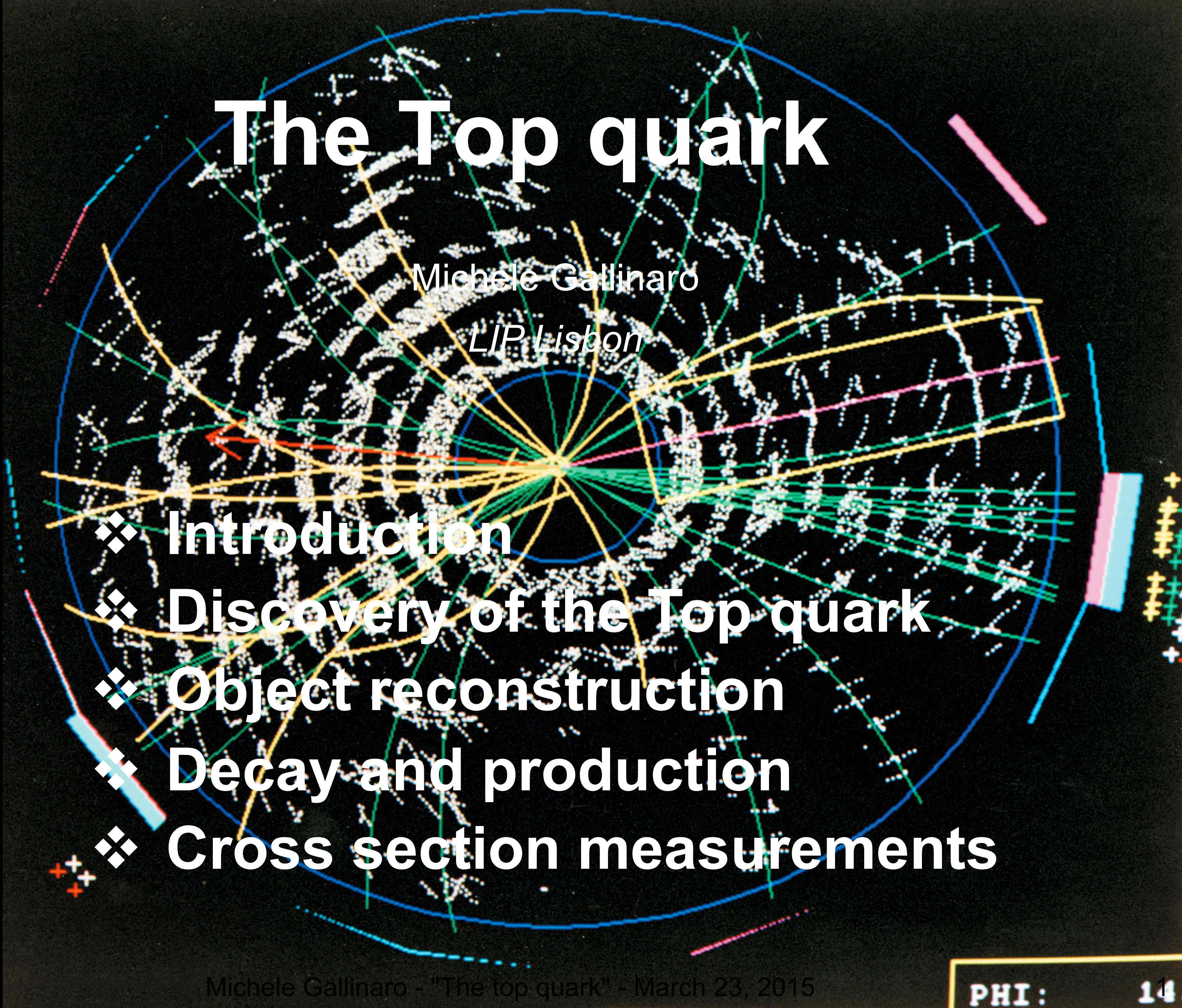



# The Top quark

Michele Gallinaro

*LIP Lisbon*

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

# Contents

will use c=1

- Introduction (discovery, object ID)
- Top pair production at the Tevatron
- Top pair production at LHC
- Properties: differential cross section

today

- Mass measurements
- Spin correlation, charge asymmetry
- Single top production
- Flavor Changing Neutral Currents (FCNC)

- Search for top partners and 4$^{th}$ generation quarks
- Search for ttbar resonances

# 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

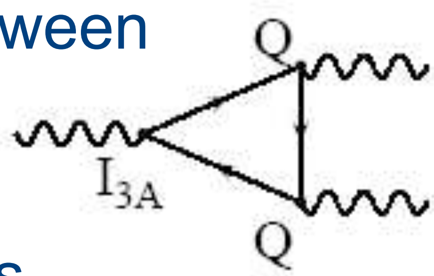
$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} \\ b \end{pmatrix}$$

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

- 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 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

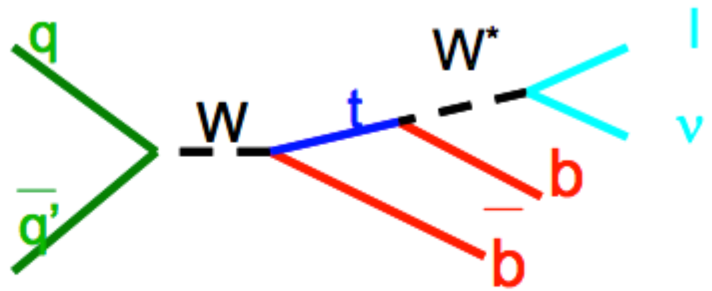
- In the SM, various EWK observables depend on the mass of the top quark


- Precision measurement of the Z decay ⇒ predictions of $M_{top}$ (consistency)
- In the period 1990- up to the discovery:
  - 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

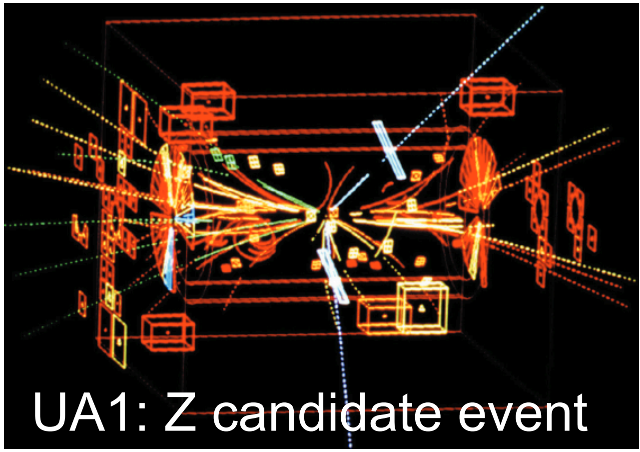
- Access to much higher energies
- Large backgrounds, low event rates
- Difficult reconstruction: jets



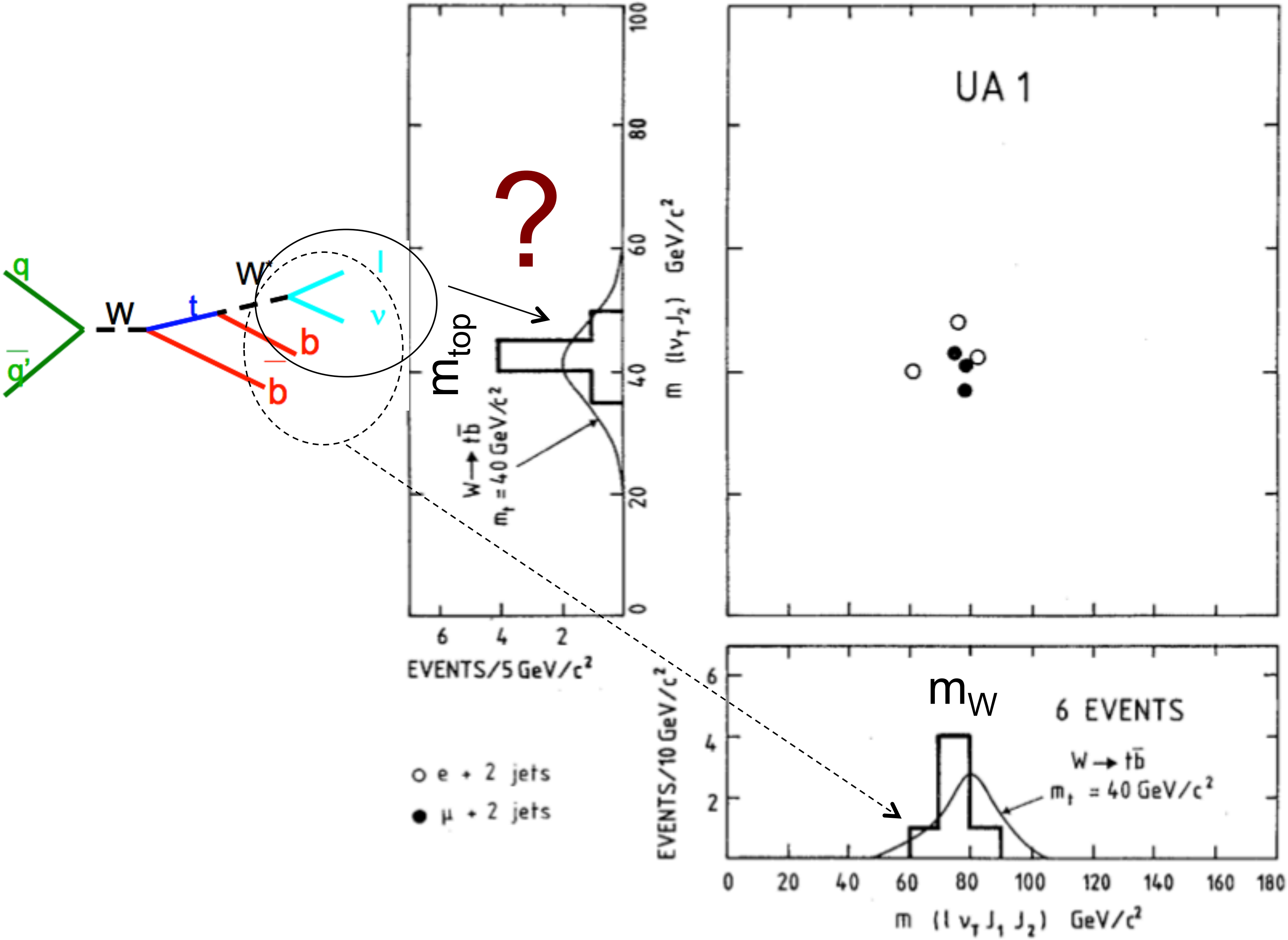

1984: UA1

- $W \rightarrow tb \rightarrow l\nu bb$
- Isolated high-$p_T$ lepton
- 2 or 3 hadronic jets
- Observe 5 events (e+ ≥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

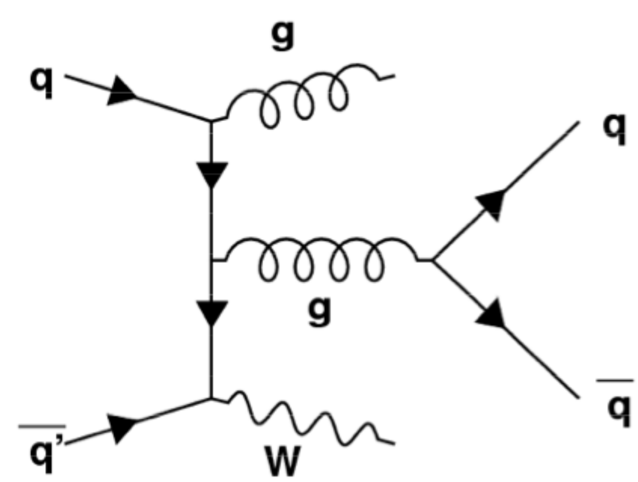


UA1: Z candidate event


q
$\bar{q}'$
W
t
W
l
ν
b
$\bar{b}$
?
$m_{top}$
UA 1
$m_W$
6 EVENTS
$W \to t\bar{b}$
$m_t = 40\ GeV/c^2$
EVENTS/5 GeV/$c^2$
EVENTS/10 GeV/$c^2$
m $(l\nu_T J_2)$ GeV/$c^2$
m $(l\nu_T J_1 J_2)$ GeV/$c^2$
o e + 2 jets
● μ + 2 jets

# Searches at hadron colliders

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

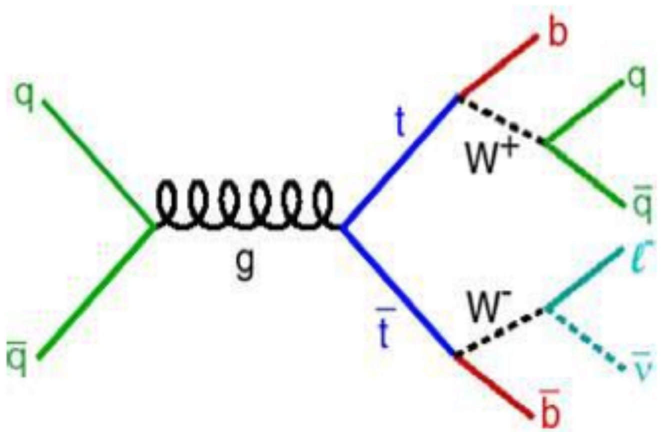
( + 23 expected if $M_{top} = 40$ GeV)

⇒conclude $M_{top}$>44 GeV

# Fermilab joins the hunt

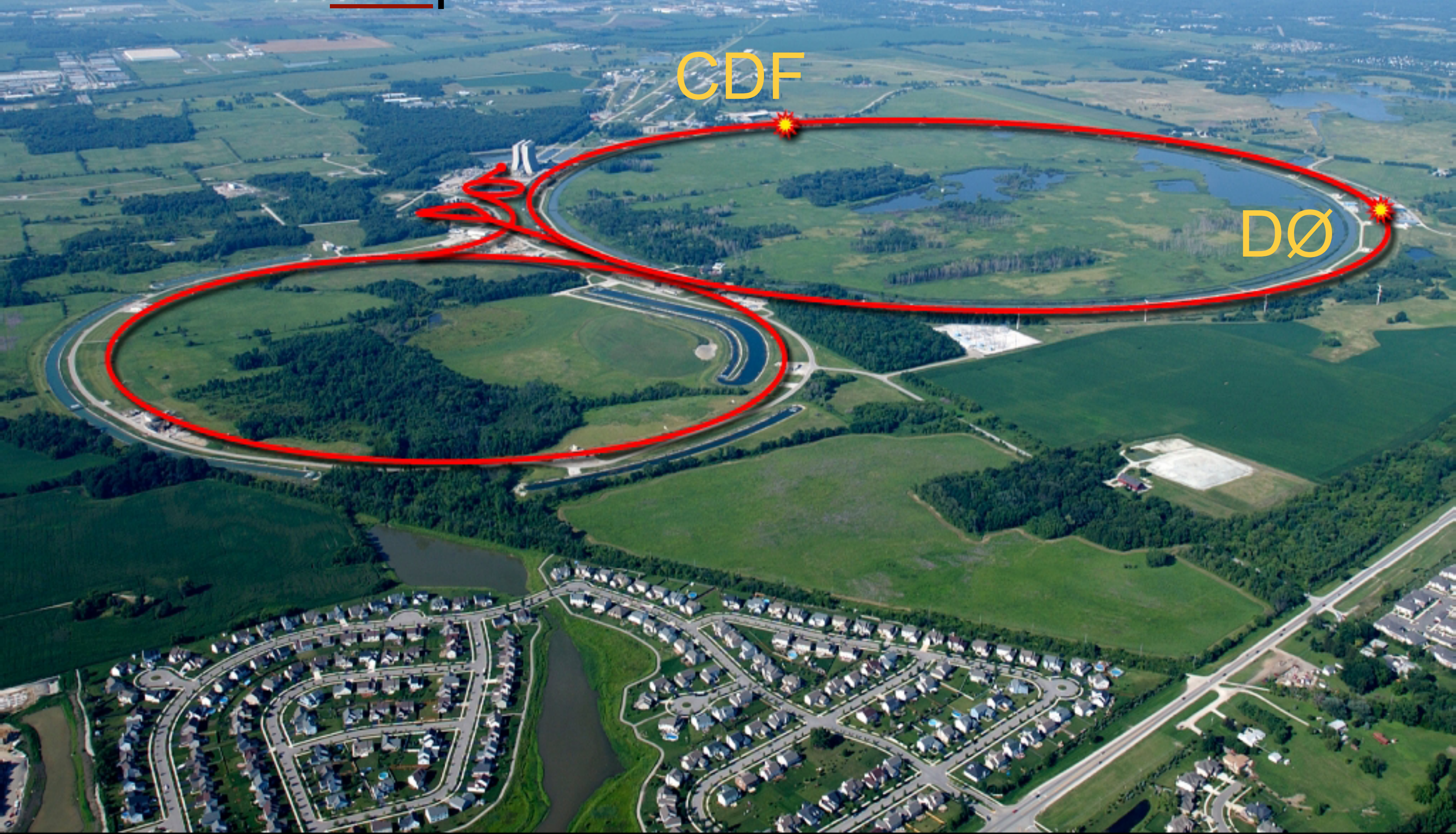
- 1988-89: at CERN, UA2 remains after the upgrades
- √1.8 TeV@FERMILAB **vs.** √0.63 TeV@CERN
- Much better reach for larger mass (only 75 GeV@UA2)
- At Tevatron, pair production dominates: $t\bar{t} \rightarrow Wb\,W\bar{b}$

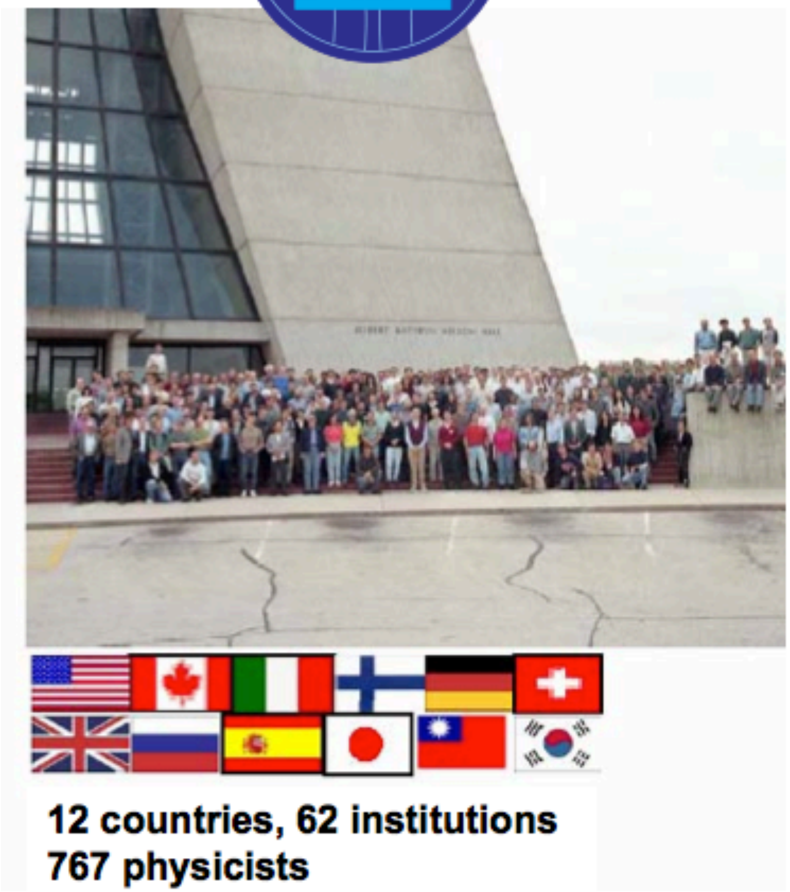
| % | $e\nu$ | $\mu\nu$ | $\tau\nu$ | $q\bar{q}$ |
|---|---|---|---|---|
| $e\nu$ | 1.2 | 2.5 | 2.5 | 14.8 |
| $\mu\nu$ | | 1.2 | 2.5 | 14.8 |
| $\tau\nu$ | | | 1.2 | 14.8 |
| $q\bar{q}$ | | | | 44.4 |

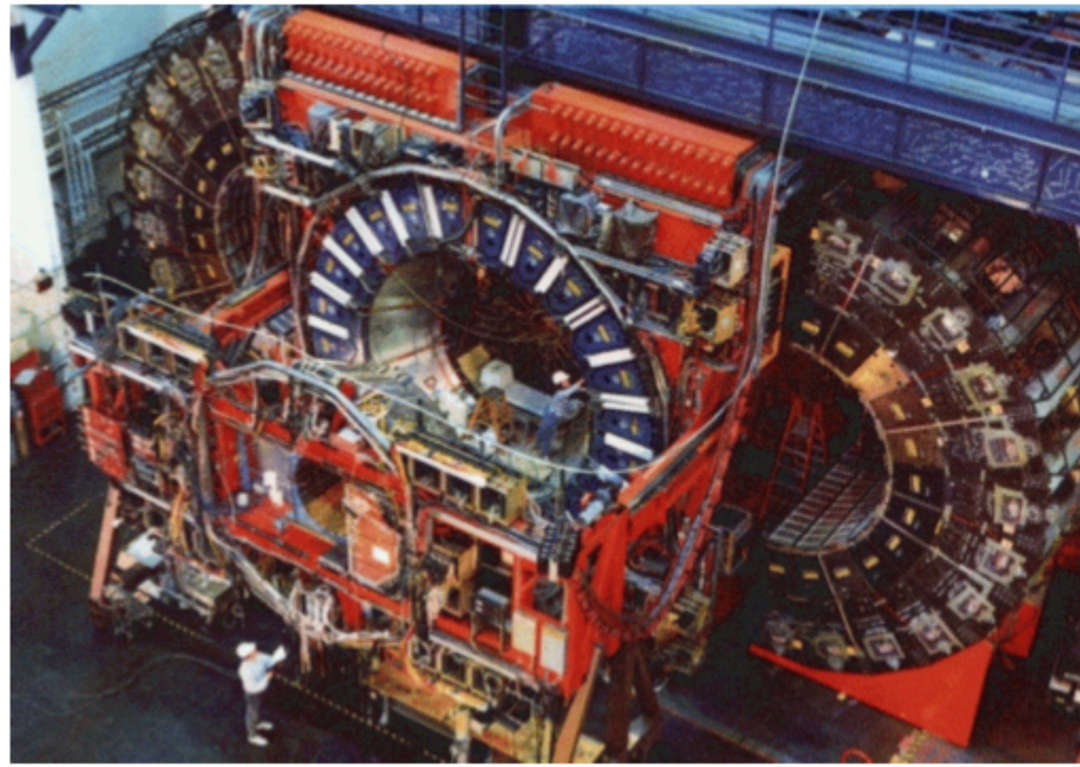


# Tevatron

Proton-antiproton collision at 1.8-2.0 TeV




12 countries, 62 institutions
767 physicists

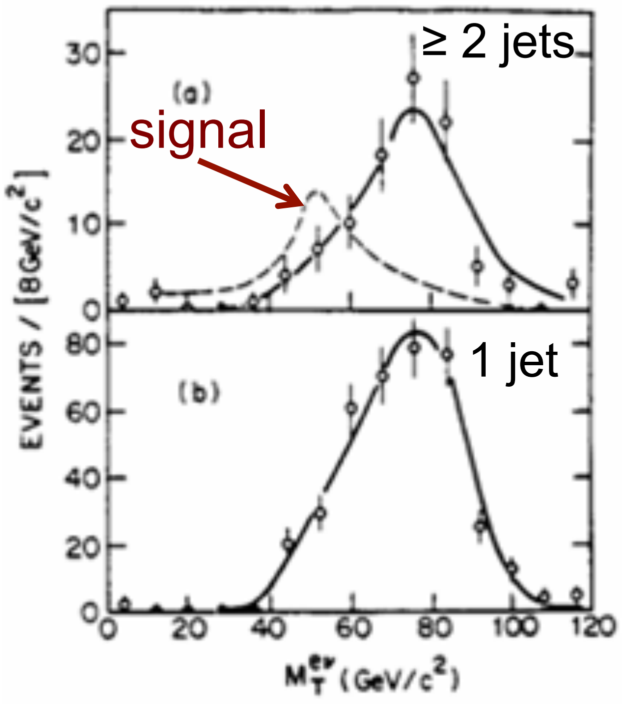


# Searches at CDF

eν+ ≥2 jets

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

⇒$M_{top}$>77 GeV




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

# Searches at CDF (cont.)

$e\mu$ 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)

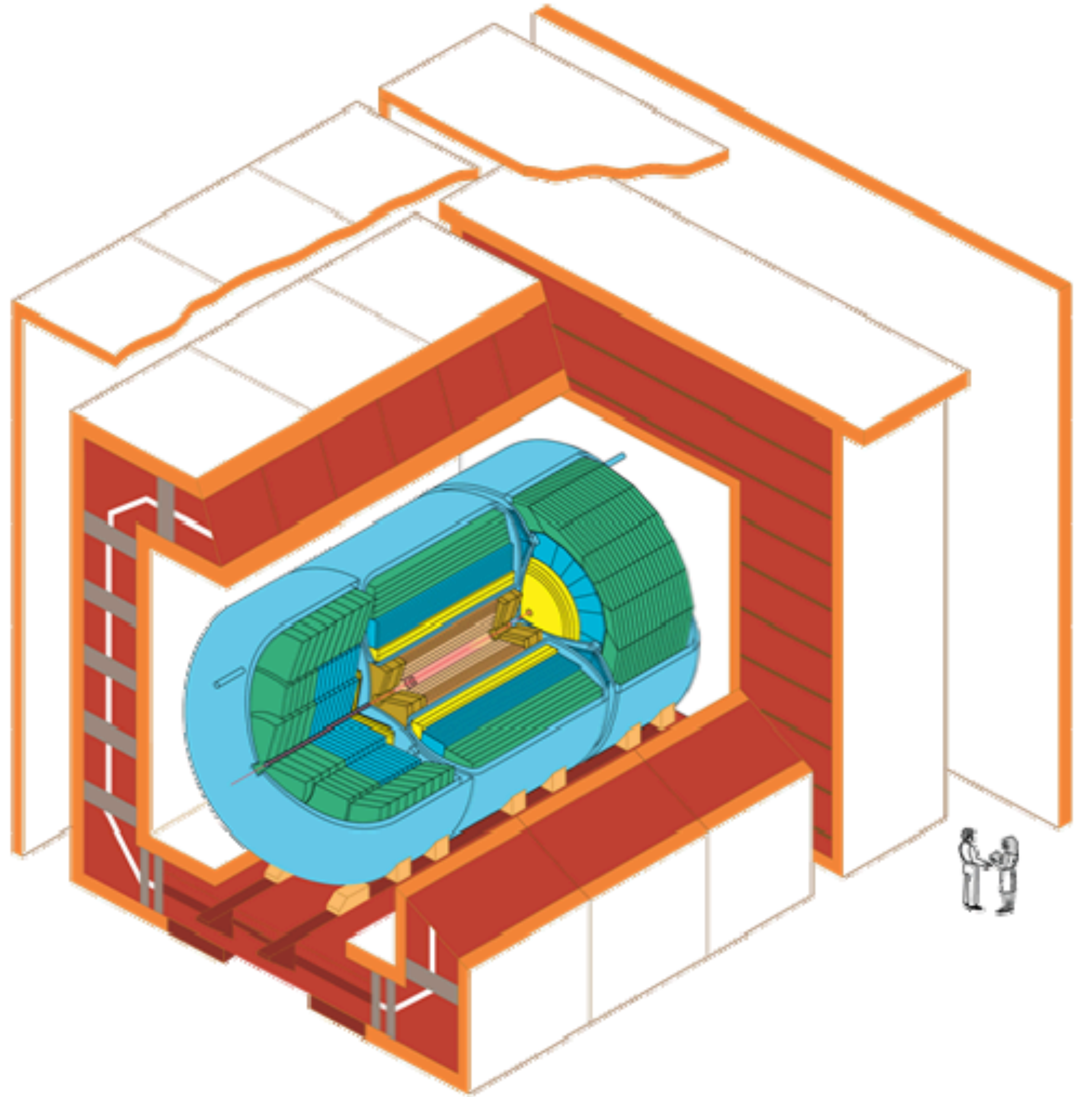
# Change of strategy: $M_{top}>M_b+M_W$

- 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:

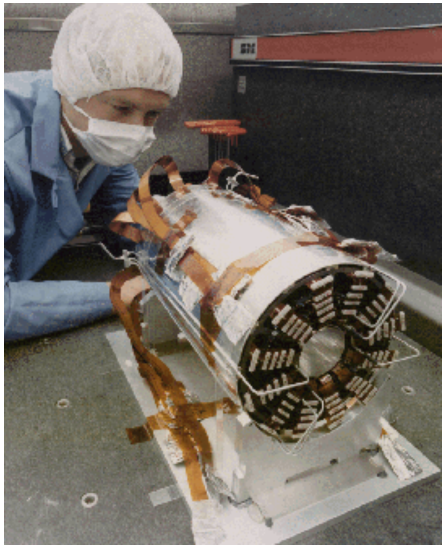
- D0: optimized search for $M_{top}$=100 GeV

| | | |
|---|---|---|
| – $e\mu$+≥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) |

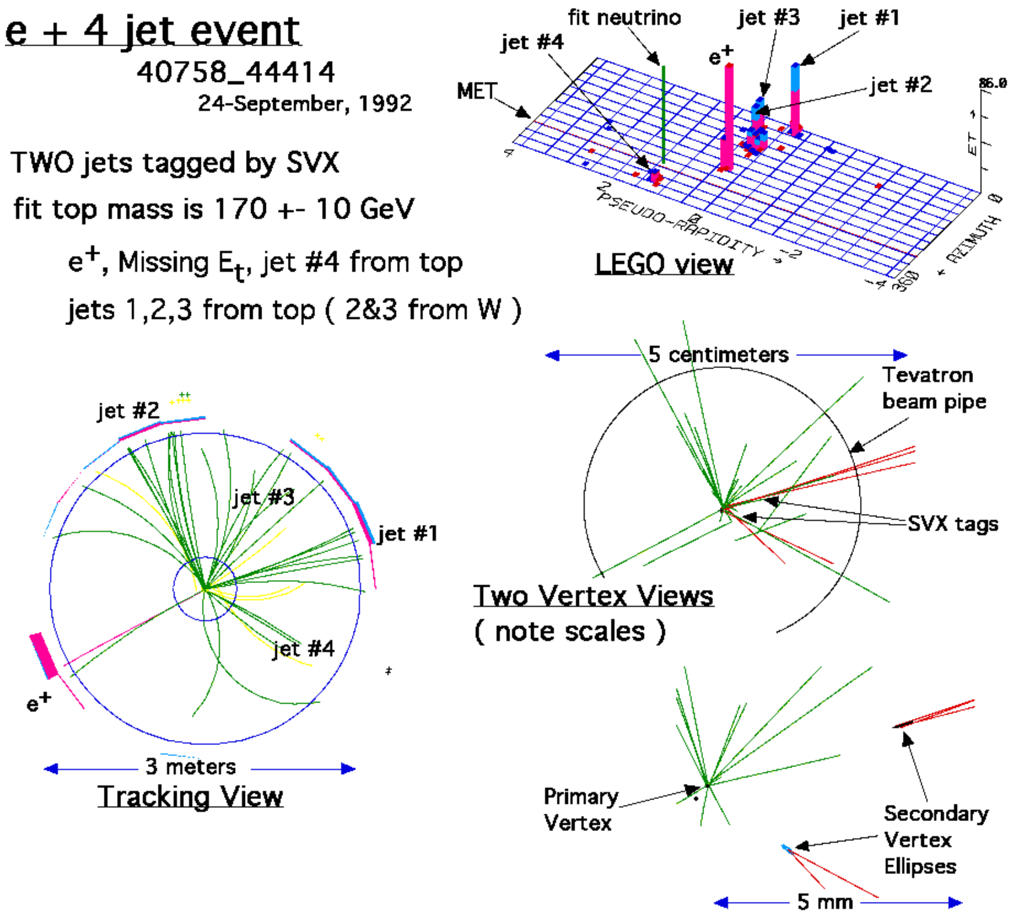
⇒$M_{top}$>131 GeV@95%CL

# 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

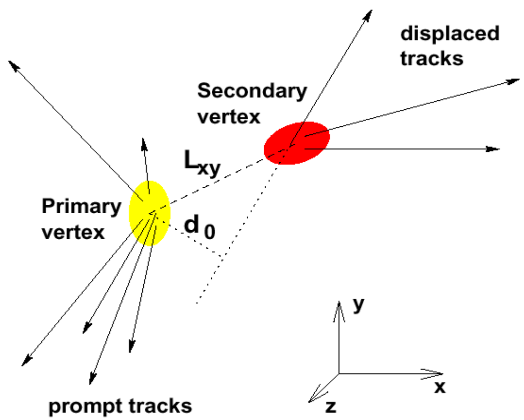


# Tagging b-jets

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

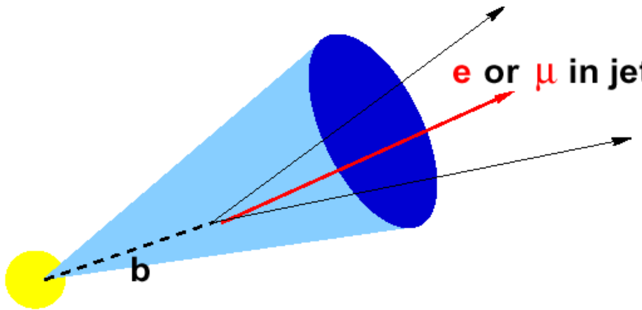
## B hadrons are long-lived

**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 | --- |

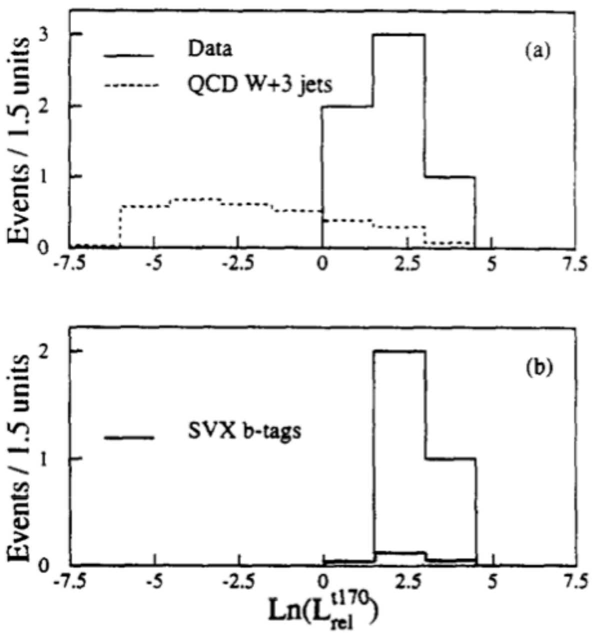
3 events in common

- 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)

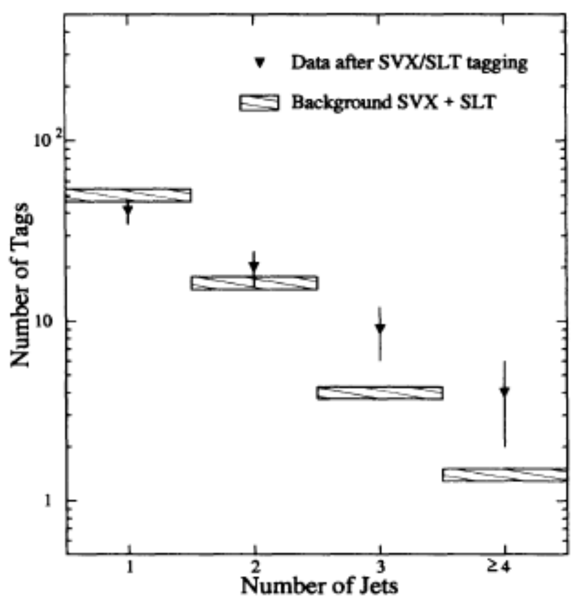
- Observed 7 events (expect 4-6 from bkg)
- No independent evidence

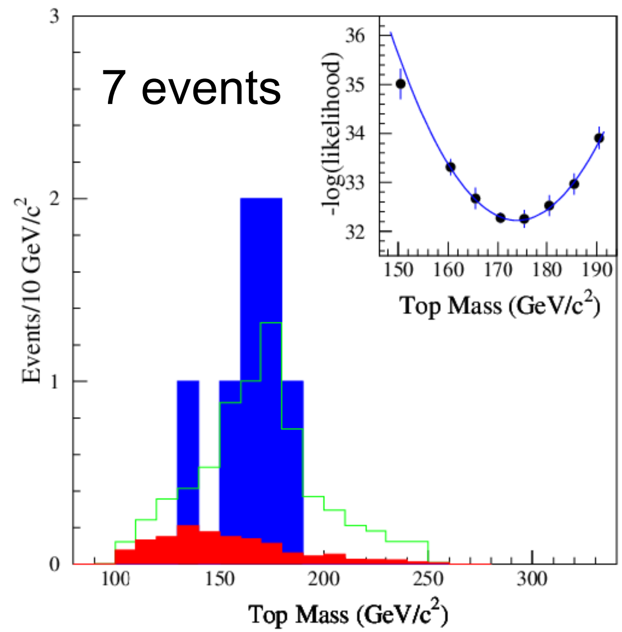
# First evidence (1994)

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.



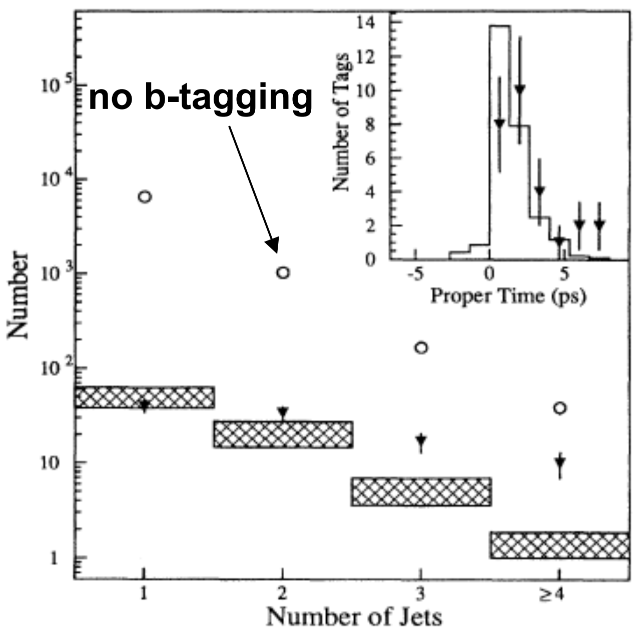



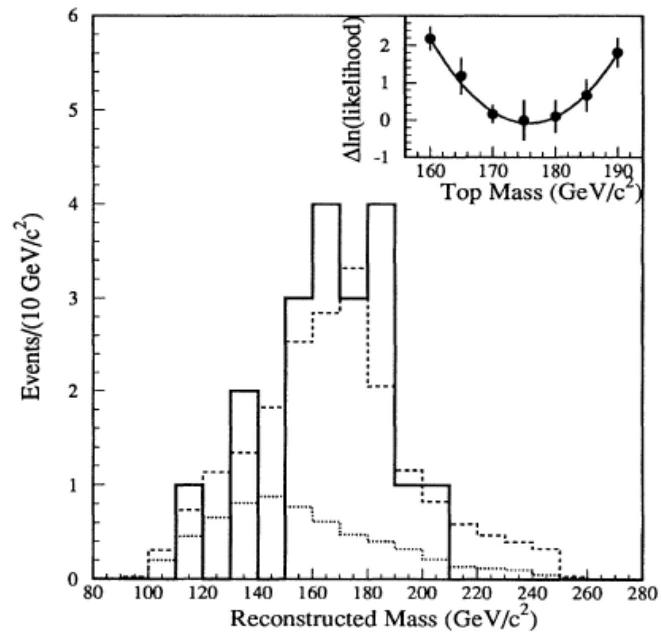
# First measurements

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 $\boxed{176 \pm 8(\text{stat}) \pm 10(\text{syst})\ \text{GeV}/c^2}$, and the $t\bar{t}$ production cross section to be $\boxed{6.8^{+3.6}_{-2.4}\ \text{pb}}$.



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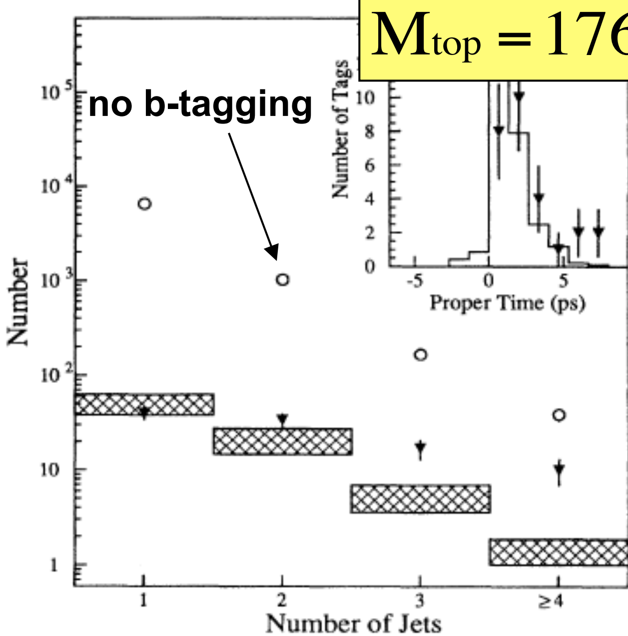
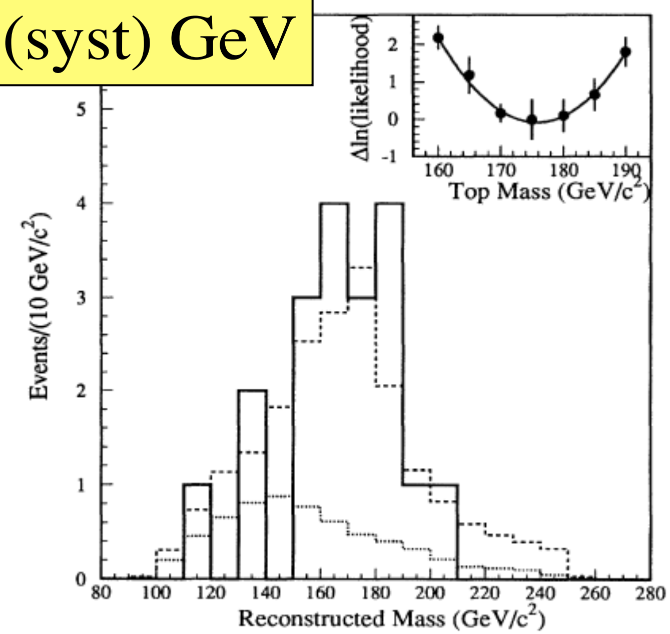
$$\sigma_{tt} = 6.8^{+3.6}_{-2.4} \text{ pb}$$

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



# First measurements

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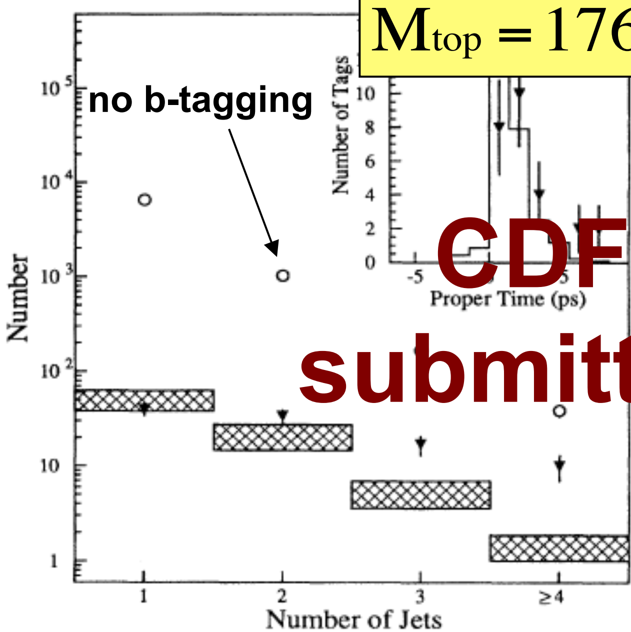
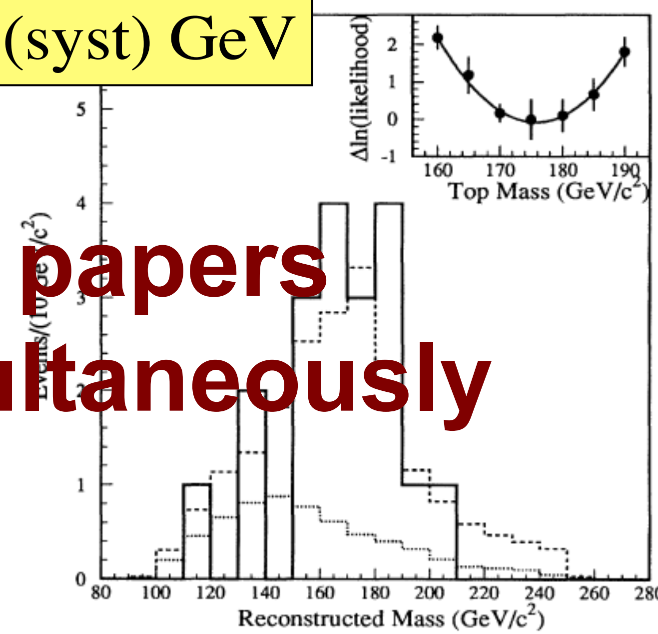
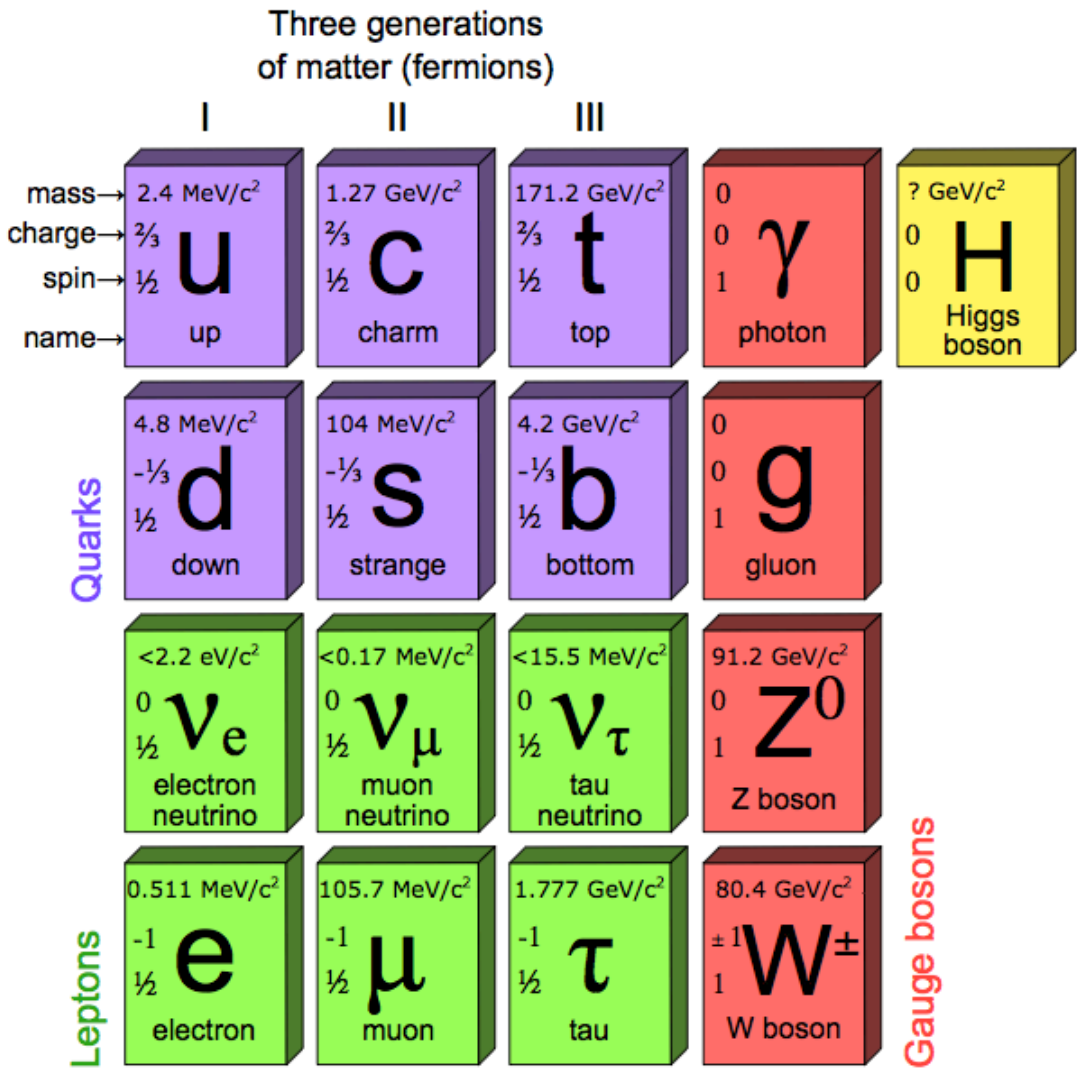



**CDF and D0 papers submitted simultaneously**

# Top quark and its relevance

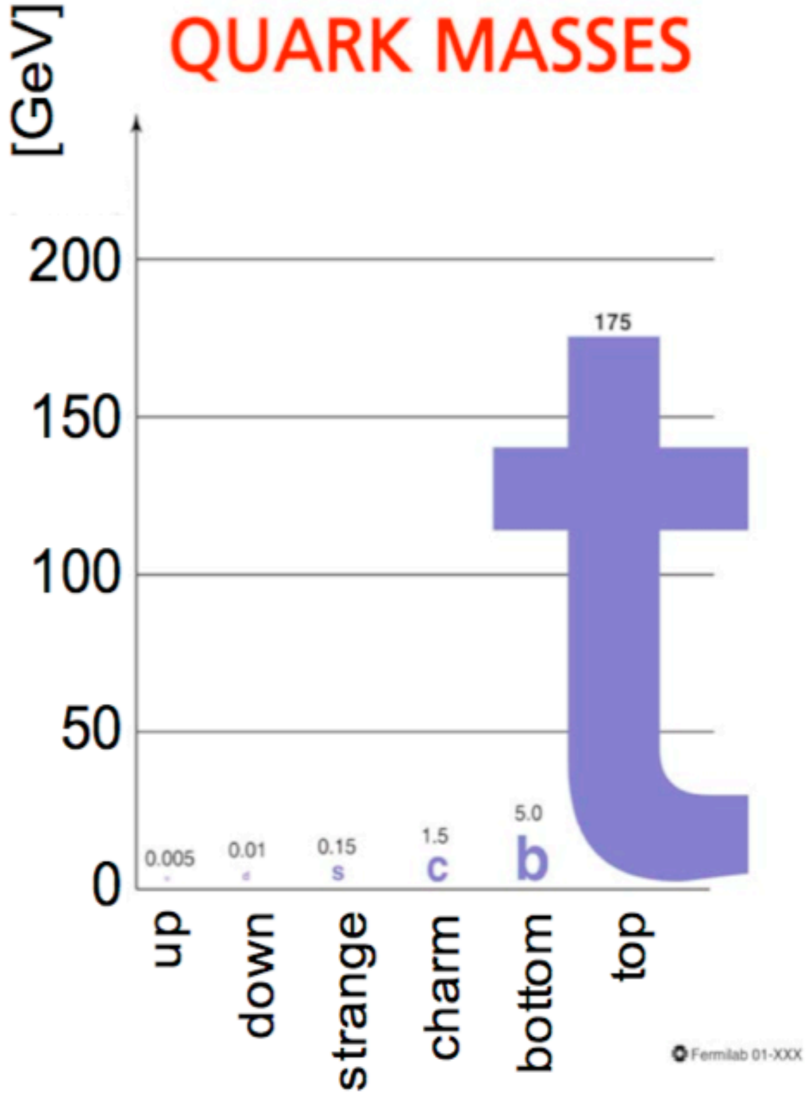
- Basics
- How to detect the top quark
- Tevatron vs LHC



# About the top quark

- The heaviest known elementary particle
- Large mass, coupling to the Higgs ~1
  ⇒no hadronization
- Several open questions
  - Is top mass generated by the Higgs mechanism?
  - Special role in EWSB mechanism?
  - Does it play a role in non-SM physics?
  - Are the couplings affected?

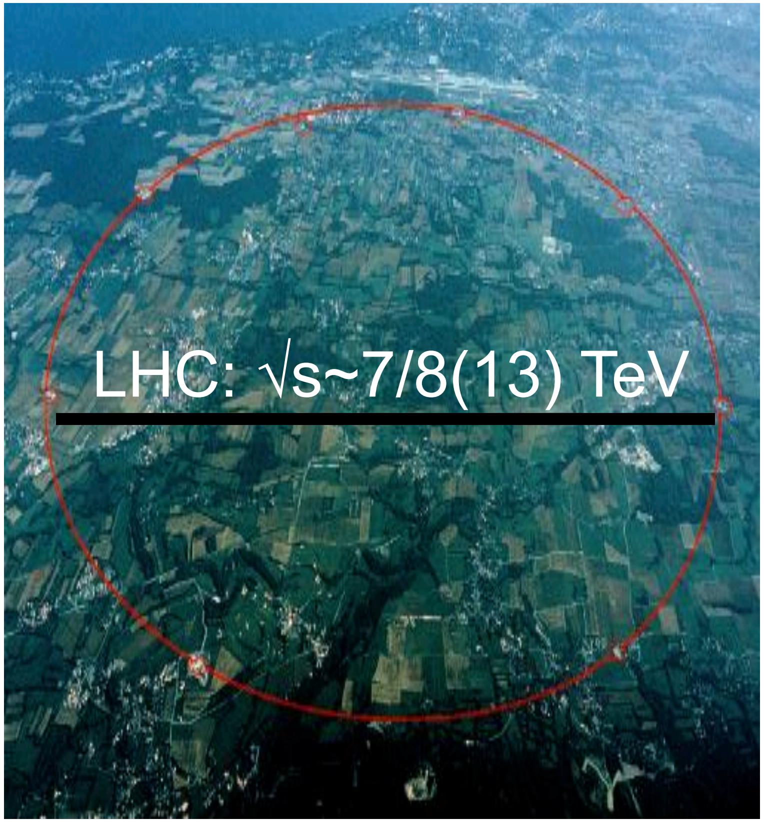
- Main background for many New Physics searches
- Top quark measurements may provide insight into physics beyond SM



# The Large Hadron Collider

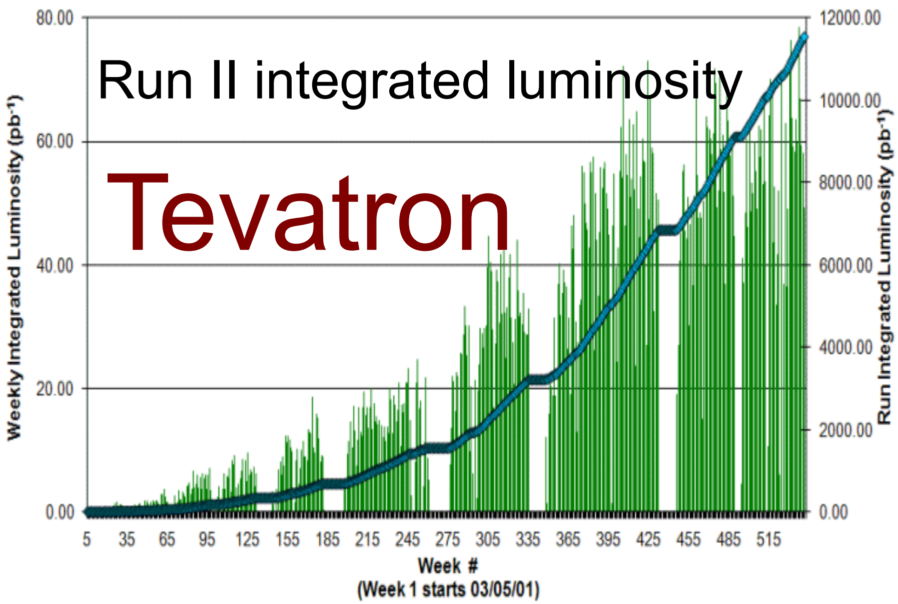
- Built to explore new energy frontiers
- First colliding beams in 2009
- started with “low” luminosity in 2010
- ~5 $fb^{-1}$@7TeV delivered in 2011
- ~20 $fb^{-1}$@8TeV in 2012

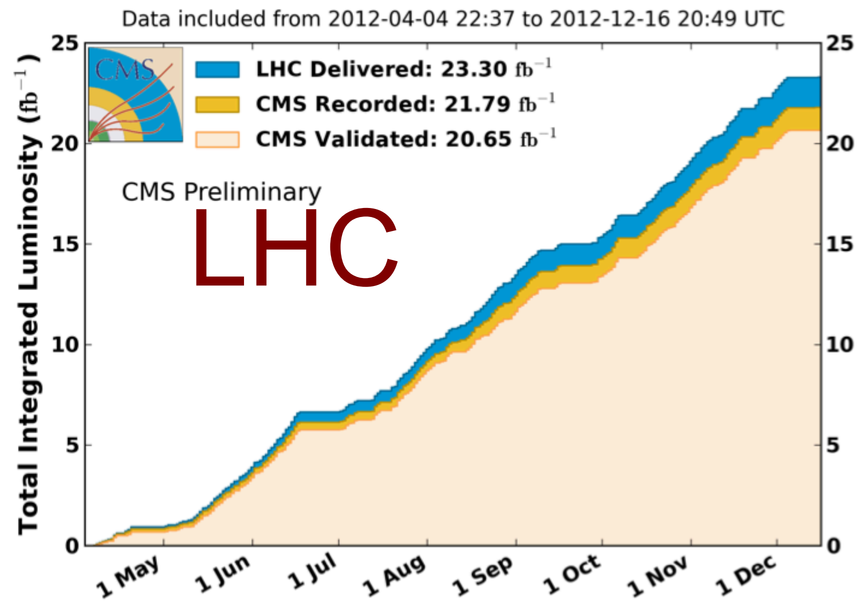
- re-establish SM measurements
- access to new physics processes




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

# Tevatron vs LHC



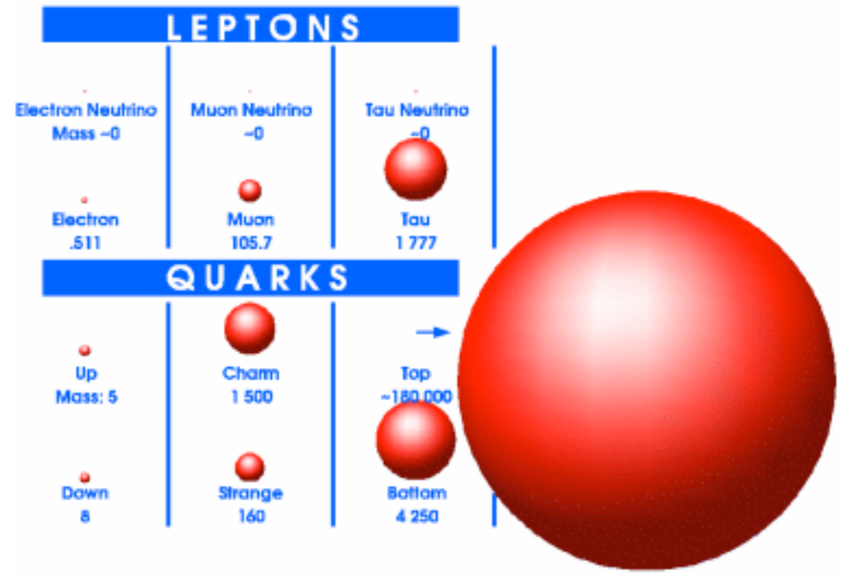

Energy: 1.96 TeV
Int. Luminosity: 12 $fb^{-1}$
Age: ~25 years
Events/exp (5.4 $fb^{-1}$)
350 ee eμμμ
3500 lepton + jets

Energy: 7/8 TeV
Int. Luminosity: 5/20 $fb^{-1}$
Age: ~3 years
Events/exp (1 $fb^{-1}$)
2500 ee eμμμ
15000 lepton + jets

# What is the Top quark?

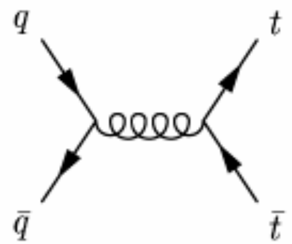
$$\text{Quarks:} \quad \begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} t \\ b \end{pmatrix}$$

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

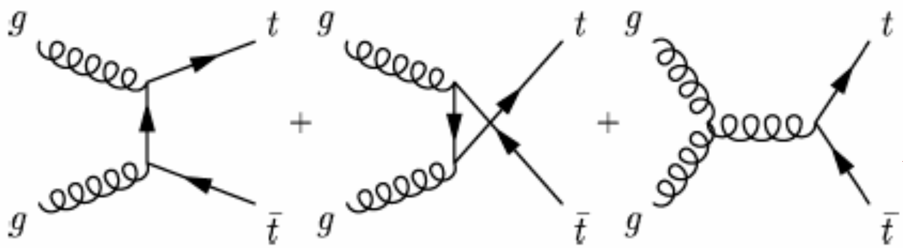



- It is the heaviest fundamental particle
  - $M_{top} = 174.3 \pm 0.6$ GeV (arXiv:1407.2682)
- Weak isospin partner of the b-quark
- Completes the SM of quarks and leptons

# How is the top quark produced?




Dominant at Tevatron




Dominant at the LHC

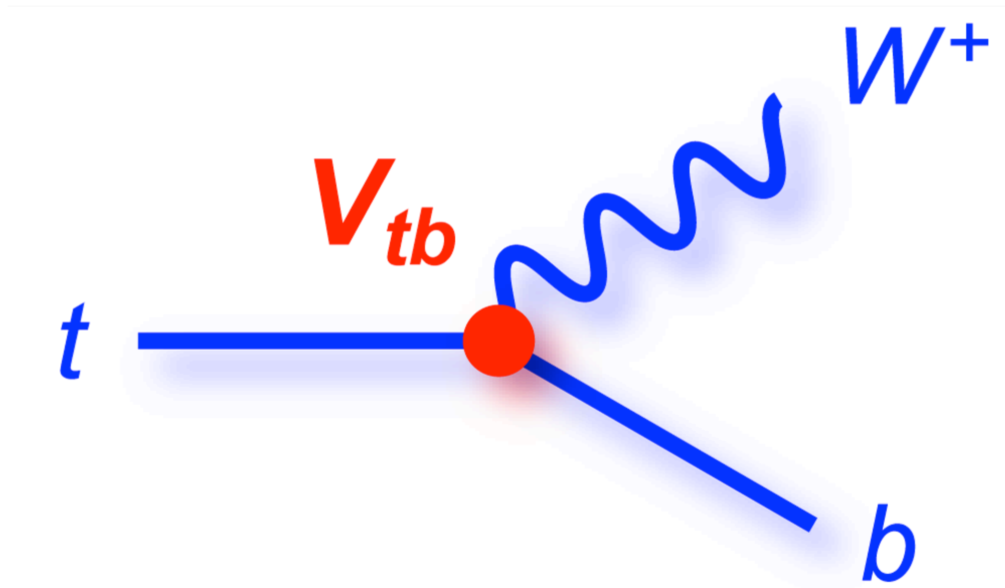
**Predicted cross sections:**

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

Czakon et al. PRL 110, 252004 (2013)

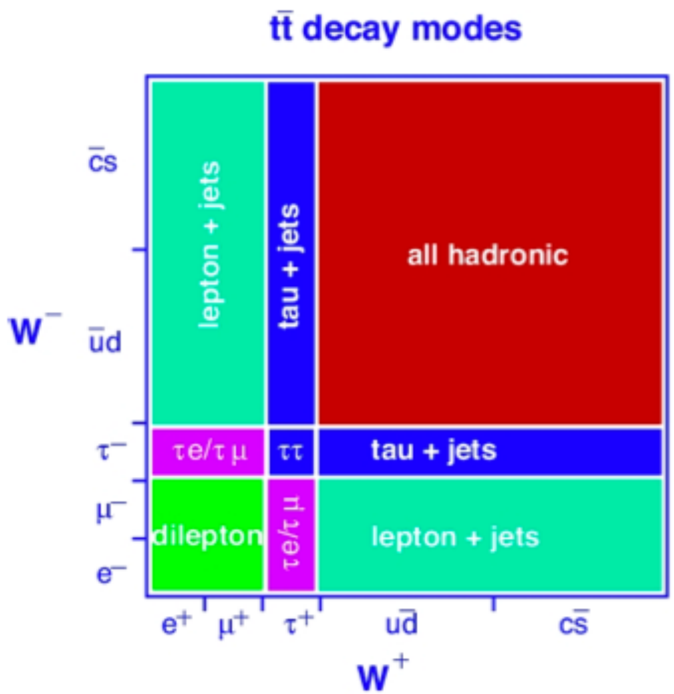
| | LHC | Tevatron |
|---|---|---|
| gg | ~85% | ~10% |
| qq | ~15% | ~90% |

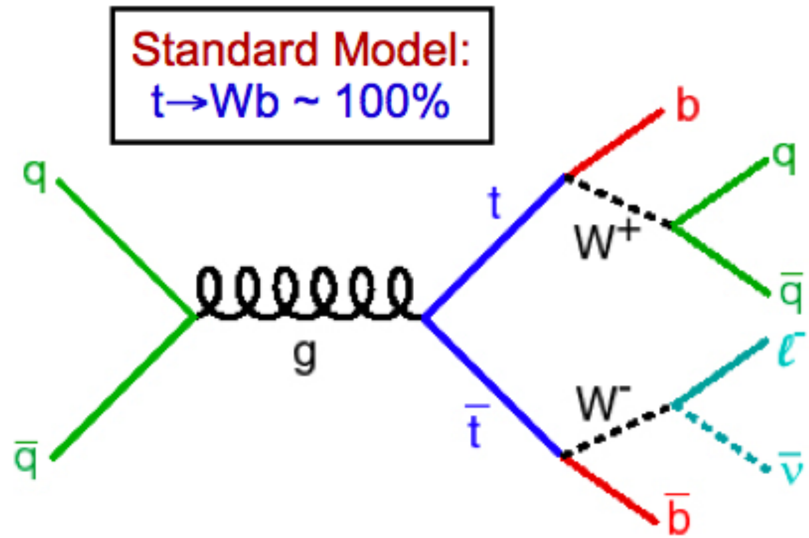
# How does a top quark decay?




- 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

# How do ttbar pairs decay?

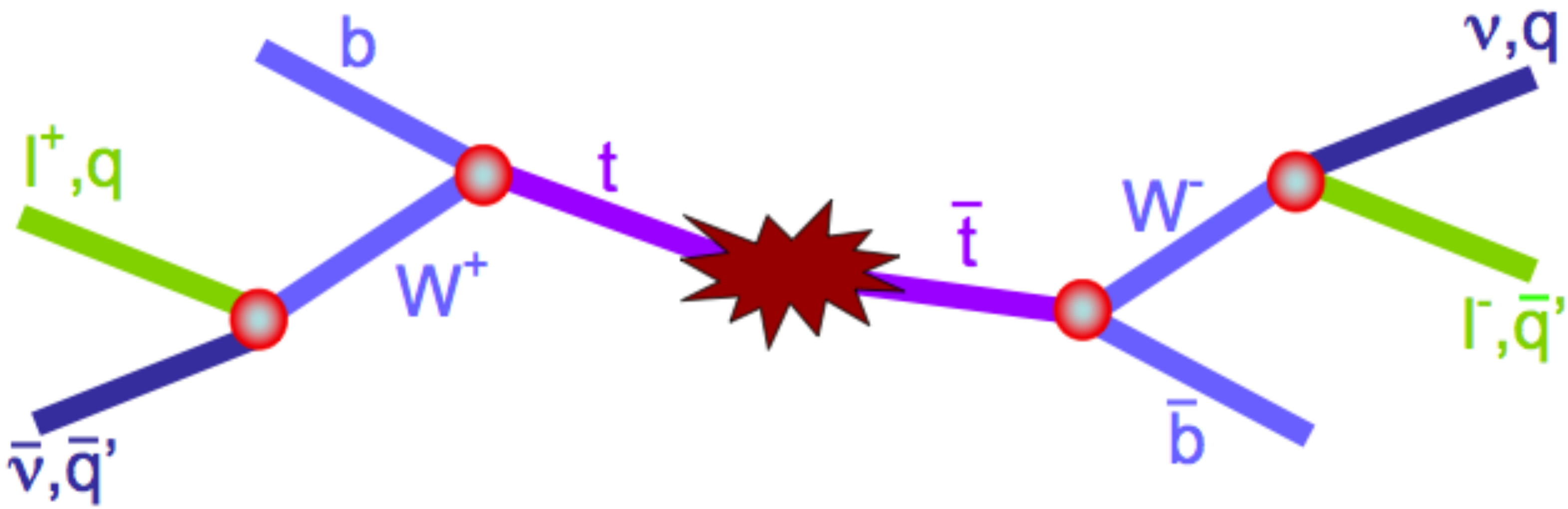



| | | | |
|---|---|---|---|
| tt → lνlνbb | di-lepton | 5% | e+μ |
| tt → lνqqbb | lepton+jets | 30% | e+μ |
| tt → qqqqbb | all hadronic | 44% | |

⇨ <u>use **all** decay channels</u>

# Interesting physics with Top quark




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

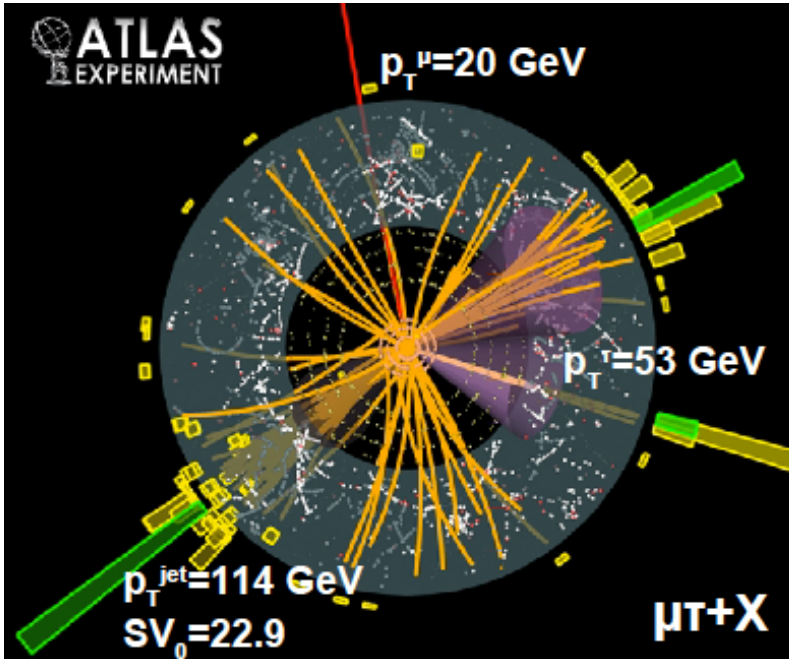
**PROPERTIES**
Mass
Kinematics
Charge
Lifetime and width
W helicity
Spin
...

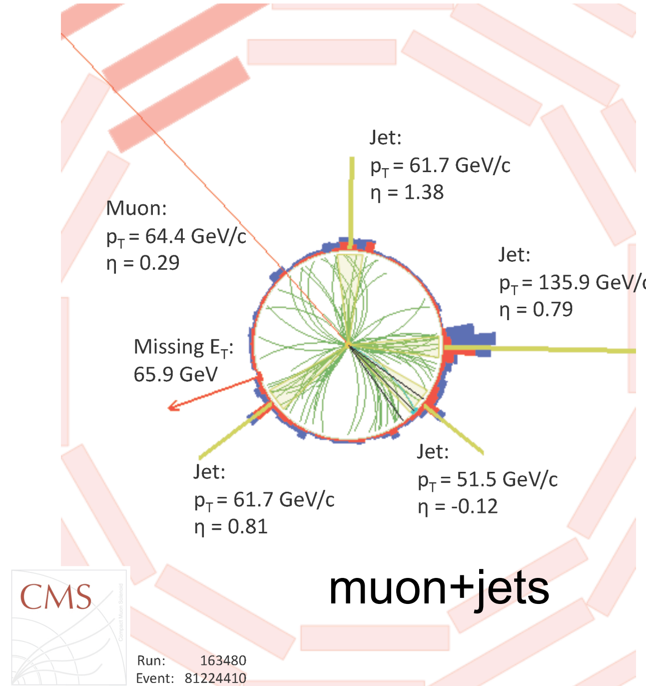
**DECAY**
Branching ratios
Charged Higgs (non-SM)
Anomalous couplings
Rare decays
CKM matrix elements
Calibration sample @LHC
...

# Particle identification

- Object identification and reconstruction

# Selection of top quark events

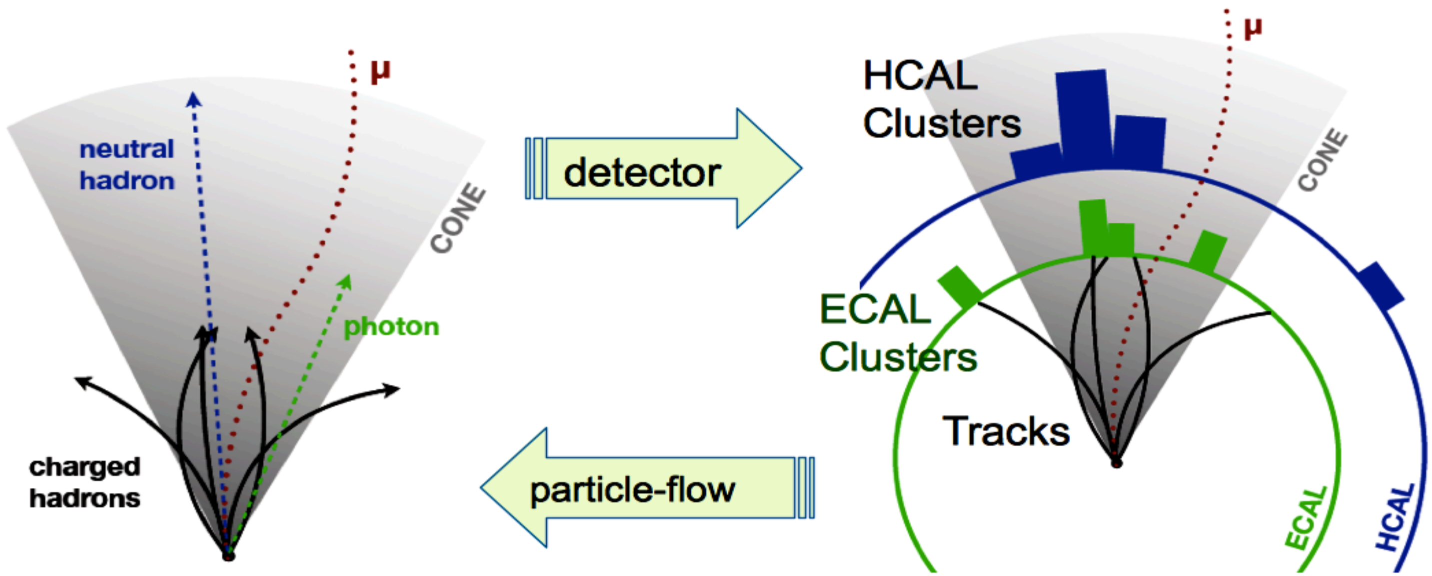



- Trigger:
  - single or double (isolated) lepton
- Leptons:
  - e/μ, $p_T$>20/30 GeV, |η|<2.5
  - Identification/reconstruction
  - Tracker/calorimeter isolation
- Jets:
  - at least 2 jets, $p_T$>30 GeV, |η|<2.5
  - anti-kT algorithm, with cone 0.4-0.5
  - b-tagging is optional
- Missing transverse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

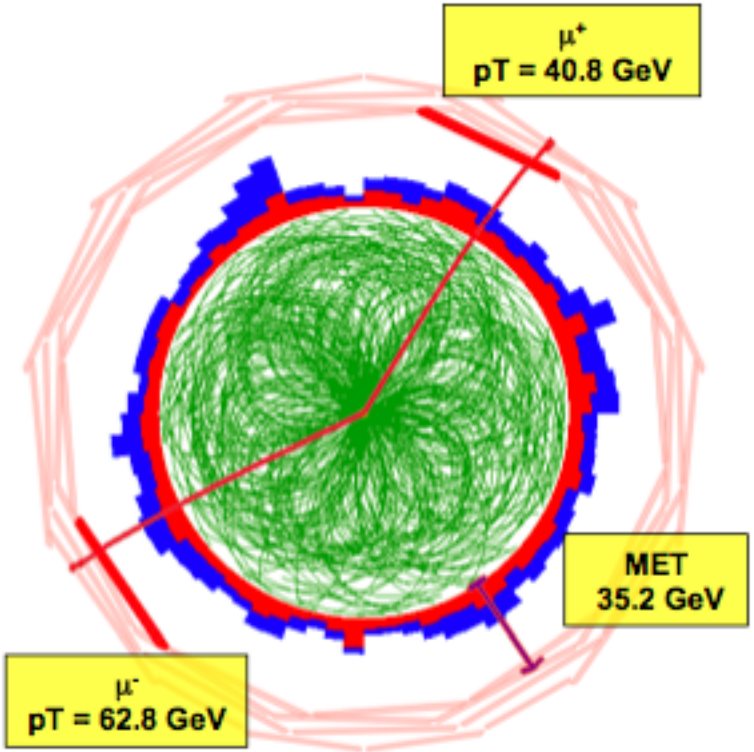
# Particle Flow event reconstruction

- 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.

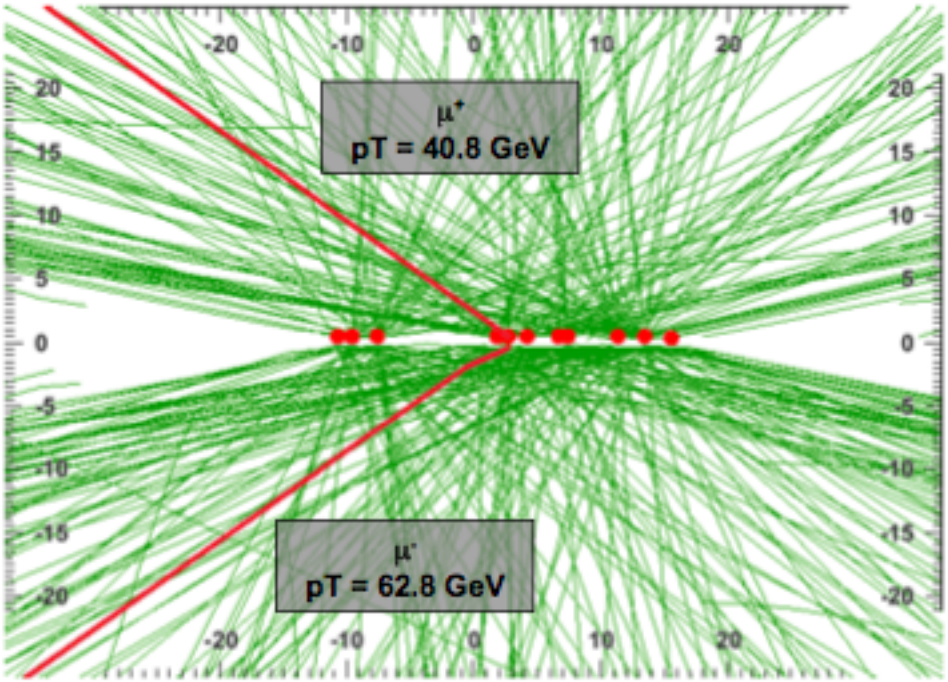


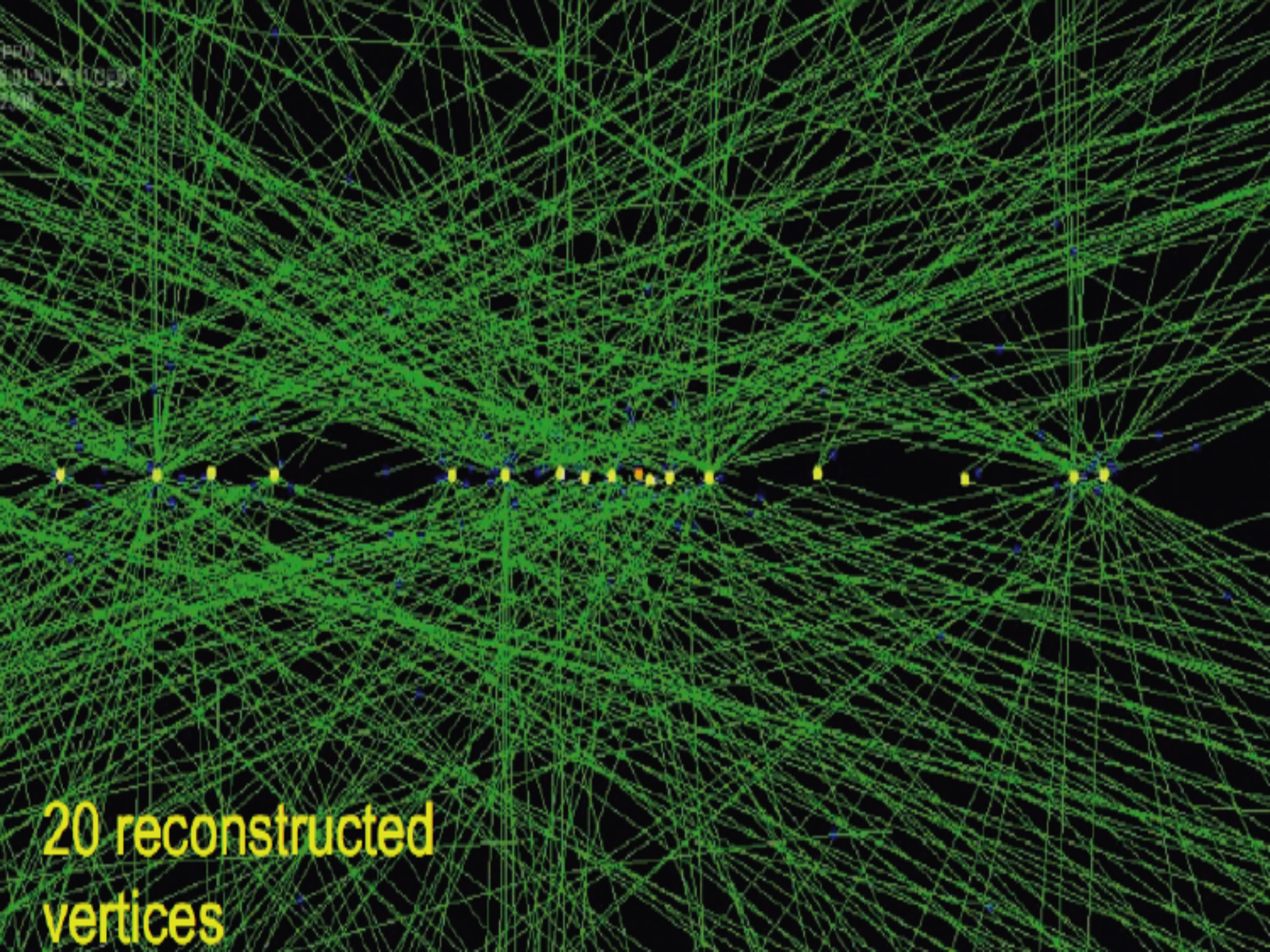
# Challenge: Pile-up

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



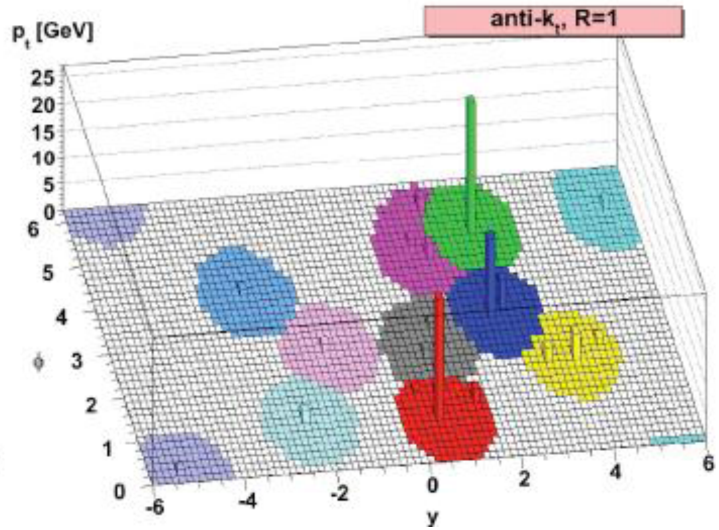

10 in-time + 10 out – of – time pileup




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

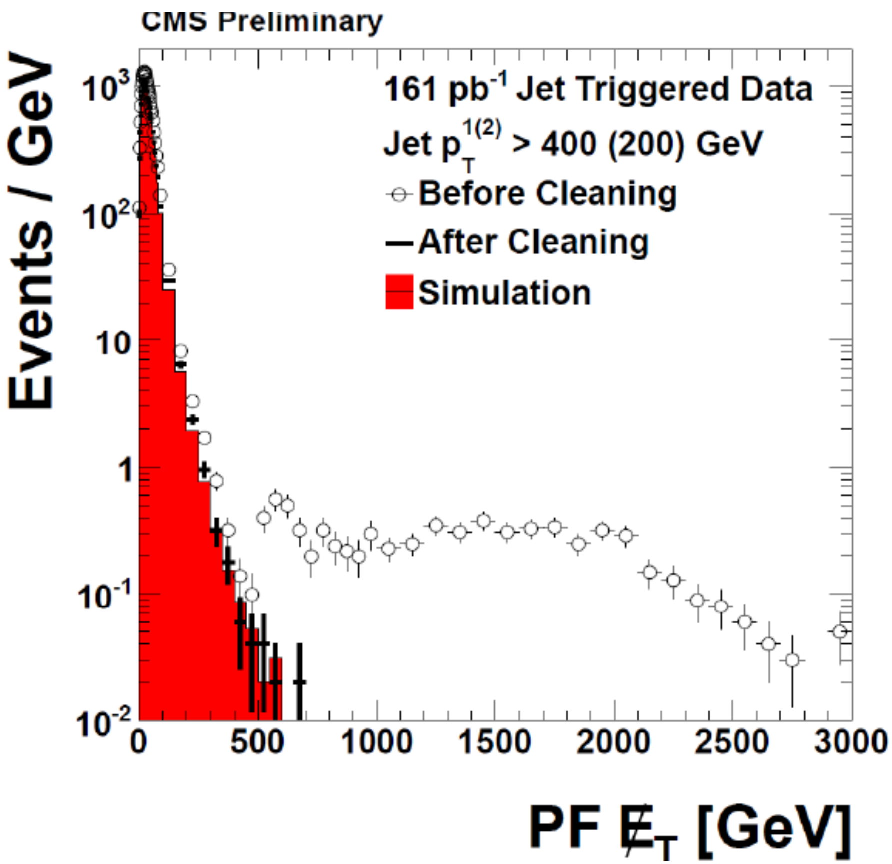
- Neutrinos (and "dark matter") escape the detector without detection
  - Also longitudinal momentum and energy of other final state particles escape undetected (along the beam-pipe)
  - Momentum is not measured along the z-direction
  - Missing momentum along z is unknown
- The momentum of the neutrinos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

transverse energy vector $$\boldsymbol{E}_T^{\text{miss}} = -\sum_i \boldsymbol{p}_T(i)$$

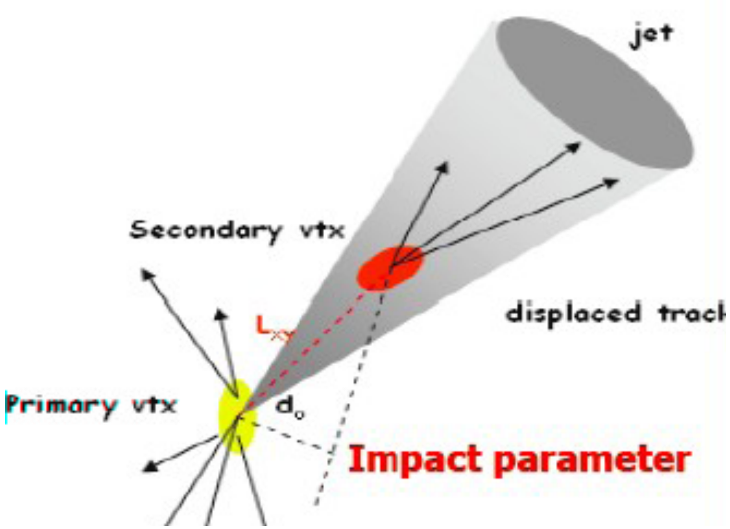
where the sum runs over the transverse momenta of all visible final state particles.

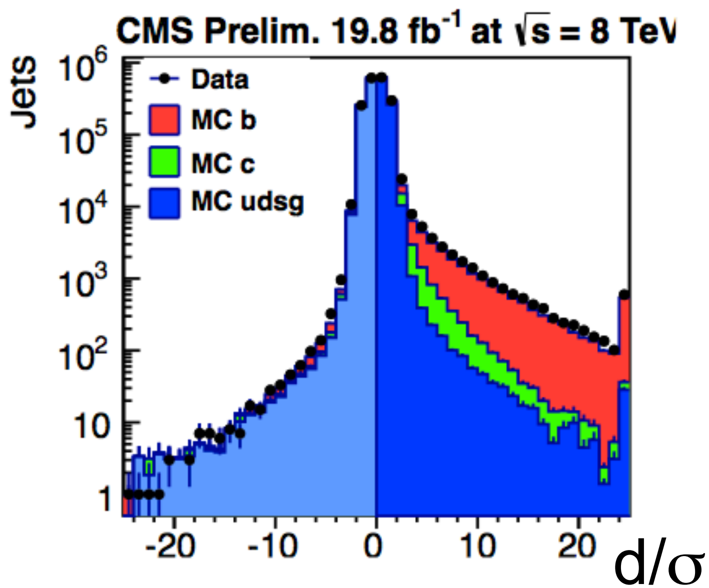
# Challenge: MET

- 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



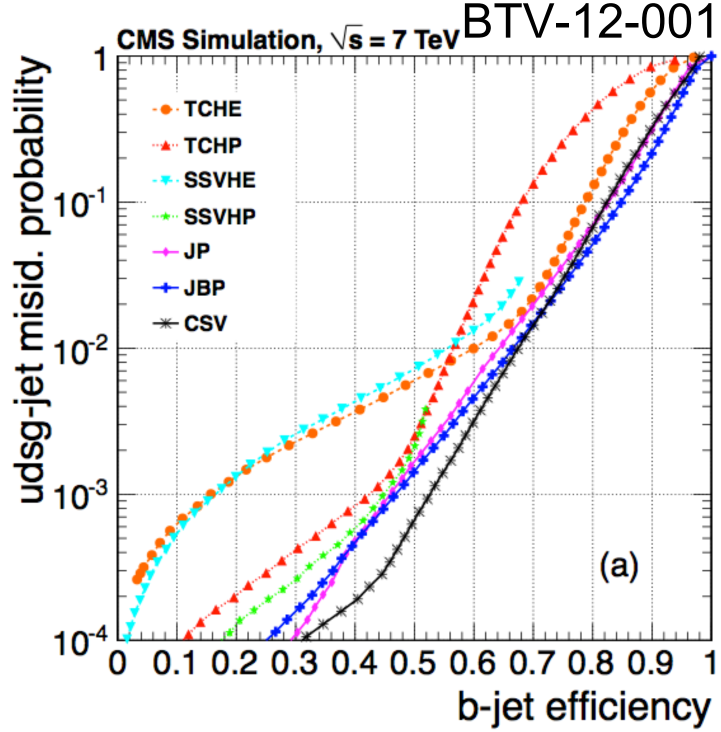



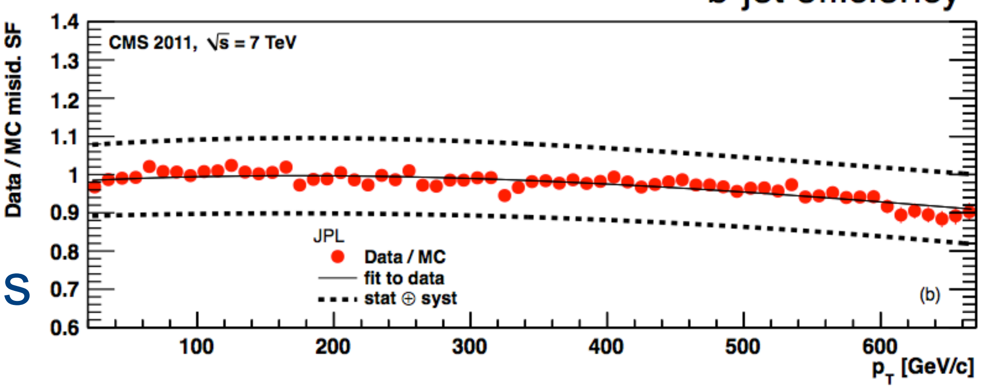

- Lifetime: $\tau_b$~1-2 psec
- Reduction of background obtained by identifying jets from b-quarks
- Two methods:
  - Secondary vertex tagging
  - Semileptonic decays of b-hadrons in jets ( $b \to l \nu_l X$ )

# b-tag: fake rates and efficiencies

- b-tag optimization: trade-off between fake rate and efficiency
- studied the performance of several different tagging working points
  - Example: Track counting algorithms $N_{tracks}$=2,3 have ``working points'' with fake rates approx. 10%, 1%, 0.1%
- Uncertainty on data/MC scale factor, depending on algorithms:
  - ~10-15% for mistags
  - ~5% for efficiencies
- Impact on top: amount and uncertainty of light flavor background for all tagged analysis

BTV-12-001



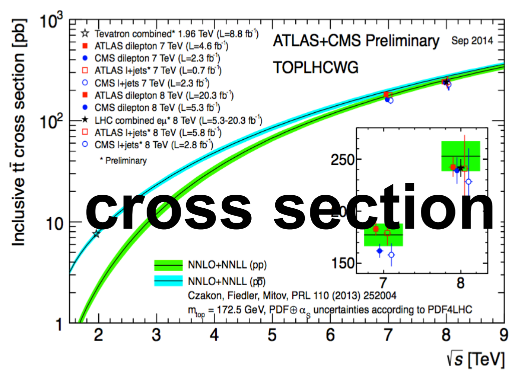
# Interesting physics with top quarks

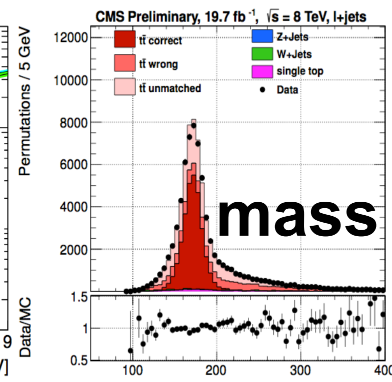
- Cross section
- Mass
- Kinematical properties
  - Is there a $X \to$ ttbar?
  - W polarization
  - Spin correlations
- Rare decays
- Single top
- Top quark is unusually heavy: maybe is it different?

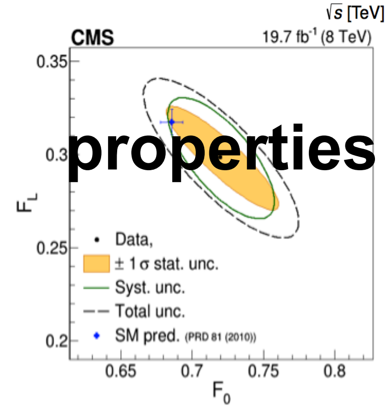
# Role of top quark physics

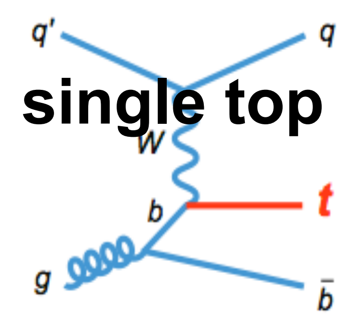
- Top quark physics after the Higgs discovery
  - Special role in EWSB mechanism?
  - Does it play a role in non-SM physics?
  - Are the couplings affected?
  - Main background for many NP searches

- Monitoring of production mechanism
- Interpretation of $m_{top}$: top, W, Higgs masses
- Are properties consistent with our understanding of EWSB?
- Is there any sign of NP in top production/decay?



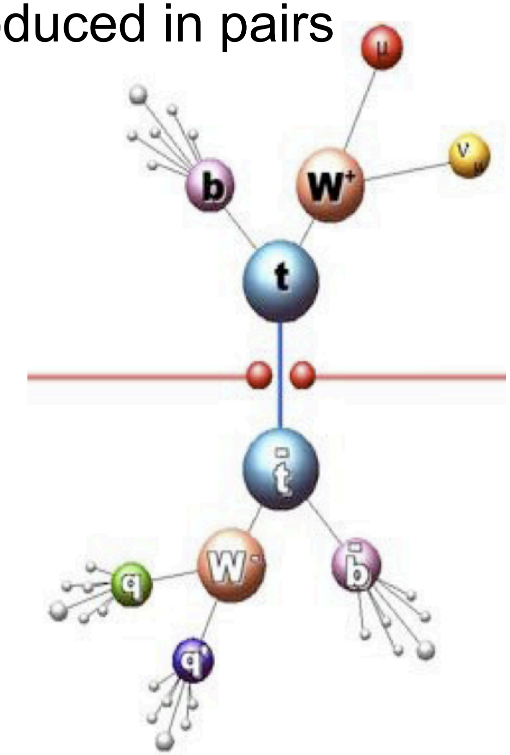



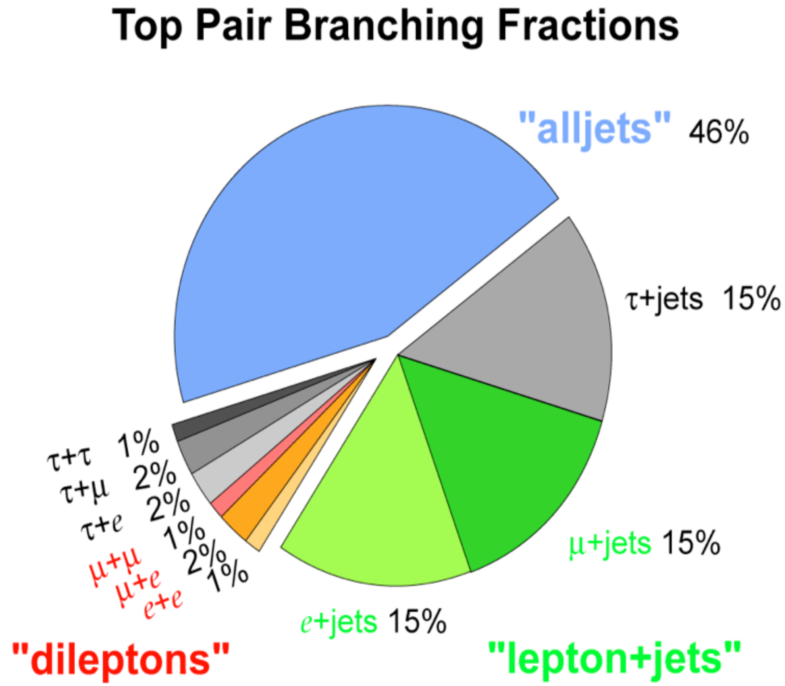
# Measurements

- Measurement of the cross section

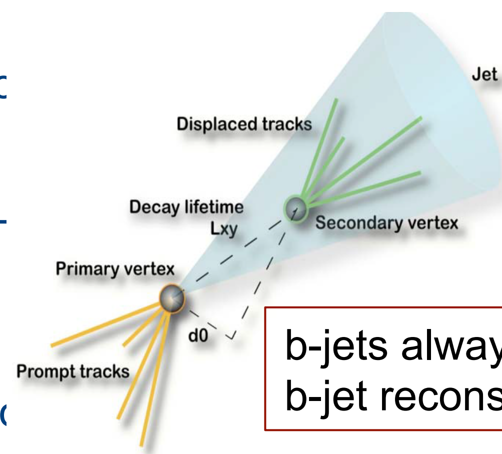
# Top quark decays

Top quarks (mostly) produced in pairs



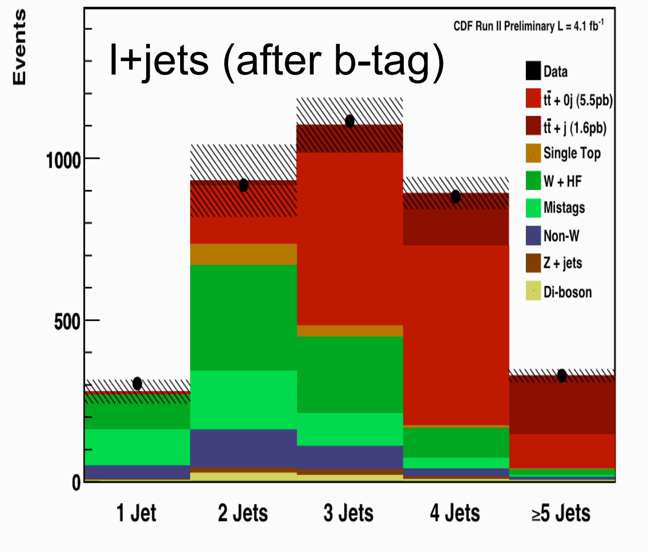

- Dilepton (ee, μμ, eμ):
  - BR~5%, 2 leptons+2 b-jets+2 neutrinc
- Lepton (e or μ) + jets
  - BR~30%, one lepton+4jets (2 from b)-neutrino
- All hadronic
  - BR~44%, 6 jets (2 from b), no neutrinc

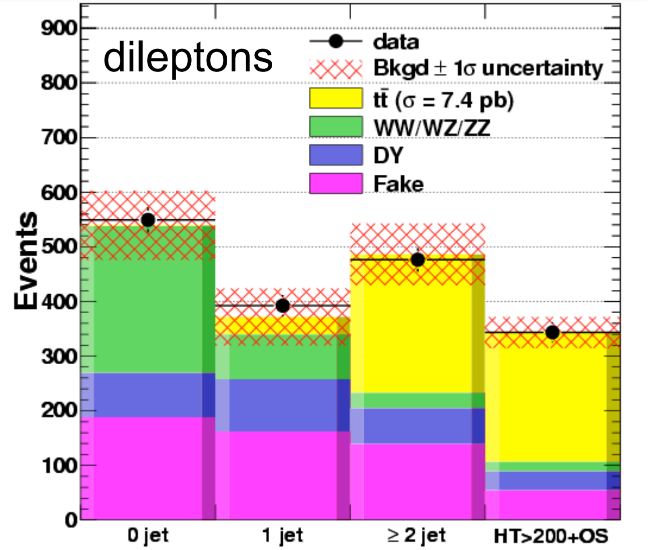



b-jets always present
b-jet reconstruction plays important role

# Top quark events

- LHC@13TeV cross section ~100 times larger than Tevatron
- goal of the LHC is searching for New Physics
- select ttbar events at LHC:
  - understand/calibrate detector
  - Measure SM quantities
- event selection includes SM control events
- ttbar final state is complex (i.e. not a 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



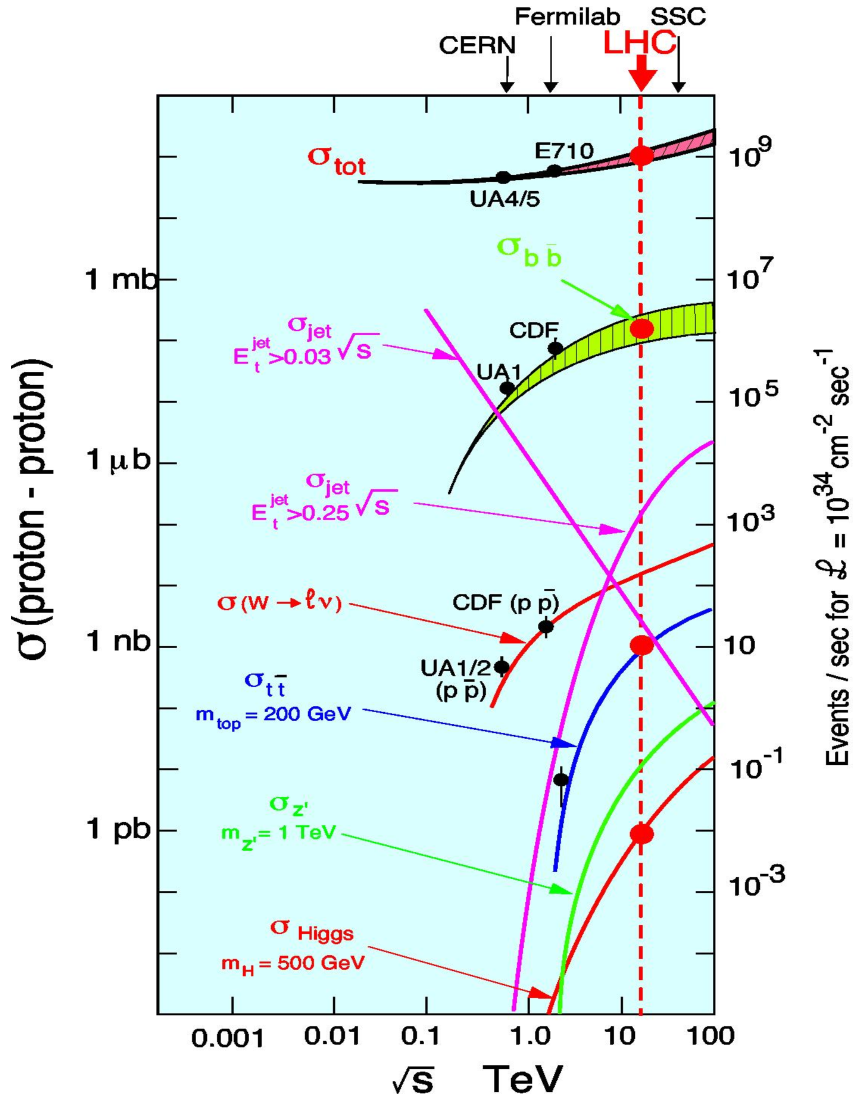
# Theory cross sections: TeV vs LHC

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

Including NNLO+NNLL approximations
PRL 110, 252004 (2013) (M. Czakon et al.)

# Top cross section at 7/8 vs 14 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 cross section drops by factor of ~5:
  - Cacciari,Frixione, Mangano, Nason, Ridolfi - arXiv:0804.2800
  - Top $\sigma$(14TeV)=950 pb
  - Top $\sigma$(7TeV)=172 pb
- Background is more “flat”



# A word about QCD background

- QCD may still be large background in Top events
- From Tevatron to LHC
  - $\sigma$(ttbar) increases by 100
  - $\sigma$(W) increases by 10

…however…

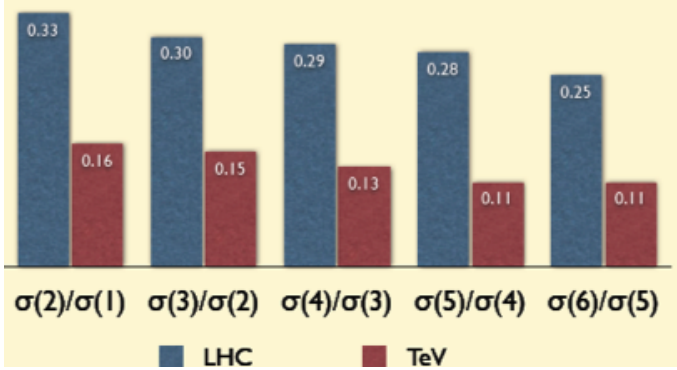
- $\sigma$(W+4 jets) increases 100 times

⇨W+jet background is large

Slide by Michelangelo Mangano

| $\sigma$xB(W→eν)[pb] | N jet=1 | N jet=2 | N jet=3 | N jet=4 | N jet=5 | N jet=6 |
|---|---|---|---|---|---|---|
| LHC | 3400 | 1130 | 340 | 100 | 28 | 7 |
| Tevatron | 230 | 37 | 5.7 | 0.75 | 0.08 | 0.009 |

$E_T$(jets) > 20 GeV , $|\eta|<2.5$ , $\Delta R>0.7$




- Ratios almost constant over a large range of multiplicities
- $O(\alpha_s)$ at Tevatron, but much bigger at LHC

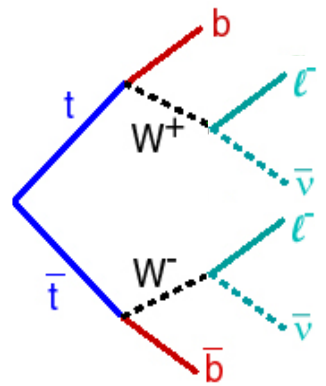
29

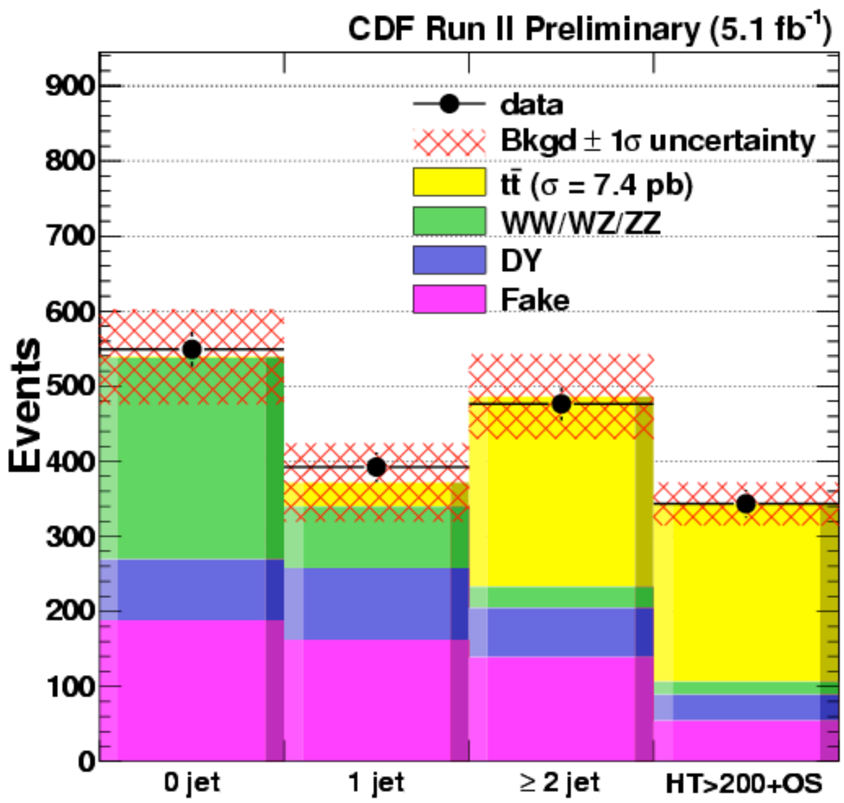
# Cross section measurement

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

- ✓ testing non-SM top production mechanisms
- ✓ top sample may contain an admixture of exotic processes

# Dilepton channel



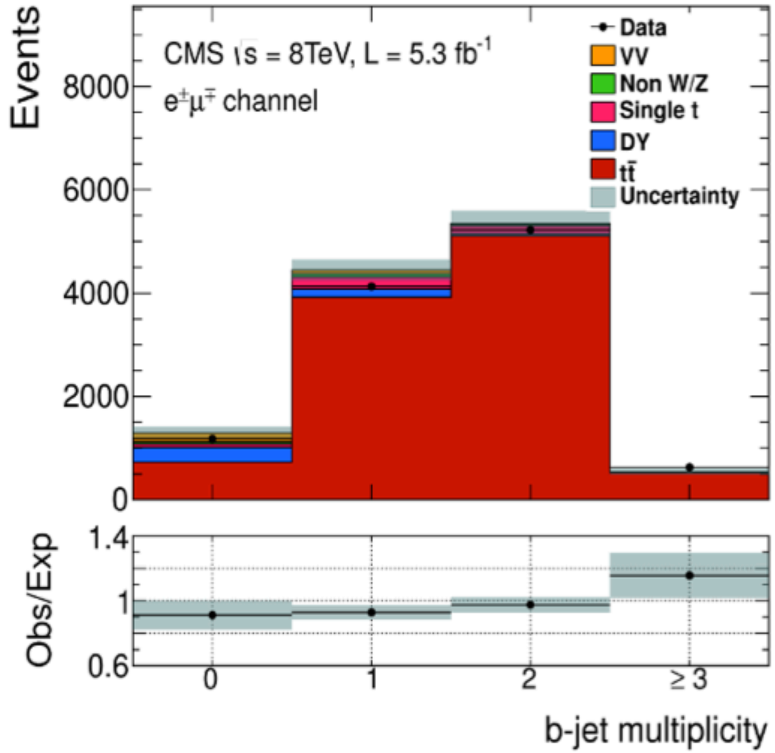

Branching Ratio (BR) ~5%
background: small

- two leptons + ≥2 jets + $\not{E}_T$
- more kinematical variables

# Dilepton channel

JHEP 02(2014)024

- Branching ratio (BR) ~5%
- Background: small
- Clean final state
  - two leptons + ≥2 jets + MET
  - kinematic variables



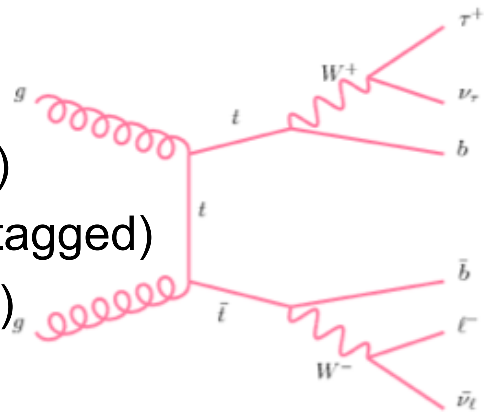

- Signal visible w/without b-tagging
- Measure cross section:
  - ee, μμ, eμ final states
  - btag (CSV): eff 85%, misID 10%
  - Cut and count
- Main systematics: JES, lepton ID, (pileup, b-tag, signal modeling)

$$\boxed{\sigma_{t\bar{t}} = 239 \pm 2\,(\mathrm{stat.}) \pm 11\,(\mathrm{syst.}) \pm 6\,(\mathrm{lum.})\,\mathrm{pb}}$$ ±5%

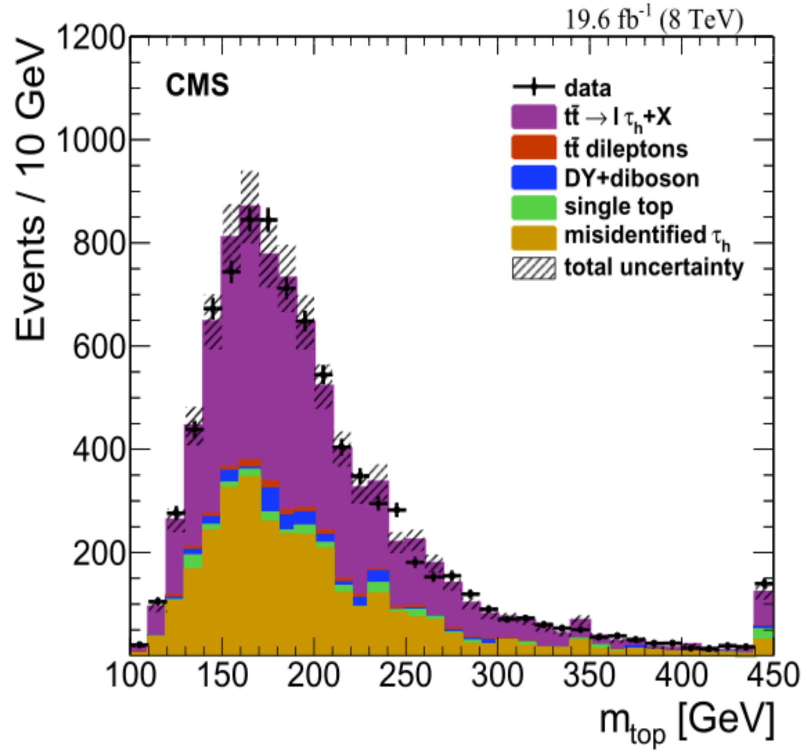
# Tau$_h$+lepton final state

PLB 739(2014)23

- Selection:
  - one isolated lepton (e/μ)
  - at least two jets (one b-tagged)
  - OS tau (hadronic decay)
  - MET



- Determine τ fakes from data
  - Expected to be dominated by quark/gluon jets
  - Estimate from multi-jet/W+jets: use data




dominant syst.: τ fakes, b-tag

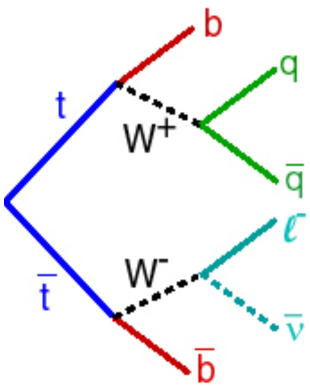
Good agreement between measurement and

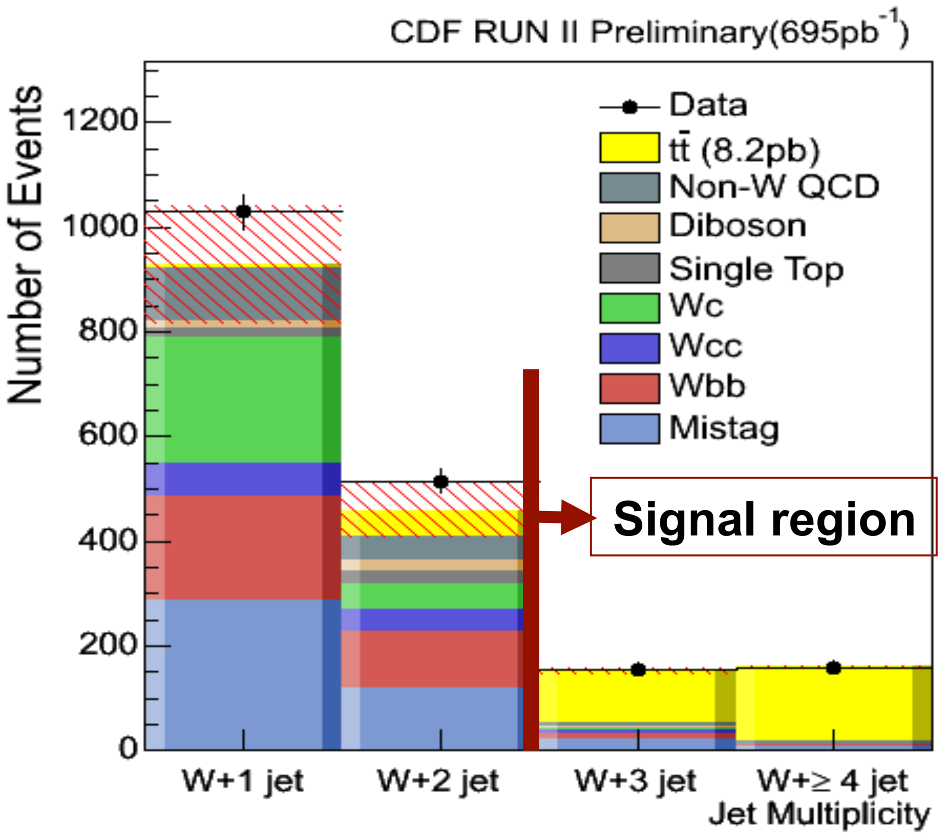
$$\sigma_{t\bar{t}}(e\tau_h) = 255 \pm 4\,(\mathrm{stat}) \pm 24\,(\mathrm{syst}) \pm 7\,(\mathrm{lumi})\ \mathrm{pb};$$

$$\sigma_{t\bar{t}}(\mu\tau_h) = 258 \pm 4\,(\mathrm{stat}) \pm 24\,(\mathrm{syst}) \pm 7\,(\mathrm{lumi})\ \mathrm{pb}$$

±10%

# Lepton + jets



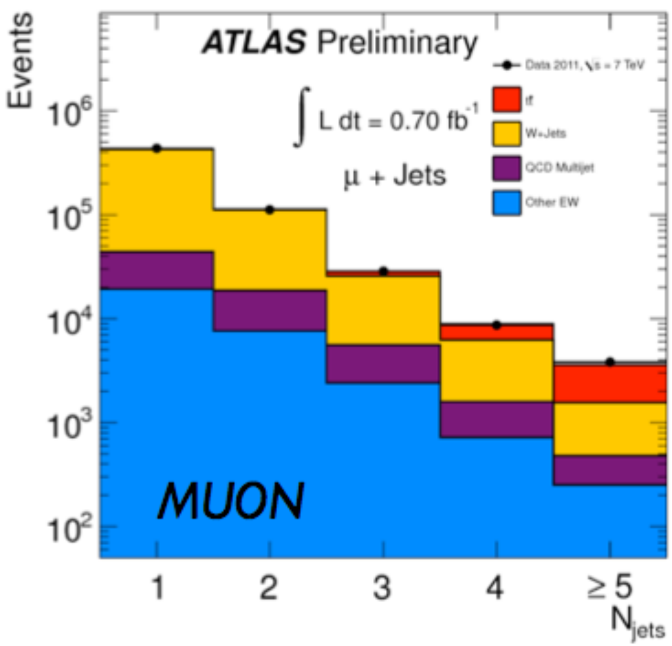

BR ~30%
background: moderate

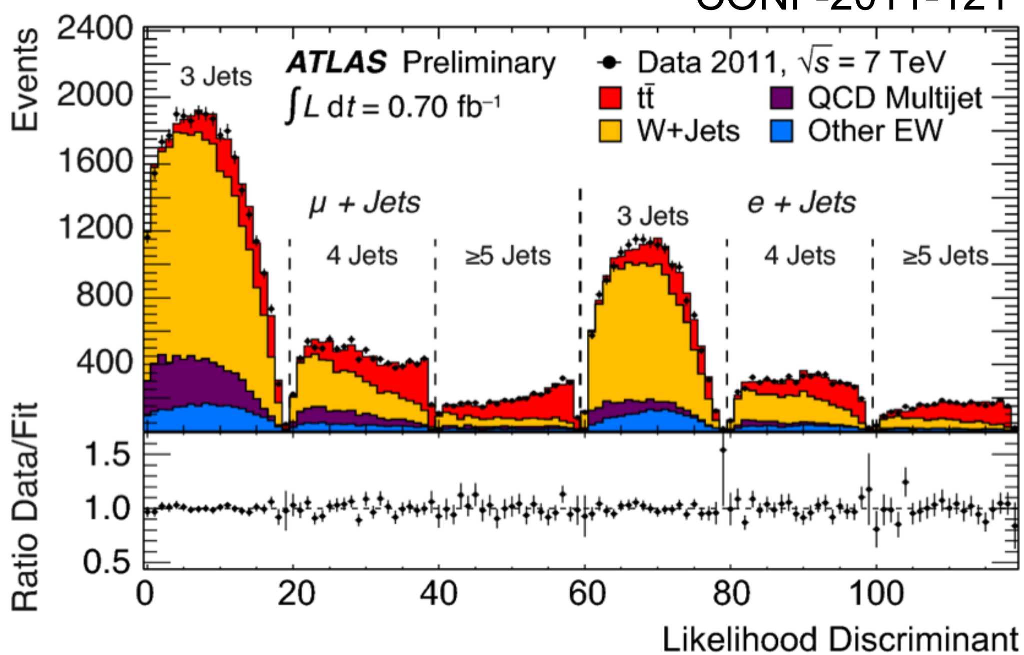
- one lepton + ≥3 jets + $\not{E}_T$
- may require b-tag

# Single lepton channel

- Include both muon and electron channels (untagged)
- Use kinematical differences between ttbar and W+jets

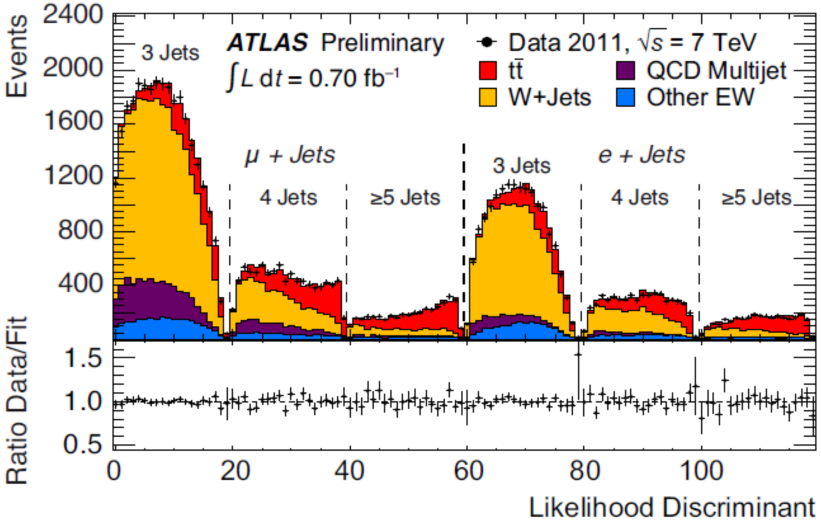
CONF-2011-121

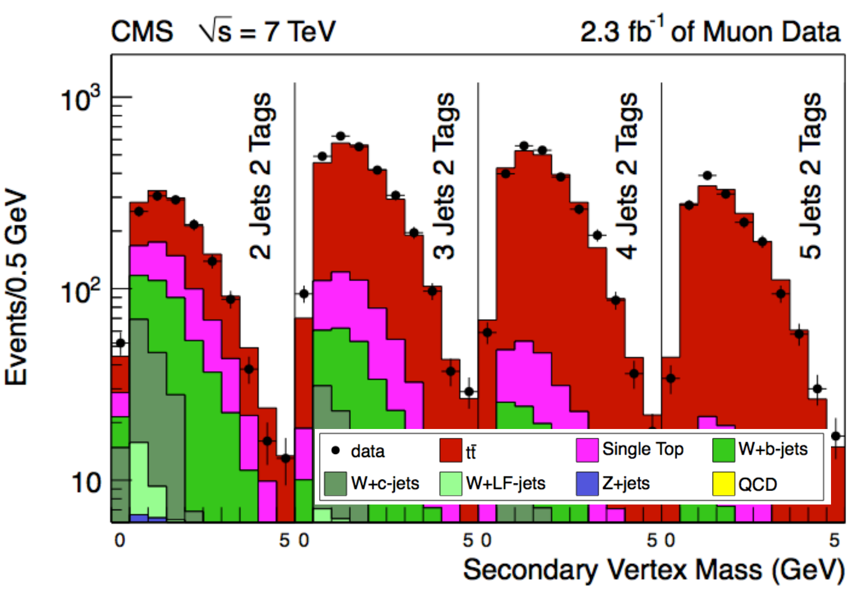



$$\sigma_{t\bar{t}} = 179.0 \pm 3.9\,(\text{stat}) \pm 9.0\,(\text{syst}) \pm 6.6\,(\text{lumi})\ \text{pb}$$

# Single lepton channel




## Main backgrounds:

- Hadronic multijet: rejected by $m_T$,MET, controlled from sidebands
- W+jets (heavy flavor)

## Use kinematics to select ttbar

- Mass of sec. vertex
- topology

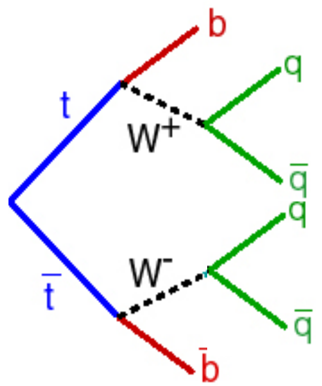
## Categorize events and extract $\sigma_{tt}$ from fit

ATLAS
179.0±3.9 (stat)±9.0 (syst)±6.6 (lumi) pb

158.1 ± 2.1 (stat.) ± 10.2 (syst.) ± 3.5 (lum.) pb.
CMS

arXiv:1212.6682

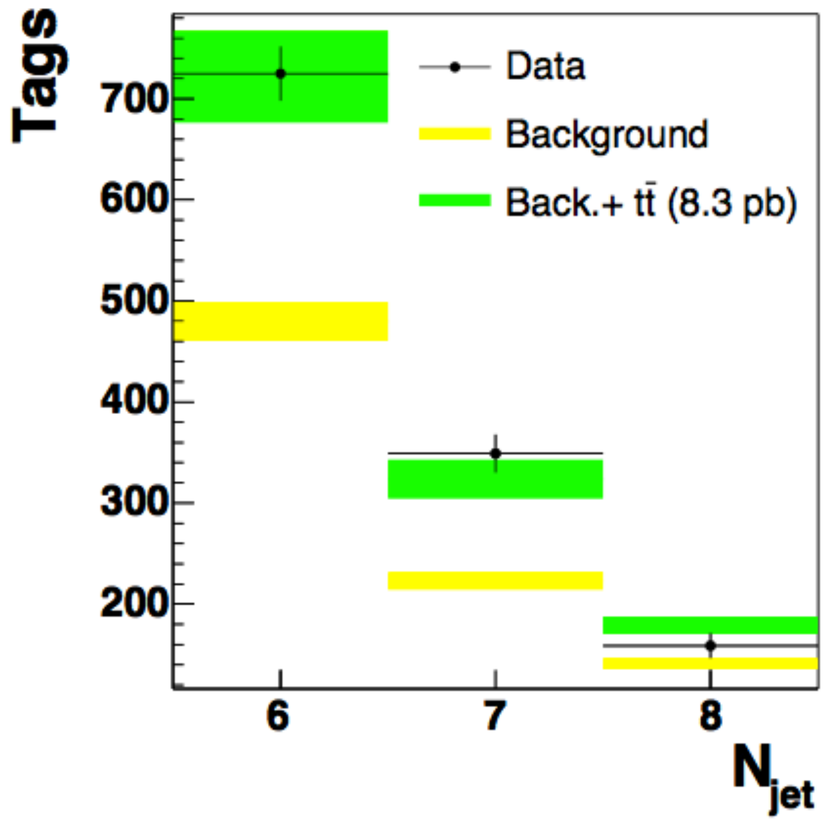
# All hadronic




BR ~44%
background: large

- ≥6 jets + kinematical selection
- optimize S/√B
- require b-tag

CDF: arXiv:0706.3790



# All-hadronic: cross section

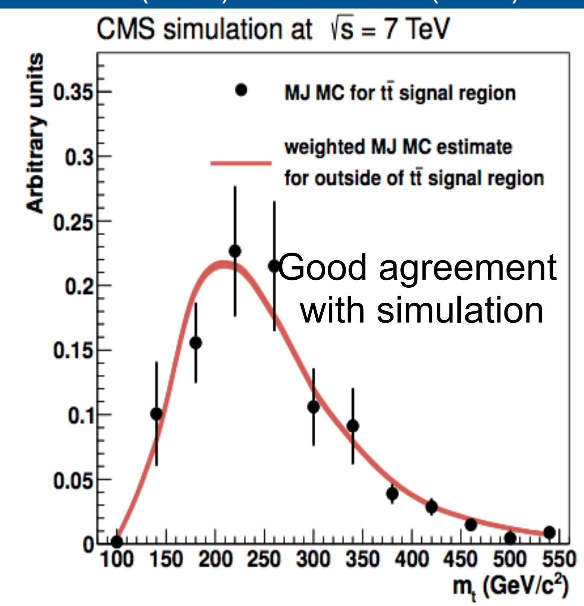
JHEP 05(2013)065. EPJC 74(2014)2758

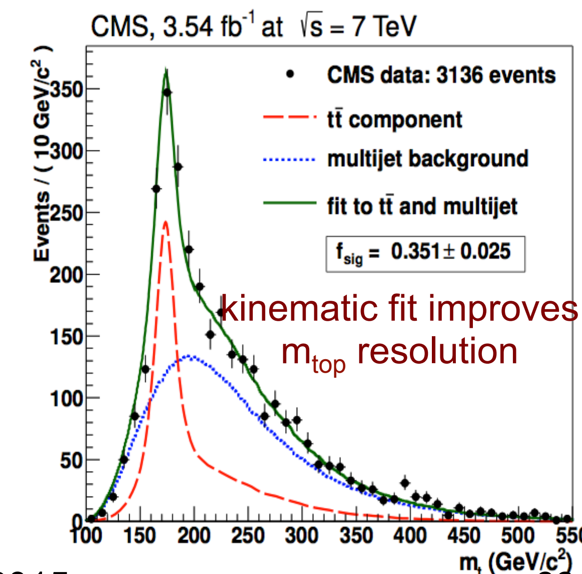
- Fully hadronic final state (BR~46%)
- Six jets and no leptons in the final state
- Reconstruct ttbar system and fit with least $\chi^2$ method
  - reconstruct both W bosons
  - $m_{top1}=m_{top2}$ are free parameters
  - b-jets are taken as b-quark candidates
  - take permutation with smallest $\chi^2$
- Multijet QCD is main background (from data)
  - Use same selection without b-tag req.
  - Re-weigh mass spectrum from anti-tagged sample
- Templates are inputs for likelihood fit for cross section measurement
  - Signal and background templates
  - Signal fraction is a free parameter

±20%

$$\boxed{\sigma_{t\bar{t}} = 139 \pm 10\,(\text{stat.}) \pm 26\,(\text{syst.}) \pm 3\,(\text{lum.})\,\text{pb}}$$

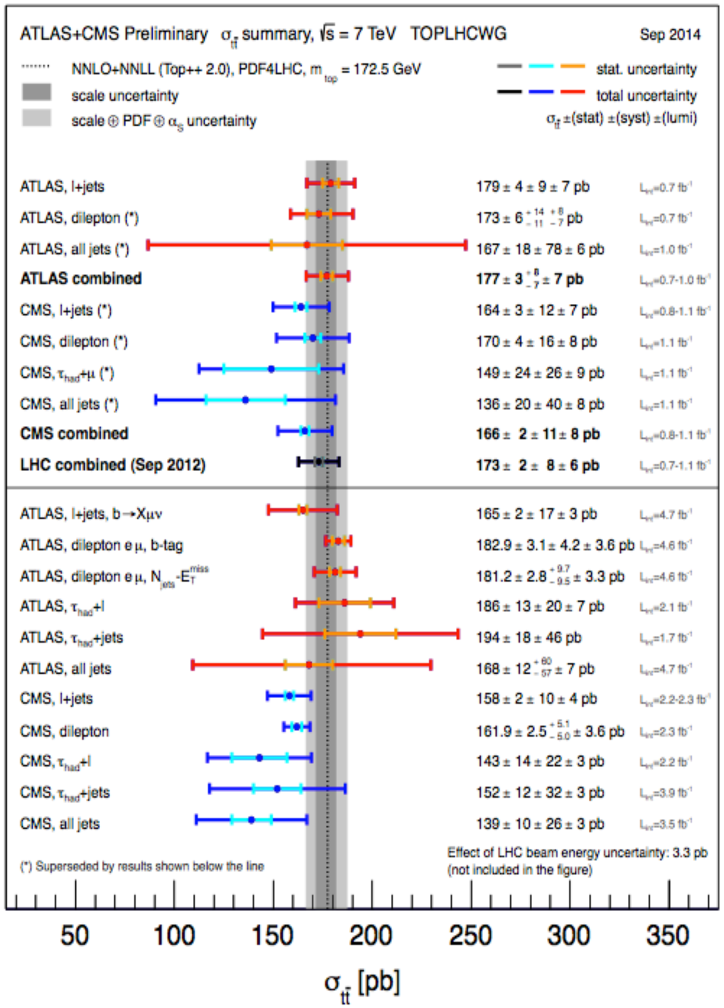
- Dominant syst.: JES, b-tag



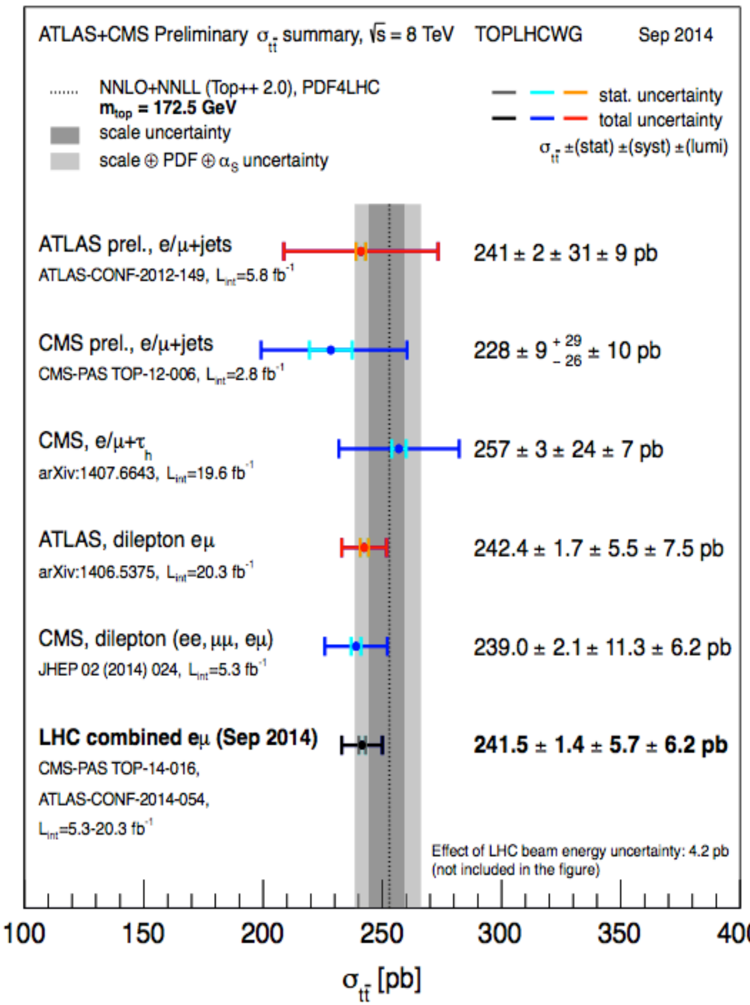



# LHC cross section measurements

## 7 TeV

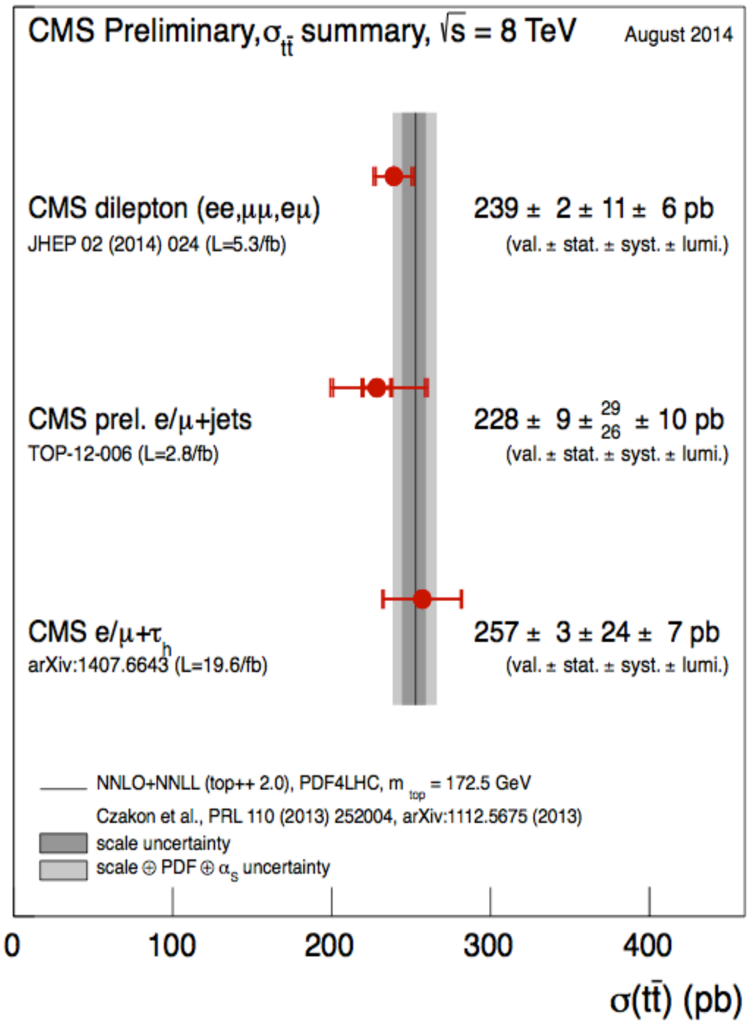



## 8 TeV

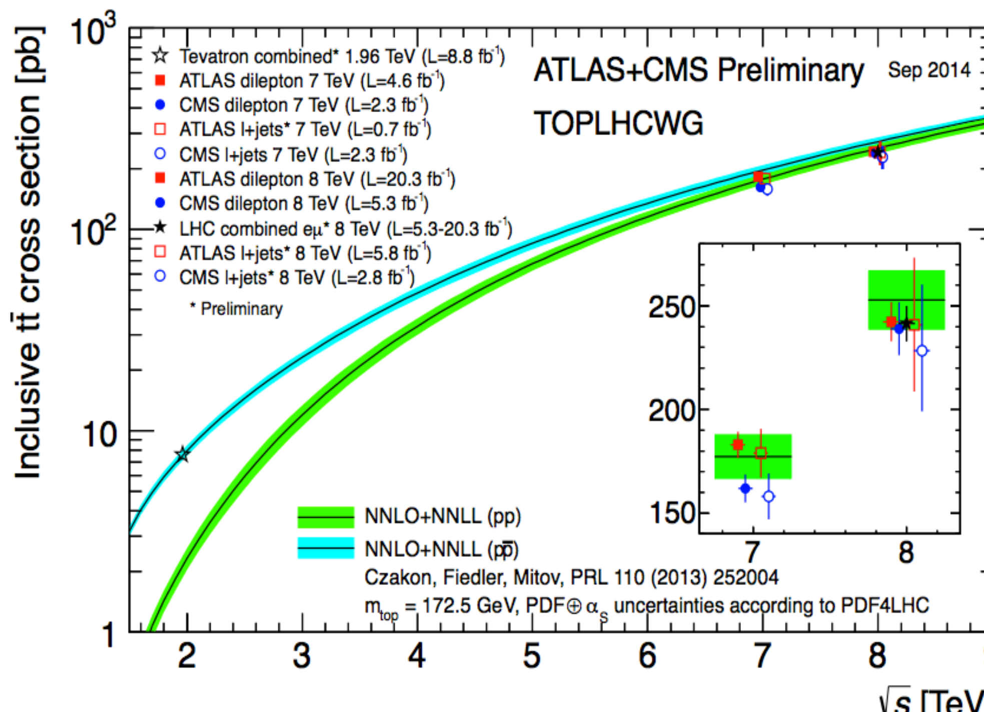


# Cross sections

±5%



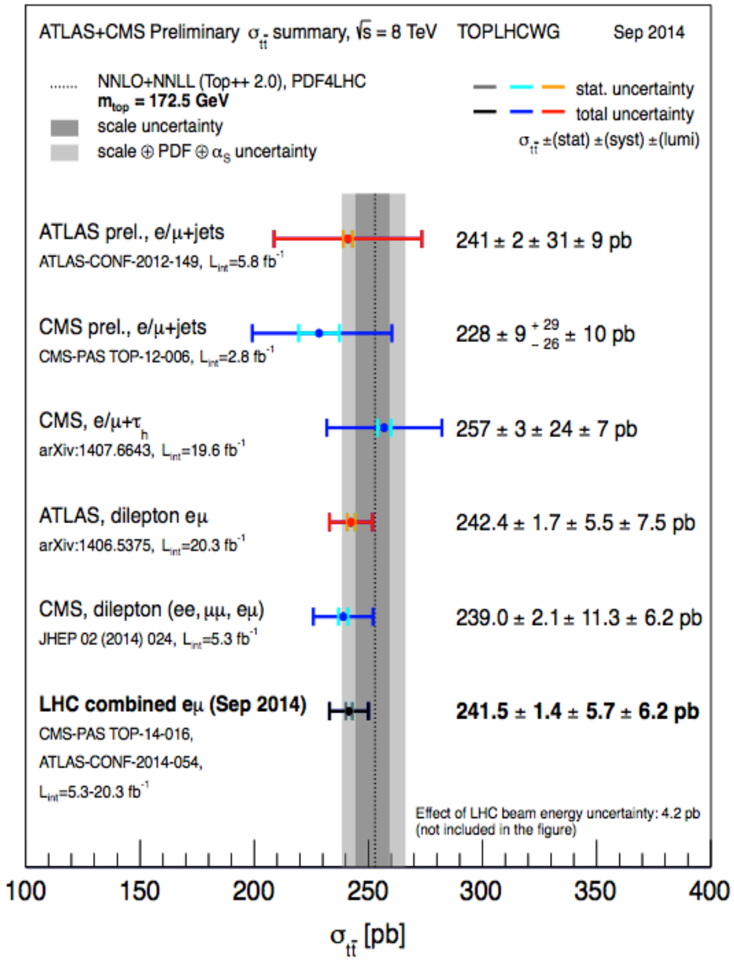

- Cross section measurements provide test of pQCD predictions
- Standard “candle”:
  - ttbar is a dominant background for NP searches
- Comparison in different channels may provide constraints on BSM



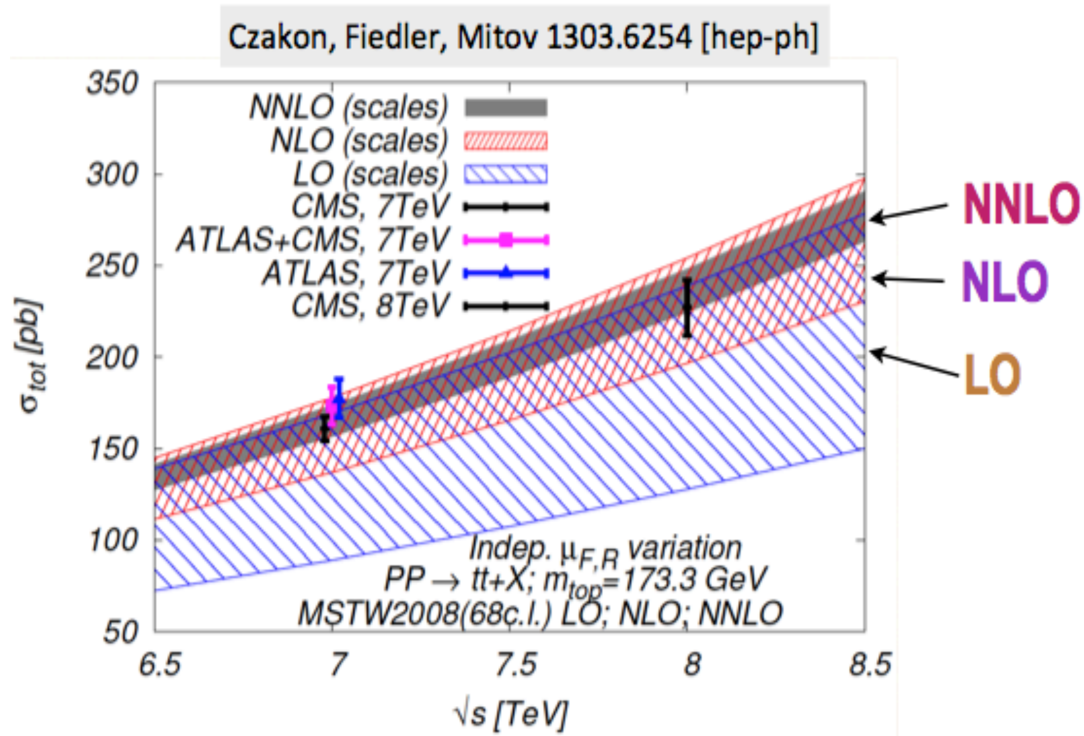
# Cross sections (cont.)

CMS-TOP-14-016

±4%




⇒meas. challenging the theory




| 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%) |

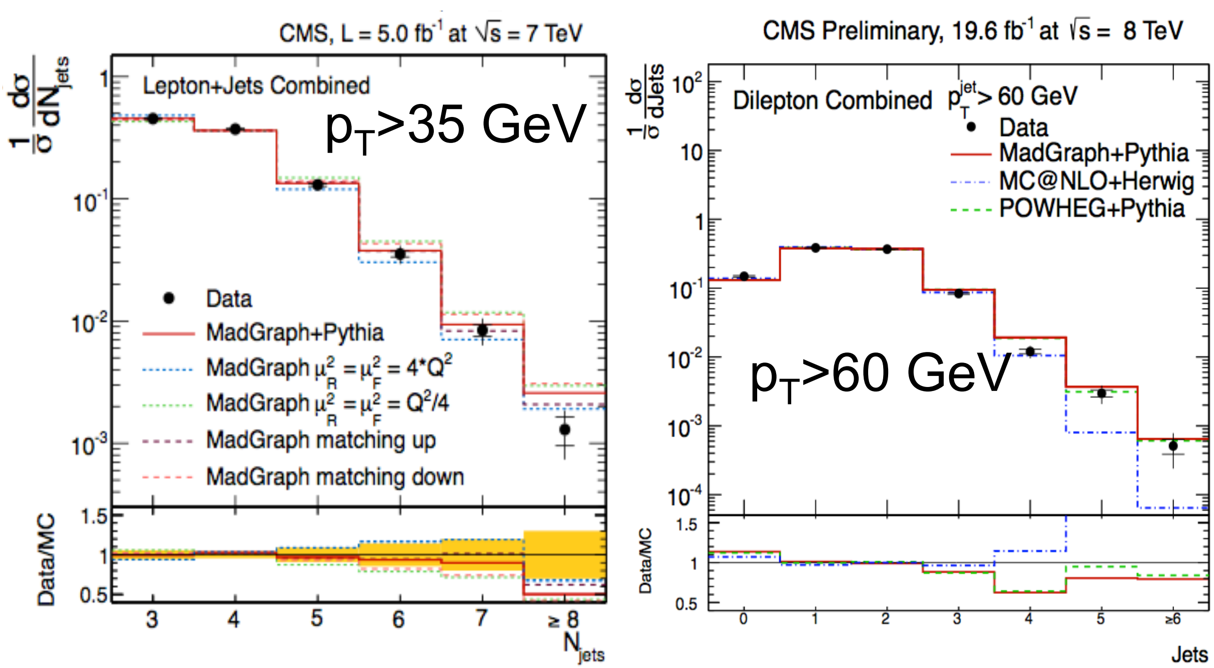
±3-5%

# Differential cross sections

CMS-TOP-12-041, arXiv:1404.3171

- Measurements performed in fiducial volume to minimize model dependency
- Improve ttbar modeling and reduce uncertainties
- Sensitive to BSM effects
- Correct for detector effects ("unfolding" to particle level) and acceptances
- Good agreement in dilepton and lepton+jet channels, at different energies
- Large uncertainties at high jet multiplicities dominated by JES and MC modeling

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

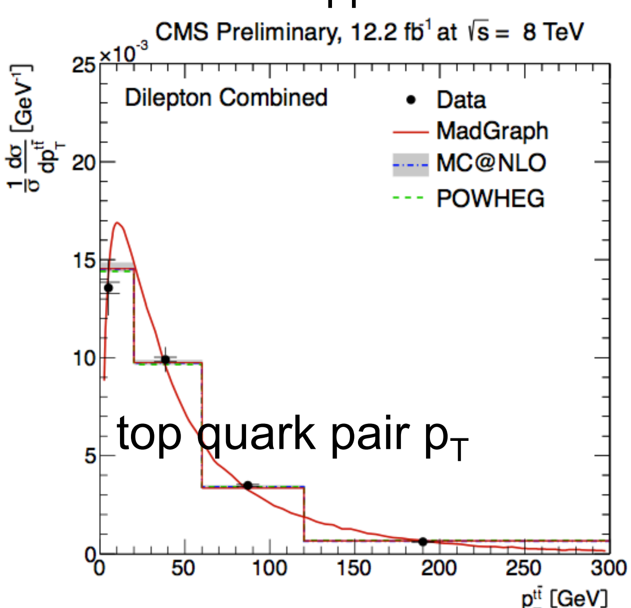


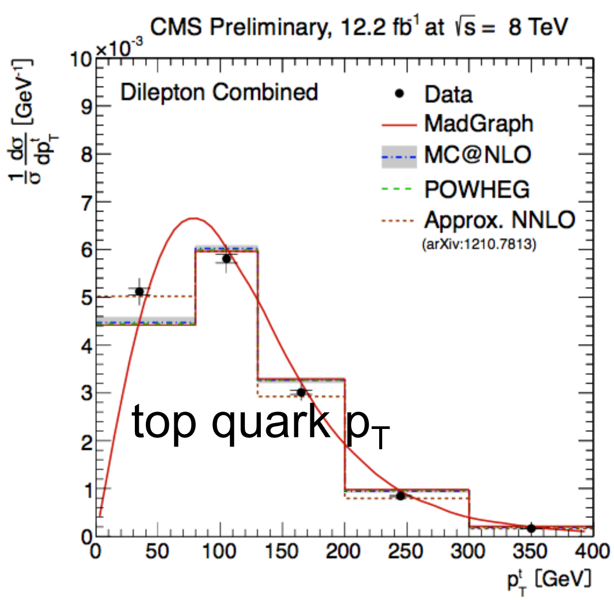
# Differential cross section

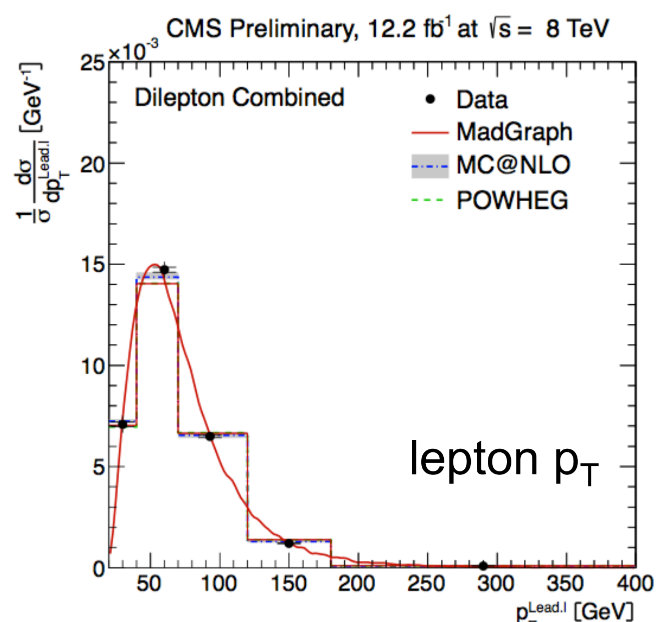
CMS-TOP-12-028

- Measure differential cross section
  - Test perturbative QCD
  - Test BSM scenarios (Z’ decays, etc) with narrow resonance
- Reconstruct event kinematic properties
- Cross sections measured as a function of $p_T$, $\eta$, invariant mass of the final state leptons, the top quarks, and the ttbar system
- Good agreement found in dilepton and lepton+jet channels
  - NNLO approx better describes data

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



# Differential cross section

CMS-TOP-12-028

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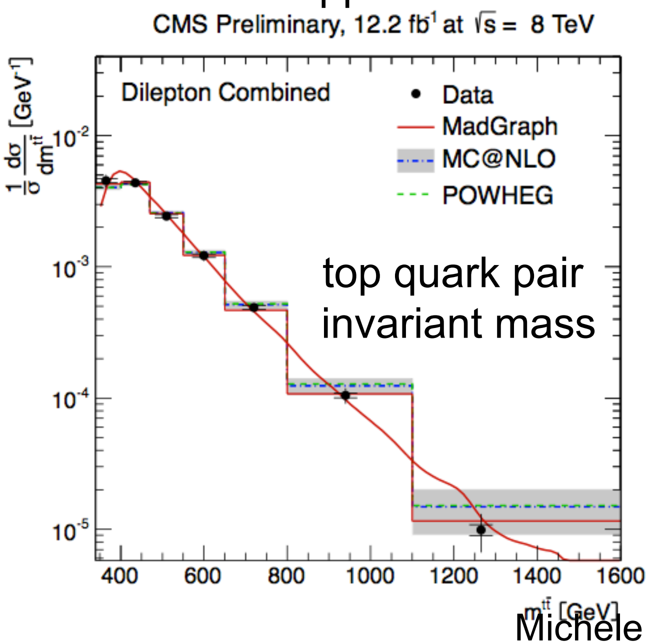
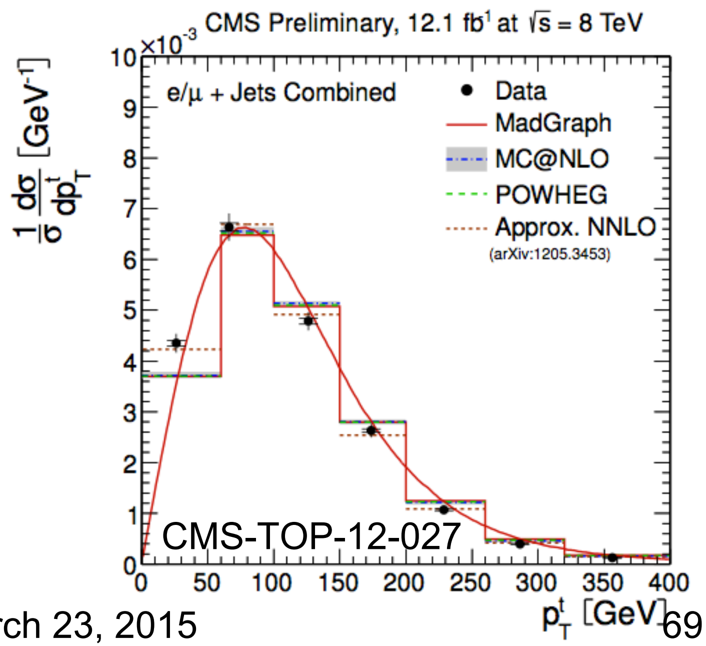
$$\frac{1}{\sigma_{t\bar{t}}}\frac{d\sigma_{t\bar{t}}}{dX}$$

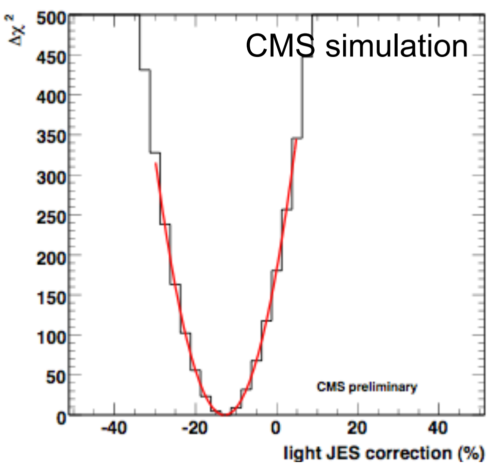


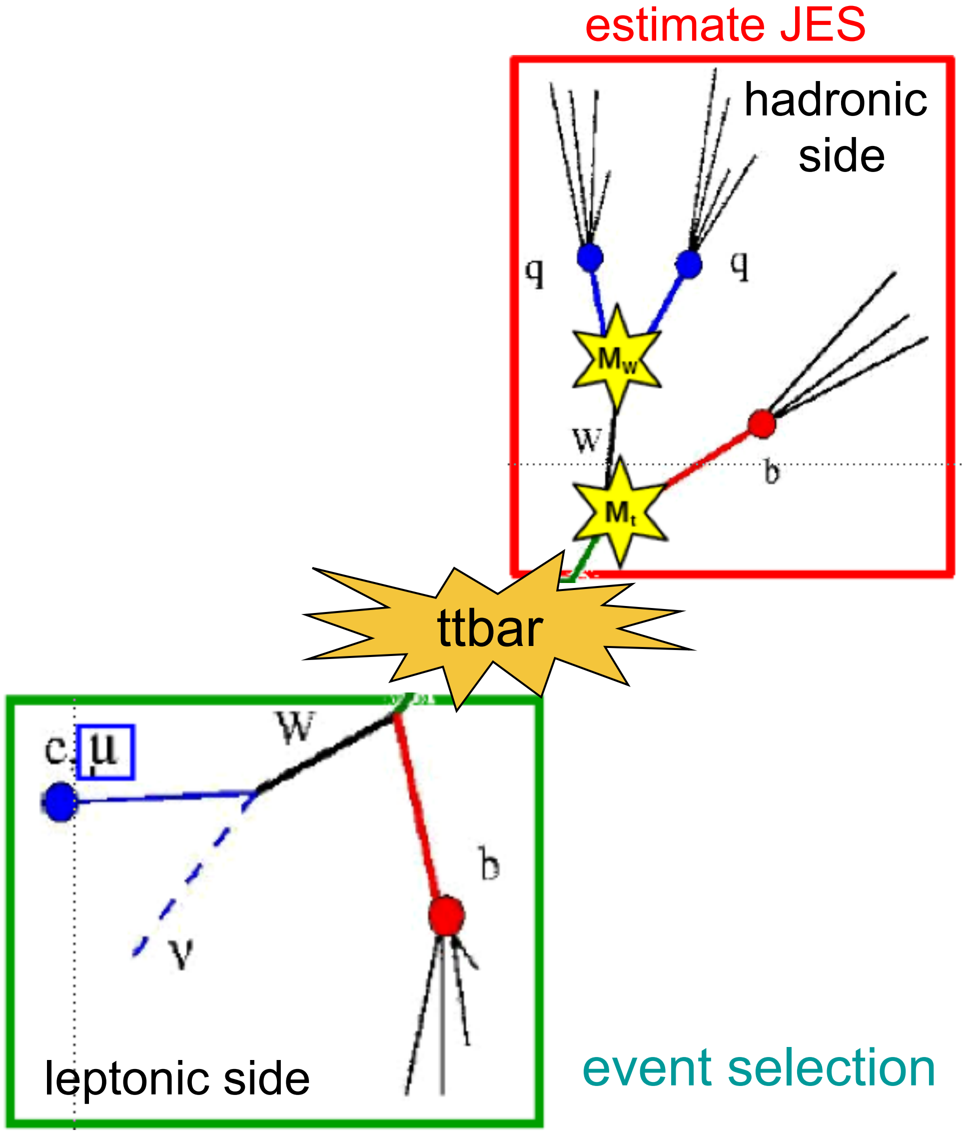



# end

# Jet energy correction from Top

- Use semi-leptonic events
  - 1 isol $\mu$ ($p_T$>30 GeV)+≥4 jets (40 GeV)
- Estimate jet energy corrections by applying event-by-event kinematical fit to W and Top masses
- Likelihood is used to assign jets
- Kinematical fit returns $P(\chi^2)$
- Find best JES by minimizing $\chi^2$



# Measuring the top mass

## Challenging:

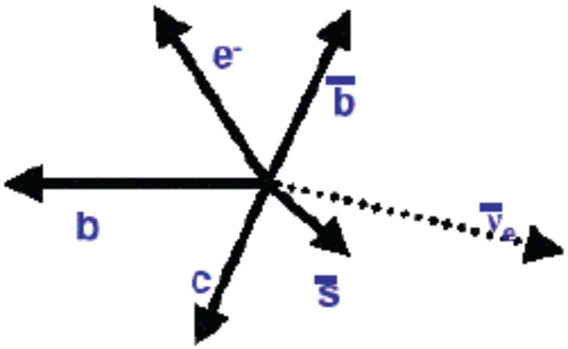
➢ **Lepton+jets**

- undetected neutrino
  - $P_x$ and $P_y$ from $E_T$ conservation
  - 2 solutions for $P_z$ from $M_W = M_{l\nu}$
- leading 4-jet combinatorics
  - 12 possible jet-parton assignments
  - 6 with 1 b-tag
  - 2 with 2 b-tags
- ISR + FSR

➢ **Dileptons**

- (less statistics)
- two undetected neutrinos
- less combinatorics: 2 jets

**LO final state:**




**experiment sees:**