Probing the SM: Top quarks and beyond

Michele Gallinaro

LIP Lisbon

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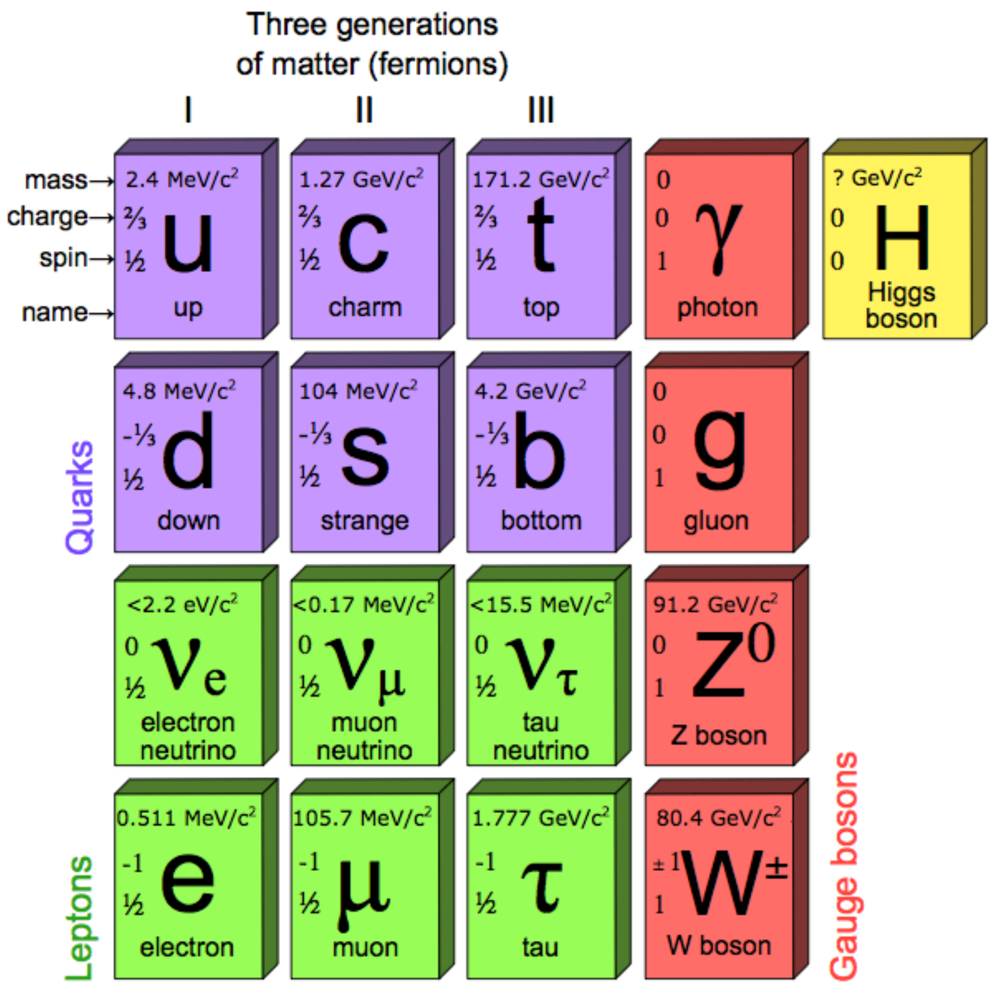
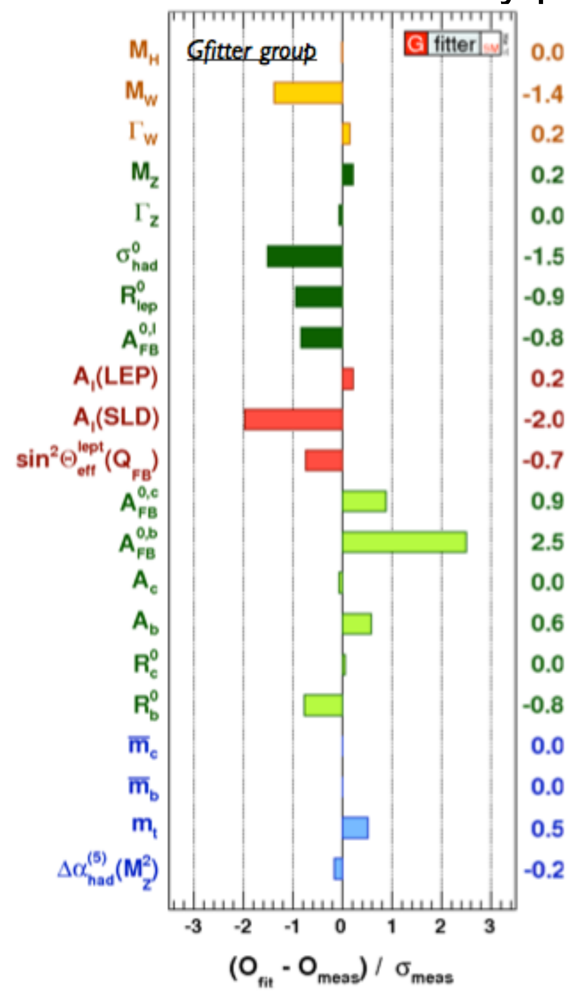
- ✓ Top quarks as window to New Physics
- ✓ Top-Higgs associated production
- ✓ Top quark signatures in SUSY
- ✓ Higgs and Dark Matter

SM confirmed by the data

Standard model of elementary particles

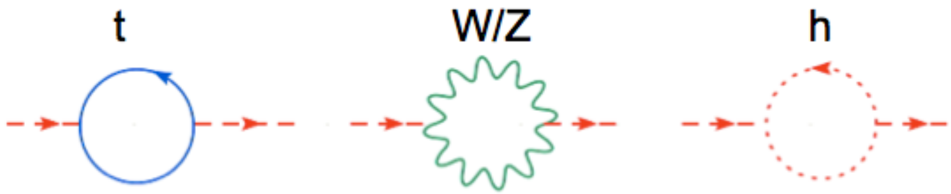




Excellent agreement with all experimental results

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:

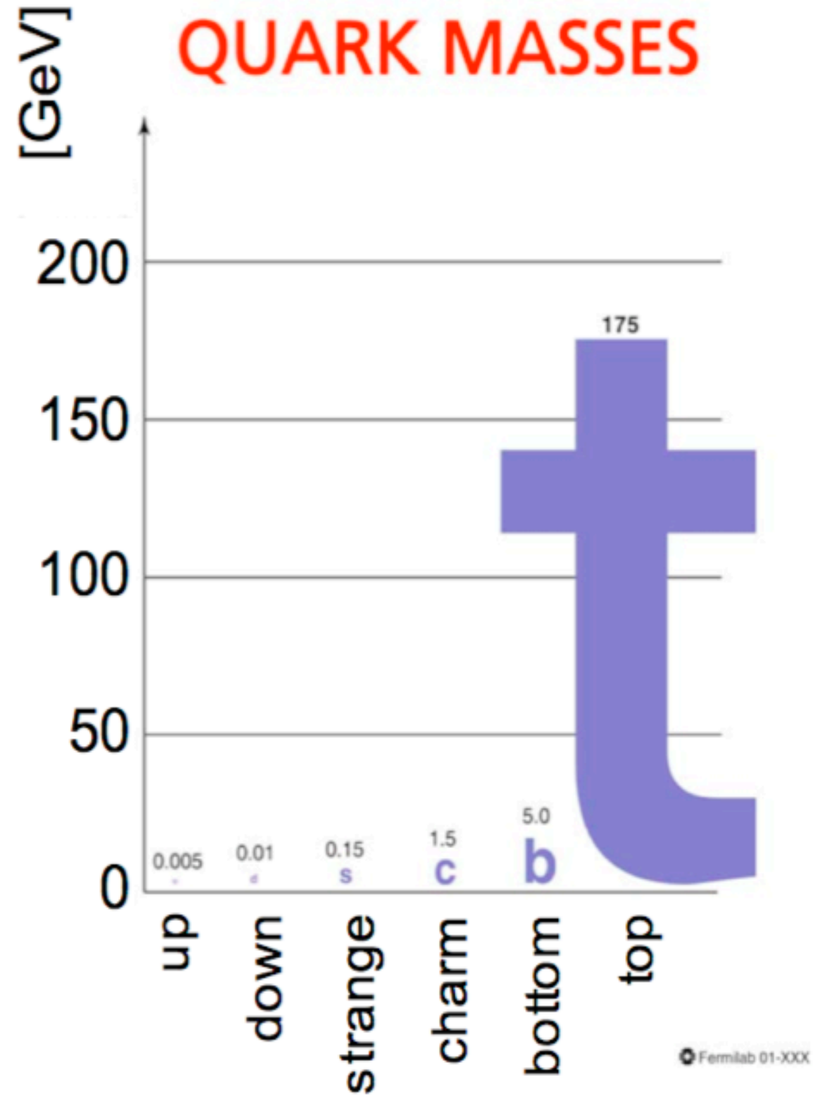
- Naturalness: There is no problem
- Weakly-coupled model at TeV scale
  - New particles to cancel SM divergences
  - Top partners: new scalar/vectors coupled to top, exotic top decays
- Strongly-coupled model at TeV scale
  - ttbar resonances, bound states, 4-top production, etc.
- New space-time structure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

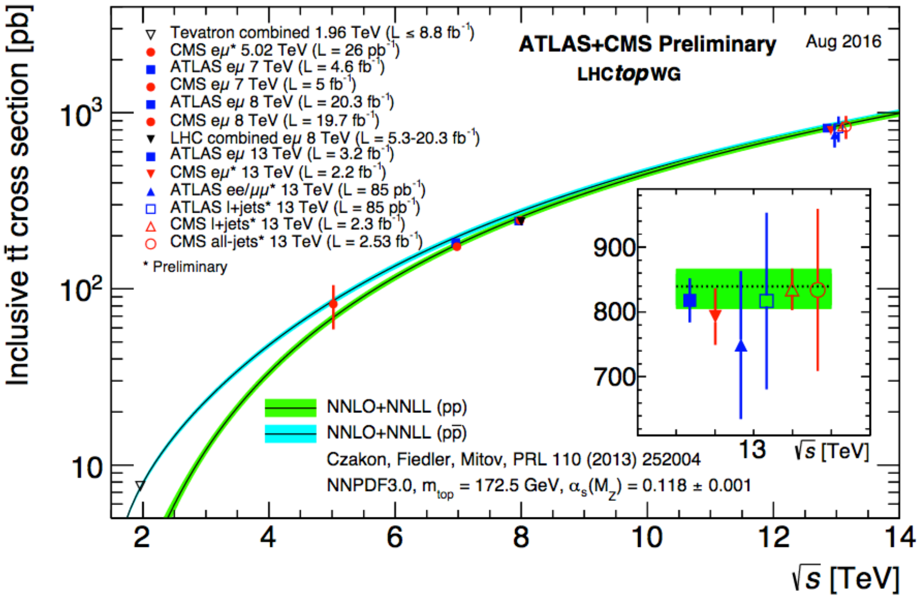


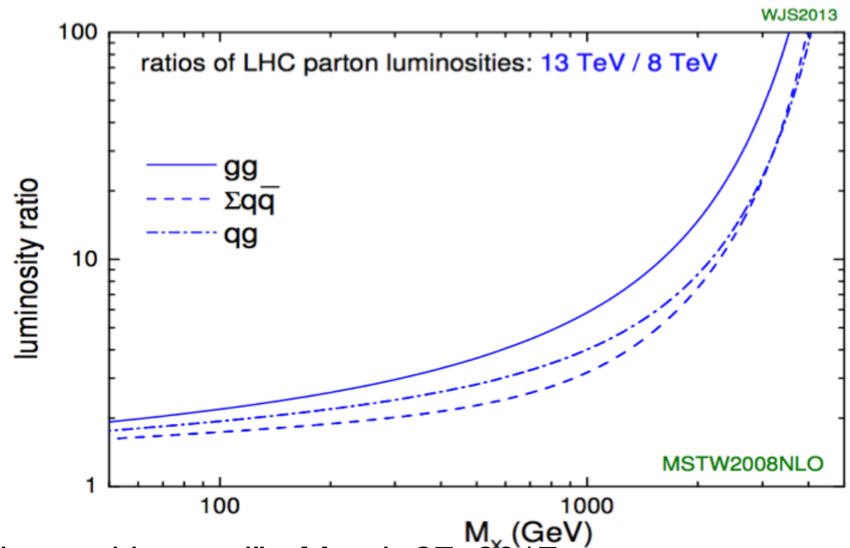
- Large samples of top quarks available
- Top quarks are main background for many New Physics searches
- Precision measurements may provide insight into physics beyond SM

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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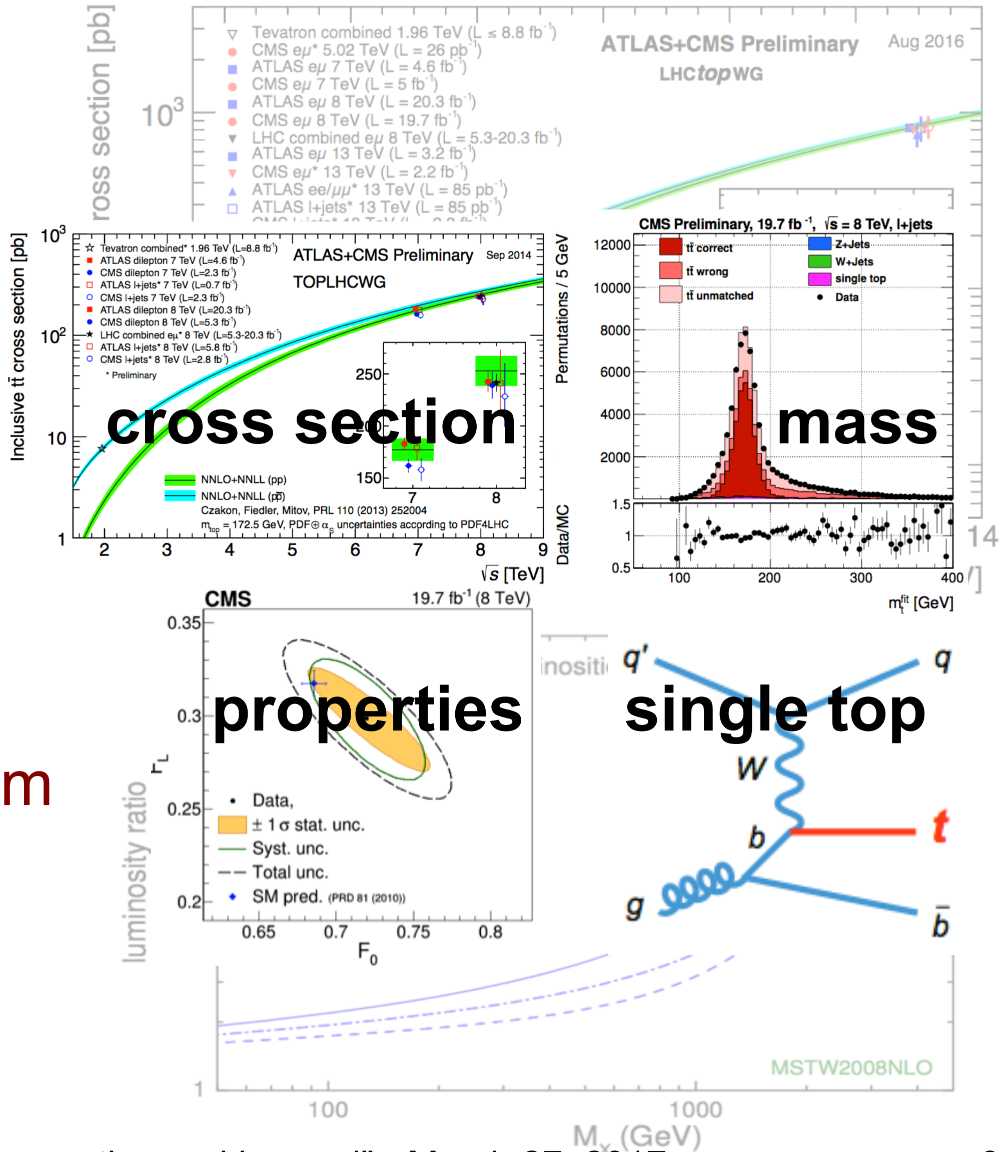
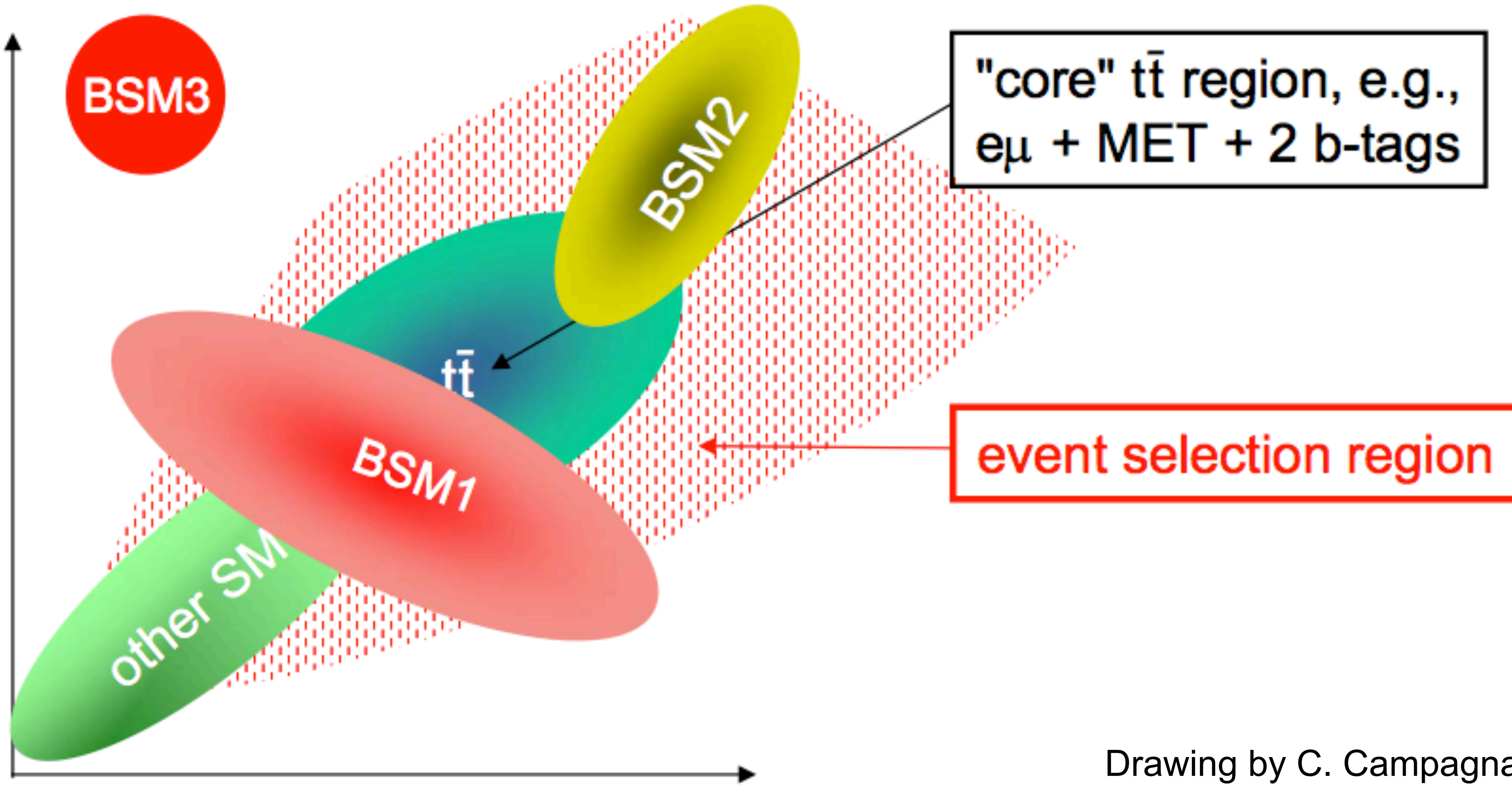
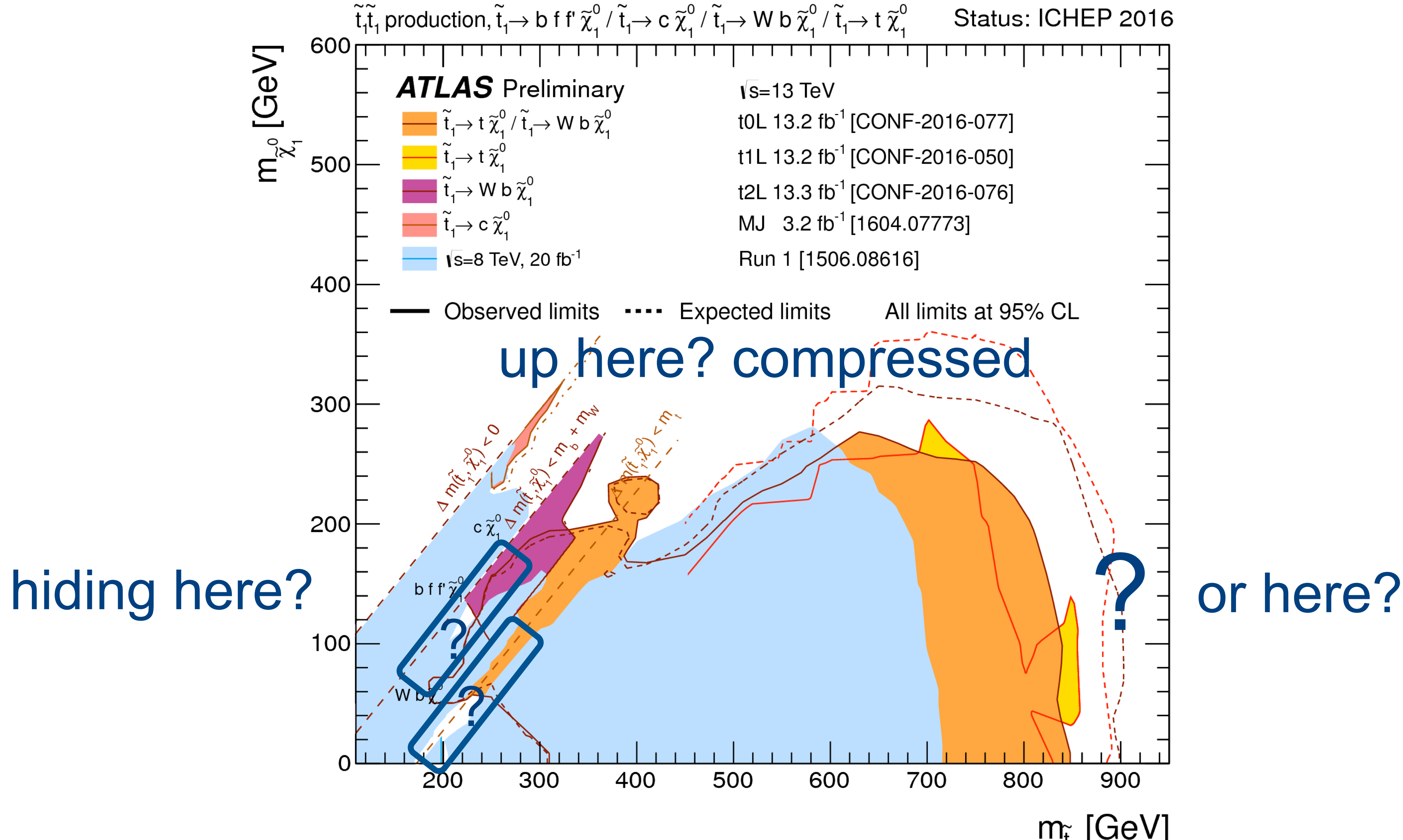


Study characteristics



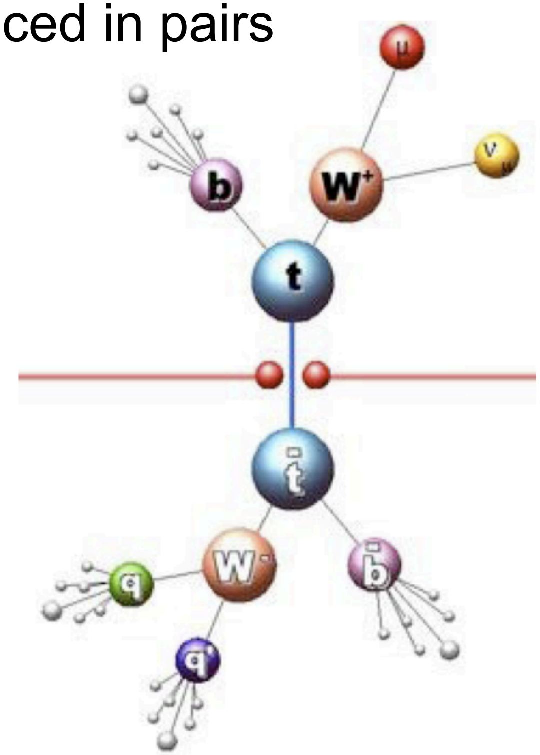
Drawing by C. Campagnari

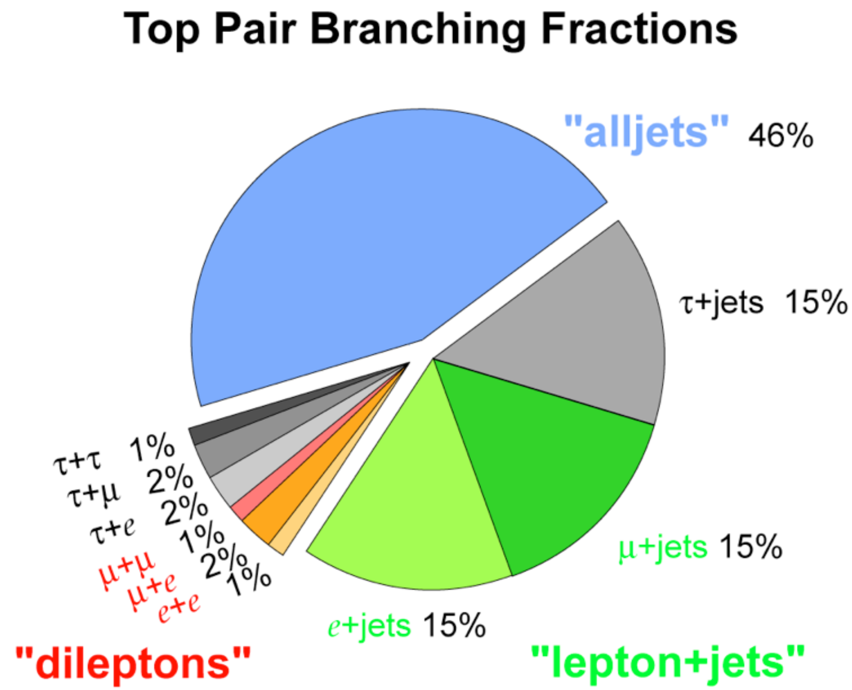
Regions hard to explore



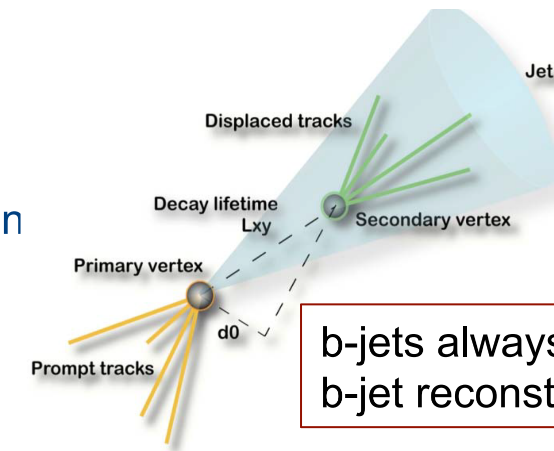
Top quark decays

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

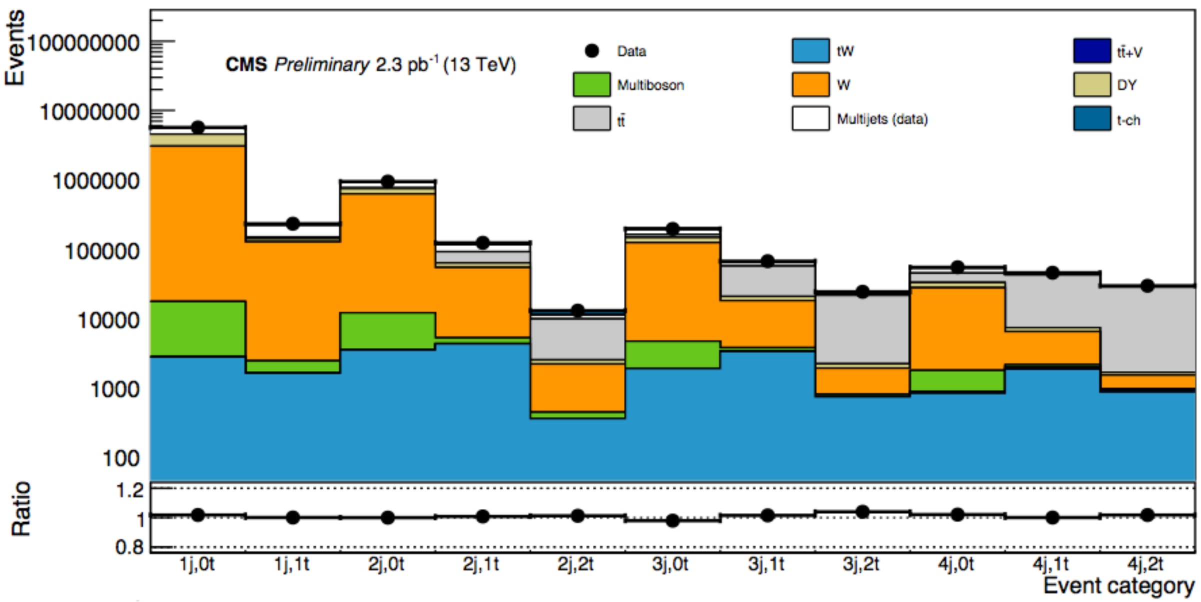


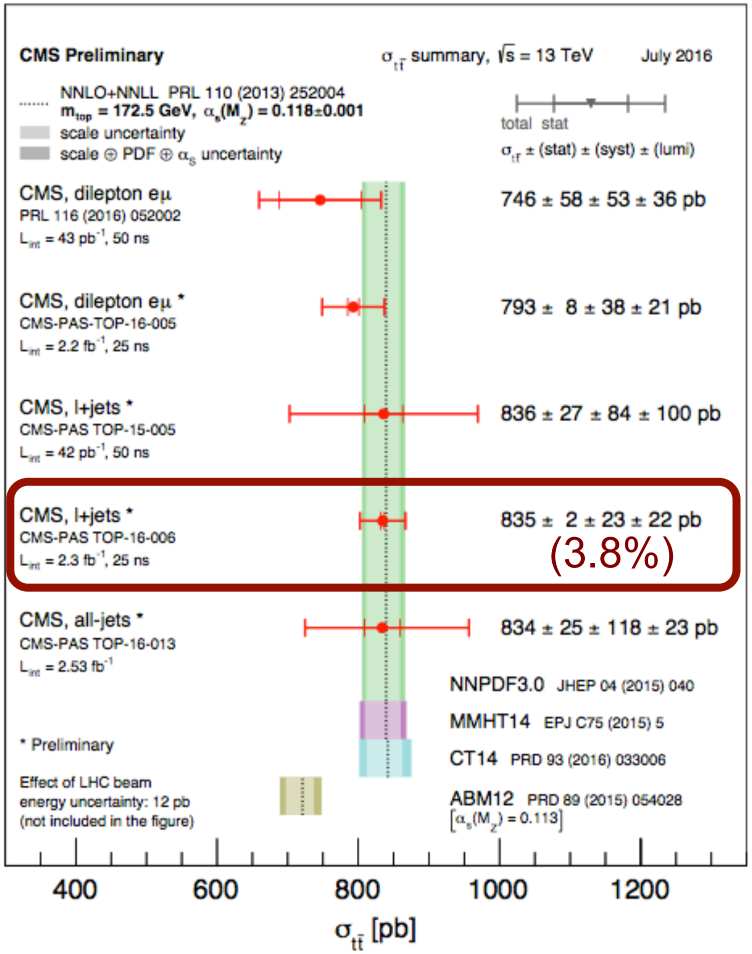
b-jets always present
b-jet reconstruction plays important role

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





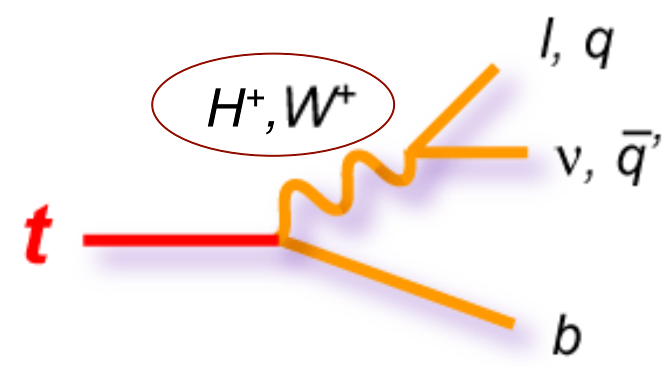
Probing the Wtb vertex

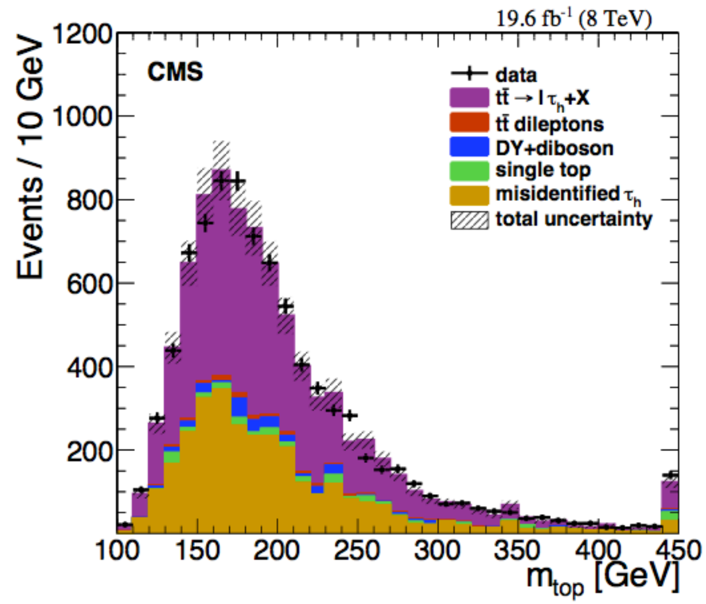
PRD 85 (2012) 112007, PLB 739 (2014) 23

Dileptons with taus

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

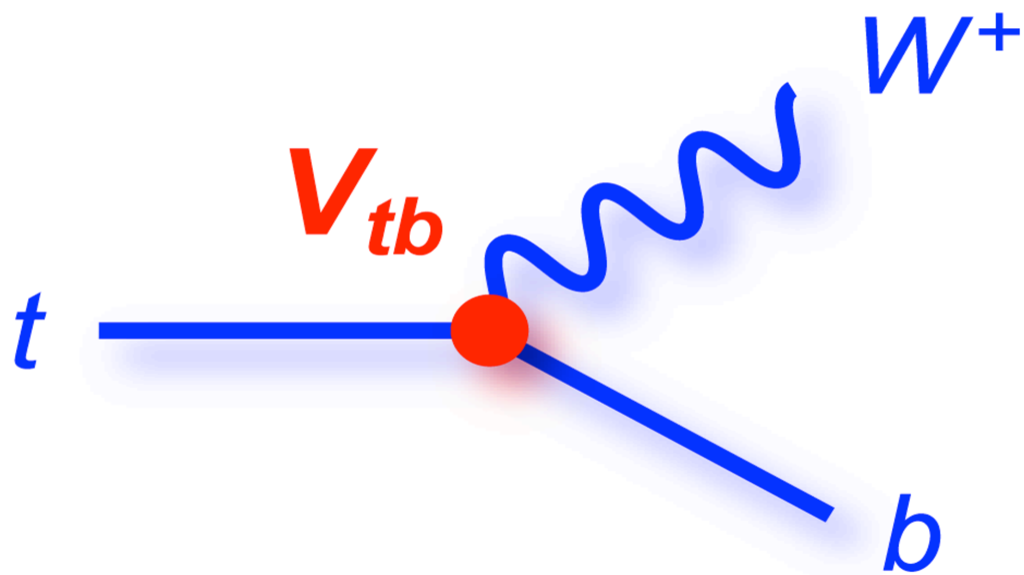
Channel	Signature	BR
Dilepton(e/μ)	*ee*,μμ,*e*μ + 2*b*-jets	4/81
Single lepton	*e*,μ + jets + 2*b*-jets	24/81
All-hadronic	jets + 2*b*-jets	36/81
Tau dilepton	*e*τ, μτ +2 *b*-jets	4/81
Tau+jets	τ + jets + 2*b*-jets	12/81





- 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?



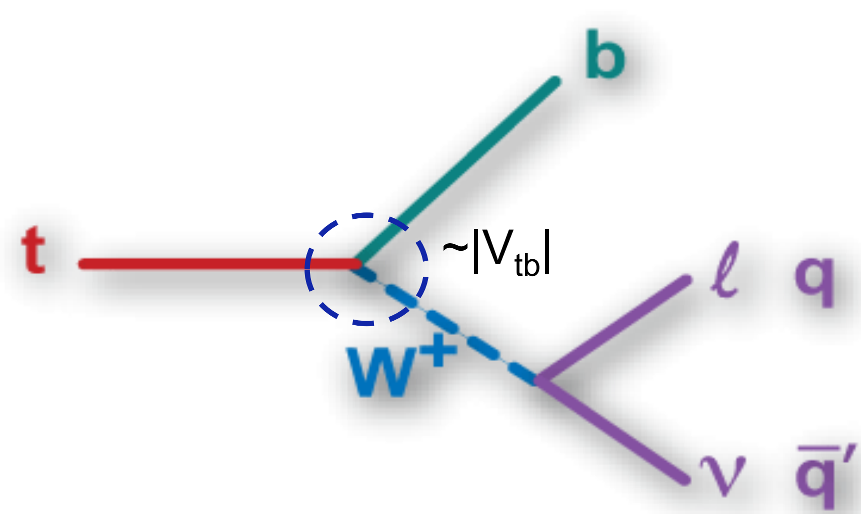
- almost always $t \rightarrow Wb$ (i.e. $V_{tb} \sim 1$)
- lifetime is short, and it decays before hadronizing
- the W is real:
  - can decay $W \rightarrow l\nu$ ($l=e,\mu,\tau$), BR~1/9 per lepton
  - can decay $W \rightarrow qq$, BR~2/3

Measure R in dilepton channel

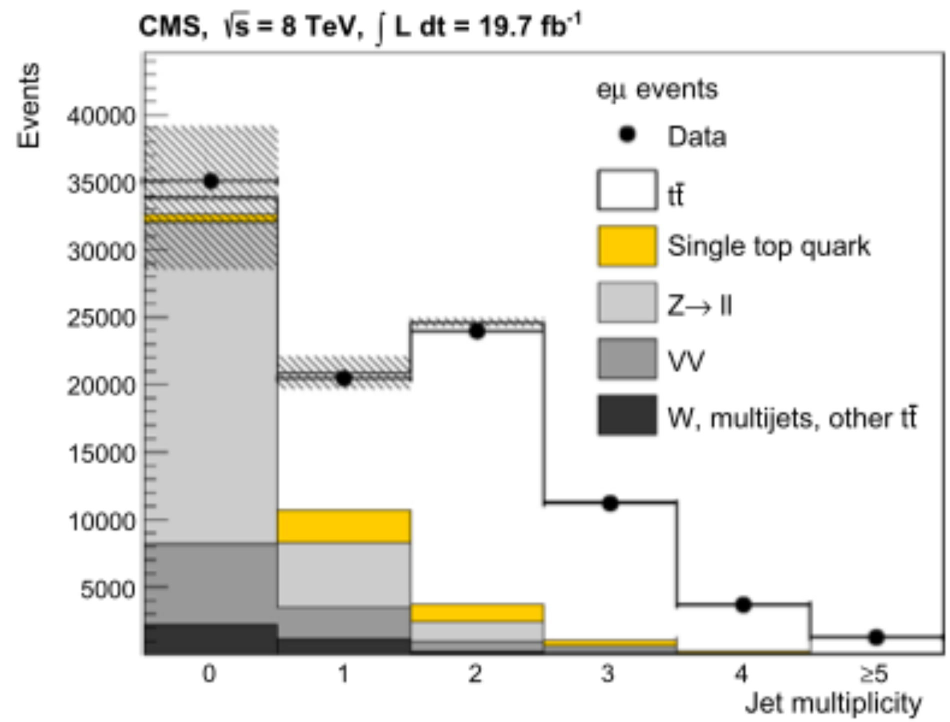
N.Cim. B125(2010)983, PLB 736(2014)33

- Probe heavy flavor content of ttbar events
- Use ttbar dilepton final state
  - small background
- Measure:

$$R \equiv \frac{BR(t \to Wb)}{BR(t \to Wq)}$$



- Selection:
  - 2 leptons+ ≥2 jets + MET
  - no b-tagging in preselection
- Goals:
  - measure ε(b) and R

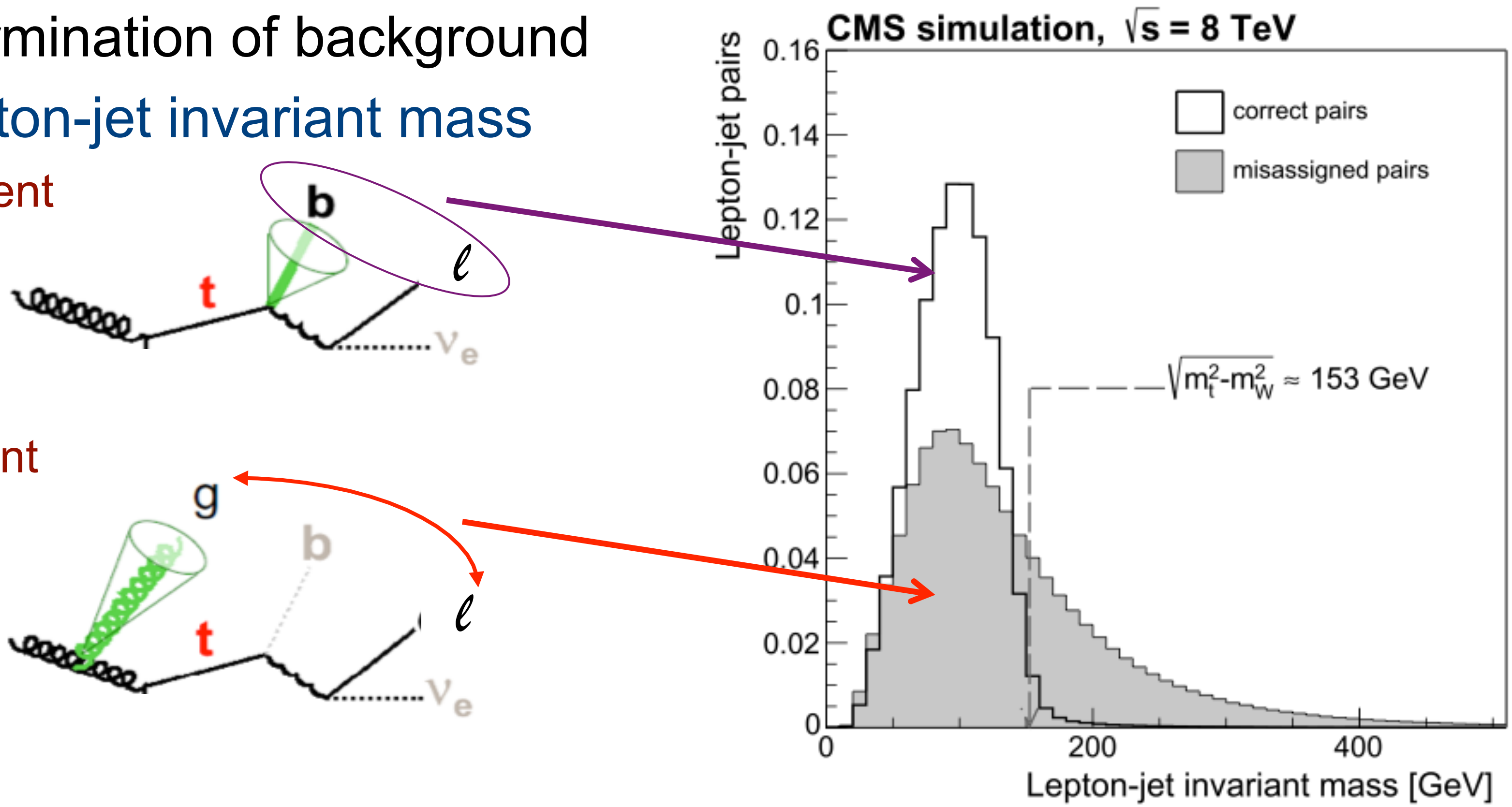


Signal or background?

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

Data-driven determination of background

- Reconstruct lepton-jet invariant mass
  - Correct assignment
  - Wrong assignment

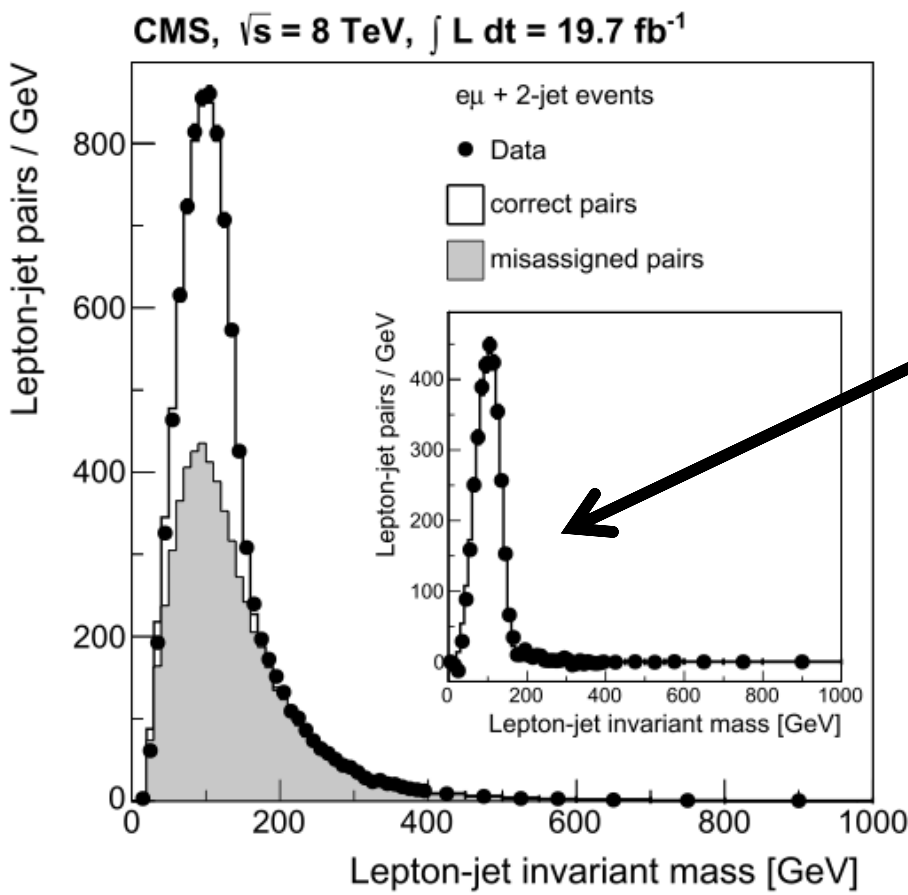


- Use tail to model background in signal region

Signal vs. background

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

Scale shape to match spectrum observed with M_{lj}>180 GeV

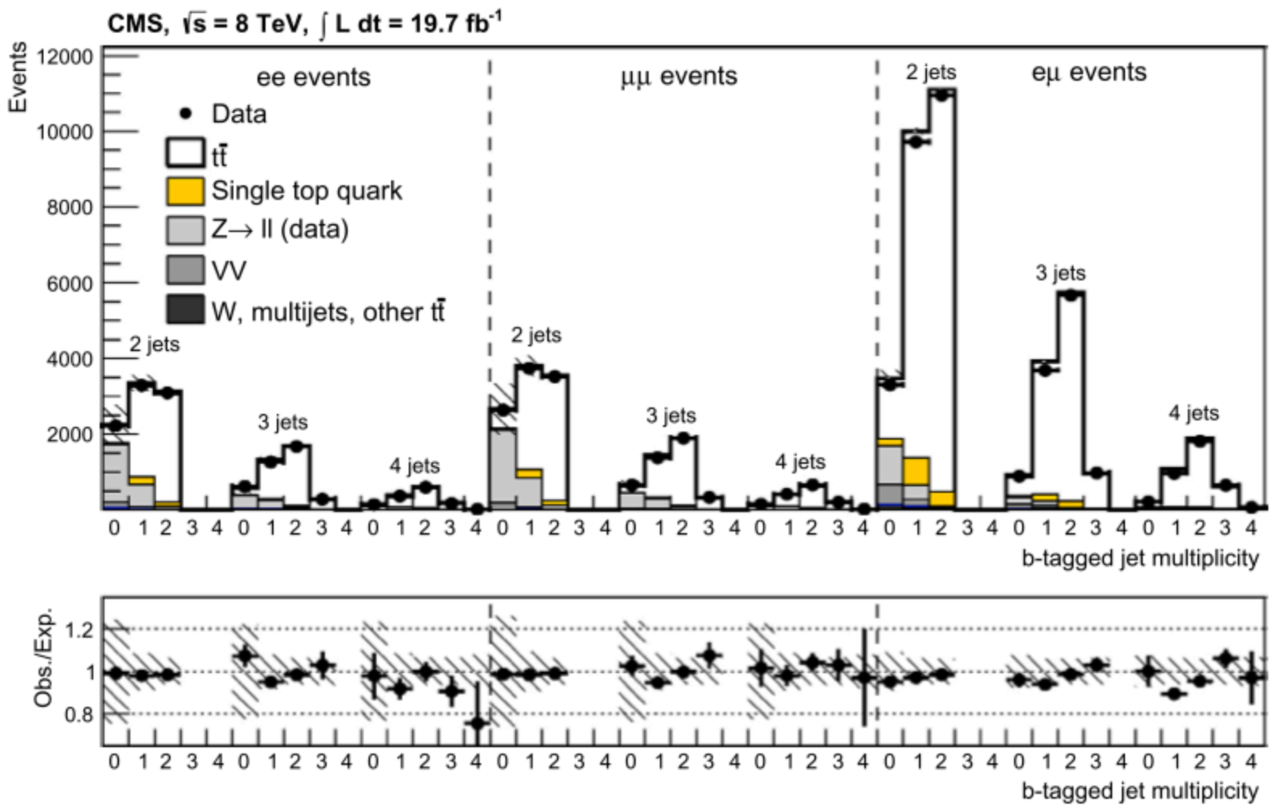


after background subtraction

Heavy flavor content

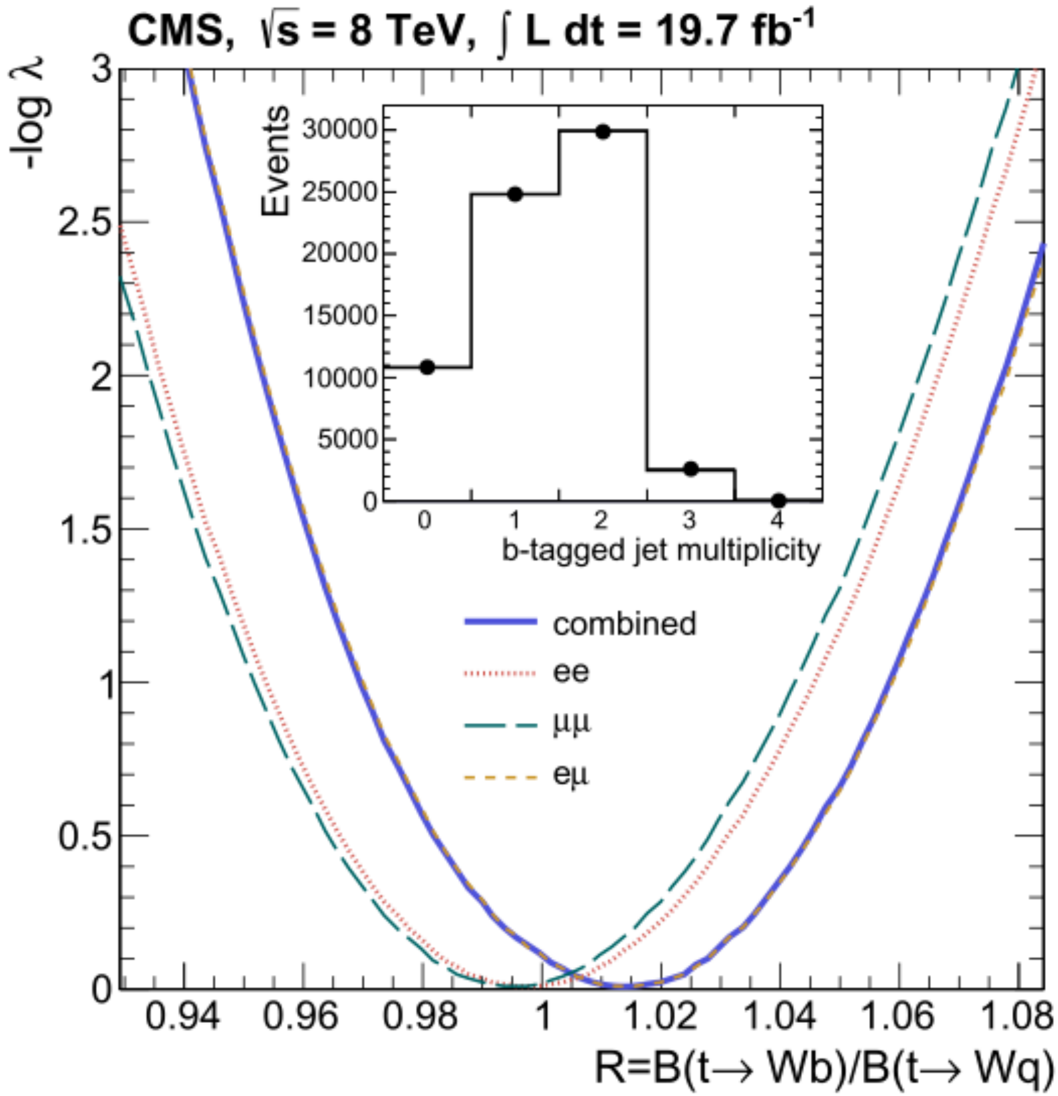
N.Cim. B125(2010)983, PLB 736(2014)33

- Measurement
  - b-tagging multiplicity parametrized as function of R ε_b, ε_q, top contribution
  - Number of reconstructed t→Wq is estimated from lepton-jet invariant mass
- R=1.01±0.03 (stat.⊕ syst.)
  - Lower boundary with confidence interval @95%CL after requiring R≤1 **⇒ R>0.955 @95%CL**



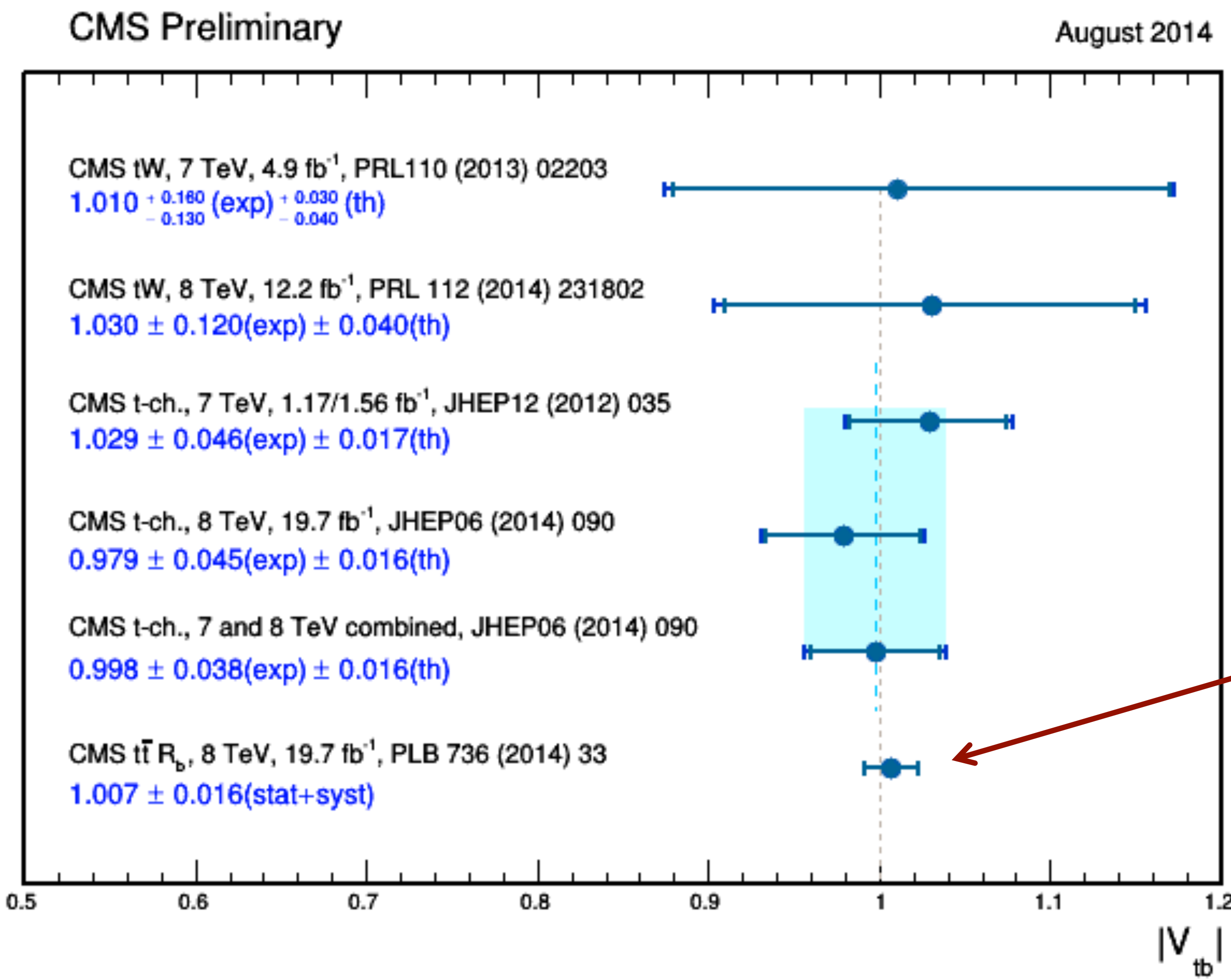
Measure R

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



- Variation of the likelihood used to measure R from data
- Fit different categories

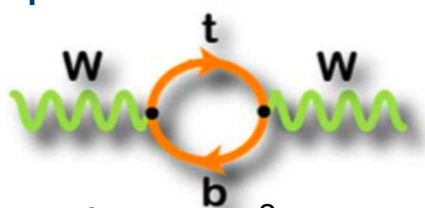
Summary of R results

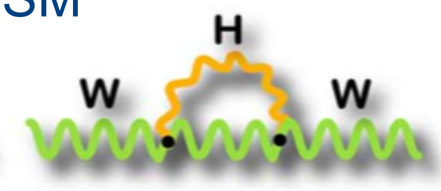


Most accurate measurement

Why top quark properties?

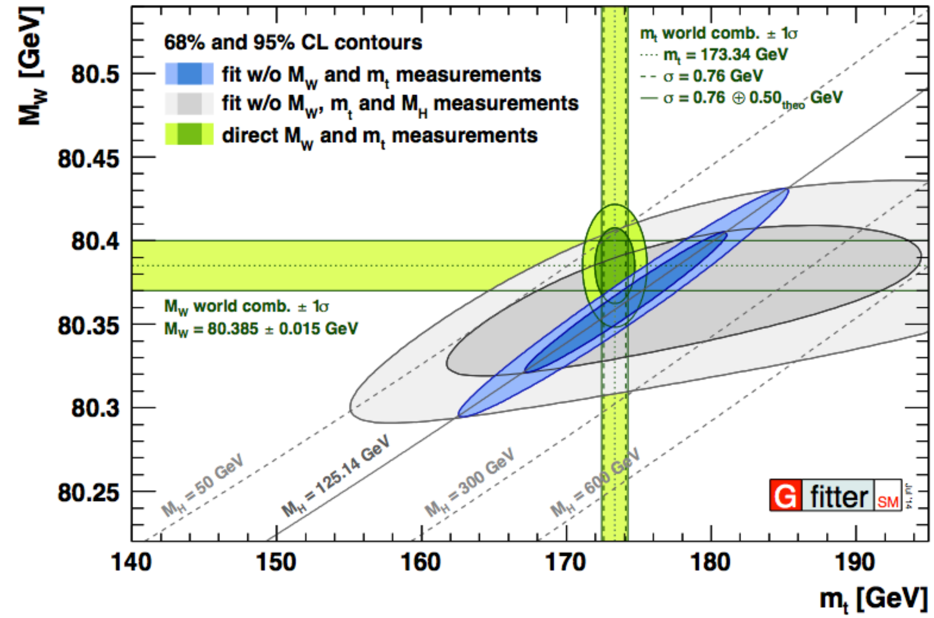
- Top quark mass is a fundamental parameter of the SM





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

- Precise measurement needed for checking consistency of the SM

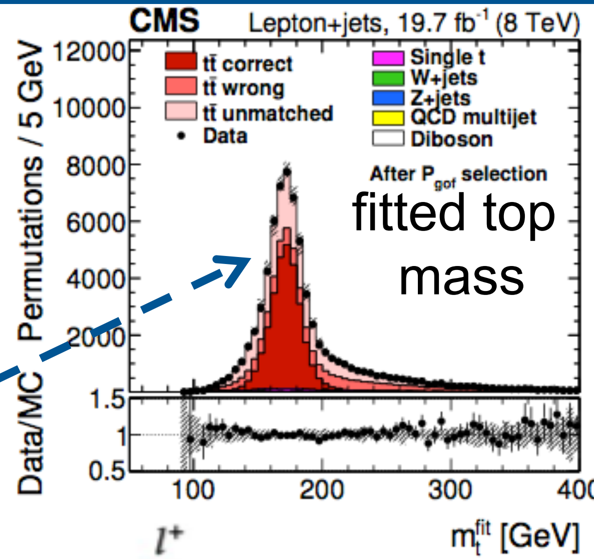


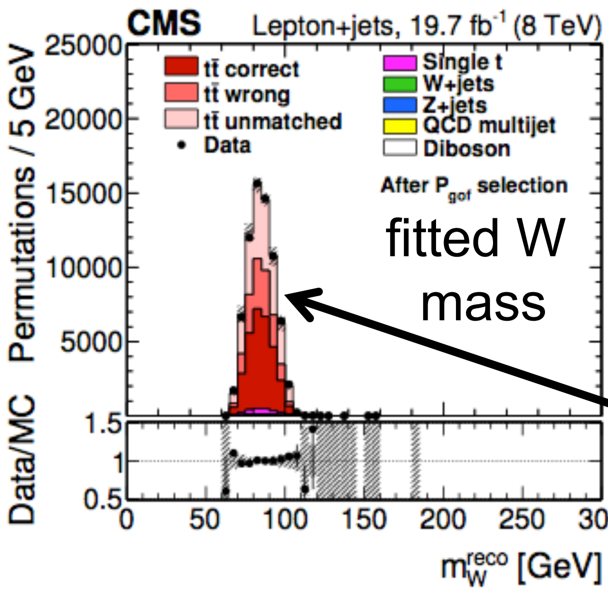
- Top is the only fermion with the mass of the order of EWSB scale
- Discovered Higgs boson fits well with precise determinations of m_W and m_{top}
- Other properties (EWK coupling, production asymmetries, etc.) are predicted by SM
- Precise measurements could reveal breakdown of SM

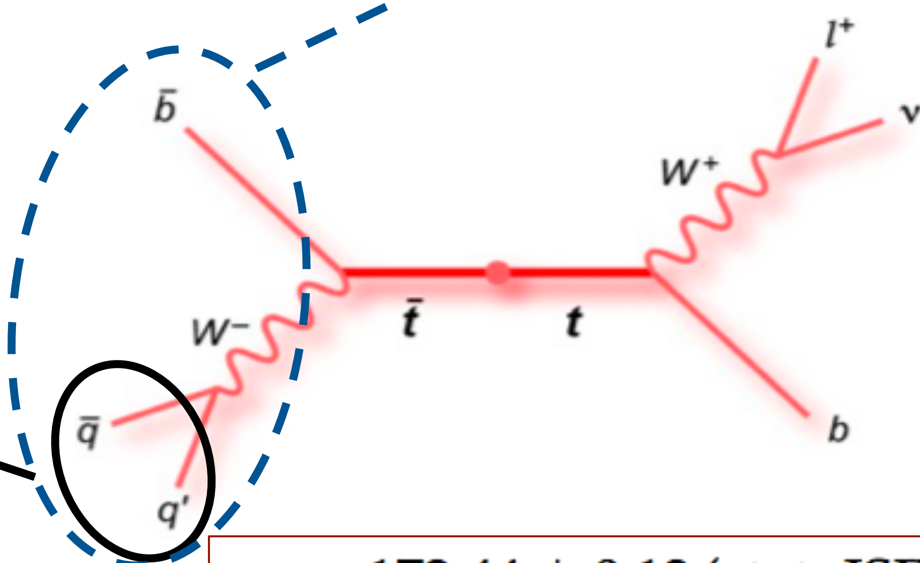
Precise mass measurement

arXiv:1509.04044

- 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





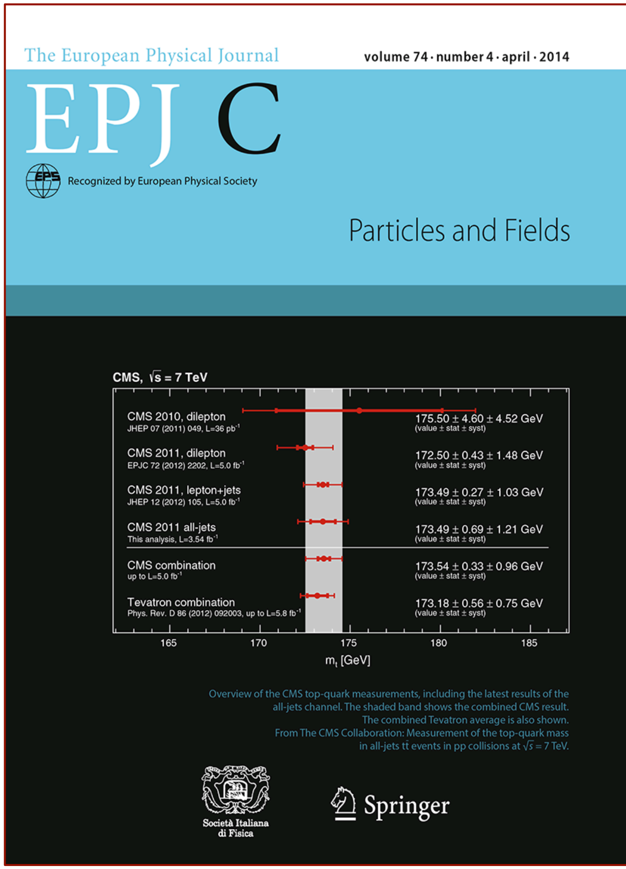


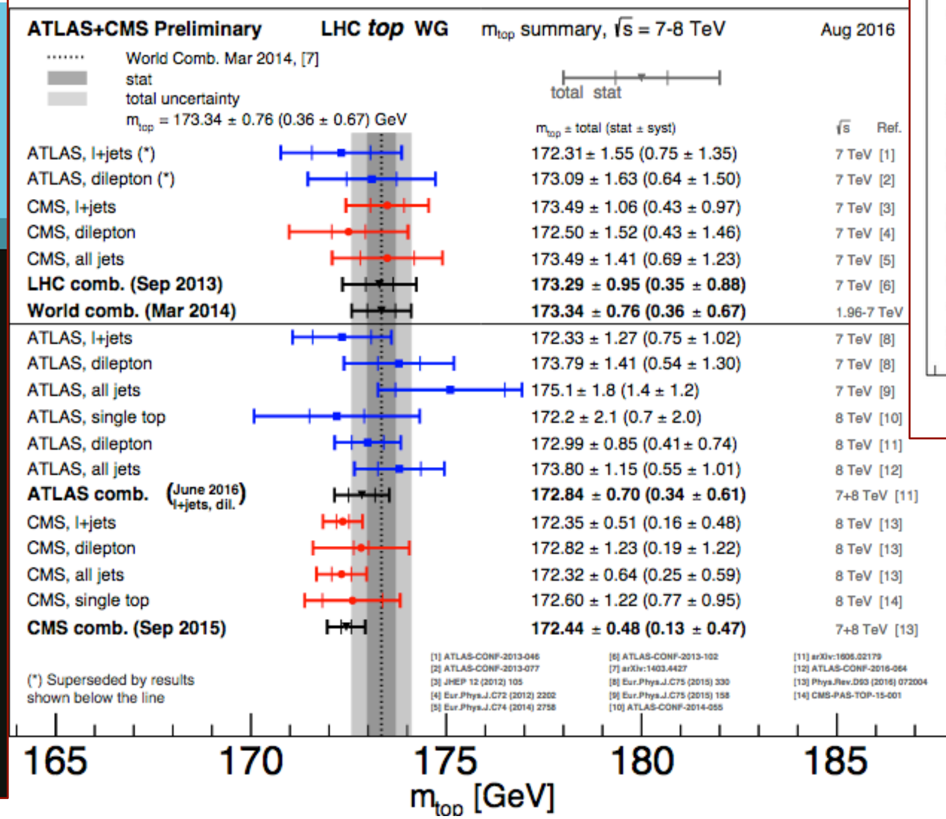
±0.3%

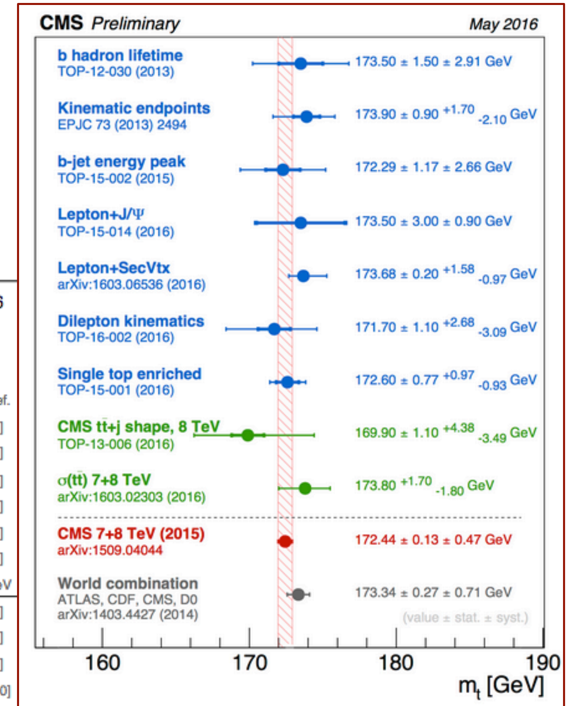
$$m_t = 172.44 \pm 0.13\,(\text{stat+JSF}) \pm 0.47\,(\text{syst})\,\text{GeV}$$

Top quark mass results

- accurate (~0.3%) measurement



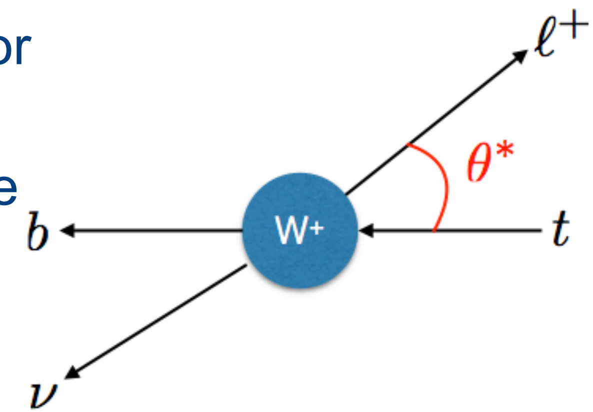


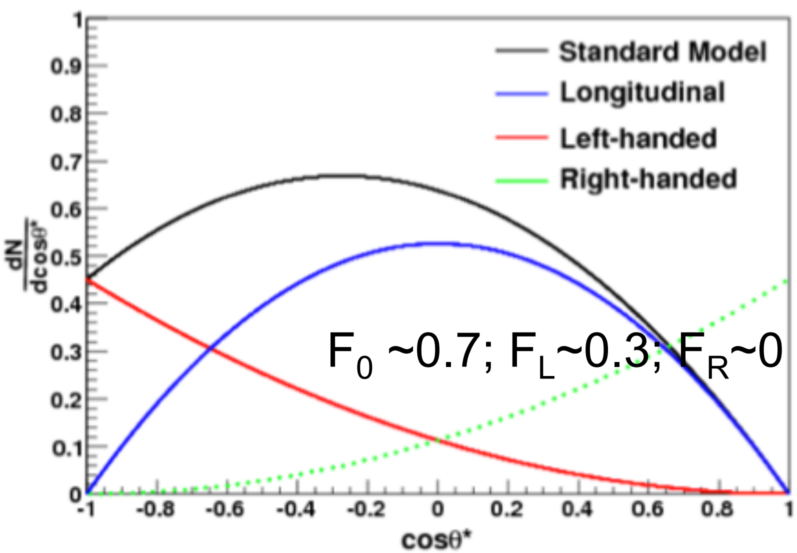


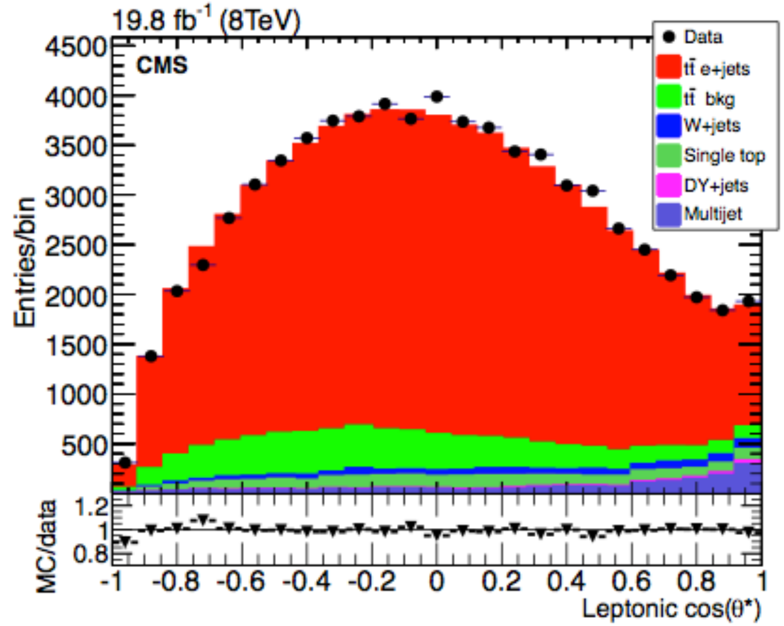
W boson polarization

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



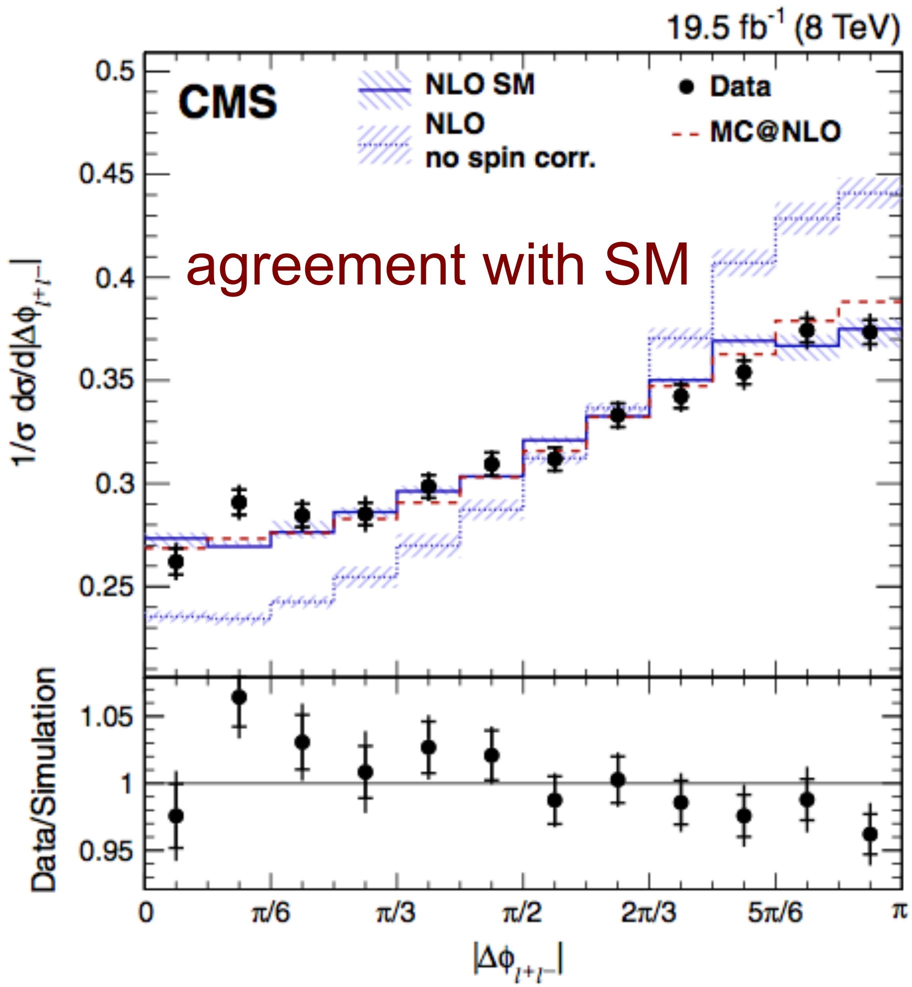




Spin correlation

PRD 93(2016)052007

- 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) ⇒ 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

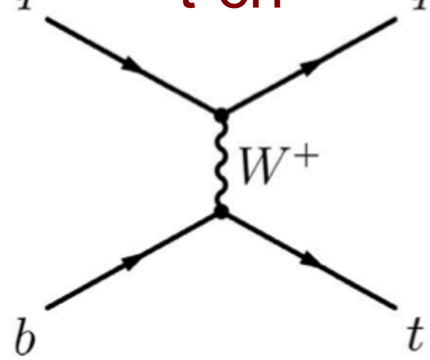


How else is Top produced?

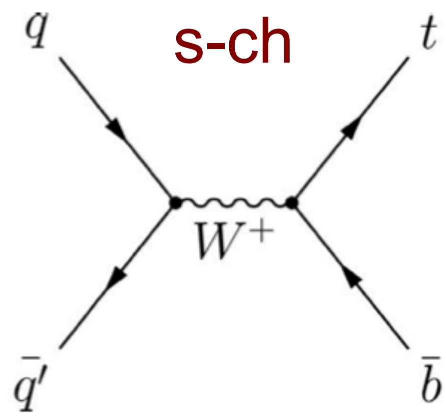
PRD102(2009)182003, PRD81(2010)054028

- Single top quark production

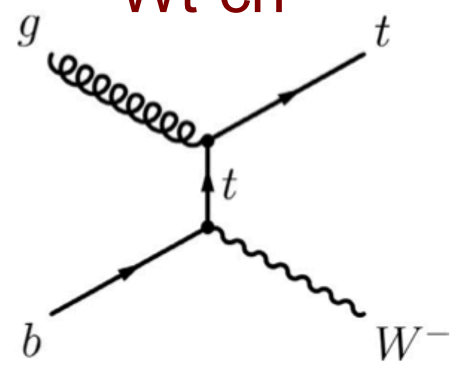
t-ch



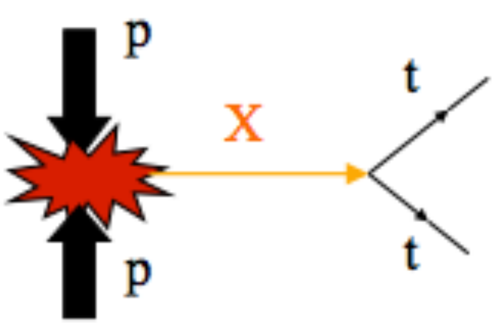
s-ch



Wt-ch



σ(13TeV) = 217 pb 10 pb 72 pb

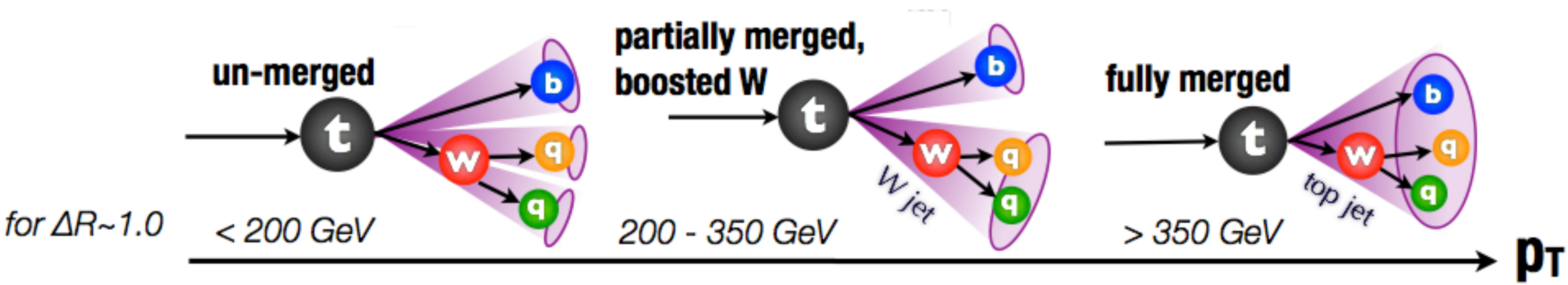


Resonance Production?
Top Color-Assisted Technicolor
OR
?????

Probing top quark production

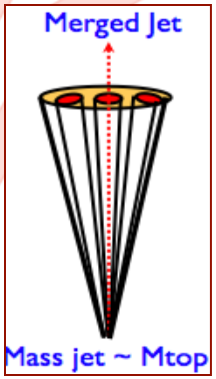
- Differential measurements
  - Testing QCD, measuring properties, searching for new physics, …
  - Function of kinematics, global variables, associated production
- Increased sensitivity: top quark pairs produced at rest
  - σ (M_{tt}>1 TeV at 13 TeV) =8 x σ(M_{tt}>1 at 8 TeV)

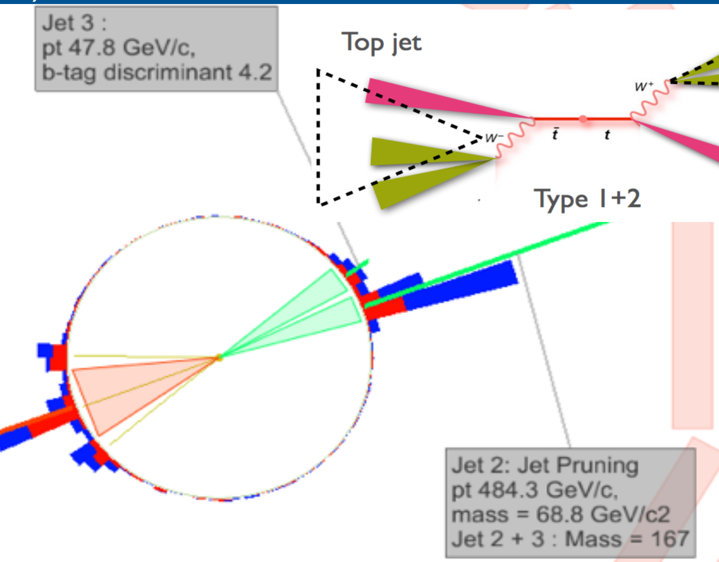
⇒Unique opportunity to probe boosted production at 13 TeV



Boosted topology

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

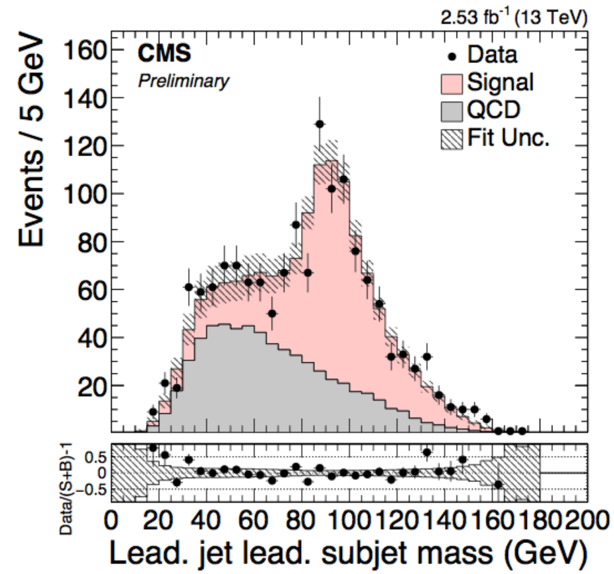


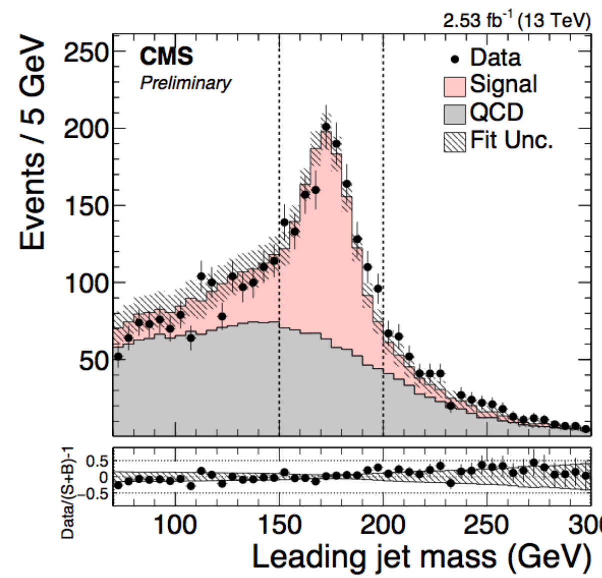


Jet 1 : Top Tagging
pt 589.1 GeV/c,
3 subjets,
mass = 186.7 GeV/c2,
minMass = 87.2 GeV/c2

see also CDF note 10234

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





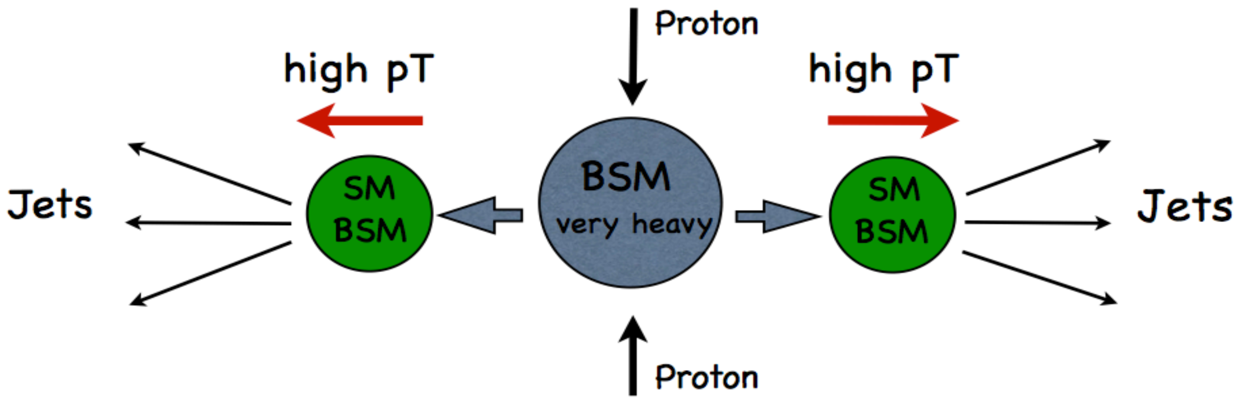
- At high energy, particles produced beyond threshold
- All-hadronic topology
  - Top p_T boosted, jets are collimated
  - Decay products and FSR collected in a “fat” jet
- Look at jet substructure
- Measure mass (no neutrinos)

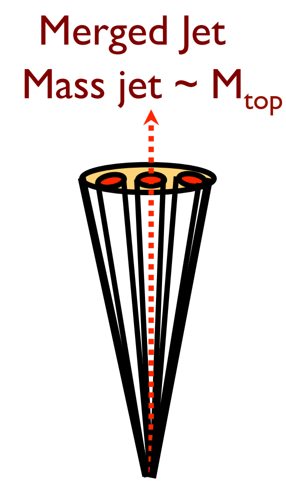
Boosted topology

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

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

- Simple approach to merge neighboring jets

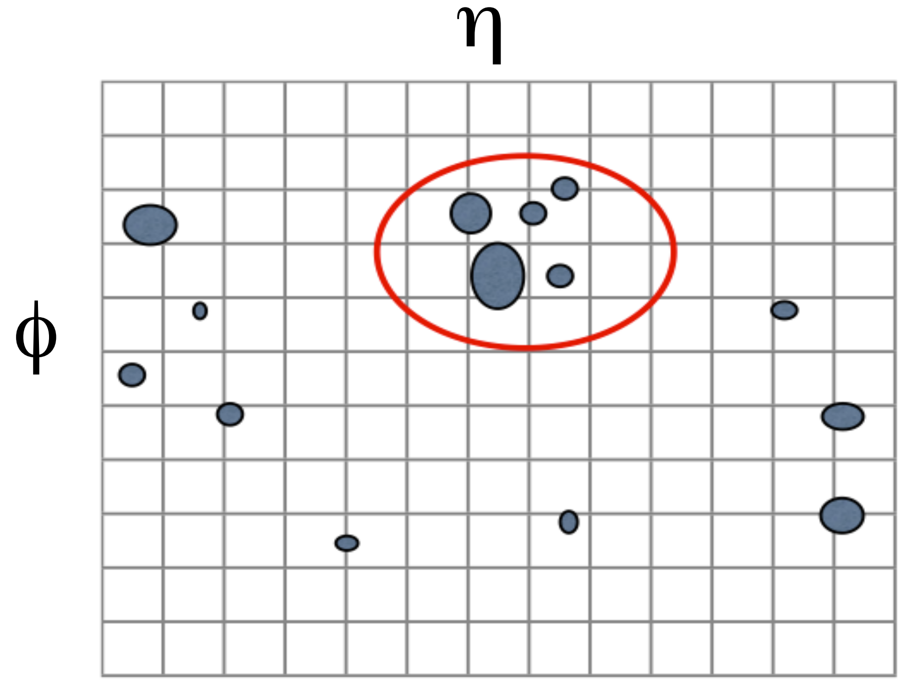




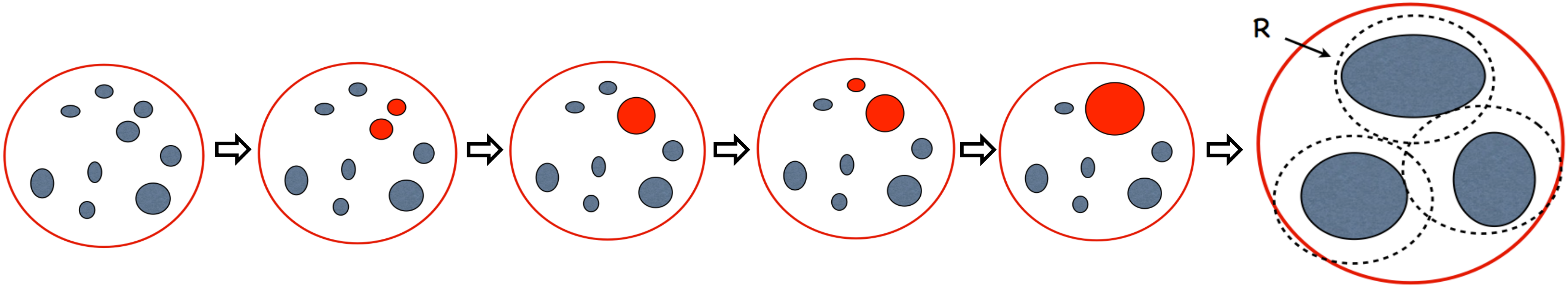
- At LHC energy, EWK scale particles produced beyond threshold
- Jets are highly collimated
- Decay products and FSR collected in a fat jet

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

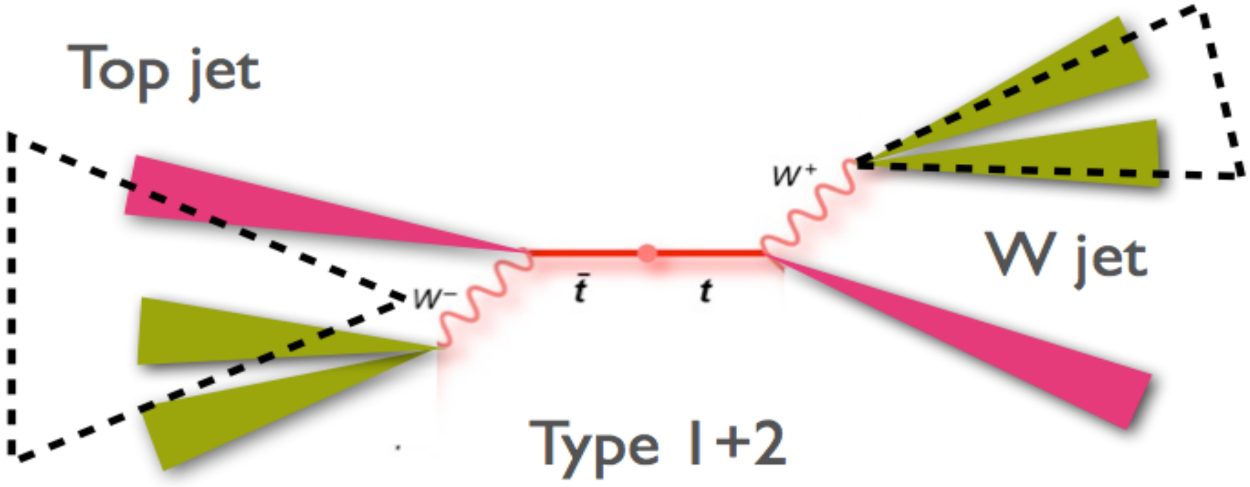


UE, ISR, Pile-up, hard interaction



Boosted topology: Top

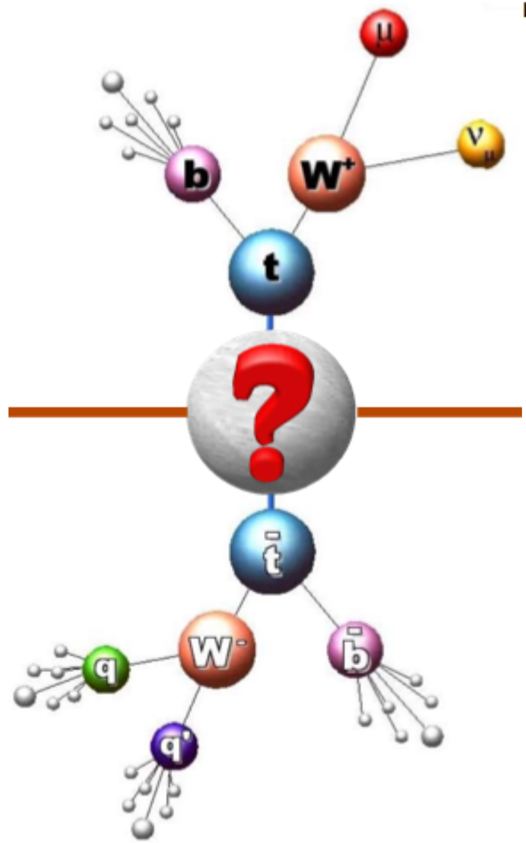
- Highly boosted top: three hadronic decays of the top are merged in one top jet
- Moderately boosted top: three hadronic decays of the top are merged in one W jet plus and one b jet candidates

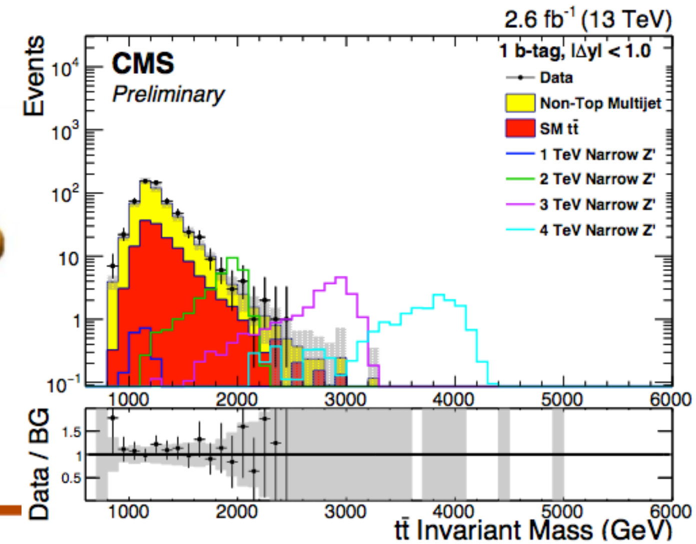


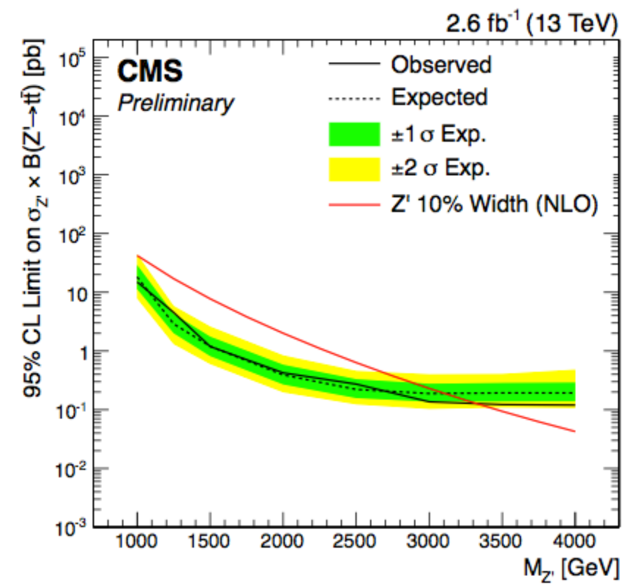
Top quark pair resonance

CMS-B2G-15-002, B2G-15-003

- 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

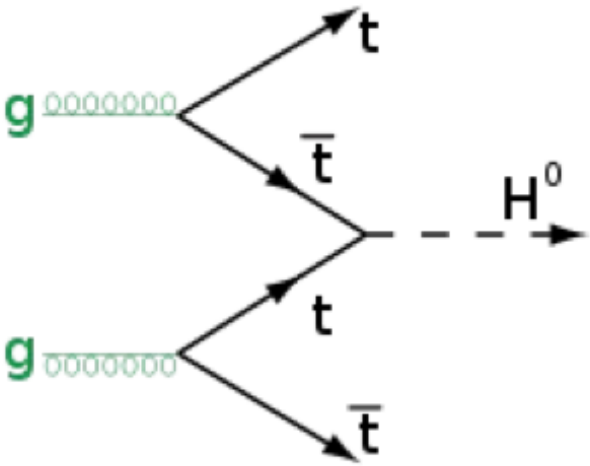




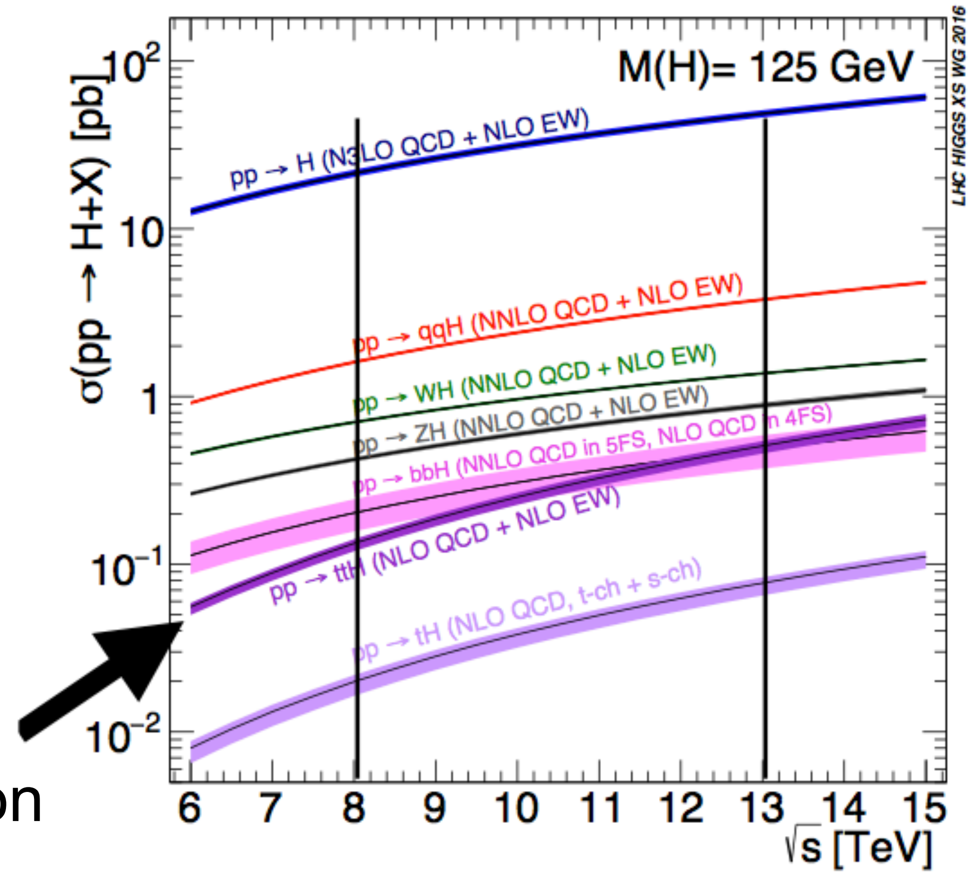


ttbar+Higgs

- 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)



ttH ~1% of total Higgs cross section

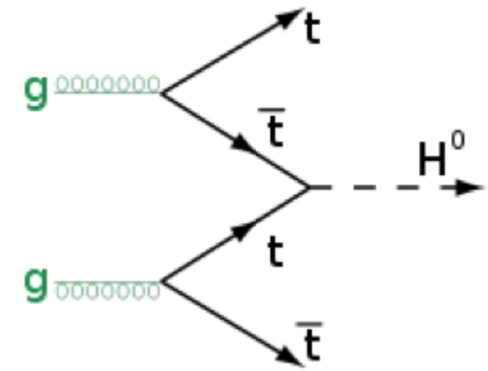
ttbar+heavy flavour

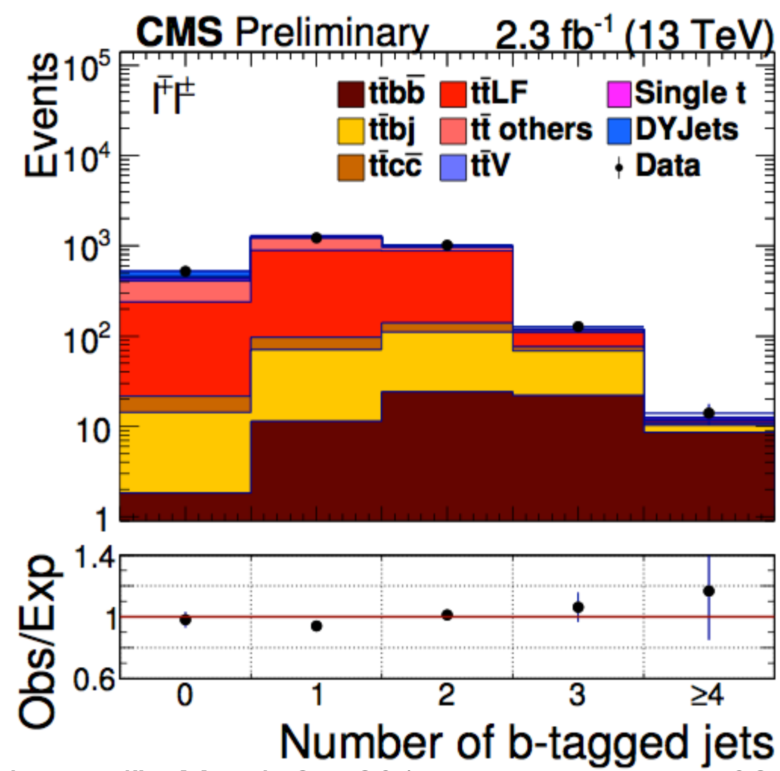
arXiv:1411.5621, TOP-16-010

- Study rate of ttbb: $\boxed{\sigma(t\bar{t}b\bar{b})/\sigma(t\bar{t}jj)}$
- 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

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

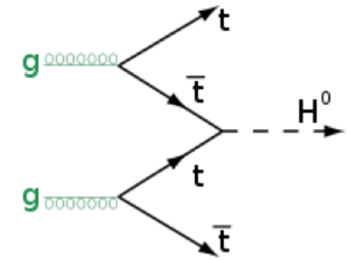
- In Run1 measured value higher but compatible (1.6σ) with NLO calculation





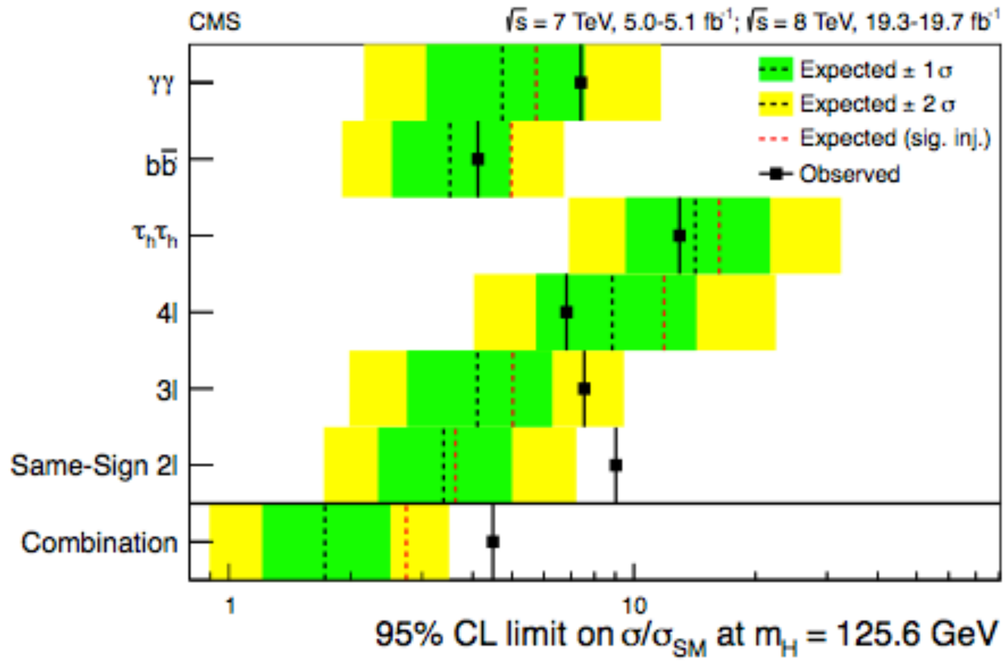
ttH

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



Run1 best fit:

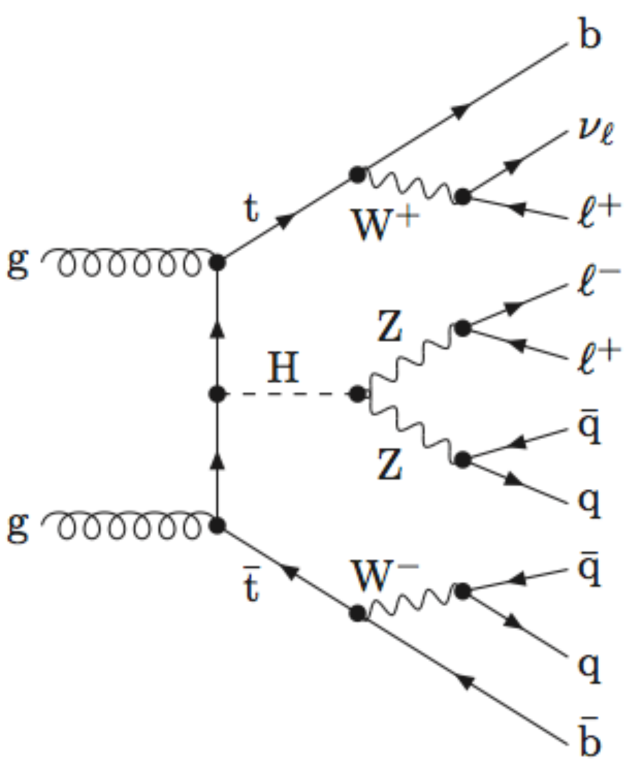
$\mu = 2.80 \pm 1.00$

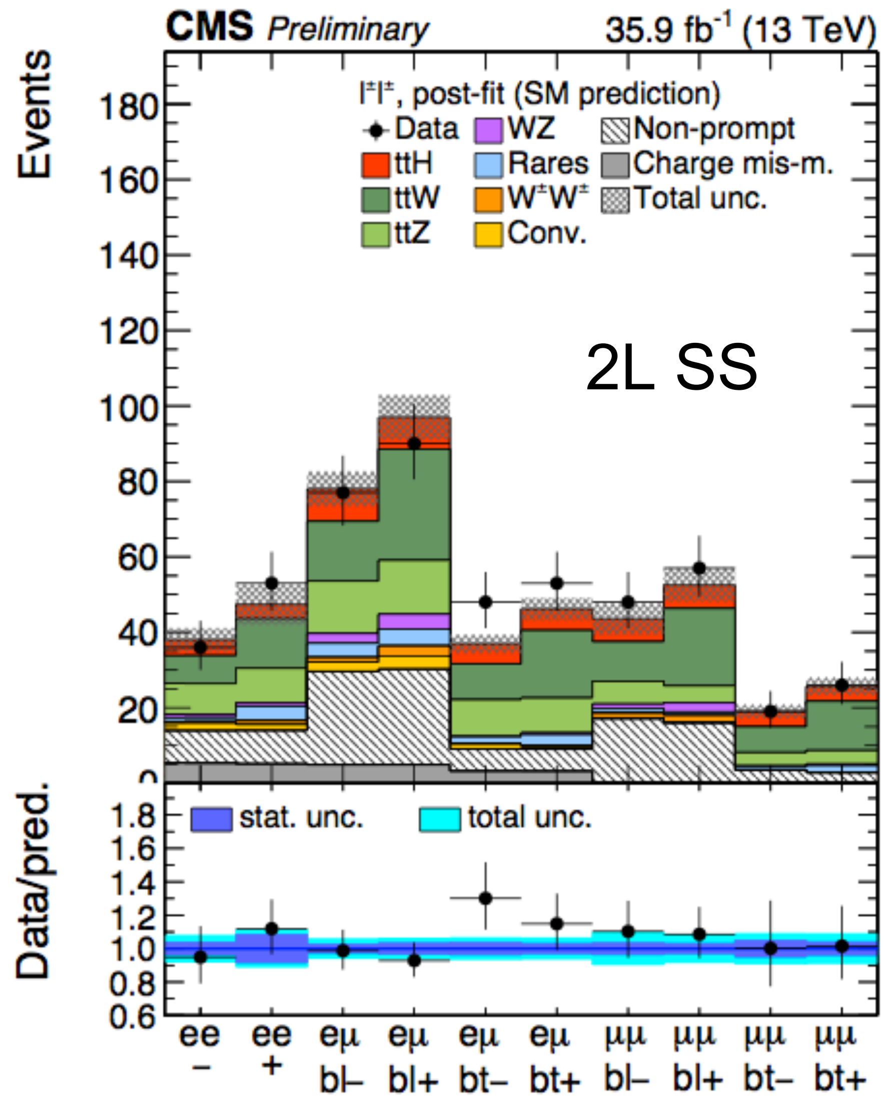


ttH: multi-leptons, ττ

- Multi-leptons: SS, 3L and 4L
- ttH with H→ττ

⇒categories per charge, flavor

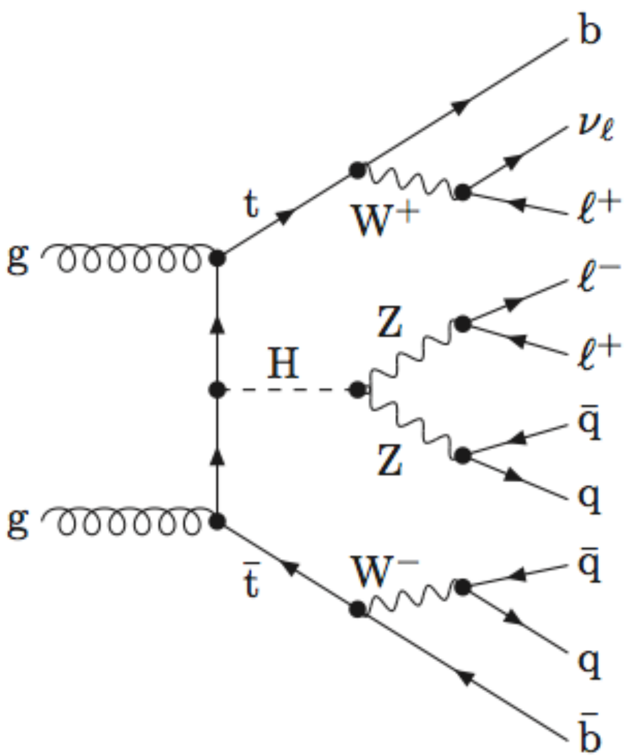


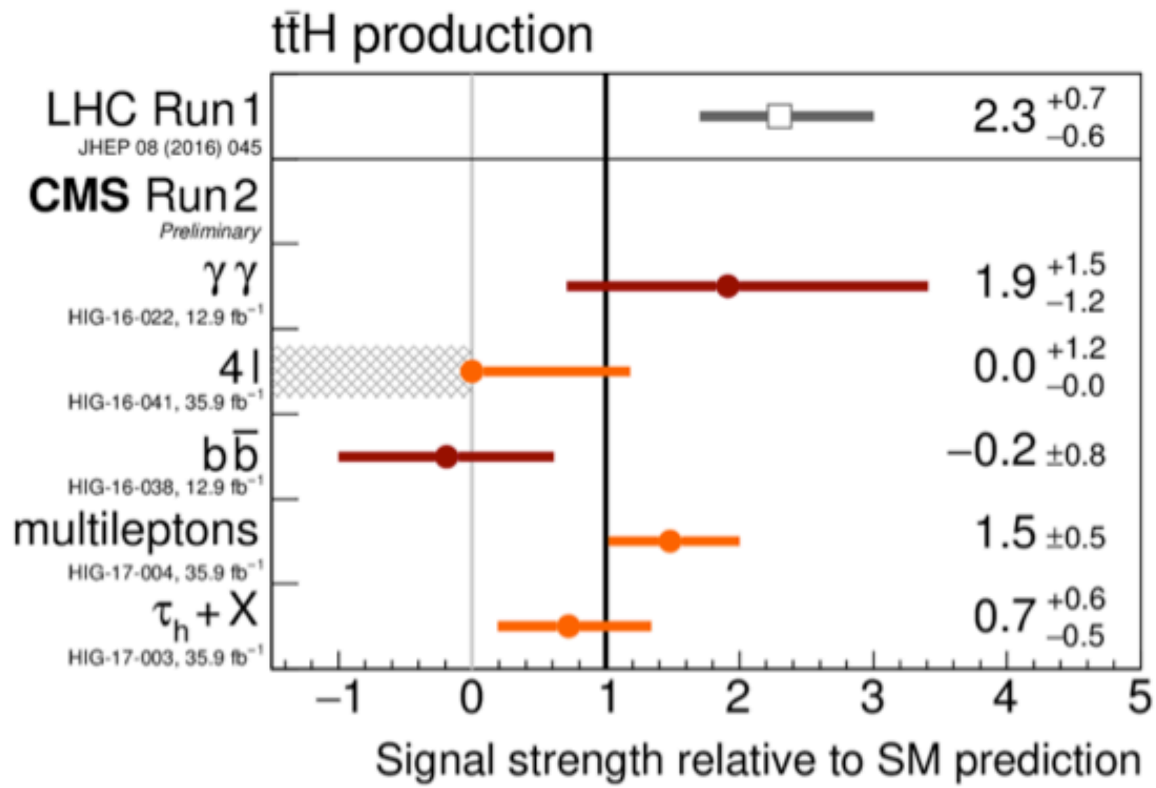


ttH: multi-leptons, $\tau\tau$

- Multi-leptons: SS, 3L and 4L
- ttH with $H \rightarrow \tau\tau$

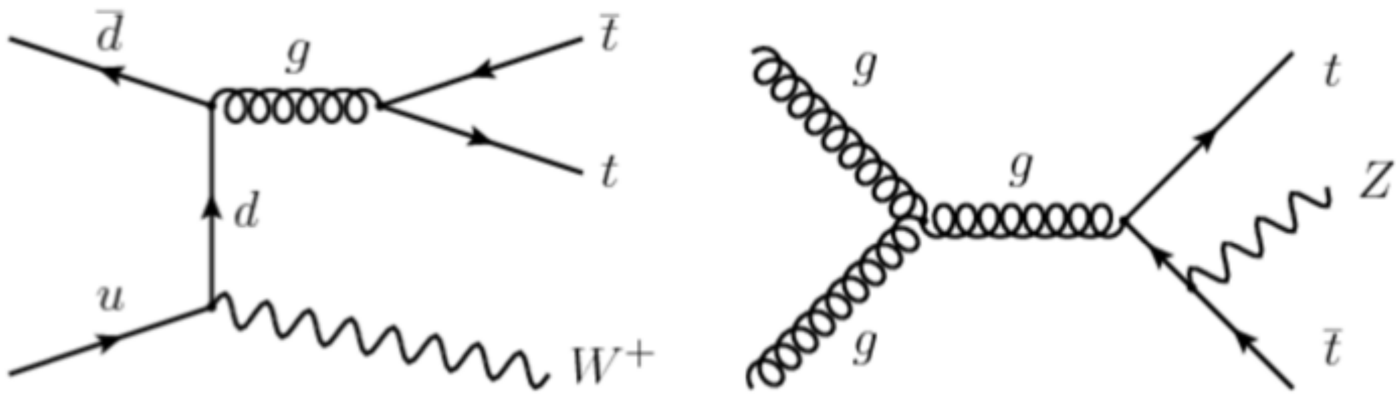
$\Rightarrow$categories per charge, flavor





ttV production (V=γ,W,Z)

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

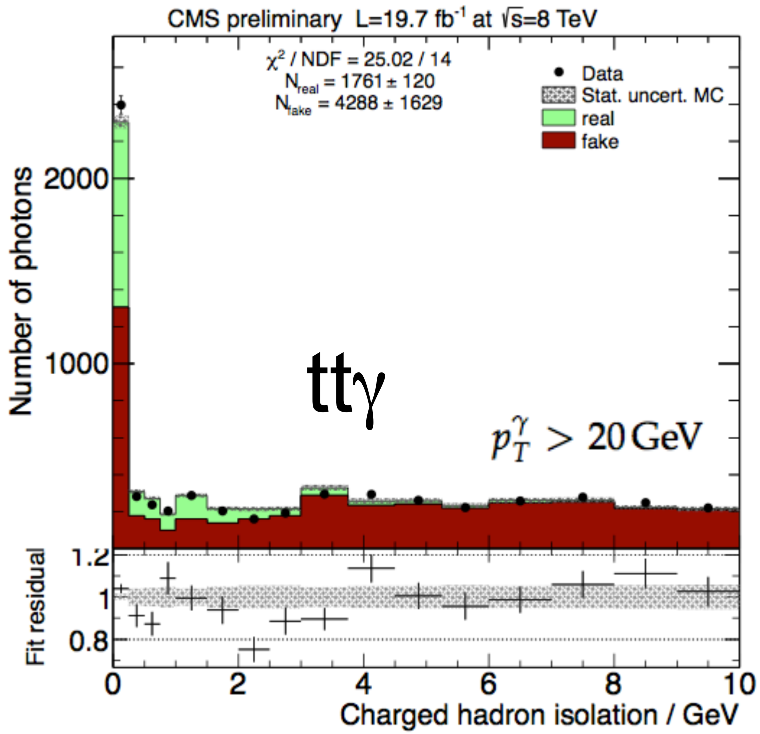


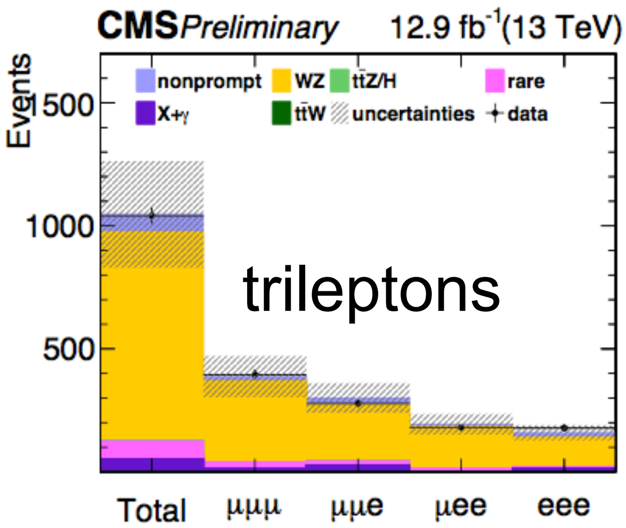
- Use multi-lepton final states
  - 2 same-sign charge leptons, 3 or 4 lepton final states

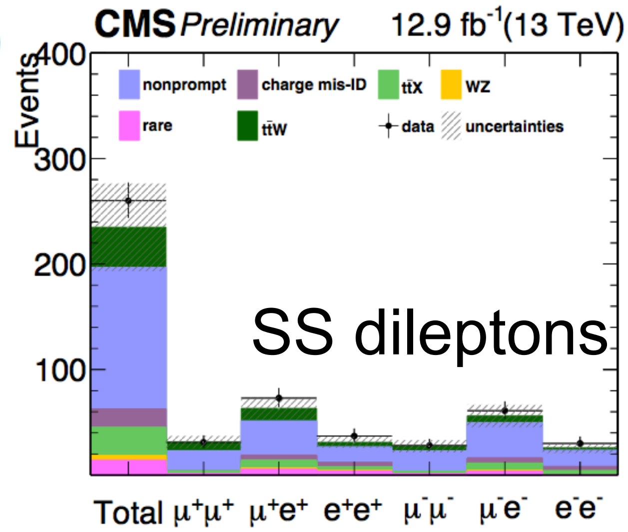
ttV production (V=γ,W,Z)

CMS-TOP-13-011, EPJC 74(2014)3060, TOP-14-008, TOP-16-017

- Measurements will give access to EW couplings of the top



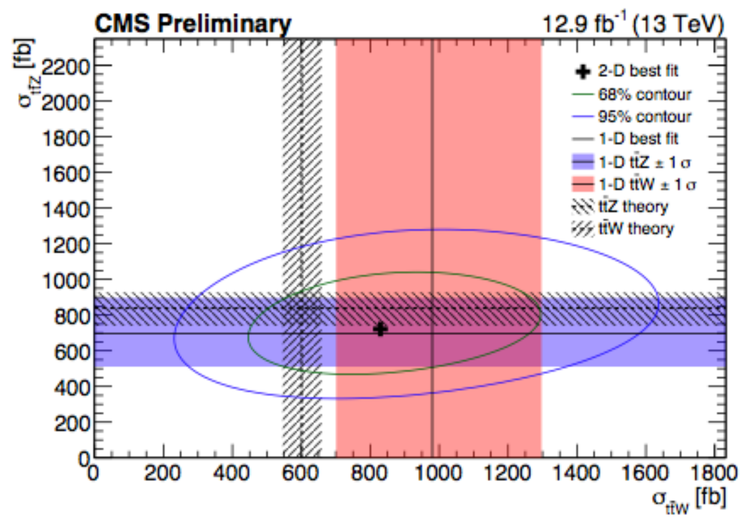




$$\sigma_{t\bar{t}\gamma} = 2.4 \pm 0.2\,(\mathrm{stat.}) \pm 0.6\,(\mathrm{syst.})\,\mathrm{pb}$$

Consistent with theoretical predictions

Combine 2- 3- and 4-lepton final states
⇒ ttV xsec in agreement with SM



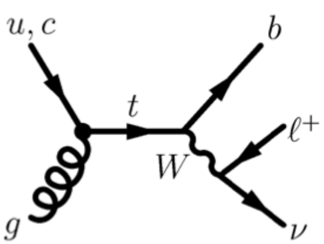
Flavor Changing Neutral Currents

- Expect small signal from SM
- …but signal may be large in BSM models

Final states:

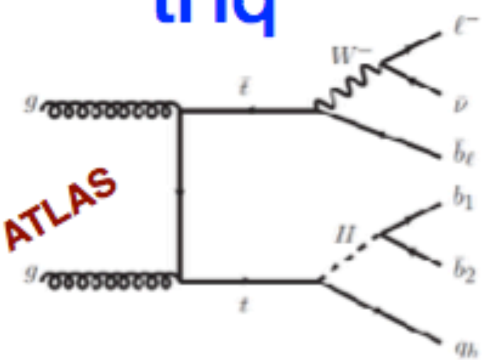
Wb

ATLAS



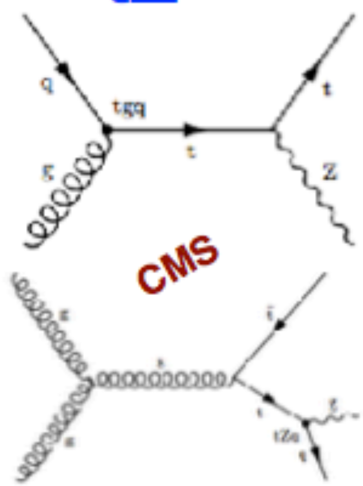
tHq

ATLAS



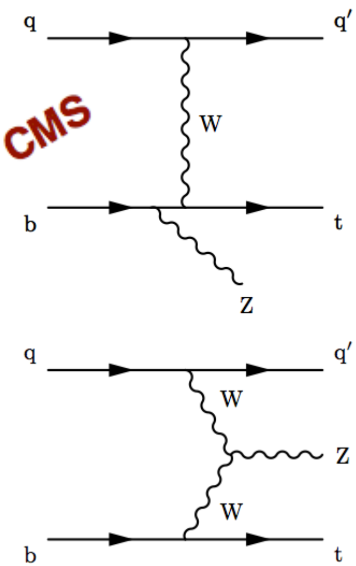
tZ

CMS



SM: tZq

CMS



Couplings:

$t \to ug$

$t \to cg$

$t \to uH$

$t \to cH$

$t \to ug$, $t \to cg$

$t \to uZ$, $t \to cZ$

$t \to tZ$

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

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

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

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

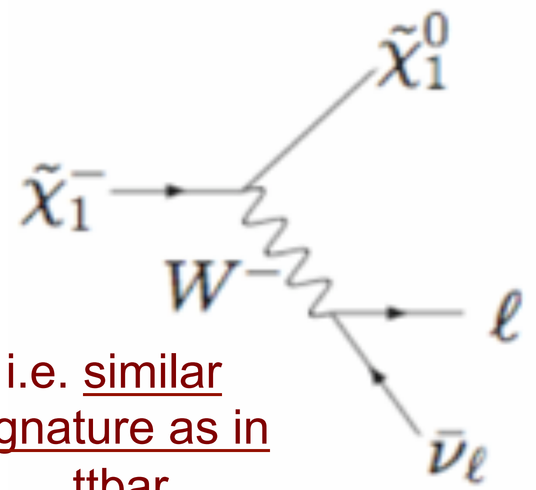
$B(t \to Zu) < 0.022\%$

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

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

Scalar top quark

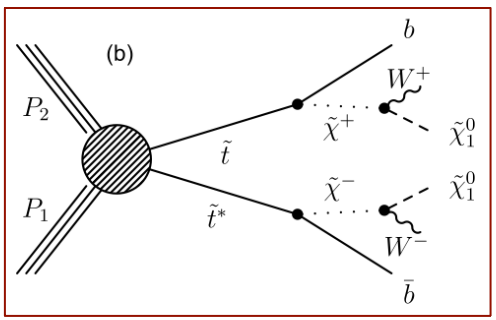
- SUSY is one plausible extension of the SM
- due to the heavy top quark, mass splitting between $\tilde{t}_1$ and $\tilde{t}_2$ can be large, such that the lighter stop $\tilde{t}_1$ can be even lighter than the top quark
- Decays dictated by mass spectrum of other SUSY particles



i.e. similar signature as in ttbar

- Light stop:

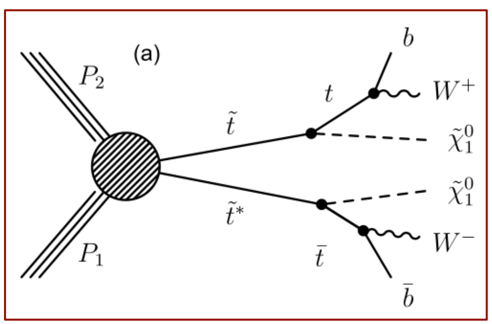
$\boxed{m_{\tilde{t}_1} \lesssim m_t}$



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

- Heavy stop:

$\boxed{\tilde{t} \to t\tilde{\chi}^0}$



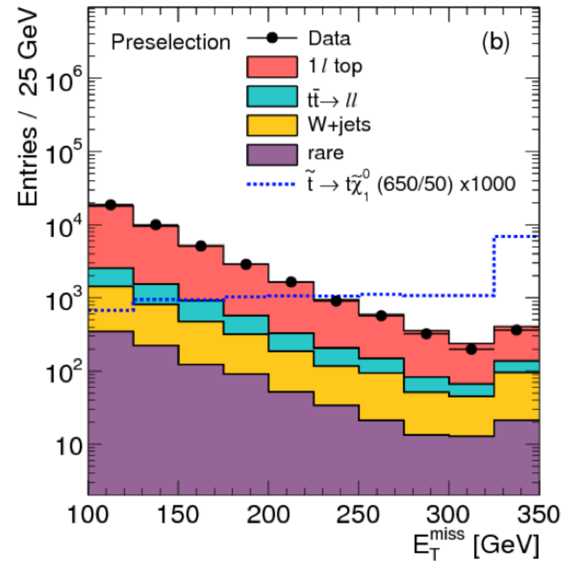
$$\tilde{t} \to t\tilde{\chi}_1^0 \to bW\tilde{\chi}_1^0$$

Top and SUSY

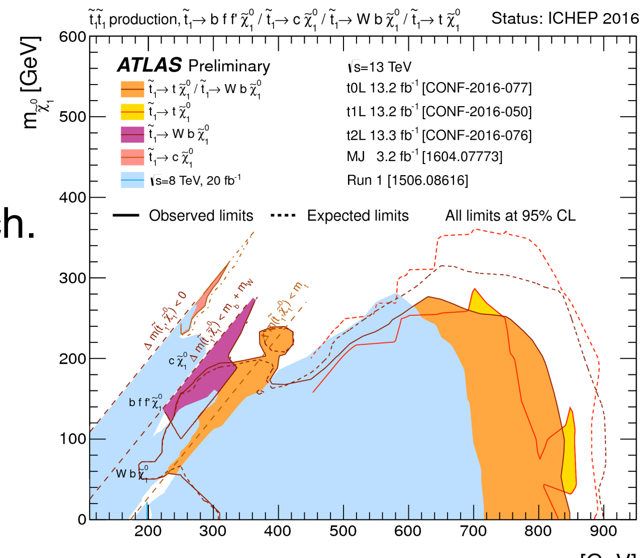
EPJC 74 (2014) 3109, arXiv:1603.02303, SUS-16-002

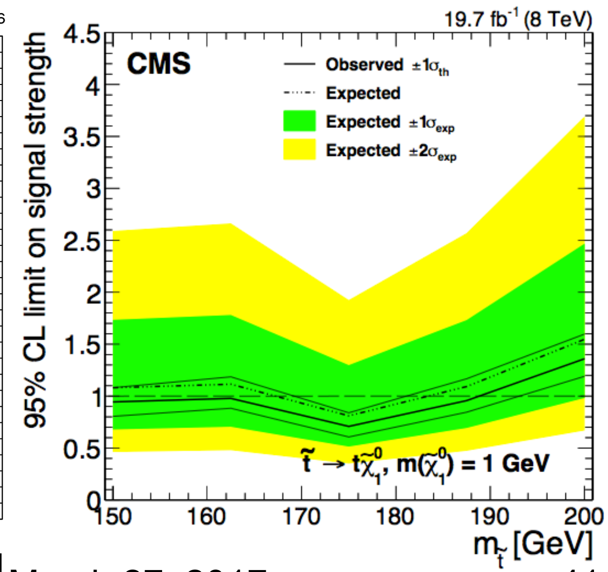
- If SUSY exists and is responsible for solution of hierarchy problem, naturalness arguments suggest that SUSY partners of top quark (*stop*) may have mass close to m_{top} to cancel top quark loop contributions to Higgs mass

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



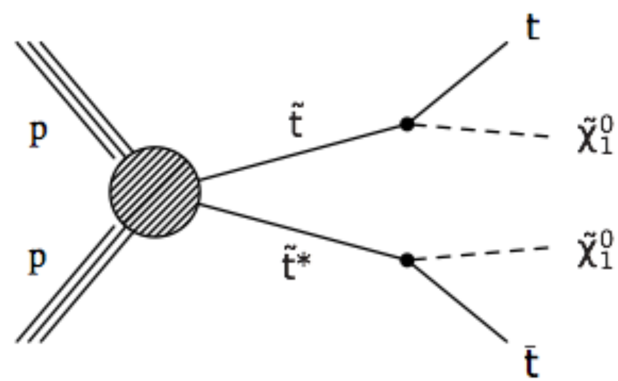
- Small predicted cross section
  - for 175GeV: 40pb@8TeV
- Stop pair production: $\boxed{t\bar{t}\tilde{\chi}_1^0\tilde{\chi}_1^0}$
  - similar to ttbar lepton+jet and dilepton ch.
  - Additional MET from neutralinos
- change in ttbar cross section

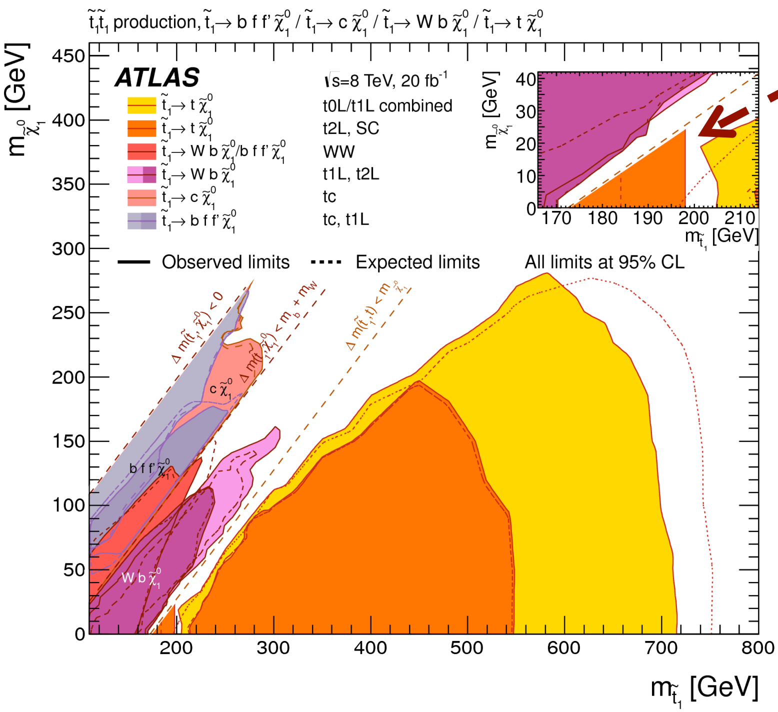


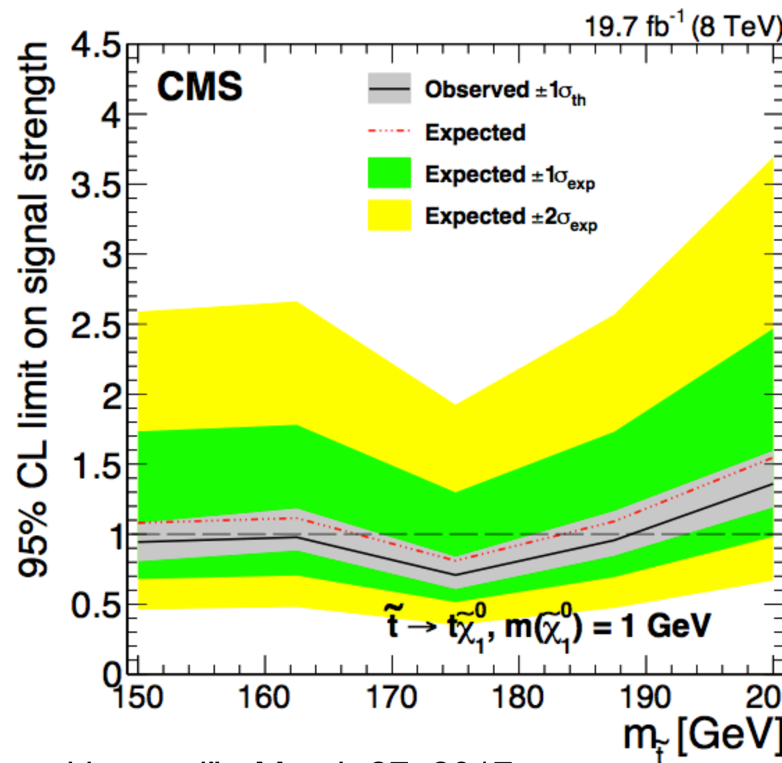


Top cross section: dileptons

- Indirect searches
- SUSY models could produce final states very similar (with additional MET)
- For ex. in dilepton channel







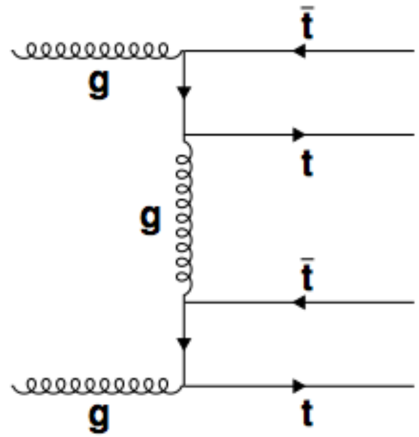
Multi-top production

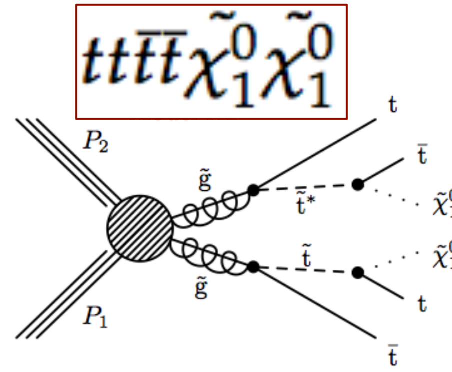
arXiv:1605.03171, TOP-16-016, 1702.06164

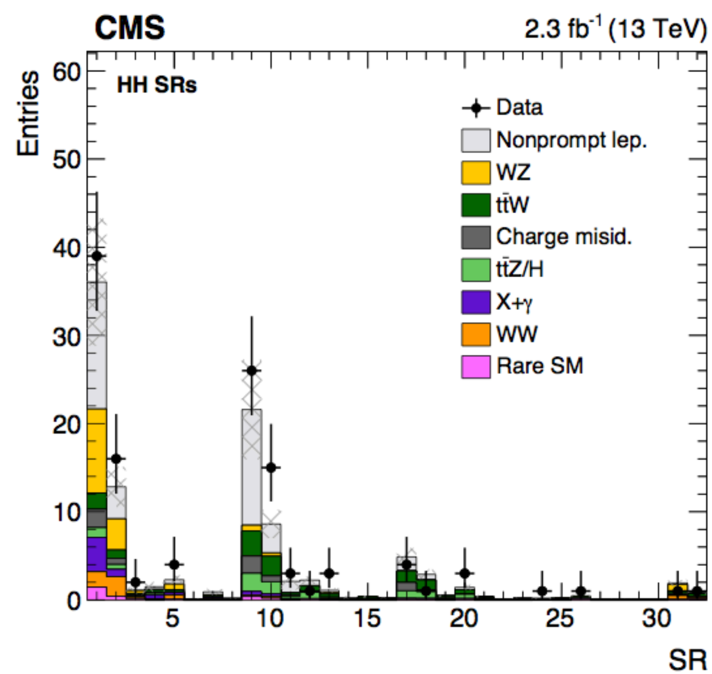
- Production of 4 tops is an attractive scenario in a number of new physics models
- The SM cross section is 9fb@13TeV

- Use lepton+jets final state
- Combination of kinematical variables and multivariate techniques
- Data are consistent with bkg expectations
- Set upper limit cross section 69fb @95%CL

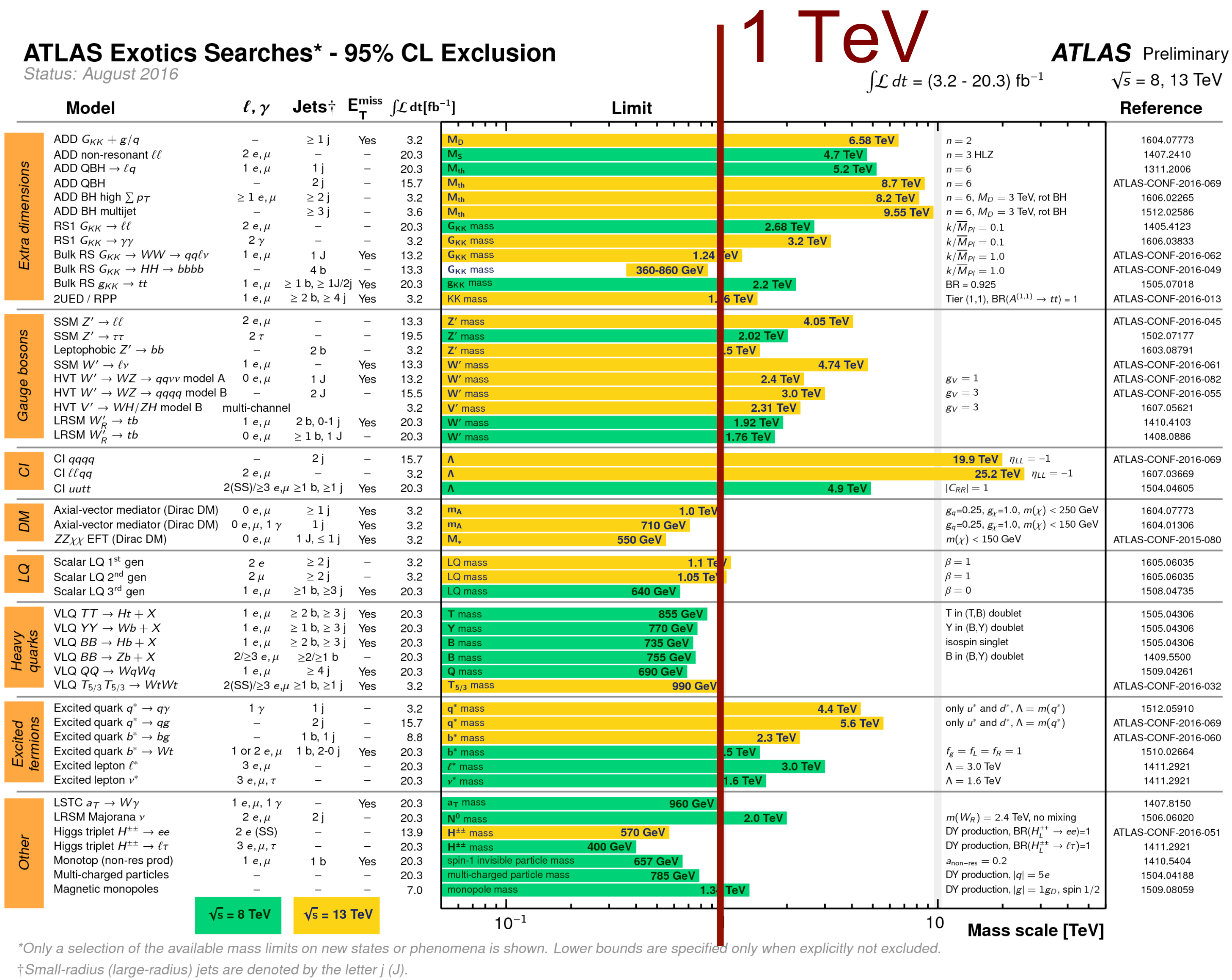
- Search for same-sign dileptons
- Several models considered
- Consider multiple search regions defined by MET, hadronic energy, number of (b-) jets, and p_T of the leptons in the events



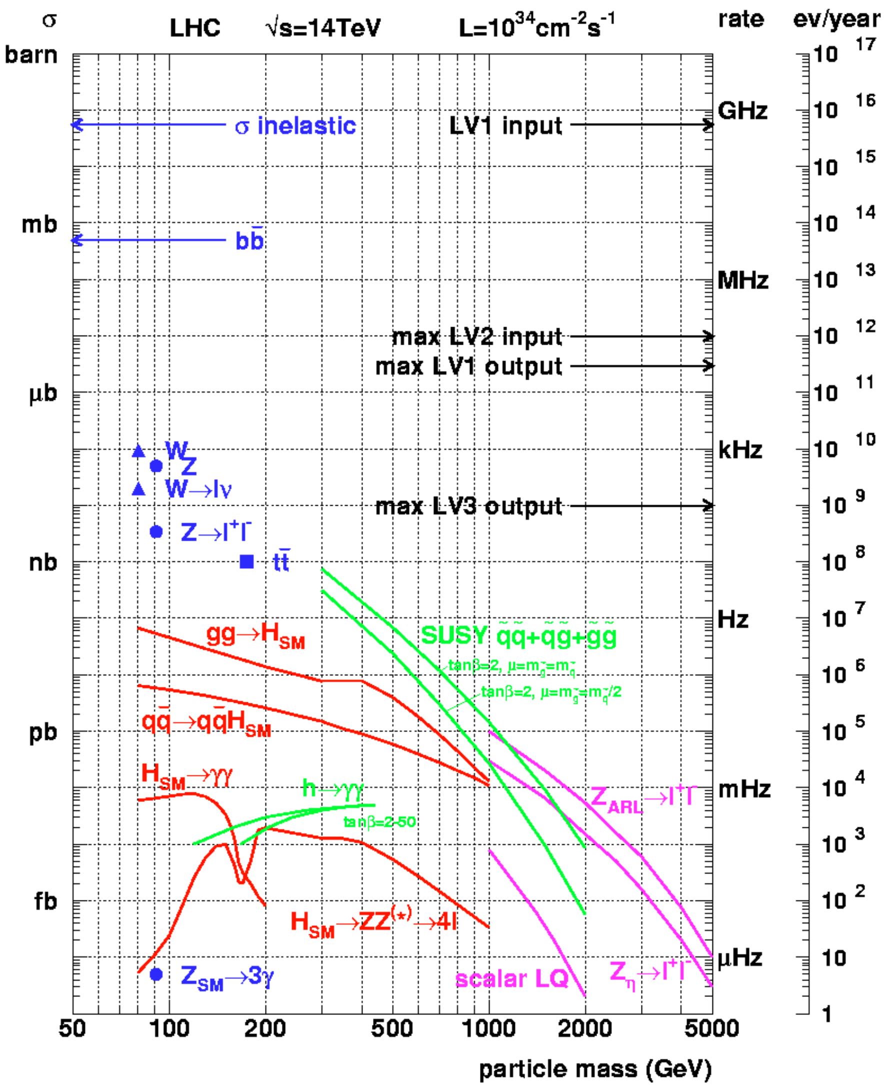




Searches for new particles



Cross sections at the LHC

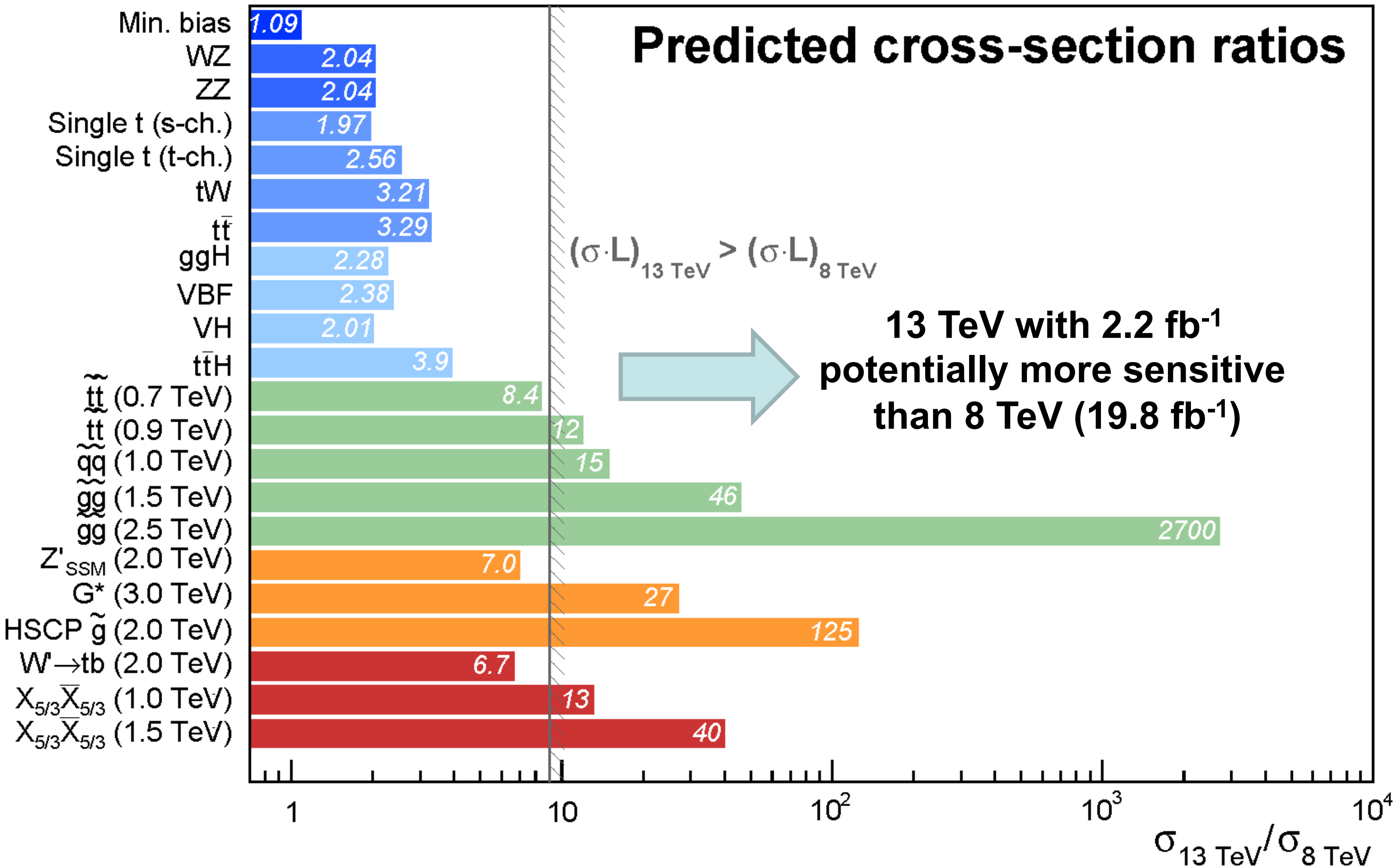


“Well known” processes, don’t need to keep all of them …

New Physics!!

This is where to look

Increased reach at 13 TeV



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 will enhance the sensitivity
  - Higgs, multi-top, boosted objects, SUSY, Dark matter, etc.