Top quarks physics: Probing the SM at the LHC

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LIP Lisbon

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- ✓ Top quarks at the LHC
- ✓ Object reconstruction
- ✓ Cross section measurements
- ✓ Properties
- ✓ Top quarks as a probe to New Physics

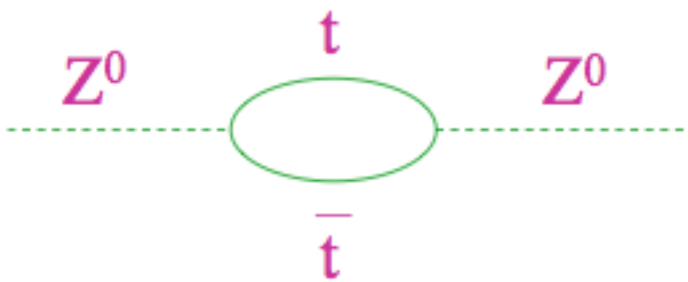
Top: A short story of the quark model

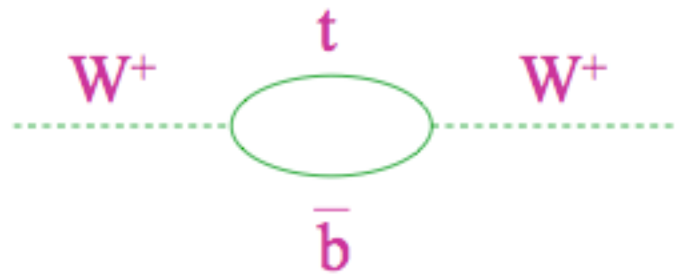
- 1964: Gell-Mann, Zweig, idea for 3 quarks, up, down, strange (u,d,s)
- 1970: Glashow, Iliopoulos, Maiani, 4 quarks, up, down, strange charm (u,d,s,c)
- 1973: Cabibbo, Kobayashi, Maskawa, add 2 quarks, top and bottom (t, b) to explain CP violation
- 1974: Ting, Richter discover charm
- 1977: Lederman (Fermilab) discovers bottom
- B weak isospin=-1/2, need +1/2 partner

$\Rightarrow$ There must be a Top quark!

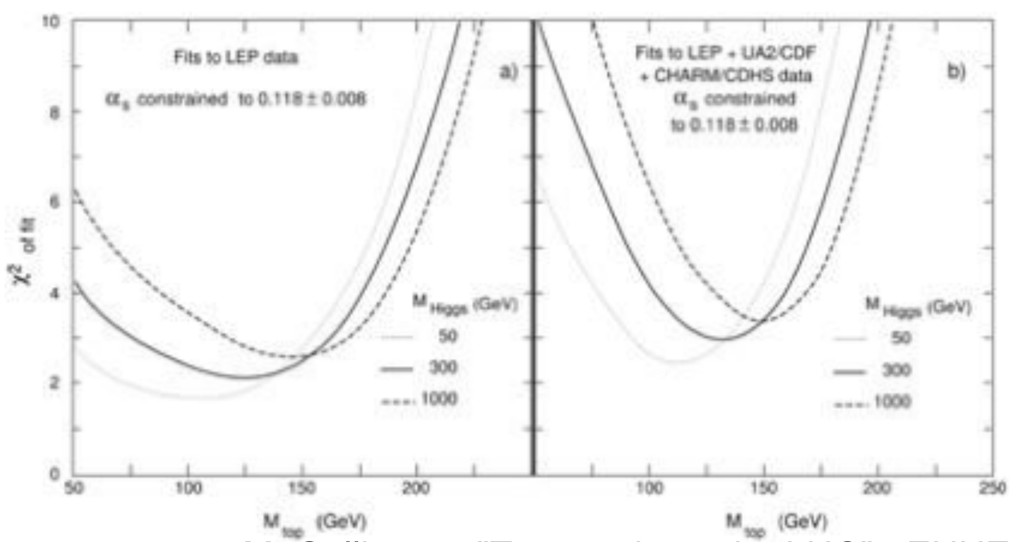
Searches for Top at e^+e^- colliders

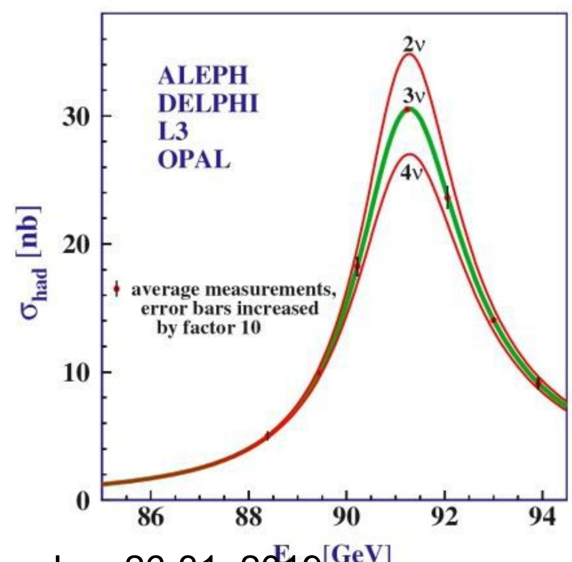
- In the SM, various EWK observables depend on the mass of the top quark





- 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



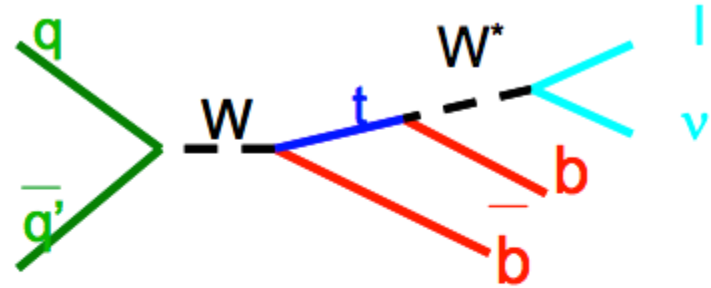


Early searches at hadron colliders

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

1983: discovery of W and Z

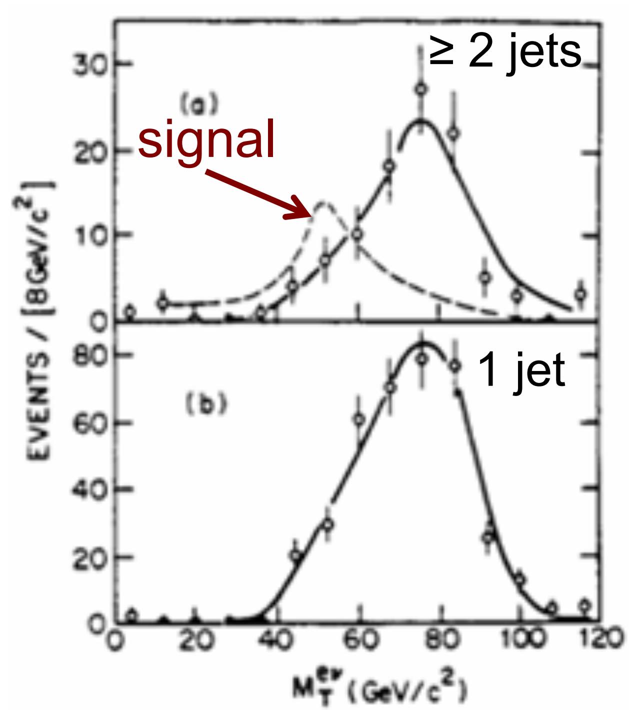


Rule of 3:

- Mass: s/c/b/t 0.5/1.5/4.5 GeV ⇒ M_{top}=15 GeV?

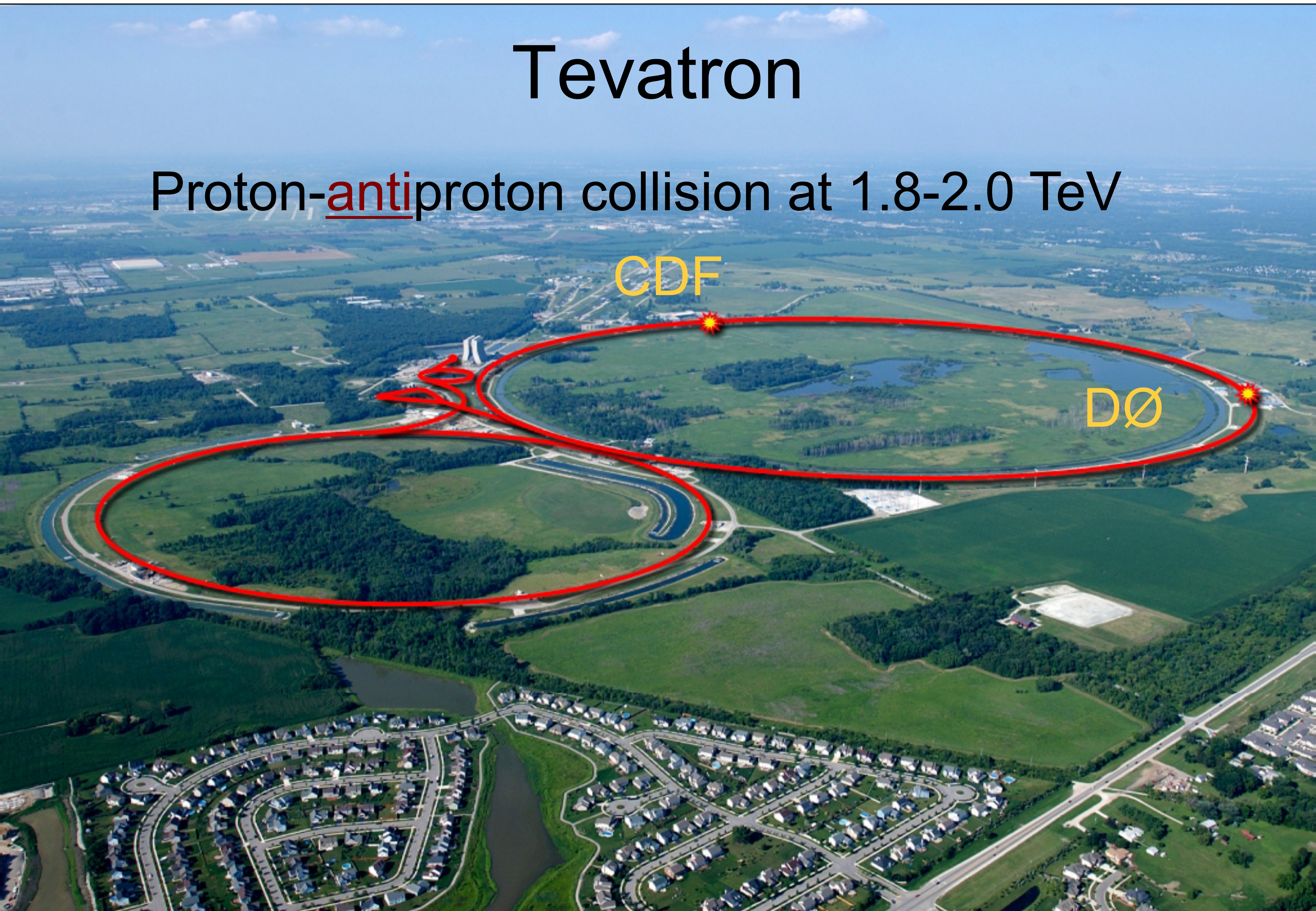
1984: UA1

- W→tb→lνbb
- Isolated high-p_T lepton
- 2 or 3 hadronic jets



Tevatron

Proton-antiproton collision at 1.8-2.0 TeV

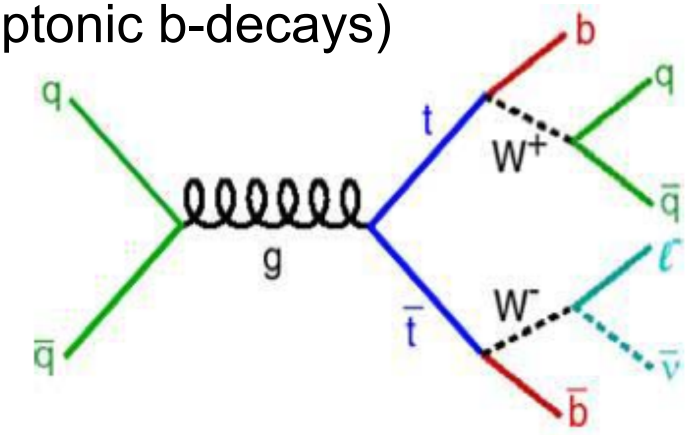


Searches for Top

- Reached kinematic limit for direct searches at e^+e^- colliders
- 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)
- Early searches on 88-89 data:
  - Dilepton: include ee, $\mu\mu$, $e\mu$ (require missing ET, Z-veto)
  - Single lepton: require low p_T muon (semi-leptonic b-decays)

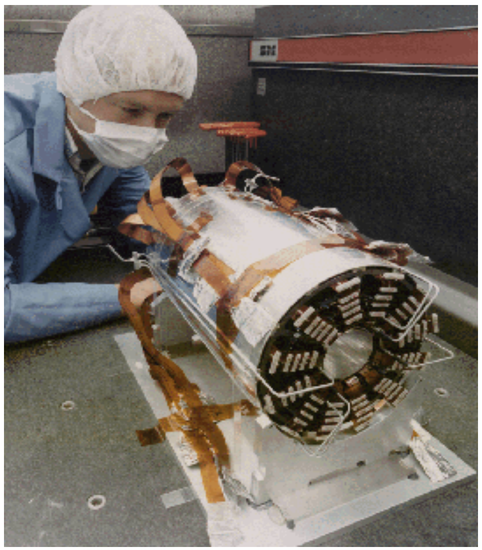
$\Rightarrow M_{top}>91$ GeV

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

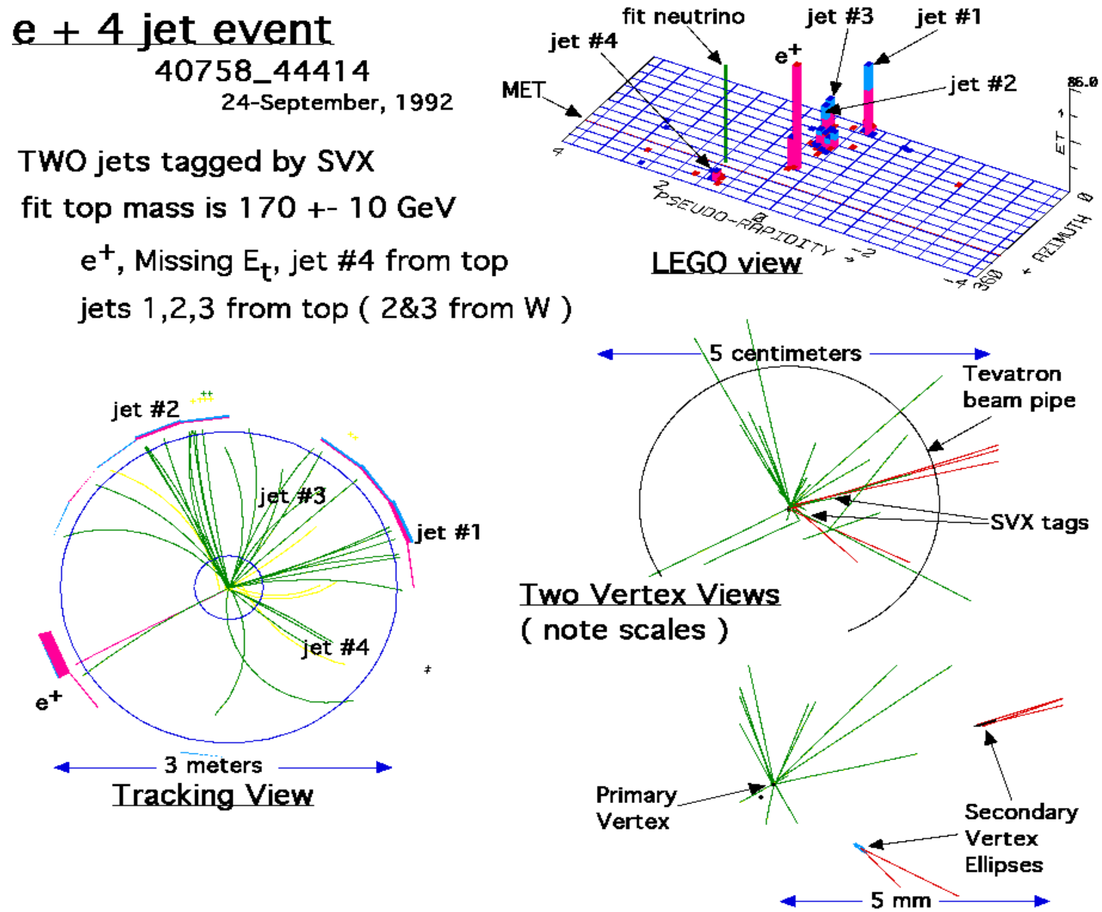


Discovery of top quark

- 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

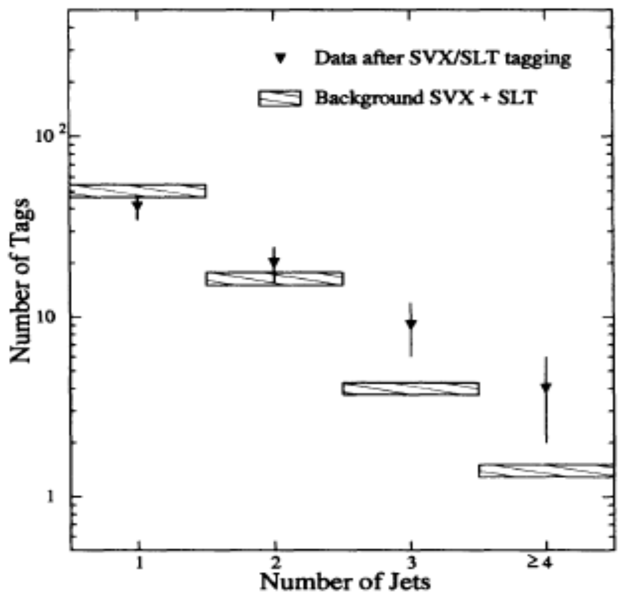


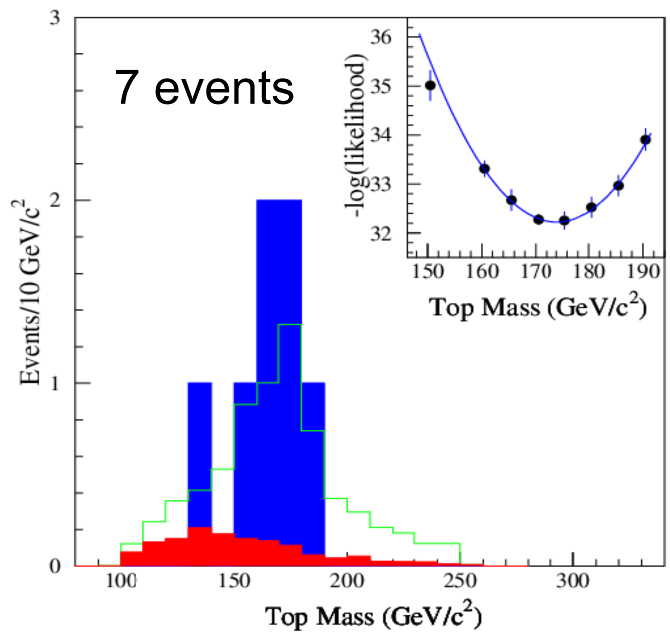
Discovery of top quark (cont.)

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

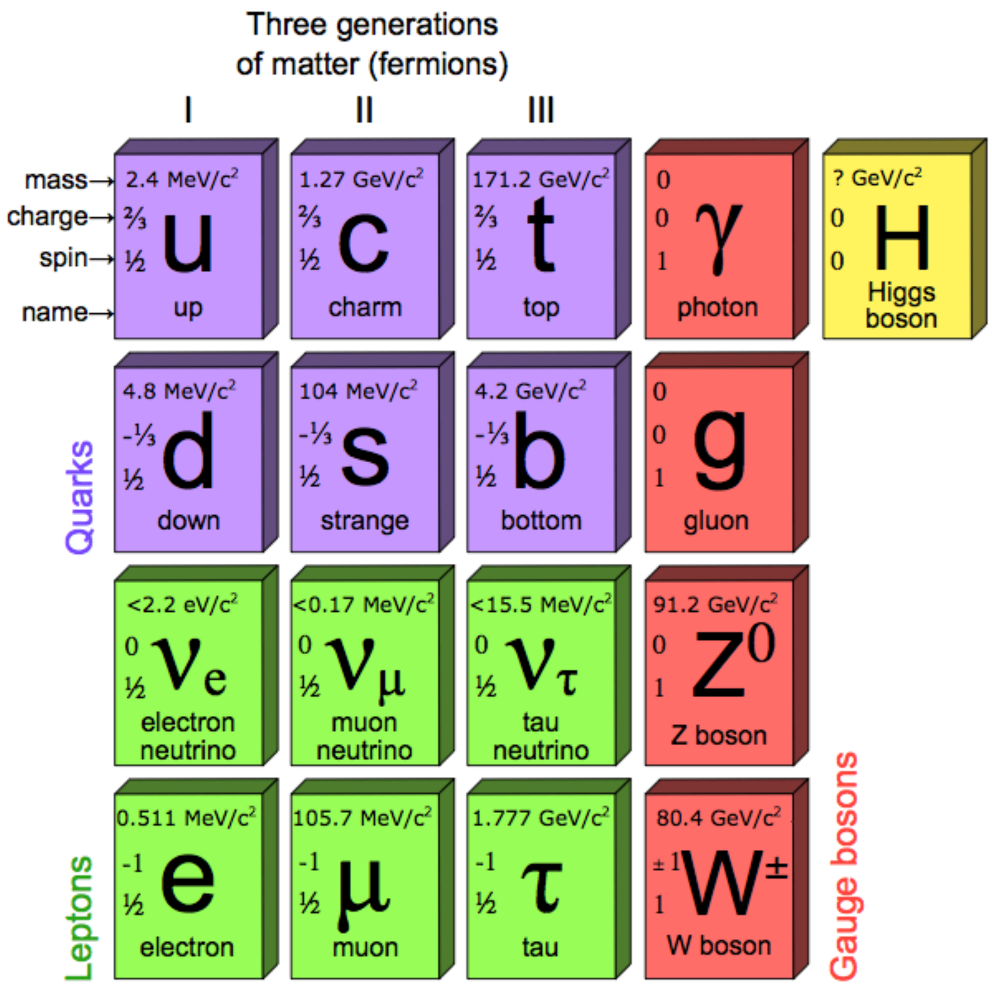
We summarize a search for the top quark with the Collider Detector at Fermilab (CDF) in a sample of $\bar{p}p$ collisions at $\sqrt{s} = 1.8$ TeV with an integrated luminosity of 19.3 pb^{-1}. We find 12 events consistent with either two W bosons, or a W boson and at least one b jet. The probability 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.

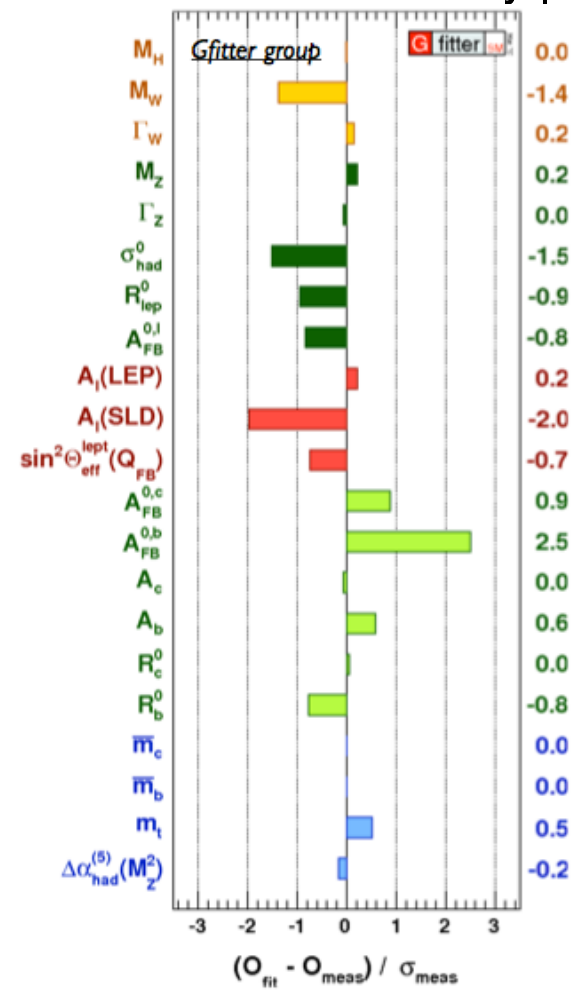




SM confirmed by the data

Standard model of elementary particles



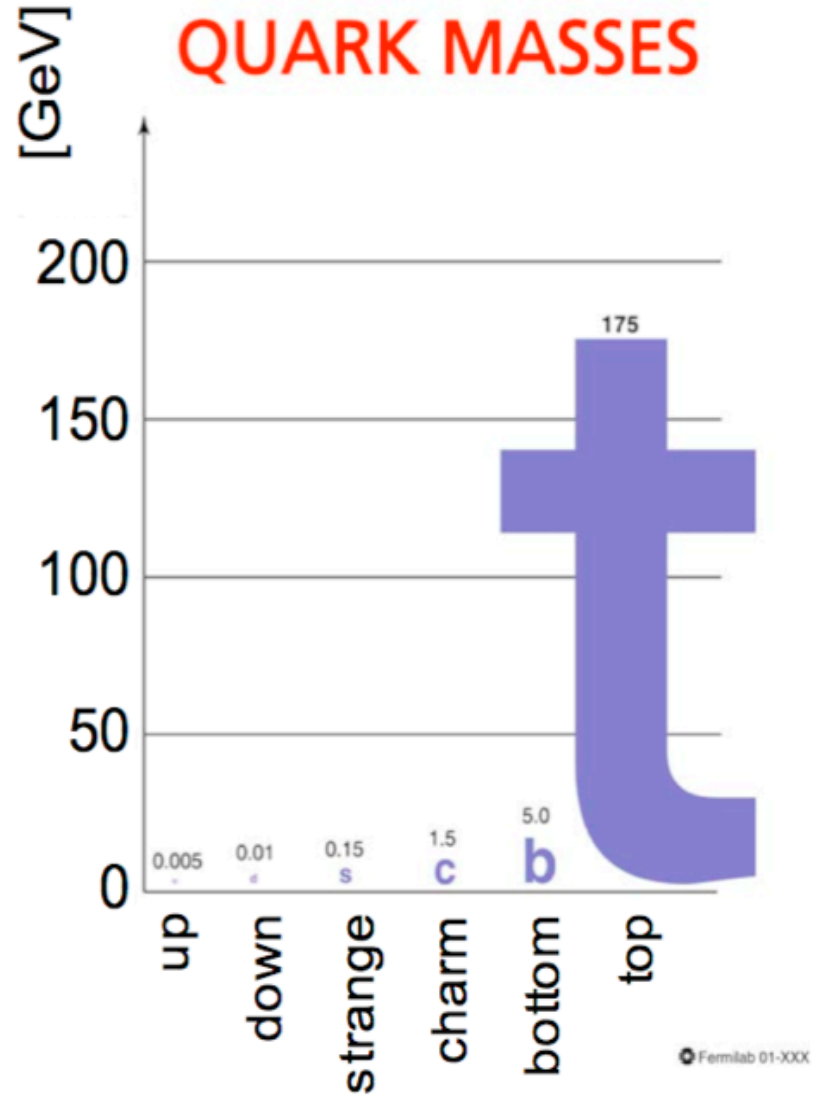


Excellent agreement with all experimental results

The top quark

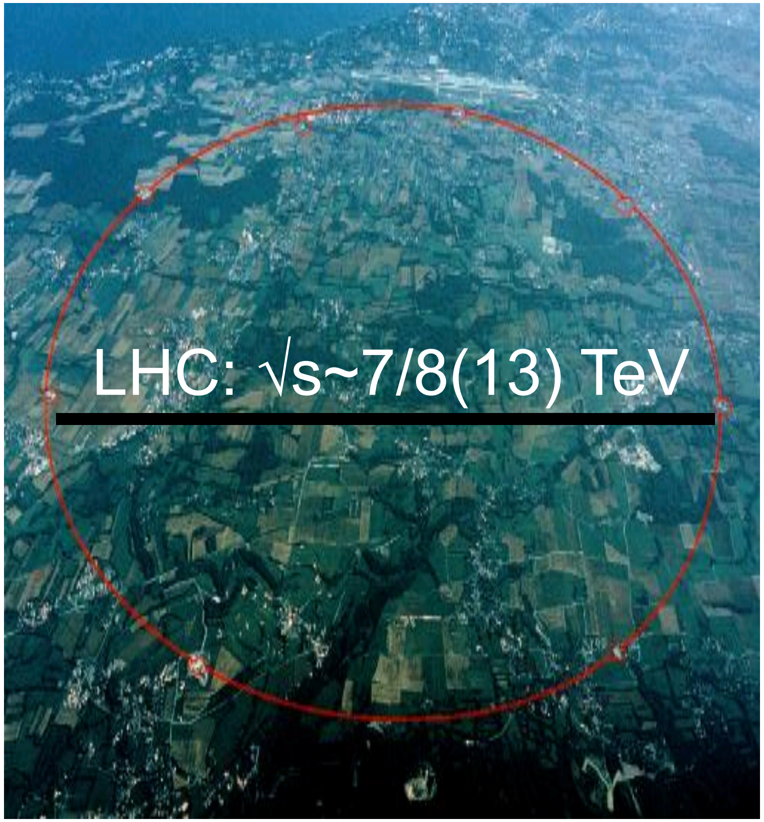
- The heaviest known elementary particle
- Large coupling to the Higgs: ~1
- Produced through strong interaction: qq, gg
- Top decays to Wb: ~100%
- Short lifetime: 4×10^{-25} sec
  - for m_{top}=175 GeV$\Rightarrow\Gamma$=1.4 GeV $\Rightarrow$no hadronization
  - bound states are not formed $\Rightarrow$ 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



The Large Hadron Collider

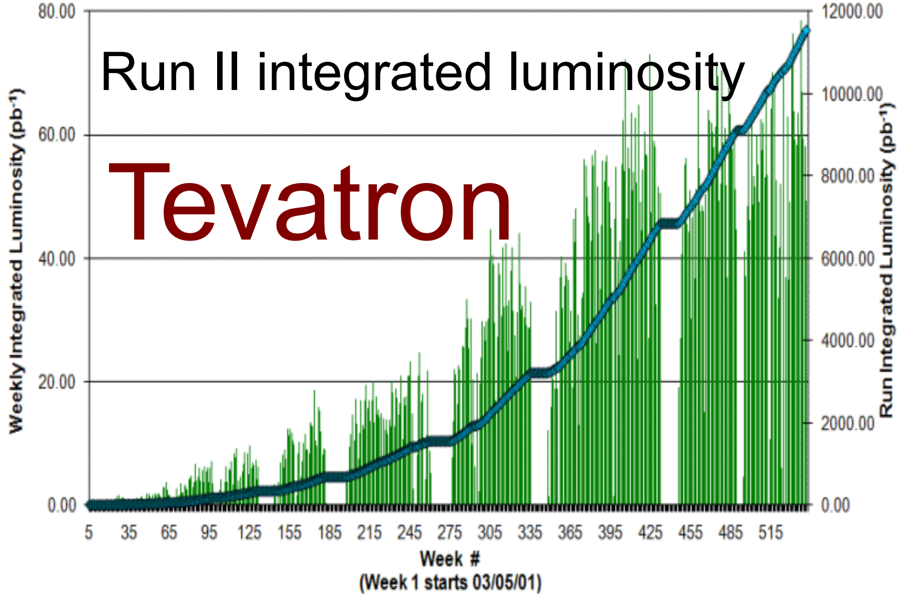
- Built to explore new energy frontiers
  - First colliding beams in 2009
  - started with “low” luminosity in 2010
  - ~5 fb^{-1}@7TeV delivered in 2011
  - ~20 fb^{-1}@8TeV in 2012
  - >150fb^{-1}@13 TeV in 2015-2018

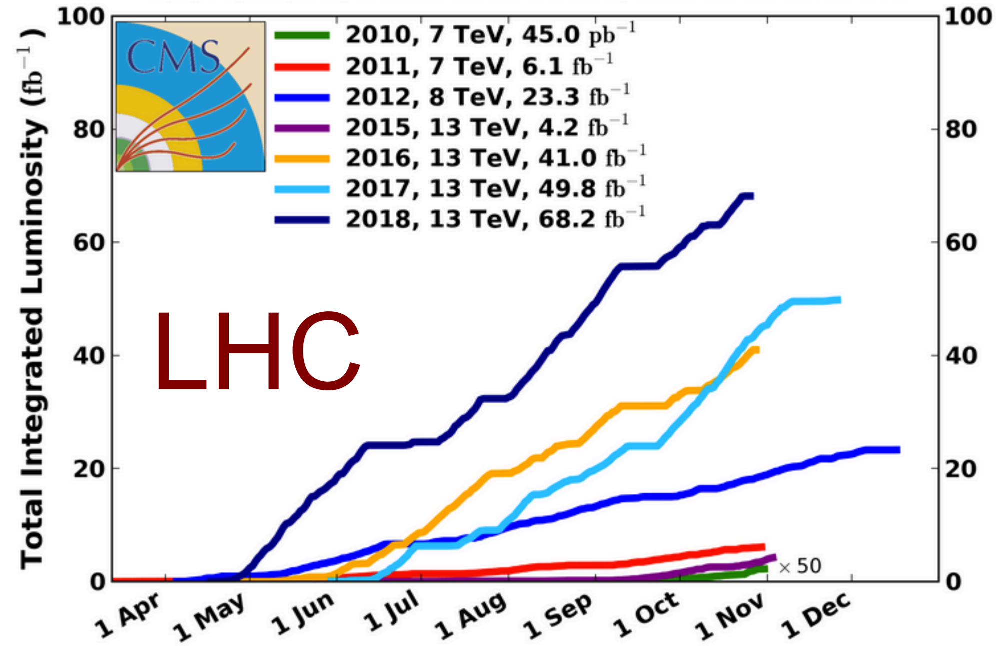


- re-establish SM measurements
- access to new physics processes

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

Tevatron vs LHC

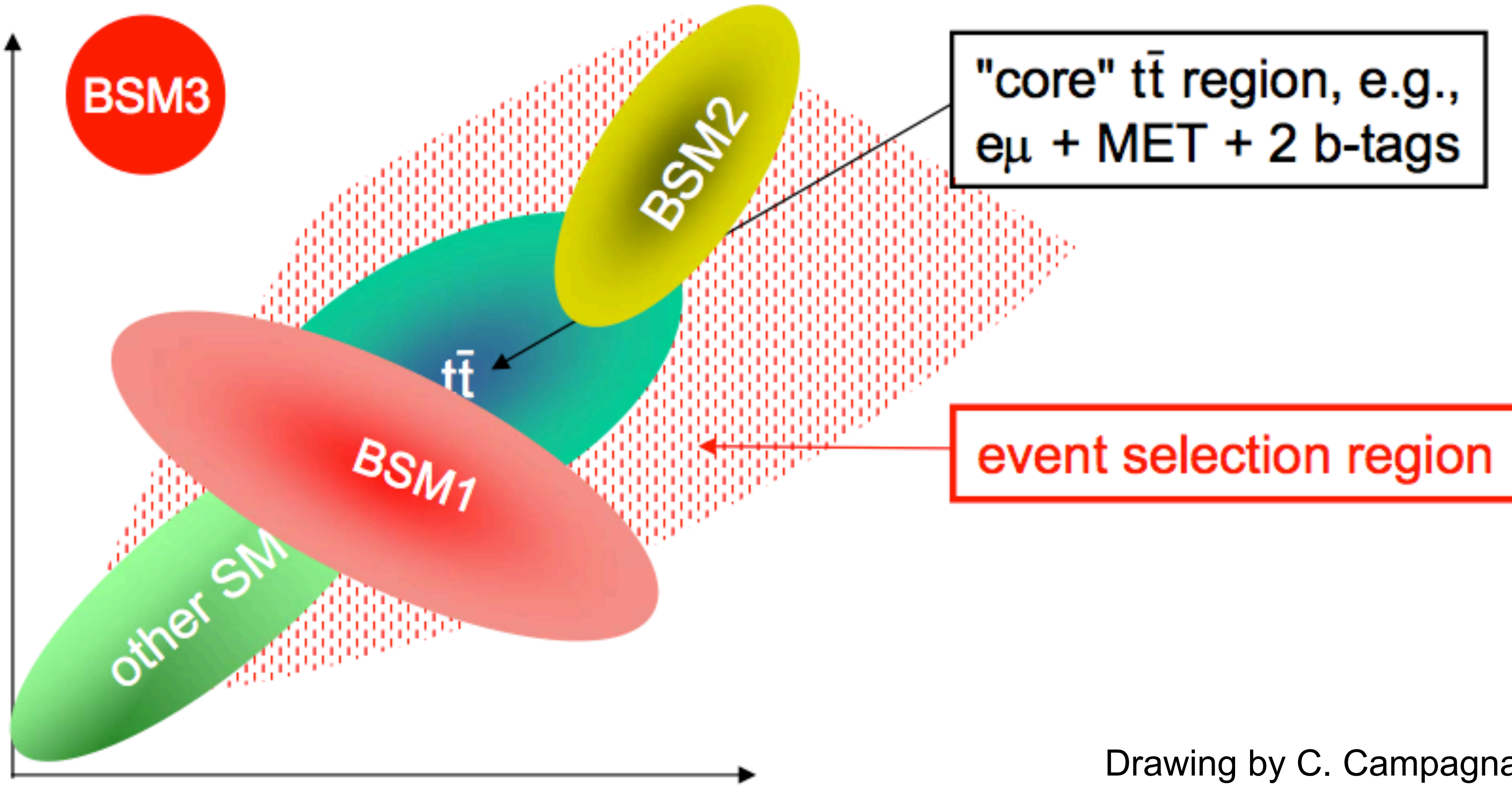




Energy: 1.96 TeV
Int. Luminosity: 12 fb^{-1}
Age: ~25 years
Events/exp (1 fb^{-1})
350 ee eμ, μμ
2k lepton + jets

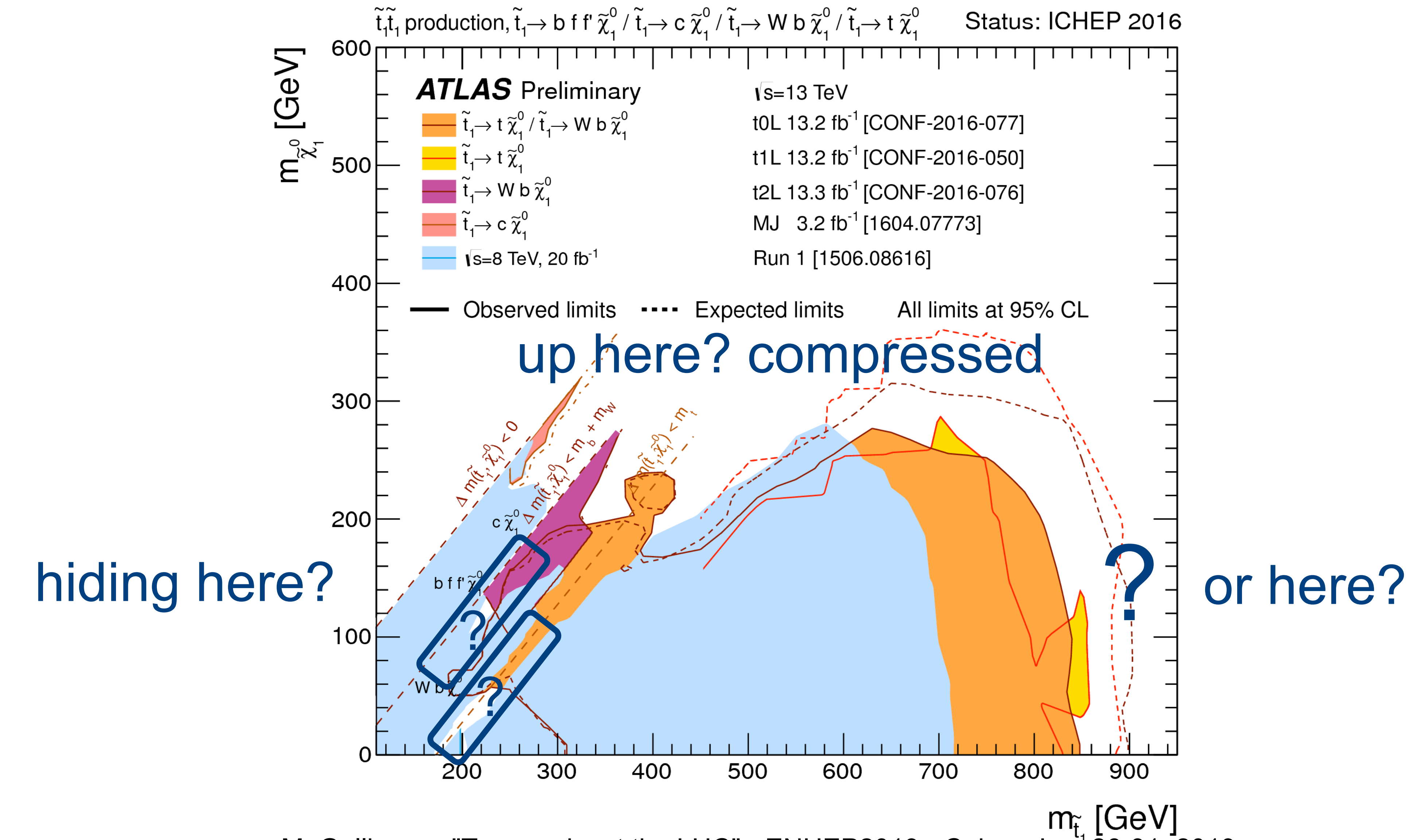
Energy: 7/8/(13) TeV
Int. Luminosity: 5/20/(150) fb^{-1}
Age: ~9 years
Events/exp (1 fb^{-1})
40k ee eμ, μμ
250k lepton + jets

Study characteristics



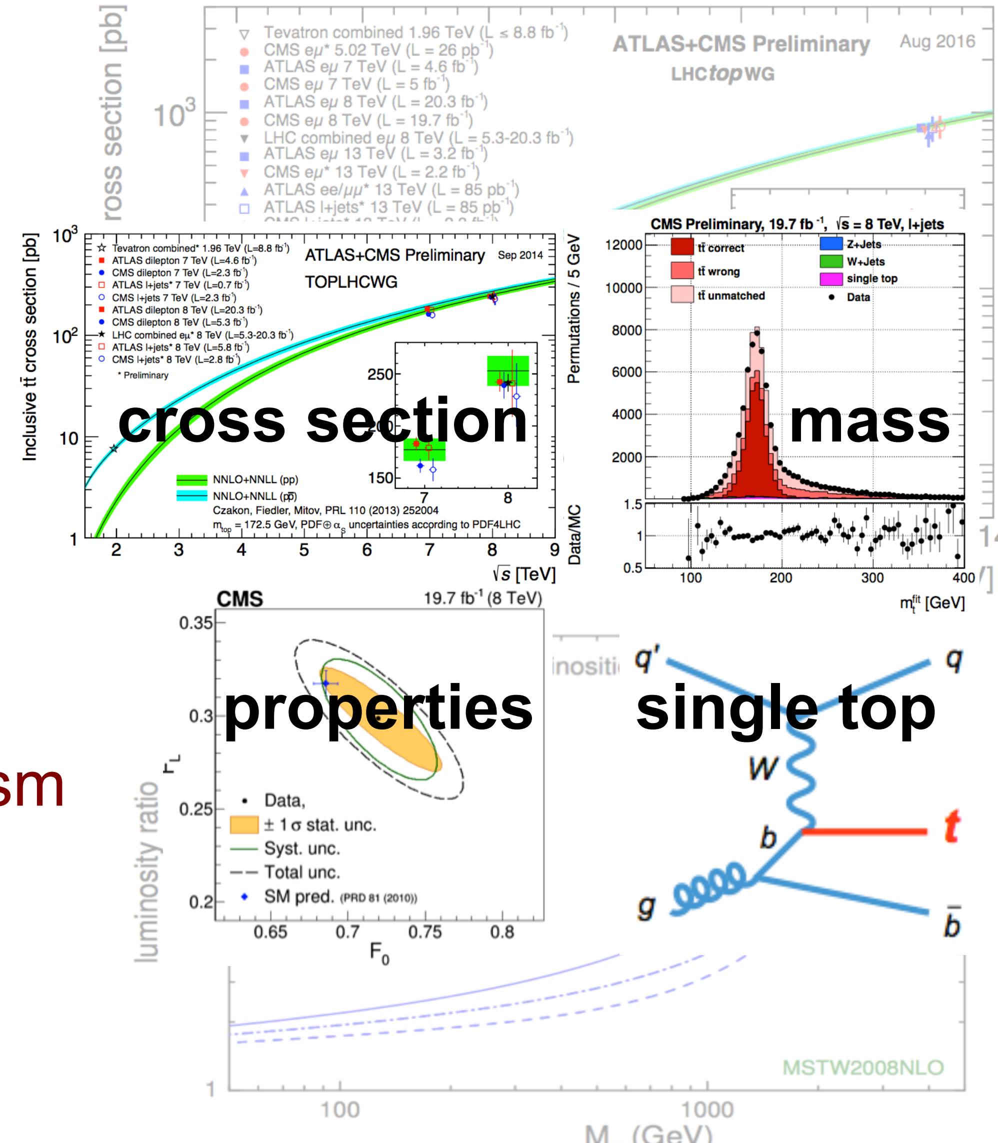
Drawing by C. Campagnari

Regions hard to explore



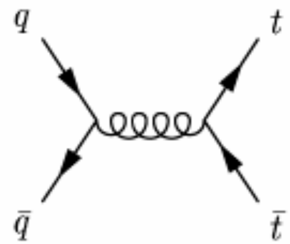
Role of top quark physics

- 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

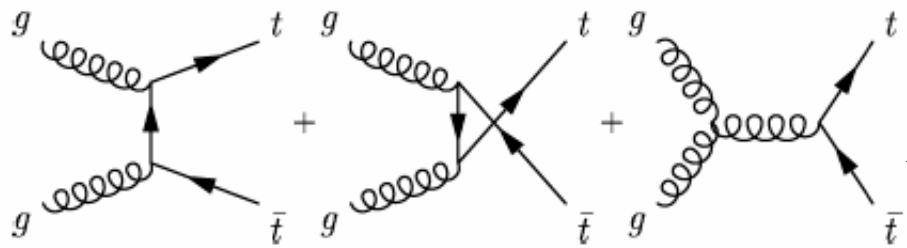


- Monitoring of production mechanism
- Is there any sign of NP in top production/decay?

How is the top quark produced?



Dominant at Tevatron



Dominant at the LHC

Predicted cross sections:

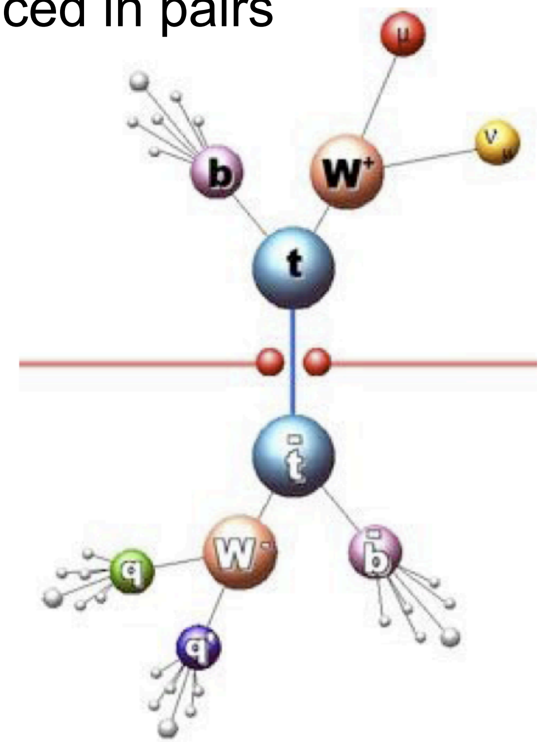
Collider	σ_{tot} [pb]	scales [pb]	PDF [pb]
Tevatron	7.164	$^{+0.110(1.5\%)}_{-0.200(2.8\%)}$	$^{+0.169(2.4\%)}_{-0.122(1.7\%)}$
LHC 7 TeV	172.0	$^{+4.4(2.6\%)}_{-5.8(3.4\%)}$	$^{+4.7(2.7\%)}_{-4.8(2.8\%)}$
LHC 8 TeV	245.8	$^{+6.2(2.5\%)}_{-8.4(3.4\%)}$	$^{+6.2(2.5\%)}_{-6.4(2.6\%)}$
LHC 14 TeV	953.6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

Czakon et al. PRL 110, 252004 (2013)

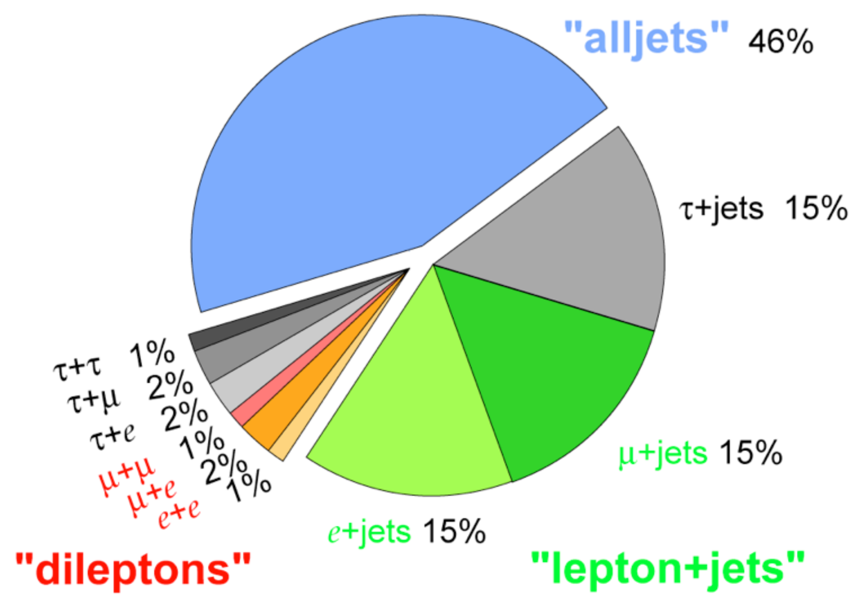
	LHC	Tevatron
gg	~85%	~10%
qq	~15%	~90%

Top quark decays

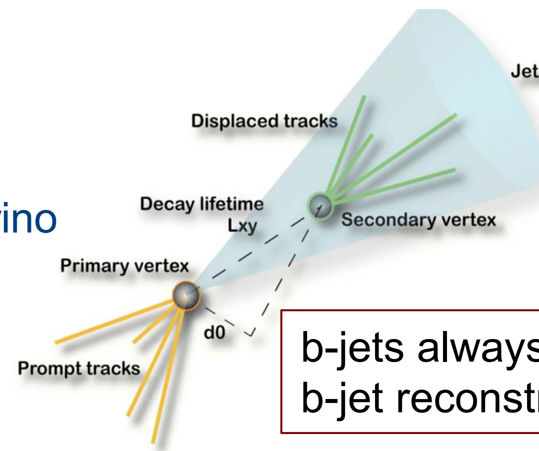
Top quarks (mostly) produced in pairs



Top Pair Branching Fractions

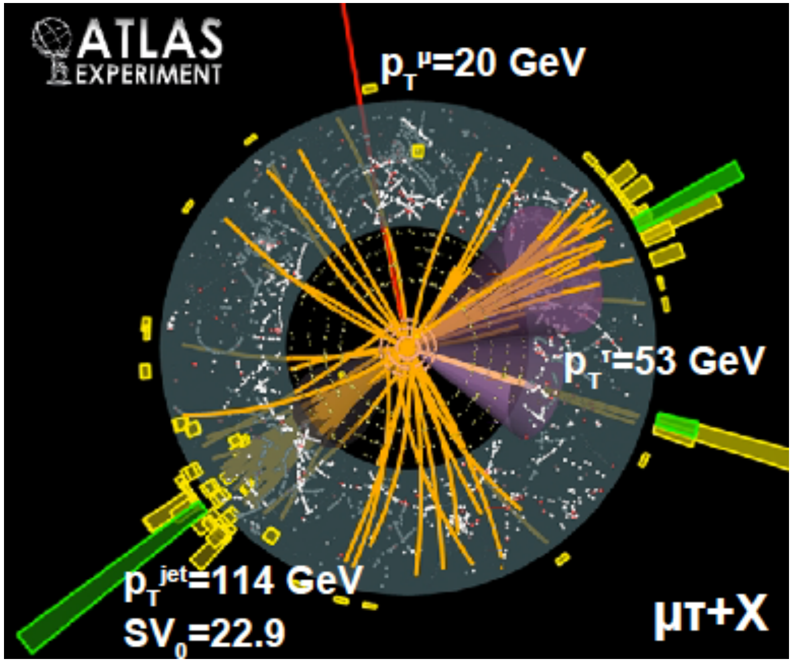


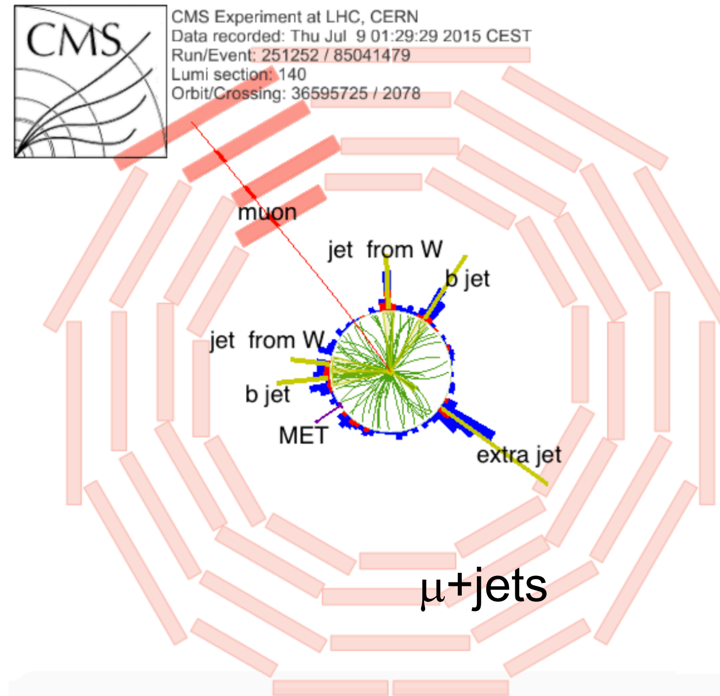
- Dilepton (ee, μμ, eμ):
  - BR~5%, 2 leptons+2 b-jets+2 neutrinos
- Lepton (e or μ) + jets
  - BR~30%, one lepton+4jets (2 from b)+1 neutrino
- All hadronic
  - BR~44%, 6 jets (2 from b), no neutrinos



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

Selection of top quark events

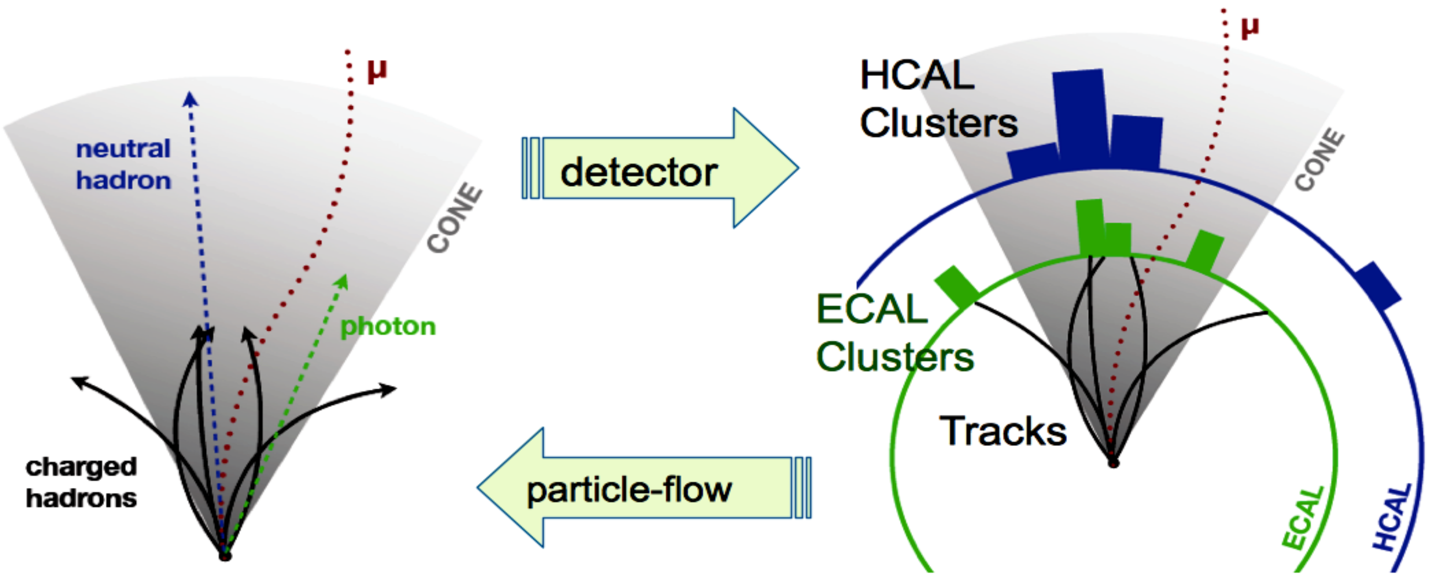




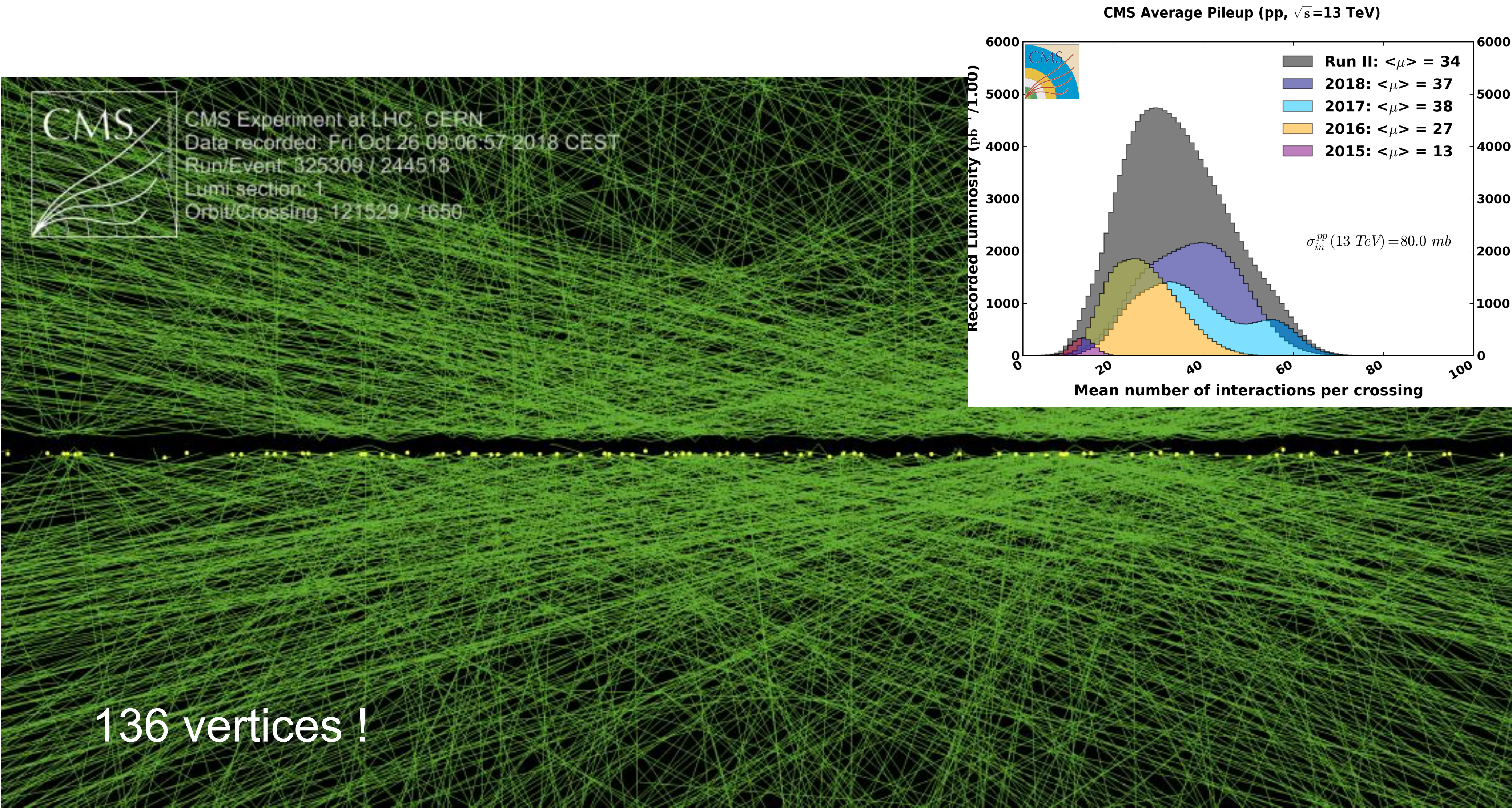
- Trigger:
  - single or double (isolated) lepton
- Leptons:
  - e/μ, p_T>20/30 GeV, $|\eta|$<2.5
  - Identification/reconstruction
  - Tracker/calorimeter isolation
- Jets:
  - at least 2 jets, p_T>30 GeV, $|\eta|$<2.5
  - anti-kT algorithm, with cone 0.4-0.5
  - b-tagging is optional
- Missing transverse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

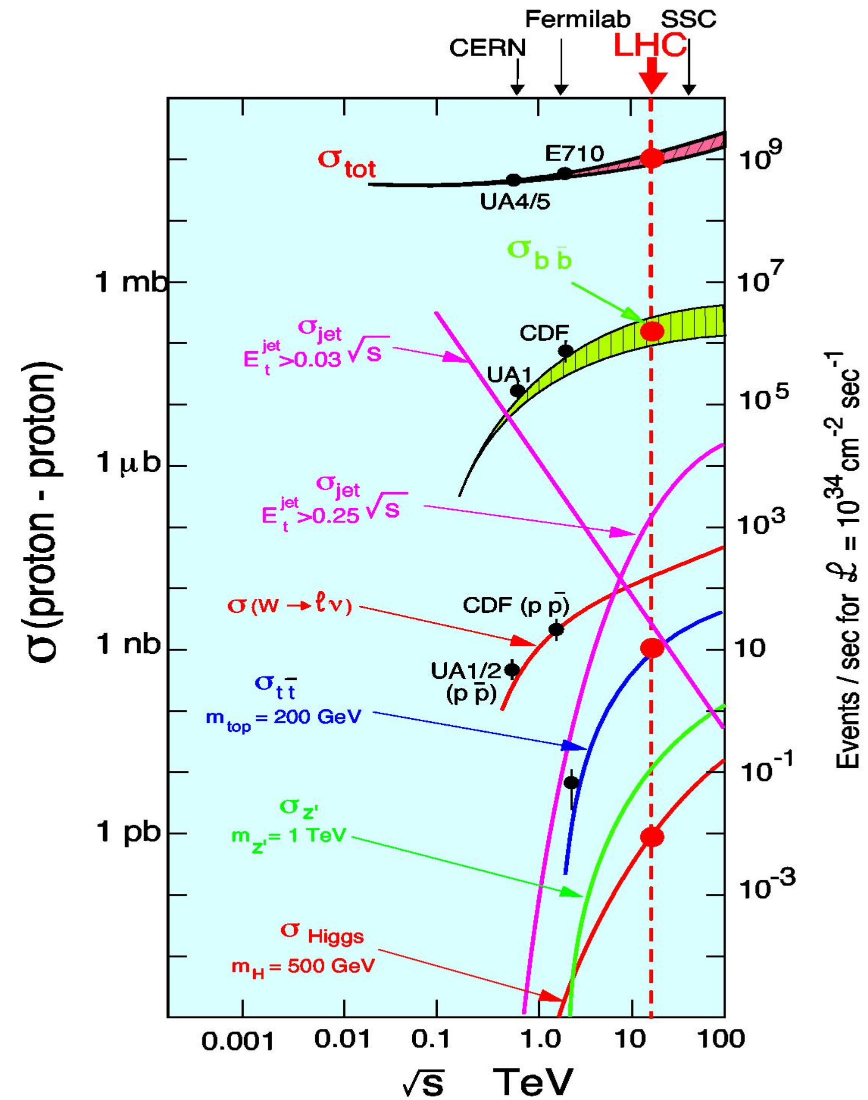


…in a challenging environment



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"



Theory cross sections: TeV vs LHC

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

Cross section measurement

Number of observed events

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

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

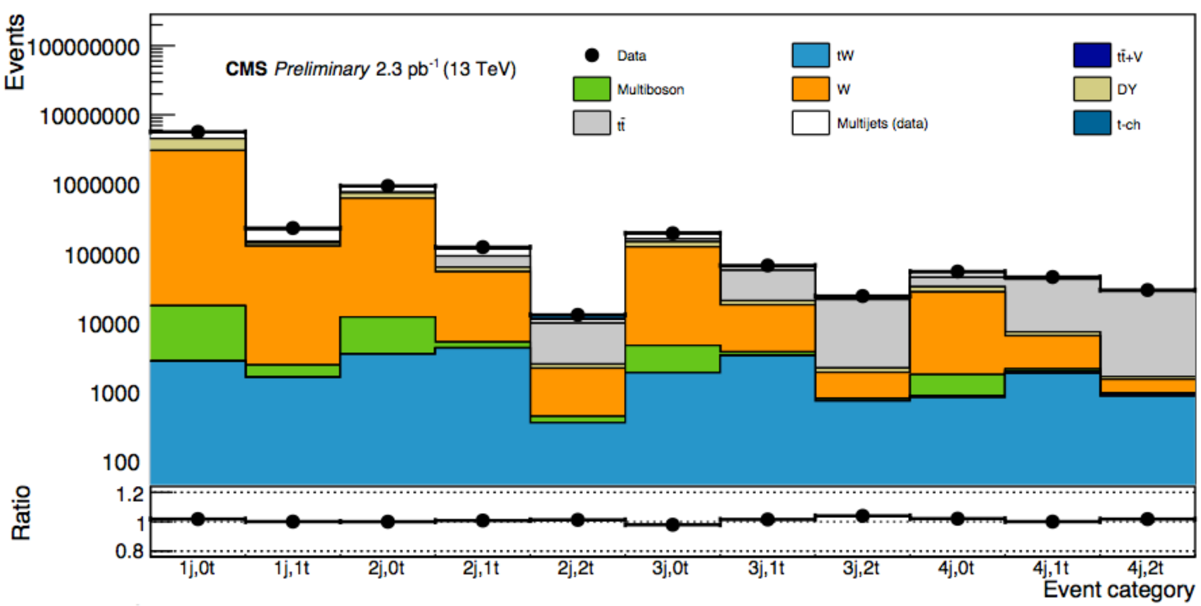
Acceptance *(experimental: detector, efficiencies, triggers)*

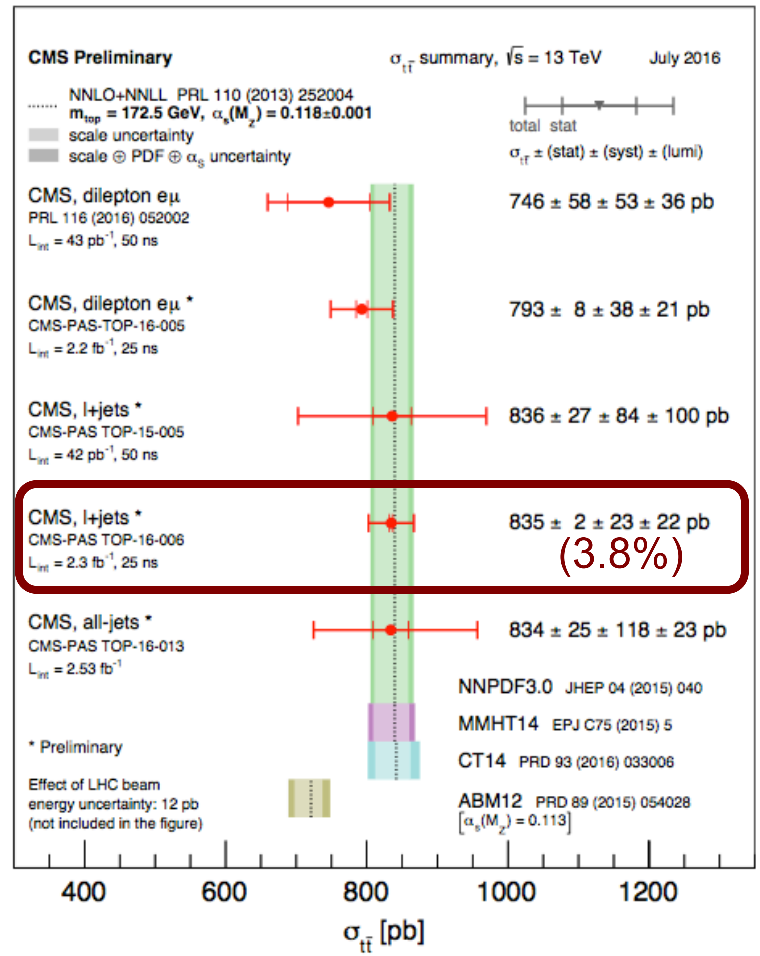
Luminosity *(determined by amount of data, accelerator, beam, etc)*

Cross section: multi-dimensional fit

CMS-TOP-16-006

- 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

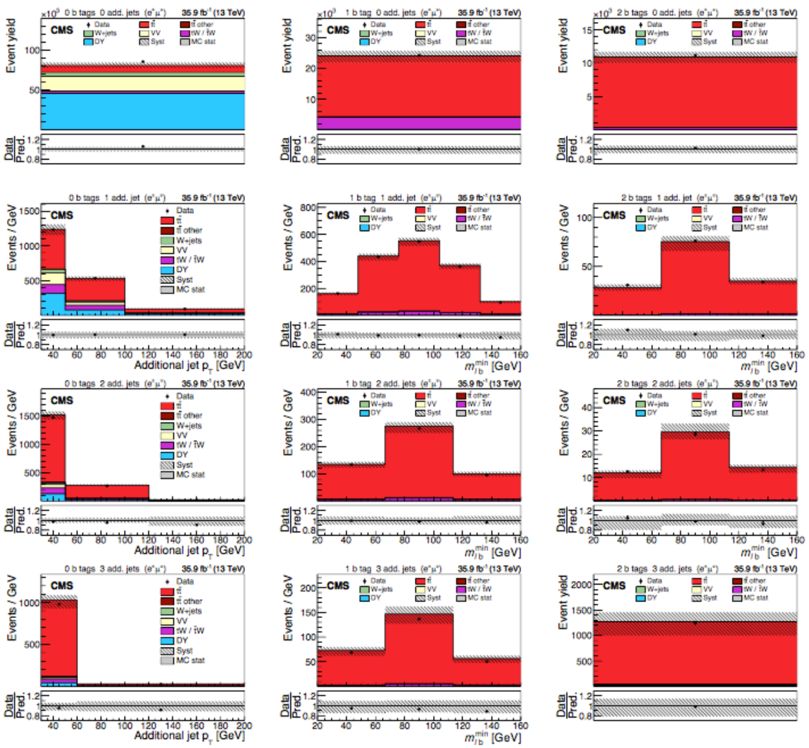
arXiv:1812.10505

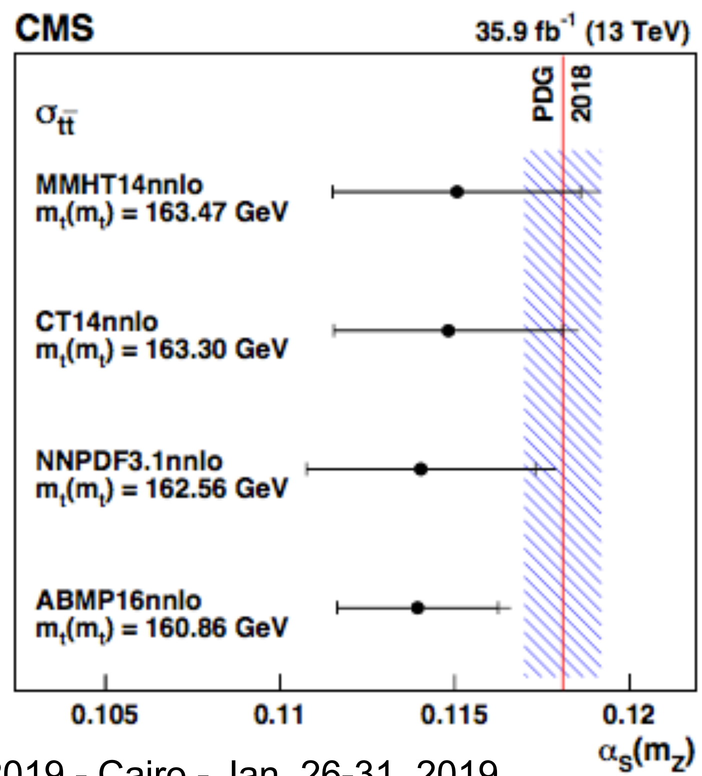
- Dilepton final state
- Simultaneous fit in ($N_{additional\ jet}$,$N_{b\text{-}jet}$) categories
- Fit of σ_{ttbar} and m(top)

(~4%)

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

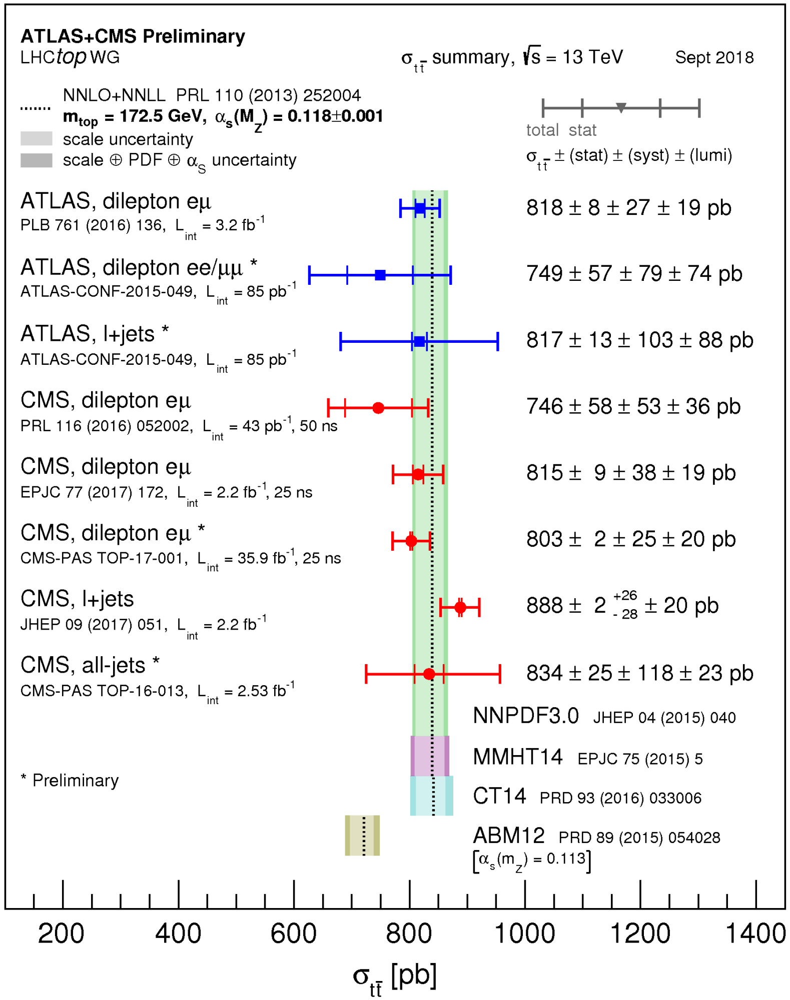
$$m_t^{MC} = 172.33 \pm 0.14\,(\text{stat})\,^{+0.66}_{-0.72}\,(\text{syst})\,\text{GeV}$$

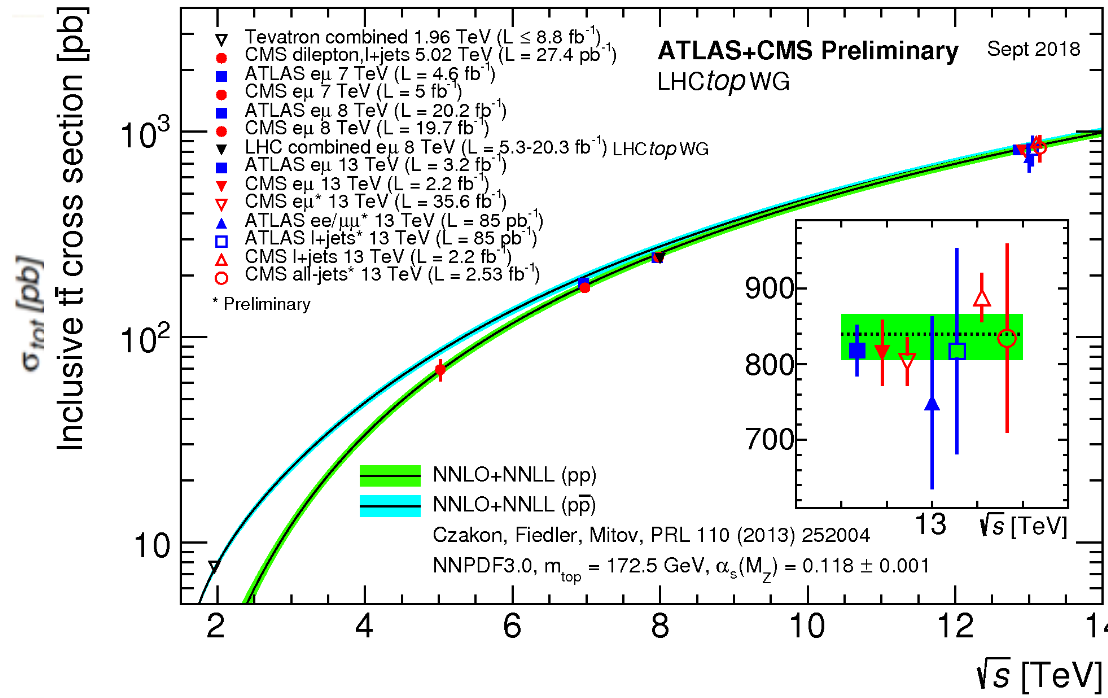




Cross sections

±4%





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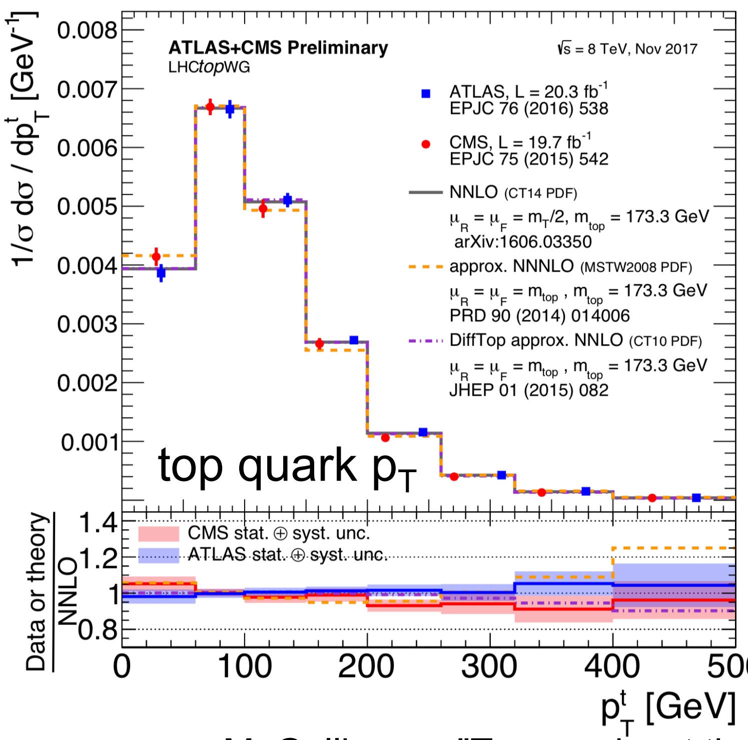
±3-5%

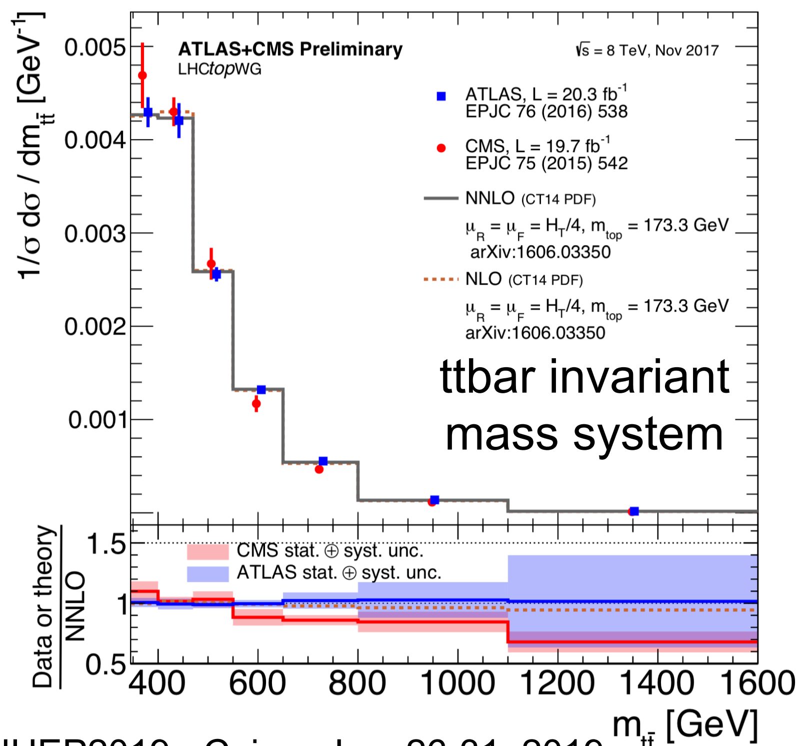
⇒measurements challenging theory

Differential cross section

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

- 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





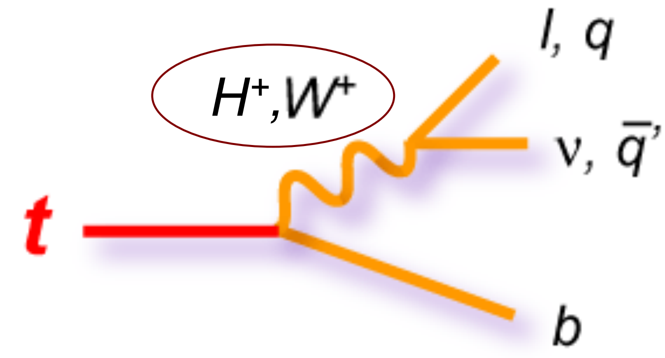
Probing the Wtb vertex

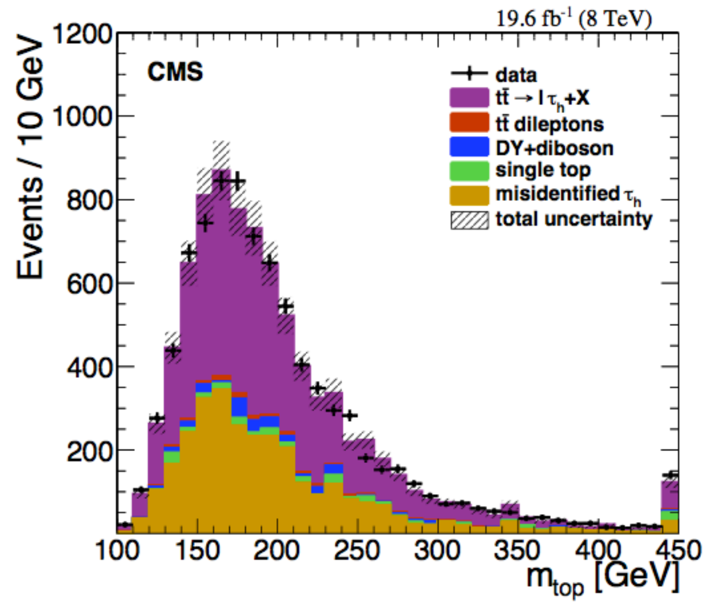
PRD 85 (2012) 112007, PLB 739 (2014) 23

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*,μμ,*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	*e*τ, μτ +2 *b*-jets	4/81
Tau+jets	τ + jets + 2*b*-jets	12/81

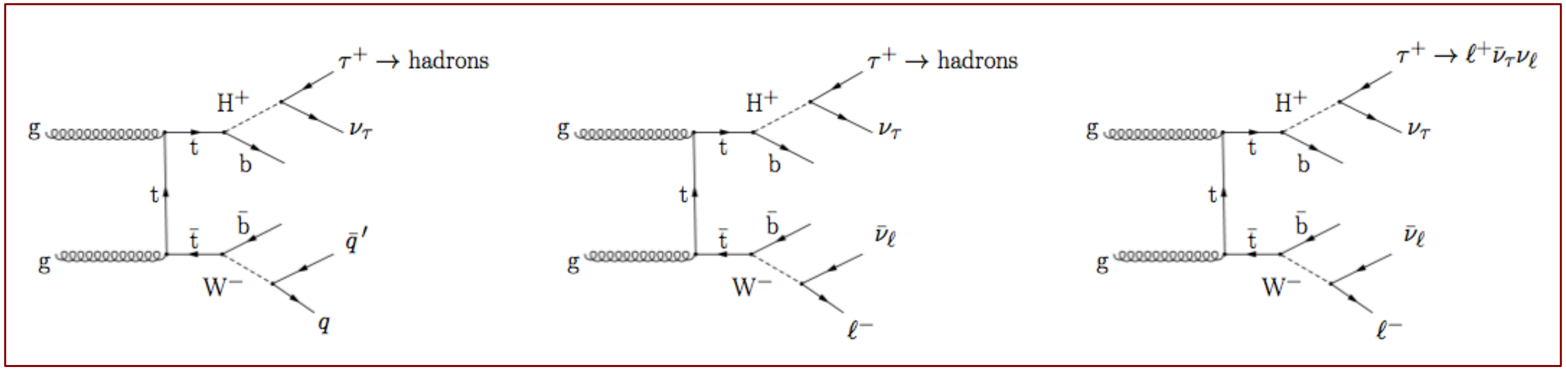




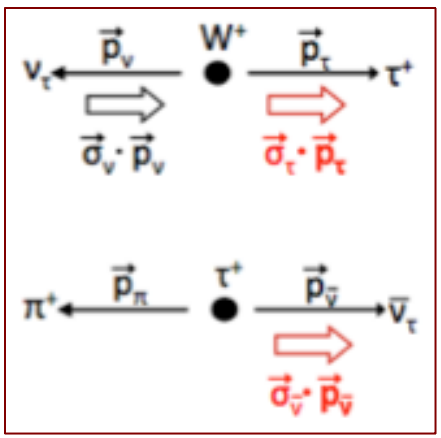
- If top quark plays special role in EWK symmetry breaking, couplings to W may change
- Charged Higgs may alter coupling to W
- Search for final states with taus: charged Higgs

Looking at tau decays

CMS-HIG-12-052

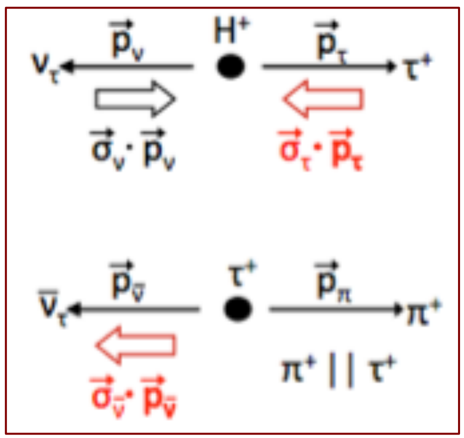


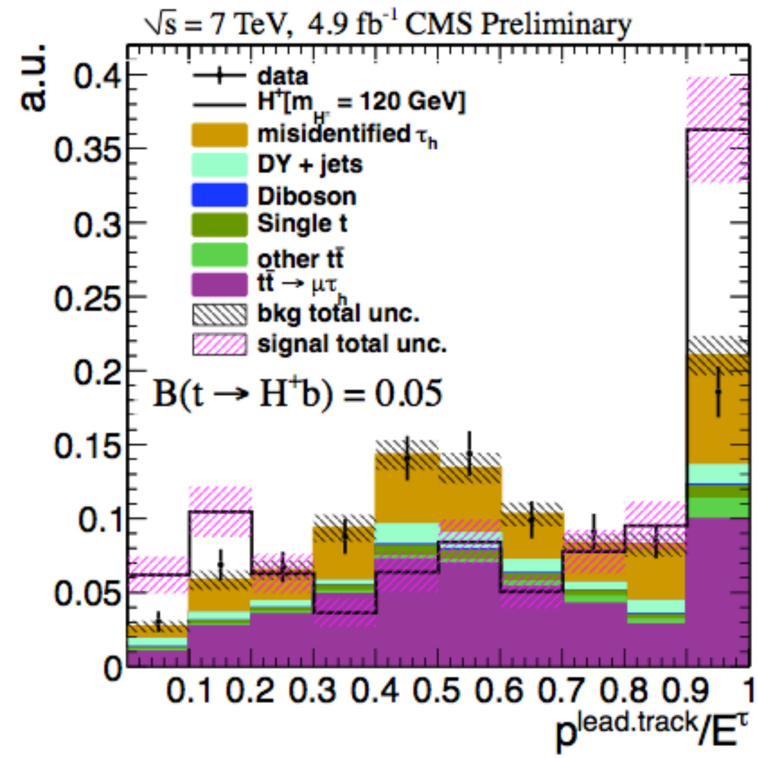
SM



vs

BSM



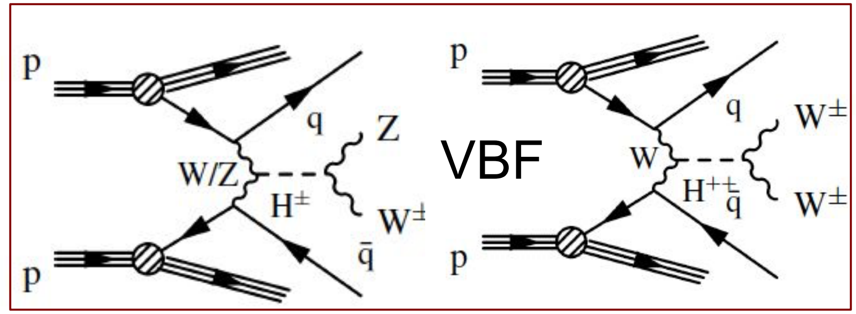


Charged Higgs

PRL119(2017)141802, PRL120(2018)081801

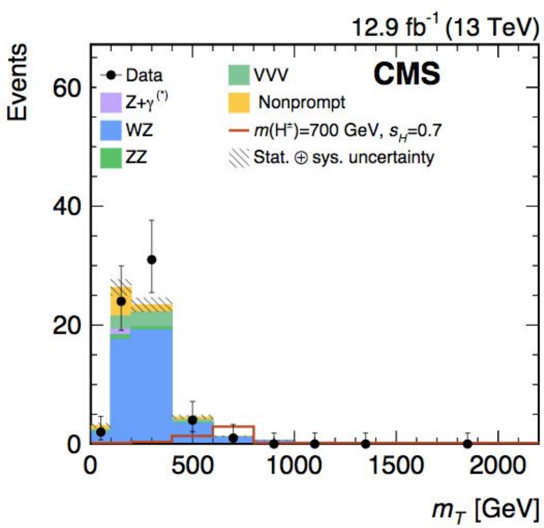
Higgs sector in MSSM contains two scalar doublets:

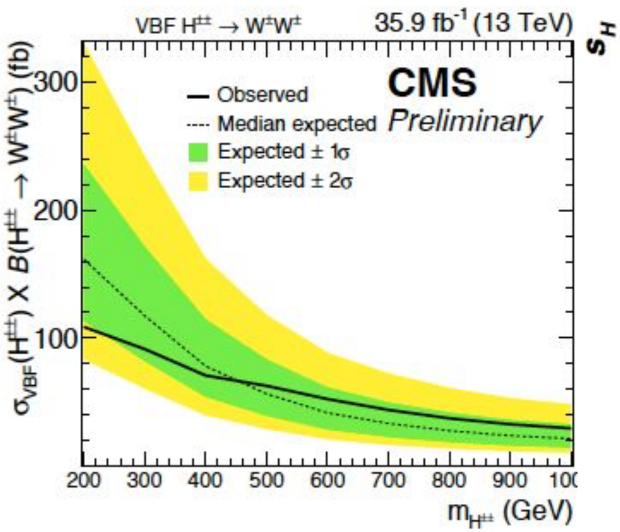
- 5 physical Higgs bosons
  - 3 neutral: CP-even ϕ=h,H CP-odd A
  - 2 charged $H^{\pm}$

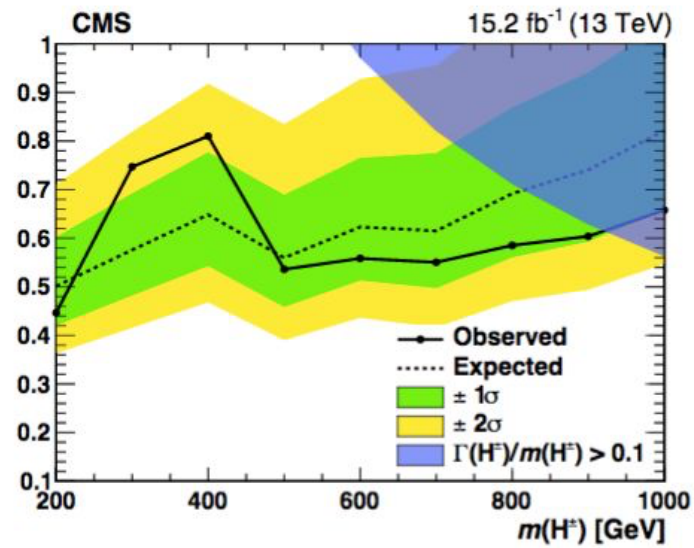


Charged H: If found, a clear indication of BSM

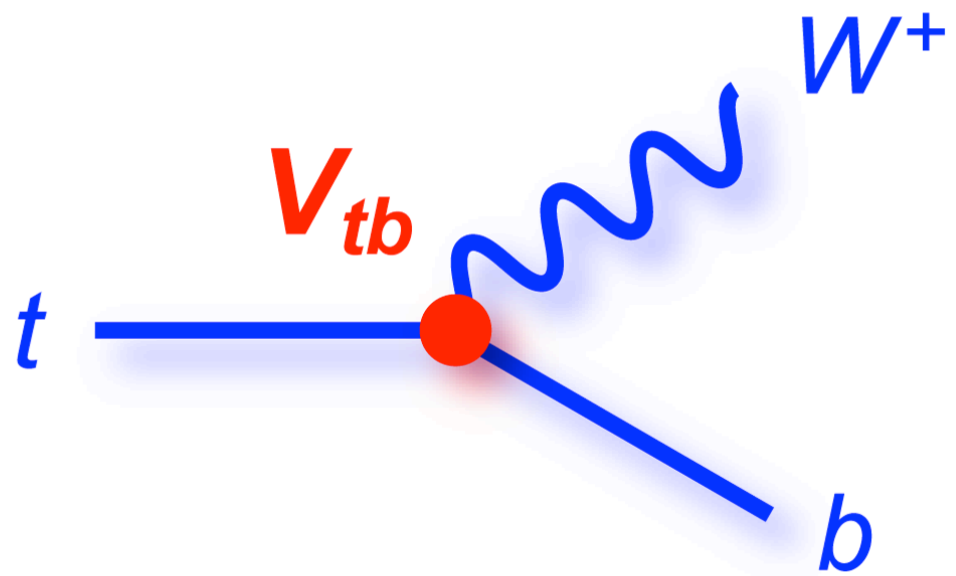
- $H^{\pm} \rightarrow W^{\pm}Z$: three lepton (two OS on Z)
- $H^{\pm\pm} \rightarrow \ell^{\pm}\ell^{\pm}Z$: same-sign leptons







How does a top quark decay?



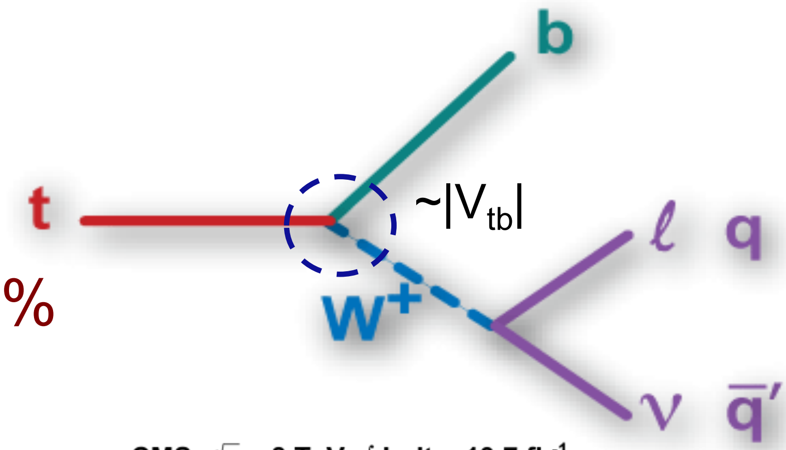
- almost always t→Wb (i.e. V_{tb}~1)
- lifetime is short, and it decays before hadronizing
- the W is real:
  - can decay W→lν (l=e,μ,τ), BR~1/9 per lepton
  - can decay W→qq, BR~2/3

Cross section in the R measurement

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

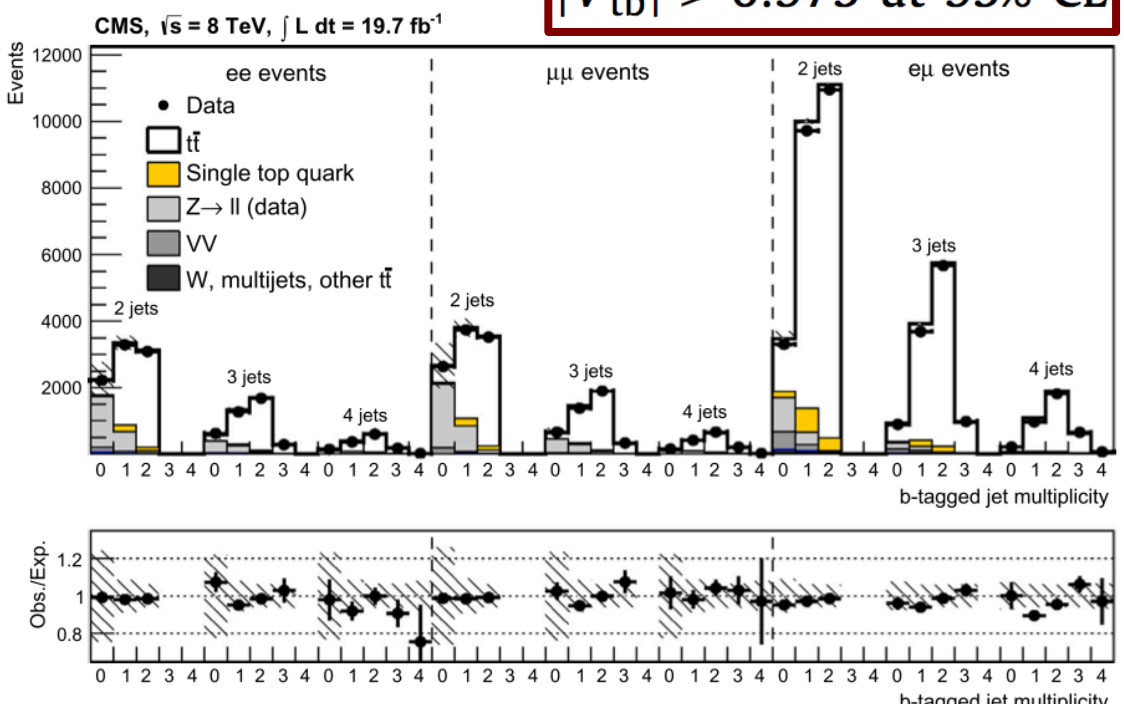
- Measure R:
- Dilepton final state

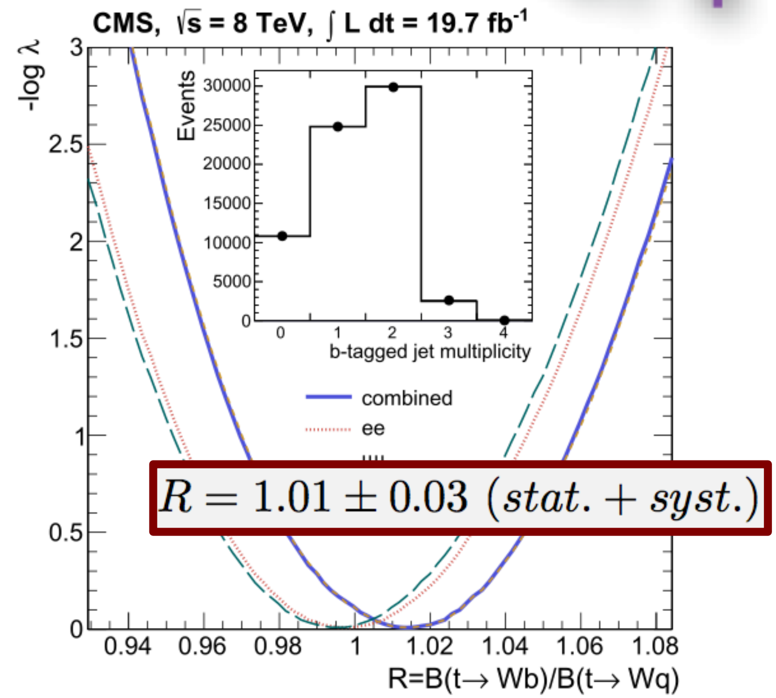
$$R \equiv \frac{BR(t \to Wb)}{BR(t \to Wq)} \approx |V_{tb}|^2$$



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

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





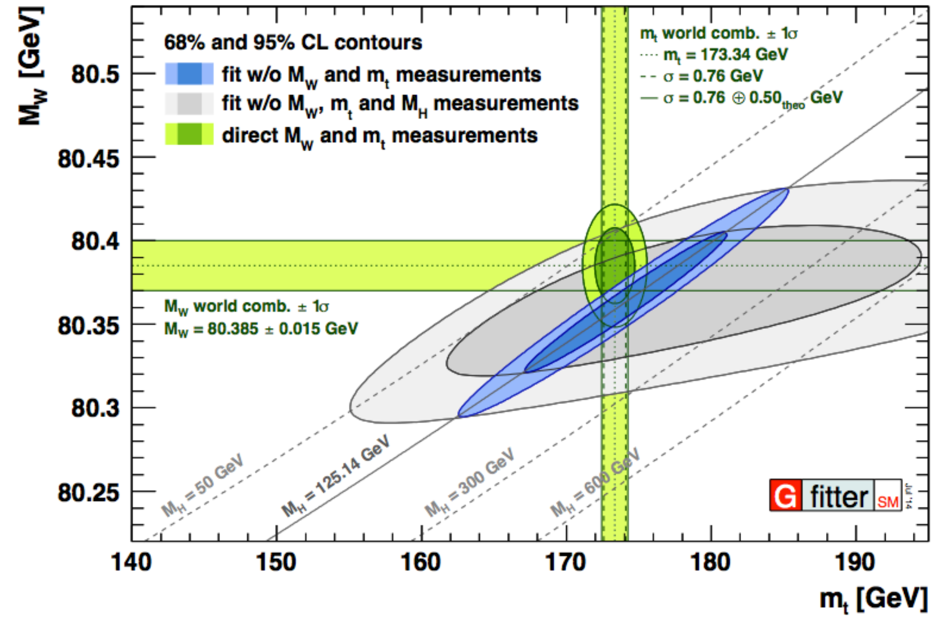
$$R = 1.01 \pm 0.03\ (stat. + syst.)$$

Top quark mass: why do we care?

- 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

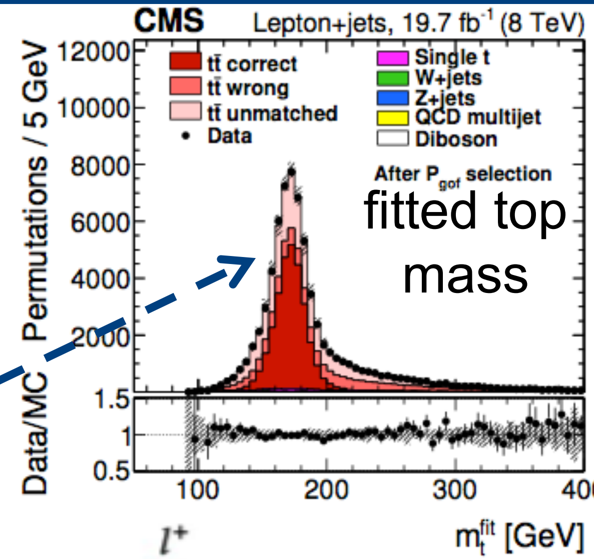


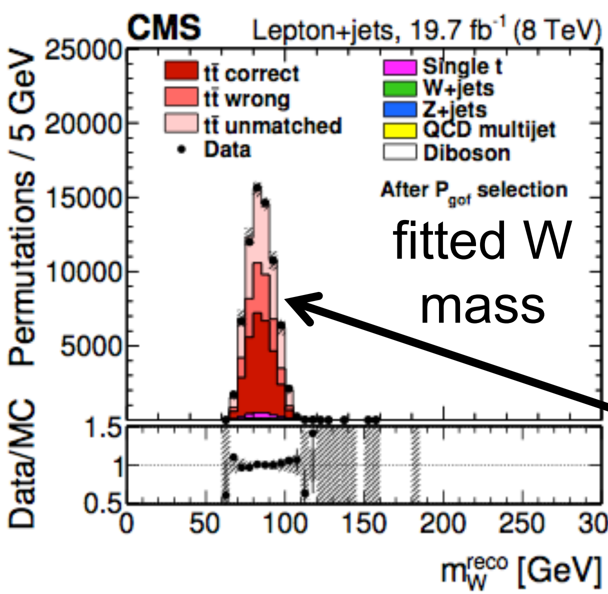
- Top is the only fermion with the mass of the order of EWSB scale
- Discovered Higgs boson fits well with precise determinations of m_W and m_{top}
- Other properties (EWK coupling, production asymmetries, etc.) are predicted by SM
- Precise measurements could reveal breakdown of SM

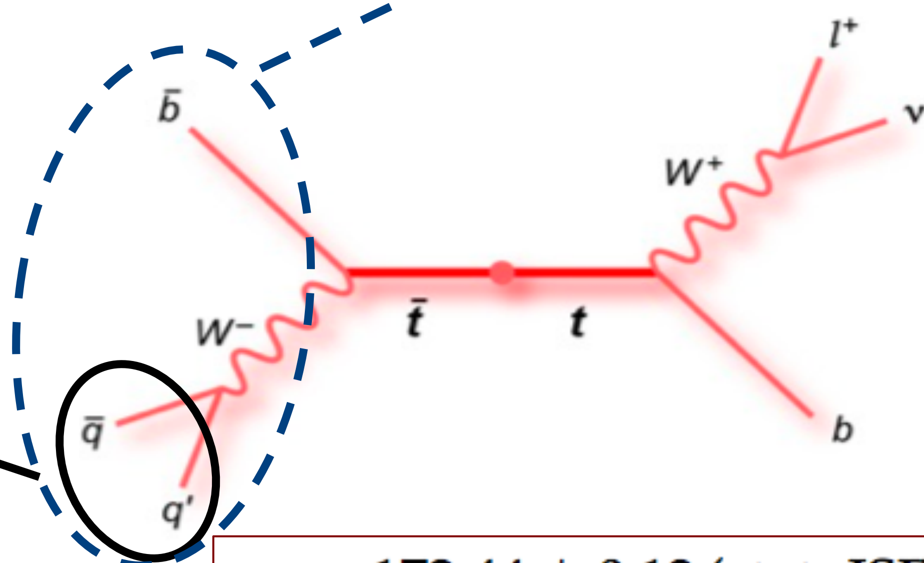
Precise mass measurement

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





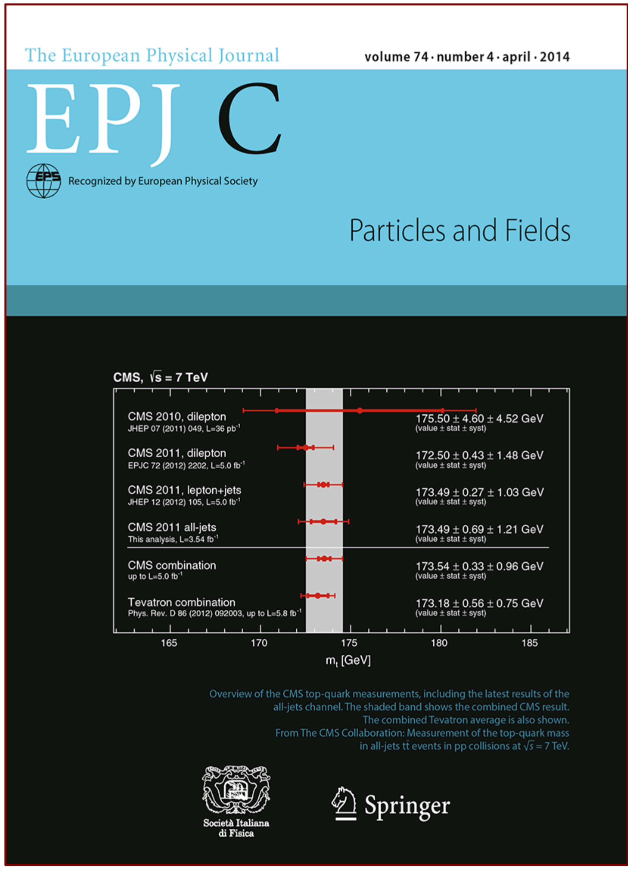


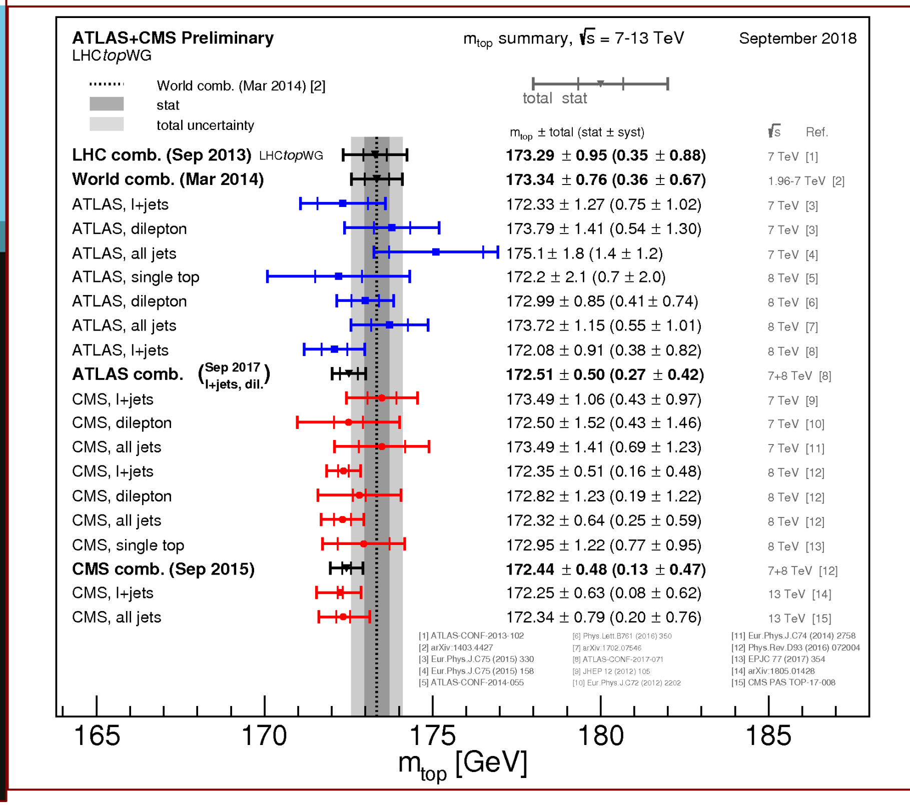
±0.3%

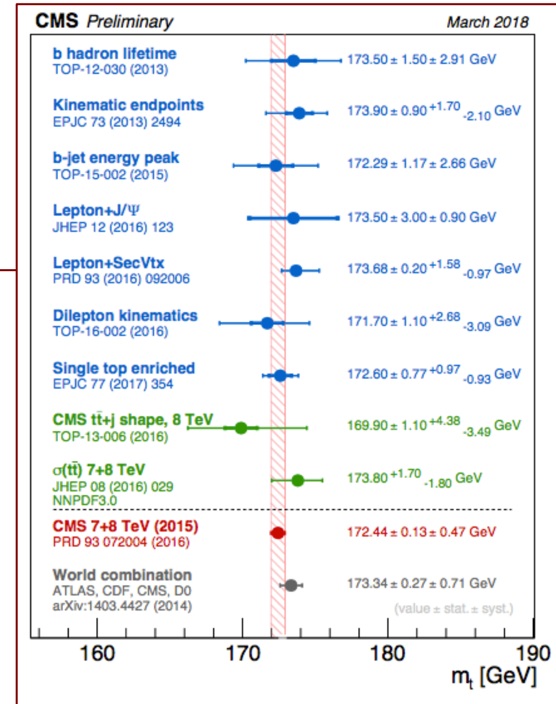
$$m_t = 172.44 \pm 0.13\,(\text{stat+JSF}) \pm 0.47\,(\text{syst})\,\text{GeV}$$

Top quark mass results

- accurate (~0.3%) measurement



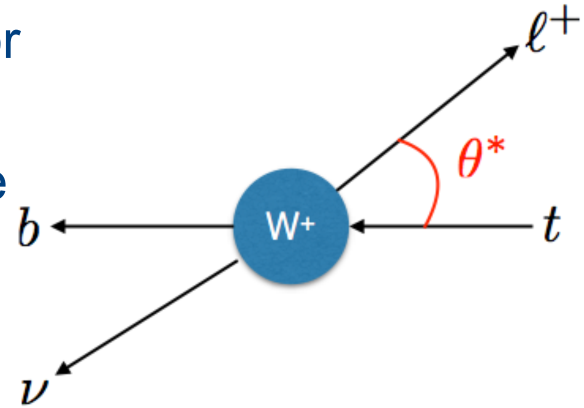


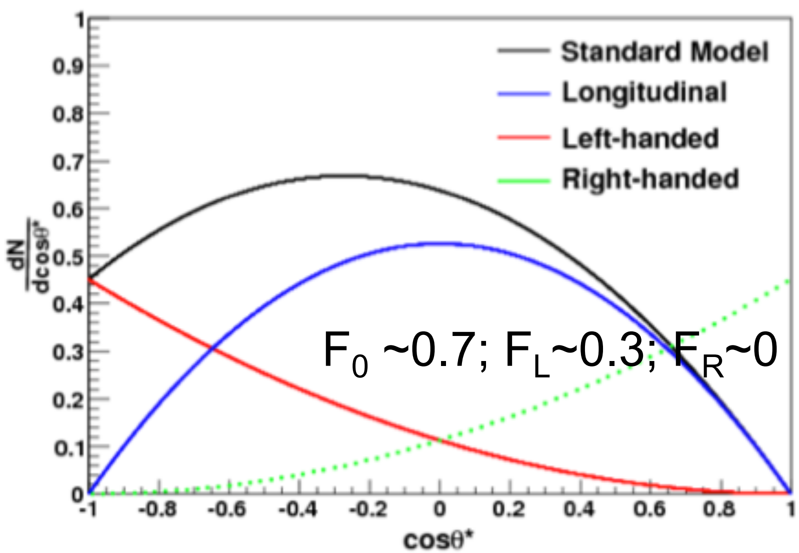


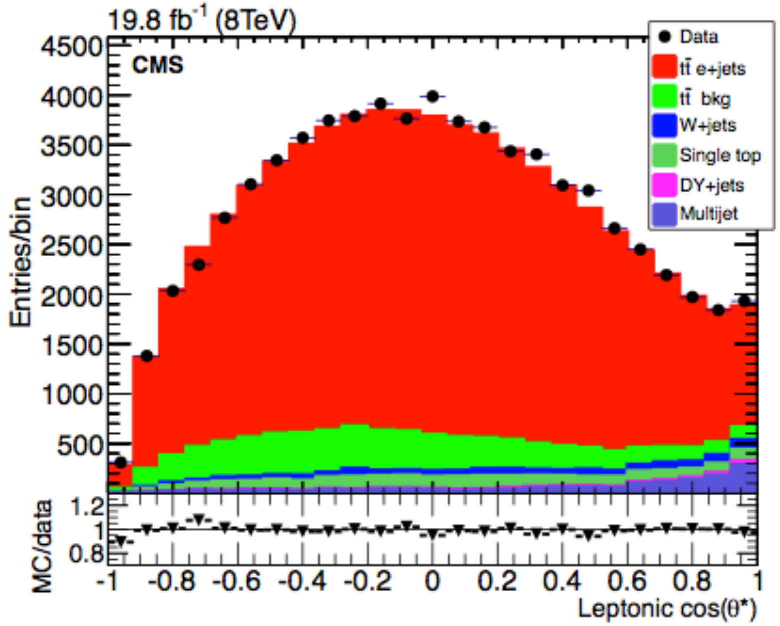
W boson polarization

arXiv:1612.02577, PRD 93(2016)052007

- W bosons can be produced with left-handed, right-handed, or longitudinal polarization
- Top decay vertex in the SM is characterized by V-A structure
  - 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



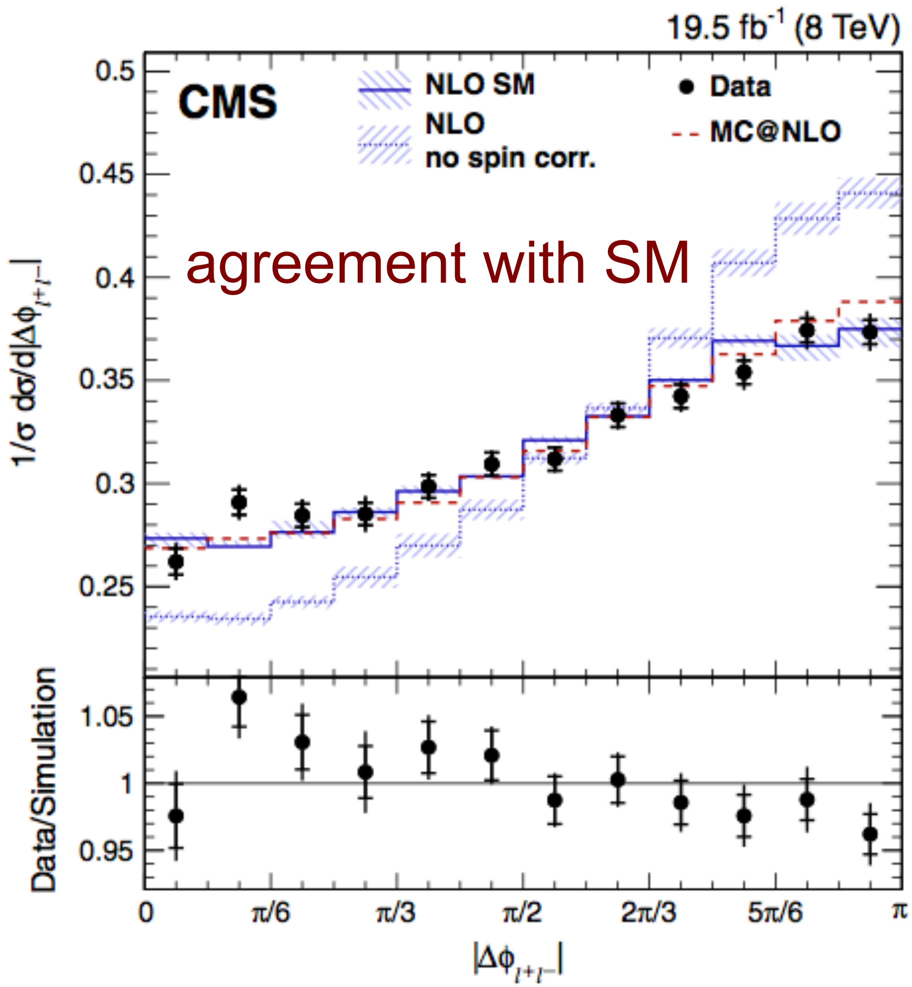




Spin correlation

PRD 93(2016)052007, ATLAS-CONF-2018-027

- Important tool for precise studies
- 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) $\Rightarrow$ 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

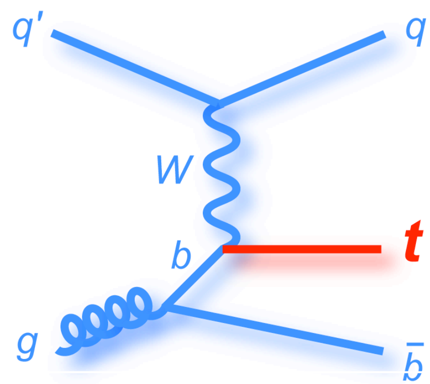


How else is Top produced?

PRD102(2009)182003, PRD81(2010)054028

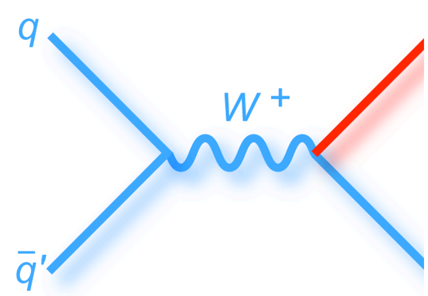
- Single top quark production

t-ch



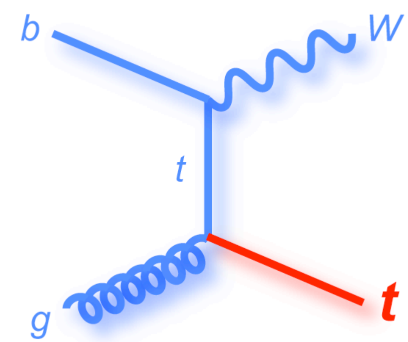
σ(13TeV) = 217 pb

s-ch

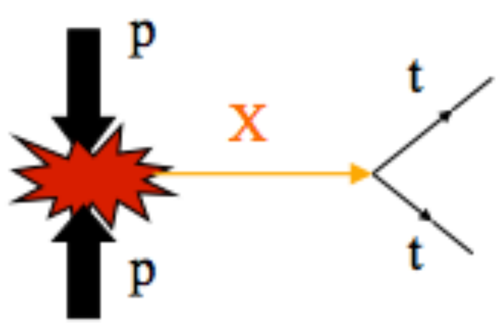


10 pb

Wt-ch



72 pb

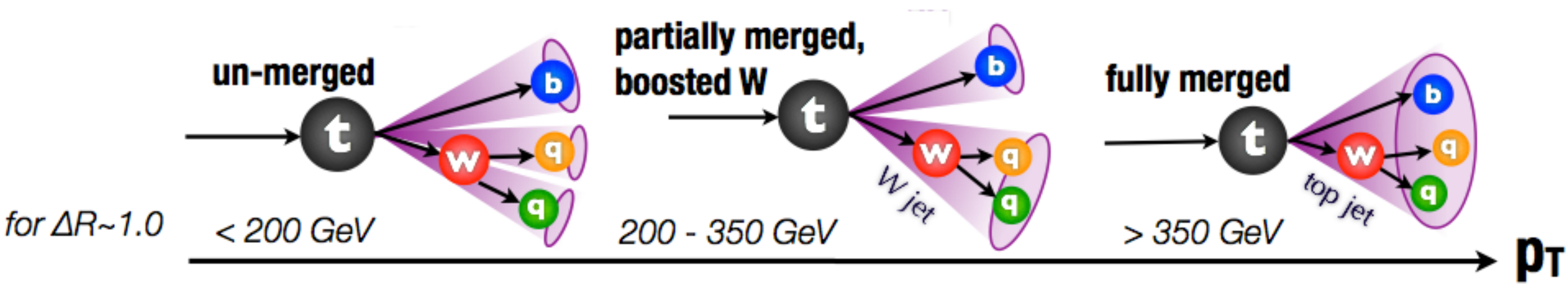


Resonance Production?
Top Color-Assisted Technicolor
OR
?????

Probing top quark production

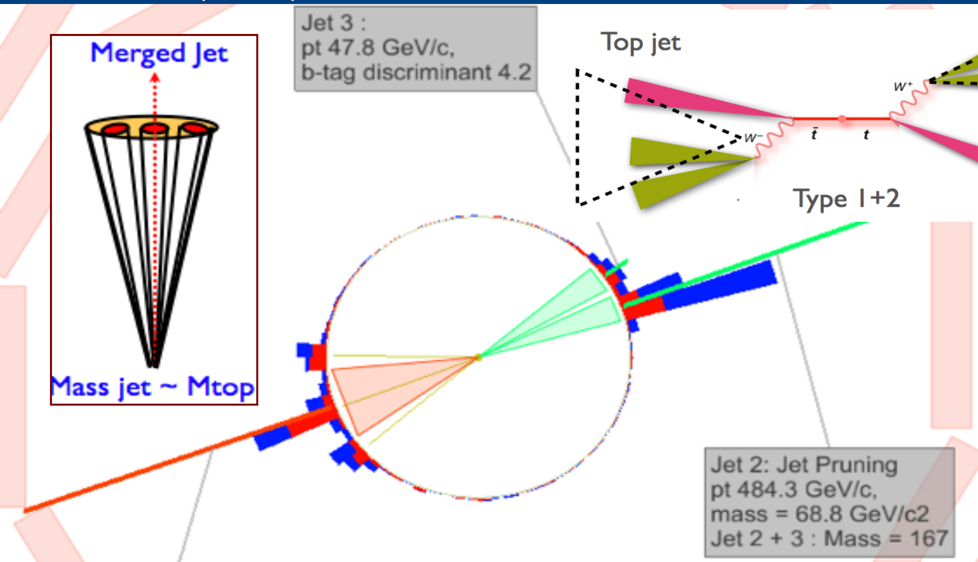
- Differential measurements
  - Testing QCD, measuring properties, searching for new physics, …
  - Function of kinematics, global variables, associated production
- Increased sensitivity: top quark pairs produced at rest
  - σ (M_{tt}>1 TeV at 13 TeV) =8 x σ(M_{tt}>1 at 8 TeV)

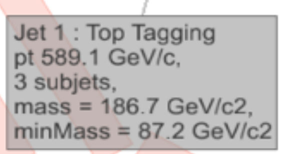
⇒Unique opportunity to probe boosted production at 13 TeV



Boosted topology

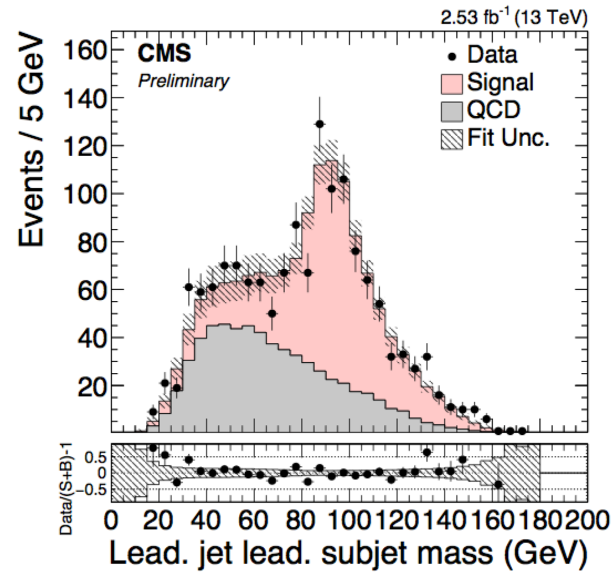
JHEP 1209(2012)029, TOP-16-013

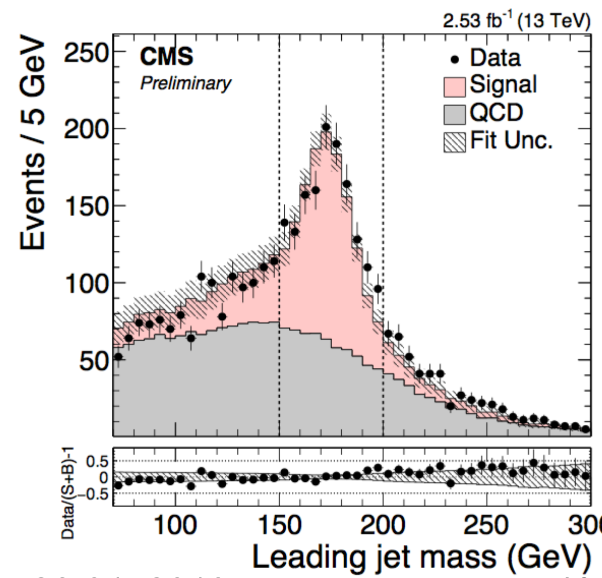




see also CDF note 10234

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





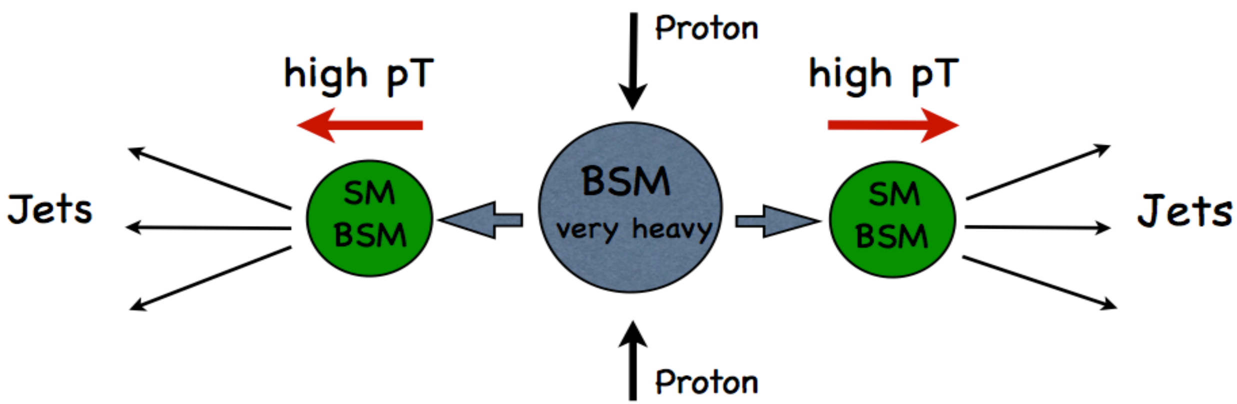
- At high energy, particles produced beyond threshold
- All-hadronic topology
  - Top p_T boosted, jets are collimated
  - Decay products and FSR collected in a “fat” jet
- Look at jet substructure
- Measure mass (no neutrinos)

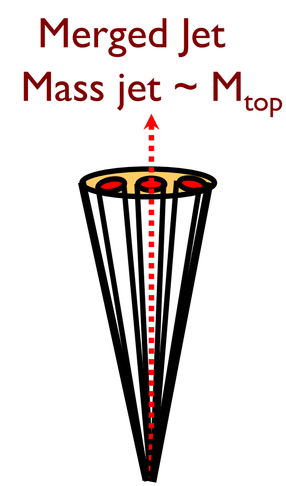
Boosted topology

- 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

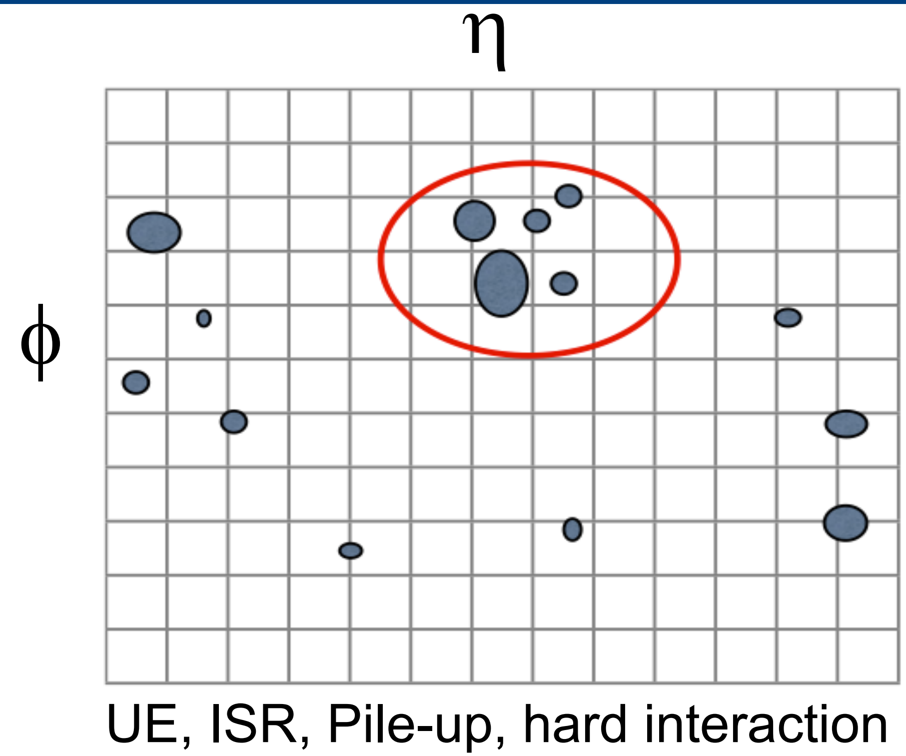


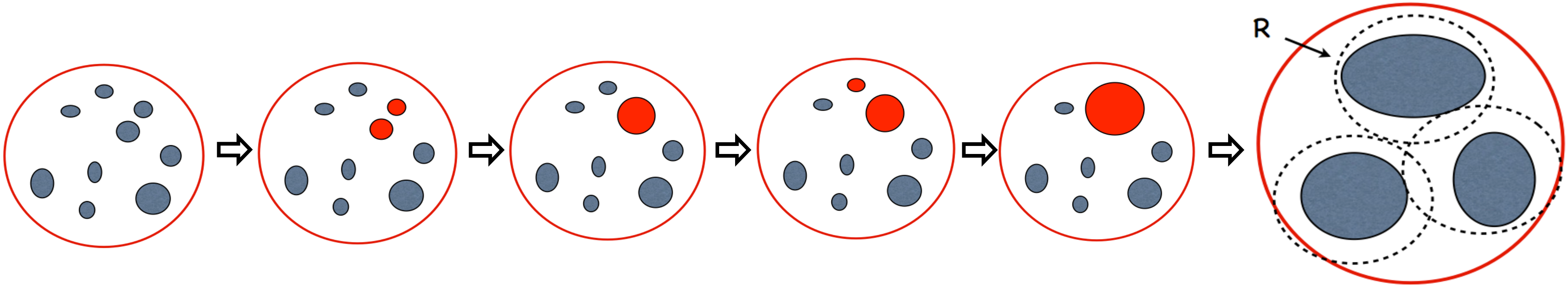


- At LHC energy, EWK scale particles produced beyond threshold
- Jets are highly collimated
- Decay products and FSR collected in a fat jet

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

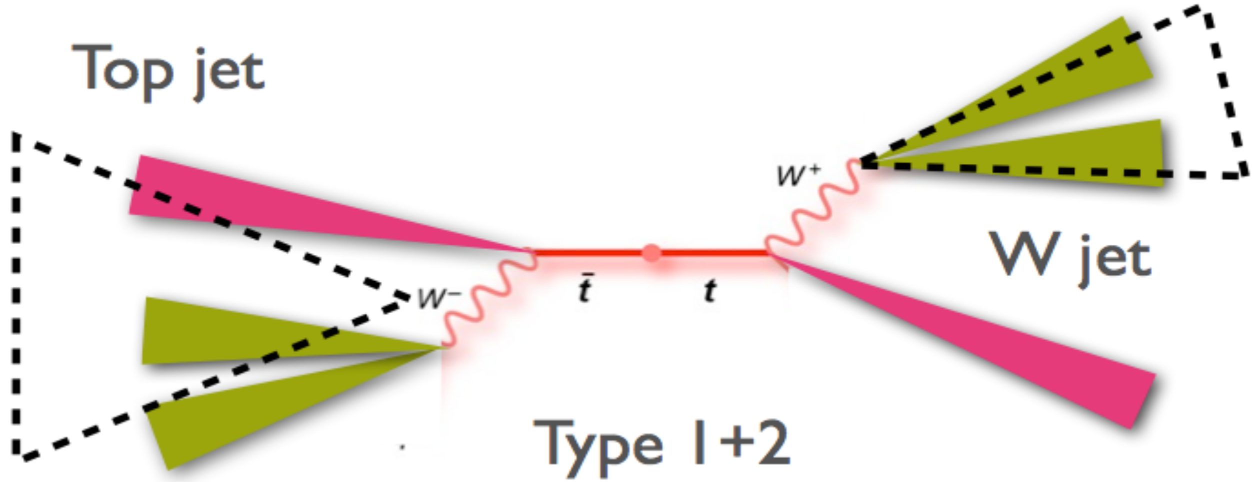




Boosted topology: Top

- Highly boosted top: three hadronic decays of the top are merged in one top jet

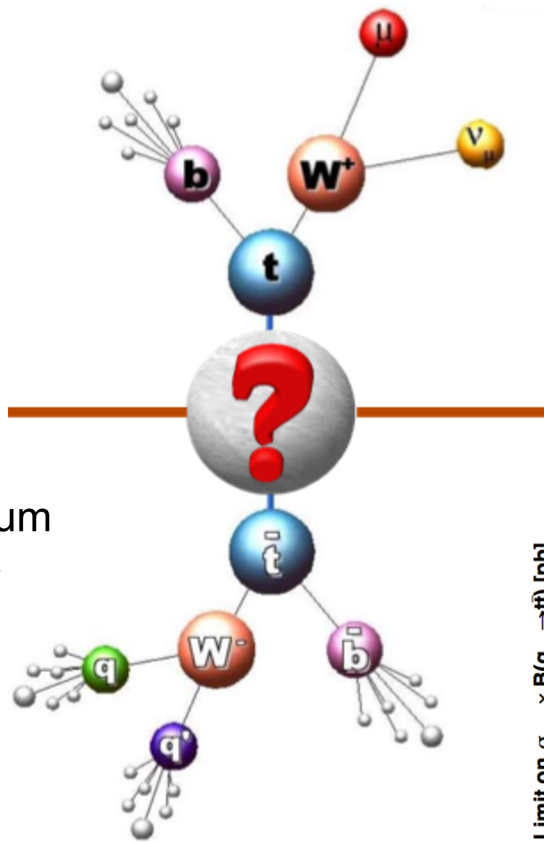
- Moderately boosted top: three hadronic decays of the top are merged in one W jet plus and one b jet candidates

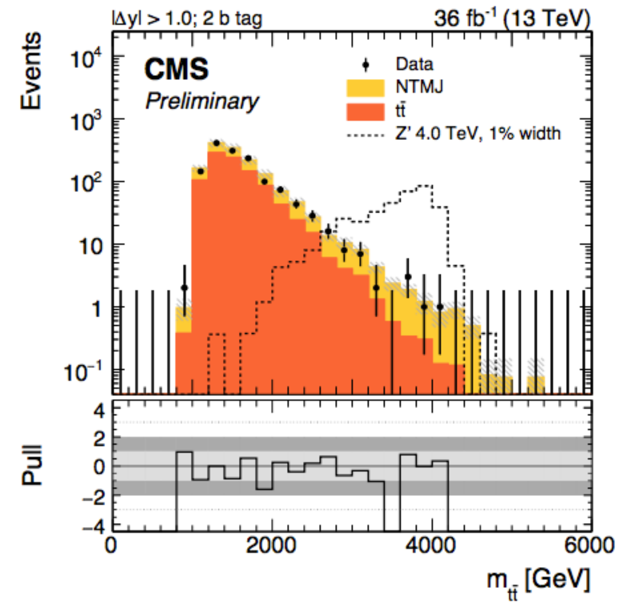


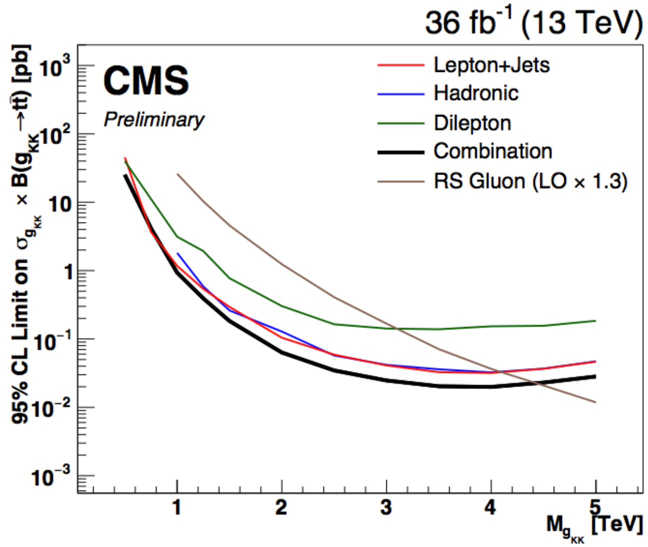
Top quark pair resonance

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

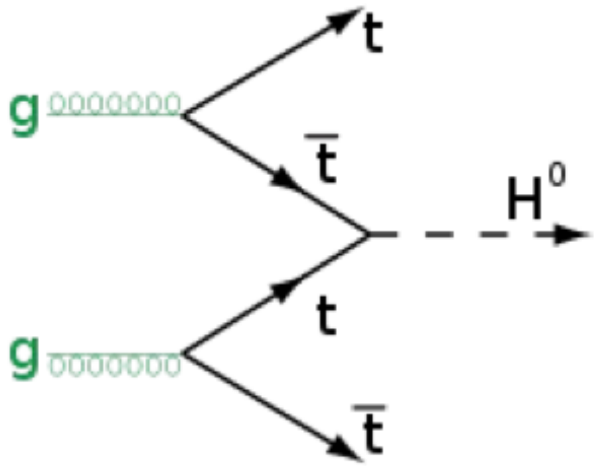






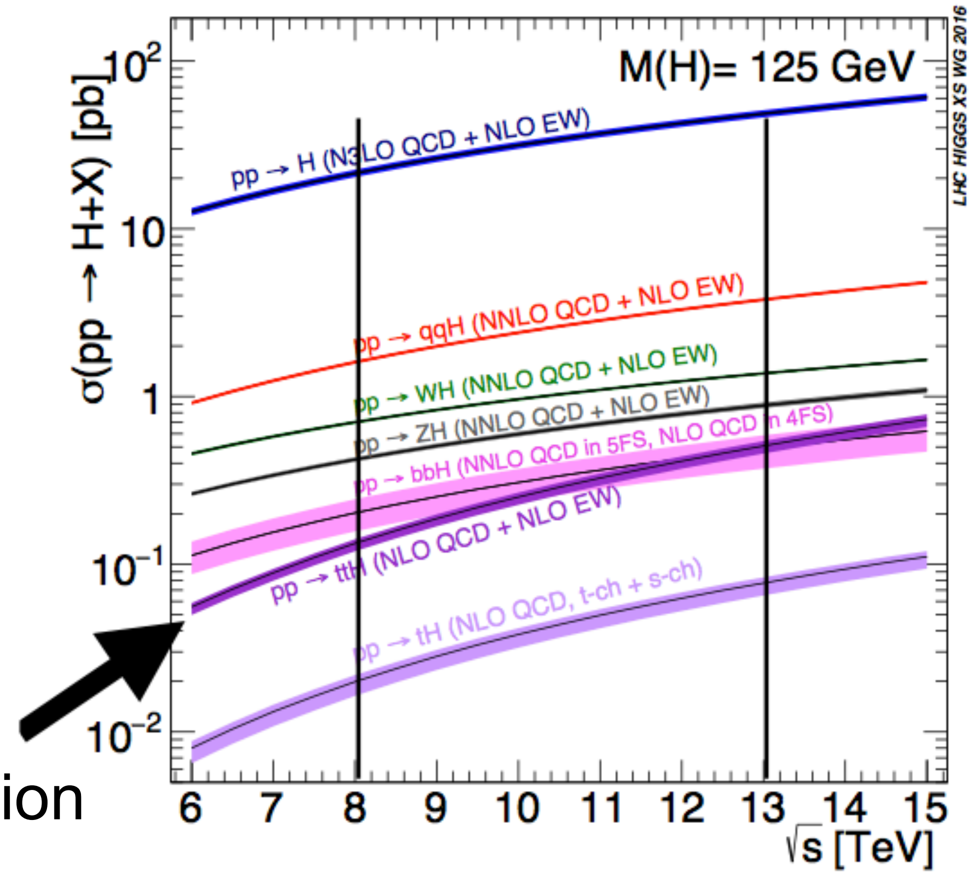
ttbar+Higgs

- ttbar produced in association with H
  - ttbar provides a "clean tag"
- direct measurement of Higgs couplings



Cross section for $t\bar{t}H$ at the LHC:
0.13 pb (8 TeV)
0.61 pb (14 TeV)

σ(ttH) ~1% of total Higgs cross section



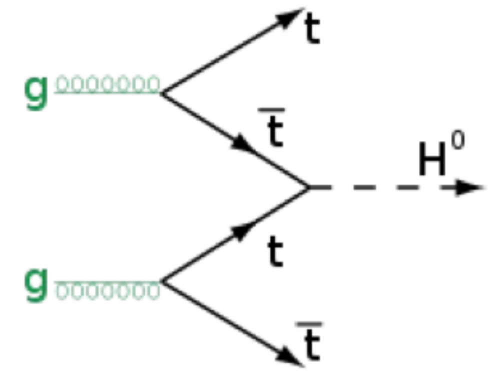
ttbar+heavy flavour

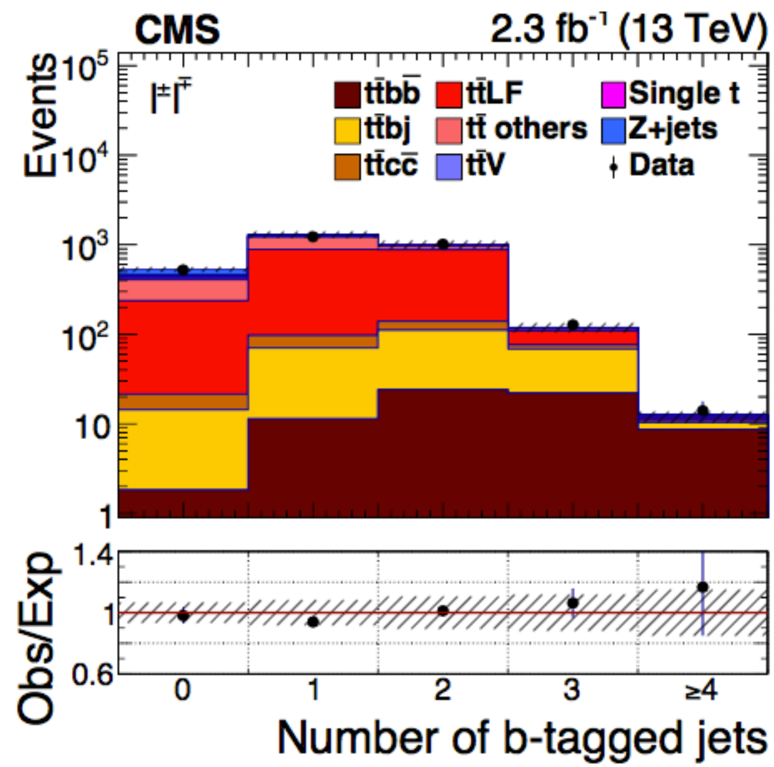
arXiv:1411.5621, PLB776(2018)355

- Study rate of ttbb: $\sigma(t\bar{t}b\bar{b})/\sigma(t\bar{t}jj)$
- Anomalous tt+jets could signal BSM final states
- First direct measurement of typical bkg to top-Higgs coupling
  - Irreducible non-resonant bkg from ttbb
- Improved theoretical understanding of ttH(bb) crucial to ttH and NP searches

$$\sigma_{t\bar{t}b\bar{b}}/\sigma_{t\bar{t}jj} = 0.022 \pm 0.003\,(\text{stat}) \pm 0.005\,(\text{syst})$$

- σ(ttbb)= $4.0 \pm 0.6\,(\text{stat}) \pm 1.3\,(\text{syst})$ pb

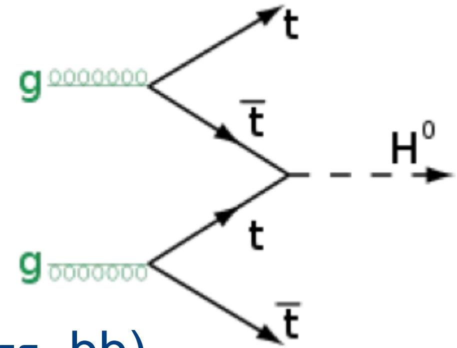


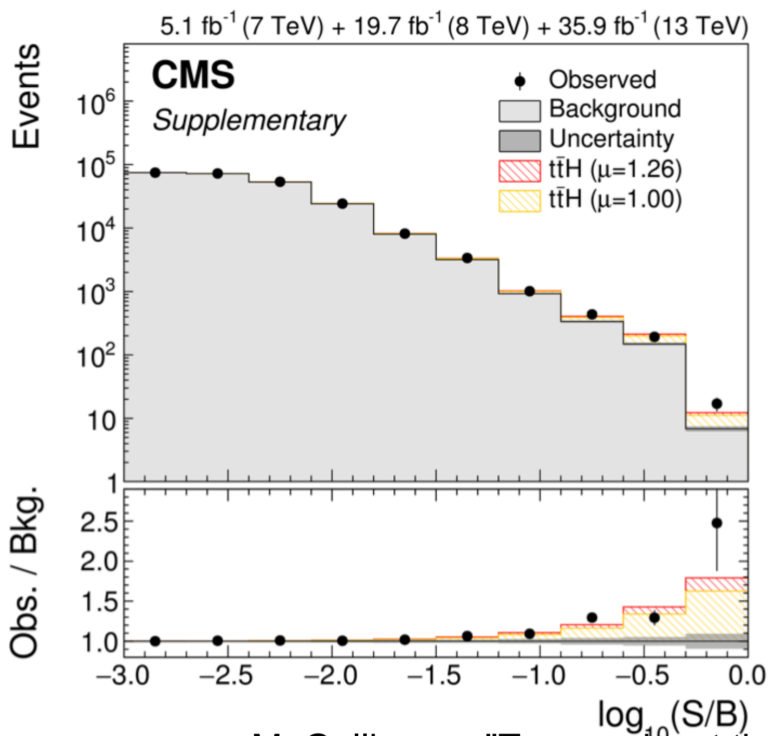


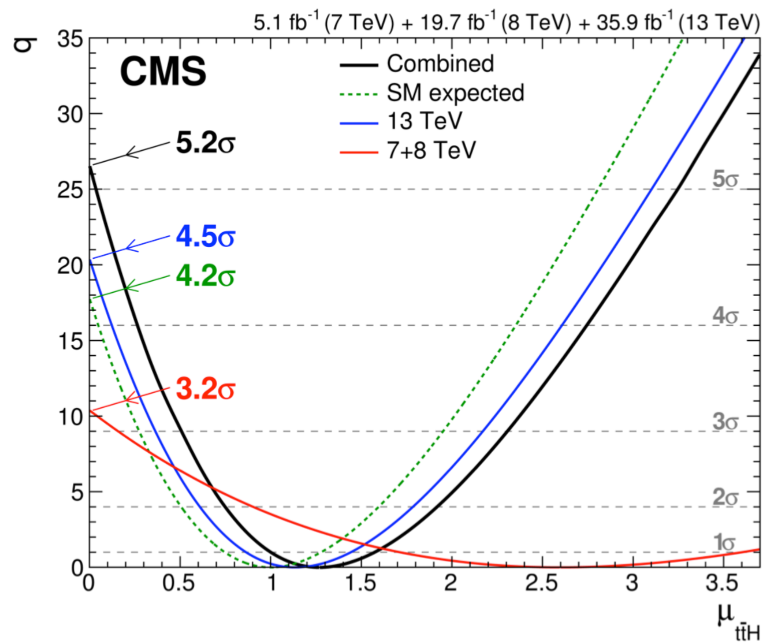
Higgs couplings to top quarks

PRL 120(2018)231801, arXiv:1806:00242

- Direct study of Top-Higgs Yukawa coupling
- Study tree-level coupling of Higgs bosons to top quarks
- Explore all accessible Higgs decay modes
- Combination of Run1 and 2016 datasets
- Independent analysis of different final states (WW, ZZ, $\gamma\gamma$, $\tau\tau$, bb)

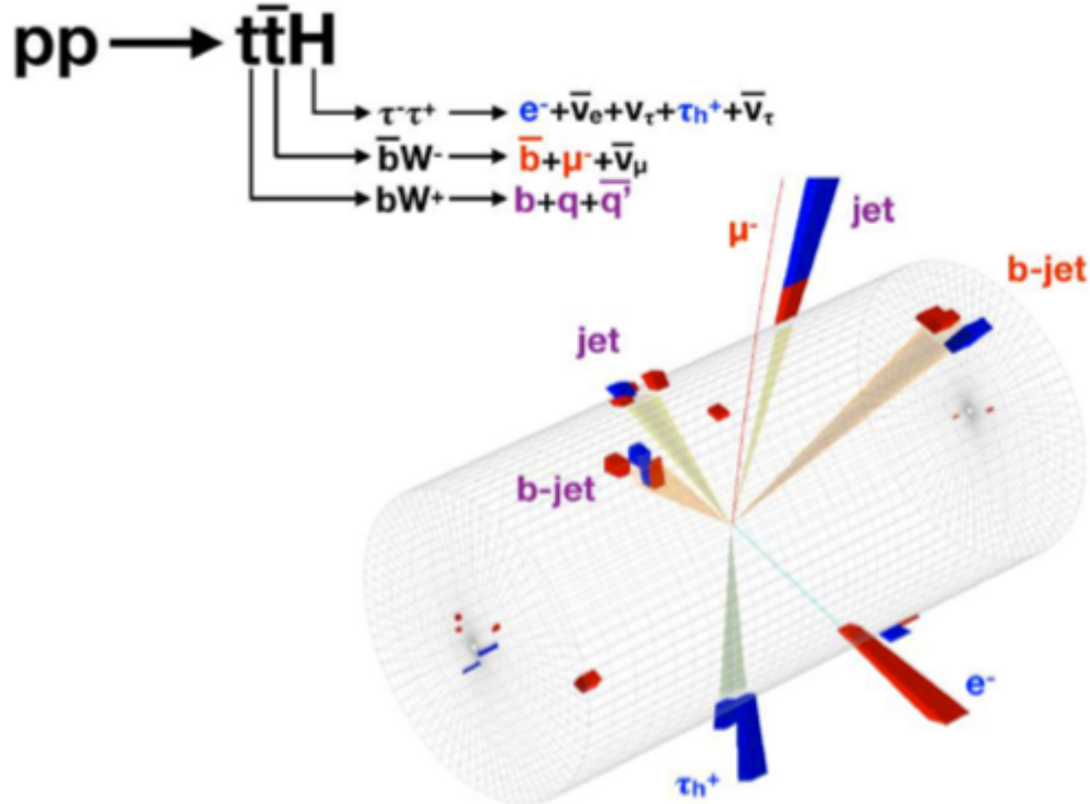






Event selection

- Improve sensitivity thanks to progress in data analysis strategies that use advanced algorithms
- Analysis workflow more efficient thanks to compressed data format

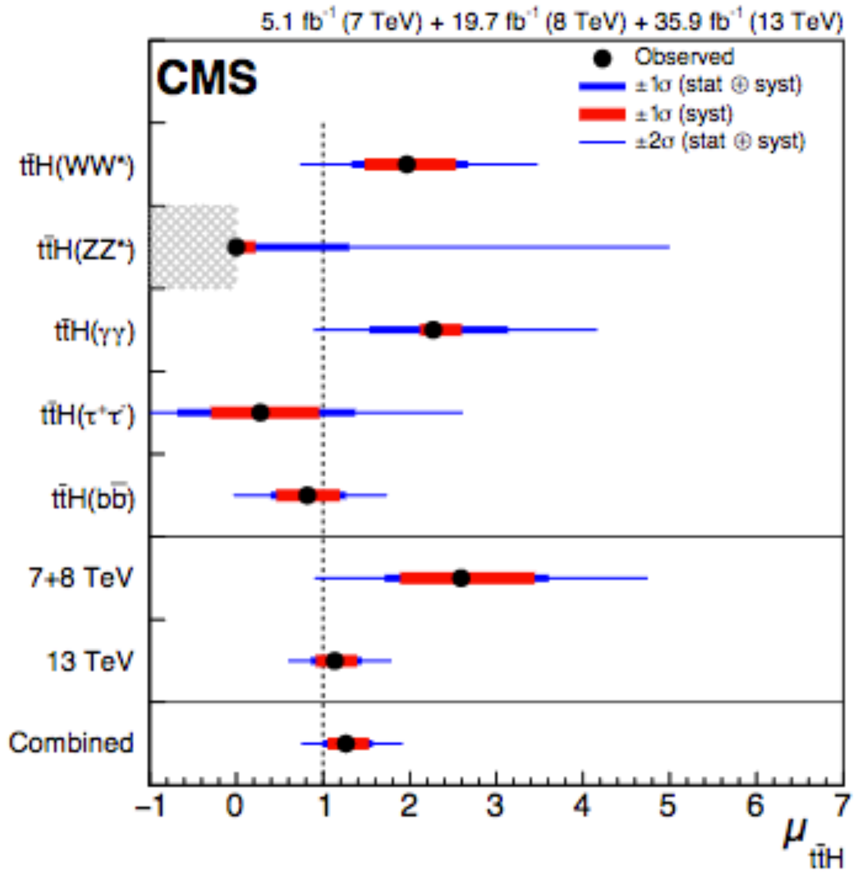


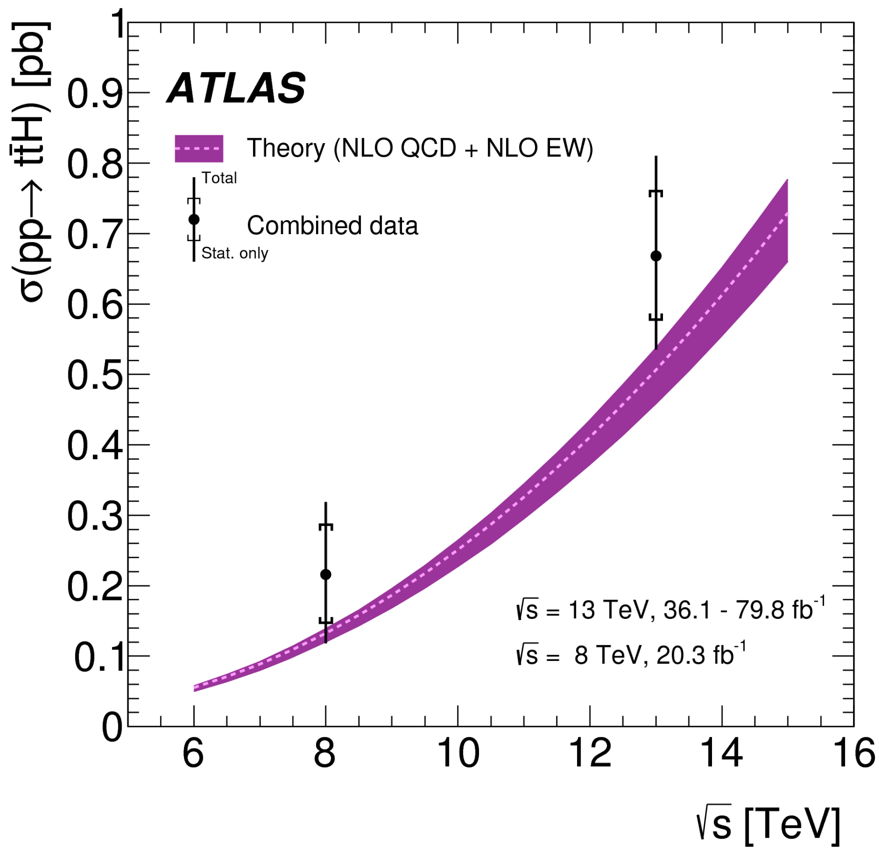
Observation of ttH

PRL 120(2018)231801, arXiv:1806:00242

- Use several event categories
- Establishes directly tree-level coupling to an up-type quark

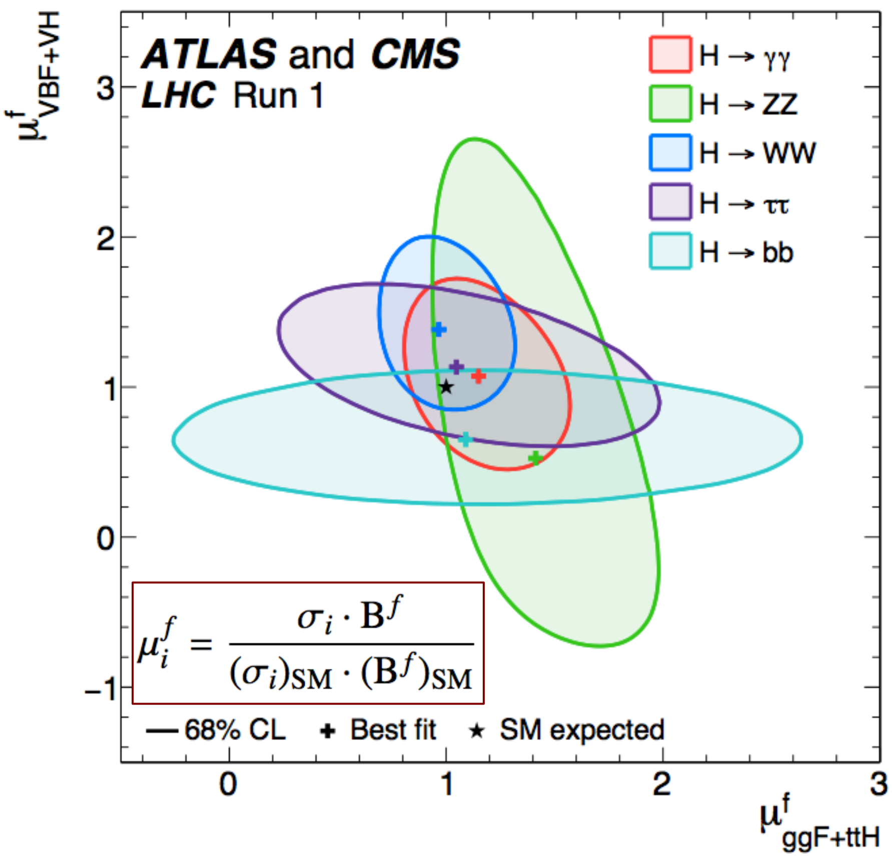
$$\mu_{t\bar{t}H} = 1.26\,^{+0.31}_{-0.26}$$

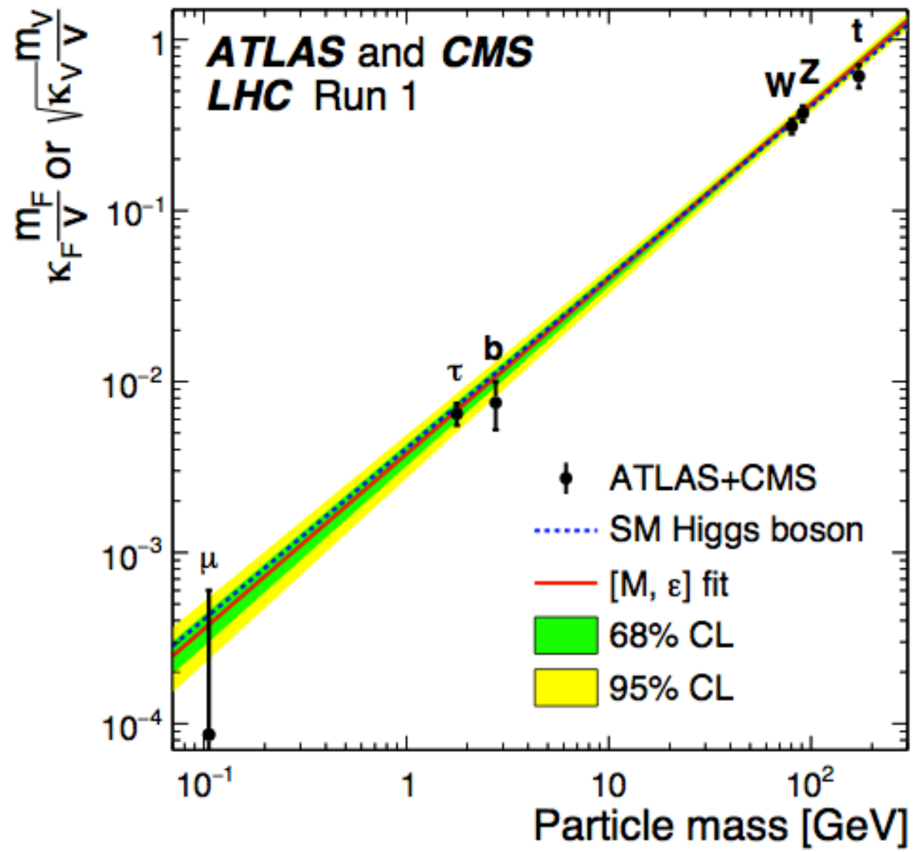




Consistency with SM

JHEP 08(2016)45, CMS-HIG-15-002, ATLAS-CONF-2015-044

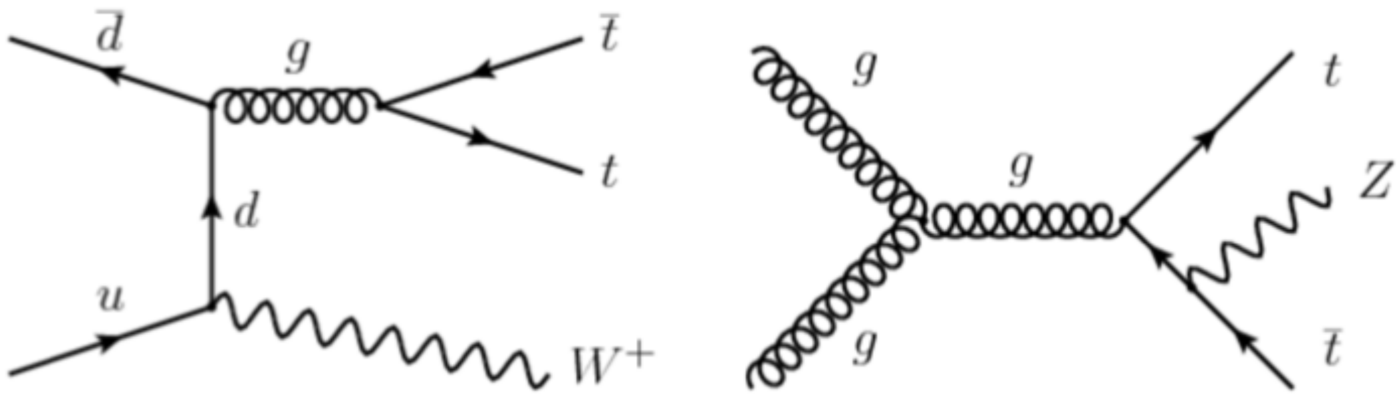




VBF+VH: boson in production
ggF+ttH: fermions in production

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

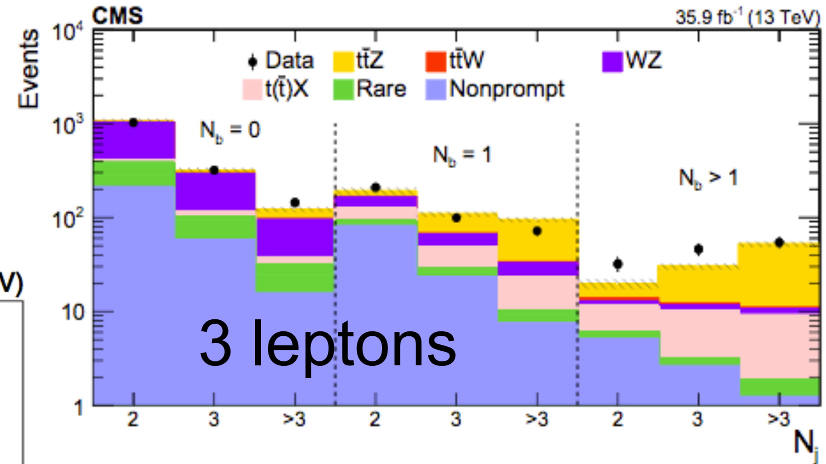


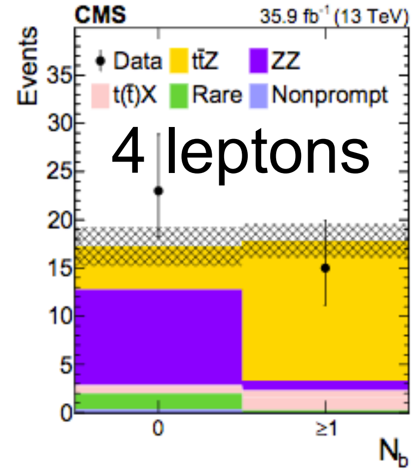
- Use multi-lepton final states
  - 2 same-sign charge leptons, 3 or 4 lepton final states

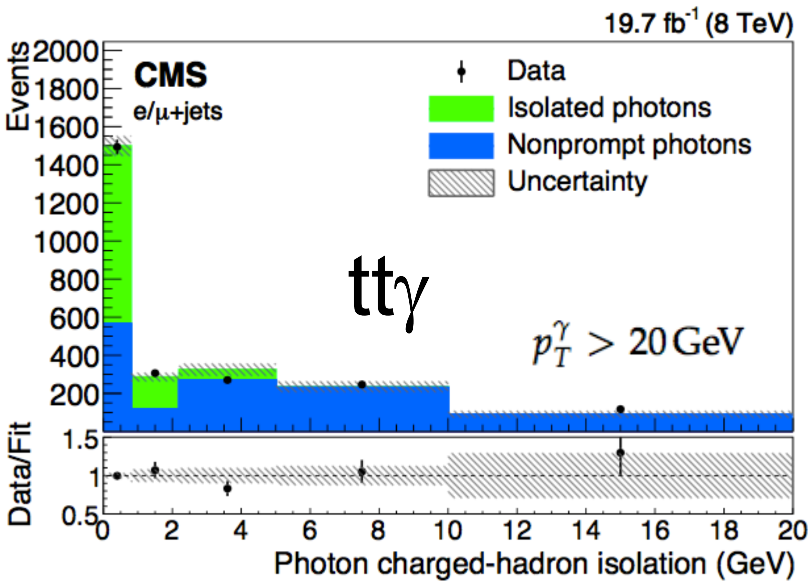
ttV production (V=γ,W,Z)

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

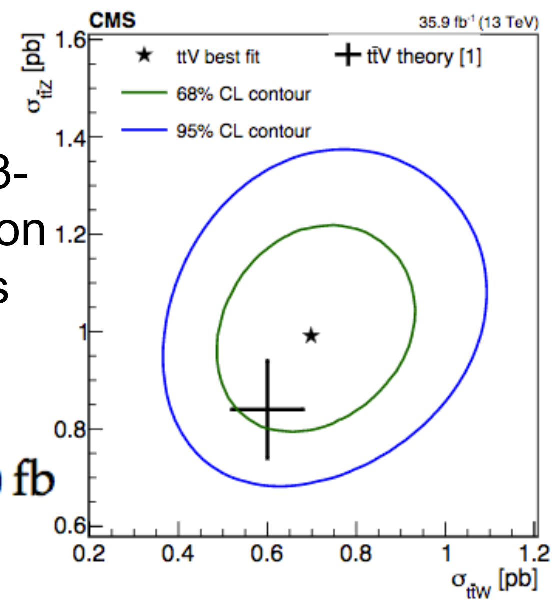
- Measurements gives access to EW couplings of the top

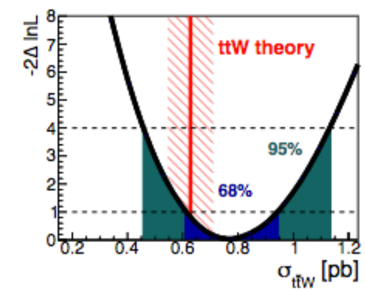


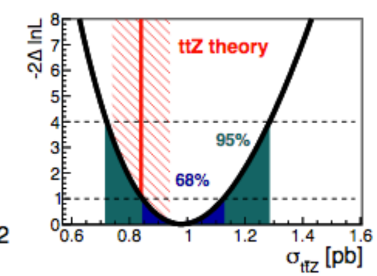




Combine 3- and 4-lepton final states







Measure σ(ττγ)=127± 27 fb

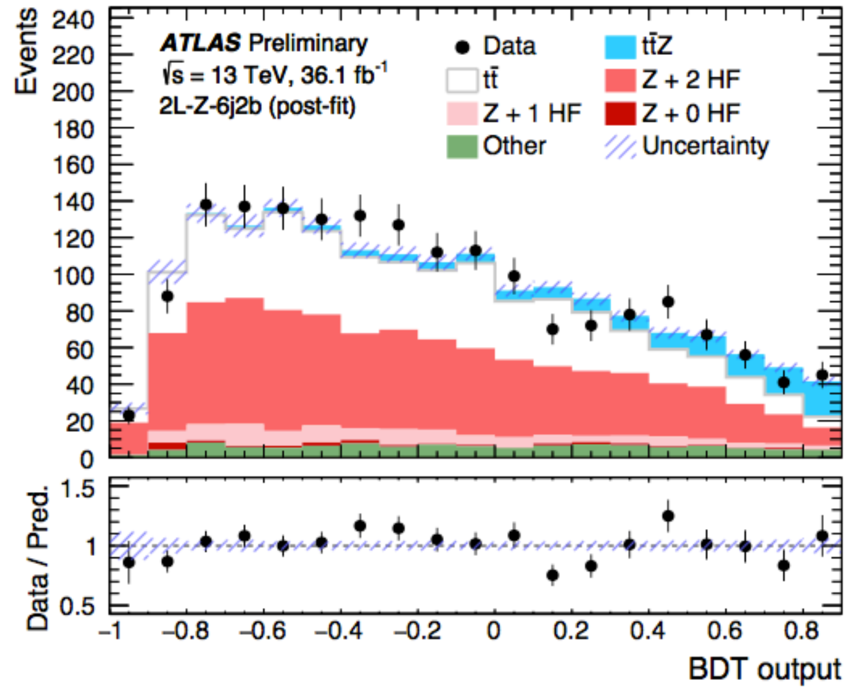
$$\sigma(\mathrm{pp} \to \mathrm{t}\gamma\mathrm{j})\mathcal{B}(\mathrm{t} \to \mu\nu\mathrm{b}) = 115 \pm 17\,(\mathrm{stat}) \pm 30\,(\mathrm{syst})\,\mathrm{fb}$$

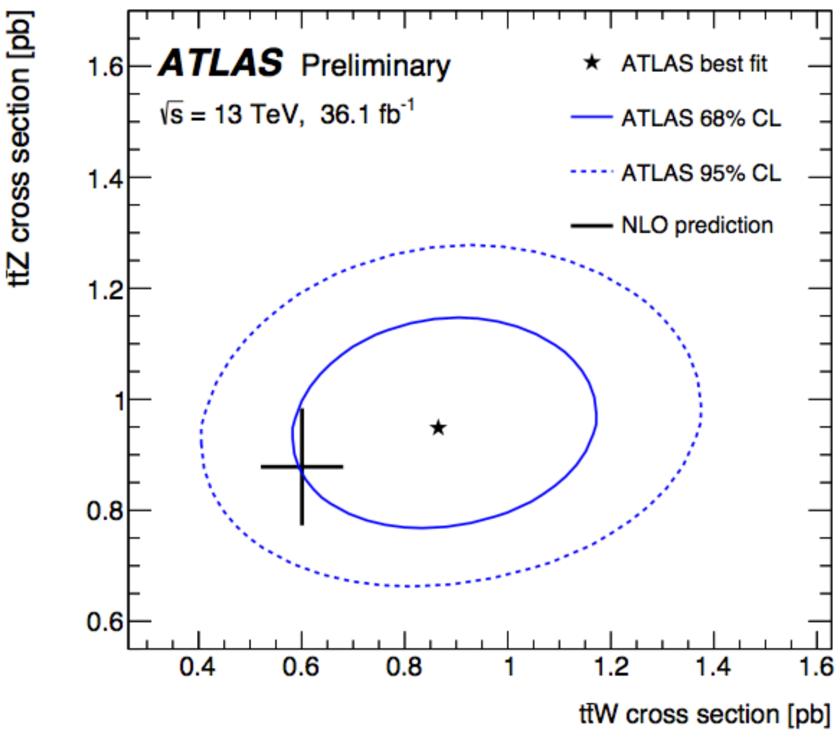
⇒ Consistent with SM predictions

ttV production (cont.)

ATLAS-2018-047

- σ(ttZ) and σ(ttW) simultaneously measured using multi-lepton events
- BDT used to suppress backgrounds
- Systematics suppressed with fit





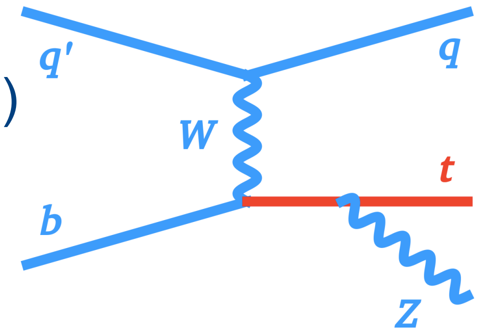
Coefficient	Expected limits at 68% and 95 % CL	Observed limits at 68% and 95 % CL
$(C_{\phi Q}^{(3)} - C_{\phi Q}^{(1)})/\Lambda^2$	[-2.1, 1.9], [-4.6, 3.7]	[-1.0, 2.7], [-3.4, 4.3]
$C_{\phi t}/\Lambda^2$	[-3.8, 2.8], [-23, 5.0]	[-2.0, 3.6], [-27, 5.7]
C_{tB}/Λ^2	[-8.3, 8.6], [-12, 13]	[-11, 10], [-15, 15]
C_{tW}/Λ^2	[-2.8, 2.8], [-4.0, 4.1]	[-2.2, 2.5], [-3.6, 3.8]

⇒ Results consistent with SM

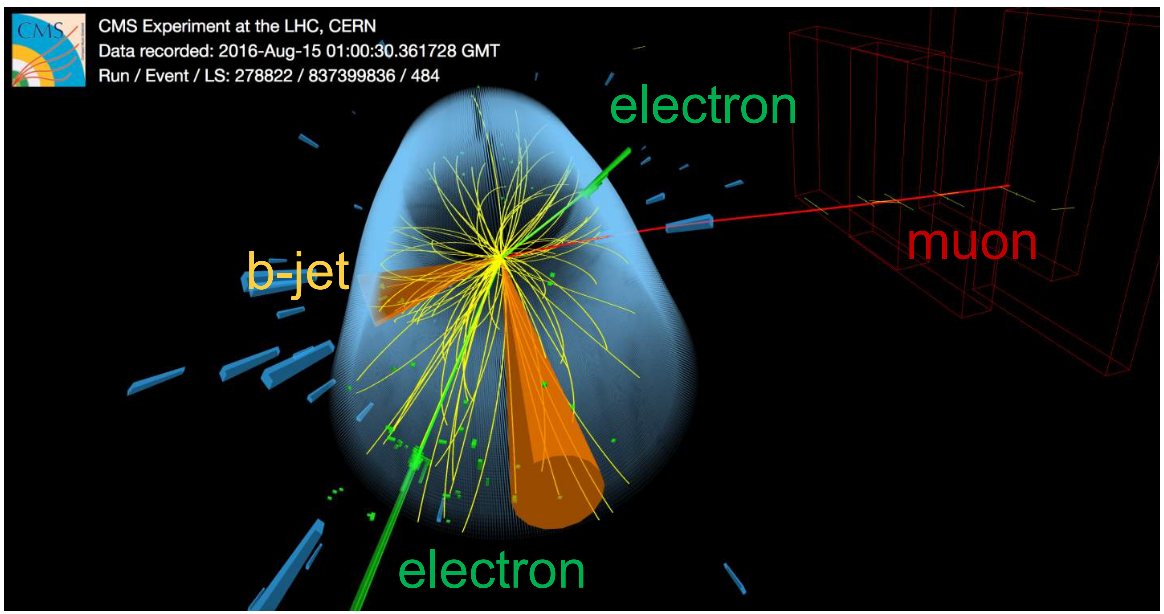
Top-Z coupling

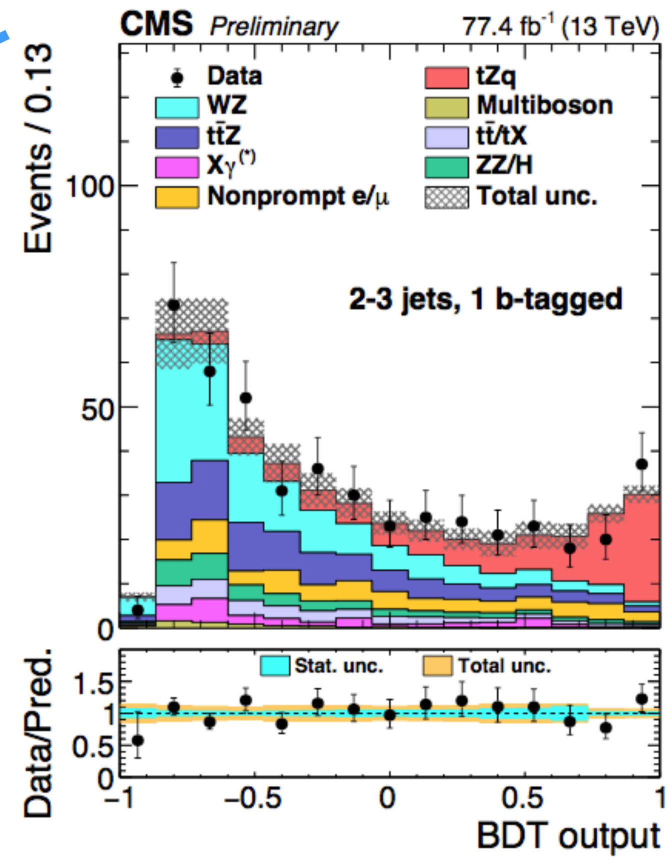
CMS-TOP-18-008

- Small production rate (~50 times smaller that that of the Higgs boson) and large backgrounds
- Formidable challenge



$$\sigma(pp \to tZq \to t\ell^+\ell^- q) = 111\ ^{+13}_{-13}\ \text{(stat)}\ ^{+11}_{-9}\ \text{(syst) fb}$$





Lepton Flavor Violation in Top decays

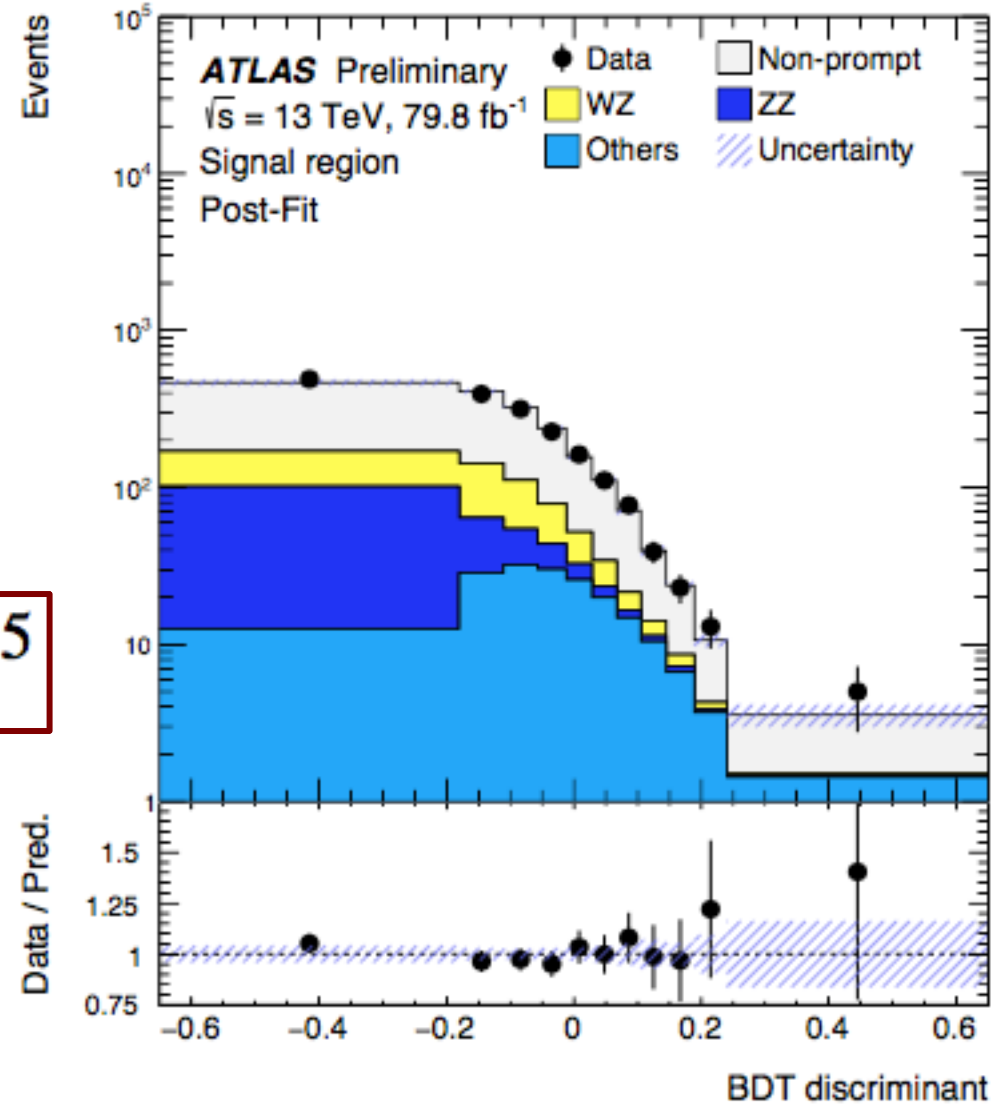
ATLAS CONF-2018-044

- Charged LFV would be evidence for BSM

$$t \to \ell^{\pm}\ell'^{\mp}q \text{ with } \ell = \{e, \mu, \tau\}$$

- Search for trilepton events
- Set limits @95%CL:

$$\mathcal{B}(t \to \ell\ell' q) < 1.86 \times 10^{-5}$$



Flavor Changing Neutral Currents

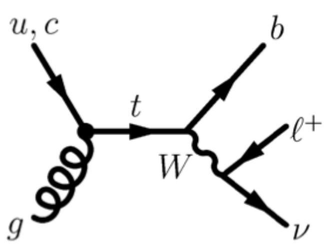
- Expect small signal from SM

…but signal may be large in BSM models

Final states:

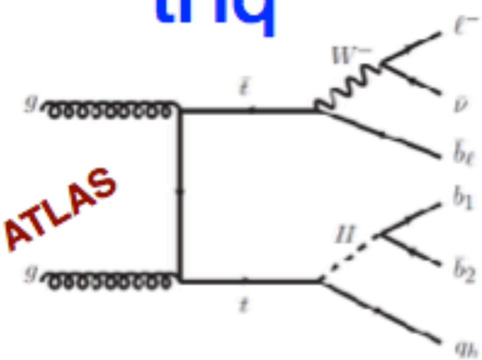
Wb

ATLAS



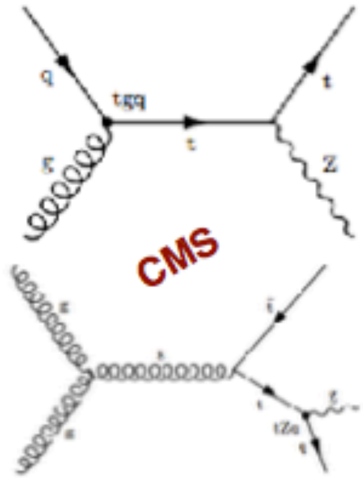
tHq

ATLAS



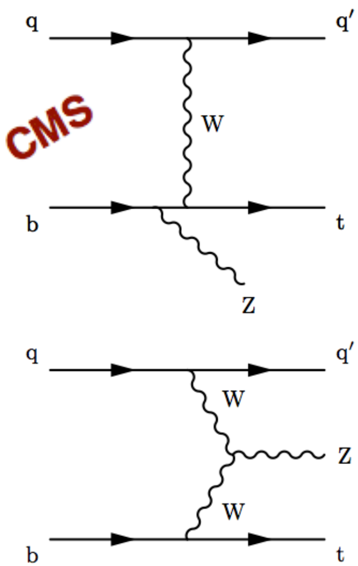
tZ

CMS



SM: tZq

CMS



Couplings:

t→ug
t→cg

t→uH
t→cH

t→ug, t→cg
t→uZ, t→cZ

t→tZ

$\sigma_{qg \to t} \times B(t \to Wb) < 3.4\,\text{pb}$

$\sigma_{qg \to t} \times B(t \to W\,b) < 2.9\,\text{pb}$

$B(t \to Hc) < 0.40\%$

$B(t \to Hu) < 0.55\%$

$B(t \to Zu) < 0.022\%$

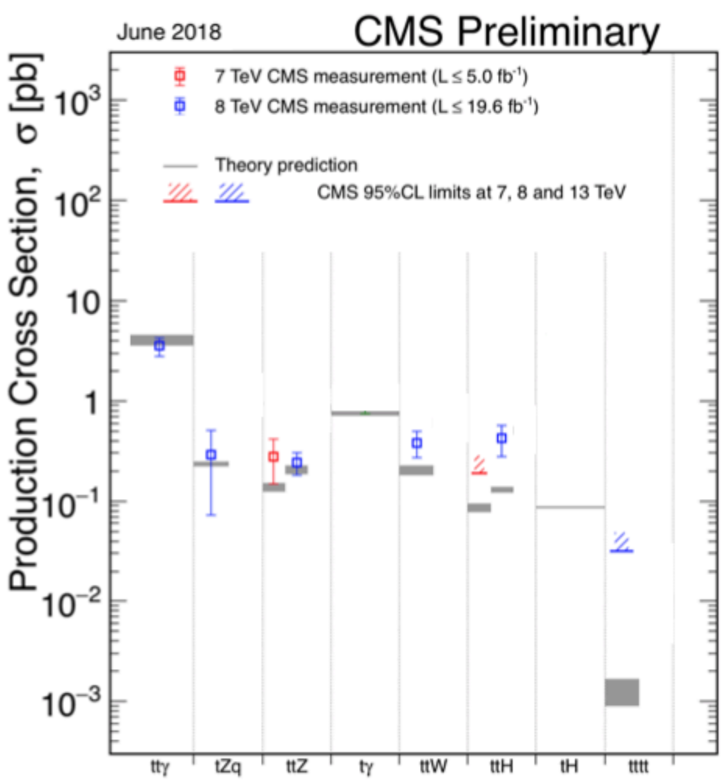
$B(t \to Zc) < 0.049\%$

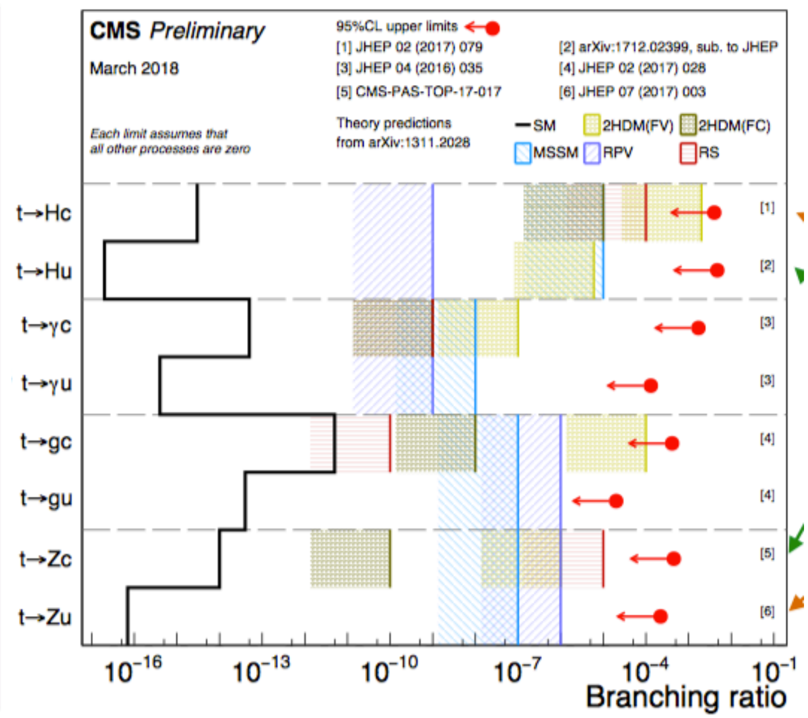
SM $\sigma(tZq) = 10^{+8}_{-7}$ fb

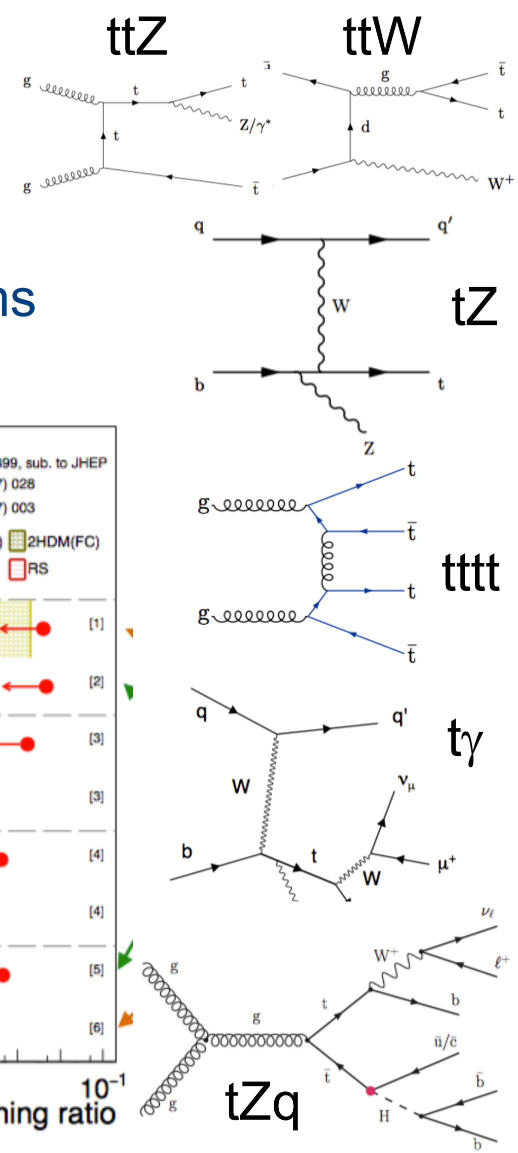
Top quarks and rare decays

arXiv:1711.02547, PLB779(2018)358, EPJC78(2018)140, CMS-TOP-17-016

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

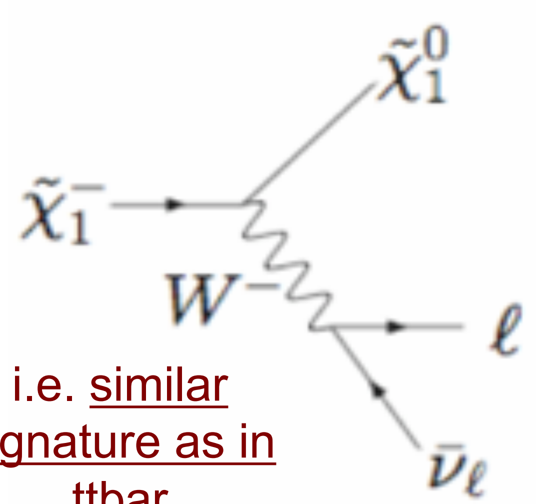






Scalar top quark

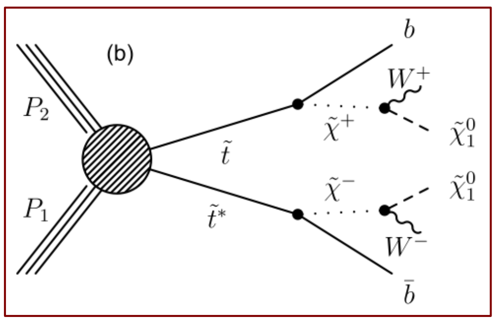
- SUSY is one plausible extension of the SM
- due to the heavy top quark, mass splitting between $\tilde{t}_1$ and $\tilde{t}_2$ can be large, such that the lighter stop $\tilde{t}_1$ can be even lighter than the top quark
- Decays dictated by mass spectrum of other SUSY particles



i.e. similar signature as in ttbar

- Light stop:

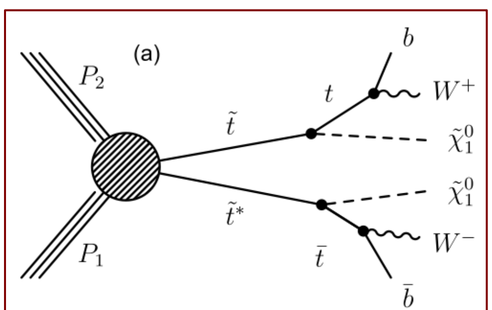
$$m_{\tilde{t}_1} \lesssim m_t$$



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

- Heavy stop:

$$\tilde{t} \rightarrow t\tilde{\chi}^0$$



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

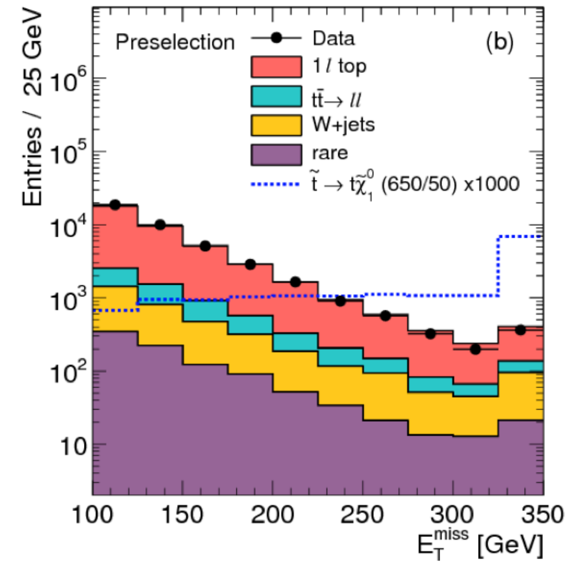
Top and SUSY

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

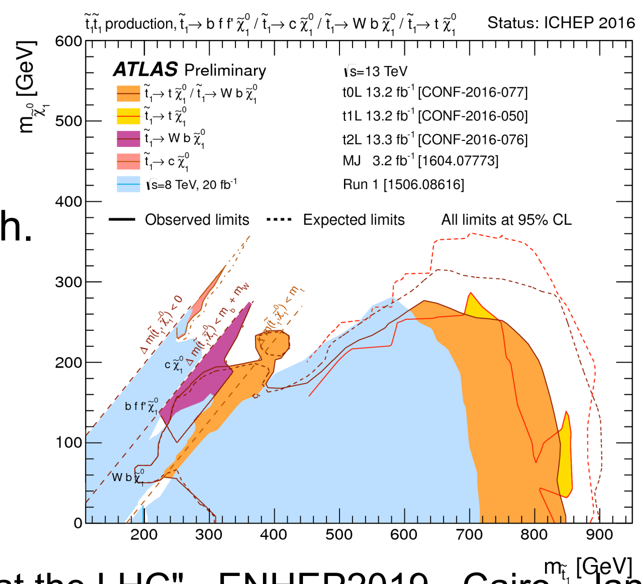
- If SUSY exists and is responsible for solution of hierarchy problem, naturalness arguments suggest that SUSY partners of top quark (*stop*) may have mass close to m_{top} to cancel top quark loop contributions to Higgs mass

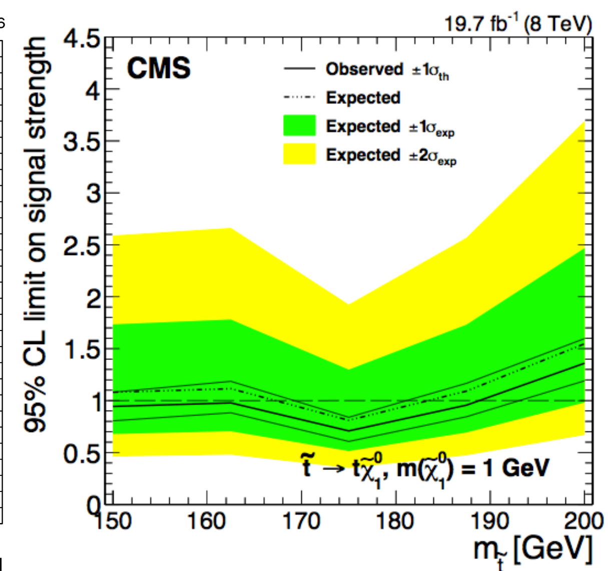
$$\tilde{t} \rightarrow t\tilde{\chi}_1^0 \rightarrow bW\tilde{\chi}_1^0$$ "heavy"

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



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





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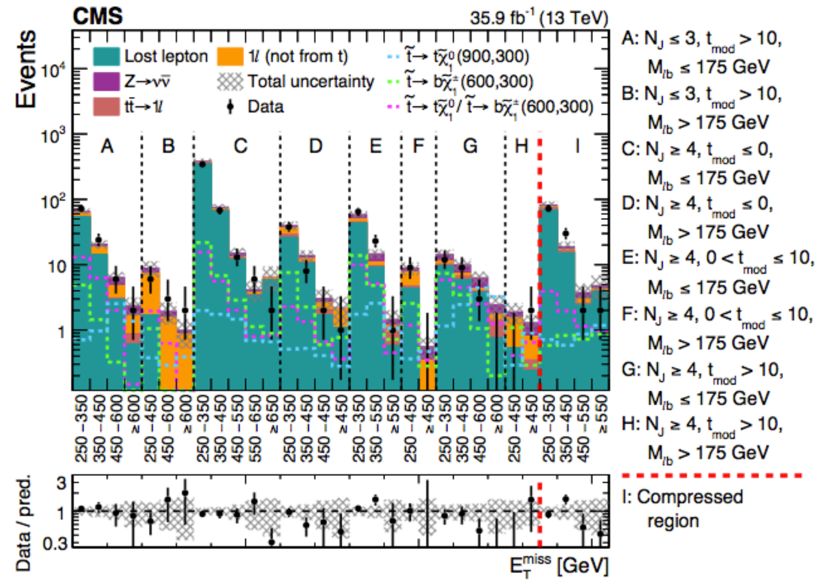
$$\tilde{t} \rightarrow t\tilde{\chi}_1^0 \rightarrow bW\tilde{\chi}_1^0 \quad \text{"heavy"}$$
$$\tilde{t} \rightarrow b\tilde{\chi}_1^+ \rightarrow bW\tilde{\chi}_1^0 \quad \text{"light"}$$



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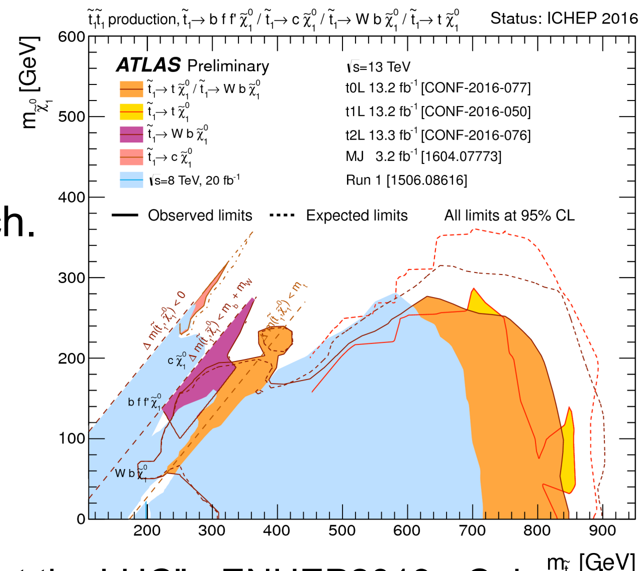
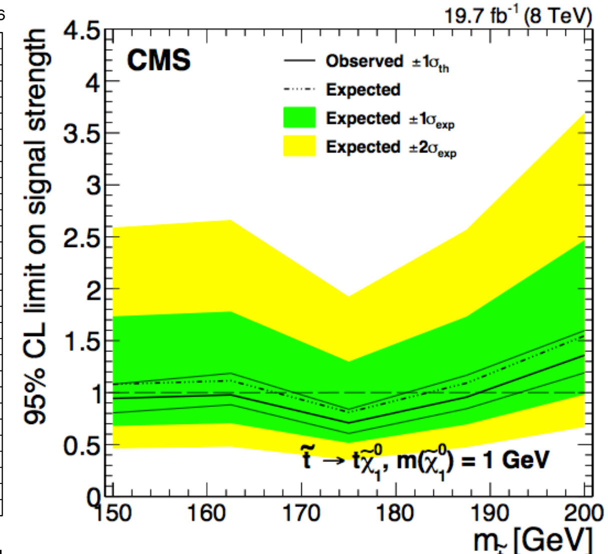
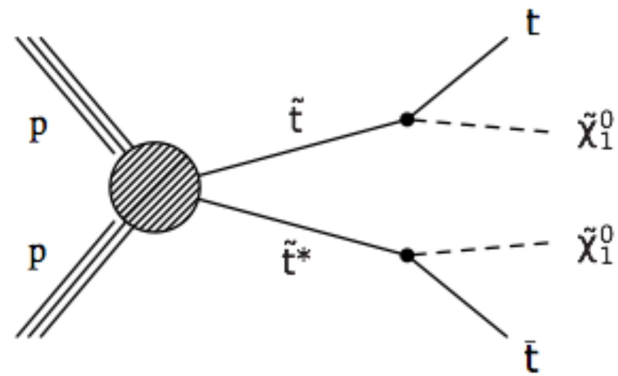


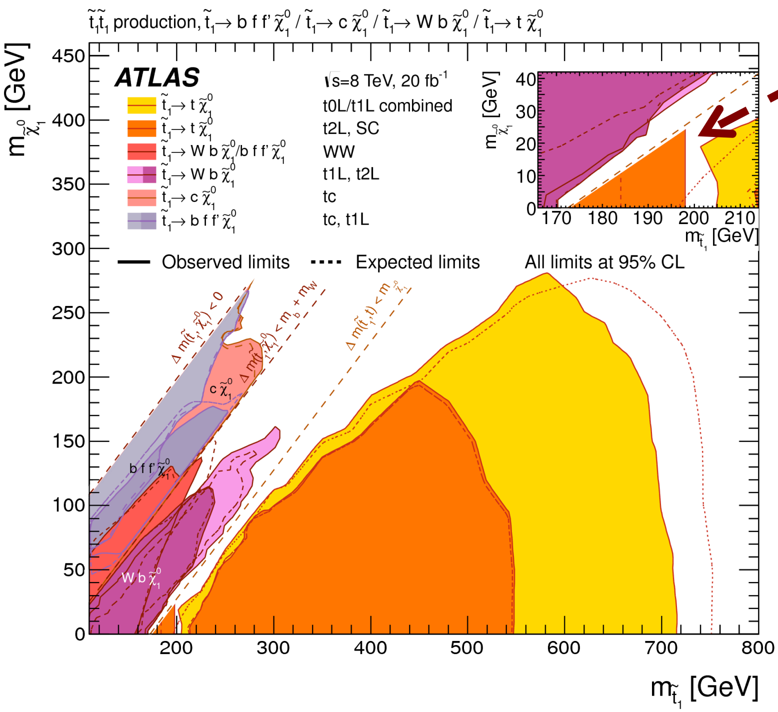


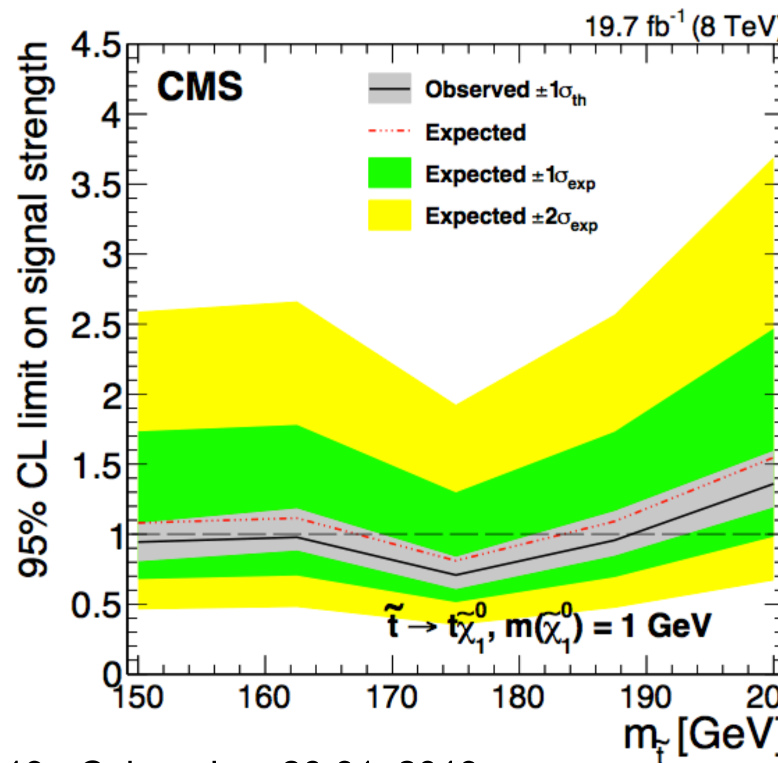
Top cross section: dileptons

CMS SUS-18-003, arXiv:1603.02303

- Indirect searches
- SUSY models could produce final states very similar (with additional MET)
- For example, dilepton channel



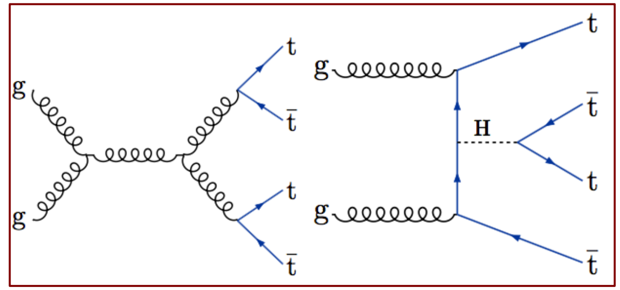




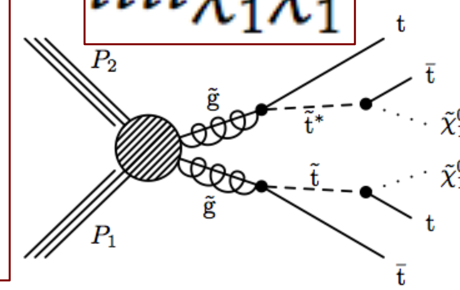
Multi-top production

arXiv:1710.10614

- Production of 4 tops is an attractive scenario in a number of new physics models
- The SM cross section is 9fb@13TeV

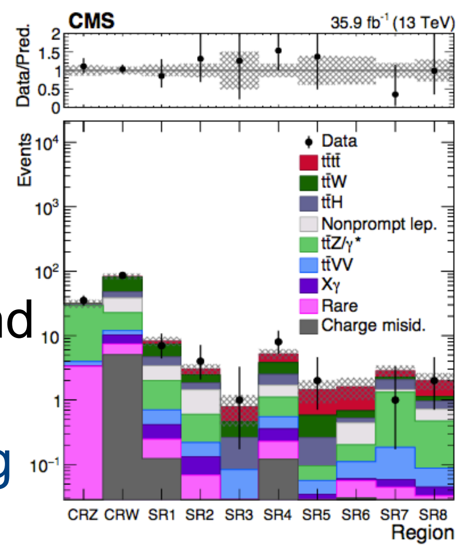


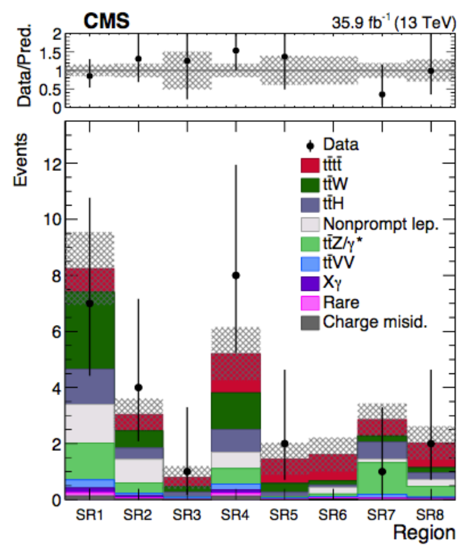
$$t\bar{t}t\bar{t}\tilde{\chi}_1^0\tilde{\chi}_1^0$$



- At least 3 leptons, SS leptons
- Combination of kinematical variables and multivariate techniques
- Measure cross section: $\sigma = 16.9^{+13.8}_{-11.4}$ fb

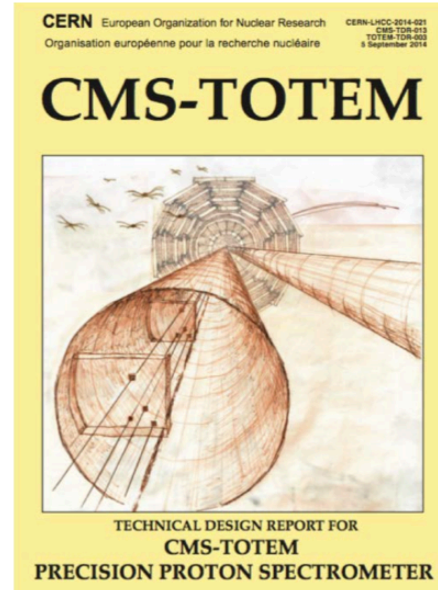
- Search for same-sign dileptons
- Several models considered
- Consider multiple search regions defined by MET, hadronic energy, number of (b-) jets, and p_T of the leptons in the events
- results used to constrain the Yukawa coupling between Top and Higgs less than 2.1*SM



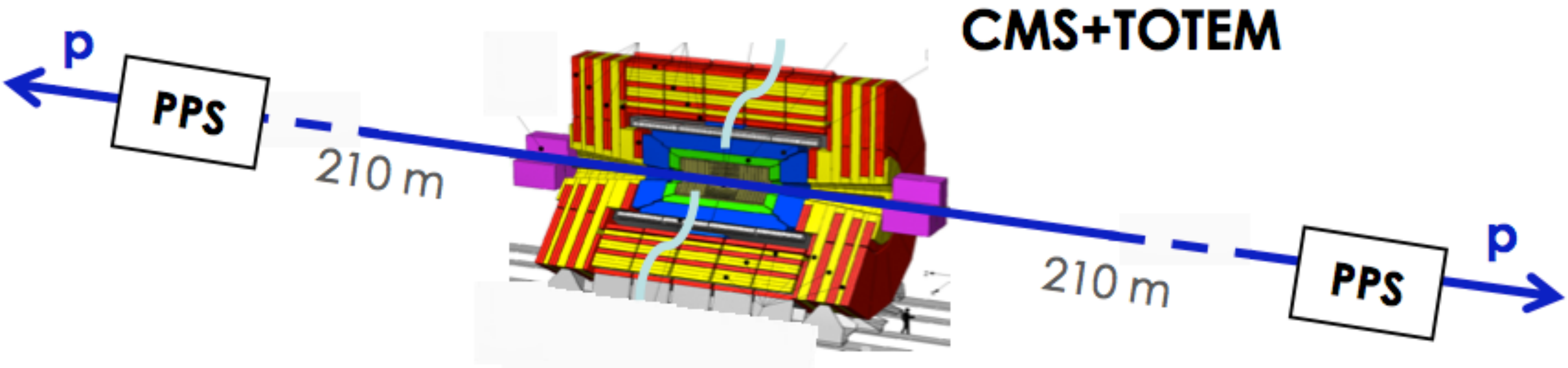


Precision Proton Spectrometer

- Joint CMS and TOTEM project that aims at measuring the surviving scattered protons on both sides of CMS in standard running conditions
- Tracking and timing detectors inside the beam pipe at ~210m from IP5
- Approved (2014), exploratory phase in 2015, data taking started in 2016, pixels installed from 2017, full detectors in 2018

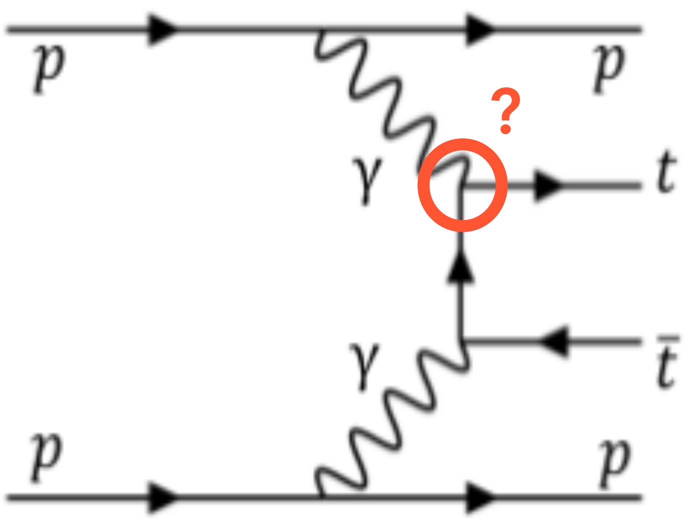


CERN-LHC-2014-021



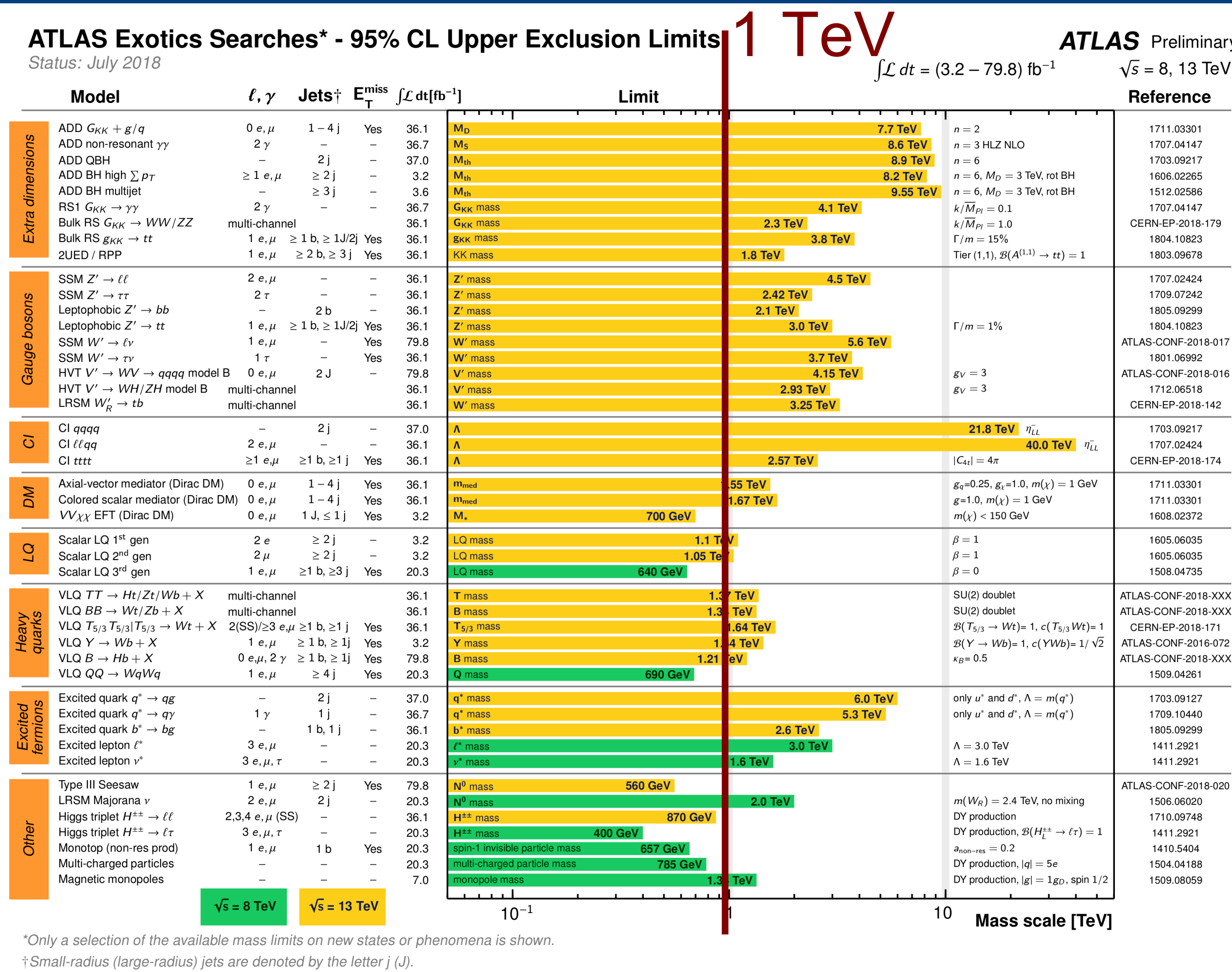
Exclusive top quark production

- Reconstruction of $t\bar{t}$ events is incomplete due to neutrinos (dileptons) etc.
- Exclusive production allows full reconstruction of $t\bar{t}$ kinematics from the leading protons with excellent momentum resolution

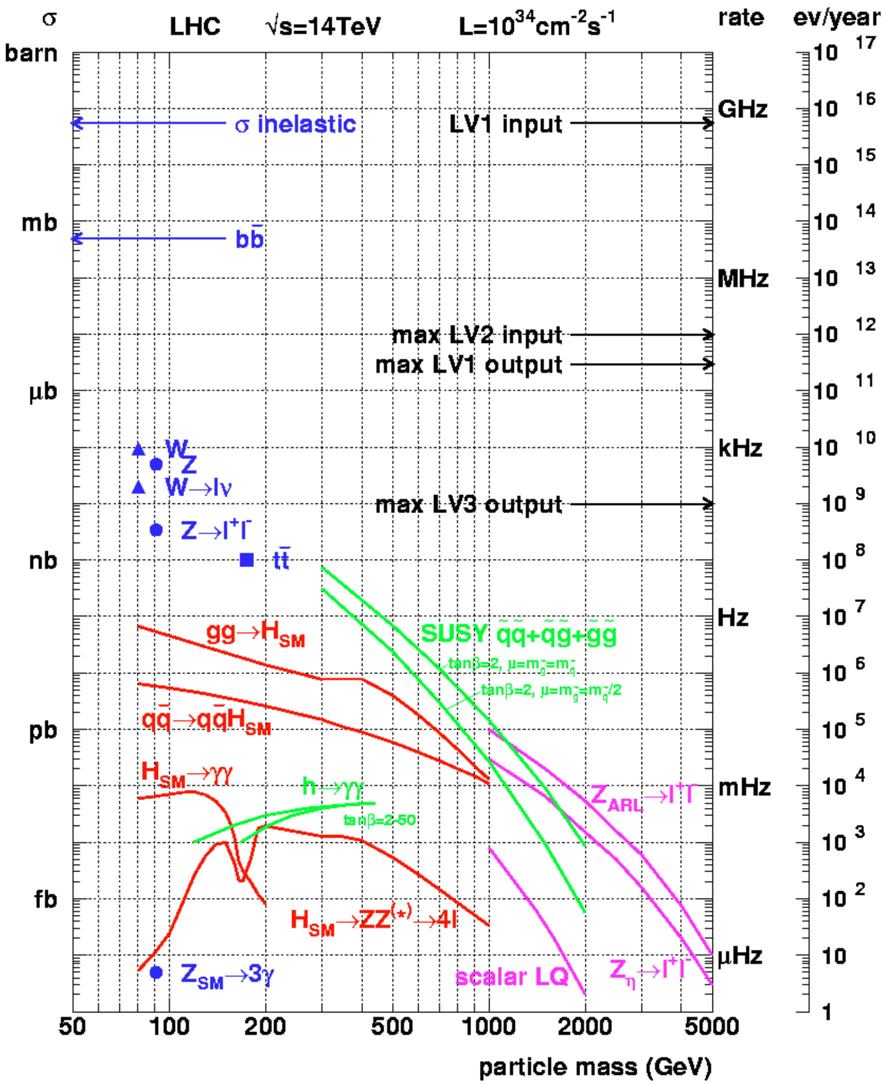


- Couplings of top quark to photons are small
- Process expected to be very sensitive to top quark anomalous couplings with the photon
- Anomalous production cross section or kinematical properties would provide hints for New Physics

Searches for new particles



Cross sections at the LHC



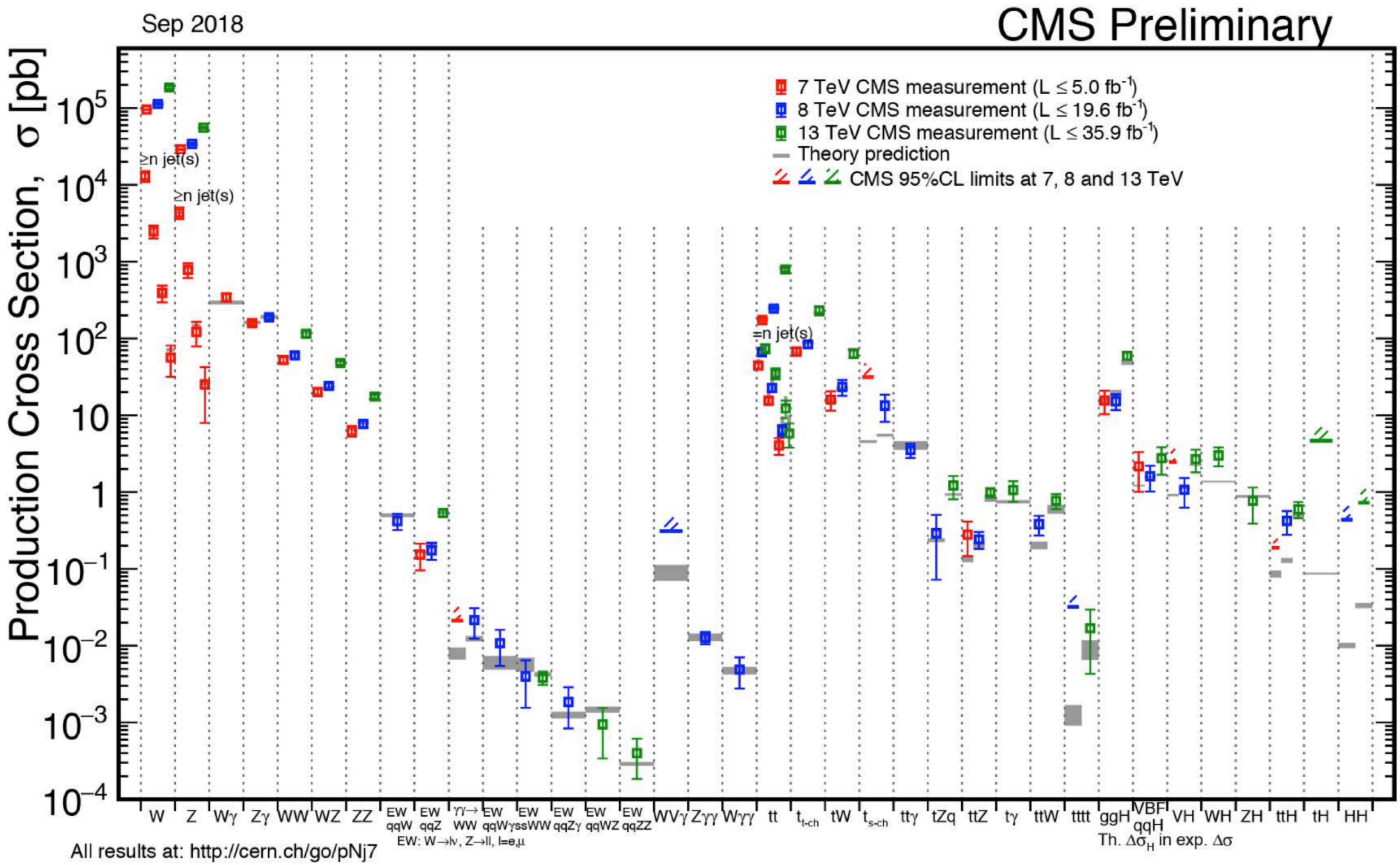
"Well known" processes, don't need to keep all of them ...

New Physics!!
This is where to look

LHC: from searches to precision

- A hadron collider at full throttle
  - Reaching the energy limit
  - In Run3, collisions at 14 TeV
  - Large datasets
- Moving from searches to precision measurements and rare processes
  - Top quarks and rare decays
  - Higgs couplings and rare decays
  - Anomalous couplings etc.
- Preparing for High-Luminosity (2026 and beyond) with improved detectors
  - Several technological challenges ahead as complexity increases

Rich and extensive set of results



Summary

- Top quarks are valuable probes of SM
- Abundant samples of top quarks at the LHC
- Extensive studies of properties
- Rare decay processes and anomalous couplings
- Excellent consistency but SM is incomplete

- Dominant background for New Physics searches
- Due to large mass, top quarks may couple to heavy objects
- Deviations from SM may indicate New Physics

Thank you!