

The Top quark

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LIP Lisbon

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



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Introduction

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

1974

With the discovery of the J/Ψ :

quarks

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

leptons

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

1975-1977

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

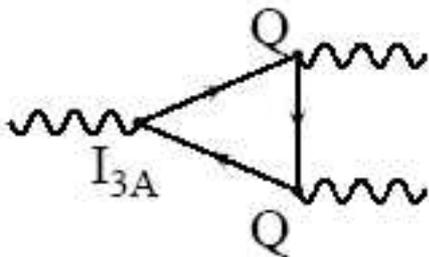
$$\begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} \\ b \end{pmatrix}$$

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

- 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

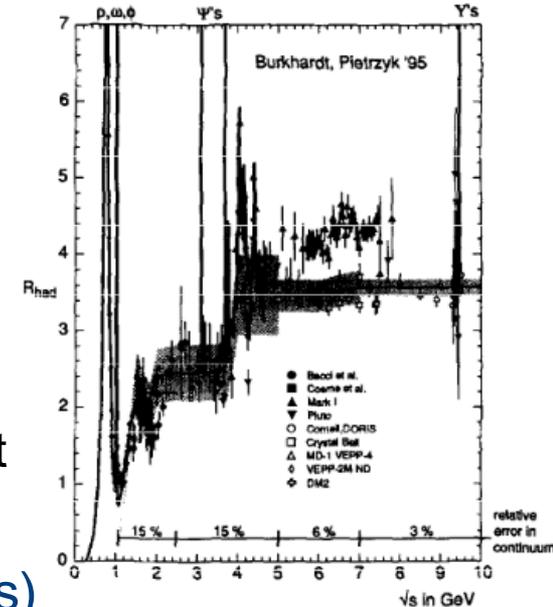
Searches at e^+e^- colliders

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

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

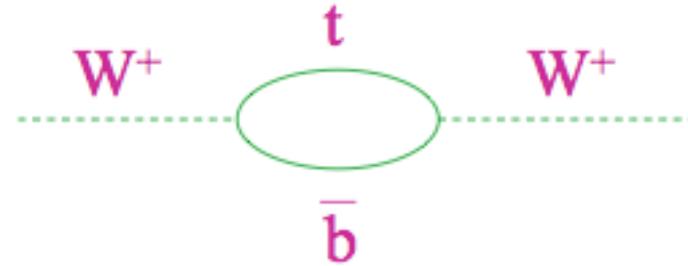
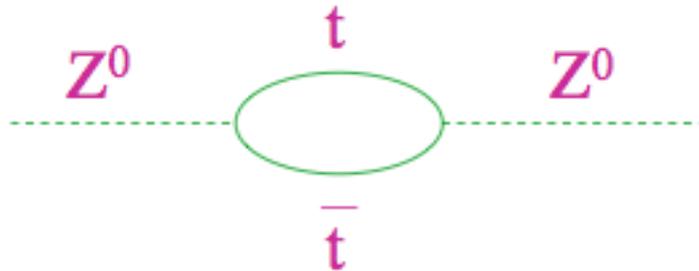
direct count of
number of quarks

- 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 ~ 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

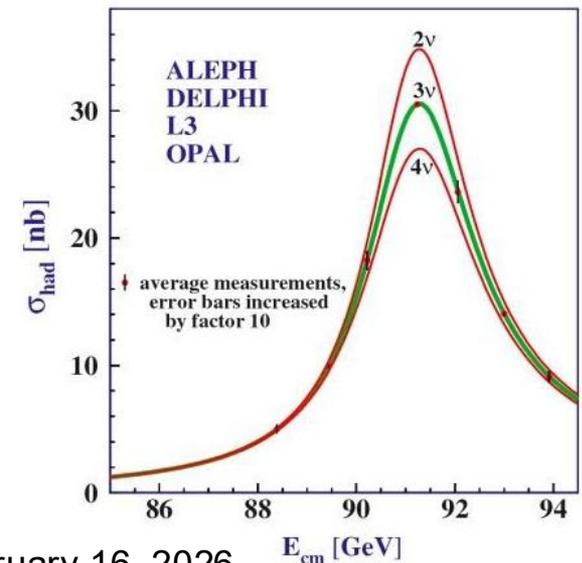
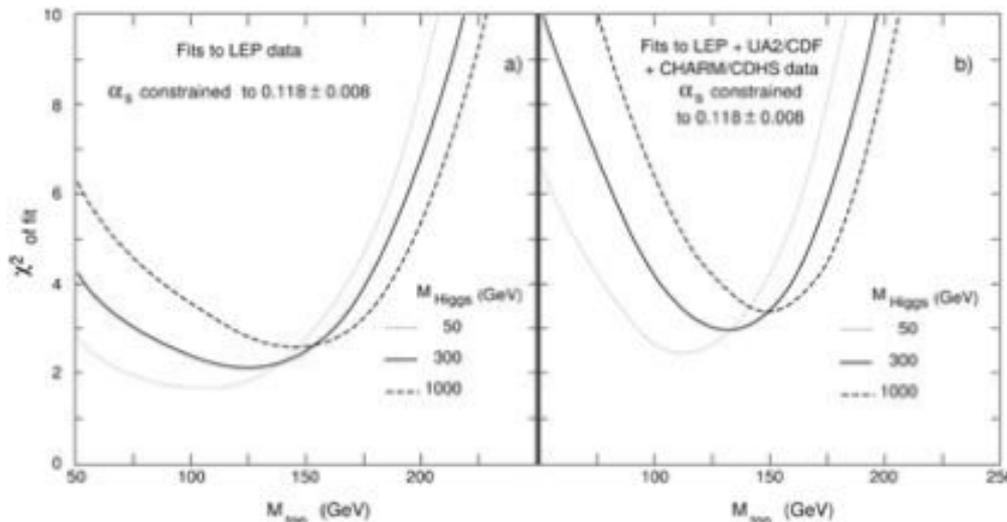


Indirect searches from e^+e^- colliders

- 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_{top}
 - Prediction upper limit < 200-220 GeV



Early searches at hadron colliders

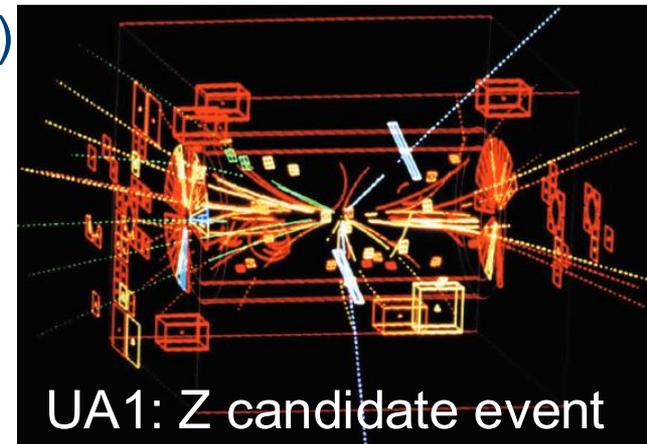
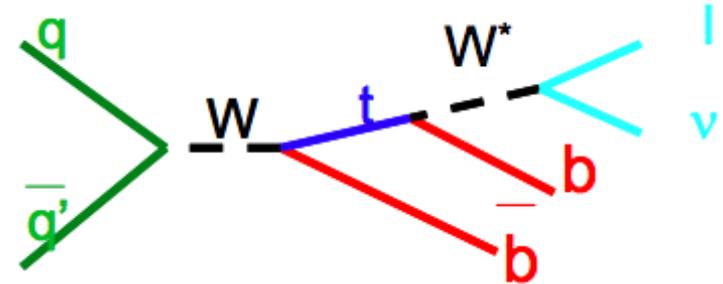
CERN Sp \bar{p} S ($\sqrt{s}=540$ GeV) built to observe W,Z

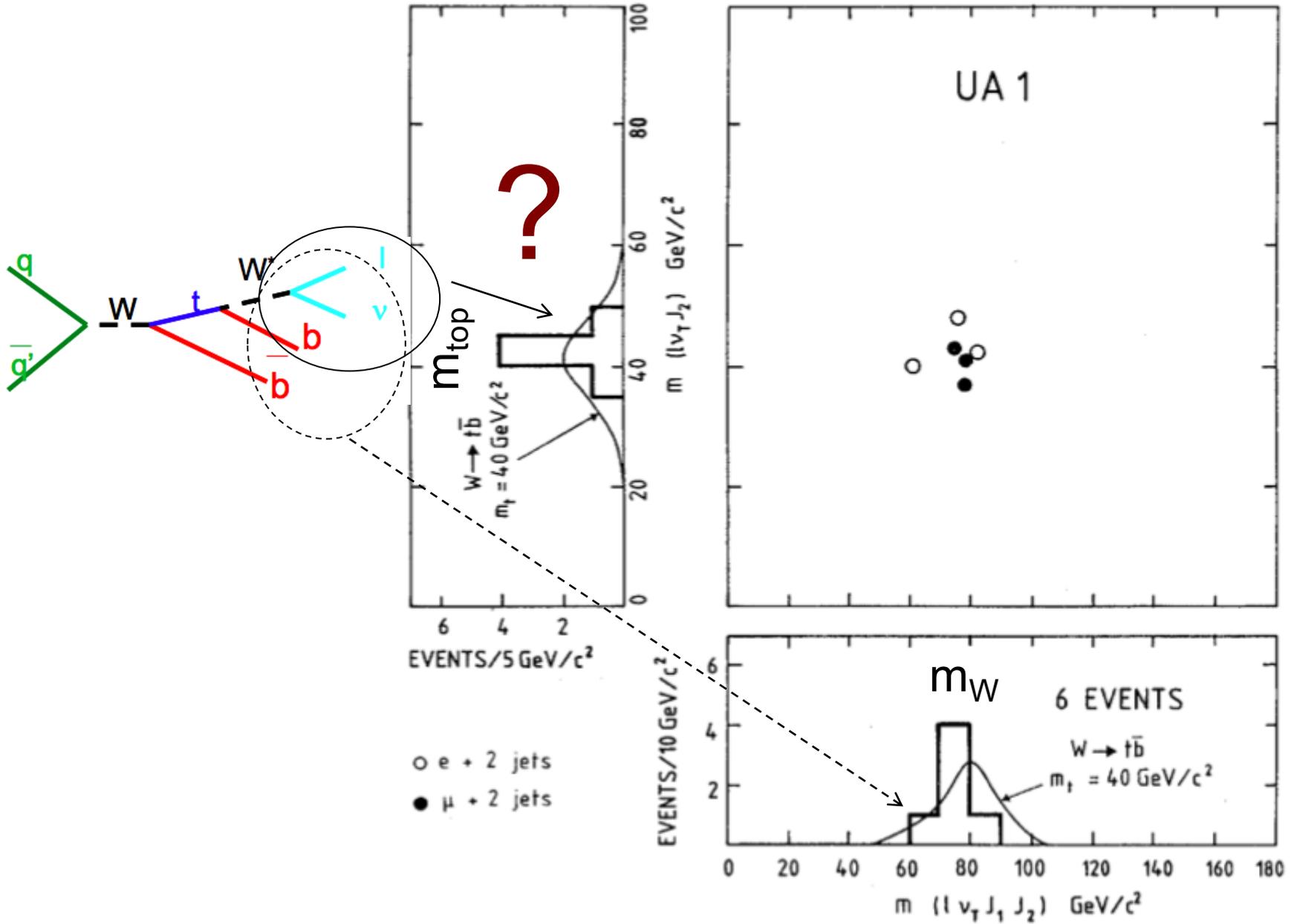
- Access to much higher energies
- Large backgrounds, low event rates
- Difficult reconstruction: jets

1984: UA1

- $W \rightarrow tb \rightarrow l\nu bb$
- 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...

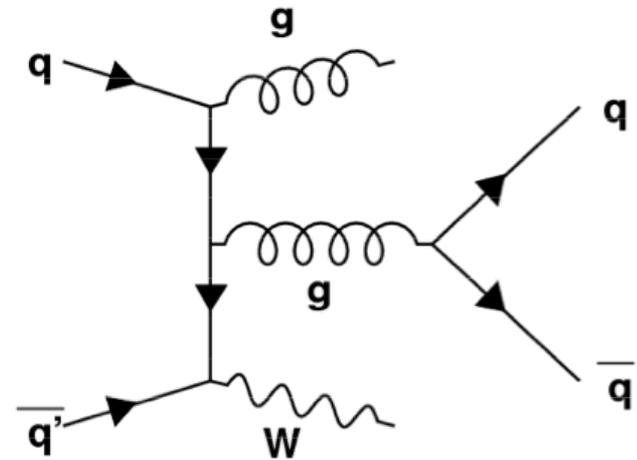
\Rightarrow W+jet background was underestimated





Searches at hadron colliders

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



channel

$\mu + \geq 2$ jets

$e + \geq 1$ jets

observed

10 events

26 events

expected background

11.5 ± 1.5 events

23.4 ± 2.8 events

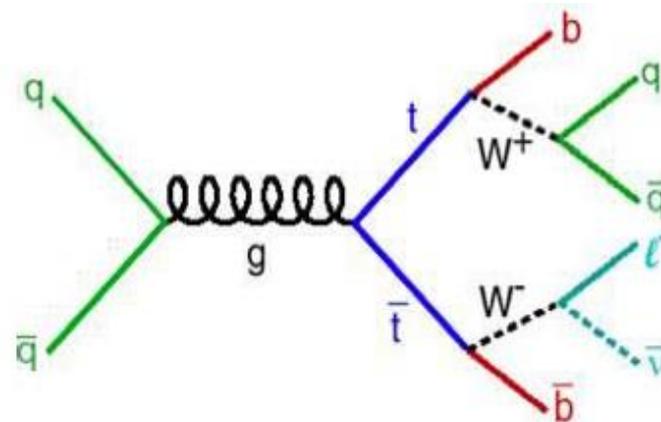
(+ 23 expected if $M_{\text{top}} = 40$ GeV)

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

Fermilab joins the hunt

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



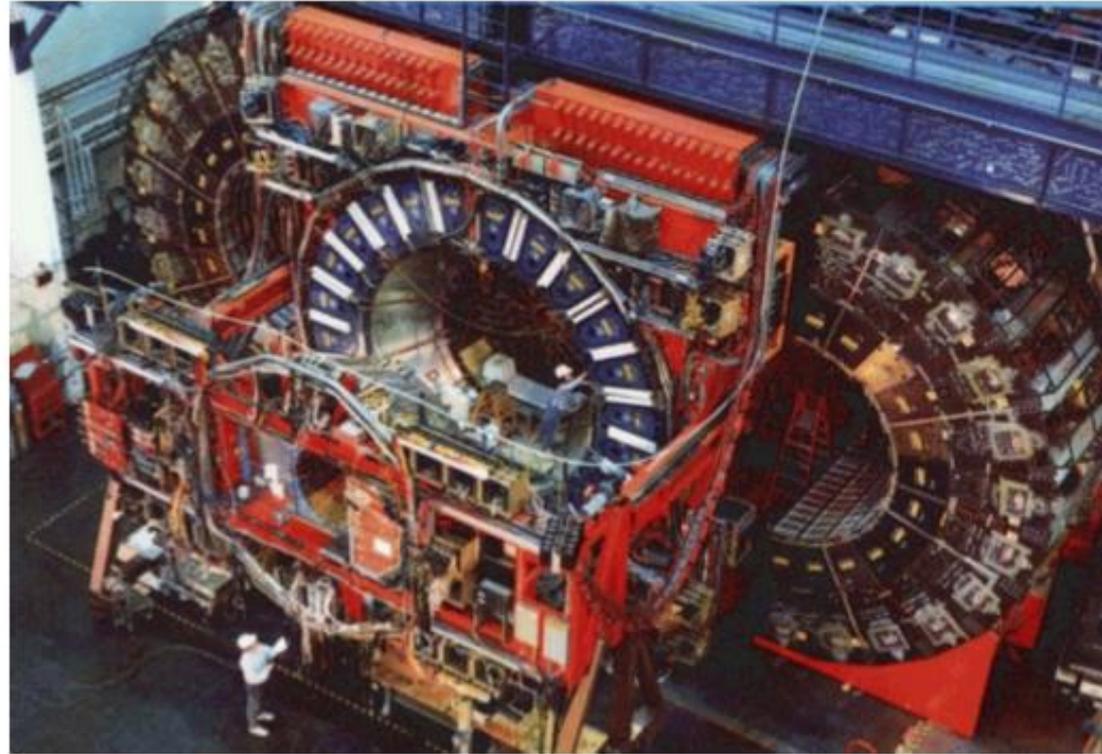
Tevatron

Proton-antiproton collision at 1.8-2.0 TeV





**12 countries, 62 institutions
767 physicists**



Searches at CDF

$e\mu$ channel

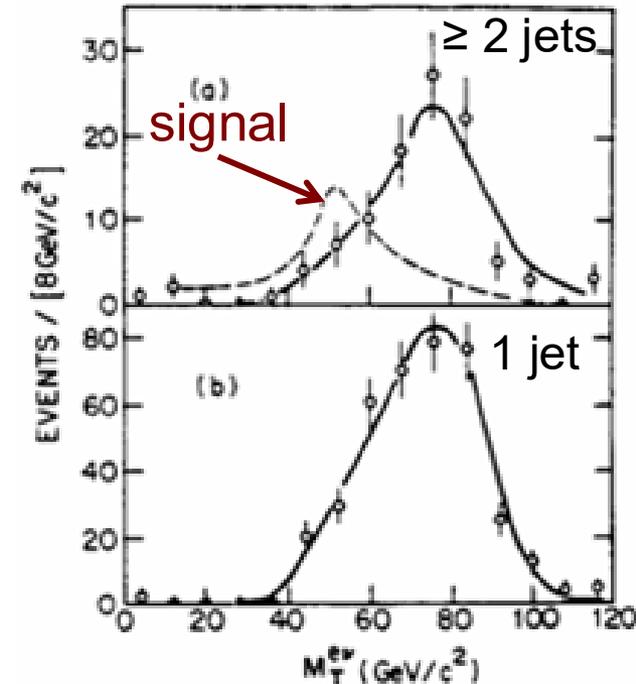
- Event rate lower: $2 \times \text{BR}(W \rightarrow e\nu)$
- Background small (no W +jets, no DY)
- Dominant background is $Z \rightarrow \tau\tau \rightarrow e\mu X$ (expect 1 evt)
- Observe 1 event (expect 7 evts for $M_{\text{top}}=70$ GeV)

$e\nu + \geq 2$ 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

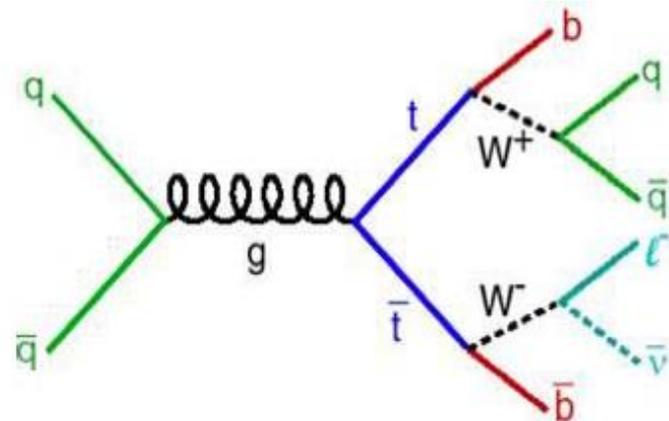
- UA2 uses similar technique: $M_{\text{top}} > 69$ GeV



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)

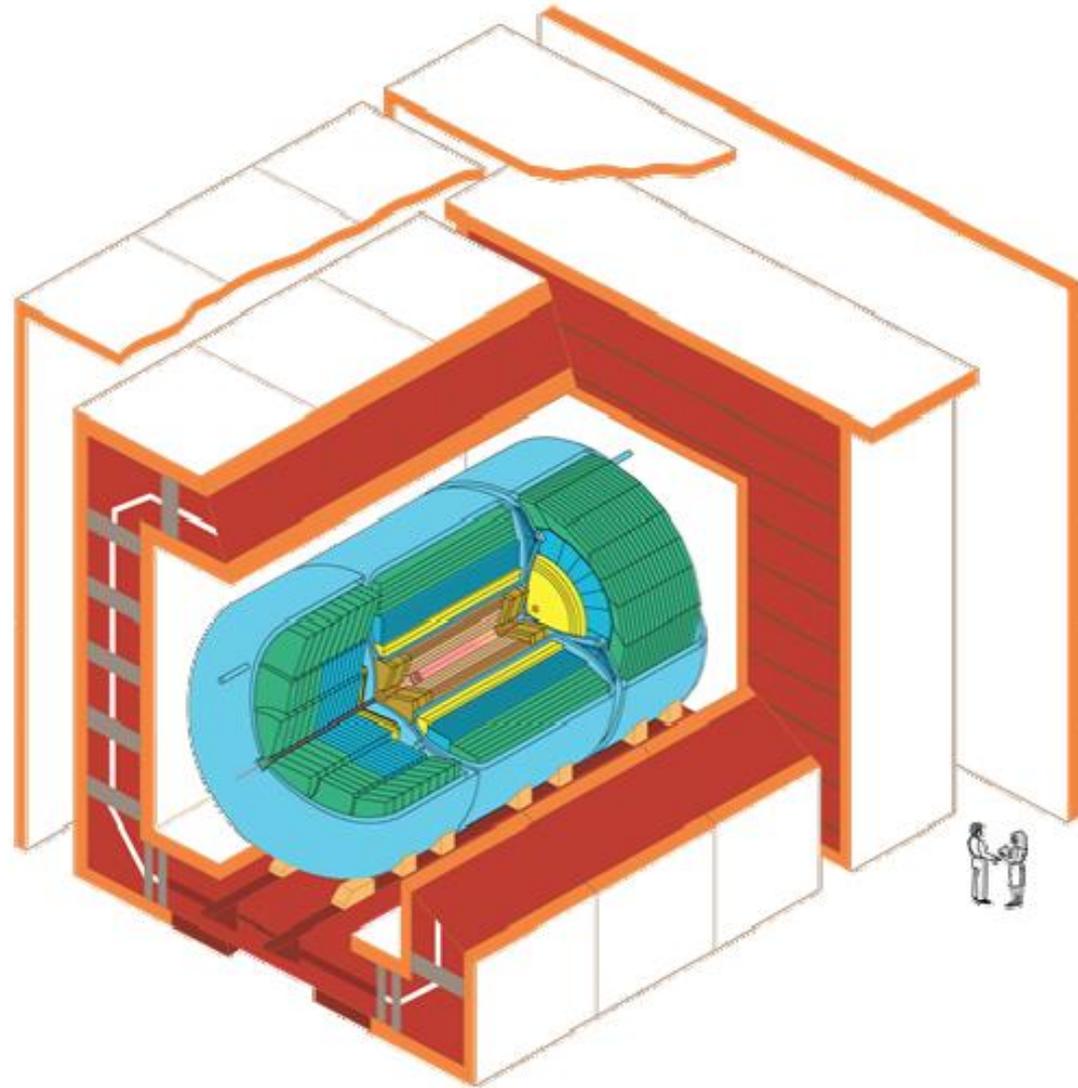
$\Rightarrow M_{\text{top}} > 91 \text{ GeV}$



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

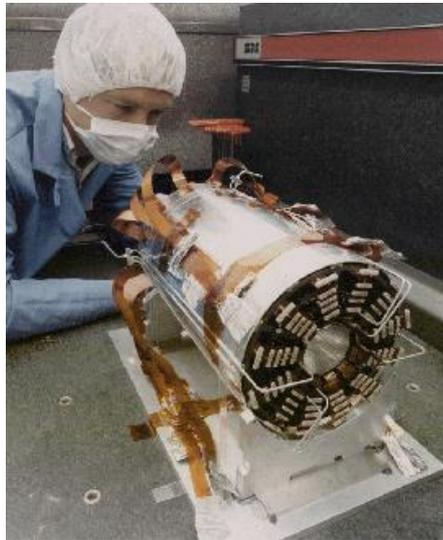
– $e\mu+\geq 1\text{jet}+\text{MET}$	1 evt	(1.1 bkg)
– $ee+\geq 1\text{jet}+\text{MET}$	1	(0.5)
– $e+\geq 4\text{jets}+\text{MET}$	1	(2.7)
□ $\mu+\geq 4\text{jets}+\text{MET}$	0	(1.6)

$\Rightarrow M_{\text{top}} > 131$ 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



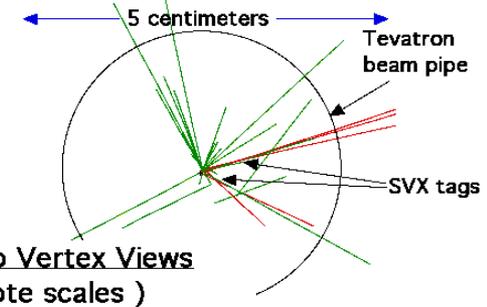
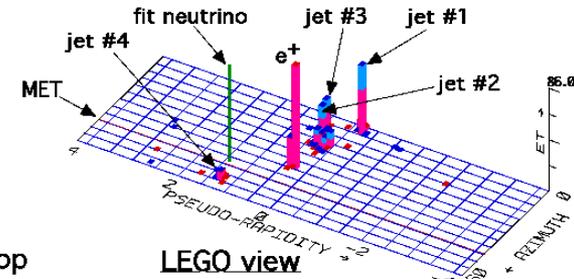
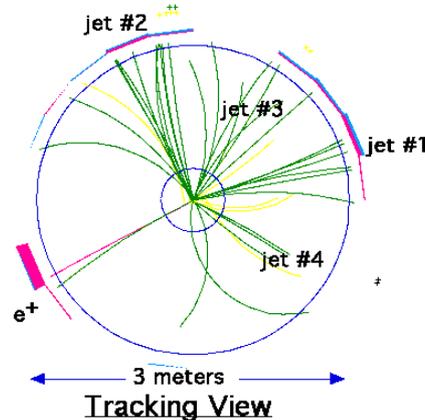
New: CDF vertex detector (SVX)
 (40 μm impact parameter resolution)
 powerful discriminant against background

$e + 4$ 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)

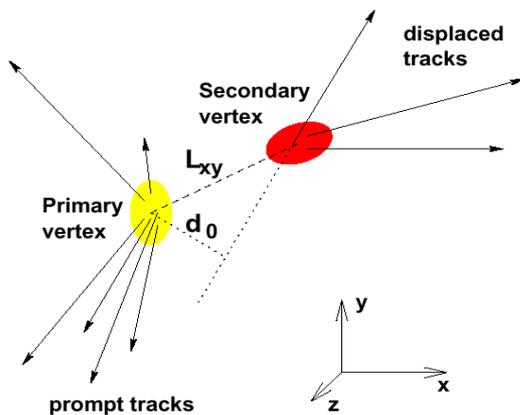


Tagging b-jets

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

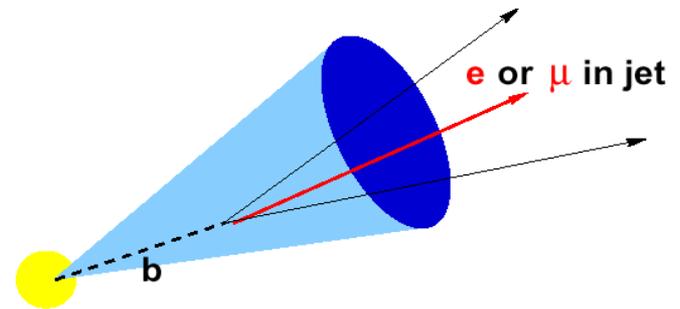
B hadrons are long-lived

Vertex displaced tracks



semileptonic B hadron decay

Soft Lepton Tagging



- $b \rightarrow lvc$ (BR $\sim 20\%$)
- $b \rightarrow c \rightarrow lvs$ (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 ± 0.3
SLT	7 tags	3.1 ± 0.3
total	12 events	---

← 3 events in
← common

- 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

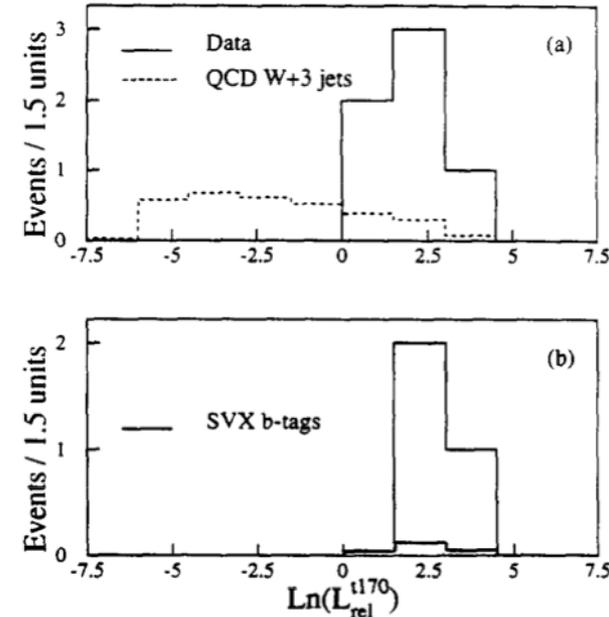
• There were also other analyses at CDF

- 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)

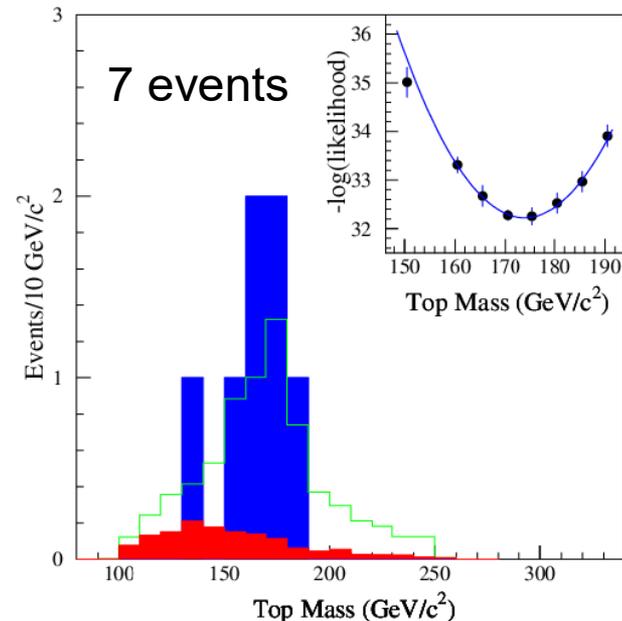
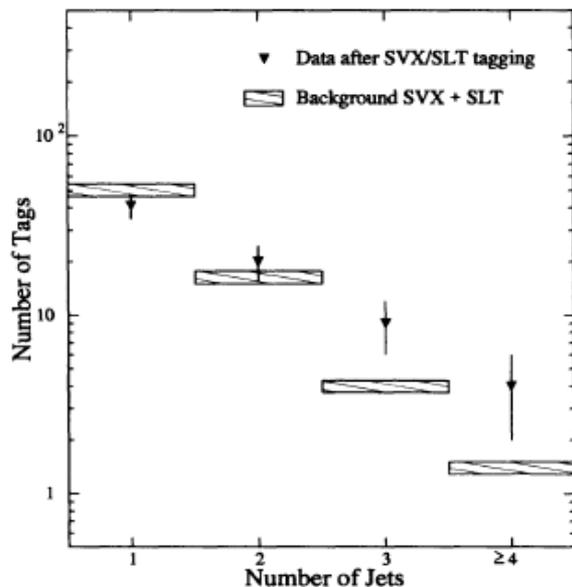
- Observed 7 events (expect 4-6 from bkg)
- No independent evidence



First evidence (1994)

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

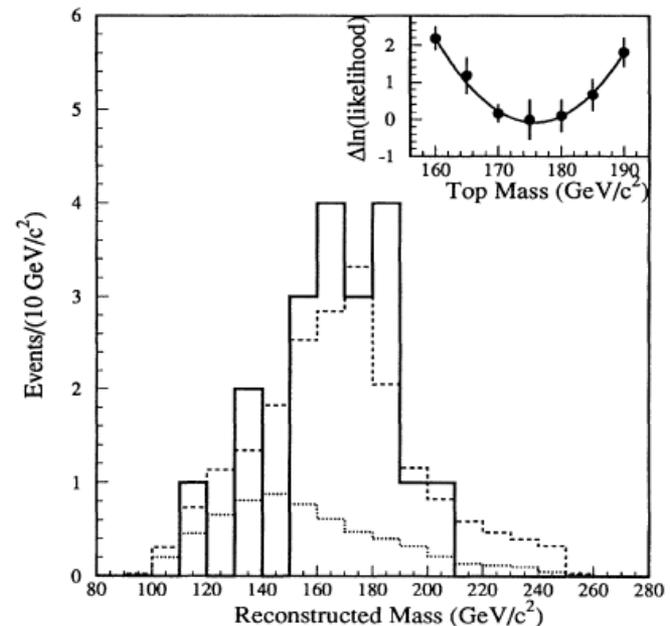
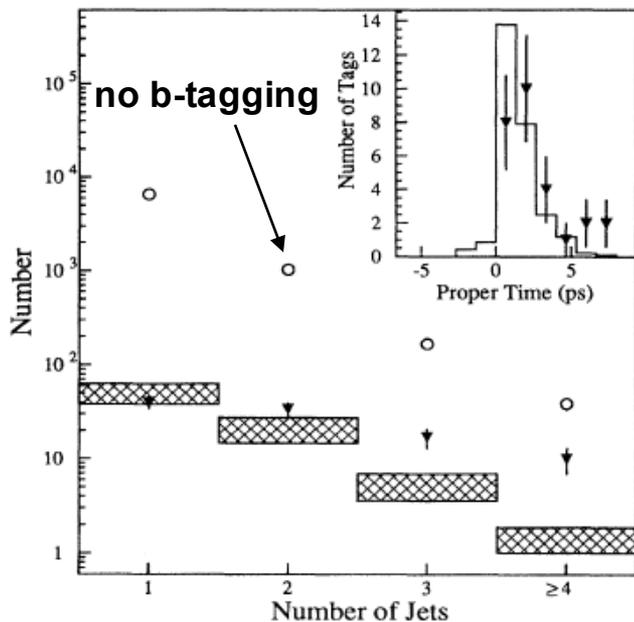
We summarize a search for the top quark with the Collider Detector at Fermilab (CDF) in a sample of $\bar{p}p$ collisions at $\sqrt{s} = 1.8$ TeV with an integrated luminosity of 19.3 pb^{-1} . We find **12 events** consistent with either two W bosons, or a W boson and at least one b jet. The probability 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 **$174 \pm 10^{+13}$** GeV/c^2 . The $t\bar{t}$ production cross section is measured to be **$13.9^{+6.1}_{-4.8}$** pb .



First measurements

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 $\sqrt{s} = 1.8 \text{ TeV}$ 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 4.8σ . 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 $6.8^{+3.6}_{-2.4} \text{ pb}$.





Fermilab - March 2, 1995

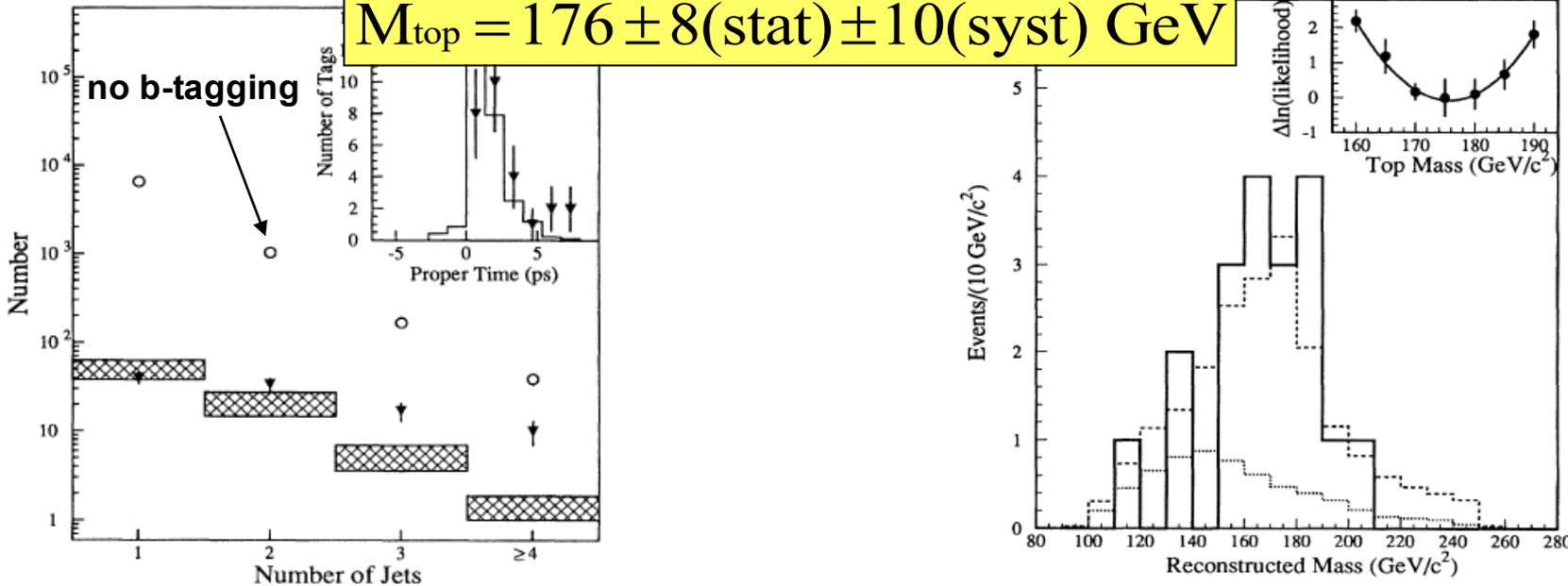
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$176 \pm 8(\text{stat}) \pm 10(\text{syst}) \text{ GeV}$ $\sigma_{tt} = 6.8^{+3.6}_{-2.4} \text{ pb}$

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

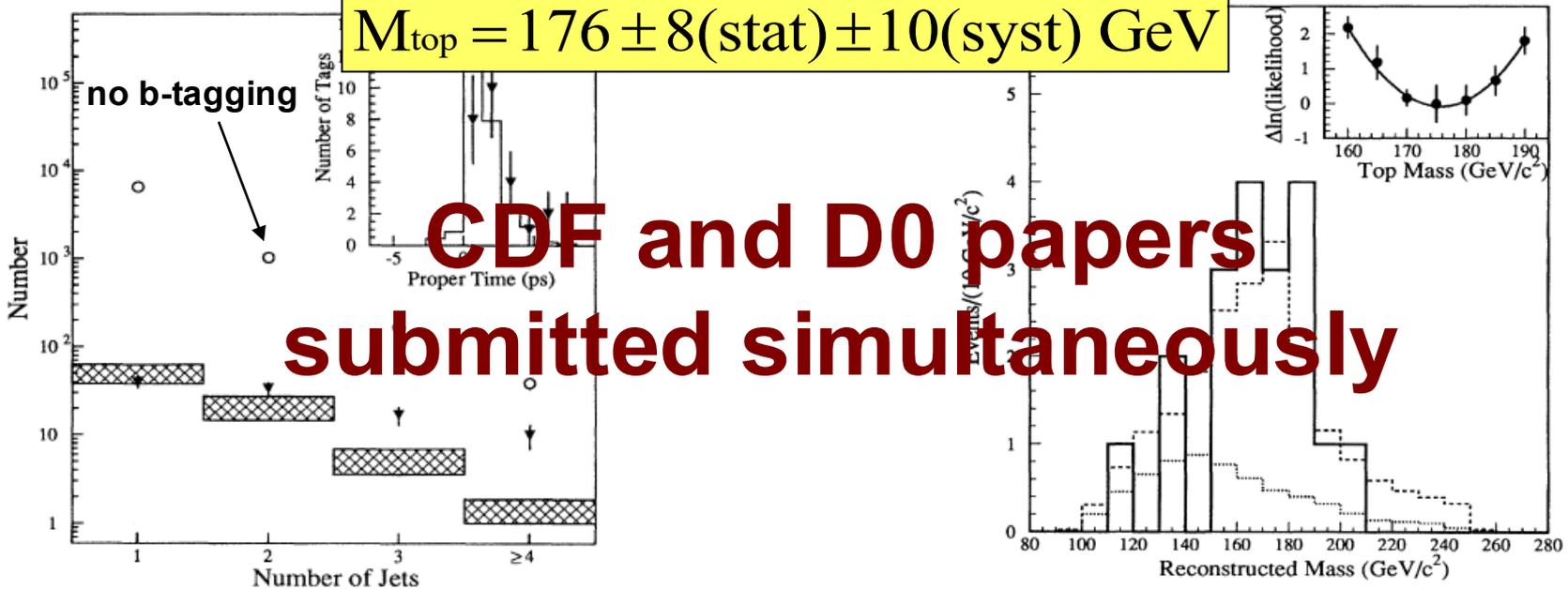


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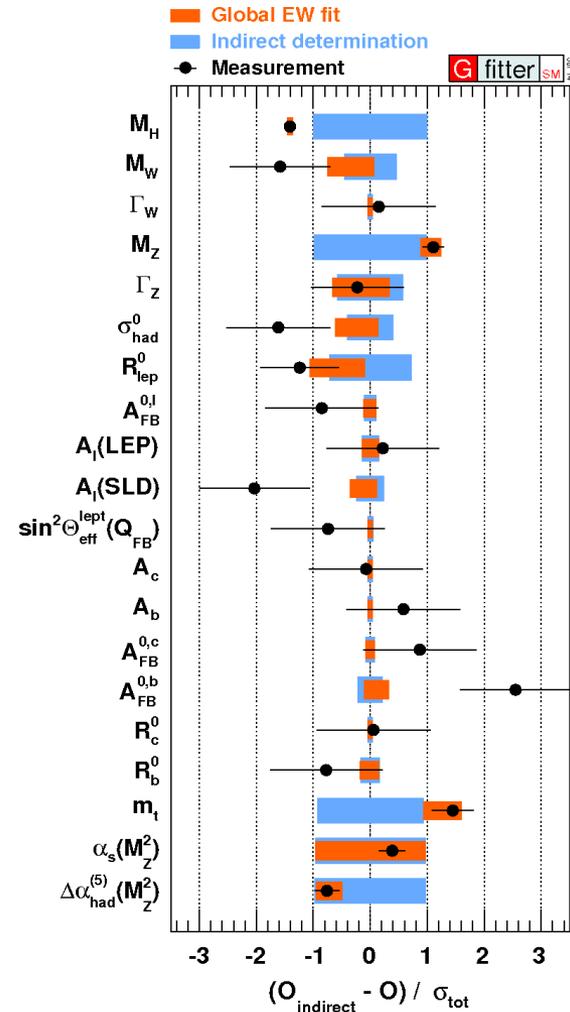
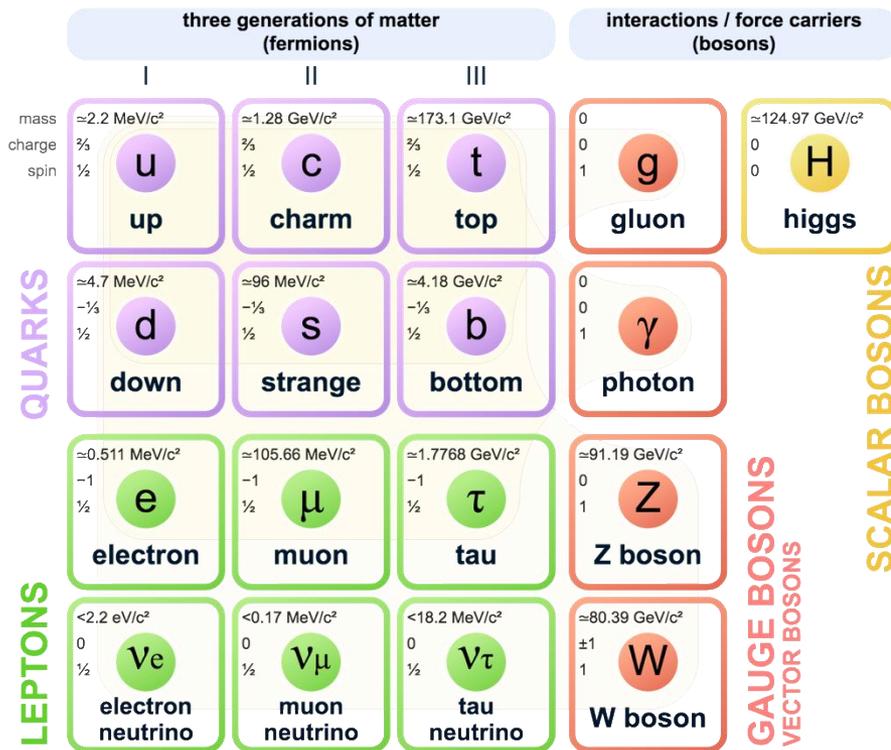
$$\sigma_{tt} = 6.8^{+3.6}_{-2.4} \text{ pb}$$
$$M_{\text{top}} = 176 \pm 8(\text{stat}) \pm 10(\text{syst}) \text{ GeV}$$



**CDF and D0 papers
submitted simultaneously**

SM confirmed by the data

Standard Model of Elementary Particles



Excellent agreement with all experimental results

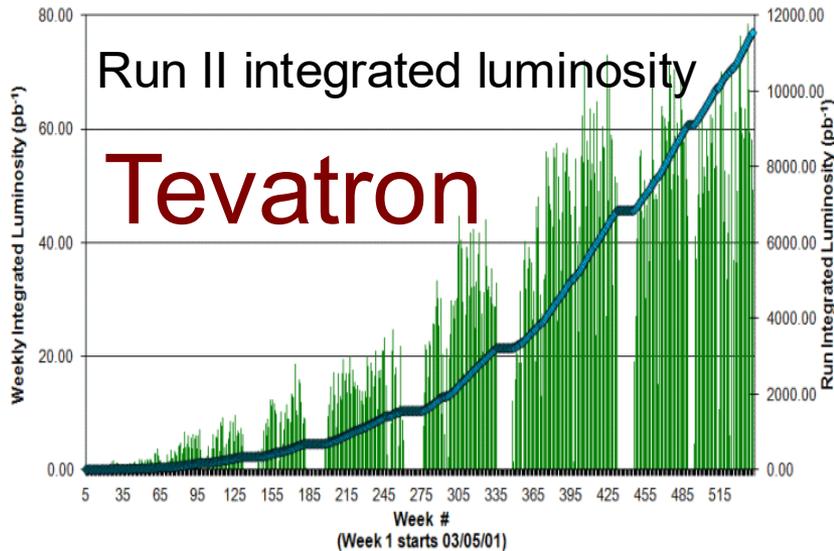
The Large Hadron Collider

- 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

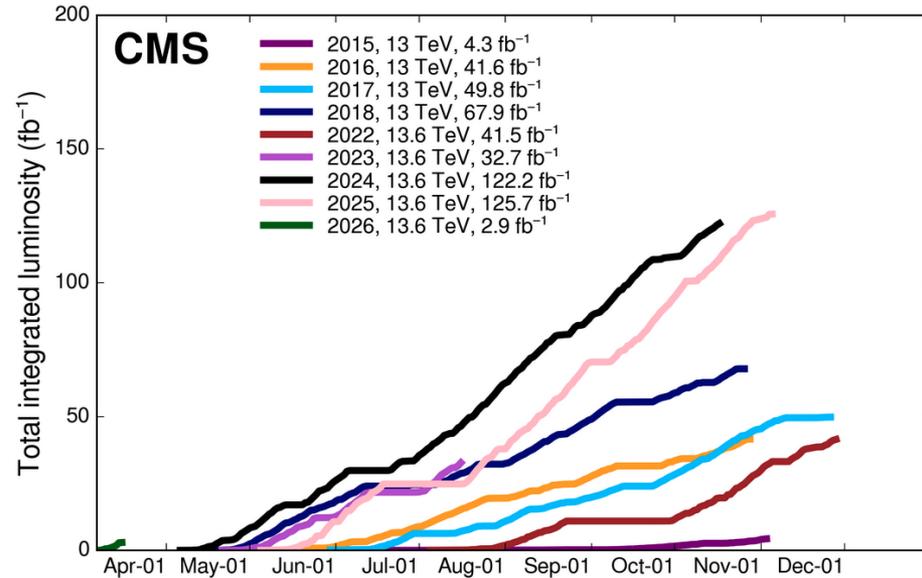


⇒ Top quarks give access to SM and BSM (?)

Tevatron vs LHC



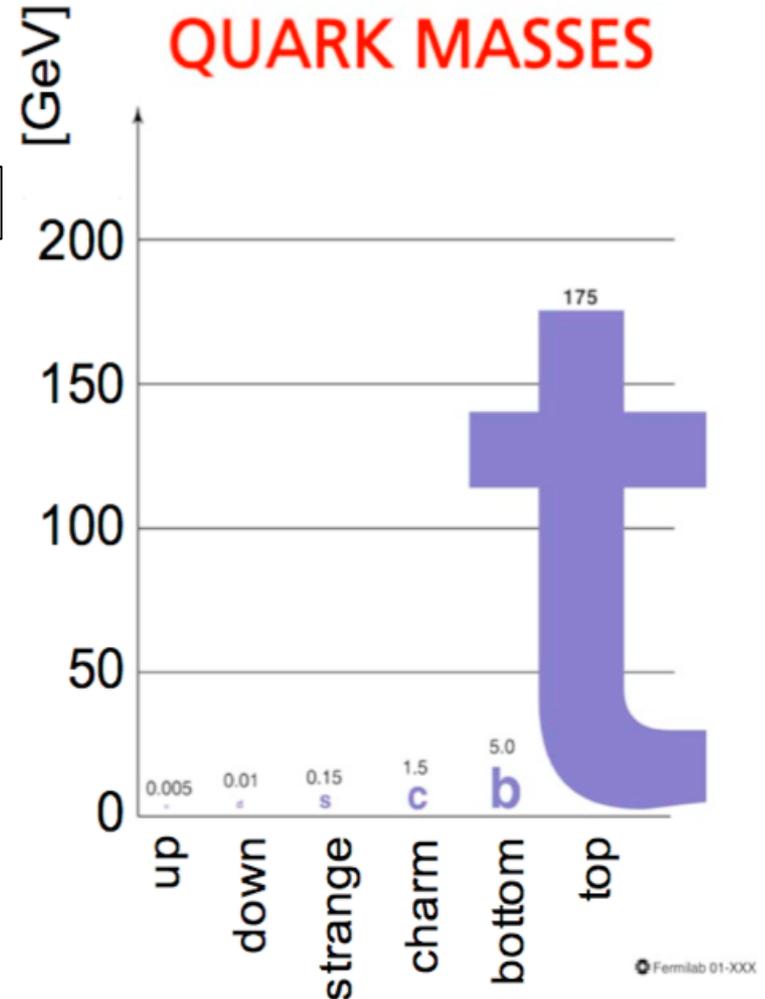
Energy: 1.96 TeV
 Int. Luminosity: 12 fb^{-1}
 Age: ~25 years
 Events/exp (1 fb^{-1})
 350 ee e μ , $\mu\mu$
 2k lepton + jets



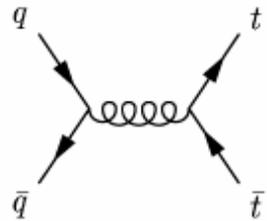
Energy: 7/8/13/13.6 TeV
 Int. Luminosity: 5/20/160/320 fb^{-1}
 Age: ~17 years
 Events/exp (1 fb^{-1})
 40k ee e μ , $\mu\mu$
 250k lepton + jets

The top quark

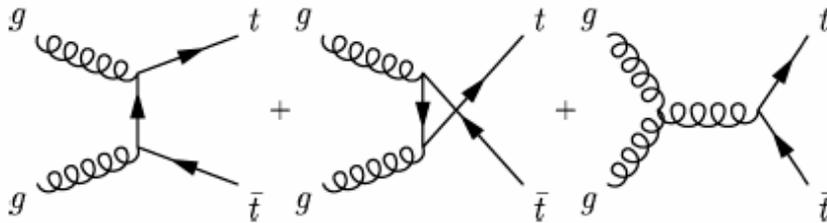
- The heaviest known elementary particle
- Large coupling to the Higgs: ~ 1
- Short lifetime $\tau = 0.4 \times 10^{-24}$ sec
 - for $m_{\text{top}} = 175$ GeV $\Rightarrow \Gamma = 1.4$ GeV \Rightarrow no hadronization
 - large contributions to EWK corrections $\sim G_F m_{\text{top}}^2$
 - very short 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

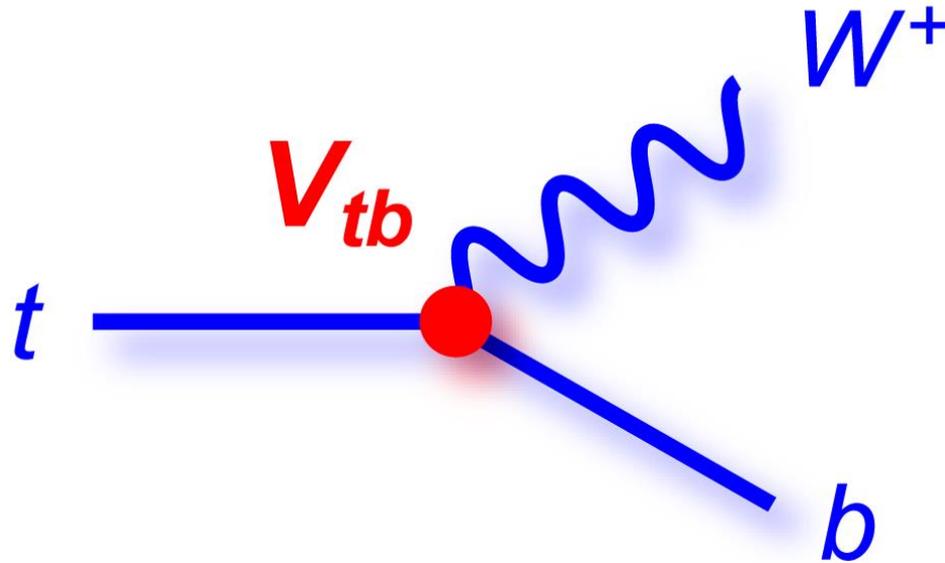
Predicted cross sections:

Collider	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%)

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

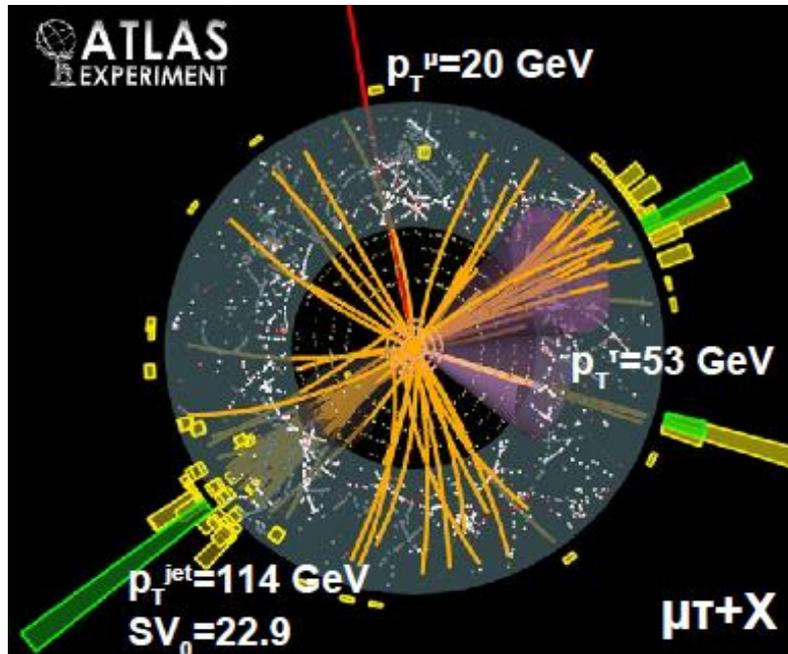
Czakon et al. PRL 110, 252004 (2013)

How does a top quark decay?

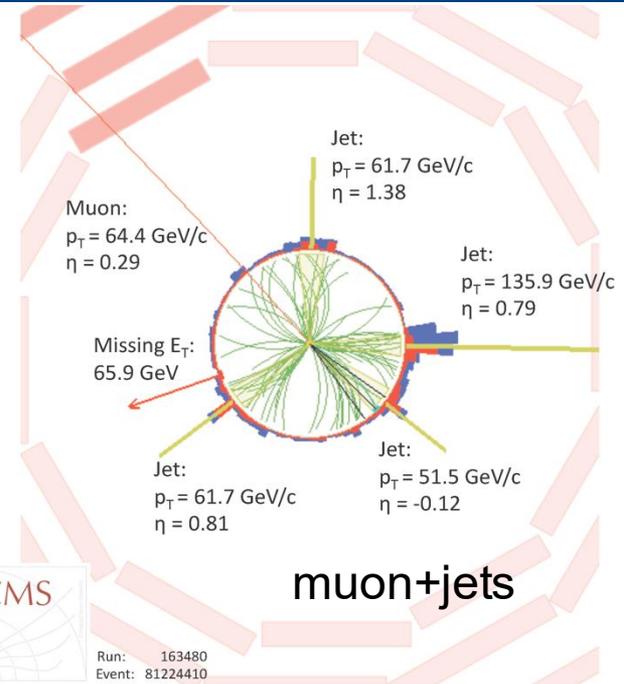


- almost always $t \rightarrow Wb$ (i.e. $V_{tb} \sim 1$)
- lifetime is short, and it decays before hadronizing
- the W is real:
 - can decay $W \rightarrow l\nu$ ($l=e,\mu,\tau$), $BR \sim 1/9$ per lepton
 - can decay $W \rightarrow qq$, $BR \sim 2/3$

Selection of top quark events



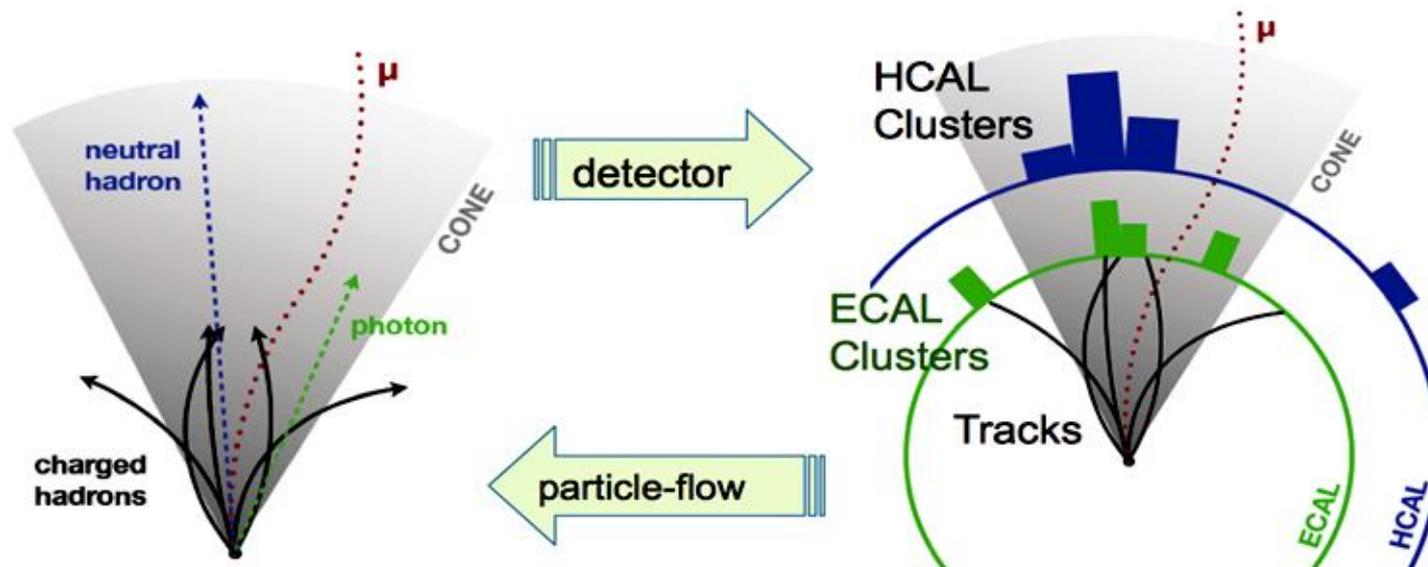
- Trigger:
 - single or double (isolated) lepton
- Leptons:
 - e/μ , $p_T > 20/30$ GeV, $|\eta| < 2.5$
 - Identification/reconstruction
 - Tracker/calorimeter isolation



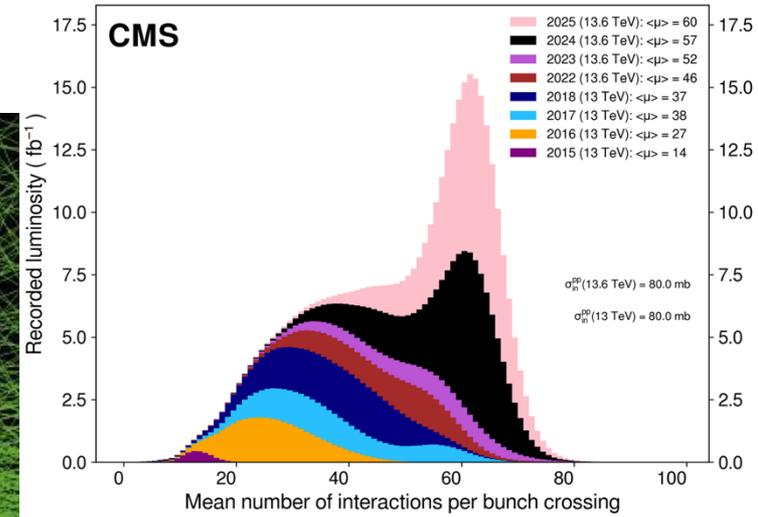
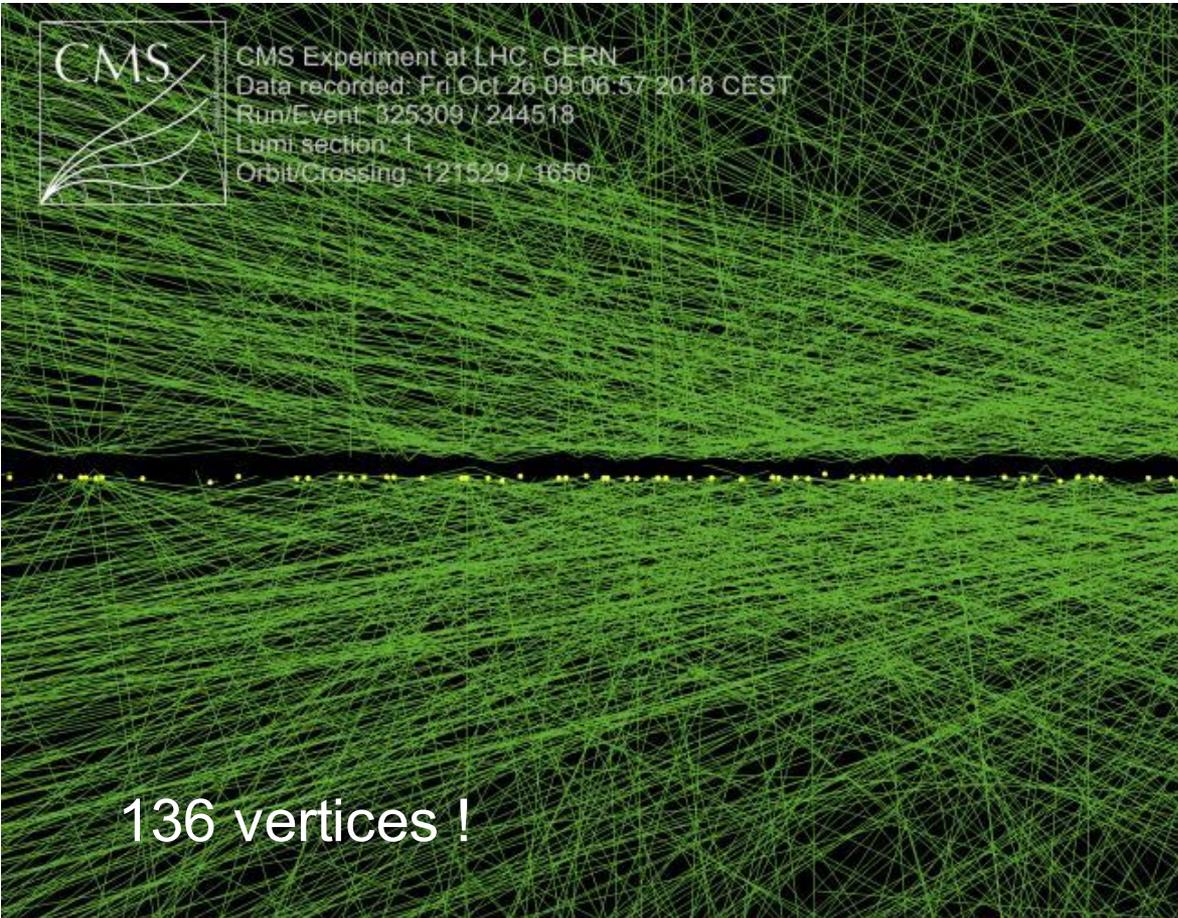
- Jets:
 - at least 2 jets, $p_T > 30$ GeV, $|\eta| < 2.5$
 - anti-kT algorithm, with cone 0.4-0.5
 - b-tagging is optional
- Missing transverse energy:
 - Typically require 30-40 GeV

Particle Flow event reconstruction

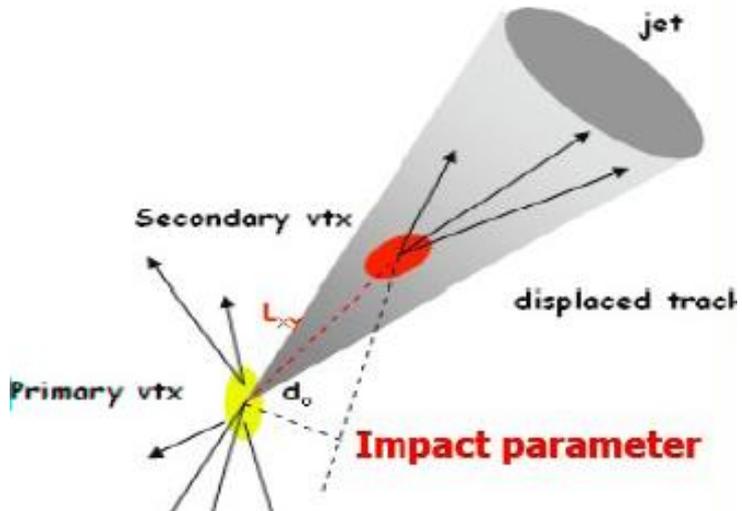
- Particle Flow (PF) combines information from all subdetectors to reconstruct particles produced in the collision
 - charged hadrons, neutral hadrons, photons, muons, electrons
 - use complementary info. from separate detectors to improve performance
 - tracks to improve calorimeter measurements
- From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



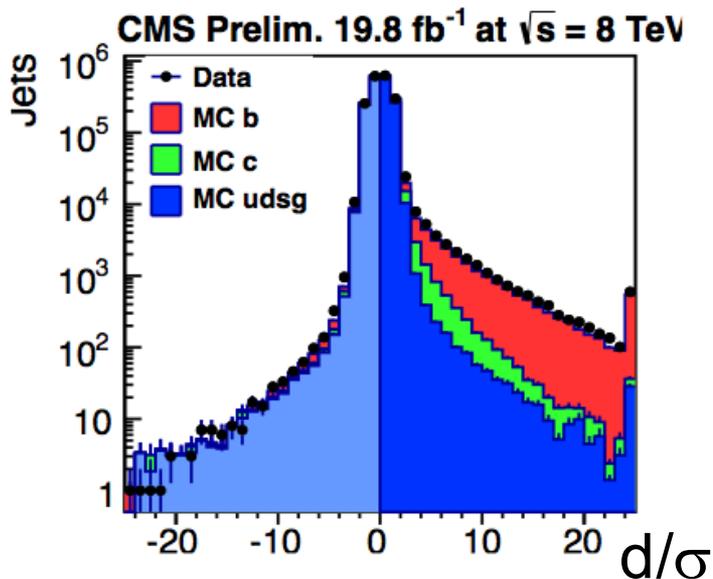
...in a challenging environment



Challenge: b-tagging

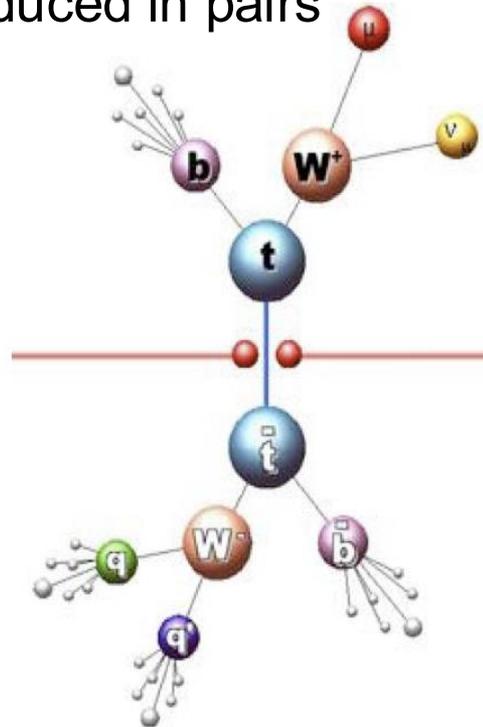


- Lifetime: $\tau_b \sim 1\text{-}2$ psec
- Reduction of background obtained by identifying jets from b-quarks
- Two methods:
 - Secondary vertex tagging
 - Semileptonic decays of b-hadrons in jets ($b \rightarrow l \nu_l X$)

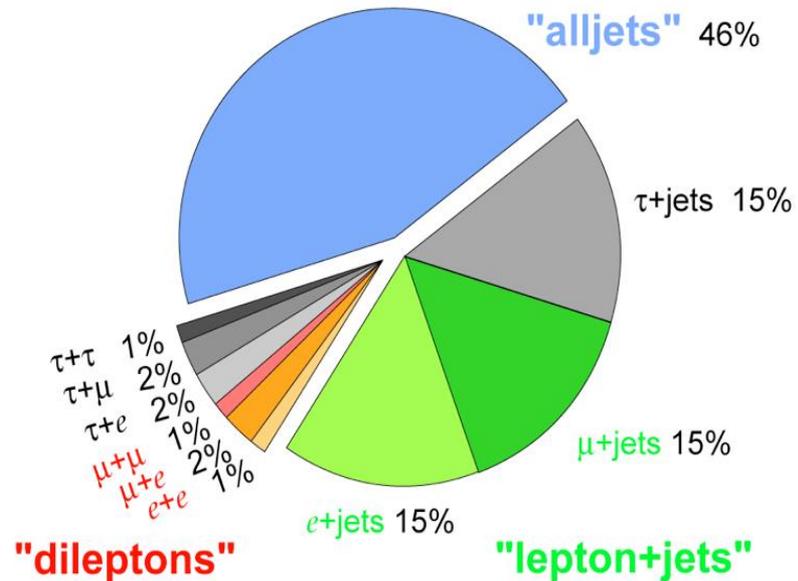


Top quark decays

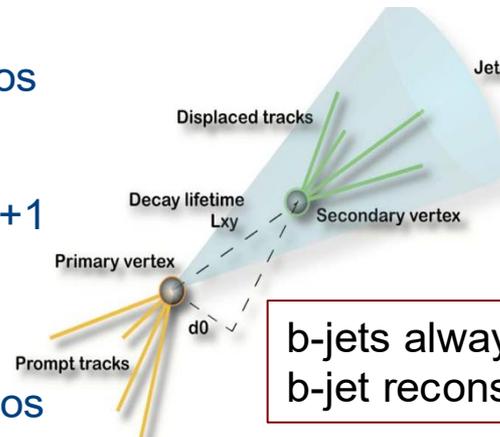
Top quarks (mostly) produced in pairs



Top Pair Branching Fractions

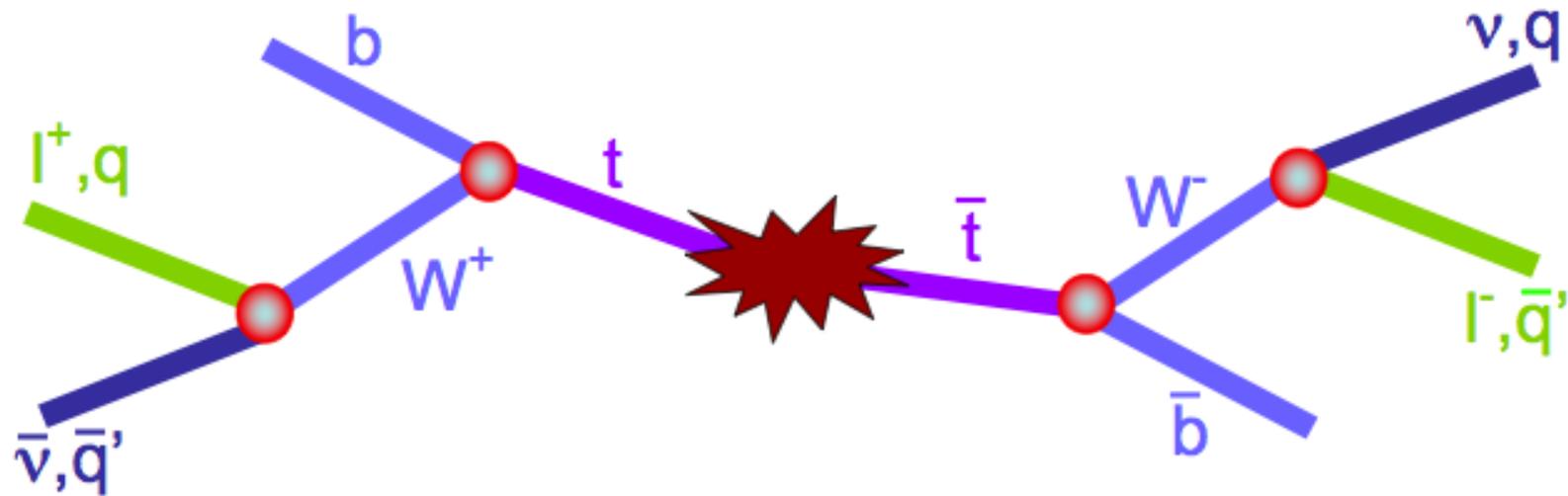


- **Dilepton ($ee, \mu\mu, e\mu$):**
 - BR~5%, 2 leptons+2 b-jets+2 neutrinos
- **Lepton (e or μ) + jets**
 - BR~30%, one lepton+4jets (2 from b)+1 neutrino
- **All hadronic**
 - BR~44%, 6 jets (2 from b), no neutrinos



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

Interesting physics with Top quark



PRODUCTION

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

PROPERTIES

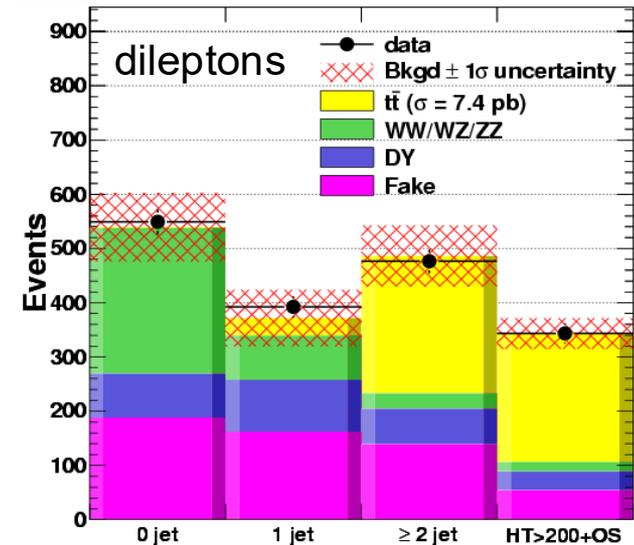
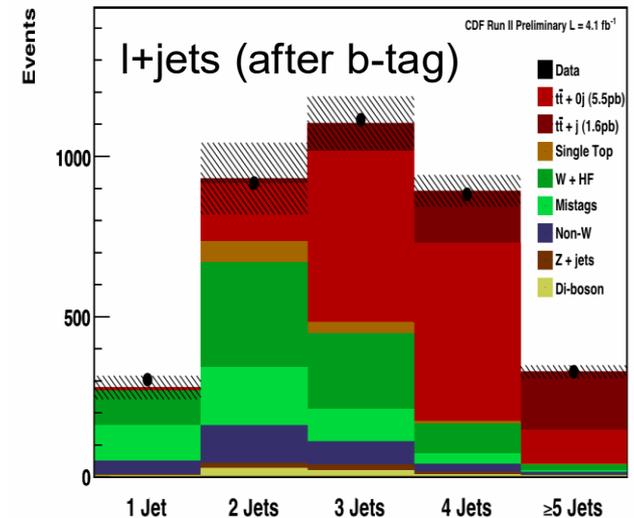
Mass
Kinematics
Charge
Lifetime and width
W helicity
Spin
...

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 $t\bar{t}$ 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



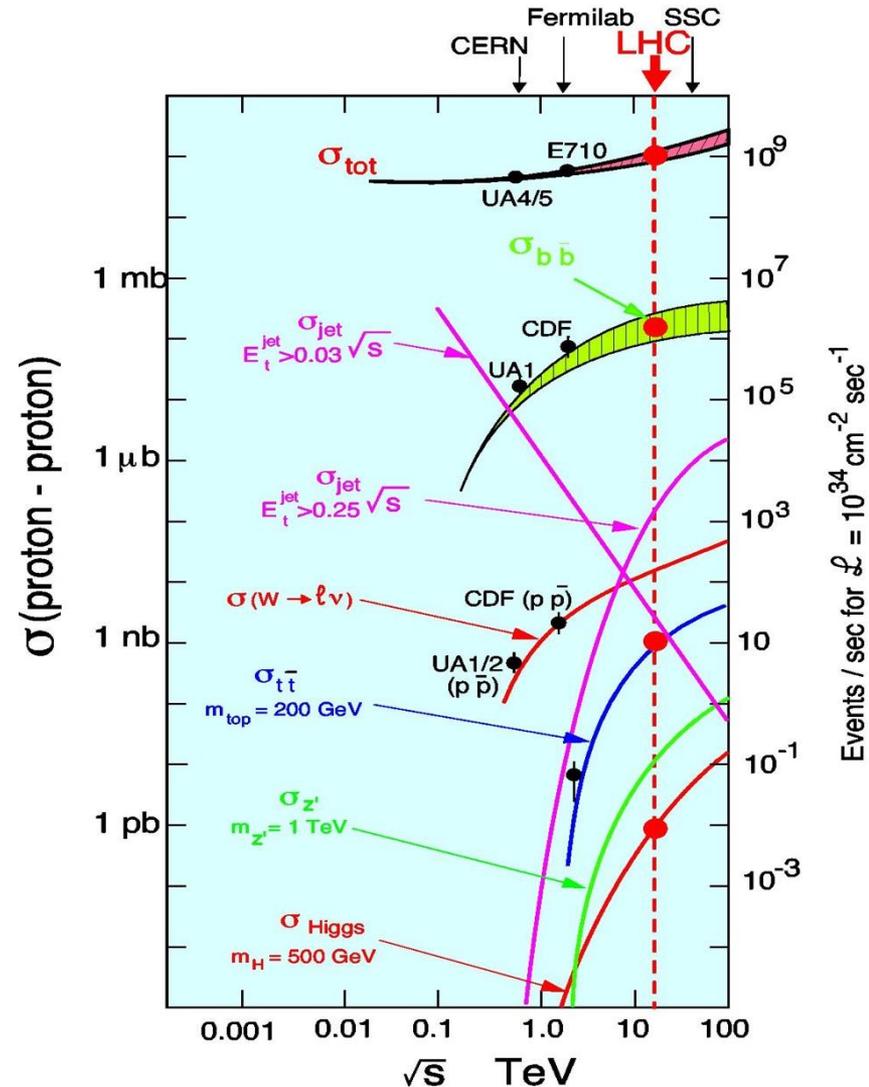
Theory cross sections: TeV vs LHC

Collider	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%)

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: N_{obs} is labeled 'Number of observed events', N_{bgd} is labeled 'Number of background events (from data, calculated from theory)', $\epsilon_{t\bar{t}}$ is labeled 'Acceptance (experimental: detector, efficiencies)', and $\int L dt$ is labeled 'Luminosity (determined by amount of data, accelerator, triggers, etc)'.

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

Number of observed events

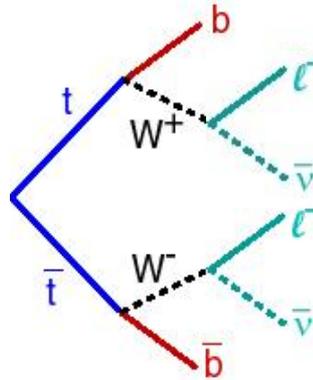
Number of background events
(from data, calculated from theory)

Acceptance
(experimental: detector, efficiencies)

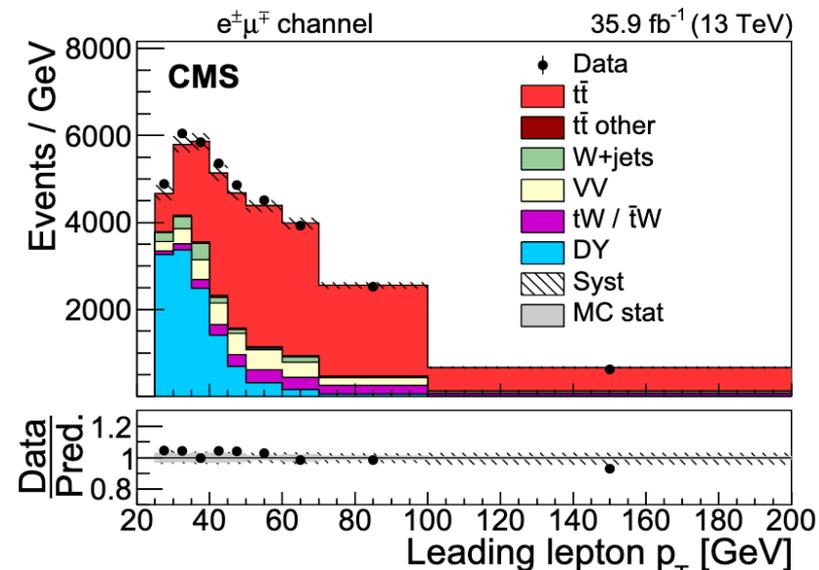
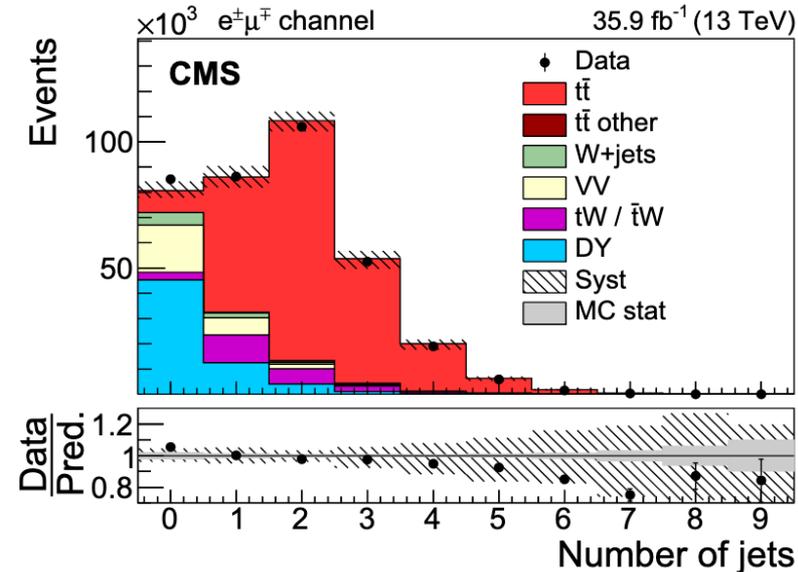
Luminosity
(determined by amount of data, accelerator, triggers, etc)

Dilepton channel

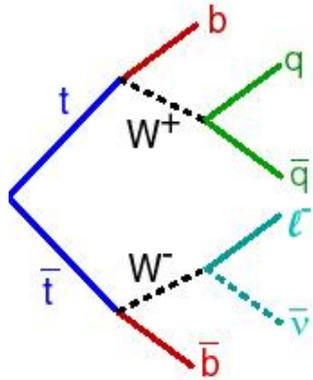
EPJC 79(2019)368



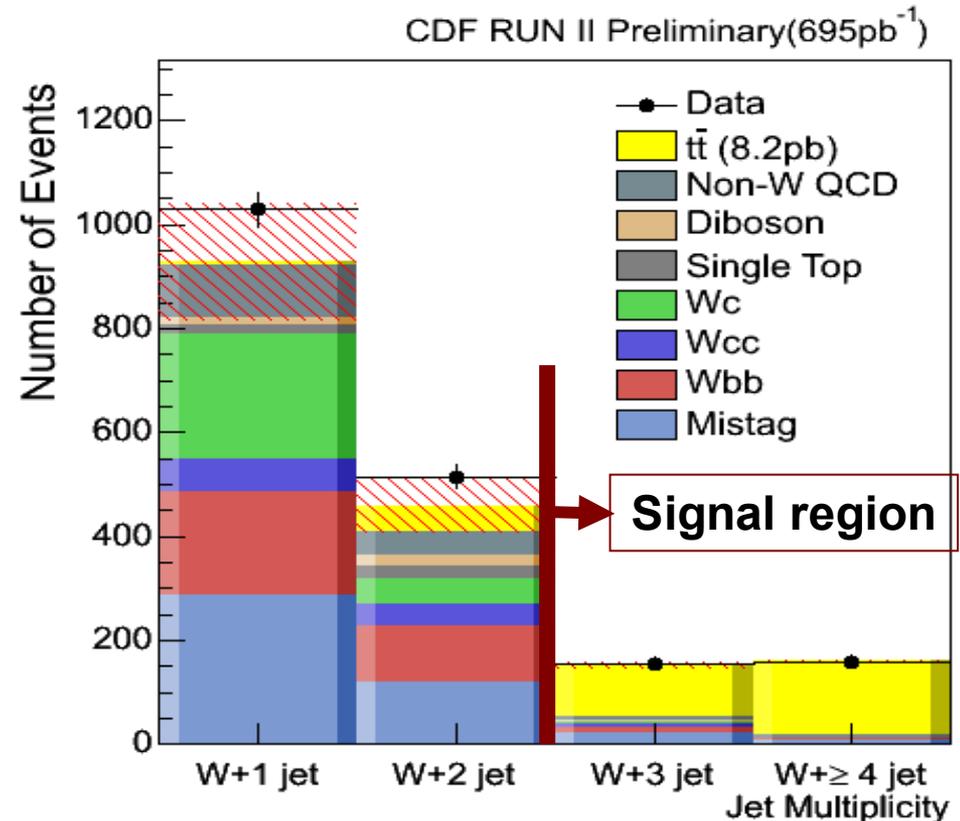
- Branching ratio (BR) $\sim 5\%$
- Background: **small**
- Clean final state
 - two leptons + ≥ 2 jets + MET
 - kinematic variables
- Signal visible w/without b-tagging
- Main systematics: JES, lepton ID, (pileup, b-tag, signal modeling)



Lepton + jets



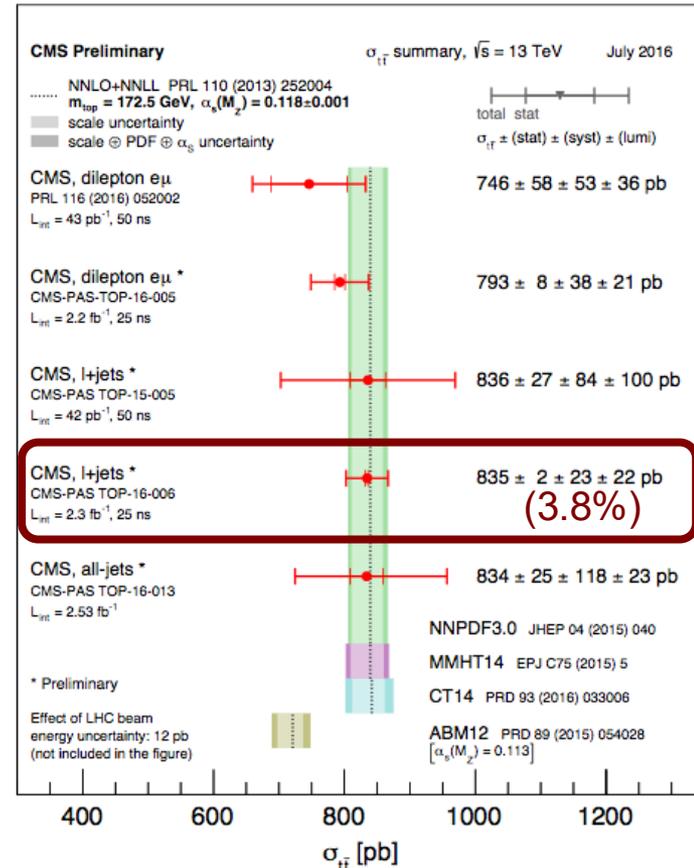
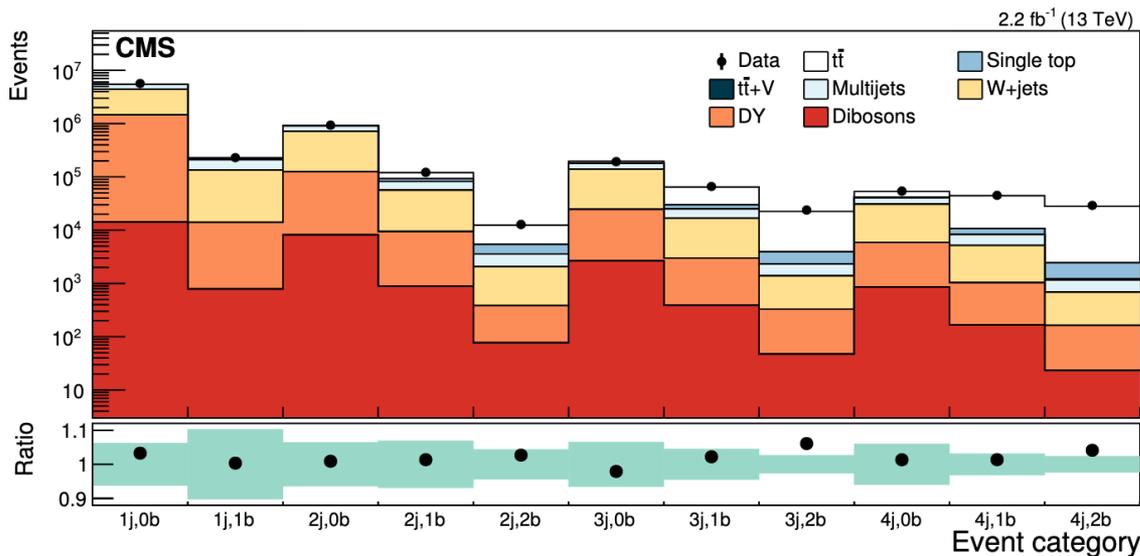
- BR $\sim 30\%$
- Background: moderate
- Selection:
 - one lepton + ≥ 3 jets + MET
 - may require b-tag
- Main backgrounds:
 - hadronic multi-jet, W+jets



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



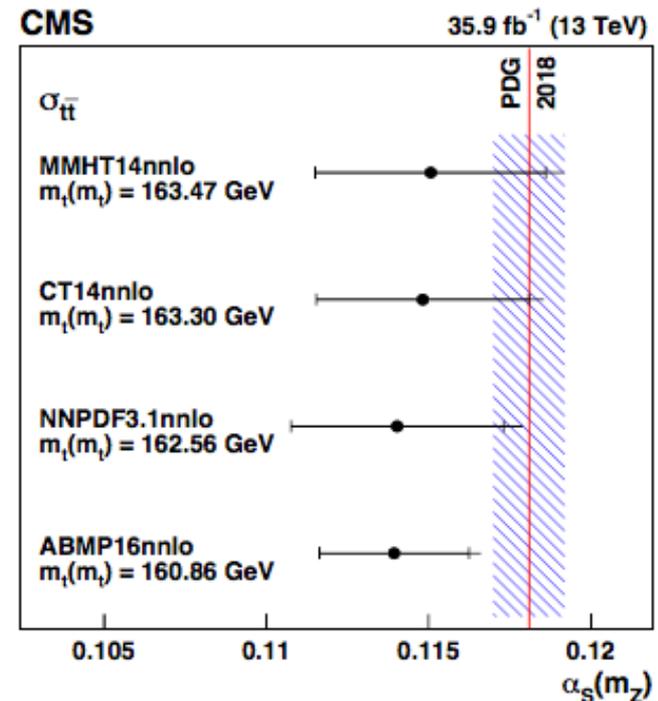
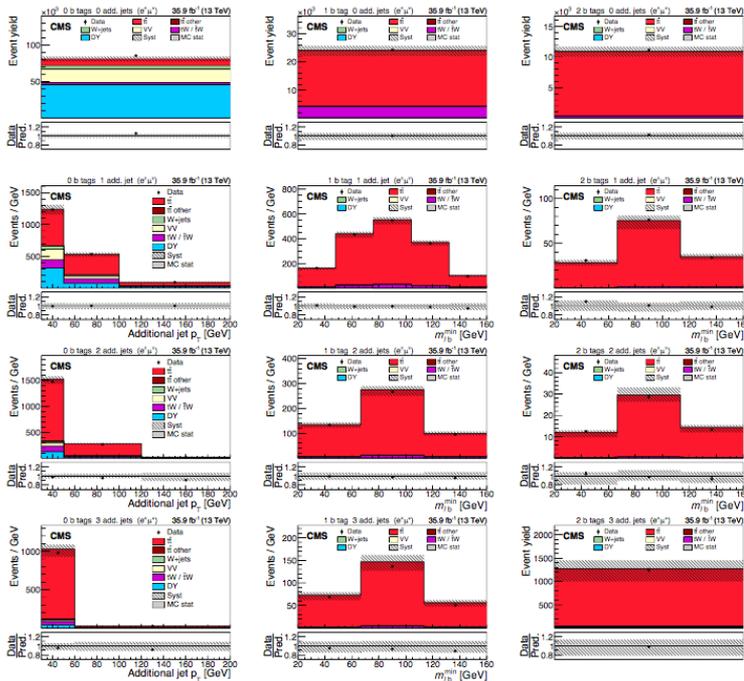
Cross section: multi-dimensional fit

- 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%)

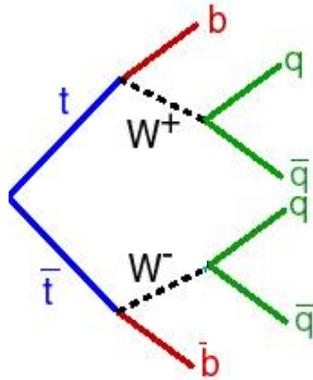
$$\sigma_{t\bar{t}} = 803 \pm 2 (\text{stat}) \pm 25 (\text{syst}) \pm 20 (\text{lumi}) \text{ pb}$$

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

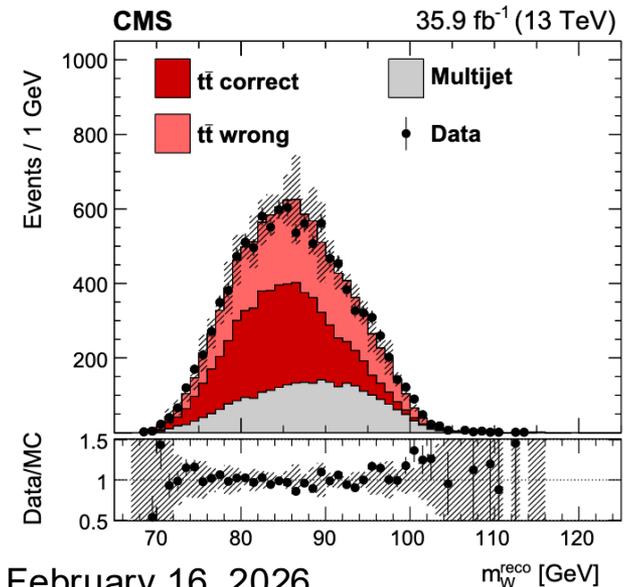
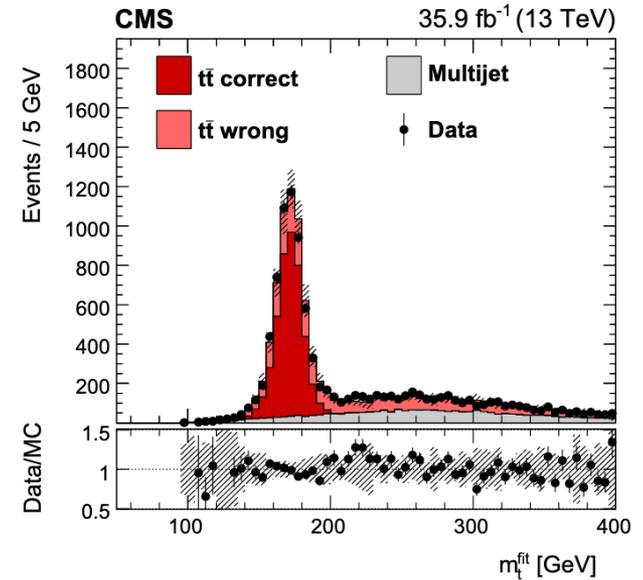


All hadronic

EPJC 79(2019)313

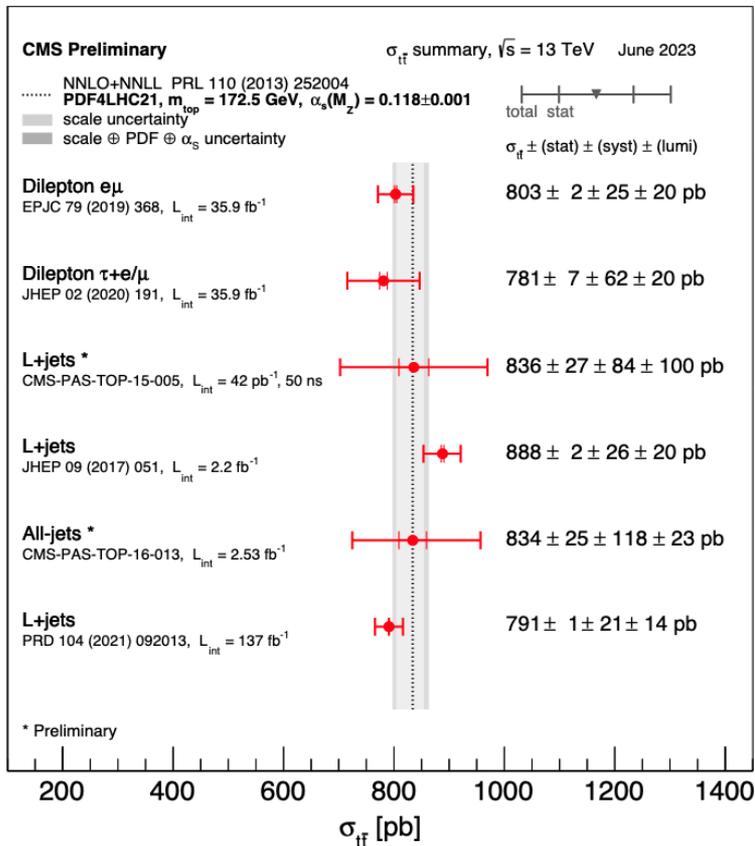


- BR $\sim 46\%$
- Background: large
- Selection:
 - ≥ 6 jets + kinematical selection
 - require 2 b-tags
- Main backgrounds:
 - hadronic multi-jet
 - same selection without b-tag



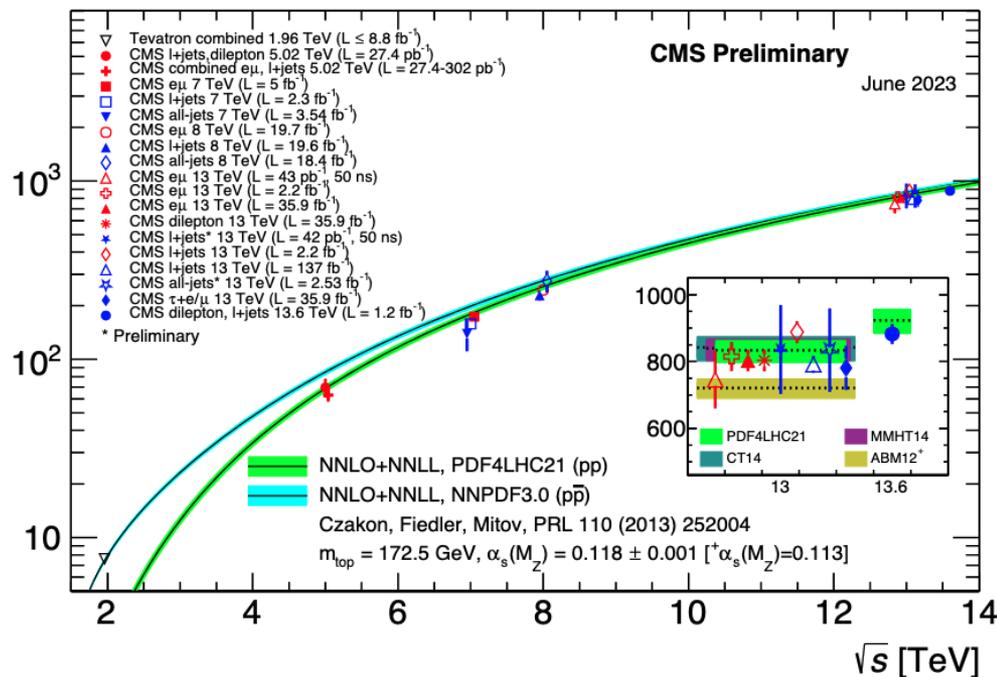
Cross sections

$\pm 4\%$



\Rightarrow measurements challenging theory

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



Collider	σ_{tot} [pb]	scales [pb]	pdf [pb]
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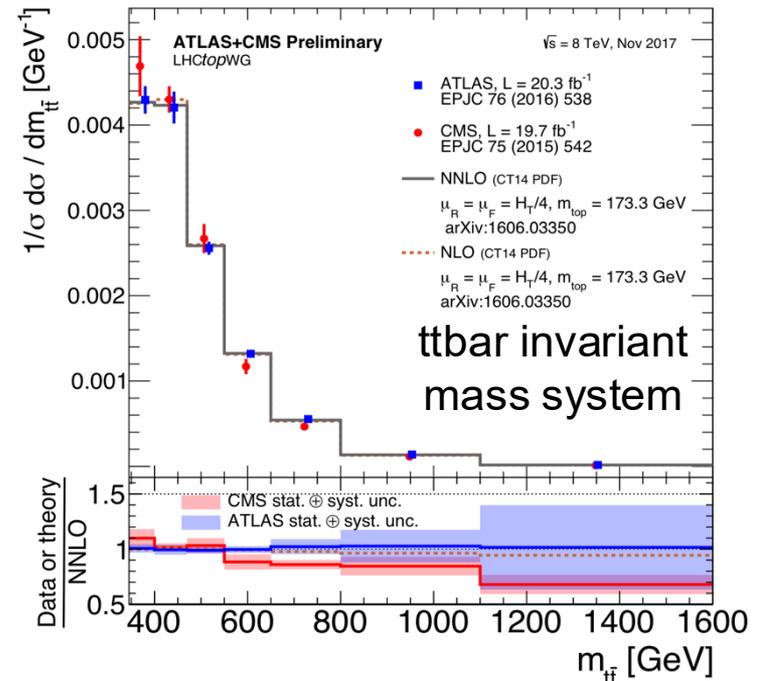
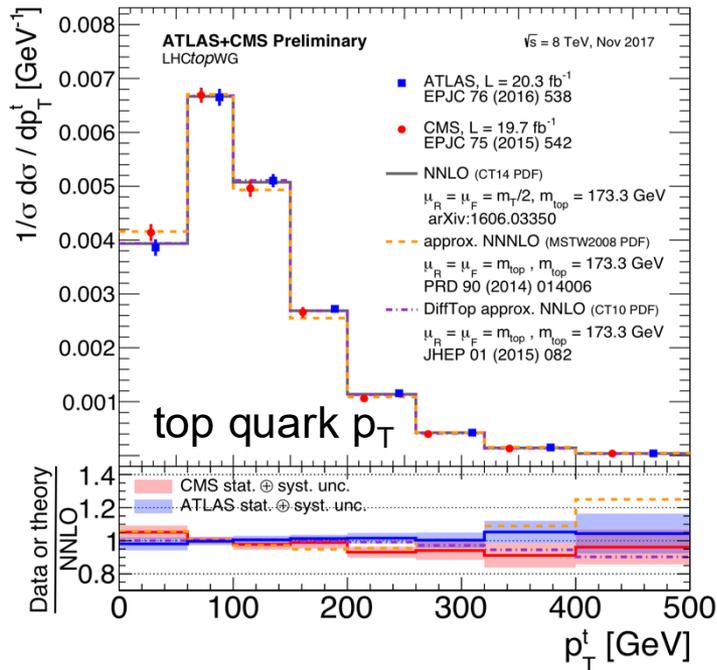
$\pm 3\text{-}5\%$

Differential cross section

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

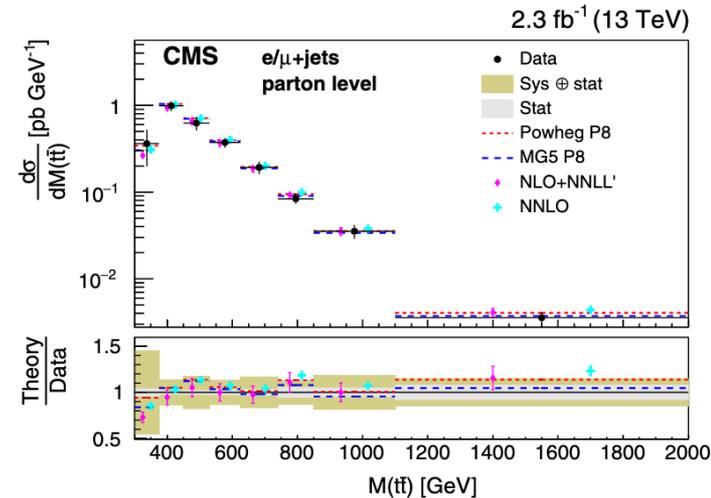
- Measure differential cross section
 - Test perturbative QCD
 - Test BSM scenarios (Z' decays, etc)
- Cross sections measured as a function of p_T , η , invariant mass of the final state leptons, top quarks, ttbar system, etc.
- Good agreement with expectations

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

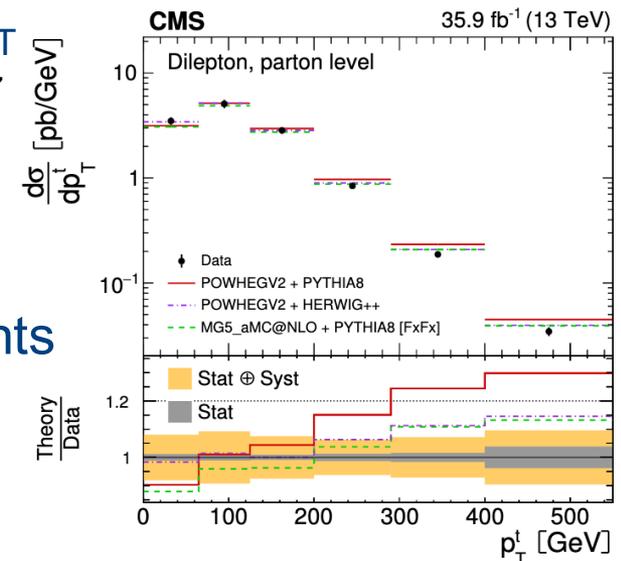


Differential cross section (cont.)

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



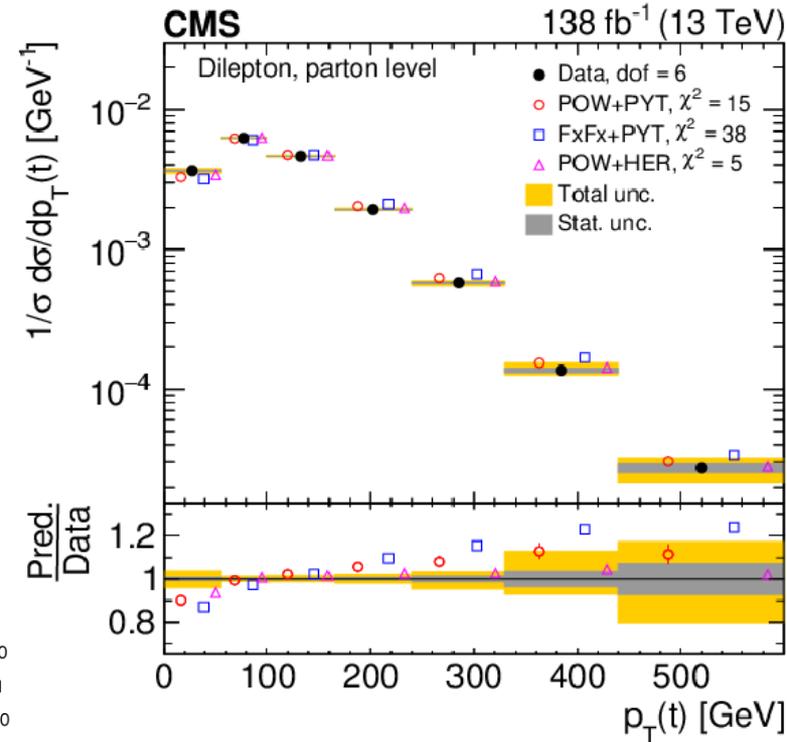
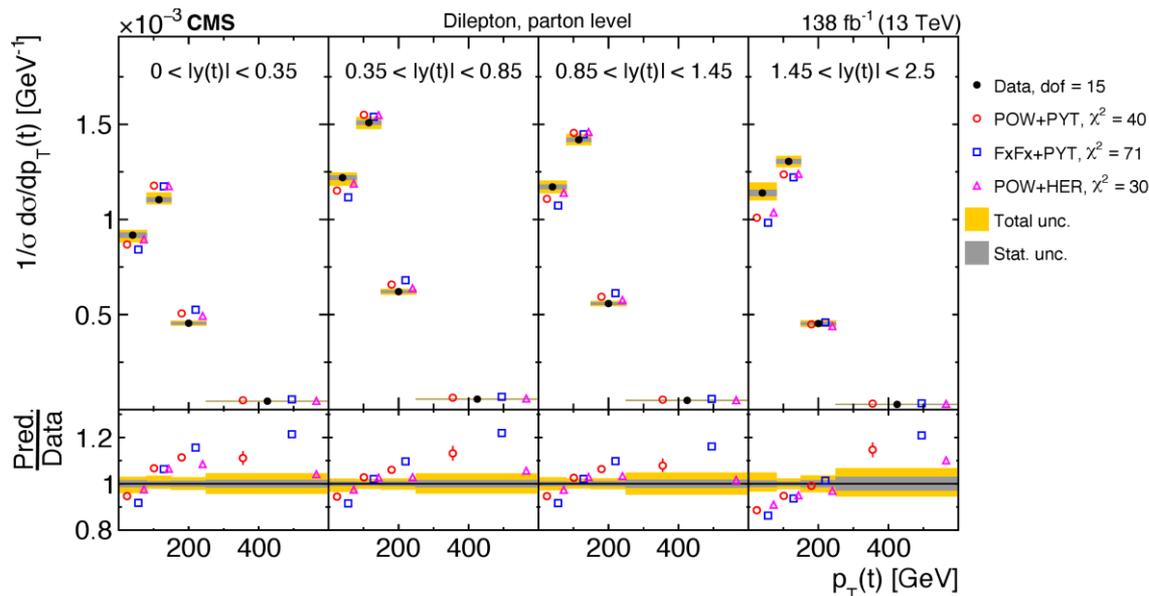
- Correct for detector effects and acceptances
- **Softer top p_T (CMS)**, agreement in ATLAS at high p_T
 - Due to momentum reshuffling, P.Nason, cern.ch/event/301787
 - FSR shower changes mass of final state partons. light partons can build sizeable mass, and t/tbar do not radiate
 - short term solution: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



Multi-differential cross section

arXiv:2402.08486

- Multi-differential cross section as a function of top and tbar 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”