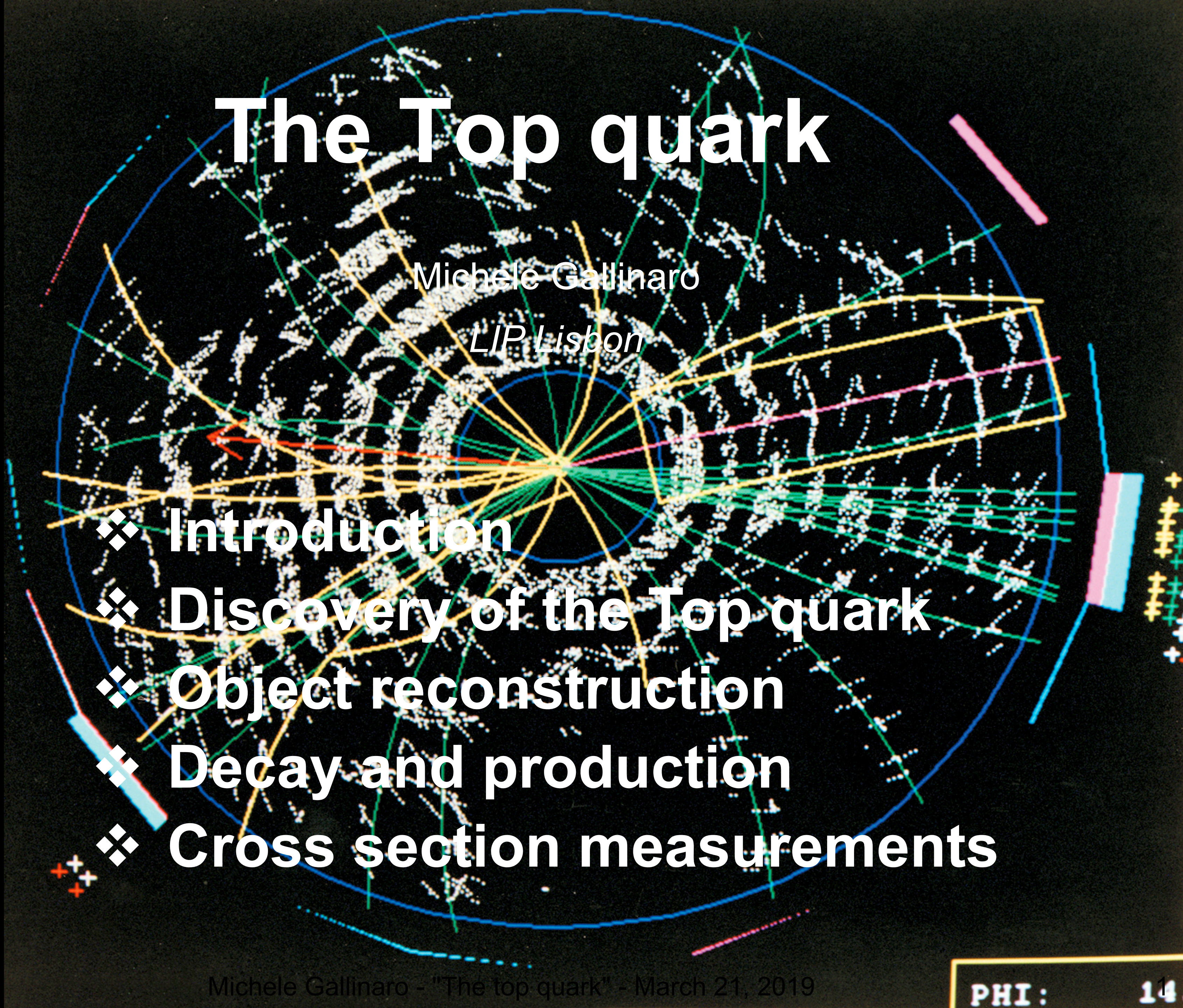
The Top quark

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

- Search for top partners and 4th generation quarks
- Search for 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

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

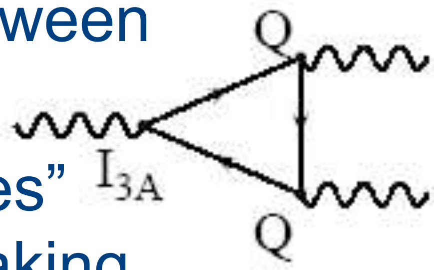
- Tau (τ) lepton in Mark I data (ν_τ from the decay kinematics)
- Discovery of the Y at Fermilab

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

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

The theory: Why?

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



$$\Sigma Q = -1 + 3 \times [2/3 + (-1/3)] = 0$$

lepton electric charge quark (up/down) charge

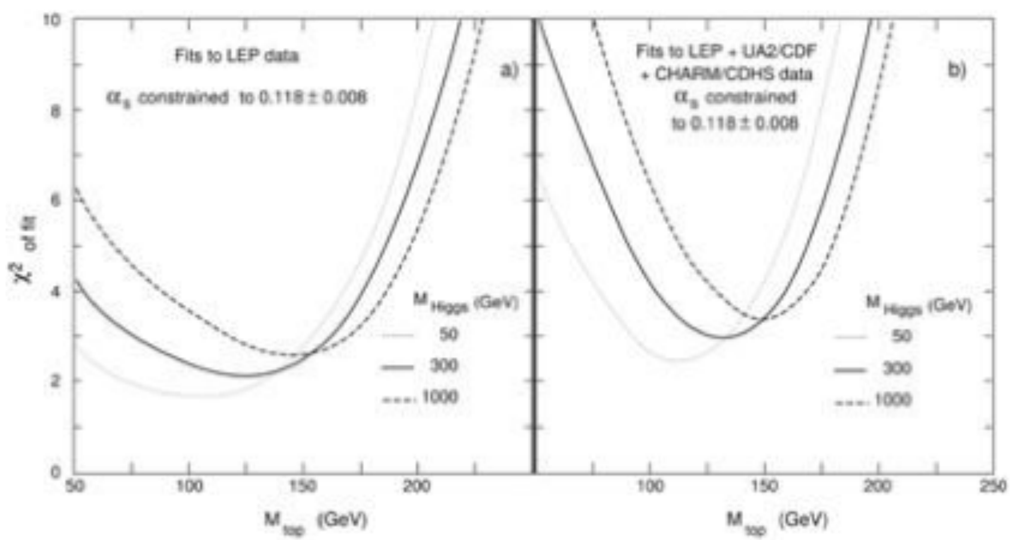
Searches at e^+e^- colliders

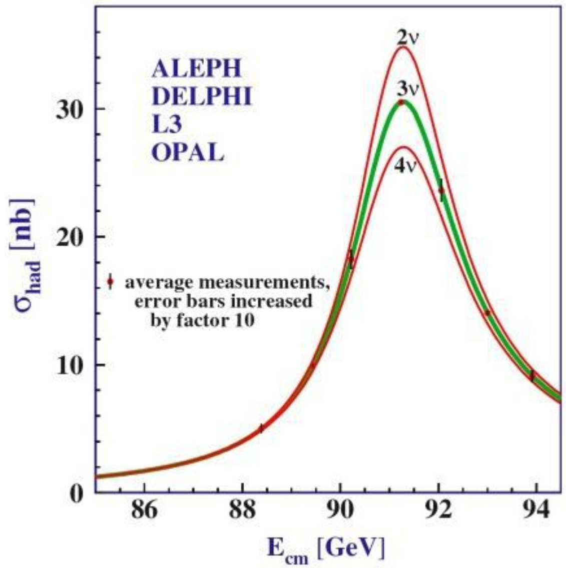
- PETRA (DESY) could reach ~20 GeV (late ‘70s)
  - Search for narrow resonance
  - Look for increase in R=(# of hadron events)/(# of $\mu\mu$ events)
  - Global event characteristics: look for spherical component
  - Negative results. Set limits: M_t>23 GeV
- TRISTAN (Japan) built to study the top quark (early ‘80s)
  - Similar search technique:
  - Could reach ~30GeV: M_t>30 GeV
- SLC/LEP (SLAC)
  - Look for $Z \rightarrow t\bar{t}$
  - M_t>45 GeV
- Reached kinematic limit for direct searches at e^+e^- colliders

Indirect searches at e^+e^- colliders

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

- Precision measurements of the EWK parameters, allow to measure virtual corrections with sufficient precision to put constraints on M_{top}
  - Prediction upper limit<200-220 GeV

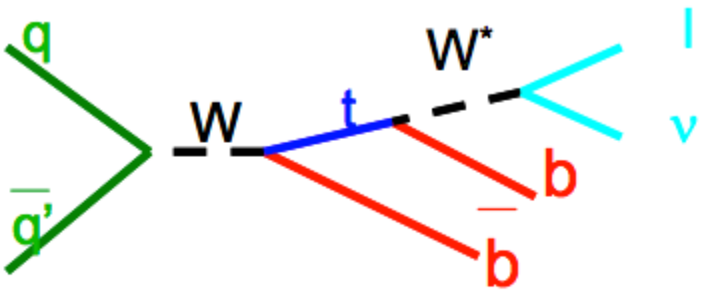




Early searches at hadron colliders

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

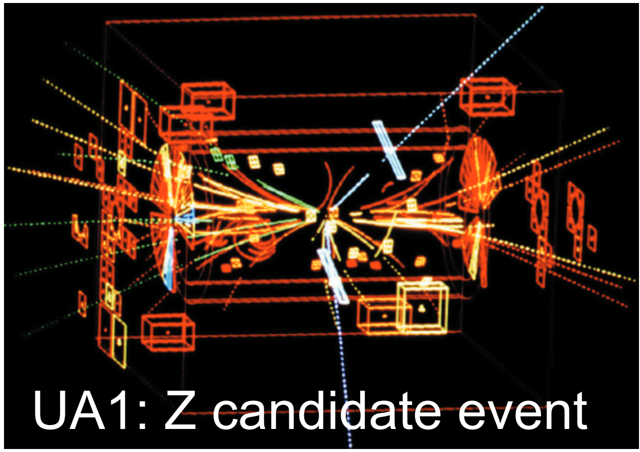
- Access to much higher energies
- Large backgrounds, low event rates
- Difficult reconstruction: jets



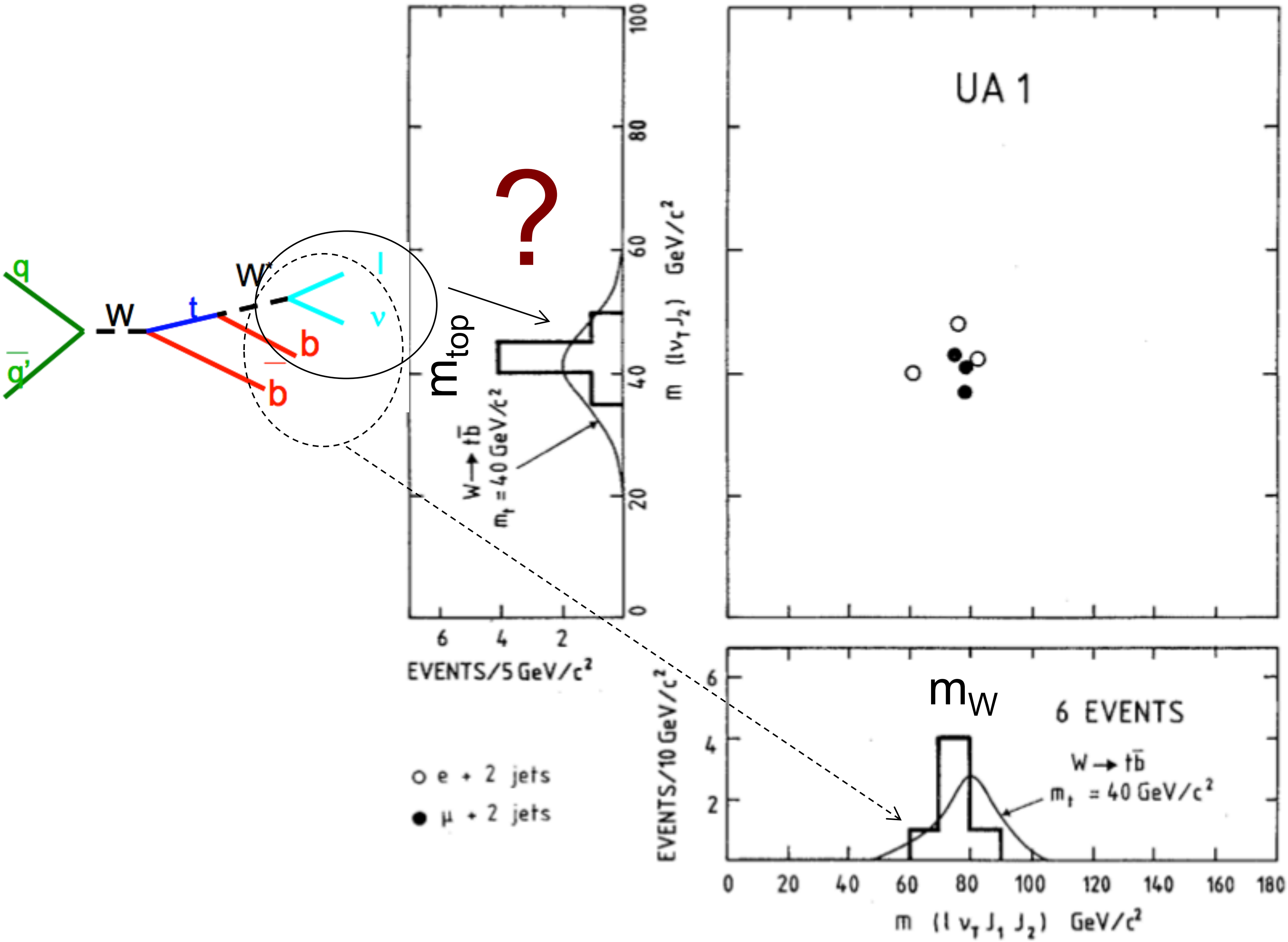
1984: UA1

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

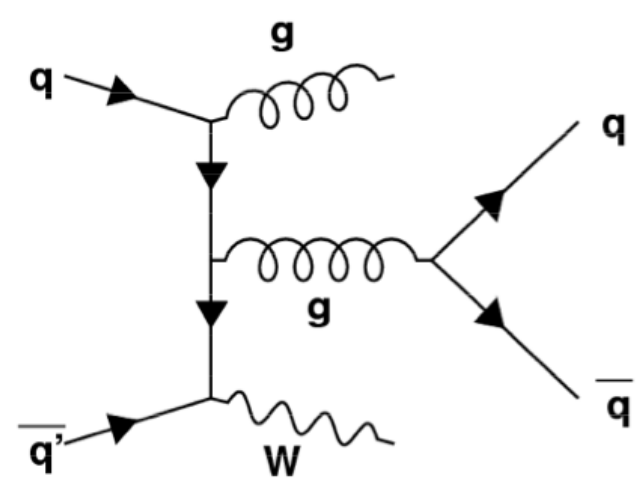


UA1: Z candidate event


q
q̄'
W
t
W
l
ν
b
b̄
?
m_top
W → t b̄
m_t = 40 GeV/c²
EVENTS/5 GeV/c²
m (lν_T J_2) GeV/c²
UA 1
m_W
6 EVENTS
EVENTS/10 GeV/c²
W → t b̄
m_t = 40 GeV/c²
m (l ν_T J_1 J_2) GeV/c²
e + 2 jets
μ + 2 jets

Searches at hadron colliders

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

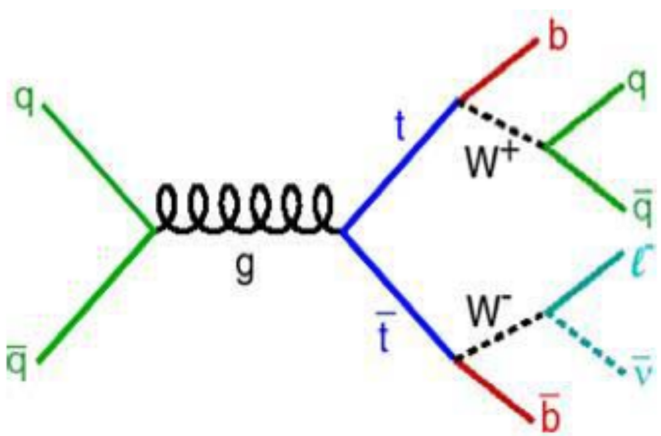
(+ 23 expected if $M_{top} = 40$ GeV)

⇒conclude M_{top}>44 GeV

Fermilab joins the hunt

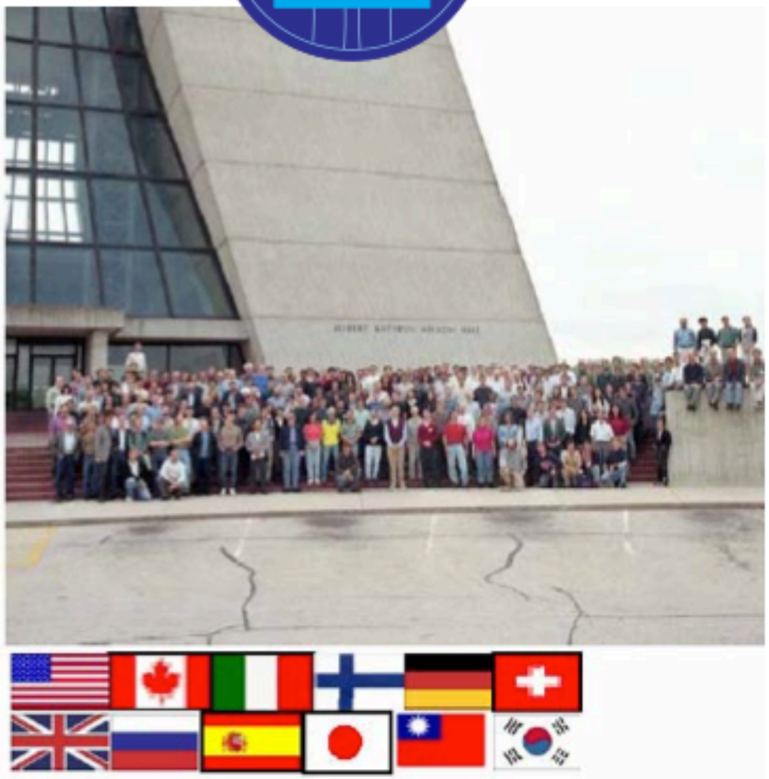
- 1988-89: at CERN, UA2 remains after the upgrades
- √1.8 TeV@Fermilab **vs.** √0.63 TeV@CERN
- Much better reach for larger mass (only 75 GeV@UA2)
- At Tevatron, pair production dominates: $t\bar{t} \rightarrow Wb\ W\bar{b}$

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

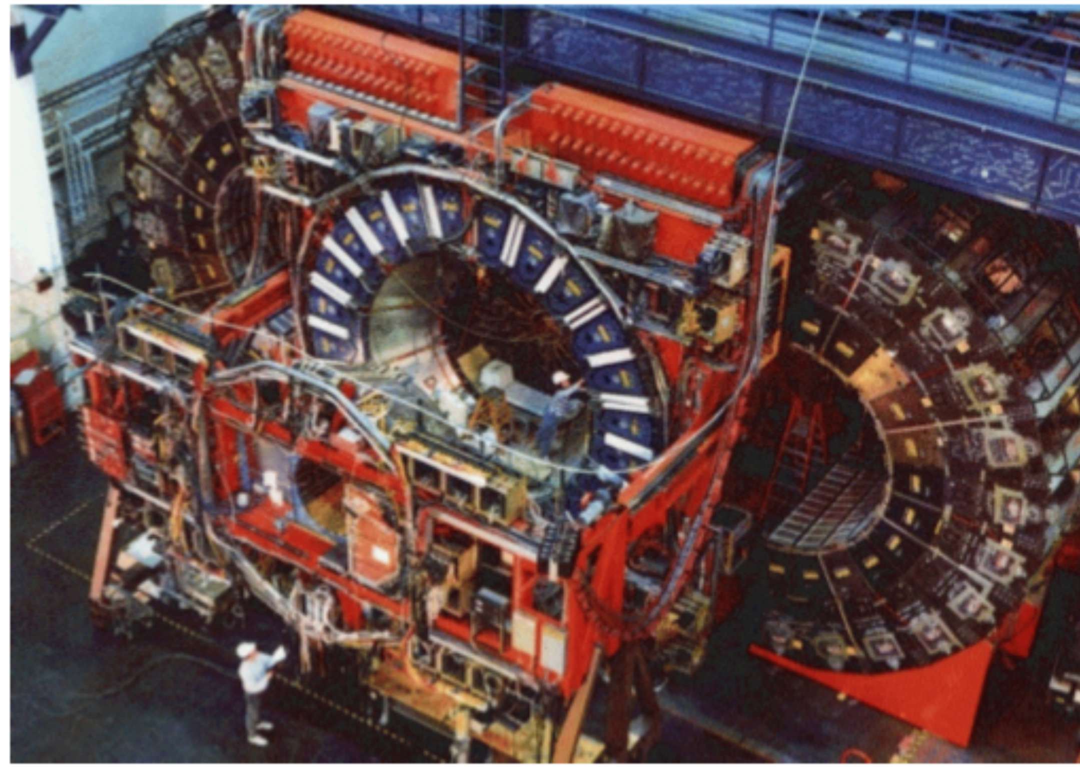


Tevatron

Proton-antiproton collision at 1.8-2.0 TeV



12 countries, 62 institutions
767 physicists



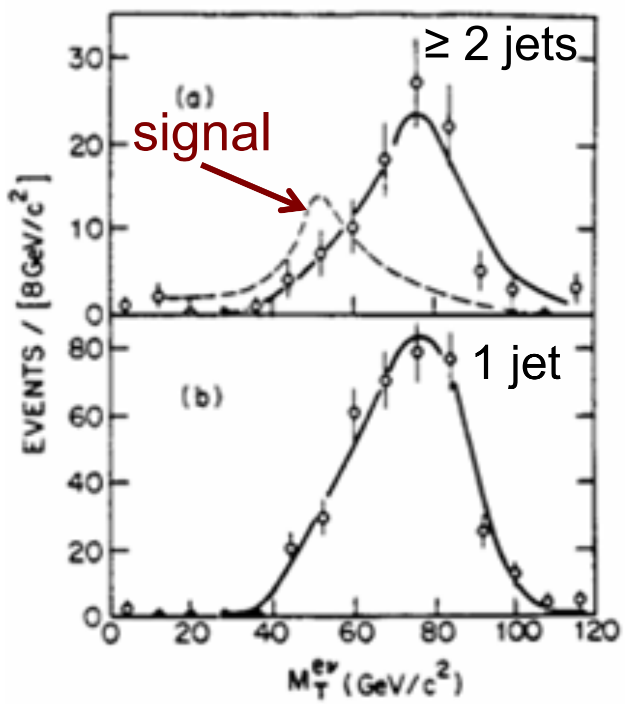
Searches at CDF

eμ channel

- Event rate lower: 2xBR(W→eν)
- Background small (no W+jets, no DY)
- Dominant background is Z→ττ→eμX (expect 1 evt)
- Observe 1 event (expect 7 evts for M_{top}=70 GeV)

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



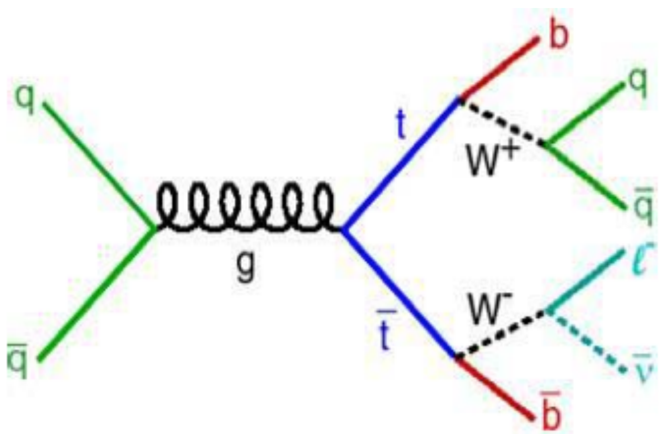
⇒M_{top}>77 GeV

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

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

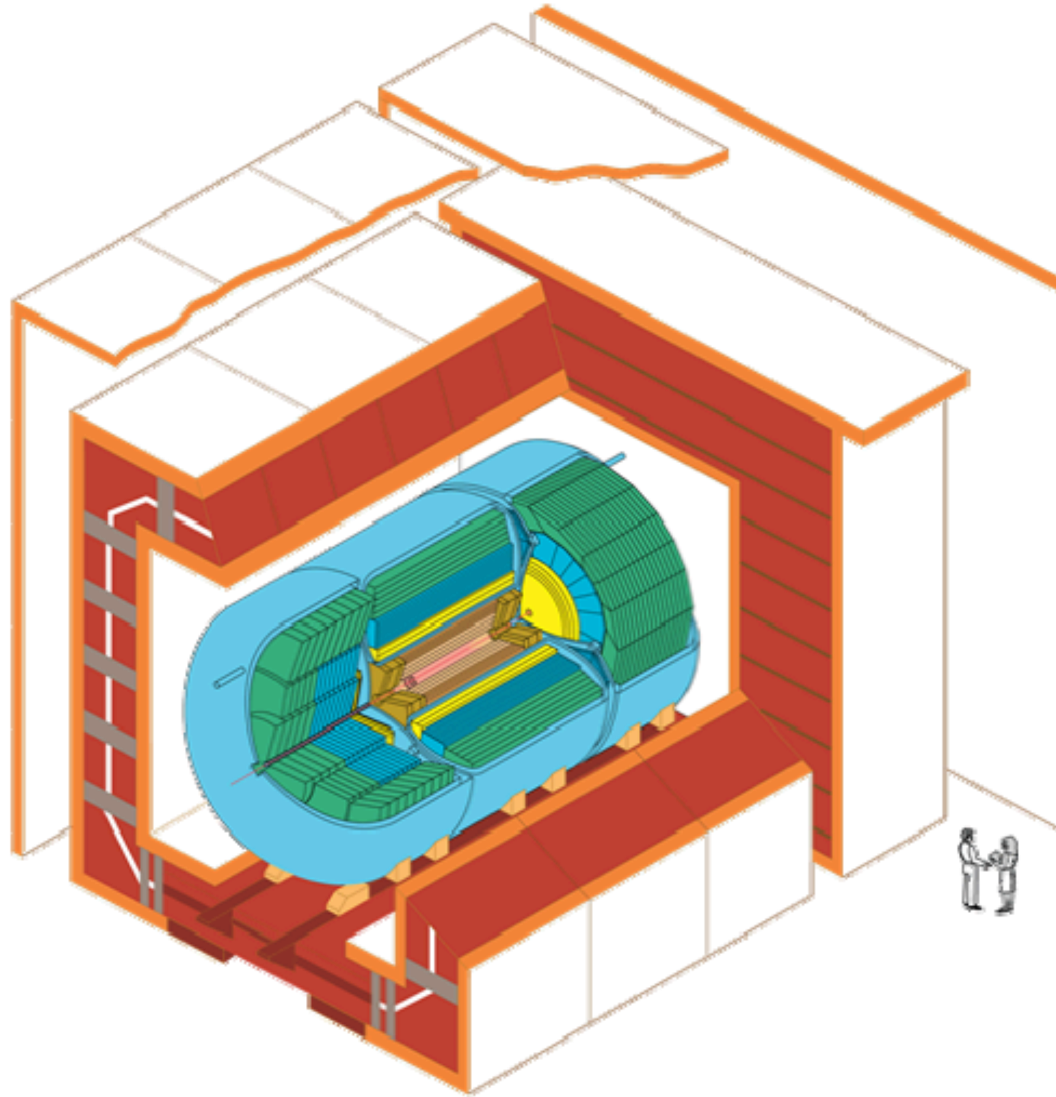
- Top quark decays to on-shell Ws: no $M_T(l\nu)$ discriminant
- Main differences:
  - background: W+jets (largely quarks and gluons)
  - signal: W+jets (2 jets are b-jets)
- CDF publication on 88-89 data:
  - Dilepton: include ee, $\mu\mu$, eμ (require missing ET, Z-veto)
  - Single lepton: require 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 collects more data (higher luminosity)
- D0: excellent calorimetry, large solid angle and coverage
- CDF: precision vertex detector, good tracker, magnetic spectrometer

Run 1A:

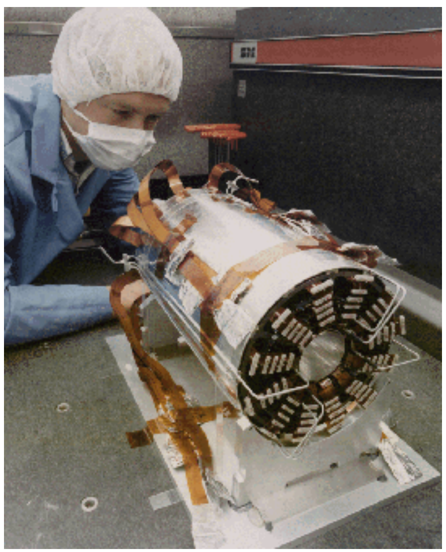
- D0: optimized search for M_{top}=100 GeV

– $e\mu$+≥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)

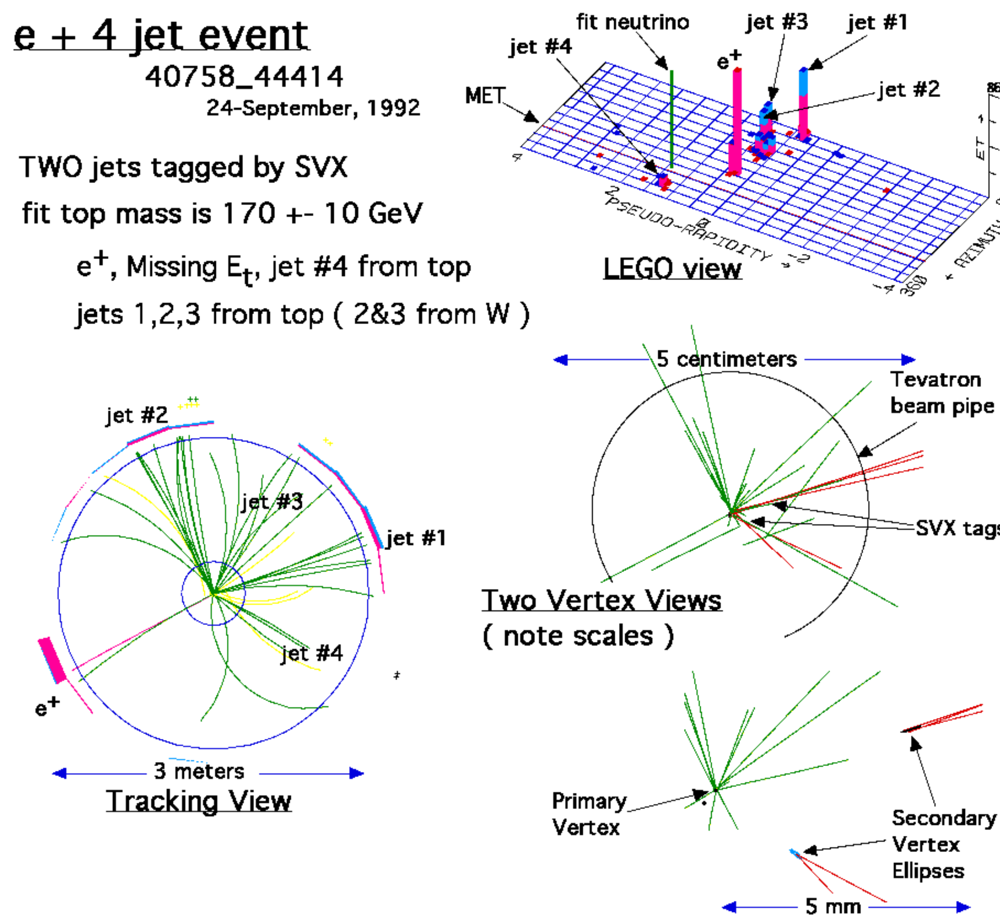
$\Rightarrow M_{top}$>131 GeV@95%CL

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

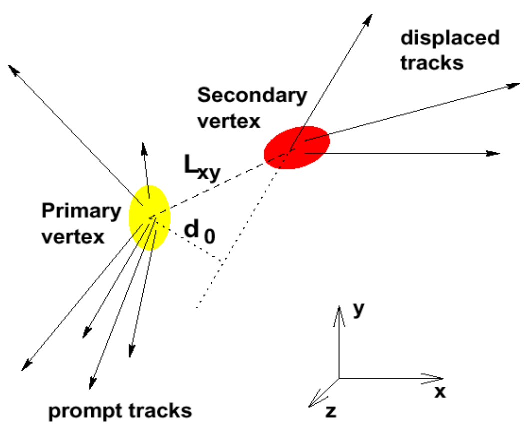


Tagging b-jets

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

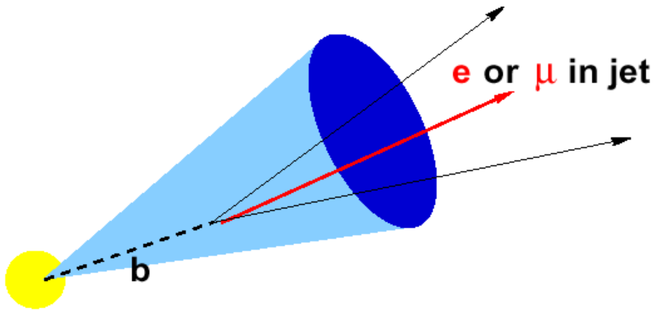
B hadrons are long-lived

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:

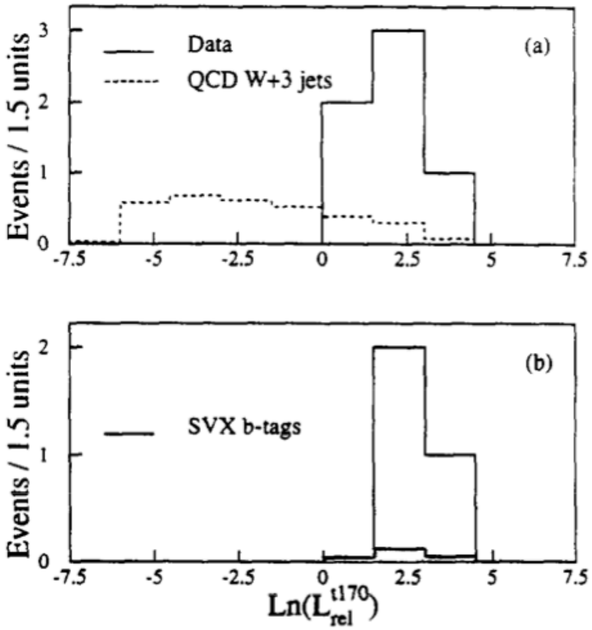
- Status report from each group (dilepton, single lepton)
- Small, not significant excess in all channels

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

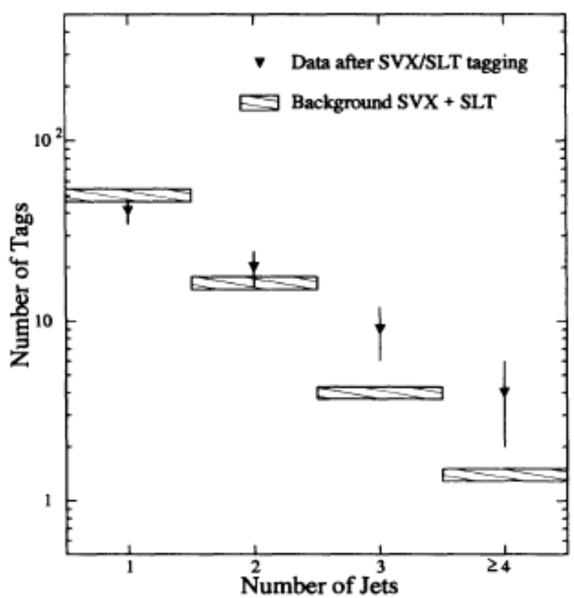
D0: added more data and re-optimized for heavy top (single- and di-lepton)
- Observed 7 events (expect 4-6 from bkg)
- No independent evidence

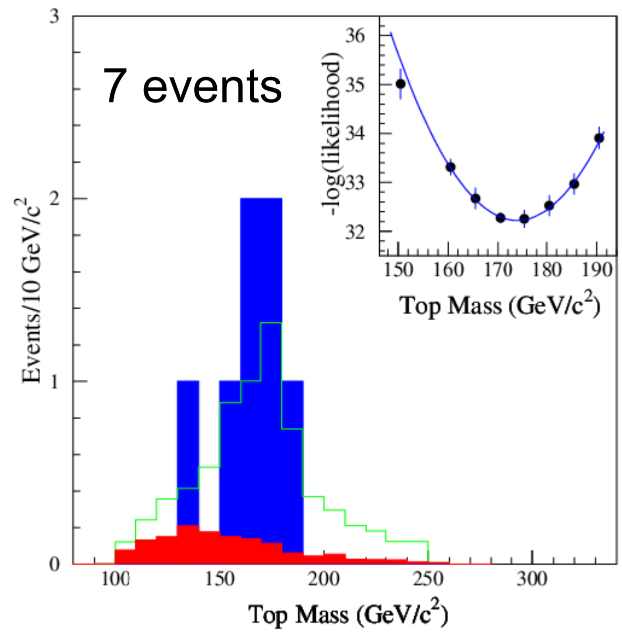
First evidence (1994)

VOLUME 73, NUMBER 2 PHYSICAL REVIEW LETTERS 11 JULY 1994

Evidence for Top Quark Production in $\bar{p}p$ Collisions at $\sqrt{s} = 1.8$ TeV

We summarize a search for the top quark with the Collider Detector at Fermilab (CDF) in a sample of $\bar{p}p$ collisions at $\sqrt{s} = 1.8$ TeV with an integrated luminosity of 19.3 pb^{-1}. We find 12 events consistent with either two W bosons, or a W boson and at least one b jet. The probability that the measured yield is consistent with the background is 0.26%. Though the statistics are too limited to establish firmly the existence of the top quark, a natural interpretation of the excess is that it is due to $t\bar{t}$ production. Under this assumption, constrained fits to individual events yield a top quark mass of $174 \pm 10^{+13}_{-12}$ GeV/c^2. The $t\bar{t}$ production cross section is measured to be $13.9^{+6.1}_{-4.8}$ pb.



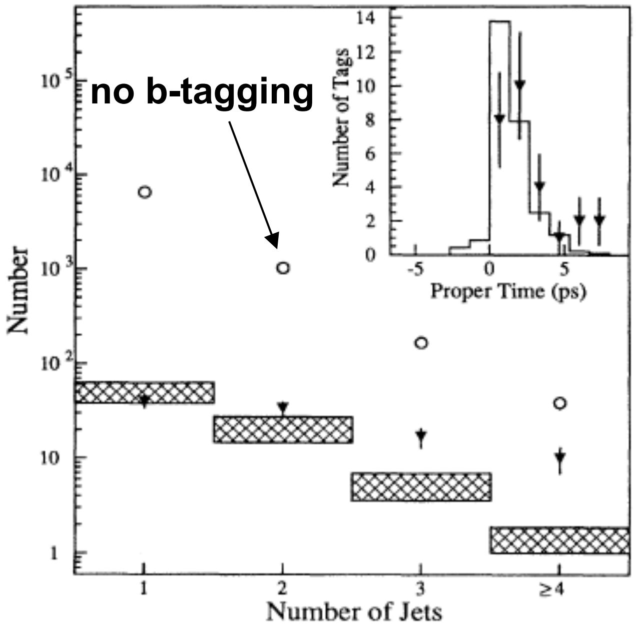


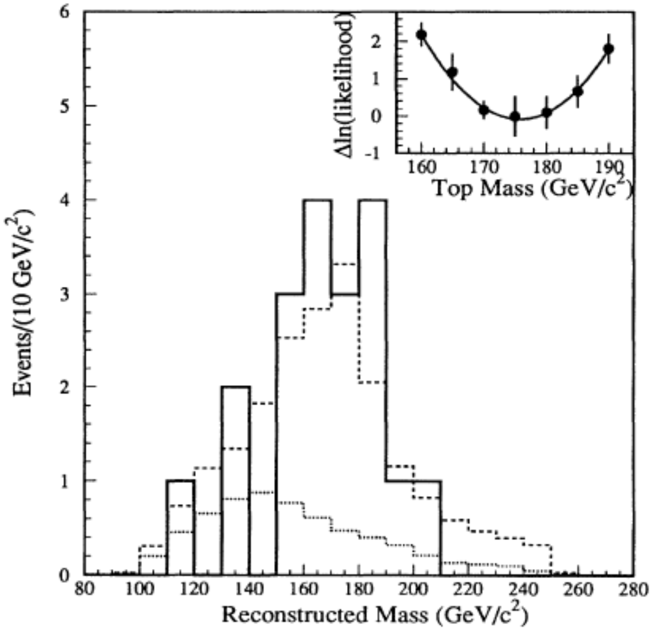
First measurements

VOLUME 74, NUMBER 14 PHYSICAL REVIEW LETTERS 3 APRIL 1995

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

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





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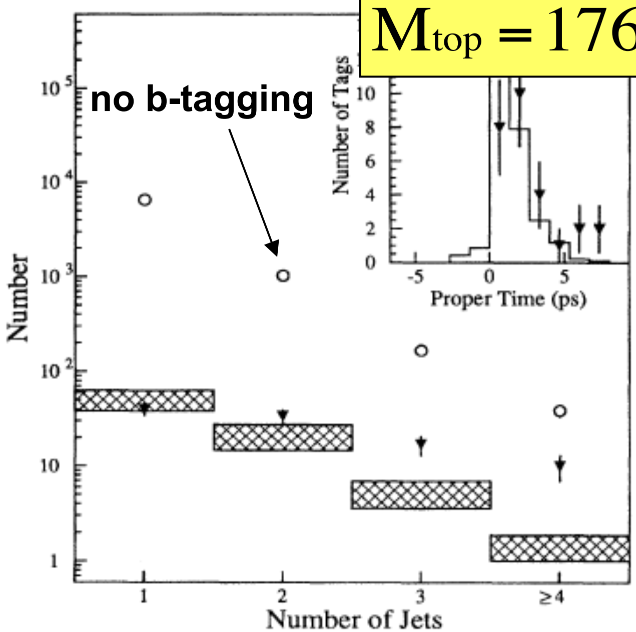
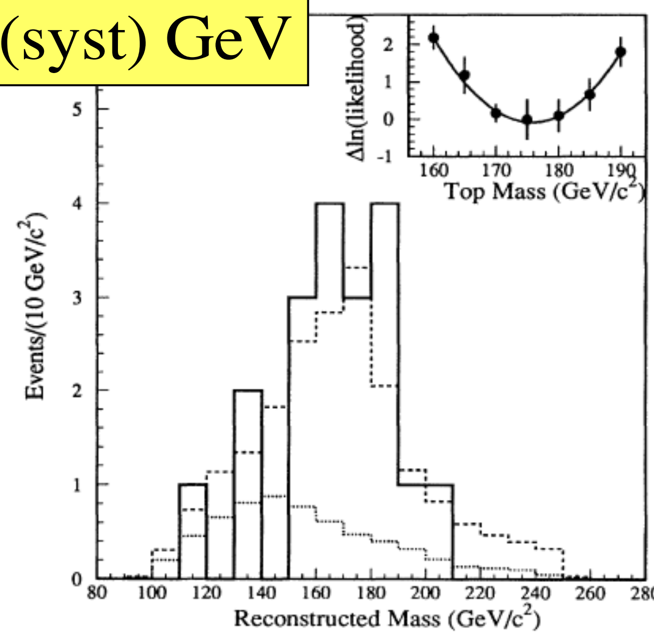
$$\sigma_{tt} = 6.8^{+3.6}_{-2.4}\ \text{pb}$$

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





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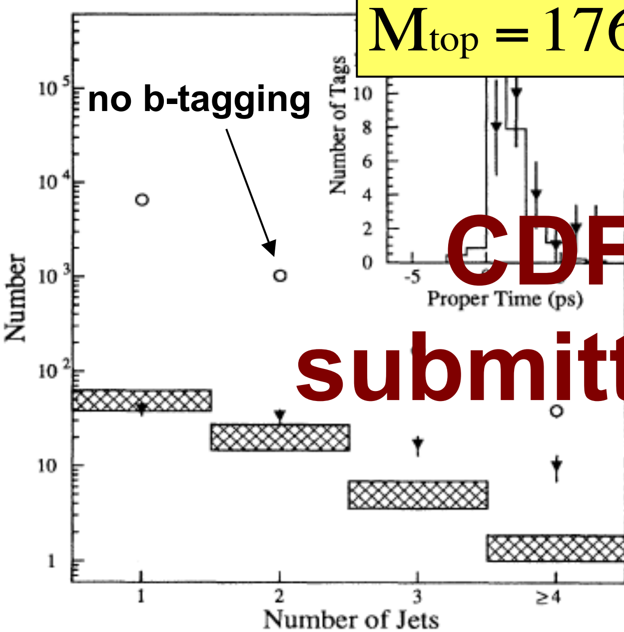
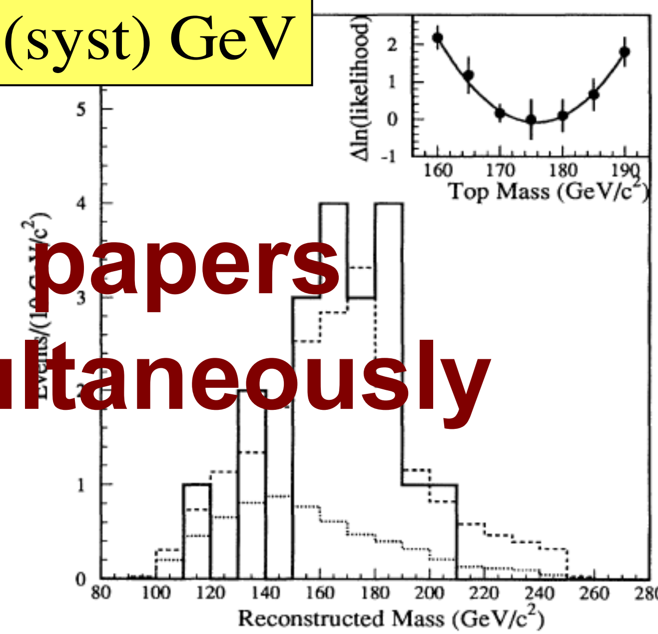
$$M_{top} = 176 \pm 8(\text{stat}) \pm 10(\text{syst})\ \text{GeV}$$

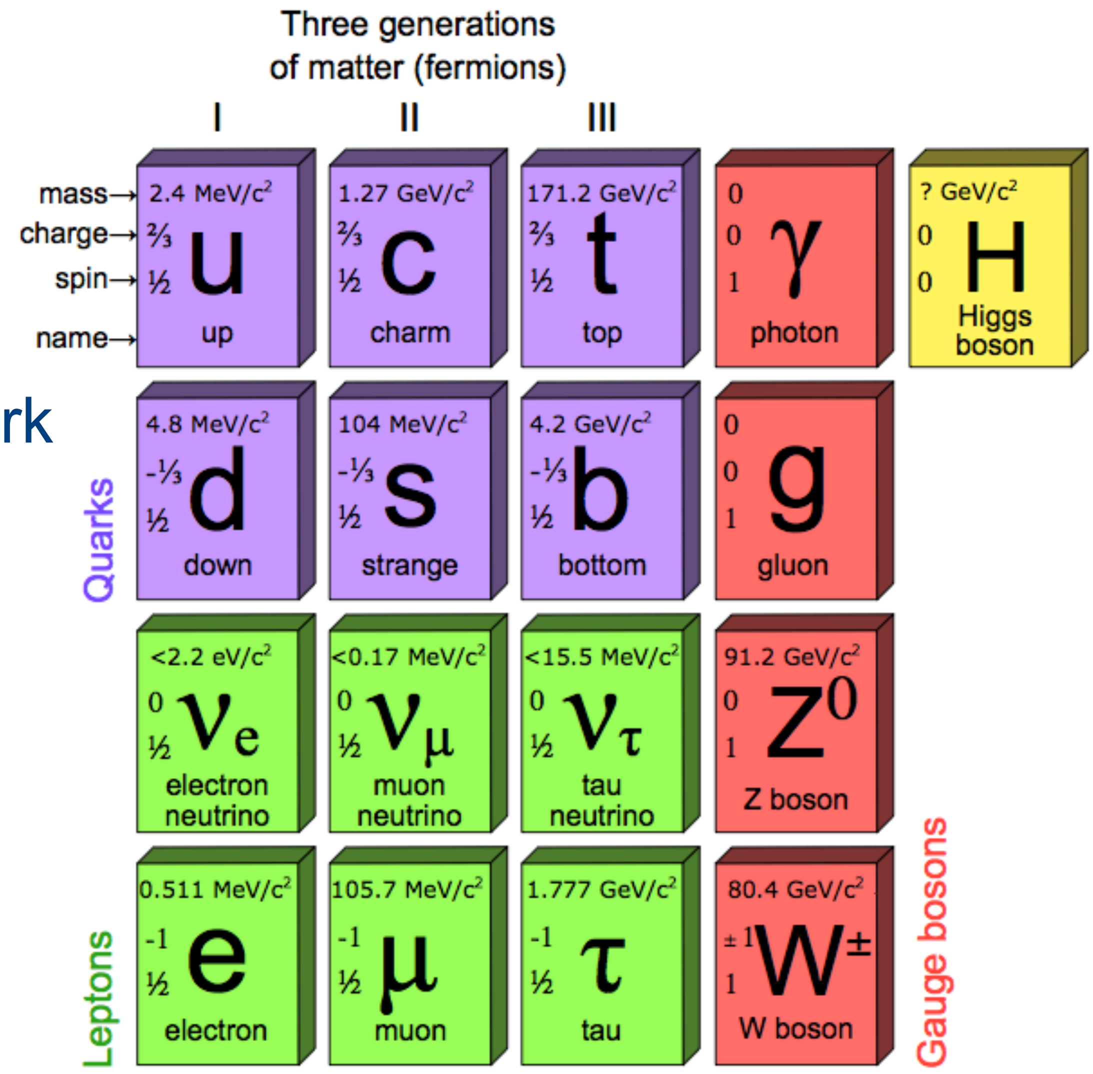




CDF and D0 papers submitted simultaneously

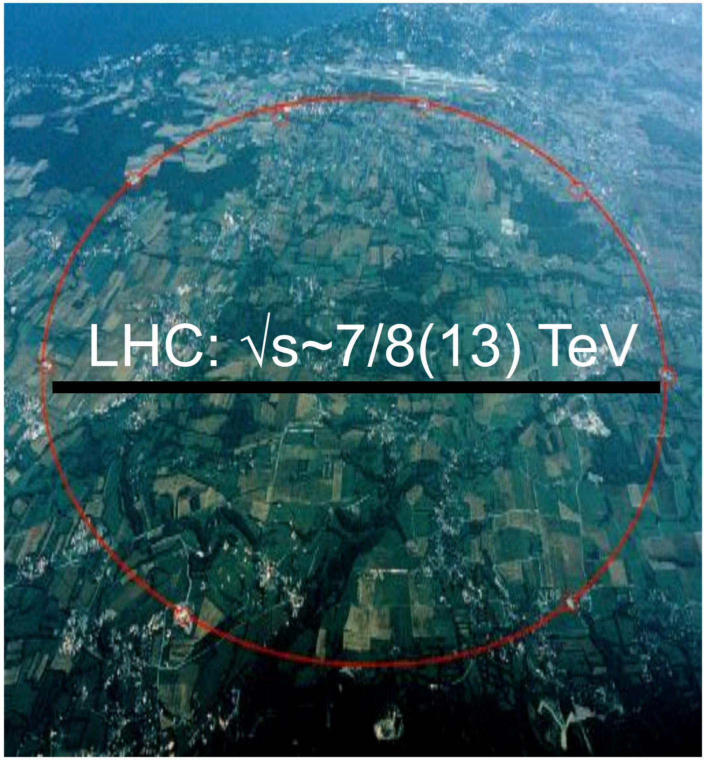
Top quark and its relevance

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



The Large Hadron Collider

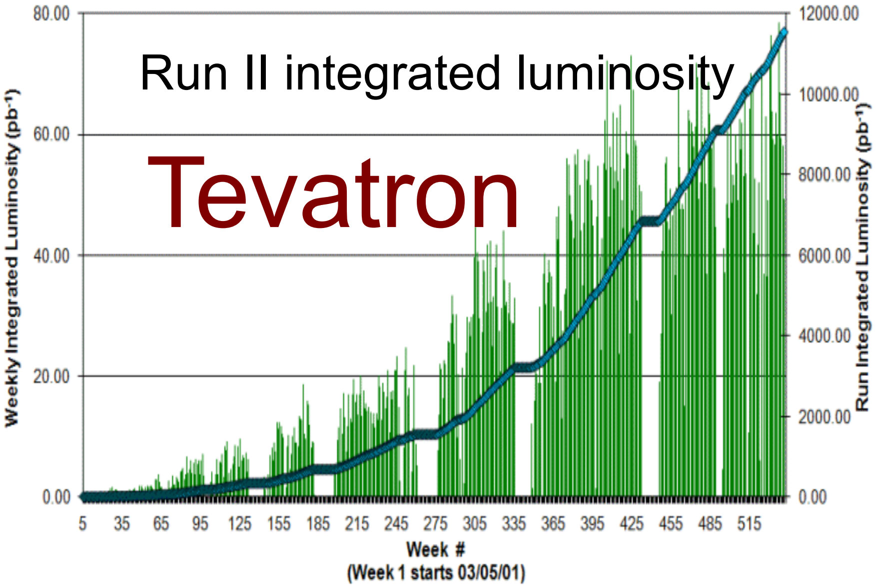
- Built to explore new energy frontiers
  - First colliding beams in 2009
  - started with “low” luminosity in 2010
  - ~5 fb^{-1}@7TeV delivered in 2011
  - ~20 fb^{-1}@8TeV in 2012
  - >150fb^{-1}@13 TeV in 2015-2018

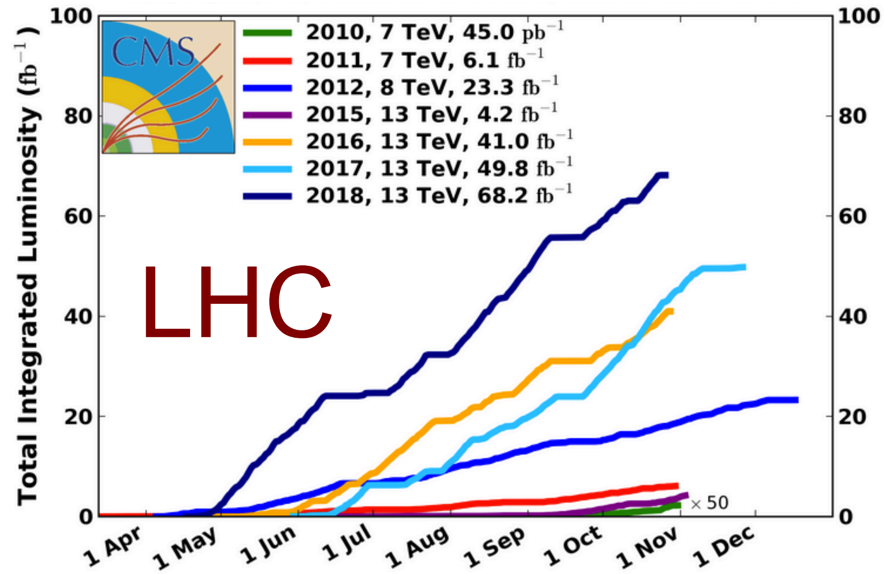


- re-establish SM measurements
- access to new physics processes

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

Tevatron vs LHC





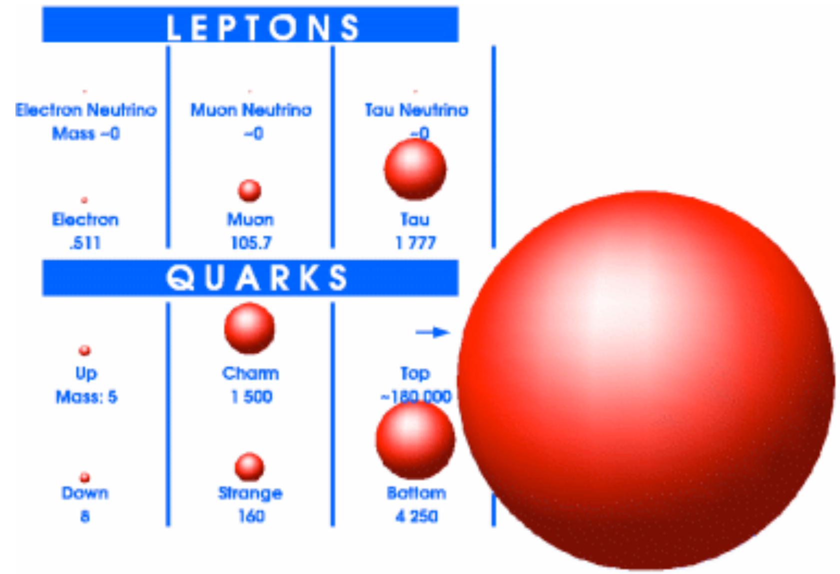
Energy: 1.96 TeV
Int. Luminosity: 12 fb^{-1}
Age: ~25 years
Events/exp (1 fb^{-1})
350 ee eμ, μμ
2k lepton + jets

Energy: 7/8/(13) TeV
Int. Luminosity: 5/20/(150) fb^{-1}
Age: ~9 years
Events/exp (1 fb^{-1})
40k ee eμ, μμ
250k lepton + jets

What is the Top quark?

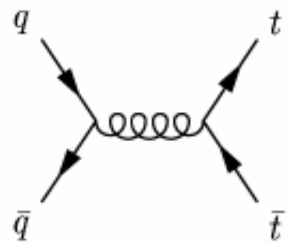
$$\text{Quarks:} \quad \begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} t \\ b \end{pmatrix}$$

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

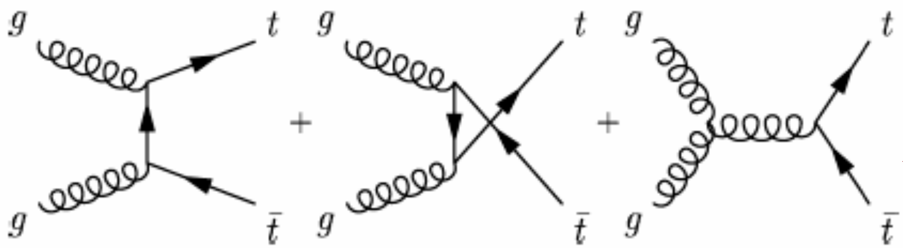


- It is the heaviest fundamental particle
  - $M_{top} = 174.3 \pm 0.6$ GeV (arXiv:1407.2682)
- Weak isospin partner of the b-quark
- Completes the SM of quarks and leptons

How is the top quark produced?



Dominant at Tevatron



Dominant at the LHC

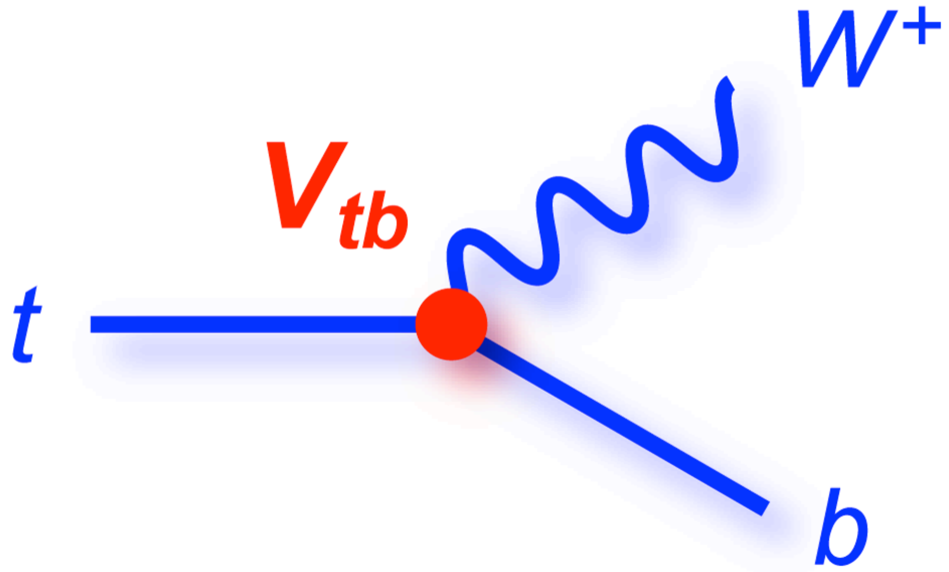
Predicted cross sections:

Collider	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)

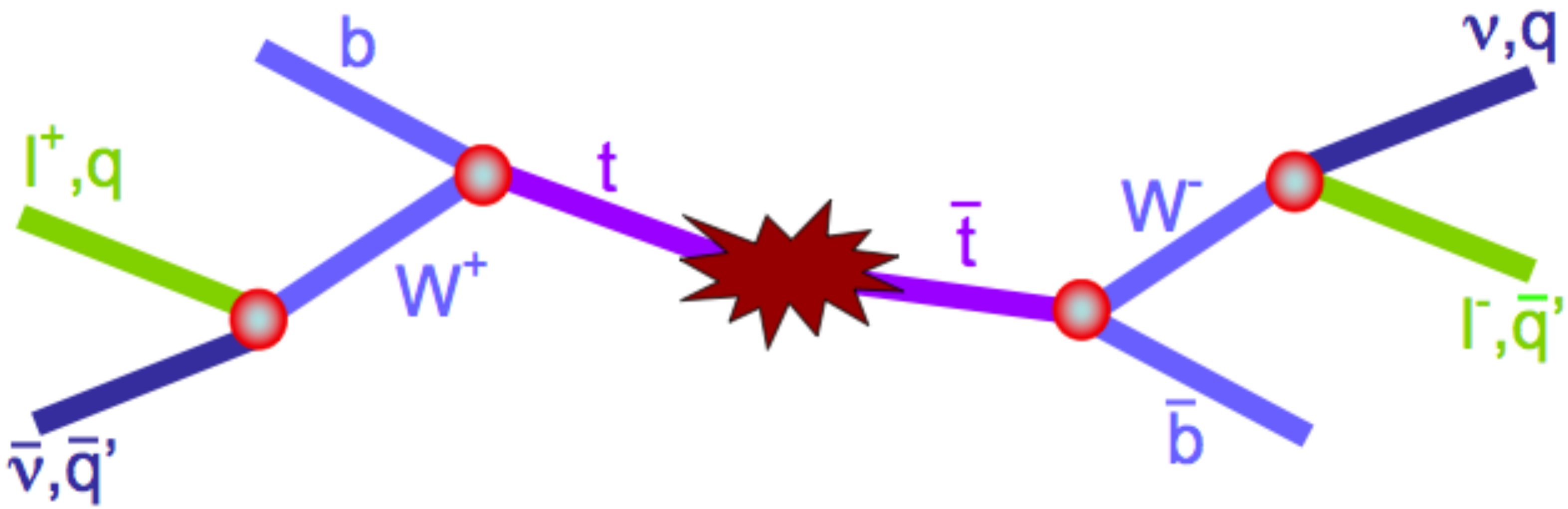
	LHC	Tevatron
gg	~85%	~10%
qq	~15%	~90%

How does a top quark decay?



- almost always t→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

Interesting physics with Top quark



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

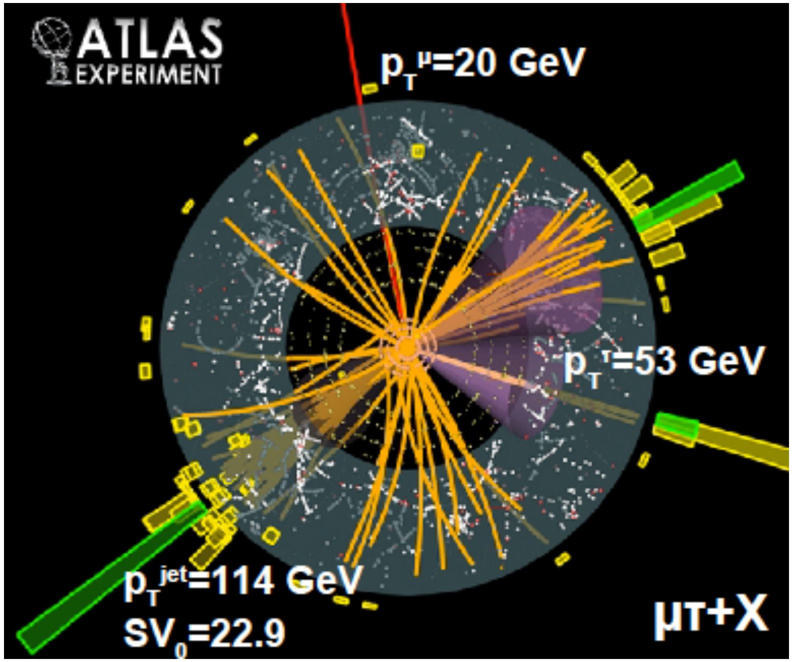
PROPERTIES
Mass
Kinematics
Charge
Lifetime and width
W helicity
Spin
...

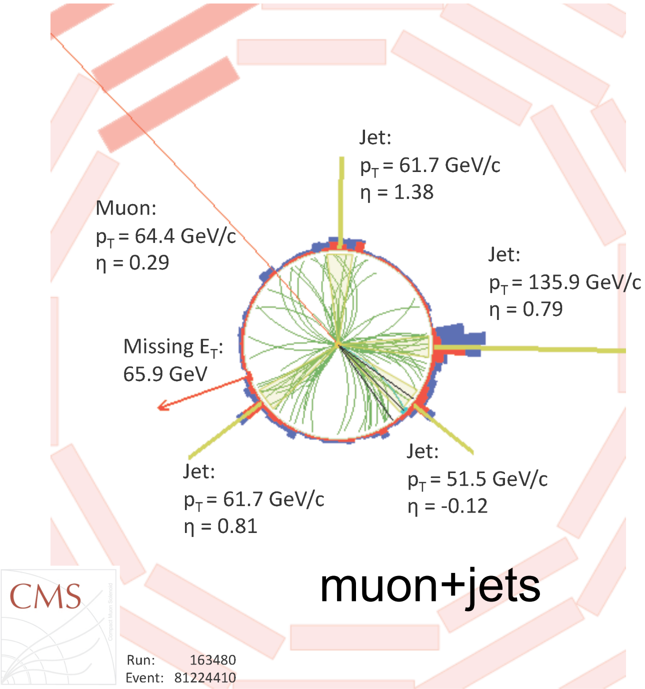
DECAY
Branching ratios
Charged Higgs (non-SM)
Anomalous couplings
Rare decays
CKM matrix elements
Calibration sample @LHC
...

Particle identification

- Object identification and reconstruction

Selection of top quark events

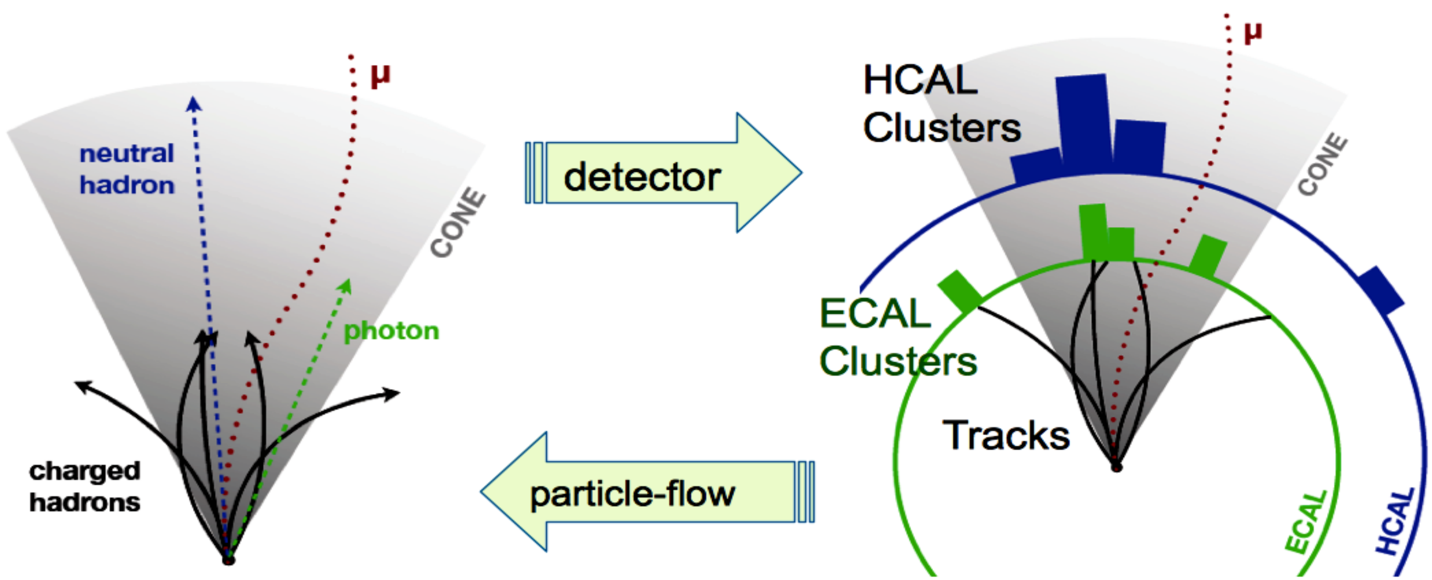




- Trigger:
  - single or double (isolated) lepton
- Leptons:
  - e/μ, p_T>20/30 GeV, |η|<2.5
  - Identification/reconstruction
  - Tracker/calorimeter isolation
- Jets:
  - at least 2 jets, p_T>30 GeV, |η|<2.5
  - anti-kT algorithm, with cone 0.4-0.5
  - b-tagging is optional
- Missing transverse energy: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

Particle Flow event reconstruction

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

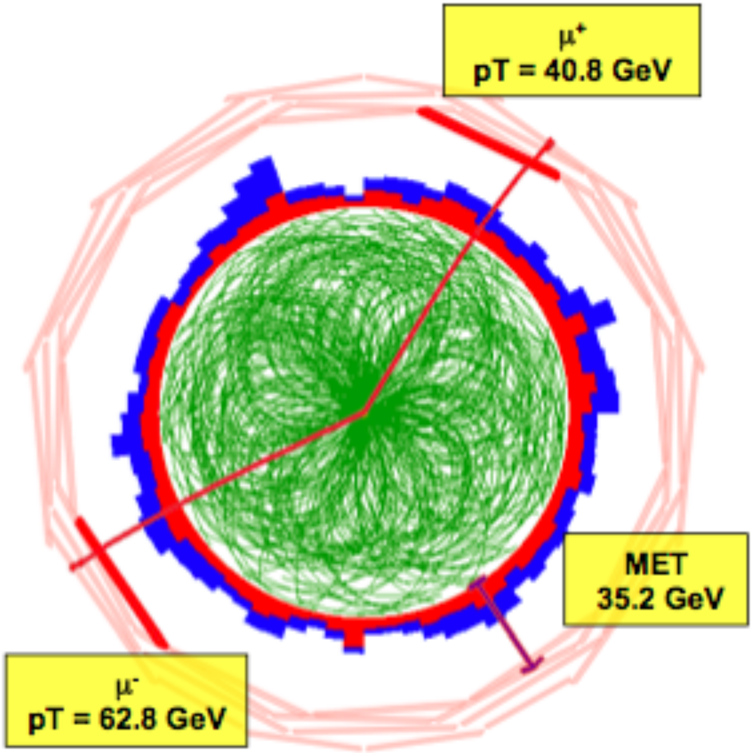


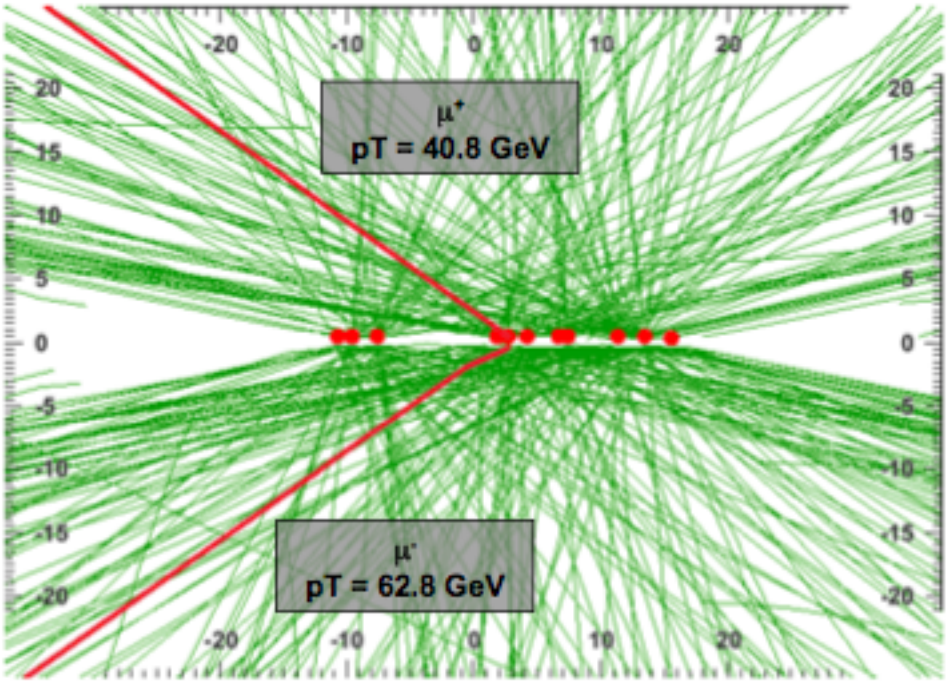
Challenge: Pile-up

$Z \rightarrow \mu\,\mu$

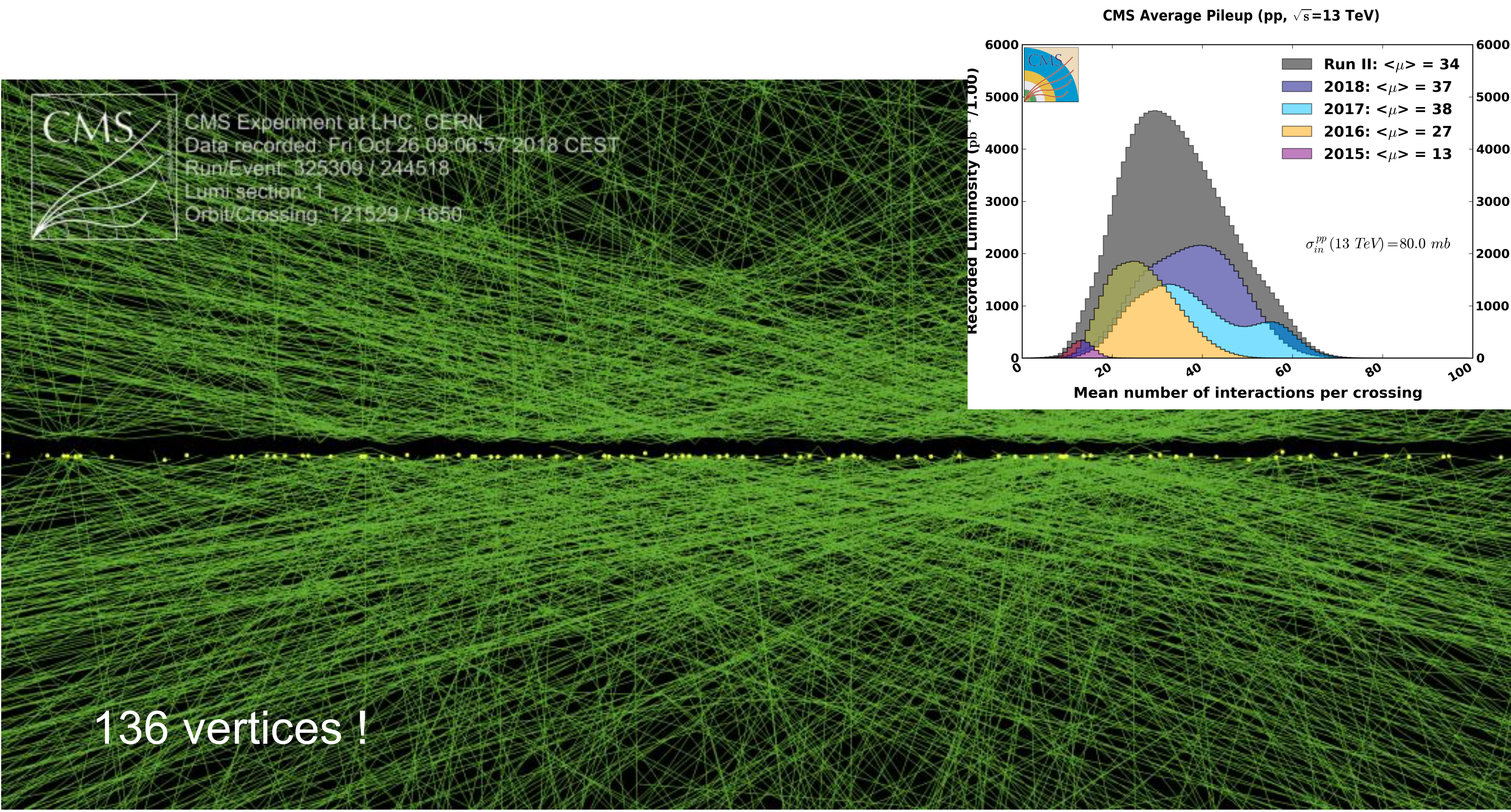
Expected MET = 0

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



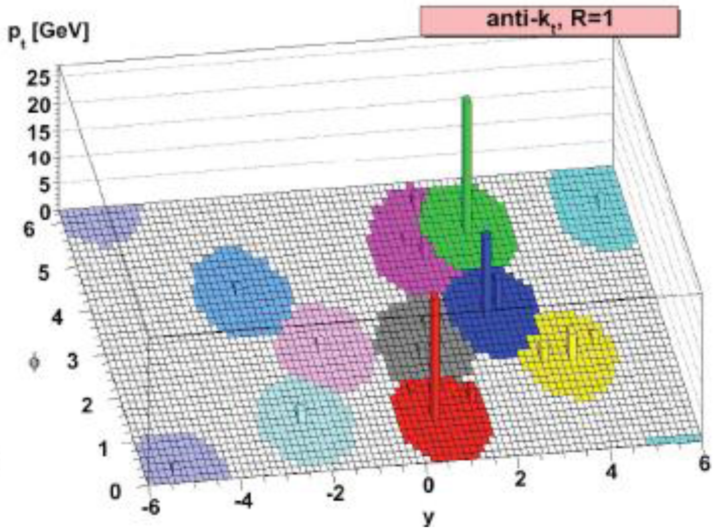


…in a challenging environment



Jet reconstruction

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



Missing transverse momentum

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

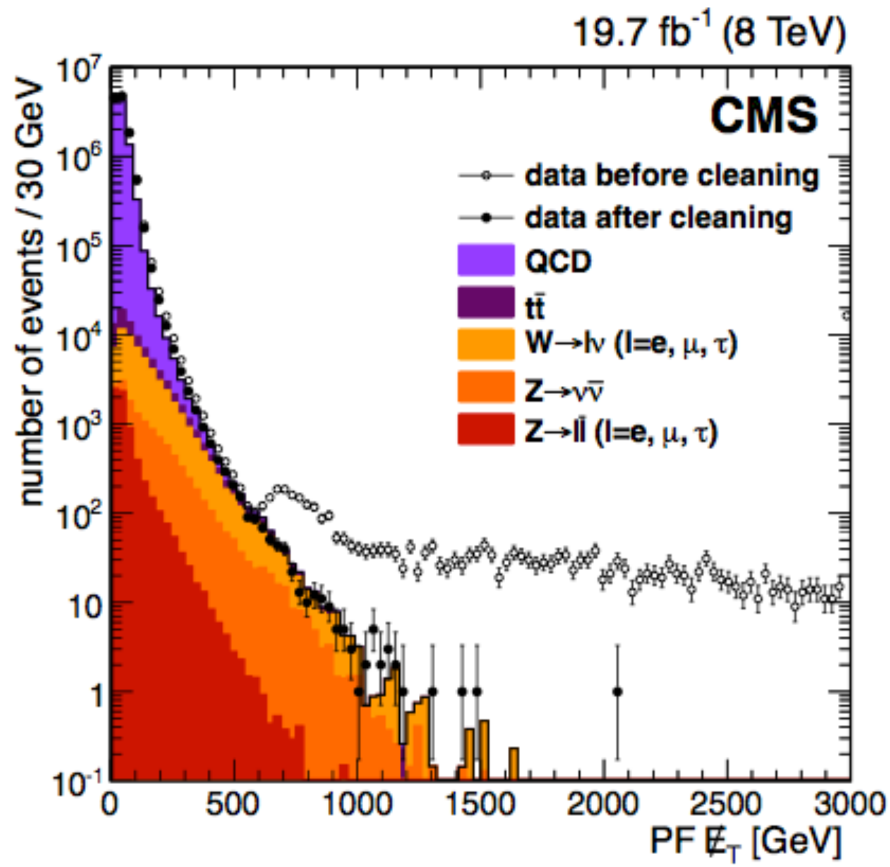
transverse energy vector

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

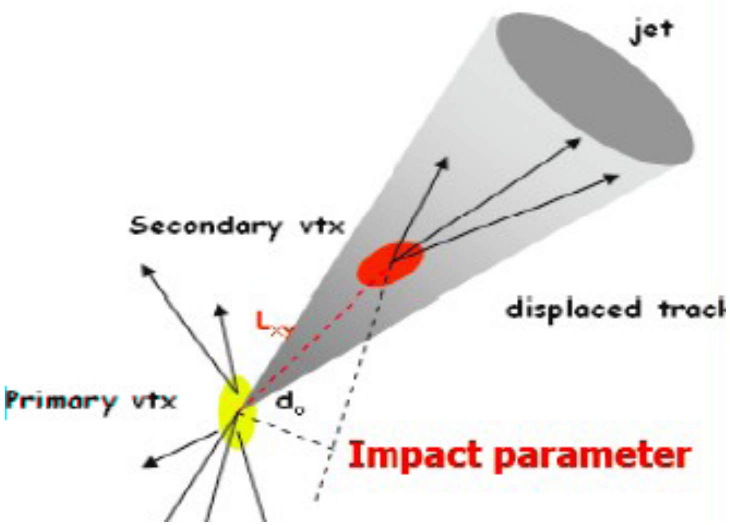
where the sum runs over the transverse momenta of all visible final state particles.

Challenge: MET

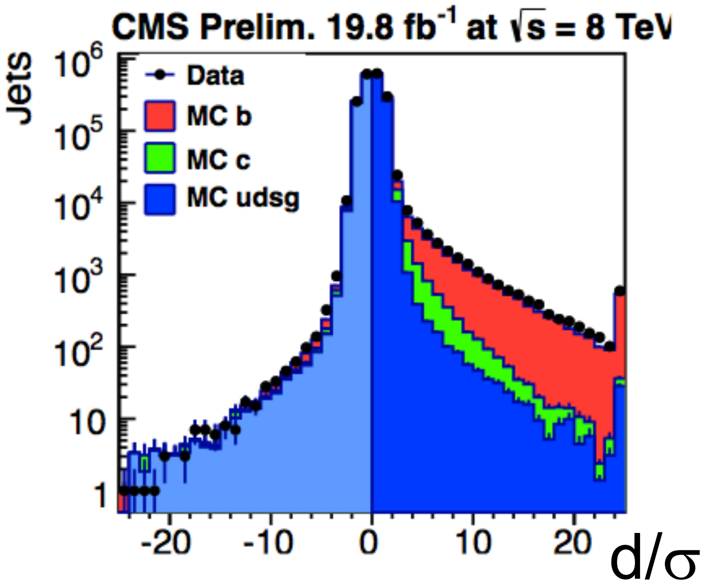
- Performance of the MET measurement depends on the measurement of ALL particles in the event
- Measurement is affected by:
  - Noise, mis-calibration, various calorimeter problems (dead channels, etc)
  - Modeling of QCD background events, pile-up, multiple interactions, …
  - Muon momentum measurement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



Challenge: b-tagging



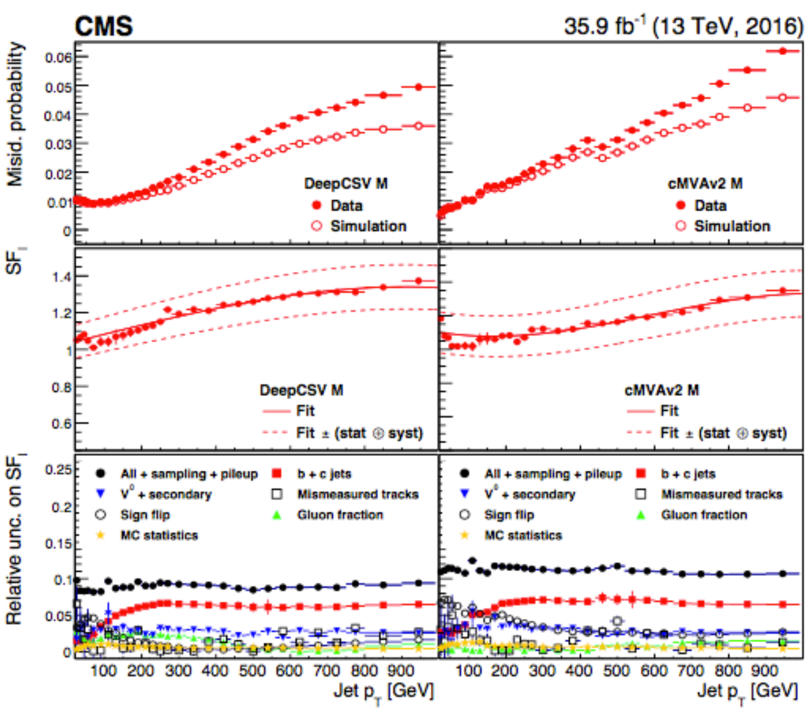
- Lifetime: τ_b~1-2 psec
- Reduction of background obtained by identifying jets from b-quarks
- Two methods:
  - Secondary vertex tagging
  - Semileptonic decays of b-hadrons in jets ($b \to l \nu_l X$)

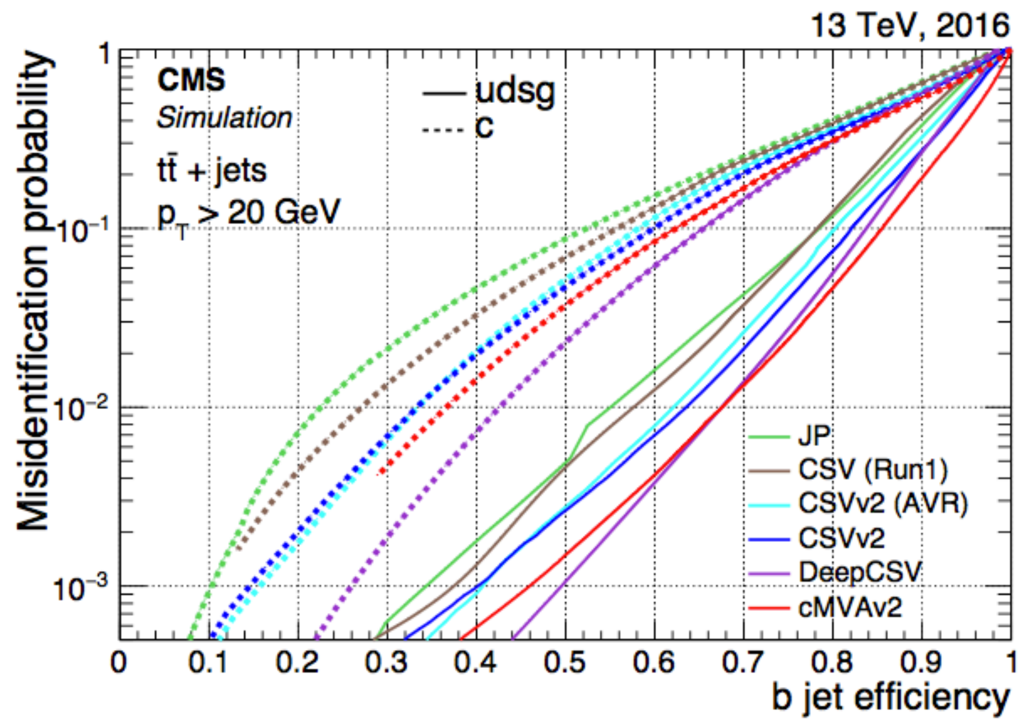


b-tag: fake rates and efficiencies

arXiv:1712.07158

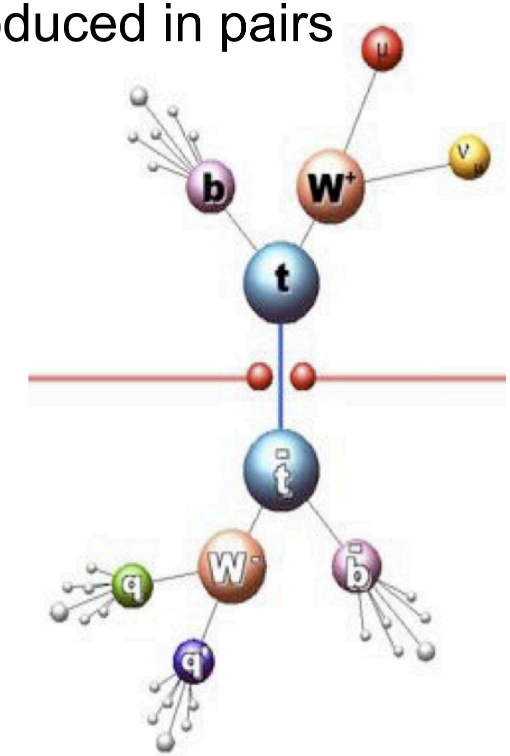
- b-tag optimization: trade-off between fake rate and efficiency
- study performance of different tagging working points
- Uncertainty on data/MC scale factor, depending on algorithms

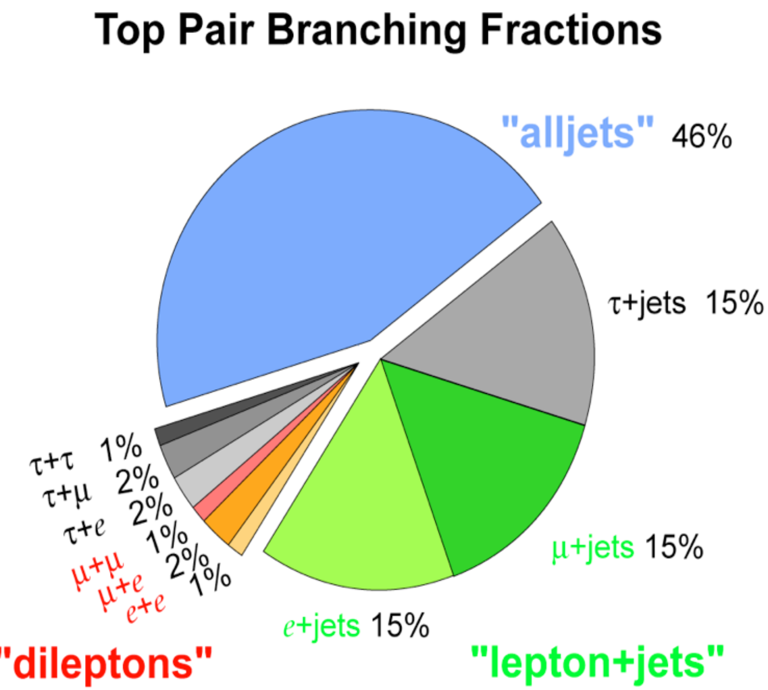




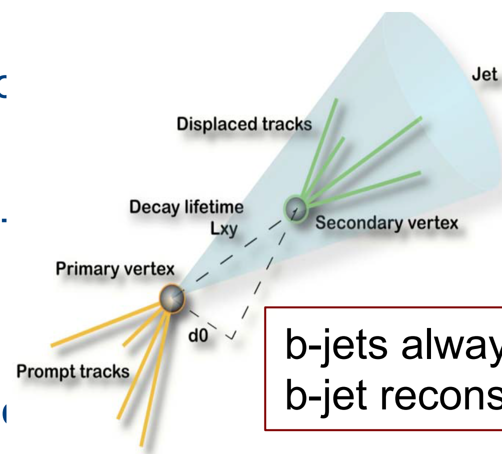
Top quark decays

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 neutrin



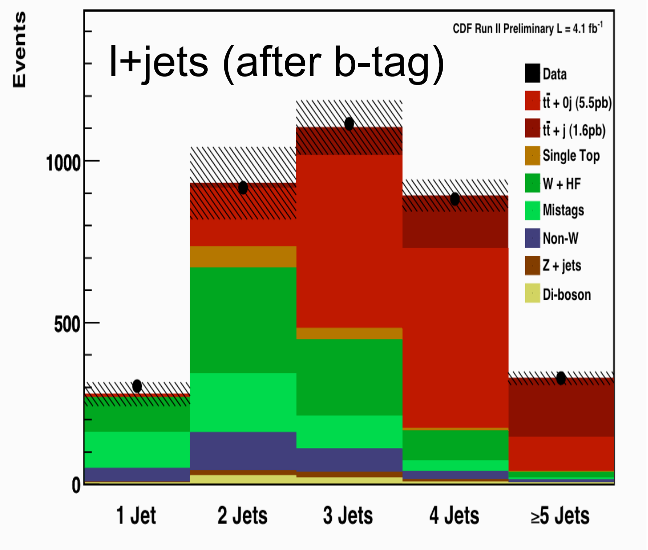
b-jets always present
b-jet reconstruction plays important role

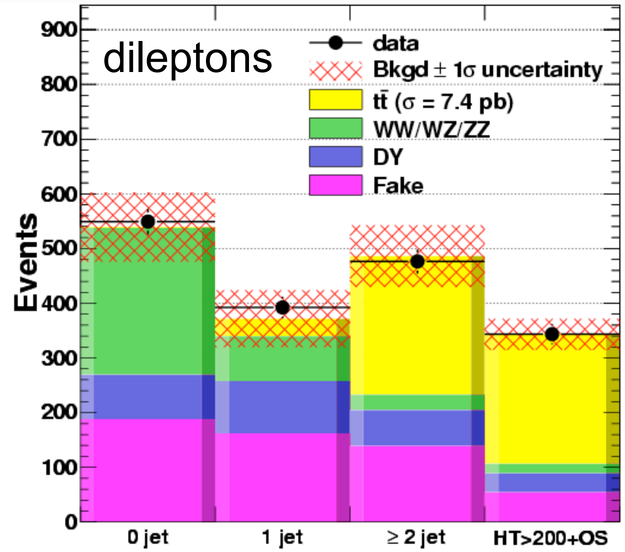
Measurements

- Measurement of the cross section

Top quark events

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





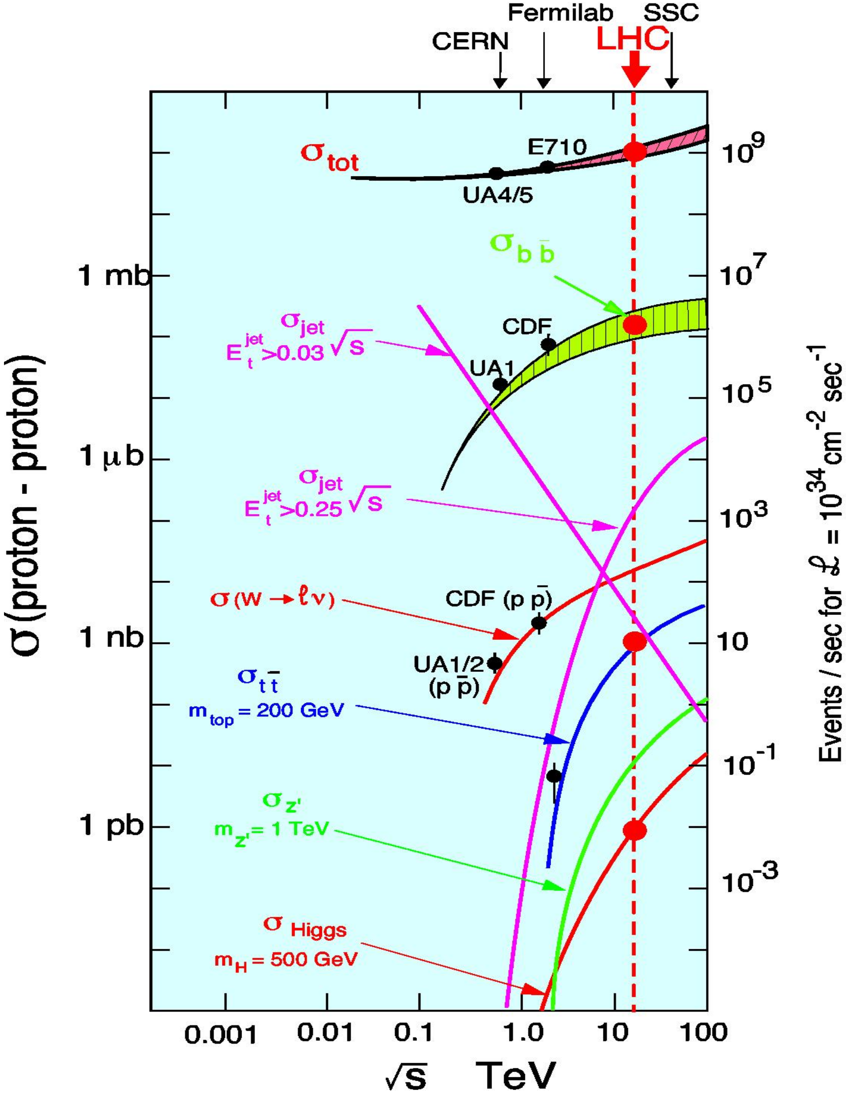
Theory cross sections: TeV vs LHC

Collider	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 13 TeV

- LHC collisions started at 7/8 TeV
- LHC design is at 14 TeV
- Top cross section drops faster than background processes at lower sqrt{s}
  - top σ(7TeV) = 172 pb
  - top σ(8TeV) = 246 pb
  - top σ(13TeV)= 832 pb
- Background is more "flat"



Cross section measurement

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

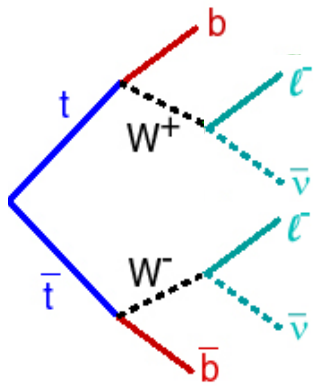
Number of observed events

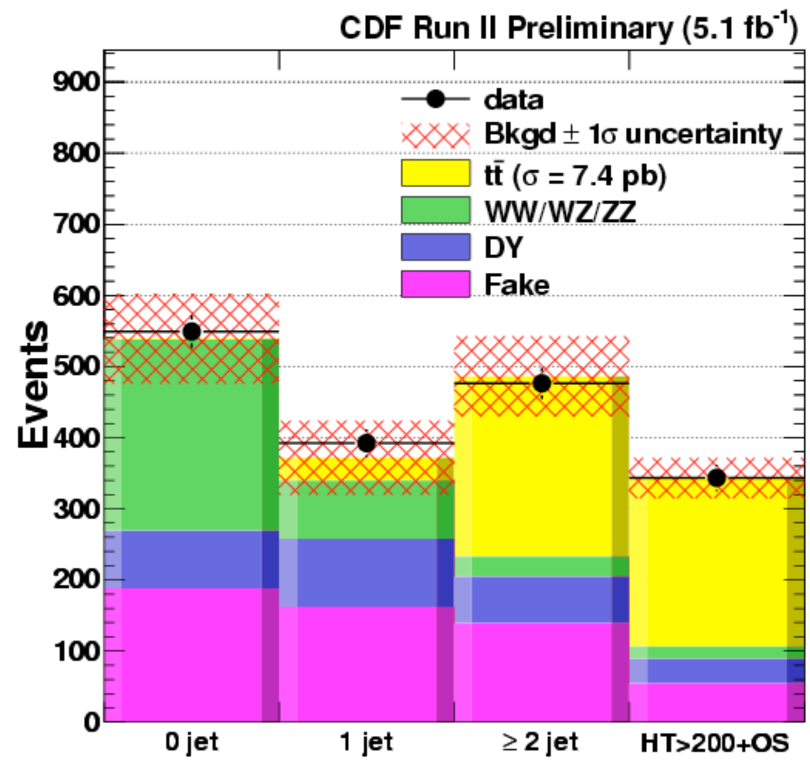
Number of background events *(from data, calculated from theory)*

Acceptance *(experimental: detector, efficiencies)*

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

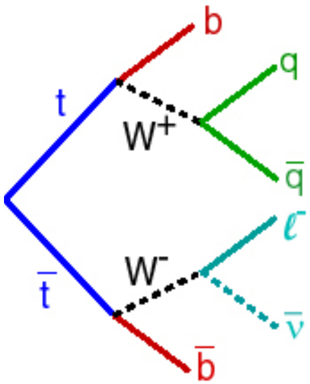
Dilepton channel





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

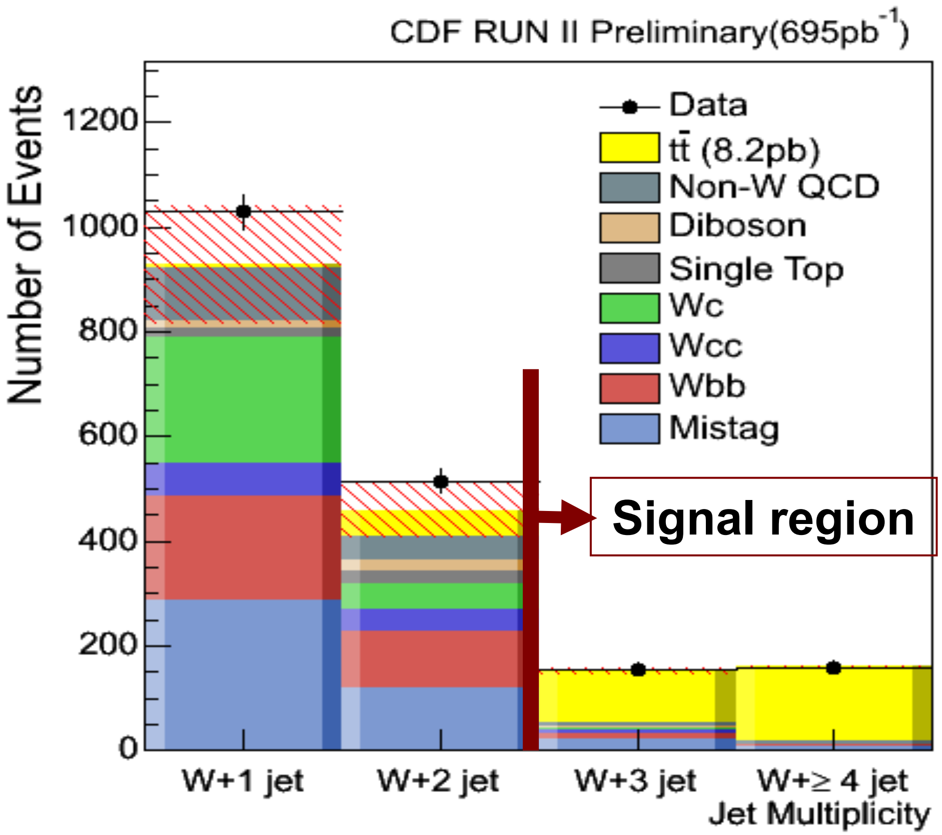
Lepton + jets



- BR ~30%
- Background: moderate

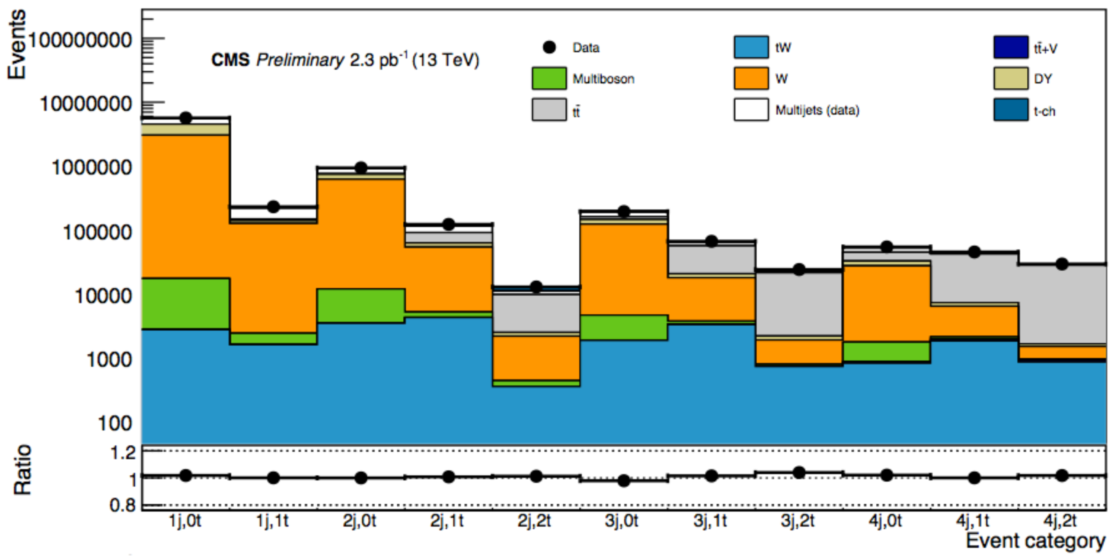
- Selection:
  - one lepton + ≥3 jets + MET
  - may require b-tag

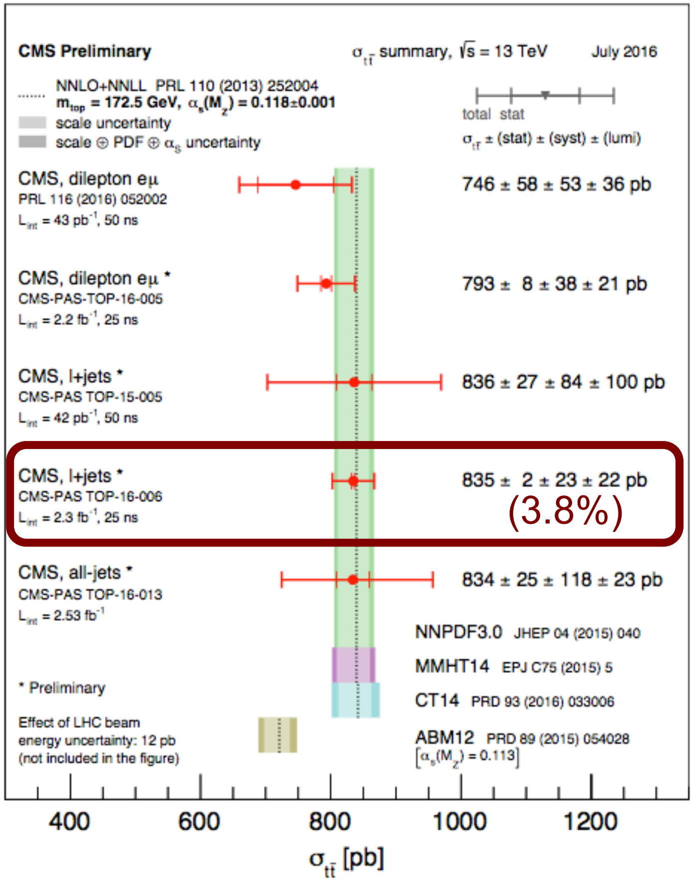
- Main backgrounds:
  - hadronic multi-jet, W+jets



Cross section: multi-dimensional fit

- Lepton+jet final state
- Keep selection as inclusive as possible
- Categorize events according to (b-) jet multiplicity
  - high-purity vs background dominated
  - Constrain systematics (JES, ISR/FSR, modeling, etc)
- Combined fit of M_{lb} to signal and backgrounds
- Precise cross section measurement





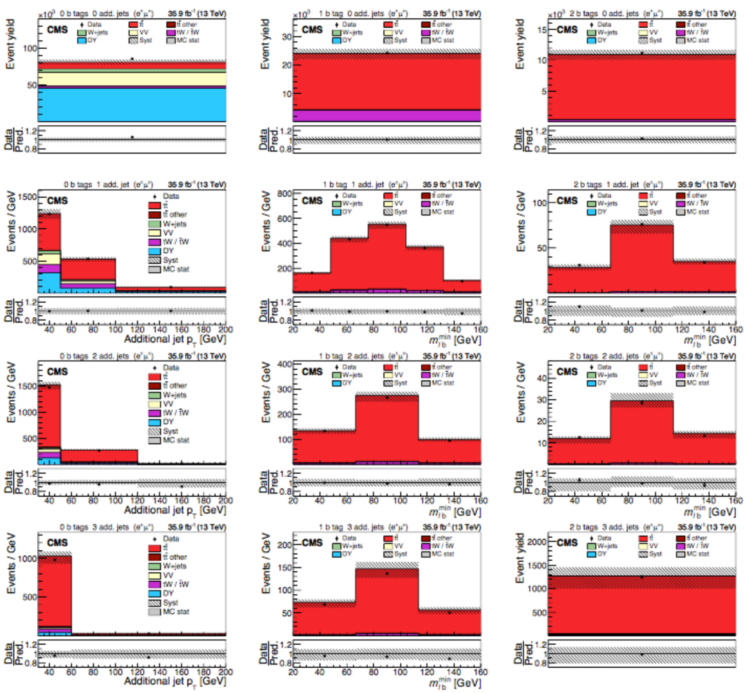
Cross section: multi-dimensional fit

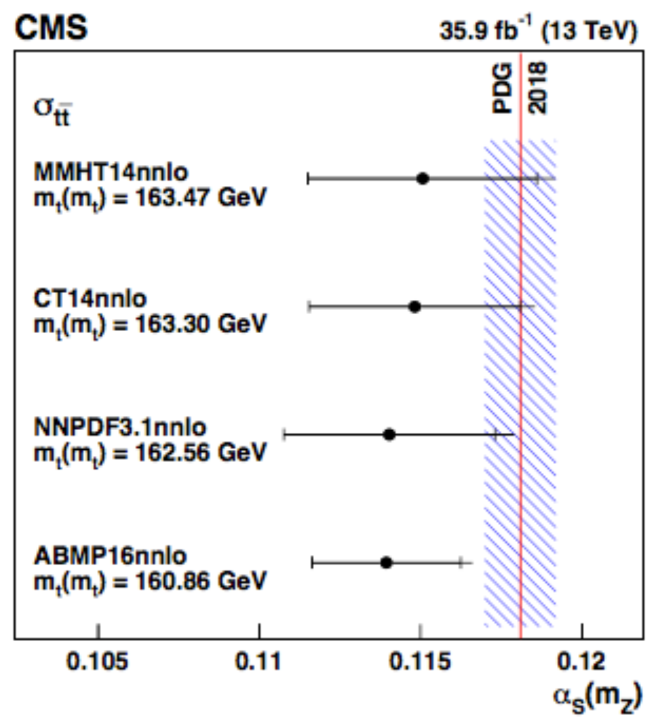
- Dilepton final state
- Simultaneous fit in ($N_{additional\ jet}$,$N_{b\text{-}jet}$) categories
- Fit of σ_{ttbar} and m(top)

(~4%)

$$\sigma_{t\bar{t}} = 803 \pm 2\,(\mathrm{stat}) \pm 25\,(\mathrm{syst}) \pm 20\,(\mathrm{lumi})\,\mathrm{pb}$$

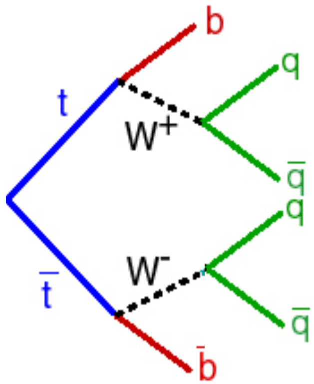
$$m_{\mathrm{t}}^{\mathrm{MC}} = 172.33 \pm 0.14\,(\mathrm{stat})\,^{+0.66}_{-0.72}\,(\mathrm{syst})\,\mathrm{GeV}$$

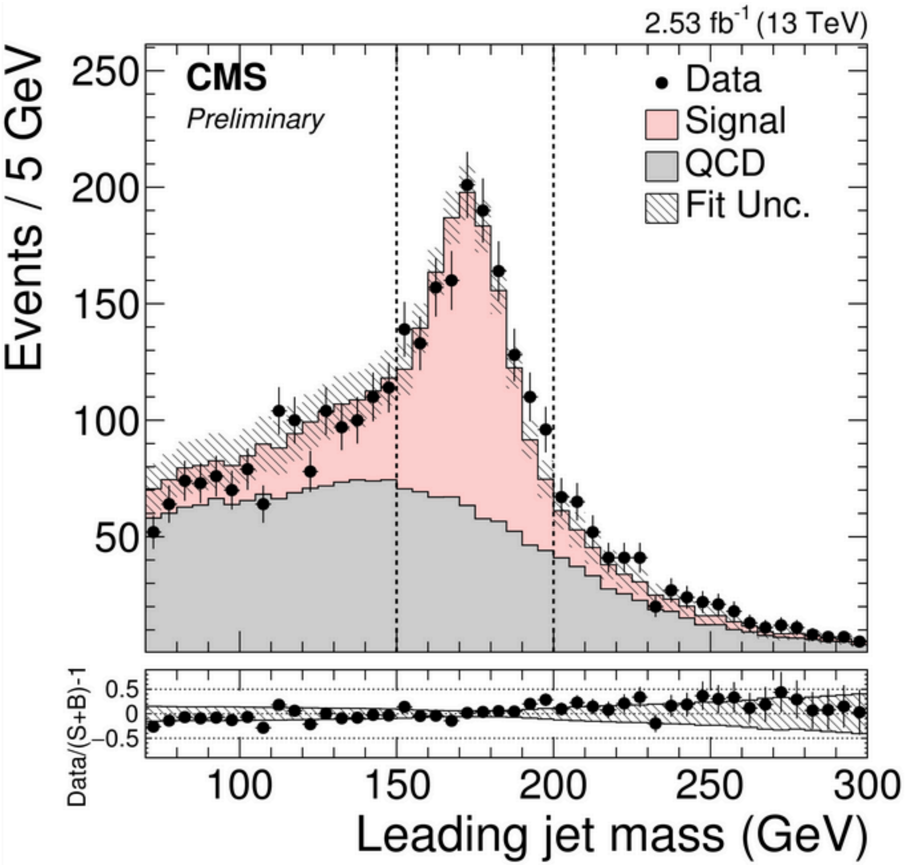




All hadronic

CMS-TOP-16-013



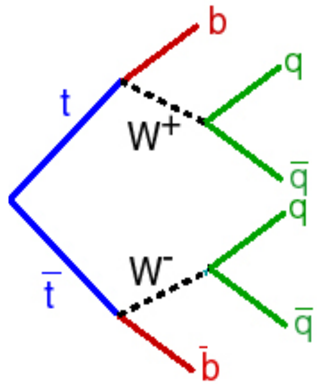


- BR ~46%
- Background: large

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

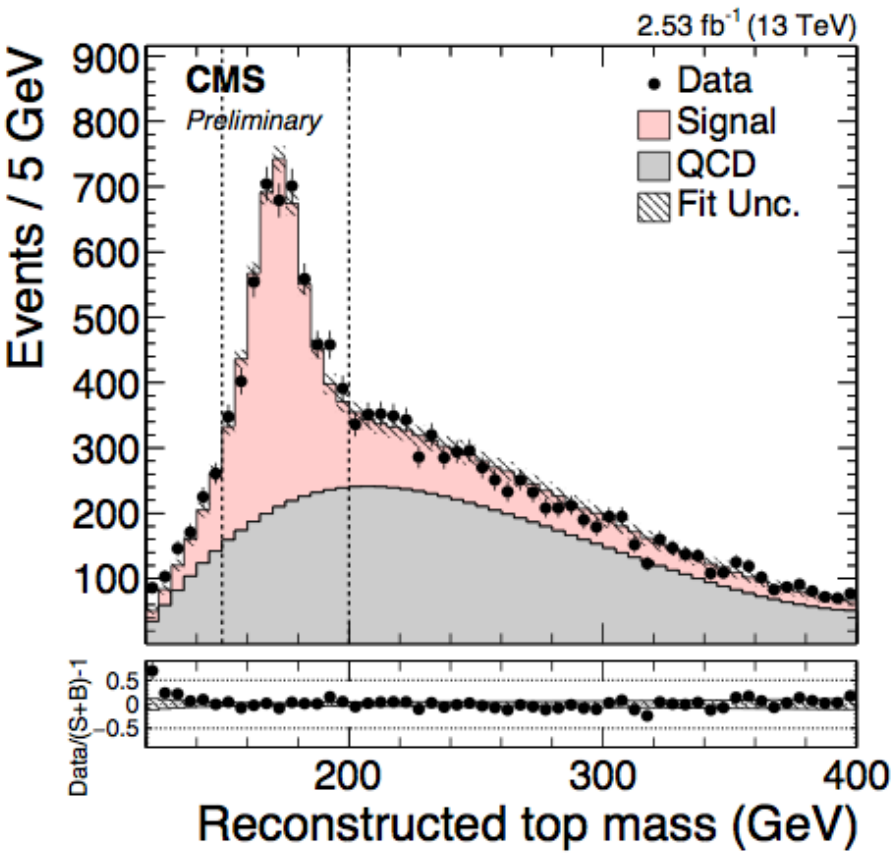
All hadronic

CMS-TOP-16-013



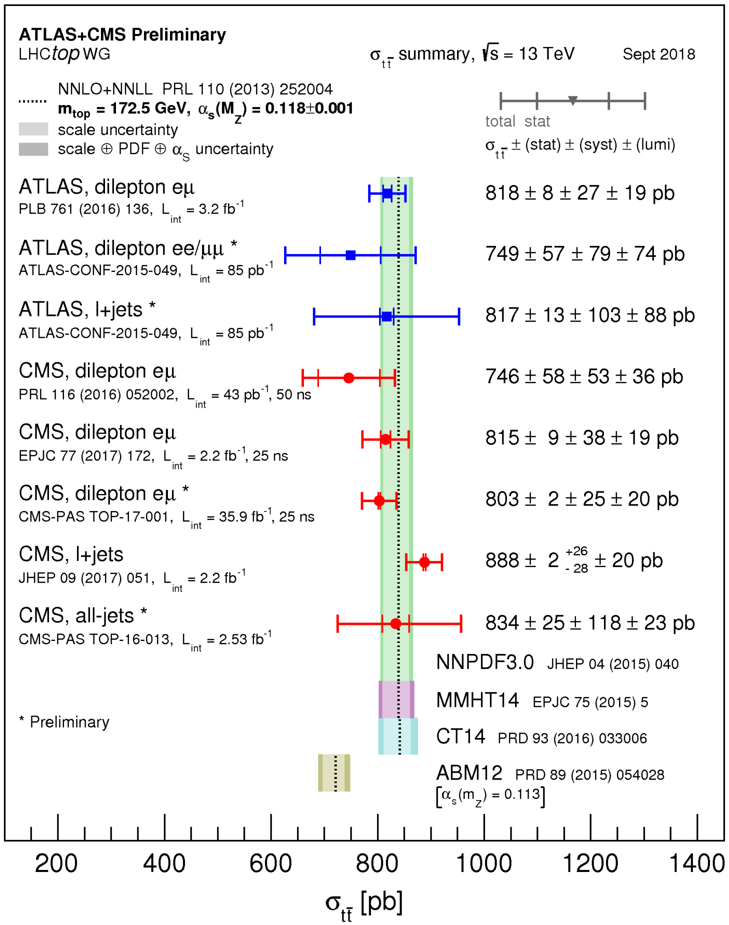
- BR ~46%
- Background: large

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

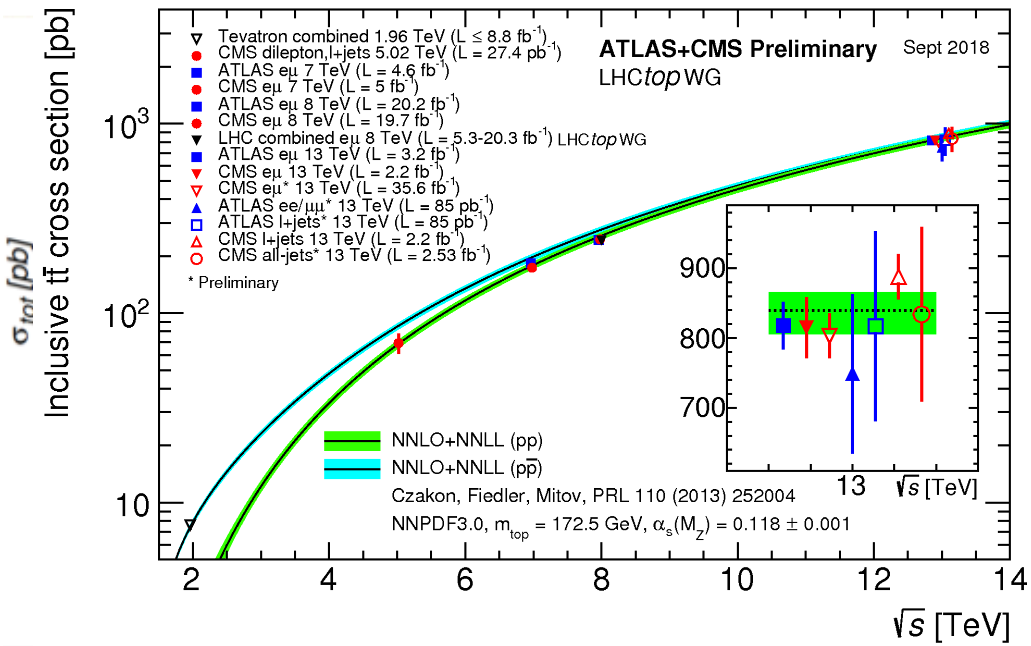


Cross sections

±4%



⇒measurements challenging theory



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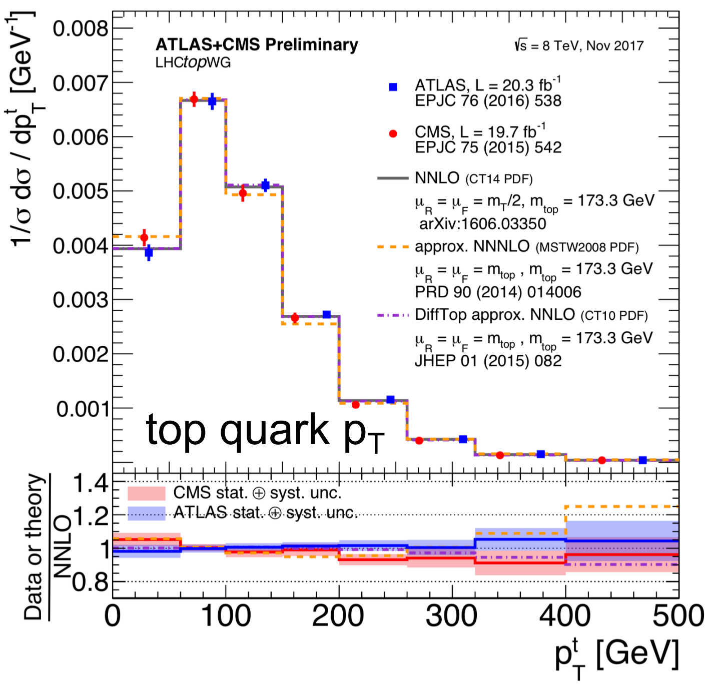
LHC 14 TeV	953.6	+22.7(2.4%) −33.9(3.6%)	+16.2(1.7%) −17.8(1.9%)

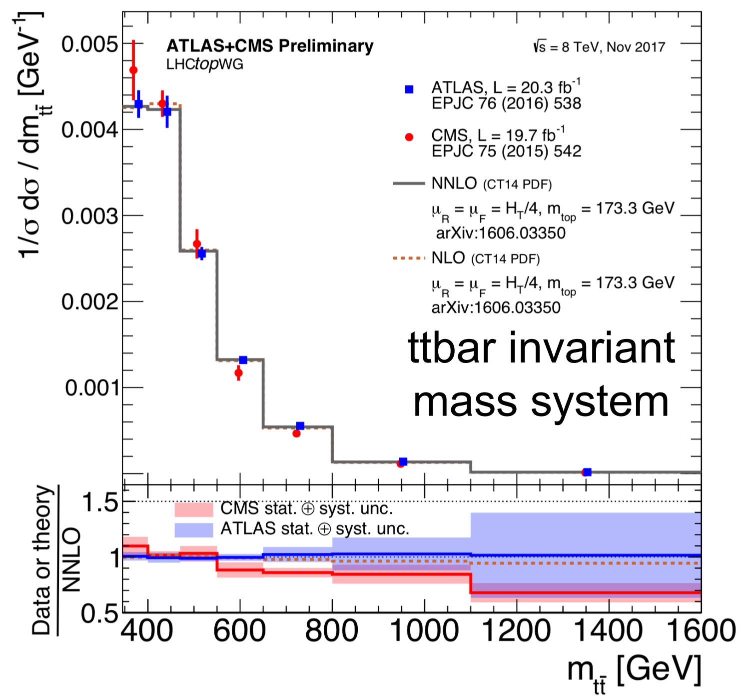
±3-5%

Differential cross section

- Measure differential cross section
  - Test perturbative QCD
  - Test BSM scenarios (Z' decays, etc)
- Cross sections measured as a function of p_T, η, invariant mass of the final state leptons, top quarks, ttbar system, etc.
- Good agreement with expectations

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





end

- Introduction on top quark
- Basic concepts on production and decays
- Cross section measurements and relevance to BSM searches

- Next lecture: ``Top quark properties and beyond”

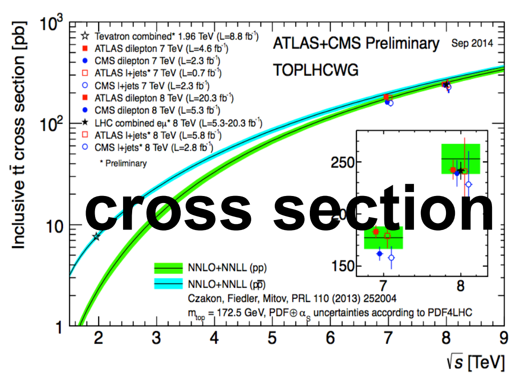
Interesting physics with top quarks

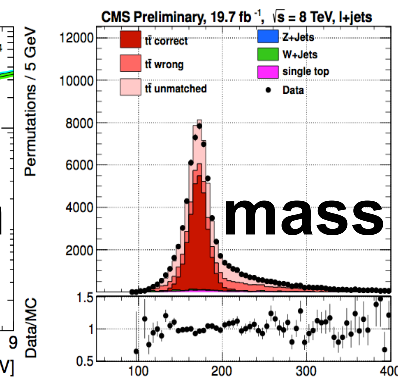
- Cross section
- Mass
- Kinematical properties
  - Is there a X→ttbar?
  - W polarization
  - Spin correlations
- Rare decays
- Single top
- Top quark is unusually heavy: maybe is it different?

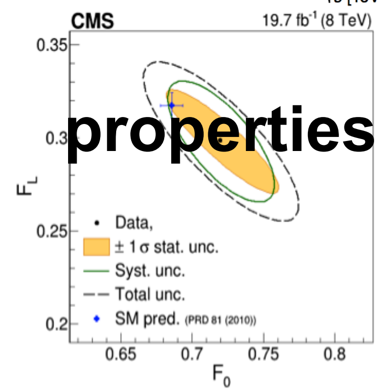
Role of top quark physics

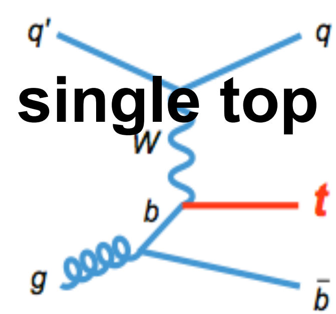
- Top quark physics after the Higgs discovery
  - Special role in EWSB mechanism?
  - Does it play a role in non-SM physics?
  - Are the couplings affected?
  - Main background for many NP searches

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



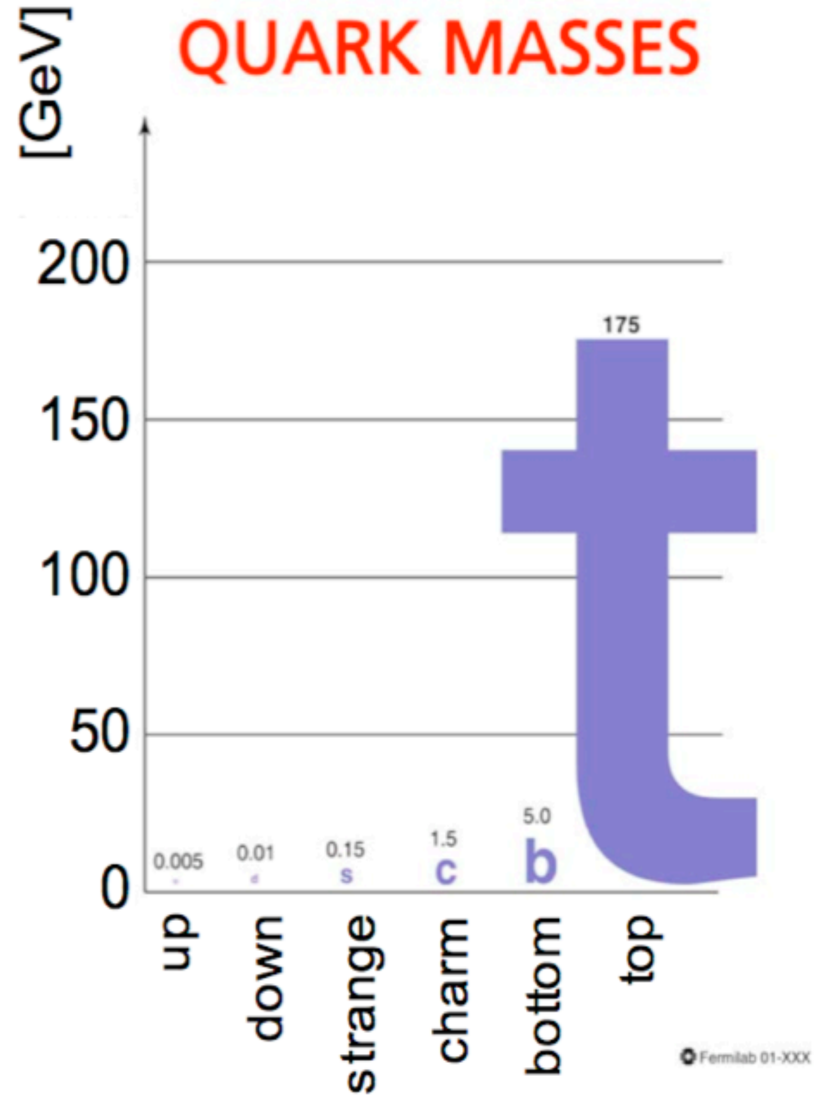






About the top quark

- The heaviest known elementary particle
- Large mass, coupling to the Higgs ~1
  - ⇒no hadronization
- Several open questions
  - – Is top mass generated by the Higgs mechanism?
  - – Special role in EWSB mechanism?
  - – Does it play a role in non-SM physics?
  - – Are the couplings affected?
- Main background for many New Physics searches
- Top quark measurements may provide insight into physics beyond SM



Collider energies for top searches

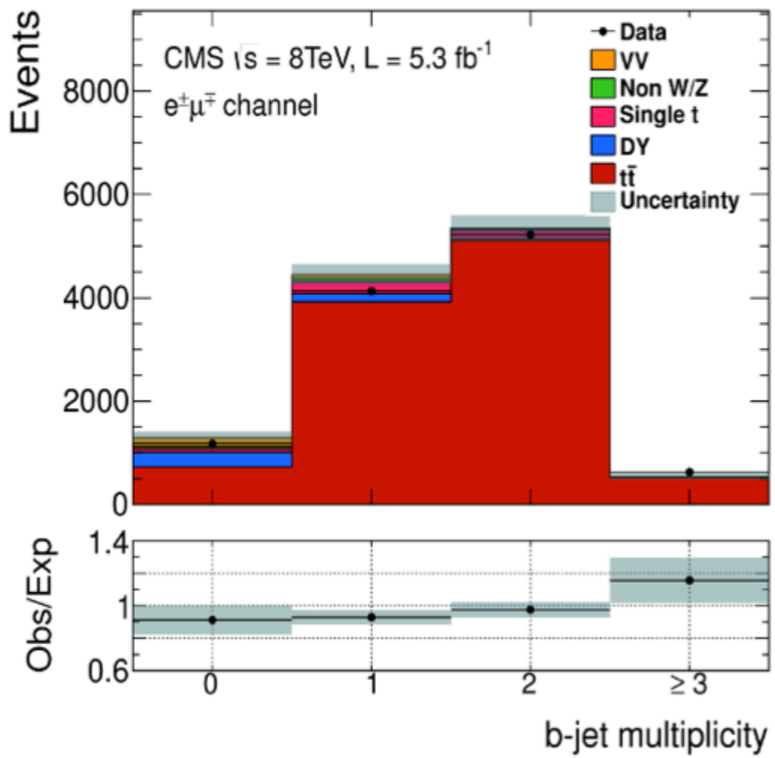
- A summary of colliders in search for the top quark

Year	Collider	Particles	References	Limit on m_t
1979-84	PETRA (DESY)	e^+e^-	[45]-[58]	> 23.3 GeV/c^2
1987-90	TRISTAN (KEK)	e^+e^-	[59]-[63]	> 30.2 GeV/c^2
1989-90	SLC (SLAC), LEP (CERN)	e^+e^-	[64]-[67]	> 45.8 GeV/c^2
1984	Sp$\bar{p}$S (CERN)	$p\bar{p}$	[70]	> 45.0 GeV/c^2
1990	Sp$\bar{p}$S (CERN)	$p\bar{p}$	[71, 72]	> 69 GeV/c^2
1991	TEVATRON (FNAL)	$p\bar{p}$	[73]-[75]	> 77 GeV/c^2
1992	TEVATRON (FNAL)	$p\bar{p}$	[76, 77]	> 91 GeV/c^2
1994	TEVATRON (FNAL)	$p\bar{p}$	[79, 80]	> 131 GeV/c^2
1995	TEVATRON (FNAL)	$p\bar{p}$	[37]	$= 174 \pm 10^{+13}_{-12}$ GeV/c^2
			[38]	$= 199^{+19}_{-21} \pm 22$ GeV/c^2

Dilepton channel

JHEP 02(2014)024

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



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

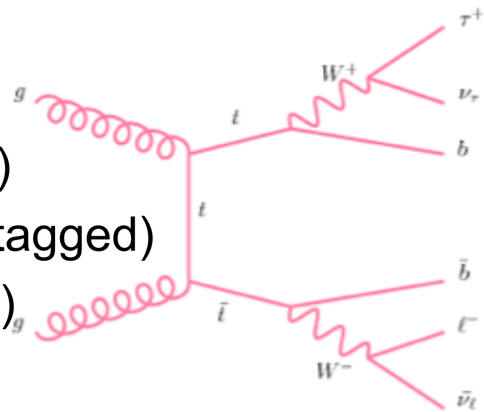
$$\sigma_{t\bar{t}} = 239 \pm 2\,(\text{stat.}) \pm 11\,(\text{syst.}) \pm 6\,(\text{lum.})\,\text{pb}$$

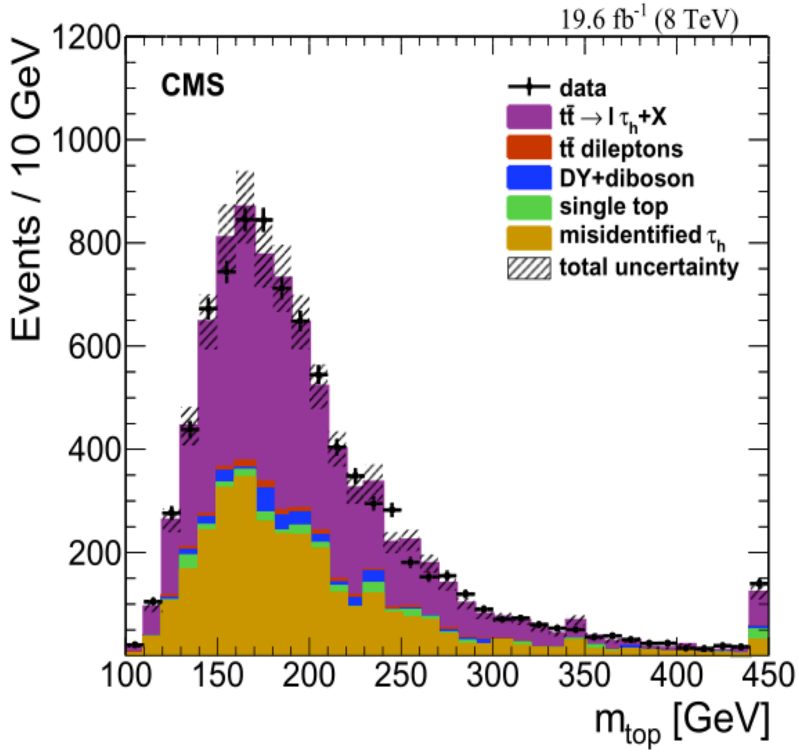
±5%

Tau$_h$+lepton final state

PLB 739(2014)23

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





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

dominant syst.: τ fakes, b-tag

Good agreement between measurement and predictions

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

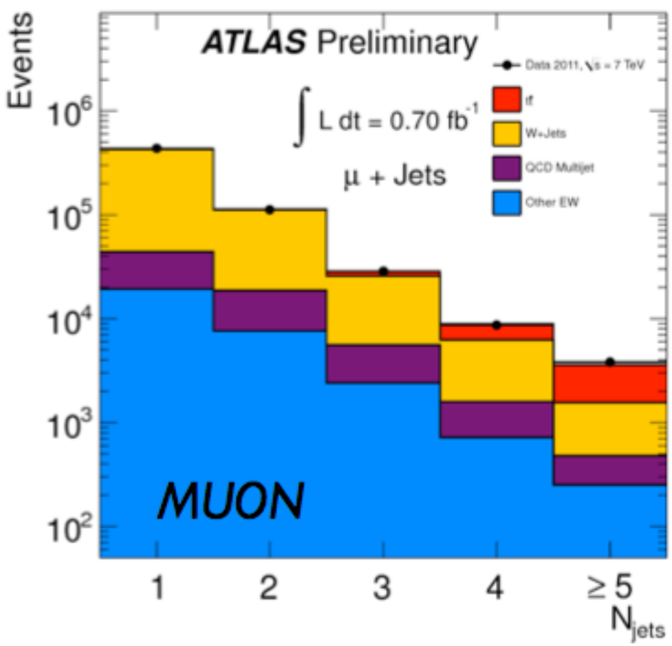
$$\sigma_{t\bar{t}}(\mu\tau_h) = 258 \pm 4\,(\text{stat}) \pm 24\,(\text{syst}) \pm 7\,(\text{lumi})\ \text{pb}$$

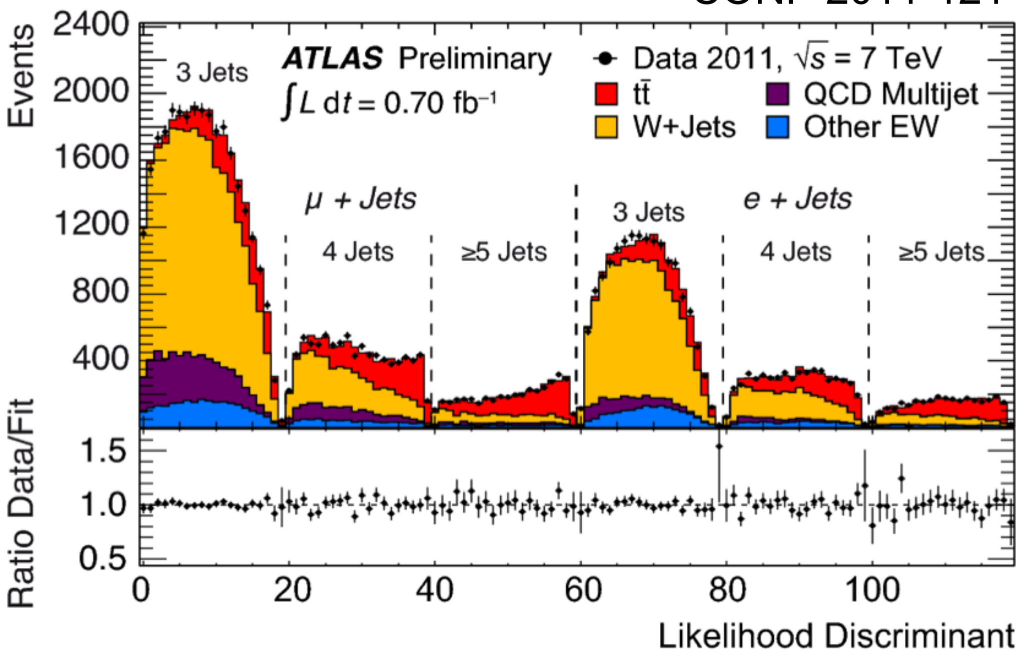
$\pm 10\%$

Single lepton channel

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

CONF-2011-121





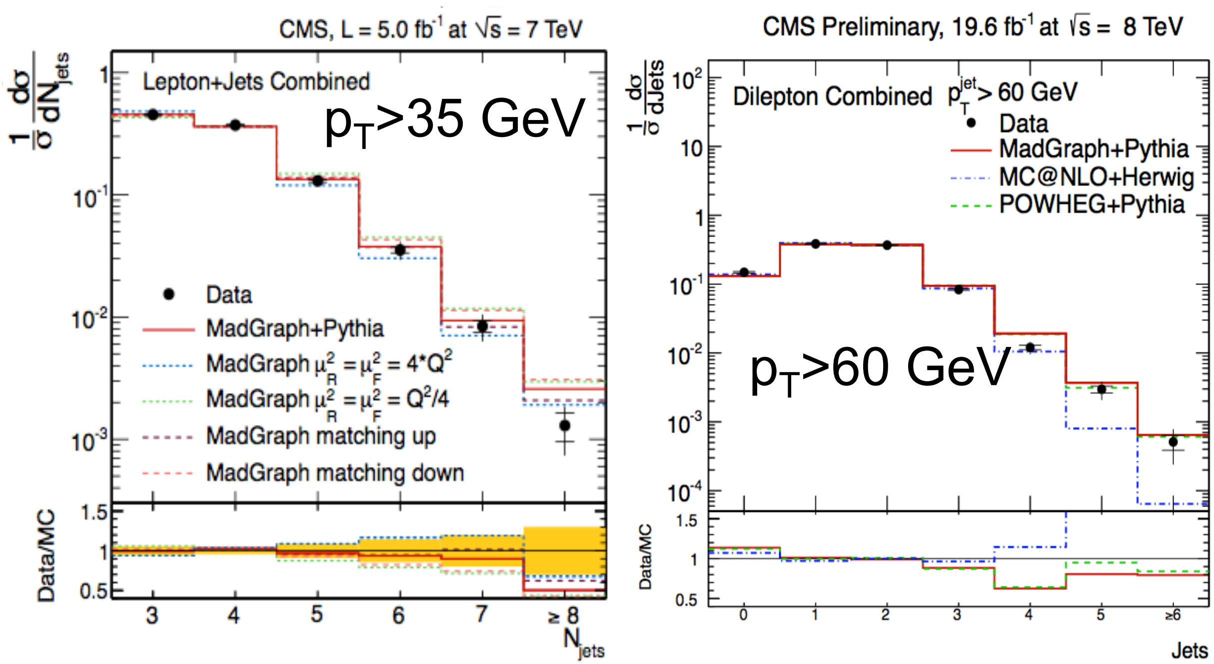
$$\sigma_{t\bar{t}} = 179.0 \pm 3.9\,(\text{stat}) \pm 9.0\,(\text{syst}) \pm 6.6\,(\text{lumi})\ \text{pb}$$

Differential cross sections

CMS-TOP-12-041, arXiv:1404.3171

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

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

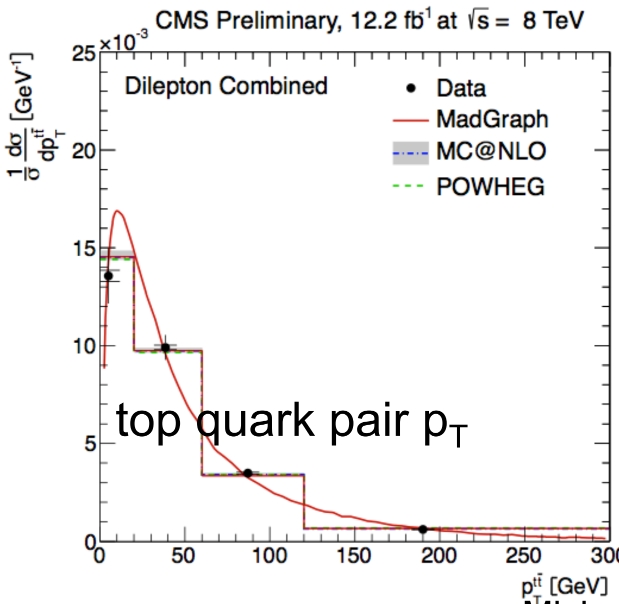


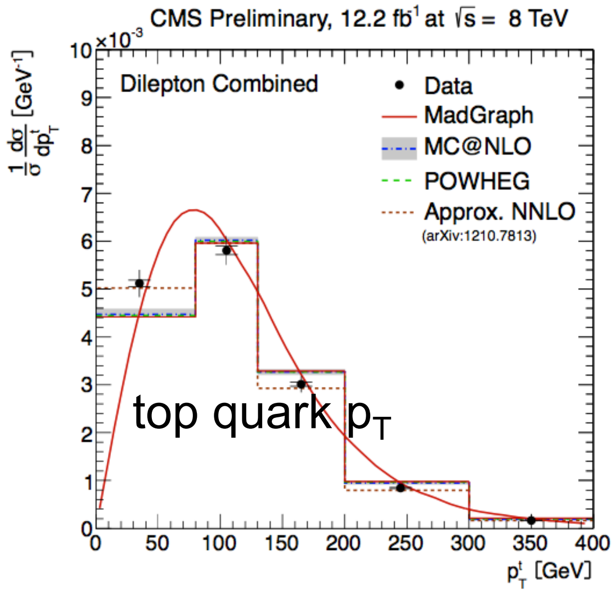
Differential cross section

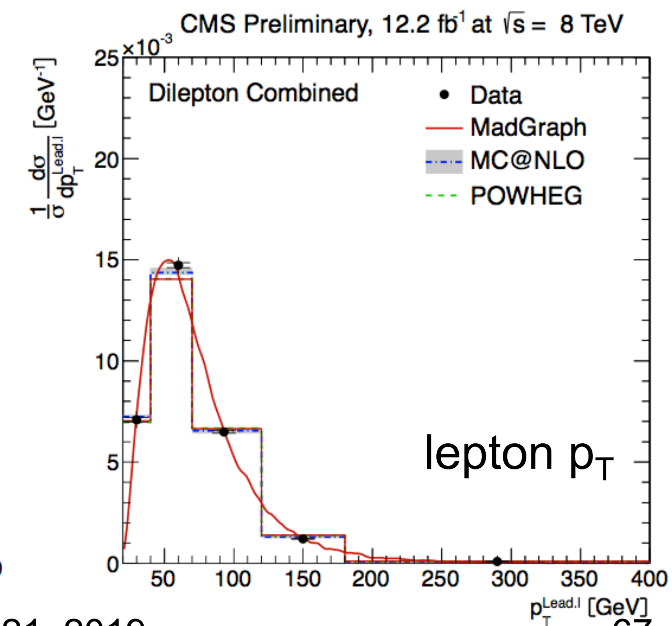
CMS-TOP-12-028

- Measure differential cross section
  - Test perturbative QCD
  - Test BSM scenarios (Z' decays, etc) with narrow resonance
- Reconstruct event kinematic properties
- Cross sections measured as a function of p_T, 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

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







Differential cross section

CMS-TOP-12-028

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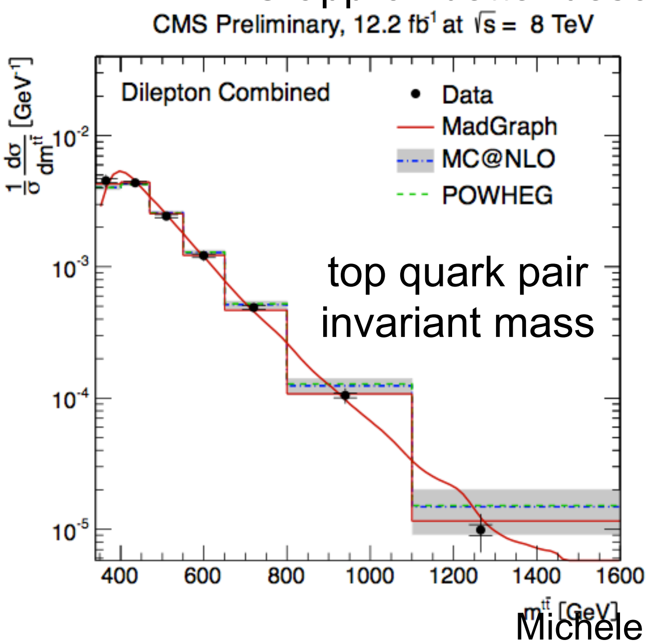
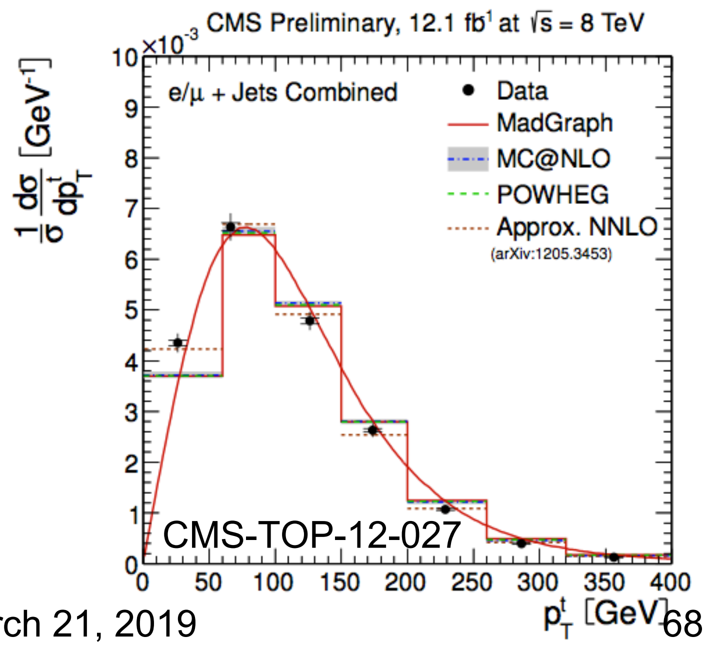
$$\frac{1}{\sigma_{t\bar{t}}} \frac{d\sigma_{t\bar{t}}}{dX}$$





All-hadronic: cross section

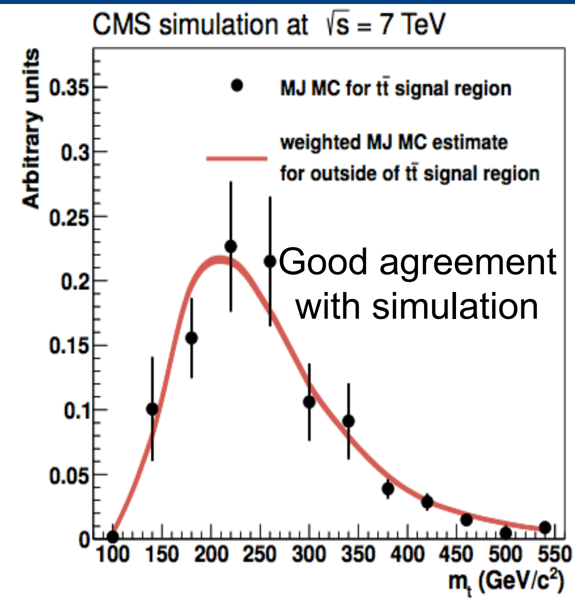
JHEP 05(2013)065. EPJC 74(2014)2758

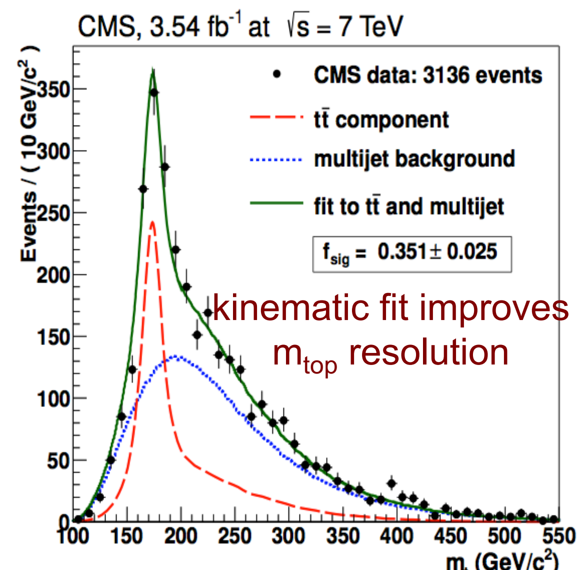
- Fully hadronic final state (BR~46%)
- Six jets and no leptons in the final state
- Reconstruct ttbar system and fit with least χ^2 method
  - reconstruct both W bosons
  - $m_{top1}=m_{top2}$ are free parameters
  - b-jets are taken as b-quark candidates
  - take permutation with smallest χ^2
- Multijet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

$\pm$20%

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

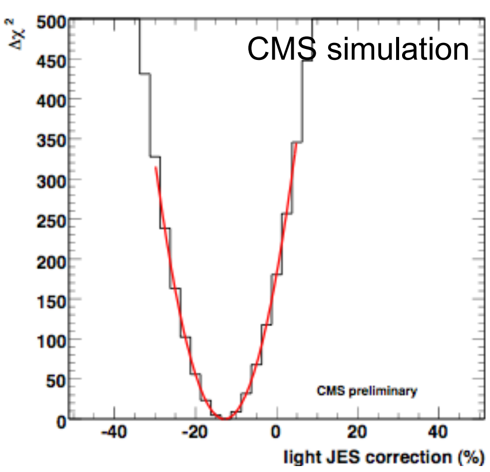
- Dominant syst.: JES, b-tag

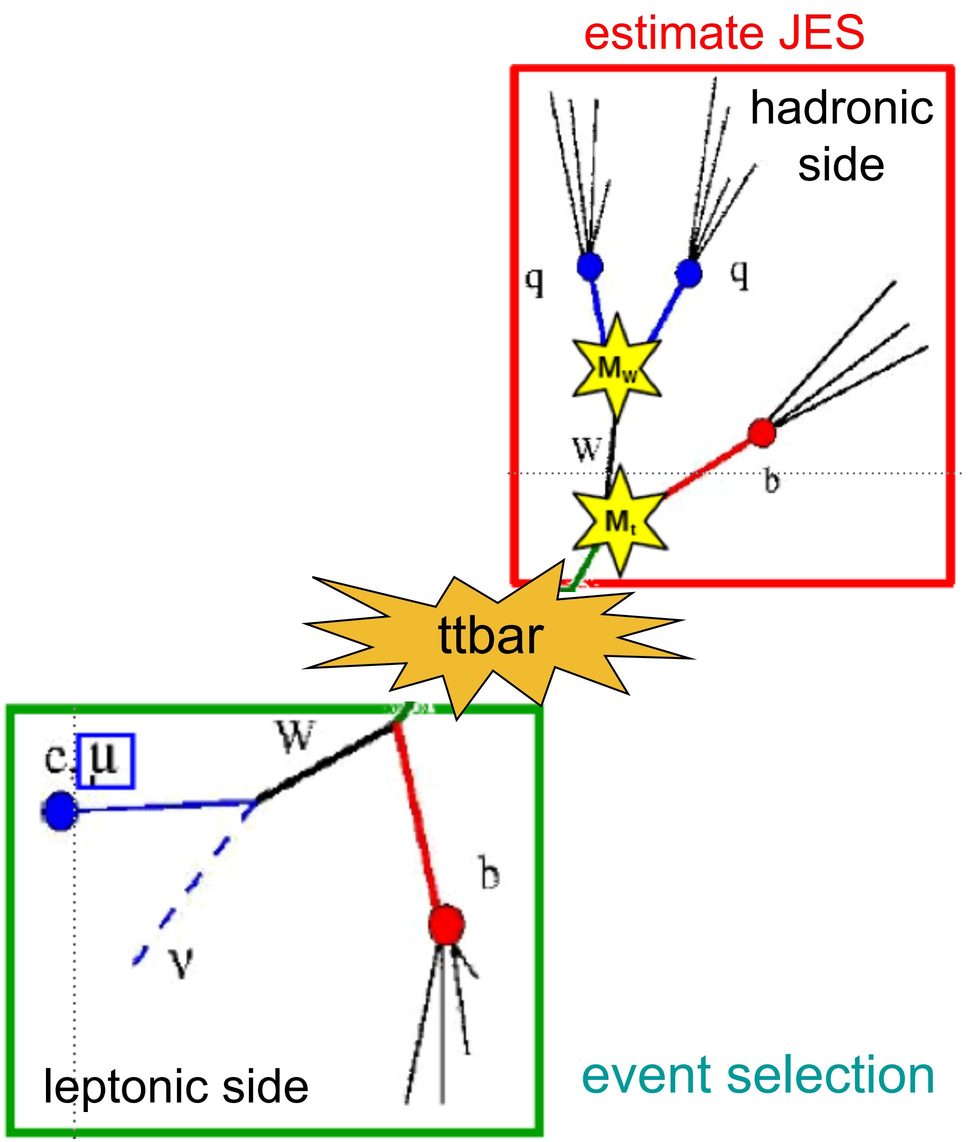




Jet energy correction from Top

- 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



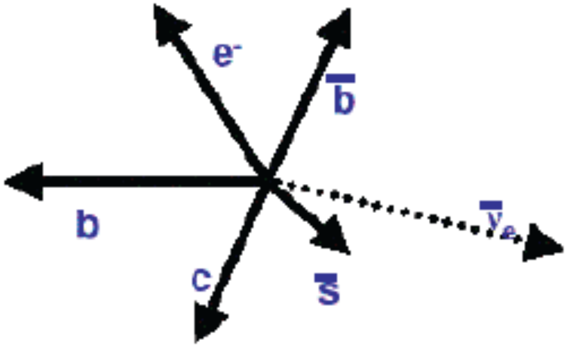


Measuring the top mass

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: