Standard Model
of Particle Physics

Introduction

T. Plehn (theory)
S. Hansmann-Menzemer (experiment)

SS 2017

Content

Introduction to Gauge Theories

- 21.04. From Theory to Feynman Rules (TP)
- 26.04. From Theory to Feynman Rules (TP)
- 28.04. From Theory to Feynman Rules (TP)

Calculating Cross Sections

- 03.05. From Matrix Element to Measurement (SHM)
- 05.05. From Matrix Element to Measurement (SHM)

QED Lagrangien

- 10.05. e+e- scattering (TP)
- 12.05. e+e- annihilation experiments (SHM)

Qantum Flavor Dynamics

- 17.05. Phenomenology of Weak Interaction (SHM)
- 19.05. Phenomenology of Weak Interaction (SHM)
- 24.05. Massive Gauge Bosons (TP)
- 26.05. Massive Gauge Bosons (TP)
- 31.05. Experimental Tests of the SM (SHM)
- 02.06. Experimental Tests of the SM (SHM)
- 07.06. Higgs Boson in the SM (TP)
- 09.06. Higgs Boson in the SM (TP)
- 14.06. Experimental Observation of the Higgs Boson (SHM)
- 16.06. More on the Higgs Boson (TP)
- 21.06. Quark Mixing and the CKM Mechanism (SHM)
- 23.06. Quark Mixing and the CKM Mechanism (SHM)
- 28.06. Quark Mixing and the CKM Mechanism (SHM)

Quantum Chromodynamics

- 30.06. Theory of QCD (TP)
- 05.07. Theory of QCD (TP)
- 07.07. Theory of QCD (TP)
- 12.07. Experimental Tests of QCD (SHM)
- 14.07. Experimental Tests of QCD (SHM)

Beyond the Standard Model

- 19.07. Limits of the Standard Model (SHM/TP)
- 21.07. Limits of the Standard Model (SHM/TP)

Organisation

Lectures

Wed 11:15-13:00 (HS2, INF 308)

Fri 9:15-11:00h (HS2, INF 308)

Tutorials (Gonzalo Alonso Alvarez, Anke Biekoetter, Jennifer Thompson)

Tue 14:15-16:00h (SR 3.403, INF 227) (1 group)

Wed 14:15-16:00h (SR 3.402, INF 227) (2 groups)

first sheet on the web today 21.04., first tutoral 25./26.04.

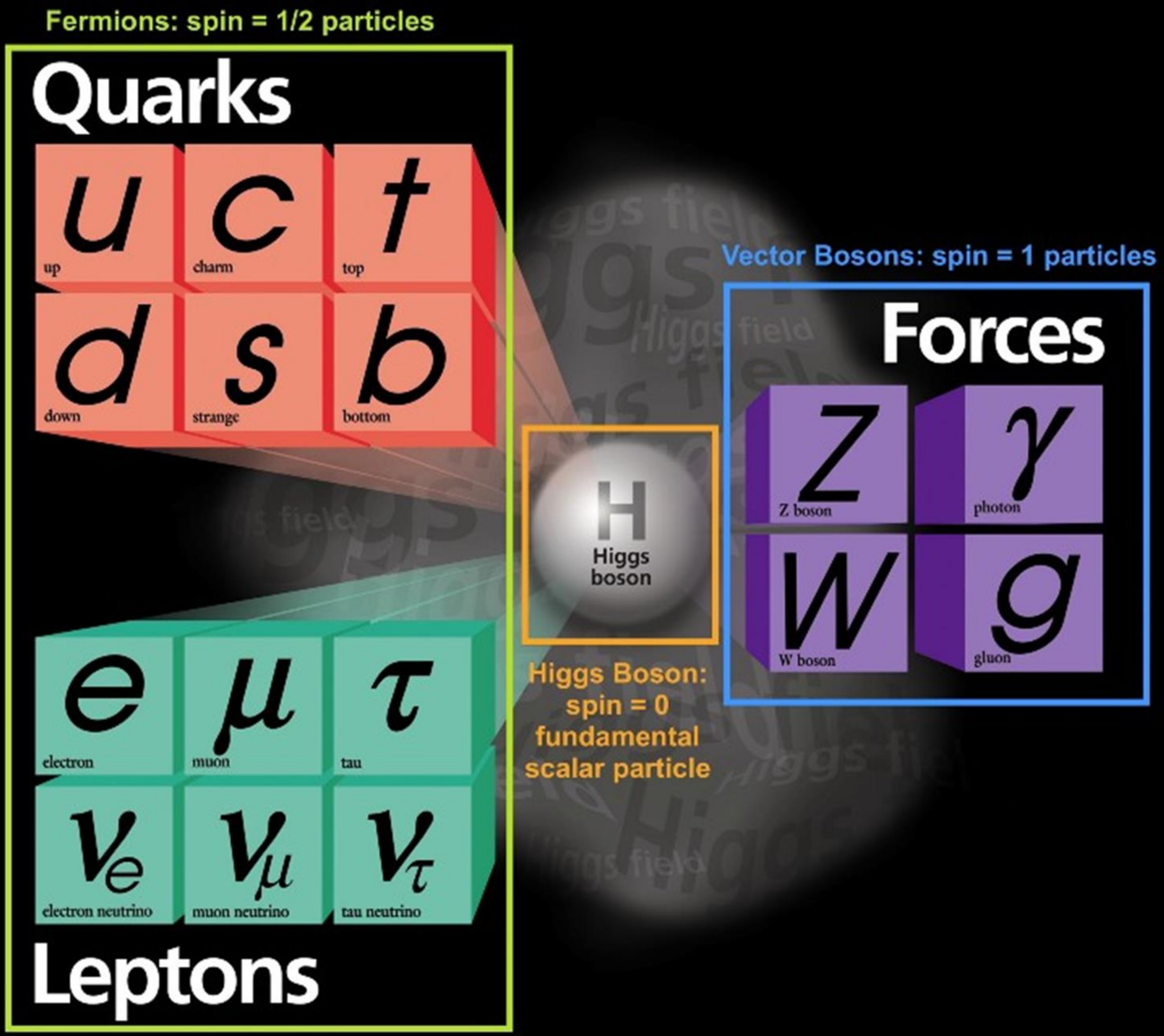
from then on Monday sheets on the web (-> 1.5 weeks to work on them)

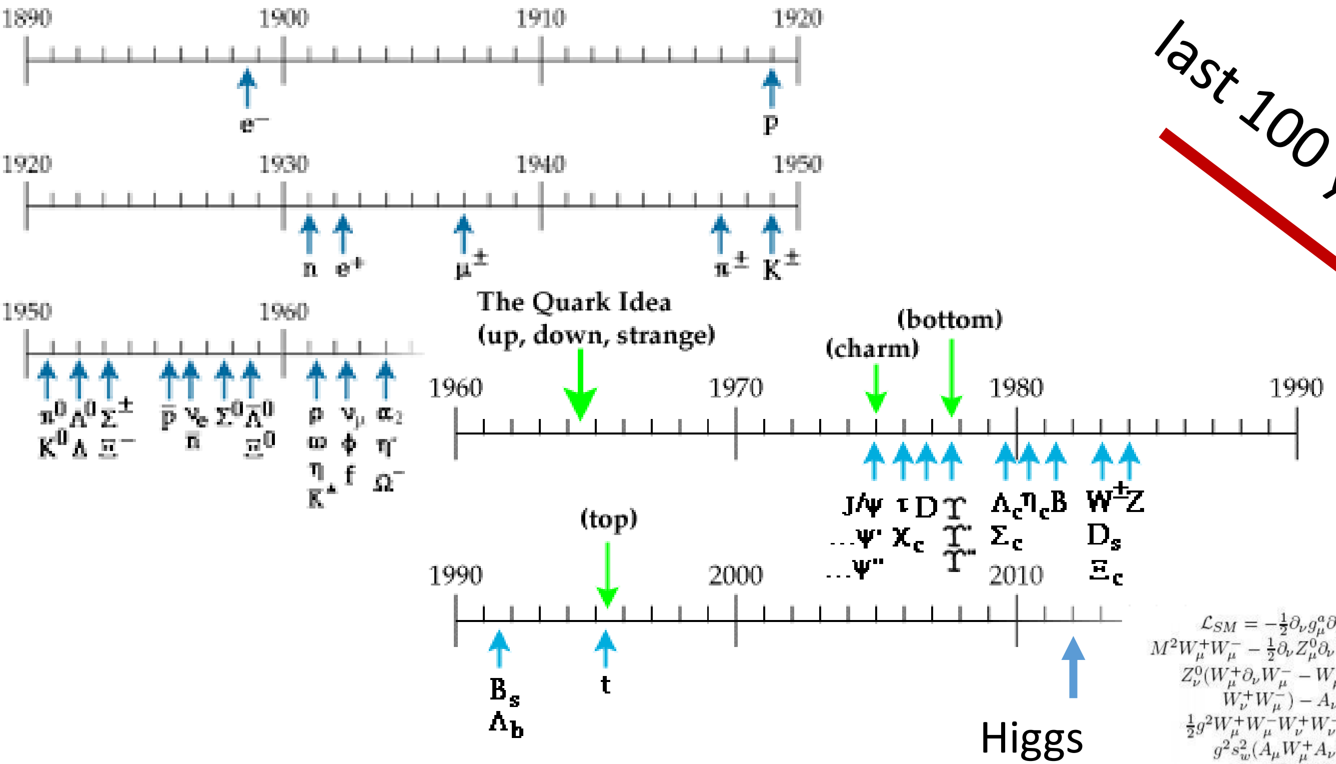
Requirements: worked on at least 50% of the exercises on the sheets
regular (and active) participation in the tutorials
present homeworks at the black board
exam at the end of the term (date still need to be fixed)

For more information (registration, literature, exercise sheets, notes, ...):
https://uebungen.physik.uni-heidelberg.de/vorlesung/20171/742

The Standard Modell

A Particle Physcisist‘s View of the World





last 100 years of Particle Physics

today understanding of particle physics is a success story of co-work of experiment and theory

$$
\begin{gathered}
\mathcal{L}_{SM} = -\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g^2_s f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - \\
M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c^2_w} M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - igc_w(\partial_\nu Z^0_\mu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - \\
Z^0_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu (W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)) - igs_w(\partial_\nu A_\mu (W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - A_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + A_\mu (W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)) - \\
\tfrac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \tfrac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c^2_w (Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + \\
g^2 s^2_w (A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w (A_\mu Z^0_\nu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - \\
2A_\mu Z^0_\mu W^+_\nu W^-_\nu) - \tfrac{1}{2}\partial_\mu H \partial_\mu H - 2M^2 \alpha_h H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \tfrac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \\
\beta_h \left(\tfrac{2M^2}{g^2} + \tfrac{2M}{g} H + \tfrac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)\right) + \tfrac{2M^4}{g^2}\alpha_h - g\alpha_h M \left(H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-\right) - \\
\tfrac{1}{8}g^2 \alpha_h \left(H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2 H^2\right) - gMW^+_\mu W^-_\mu H - \\
\tfrac{1}{2}g\tfrac{M}{c^2_w} Z^0_\mu Z^0_\mu H - \tfrac{1}{2}ig \left(W^+_\mu (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - W^-_\mu (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0)\right) + \\
\tfrac{1}{2}g \left(W^+_\mu (H \partial_\mu \phi^- - \phi^- \partial_\mu H) + W^-_\mu (H \partial_\mu \phi^+ - \phi^+ \partial_\mu H)\right) + \tfrac{1}{2}g\tfrac{1}{c_w}(Z^0_\mu (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) + \\
M \left(\tfrac{1}{c_w} Z^0_\mu \partial_\mu \phi^0 + W^+_\mu \partial_\mu \phi^- + W^-_\mu \partial_\mu \phi^+\right) - ig\tfrac{s^2_w}{c_w} M Z^0_\mu (W^+_\mu \phi^- - W^-_\mu \phi^+) + igs_w M A_\mu (W^+_\mu \phi^- - \\
W^-_\mu \phi^+) - ig\tfrac{1-2c^2_w}{2c_w} Z^0_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + igs_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \\
\tfrac{1}{4}g^2 W^+_\mu W^-_\mu \left(H^2 + (\phi^0)^2 + 2\phi^+\phi^-\right) - \tfrac{1}{8}g^2 \tfrac{1}{c^2_w} Z^0_\mu Z^0_\mu \left(H^2 + (\phi^0)^2 + 2(2s^2_w - 1)^2 \phi^+\phi^-\right) - \\
\tfrac{1}{2}g^2 \tfrac{s^2_w}{c_w} Z^0_\mu \phi^0 (W^+_\mu \phi^- + W^-_\mu \phi^+) - \tfrac{1}{2}ig^2 \tfrac{s^2_w}{c_w} Z^0_\mu H (W^+_\mu \phi^- - W^-_\mu \phi^+) + \tfrac{1}{2}g^2 s_w A_\mu \phi^0 (W^+_\mu \phi^- + \\
W^-_\mu \phi^+) + \tfrac{1}{2}ig^2 s_w A_\mu H (W^+_\mu \phi^- - W^-_\mu \phi^+) - g^2 \tfrac{s_w}{c_w}(2c^2_w - 1) Z^0_\mu A_\mu \phi^+\phi^- - g^2 s^2_w A_\mu A_\mu \phi^+\phi^- + \\
\tfrac{1}{2}ig_s \lambda^a_{ij}(\bar{q}^\sigma_i \gamma^\mu q^\sigma_j) g^a_\mu - \bar{e}^\lambda(\gamma\partial + m^\lambda_e) e^\lambda - \bar{\nu}^\lambda(\gamma\partial + m^\lambda_\nu)\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + m^\lambda_u) u^\lambda_j - \bar{d}^\lambda_j(\gamma\partial + m^\lambda_d) d^\lambda_j + \\
igs_w A_\mu \left(-(\bar{e}^\lambda \gamma^\mu e^\lambda) + \tfrac{2}{3}(\bar{u}^\lambda_j \gamma^\mu u^\lambda_j) - \tfrac{1}{3}(\bar{d}^\lambda_j \gamma^\mu d^\lambda_j)\right) + \tfrac{ig}{4c_w} Z^0_\mu \{(\bar{\nu}^\lambda \gamma^\mu (1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda \gamma^\mu (4s^2_w - \\
1 - \gamma^5) e^\lambda) + (\bar{d}^\lambda_j \gamma^\mu (\tfrac{4}{3}s^2_w - 1 - \gamma^5) d^\lambda_j) + (\bar{u}^\lambda_j \gamma^\mu (1 - \tfrac{8}{3}s^2_w + \gamma^5) u^\lambda_j)\} + \\
\tfrac{ig}{2\sqrt{2}} W^+_\mu \left((\bar{\nu}^\lambda \gamma^\mu (1+\gamma^5) U^{lep}{}_{\lambda\kappa} e^\kappa) + (\bar{u}^\lambda_j \gamma^\mu (1+\gamma^5) C_{\lambda\kappa} d^\kappa_j)\right) + \\
\tfrac{ig}{2\sqrt{2}} W^-_\mu \left((\bar{e}^\kappa U^{lep\dagger}{}_{\kappa\lambda} \gamma^\mu (1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\kappa\lambda} \gamma^\mu (1+\gamma^5) u^\lambda_j)\right) + \\
\tfrac{ig}{2M\sqrt{2}} \phi^+ \left(-m^\kappa_e (\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa} (1-\gamma^5) e^\kappa) + m^\lambda_\nu (\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa} (1+\gamma^5) e^\kappa\right) + \\
\tfrac{ig}{2M\sqrt{2}} \phi^- \left(m^\lambda_e (\bar{e}^\lambda U^{lep\dagger}_{\lambda\kappa} (1+\gamma^5)\nu^\kappa) - m^\kappa_\nu (\bar{e}^\lambda U^{lep\dagger}_{\lambda\kappa} (1-\gamma^5)\nu^\kappa\right) - \tfrac{g}{2}\tfrac{m^\lambda_\nu}{M} H (\bar{\nu}^\lambda \nu^\lambda) - \\
\tfrac{g}{2}\tfrac{m^\lambda_e}{M} H (\bar{e}^\lambda e^\lambda) + \tfrac{ig}{2}\tfrac{m^\lambda_\nu}{M} \phi^0 (\bar{\nu}^\lambda \gamma^5 \nu^\lambda) - \tfrac{ig}{2}\tfrac{m^\lambda_e}{M} \phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda) - \tfrac{1}{4}\bar{\nu}_\lambda M^R_{\lambda\kappa} (1-\gamma_5)\hat{\nu}_\kappa - \\
\tfrac{1}{4}\overline{\bar{\nu}_\lambda M^R_{\lambda\kappa} (1-\gamma_5)\hat{\nu}_\kappa} + \tfrac{ig}{2M\sqrt{2}} \phi^+ \left(-m^\kappa_d (\bar{u}^\lambda_j C_{\lambda\kappa} (1-\gamma^5) d^\kappa_j) + m^\lambda_u (\bar{u}^\lambda_j C_{\lambda\kappa} (1+\gamma^5) d^\kappa_j\right) + \\
\tfrac{ig}{2M\sqrt{2}} \phi^- \left(m^\lambda_d (\bar{d}^\lambda_j C^\dagger_{\lambda\kappa} (1+\gamma^5) u^\kappa_j) - m^\kappa_u (\bar{d}^\lambda_j C^\dagger_{\lambda\kappa} (1-\gamma^5) u^\kappa_j\right) - \tfrac{g}{2}\tfrac{m^\lambda_u}{M} H (\bar{u}^\lambda_j u^\lambda_j) - \tfrac{g}{2}\tfrac{m^\lambda_d}{M} H (\bar{d}^\lambda_j d^\lambda_j) + \\
\tfrac{ig}{2}\tfrac{m^\lambda_u}{M} \phi^0 (\bar{u}^\lambda_j \gamma^5 u^\lambda_j) - \tfrac{ig}{2}\tfrac{m^\lambda_d}{M} \phi^0 (\bar{d}^\lambda_j \gamma^5 d^\lambda_j)
\end{gathered}
$$

Standard Model

Some Milestones of the Standard Model

1964	Higgs-Mechanism (Brout, Engler, Higgs)
1967/68	Standard Model (Glashow, Salam, Weinberg)
1971	Renormalizibility of non-abelian theories (´t Hooft, Veltmann)
1973	Asymptotic freedom of QCD (Gross, Politzer, Wilzcek)
1973	Discovery of Neutral Currents (Gargamelle, CERN)
1974	Discovery of 4th Quark (SLCAC & BNL)
1979	Discovery of the gluon (PETRA, DESY)
1983	Observation of W and Z (UA 1/2, CERN)
1988	Tevatron start: Top Physics, Higgs Searches .... (Fermilab)
1989	LEP start: electroweak precision physics ... (CERN)
1991	HERA start: Investigation of the proton .... (DESY)
1995	Discovery of the Top (Tevatron, Fermilab)
2000	Start of B Factories (Belle @ KEK, BABAR @ SLAC),
2001	CP violation in the B System (Belle, BABAR)
2009	LHC @ CERN : First collisions
2012	Discovery of the Higgs Boson

Often new experimental techniques
have been the key to the next
milestone on the way to the SM

Interplay Theory-Exeriment

some examples

Prediction of the Anti-electron (1928)
Discovery of Positron (1932)

Prediction of mesons (1935)
Discovery of the pion (1947)

Prediction of the neutrino (1930)
Discovery of the electron neutrino (1957)

Prediction of the muon neutrino (1950th)
Discovery of the muon neutrino (1962)

Discovery of CP violation (1964)
Prediction of a third quark family (1973)
Dicovery of the B quark (1977)
Discovery of the top quark (1995)

Prediction of the Higgs mechanism (1964)
Discovery of the Higgs particle (2012)

Discovery of Antimatter

Paul Dirac (1928)

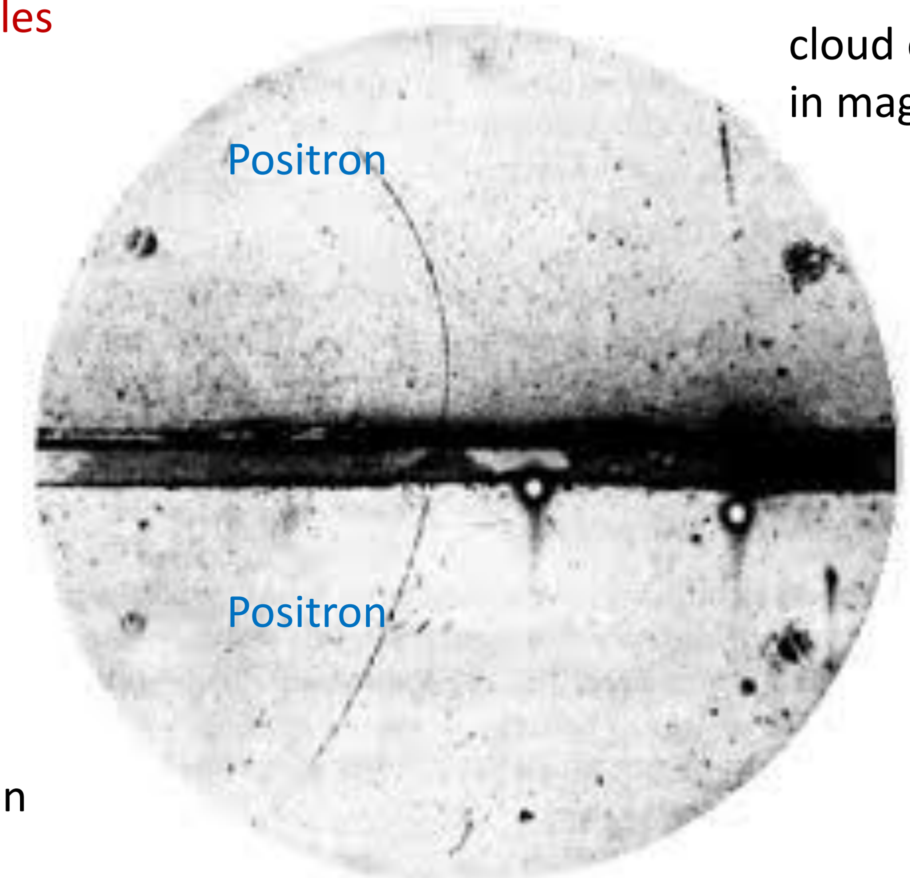
Field equation based on rel. Energy-momentum relation

$$E^2 = m^2 + p^2$$

Negative energy solution → antiparticles

Carl Anderson (1932)

Nobel prize 1936



cloud chamber
in magnetic field

6 mm lead plate

63 MeV positron passing through
Lead plate emerging a 23 MeV positron

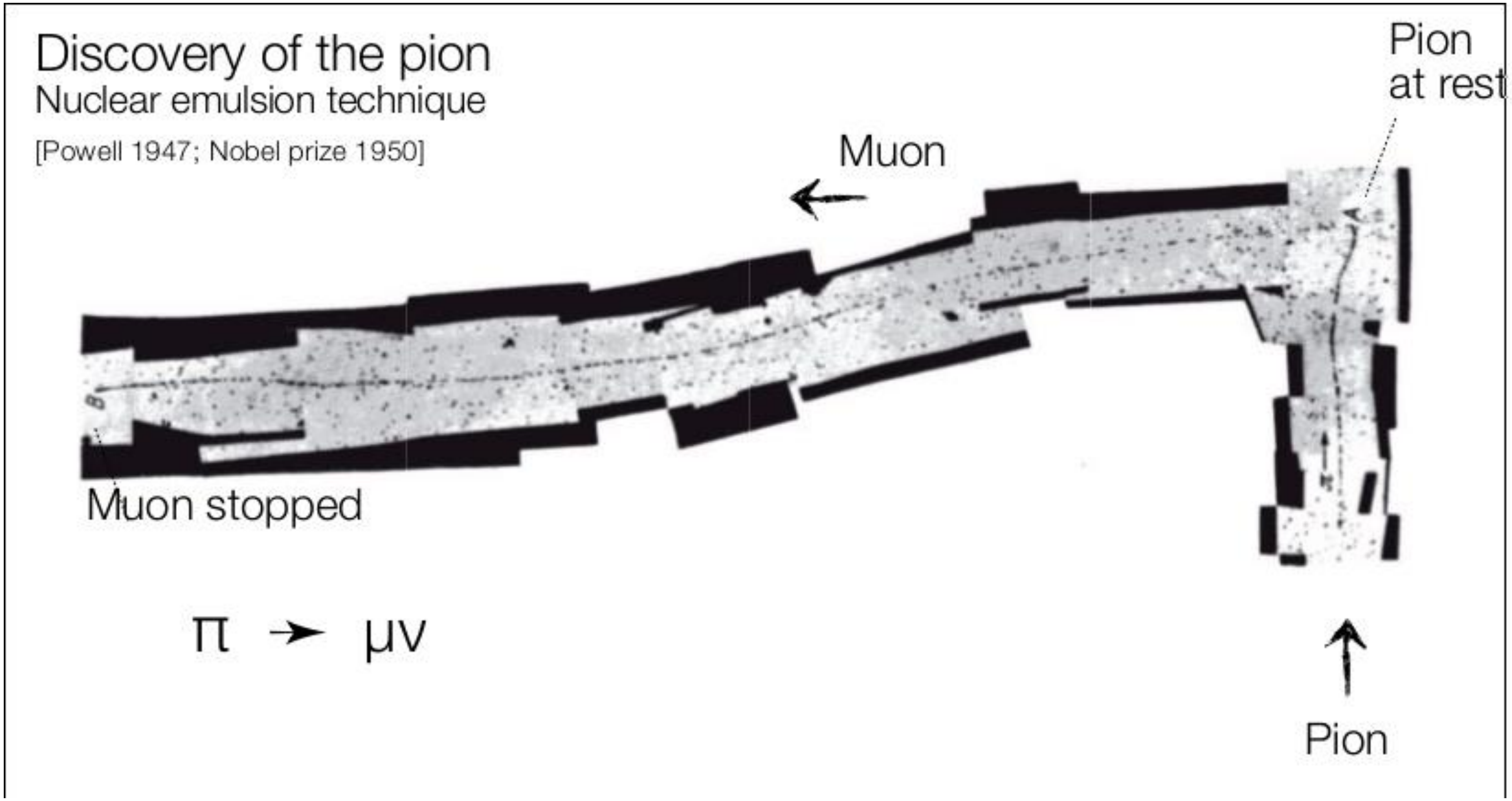
The length of this latter pass is at least ten times greater than the possible length of a proton path of this curvature

Prediction of the pion

H. Yukawa predicted 1935 mesons as
carriers of the nuclear force (Nobel Prize 1949)

meson mass ~ ħc/(range of force) **range ~ 1 fm → m ~ 200 MeV**

(m_π ~ 140 MeV)



Discovery of the pion

Nuclear emulsion technique

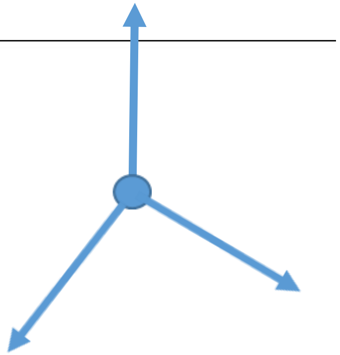
[Powell 1947; Nobel prize 1950]

Prediction of Neutrinos
n -> p + e + ??

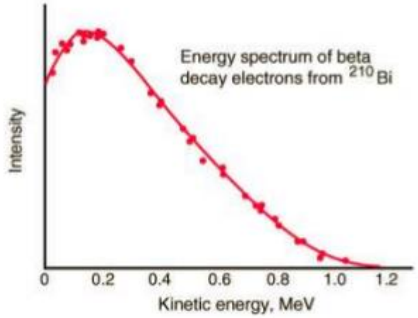
2-body decay

fixed enery

3-body decay



continuous spectrum



- 1926: Problem in β spectrum
- 1930: Pauli postulates “neutron”

Physikalisches Institut der Eidgenössischen Technischen Hochschule, Zürich, den 4. Dezember 1930:

Liebe radioaktive Damen und Herren,

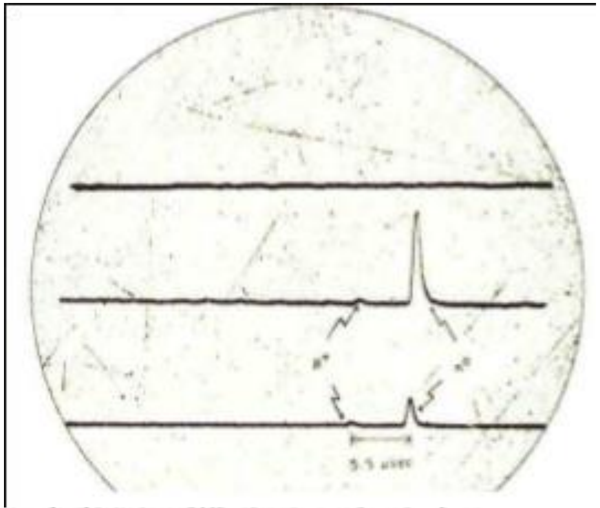
wie der Überbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts... des kontinuierlichen Beta–Spektrums auf einen verzweifelten Ausweg verfallen, um ... den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche das Ausschließungsprinzip befolgen und sich von Lichtquanten außerdem noch dadurch unterscheiden, daß sie nicht mit Lichtgeschwindigkeit laufen. Ihre Masse müßte von derselben Größenordnung wie die Elektronenmasse sein. Ich traue mich vorläufig nicht, etwas über diese Idee zu publizieren, und wende mich vertrauensvoll an Euch, liebe Radioaktive, mit der Frage, wie es um den experimentellen Nachweis stände, wenn dieses Neutron ein ebensolches oder etwa 100 mal größeres Durchdringungsvermögen besitzen würde wie ein Röntgenstrahl.

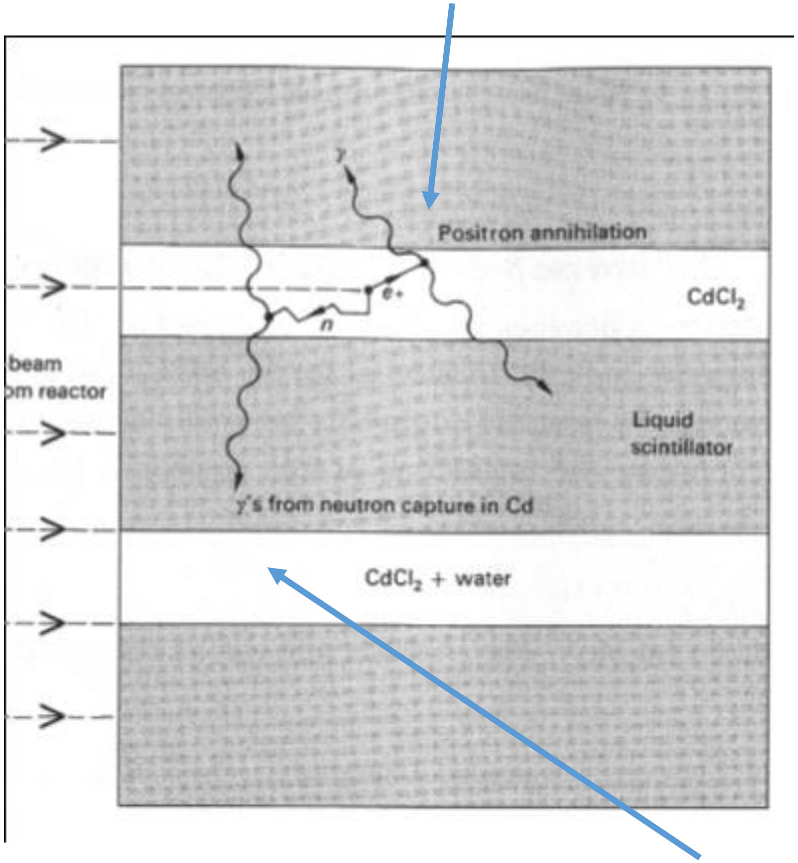
Ich gebe zu, daß mein Ausweg vielleicht von vornherein wenig wahrscheinlich erscheinen mag, weil man die Neutronen, wenn sie existieren, wohl längst gesehen hätte. Aber nur wer wagt, gewinnt, und der Ernst der Situation beim kontinuierlichen Beta–Spektrum wird durch einen Ausspruch meines verehrten Vorgängers im Amte, Herrn Debye, beleuchtet, der mir kürzlich gesagt hat: 'Oh, daran soll man am besten gar nicht denken, so wie an die neuen Steuern.' Darum soll man jeden Weg zur Rettung ernstlich diskutieren. Also, liebe Radioaktive, prüfet und richtet. Leider kann ich nicht persönlich in Tübingen erscheinen, da ich infolge eines in der Nacht vom 6. zum 7. Dezember in Zürich stattfinden Balles hier unabkömmlich bin.

Mit vielen Grüßen an Euch, Euer untertänigster Diener ... Wolfgang Pauli

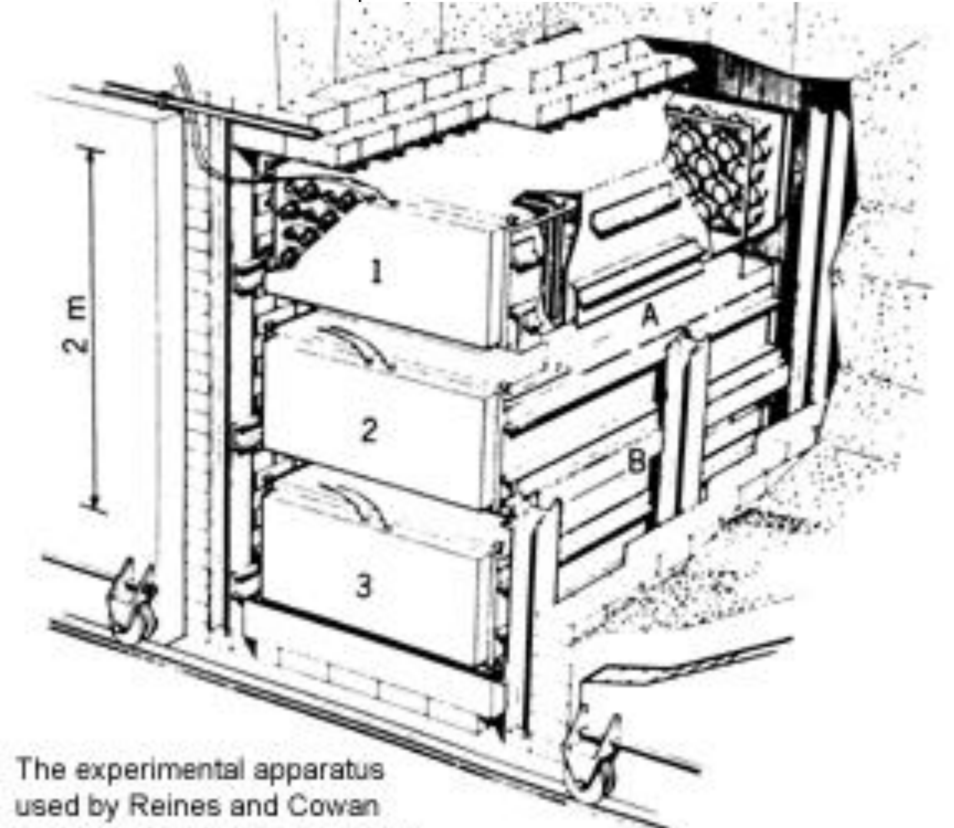
Discovery of the electron (anti) neutrino (1956) (NP 1985)

$$\overline{\nu_e} + p \rightarrow n + e^+$$





$$n +^{108} Cd \rightarrow^{109} Cd* \rightarrow^{109} Cd + \gamma$$

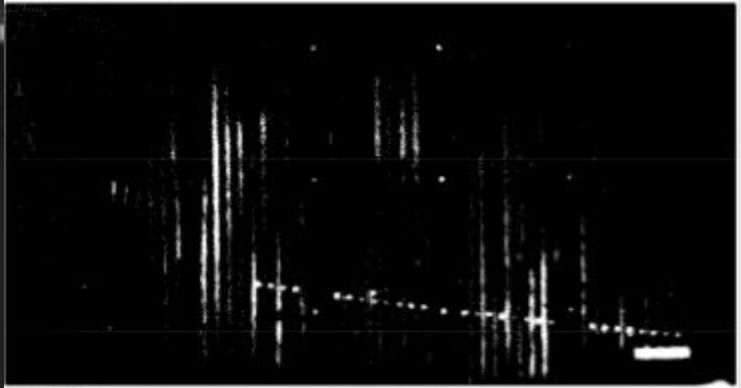


The experimental apparatus used by Reines and Cowan to detect the electron neutrino.

Discovery of the muon neutrino

Leon M. Lederman
Melvin Schwartz
Jack Steinberger

[Nobel prize 1988]

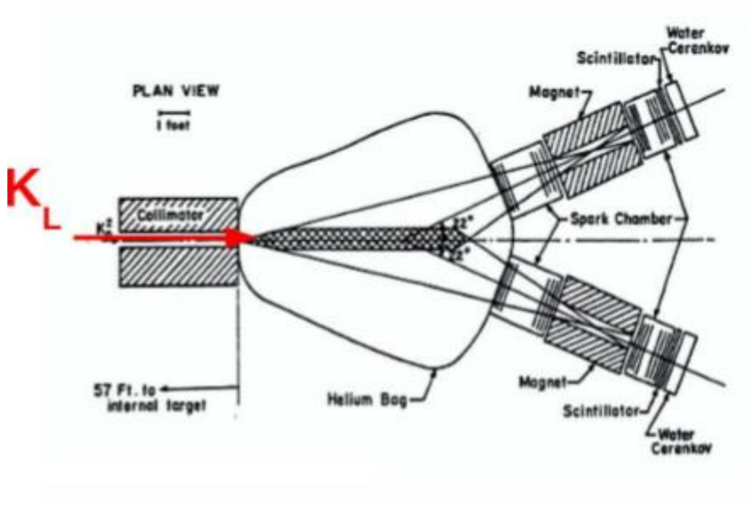


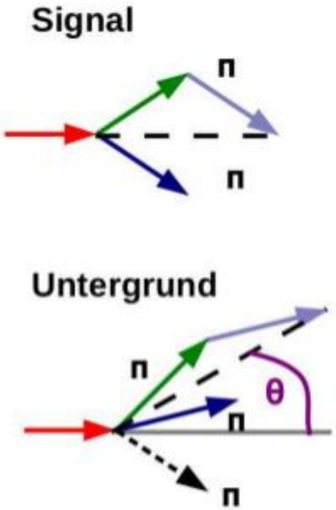
Single muon event from
Original publication

Melvin Schwatz in front of the spark chamber
Used to discover the muon neutrino

Discovery of CP violation (1964)

(we will spend a whole lecture to undertand why $K_L \rightarrow \pi\pi$ is CP violating)





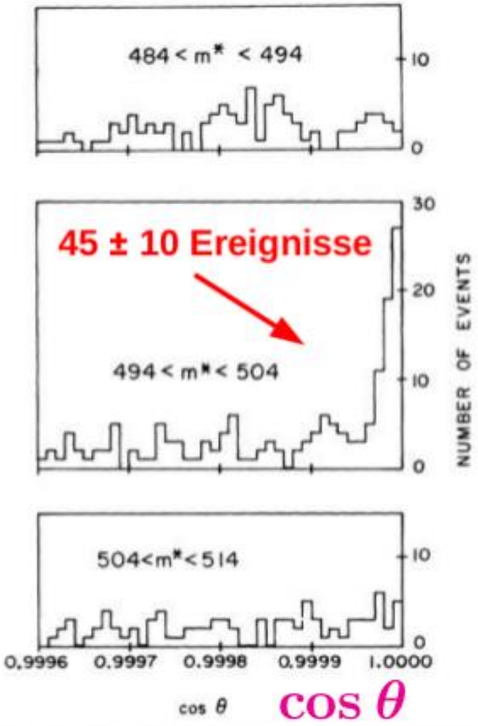


FIG. 3. Angular distribution in three mass ranges for events with cosθ > 0.9995.

45 ± 10 $K_L \rightarrow \pi\pi$ event (ε ~0.2%)

Nobel prize Cronin and Fitch (1980)

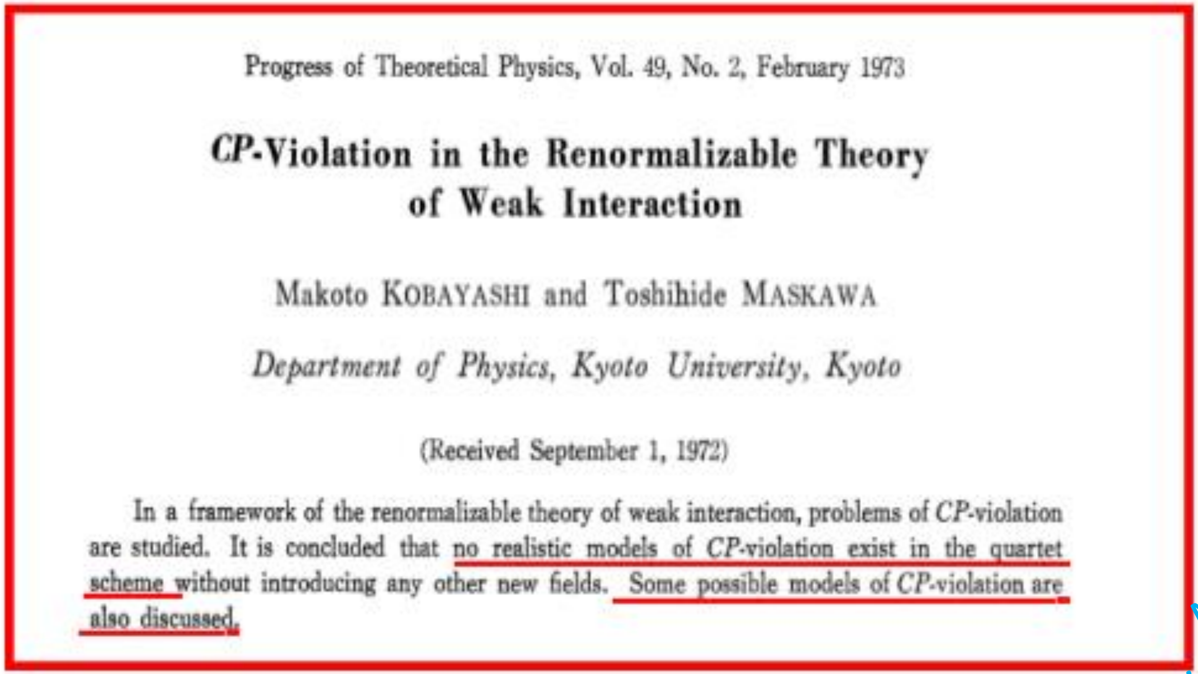
Predition of the third quark family

the power of indirect searches

Makoto Kobayashi

Toshihide Maskawa

Only 3 quarks where known at that time!



Progress of Theoretical Physics, Vol. 49, No. 2, February 1973

CP-Violation in the Renormalizable Theory of Weak Interaction

Makoto KOBAYASHI and Toshihide MASKAWA

Department of Physics, Kyoto University, Kyoto

(Received September 1, 1972)

In a framework of the renormalizable theory of weak interaction, problems of CP-violation are studied. It is concluded that no realistic models of CP-violation exist in the quartet scheme without introducing any other new fields. Some possible models of CP-violation are also discussed.

Nobel Prize 2008
(after discovery of CPV in B system)

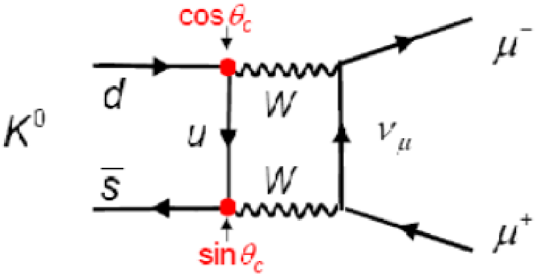
Prediction of the Charm Quark

the power of indirect searches

Observed branching ratio $K^0 \rightarrow \mu^+\mu^-$

$$\frac{BR(K_L \rightarrow \mu^+\mu^-)}{BR(K_L \rightarrow all)} = (7.2 \pm 0.5) \times 10^{-9}$$

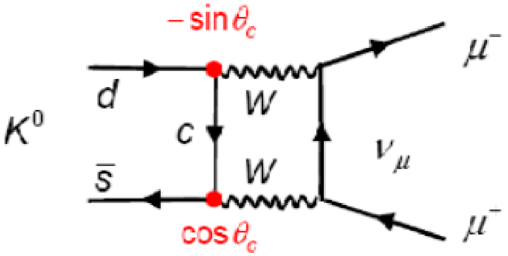
In contradiction with theoretical expectations in the 3 quark model



$M \sim \sin\theta_c \cos\theta_c$

➡ Glashow, Iliopolus, Maiani (1970):

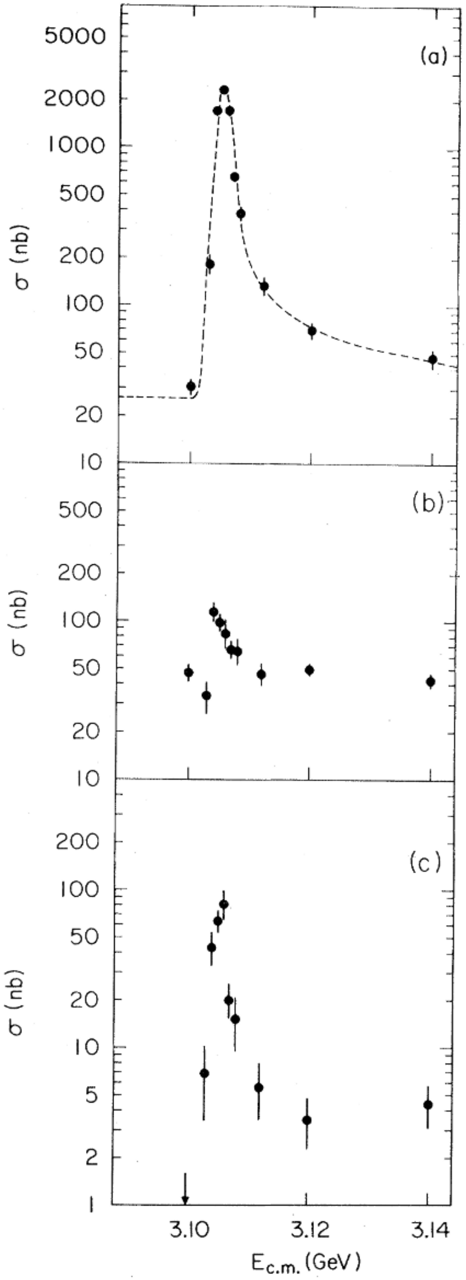
Prediction of a 2nd up type quark, additional Feynman graph cancels the "u box graph"



$M \sim -\sin\theta_c \cos\theta_c$

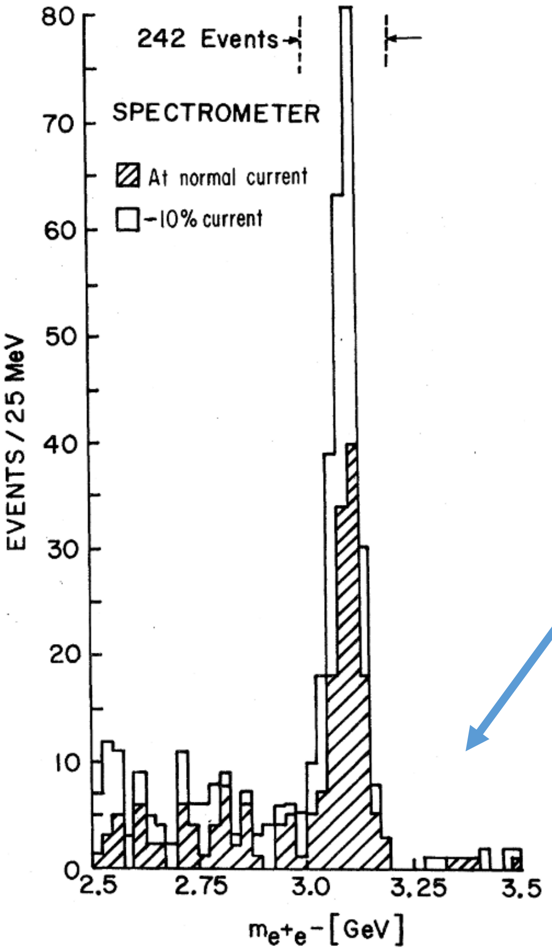
Δm_k + BR($K_L \rightarrow \mu^+\mu^-$)
$\rightarrow$ Prediction of m(c) $\approx$ 1.5 GeV

Discovery of the c-quark



$$e^+e^- \to J/\Psi \begin{array}{ll} \to h^+h^- & \text{(a)} \\ \to \mu^+\mu^- & \text{(b)} \\ \to e^+e^- & \text{(c)} \end{array}$$

(Ting)

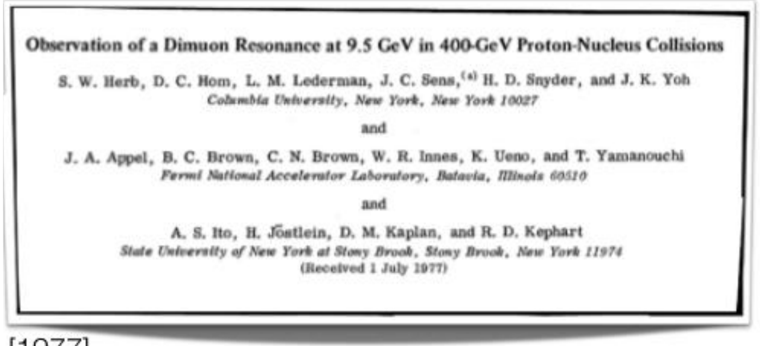


$$p + Be \to J/\Psi(\to e^+e^-) + X$$

(Burton + Richter)

November Revolution (1974)
NP for both teams (1976)

Discovery of the b-quark (1977)



Observation of a Dimuon Resonance at 9.5 GeV in 400-GeV Proton-Nucleus Collisions

S. W. Herb, D. C. Hom, L. M. Lederman, J. C. Sens,(a) H. D. Snyder, and J. K. Yoh
Columbia University, New York, New York 10027

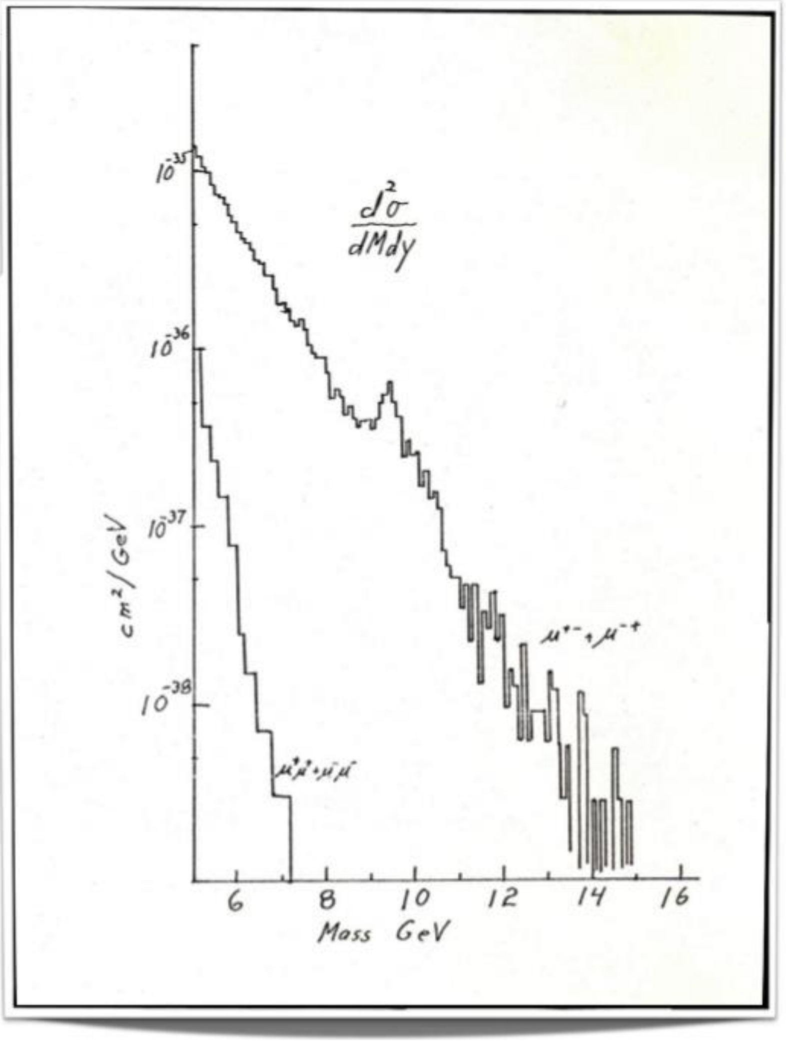
and

J. A. Appel, B. C. Brown, C. N. Brown, W. R. Innes, K. Ueno, and T. Yamanouchi
Fermi National Accelerator Laboratory, Batavia, Illinois 60510

and

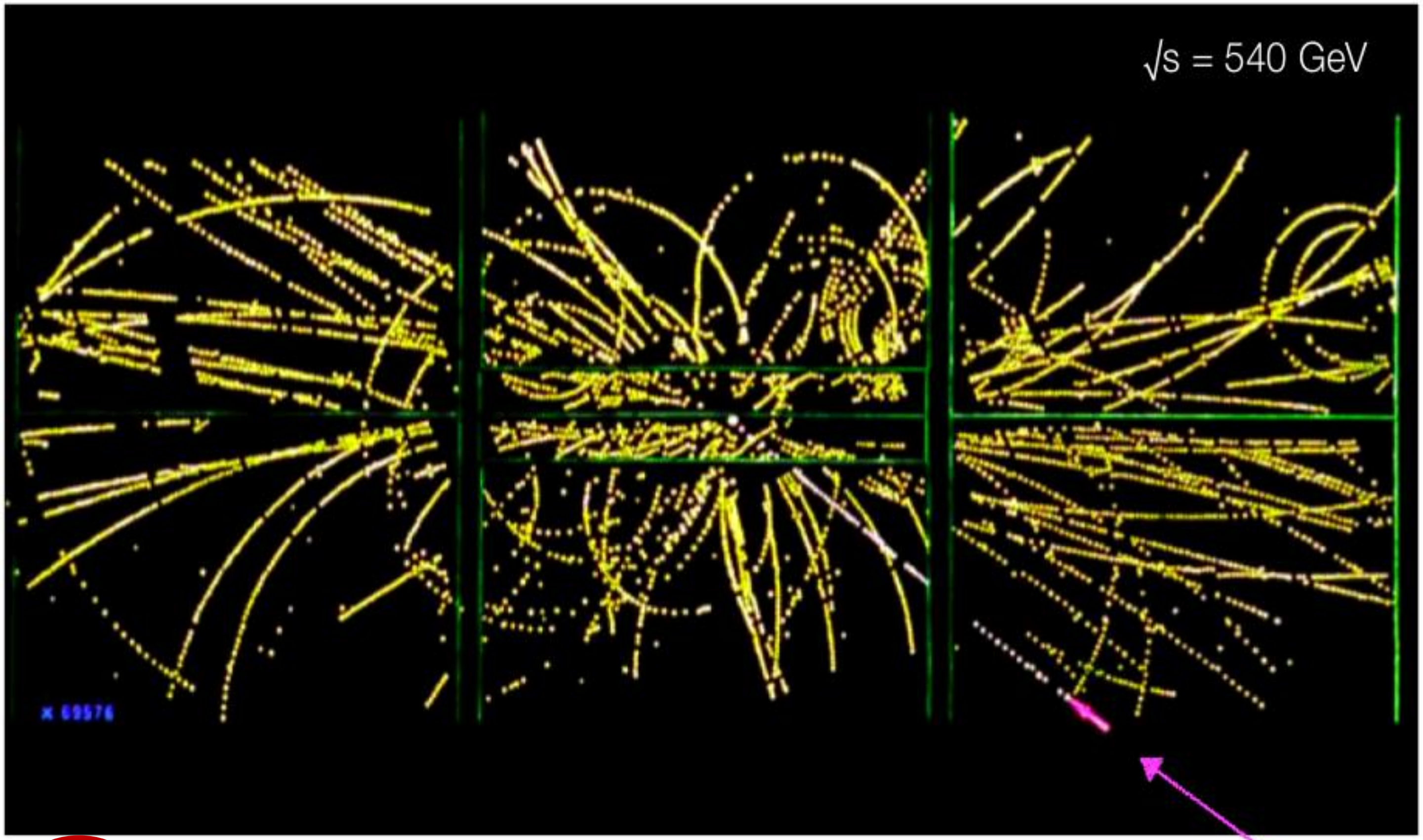
A. S. Ito, H. Jöstlein, D. M. Kaplan, and R. D. Kephart
State University of New York at Stony Brook, Stony Brook, New York 11974
(Received 1 July 1977)

[1977]



Graph from the special edition of
the *Village Crier* announcing the discovery …

Discovery of the W and Z



the underlying event is the price to pay for higher CME in hadron collisions

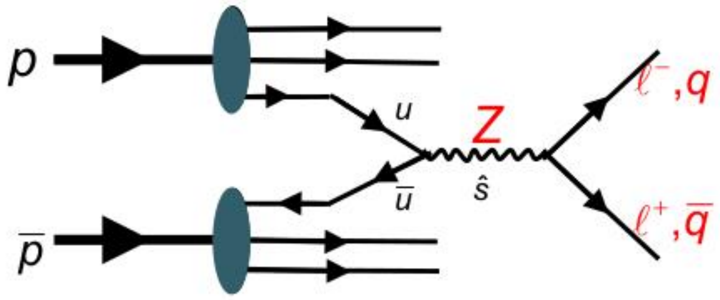
electron

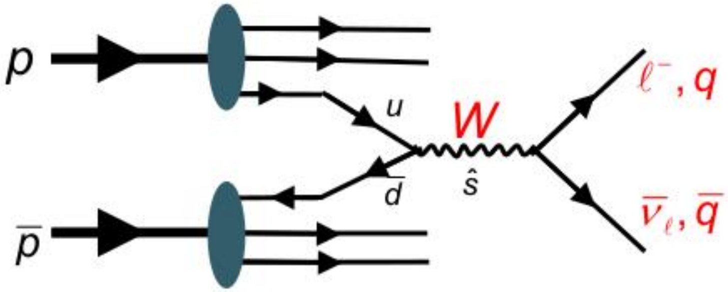
$$p\bar{p} \rightarrow W + X \rightarrow \ell\bar{\nu}_\ell + X$$

The key to the discovery of the heavy particles of the SM (W, Z, top, Higgs) are the **accelerators**. The Nobel prize (1984) for the discovery of the W and Z was assigned jointly to **Rubbia,** spokesperson of UA1 and to **Van Der Meer**, who invented stochastic cooling, the preresquisit to achieve required CME.

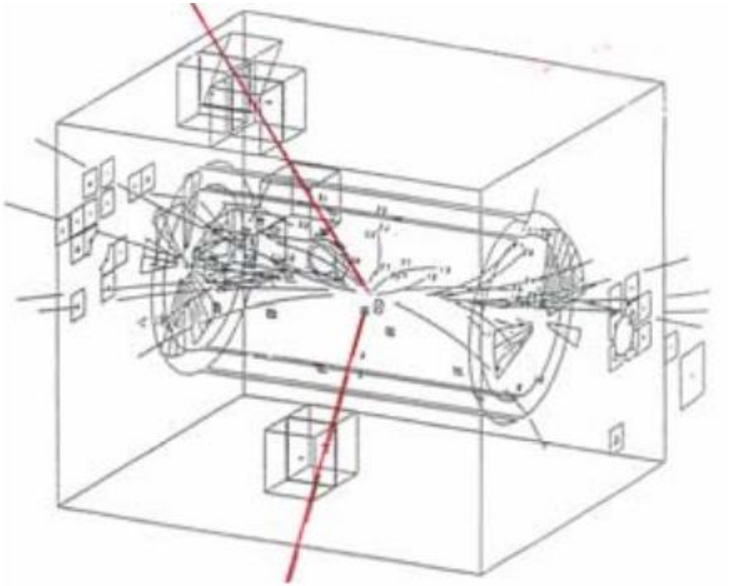
Discovery of the W and Z

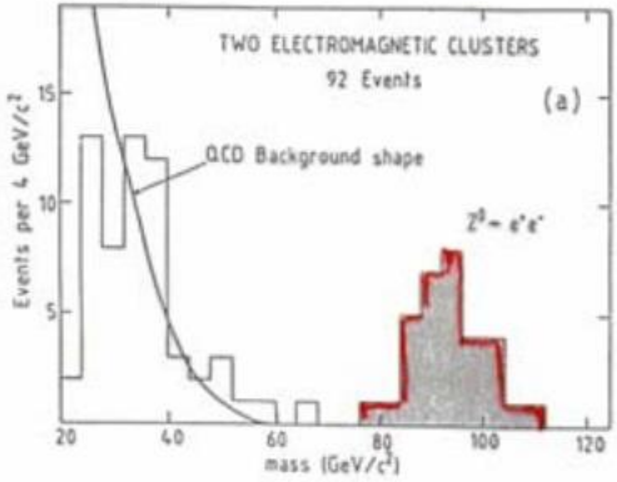
$$p\bar{p} \to Z + X \to \ell^+\ell^- + X$$



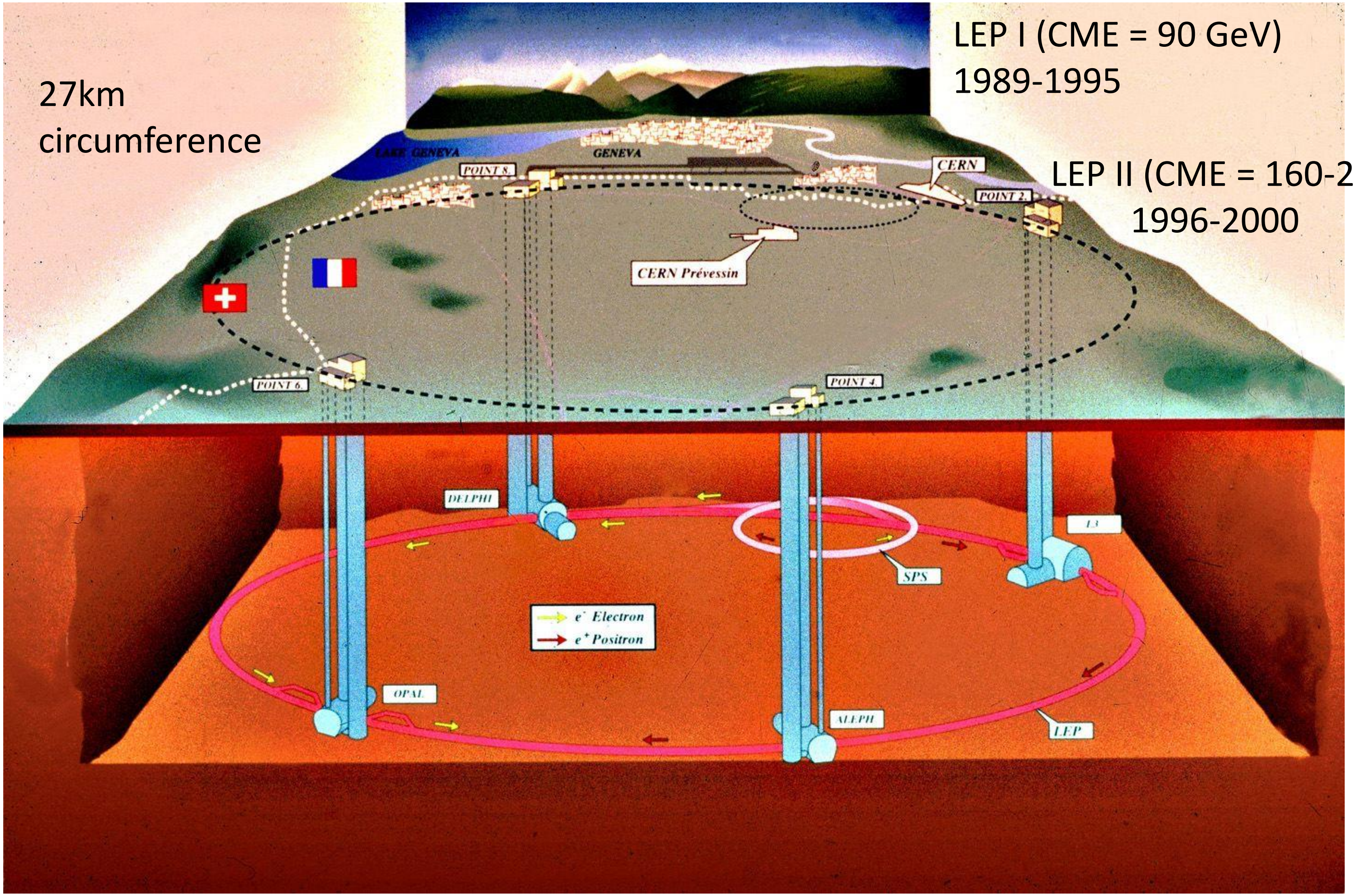


$$p\bar{p} \to W + X \to \ell\bar{\nu}_\ell + X$$





LEP Collider (**L**arge **E**lectron **P**ositron Collider)

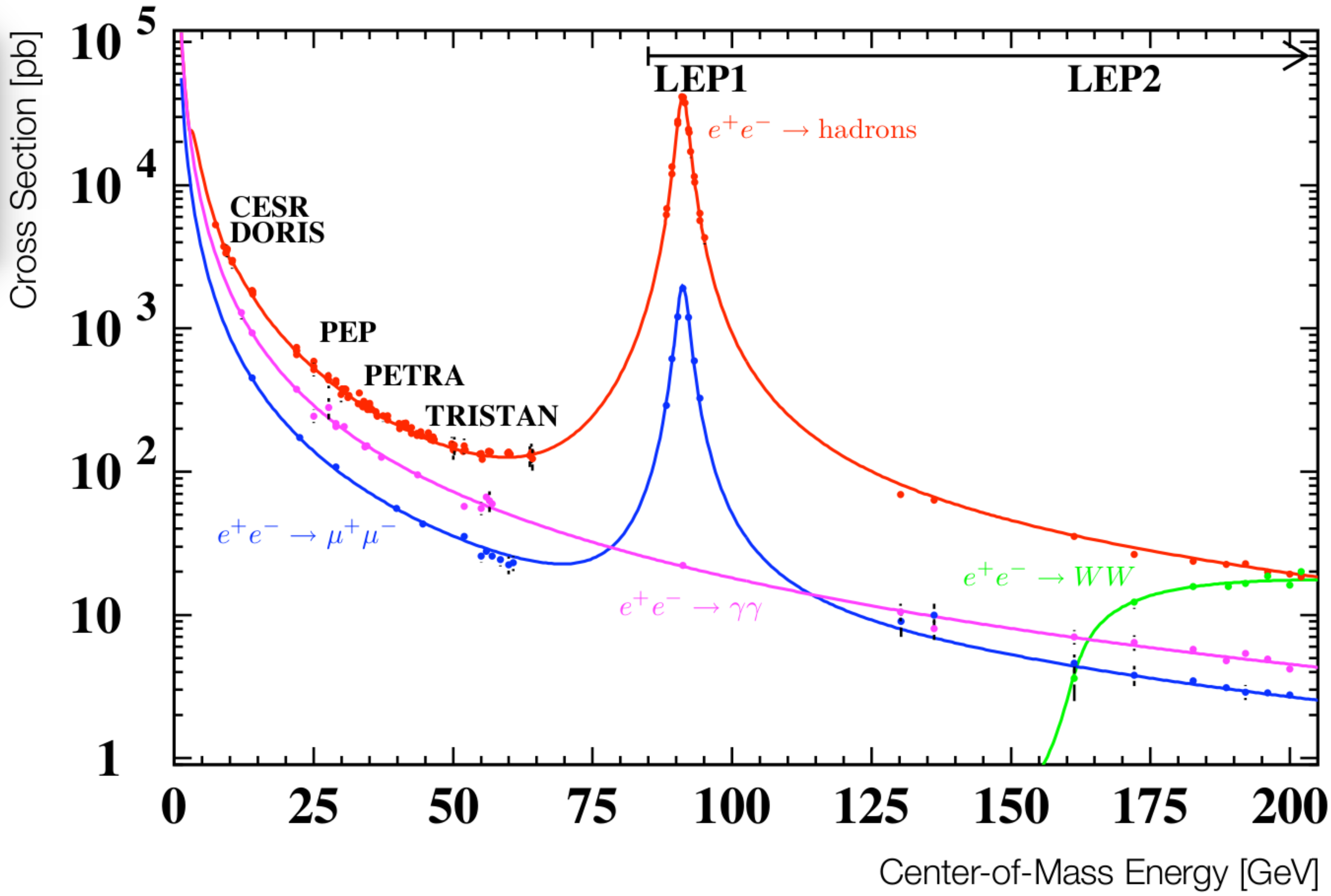


27km
circumference

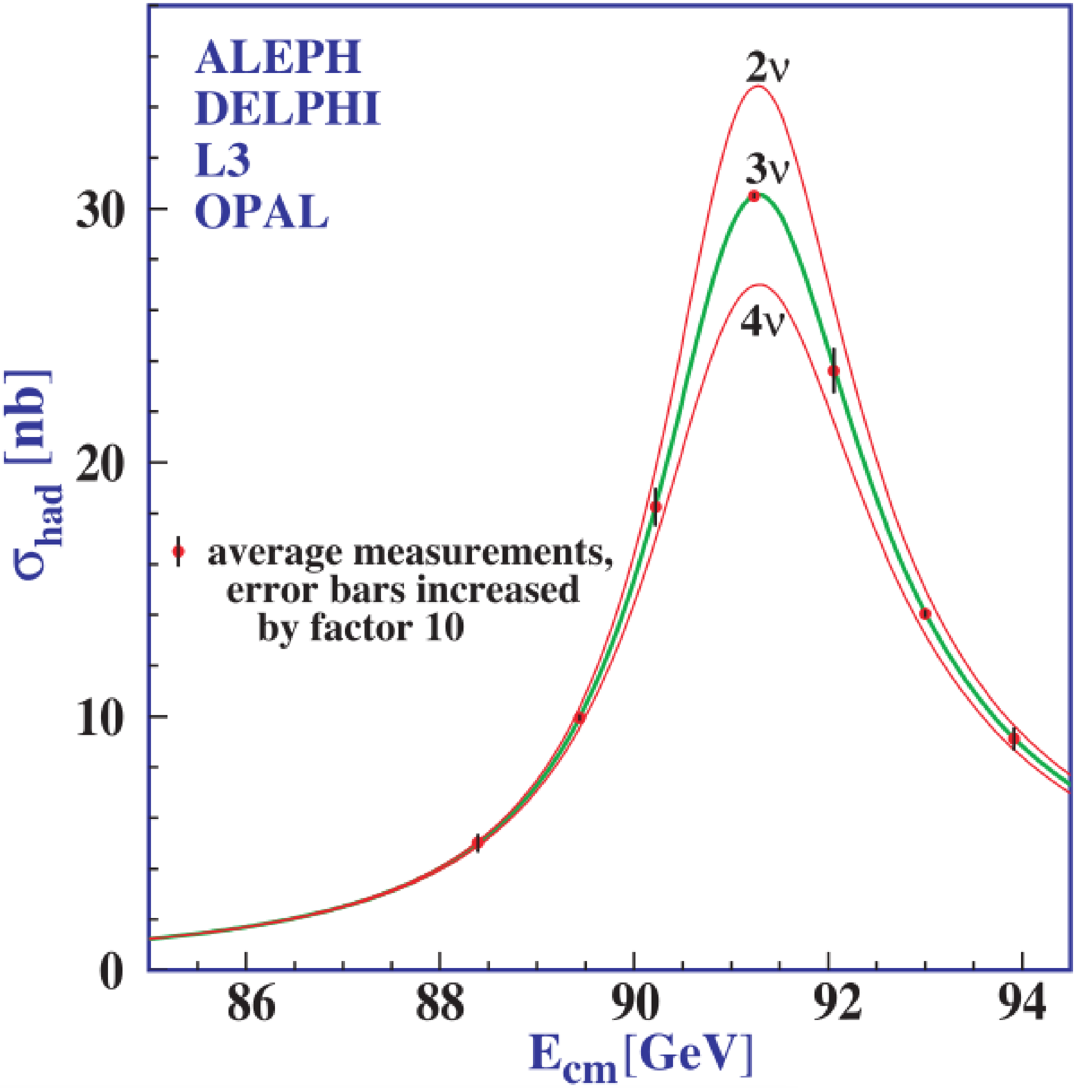
LEP I (CME = 90 GeV)
1989-1995

LEP II (CME = 160-200 GeV)
1996-2000

LEP I: Precision measurements of the Z



3 light neutrino families



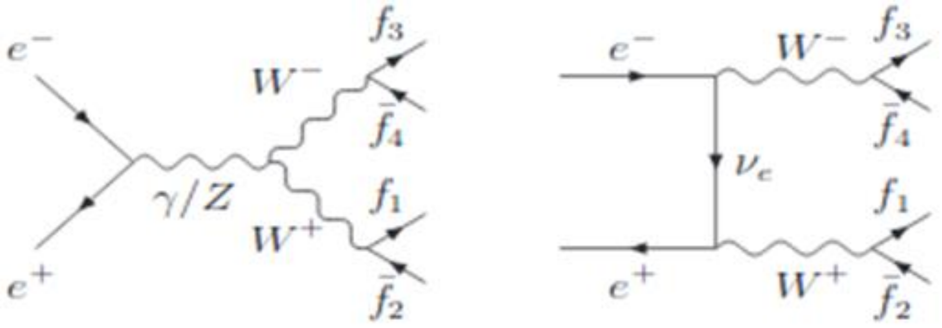
$e^+e^- \rightarrow \text{hadrons}$

$$\boxed{\sigma_f^{\text{peak}} = \frac{12\pi}{M_Z^2}\frac{\Gamma_e\Gamma_f}{\Gamma_Z^2}}$$

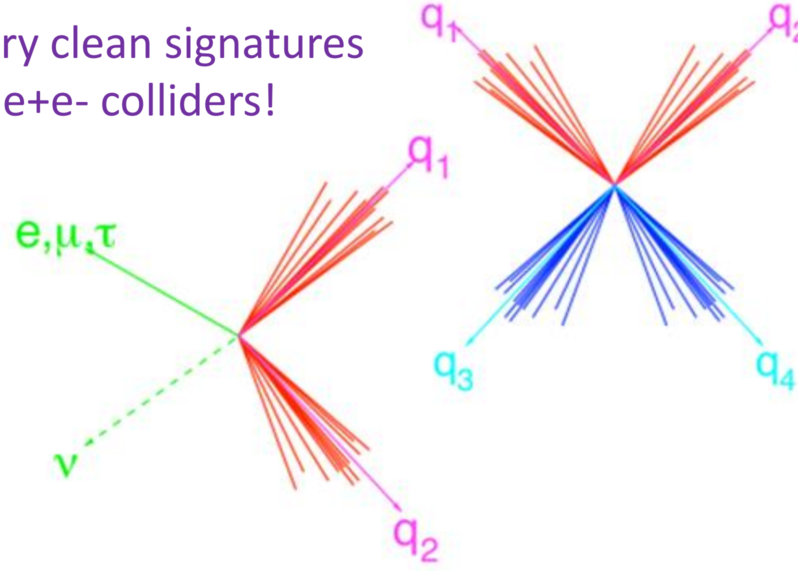
with $\Gamma_Z = \Gamma_\ell + \Gamma_{\text{had}} + n\Gamma_\nu$

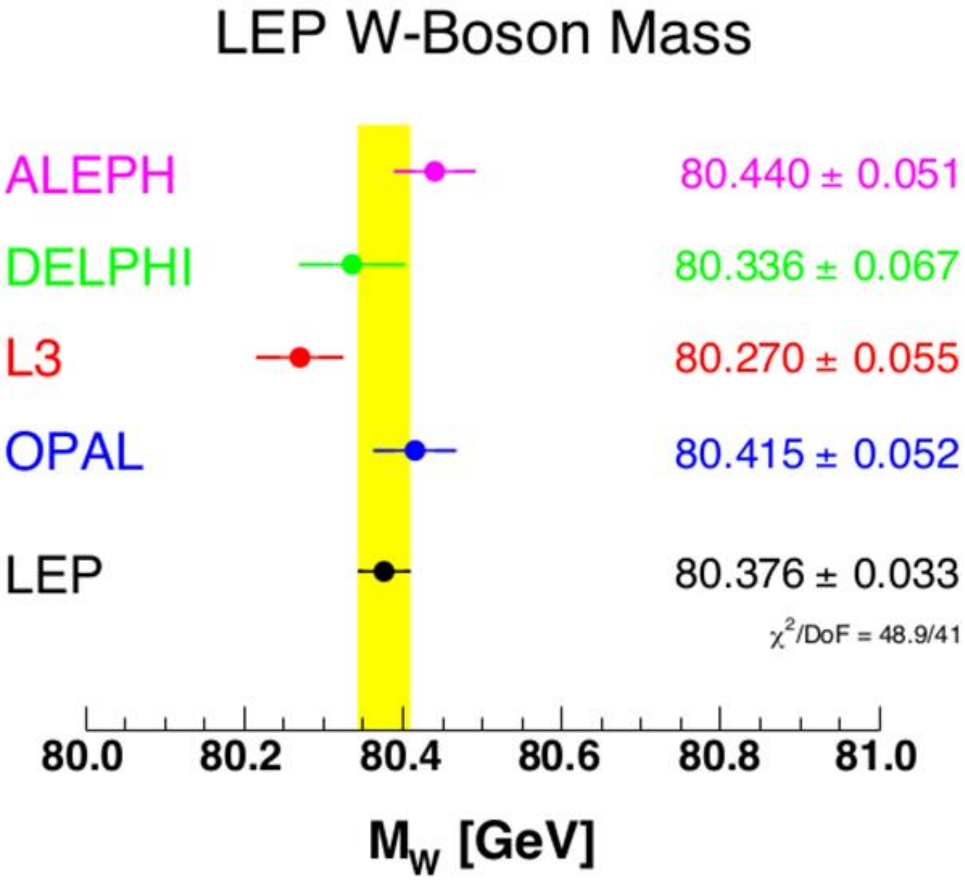
M_Z : Mass, resonance position
Γ_e, Γ_h : Partial widths
Γ_Z : Total width

→ 3 light neutrinos

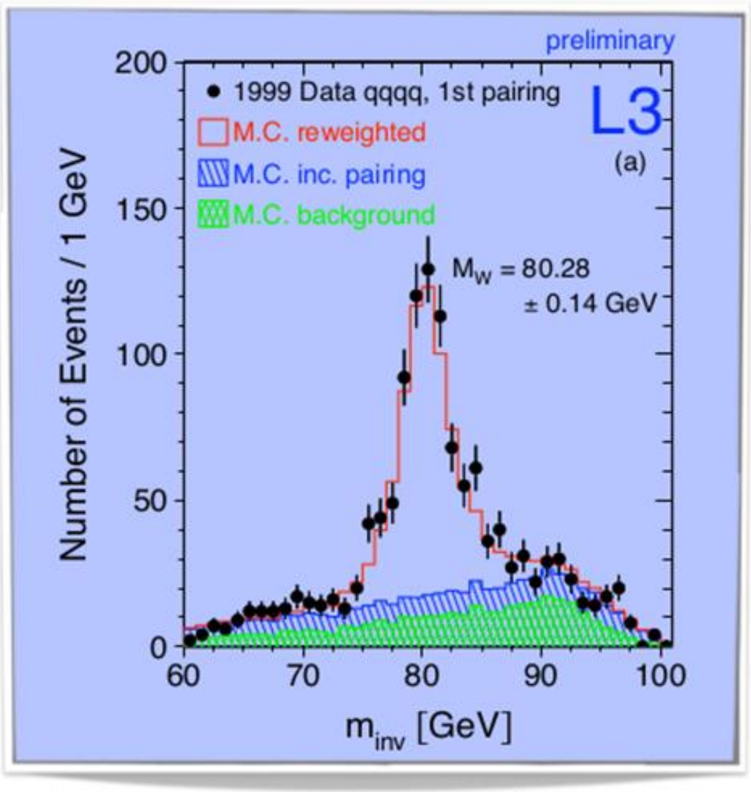


very clean signatures
in e+e- colliders!





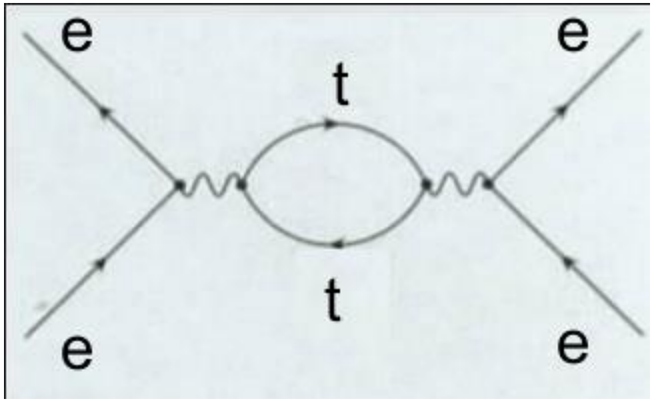
LEP EWWG arXiv:1302.3415]

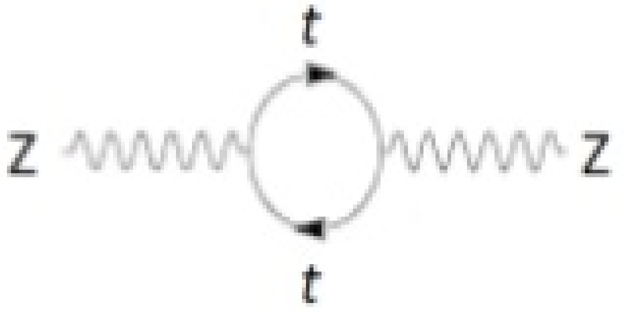


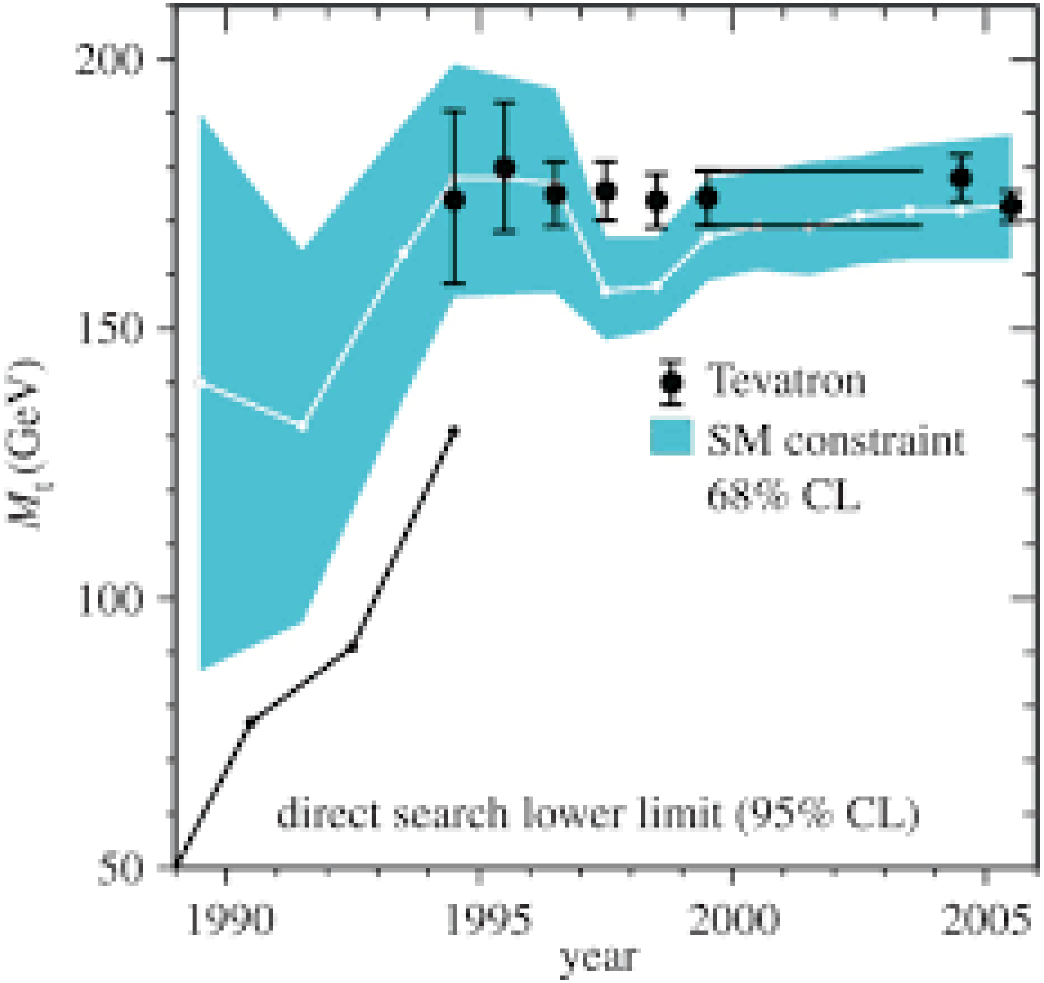
$e^+e^- \to W^+W^- \to qqqq$

Top mass prediction

the power of indirect searches







Top Discovery

Tevatron
[Fermilab]

$\sqrt{s} = 2$ TeV

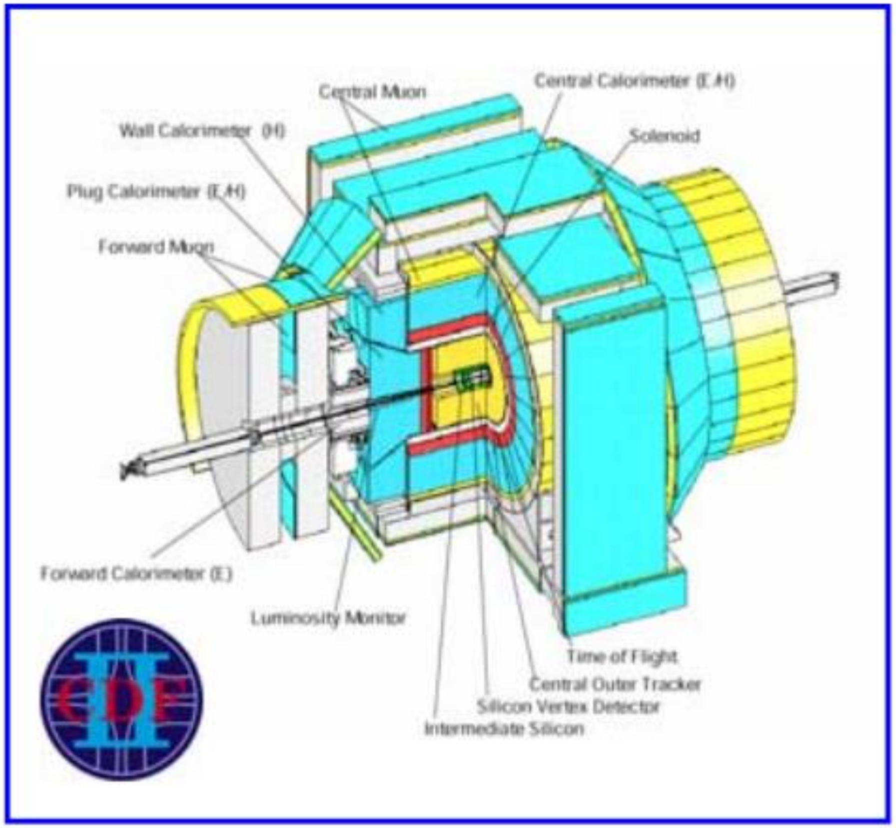
$L = 5 \cdot 10^{32}$ cm^{-2}

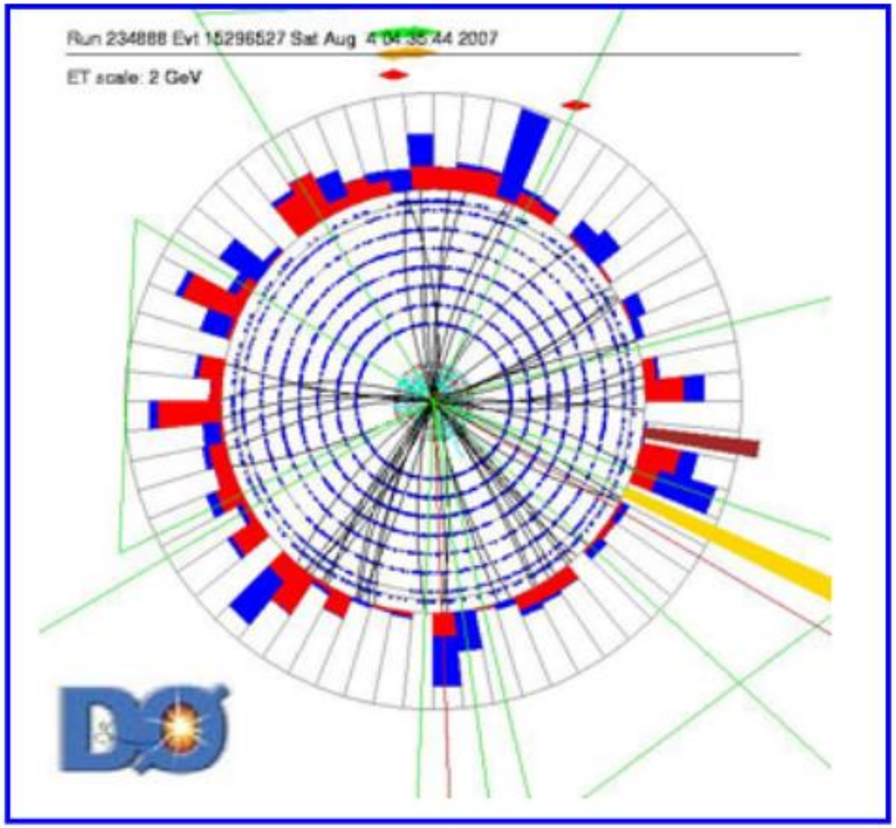
s-1

Discovery of the Top

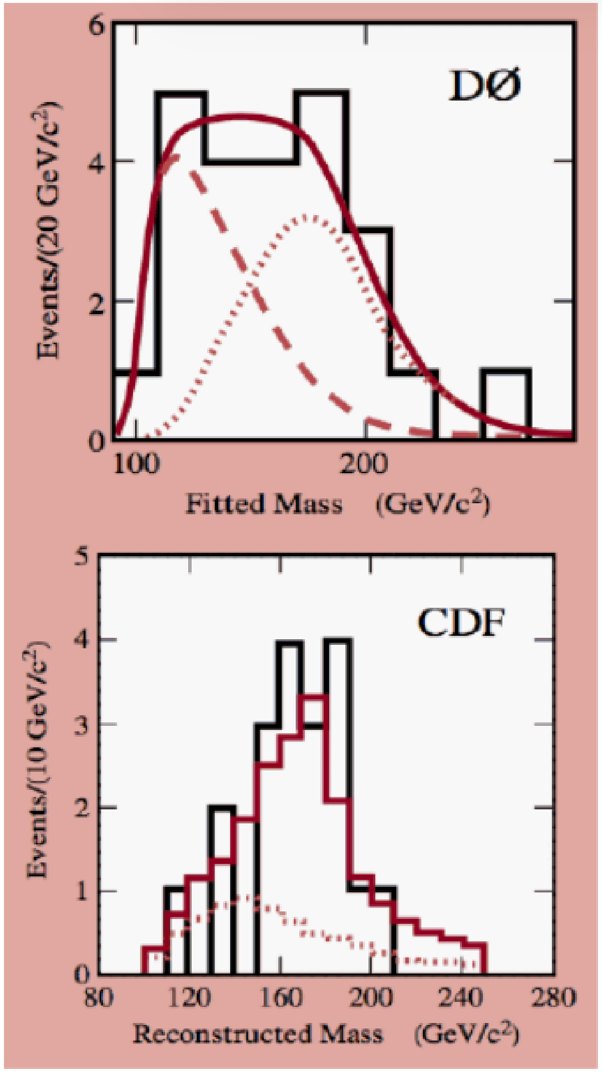
makes a huge difference for top production

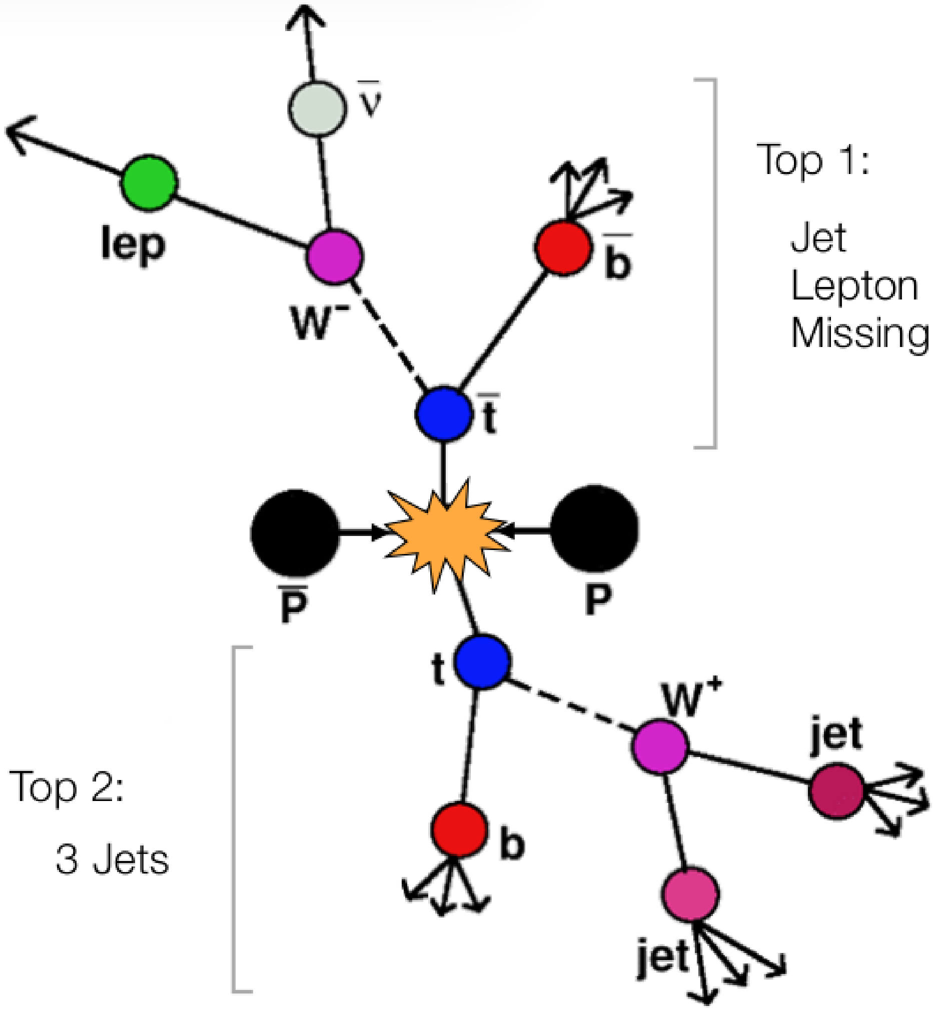
$p\bar{p}$ Collider with $\sqrt{s}$ = 1.8 TeV (Run I), 1.96 TeV (Run II)





Discovery of the Top (1995)





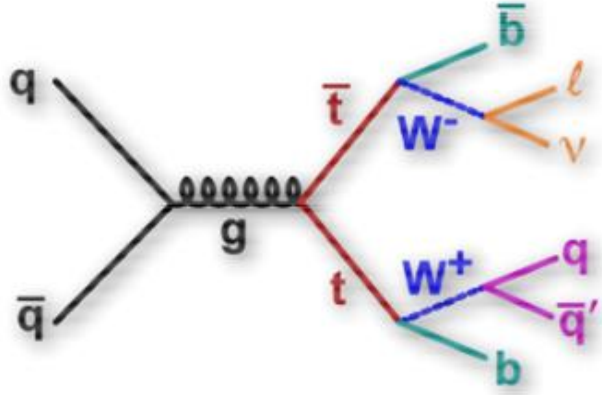
Top 1:

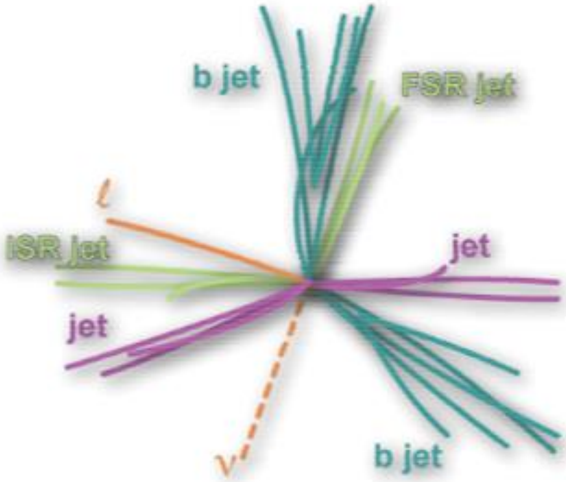
Jet
Lepton
Missing E_T

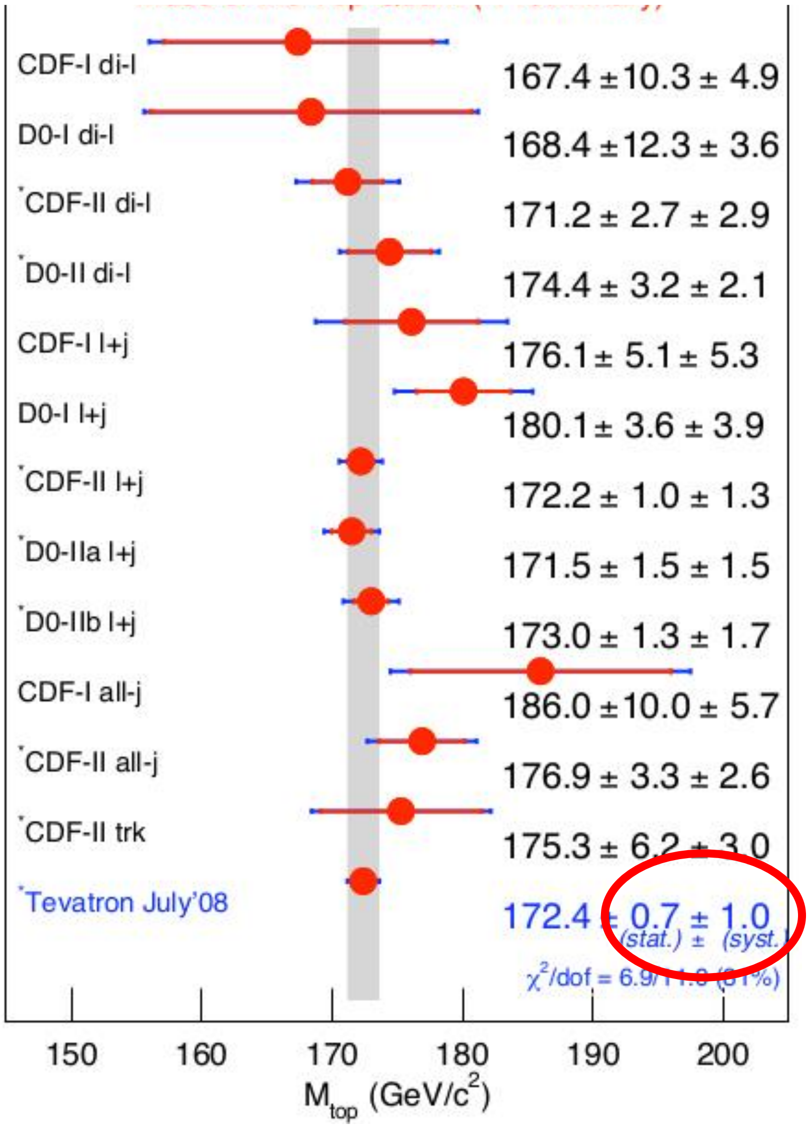
Top 2:

3 Jets

Top mass at the end of the Tevatron



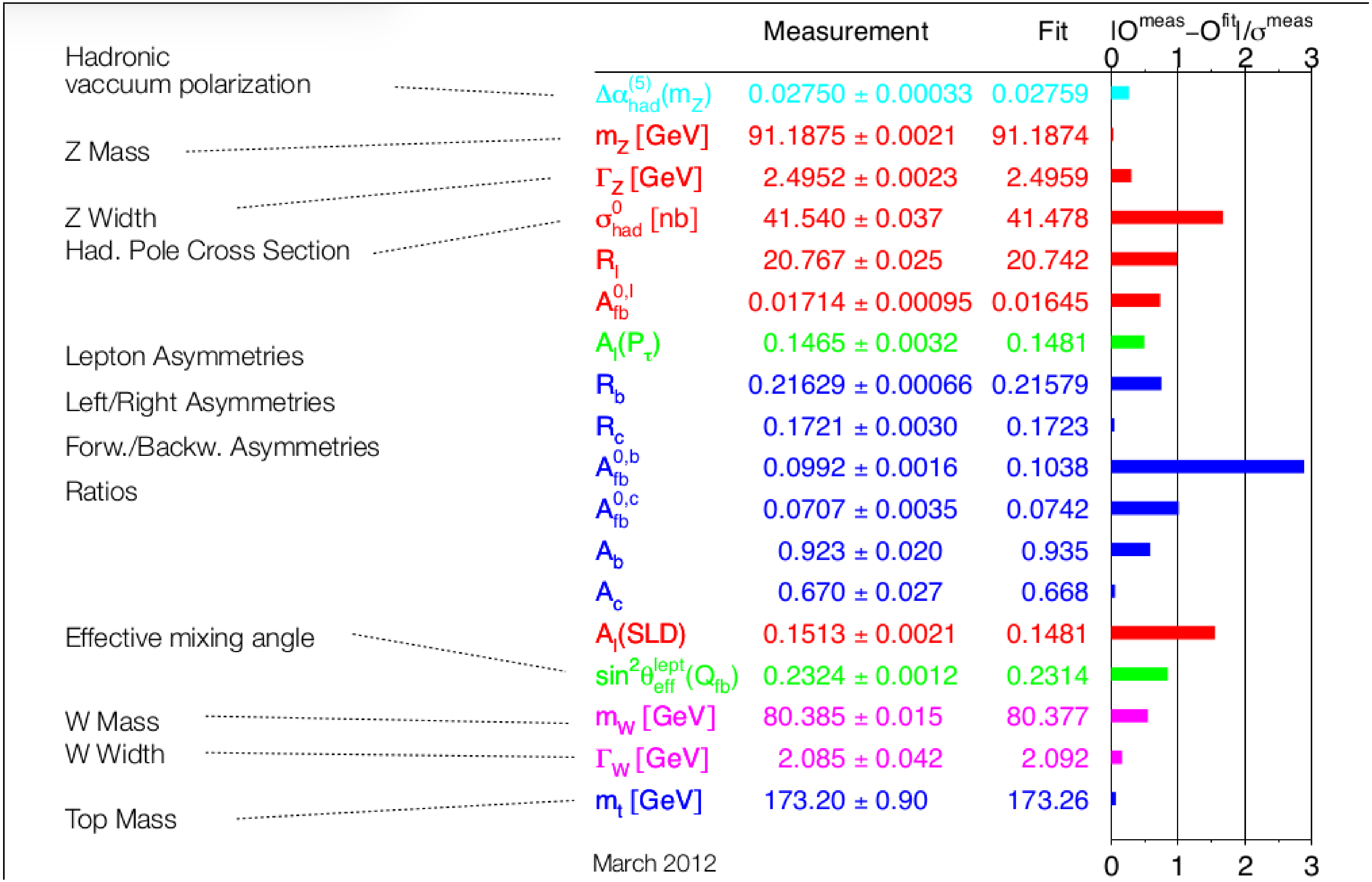




Electroweak precision measurements

@ LEP (+ Tevatron)

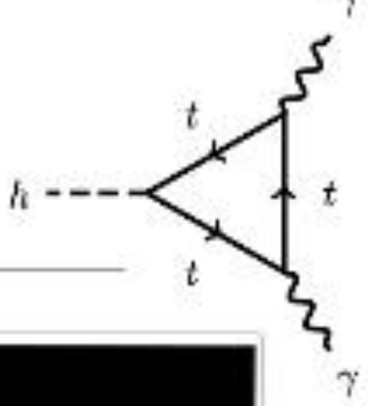
Took LHC a while to catch up with this precision (systematic uncertainties)

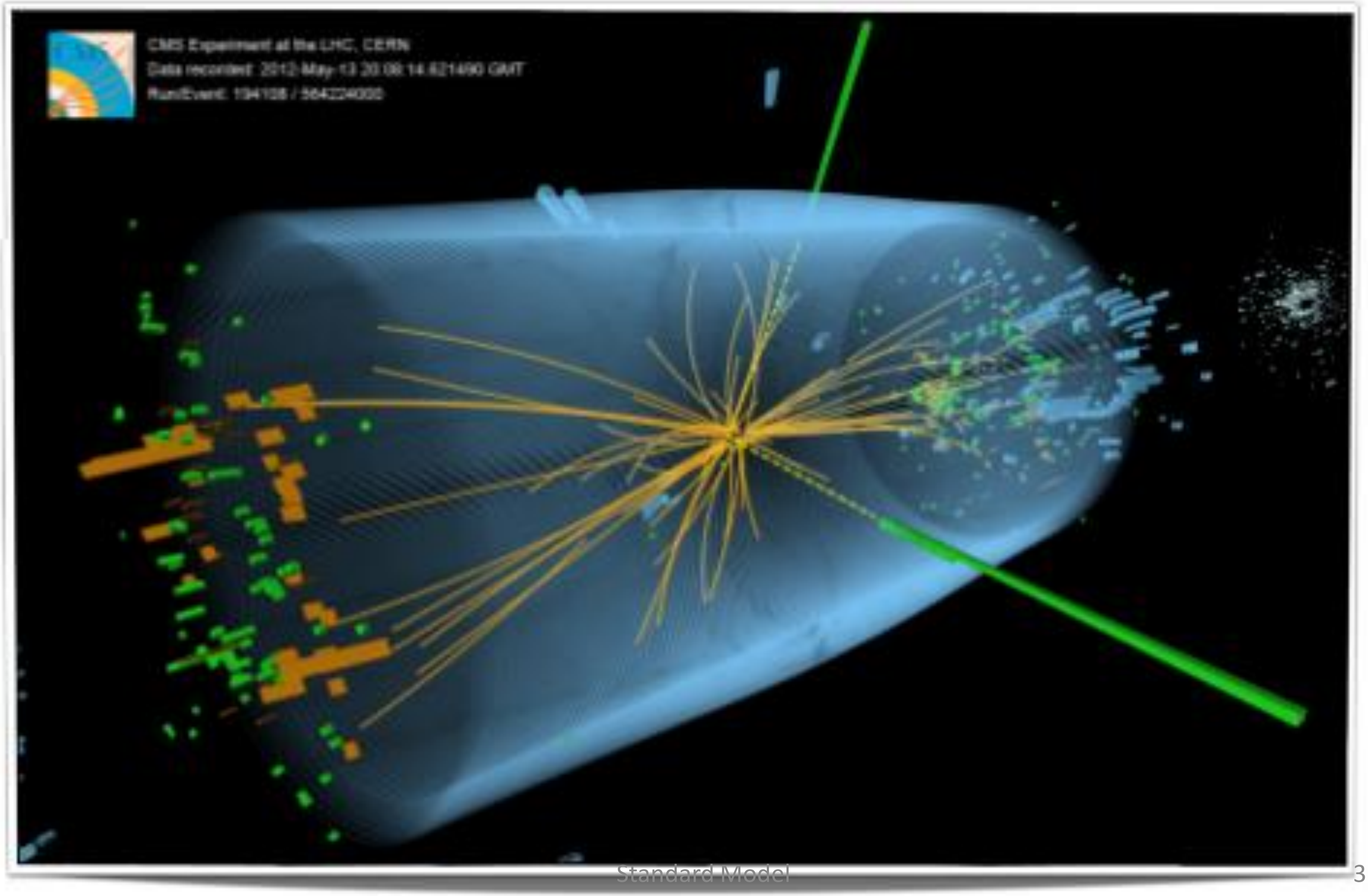


	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02750 ± 0.00033	0.02759
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ_{had}^{0} [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	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

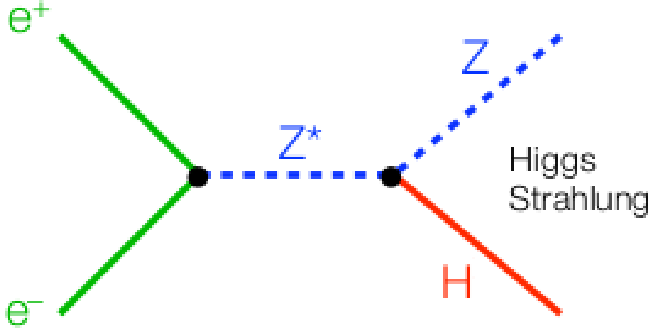
March 2012

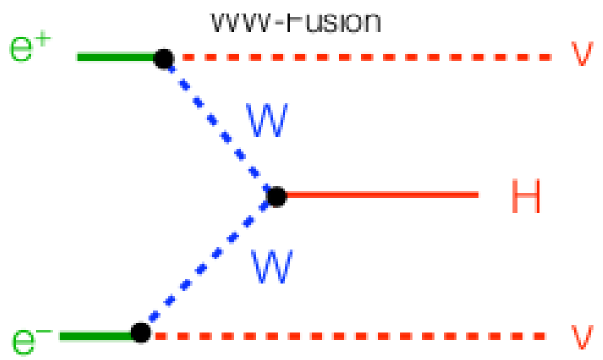
The Hunt for the Higgs …

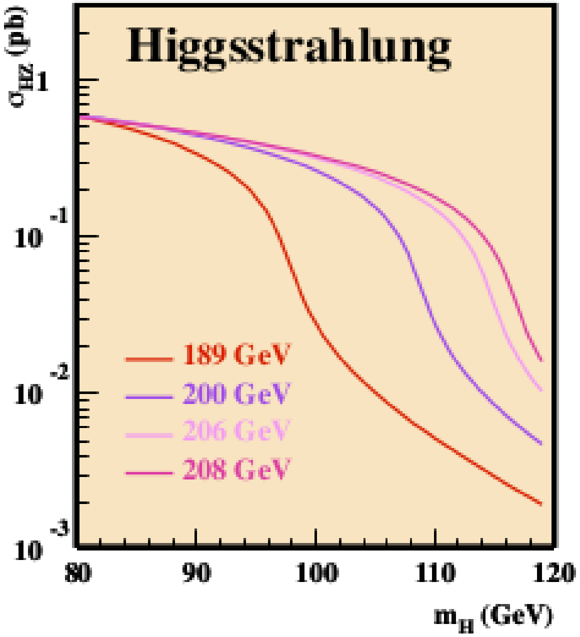


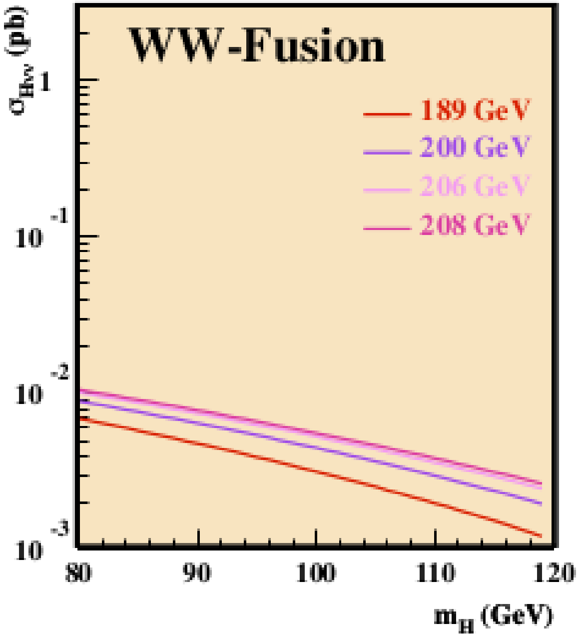


Higgs Searches at LEP



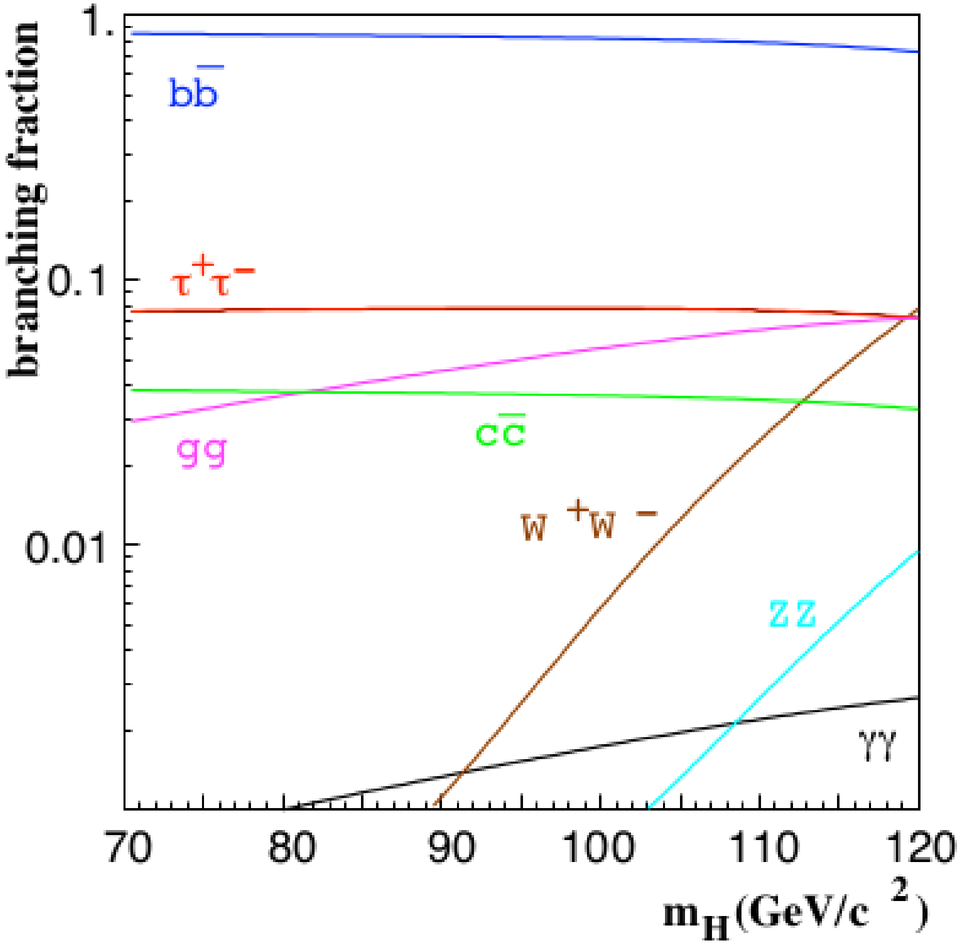






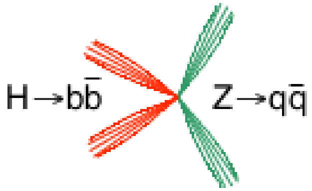
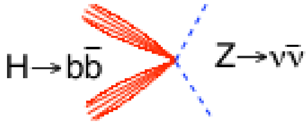
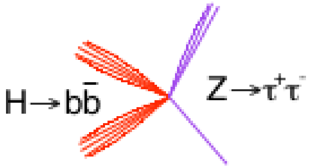
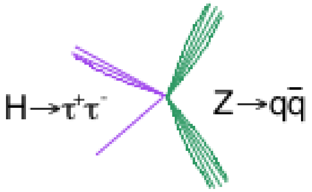
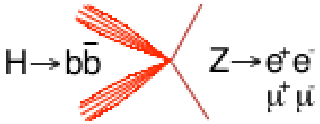
} CME of energy scan of LEP

Higgs Decays at LEP Energies

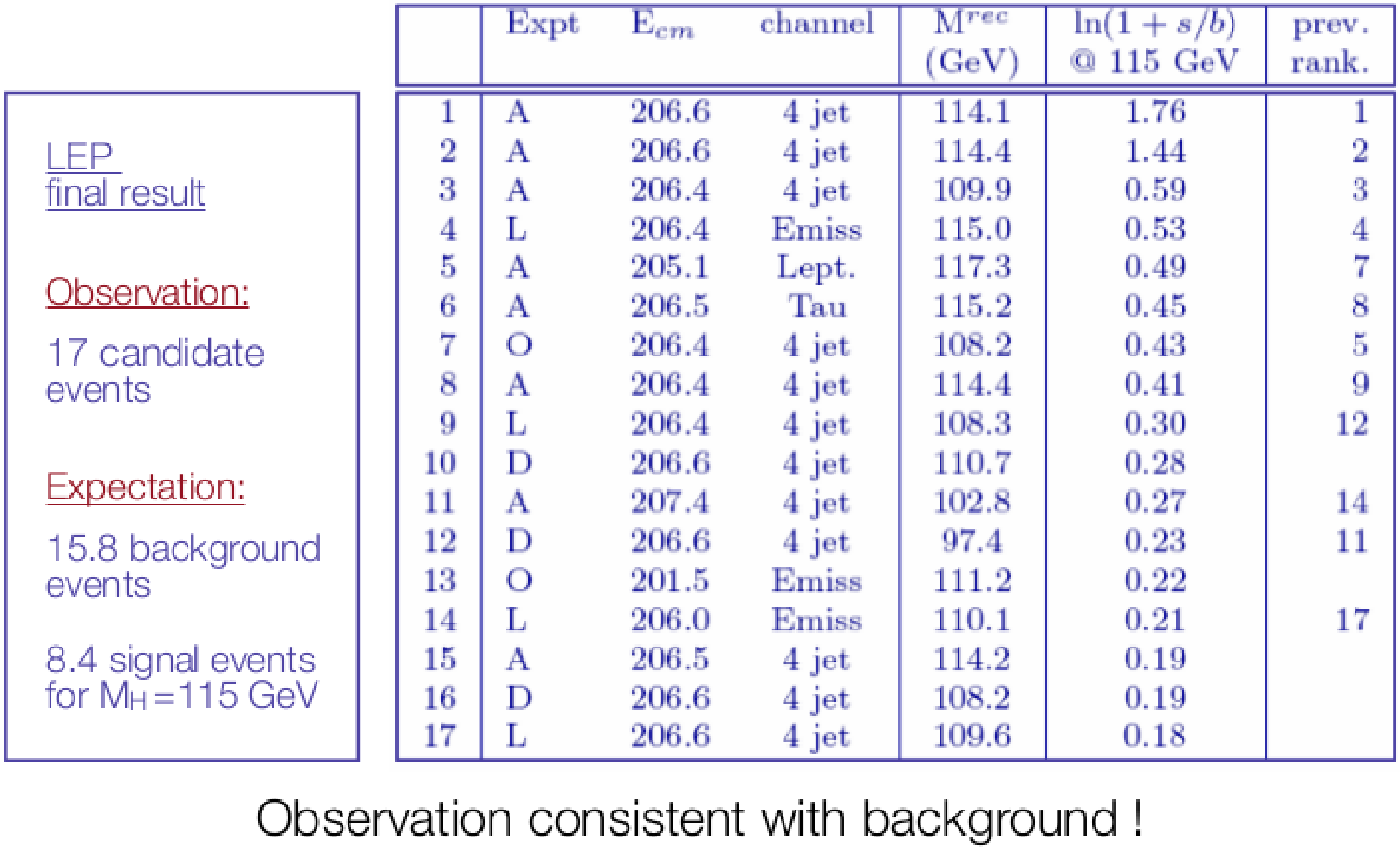


bb-decay
dominant !!

Higgs Signatures at LEP

	4-jets	51%	WW → qqqq ZZ → qqqq QCD 4-jets
	missing energy	15%	WW → qqlν ZZ → bbνν
	τ-channel	2.4%	WW → qqτν ZZ → bbττ ZZ → qqττ QCD low mult. jets
	τ-channel	5.1%	
	lepton channel	4.9%	ZZ → bbee ZZ → bbμμ

LEP Higgs Candidates



LEP final result

Observation:

17 candidate events

Expectation:

15.8 background events

8.4 signal events for $M_H = 115$ GeV

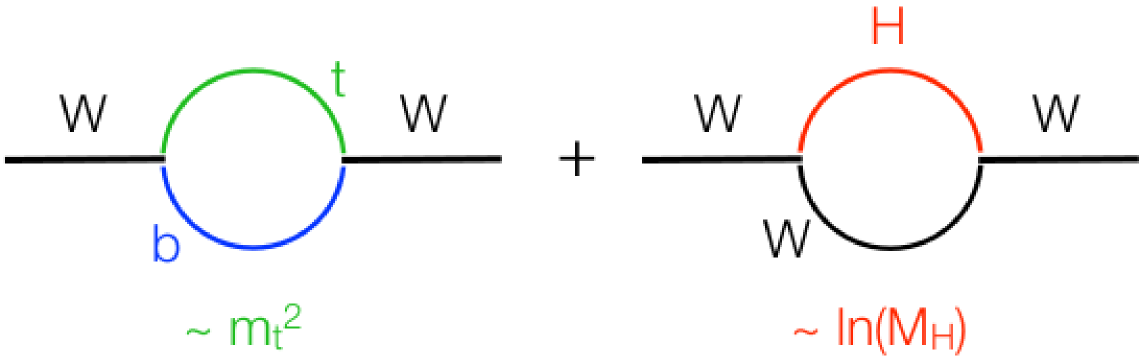
	Expt	E_{cm}	channel	M^{rec} (GeV)	$\ln(1+s/b)$ @ 115 GeV	prev. rank.
1	A	206.6	4 jet	114.1	1.76	1
2	A	206.6	4 jet	114.4	1.44	2
3	A	206.4	4 jet	109.9	0.59	3
4	L	206.4	Emiss	115.0	0.53	4
5	A	205.1	Lept.	117.3	0.49	7
6	A	206.5	Tau	115.2	0.45	8
7	O	206.4	4 jet	108.2	0.43	5
8	A	206.4	4 jet	114.4	0.41	9
9	L	206.4	4 jet	108.3	0.30	12
10	D	206.6	4 jet	110.7	0.28	
11	A	207.4	4 jet	102.8	0.27	14
12	D	206.6	4 jet	97.4	0.23	11
13	O	201.5	Emiss	111.2	0.22	
14	L	206.0	Emiss	110.1	0.21	17
15	A	206.5	4 jet	114.2	0.19	
16	D	206.6	4 jet	108.2	0.19	
17	L	206.6	4 jet	109.6	0.18	

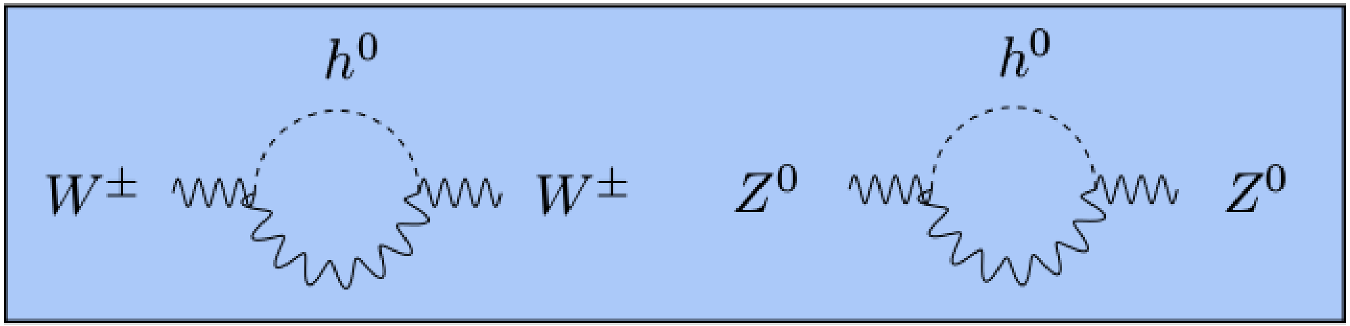
Observation consistent with background !

Loop Corrections

the power of indirect searches

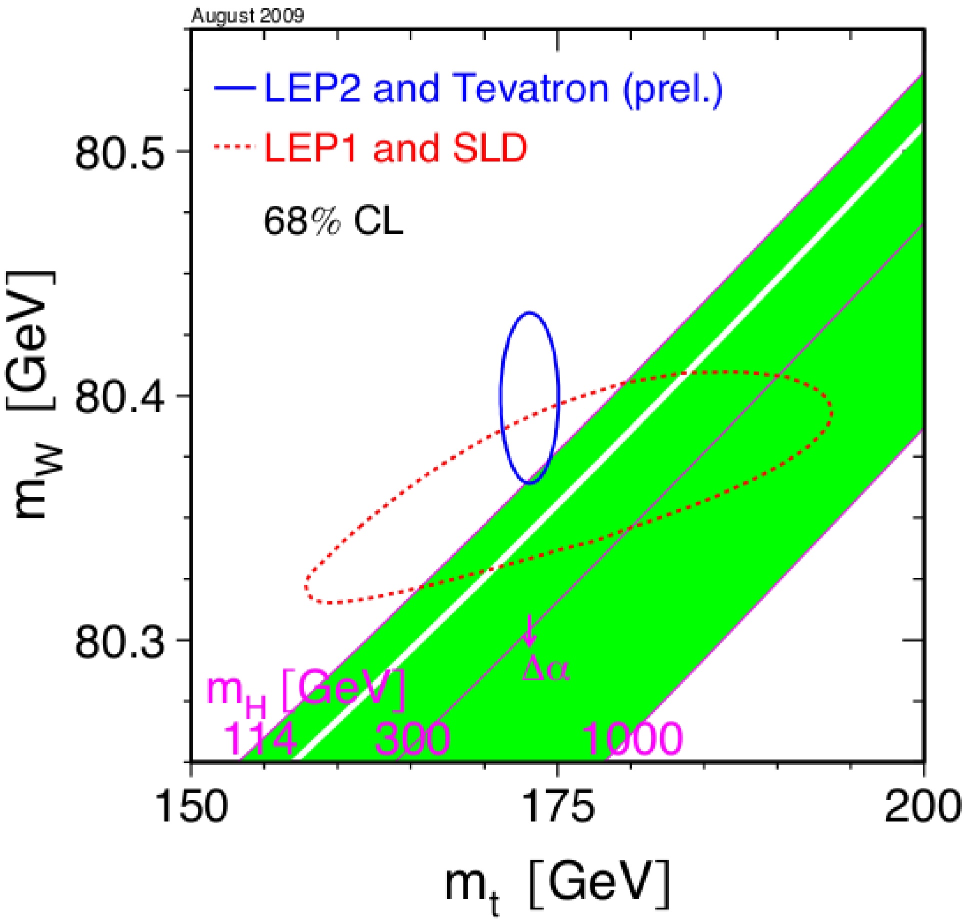
$$M_W = M_{W,\mathrm{Born}} + \ldots$$





Loop Corrections

the power of indirect searches



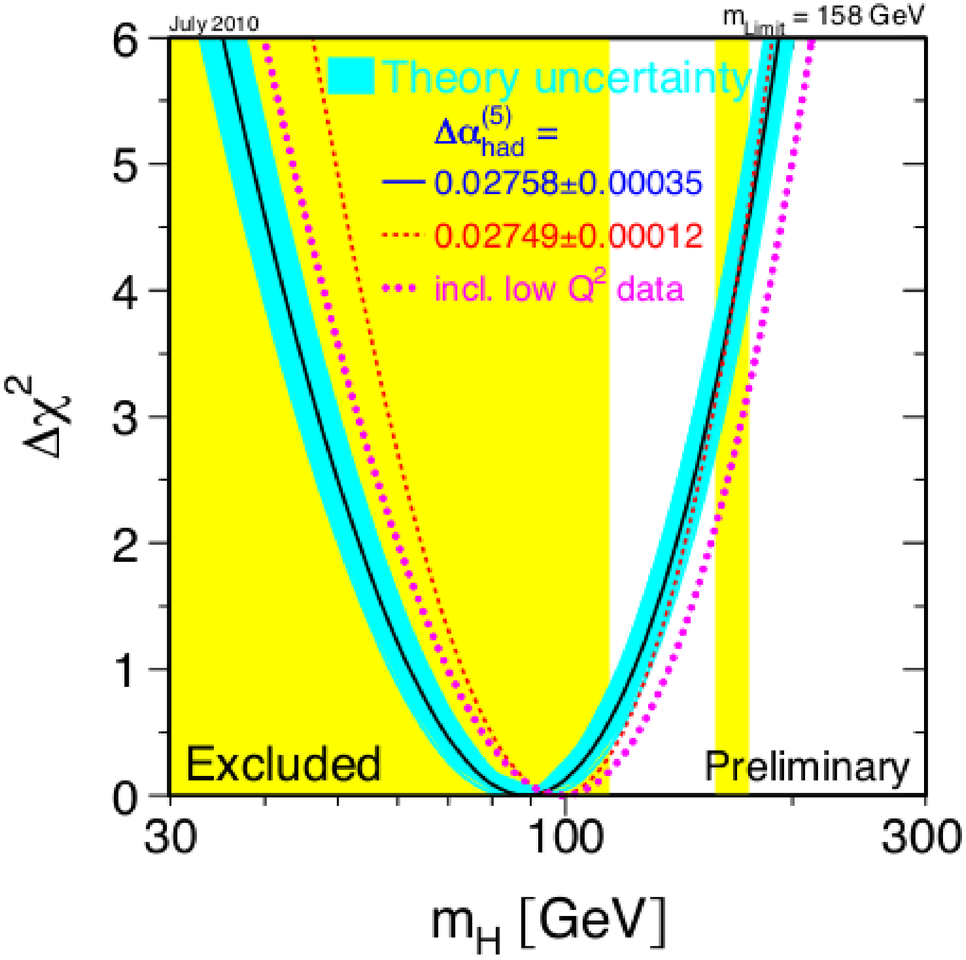
Last update
before LHC start:

2009

Higgs
should be light !

Loop Corrections

the power of indirect searches



EW-Fits:

$M_H = 89^{+35}_{-26}$ GeV

$M_H < 158$ GeV @ 95% CL

From direct
search at LEP:

$M_H > 114$ GeV

@ 95% CL

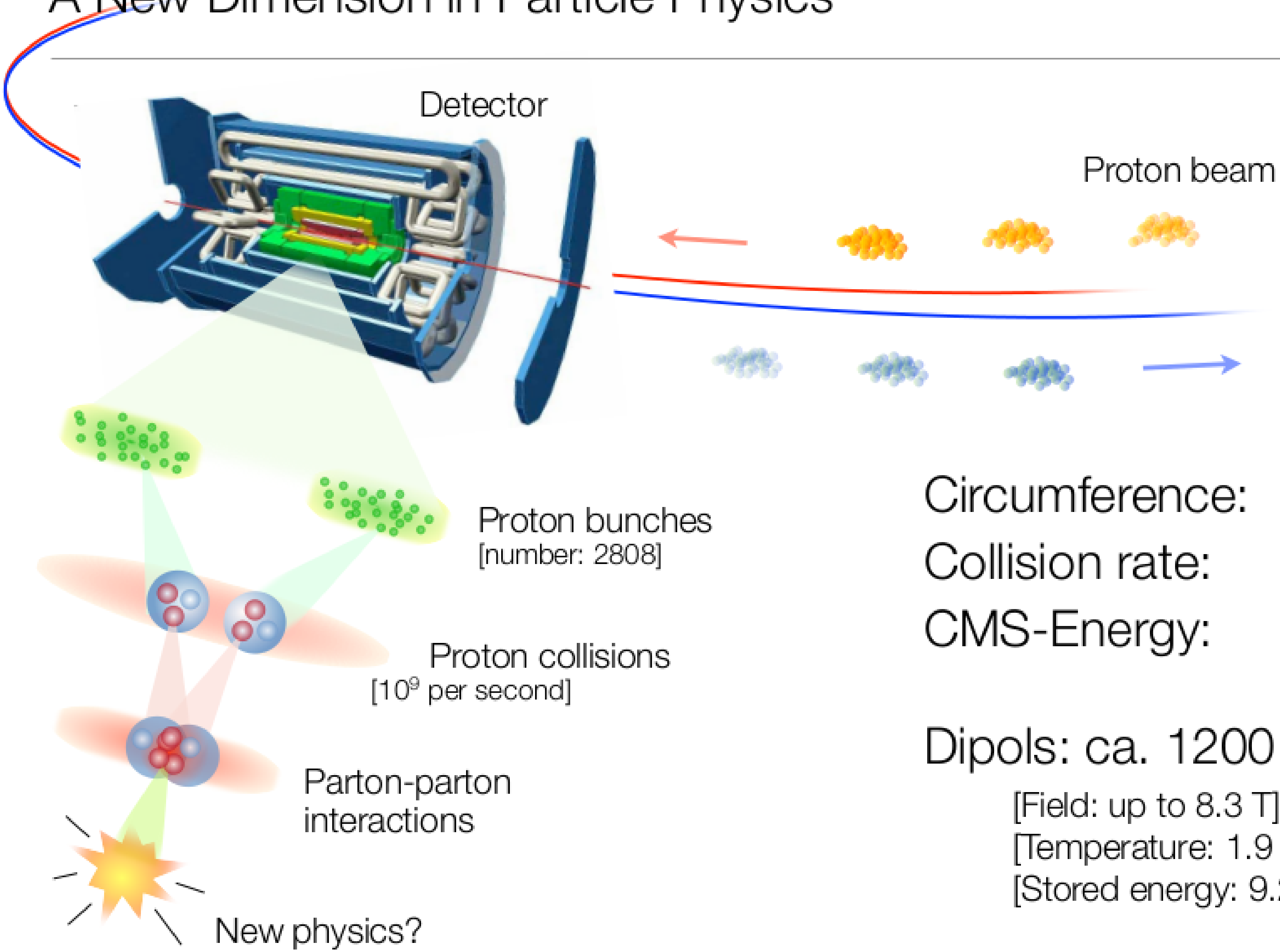
eV

[Status: Summer 2010]

The LHC and the Higgs

The LHC

A New Dimension in Particle Physics



Detector

Proton beam

Proton bunches
[number: 2808]

Proton collisions
[10^9 per second]

Parton-parton
interactions

New physics?

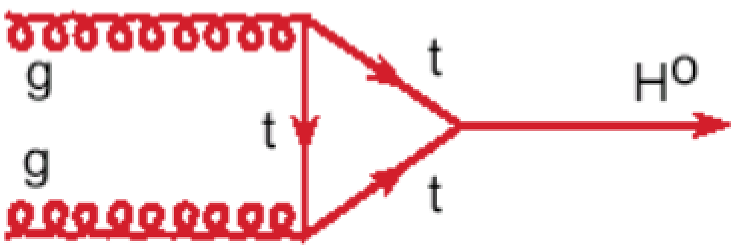
Circumference: 27 km
Collision rate: 40 MHz
CMS-Energy: 14 TeV

Dipols: ca. 1200

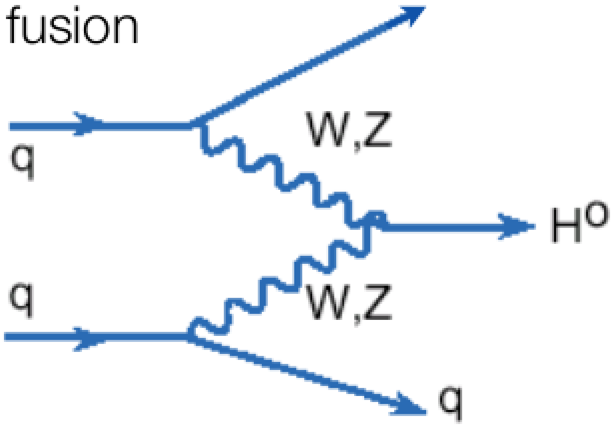
[Field: up to 8.3 T]
[Temperature: 1.9 K]
[Stored energy: 9.2 GJ]

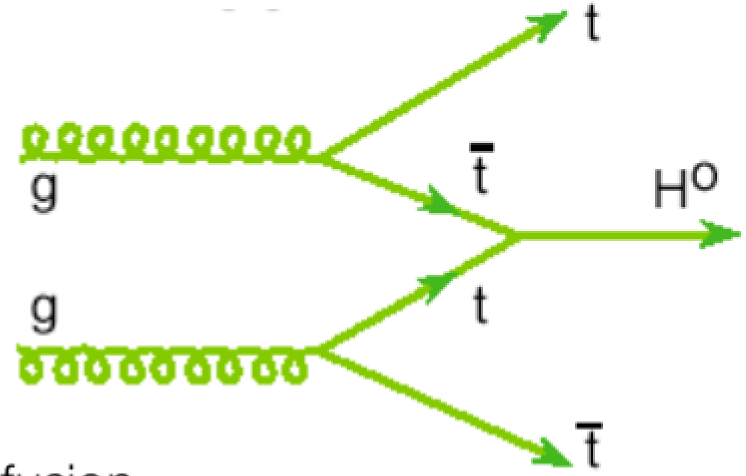
Higgs Production Mechanisms

Gluon fusion

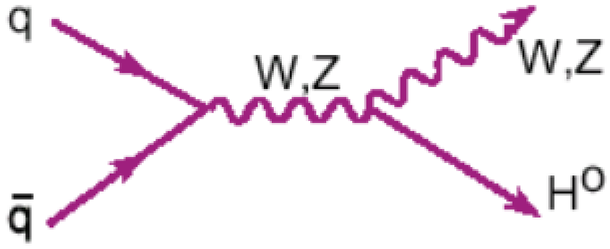


Vector
boson fusion



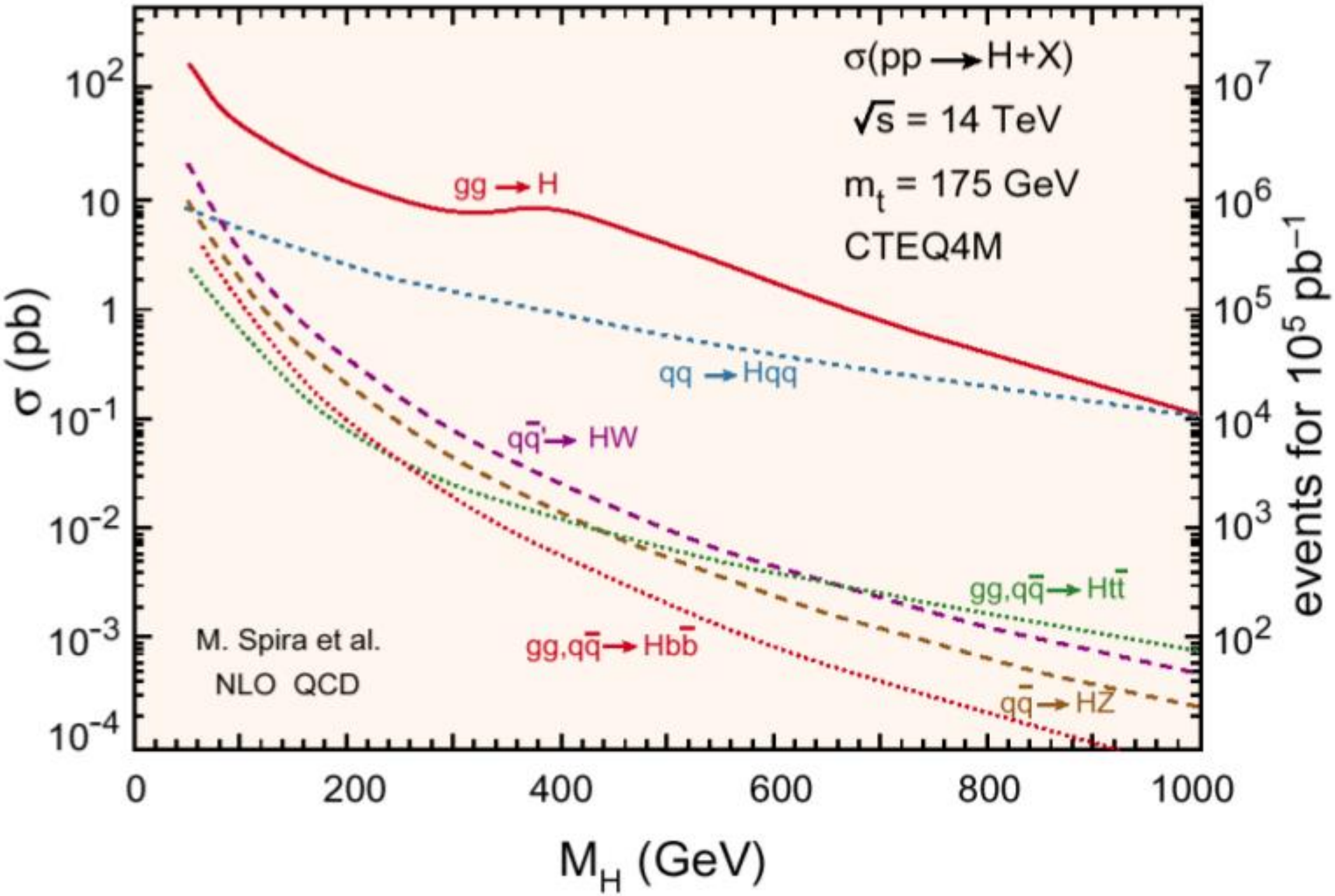


$t\bar{t}$-fusion

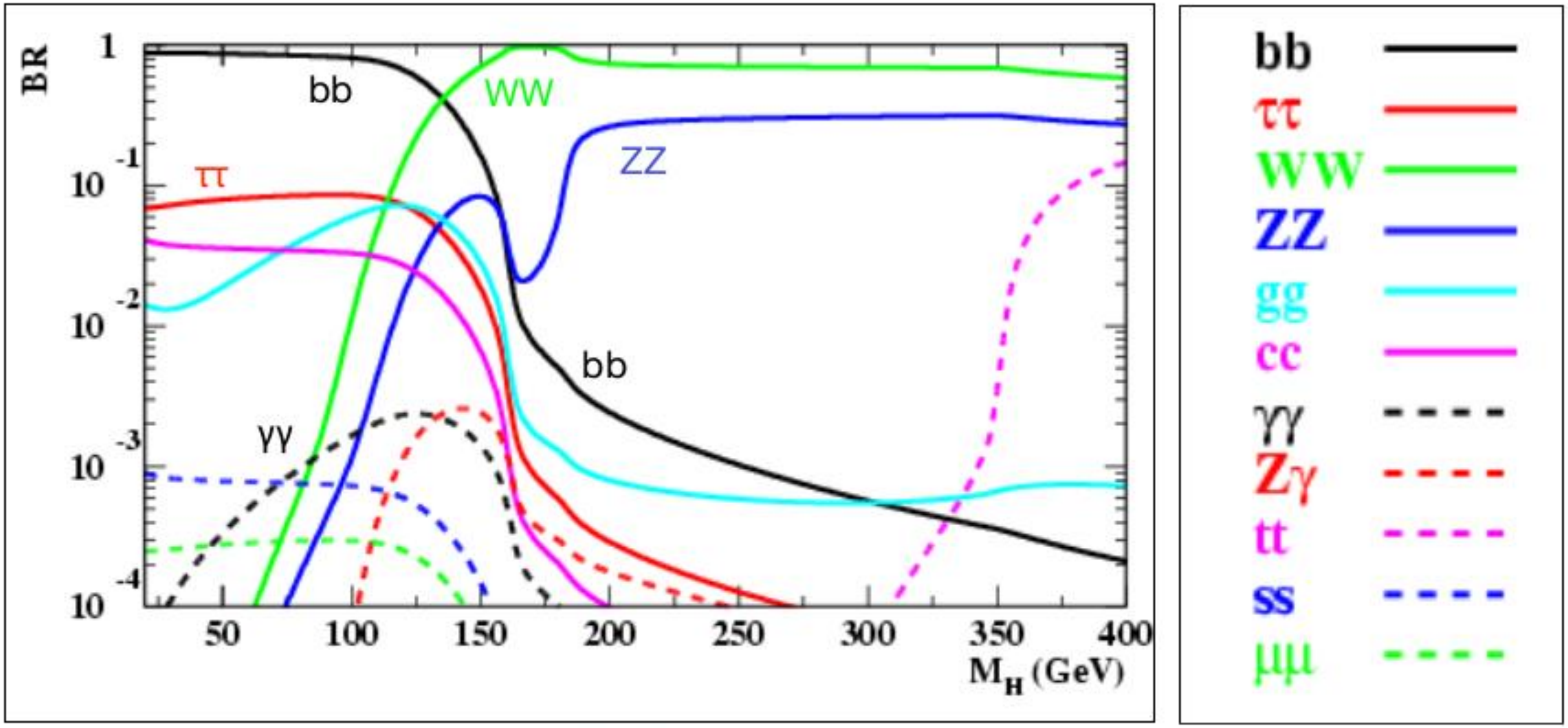


Associated
production

Higgs Production Cross Sections

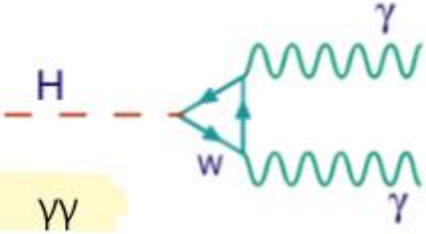


Higgs Boson Decays



For M < 135 GeV: H ➛ bb, ττ dominant

For M > 135 GeV: H ➛ WW, ZZ dominant

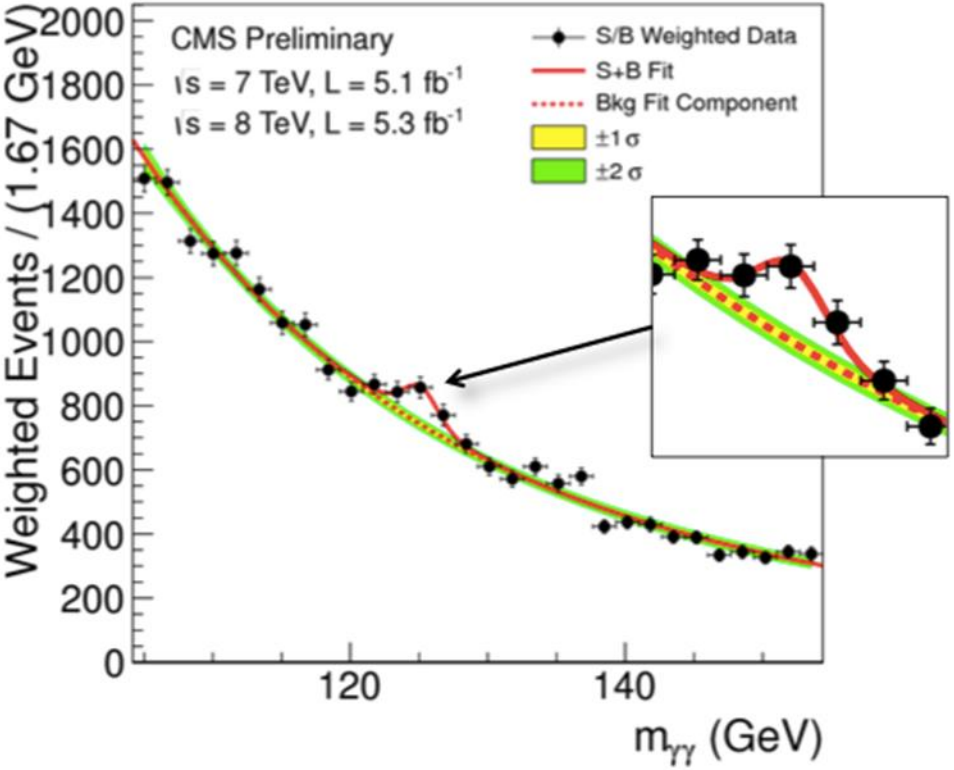


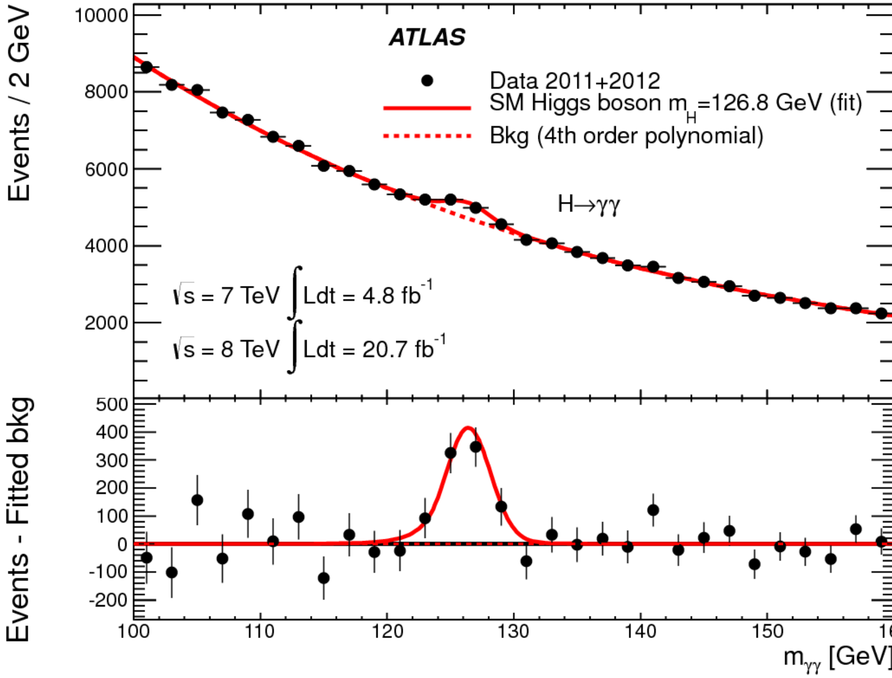
Tiny but also important: H ➛ γγ

Higgs Discovery

Nobel Prize in 2013

Higgs and Engler met the fist time at the Higgs anouncement 4. July 2012 at CERN





The big open questions

Are there extra dimensions of space ?

How can we solve the mystery of Dark Energy ?

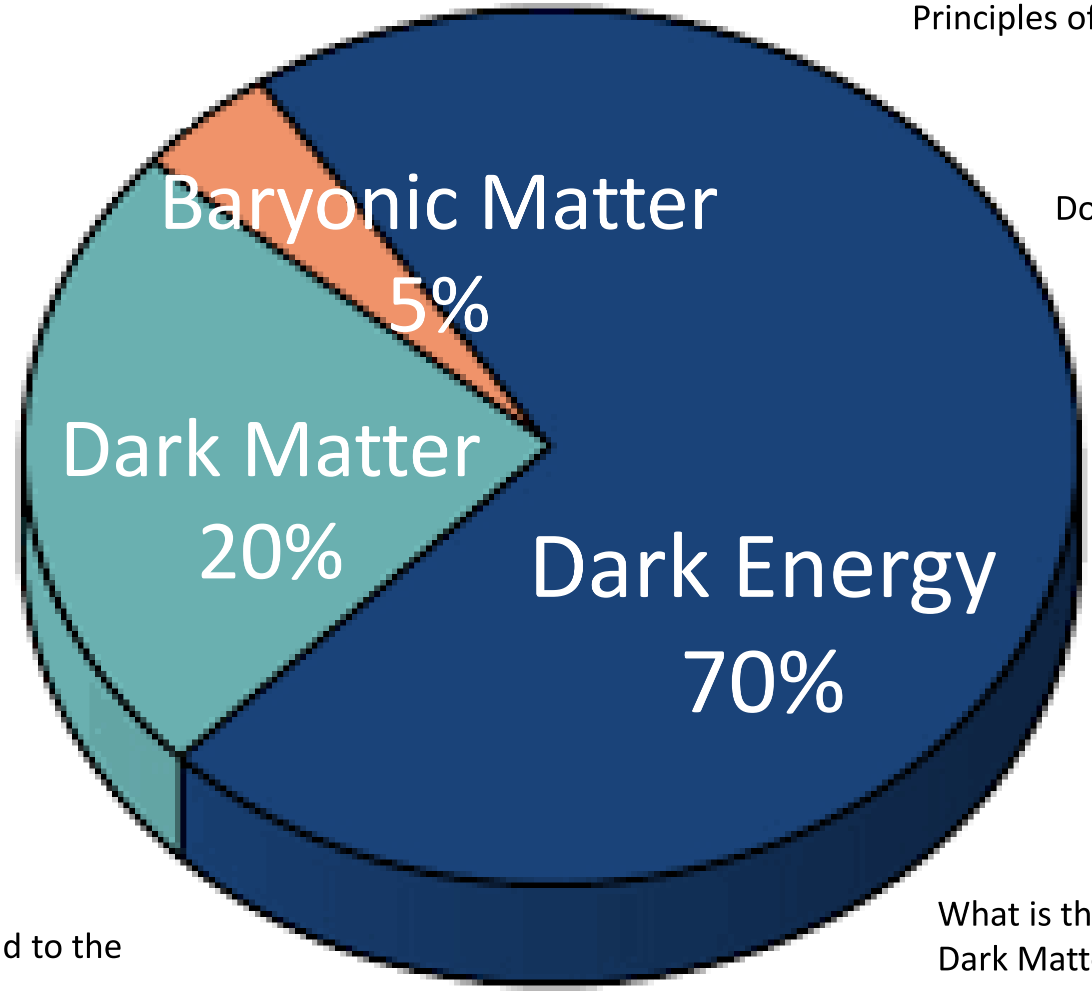
Are there undiscovered Principles of nature ?

Why are there so many Kinds of particles ?

Do all forces unify ?

How much finetuning Is natural ?

How to explain the masses of neutrinos ?



What happend to the antimatter ?

What is the nature of Dark Matter ?

MARCH FOR SCIENCE

EARTH DAY

APRIL 22, 2017

#MarchForScience