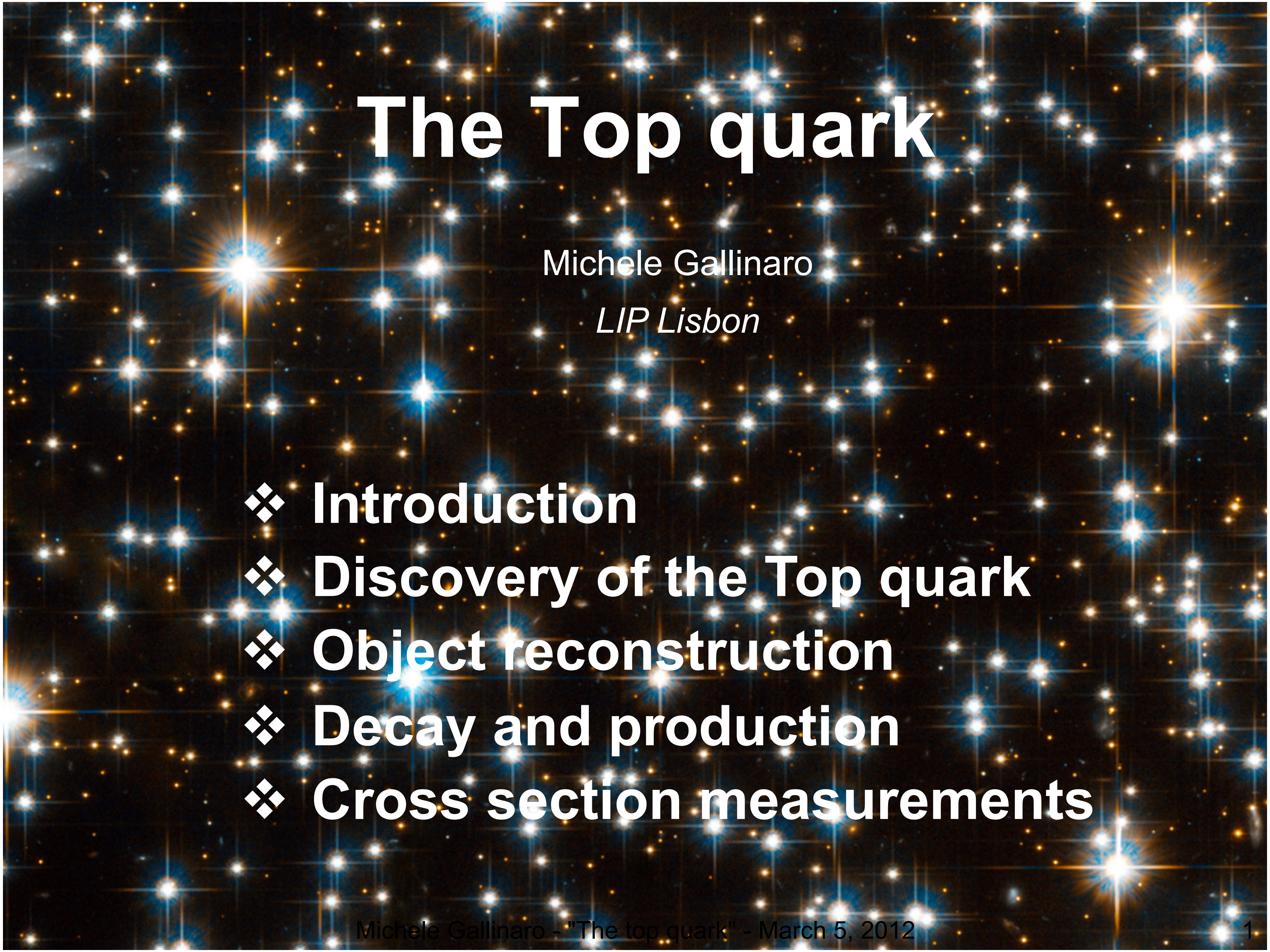


The Top quark

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

today

- Properties, mass
- A_{FB} and charge asymmetry, etc.

- Single top production
- Flavor Changing Neutral Currents (FCNC)

- Search for top partners and 4th 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 (τ) lepton in Mark I data (ν_τ from the decay kinematics)
- Discovery at Fermilab of the Y

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

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

- 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?

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

Predictions from Z decays

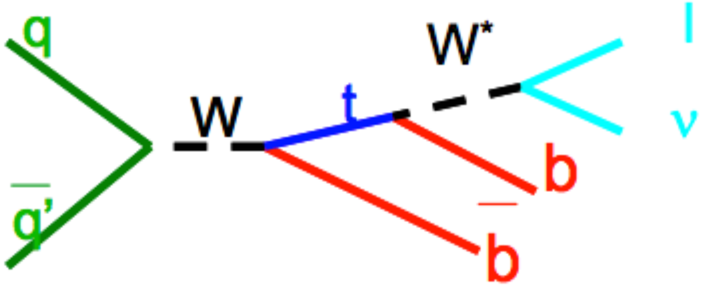
- In the SM, various EWK observables depend on the mass of the top quark

- 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

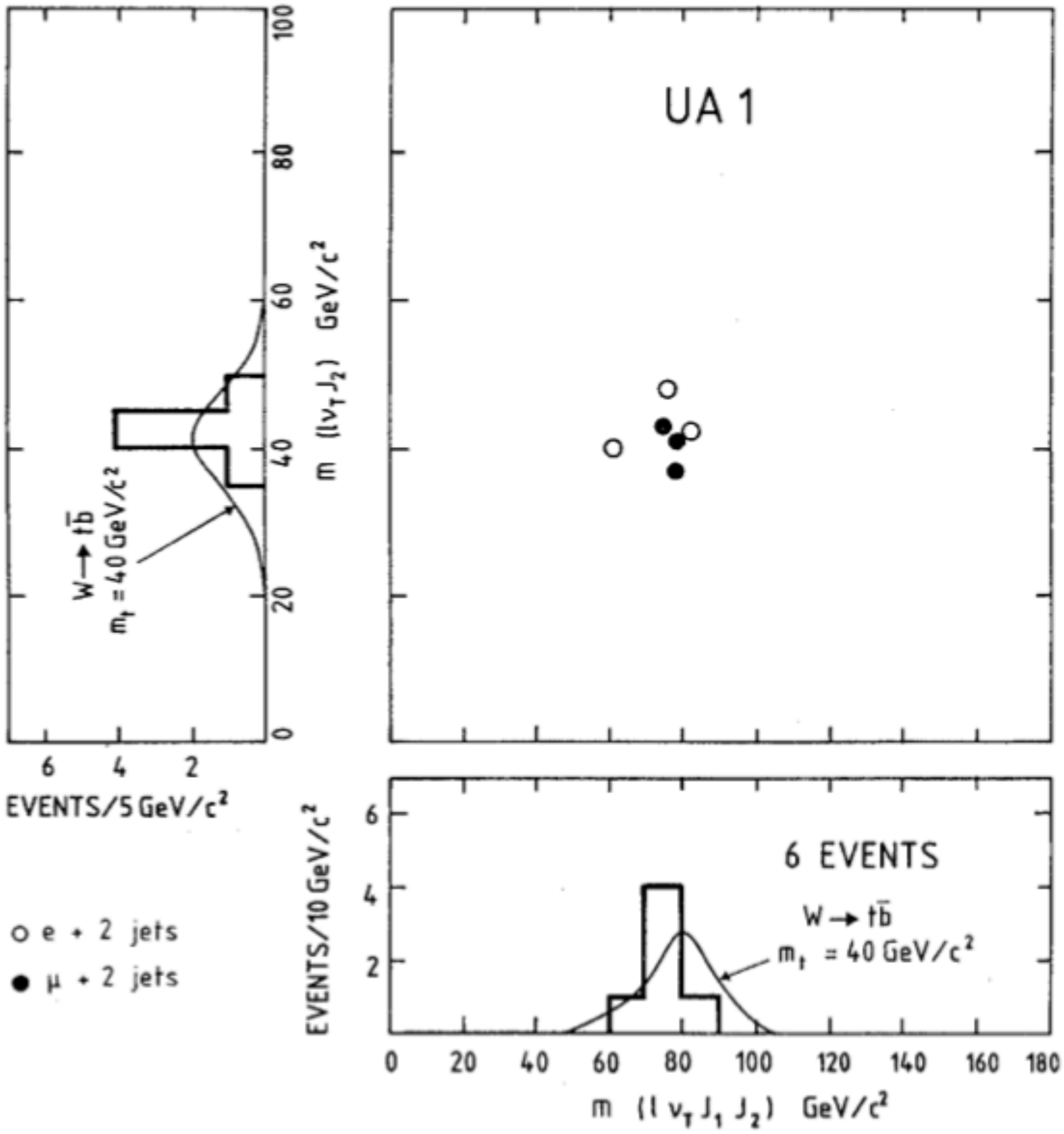
CERN $Sp\bar{p}S$ ($\sqrt{s}$=540 GeV) built to observe W,Z

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



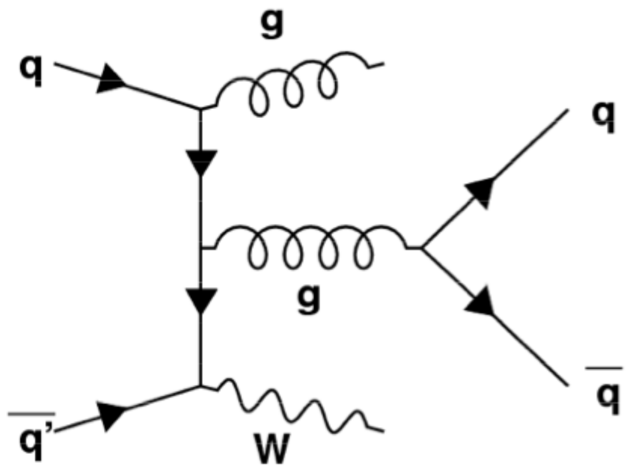
1984: UA1

- $W \to tb \to l\nu bb$
- 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

UA 1
m (l ν_T J_2) GeV/c²
0
20
40
60
80
100
W → t b̄
m_t = 40 GeV/c²
6
4
2
EVENTS/5 GeV/c²
○ e + 2 jets
● μ + 2 jets
6 EVENTS
W → t b̄
m_t = 40 GeV/c²
EVENTS/10 GeV/c²
6
4
2
0
20
40
60
80
100
120
140
160
180
m (l ν_T J_1 J_2) GeV/c²

Searches at hadron colliders

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



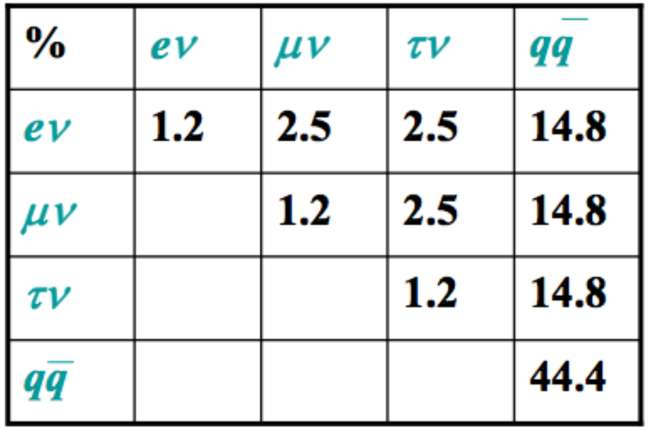
channel	observed	expected background
$\mu + \geq 2$ jets	10 events	11.5 ± 1.5 events
$e + \geq 1$ jets	26 events	23.4 ± 2.8 events

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

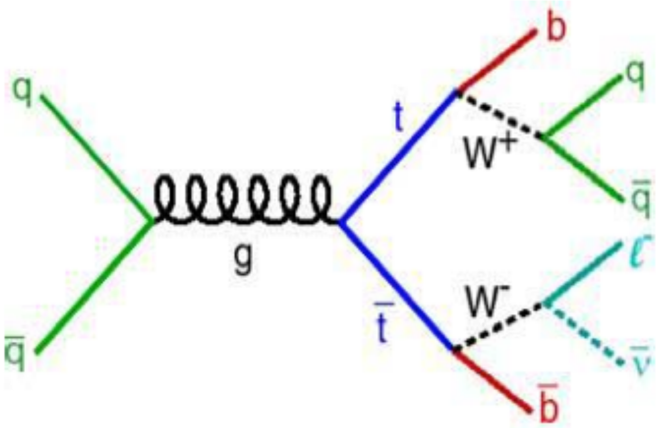
$\Rightarrow$conclude M_{top}>44 GeV

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: $t\bar{t} \rightarrow Wb\, W\bar{b}$

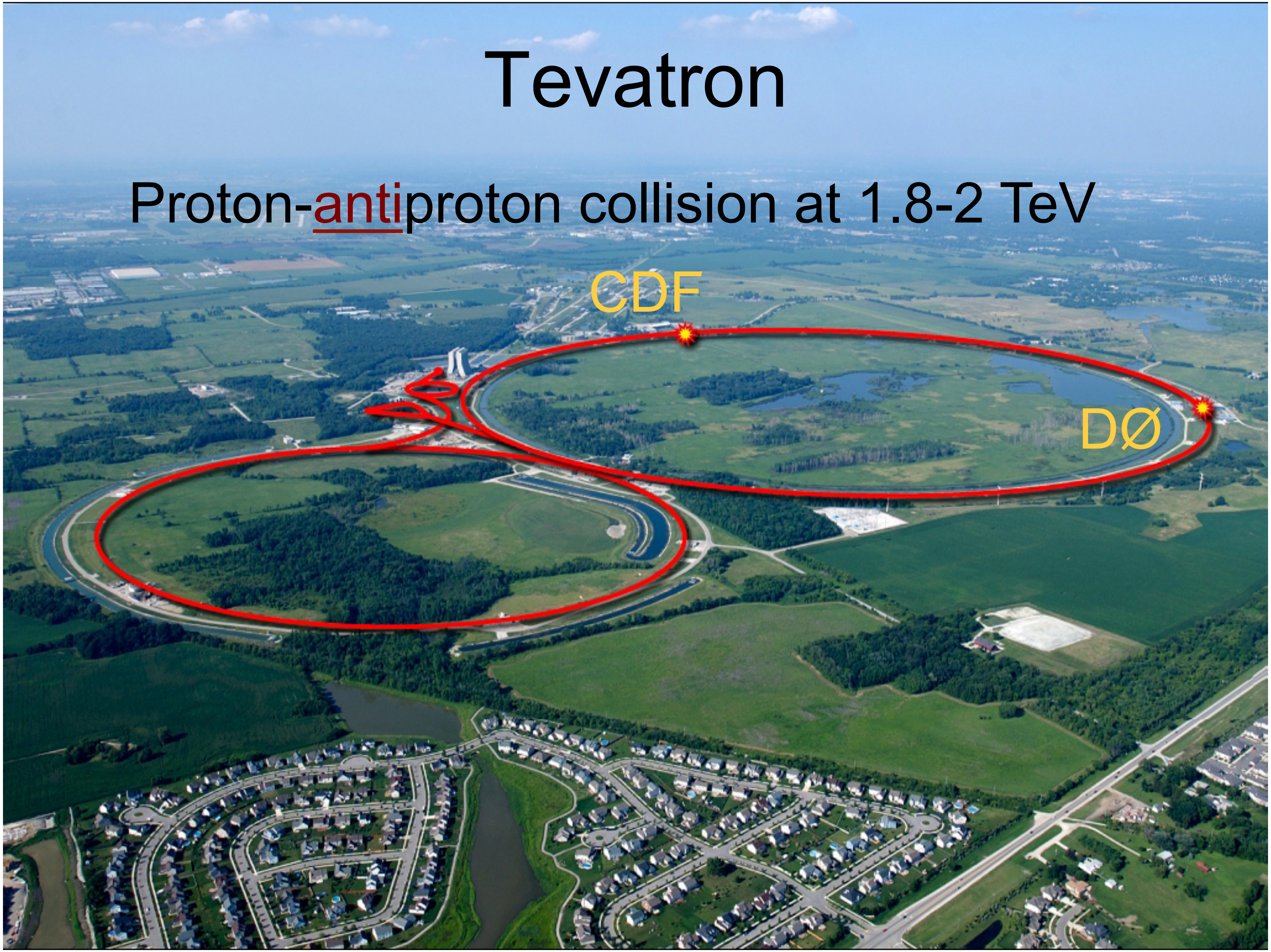


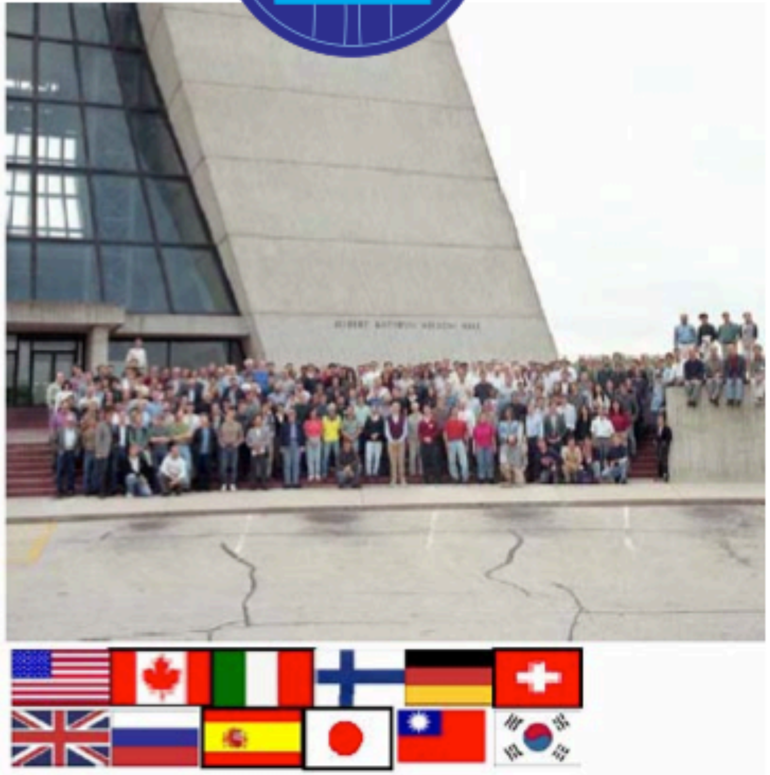
%	$e\nu$	$\mu\nu$	$\tau\nu$	$q\bar{q}$
$e\nu$	1.2	2.5	2.5	14.8
$\mu\nu$		1.2	2.5	14.8
$\tau\nu$			1.2	14.8
$q\bar{q}$				44.4



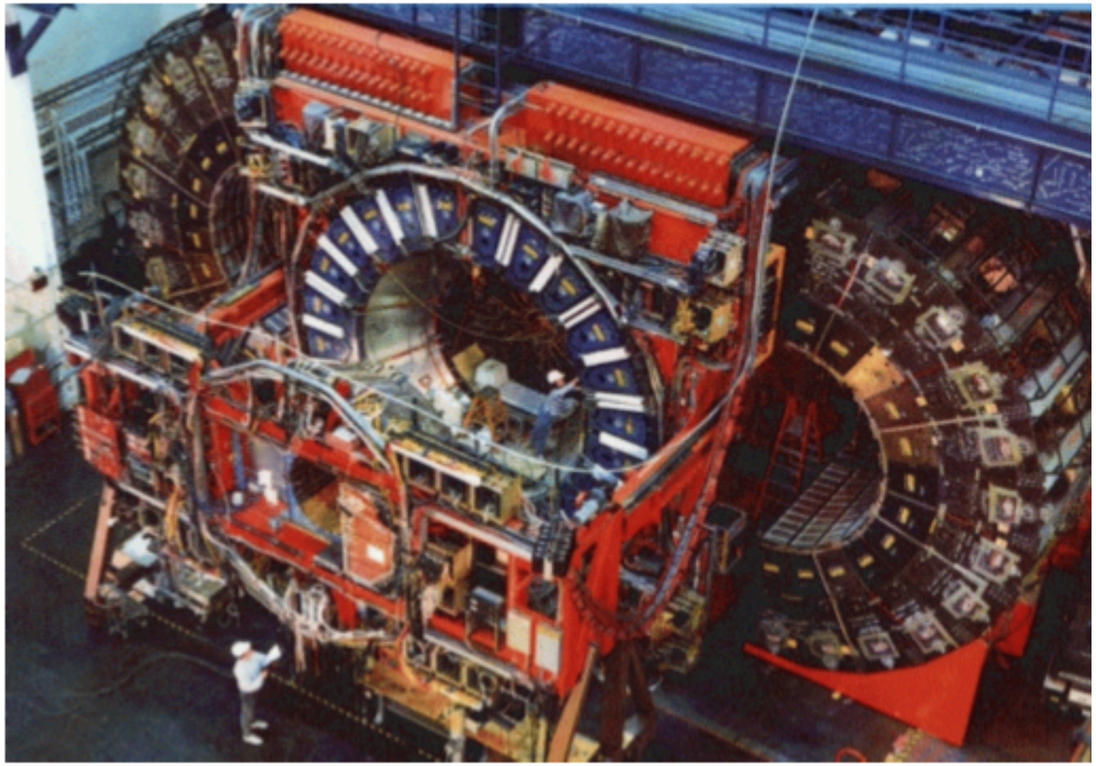
Tevatron

Proton-antiproton collision at 1.8-2 TeV





12 countries, 62 institutions
767 physicists

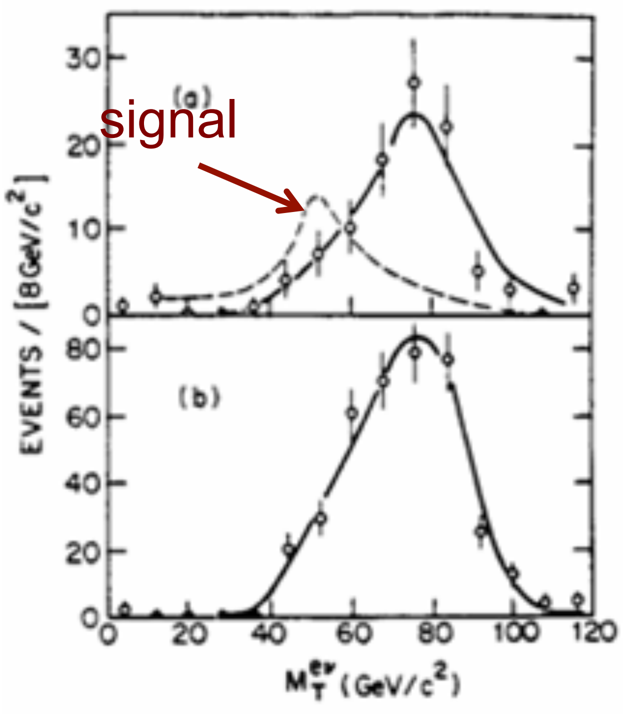


Searches at CDF

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.)

eμ channel

- Event rate much lower: 2xBR(W→eν)
- Background very small
- No W+jets
- No Drell-Yan
- Dominant background is Z→ττ→eμX (expect 1 event)
- Observe 1 event

⇒M_{top}>72 GeV (expect 7 events for M_{top}=70 GeV)

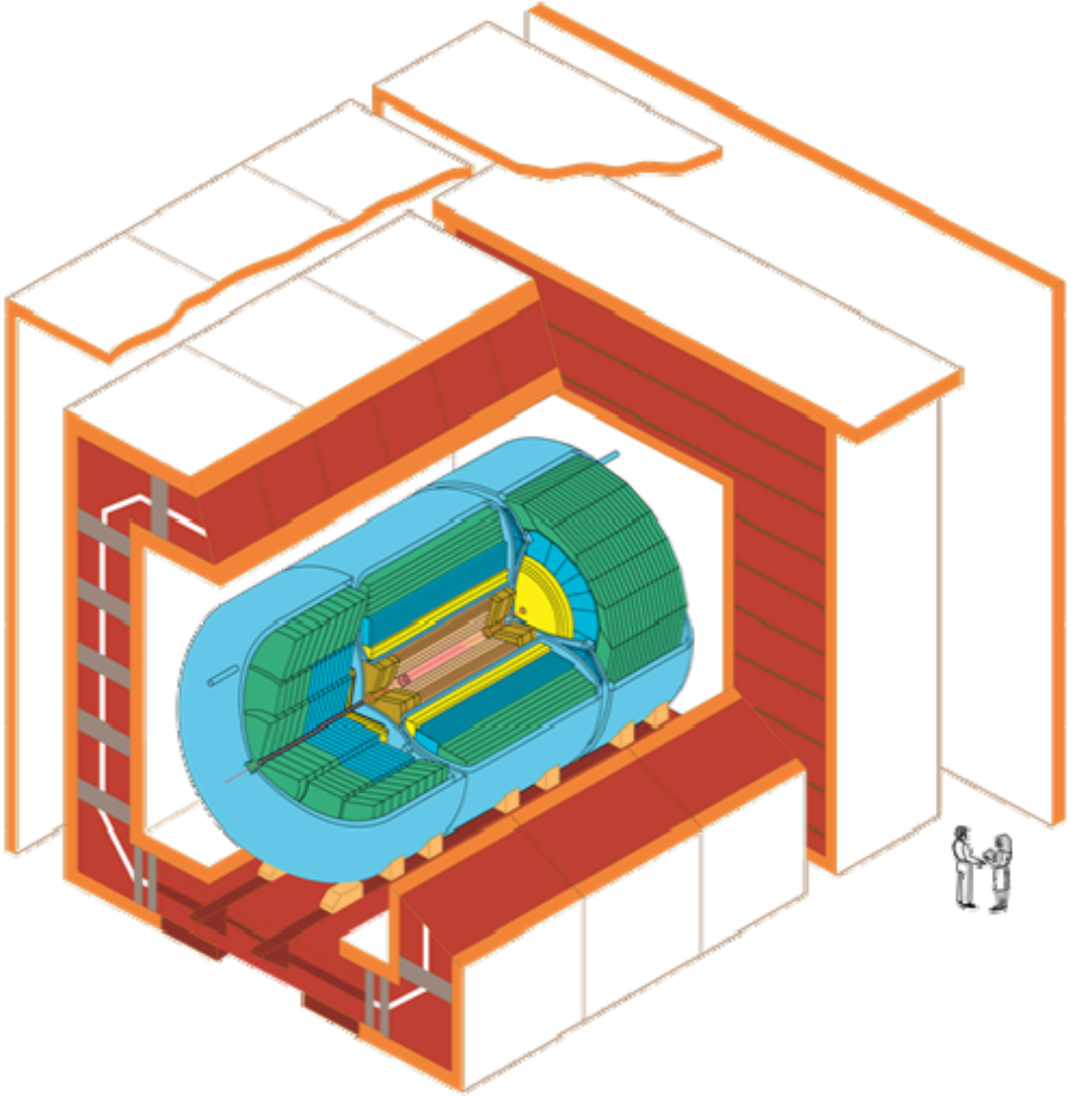
Change of strategy: $M_{top}>M_b+M_W$

- Top 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, $\mu\mu$, eμ (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



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_{top}=100 GeV

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

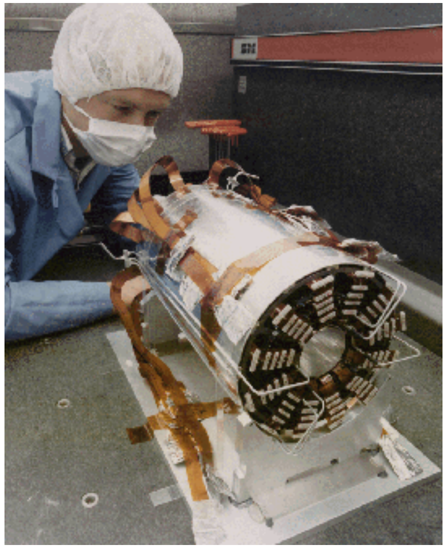
⇒M_{top}>131 GeV@95%CL

Detecting the top quark at CDF

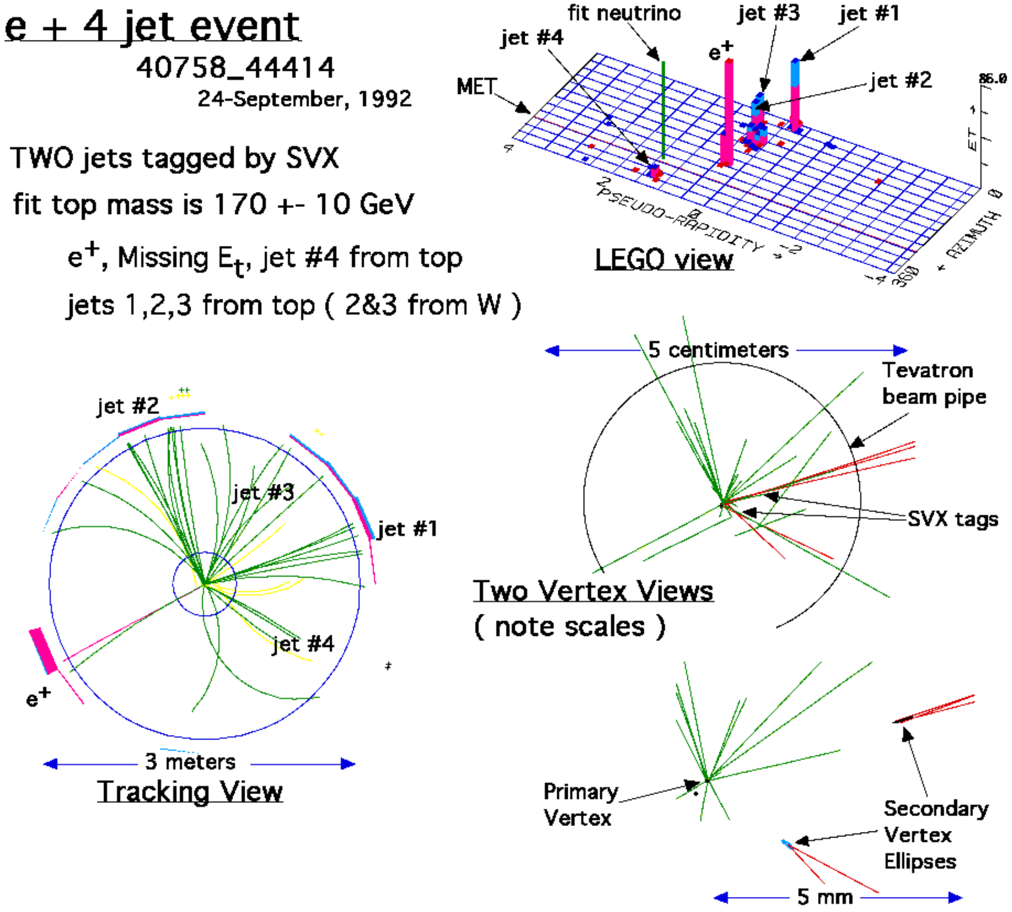
- Strategy
  - dilepton: +2 jets
  - single lepton: b-tagging

    1) soft e/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

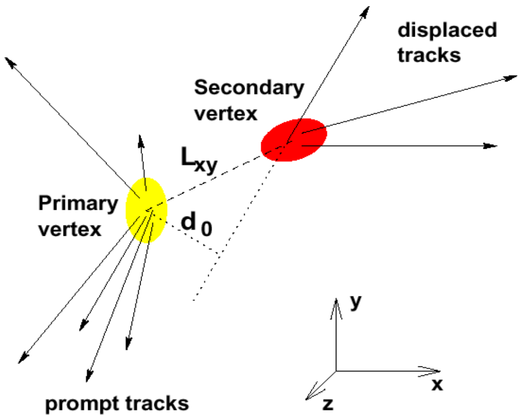
TWO jets tagged by SVX
fit top mass is 170 +- 10 GeV
e^+, Missing E_t, jet #4 from top
jets 1,2,3 from top (2&3 from W)

Tagging b-jets

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

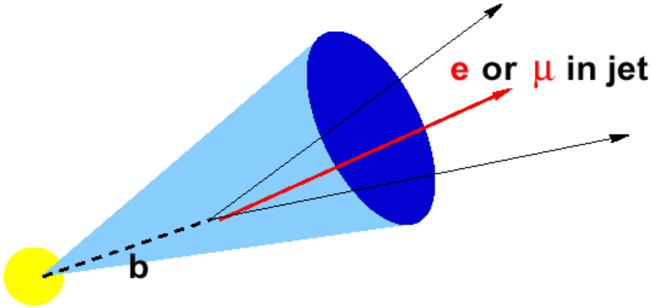
B hadrons are long-lived

Vertex displaced tracks



semileptonic B hadron decay

Soft Lepton Tagging



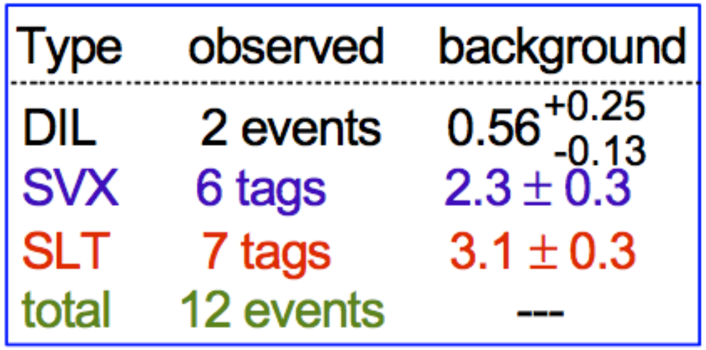
- $b \to \ell \nu c$ (BR $\sim 20\%$)
- $b \to c \to \ell \nu s$ (BR $\sim 20\%$)

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 ± 0.3
SLT	7 tags	3.1 ± 0.3
total	12 events	---

3 events in common

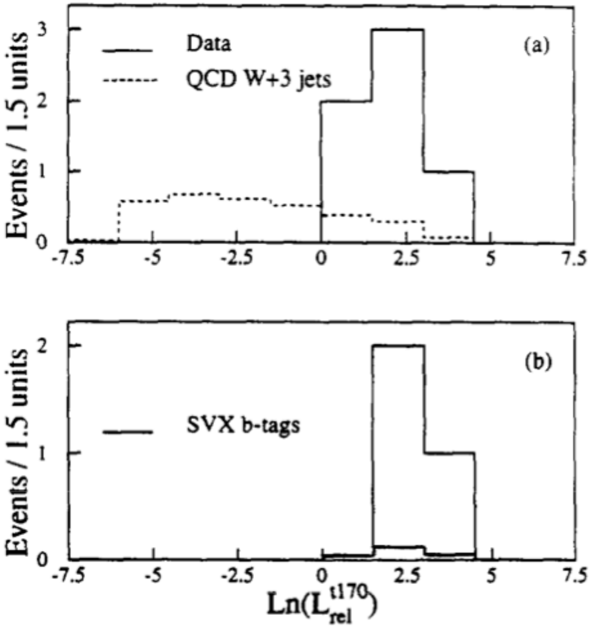
- In total, an excess of events
- Background fluctuation probability: 2.8σ
- Skepticism, additional studies, cross-checks
- Additional 8 months before making the results public

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)

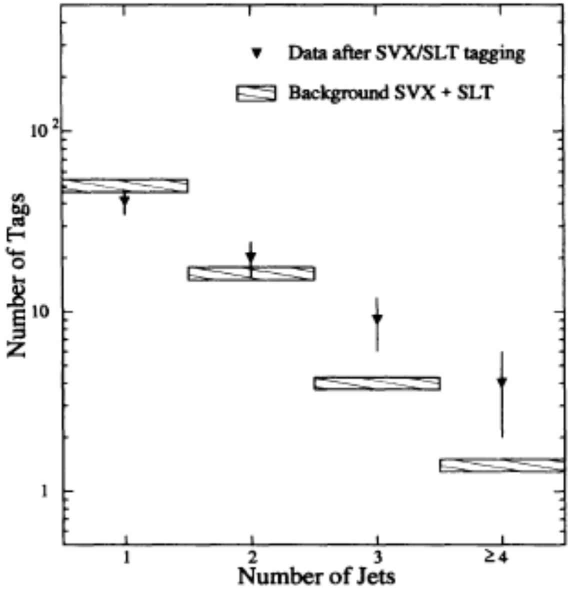
- Observed 7 events (expect 4-6 from bkg)
- No independent evidence

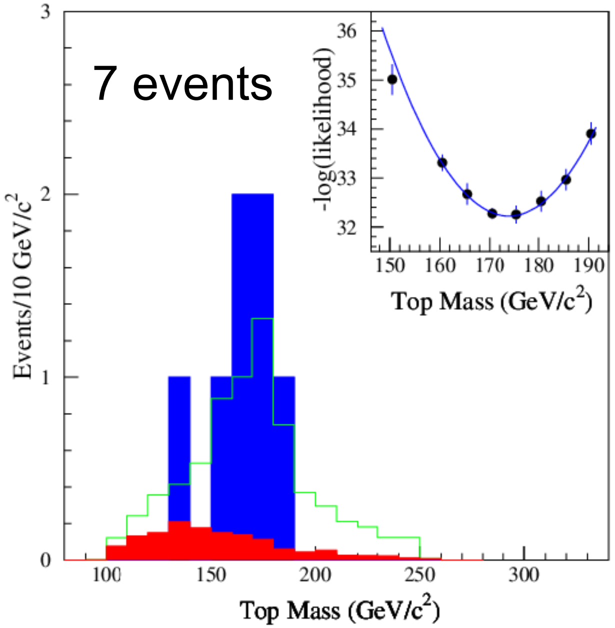
First evidence (1994)

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 $174 \pm 10^{+13}_{-12}$ GeV/c^2. The $t\bar{t}$ production cross section is measured to be $13.9^{+6.1}_{-4.8}$ pb.



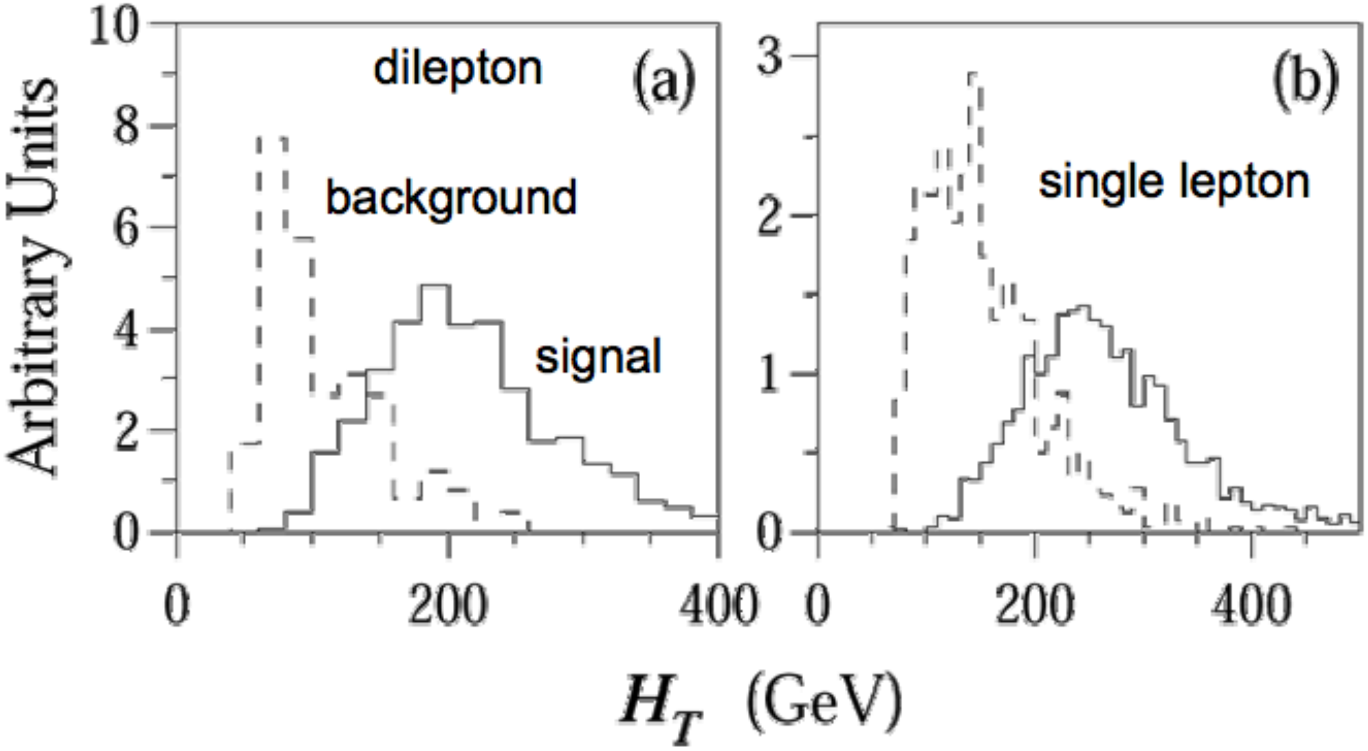

7 events

Discovery

By early 1995 (Run 1A+1B), x3.5 data

D0 further optimized for high mass:

- Require H_T (ΣE_T of all objects) to suppress the background: improves S/B by ~x2.5

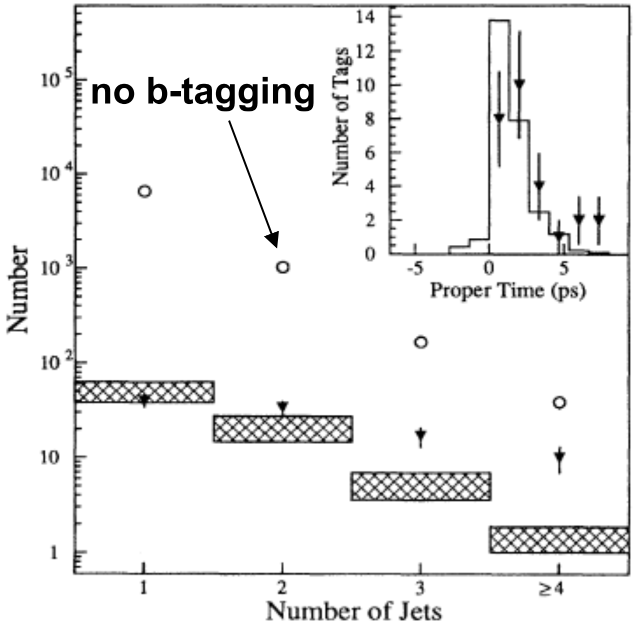


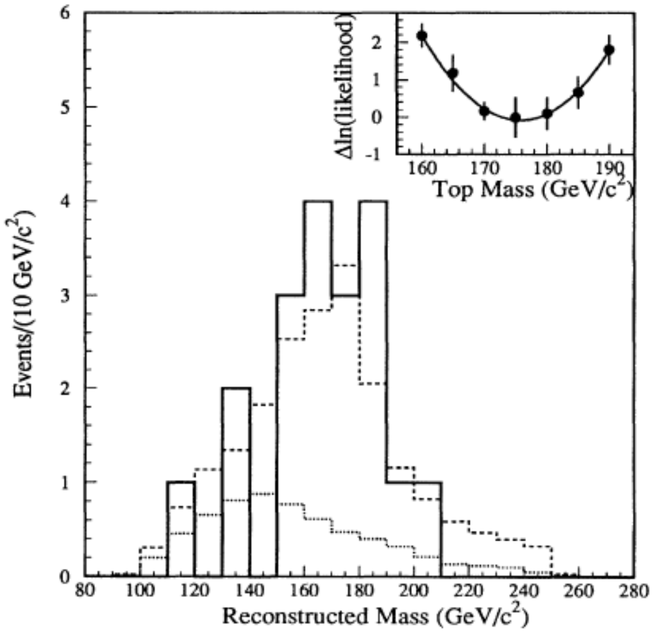
First measurements

VOLUME 74, NUMBER 14 PHYSICAL REVIEW LETTERS 3 APRIL 1995

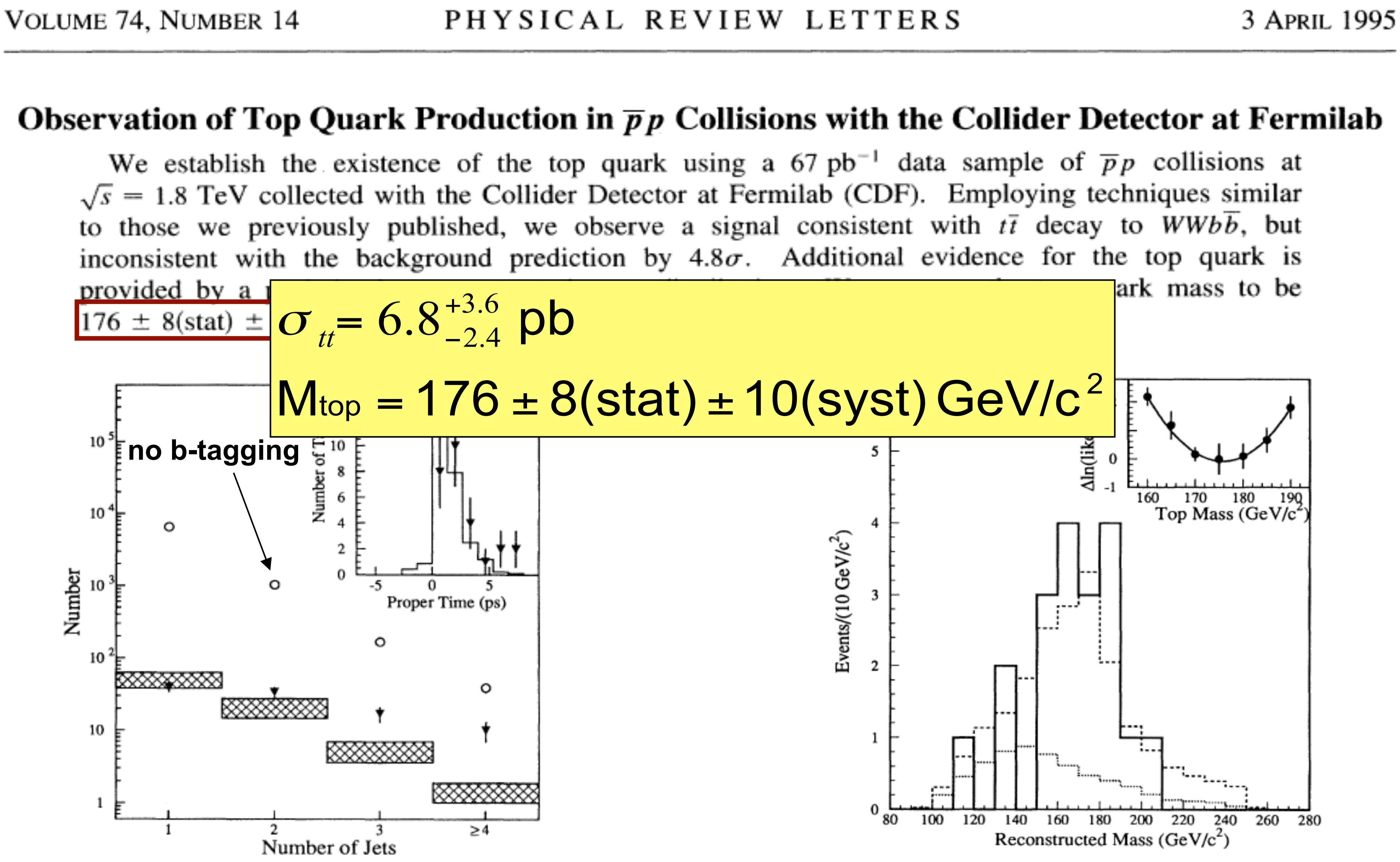
Observation of Top Quark Production in $\overline{p}p$ Collisions with the Collider Detector at Fermilab

We establish the existence of the top quark using a 67 pb^{-1} data sample of $\overline{p}p$ 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 $t\overline{t}$ decay to $WWb\overline{b}$, 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 $\boxed{176 \pm 8(\mathrm{stat}) \pm 10(\mathrm{syst})\ \mathrm{GeV}/c^2}$, and the $t\overline{t}$ production cross section to be $\boxed{6.8^{+3.6}_{-2.4}\ \mathrm{pb}}$





First measurements



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ark mass to be

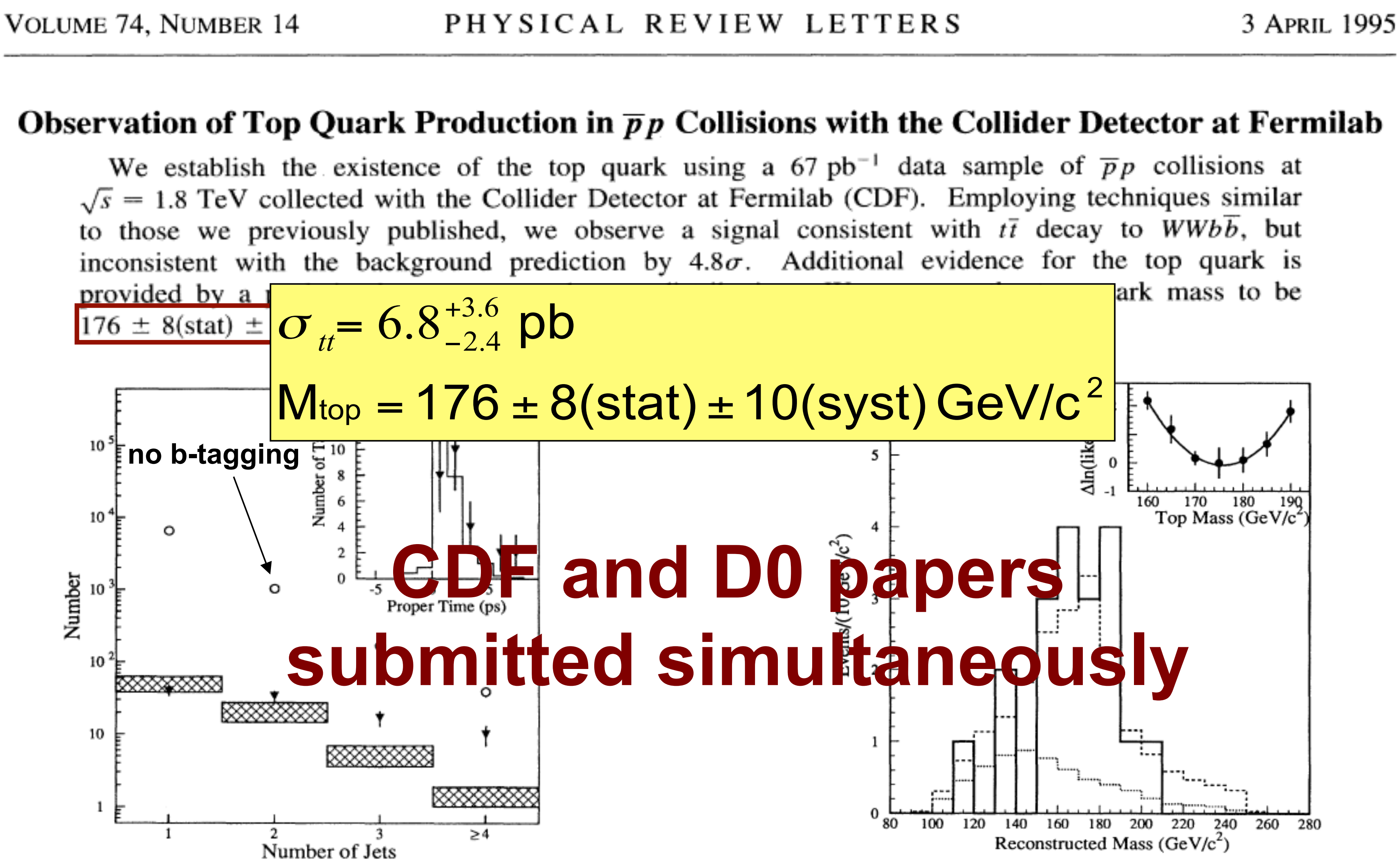
176 ± 8(stat) ±

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

$$M_{top} = 176 \pm 8(stat) \pm 10(syst)\ GeV/c^2$$

no b-tagging

First measurements



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ark mass to be

176 ± 8(stat) ±

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

$$M_{top} = 176 \pm 8(\mathrm{stat}) \pm 10(\mathrm{syst})\ \mathrm{GeV/c}^2$$

no b-tagging

CDF and D0 papers submitted simultaneously

Top quark and its relevance

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

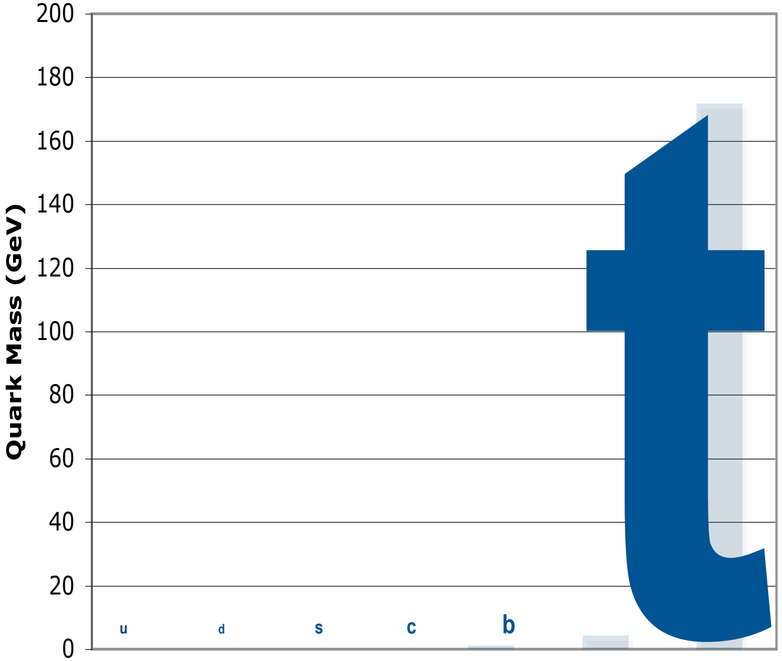
About the top quark

- Special: heaviest known elementary particle
- Coupling to the Higgs ~1
- For M_{top}=175 GeV⇒Γ=1.4 GeV
  ⇒no hadronization
- Special role in EWK symmetry breaking?

- Study of top quark properties

- Precision measurements may provide insight into physics beyond SM
- Special sector for searches for new physics

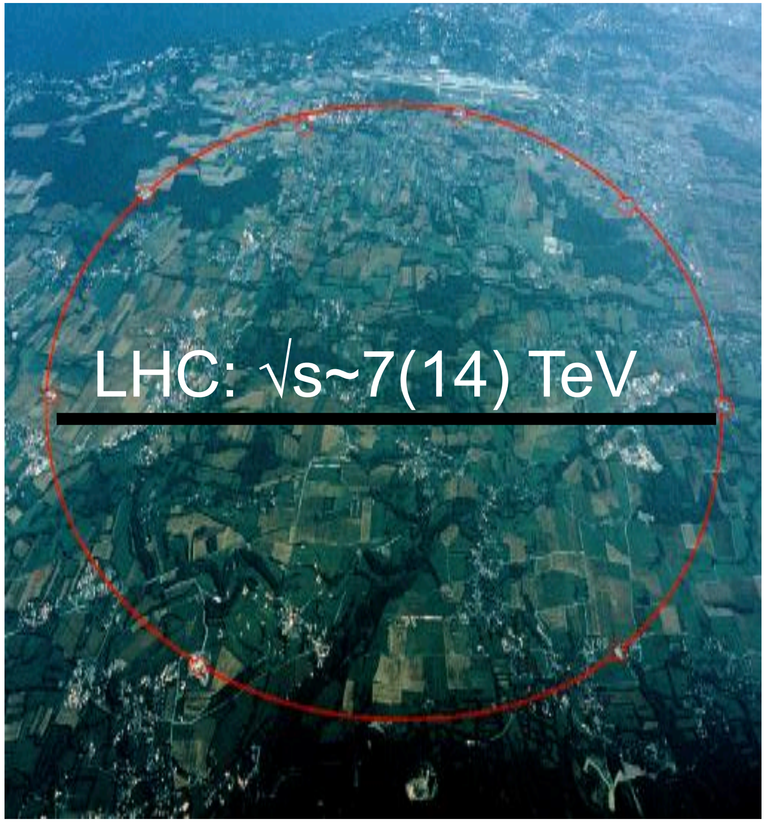
quark masses



The Large Hadron Collider

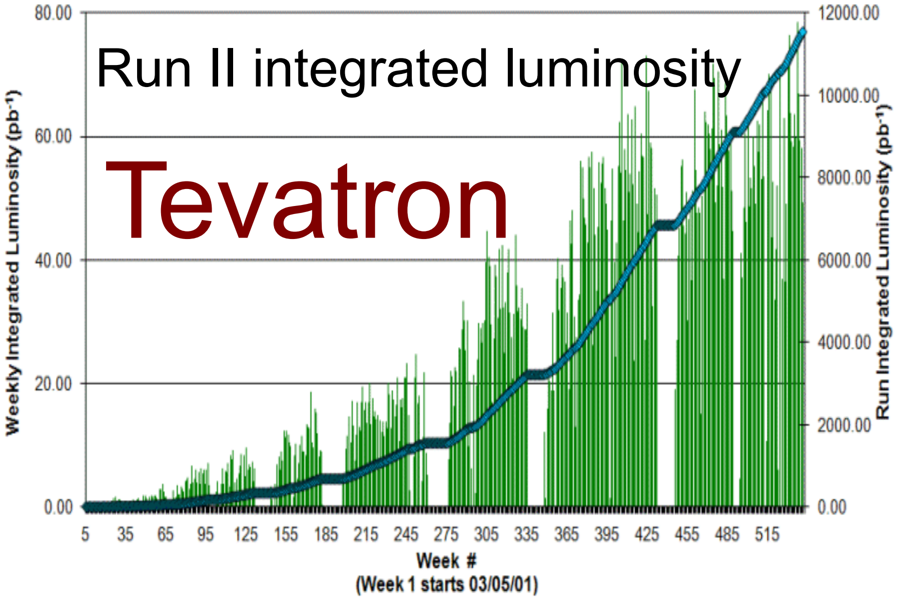
- Built to explore new energy frontiers
- First colliding beams in 2009
- started with “low” luminosity in 2010
- ~5 fb^{-1}@7TeV delivered in 2011
- ~15 (?) fb^{-1}@8TeV in 2012

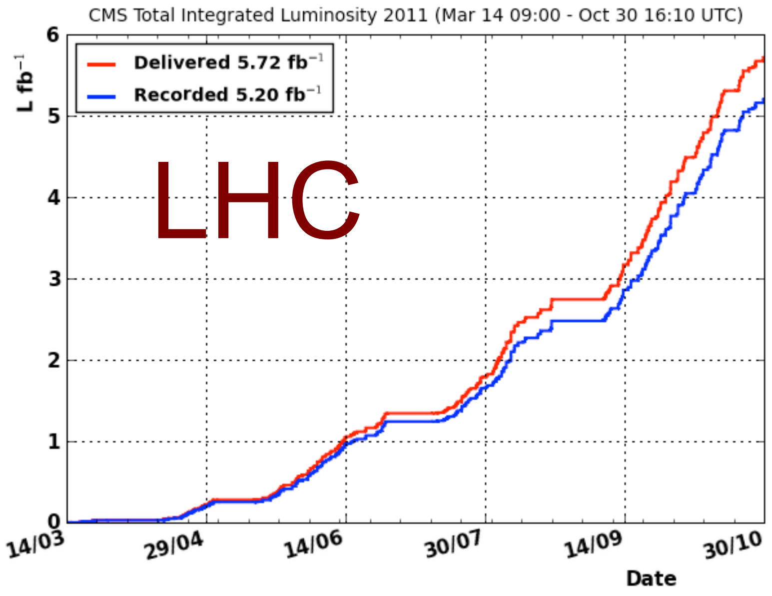
- re-establish SM measurements
- access to new physics processes



⇨ 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 TeV
Int. Luminosity: 5 fb^{-1}
Age: ~2 years
Events/exp (1 fb^{-1})
2500 ee eμμμ
15000 lepton + jets

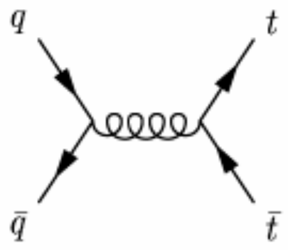
What is the Top quark?

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

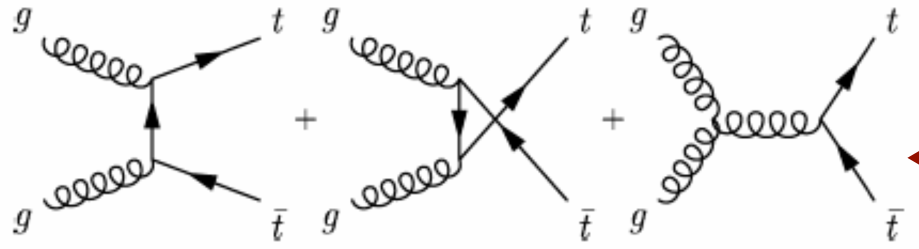
$$\text{Leptons:}\quad \begin{pmatrix} \nu_e \\ e \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$$

- It is the heaviest fundamental particle
  - $M_{top} = 173.2 \pm 0.9$ GeV/c^2 (hep-ex/1107.5255v3)
- 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:

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

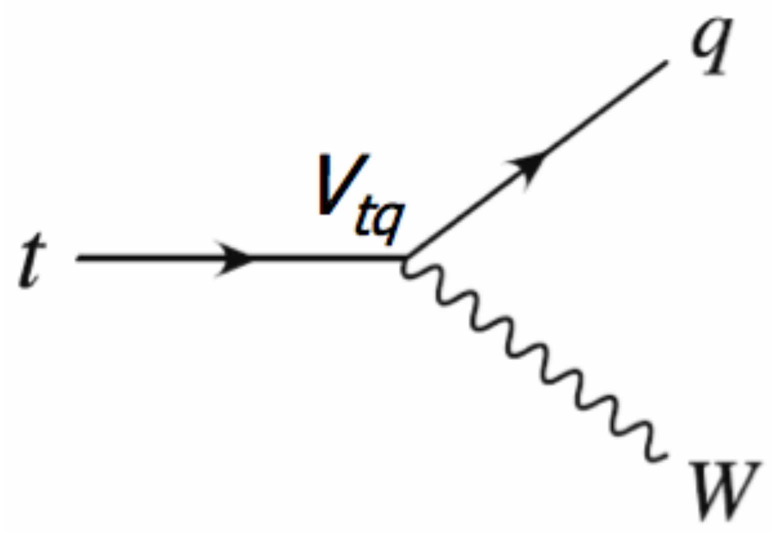
$\sqrt{s} = 7$ TeV: $\sigma(pp \to t\bar{t})_{NNLOapprox} = 164.6^{+11.4}_{-15.7}$ pb

.

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

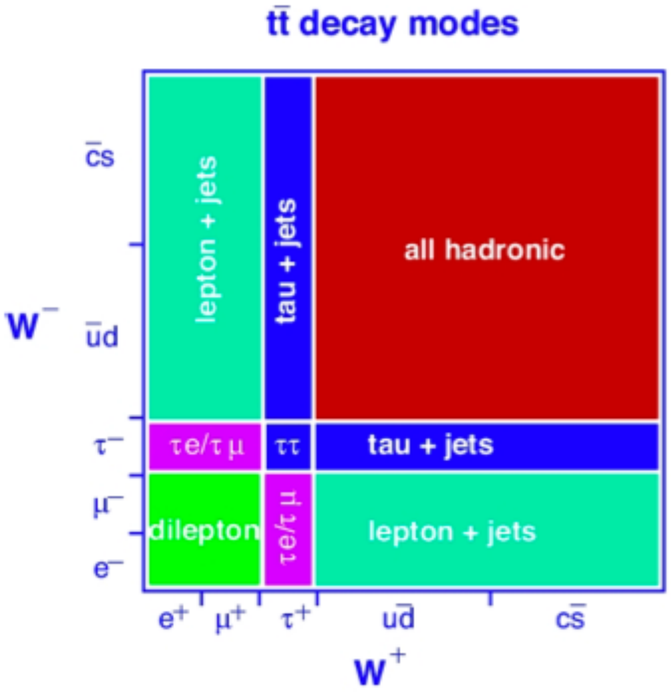
	LHC	Tevatron
gg	~85%	~10%
qq	~15%	~90%

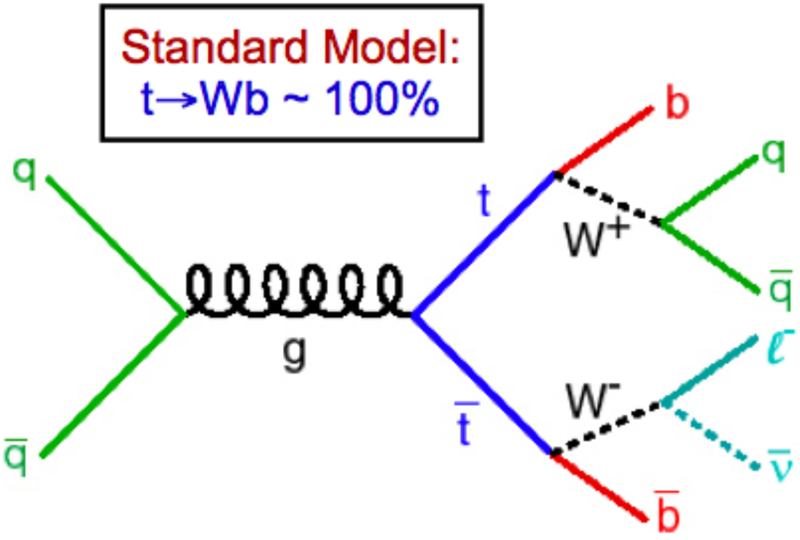
How does a top quark decay?



- almost always t→Wb (i.e. V_{tb}~1)
- lifetime is short, and it decays before hadronizing
- the W is real:
  - can decay W→lν (l=e,μ,τ), BR~1/9 per lepton
  - can decay W→qq, BR~2/3

How do ttbar pairs decay?

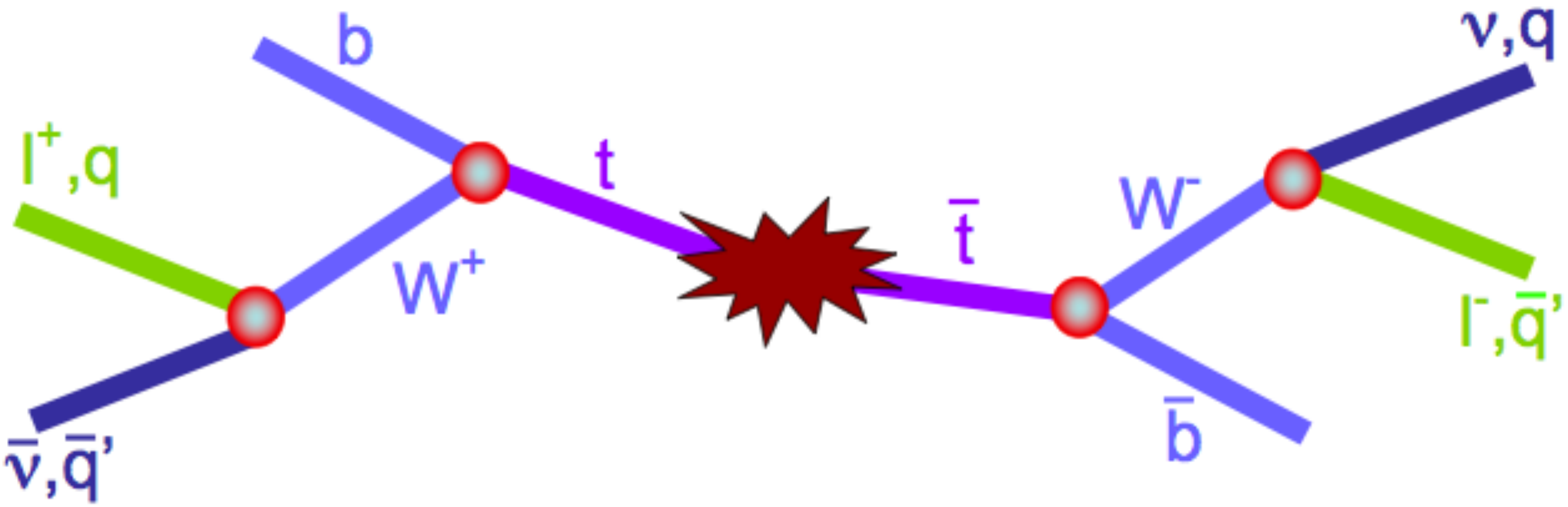



Standard Model:
t→Wb ~ 100%

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

⇨ use **all** decay channels

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
...

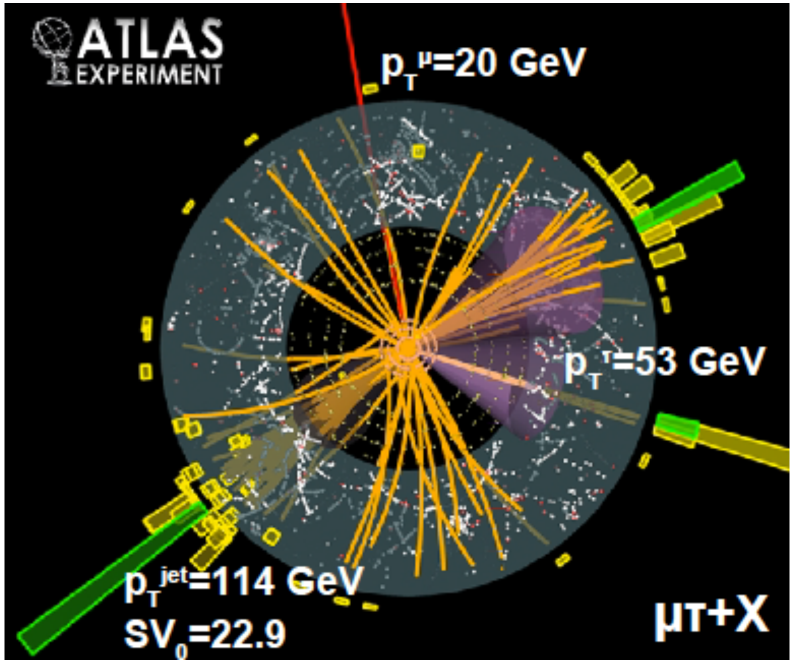
DECAY

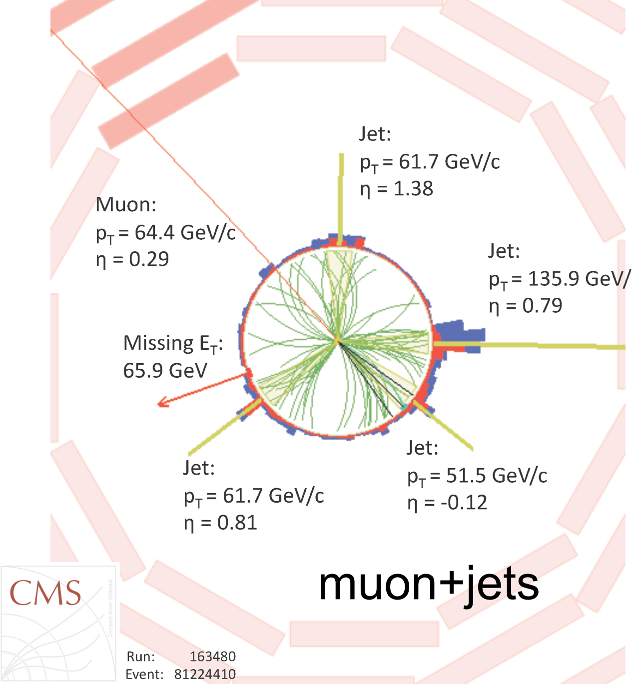
Branching ratios
Charged Higgs (non-SM)
Anomalous couplings
Rare decays
CKM matrix elements
Calibration sample @LHC
...

Particle identification

- Object identification and reconstruction

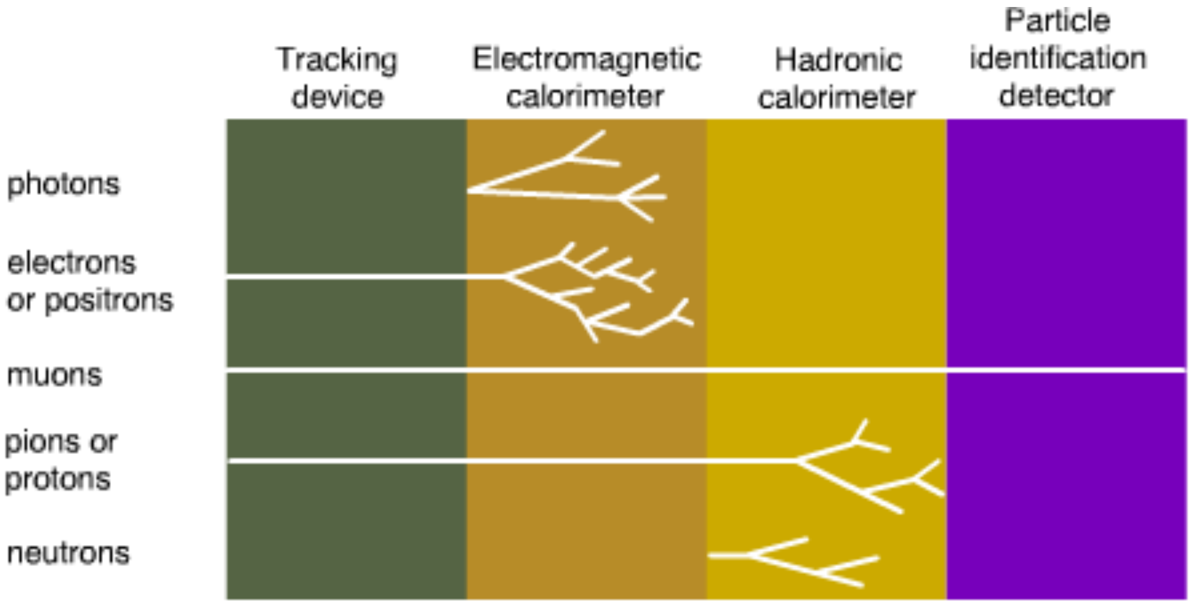
Selection of top quark events





- 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

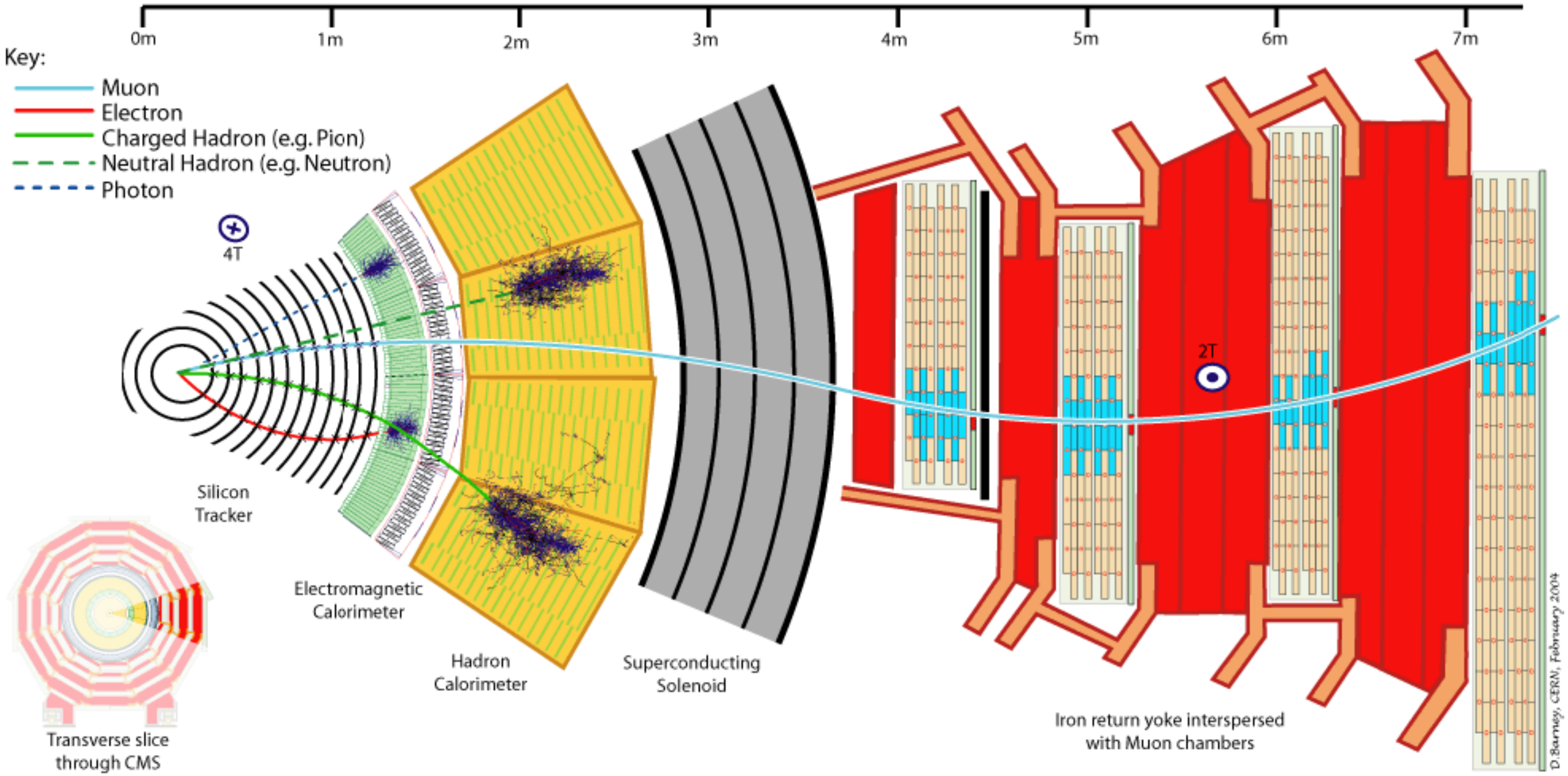
Particle detection



Need efficient:

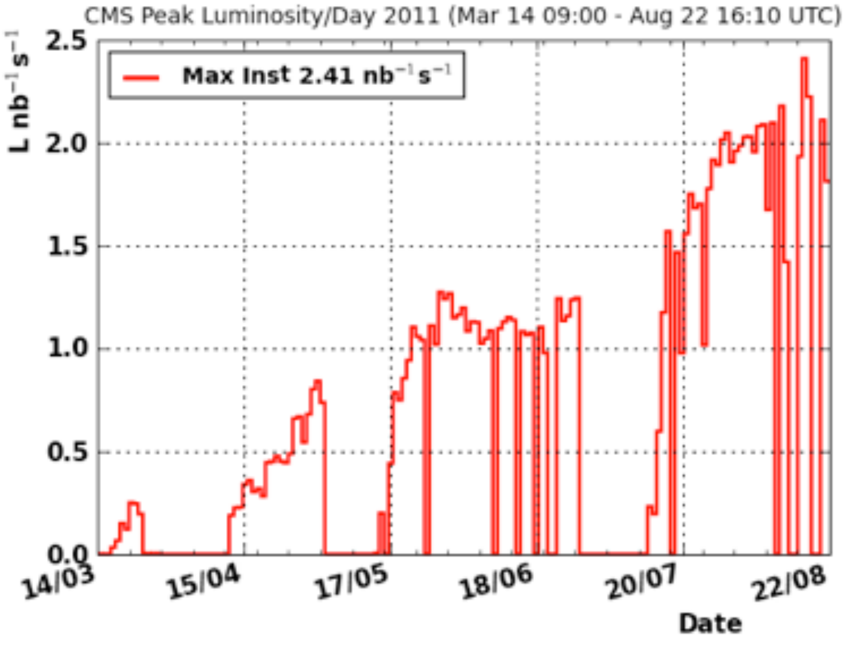
- Electron, muon, tau reconstruction
- jet reconstruction
- b-tagging capability

- “Onion”-like structure
- Each layer measures E and/or p of particles
- Redundancy of measurements


0m
1m
2m
3m
4m
5m
6m
7m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
Transverse slice through CMS
D.Barney, CERN, February 2004

Challenge: trigger rate

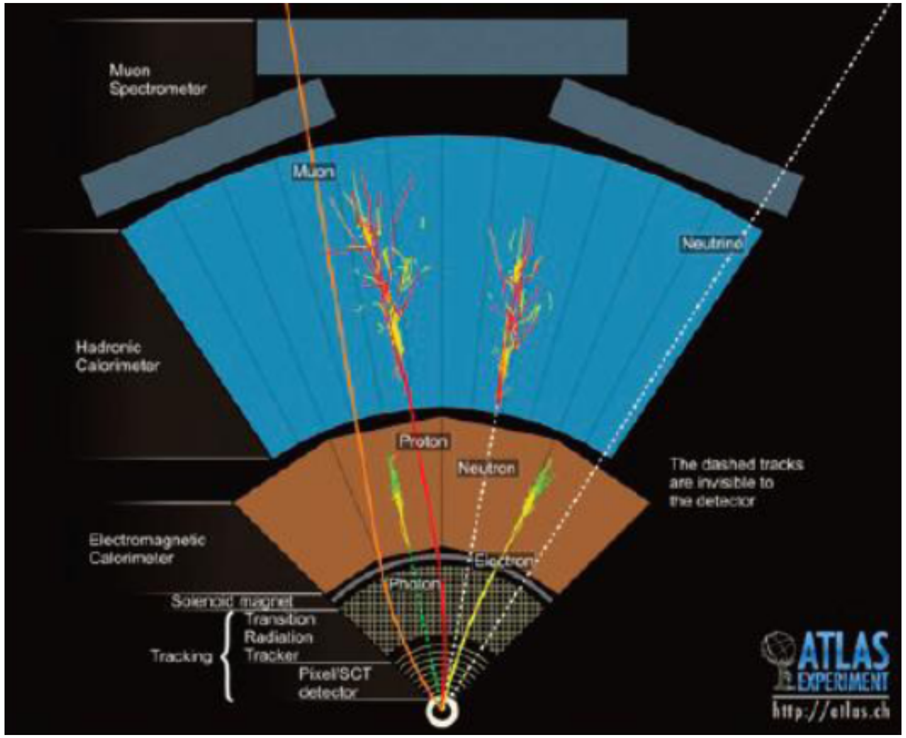
- Max lumi in 2010: 2e32 $cm^{-2}s^{-1}$
- 2011 started at this luminosity, then increased by one order of magnitude
- Challenging order of magnitude increase for triggering on W bosons
- IsoMu17 rate ~ 4.4 Hz@2e32 $cm^{-2}s^{-1}$
- 44 Hz at 2e33 $cm^{-2}s^{-1}$
- Trigger thresholds important to understand because they often drive the analysis selection



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
  - Can use complementary information from separate detectors to improve performance
  - Esp. use tracks to improve calorimeter measurements
- From list of particles, can construct higher-level objects
  - Jets, b-jets, taus, isolated leptons and photons, MET, etc.
  - Jets = anti-kT, size of R=0.5

Electron and photon reconstruction



Photon:

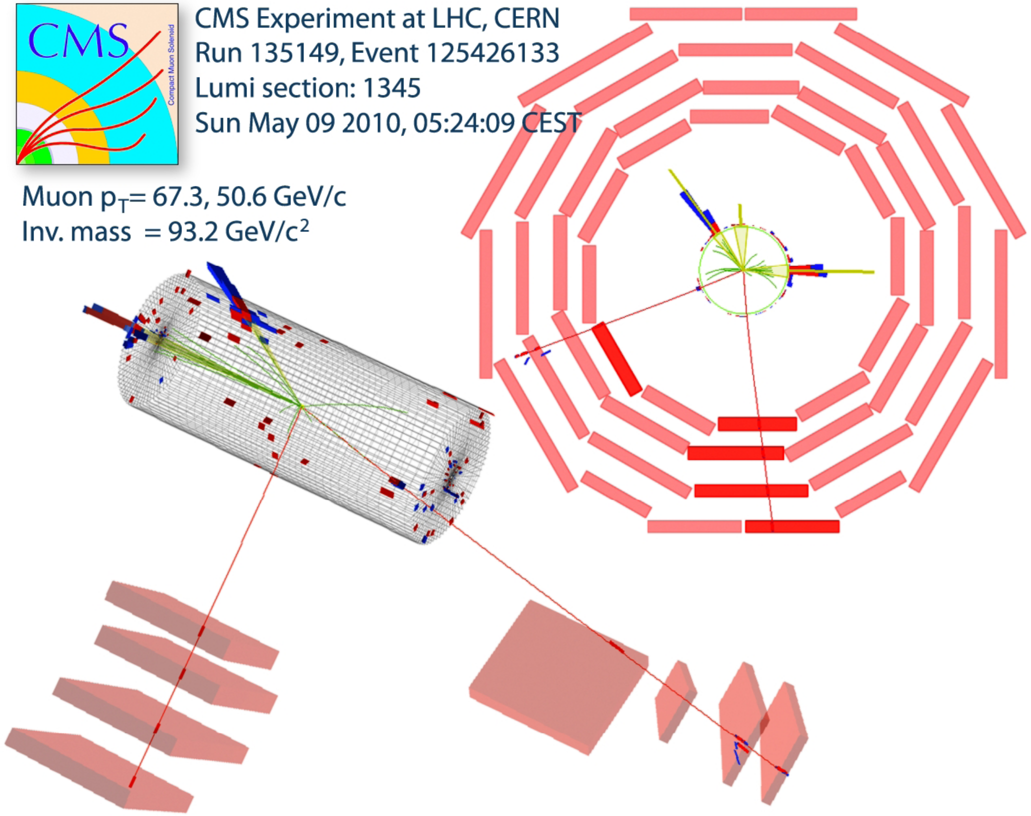
- No track in inner detector
- Electromagnetic shower in EM calorimeter
- No signal in Hadronic calorimeter

Electron:

- Track in inner detector
- Electromagnetic shower in EM calorimeter
- No signal in Hadronic calorimeter

Muon reconstruction

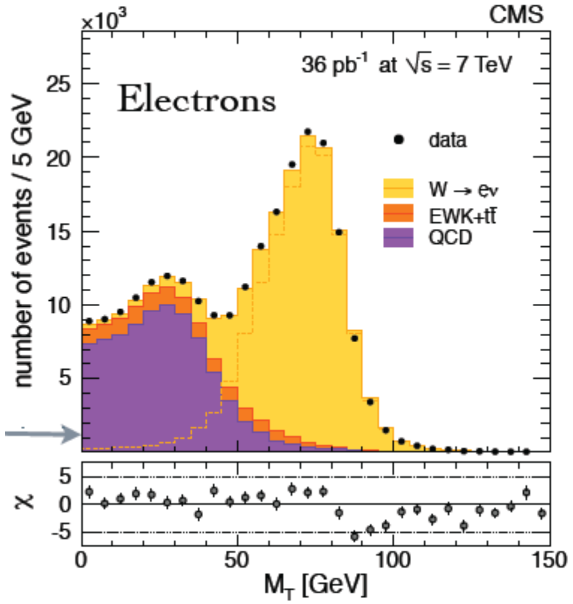
- Minimum ionizing track in all detectors (about 3 GeV loss in the calorimeter)
- At high momentum (few hundred GeV), bremsstrahlung in the calorimeter can be significant
- Momentum measurement in inner detector, muon system

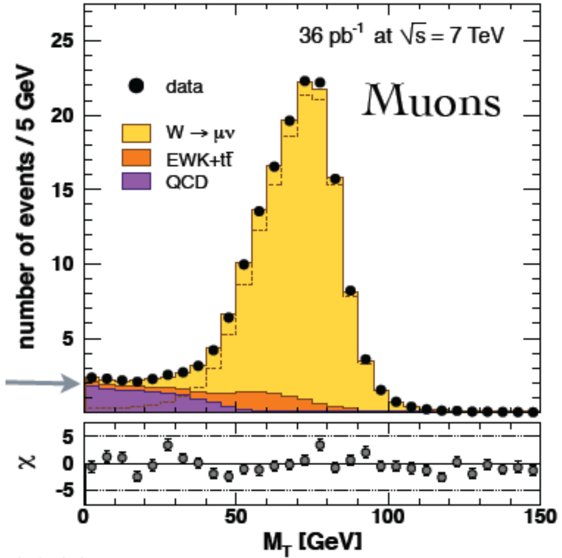


A di-muon event at CMS

Electrons and muons

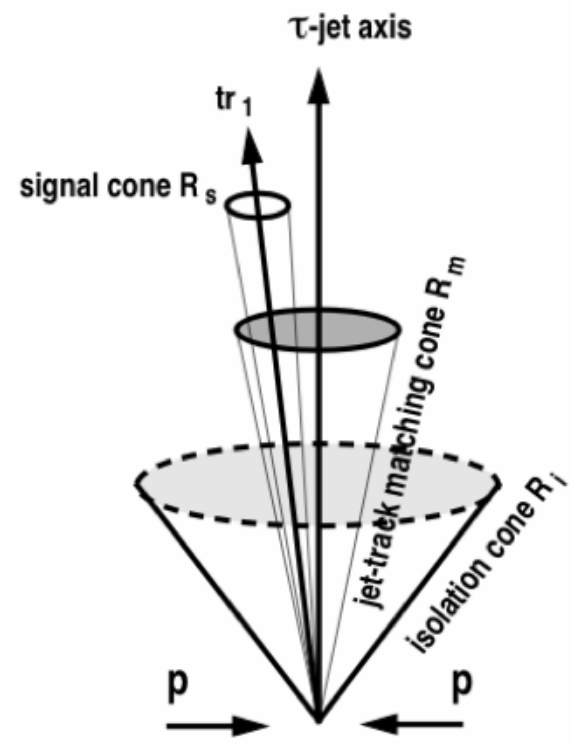
- W/Z cross section measurement with 36/pb demonstrated that leptons and their “fake” rates can be modeled well
- Muons have fewer “fakes” than electrons
- Can construct analysis to minimize this impact: trade-off between efficiency and fake rate
- Impact on Top: ⇒efficiency, QCD estimate & modeling





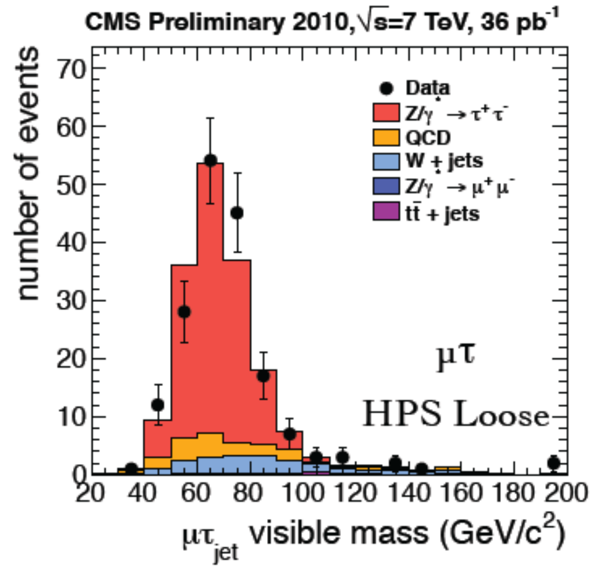
Tau identification

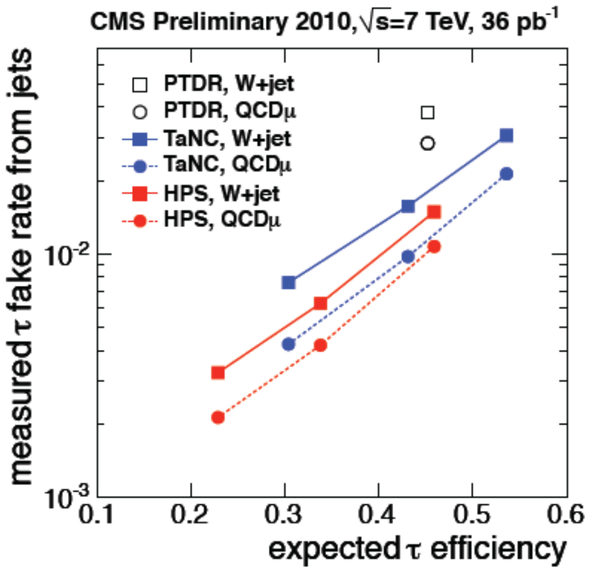
- Tau leptons decay 65% to hadrons (i.e. jets) and 35% to leptons
  - Hadronic tau decays are reconstructed as a narrow jet with small number of tracks
  - Leptonic tau decays are similar to “prompt” leptons, but lepton transverse momentum is softer (3-body decay)
- Hadronic tau decays
  - Main background is from jets/electrons
  - Hadronic taus are identified using tracking and calorimeter information (search for isolated track(s), often produce neutral pions)



Taus (hadronic decays)

- Hadronic tau reconstruction studied with W/Z
- Several algorithms available offering trade-off between efficiency and purity
- Hadron-Plus-Strips (HPS) algorithm
  - eff 0.45±0.03 (7% relative unc.)
  - fake rate 0.02±0.003 (15% relative unc.)
- Impact on top: efficiency, fake estimate, modeling



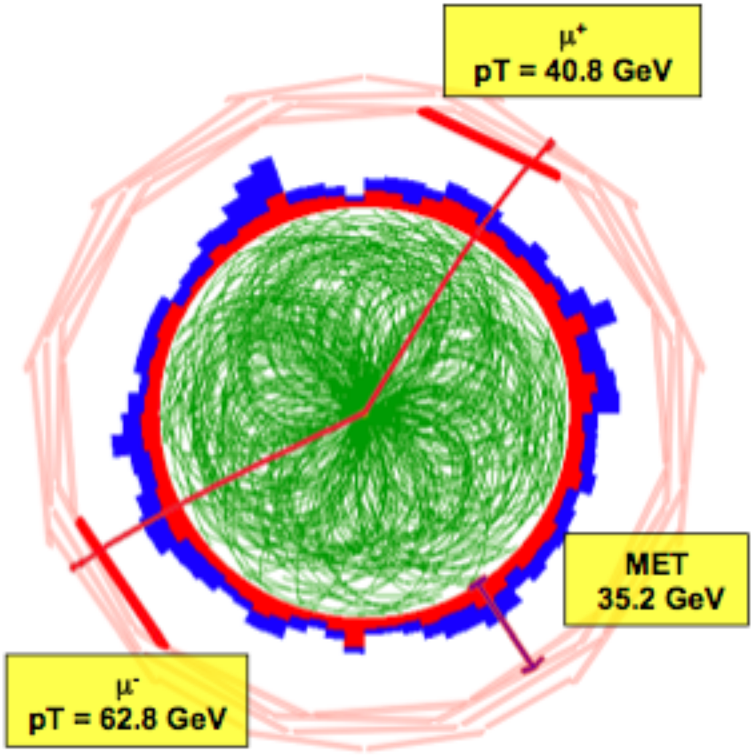


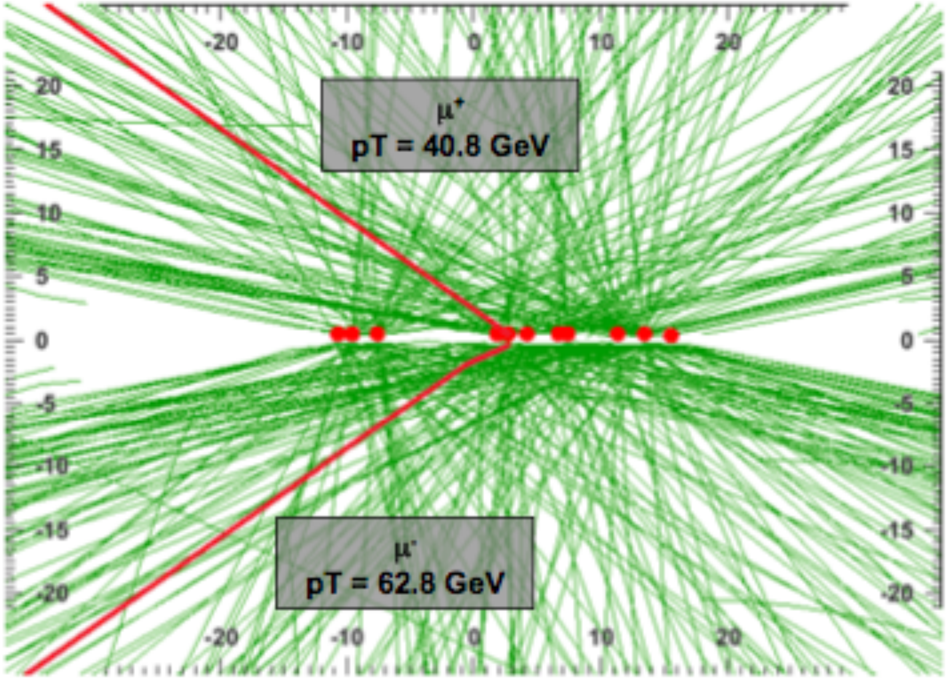
Challenge: Pile-up

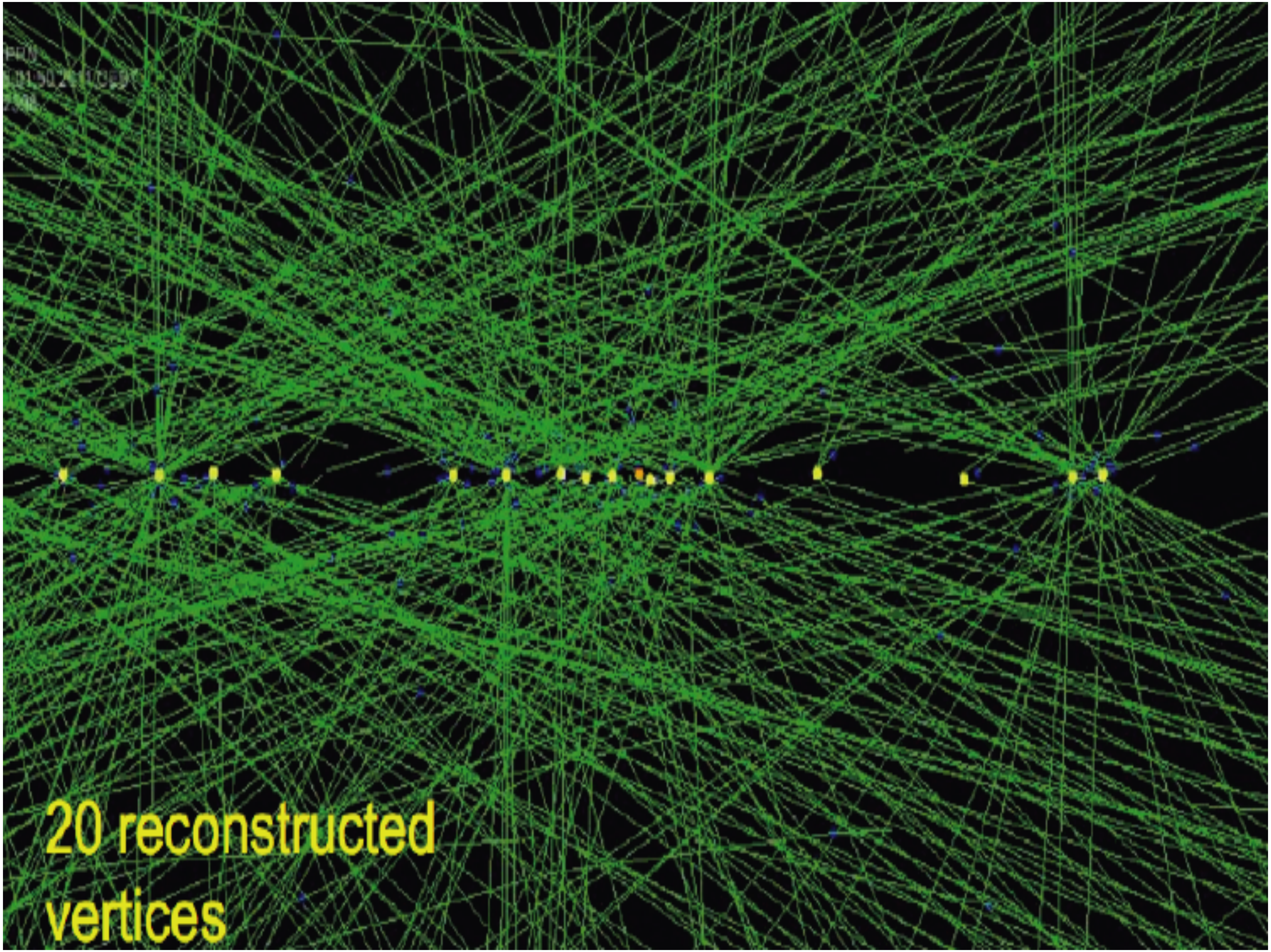
$Z \rightarrow \mu\,\mu$

Expected MET = 0

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



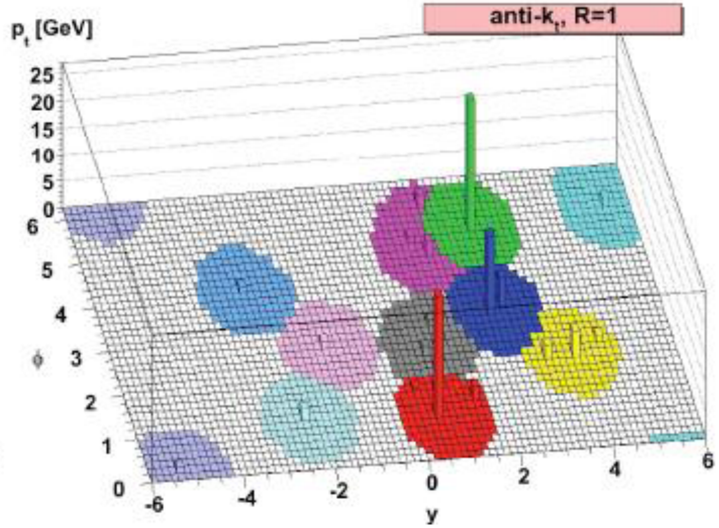




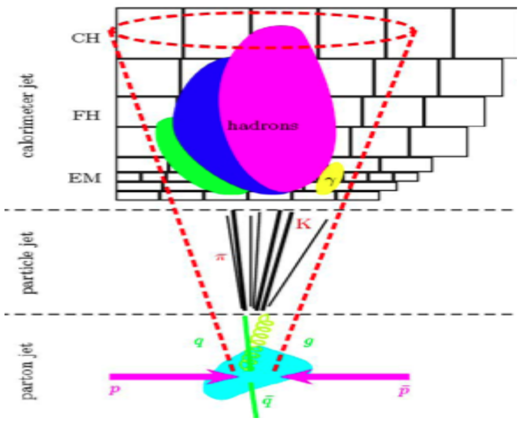
20 reconstructed vertices

Jet reconstruction

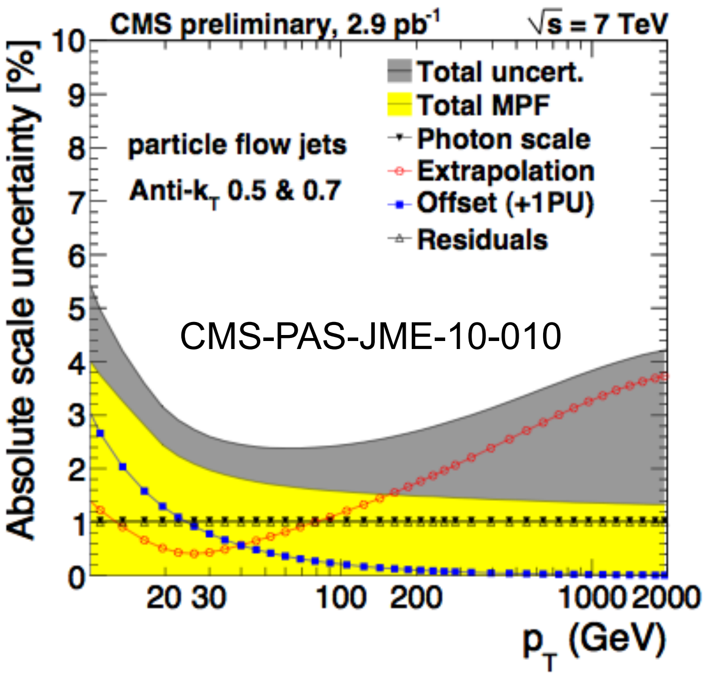
- A “jet” is a cluster of energy deposited in a “small” $\eta-\phi$ region of the detector
  - It is not a unique object, it is defined by the jet algorithm (different choices yield different jets)
- The jet algorithm uses detector reconstructed objects (clusters, tracks, combined objects)
- It is “safe”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



Challenge: jet reconstruction



- measurements (for example Top mass) needs parton information, but we measure jets
- Use calorimeter information to correct jets to particle level
- Jet energy scale (JES) is large source of uncertainty
  - Look at quantities insensitive to JES (e.g. lepton p_T)
  - "b-jet" tag helps reducing number of permutations
- JES "in-situ" calibration in ttbar events
  - Use W→jj constraint to measured W mass
  - Can be used in lepton+jets (and all-hadronic) channel



CMS-PAS-JME-10-010

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

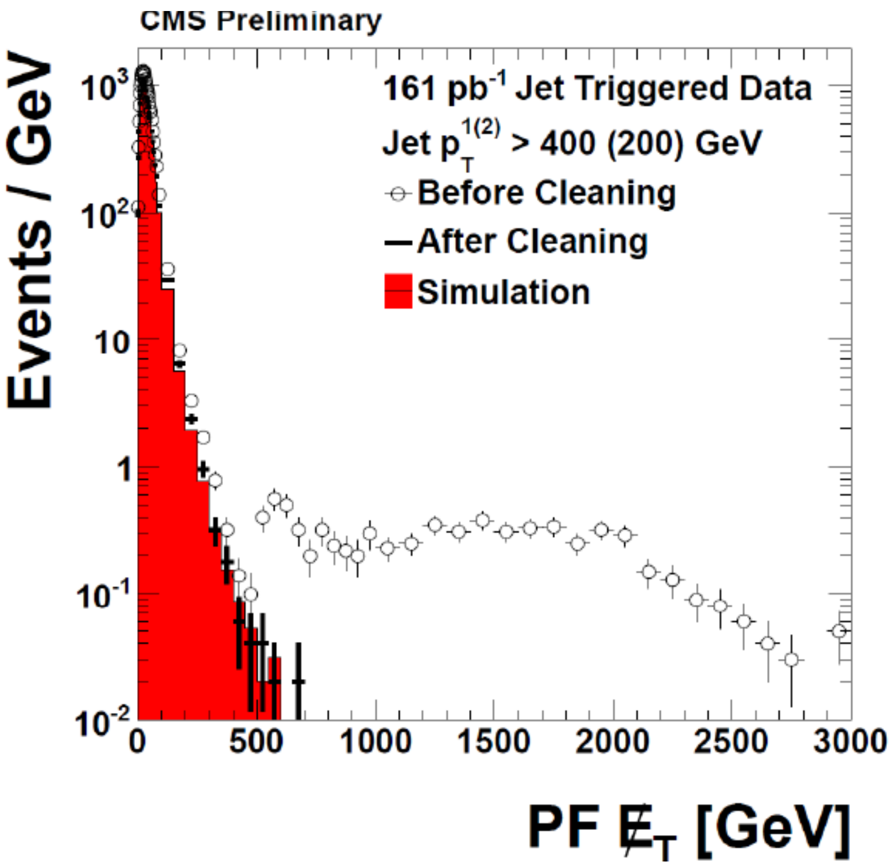
transverse energy vector

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

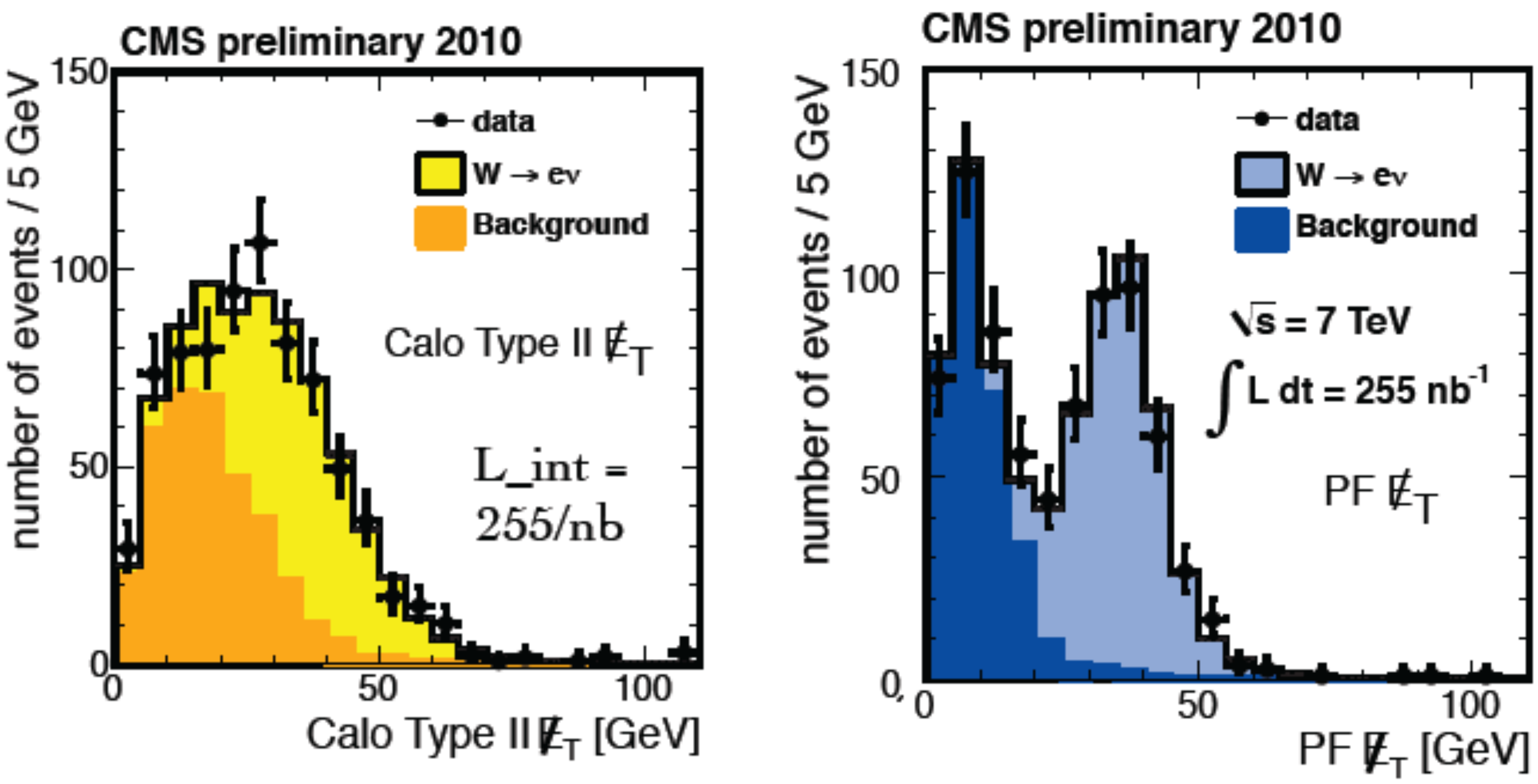
where the sum runs over the transverse momenta of all visible final state particles.

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



MET reco: PF vs Calo



- Study of MET in W→eν events from early 2010
- Particle Flow improves MET resolution, making W's easier to distinguish from background

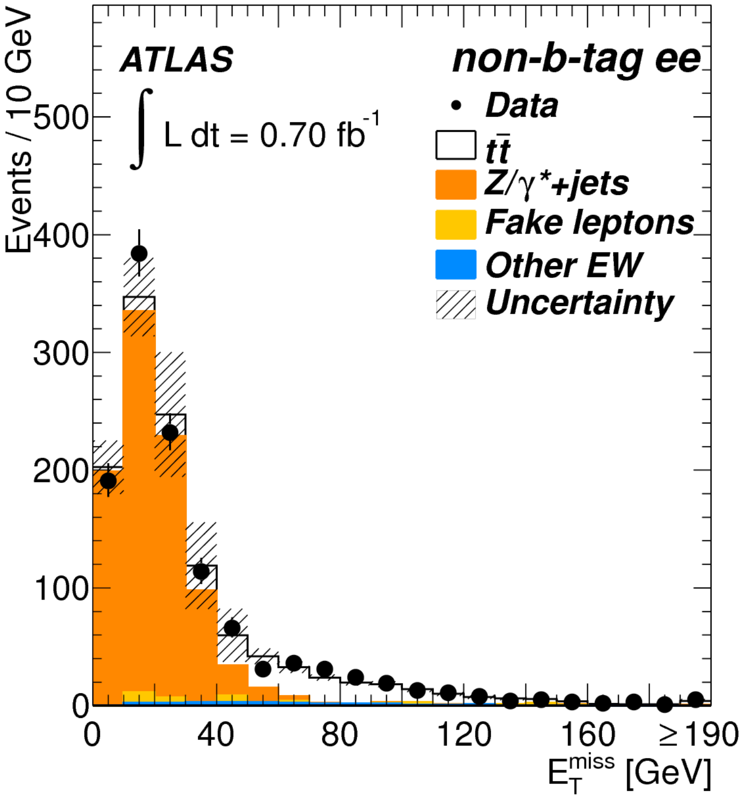
Missing transverse energy

Reconstruction

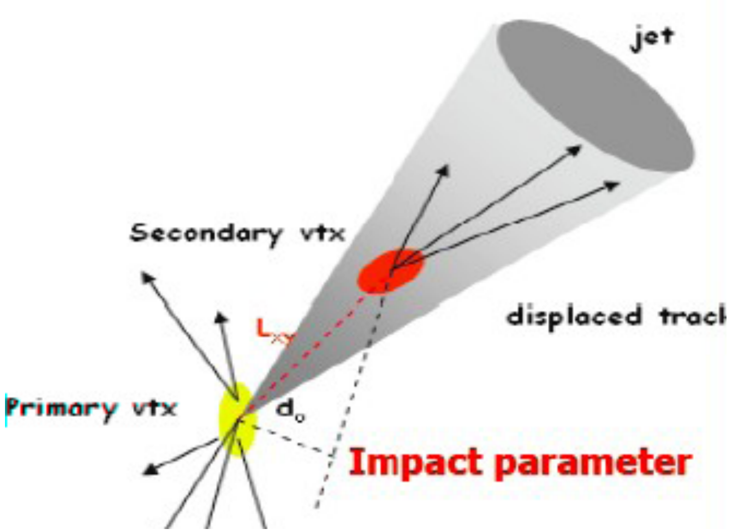
- ATLAS: jets plus electrons, muons and any additional “calo” clusters
- CMS: using Particle Flow objects

Selection applied for ee and $\mu\mu$

- Suppress multijet and Drell-Yan backgrounds

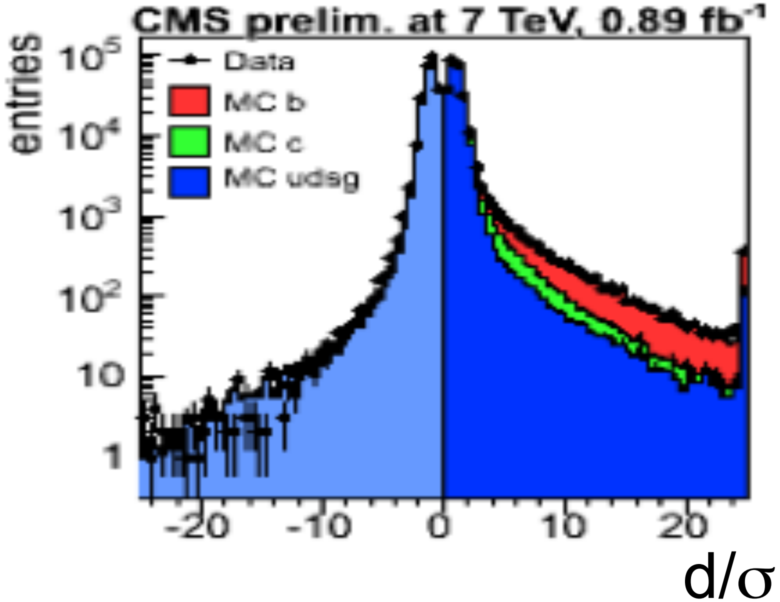


Challenge: b-tagging



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

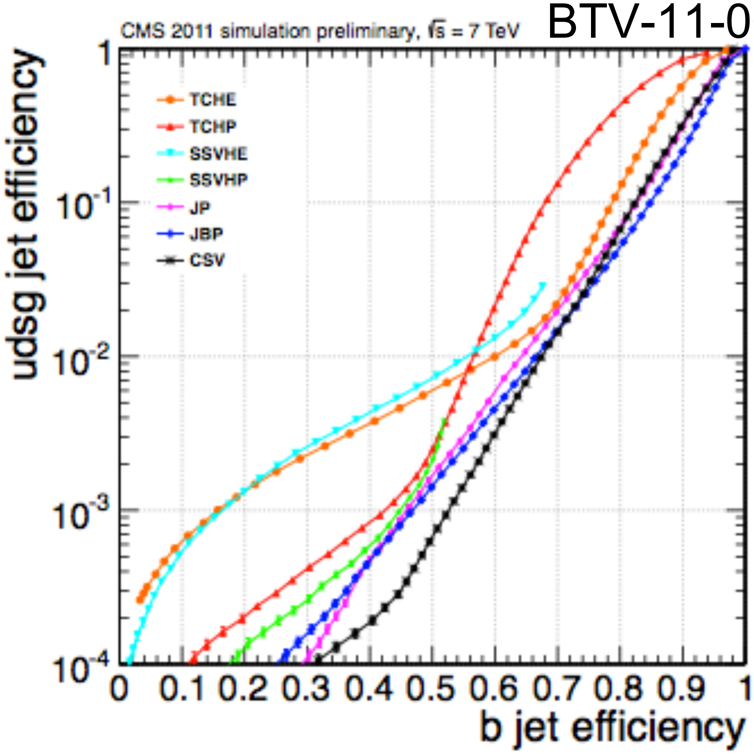
$(b \rightarrow \ell \nu_\ell X)$

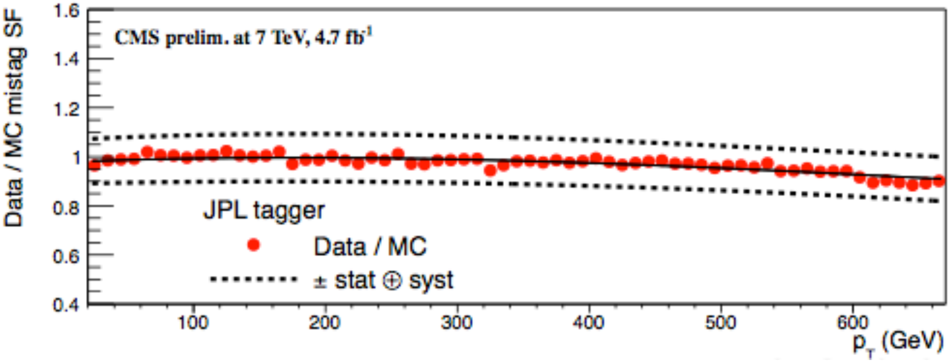


b-tag: fake rates and efficiencies

- b-tag optimization: trade-off between fake rate and efficiency
- CMS has 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-11-004





Measurements

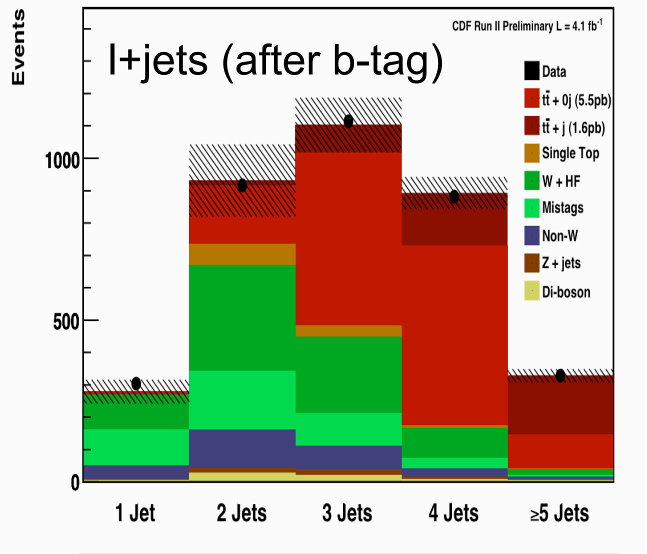
- Measurement of the cross section

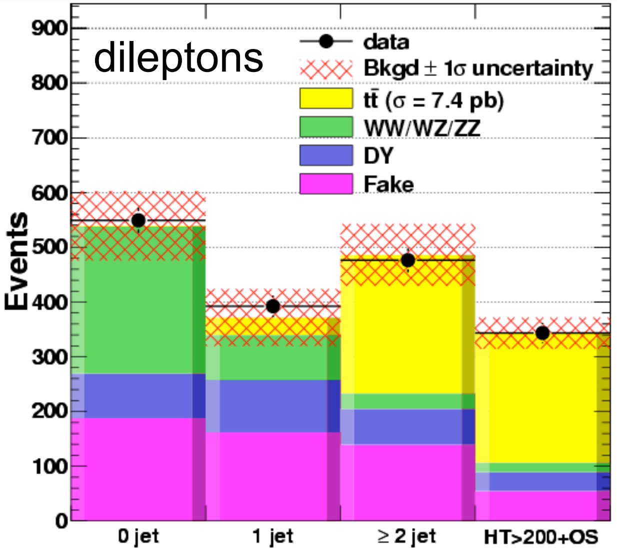
Interesting physics with top quarks

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

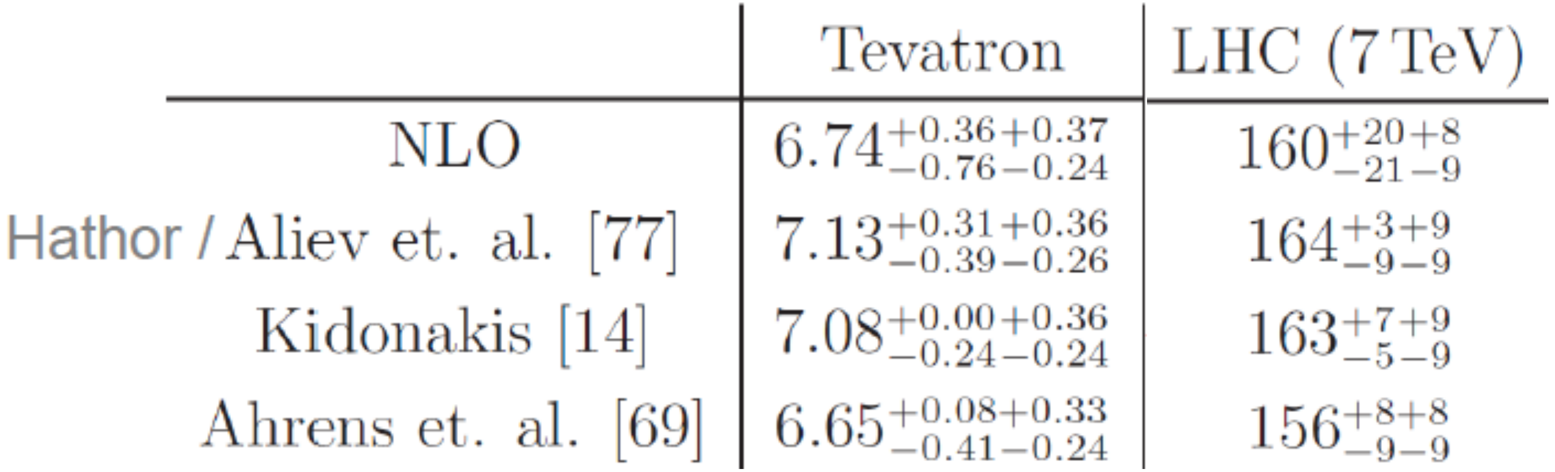
Top quark events

- cross section ~20 times larger at LHC@7TeV
- 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



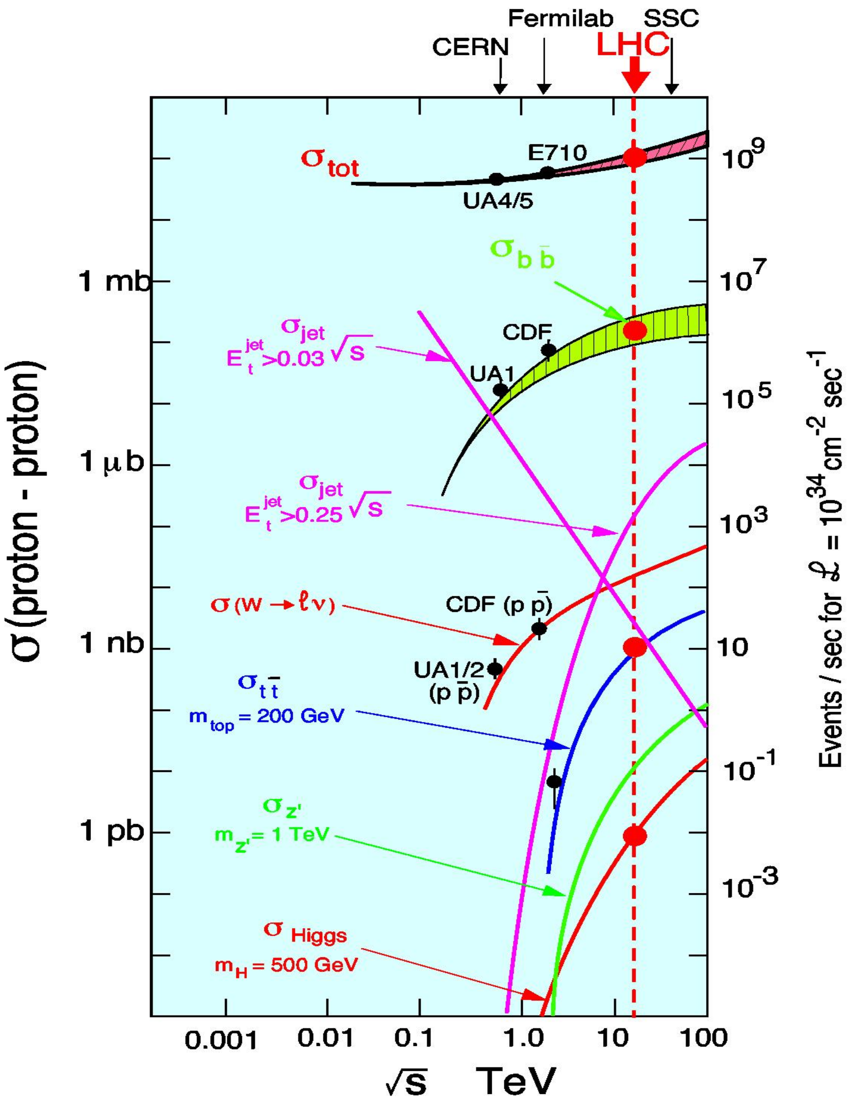
	Tevatron	LHC (7 TeV)
NLO	$6.74^{+0.36+0.37}_{-0.76-0.24}$	160^{+20+8}_{-21-9}
Hathor / Aliev et. al. [77]	$7.13^{+0.31+0.36}_{-0.39-0.26}$	164^{+3+9}_{-9-9}
Kidonakis [14]	$7.08^{+0.00+0.36}_{-0.24-0.24}$	163^{+7+9}_{-5-9}
Ahrens et. al. [69]	$6.65^{+0.08+0.33}_{-0.41-0.24}$	156^{+8+8}_{-9-9}

scale unc. ~5%

PDF unc. ~5%

Top cross section at 7 vs 14 TeV

- LHC collisions started at 7 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 σ(14TeV)=908 pb
  - Top σ(7TeV)=165 pb
- Background is more "flat"



A word about QCD background

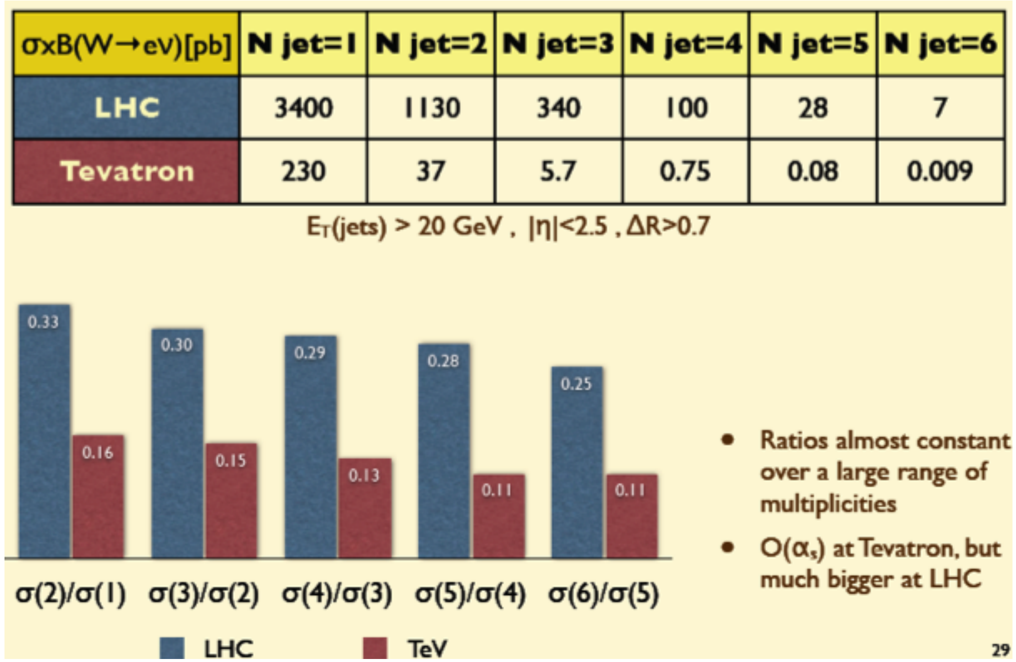
- QCD may still be large background in Top events
- From Tevatron to LHC
  - σ(ttbar) increases by 100
  - σ(W) increases by 10

…however…

- σ(W+4 jets) increases 100 times

⇨W+jet background is large

Slide by Michelangelo Mangano



$\sigma \times B(W \to e\nu)$[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

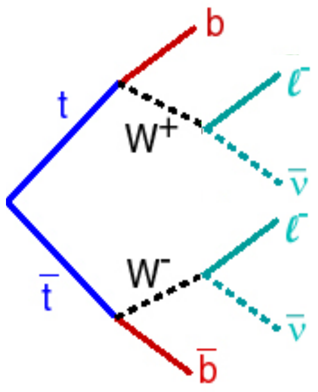
Cross section measurement

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

✓ testing non-SM top production mechanisms

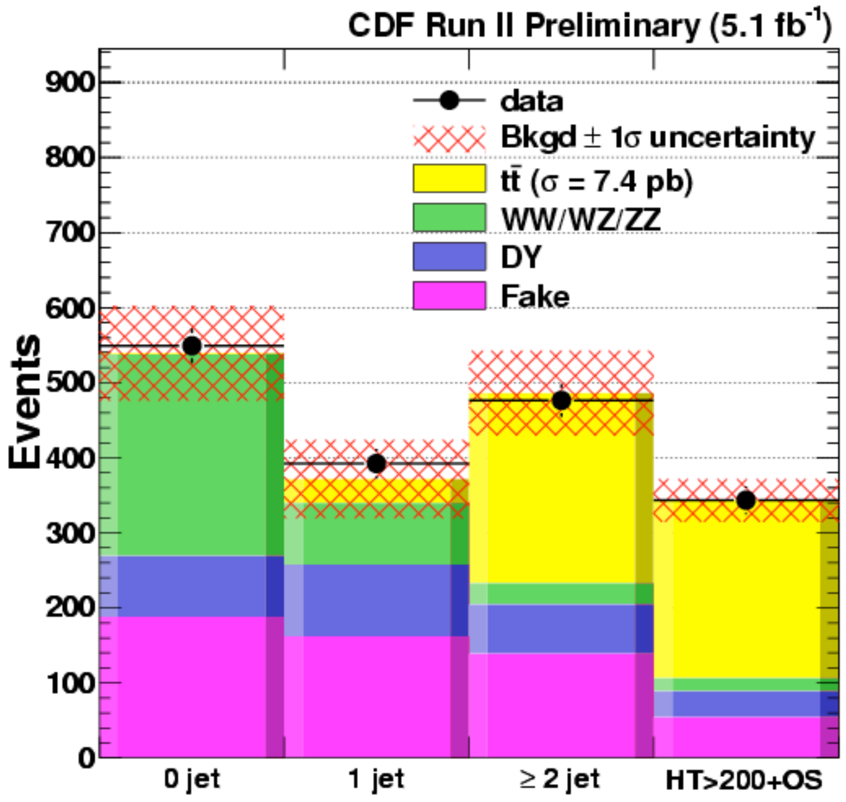
✓ top sample may contain an admixture of exotic processes

Dilepton channel



Branching Ratio (BR) ~5%
background: small

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



Dilepton channel

- Cleanest signature and lowest BR
- Main backgrounds
  - Drell-Yan (veto Z window in ee/$\mu\mu$, and rescale DY contribution from data)
  - Single top and VV (from MC)
  - Fake leptons (fake rate/efficiency)

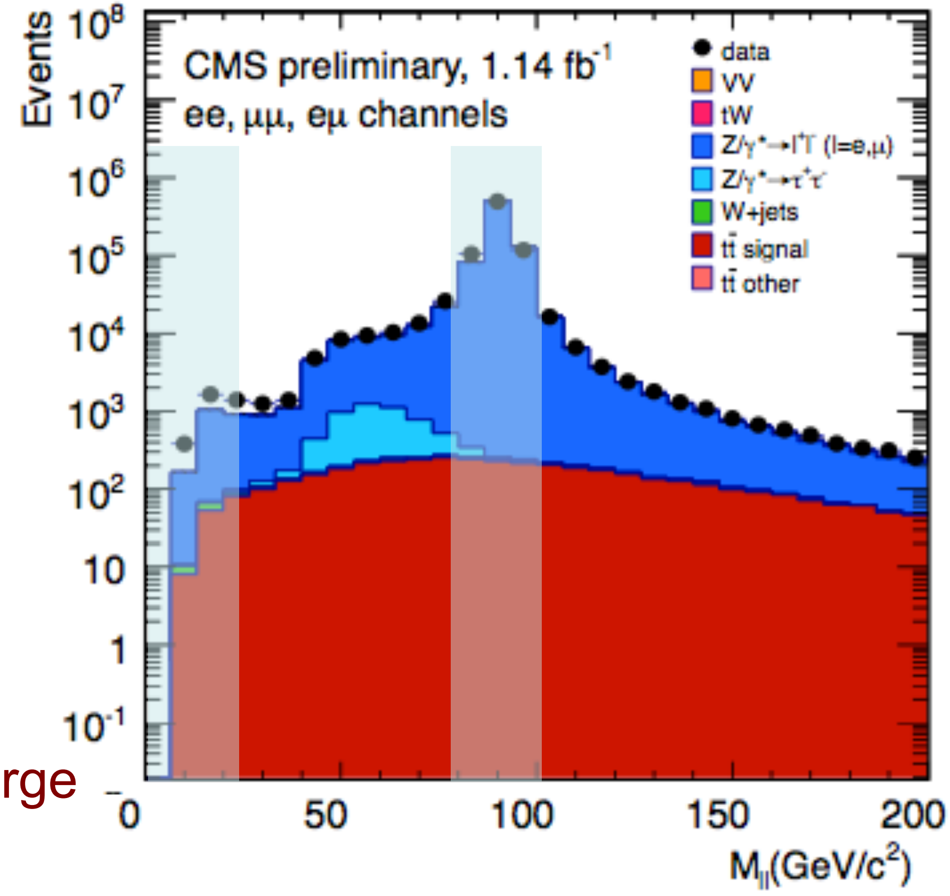
CMS: dilepton trigger

- Isolated lepton p_T>20 GeV, $|\eta|$<2.4

ATLAS single lepton trigger

- Isolated electron/muon p_T>25(20)GeV
- Require two leptons with opposite charge
- Reject b-quark production & low mass Drell-Yan resonances production
- Z veto and suppress Z+jet backgrounds

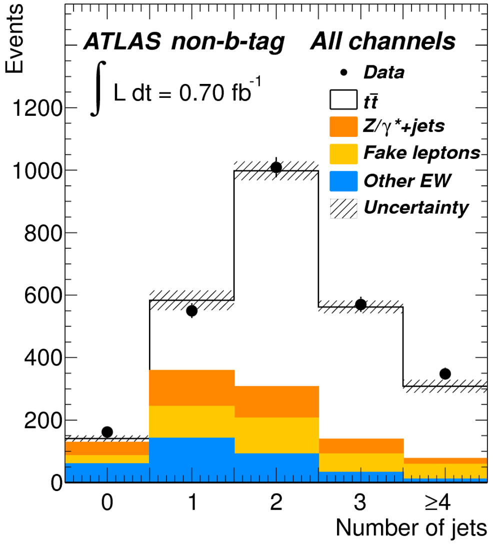
TOP-11-005



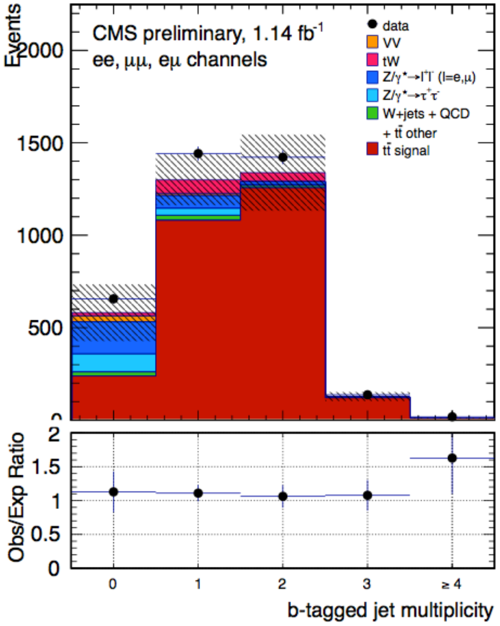
Dilepton channel

- Signal visible w/without b-tagging
- Measure cross section:
  - Profile likelihood
  - Cut and count
- Main systematics: jet energy scale, pileup, signal modeling

arXiv:1202.4892



TOP-11-005



$$\sigma_{t\bar{t}} = 176 \pm 5(\text{stat.})^{+14}_{-11}(\text{syst.}) \pm 8(\text{lum.})\ \text{pb}$$

ATLAS

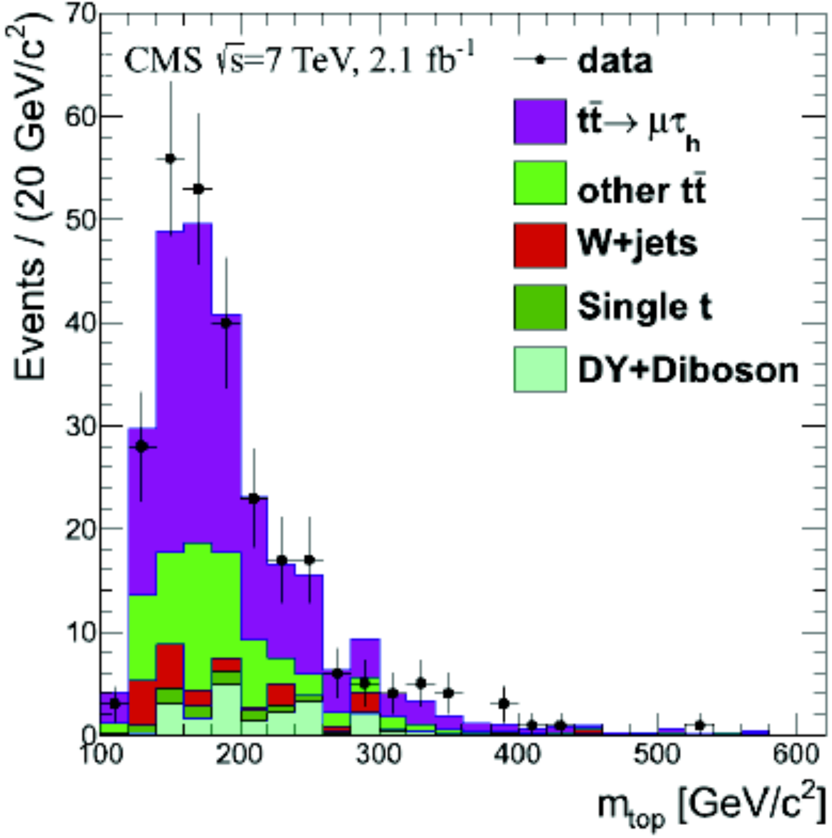
$$\sigma_{t\bar{t}} = 169.9 \pm 3.9\ (\text{stat.}) \pm 16.3\ (\text{syst.}) \pm 7.6\ (\text{lumi.})\text{pb}$$

CMS

Tau dilepton channel

- Selection:
  - – one isolated lepton (e/μ)
  - – OS tau
  - – at least two jets (one b-tagged)
  - – MET>30 (45) GeV
- Determine τ fakes from data
  - – Expected to be dominated by light flavor jet contribution
  - – In W+jets gluon contribution canceled by OS-SS
  - – Conservative approach: average W+jets and QCD

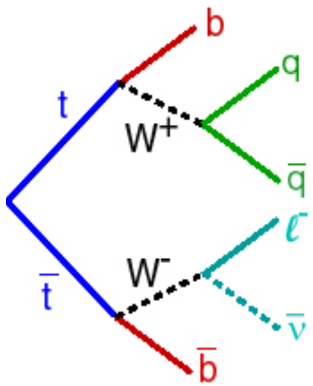
TOP-11-006

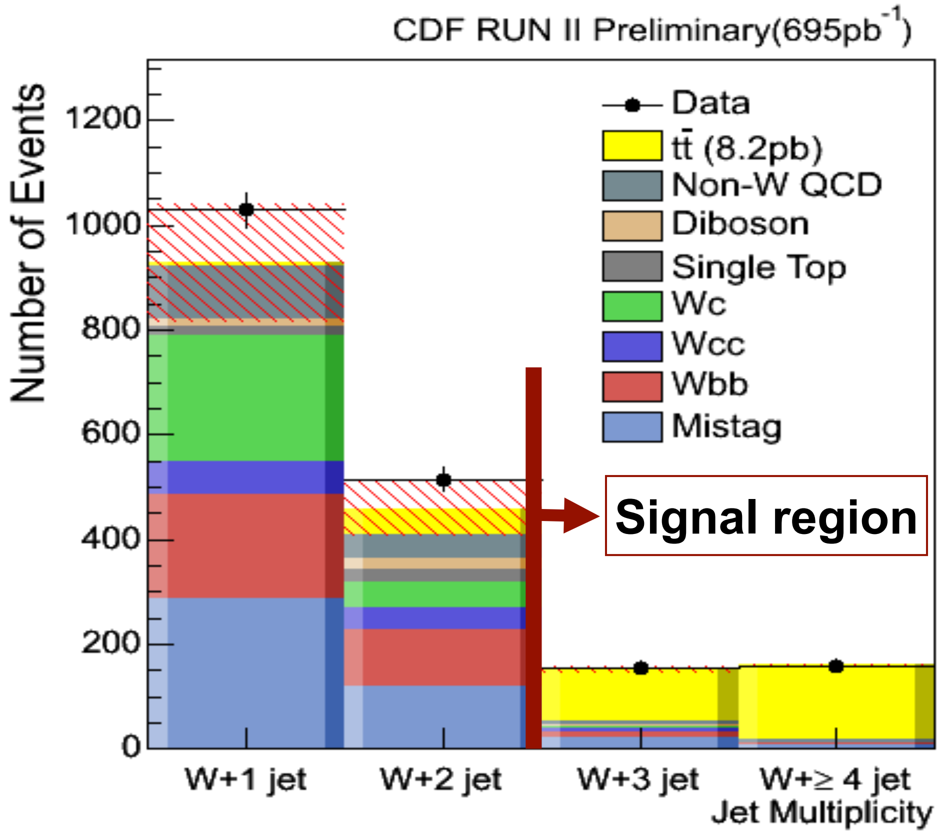


CONF-2011-119 $142 \pm 21\ (\text{stat.}) \pm^{20}_{16}\ (\text{syst.}) \pm 5\ (\text{lumi.})\ \ \text{pb}$ ATLAS

TOP-11-006 $\sigma_{t\bar{t}} = 151 \pm 15(\text{stat.}) \pm 23(\text{syst.}) \pm 7(\text{lumi.})\ \text{pb}$ CMS

Lepton + jets





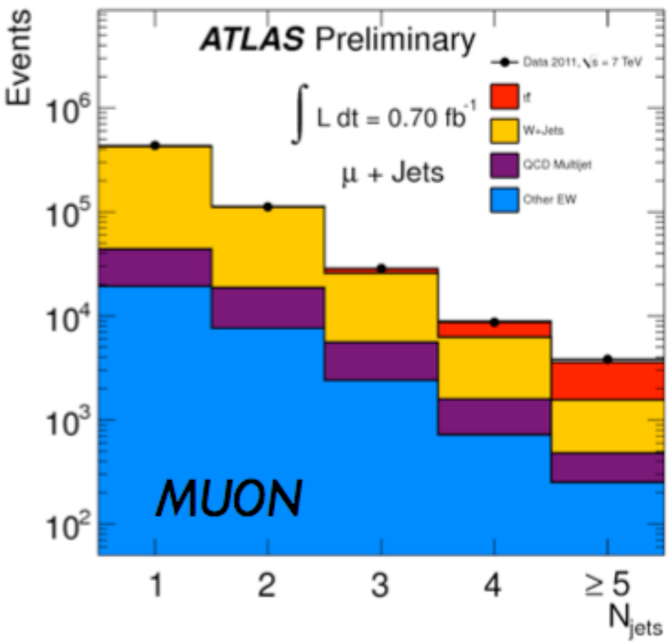
Signal region

BR ~30%
background: moderate

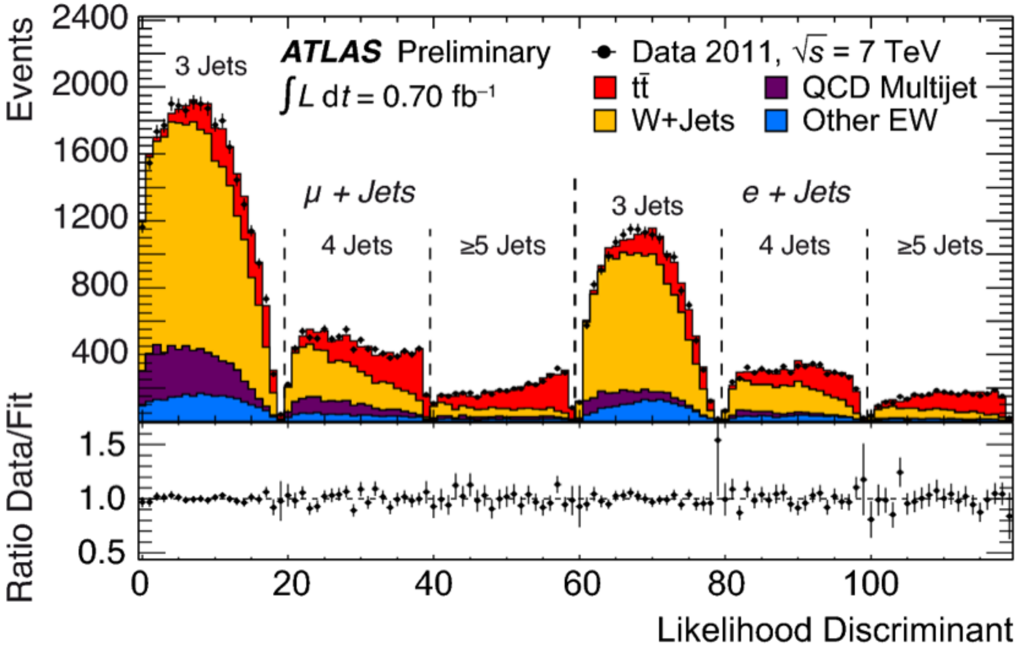
- ➢one lepton + ≥3 jets + $\not{E}_T$
- ➢may require b-tag

Single lepton channel

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

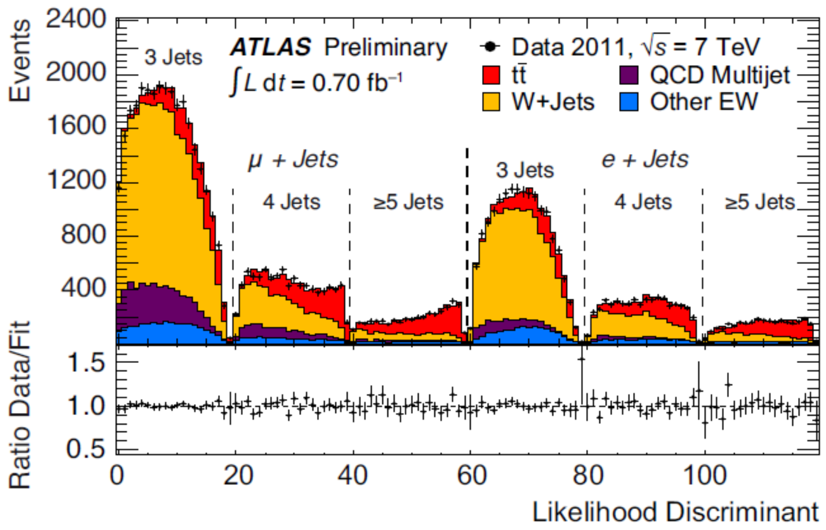


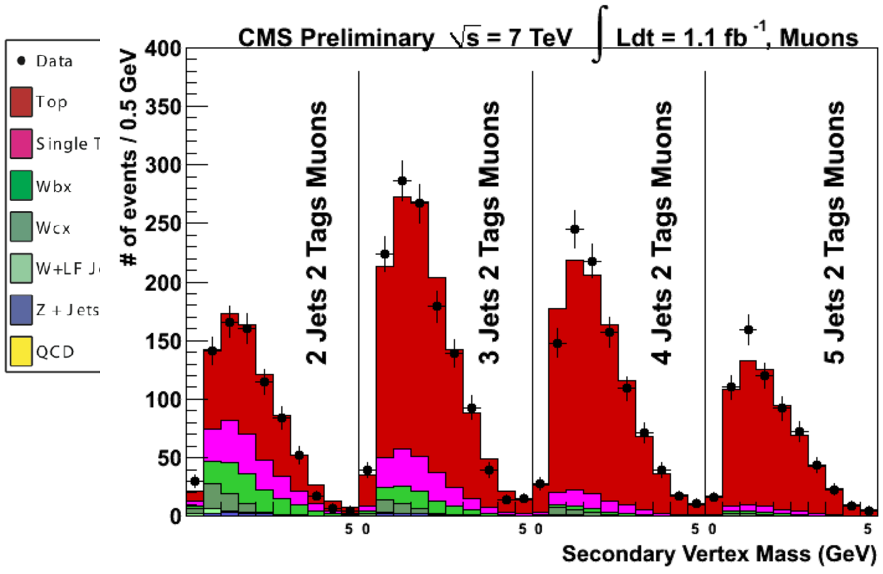
CONF-2011-121



$$\boxed{\sigma_{t\bar{t}} = 179.0\pm3.9\,(\mathrm{stat})\pm9.0\,(\mathrm{syst})\pm6.6\,(\mathrm{lumi})\ \mathrm{pb}}$$

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 σ_{tt} from fit

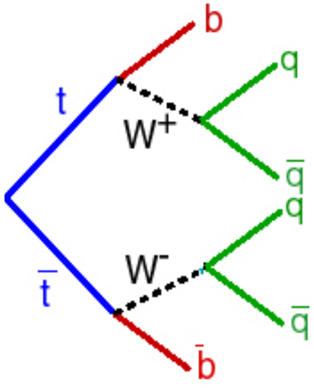
ATLAS

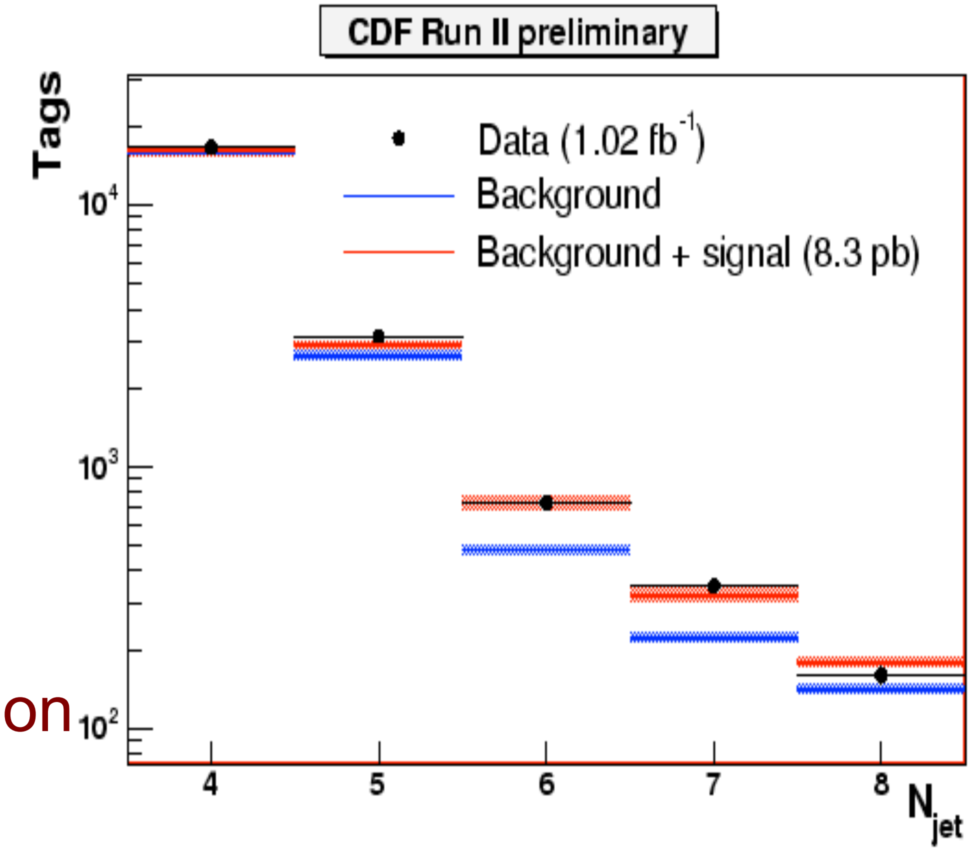
179.0±3.9 (stat)±9.0 (syst)±6.6 (lumi) pb

164.4 ± 2.8(stat.) ± 11.9(syst.) ± 7.4(lum.) pb

CMS

All hadronic



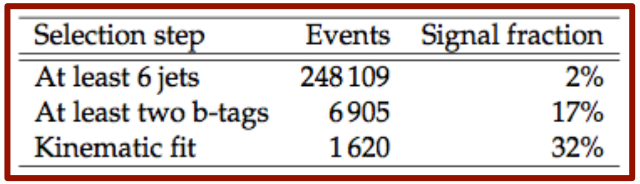


BR ~44%
background: large

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

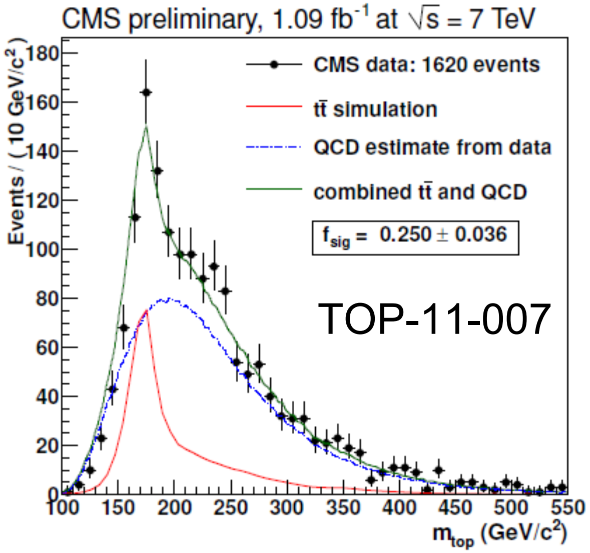
All hadronic

- Large BR, but large bkg
- Select at least 6 jets
  - b-tagging reduces combinatorics

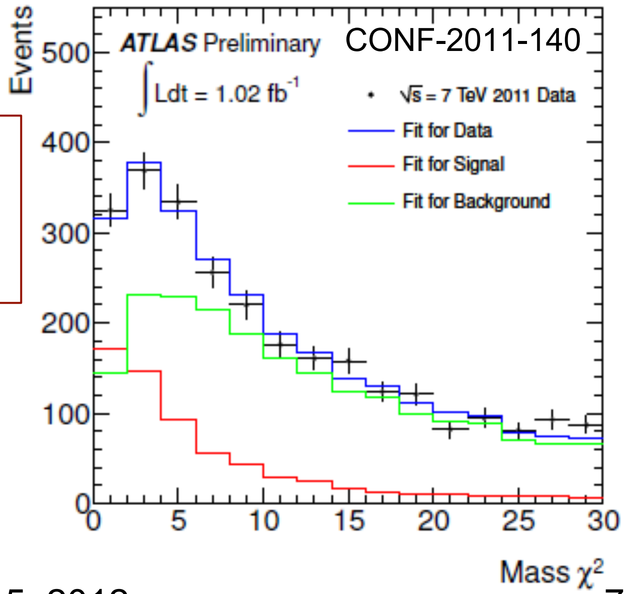


Selection step	Events	Signal fraction
At least 6 jets	248 109	2%
At least two b-tags	6 905	17%
Kinematic fit	1 620	32%

- Top cross section from unbinned maximum likelihood to the reconstructed top mass
- Multijet QCD is main background (modeled from data)
  - Use events with 4-5 jets
  - Re-weigh mass spectrum from anti-tagged sample



TOP-11-007



CONF-2011-140

Fit χ^2 or top mass
(signal from generator, background data-driven)

- Results:

ATLAS

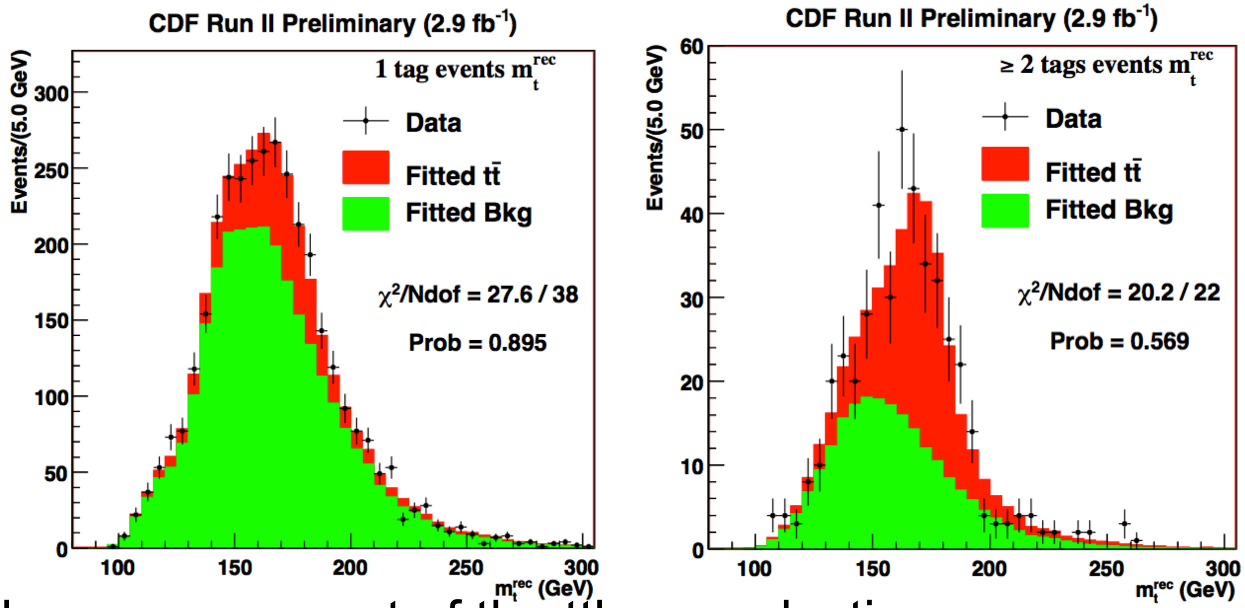
$$\sigma(pp \to t\bar{t}) = 167 \pm 18\ (\text{stat.})\ \pm 78\ (\text{syst.})\ \pm 6\ (\text{lum.})\ \text{pb}$$

$$136 \pm 20\ (\text{stat.}) \pm 40\ (\text{sys.}) \pm 8\ (\text{lumi.})\ \text{pb}$$

CMS

All hadronic at the Tevatron

Top reconstructed invariant mass with 1 b-tag and ≥2 b-tags



The measurement of the ttbar production cross section is performed through a likelihood fit:

$$\mathcal{L} = \mathcal{L}_{1\,tag} \times \mathcal{L}_{\geq 2\,tags} \times \mathcal{L}_L$$

lumi

$$\mathcal{L}_{1,\geq 2\,tags} = \mathcal{L}_{n_s} \times \mathcal{L}_{\epsilon}$$

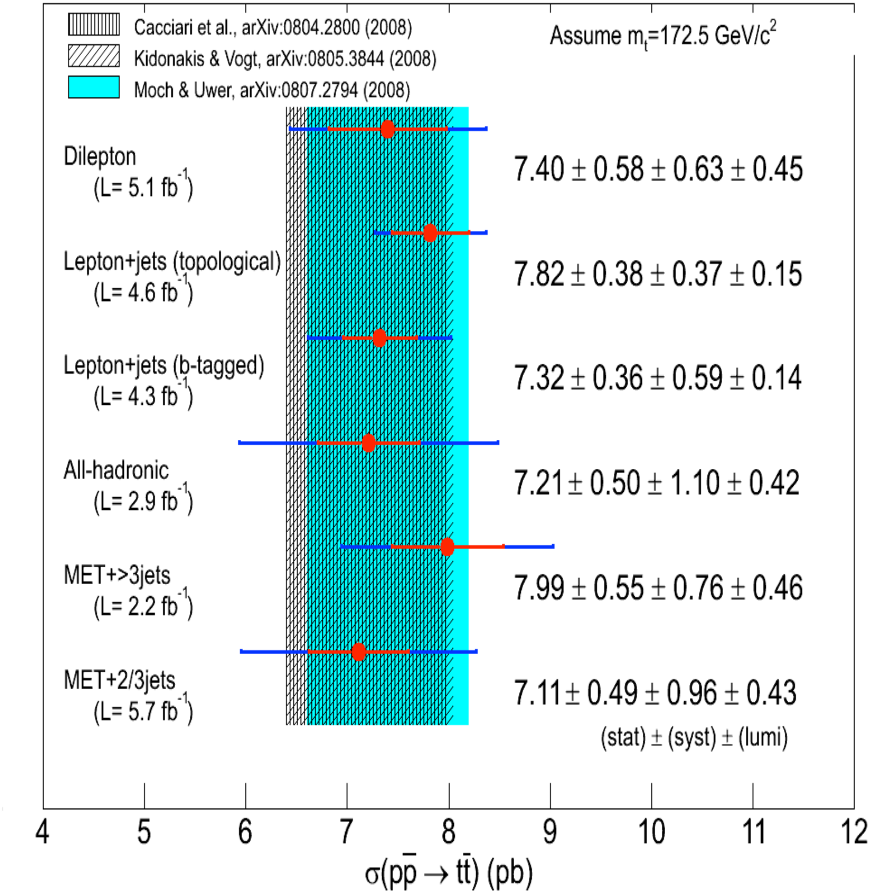
signal yield signal efficiency

$$\boxed{\mathcal{L}(\sigma_{t\bar{t}}) = e^{-(\sigma_{t\bar{t}}\cdot\epsilon\cdot L - n_s)^2/2\sigma_{n_s}^2}}$$

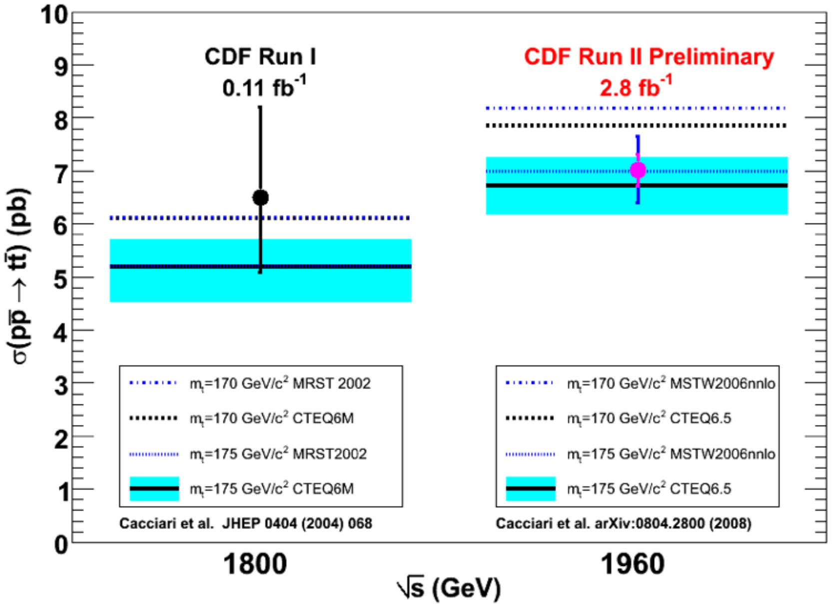
$$\boxed{\sigma_{t\bar{t}} = 7.21 \pm 0.50\,(stat) \pm 1.37\,(syst) \pm 0.42\,(lumi)\ \text{pb}}$$

Cross section at the Tevatron

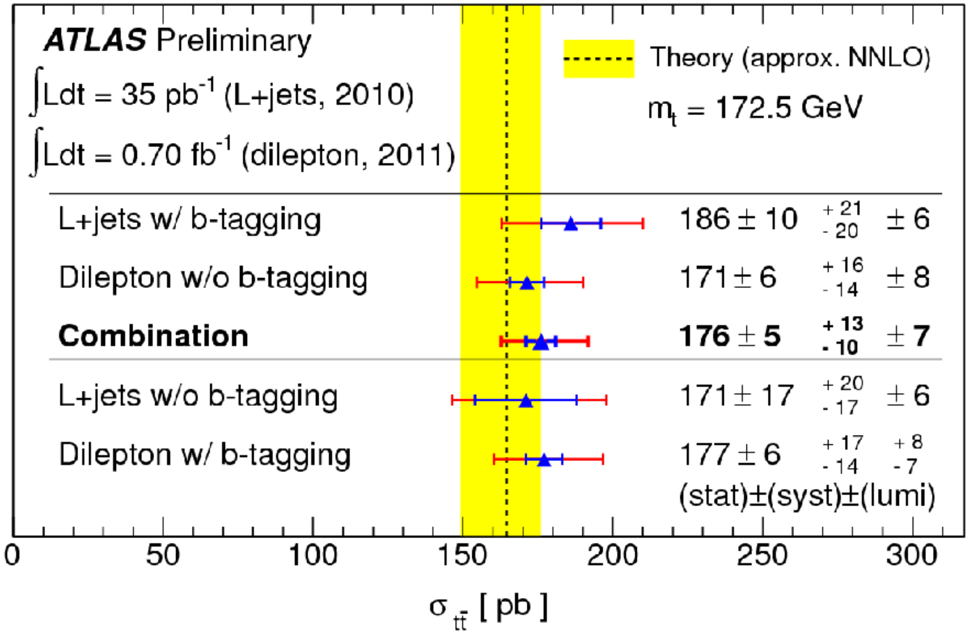
Aug. 2009

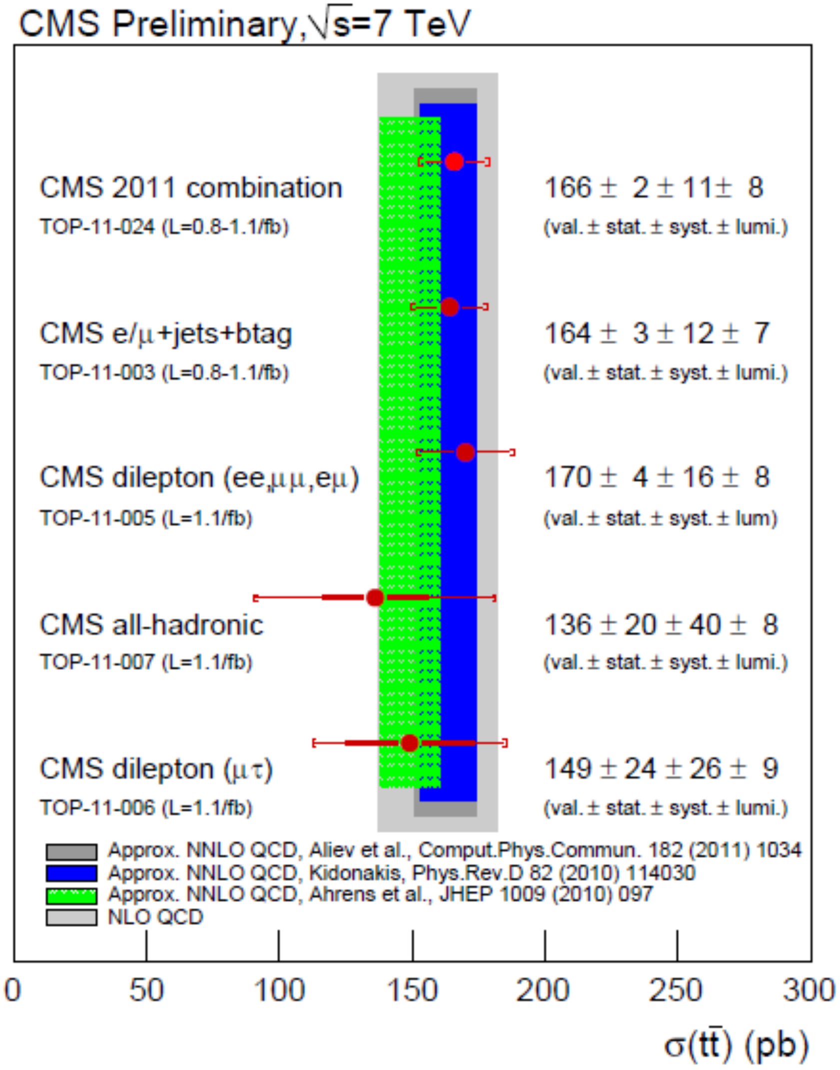


- Good agreement with expectations
- Everything else we know of ttbar agrees with SM



Top cross sections at 7 TeV





Good agreement between measurements and predictions for all decay modes

end