PHYSICS AT THE LARGE ELECTRON-POSITRON COLLIDER

Ugo Amaldi
TERA Foundation

1958: Postgraduate School in Nuclear Physics

First lesson of the course on Theoretical Physics

Bruno defined "fields" as systems with an infinite number of degrees of freedom

Lagrangian density
+
symmetry

First lesson of the course on Theoretical Physics

Bruno defined "fields" as systems with an infinite number of degrees of freedom

Emmy Noether (1982-1935)

Lagrangian density
+
symmetry

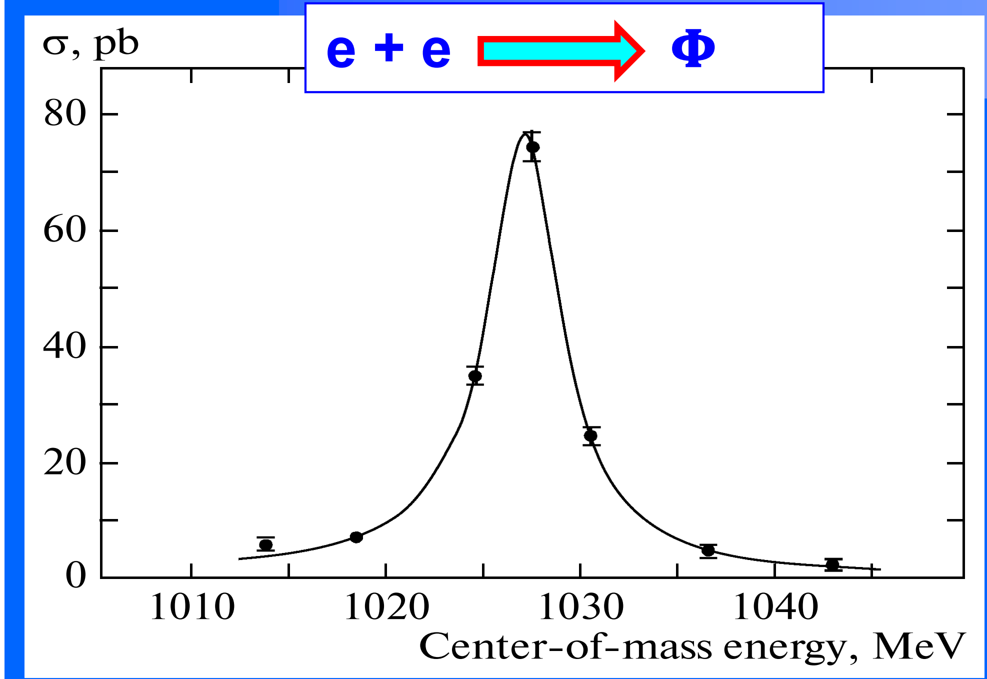
↓

invariant quantity

May 1963: “Congressino” di Frascati

Durante coffee break congressino Frascati
Touschek mi chiede se voglio prendere
l'incarico di preparare esperienze in una delle
sezioni dritte di Adone. Rispondo che ci penserò
Tornando a Roma parlo a Matthiae di questo –
Giovedì 9/5/63 (o 10/5 ?)

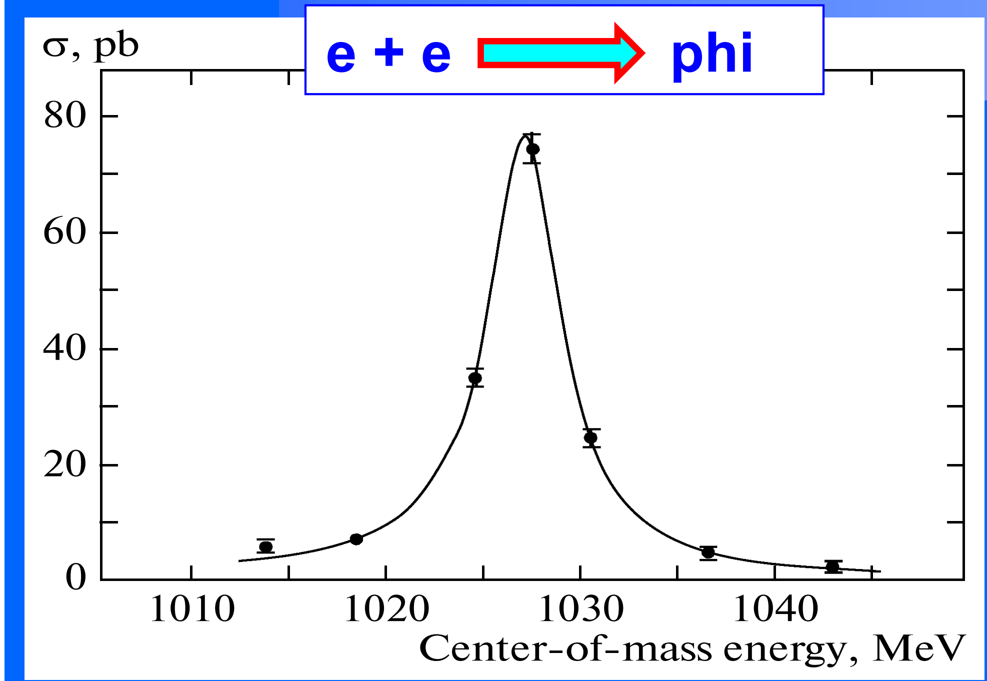
1965: Bruno's office at la Sapienza



U.A and G. Matthiae preparing an experiment to study the phi-meson at ADONE

To compute radiative corrections U.A. had use the method of Paul Kessler

"Do you know Paul Kessler ?"



1965: Bruno’s office at la Sapienza

U.A and G. Matthiae preparing an experiment to study phi-meson decays at ADONE

To compute radiative corrections U.A. had use Paul Kessler‘s method

“Do you know Paul Kessler ?”

“Io conosco solo le Gemelle Kessler”

Corriere della Sera - 22 July 1978
WHO WAS THE MAN OF No 137 ?

Corriere della Sera - 22 July 1978
WHO WAS THE MAN OF No 137 ?

"…because the real problem is the number of this room"

1978: Hôpital de la Tour, Meyrin

Corriere della Sera - 22 July 1978
WHO WAS THE MAN OF No 137 ?

"…because the real problem is the number of this room"

"This is the problem around which I have hovered throughout my life without success "

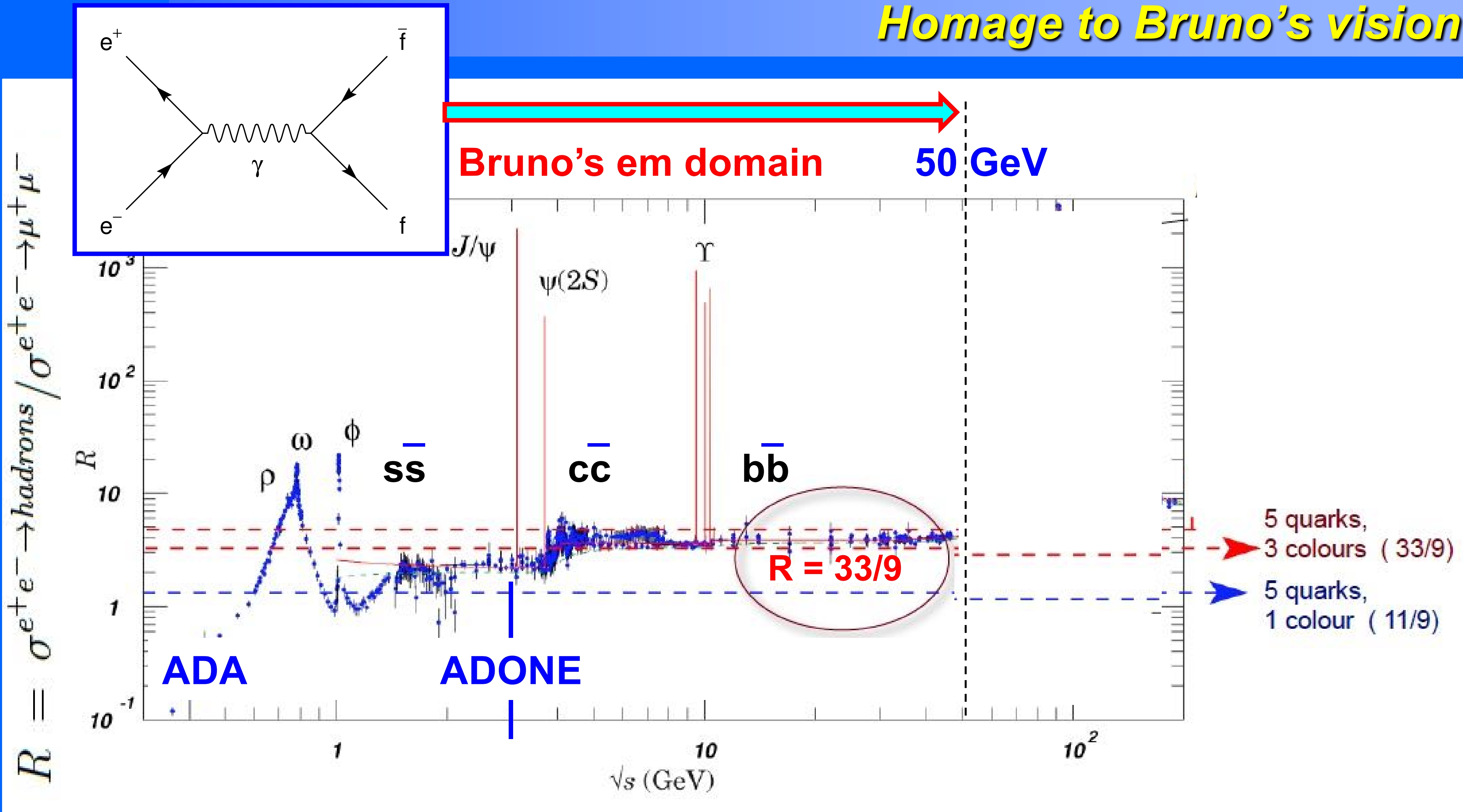
Corriere della Sera - 22 July 1978
WHO WAS THE MAN OF No 137 ?

“…because the real problem is the number of this room”

“This is the problem around which I have hovered throughout my life without success “

“Also Pauli before dying was put in a room number 137”

Homage to Bruno's vision



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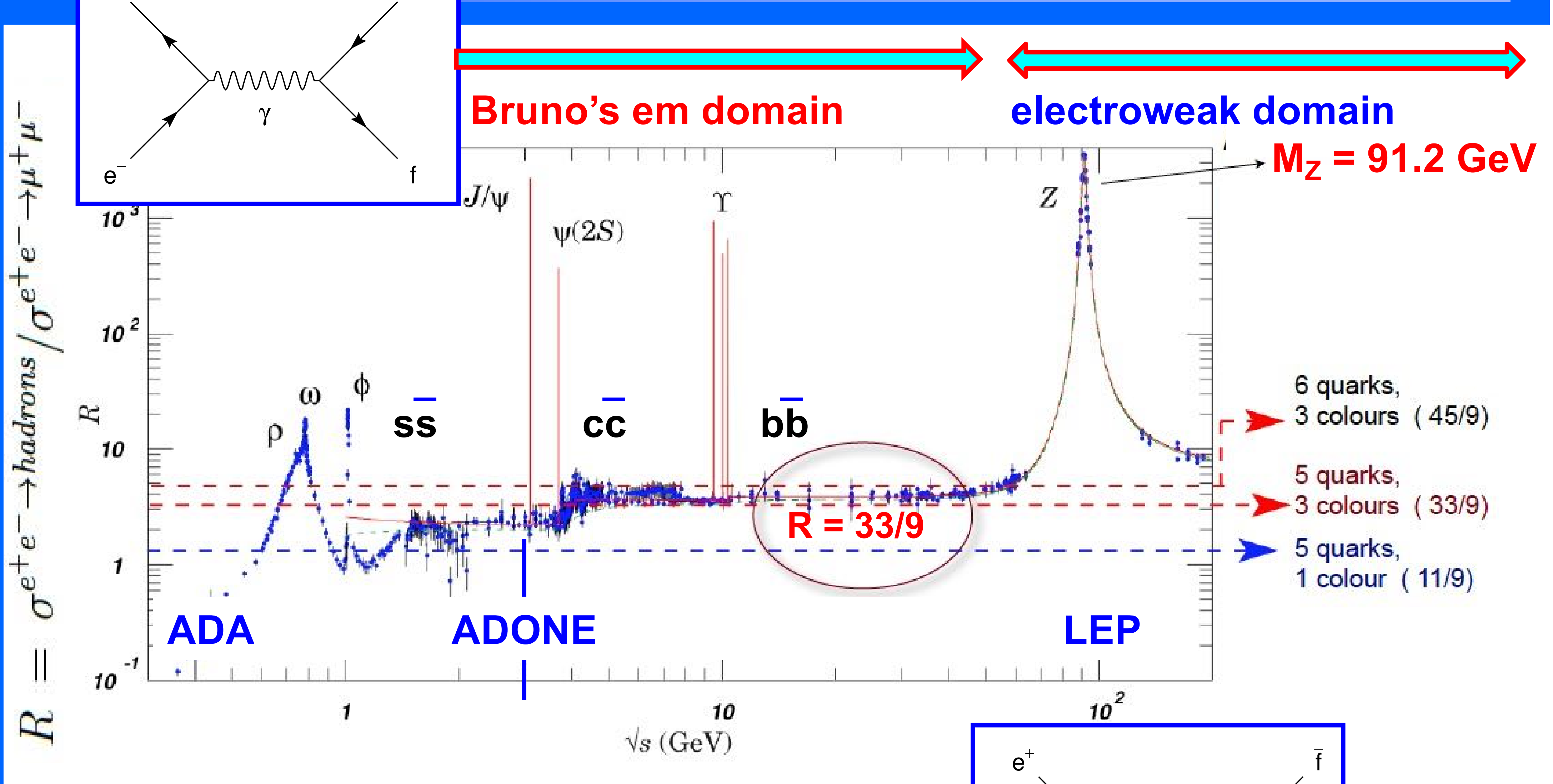
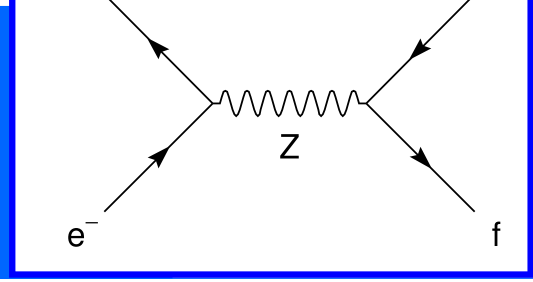
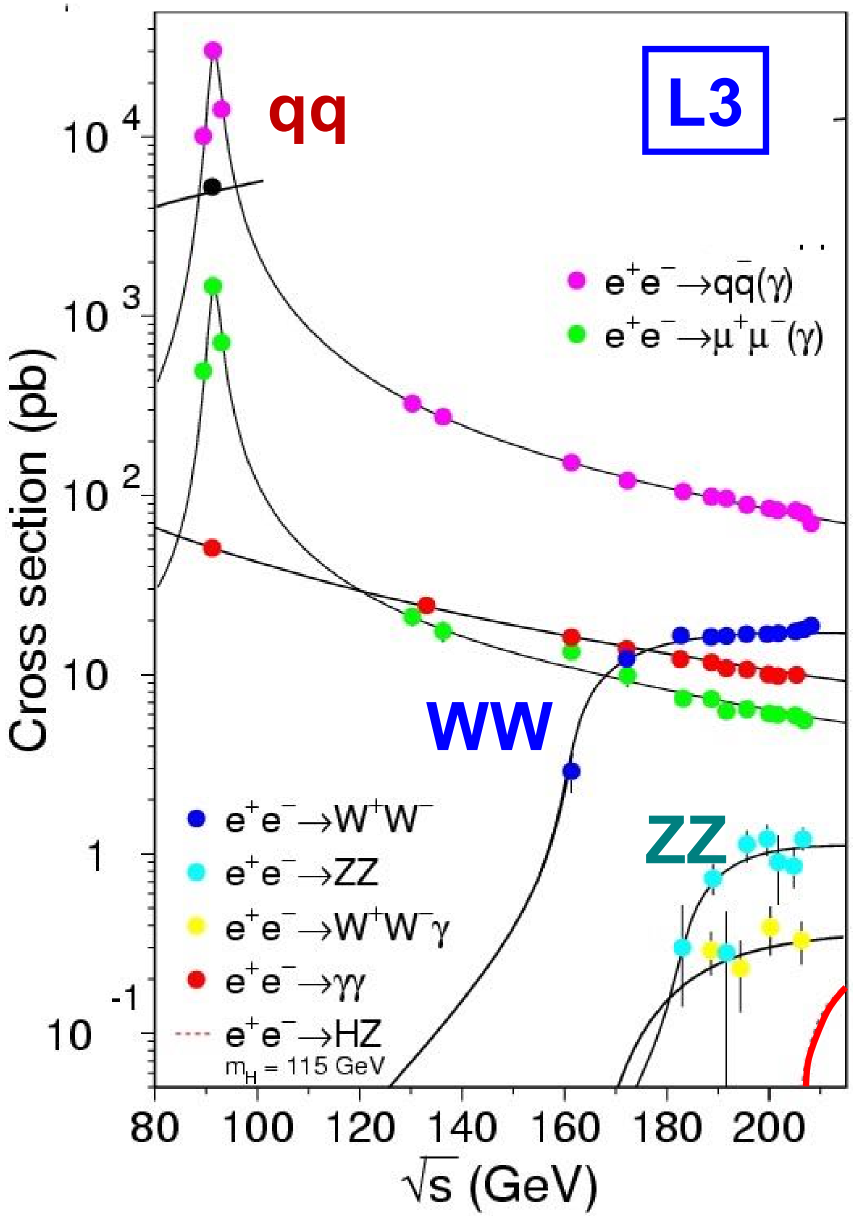




...age to Bruno's vision

4 detectors:
4 x 4 10^6 Z evts

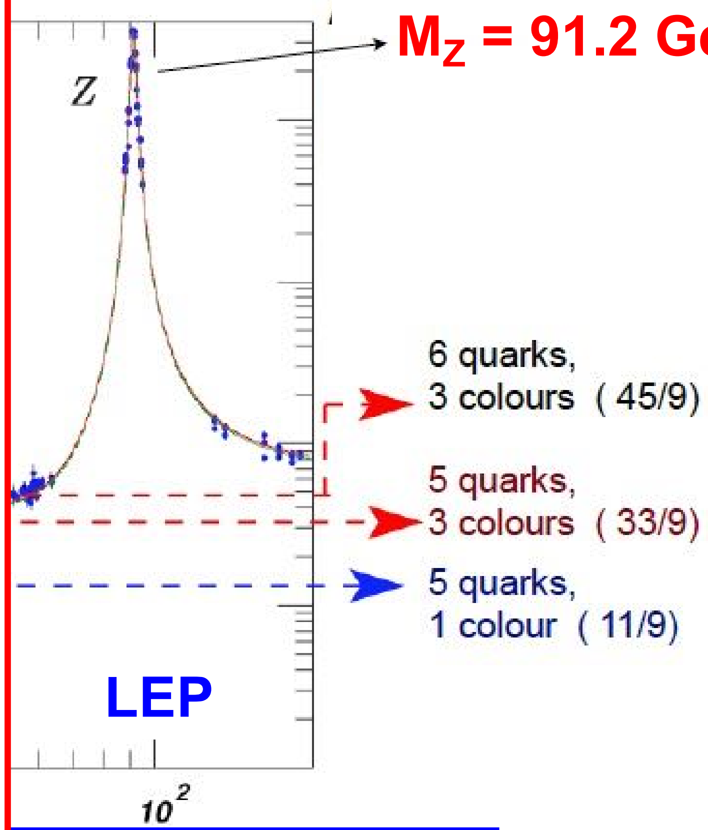


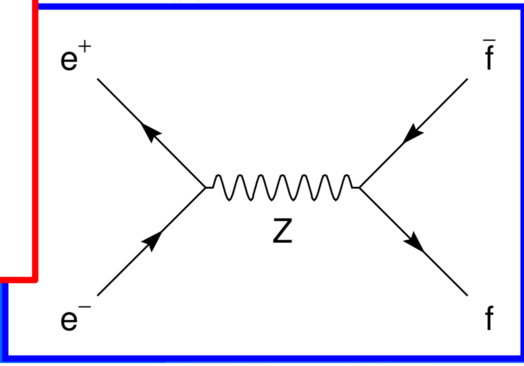
4 x10^4 WW evts

H(115 GeV)

electroweak domain

M_Z = 91.2 GeV

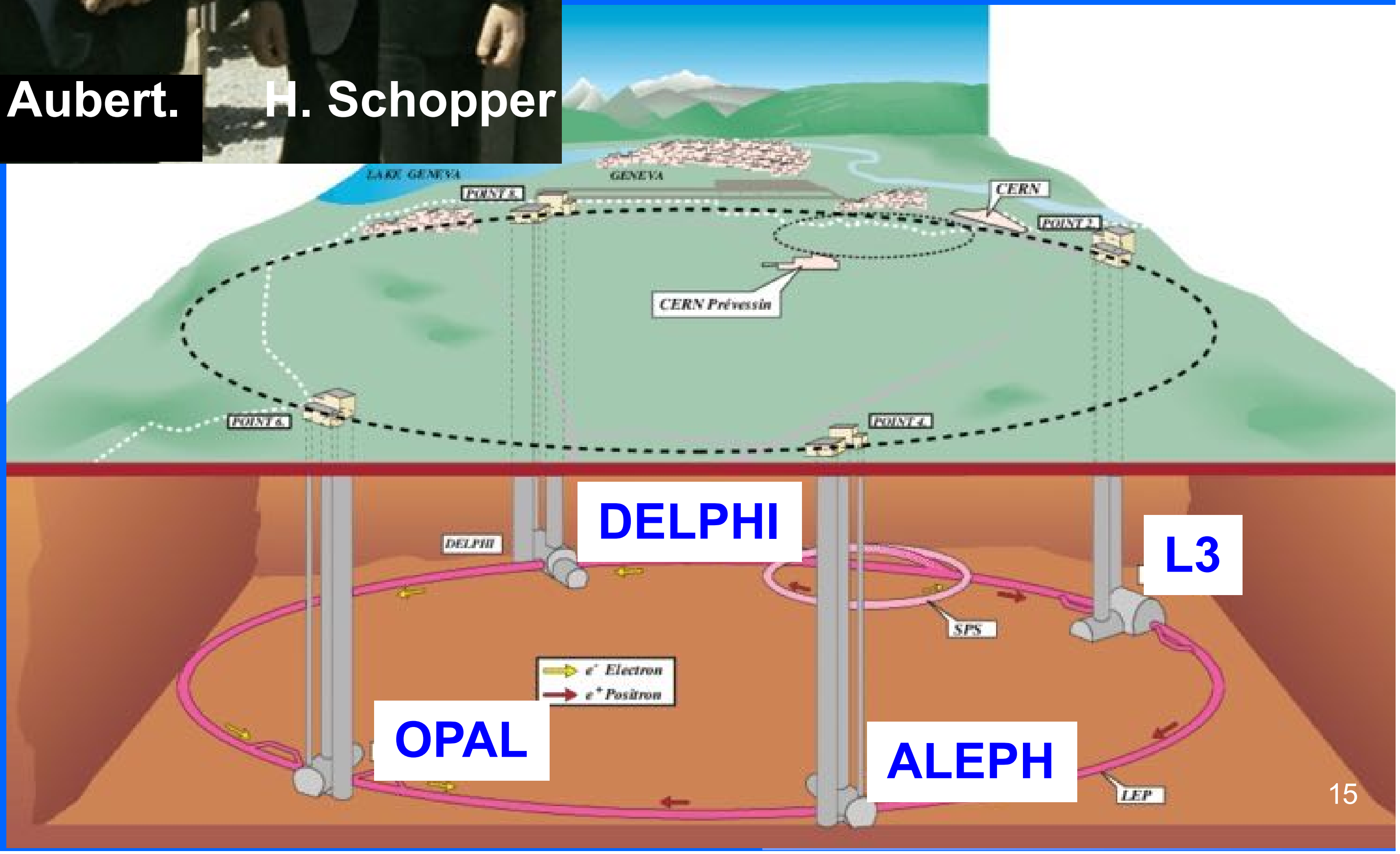


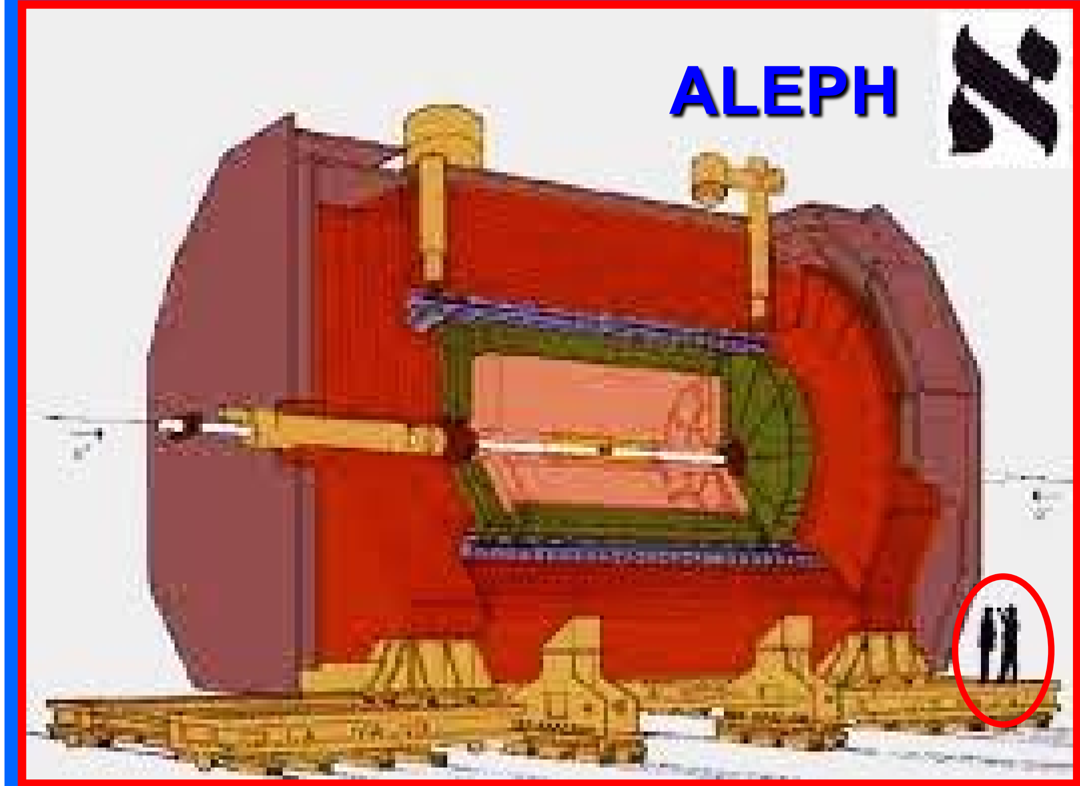


Physics at LEP

LEP tunnel + 4 large-coverage detectors

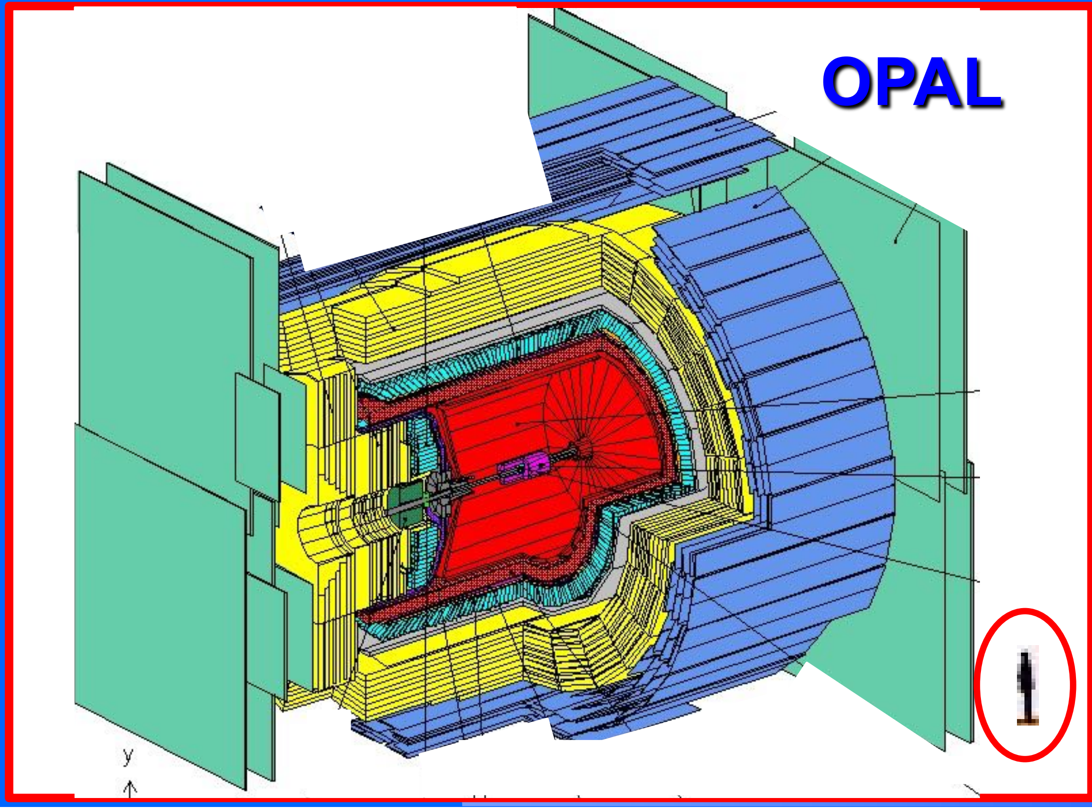
September 1983
Ground-breaking ceremony





2 general purpose detectors

SC coil: 1.5 T
2 layers of silicon microstrips
Large Time Projection Chamber
EM-calorimeter: lead-wire chambers



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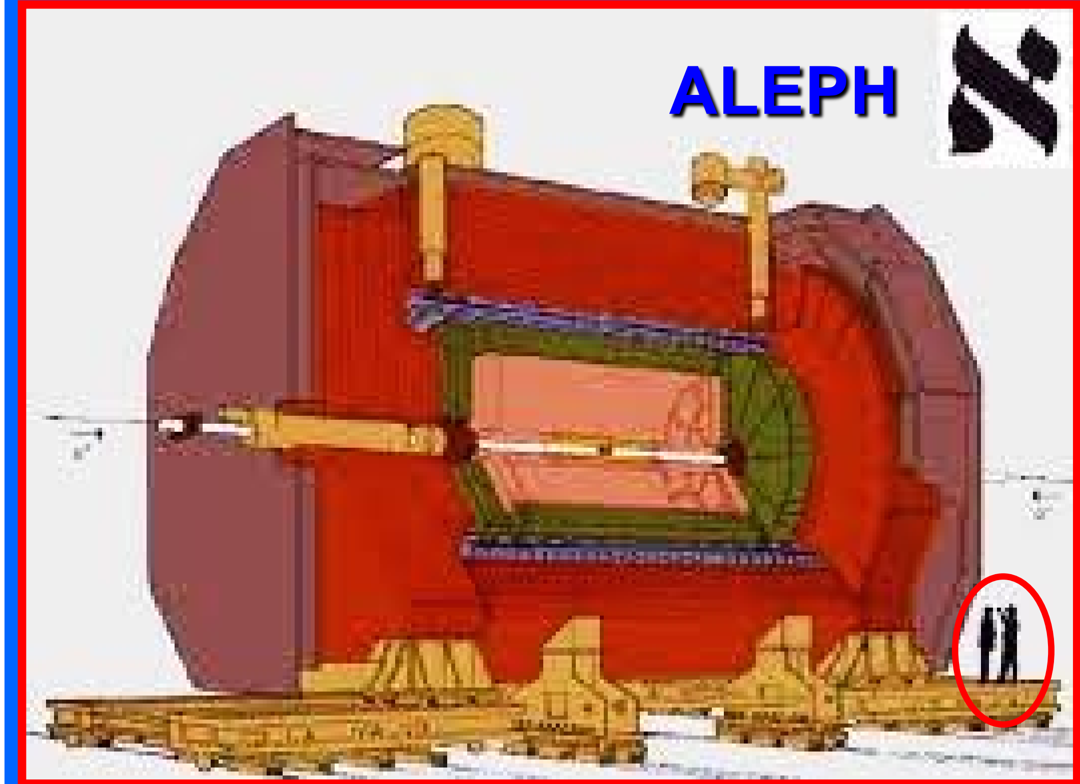
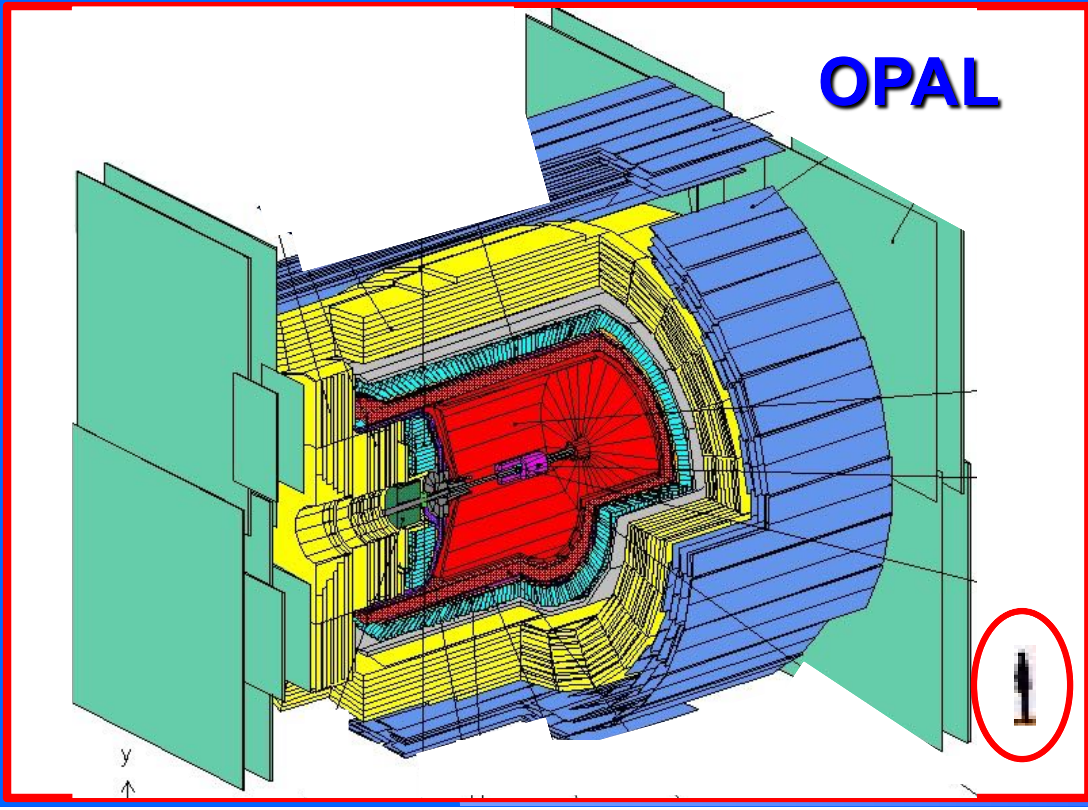
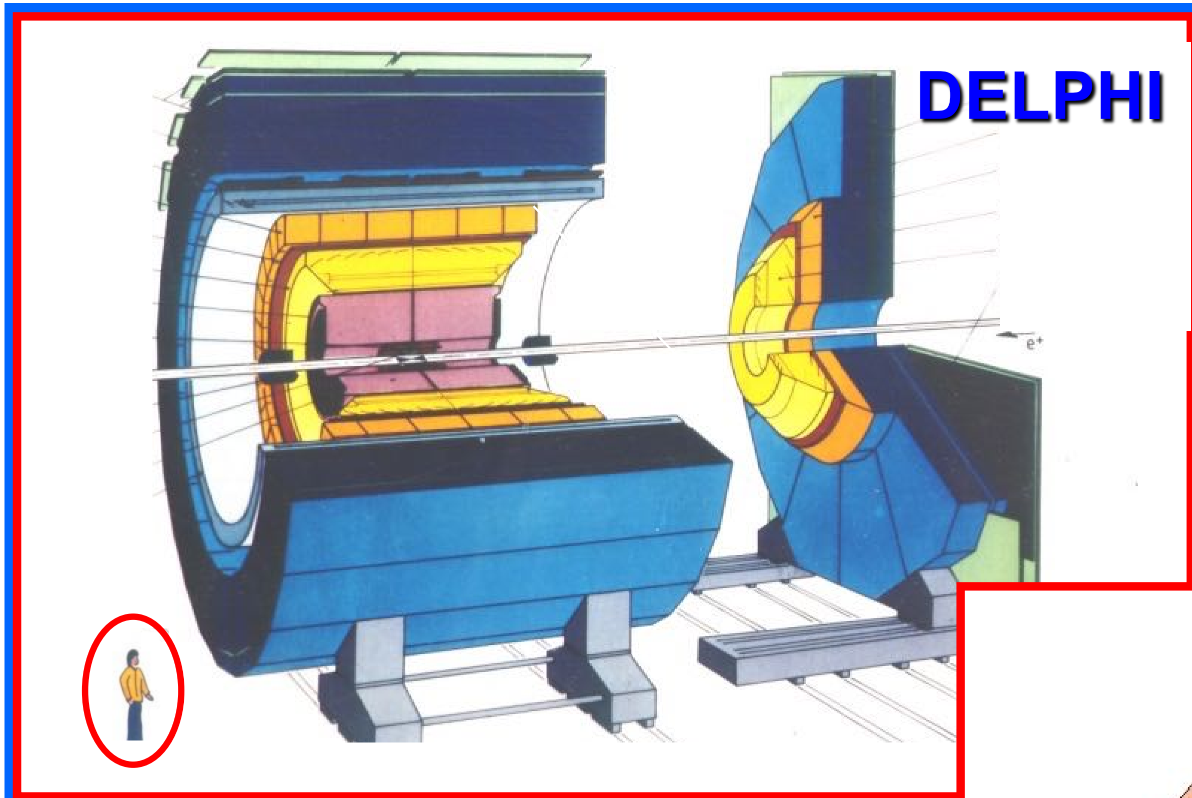


SC coil: 1.5 T
2 layers of silicon microstrips
Large Time Projection Chamber
EM-calorimeter: lead-wire chambers

Upgraded JADE
Room temperature coil: 0.4 T
2 layers of silicon microstrips
central Jet Chamber

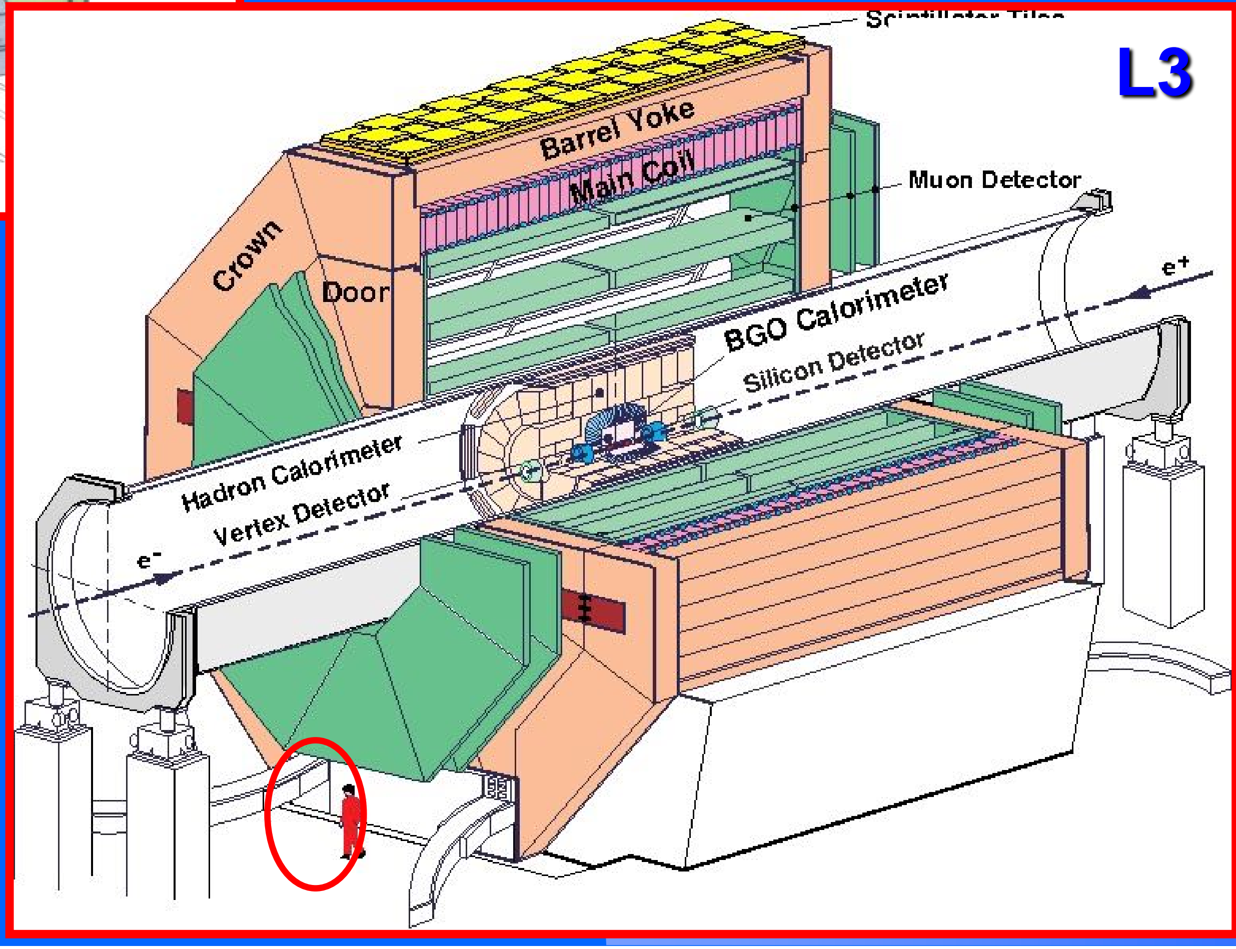
EM-calorimeter
588 lead-glass Cherenkov counters

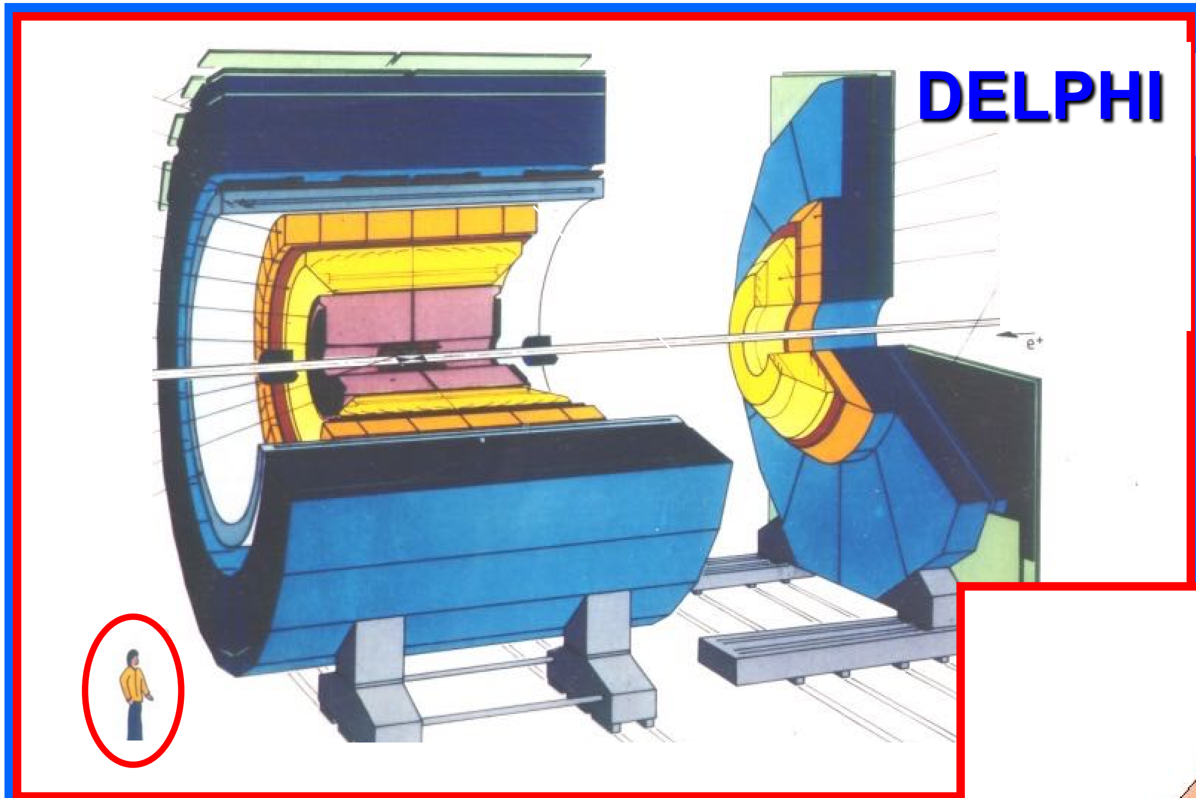




2 specialized detectors

SC coil: 1.2 tesla
3 layers of silicon microstrips
Time Projection Chamber
2 Ring Imaging Cherenkov counters RICHs
EM-calorimeter: HPC





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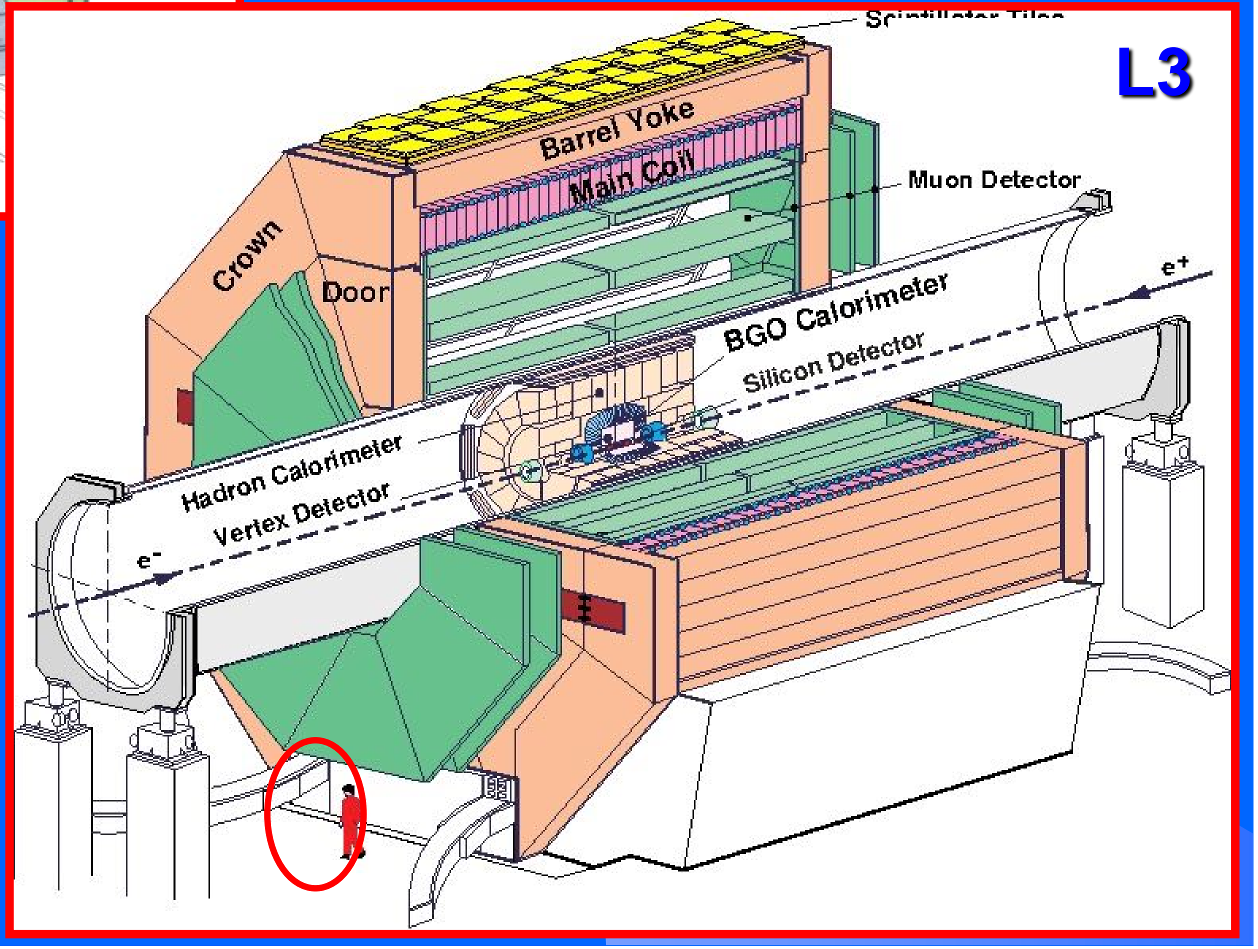


Room temperature coil: 0.5 T
2 layers of silicon microstrips
Accurate Time Expasion Chamber
EM-calorimeter:
10,734 Bismut Germanate Oxide

Large muon chamber system

1. Quantum ChromoDynamics
SU(3) with coupling α_s

The starting point

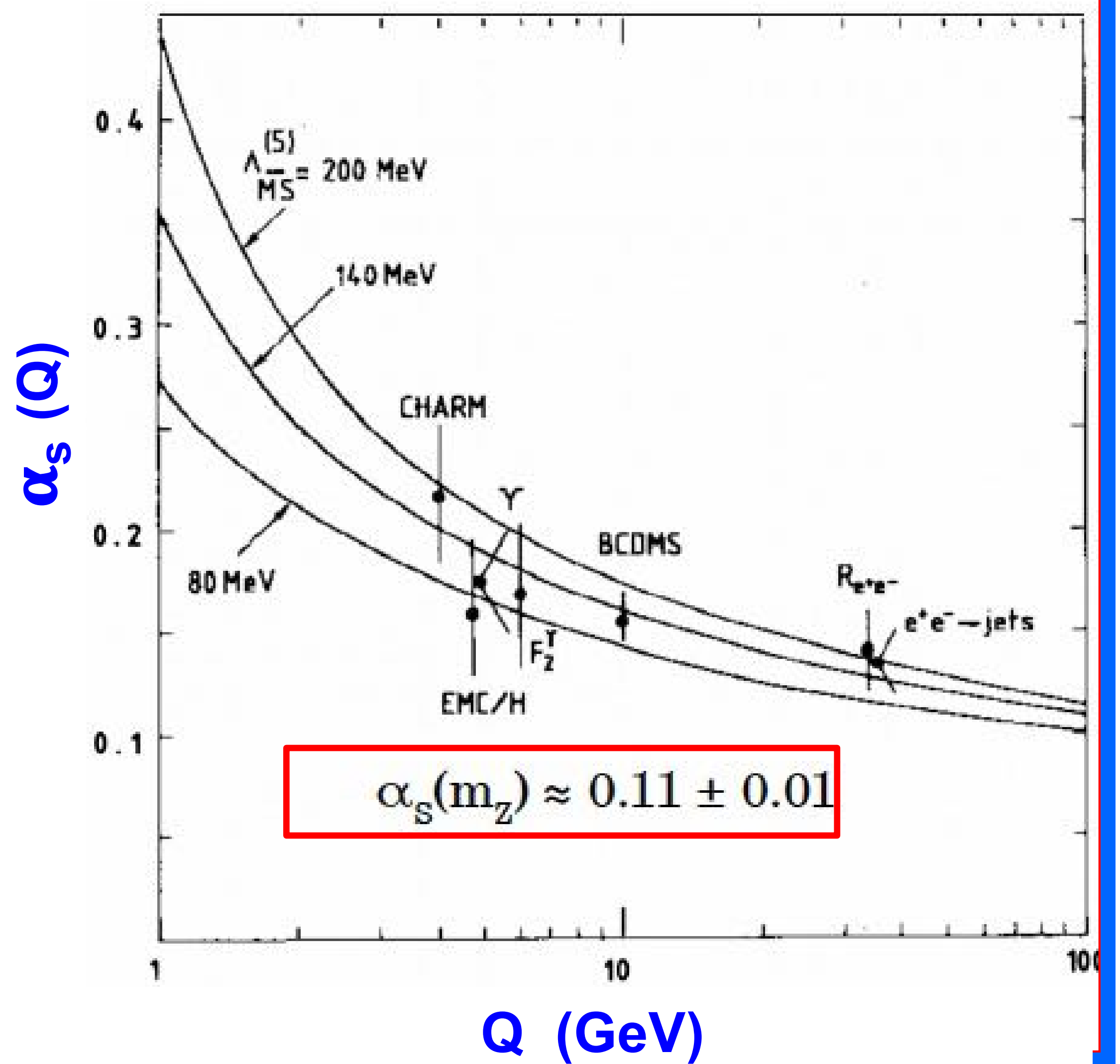
Before LEP

G. Altarelli 1989

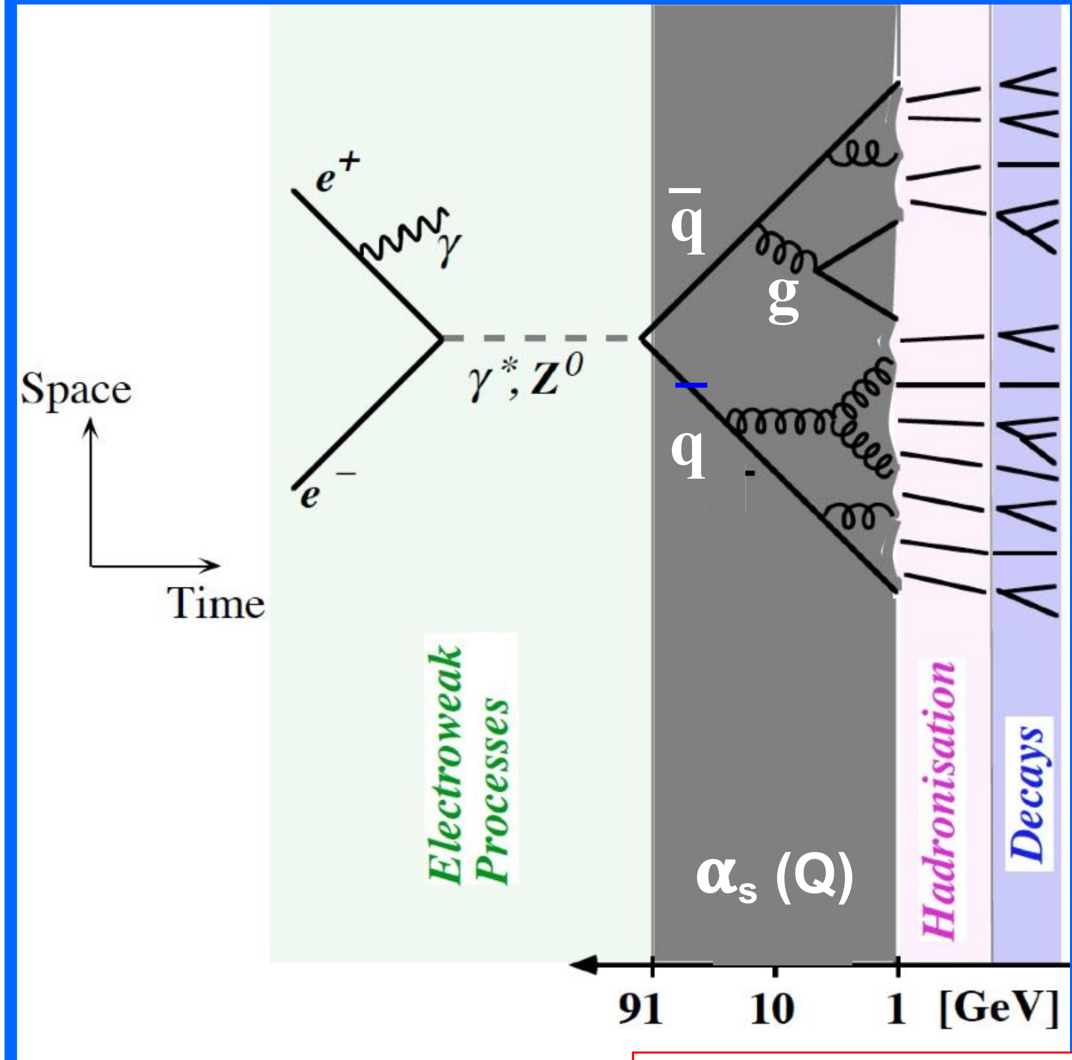
"At present, it is fair to say that the experimental support of QCD is quite solid and quantitative. The forthcoming experiments at pp colliders, at LEP, SLC, and HERA will certainly be very important with their great potential for extending the experimental investigation of the validity of QCD."

[Ann. Rev. Nucl. Part. Sci. 39 (1989) 357]

Running of the strong coupling α_s



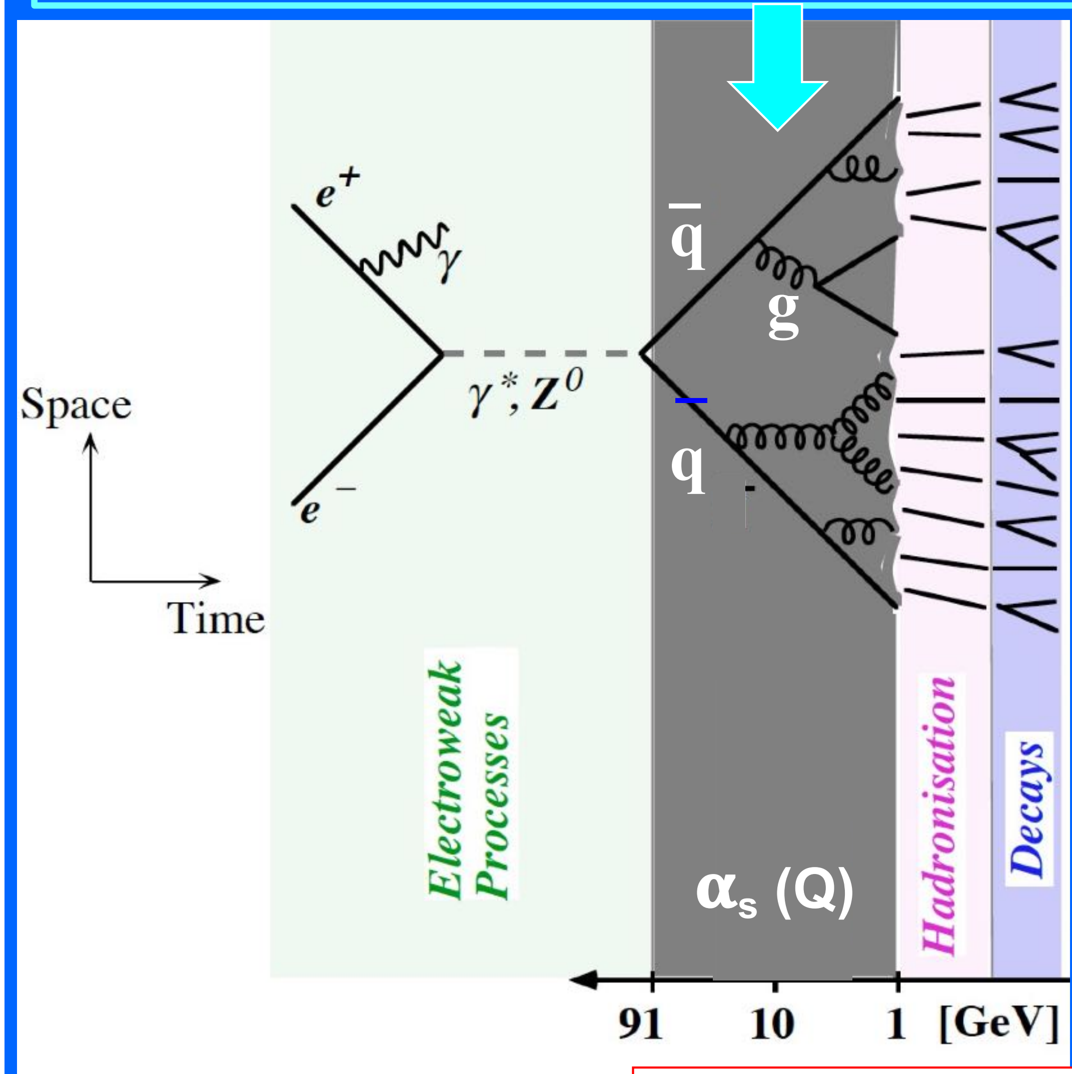
QCD and hadronization models at LEP -1



Q = energy scale

QCD and hadronization models at LEP -1

NLO: next-to-leading order - O($\alpha_s{}^2$)
NLLA: next-to-leading-logarithmic approximation



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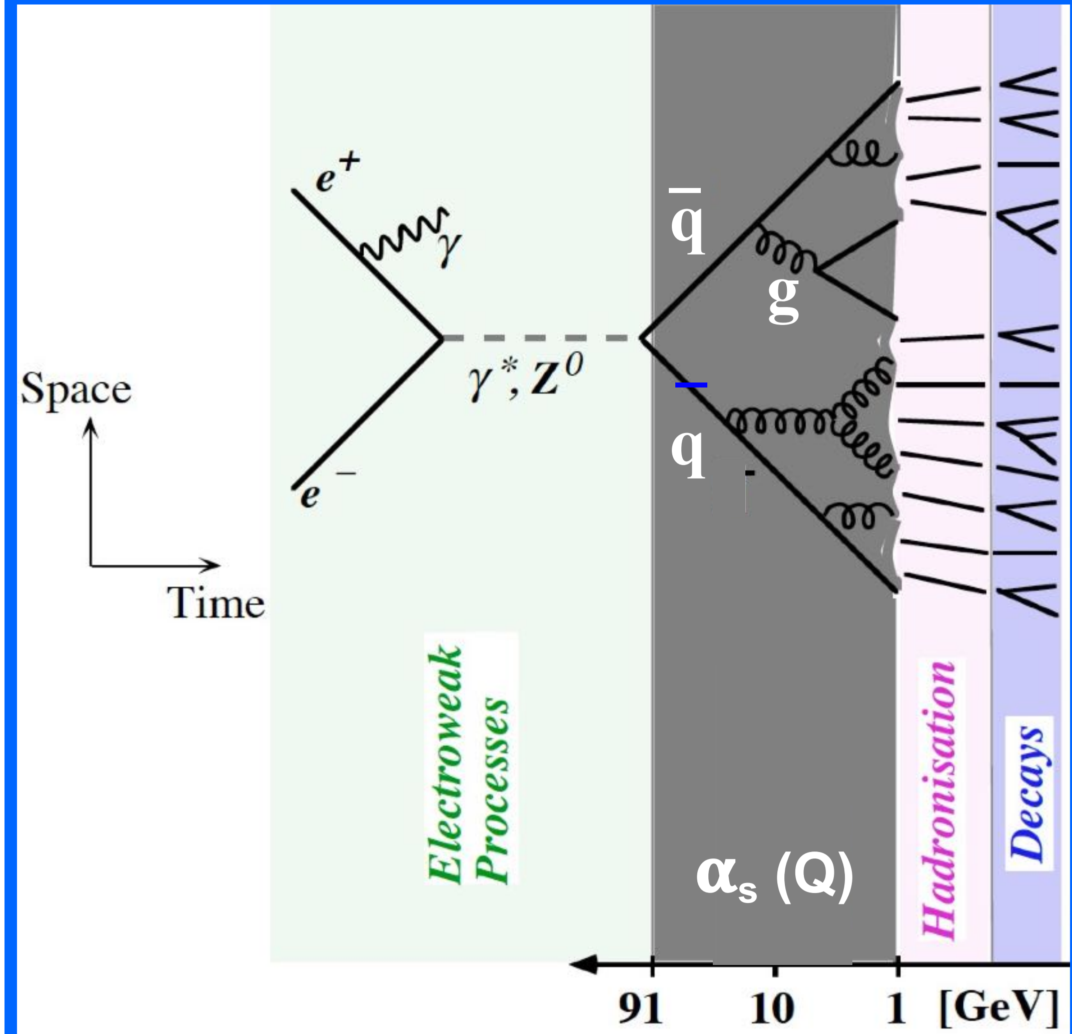
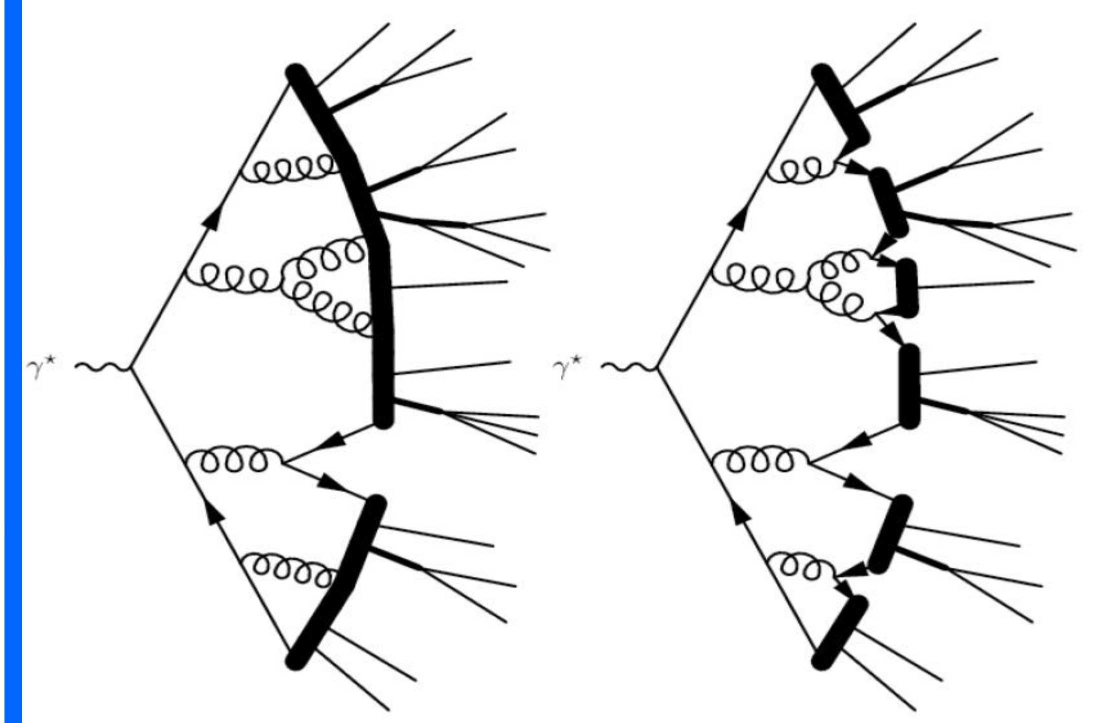
QCD and hadronization models at LEP -1



Q = energy scale

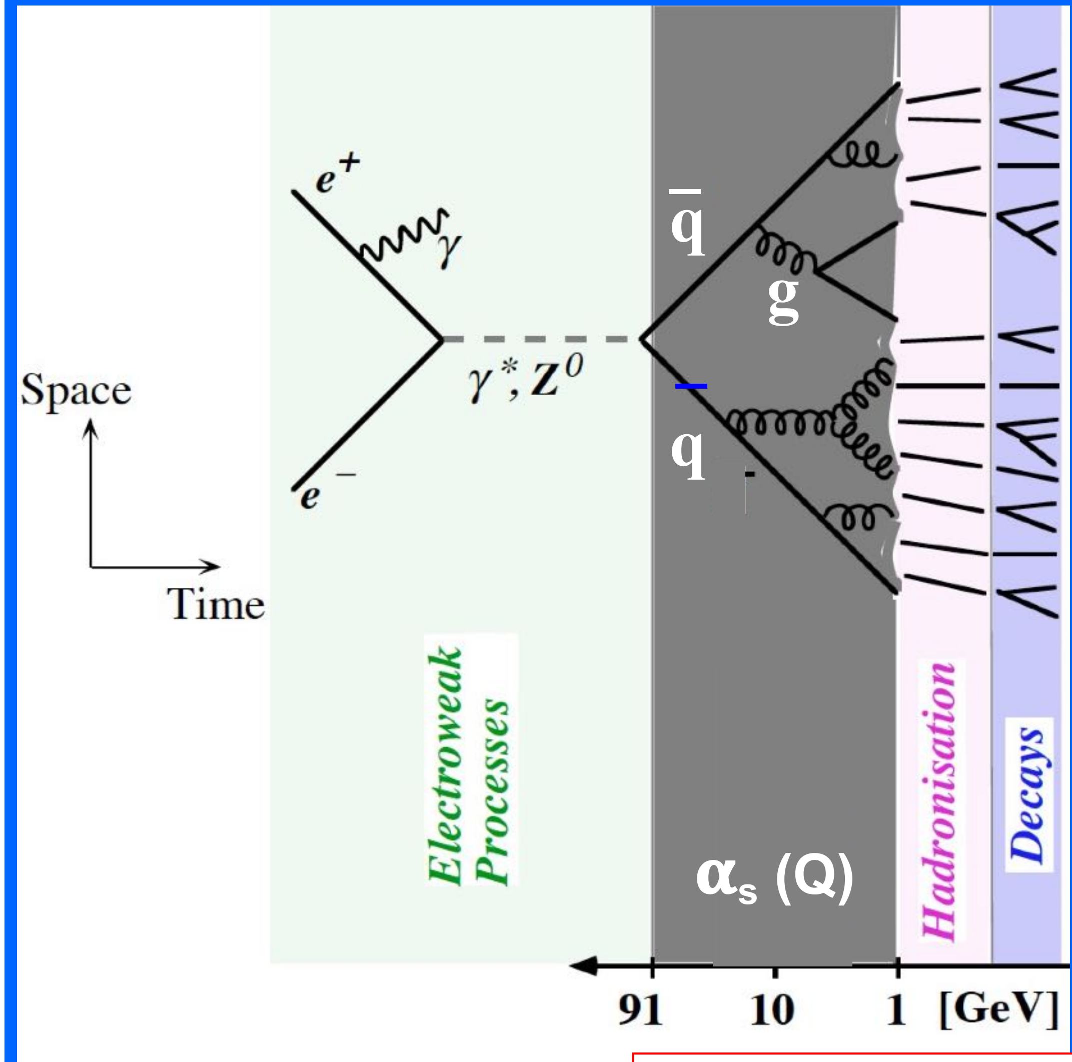
Models of hadronization

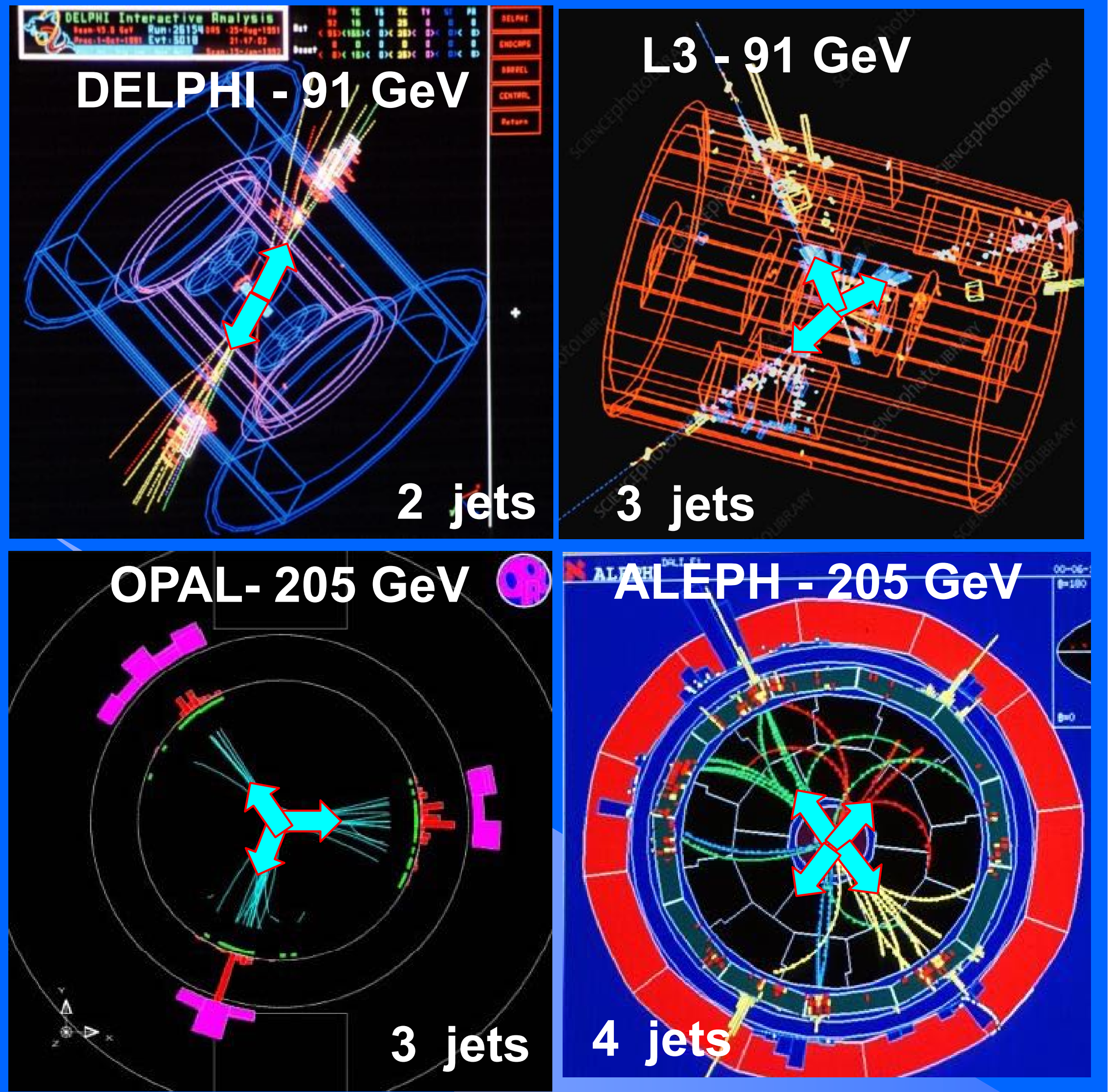


String fragmentation JETSET/PYTHIA

Cluster fragmentation HERWIG

QCD and hadronization models at LEP -1





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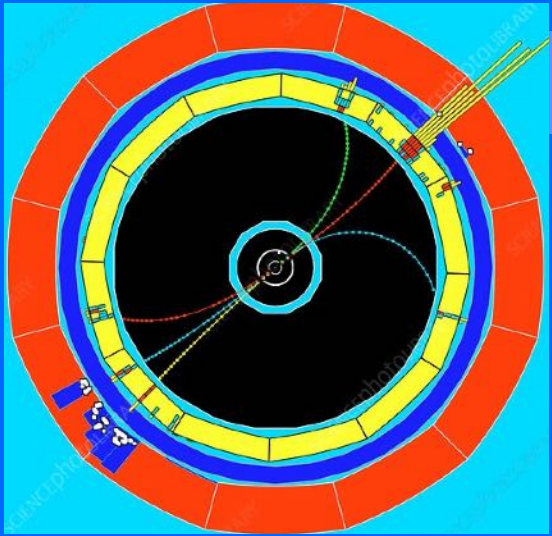
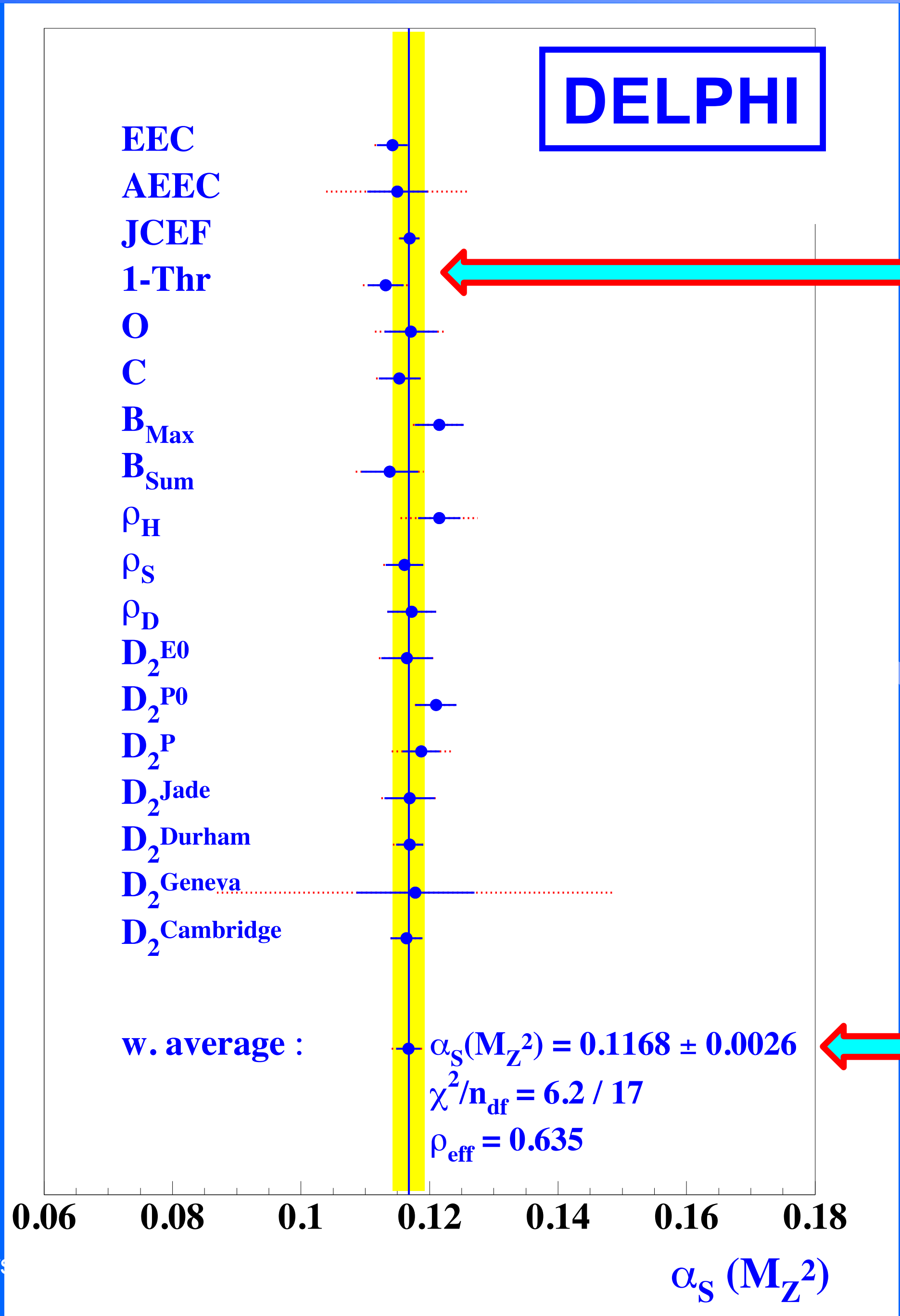


Results of jet measurements

- **Tau decays: ALEPH** $\alpha_s(m_\tau^2) = 0.340 \pm 0.005_{\text{exp}} \pm 0.014_{\text{th}}$
- **Event shapes - Example: Thrust** $T = \max_{\hat{n}} \left(\frac{\sum_i |\vec{p_i} \cdot \hat{n}|}{\sum_i |\vec{p_i}|} \right)$
- **3-jet event production rate**
- **4-jet event production rate**

Many variables can be used to describe the event shape



Thrust

$\alpha_S(M_Z^2) = 0.1168 \pm 0.0026$

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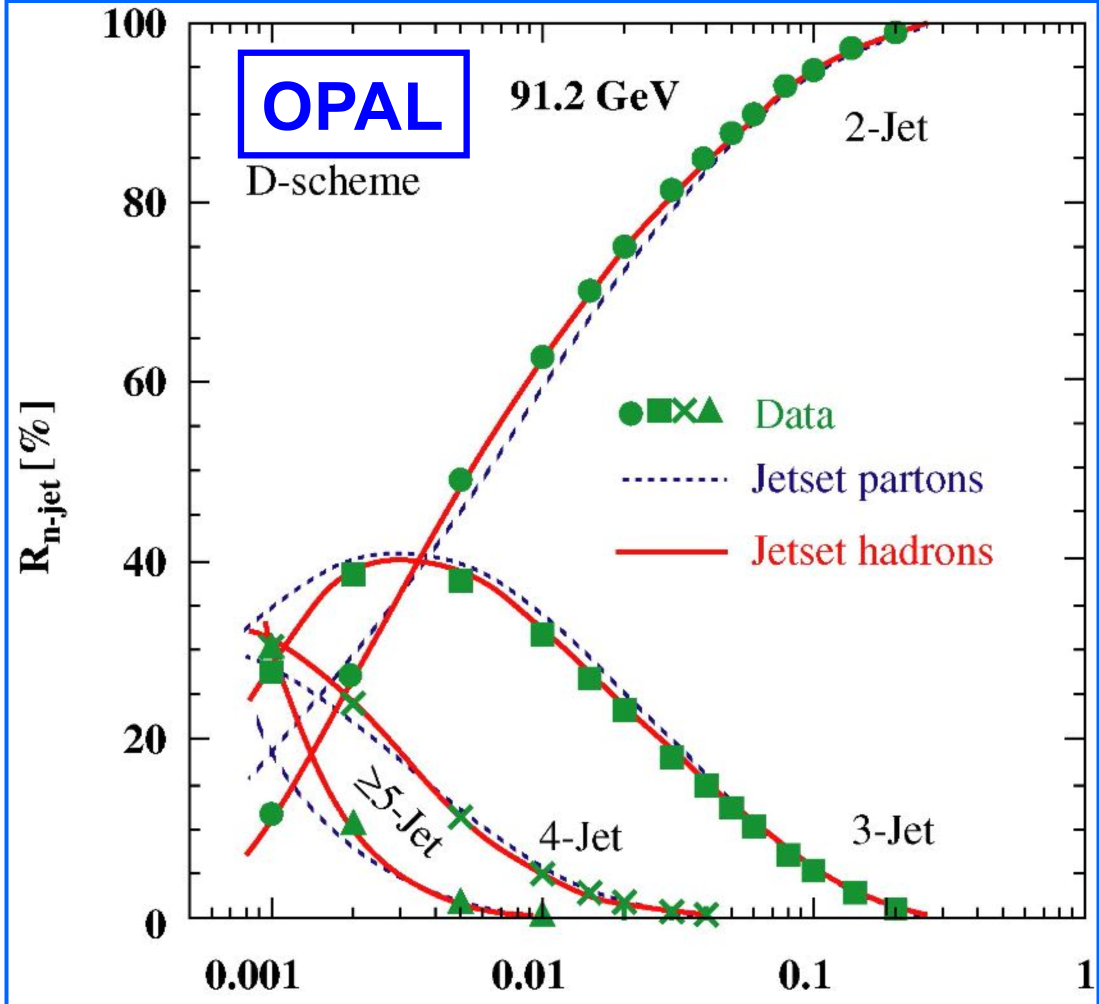
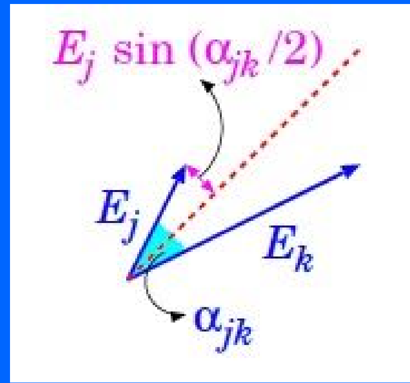
Fractions of events with different numbers of jets

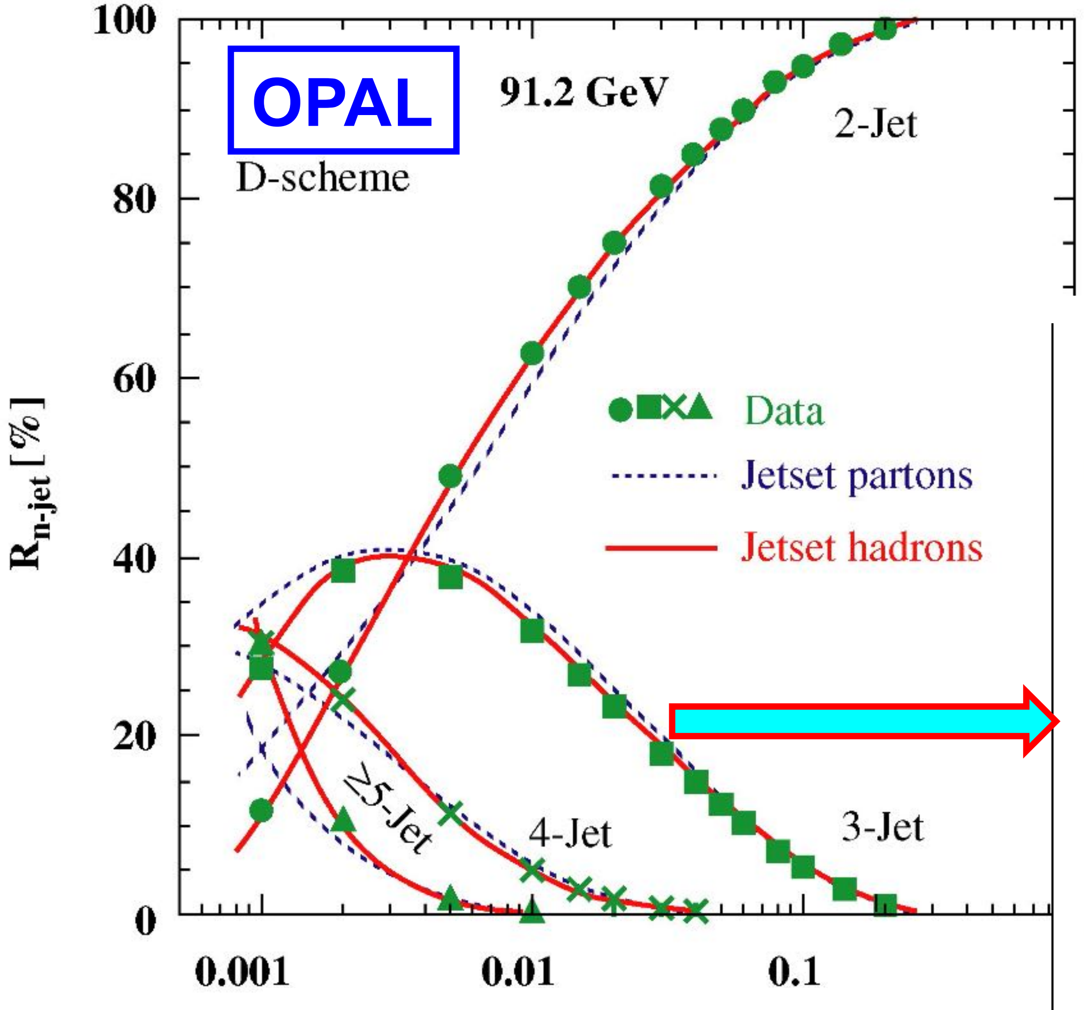


y_{cut} = resolution parameter



$$y_{jk} = 4\frac{\min\{E_j^2; E_k^2\}}{Q^2}\sin^2\left(\frac{\alpha_{jk}}{2}\right)$$

Fractions of events with different numbers of jets



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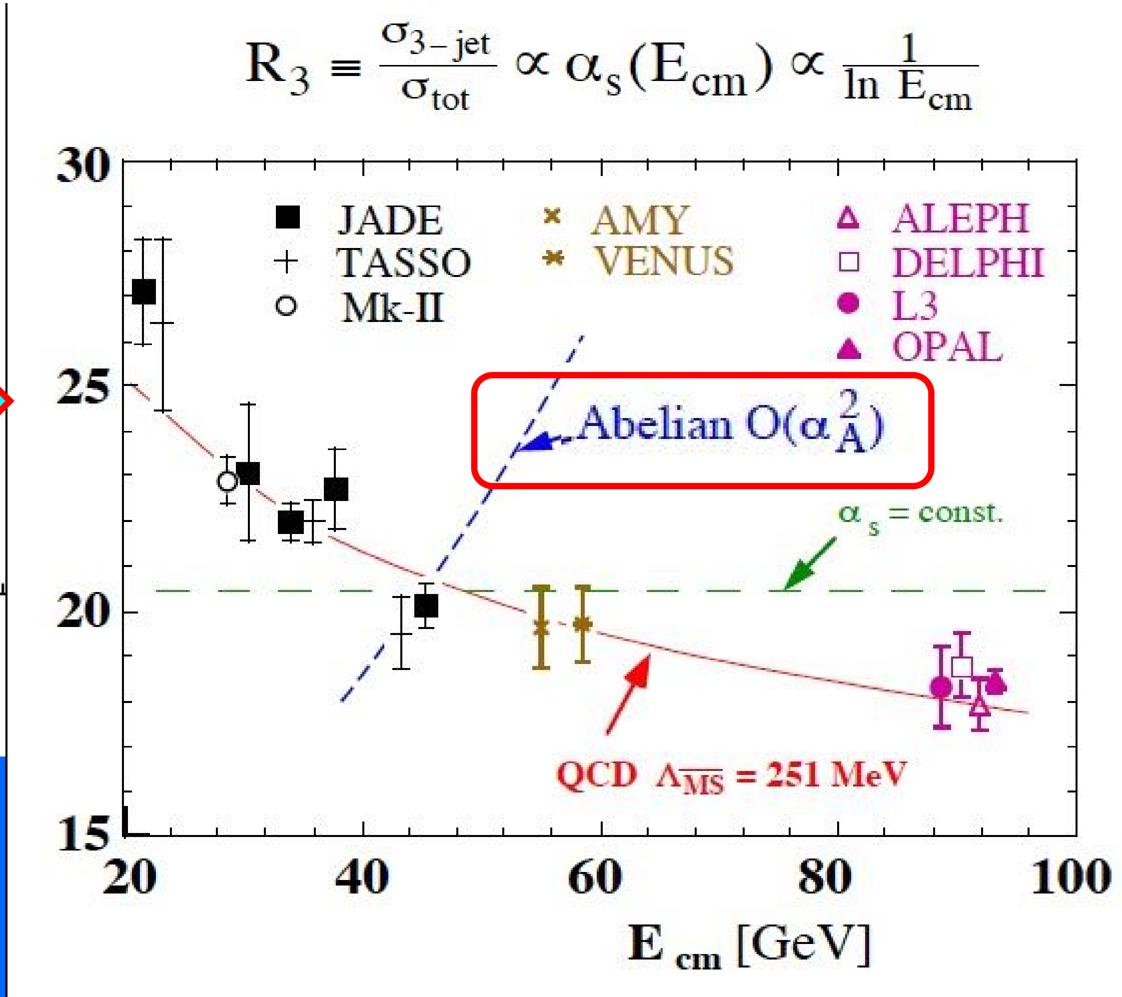
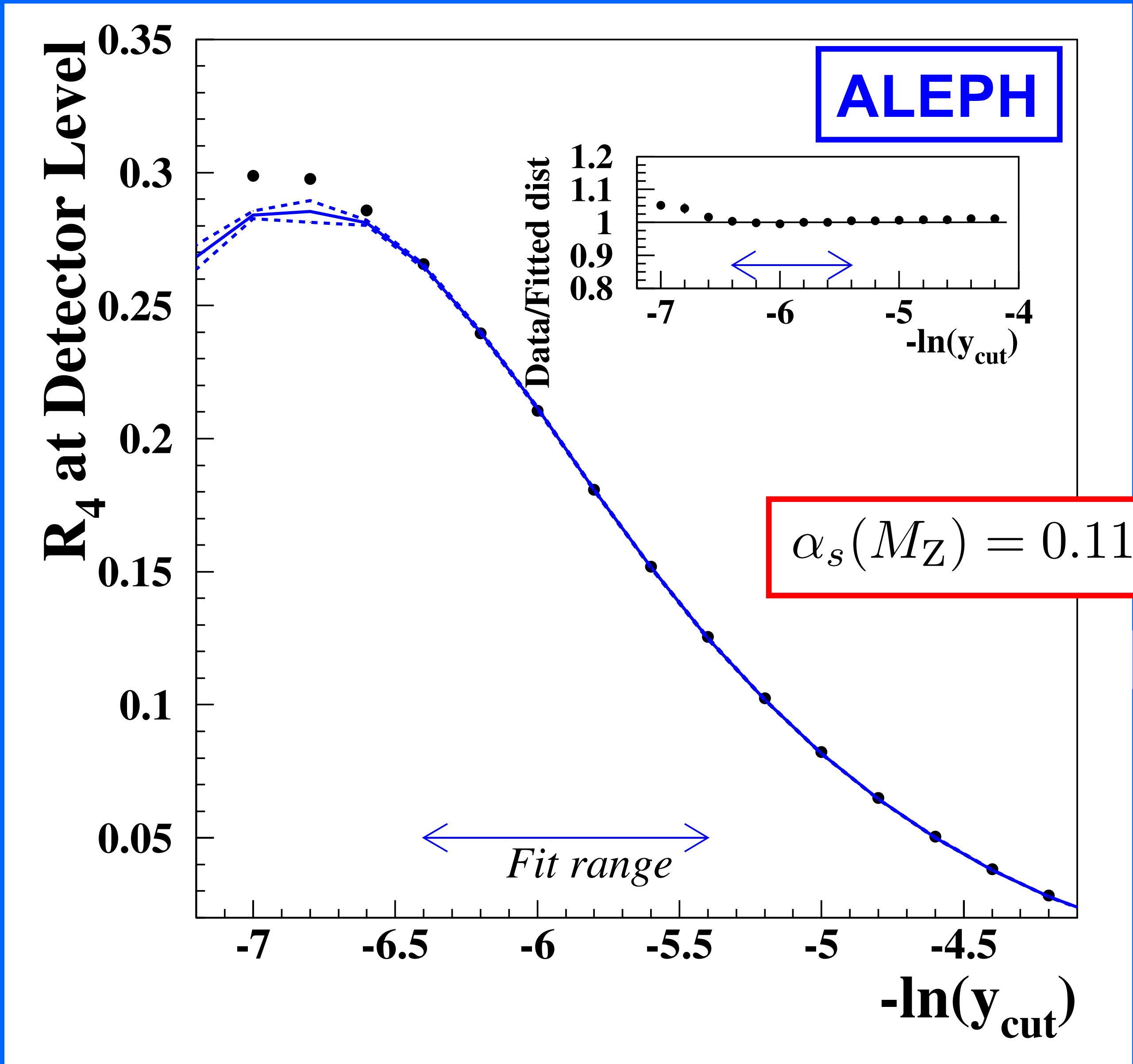


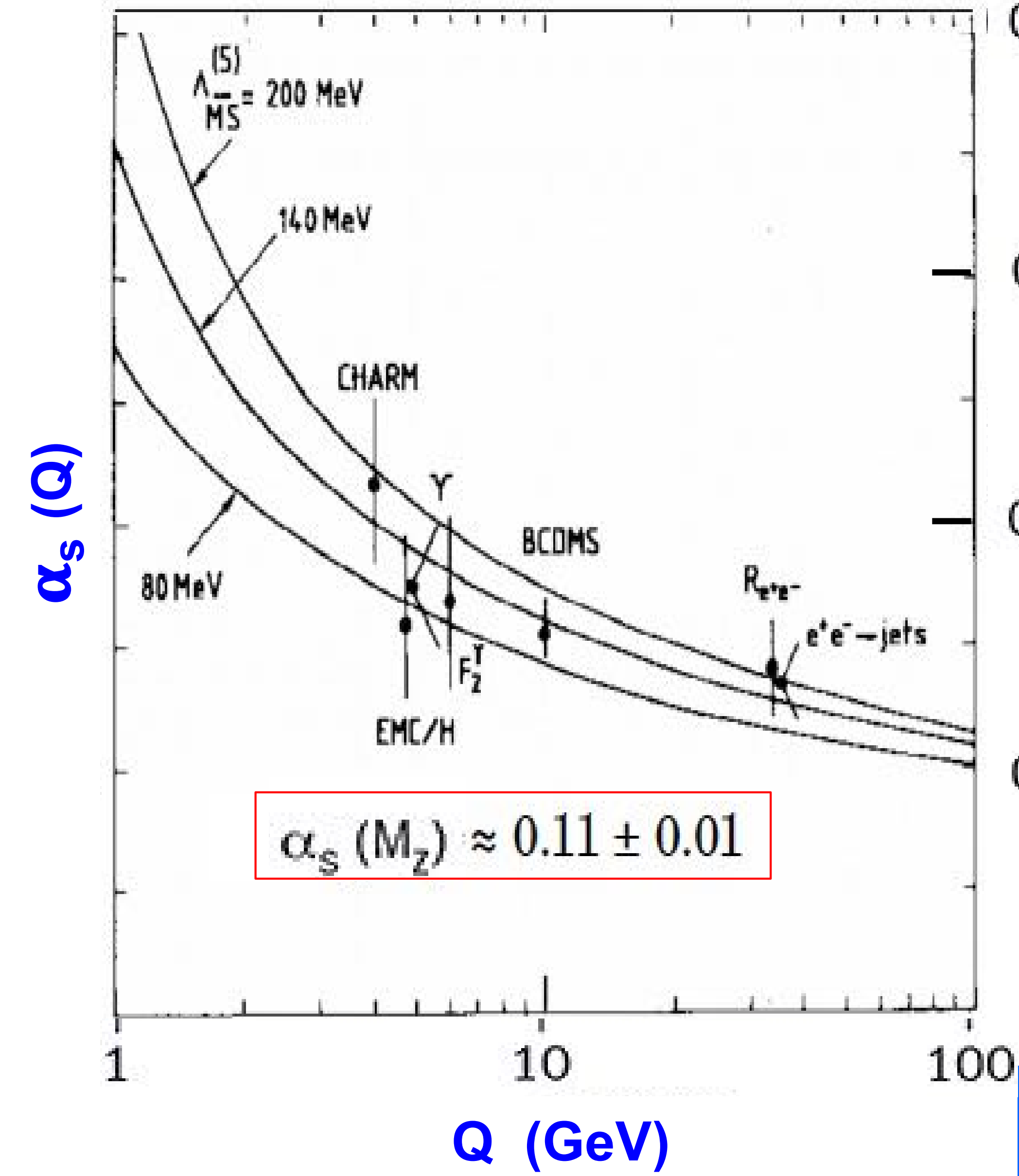
Production rate of 4-jet events

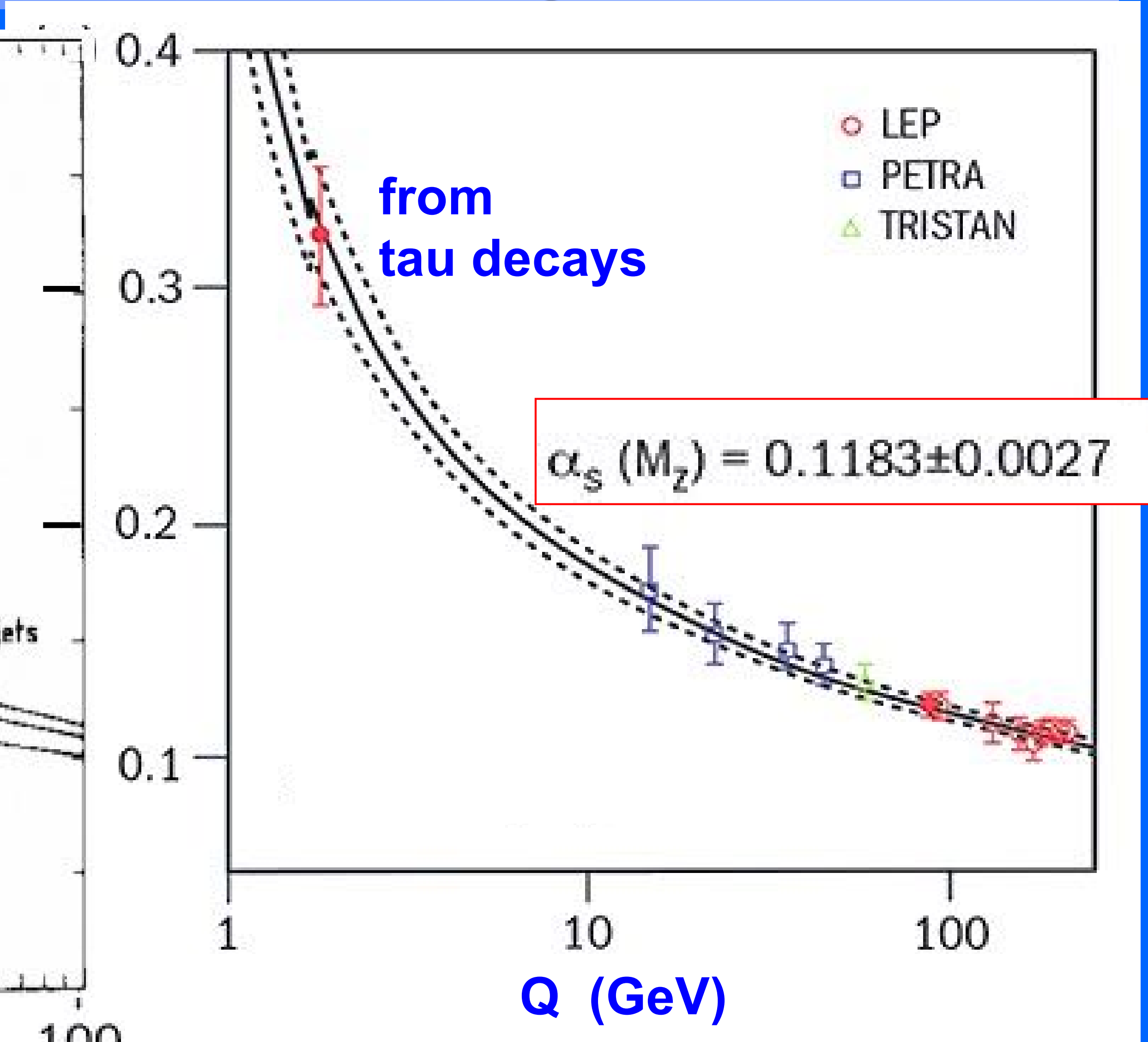


$$R_4 \equiv \frac{\sigma_{4\text{-jet}}}{\sigma_{tot}} \propto \alpha_s^2(E_{cm})$$

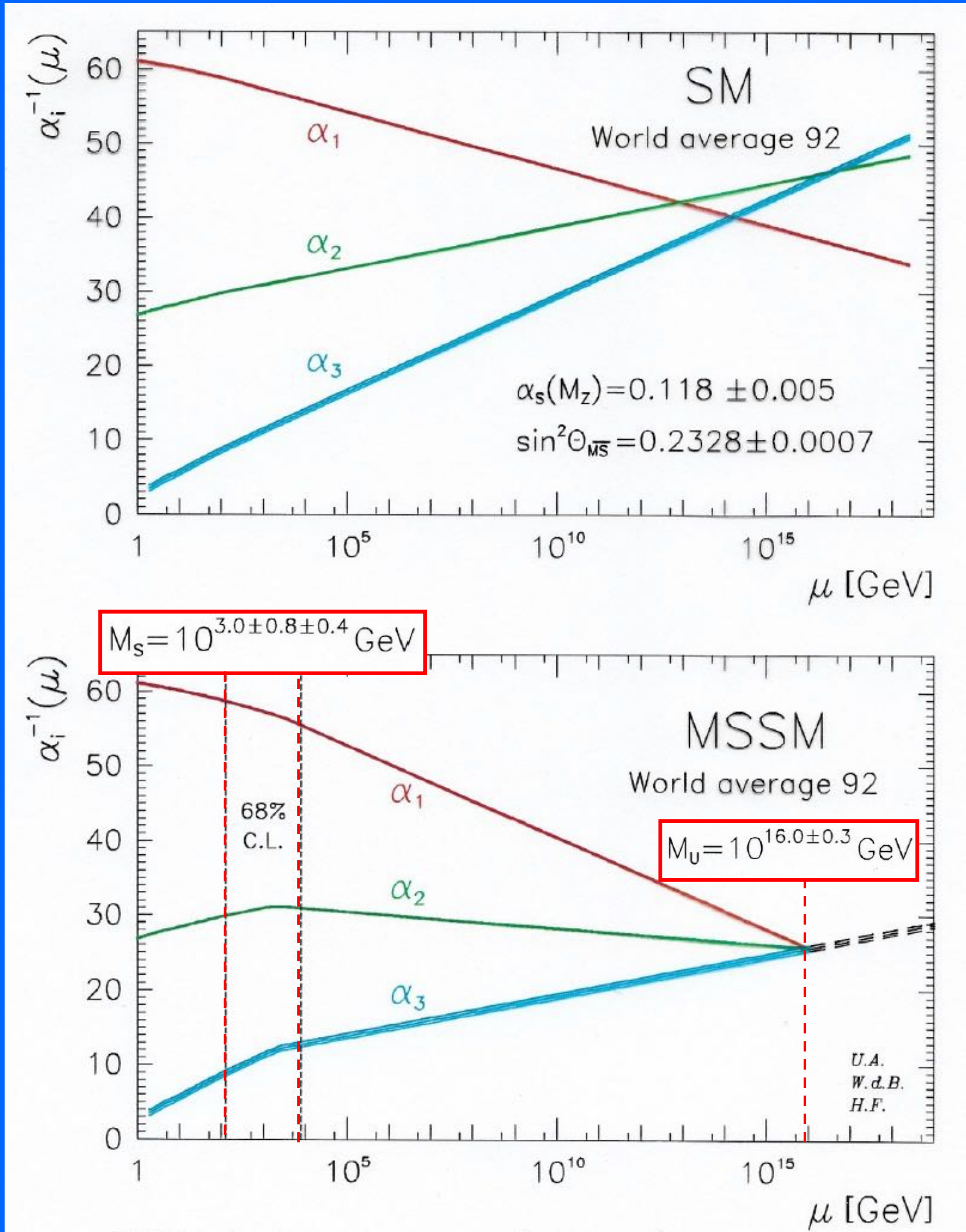
$$\alpha_s(M_Z) = 0.1170 \pm 0.0001(\text{stat}) \pm 0.0013(\text{sys})$$

Running of the strong coupling from electron-positron collisions





Unification of the couplings in the Minimal Supersymmetric Model



U.A. Wim de Boer
Hermann Furstenau

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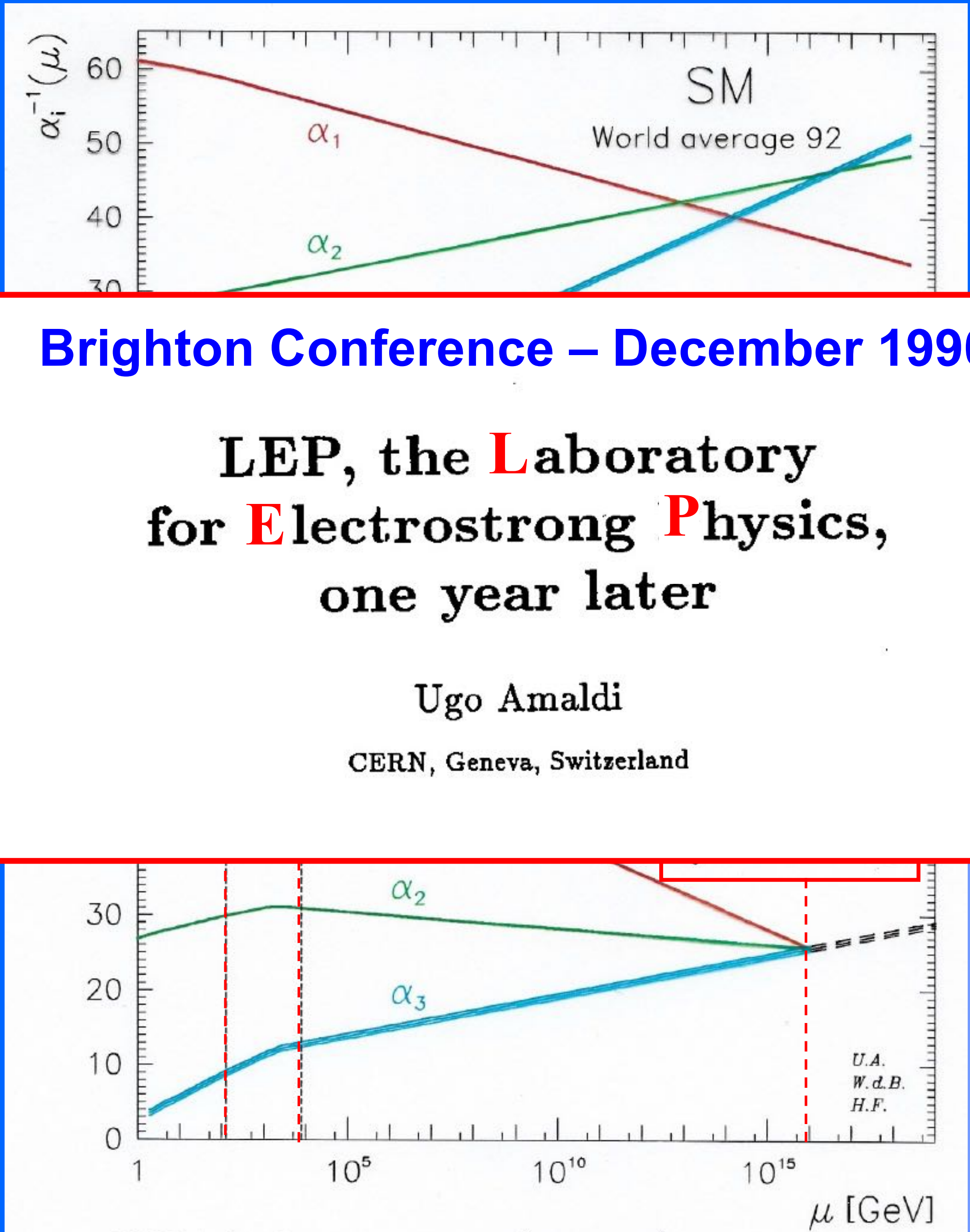

Brighton Conference – December 1990

LEP, the Laboratory for Electrostrong Physics, one year later

Ugo Amaldi

CERN, Geneva, Switzerland

Wim de Boer

nn Furstenau

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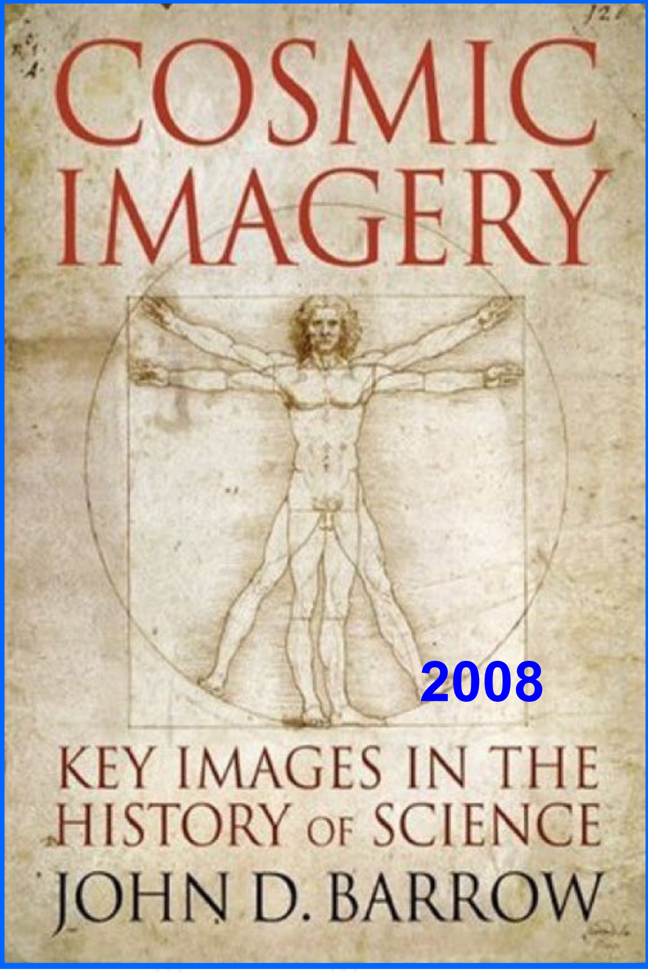
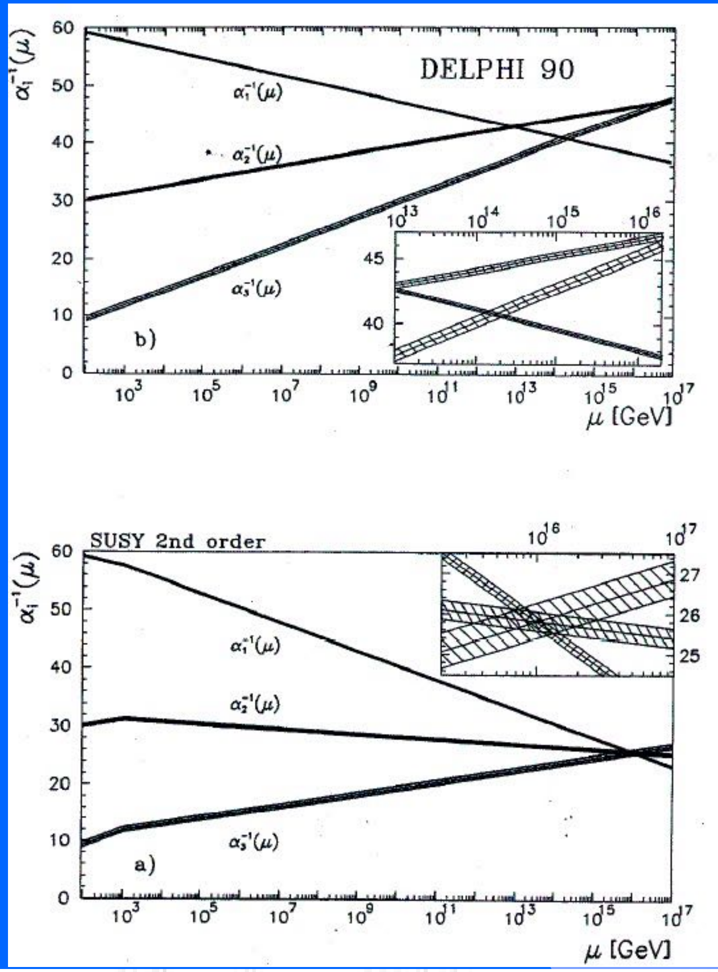




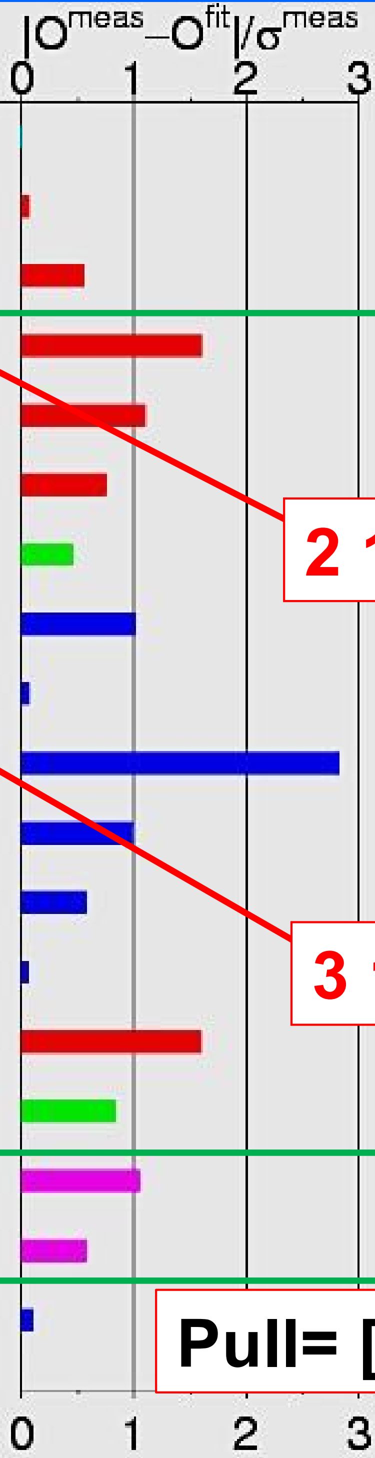
U.A. Wim de Boer
Hermann Furstenau
PL B260 (1991) 447

The simple suggestive picture of the three-fold intersection of the strengths of the electromagnetic, weak, and strong forces of Nature is a simple symbol of the Universe's deep unity in the face of superficial diversity, which is what we mean by beauty.

2. Electroweak interactions
U(1) x SU(2) with couplings α_1 and α_2

Overview of all LEP results

	Measurement	Fit
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4965
σ^0_{had} [nb]	41.540 ± 0.037	41.481
R_l	20.767 ± 0.025	20.739
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01642
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1480
R_b	0.21629 ± 0.00066	0.21562
R_c	0.1721 ± 0.0030	0.1723
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1037
$A^{0,c}_{fb}$	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	0.1480
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.425 ± 0.034	80.389
Γ_W [GeV]	2.133 ± 0.069	2.093
m_t [GeV]	178.0 ± 4.3	178.5



2 10^{-5}

3 10^{-3}

Z-boson mass and width

W-boson mass and width

Pull= [X(expt) - X(theory)] / σ_X

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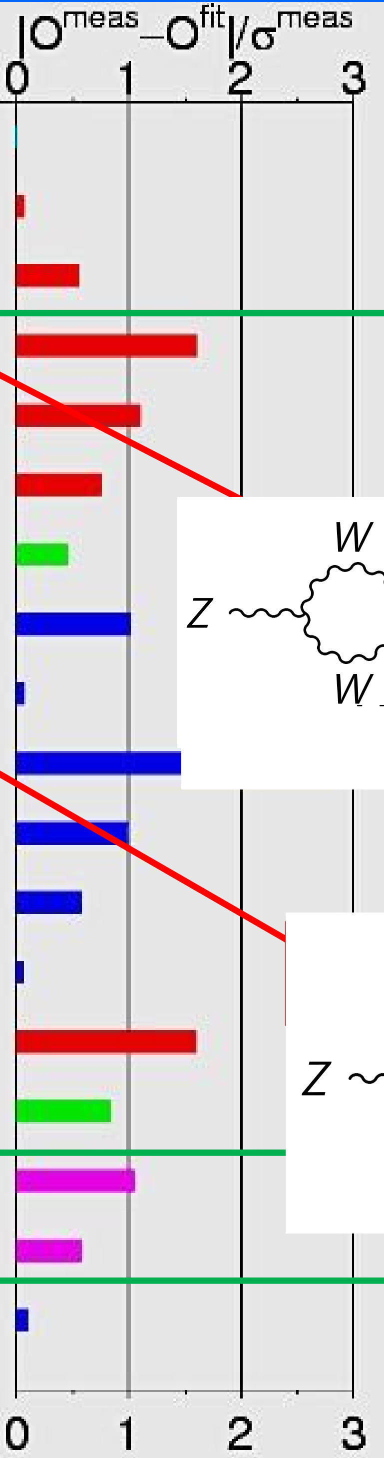
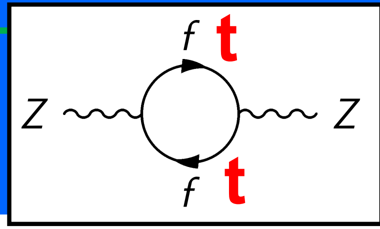
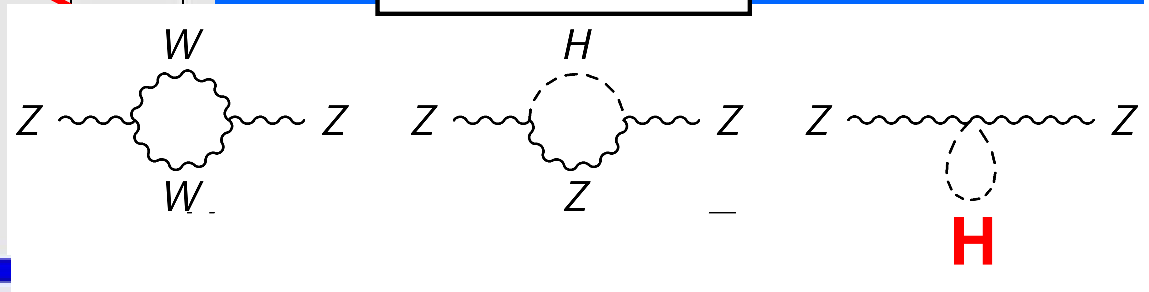
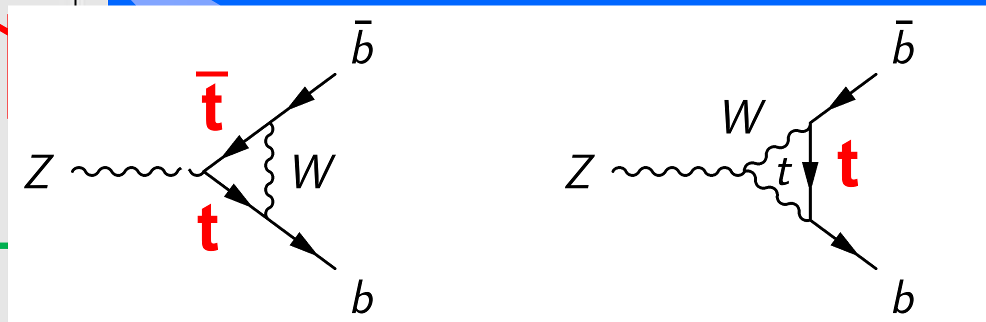


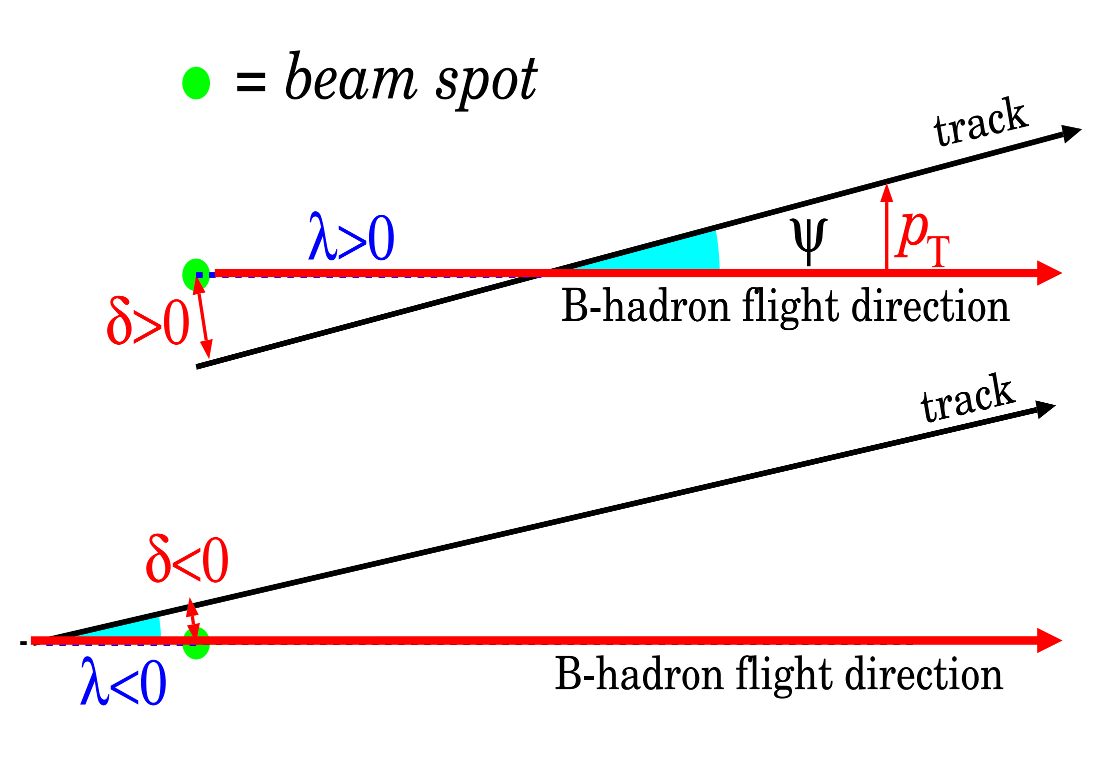
RADIATIVE CORRECTIONS

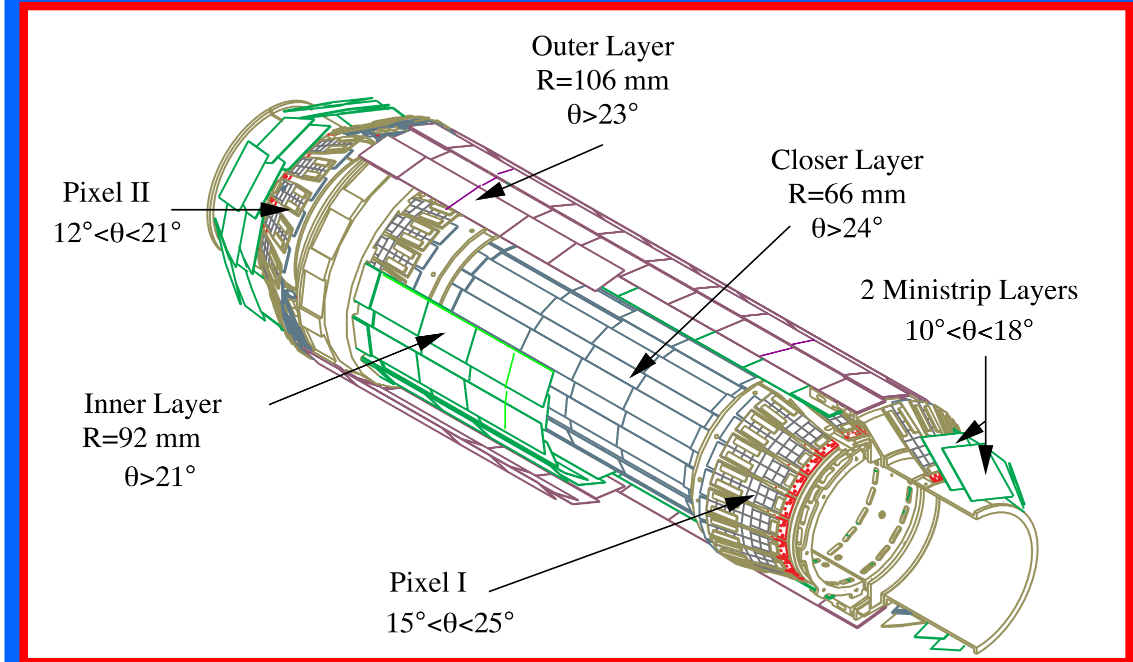




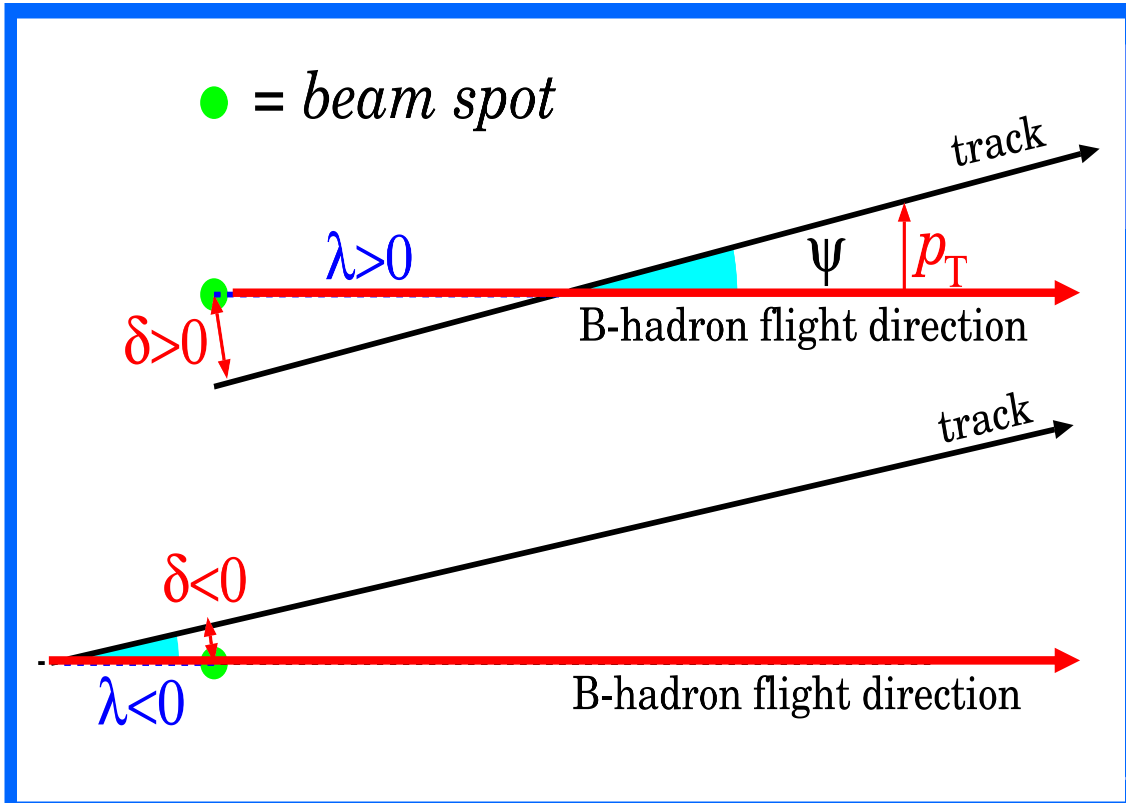


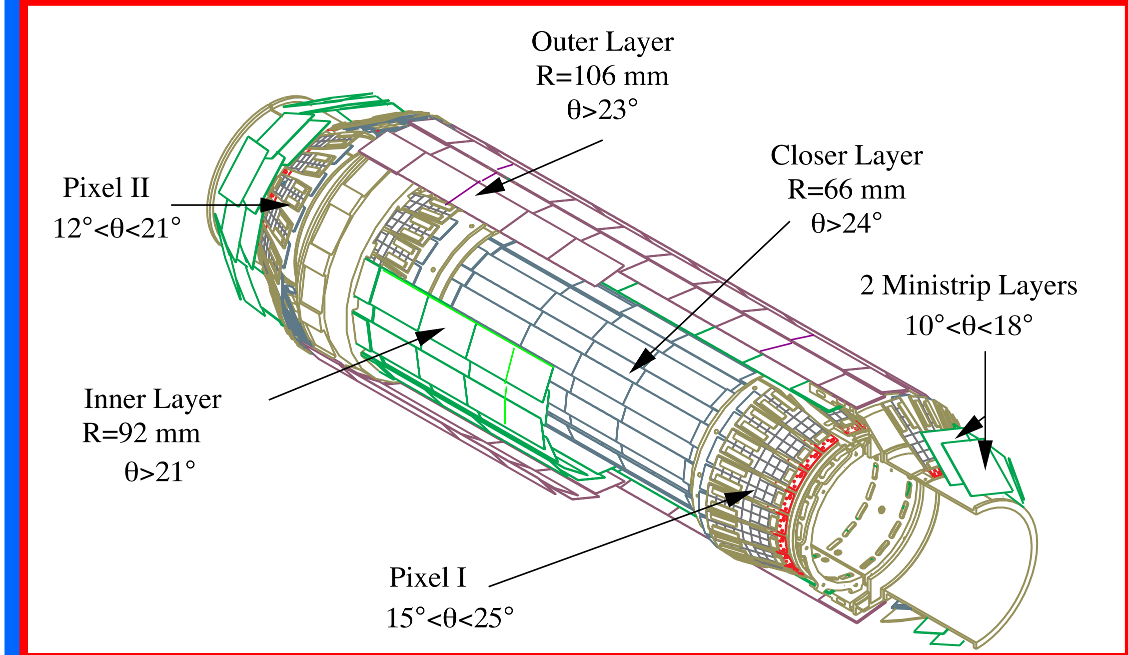
Microstrip silicon detectors for b-tagging

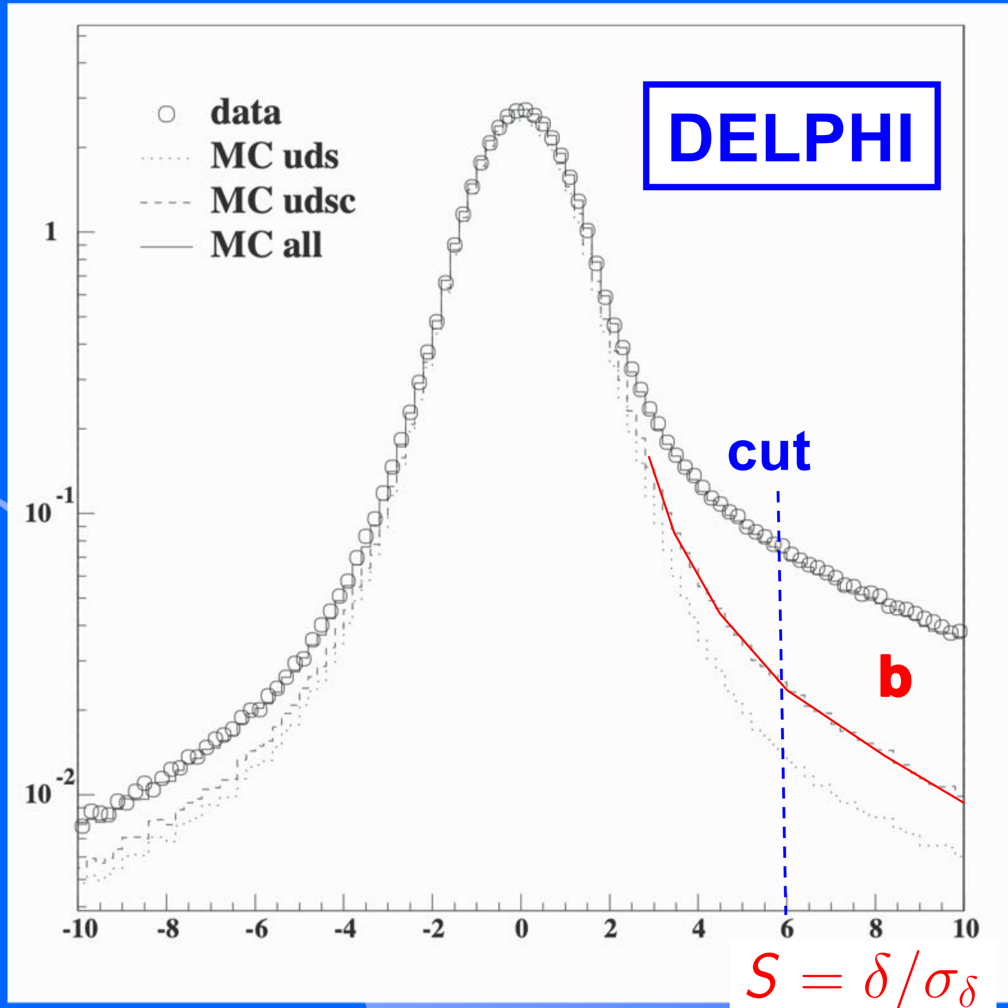




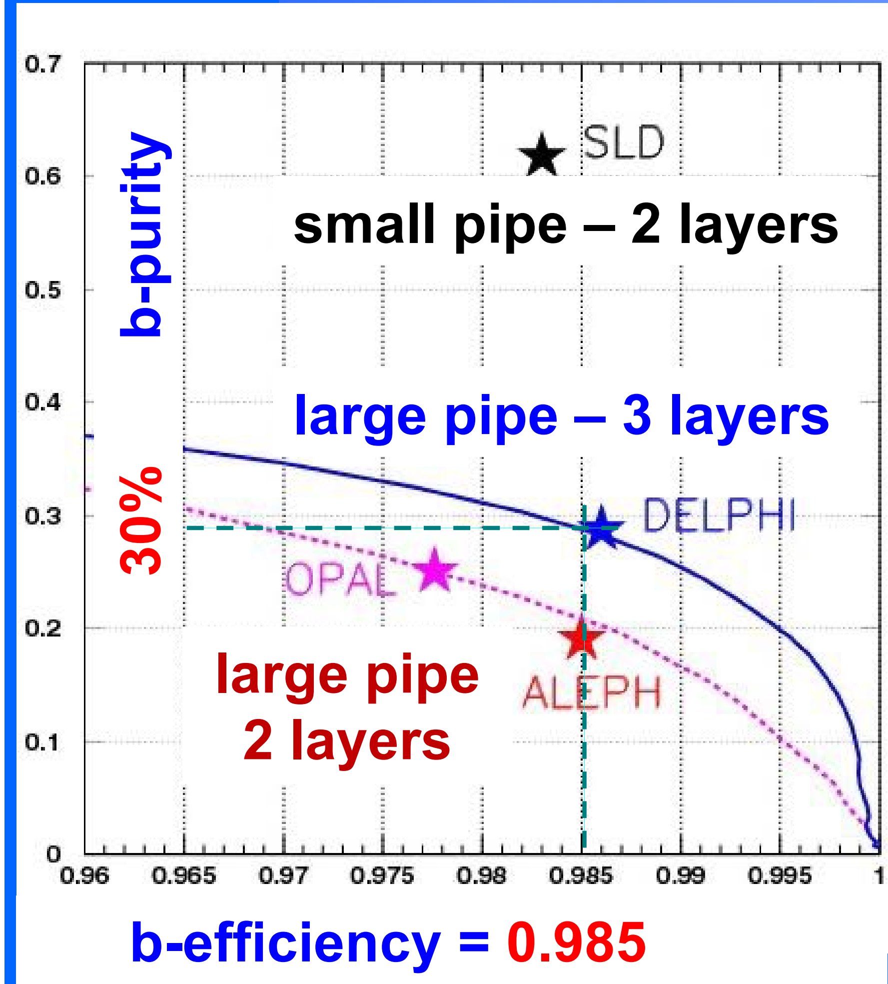
Microstrip silicon detectors for b-tagging







Production rate of b quarks



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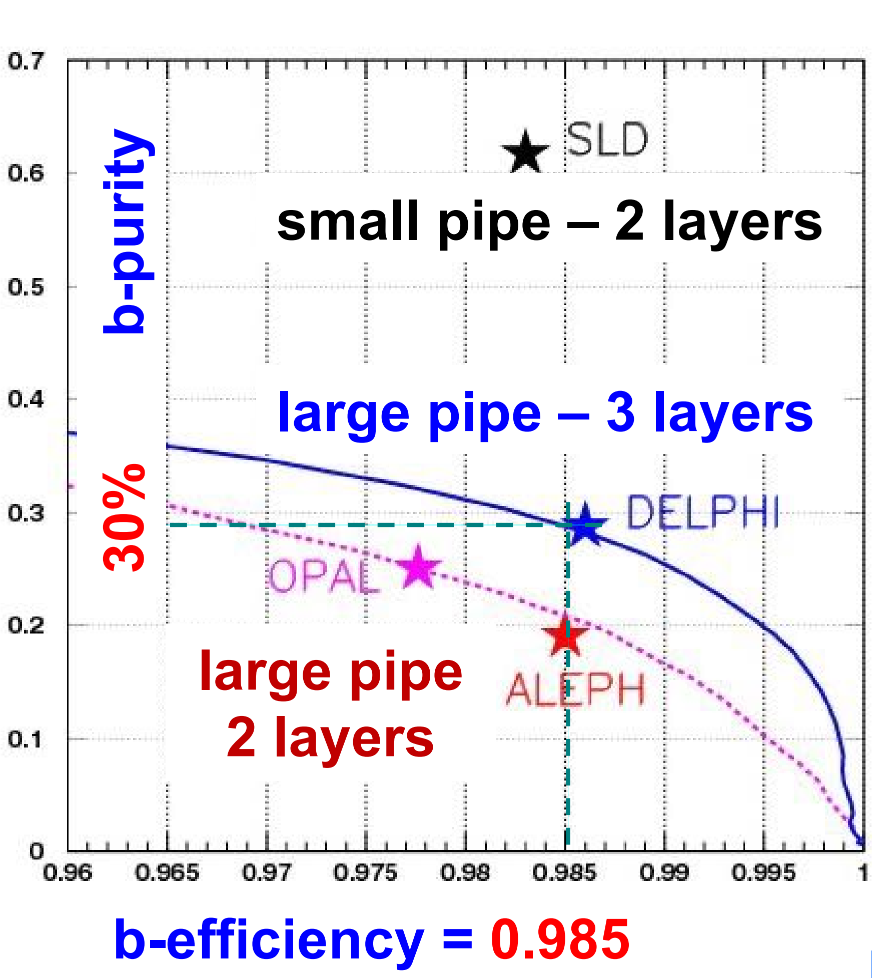
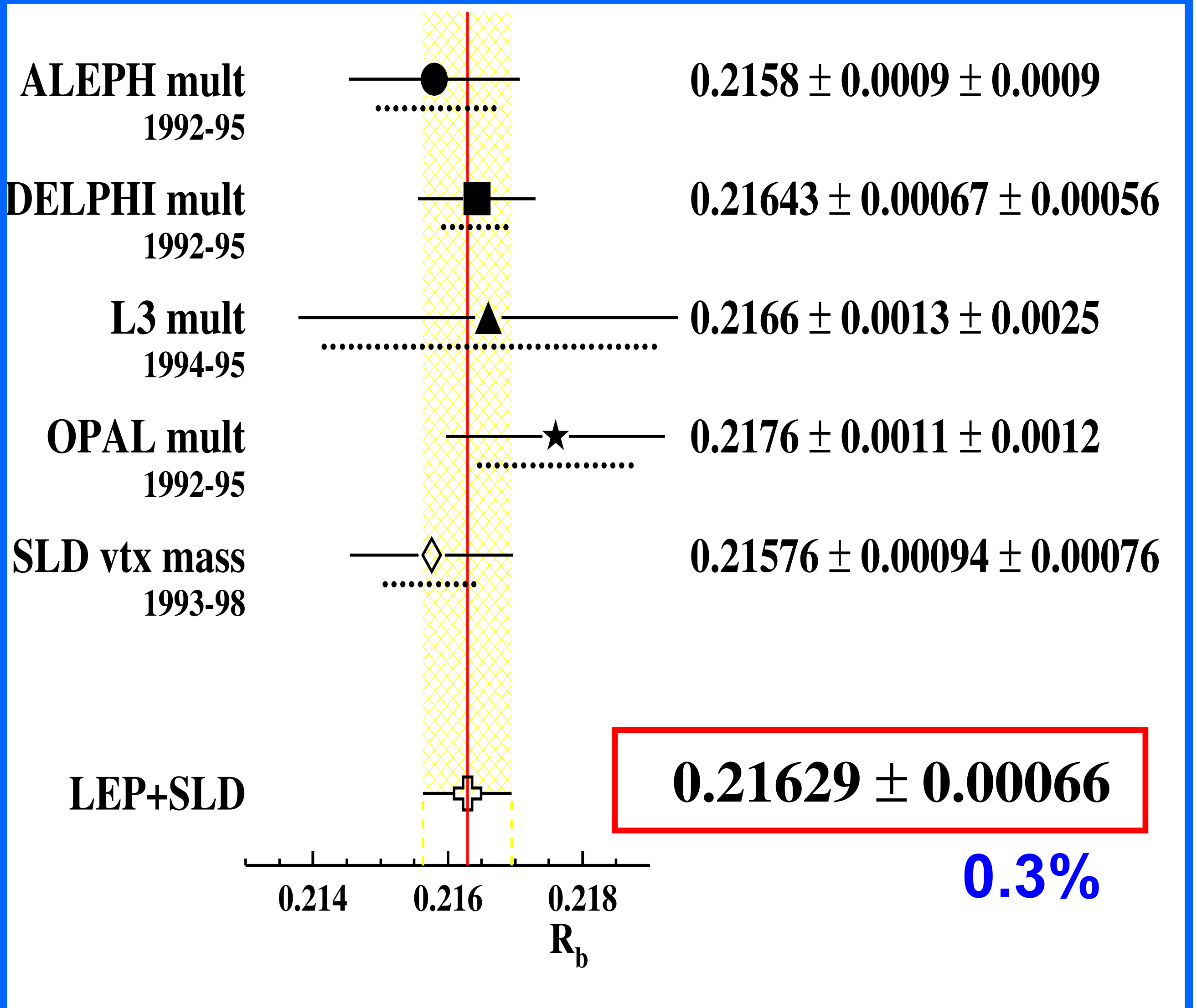
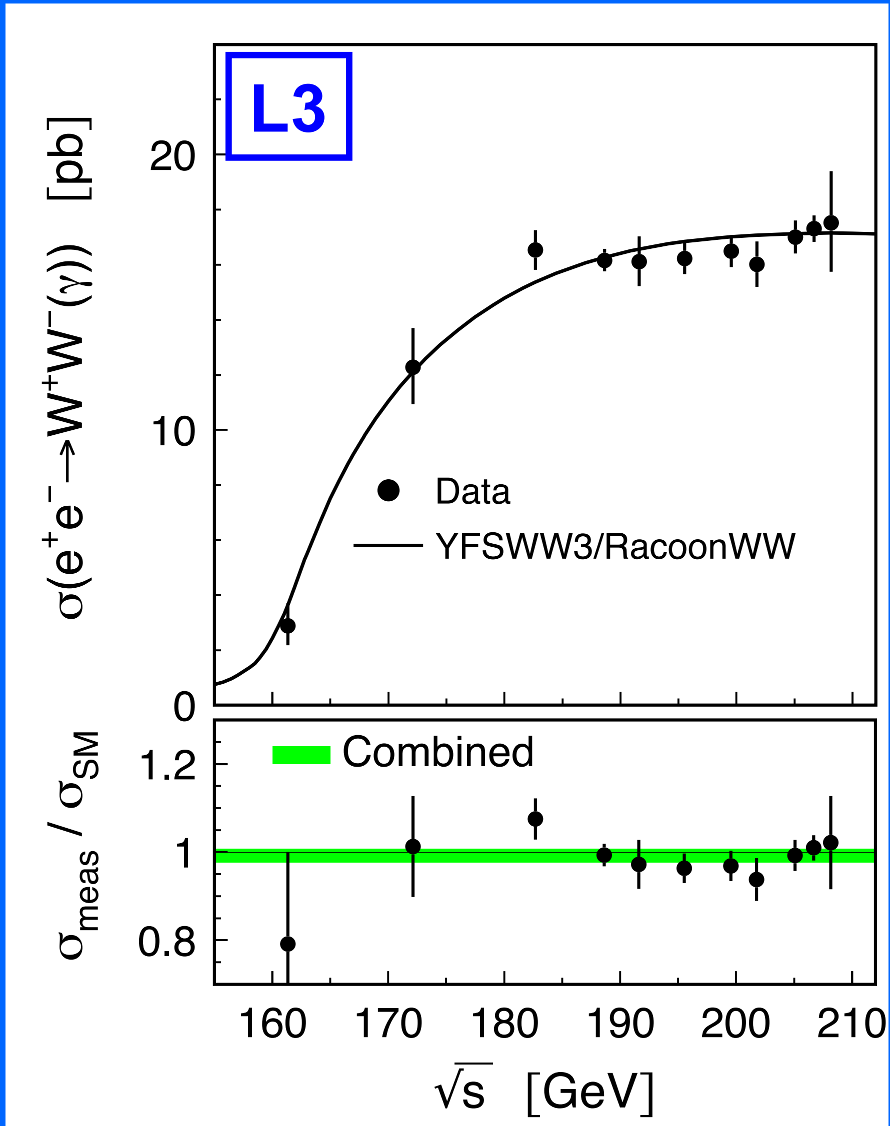
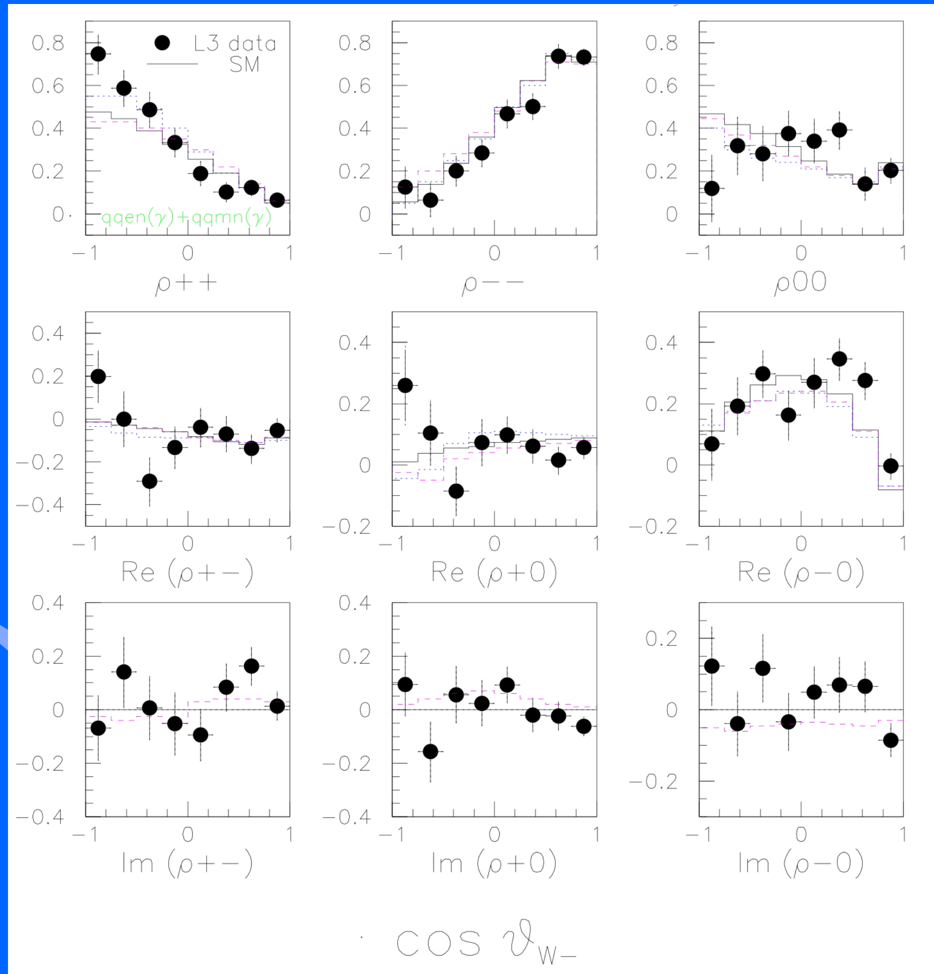




Only one result from LEP II: WW production





Elements of the W-boson spin density matrix versus the W production angle

LEP Electroweak Working Group: determination of the top-quark and Higgs masses

Moriond 1994 – LEP average:

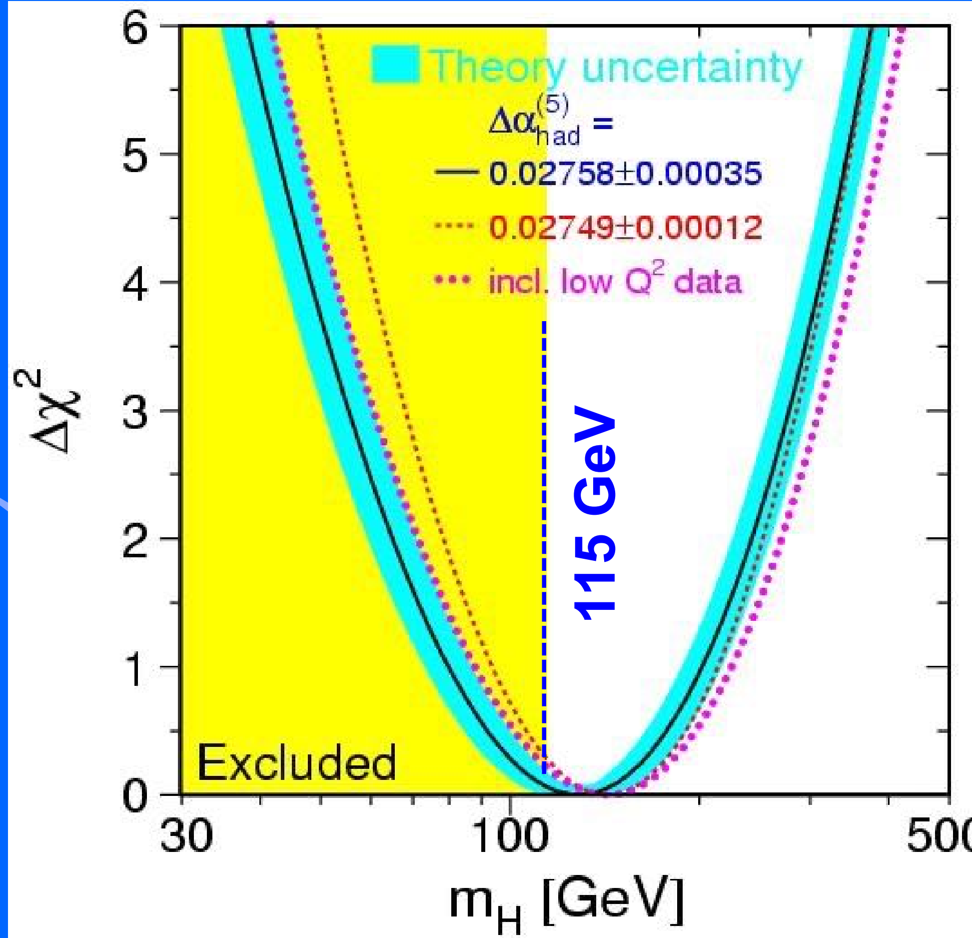
$$m_t = 172\,^{+13}_{-14}\,^{+18}_{-20}\ \text{GeV}$$

Few months later CDF 12 top decays:

$$m_t = 174 \pm 10\,^{+13}_{-14}\ \text{GeV}$$

Final result:

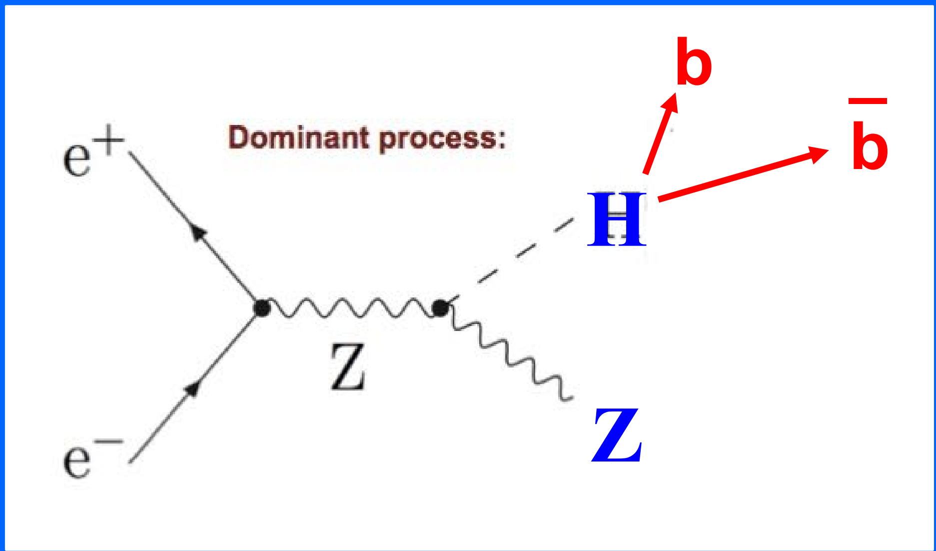
$$m_t = 178.0 \pm 4.3\ \text{GeV}$$

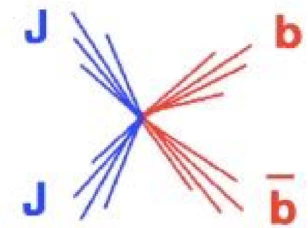
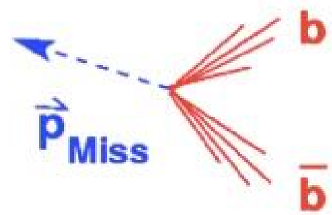
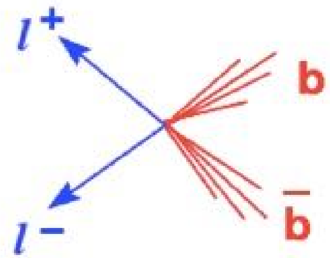


115 GeV – 295 GeV (95% CL)

3. In search of the Standard Model Higgs

Main production channels



Channel	Topology	BR
4 jets		~ 64 %
2 b-jets + missing momentum ($Z \to \nu\nu$)		~ 18 %
2 b-jets + lepton pair ($Z \to ll$)		~ 9 %

B-tagging is very important to fight the background

Maximum reach of LEP in the Higgs search

Search fot neutral Higgs at LEP 2000

Presented by Sau Lan Wu

ECFA WORKSHOP on LEP 200

Aachen 1986 – CERN-EP/9/-40

we conclude that at $E_{cm} = 200$ GeV, $500 pb^{-1}$ integrated luminosity, one can get $\boxed{\text{significant signals of Higgs masses up to about 70 GeV}}$ from the process $e^+e^- \rightarrow H^\circ Z^\circ \rightarrow 4$ jets. $\boxed{\text{It is difficult to extend the Higgs mass to 80 GeV}}$ (due to $W^\pm$) or 90 GeV (due to Z°).

($E_{cm} = 2\ E_b$)

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Eventually : mass limit $M_H = 2\ E_b$ - 100 GeV limited by

radiated energy/turn

$$U_0 = C_\gamma \frac{E_b^4}{\rho},$$

3 GeV/turn @ 100 GeV

Room temperature and superconducting accelerating cavities

56 room-temperature cavities : 1.5 MeV/m

288 superconducting niobium sputtered on copper cavities
6 - 7.5 MeV/m
(500 meters !)

Cut of a 352 MHz niobium sputtered SC cavity

Room temperature and superconducting accelerating cavities

56 room-temperature cavities : 1.5 MeV/m

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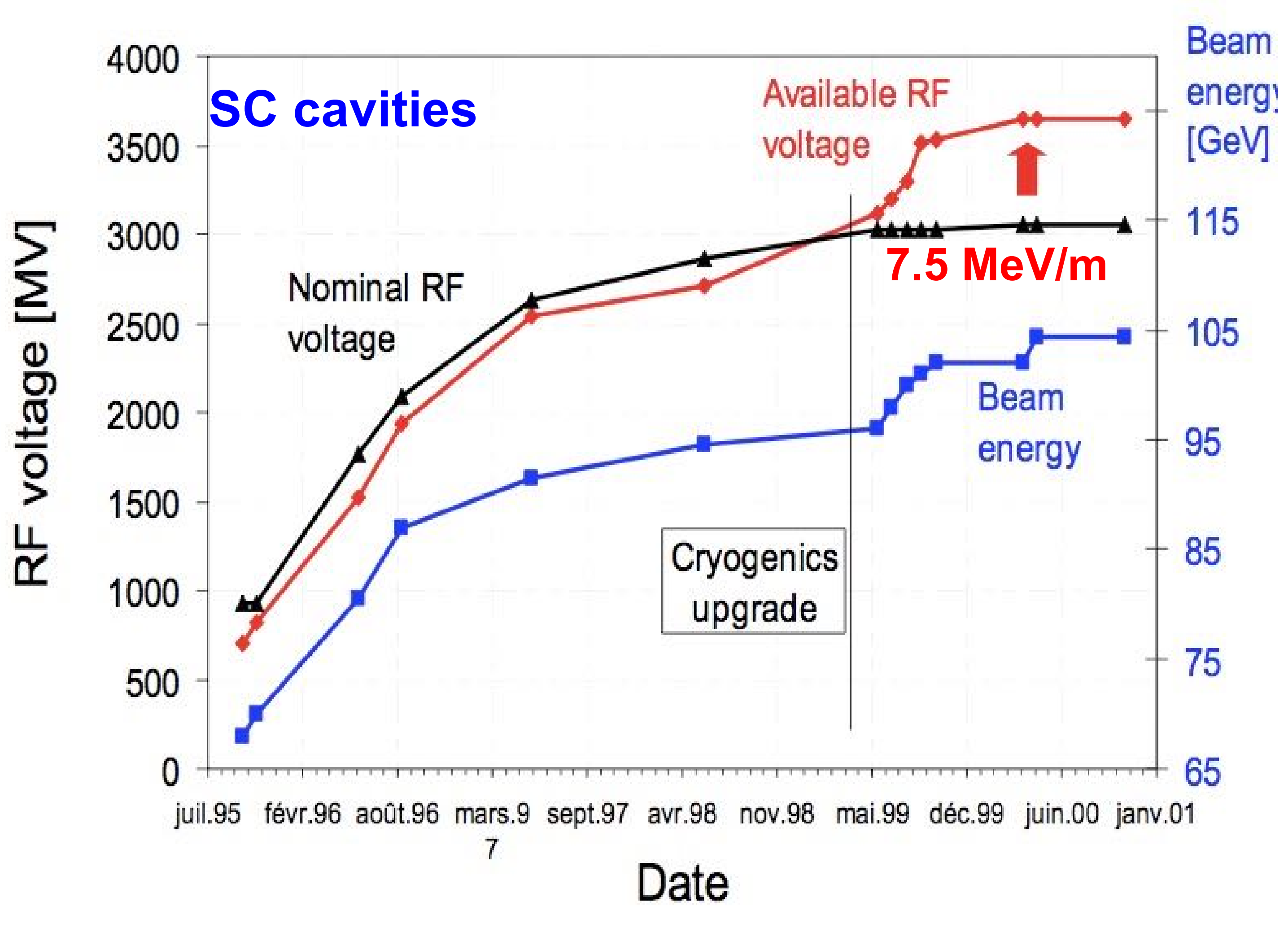


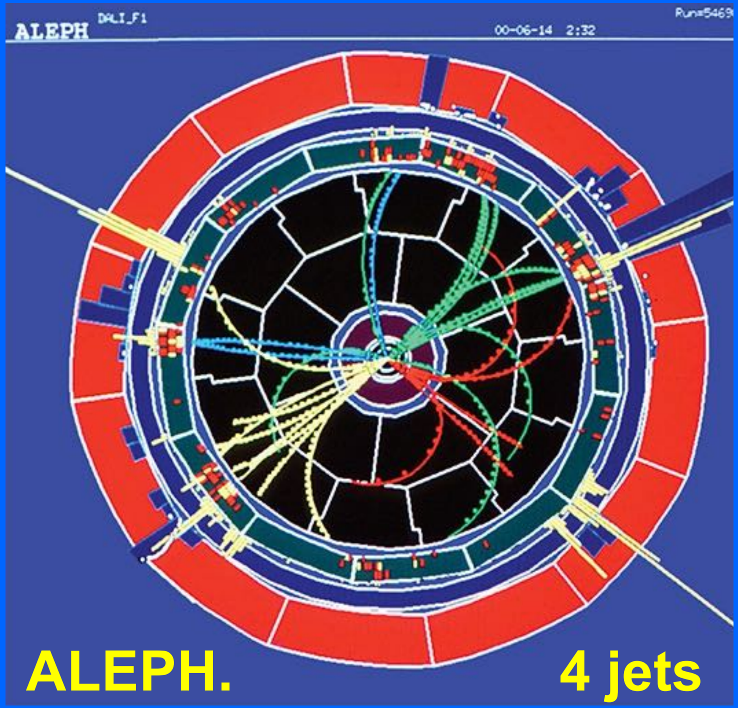
Cut of a 352 MHz niobium coated SC cavity

Chronology in the year 2000

- by midsummer: one high-mass candidate in ALEPH, 4 jets, reconstructed mass ~114 GeV
- by Sep 5: two more 4-jet candidates in ALEPH
- by Nov 3: 70% more data at E_{CM} ~ 206.6 GeV

2500 pb^{-1} between 189 – 209 GeV of which 540 pb^{-1} at 2E ≥ 206 GeV

G. Dissertori 2015
D. Treille 2019



Chronology in the year 2000

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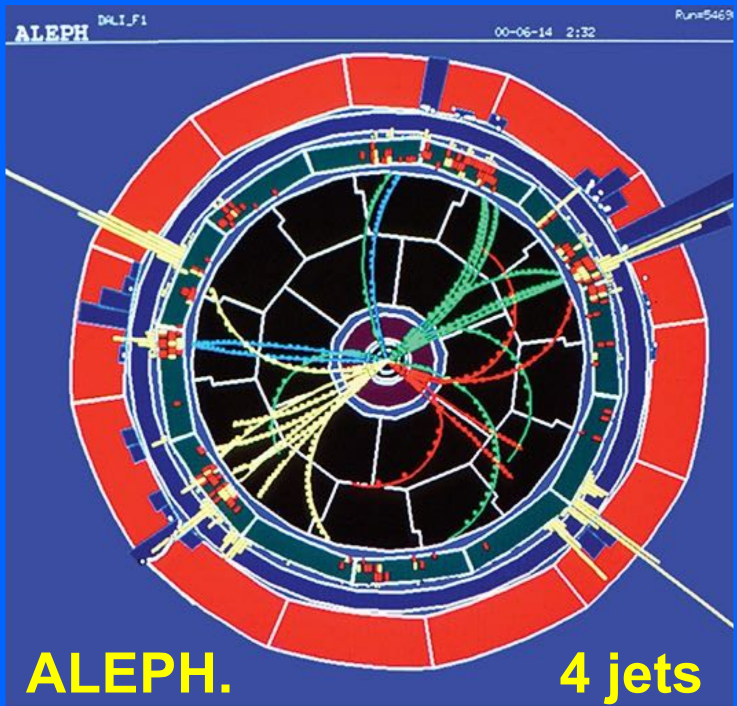
- by Sep 5: two more 4-jet candidates in ALEPH
- by Nov 3: 70% more data at E_{CM} ~ 206.6 GeV

10 evts with largest $(s/b)_{115}$:

2500 pb^{-1} between 189 – 209 GeV of which 540 pb^{-1} at 2E ≥ 206 GeV

weight for a test mass = 115 GeV

G. Dissertori 2015
D. Treille 2019



	EXP	Channel	M (GeV)	w
1	ALEPH	4-jet	114.3	1.73
2	ALEPH	4-jet	112.9	1.21
3	ALEPH	4-jet	110.0	0.64
4	L3	E-miss	115.0	0.53
5	OPAL	4-jet	110.7	0.53
6	DELPHI	4-jet	114.3	0.49
7	ALEPH	Lept	118.1	0.47
8	ALEPH	Tau	115.4	0.41
9	OPAL	4-jet	112.6	0.40
10	ALEPH	4-jet	114.5	0.40

Combined LEP result at M_H = 115 GeV is in excess of the "background-only" hypothesis by 1.7 standard deviations.

Lower bound (95%CL) on the SM Higgs boson mass is M_H = 114.4 GeV

The legacy of LEP to the LHC experiments

STANDARD MODEL

Hadronization models and Montecarlo programs

Material legacy, beyond the 27 km tunnel

Microstrip and pixel silicon detectors

ALEPH DELPHI L3 OPAL	→	ALICE ATLAS CMS LHCb

Material legacy, beyond the 27 km tunnel

Microstrip and pixel silicon detectors	ALEPH DELPHI L3 OPAL	→	ALICE ATLAS CMS LHCb
Large room temperature magnet	L3	→	ALICE
Large arrays of crystal to measure γ/e energies	L3	→	CMS

Material legacy, beyond the 27 km tunnel

Technology	LEP experiments		LHC experiments
Microstrip and pixel silicon detectors	ALEPH DELPHI L3 OPAL	→	ALICE ATLAS CMS LHCb
Large room temperature magnet	L3	→	ALICE
Large arrays of crystal to measure γ/e energies	L3	→	CMS
TPC = Time Projection drift Chamber	ALEPH DELPHI	→	ALICE
RICHs = Ring Imaging CHerenkov counters	DELPHI	→	LHCb

THE END