

The Top quark

Michele Gallinaro

LIP Lisbon

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

Contents

- Introduction (discovery, object ID)
- Top pair production at the Tevatron
- Top pair production at LHC



today

will use $c=1$

- Properties: differential cross section
- Mass measurements
- Spin correlation, charge asymmetry
- Single top production
- Flavor Changing Neutral Currents (FCNC)
- Search for top partners and 4th generation quarks
- Search for $t\bar{t}$ resonances

Introduction

- Discovery
- introduction to the top quark

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

- Tau (τ) lepton in Mark I data (ν_τ from the decay kinematics)
- Discovery of the Y at Fermilab

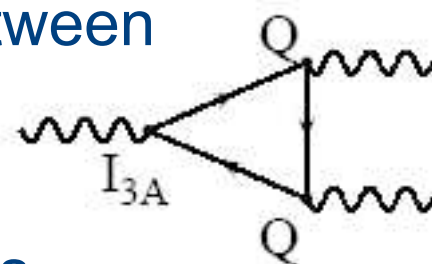
$$\begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} \\ b \end{pmatrix}$$

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

- 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

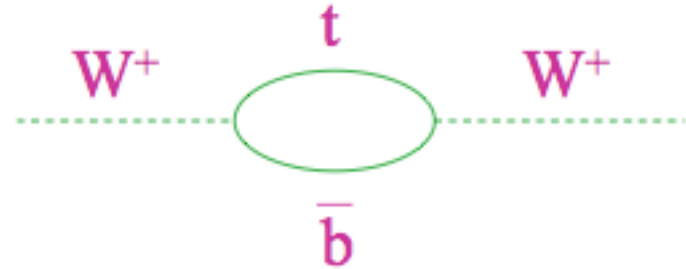
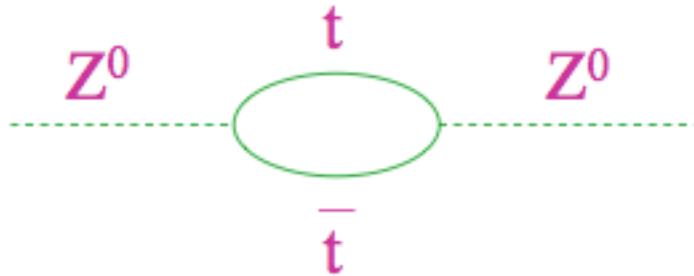
quark (up/down) charge

Searches in e^+e^- collisions

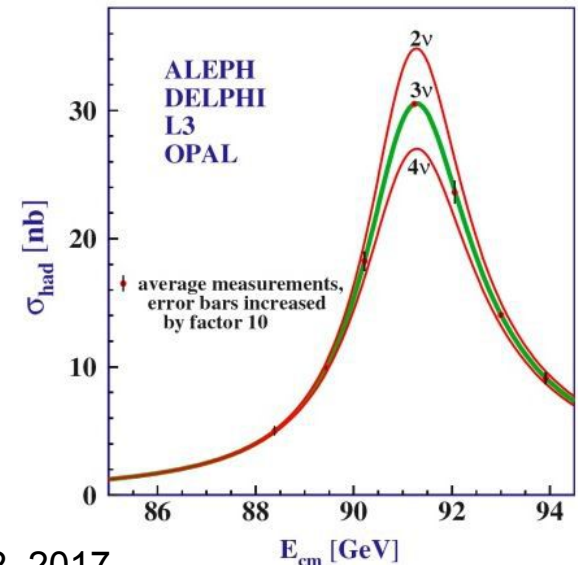
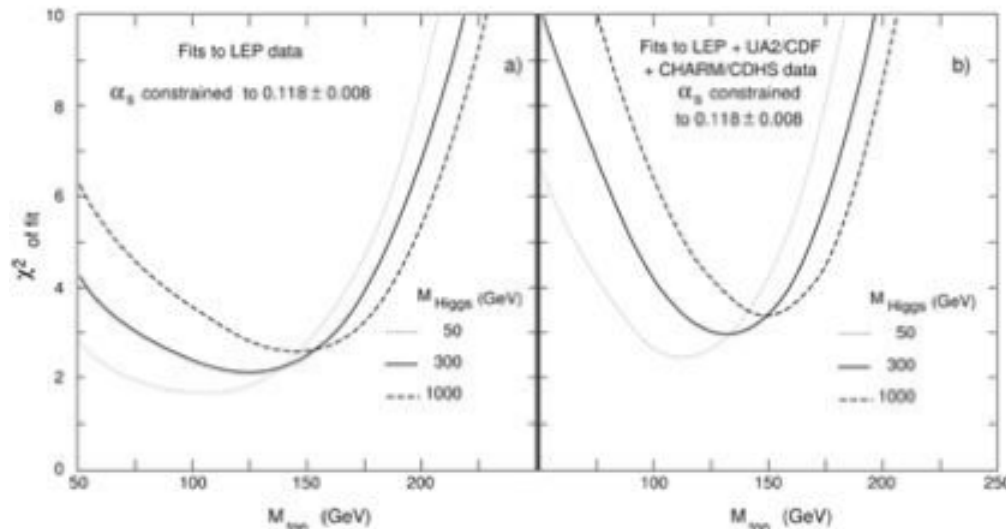
- PETRA could reach ~ 20 GeV (late '70s)
 - Search for narrow resonance
 - Look for increase in $R = (\# \text{ of hadron events}) / (\# \text{ of } \mu\mu \text{ events})$
 - Global event characteristics: look for spherical component
 - Negative results. Set limits: $M_t > 23$ GeV
- TRISTAN (~ 30 GeV) built to study the top quark (early '80s)
 - Similar search technique:
 - $M_t > 30$ GeV
- SLC/LEP
 - 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

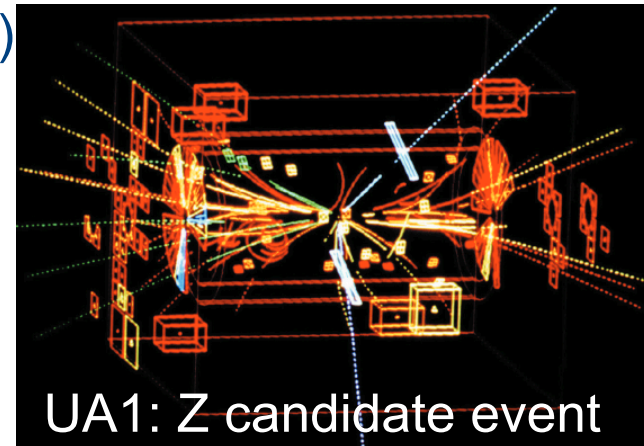
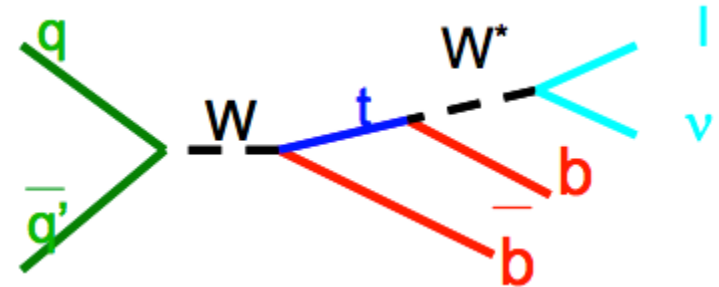
CERN Sp \bar{p} S ($\sqrt{s}=540$ GeV) built to observe W,Z

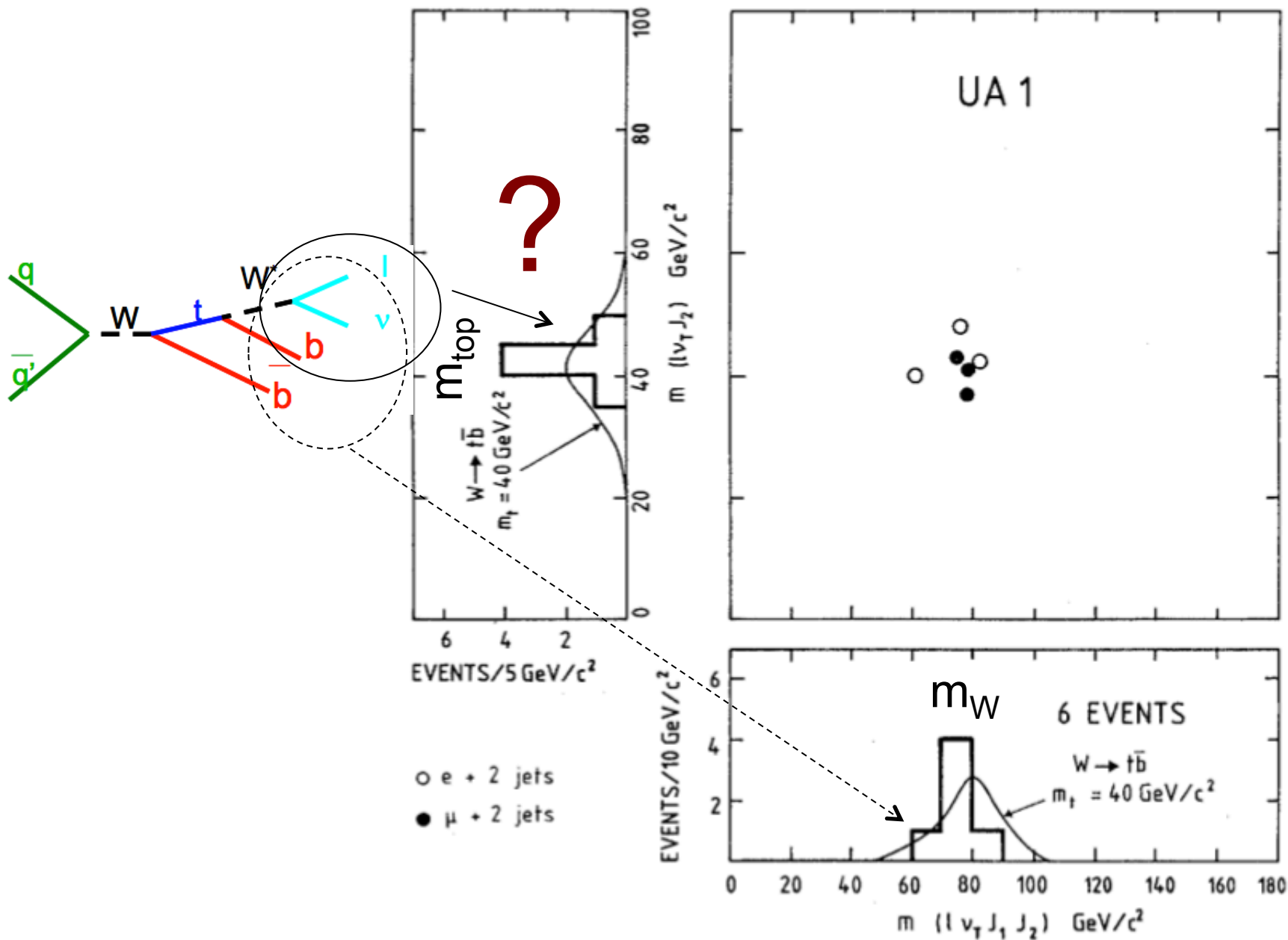
- Access to much higher energies
- Large backgrounds, low event rates
- Difficult reconstruction: jets

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...

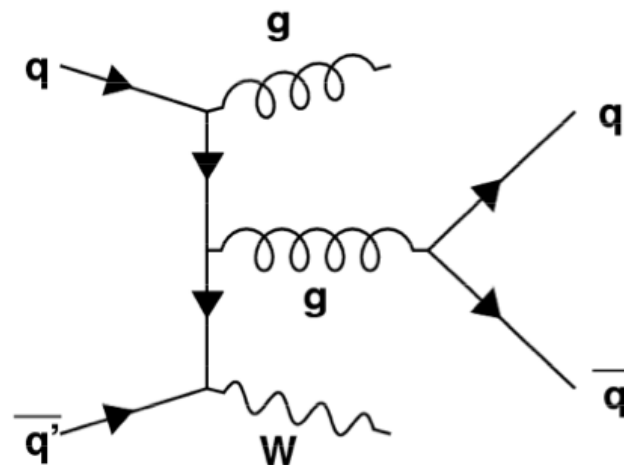
\Rightarrow W+jet background was underestimated





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 , $b\bar{b}/c\bar{c}$



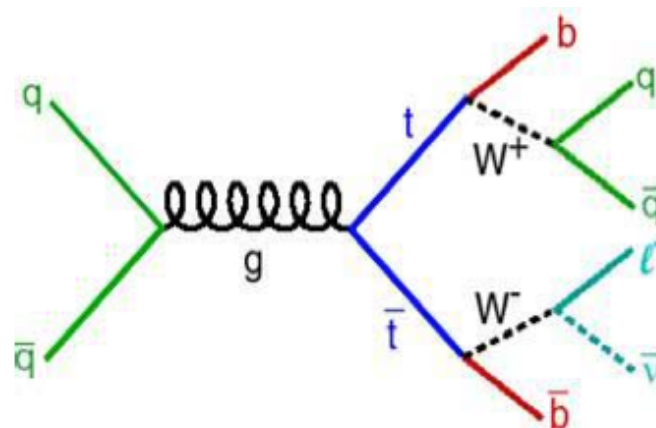
<u>channel</u>	<u>observed</u>	<u>expected background</u>
$\mu + \geq 2 \text{ jets}$	10 events	$11.5 \pm 1.5 \text{ events}$
$e + \geq 1 \text{ jets}$	26 events	$23.4 \pm 2.8 \text{ events}$
	(+ 23 expected if $M_{\text{top}} = 40 \text{ GeV}$)	

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

Fermilab joins the hunt

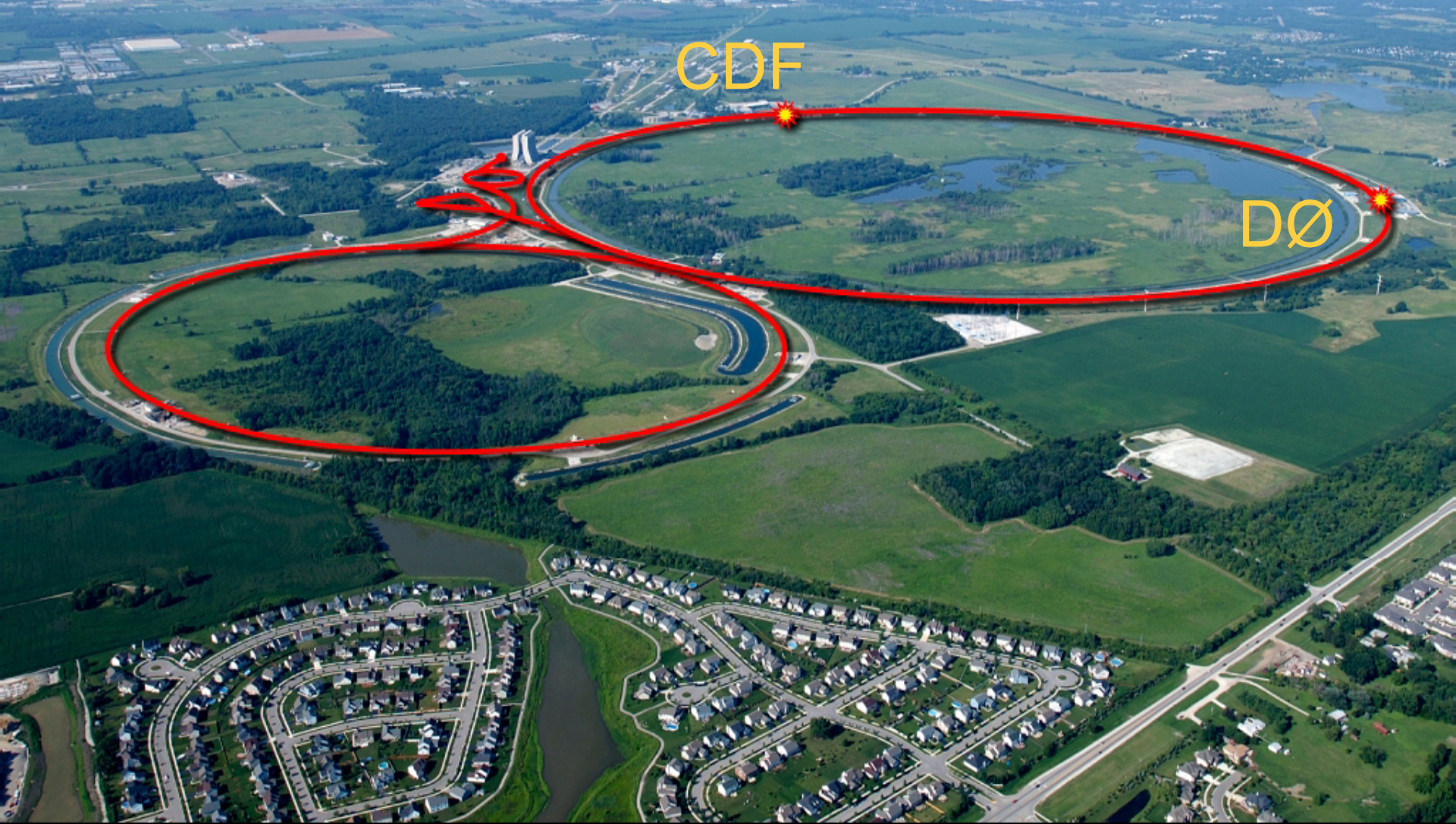
- 1988-89: at CERN, UA2 remains after the upgrades
- $\sqrt{1.8 \text{ TeV@Fermilab}}$ vs. $\sqrt{0.63 \text{ TeV@CERN}}$
- Much better reach for larger mass (only 75 GeV@UA2)
- At Tevatron, pair production dominates: $t\bar{t} \rightarrow Wb W\bar{b}$

%	$e\nu$	$\mu\nu$	$\tau\nu$	$q\bar{q}$
$e\nu$	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



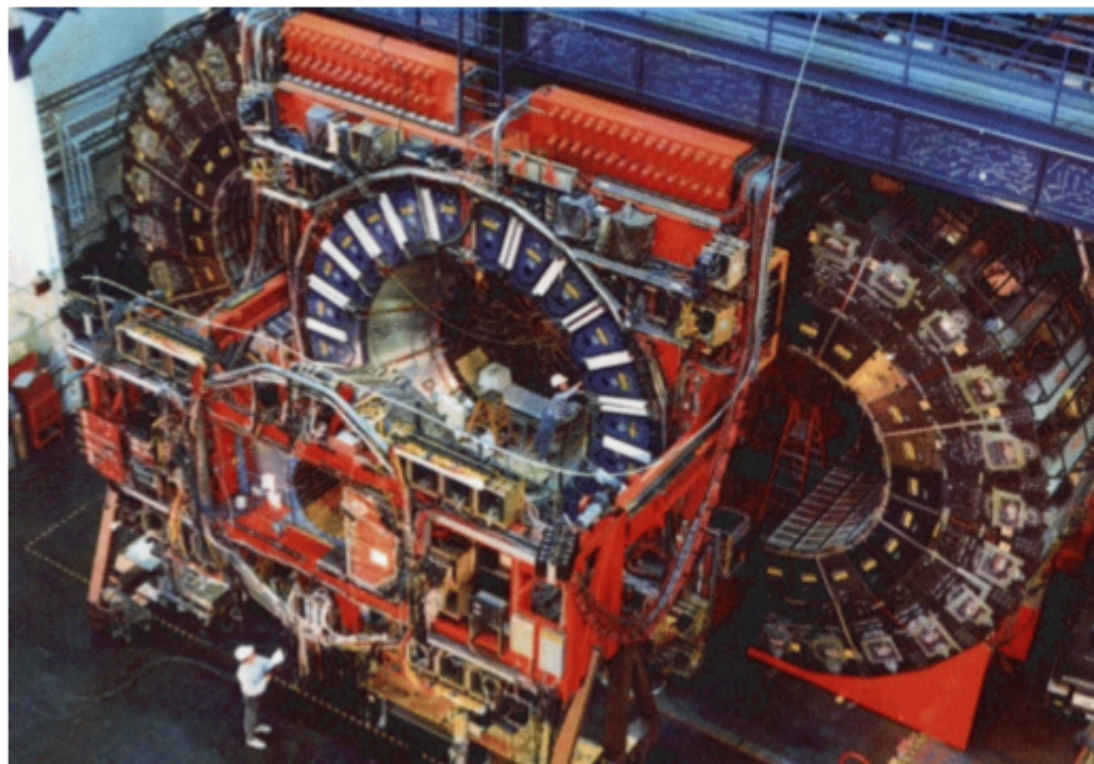
Tevatron

Proton-antiproton collision at 1.8-2.0 TeV





**12 countries, 62 institutions
767 physicists**

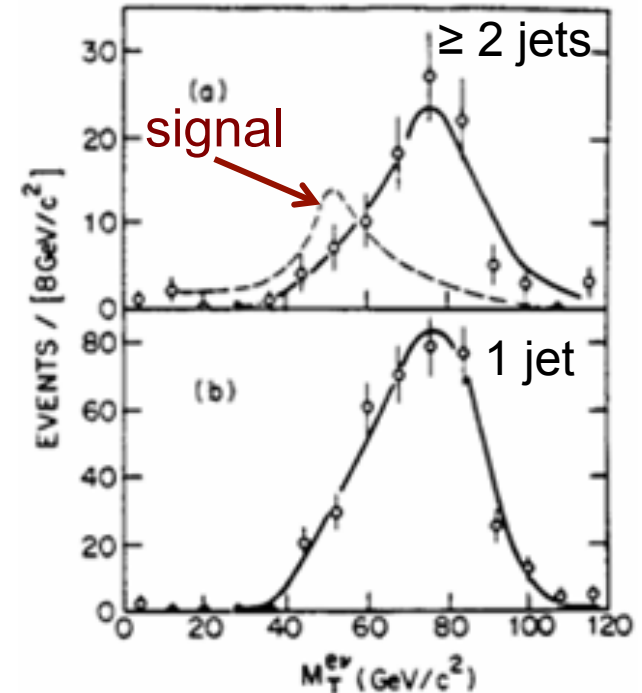


Searches at CDF

$e\nu + \geq 2$ jets

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

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



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

Searches at CDF (cont.)

$e\mu$ channel

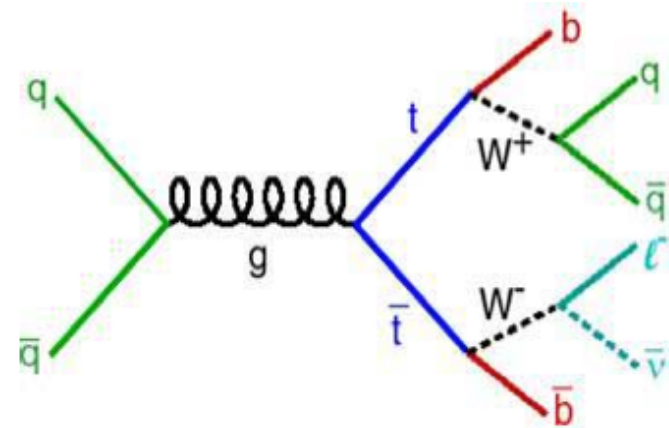
- Event rate much lower: $2 \times \text{BR}(W \rightarrow e\nu)$
- Background very small (no W +jets, no Drell-Yan)
- Dominant background is $Z \rightarrow \tau\tau \rightarrow e\mu X$ (expect 1 event)
- Observe 1 event

$\Rightarrow M_{\text{top}} > 72 \text{ GeV}$ (expect 7 events for $M_{\text{top}} = 70 \text{ GeV}$)

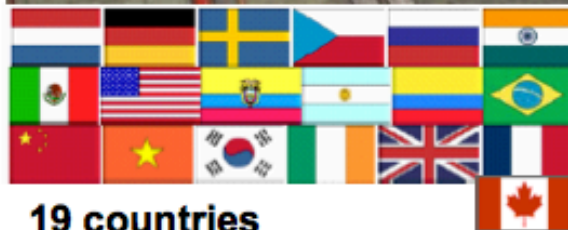
Change of strategy: $M_{\text{top}} > M_b + M_W$

- 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)

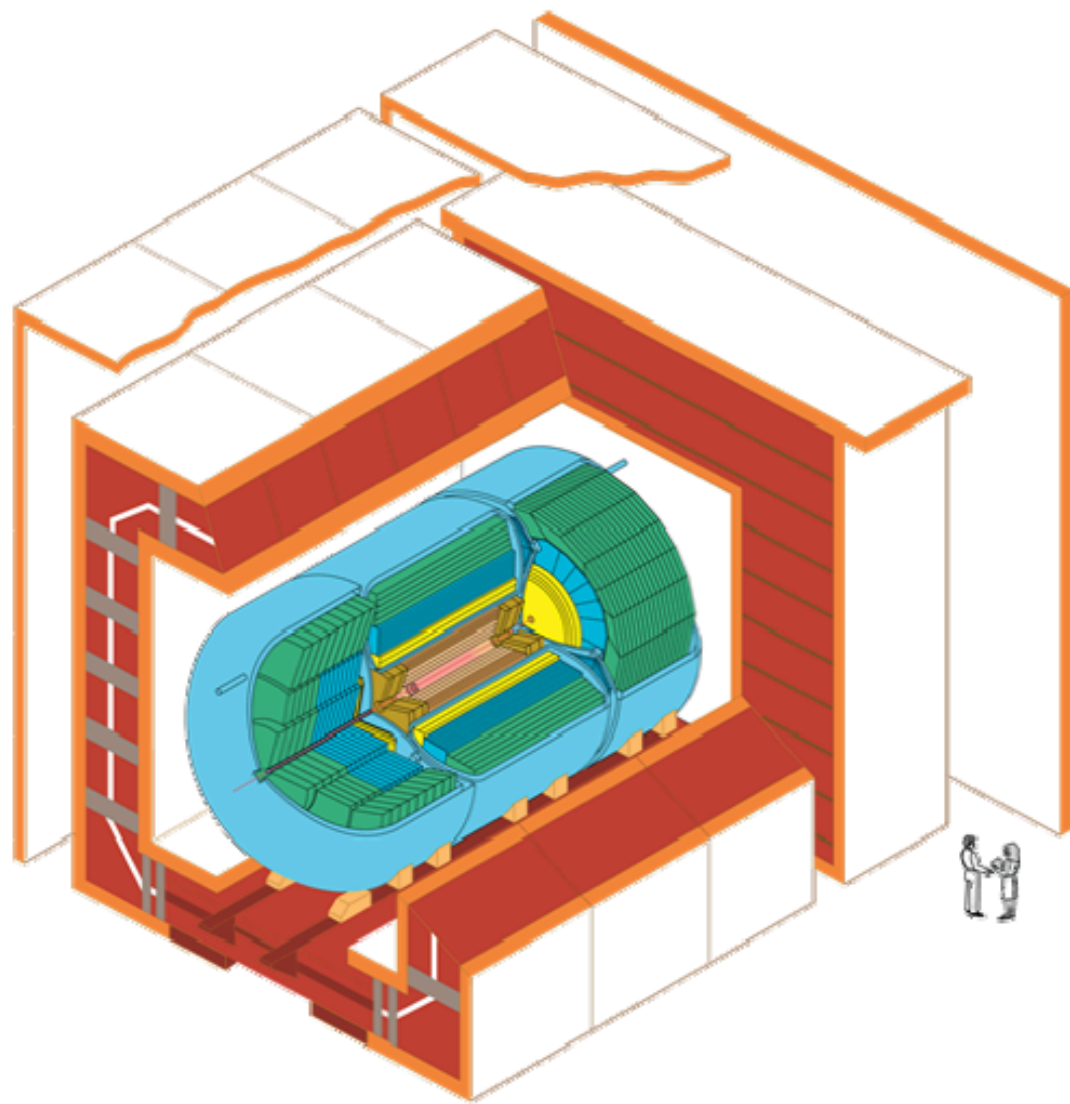
$\Rightarrow M_{\text{top}} > 91 \text{ GeV}$



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

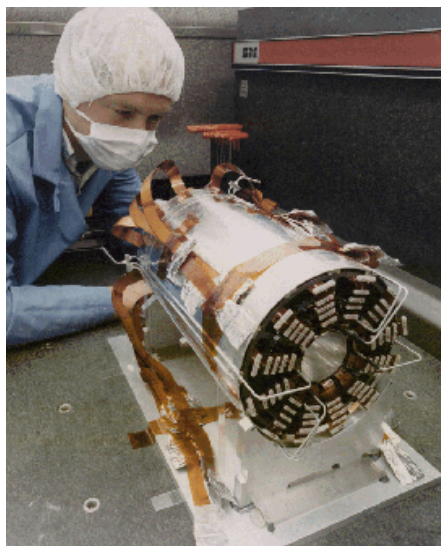
– $e\mu + \geq 1\text{jet} + \text{MET}$	1 evt	(1.1 bkg)
– $ee + \geq 1\text{jet} + \text{MET}$	1	(0.5)
– $e + \geq 4\text{jets} + \text{MET}$	1	(2.7)
– $\mu + \geq 4\text{jets} + \text{MET}$	0	(1.6)

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

Detecting the top quark at CDF

- Strategy

- dilepton: +2 jets
- single lepton: b-tagging
 - 1) soft e/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

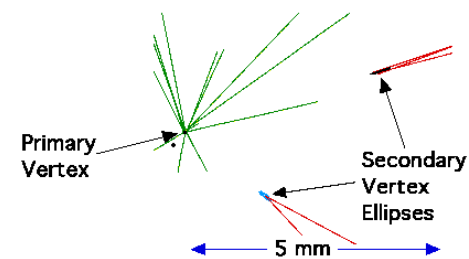
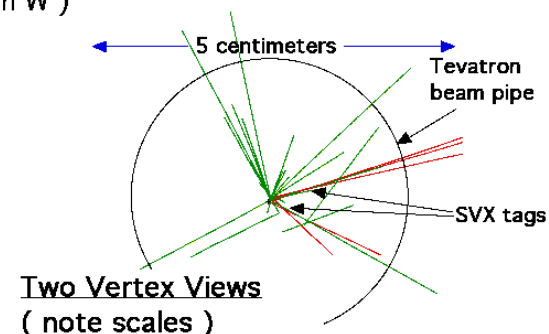
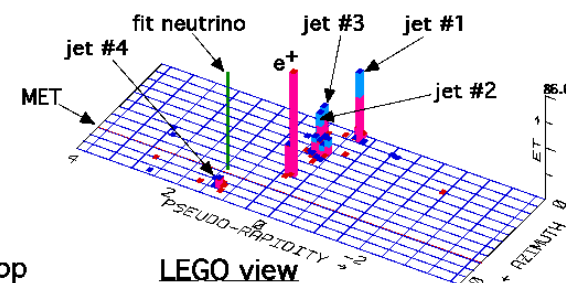
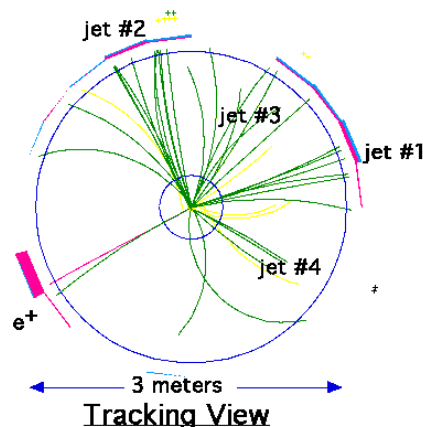
24-September, 1992

TWO jets tagged by SVX

fit top mass is 170 ± 10 GeV

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

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

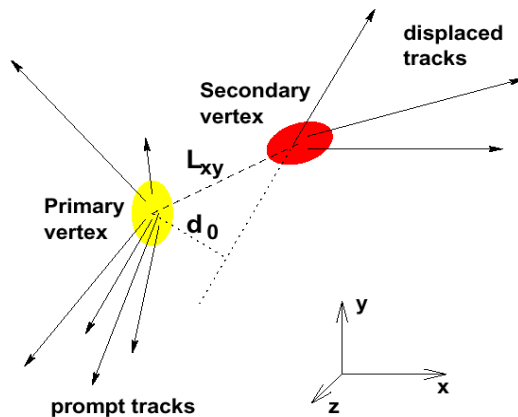


Tagging b-jets

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

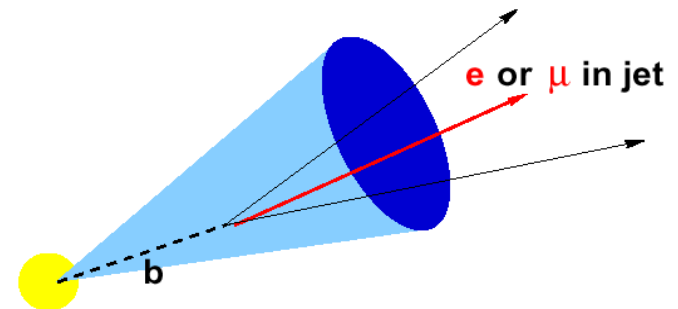
B hadrons are long-lived

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 ± 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

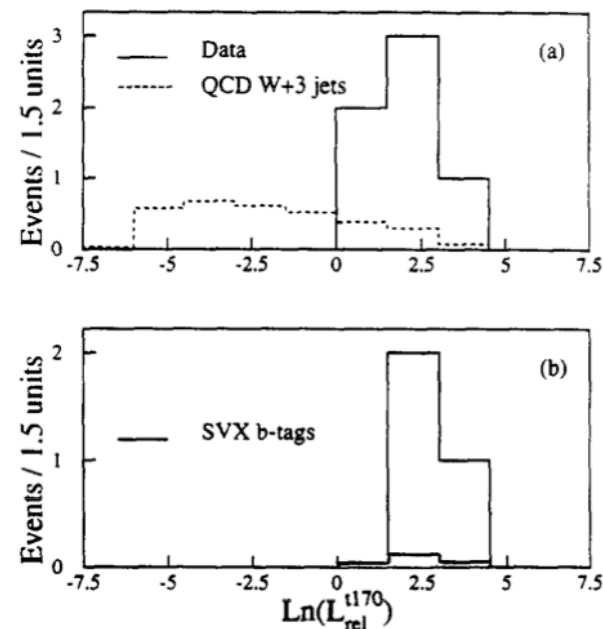
• There were also other analyses at CDF

- 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)

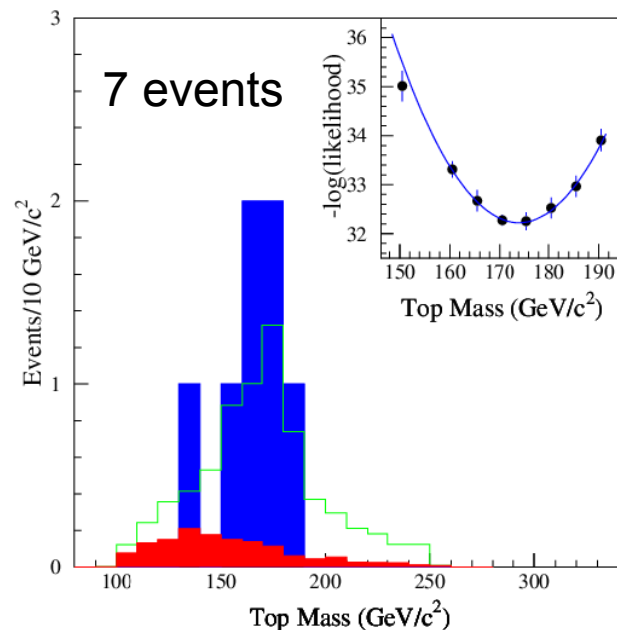
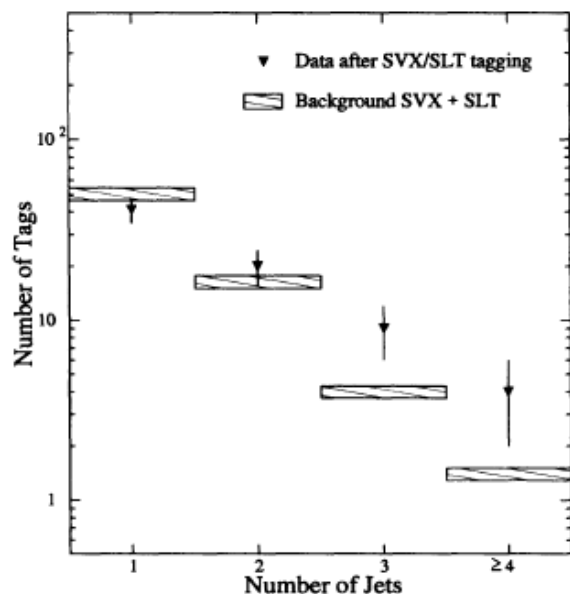
VOLUME 73, NUMBER 2

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



First measurements

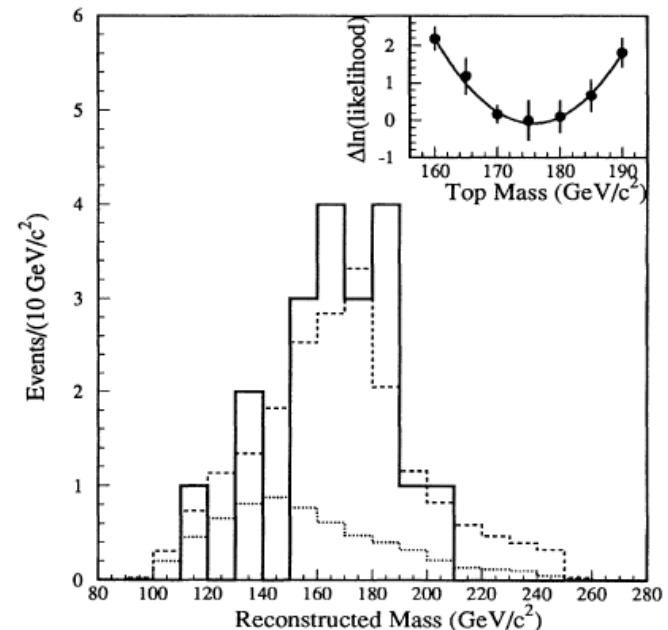
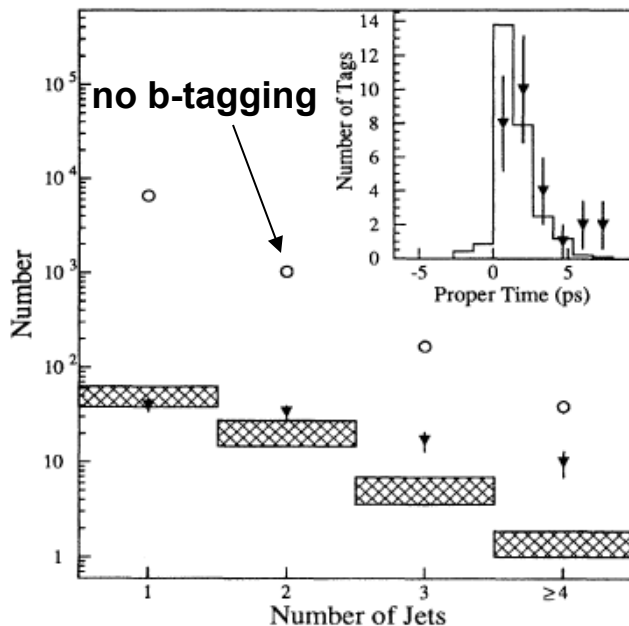
VOLUME 74, NUMBER 14

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



First measurements

VOLUME 74, NUMBER 14

PHYSICAL REVIEW LETTERS

3 APRIL 1995

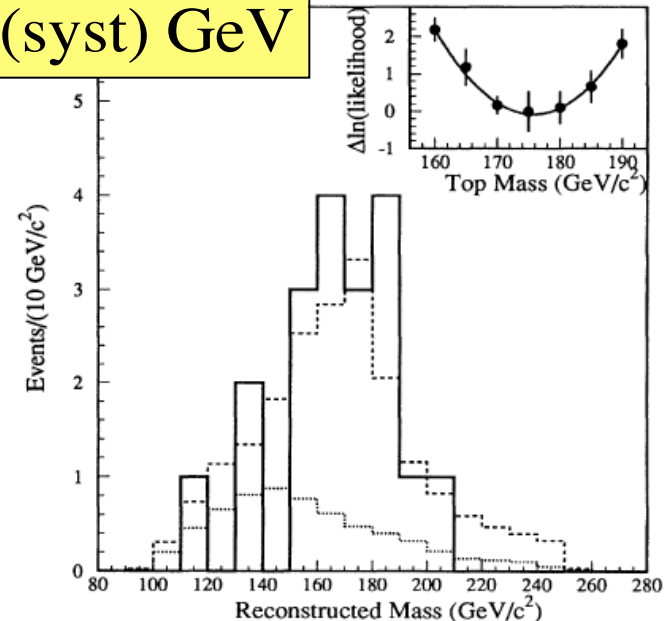
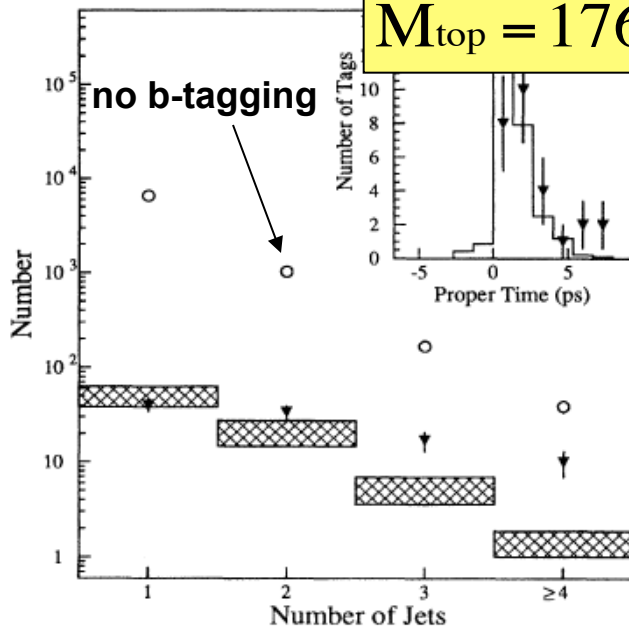
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$176 \pm 8(\text{stat}) \pm 10(\text{syst}) \text{ GeV}$

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

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



First measurements

VOLUME 74, NUMBER 14

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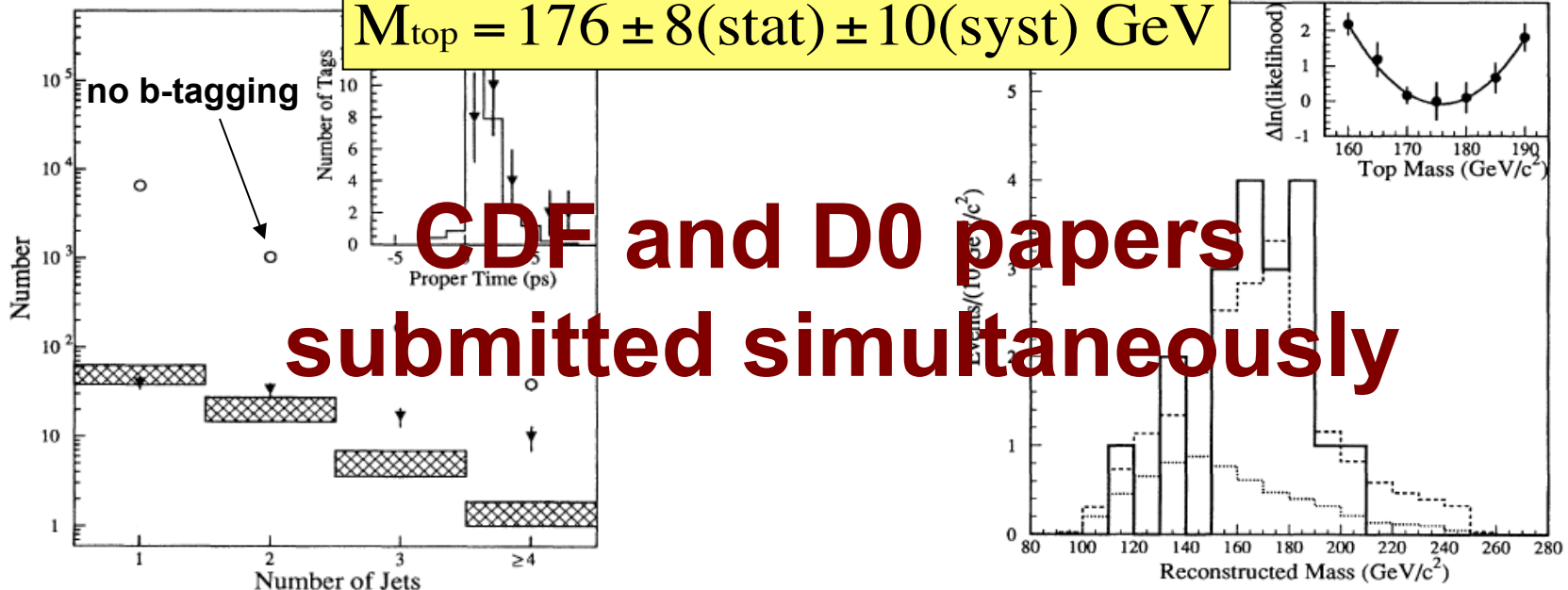
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$$\sigma_{t\bar{t}} = 6.8^{+3.6}_{-2.4} \text{ pb}$$

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



Top quark and its relevance

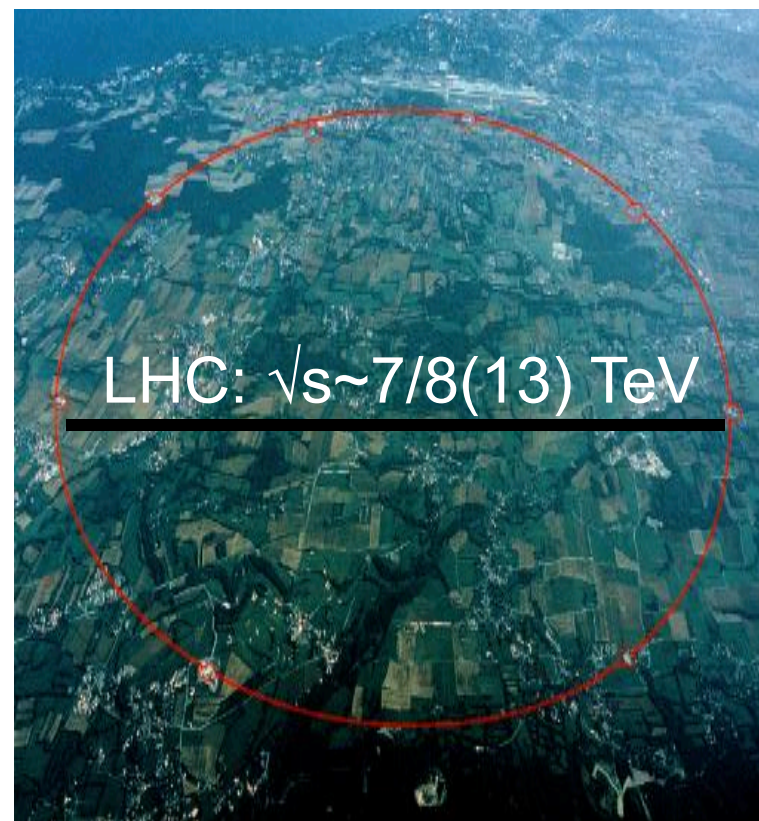
- Basics
- How to detect the top quark
- Tevatron vs LHC

Three generations of matter (fermions)

	I	II	III		
mass	2.4 MeV/c ²	1.27 GeV/c ²	171.2 GeV/c ²	0	? GeV/c ²
charge	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0	0
spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	0
name	u up	c charm	t top	γ photon	H Higgs boson
Quarks	4.8 MeV/c ²	104 MeV/c ²	4.2 GeV/c ²	0	
	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	0	
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
	d down	s strange	b bottom	g gluon	
Leptons	<2.2 eV/c ²	<0.17 MeV/c ²	<15.5 MeV/c ²	91.2 GeV/c ²	
	0	0	0	0	
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	Z⁰ Z boson	
	0.511 MeV/c ²	105.7 MeV/c ²	1.777 GeV/c ²	80.4 GeV/c ²	
	-1	-1	-1	± 1	
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
	e electron	μ muon	τ tau	W[±] W boson	
					Gauge bosons

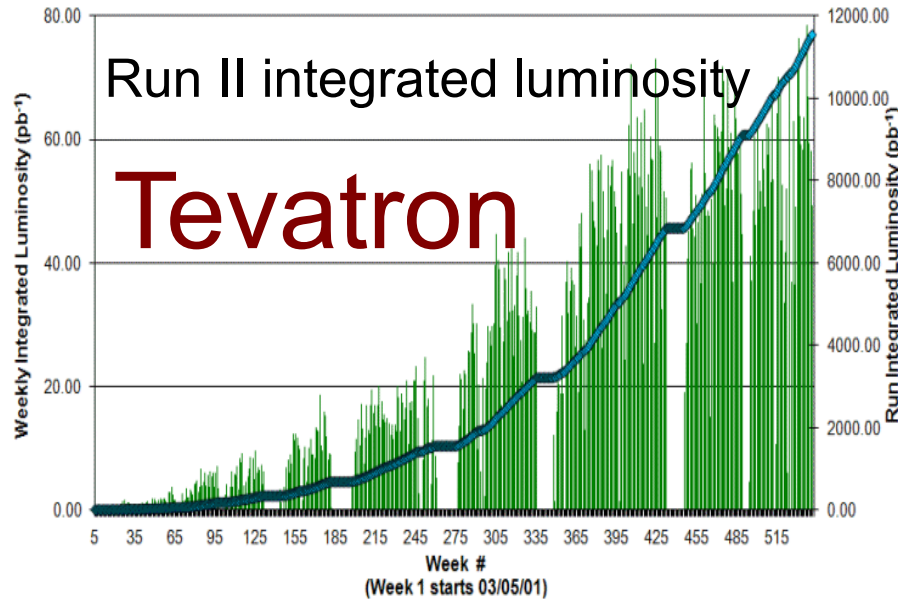
The Large Hadron Collider

- 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
 - $\sim 2 \text{ fb}^{-1}$ @ 13 TeV in 2015
 - $\sim 36 \text{ fb}^{-1}$ @ 13 TeV in 2016
- re-establish SM measurements
- access to new physics processes

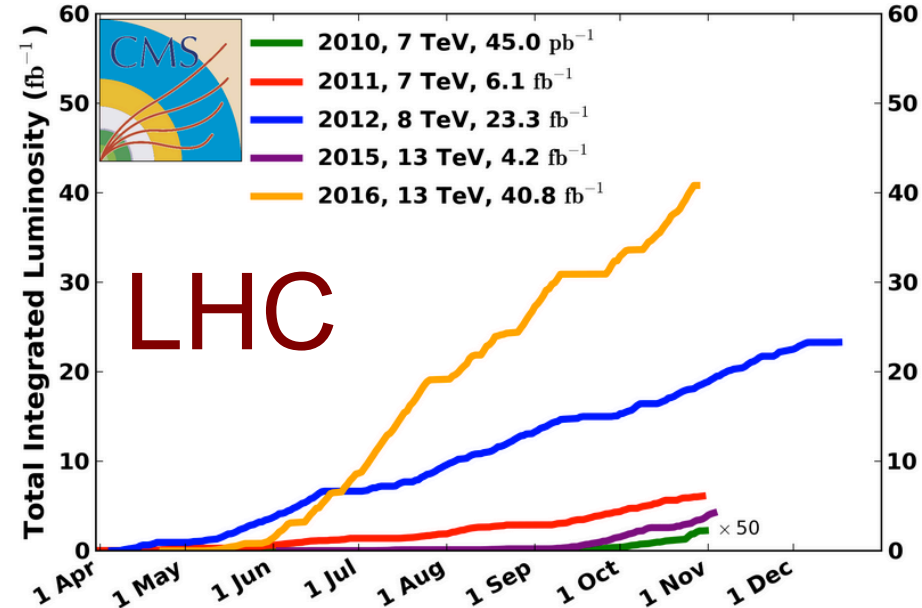


⇒ Top quarks give access to SM and BSM (?)

Tevatron vs LHC



Energy: 1.96 TeV
 Int. Luminosity: 12 fb^{-1}
 Age: ~25 years
 Events/exp (1 fb^{-1})
 400 ee $e\mu$, $\mu\mu$
 3.5k lepton + jets



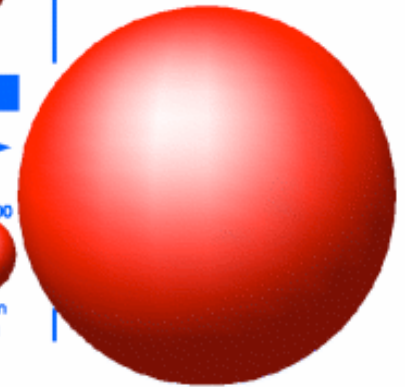
Energy: 7/8/(13) TeV
 Int. Luminosity: 5/20/(40) fb^{-1}
 Age: ~8 years
 Events/exp (1 fb^{-1})
 40k ee $e\mu$, $\mu\mu$
 350k lepton + jets

What is the Top quark?

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

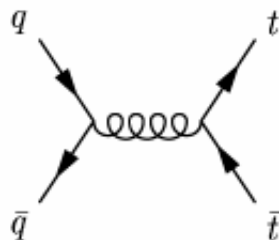
Leptons: $\begin{pmatrix} \nu_e \\ e \end{pmatrix}$ $\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}$ $\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$

LEPTONS		
Electron Neutrino Mass ~0	Muon Neutrino ~0	Tau Neutrino ~0
Electron .511	Muon 105.7	Tau 1 777
QUARKS		
Up Mass: 5	Charm 1 500	Top ~180 000
Down 6	Strange 160	Bottom 4 250

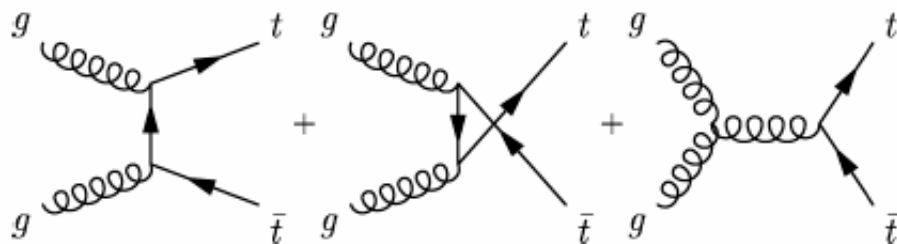


- It is the heaviest fundamental particle
 - $M_{\text{top}} = 174.3 \pm 0.6 \text{ GeV}$ (arXiv:1407.2682)
- Weak isospin partner of the b-quark
- Completes the SM of quarks and leptons

How is the top quark produced?



← Dominant at Tevatron



← Dominant at the LHC

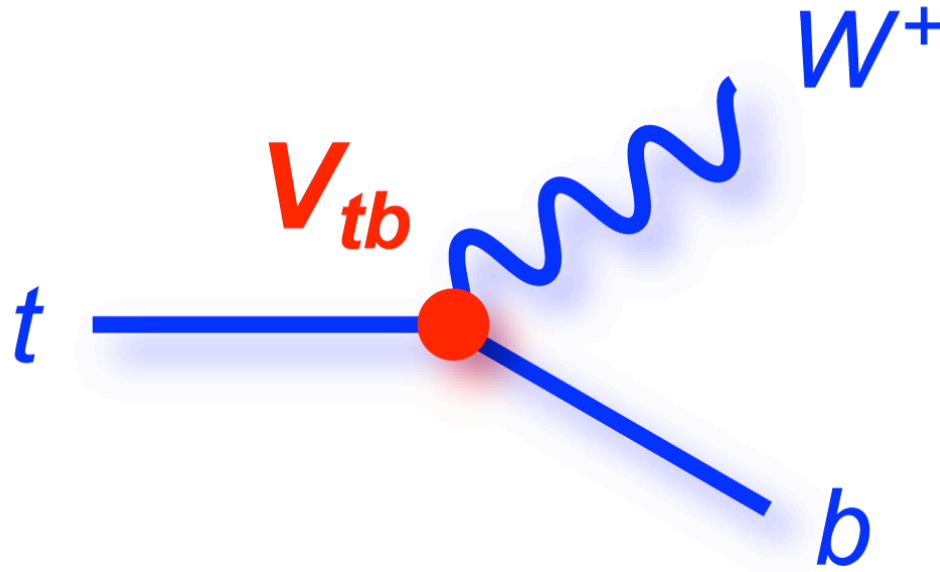
Predicted cross sections:

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

Czakon et al. PRL 110, 252004 (2013)

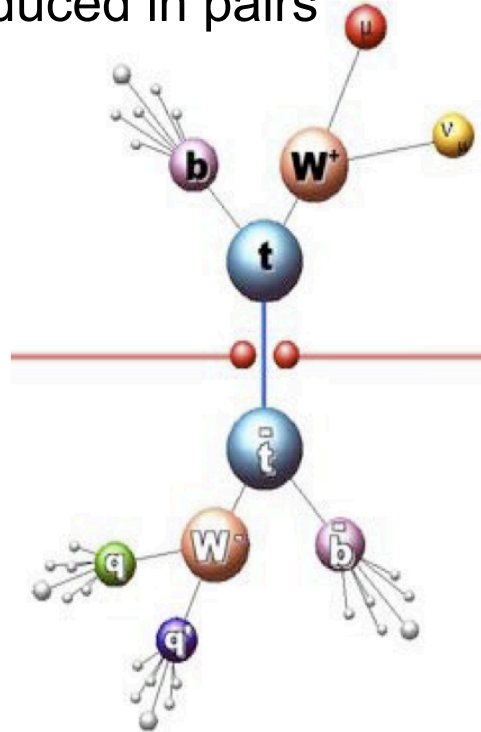
How does a top quark decay?



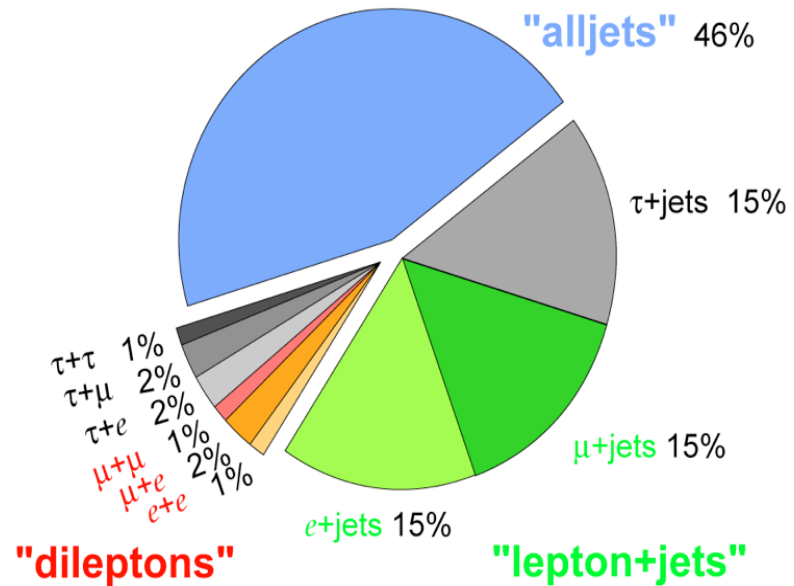
- almost always $t \rightarrow Wb$ (i.e. $V_{tb} \sim 1$)
- lifetime is short, and it decays before hadronizing
- the W is real:
 - can decay $W \rightarrow l\nu$ ($l=e,\mu,\tau$), $BR \sim 1/9$ per lepton
 - can decay $W \rightarrow qq$, $BR \sim 2/3$

Top quark decays

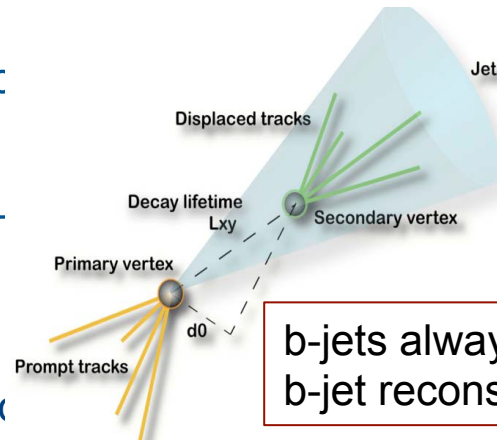
Top quarks (mostly) produced in pairs



Top Pair Branching Fractions

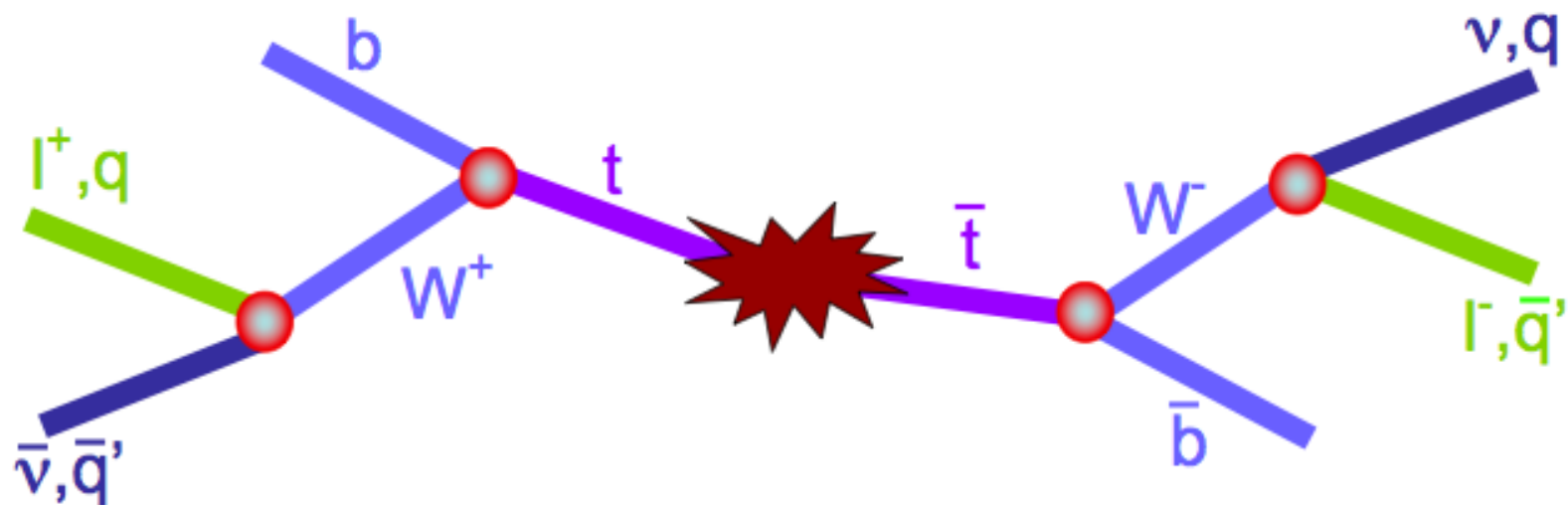


- Dilepton (ee , $\mu\mu$, $e\mu$):
 - BR~5%, 2 leptons+2 b-jets+2 neutrino
- Lepton (e or μ) + jets
 - BR~30%, one lepton+4jets (2 from b)-neutrino
- All hadronic
 - BR~44%, 6 jets (2 from b), no neutrino



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
...

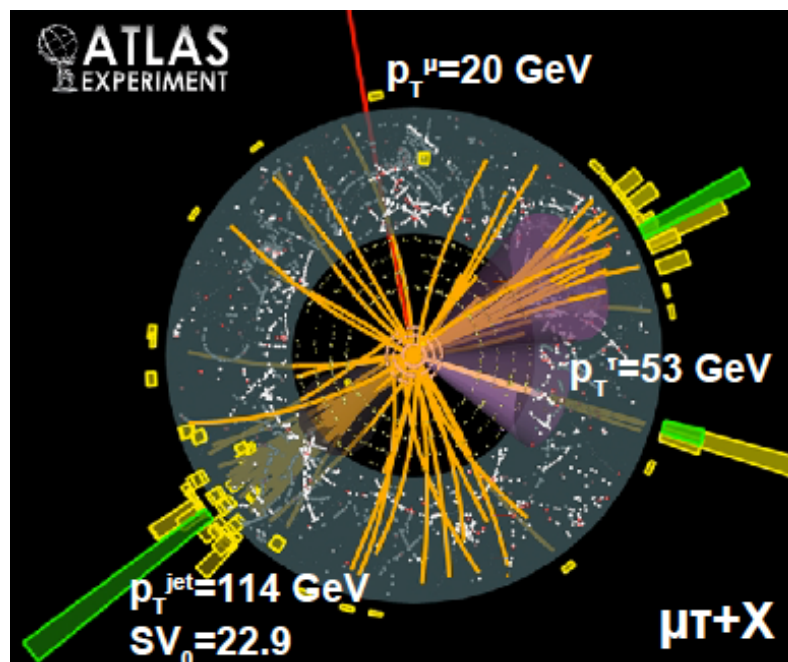
DECAY

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

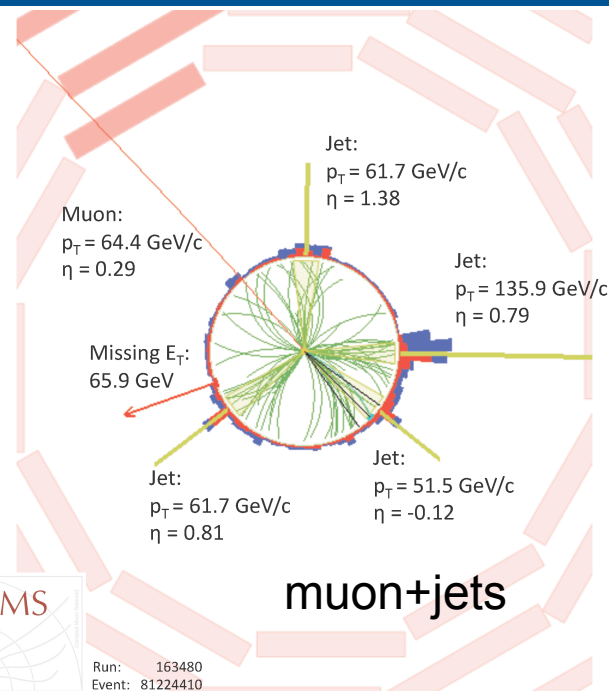
Particle identification

- Object identification and reconstruction

Selection of top quark events



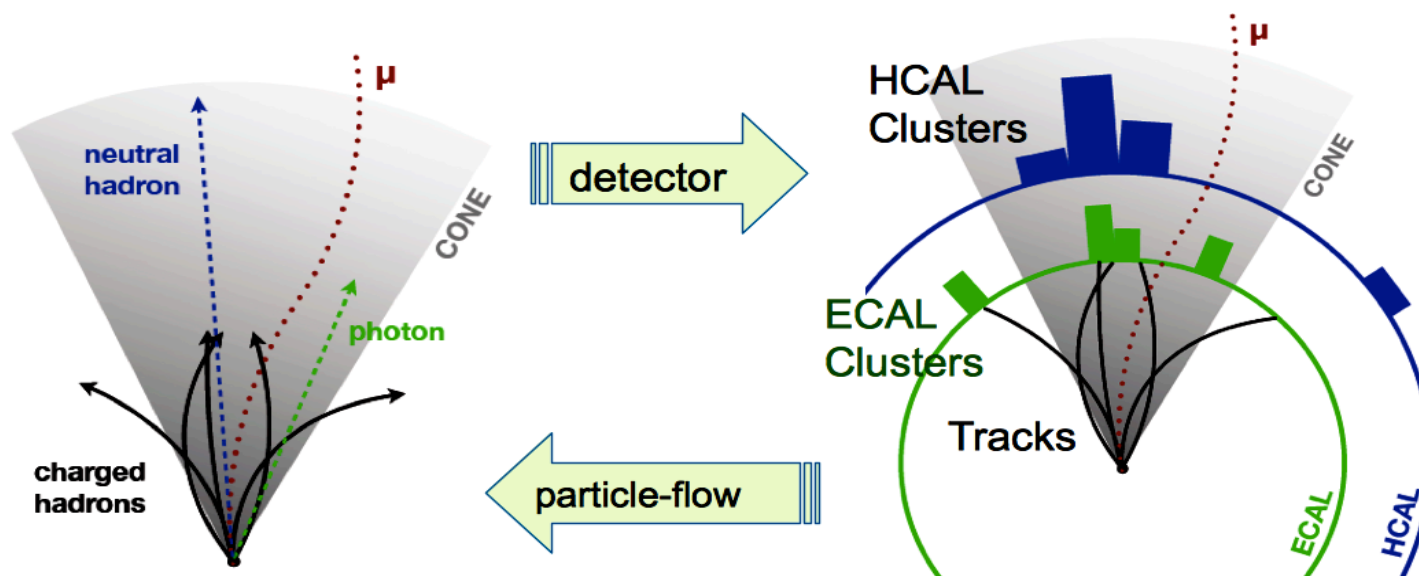
- Trigger:
 - single or double (isolated) lepton
- Leptons:
 - e/μ , $p_T > 20/30 \text{ GeV}$, $|\eta| < 2.5$
 - Identification/reconstruction
 - Tracker/calorimeter isolation



- Jets:
 - at least 2 jets, $p_T > 30 \text{ GeV}$, $|\eta| < 2.5$
 - 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

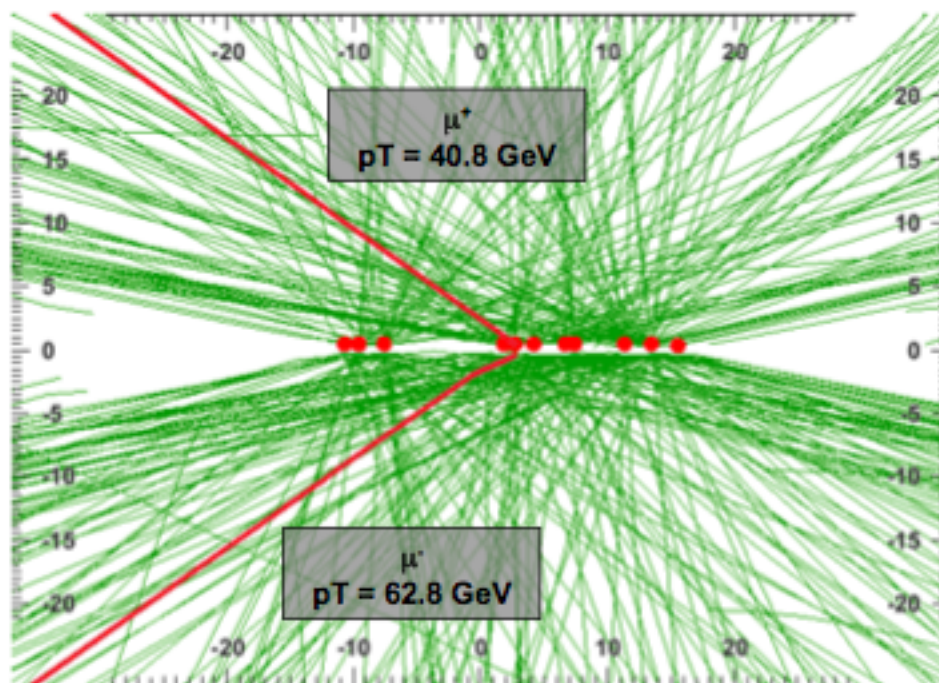
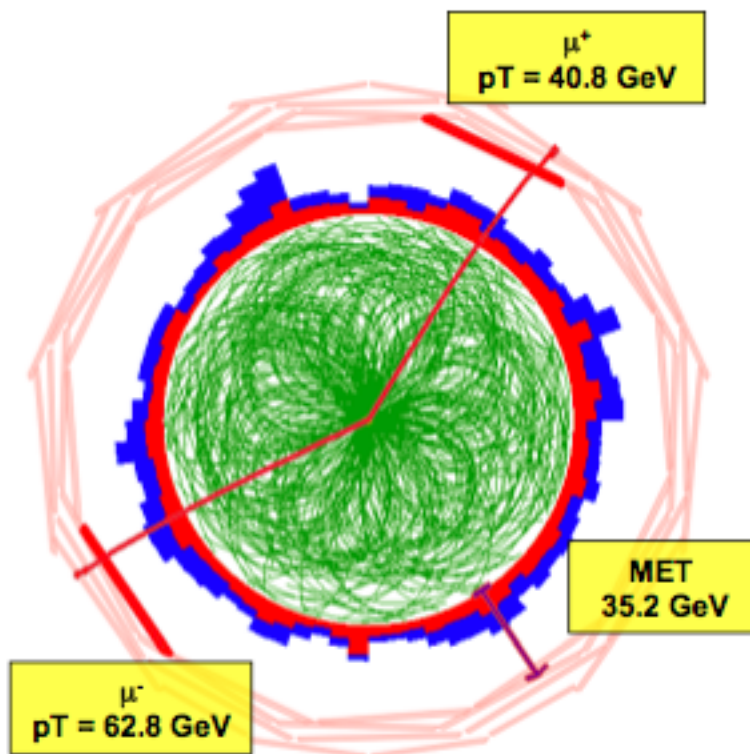
- Particle Flow (PF) combines information from all subdetectors to reconstruct particles produced in the collision
 - charged hadrons, neutral hadrons, photons, muons, electrons
 - use complementary info. from separate detectors to improve performance
 - tracks to improve calorimeter measurements
- From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



Challenge: Pile-up

$Z \rightarrow \mu \mu$
Expected MET = 0

10 in-time + 10 out-of-time
pileup

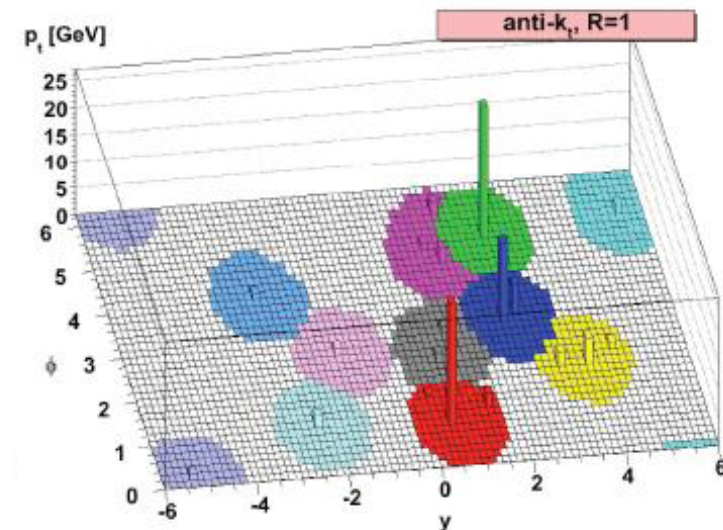


PDF
101.502400000
2000

20 reconstructed
vertices

Jet reconstruction

- A “jet” is a cluster of energy deposited in a “small” η - ϕ region of the detector
 - It is not a unique object, it is defined by the jet algorithm (different choices yield different jets)
- The jet algorithm uses detector reconstructed objects (clusters, tracks, combined objects)
- It is “safe” to higher order effects when it does not change jet quantities
- Efficient and pure: jets correspond to partons



Missing transverse momentum

- **Neutrinos** (and “dark matter”) escape the detector without detection
 - Also longitudinal momentum and energy of other final state particles escape undetected (along the beam-pipe)
 - Momentum is not measured along the z-direction
 - Missing momentum along z is unknown
- The momentum of the neutrinos can be reconstructed in the transverse plane
- Momentum which is **missing** to balance the total momentum to zero

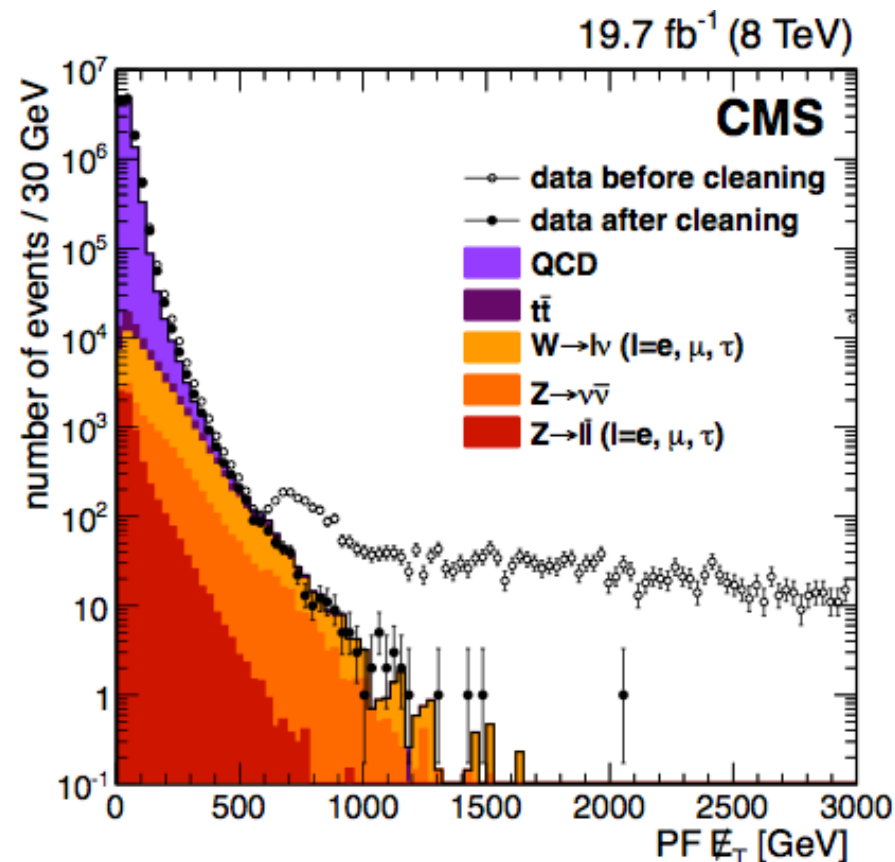
transverse energy vector

$$\mathbf{E}_T^{\text{miss}} = - \sum_i \mathbf{p}_T(i)$$

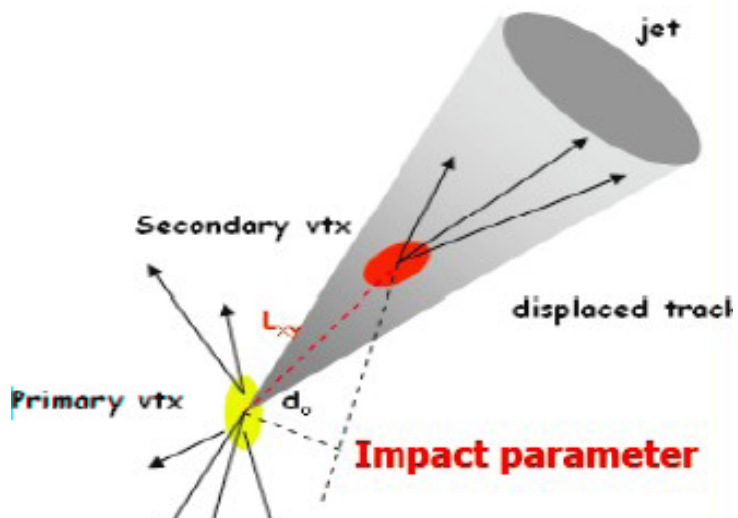
where the sum runs over the transverse momenta of all visible final state particles.

Challenge: MET

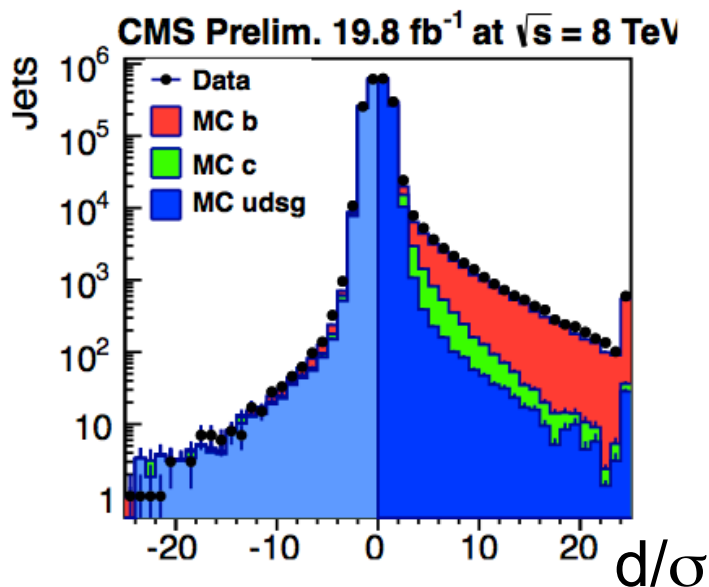
- Performance of the MET measurement depends on the measurement of ALL particles in the event
- Measurement is affected by:
 - Noise, mis-calibration, various calorimeter problems (dead channels, etc)
 - Modeling of QCD background events, pile-up, multiple interactions, ...
 - Muon momentum measurement (muons inside jets)
 - Cosmic background events
 - Beam halo (i.e. collisions upstream of detector, parallel to beam)
- MET significance



Challenge: b-tagging



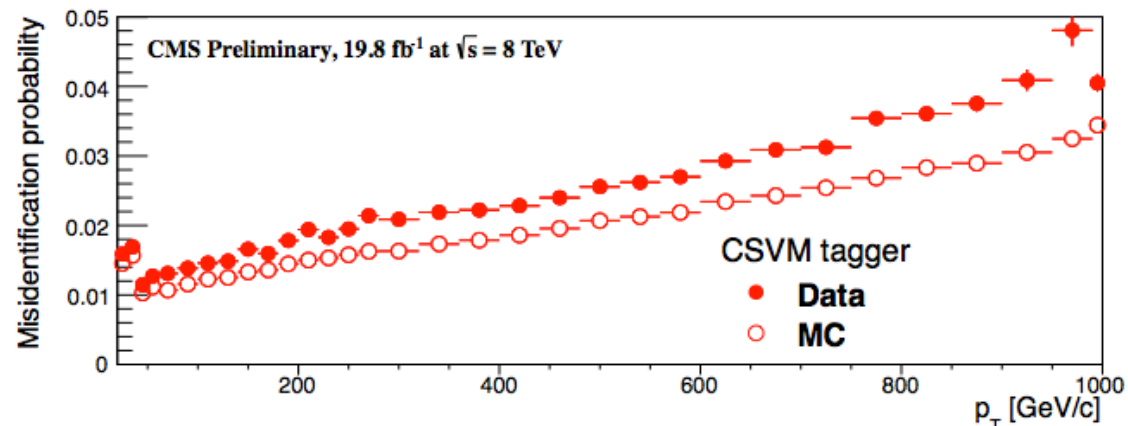
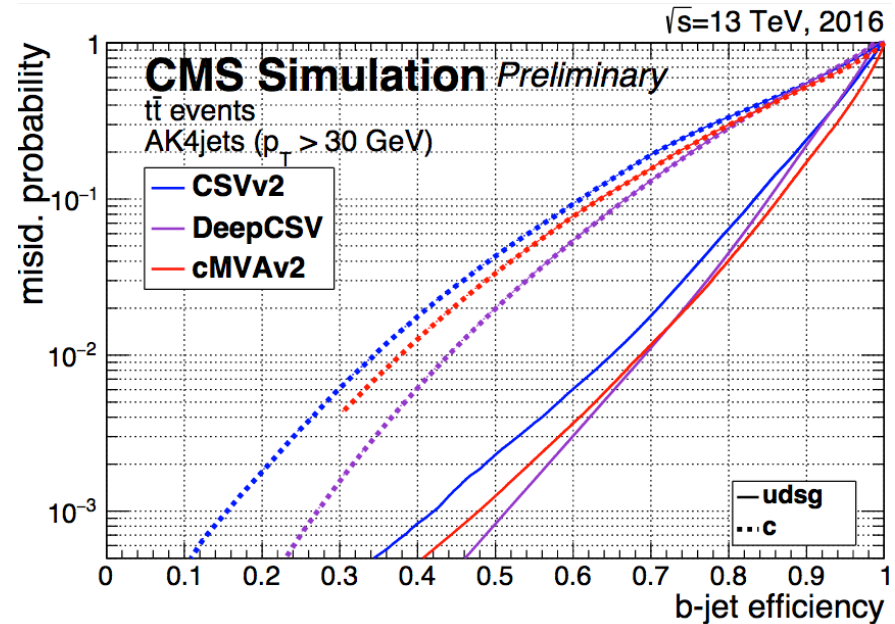
- Lifetime: $\tau_b \sim 1\text{-}2$ psec
- Reduction of background obtained by identifying jets from b-quarks
- Two methods:
 - Secondary vertex tagging
 - Semileptonic decays of b-hadrons in jets ($b \rightarrow l \nu_l X$)



b-tag: fake rates and efficiencies

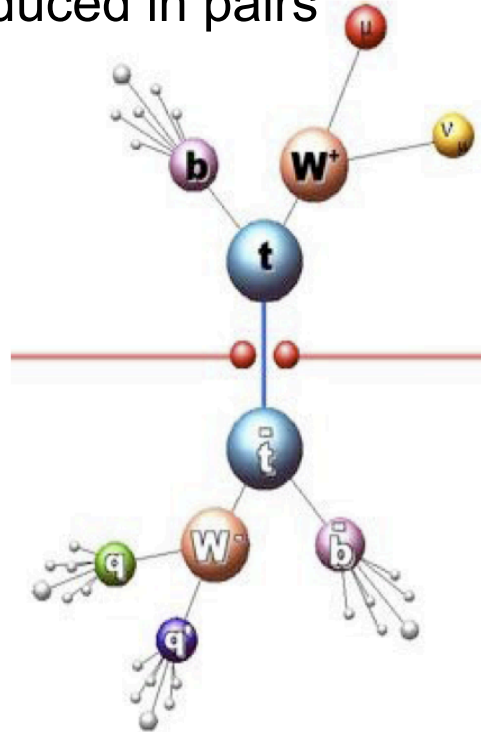
BTv-16-001

- b-tag optimization: trade-off between fake rate and efficiency
- studied the performance of different tagging working points
- Uncertainty on data/MC scale factor, depending on algorithms

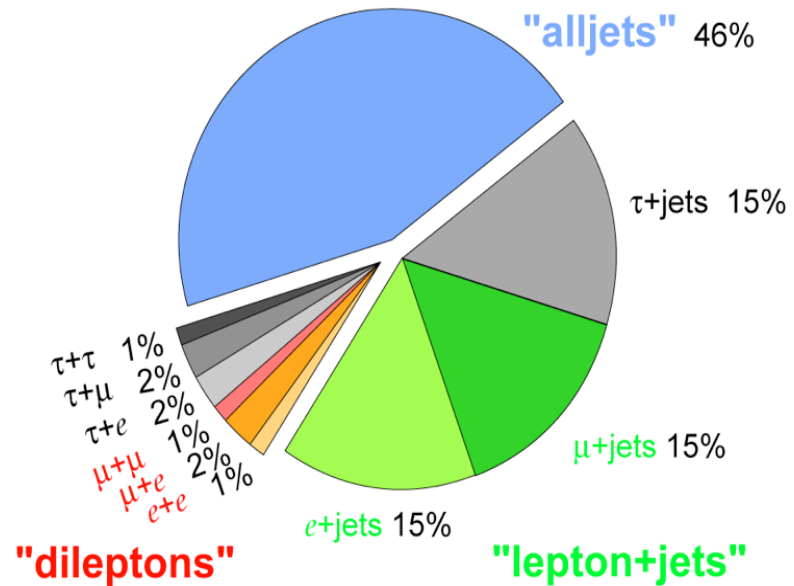


Top quark decays

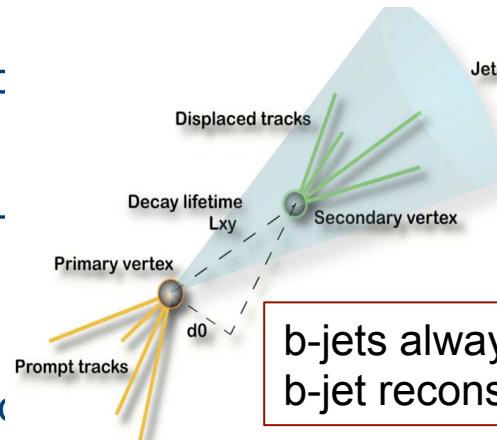
Top quarks (mostly) produced in pairs



Top Pair Branching Fractions



- Dilepton (ee , $\mu\mu$, $e\mu$):
 - BR~5%, 2 leptons+2 b-jets+2 neutrino
- Lepton (e or μ) + jets
 - BR~30%, one lepton+4jets (2 from b)-neutrino
- All hadronic
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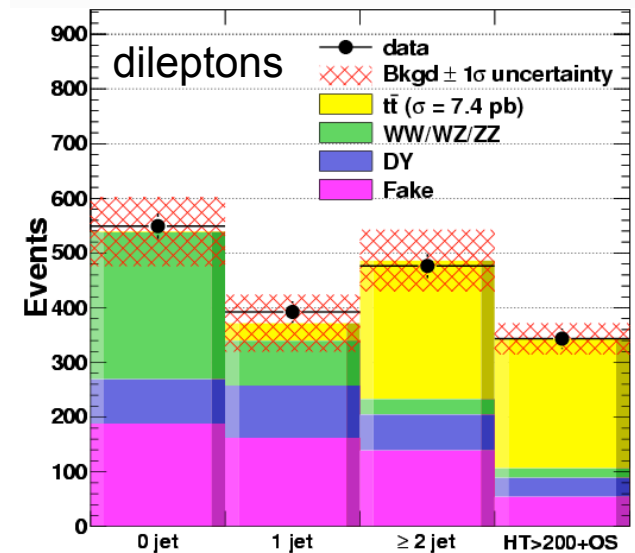
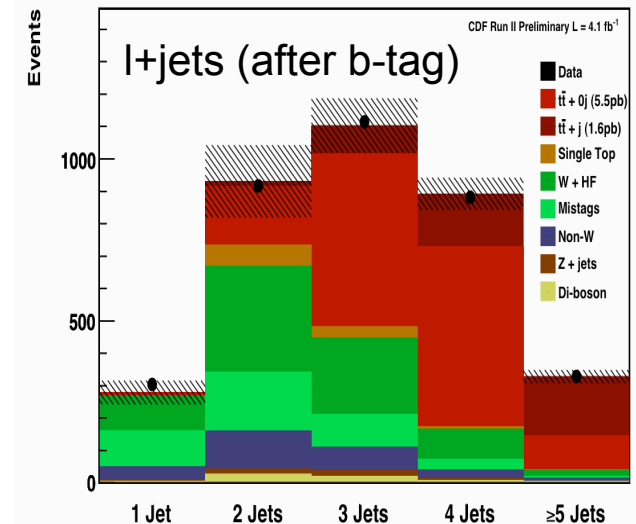
b-jets always present
b-jet reconstruction plays important role

Measurements

- Measurement of the cross section

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



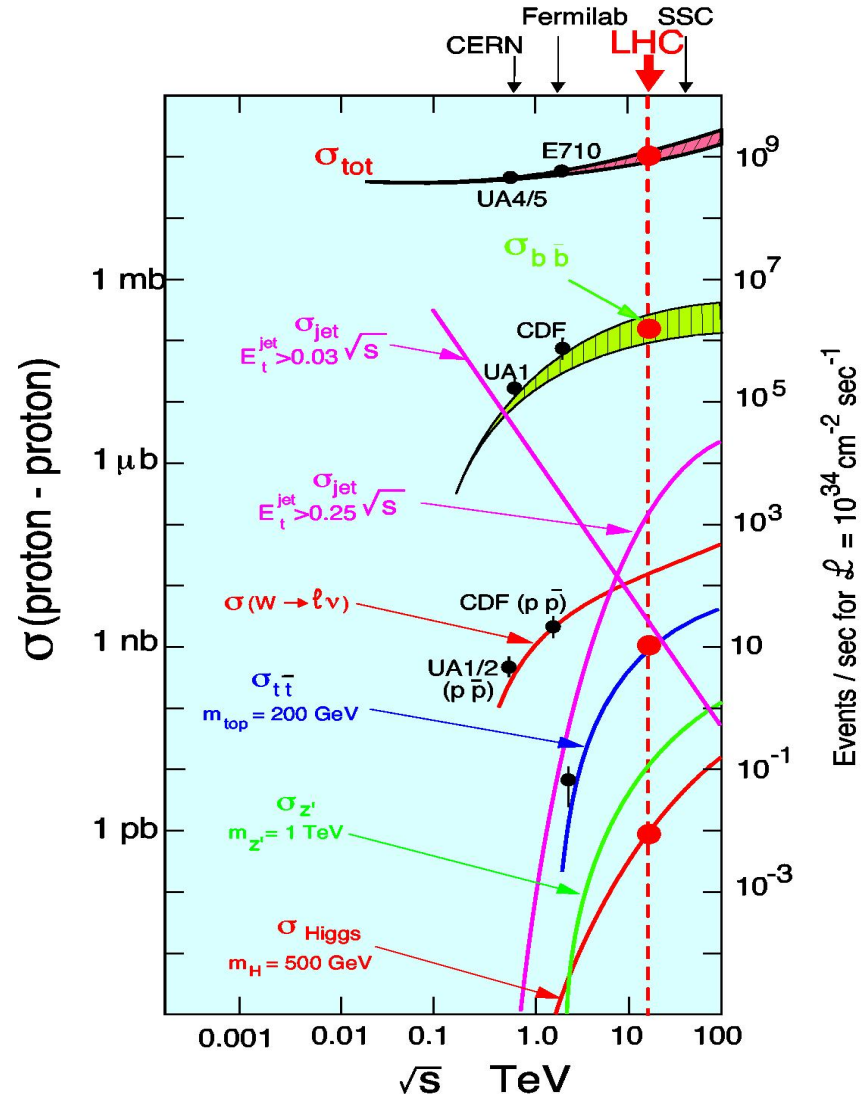
Theory cross sections: TeV vs LHC

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%)
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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%)

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”



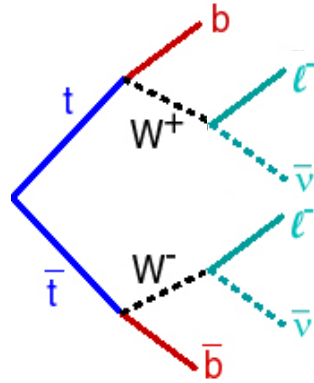
Cross section measurement

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:

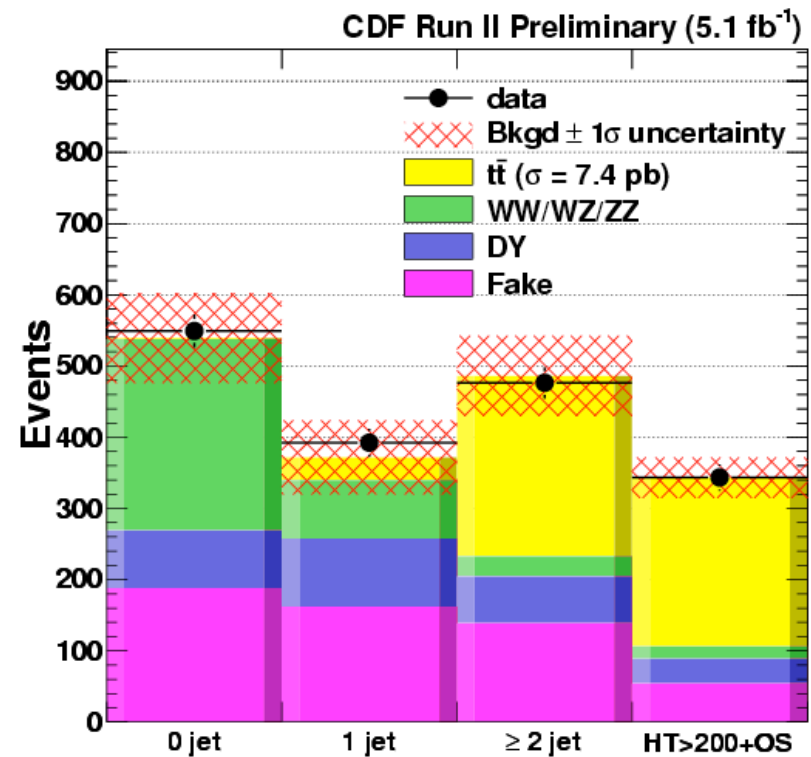
- An arrow from "Number of observed events" points to N_{obs} .
- An arrow from "Number of background events (from data, calculated from theory)" points to N_{bgd} .
- An arrow from "Acceptance (experimental: detector, efficiencies)" points to $\epsilon_{t\bar{t}}$.
- An arrow from "Luminosity (determined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

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

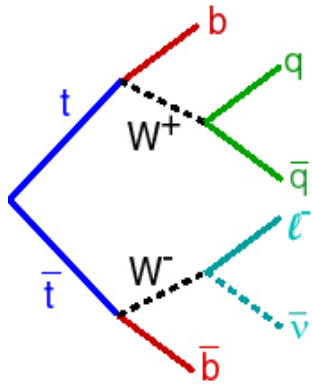
Dilepton channel



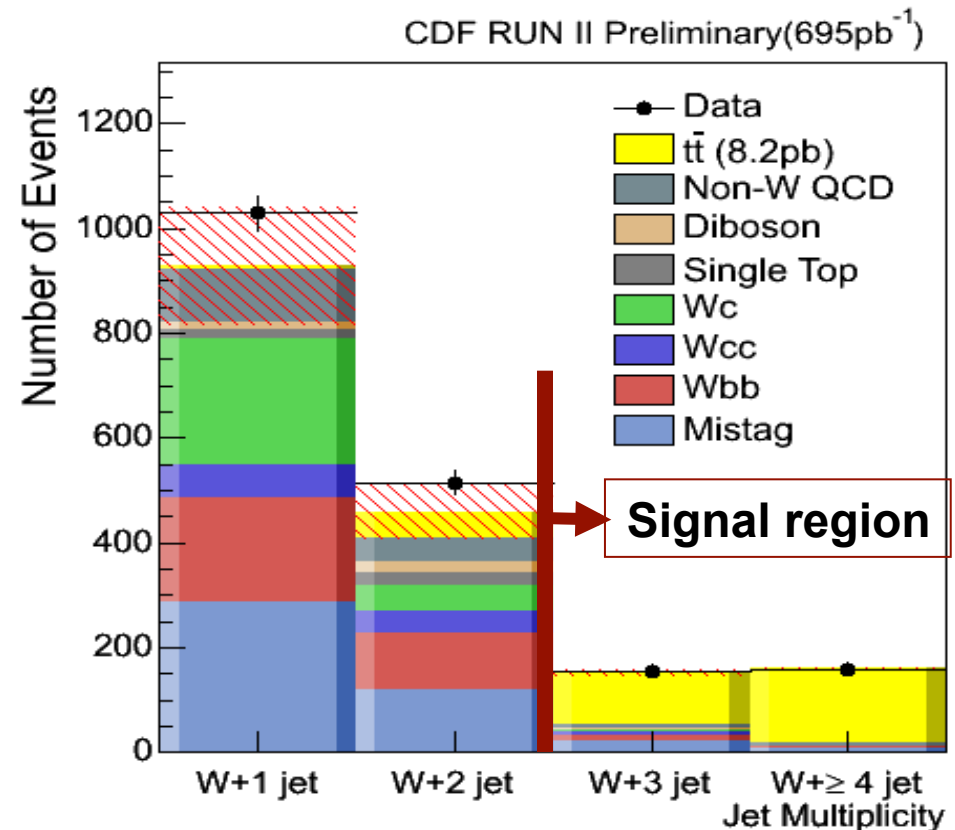
- Branching ratio (BR) $\sim 5\%$
- Background: **small**
- Clean final state
 - two leptons + ≥ 2 jets + MET
 - kinematic variables
- Signal visible w/without b-tagging
- Main systematics: JES, lepton ID, (pileup, b-tag, signal modeling)



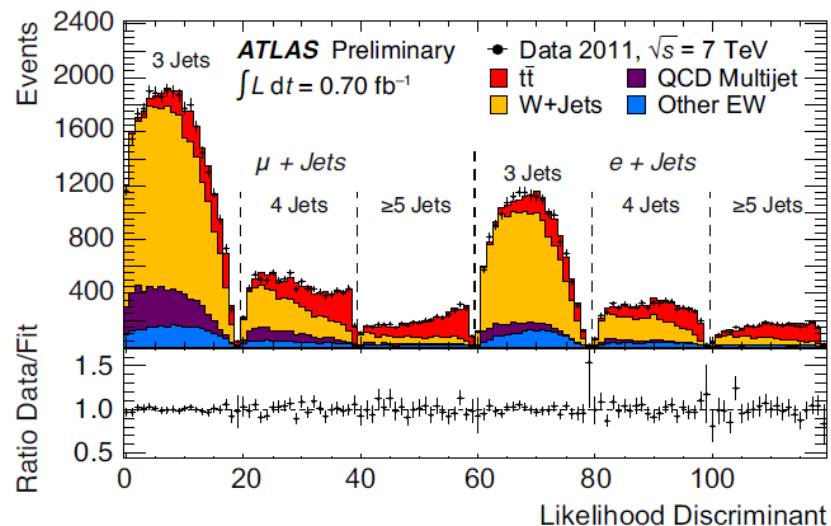
Lepton + jets



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



Lepton + jets channel (cont.)

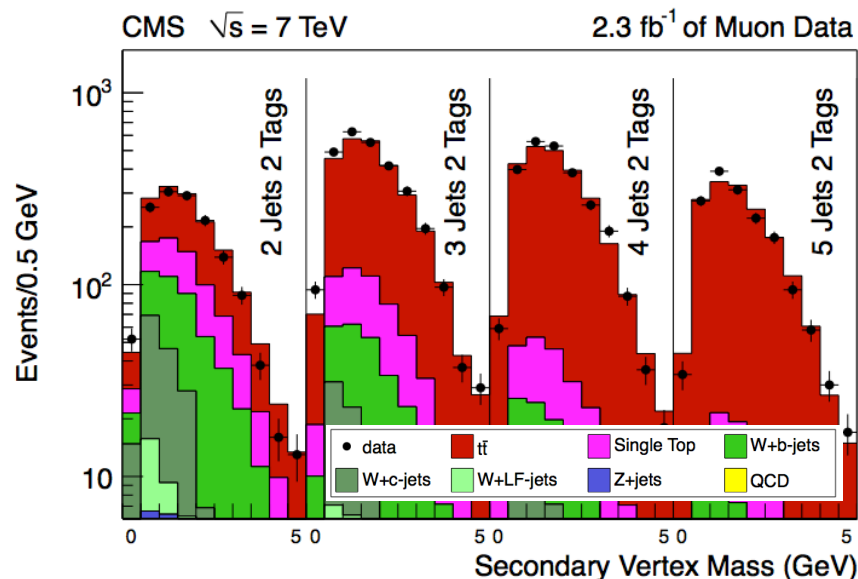


Use kinematics to select $t\bar{t}$

– mass of sec. vertex

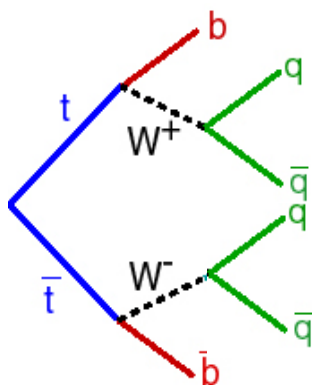
– topology, etc.

Categorize events and extract $\sigma_{t\bar{t}}$ from fit

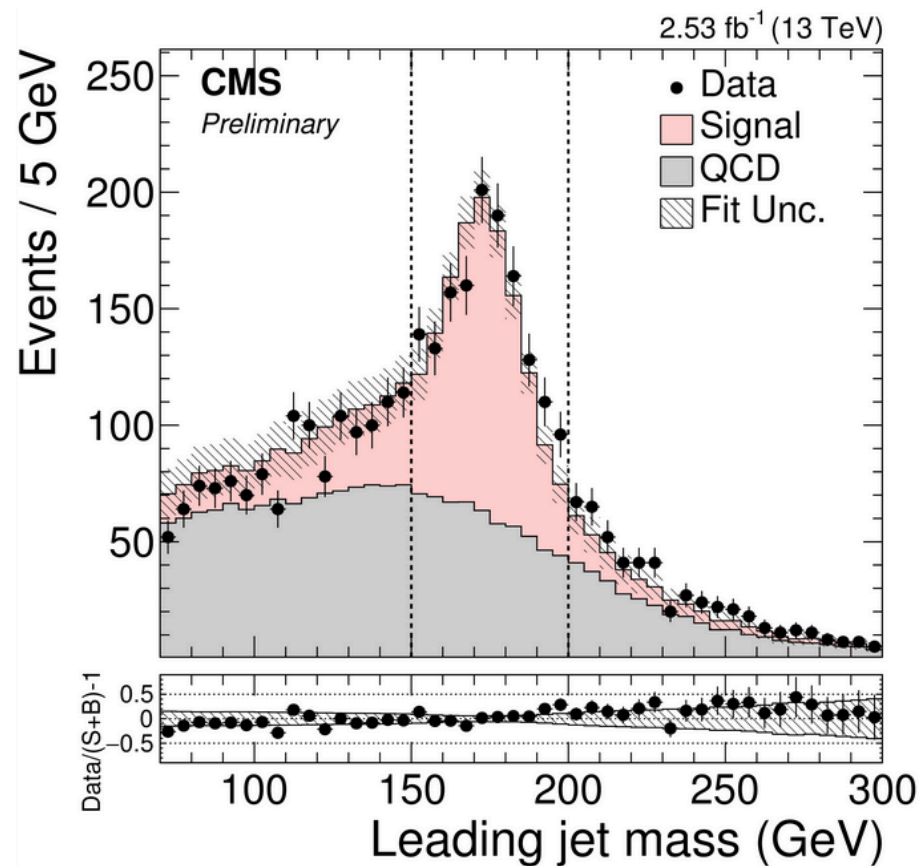


All hadronic

CMS-PAS-TOP-16-013

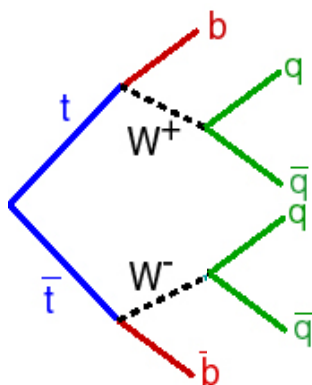


- BR $\sim 46\%$
- Background: large
- Selection:
 - ≥ 6 jets + kinematical selection
 - require b-tag
- Main backgrounds:
 - hadronic multi-jet

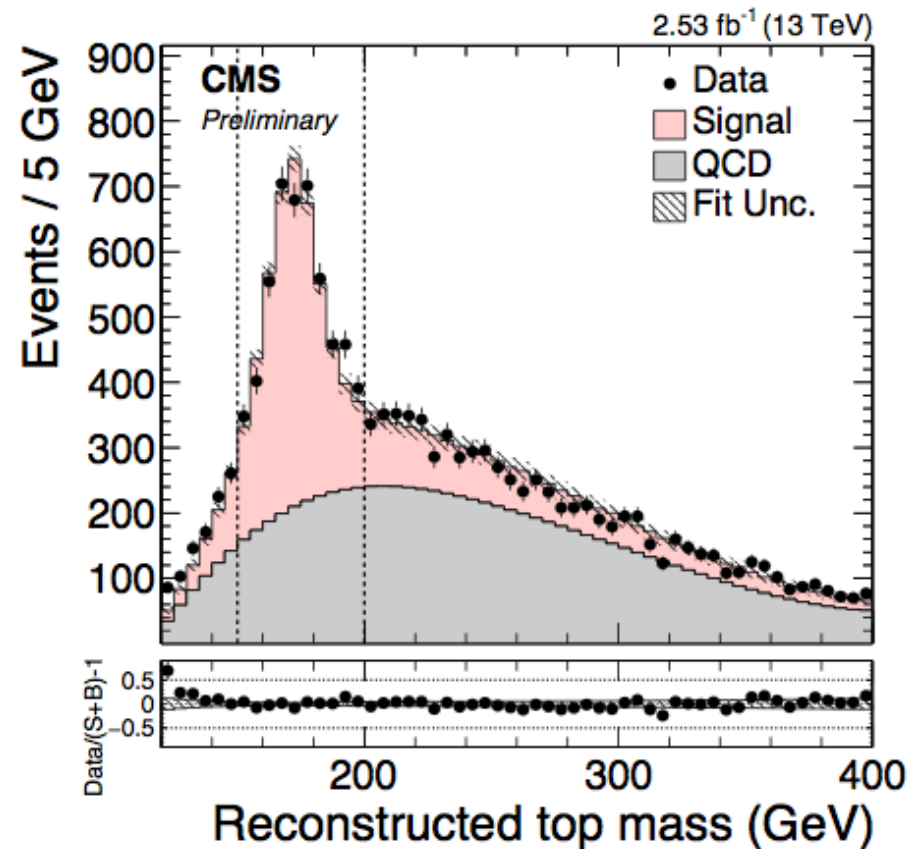


All hadronic

CMS-PAS-TOP-16-013

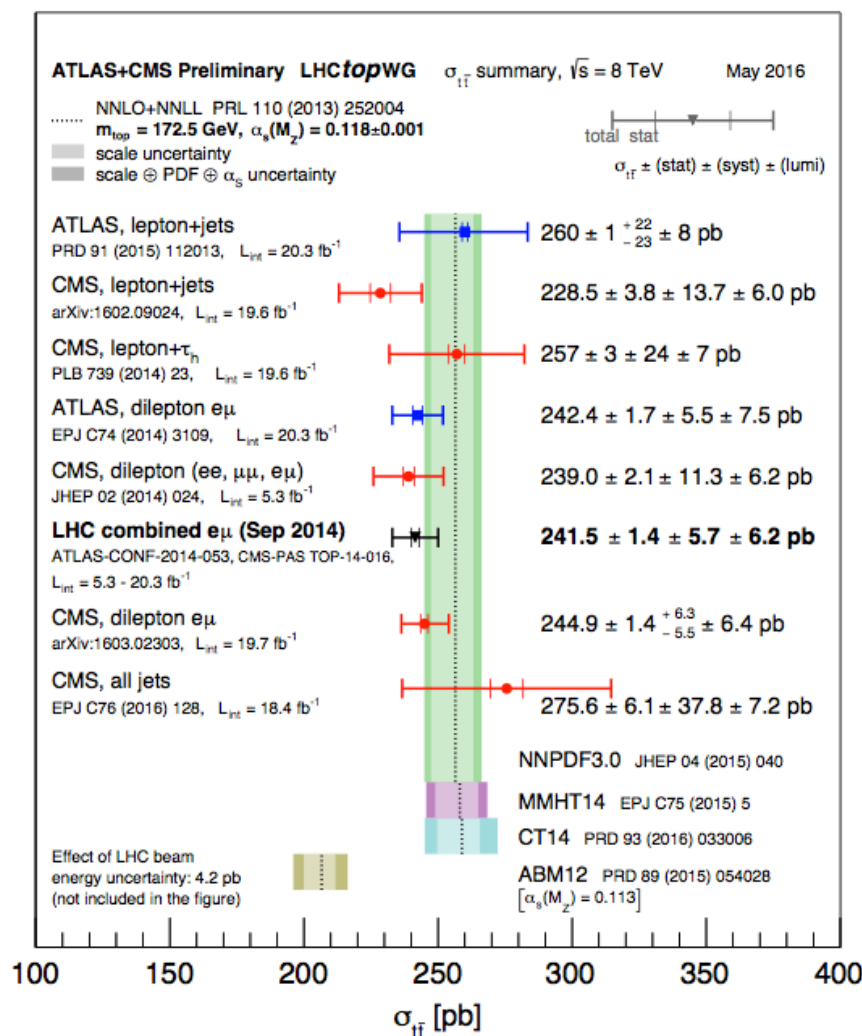


- BR ~46%
- Background: large
- Selection:
 - ≥ 6 jets + kinematical selection
 - require b-tag
- Main backgrounds:
 - hadronic multi-jet
 - same selection without b-tag

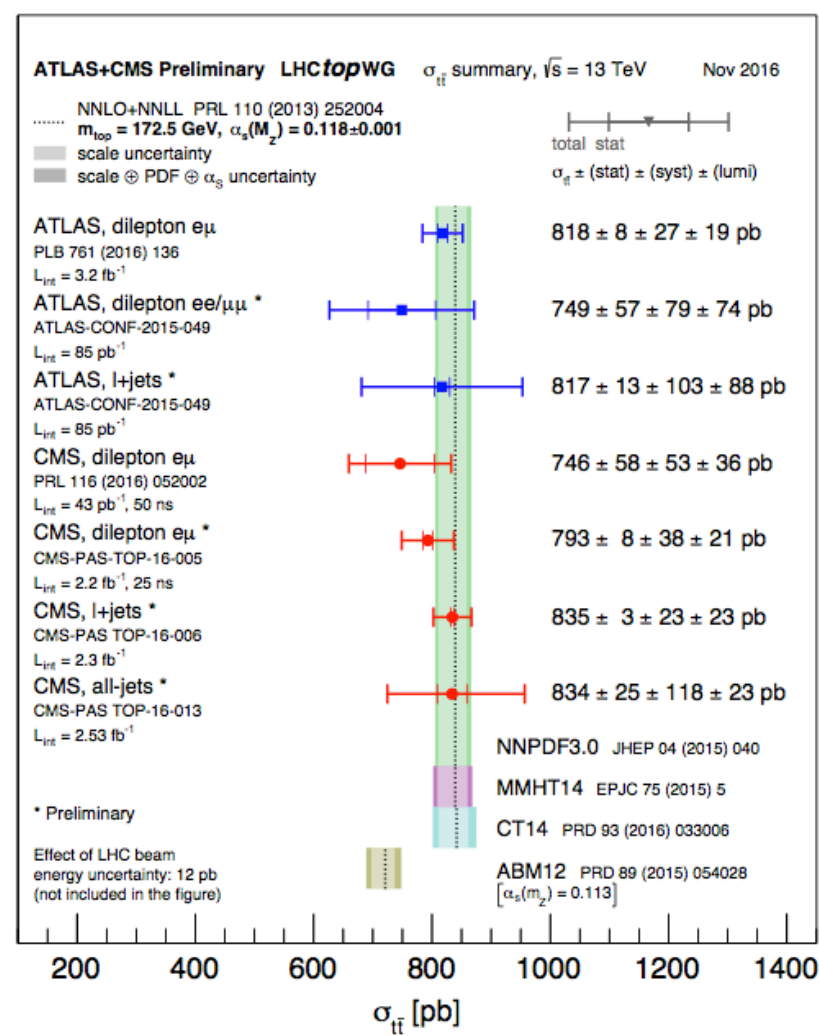


LHC cross section measurements

8 TeV

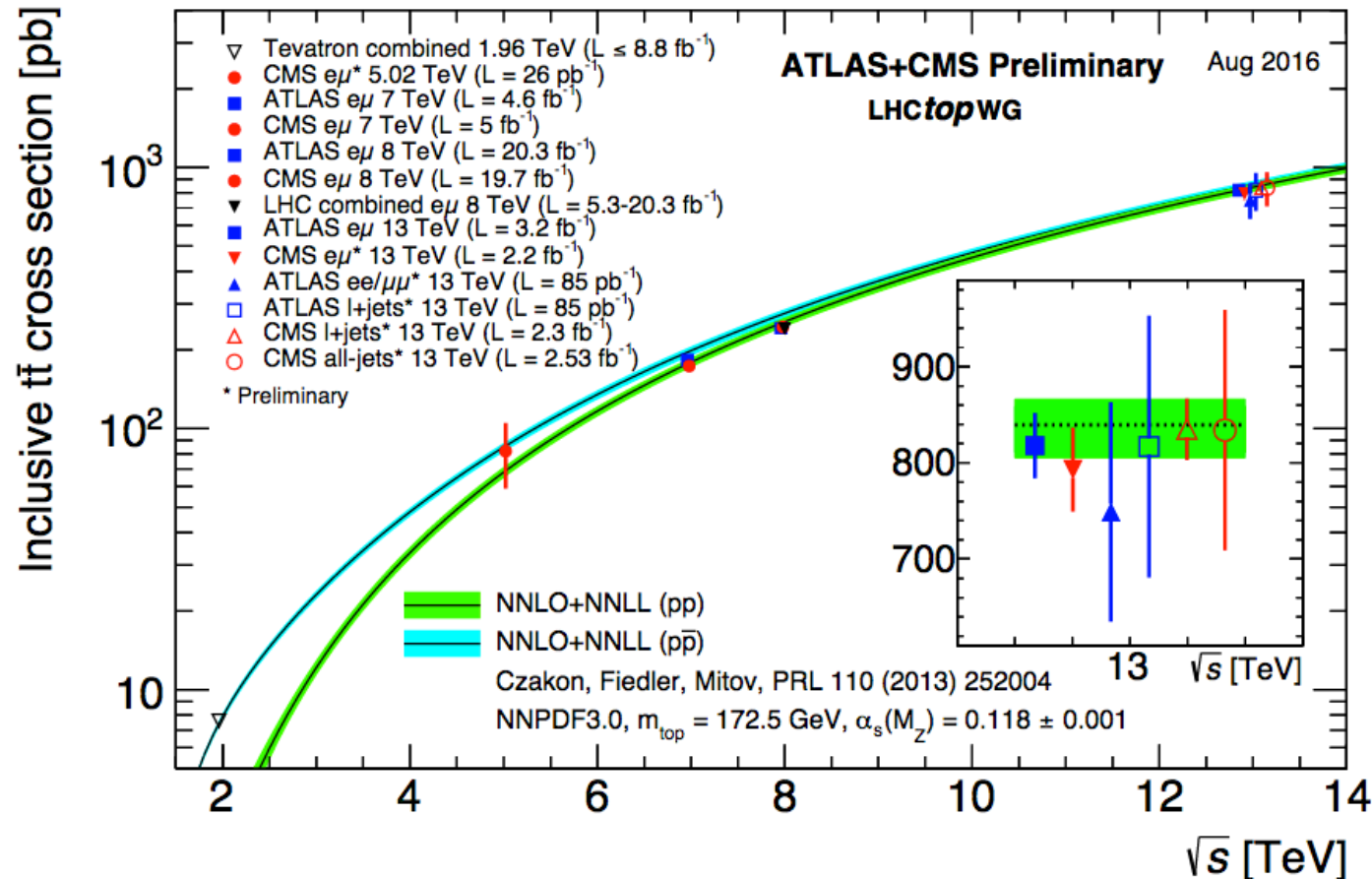


13 TeV



Cross sections

- Cross section measurements provide test of pQCD predictions
- Standard “candle”: $t\bar{t}$ is a dominant background for NP searches
- Comparison in different channels may provide constraints on BSM

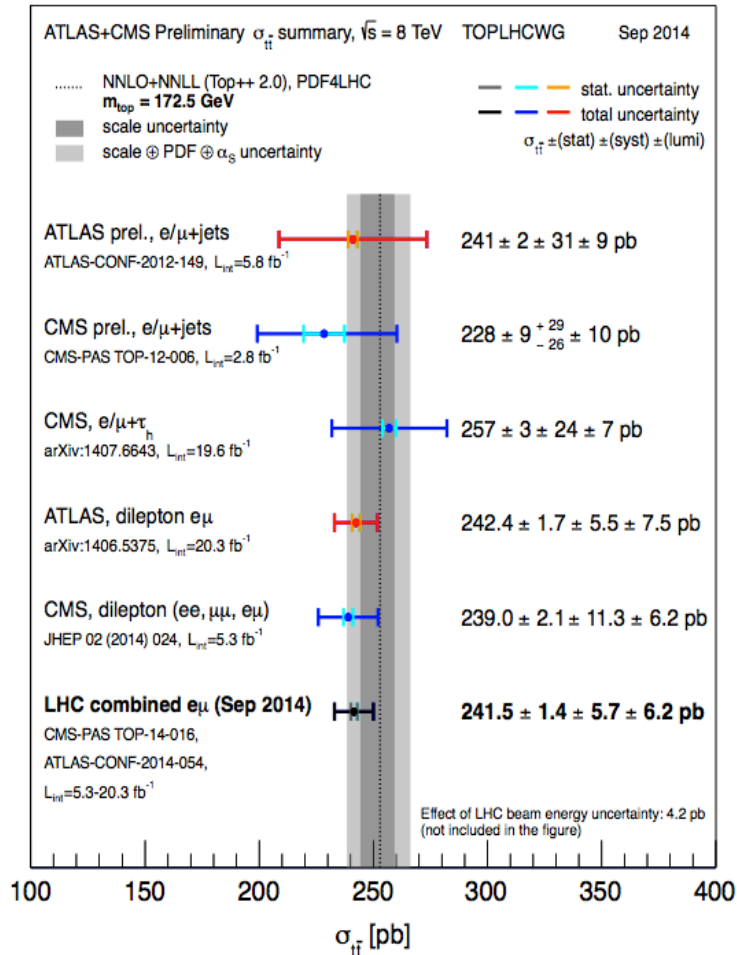


$\pm 5\%$

Cross sections (cont.)

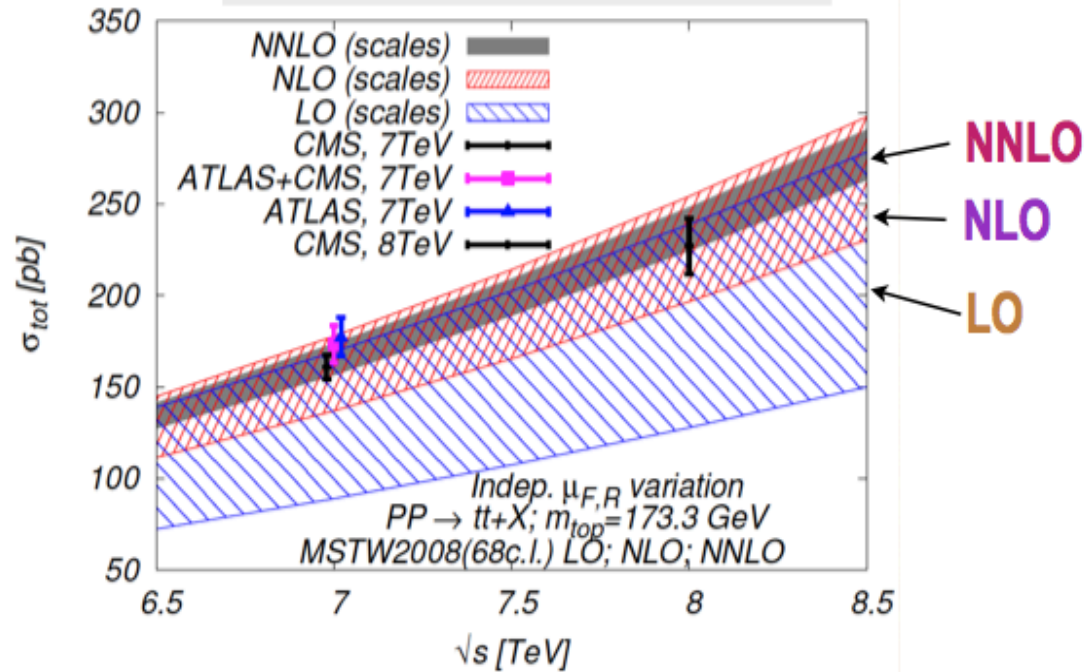
CMS-TOP-14-016

$\pm 4\%$



\Rightarrow meas. challenging the theory

Czakon, Fiedler, Mitov 1303.6254 [hep-ph]



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

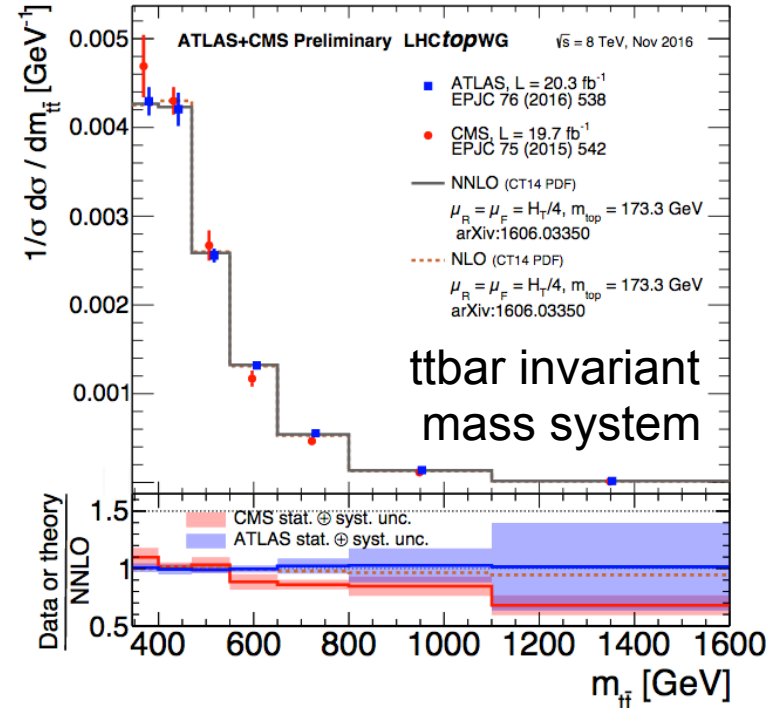
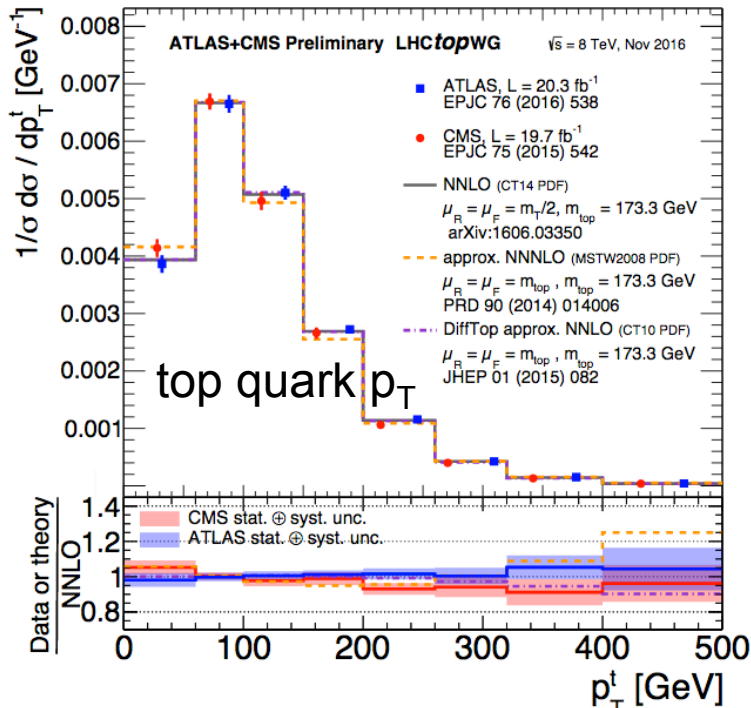
Differential cross section

- Measure differential cross section

- Test perturbative QCD
- Test BSM scenarios (Z' decays, etc) with narrow resonance

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

- Cross sections measured as a function of p_T , η , invariant mass of the final state leptons, top quarks, and the $t\bar{t}$ system
- Good agreement found in dilepton and lepton+jet channels



end

- Introduction on top quark
- Basic concepts on production and decays
- Cross section measurements and relevance to BSM searches
- Next lecture: ``Top quark properties and beyond''