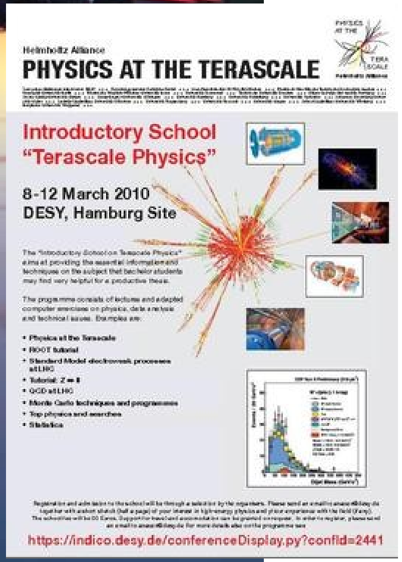
Physics of the Top Quark
Lecture 1

Arnulf Quadt


Helmholtz Alliance
PHYSICS AT THE TERASCALE

Introductory School
"Terascale Physics"

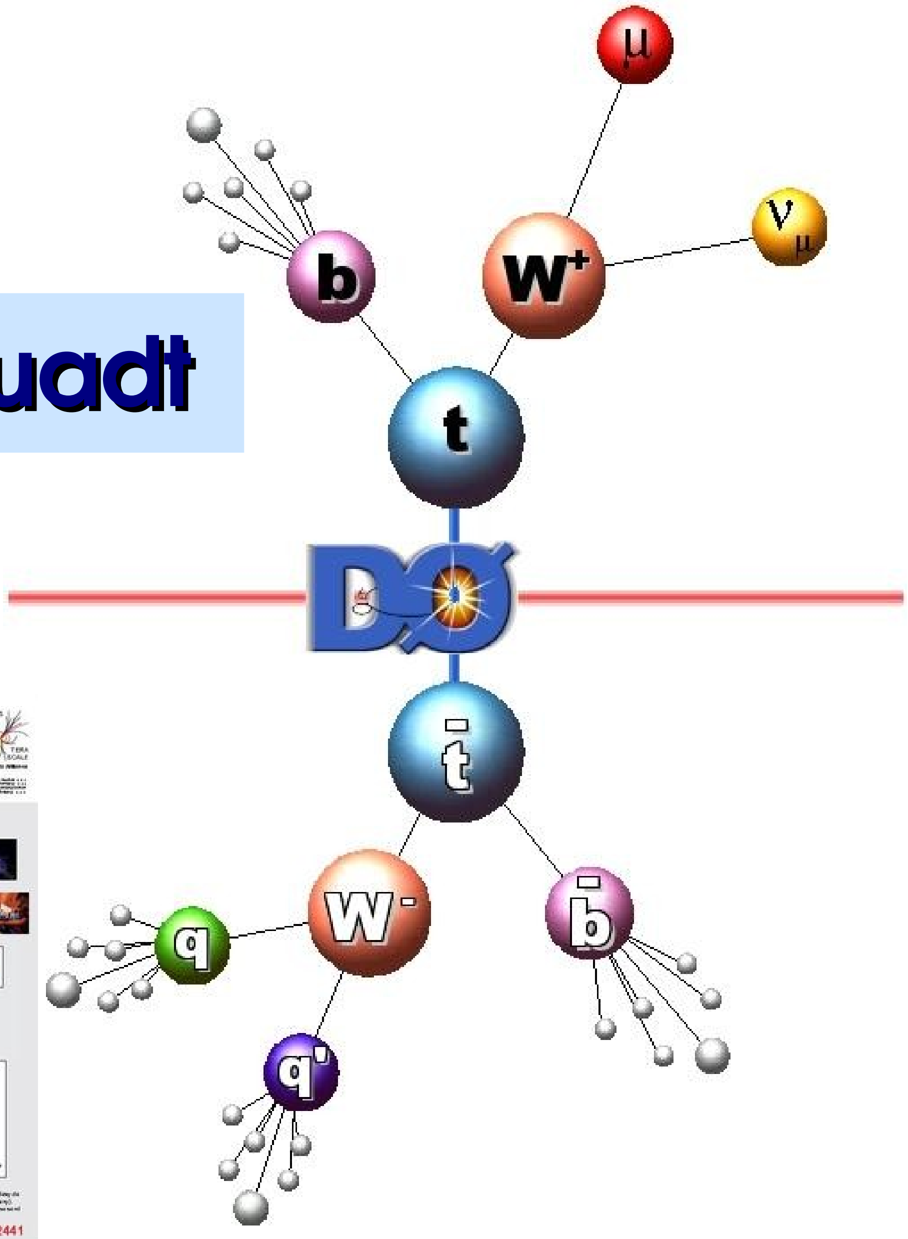
8-12 March 2010
DESY, Hamburg Site

The "Introductory School on Terascale Physics" aims at providing the essential information and techniques on the subject that bachelor students may find very helpful for a productive thesis.

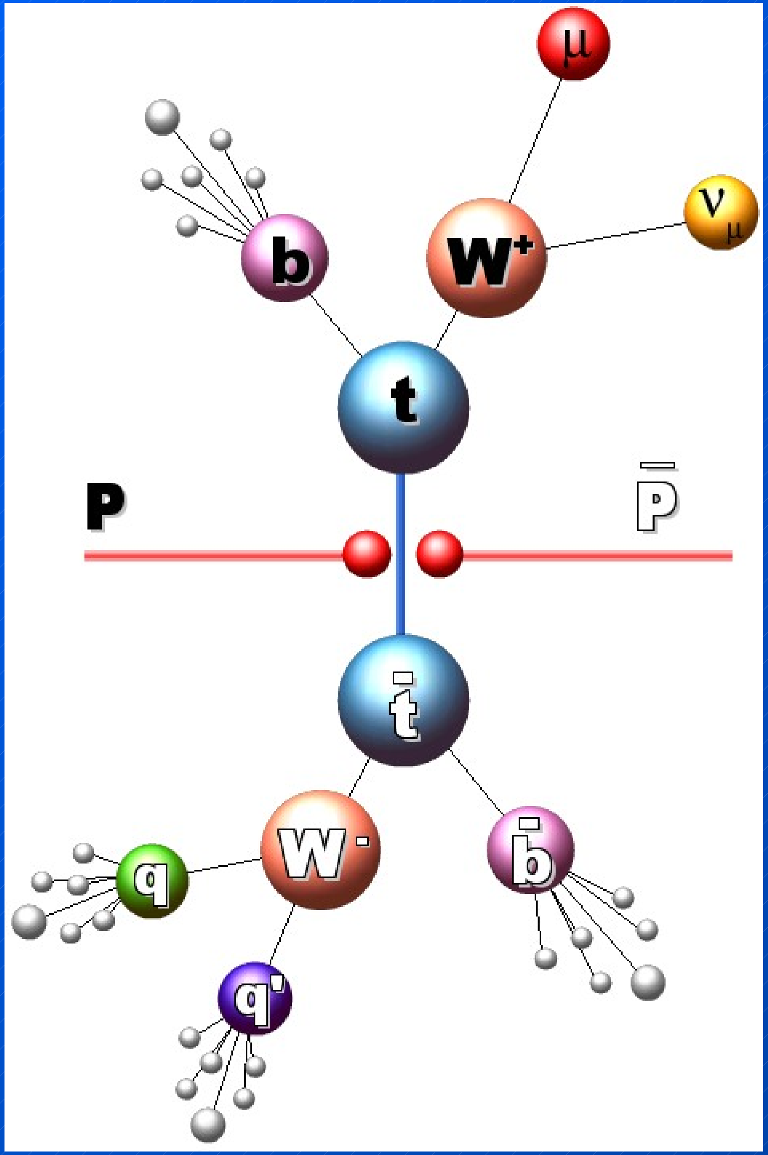
The programme consists of lectures and adapted computer exercises on physics, data analysis and technical issues. Examples are:

- Physics at the Terascale
- ROOT tutorial
- Standard Model electroweak processes at LHC
- QCD at LHC
- Monte Carlo techniques and programmes
- Top physics and searches
- Statistics

https://indico.desy.de/conferenceDisplay.py?confId=2441



Top Quark Physics



Part 1

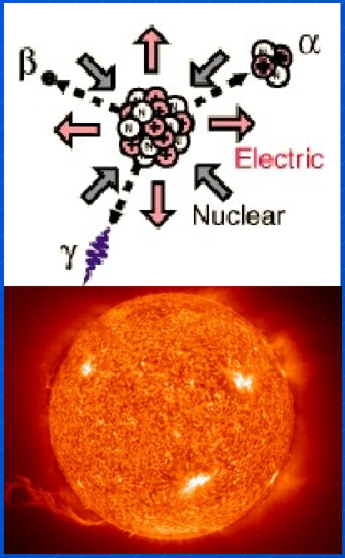
- Introduction
- discovery of the top quark
- experimental tools

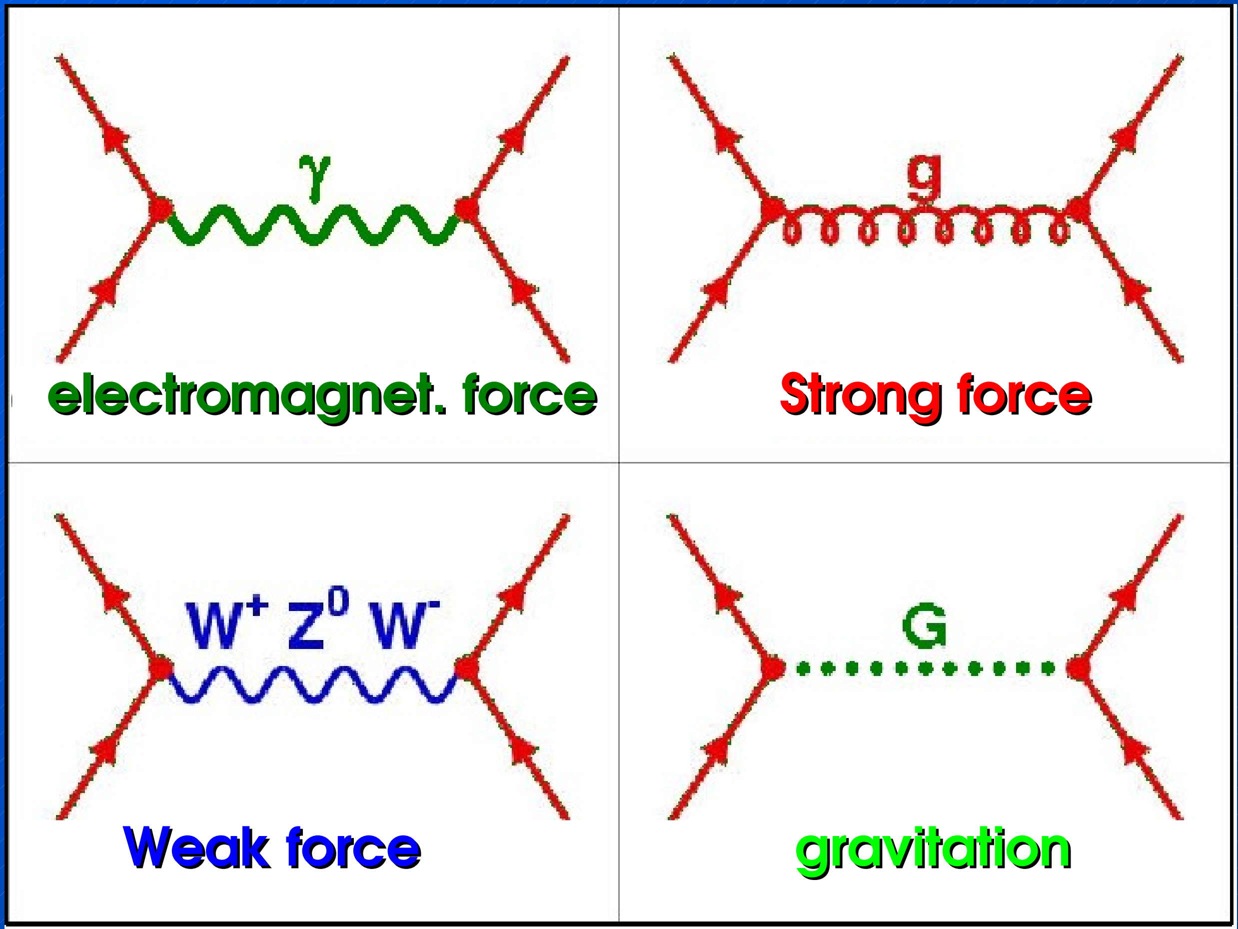
Part 2

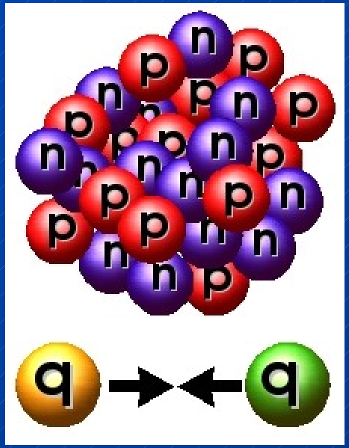
- top-antitop quark production (strong)
- ttbar Xsec (experimental)
- single-top quark production (weak)
- top quark mass
- top quark charge and spin
- W helicity in top quark decays

Introduction

Fundamental Forces

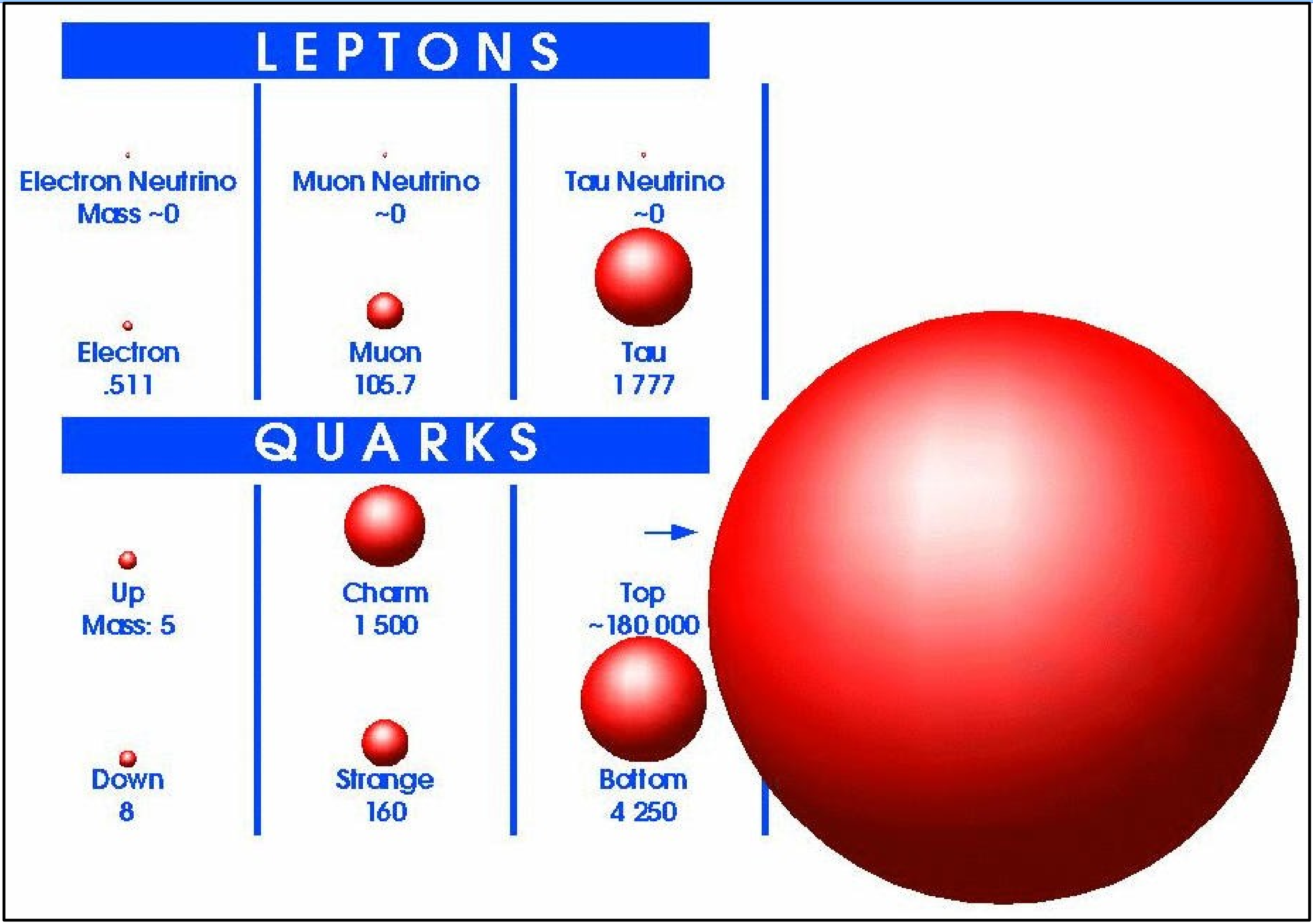




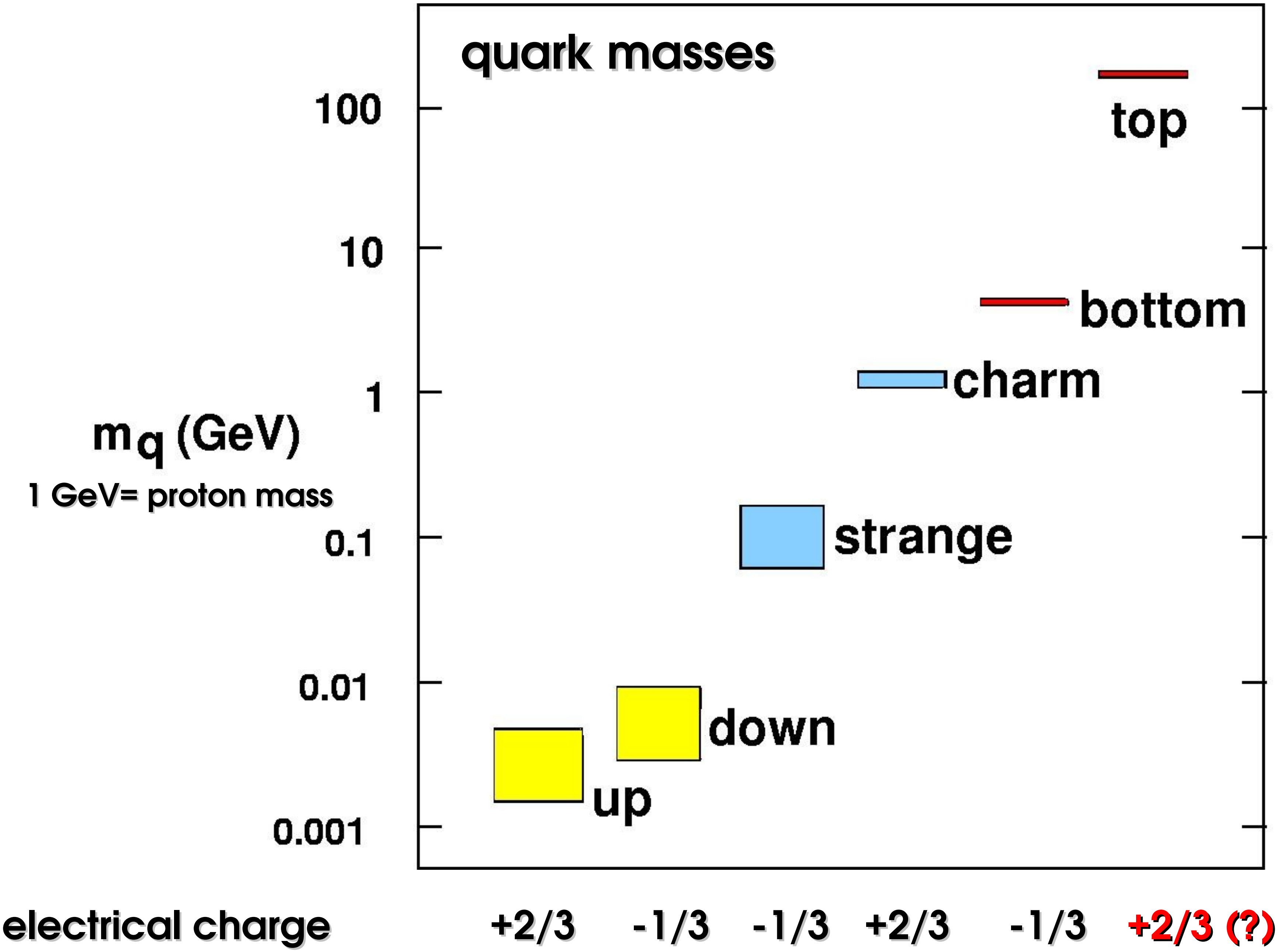


"The Particle Zoo"

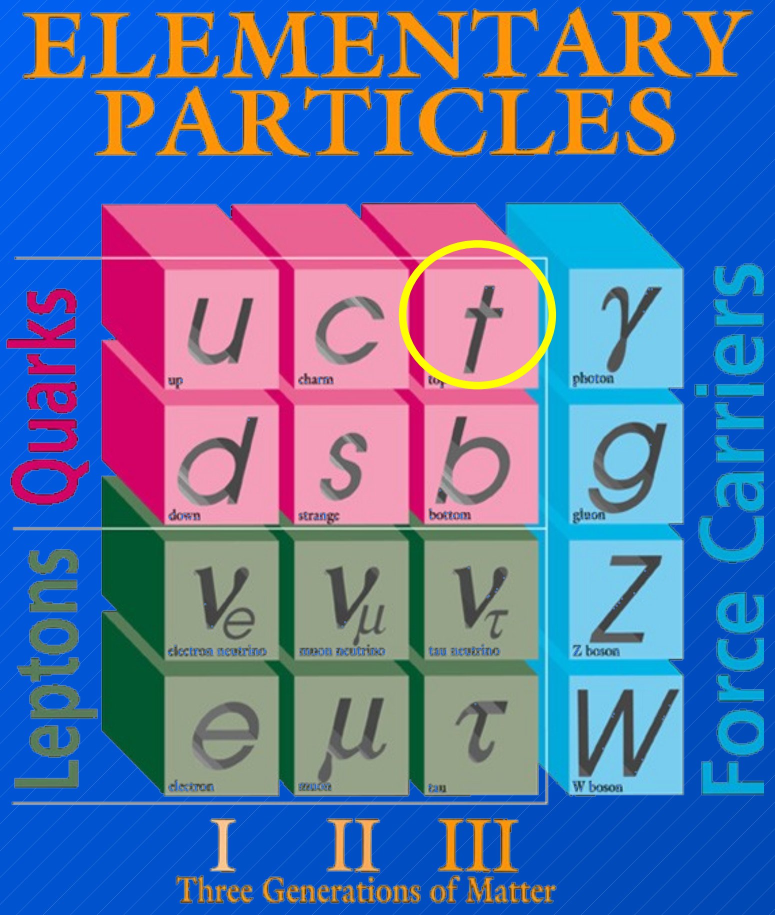
Fermions in the Standard Model

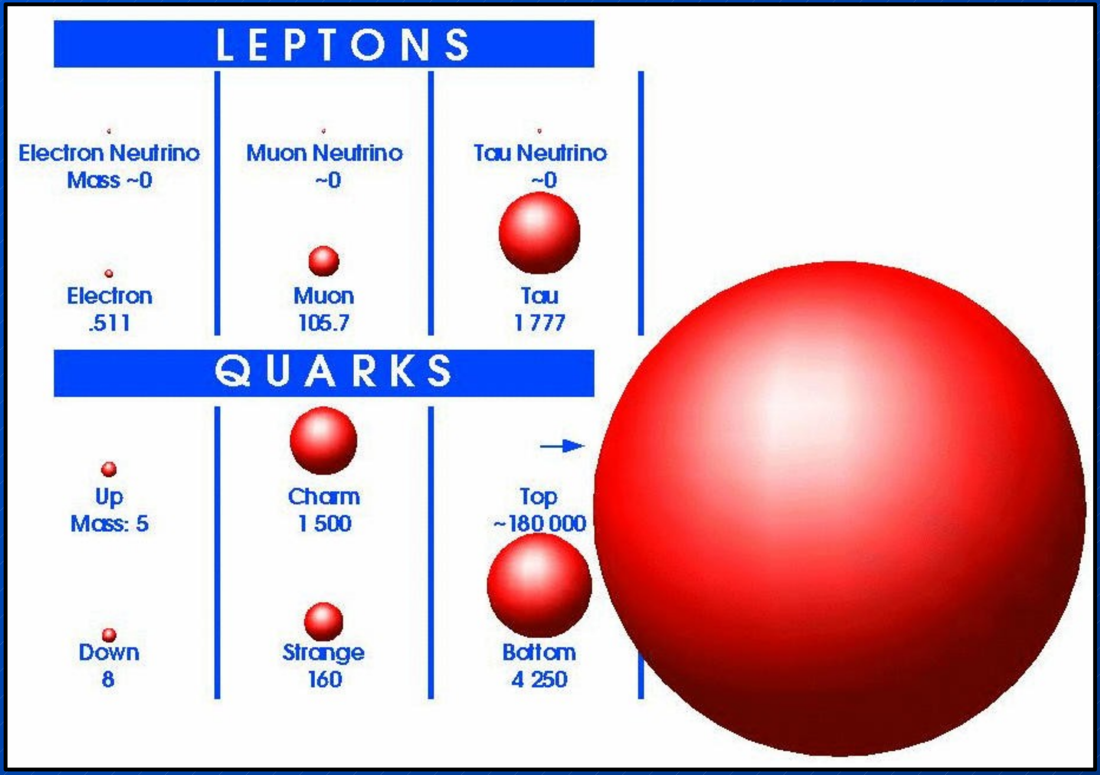


Quark Properties



Top Quark in the Standardmodel



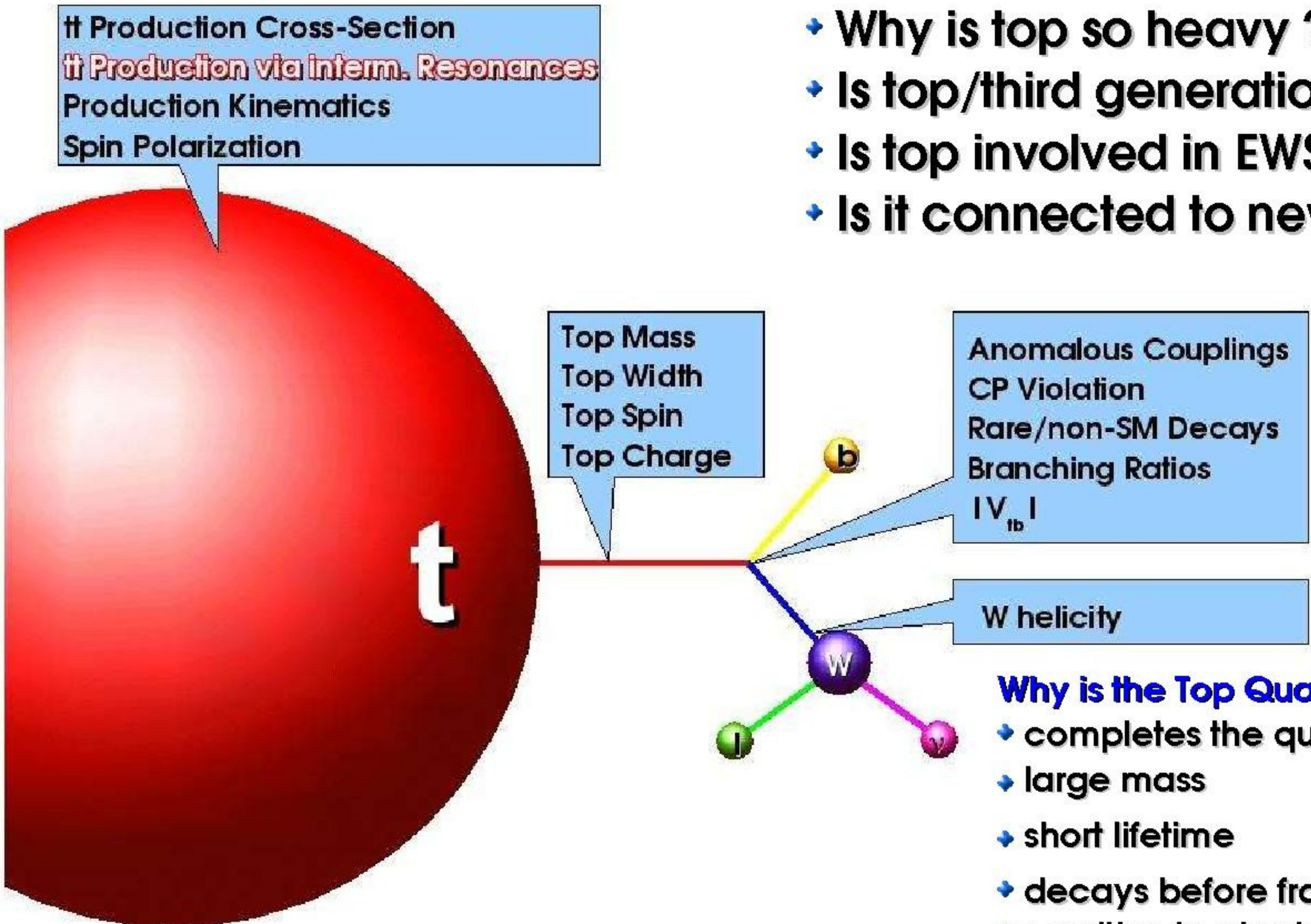


Higgs-Boson coupling to fermions : $g \sim m_f$

$m_t \sim v/\sqrt{2}$, Yukawa coupling $\lambda_t \sim 1$

Top Quark Physics

Run I : top quark discovery



Run II: with high precision answer ...

- Why is top so heavy ?
- Is top/third generation special ?
- Is top involved in EWSB ?
- Is it connected to new physics ?

Why is the Top Quark so interesting ?

- completes the quark sector
- large mass $m_{top} \sim 175$ GeV / c^2
- short lifetime $\tau \sim 5 \cdot 10^{-25}\text{s} \ll \Lambda^{-1}_{QCD}$
- decays before fragmenting
- sensitive to physics beyond the SM

Discovery of the Top Quark

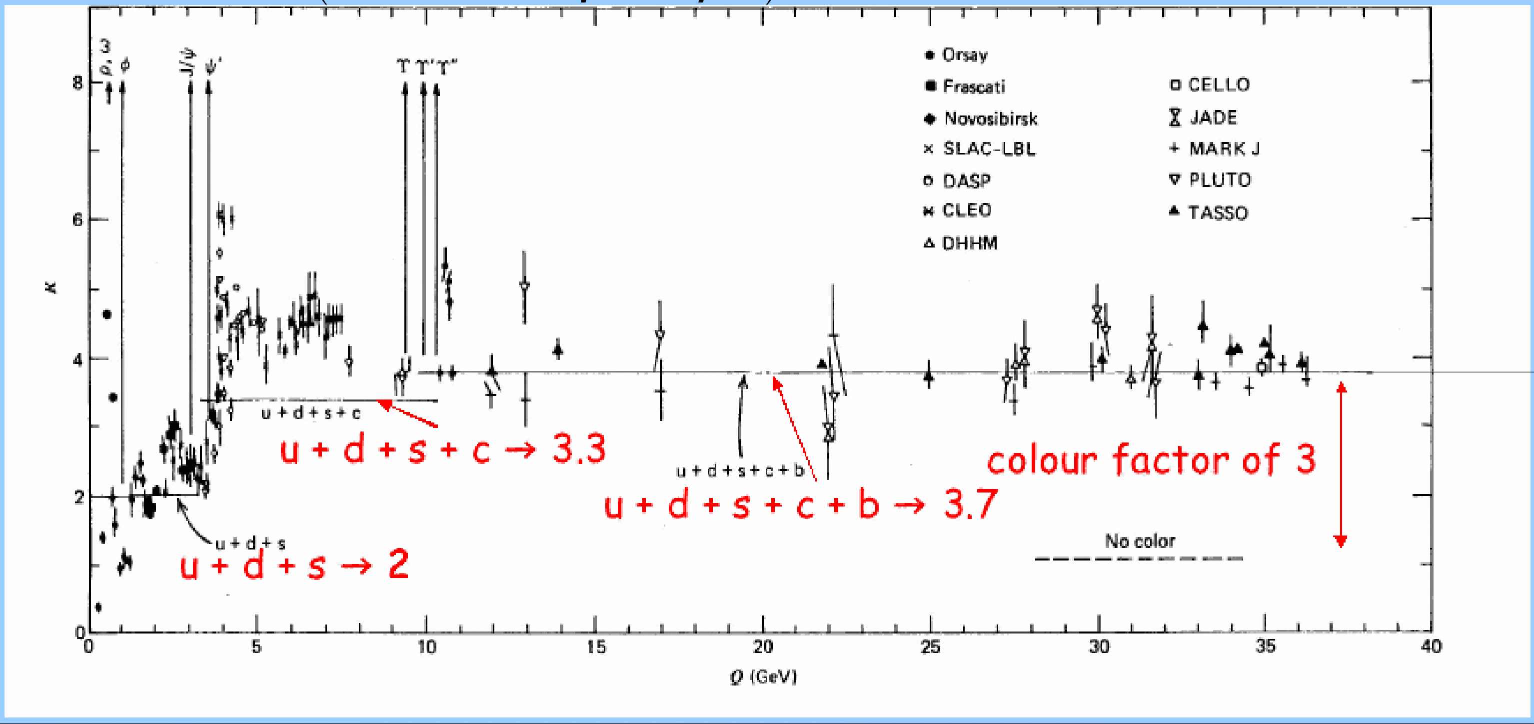
History of Particle Discoveries

Quarks	Up/Down	1968	SLAC	1990 Nobel Prize
	Strange	1964	BNL	1980 Nobel Prize
	Charm	1974	SLAC/BNL	1976 Nobel Prize
	Bottom	1977	Fermilab	
	Top	1995	Fermilab	
Leptons	Electron	1897	Thomson	1906 Nobel Prize
	E-Neutrino	1956	Reactor	1995 Nobel Prize
	Muon	1937	Cosmic Rays	
	Mu-Neutrino	1962	BNL	1998 Nobel Prize
	Tau	1976	SLAC	1995 Nobel Prize
	Tau-Neutrino	2000	Fermilab	first direct evidence
Exchange Bosons	Photon	1905	Planck/Einstein	1918/1921 Nobel Prize
	Gluon	1979	DESY	1995 EPS Prize
	W/Z	1983	CERN	1984 Nobel Prize

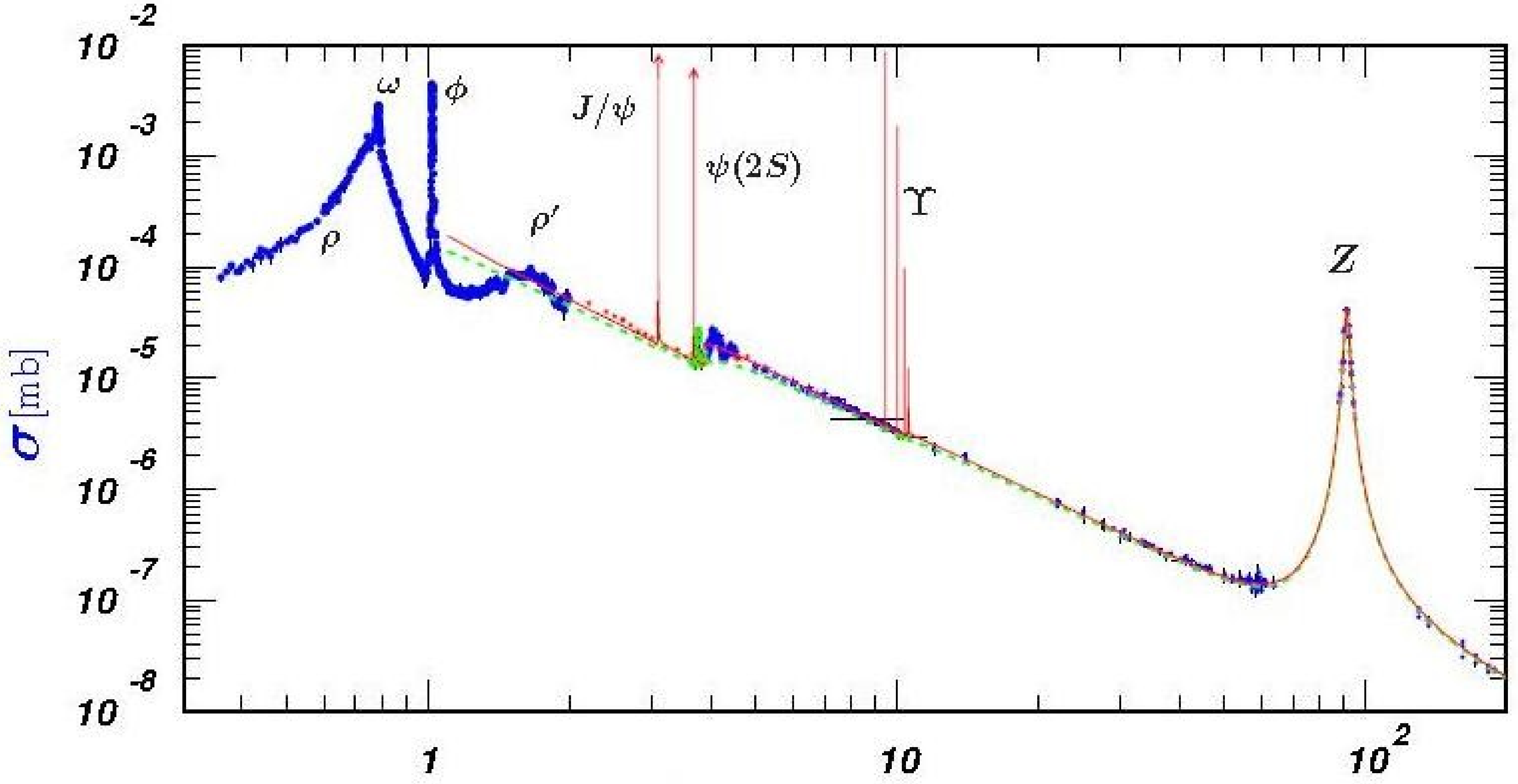
... Theory (QCD, CKM, ...) and
Technology also awarded the Nobel Prize ...

History of the Top Quark Search

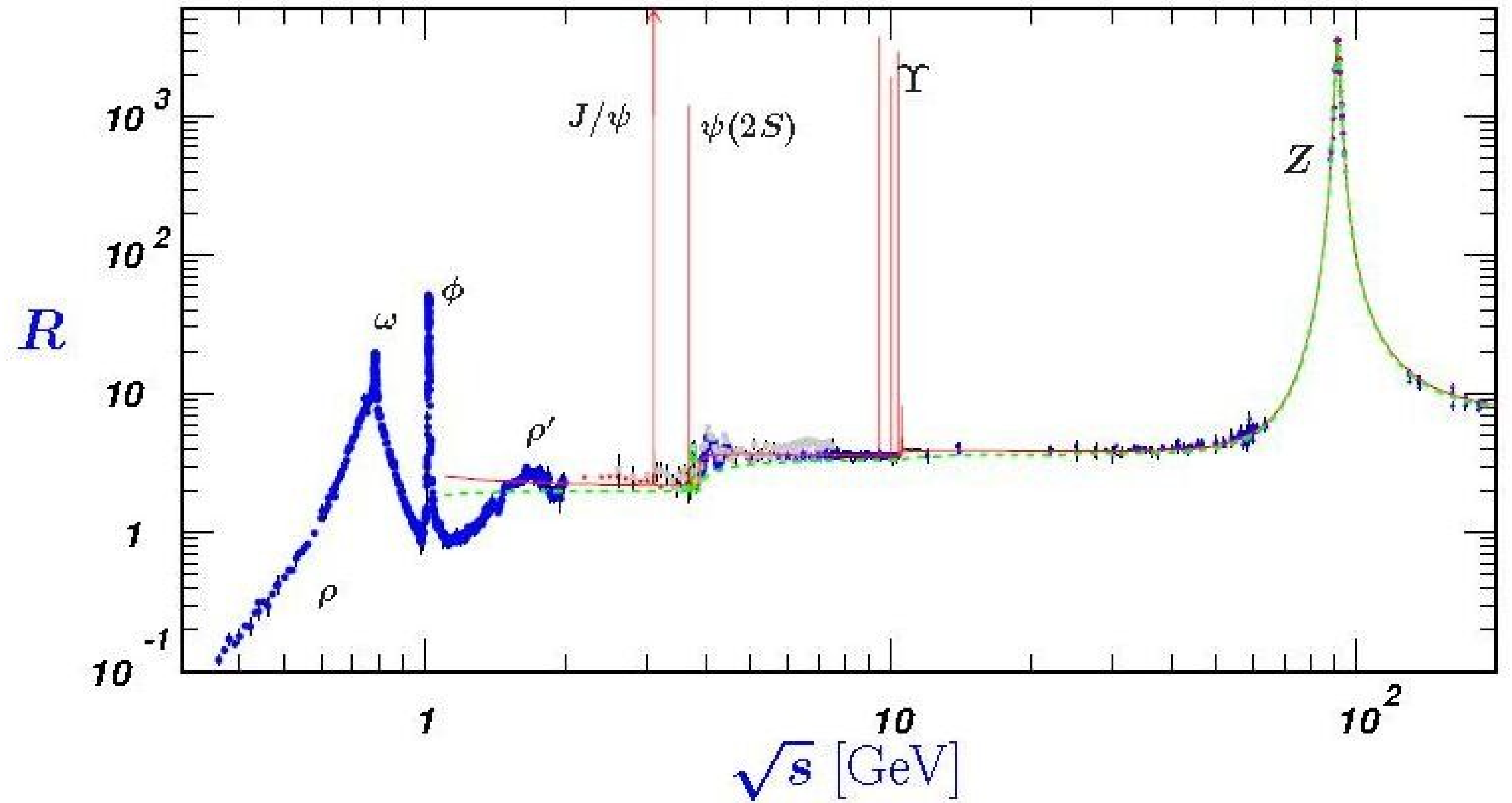
$$R = \frac{\sigma\left(e^+ + e^- \to hadrons\right)}{\sigma\left(e^+ + e^- \to \mu^+ + \mu^-\right)} = \frac{3\sum\left(quark\ charge\right)^2}{1^2}$$



History of the Top Quark Search



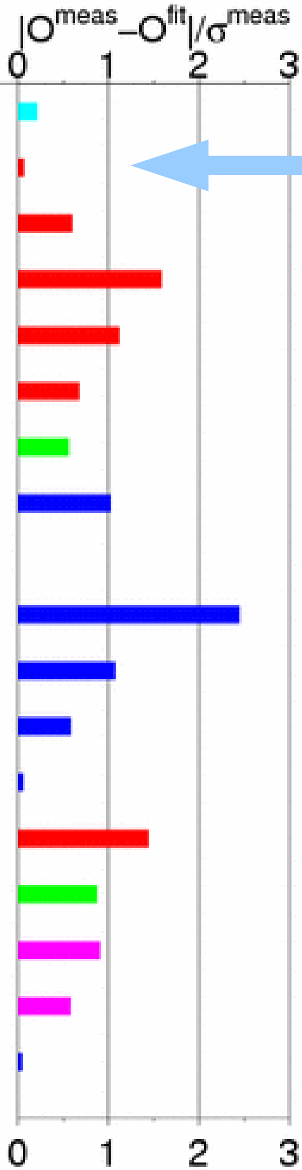
History of the Top Quark Search



Electroweak Precision Data

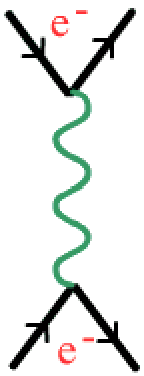
Summer 2004

	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02761 ± 0.00036	0.02769
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4966
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	0.01650
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1483
R_b	0.21630 ± 0.00066	0.21562
R_c	0.1723 ± 0.0031	0.1723
$A^{0,b}_{fb}$	0.0998 ± 0.0017	0.1040
$A^{0,c}_{fb}$	0.0706 ± 0.0035	0.0744
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.026	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1483
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.425 ± 0.034	80.394
Γ_W [GeV]	2.133 ± 0.069	2.093
m_t [GeV]	178.0 ± 4.3	178.2

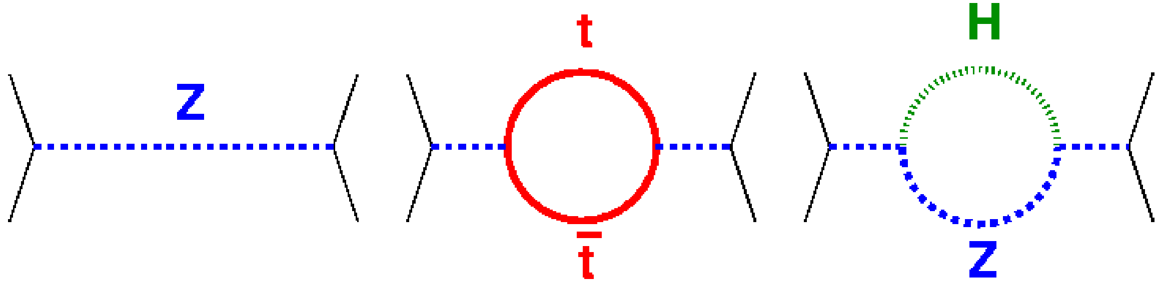


Z^0-mass measured with 0.02 ‰ precision

... need to consider quantum fluctuations ...

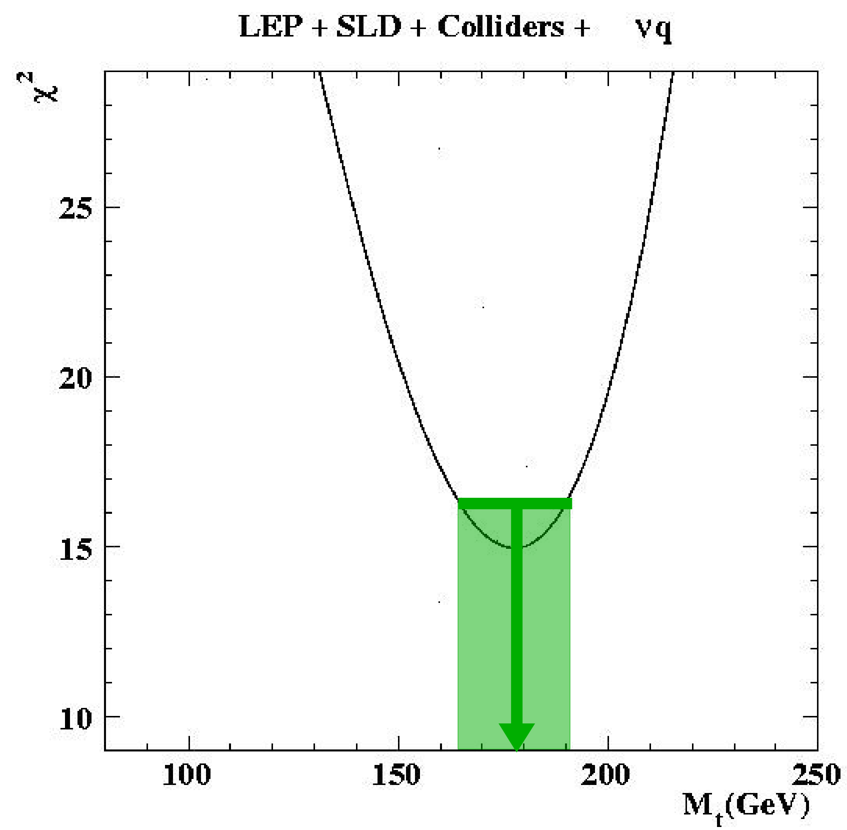


Top-Quark Mass Prediction



$$M_Z^2 = M_Z^{2\ 0.\mathrm{order}} \,/\, (1 - \Delta)$$

$$\Delta \approx \ldots\ m_t^2\ \ldots + \ldots\ \ln m_h\ \ldots$$

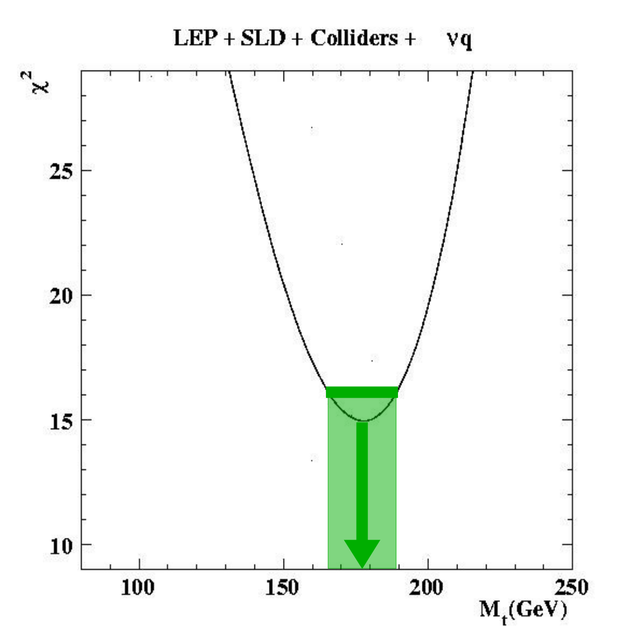


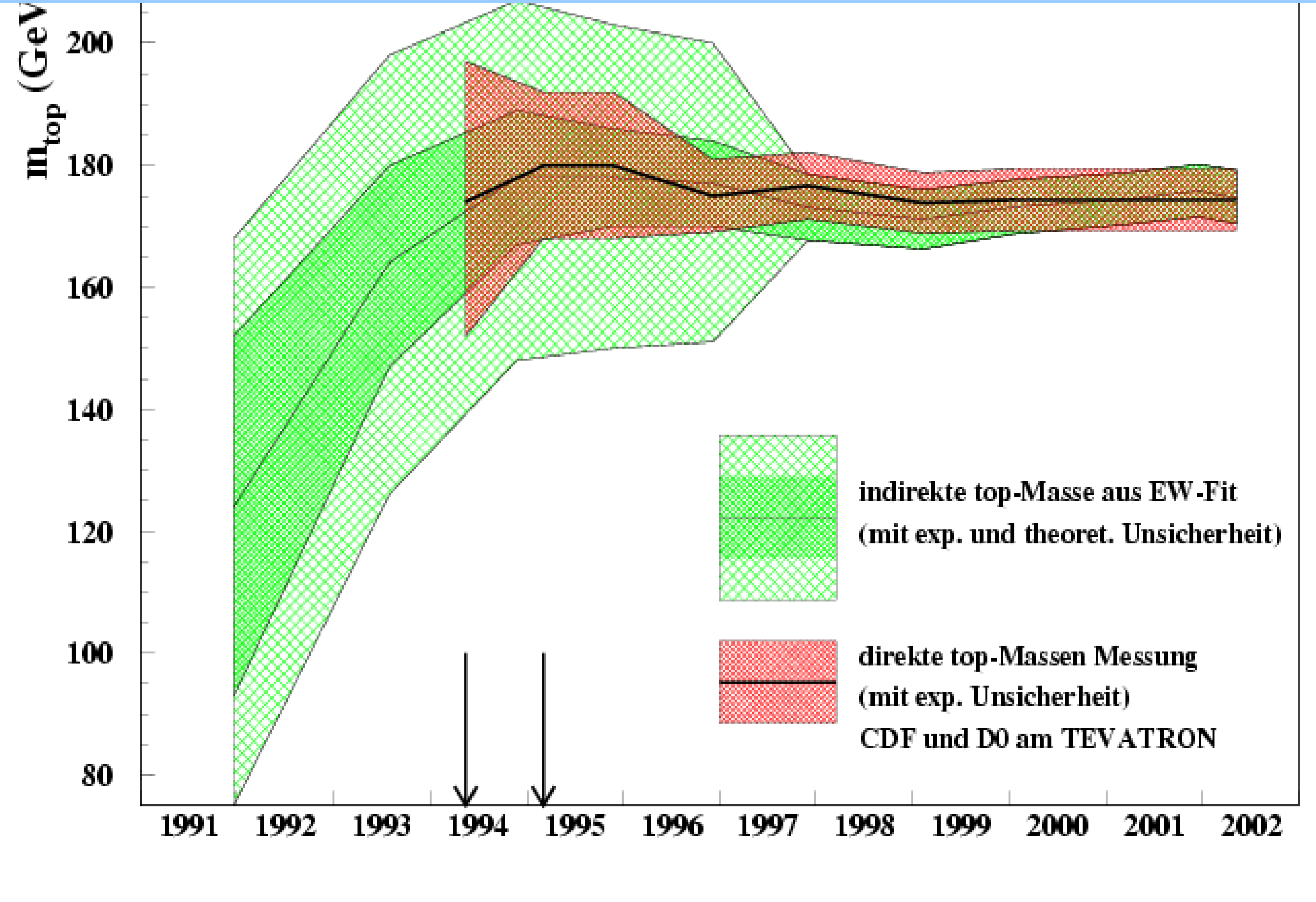
comparison :

precision measurement ⇔ correction

⇨ top quark mass prediction

Discovery of the Top Quark

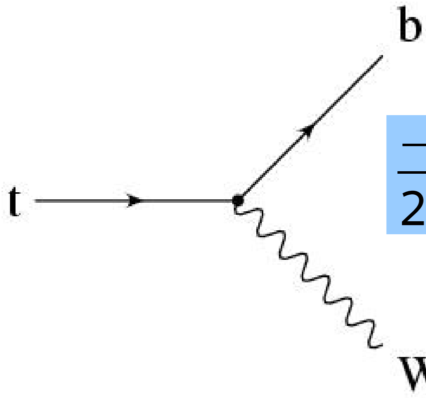




... discovered the top exactly where it was expected ...

Top Quark Lifetime

top quark decay :



$$\frac{-i\,g}{2\sqrt{2}}\,\bar{t}\,\gamma^{\mu}\left(1-\gamma^{5}\right)V_{tb}\,b\,W_{\mu}$$

$m_{top} \gg m_W$ ⇨ <u>real W</u> in top decay

$$\tau_t \sim \frac{1}{\left|V_{tb}\right|^2}\cdot\frac{1}{m_t^3} \approx 5\cdot 10^{-25}\,s$$

compare to b-quark:

$$\tau_b \sim \frac{1}{a\left|V_{cb}\right|^2 + b\left|V_{ub}\right|^2}\cdot\frac{1}{m_b^5} \approx 1.5\cdot 10^{-12}\,s$$

⇨ <u>the top quark is special :</u>

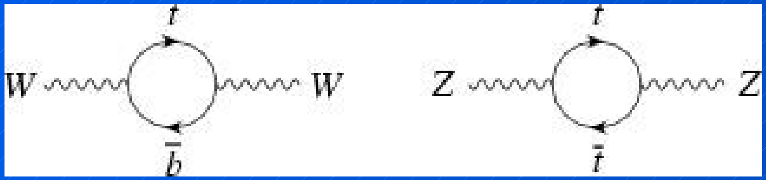
- completes quark sector
- large m_{top} ~ 180 GeV
- top decays fast as bare quark, no hadronization ($\tau_{had} \sim 10^{-23}$ s)
- top spin not depolarized by chromomagnetic interactions
- connection to EW symmetry breaking and new physics ... ?

Higgs-Boson coupling to fermions : $g \sim m_f$

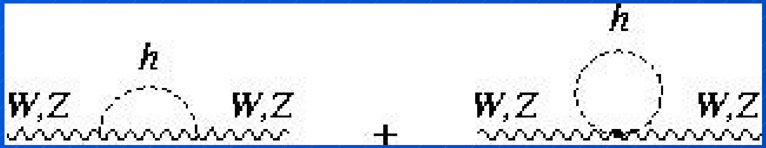
$m_t \sim v/\sqrt{2}$, Yukawa coupling $\lambda_t \sim 1$

Top Quark in the Standardmodel

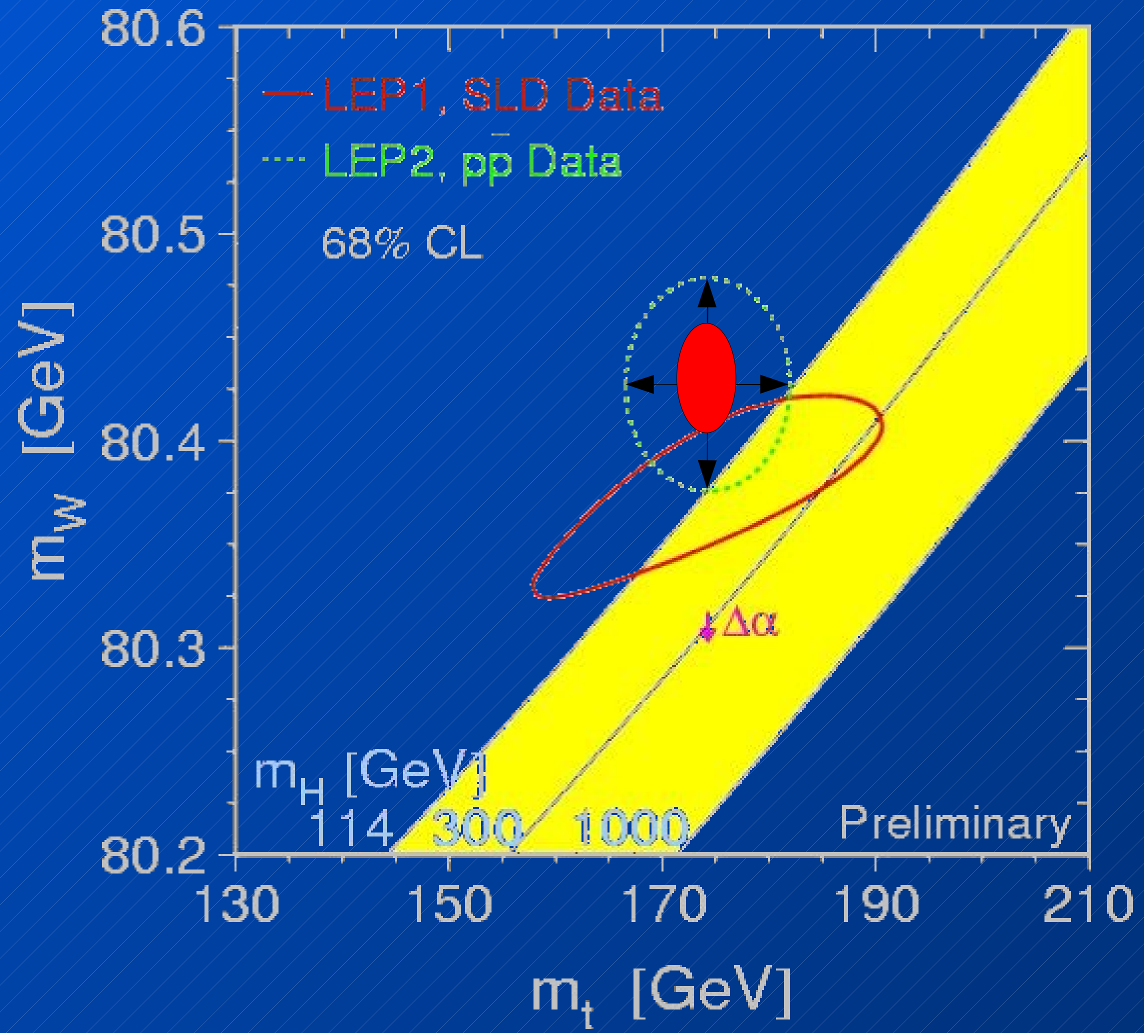
corrections to W and Z boson mass from top quark and Higgs boson loops allow prediction of the top quark and the Higgs boson mass



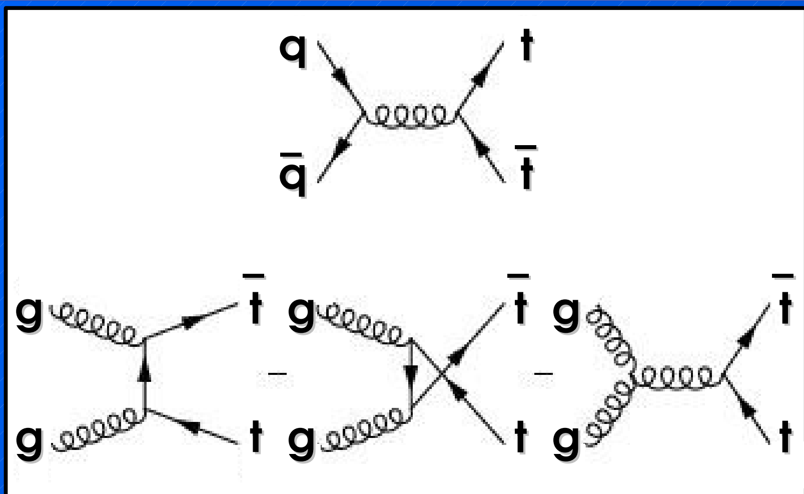
corrections: ~ m_{top}^2



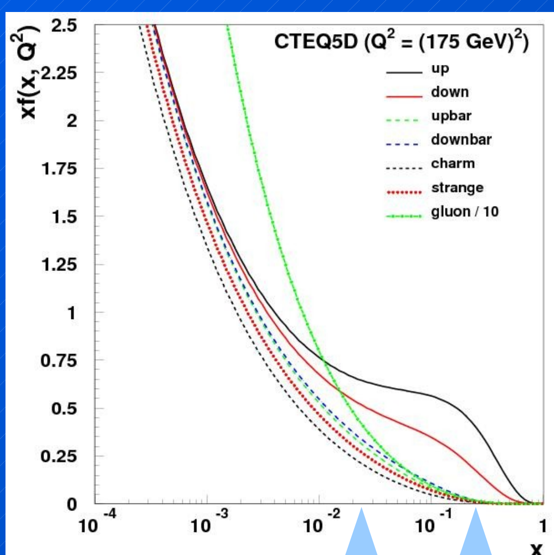
corrections: ~ ln (m_{higgs})



Strong Top Quark Production

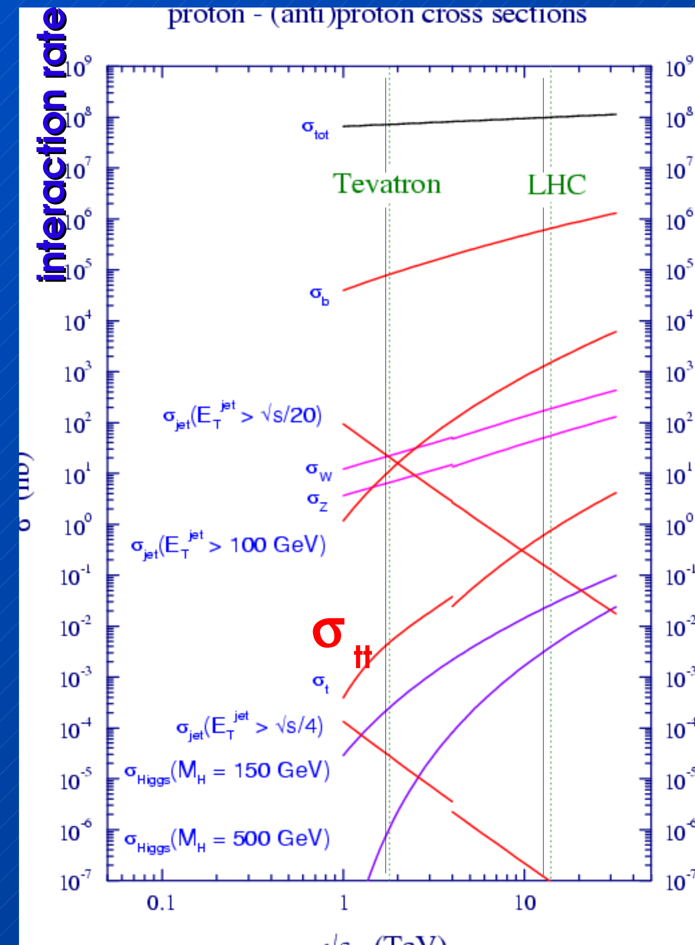


	Tevatron	LHC
$q\bar{q}$ ~	85 %	15%
gg ~	15 %	85%



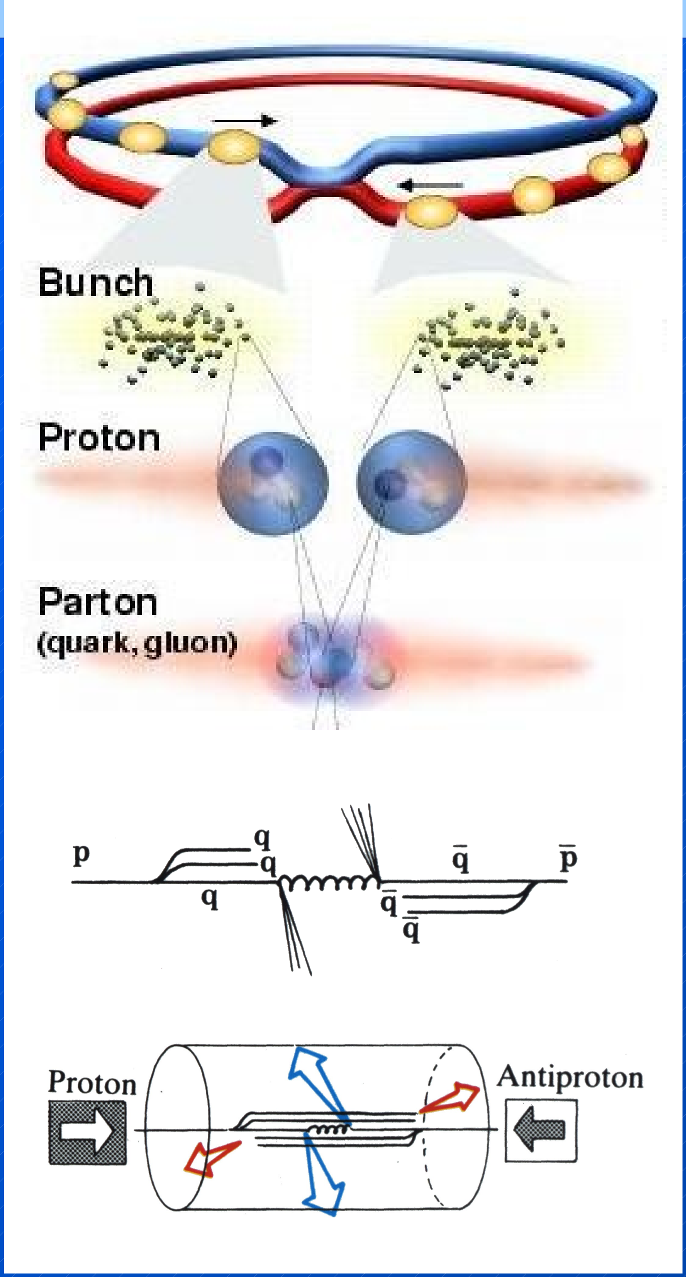
LHC Tevatron

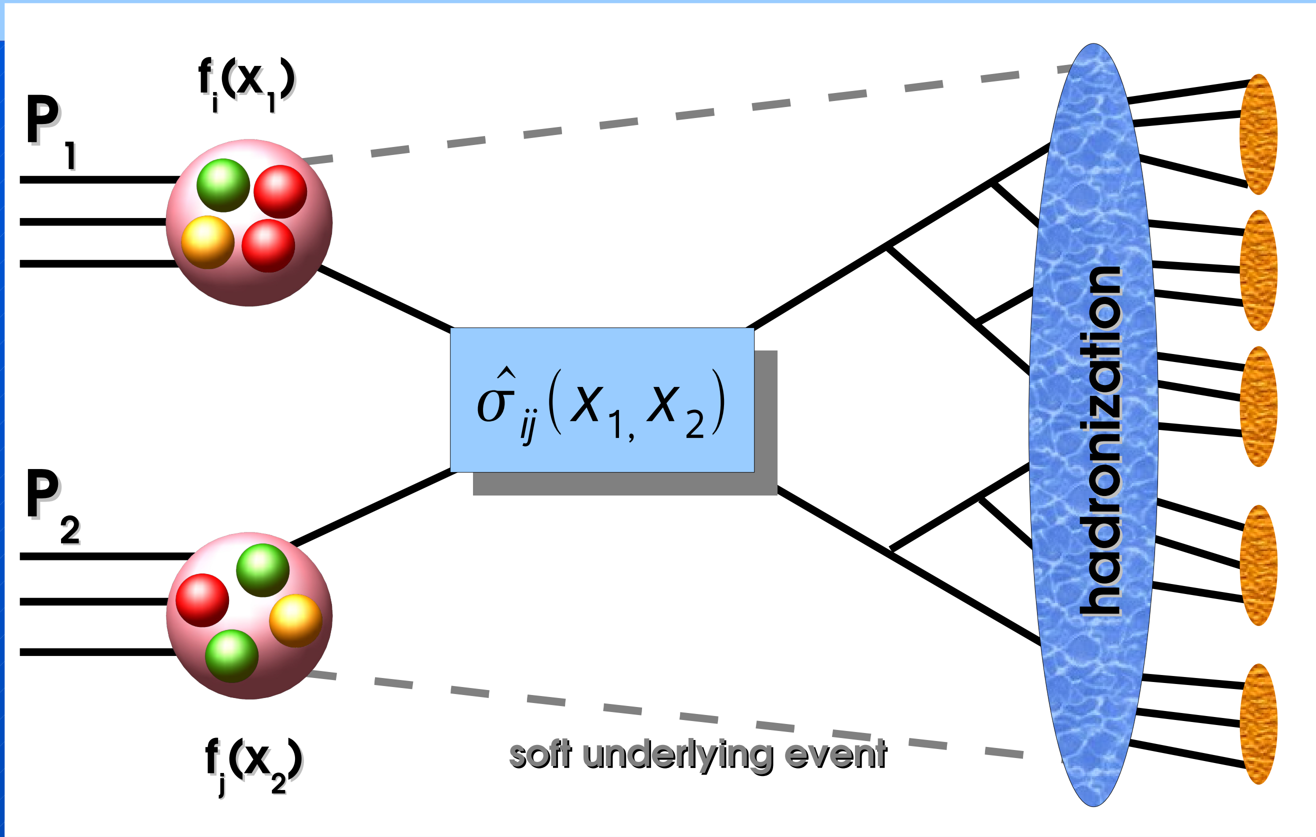
	Run I	Run II (2 fb^{-1})	LHC (10 fb^{-1})
nr ttbar (m_t sample $\geq$ 1 b-tag)	20	800	8 * 10^6



Experimental Tools

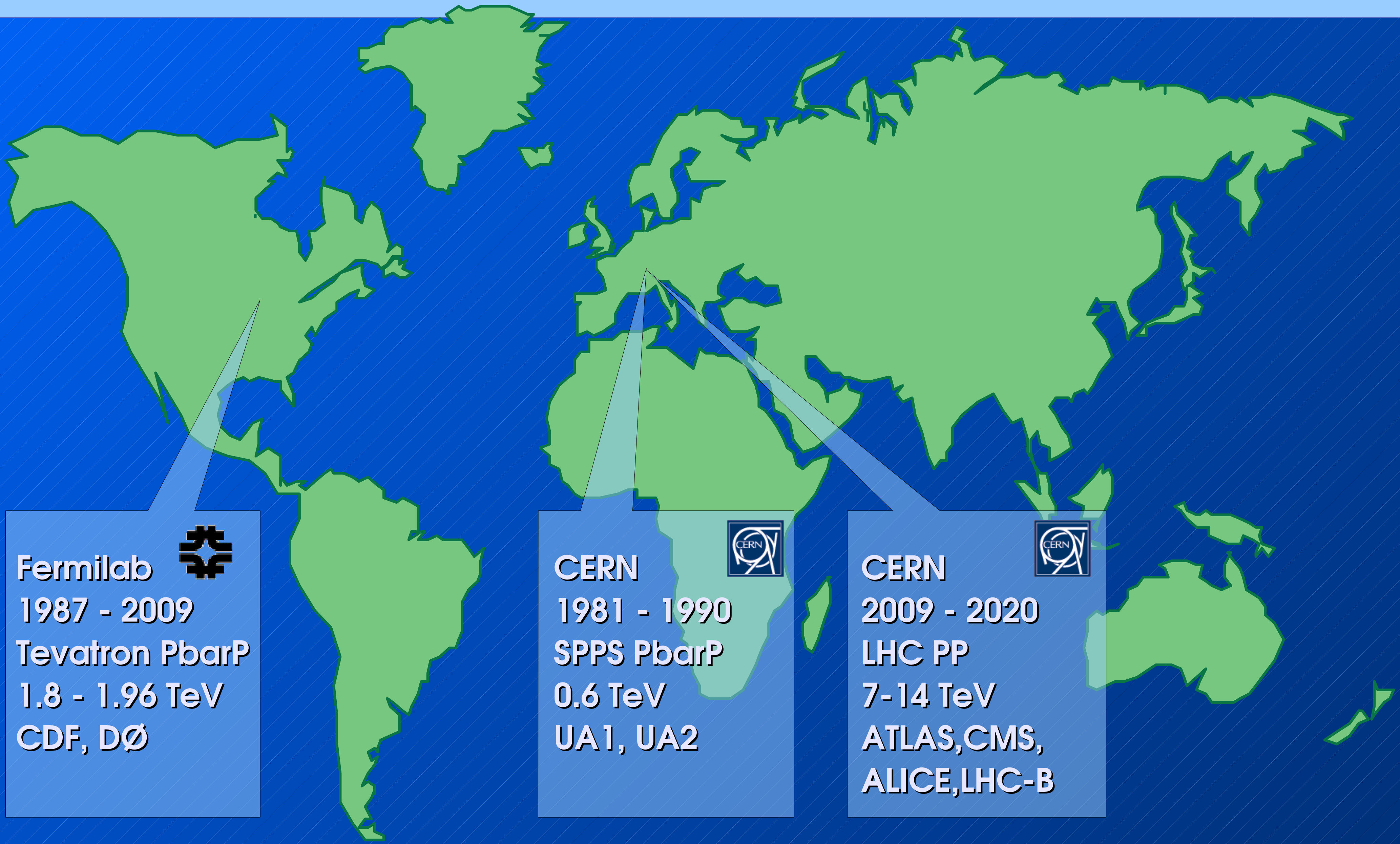
Parton-Parton Interactions





non-perturbative universal PDFs	hard interaction	hadron shower

Hadron Colliders

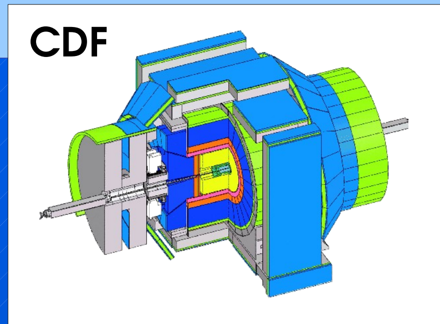


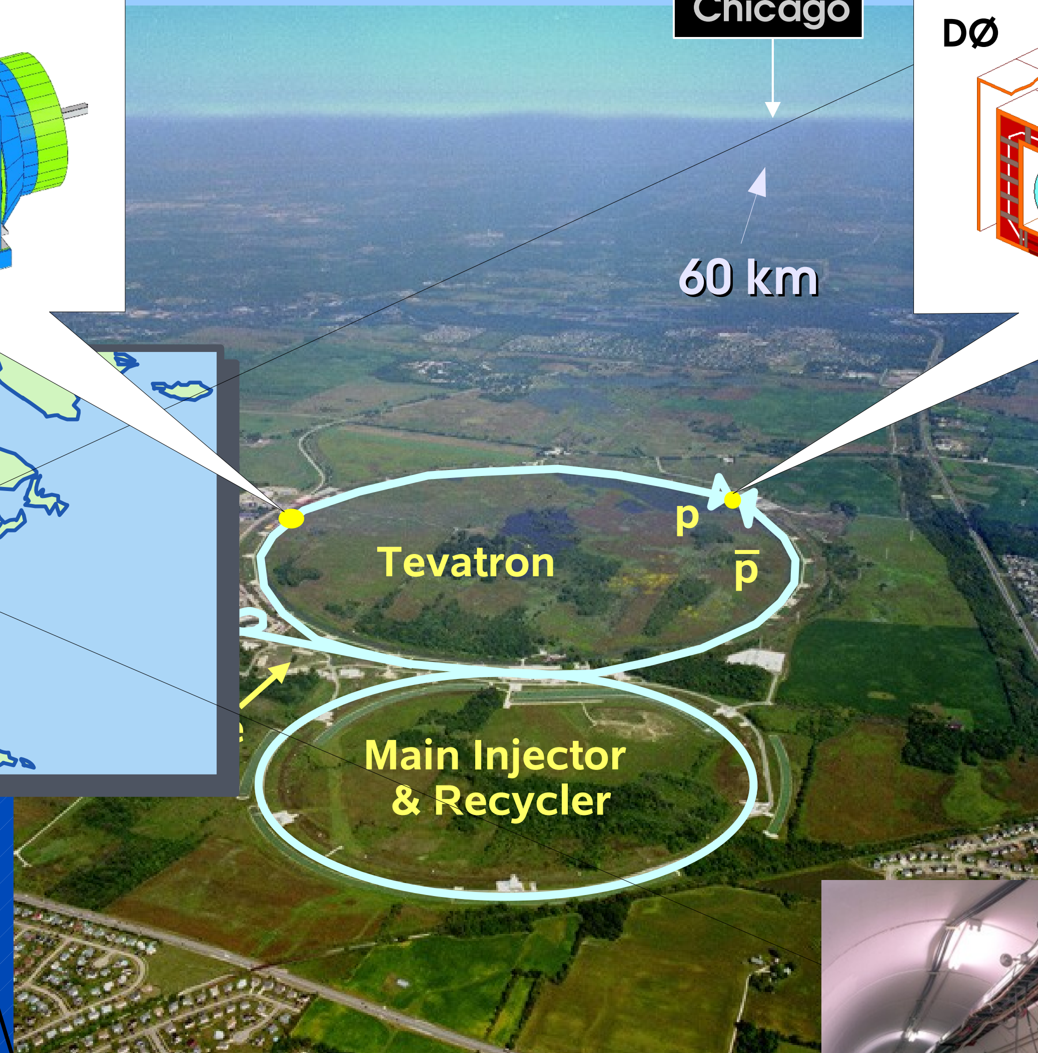
Fermilab
1987 - 2009
Tevatron PbarP
1.8 - 1.96 TeV
CDF, DØ

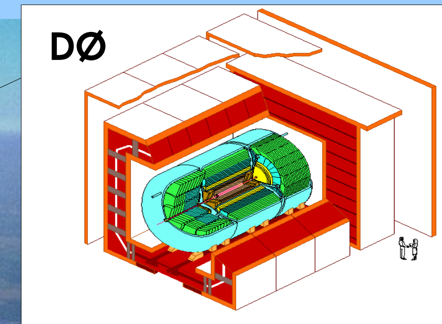
CERN
1981 - 1990
SPPS PbarP
0.6 TeV
UA1, UA2

CERN
2009 - 2020
LHC PP
7-14 TeV
ATLAS,CMS,
ALICE,LHC-B

The TEVATRON at Fermilab (1)







$\sqrt{s} = 1.96$ TeV
$\Delta t = 396$ ns

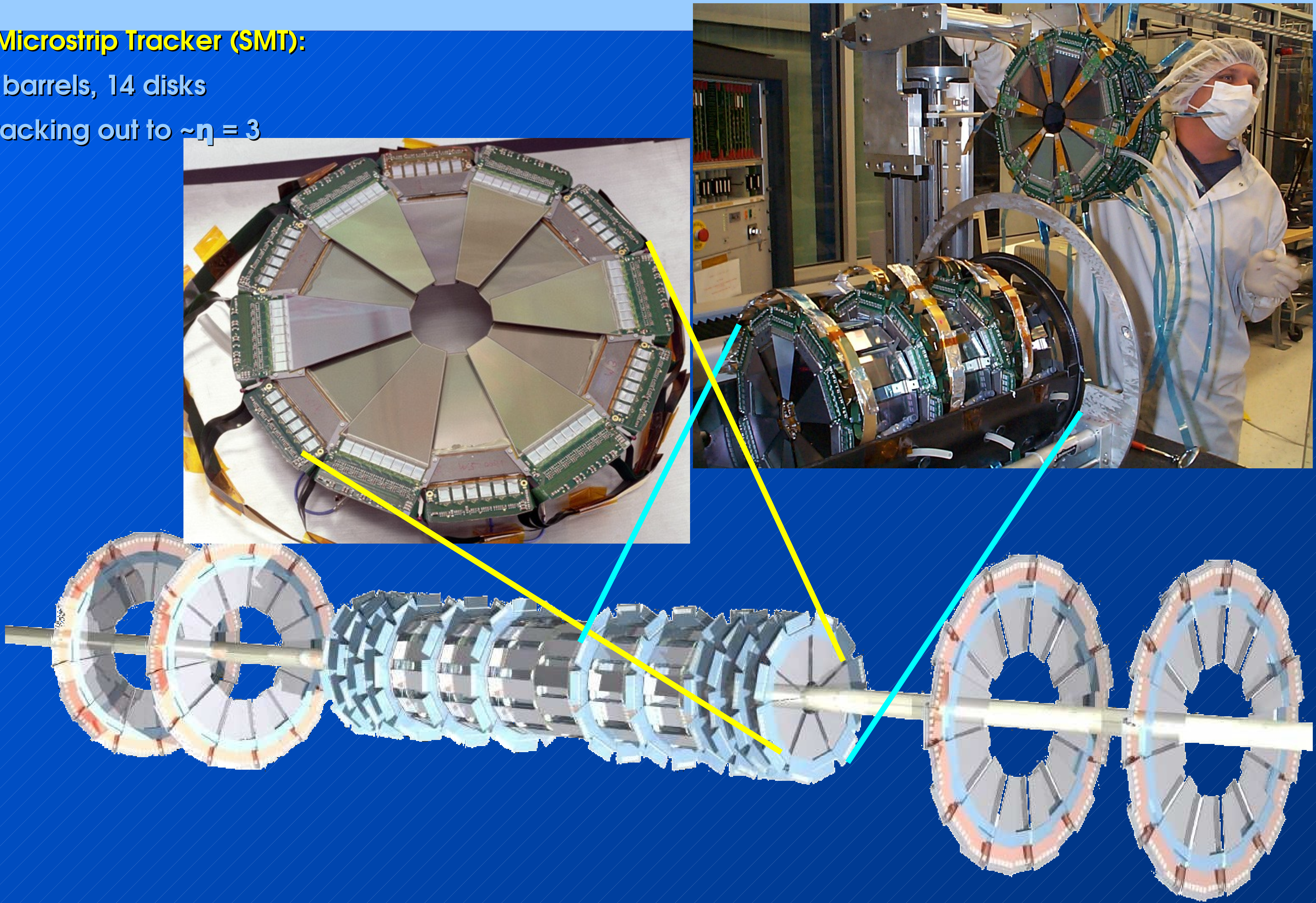
Run I 1987 (92)-95 $L_{int} \sim 125\ pb^{-1}$

Run II 2001-09(?)

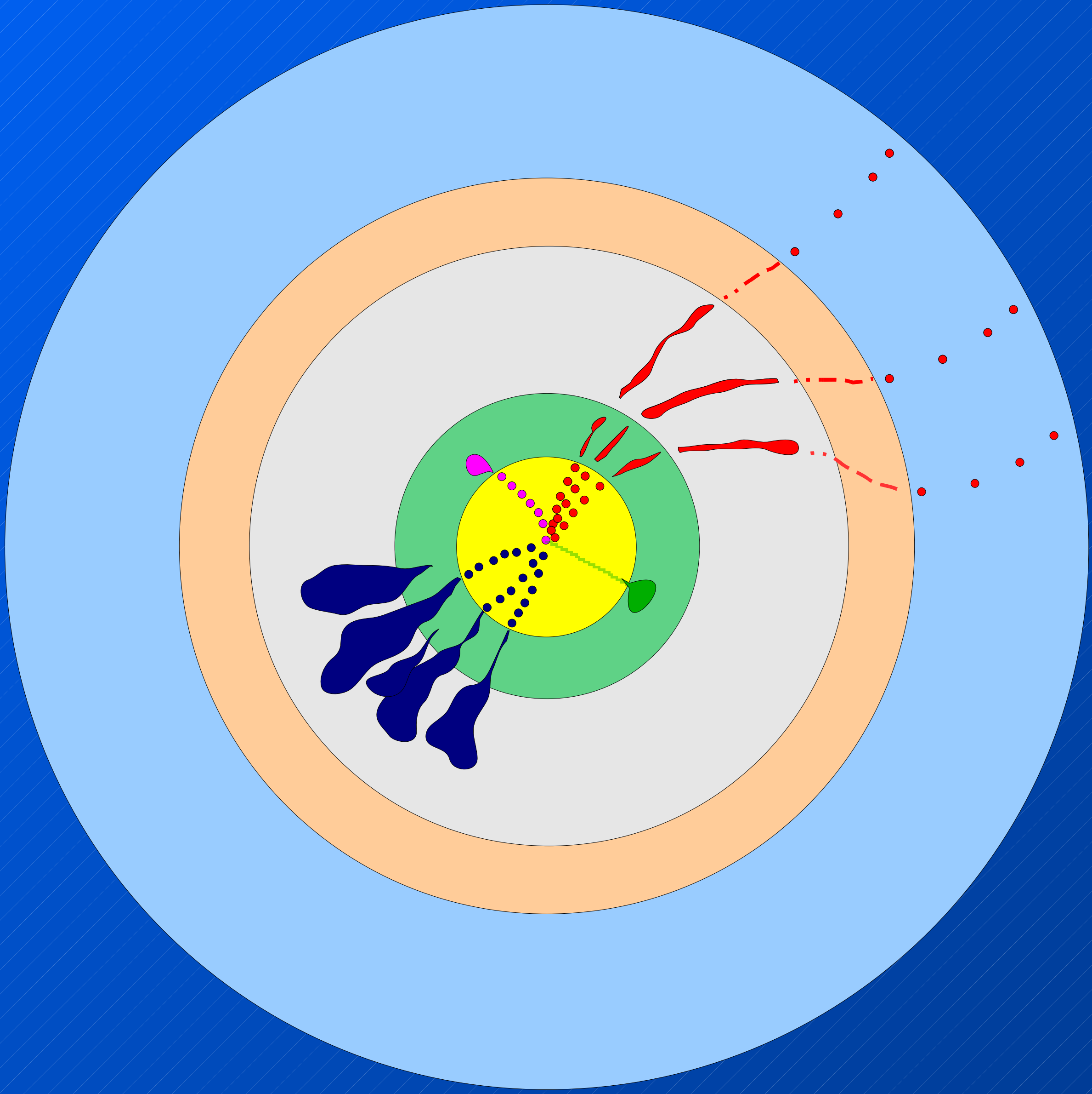
> 40- to 90-times larger dataset at increased energy

The DØ Silicon Tracker

- **Silicon Microstrip Tracker (SMT):**
  - 6 barrels, 14 disks
  - Tracking out to ~η = 3



Particle Identification



Muon (high energy)

(medium ene.)

(low energy)

Photon

Electron

Quark → Jet

Tracking detector

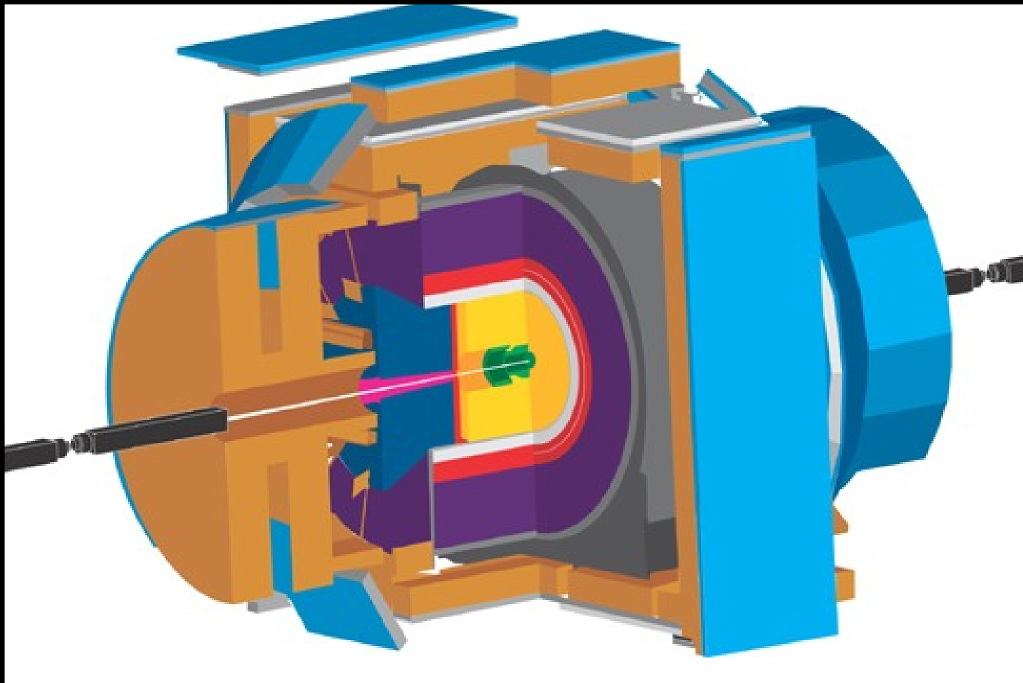
Electron calorimeter

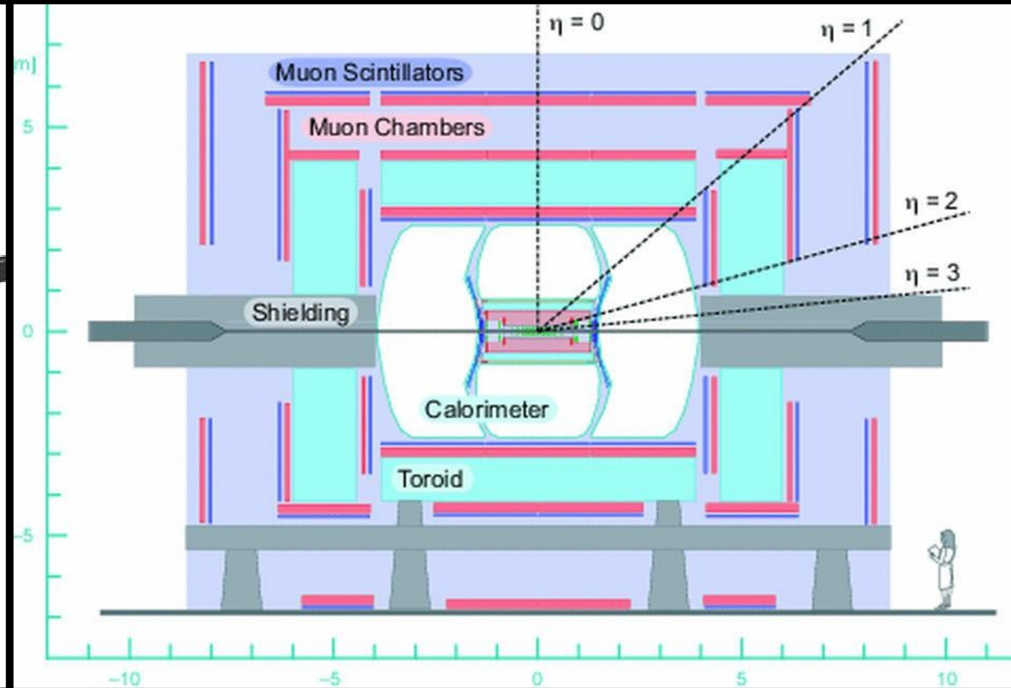
Hadron calorimeter

Magnet coil

Muon chambers

The CDF and DØ Experiment





- inner tracking detectors
  silicon micro vertex detectors
  drift chamber or scintillating fiber tracker
- solenoid magnet (bending of charged particles)
- electromagnetic and hadronic calorimeter
- muon chambers
- fast trigger and data acquisition systems

The DØ Experiment

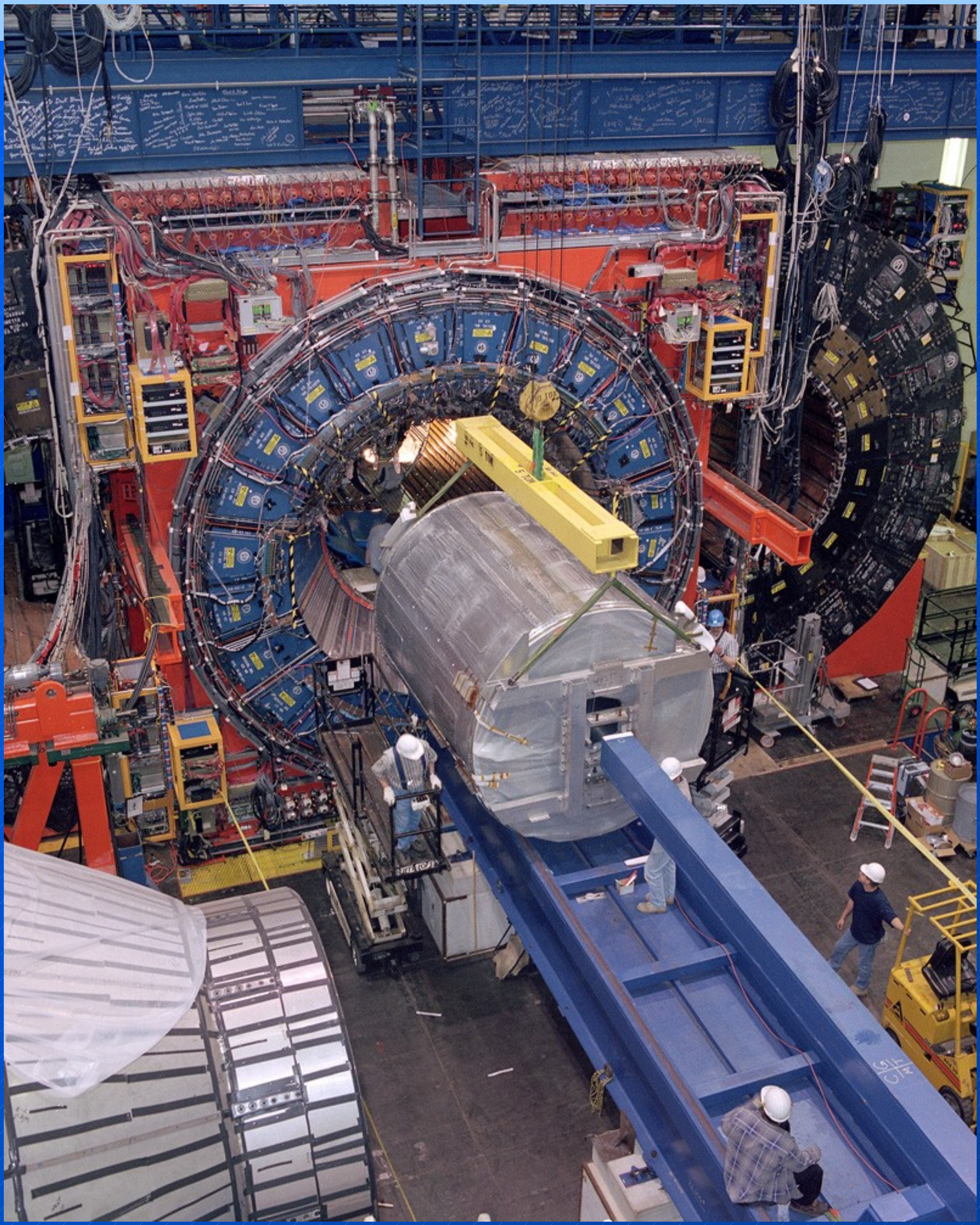
Uranium/Liquid Argon calorimeter

<u>resolutions:</u>

EM: $\sigma_E/E = 15\% / \mathrm{sqrt}(E)$

HAD: $\sigma_E/E = 50\% / \mathrm{sqrt}(E)$

The CDF Experiment

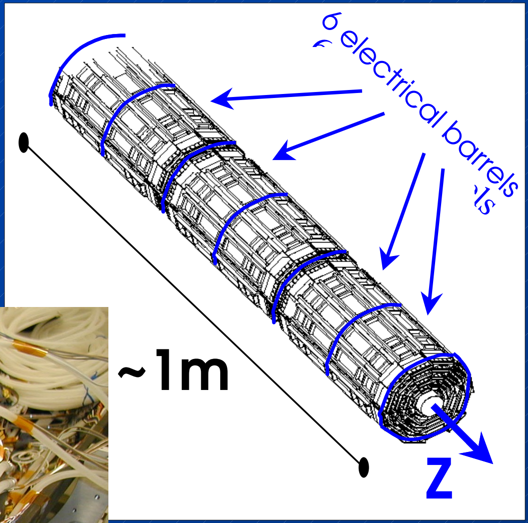


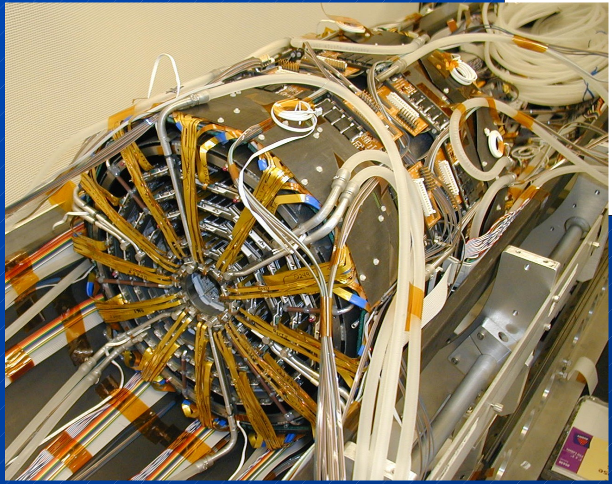
drift chamber (COT)
radius 40 - 137 cm, |z| < 160 cm
60 axial, 24 stereo hits (3°)

scintillator based calorimeter

EM: σ_E/E = 13.5% / sqrt(E)

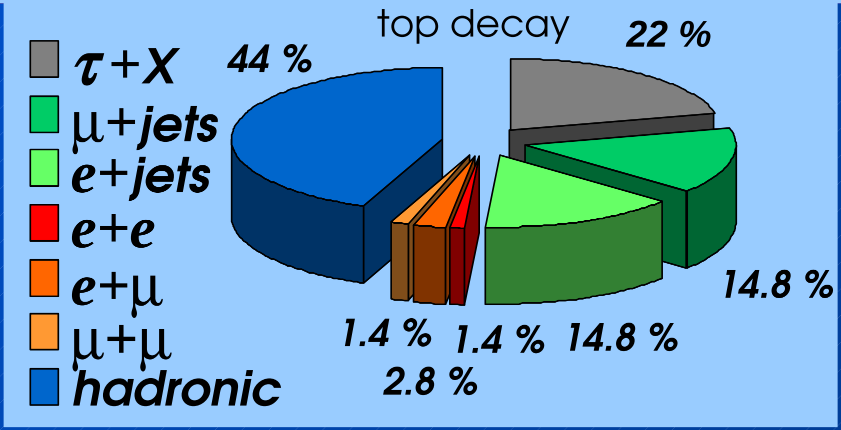
HAD: σ_E/E = 50% / sqrt(E)





W-Decay Determines Topology

Top quarks decay predominantly (~100%) to a W-Boson and a b-quark



Top-Antitop Signatures:

`dilepton channel'

5% : 2 jets, 2 charged leptons, 2 ν

'lepton+jets channel'

30%: 4 jets, 1 charged lepton, 1 ν

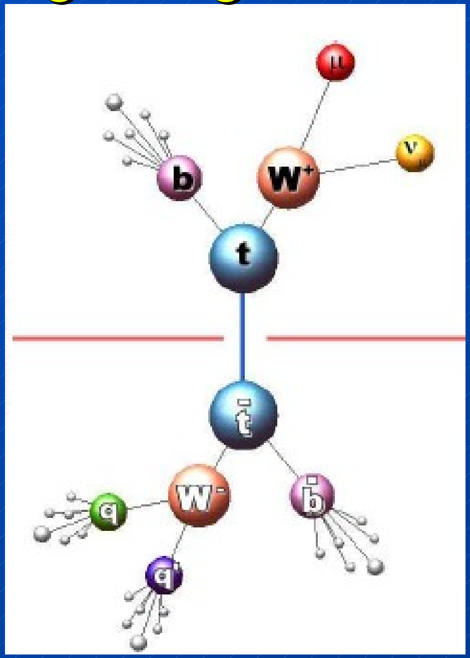
'all-jets channel'

40%: 6 jets

always 2 jets are b-jets

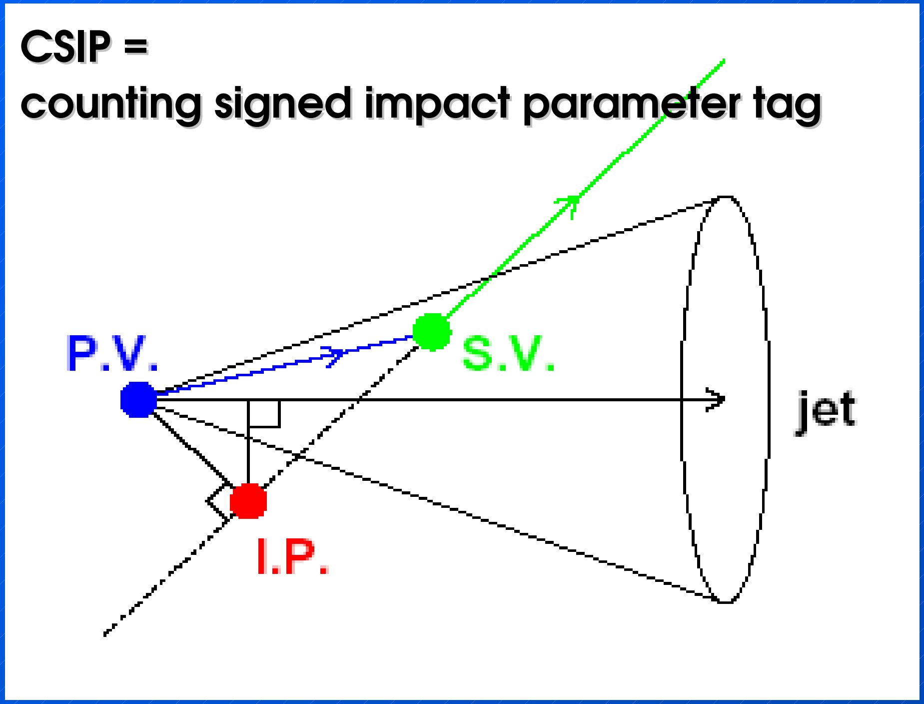
also look for lifetime- or μ-tag

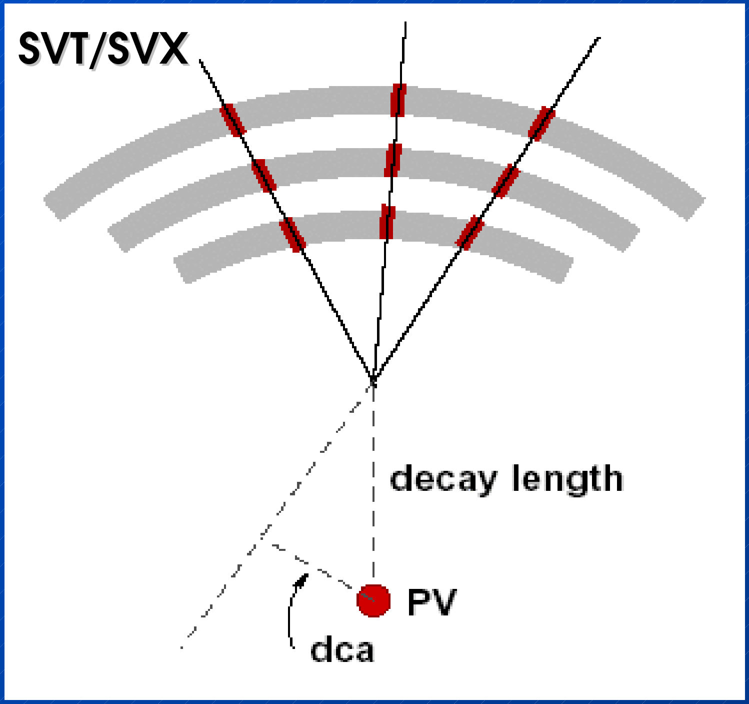
signal signature



let's look at the various topologies ...

b-tagging in CDF and DØ



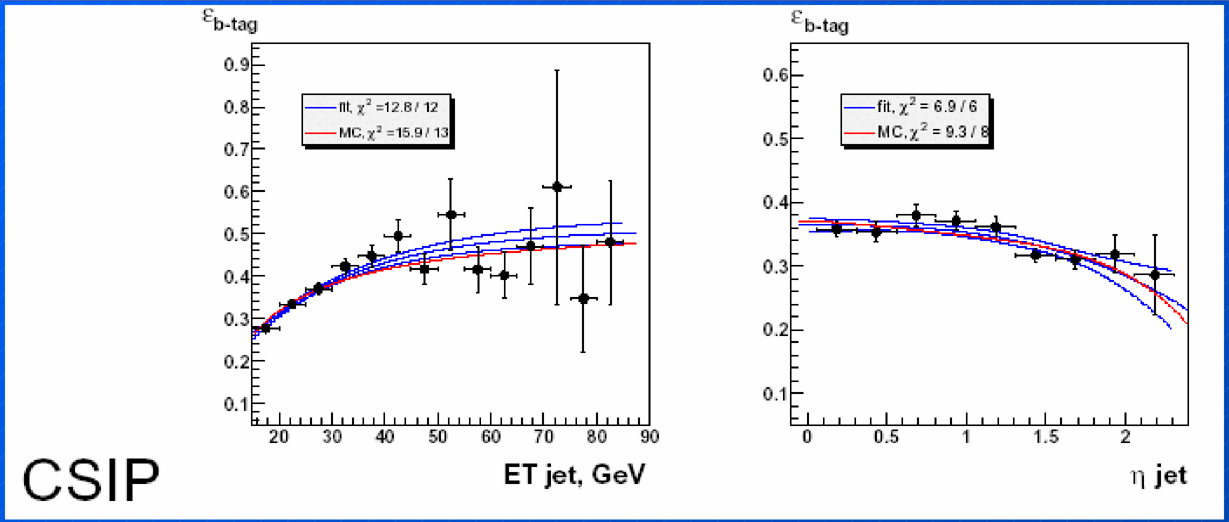


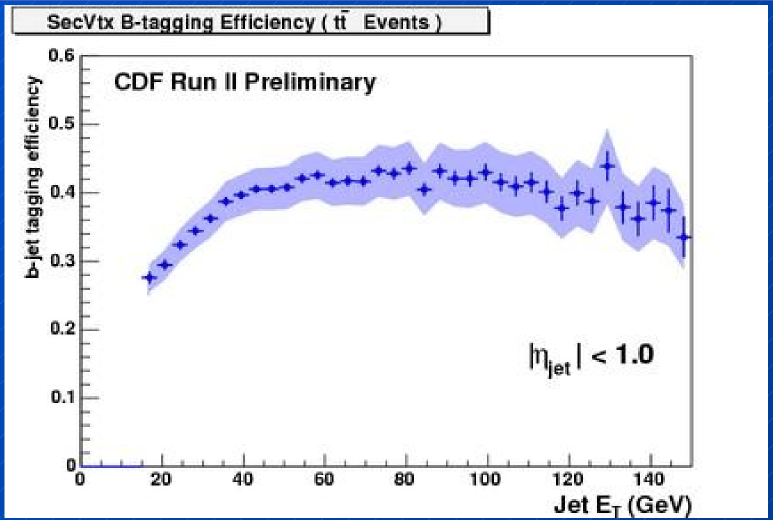
- count the number of track with large positive DCA significance σ
- jet is tagged if
  $N_{tr}(\sigma>2)>3$ or
  $N_{tr}(\sigma>3)>2$

- explicitely reconstruct 3d vertices out of track jets
- cut on decay length significance

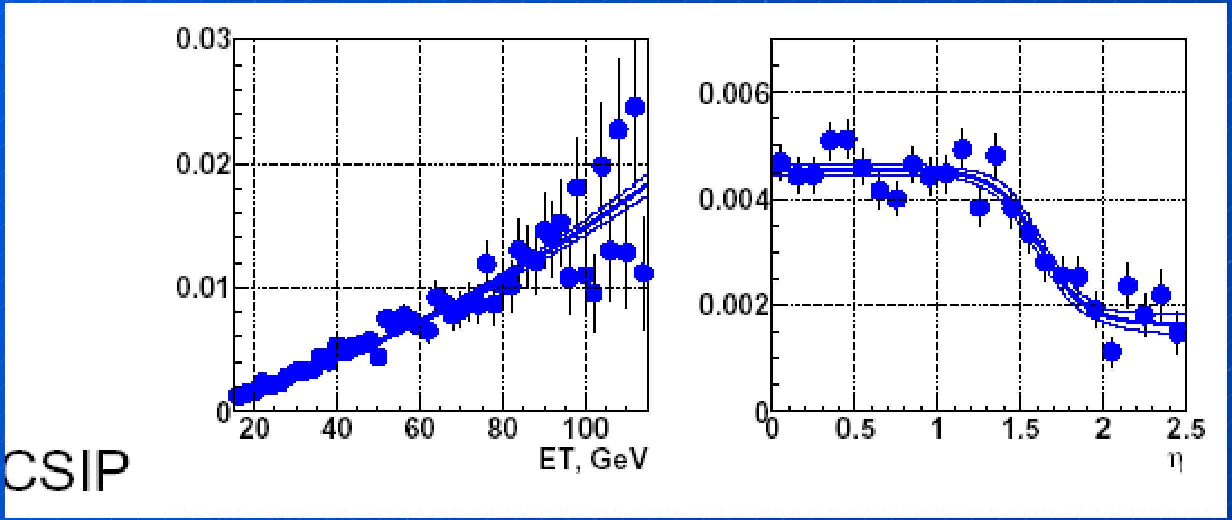
⇨ can also tag muon in jet from soft-lepton decay

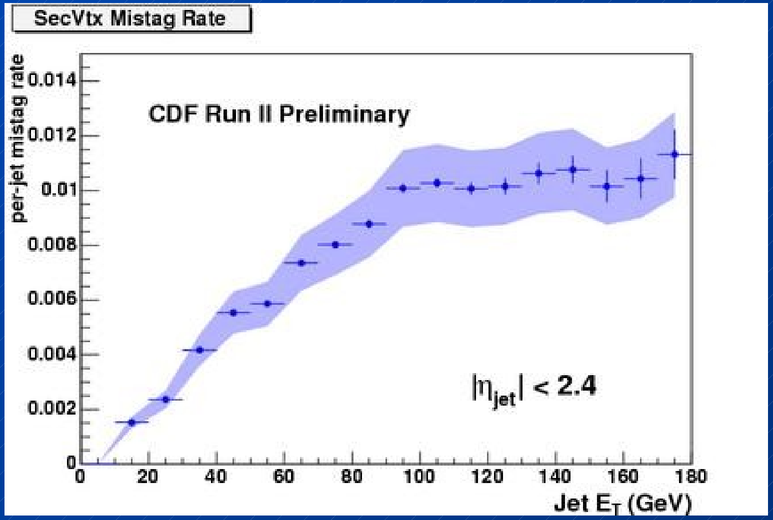
b-tagging Efficiency and Fake Rate





measured in muon-tagged jet sample

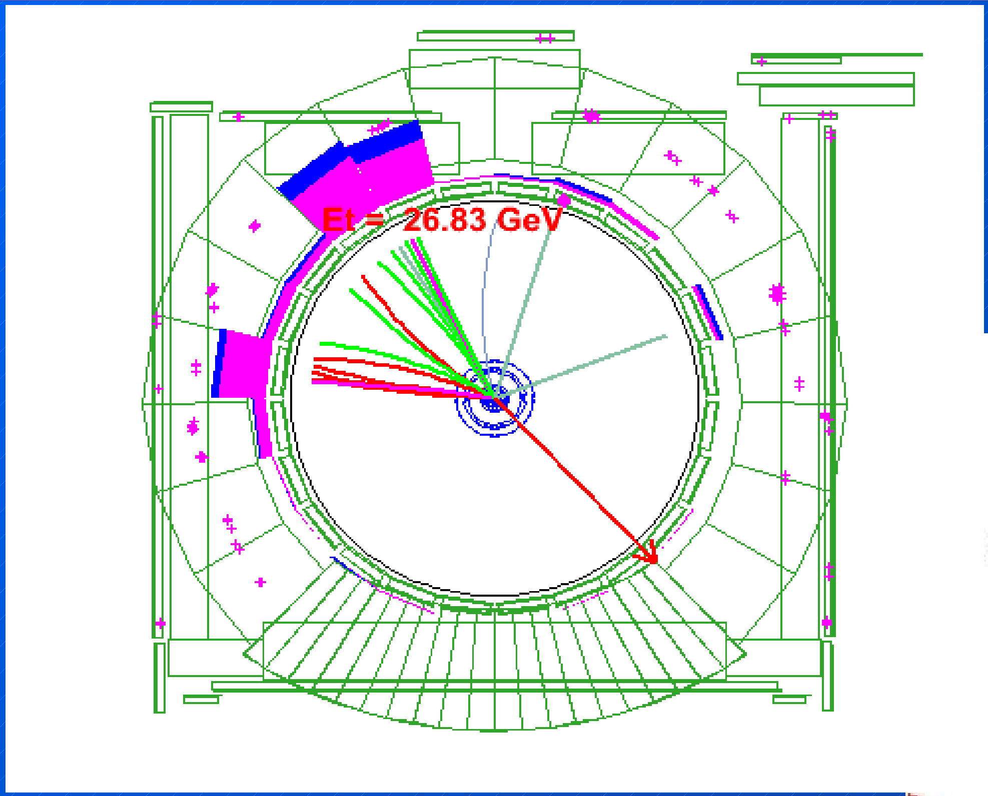


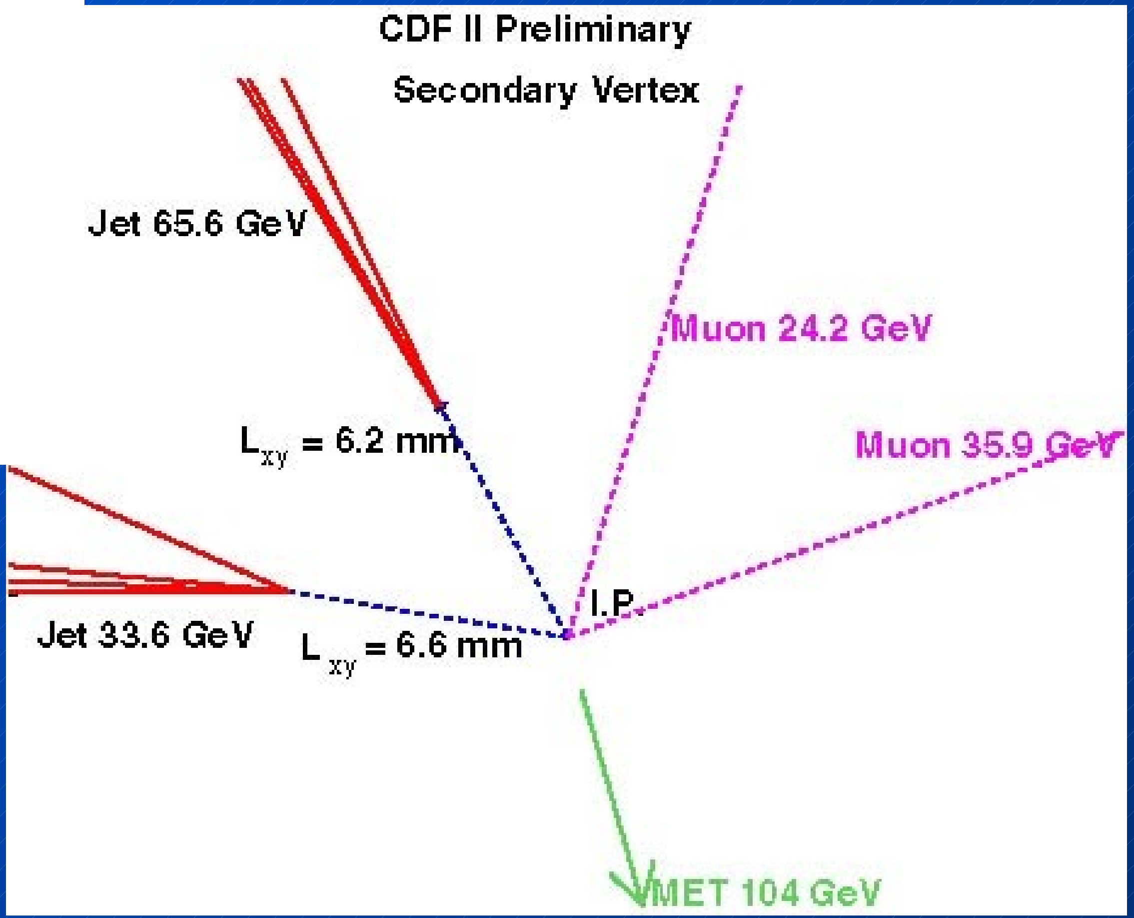


measured in inclusive sample, converted to light-tag rate using MC

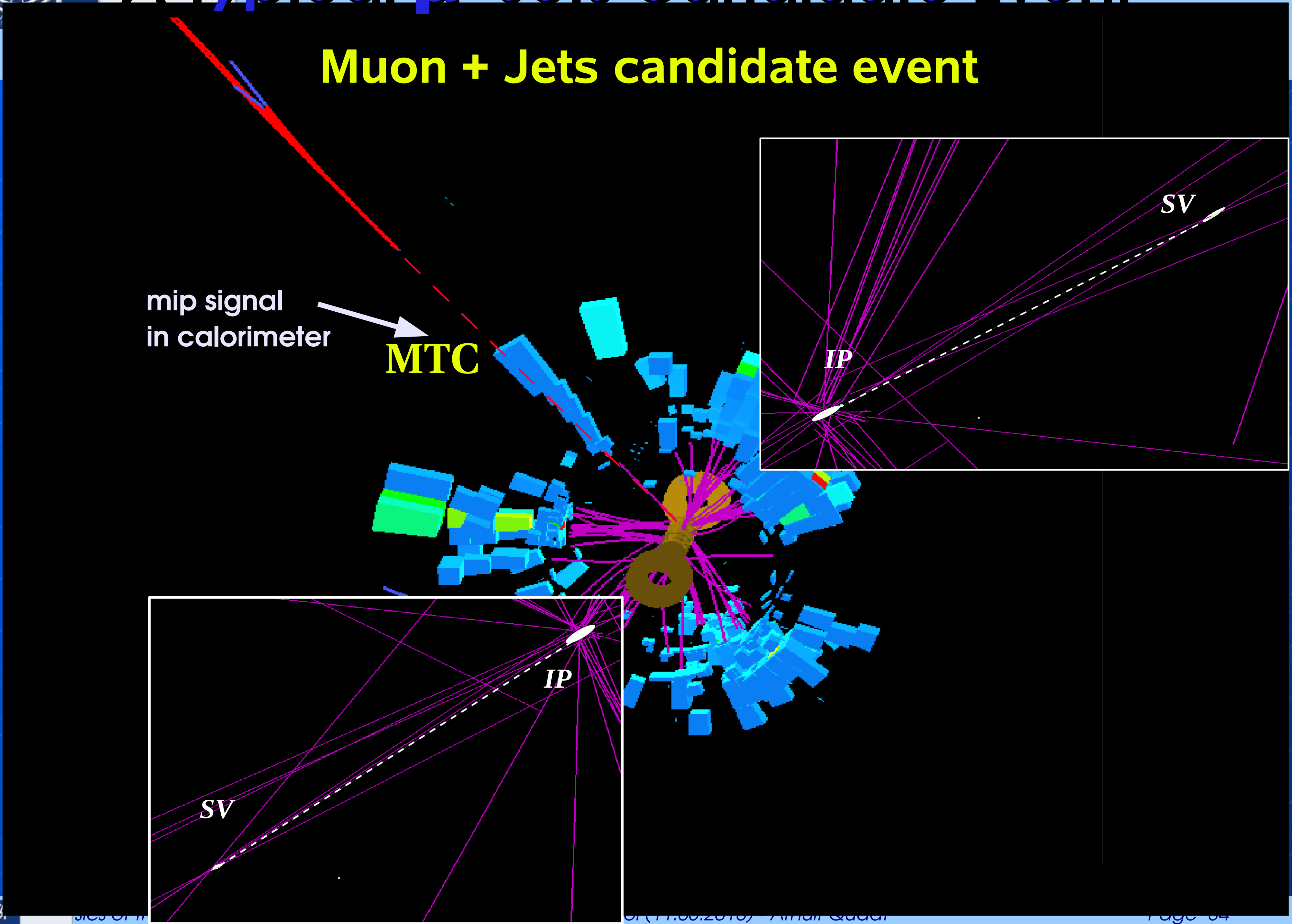
DØ CSIP/SVT slightly higher/lower fake rate ⇒ CDF/DØ similar performance

An Example μμ-Event





A Typical μ+Jets Candidate Event



Search for and Discovery of the Top Quark

Table 1.2. History of the search for the top quark at e^+e^- and at hadron colliders. The quoted uncertainties for the top quark mass from the 1995 discovery publications are statistical and systematic uncertainties, respectively.

Year	Collider	Particles	References	Limit on m_t
1979-84	PETRA (DESY)	e^+e^-	[50]-[63]	> 23.3 GeV/c^2
1987-90	TRISTAN (KEK)	e^+e^-	[64]-[68]	> 30.2 GeV/c^2
1989-90	SLC (SLAC), LEP (CERN)	e^+e^-	[69]-[72]	> 45.8 GeV/c^2
1984	Sp$\bar{p}$S (CERN)	$p\bar{p}$	[75]	> 45.0 GeV/c^2
1990	Sp$\bar{p}$S (CERN)	$p\bar{p}$	[76, 77]	> 69 GeV/c^2
1991	TEVATRON (FNAL)	$p\bar{p}$	[78]-[80]	> 77 GeV/c^2
1992	TEVATRON (FNAL)	$p\bar{p}$	[81, 82]	> 91 GeV/c^2
1994	TEVATRON (FNAL)	$p\bar{p}$	[84, 85]	> 131 GeV/c^2
1995	TEVATRON (FNAL)	$p\bar{p}$	[42]	$= 174 \pm 10^{+13}_{-12}$ GeV/c^2
			[43]	$= 199^{+19}_{-21} \pm 22$ GeV/c^2

Search for and Discovery of the Top Quark

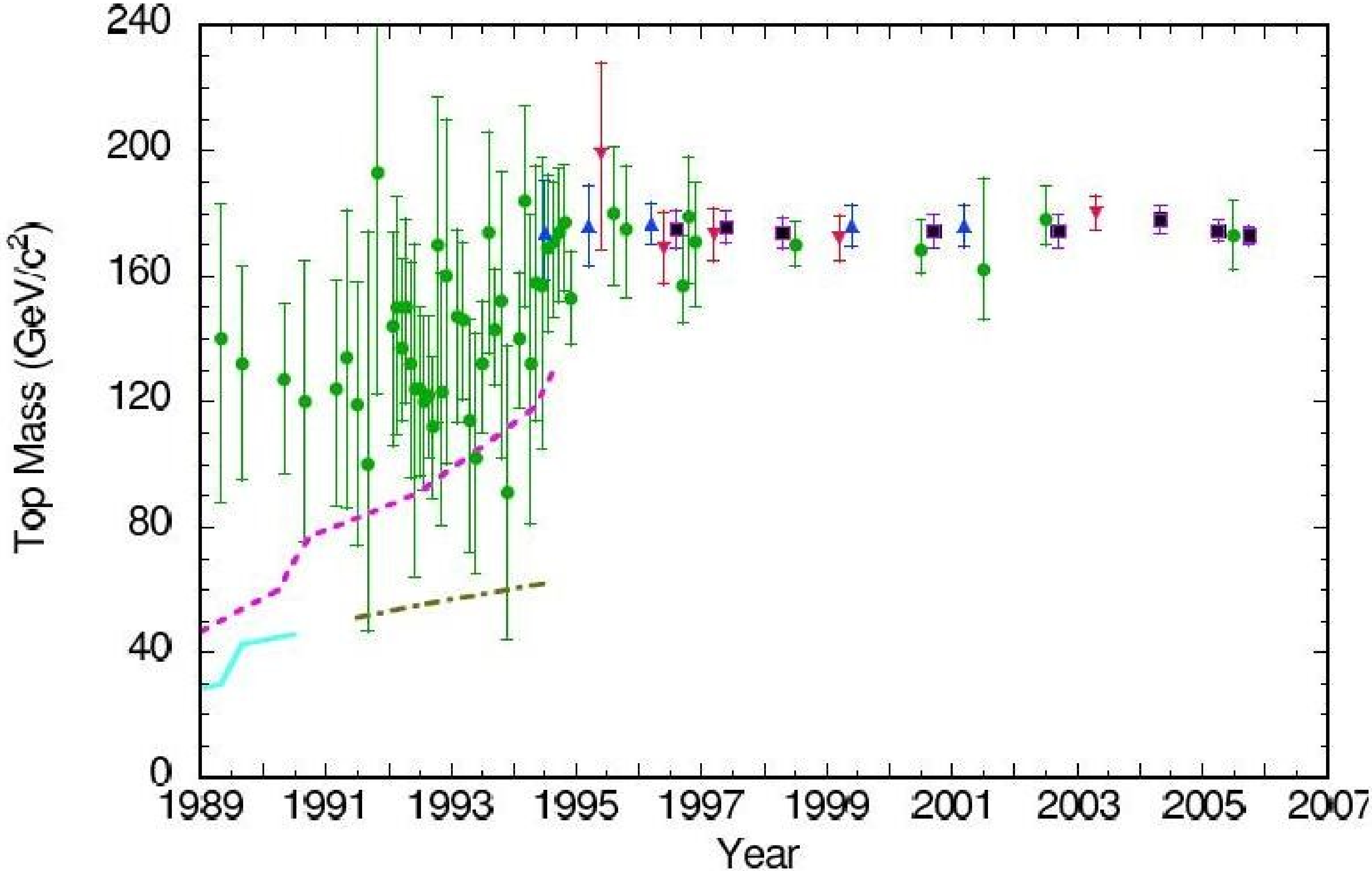


Fig. 1.12. History of the limits on or measurements of the top quark mass (updated Sept. 1995 by C. Quigg from [89]: (•) Indirect bounds on the top-quark mass from precision electroweak data; (■) World-average direct measurement of the top-quark mass (including preliminary results); (▲) published CDF and (▼) DØ measurements; Lower bounds from $p\bar{p}$ colliders $Sp\bar{p}S$ and the TEVATRON are shown as dash-dotted and dashed lines, respectively, and lower bounds from e^+e^- colliders (PETRA, TRISTAN, LEP and SLC) are shown as a solid light grey line.