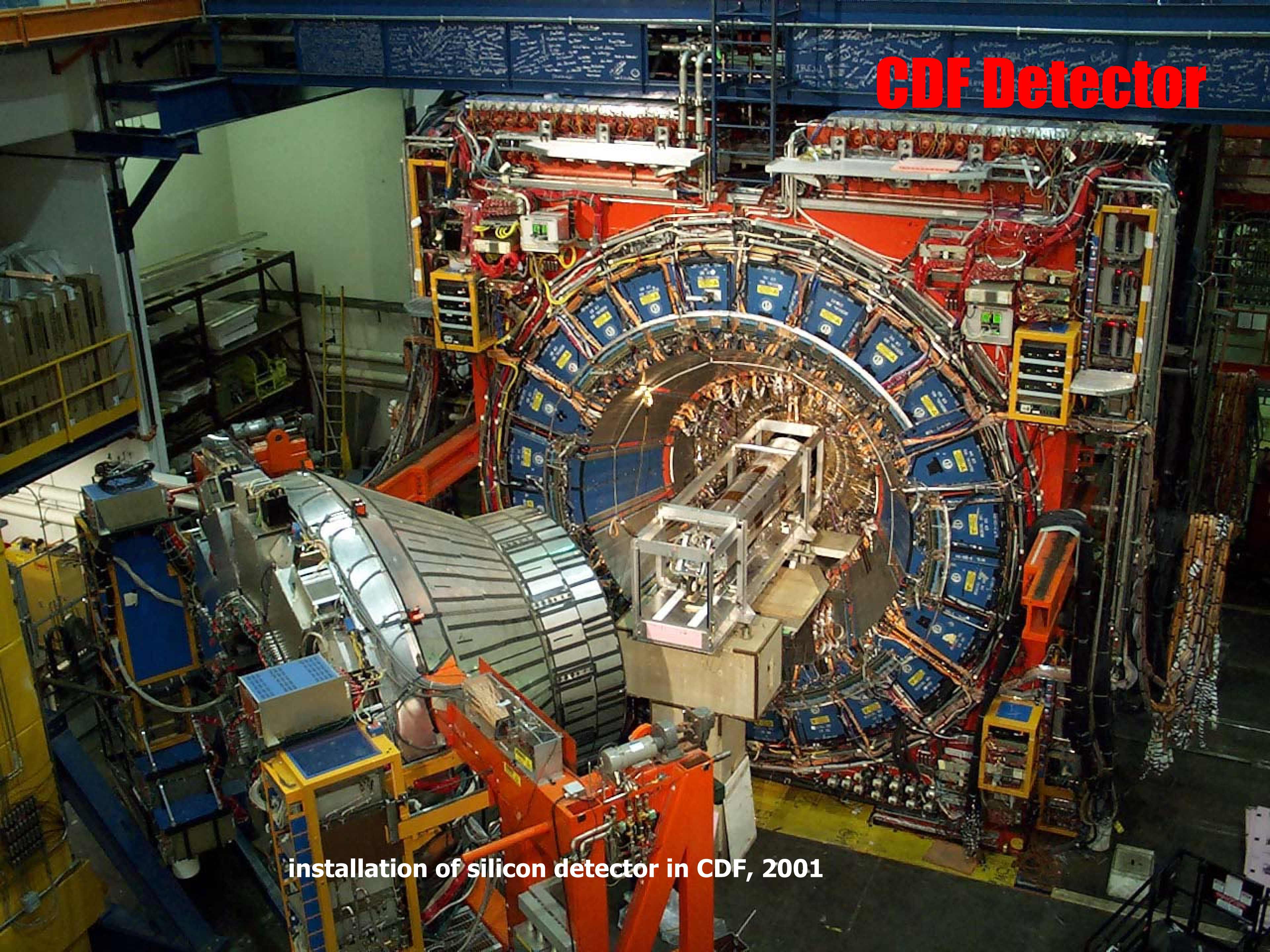
Tevatron at Fermilab

- colliding p and $\bar{p}$ beams
- beam energy $\approx$ 900 GeV
- produce $W^{\pm}$ and Z^0 bosons and more...
- 2 detectors: CDF and DØ
- between 1992 and 1995
  - recorded 10^5 W and 10^4 Z^0 decays



Tevatron at Fermilab
CDF
DØ
2 km

CDF Detector

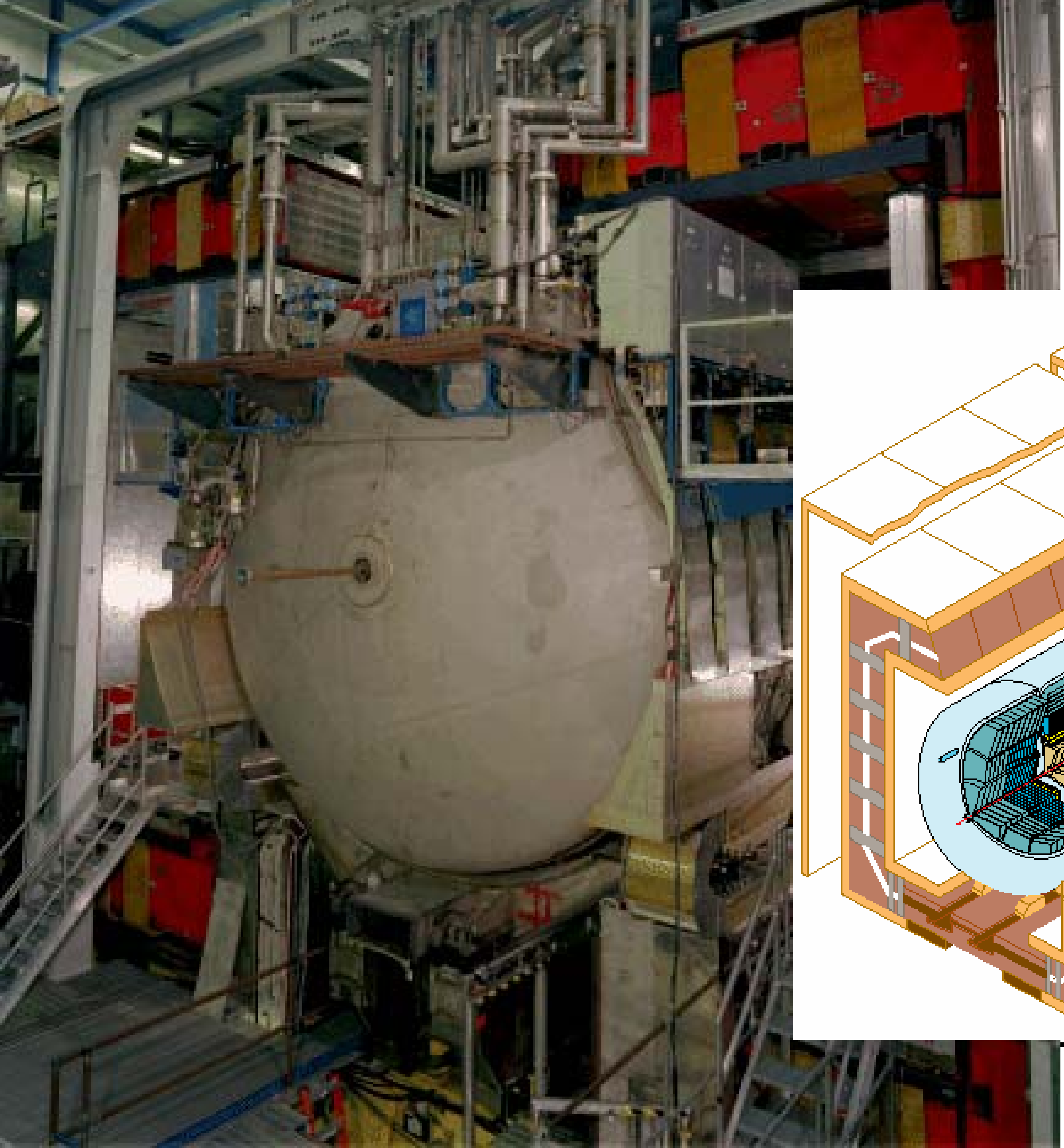


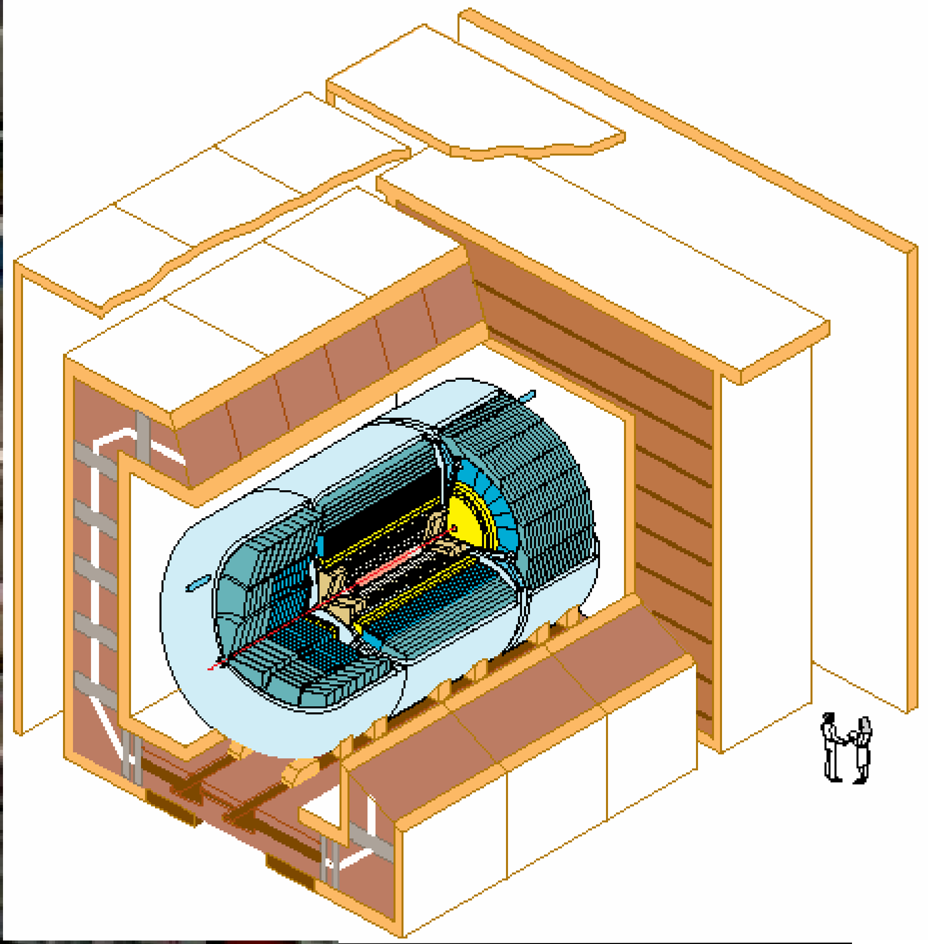
installation of silicon detector in CDF, 2001

DØ Detector

DØ detector installed in the Collision Hall, January 2001

DØ detector



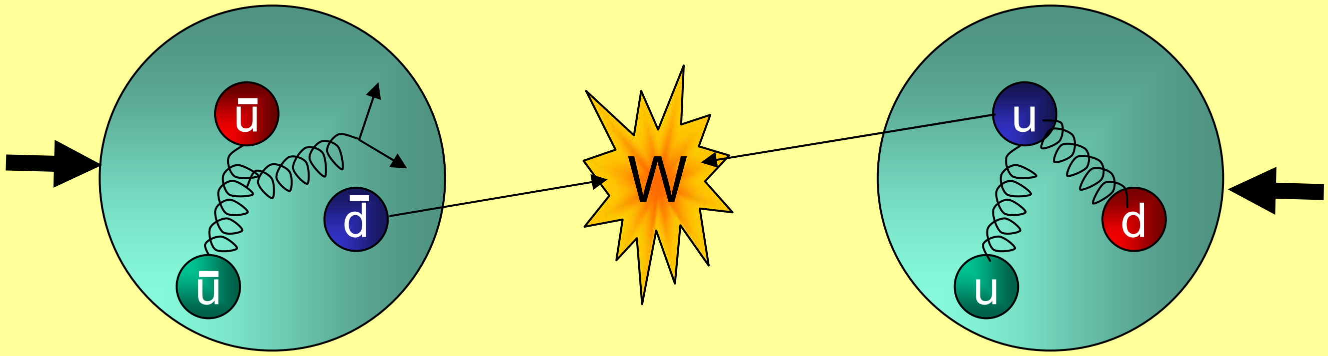


hadron colliders

- protons/antiprotons are not elementary
  - de Broglie wavelength of 900 GeV protons

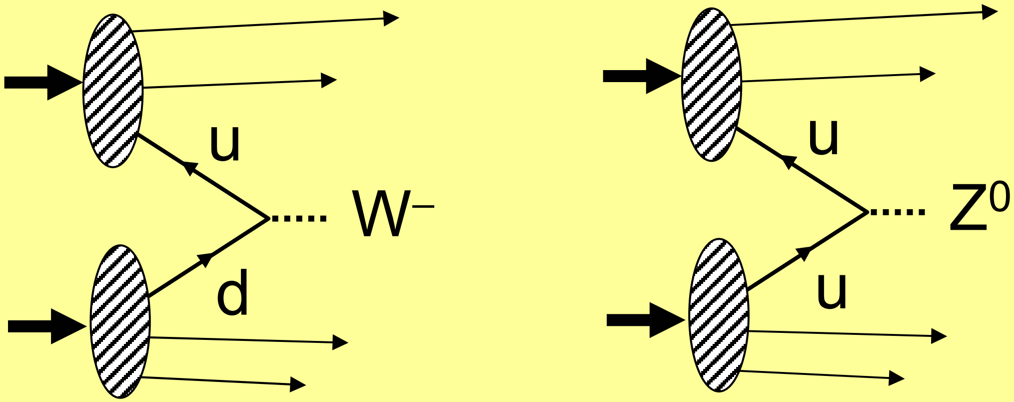
$$\lambda = \frac{hc}{E} = 10^{-18}\,\mathrm{m} \ll \text{size of the proton} \approx 10^{-15}\,\mathrm{m}$$

  - quark-antiquark and quark-gluon scattering

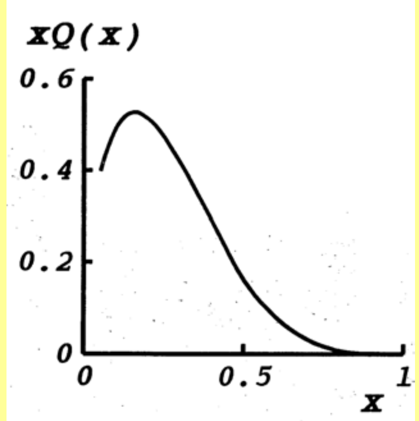


hadron colliders

- W and Z production in proton-antiproton collisions



  - W or Z are not the only particles produced
    - underlying event
  - quarks have a distribution of momenta
    - W or Z momentum not known
  - u and d quarks participate
    - both W and Z can be produced



parton distribution functions

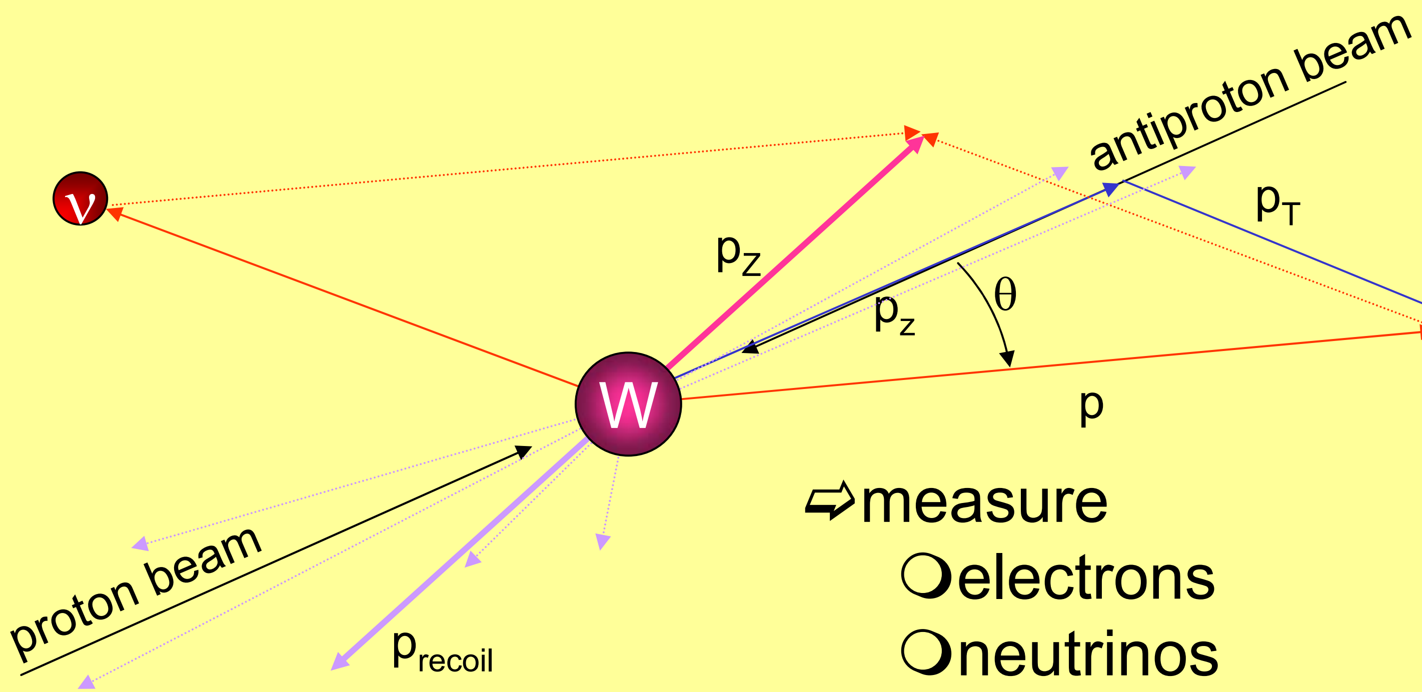
hadron colliders

➲W and Z decays

$W \to ud, cs$	68.5%	swamped by $pp \to qq, gg$
$W \to \tau\nu$	10.5%	$\tau \to \pi/e/\mu + \nu$'s
$W \to \mu\nu$	10.5%	momentum resolution
$W \to e\nu$	10.5%	best
$Z \to qq$	69.9%	swamped by $pp \to qq, gg$
$Z \to \nu\nu$	20.0%	invisible
$Z \to \tau^+ \tau^-$	3.4%	$\tau \to \pi/e/\mu + \nu$'s
$Z \to \mu^+ \mu^-$	3.4%	momentum resolution
$Z \to e^+ e^-$	3.4%	best

hadron colliders

➲anatomy of a $W \to e\nu$ event



⇨measure
- electrons
- neutrinos
- recoil (everything else)

DØ detector

neutrino signature

- neutrino
  - measure

    nothing
  - momentum conservation

$$\vec{p}_p + \vec{p}_{\bar{p}} = 0 = \vec{p}_e + \vec{p}_\nu + \vec{p}_{recoil} \quad \text{but don't know } p_z^{recoil}$$

$$\Rightarrow 0 = \vec{p}_T^e + \vec{p}_T^\nu + \vec{p}_T^{recoil}$$

$$\Rightarrow \vec{p}_T^\nu = -\vec{p}_T^e - \vec{p}_T^{recoil} \quad \text{missing } p_T$$

W mass measurement

- W boson

  Z mass measurement

  - measure

$$\left.\begin{aligned}\vec{p}_T^{\,W} &= \vec{p}_T^{\,e} + \vec{\not{p}}_T \\ E_T^W &= p_T^e + \not{p}_T\end{aligned}\right\} \Rightarrow M_T{}^2 = \left(E_T^W\right)^2 - \left(p_T^W\right)^2 \le M_W^2$$

  - M_T is not invariant

    depends on $p_T{}^W$ and parton distribution functions

    detector acceptances

  - need a detailed model of

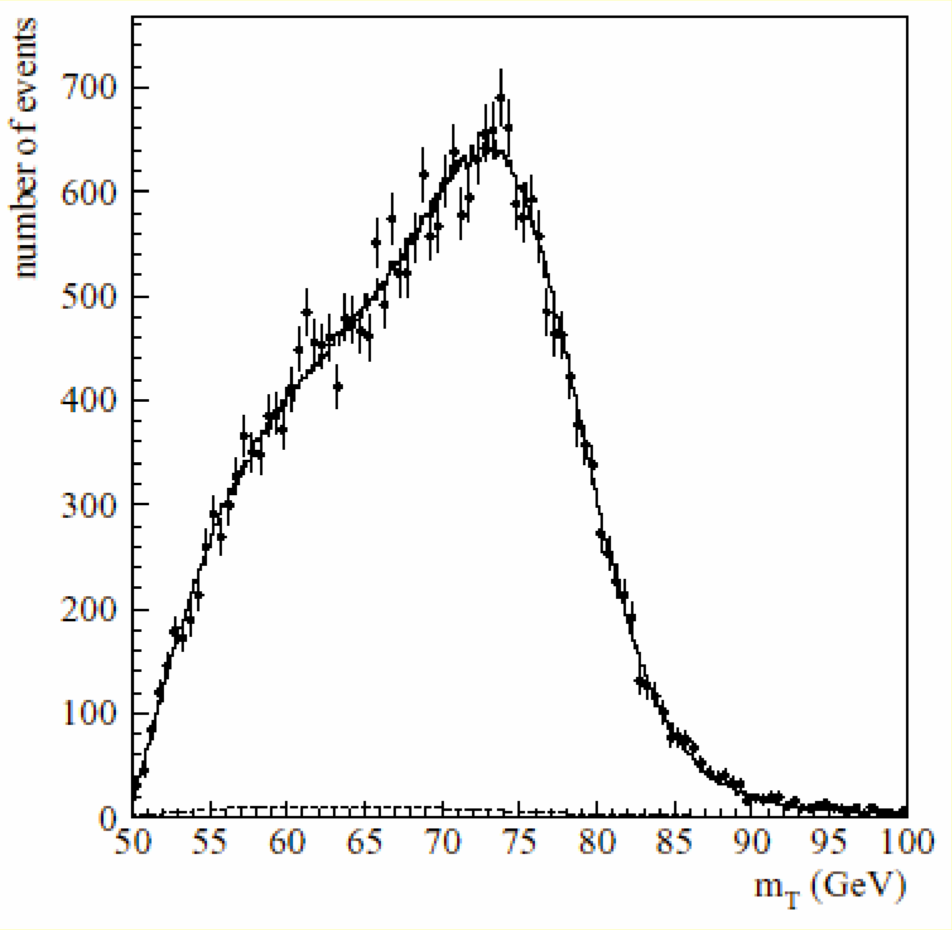
    W boson production

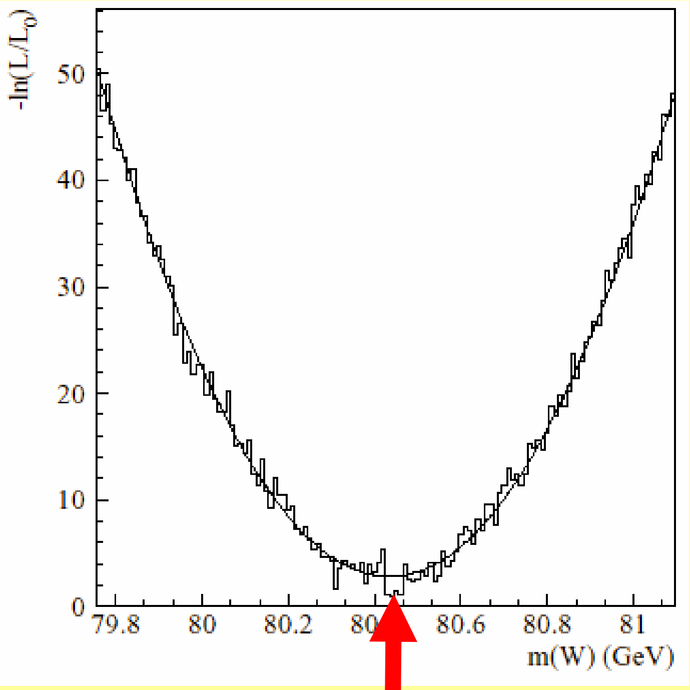
    detector

why transverse mass?

W mass fit

➲maximum likelihood fit





M_W=80.45±0.07 GeV

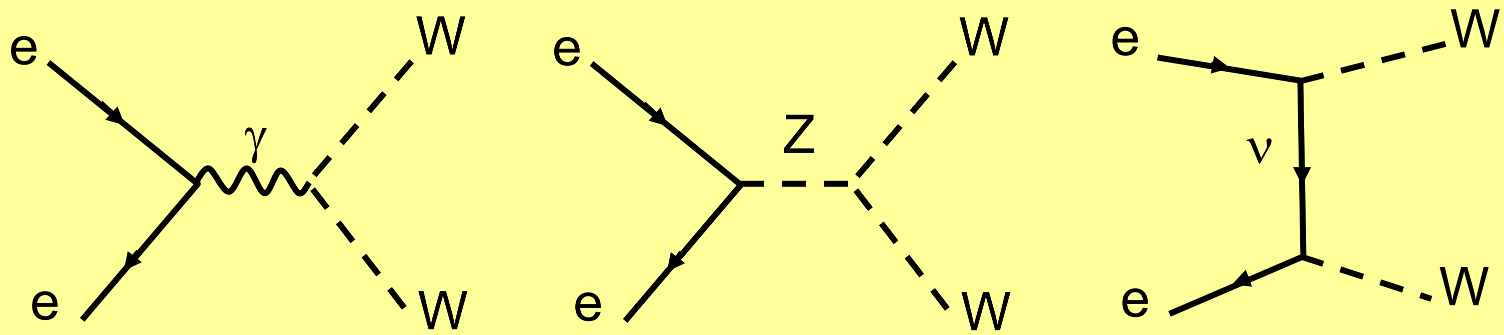
systematic uncertainties

- inputs to MC model affect measurement
  - parton distribution functions
  - p_T distribution of W
  - radiative corrections to W decay
  - detector model
- general procedure
  - constrain input parameters
  - vary parameters within the allowed range
  - determine the effect on the mass measurement

$$m_W = 80.443 \pm 0.079\,\text{GeV}\ \ (\text{CDF})$$
$$m_W = 80.483 \pm 0.084\,\text{GeV}\ \ (\text{D0})$$

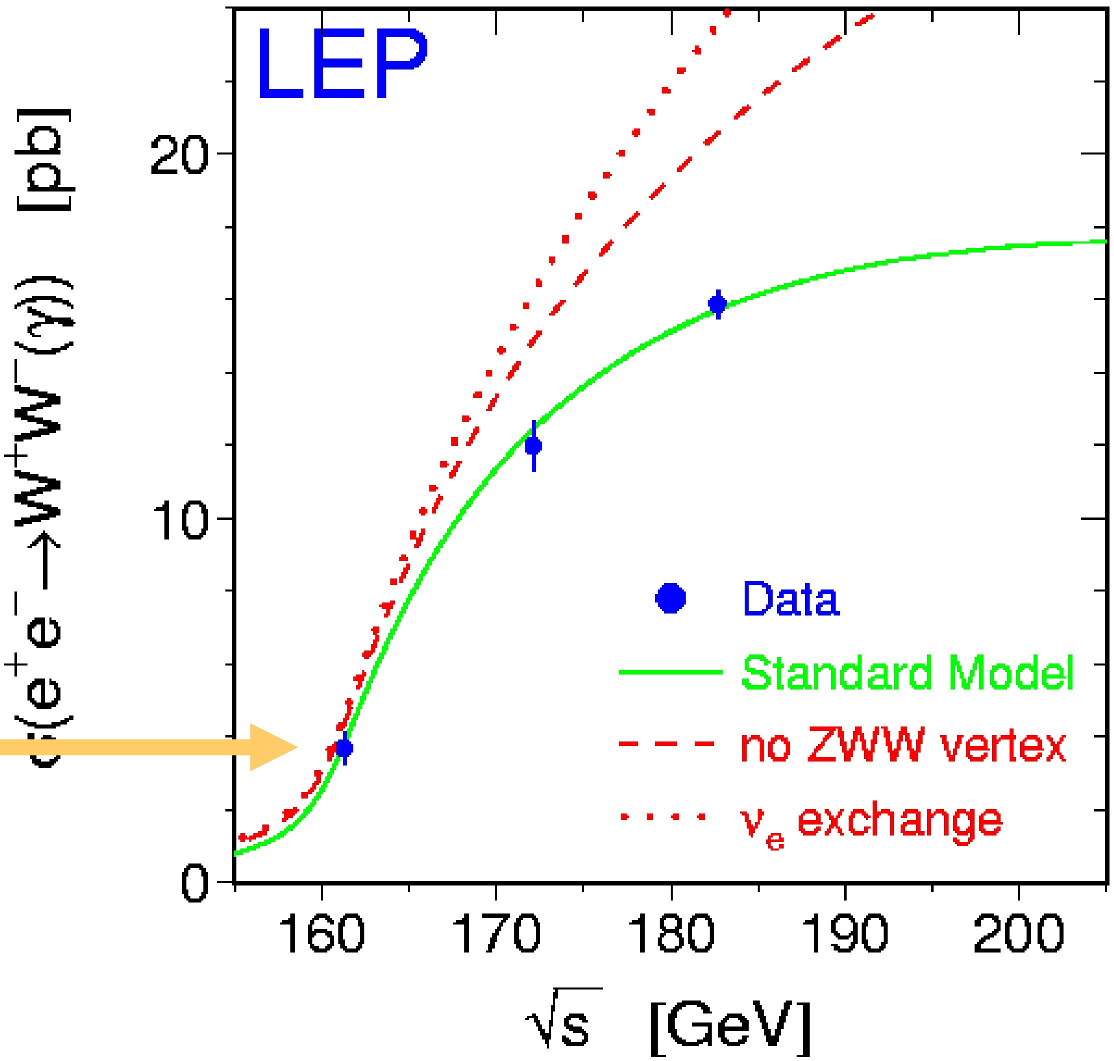
LEP-II

- ➲1996-2000 LEP operated above WW threshold
- ➲$\sqrt{s}$ = 161-209 GeV
- ➲W^+W^- pair production



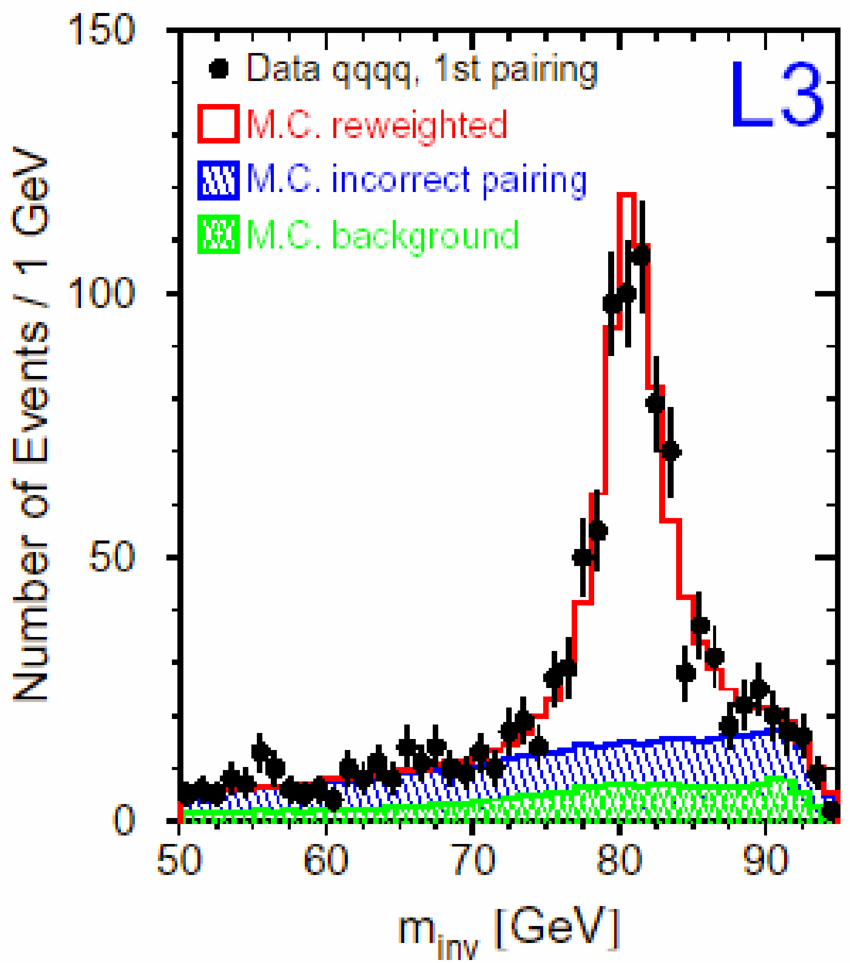
W mass at threshold

- W mass
  = 80.40 GeV
  ± 0.20 (stat)
  ± 0.07 (syst)
  ± 0.03 (beam)
- from σ_{WW} at $\sqrt{s} = 161$ GeV



W mass from direct reconstruction

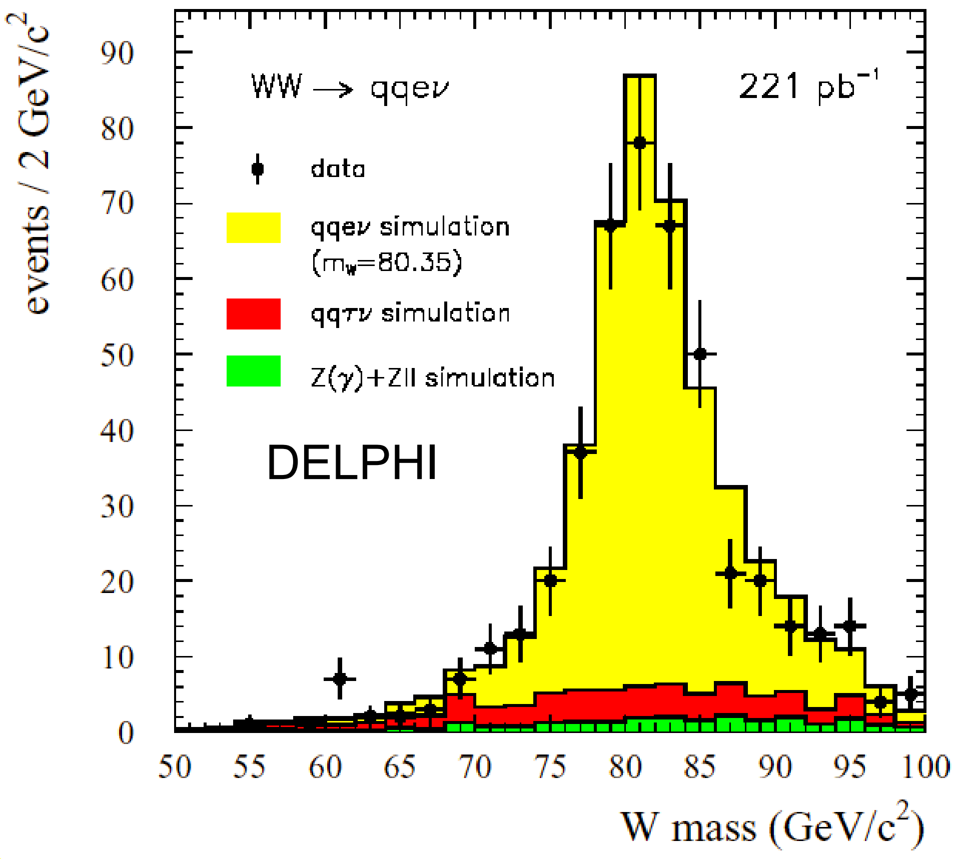
- $WW \rightarrow q\bar{q}q\bar{q}$
  - reconstruct 4 jets
  - 5C fit (E, p, $m_1 = m_2$)
  - 3 possible jet pairings
    - combinatoric background
  - quarks are created so close together that their fragmentation is not independent
    - color-reconnection
    - Bose-Einstein correlations



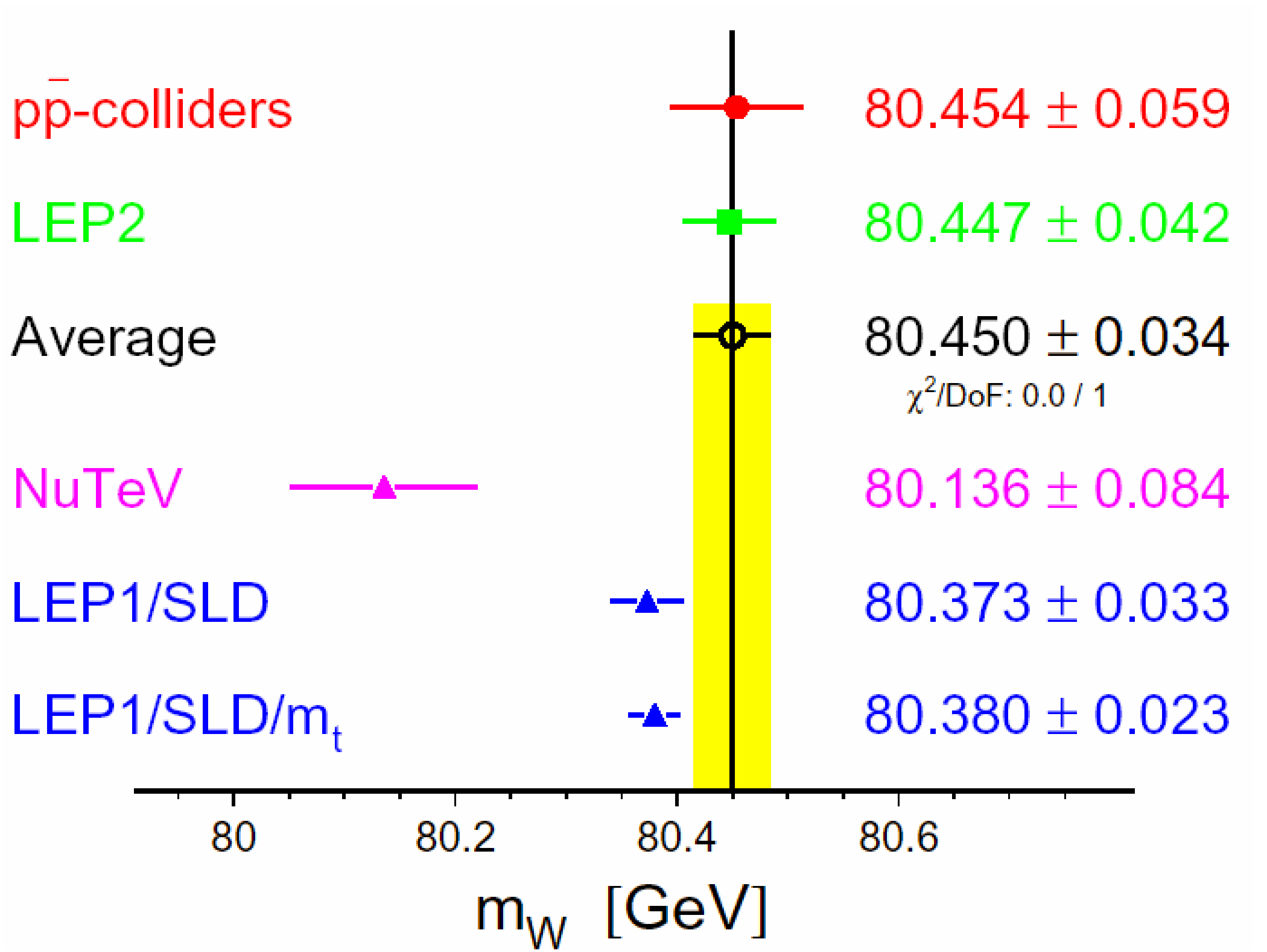
- $m_W = 80.457 \pm 0.030(\text{stat}) \pm 0.054(\text{syst})$ GeV

W mass from direct reconstruction

- ➲ $WW \rightarrow qq\ell\nu$
  - ⇨ neutrino not detected
  - ⇨ 2C fit (E, p, $m_1 = m_2$)
  - ⇨ m_W = 80.448 GeV ± 0.033(stat) GeV ± 0.028(syst) GeV

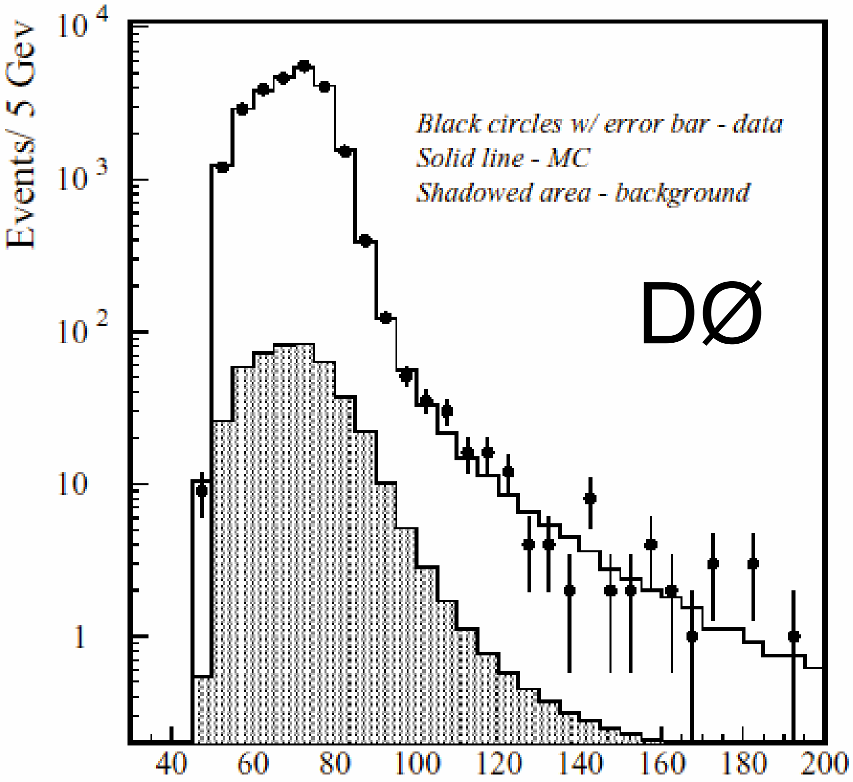


world average



direct measurement of W width

- Tevatron
  - tail of m_T spectrum
  - $\Gamma_W = 2.115 \pm 0.105$ GeV
- LEP-II
  - width of invariant mass distributions
  - $\Gamma_W = 2.150 \pm 0.091$ GeV



indirect measurement of W width

- Tevatron
  - indirect measurement from ratio of σB

$$R = \frac{\sigma_W B_{W\to e\nu}}{\sigma_Z B_{Z\to ee}} \Rightarrow B_{W\to e\nu} = R\frac{\sigma_Z}{\sigma_W} B_{Z\to ee}$$

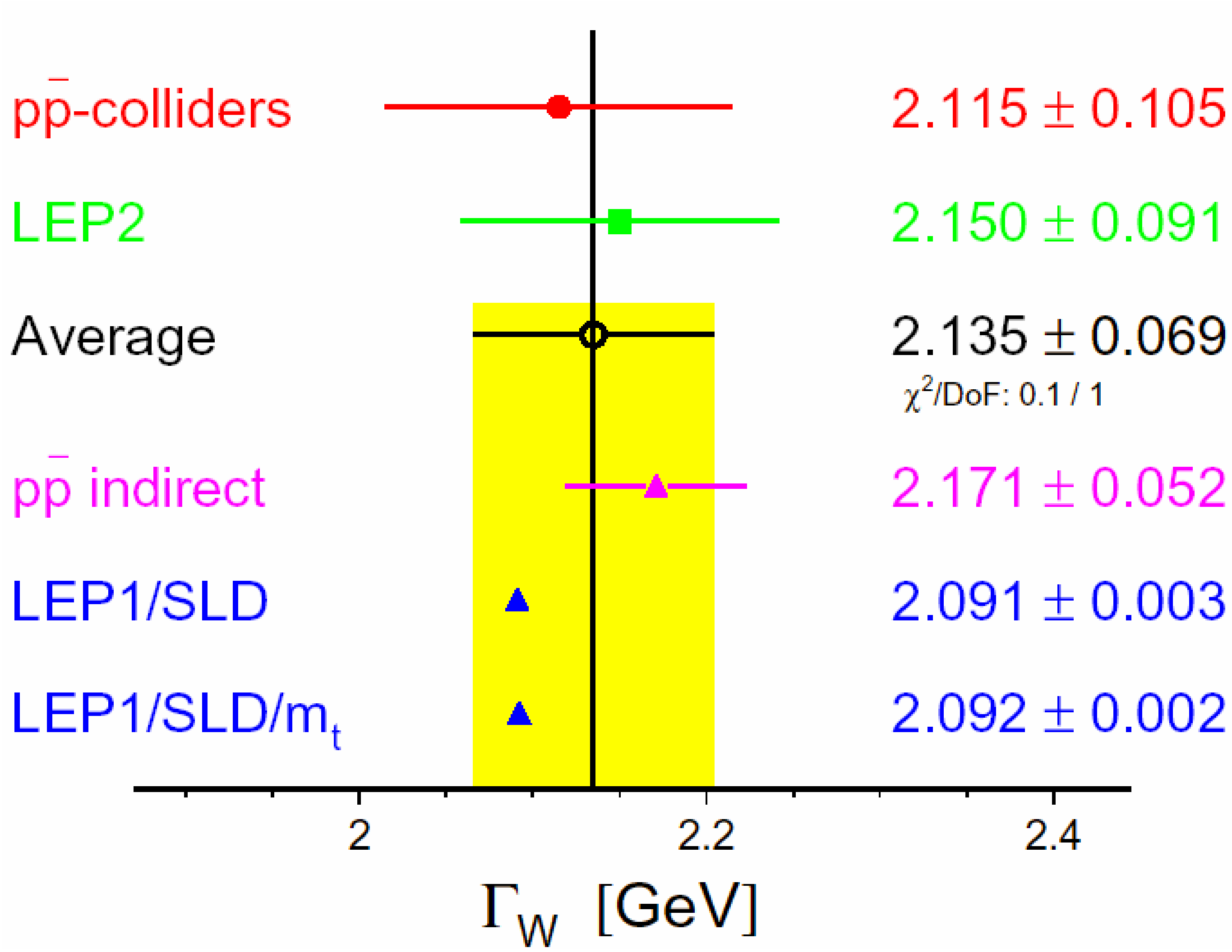
$$\Gamma_W = \frac{\Gamma_{W\to e\nu}}{B_{W\to e\nu}}$$

standard model

LEP

  - $\Gamma_W = 2.171 \pm 0.052$ GeV

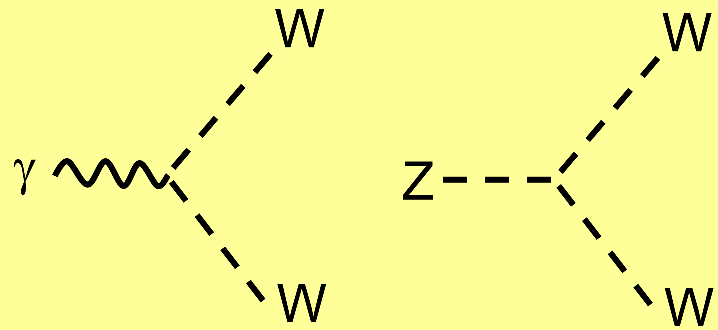
W width



$p\bar{p}$-colliders
2.115 ± 0.105
LEP2
2.150 ± 0.091
Average
2.135 ± 0.069
χ^2/DoF: 0.1 / 1
$p\bar{p}$ indirect
2.171 ± 0.052
LEP1/SLD
2.091 ± 0.003
LEP1/SLD/m_t
2.092 ± 0.002
2
2.2
2.4
Γ_W [GeV]

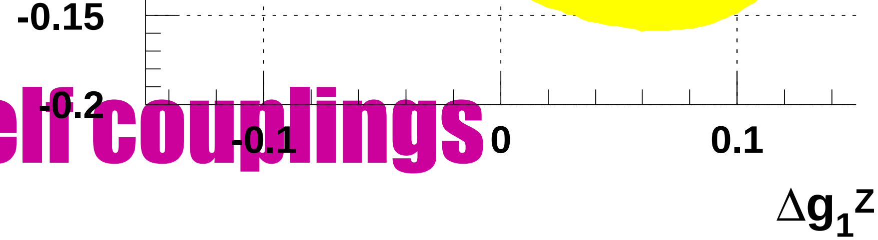
gauge boson self couplings

- the SU(2)×U(1) theory predicts

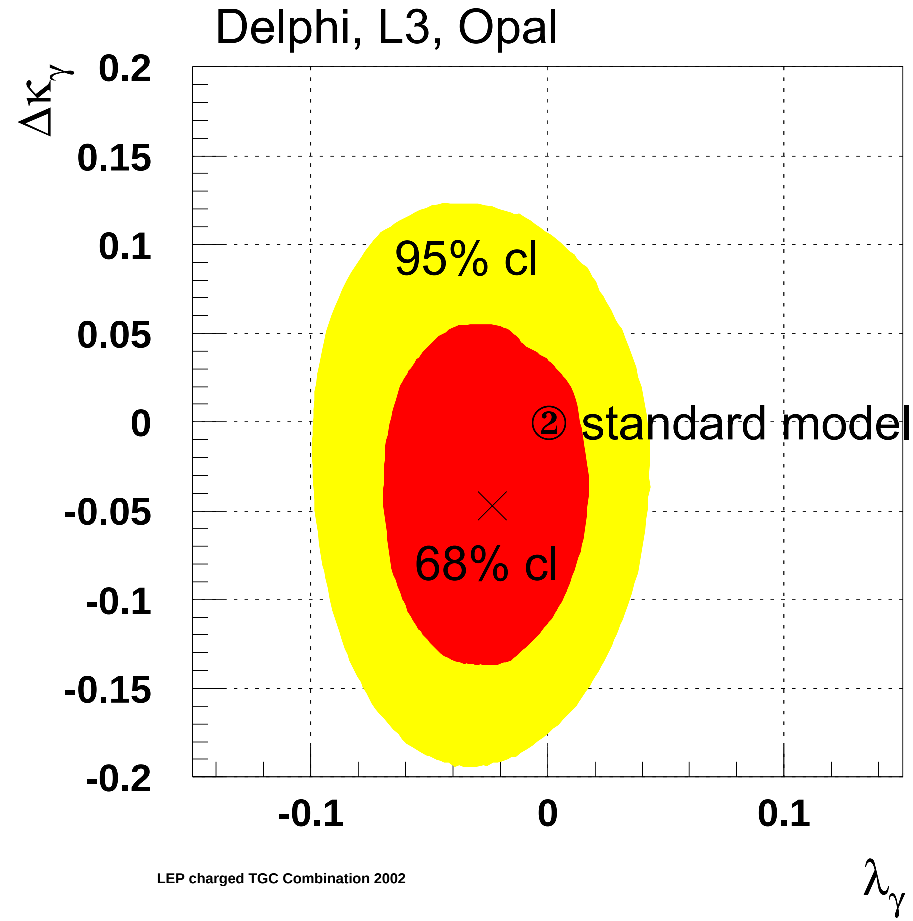


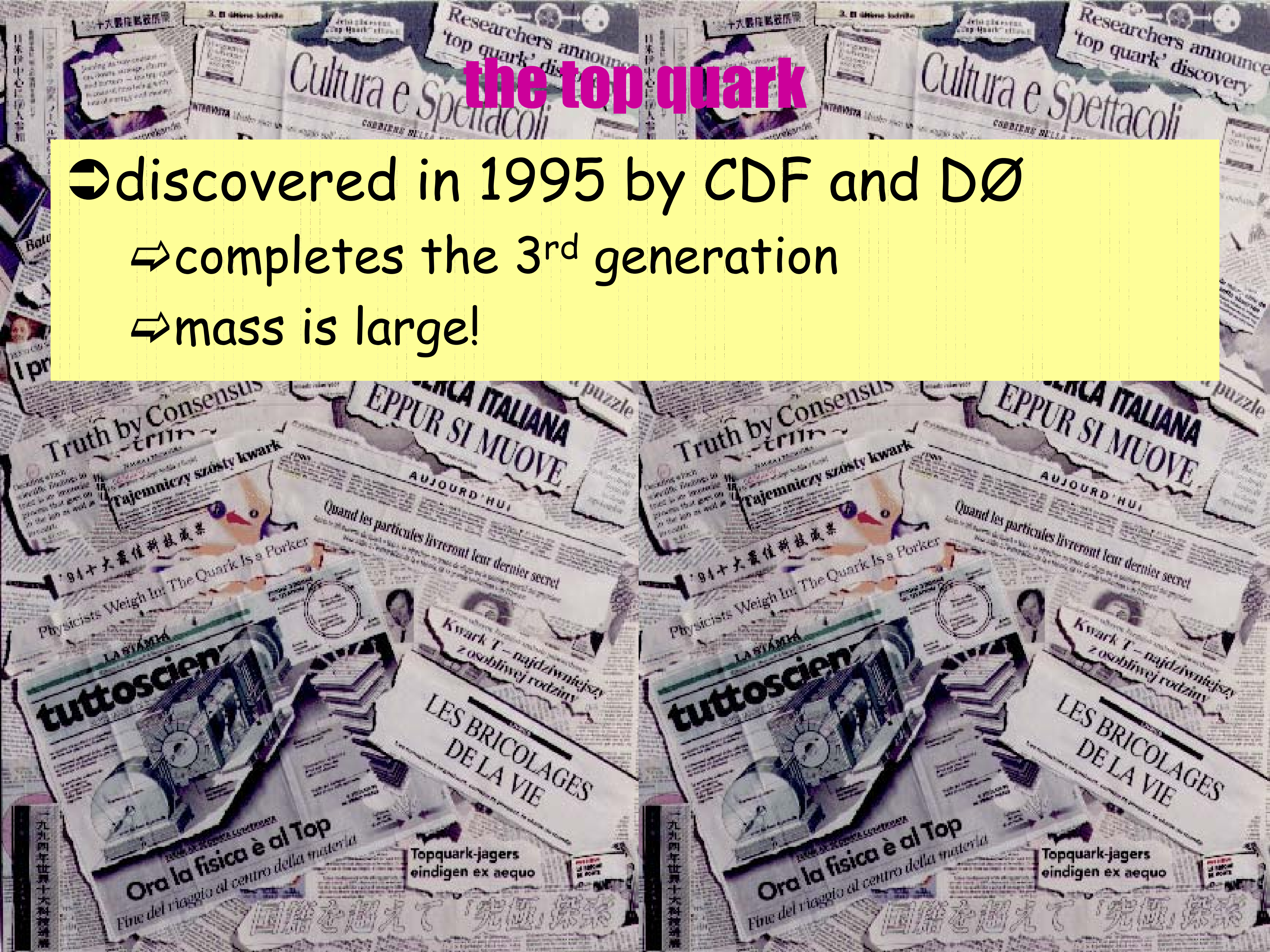
  - seven Lorentz-invariant amplitudes each
  - five constrained by electromagnetic gauge invariance and neutron dipole moment
  - constrain two couplings, κ, λ
  - Tevatron: Wγ, WW, WZ production
  - LEP-II: WW production

gauge boson self couplings



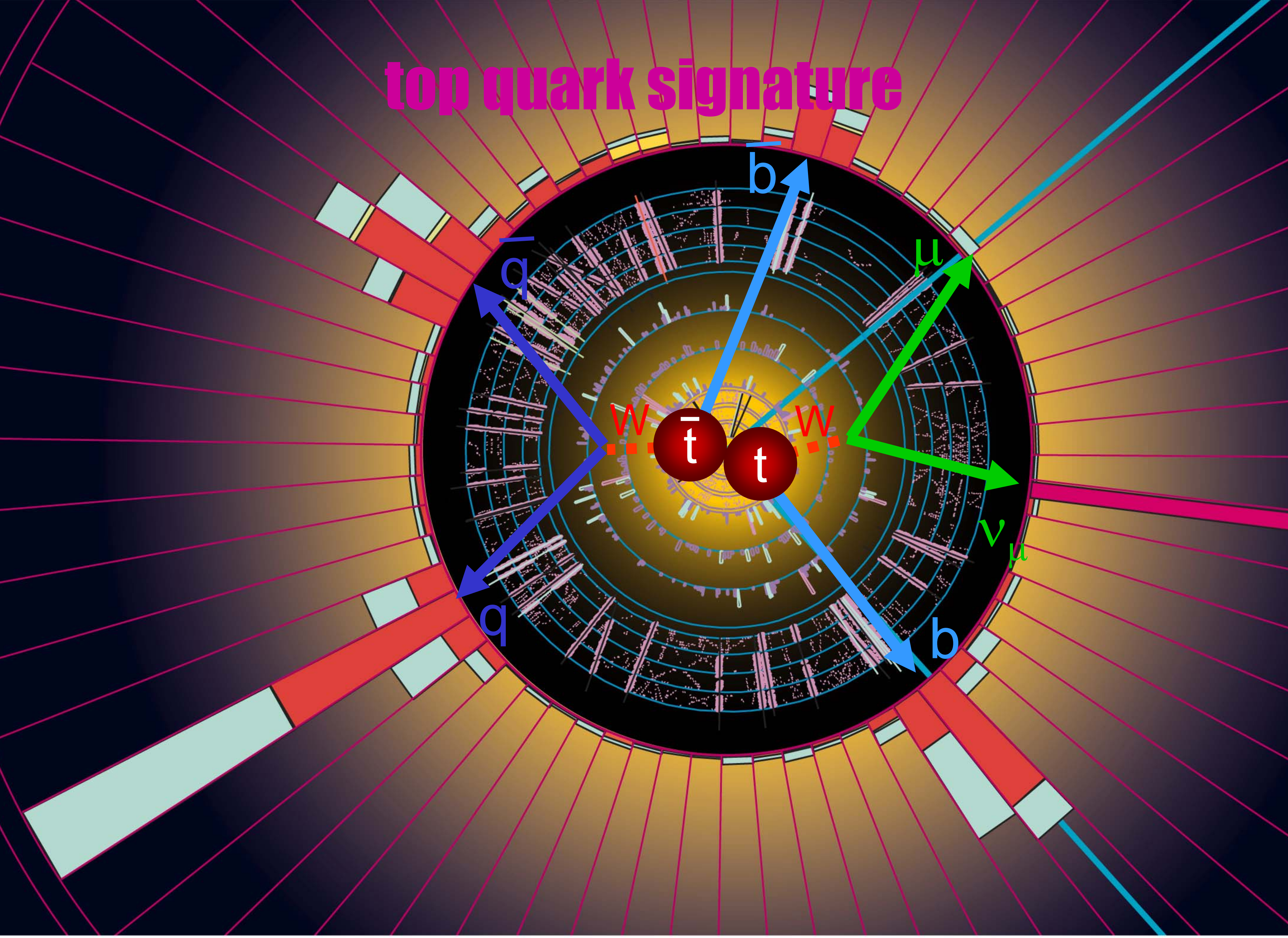
- in standard model
  - $\kappa = 1$ ($\Delta\kappa = 0$)
  - $\lambda = 0$
- if $W\gamma$ have only electromagnetic couplings
  - $\kappa = 0$ ($\Delta\kappa = -1$)
  - $\lambda = 0$
  - excluded





the top quark

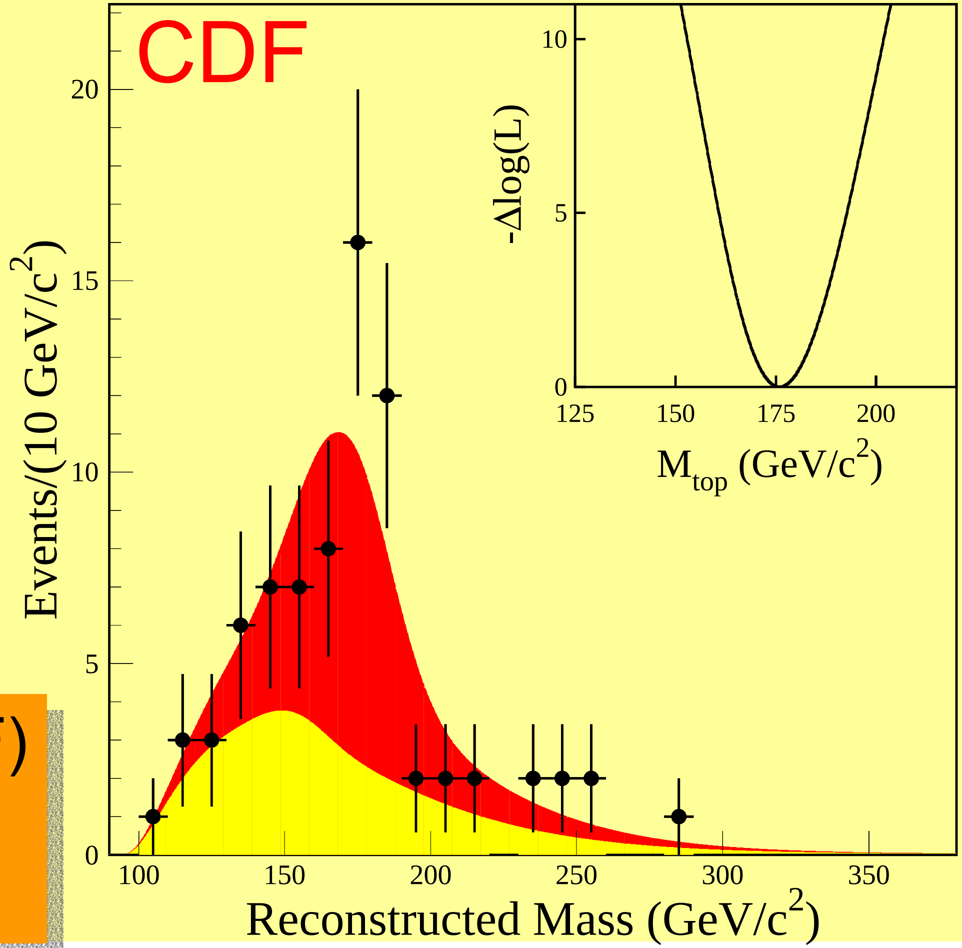
- discovered in 1995 by CDF and DØ
  - completes the 3rd generation
  - mass is large!



Fermilab #97-1889

top mass measurement

- measure lepton, 4 jets, missing p_T
  - 1 unknown
  - 3 constraints
  - 1C kinematic fit
  - compare to MC



m_{top} = 176.0±6.5 GeV (CDF)
m_{top} = 172.1±7.1 GeV (DØ)
m_{top} = 174.3±5.1 GeV

does it all fit?

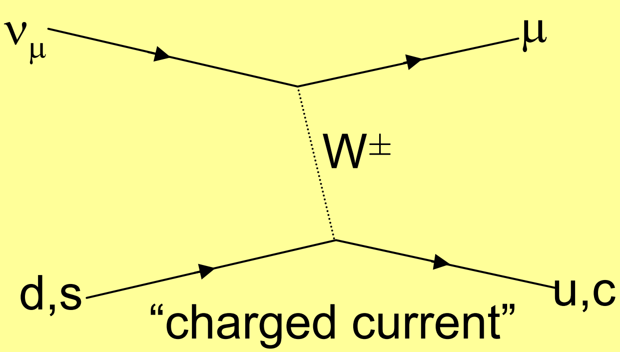
- global electroweak fit
  - include W mass, width and top mass measurements

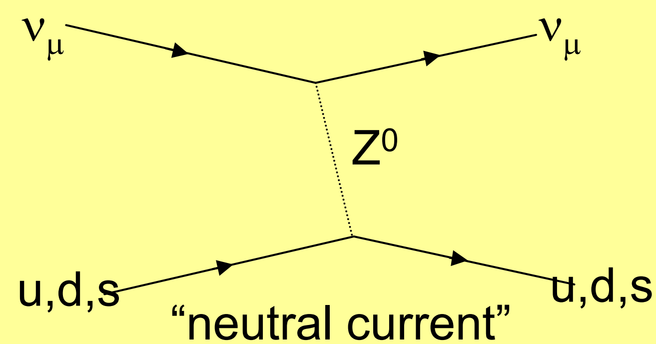
$$\left.\begin{aligned} m_t &= 175.8 \pm 4.3\,\text{GeV} \\ m_H &= 81^{+49}_{-32}\,\text{GeV} \\ \sin^2\theta_w &= 0.22255 \pm 0.00036 \\ M_W &= 80.403 \pm 0.019\,\text{GeV} \end{aligned}\right\} \chi^2 = 19.6/14\,dof \quad (14\%)$$

  - consistent with standard model

yet another way to measure $\sin^2\theta_W$

➲ charged/neutral current cross section





⇨ $R^\nu = \dfrac{\sigma_{NC}^{\nu}}{\sigma_{CC}^{\nu}}$ is a function of $\sin^2\theta_W$

but sensitive to sea quark contributions

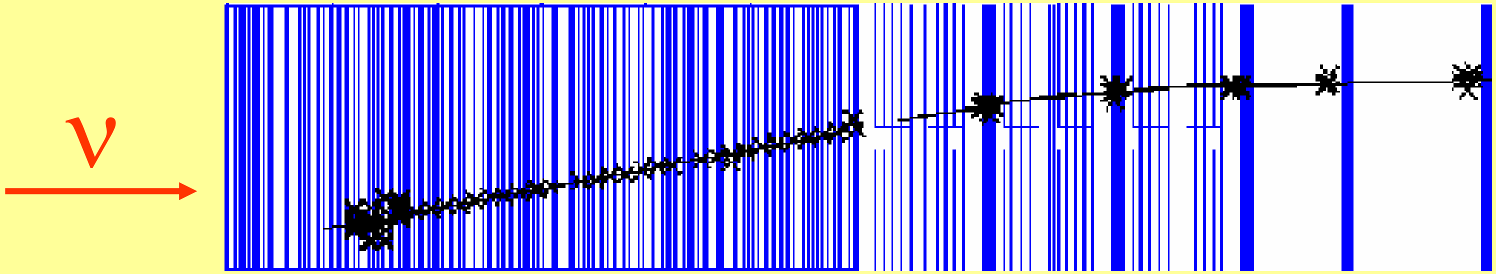
⇨ $R = \dfrac{\sigma_{NC}^{\nu} - \sigma_{NC}^{\bar{\nu}}}{\sigma_{CC}^{\nu} - \sigma_{CC}^{\bar{\nu}}}$ sea quark contributions cancel

but measure ν and ν separately

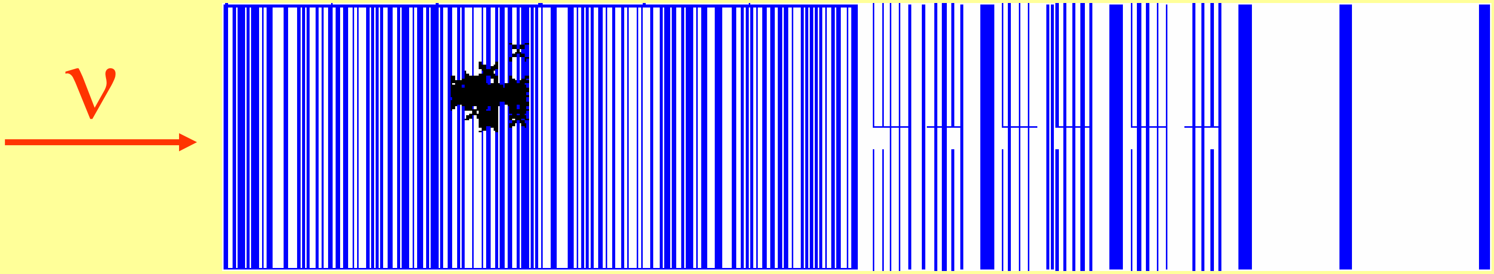

NuTeV
“Nu”trinos at the “Tev”atron
toroidal muon spectrometer
target/calorimeter
iron
liquid scintillator
drift chambers

NuTeV

- fixed target experiment $p \rightarrow \pi, K \rightarrow \nu_\mu$
  - two beams: ν and $\bar{\nu}$
  - charged current events



  - neutral current events



NuTeV

- result
  - NuTeV
    $\sin^2\theta_w = 0.2277 \pm 0.0013\ (\text{stat}) \pm 0.0009\ (\text{syst})$
  - global electroweak fit:
    $\sin^2\theta_w = 0.22255 \pm 0.00036$
  - 3 standard deviation discrepancy

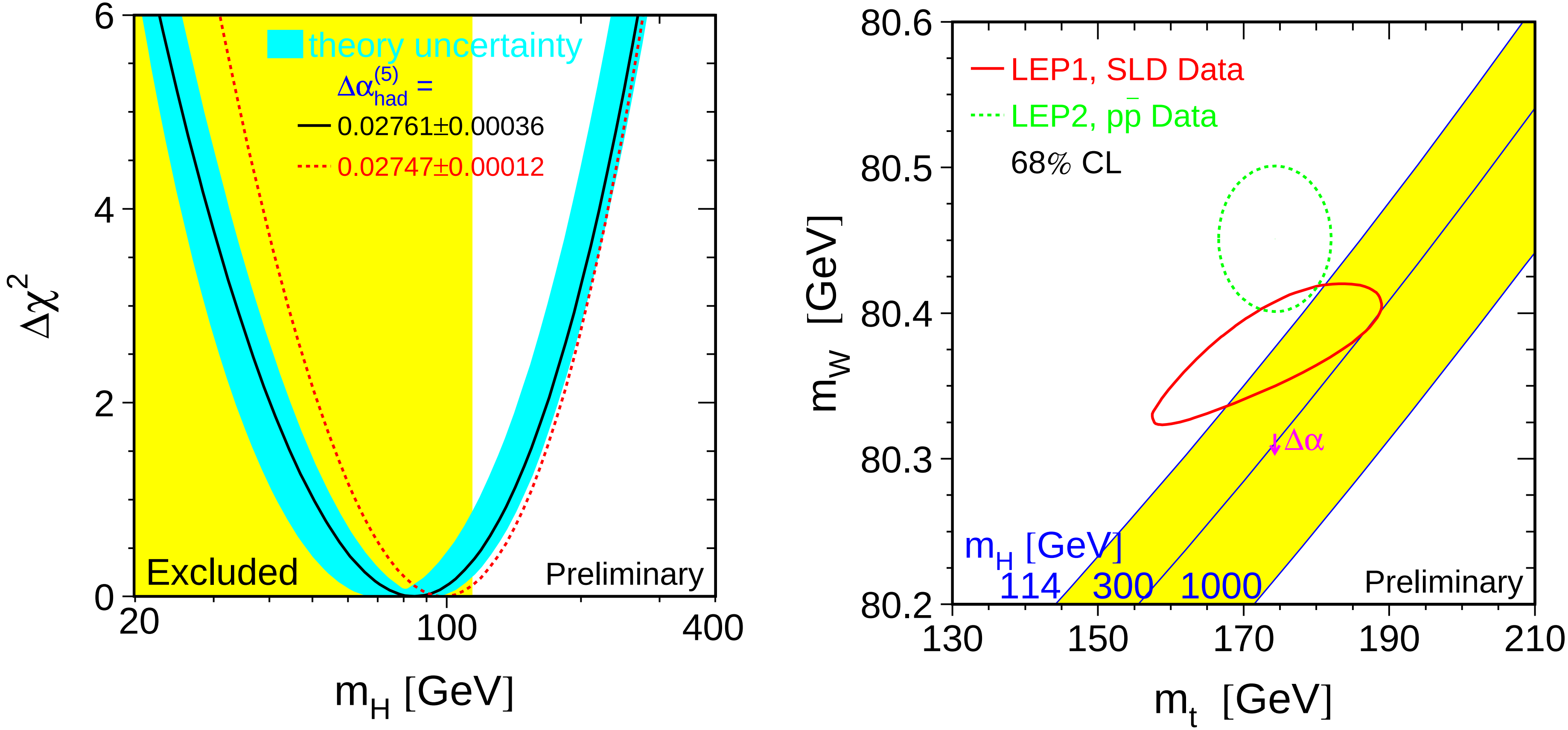
does it still all fit?

- global electroweak fit
  - include $\sin^2\theta_w$ from NuTeV

$$\left.\begin{aligned} m_t &= 174.7 \pm 4.4\,\text{GeV} \\ m_H &= 85^{+54}_{-34}\,\text{GeV} \\ \sin^2\theta_w &= 0.22272 \pm 0.00036 \\ M_W &= 80.394 \pm 0.018\,\text{GeV} \end{aligned}\right\} \chi^2 = 28.8/15\ dof \quad (1.7\%)$$

  - still consistent with standard model?

precision measurements



Outline

- the standard model
- experimental confirmation
- precision measurements
- does it fit?
- future prospects
  - Tevatron Run 2
  - LHC
  - linear collider
- are we done?
- summary

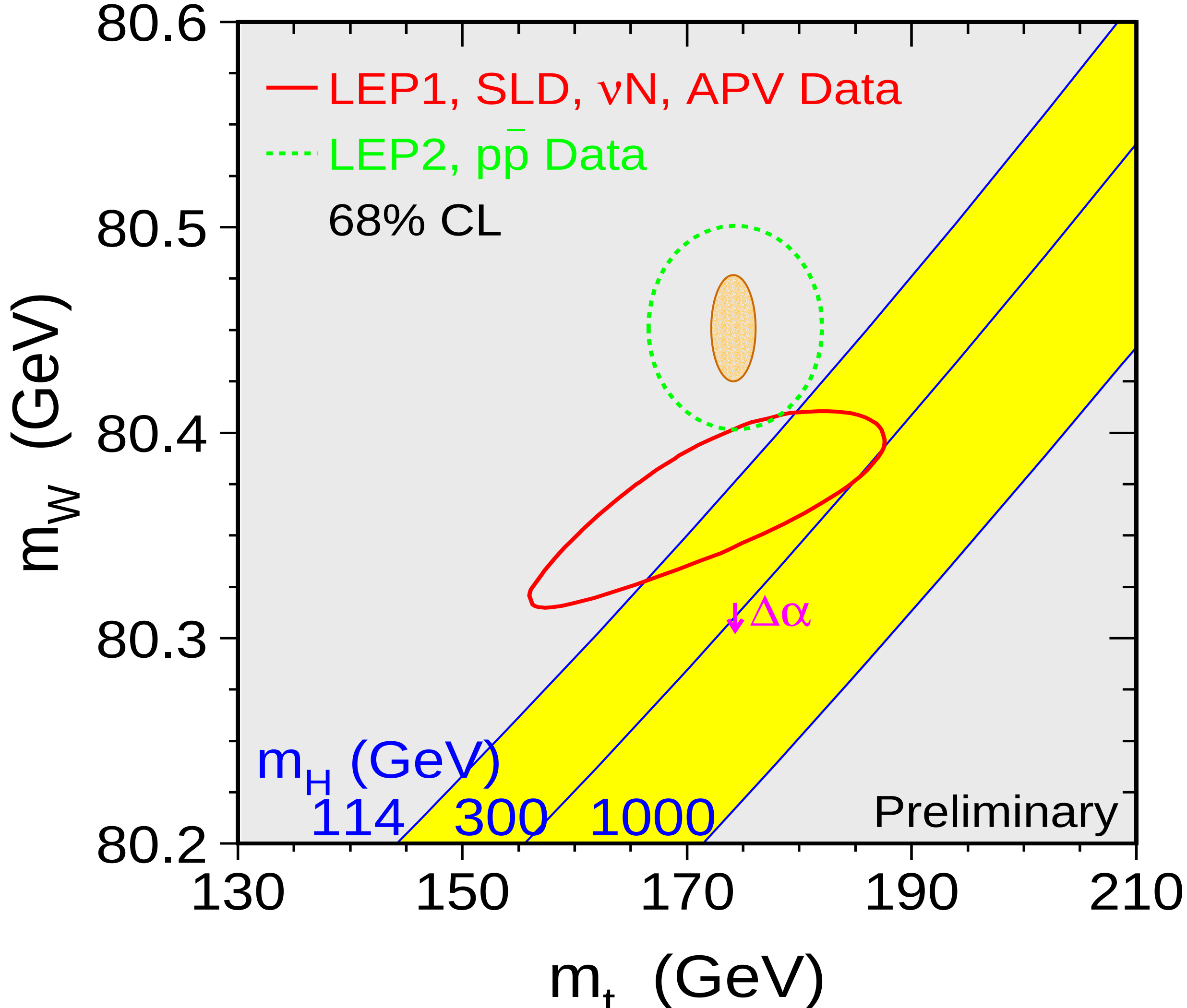
Tevatron upgrade

- Main Injector
  - $2\pi r$ = 3.3 km
  - 8→150 GeV p synchrotron
  - 8→120 GeV to p, fixed target
  - 150→8 GeV for p recovery
  - 344 dipoles, 208 quads
- p Source
  - upgrades to target, Li lens
  - debuncher and accumulator stochastic cooling systems
- Recycler
  - 8 GeV p storage ring
  - 416 permanent magnets

Tevatron run 2

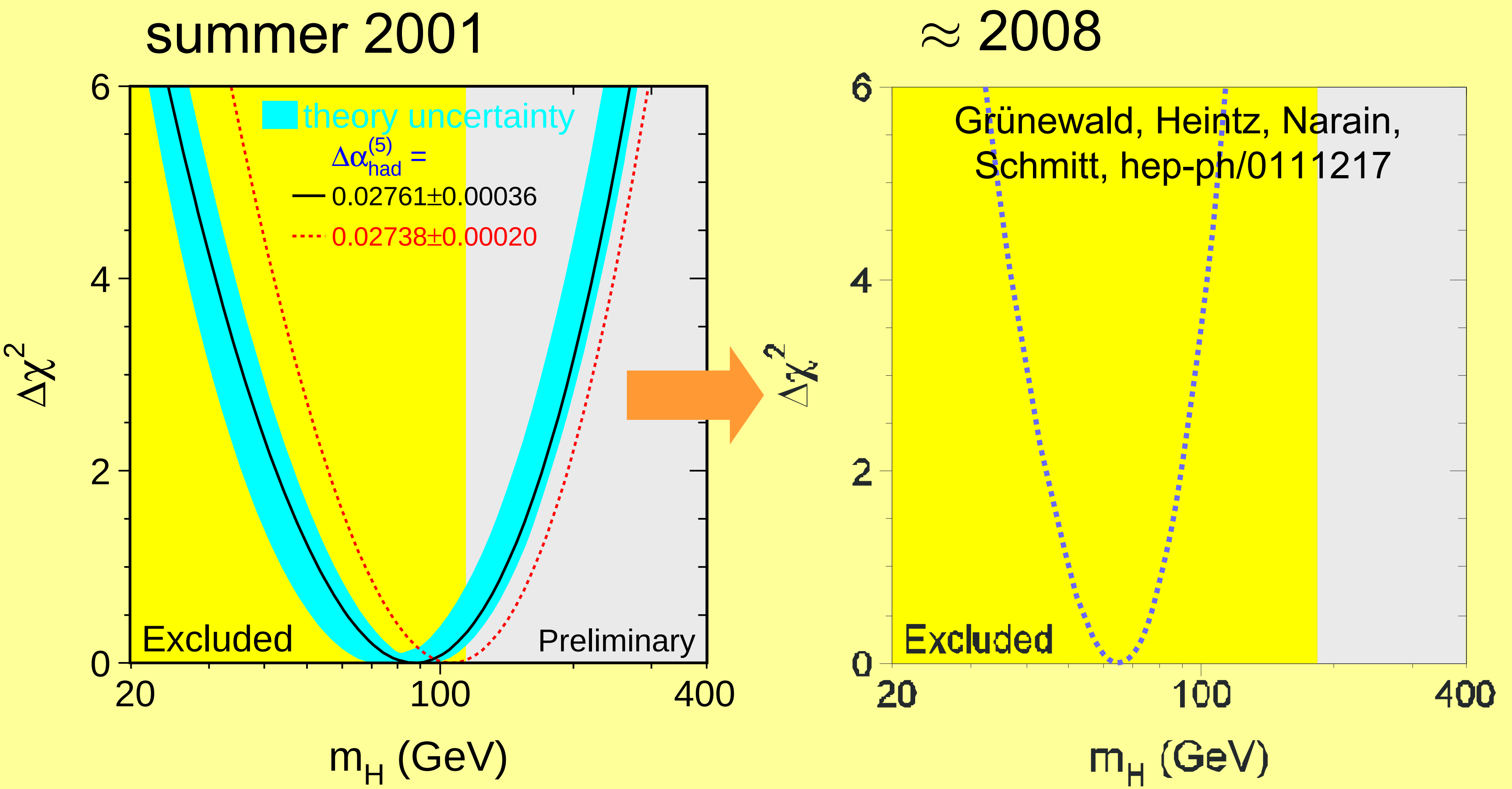
- now until LHC is competitive...
- $\sqrt{s}$ = 1.96 TeV
  - Run 2A (<2005)
    $\mathcal{L} \approx 10^{32}$ cm^{-2}s^{-1}, $\int \mathcal{L} dt \approx 2$ fb^{-1}
  - Run 2B (>2005)
    $\mathcal{L} \approx 5 \times 10^{32}$ cm^{-2}s^{-1}, $\int \mathcal{L} dt \approx 13$ fb^{-1}
- W mass to 27-17 MeV
- top mass to 2.8-1.3 GeV
- Higgs → see next lecture

Tevatron run 2



can we exclude the standard model?

➲global electroweak fit



beyond Run 2

- LHC (starts in 2006?)
  - pp collisions at $\sqrt{s}$ = 14 TeV
  - M_W, m_{top}
  - Higgs
  - phenomena beyond standard model
- linear collider (starts before I retire?)
  - e^+e^- collisions at $\sqrt{s} \approx$ 500 GeV
  - Giga-Z option
  - M_W
  - m_{top}
  - precision study of Higgs...?

are we done?

- shortcomings of the standard model
  - too many free parameters
  - Higgs mechanism put in by hand
  - light fundamental scalar requires fine tuning (hierarchy problem)
  - keeping the Higgs coupling finite as $Q^2 \rightarrow \infty$, drives it to zero at low Q^2 (triviality problem)
  - does the Higgs exist?
  - only e&m and weak force truly unified
  - does not describe gravity

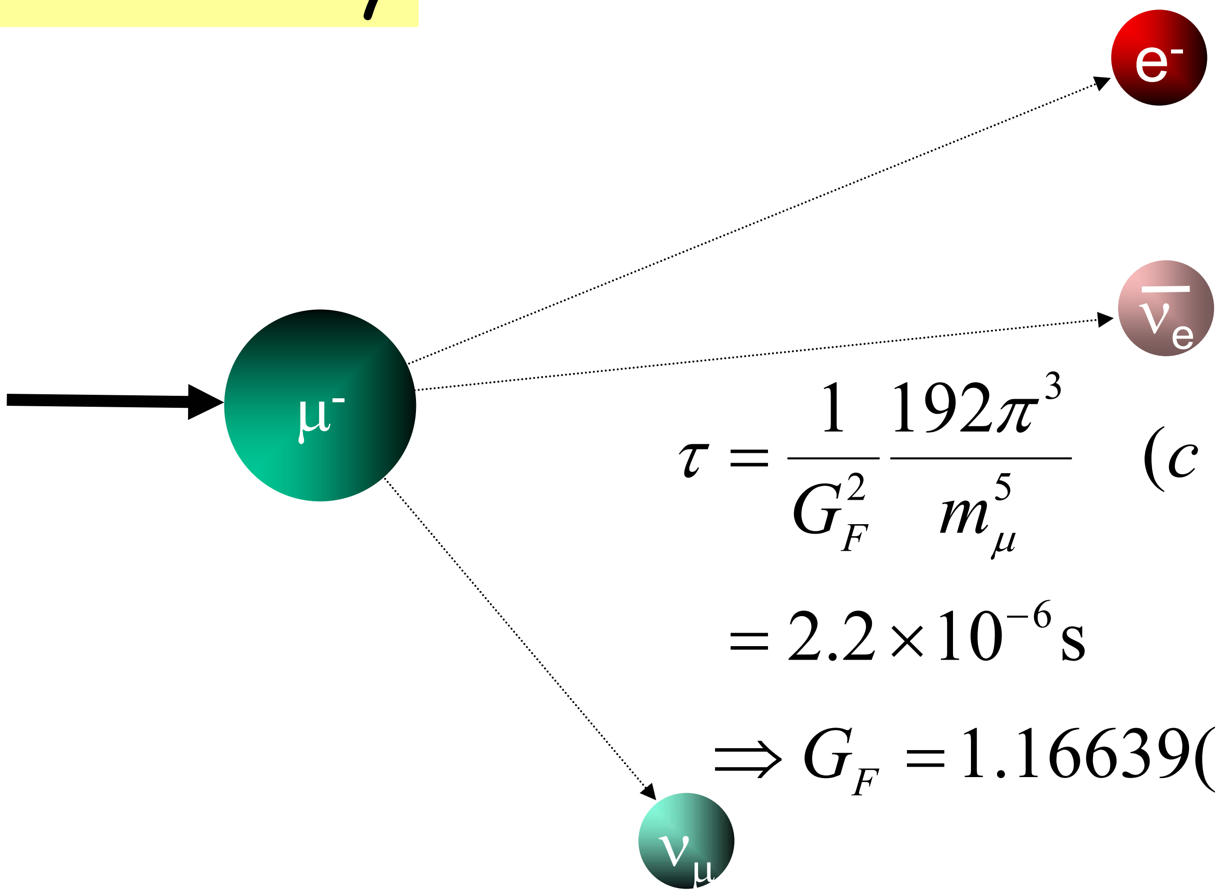
"Putting a box around it, I'm afraid, does not make it a unified theory."

summary

- standard model
  - unifies electroweak interaction into one gauge theory
  - strong interaction
  - many predictions confirmed precisely by experiment
  - some hints of discrepancies at the 3 sigma level
  - theoretically unsatisfying
- your charge
  - find physics beyond the standard model

weak interactions

➲muon decay



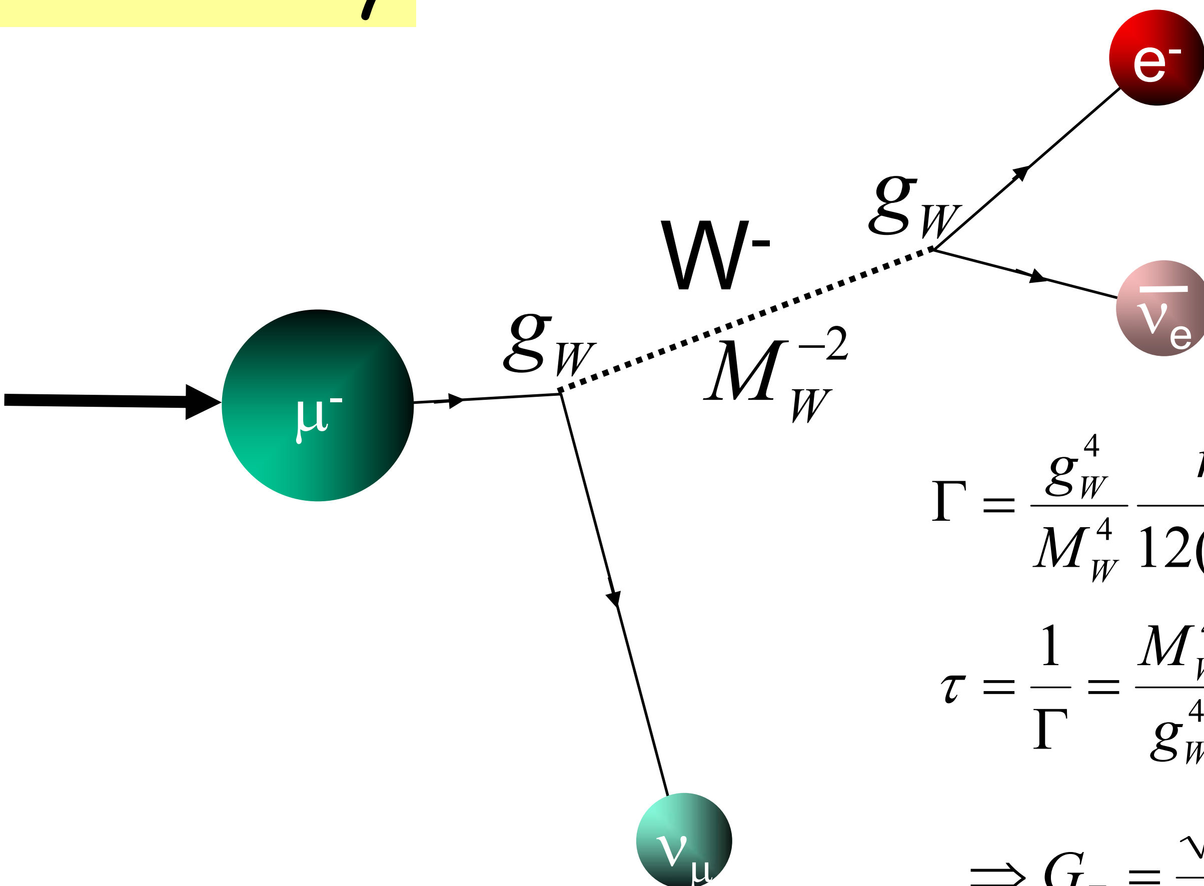
$$\tau = \frac{1}{G_F^2}\frac{192\pi^3}{m_\mu^5} \quad (c = \hbar = 1)$$

$$= 2.2\times 10^{-6}\,\mathrm{s}$$

$$\Rightarrow G_F = 1.16639(1)\times 10^{-5}\,\mathrm{GeV}^{-2}$$

weak interactions

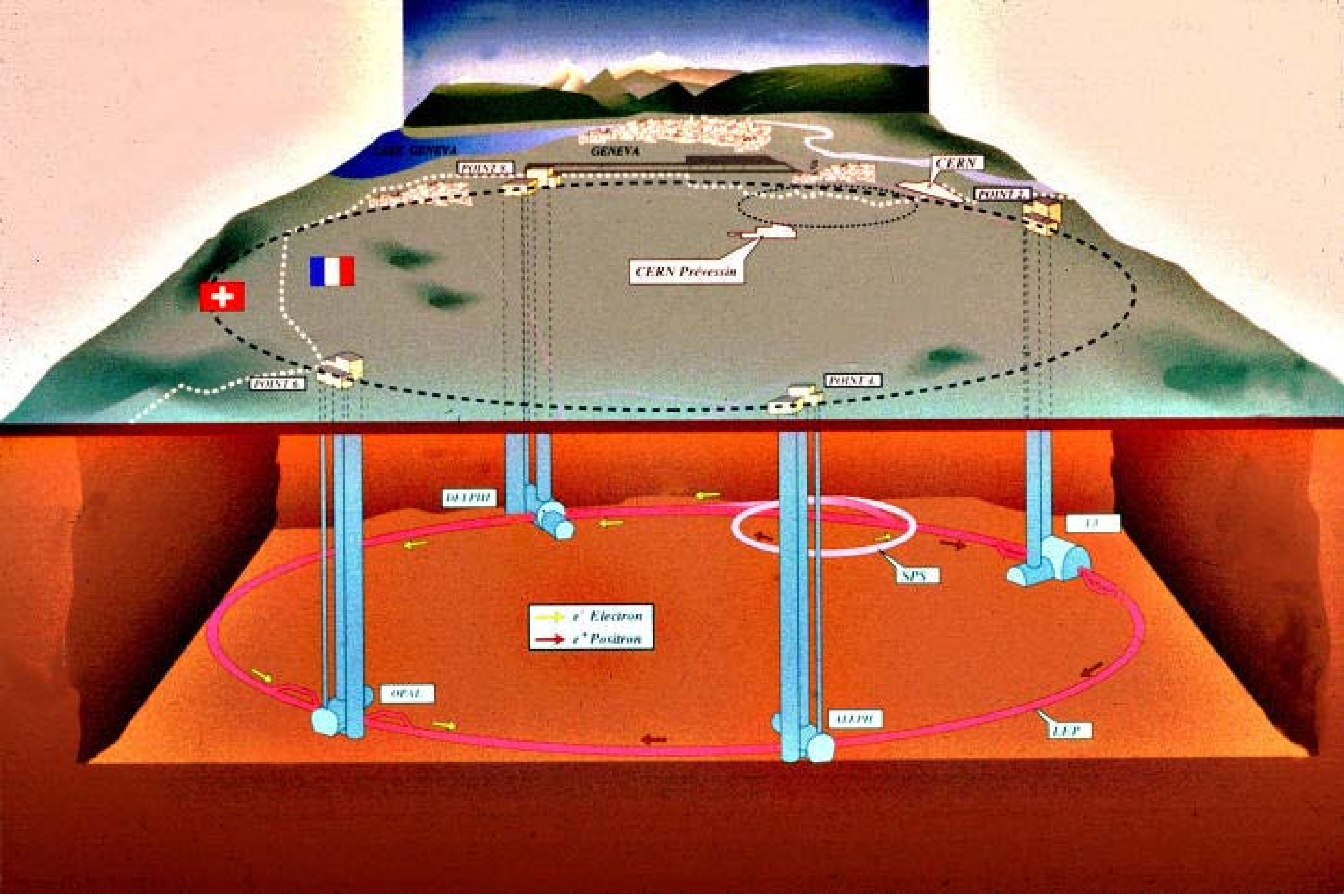
➲muon decay



$$\Gamma = \frac{g_W^4}{M_W^4} \frac{m_\mu^5}{12(8\pi)^3}$$

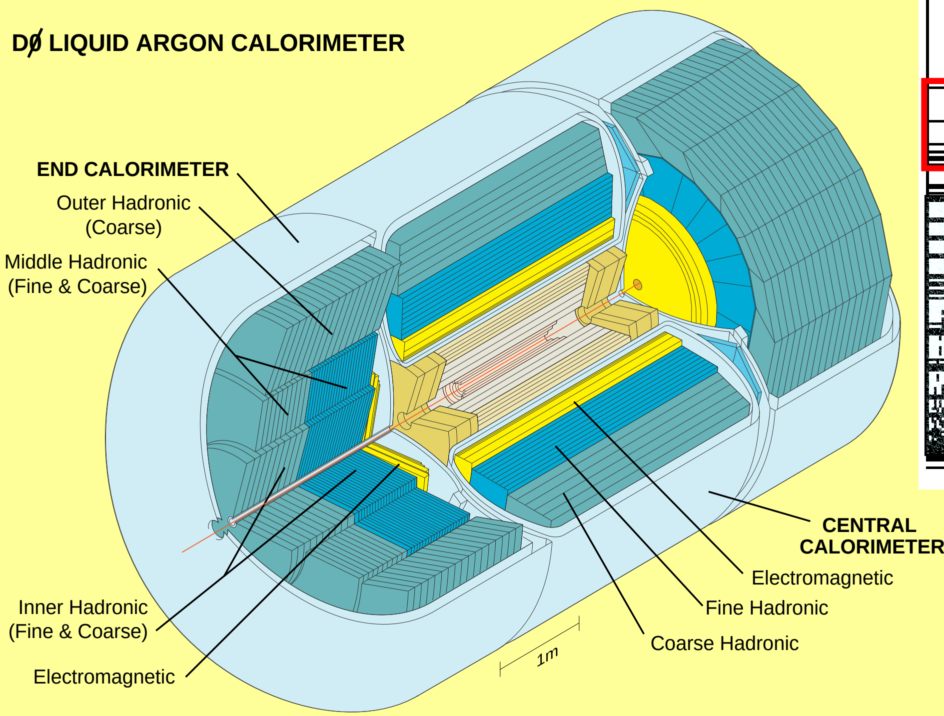
$$\tau = \frac{1}{\Gamma} = \frac{M_W^4}{g_W^4} \frac{12(8\pi)^3}{m_\mu^5}$$

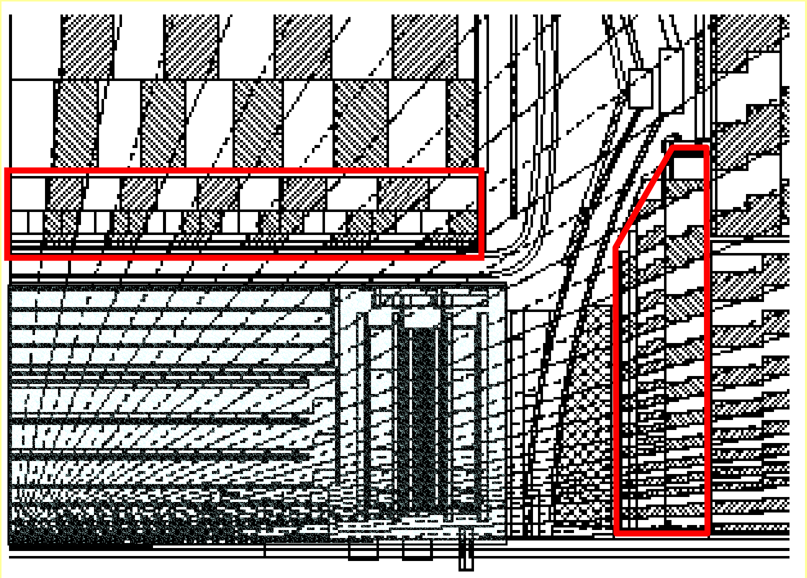
$$\Rightarrow G_F = \frac{\sqrt{2} g_W^2}{8 M_W^2}$$


GENEVA
CERN
CERN Prévessin
DELPHI
SPS
e^- Electron
e^+ Positron
OPAL
ALEPH
LEP

DØ detector

- calorimeter
  - measure energy and position





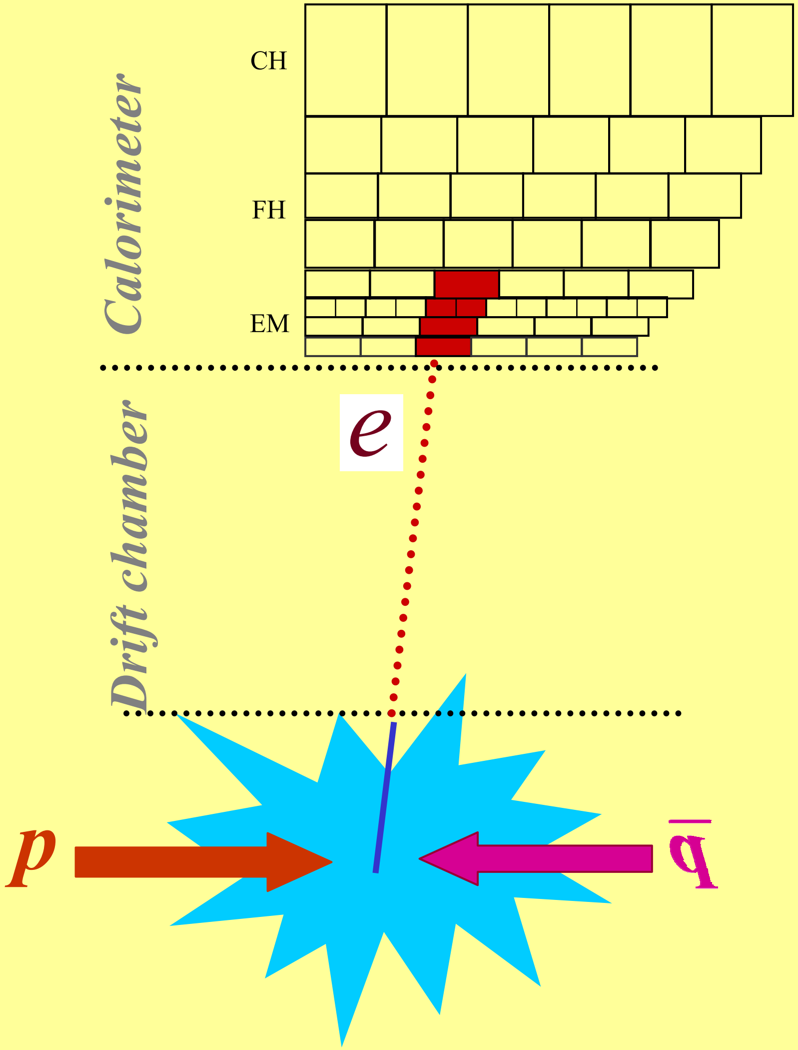
- drift chambers
  - measure direction

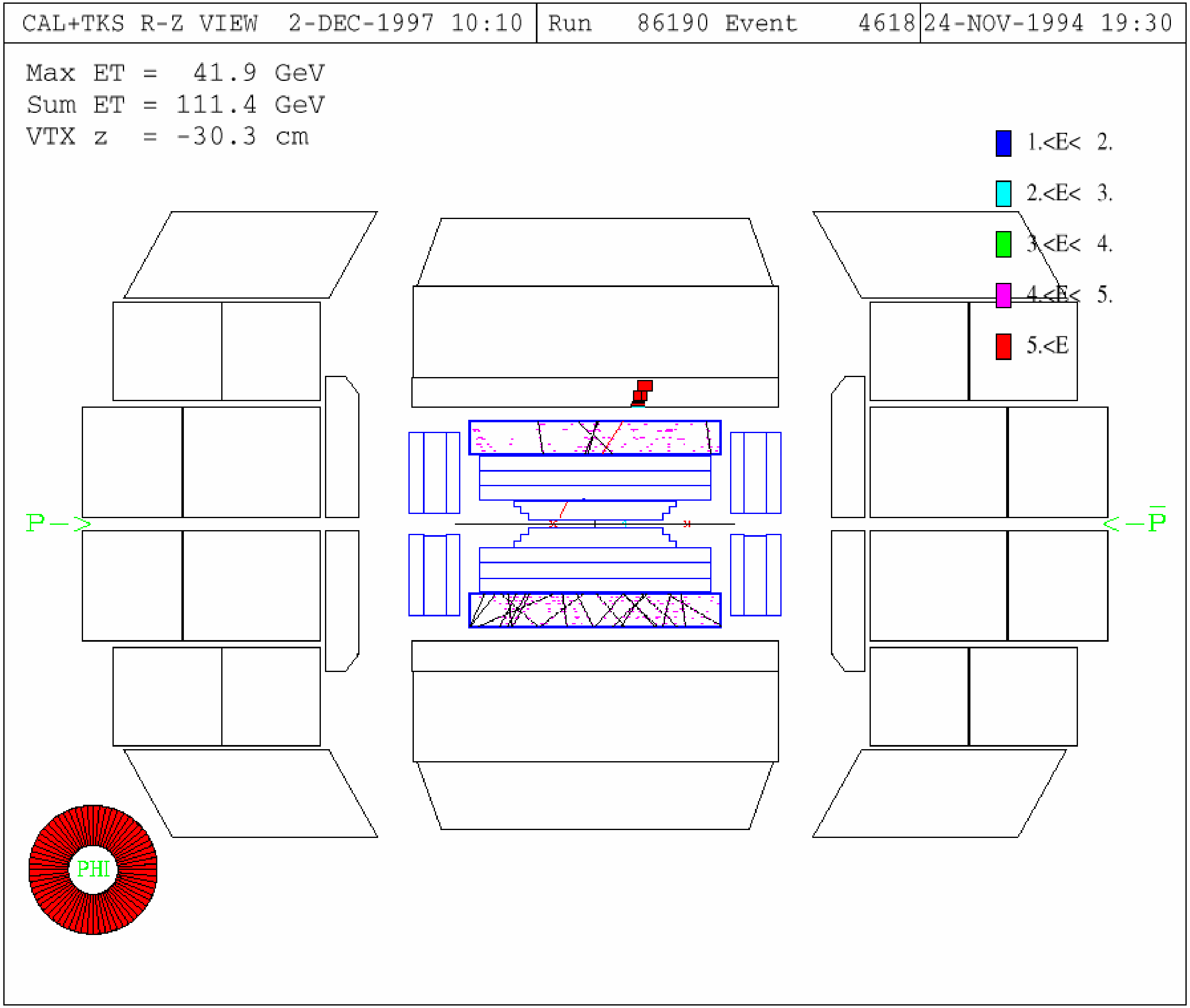
electron signature

- electron
  - measure
    - energy E
    - direction θ, ϕ
  - calculate
    - momentum

$$\vec{p} = \frac{E}{c}\begin{pmatrix} \cos\phi\sin\theta \\ \sin\phi\sin\theta \\ \cos\theta \end{pmatrix}$$

$$p_T = \frac{E}{c}\sin\theta$$



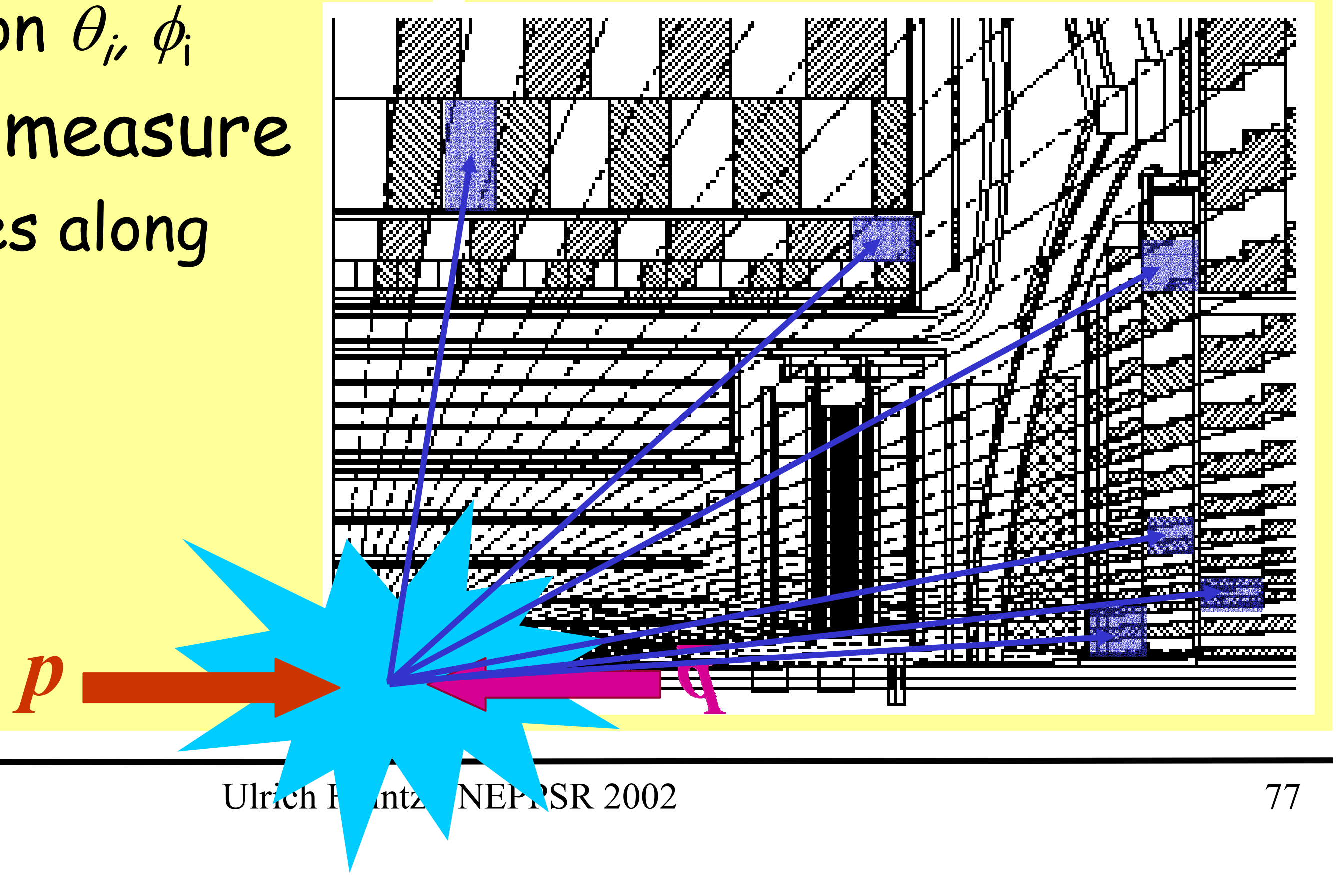

CAL+TKS R-Z VIEW 2-DEC-1997 10:10
Run 86190 Event 4618
24-NOV-1994 19:30
Max ET = 41.9 GeV
Sum ET = 111.4 GeV
VTX z = -30.3 cm
1.<E< 2.
2.<E< 3.
3.<E< 4.
4.<E< 5.
5.<E
P->
<-$\bar{P}$
PHI

measuring the W

- recoil
  - measure
    - energy in cell i E_i
    - direction θ_i, ϕ_i
  - cannot measure
    - particles along beam

- calculate

$$\vec{p}_T^{\,recoil} = \sum_{cells \neq electron} \vec{p}_T^{\,i}$$



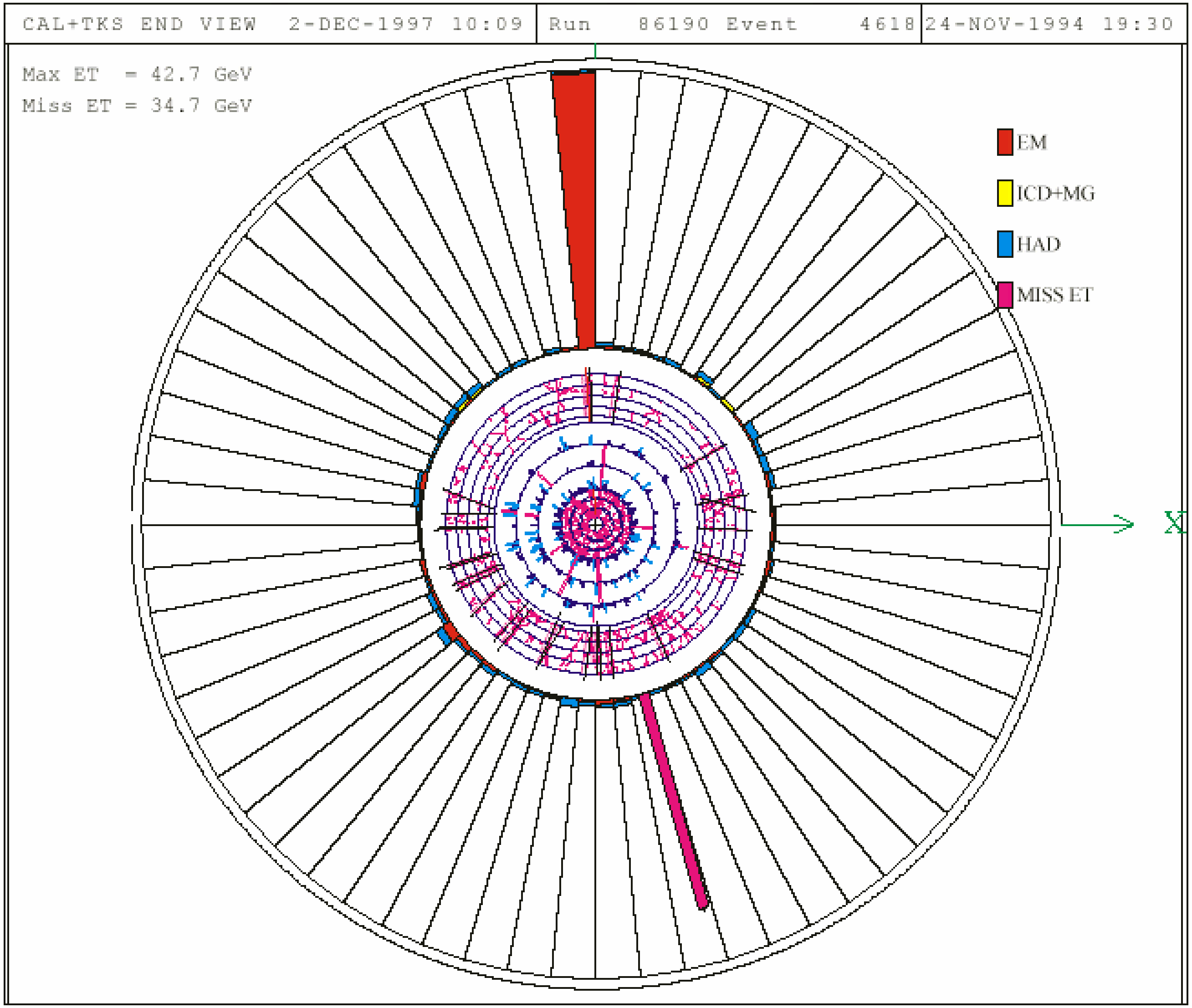
neutrino signature

- neutrino
  - measure
    nothing
  - momentum conservation

$$\vec{p}_p + \vec{p}_{\bar{p}} = 0 = \vec{p}_e + \vec{p}_\nu + \vec{p}_{recoil} \quad \text{but don't know } p_z^{recoil}$$

$$\Rightarrow 0 = \vec{p}_T^{\,e} + \vec{p}_T^{\,\nu} + \vec{p}_T^{\,recoil}$$

$$\Rightarrow \vec{p}_T^{\,\nu} = -\vec{p}_T^{\,e} - \vec{p}_T^{\,recoil} \quad \text{missing } p_T$$



CAL+TKS END VIEW 2-DEC-1997 10:09
Run 86190 Event 4618
24-NOV-1994 19:30
Max ET = 42.7 GeV
Miss ET = 34.7 GeV
EM
ICD+MG
HAD
MISS ET
X

Z mass measurement

- Z boson
  - measure

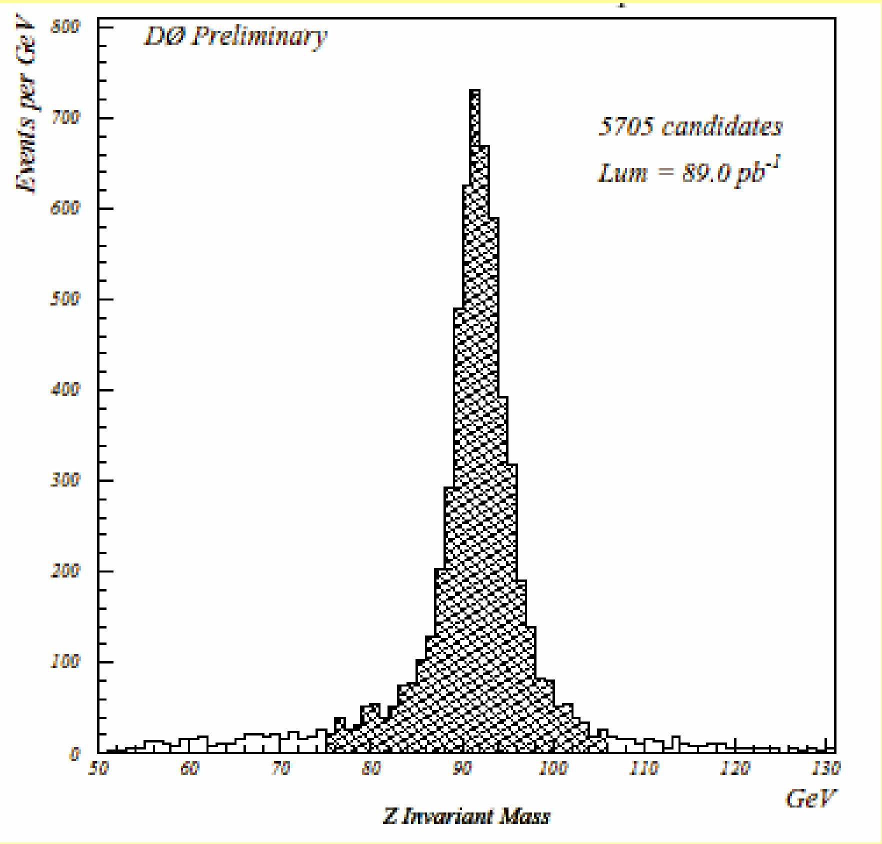
$$\vec{p}_Z = \vec{p}_{e^-} + \vec{p}_{e^+}$$

$$E_Z = E_{e^-} + E_{e^+}$$

$$M_Z{}^2 = E_Z^2 - p_Z^2$$

  - M_Z is invariant
    no dependence on $p_T{}^Z$
  - fit to Breit-Wigner
    ⇒ done (sort of…)

W mass measurement



W mass measurement

- W boson
  - measure

$$\left.\begin{aligned}\vec{p}_T^{\,W} &= \vec{p}_T^{\,e} + \vec{\not{p}}_T \\ E_T^W &= p_T^e + \not{p}_T\end{aligned}\right\} \Rightarrow M_T{}^2 = \left(E_T^W\right)^2 - \left(p_T^W\right)^2 \le M_W^2$$

  - M_T is not invariant

    depends on $p_T{}^W$ and parton distribution functions

    detector acceptances
  - need a detailed model of

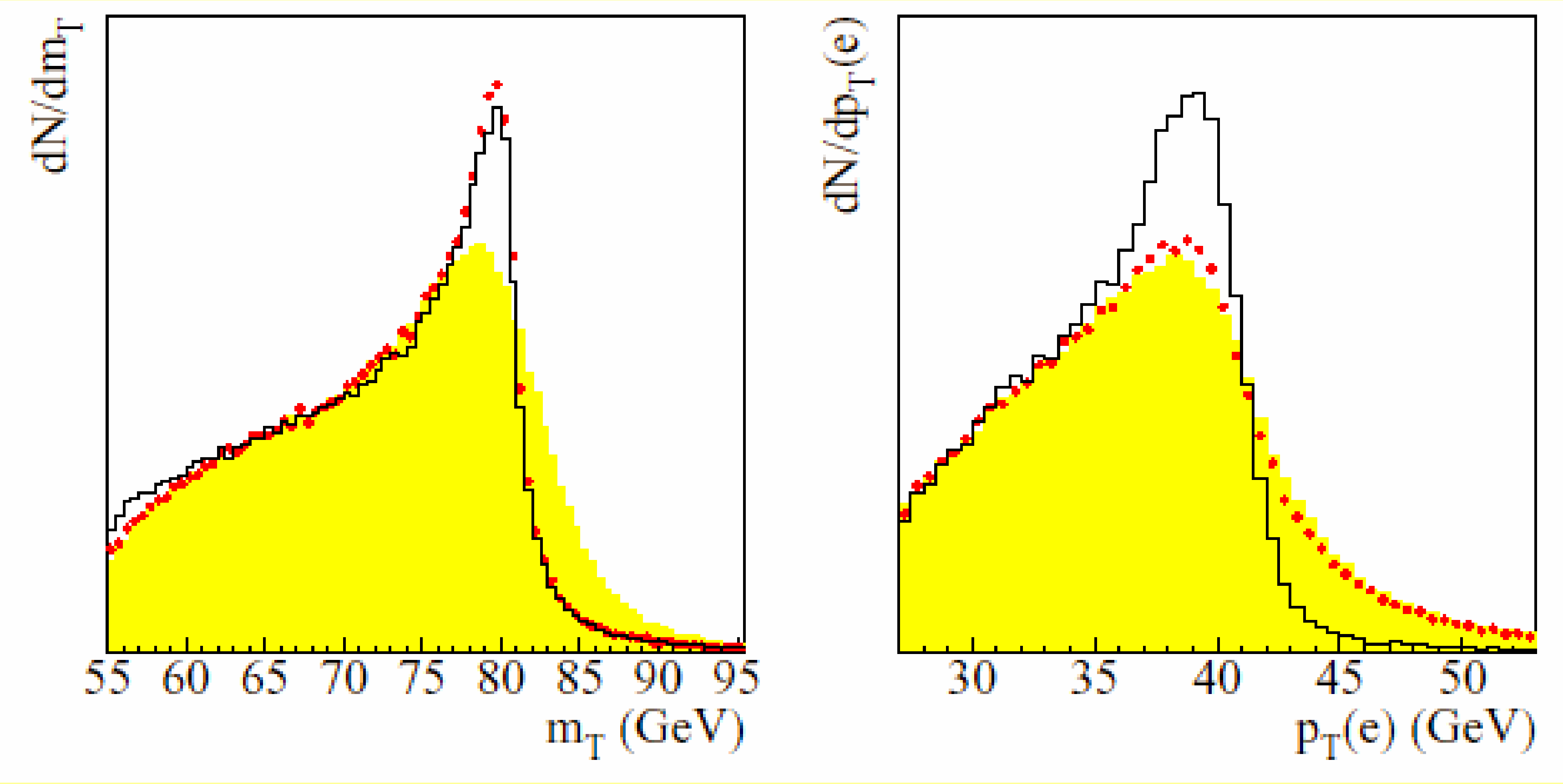
    W boson production

    detector

why transverse mass?

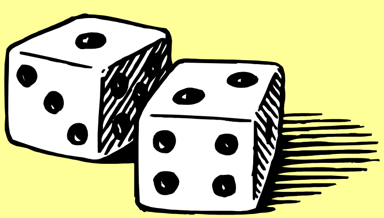
➲ W boson

W mass measurement

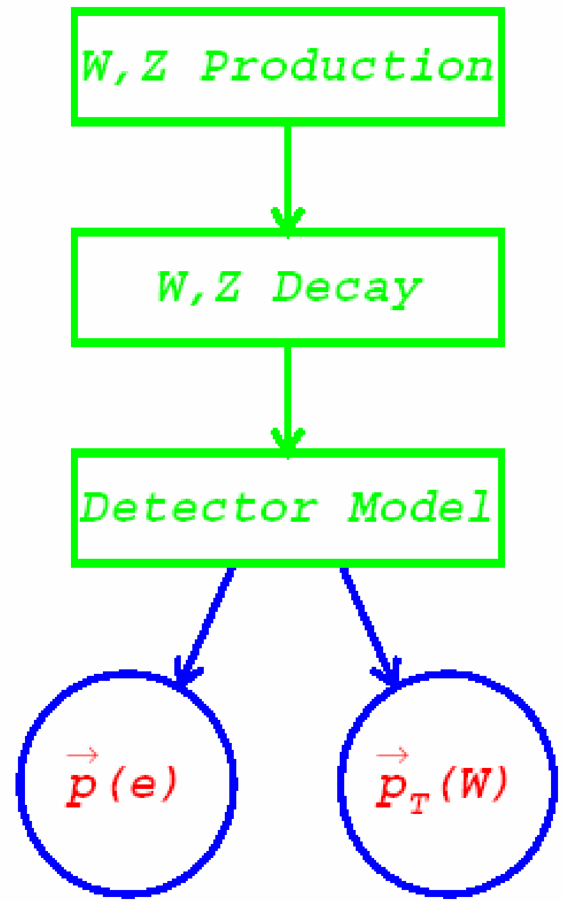


Monte Carlo model

➲ computer simulation
- ⇨ pick random p_W, M_W from distribution
- ⇨ pick random decay angles from distribution
- ⇨ simulate detector response
- ⇨ p_e and p_T^{recoil}



do this billions of times....



References

- Thomas Junk, CERN (ITP 4/18/01) Searches for the Higgs Boson at LEP
- Llewellyn Smith, on the determination of sin2θ in semileptonic neutrino interactions (KEK scan 83-4-300)
- K. McFarland "A Departure From Prediction: ewk Physics at NuTeV", FNAL Wine & Cheese October 26, 2001
- D0 "Limits on anomalous WWγ couplings from...", March 14, 1997
- S. Schmidt-Kärst "W mass measurements using fully hadronic events at LEPII", ICHEP 2000, Osaka
- R. Ströhmer "W measurements using semileptonic and fully leptonic events at LEPII". ICHEP 2000, Osaka
- LEPEWWG/MASS/2000-01 "Combined preliminary results on mass and with of W boson by LEP"
- Glenzinski, Heintz, "Precision measurements of the W boson mass"
- LEP electroweak working group summer 2002 plots
- LEPEWWG/2002-01 "Combination of preliminary ewk measurements and constraints on the sm"
- Heintz "Electroweak Measurements from Fermilab", APS centennial meeting 1999