# The Top quark


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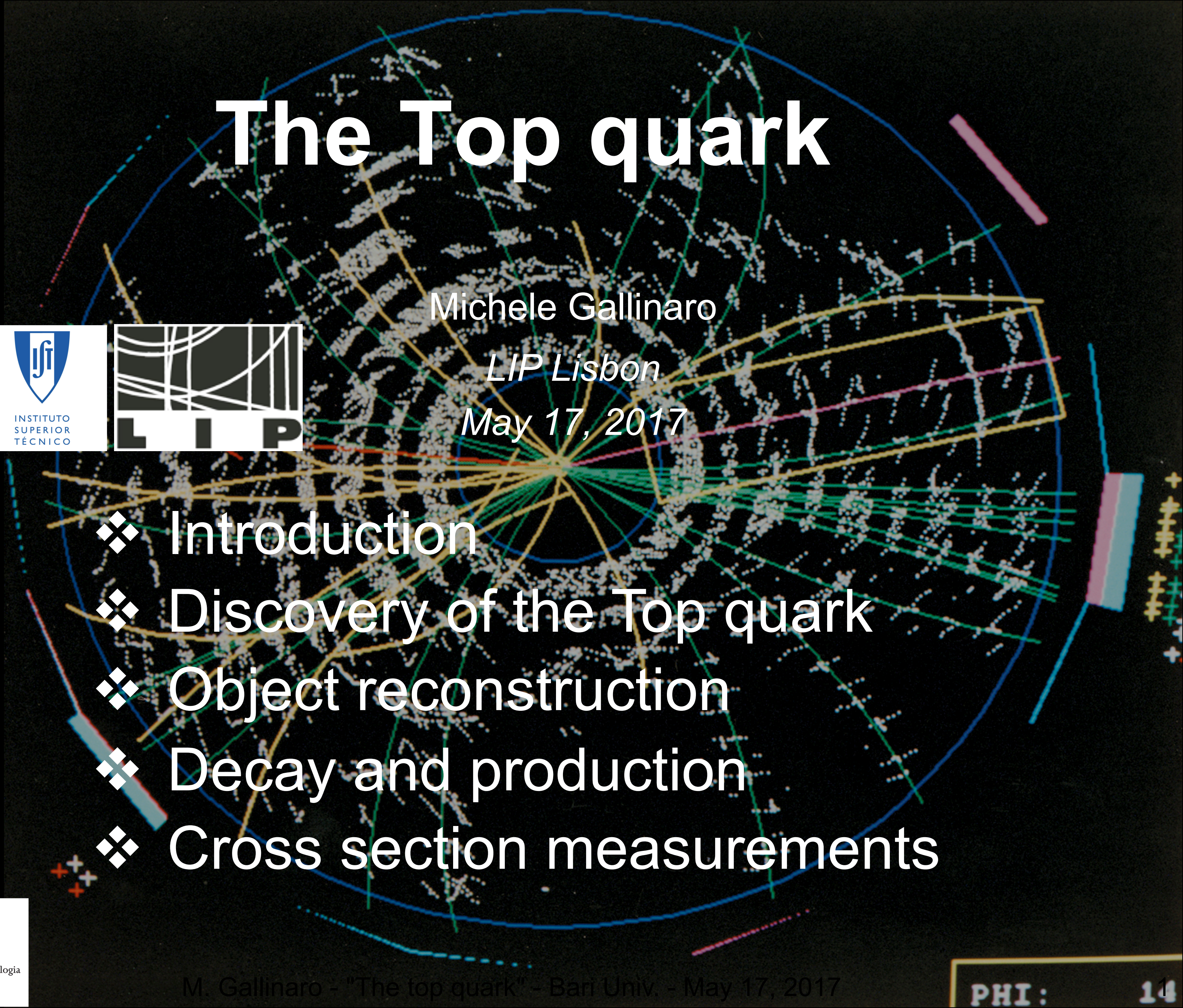
*LIP Lisbon*


*May 17, 2017*




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

# Agenda

Title: “Searches for BSM physics at the LHC”

Tentative agenda:

- Experimental program at the LHC (Tue. 3pm)
- SM, and Top quarks as probe to New Physics (Wed. 10:30am, 3pm)
- Higgs boson and beyond (Thu. 10am)

- Searches for New Physics (Thu. 4pm) - seminar

# Introduction

- Discovery
- introduction to the top quark

# 1974

With the discovery of the J/Ψ:

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

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

# 1975-1977

- Tau ($\tau$) lepton in Mark I data ($\nu_\tau$ from the decay kinematics)
- Discovery of the Y at Fermilab

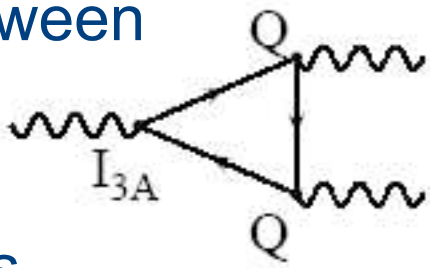
$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} \\ b \end{pmatrix}$$

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

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

# The theory: Why?

- The SM is not a "renormalizable" gauge theory in the absence of the top quark
- Renormalizability is a crucial feature, enabling the SM to be theoretically consistent and be usable as a tool to compute the rate of subnuclear processes between quarks, leptons, and gauge bosons
- Diagrams containing so-called "triangle anomalies" (right), cancel their contributions, thus avoid breaking the renormalizability of the SM, only if the sum of electric charges of all fermions circulating in the triangular loop is zero: $\Sigma Q = -1 + 3 \times [2/3 + (-1/3)] = 0$



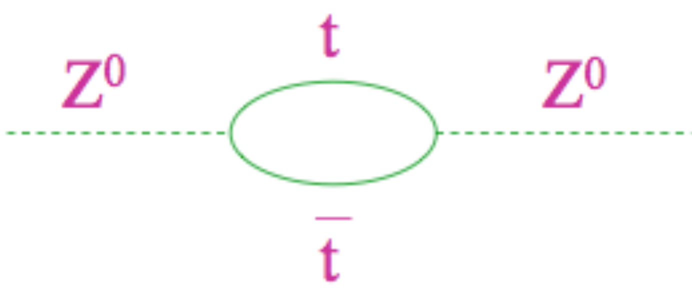

lepton electric charge quark (up/down) charge

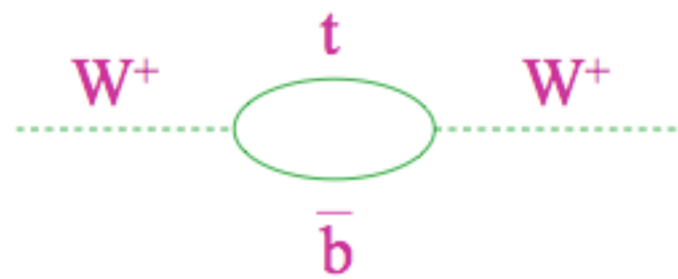
# Searches in $e^+e^-$ collisions

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

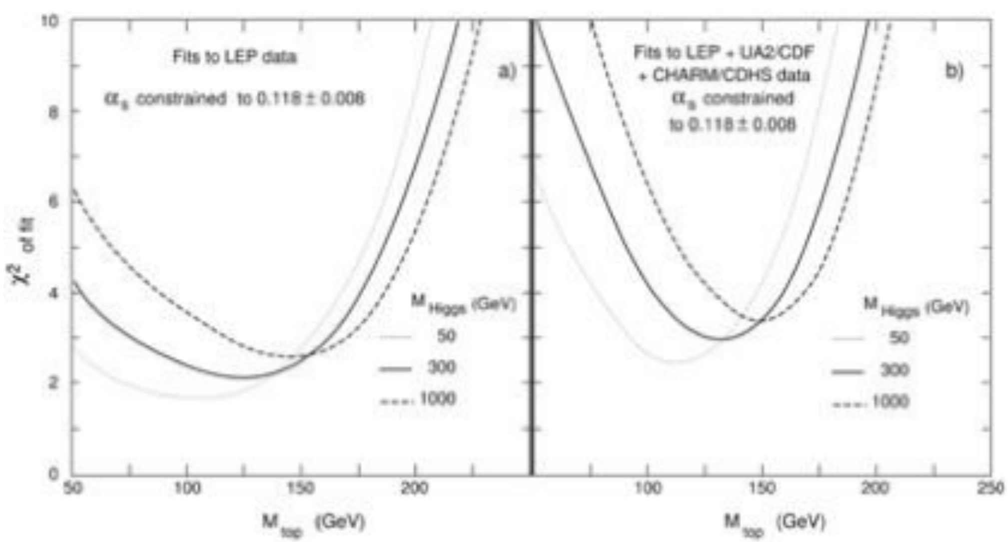
# Indirect searches from $e^+e^-$ colliders

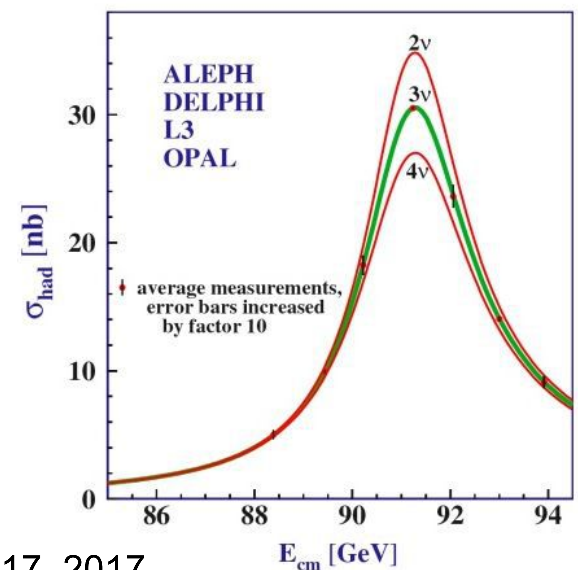
- In the SM, various EWK observables depend on the mass of the top quark




- 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

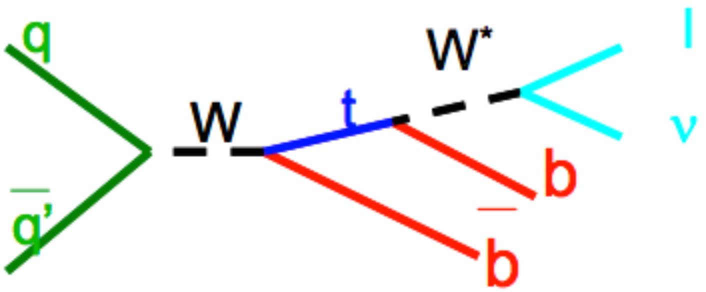


# Early searches at hadron colliders

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

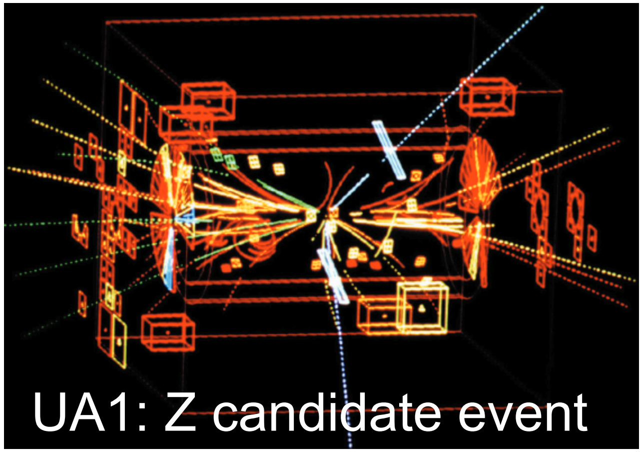
- Access to much higher energies
- Large backgrounds, low event rates
- Difficult reconstruction: jets

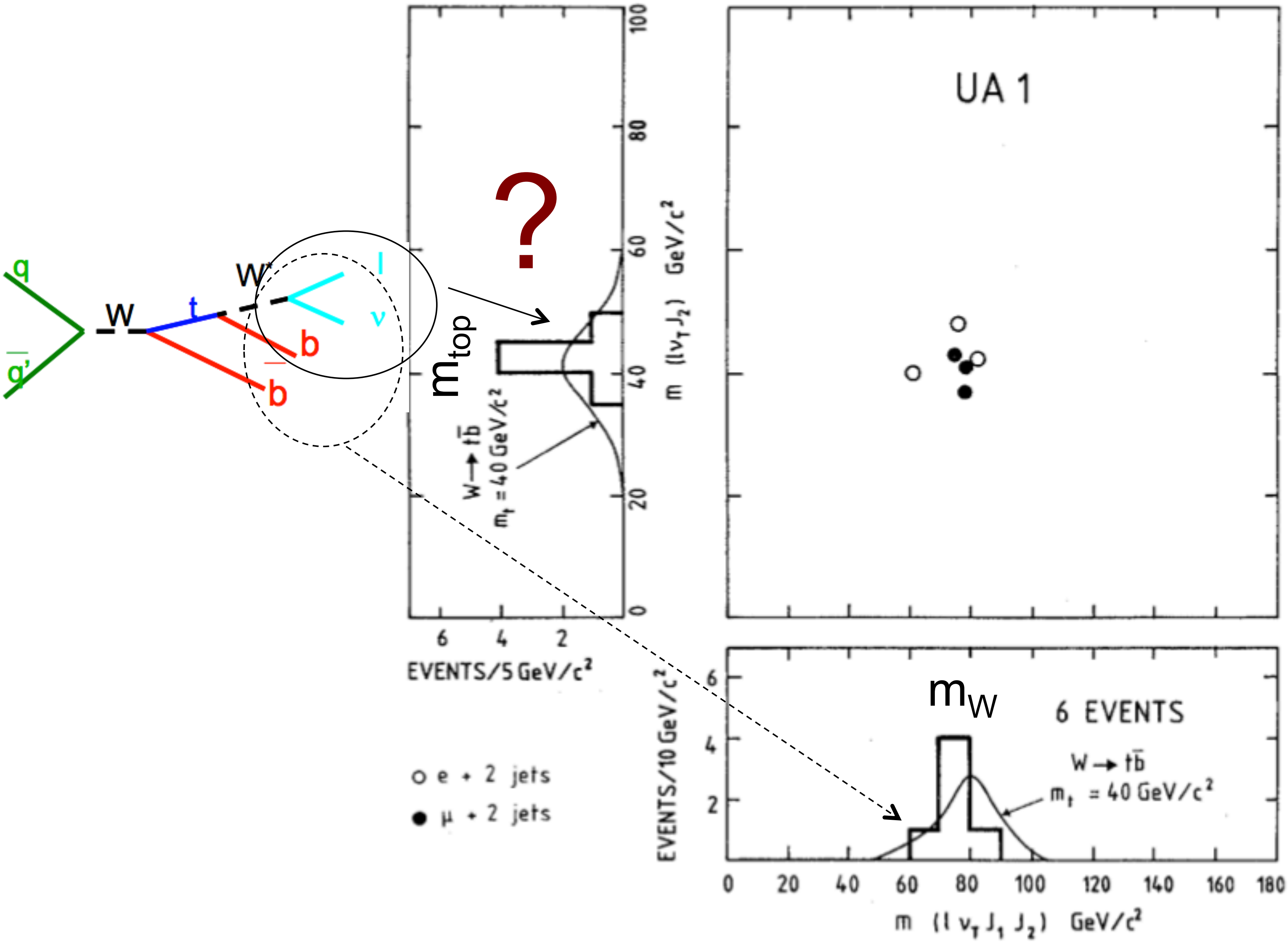



1984: UA1

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

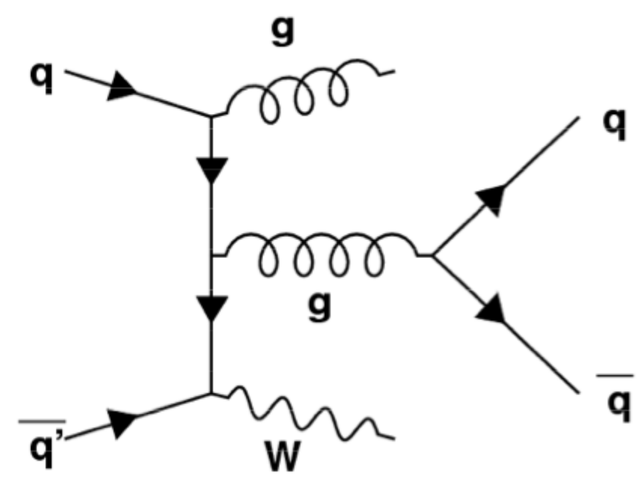
⇒W+jet background was underestimated




q
q̄'
W
t
W
l
ν
b
b̄
?
$m_{top}$
UA 1
$W \to t\bar{b}$
$m_t = 40$ GeV/c$^2$
EVENTS/5 GeV/c$^2$
m (l$\nu_T$ J$_2$) GeV/c$^2$
○ e + 2 jets
● μ + 2 jets
$m_W$
6 EVENTS
EVENTS/10 GeV/c$^2$
m (l $\nu_T$ J$_1$ J$_2$) GeV/c$^2$

# Searches at hadron colliders

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




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

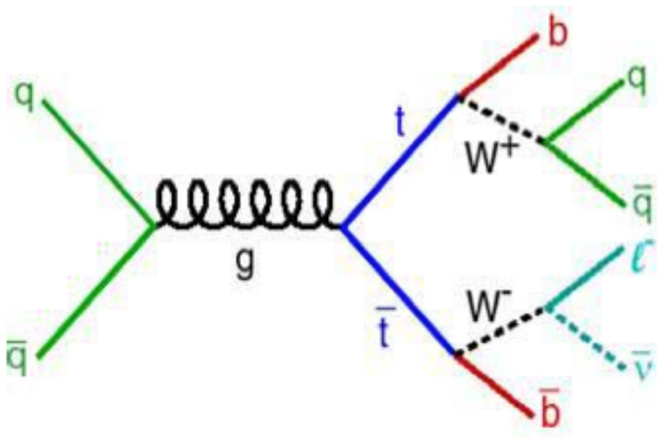
( + 23 expected if $M_{top} = 40$ GeV)

⇒conclude $M_{top}$>44 GeV

# Fermilab joins the hunt

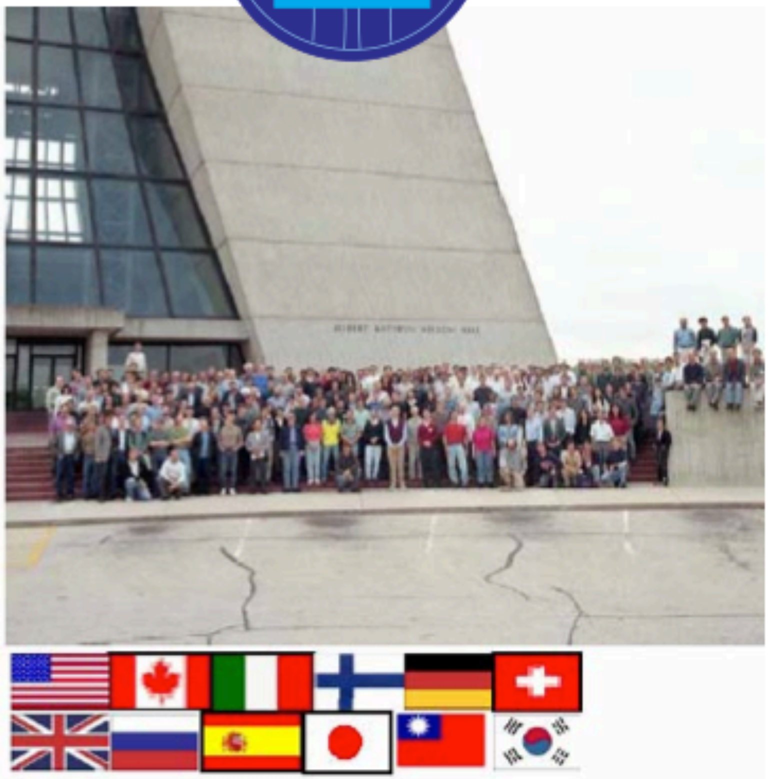
- 1988-89: at CERN, UA2 remains after the upgrades
- $\sqrt{}$1.8 TeV@Fermilab **vs.** $\sqrt{}$0.63 TeV@CERN
- Much better reach for larger mass (only 75 GeV@UA2)
- At Tevatron, pair production dominates: $t\bar{t} \rightarrow Wb\, W\bar{b}$

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

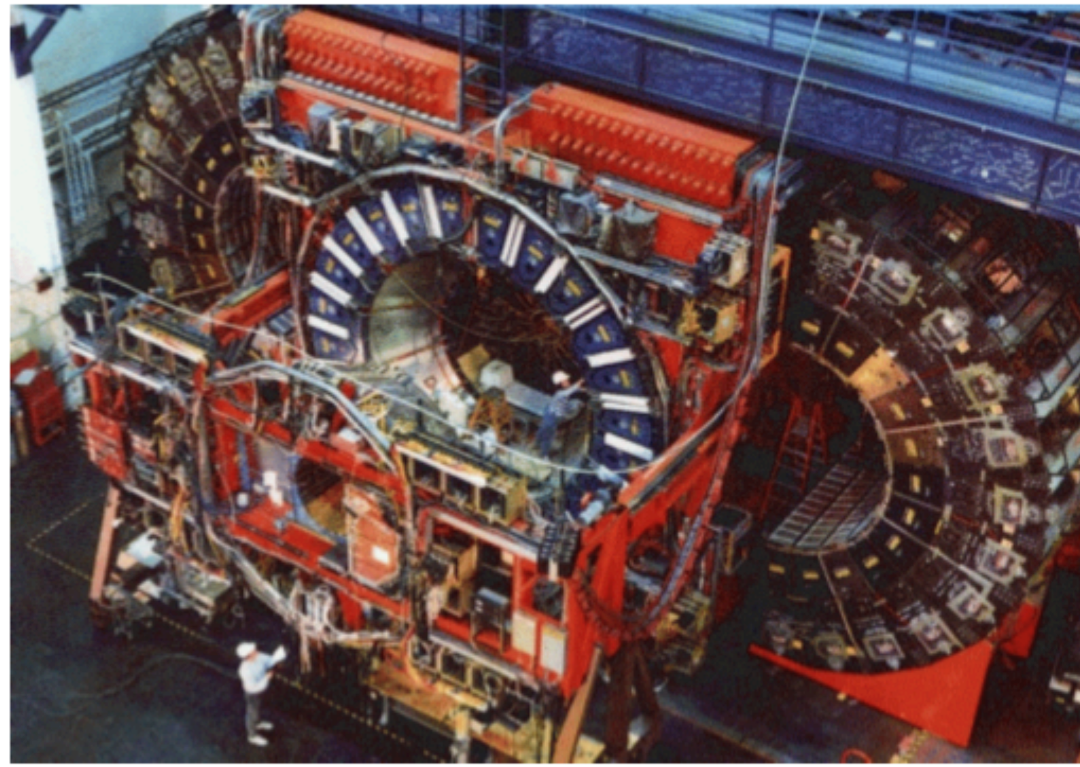


# Tevatron

Proton-antiproton collision at 1.8-2.0 TeV



**12 countries, 62 institutions**
**767 physicists**

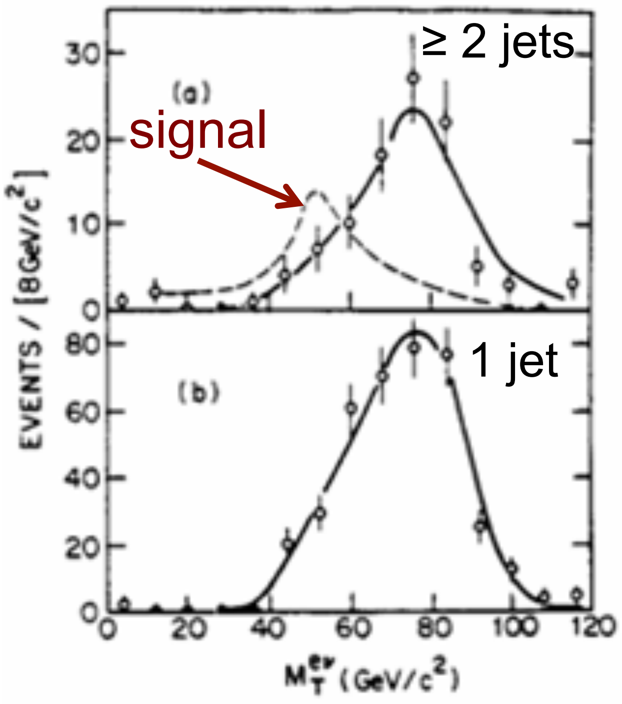


# Searches at CDF

$e\nu + \geq 2$ jets

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

$\Rightarrow M_{top}$>77 GeV




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

# Searches at CDF (cont.)

## eμ channel

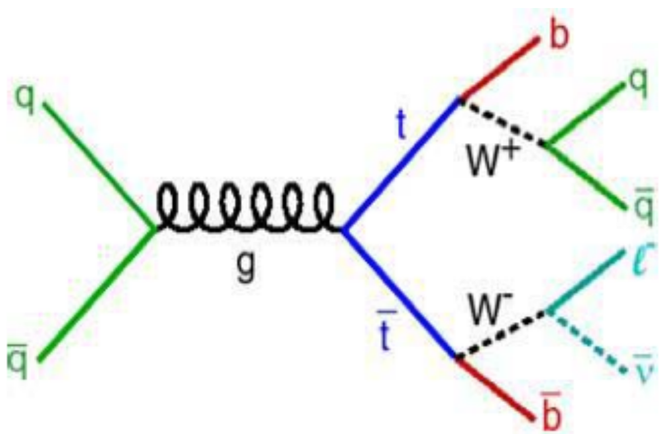
- Event rate much lower: 2xBR($W \rightarrow e\nu$)
- Background very small (no W+jets, no Drell-Yan)
- Dominant background is $Z \rightarrow \tau\tau \rightarrow e\mu X$ (expect 1 event)
- Observe 1 event

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

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

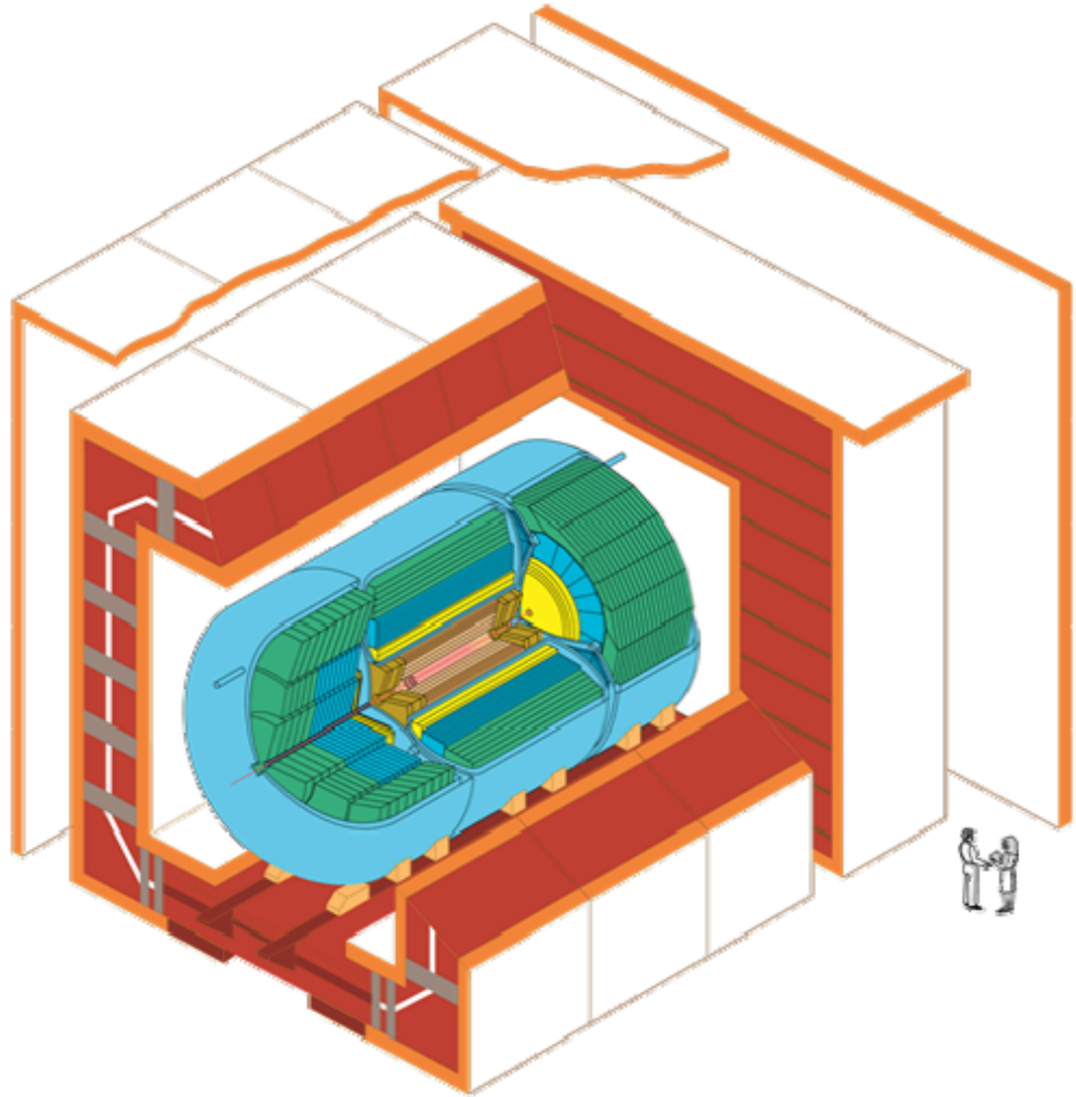
- Top quark decays to on-shell Ws: no $M_T(l\nu)$ discriminant
- Main differences:
  - background: W+jets (largely quarks and gluons)
  - signal: W+jets (2 jets are b-jets)
- CDF publication on 88-89 data:
  - Dilepton: include ee, $\mu\mu$, e$\mu$ (require missing ET, Z-veto)
  - Single lepton: require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

$\Rightarrow M_{top}>91$ GeV



# D0 joins the hunt

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



DØ Detector

# Searches at Tevatron: CDF and D0

## 1992-1995

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

## Run 1A:

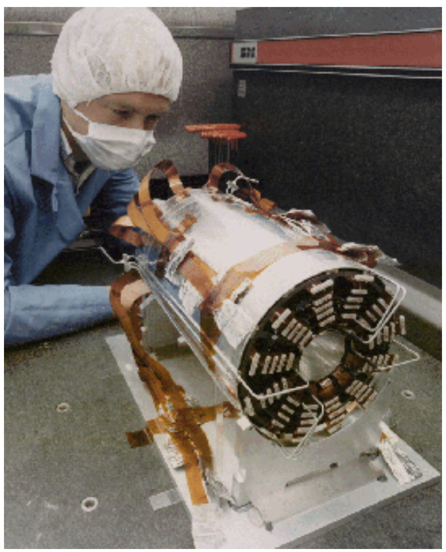
- D0: optimized search for $M_{top}$=100 GeV

| | | |
|---|---|---|
| – $e\mu$+≥1jet+MET | 1 evt | (1.1 bkg) |
| – ee+≥1jet+MET | 1 | (0.5) |
| – e+≥4jets+MET | 1 | (2.7) |
| – $\mu$+≥4jets+MET | 0 | (1.6) |

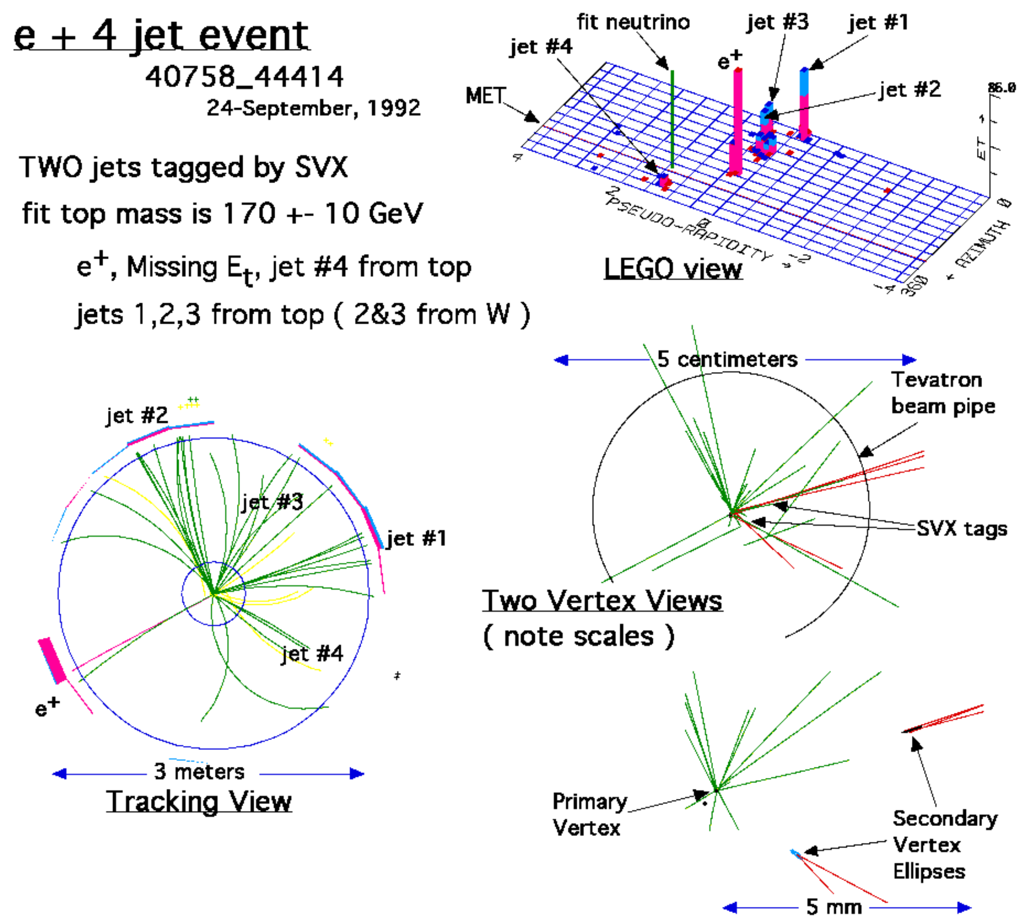
⇒$M_{top}$>131 GeV@95%CL

# Detecting the top quark at CDF

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



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

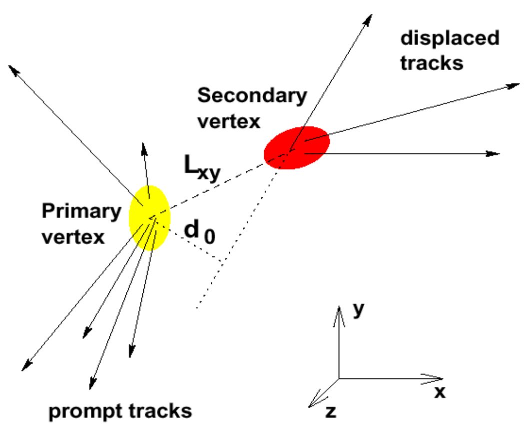


# Tagging b-jets

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

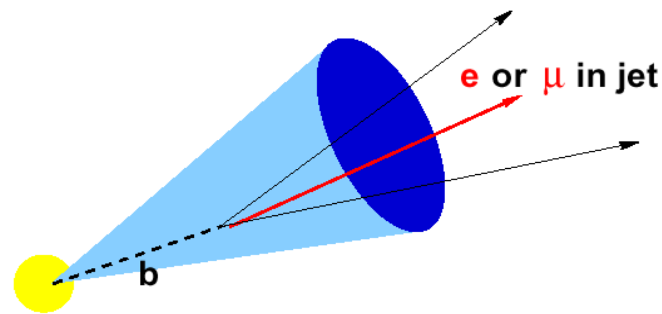
## B hadrons are long-lived

### Vertex displaced tracks




## semileptonic B hadron decay

### Soft Lepton Tagging




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

| Vertex displaced tracks | | Soft Lepton Tagging |
|---|---|---|
| **55%** | ← **Top Event Tagging Efficiency** → | **15%** |
| **0.5%** | ← **False Tag Rate (QCD jets)** → | **3.6%** |

# 1993

Coll. Meeting, Aug. 1993:

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

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

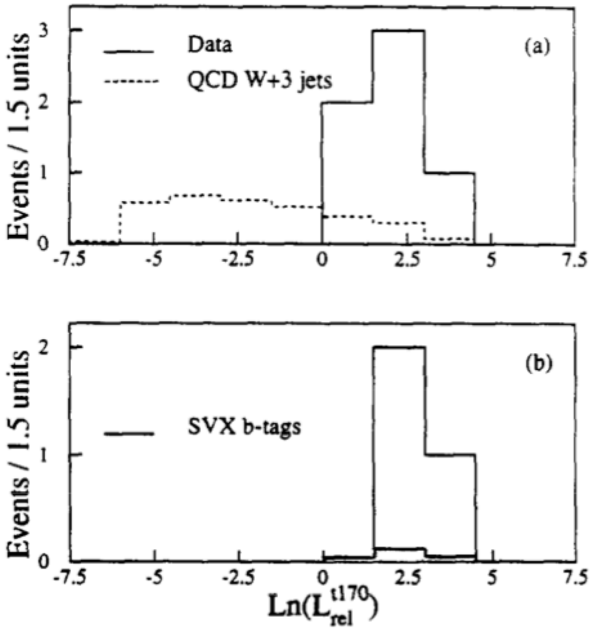
3 events in common

- 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)

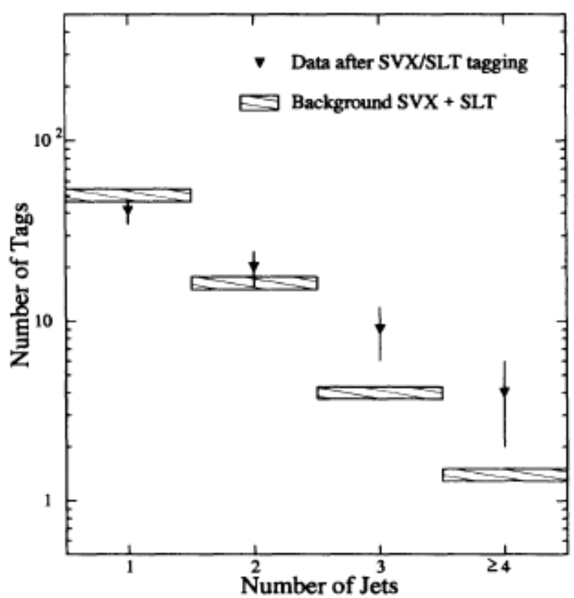
- Observed 7 events (expect 4-6 from bkg)
- No independent evidence

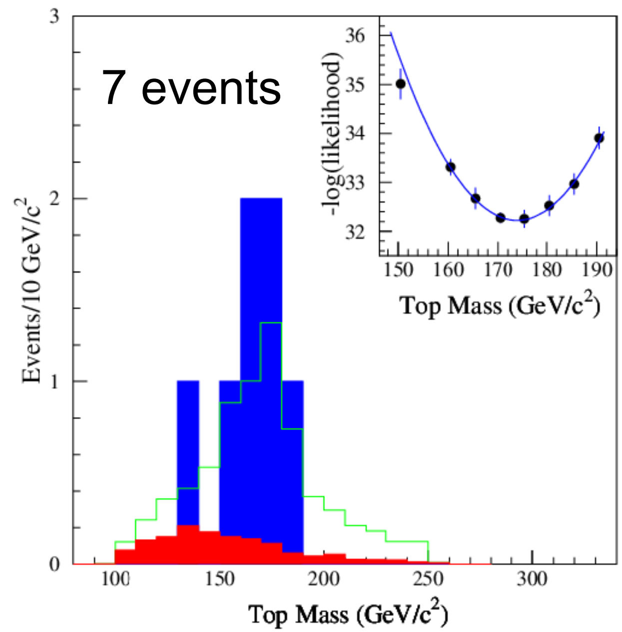
# First evidence (1994)

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 pb$^{-1}$. We find 12 events consistent with either two $W$ bosons, or a $W$ boson and at least one $b$ jet. The probability that the measured yield is consistent with the background is 0.26%. Though the statistics are too limited to establish firmly the existence of the top quark, a natural interpretation of the excess is that it is due to $t\bar{t}$ production. Under this assumption, constrained fits to individual events yield a top quark mass of $174 \pm 10^{+13}_{-12}$ GeV/$c^2$. The $t\bar{t}$ production cross section is measured to be $13.9^{+6.1}_{-4.8}$ pb.



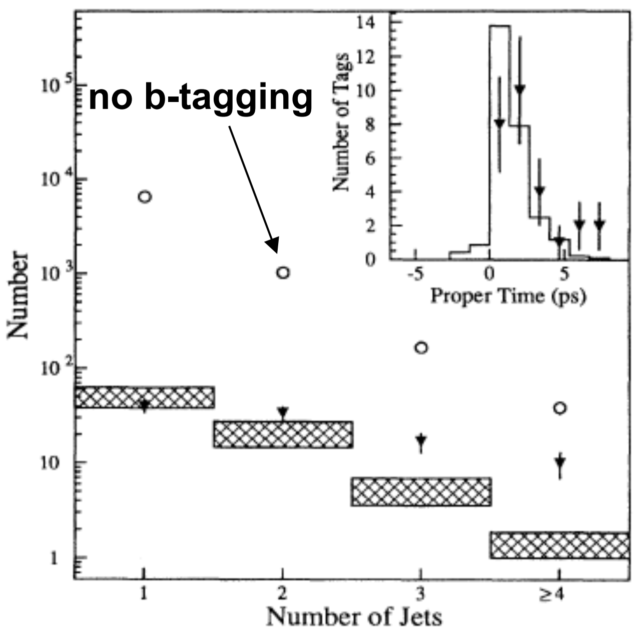



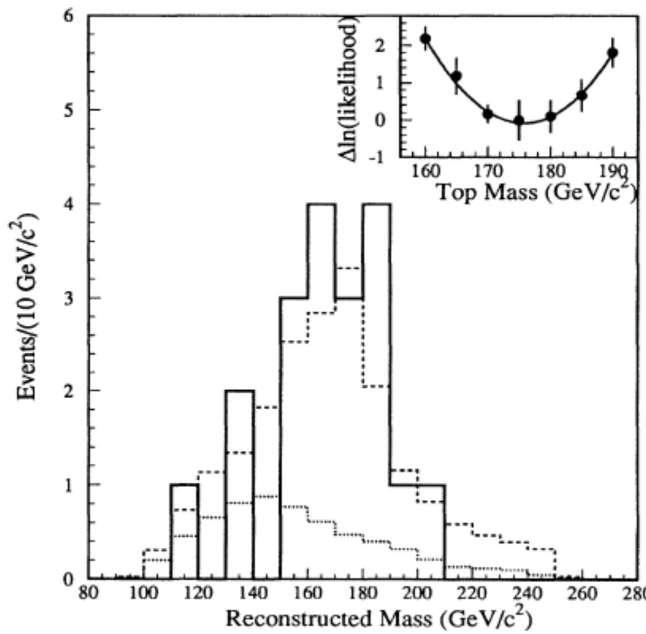
# First measurements

VOLUME 74, NUMBER 14 PHYSICAL REVIEW LETTERS 3 APRIL 1995

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

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



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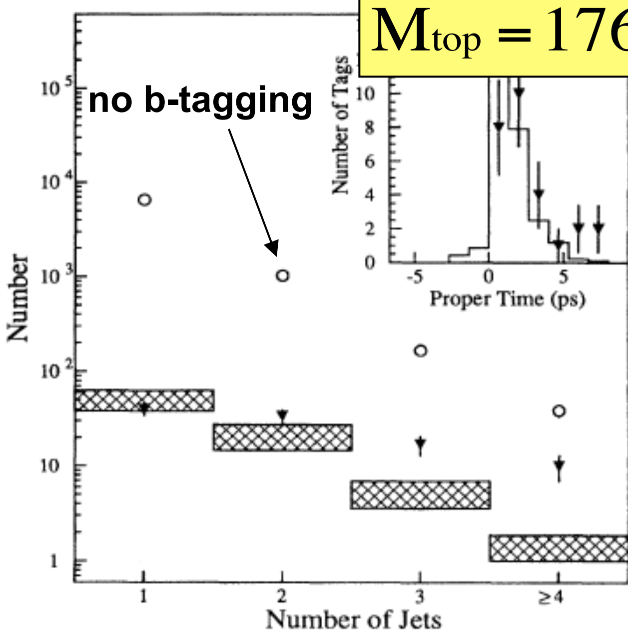
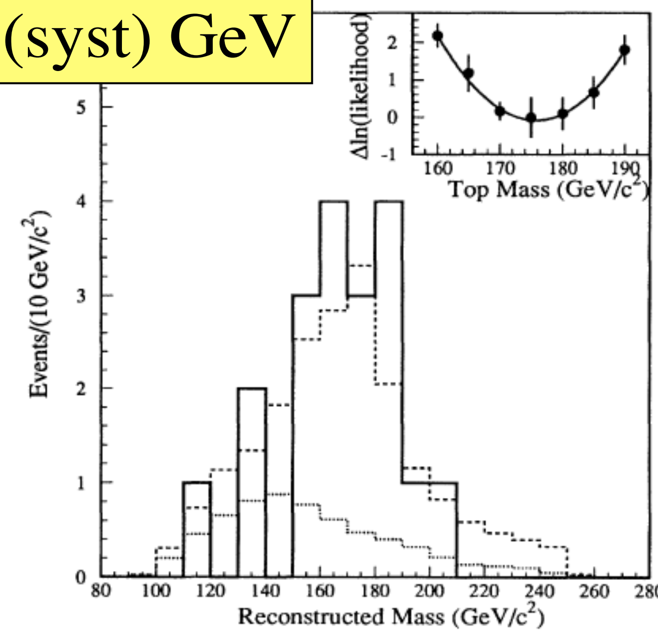
$$\sigma_{tt} = 6.8^{+3.6}_{-2.4}\ \text{pb}$$

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



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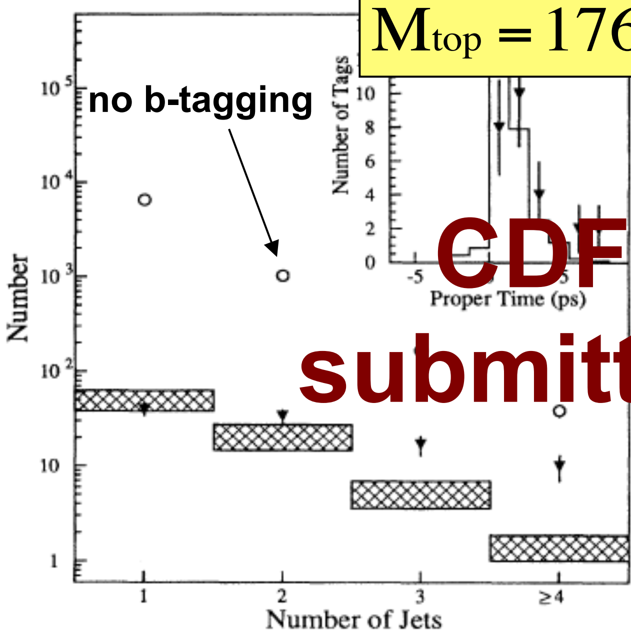
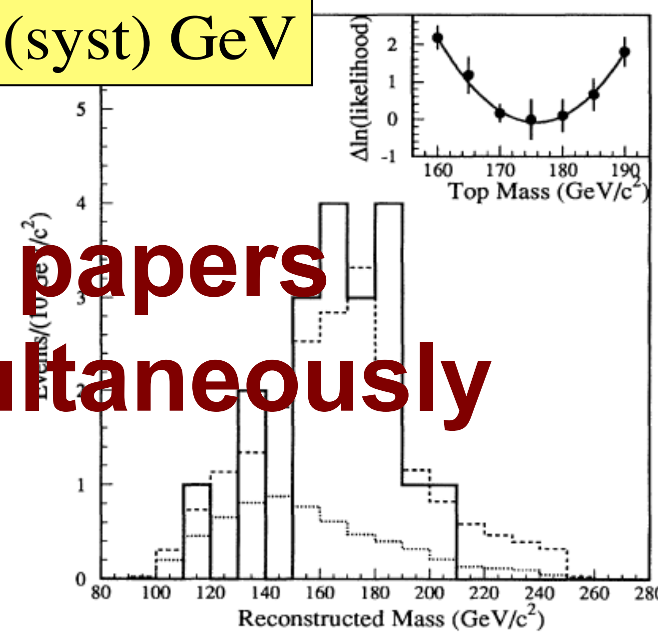
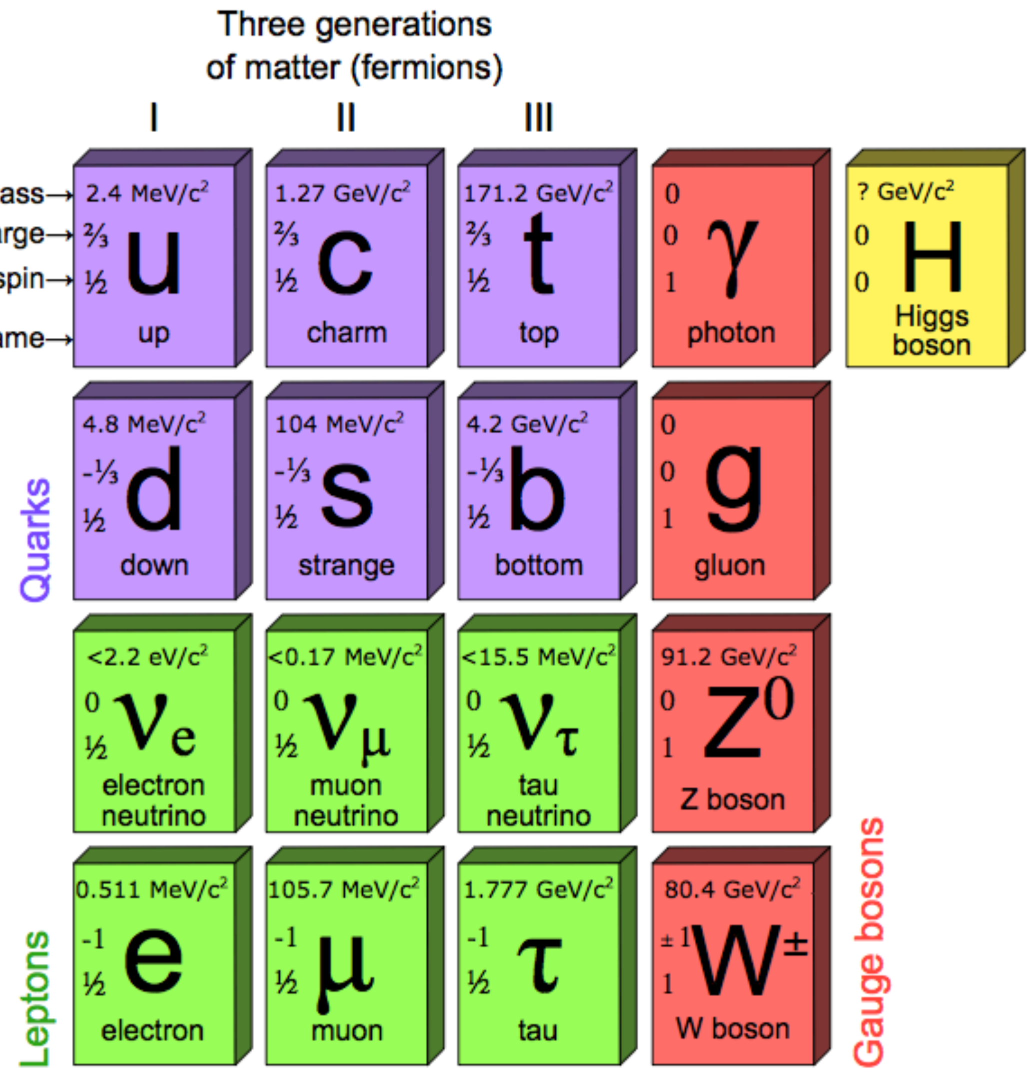



**CDF and D0 papers submitted simultaneously**

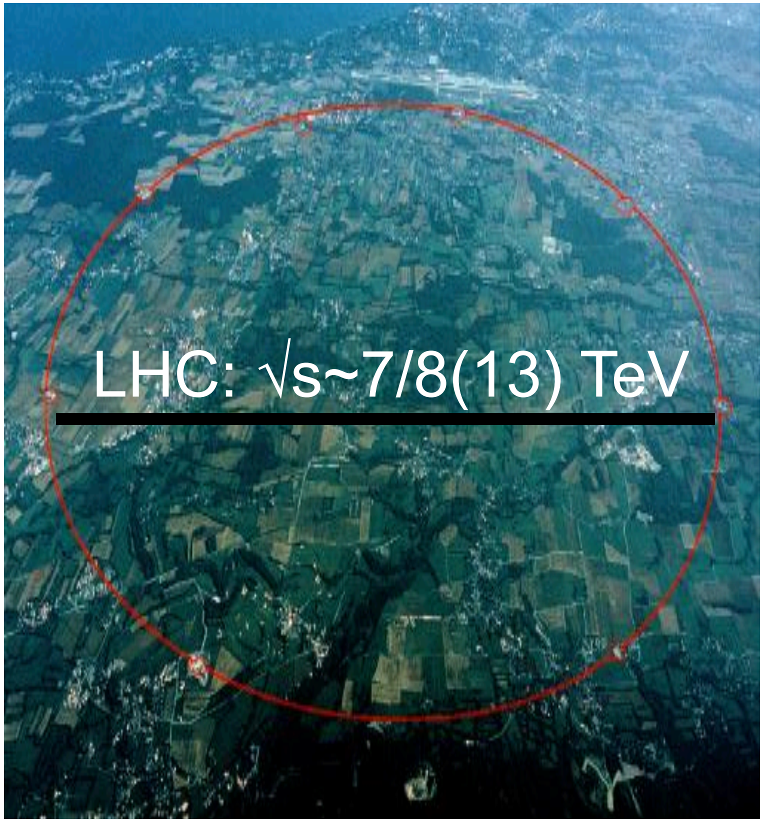
# Top quark and its relevance

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



# The Large Hadron Collider

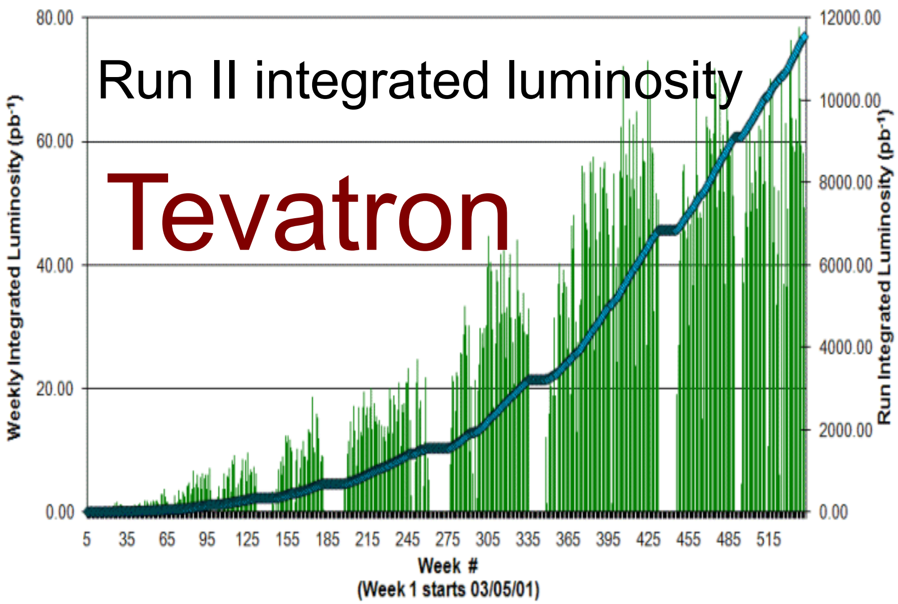
- Built to explore new energy frontiers
  - First colliding beams in 2009
  - started with "low" luminosity in 2010
  - ~5 $fb^{-1}$@7TeV delivered in 2011
  - ~20 $fb^{-1}$@8TeV in 2012
  - ~2 $fb^{-1}$@13TeV in 2015
  - ~36$fb^{-1}$@13 TeV in 2016

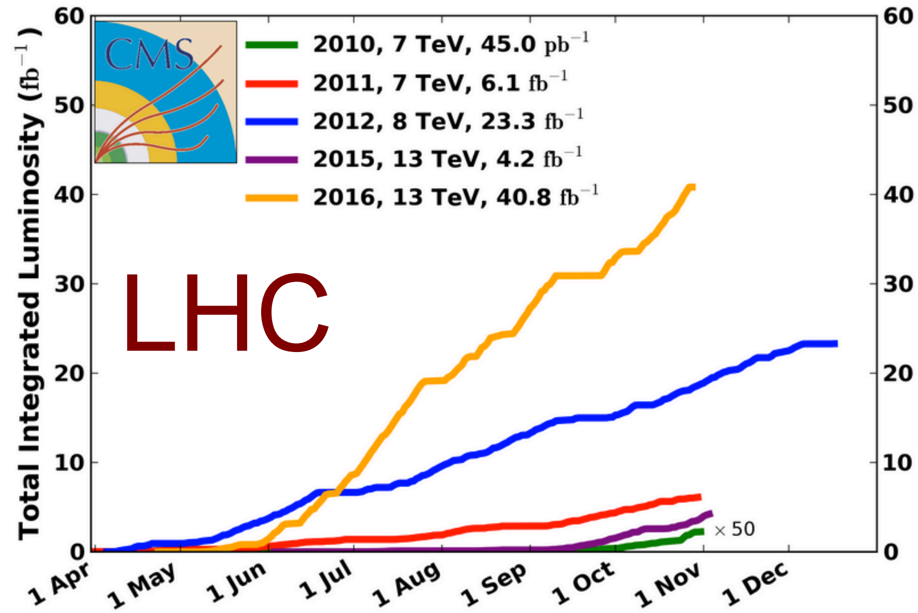



- re-establish SM measurements
- access to new physics processes

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

# Tevatron vs LHC



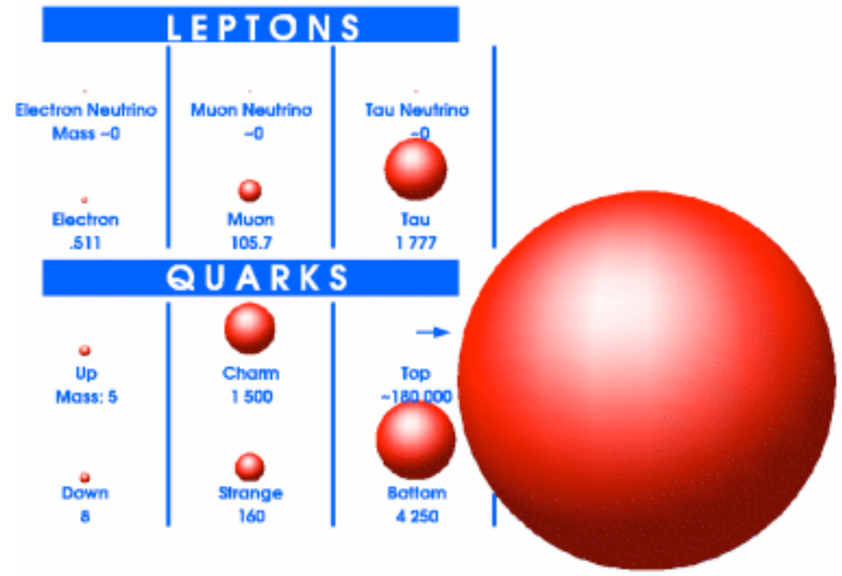

Energy: 1.96 TeV
Int. Luminosity: 12 $fb^{-1}$
Age: ~25 years
Events/exp (1 $fb^{-1}$)
400 ee eμ, μμ
3.5k lepton + jets

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

# What is the Top quark?

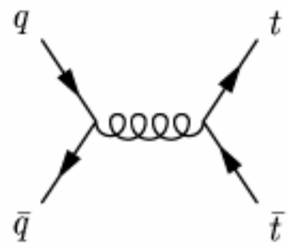
$$\text{Quarks:} \quad \begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} t \\ b \end{pmatrix}$$

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

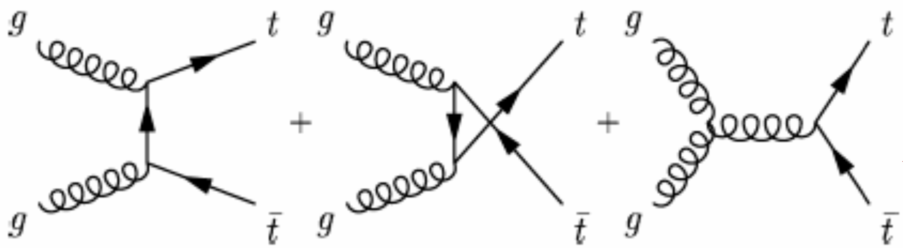



- It is the heaviest fundamental particle
  - $M_{top} = 174.3 \pm 0.6$ GeV (arXiv:1407.2682)
- Weak isospin partner of the b-quark
- Completes the SM of quarks and leptons

# How is the top quark produced?




Dominant at Tevatron




Dominant at the LHC

**Predicted cross sections:**

The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

For $m_t = 172.5$ GeV

$\sqrt{s} = 1.96$ TeV: $\sigma(pp \to t\bar{t})_{NNLOapprox} = 7.46^{+0.48}_{-0.67}$ pb

$\sqrt{s} = 7$ TeV: $\sigma(pp \to t\bar{t})_{NNLOapprox} = 164.6^{+11.4}_{-15.7}$ pb

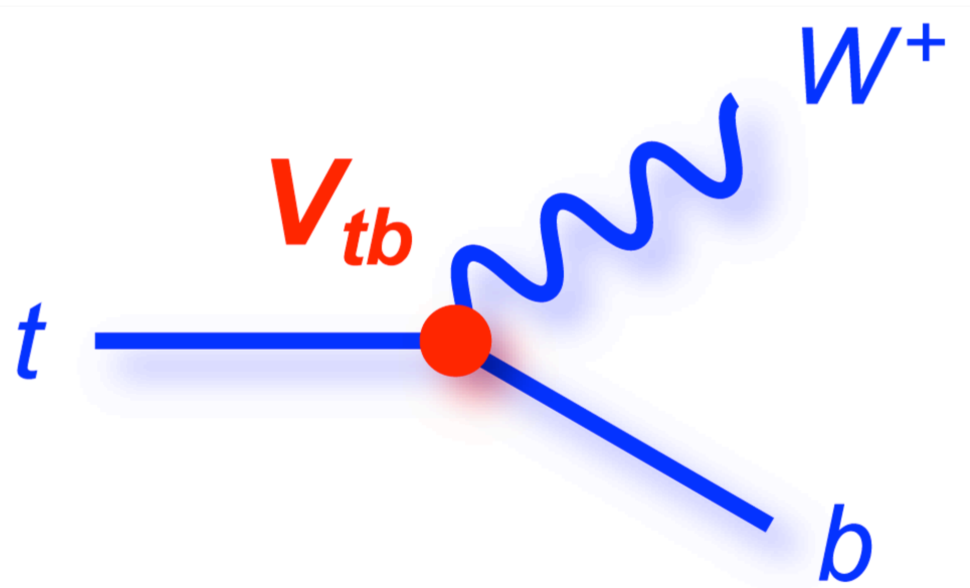
.


Lanenfeld et al. PRD 80, 054009 (2009)
Aliev et al., Comp. Phys. Comm. 182, 1034 (2011)
Kidonakis, Phys. Rev. D82, 114030 (2010)
Ahrens et al., JHEP 1009, 097 (2010) arXiv:1105.5824


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

Czakon et al. PRL 110, 252004 (2013)

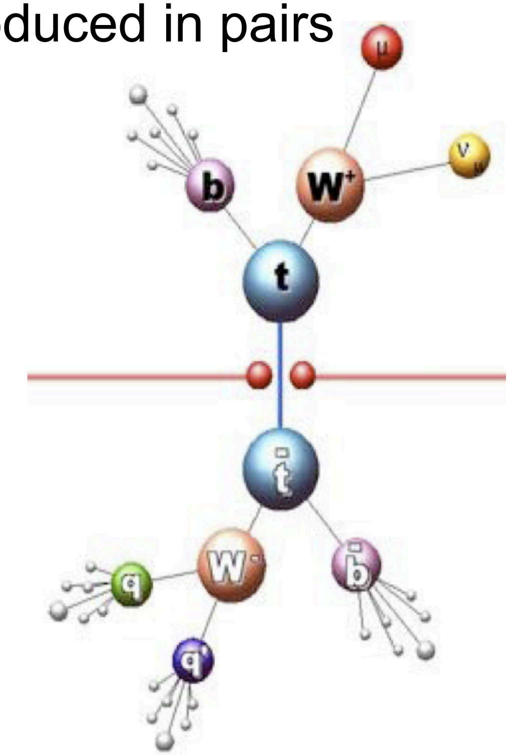
# How does a top quark decay?

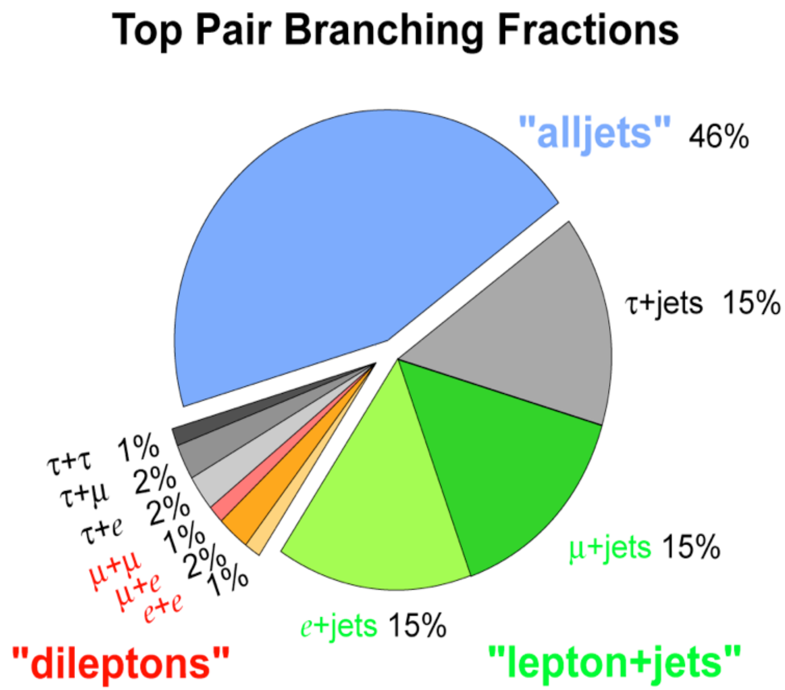



- almost always $t \rightarrow Wb$ (i.e. $V_{tb} \sim 1$)
- lifetime is short, and it decays before hadronizing
- the W is real:
  - can decay $W \rightarrow l\nu$ ($l=e,\mu,\tau$), BR~1/9 per lepton
  - can decay $W \rightarrow qq$, BR~2/3

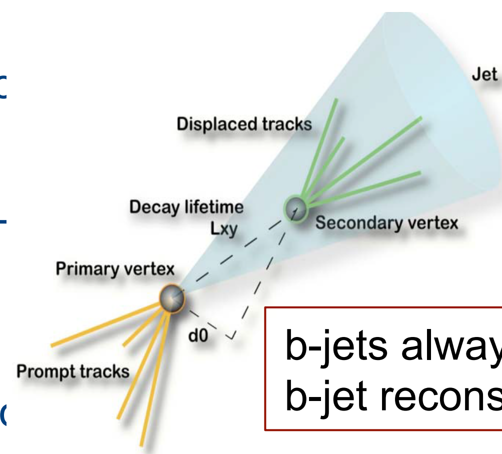
# Top quark decays

Top quarks (mostly) produced in pairs



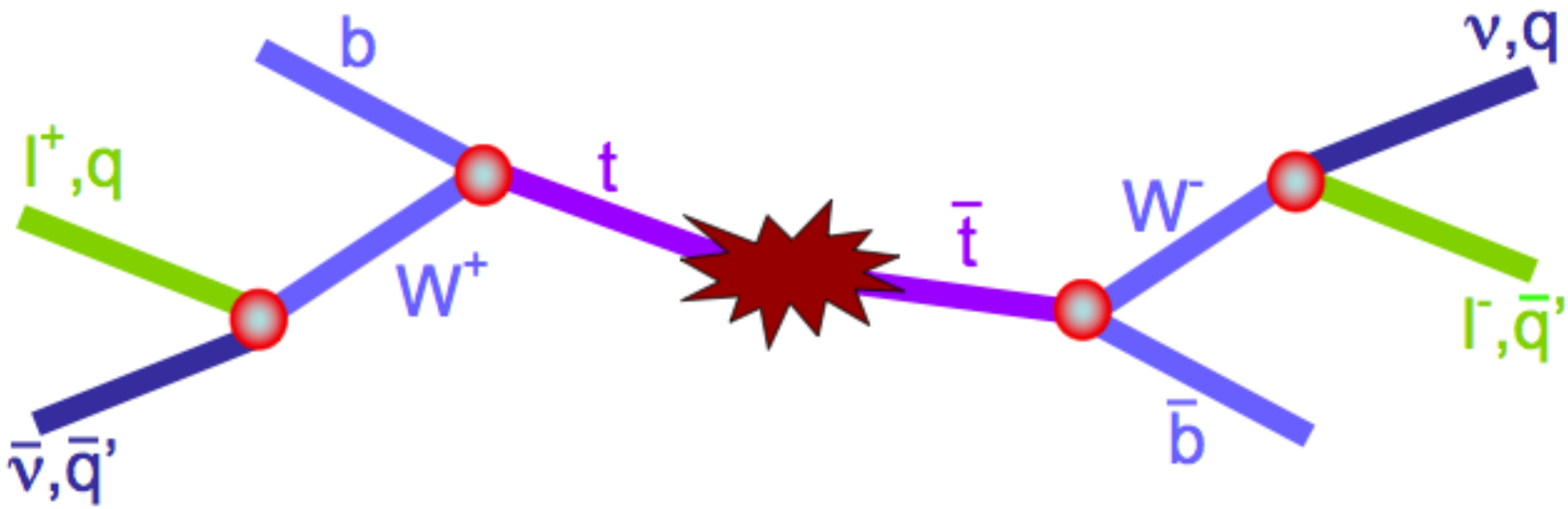




- Dilepton (ee, μμ, eμ):
  - BR~5%, 2 leptons+2 b-jets+2 neutrinc
- Lepton (e or μ) + jets
  - BR~30%, one lepton+4jets (2 from b)+ neutrino
- All hadronic
  - BR~44%, 6 jets (2 from b), no neutrinc




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

# Interesting physics with Top quark




**PRODUCTION**

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

**PROPERTIES**

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

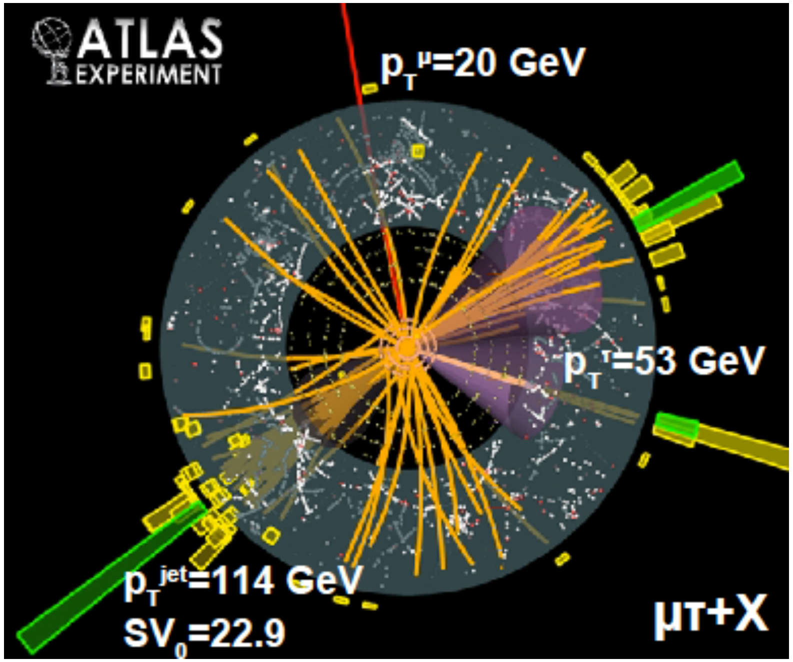
**DECAY**

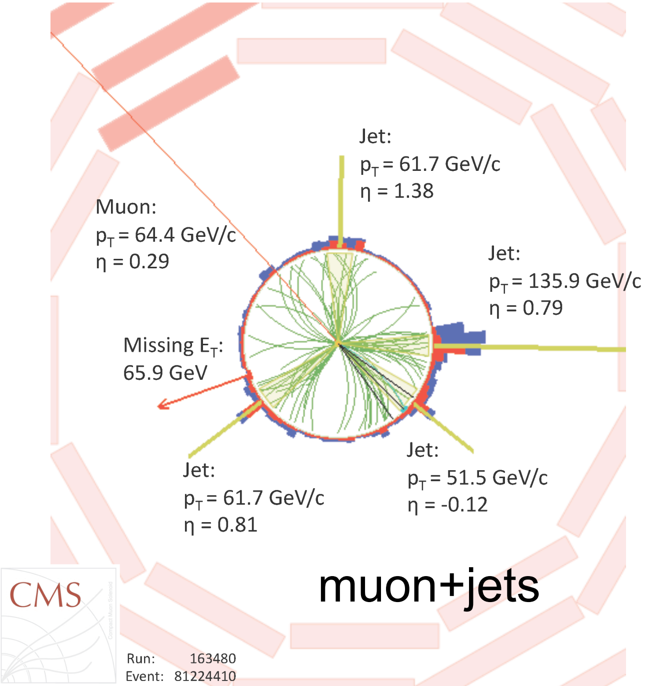
Branching ratios
Charged Higgs (non-SM)
Anomalous couplings
Rare decays
CKM matrix elements
Calibration sample @LHC
...

# Particle identification

- Object identification and reconstruction

# Selection of top quark events

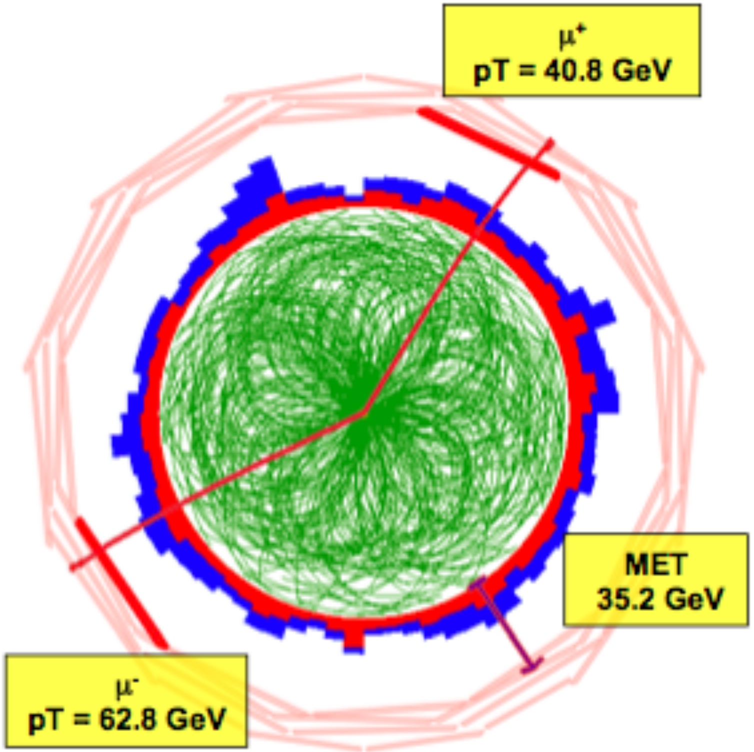


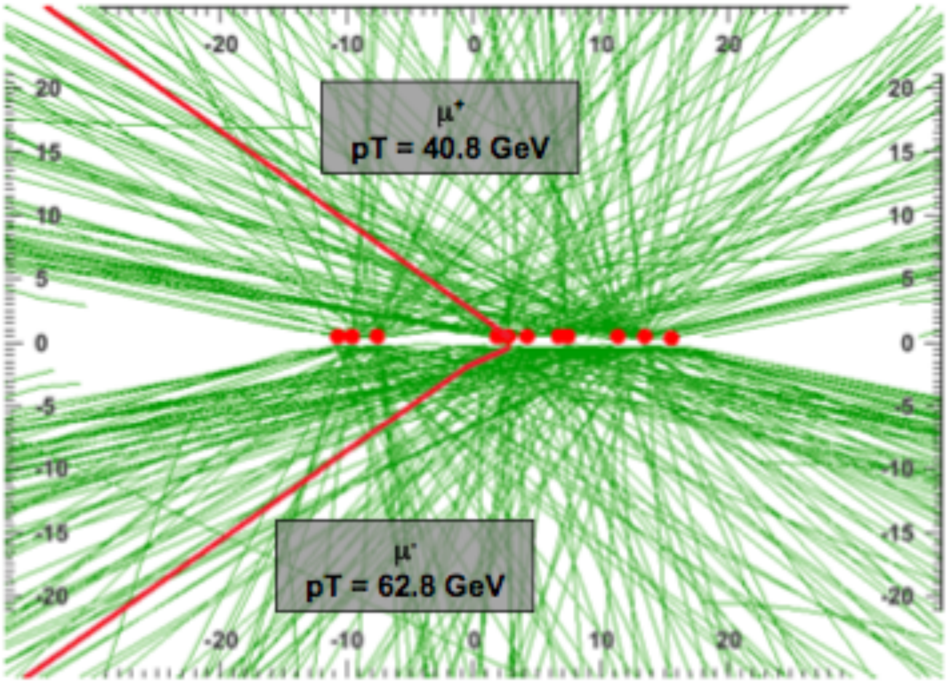

- Trigger:
  - single or double (isolated) lepton
- Leptons:
  - e/μ, $p_T$>20/30 GeV, |η|<2.5
  - Identification/reconstruction
  - Tracker/calorimeter isolation
- Jets:
  - at least 2 jets, $p_T$>30 GeV, |η|<2.5
  - anti-kT algorithm, with cone 0.4-0.5
  - b-tagging is optional
- Missing transverse energy:
  - Typically require 30-40 GeV

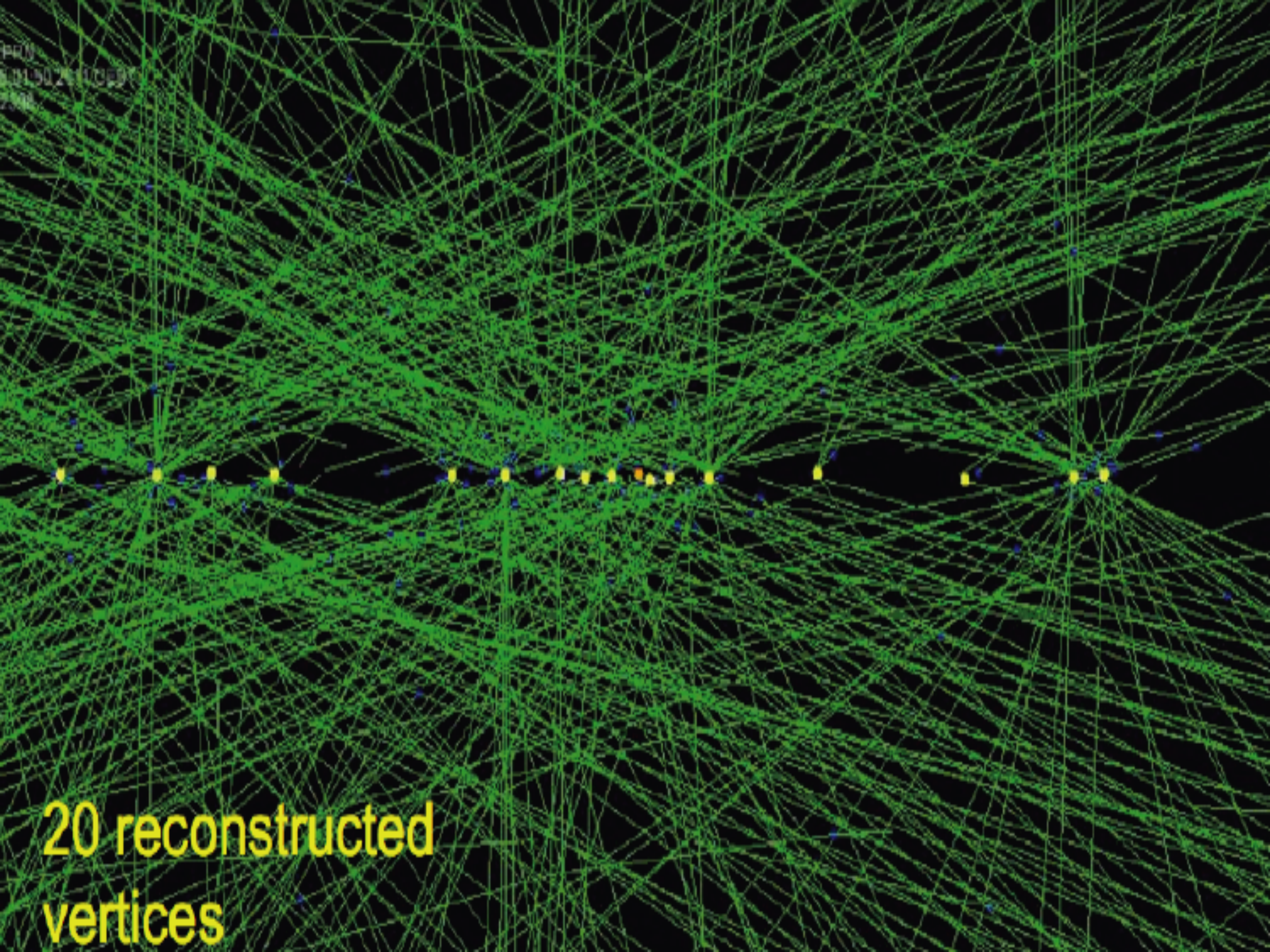
# Challenge: Pile-up

$Z \to \mu\,\mu$
Expected MET = 0



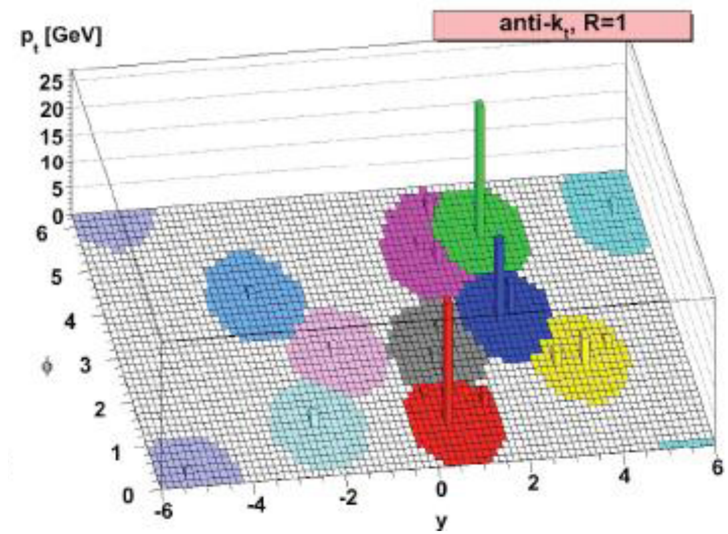

10 in-time + 10 out – of – time pileup




20 reconstructed
vertices

# Jet reconstruction

- A "jet" is a cluster of energy deposited in a "small" $\eta-\phi$ 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

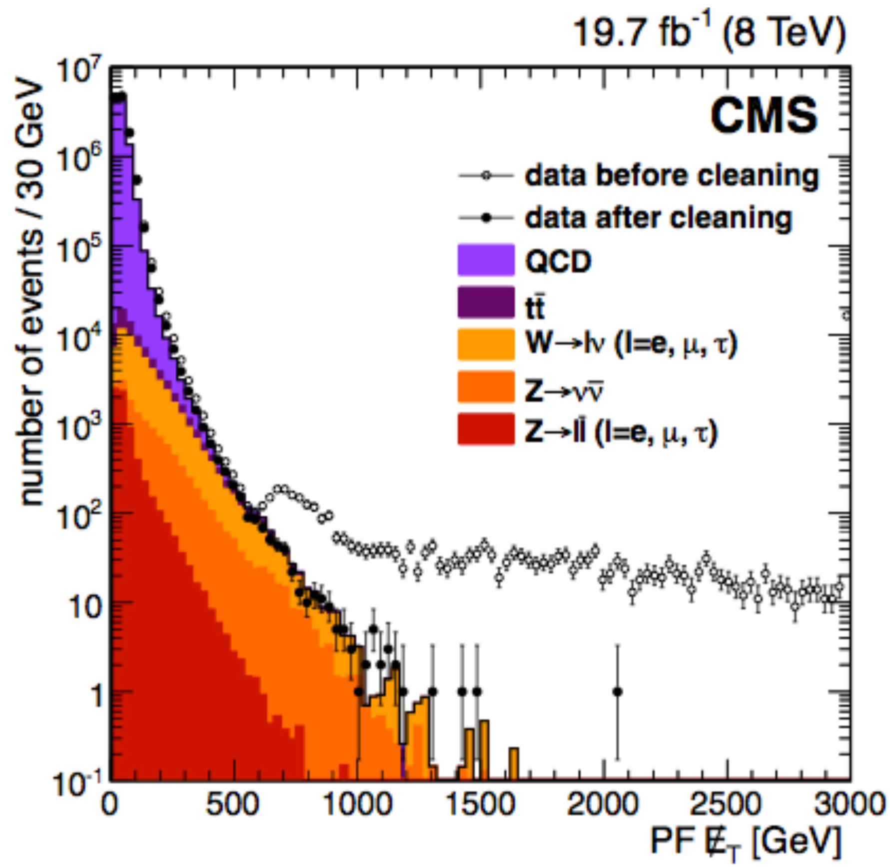
transverse energy vector

$$\boldsymbol{E}_T^{\mathrm{miss}} = -\sum_i \boldsymbol{p}_T(i)$$

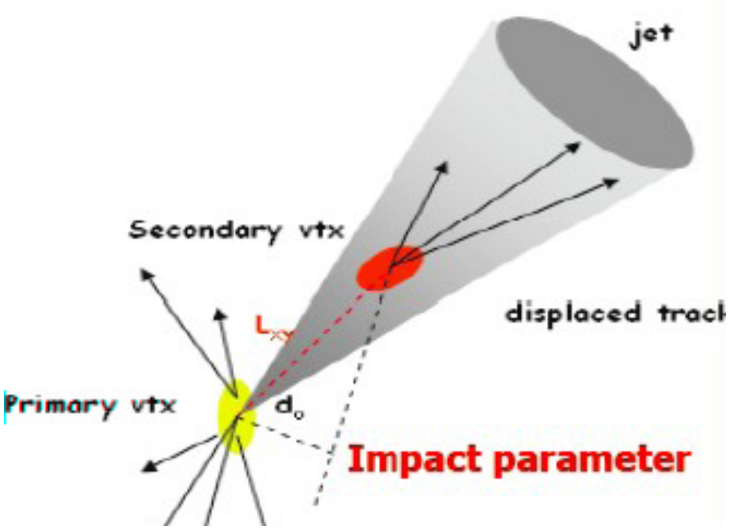
where the sum runs over the transverse momenta of all visible final state particles.

# 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

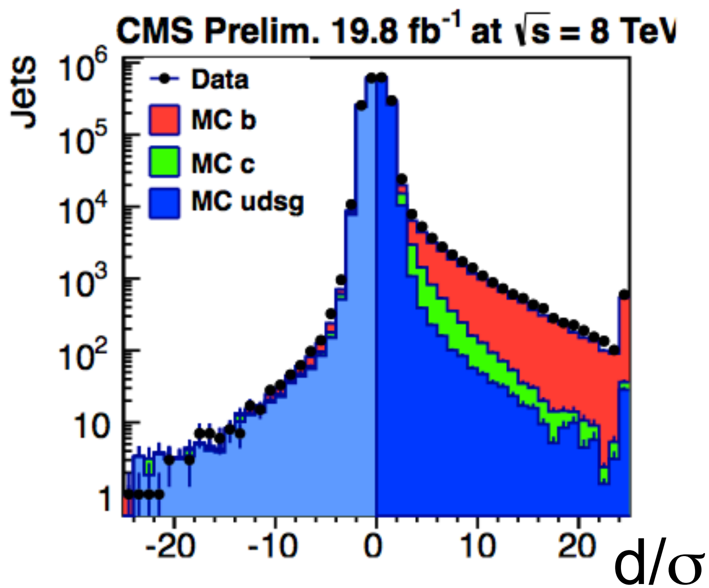


# Challenge: b-tagging




- Lifetime: $\tau_b$~1-2 psec
- Reduction of background obtained by identifying jets from b-quarks
- Two methods:
  - Secondary vertex tagging
  - Semileptonic decays of b-hadrons in jets

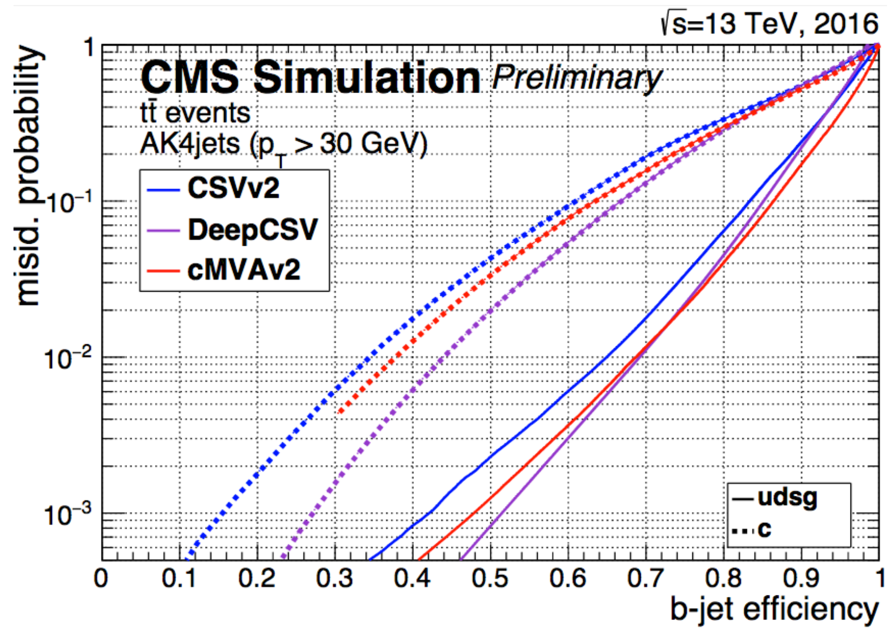
$$( b \rightarrow \ell \nu_\ell X )$$

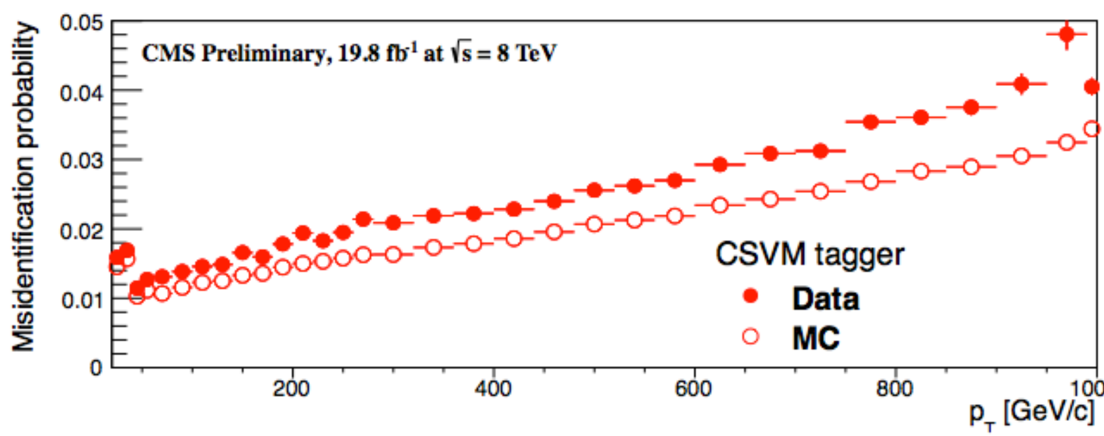



# b-tag: fake rates and efficiencies

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



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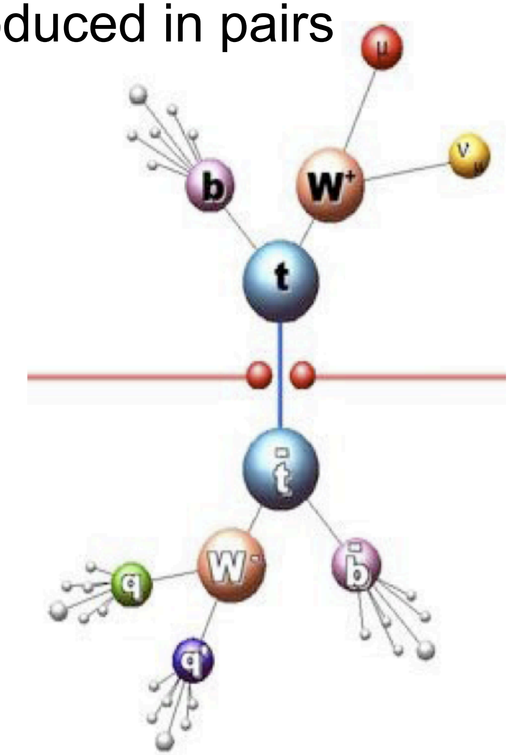
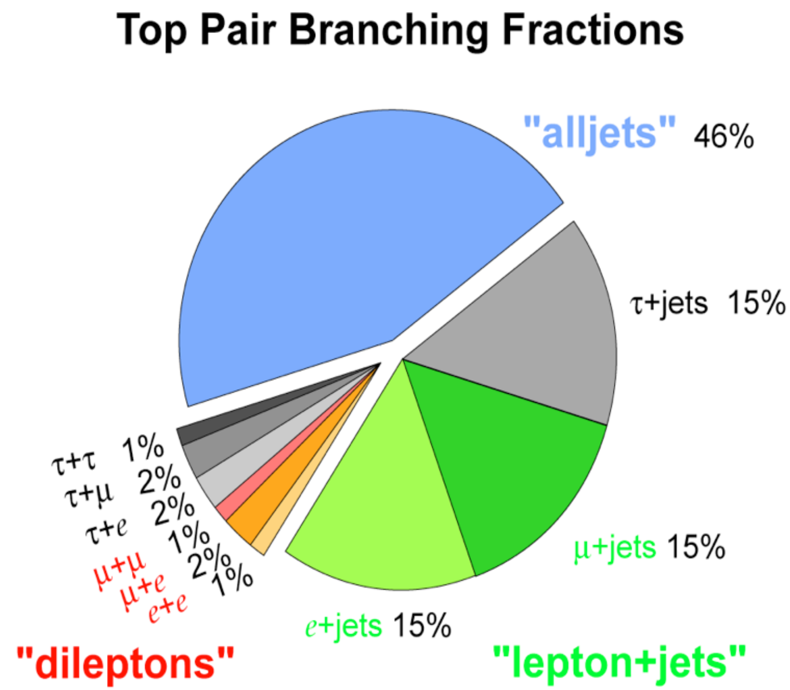
Top quarks (mostly) produced in pairs




- Dilepton (ee, μμ, eμ):
  - BR~5%, 2 leptons+2 b-jets+2 neutrinos
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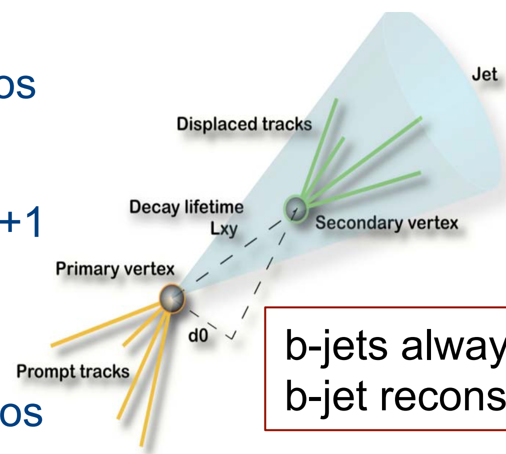
- All hadronic
  - BR~44%, 6 jets (2 from b), no neutrinos



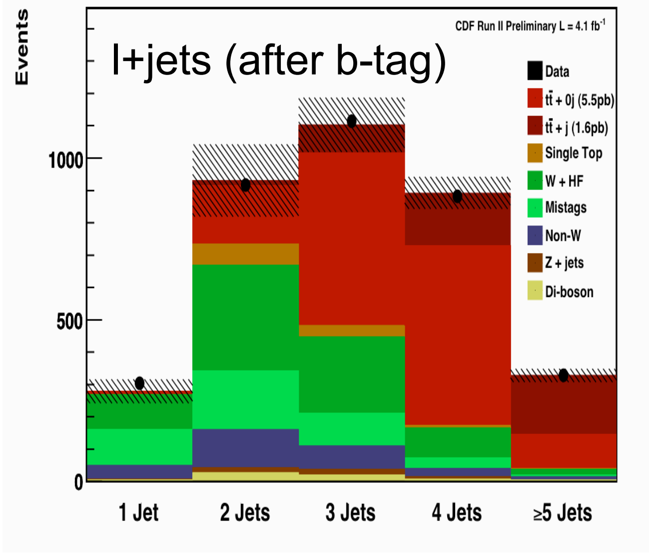

b-jets always present
b-jet reconstruction plays important role

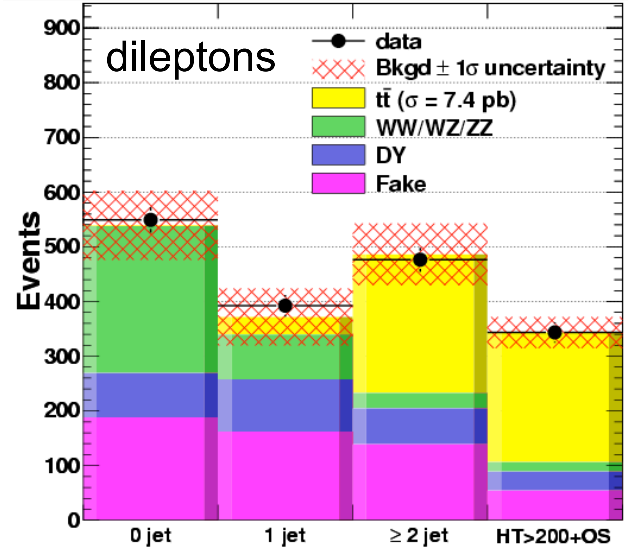
# Measurements

- Measurement of the cross section

# Top quark events

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



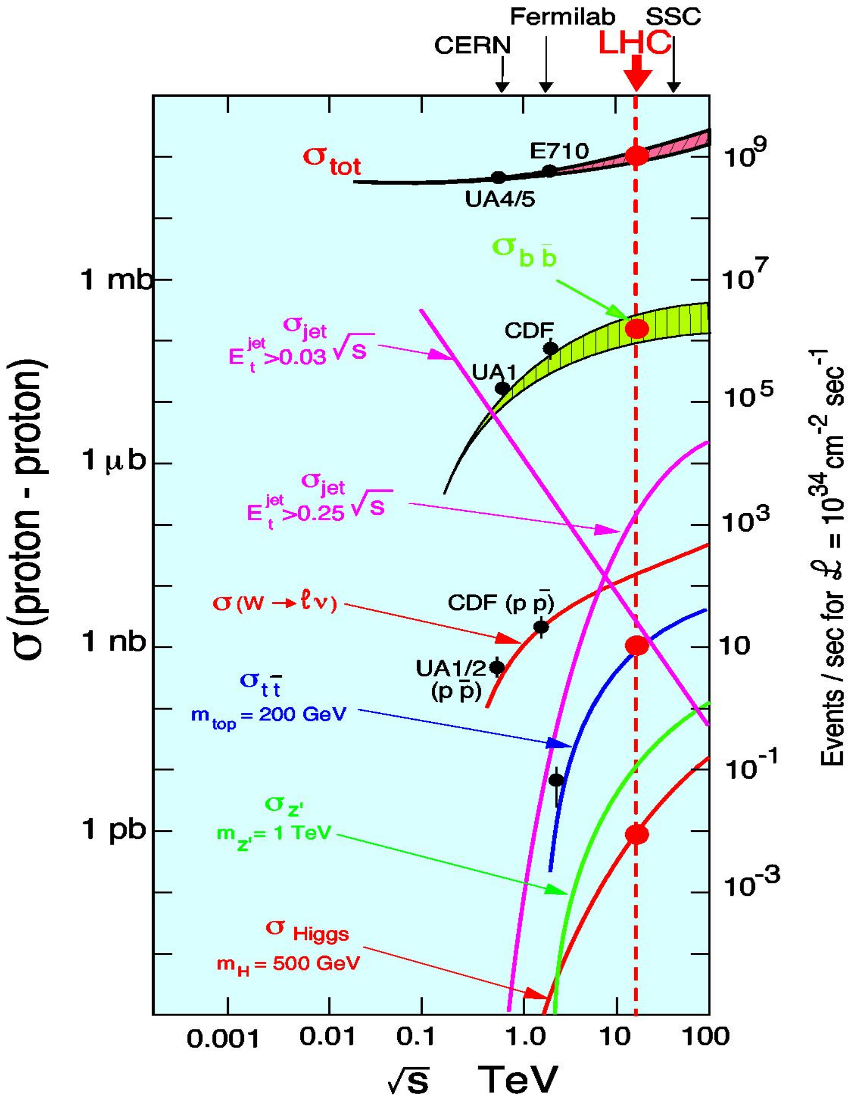
# Theory cross sections: TeV vs LHC

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



# Cross section measurement

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

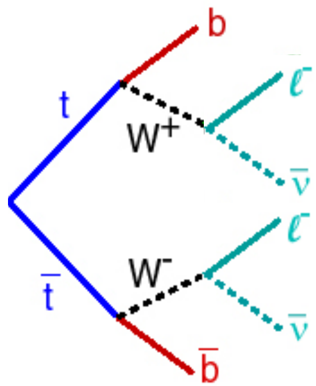
Number of observed events

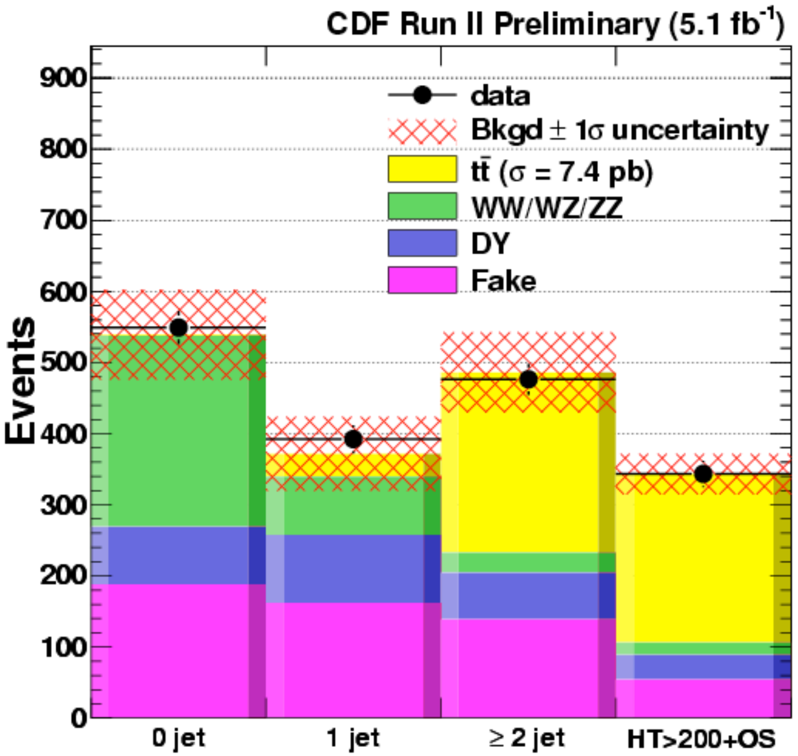
Number of background events *(from data, calculated from theory)*

Acceptance *(experimental: detector, efficiencies)*

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

# Dilepton channel



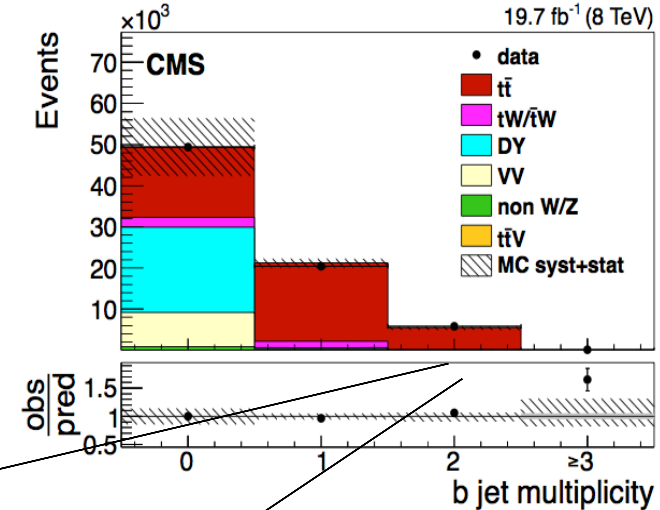

- Branching ratio (BR) ~5%
- Background: small

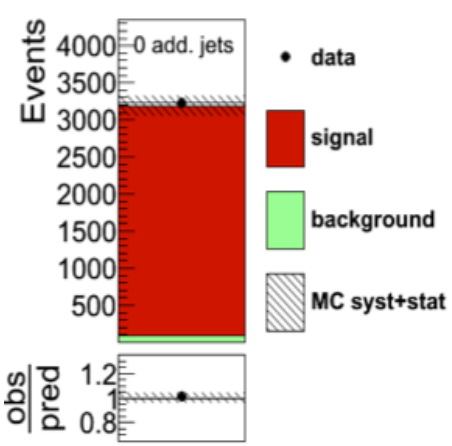
- Clean final state
  - two leptons + ≥2 jets + MET
  - kinematic variables
- Signal visible w/without b-tagging
- Main systematics: JES, lepton ID, (pileup, b-tag, signal modeling)

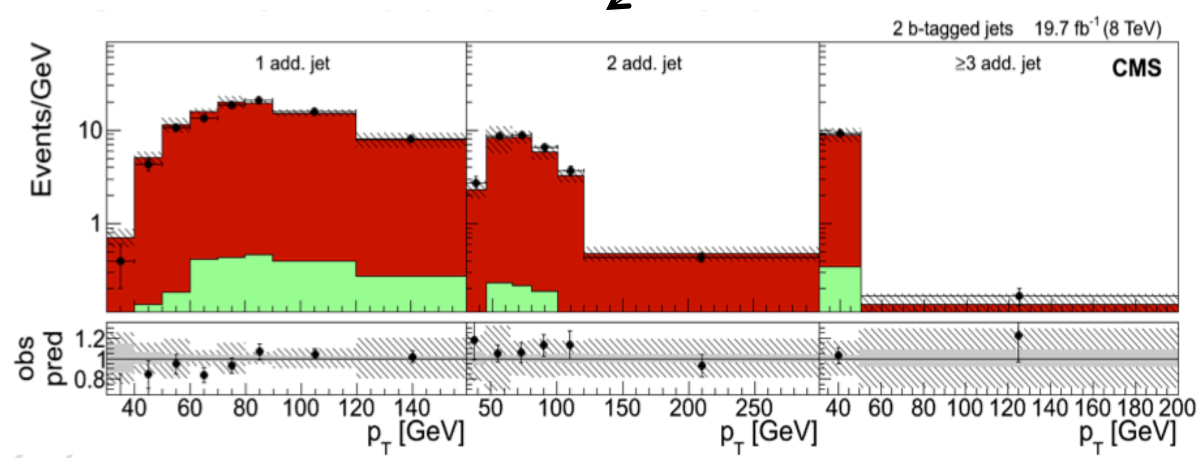
# Cross section: multi-dimensional fit

CMS-TOP-13-004

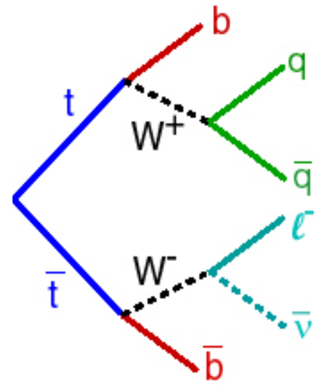
- Look into finer details
- Keep selection as inclusive as possible
- Re-calibrate in-situ ($\varepsilon_b$, …)
- Categorize: high-purity vs background dominated
- Constrain systematics (JES, ISR/FSR, modeling, etc)



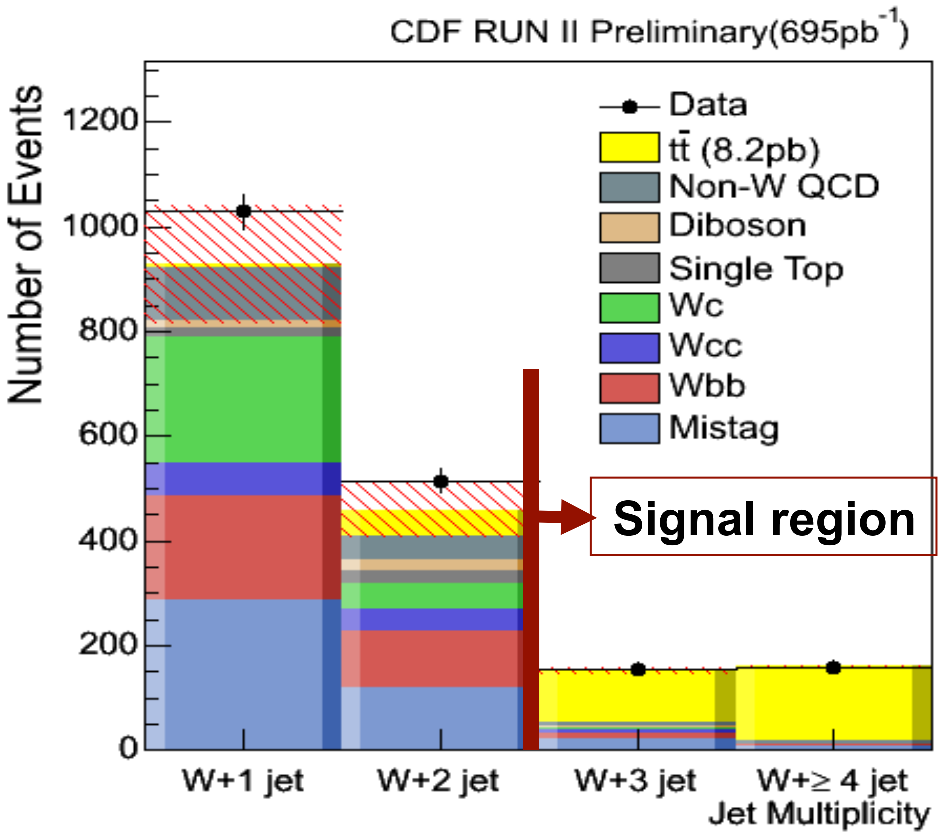
# Lepton + jets



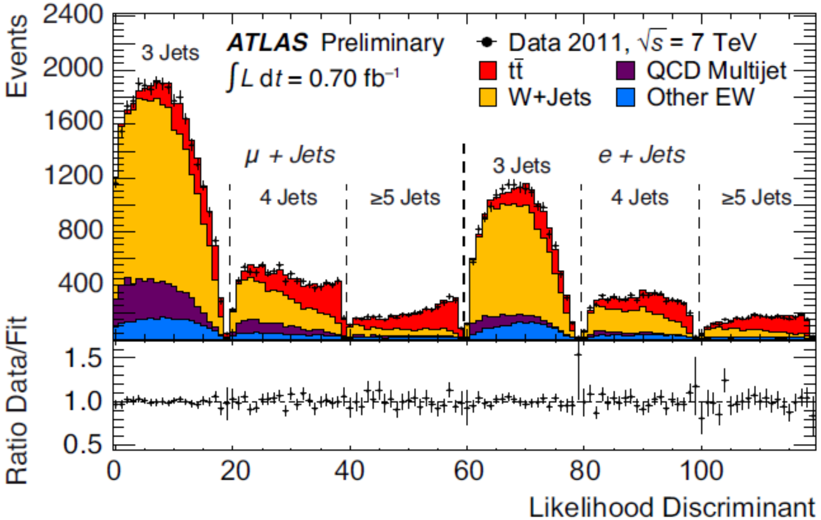

- BR ~30%
- Background: moderate

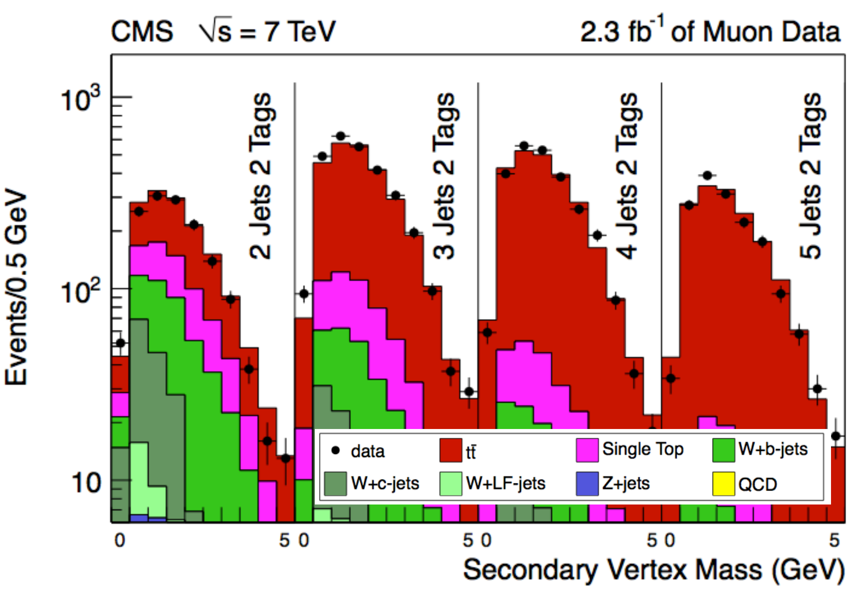
- Selection:
  - one lepton + ≥3 jets + MET
  - may require b-tag

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



# Lepton + jets channel (cont.)



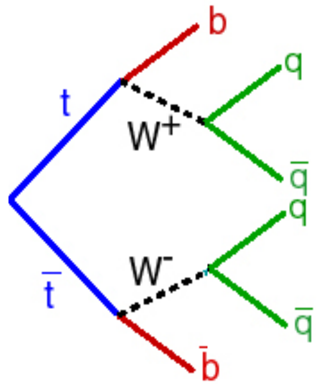

Use kinematics to select ttbar

- mass of sec. vertex
- topology, etc.

Categorize events and extract $\sigma_{tt}$ from fit

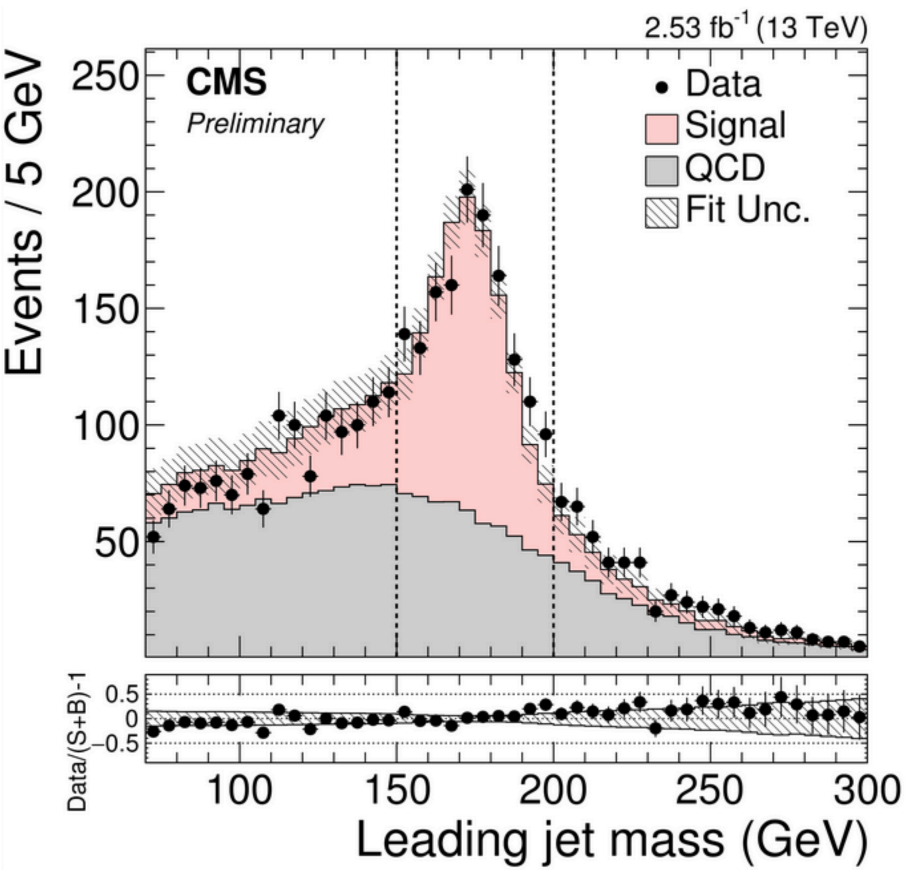
# All hadronic

CMS-PAS-TOP-16-013



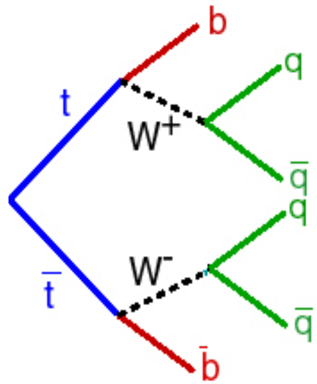

- BR ~46%
- Background: large

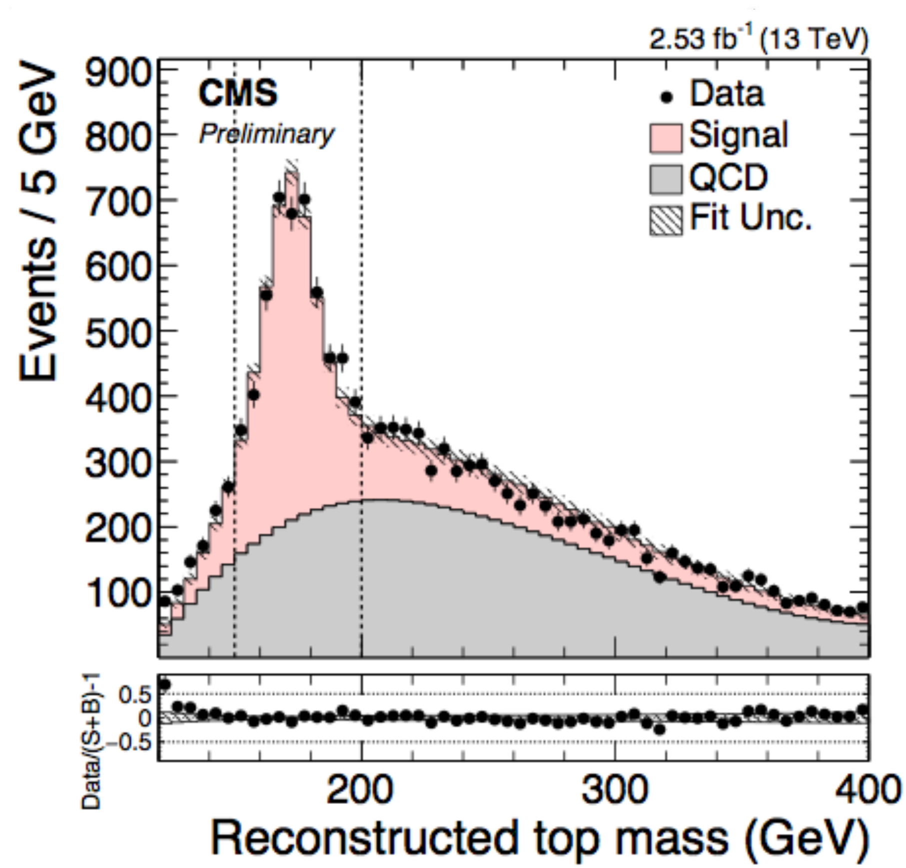
- Selection:
  - ≥6 jets + kinematical selection
  - require b-tag
- Main backgrounds:
  - hadronic multi-jet



# All hadronic

CMS-PAS-TOP-16-013



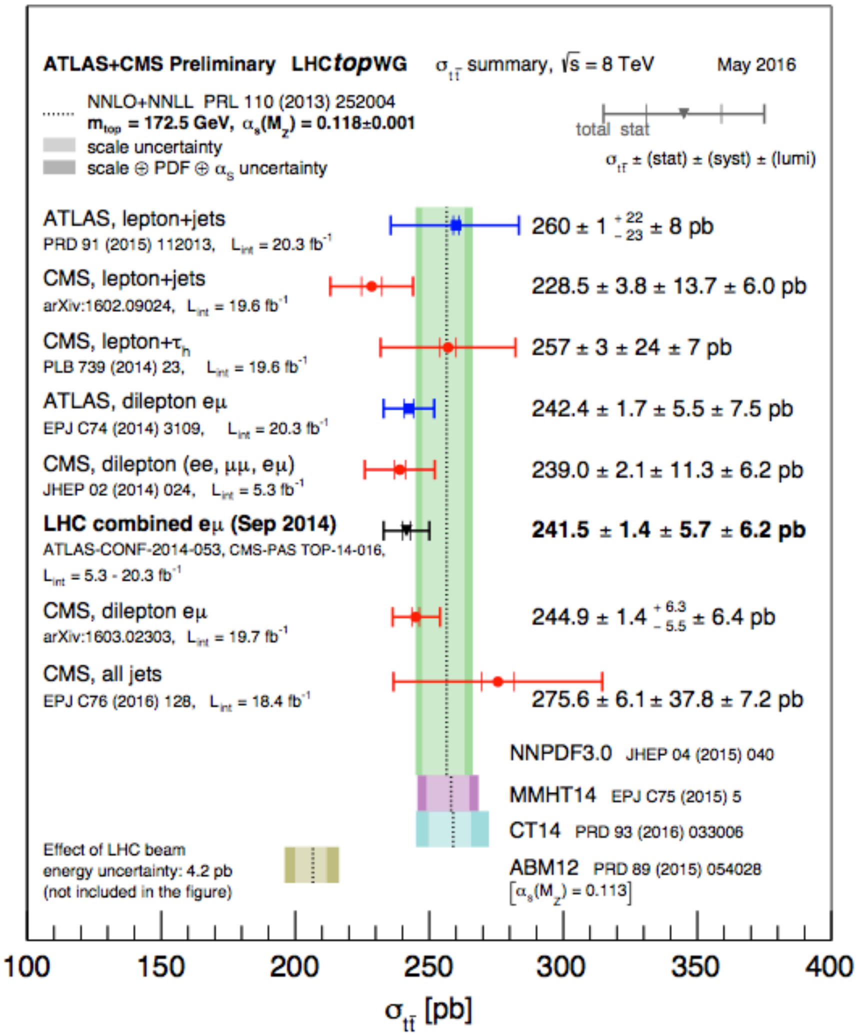




- BR ~46%
- Background: large

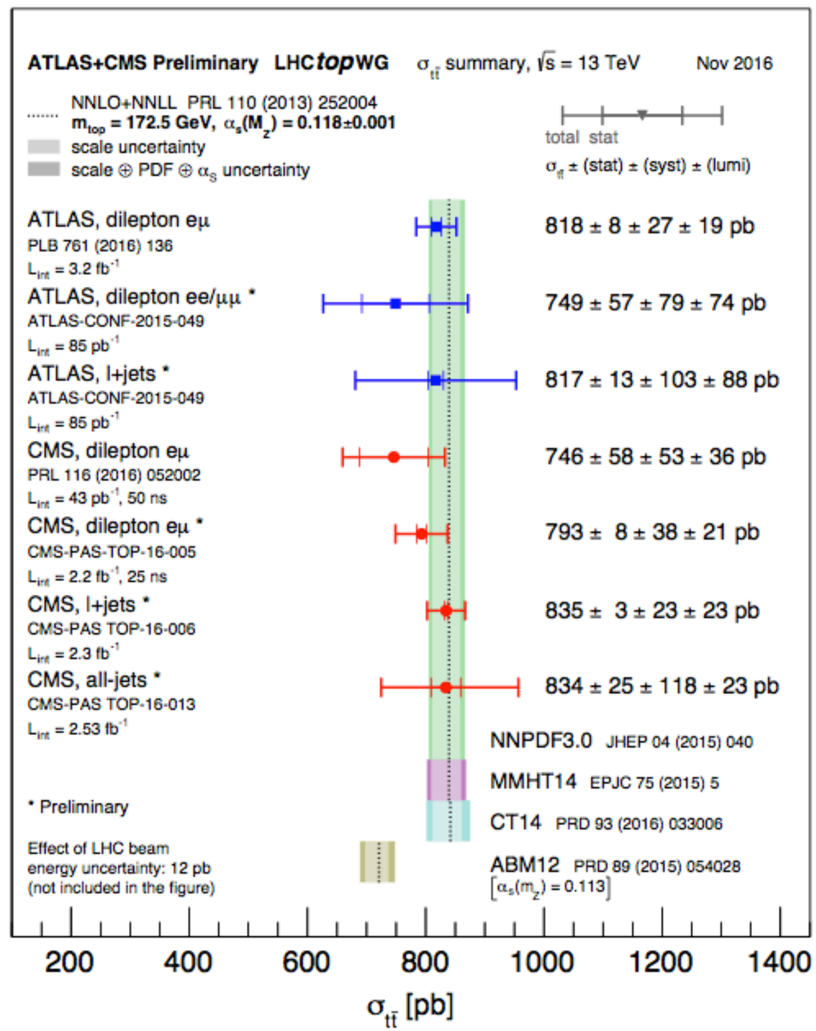
- Selection:
  - ≥6 jets + kinematical selection
  - require b-tag
- Main backgrounds:
  - hadronic multi-jet
  - same selection without b-tag

# LHC cross section measurements

## 8 TeV

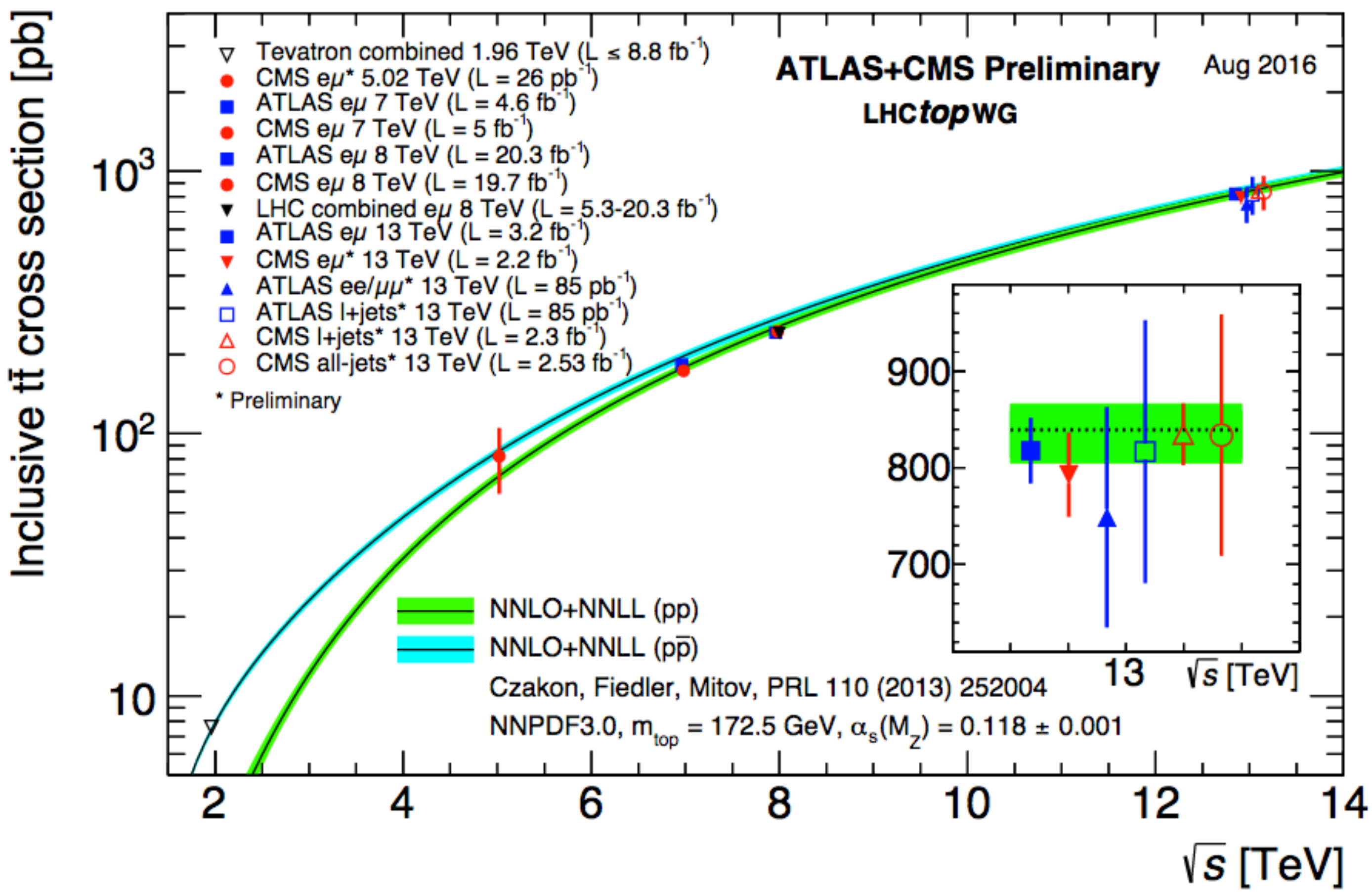



## 13 TeV



# Cross sections

- Cross section measurements provide test of pQCD predictions
- Standard "candle": ttbar is a dominant background for NP searches
- Comparison in different channels may provide constraints on BSM

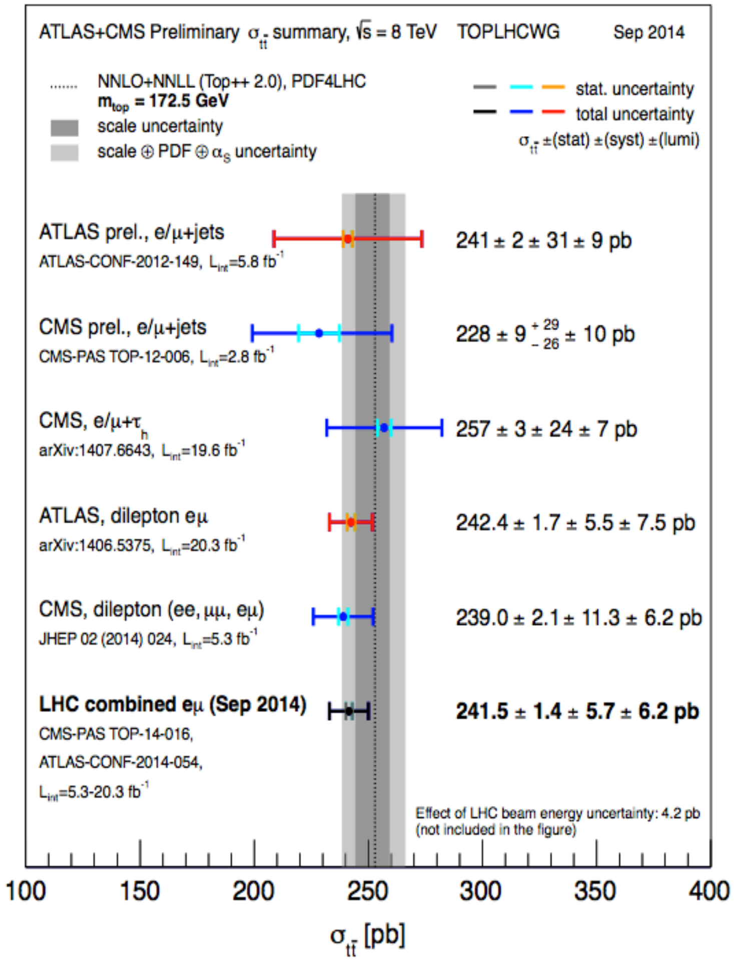



±5%

# Cross sections (cont.)

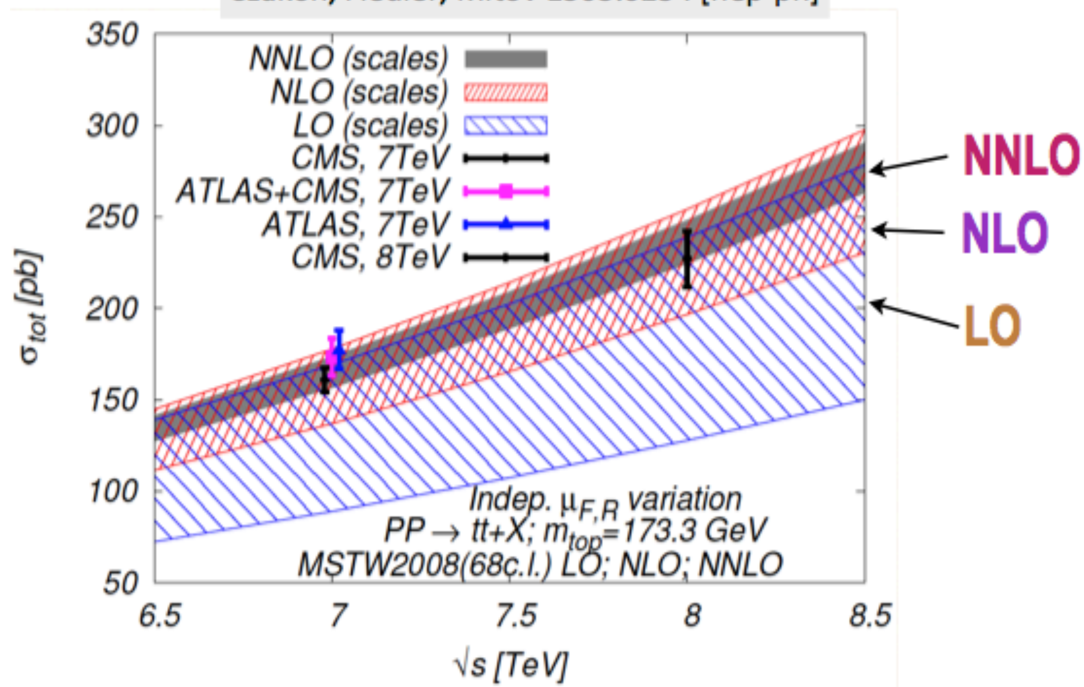
CMS-TOP-14-016

±4%




⇒meas. challenging the theory

Czakon, Fiedler, Mitov 1303.6254 [hep-ph]




| Collider | $\sigma_{tot}$ [pb] | scales [pb] | pdf [pb] |
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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%) |

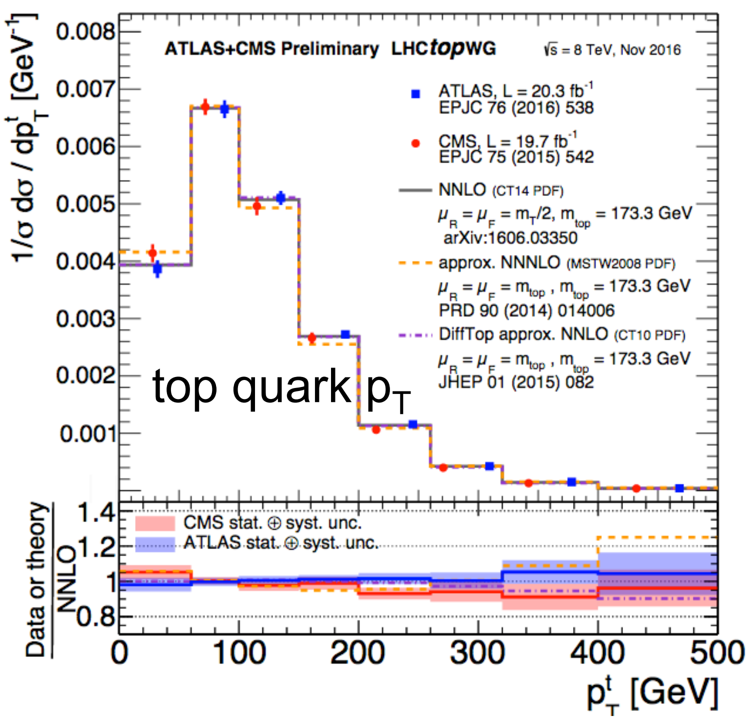
±3-5%

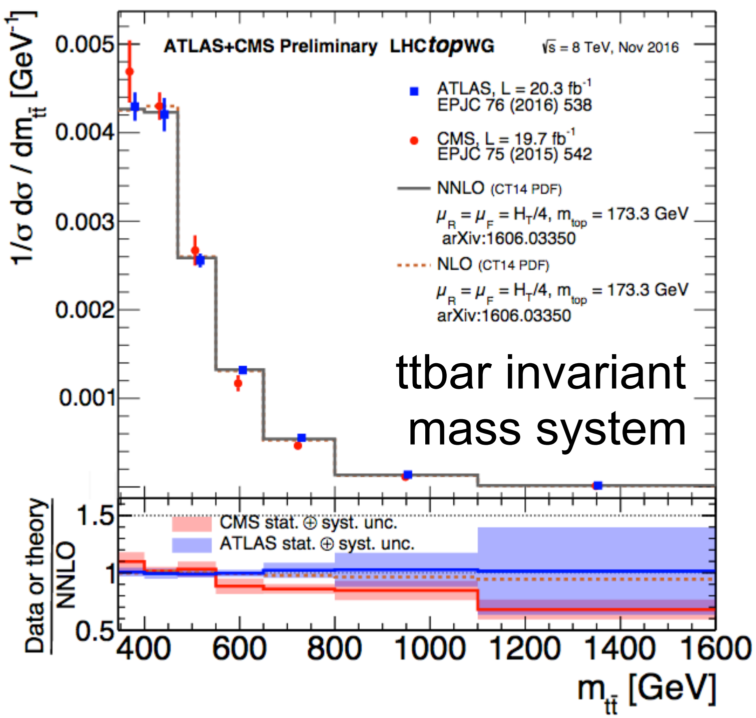
# Differential cross section

- Measure differential cross section
  – Test perturbative QCD
  – Test BSM scenarios (Z' decays, etc) with narrow resonance

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

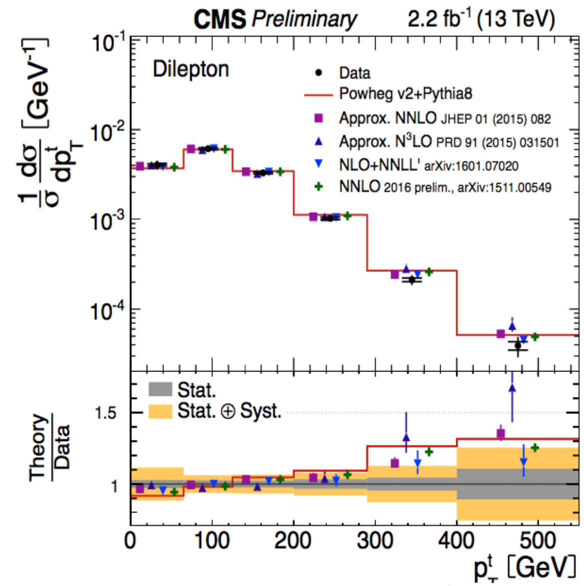
- Cross sections measured as a function of $p_T$, $\eta$, invariant mass of the final state leptons, top quarks, and the ttbar system
- Good agreement found in dilepton and lepton+jet channels

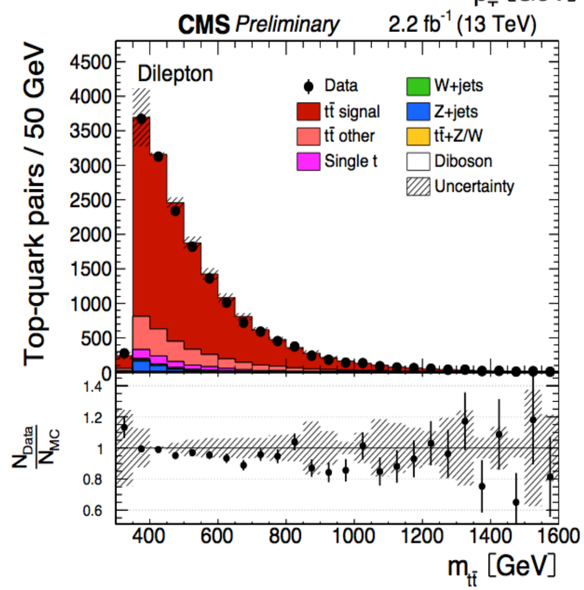


# Differential cross section (cont.)

EPJC 73(2013) 2339, CMS-TOP-12-027, TOP-15-013, TOP-16-011, arXiv:1610.04191




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

# 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”