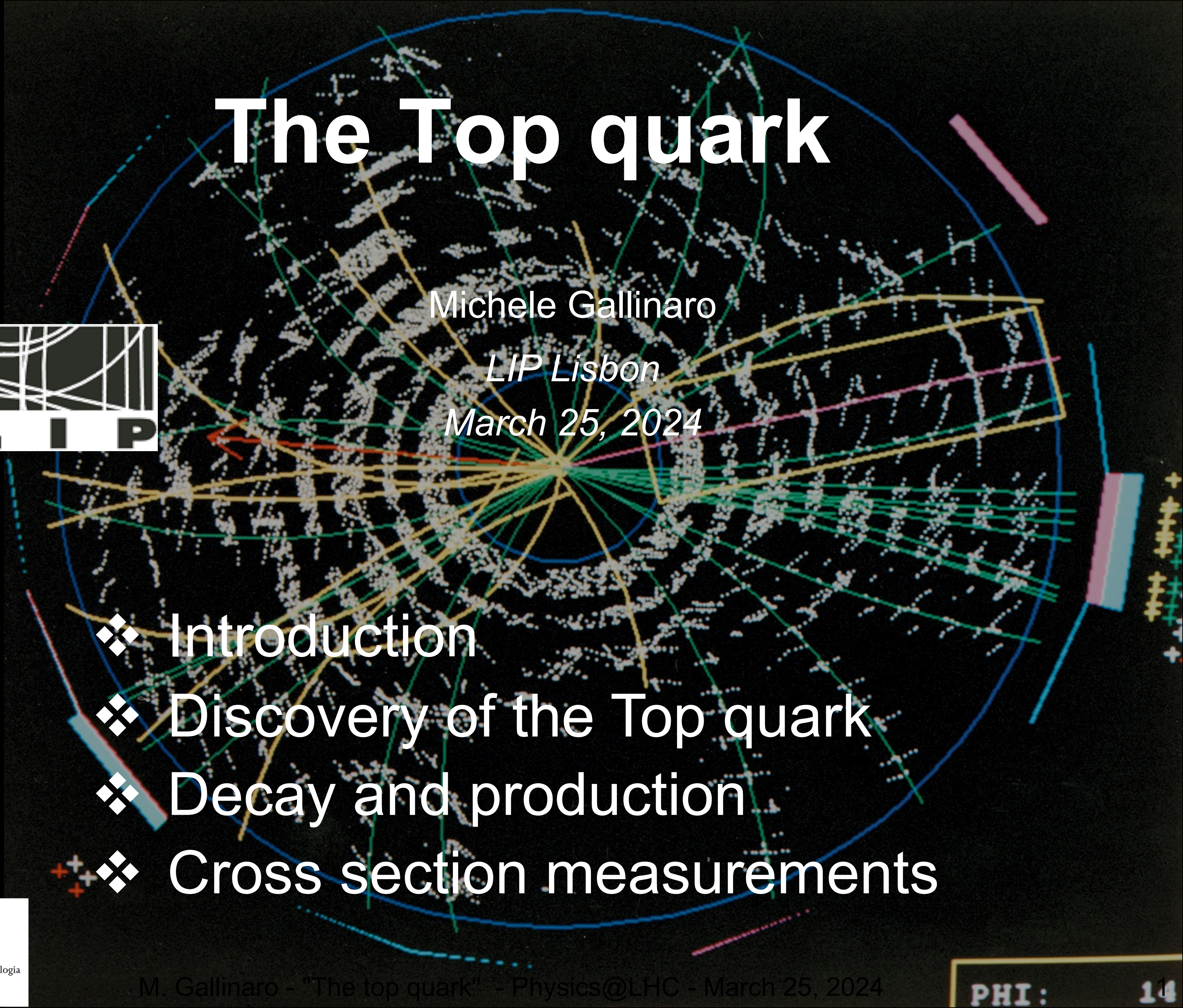


The Top quark

Michele Gallinaro

LIP Lisbon

March 25, 2024

- Introduction
- Discovery of the Top quark
- Decay and production
- Cross section measurements

Introduction

- Pre-discovery
- Motivation: theory and experiment
- Experimental results on top quark events
- First measurements

1974

With the discovery of the J/Ψ:

quarks $\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix}$

leptons $\begin{pmatrix} \nu_e \\ e \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}$

1975-1977

- Discovery of tau (τ) lepton at SLAC (1975): Mark-I expt. (ν_τ from the decay kinematics)
- Discovery of the Y ($b\bar{b}$) at Fermilab (1977)

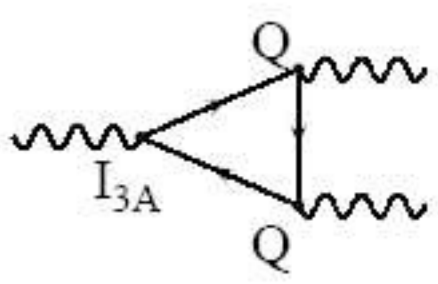
$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} \\ b \end{pmatrix}$$

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$$

- b: non SM? iso-singlet? SM iso-doublet?
- 1984: DESY measurement of $e^+e^- \rightarrow b\bar{b}$ FB asymmetry: (22.5 ± 6.5)%
  - cf. 25.2% SM iso-doublet, 0% iso-singlet
- If SM is correct there must be a iso-doublet partner, the top quark
- Mass? b/c/s 4.5/1.5/0.5: Mass=15 GeV?

The theory: Why?

- The SM is not a “renormalizable” gauge theory in the absence of the top quark
- Renormalizability is a crucial feature, enabling the SM to be theoretically consistent and be usable as a tool to compute the rate of subnuclear processes between quarks, leptons, and gauge bosons
- Diagrams containing so-called “triangle anomalies” (right), cancel their contributions, thus avoid breaking the renormalizability of the SM, only if the sum of electric charges of all fermions circulating in the triangular loop is zero:



$$\Sigma Q = -1 + 3 \times [2/3 + (-1/3)] = 0$$

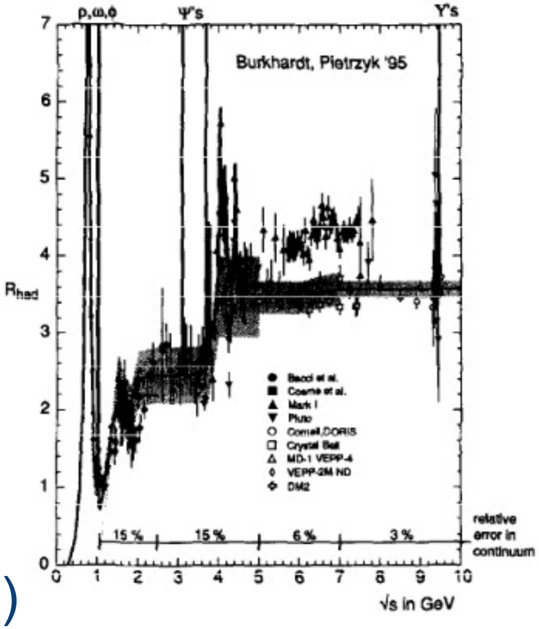
lepton electric charge   quark (up/down) charge

Searches at e^+e^- colliders

- PETRA (DESY) could reach ~20 GeV (late '70s)
  - Search for narrow resonance
  - Look for increase in R=(# of hadron events)/(# of μμ evts)

$$R \equiv \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)} = 3\sum_f Q_f^2$$

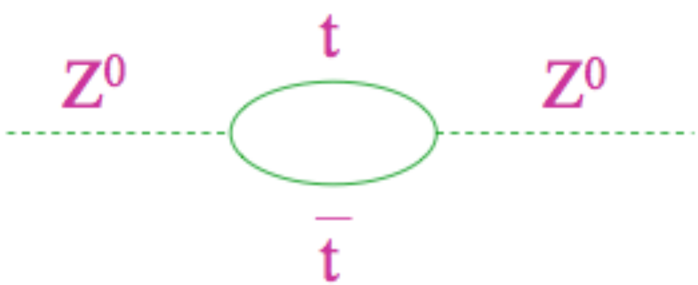
direct count of number of quarks

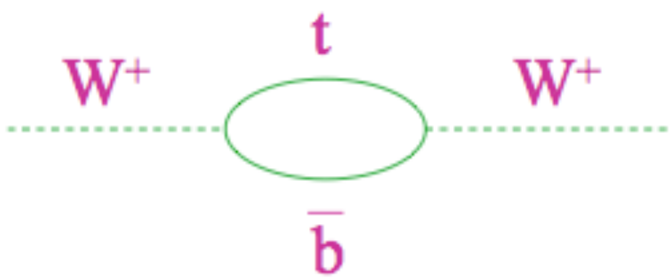


  - Global event characteristics: look for spherical component
  - Negative results. Set limits: M_t>23 GeV
- TRISTAN (Japan) built to study the top quark (early '80s)
  - Similar search technique:
  - Could reach ~30GeV: M_t>30 GeV
- SLC/LEP (SLAC)
  - Look for $Z \to t\bar{t}$
  - M_t>45 GeV
- Reached kinematic limit for direct searches at e^+e^- colliders

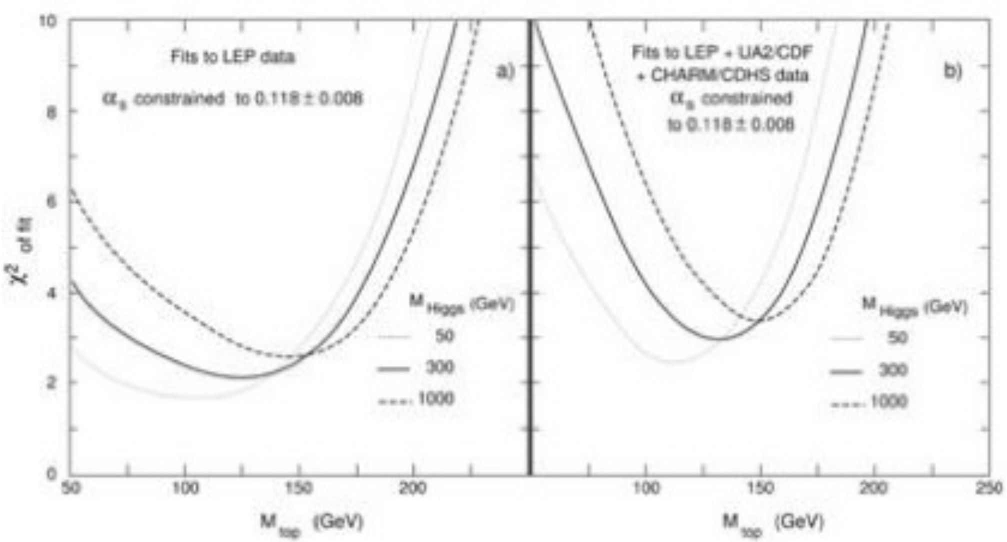
Indirect searches from e^+e^- colliders

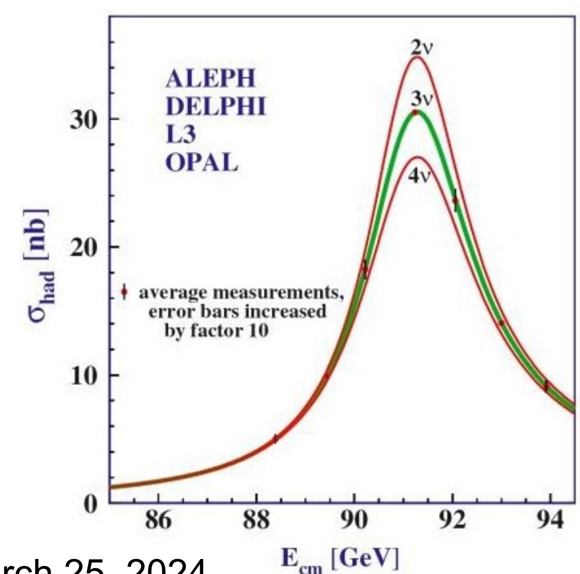
- In the SM, various EWK observables depend on the mass of the top quark





- Precision measurements of the EWK parameters, allow to measure virtual corrections with sufficient precision to put constraints on M_{top}
  - Prediction upper limit<200-220 GeV

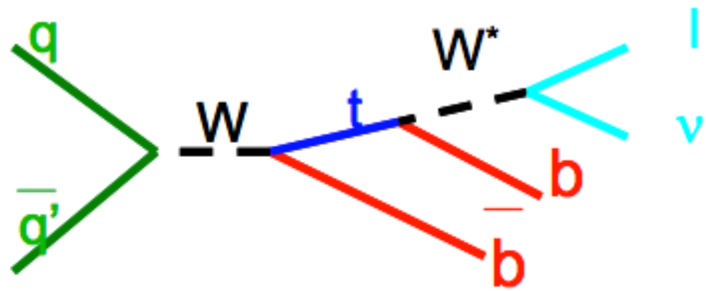




Early searches at hadron colliders

CERN $Sp\bar{p}S$ ($\sqrt{s}$=540 GeV) built to observe W,Z

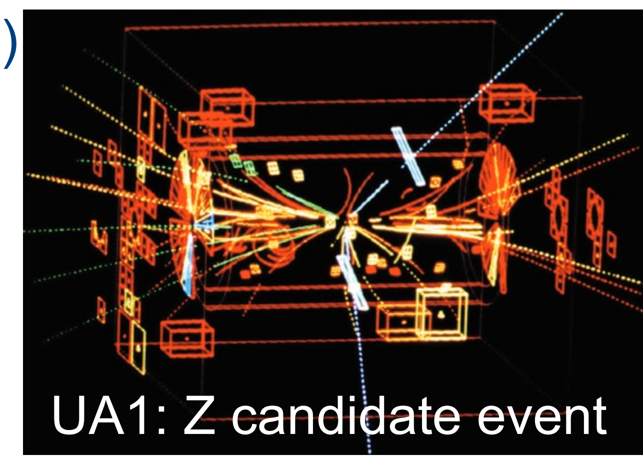
- Access to much higher energies
- Large backgrounds, low event rates
- Difficult reconstruction: jets

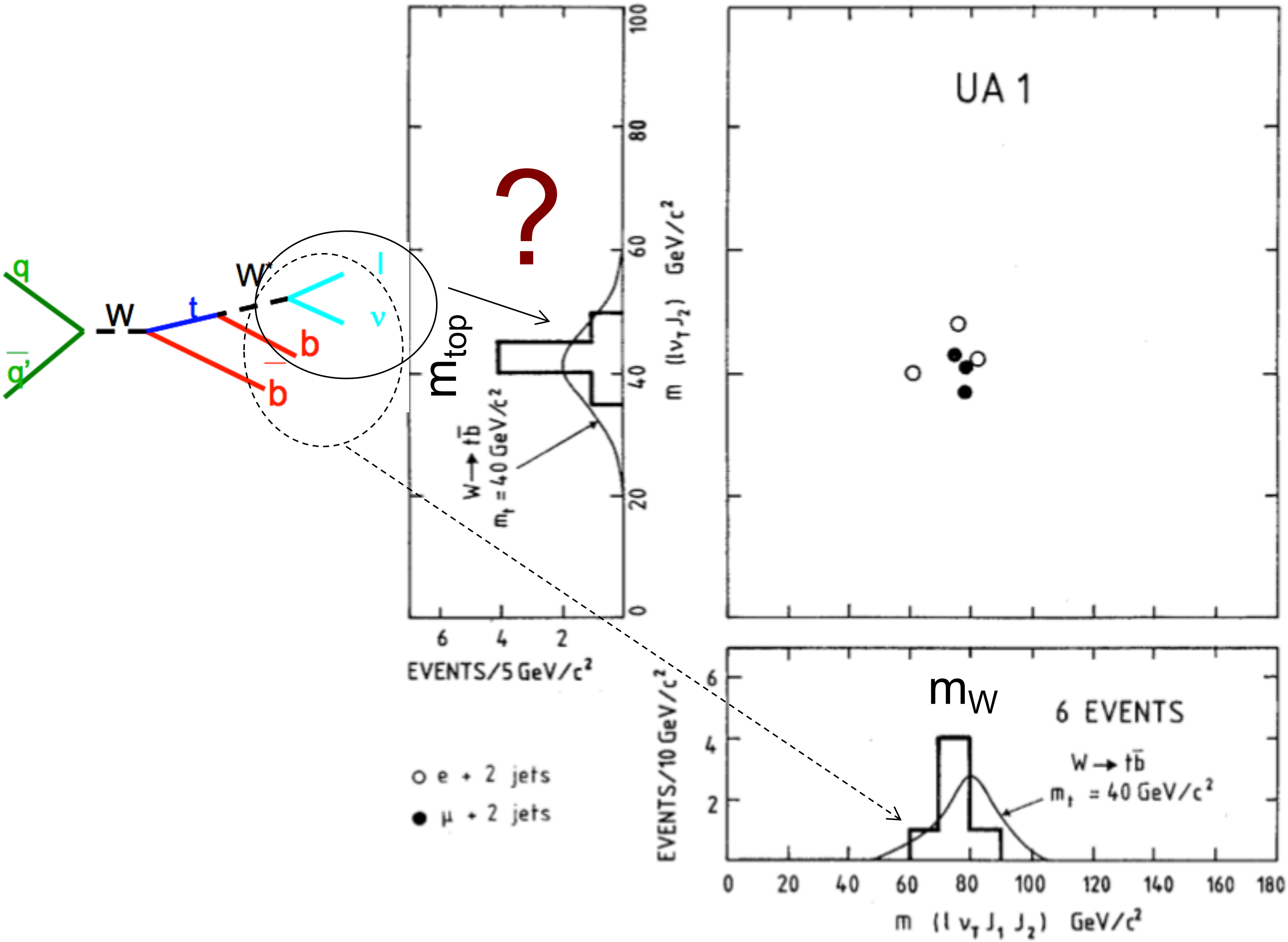


1984: UA1

- $W \to tb \to l\nu bb$
- Isolated high-p_T lepton
- 2 or 3 hadronic jets
- Observe 5 events (e+ ≥2 jets), 4 events (μ+ ≥2 jets)
- Expected background: 0.2 events
  - Fake leptons dominate; bbar/ccbar negligible
- Result consistent with M_{top}=40±10 GeV
- Stop before claiming discovery…

⇒W+jet background was underestimated

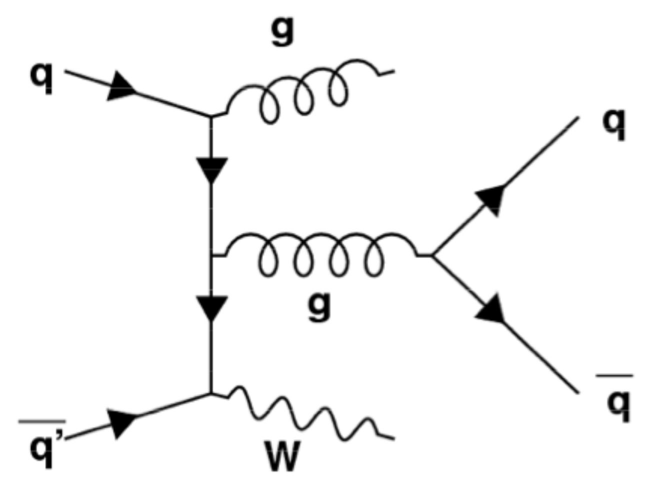




q
q'
W
t
W*
l
ν
b
b
?
m_top
W → tb̄
m_t = 40 GeV/c²
EVENTS/5 GeV/c²
m (lν_T J_2) GeV/c²
UA 1
m_W
6 EVENTS
W → tb̄
m_t = 40 GeV/c²
EVENTS/10 GeV/c²
m (l ν_T J_1 J_2) GeV/c²
○ e + 2 jets
● μ + 2 jets

Searches at hadron colliders

- 1988 UA1
- Larger data sample (x6, total of 600nb^{-1})
- Improved understanding of the backgrounds
- Fake leptons, W+jets, DY, J/Ψ, bbar/ccbar



channel	observed	expected background
$\mu + \geq 2$ jets	10 events	11.5 ± 1.5 events
$e + \geq 1$ jets	26 events	23.4 ± 2.8 events

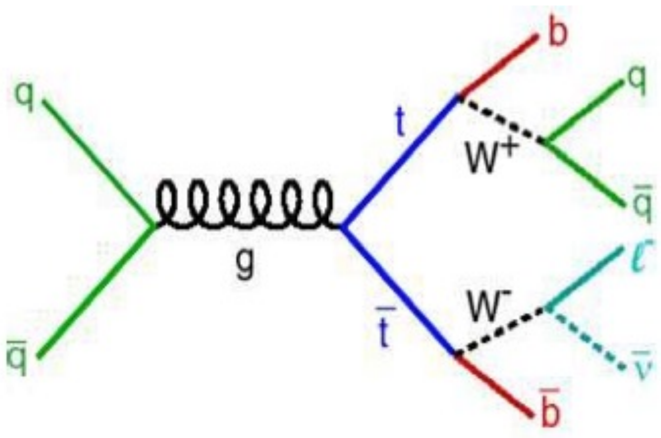
(+ 23 expected if $M_{top} = 40$ GeV)

⇒conclude M_{top}>44 GeV

Fermilab joins the hunt

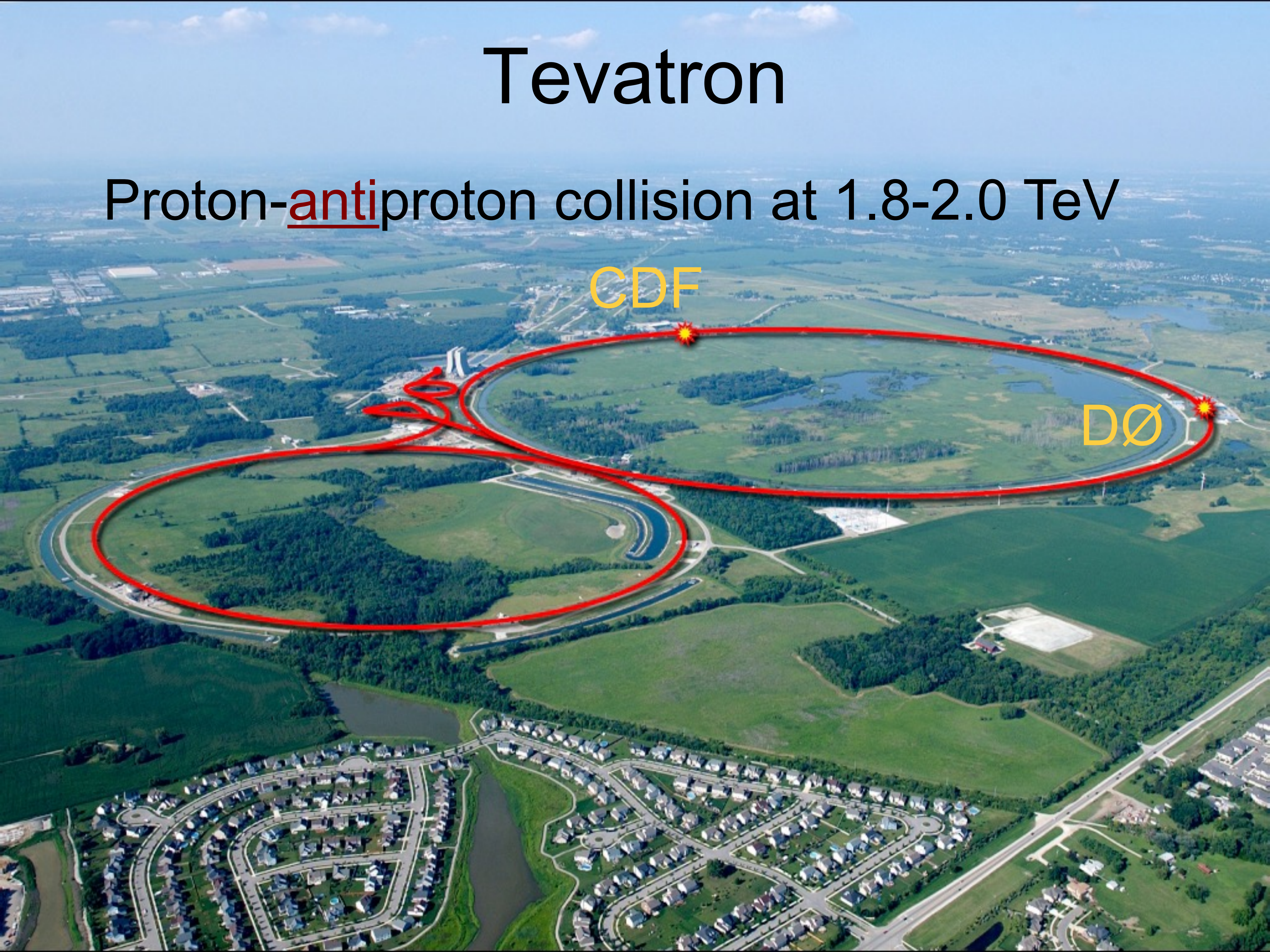
- 1988-89: at CERN, UA2 remains after the upgrades
- √1.8 TeV@Fermilab vs. √0.63 TeV@CERN
- Much better reach for larger mass (only 75 GeV@UA2)
- At Tevatron, pair production dominates: $t\bar{t} \rightarrow Wb\,W\bar{b}$

%	$e\nu$	$\mu\nu$	$\tau\nu$	$q\bar{q}$
$e\nu$	1.2	2.5	2.5	14.8
$\mu\nu$		1.2	2.5	14.8
$\tau\nu$			1.2	14.8
$q\bar{q}$				44.4

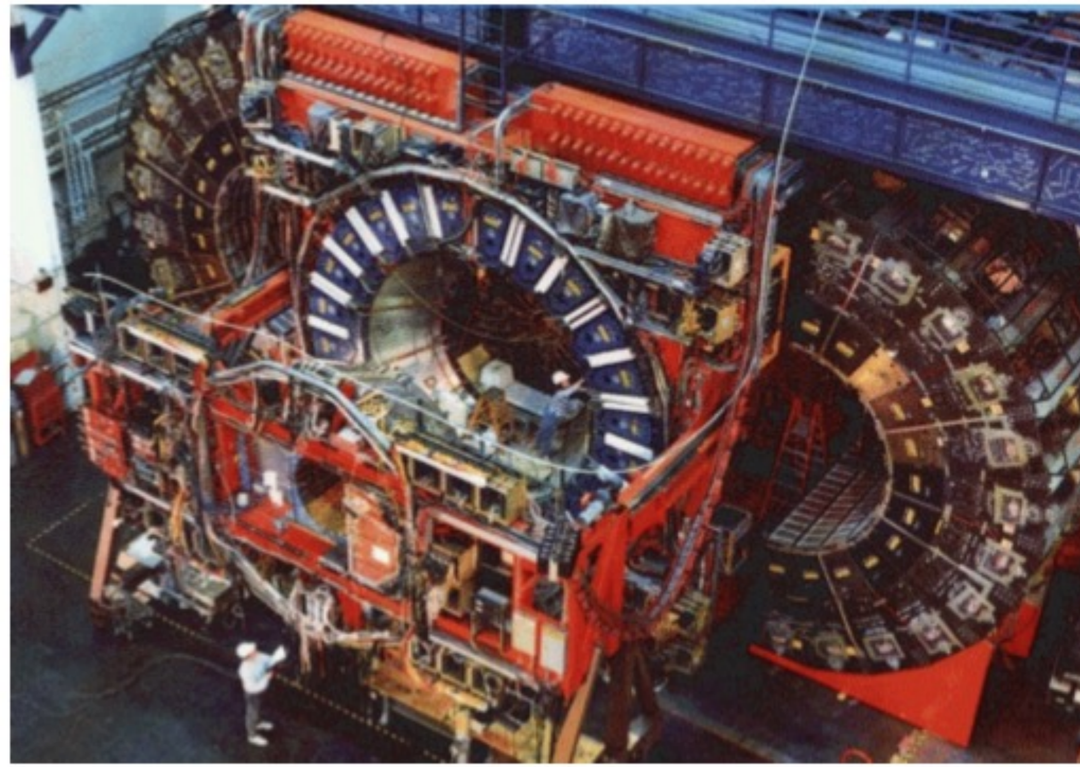


Tevatron

Proton-antiproton collision at 1.8-2.0 TeV



12 countries, 62 institutions
767 physicists



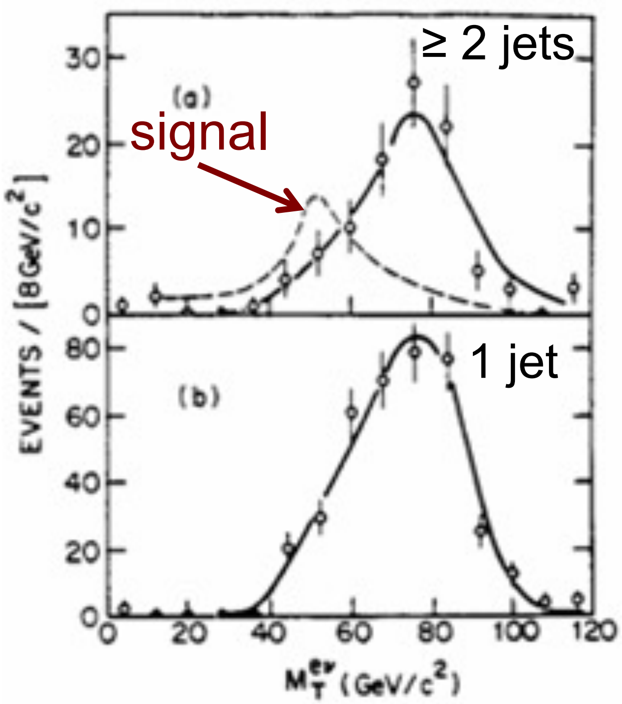
Searches at CDF

eμ channel

- Event rate lower: 2xBR(W→eν)
- Background small (no W+jets, no DY)
- Dominant background is Z→ττ→eμX (expect 1 evt)
- Observe 1 event (expect 7 evts for M_{top}=70 GeV)

eν+ ≥2 jets

- Dominant background: W+jets
- Discriminant: eν transverse mass
  - Background: W on-shell
  - Signal: W off-shell for M_{top}=40-80 GeV



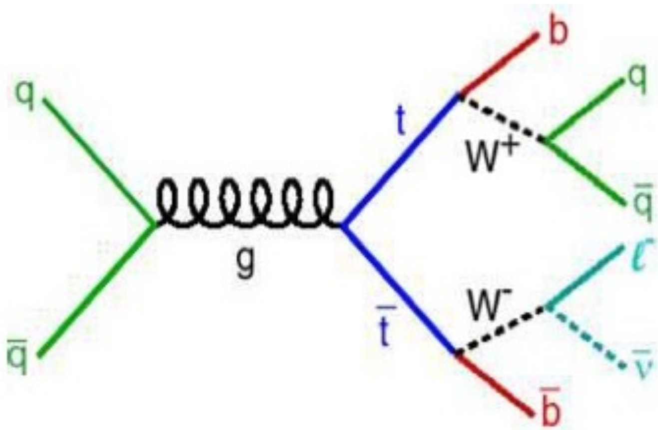
⇒M_{top}>77 GeV

- UA2 uses similar technique: M_{top}>69 GeV

Change of strategy: $M_{top} > M_b + M_W$

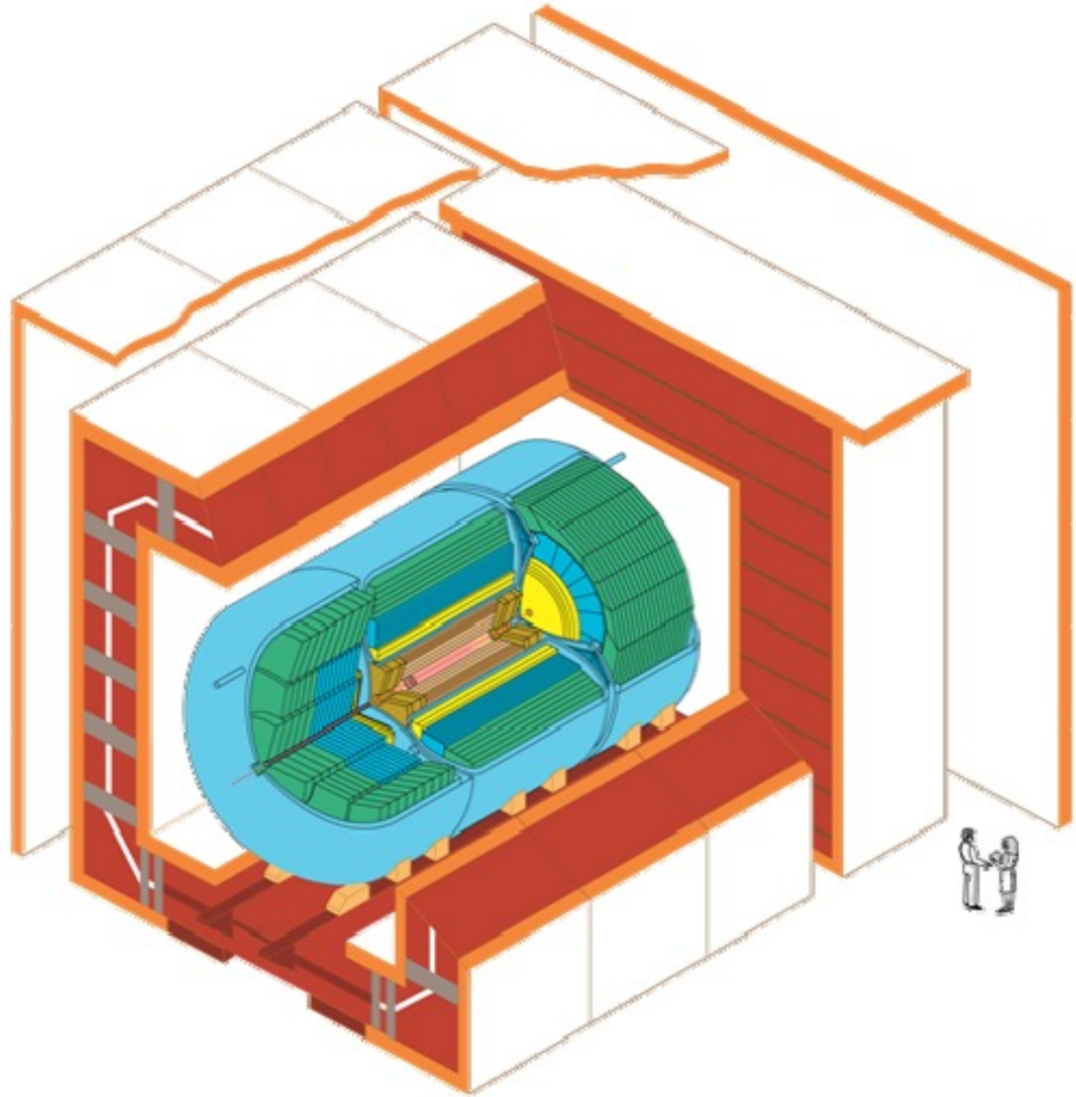
- Top quark decays to on-shell Ws: no $M_T(l\nu)$ discriminant
- Main differences:
  - background: W+jets (largely quarks and gluons)
  - signal: W+jets (2 jets are b-jets)
- CDF publication on 88-89 data:
  - Dilepton: include ee, $\mu\mu$, eμ (require missing ET, Z-veto)
  - Single lepton: require low p_T muon (semi-leptonic b-decays)

$\Rightarrow M_{top} > 91$ GeV



D0 joins the hunt

19 countries
83 institutions, 664 physicists



DØ Detector

Searches at Tevatron: CDF and D0

1992-1995

- Tevatron with higher luminosity
- D0: excellent calorimetry, large solid angle and coverage
- CDF: precision vertex detector, good tracker, magnetic spectrometer

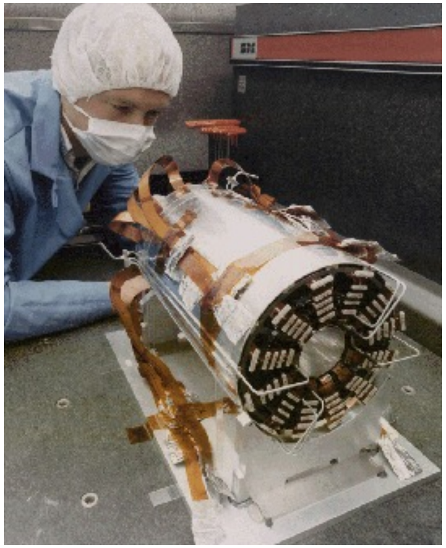
Run 1A:

- D0: optimized search for M_{top}=100 GeV
  - $e\mu$+≥1jet+MET 1 evt (1.1 bkg)
  - ee+≥1jet+MET 1 (0.5)
  - e+≥4jets+MET 1 (2.7)
  - μ+≥4jets+MET 0 (1.6)

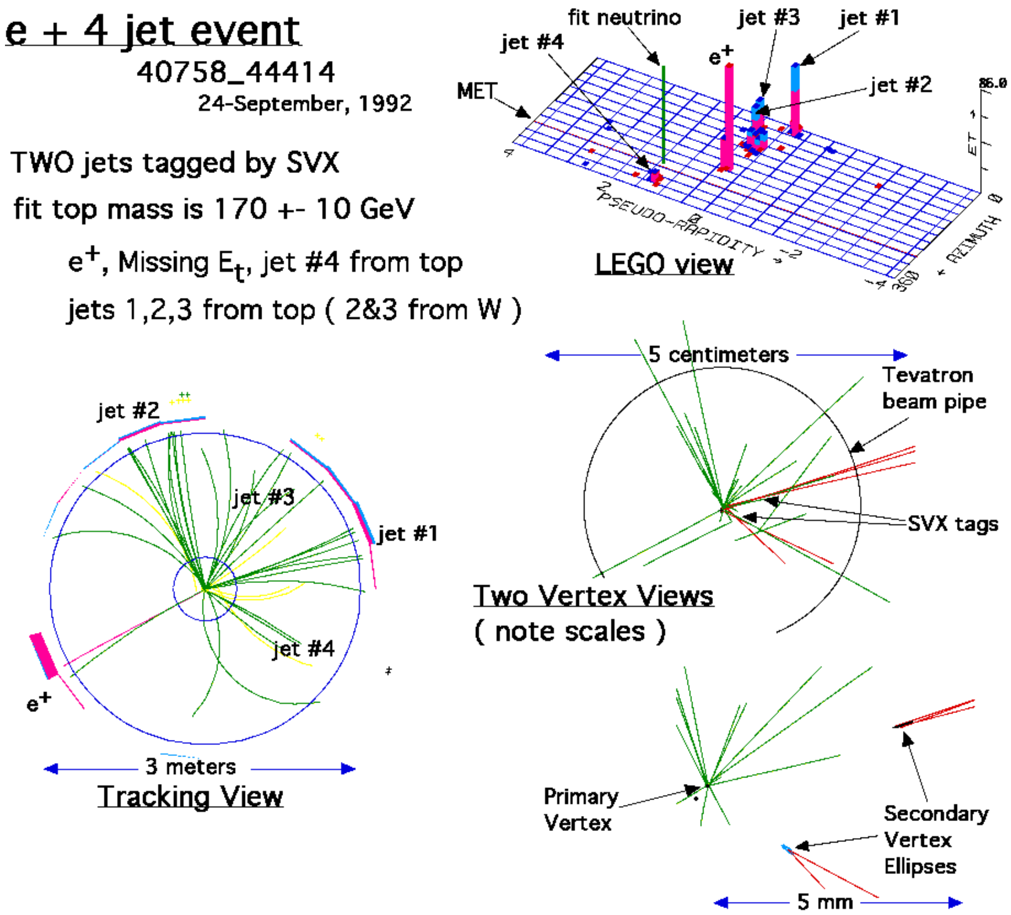
⇒M_{top}>131 GeV@95%CL

Detecting the top quark at CDF

- Strategy
  - dilepton: +2 jets
  - single lepton: b-tagging
    1) soft e/μ: semi-leptonic b-decay
    2) secondary vertex



New: CDF vertex detector (SVX)
(40 μm impact parameter resolution)
powerful discriminant against background

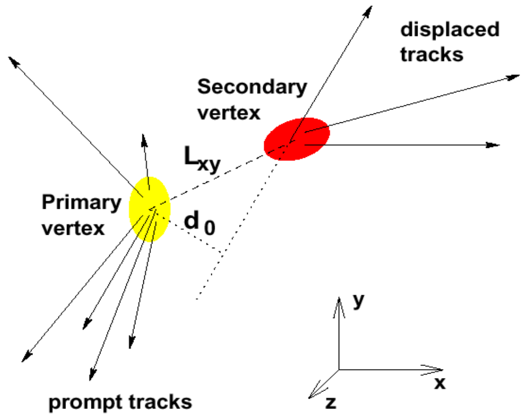


Tagging b-jets

- Top events contain B hadrons
- Only 1-2% of dominant W+jets background contains heavy flavor

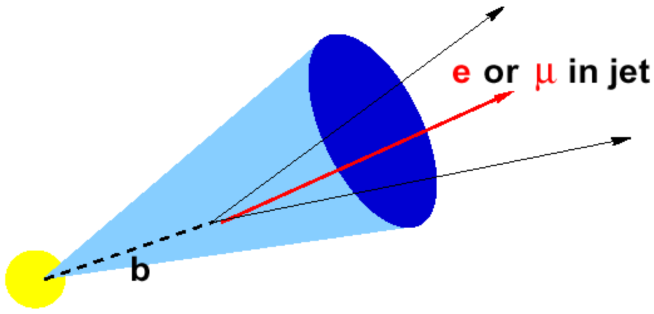
B hadrons are long-lived

Vertex displaced tracks



semileptonic B hadron decay

Soft Lepton Tagging



- $b \to \ell \nu c$ (BR $\sim$ 20%)
- $b \to c \to \ell \nu s$ (BR $\sim$ 20%)

55%	← Top Event Tagging Efficiency →	15%
0.5%	← False Tag Rate (QCD jets) →	3.6%

1993

Coll. Meeting, Aug. 1993:

- Status report from each group (dilepton, single lepton)
- Small, not significant excess in all channels

Type	observed	background
DIL	2 events	$0.56^{+0.25}_{-0.13}$
SVX	6 tags	2.3 ± 0.3
SLT	7 tags	3.1 ± 0.3
total	12 events	---

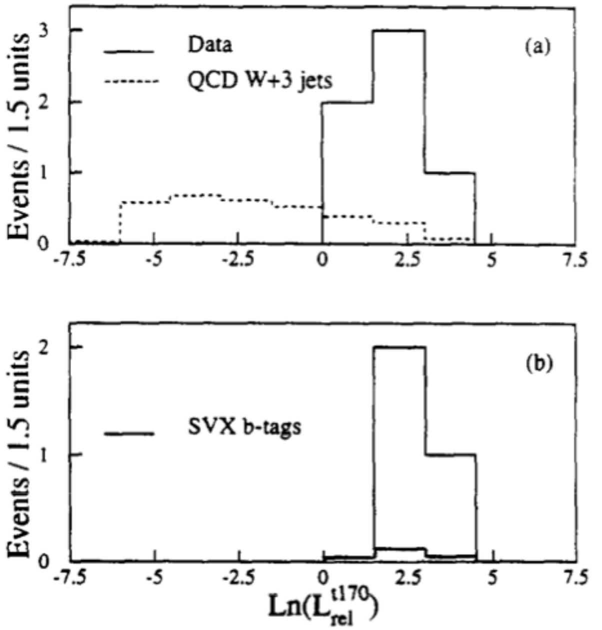
3 events in common (SVX, SLT)

- In total, an excess of events
- Background fluctuation probability: 2.8σ
- Skepticism, additional studies, cross-checks
- Additional 8 months before making the results public

Final steps: CDF and D0

CDF: counting experiment yields 2.8σ

- Few checks: no major discrepancy
- Other checks consistent with presence of signal
- Mass distribution looked good



- There were also other analyses at CDF
  - Difference of jet E_T spectra for signal and bkg
  - Separate two component for signal and bkg
  - CDF chose not to use those for first publication
- Use “counting” experiment

D0: added more data and re-optimized for heavy top (single and dilepton)

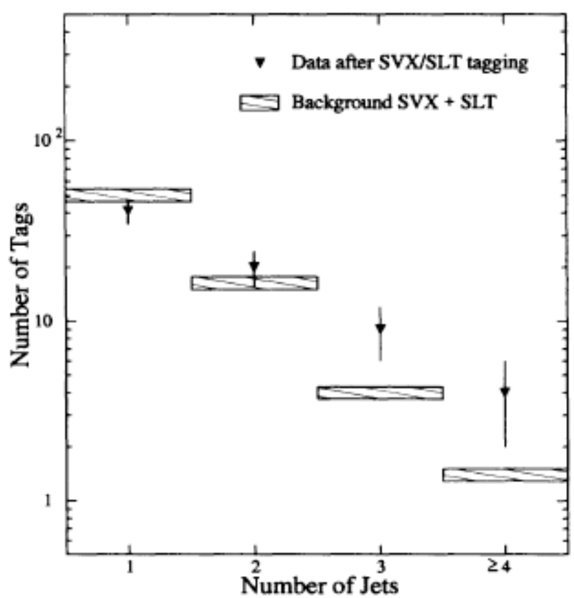
- Observed 7 events (expect 4-6 from bkg)
- No independent evidence

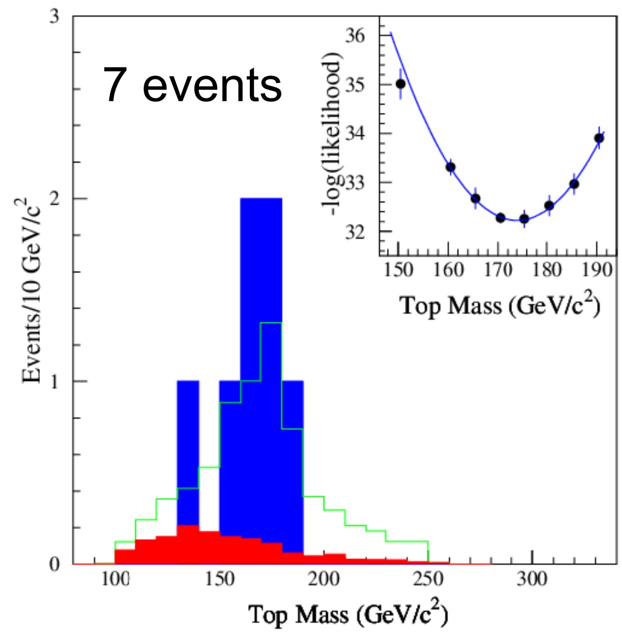
First evidence (1994)

VOLUME 73, NUMBER 2 PHYSICAL REVIEW LETTERS 11 JULY 1994

Evidence for Top Quark Production in $\bar{p}p$ Collisions at $\sqrt{s} = 1.8$ TeV

We summarize a search for the top quark with the Collider Detector at Fermilab (CDF) in a sample of $\bar{p}p$ collisions at $\sqrt{s} = 1.8$ TeV with an integrated luminosity of 19.3 pb^{-1}. We find 12 events consistent with either two W bosons, or a W boson and at least one b jet. The probability that the measured yield is consistent with the background is 0.26%. Though the statistics are too limited to establish firmly the existence of the top quark, a natural interpretation of the excess is that it is due to $t\bar{t}$ production. Under this assumption, constrained fits to individual events yield a top quark mass of $174 \pm 10^{+13}_{-12}$ GeV/c^2. The $t\bar{t}$ production cross section is measured to be $13.9^{+6.1}_{-4.8}$ pb.



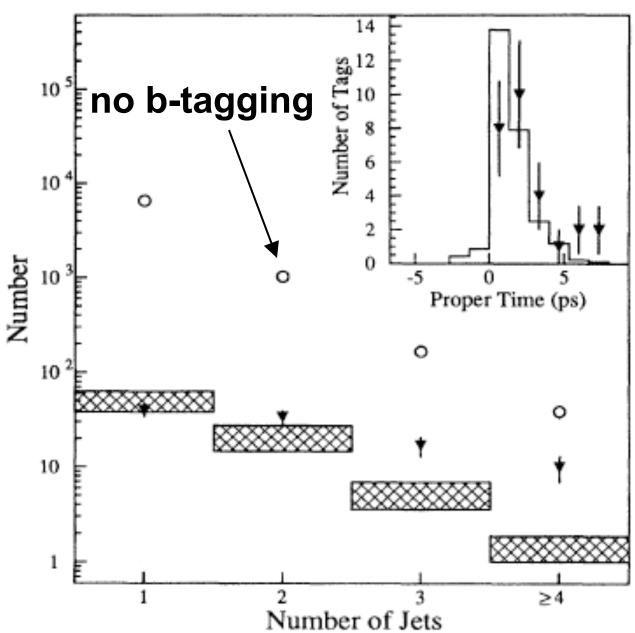


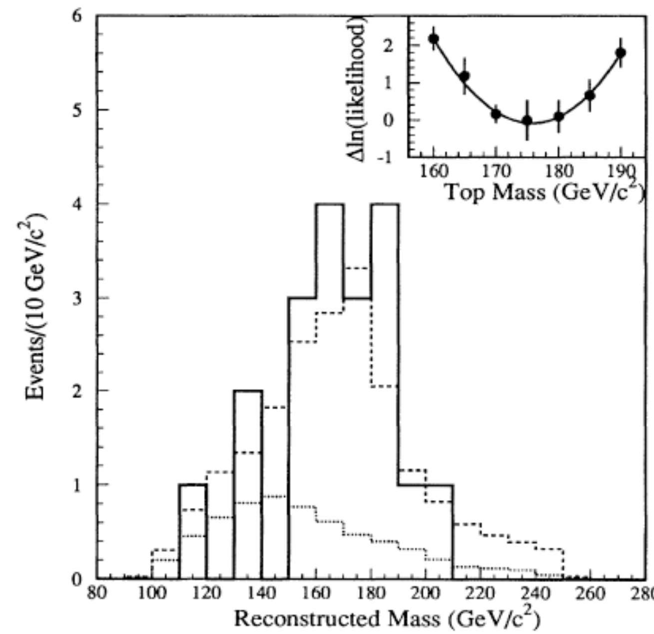
First measurements

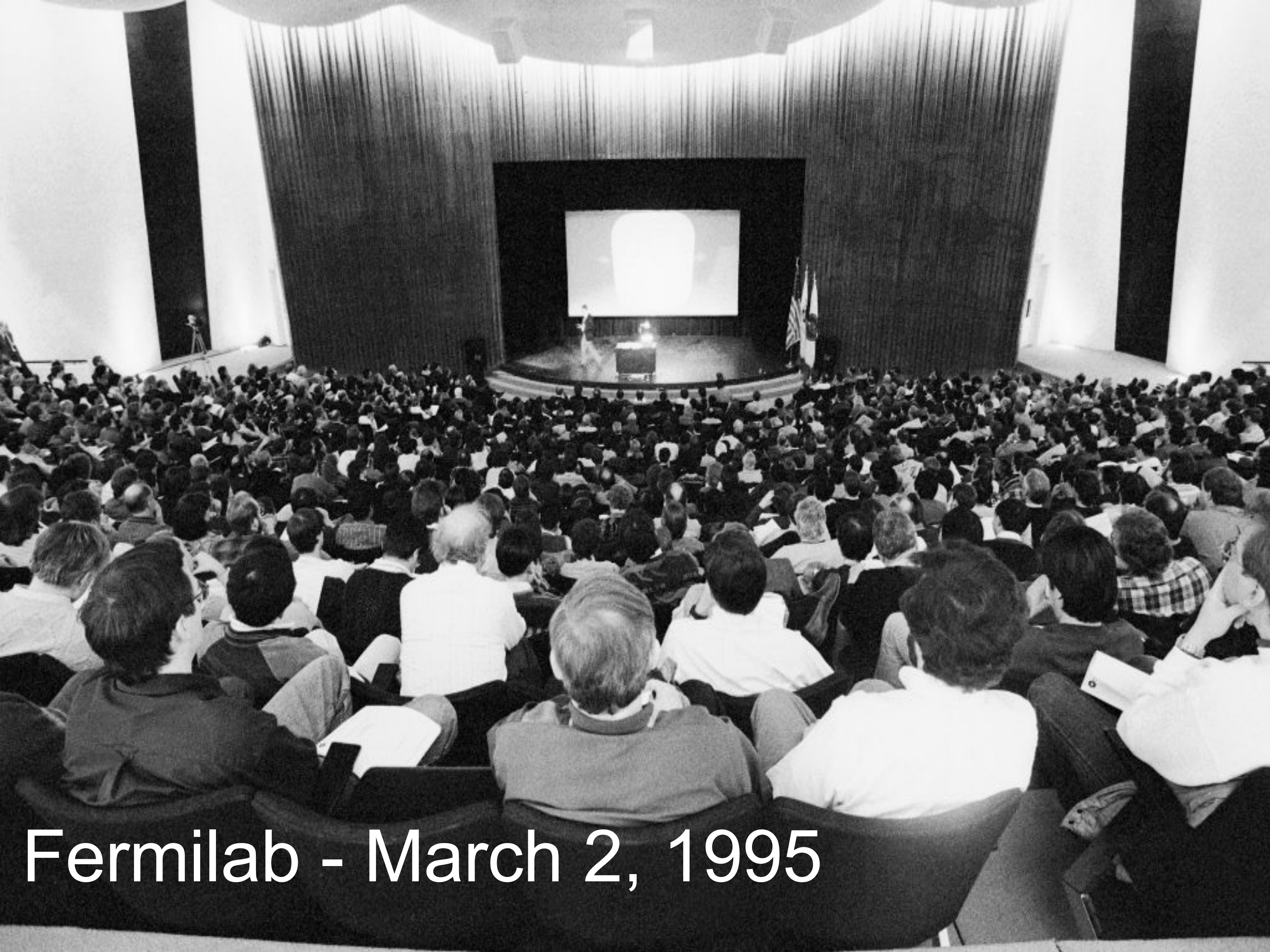
VOLUME 74, NUMBER 14 PHYSICAL REVIEW LETTERS 3 APRIL 1995

Observation of Top Quark Production in $\bar{p}p$ Collisions with the Collider Detector at Fermilab

We establish the existence of the top quark using a 67 pb^{-1} data sample of $\bar{p}p$ collisions at $\sqrt{s} = 1.8$ TeV collected with the Collider Detector at Fermilab (CDF). Employing techniques similar to those we previously published, we observe a signal consistent with $t\bar{t}$ decay to $WWb\bar{b}$, but inconsistent with the background prediction by 4.8σ. Additional evidence for the top quark is provided by a peak in the reconstructed mass distribution. We measure the top quark mass to be $176 \pm 8(\text{stat}) \pm 10(\text{syst})\ \text{GeV}/c^2$, and the $t\bar{t}$ production cross section to be $6.8^{+3.6}_{-2.4}$ pb.






Fermilab - March 2, 1995

First measurements

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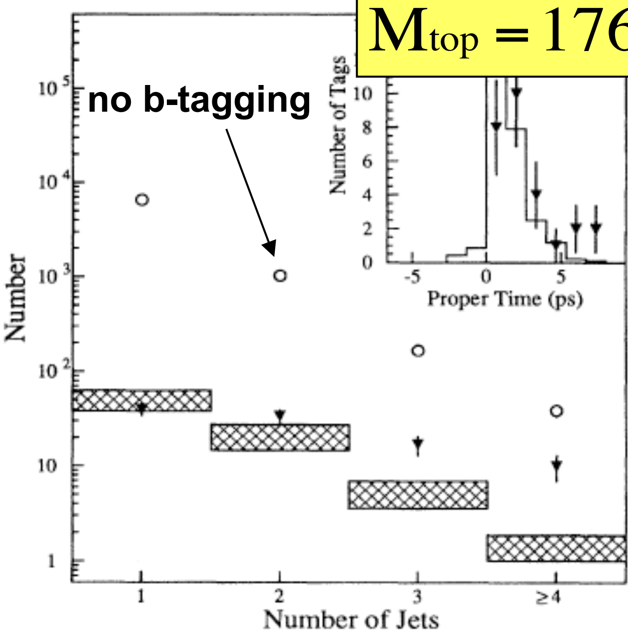
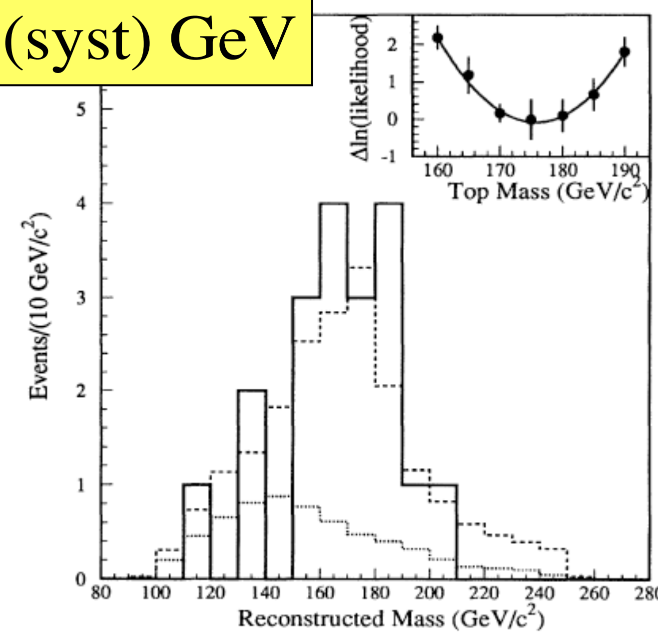
$$\sigma_{tt} = 6.8^{+3.6}_{-2.4} \text{ pb}$$

$$M_{top} = 176 \pm 8(\text{stat}) \pm 10(\text{syst}) \text{ GeV}$$





First measurements

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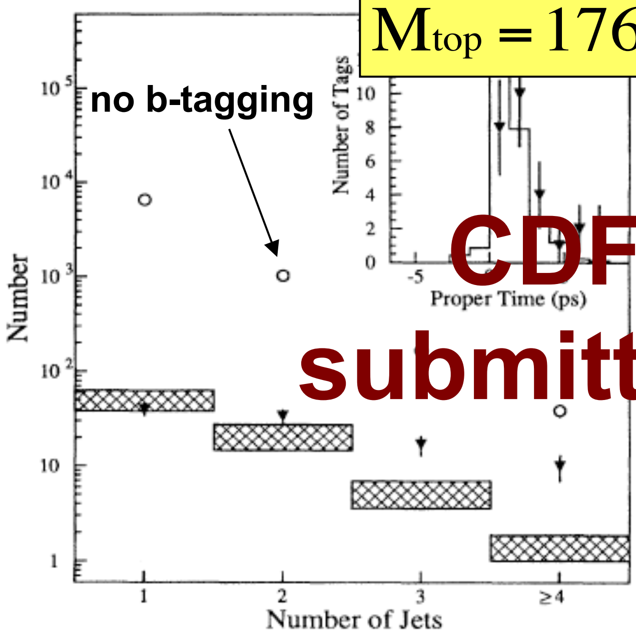
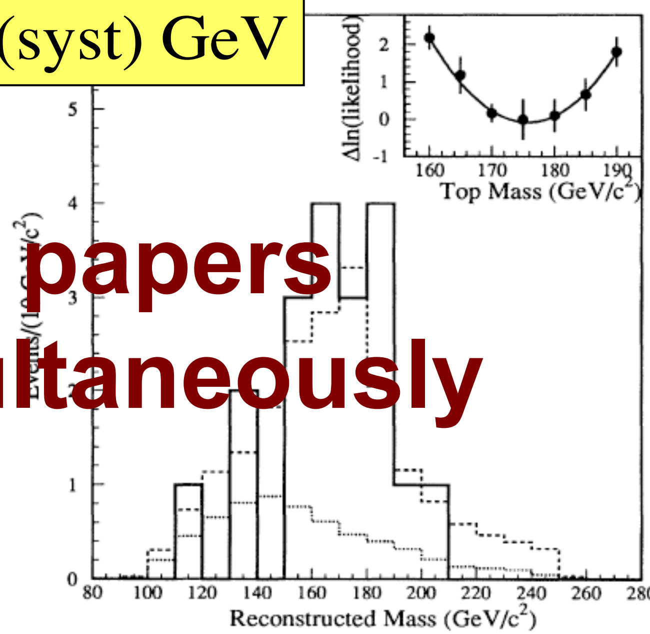
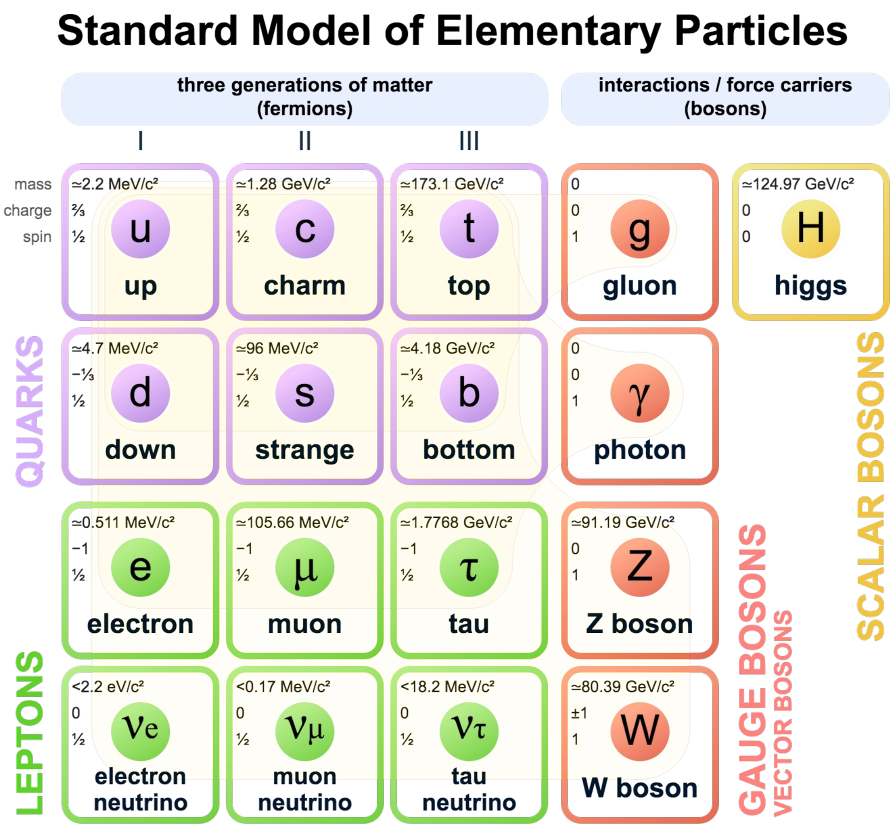
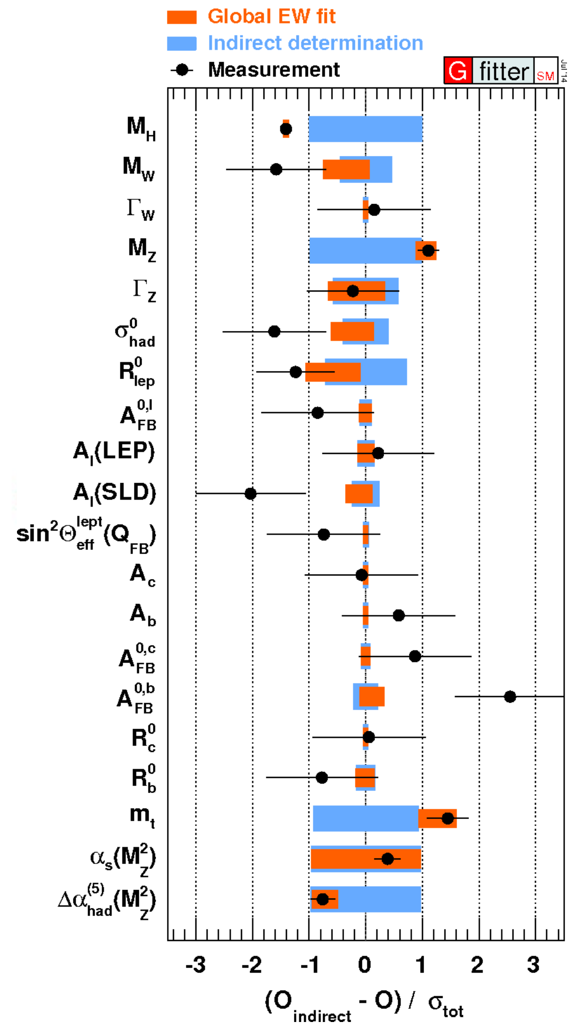




CDF and D0 papers submitted simultaneously

SM confirmed by the data

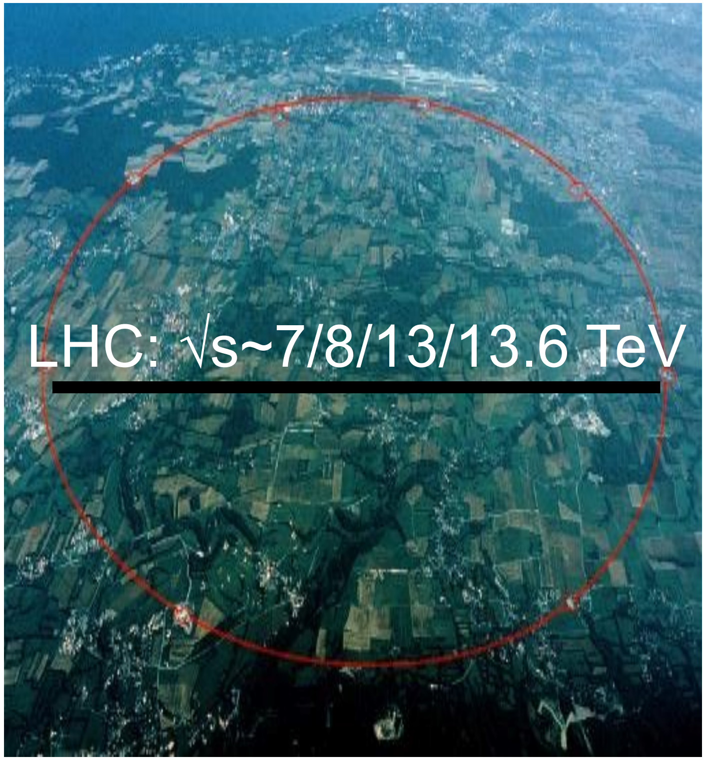




Excellent agreement with all experimental results

The Large Hadron Collider

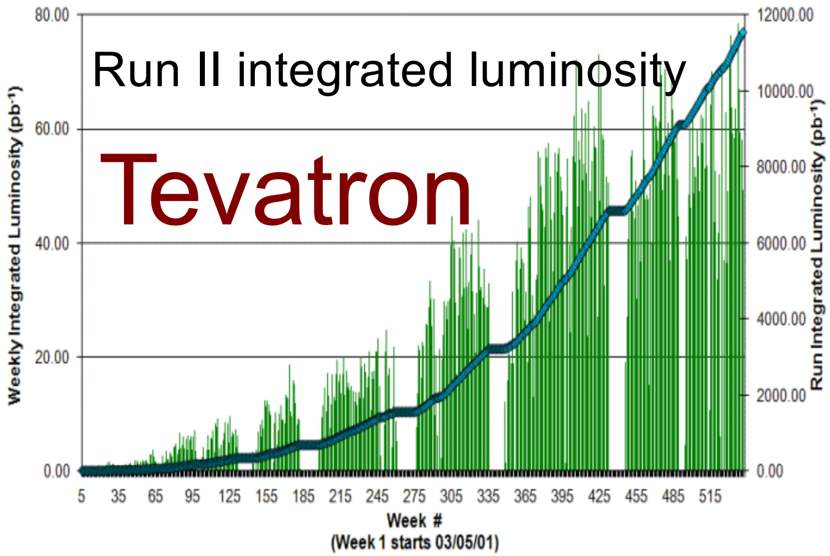
- Built to explore new energy frontiers
  - First colliding beams in 2009
  - started with “low” luminosity in 2010
  - ~5 fb^{-1}@7TeV delivered in 2011
  - ~20 fb^{-1}@8TeV in 2012
  - >150fb^{-1}@13 TeV in 2015-2018
  - >~50fb^{-1}@13.6 TeV in 2022-

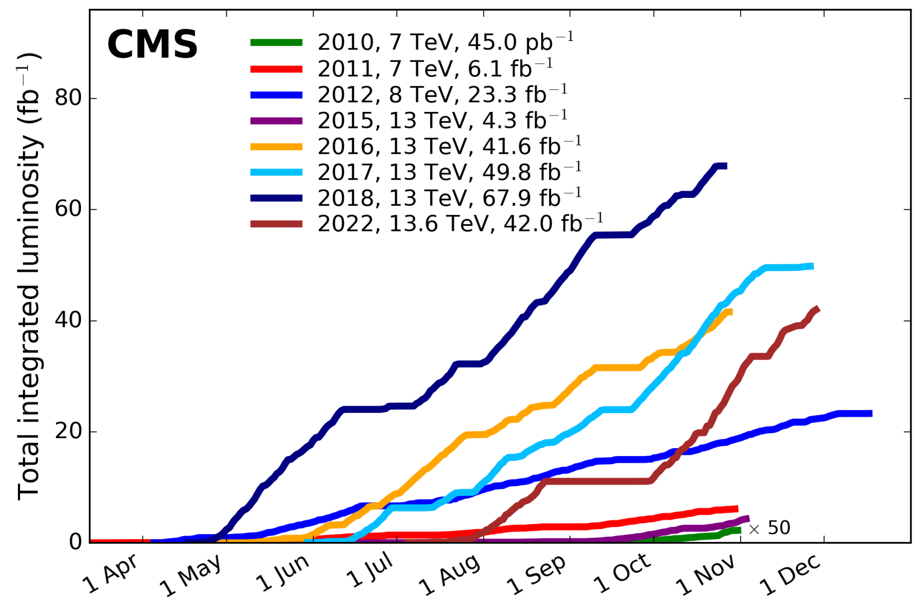


- re-establish SM measurements
- access to new physics processes

⇨ Top quarks give access to SM and BSM (?)

Tevatron vs LHC





Energy: 1.96 TeV
Int. Luminosity: 12 fb^{-1}
Age: ~25 years
Events/exp (1 fb^{-1})
350 ee eμ, μμ
2k lepton + jets

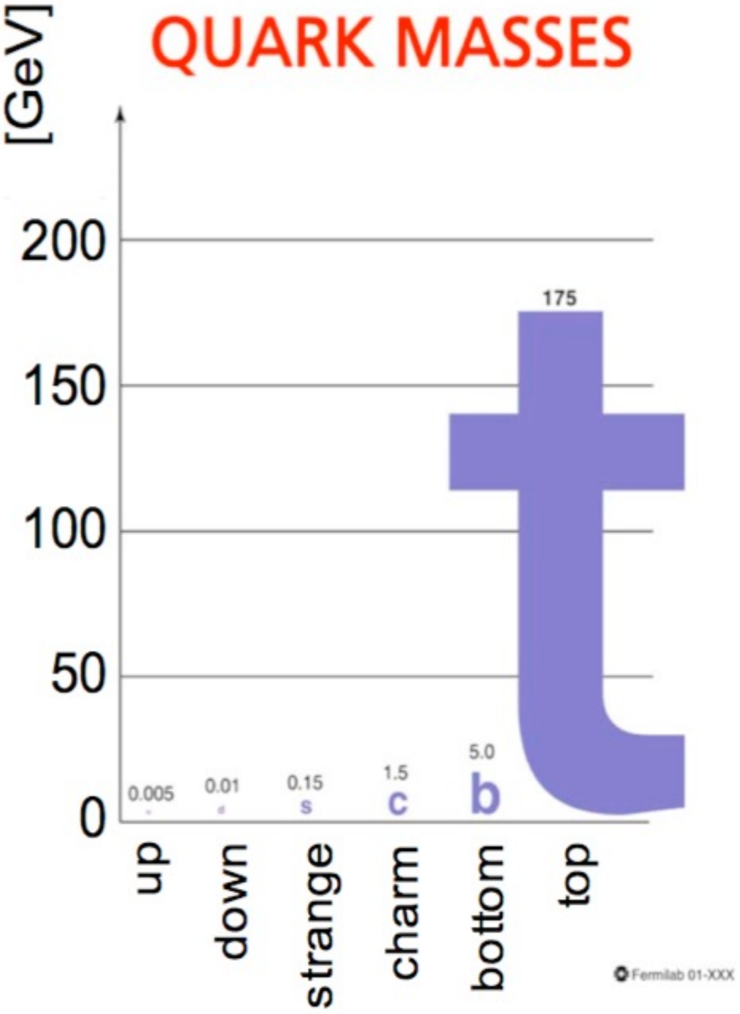
Energy: 7/8/13 TeV
Int. Luminosity: 5/20/150 fb^{-1}
Age: ~14 years
Events/exp (1 fb^{-1})
40k ee eμ, μμ
250k lepton + jets

The top quark

- The heaviest known elementary particle
- Large coupling to the Higgs: ~1
- Short lifetime

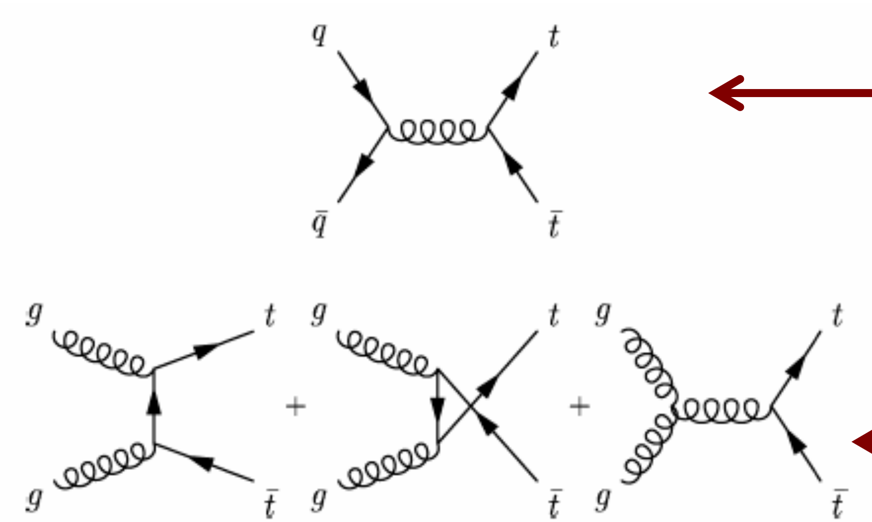
τ=0.4x10^{-24} sec

  - for m_{top}=175 GeV⇒Γ=1.4 GeV ⇒no hadronization
  - large contributions to EWK corrections ~$G_F m_{top}^2$
  - very short lifetime ⇒ bound states are not formed ⇒ opportunity to study a free quark



- Large samples of top quarks available
- Top quarks are main background for many New Physics searches
- Precision measurements may provide insight into physics beyond SM

How is the top quark produced?



Dominant at Tevatron

Dominant at the LHC

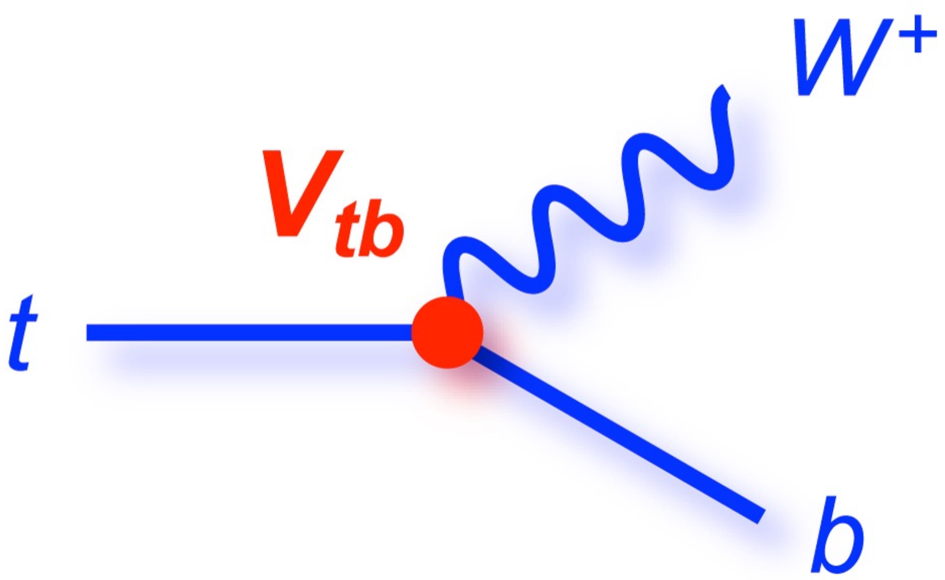
Predicted cross sections:

Collider	σ_{tot} [pb]	scales [pb]	PDF [pb]
Tevatron	7.164	$^{+0.110(1.5\%)}_{-0.200(2.8\%)}$	$^{+0.169(2.4\%)}_{-0.122(1.7\%)}$
LHC 7 TeV	172.0	$^{+4.4(2.6\%)}_{-5.8(3.4\%)}$	$^{+4.7(2.7\%)}_{-4.8(2.8\%)}$
LHC 8 TeV	245.8	$^{+6.2(2.5\%)}_{-8.4(3.4\%)}$	$^{+6.2(2.5\%)}_{-6.4(2.6\%)}$
LHC 14 TeV	953.6	$^{+22.7(2.4\%)}_{-33.9(3.6\%)}$	$^{+16.2(1.7\%)}_{-17.8(1.9\%)}$

Czakon et al. PRL 110, 252004 (2013)

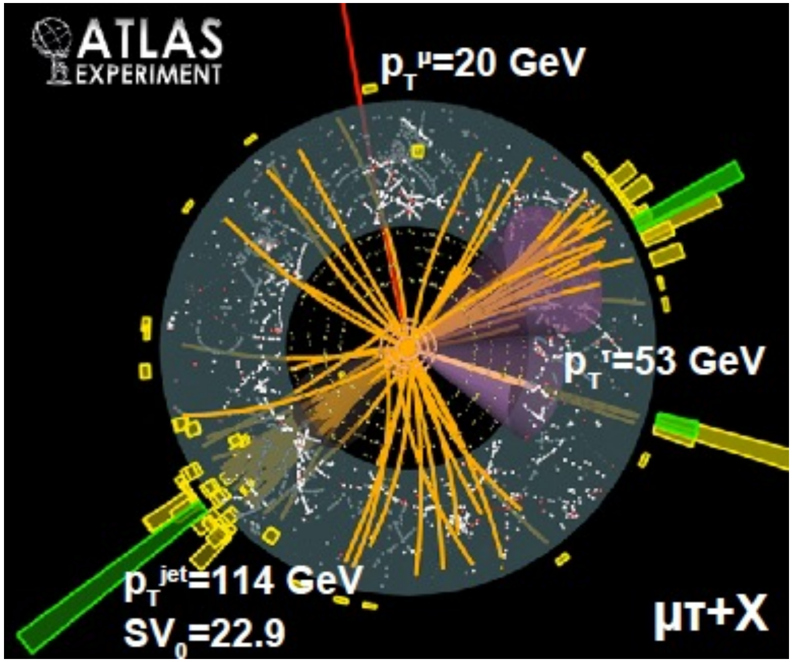
	LHC	Tevatron
gg	~85%	~10%
qq	~15%	~90%

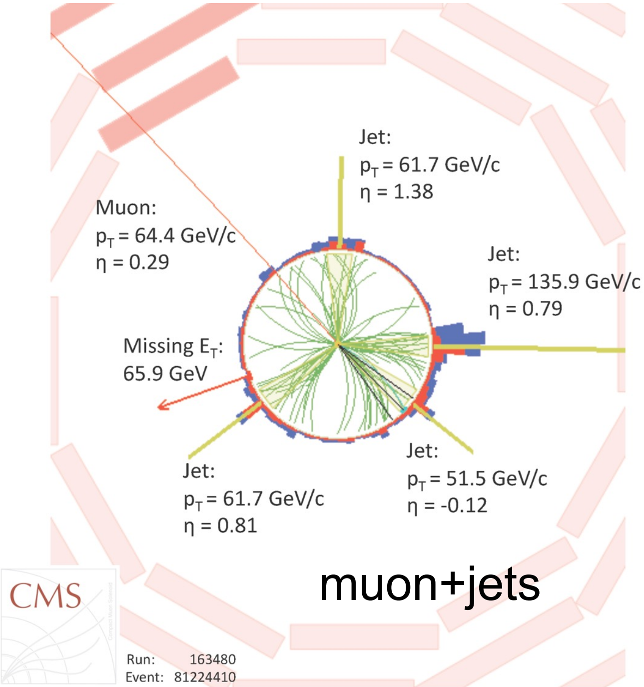
How does a top quark decay?



- almost always $t \to Wb$ (i.e. $V_{tb} \sim 1$)
- lifetime is short, and it decays before hadronizing
- the W is real:
  - can decay $W \to l\nu$ ($l = e, \mu, \tau$), BR~1/9 per lepton
  - can decay $W \to qq$, BR~2/3

Selection of top quark events



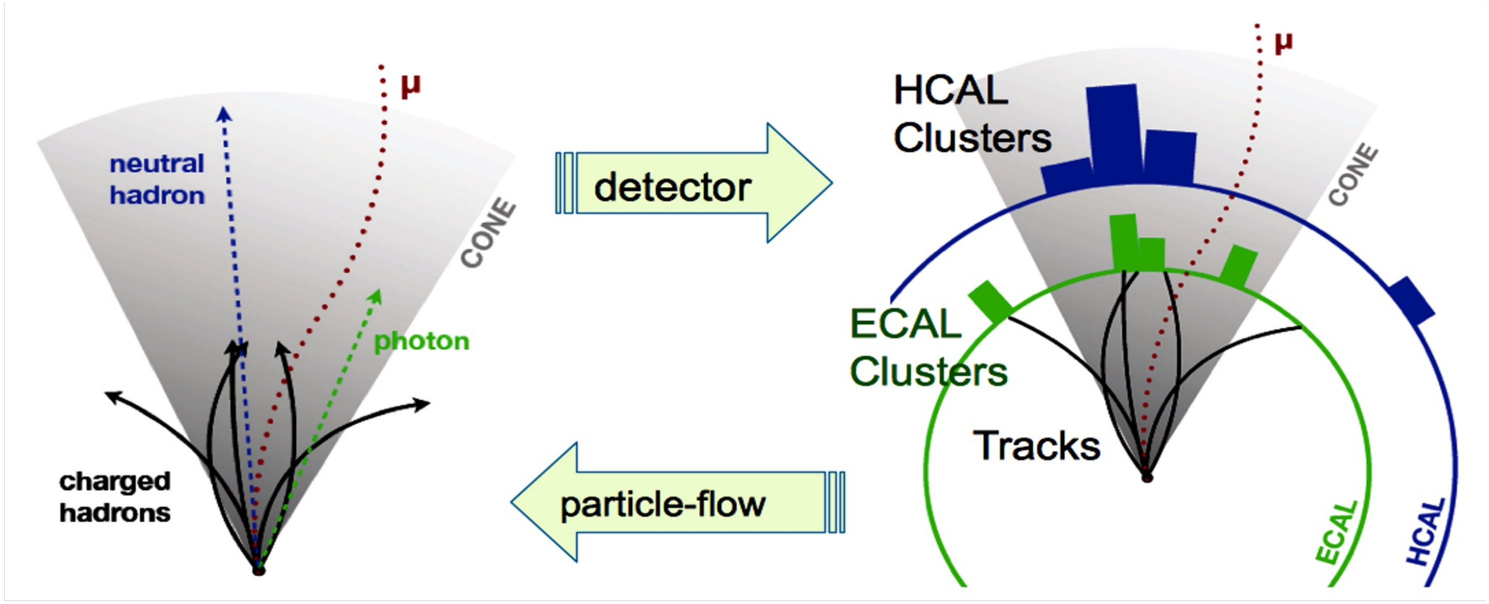


- Trigger:
  - single or double (isolated) lepton
- Leptons:
  - e/μ, p_T>20/30 GeV, $|\eta|$<2.5
  - Identification/reconstruction
  - Tracker/calorimeter isolation

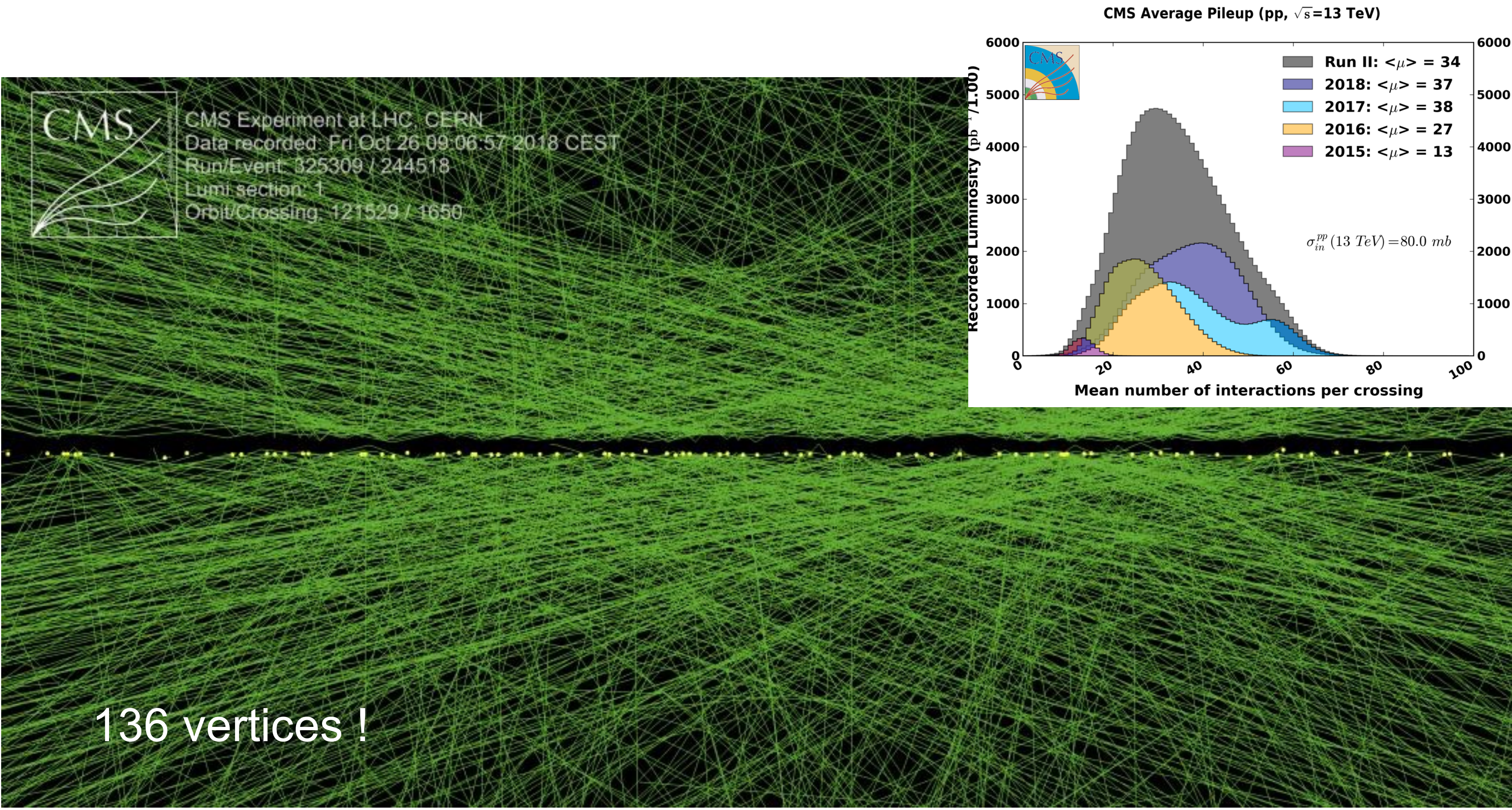
- Jets:
  - at least 2 jets, p_T>30 GeV, $|\eta|$<2.5
  - anti-kT algorithm, with cone 0.4-0.5
  - b-tagging is optional
- Missing transverse energy:
  - Typically require 30-40 GeV

Particle Flow event reconstruction

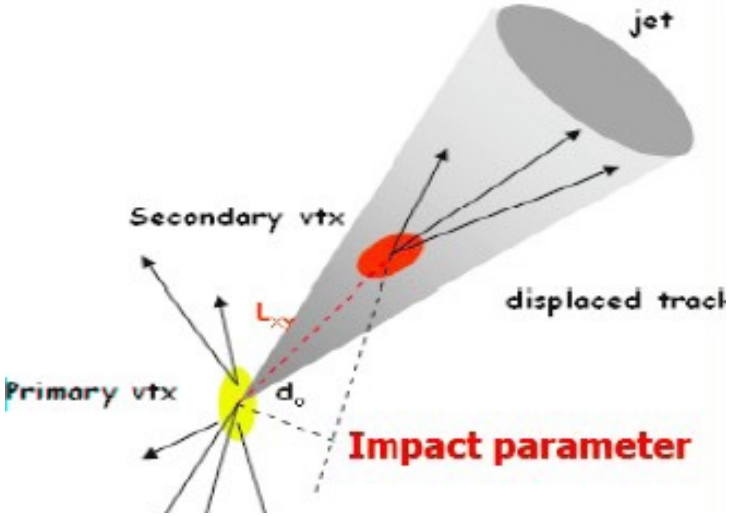
- Particle Flow (PF) combines information from all subdetectors to reconstruct particles produced in the collision
  - charged hadrons, neutral hadrons, photons, muons, electrons
  - use complementary info. from separate detectors to improve performance
  - tracks to improve calorimeter measurements
- From list of particles, can construct higher-level objects
  - Jets, b-jets, taus, isolated leptons and photons, MET, etc.



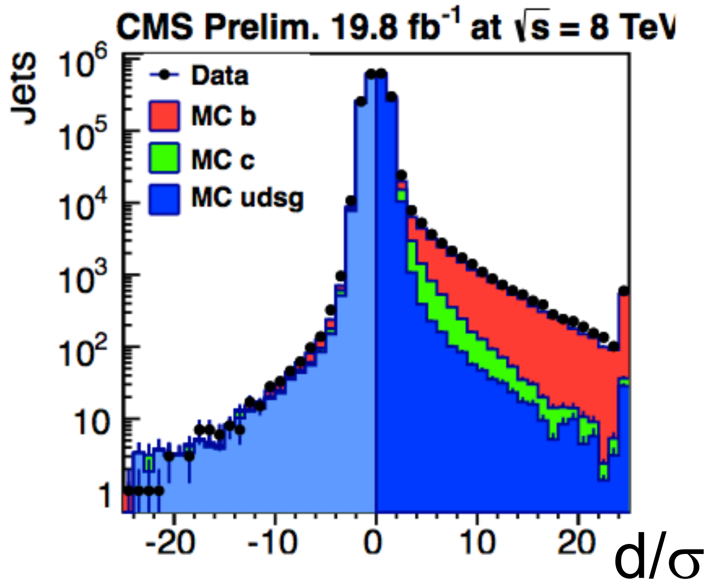
…in a challenging environment



Challenge: b-tagging

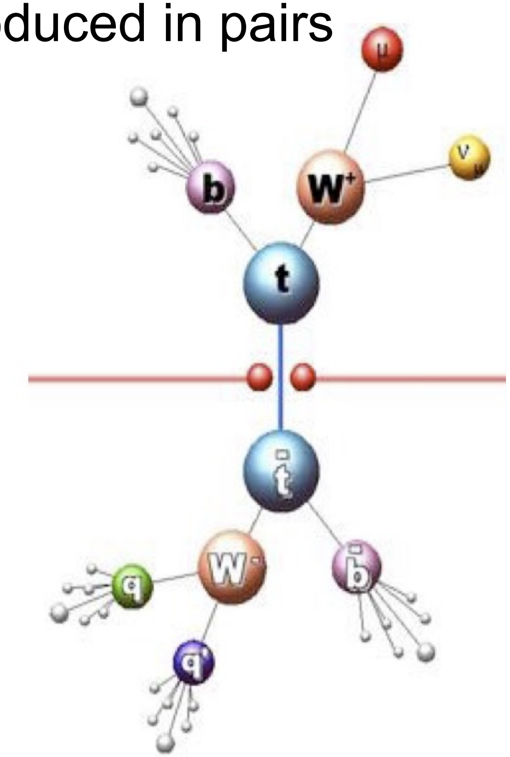


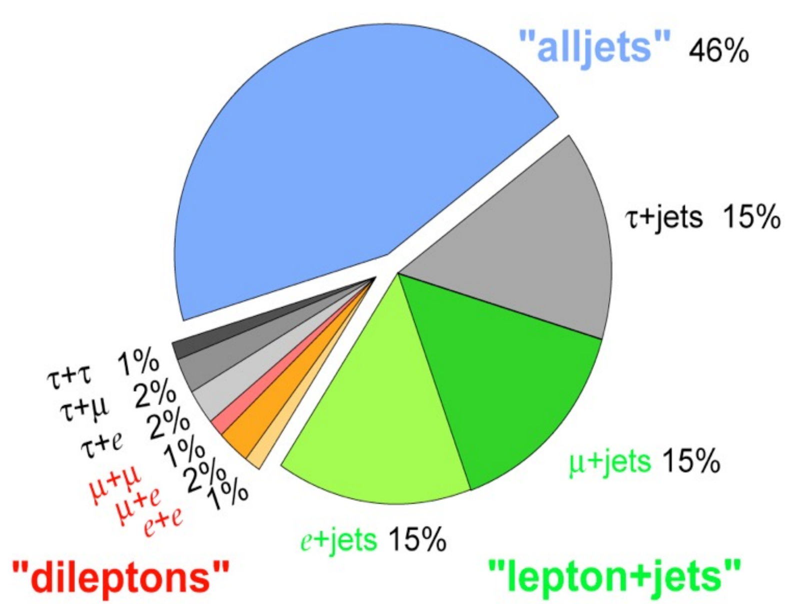
- Lifetime: τ_b~1-2 psec
- Reduction of background obtained by identifying jets from b-quarks
- Two methods:
  - Secondary vertex tagging
  - Semileptonic decays of b-hadrons in jets ($b \rightarrow l \nu_l X$)



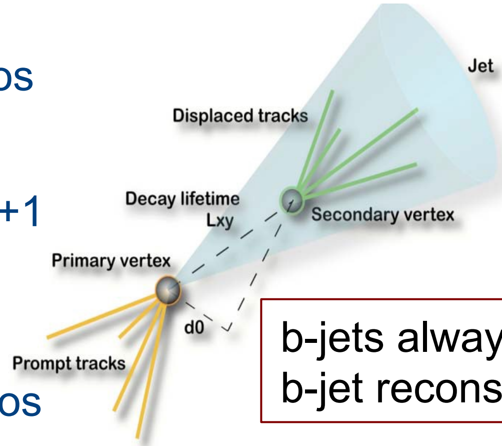
Top quark decays

Top quarks (mostly) produced in pairs



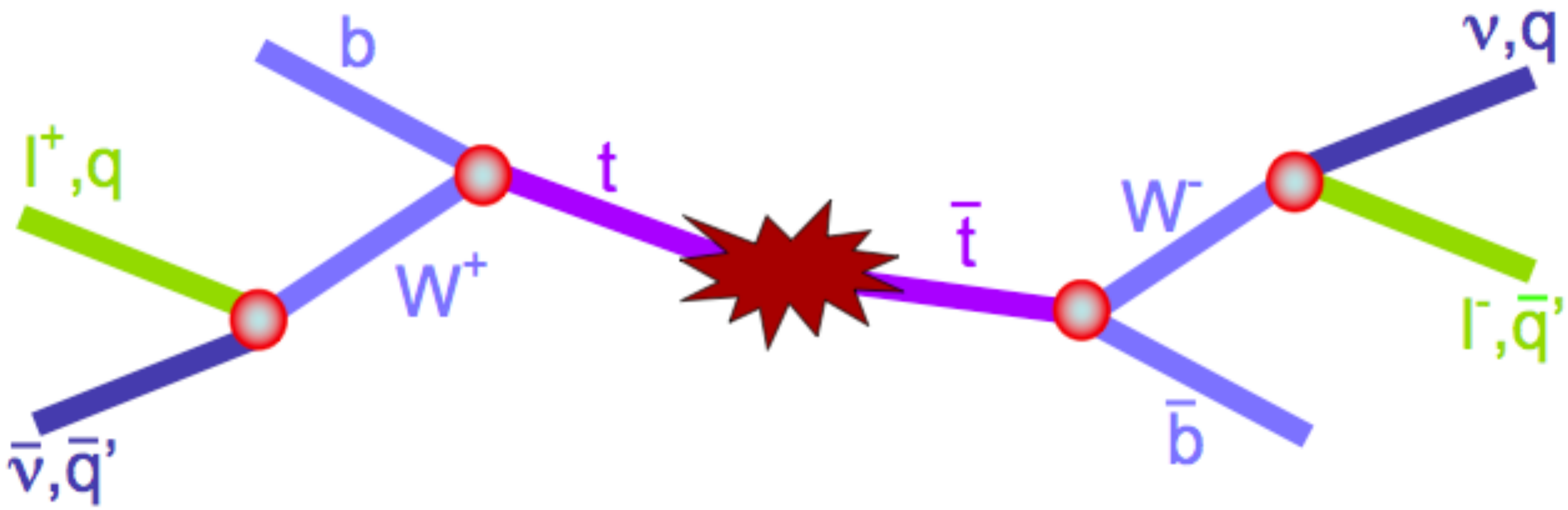


- Dilepton (ee, μμ, eμ):
  - BR~5%, 2 leptons+2 b-jets+2 neutrinos
- Lepton (e or μ) + jets
  - BR~30%, one lepton+4jets (2 from b)+1 neutrino
- All hadronic
  - BR~44%, 6 jets (2 from b), no neutrinos



b-jets always present
b-jet reconstruction plays important role

Interesting physics with Top quark



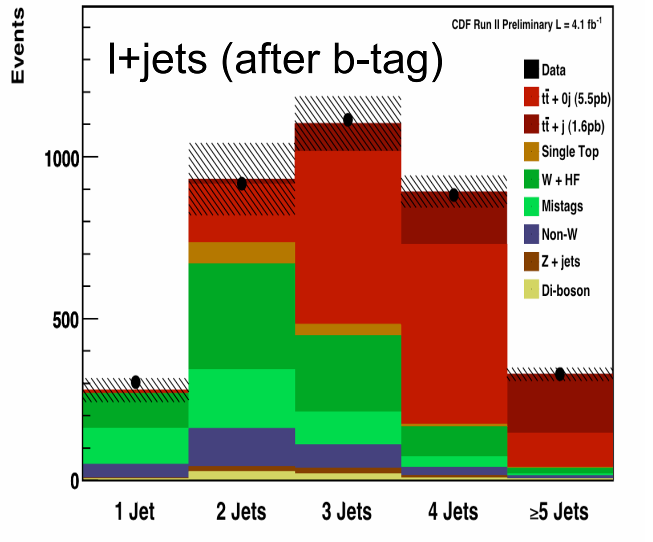
PRODUCTION
Cross section
Resonances X→tt
Fourth generation t'
Spin-correlations
New physics (SUSY)
Flavour physics (FCNC)
...

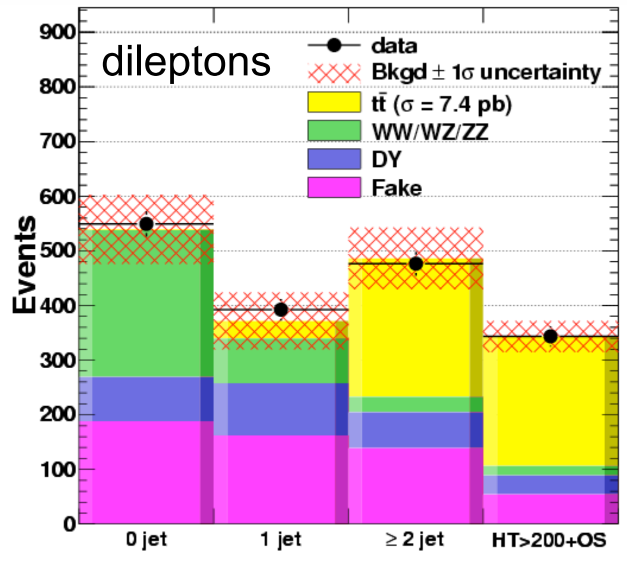
PROPERTIES
Mass
Kinematics
Charge
Lifetime and width
W helicity
Spin
...

DECAY
Branching ratios
Charged Higgs (non-SM)
Anomalous couplings
Rare decays
CKM matrix elements
Calibration sample @LHC
...

Top quark events

- LHC@13TeV cross section ~100 times larger than Tevatron
- select ttbar events at LHC:
  - understand/calibrate detector
  - measure properties
- event selection includes SM control events
- ttbar final state is complex (ie not mass peak)
- Top quarks and new physics:
  - ttbar sample may contain new physics
  - look at jet multiplicity bins (since ttbar is background e.g. for SUSY), or other variables





Theory cross sections: TeV vs LHC

Collider	σ_{tot} [pb]	scales [pb]	PDF [pb]
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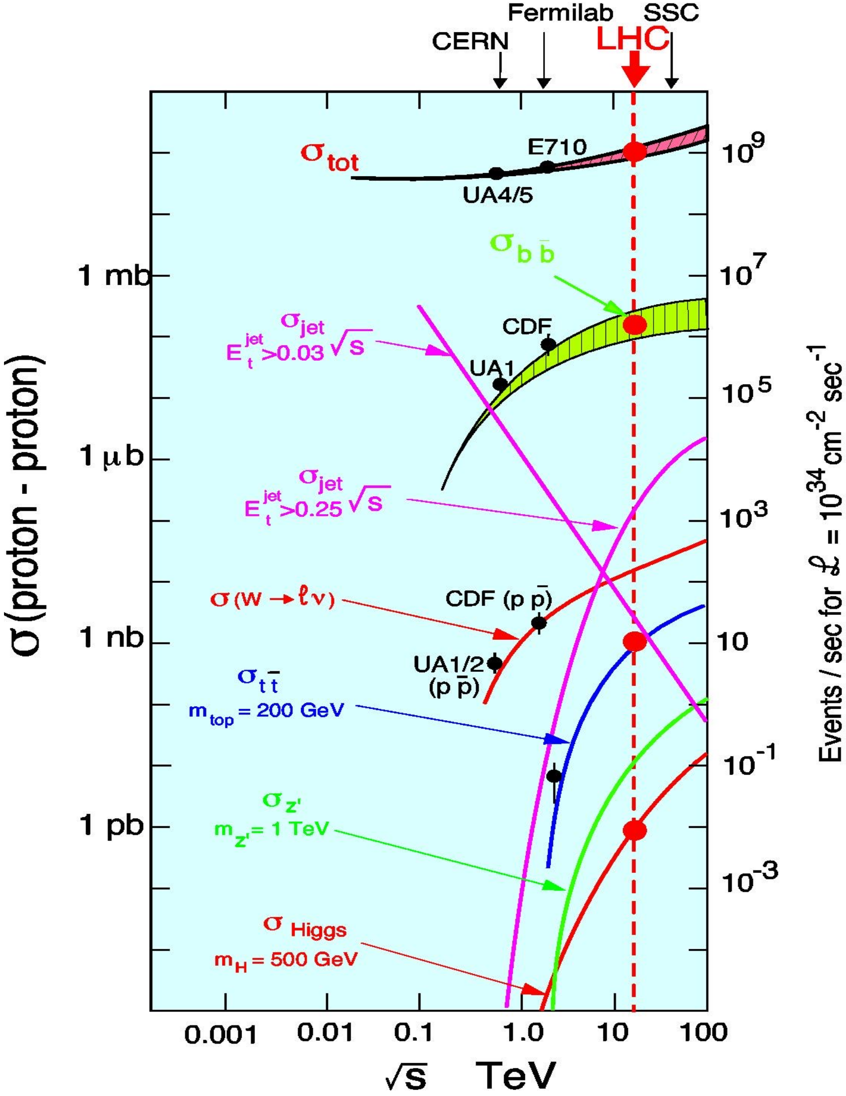
Including NNLO+NNLL approximations
PRL 110, 252004 (2013) (M. Czakon et al.)

Top cross section at 7/8 vs 13 TeV

- LHC collisions started at 7/8 TeV
- LHC design is at 14 TeV
- Top cross section drops faster than background processes at lower sqrt{s}
  - top σ(7TeV) = 172 pb
  - top σ(8TeV) = 246 pb
  - top σ(13TeV)= 832 pb
- Background is more "flat"



Cross section measurement

Number of observed events

Number of background events *(from data, calculated from theory)*

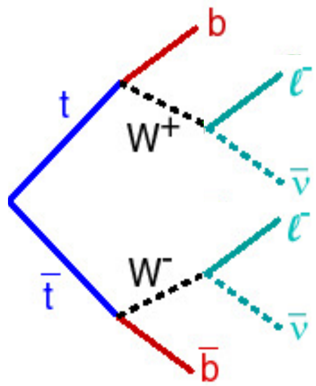
$$\sigma_{t\bar{t}} = \frac{N_{obs} - N_{bgd}}{\varepsilon_{t\bar{t}} \cdot \int L dt}$$

Acceptance *(experimental: detector, efficiencies)*

Luminosity *(determined by amount of data, accelerator, triggers, etc)*

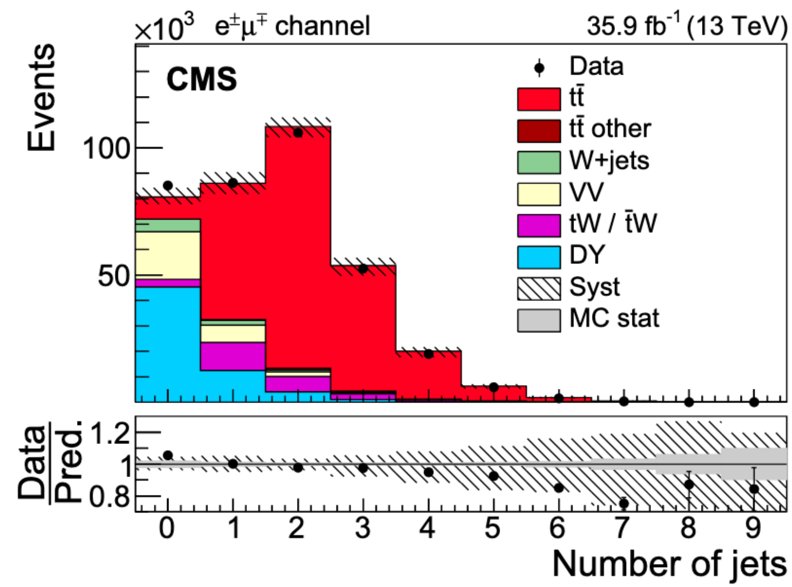
Dilepton channel

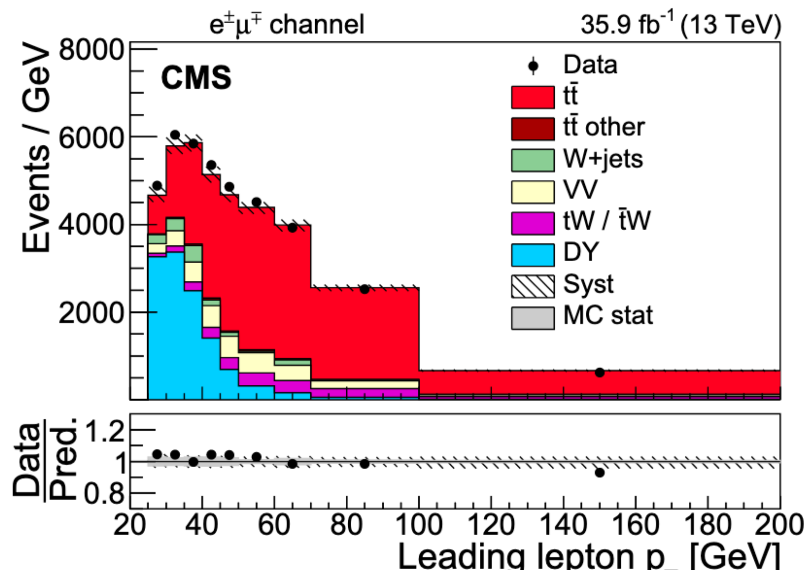
EPJC 79(2019)368



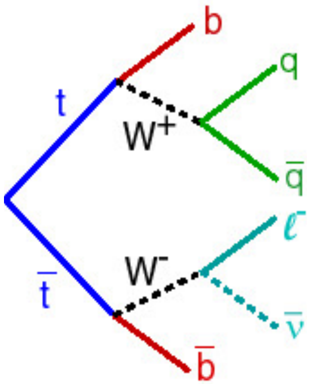
- Branching ratio (BR) ~5%
- Background: small

- Clean final state
  - two leptons + ≥2 jets + MET
  - kinematic variables
- Signal visible w/without b-tagging
- Main systematics: JES, lepton ID, (pileup, b-tag, signal modeling)





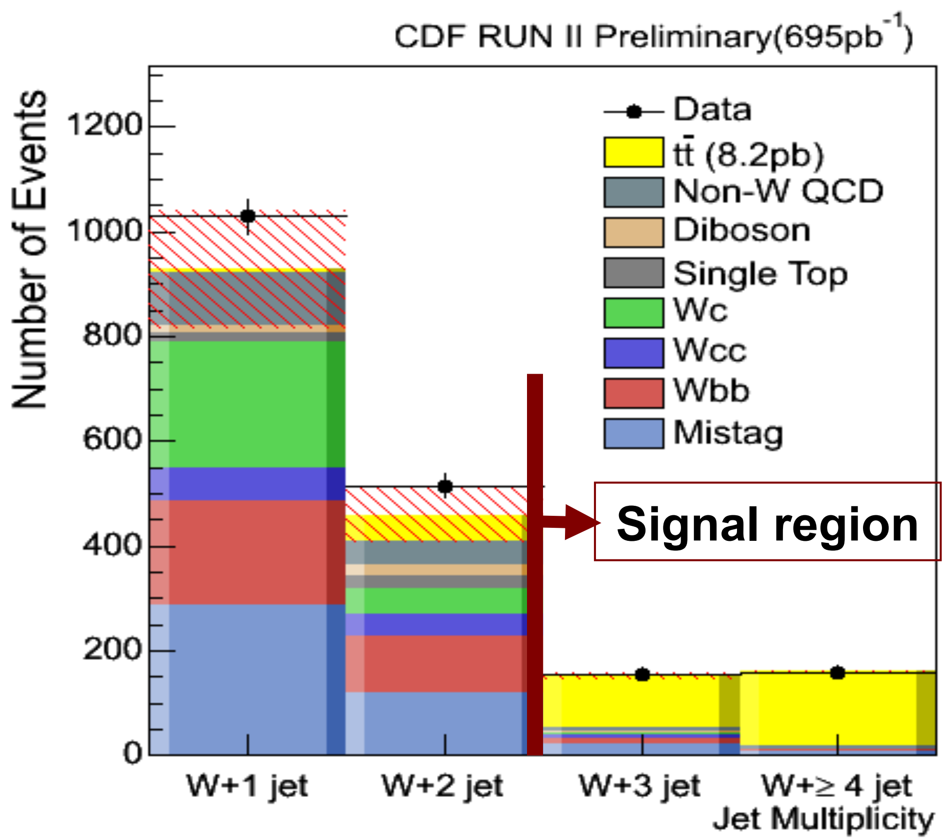
Lepton + jets



- BR ~30%
- Background: moderate

- Selection:
  - one lepton + ≥3 jets + MET
  - may require b-tag

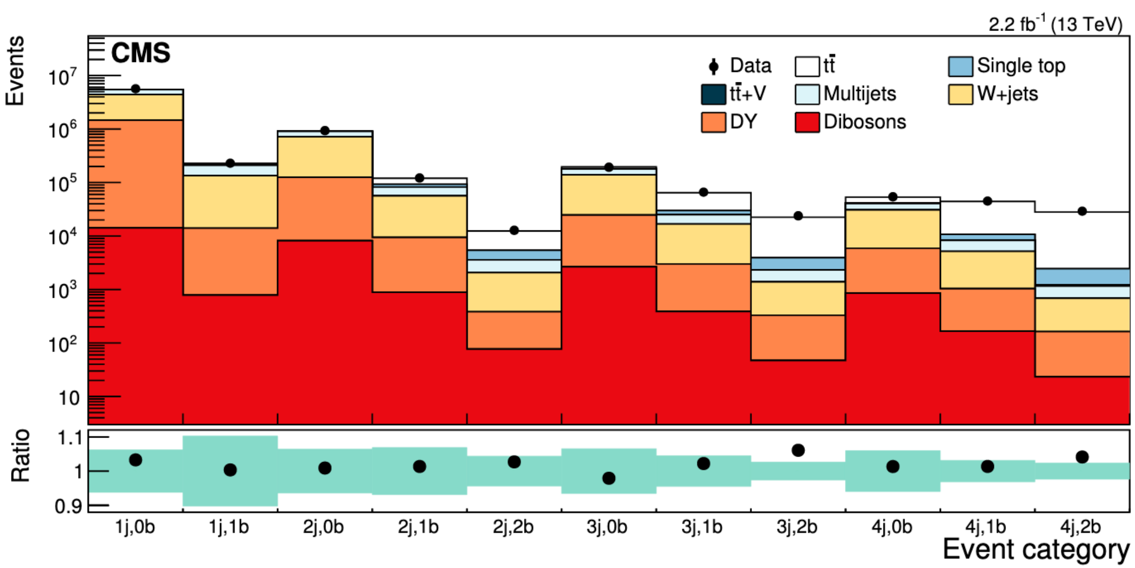
- Main backgrounds:
  - hadronic multi-jet, W+jets

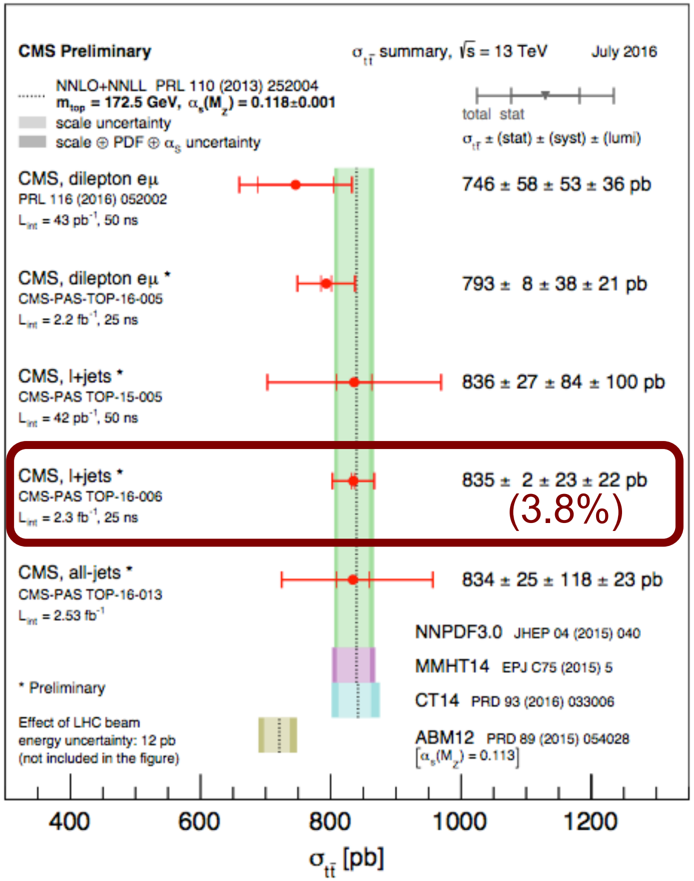


Cross section: multi-dimensional fit

JHEP 09(2017)051

- Lepton+jet final state
- Keep selection as inclusive as possible
- Categorize events according to (b-) jet multiplicity
  - high-purity vs background dominated
  - Constrain systematics (JES, ISR/FSR, modeling, etc)
- Combined fit of M_{lb} to signal and backgrounds
- Precise cross section measurement





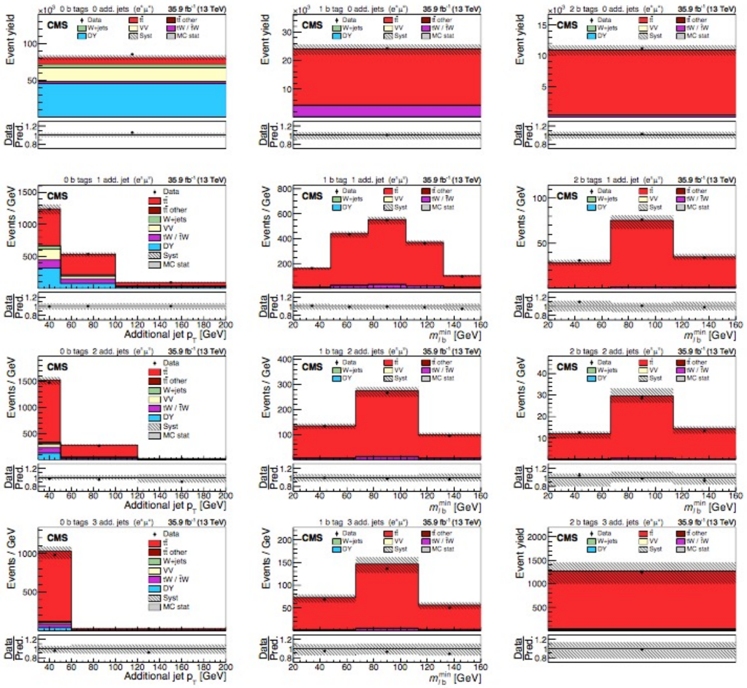
Cross section: multi-dimensional fit

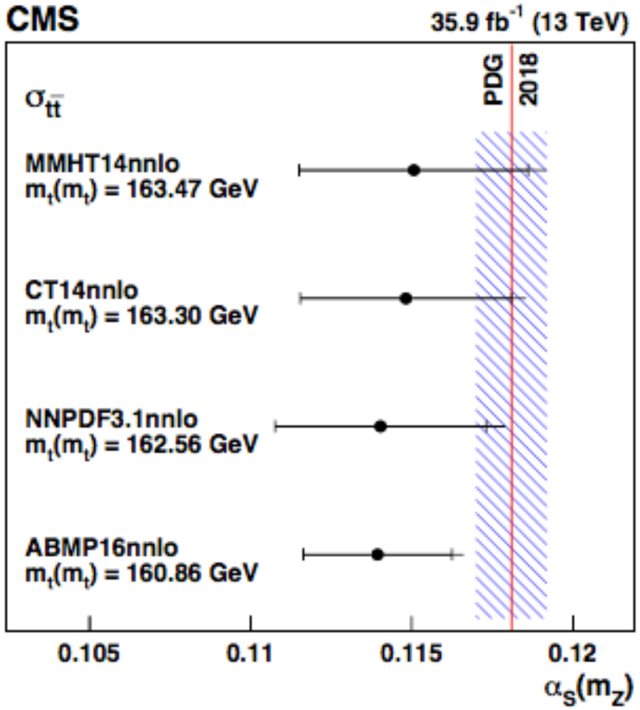
- Dilepton final state
- Simultaneous fit in ($N_{additional\ jet}$,$N_{b\text{-}jet}$) categories
- Fit of σ_{ttbar} and m(top)

(~4%)

$$\sigma_{t\bar{t}} = 803 \pm 2\,(\text{stat}) \pm 25\,(\text{syst}) \pm 20\,(\text{lumi})\,\text{pb}$$

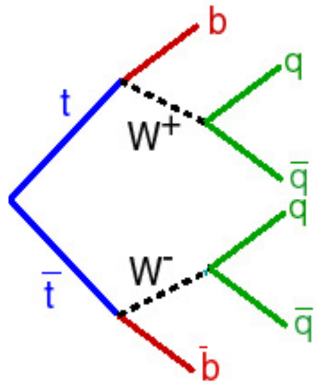
$$m_t^{MC} = 172.33 \pm 0.14\,(\text{stat})\,^{+0.66}_{-0.72}\,(\text{syst})\,\text{GeV}$$





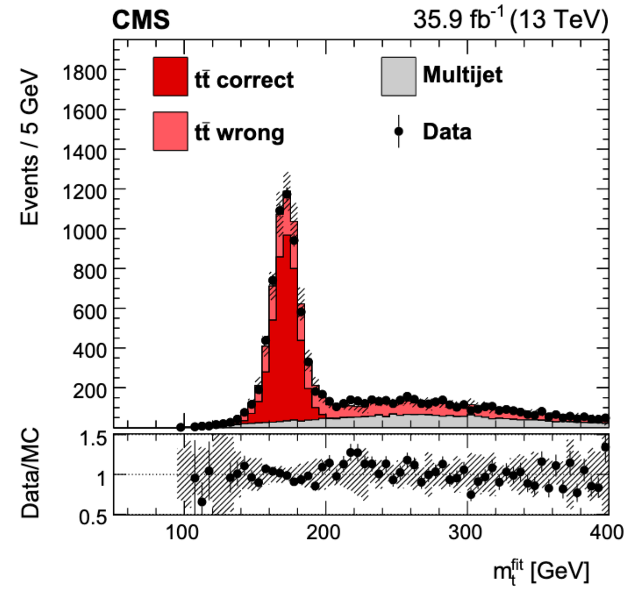
All hadronic

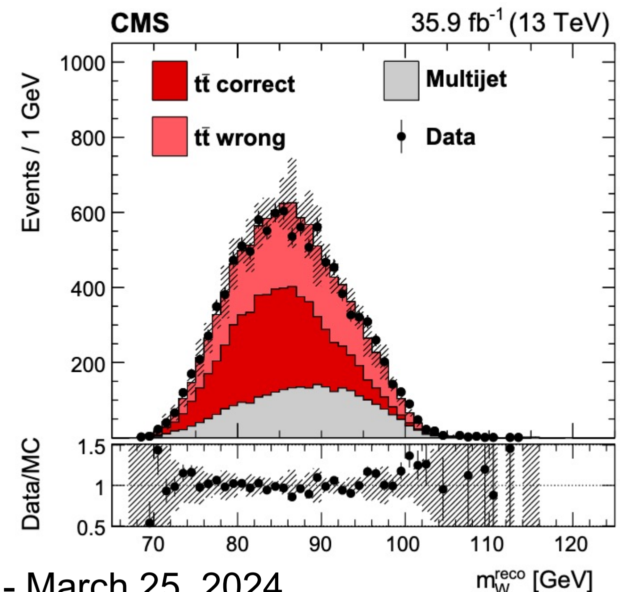
EPJC 79(2019)313



- BR ~46%
- Background: large

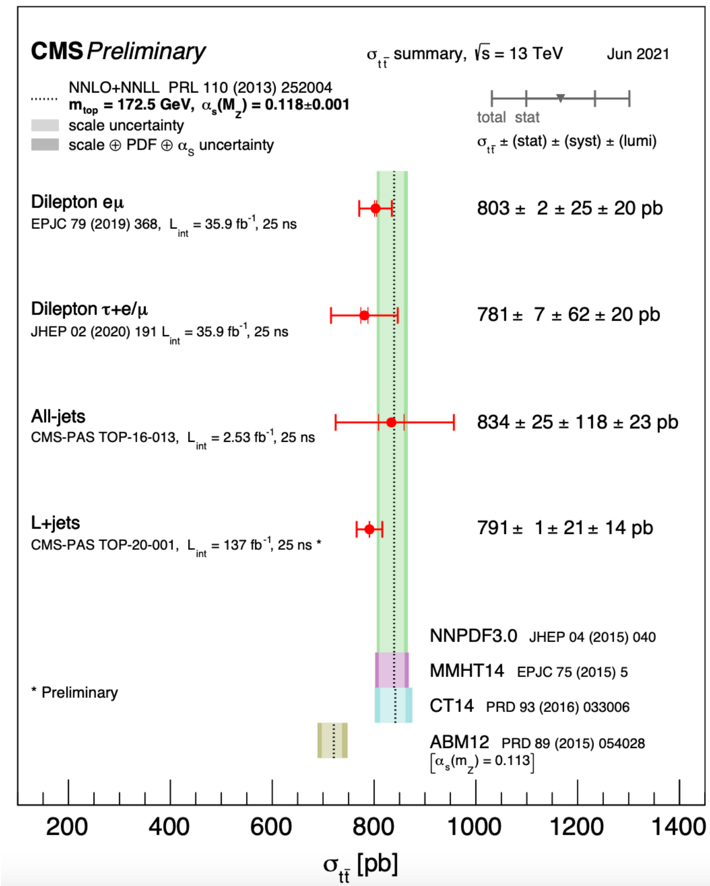
- Selection:
  - ≥6 jets + kinematical selection
  - require 2 b-tags
- Main backgrounds:
  - hadronic multi-jet
  - same selection without b-tag

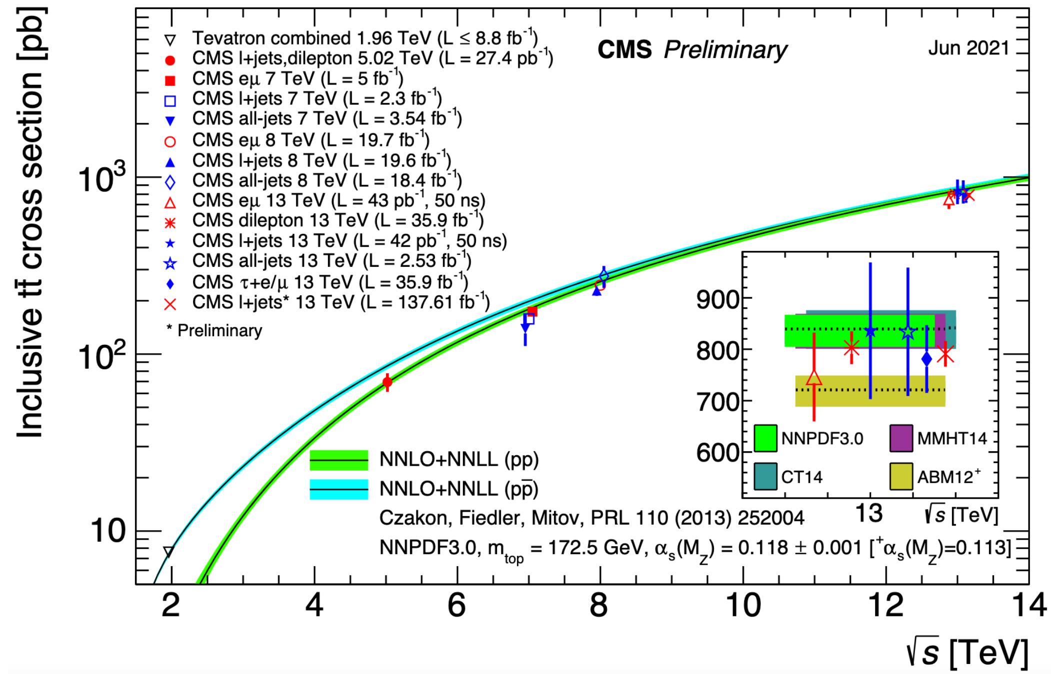




Cross sections

±4%





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±3-5%

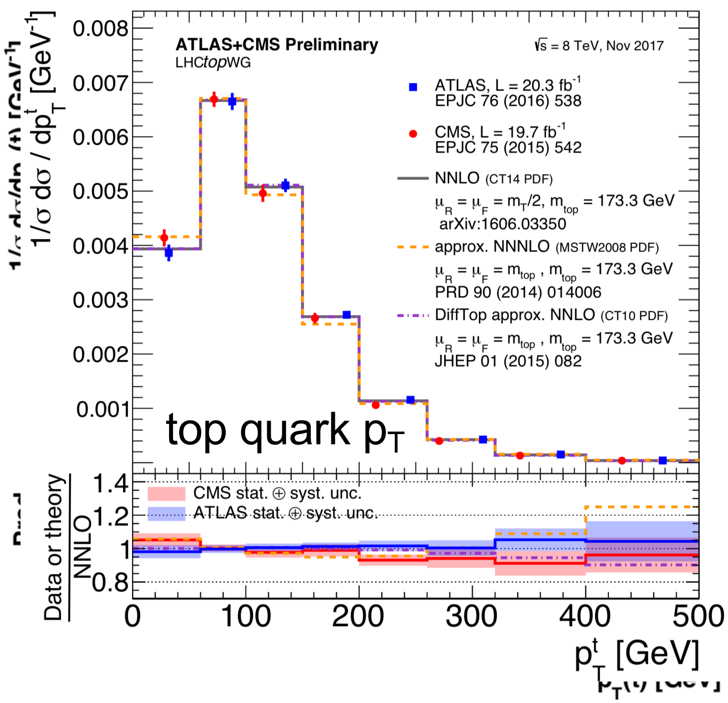
⇒measurements challenging theory

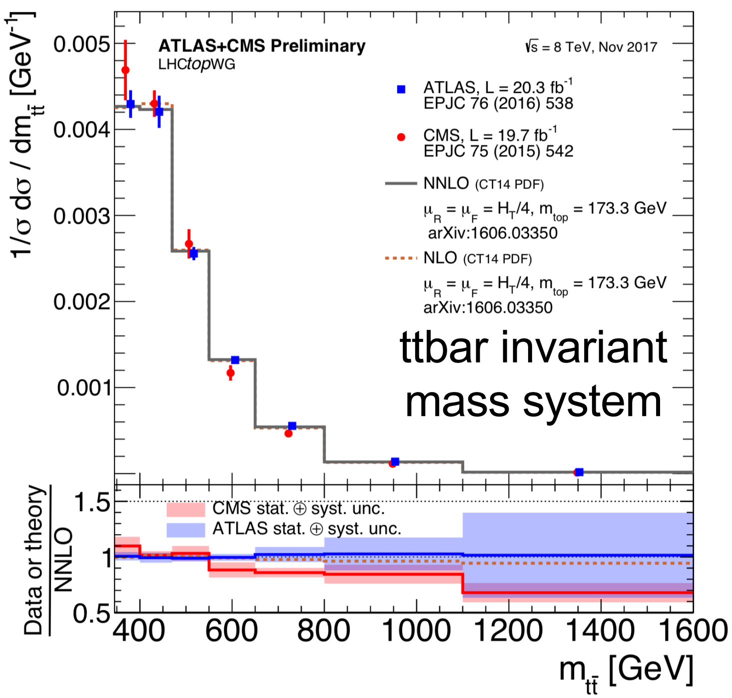
Differential cross section

EPJC 73(2013) 2339, arXiv:1610.04191, TOP-20-001, TOP-20-006

- Measure differential cross section
  - Test perturbative QCD
  - Test BSM scenarios (Z' decays, etc)
- Cross sections measured as a function of p_T, η, invariant mass of the final state leptons, top quarks, ttbar system, etc.
- Good agreement with expectations

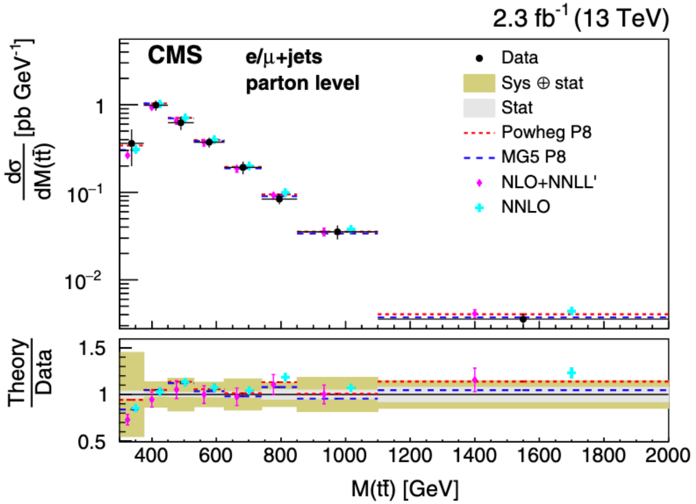
$$\frac{1}{\sigma_{t\bar{t}}}\frac{d\sigma_{t\bar{t}}}{dX}$$



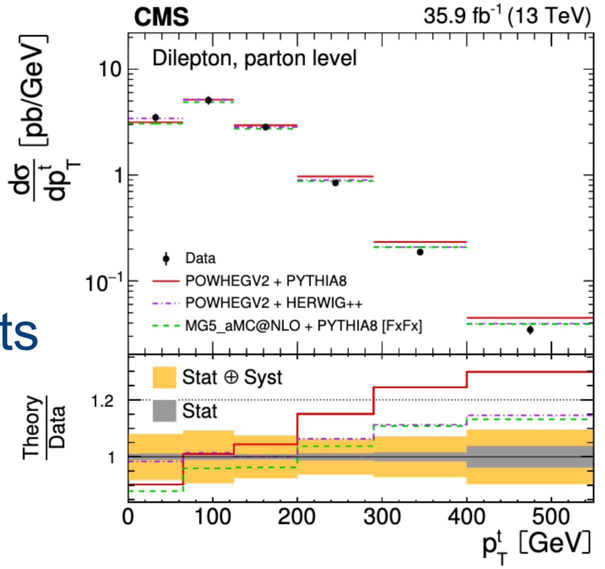


Differential cross section (cont.)

PRD 95(2017)092001, JHEP 02(2019)149



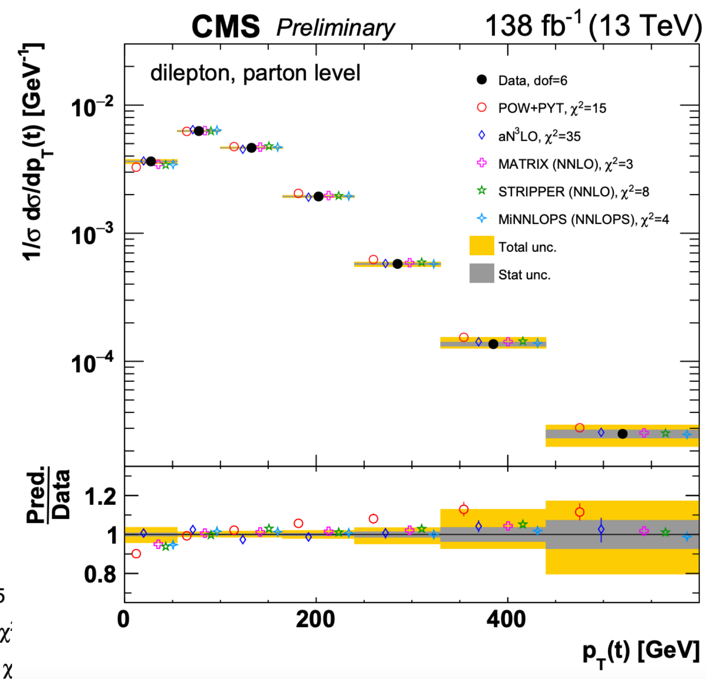
- Correct for detector effects and acceptances
- Softer top p_T (CMS), agreement in ATLAS at high p_T
  - Due to momentum reshuffling, P.Nason, cern.ch/event/301787
  - FSR shower changes mass of final state partons. light partons can build sizeable mass, and t/tbar do not radiate
  - short term solution: consider difference as uncertainty
- Impact on ttH/SUSY/etc searches, tails of ttbar events
- Measure ttbar invariant mass
  - Rate/shape reproduced within uncertainties

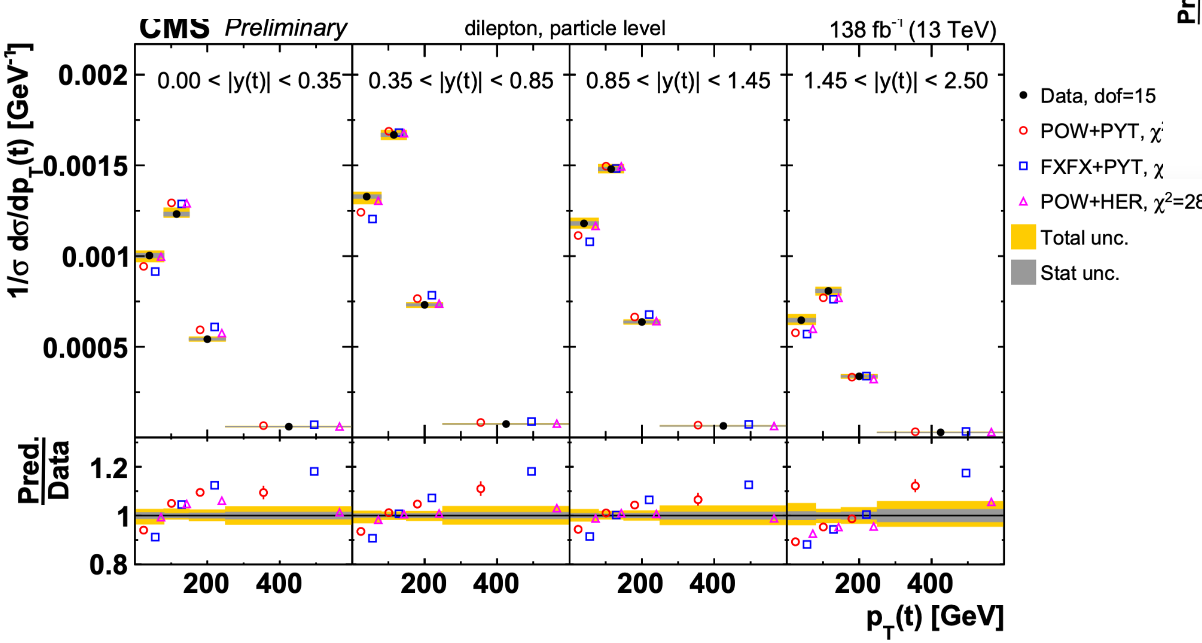


Multi-differential cross section

TOP-20-006

- Multi-differential cross section as a function of top and ttbar kinematics, decay products and additional jets
- Sensitive to SM parameters m_t and α_S
- Total uncertainty reduced by a factor of ~2 wrt previous analyses





Summary

- Introduction on top quark
- Basic concepts on production and decays
- Cross section measurements and relevance to BSM searches

- Next lecture: ``Top quarks as probe to New Physics”