The 3rd generation quarks

Matteo Negrini
INFN-Bologna

Hint for a 3rd quark generation

The discovery of the charm quark in 1974 closed the 2 quark generations

Kobayashi and Maskawa in 1973 (Nobel 2008) pointed out that CP violation can not occur if the flavor-changing weak interaction occurs between 2 quark generations but is possible with 3 generations (extension of Cabibbo theory)

If so, the weak interaction down-type partners of the up-type quarks would result from the unitary complex matrix:

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

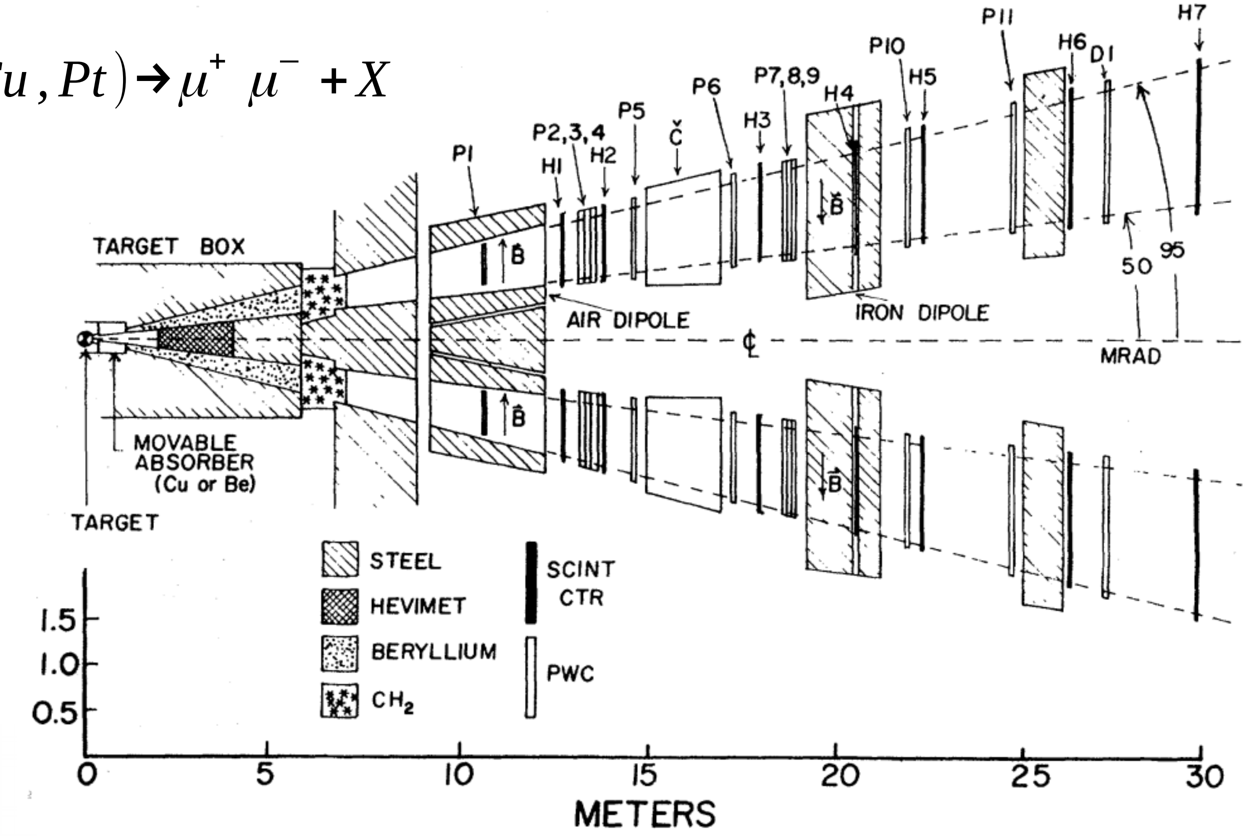
containing a non-trivial complex phase, responsible of CP violation.

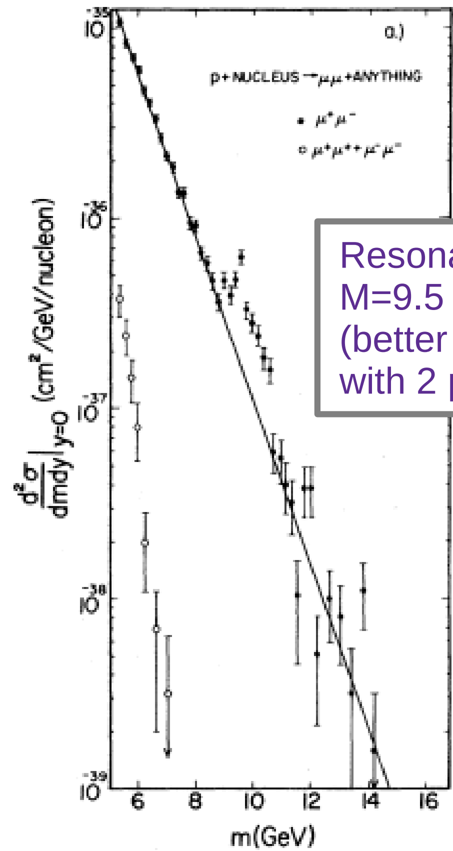
INFN

Discovery of the Υ resonances

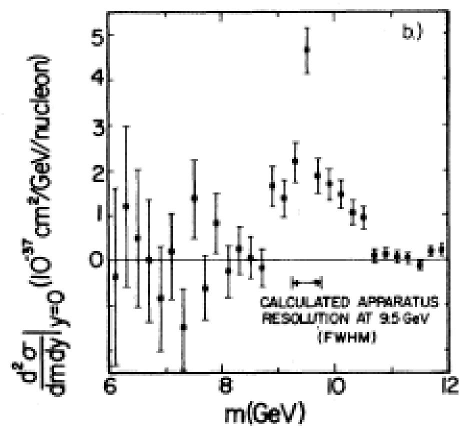
Lederman et al. (1977)
Look for peaks in the μ+μ- mass spectrum at energies > 3 GeV using 400 GeV proton collisions on target at Fermilab. Detector: 2 arms magnetic spectrometer (mass resolution Δm/m~2%)

$$p+(Cu,Pt)\rightarrow\mu^{+}\ \mu^{-}\ +X$$





Resonance at M=9.5 GeV (better agreement with 2 peaks)



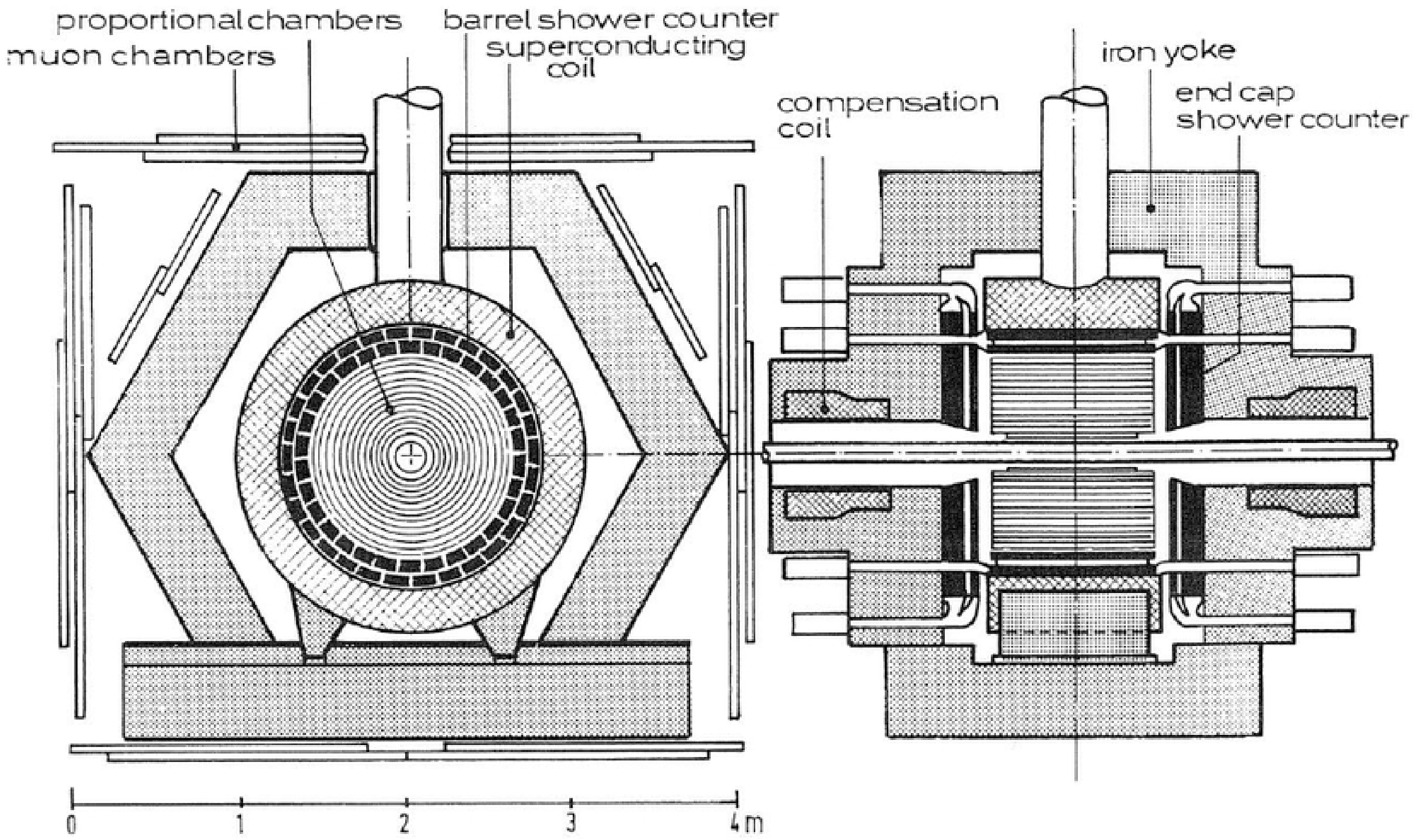
Discovery of the Y resonances

PLUTO and DASP-II (1978)

Soon after, the Y resonances were studied in $e^+ e^-$ annihilations at the DORIS storage ring at DESY (center of mass energy up to 10 GeV)

Resolved the 2 states Y and Y', and determine the b-quark charge

The PLUTO detector



Discovery of the Y resonances

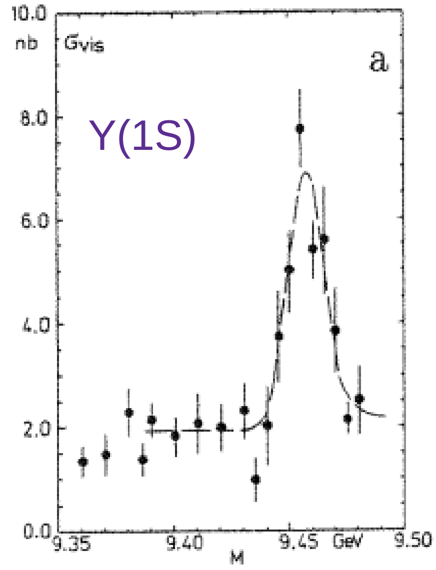
Observation of the process
$e^+ e^- \rightarrow$ hadrons

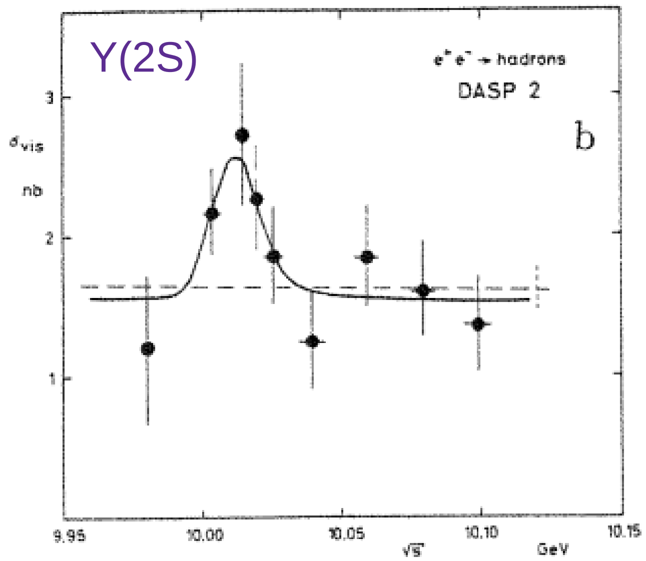
The integral of the Breit-Wigner is:

$$\int \sigma_{BW}\, dE = \frac{6\pi^2}{M_R^2} \frac{\Gamma_{ee}\Gamma_{had}}{\Gamma_{tot}}$$

Assuming $\Gamma_{had} \approx \Gamma_{tot}$ it was determined Γ_{ee}~1 keV

This value, in the quarkonium model explanation as bound $b\bar{b}$ state, favors the b-quark charge assignment to be -1/3



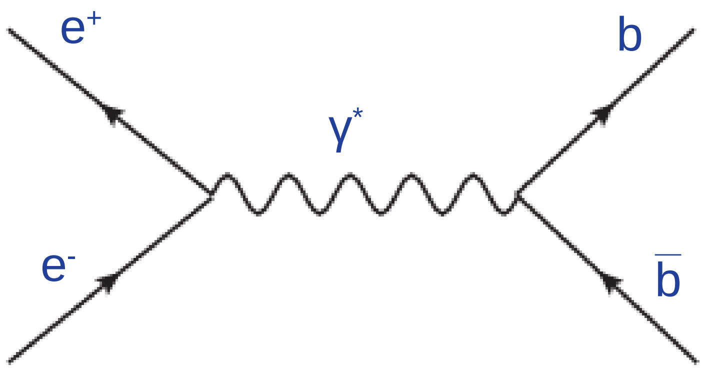


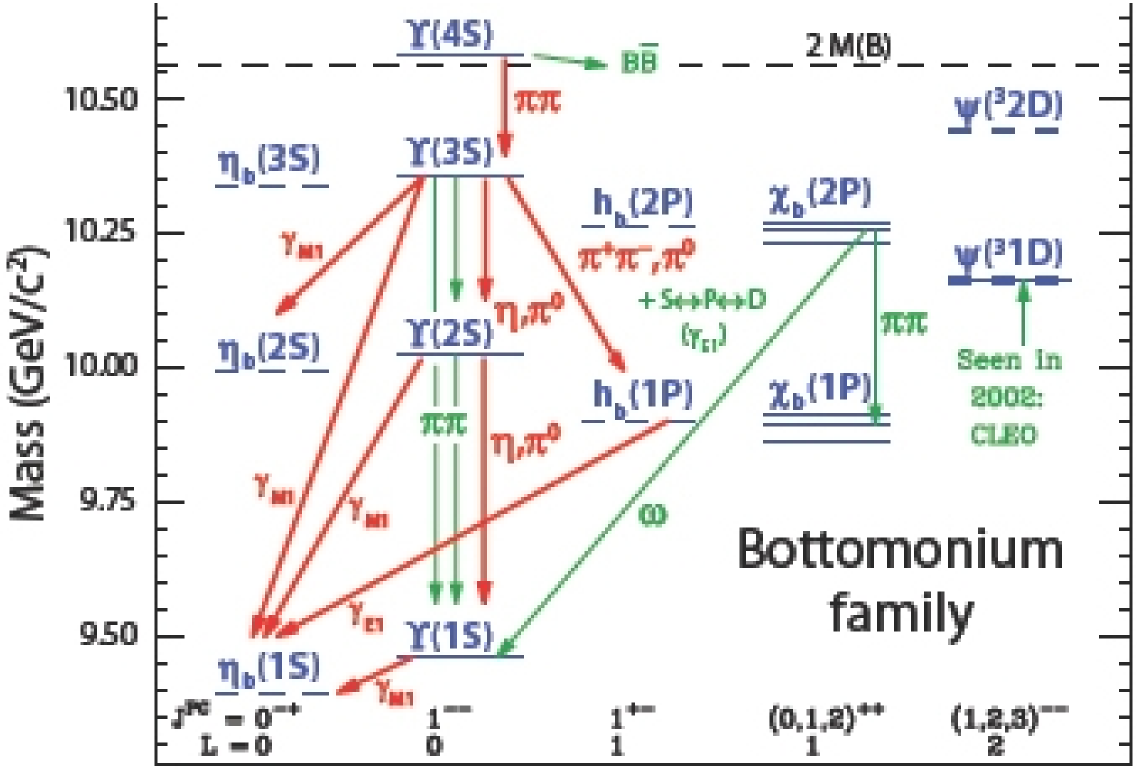
DASP 2 results

The bottomonium family

A family of states with different quantum numbers
Analogy: hydrogen atom (or charmonium)

Formation in e^+e^- annihilation implies the photon quantum numbers: $J^{PC}=1^{--}$





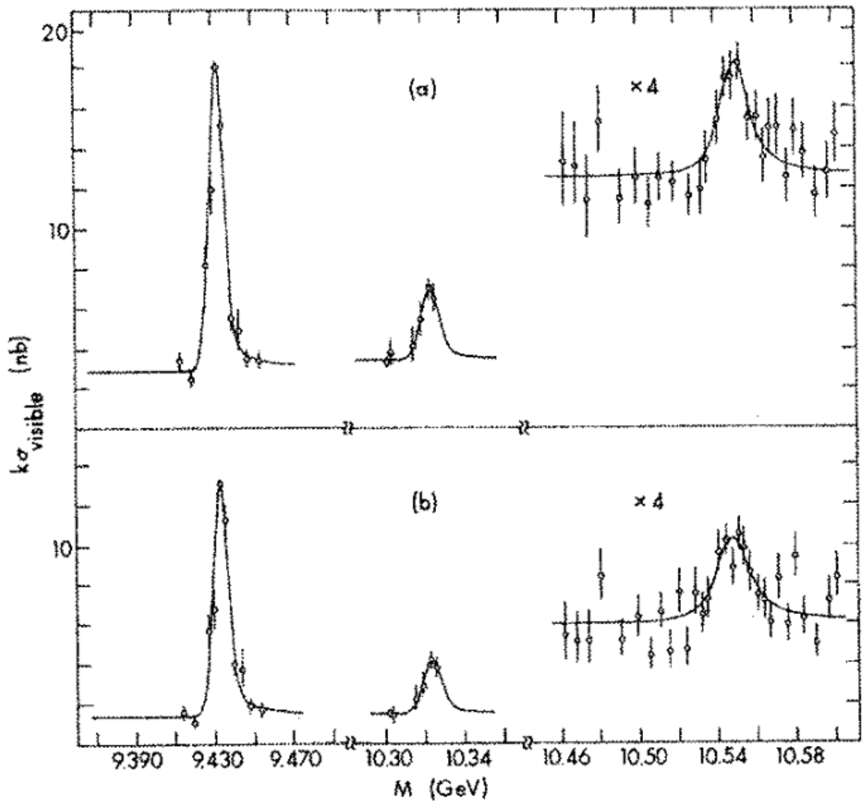
Other states accessible through decays, or direct production in hadronic collisions

The Υ(4S)

State with mass M=10.58 GeV observed at Cornell (1980)

Broader than the ones with smaller mass Γ=20 MeV ($\Gamma_{\Upsilon(1S)}$=54 keV)
Above the $B\bar{B}$ production threshold, where B mesons are bound states of a b-(anti)quark with a u/d-(anti)quark :
$\Upsilon(4S) \rightarrow B^0\bar{B}^0$ and $\Upsilon(4S) \rightarrow B^+B^-$ are the main decay modes (>96%)

Huge experimental applications in the study of CP violation in the bottom sector



Chasing for a top quark

Everyone convinced that a 6th quark (top quark), the charged +3/2 member of 3rd quark generation, should exist.
Expected mass larger than the one of the b-quark.

What to look for:

- $t\bar{t}$ resonances
- the decay: $W^+ \rightarrow t\,\bar{b}$ (or charge conj.) possible if $m_t+m_b<m_W$

Increasing limits at e^+e^- colliders:

- PETRA (DESY): m_t>23 GeV (1984)
- TRISTAN (KEK): m_t>30 GeV (late 80's)

Searches pass to hadron colliders.

- SppS (CERN): m_t>70 GeV (1989)

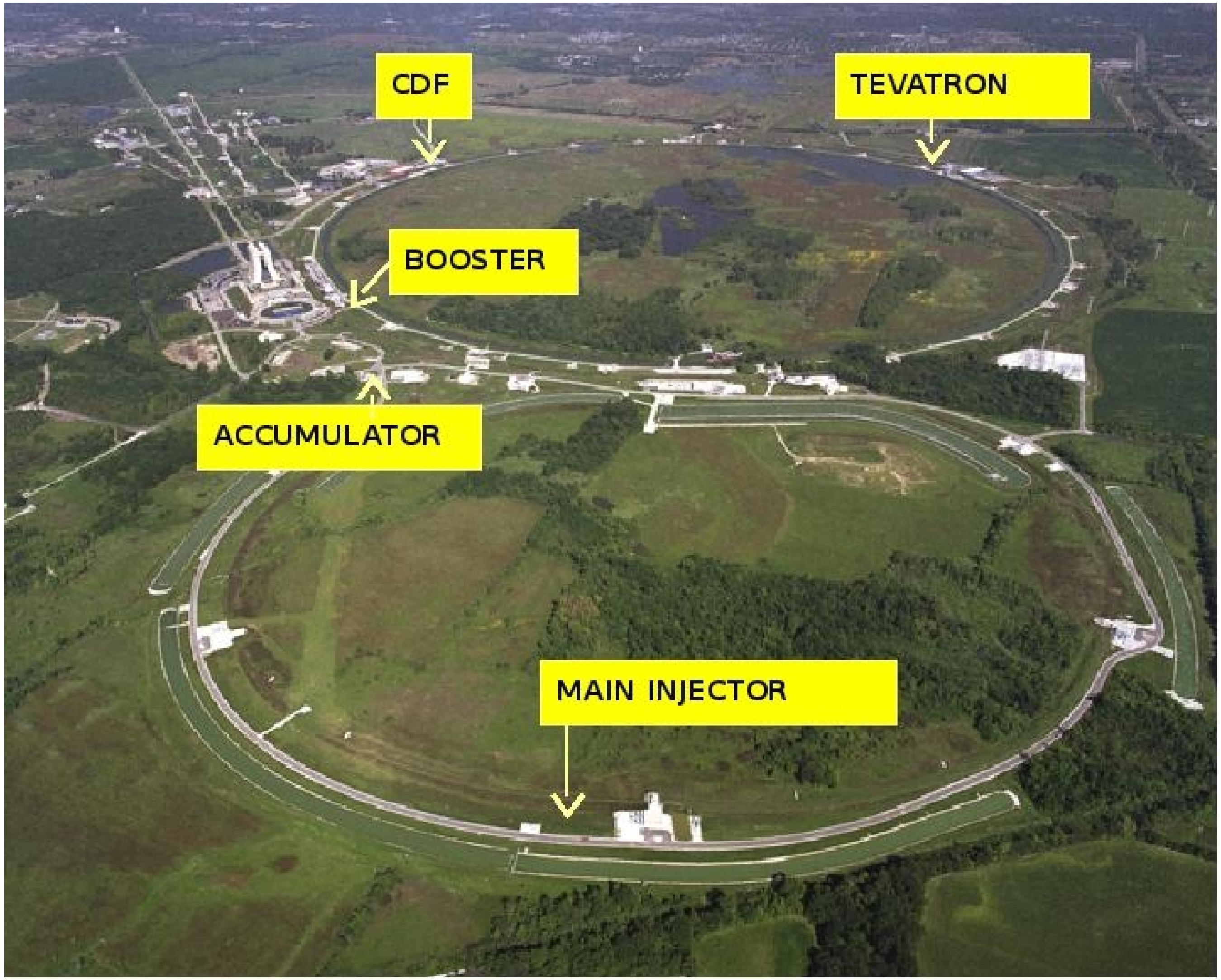
INFN

CDF and D0 experiments at the Tevatron

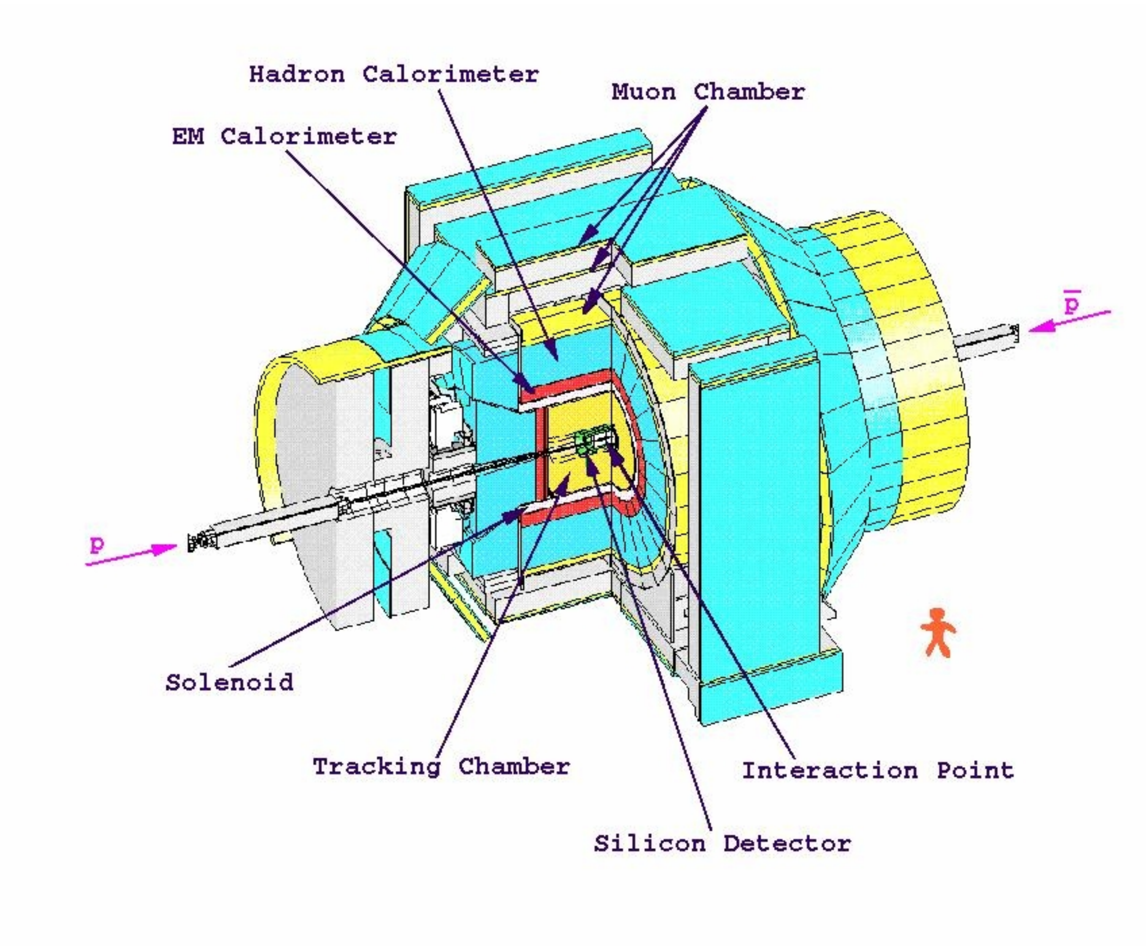
CDF experiment at Tevatron (Fermilab, 1994)

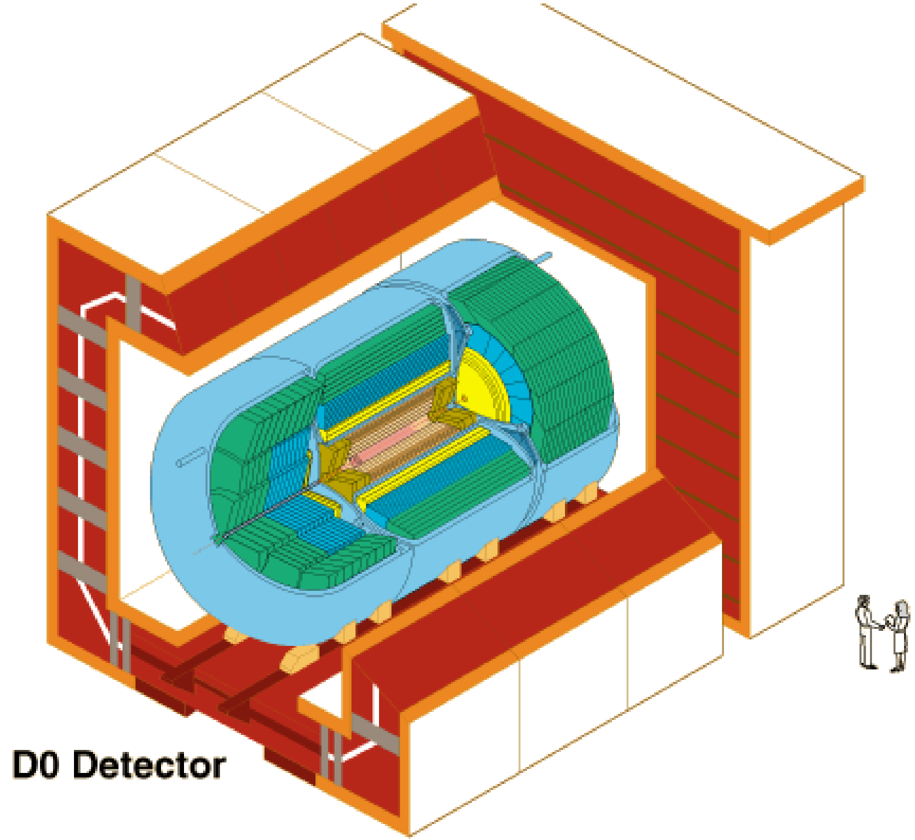
$p\bar{p}$ collisions at 2 TeV

The only place (until the LHC turned on) where to study the top quark



CDF and D0 experiments at the Tevatron





Search for the top quark at hadron colliders

Look for $t\bar{t}$ pair production, can occur in 2 ways: $q\bar{q} \rightarrow t\bar{t}$ and $gg \rightarrow t\bar{t}$

Since $m_t >> m_W$ the main (practically the only) decay channel is $t \rightarrow bW$

The lifetime (10^{-25} s) is lower than the hadronization time-scale (10^{-23} s) so the quark decays before to hadronize (top mesons or "toponium" states do not exist)

The W can decay hadronically ($W \rightarrow q\bar{q}$) or leptonically ($W \rightarrow l\nu$)

The presence of 2 top quarks in the event originates 3 topologies:

- dilepton events
- single lepton events
- all-hadronic events

all topologies contain 2 b-jets

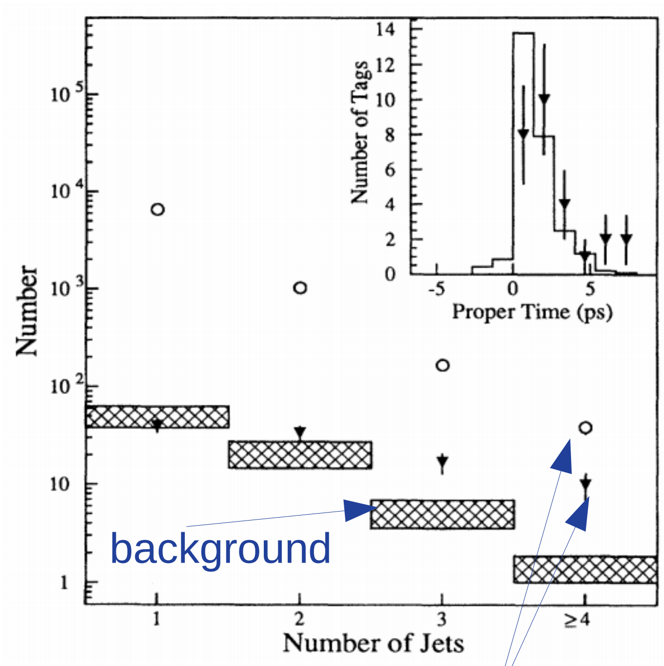
The presence of leptons in the final state in hadronic collisions helps in background reduction

INFN

Observation of the top quark

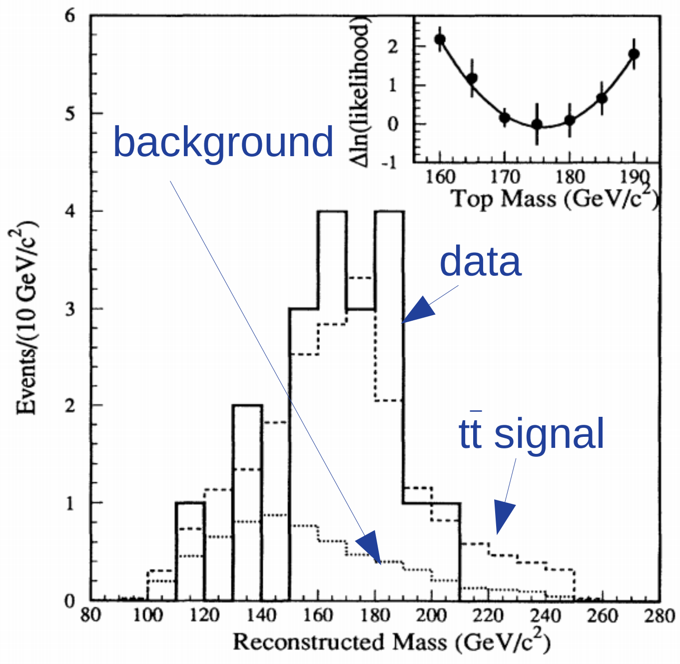
CDF and D0 at the Tevatron (Fermilab, 1995)
After first evidence of a 2.8σ excess by CDF in 1994

CDF



Number of events before and after secondary vertex tagging
Excess for $N_{jets}>2$

CDF

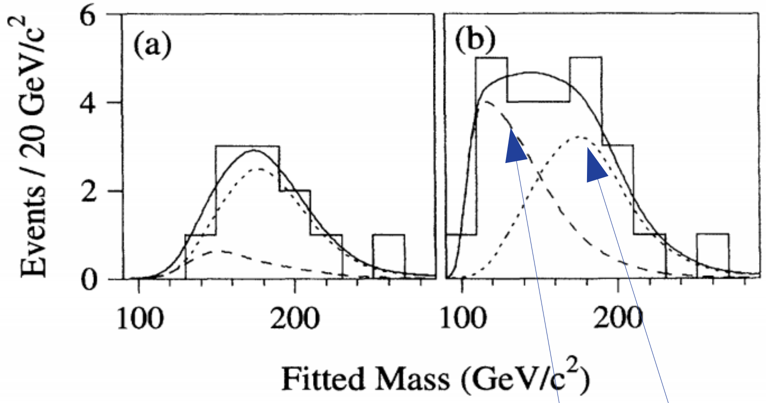


m_{top} = 176 ± 8 ± 10 GeV

D0

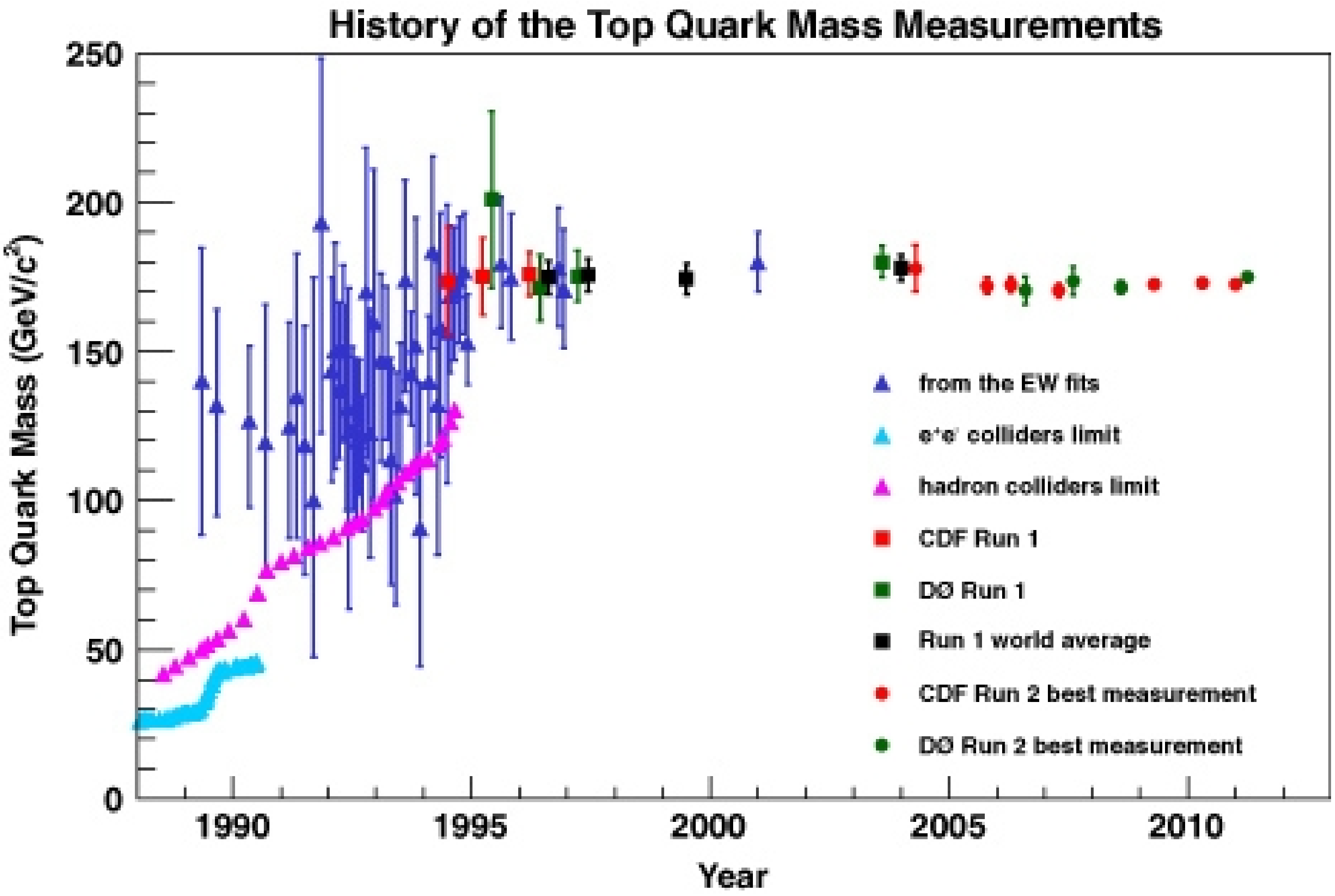
standard selection

loose selection



$t\bar{t}$ signal

History of top quark mass measurements

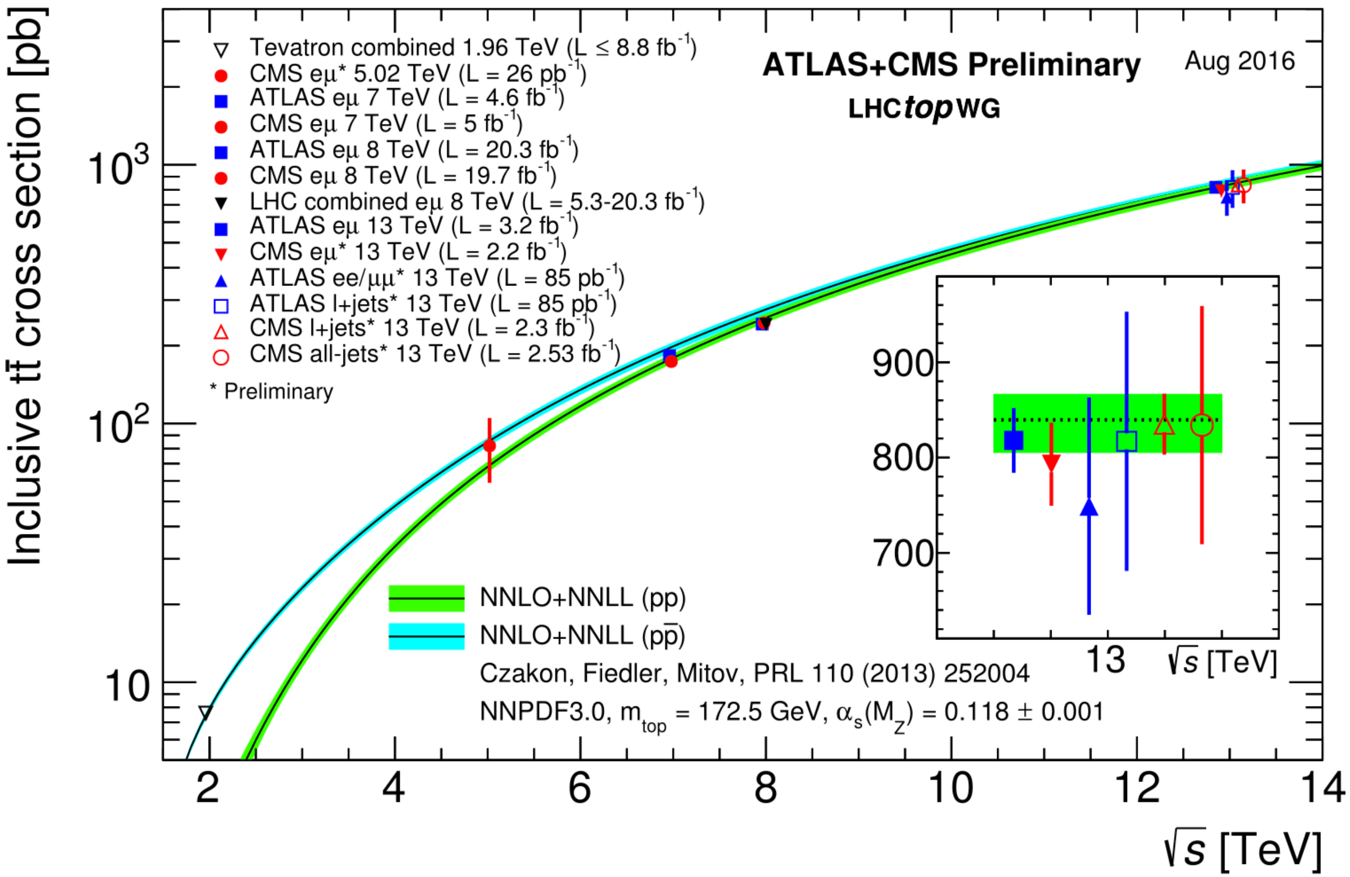


Top quark physics today

Top quarks copiously produced at the LHC

- Tevatron: $\sigma_{tt} = 8$ pb
- LHC-13 TeV: $\sigma_{tt} = 830$ pb

Top quark physics allows precision tests of the Standard Model



Elementary particles in the SM