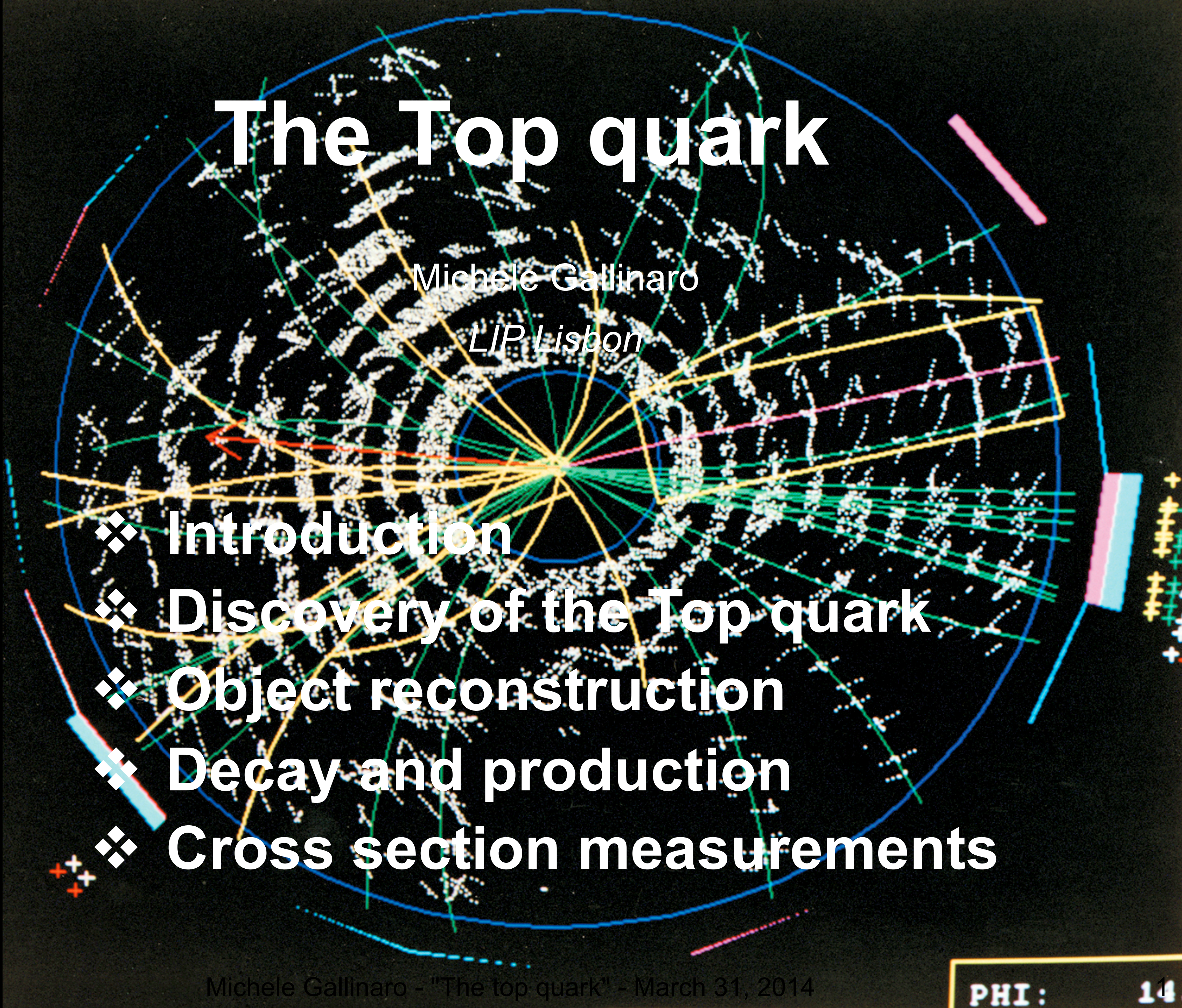


The Top quark

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
- Mass measurements

today

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

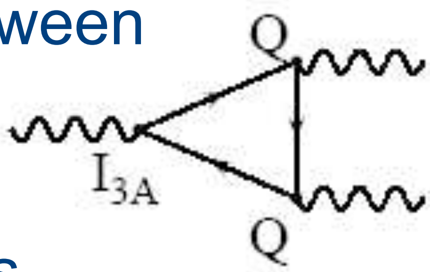
$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} \\ b \end{pmatrix}$$

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

- 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?

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

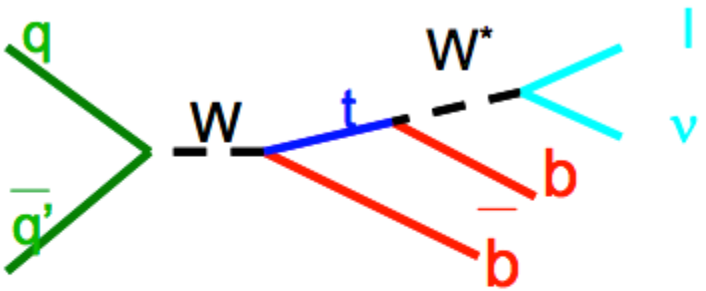
- In the SM, various EWK observables depend on the mass of the top quark

- 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

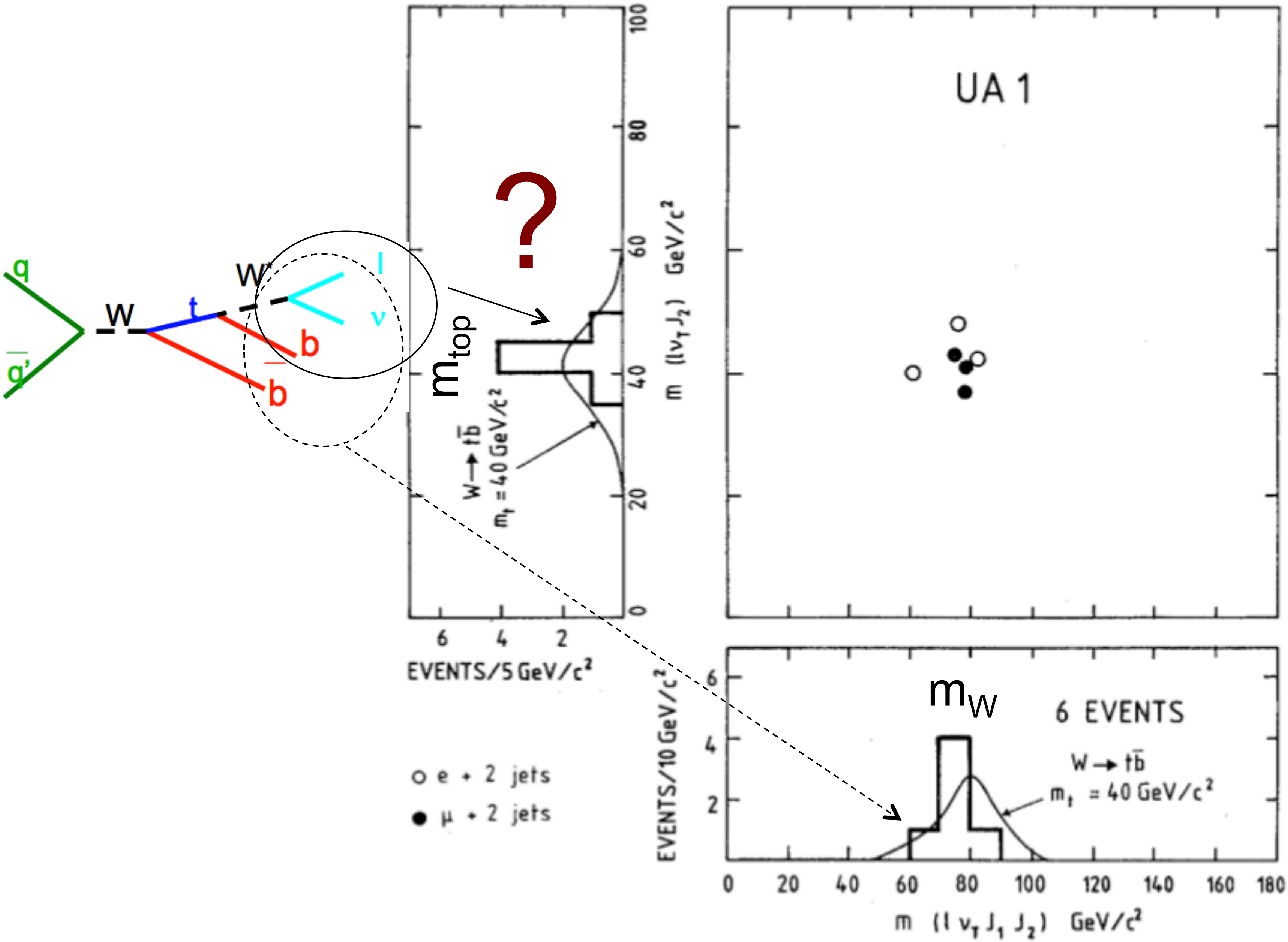
- – Access to much higher energies
- – Large backgrounds, low event rates
- – Difficult reconstruction: jets



1984: UA1

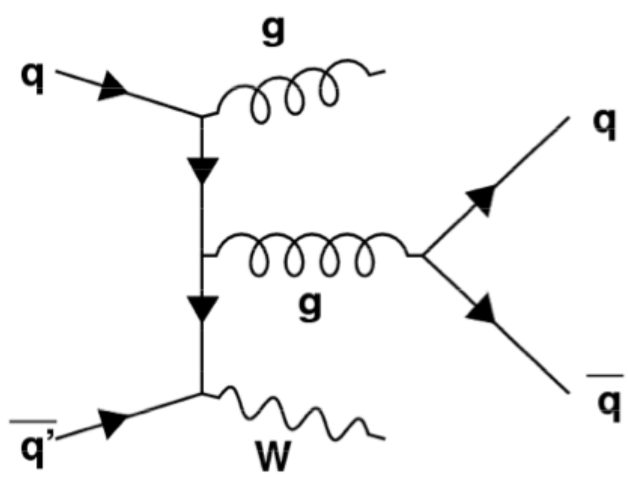
- $W \to tb \to l\nu bb$
- Isolated high-p_T lepton
- 2 or 3 hadronic jets
- Observe 5 events (e+ ≥2 jets), 4 events (μ+ ≥2 jets)
- Expected background: 0.2 events
  - – Fake leptons dominate; bbar/ccbar negligible
- Result consistent with M_{top}=40±10 GeV
- Stop before claiming discovery…

⇒W+jet background was underestimated


q
q̄'
W
t
W
l
ν
b
b̄
?
m_{top}
UA 1
m (lν_T J_2) GeV/c²
W → tb̄
m_t = 40 GeV/c²
EVENTS/5 GeV/c²
o e + 2 jets
● μ + 2 jets
m_W
6 EVENTS
W → tb̄
m_t = 40 GeV/c²
EVENTS/10 GeV/c²
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

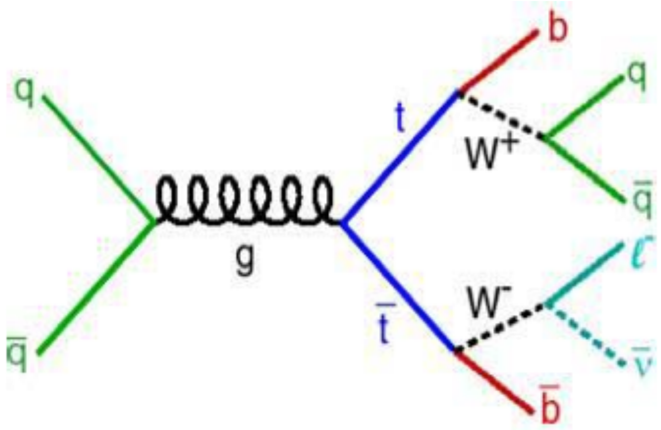
(+ 23 expected if $M_{top} = 40$ GeV)

⇒conclude M_{top}>44 GeV

Fermilab joins the hunt

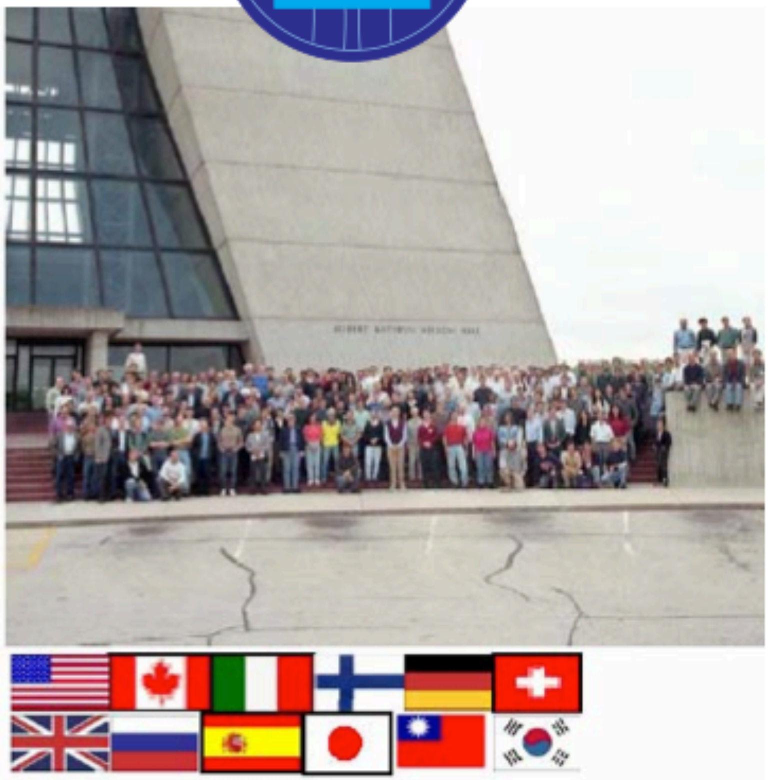
- 1988-89: at CERN, UA2 remains after the upgrades
- √1.8 TeV@FERMILAB **vs.** √0.63 TeV@CERN
- Much better reach for larger mass (only 75 GeV@UA2)
- At Tevatron, pair production dominates: $t\bar{t} \rightarrow Wb\,W\bar{b}$

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

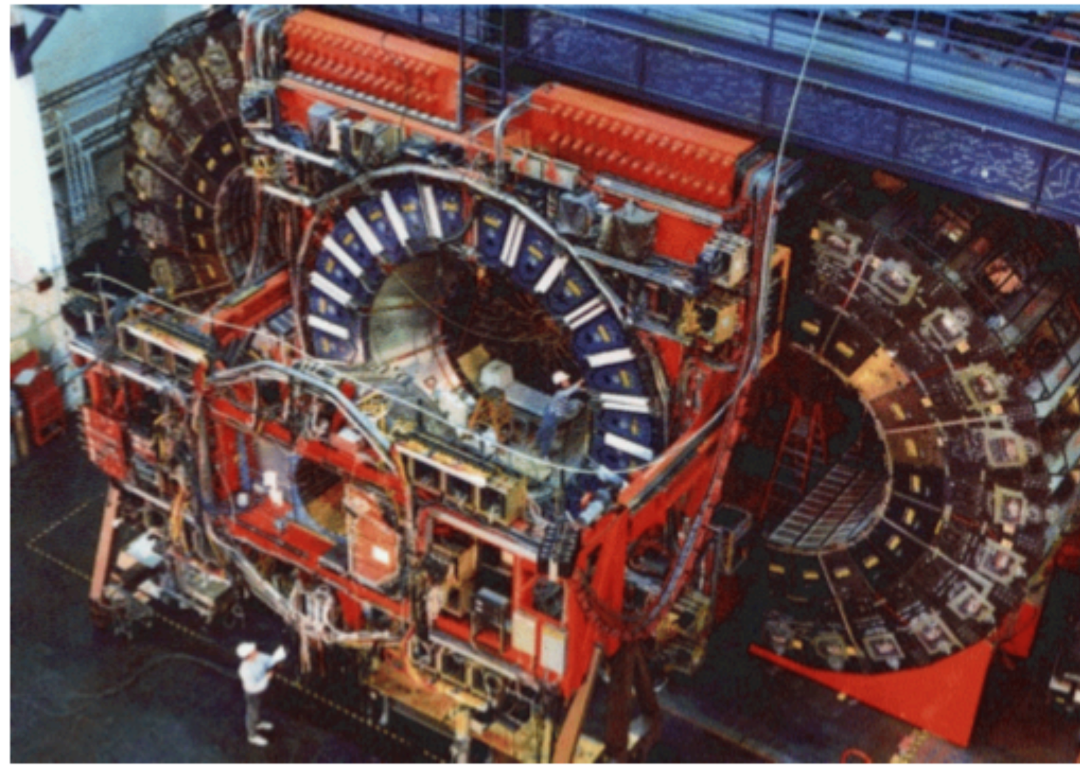


Tevatron

Proton-antiproton collision at 1.8-2.0 TeV



12 countries, 62 institutions
767 physicists

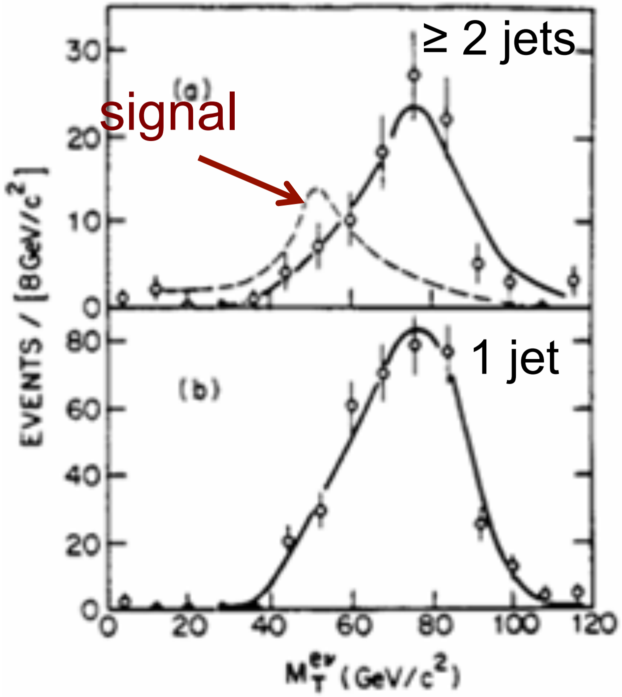


Searches at CDF

$e\nu + \geq 2$ 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.)

$e\mu$ channel

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

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

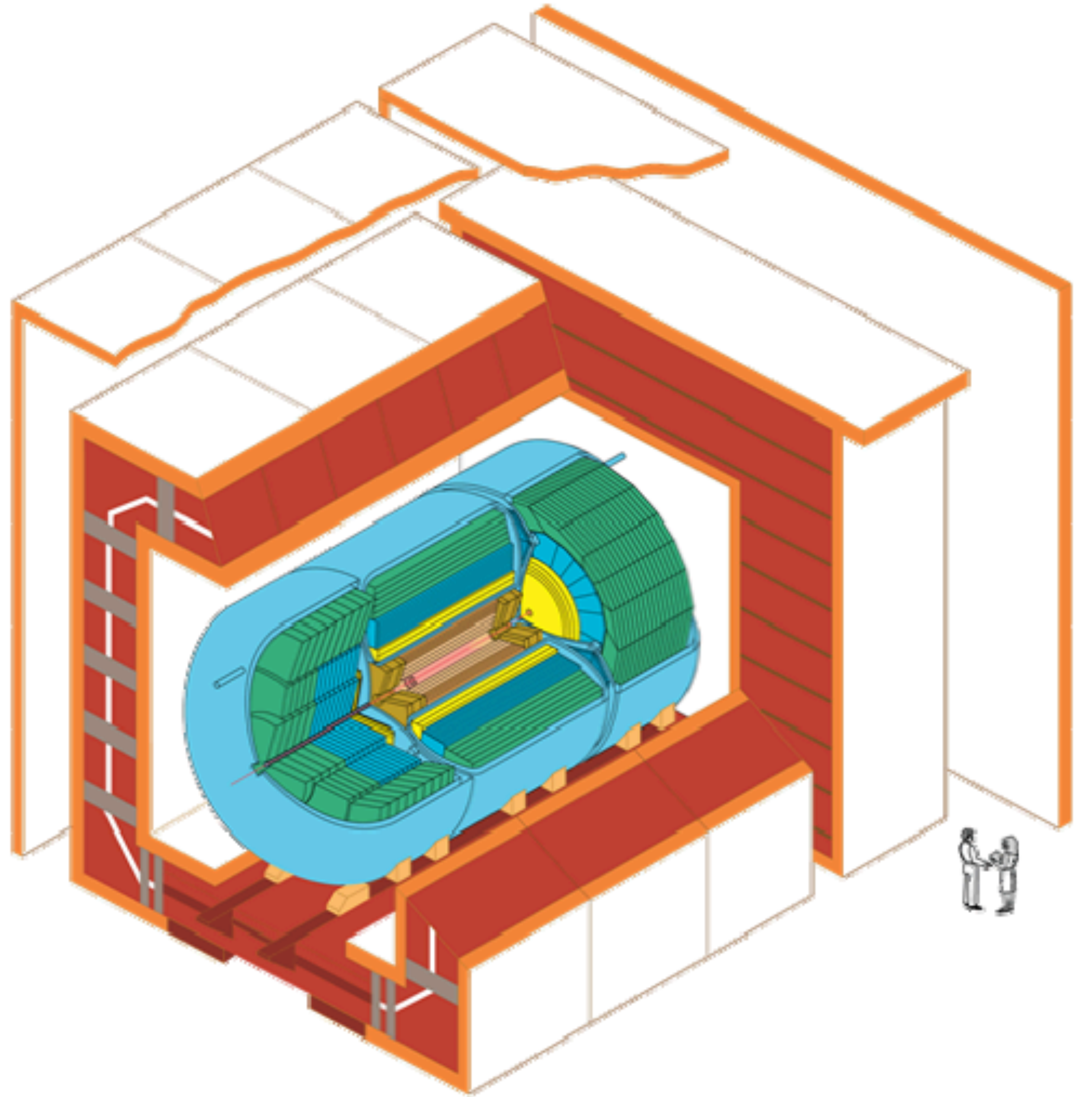
Change of strategy: $M_{top} > M_b + M_W$

- 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, $\mu\mu$, 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



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:

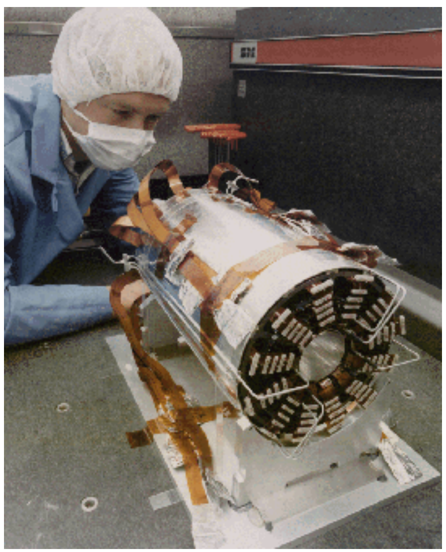
- D0: optimized search for M_{top}=100 GeV

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

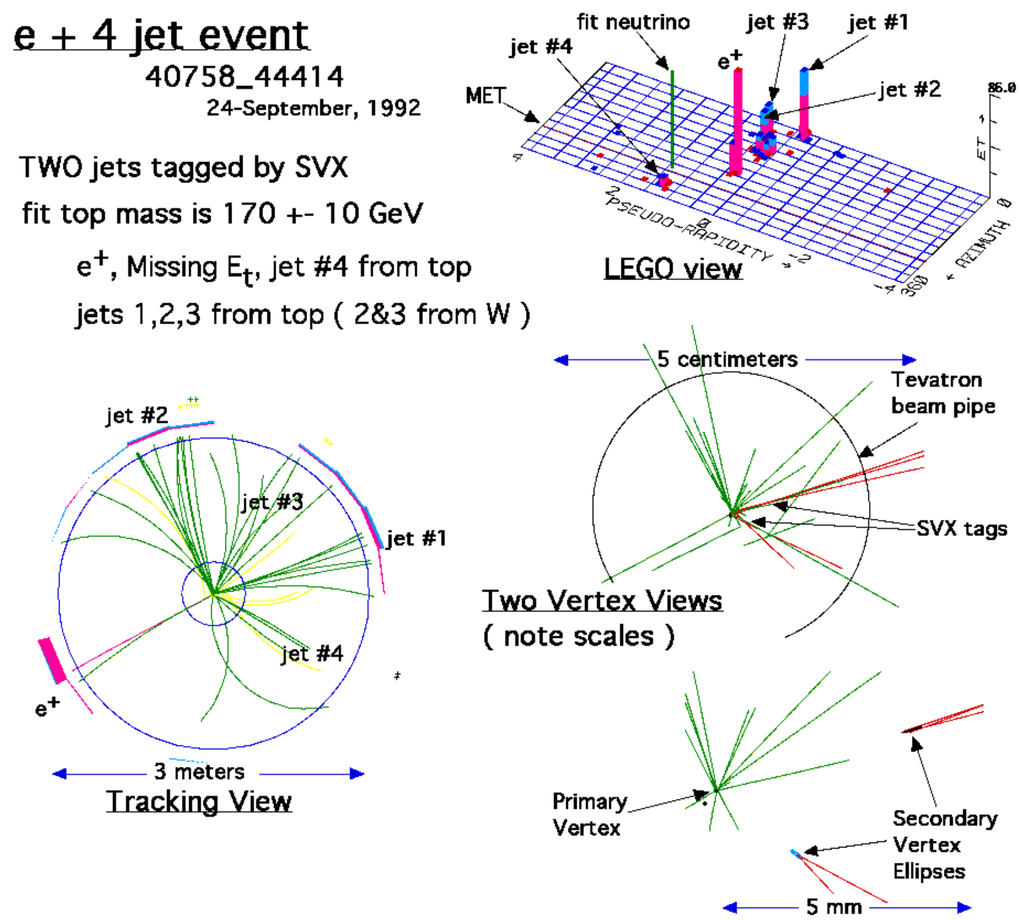
$\Rightarrow M_{top}$>131 GeV@95%CL

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

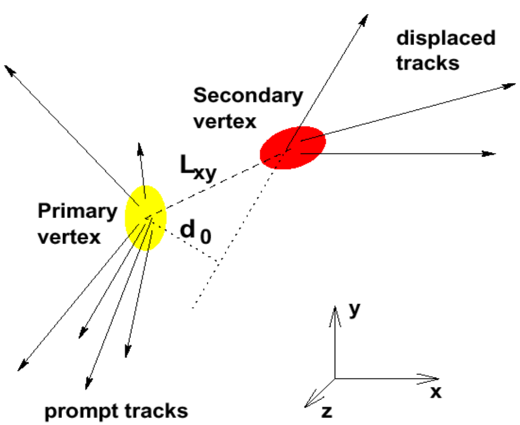


Tagging b-jets

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

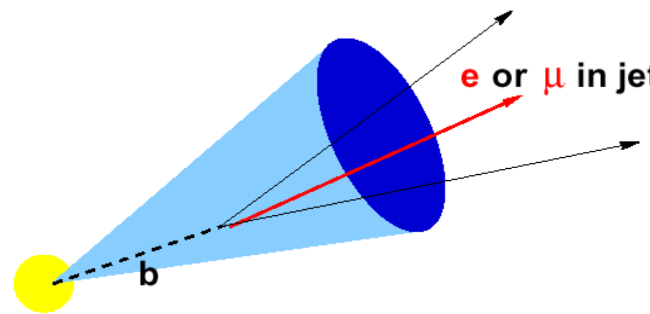
B hadrons are long-lived

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

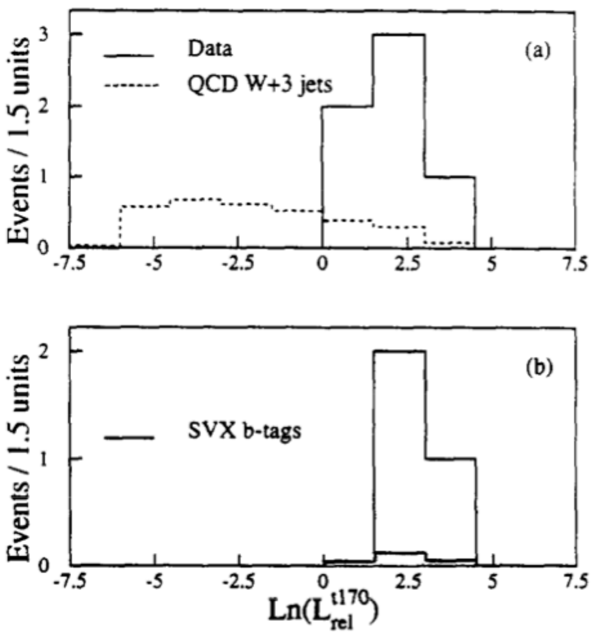
← 3 events in common (SVX, SLT)

- 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)

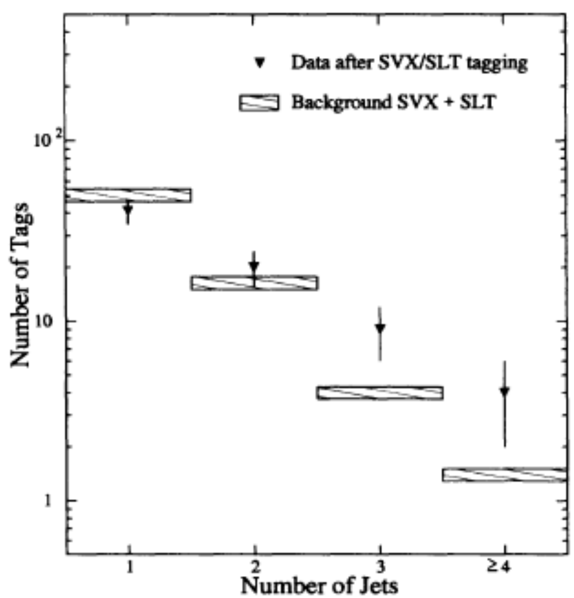
- Observed 7 events (expect 4-6 from bkg)
- No independent evidence

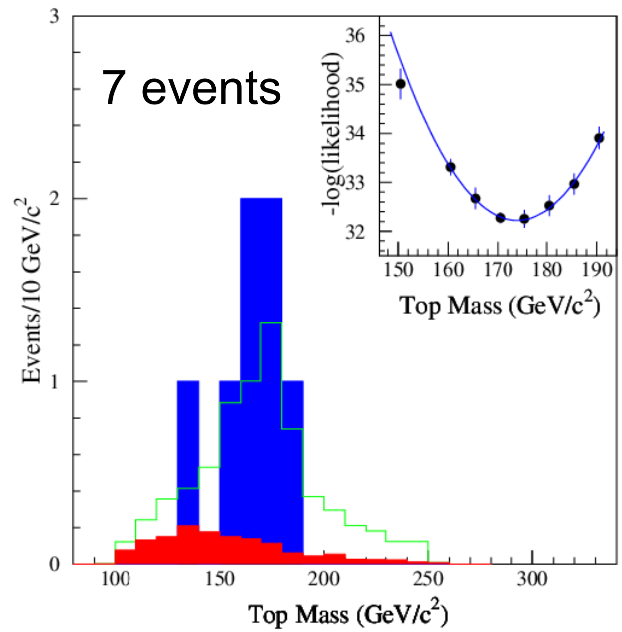
First evidence (1994)

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.



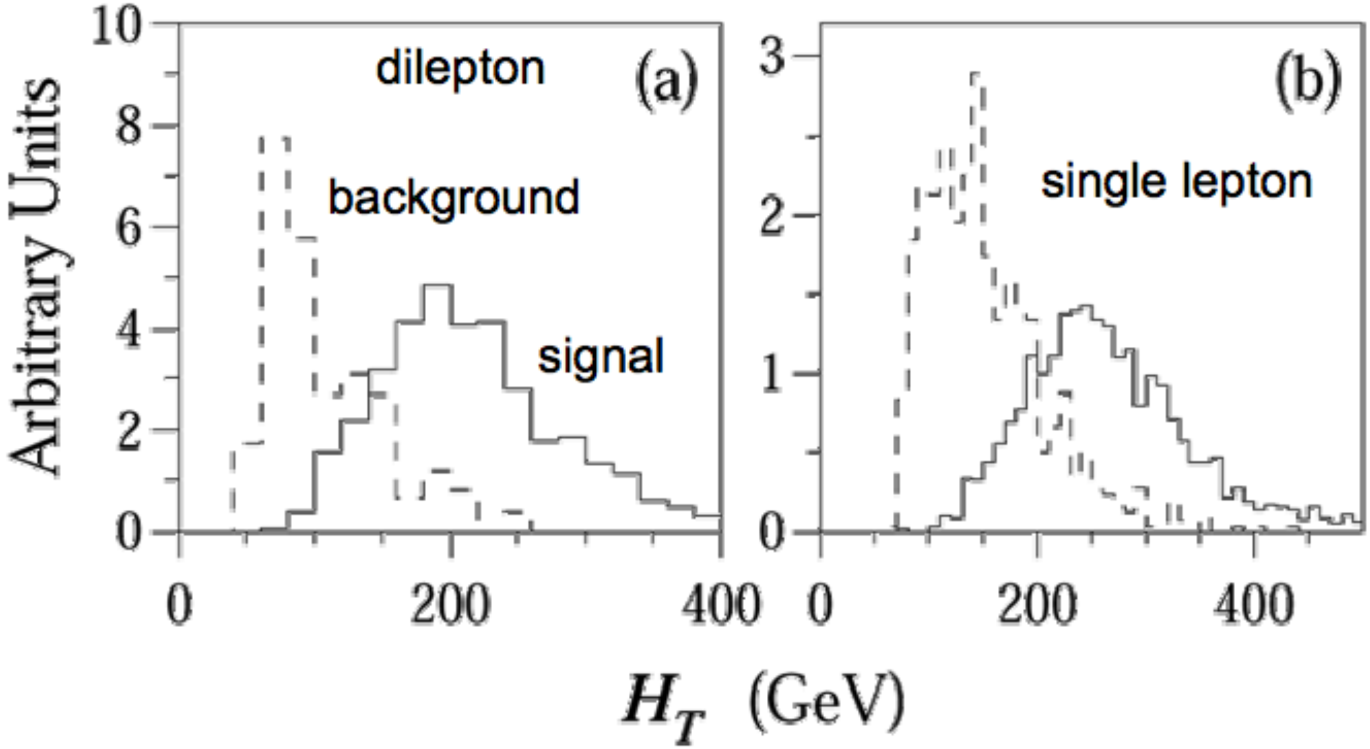


Discovery

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

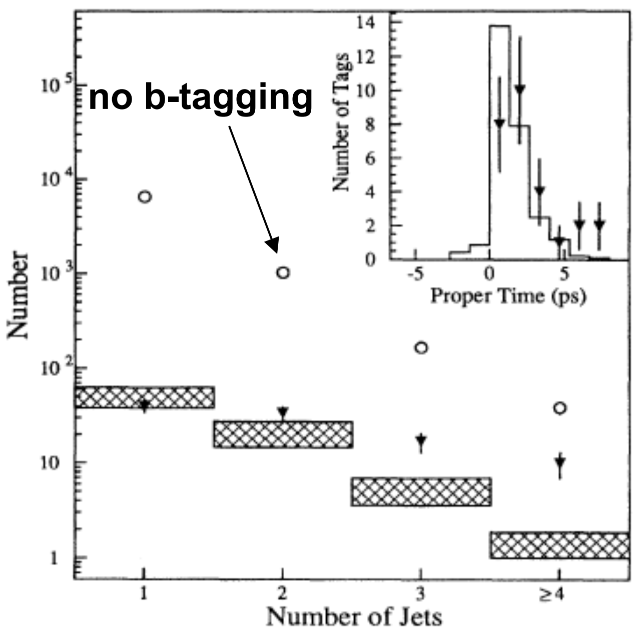


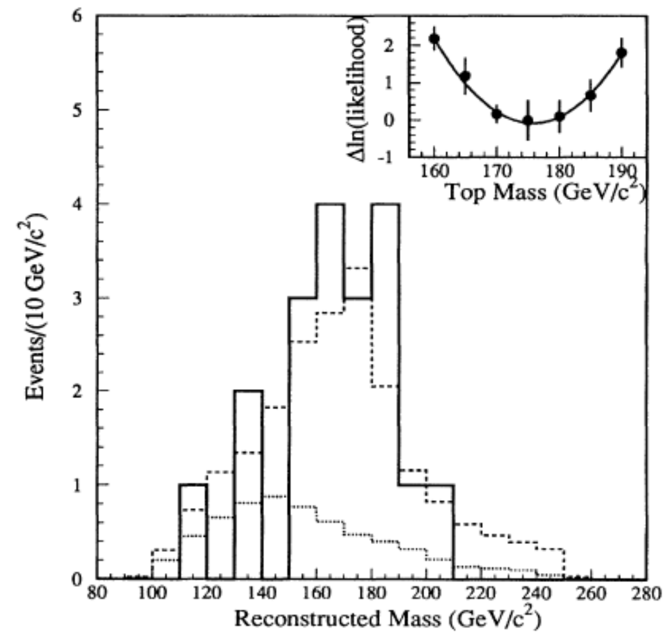
First measurements

VOLUME 74, NUMBER 14 PHYSICAL REVIEW LETTERS 3 APRIL 1995

Observation of Top Quark Production in $\bar{p}p$ 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 4.8σ. Additional evidence for the top quark is provided by a peak in the reconstructed mass distribution. We measure the top quark mass to be $176 \pm 8(\text{stat}) \pm 10(\text{syst})$ GeV/c^2, and the $t\bar{t}$ production cross section to be $6.8^{+3.6}_{-2.4}$ pb.





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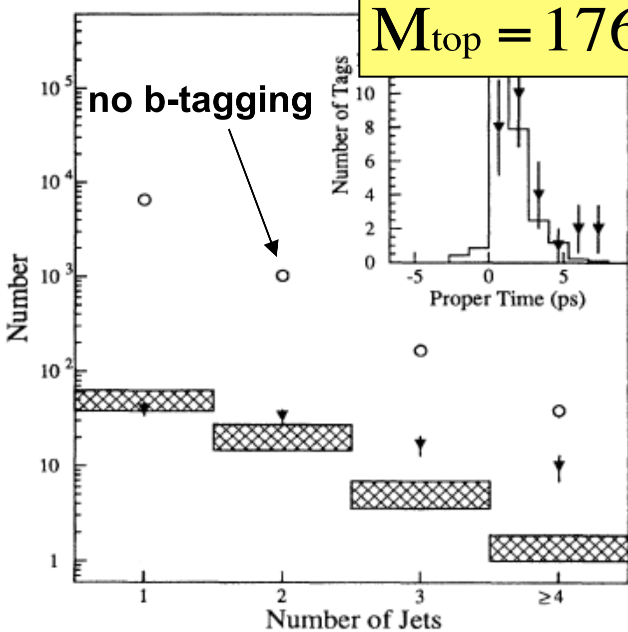
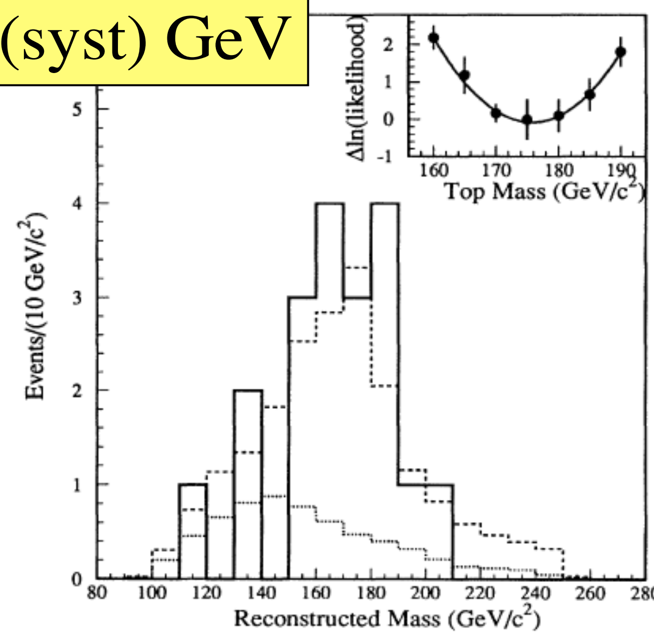
$$\sigma_{tt} = 6.8^{+3.6}_{-2.4}\ \text{pb}$$

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





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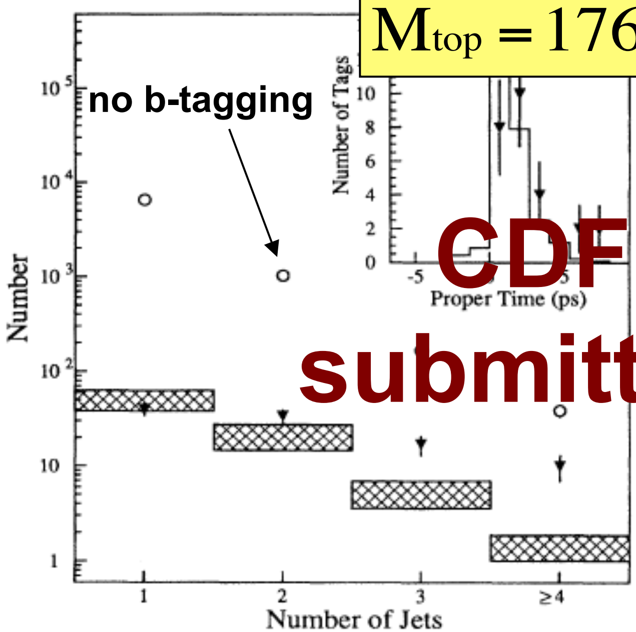
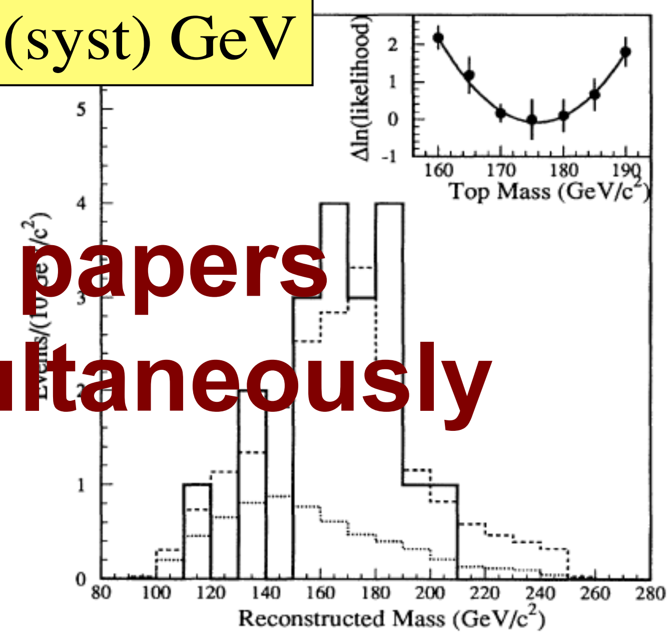
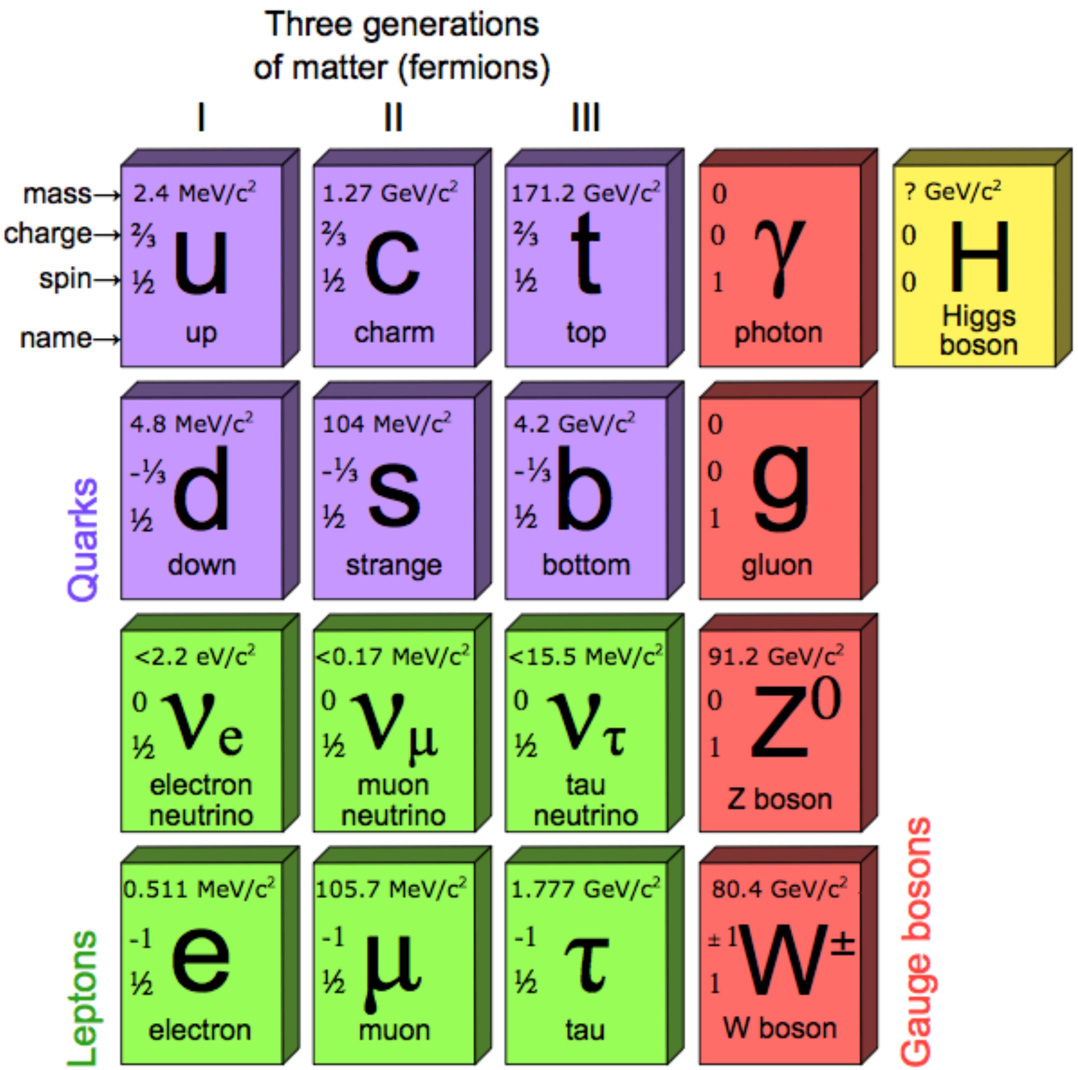




CDF and D0 papers submitted simultaneously

Top quark and its relevance

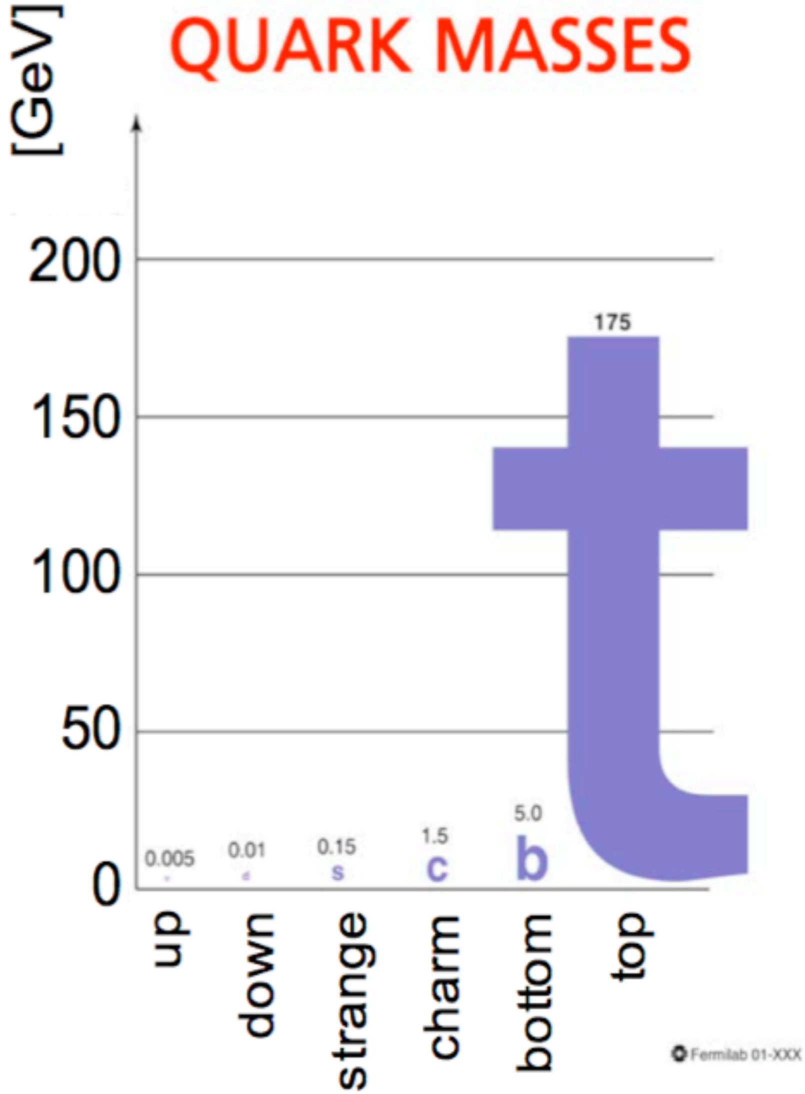
- Basics
- How to detect the top quark
- Tevatron vs LHC



About the top quark

- The heaviest known elementary particle
- Large mass, coupling to the Higgs ~1
  $\Rightarrow$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?

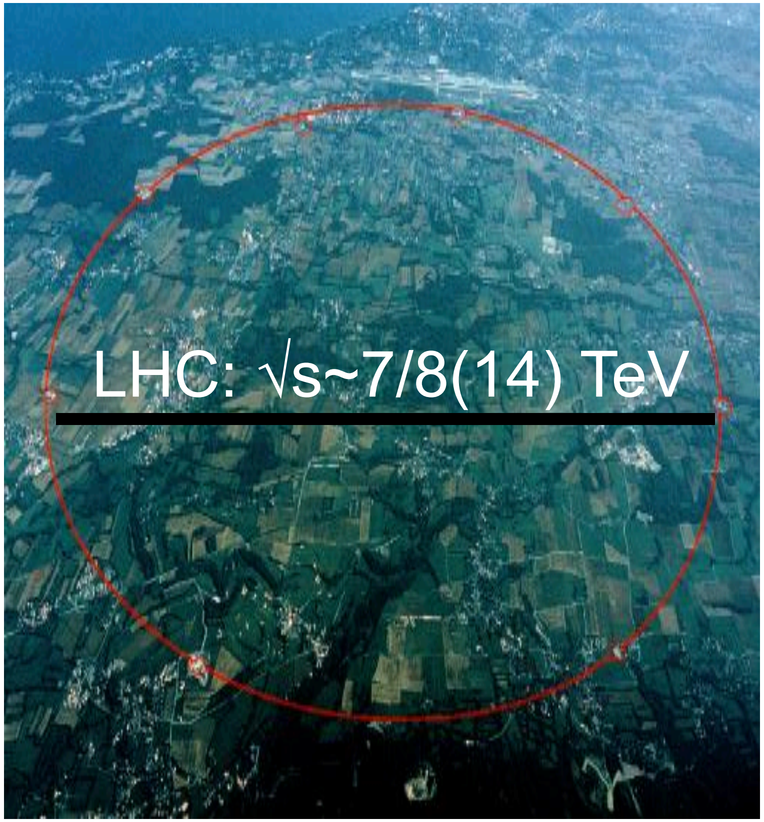
- Main background for many New Physics searches
- Top quark measurements may provide insight into physics beyond SM



The Large Hadron Collider

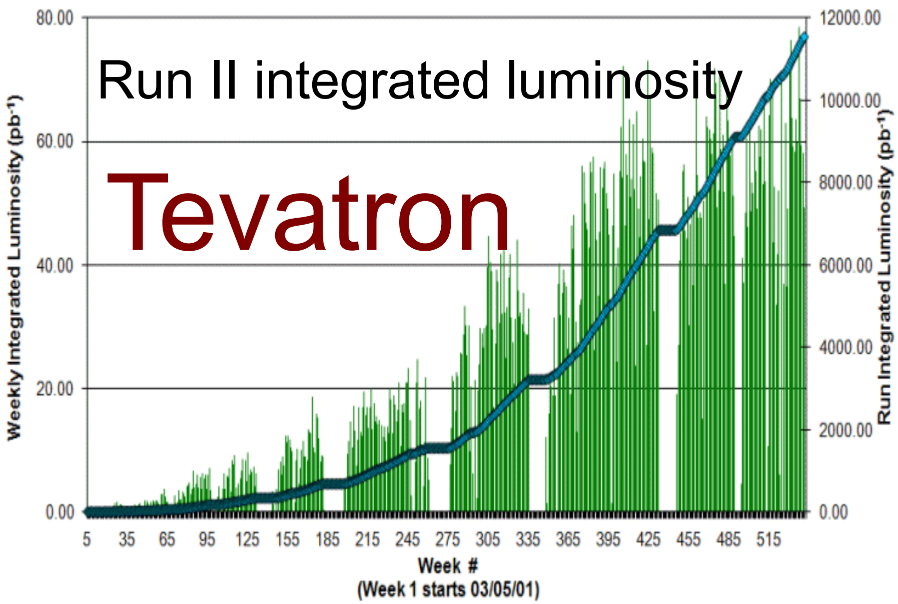
- Built to explore new energy frontiers
- First colliding beams in 2009
- started with "low" luminosity in 2010
- ~5 fb^{-1}@7TeV delivered in 2011
- ~20 fb^{-1}@8TeV in 2012

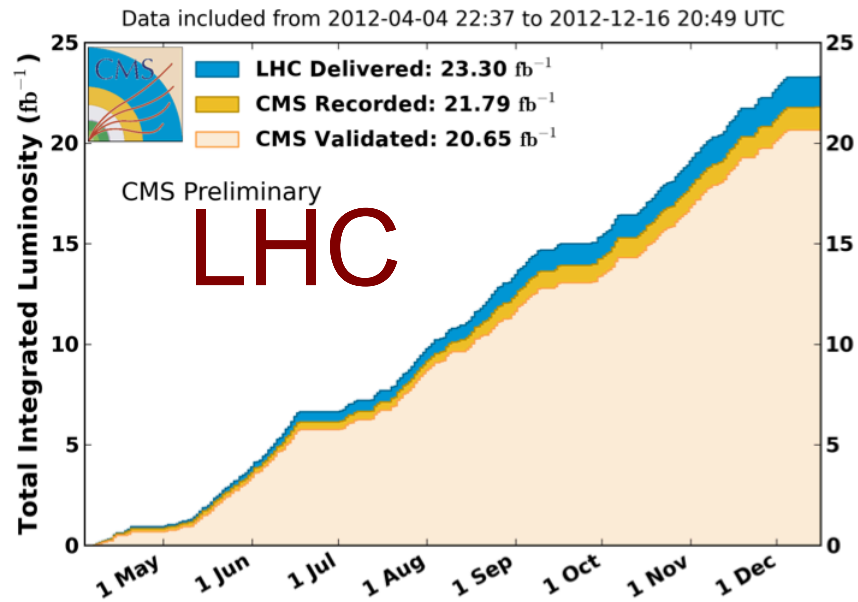
- re-establish SM measurements
- access to new physics processes



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

Tevatron vs LHC





Tevatron	LHC
Energy: 1.96 TeV	Energy: 7/8 TeV
Int. Luminosity: 12 fb^{-1}	Int. Luminosity: 5/20 fb^{-1}
Age: ~25 years	Age: ~3 years
Events/exp (5.4 fb^{-1})	Events/exp (1 fb^{-1})
350 ee eμμμ	2500 ee eμμμ
3500 lepton + jets	15000 lepton + jets

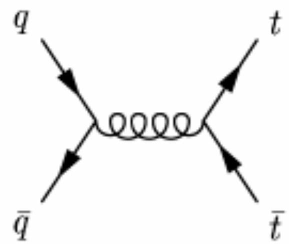
What is the Top quark?

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

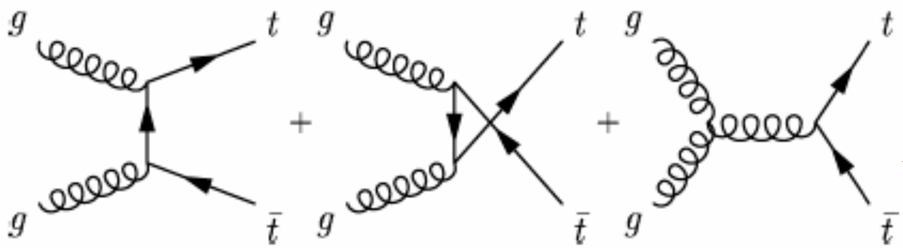
$$\text{Leptons:} \quad \begin{pmatrix} \nu_e \\ e \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$$

- It is the heaviest fundamental particle
  - $M_{top} = 173.2 \pm 0.9$ GeV (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

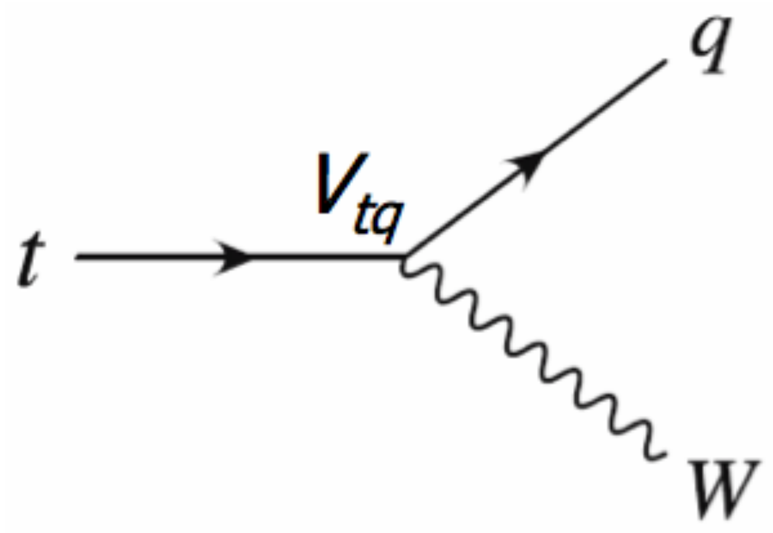
Predicted cross sections:

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

Czakon et al. PRL 110, 252004 (2013)

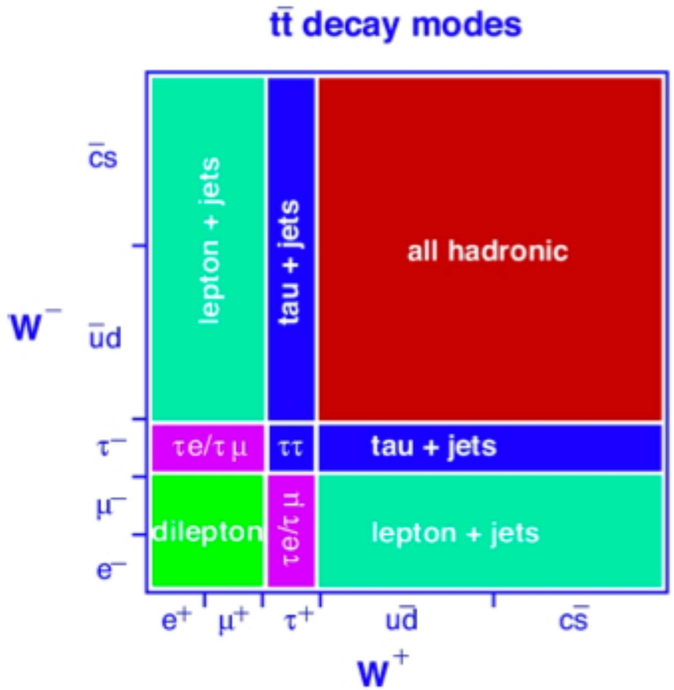
	LHC	Tevatron
gg	~85%	~10%
qq	~15%	~90%

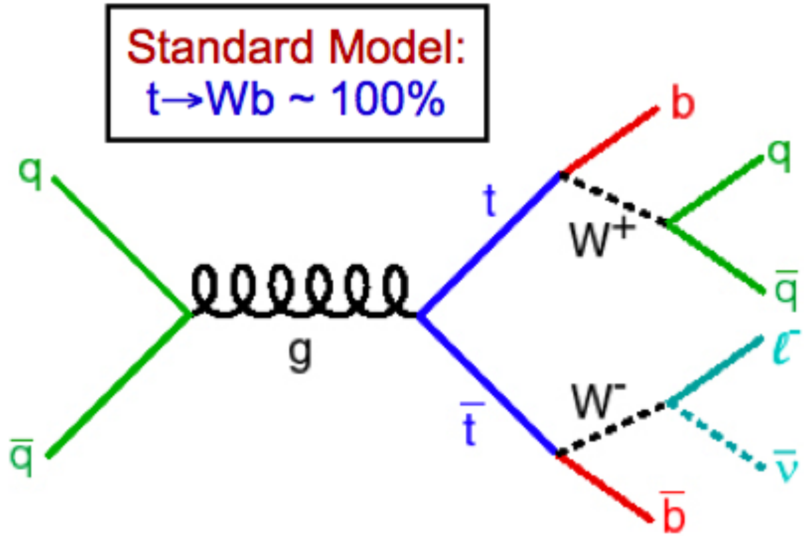
How does a top quark decay?



- almost always $t \rightarrow Wb$ (i.e. V_{tb}~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?

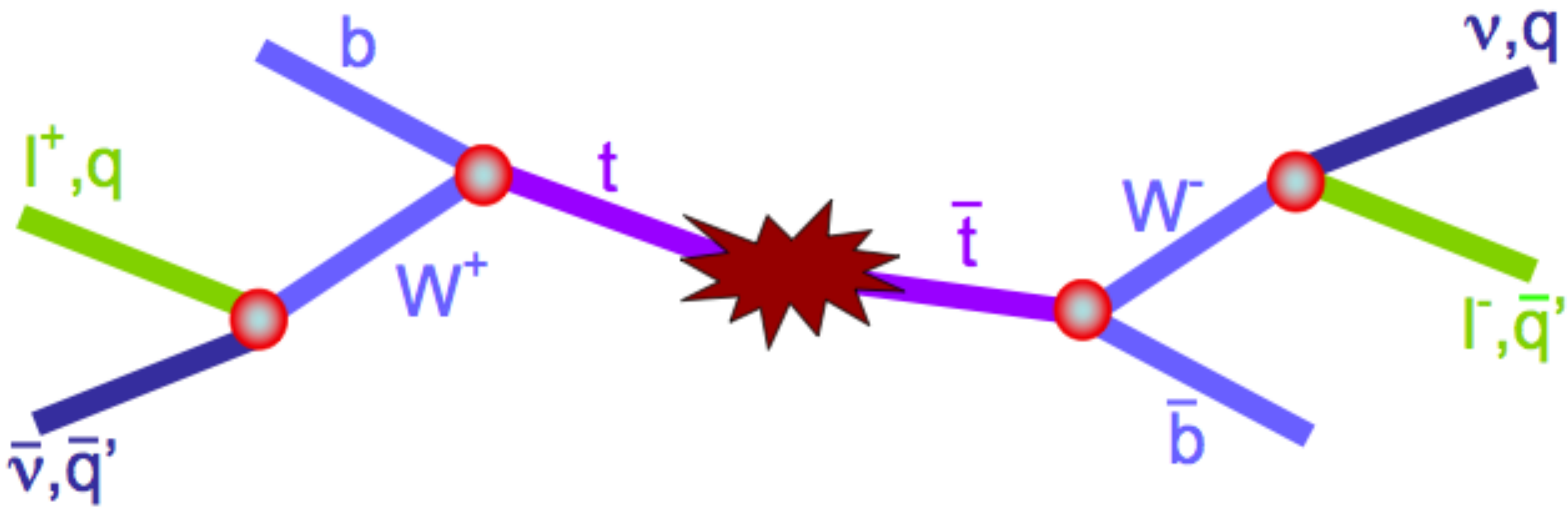




tt → lνlνbb	di-lepton	5%	e+μ
tt → lνqqbb	lepton+jets	30%	e+μ
tt → qqqqbb	all hadronic	44%	

⇨ 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)
...

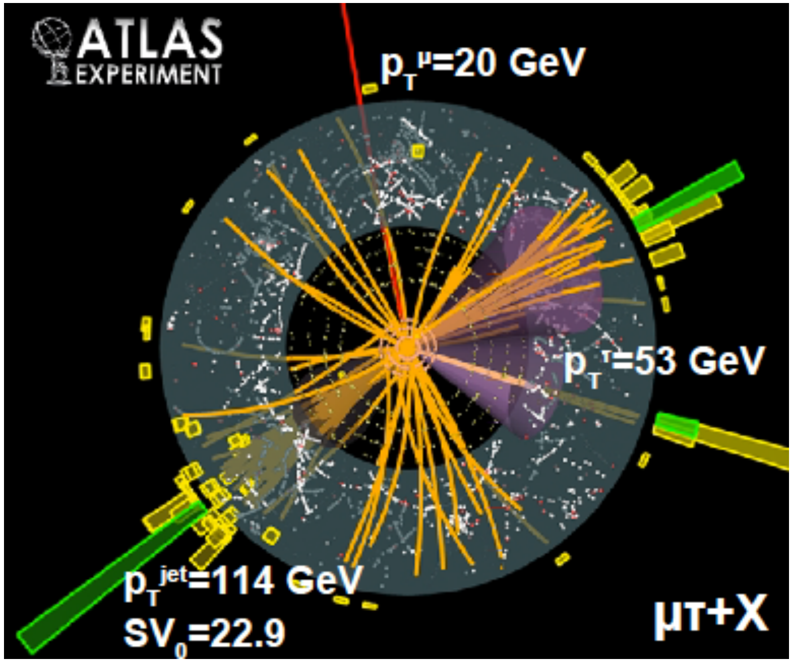
PROPERTIES
Mass
Kinematics
Charge
Lifetime and width
W helicity
Spin
...

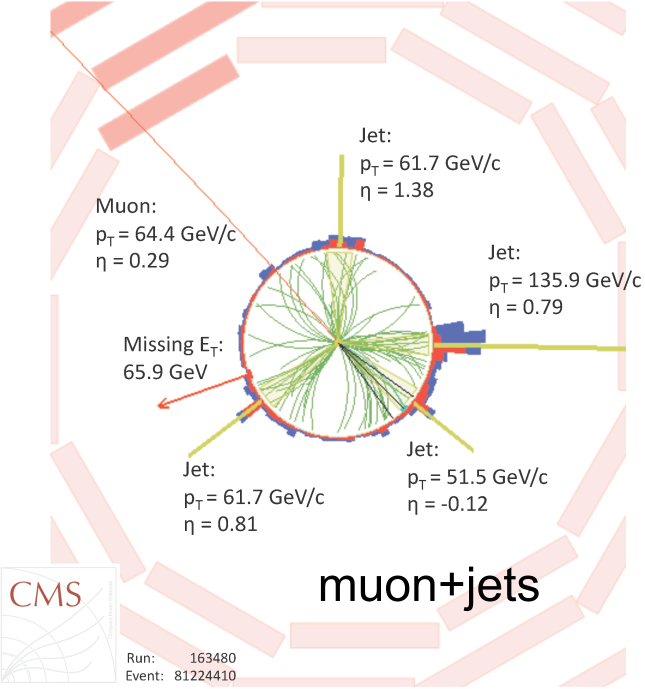
DECAY
Branching ratios
Charged Higgs (non-SM)
Anomalous couplings
Rare decays
CKM matrix elements
Calibration sample @LHC
...

Particle identification

- Object identification and reconstruction

Selection of top quark events

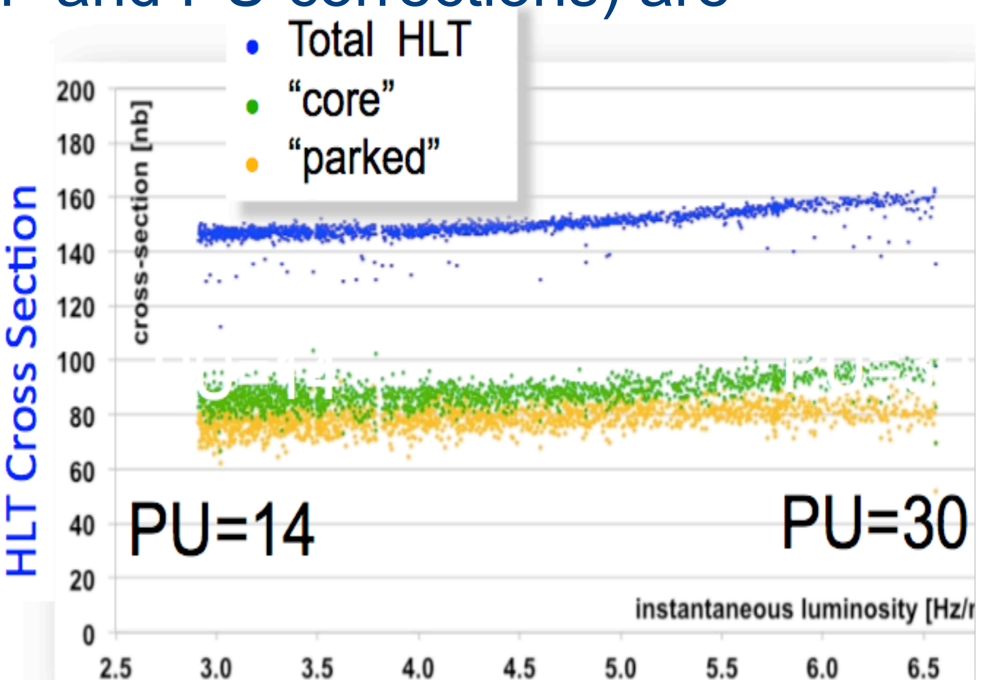




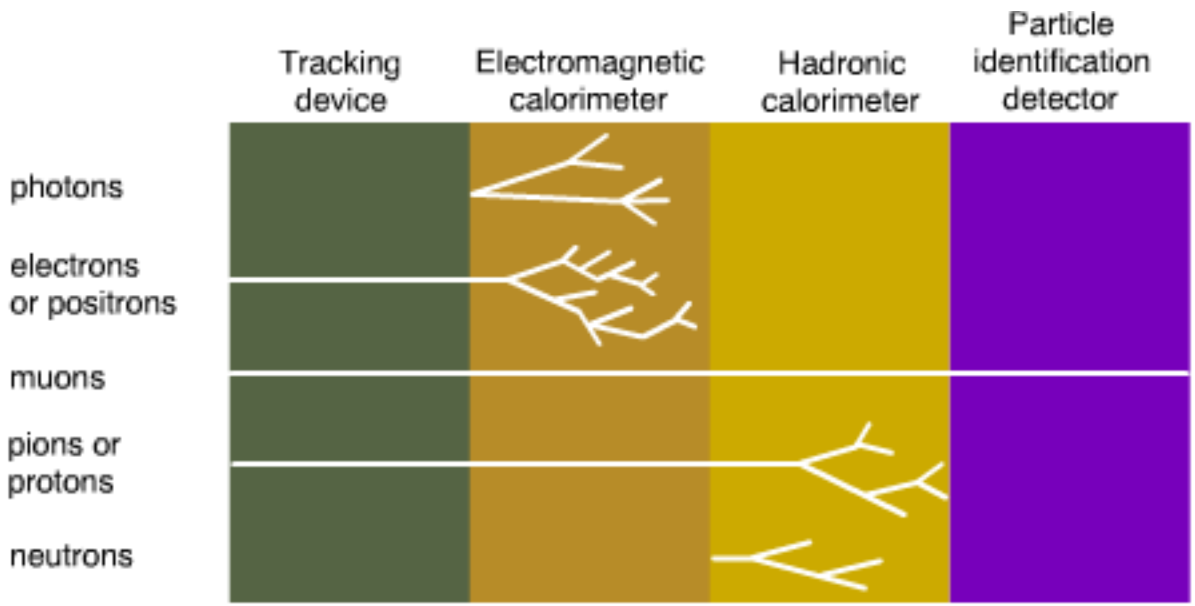
- Trigger:
  - single or double (isolated) lepton
- Leptons:
  - e/μ, p_T>20/30 GeV, |η|<2.5
  - Identification/reconstruction
  - Tracker/calorimeter isolation
- Jets:
  - at least 2 jets, p_T>30 GeV, |η|<2.5
  - anti-kT algorithm, with cone 0.4-0.5
  - b-tagging is optional
- Missing transverse energy: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

Trigger

- Trigger system is a very simple concept: two levels
  - L1 is hardwired to a flexible/programmable High Level Trigger
- Challenge is to keep "reasonable" rate cross section with varying pile-up conditions, without "loosing" physics
- Full use of the flexible HLT system
- Some of the offline features (PF and PU corrections) are implemented online



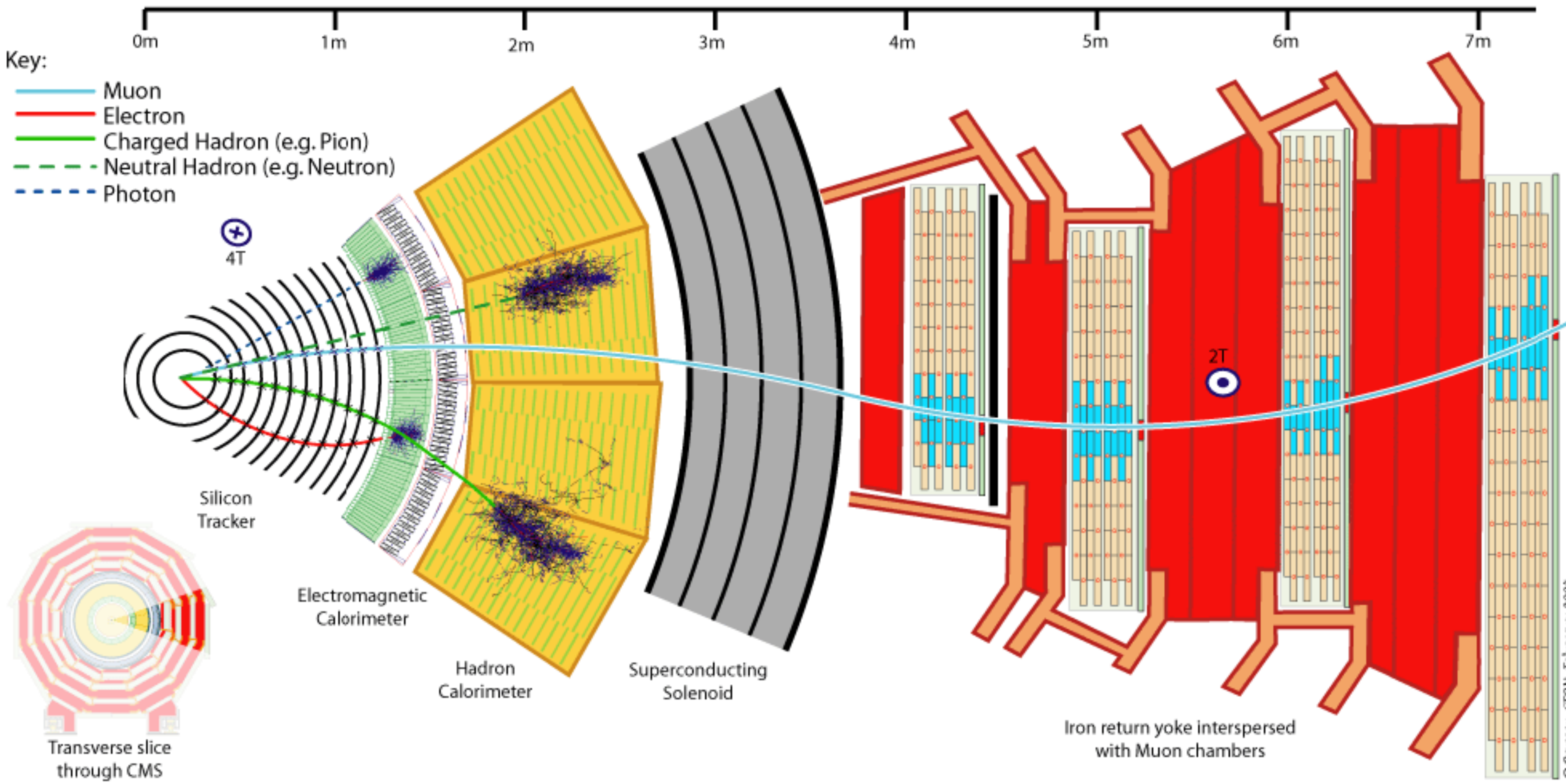
Particle detection



Need efficient:

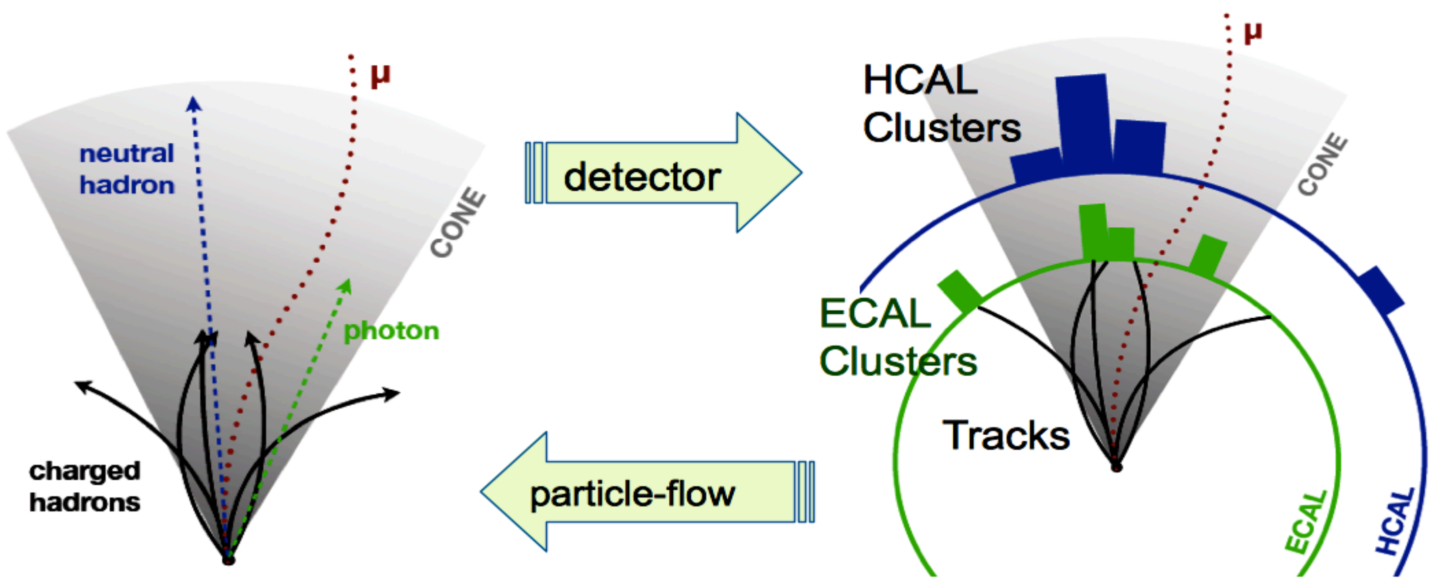
- Electron, muon, tau reconstruction
- jet reconstruction
- b-tagging capability

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

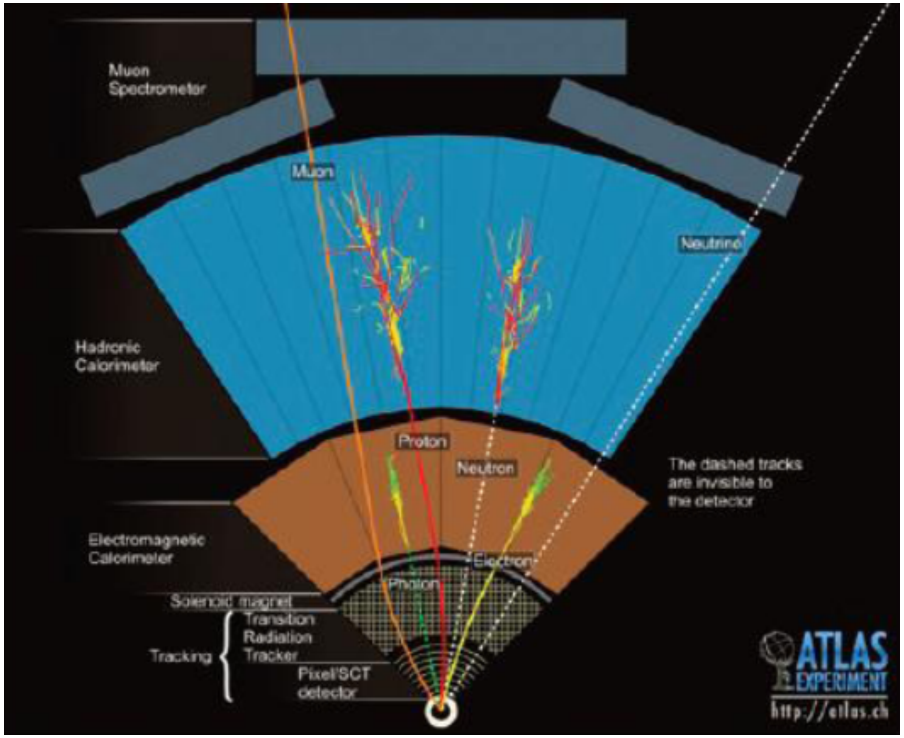

0m
1m
2m
3m
4m
5m
6m
7m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
Transverse slice through CMS
D.Barney, CERN, February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

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.



Electron and photon reconstruction



Photon:

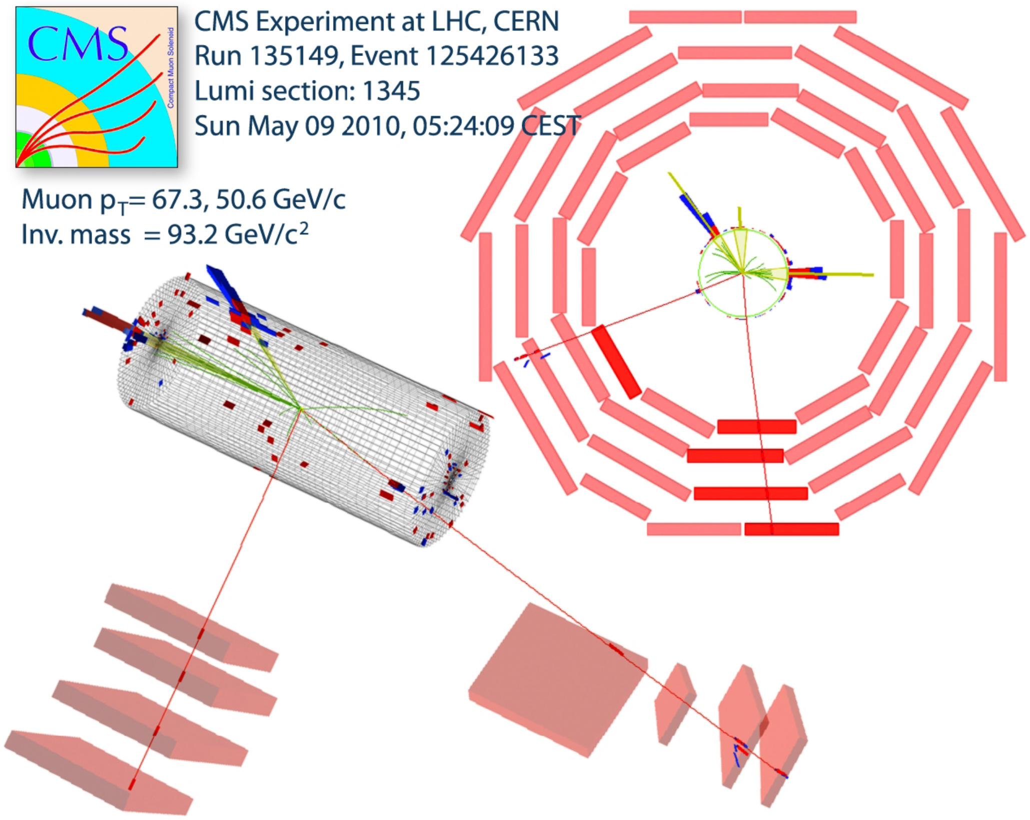
- No track in inner detector
- Electromagnetic shower in EM calorimeter
- No signal in Hadronic calorimeter

Electron:

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

Muon reconstruction

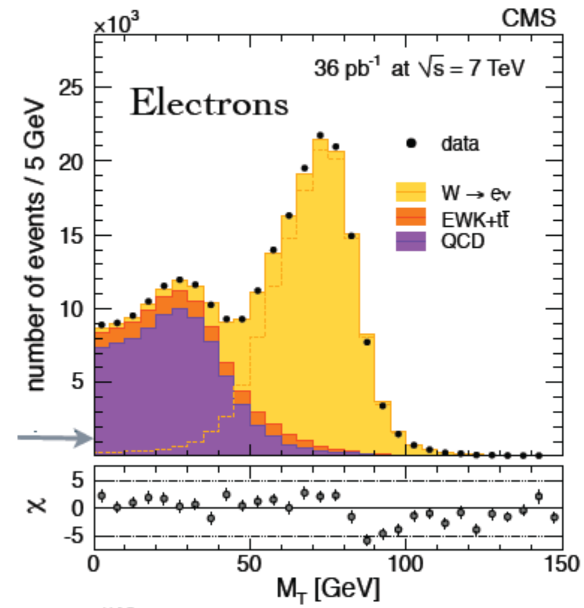
- Minimum ionizing track in all detectors (about 3 GeV loss in the calorimeter)
- At high momentum (few hundred GeV), bremsstrahlung in the calorimeter can be significant
- Momentum measurement in inner detector, muon system

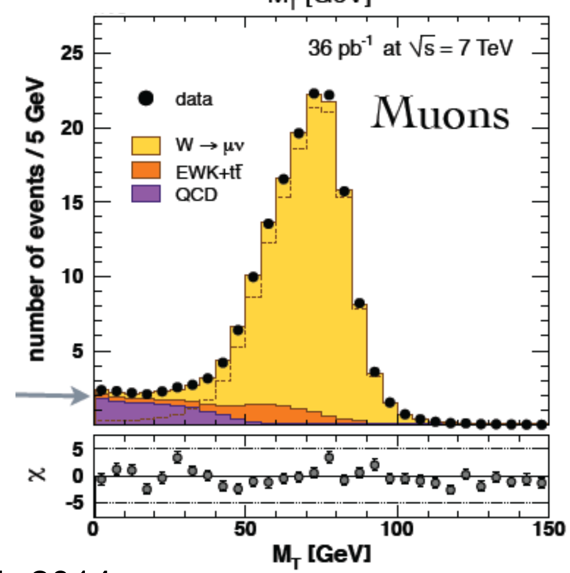


A di-muon event at CMS

Electrons and muons

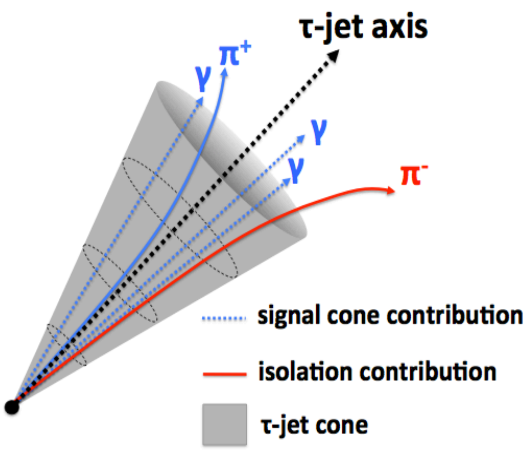
- W/Z cross section measurement with 36/pb demonstrated that leptons and their “fake” rates can be modeled well
- Muons have fewer “fakes” than electrons
- Can construct analysis to minimize this impact: trade-off between efficiency and fake rate
- Impact on Top: ⇒efficiency, QCD estimate & modeling

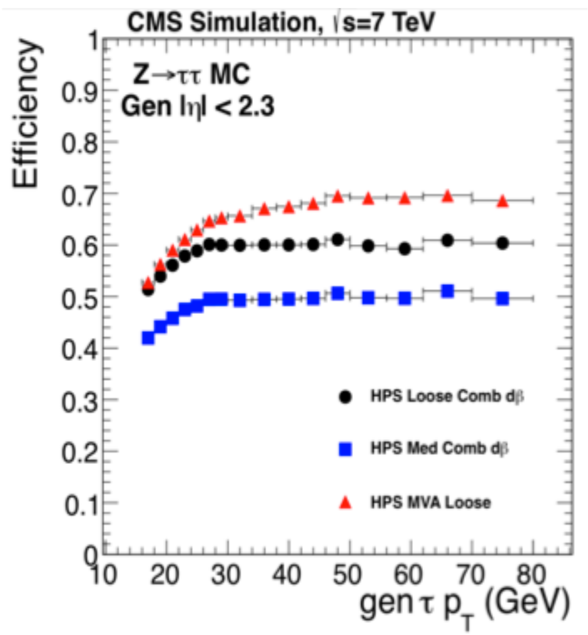




Tau jet identification

- Taus decay 65% to hadrons (i.e. jets) and 35% to leptons
  - Hadronic tau decays are reconstructed with PFlow
  - narrow jet with few tracks
  - Leptonic tau decays are similar to prompt leptons (lepton p_T is softer, 3-body decay)
- Hadronic tau decays
  - Main background from jets/electrons
  - Identified based on decay modes, charged hadrons, and ECAL deposits
- ``Hadron Plus Strips'' (HPS) algorithm
  - Uses photon conversion in tracker ($\gamma \to e^+e^-$)
  - Combines PF EM particles (γ,$e^\pm$) in "strips"
  - "strips" are combined with PF charged hadrons
  - Individual decay modes are reconstructed
- Fake Rate ~3% for 70% efficiency

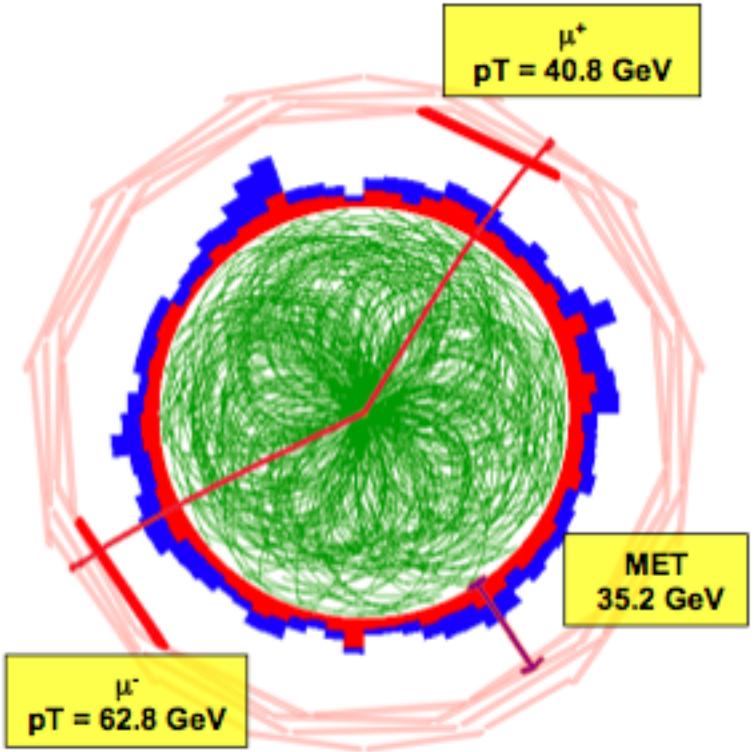


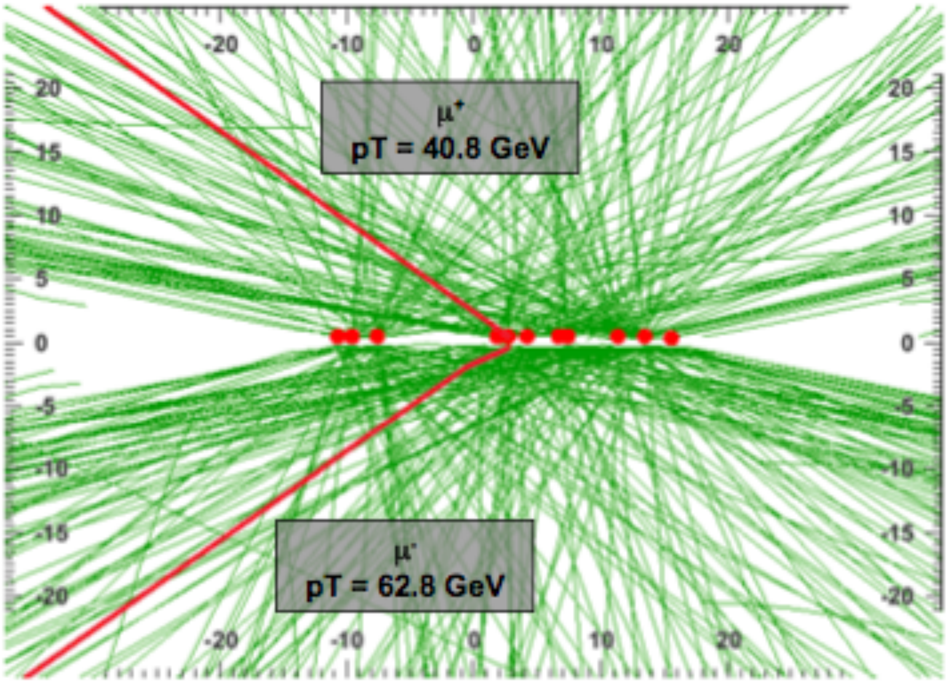


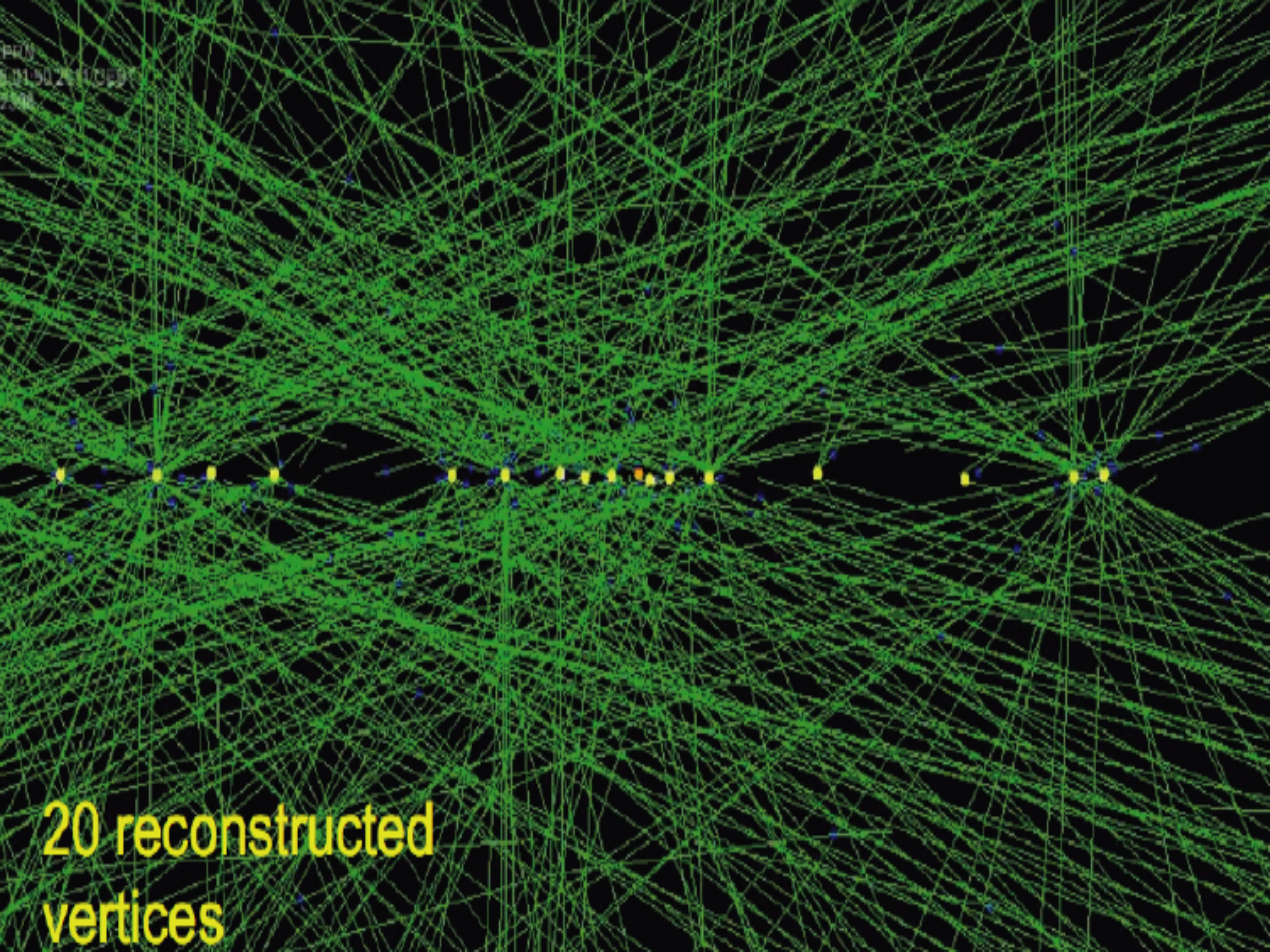
Challenge: Pile-up

Z → μ μ
Expected MET = 0

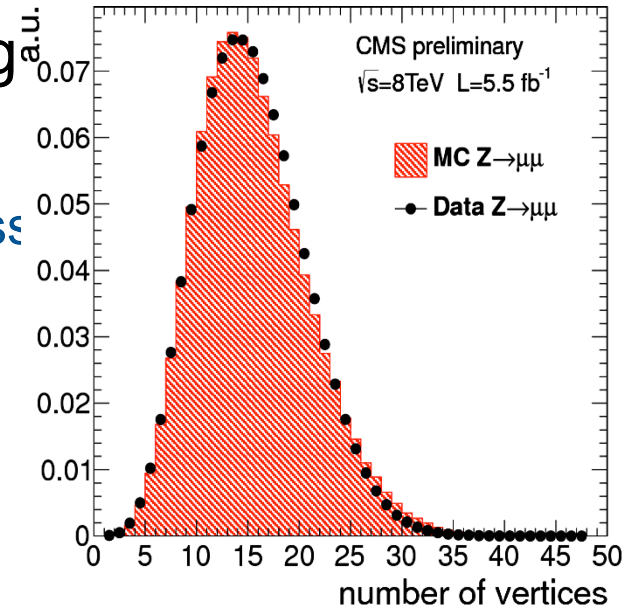
10 in-time + 10 out – of – time pileup



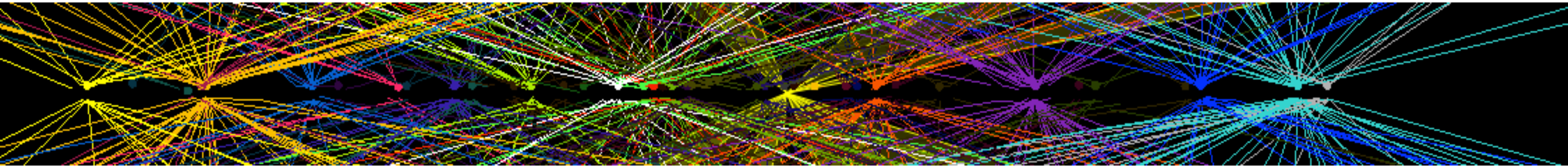



20 reconstructed
vertices

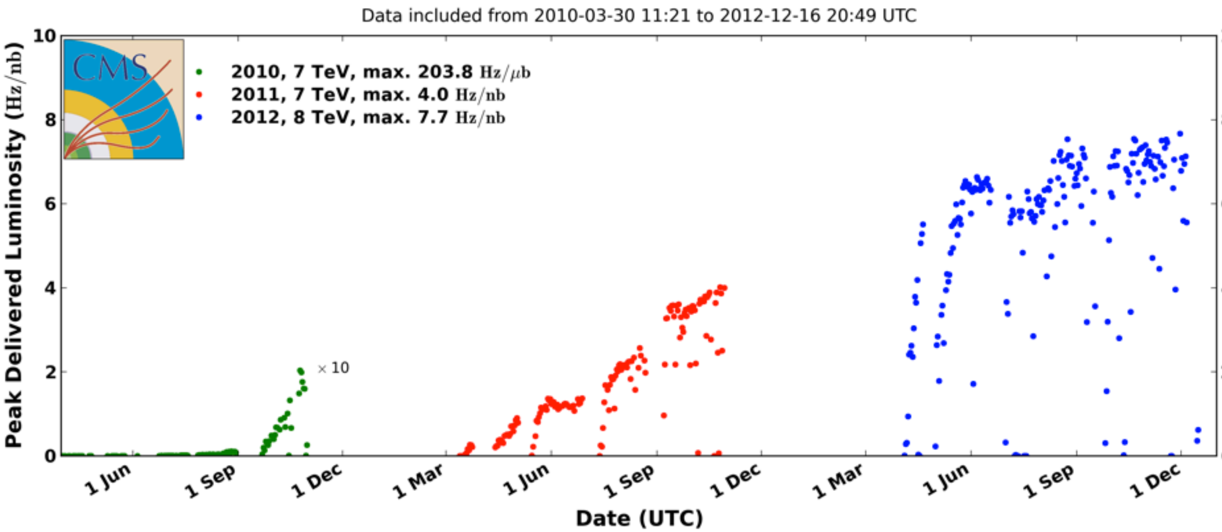
Pile-up



- About ~30 pp collisions per bunch crossing
- High multiplicity
  - ~1-2 thousand low energy charged particles/cross
  - ~1-2 thousand low energy photons/crossing
- Challenge to reconstruct hard collisions
  - Jets and MET reconstruction
  - Lepton isolation
- Assignment of particles to primary vertex
  - Particle flow reconstruction
  - Neutral energy: event-by-event energy subtraction



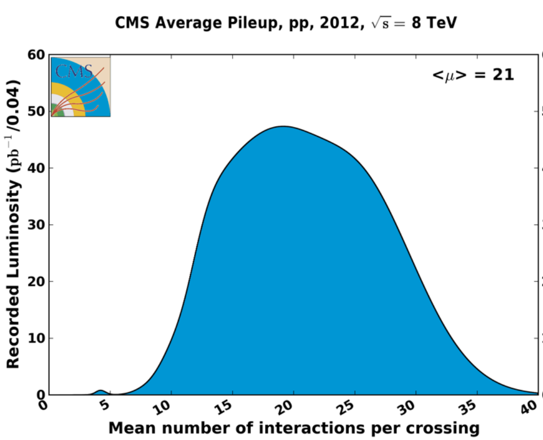
Pile-up in 2012

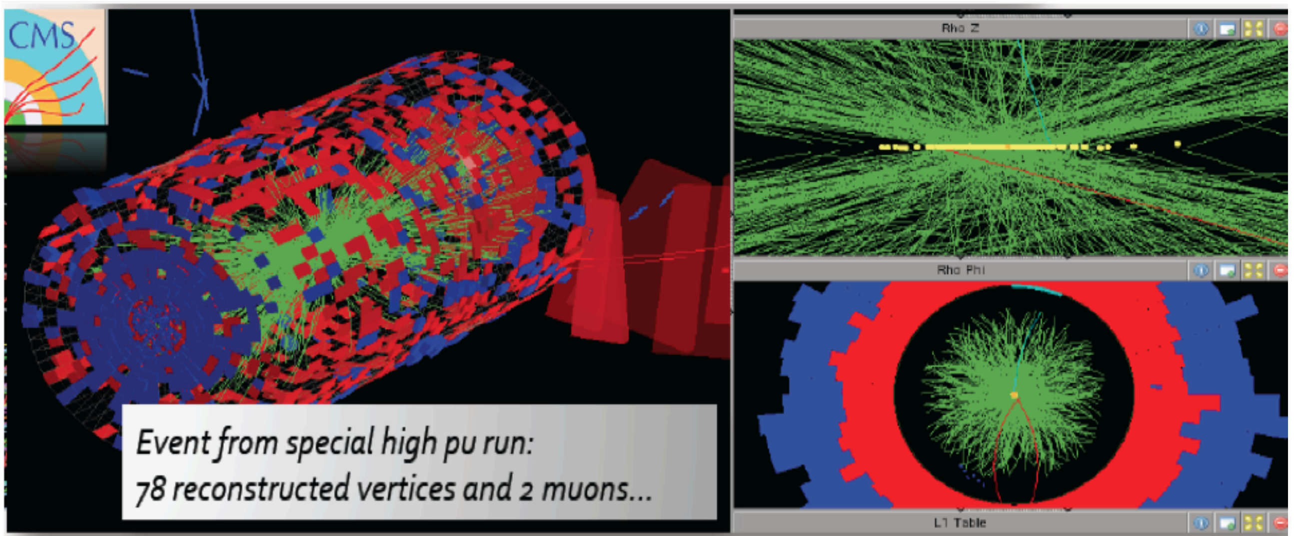


Peak: ~40 pileup events

Design value: 25 pileup evts

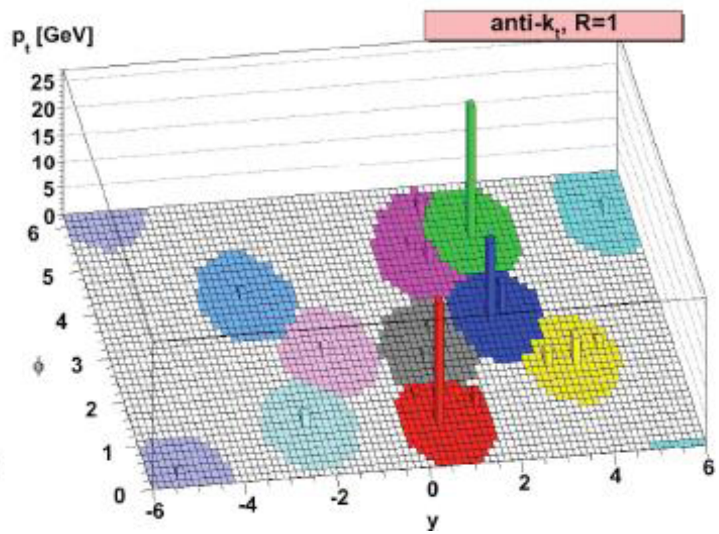
($L=10^{34} cm^{-2} sec^{-1}$, 25 nsec)





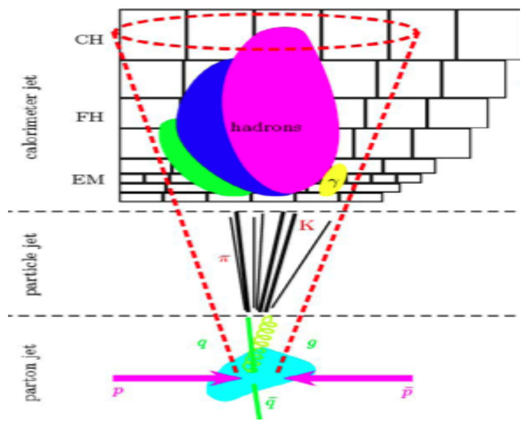
Jet reconstruction

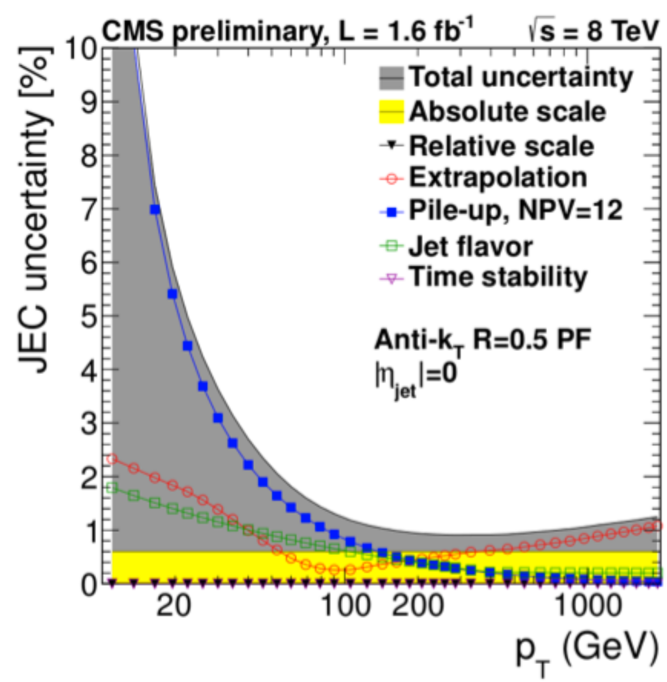
- A "jet" is a cluster of energy deposited in a "small" $\eta-\phi$ region of the detector
  - It is not a unique object, it is defined by the jet algorithm (different choices yield different jets)
- The jet algorithm uses detector reconstructed objects (clusters, tracks, combined objects)
- It is "safe" 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
- Contribution of uncertainty sources depend on p_T, η
- Use calorimeter information to correct jet energy to particle level
- Jet energy corrections:
  - 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 $W \to jj$ constraint to measured W mass
  - Can be used in lepton+jets (and all-hadronic) channel





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

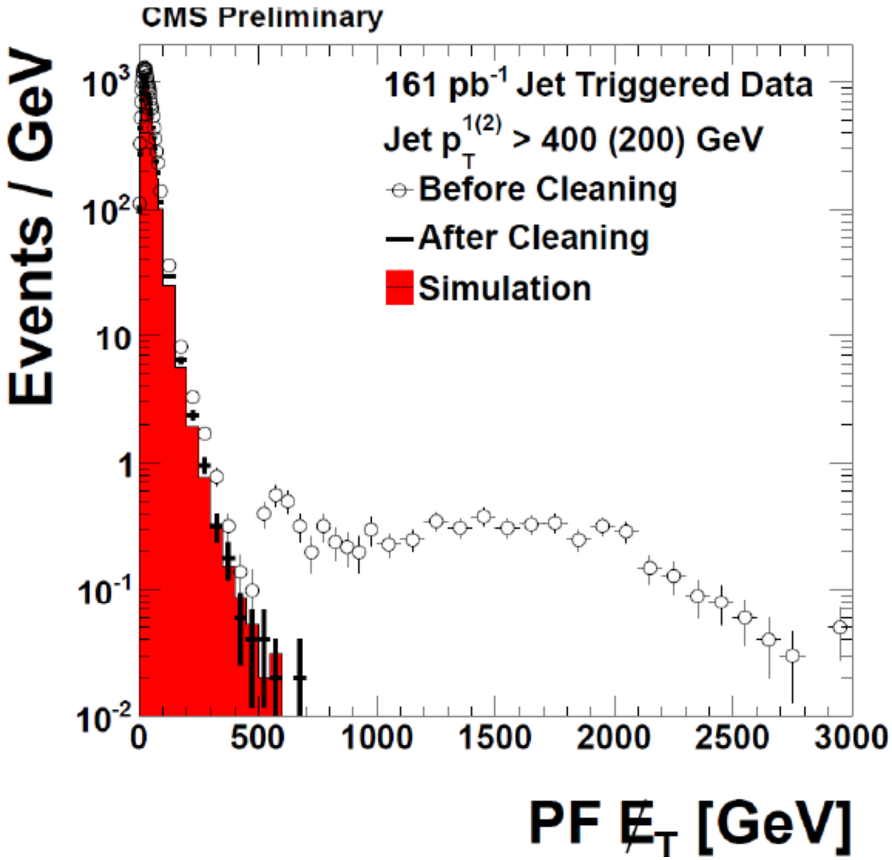
transverse energy vector

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

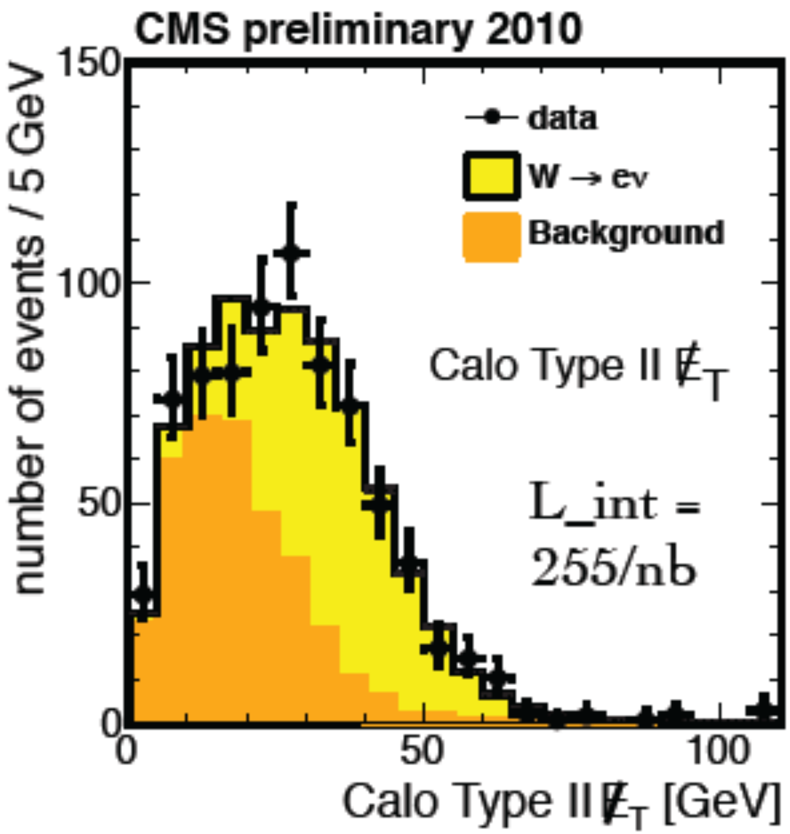
where the sum runs over the transverse momenta of all visible final state particles.

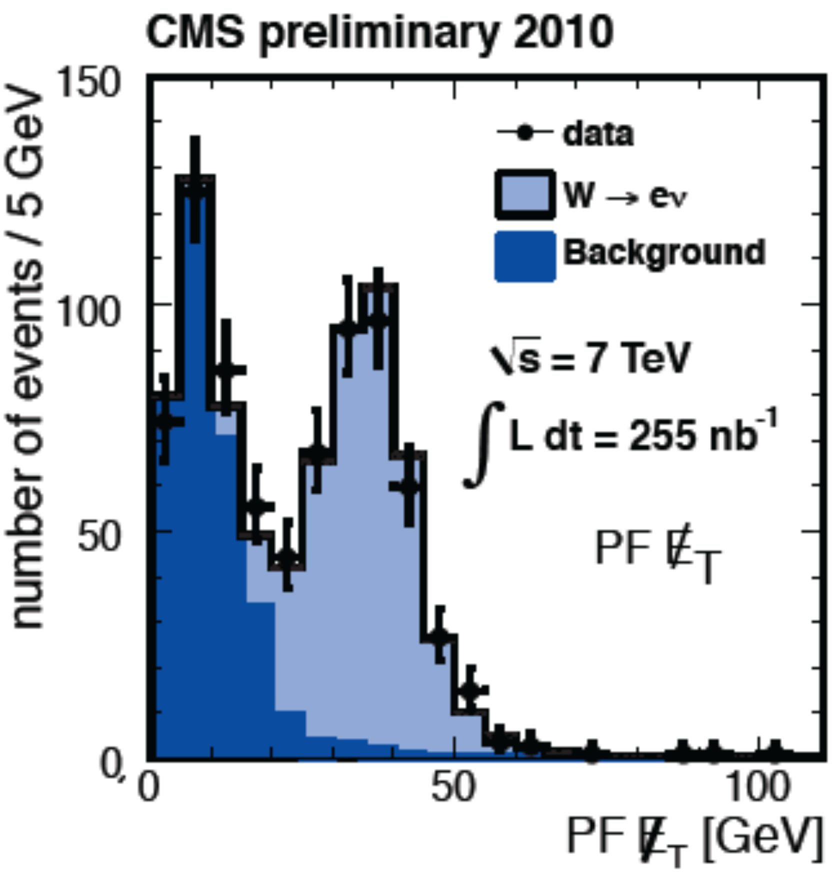
Challenge: MET

- 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



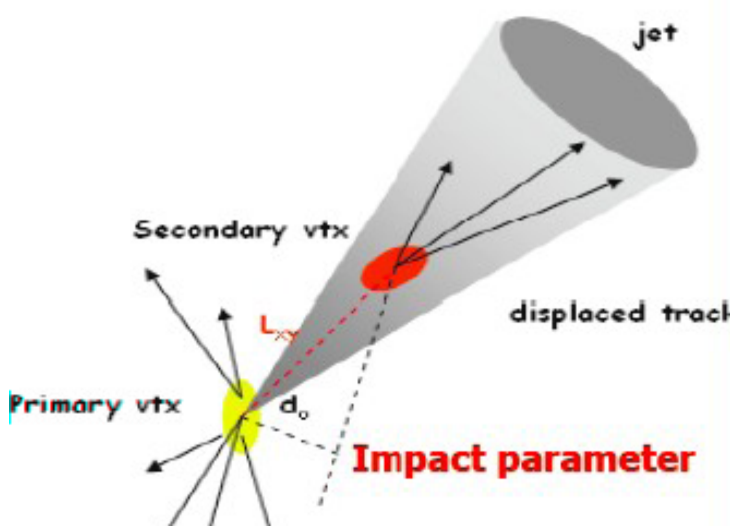
MET reco: PF vs Calo





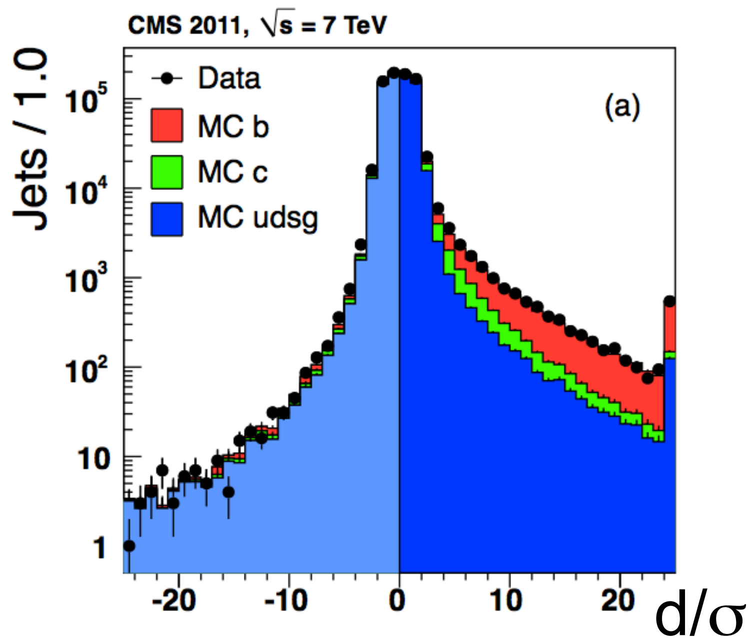
- Study of MET in W→eν events from early 2010
- Particle Flow improves MET resolution, making W's easier to distinguish from background

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

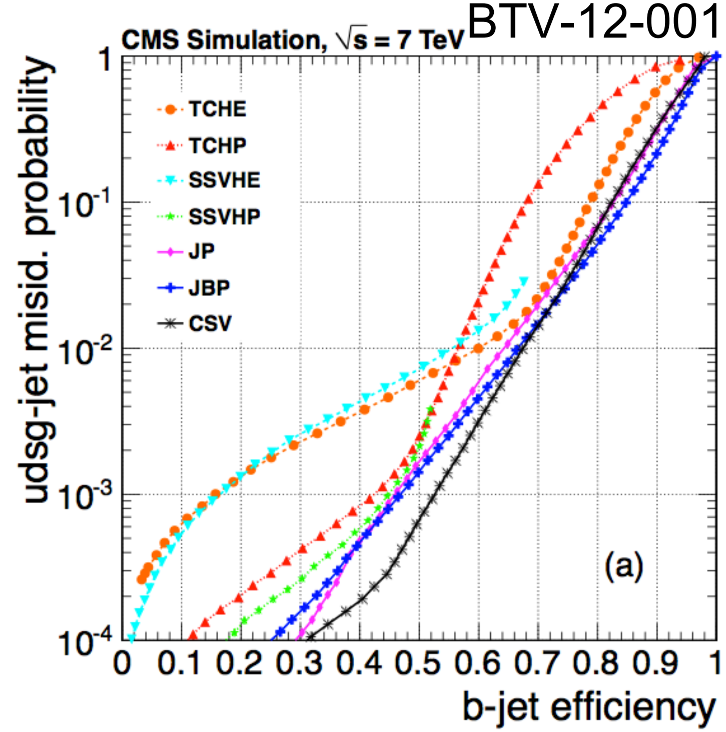
$$(b \rightarrow l \, \nu_l \, X)$$

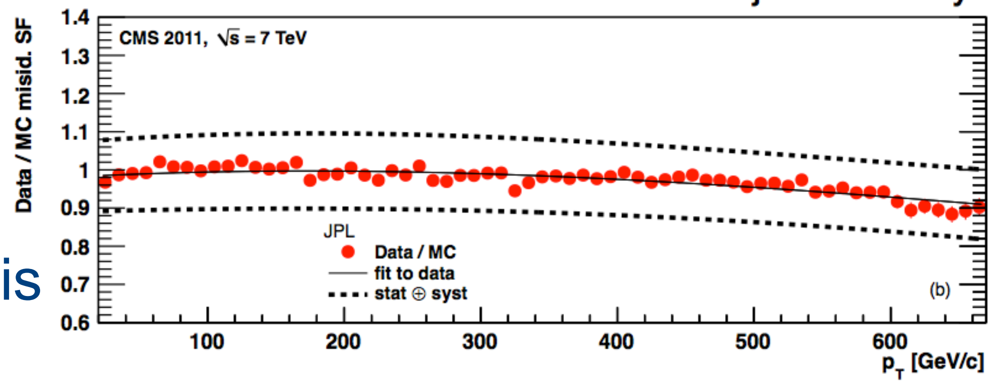


b-tag: fake rates and efficiencies

- 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





Measurements

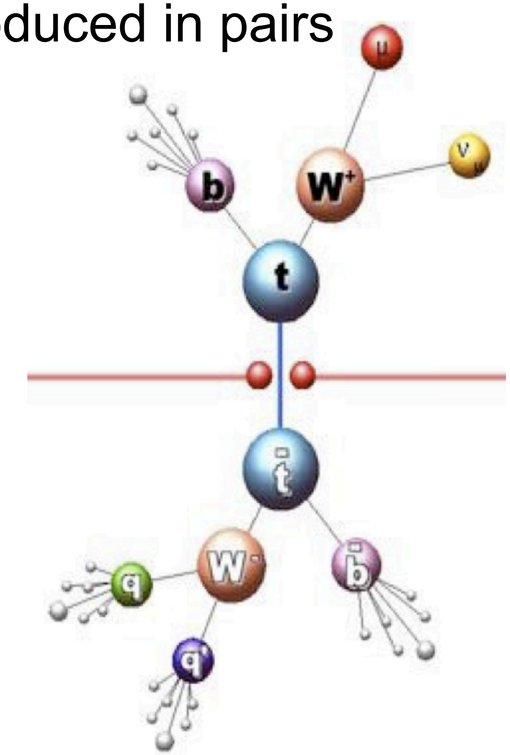
- Measurement of the cross section

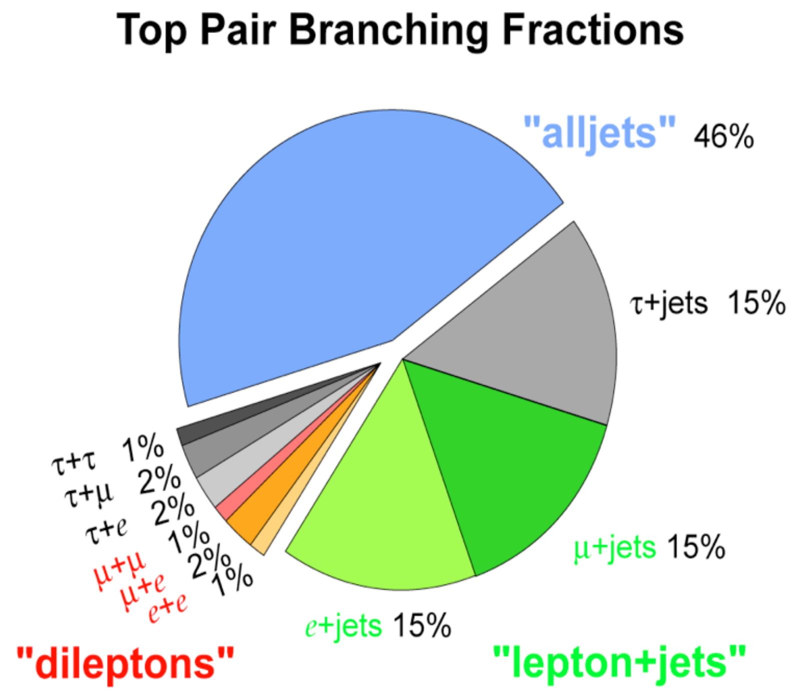
Interesting physics with top quarks

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

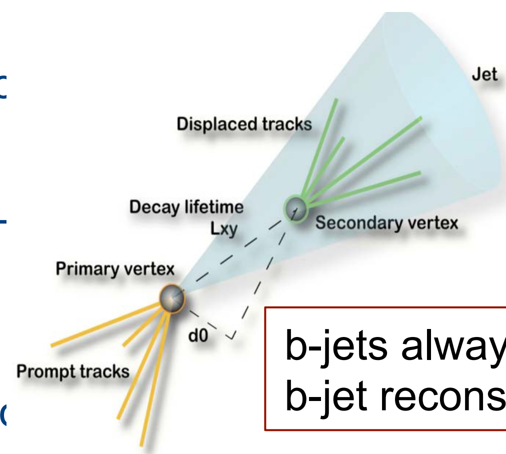
Top quark decays

Top quarks (mostly) produced in pairs





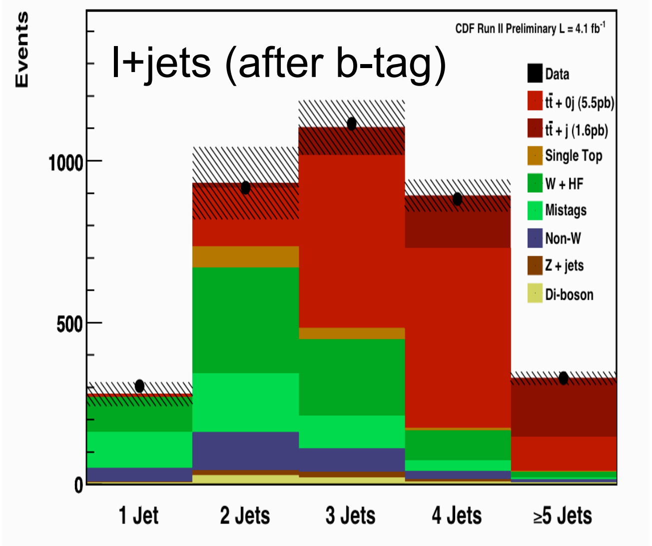
- Dilepton (ee, μμ, eμ):
  - BR~5%, 2 leptons+2 b-jets+2 neutrinc
- Lepton (e or μ) + jets
  - BR~30%, one lepton+4jets (2 from b)+ neutrino
- All hadronic
  - BR~44%, 6 jets (2 from b), no neutrinc

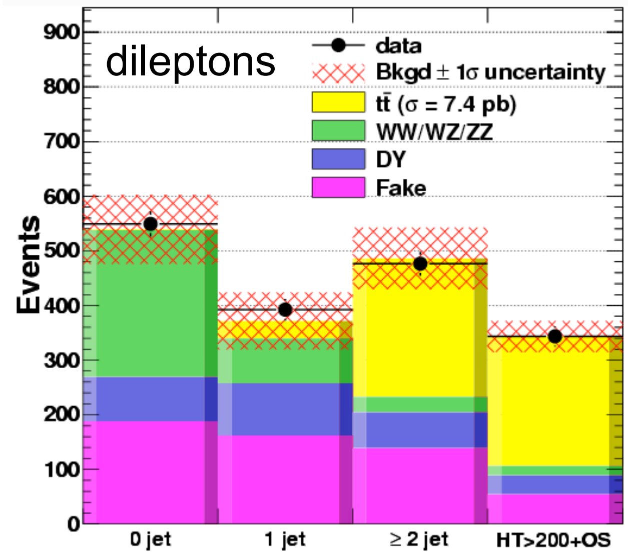


b-jets always present
b-jet reconstruction plays important role

Top quark events

- 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





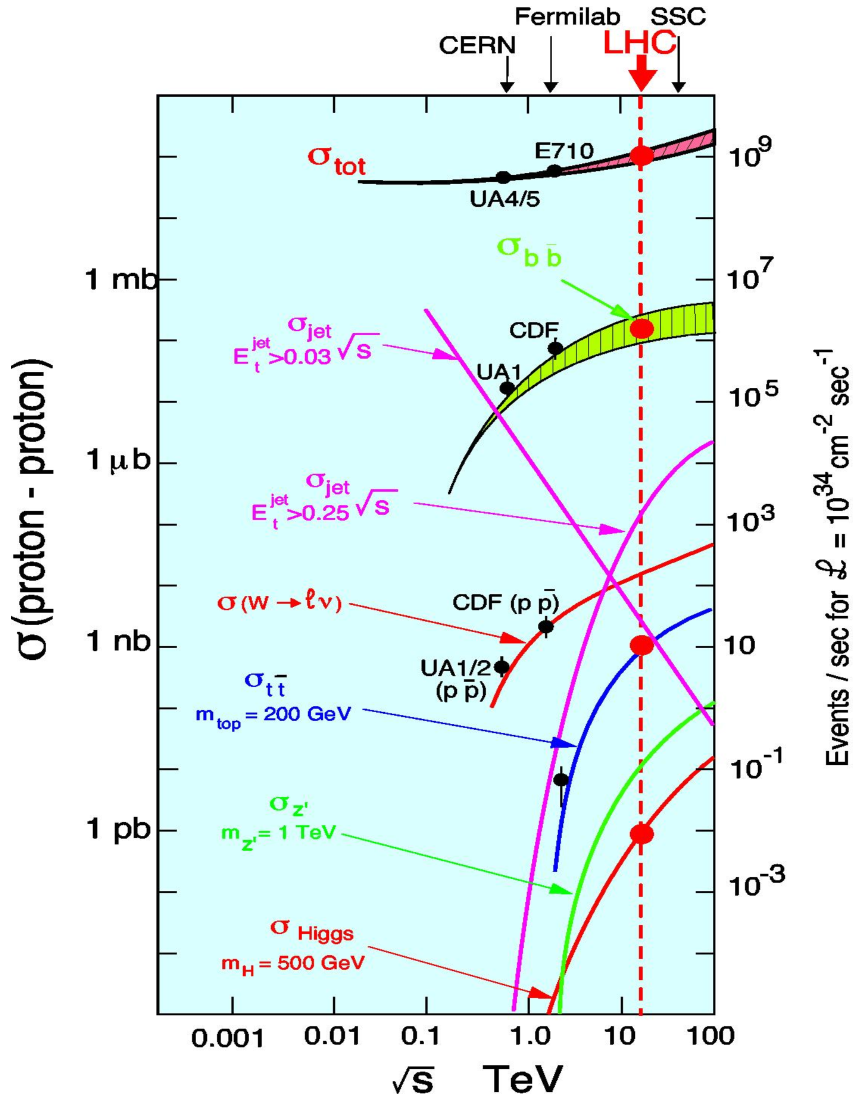
Theory cross sections: TeV vs LHC

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

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

Top cross section at 7/8 vs 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 σ(14TeV)=950 pb
  - Top σ(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
  - σ(ttbar) increases by 100
  - σ(W) increases by 10

…however…

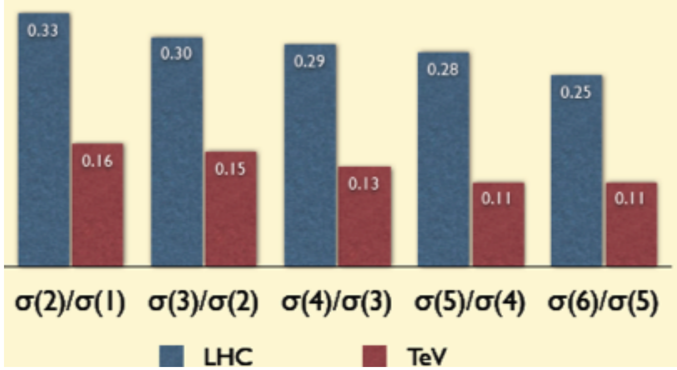
- σ(W+4 jets) increases 100 times

⇨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 , ΔR>0.7



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

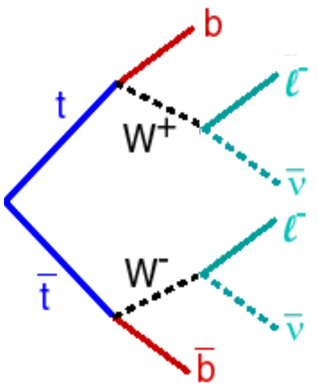
29

Cross section measurement

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

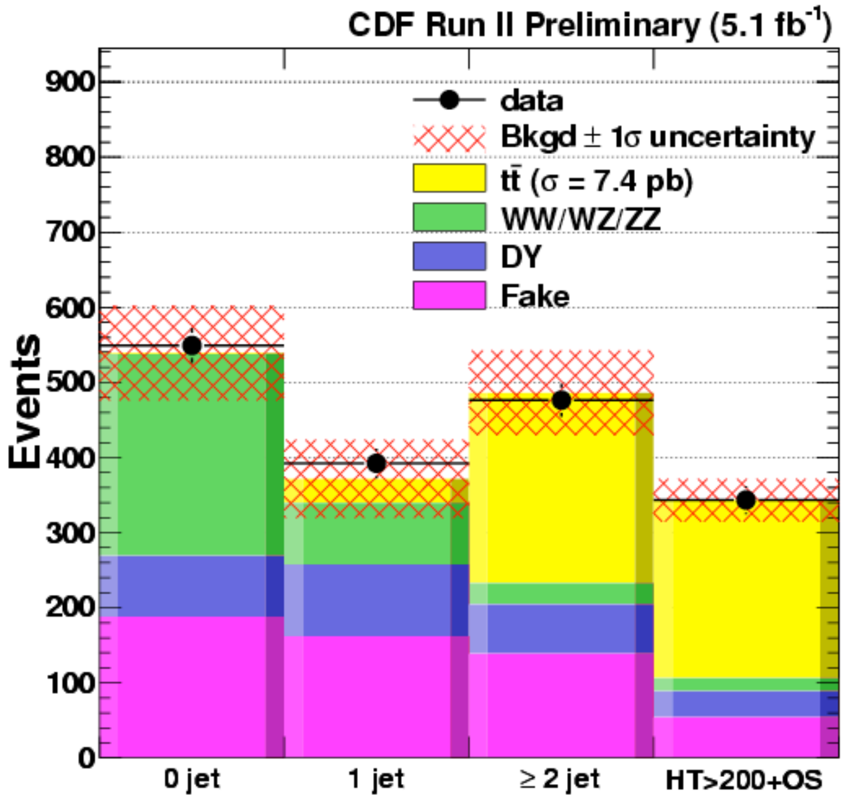
- ✓ testing non-SM top production mechanisms
- ✓ top sample may contain an admixture of exotic processes

Dilepton channel



Branching Ratio (BR) ~5%
background: small

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



Dilepton channel

- 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)

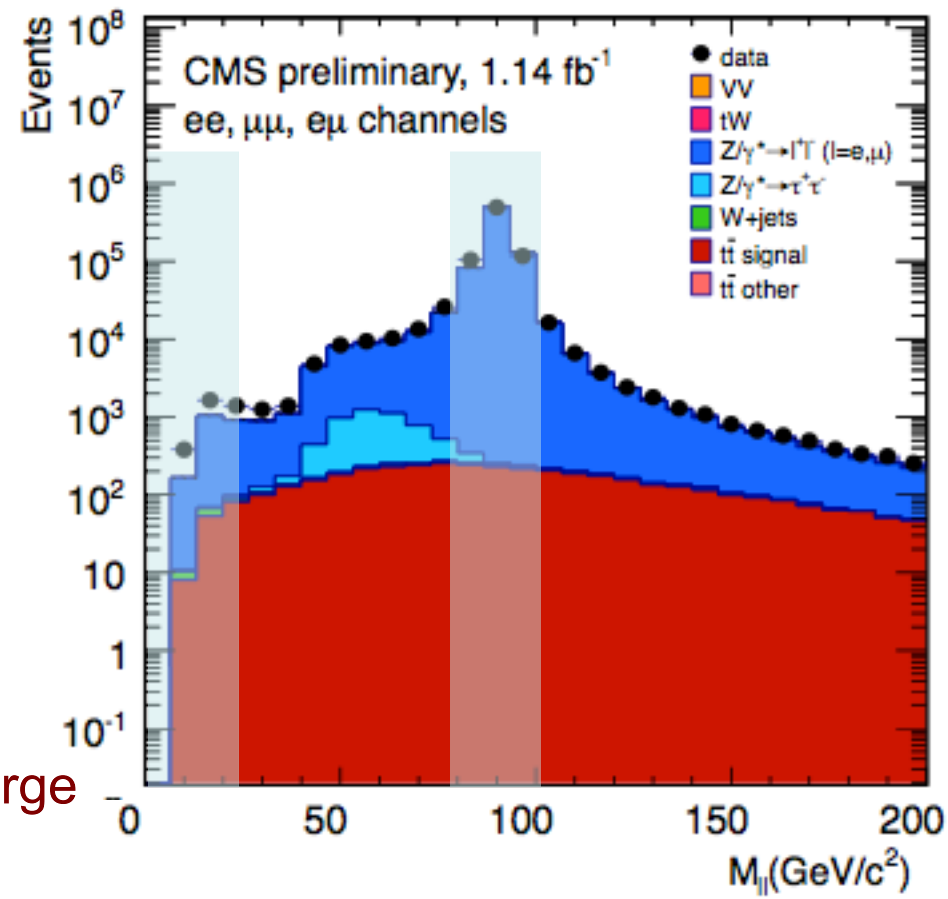
CMS: dilepton trigger

- 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

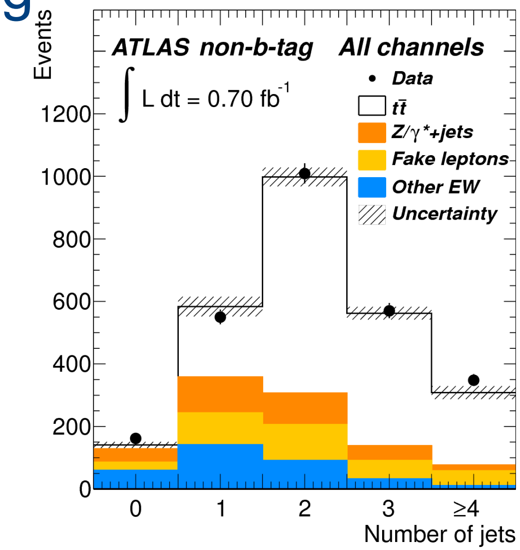
TOP-11-005



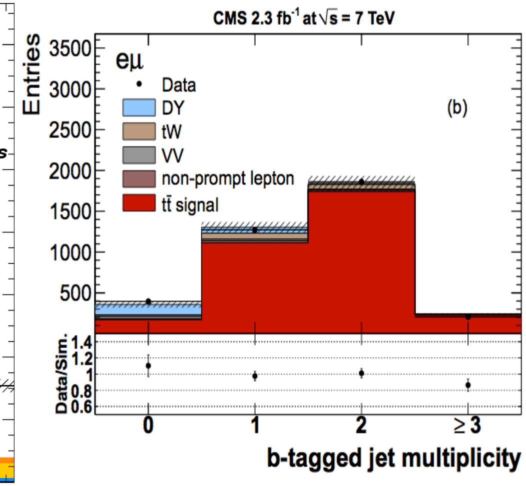
Dilepton channel

- 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



JHEP11(2012)067



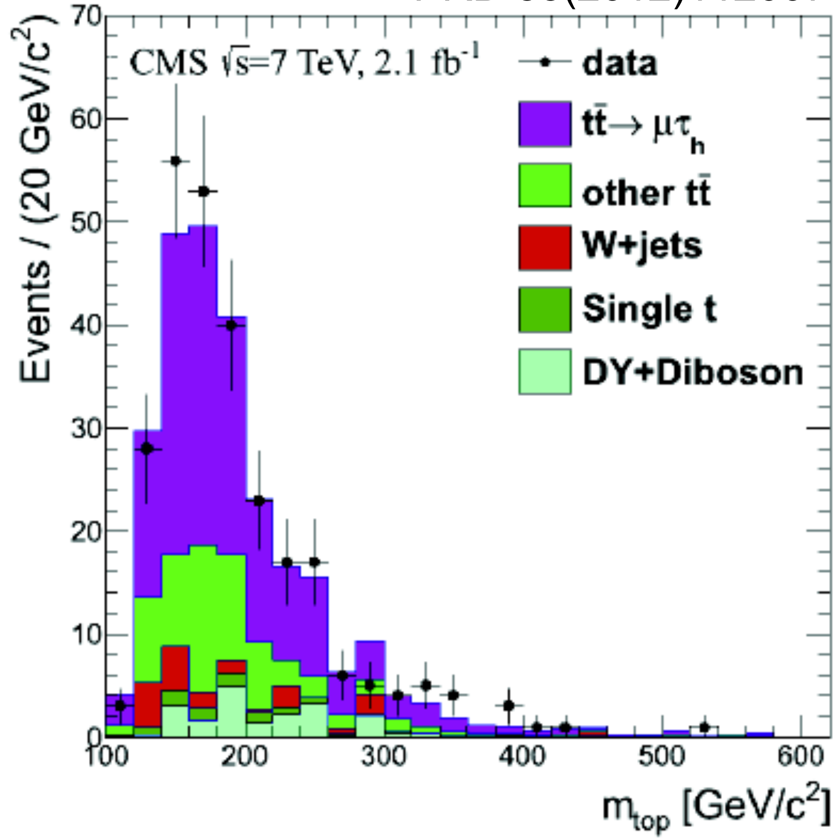
$$\sigma_{t\bar{t}} = 176 \pm 5(\text{stat.})^{+14}_{-11}(\text{syst.}) \pm 8(\text{lum.})\ \text{pb}$$ ATLAS

$$\sigma_{t\bar{t}} = 161.3 \pm 2.5\,(\text{stat.})\,^{+5.3}_{-5.2}\,(\text{syst.}) \pm 3.6\,(\text{lumi.})\,\text{pb},$$ CMS

Tau dilepton channel

PRD 85(2012)112007

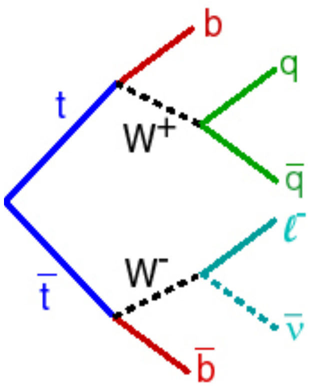
- Selection:
  - one isolated lepton (e/μ)
  - OS tau
  - at least two jets (one b-tagged)
  - MET>30 (45) GeV
- Determine τ fakes from data
  - Expected to be dominated by light flavor jet contribution
  - In W+jets gluon contribution canceled by OS-SS
  - Conservative approach: average W+jets and QCD

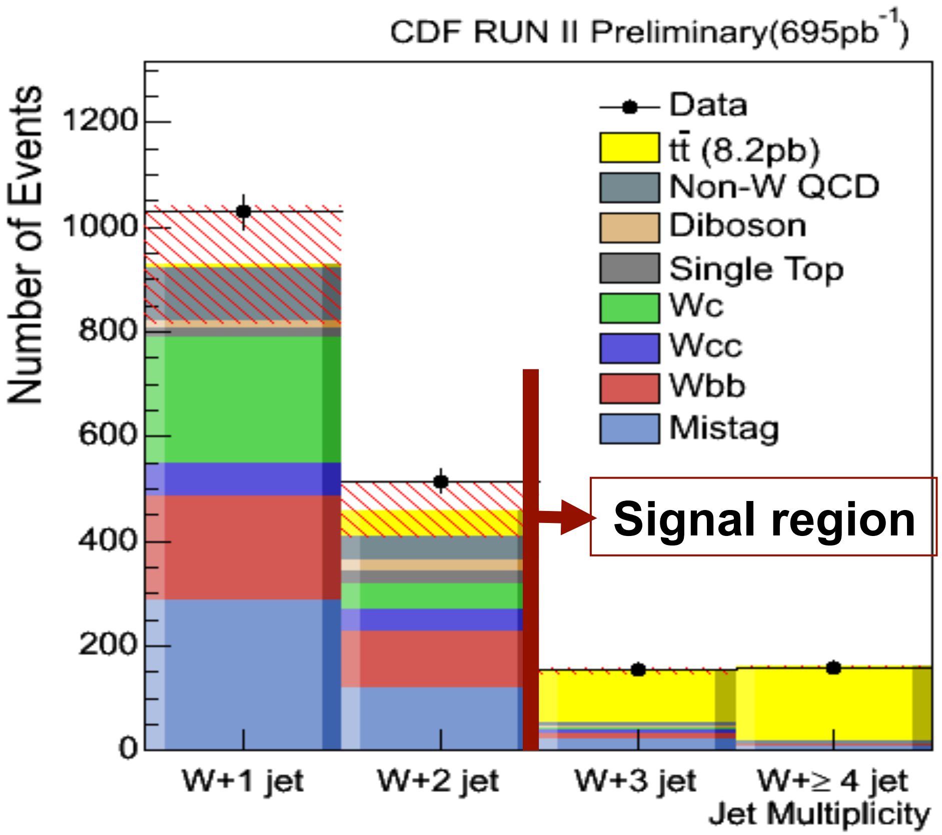


$$\sigma_{t\bar{t}} = 186 \pm 13\ \textbf{(stat.)} \pm 20\ \textbf{(syst.)} \pm 7\text{(lumi.) pb,}$$ ATLAS

$$\sigma_{t\bar{t}} = 143 \pm 14\text{(stat.)} \pm 22\text{(syst.)} \pm 3\text{(lumi.) pb}$$ CMS

Lepton + jets





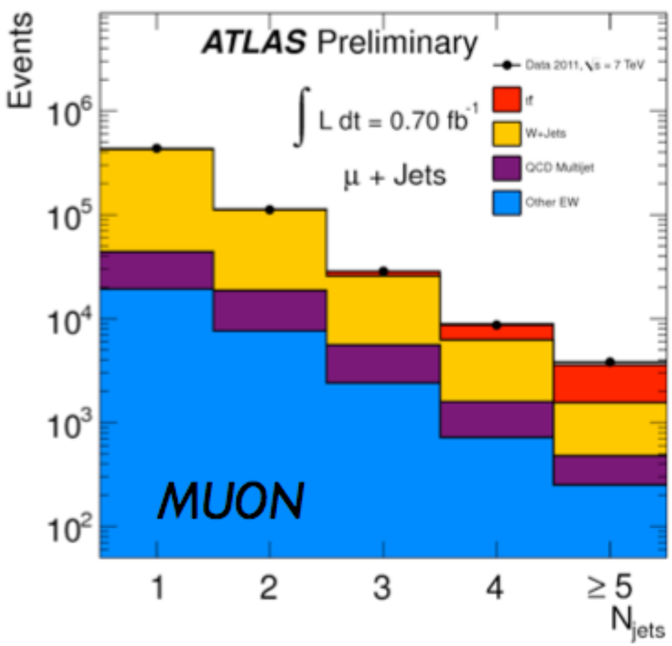
BR ~30%
background: moderate

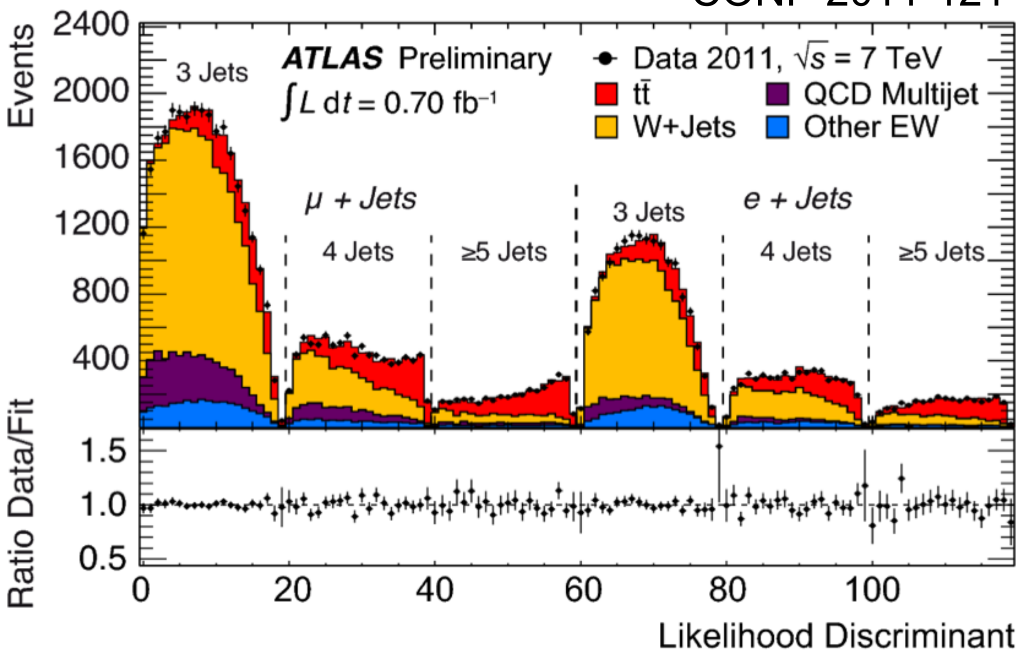
- one lepton + ≥3 jets + $\not{E}_T$
- may require b-tag

Single lepton channel

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

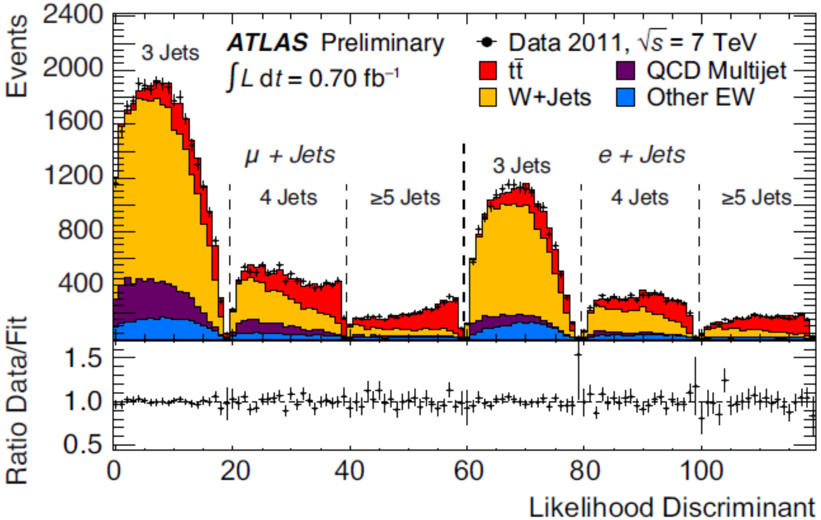
CONF-2011-121

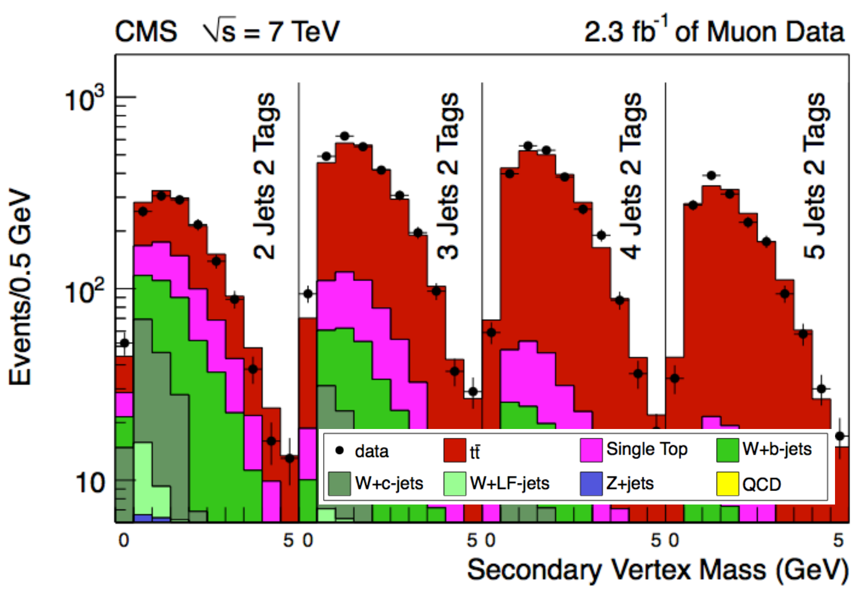




$$\sigma_{t\bar{t}} = 179.0 \pm 3.9\,(\text{stat}) \pm 9.0\,(\text{syst}) \pm 6.6\,(\text{lumi})\ \text{pb}$$

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 σ_{tt} from fit

ATLAS

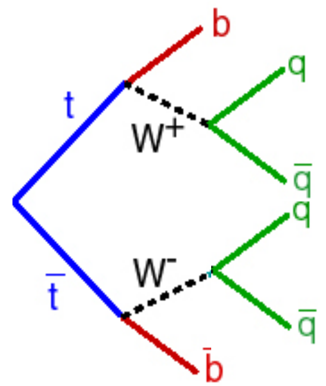
$179.0 \pm 3.9\ (\mathrm{stat}) \pm 9.0\ (\mathrm{syst}) \pm 6.6\ (\mathrm{lumi})\ \mathrm{pb}$

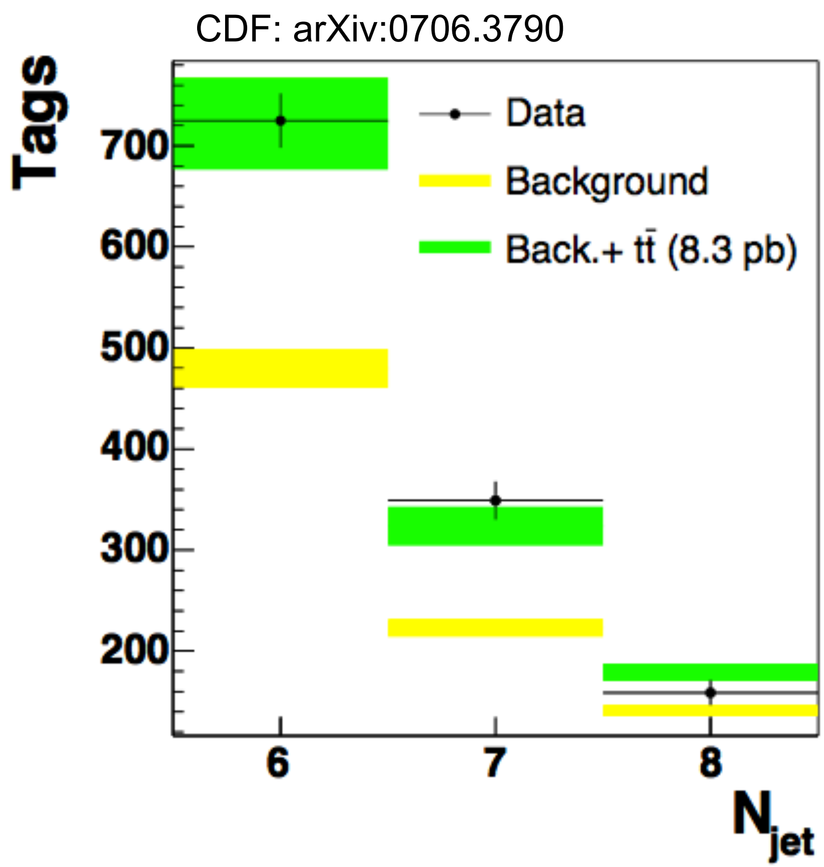
$158.1 \pm 2.1\ (\mathrm{stat.}) \pm 10.2\ (\mathrm{syst.}) \pm 3.5\ (\mathrm{lum.})\ \mathrm{pb.}$

CMS

arXiv:1212.6682

All hadronic





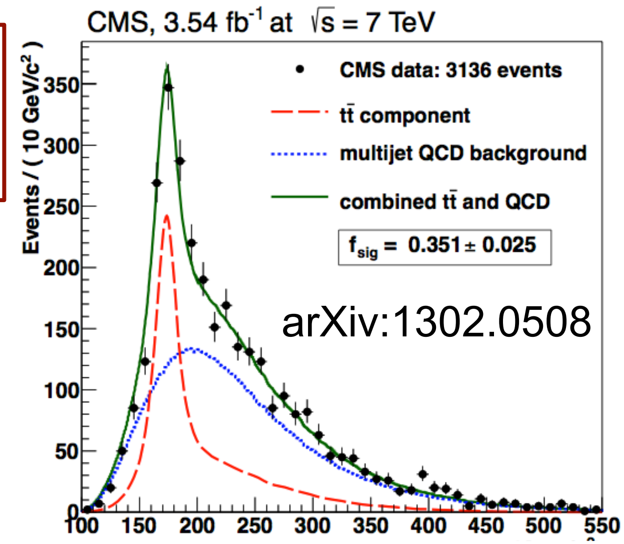
BR ~44%
background: large

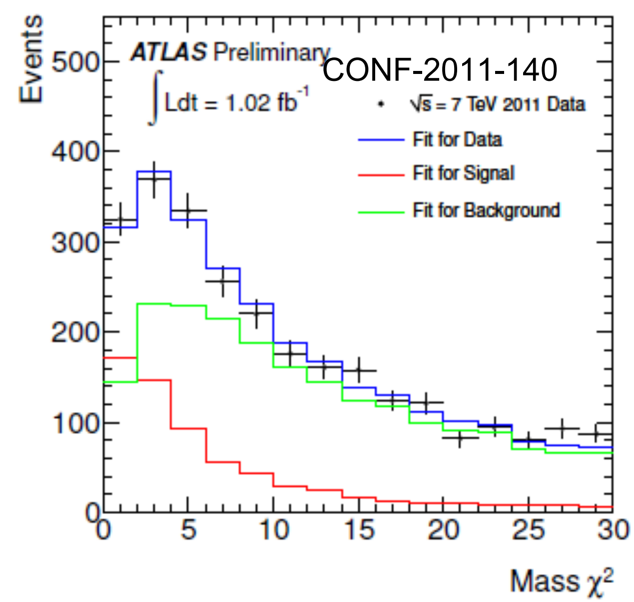
- ≥6 jets + kinematical selection
- optimize S/√B
- require b-tag

All hadronic

Selection	Events	Fraction of $t\bar{t}$
At least 6 jets	786 741	0.02
At least two b-tags	21 783	0.18
Kinematic fit	3 136	0.41

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





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

- Results:

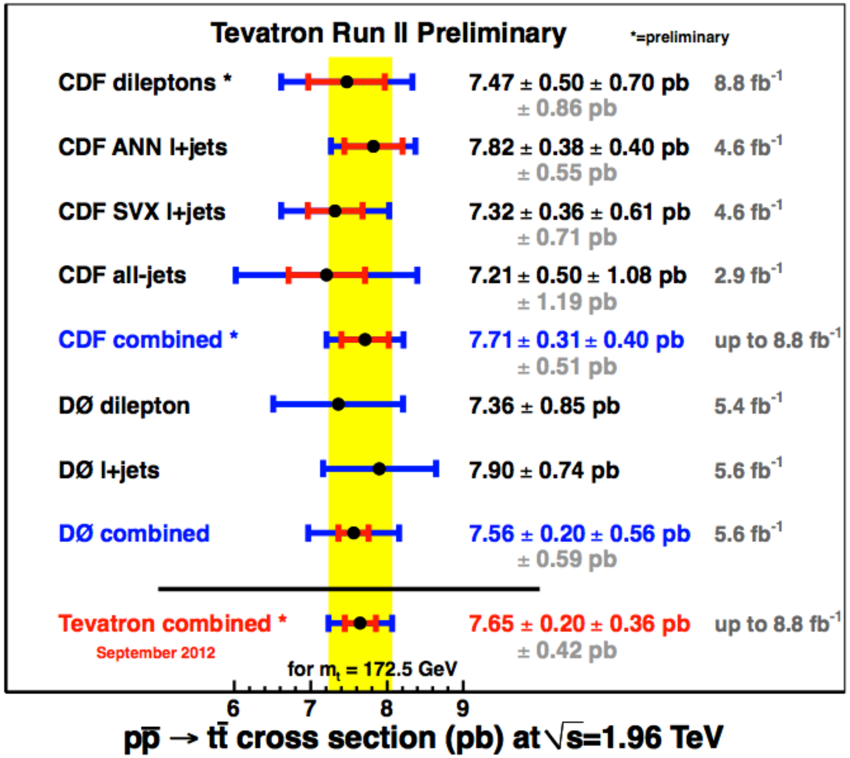
ATLAS

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

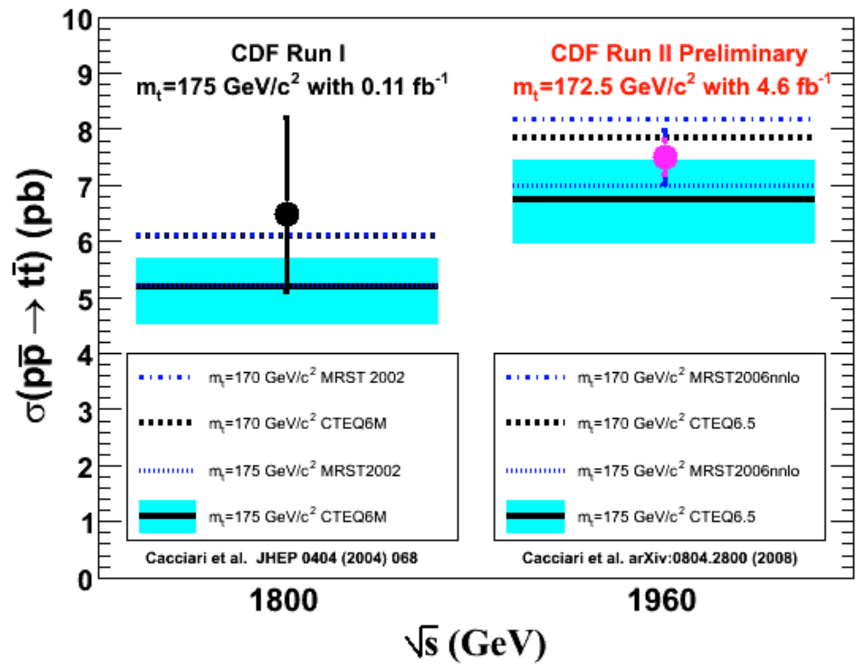
$$139 \pm 10\,(\text{stat.}) \pm 26\,(\text{syst.}) \pm 3\,(\text{lum.})\ \text{pb}$$

CMS

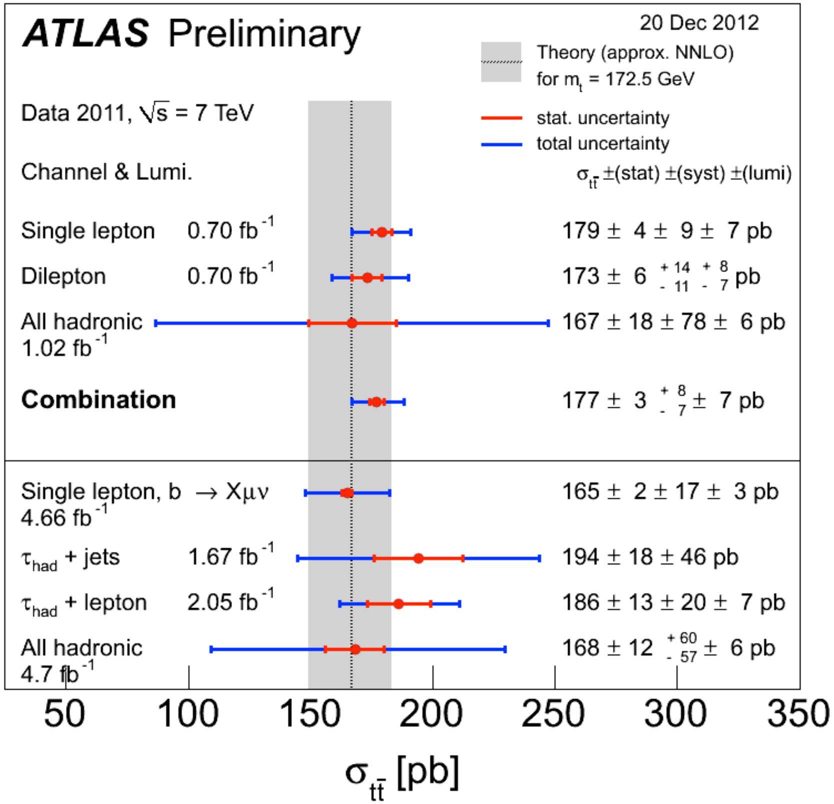
Cross section at the Tevatron

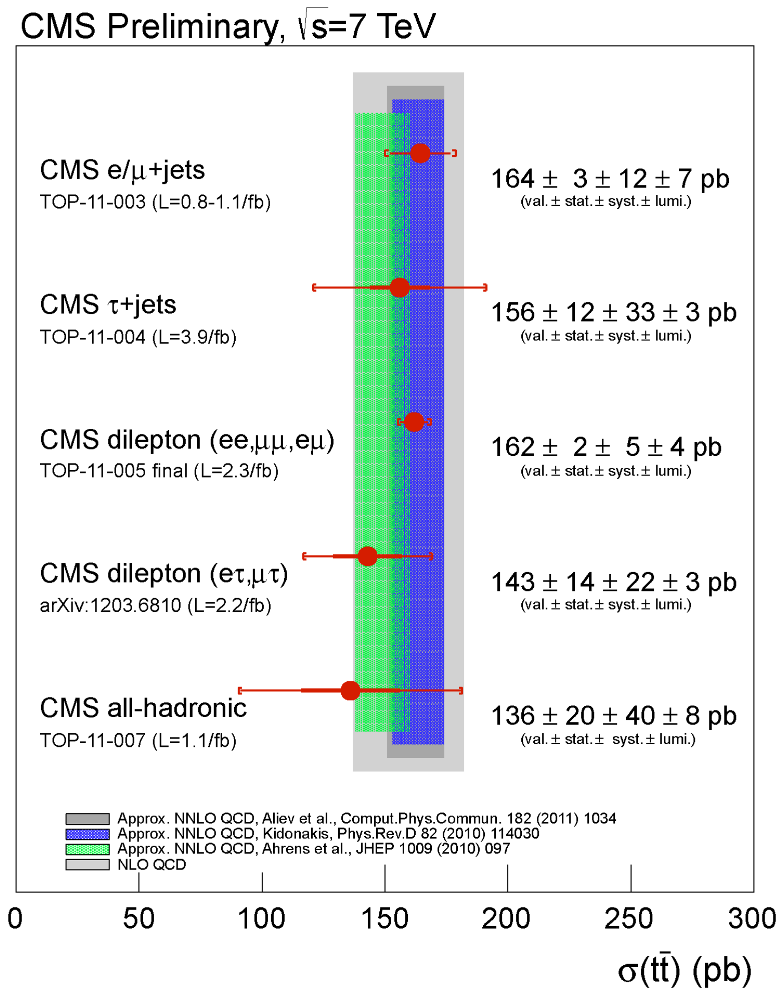


- Good agreement with expectations
- Everything else we know of ttbar agrees with SM



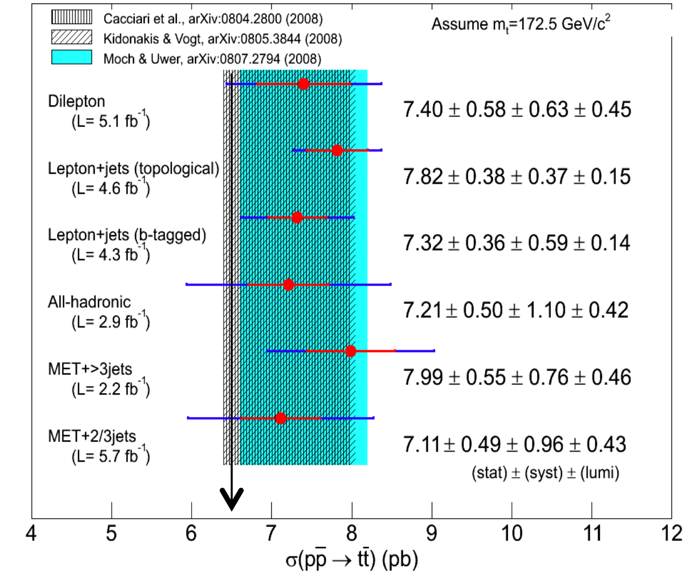
Top cross sections at 7 TeV

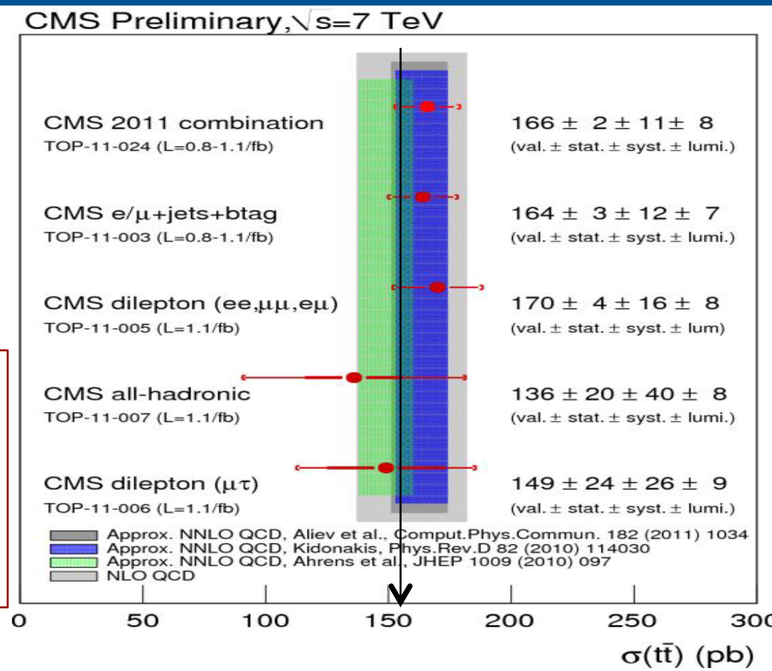




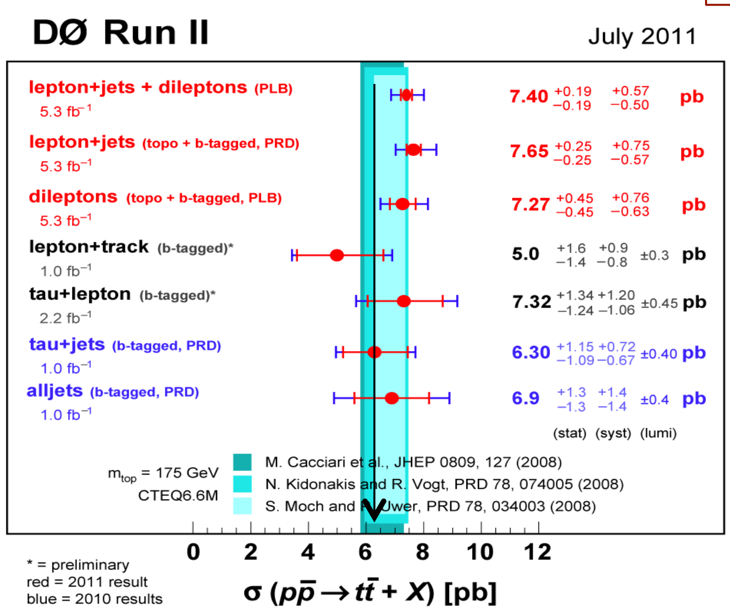
Good agreement between measurements and predictions for all decay modes

Cross section measurements



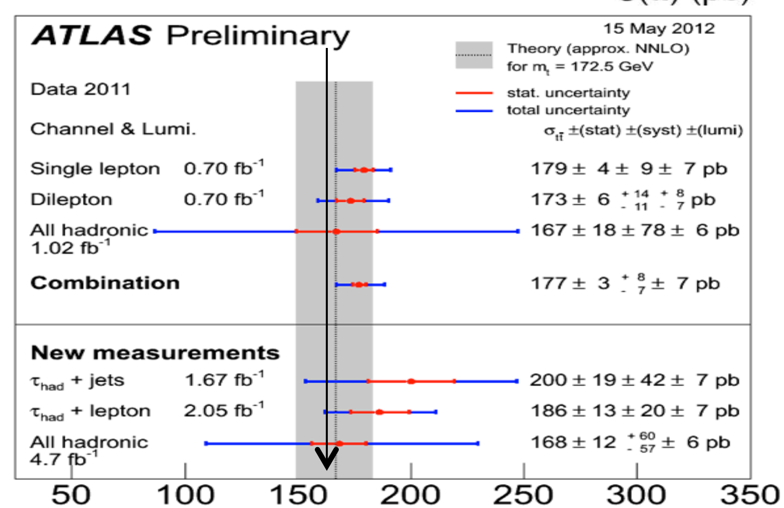


Ahrens et al. (1105.5824) predict lower cross section

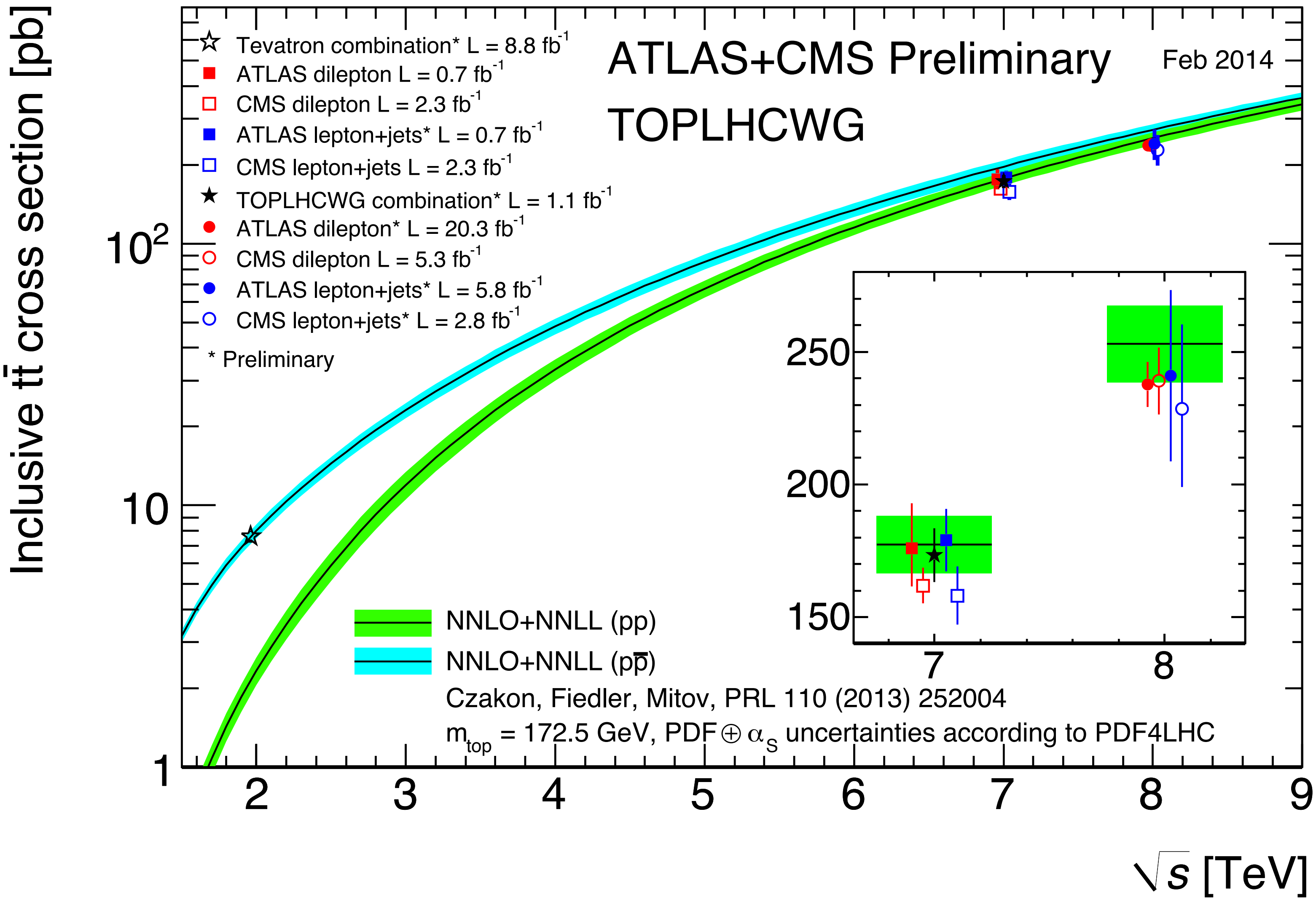


Hint for NP?

⇒not yet



Current status

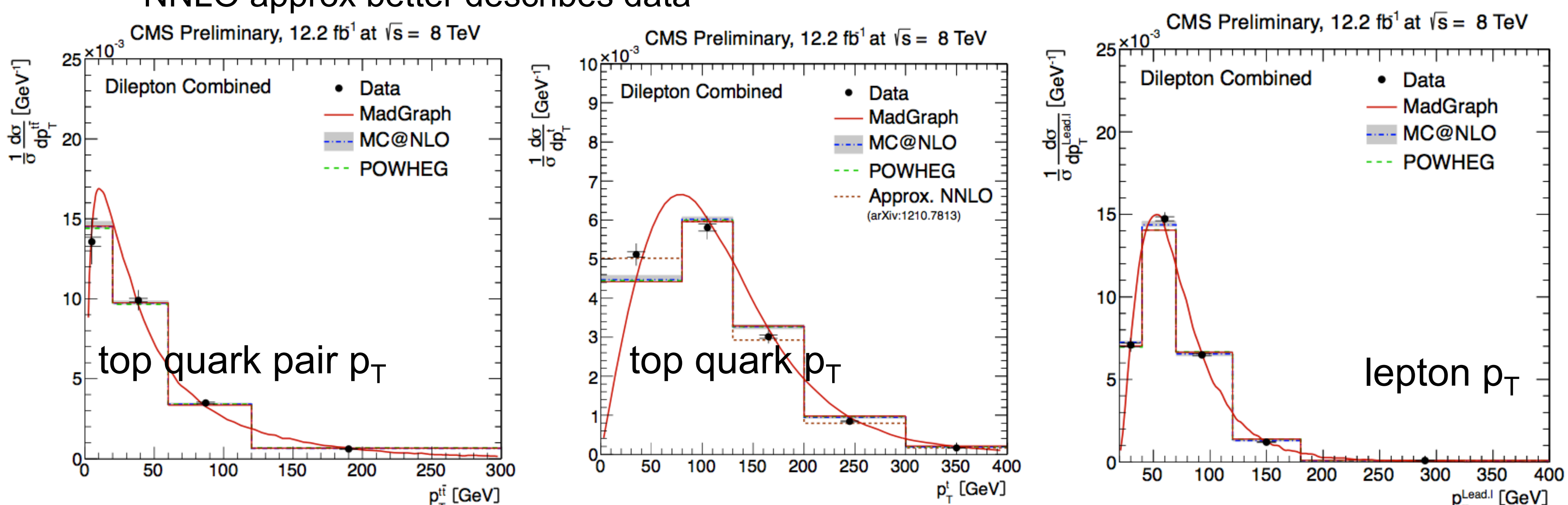


Differential cross section

CMS-TOP-12-028

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

- 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, η, 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



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CMS-TOP-12-028

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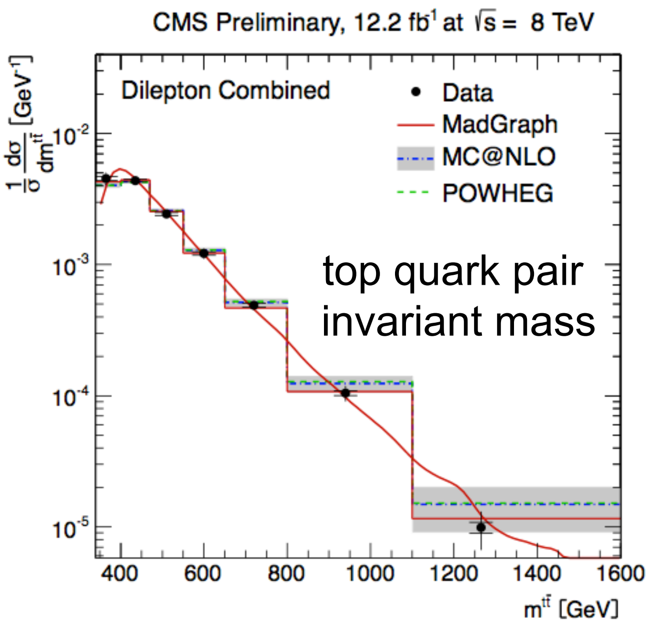
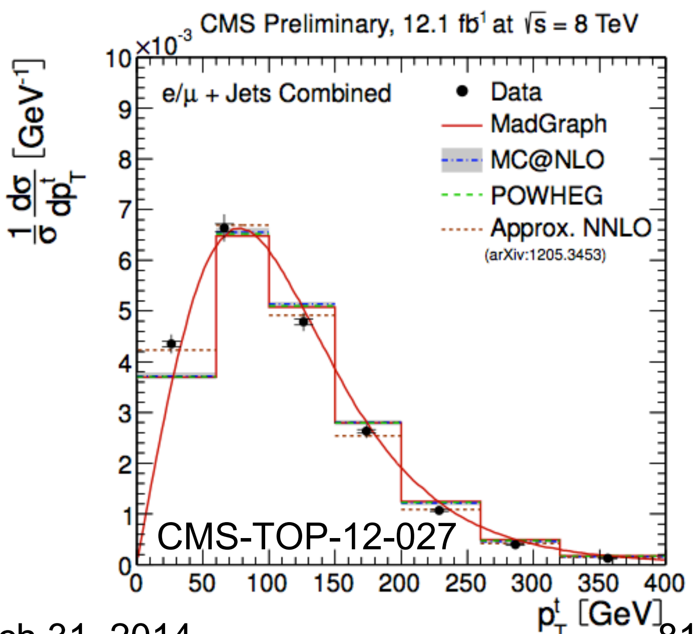
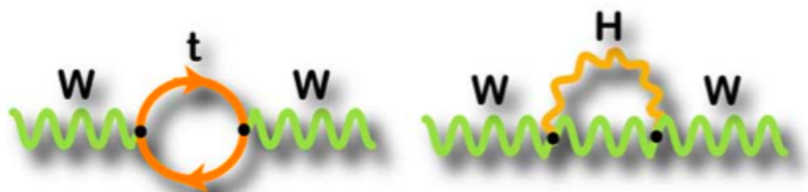




Top quark mass

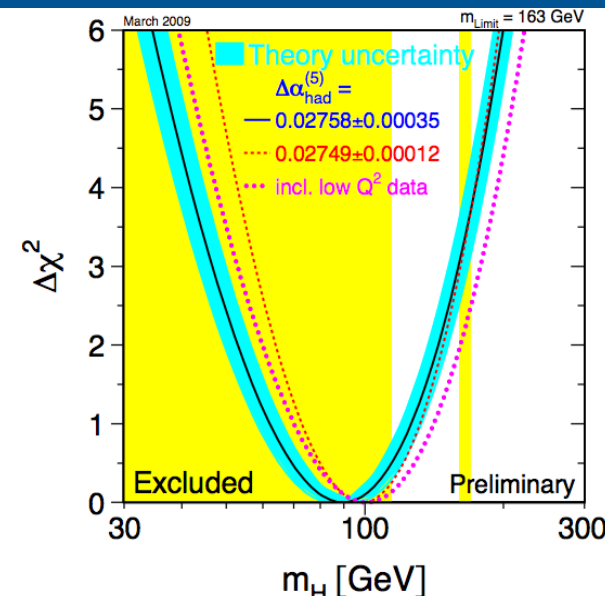
Top quark mass and constraints

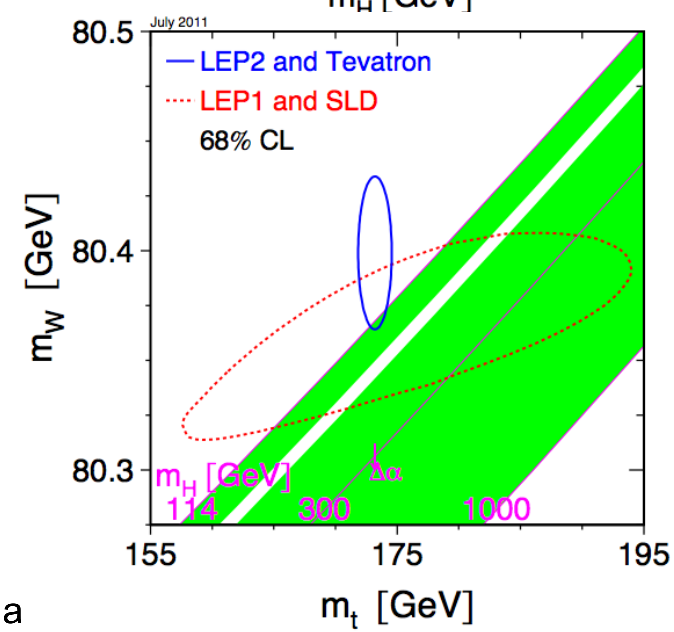
- Top quark mass is a fundamental parameter of the SM
  - Known with good accuracy from the Tevatron: 173.2±0.9 GeV (arXiv:1107.5255)
  - Indirect constraint on the Higgs boson mass via EW corrections
  - $\Rightarrow m_H = 92^{+34}_{-26}$ GeV or <161 GeV



$\delta m_W \propto m_t^2$ $\delta m_W \propto \log m_H$

- Top is the only fermion with the mass of the order of EWSB scale
- Measuring precisely m_W and m_{top}
  - Test consistency of SM
  - Search for new Physics





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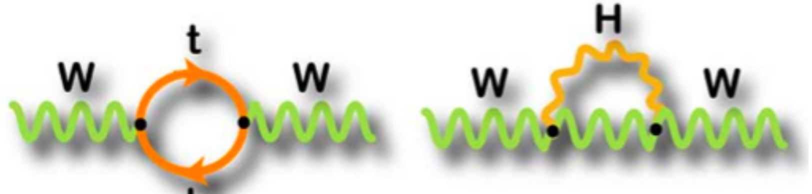

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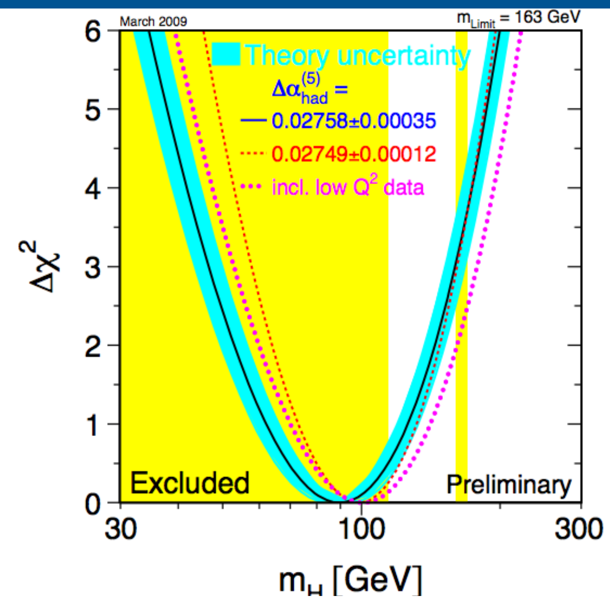
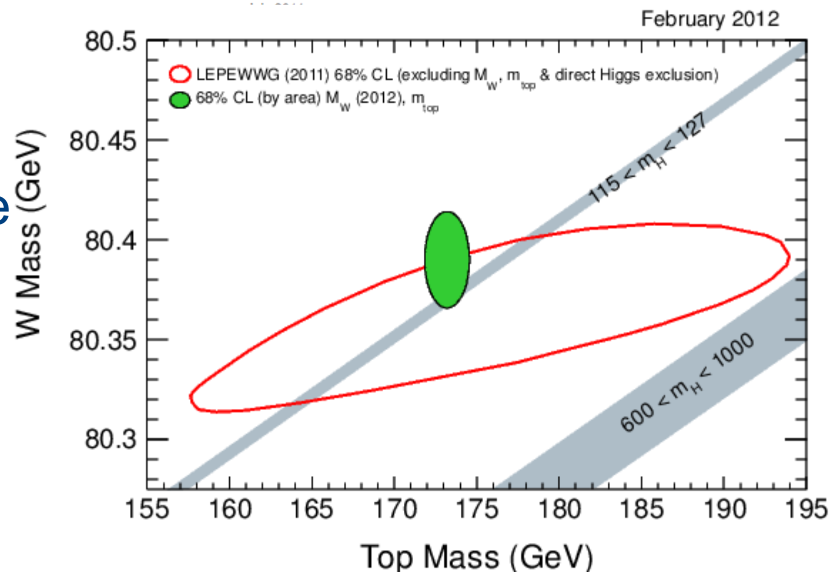
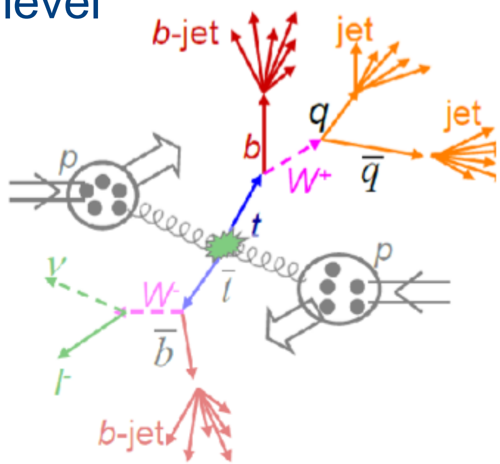


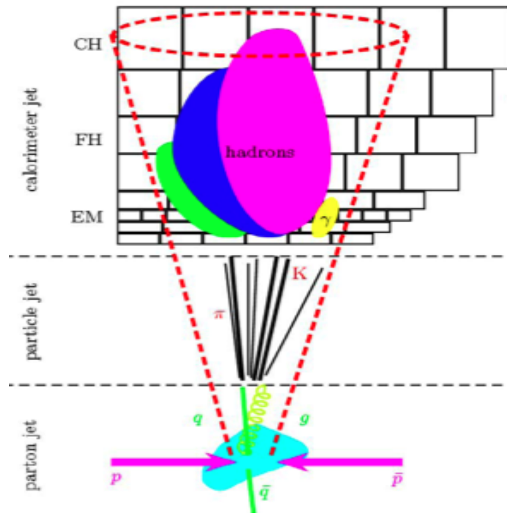


- Top is the only fermion with the mass of the order of EWSB scale
- Measuring precisely m_W and m_{top}
  - Test consistency of SM
  - Search for new Physics

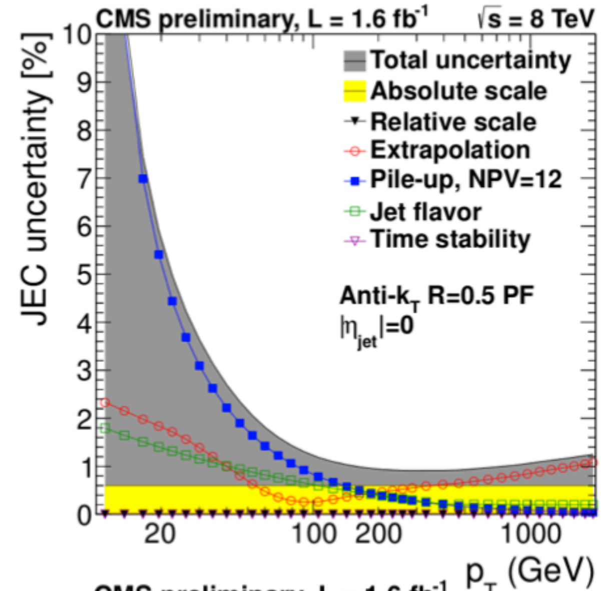
Jet reconstruction in Top events

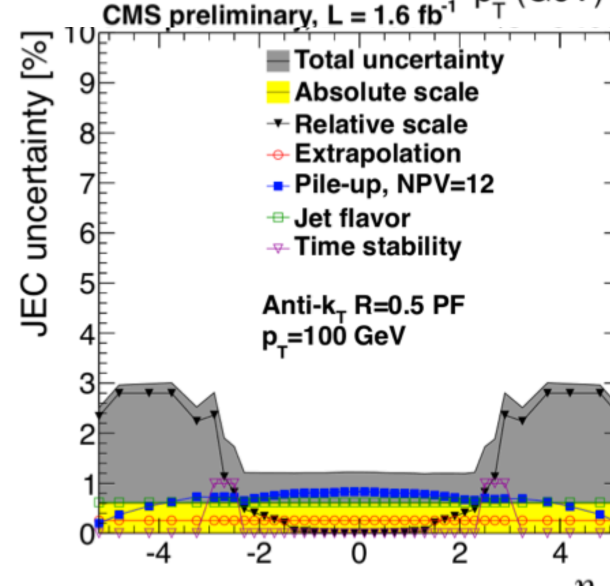
- Top mass measurement needs parton information, but we measure jets
- Use calorimeter information to correct jets to particle level





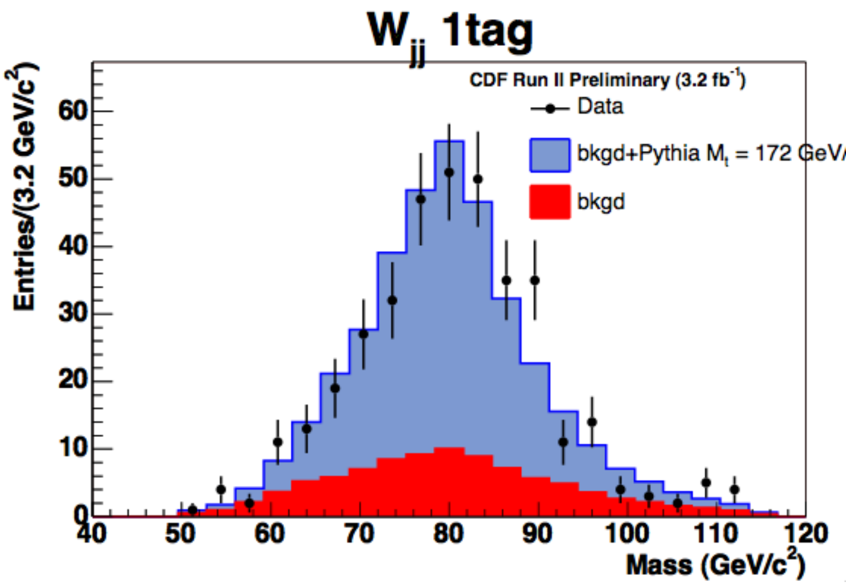
- Contribution of uncertainty sources depend on p_T, η
- Jet energy correction uncertainty:
  - Look at quantities insensitive to JES (e.g. lepton p_T)
  - "b-jet" tag helps reducing number of permutations
- JES "in-situ" calibration in ttbar events
  - Use W→jj constraint to measured W mass





Top as a calibration tool

- Top quarks can be used as calibration tool
  - Top mass, W mass, b/q jets
- can determine:
  - b-tagging efficiency
  - jet energy scale

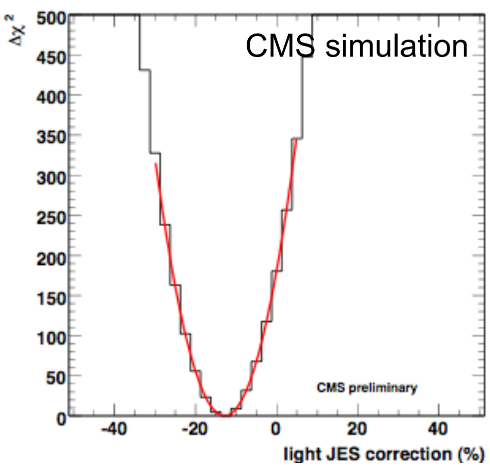


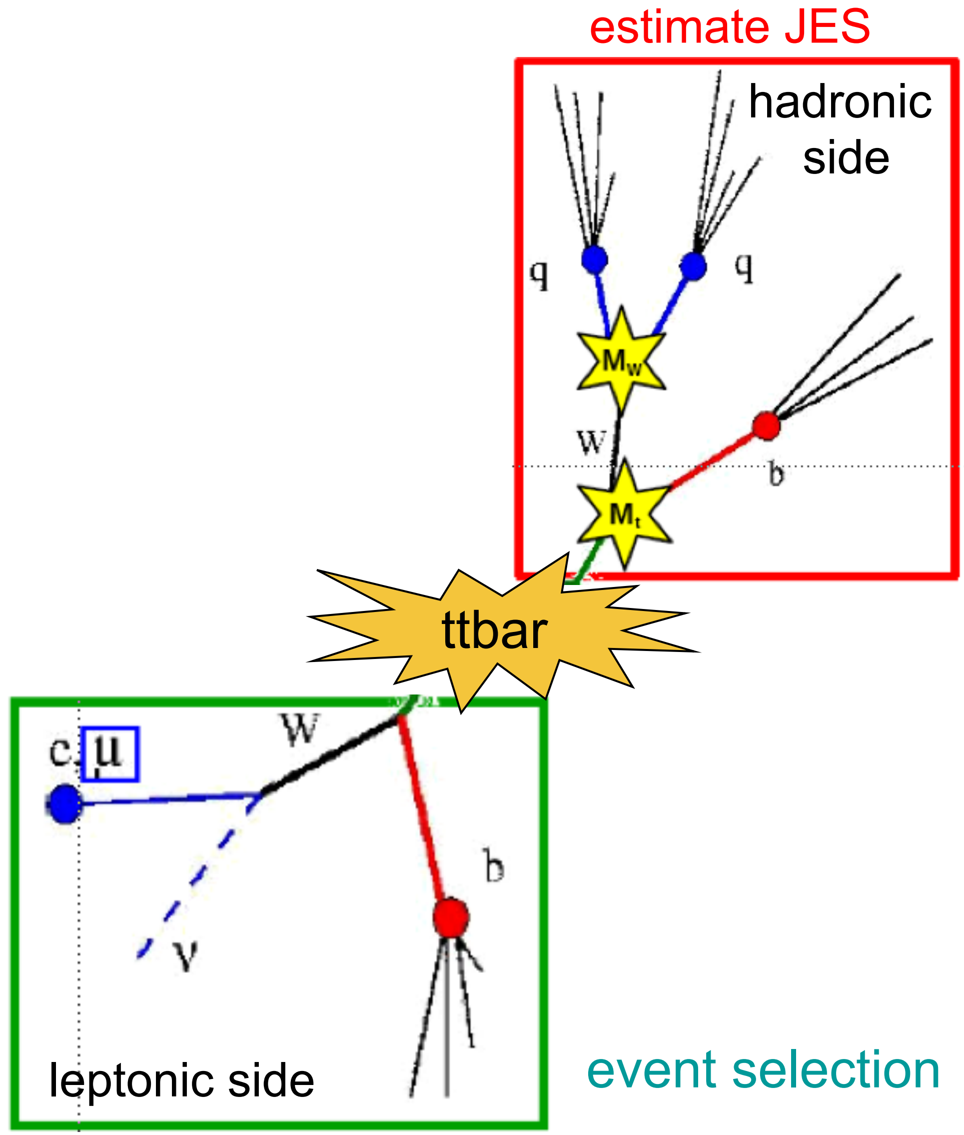
…or alternatively…

- use b-tag as a probe
  - compare rates in different b-tag multiplicity bins
  - is the signal, ttbar or not?
- BSM may appear in the sample and "distort" the distribution

Jet energy correction from Top

- Use semi-leptonic events
  - –1 isol μ (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 χ^2



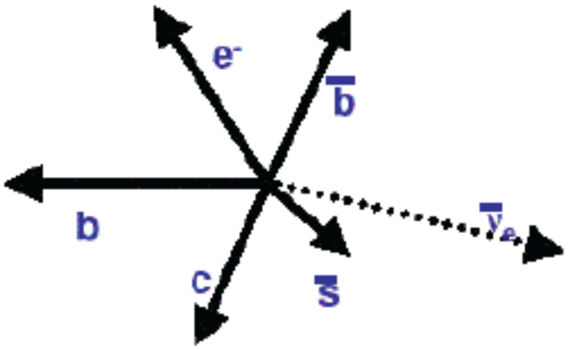


Measuring the top mass

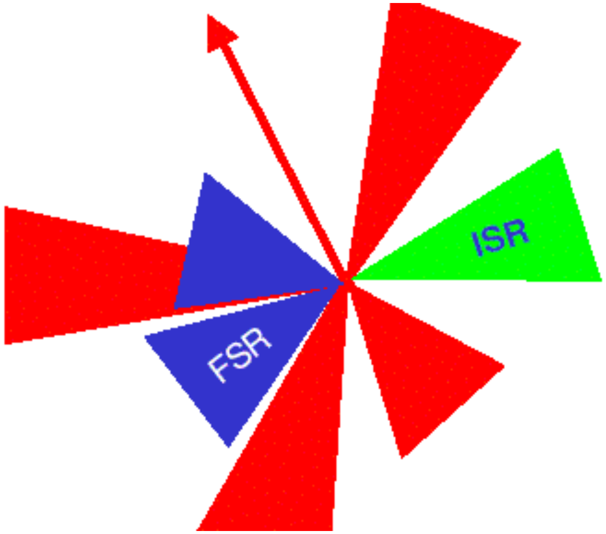
Challenging:

- **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:

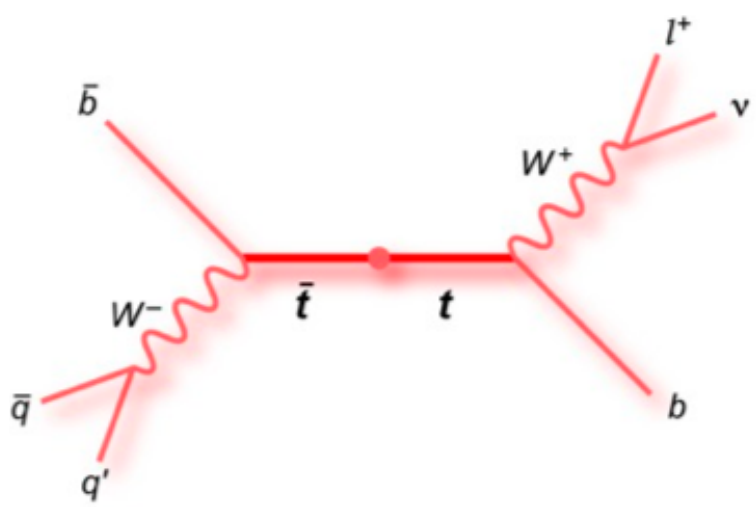


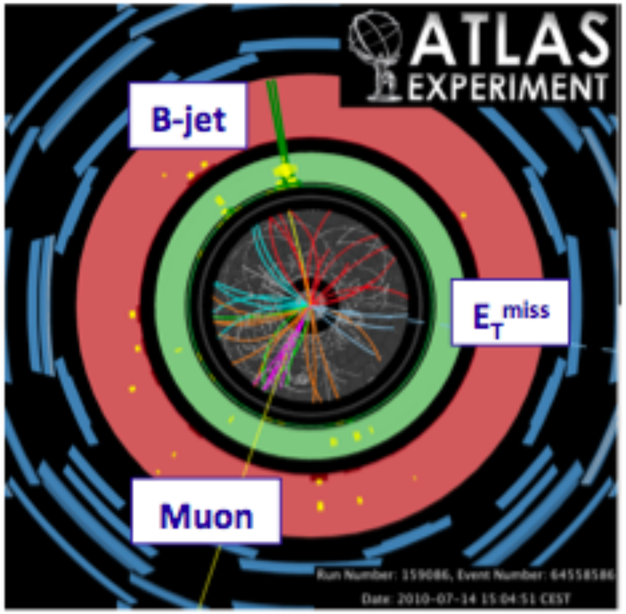
experiment sees:



Lepton+jet channel

- Best channel (for now) to measure top quark mass
- Compromise between large branching ratio (BR=30%) and a good background rejection
- Well defined final state (1 lepton, one neutrino, 2 b-jets, $W \to qq'$)

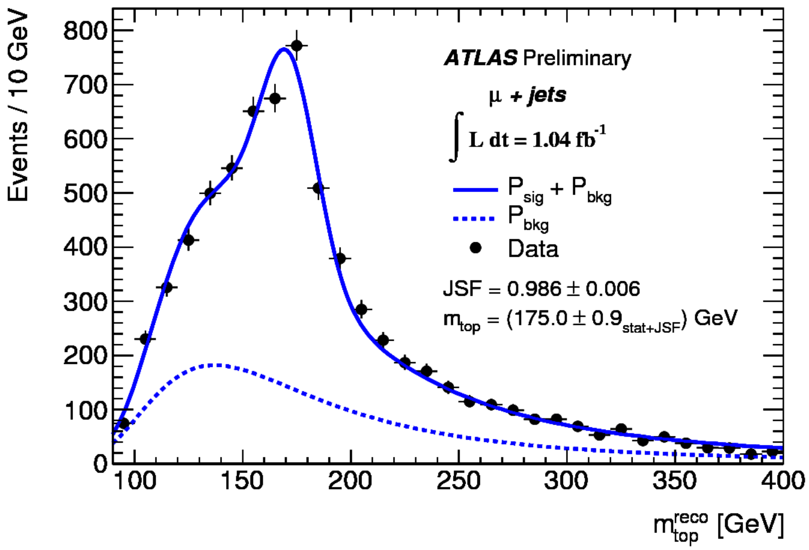




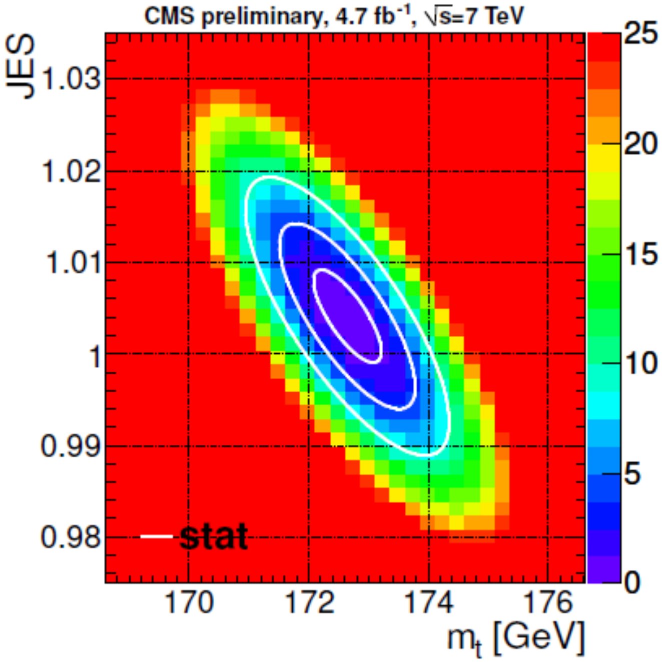
Lepton+jet channel

- in-situ calibration of the light quark JES from W→ qq'

ATLAS: template fit as function of JES and top quark mass



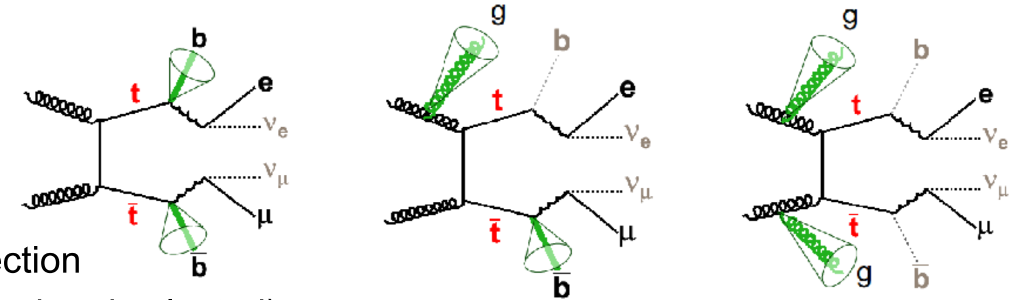
CMS: kinematic fit + "ideogram" method combine event-per-event likelihood



⇨m_{top}=174.4 ± 0.6 (stat) ± 2.3 (syst) GeV ATLAS CONF-2011-120

172.6 ± 0.6 (stat) ± 1.2 (syst) GeV CMS PAS-11-015

Dilepton channel: challenges



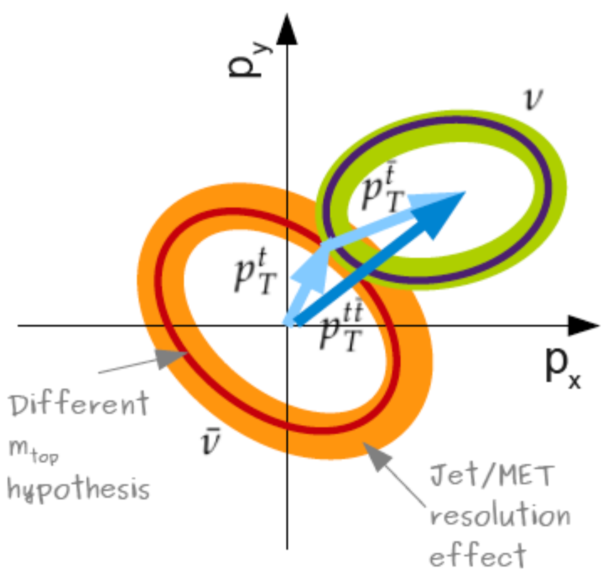
- Combinatorics
  - Identify top quark decay products
  - Ambiguity
  - ISR/FSR introduces further complexity for selection

  (~70% of the events have both b-jets reconstructed and selected)

- Missing transverse energy
  - Constrains the contribution from undetected particles
  - In the dilepton channel: 2 neutrinos ⇒ $\vec{E}_T^{miss} = \vec{p}_T^{\nu} + \vec{p}_T^{\bar{\nu}}$

- Jet energy scale
  - m_{top} reconstruction requires measuring the parton energy
  - parton→jet affected by resolution and absolute energy scale

- Pile-up
  - Jet energy scale, MET measurement, extra jets/leptons
  - $N_{pileup} \approx 6$ (21) for most of data collected in 2011 (2012)

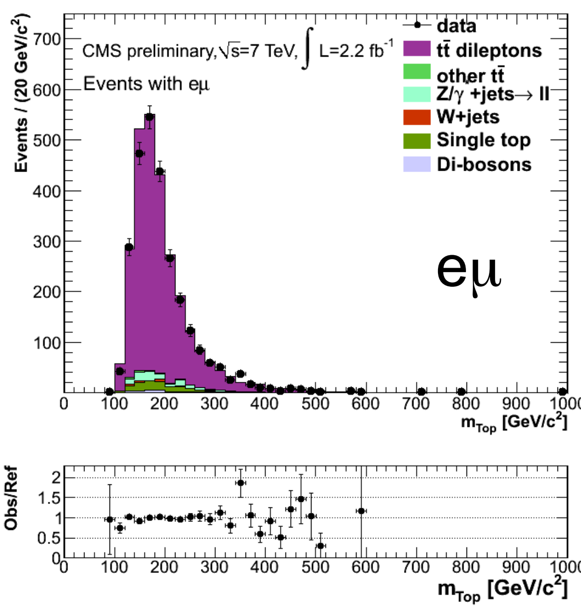


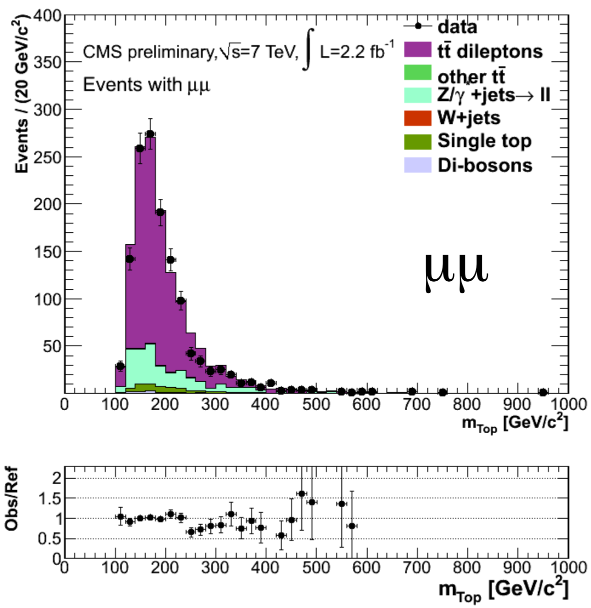
Reconstructed mass

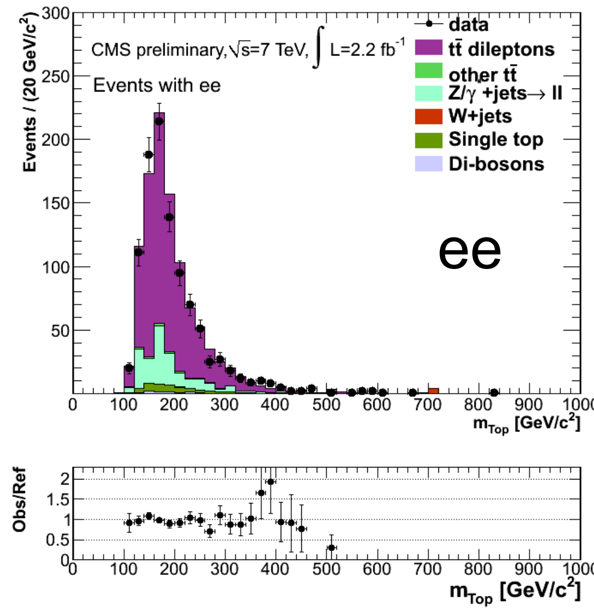
CMS-PAS-TOP-11-016

- Select events
- Reconstruct mass

Process	Pre-selection	KINb	=1 b-tag	≥ 2 b-tags
Di-bosons	73 ± 14	55 ± 10	18 ± 4	4 ± 1
Single top	247 ± 92	182 ± 68	88 ± 33	76 ± 29
W+jets	22 ± 10	16 ± 8	8 ± 6	-
$Z/\gamma^* \to \ell\ell$	1091 ± 97	756 ± 71	238 ± 29	47 ± 11
other $t\bar{t}$	32 ± 4	28 ± 3	11 ± 2	14 ± 2
$t\bar{t}$ dileptons	5057 ± 463	4209 ± 385	1379 ± 127	2623 ± 240
total expected	6522 ± 482	5246 ± 398	1742 ± 134	2765 ± 242
data	6358	5047	1692	2620



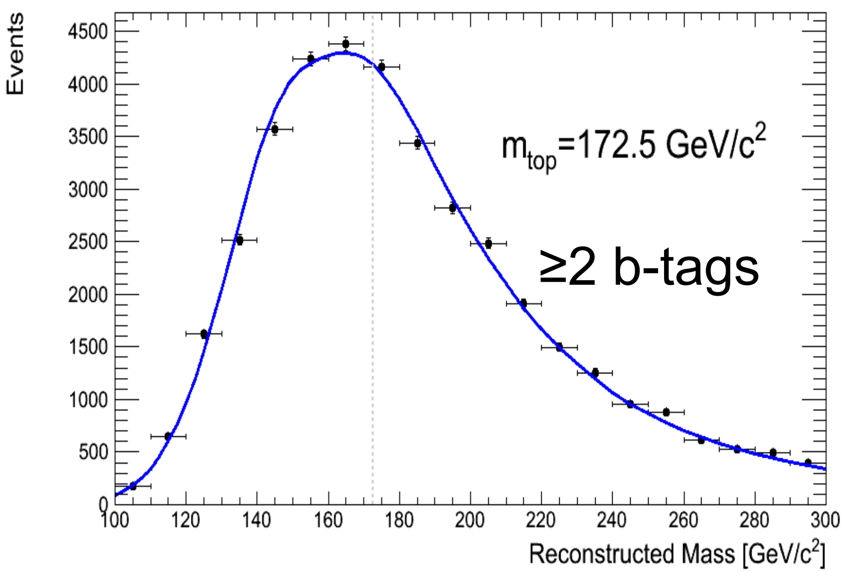


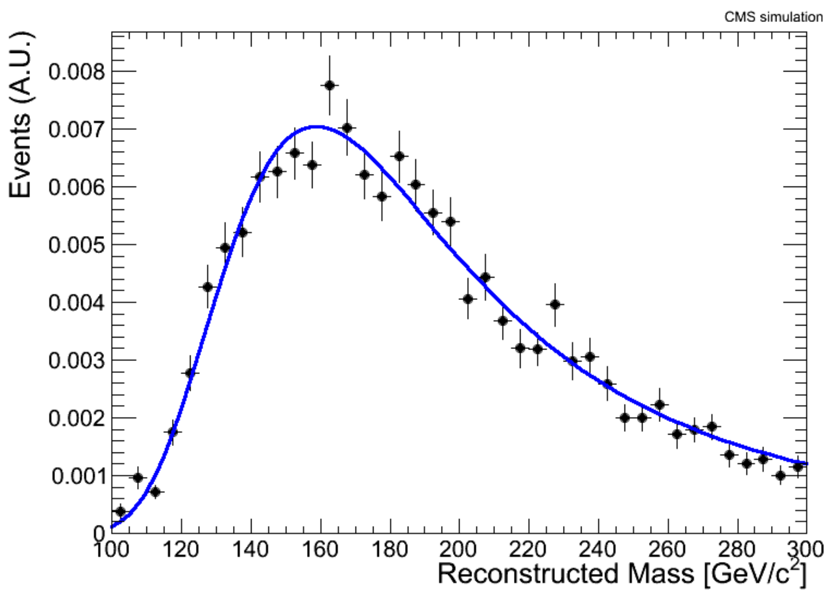


Signal and background

- Signal component in the mass spectrum modelled: simulation
- Fit: Landau+Gaussian
- Categories: =1 and ≥2 b-tags

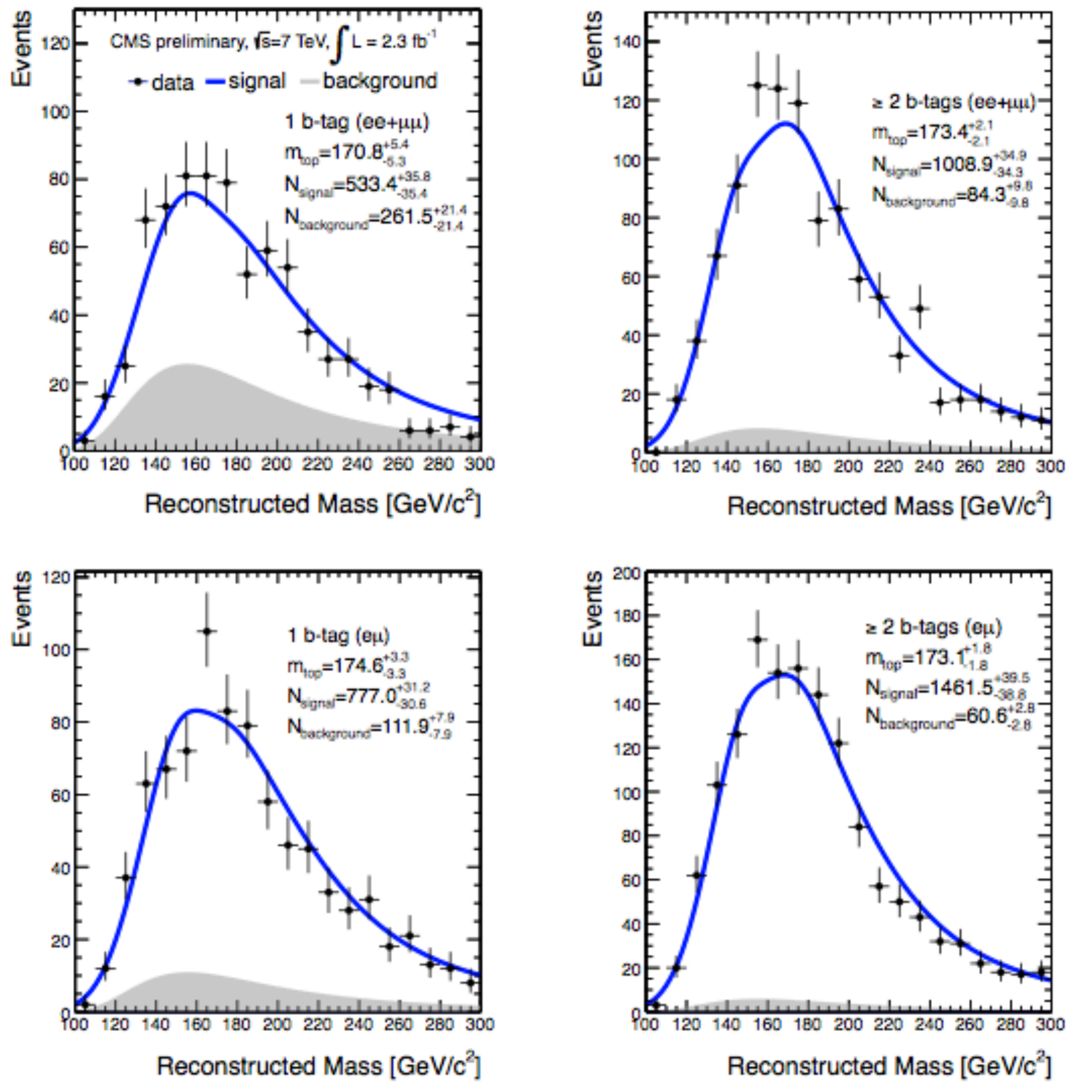
- Background component in the mass spectrum modelled with data+simulation
- Fit: Landau





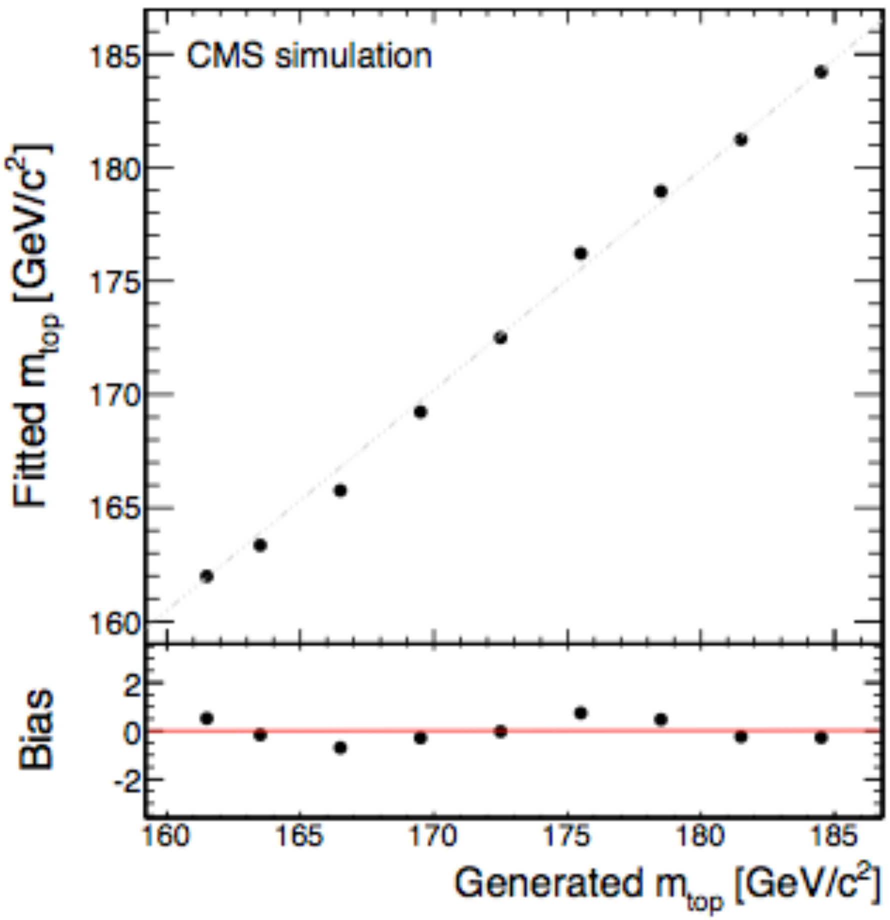
Reconstructed mass

- Top quark mass is reconstructed in different categories
- Signal and background shapes



Correct for the bias

- Check and correct for the bias in the measurement

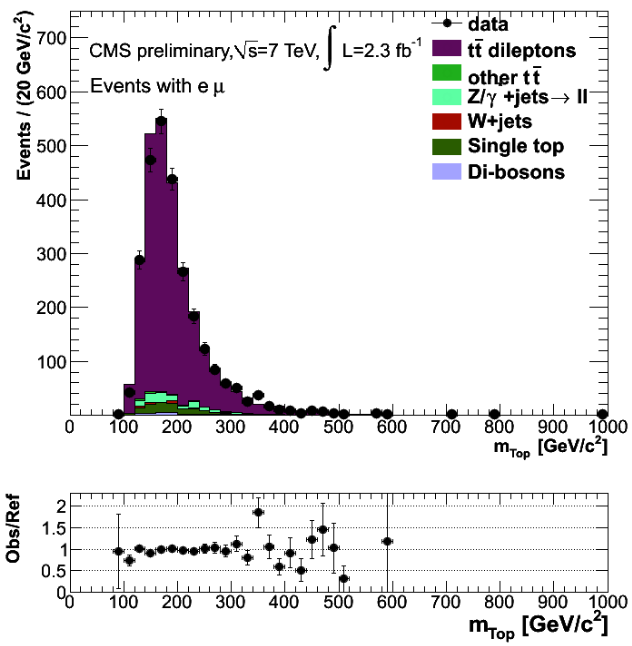


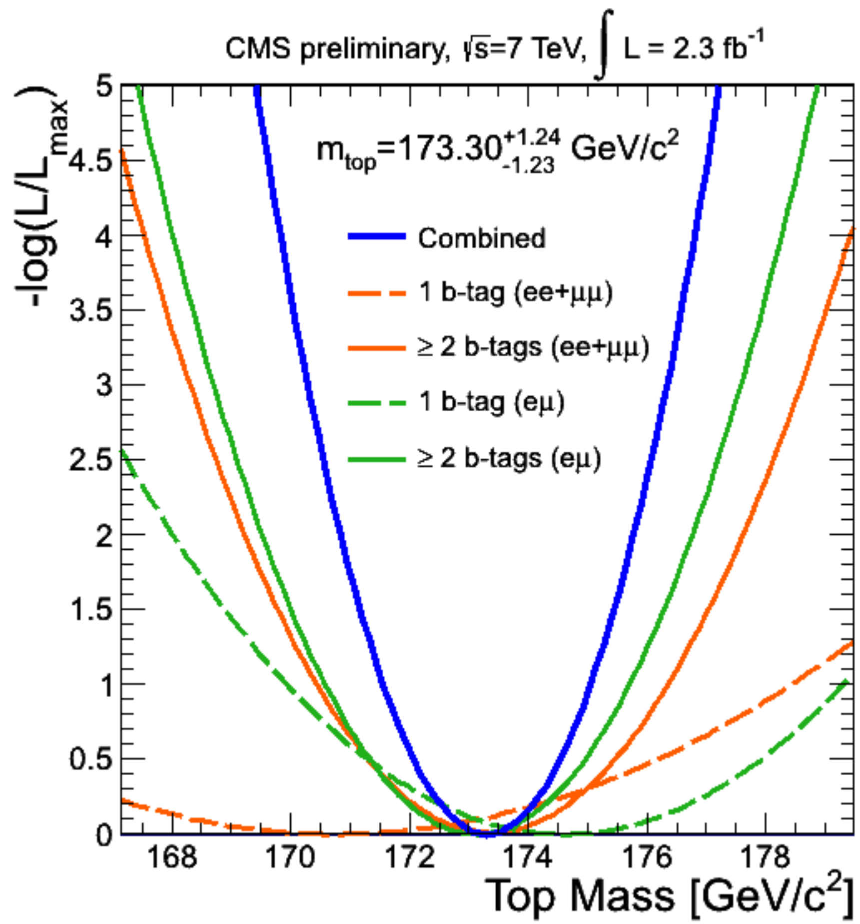
Do not forget the systematics

- Jet energy scale (JES) is the largest unc.
  - JES is varied up and down and difference in m_{top} is accounted for as systematics
  - Flavor (b) specific uncertainty added in quadrature
- Other systematics:
  - Difference with respect to reference sample used for signal
  - MC: compare Alpgen and Powheg with Madgraph
  - Vary factorization/matching scale, ISR/FSR

Source	Δm_{top} (GeV/c^2)
JES	$^{+1.90}_{-2.00}$
flavor-JES	$^{+1.08}_{-1.13}$
JER	± 0.30
LES	$^{+0.12}_{-0.18}$
Unclustered E_T^{miss}	± 0.43
Fit calibration	± 0.40
DY normalization	± 0.40
Factorization scale	± 0.41
Jet parton matching scale	± 0.65
Pile-up	± 0.19
b-tagging uncertainty	± 0.30
mis-tagging uncertainty	± 0.43
MC generator	± 0.14
PDF uncertainty	± 0.39
Total	$^{+2.52}_{-2.63}$

Final fit

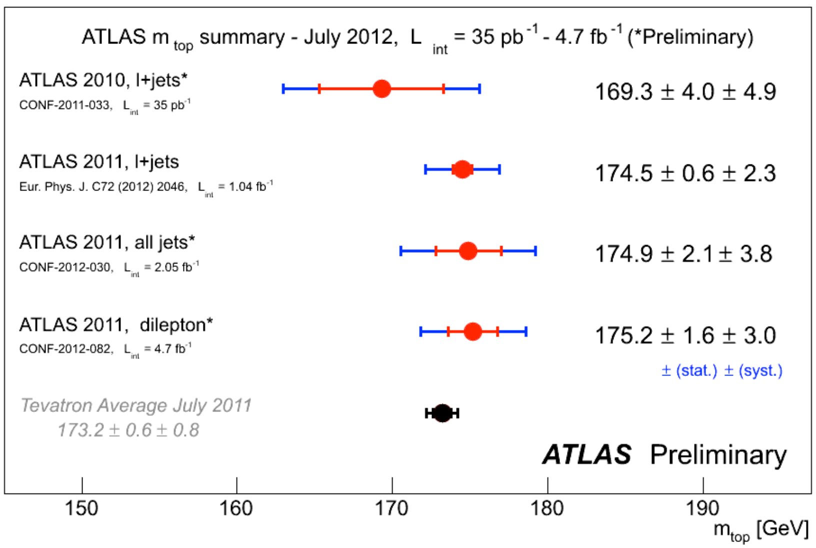


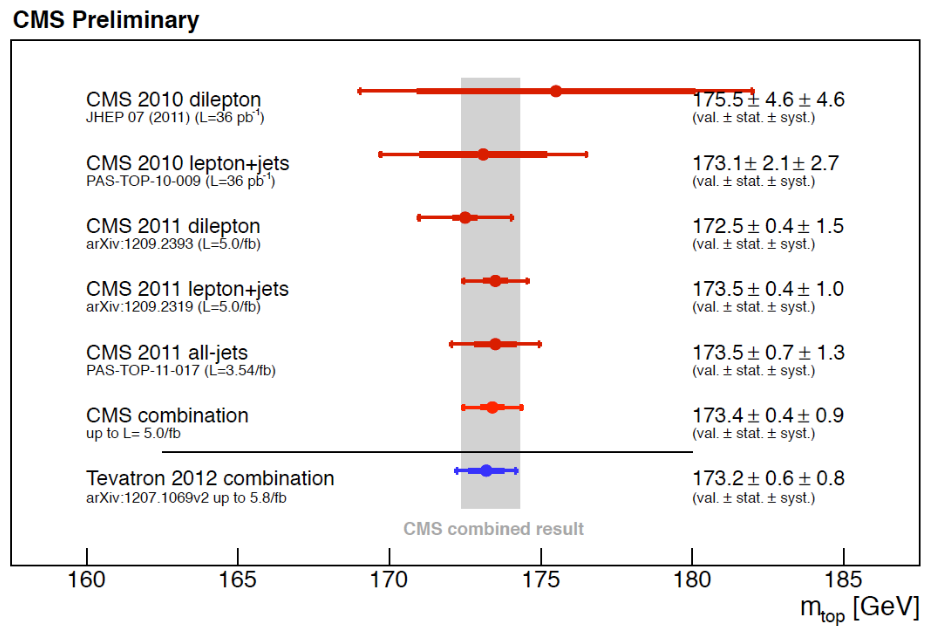


$$m_{\text{top}} = 173.3 \pm 1.2(\text{stat.})^{+2.5}_{-2.6}(\text{syst.})\ \text{GeV}/c^2$$

CMS TOP-11-016

Summary of mass measurements

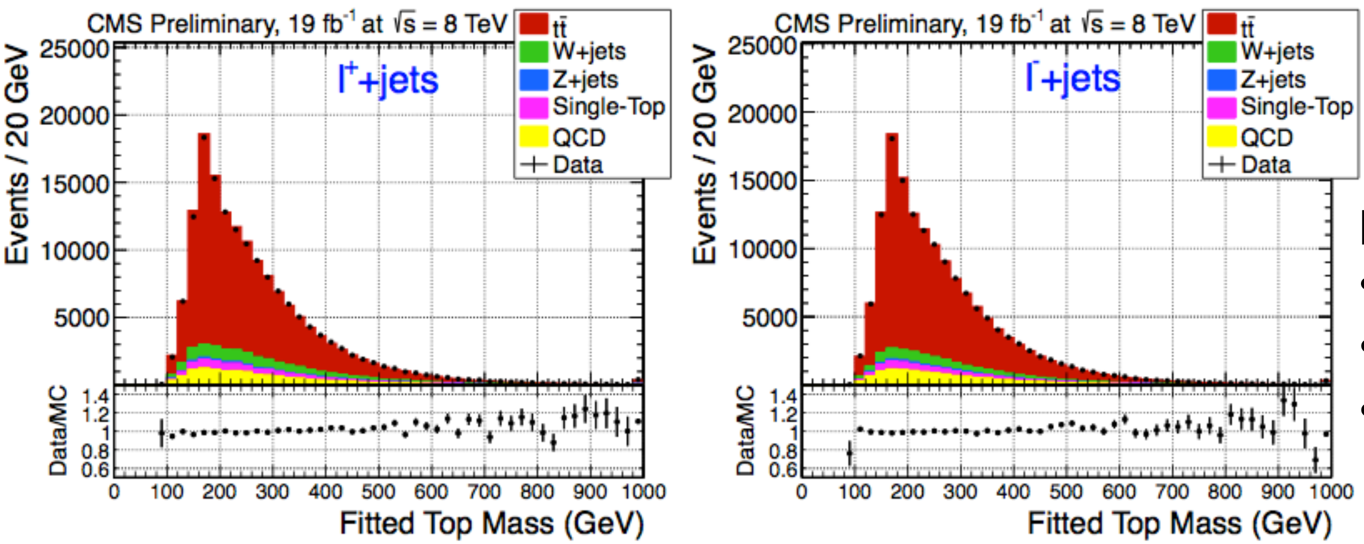




Mass difference measurement

CMS TOP-12-028

- CPT invariance ⇒ mass of particle=mass of anti-particle
- Top quark decays before hadronizing ⇒ Δm can be measured directly
- Use lepton+jet final state



Dominant systematics:
- b vs bbar jet response
- signal fraction
- b vs bbar tagging

$$\Delta m_t = m_t^{had} - m_{\bar{t}}^{had} = -272 \pm 196\ (stat.) \pm 121\ (syst.)\ MeV$$

end