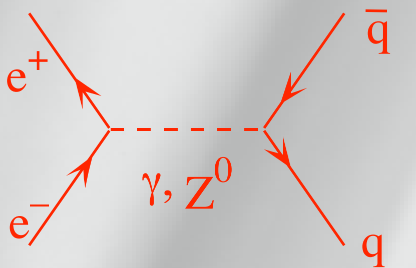
Standard Model precision measurements

at high energies

basically: LEP, (SLC, ILC)

- e^+e^- accelerators: LEP, SLC, ILC
- the OPAL experiment at LEP
- LEP final states
- Z^0 resonance and the Standard Model of electroweak interactions
- measurements of electroweak parameters
- some highlights ...
- search for the Higgs-Boson
- further topics at LEP

Standard Model precision measurements



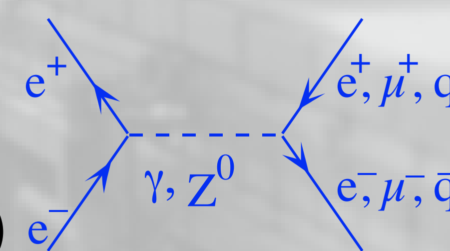
; e^+e^- annihilation:

- point-like particles
- well known quantum numbers and energies of initial and final state
- no hadronic (strong) interactions in and with initial state; no „underlying" or remnant event

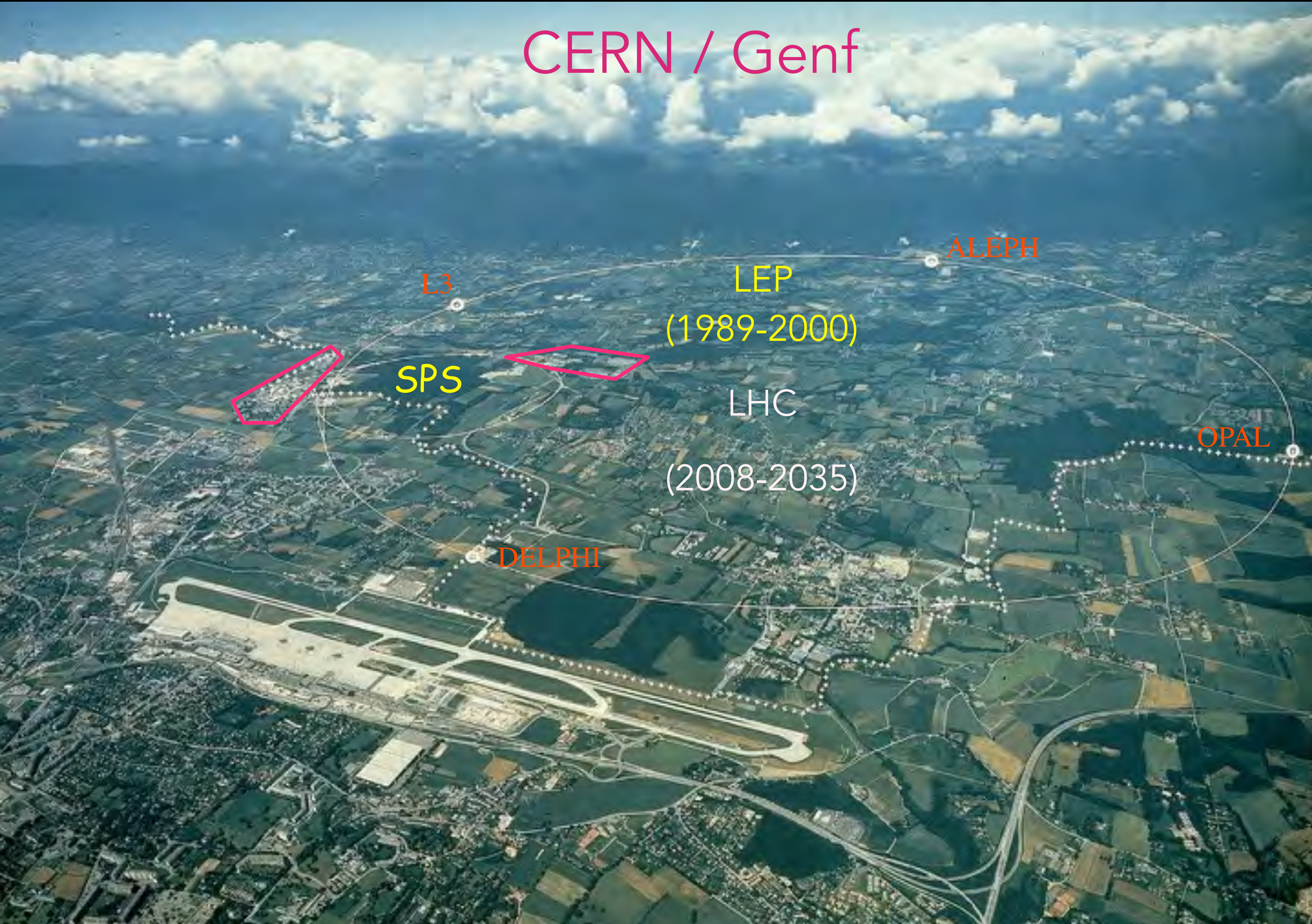
<—> precision!

technical requirements:

- precise knowledge of e^+e^- energies (accelerator)
- precise knowledge of luminosity (special detectors)
- precise measurement & classification of all final states (detectors)



CERN / Genf



LEP-Parameter

(Electron - Positron Collider at centre-of-mass energies E_{cm} up to 209 GeV)

	LEP-I	LEP-II
Strahlenergie bis	55 GeV	≈ 100 GeV
Magnet-Dipolfeld	0.065 T	0.111 T
Beschl.-Spannung pro Umlauf	260 MeV	2700 MeV
Klystron Leistung	16 MW	16 MW
Hohlraumresonatoren	Cu (normalleitend) 128 in P2 und P6	Cu-Nb (supraleitend) 272 in P2,4,6,8
Beschleunigungsspannung	1.5 MV/m	6 MV/m
Strahlstöme	3 mA	5 mA
Zahl der e^+e^- Pakete	4 x 4	4 x 4 (x 2 bunchlets)
max Luminosität	$1.6 \cdot 10^{31}$ $cm^{-2}s^{-1}$	$5 \cdot 10^{31}$ $cm^{-2}s^{-1}$
Energieunschärfe	70 MeV	280 MeV
sys. Energiefehler	1.4 MeV	25-30 MeV
Strahllebensdauer:	≈ 6 - 8 h	≈ 5 h

Energiekalibration: durch **resonante Depolarisation** der sich selbständig aufbauenden Strahlpolarisation; durchgeführt bei geeigneten Strahlenergien (z.Z. bis ca 55 GeV), sowie Extrapolation auf höhere Energien mit flux-loop-Messungen.

max. Strahlenergie: 104.5 GeV -> $\sqrt{s}$ = 209 GeV (Herbst 2000)

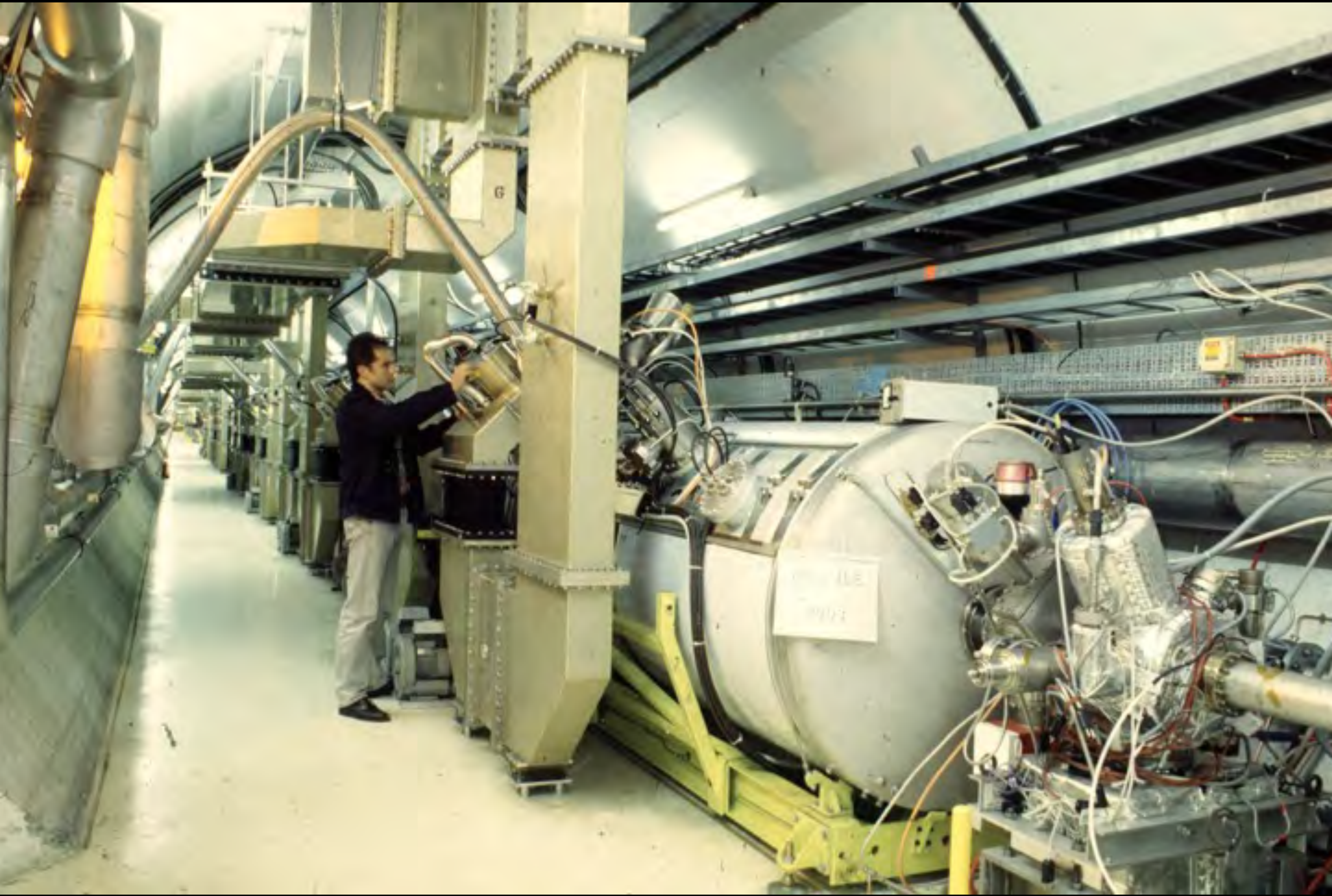
Quadrupol-Magnets

(focussing)

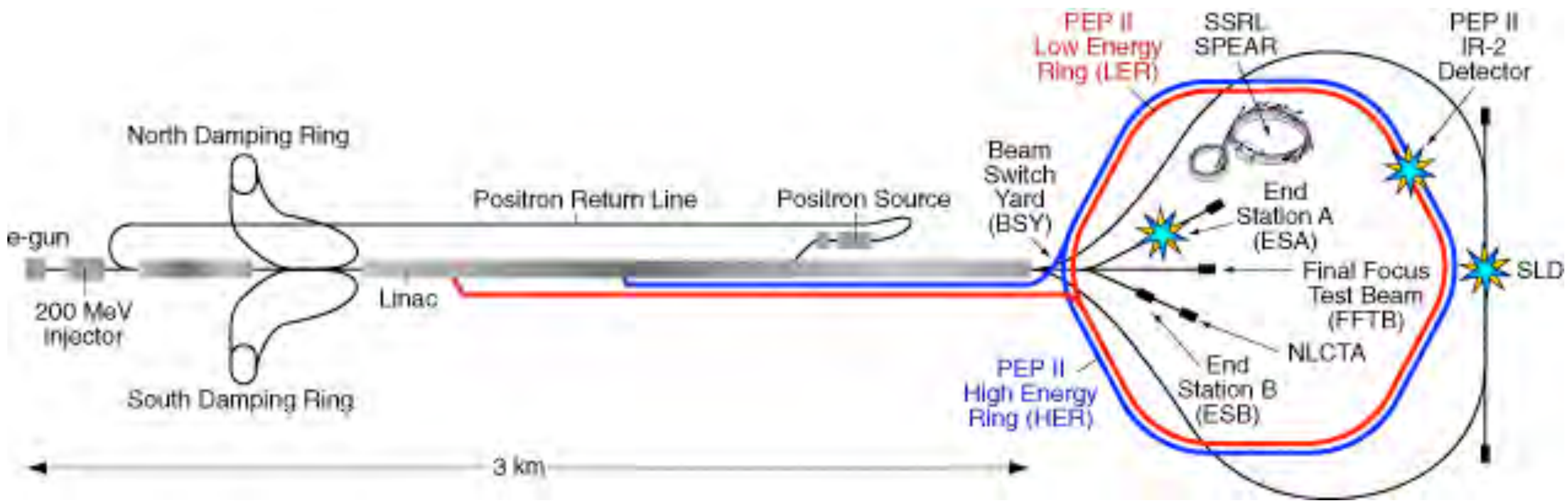
Dipol-Magnets

(circular path)

LEP - superconducting accelerating cavities



SLAC Linear Collider (SLC)



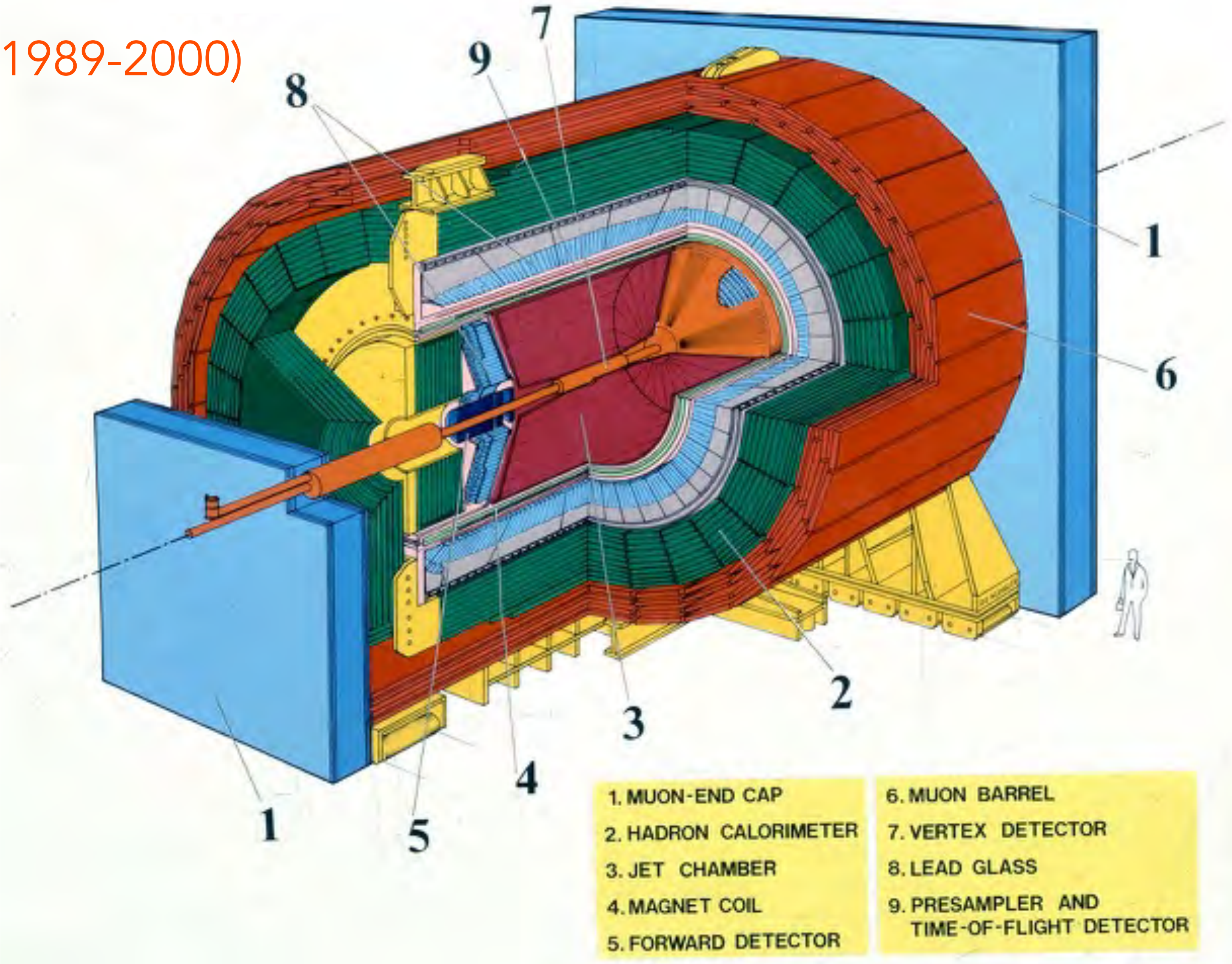
- e^- up to 50 GeV; fixed-target program (until 1980's)
- e^- and e^+ for PEP-I storage rings (E_{cm} = 29 GeV; early 1980's)
- e^- and e^+ for SLC collider ($E_{cm} = M_Z$ ~ 91 GeV; 1989 - 1999)
- e^- and e^+ for PEP-II storage rings (E_{cm} ~10 GeV; 1999 - 2008)

SLC:

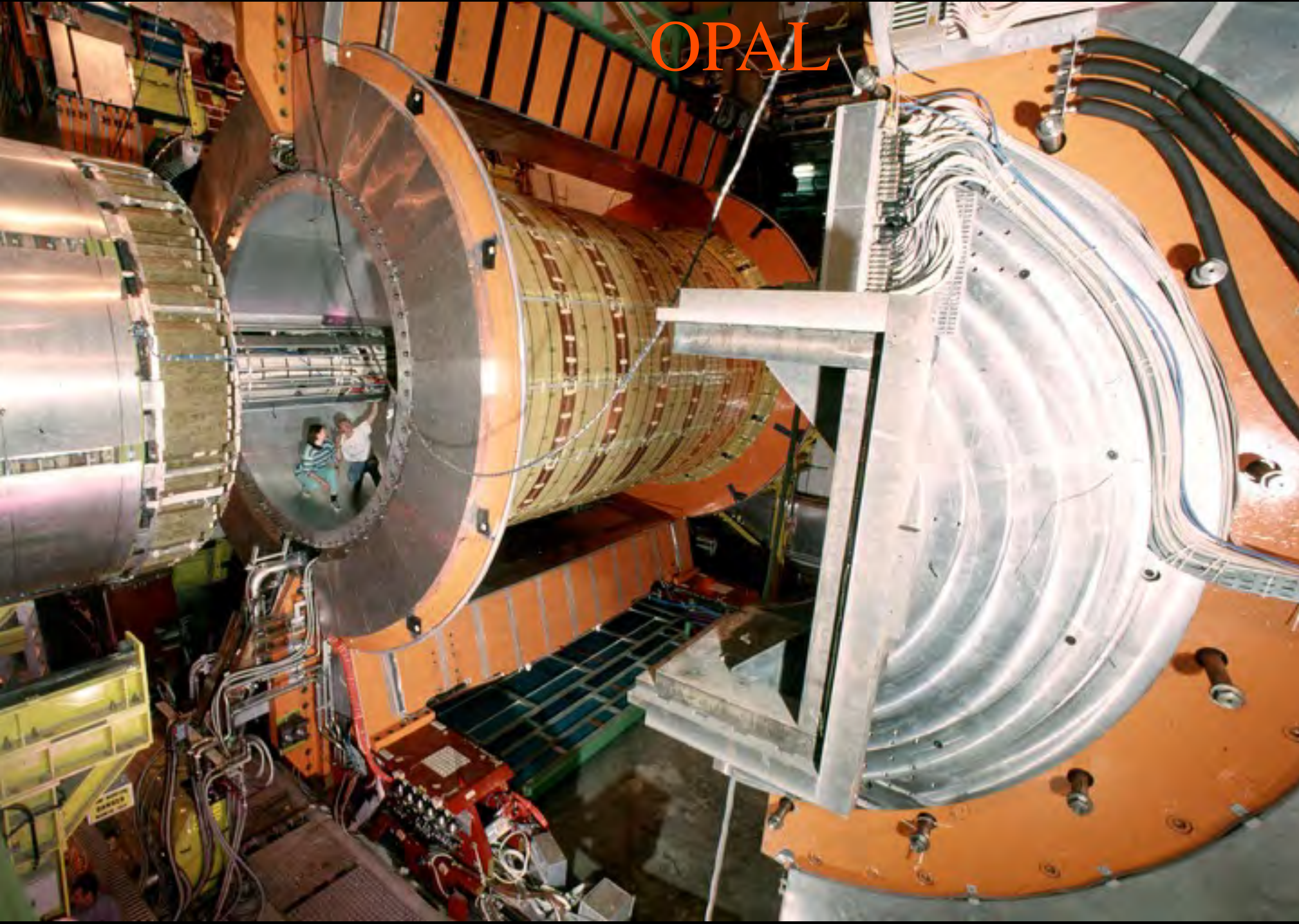
– substantially smaller luminosities and data statistics than LEP (e-, e+ are not recycled but are dumped after each collision)

+ polarisation of e^- beam up to 80% (polarised e- -source; conservation of polarisation due to ~absence of synchrotron radiation)

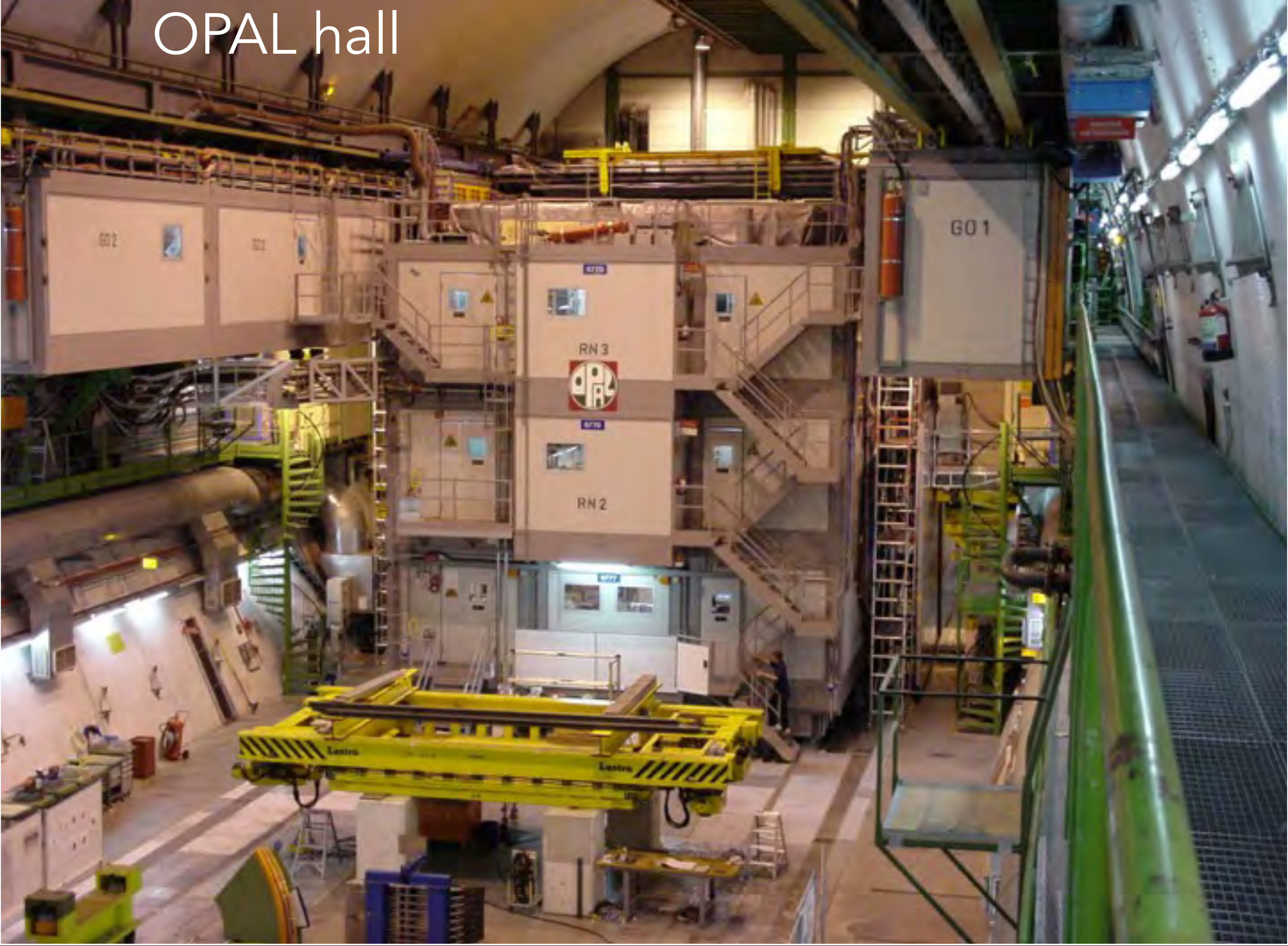
The OPAL Detector at LEP (1989-2000)



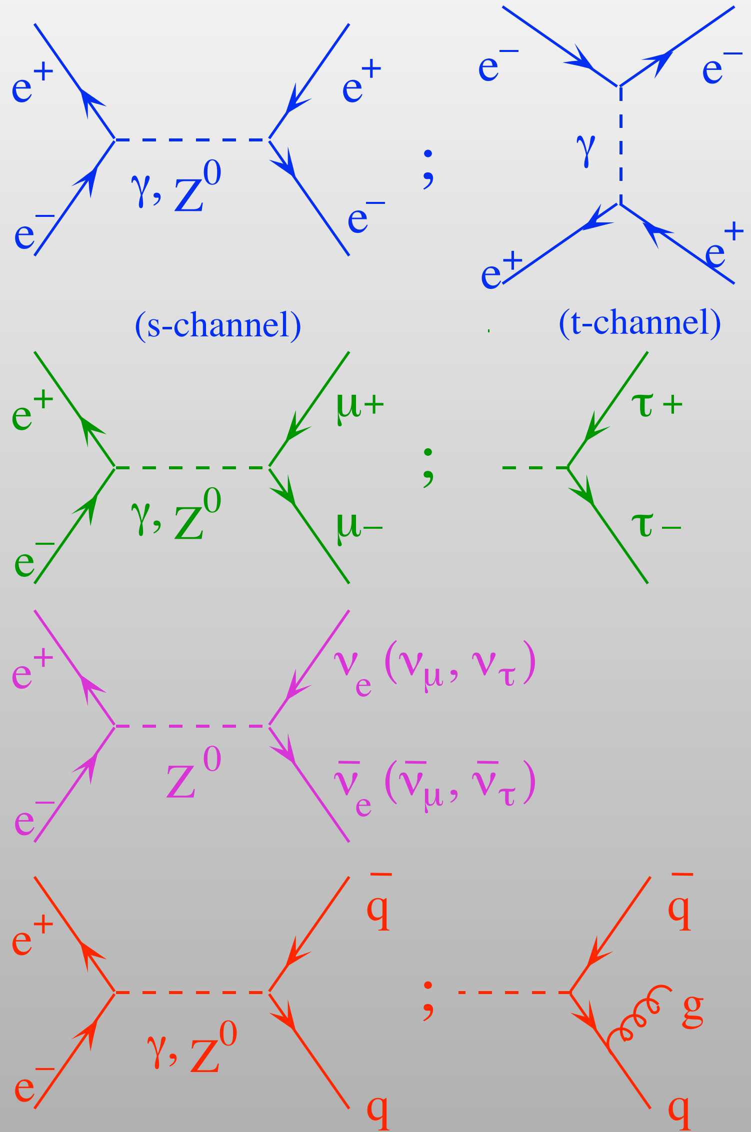
OPAL



OPAL hall



final states of high energy reactions at LEP



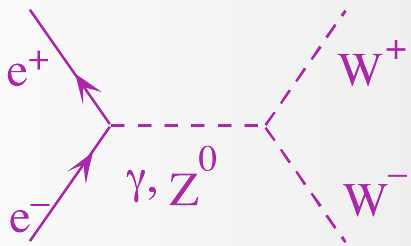
Bhabha-scattering

μ−, τ−pair-production

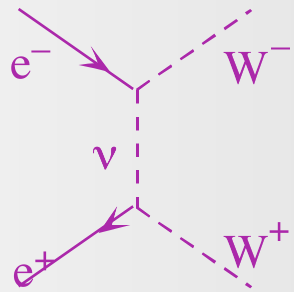
Neutrino-pair-production
("invisible")

Quark-Antiquark-pairs
plus Gluons:
hadronic final states
(dominant channel!)

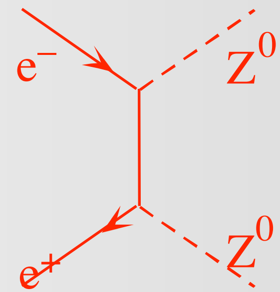
final states of high energy reactions at LEP



(s-Kanal)

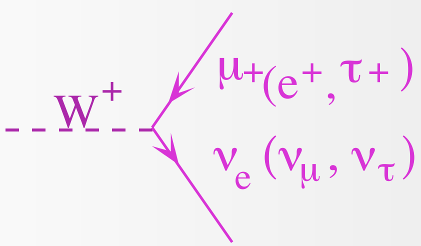


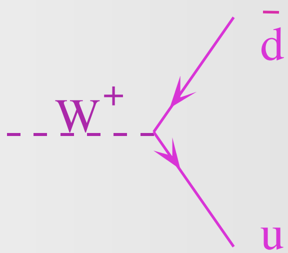
(t-Kanal)



W/Z - pair production (LEP - II)

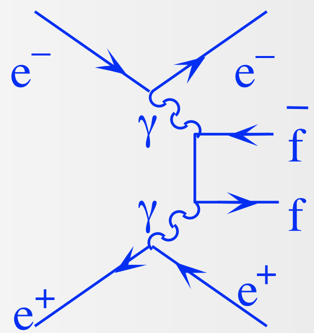
with:



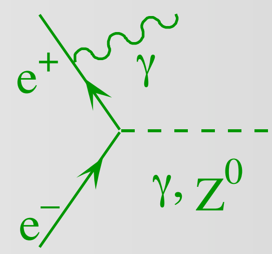


(W-decays;
Z-decays as above)

further important processes:

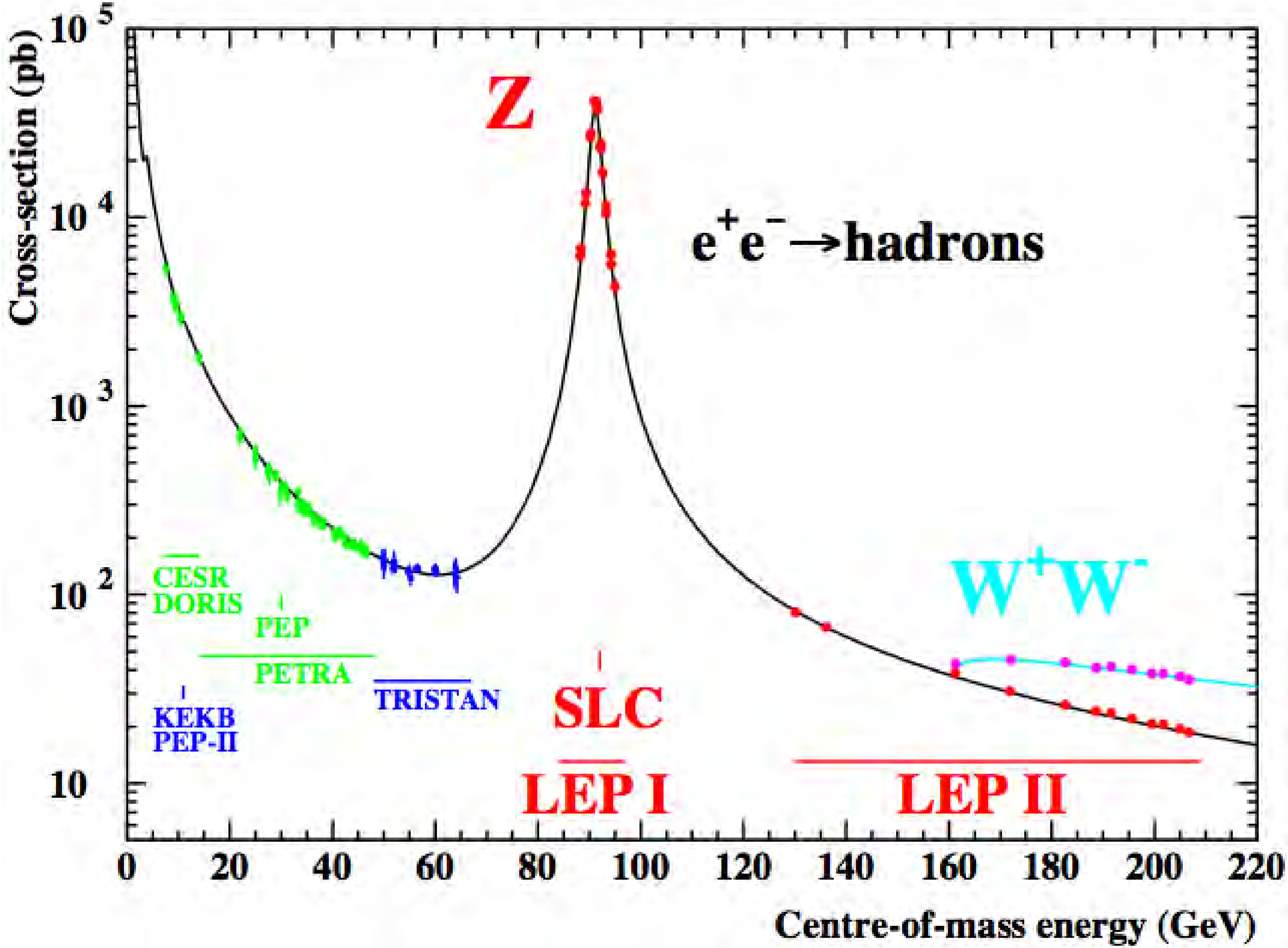


2-Photon - processes



Bremsstrahlung in initial state (suppressed at Z^0 resonance)

hadronic cross section

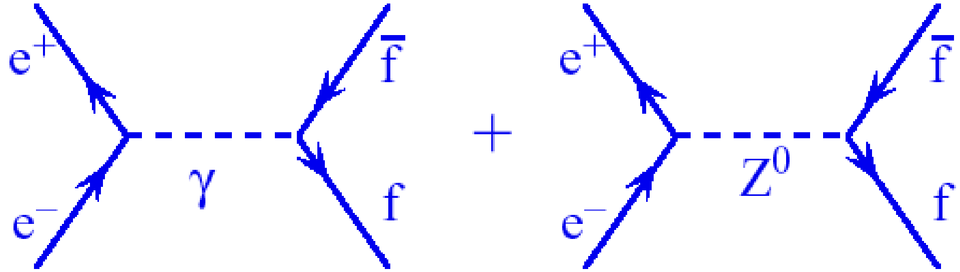


Z^0-Resonance and the Standard Model of Electroweak Interactions

minimal *SM* in lowest order („*Born Approximation*") describes processes like $e^+e^- \rightarrow f\bar{f}$ using only 3 free parameters:

α	[fine structure constant]
G_F	[Fermi constant; from μ lifetime]
$\sin^2\theta_W$	[weak mixing angle; from ν-N-scattering]

or: α , G_F and M_Z (since $\sin^2\theta_W \cos^2\theta_W = \frac{\pi\alpha}{G_F\sqrt{2}} \frac{1}{M_Z^2}$)



$$(f, \bar{f}) \equiv (e^+, e^-), \; (\mu^+, \mu^-), (\tau^+, \tau^-) ;$$
$$(\nu_e, \bar{\nu}_e), \; (\nu_\mu, \bar{\nu}_\mu), (\nu_\tau, \bar{\nu}_\tau) ;$$
$$(u, \bar{u}), \; (c, \bar{c}), \; (t, \bar{t}) ;$$
$$(d, \bar{d}), \; (s, \bar{s}), \; (b, \bar{b}) .$$

cross sections around Z^0 resonance ($f \neq e$):

$$\sigma_f(s) = \sigma_f^0 \cdot \frac{s\,\Gamma_Z}{\left(s - M_Z^2\right)^2 + M_Z^2\,\Gamma_Z^2} + \text{"}\gamma\text{"} + \text{"}\gamma Z\text{"}$$

$$\sigma_f^0 = \frac{12\,\pi}{M_Z^2} \cdot \frac{\Gamma_e\,\Gamma_f}{\Gamma_Z^2}$$ (pole cross sections; $\sum \Gamma_f = \Gamma_Z$)

Measurement of s-dependent cross sections around the Z^0 resonance and adjustment of $\sigma_f(s)$, σ_f^0 provides model independent results for:

$$M_Z\,,\ \Gamma_Z\,, \Gamma_f\,,\ \sigma_f^0\,.$$

SM : Γ_f are <u>no free parameters,</u> they are parametrised as functions of the *vector* and *axial vector constants:*

$$\Gamma_f = \frac{G_f\, M_Z^3}{6\pi\,\sqrt{2}} \cdot [g_{a,f}{}^2 + g_{v,f}{}^2] \cdot N_{c,f}$$

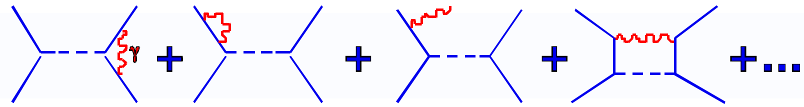
$N_{c,f}$: *colour factor;* $\equiv 3$ *for quarks,* $\equiv 1$ *for leptons.*

$g_{a,f} = I_{3,f}$ (3rd component of weak isospin; $= \pm 1/2$)

$g_{v,f} = I_{3,f} - 2\,Q\,\sin^2\theta_w$

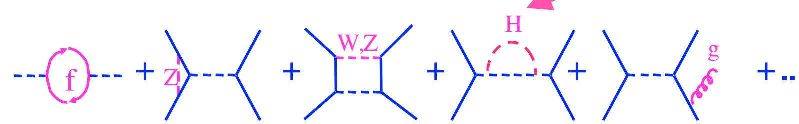
radiation corrections in Standard Model:

photonic corrections:



corrections ~ 100%, selection dependent;
factorisable: $(1 + \delta_{rad})$

non-photonic corrections:



corrections ~ 10%, selection independent;
can be absorbed in running couplings:

- $\sin^2\theta_{eff}(s)$
- $\alpha(s) = \frac{\alpha}{1-\Delta\alpha}$; $\Delta\alpha = 0.064$ bei $\sqrt{s} = M_Z$
- $N_{c,f}\left(1 + \frac{\alpha_s}{\pi} + 1.4\left(\frac{\alpha_s}{\pi}\right)^2 + \ldots\right)$ (für Quarks)
- $\frac{M_W^2}{M_Z^2} = \rho \cdot \cos^2\theta_w$ mit $\rho = \frac{1}{1-\Delta\rho}$; $\Delta\rho = 0.0026\,\frac{M_t^2}{M_z^2} - 0.0015\,\ln\left(\frac{M_H}{M_w}\right)$

insertion of running couplings in “Born”-approximation :

partial Z decay widths $\Gamma_f = \frac{G_f\, M_z^3}{6\pi\sqrt{2}}\left[g_{a,f}^2 + g_{v,f}^2\right] N_{c,f}$ (and also

cross sections) acquire dependence on:

- **M_t**
- **M_H**
- α_s

==> indirect determination (fit) of M_t, M_H, and α_s from combination of all available electroweak observables

(differential cross sections, partial decay widths, forward-backward asymmetries, τ-polarisation, left-right asymmetries (SLC))

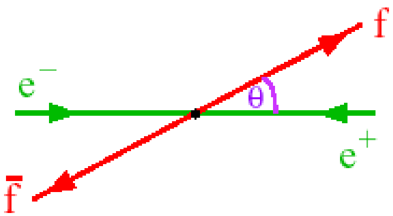
$g_{a,f} = I_{3,f}$ (3. Komponente schw. Isospin; $= \pm 1/2$)

$g_{v,f} = I_{3,f} - 2Q\sin^2\theta_w$

Further Observables to be measured:

- differential cross sections:

$$\frac{d\sigma_f}{d\cos\theta} \propto A \cdot \left(1+\cos^2\theta\right) + B \cdot \cos\theta$$



A and B include terms for γ- and Z^0-exchange as well as for γ-Z^0-interference, which depend on

$\left(g_{a,e}^2 + g_{v,e}^2\right)$, $\left(g_{a,f}^2 + g_{v,f}^2\right)$, $\left(g_{a,e} \cdot g_{a,f}\right)$, $\left(g_{v,e} \cdot g_{v,f}\right)$, and on

the relativistic Breit-Wigner resonance, $\dfrac{s}{s - M_Z^2 + is\Gamma_Z / M_Z}$.

- forward-backward asymmetries:

$$A_{FB} = \frac{N_F - N_B}{N_F + N_B}$$

N_F: number of events with $\theta < \pi/2$
N_B: number of events with $\pi/2 < \theta < \pi$

on the Z^0 pole: $$A_{FB}^{0,f} = \frac{3}{4} \mathcal{A}_e \mathcal{A}_f$$

with $$\mathcal{A}_f = \frac{2 g_{v,f} \cdot g_{a,f}}{g_{v,f}^2 + g_{a,f}^2} \qquad \left[\approx \frac{g_{v,f}}{g_{a,f}} \quad \text{for leptons} \right]$$

- final state polarisations of leptons:

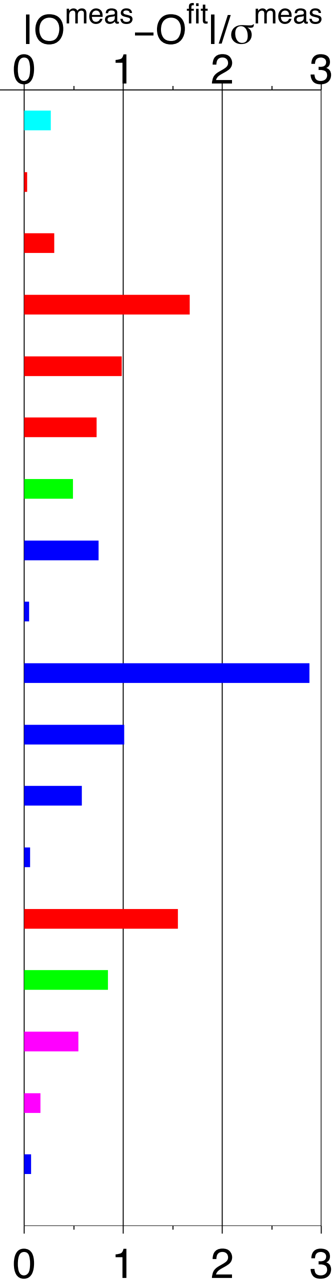
$$\mathcal{P}_f = \frac{1}{\sigma_{tot}} \cdot \left(\sigma_f(h=+1) - \sigma_f(h=-1) \right)$$

$$\mathcal{P}_f(s = M_Z) = -\mathcal{A}_f$$

$$A_{FB}^{\mathcal{P}_f}(s = M_Z) = -\frac{3}{4} \mathcal{A}_e$$

measurements and determinations of elektroweak parameters

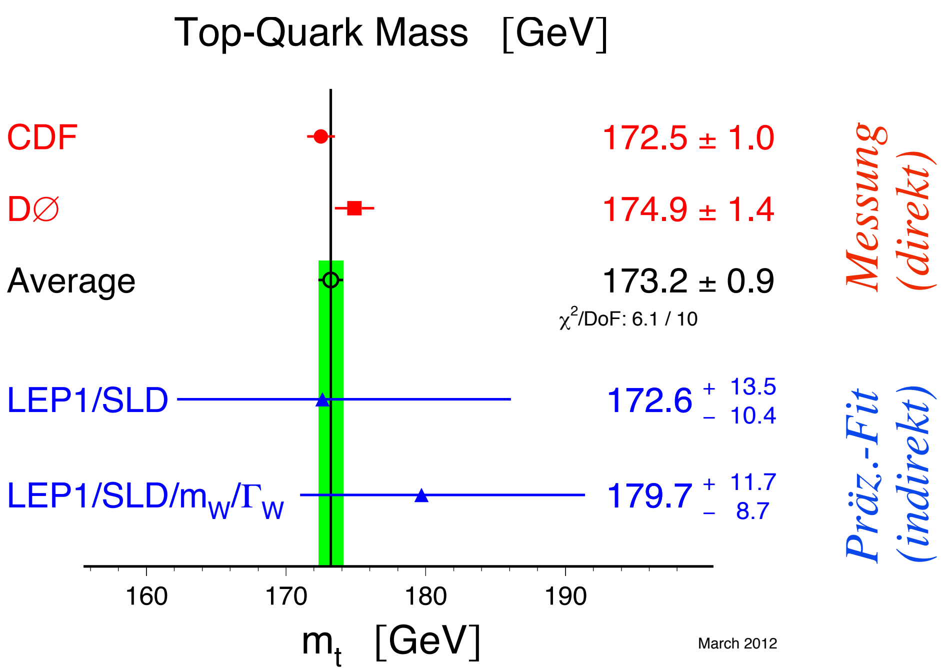
	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02750 ± 0.00033	0.02759
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ_{had}^{0} [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.385 ± 0.015	80.377
Γ_W [GeV]	2.085 ± 0.042	2.092
m_t [GeV]	173.20 ± 0.90	173.26

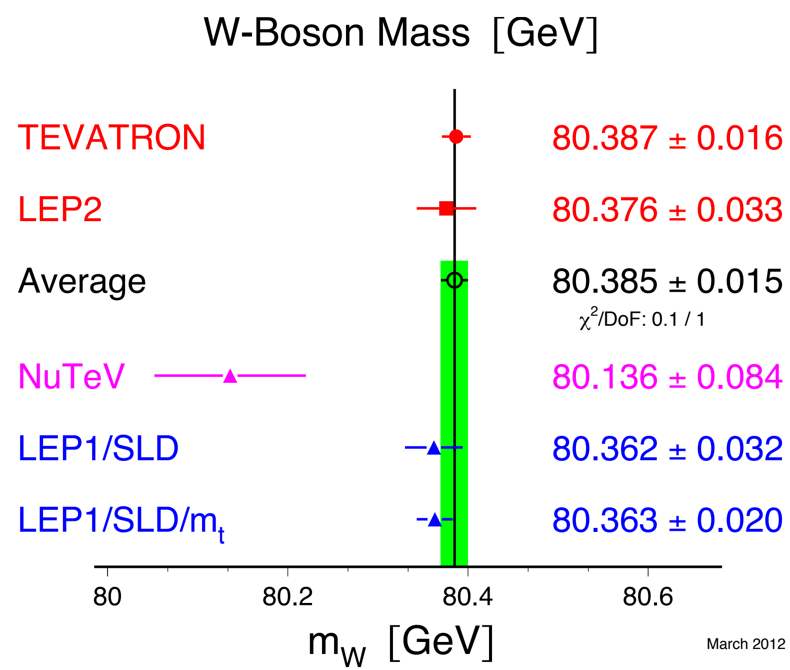


March 2012

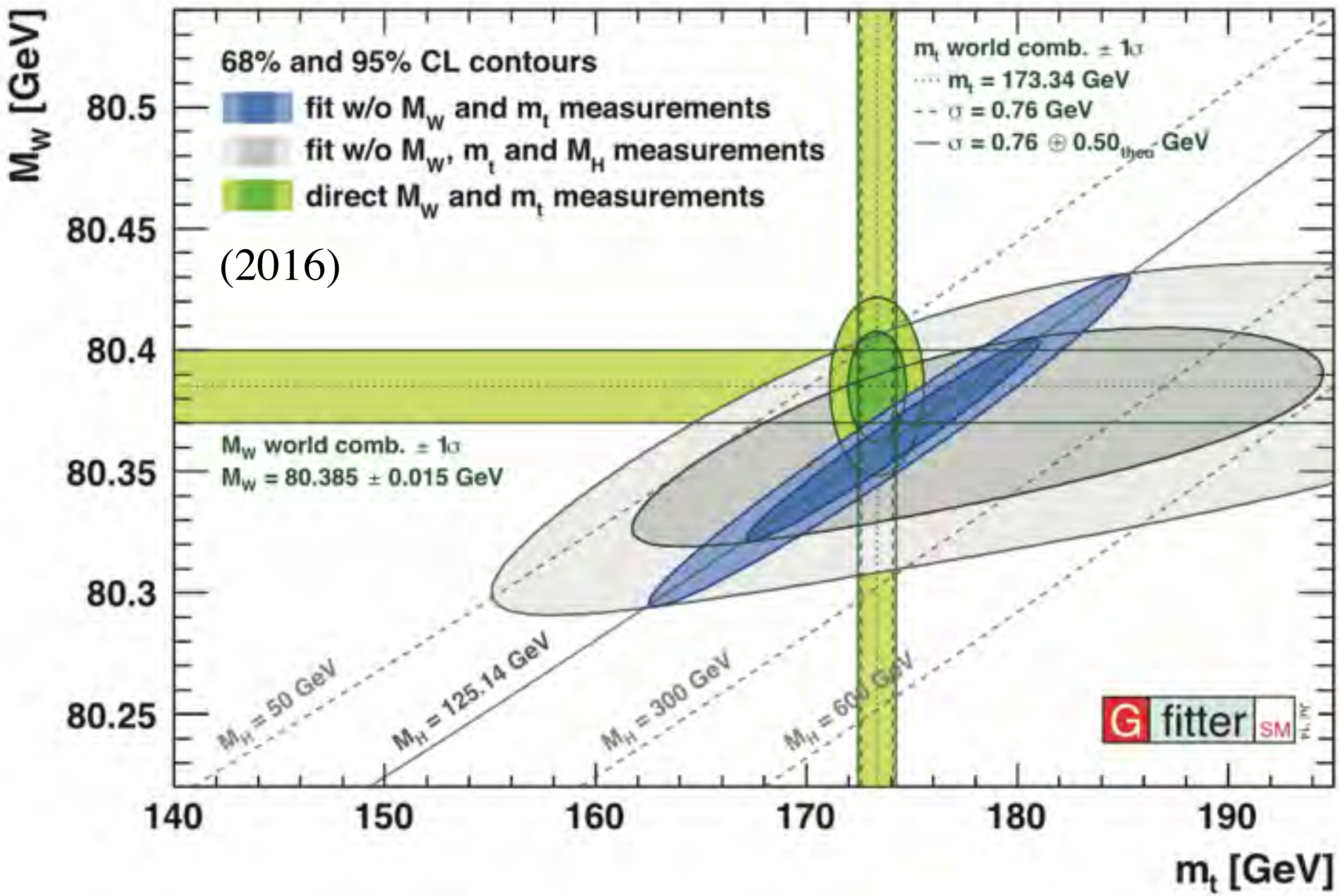
includes data from Tevatron: M_t, M_W

measurements and determinations of elektroweak parameters





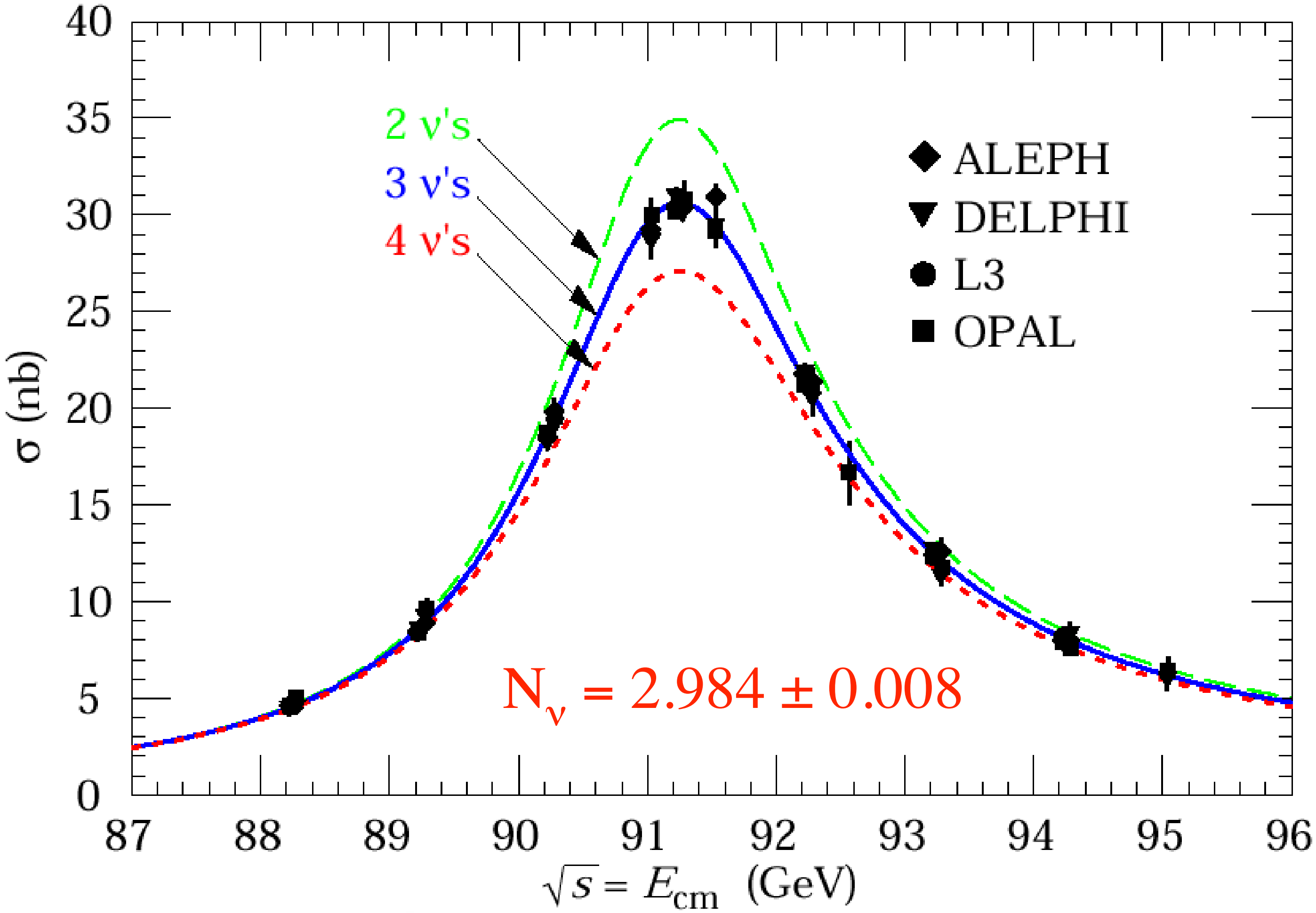
measurements and determinations of elektroweak parameters



Highlights at LEP:

line shape of the Z^0- Boson at LEP:

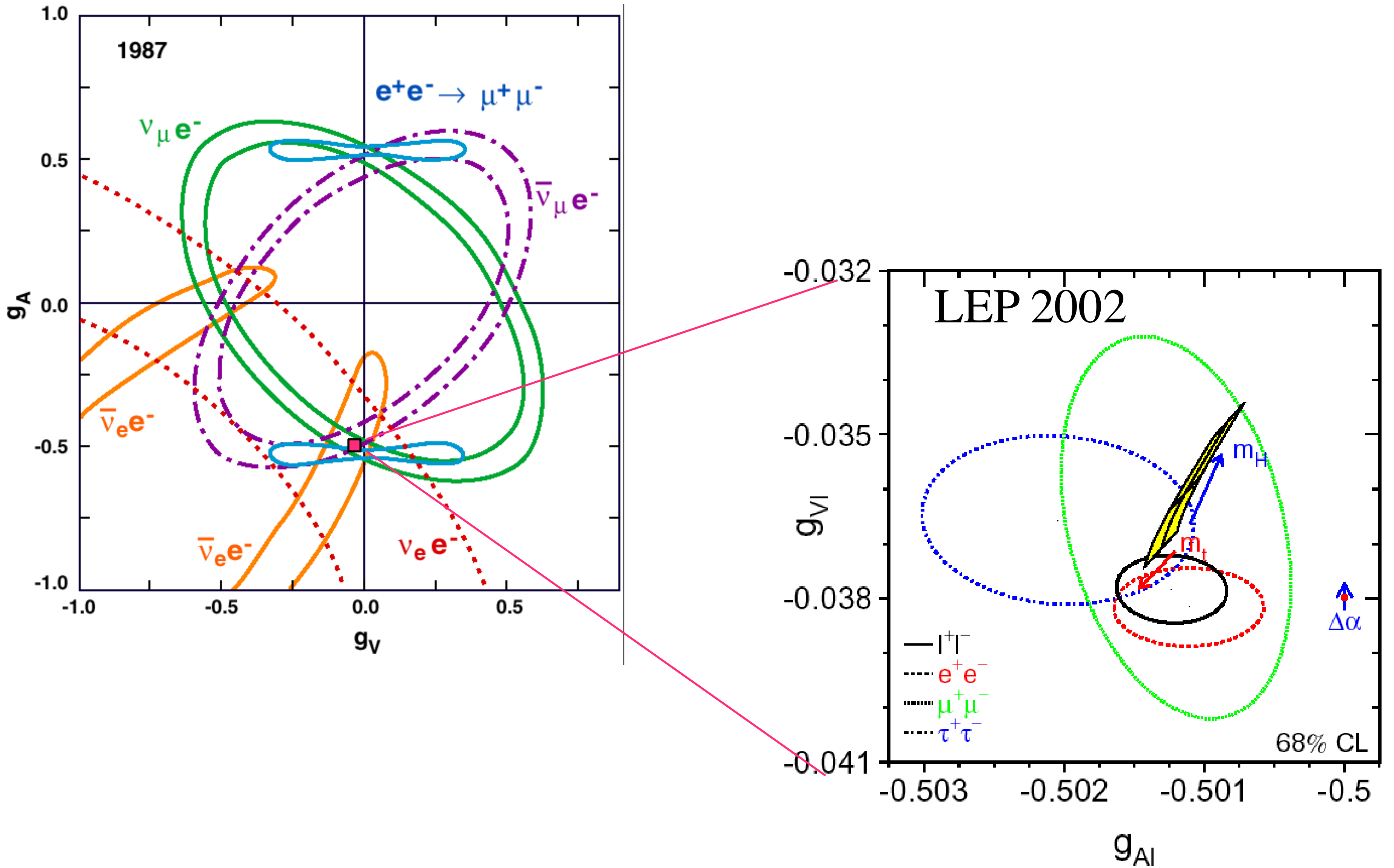
there are exactly 3 generations of light Neutrinos



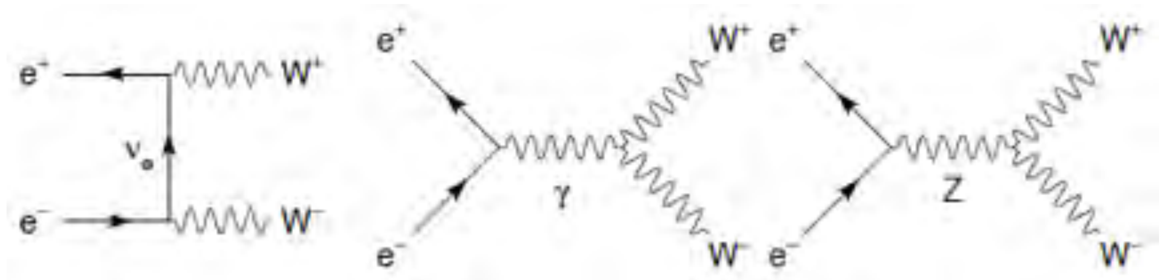
- M_Z = (91.1875 ± 0.0021) GeV
  (...after correcting for phases of the moon and for TGV time schedule!)

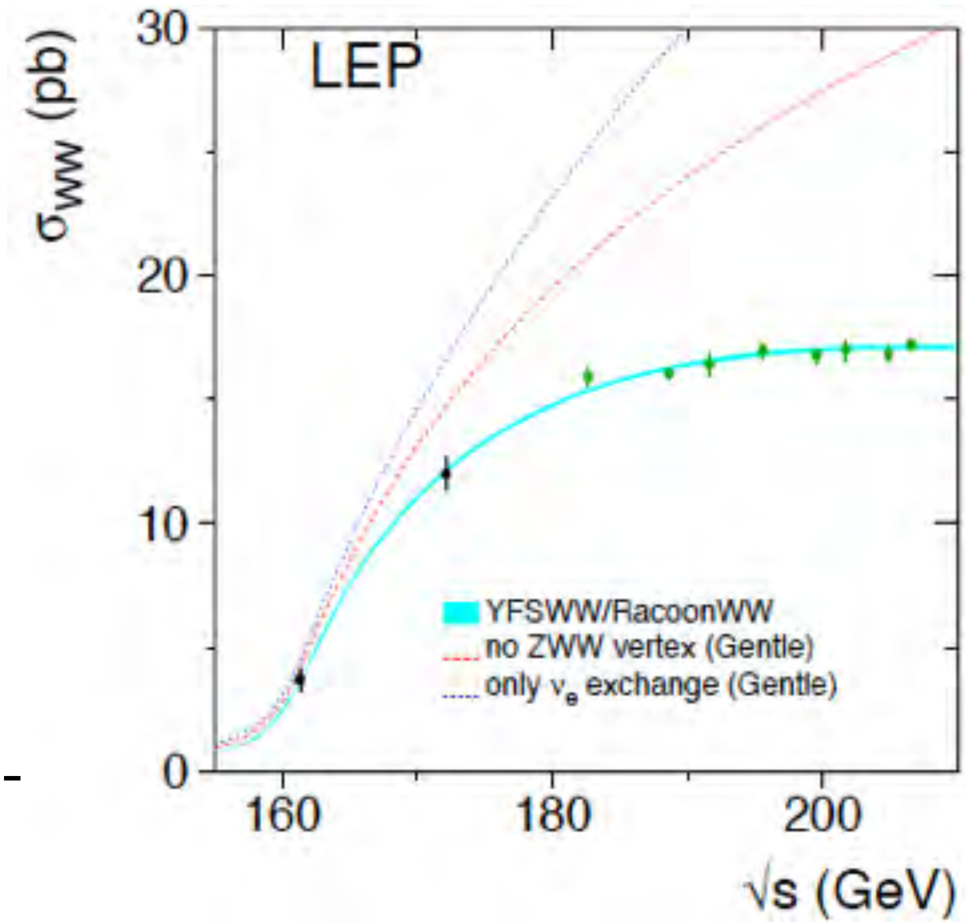
Highlights at LEP:

precision results on electroweak axial- und vector couplings



e^+e^- –> WW

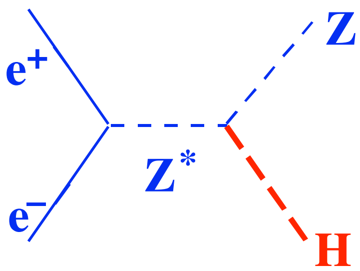


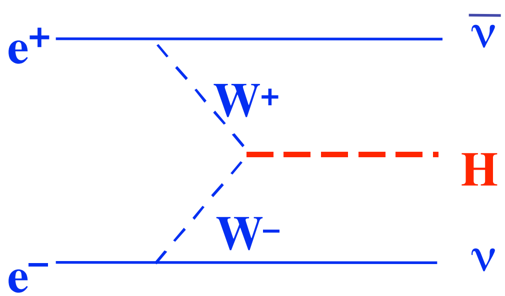


(Evidence for Boson-Boson-coupling!)

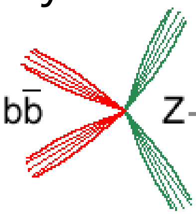
direct Higgs searches in e^+e^- annihilations

Production:

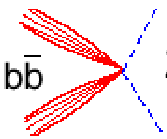




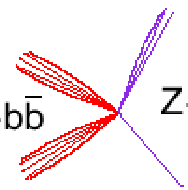
decay channel (e+e– –> HZ): background:



$H \to b\bar{b}$ $Z \to q\bar{q}$ **4-Jet-Kanal** 51% — $WW \to qqqq, ZZ \to bbqq$, QCD 4jets

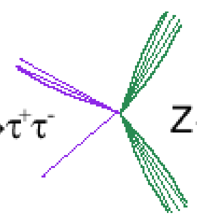


$H \to b\bar{b}$ $Z \to \nu\bar{\nu}$ **Neutrino-Kanal** 15% — $WW \to ql\nu, ZZ \to bb\nu\nu$

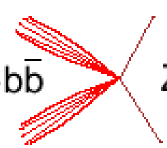


$H \to b\bar{b}$ $Z \to \tau^+\tau^-$ 2.4%

Tau-Kanal — $WW \to qq\tau\nu, ZZ \to qq\tau\tau$, QCD (low-mult. jets)



$H \to \tau^+\tau^-$ $Z \to q\bar{q}$ 5.1%



$H \to b\bar{b}$ $Z \to e^+e^-, \mu^+\mu^-$ **Lepton-Kanal** 4.9% — $ZZ \to bbll$

includes about 80% of all final states with about 40-50% selection efficiencies

direct Higgs searches in e^+e^- annihilations

analysis:

- each experiment determines 3 observables, for each hypothetical Higgs-mass, and for each decay channel:

  – N_{obs} (number of candidate events)
  – N_{sig} (number of expected signal events - from model calculations)
  – N_{BG} (number of expected background events - from model calcs.)

- statistical evaluation based on "likelyhood"parameters: test-statistics; likelyhood functions; confidence intervals. [Junk, Bock]

- combination of results from various decay channels and from all 4 LEP experiments

direct Higgs searches in e^+e^- annihilations

status July 2000: no hint for the Higgs; $M_H > 113.3$ GeV/c² (95% CL)

[final status July 2001: $M_H > 114.1$ GeV/c²]

5. Sept. 2000: ALEPH sees excess in 4-Jet channel, compatible with $M_H \sim 115$ GeV/c². LEP-combination: 2.2 σ excess over background

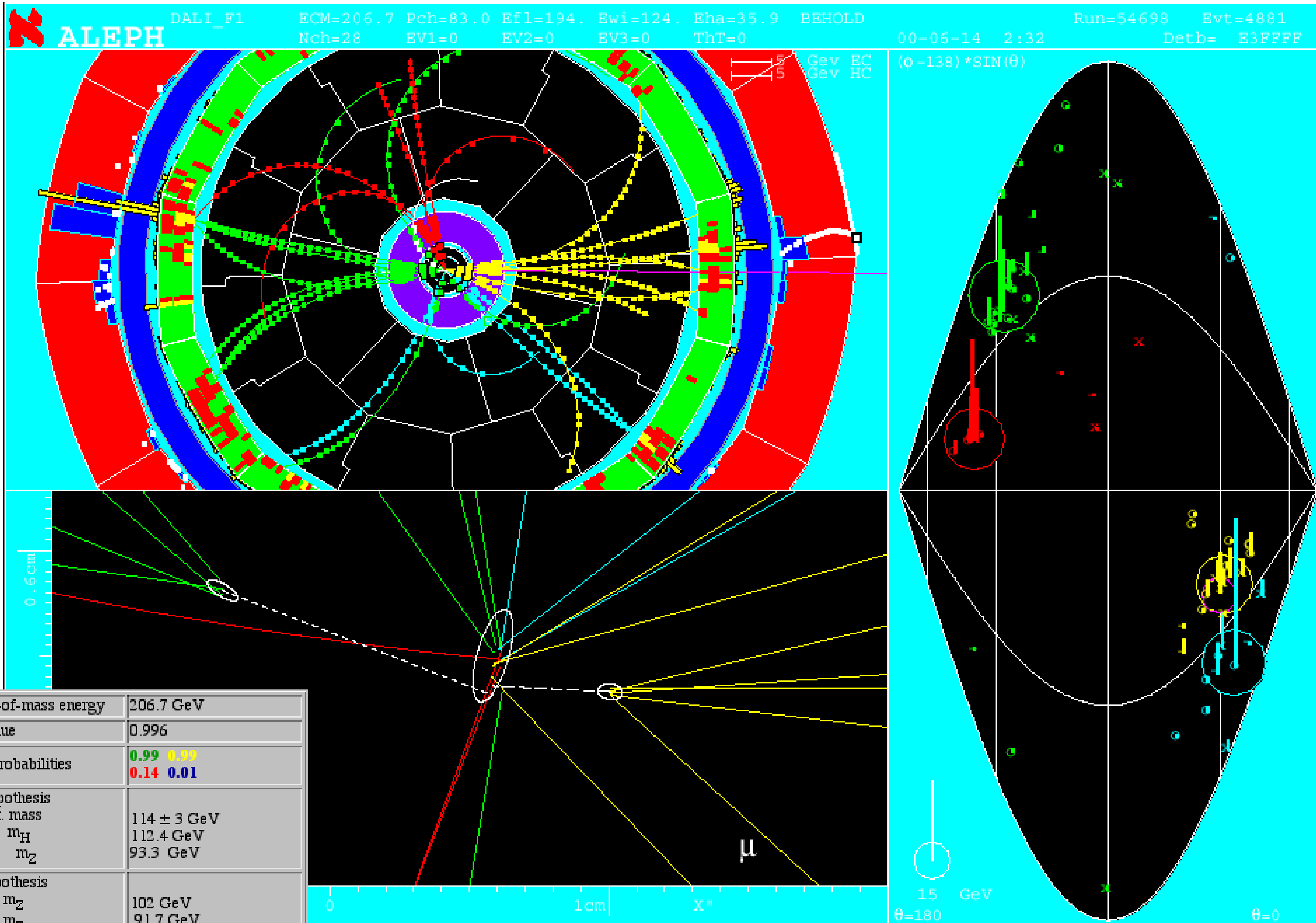
14. Sept. 2000: LEP-shutdown extended by 1 month, until 2. November 2000

3. Nov. 2000: further candidate events increase significance to 2.9 σ. LEP-experiments ask for LEP run in 2001

[status July 2001: after re-analyses (calibration) only 2.1 σ !]

8. Nov. 2000: LEP irrevocably shut down.

direct Higgs searches in e^+e^- annihilations



Centre-of-mass energy	206.7 GeV
NN value	0.996
b-tag probabilities	0.99 0.99 0.14 0.01
HZ hypothesis reconst. mass 5C fit: m_H m_Z	 114 ± 3 GeV 112.4 GeV 93.3 GeV
ZZ hypothesis m_Z m_Z	 102 GeV 91.7 GeV

indirect Higgs searches in e^+e^- annihilations

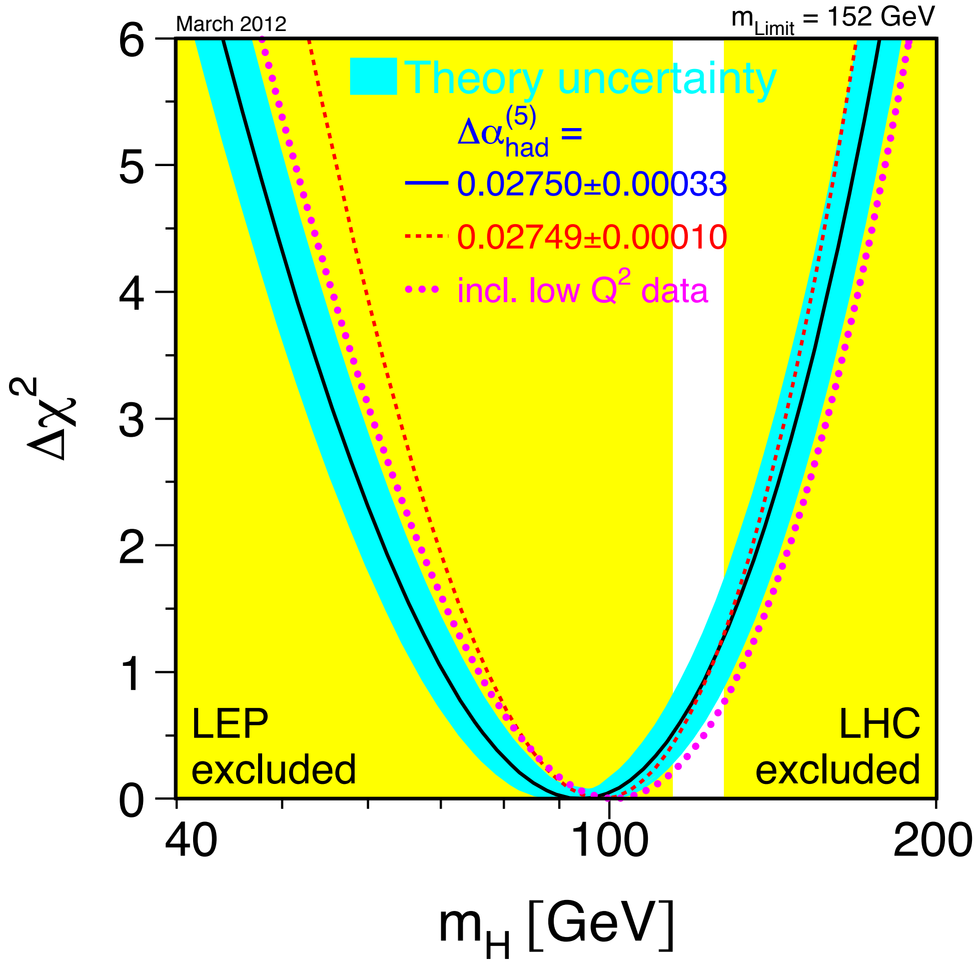
(from radiation corrections / global fits)

	- 1 - LEP including LEP-II m_W, Γ_W	- 2 - all Z-pole data	- 3 - all Z-pole data plus m_t	- 4 - all Z-pole data plus m_W, Γ_W	- 5 - all data except NuTeV	- 6 - all data
m_t [GeV]	184^{+13}_{-11}	171^{+11}_{-9}	$173.6^{+4.7}_{-4.6}$	180^{+11}_{-9}	$175.4^{+4.3}_{-4.2}$	$174.3^{+4.5}_{-4.3}$ *
m_H [GeV]	228^{+367}_{-136}	81^{+107}_{-40}	99^{+64}_{-40}	117^{+161}_{-63}	78^{+48}_{-31}	81^{+52}_{-33}
$\log(m_H/\text{GeV})$	$2.36^{+0.42}_{-0.39}$	$1.91^{+0.37}_{-0.30}$	$1.99^{+0.22}_{-0.23}$	$2.07^{+0.38}_{-0.33}$	$1.89^{+0.21}_{-0.22}$	$1.91^{+0.22}_{-0.23}$
$\alpha_S(m_Z^2)$	0.1199 ± 0.0030	0.1186 ± 0.0027	0.1187 ± 0.0027	0.1185 ± 0.0027	0.1181 ± 0.0027	0.1183 ± 0.0027
χ^2/d.o.f. (P)	13.3/9 (15%)	14.8/10 (14%)	14.9/11 (19%)	17.9/12 (12%)	20.5/14 (11%)	29.7/15 (1.3%)
$\sin^2\theta_{\text{eff}}^{\text{lept}}$	0.23160 $\pm$0.00018	0.23145 $\pm$0.00016	0.23145 $\pm$0.00016	0.23135 $\pm$0.00015	0.23131 $\pm$0.00015	0.23136 $\pm$0.00015
$\sin^2\theta_W$	0.22284 $\pm$0.00053	0.22313 $\pm$0.00063	0.22299 $\pm$0.00045	0.22240 $\pm$0.00045	0.22255 $\pm$0.00036	0.22272 $\pm$0.00036
m_W [GeV]	80.388 ± 0.027	80.373 ± 0.032	80.380 ± 0.023	80.410 ± 0.023	80.403 ± 0.019	80.394 ± 0.019

Table 16.2: Results of the fits to: (1) LEP data alone, (2) all Z-pole data (LEP-1 and SLD), (3) all Z-pole data plus direct m_t determinations, (4) all Z-pole data plus direct m_W and direct Γ_W determinations, (5) all data (including APV) except NuTeV, and (6) all data. As the sensitivity to m_H is logarithmic, both m_H as well as $\log(m_H/\text{GeV})$ are quoted. The bottom part of the table lists derived results for $\sin^2\theta_{\text{eff}}^{\text{lept}}$, $\sin^2\theta_W$ and m_W. See text for a discussion of theoretical errors not included in the errors above.

* $M_H < 185$ GeV (95% c.l.)

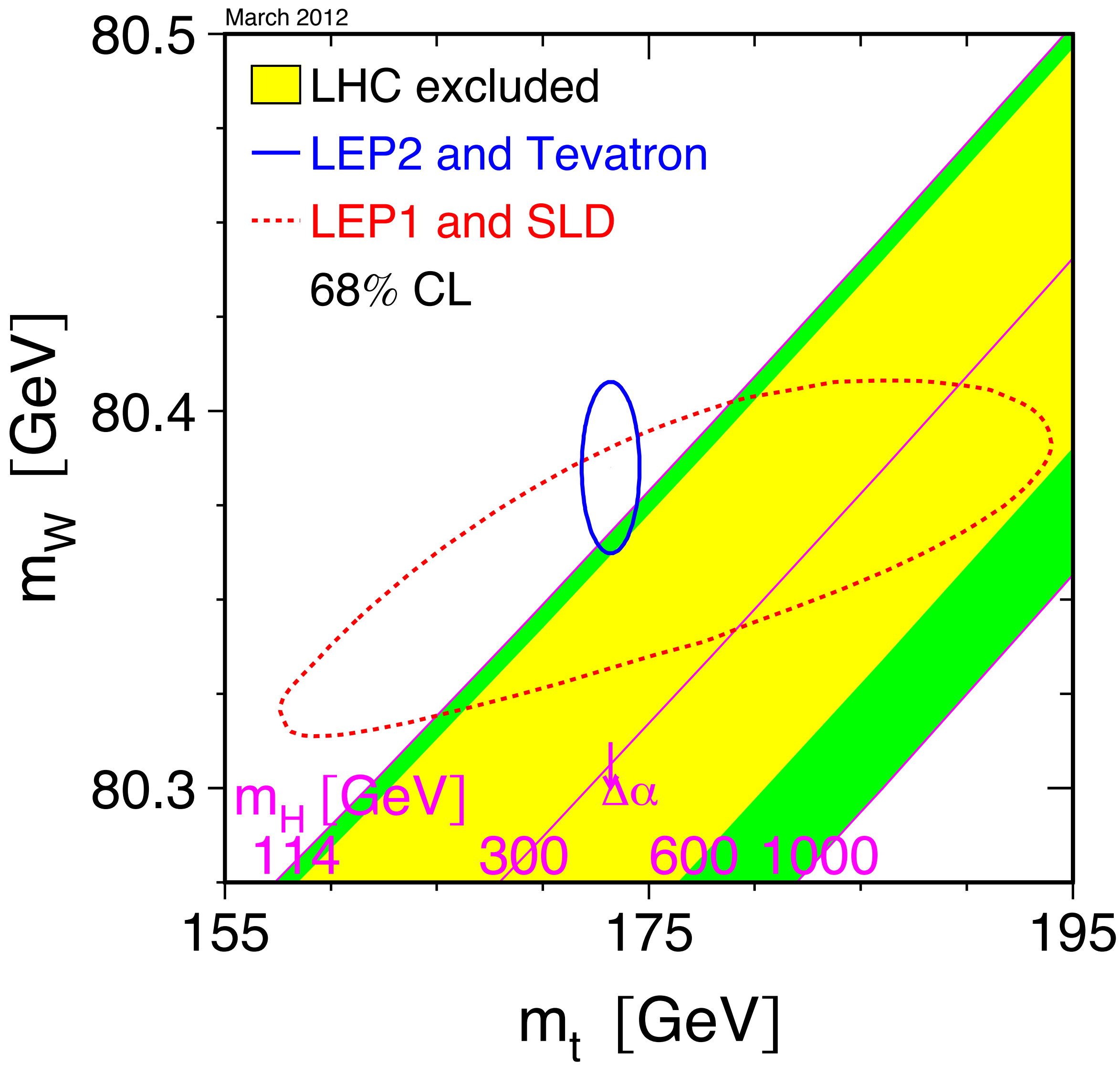
*in*direct Higgs searches in e^+e^- annihilations



from direct search: 114.1(LEP) 115.5 (LHC) < M_H < 131 GeV/c^2 (LHC)

indirectly radiation corrections: M_H < 186 (157) GeV/c^2 (95% CL)

Juli 2012: Higgs discovered at LHC; 2015: $M_H = 125.09 \pm 0.24$ GeV comparison of direct measurement with fit of radiative corrections:



(m_t, m_w measured)

(fit, from rad. corr.)

- good agreement
- „light Higgs“ preferred from rad. corr.

further topics at LEP:

- Tests of Strong Interaction (QCD)
- Physics of heavy Quarks
- Search for new particles (SUSY et al...)
- 2-Photon Physics
- ... (~ 1400 Publications 1989 - 2002)

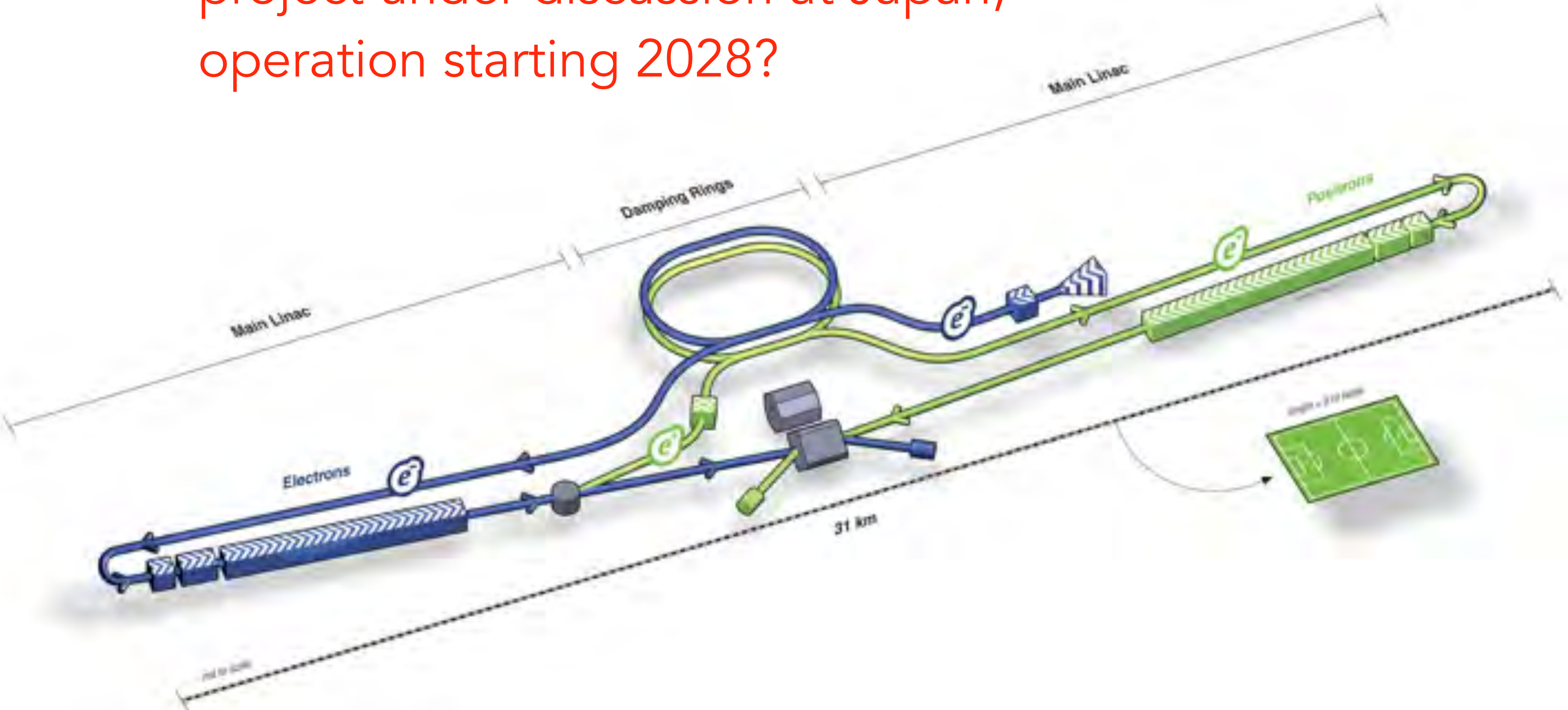
Future: ILC (?); CLIC (??)
FCC-ee (??)

International Linear Collider (ILC)

500 GeV c.m. e+e–

L ~ $2 \cdot 10^{34}$ cm^{-2}s^{-1} (400 x LEP)

project under discussion at Japan;
operation starting 2028?



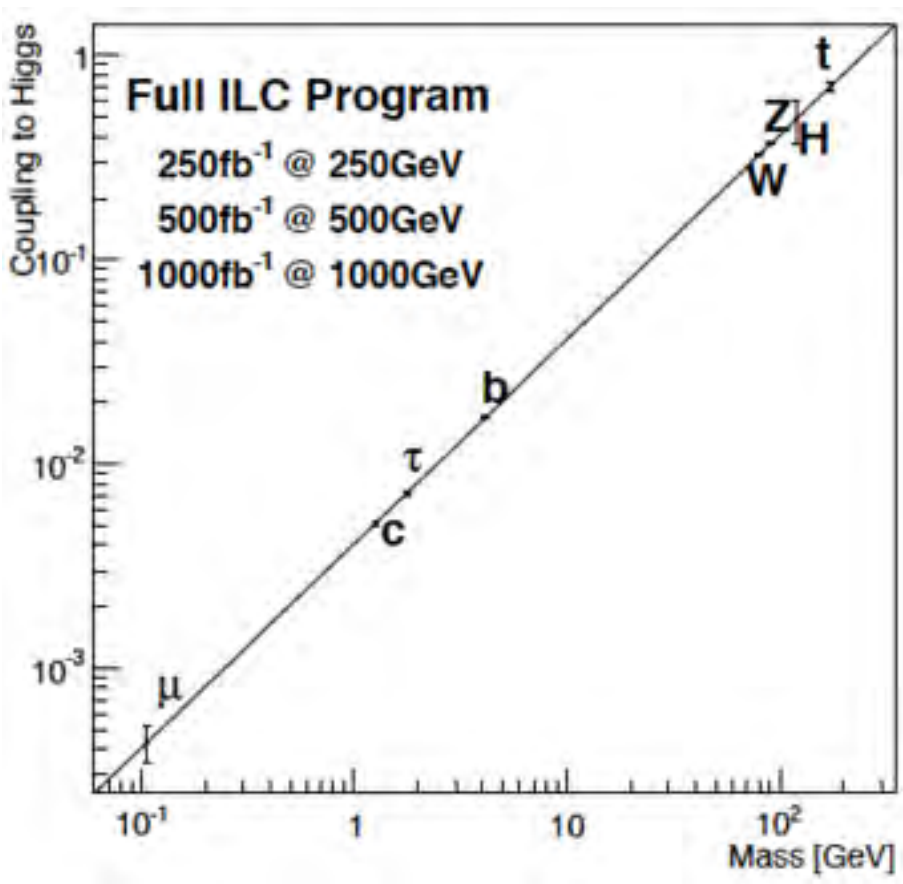
International Linear Collider (ILC)
physics menu

Energy	Reaction	Physics Goal	Polarization
91 GeV	$e^+e^- \to Z$	ultra-precision electroweak	A
160 GeV	$e^+e^- \to WW$	ultra-precision W mass	H
250 GeV	$e^+e^- \to Zh$	precision Higgs couplings	H
350–400 GeV	$e^+e^- \to t\bar{t}$	top quark mass and couplings	A
	$e^+e^- \to WW$	precision W couplings	H
	$e^+e^- \to \nu\bar{\nu}h$	precision Higgs couplings	L
500 GeV	$e^+e^- \to f\bar{f}$	precision search for Z'	A
	$e^+e^- \to t\bar{t}h$	Higgs coupling to top	H
	$e^+e^- \to Zhh$	Higgs self-coupling	H
	$e^+e^- \to \tilde{\chi}\tilde{\chi}$	search for supersymmetry	B
	$e^+e^- \to AH, H^+H^-$	search for extended Higgs states	B
700–1000 GeV	$e^+e^- \to \nu\bar{\nu}hh$	Higgs self-coupling	L
	$e^+e^- \to \nu\bar{\nu}VV$	composite Higgs sector	L
	$e^+e^- \to \nu\bar{\nu}t\bar{t}$	composite Higgs and top	L
	$e^+e^- \to \tilde{t}\tilde{t}^*$	search for supersymmetry	B

ILC: precision of Higgs coupling

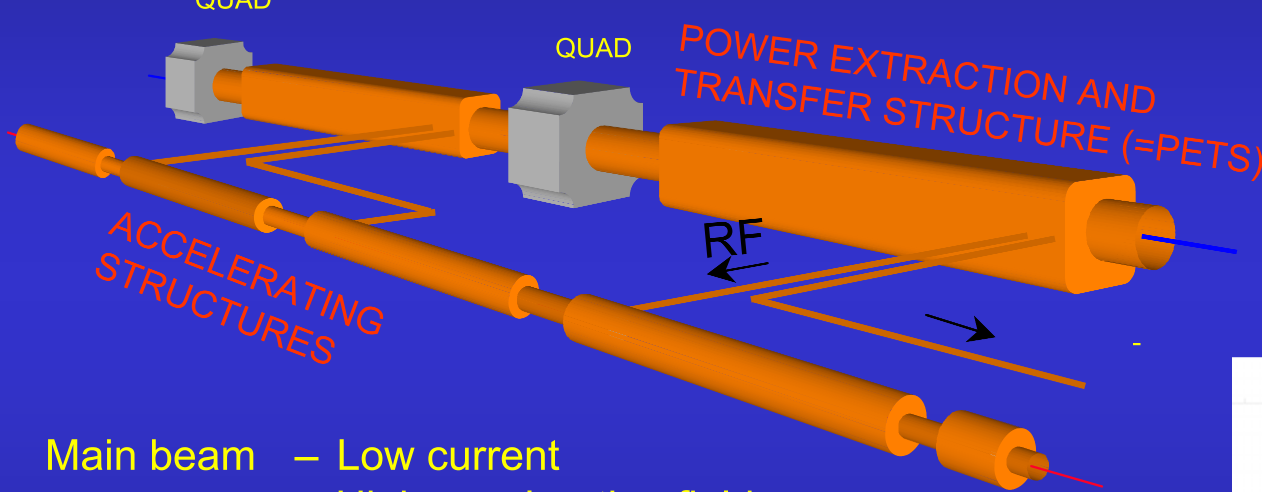
Mode	LHC	ILC(250)	ILC500	ILC(1000)
WW	4.1 %	1.9 %	0.24 %	0.17 %
ZZ	4.5 %	0.44 %	0.30 %	0.27 %
$b\bar{b}$	13.6 %	2.7 %	0.94 %	0.69 %
gg	8.9 %	4.0 %	2.0 %	1.4 %
$\gamma\gamma$	7.8 %	4.9 %	4.3 %	3.3 %
$\tau^+\tau^-$	11.4 %	3.3 %	1.9 %	1.4 %
$c\bar{c}$	–	4.7 %	2.5 %	2.1 %
$t\bar{t}$	15.6 %	14.2 %	9.3 %	3.7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

ILC: precision of Higgs coupling



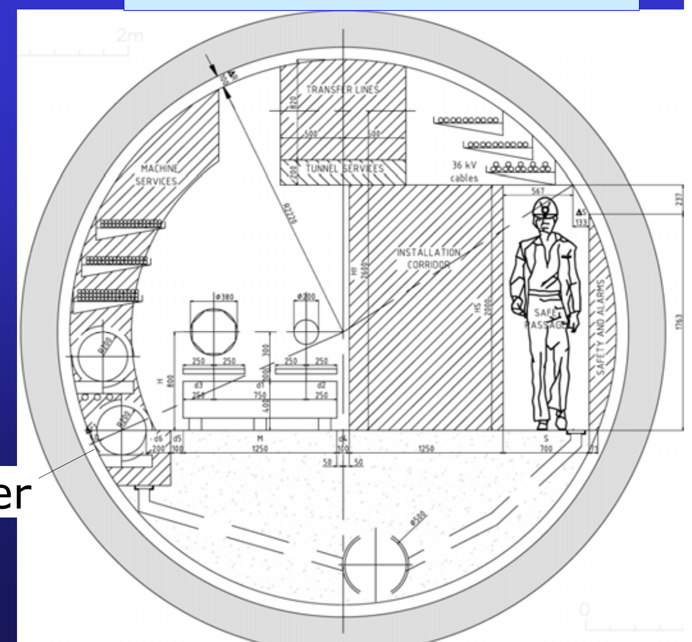
CLIC TWO-BEAM SCHEME

Drive beam - High current
- Low decelerating field



Main beam – Low current
- High accelerating field

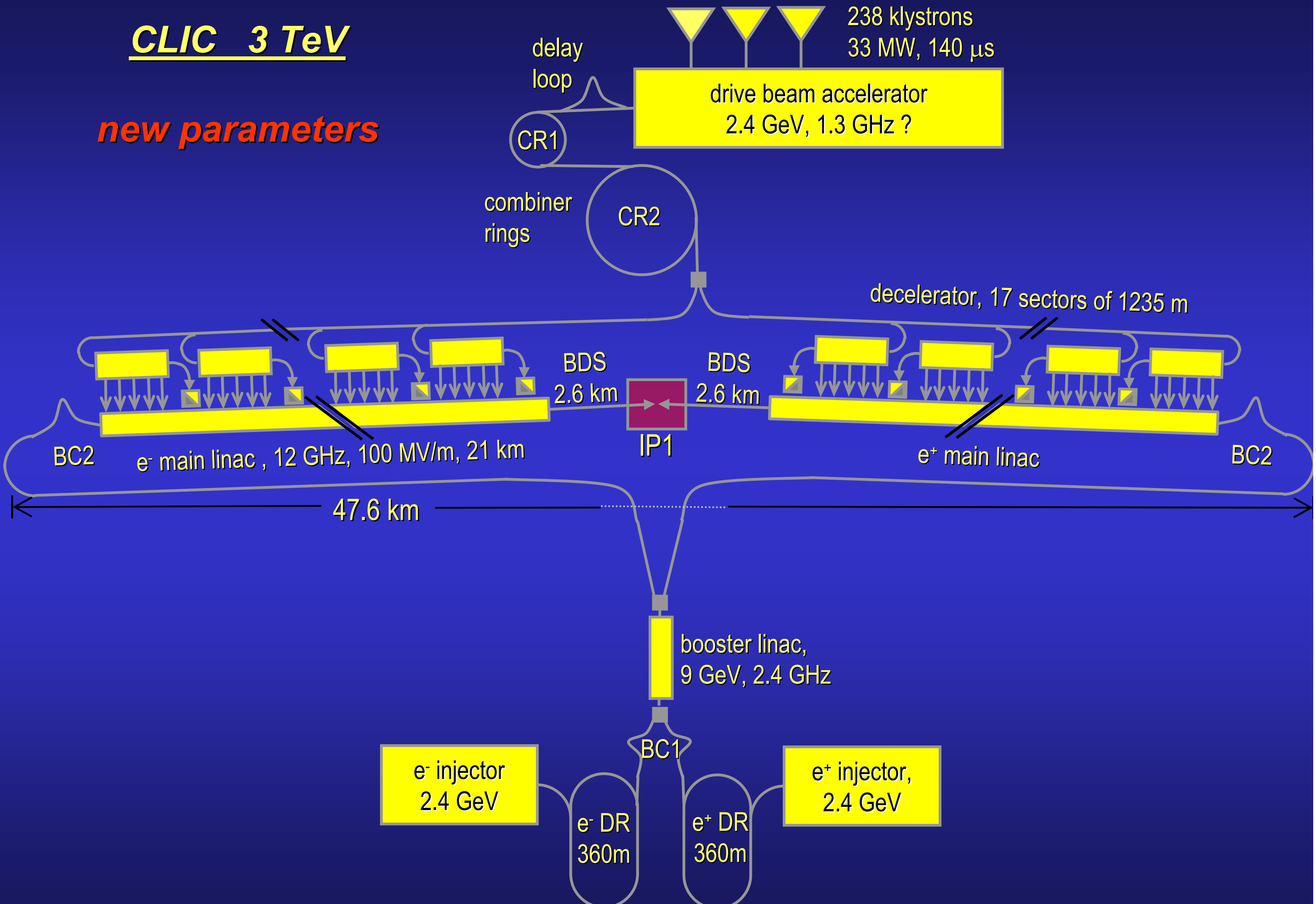
CLIC TUNNEL CROSS-SECTION



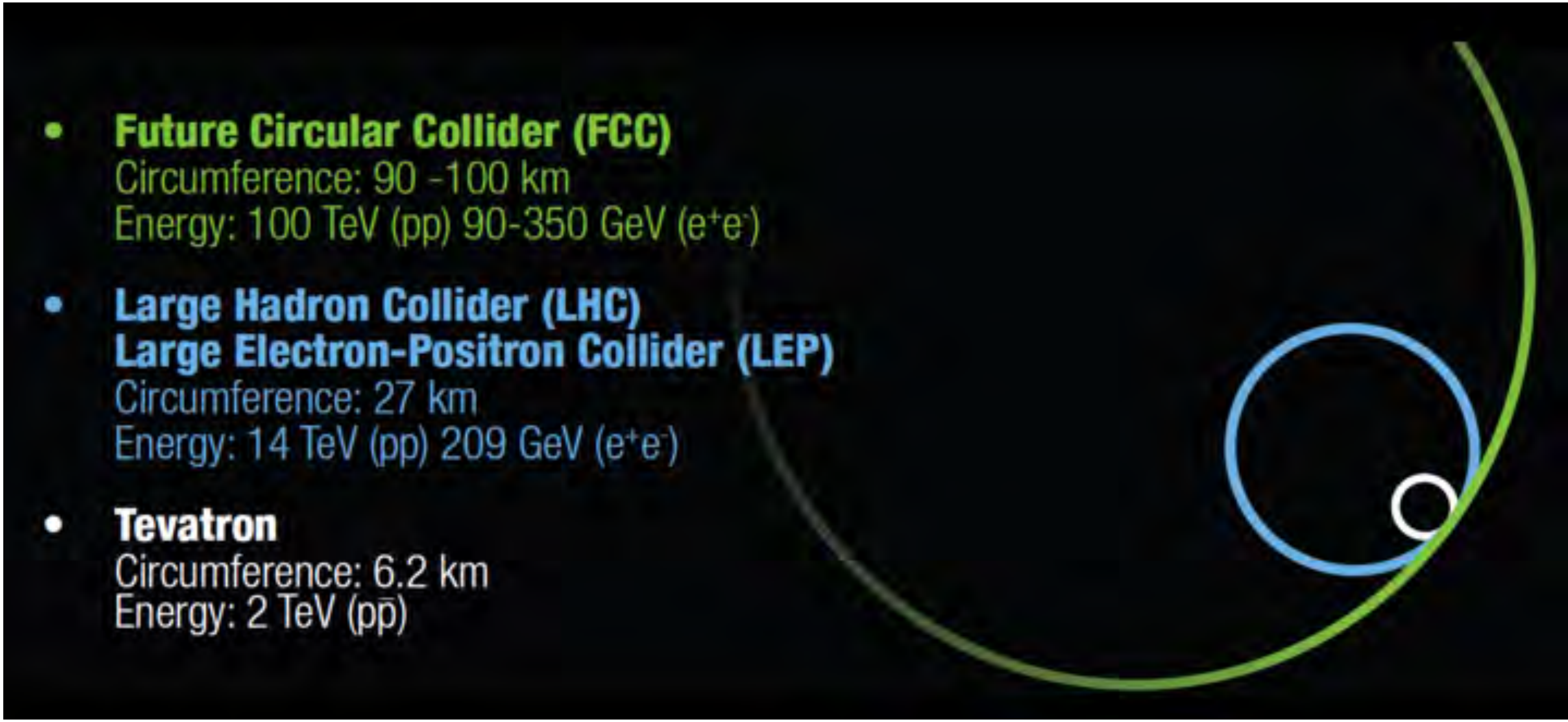
4.5 m diameter

CLIC 3 TeV

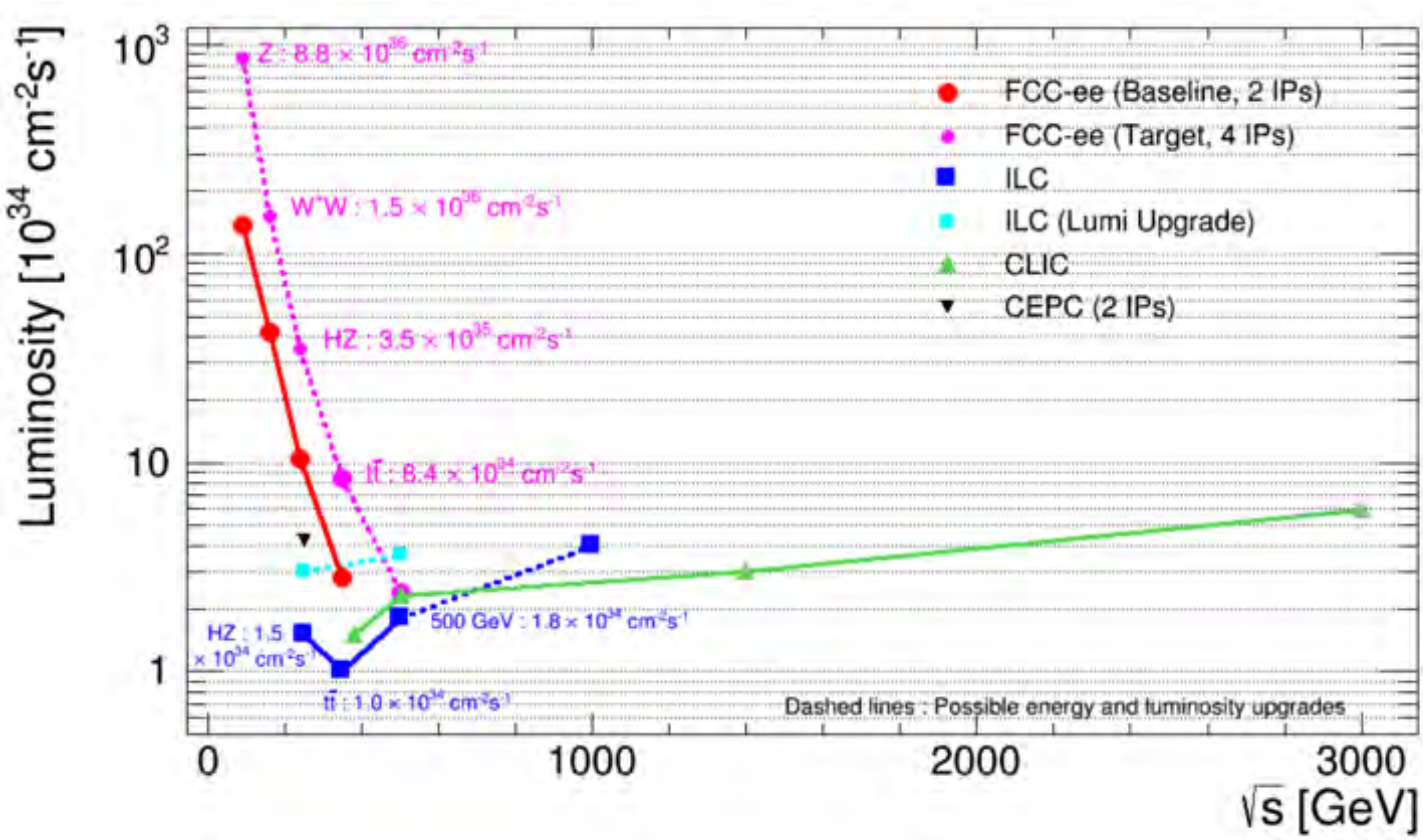
new parameters



future circular collider (FCC)



future e^+e^- colliders



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LEP Electroweak Working Group: http://lepewwg.web.cern.ch/LEPEWWG

www.linearcollider.org

next lecture: „QCD and Jet-Physics at e+e- colliders“, 29.5.17