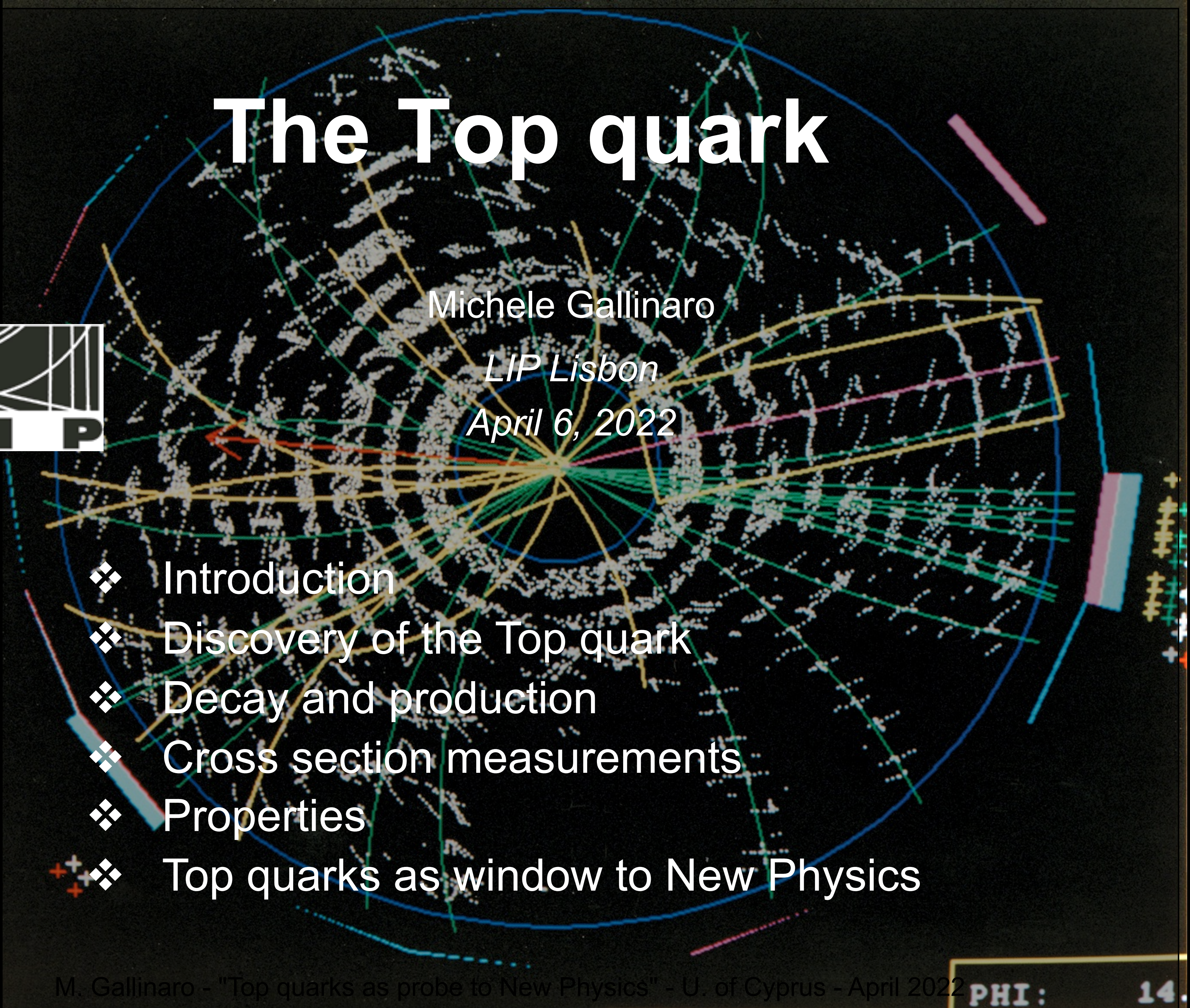


The Top quark

Michele Gallinaro

LIP Lisbon

April 6, 2022

- Introduction
- Discovery of the Top quark
- Decay and production
- Cross section measurements
- Properties
- Top quarks as window to New Physics

Introduction

- Pre-discovery
- Motivation: theory and experiment
- First top quark events in the data!
- First measurements

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 of the Y at Fermilab

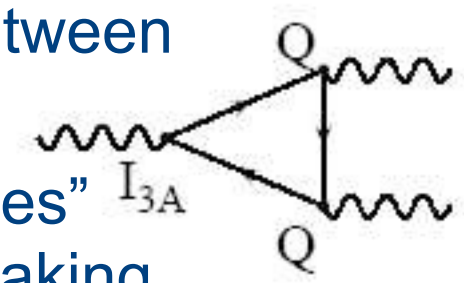
$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} \\ b \end{pmatrix}$$

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

- b: non SM? iso-singlet? SM iso-doublet?
- 1984: DESY measurement of $e^+e^-\rightarrow b\bar{b}$ FB asymmetry: $(22.5 \pm 6.5)\%$
  - – 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)

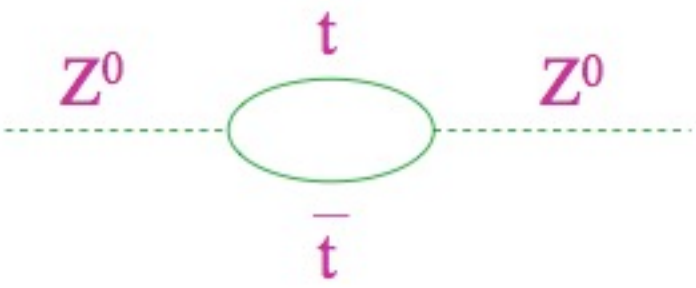
$$\boxed{R \equiv \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)} = 3\sum_f Q_f^2}$$

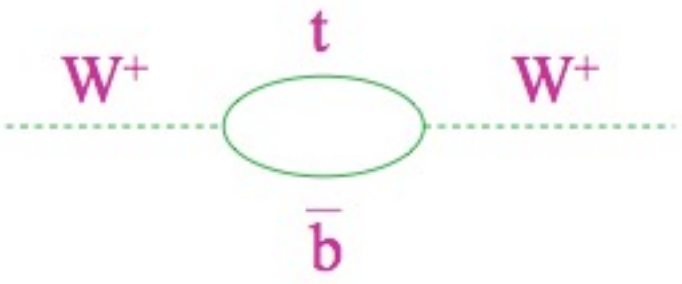
direct count of
number of quarks

  - 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 $Z \to t\bar{t}$
  - M_t>45 GeV
- Reached kinematic limit for direct searches at e^+e^- colliders

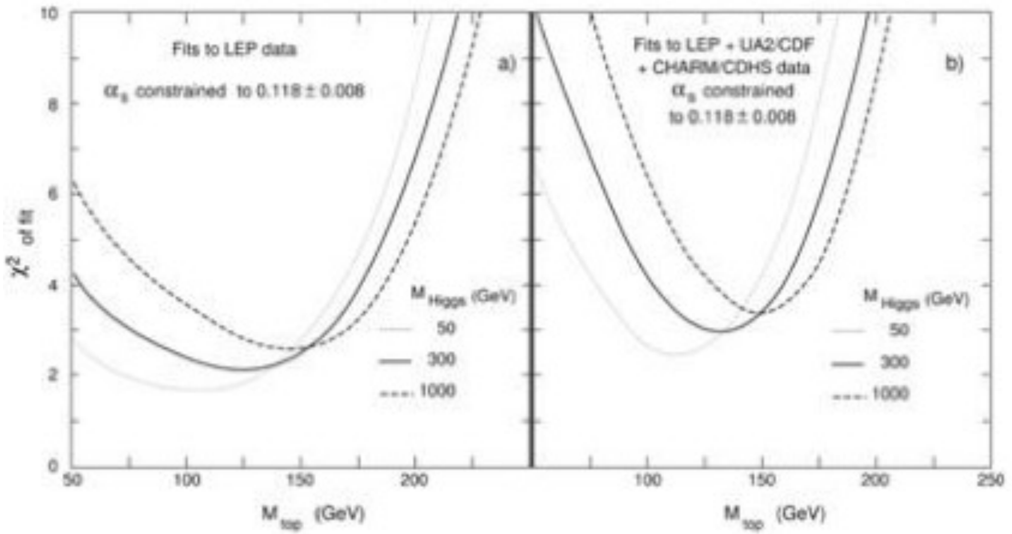
Indirect searches from e^+e^- colliders

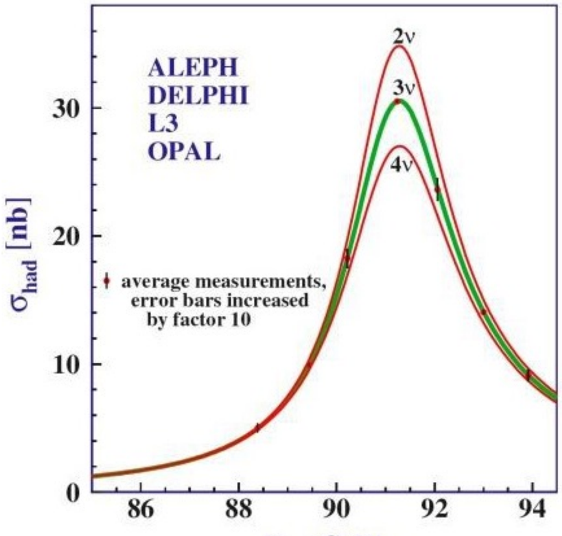
- In the SM, various EWK observables depend on the mass of the top quark





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

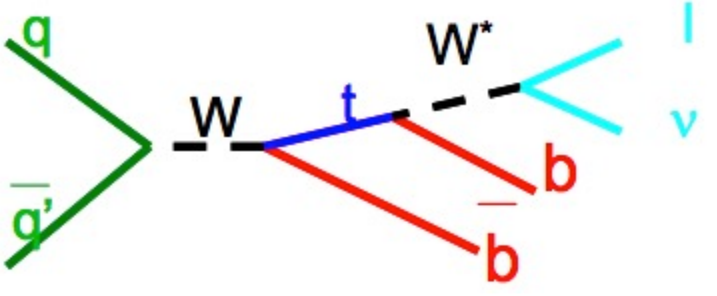




Early searches at hadron colliders

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

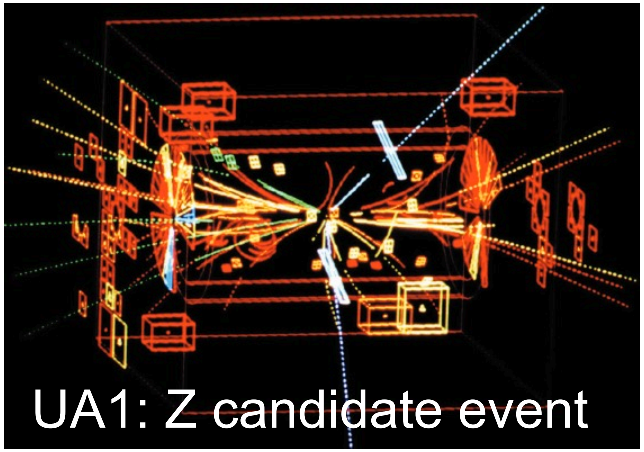
  - Access to much higher energies
  - Large backgrounds, low event rates
  - Difficult reconstruction: jets



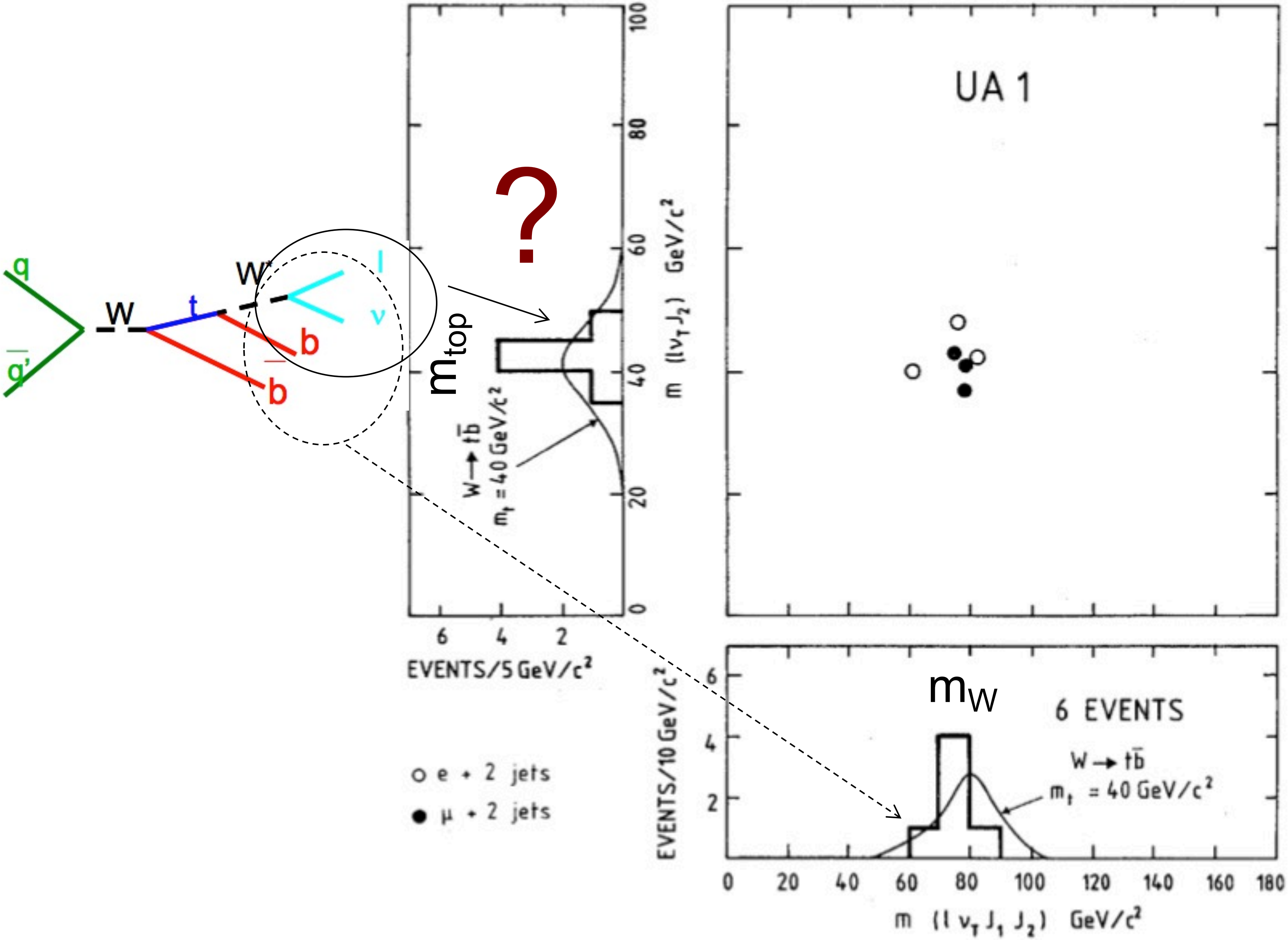
1984: UA1

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

⇒W+jet background was underestimated

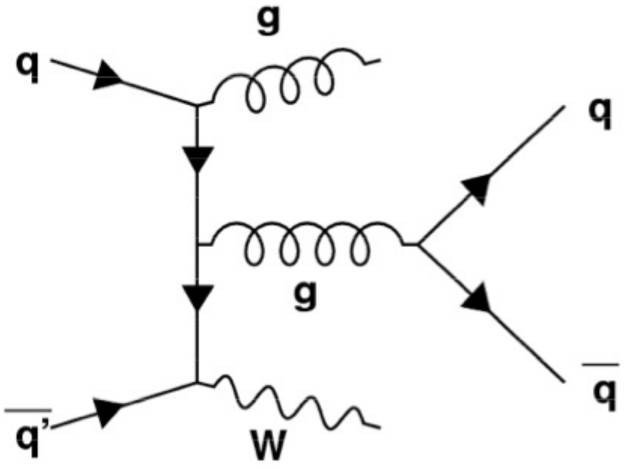


UA1: Z candidate event


q
q̄'
W
t
W
l
ν
b
b̄
?
m_{top}
100
80
60
40
20
0
6
4
2
EVENTS/5 GeV/c²
m (lν_T J_2) GeV/c²
W → tb̄
m_t = 40 GeV/c²
UA 1
○ e + 2 jets
● μ + 2 jets
m_W
6 EVENTS
W → tb̄
m_t = 40 GeV/c²
EVENTS/10 GeV/c²
6
4
2
0
20
40
60
80
100
120
140
160
180
m (l ν_T J_1 J_2) GeV/c²

Searches at hadron colliders

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



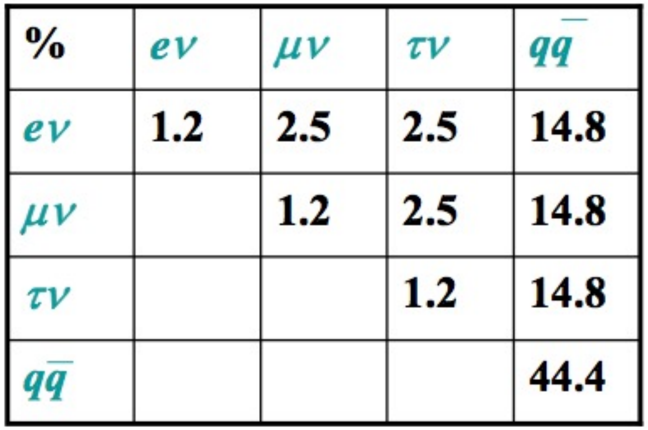
channel	observed	expected background
$\mu + \geq 2$ jets	10 events	11.5 ± 1.5 events
$e + \geq 1$ jets	26 events	23.4 ± 2.8 events

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

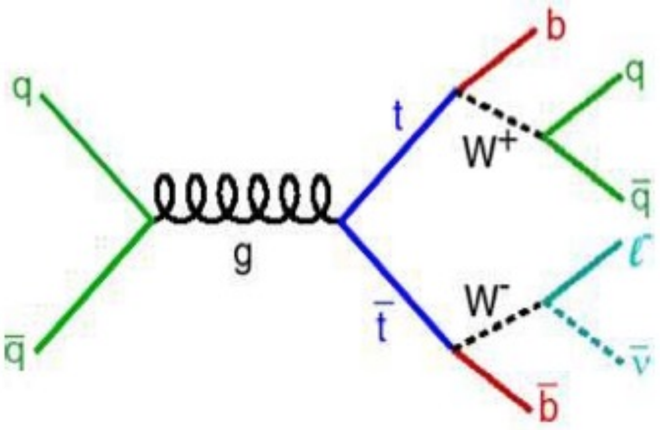
⇒conclude M_{top}>44 GeV

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

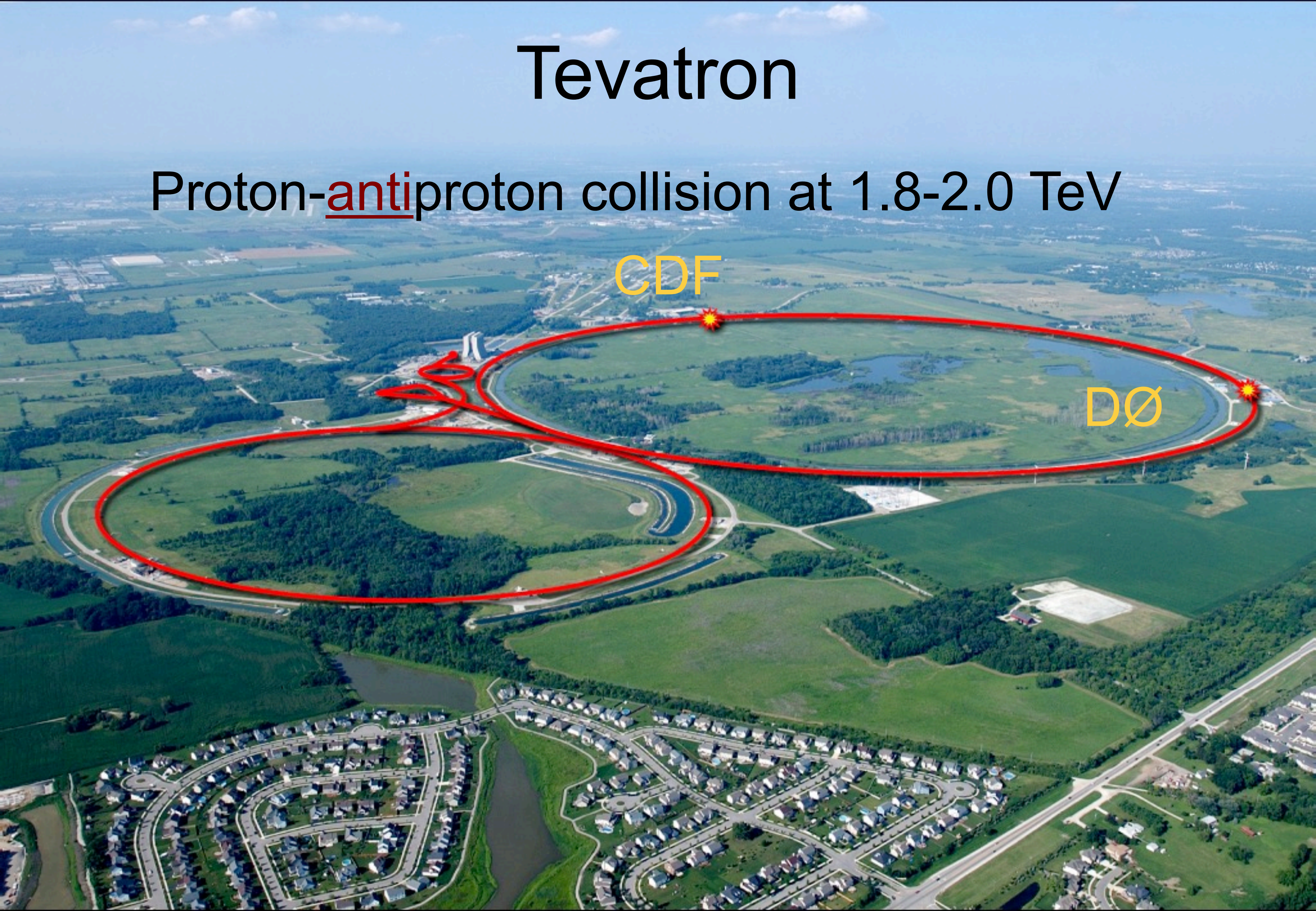


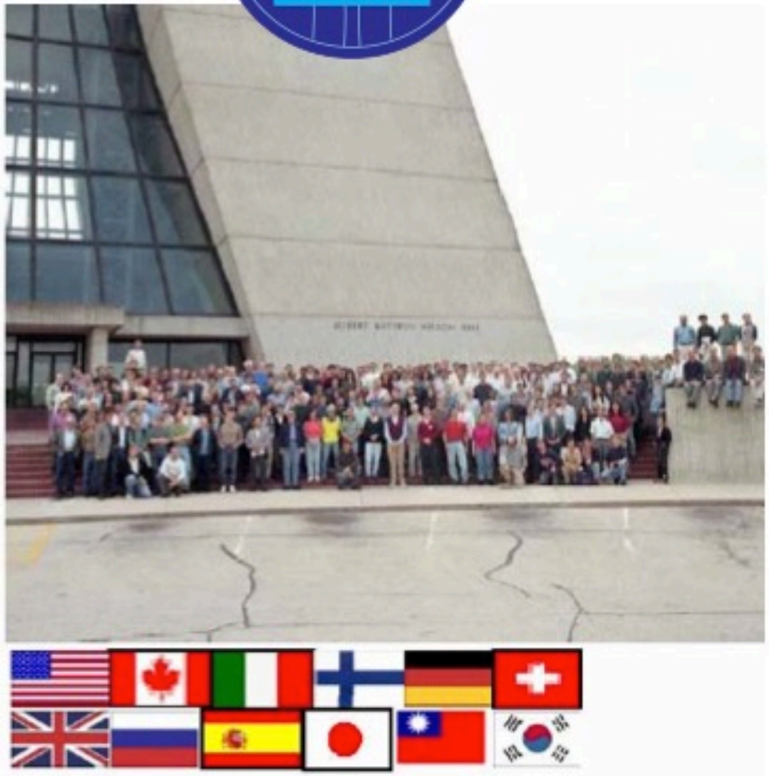
%	$e\nu$	$\mu\nu$	$\tau\nu$	$q\bar{q}$
$e\nu$	**1.2**	**2.5**	**2.5**	**14.8**
$\mu\nu$		**1.2**	**2.5**	**14.8**
$\tau\nu$			**1.2**	**14.8**
$q\bar{q}$				**44.4**



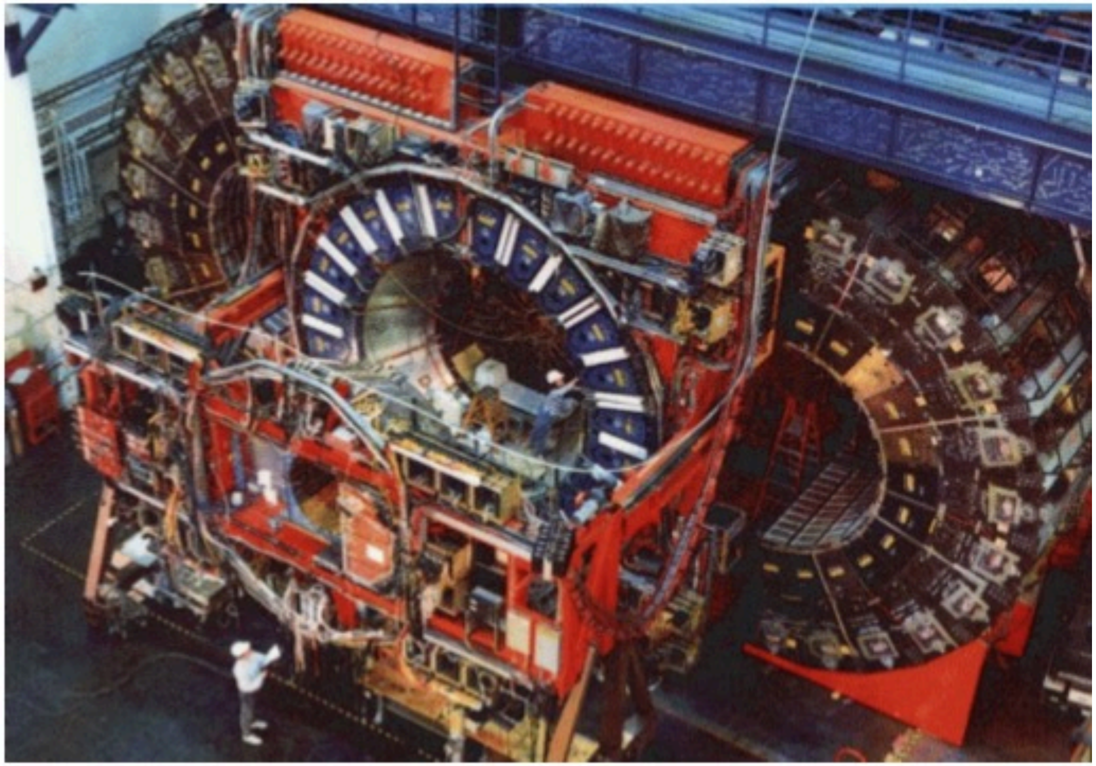
Tevatron

Proton-antiproton collision at 1.8-2.0 TeV





12 countries, 62 institutions
767 physicists



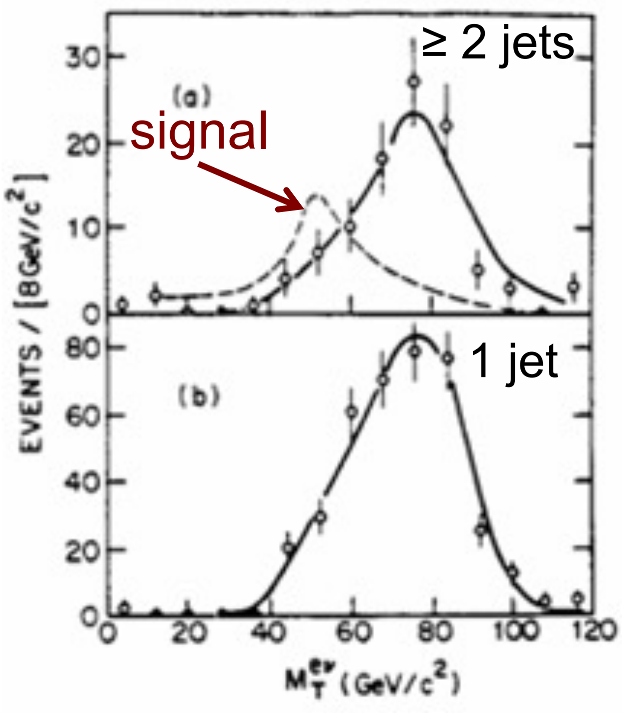
Searches at CDF

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



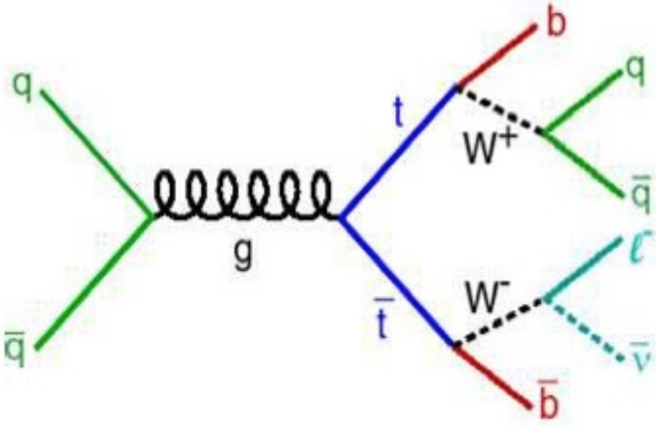
⇒M_{top}>77 GeV

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

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

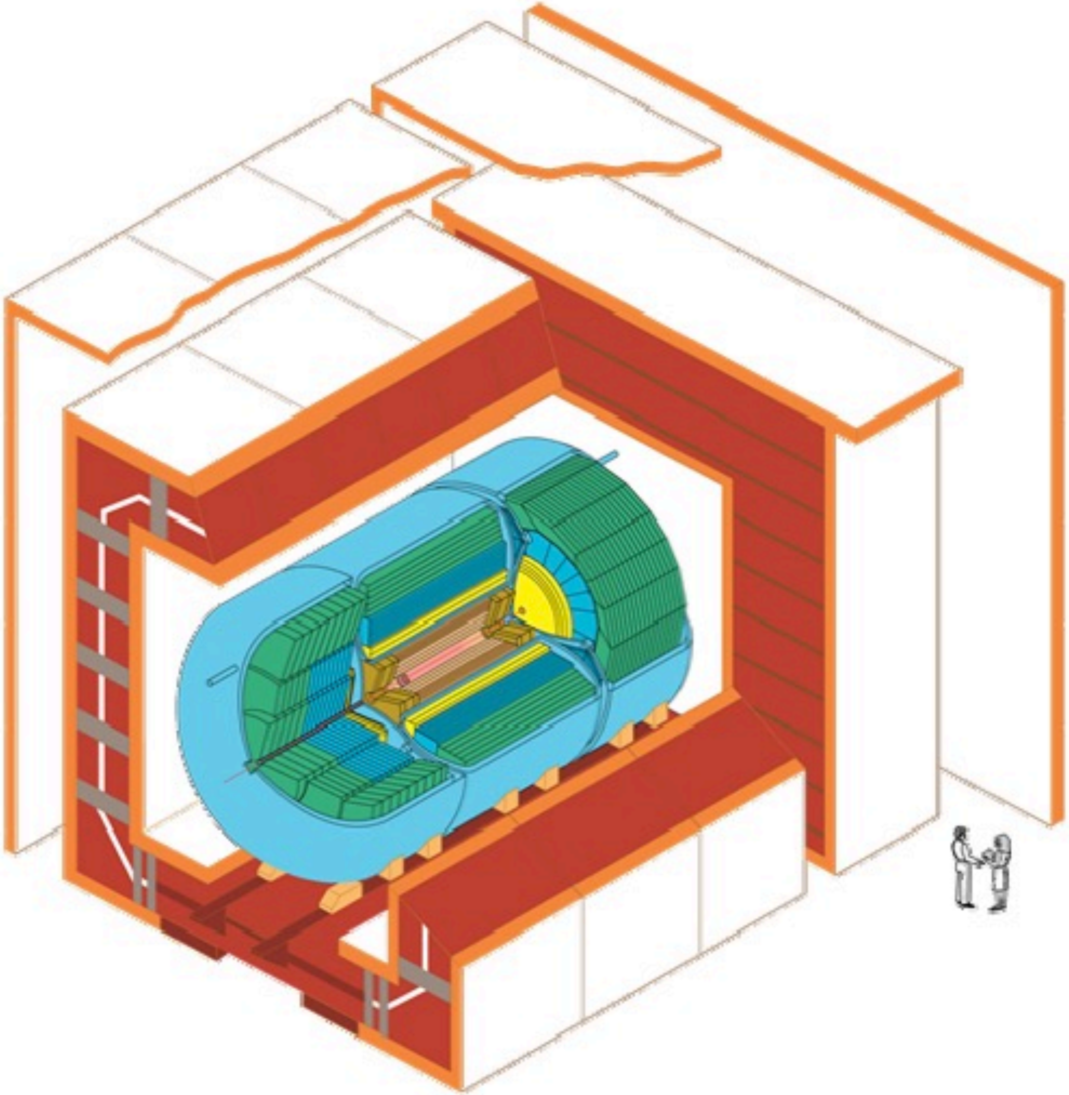
- Top quark decays to on-shell Ws: no $M_T(l\nu)$ discriminant
- Main differences:
  - background: W+jets (largely quarks and gluons)
  - signal: W+jets (2 jets are b-jets)
- CDF publication on 88-89 data:
  - Dilepton: include ee, $\mu\mu$, eμ (require missing ET, Z-veto)
  - Single lepton: require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

$\Rightarrow M_{top}>91$ GeV



D0 joins the hunt

19 countries
83 institutions, 664 physicists



D0 Detector

Searches at Tevatron: CDF and D0

1992-1995

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

Run 1A:

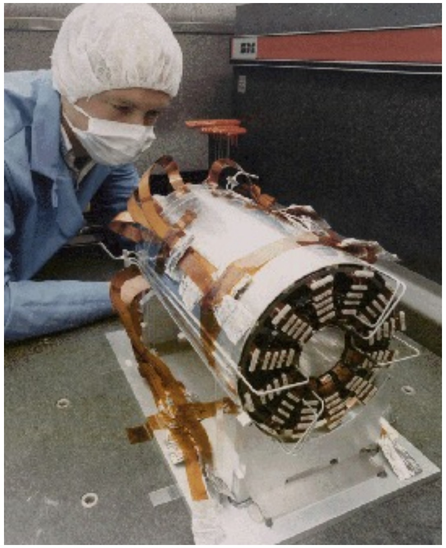
- D0: optimized search for M_{top}=100 GeV

– eμ+≥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)

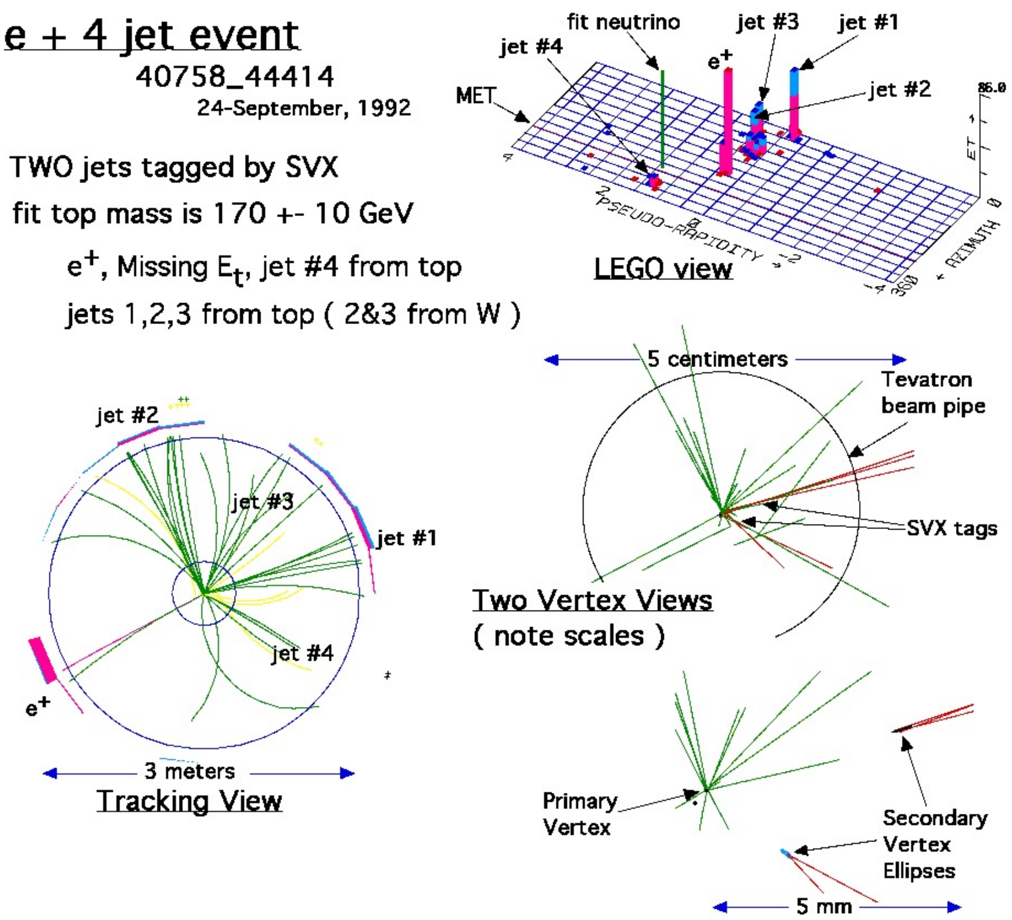
⇒M_{top}>131 GeV@95%CL

Detecting the top quark at CDF

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



New: CDF vertex detector (SVX)
(40 μm impact parameter resolution)
powerful discriminant against background



e + 4 jet event
40758_44414
24-September, 1992

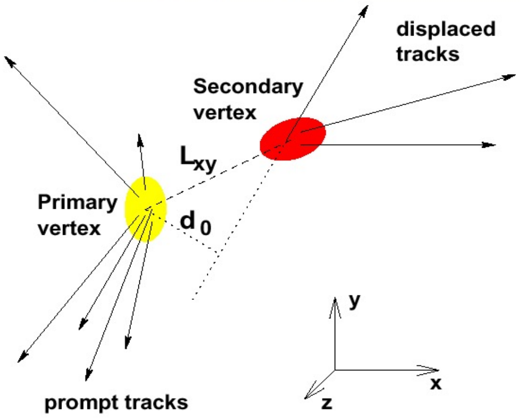
TWO jets tagged by SVX
fit top mass is 170 +- 10 GeV
e^+, Missing E_t, jet #4 from top
jets 1,2,3 from top (2&3 from W)

Tagging b-jets

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

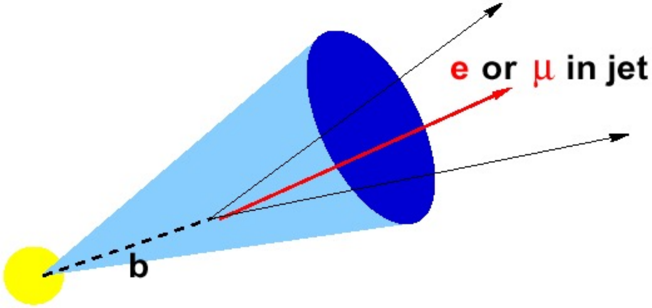
B hadrons are long-lived

Vertex displaced tracks



semileptonic B hadron decay

Soft Lepton Tagging



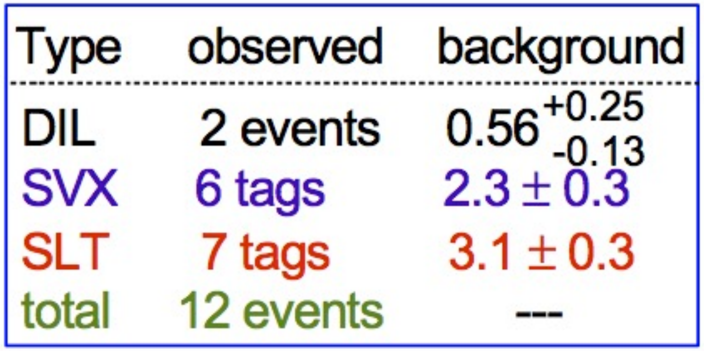
- $b \rightarrow \ell \nu c\ (\mathrm{BR} \sim 20\%)$
- $b \rightarrow c \rightarrow \ell \nu s\ (\mathrm{BR} \sim 20\%)$

55%	← **Top Event Tagging Efficiency** →	**15%**
0.5%	← **False Tag Rate (QCD jets)** →	**3.6%**

1993

Coll. Meeting, Aug. 1993:

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

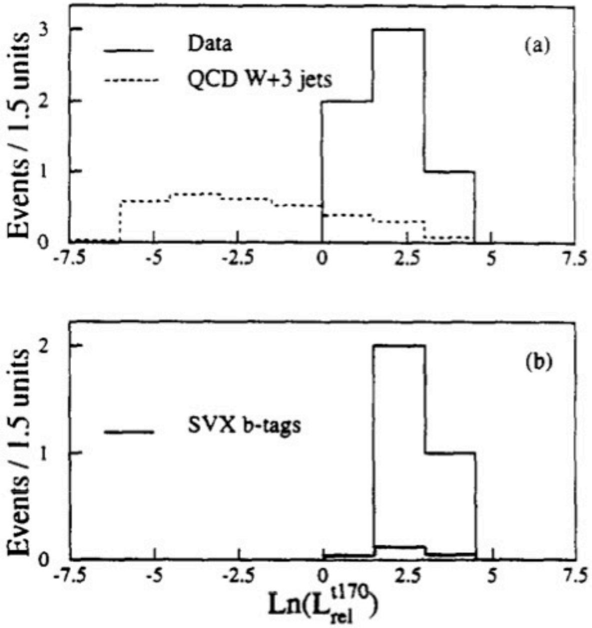


Type	observed	background
DIL	2 events	$0.56^{+0.25}_{-0.13}$
SVX	6 tags	2.3 ± 0.3
SLT	7 tags	3.1 ± 0.3
total	12 events	---

3 events in common

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

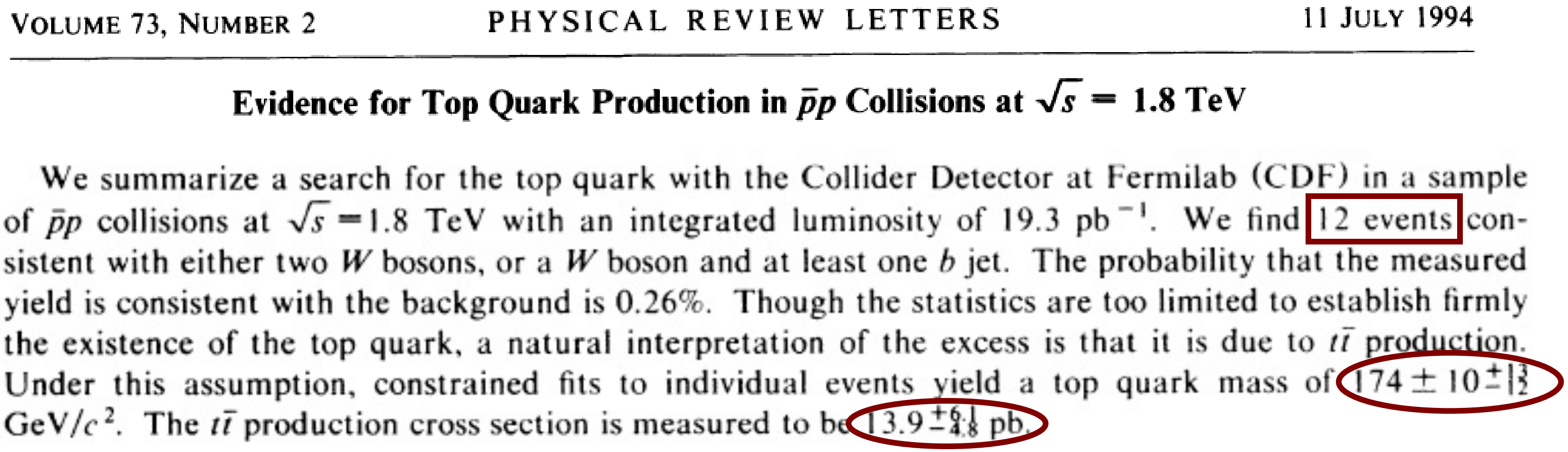
Final steps: CDF and D0



CDF: counting experiment yields 2.8σ
  - Few checks: no major discrepancy
  - Other checks consistent with presence of signal
  - Mass distribution looked good
- There were also other analyses at CDF
  - Difference of jet E_T spectra for signal and bkg
  - Separate two component for signal and bkg
  - CDF chose not to use those for first publication
- Use "counting" experiment

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

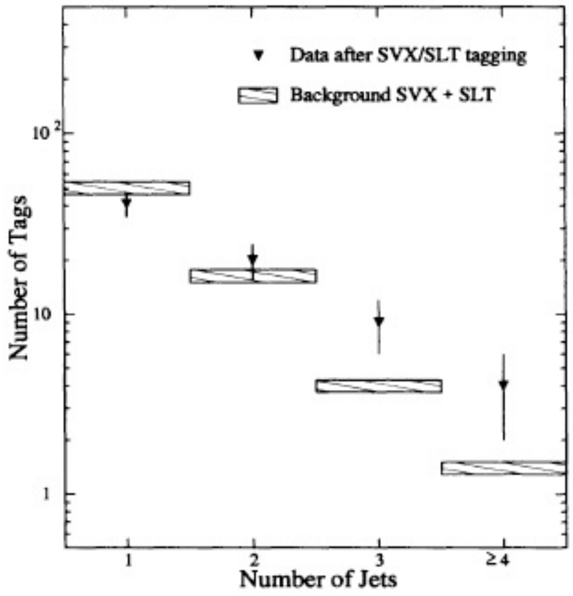
First evidence (1994)

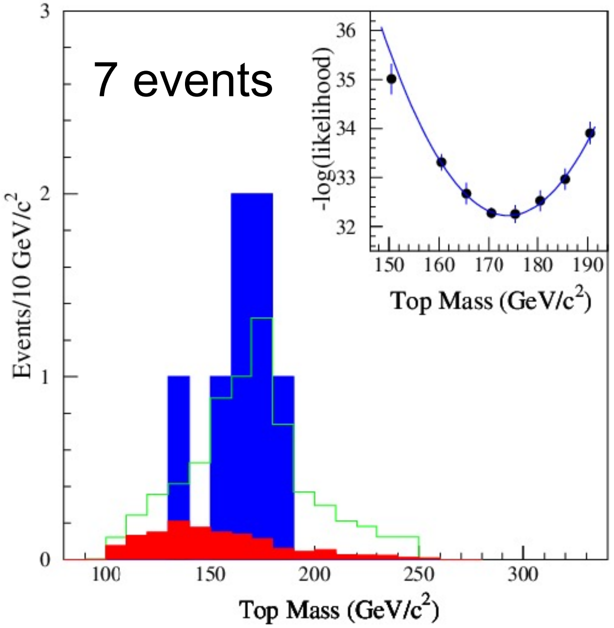


VOLUME 73, NUMBER 2 PHYSICAL REVIEW LETTERS 11 JULY 1994

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

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



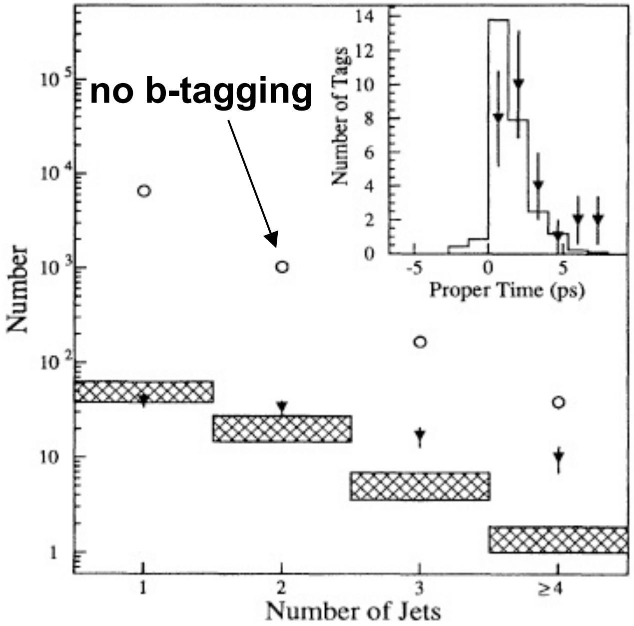


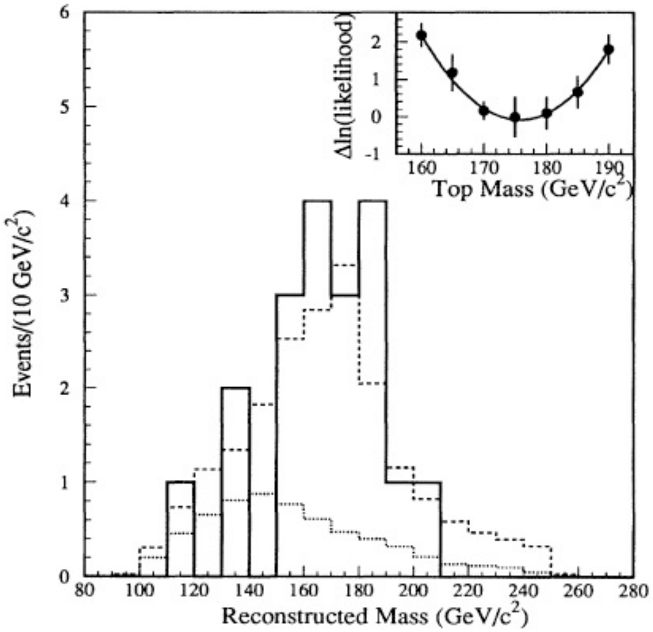
First measurements

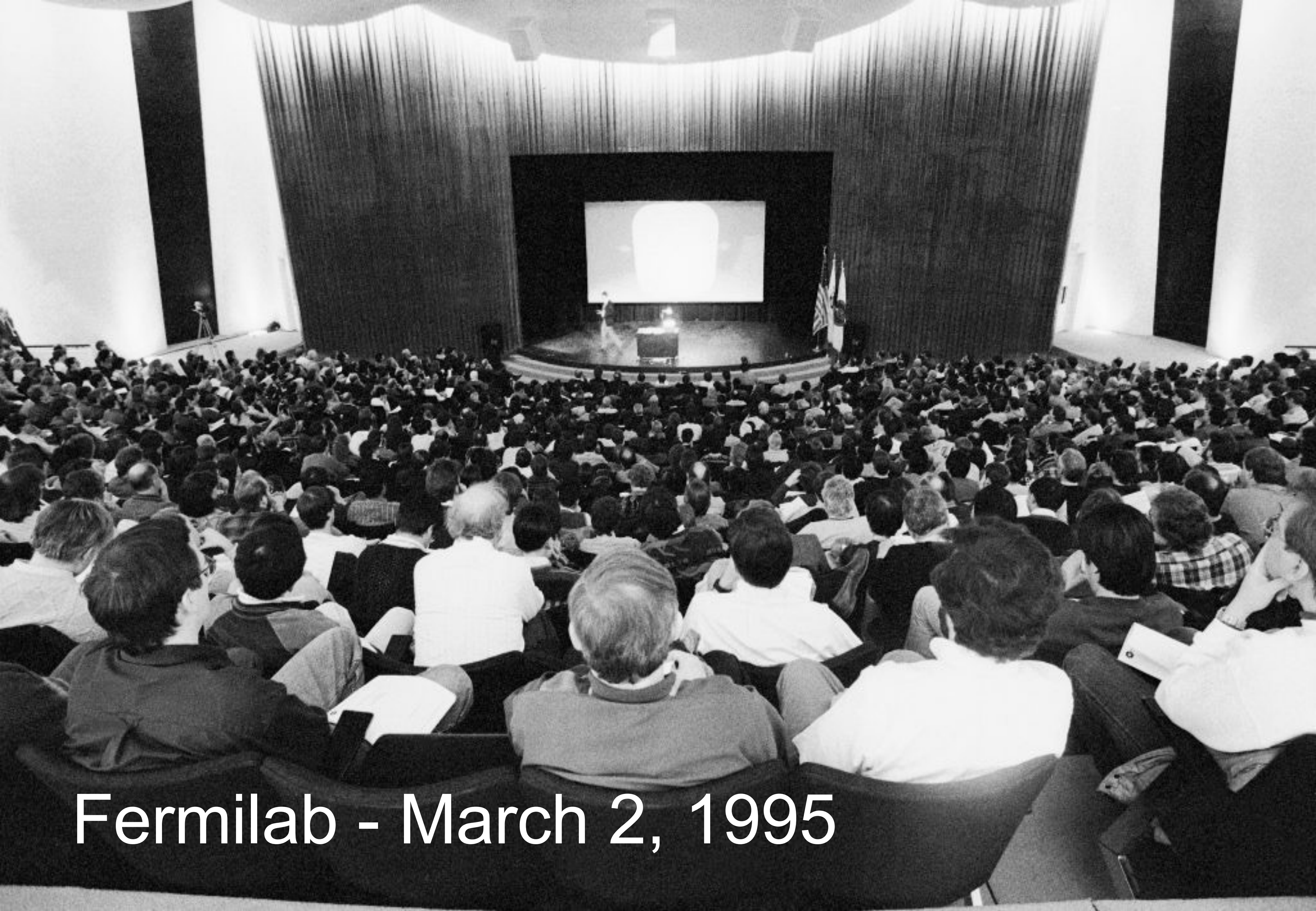
VOLUME 74, NUMBER 14 PHYSICAL REVIEW LETTERS 3 APRIL 1995

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.







Fermilab - March 2, 1995

First measurements

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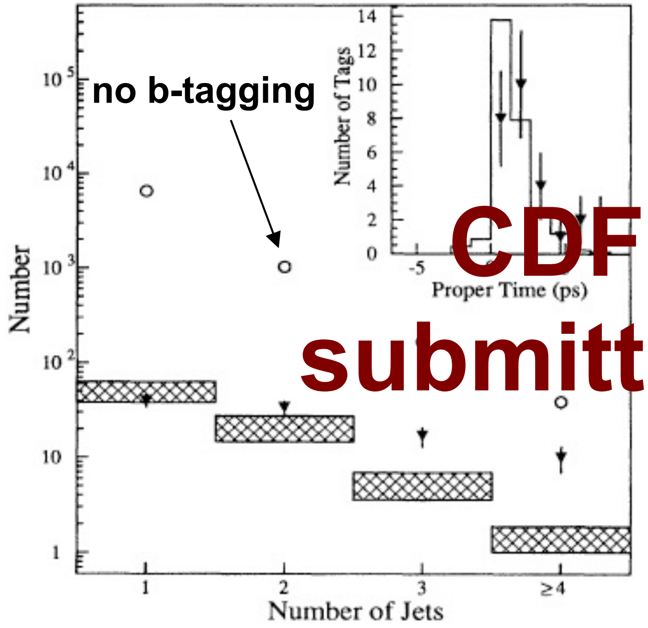
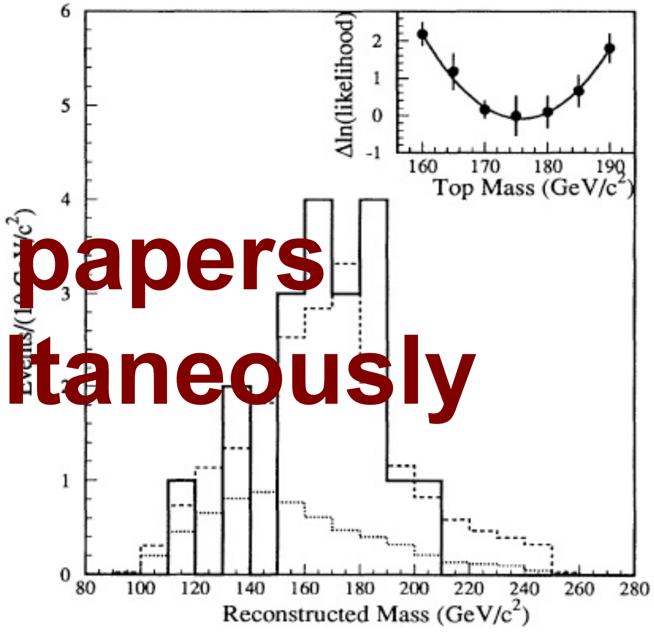
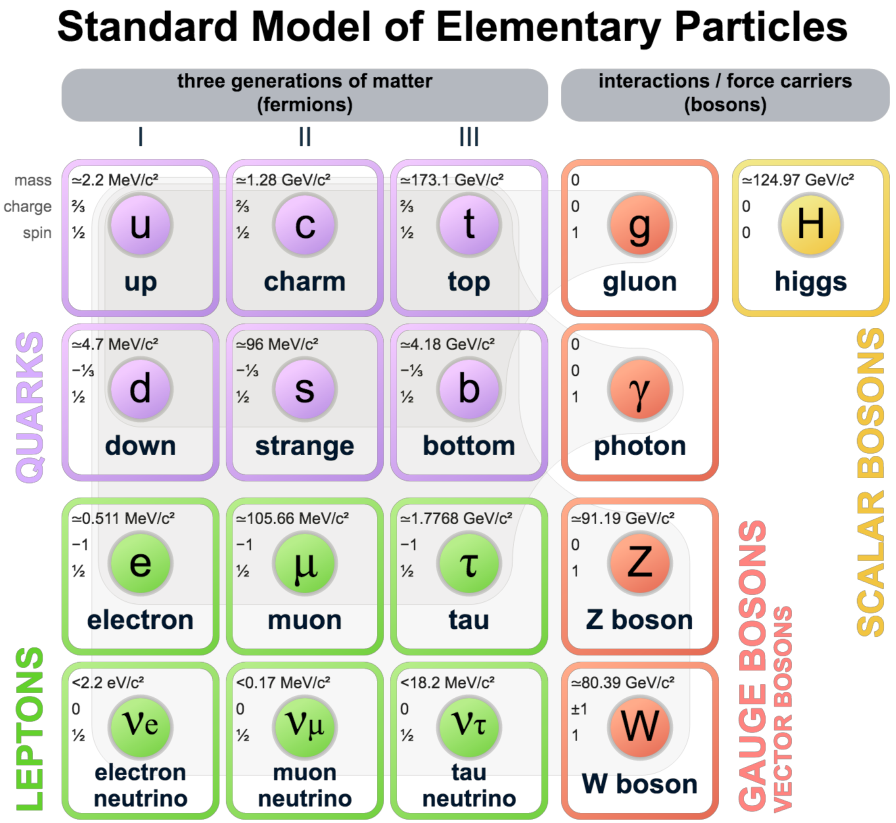


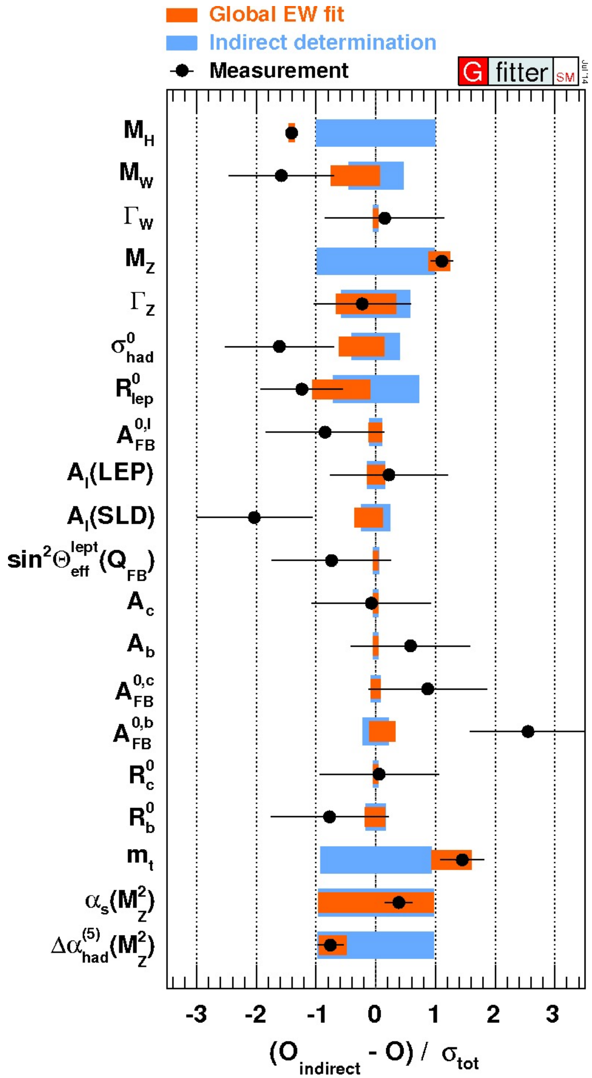
no b-tagging



CDF and D0 papers submitted simultaneously

SM confirmed by the data



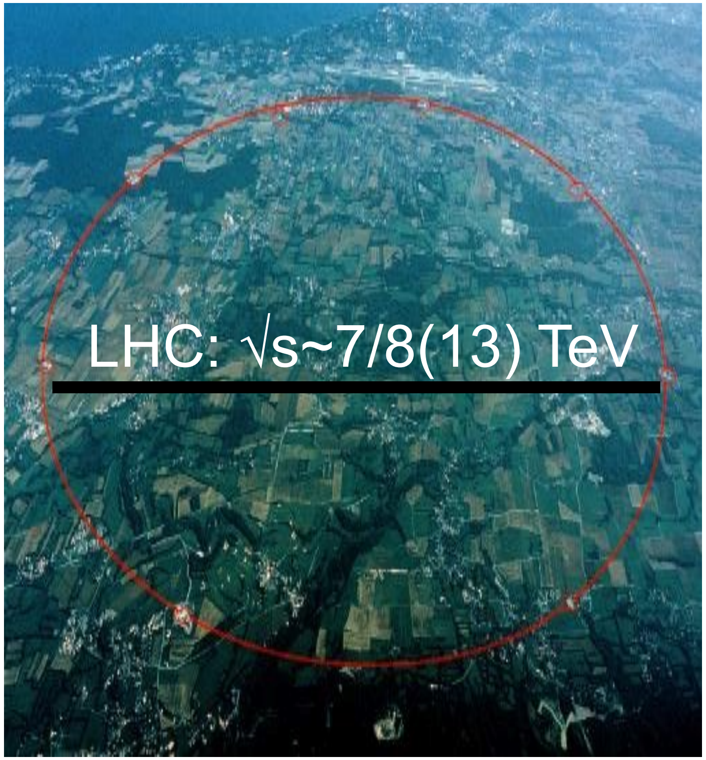


Excellent agreement with all experimental results

The Large Hadron Collider

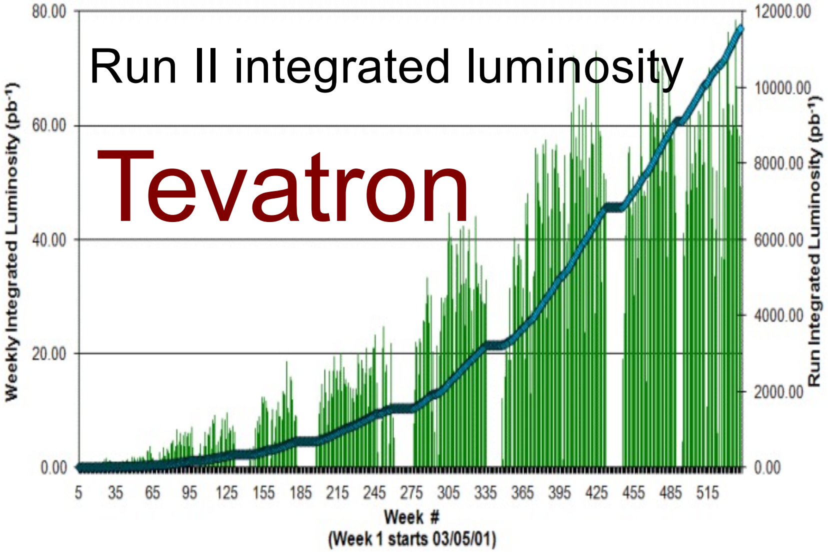
- Built to explore new energy frontiers
  - First colliding beams in 2009
  - started with “low” luminosity in 2010
  - ~5 fb^{-1}@7TeV delivered in 2011
  - ~20 fb^{-1}@8TeV in 2012
  - >150fb^{-1}@13 TeV in 2015-2018

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

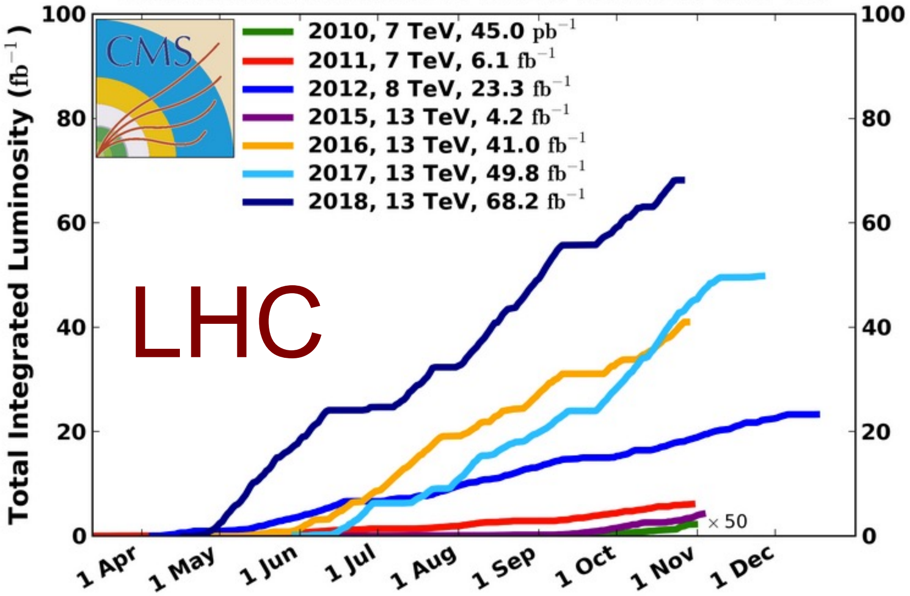


⇨ Top quarks give access to SM and BSM (?)

Tevatron vs LHC


Run II integrated luminosity

Tevatron


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

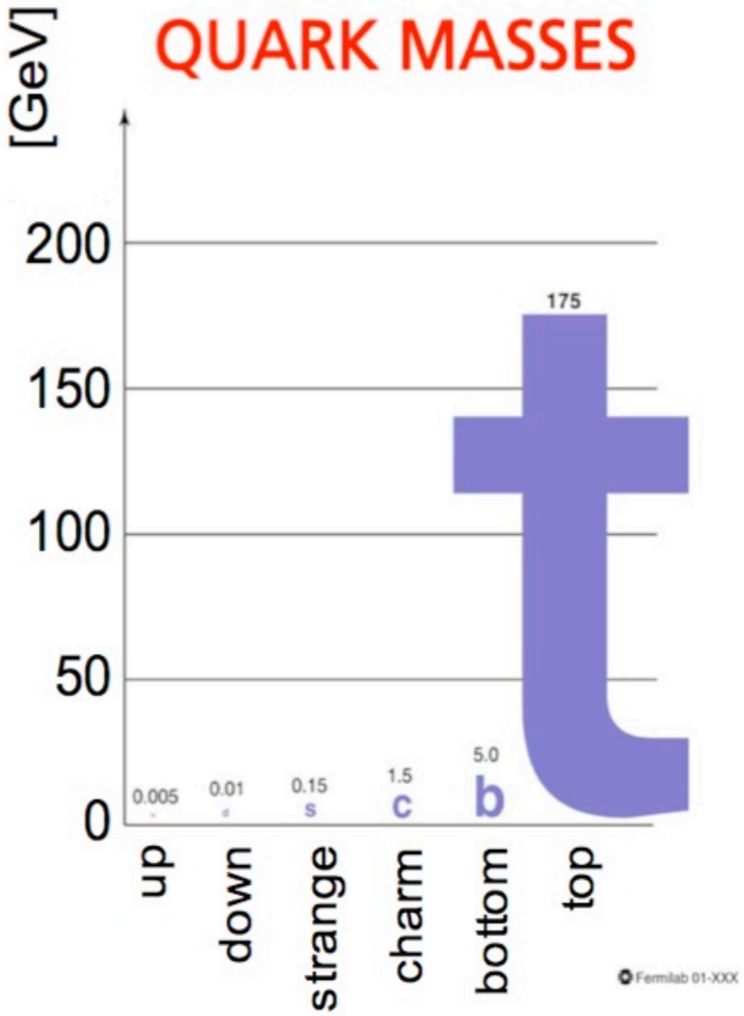
The top quark

- The heaviest known elementary particle
- Large coupling to the Higgs: ~1
- Short lifetime

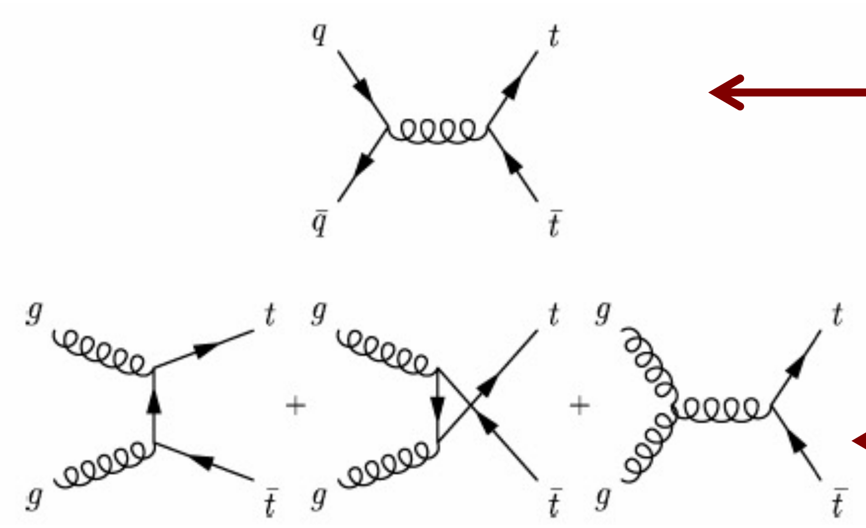
τ=0.4x10^{-24} sec

  - for m_{top}=175 GeV⇒Γ=1.4 GeV ⇒no hadronization
  - large contributions to EWK corrections ~$G_F m_{top}^2$
  - very short lifetime ⇒ bound states are not formed
    ⇒ opportunity to study a free quark

- Large samples of top quarks available
- Top quarks are main background for many New Physics searches
- Precision measurements may provide insight into physics beyond SM



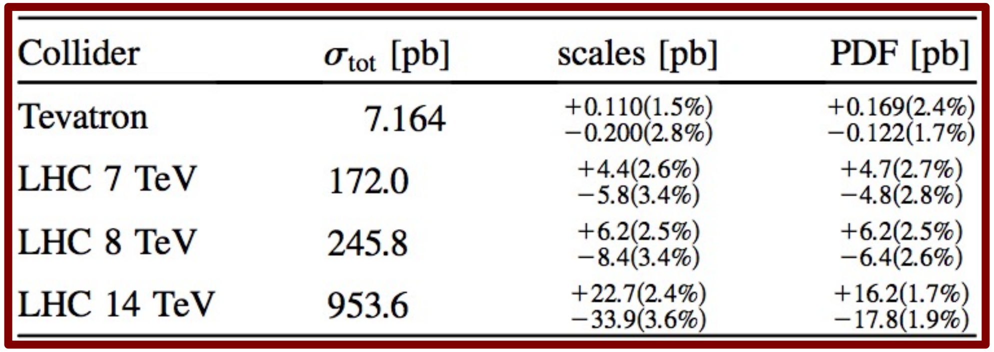
How is the top quark produced?



Dominant at Tevatron

Dominant at the LHC

Predicted cross sections:



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Tevatron	7.164	+0.110(1.5%) −0.200(2.8%)	+0.169(2.4%) −0.122(1.7%)
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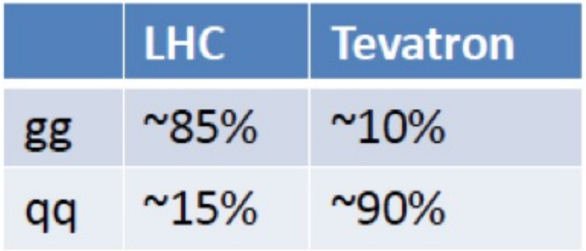
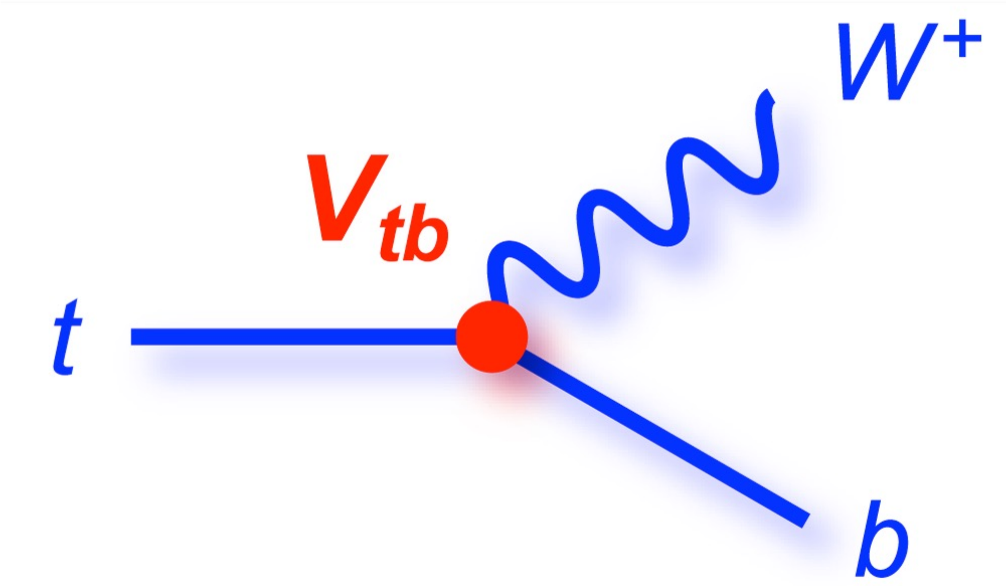
Czakon et al. PRL 110, 252004 (2013)



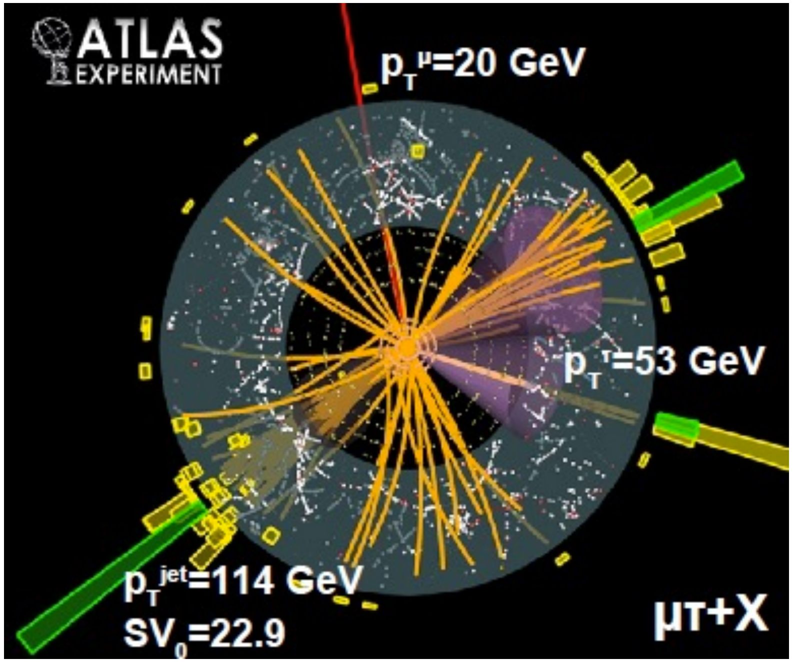
	LHC	Tevatron
gg	~85%	~10%
qq	~15%	~90%

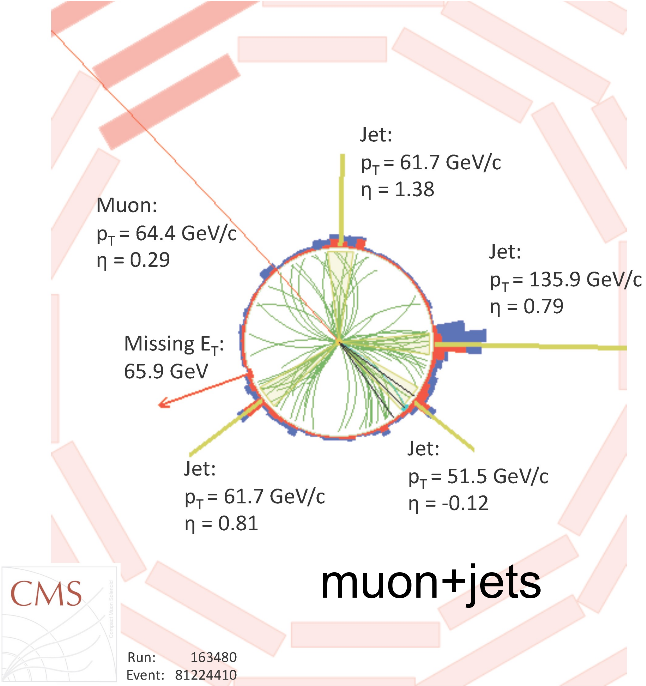
How does a top quark decay?



- 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

Selection of top quark events



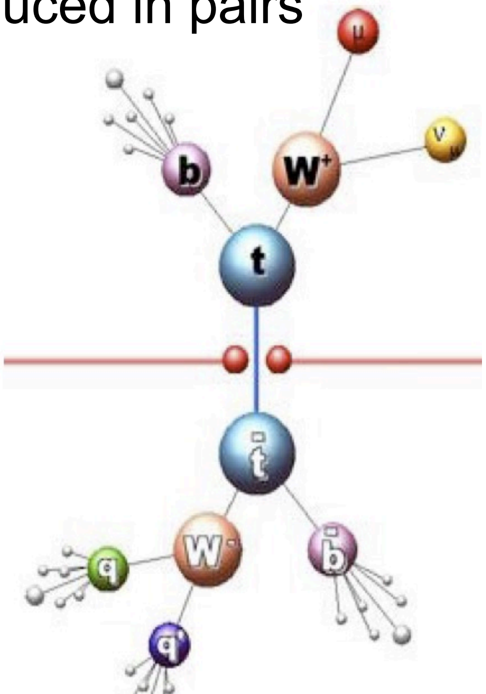


- Trigger:
  - single or double (isolated) lepton
- Leptons:
  - e/μ, p_T>20/30 GeV, |η|<2.5
  - Identification/reconstruction
  - Tracker/calorimeter isolation

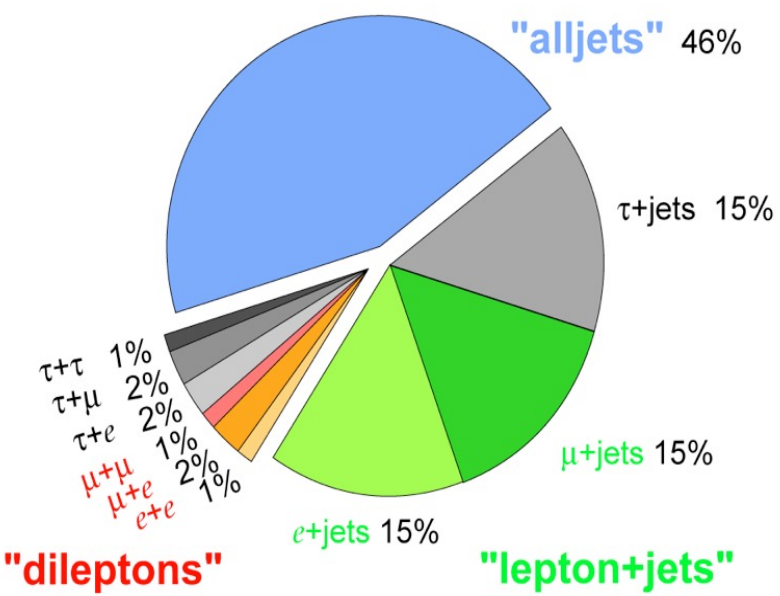
- Jets:
  - at least 2 jets, p_T>30 GeV, |η|<2.5
  - anti-kT algorithm, with cone 0.4-0.5
  - b-tagging is optional
- Missing transverse energy:
  - Typically require 30-40 GeV

Top quark decays

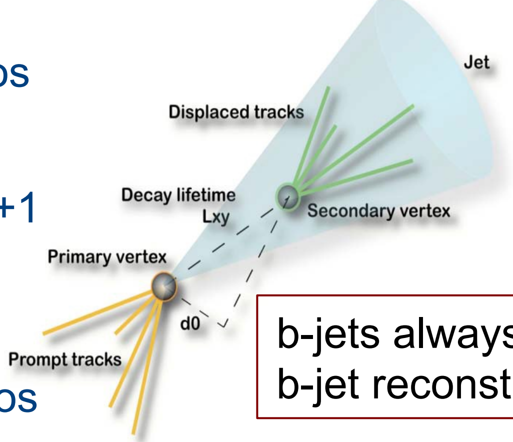
Top quarks (mostly) produced in pairs



Top Pair Branching Fractions

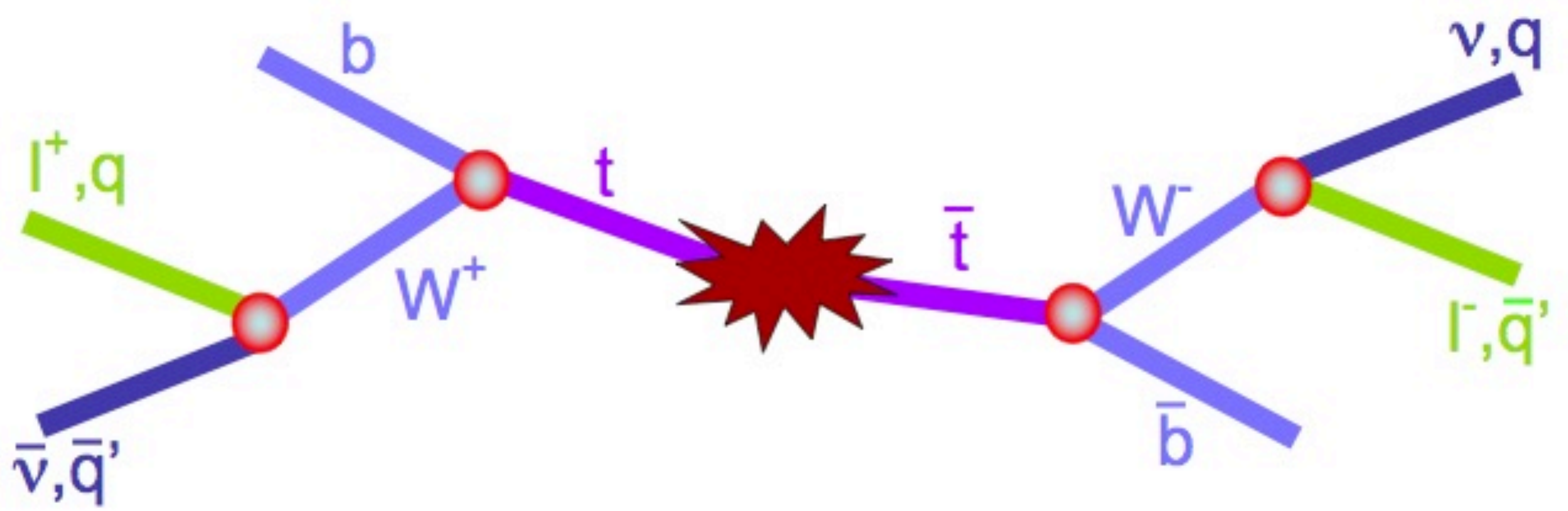


- Dilepton (ee, μμ, eμ):
  - BR~5%, 2 leptons+2 b-jets+2 neutrinos
- Lepton (e or μ) + jets
  - BR~30%, one lepton+4jets (2 from b)+1 neutrino
- All hadronic
  - BR~44%, 6 jets (2 from b), no neutrinos



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

Interesting physics with Top quark



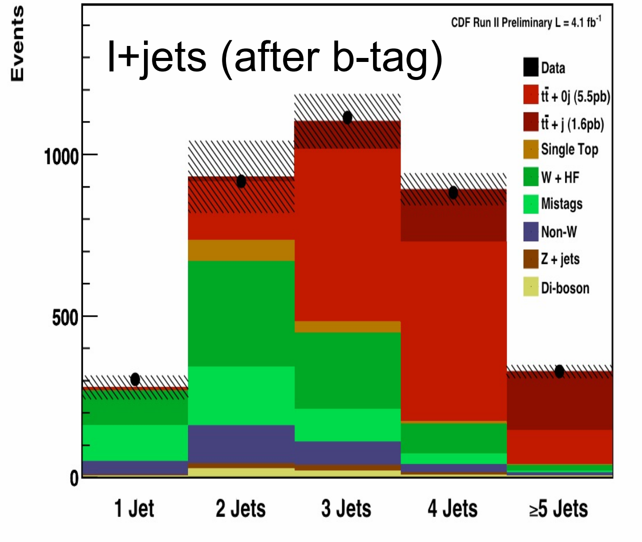
PRODUCTION
Cross section
Resonances X→tt
Fourth generation t’
Spin-correlations
New physics (SUSY)
Flavour physics (FCNC)
...

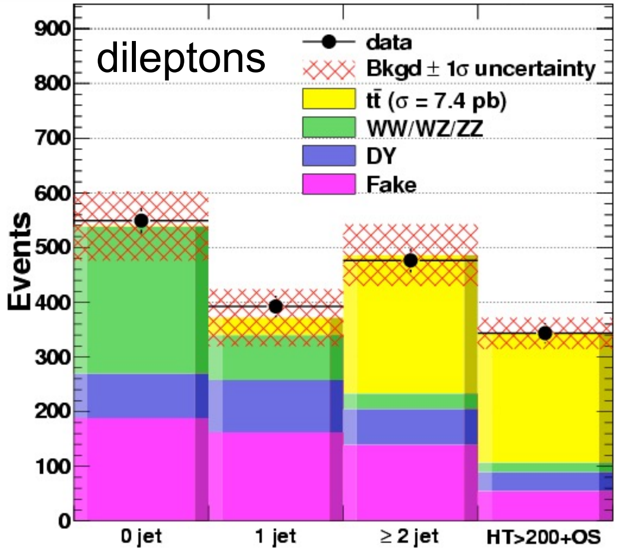
PROPERTIES
Mass
Kinematics
Charge
Lifetime and width
W helicity
Spin
...

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

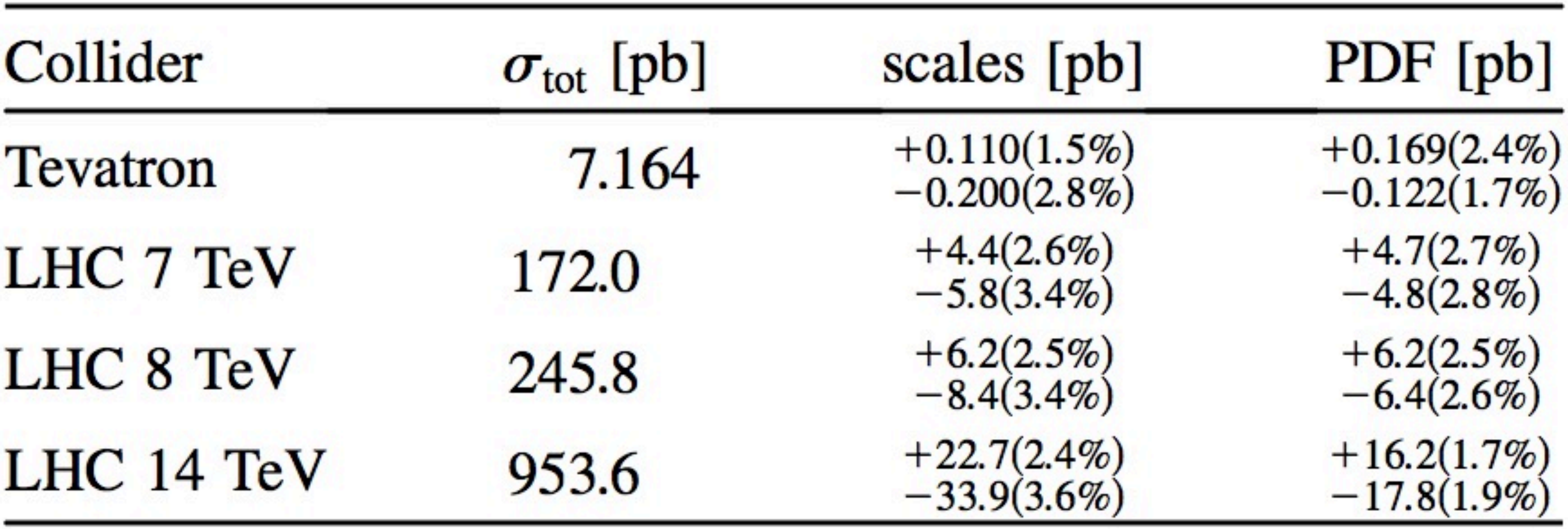
Top quark events

- 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



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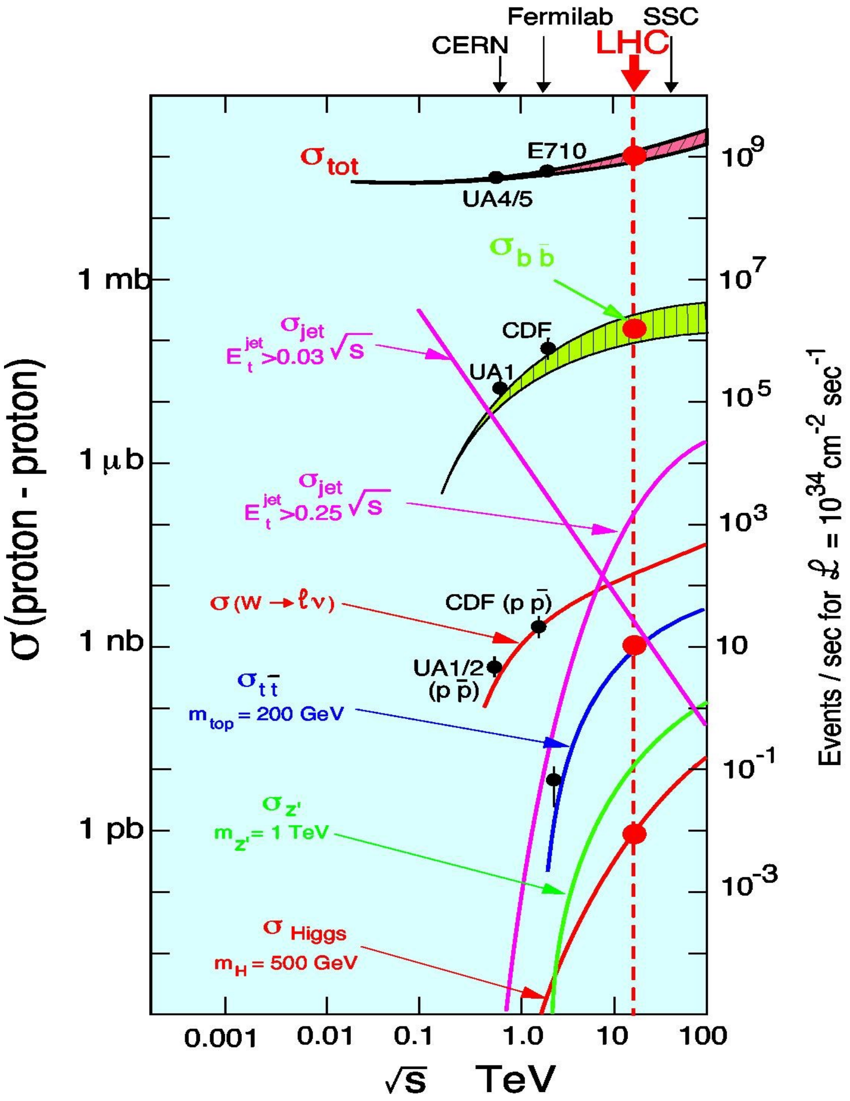
Including NNLO+NNLL approximations
PRL 110, 252004 (2013) (M. Czakon et al.)

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

Number of observed events

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

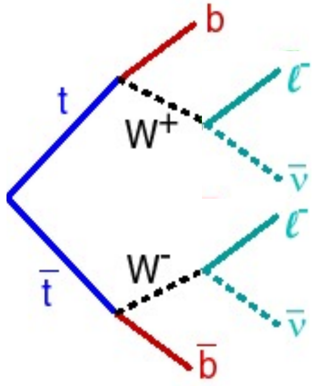
$$\sigma_{t\bar{t}} = \frac{N_{obs} - N_{bgd}}{\varepsilon_{t\bar{t}} \cdot \int L dt}$$

Acceptance *(experimental: detector, efficiencies)*

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

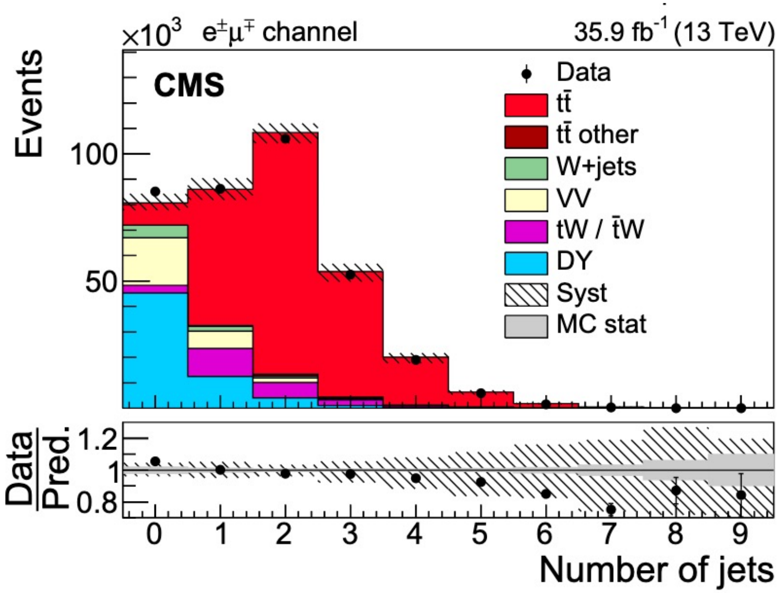
Dilepton channel

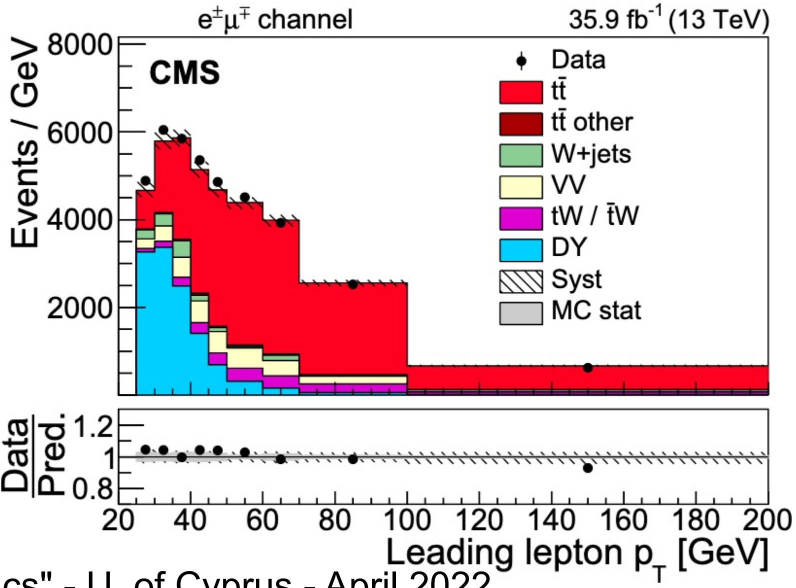
EPJC 79(2019)368



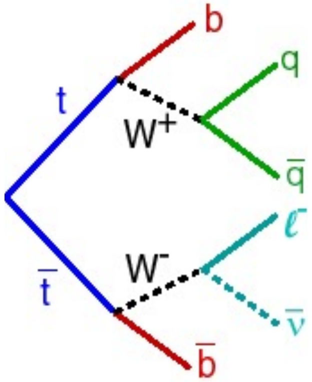
- Branching ratio (BR) ~5%
- Background: small

- 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)



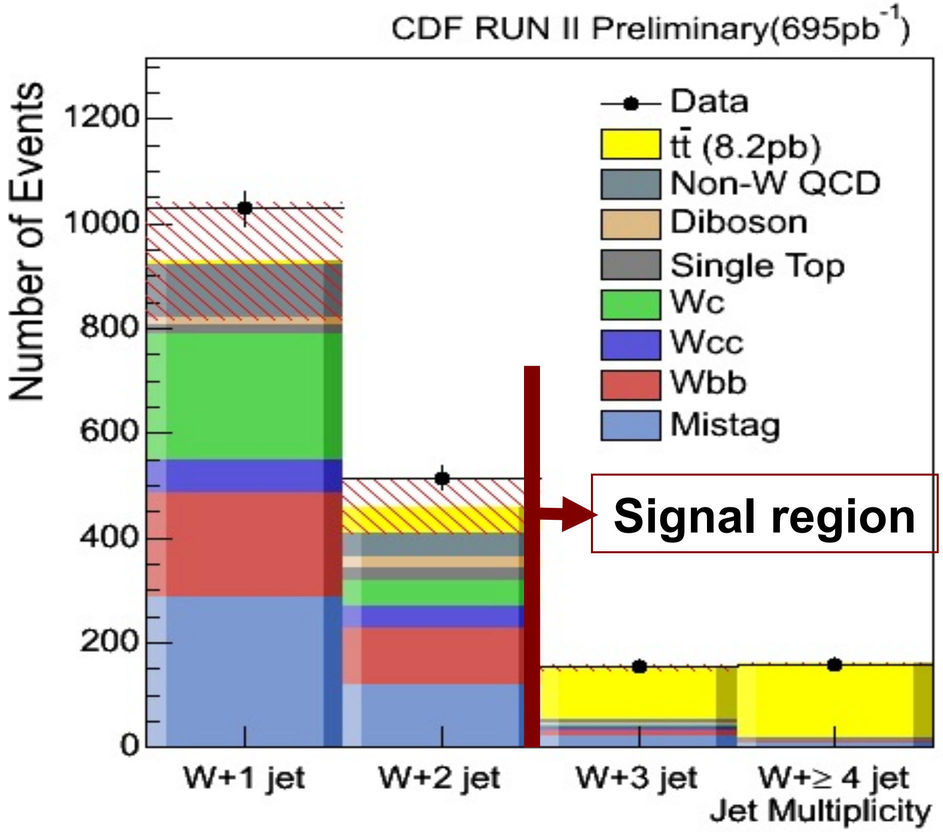


Lepton + jets



- BR ~30%
- Background: moderate

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



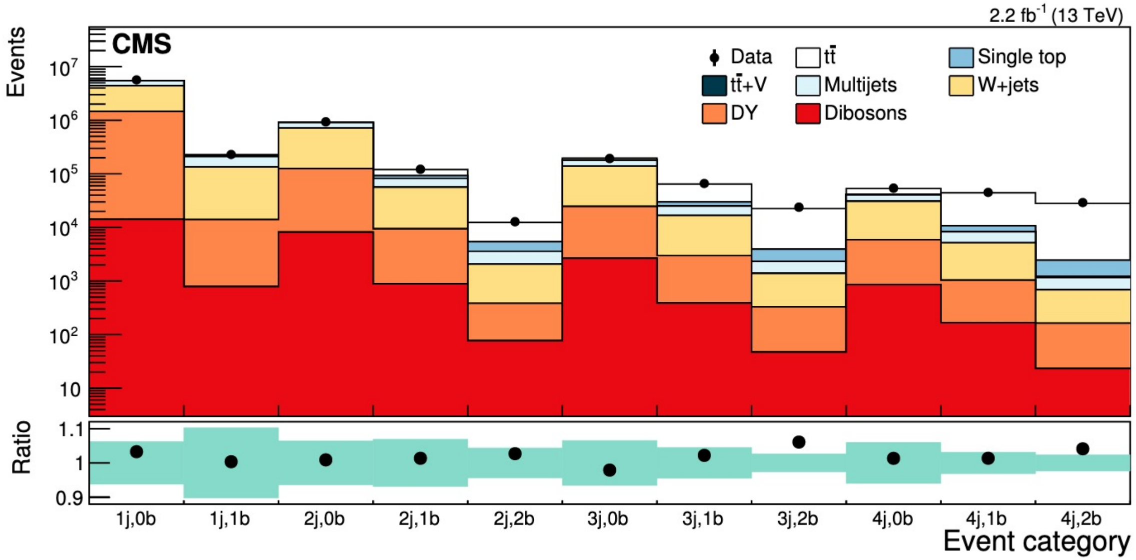
Signal region

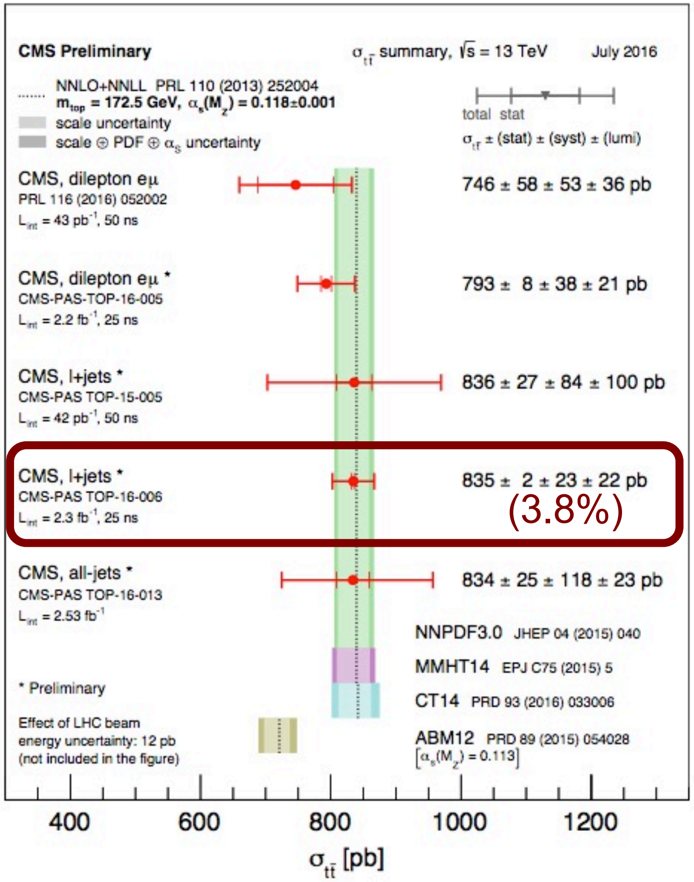
- Main backgrounds:
  - hadronic multi-jet, W+jets

Cross section: multi-dimensional fit

JHEP 09(2017)051

- 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





(3.8%)

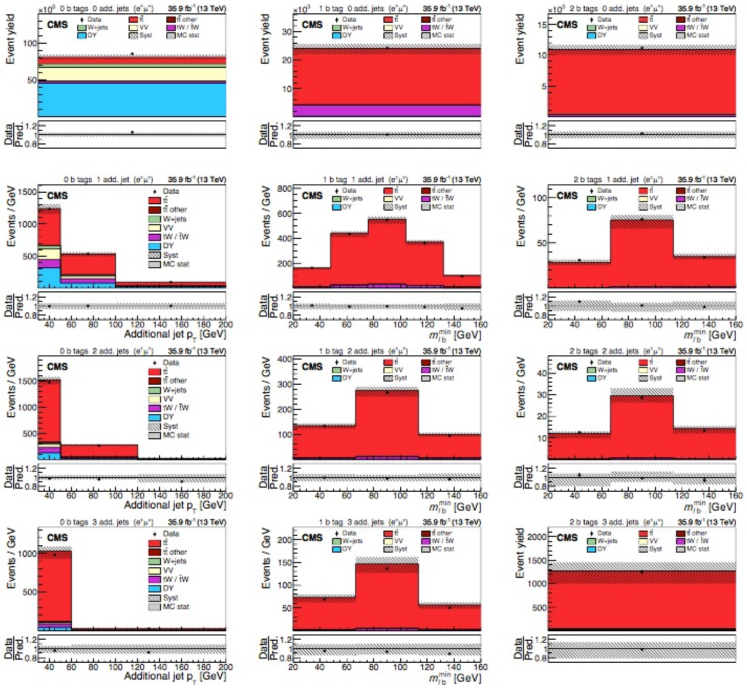
Cross section: multi-dimensional fit

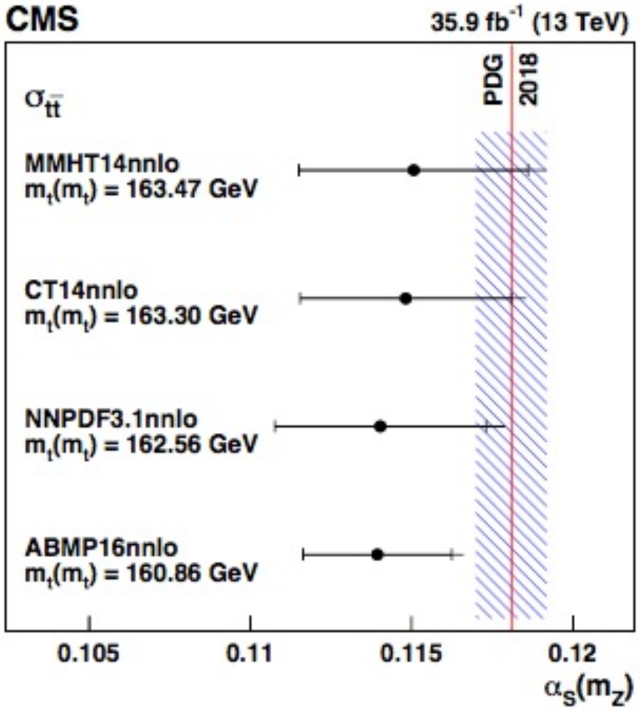
- Dilepton final state
- Simultaneous fit in ($N_{\text{additional jet}}$,$N_{\text{b-jet}}$) categories
- Fit of σ_{ttbar} and m(top)

(~4%)

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

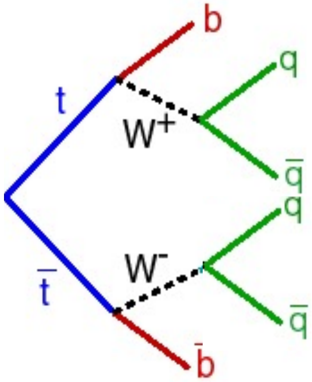
$$m_{t}^{\text{MC}} = 172.33 \pm 0.14\,(\text{stat})\,^{+0.66}_{-0.72}\,(\text{syst})\,\text{GeV}$$





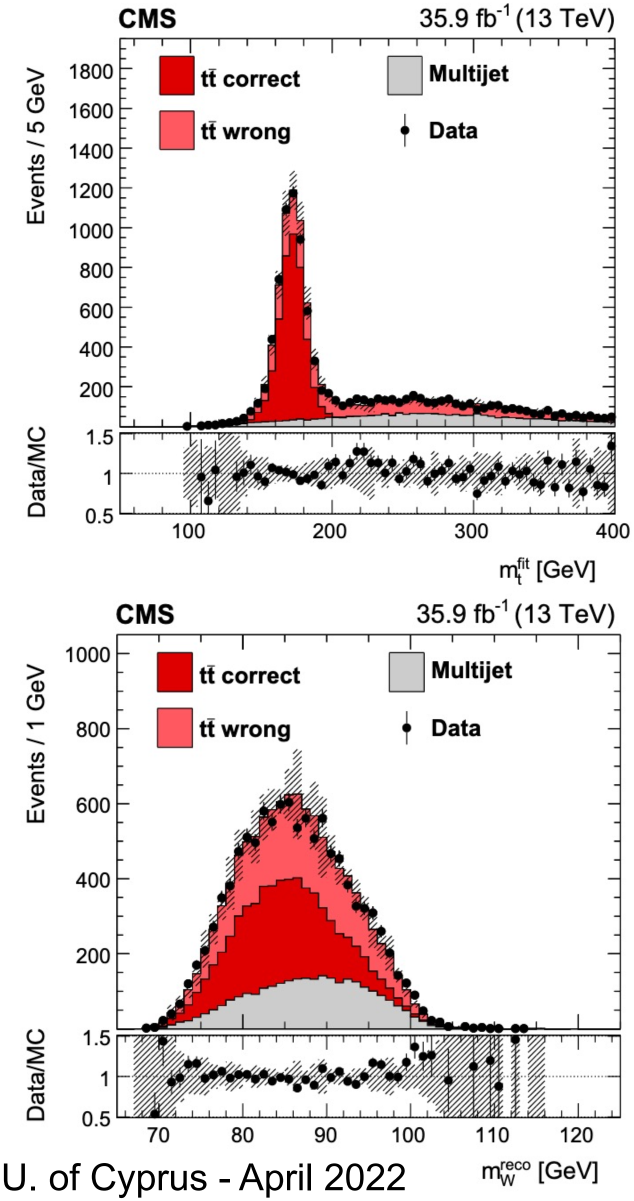
All hadronic

EPJC 79(2019)313



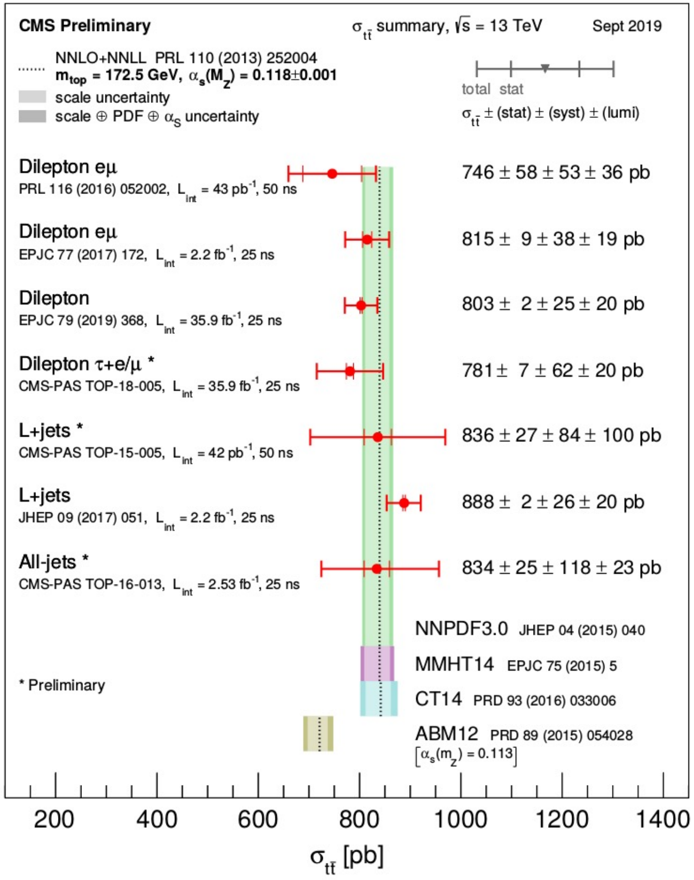
- BR ~46%
- Background: large

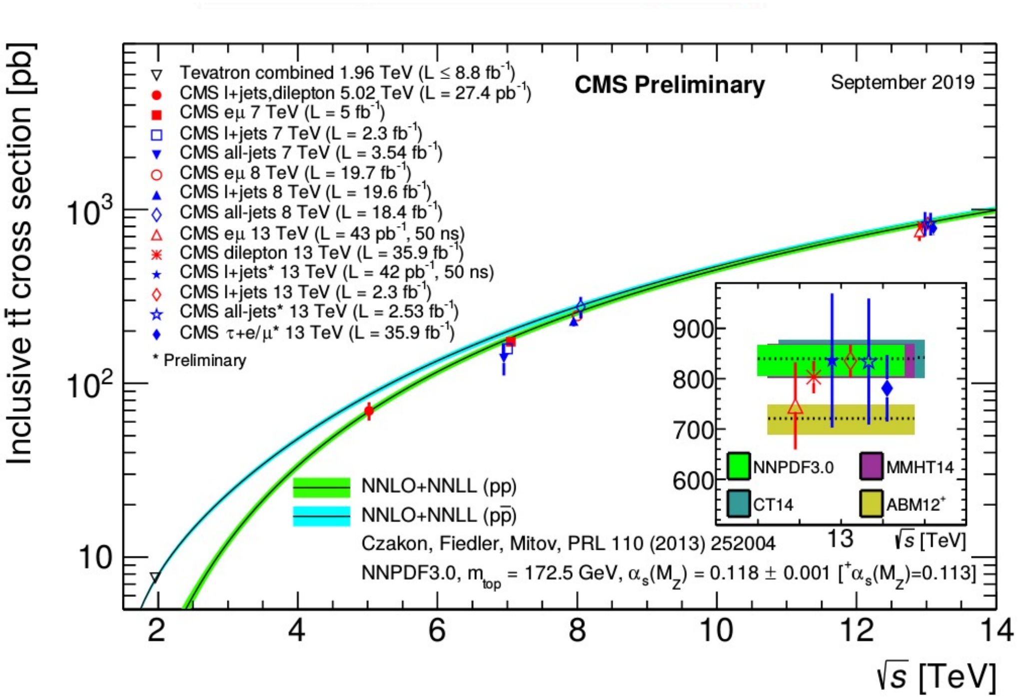
- Selection:
  - ≥6 jets + kinematical selection
  - require 2 b-tags
- Main backgrounds:
  - hadronic multi-jet
  - same selection without b-tag

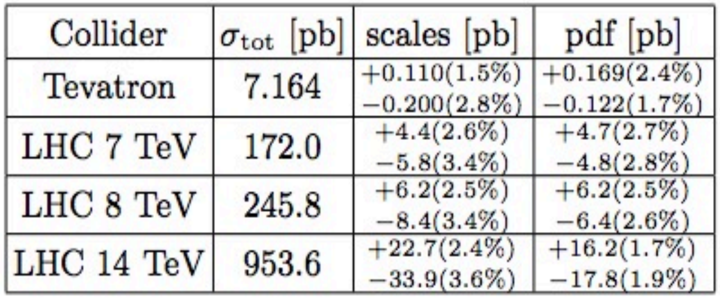


Cross sections

±4%







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±3-5%

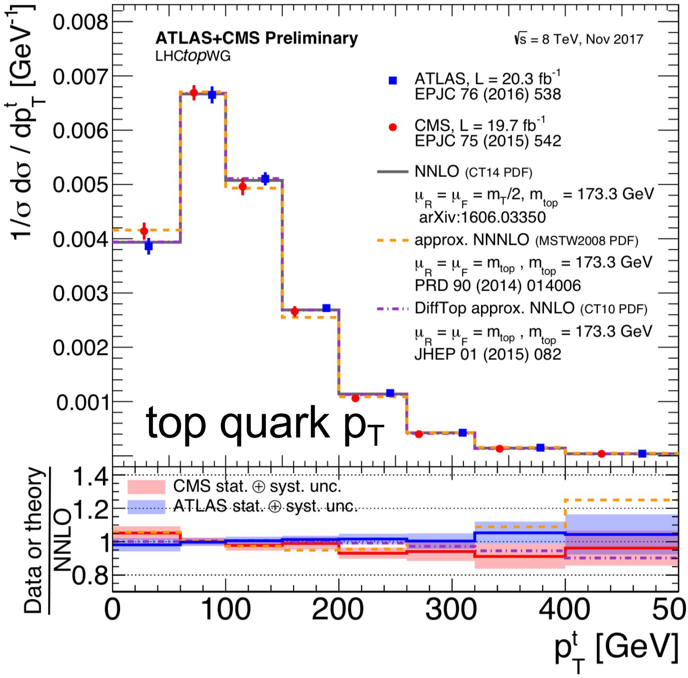
⇒measurements challenging theory

Differential cross section

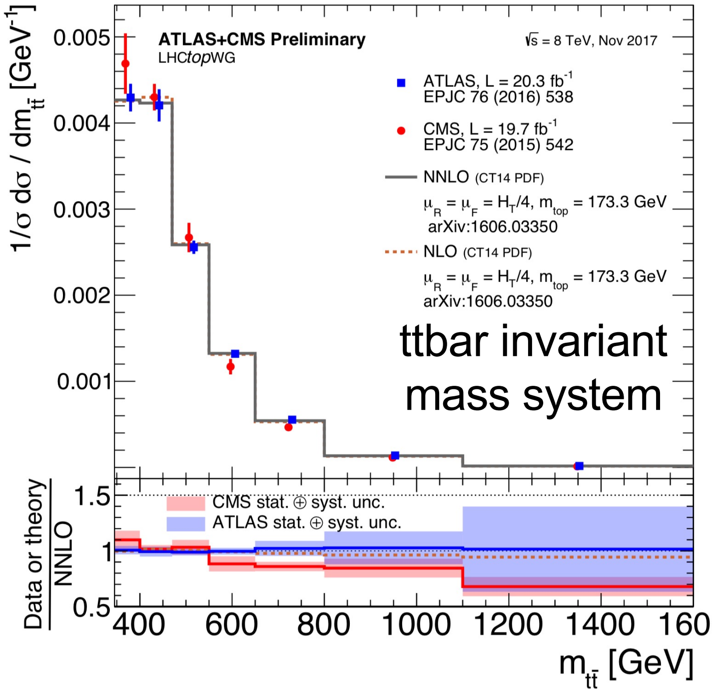
EPJC 73(2013) 2339, arXiv:1610.04191

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

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



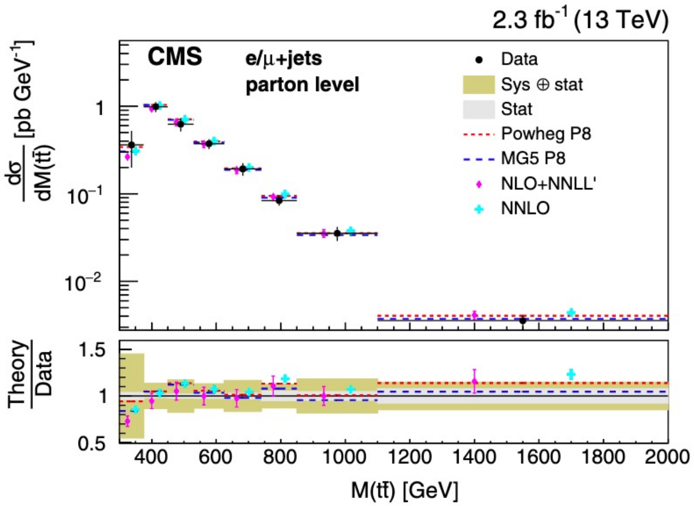
top quark p_T



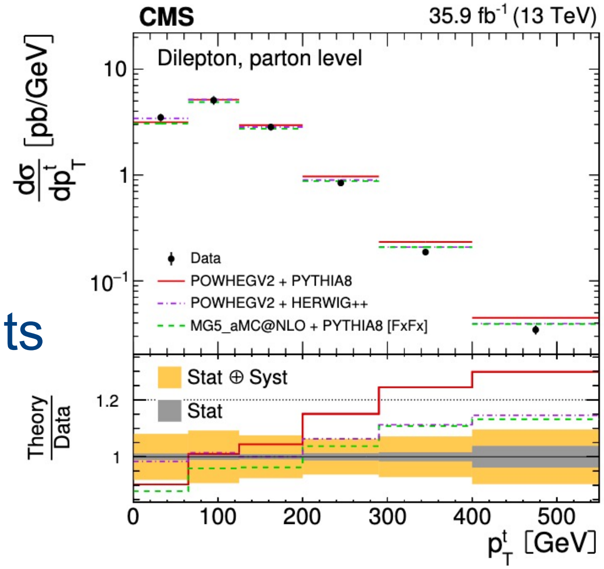
ttbar invariant mass system

Differential cross section (cont.)

PRD 95(2017)092001, JHEP 02(2019)149

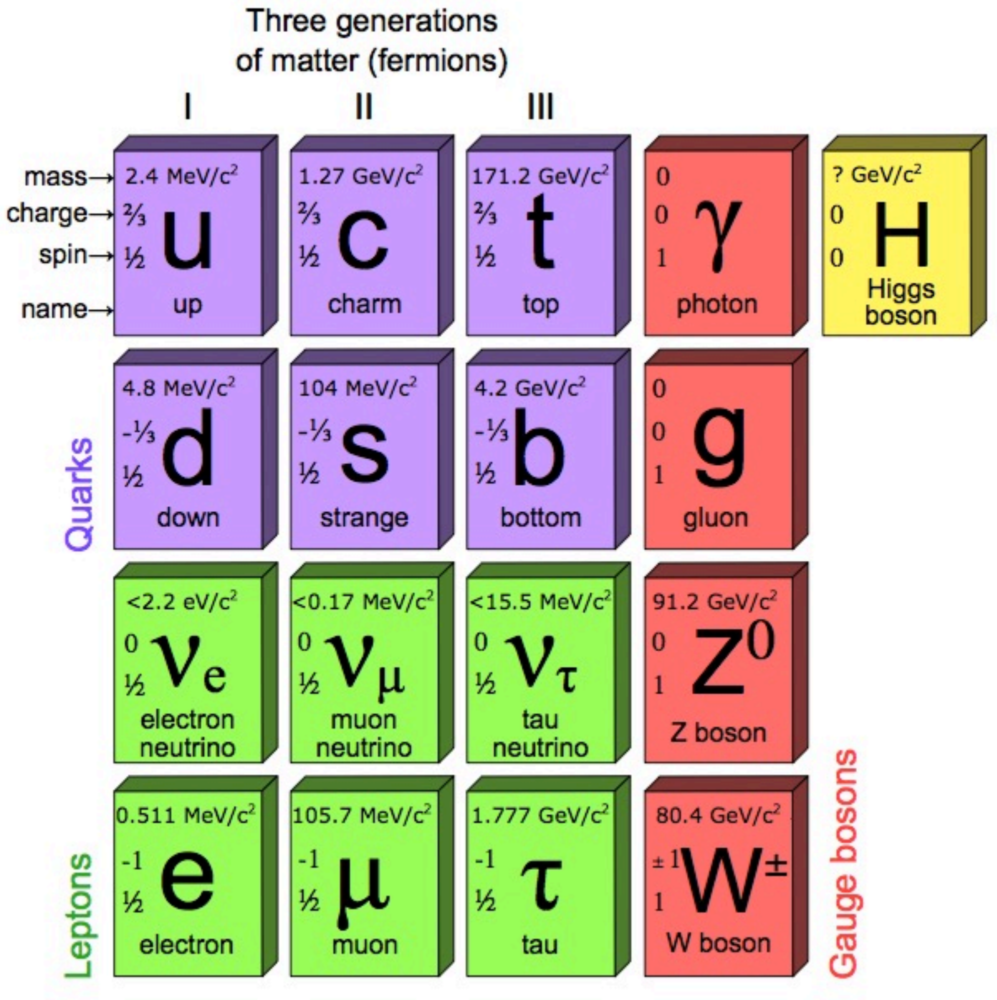


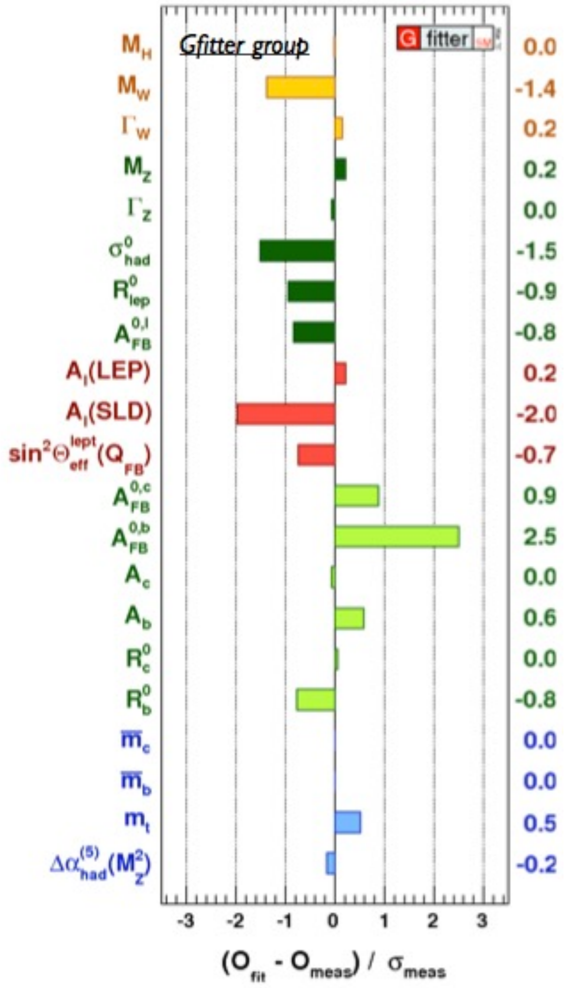
- Correct for detector effects and acceptances
- Softer top p_T (CMS), agreement in ATLAS at high p_T
  - – Due to momentum reshuffling, P.Nason, cern.ch/event/301787
  - – FSR shower changes mass of final state partons. light partons can build sizeable mass, and t/tbar do not radiate
  - – short term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



SM confirmed by the data

Standard model of elementary particles

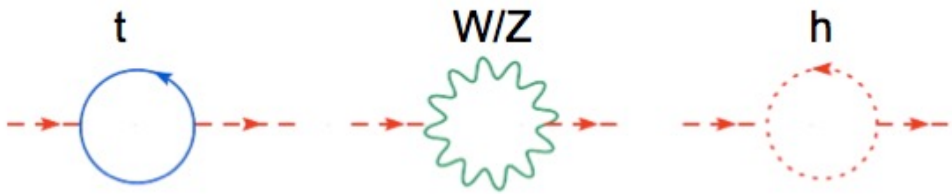




Excellent agreement with all experimental results

Top quarks as window to BSM physics

Top quark affects stability of Higgs mass



Contributions grow with Λ:

$$m^2 = m_0^2 + g^2\Lambda^2$$

Cancellation?

Solutions:

- Naturalness: There is no problem
- Weakly-coupled model at TeV scale
  - New particles to cancel SM divergences
  - Top partners: new scalar/vectors coupled to top, exotic top decays
- Strongly-coupled model at TeV scale
  - ttbar resonances, bound states, 4-top production, etc.
- New space-time structure
  - Introduce extra space dimensions to lower Planck scale cutoff to ~1TeV
  - KK excitations

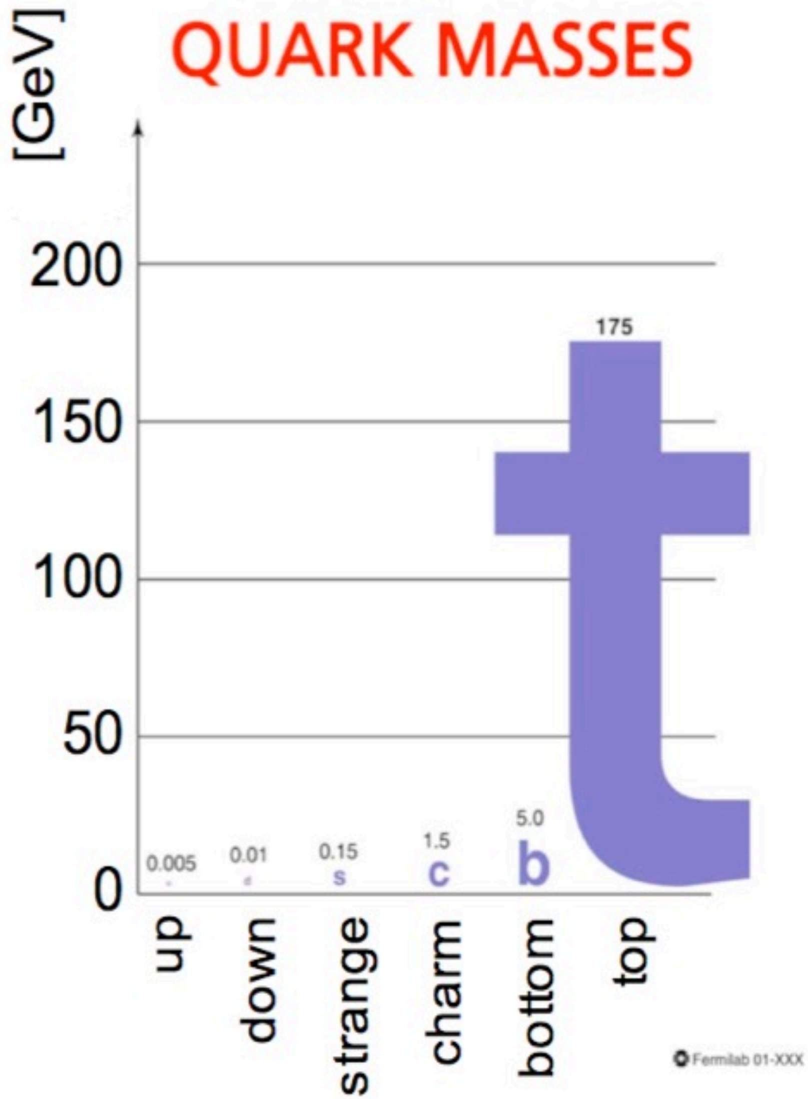
The top quark

- The heaviest known elementary particle
- Large coupling to the Higgs: ~1
- Short lifetime

  τ=0.4x10^{-24} sec

  - for m_{top}=175 GeV⇒Γ=1.4 GeV ⇒no hadronization
  - large contributions to EWK corrections ~$G_F m_{top}^2$
  - very short lifetime ⇒ bound states are not formed ⇒ opportunity to study a free quark

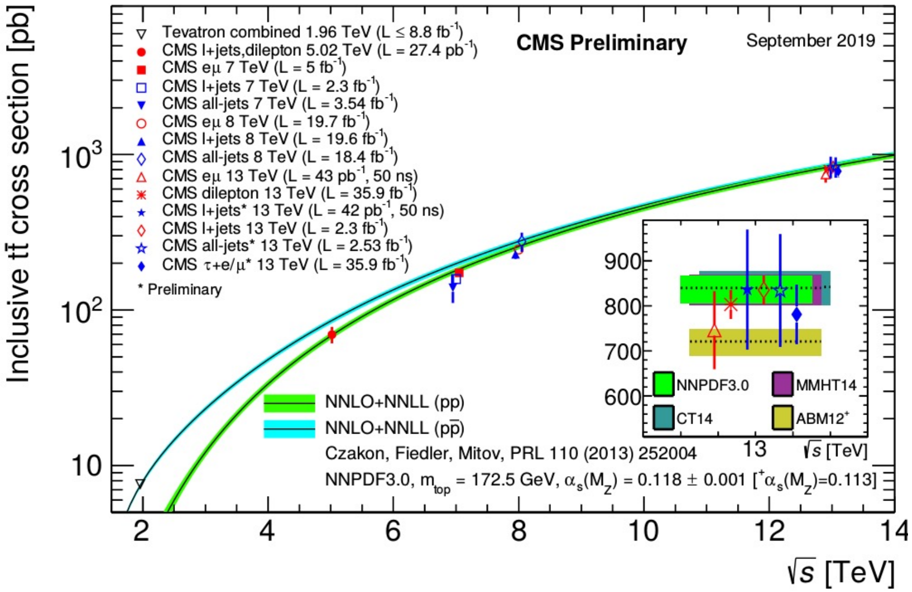
- Large samples of top quarks available
- Top quarks are main background for many New Physics searches
- Precision measurements may provide insight into physics beyond SM

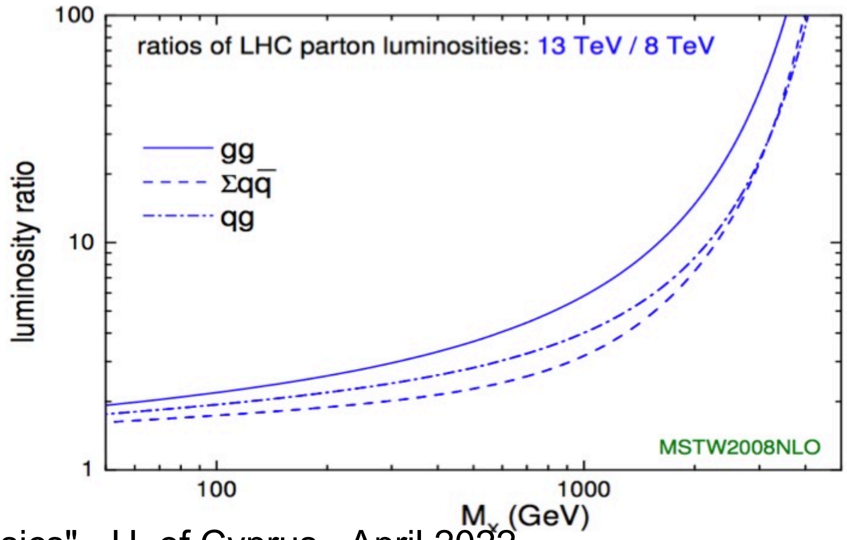


Role of top quark physics

- Top quark physics after the Higgs discovery
  - Heavy particle, preferential coupling?
  - 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
- Is there any sign of NP in top production/decay?





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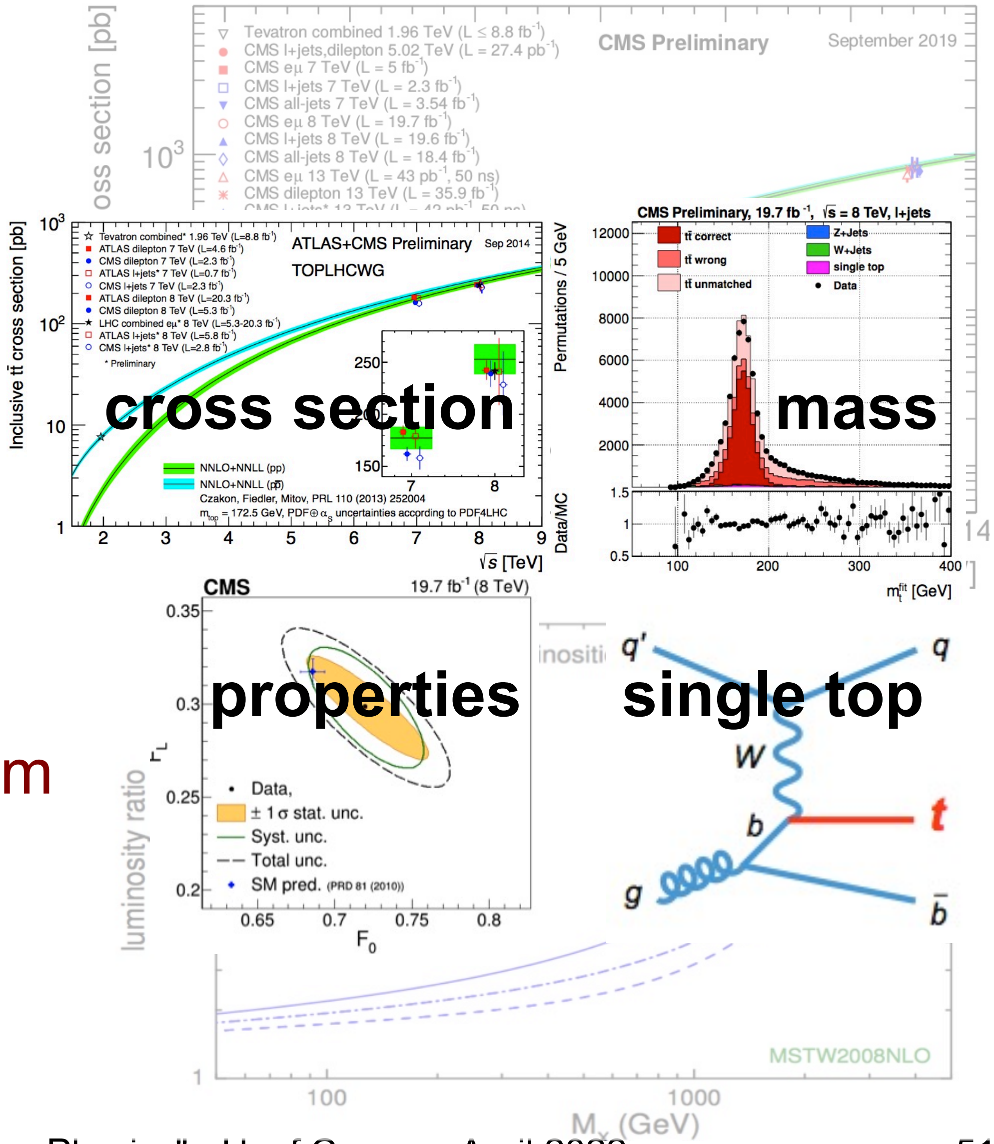
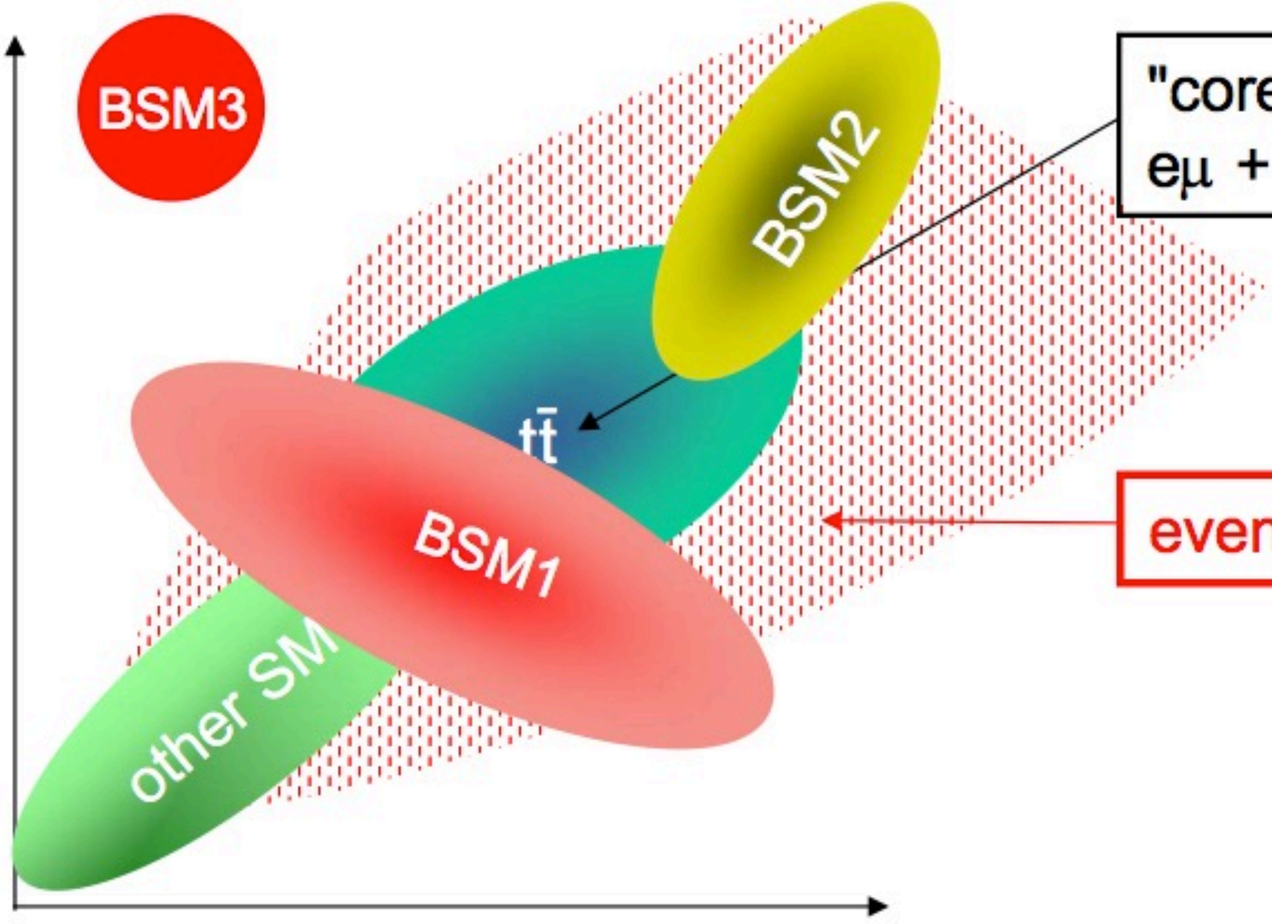


Study characteristics



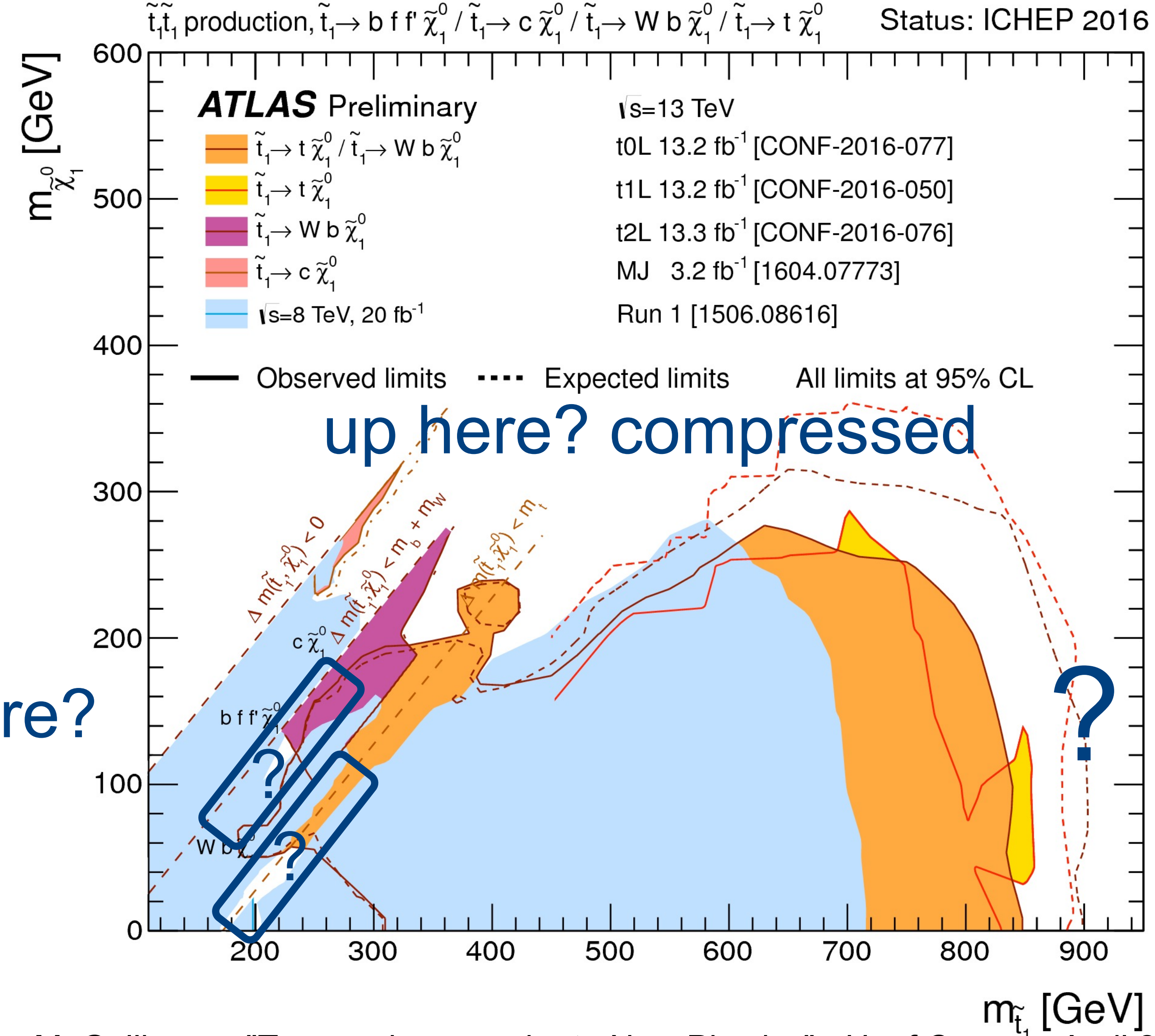
"core" $t\bar{t}$ region, e.g., eμ + MET + 2 b-tags

event selection region

Drawing by C. Campagnari

Regions hard to explore

hiding here?



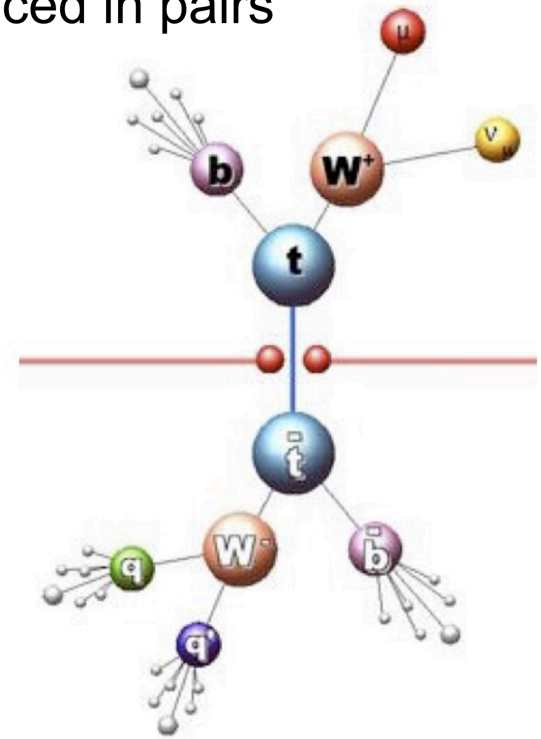
up here? compressed

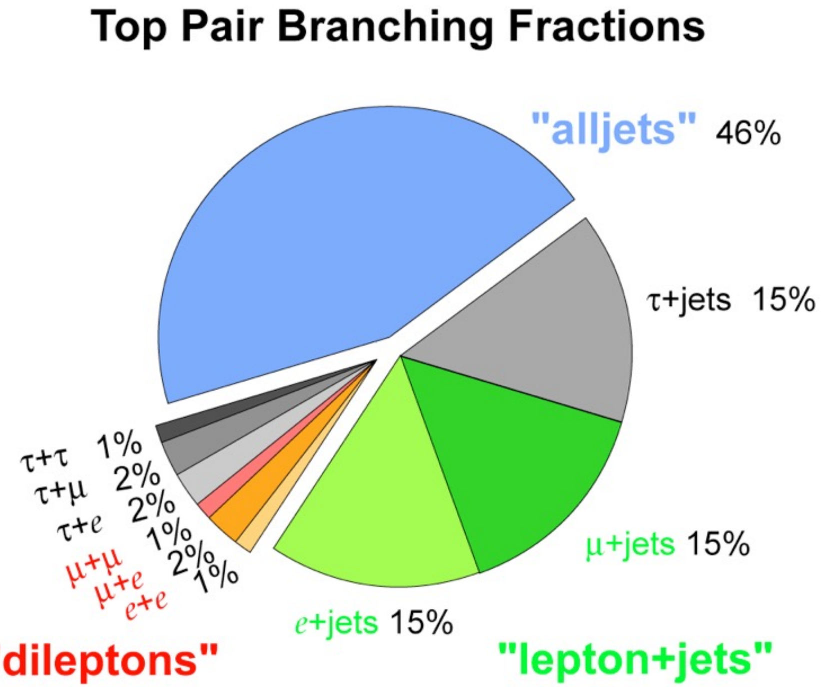
?

or here?

Top quark decays

Top quarks (mostly) produced in pairs





- Dilepton (ee, μμ, eμ):
  - – BR~5%, 2 leptons+2 b-jets+2 neutrinos
- Lepton (e or μ) + jets
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- All hadronic
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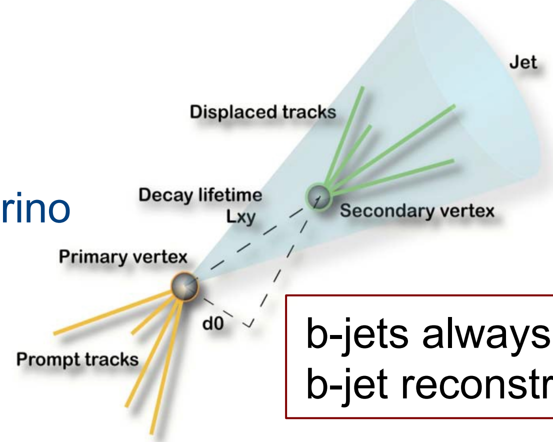

b-jets always present
b-jet reconstruction plays important role

Differential cross section

CMS-TOP-20-006

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

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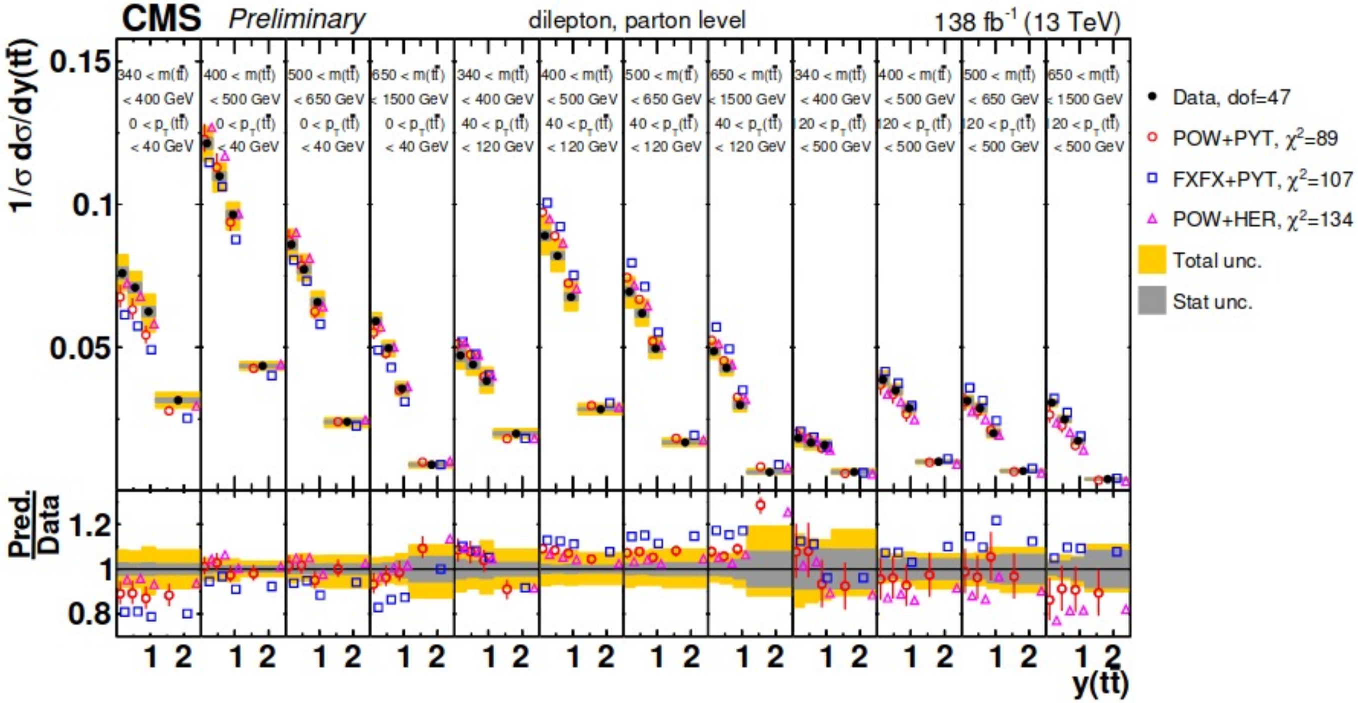


Probing the Wtb vertex

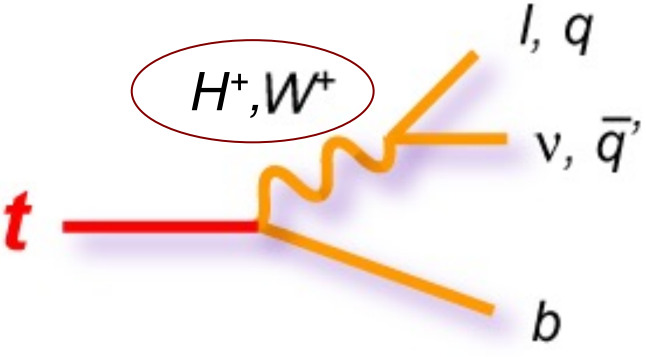
PRD 85(2012)112007, PLB 739(2014)23, JHEP 02(2020)191

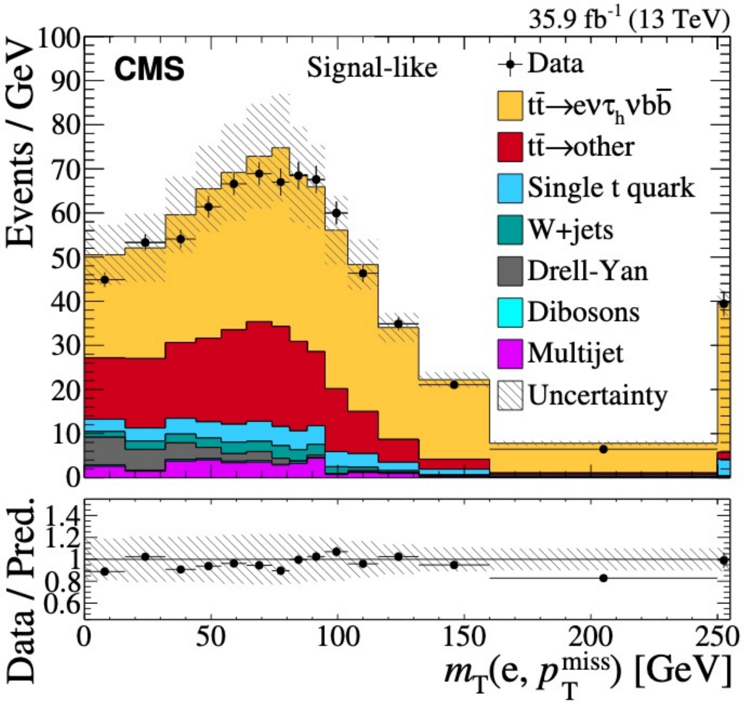
Dileptons with taus

- cross section measurement including τs
- Includes only 3rd generation quarks/leptons
- Syst unc: tauId, fakes

Channel	Signature	BR
Dilepton(e/μ)	*ee*,$\mu\mu$,*e*μ + 2*b*-jets	4/81
Single lepton	*e*,μ + jets + 2*b*-jets	24/81
All-hadronic	jets + 2*b*-jets	36/81
Tau dilepton	eτ, $\mu\tau$ +2 *b*-jets	4/81
Tau+jets	τ + jets + 2*b*-jets	12/81

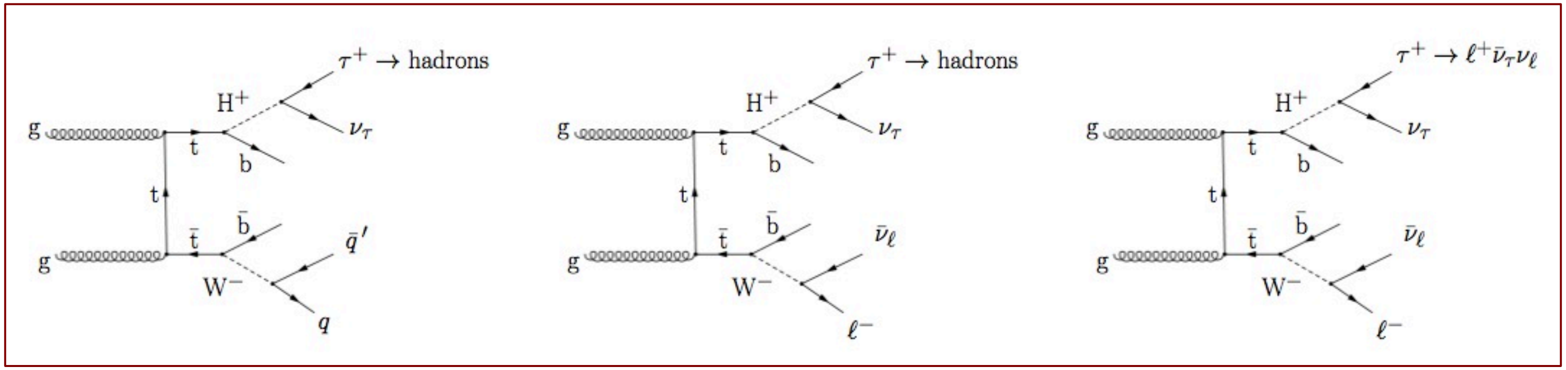
- If top quark plays special role in EWK symmetry breaking, couplings to W may change
- Charged Higgs may alter coupling to W
- Search for final states with taus: charged Higgs





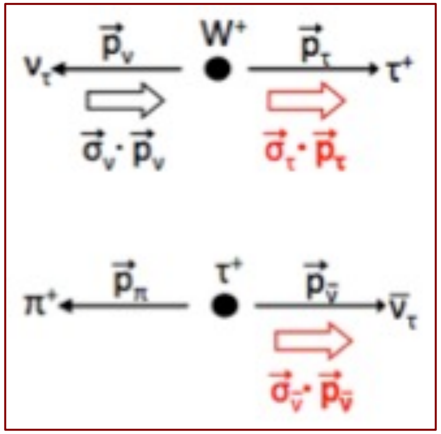
Looking at tau decays

CMS-HIG-12-052

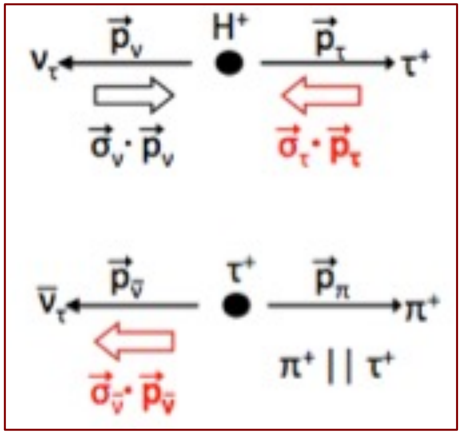


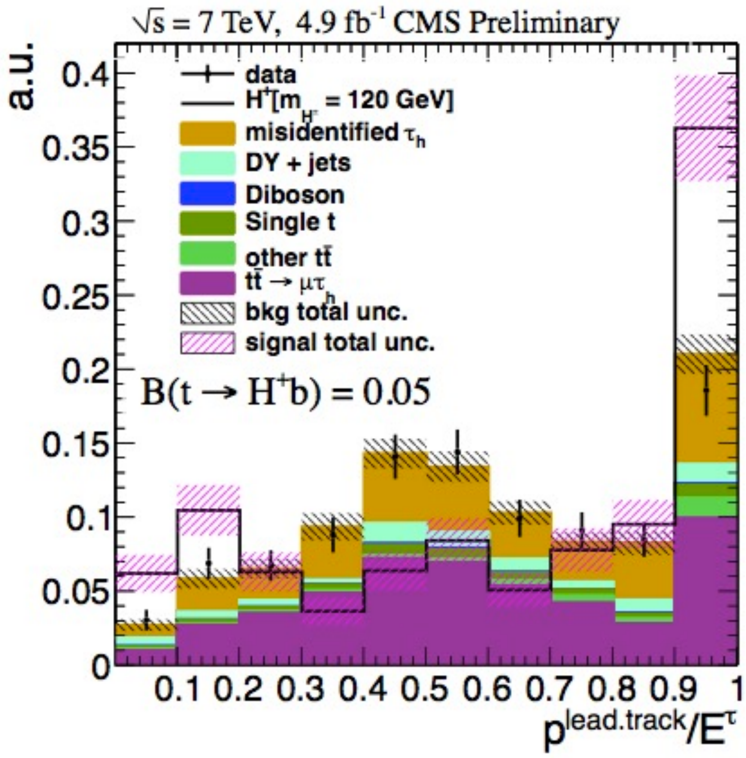
SM

BSM



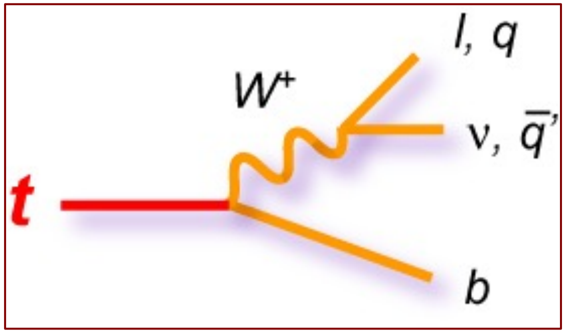
VS



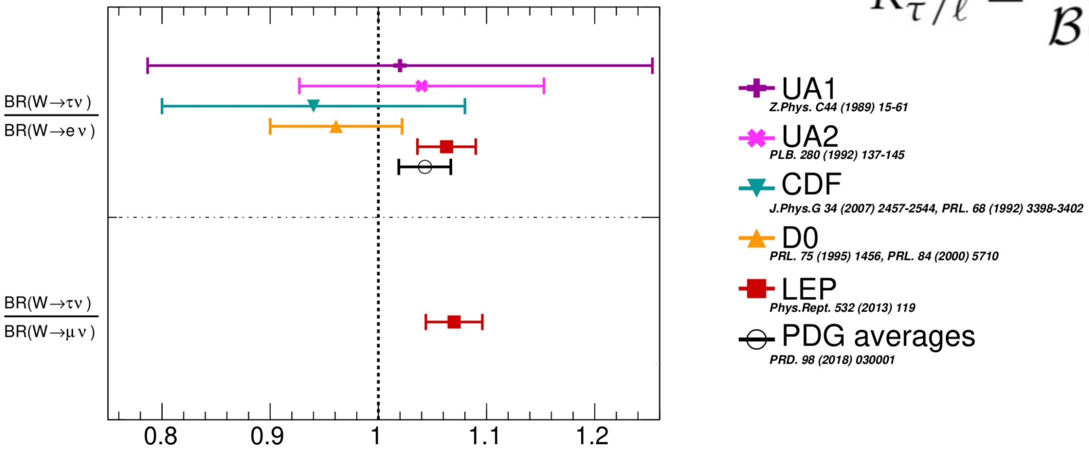


W boson branching fractions

- Precise measurement of the W boson BRs (electrons, muons, taus)
  - Use events with WW and W+jets
  - Multiple categories used
  - Maximum likelihood simultaneous fitting of templates to data in each category



- Most precise determination of B(W⟶lν) from LEP has 2.6σ deviation from LFU



$$R_{\tau/\ell} = \frac{2\,\mathcal{B}(\mathrm{W}\to\tau\overline{\nu}_\tau)}{\mathcal{B}(\mathrm{W}\to\mathrm{e}\overline{\nu}_\mathrm{e})+\mathcal{B}(\mathrm{W}\to\mu\overline{\nu}_\mu)} = 1.066\pm0.025$$

Lepton Flavour Universality

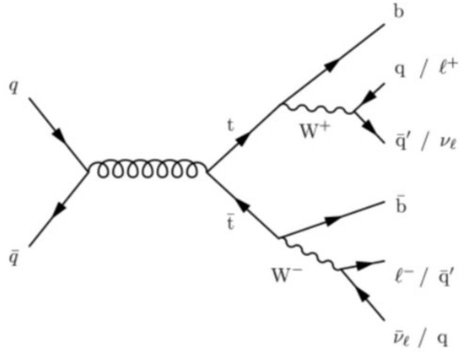
arXiv:2007.14040, CMS-SMP-18-011

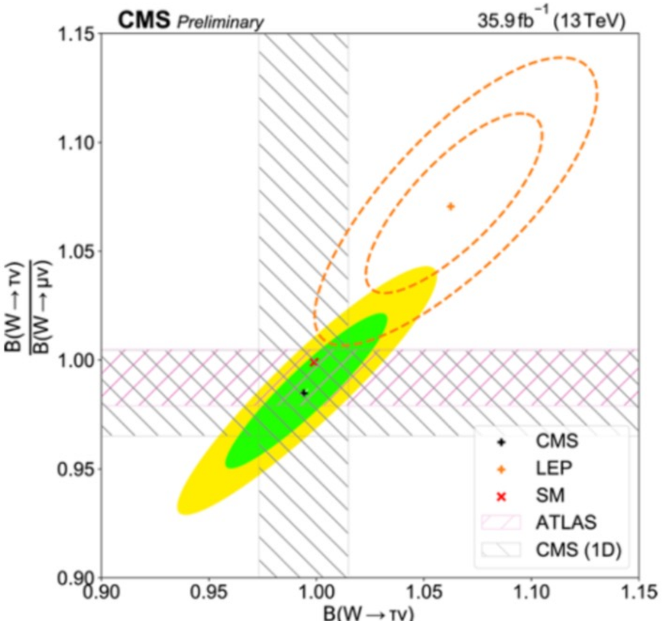
Resolving an old discrepancy from LEP

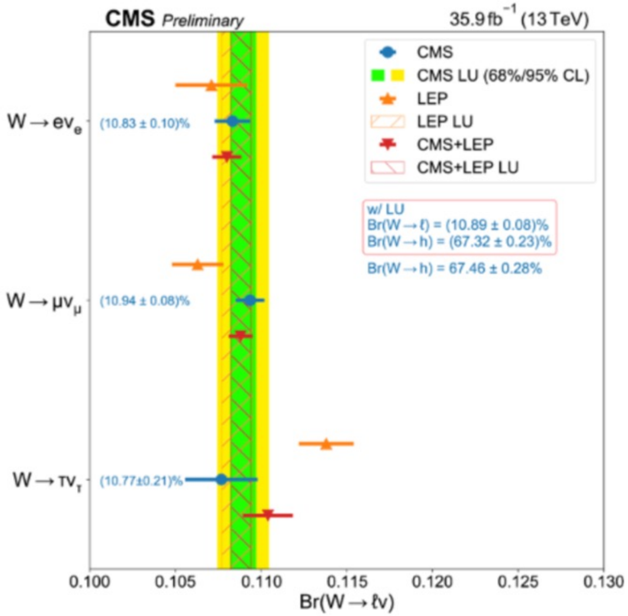
Strategy :
Use W bosons
from top quarks

	CMS	LEP
$\mathcal{B}(W \to e\bar{\nu}_e)$	$(10.83 \pm 0.01 \pm 0.10)\%$	$(10.71 \pm 0.14 \pm 0.07)\ \%$
$\mathcal{B}(W \to \mu\bar{\nu}_\mu)$	$(10.94 \pm 0.01 \pm 0.08)\%$	$(10.63 \pm 0.13 \pm 0.07)\ \%$
$\mathcal{B}(W \to \tau\bar{\nu}_\tau)$	$(10.77 \pm 0.05 \pm 0.21)\%$	$(11.38 \pm 0.17 \pm 0.11)\ \%$
$\mathcal{B}(W \to h)$	$(67.46 \pm 0.04 \pm 0.28)\%$	
with LU		
$\mathcal{B}(W \to \ell\bar{\nu})$	$(10.89 \pm 0.01 \pm 0.08)\%$	$(10.86 \pm 0.06 \pm 0.09)\%$
$\mathcal{B}(W \to h)$	$(67.32 \pm 0.02 \pm 0.23)\%$	$(67.41 \pm 0.18 \pm 0.20)\%$

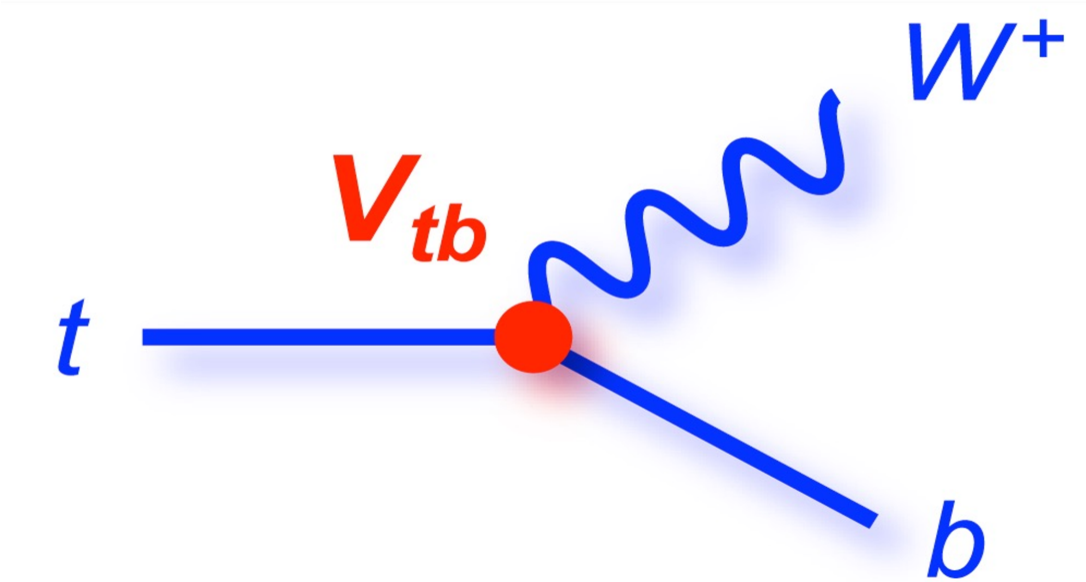
Many more Ws
than at LEP







How does a top quark decay?



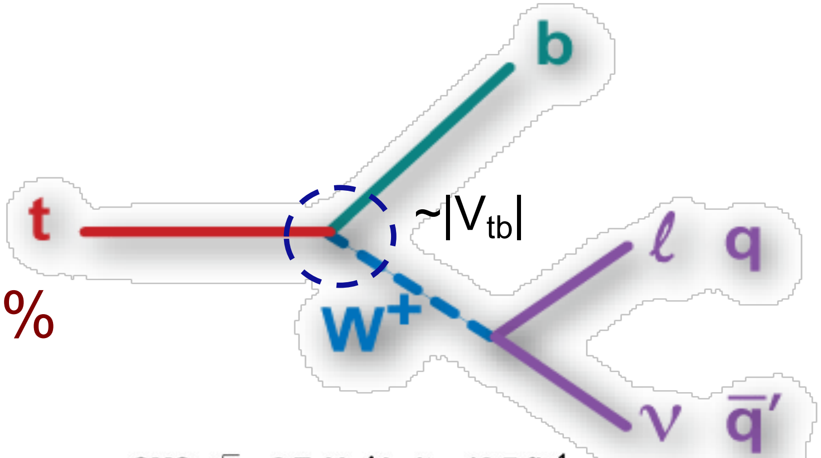
- almost always t→Wb (i.e. V_{tb}~1)
- lifetime is short, and it decays before hadronizing
- the W is real:
  - can decay W→lν (l=e,μ,τ), BR~1/9 per lepton
  - can decay W→qq, BR~2/3

Cross section in the R measurement

N.Cim. B125(2010)983, PLB 736(2014)33

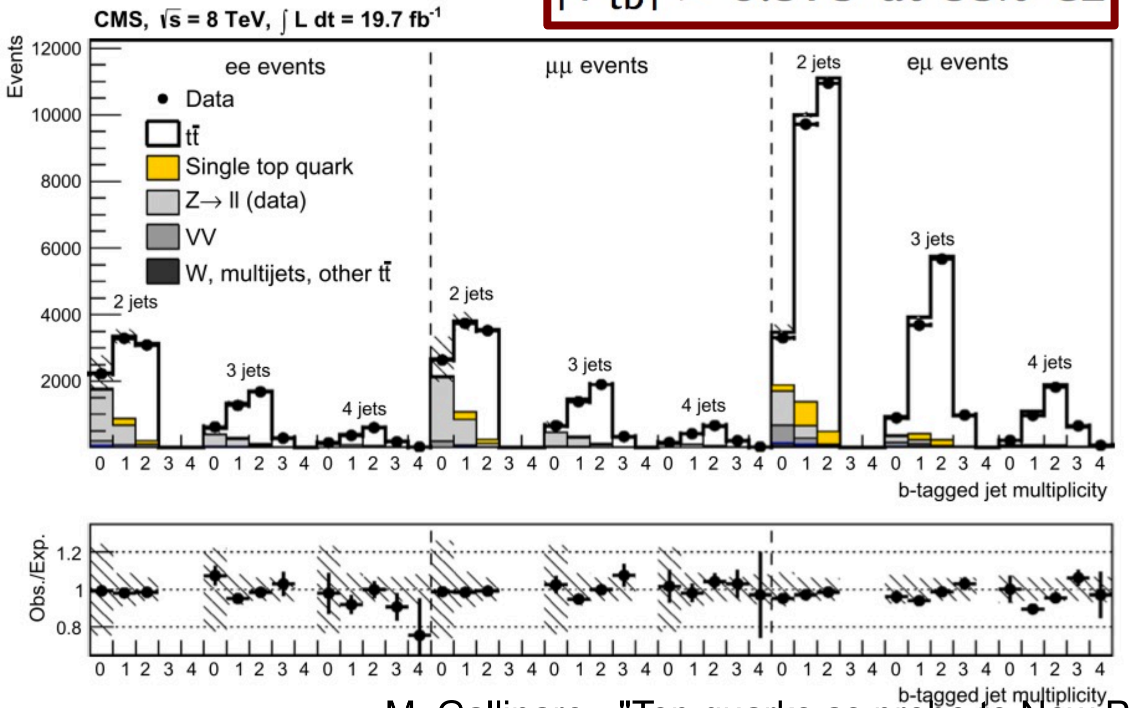
- Measure R:
- Dilepton final state

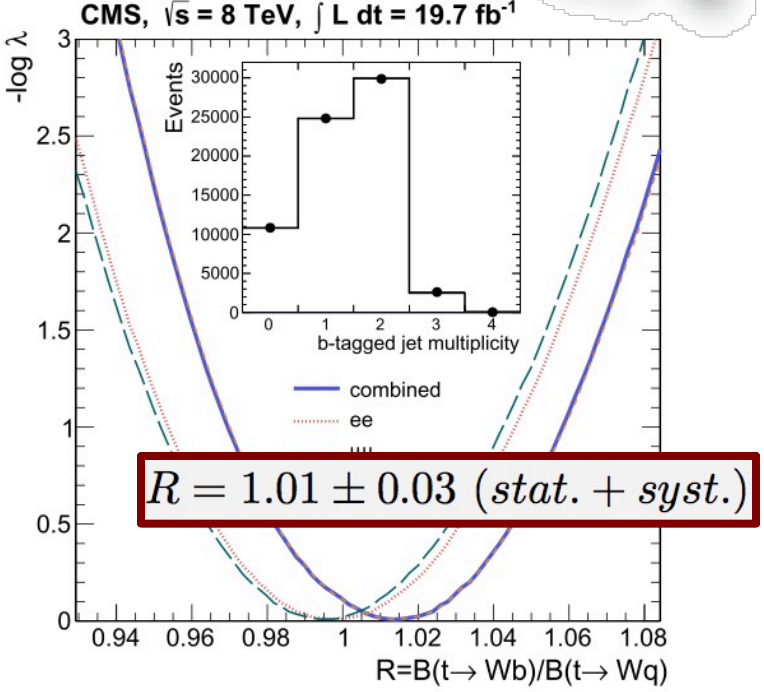
$$R \equiv \frac{BR(t \rightarrow Wb)}{BR(t \rightarrow Wq)} \approx |V_{tb}|^2$$



$$\sigma(t\bar{t}) = 238 \pm 1\,(\mathrm{stat.}) \pm 15\,(\mathrm{syst.})\ \mathrm{pb}$$ ±6%

$$|V_{tb}| > 0.975 \text{ at } 95\%\ \mathrm{CL}$$

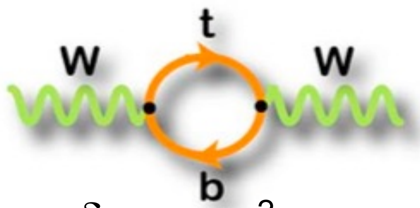




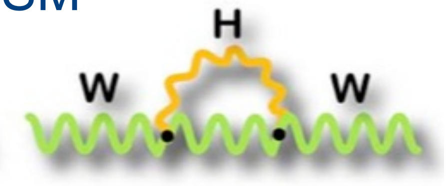
$$R = 1.01 \pm 0.03\ (stat. + syst.)$$

Top quark mass

- Top quark mass is a fundamental parameter of the SM

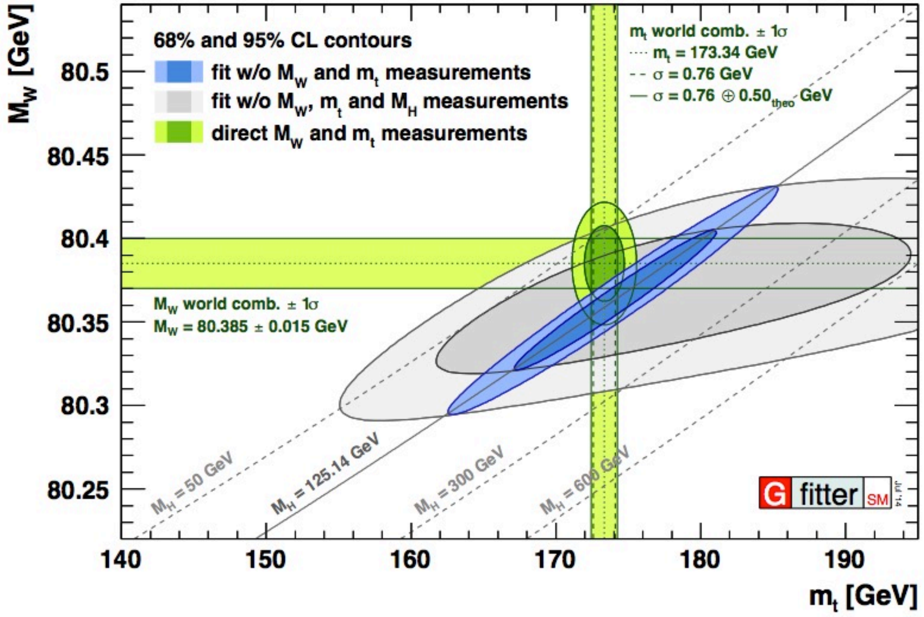


$\delta m_W \propto m_t^2$



$\delta m_W \propto \log m_h$

- Precise measurement needed for checking consistency of the SM

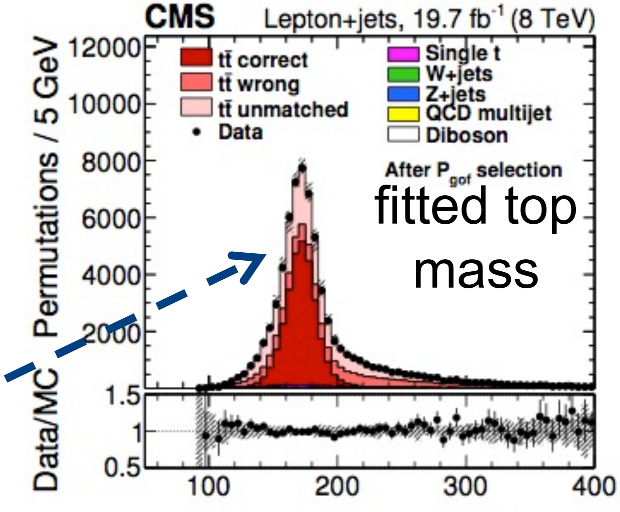


- Top is the only fermion with the mass of the order of EWSB scale
- Discovered Higgs boson fits well with precise determinations of m_W and m_{top}
- Other properties (EWK coupling, production asymmetries, etc.) are predicted by SM
- Precise measurements could reveal breakdown of SM

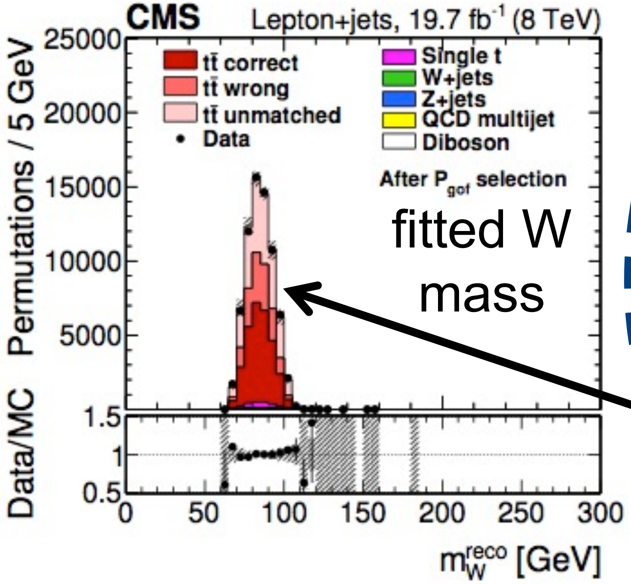
Precise mass measurement

arXiv:1509.04044, EPJC78(2018)891

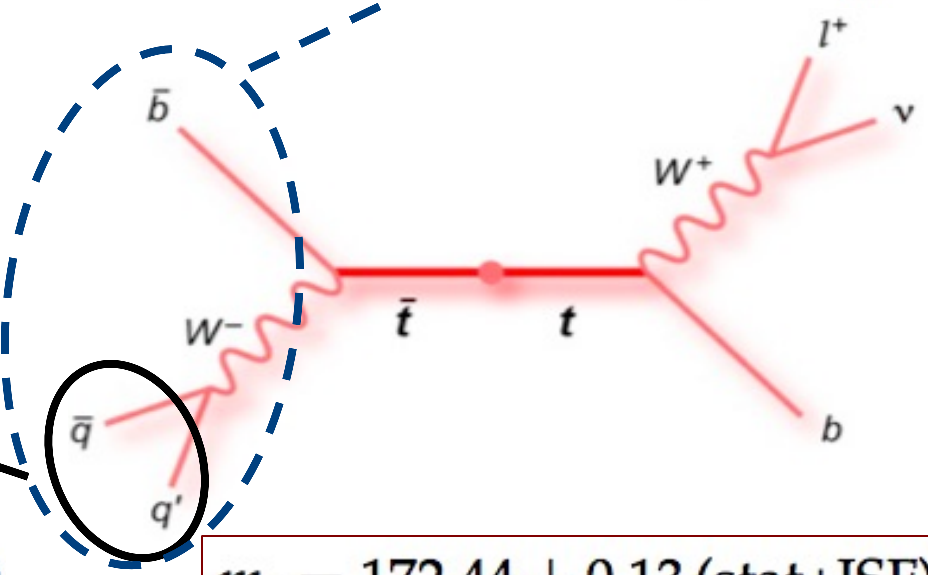
- Select lepton+jet final state
  - – Best channel to measure m_{top}
  - – well defined final state (1 lepton, 1ν, 2b $W_{qq'}$)
- Select ttbar events: hadronic decays (m_{top}, m_W)
- Kinematic fit: constrain W mass, top-antitop masses
  - – In-situ JES calibration
- Measure m_{top} and JSF



fitted top mass



fitted W mass

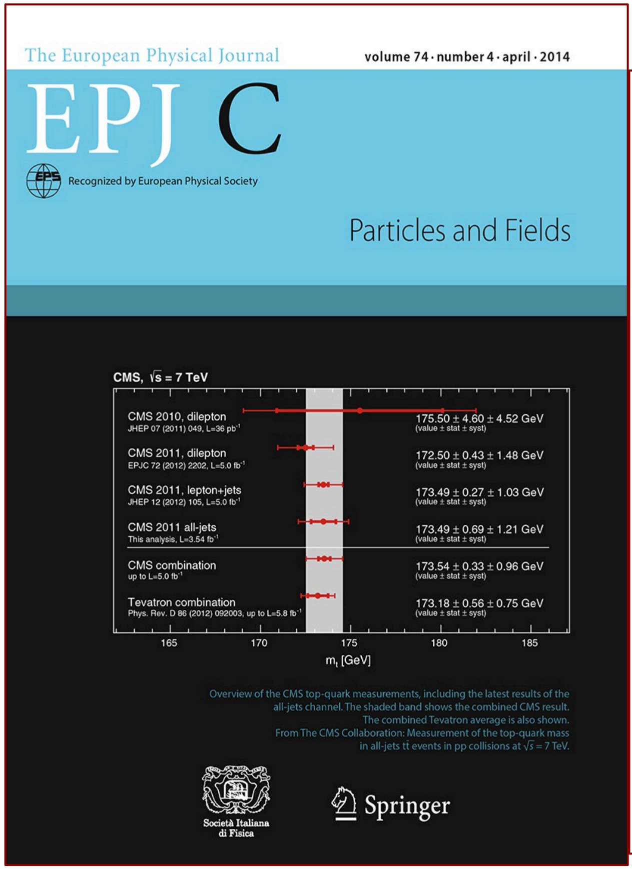


±0.3%

$$\boxed{m_t = 172.44 \pm 0.13\,(\text{stat+JSF}) \pm 0.47\,(\text{syst})\,\text{GeV}}$$

Top quark mass results

- accurate (~0.3%) measurement



The European Physical Journal

volume 74 · number 4 · april · 2014

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Particles and Fields

Overview of the CMS top-quark measurements, including the latest results of the all-jets channel. The shaded band shows the combined CMS result. The combined Tevatron average is also shown. From The CMS Collaboration: Measurement of the top-quark mass in all-jets $t\bar{t}$ events in pp collisions at $\sqrt{s}$ = 7 TeV.

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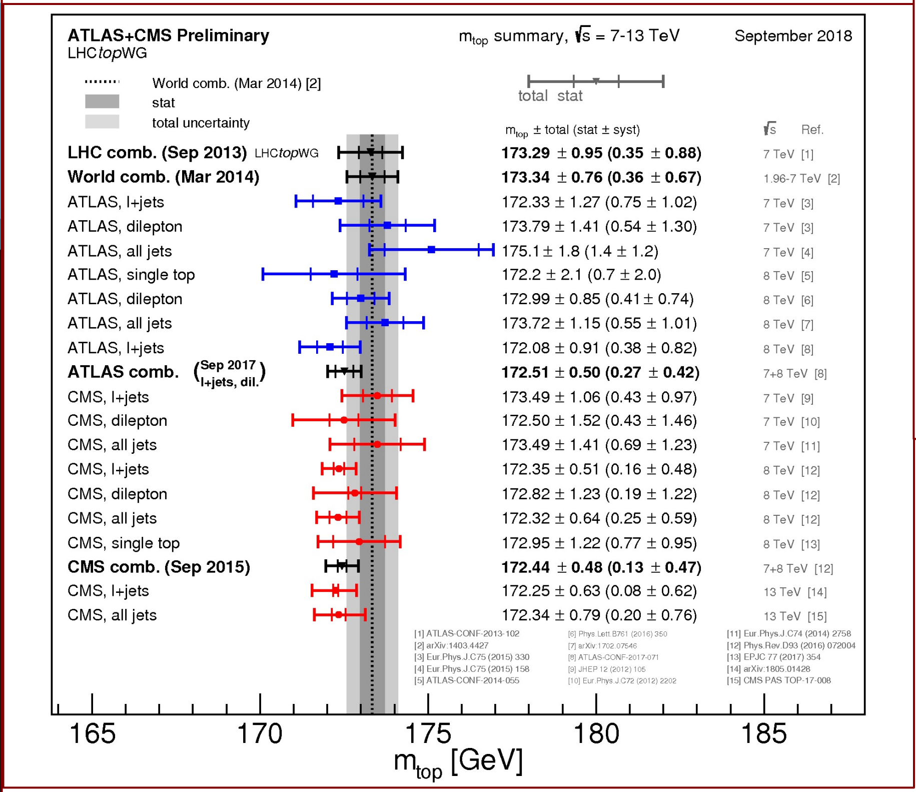
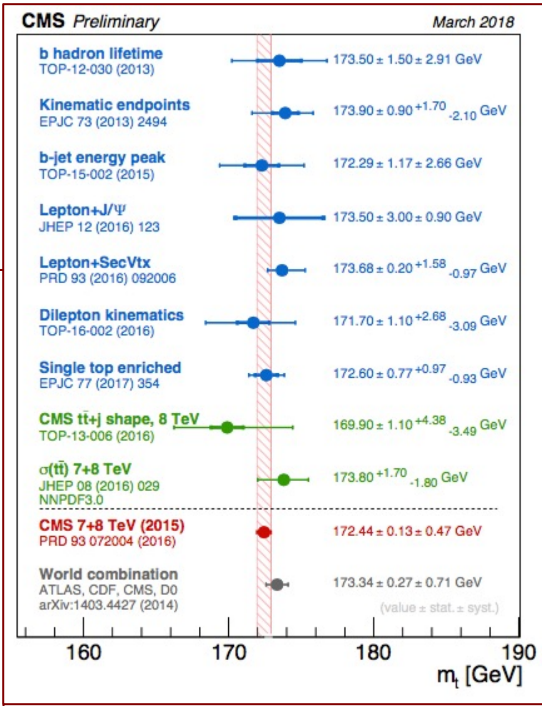
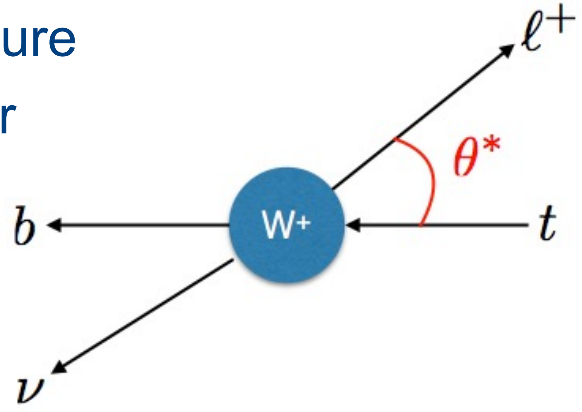


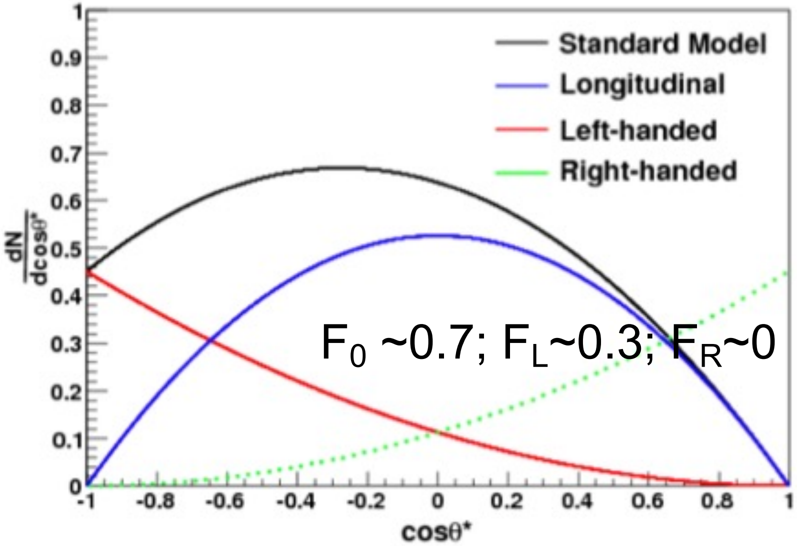


W boson polarization

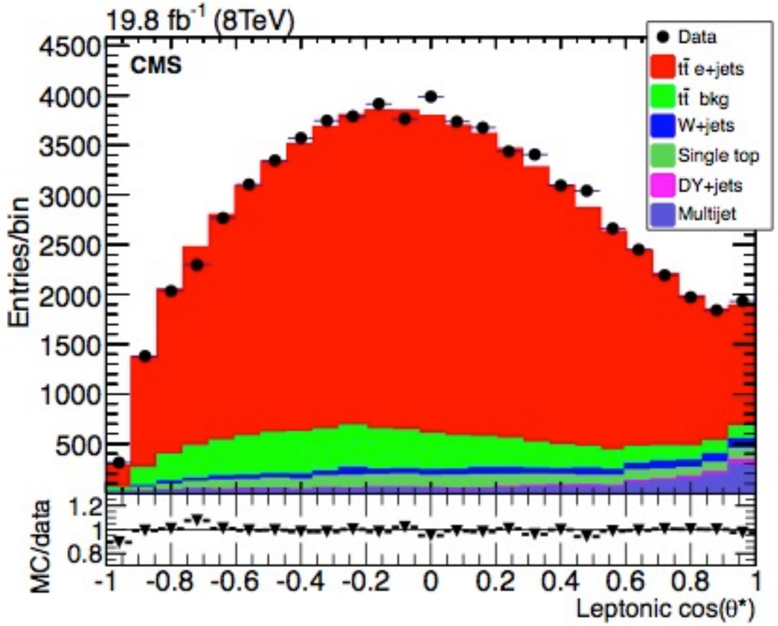
arXiv:1612.02577, PRD 93(2016)052007

- Properties of Wtb vertex in SM is characterized by V-A structure
- W bosons can be produced with left-handed, right-handed, or longitudinal polarization
  - – Fractions of polarization states are well predicted
- Can probe by measuring the angular distributions of the W boson decay products
- New physics could alter the polarization





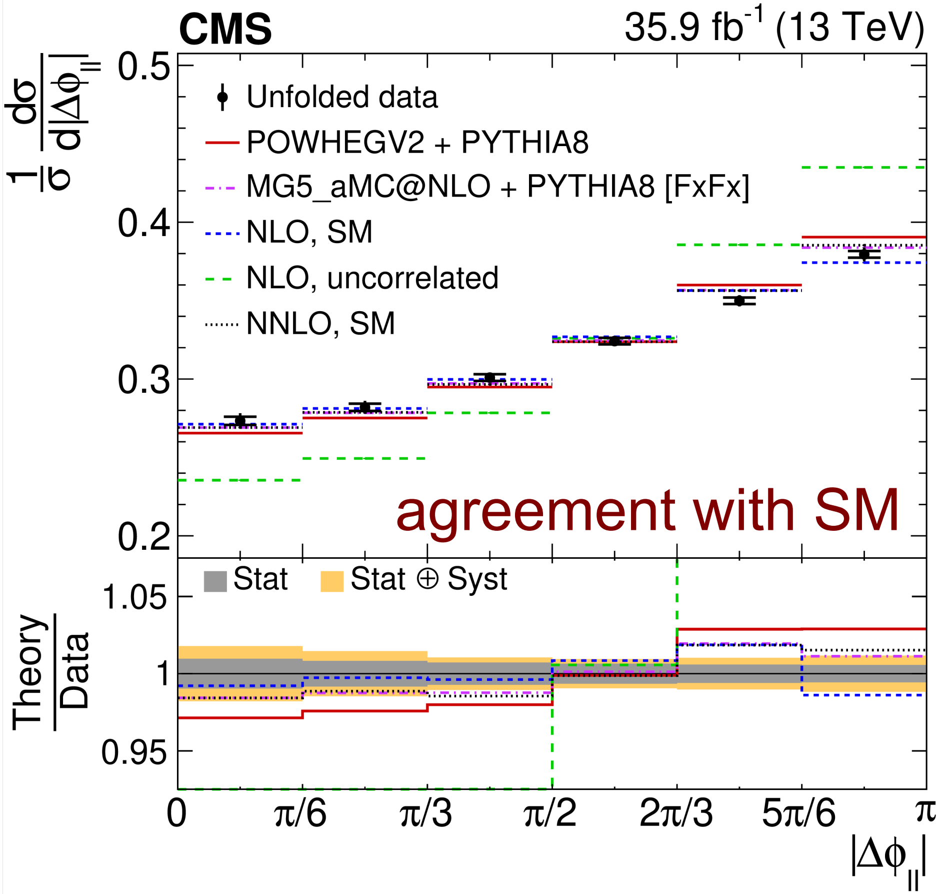
F_0 ~0.7; F_L~0.3; F_R~0



Spin correlation

PRD 100(2019)072002, ATLAS-CONF-2018-027

- Top quark produced are not polarized
  - …but spins between quark and anti-quark are correlated
- Top quark decays before spins decorrelate
  - It decays before hadronization ($\tau \sim 10^{-25}$ s) ⇒ spin information transmitted to decay products
  - No need to reconstruct full ttbar system
- Spin correlation depends on production mode
- It may differ from SM expectations
  - Decays to charged Higgs and b quark ($t \rightarrow H^{+}b$)
  - Other BSM scenarios

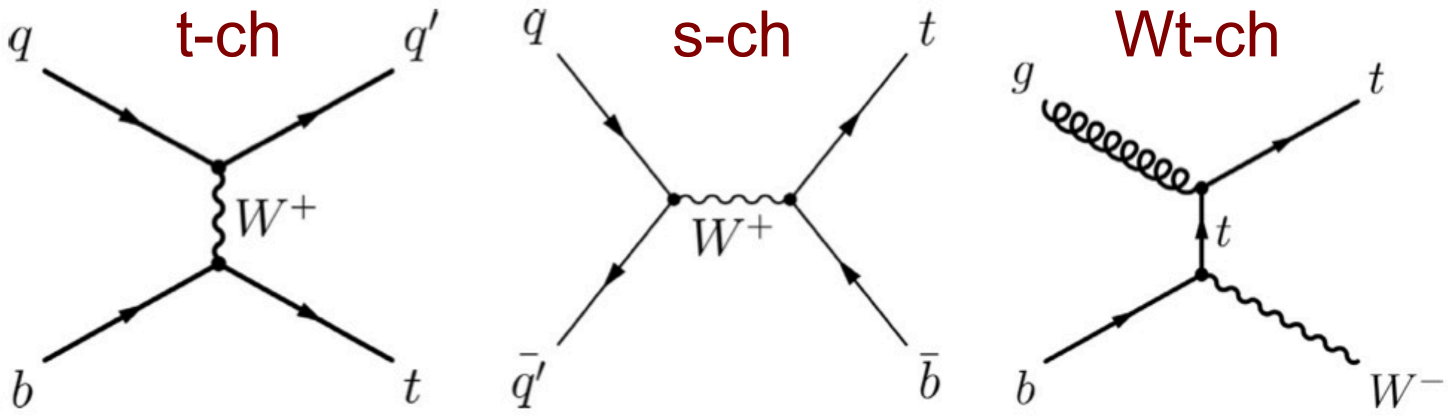


agreement with SM

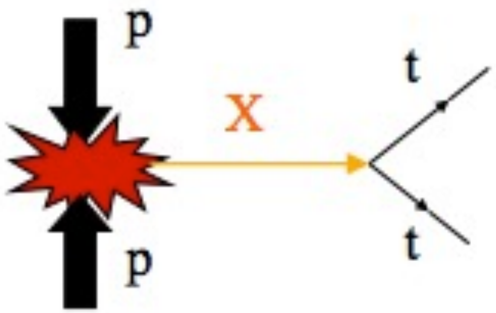
How else is Top produced?

PRD102(2009)182003, PRD81(2010)054028

- Single top quark production



σ(13TeV) = 217 pb 10 pb 72 pb

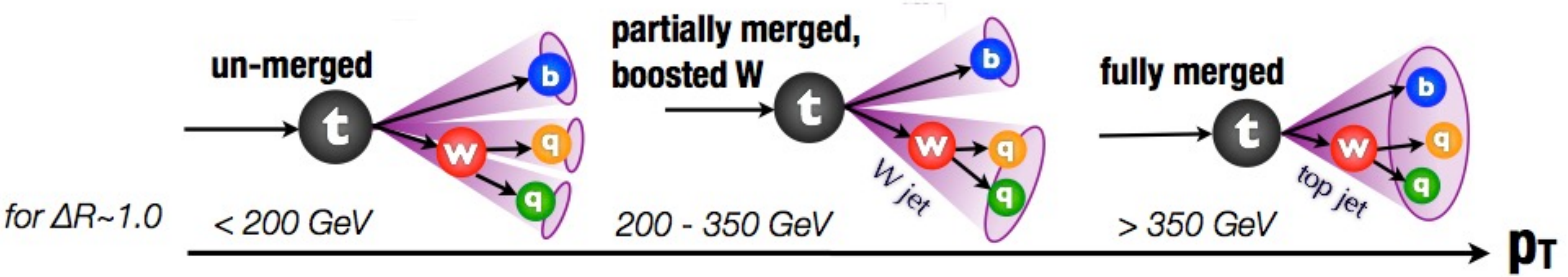


Resonance Production?
Top Color-Assisted Technicolor
OR
?????

Probing top quark production

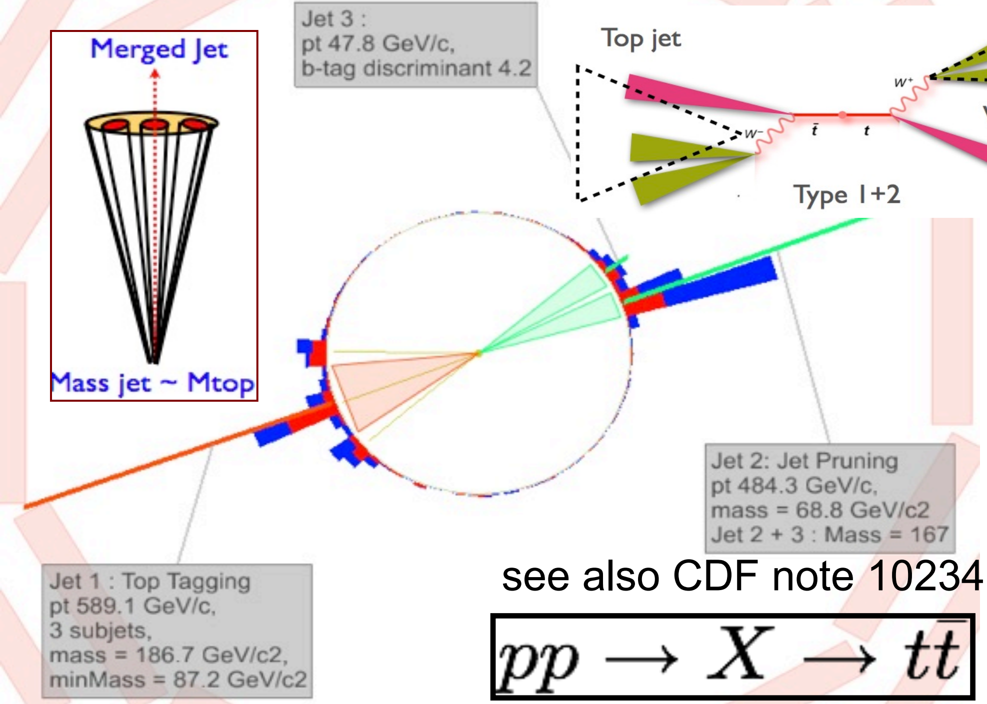
- Differential measurements
  - Testing QCD, measuring properties, searching for new physics, …
  - Function of kinematics, global variables, associated production
- Increased sensitivity: top quark pairs produced at rest
  - σ (M_{tt}>1 TeV at 13 TeV) =8 x σ(M_{tt}>1 at 8 TeV)

⇒Unique opportunity to probe boosted production at 13 TeV



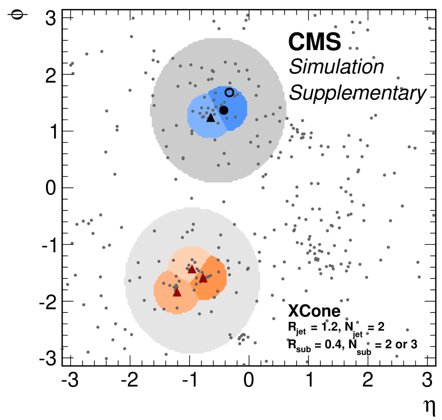
Boosted topology

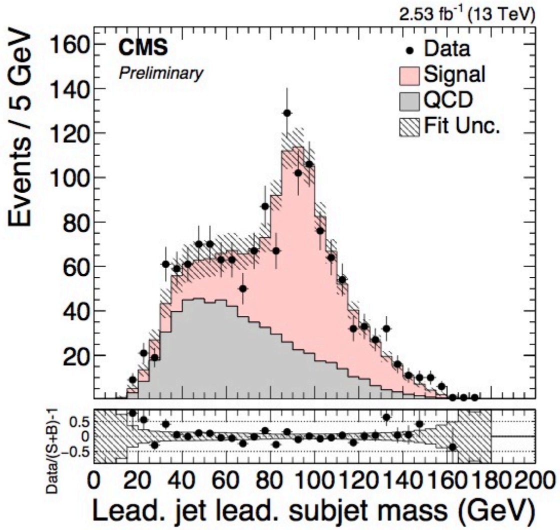
JHEP 1209(2012)029, TOP-16-013, PRL 124(2020) 202001

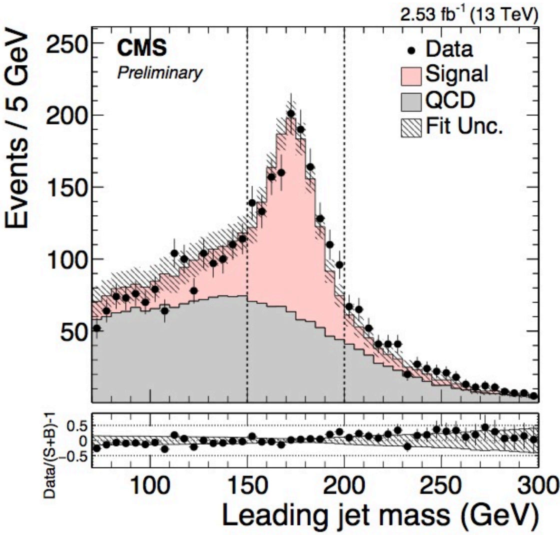


see also CDF note 10234

$$\boxed{pp \to X \to t\bar{t}}$$







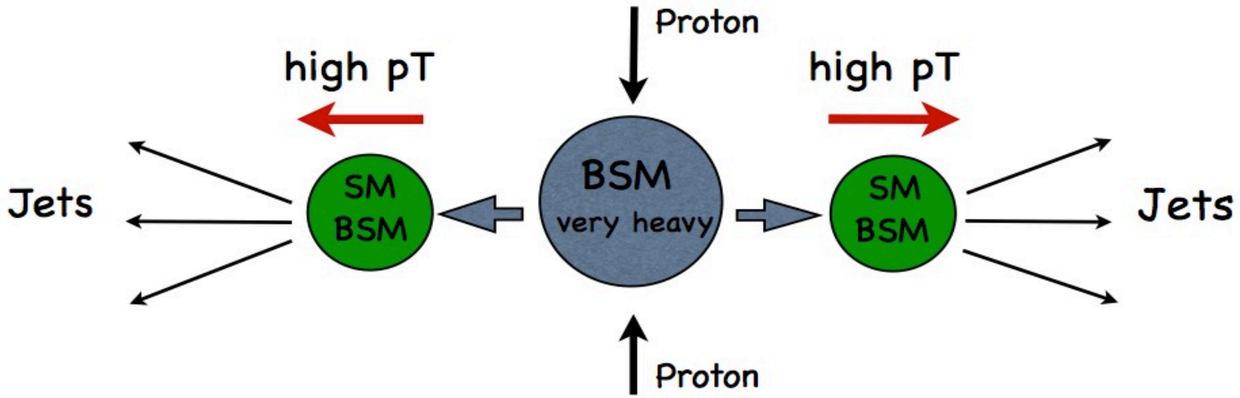
- At high energy, particles produced beyond threshold
- All-hadronic topology
  - Top p_T boosted, jets are collimated
  - Decay products and FSR collected in a “fat” jet
- Look at jet substructure
- Measure mass (no neutrinos)

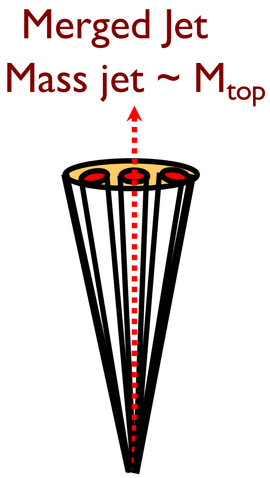
Boosted topology

- In many models there is high potential to discover new physics in the top sector in search for heavy resonances

$$pp \rightarrow X \rightarrow t\bar{t}$$

- Simple approach to merge neighboring jets

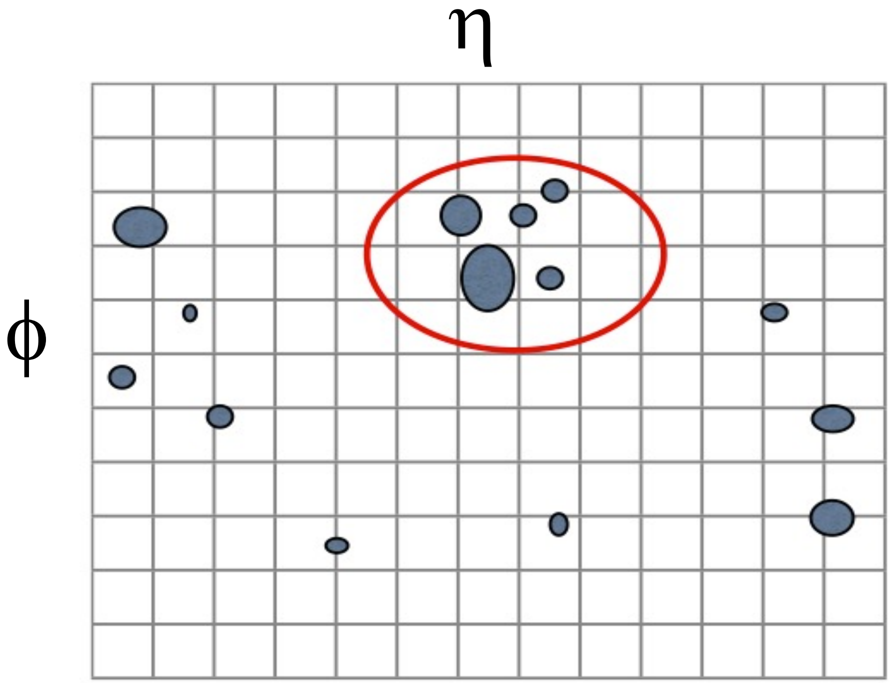




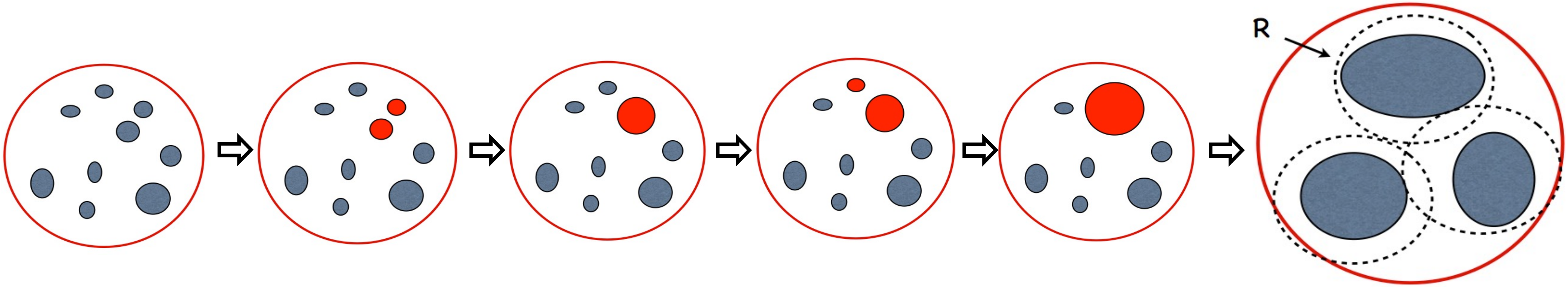
- At LHC energy, EWK scale particles produced beyond threshold
- Jets are highly collimated
- Decay products and FSR collected in a fat jet

Jet/Event selection

- Locate hadronic energy deposit in detector by choosing initial jet finding algorithm
- Impose jet selection cuts on fat jet
  - Recombine jet constituents with new algorithm
  - Filtering: recombine n sub-jets min d(i,j)
  - Trimming: recombine sub-jets with min p_T
- Minimum distance between jets is R



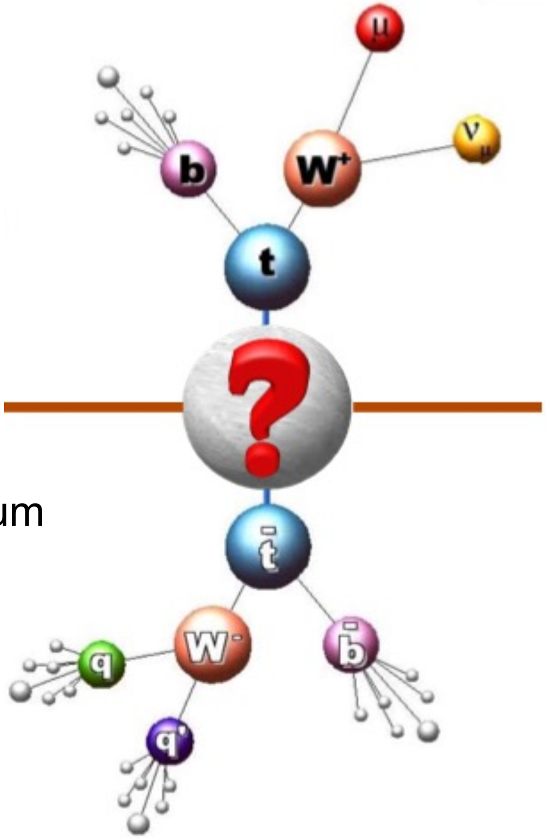
UE, ISR, Pile-up, hard interaction

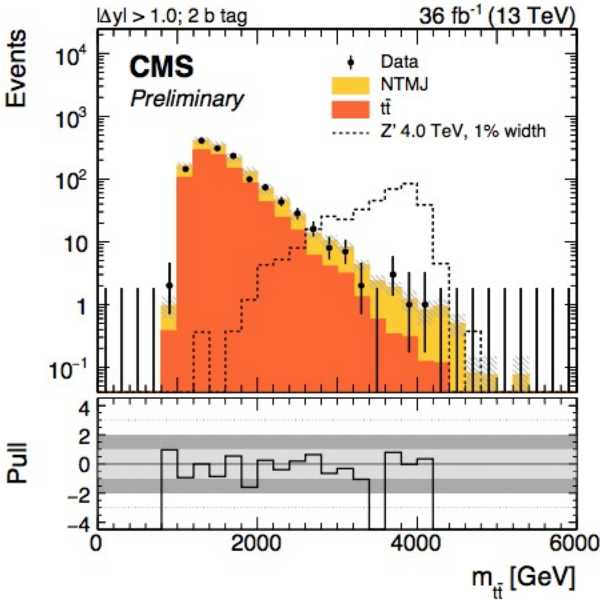


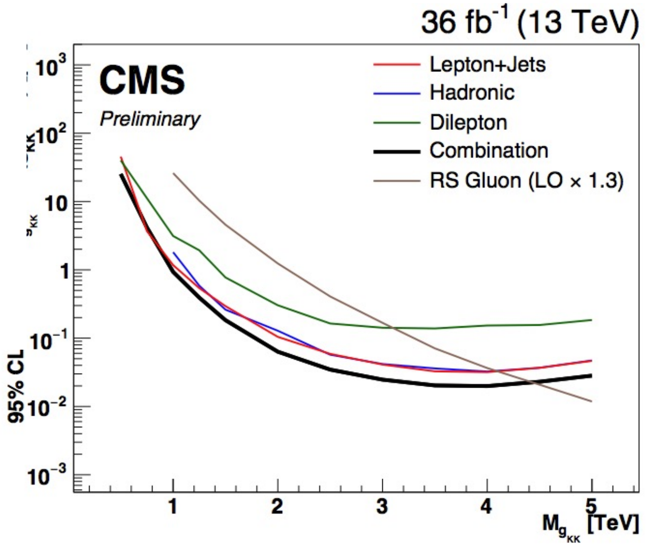
Top quark pair resonance

CMS-B2G-17-017, EPJC78(2018)565

- No resonance expected in SM
- Why is top so heavy?
  - – new physics?
  - – is third generation ‘special’?
- Search for massive neutral bosons decaying via a ttbar quark pair
- Experimental check
  - – search for bump in the inv. mass spectrum
  - – progressive loss in reconstruction ability due to jet merging
  - – reconstruct M_{ttbar} in different categories (e/μ, *n*-jets, *n* b-tags)
  - – l+jet events: full event reconstruction
  - – Subdivide in categories

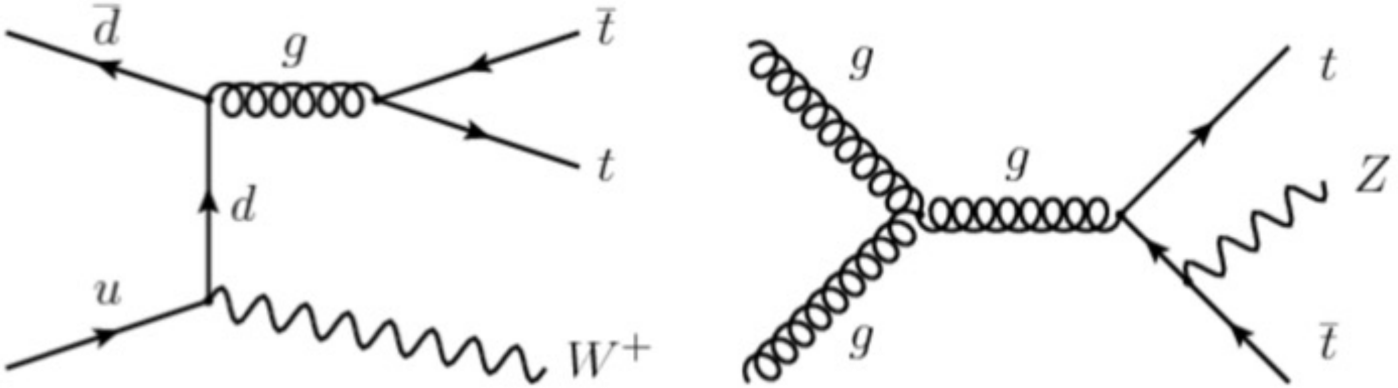






ttV production (V=γ,W,Z)

- Large datasets give access to rare tt+W and tt+Z processes
- ttZ: direct probe of top-Z coupling (new physics?)
- ttW: important background to NP searches

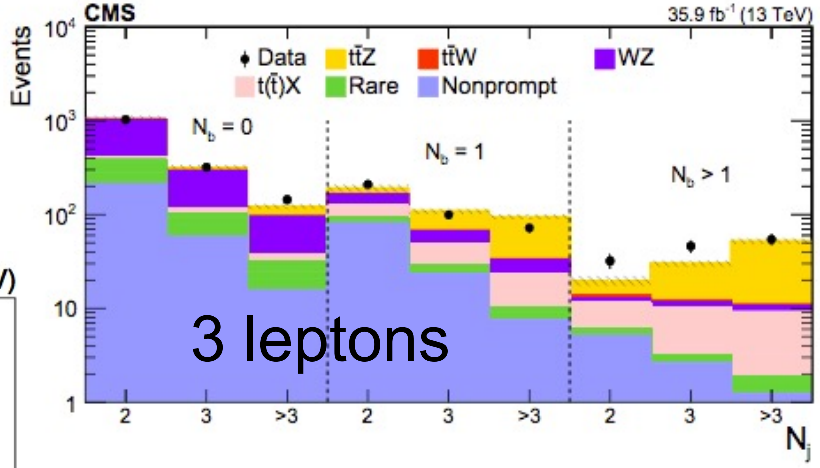


- Use multi-lepton final states
  - 2 same-sign charge leptons, 3 or 4 lepton final states

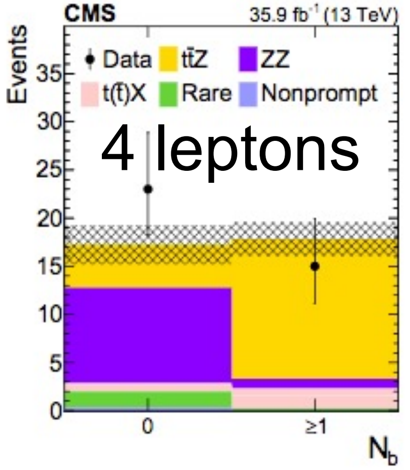
ttV production (V=γ,W,Z)

arXiv:1808.02913, JHEP08(2018)011, JHEP10(2017)006

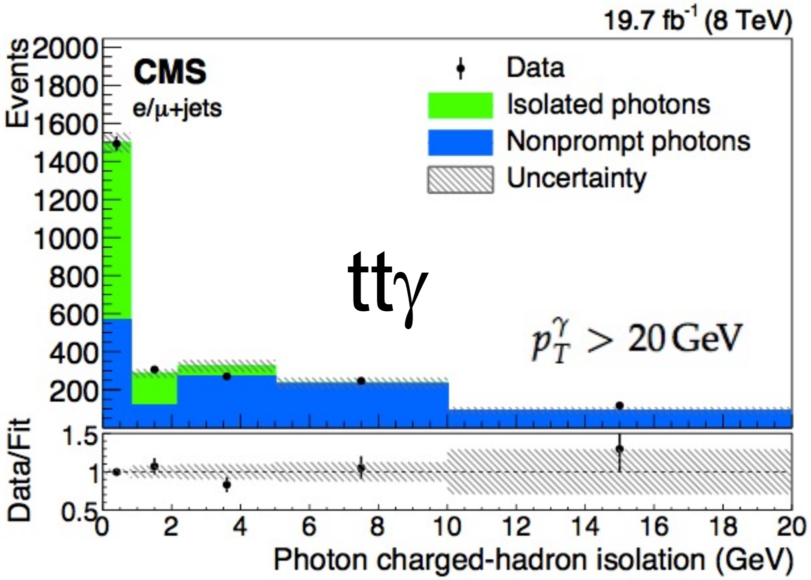
- Measurements gives access to EW couplings of the top



3 leptons



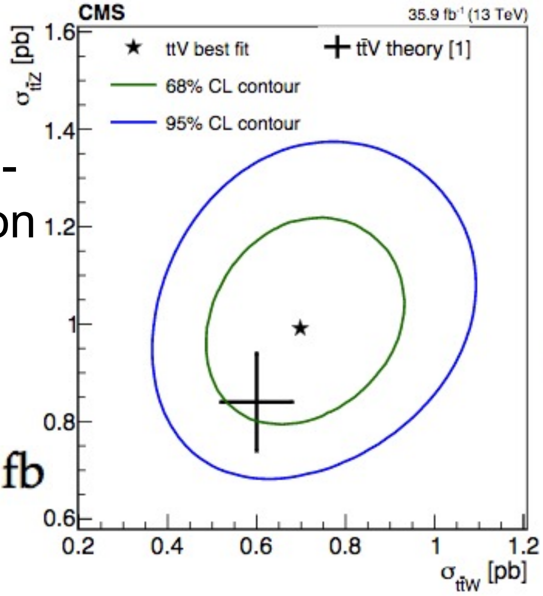
4 leptons

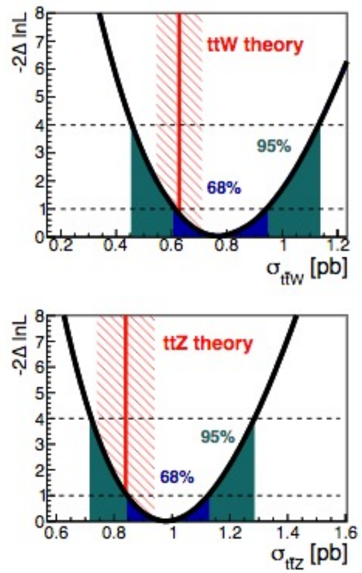


ttγ

$p_T^\gamma > 20\,\mathrm{GeV}$

Combine 3- and 4-lepton final states





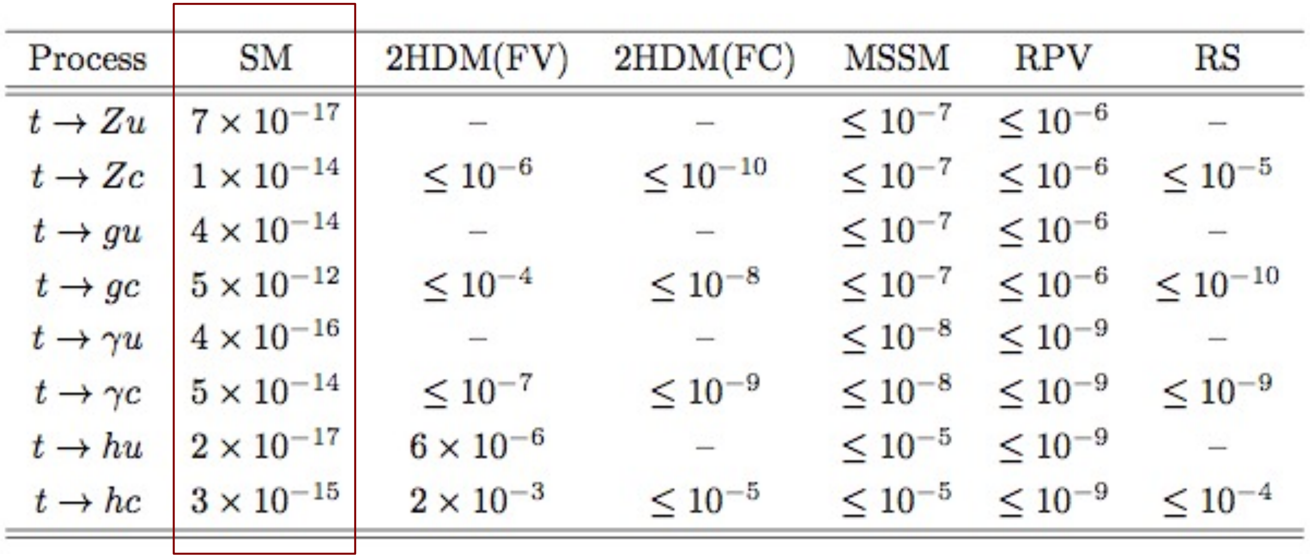
Measure $\sigma(\tau\tau\gamma)$=127± 27 fb

$$\sigma(\mathrm{pp}\to \mathrm{t}\gamma\mathrm{j})\mathcal{B}(\mathrm{t}\to\mu\nu\mathrm{b}) = 115\pm17\,(\mathrm{stat})\pm30\,(\mathrm{syst})\,\mathrm{fb}$$

⇒ Consistent with SM predictions

Flavor Changing Neutral Currents

- FCNC: top couples to light quarks (u/c) and neutral bosons (γ,Z,H,g)
- Forbidden at tree level in SM
- Very small rates predicted
- Deviations would give hint for NP



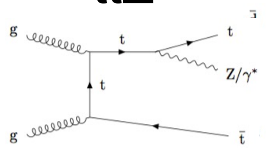
Process	SM	2HDM(FV)	2HDM(FC)	MSSM	RPV	RS
$t \to Zu$	7×10^{-17}	–	–	$\lesssim 10^{-7}$	$\lesssim 10^{-6}$	–
$t \to Zc$	1×10^{-14}	$\lesssim 10^{-6}$	$\lesssim 10^{-10}$	$\lesssim 10^{-7}$	$\lesssim 10^{-6}$	$\lesssim 10^{-5}$
$t \to gu$	4×10^{-14}	–	–	$\lesssim 10^{-7}$	$\lesssim 10^{-6}$	–
$t \to gc$	5×10^{-12}	$\lesssim 10^{-4}$	$\lesssim 10^{-8}$	$\lesssim 10^{-7}$	$\lesssim 10^{-6}$	$\lesssim 10^{-10}$
$t \to \gamma u$	4×10^{-16}	–	–	$\lesssim 10^{-8}$	$\lesssim 10^{-9}$	–
$t \to \gamma c$	5×10^{-14}	$\lesssim 10^{-7}$	$\lesssim 10^{-9}$	$\lesssim 10^{-8}$	$\lesssim 10^{-9}$	$\lesssim 10^{-9}$
$t \to hu$	2×10^{-17}	6×10^{-6}	–	$\lesssim 10^{-5}$	$\lesssim 10^{-9}$	–
$t \to hc$	3×10^{-15}	2×10^{-3}	$\lesssim 10^{-5}$	$\lesssim 10^{-5}$	$\lesssim 10^{-9}$	$\lesssim 10^{-4}$

Top quarks and rare decays

arXiv:1711.02547, PLB779(2018)358, EPJC78(2018)140, PRL 121(2018)221802

- Heaviest fundamental particle
- Study naked quark, decays before hadronization
- Strongly interacting with EWK sector and Higgs
- Anomalous couplings: Wtb vertex may include BSM terms

ttZ



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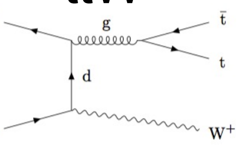

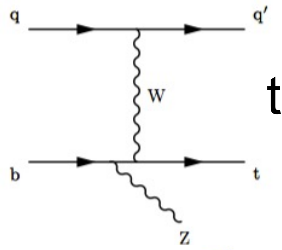

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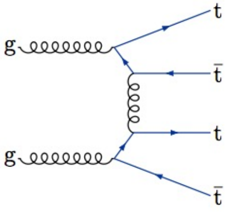

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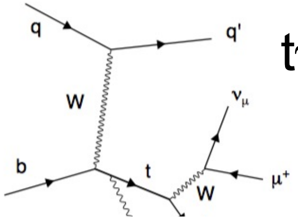
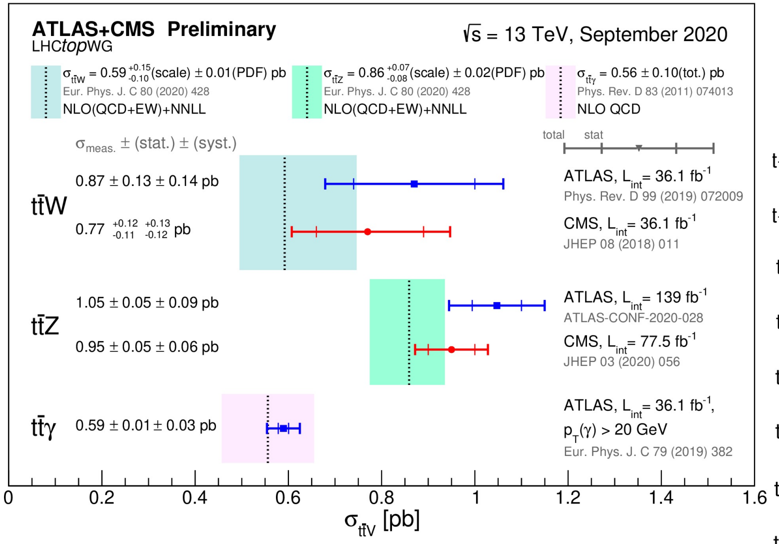
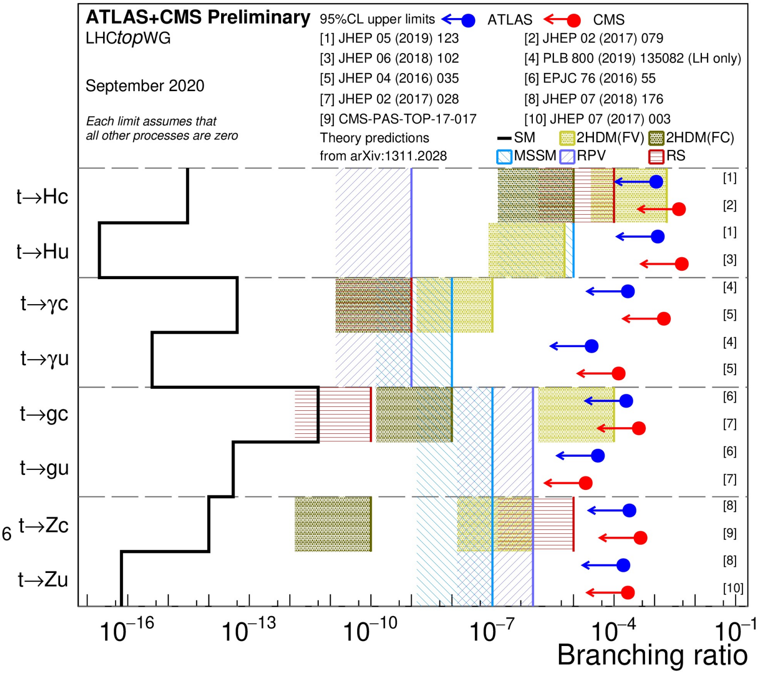
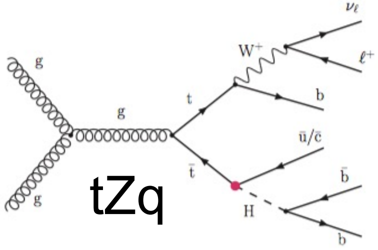


tγ





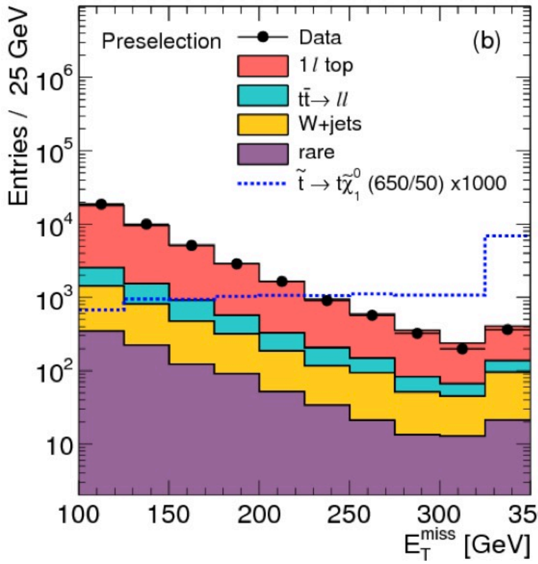


tZq

Top and SUSY

EPJC 74 (2014) 3109, arXiv:1603.02303, SUS-16-002, JHEP10(2017)019

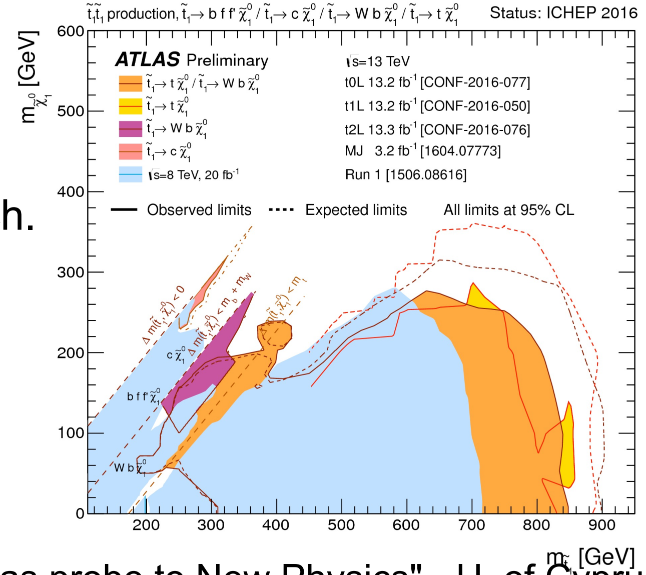
- If SUSY exists and is responsible for solution of hierarchy problem, naturalness arguments suggest that SUSY partners of top quark (*stop*) may have mass close to m_{top} to cancel top quark loop contributions to Higgs mass

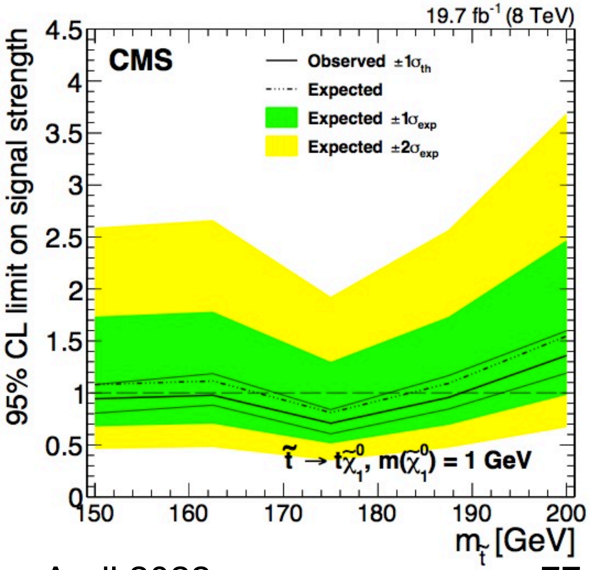


$$\tilde{t}\rightarrow t\tilde{\chi}_1^0\rightarrow bW\tilde{\chi}_1^0$$ "heavy"

$$\tilde{t}\rightarrow b\tilde{\chi}_1^+\rightarrow bW\tilde{\chi}_1^0$$ "light"

- Small predicted cross section
  - for 175GeV: 40pb@8TeV
- Stop pair production: $\boxed{t\bar{t}\tilde{\chi}_1^0\tilde{\chi}_1^0}$
  - similar to ttbar lepton+jet and dilepton ch.
  - additional MET from neutralinos
- change in ttbar cross section





Multi-top production

arXiv:1605.03171, 1702.06164, EPJC 80(2020)75 , ATLAS-CONF-2021-013

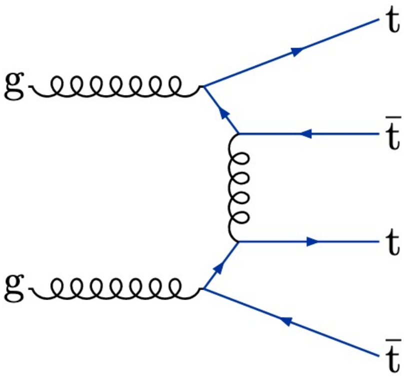
- Production of 4 tops is an attractive scenario in a number of new physics models
- The SM cross section is 12fb@13TeV

- Use dilepton and lepton+jets final states
- Combination of kinematical variables and BDT
- Search for same-sign dileptons, or >2 leptons

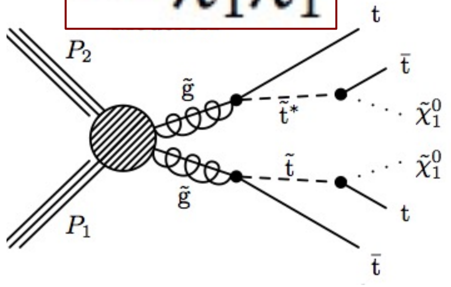
- Consider multiple control- and search-regions defined by MET, hadronic energy, number of (b-) jets, and p_T of the leptons in the events

- Measure cross section: σ= $12.6^{+5.8}_{-5.2}$ fb

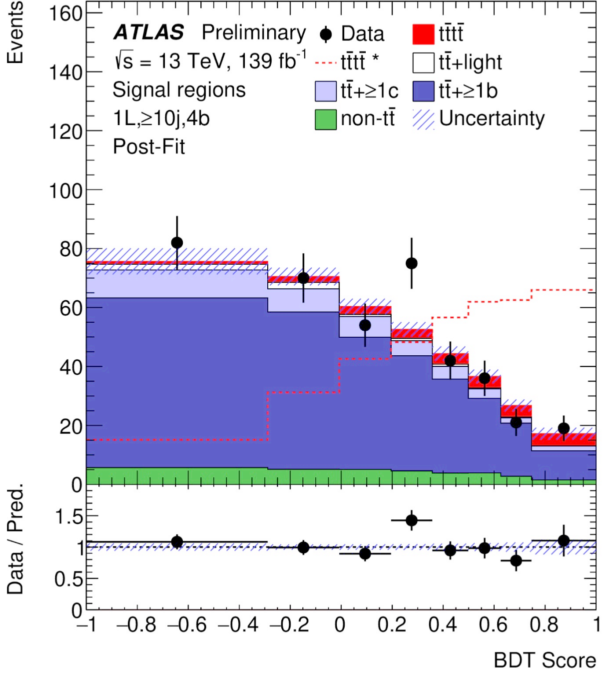
- Limits on Yukawa couplings: $|y_t/y_t^{SM}| < 1.7$



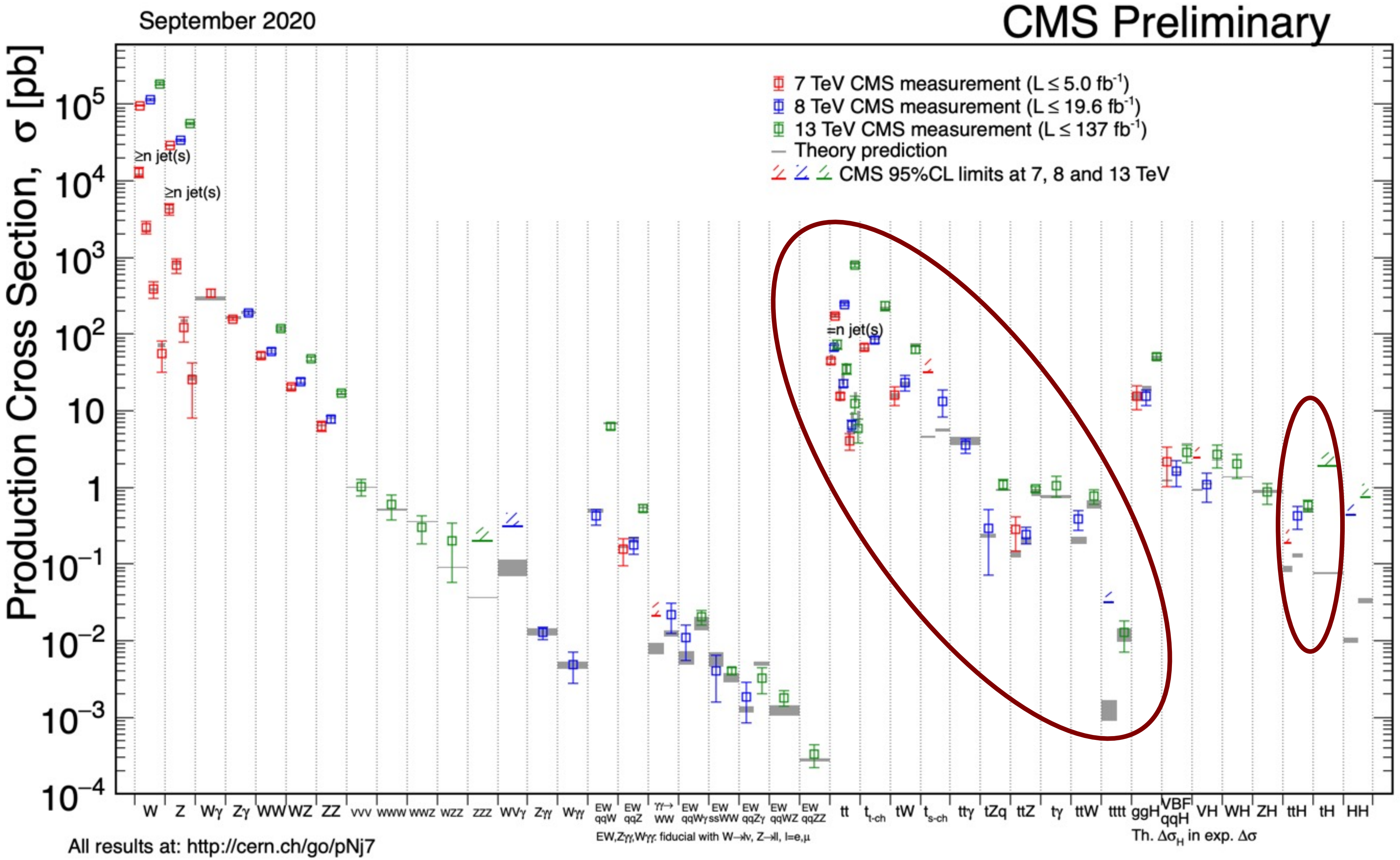
$t t \bar{t}\bar{t}\tilde{\chi}_1^0\tilde{\chi}_1^0$



*: normalised to total Bkg.



Rich and extensive set of results



Summary

- Top quarks are valuable probes of SM
- Excellent consistency but SM is incomplete
  - Extensions foresee existence of additional bosons
  - Searches for BSM bosons ongoing
- Dominant background for New Physics searches
- Due to large mass, top quarks may couple to heavy objects
- Deviations from SM may indicate New Physics
- More data and improved algorithms will enhance the sensitivity
  - Higgs, multi-top, boosted objects, SUSY, Dark matter, etc.