# Probing the SM: Top quarks and Higgs

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*LIP Lisbon*

BUE, December 7, 2016

- ✓ Introduction
- ✓ Top quarks as window to New Physics
- ✓ Top-Higgs associated production
- ✓ Top quark signatures in SUSY

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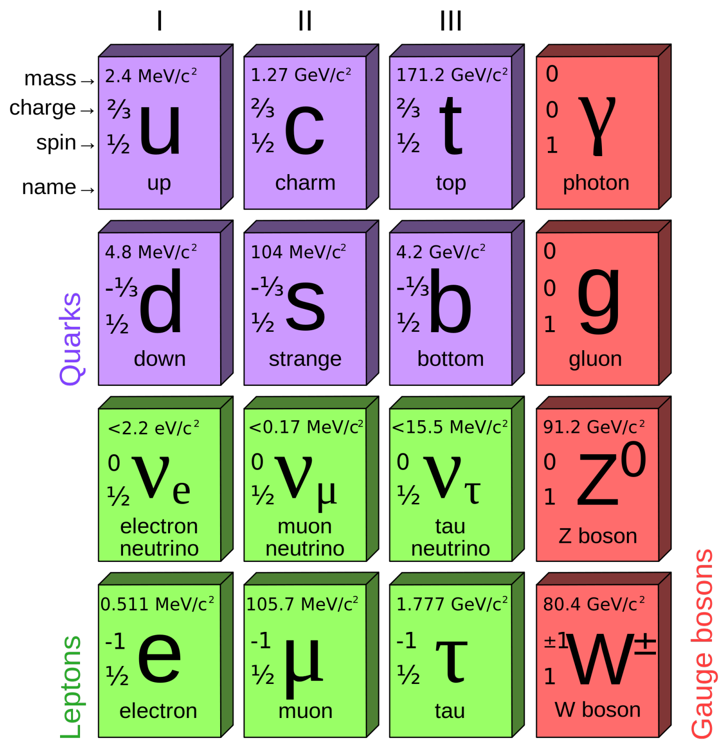
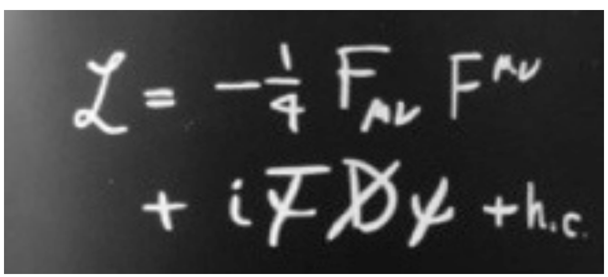
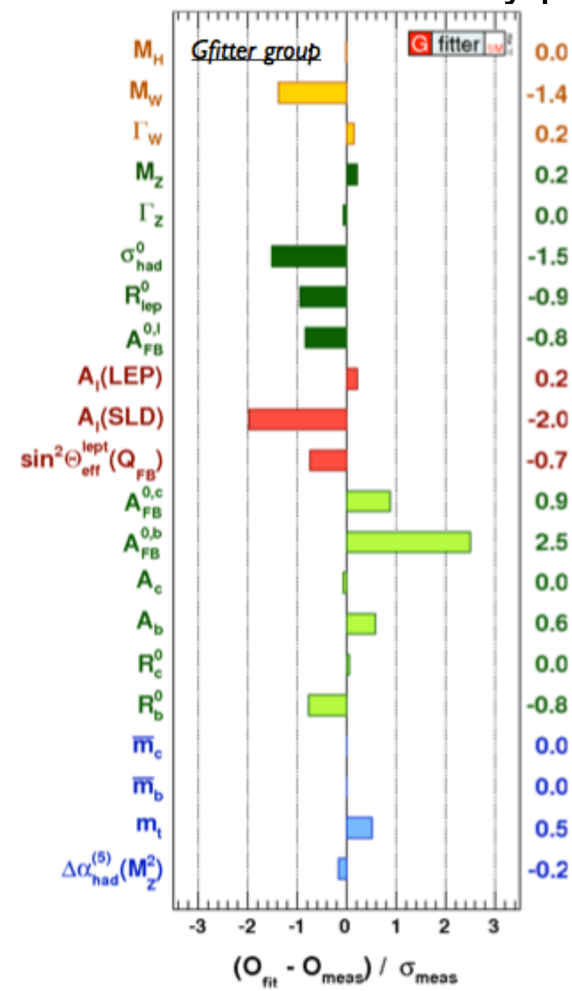
# SM confirmed by the data

Standard model of elementary particles




Excellent agreement with all experimental results

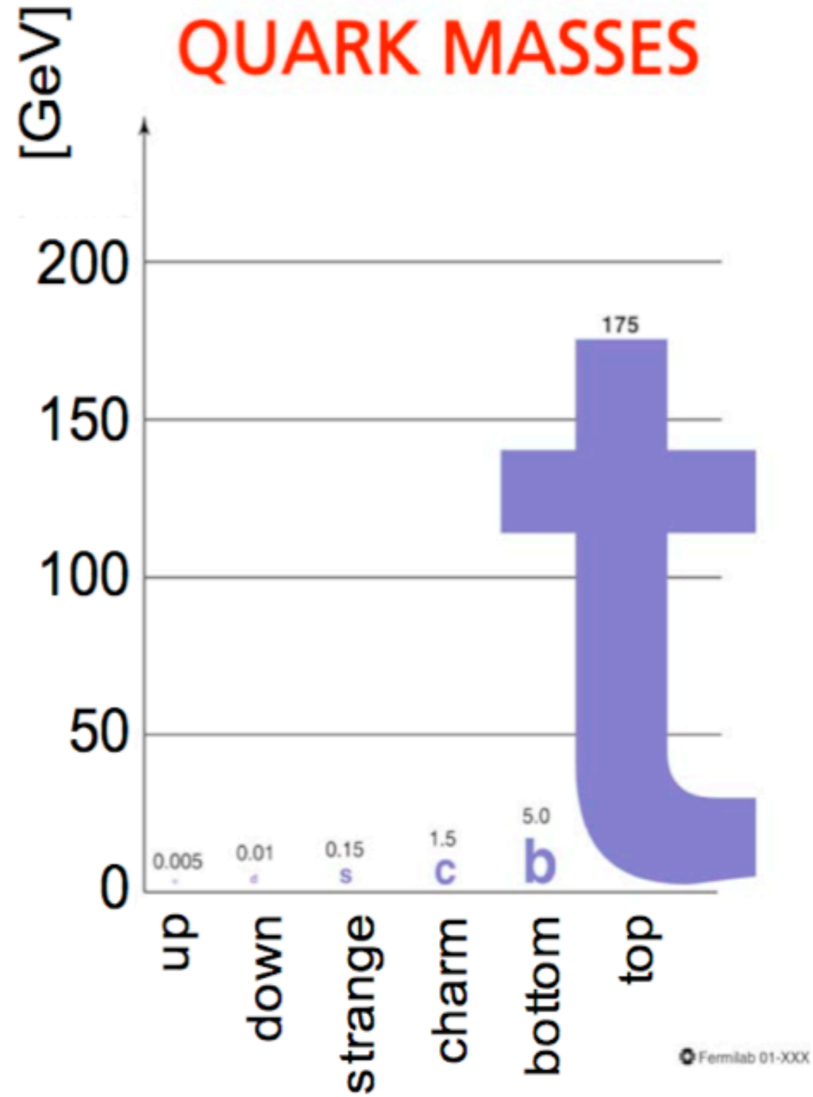
# The top quark

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

$\tau$=0.4x$10^{-24}$ sec

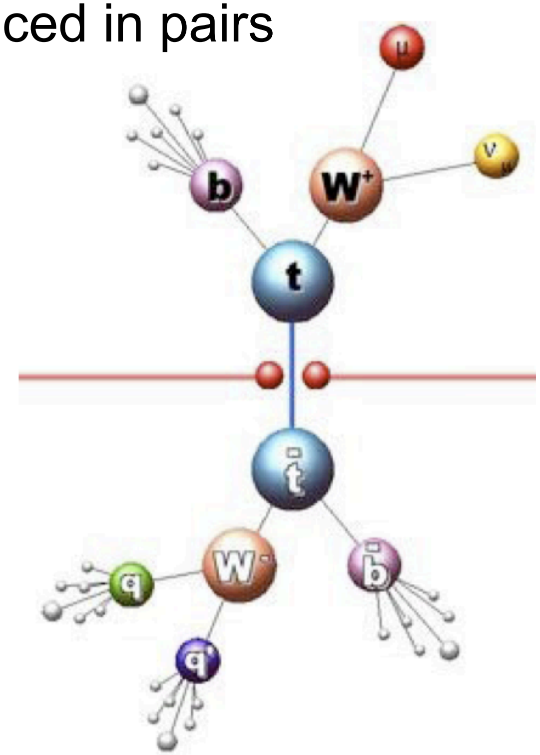
  - for $m_{top}$=175 GeV⇒$\Gamma$=1.4 GeV ⇒no hadronization
  - large contributions to EWK corrections ~$G_F m_{top}^2$
  - very short lifetime ⇒ bound states are not formed ⇒ opportunity to study a free quark

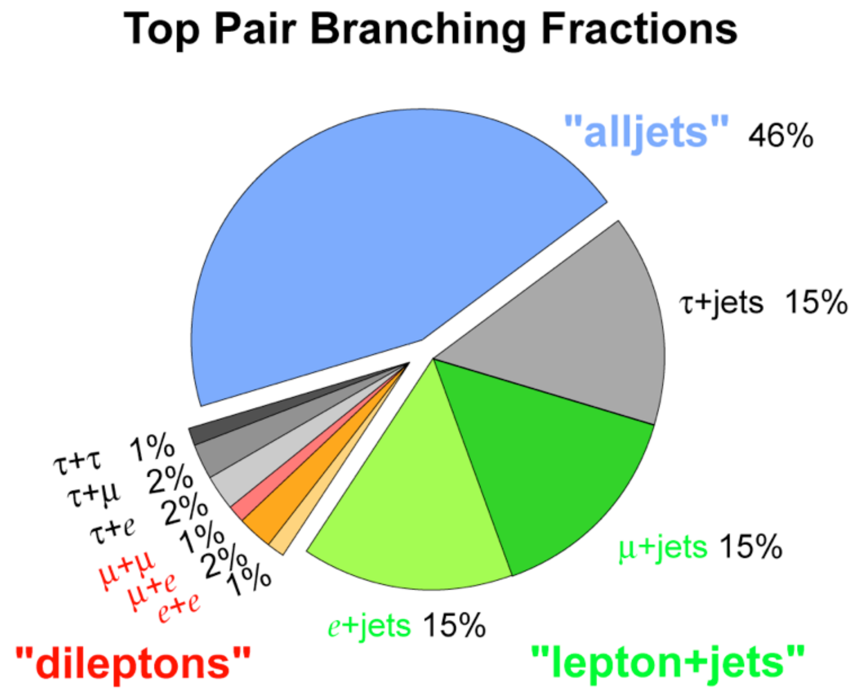
- Large samples of top quarks available
- Top quarks are main background for many New Physics searches
- Precision measurements may provide insight into physics beyond SM



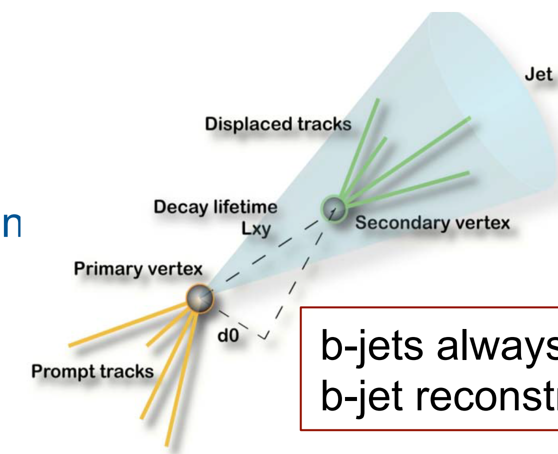
# Top quark decays

Top quarks (mostly) produced in pairs




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



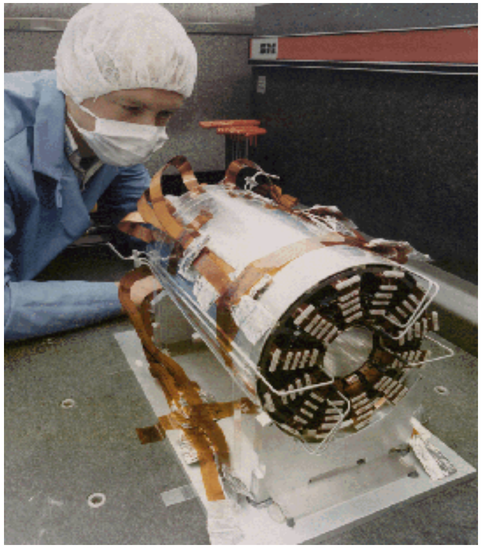

b-jets always present
b-jet reconstruction plays important role

# Discovery of top quark (1994)

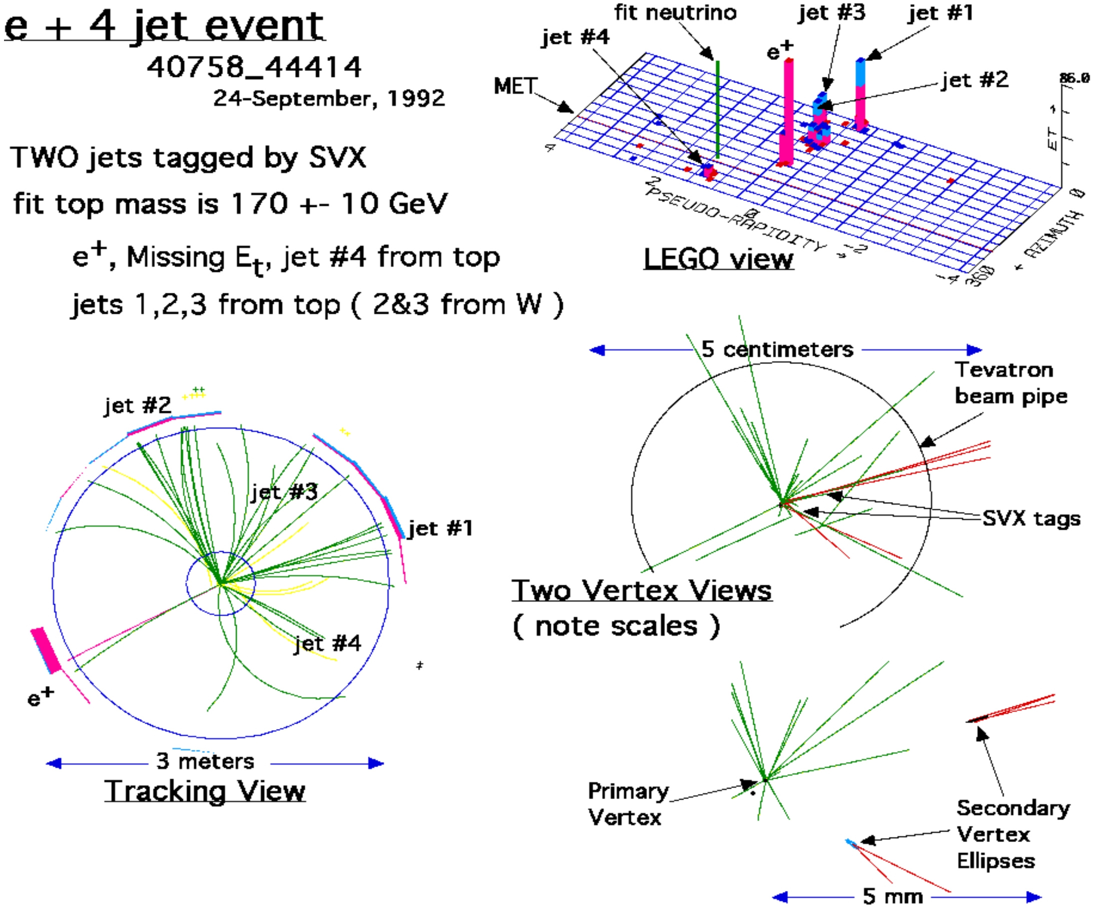
- Strategy
  - dilepton: +2 jets
  - single lepton: b-tagging

    1) soft e/$\mu$: semi-leptonic b-decay

    2) secondary vertex



New: CDF vertex detector (SVX)
(40 $\mu$m impact parameter resolution)
powerful discriminant against background

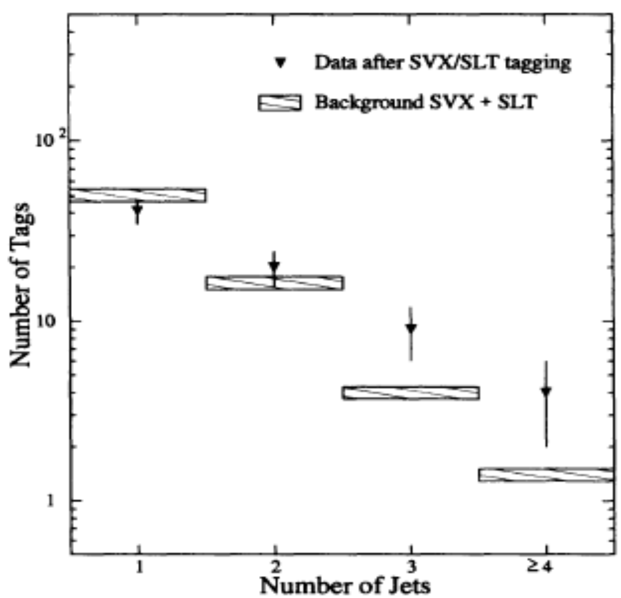


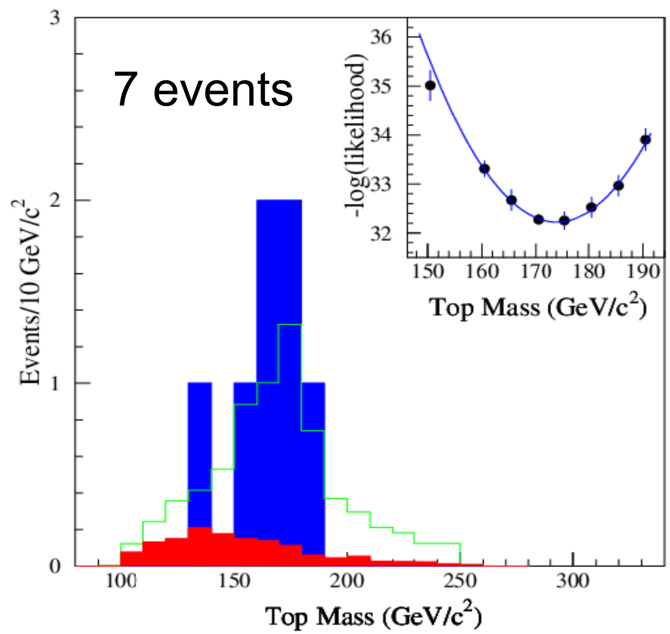
# Discovery of top quark (cont.)

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**

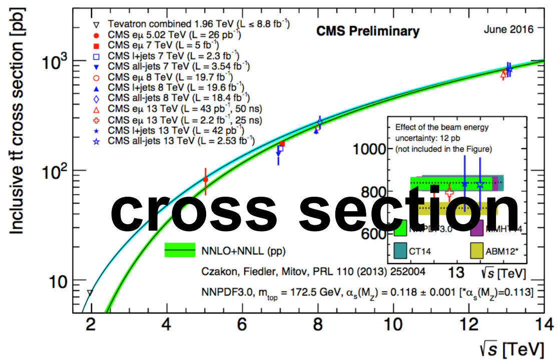
We summarize a search for the top quark with the Collider Detector at Fermilab (CDF) in a sample of $\bar{p}p$ collisions at $\sqrt{s} = 1.8$ TeV with an integrated luminosity of 19.3 pb$^{-1}$. We find 12 events consistent with either two $W$ bosons, or a $W$ boson and at least one $b$ jet. The probability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

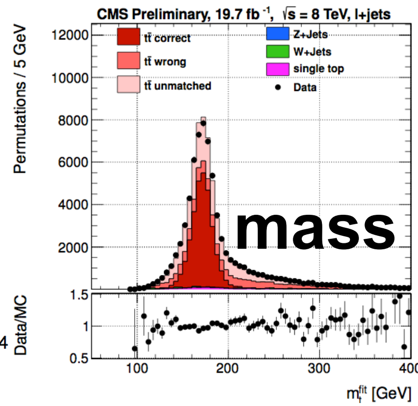


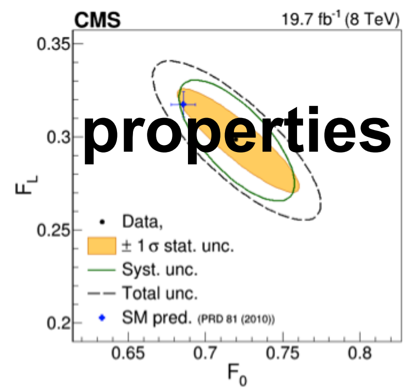



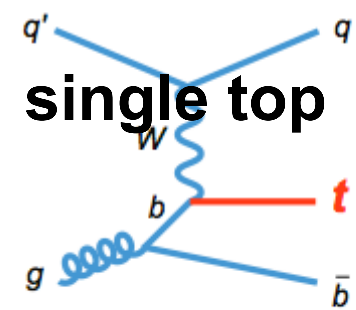
# Top quarks and BSM

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



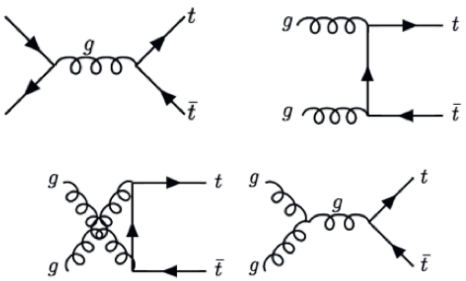



# Cross sections

arXiv:1112.5675



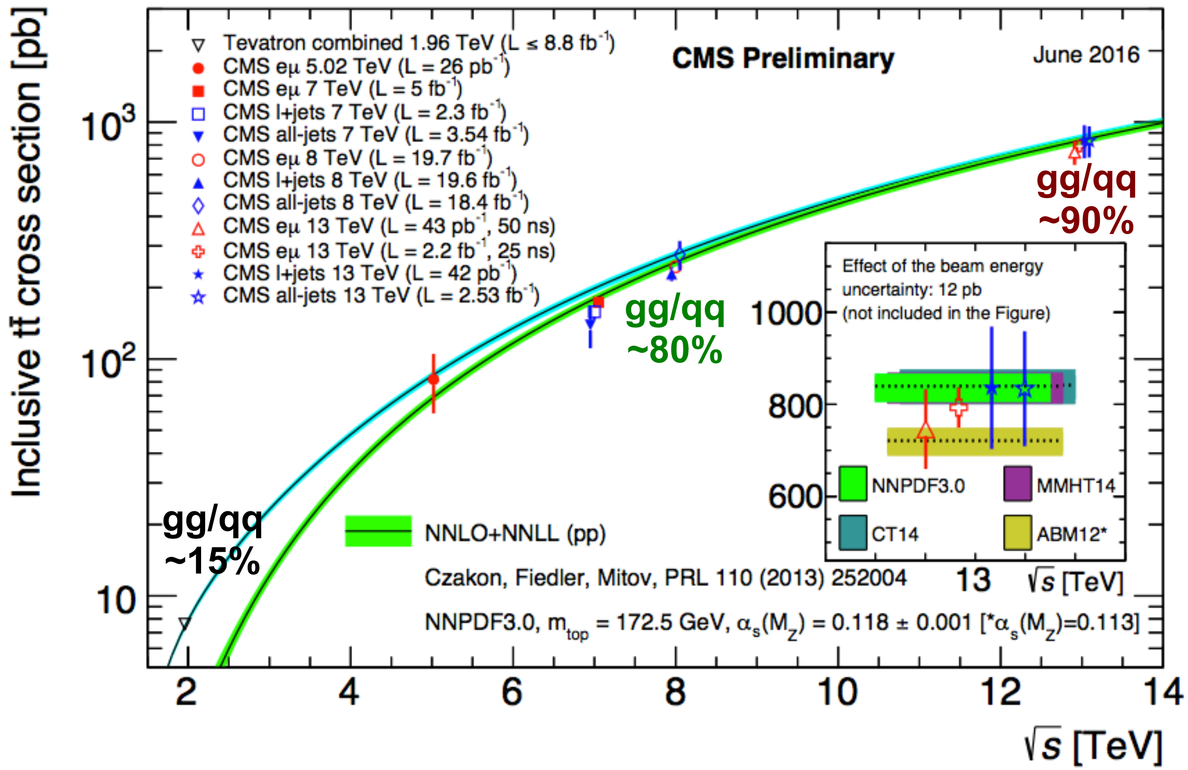
$$\sigma(7\ \text{TeV}) = 177\ \text{pb} \pm 7\%$$

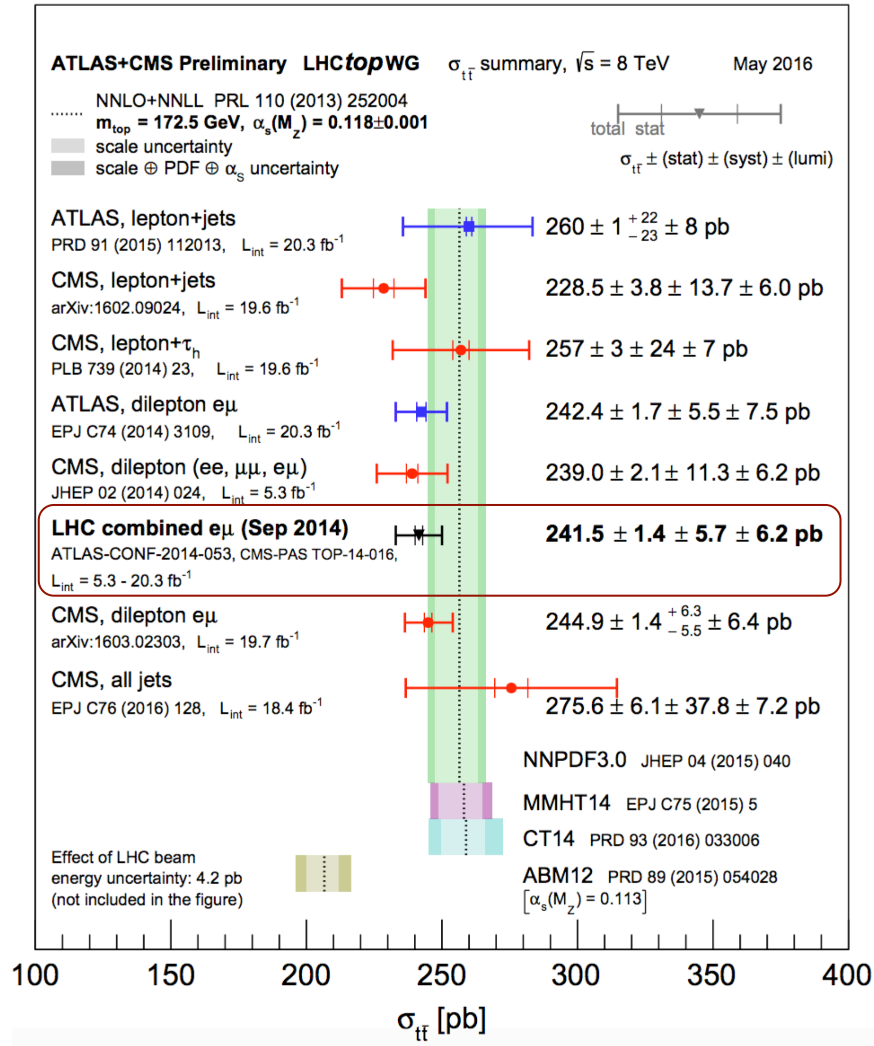
$$\sigma(8\ \text{TeV}) = 253\ \text{pb} \pm 6\%$$

$$\sigma(13\ \text{TeV}) = 832\ \text{pb} \pm 5\%$$

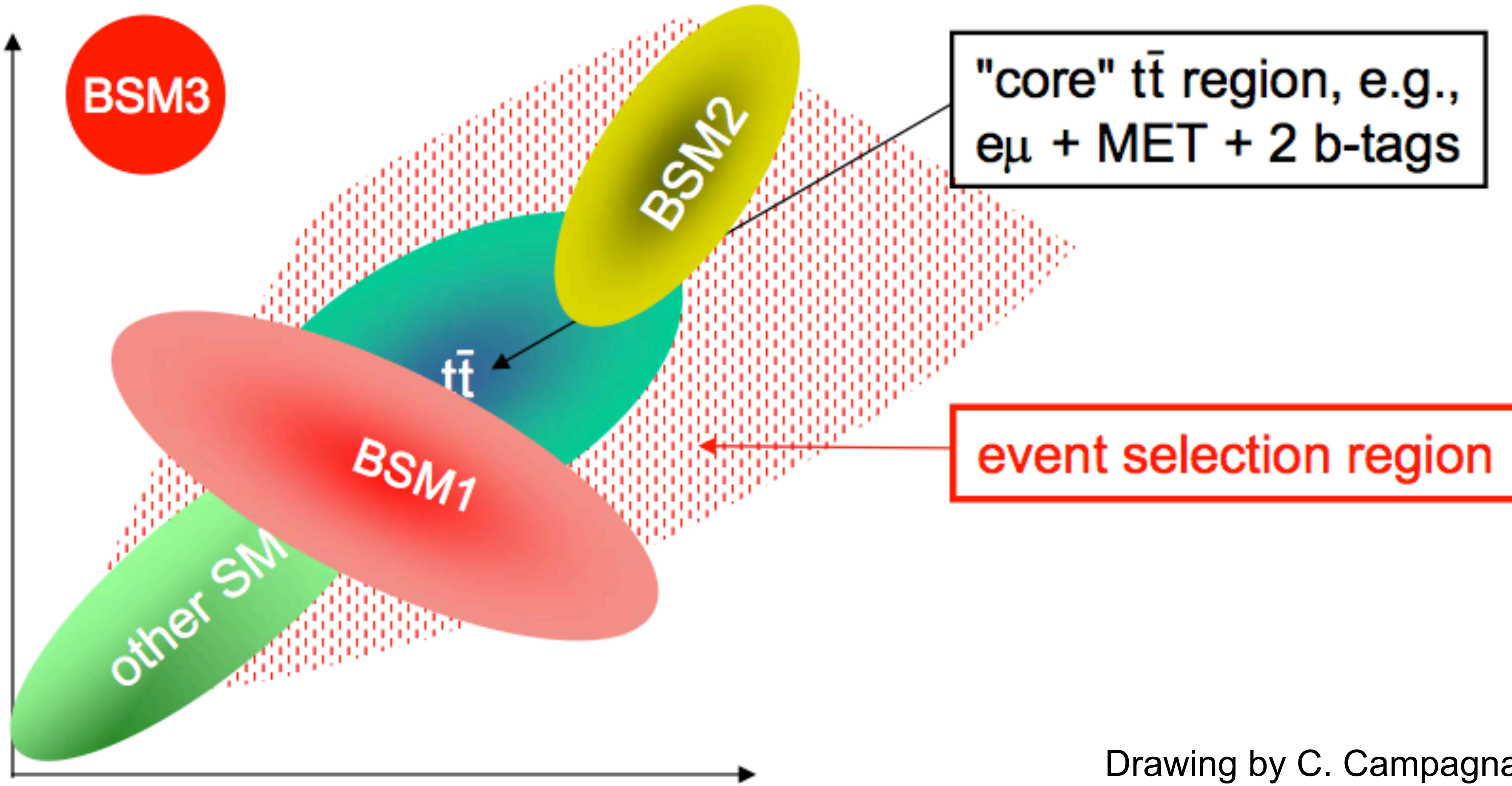
$$R_{13/8} = 3.28$$

NNLO+NNLL predictions (arXiv:1112.5675)



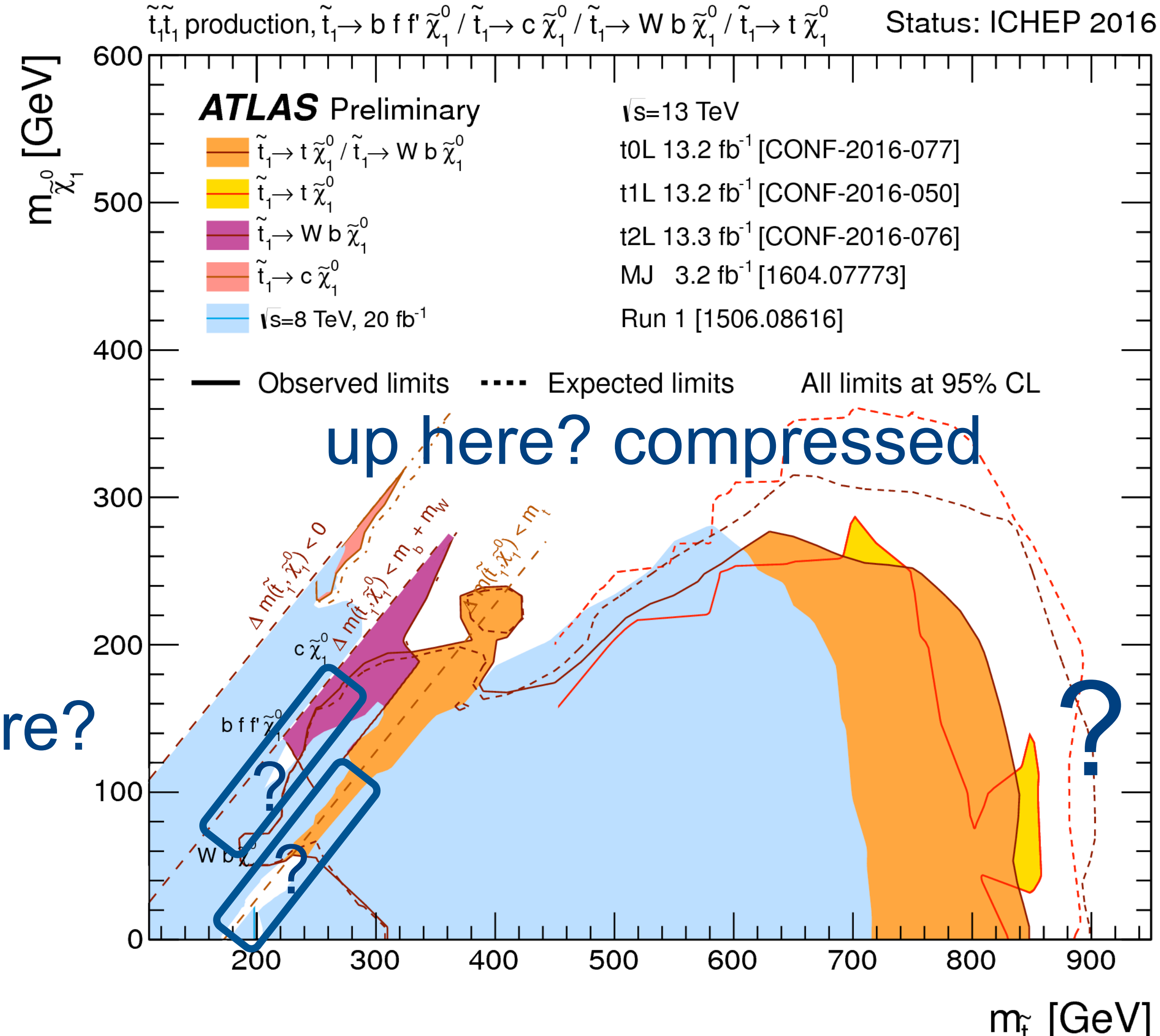
# Study characteristics




Drawing by C. Campagnari

# Regions hard to explore

hiding here?




or here?

# Cross section measurement

Number of observed events

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

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

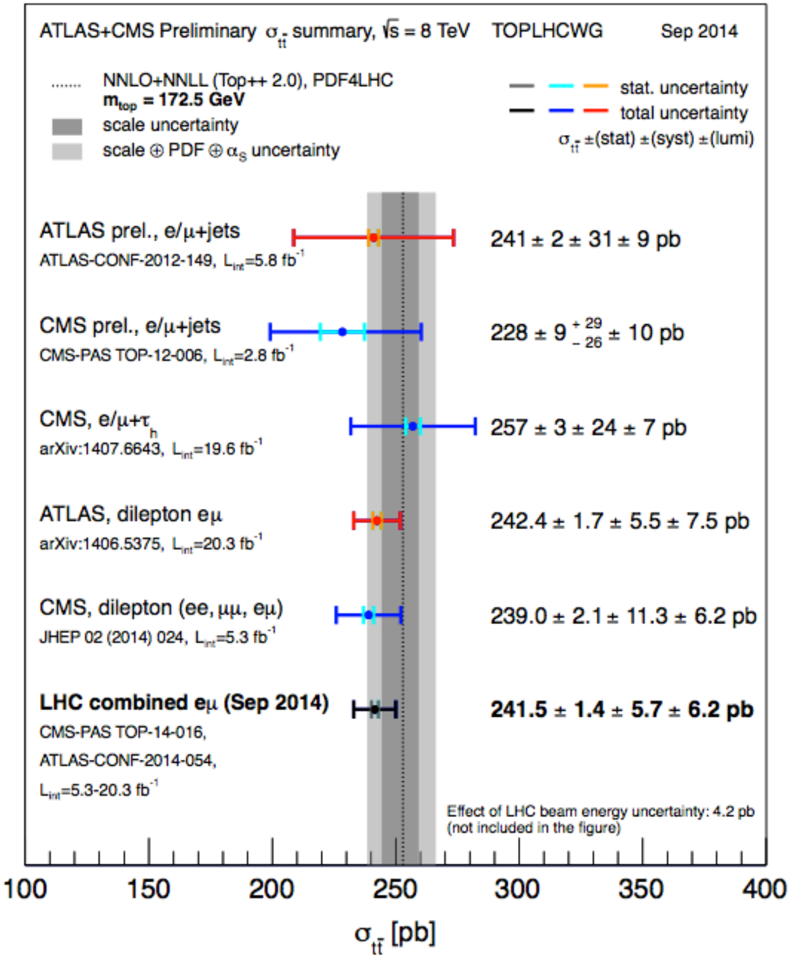
Acceptance *(experimental: detector, efficiencies)*

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

# Cross sections (cont.)

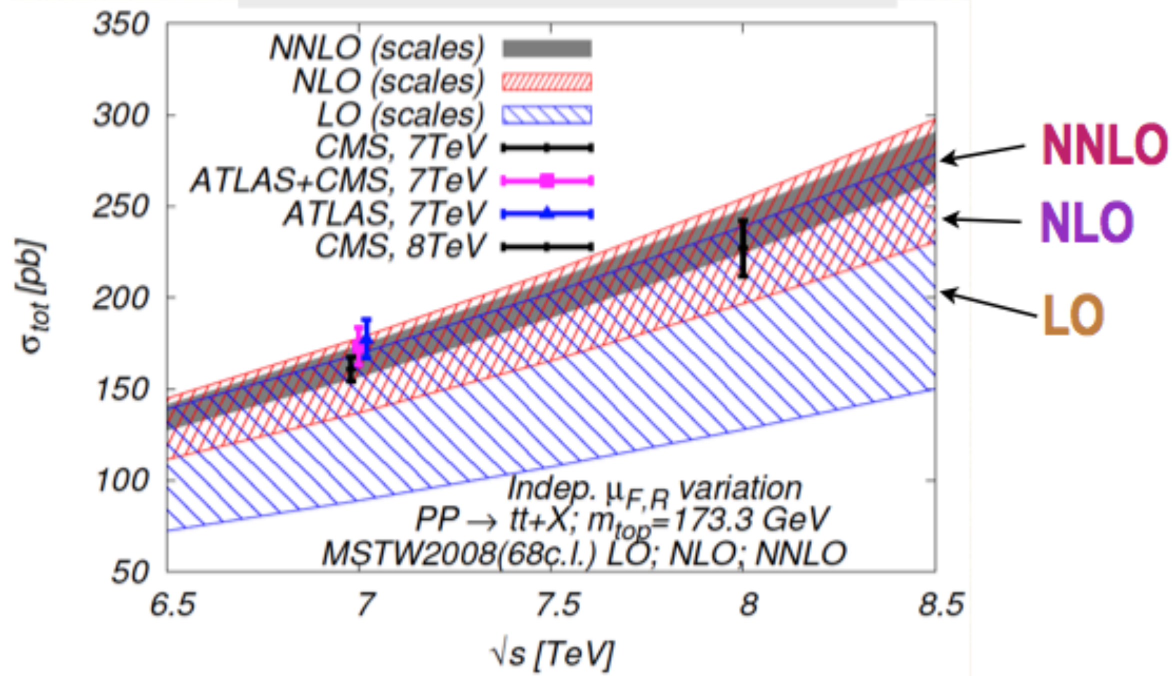
CMS-TOP-14-016

±4%




⇒meas. challenging the theory

Czakon, Fiedler, Mitov 1303.6254 [hep-ph]



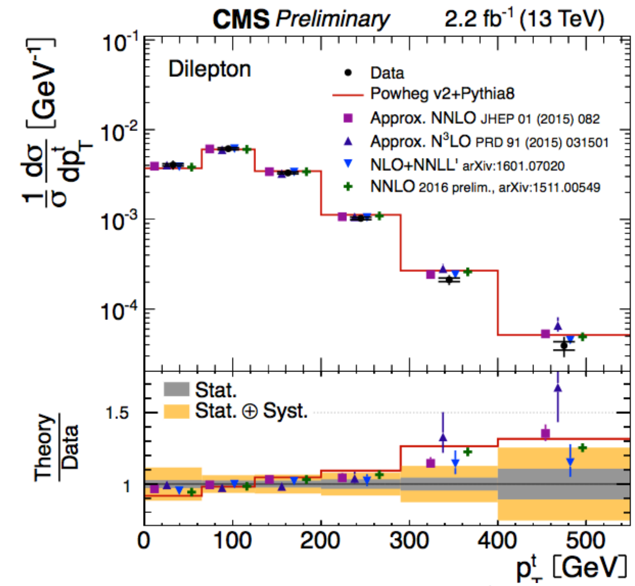

| Collider | $\sigma_{\rm tot}$ [pb] | scales [pb] | pdf [pb] |
|---|---|---|---|
| Tevatron | 7.164 | +0.110(1.5%) −0.200(2.8%) | +0.169(2.4%) −0.122(1.7%) |
| LHC 7 TeV | 172.0 | +4.4(2.6%) −5.8(3.4%) | +4.7(2.7%) −4.8(2.8%) |
| LHC 8 TeV | 245.8 | +6.2(2.5%) −8.4(3.4%) | +6.2(2.5%) −6.4(2.6%) |
|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

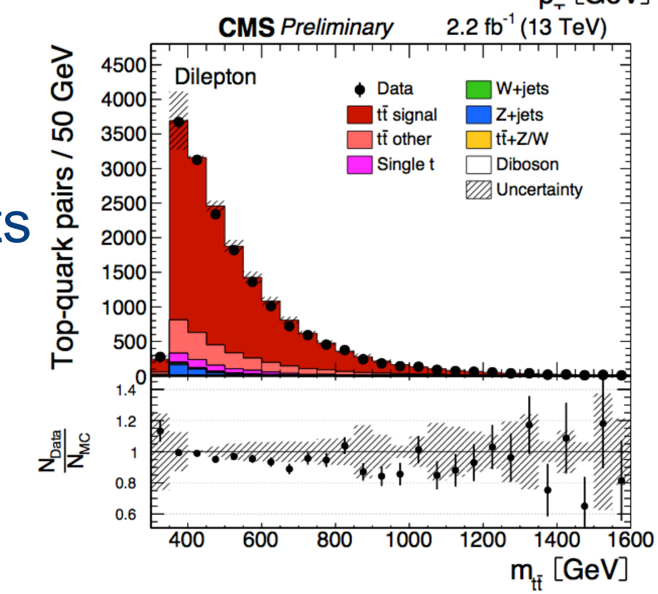
±3-5%

# Differential cross sections

EPJC 73(2013) 2339, CMS-TOP-12-027, TOP-15-013, TOP-16-011, arXiv:1610.04191

- Measure differential cross section
  - Test perturbative QCD
  - Improve ttbar modeling and reduce uncertainties
  - Test BSM scenarios (Z' decays, etc) with narrow resonance
- 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

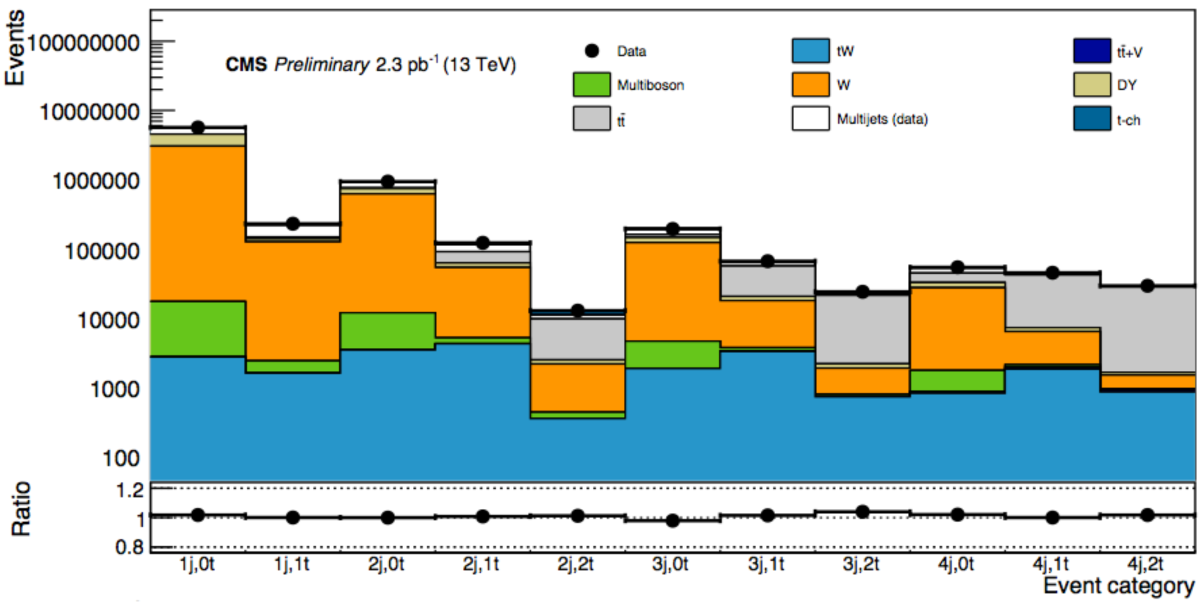


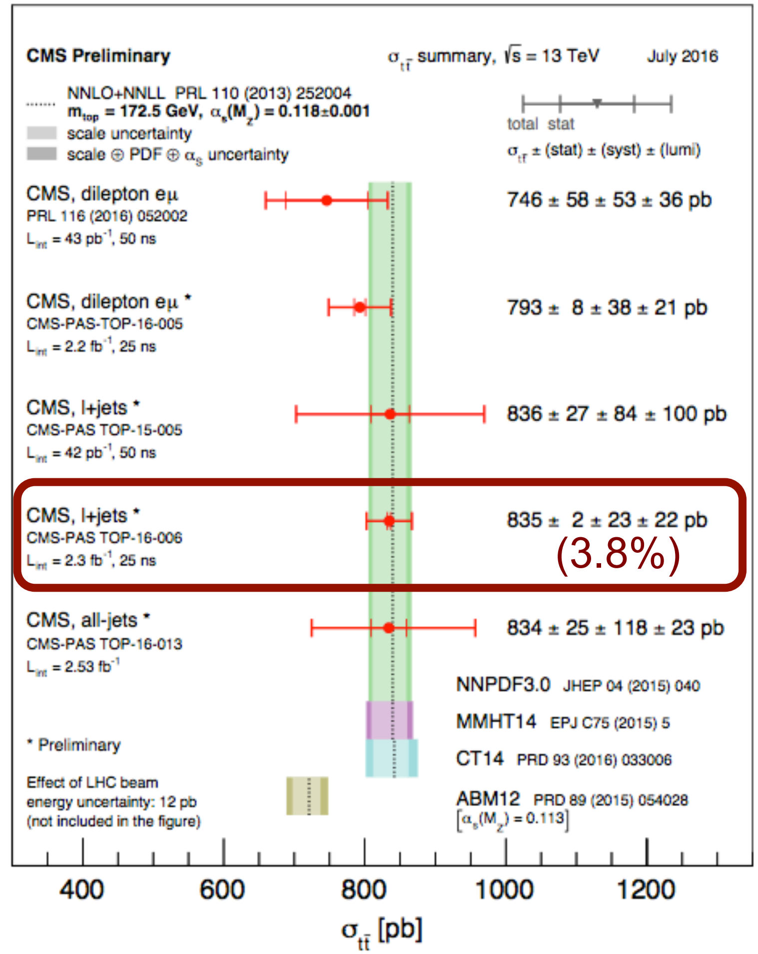



# Cross section: multi-dimensional fit

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



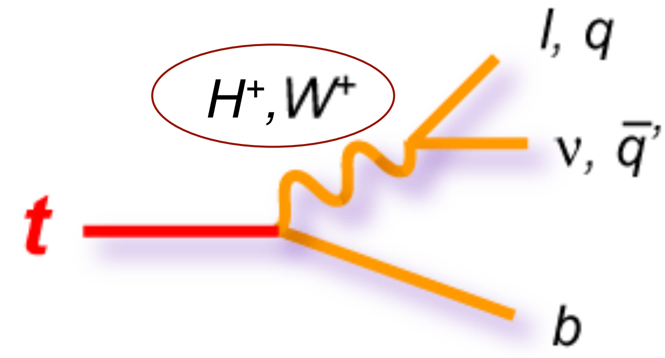



# Probing the Wtb vertex

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

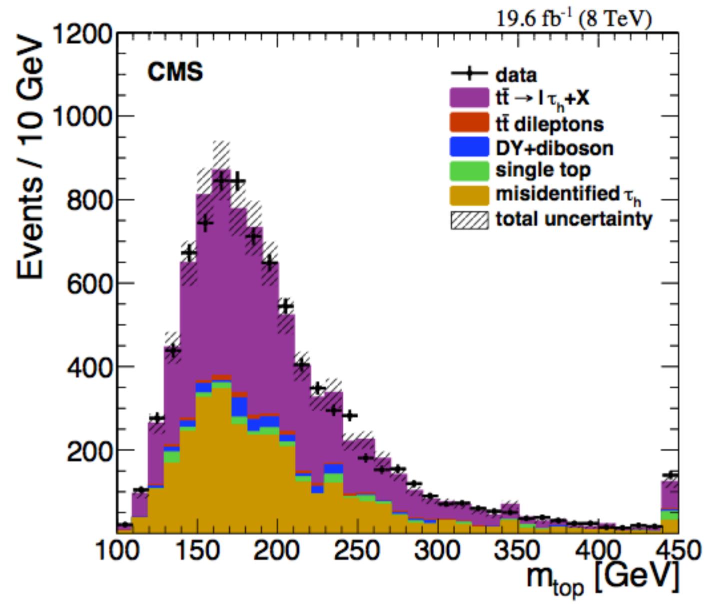
## Dileptons with taus

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

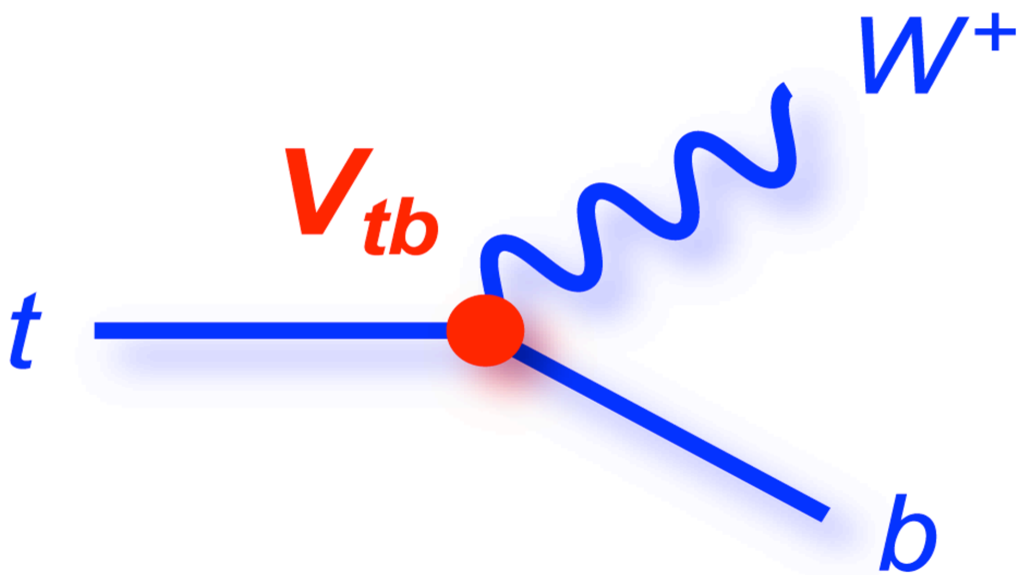



| Channel | Signature | BR |
|---|---|---|
| Dilepton(e/μ) | *ee*,μμ,*e*μ + 2*b*-jets | 4/81 |
| Single lepton | *e*,μ + jets + 2*b*-jets | 24/81 |
| All-hadronic | jets + 2*b*-jets | 36/81 |
| Tau dilepton | *e*τ, μτ +2 *b*-jets | 4/81 |
| Tau+jets | τ + jets + 2*b*-jets | 12/81 |

- 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



# How does a top quark decay?



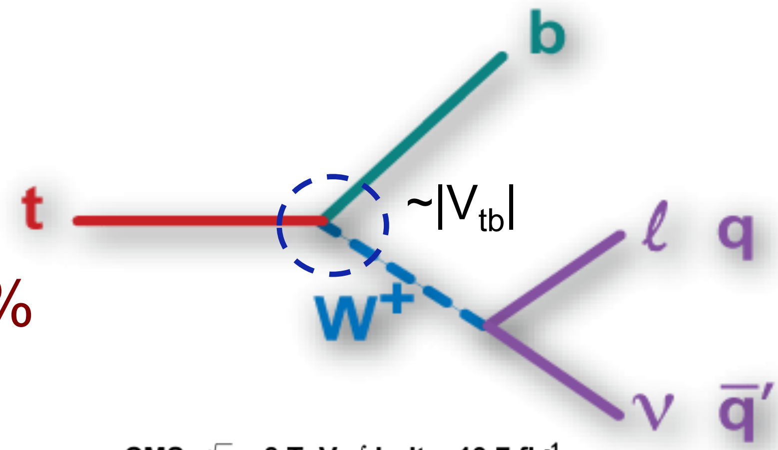

- almost always $t \rightarrow Wb$ (i.e. $V_{tb} \sim 1$)
- lifetime is short, and it decays before hadronizing
- the W is real:
  - can decay $W \rightarrow l\nu$ ($l = e, \mu, \tau$), BR~1/9 per lepton
  - can decay $W \rightarrow qq$, BR~2/3

# Cross section in the R measurement

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

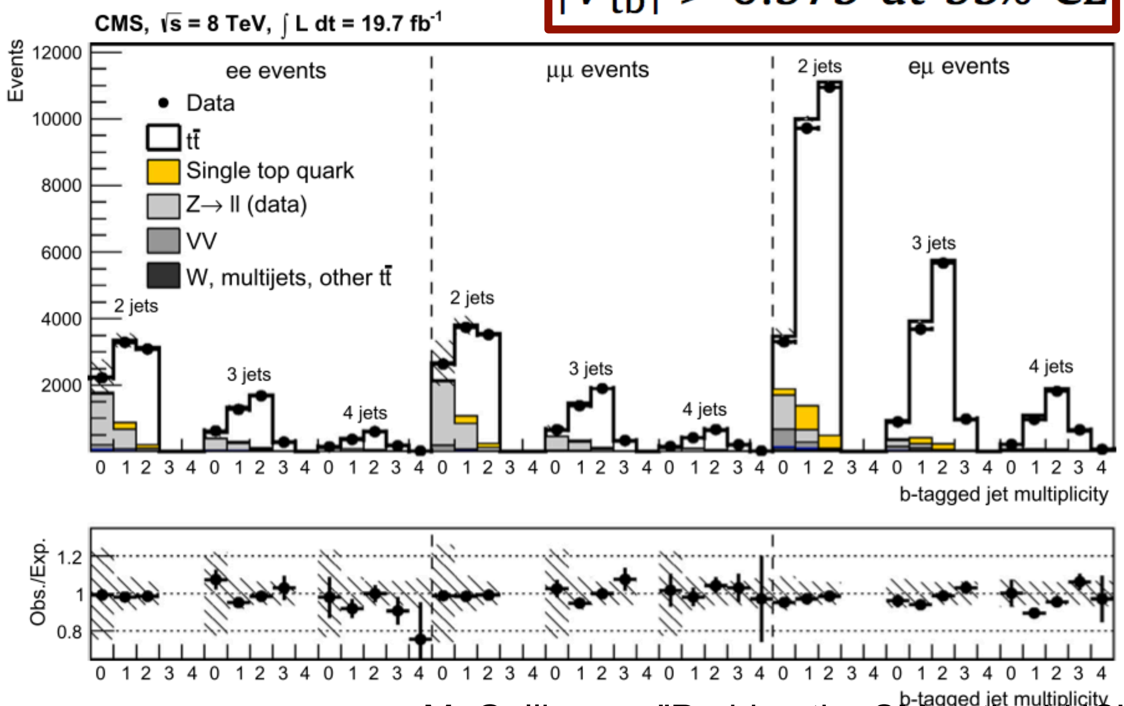
- Measure R:
- Dilepton final state

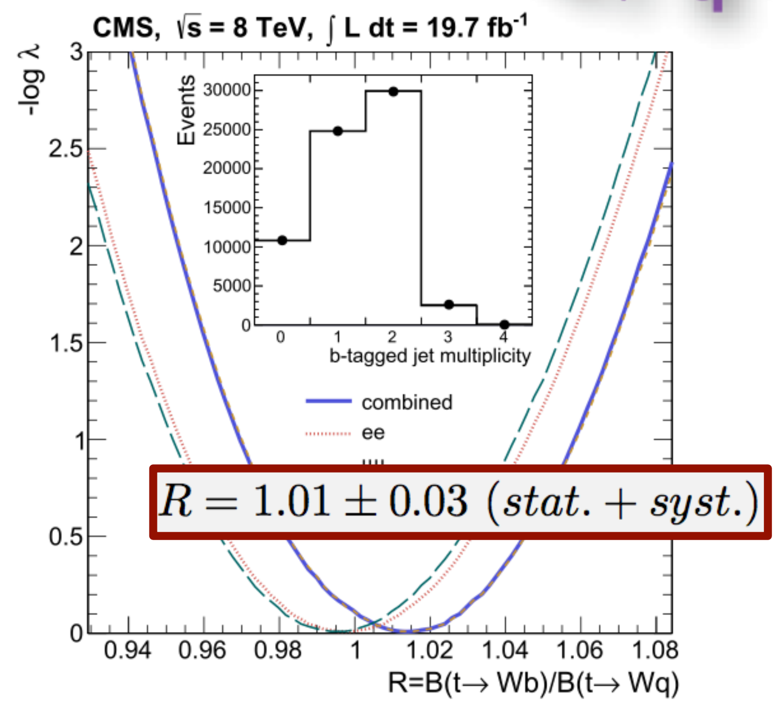
$$R \equiv \frac{BR(t \to Wb)}{BR(t \to Wq)} \approx |V_{tb}|^2$$




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

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



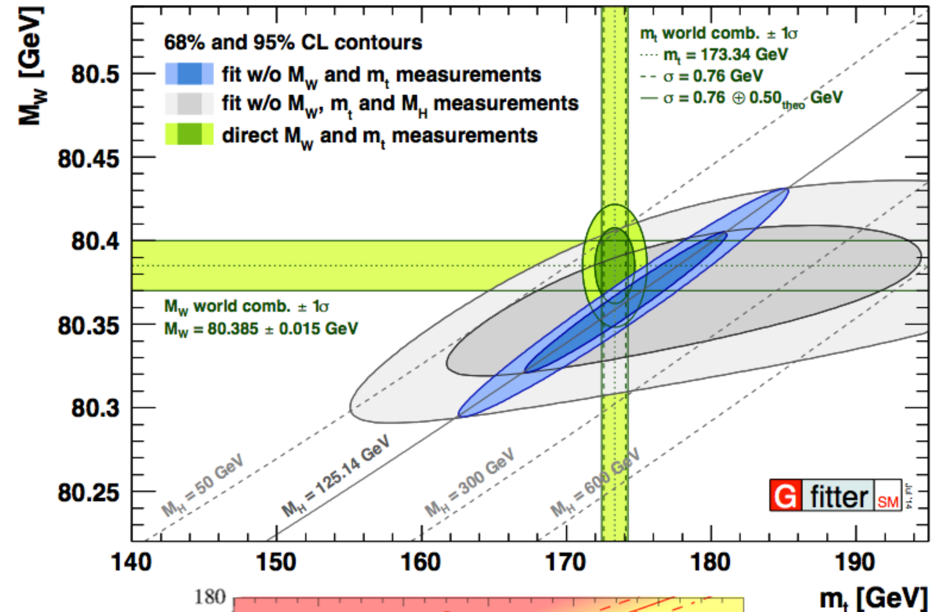

$$R = 1.01 \pm 0.03\ (stat. + syst.)$$

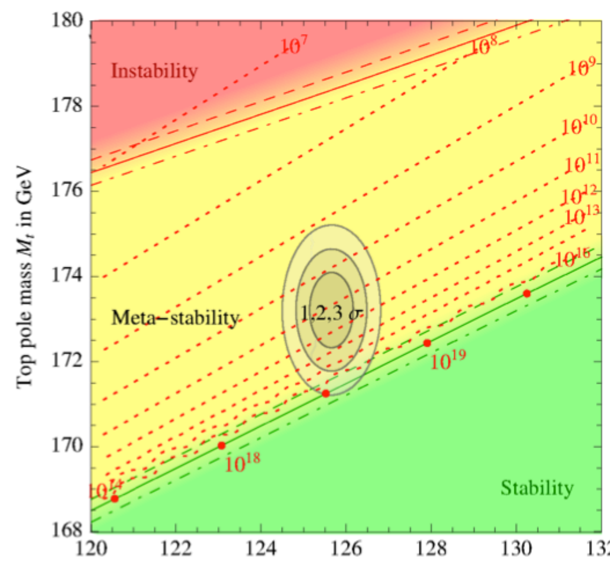
# Top quark mass: why do we care?

- Top quark mass is a fundamental parameter of the SM


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

- 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 $m_{top}$
  - Highly fine-tuned situation
  - ~1GeV is all it takes to tip the scales
- Run2 will allow for discrimination between SM and MSSM scenario (?)
- The fate of the Universe might depend on $\Delta m_{top}$~1 GeV

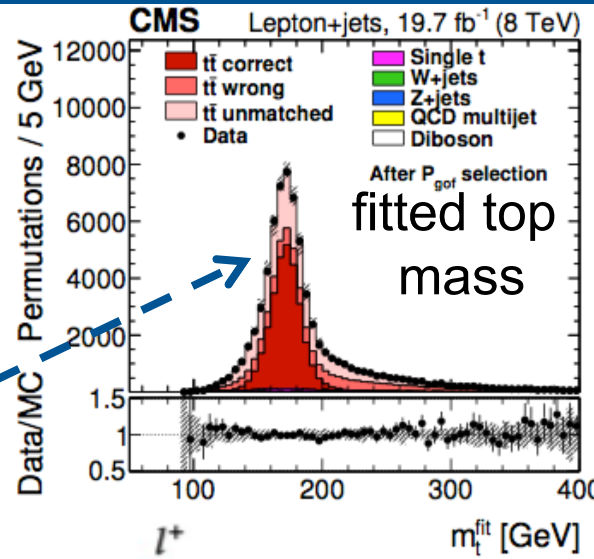


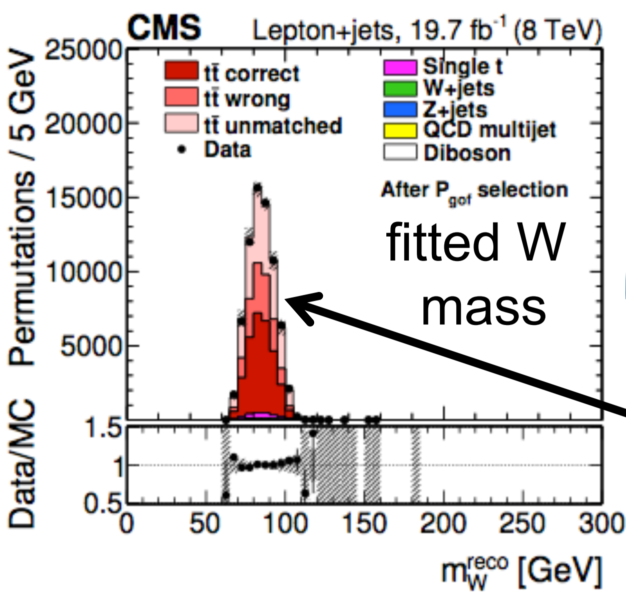



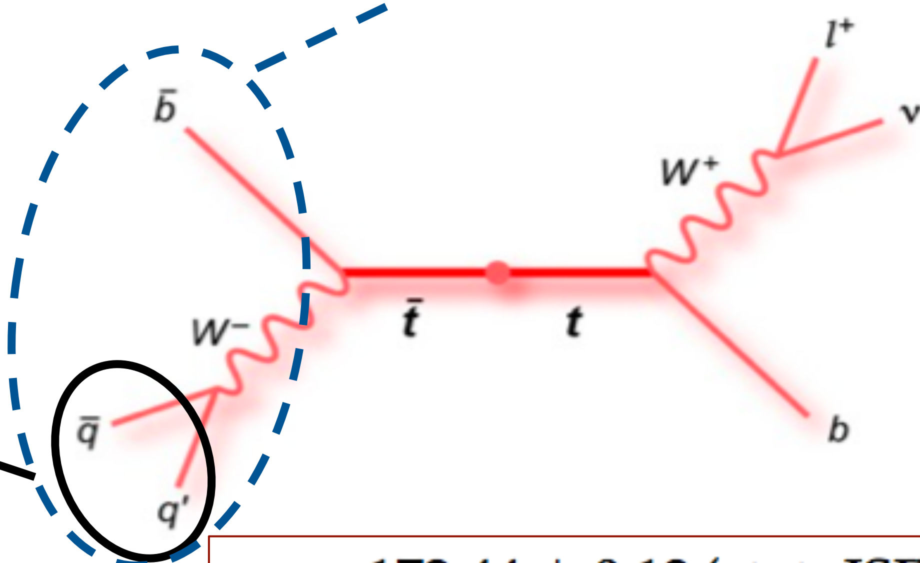
# Precise mass measurement

arXiv:1509.04044

- Select lepton+jet final state
  - Best channel to measure $m_{top}$
  - well defined final state (1 lepton, 1$\nu$, 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



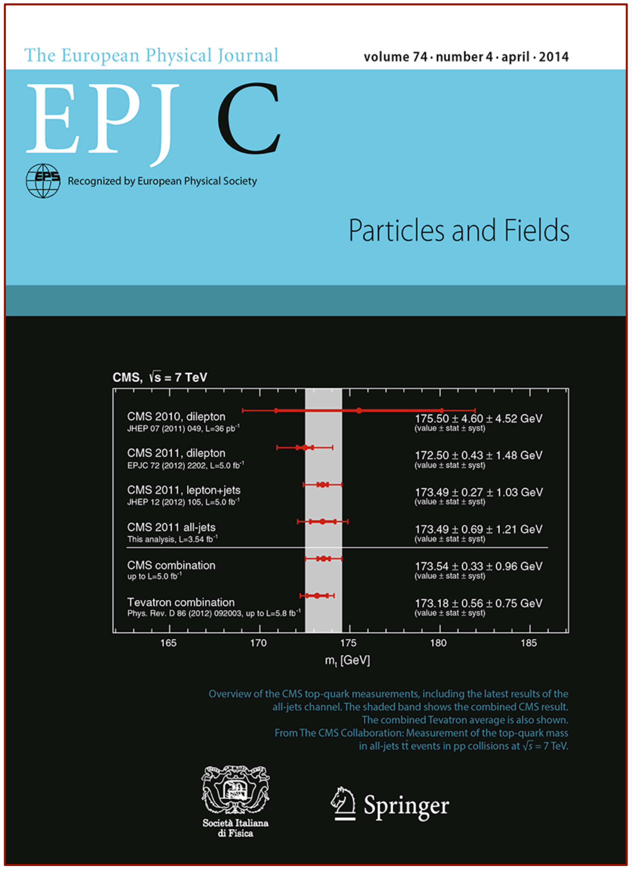



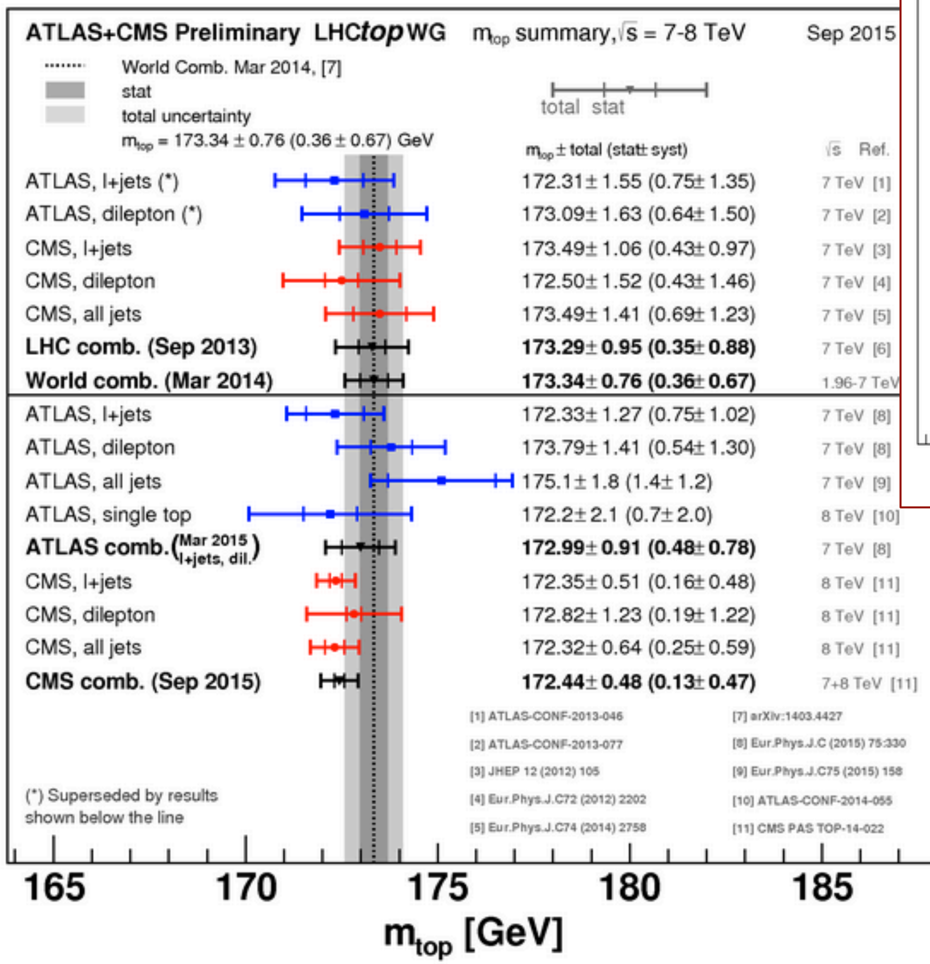

±0.3%

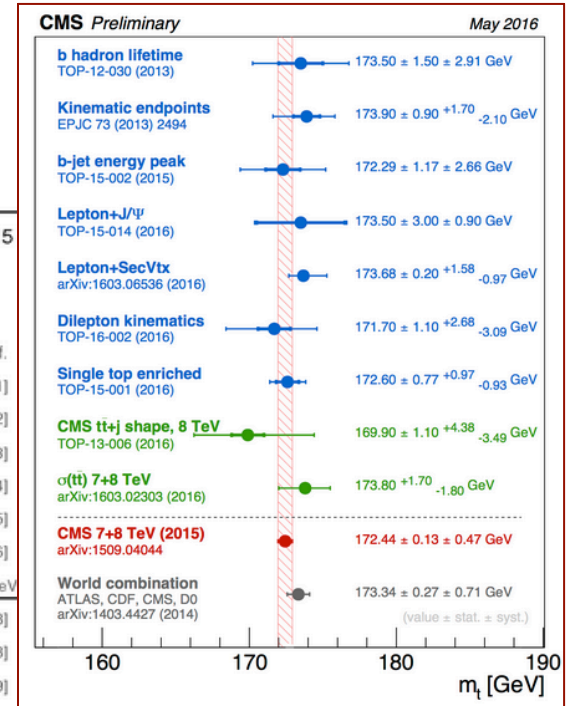
$$m_t = 172.44 \pm 0.13\,(\text{stat+JSF}) \pm 0.47\,(\text{syst})\,\text{GeV}$$

# Top quark mass results

- accurate (~0.3%) measurement



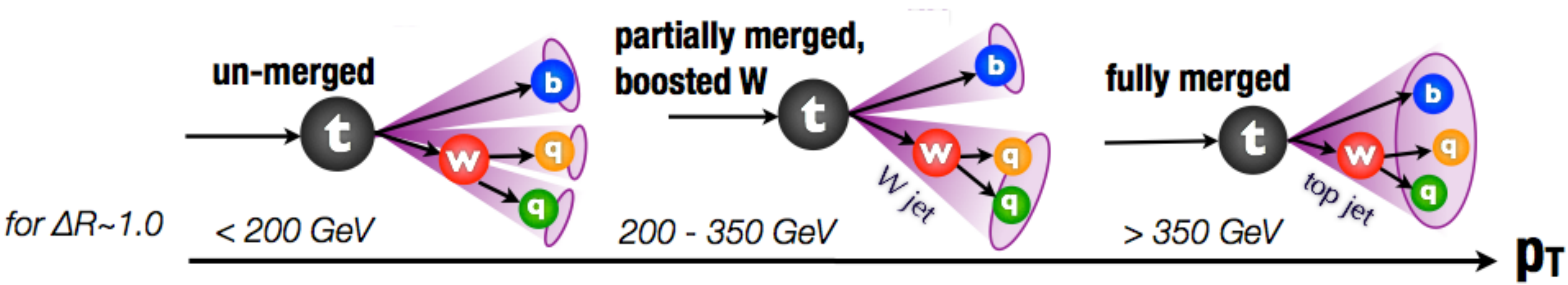



# Probing top quark production

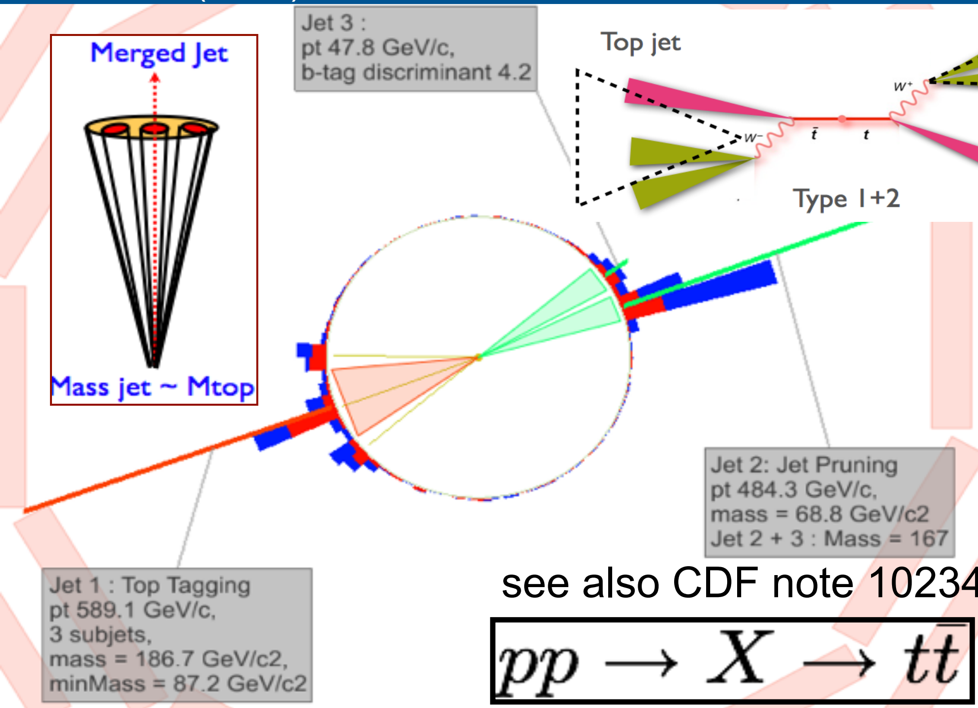
- Differential measurements
  - Testing QCD, measuring properties, searching for new physics, …
  - Function of kinematics, global variables, associated production
- Increased sensitivity: top quark pairs produced at rest
  - $\sigma$ ($M_{tt}$>1 TeV at 13 TeV) =8 x $\sigma$($M_{tt}$>1 at 8 TeV)
- New physics may manifest in final states with boosted top quarks
  - Challenge: Reconstruction of boosted top quarks ($p_T$~2M/R)

⇒Unique opportunity to probe boosted production at 13 TeV



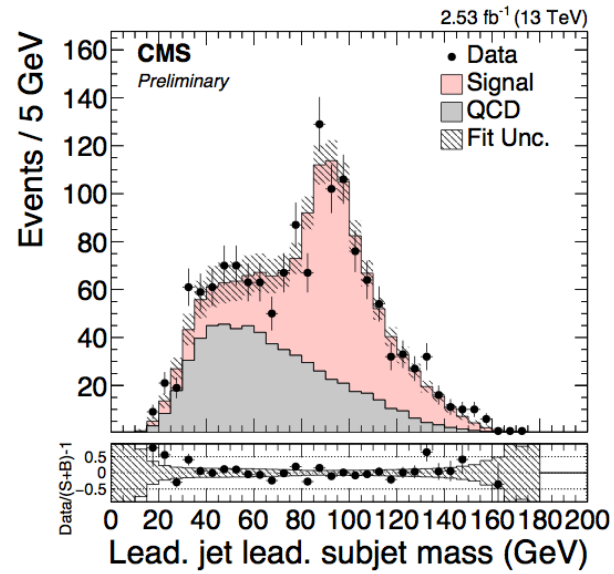
# Boosted topology

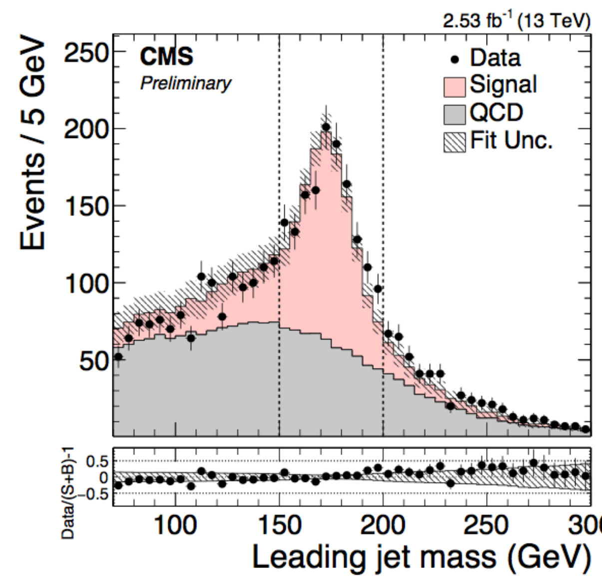
JHEP 1209(2012)029, TOP-16-013




see also CDF note 10234

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



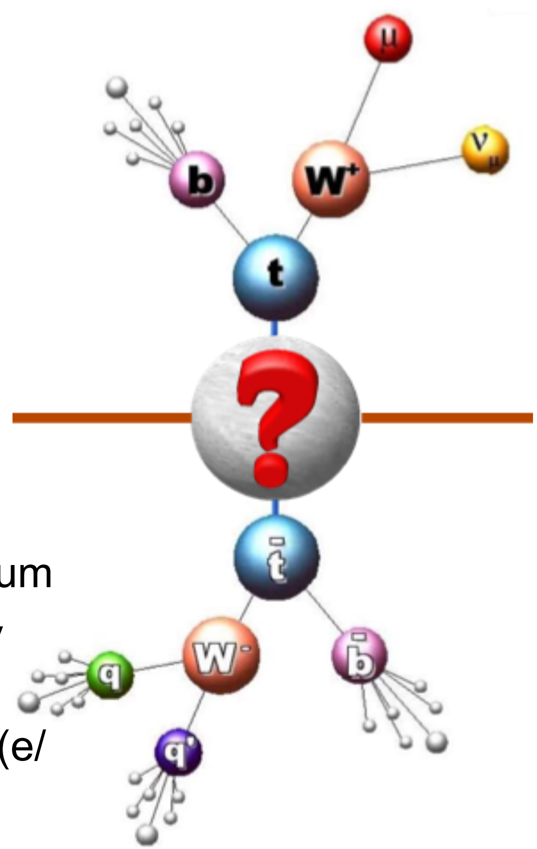



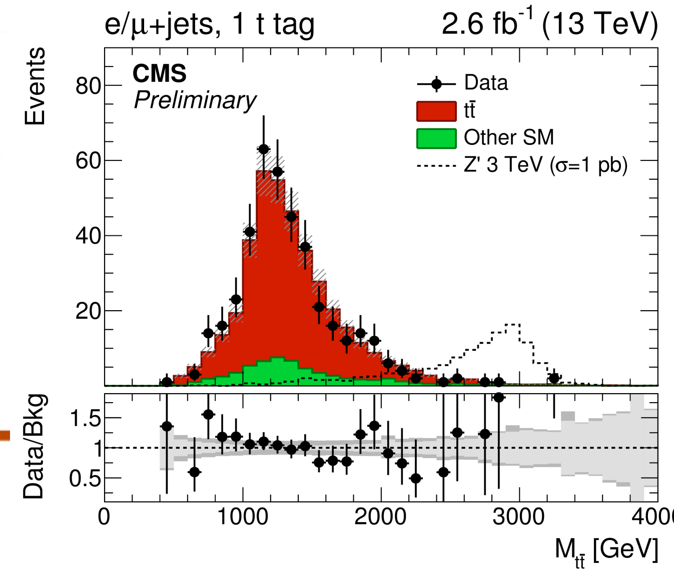

- At high energy, particles produced beyond threshold
- All-hadronic topology
  - Top $p_T$ boosted, jets are collimated
  - Decay products and FSR collected in a “fat” jet
- Look at jet substructure
- Measure mass (no neutrinos)

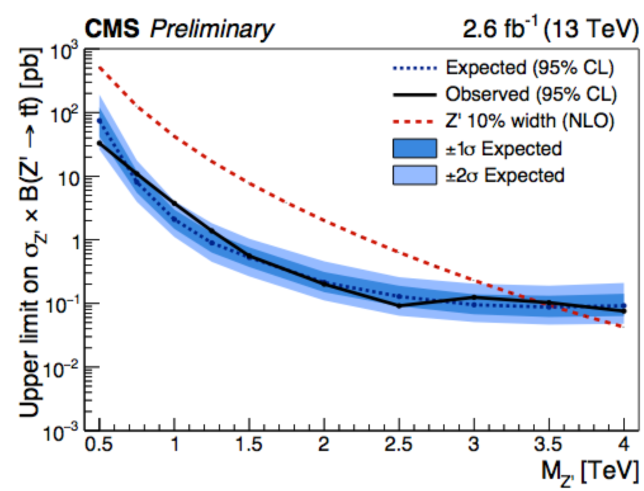
# Top quark pair resonance

CMS-B2G-15-002

- 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/ $\mu$, *n*-jets, *n* b-tags)
  - l+jet events: full event reconstruction

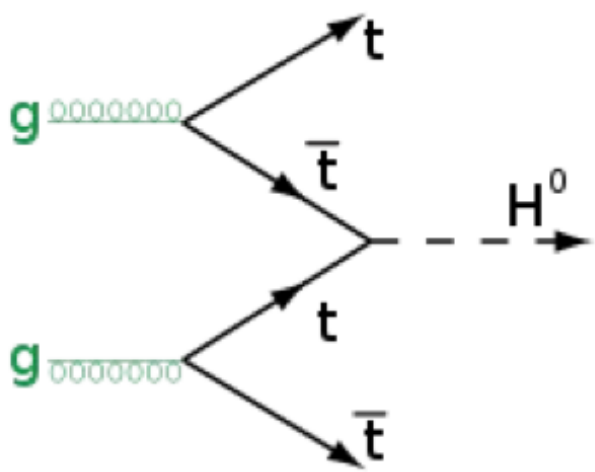


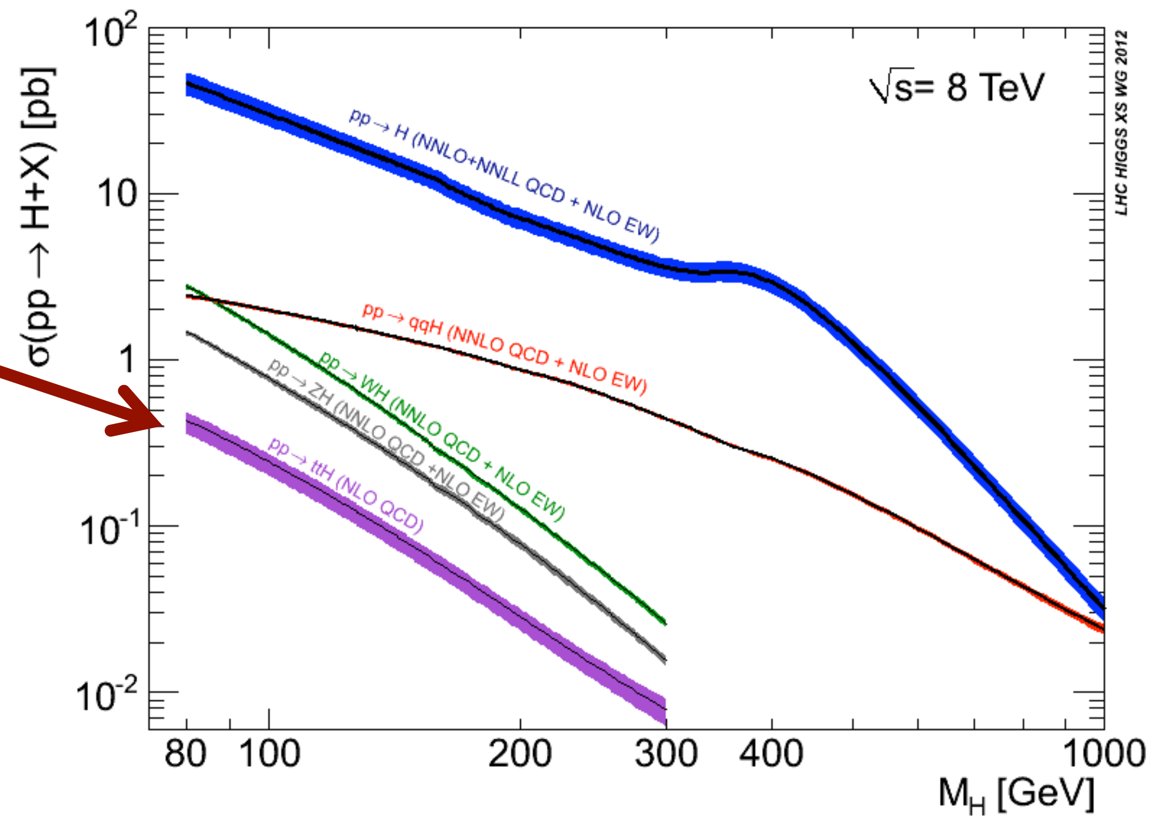



# ttbar+Higgs

- ttbar produced in association with H
  - ttbar is 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)

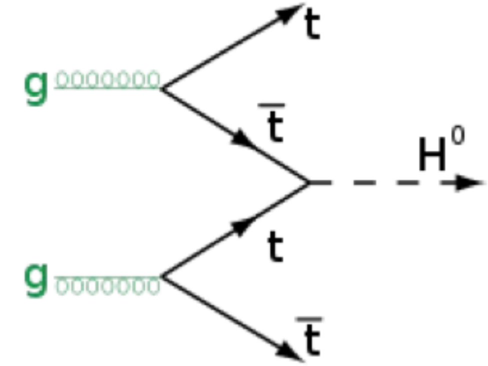
# ttbar+heavy flavour

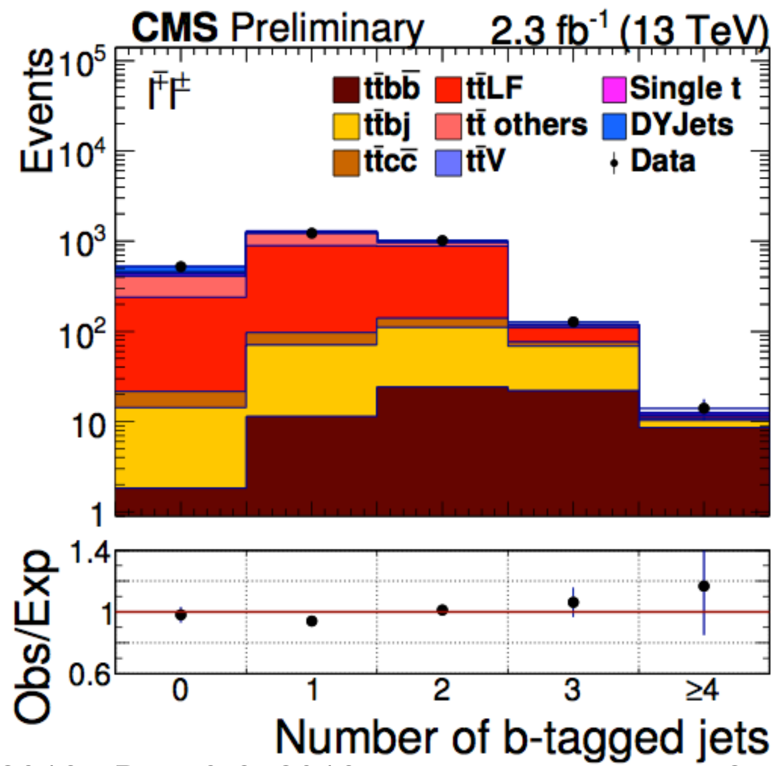
arXiv:1411.5621, TOP-16-010

- 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

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

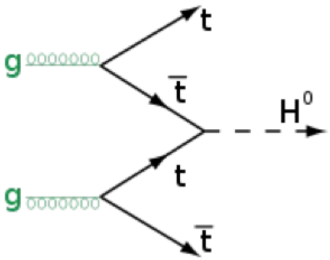
- In Run1 measured value higher but compatible (1.6σ) with NLO calculation



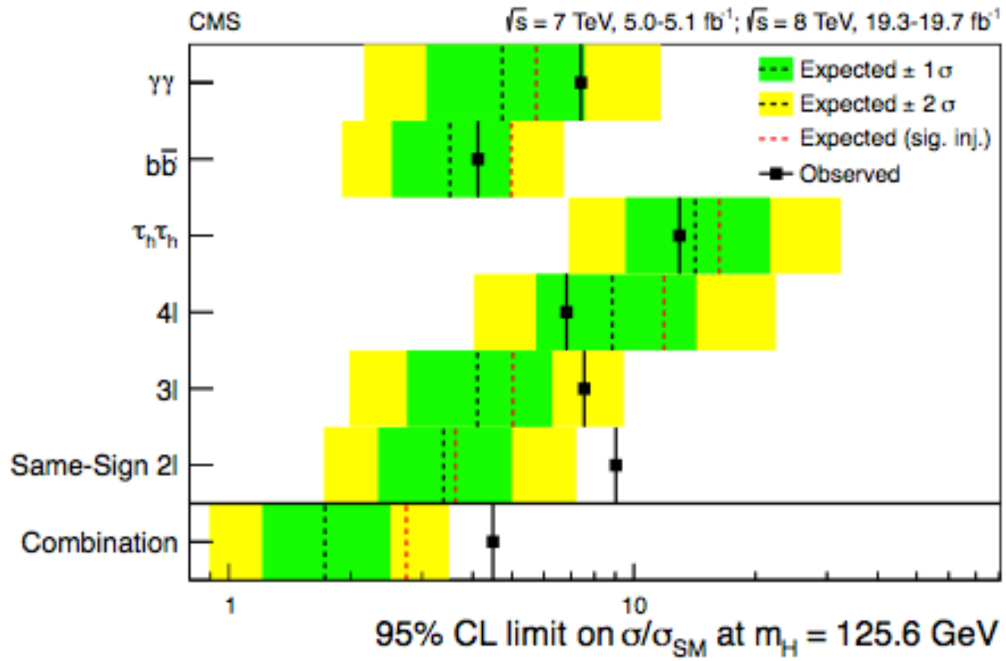
# ttH

- Direct study of top Yukawa coupling
- Explore all accessible Higgs decay modes
  - H→bb,WW,ZZ with multilepton final states



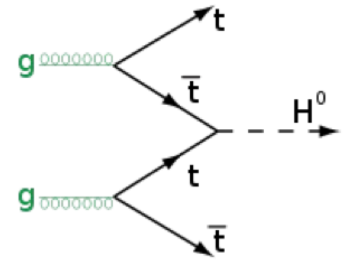

Run1 best fit:

μ=2.80±1.00



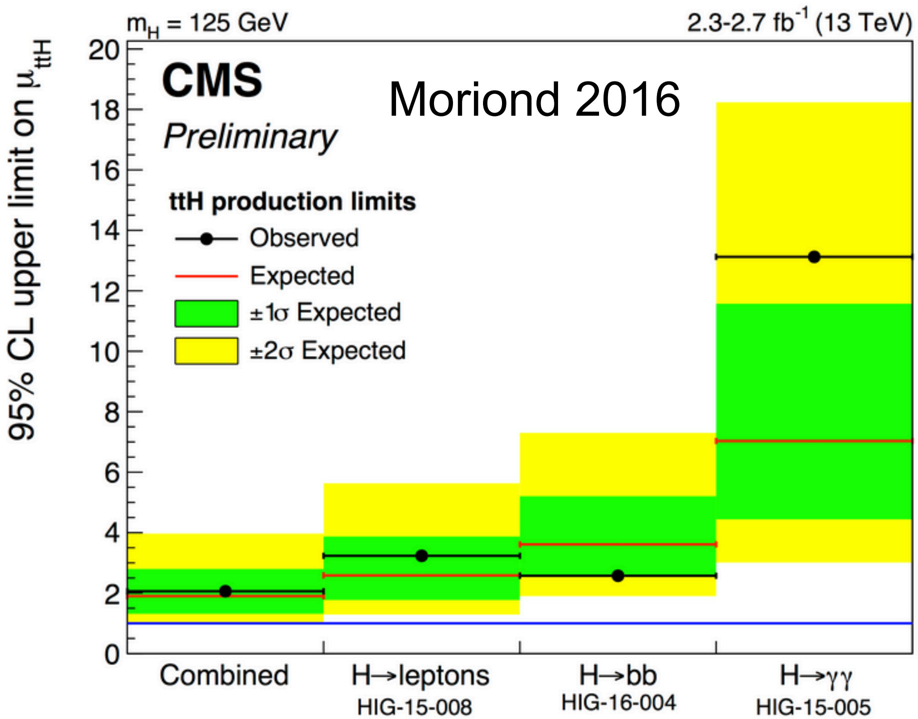
# ttH (cont.)

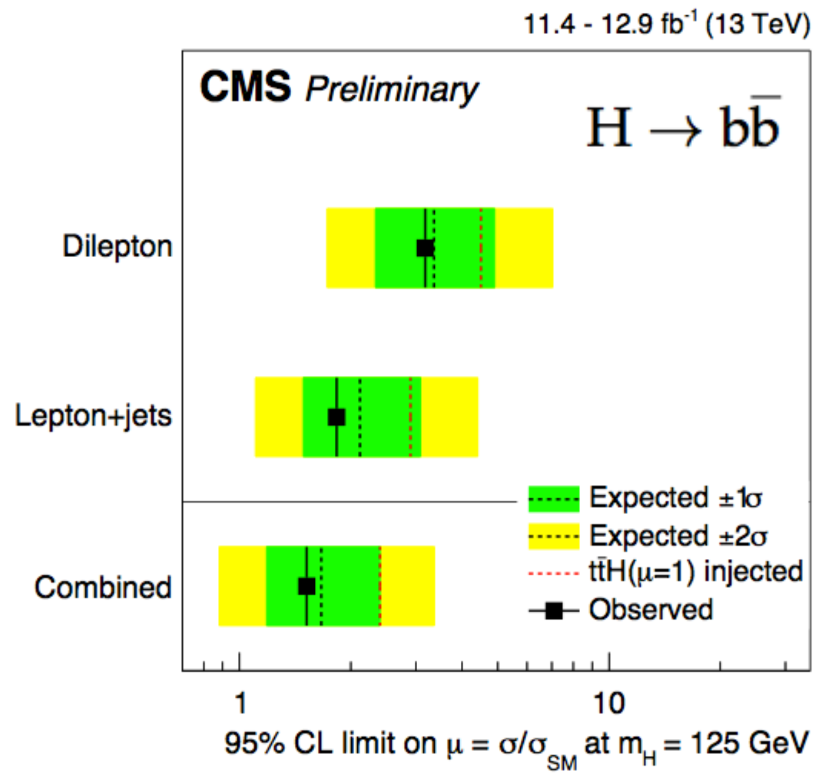
- Direct study of top Yukawa coupling
- Explore all accessible Higgs decay modes
  - H→bb,WW,ZZ with multilepton final states
- Key search in Run2: approaching sensitivity




Run2 preliminary:

$\mu=0.15\pm0.95$

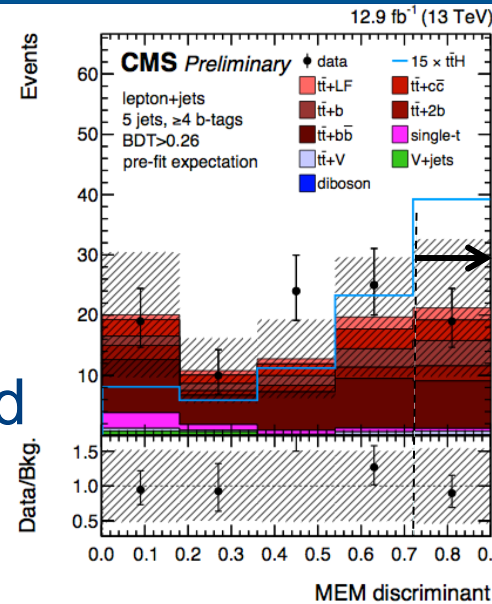


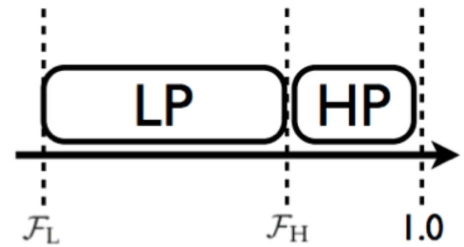



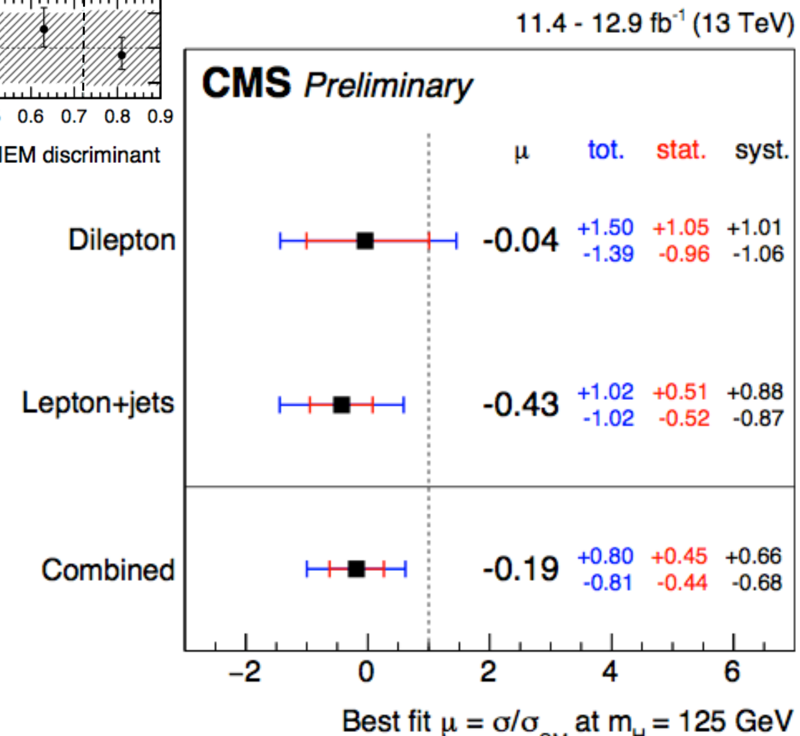
# ttH, H→bb

JHEP 09(2014)087, EPJC 75(2015)251, HIG-16-038

- Study ttH(→bb) final state
- Select SL and DL events
- Categorize $N_{jets}$,$N_{lep}$,$N_{btags}$
- Assign events a b-tag likelihood
- low- and high-purity categories
  - Signal: ttH
  - Background: tt+bb
- ttH and tH allows direct access to Yukawa coupling



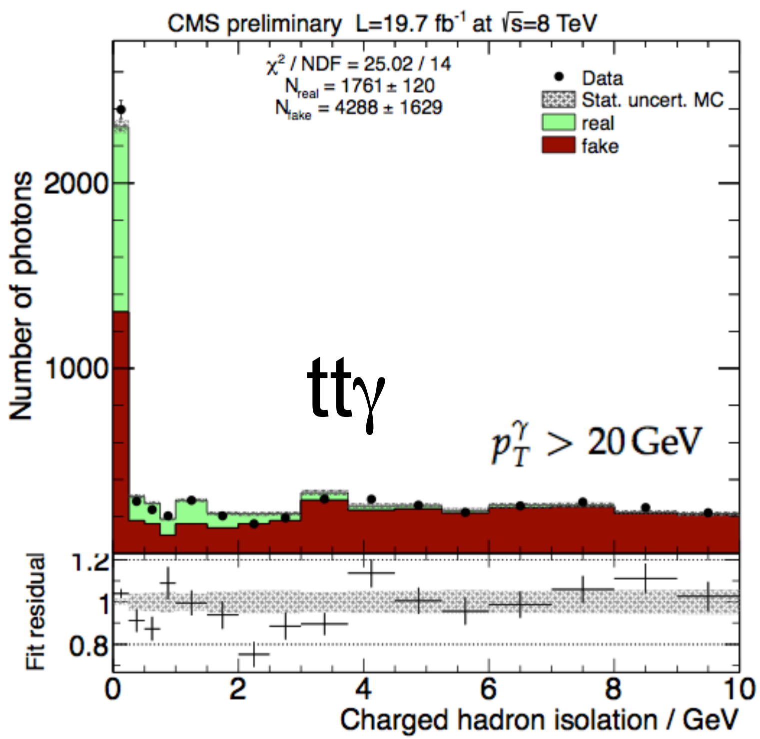



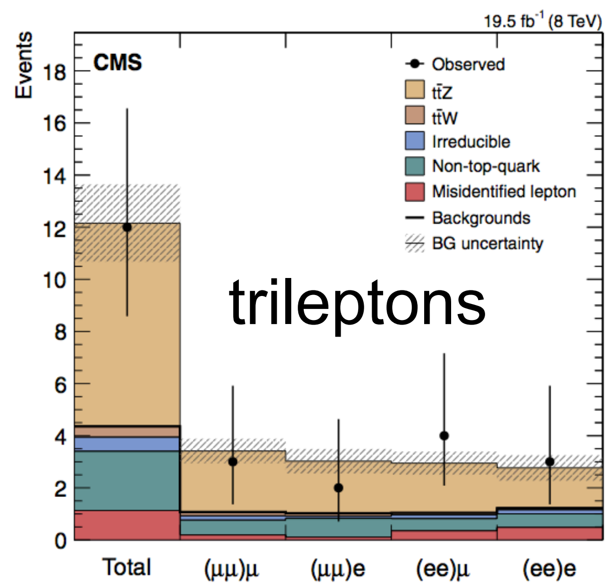



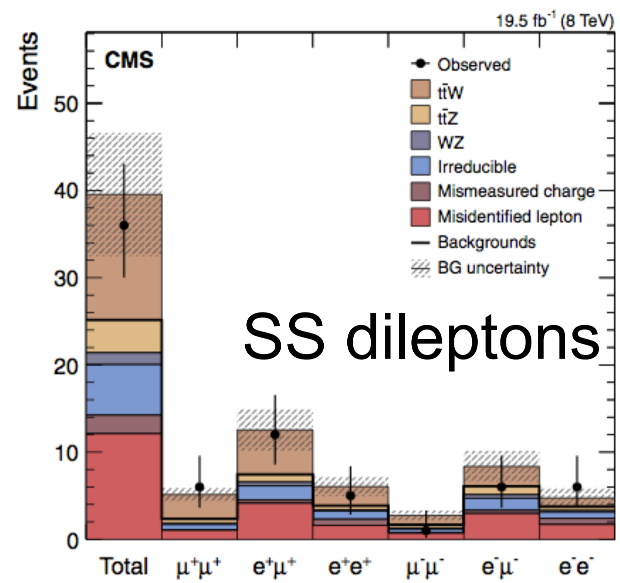
# ttV (V=γ,Z,W)

CMS-TOP-13-011, EPJC 74(2014)3060, TOP-14-008

- Measurements will give access to EW couplings of the top

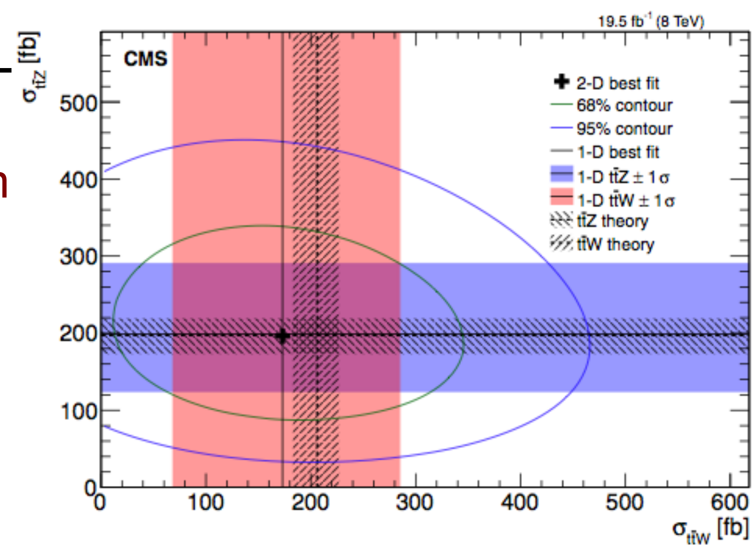



Combine 2- 3- and 4-lepton final states

⇒ ttV xsec 3.7σ from bkg-only hypothesis

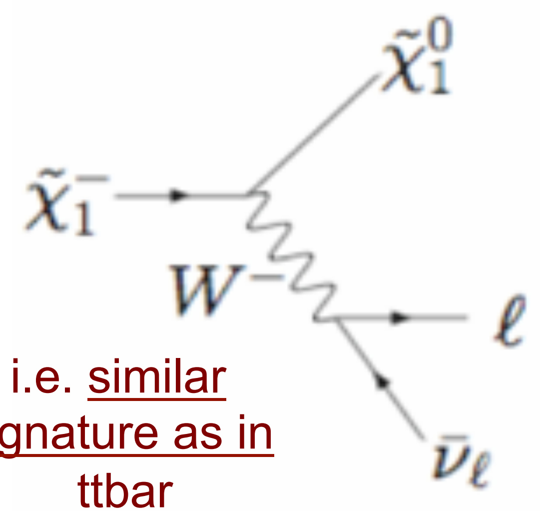



$$\sigma_{t\bar{t}\gamma} = 2.4 \pm 0.2\,(\text{stat.}) \pm 0.6\,(\text{syst.})\,\text{pb}$$

Consistent with theoretical predictions

# Scalar top quark

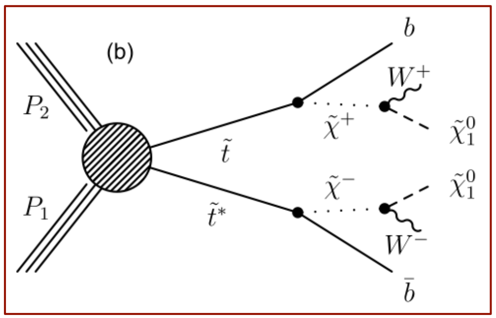
- SUSY is one plausible extension of the SM
- due to the heavy top quark, mass splitting between $\tilde{t}_1$ and $\tilde{t}_2$ can be large, such that the lighter stop $\tilde{t}_1$ can be even lighter than the top quark
- Decays dictated by mass spectrum of other SUSY particles




i.e. similar signature as in ttbar

- Light stop:

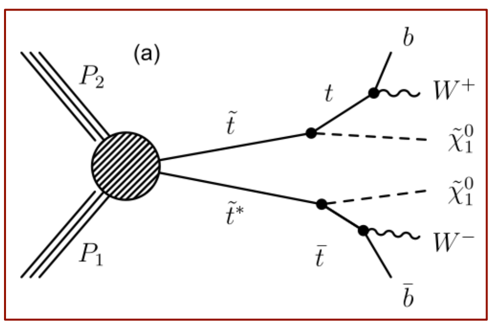
$$m_{\tilde{t}_1} \lesssim m_t$$




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

- Heavy stop:

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




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

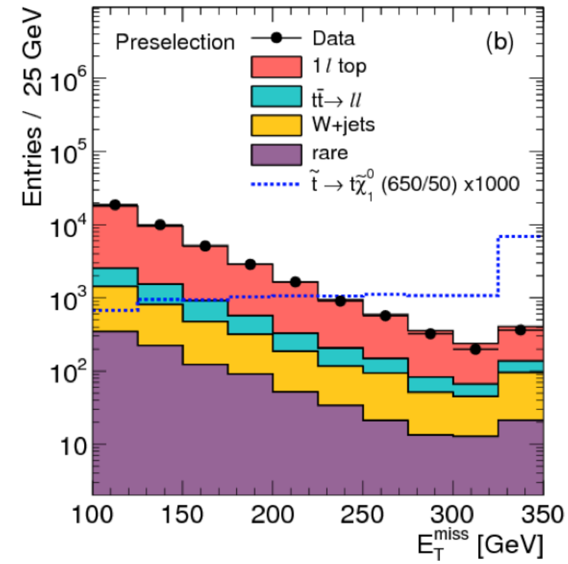
# Top and SUSY

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

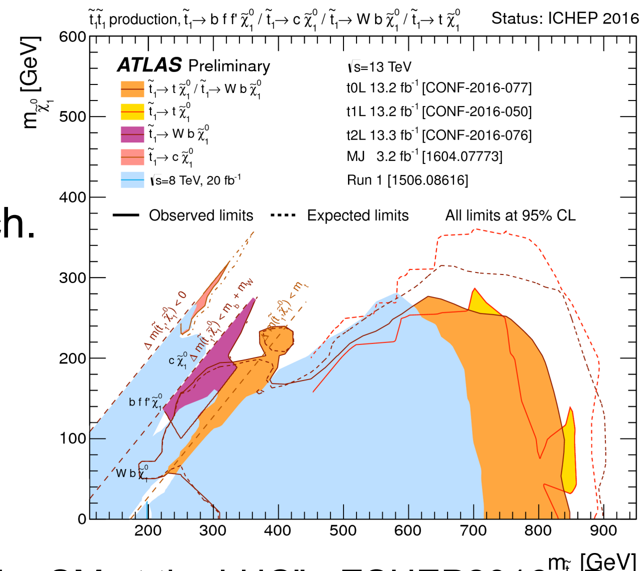
- If SUSY exists and is responsible for solution of hierarchy problem, naturalness arguments suggest that SUSY partners of top quark (*stop*) may have mass close to $m_{top}$ to cancel top quark loop contributions to Higgs mass

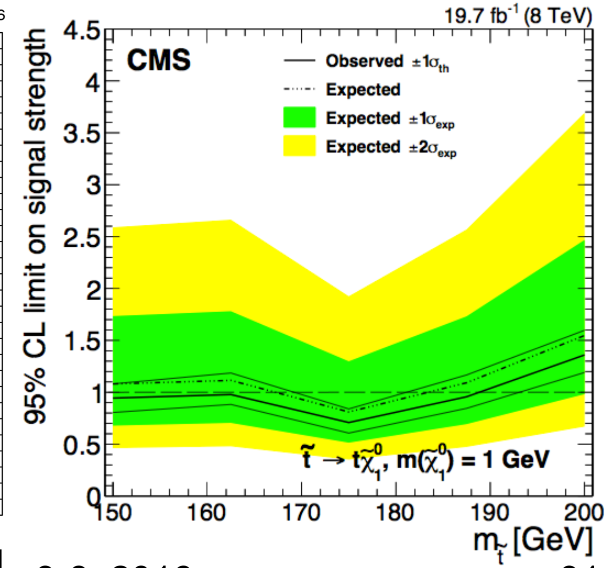
$$\tilde{t} \to t\tilde{\chi}_1^0 \to bW\tilde{\chi}_1^0$$ "heavy"

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



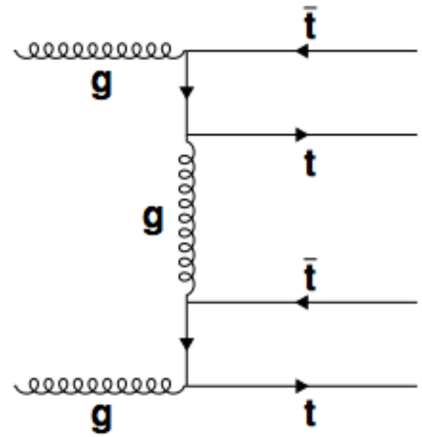
# Multi-top production

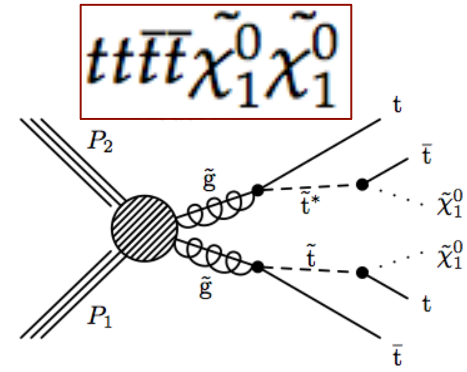
JHEP 11(2014)154, JHEP 01(2014)163, arXiv:1605.03171, TOP-16-016

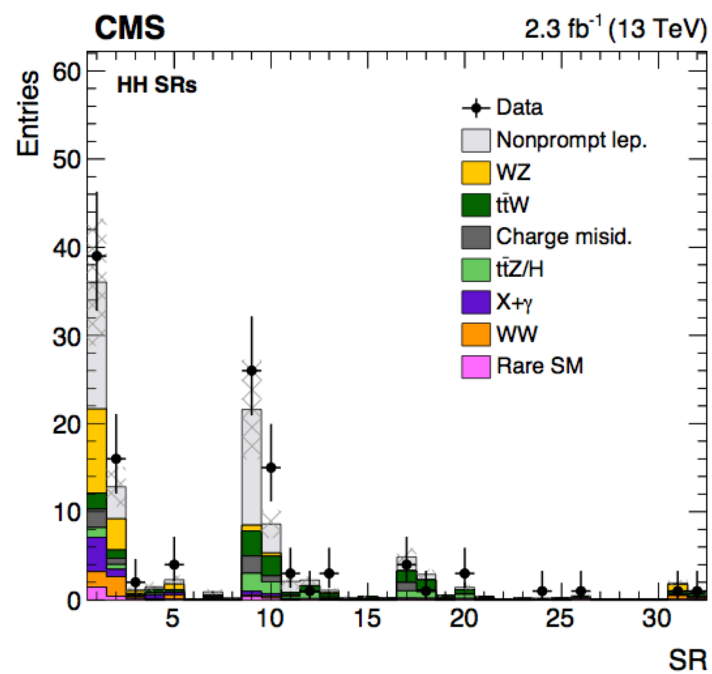
- Production of 4 tops is an attractive scenario in a number of new physics models
- The SM cross section is 9fb (~1fb@8TeV)

- Use lepton+jets final state
- Combination of kinematical variables and multivariate techniques
- Data are consistent with bkg expectations
- Set upper limit cross section 119fb @95%CL

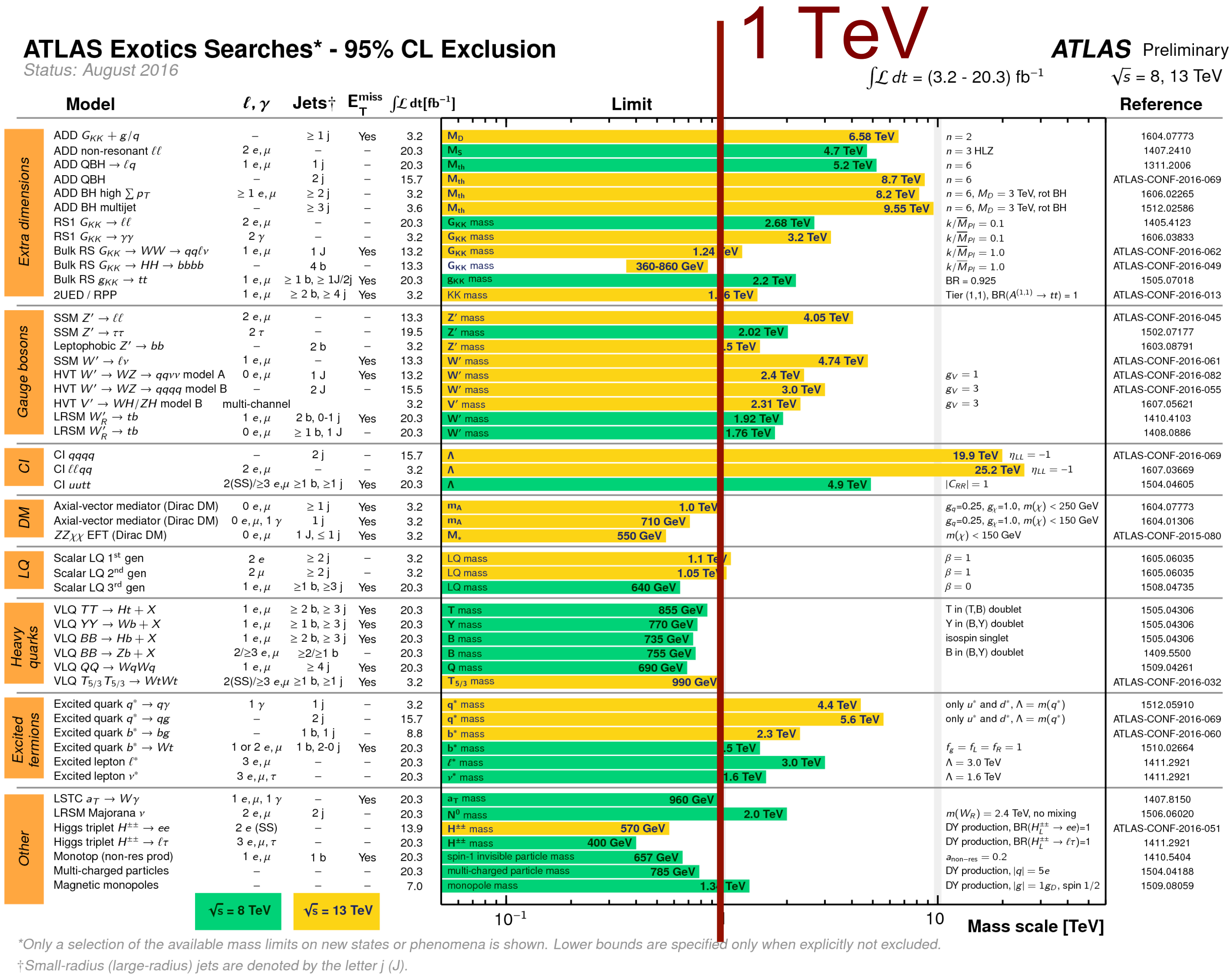
- Search for same-sign dileptons
- Several models considered
- Consider multiple search regions defined by MET, hadronic energy, number of (b-) jets, and $p_T$ of the leptons in the events



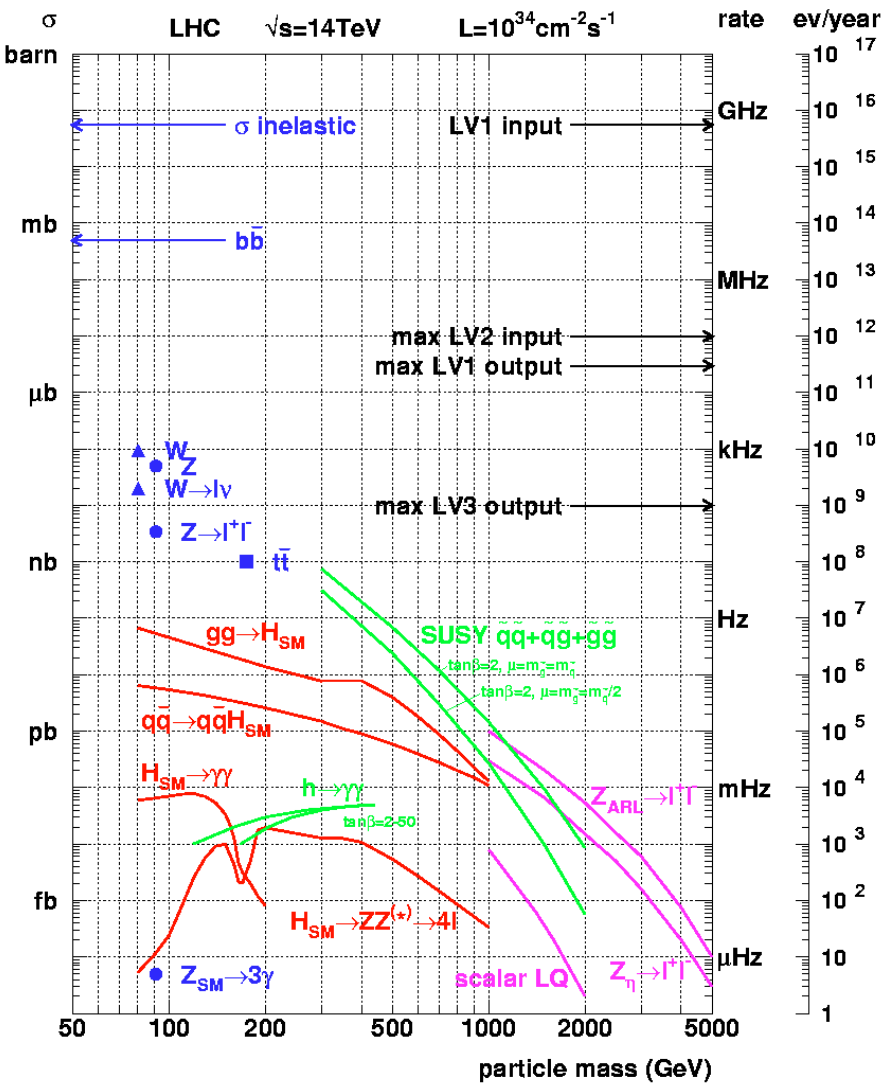



# Searches for new particles



# Cross sections at the LHC

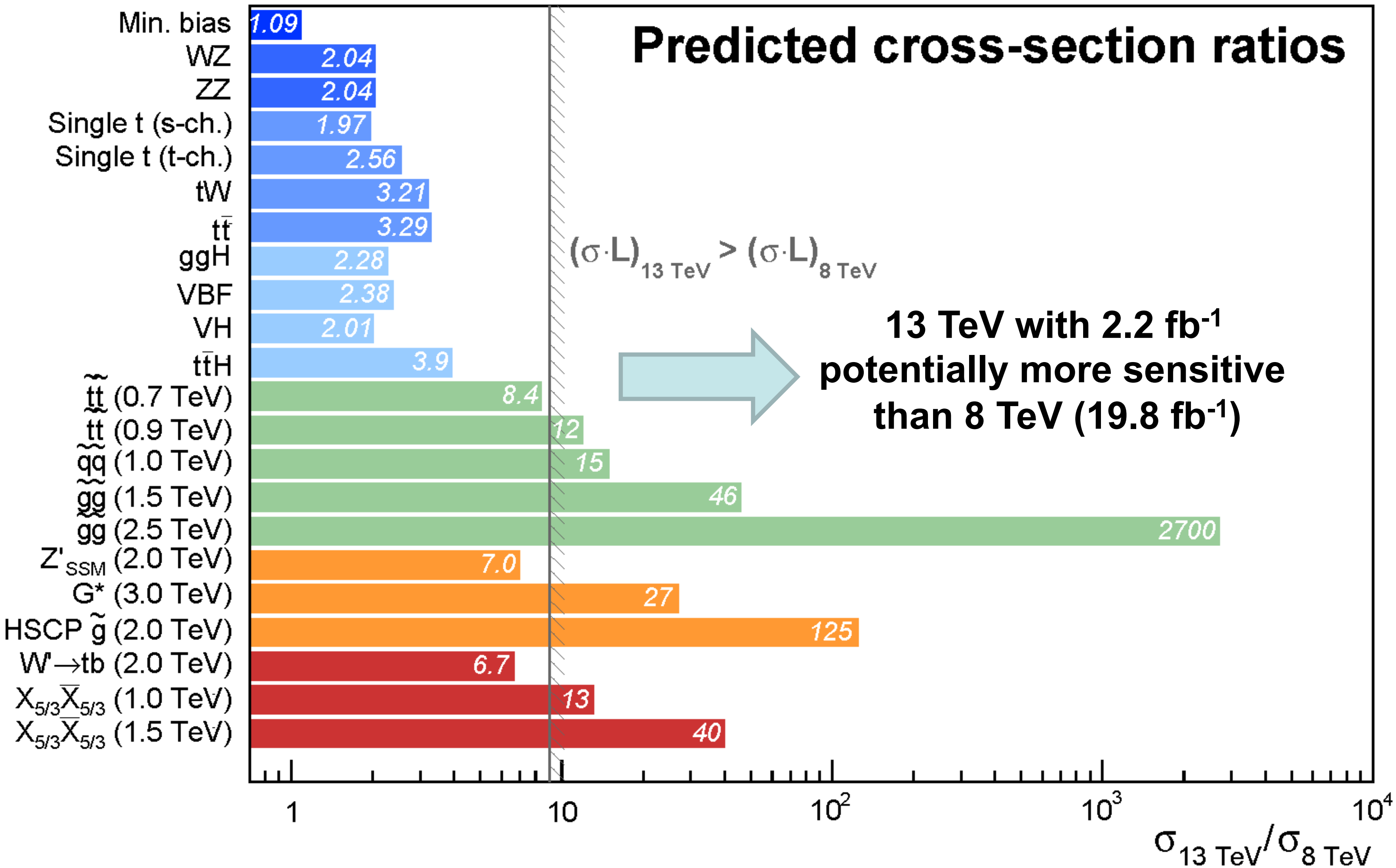



"Well known" processes, don't need to keep all of them …

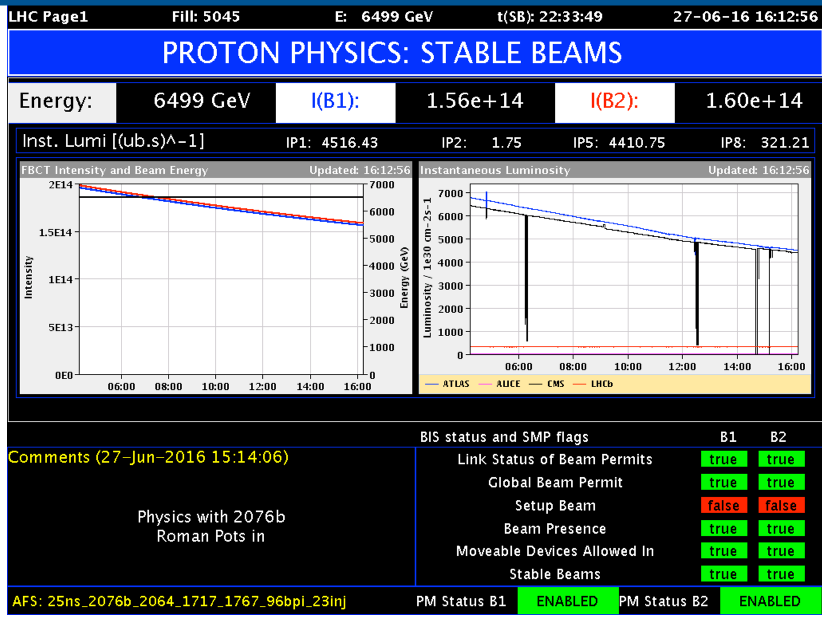
New Physics!!

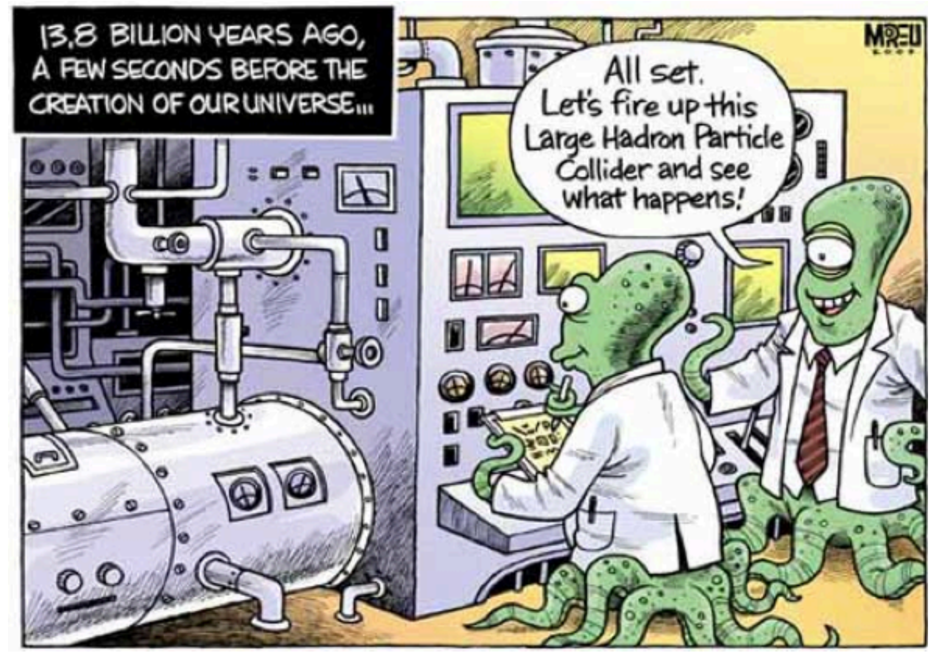
This is where to look

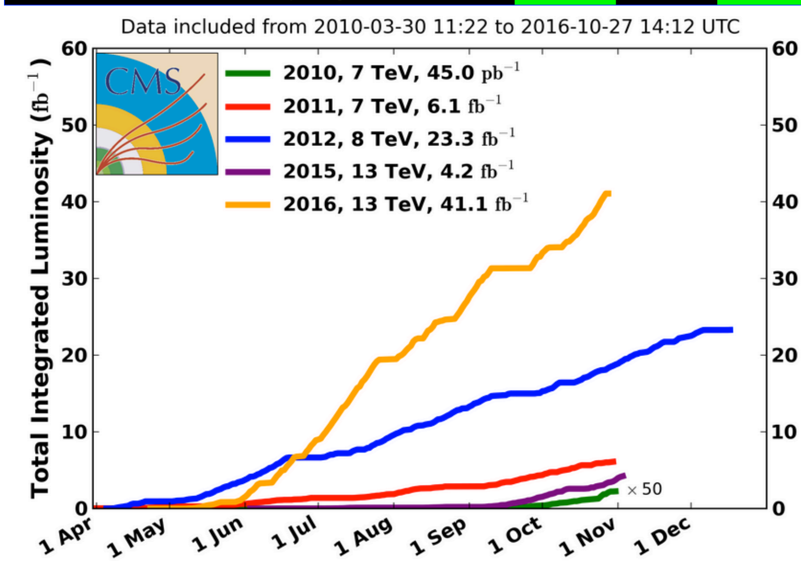
# Increased reach at 13 TeV



# What next?




- LHC is breaking “luminosity” records
  - high operation efficiency
  - surpassed $L_{inst}$=1x10$^{34}$ cm$^{-2}$s$^{-1}$
  - More than 40/fb delivered in 2016

# Summary

- Excellent consistency but SM is incomplete
- Top quark physics as a probe to BSM

- Excellent performance of the LHC
  - After LS1, increased energy to 13 TeV
- Searches provide no hints for BSM physics yet