Standard Model of Particle Physics

Lecturer: ***Tilman Plehn***
Ulrich Uwer

Monday	11:15 - 13:00	Phil 12 gHS
Wednesday	11:15 - 13:00	Phil 12 gHS
Tutorials Tue	Tue morning / Thu afternoon	

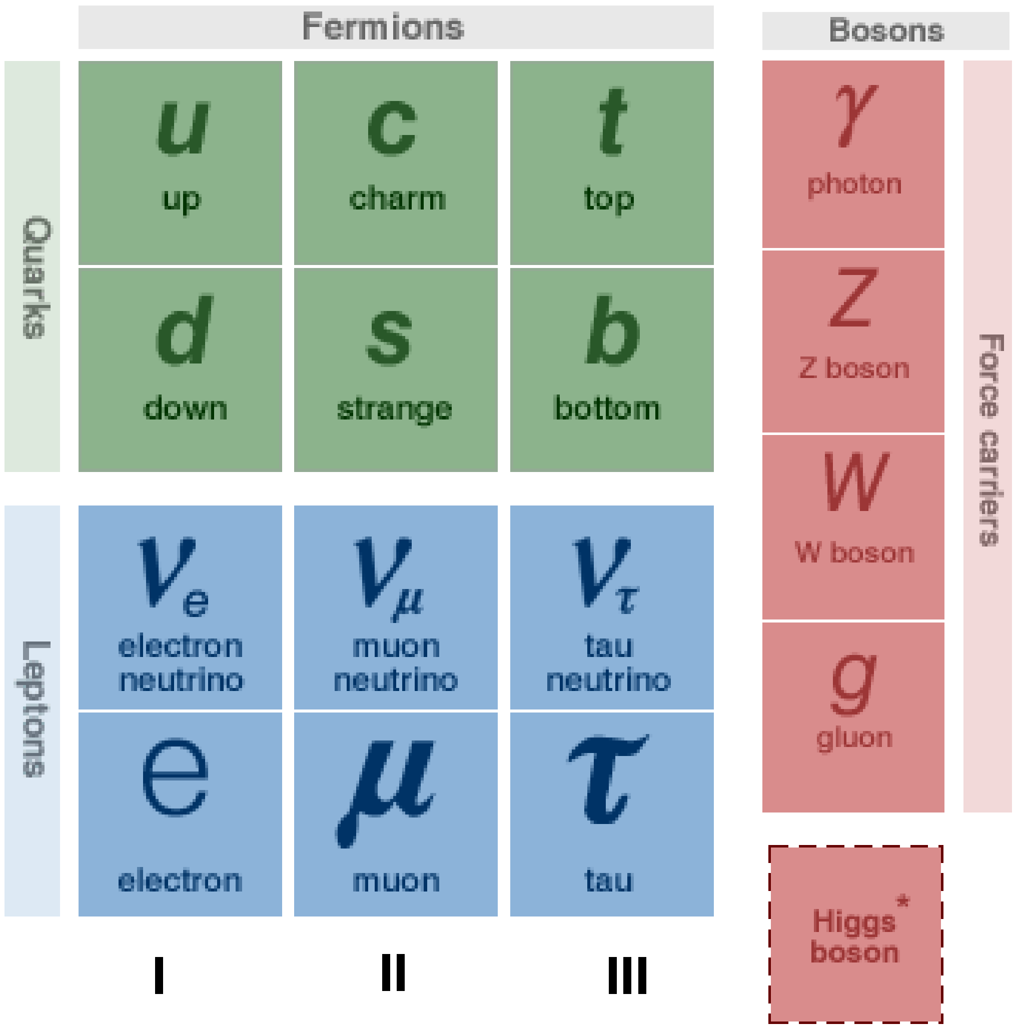
http://www.physi.uni-heidelberg.de/~uwer/lectures/StandardModel/

Contents

1) Introduction
2) QED
3) Electroweak Standard Model
4) Strong interaction: QCD

} Theory + experimental tests

Standard Model*) of Particle Physics



Based on the principle of local gauge invariance

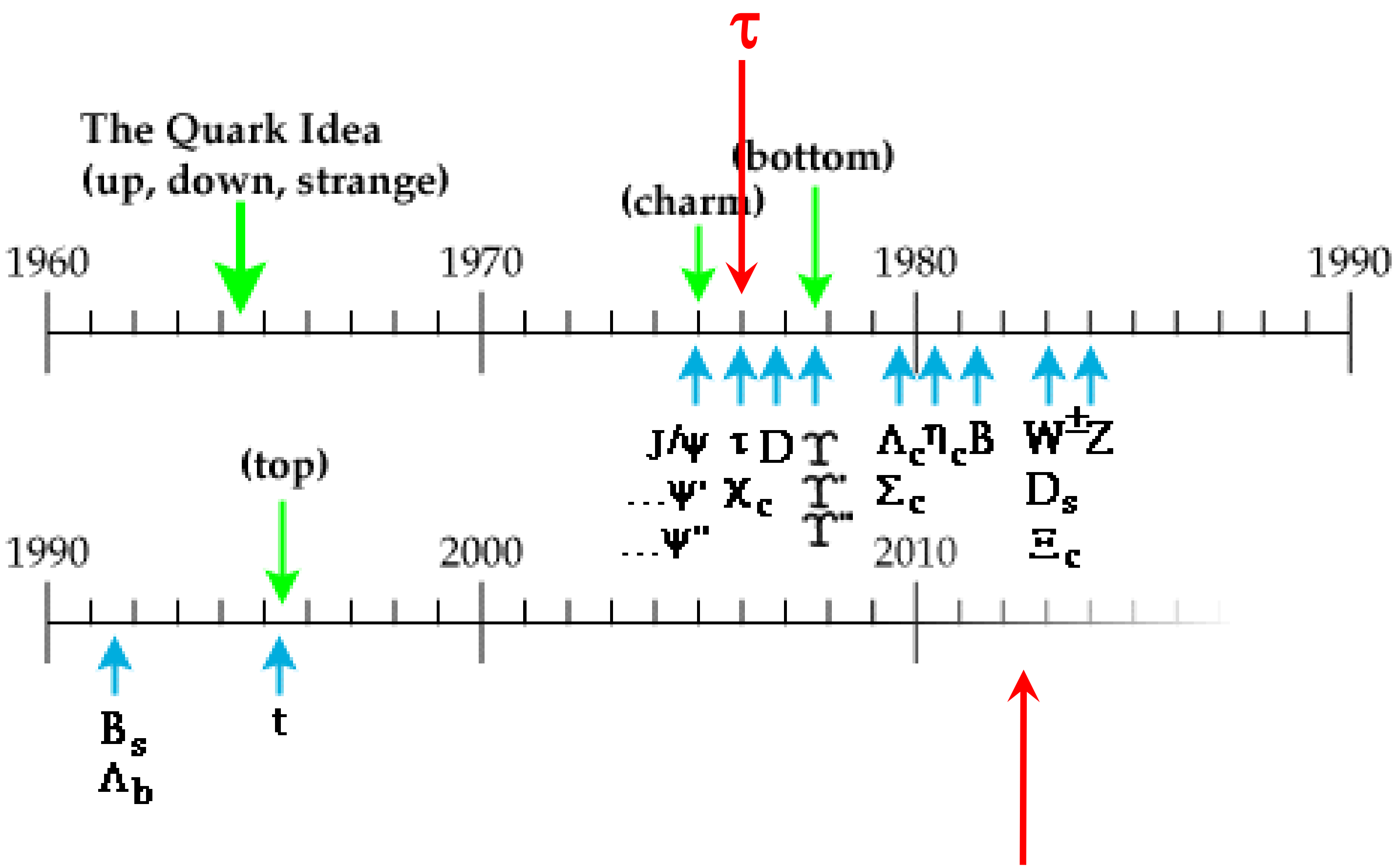
$$SU_C(3)\times SU_L(2)\times U_Y(1)$$

⇦ 12 gauge fields

⇦ Not yet directly observed

*) S. L. Glashow, A. Salam and S. Weinberg, 1967/8

Timeline of Particle Discoveries



Higgs?

Origin of symmetry breaking?

Experimental SM Tests (selection)

1967/8 Standard Model, S. L. Glashow, A. Salam and S. Weinberg

1971 Renormalizability of non-abelian gauge theories, G. `t Hooft and M. Veltman

1973 Asymptotic freedom of QCD, D. Gross, D. Politzer and F. Wilzcek;
Explaination of CP violation: 3 quark generation, M.Kobayashi, T.Maskawa

1973 Discovery of Neutral Currents: „Z-Boson exchange“ (Gargamelle, CERN)

1974 Discovery of the 4th quark (SLAC / BNL) → „November Revolution“

1975 Discovery of the Tau-Lepton

1979 Discovery of the gluon (DESY)

1983 Observation of W and Z bosons (UA1/2, CERN)

1989 Start of LEP I: Precision Z-physics measurement of radiative corrections

1995 Discovery of the Top-Quark at TEVATRON

1996 Start of LEP II: W Pair production and Higgs search (until Nov 2000)

2001 Start of TEVATRON Run II:
Precision measurement of Top-Quark and W-Boson properties, B physics

2009 Start of LHC ⇒ Discovery of the Higgs boson, New Physics?

Discovery of Tau-Lepton

Unexpected, although 3rd generation predicted by Kobayashi and Maskawa

MARK I (SLAC), 1975, M.Perl et al.

Nobel Prize 1995 for M.Perl

Evidence for Anomalous Lepton Production in e^+-e^- Annihilation*

M. L. Perl, G. S. Abrams, A. M. Boyarski, M. Breidenbach, D. D. Briggs, F. Bulos, W. Chinowsky, J. T. Dakin,† G. J. Feldman, C. E. Friedberg, D. Fryberger, G. Goldhaber, G. Hanson, F. B. Heile, B. Jean-Marie, J. A. Kadyk, R. R. Larsen, A. M. Litke, D. Lüke,‡ B. A. Lulu, V. Lüth, D. Lyon, C. C. Morehouse, J. M. Paterson, F. M. Pierre,§ T. P. Pun, P. A. Rapidis, B. Richter, B. Sadoulet, R. F. Schwitters, W. Tanenbaum, G. H. Trilling, F. Vannucci,∥ J. S. Whitaker, F. C. Winkelmann, and J. E. Wiss

Lawrence Berkeley Laboratory and Department of Physics, University of California, Berkeley, California 94720, and Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

(Received 18 August 1975)

We have found events of the form $e^+ + e^- \rightarrow e^\pm + \mu^\mp$ + missing energy, in which no other charged particles or photons are detected. Most of these events are detected at or above a center-of-mass energy of 4 GeV. The missing-energy and missing-momentum spectra require that at least two additional particles be produced in each event. We have no conventional explanation for these events.

We have found 64 events of the form

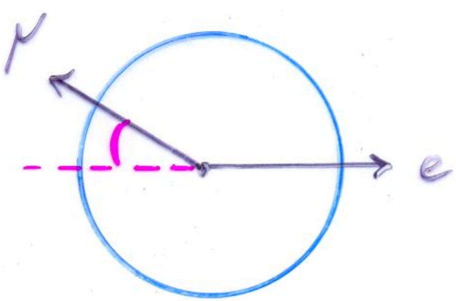
$$e^+ + e^- \rightarrow e^\pm + \mu^\mp + \geq 2 \text{ undetected particles} \qquad (1)$$

for which we have no conventional explanation. The undetected particles are charged particles or photons which escape the 2.6π sr solid angle of the detector, or particles very difficult to detect such as neutrons, $K_L{}^0$ mesons, or neutrinos. Most of these events are observed at center-of-mass energies at, or above, 4 GeV. These events were found using the Stanford Linear Accelerator Center–Lawrence Berkeley Laboratory (SLAC-

TABLE I. Distribution of 513 two-prong events, obtained at $E_{c.m.}$ = 4.8 GeV, which meet the criteria $|\vec{p}_1| > 0.65$ GeV/c, $|\vec{p}_2| > 0.65$ GeV/c, and $\theta_{copl} > 20°$. Events are classified according to the number N_γ of photons detected, the total charge, and the nature of the particles. All particles not identified as e or μ are called h for hadron.

Particles \ N_γ	0	1	>1	0	1	>1
	Total charge = 0			Total charge = ±2		
e-e	40	111	55	0	1	0
e-μ	24	8	8	0	0	3
μ-μ	16	15	6	0	0	0
e-h	20	21	32	2	3	3
μ-h	17	14	31	4	0	5
h-h	14	10	30	10	4	6

$e^+e^- \rightarrow$



Explanation:

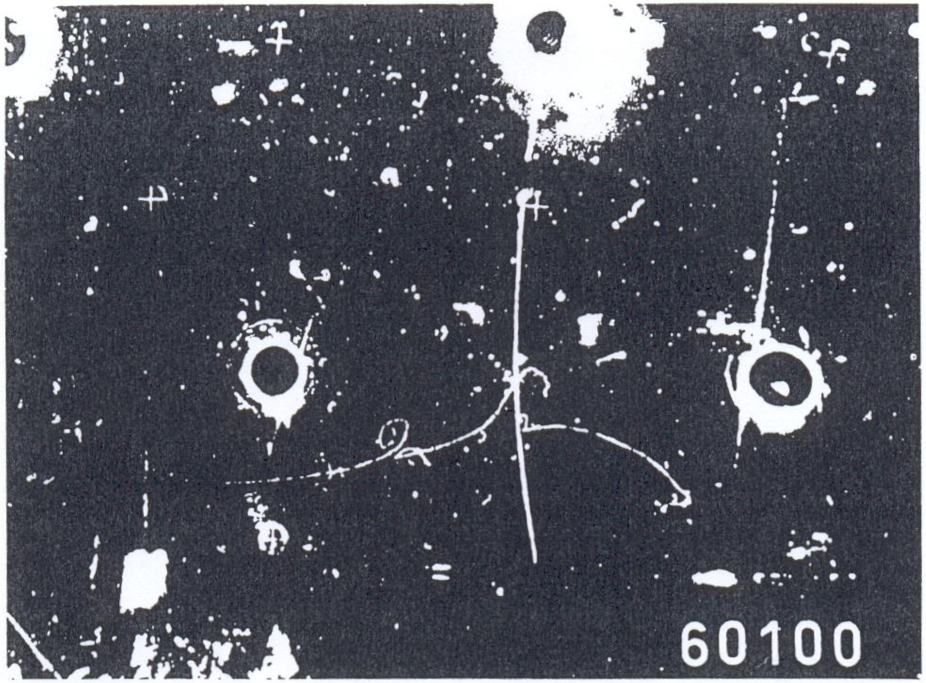
$$e^+e^- \rightarrow \tau^+ \tau^-$$

$$\tau^- \rightarrow e^- \bar{\nu}_e \nu_\tau$$

$$\tau^+ \rightarrow \mu^+ \nu_\mu \bar{\nu}_\tau$$

Discovery of Neutral Currents (1973)

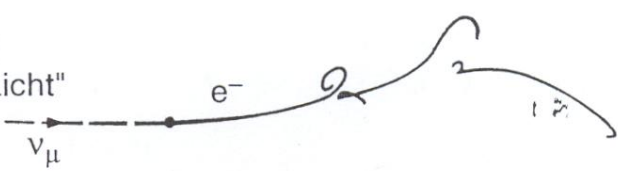
Gargamelle, CERN



a)

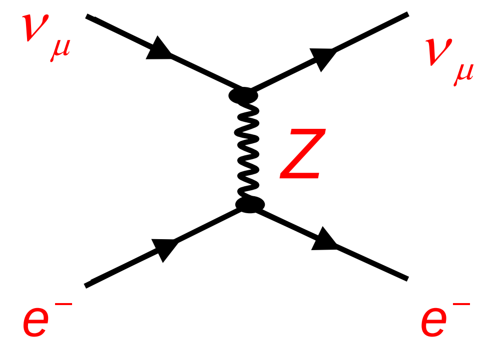
Neutraler Strom
= "schwaches Licht"

b)



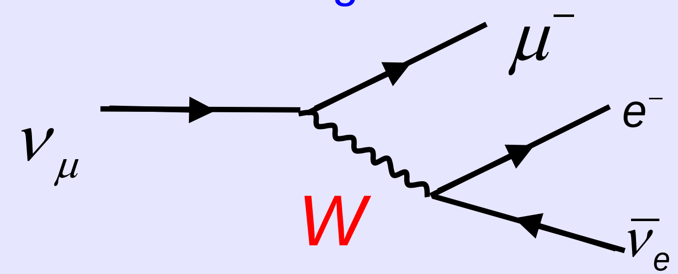
(1 out of 3 (!) recoded $\nu e \rightarrow \nu e$ events)

$$\nu_\mu + e^- \rightarrow \nu_\mu + e^-$$



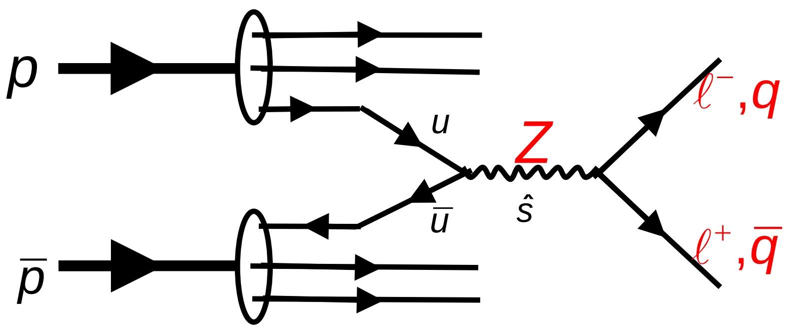
$$R_\nu = \frac{\sigma_{NC}(\nu N \rightarrow \nu X)}{\sigma_{CC}(\nu N \rightarrow \mu X)} = 0.307 \pm 0.008$$

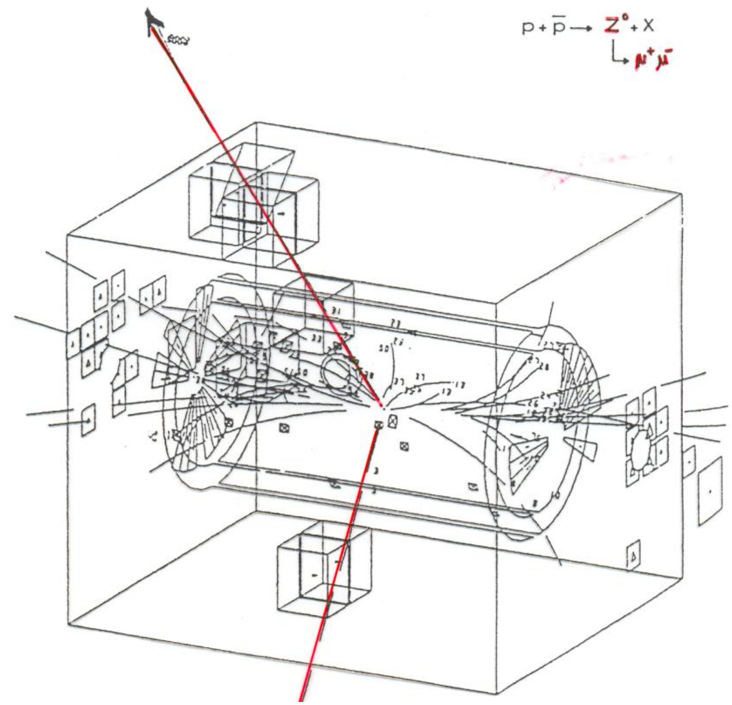
Reminder: charged current



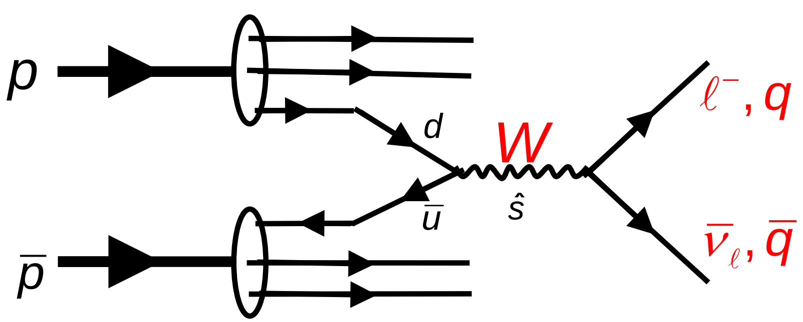
Discovery of Z and W Boson (1983)

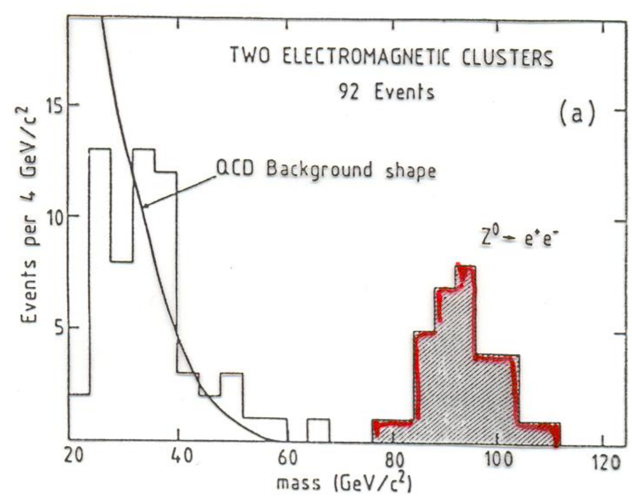
$$p\bar{p} \to Z \to f\bar{f} + X \quad (\sqrt{s} = 540\,\text{GeV})$$





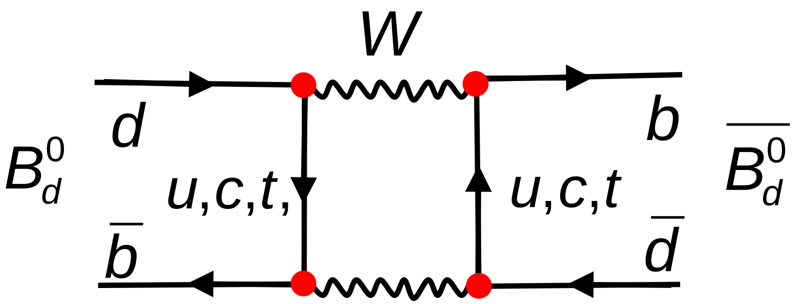
$$p\bar{p} \to W \to \ell\,\bar{\nu}_\ell + X$$

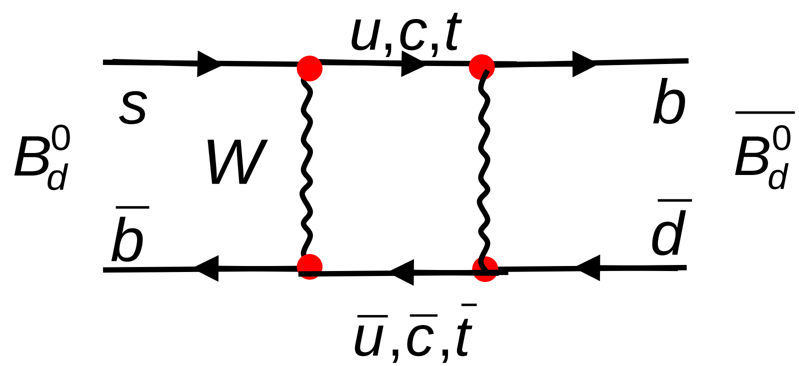


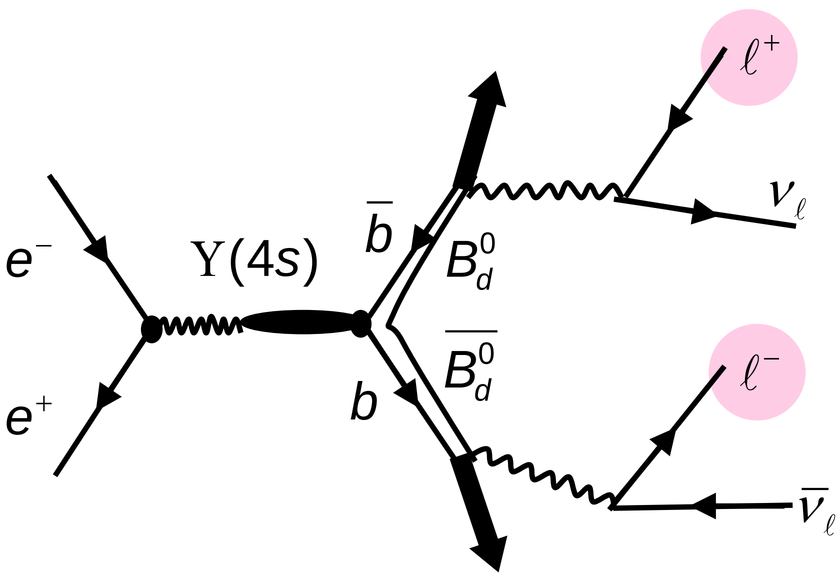


Electroweak radiative corrections

Neutral B meson mixing:







Unmixed: $B^0\overline{B}^0 \to \ell^+\ell^-$

Mixed: $B^0B^0 \to \ell^+\ell^+$, $\overline{B}^0\overline{B}^0 \to \ell^-\ell^-$ } Same charge

Observed in 1987 by the ARGUS collaboration.

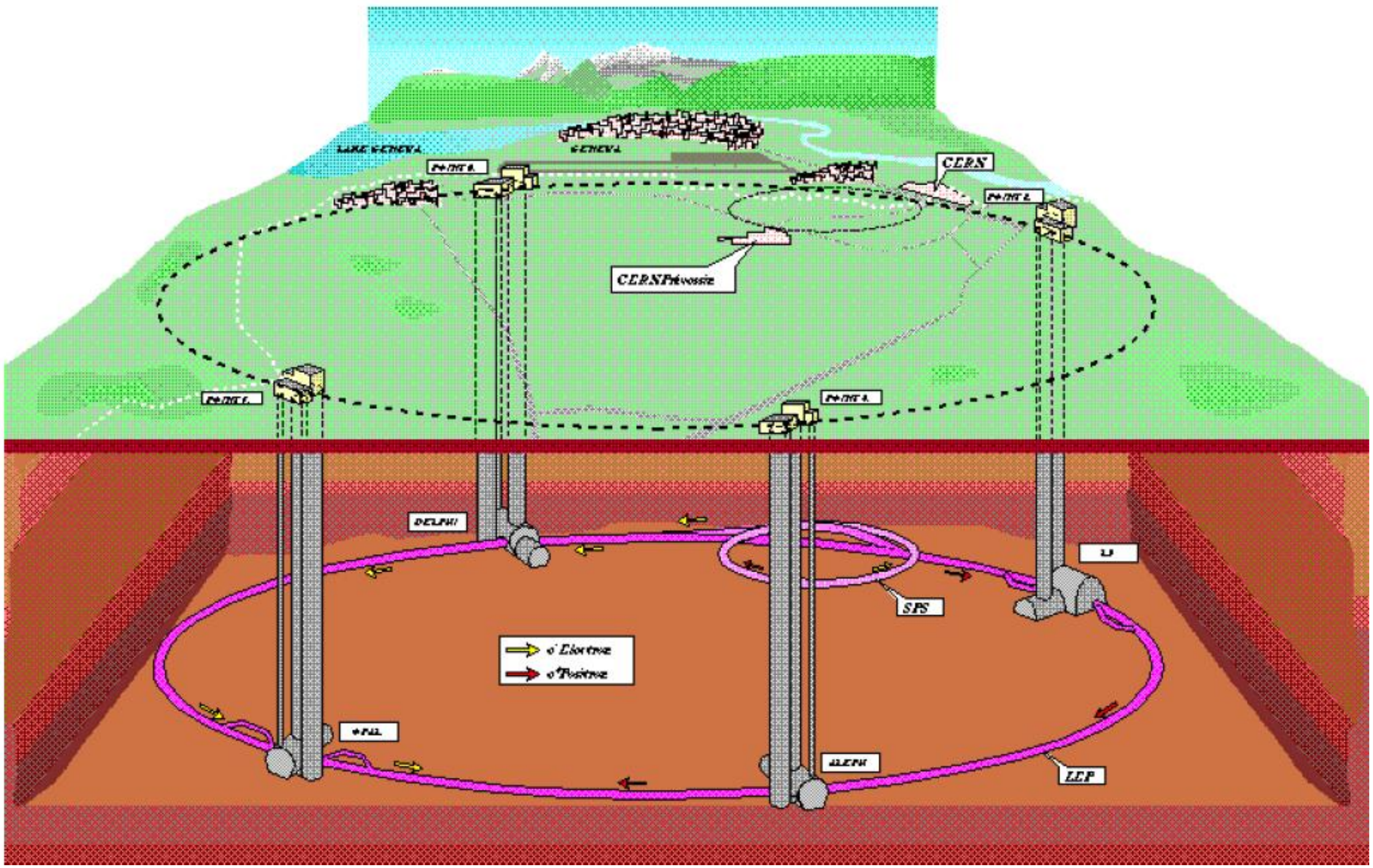
From the observation ARGUS concluded that m_t > 50 GeV.

Large Electron Positron Collider

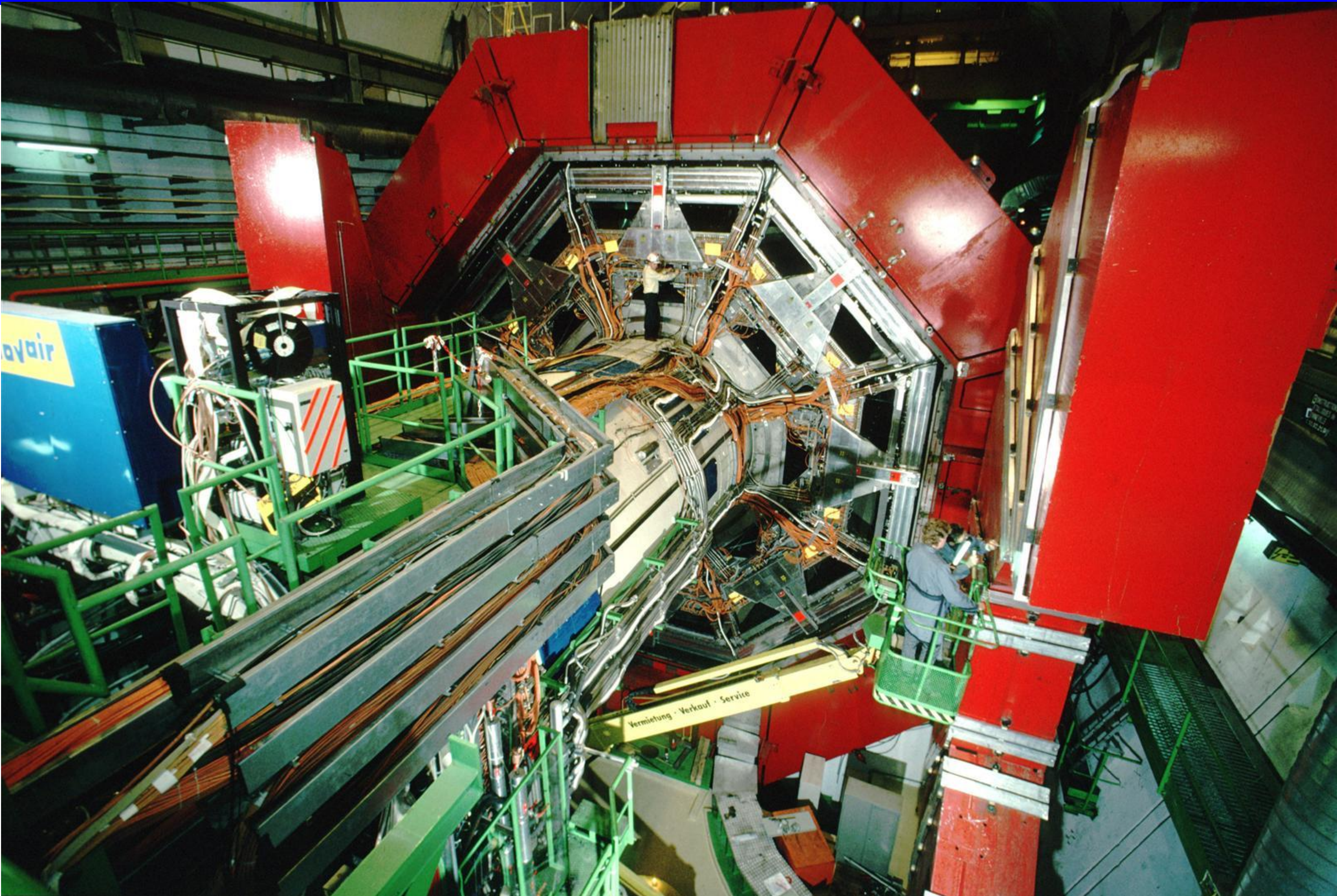
Test of electroweak theory using Z and W bosons.

Electron Positron Annihilation: LEP-I: √s ≈ 90 GeV (1989-1995)

LEP-II: √s = 160…207 GeV (1996-2000)



L3 Experiment @ LEP



LEP I: Z-Boson Factory

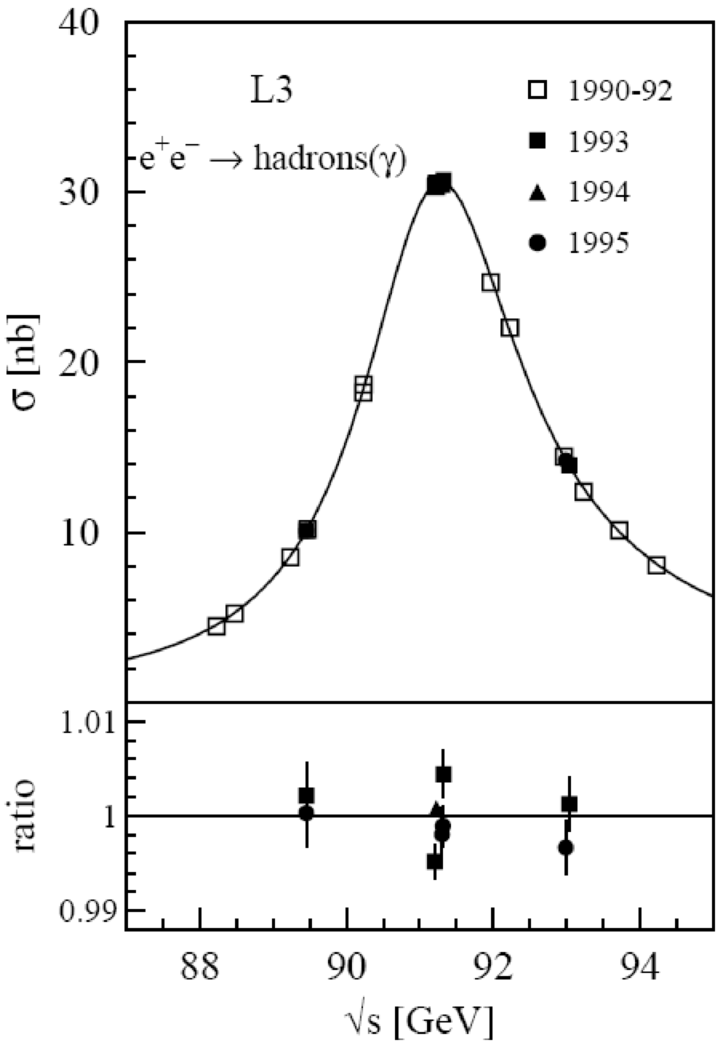
4 experiments: ALEPH, DELPHI, L3, OPAL

Number of Events										
	$Z \to q\bar{q}$					$Z \to \ell^+\ell^-$				
Year	A	D	L	O	LEP	A	D	L	O	LEP
1990/91	433	357	416	454	1660	53	36	39	58	186
1992	633	697	678	733	2741	77	70	59	88	294
1993	630	682	646	649	2607	78	75	64	79	296
1994	1640	1310	1359	1601	5910	202	137	127	191	657
1995	735	659	526	659	2579	90	66	54	81	291
Total	4071	3705	3625	4096	15497	500	384	343	497	1724

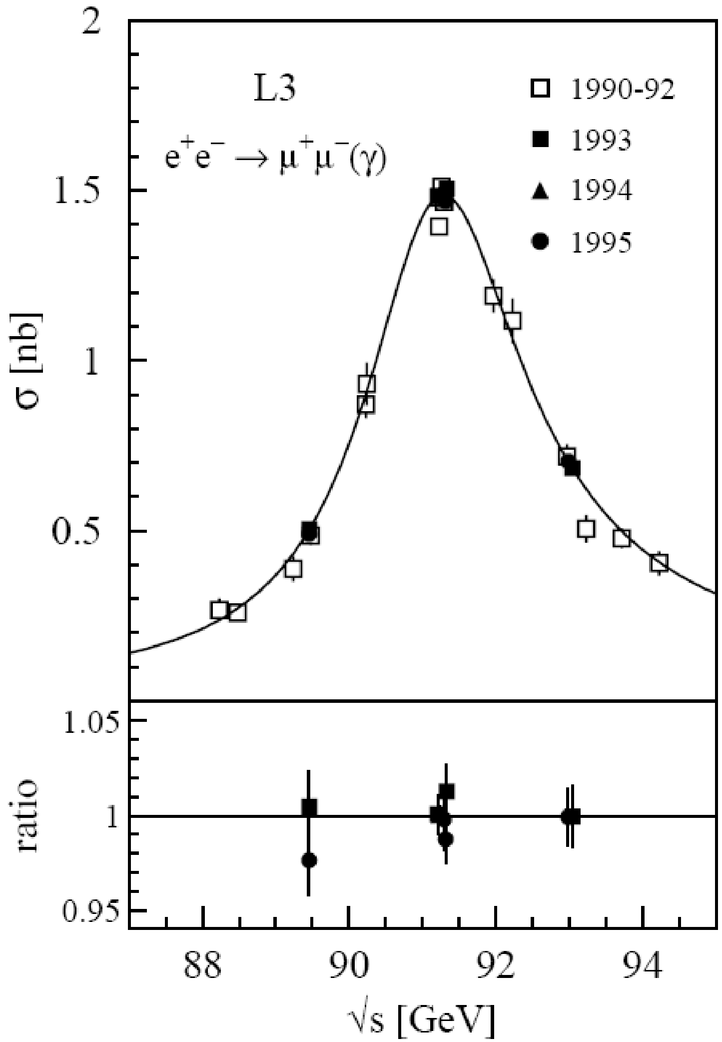
Table 1.2: The $q\bar{q}$ and $\ell^+\ell^-$ event statistics, in units of 10^3, used for Z analyses by the experiments ALEPH (A), DELPHI (D), L3 (L) and OPAL (O).

Resonance Shape

$e^+e^- \rightarrow hadrons$



$e^+e^- \rightarrow \mu^+\mu^-$



Resonance looks the same, independent of final state: Propagator the same

Z Boson Properties

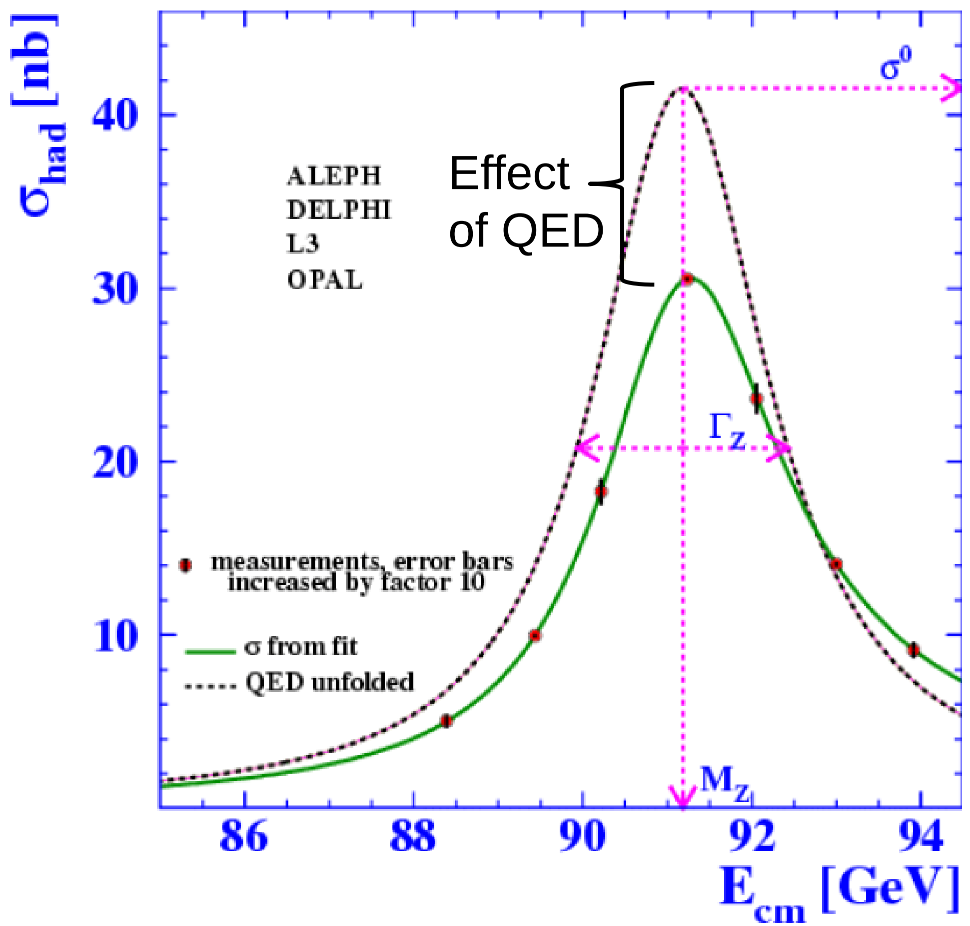
At the Z pole: $\sigma \approx \sigma_Z$

$$\sigma(s) = 12\pi \frac{\Gamma_e \Gamma_\mu}{M_Z^2} \cdot \frac{s}{(s - M_Z^2)^2 + M_Z^2 \Gamma_Z^2}$$

Peak: $\sigma_0 = \frac{12\pi}{M_Z^2} \frac{\Gamma_e \Gamma_\mu}{\Gamma_Z^2}$

- Resonance position → M_Z
- Height → $\Gamma_e \Gamma_\mu$
- Width → Γ_Z

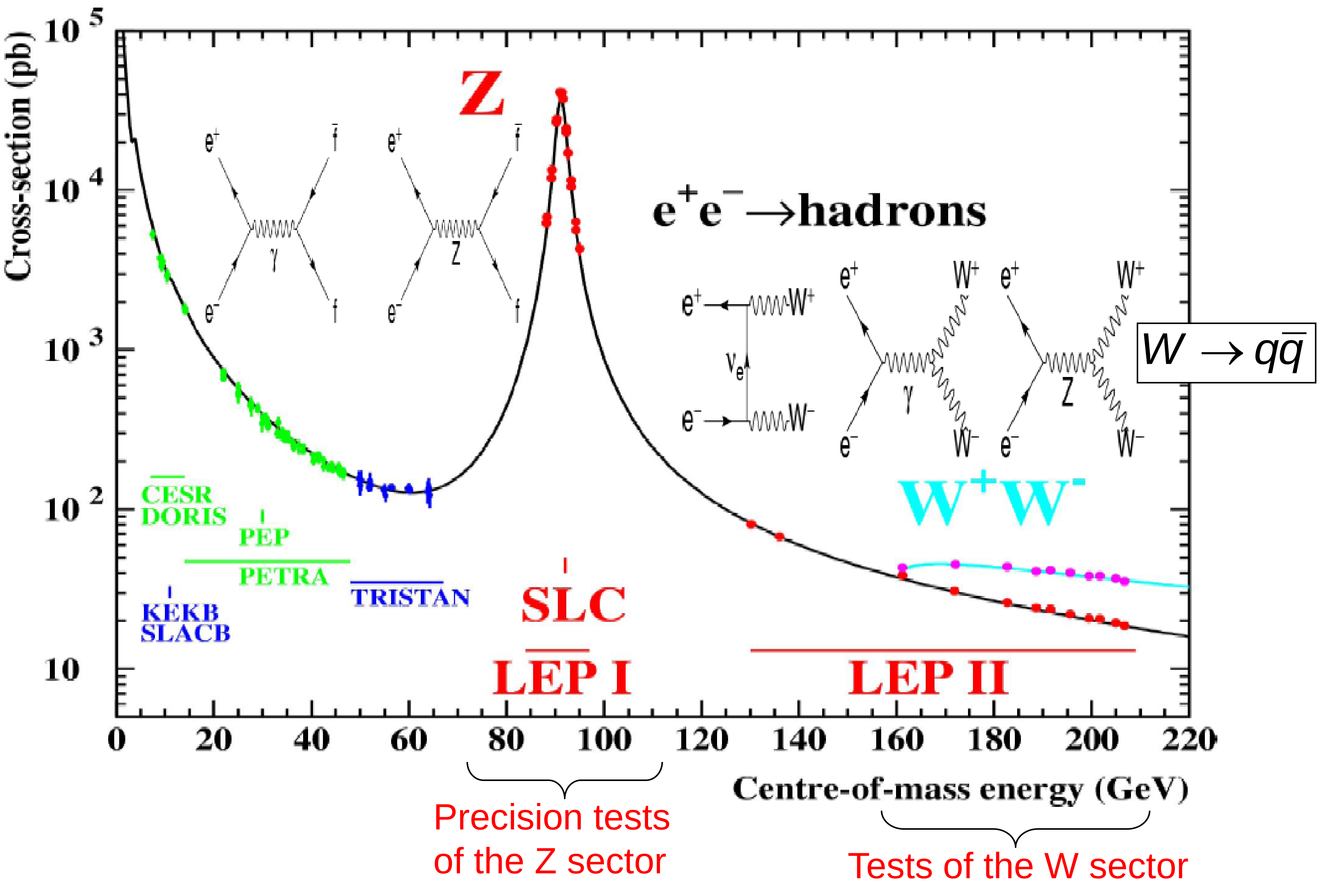
$e^+e^- \rightarrow$ Hadrons



M_Z = 91.1876 ± 0.0021 GeV ±23 ppm (*)

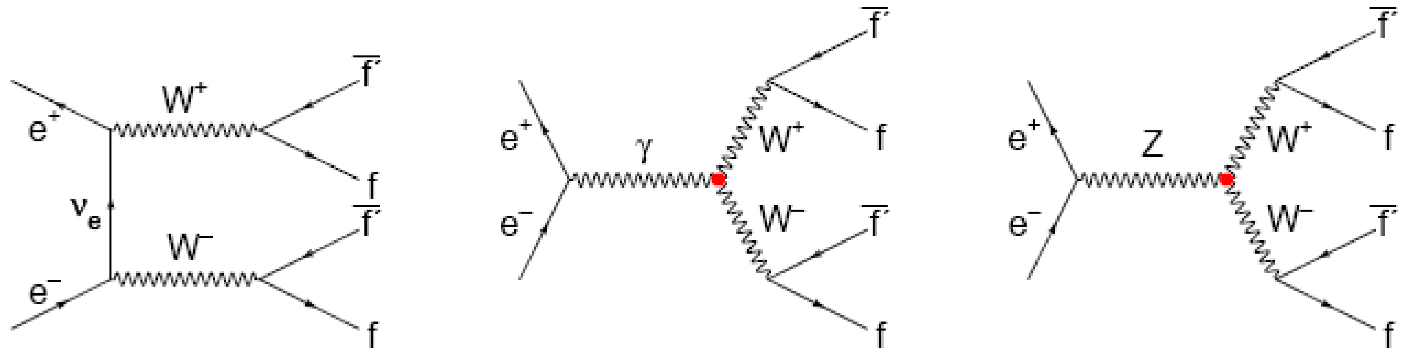
*) error of the LEP energy determination: ±1.7 MeV (19 ppm)

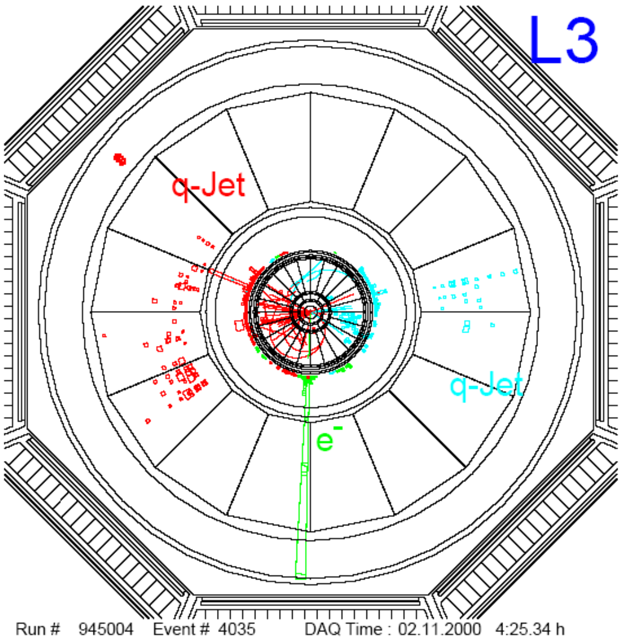
SM Test in e+e- Annihilation

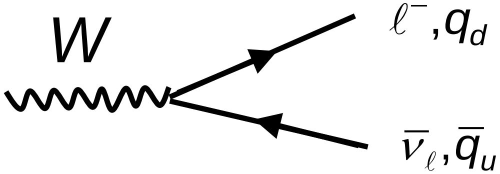


LEP 200: W Pair Production

$$e^+e^- \to WW \to f\bar{f}f\bar{f}$$

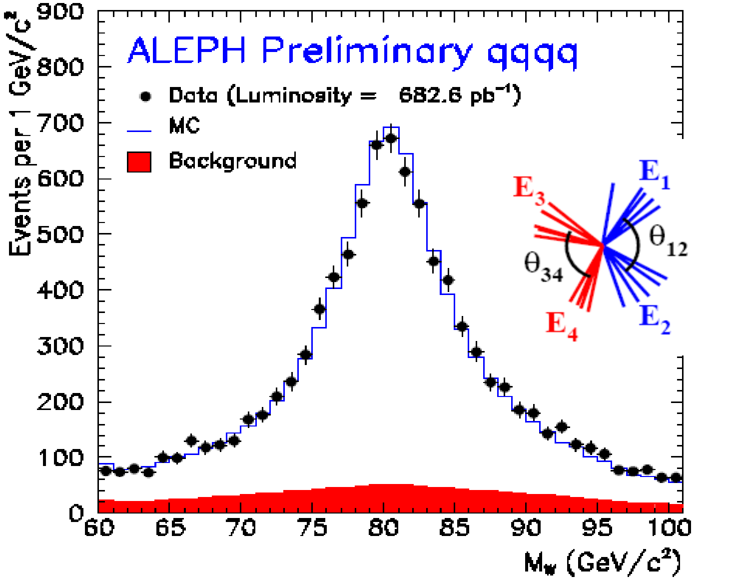


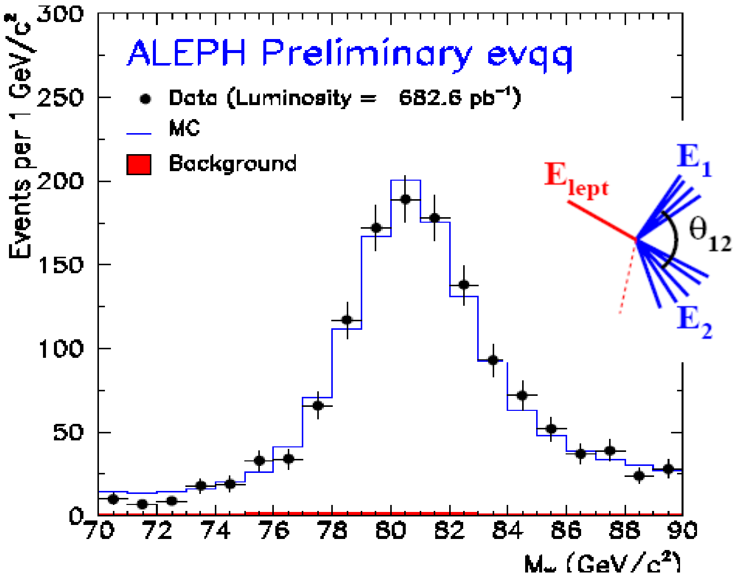


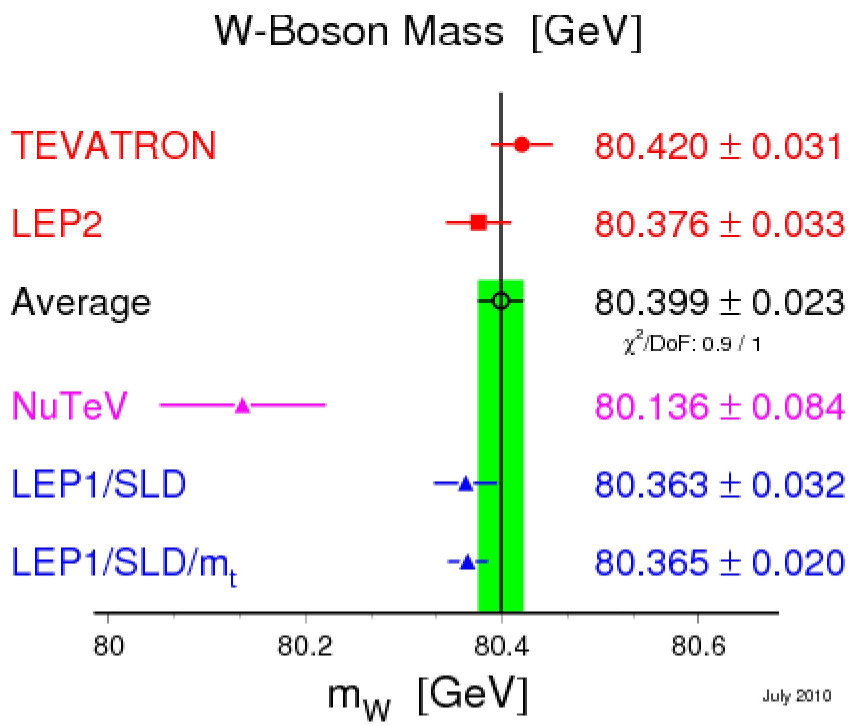


$$WW \to \begin{cases} qq\ell\nu & 44\% \\ qqqq & 45\% \\ \ell\nu\ell\nu & 11\% \end{cases}$$

W Mass Measurement at LEP







Sensitivity to Higher Order Corrections

Lowest order SM predictions

$$\rho = \frac{m_W^2}{m_Z^2 \cos^2\theta_W} = 1 \quad\Longrightarrow\quad \bar{\rho} = 1 + \Delta\rho$$

$$\sin^2\theta_W = 1 - \frac{m_W^2}{m_Z^2} \quad\Longrightarrow\quad \sin^2\theta_{\mathrm{eff}} = (1 + \Delta\kappa)\sin^2\theta_W$$

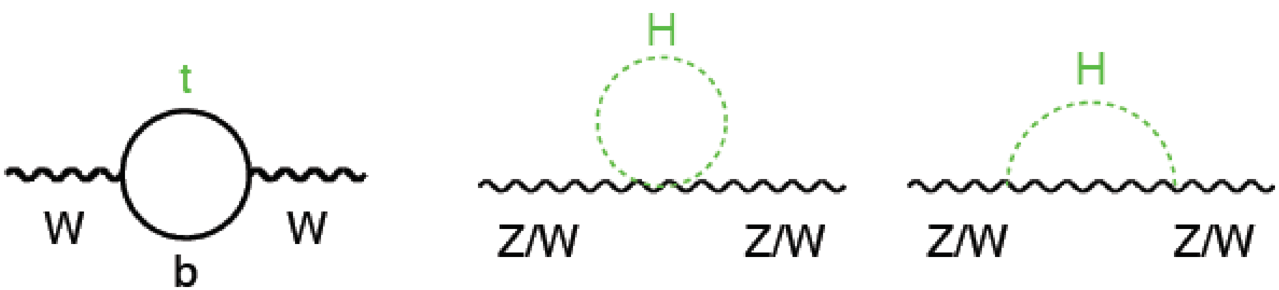
$$m_W^2 = \frac{\pi\alpha}{\sqrt{2}\sin^2\theta_W G_F} \quad\Longrightarrow\quad m_W^2 = \frac{\pi\alpha}{\sqrt{2}\sin^2\theta_W G_F}(1 + \Delta r)$$

$$\alpha(0) \quad\Longrightarrow\quad \alpha(m_Z^2) = \frac{\alpha(0)}{1 - \Delta\alpha}$$

Including radiative corrections

with : $\Delta\alpha = \Delta\alpha_{\mathrm{lept}} + \Delta\alpha_{\mathrm{top}} + \Delta\alpha_{\mathrm{had}}^{(5)}$

$$\Delta\rho, \Delta\kappa, \Delta r = f\left(m_t^2, \log(m_H), \ldots\right)$$



Top Mass from Radiative Corrections

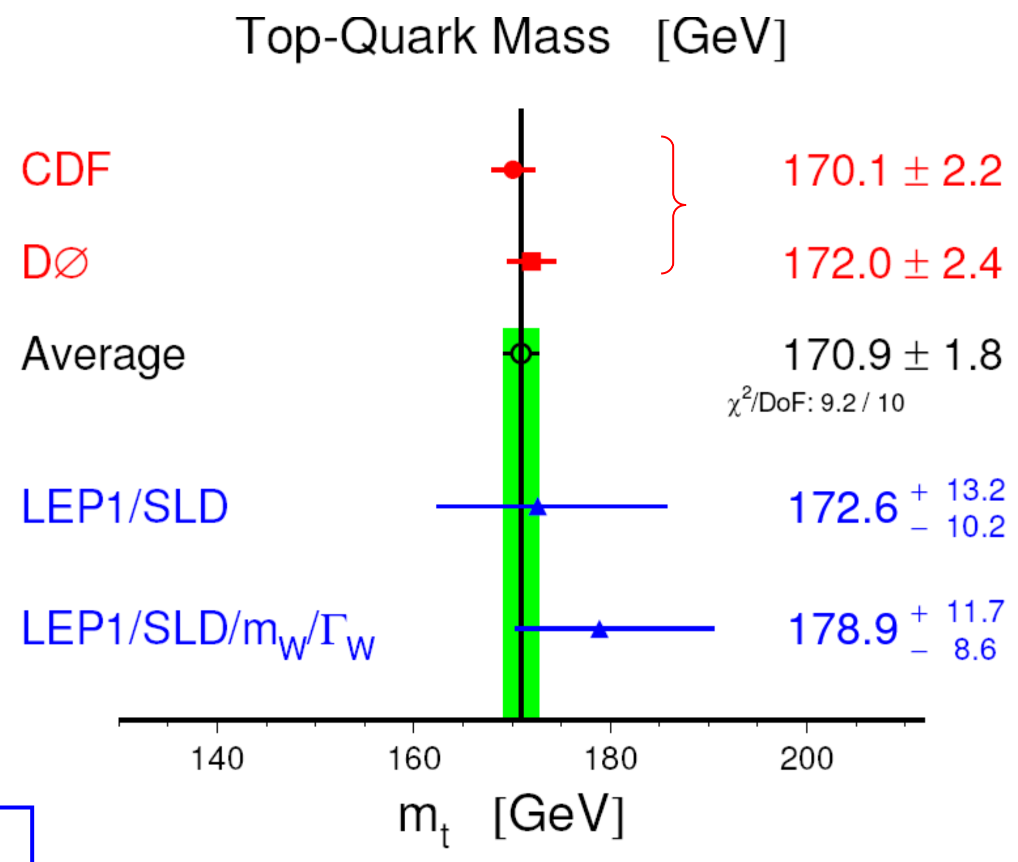
$$\Delta r(m_t, M_H) = -\frac{3\alpha\cos^2\theta_w}{16\pi\sin^4\theta_w}\frac{m_t^2}{M_W^2} - \frac{11\alpha}{48\pi\sin^2\theta_w}\ln\frac{M_H^2}{M_W^2} + \ldots$$

The measurement of the radiative corrections, e.g.

$$\sin^2\theta_{eff} \equiv \frac{1}{4}(1 - \bar{g}_V/\bar{g}_A)$$

$$\sin^2\theta_{eff} = (1 + \Delta\kappa)\sin^2\theta_w$$

Allows the indirect determination of the unknown parameters m_t and M_H.



Prediction of m_t by LEP before the discovery of the top at TEVATRON.

Higgs Mass from Radiative Corrections

… using all available electro-weak data

$$\Delta r(m_t, M_H) = -\frac{3\alpha\cos^2\theta_w}{16\pi\sin^4\theta_w}\frac{m_t^2}{M_W^2} - \frac{11\alpha}{48\pi\sin^2\theta_w}\ln\frac{M_H^2}{M_W^2} + \dots$$

Fits to electro-weak data:

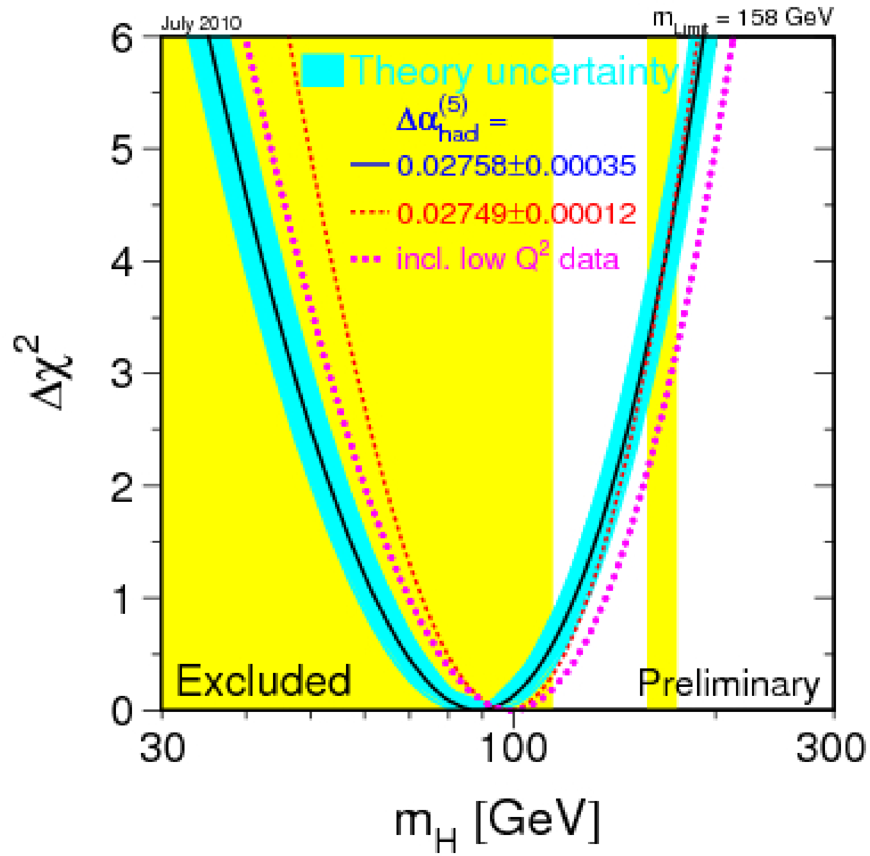
$m_H = 89^{+35}_{-26}$ GeV

$m_H < 158$ GeV (95% CL)

Assumption for fit:

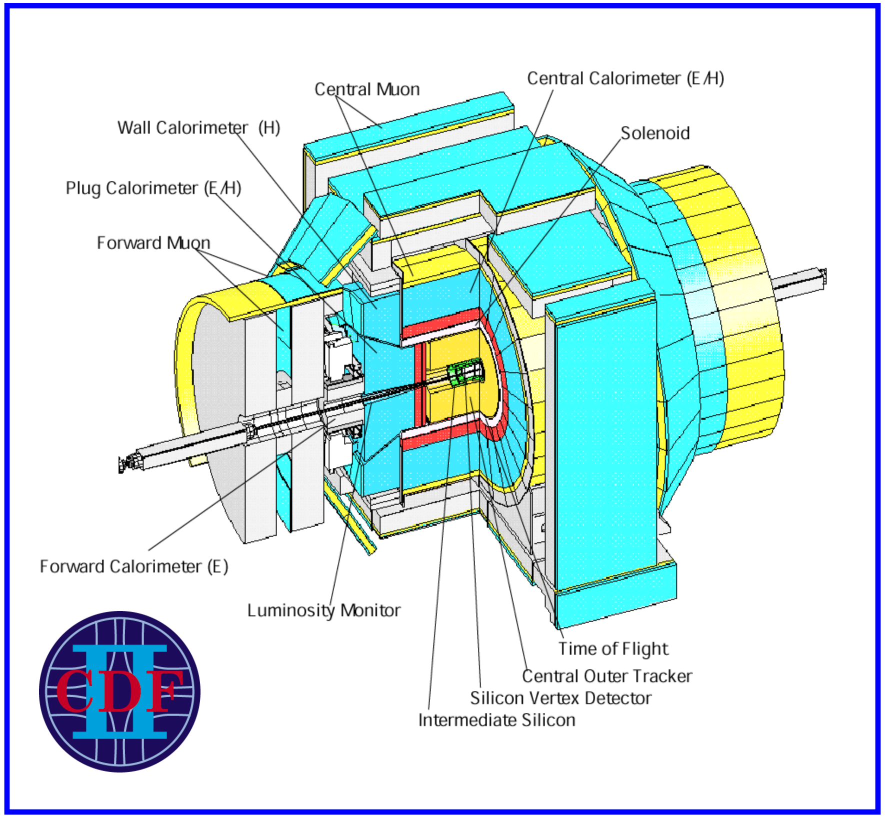
- SM including Higgs
- No confirmation of Higgs mechanism

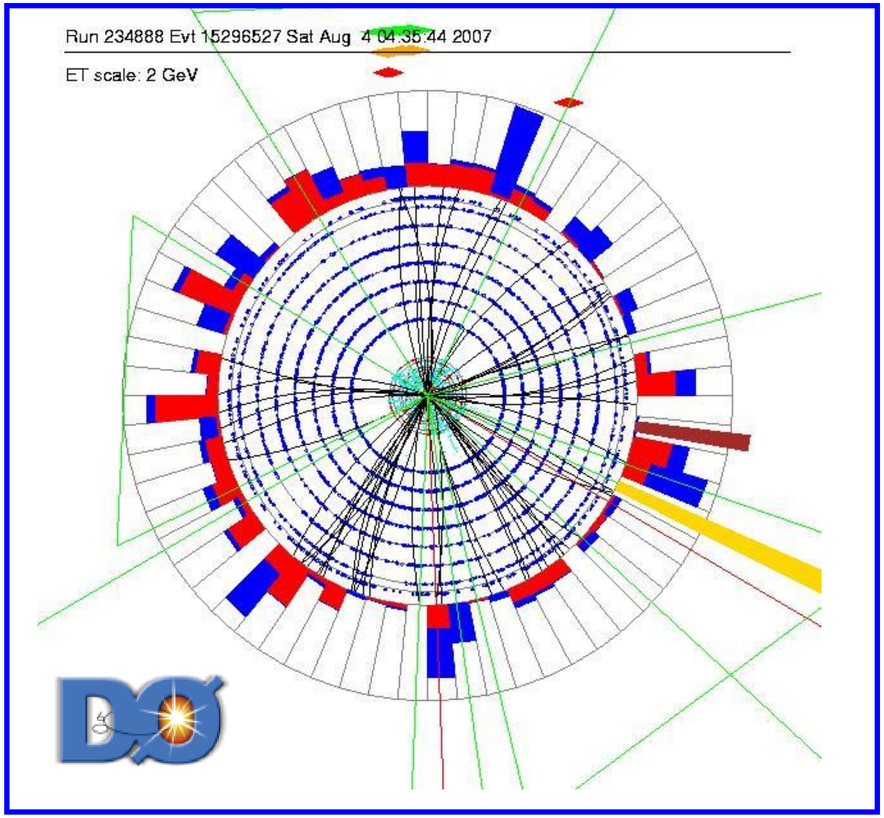
Higgs seems to be light!



TEVATRON

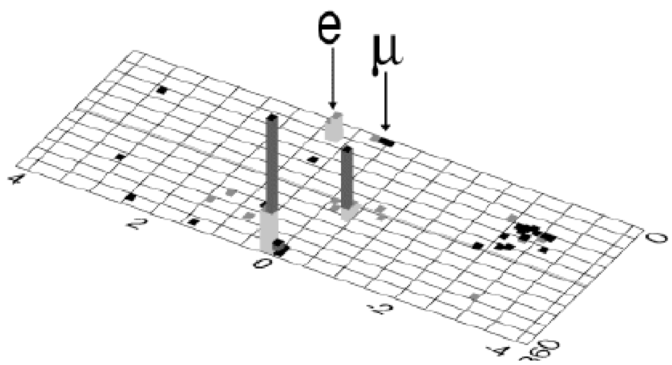
$p\bar{p}$ Collider with $\sqrt{s}$=1.96 TeV

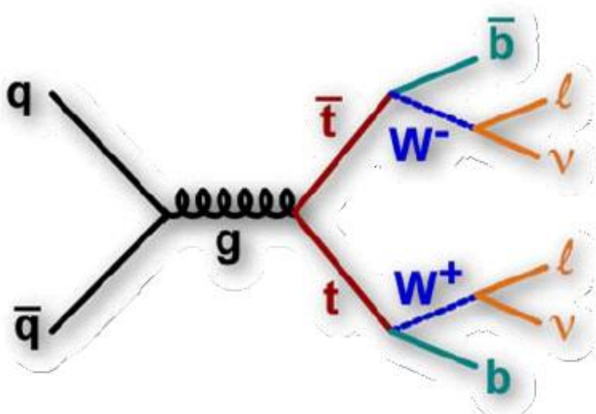


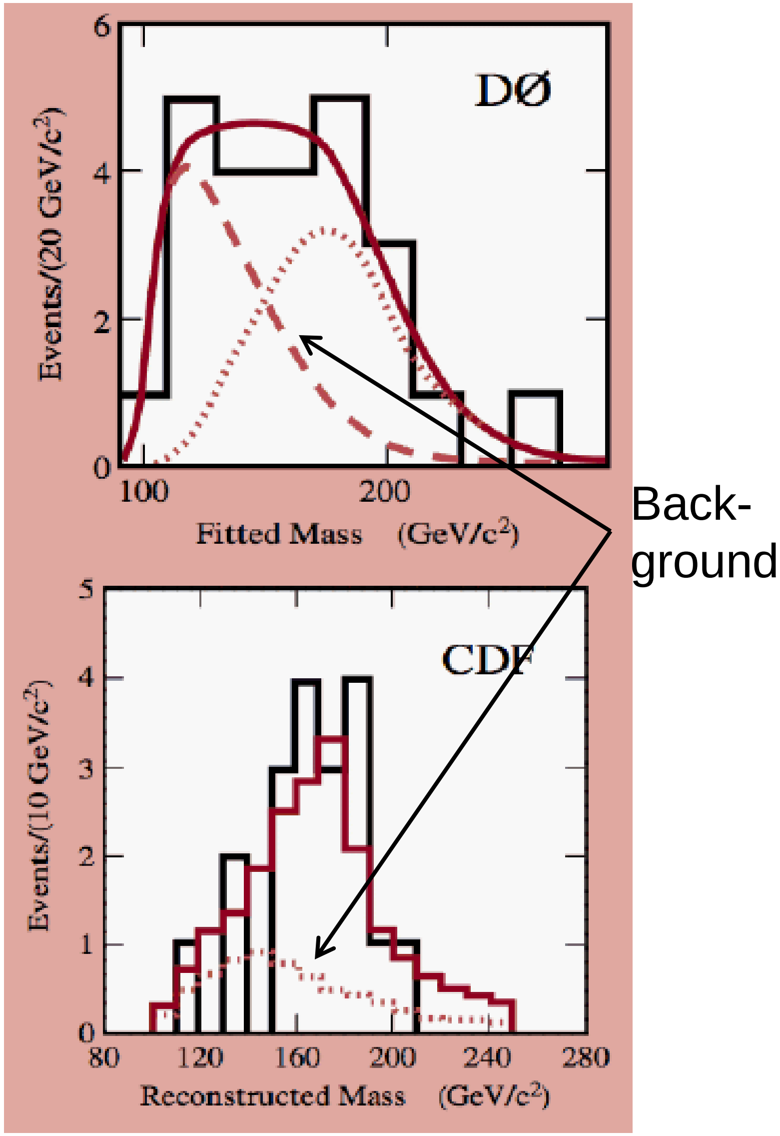


Top Quark Discovery at TEVATRON

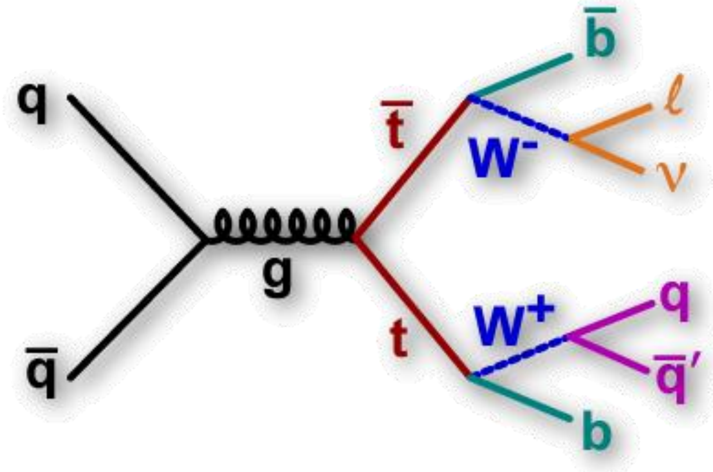
Tevatron Run 1
1994-5

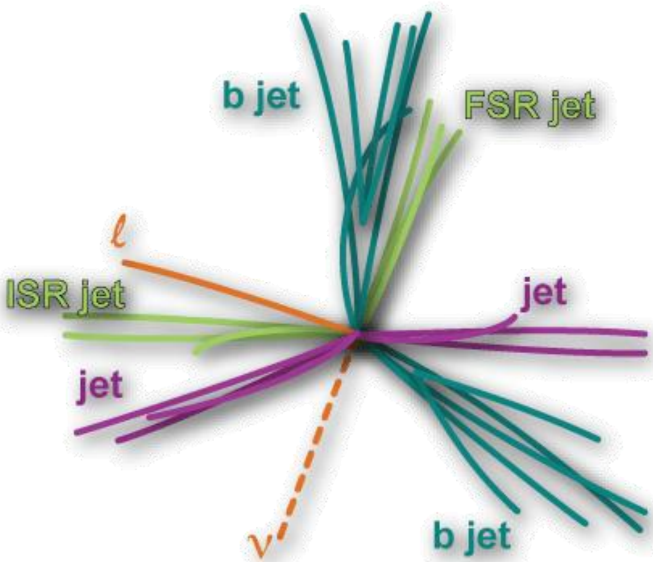


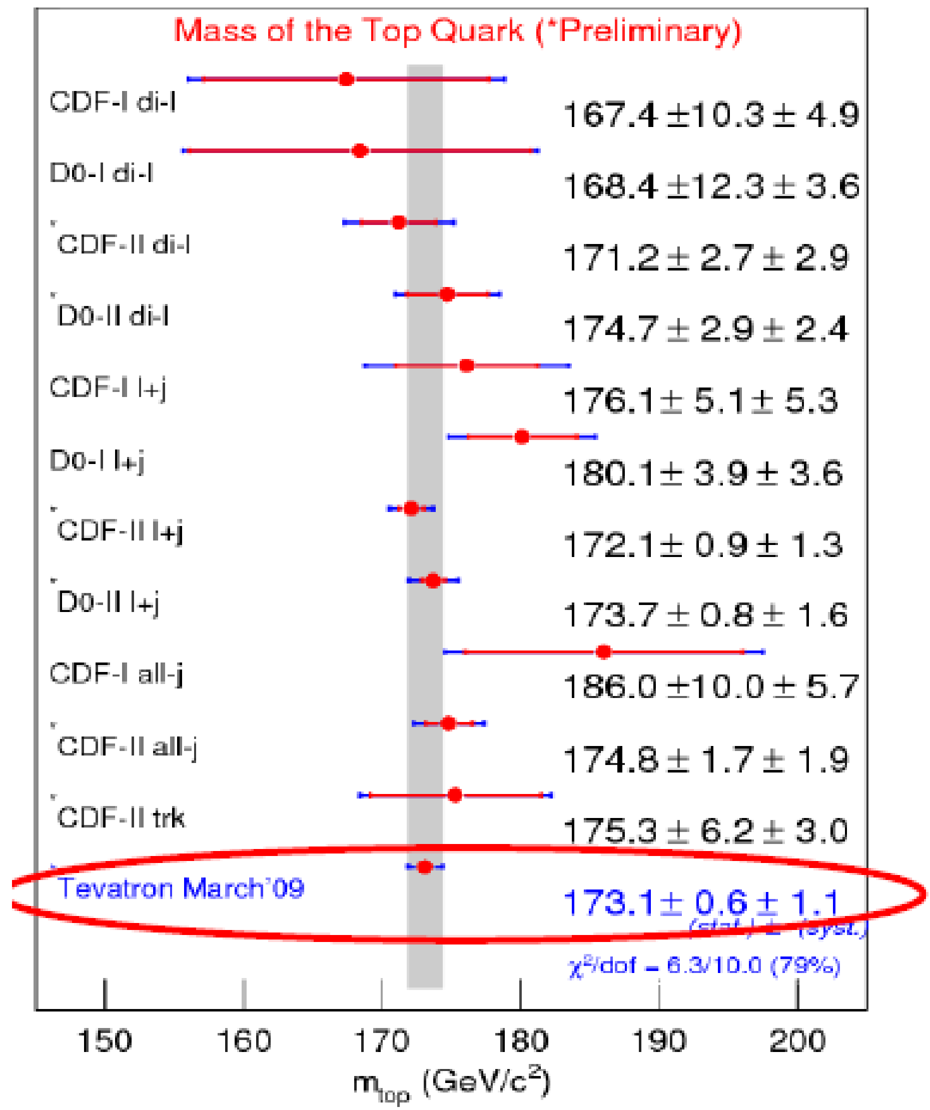




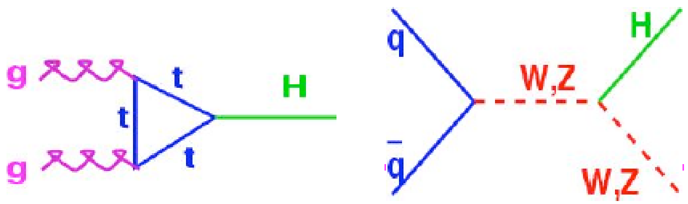
Precision Top Mass Measurement

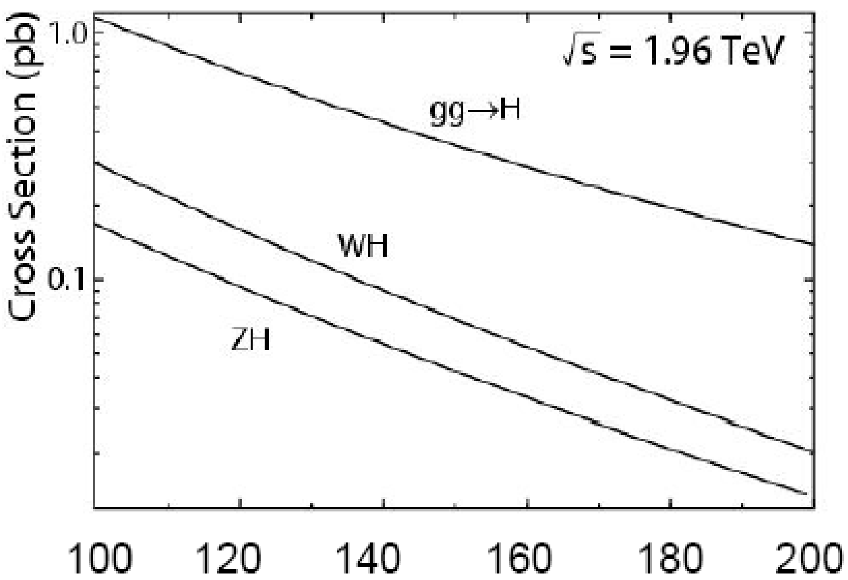


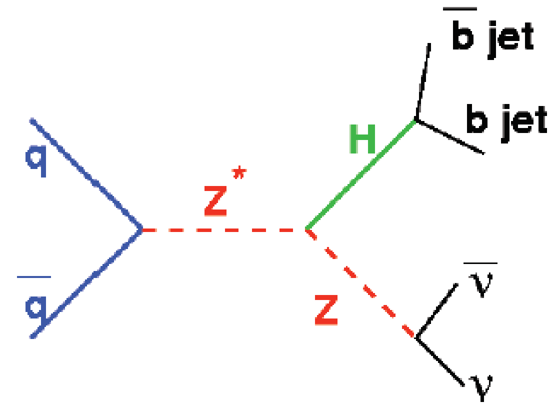


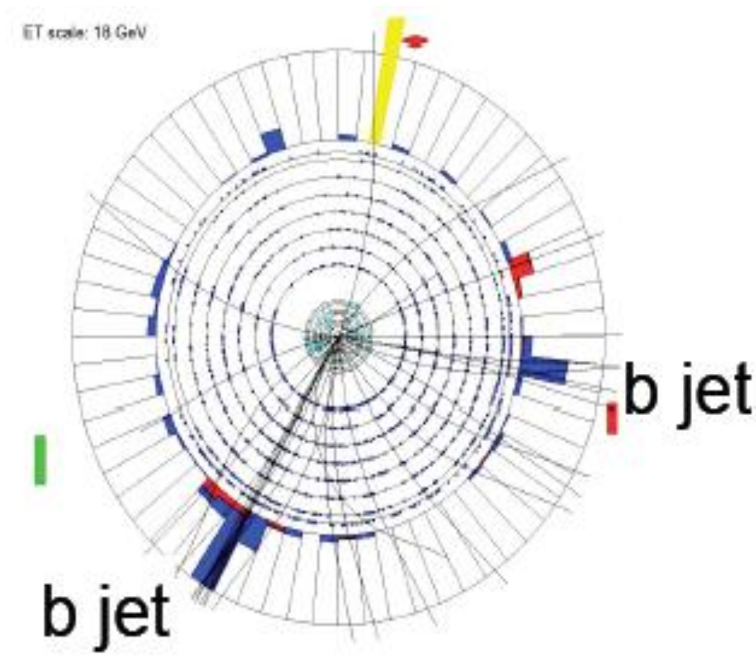


Higgs Search at TEVATRON





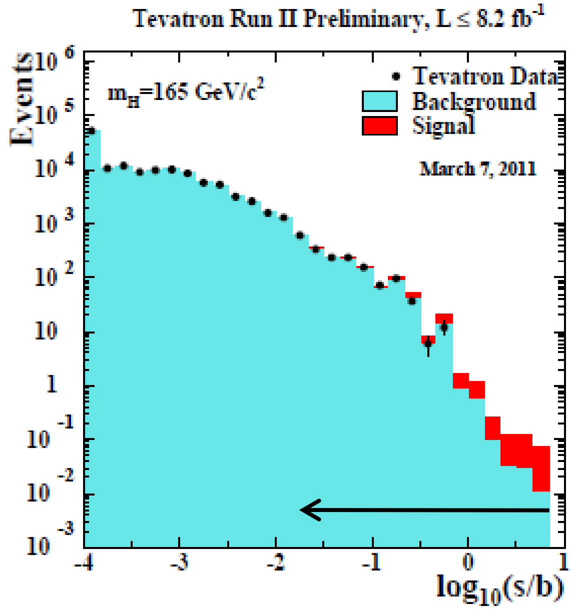


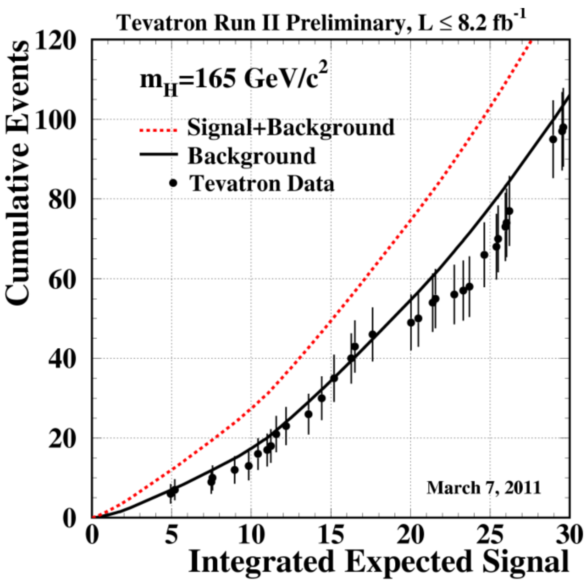


~1 Higgs event every 10^{12} events

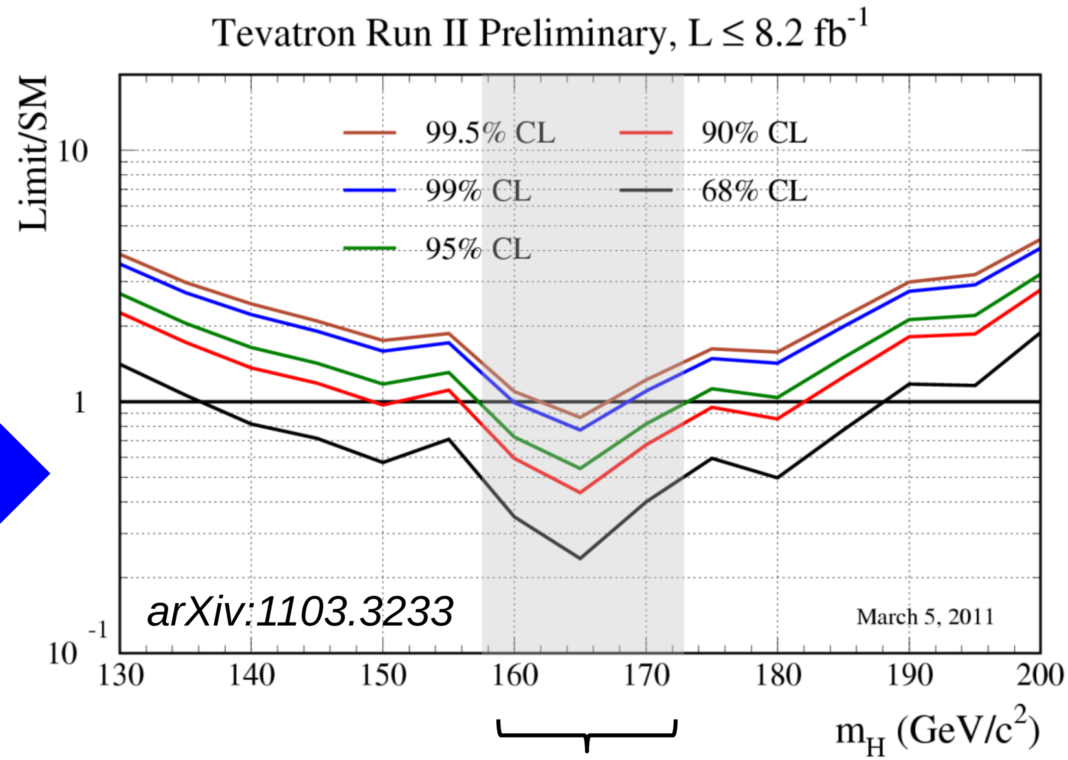
Many decay channels!

Higgs Search at TEVATRON





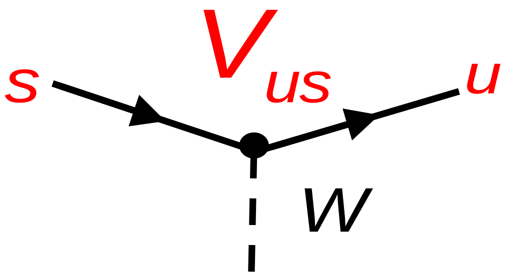
Moriond 2011



Higgs excluded for
$m_H \in$ [158, 173] Gev @ 95% C.L.

Quark Mixing and CP Violation

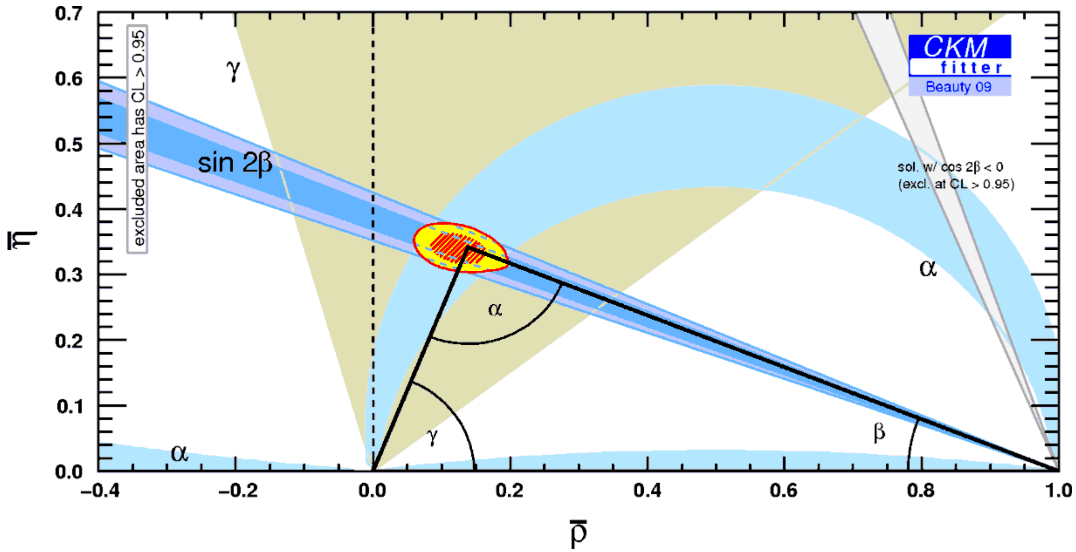
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \cdot \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$



Unitarity $\Rightarrow$ $V_{ud}V_{ub}^{*} + V_{cd}V_{cb}^{*} + V_{td}V_{tb}^{*} = 0$

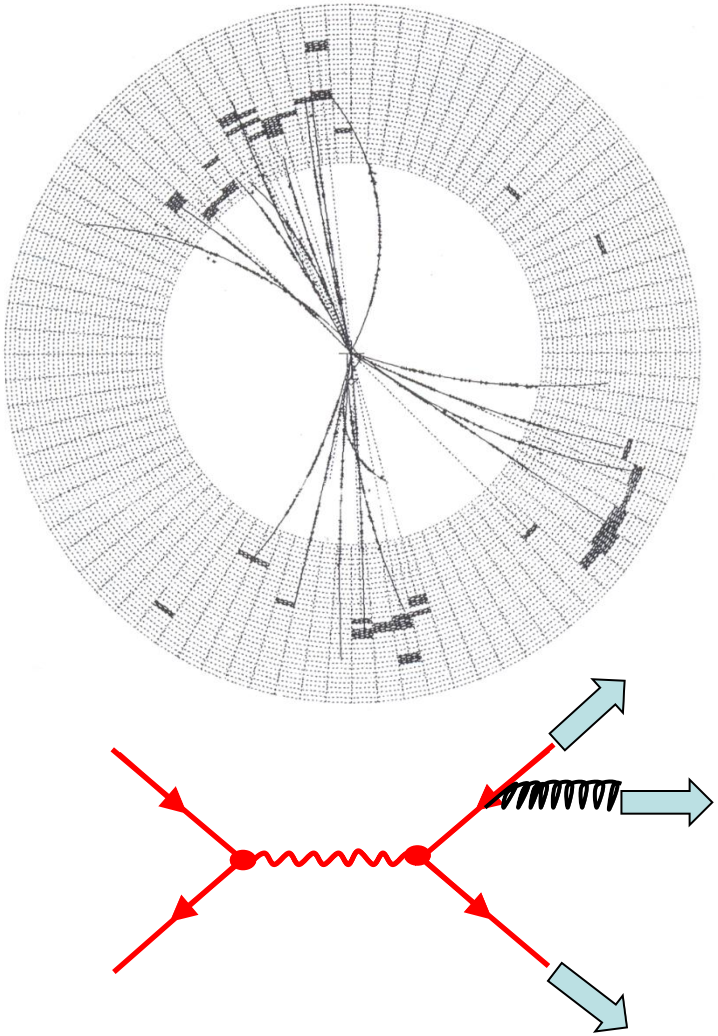
CKM mechanism explains CP violation and predicts large effect in B decays

Angles measured from CP violation in B decays:
CKM mechanism confirmed !

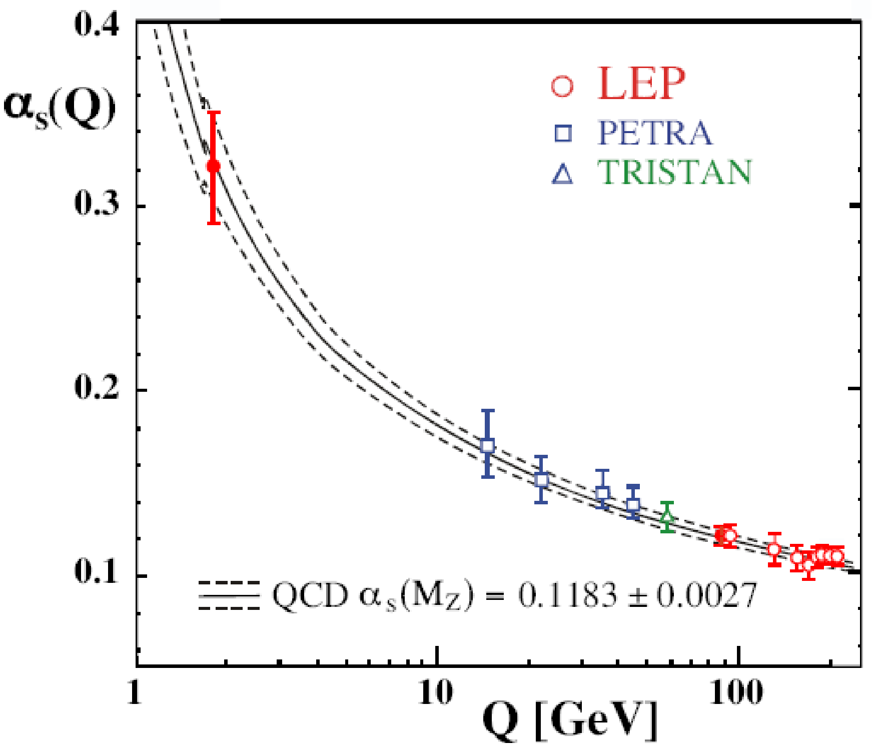


Strong Interaction

Discovery of the gluon (1979)



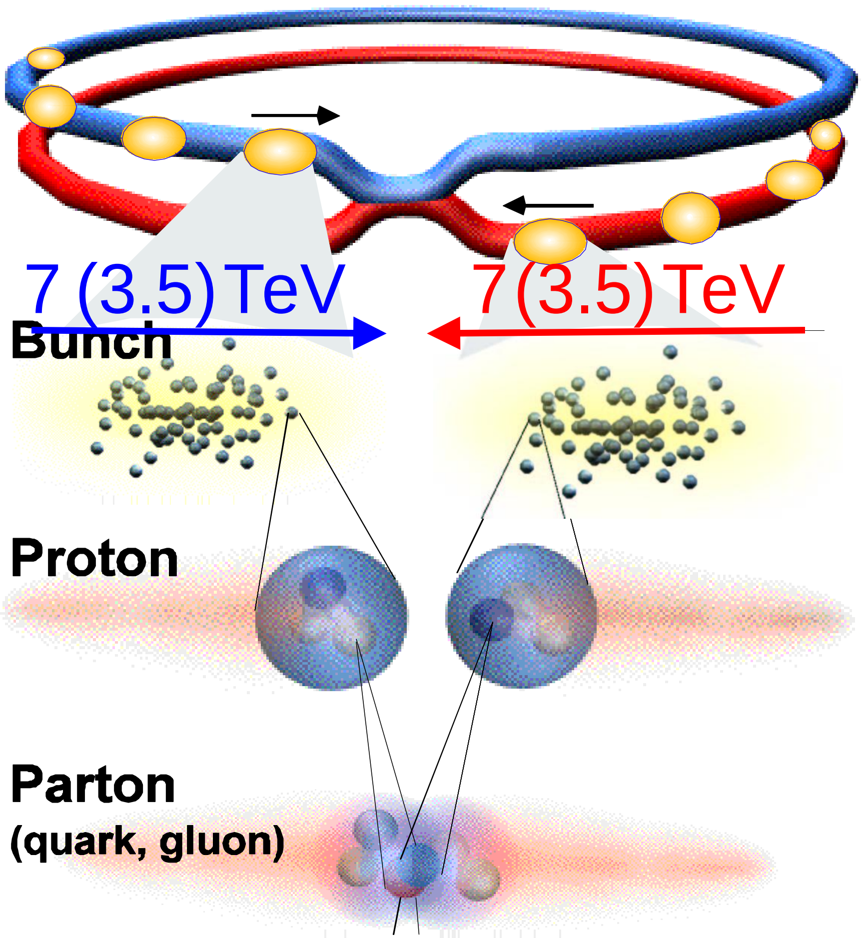
Running of α_s



… and asymptotic freedom

Large Hadron Collider

Large Hadron Collider



Design:

Proton – Proton Pakete:

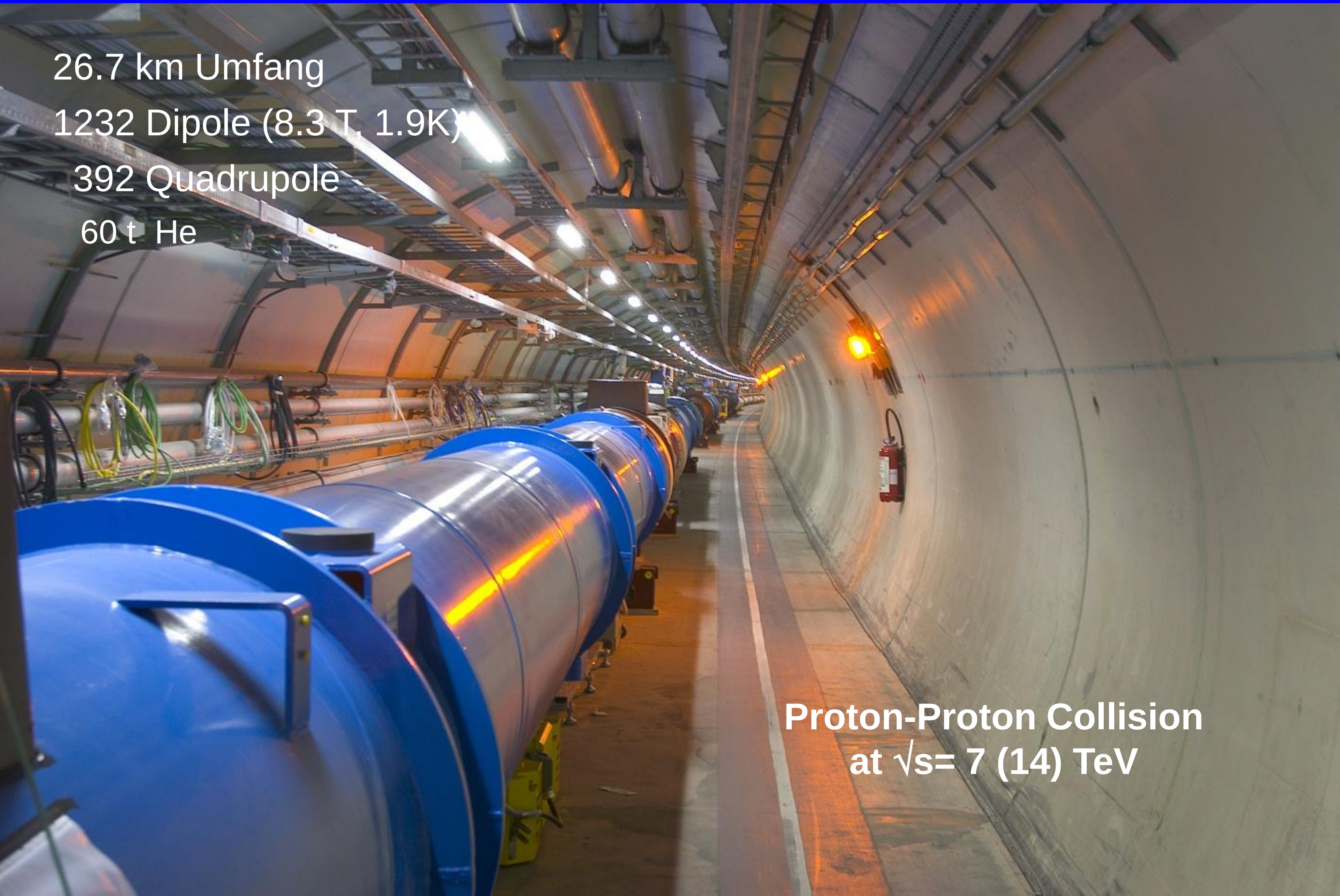
2835 x 2835 (1404 x 1404)

10^{11} Protonen / Paket

Crossing-Rate: 40 MHz

Kollisionen: 10^8 bis 10^9 Hz

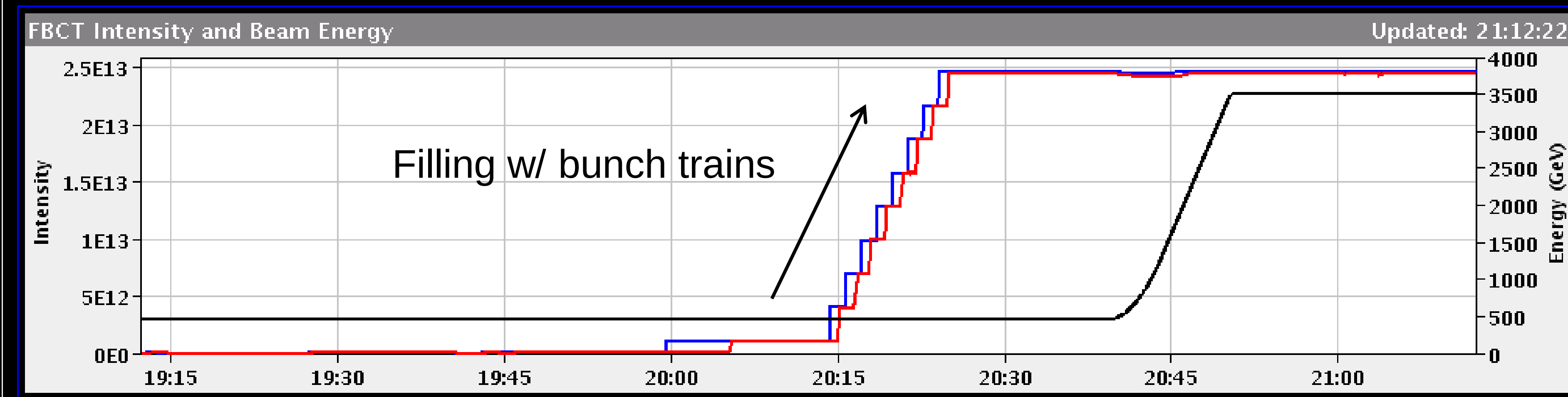
Large Hadron Collider



LHC Page1 Fill: 1645 E: 3500 GeV 22-03-2011 21:12:25

PROTON PHYSICS: ADJUST

Energy:	3500 GeV	I(B1):	2.48e+13	I(B2):	2.44e+13



Comments 22-03-2011 20:22:16 :

filling

next fill with 200 bunches

BIS status and SMP flags	B1	B2
Link Status of Beam Permits	true	true
Global Beam Permit	true	true
Setup Beam	false	false
Beam Presence	true	true
Moveable Devices Allowed In	false	false
Stable Beams	false	false

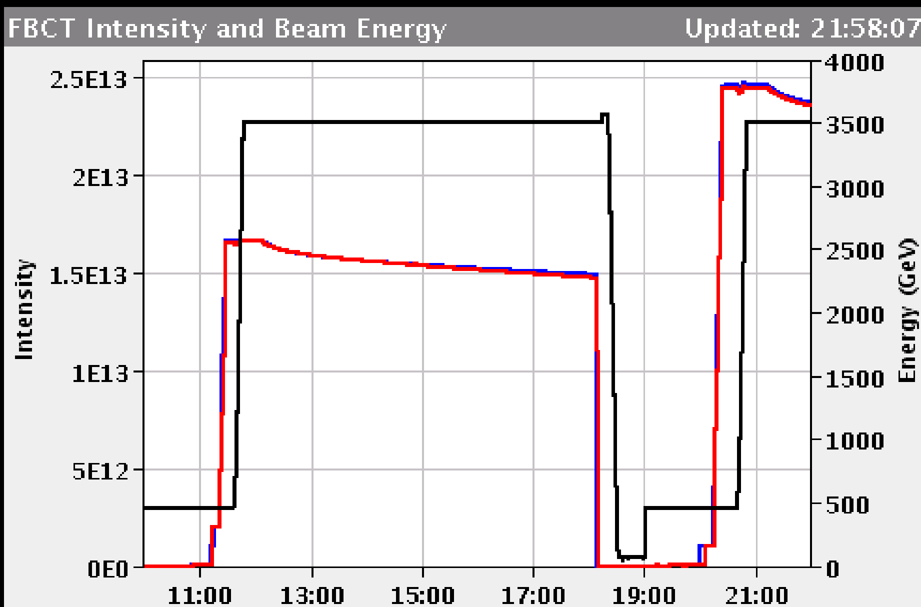
AFS: 75ns_200b_194_178_188_24bpi9inj

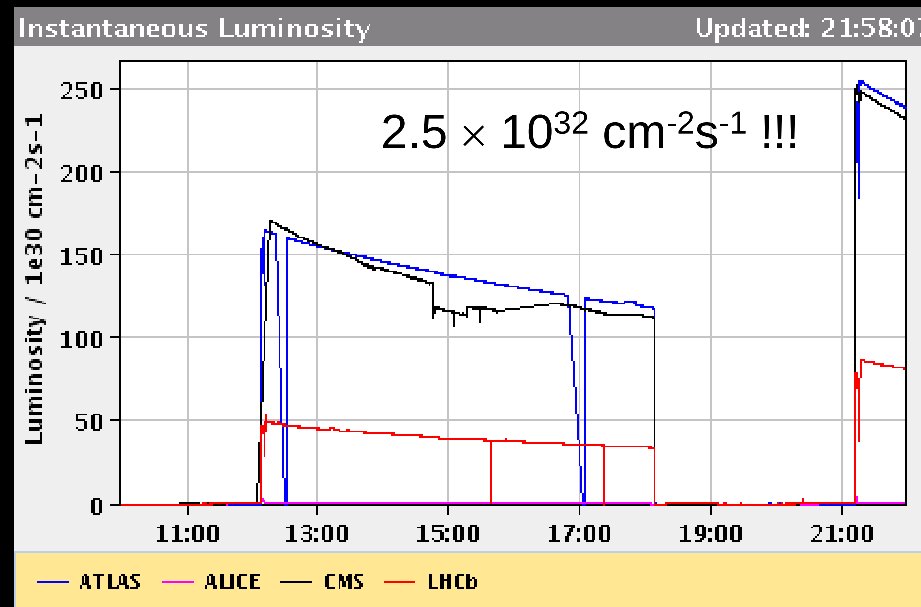
PM Status B1 ENABLED PM Status B2 ENABLED

LHC Page1 | Fill: 1645 | E: 3500 GeV | 22-03-2011 21:58:06

PROTON PHYSICS: STABLE BEAMS

Energy:	3500 GeV	I(B1):	2.38e+13	I(B2):	2.35e+13





Comments 22-03-2011 21:21:07 :

STABLE BEAMS

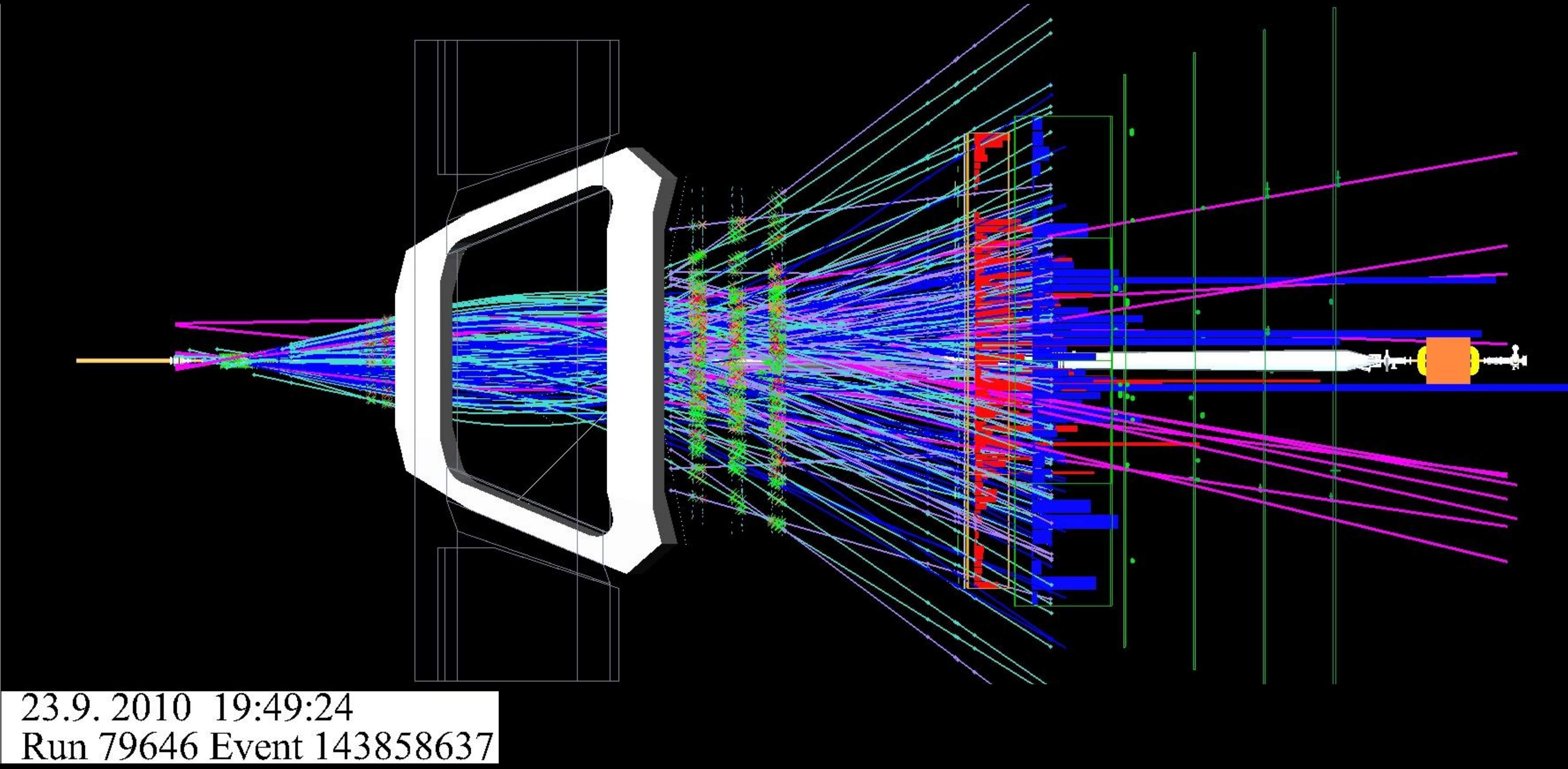
2010 record passed !!!!

BIS status and SMP flags	B1	B2
Link Status of Beam Permits	true	true
Global Beam Permit	true	true
Setup Beam	false	false
Beam Presence	true	true
Moveable Devices Allowed In	true	true
Stable Beams	true	true

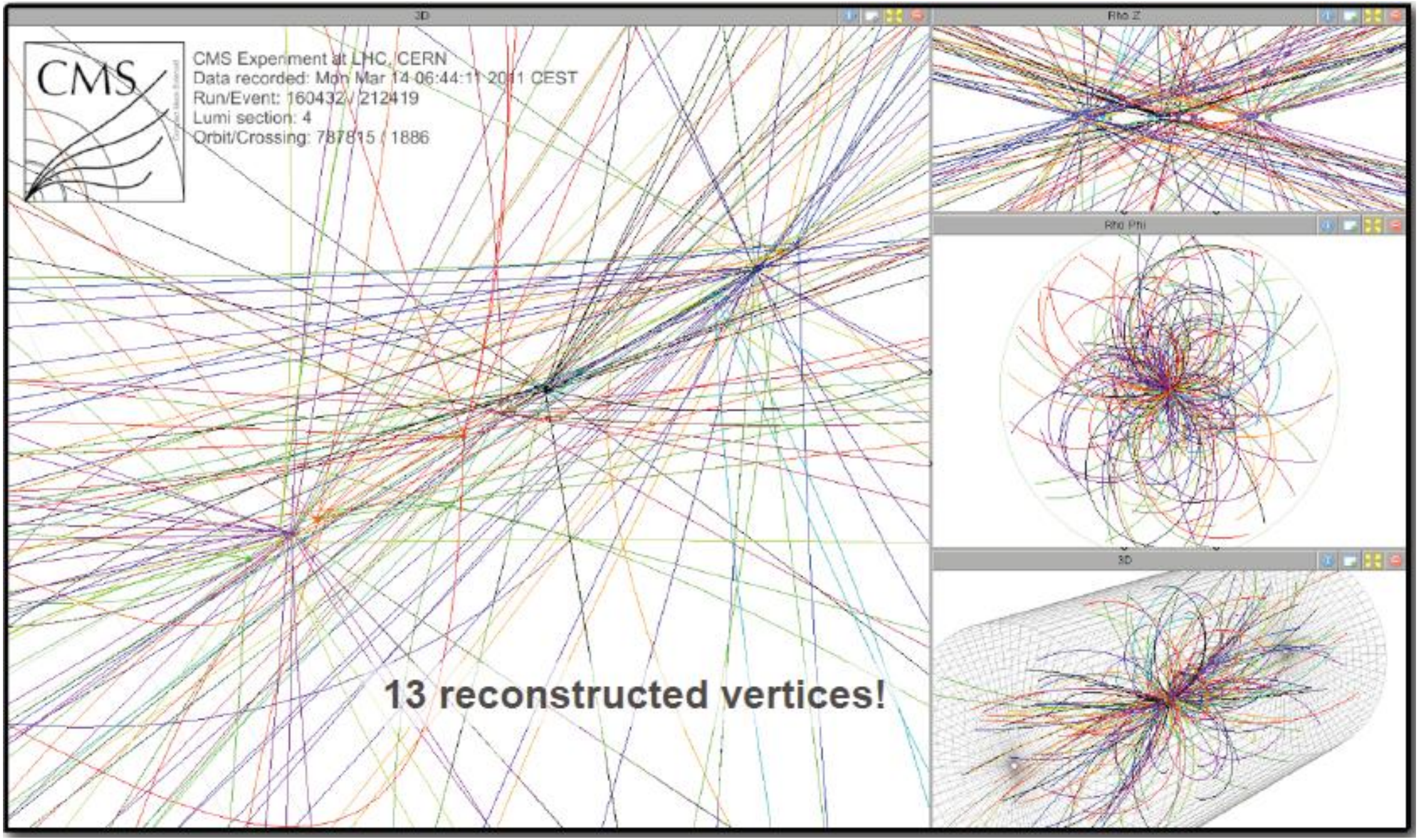
AFS: 75ns_200b_194_178_188_24bpi9inj

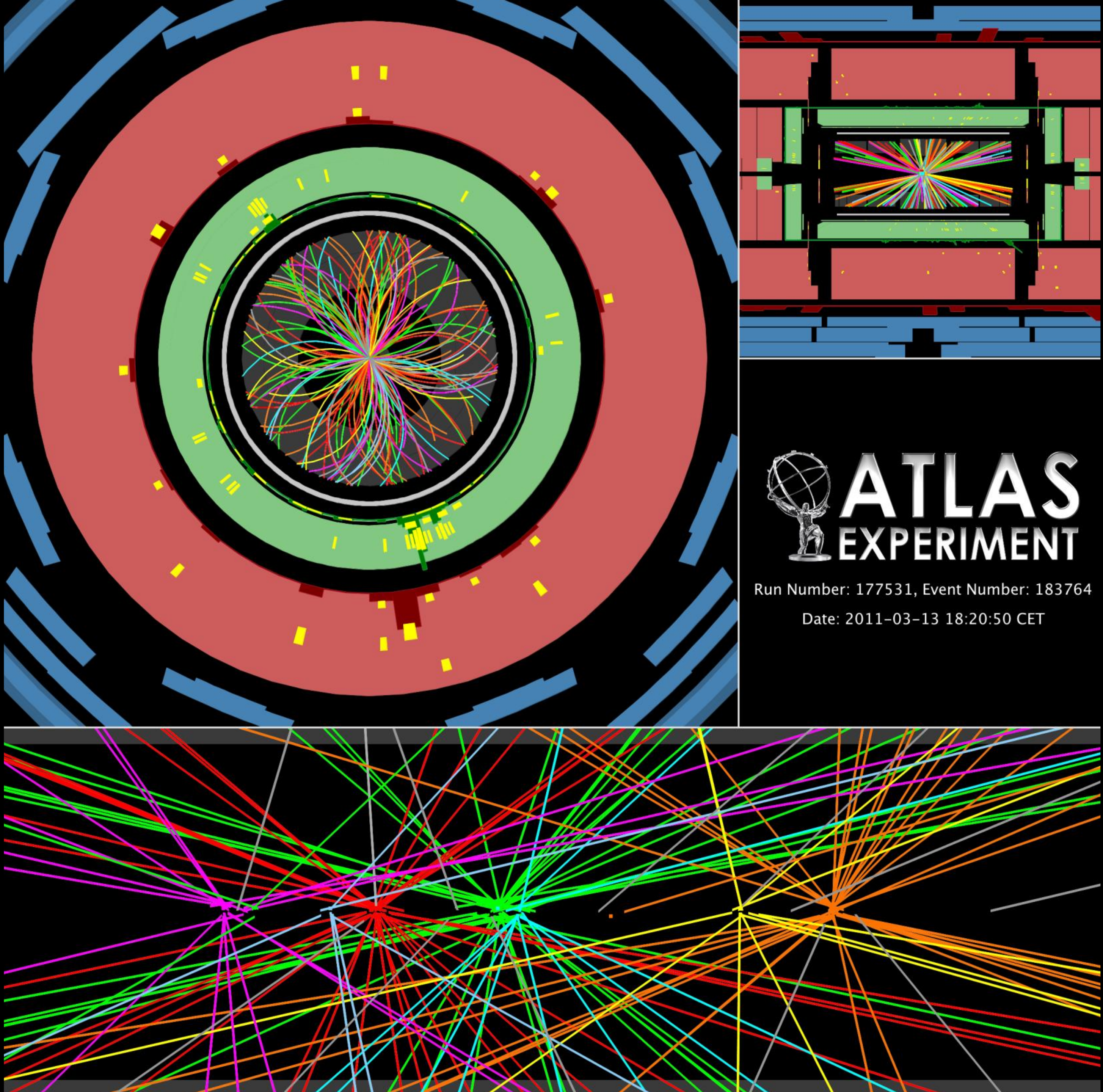
PM Status B1 ENABLED | PM Status B2 ENABLED

pp event in LHCb

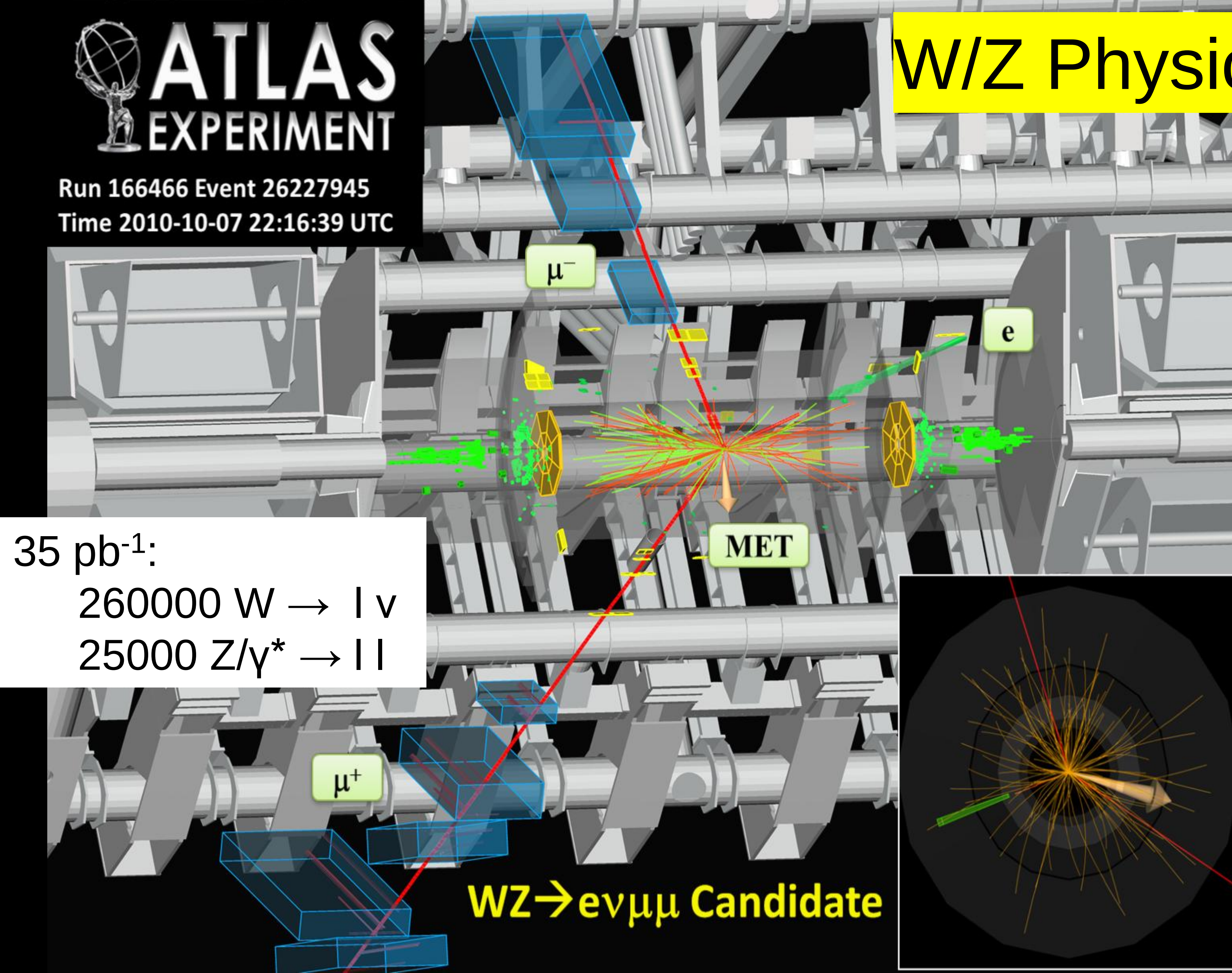


CMS event with 13 pp interactions




ATLAS
EXPERIMENT
Run Number: 177531, Event Number: 183764
Date: 2011-03-13 18:20:50 CET

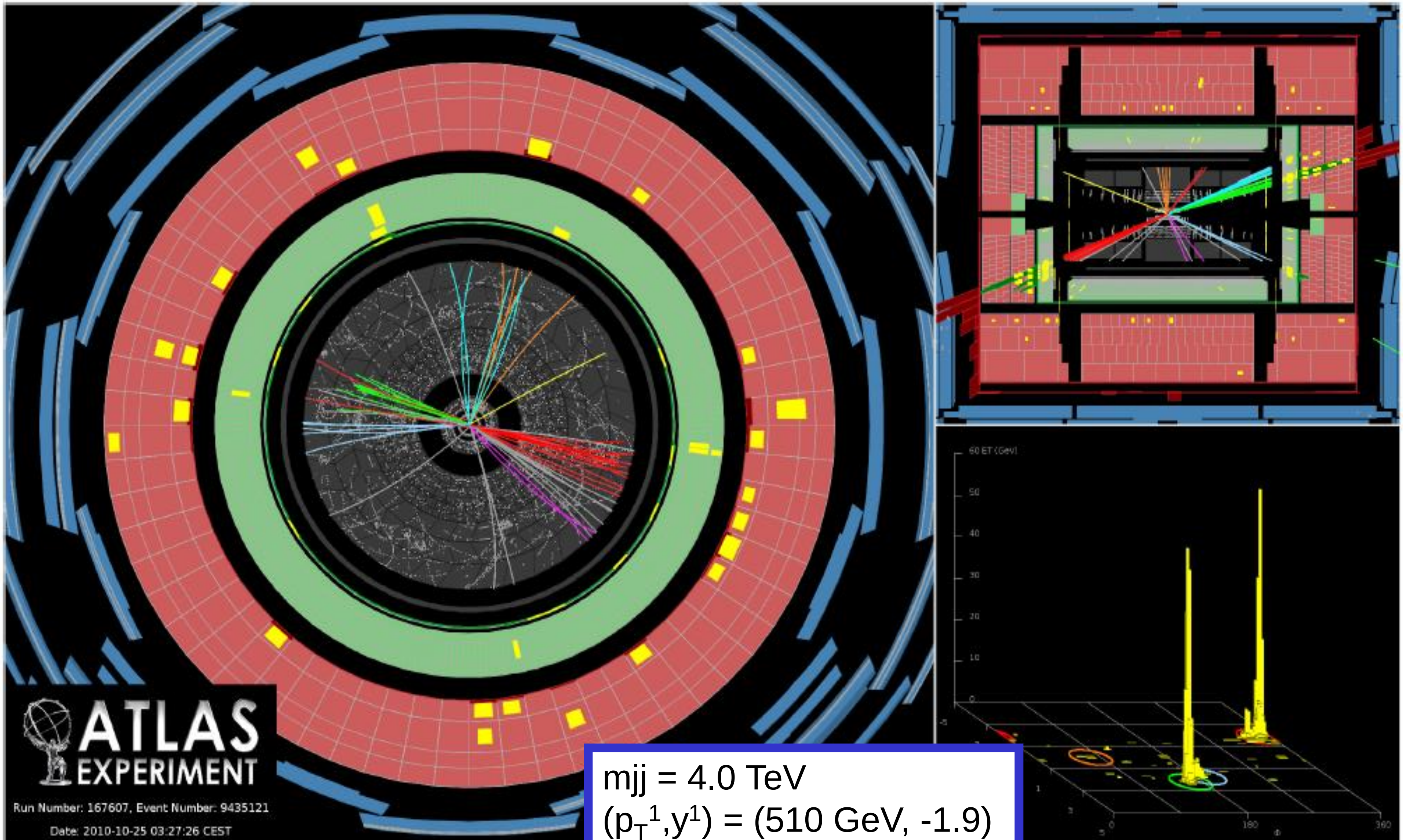
W/Z Physics



35 pb^{-1}:

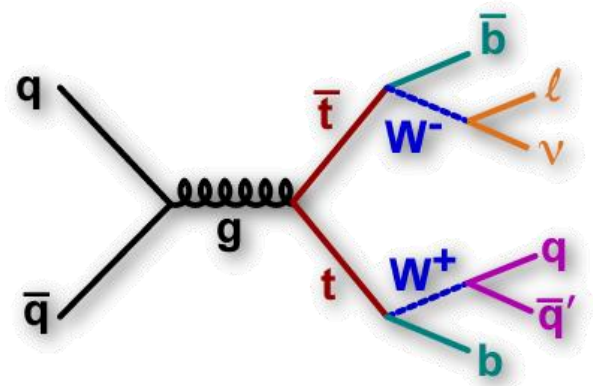
- 260000 $W \rightarrow l\,\nu$
- 25000 $Z/\gamma^* \rightarrow l\,l$

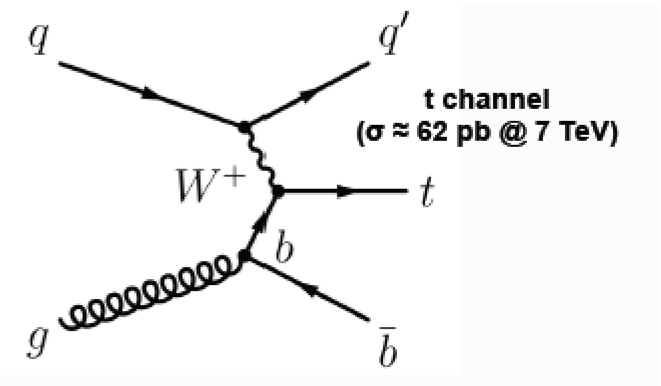
ATLAS Highest Mass Di-jet Event

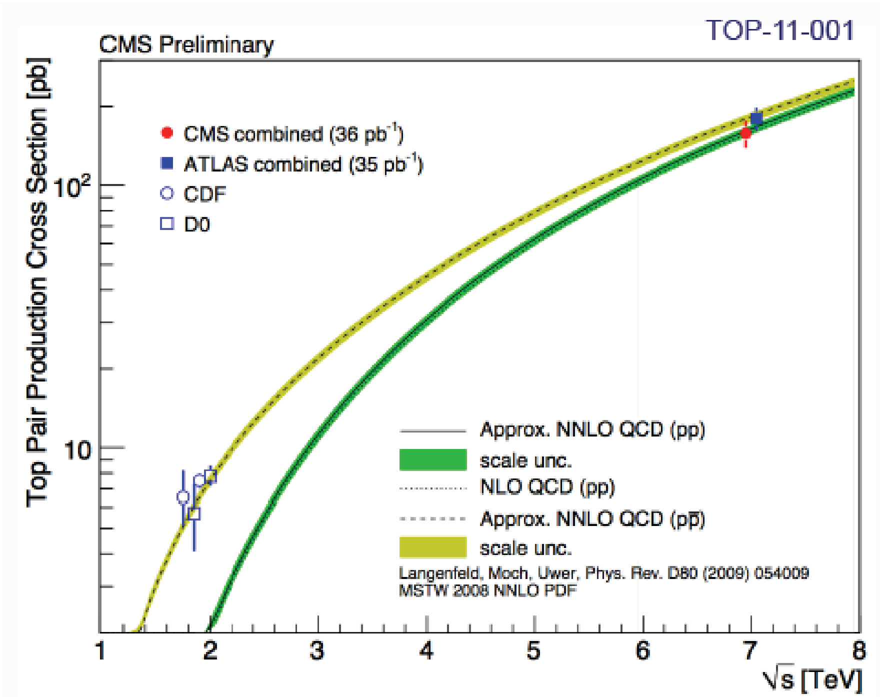


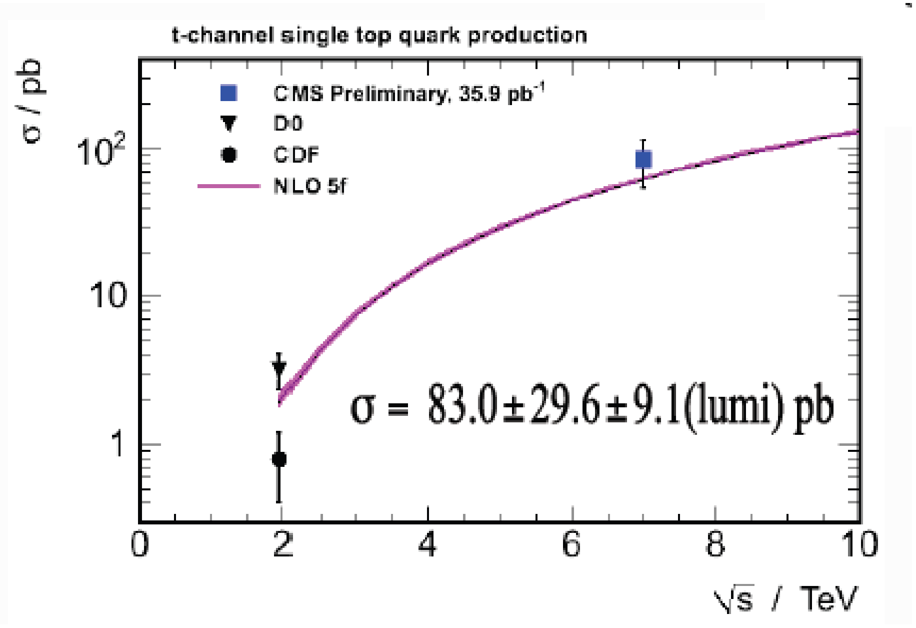
mjj = 4.0 TeV
(p_T^1, y^1) = (510 GeV, -1.9)
(p_T^2, y^2) = (510 GeV, 2.2)

Top Quark Physics

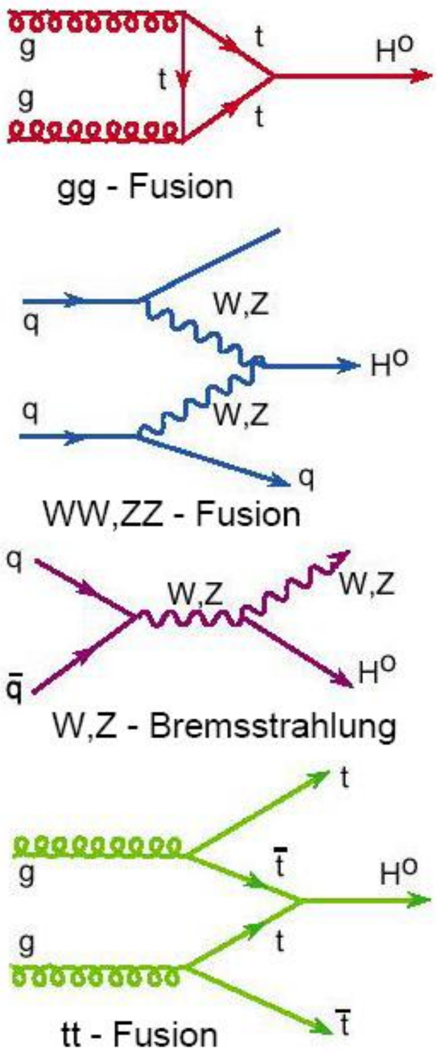




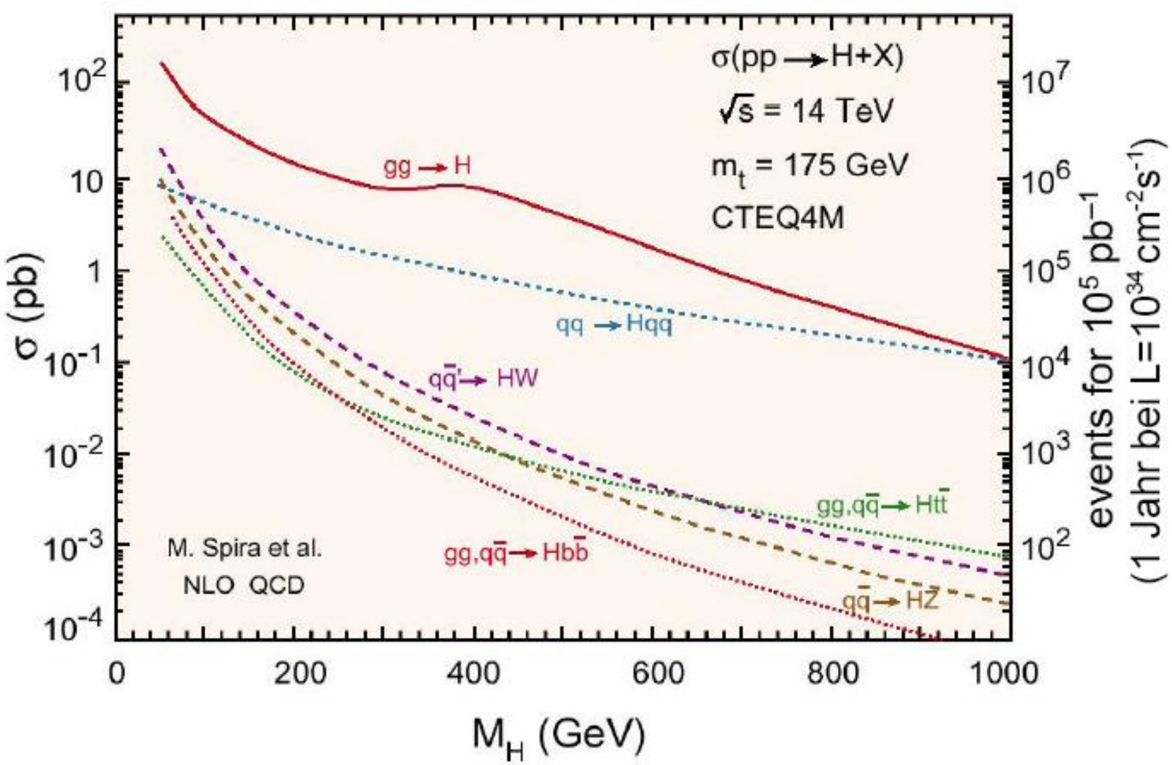




Higgs Physics at LHC

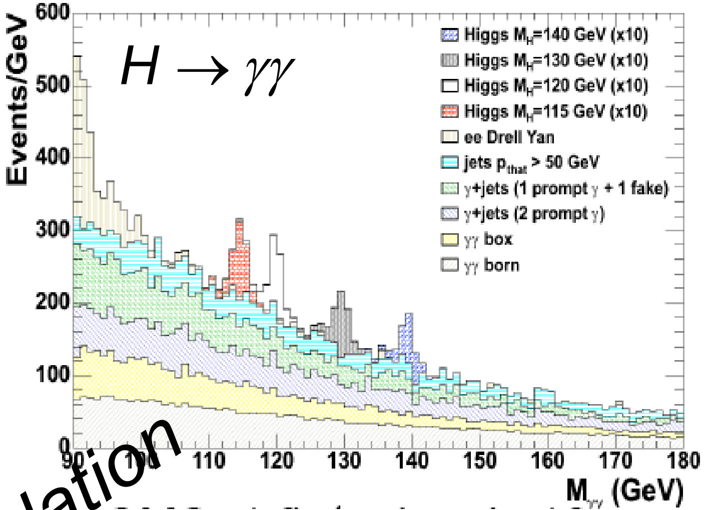


- $p + p \rightarrow H + X$

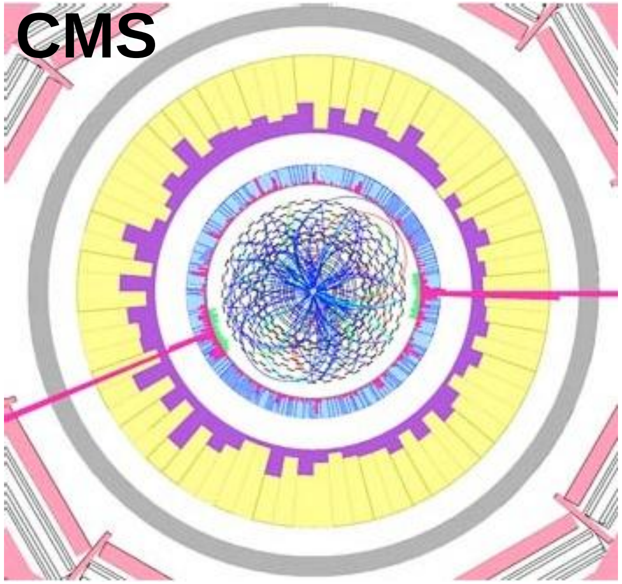


Production cross section is 2 orders of magnitude larger than at TEVATRON.

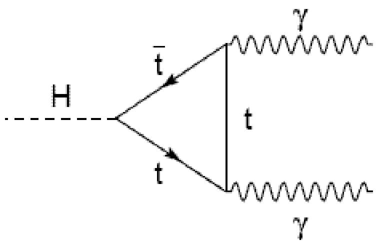
Relevant Higgs Decay Channels



simulation



- $m_H < 150$ GeV:



Also $H \to \tau\tau$ is important

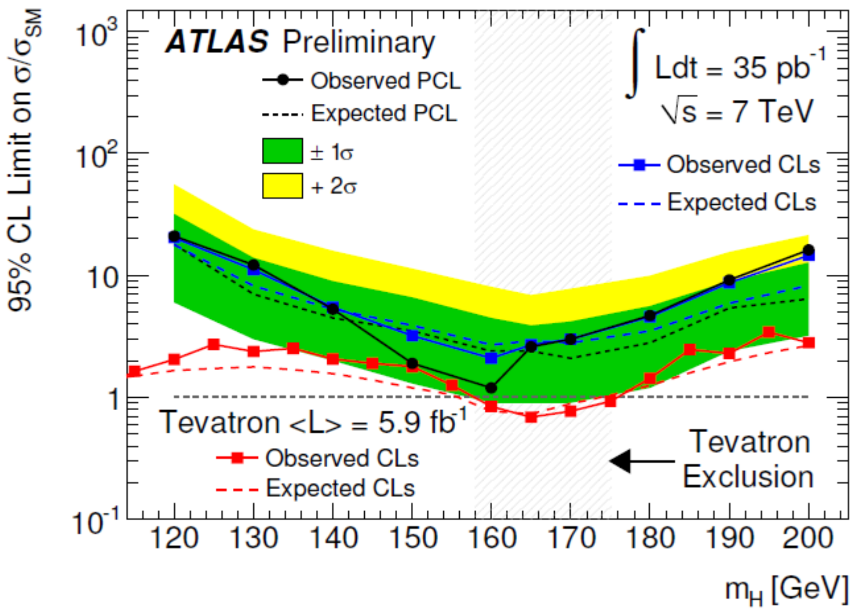
- 150 GeV < m_H < 1 TeV

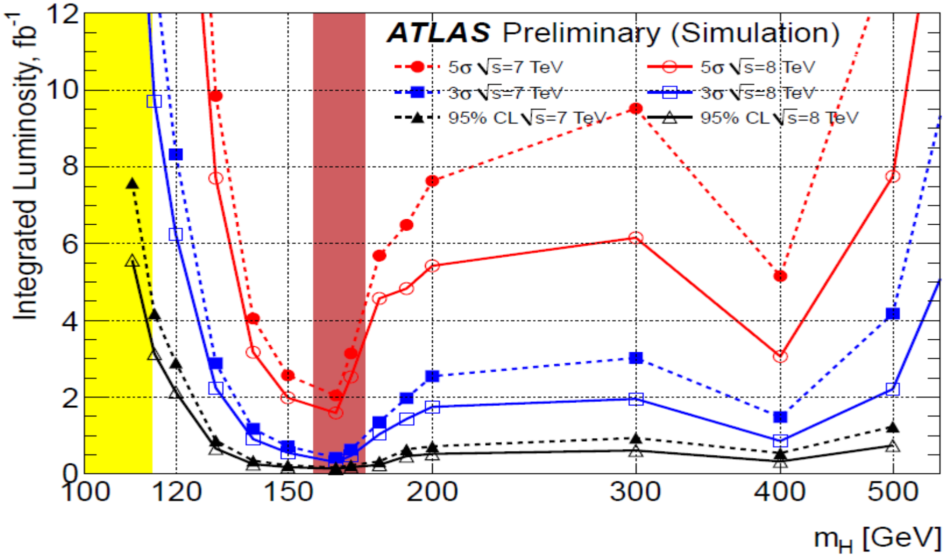
$$H \to ZZ^{(*)}$$

$$H \to W^+W^-$$

ATLAS Higgs Sensitivity

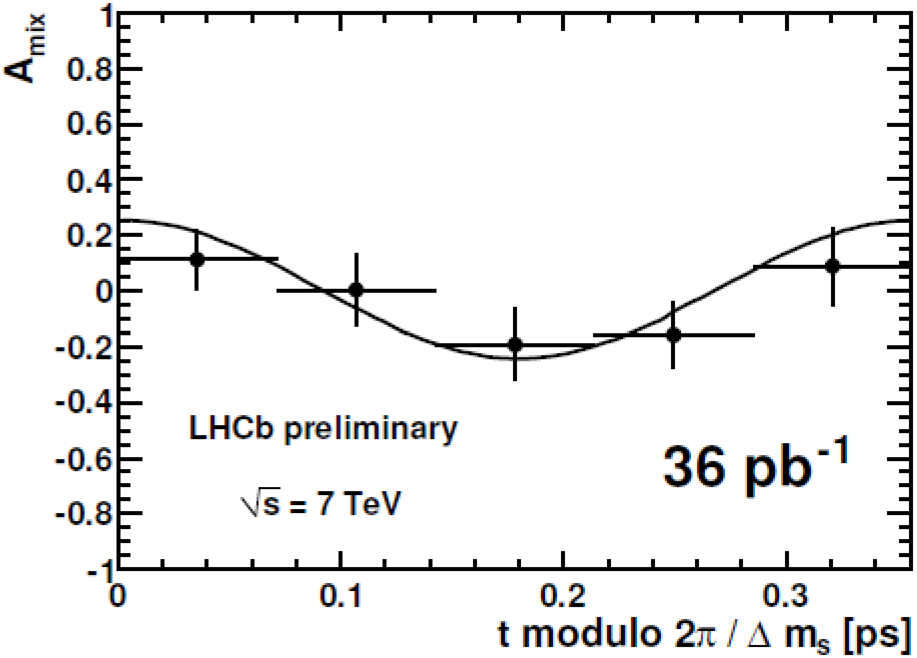
H→WW→lνlν





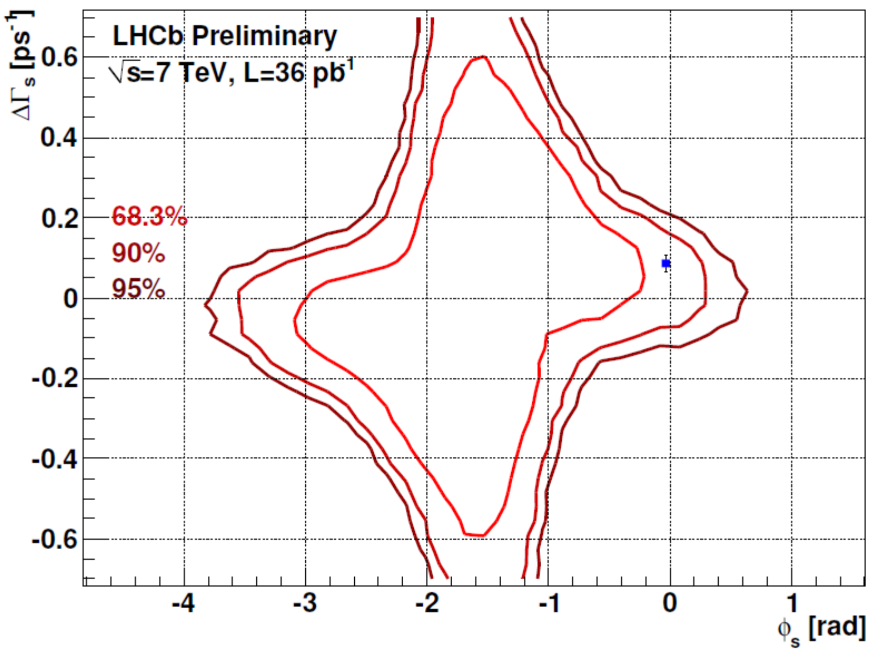
Precision Flavor Physics

$B_s \Leftrightarrow \overline{B}_s$ oscillation



$\Delta m_s = 17.63 \pm 0.11$ (stat) $\pm$ 0.04 (syst) ps^{-1}

CP Violation in $B_s \rightarrow J/\psi\phi$



CP violating CKM phase:

$\phi_s \in$ [-2.7, -0.5] rad at 68% CL

$\phi_s \in$ [-3.5, 0.2] rad at 95% CL

Standard Model prediction: ϕ_s = 0.036

Shortcomings of the Standard Model

Experimental findings

- Neutrino masses and mixing
- Baryogenesis (matter anti-matter symmetry)
- Dark matter

Conceptual problems

- Quadratic divergences in radiative Higgs mass corrections: „fine tuning“ problem
- Origine of the three generations
- Explanation of masses
- Origin of gauge symmetries / quantum numbers
- Unification with gravity

⬇

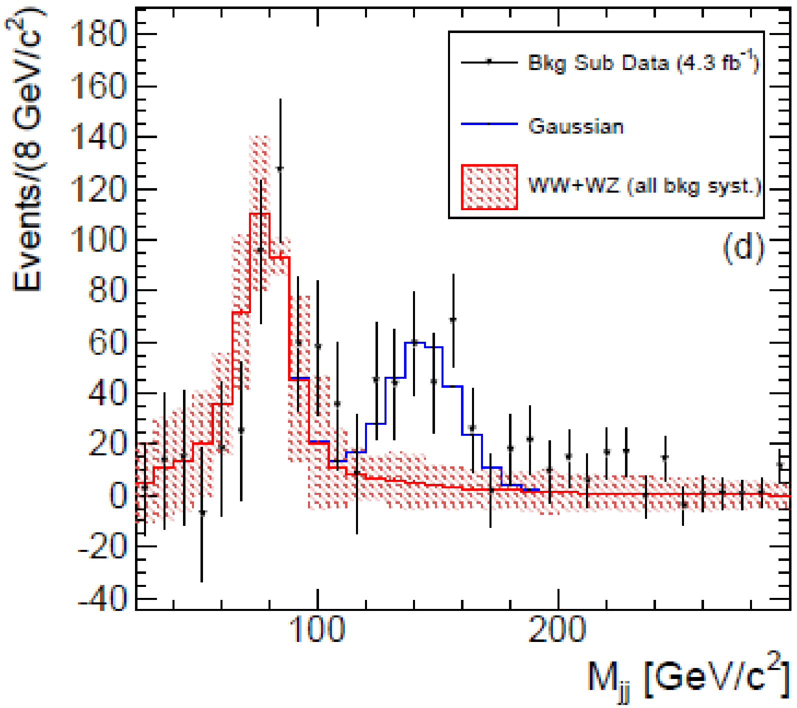
There must be new physics beyond the Standard Model

Physics Beyond the Standard Model?

Möglicher Sensationsfund -
Forscher rätseln über neue Naturkraft

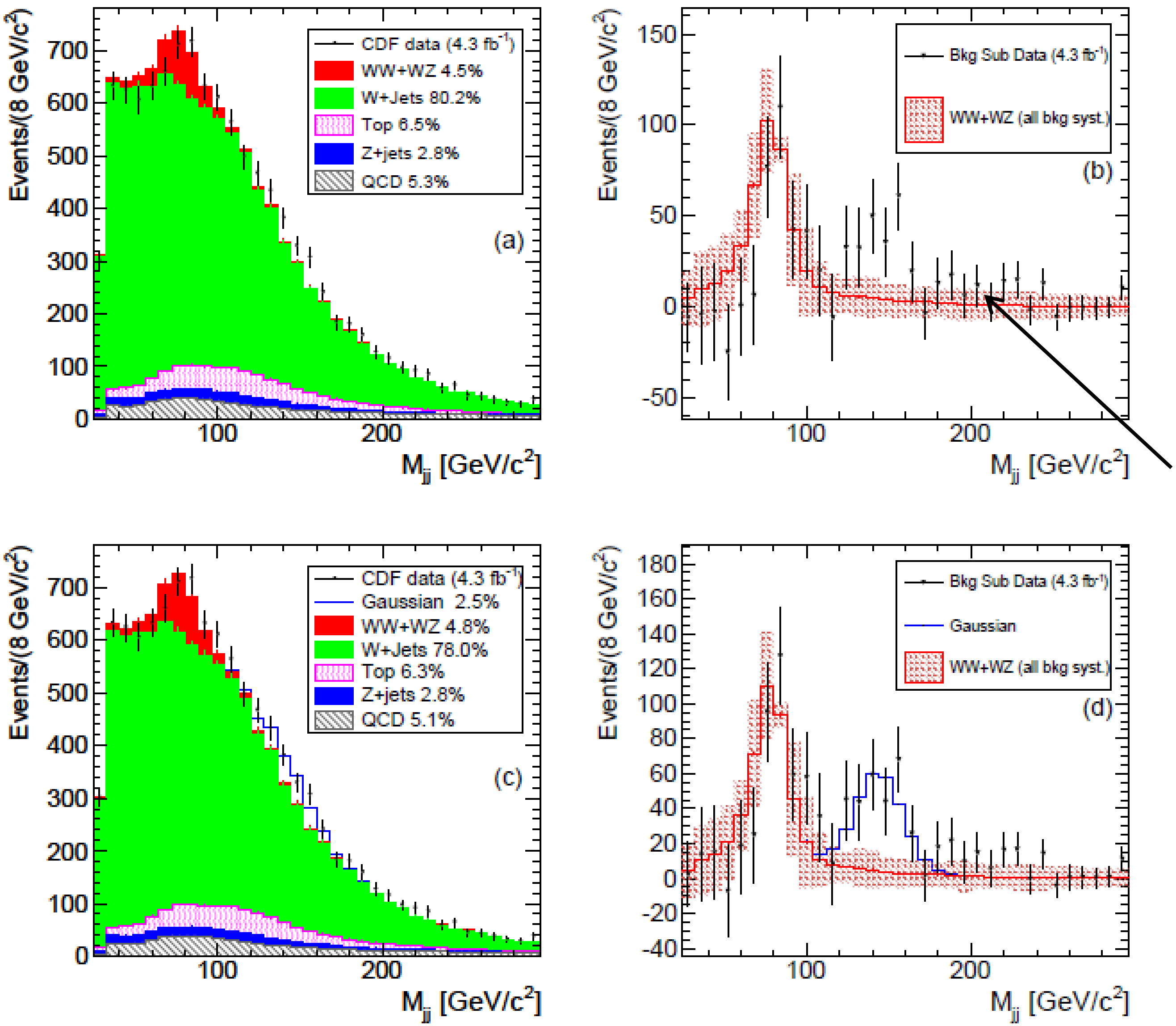
In der Physik bahnt sich eine Sensation an: Forscher haben möglicherweise eine bisher unbekannte Grundkraft der Natur entdeckt. Sollten sich die Daten aus einem US-Teilchenbeschleuniger bestätigen, wäre es wohl die wichtigste physikalische Entdeckung der vergangenen Jahrzehnte.

Spiegel Online, 7. April 2011



CDF – Invariant di-jet mass

CDF Collaboration arXiv:1104.0699



Events: W + jet jet

↓

(lepton + $\not{E}_T$)

M_{jj} = inv. mass (jet jet)

χ^2 (full range) = 77/84

χ^2 (120-160GeV) = 26/20

Adding a gaussian:

χ^2 (full range) = 57/81

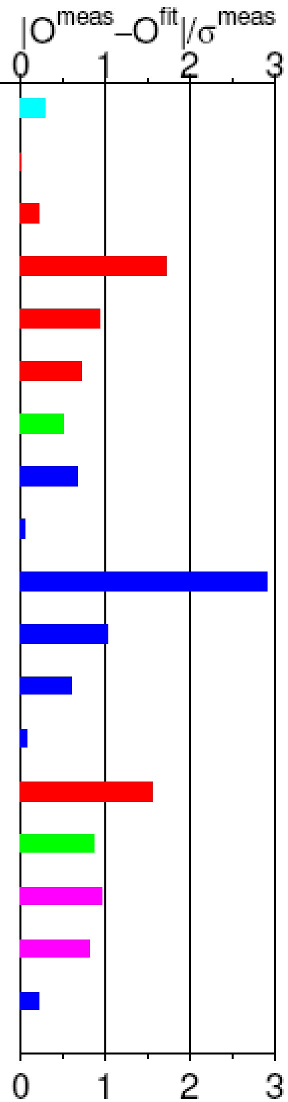
χ^2 (120-160GeV) = 11/20

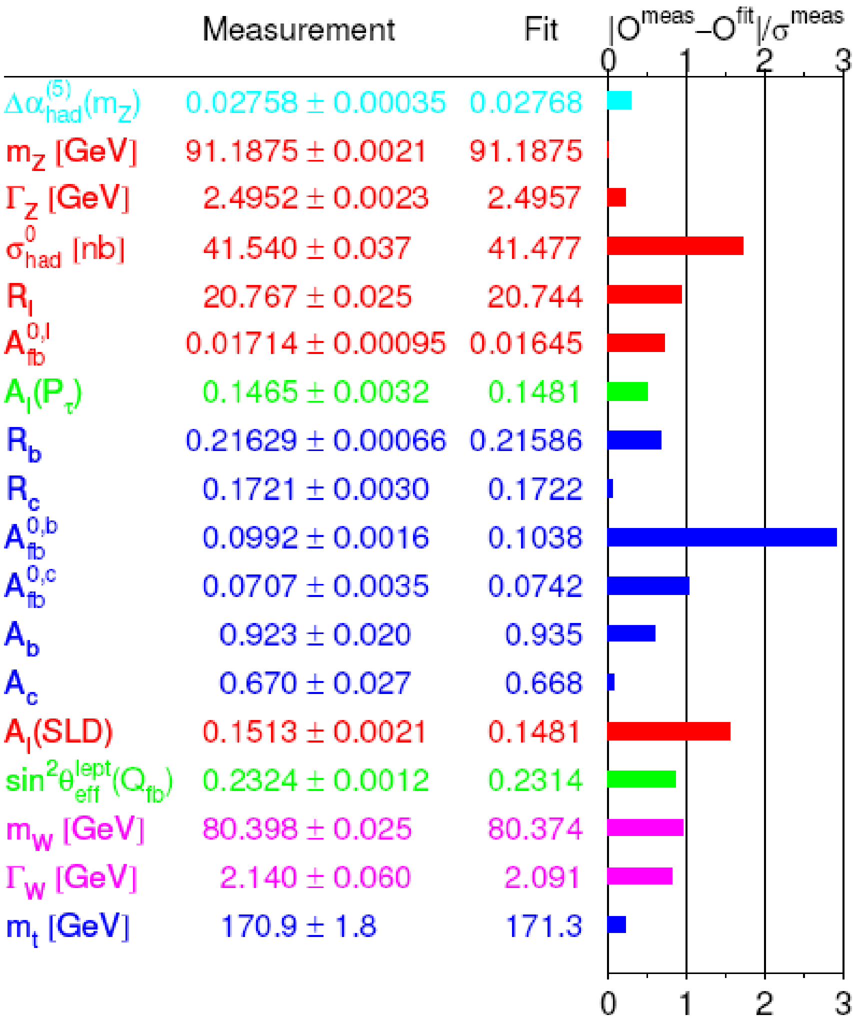
“3.2σ” peak

Not compatible with
SM W+H production

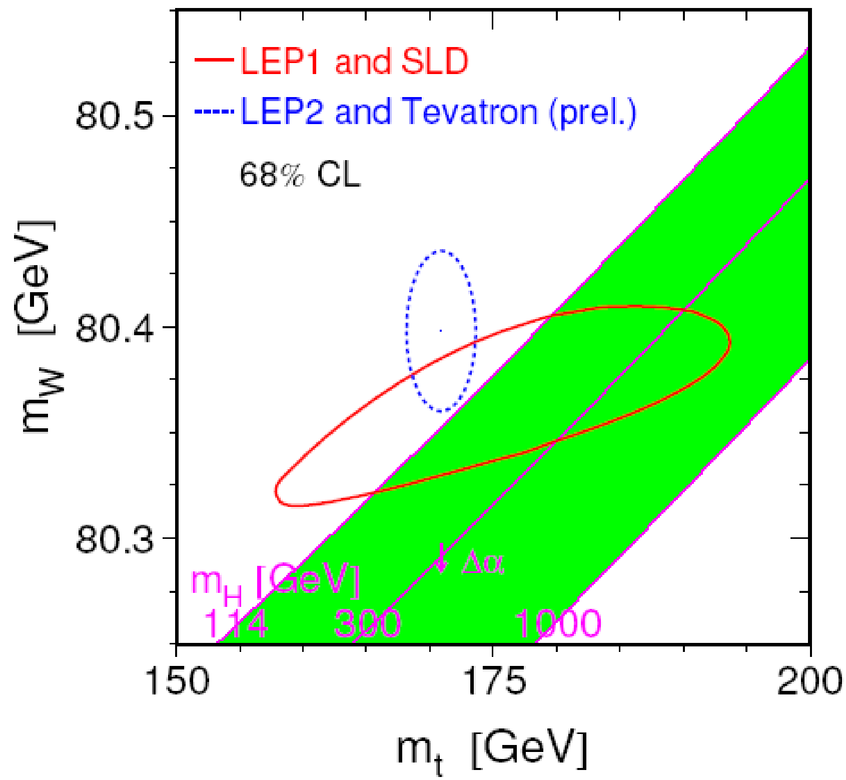
Summary

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02768
m_Z [GeV]	91.1875 ± 0.0021	91.1875
Γ_Z [GeV]	2.4952 ± 0.0023	2.4957
σ_{had}^0 [nb]	41.540 ± 0.037	41.477
R_l	20.767 ± 0.025	20.744
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21586
R_c	0.1721 ± 0.0030	0.1722
$A_{fb}^{0,b}$	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]	80.398 ± 0.025	80.374
Γ_W [GeV]	2.140 ± 0.060	2.091
m_t [GeV]	170.9 ± 1.8	171.3

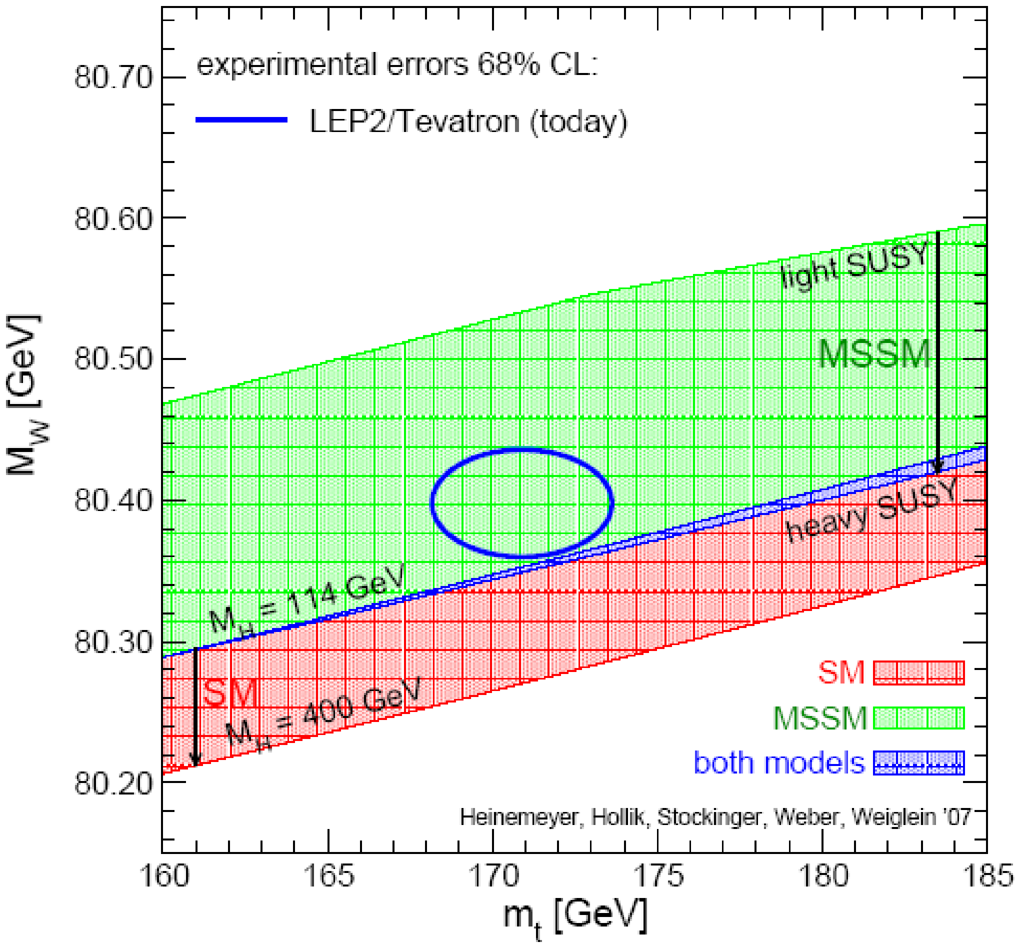




Measurement
Fit
|O^meas − O^fit|/σ^meas
0 1 2 3
Δα^(5)_had(m_Z) 0.02758 ± 0.00035 0.02768
m_Z [GeV] 91.1875 ± 0.0021 91.1875
Γ_Z [GeV] 2.4952 ± 0.0023 2.4957
σ^0_had [nb] 41.540 ± 0.037 41.477
R_l 20.767 ± 0.025 20.744
A^0,l_fb 0.01714 ± 0.00095 0.01645
A_l(P_τ) 0.1465 ± 0.0032 0.1481
R_b 0.21629 ± 0.00066 0.21586
R_c 0.1721 ± 0.0030 0.1722
A^0,b_fb 0.0992 ± 0.0016 0.1038
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 0.1481
sin^2θ^lept_eff(Q_fb) 0.2324 ± 0.0012 0.2314
m_W [GeV] 80.398 ± 0.025 80.374
Γ_W [GeV] 2.140 ± 0.060 2.091
m_t [GeV] 170.9 ± 1.8 171.3
0 1 2 3



LEP1 and SLD
LEP2 and Tevatron (prel.)
68% CL
80.5
80.4
80.3
m_W [GeV]
Δα
m_H [GeV]
114 300 1000
150 175 200
m_t [GeV]



MSSM band:
scan over
SUSY masses

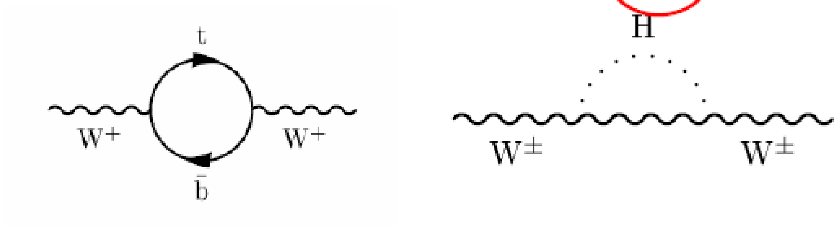
overlap:
SM is MSSM-like
MSSM is SM-like

SM band:
variation of M_H^{SM}

Beispiel: Masse des W-Bosons:

$$M_W = \left(\frac{\pi\alpha}{\sqrt{2}G_F}\right)^{1/2} \frac{1}{\sin\theta_W\sqrt{1-\Delta r}}$$

Beitrag aus Strahlungskorrekturen

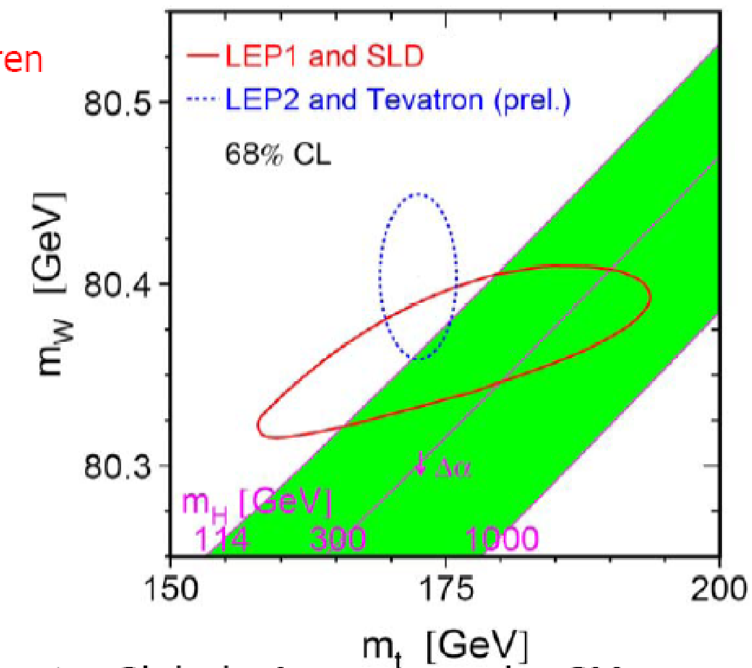


- Auch Teilchen mit Massen höher als $\sqrt{s}$ laufen in den Loops (virtuell !).
- Fermionschleifen dominiert von Top Quark

$$\Delta r_w(m_t, M_H) = -\frac{3\alpha c_w^2}{16\pi s_w^4}\frac{m_t^2}{M_W^2} + \frac{11\alpha}{48\pi s_w^2}\ln\frac{M_H^2}{M_W^2} + \ldots$$

- Strahlungskorrekturen sind für alle Observablen relevant (auch Z-Pol)

- "indirekte Bestimmung"



- Globale Anpassung der SM Parameter (Fit)

$$\Delta r(m_t, M_H) = -\frac{3\alpha\cos^2\theta_w}{16\pi\sin^4\theta_w}\frac{m_t^2}{M_W^2} - \frac{11\alpha}{48\pi\sin^2\theta_w}\ln\frac{M_H^2}{M_W^2} + \ldots$$

Z line shape parameters (LEP average)

M_Z	= 91.1876 ± 0.0021 GeV	±23 ppm (*)	
Γ_Z	= 2.4952 ± 0.0023 GeV	±0.09 %	3 leptons are treated independently
Γ_{had}	= 1.7458 ± 0.0027 GeV		
Γ_e	= 0.08392 ± 0.00012 GeV		
Γ_μ	= 0.08399 ± 0.00018 GeV		
Γ_τ	= 0.08408 ± 0.00022 GeV		
Γ_Z	= 2.4952 ± 0.0023 GeV		Assuming lepton universality: $\Gamma_e = \Gamma_\mu = \Gamma_\tau$
Γ_{had}	= 1.7444 ± 0.0022 GeV		
Γ_e	= 0.083985 ± 0.000086 GeV		

test of lepton universality

*) error of the LEP energy determination: ±1.7 MeV (19 ppm)

http://lepewwg.web.cern.ch/

W Mass: Prediction versus Measurement