

# The Top quark

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



INSTITUTO  
SUPERIOR  
TÉCNICO



**FCT**

Fundação para a Ciência e a Tecnologia  
MINISTÉRIO DA CIÊNCIA, TECNOLOGIA E ENSINO SUPERIOR

# Introduction

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

# 1974

With the discovery of the  $J/\Psi$ :

**quarks**

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

**leptons**

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



# 1975-1977

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

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

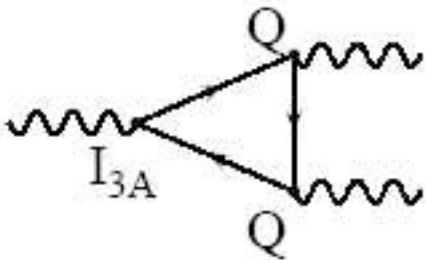
$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$$

- b: non SM? iso-singlet? SM iso-doublet?
- 1984: DESY measurement of  $e^+e^- \rightarrow b\bar{b}$  FB asymmetry:  $(22.5 \pm 6.5)\%$ 
  - 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

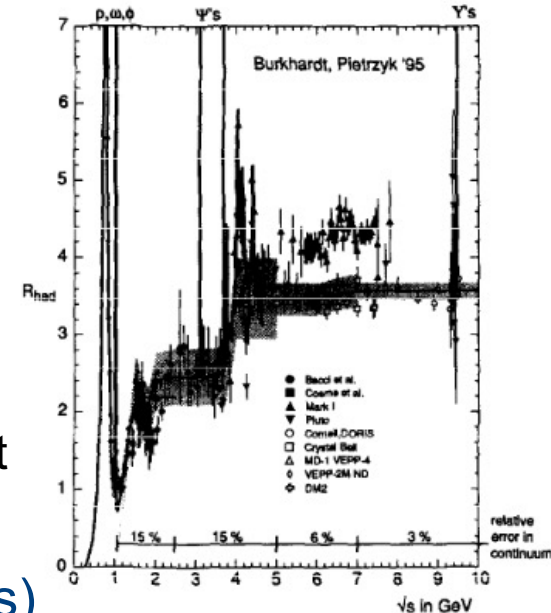
# Searches at $e^+e^-$ colliders

- PETRA (DESY) could reach  $\sim 20$  GeV (late '70s)
  - Search for narrow resonance
  - Look for increase in  $R=(\# \text{ of hadron events})/(\# \text{ of } \mu\mu \text{ evts})$

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

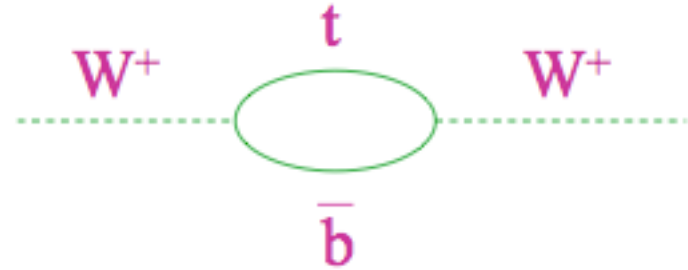
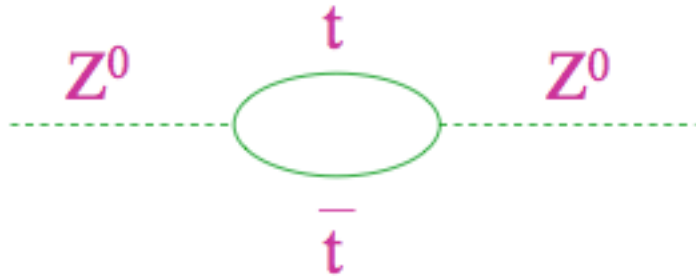
direct count of  
number of quarks

- 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  $\sim 30$  GeV:  $M_t > 30$  GeV
- SLC/LEP (SLAC)
  - Look for  $Z \rightarrow t\bar{t}$
  - $M_t > 45$  GeV
- Reached kinematic limit for direct searches at  $e^+e^-$  colliders

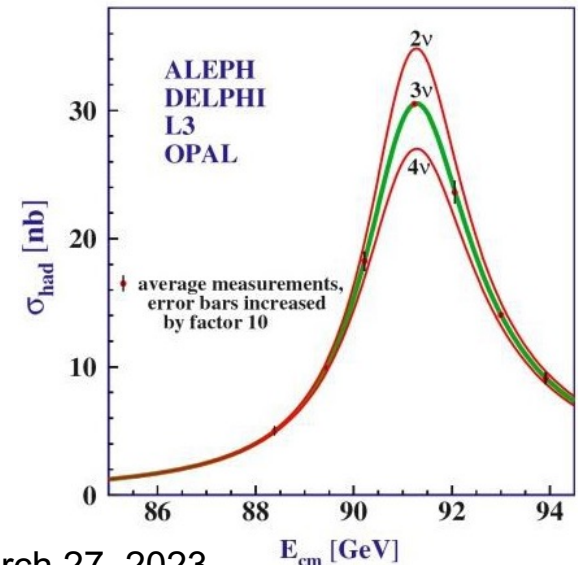
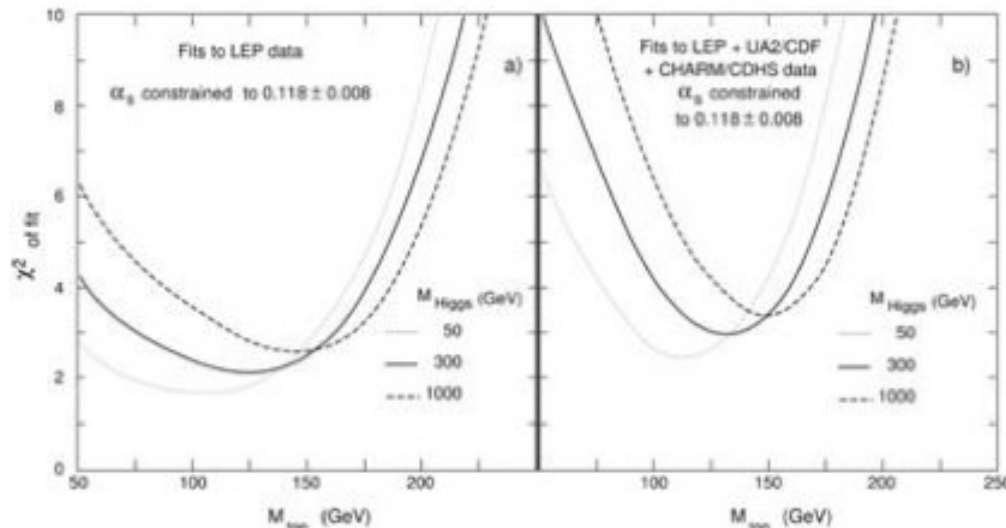


# Indirect searches from $e^+e^-$ colliders

- 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  $M_{\text{top}}$ 
  - Prediction upper limit  $< 200\text{--}220$  GeV





# Early searches at hadron colliders

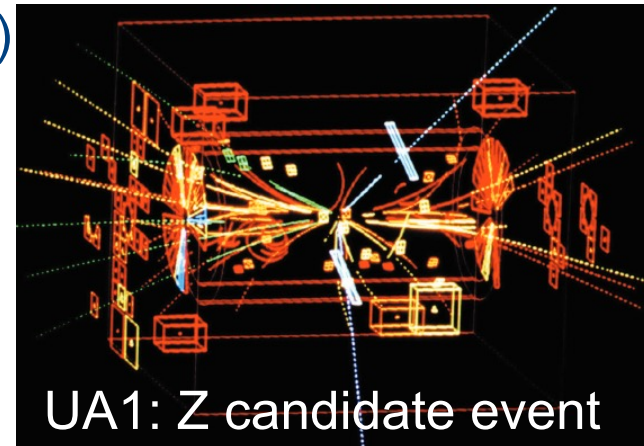
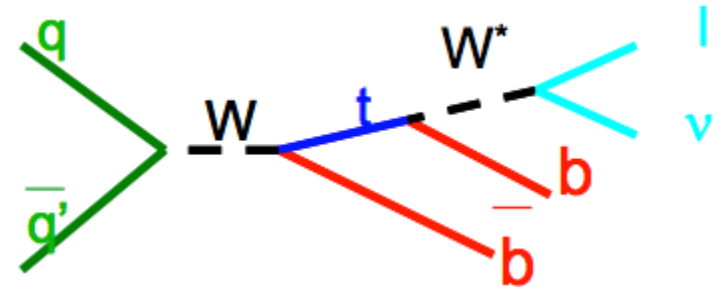
CERN Sp $\bar{p}$ S ( $\sqrt{s}=540$  GeV) built to observe W,Z

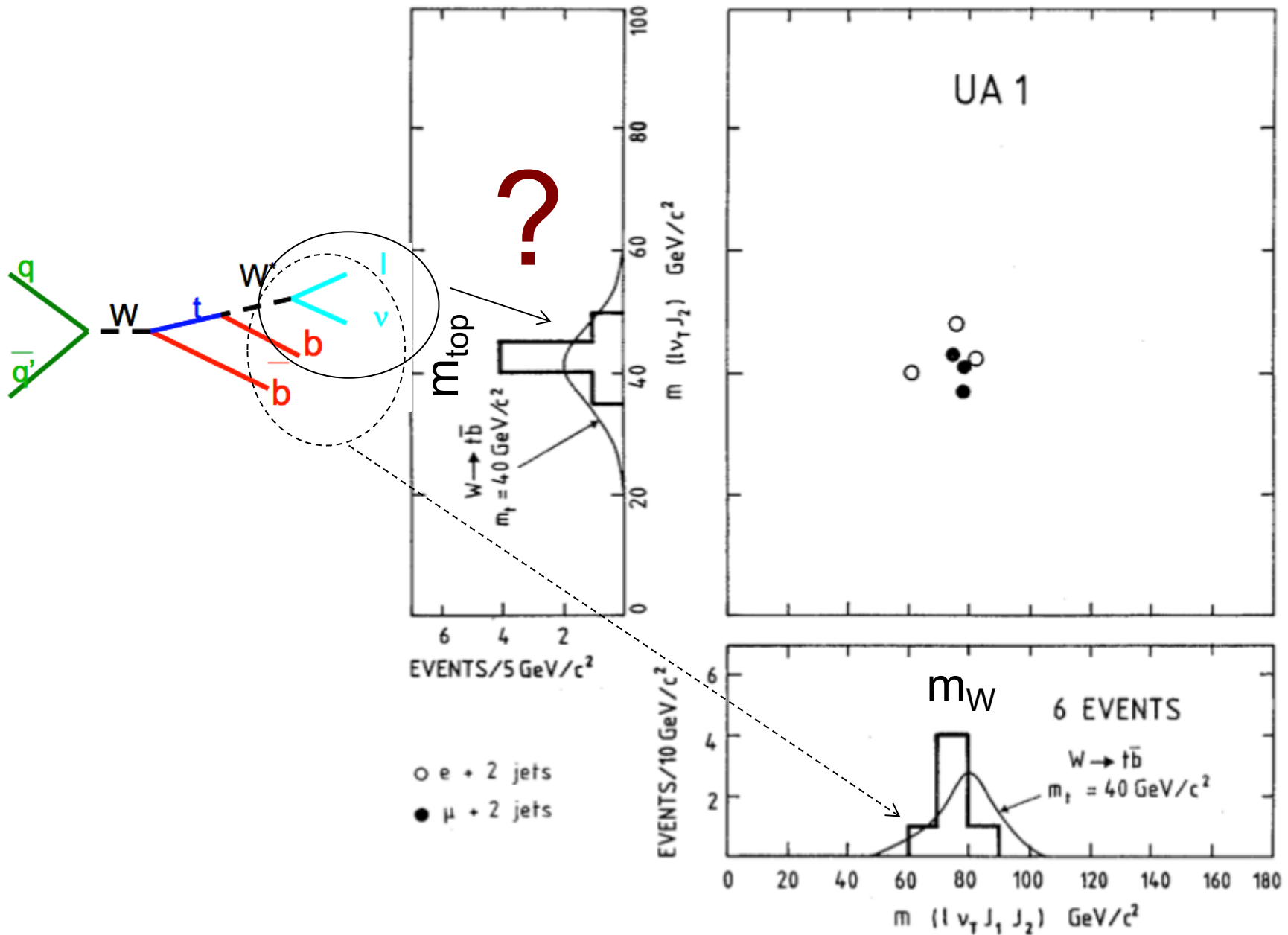
- Access to much higher energies
- Large backgrounds, low event rates
- Difficult reconstruction: jets

1984: UA1

- $W \rightarrow tb \rightarrow l \nu bb$
- Isolated high- $p_T$  lepton
- 2 or 3 hadronic jets
- Observe 5 events ( $e^+ \geq 2$  jets), 4 events ( $\mu^+ \geq 2$  jets)
- Expected background: 0.2 events
  - Fake leptons dominate;  $b\bar{b}/c\bar{c}$  negligible
- Result consistent with  $M_{\text{top}} = 40 \pm 10$  GeV
- Stop before claiming discovery...

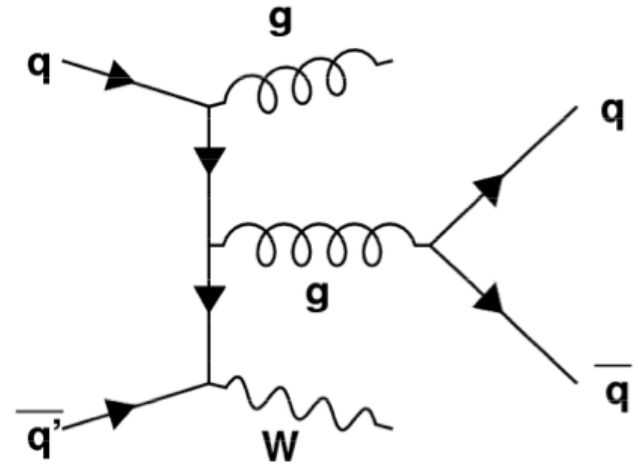
$\Rightarrow$  W+jet background was underestimated





# Searches at hadron colliders

- 1988 UA1
- Larger data sample (x6, total of  $600\text{nb}^{-1}$ )
- Improved understanding of the backgrounds
- Fake leptons, W+jets, DY,  $J/\Psi$ ,  $b\bar{b}/c\bar{c}$



<u>channel</u>	<u>observed</u>	<u>expected background</u>
$\mu + \geq 2 \text{ jets}$	10 events	$11.5 \pm 1.5 \text{ events}$
$e + \geq 1 \text{ jets}$	26 events	$23.4 \pm 2.8 \text{ events}$
	<b>( + 23 expected if <math>M_{\text{top}} = 40 \text{ GeV}</math> )</b>	

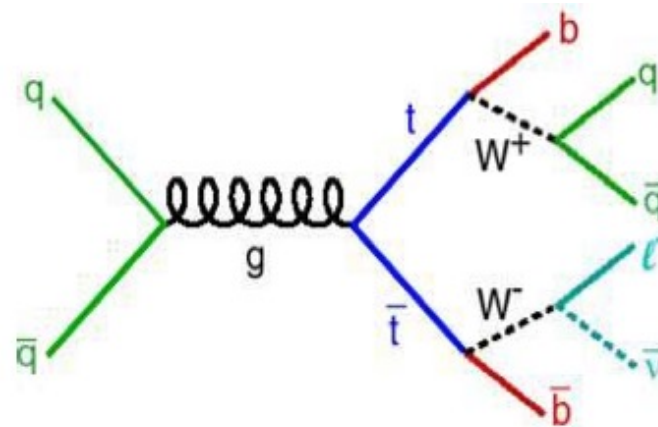
$\Rightarrow$ conclude  $M_{\text{top}} > 44 \text{ GeV}$



# Fermilab joins the hunt

- 1988-89: at CERN, UA2 remains after the upgrades
- $\sqrt{1.8 \text{ TeV@Fermilab}}$  vs.  $\sqrt{0.63 \text{ TeV@CERN}}$
- 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

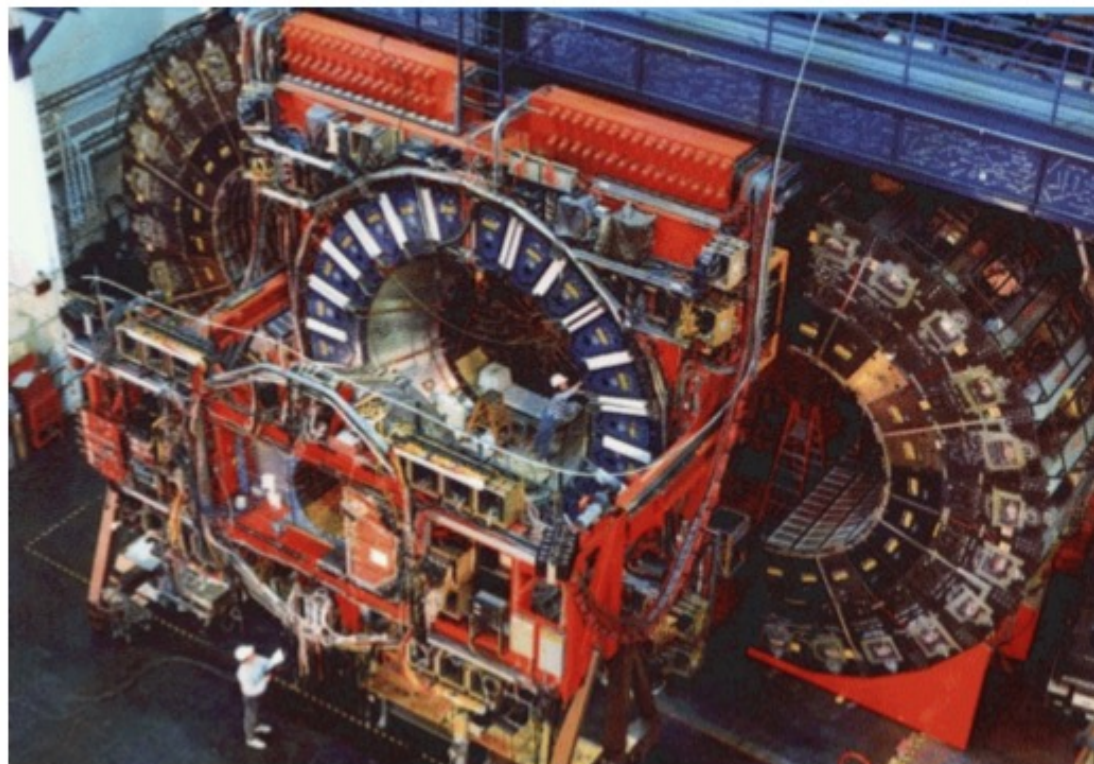
Proton-antiproton collision at 1.8-2.0 TeV







**12 countries, 62 institutions  
767 physicists**





# Searches at CDF

## $e\mu$ channel

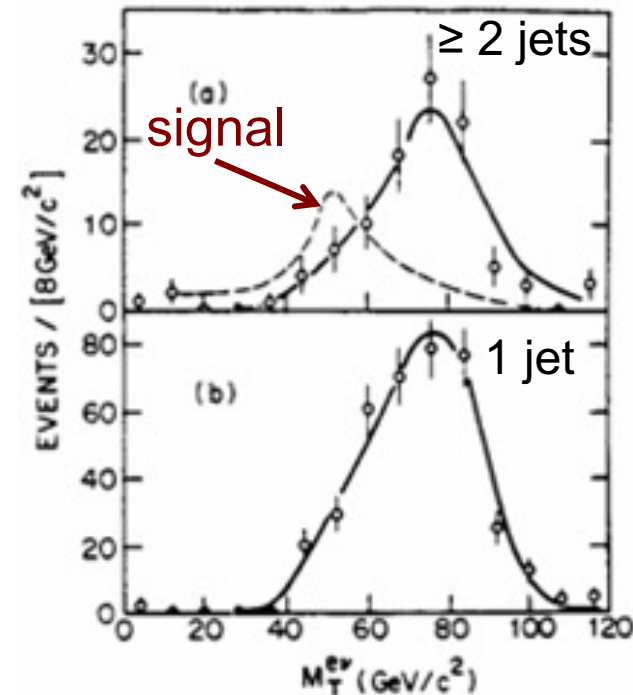
- Event rate lower:  $2 \times \text{BR}(W \rightarrow e\nu)$
- Background small (no  $W$ +jets, no  $DY$ )
- Dominant background is  $Z \rightarrow \tau\tau \rightarrow e\mu X$  (expect 1 evt)
- Observe 1 event (expect 7 evts for  $M_{\text{top}} = 70$  GeV)

## $e\nu + \geq 2$ jets

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

$\Rightarrow M_{\text{top}} > 77$  GeV

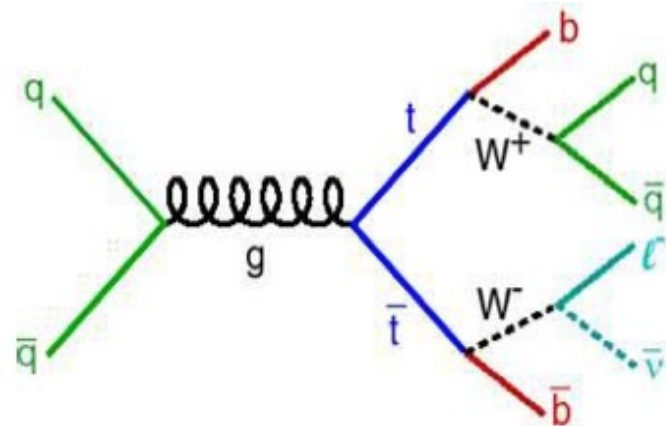
- UA2 uses similar technique:  $M_{\text{top}} > 69$  GeV



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

- 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  $ee$ ,  $\mu\mu$ ,  $e\mu$  (require missing ET, Z-veto)
  - Single lepton: require low  $p_T$  muon (semi-leptonic b-decays)

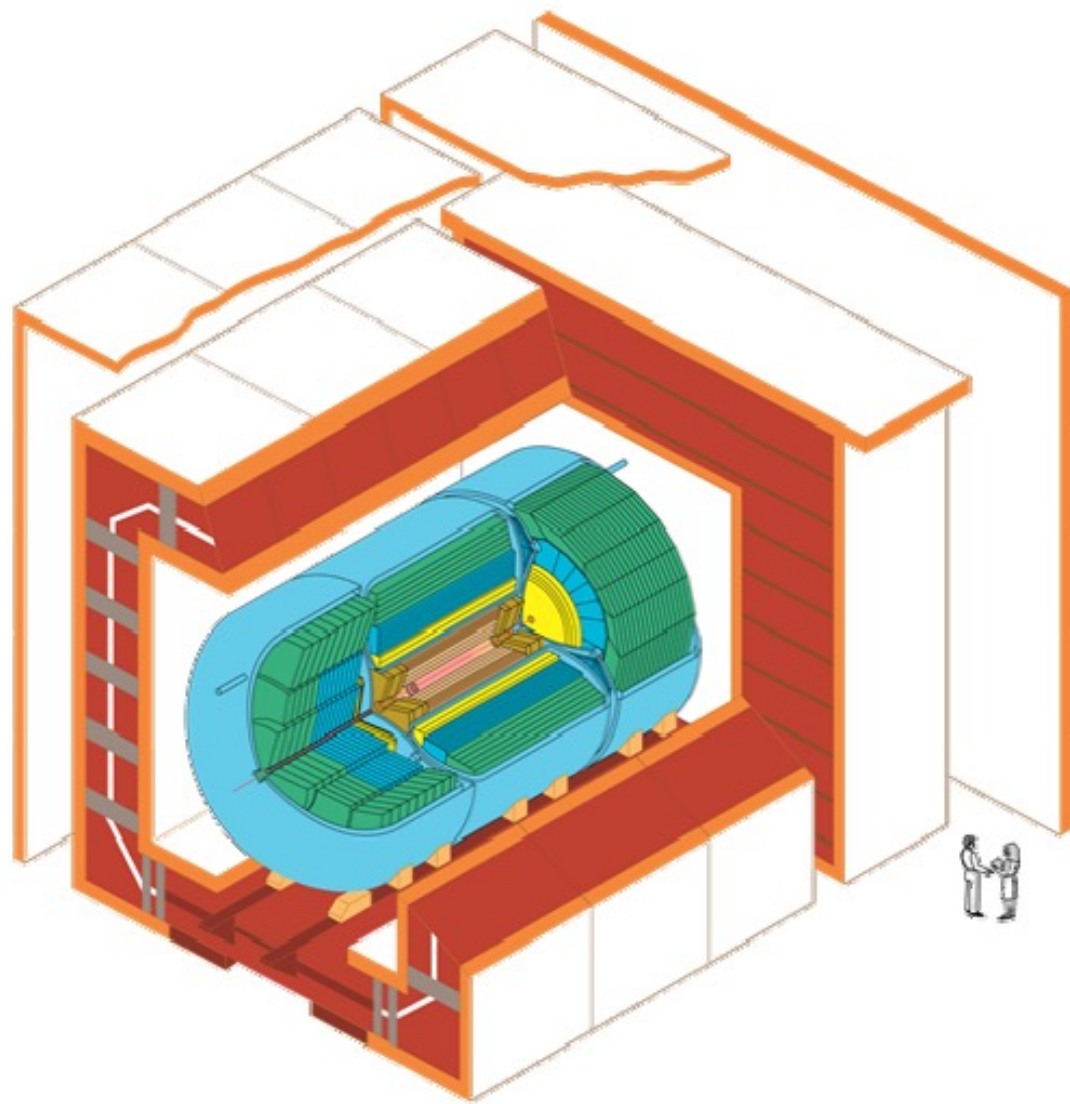
$\Rightarrow M_{\text{top}} > 91 \text{ GeV}$



# D0 joins the hunt



**19 countries**  
**83 institutions, 664 physicists**



**D0 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  $M_{\text{top}}=100$  GeV

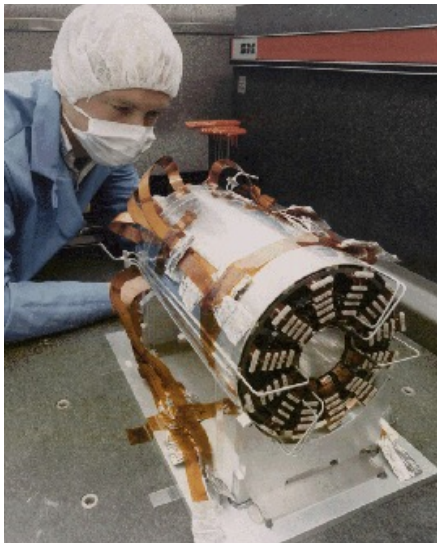
– $e\mu + \geq 1\text{jet} + \text{MET}$	1 evt	(1.1 bkg)
– $ee + \geq 1\text{jet} + \text{MET}$	1	(0.5)
– $e + \geq 4\text{jets} + \text{MET}$	1	(2.7)
– $\mu + \geq 4\text{jets} + \text{MET}$	0	(1.6)

$\Rightarrow M_{\text{top}} > 131 \text{ GeV} @ 95\% \text{CL}$

# Detecting the top quark at CDF

- Strategy

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



New: CDF vertex detector (SVX)  
(40  $\mu\text{m}$  impact parameter resolution)  
powerful discriminant against background

## $e + 4$ jet event

40758\_44414

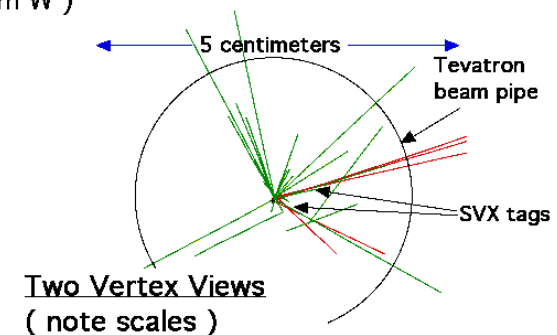
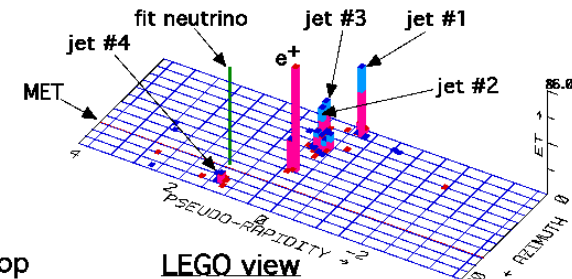
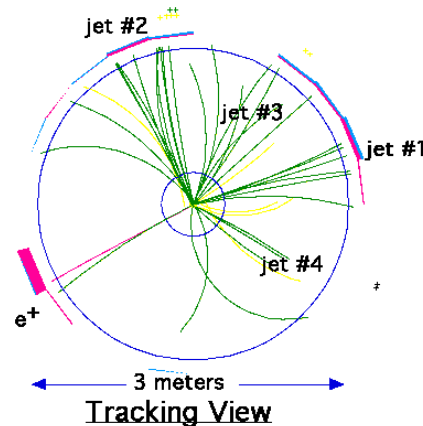
24-September, 1992

TWO jets tagged by SVX

fit top mass is  $170 \pm 10$  GeV

$e^+$ , Missing  $E_T$ , jet #4 from top

jets 1,2,3 from top ( 2&3 from W )

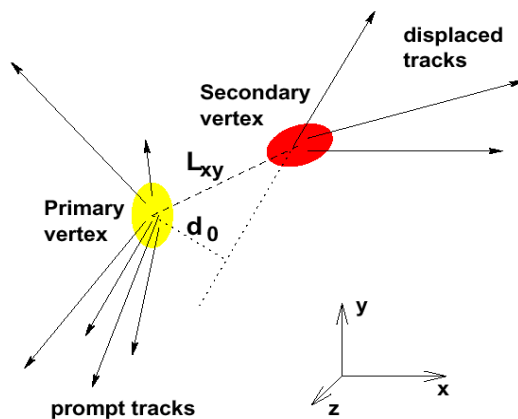


# Tagging b-jets

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

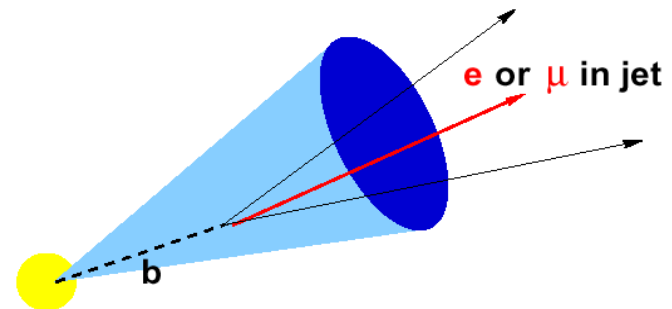
B hadrons are long-lived

Vertex displaced tracks



semileptonic B hadron decay

Soft Lepton Tagging



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

55%

0.5%

Top Event Tagging Efficiency

False Tag Rate (QCD jets)

15%

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	$2.3 \pm 0.3$
SLT	7 tags	$3.1 \pm 0.3$
total	12 events	---

← 3 events in  
← common

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

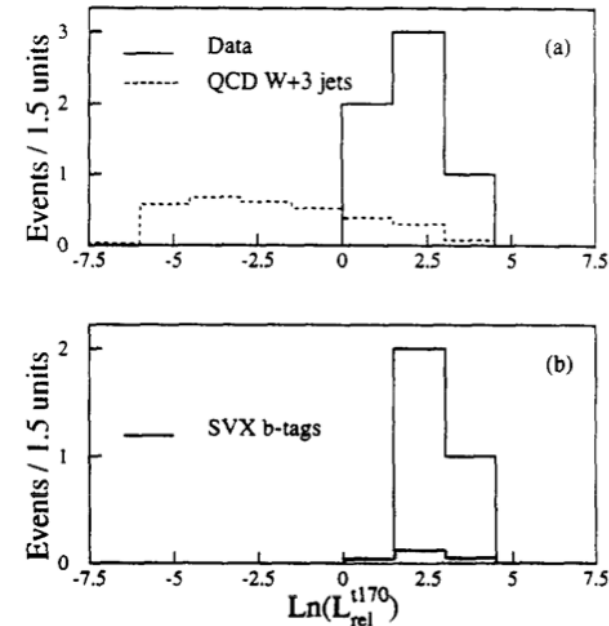
# Final steps: CDF and D0

**CDF:** counting experiment yields  $2.8\sigma$

- 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)

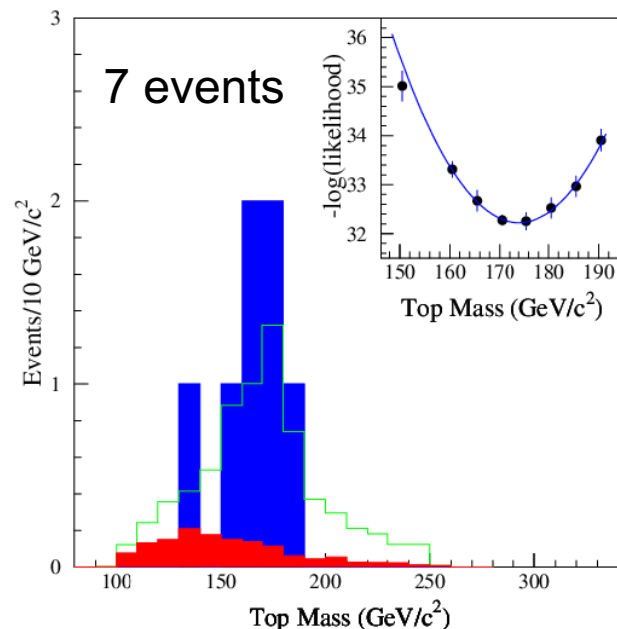
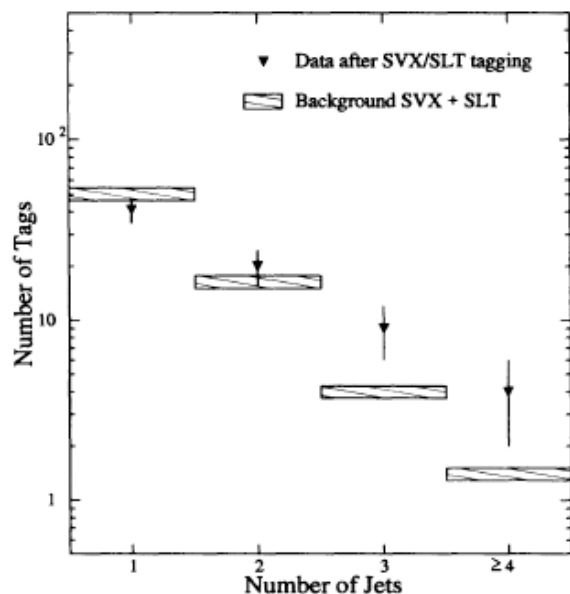
VOLUME 73, NUMBER 2

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  $19.3 \text{ pb}^{-1}$ . 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  $174 \pm 10 \pm 3 \text{ GeV}/c^2$ . The  $t\bar{t}$  production cross section is measured to be  $13.9^{+6.1}_{-4.8} \text{ pb}$ .



# First measurements

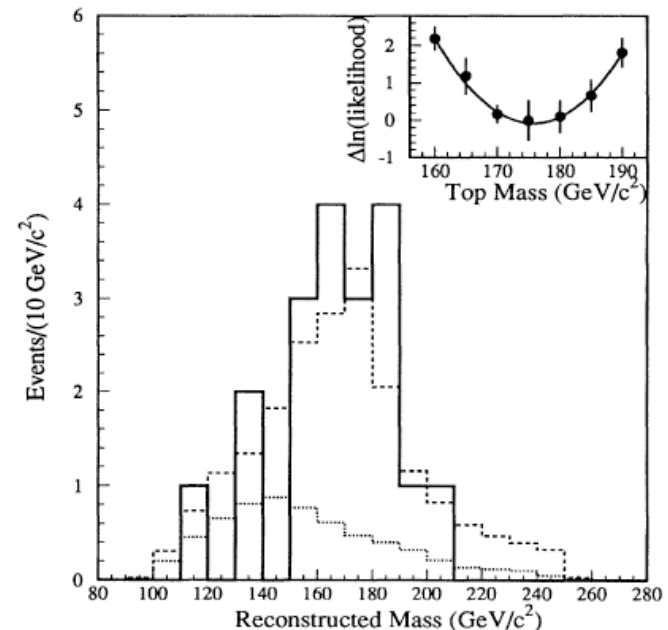
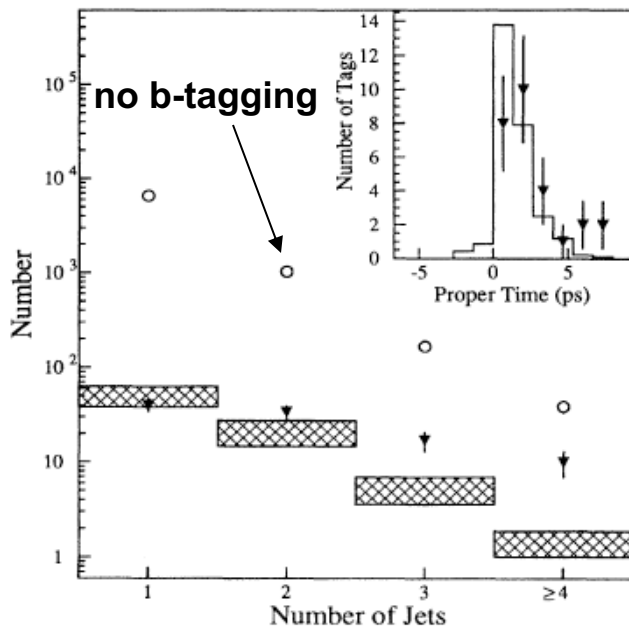
VOLUME 74, NUMBER 14

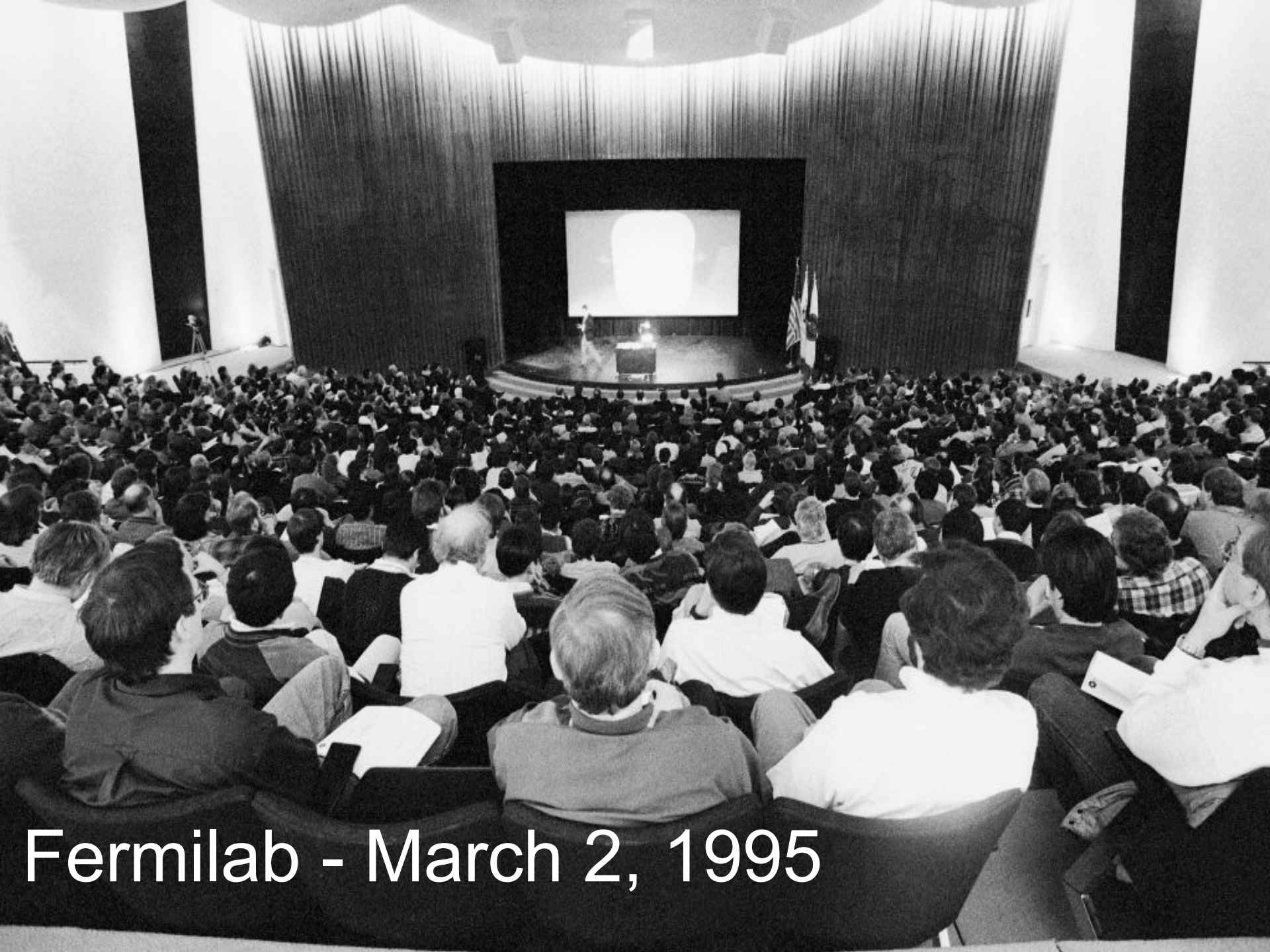
PHYSICAL REVIEW LETTERS

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  $67 \text{ pb}^{-1}$  data sample of  $\bar{p}p$  collisions at  $\sqrt{s} = 1.8 \text{ TeV}$  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  $4.8\sigma$ . 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  $6.8^{+3.6}_{-2.4} \text{ pb}$ .





Fermilab - March 2, 1995

# First measurements

VOLUME 74, NUMBER 14

PHYSICAL REVIEW LETTERS

3 APRIL 1995

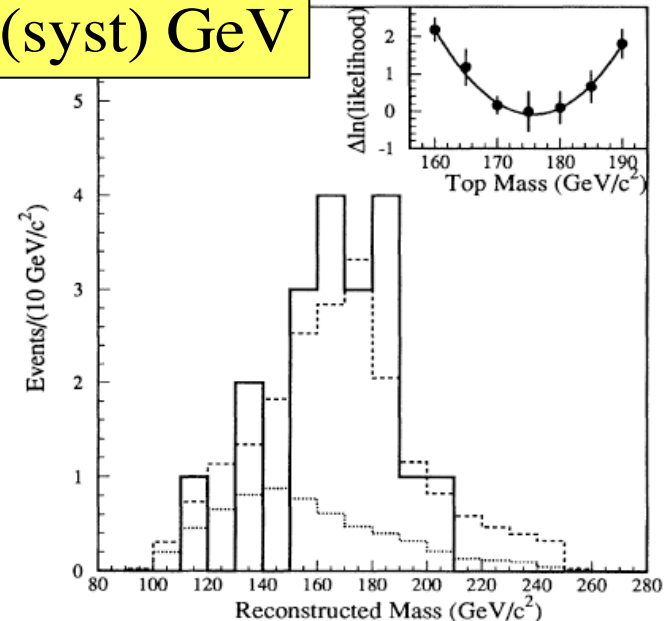
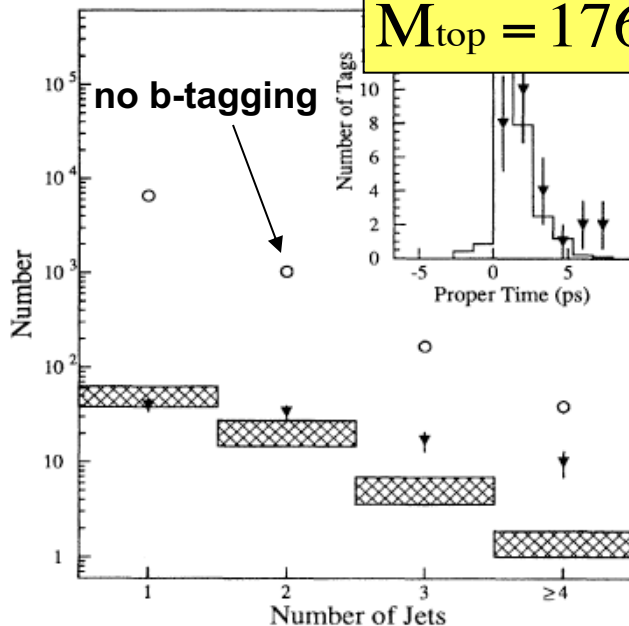
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$176 \pm 8(\text{stat}) \pm 10(\text{syst}) \text{ GeV}$

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

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





# First measurements

VOLUME 74, NUMBER 14

PHYSICAL REVIEW LETTERS

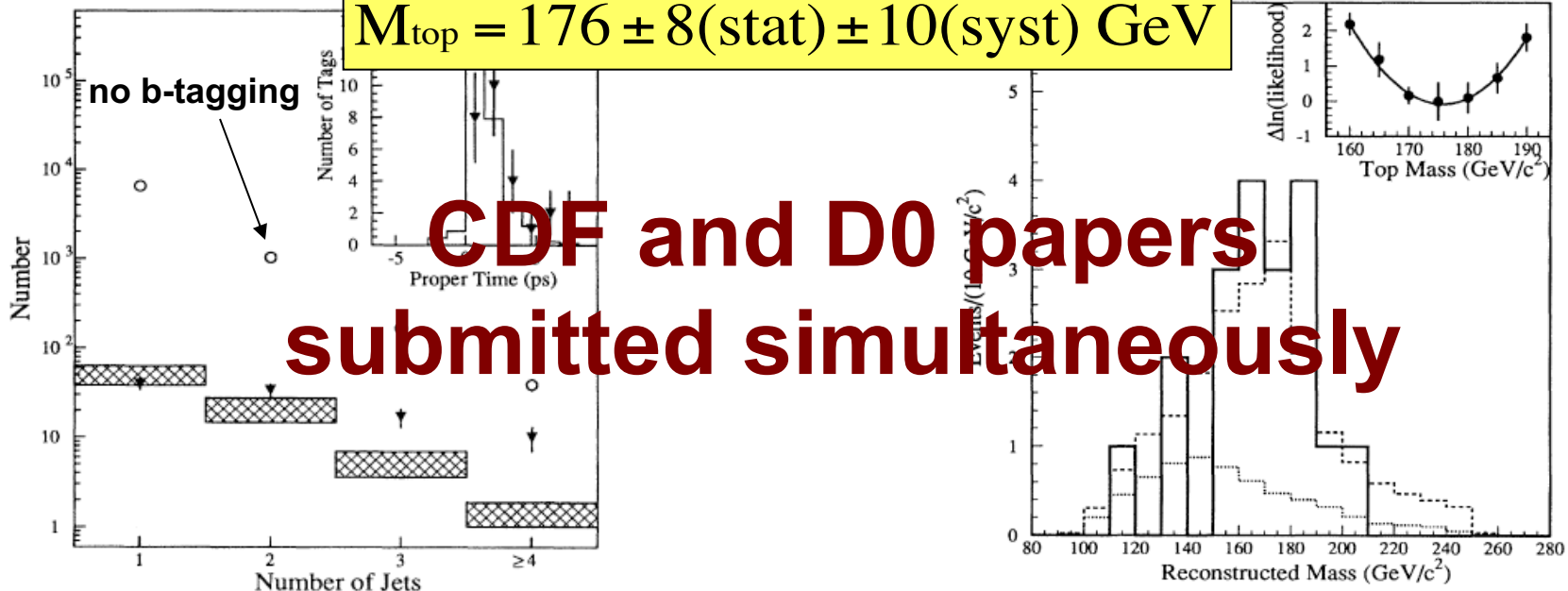
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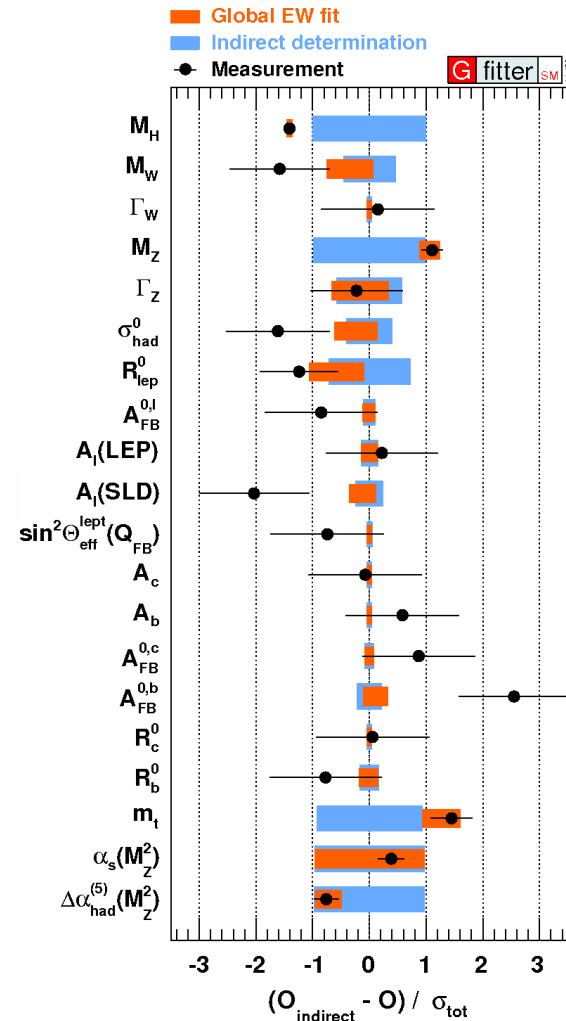
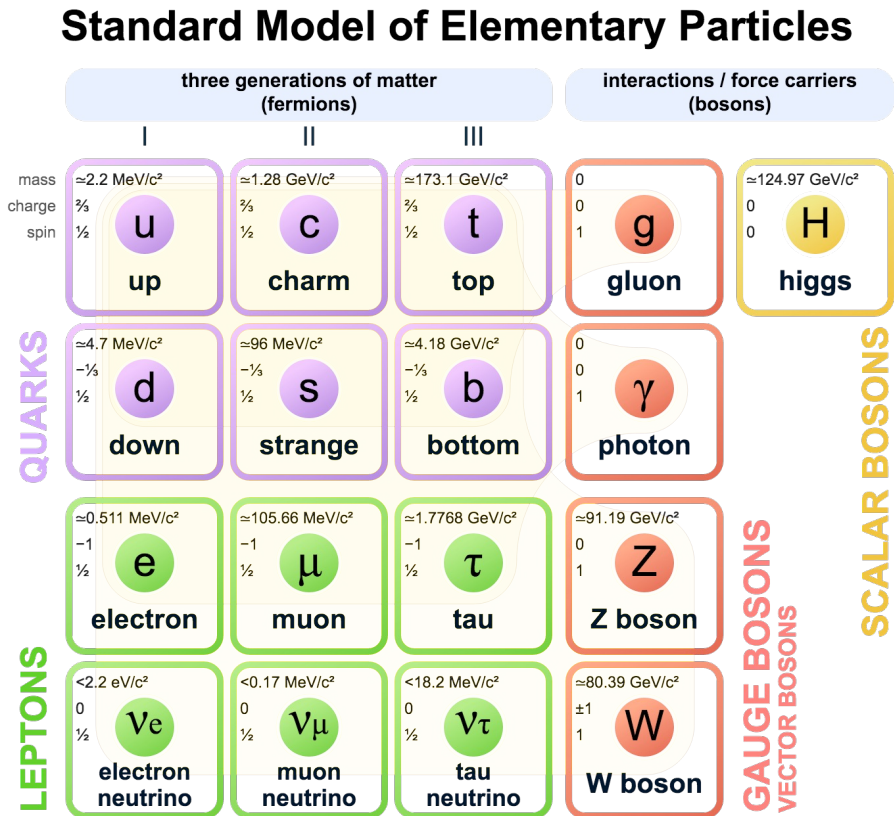
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$$\sigma_{t\bar{t}} = 6.8^{+3.6}_{-2.4} \text{ pb}$$

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



# SM confirmed by the data



Excellent agreement with all experimental results

# The Large Hadron Collider

- Built to explore new energy frontiers

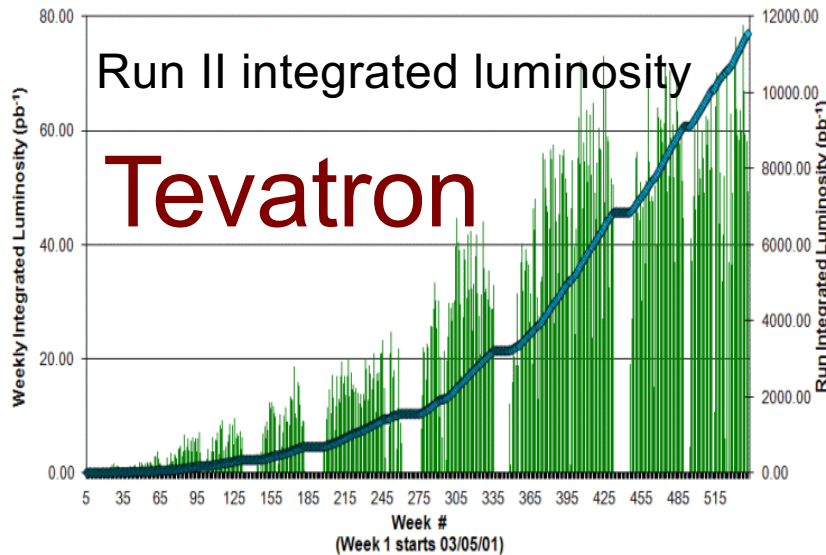
- First colliding beams in 2009
- started with “low” luminosity in 2010
- $\sim 5 \text{ fb}^{-1}$  @ 7 TeV delivered in 2011
- $\sim 20 \text{ fb}^{-1}$  @ 8 TeV in 2012
- $> 150 \text{ fb}^{-1}$  @ 13 TeV in 2015-2018
- $> \sim 50 \text{ fb}^{-1}$  @ 13.6 TeV in 2022-

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

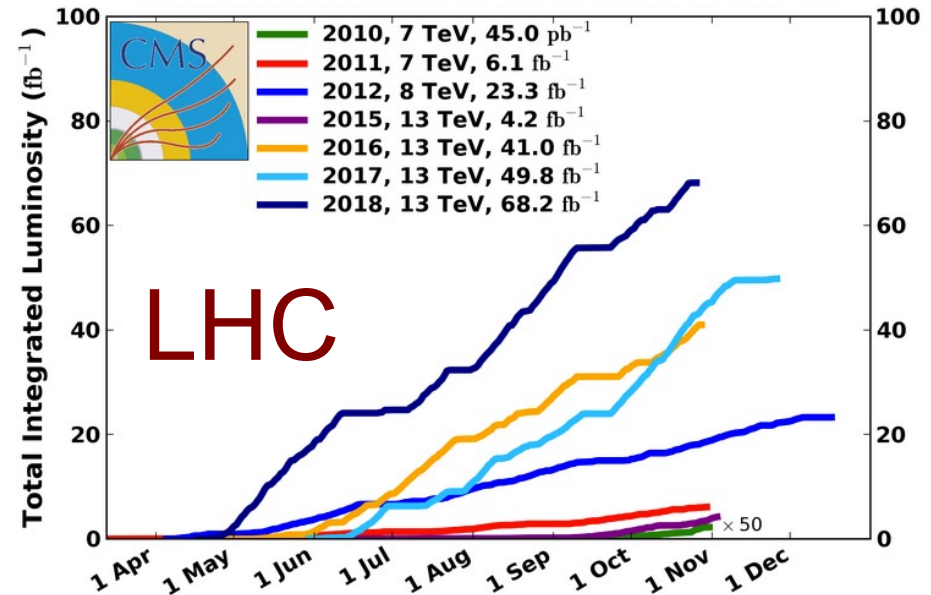


⇒ Top quarks give access to SM and BSM (?)

# Tevatron vs LHC



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



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

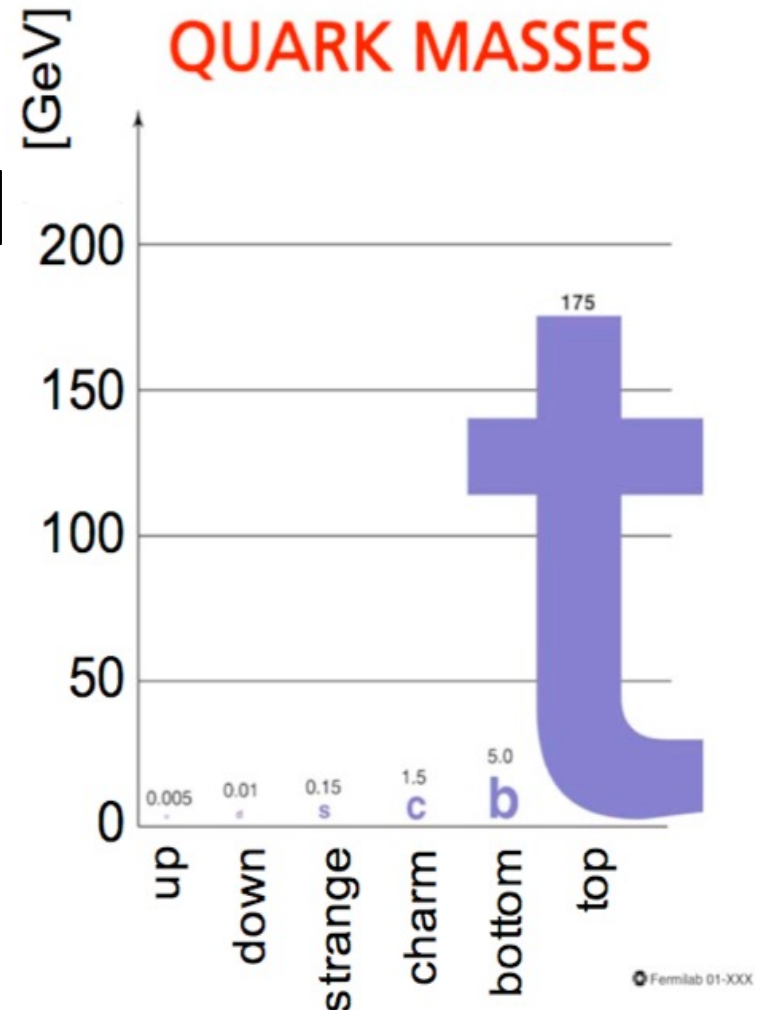


# The top quark

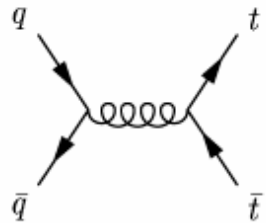
- The heaviest known elementary particle
- Large coupling to the Higgs:  $\sim 1$
- Short lifetime

$\tau = 0.4 \times 10^{-24} \text{ sec}$

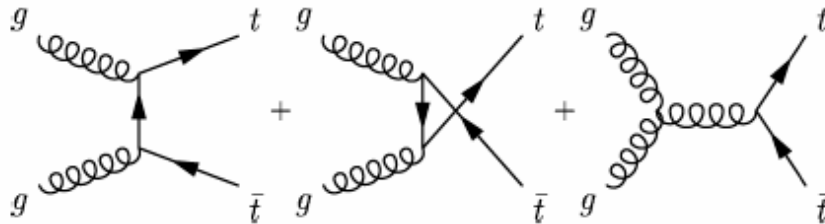
  - for  $m_{\text{top}} = 175 \text{ GeV} \Rightarrow \Gamma = 1.4 \text{ GeV} \Rightarrow$  no hadronization
  - large contributions to EWK corrections  $\sim G_F m_{\text{top}}^2$
  - very short lifetime  $\Rightarrow$  bound states are not formed  $\Rightarrow$  opportunity to study a free quark
-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

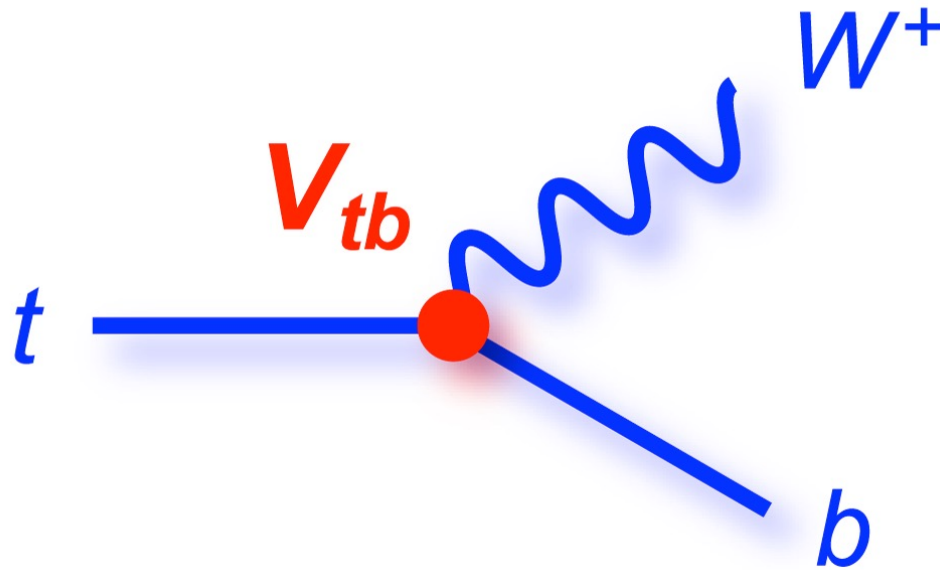
## Predicted cross sections:

Collider	$\sigma_{\text{tot}}$ [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%)

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

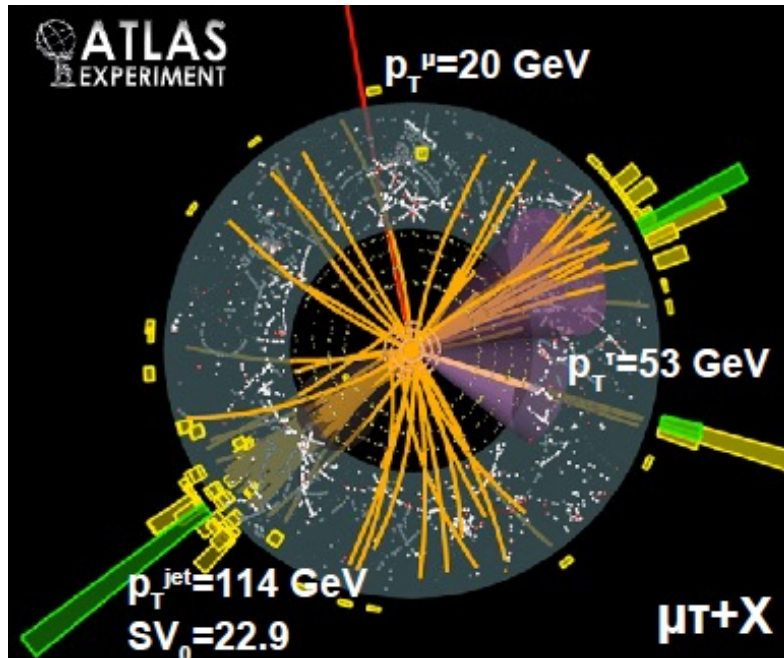
Czakon et al. PRL 110, 252004 (2013)

# How does a top quark decay?

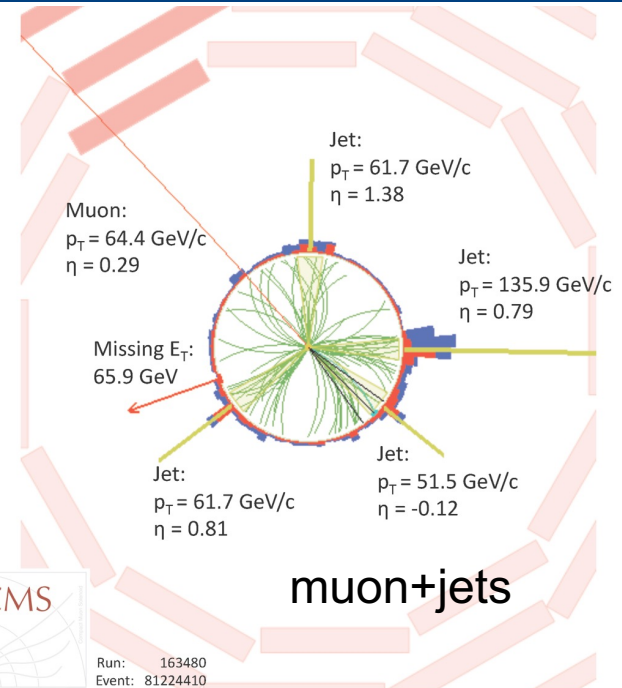


- almost always  $t \rightarrow Wb$  (i.e.  $V_{tb} \sim 1$ )
- lifetime is short, and it decays before hadronizing
- the  $W$  is real:
  - can decay  $W \rightarrow l\nu$  ( $l=e, \mu, \tau$ ),  $BR \sim 1/9$  per lepton
  - can decay  $W \rightarrow qq$ ,  $BR \sim 2/3$

# Selection of top quark events



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

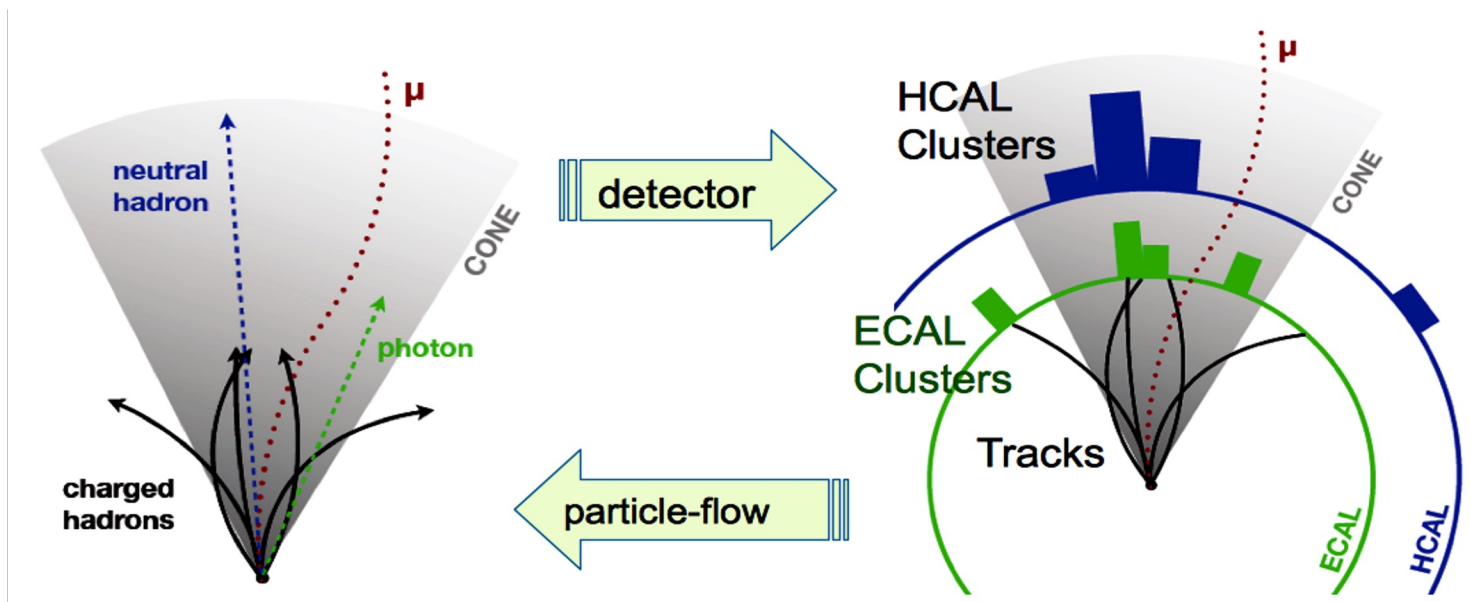


- Jets:
  - at least 2 jets,  $p_T > 30$  GeV,  $|\eta| < 2.5$
  - anti-kT algorithm, with cone 0.4-0.5
  - b-tagging is optional
- Missing transverse energy:
  - Typically require 30-40 GeV



# 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.

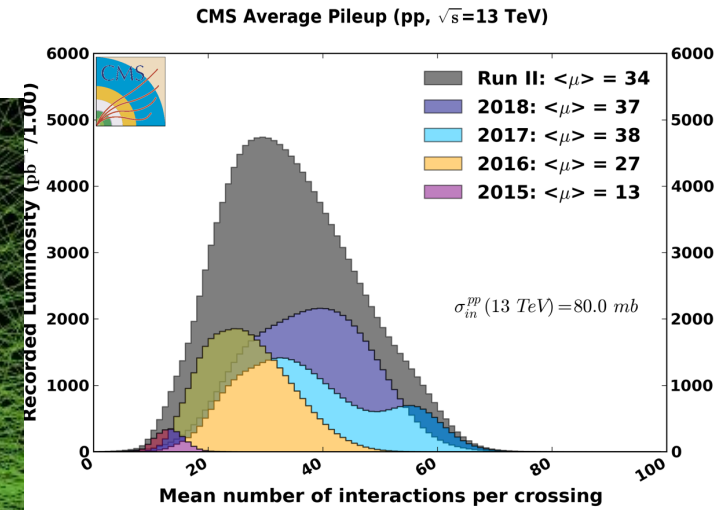


# ...in a challenging environment



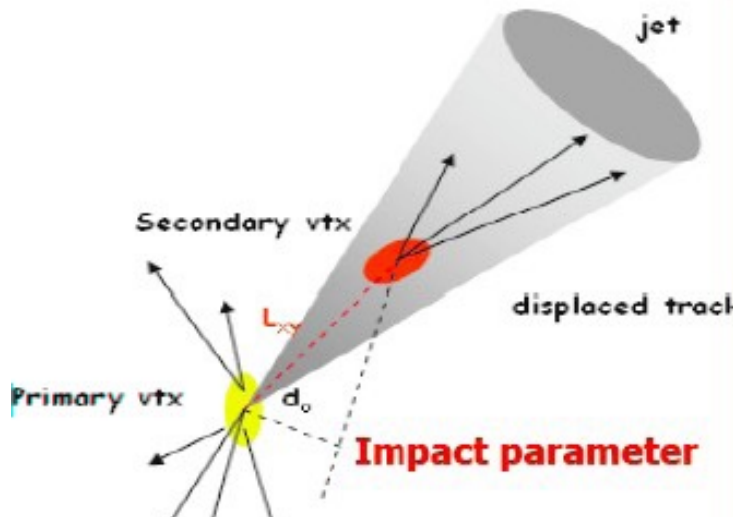
CMS Experiment at LHC, CERN  
Data recorded: Fri Oct 26 09:06:57 2018 CEST  
Run/Event: 325309 / 244518  
Lumi section: 1  
Orbit/Crossing: 121529 / 1650

136 vertices !

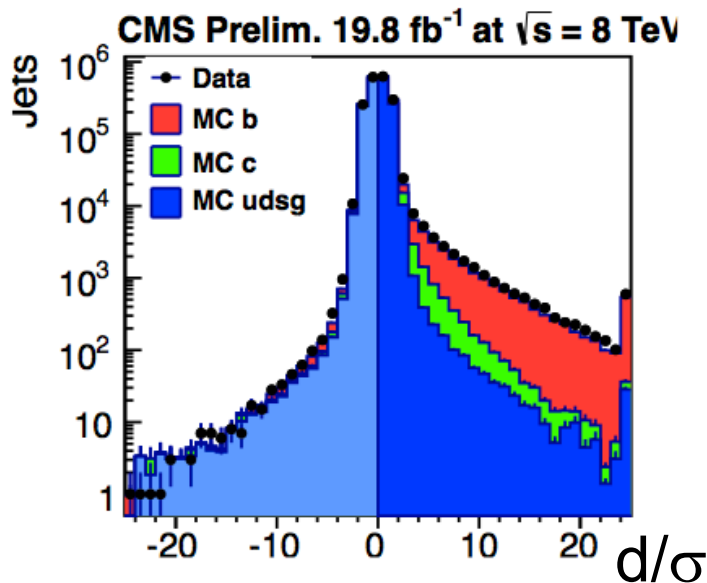




# Challenge: b-tagging

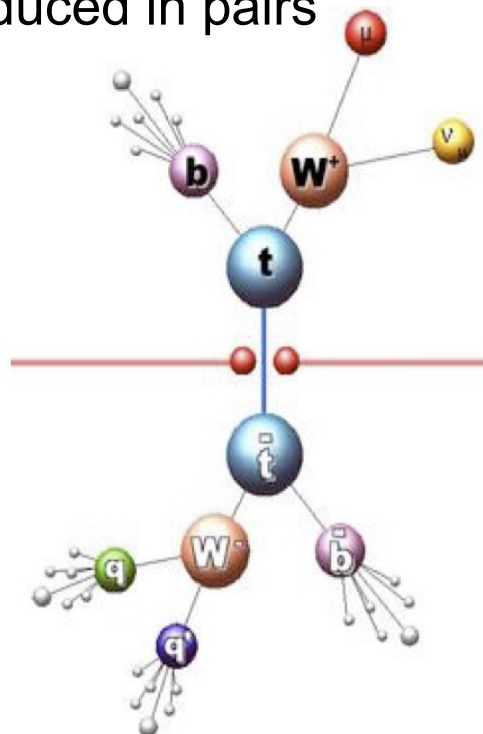


- Lifetime:  $\tau_b \sim 1\text{-}2$  psec
- Reduction of background obtained by identifying jets from b-quarks
- Two methods:
  - Secondary vertex tagging
  - Semileptonic decays of b-hadrons in jets ( $b \rightarrow l \nu_l X$ )

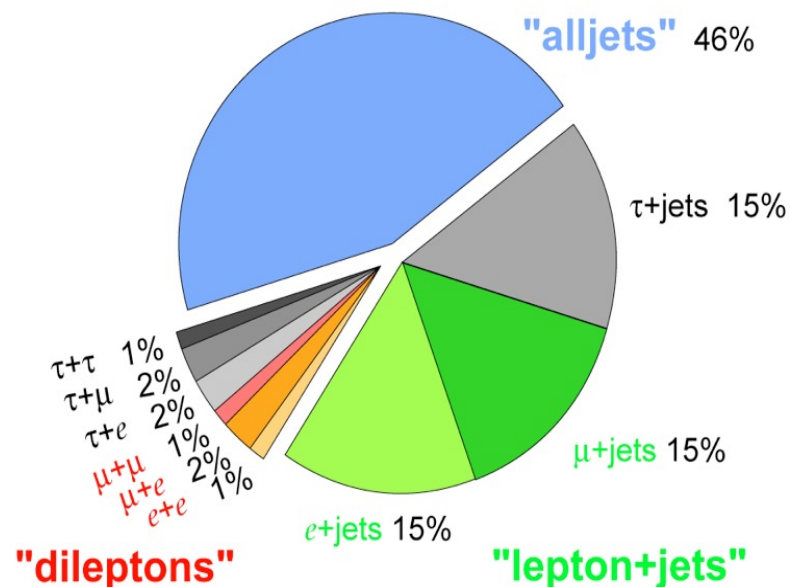


# Top quark decays

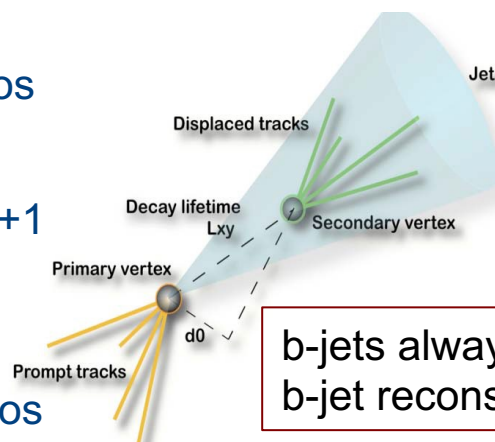
Top quarks (mostly) produced in pairs



Top Pair Branching Fractions

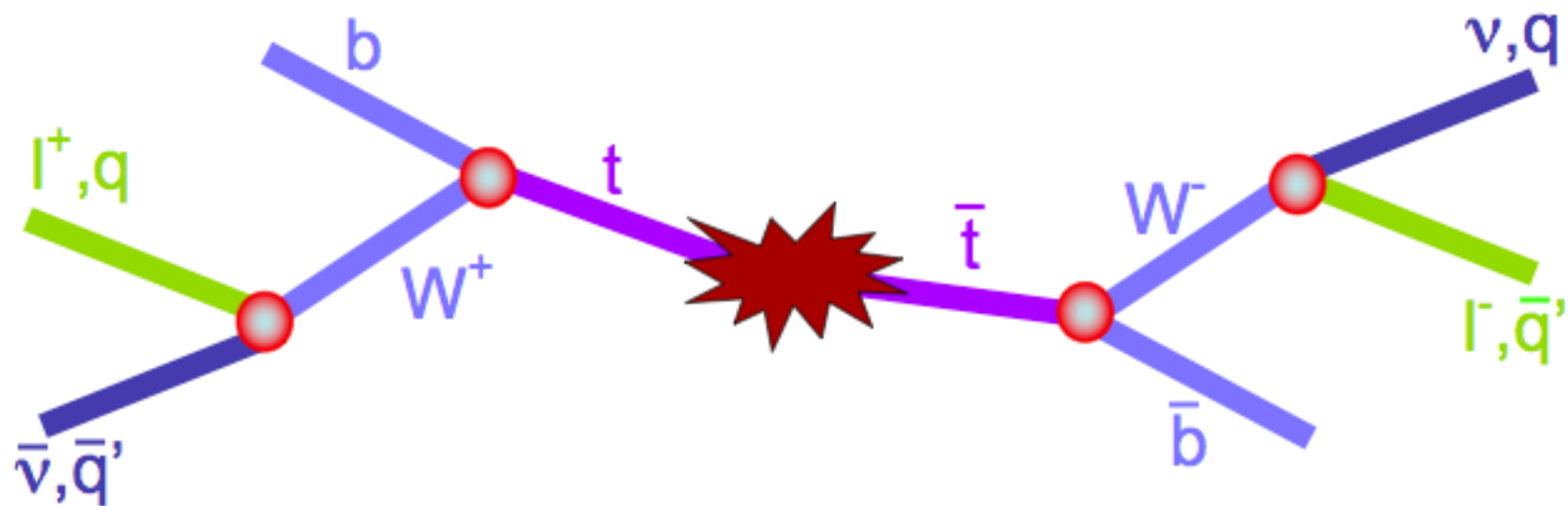


- **Dilepton ( $ee, \mu\mu, e\mu$ ):**
  - BR~5%, 2 leptons+2 b-jets+2 neutrinos
- **Lepton ( $e$  or  $\mu$ ) + jets**
  - BR~30%, one lepton+4jets (2 from b)+1 neutrino
- **All hadronic**
  - BR~44%, 6 jets (2 from b), no neutrinos



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

# Interesting physics with Top quark



## PRODUCTION

Cross section  
Resonances  $X \rightarrow t\bar{t}$   
Fourth generation  $t'$   
Spin-correlations  
New physics (SUSY)  
Flavour physics (FCNC)  
...

## PROPERTIES

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

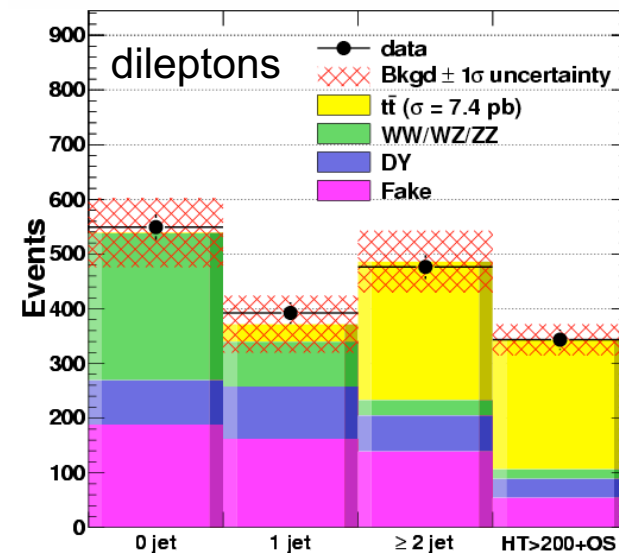
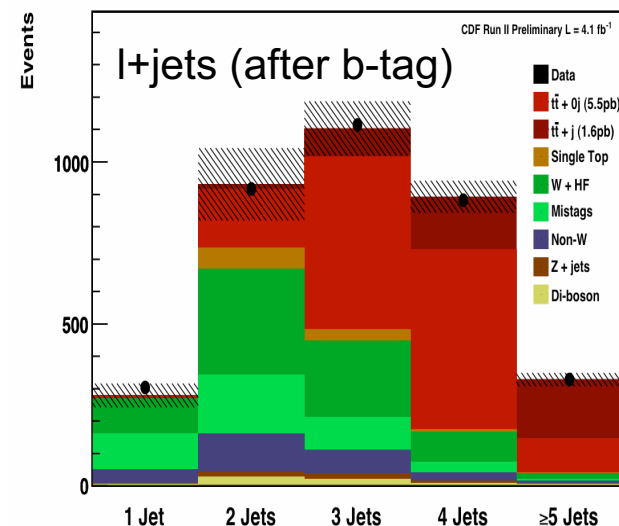
## DECAY

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



# Top quark events

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



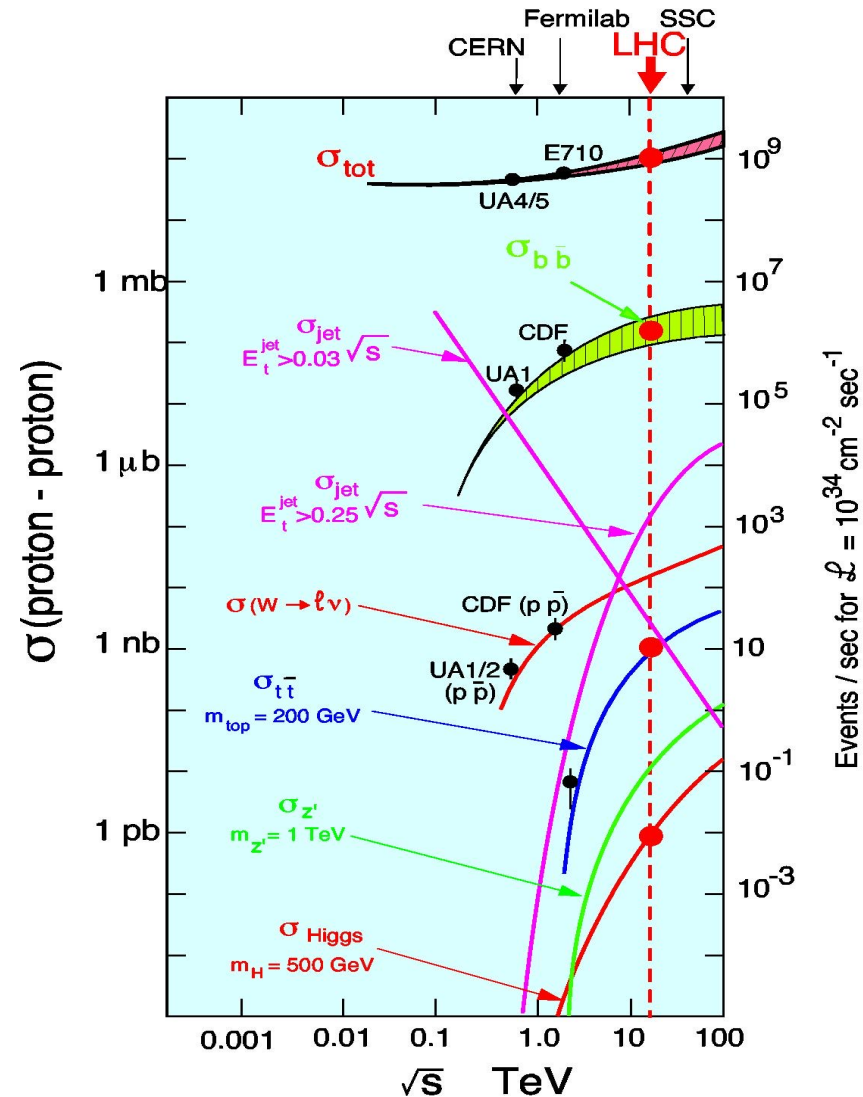
# Theory cross sections: TeV vs LHC

Collider	$\sigma_{\text{tot}}$ [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%)

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  $\sigma(7\text{TeV}) = 172 \text{ pb}$
  - top  $\sigma(8\text{TeV}) = 246 \text{ pb}$
  - top  $\sigma(13\text{TeV}) = 832 \text{ pb}$
- Background is more “flat”



# Cross section measurement

The diagram shows the formula for the cross-section  $\sigma_{t\bar{t}}$  on a yellow background. Four arrows point from descriptive text to parts of the formula: 

- An arrow from "Number of observed events" points to  $N_{obs}$ .
- An arrow from "Number of background events (from data, calculated from theory)" points to  $N_{bgd}$ .
- An arrow from "Acceptance (experimental: detector, efficiencies)" points to  $\epsilon_{t\bar{t}}$ .
- An arrow from "Luminosity (determined by amount of data, accelerator, triggers, etc)" points to  $\int L dt$ .

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

Number of observed events

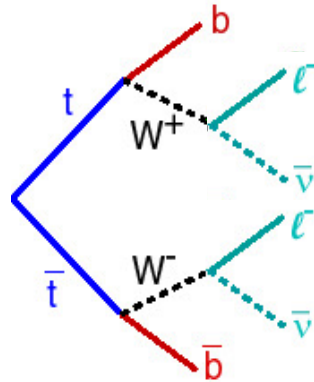
Number of background events  
(from data, calculated from theory)

Acceptance  
(experimental: detector, efficiencies)

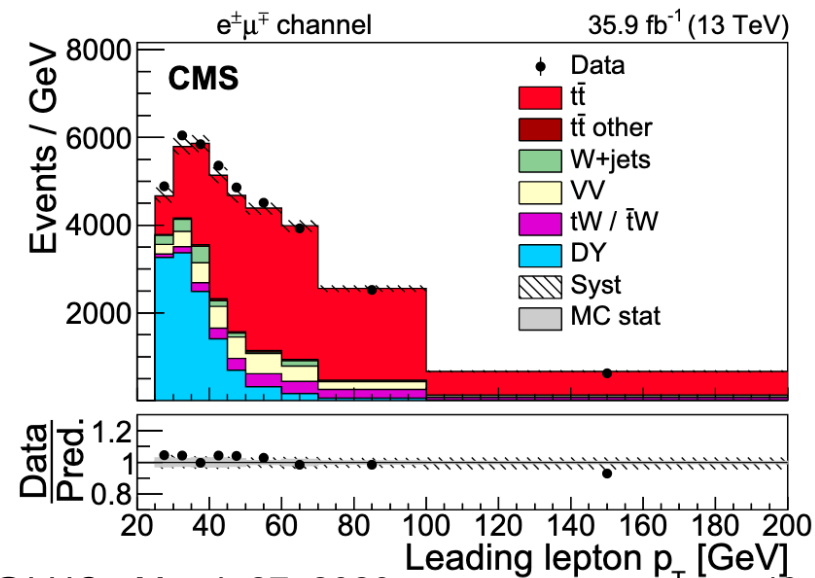
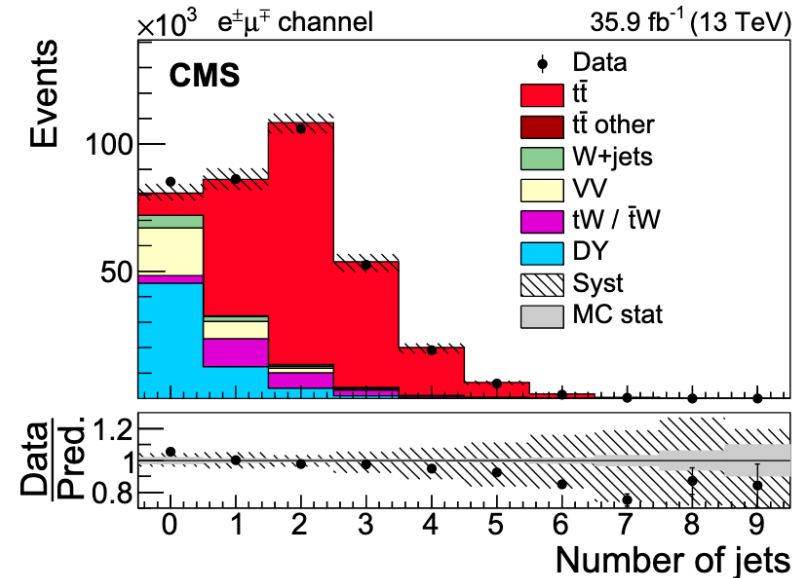
Luminosity  
(determined by amount of data, accelerator, triggers, etc)

# Dilepton channel

EPJC 79(2019)368

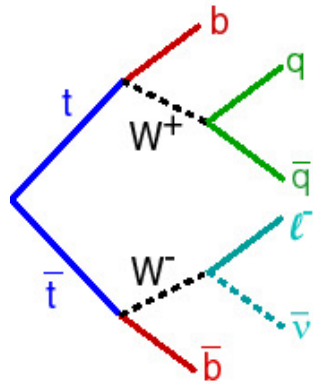


- Branching ratio (BR)  $\sim 5\%$
- Background: **small**
- Clean final state
  - two leptons +  $\geq 2$  jets + MET
  - kinematic variables
- Signal visible w/without b-tagging
- Main systematics: JES, lepton ID, (pileup, b-tag, signal modeling)

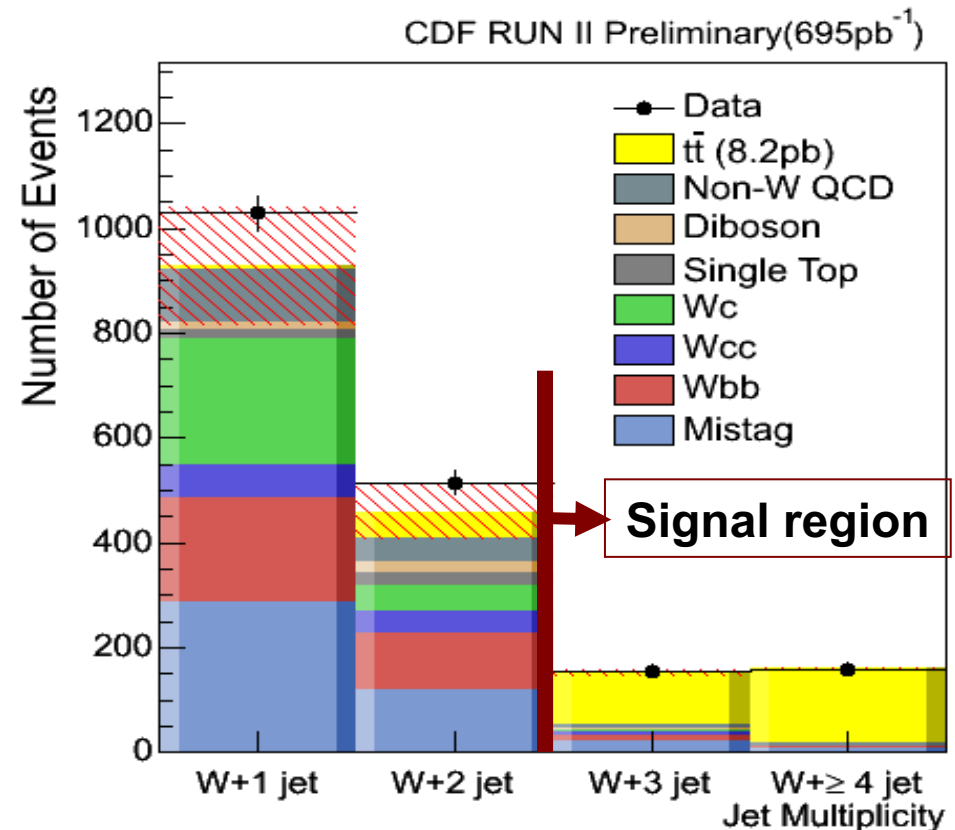




# Lepton + jets



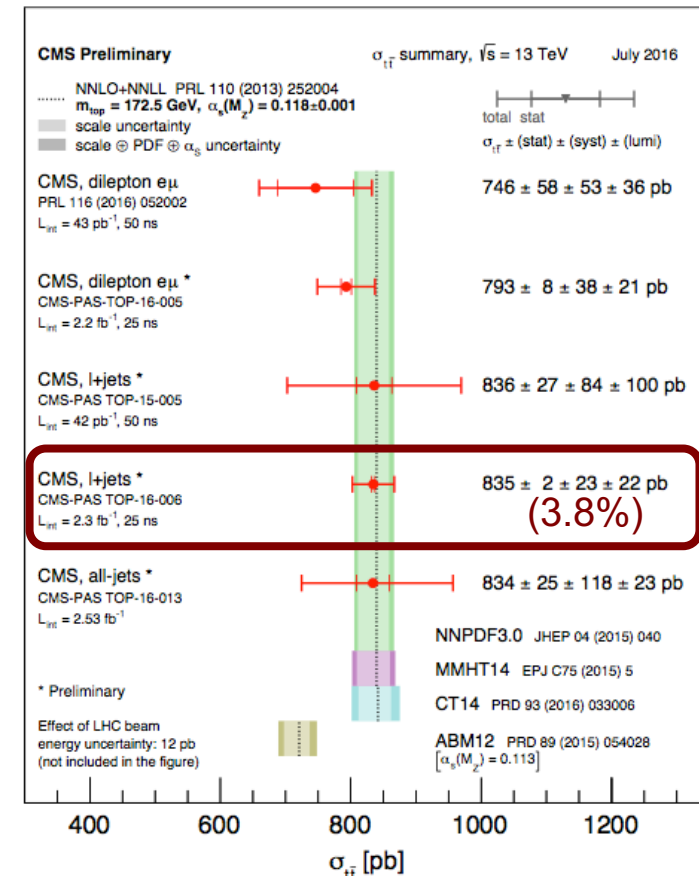
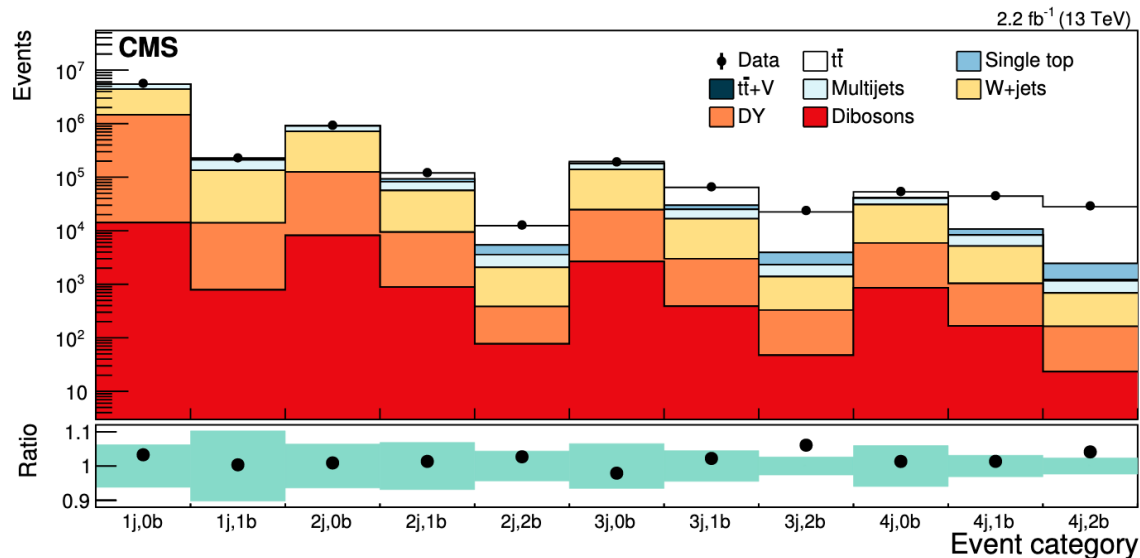
- BR  $\sim 30\%$
- Background: moderate
- Selection:
  - one lepton +  $\geq 3$  jets + MET
  - may require b-tag
- Main backgrounds:
  - hadronic multi-jet, W+jets



# 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



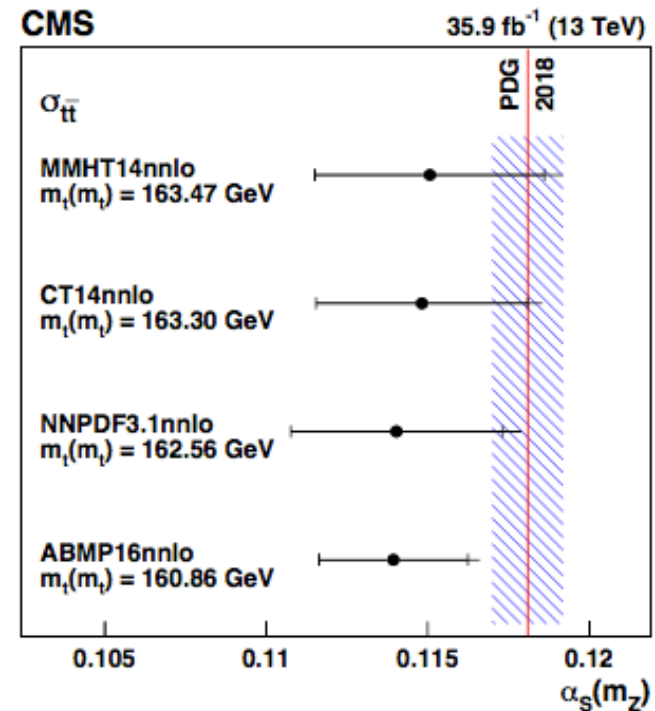
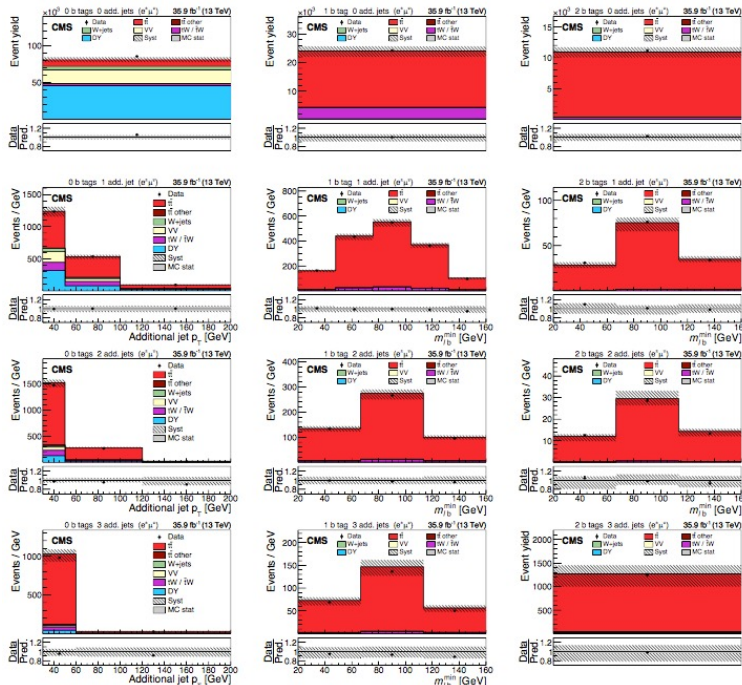
# Cross section: multi-dimensional fit

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

(~4%)

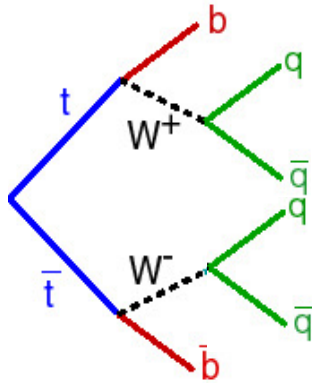
$$\sigma_{t\bar{t}} = 803 \pm 2 (\text{stat}) \pm 25 (\text{syst}) \pm 20 (\text{lumi}) \text{ pb}$$

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

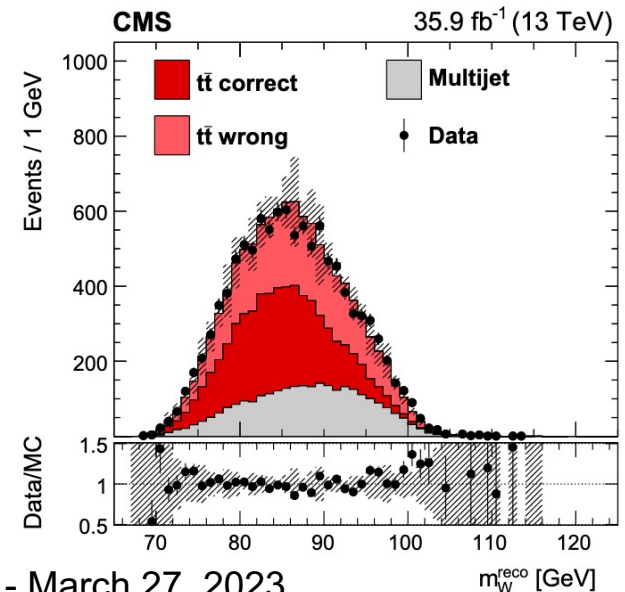
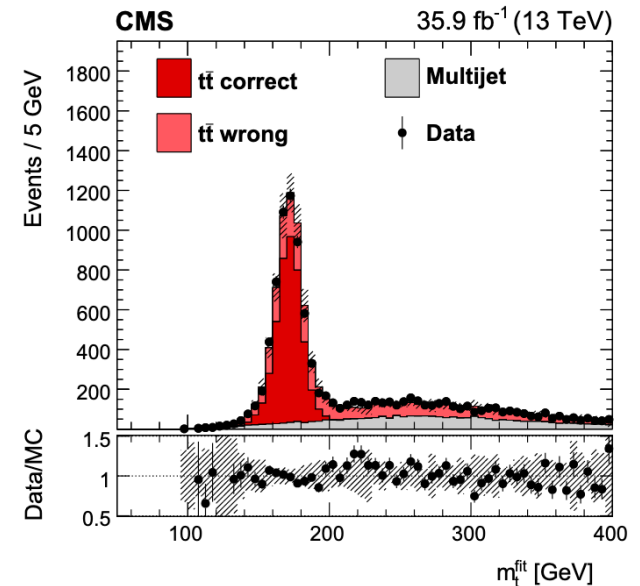


# All hadronic

EPJC 79(2019)313

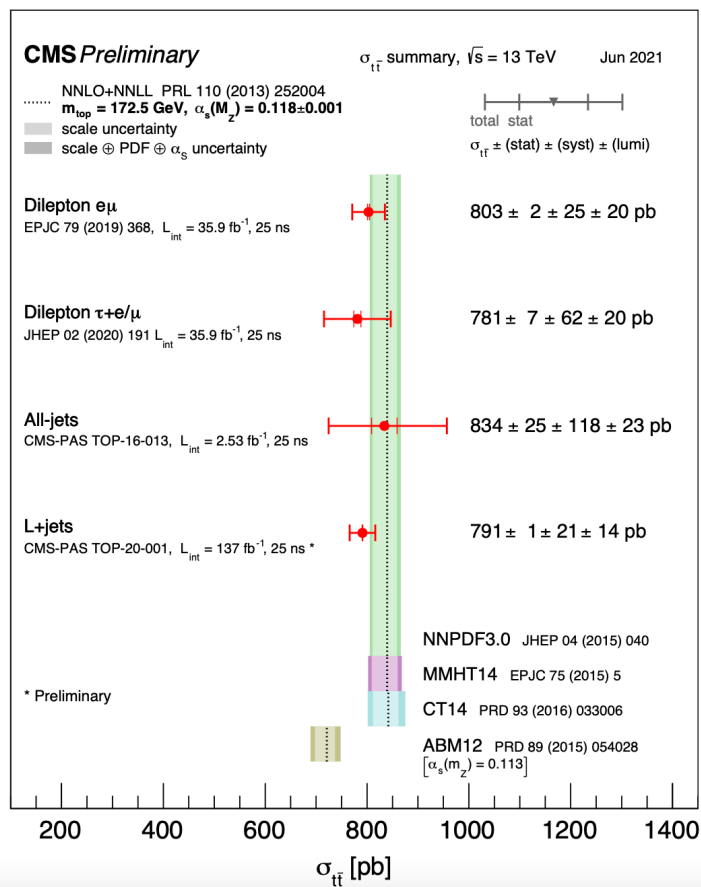


- BR ~46%
- Background: large
- Selection:
  - $\geq 6$  jets + kinematical selection
  - require 2 b-tags
- Main backgrounds:
  - hadronic multi-jet
  - same selection without b-tag



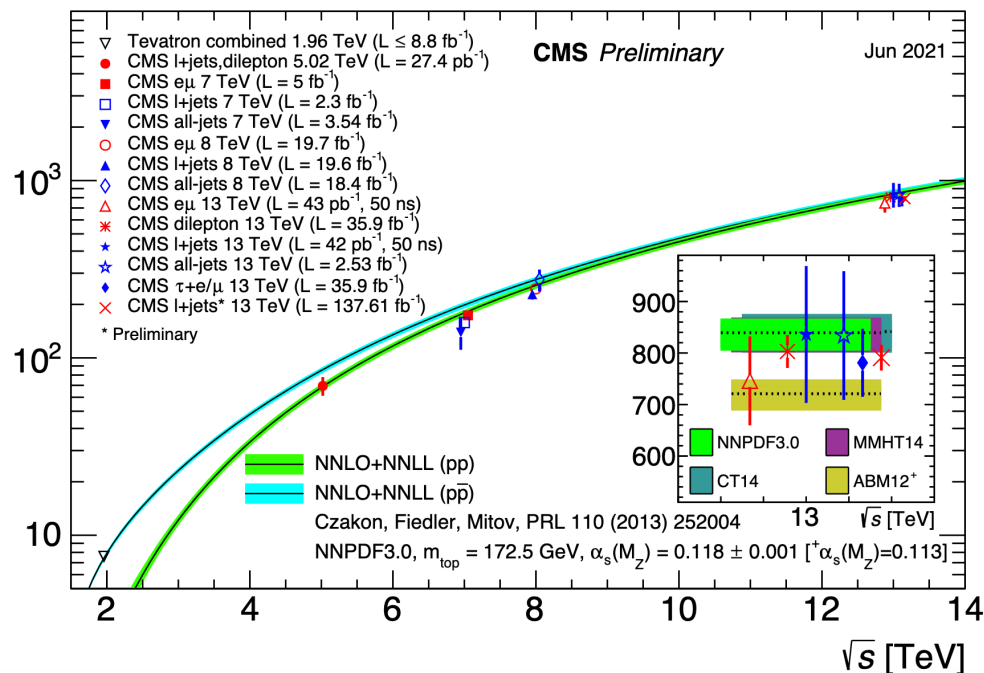
# Cross sections

$\pm 4\%$



$\Rightarrow$  measurements challenging theory

Inclusive  $t\bar{t}$  cross section [pb]



Collider	$\sigma_{\text{tot}}$ [pb]	scales [pb]	pdf [pb]
Tevatron	7.164	+0.110(1.5%) -0.200(2.8%)	+0.169(2.4%) -0.122(1.7%)
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LHC 14 TeV	953.6	+22.7(2.4%) -33.9(3.6%)	+16.2(1.7%) -17.8(1.9%)

$\pm 3-5\%$

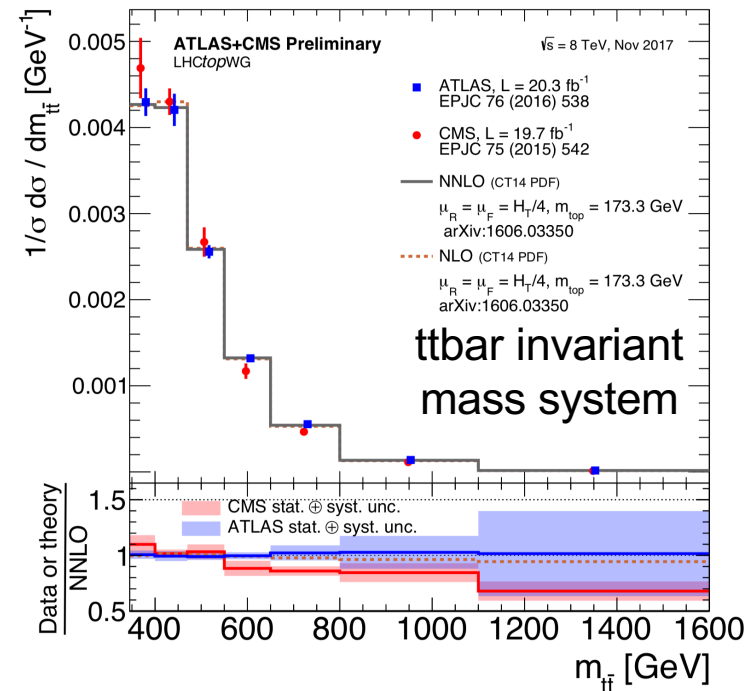
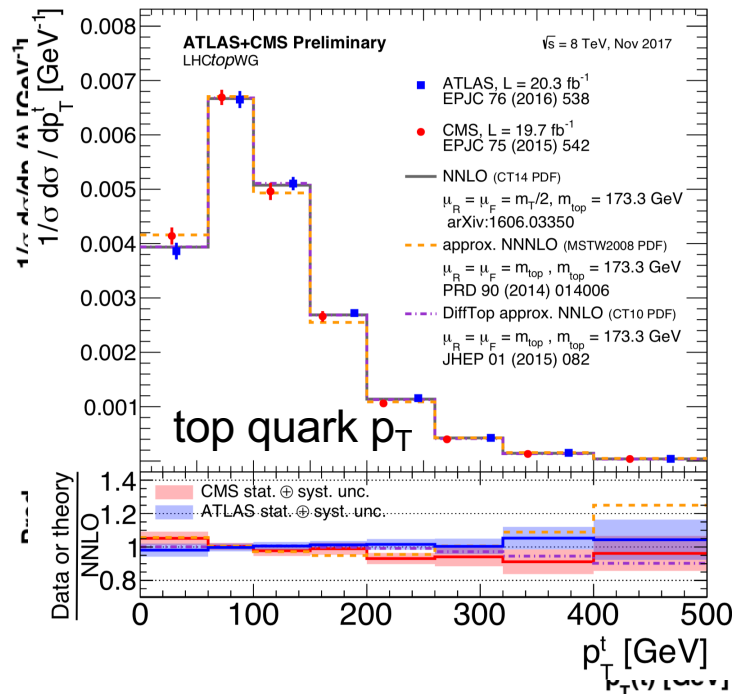


# Differential cross section

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  $p_T$ ,  $\eta$ , invariant mass of the final state leptons, top quarks, ttbar system, etc.
- Good agreement with expectations

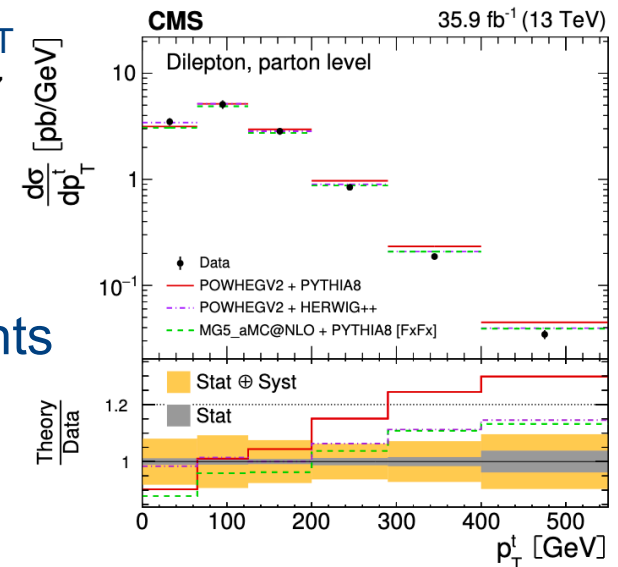
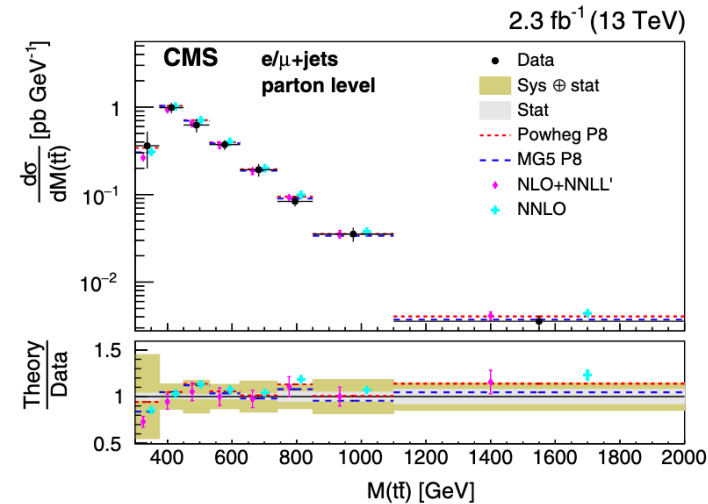
$$\frac{1}{\sigma_{t\bar{t}}} \frac{d\sigma_{t\bar{t}}}{dX}$$



# Differential cross section (cont.)

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

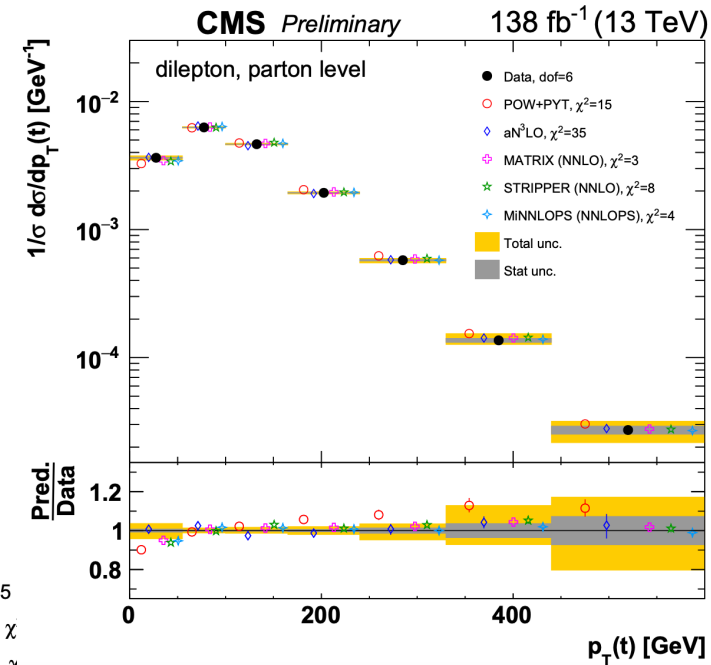
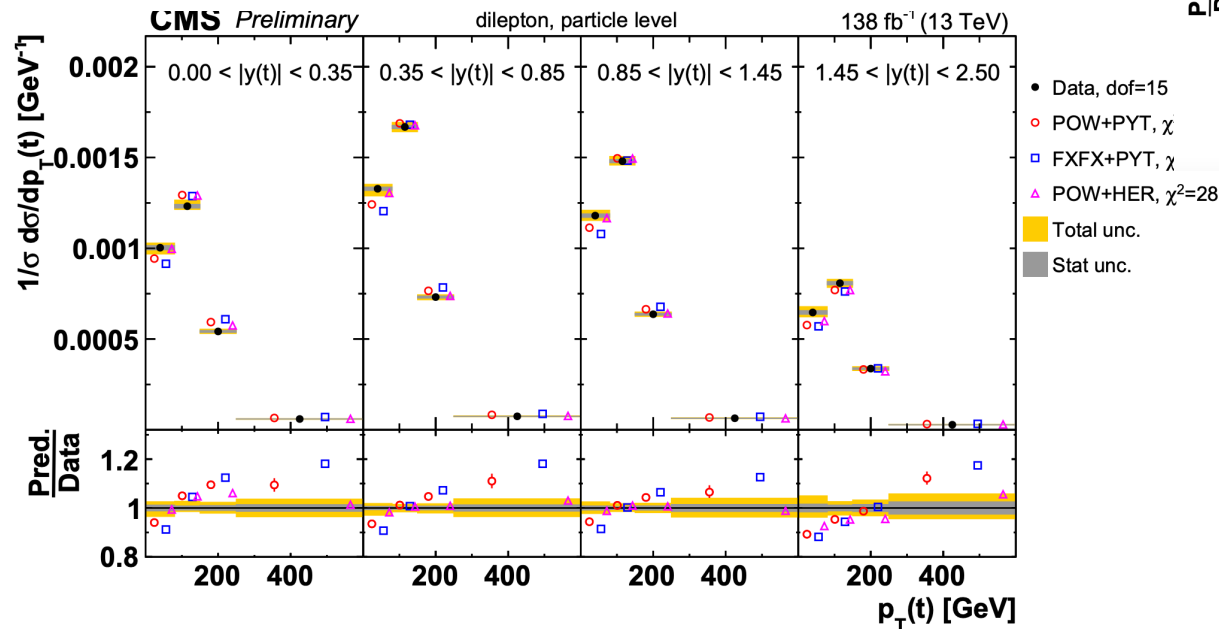
- Correct for detector effects and acceptances
- **Softer top  $p_T$  (CMS)**, agreement in ATLAS at high  $p_T$ 
  - Due to momentum reshuffling, P.Nason, [cern.ch/event/301787](http://cern.ch/event/301787)
  - FSR shower changes mass of final state partons. light partons can build sizeable mass, and  $t/\bar{t}$  do not radiate
  - short term solution: consider difference as uncertainty
- Impact on  $t\bar{t}H$ /SUSY/etc searches, tails of  $t\bar{t}$  events
- Measure  $t\bar{t}$  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  $\alpha_s$
- Total uncertainty reduced by a factor of  $\sim 2$  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”