The Development of Particle Physics

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Discovery of the top quark

- Introduction: hunt for top-quark.
- Signatures of top-quark.
- CDF and D0 at Fermilab.
- Events with top-quark.
- Data analysis and simulations.
- Results.
- Conclusions.

A hunt for top-quark.

- After the discovery of the *b* (bottom) quark, it became obvious that there should be an isospin partner of *b*-quark – *t* (top) quark, to complete the third generation of quarks. Initial prediction for *t*-quark mass - 15 GeV.
- The hunt started at SLAC and DESY, continued at CERN with higher energy beams (SppS and later at LEP) and moved to Fermilab in 1988 when the new accelerator giving 900 GeV protons and antiprotons became operational.
- At that time the lower limit on *t*-quark mass was 41 GeV, that was moved up to about 77 GeV in 2 years. It became obvious that top could not be produced in a decay: $W^+ \rightarrow t + \underline{b}$. So top could only be found if created in pair with anti-top: this required the energy twice the top mass.
- Since 1990 only Fermilab with the highest energy beams was capable to produce top-quarks, which can be detected with CDF - Collider Detector at Fermilab, and D0.

Predictions for top events

- Only 1 out of 10^{10} collisions generates $t\underline{t}$-pair: production cross-section - 5 pb, compared to the total cross-section of 60 mb.
- Very short lifetime - $<10^{-24}$ s; it will decay before it can hadronise.
- Charge = $2/3e$.
- If heavy enough, top will decay into W^+ and b, so $t\underline{t}$-pair will produce a pair of Ws and $b\underline{b}$.
- Both W and b are unstable with b living much longer ($\sim 10^{-12}$ s for B-mesons) - difficult to detect. Moreover, quarks are never seen individually, always joint in hadrons - jets; b-quarks travel as parts of mesons or baryons.
- W can decay into a pair of leptons (for example, electron + electron neutrino) or a pair of quarks (pair of jets); $b\underline{b}$-pair will give a pair of jets.

Top signatures

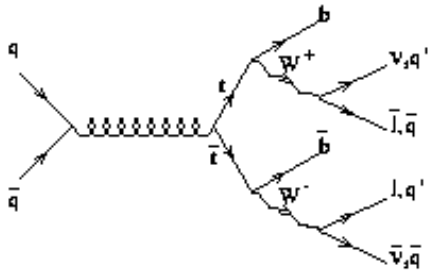


Figure 1: Tree level top quark production by $q\bar{q}$ annihilation followed by the Standard Model top quark decay chain.

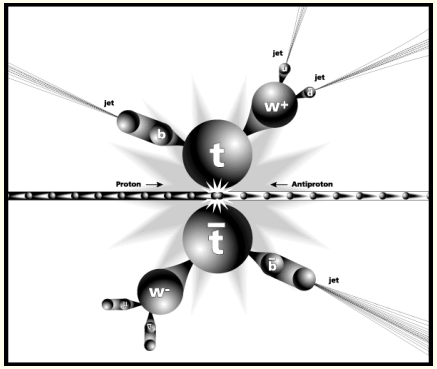
Decay mode	Branching ratio
$t\bar{t} \longrightarrow (q\bar{q}'b)(q\bar{q}'\bar{b})$	36/81
$t\bar{t} \longrightarrow (q\bar{q}'b)(\ell\nu\bar{b})$	12/81
$t\bar{t} \longrightarrow (q\bar{q}'b)(\mu\nu\bar{b})$	12/81
$t\bar{t} \longrightarrow (q\bar{q}'b)(\tau\nu\bar{b})$	12/81
$t\bar{t} \longrightarrow (\ell\nu b)(\mu\nu\bar{b})$	2/81
$t\bar{t} \longrightarrow (\ell\nu b)(\tau\nu\bar{b})$	2/81
$t\bar{t} \longrightarrow (\mu\nu b)(\tau\nu\bar{b})$	2/81
$t\bar{t} \longrightarrow (\ell\nu b)(\ell\nu\bar{b})$	1/81
$t\bar{t} \longrightarrow (\mu\nu b)(\mu\nu\bar{b})$	1/81
$t\bar{t} \longrightarrow (\tau\nu b)(\tau\nu\bar{b})$	1/81

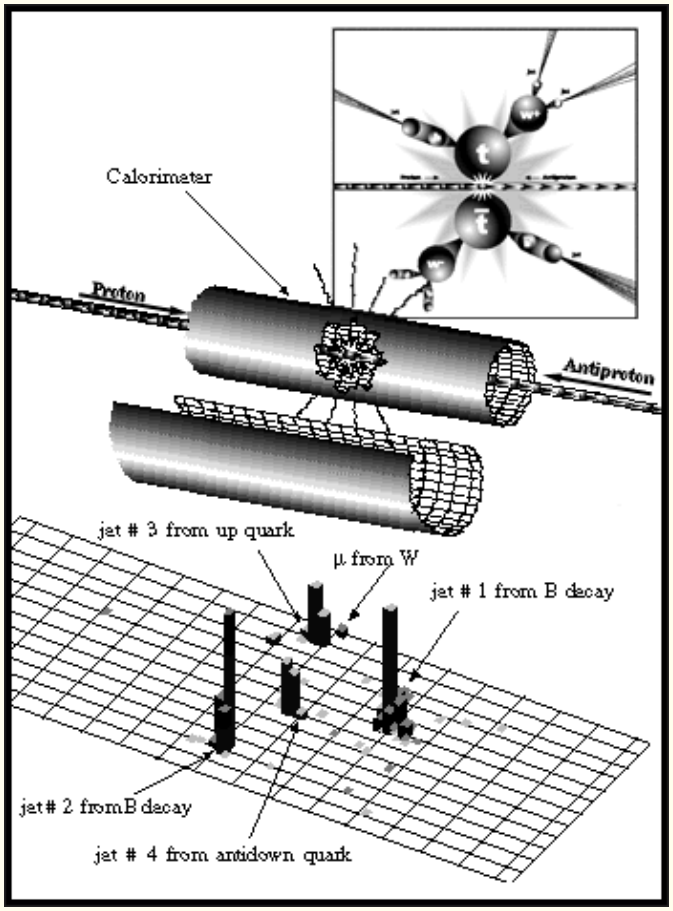
Table 1: Decay modes for a $t\bar{t}$ pair and their approximate branching ratios (to lowest order) assuming charged-current decays. The symbol q stands for a light quark: u,d,c,s.

- Signature:
  - 2 leptons + missing energy + 2 jets ($b\underline{b}$) - dilepton channel;
  - 1 lepton + missing energy + 4 jets ($b\underline{b}W$) - single-lepton channel;
  - 6 jets ($b\underline{b}W^+W^-$).
- 6 jets is the most probable case but has a large background.
- CDF searched for single-lepton and di-lepton channels.

Energy for particle production

Centre-of-momentum (mass) energy:
Two particles *A* and *B* collide: the total four momentum squared of the system is:



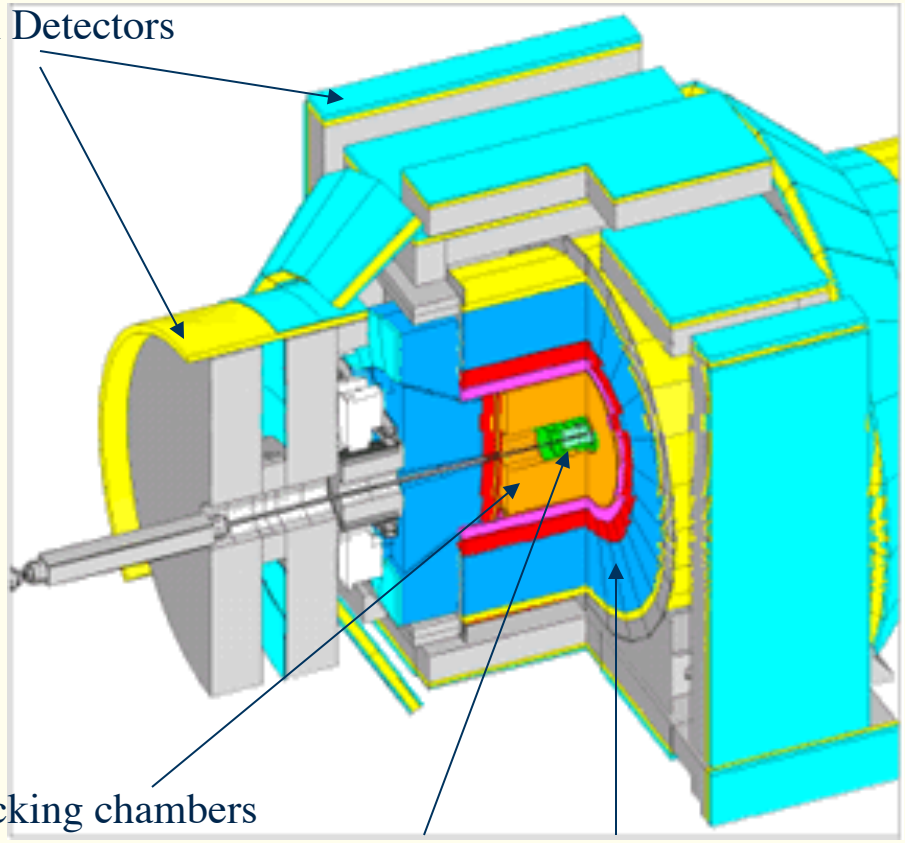


$$p^2 = (\vec{p}_A + \vec{p}_B)^2 - (E_A + E_B)^2 = -m_A^2 - m_B^2 + 2\vec{p}_A \cdot \vec{p}_B - 2E_A E_B$$

The centre-of-momentum (mass) system (cms) is defined as the reference frame in which the total 3-momentum is 0. Suppose *s* is the total energy squared in cms. Then $p^2 = -s$ - invariant parameter.

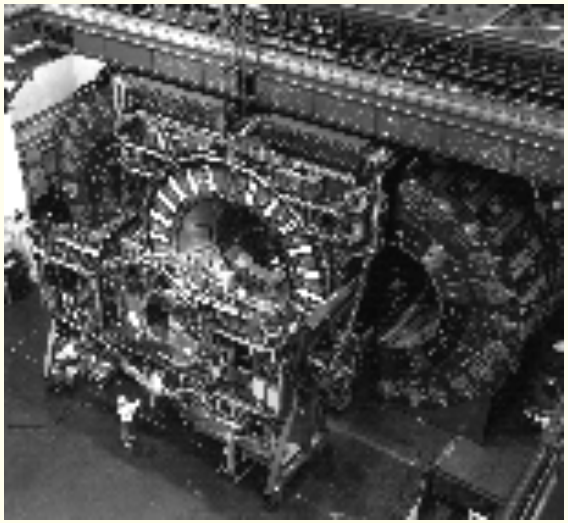
Colliding beams: $s \approx 4\, E_A\, E_B$ if $E_A, E_B >> m_A, m_B$.
Fixed target: $s \approx 2\, E_A\, m_B$ if $E_A >> m_A, m_B, E_B = m_B$.
Important for determining the energy available for particle production.

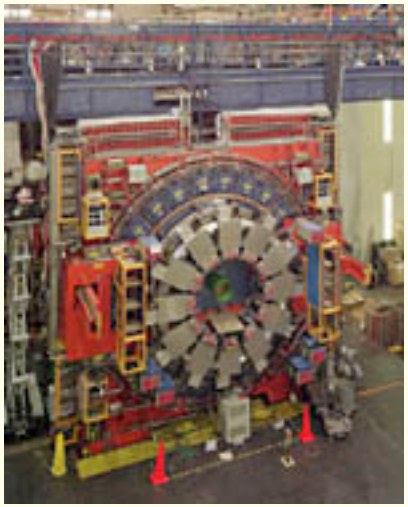
CDF



- Key issue: to track particles in jets very precisely to find the point where *b*-quark decayed and identify it as *b*-quark (using its life time).
- Important part of the detector: Silicon Microstrip Detector - vertex detector, precision 15 microns.

CDF and D0



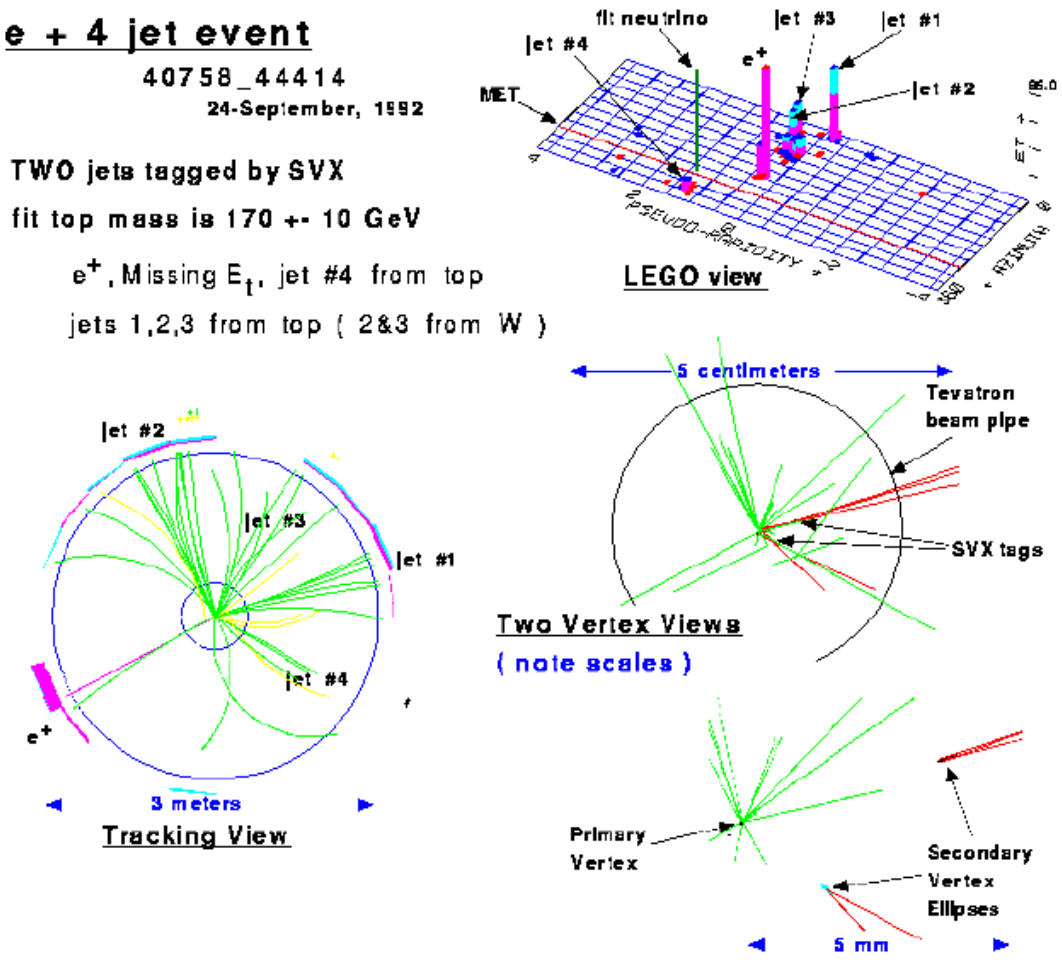


CDF - Collider Detector at Fermilab

D0 at Fermilab

CDF Collaboration

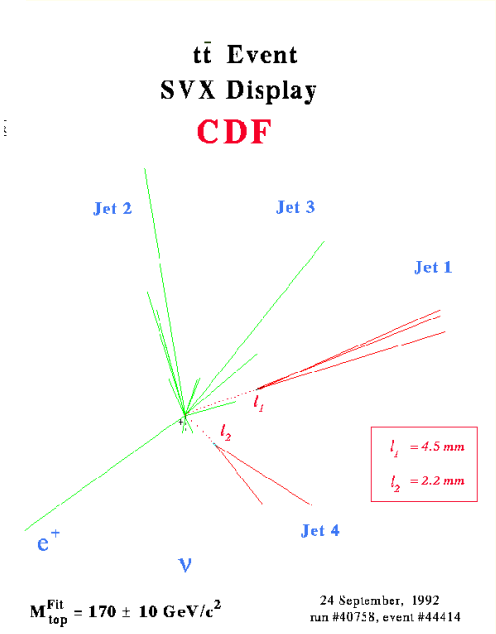
Top events: single-lepton channel



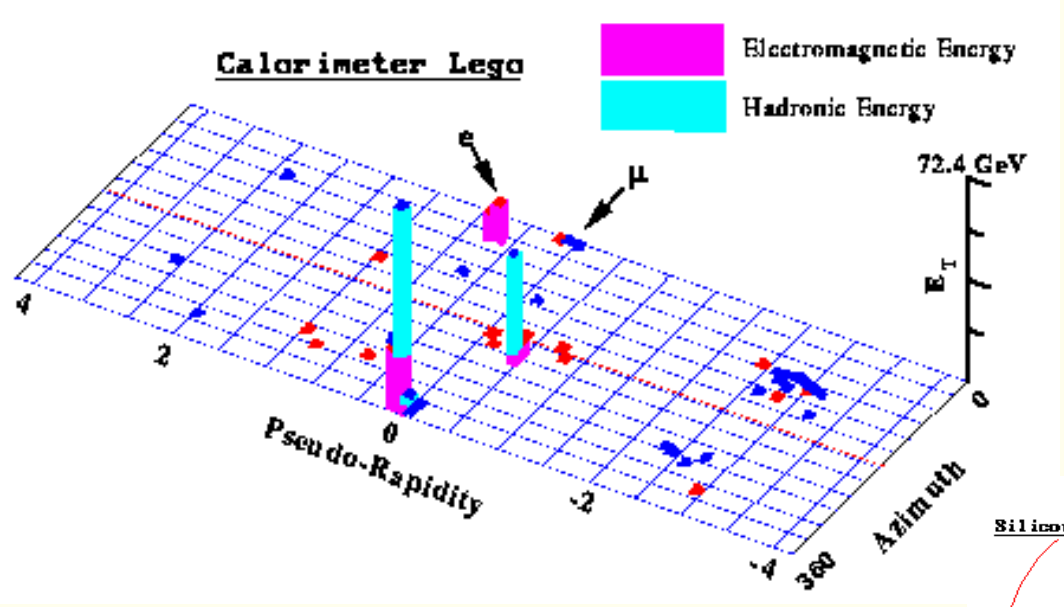
pseudorapidity: $\eta = -\ln(\tan(\theta/2))$

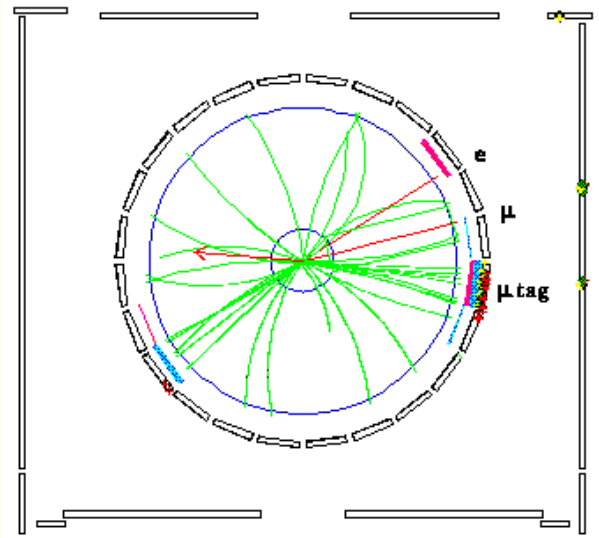
SVX tag - reconstruction of secondary vertices from *b*-decay

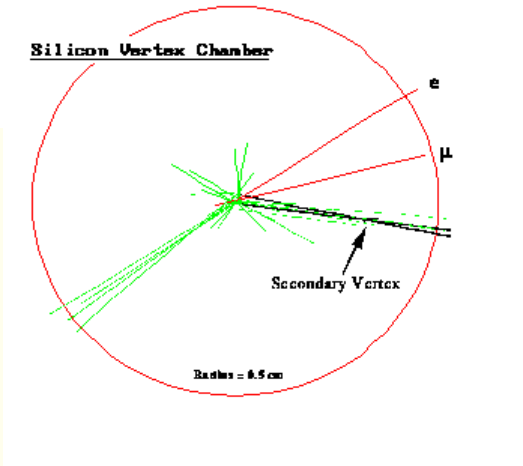
SLT tag - additional leptons from *b*-quark semileptonic decay



Top events: dilepton channel

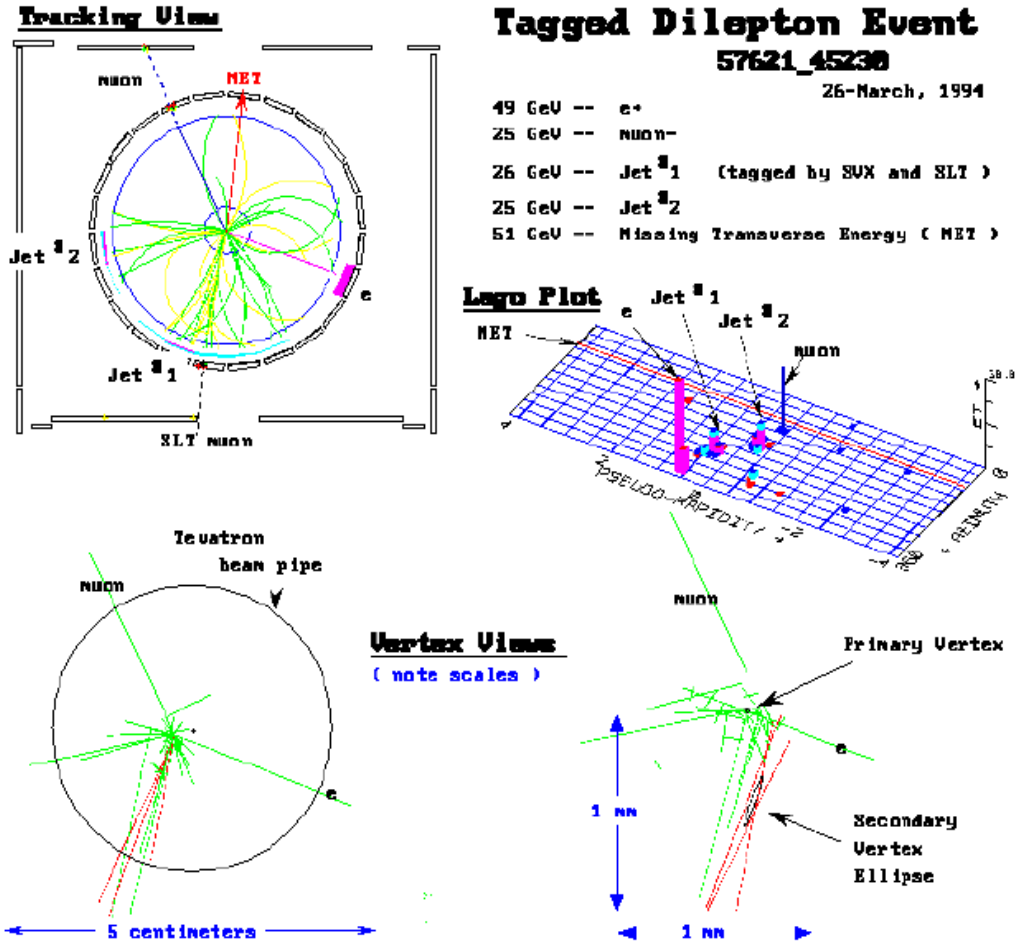




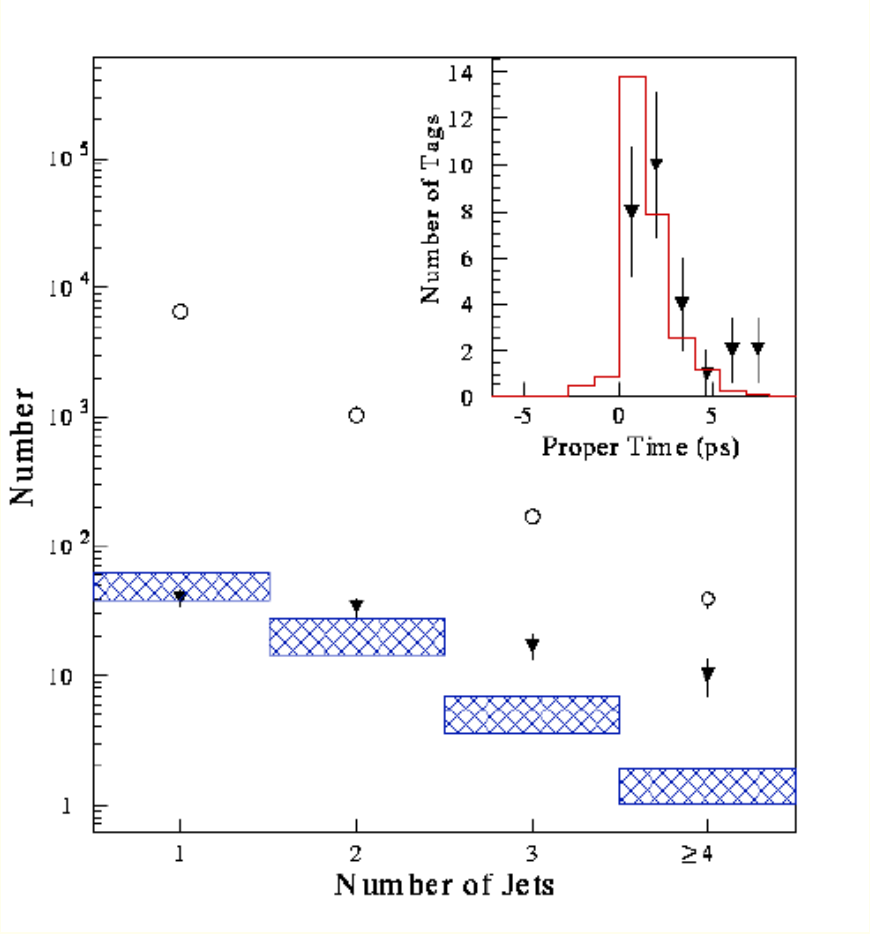


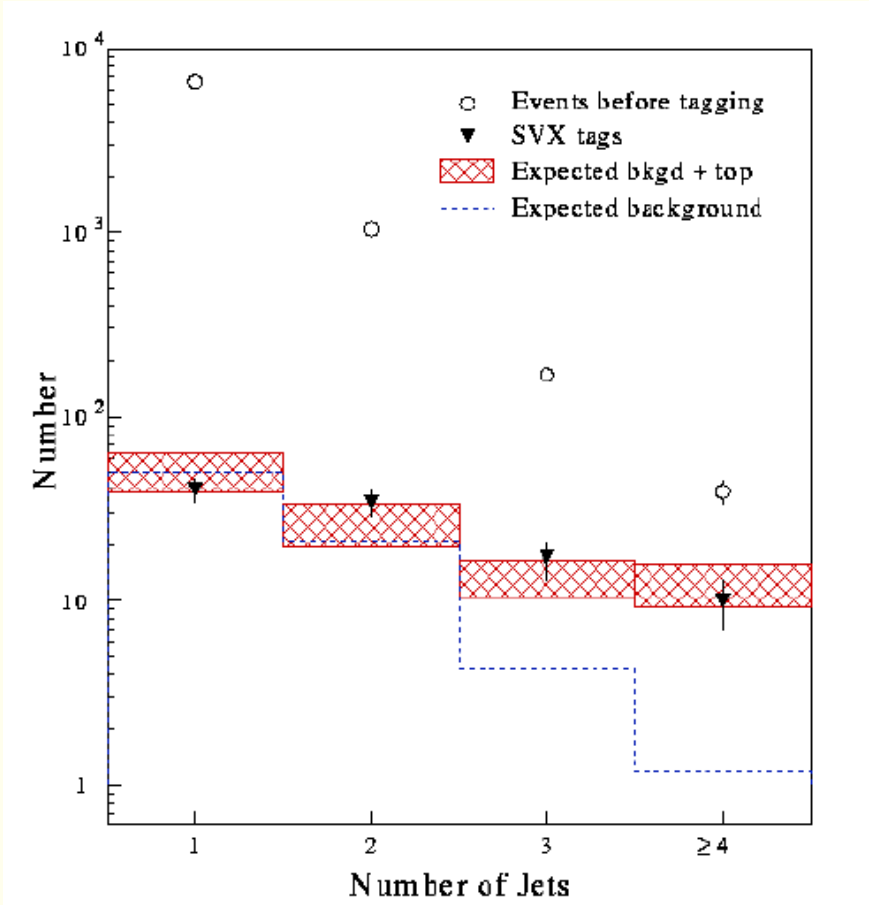
Top events: dilepton channel

- Two leptons with E_T (P_T) > 20 GeV with opposite charge and $|\eta|<1.0$ (central region); one lepton for single-lepton channel.
- Large missing energy: $\not\!\!E_T$ > 25 GeV.
- At least two jets with E_T>10 GeV and $|\eta|<2.0$; at least 3 jets for single-lepton channel.
- SVX or SLT tag for single-lepton channel.
- Background: Drell-Yan lepton pair production, *WW*, *bb* - different signature but some possibility of mimicking still remained.



Data and simulations



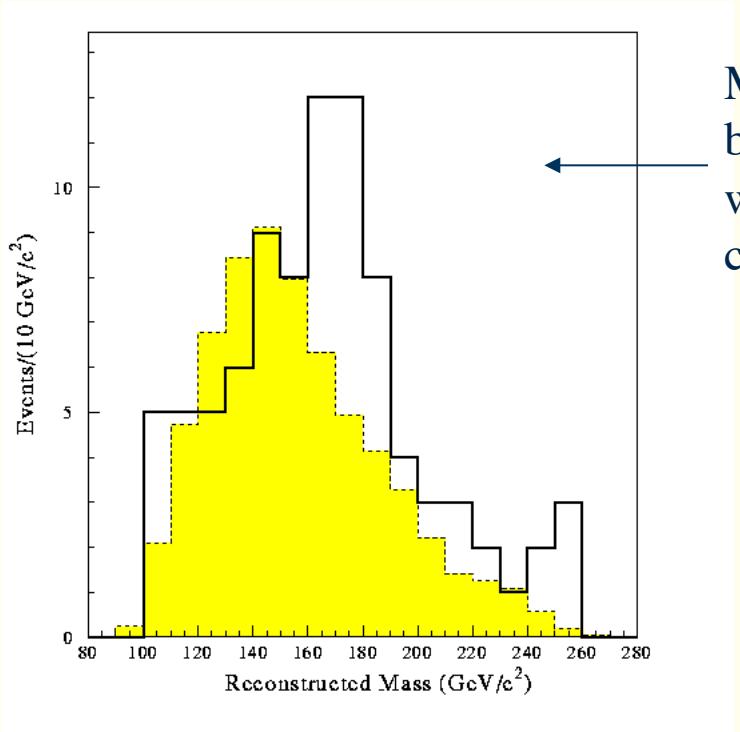


Results

Channel:	SVX	SLT	Dilepton
observed	27 tags	23 tags	6 events
expected background	6.7 ± 2.1	15.4 ± 2.0	1.3 ± 0.3
background probability	2×10^{-5}	6×10^{-2}	3×10^{-3}

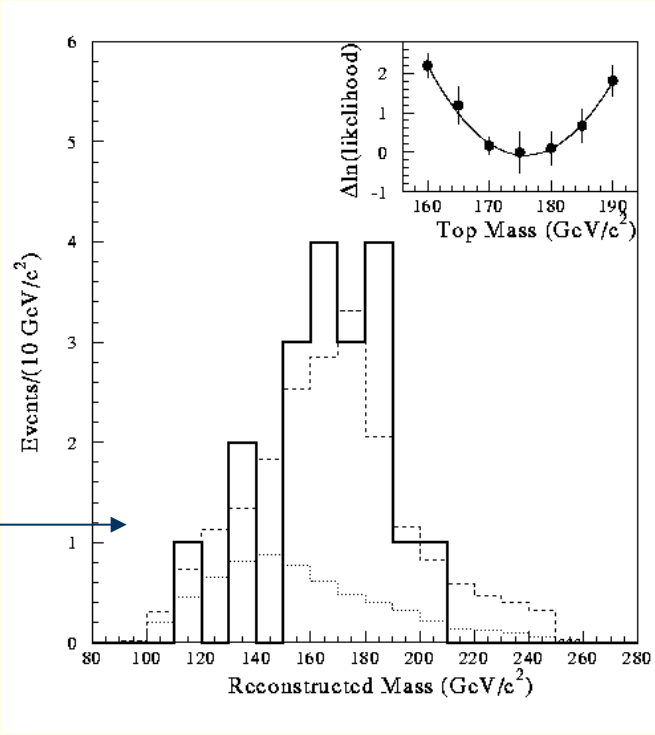
The numbers of tags or events observed in the three channels along with the expected background and the probability that the background would fluctuate to the observed number or more.

Reconstruction of the mass of top-quark



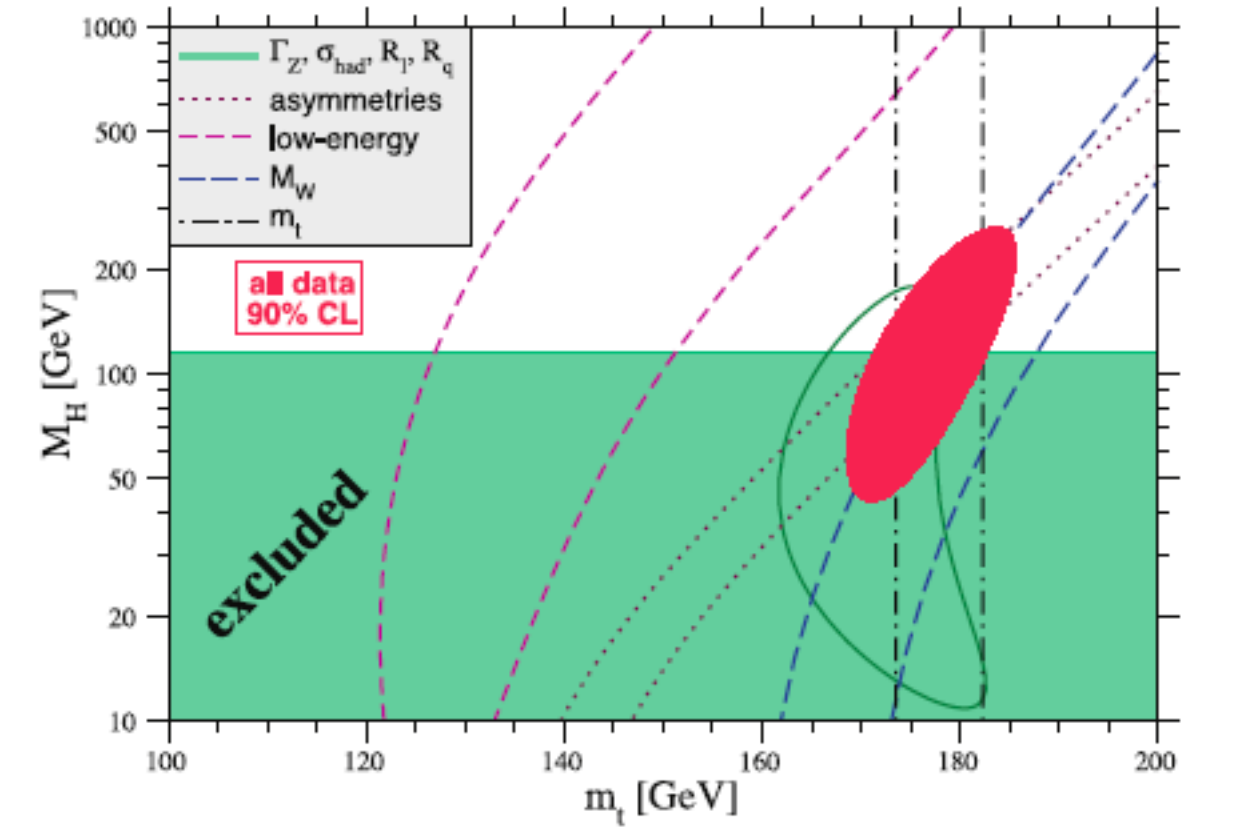
Mass distributions before tagging with background calculations

Mass distributions after SVX and SLT tagging with background calculations



- Top mass was reconstructed using kinematics of 19 single lepton events (W + ≥4 jets):
  - Energy and momentum from CTC and calorimeters.
  - Adding missing neutrino energy, lepton energy and 4 highest energy jets.

Mass of the Higgs-boson



- Allowed region for the standard model Higgs-boson mass: all constraints included.

Conclusions

- It took almost 2 decades to observe the top-quark after its existence became apparent with the discovery of the bottom-quark.
- The discovery required advances in accelerator and detection technology to achieve energies high enough to produce the top-quark and to tag events using vertex detector.
- In 1990's, CDF and D0 ran side-by-side at Fermilab looking for the top quark.
- They both observed single-lepton and dilepton decay channels of the top-quark decay as a proof of its existence.
- M_{top}=176±8 GeV and 199±30 GeV according to CDF and D0, respectively; at the end of Tevatron operation: 178.0±4.3 GeV.
- More accurate measurements of the top mass have been done at LHC.

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