

Probing the SM: Top quarks and beyond

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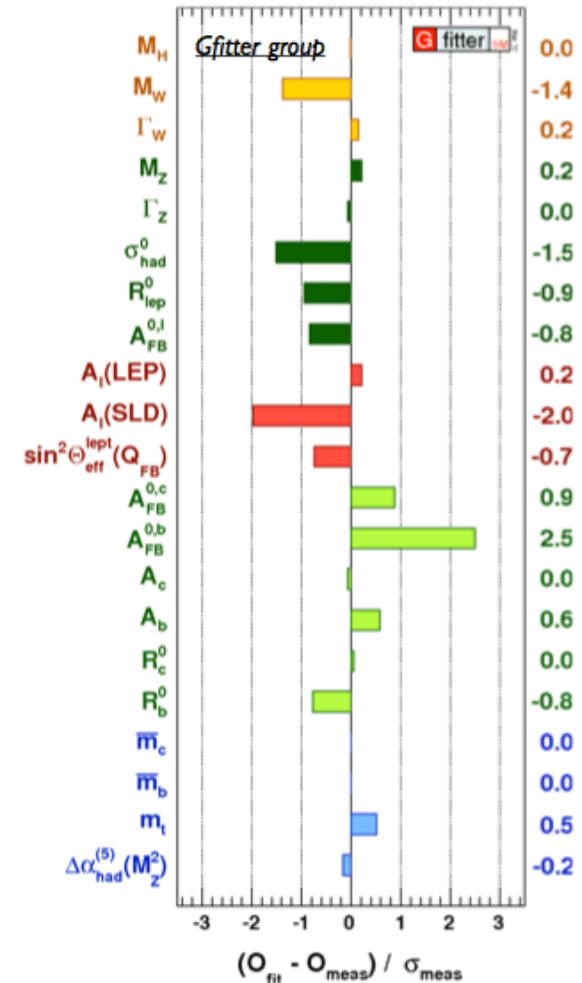
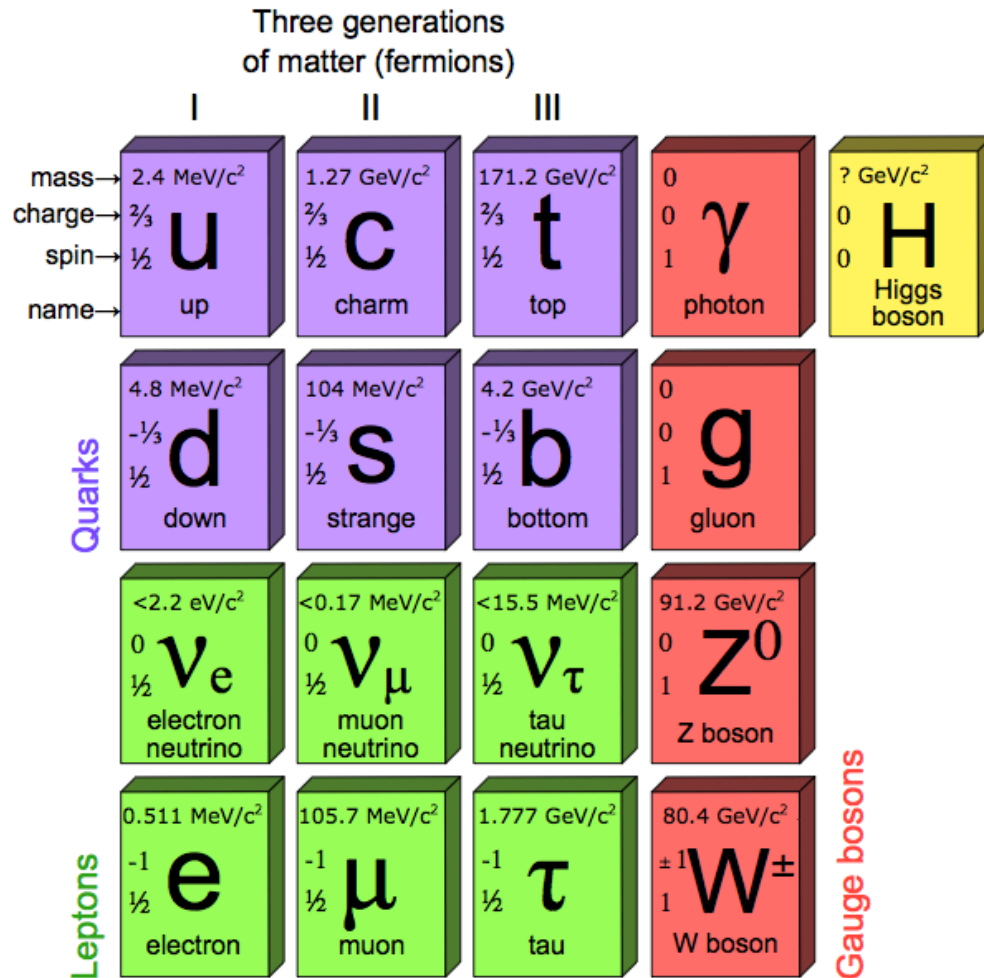


- ✓ Top quarks as window to New Physics
- ✓ Top-Higgs associated production
- ✓ Top quark signatures in SUSY
- ✓ Top and Dark Matter



SM confirmed by the data

Standard model of elementary particles

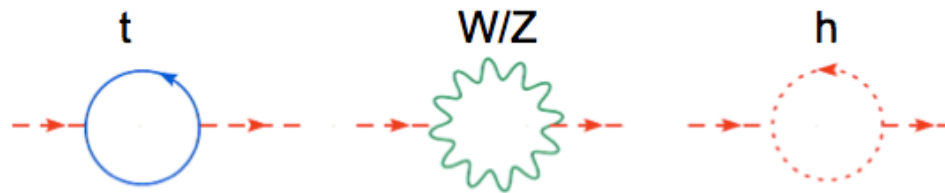


Excellent agreement with all experimental results

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?

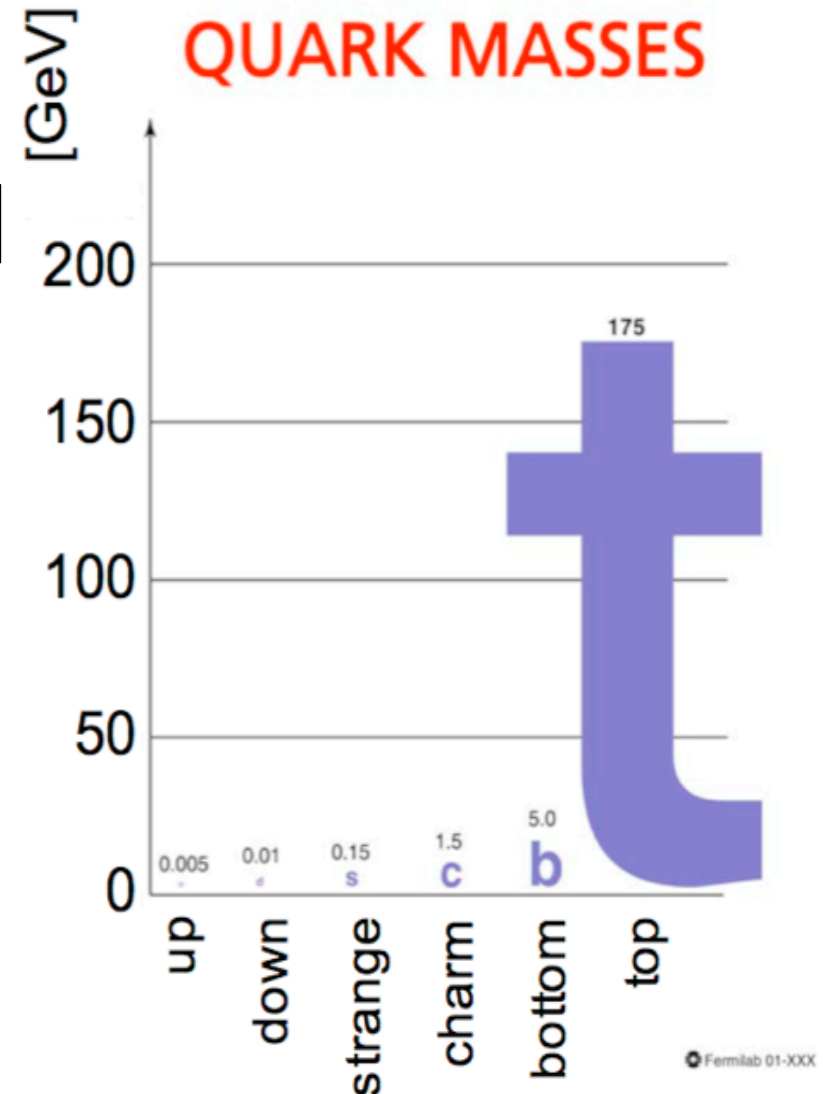
Solutions:

- 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
 - $t\bar{t}$ resonances, bound states, 4-top production, etc.
- New space-time structure
 - Introduce extra space dimensions to lower Planck scale cutoff to $\sim 1\text{TeV}$
 - KK excitations

The top quark

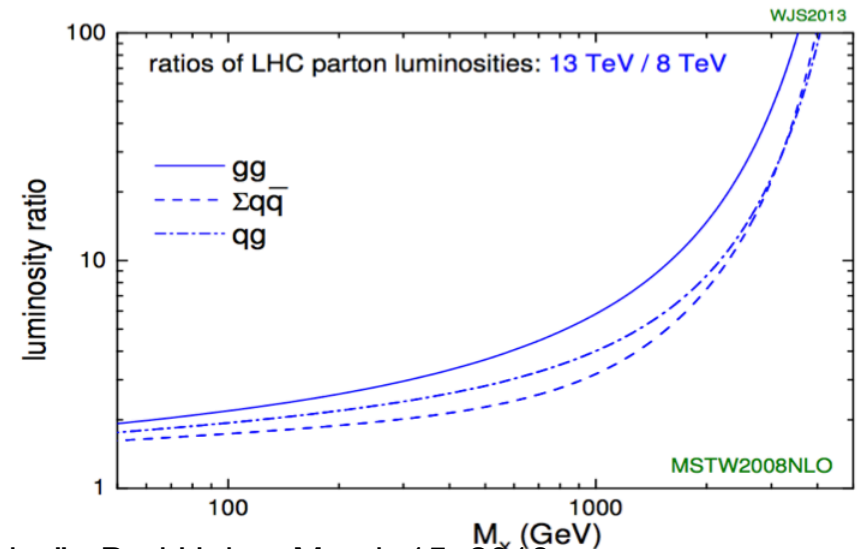
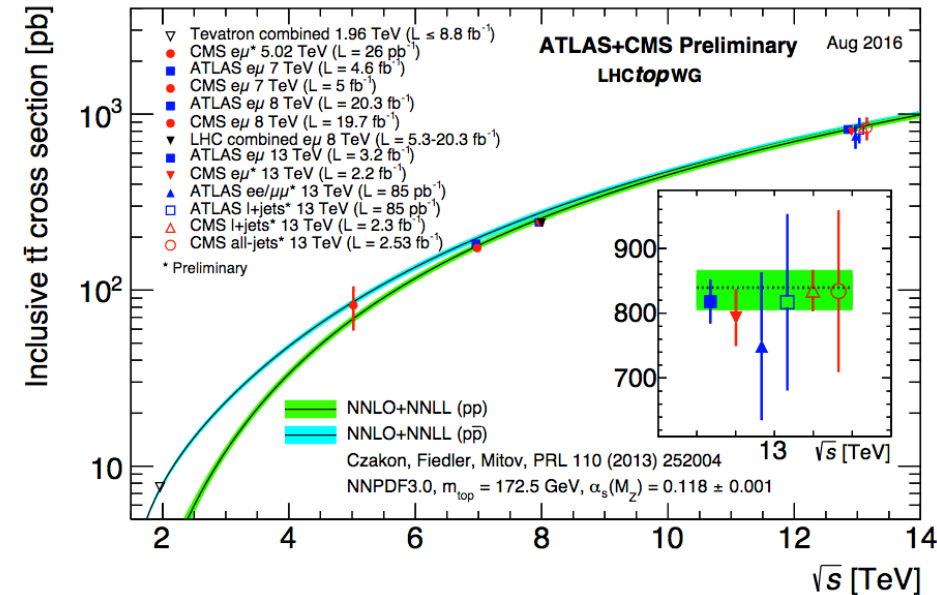
- The heaviest known elementary particle
- Large coupling to the Higgs: ~ 1
- Short lifetime
 - for $m_{\text{top}} = 175 \text{ GeV} \Rightarrow \Gamma = 1.4 \text{ GeV} \Rightarrow$ no hadronization
 - large contributions to EWK corrections $\sim G_F m_{\text{top}}^2$
 - very short lifetime \Rightarrow 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

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



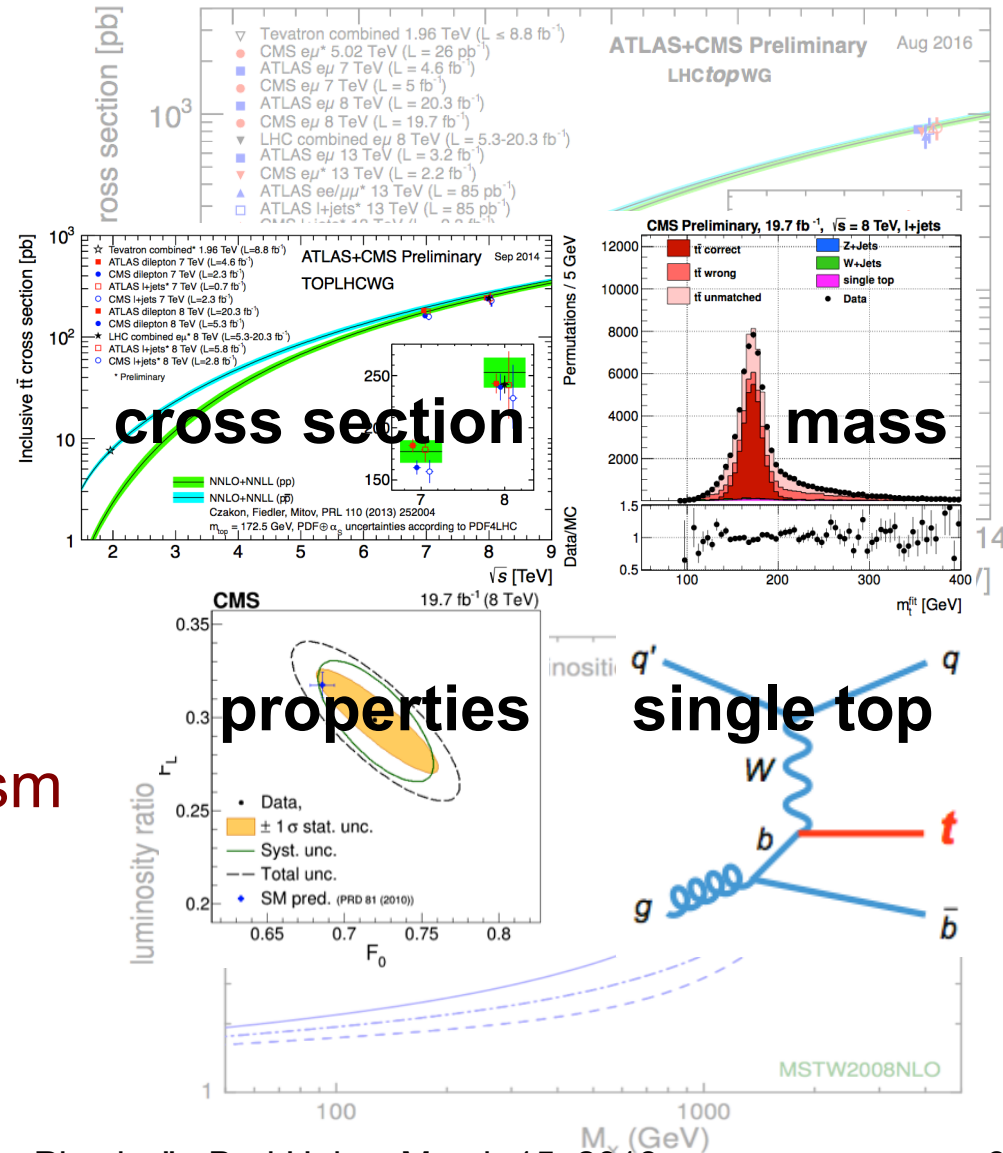
Role of top quark physics

- 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?

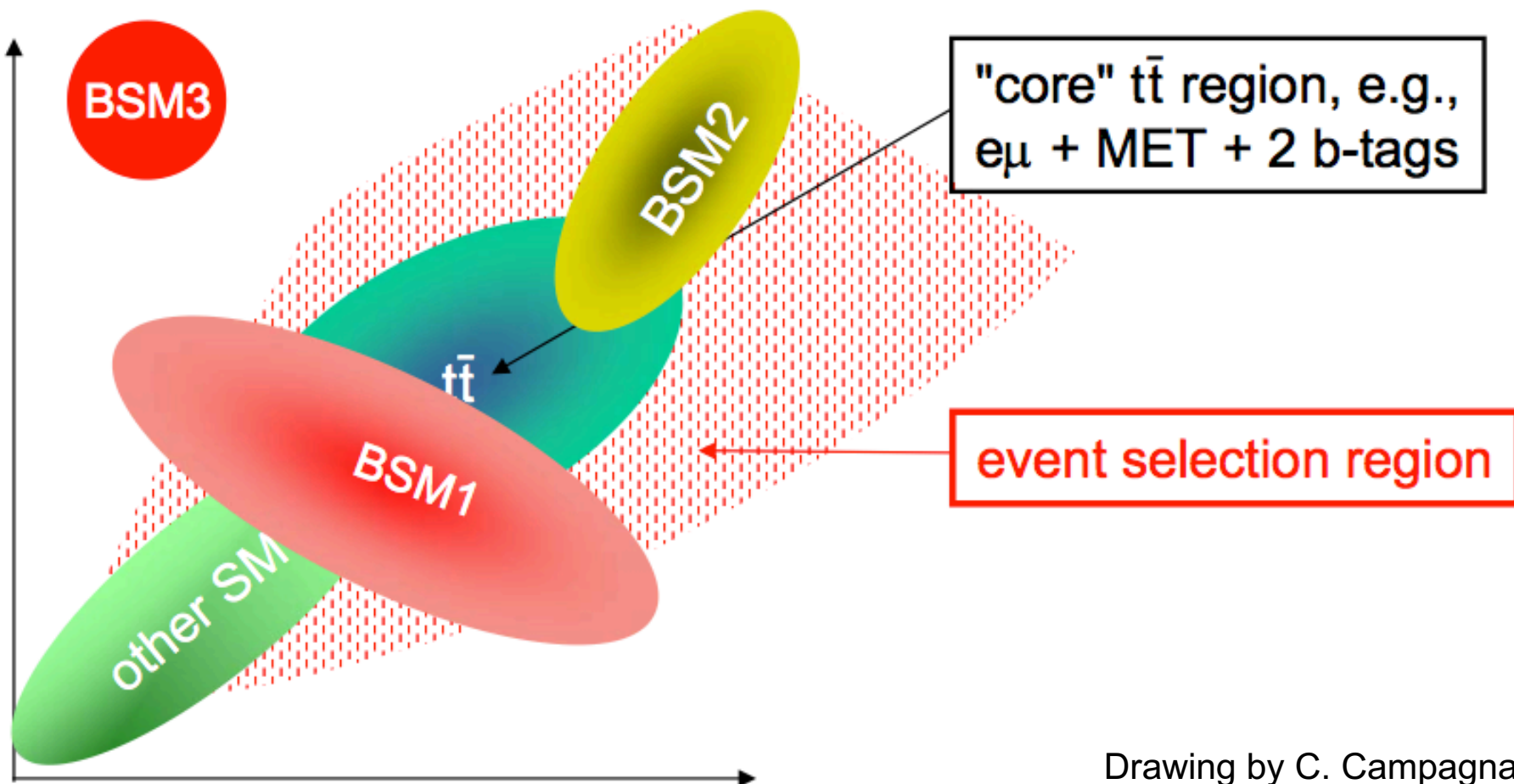


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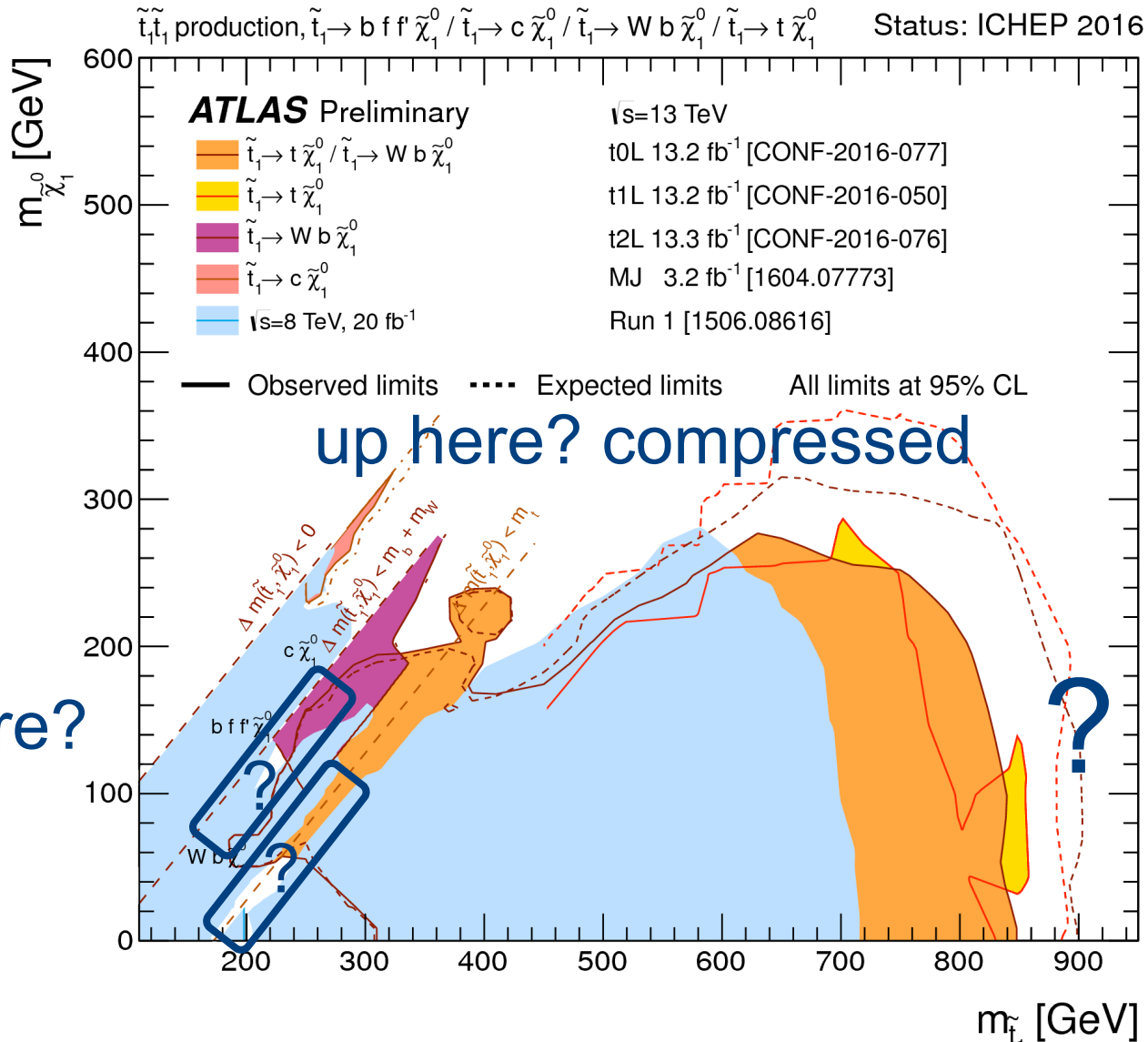


Study characteristics



Drawing by C. Campagnari

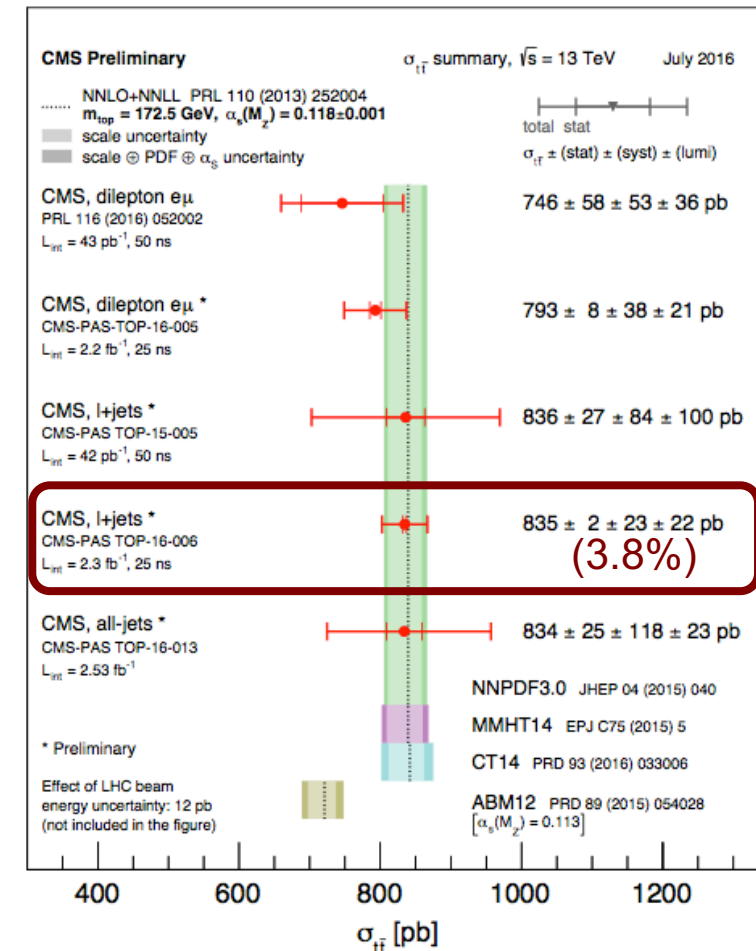
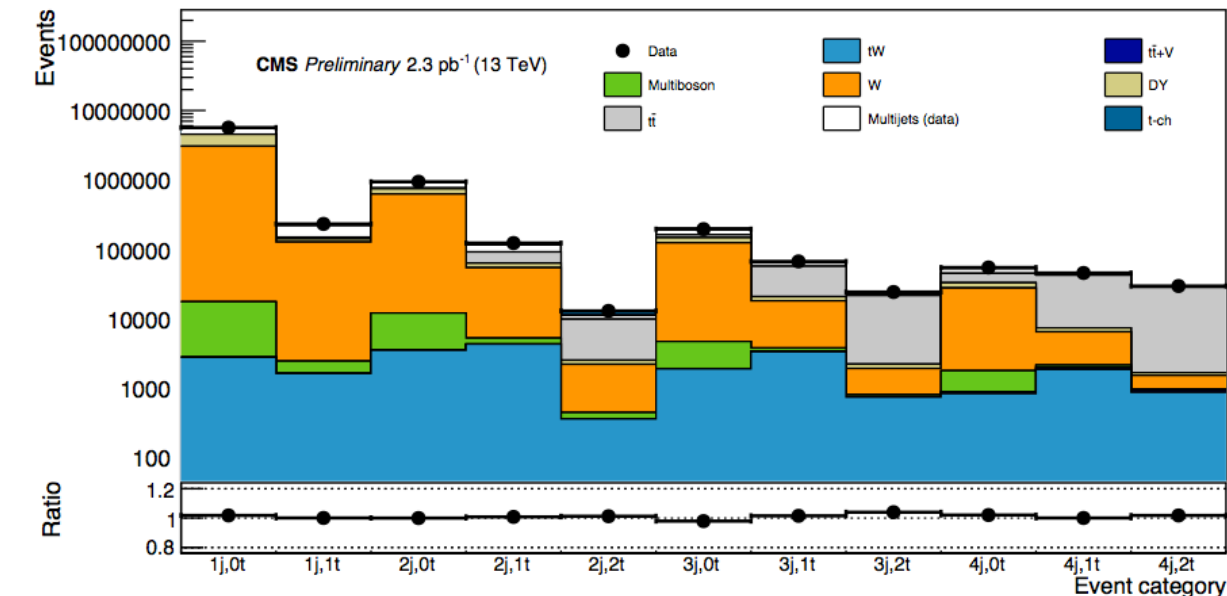
Regions hard to explore



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

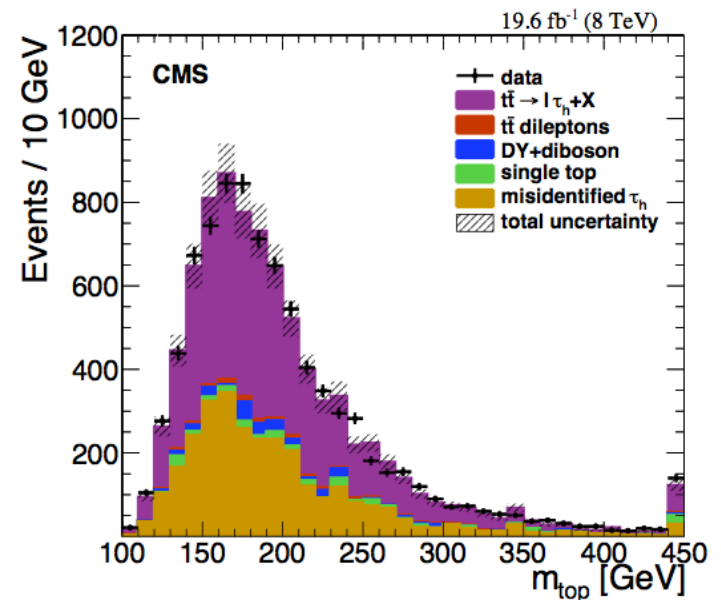
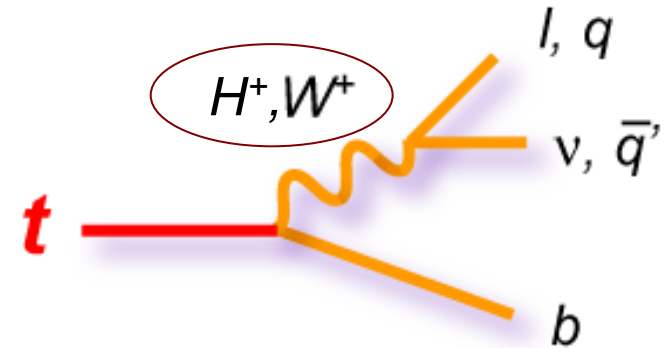
PRD 85 (2012) 112007, PLB 739 (2014) 23

Dileptons with taus

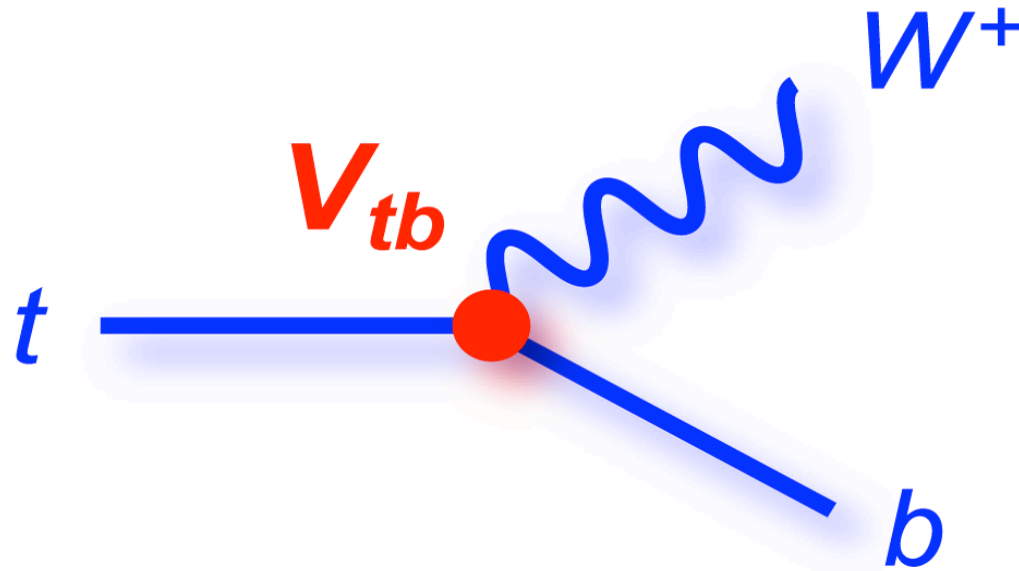
- cross section measurement including τ s
- Includes only 3rd generation quarks/leptons
- Syst unc: τ auld, fakes

Channel	Signature	BR
Dilepton(e/μ)	$ee, \mu\mu, e\mu + 2b$ -jets	4/81
Single lepton	$e, \mu + \text{jets} + 2b$ -jets	24/81
All-hadronic	$\text{jets} + 2b$ -jets	36/81
Tau dilepton	$e\tau, \mu\tau + 2b$ -jets	4/81
Tau+jets	$\tau + \text{jets} + 2b$ -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?



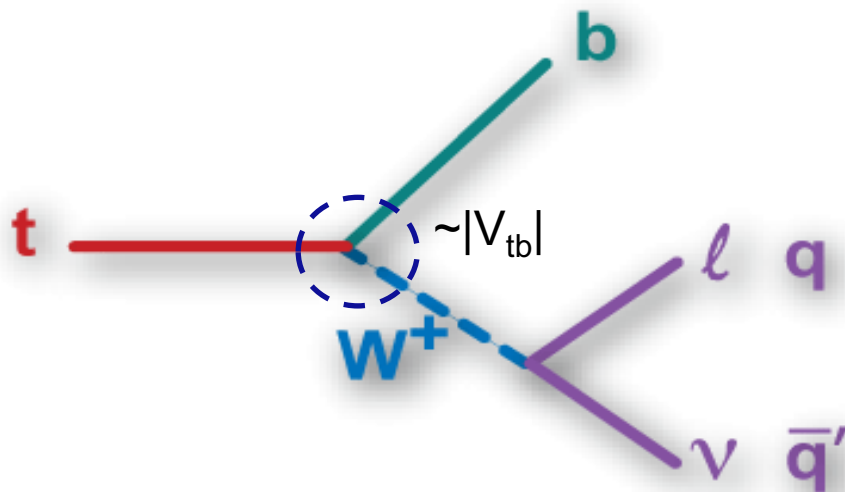
- almost always $t \rightarrow Wb$ (i.e. $V_{tb} \sim 1$)
- lifetime is short, and it decays before hadronizing
- the W is real:
 - can decay $W \rightarrow l\nu$ ($l=e,\mu,\tau$), $BR \sim 1/9$ per lepton
 - can decay $W \rightarrow qq$, $BR \sim 2/3$

Measure R in dilepton channel

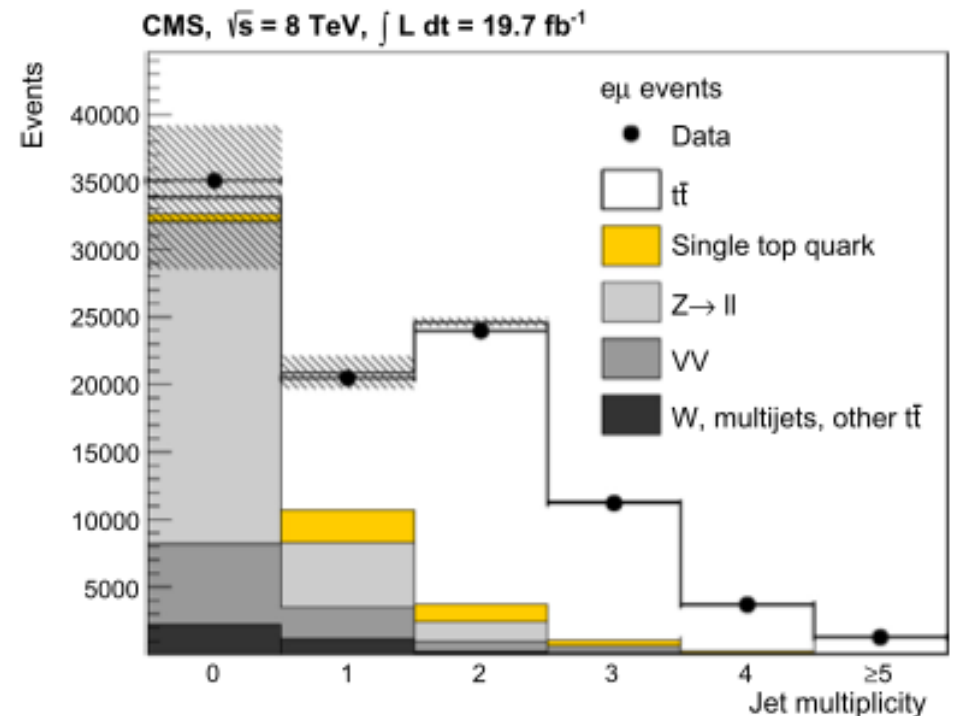
N.Cim. B125(2010)983, PLB 736(2014)33

- Probe heavy flavor content of $t\bar{t}$ events
- Use $t\bar{t}$ dilepton final state
 - small background
- Measure:

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



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



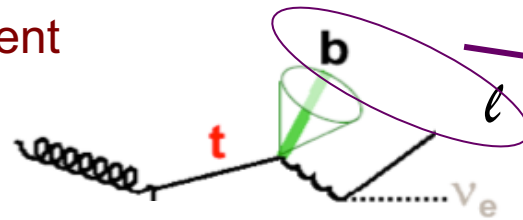
Signal or background?

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

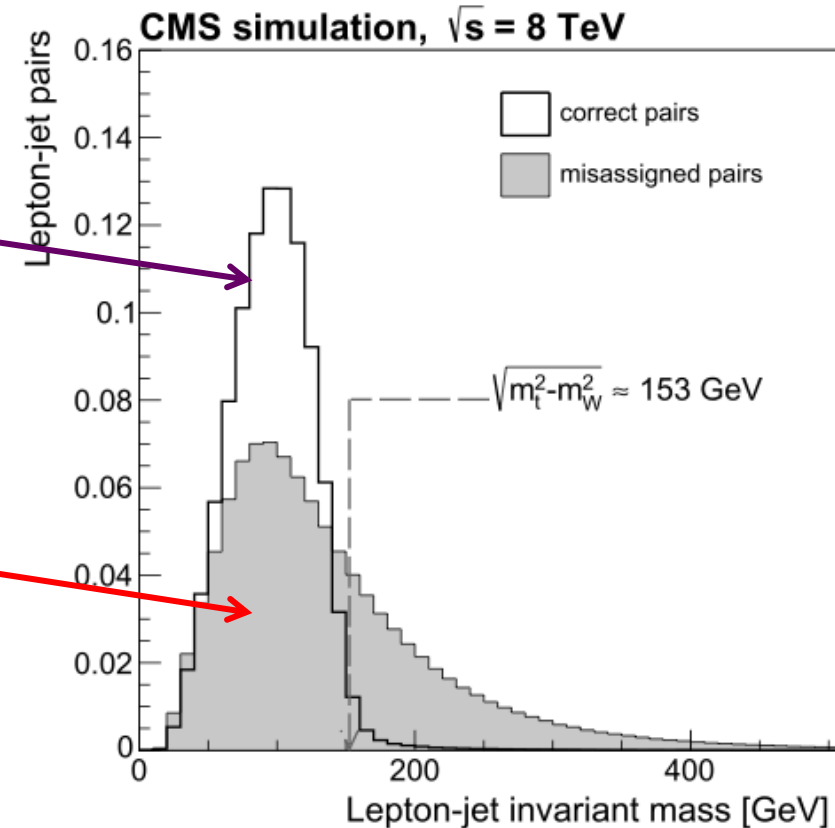
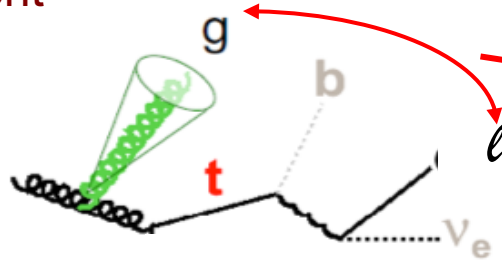
Data-driven determination of background

- Reconstruct lepton-jet invariant mass

- Correct assignment



- Wrong assignment

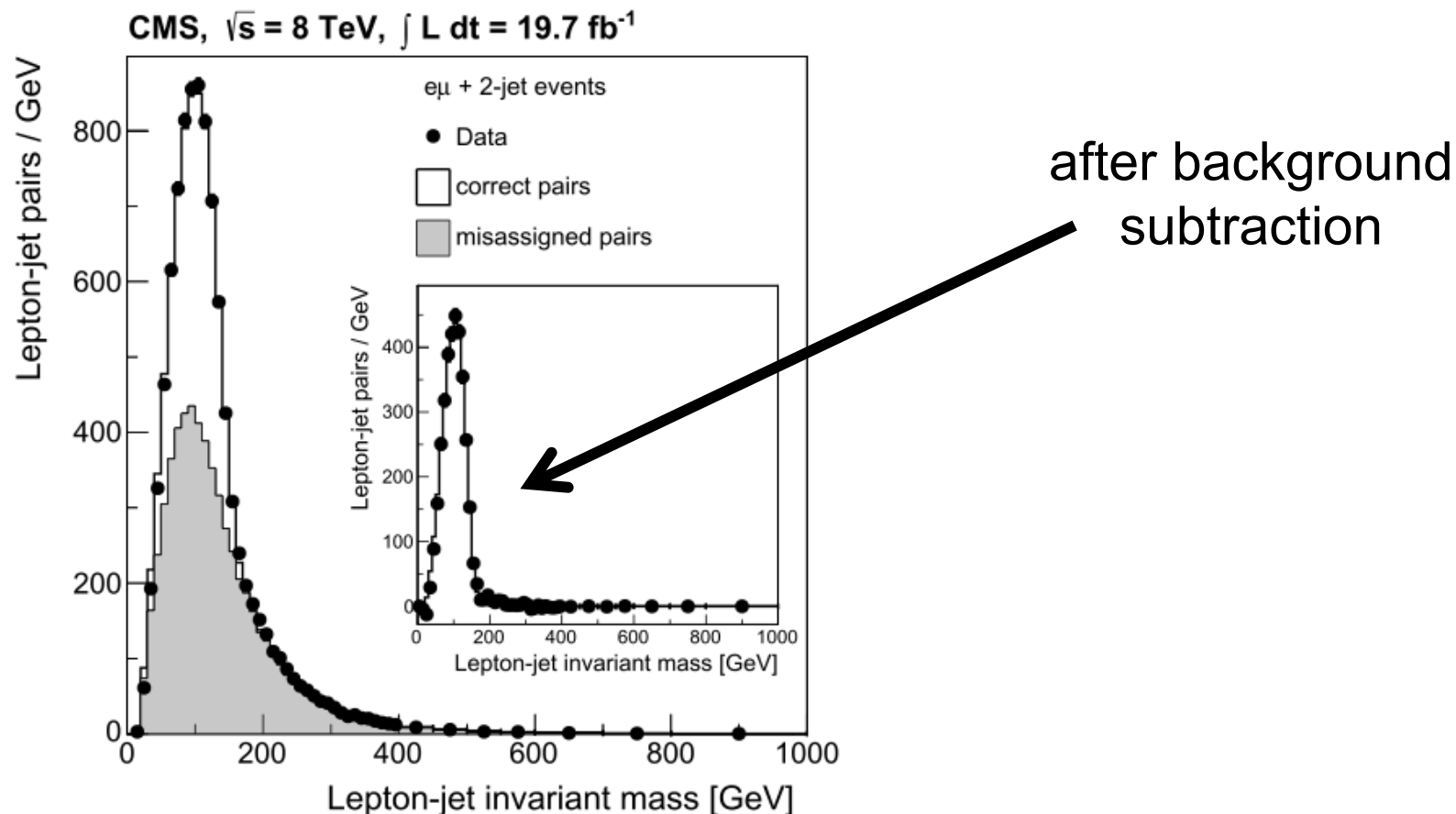


- Use **tail** to model background in **signal** region

Signal vs. background

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

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



Heavy flavor content

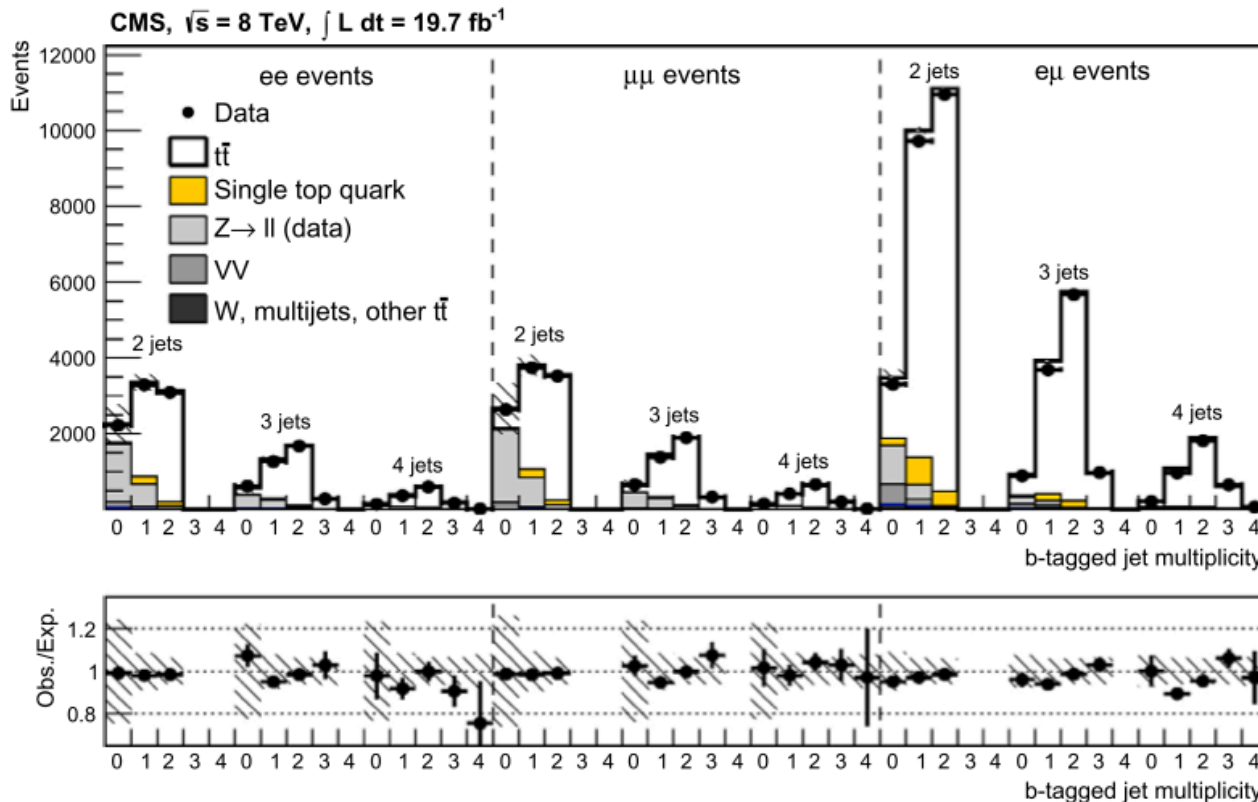
N.Cim. B125(2010)983, PLB 736(2014)33

- Measurement

- b-tagging multiplicity parametrized as function of R , ε_b , ε_q , top contribution
- Number of reconstructed $t \rightarrow Wq$ is estimated from lepton-jet invariant mass

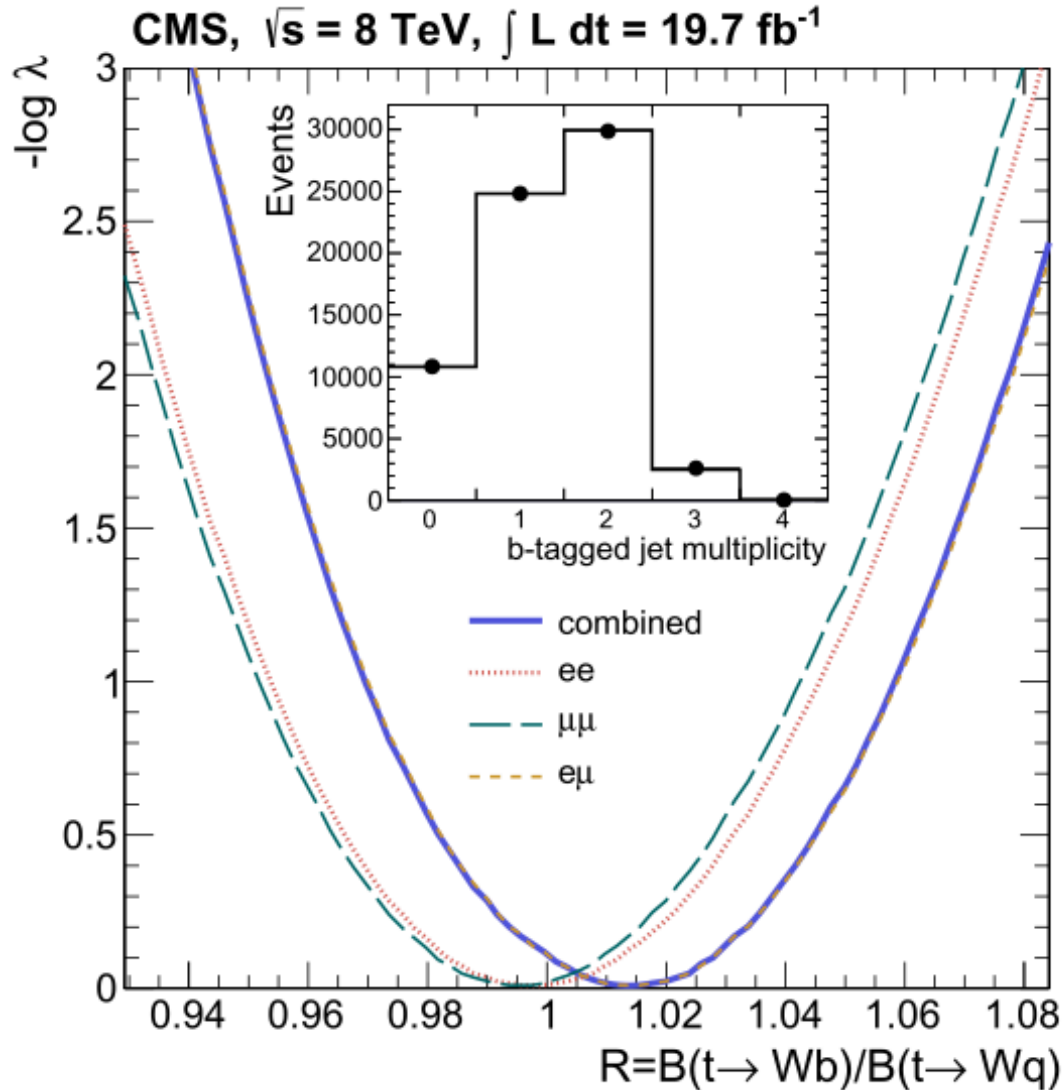
- $R = 1.01 \pm 0.03$ (stat. \oplus syst.)

- Lower boundary with confidence interval @95%CL after requiring $R \leq 1 \Rightarrow R > 0.955$ @95%CL



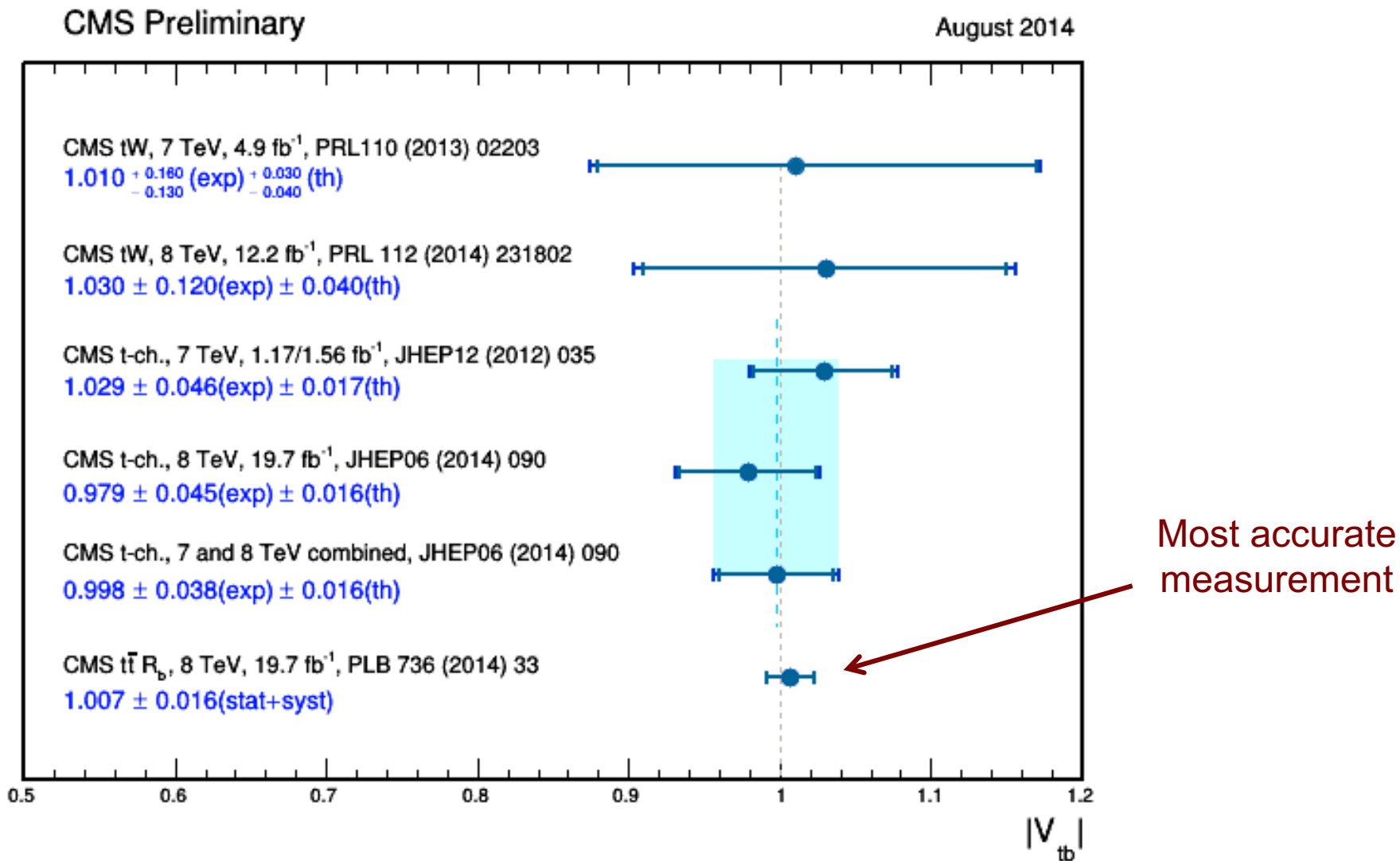
Measure R

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

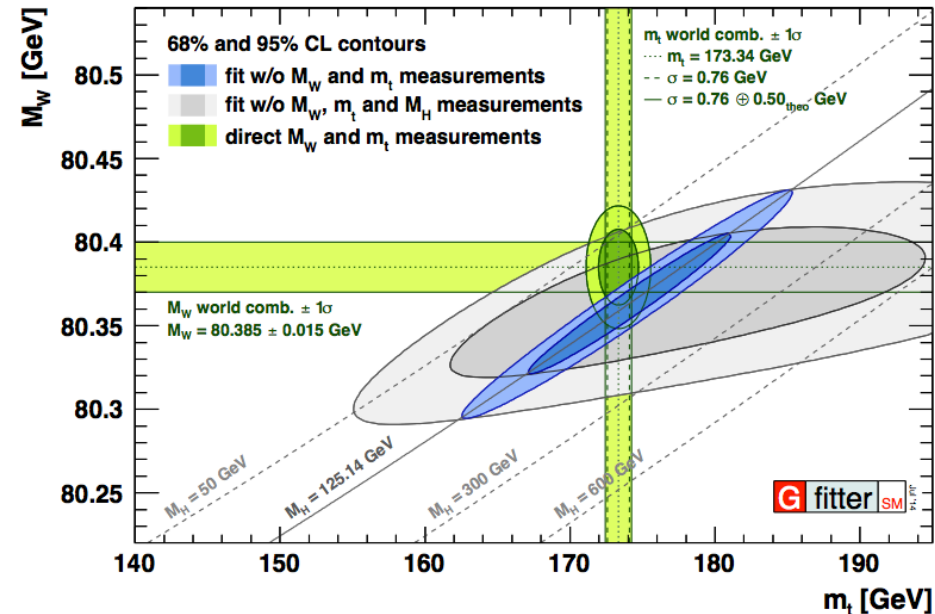


Why top quark properties?

- Top quark mass is a fundamental parameter of the SM



- Precise measurement needed for checking consistency of the SM

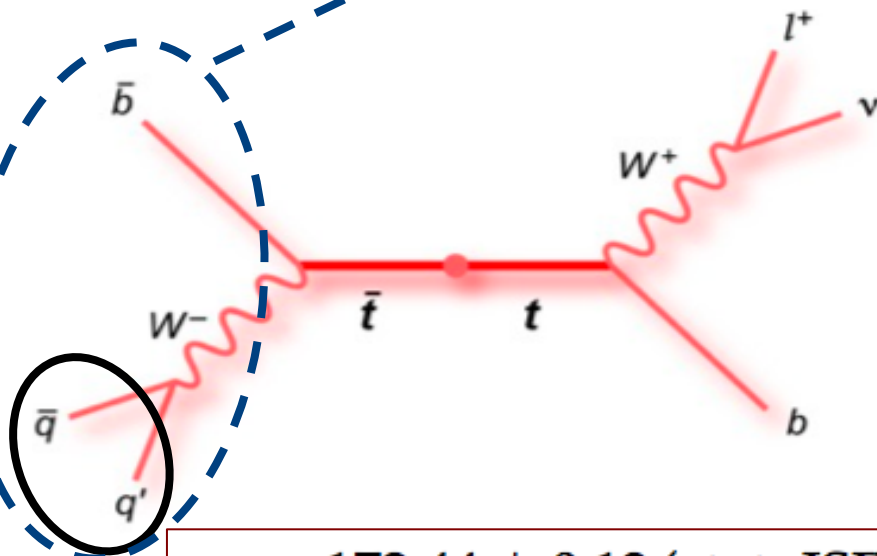
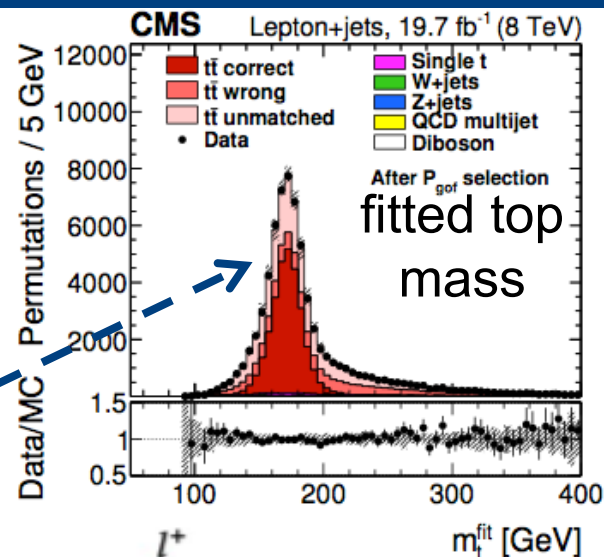
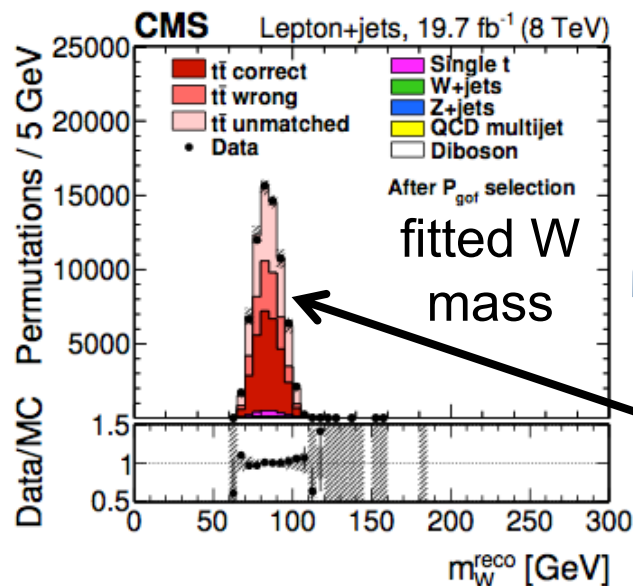


- Top is the only fermion with the mass of the order of EWSB scale
- Discovered Higgs boson fits well with precise determinations of m_W and m_{top}
- Other properties (EWK coupling, production asymmetries, etc.) are predicted by SM
- Precise measurements could reveal breakdown of SM

Precise mass measurement

arXiv:1509.04044

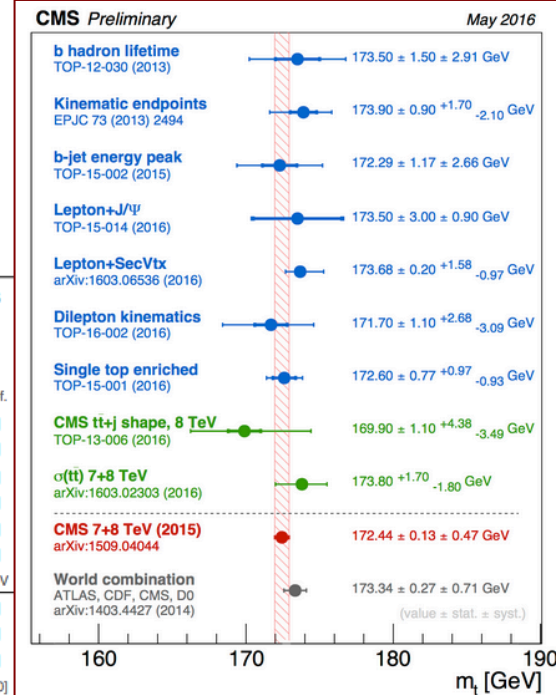
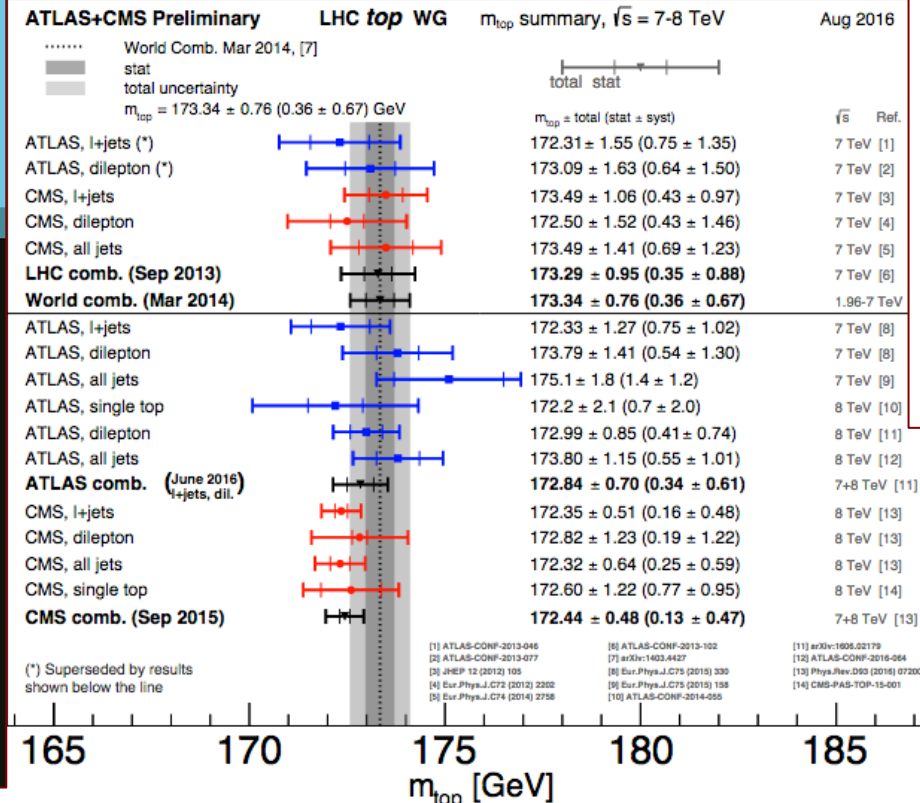
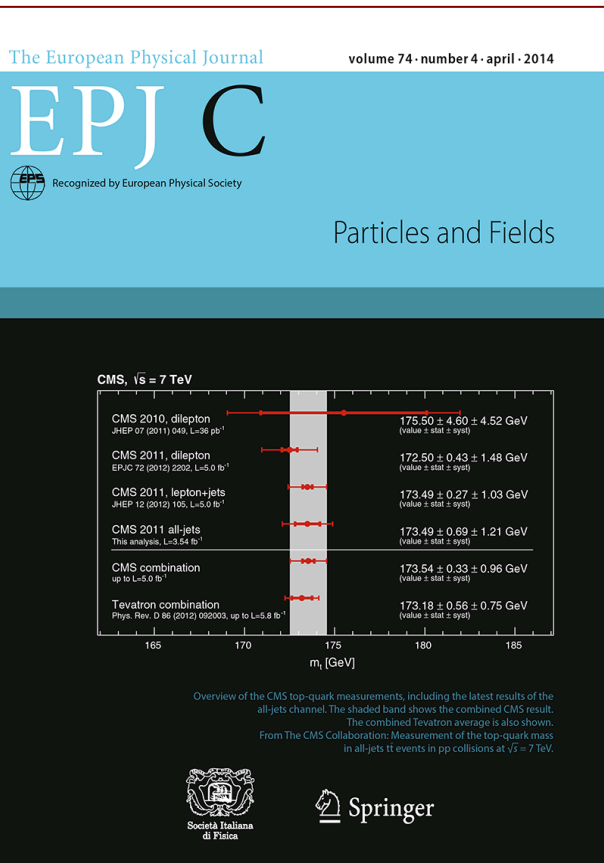
- Select lepton+jet final state
 - Best channel to measure m_{top}
 - well defined final state (1 lepton, 1 ν , 2b $W_{\text{qq'}}$)
- Select $t\bar{t}$ events: hadronic decays (m_{top} , m_W)
- Kinematic fit: constrain W mass, top-antitop masses
 - In-situ JES calibration
- Measure m_{top} and JSF



$$m_t = 172.44 \pm 0.13 \text{ (stat+JSF)} \pm 0.47 \text{ (syst) GeV} \quad \pm 0.3\%$$

Top quark mass results

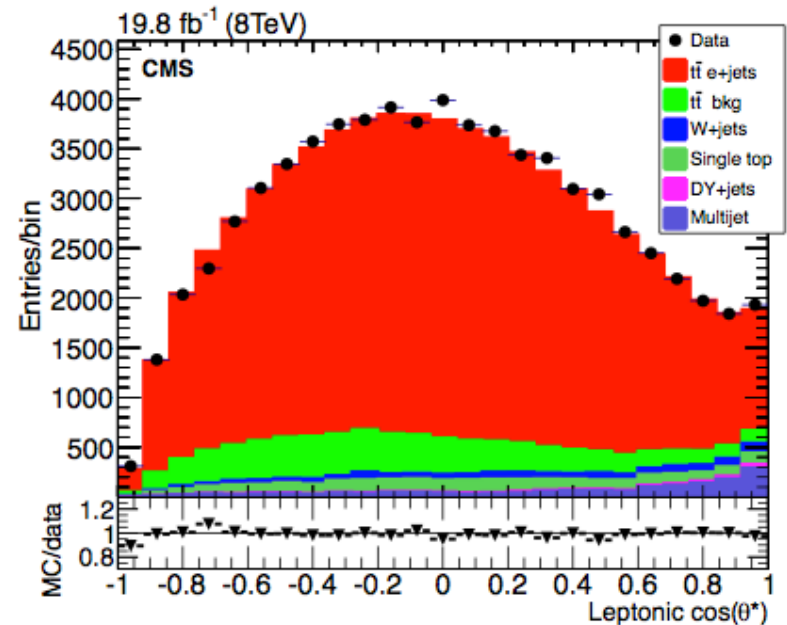
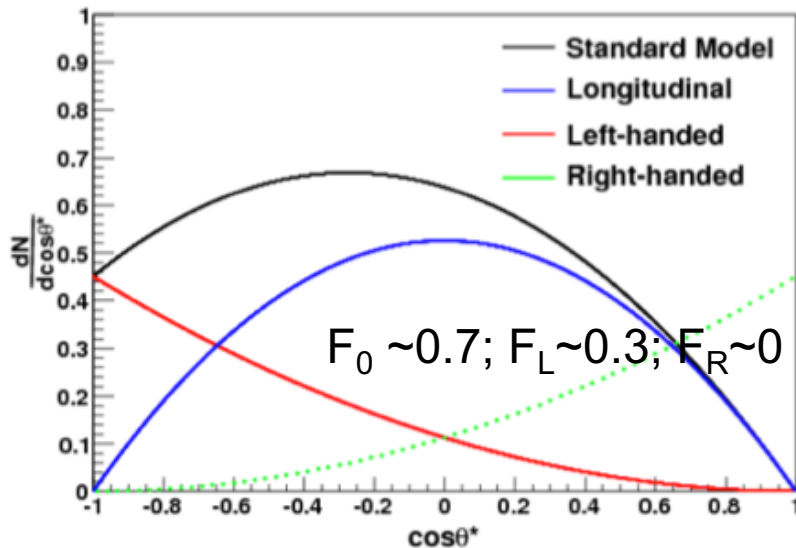
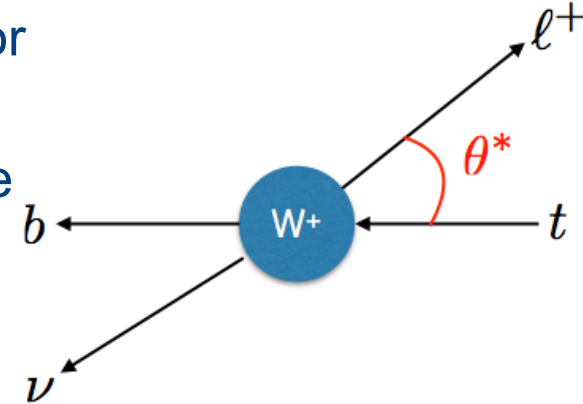
- accurate ($\sim 0.3\%$) measurement



W boson polarization

arXiv:1612.02577, PRD 93(2016)052007

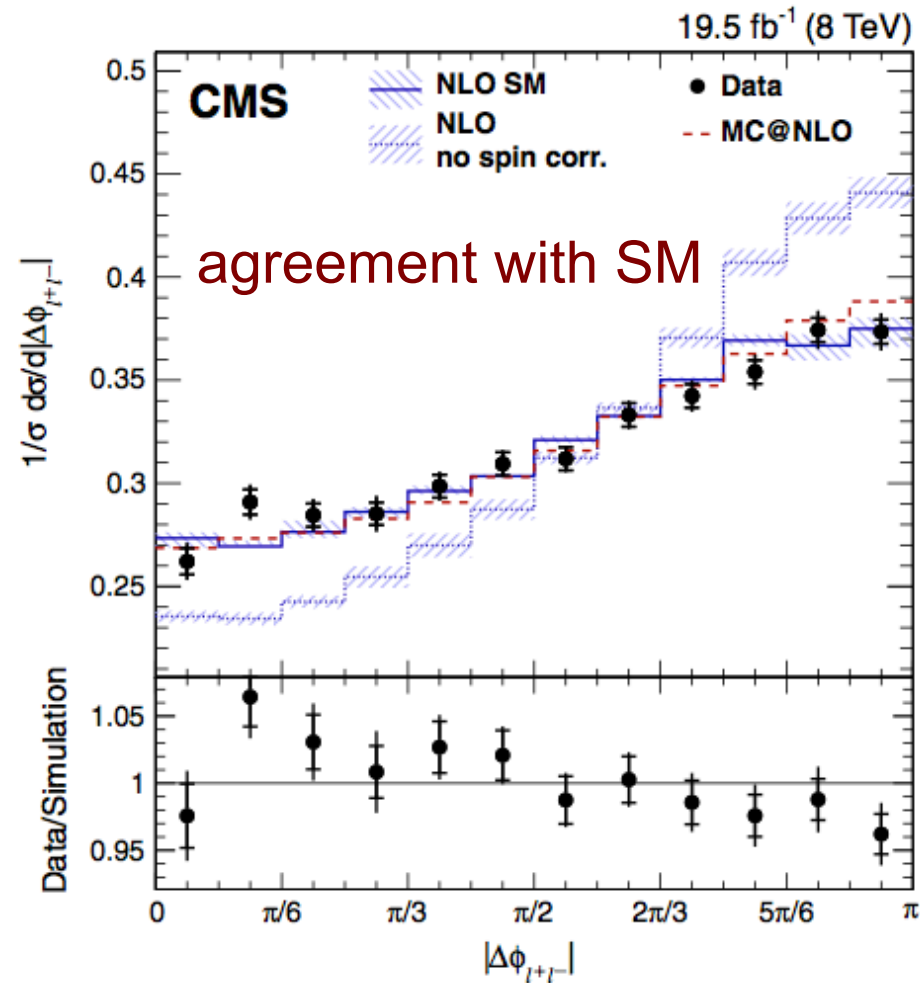
- W bosons can be produced with left-handed, right-handed, or longitudinal polarization
- Top decay vertex in the SM is characterized by V-A structure
 - Fractions of polarization states are well predicted
- Can probe by measuring the angular distributions of the W boson decay products
- New physics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



Spin correlation

PRD 93(2016)052007

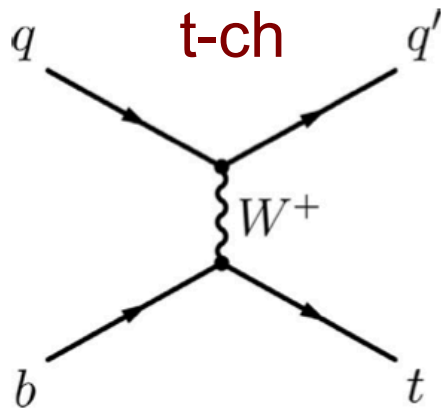
- Important tool for precise studies
- Top quark produced are not polarized
 - ...but spins between quark and anti-quark are correlated
- Top quark decays before spins decorrelate
 - It decays before hadronization ($\tau \sim 10^{-25}$ s) \Rightarrow spin information transmitted to decay products
 - No need to reconstruct full $t\bar{t}$ 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



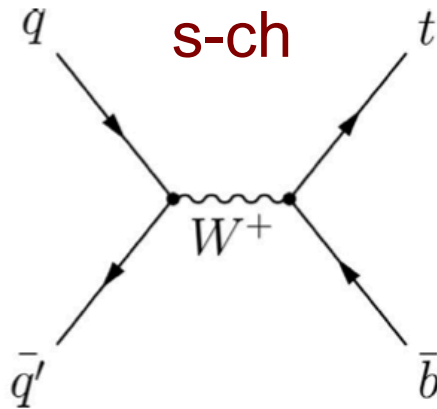
How else is Top produced?

PRD102(2009)182003, PRD81(2010)054028

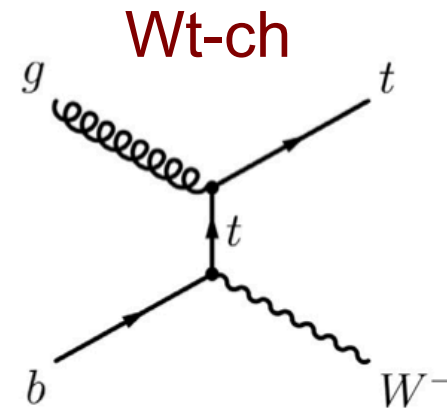
- Single top quark production



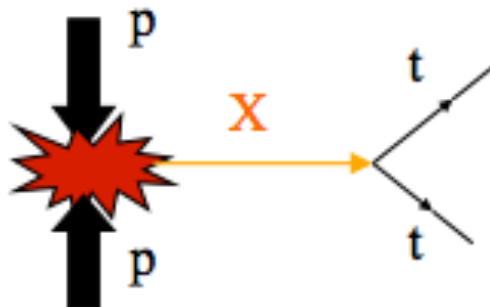
$\sigma(13\text{TeV}) = 217 \text{ pb}$



10 pb



72 pb



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

Probing top quark production

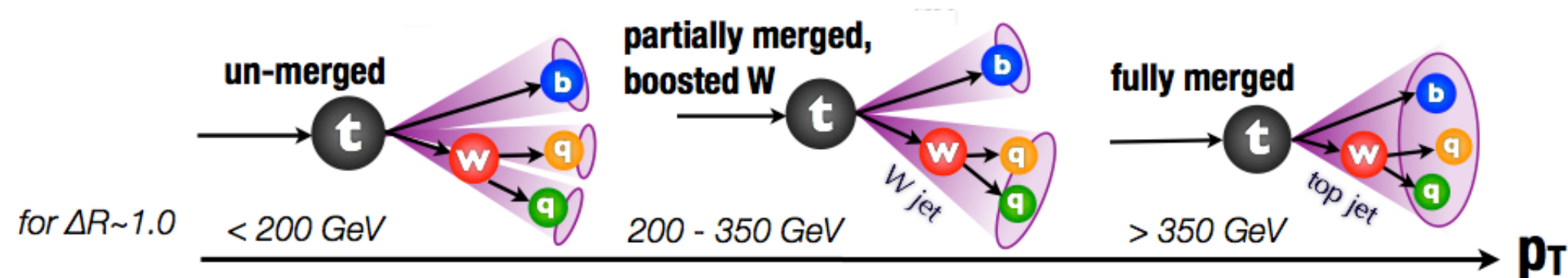
- Differential measurements

- Testing QCD, measuring properties, searching for new physics, ...
- Function of kinematics, global variables, associated production

- Increased sensitivity: top quark pairs produced at rest

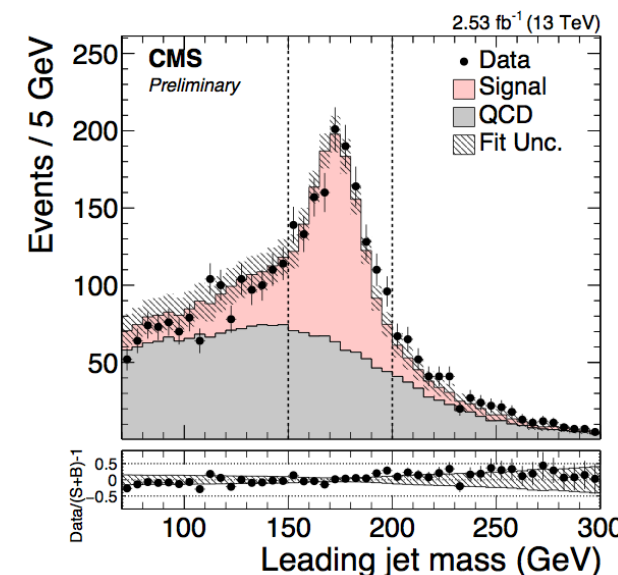
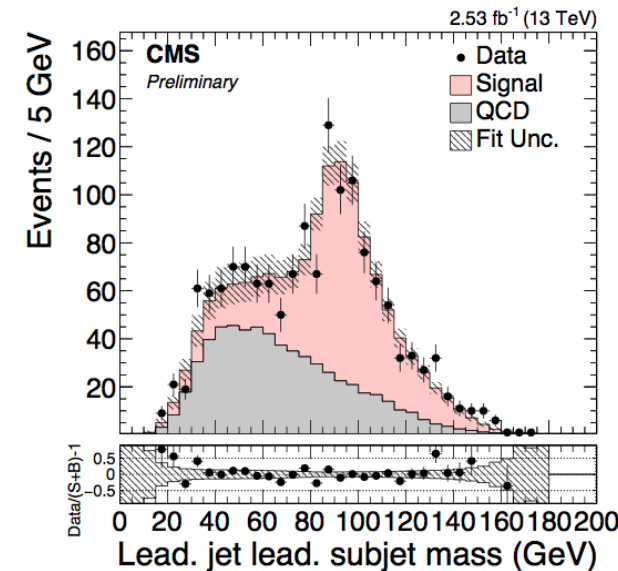
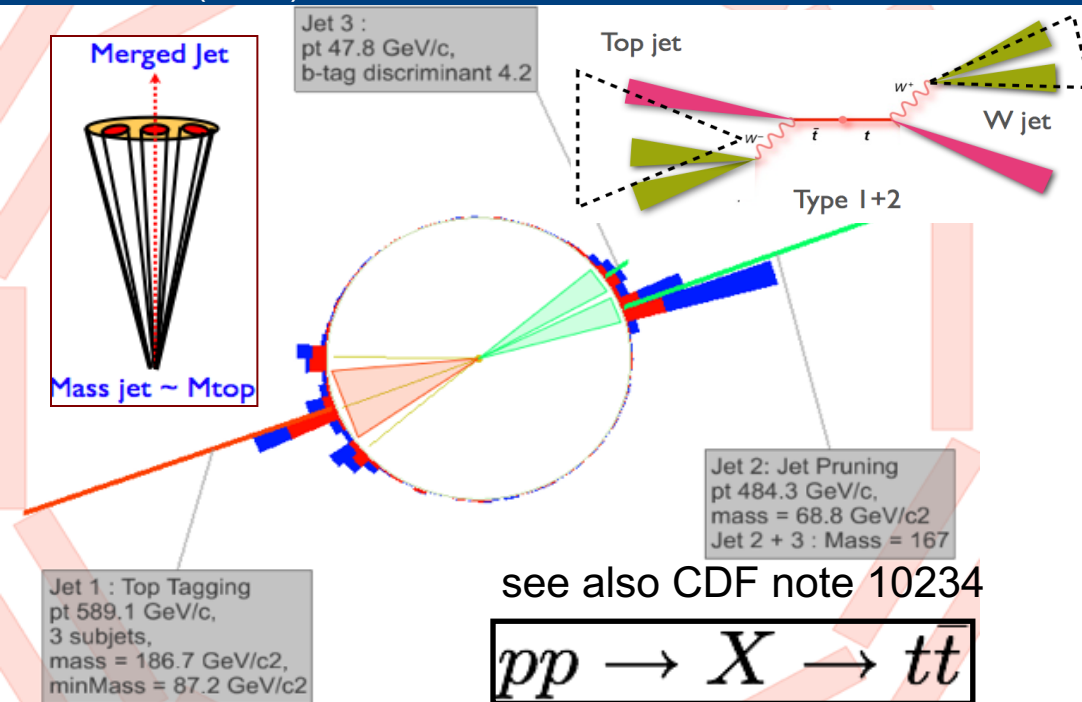
- $\sigma(M_{t\bar{t}} > 1 \text{ TeV at } 13 \text{ TeV}) = 8 \times \sigma(M_{t\bar{t}} > 1 \text{ at } 8 \text{ TeV})$

⇒ Unique opportunity to probe boosted production at 13 TeV



Boosted topology

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



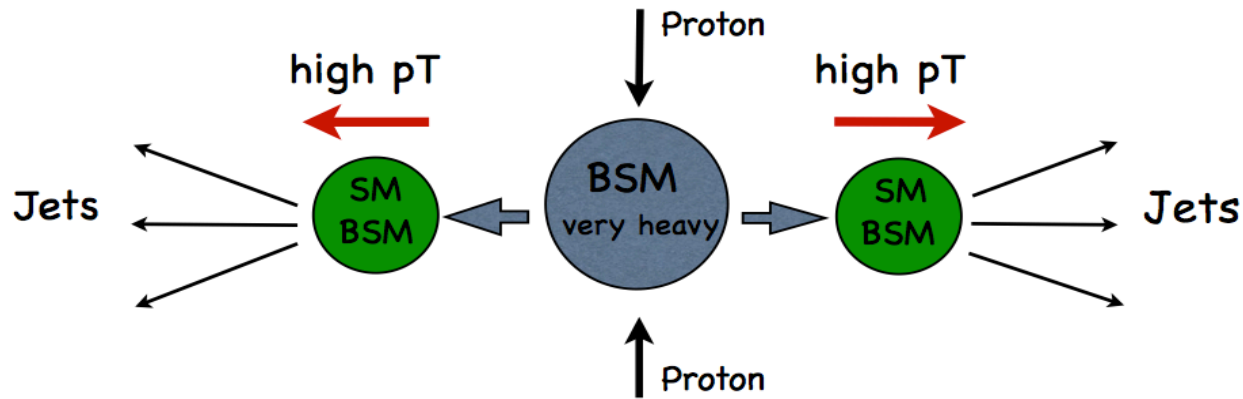
- At high energy, particles produced beyond threshold
- All-hadronic topology
 - Top p_T boosted, jets are collimated
 - Decay products and FSR collected in a “fat” jet
- Look at jet substructure
- Measure mass (no neutrinos)

Boosted topology

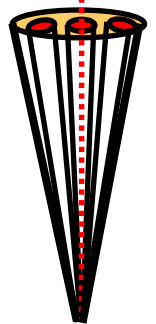
- In many models there is high potential to discover new physics in the top sector in search for heavy resonances

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

- Simple approach to merge neighboring jets



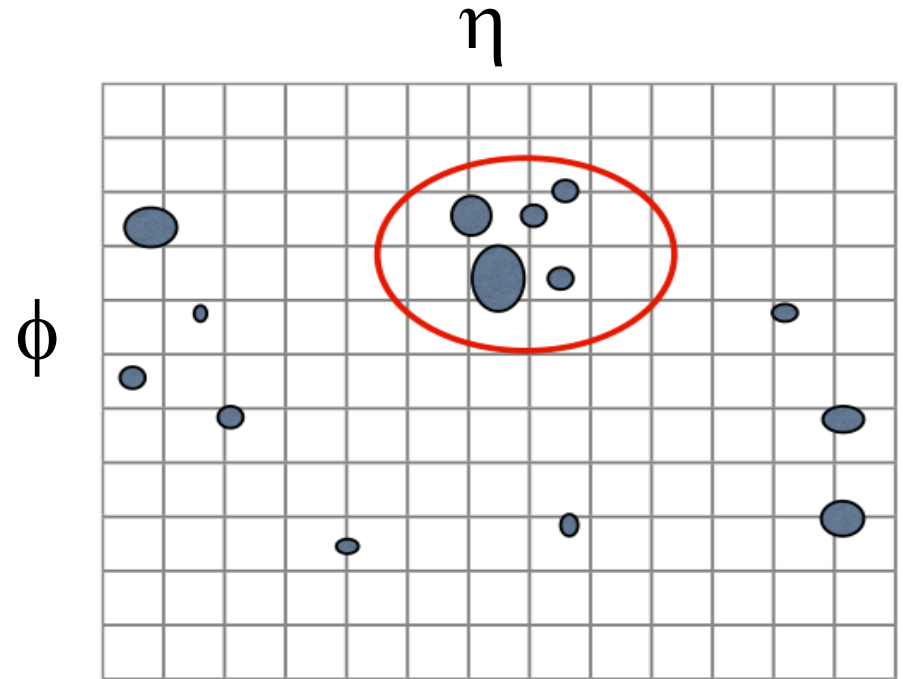
Merged Jet
Mass jet $\sim M_{\text{top}}$



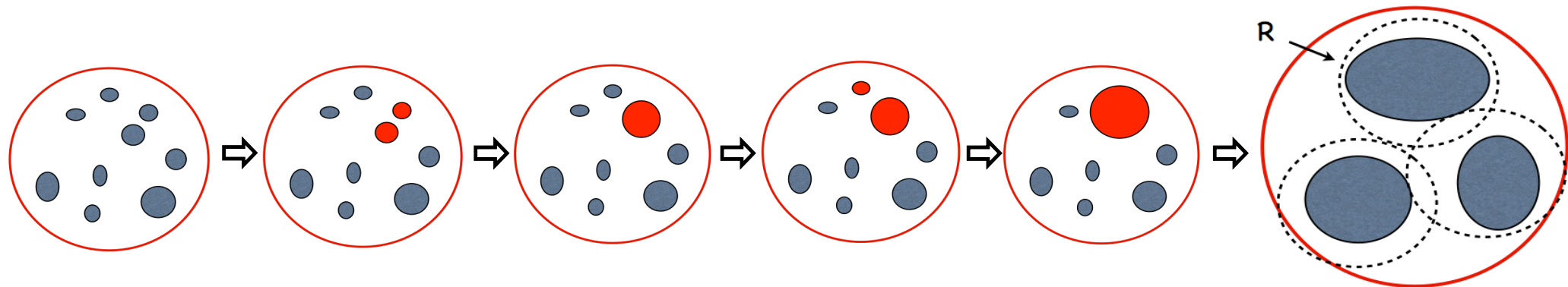
- At LHC energy, EWK scale particles produced beyond threshold
- Jets are highly collimated
- Decay products and FSR collected in a fat jet

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

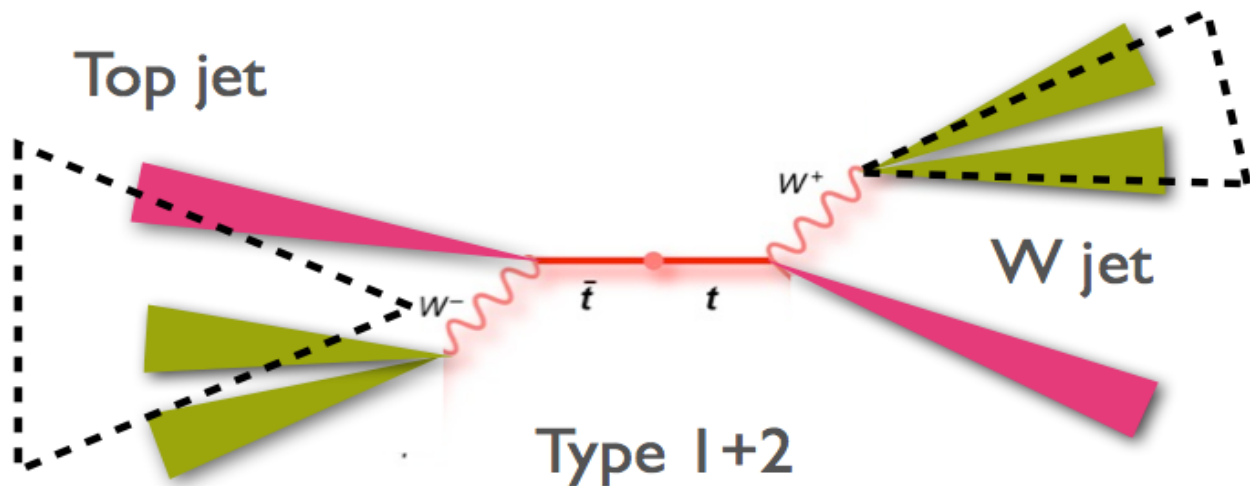


UE, ISR, Pile-up, hard interaction



Boosted topology: Top

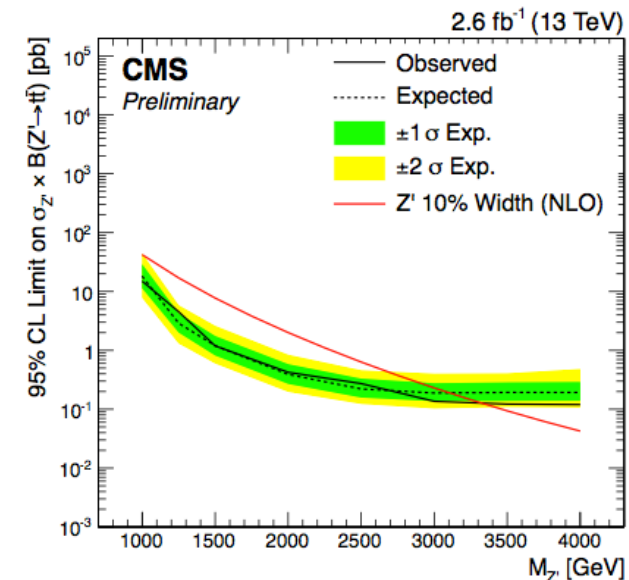
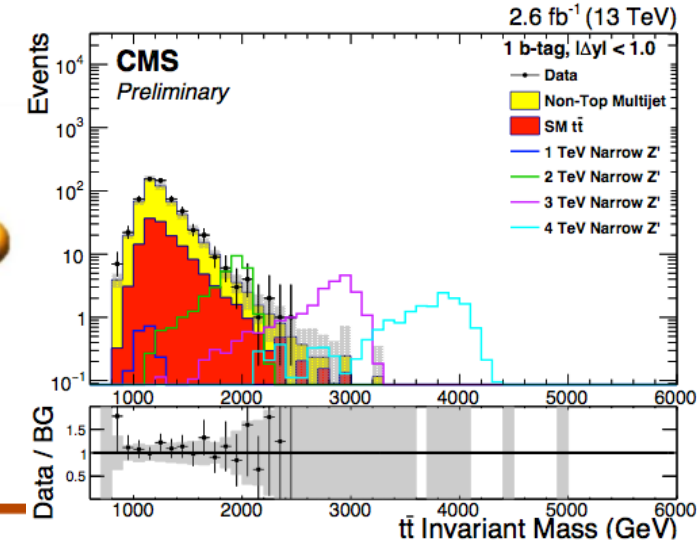
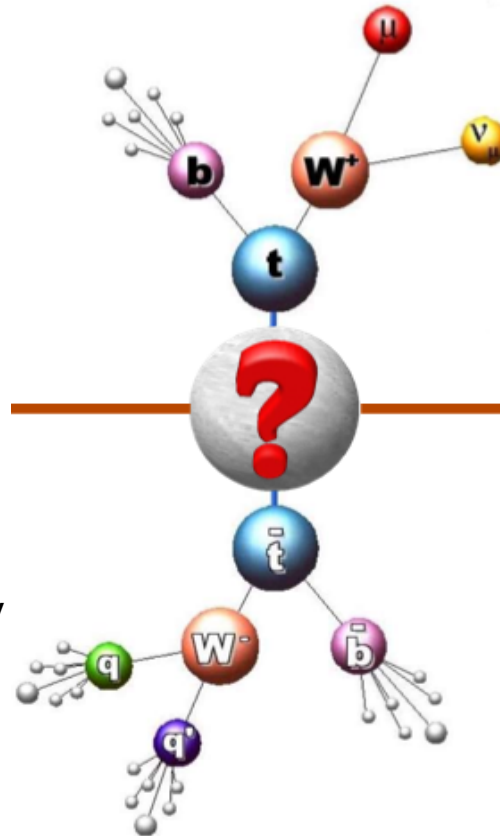
- **Highly boosted top:** three hadronic decays of the top are merged in one top jet
- **Moderately boosted top:** three hadronic decays of the top are merged in one W jet plus and one b jet candidates



Top quark pair resonance

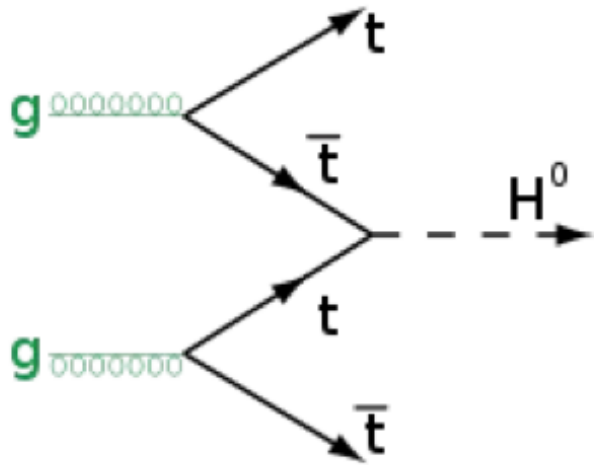
CMS-B2G-15-002, B2G-15-003

- No resonance expected in SM
- Why is top so heavy?
 - new physics?
 - is third generation 'special'?
- Search for massive neutral bosons decaying via a $t\bar{t}$ quark pair
- Experimental check
 - search for bump in the inv. mass spectrum
 - progressive loss in reconstruction ability due to jet merging
 - reconstruct $M_{t\bar{t}}$ in different categories (e/μ , n -jets, n b-tags)
 - 1+jet events: full event reconstruction



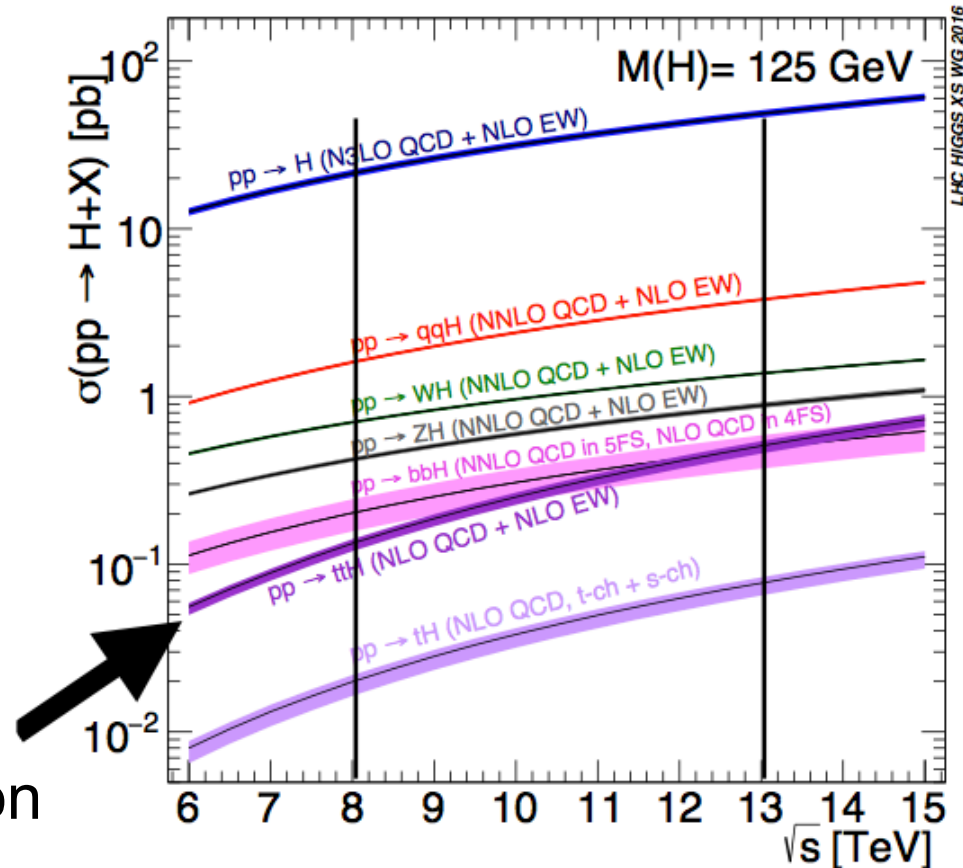
$t\bar{t}$ +Higgs

- $t\bar{t}$ produced in association with H
 - $t\bar{t}$ 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)

$t\bar{t}H \sim 1\%$ of total Higgs cross section



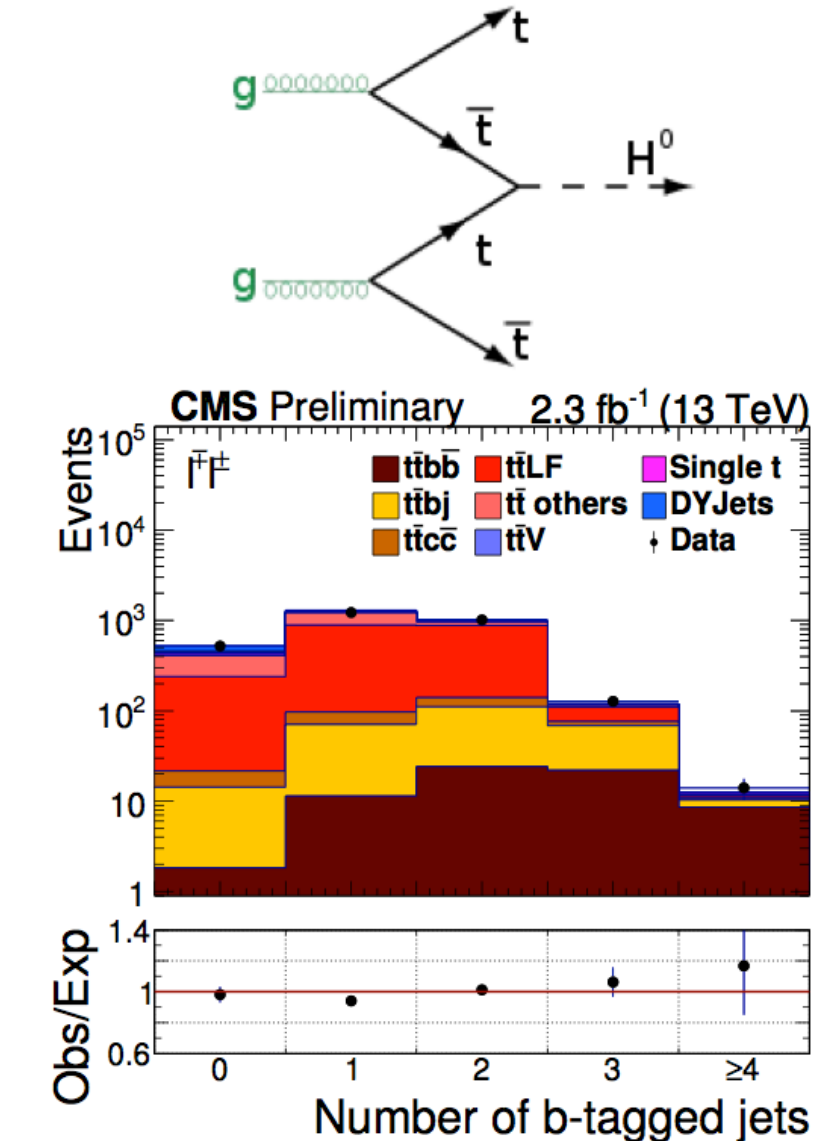
$t\bar{t}$ bar+heavy flavour

arXiv:1411.5621, TOP-16-010

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



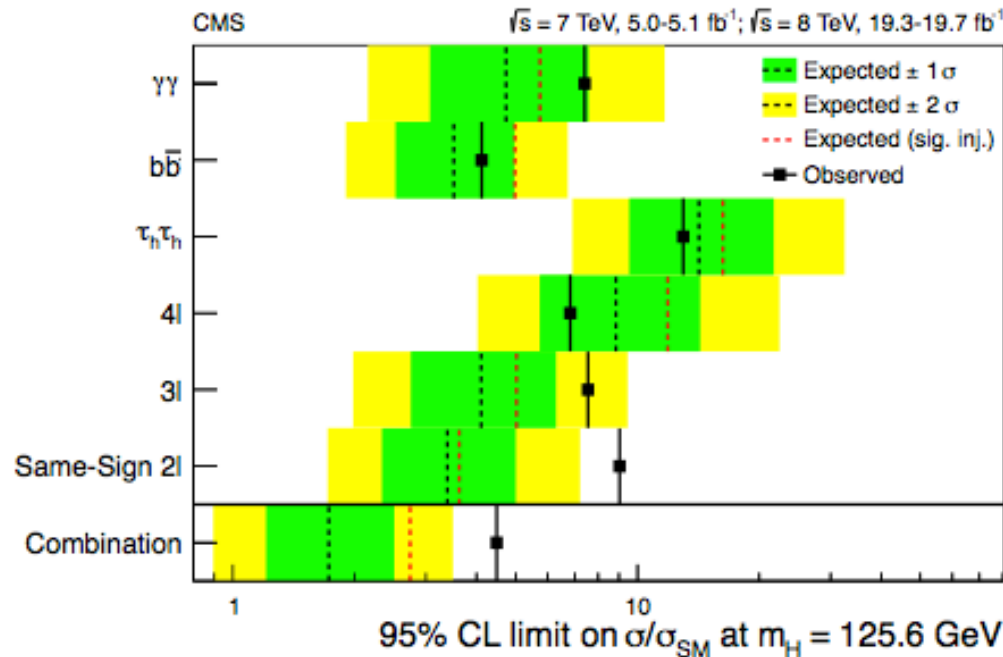
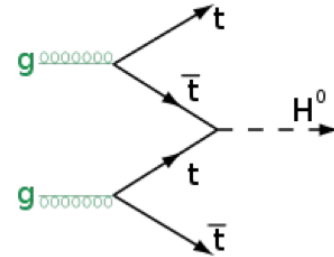
ttH

JHEP09(2014)087

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

Run1 best fit:

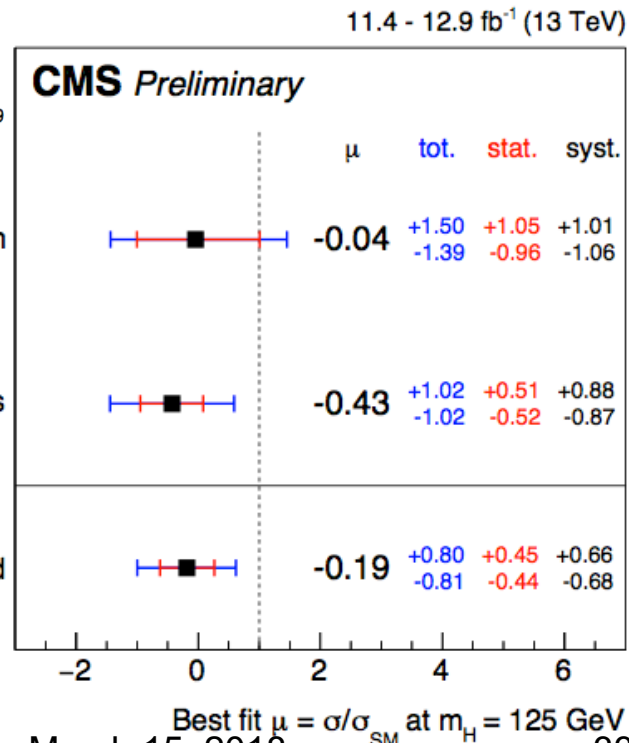
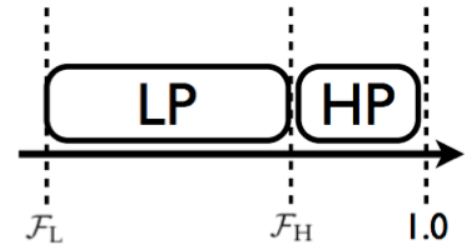
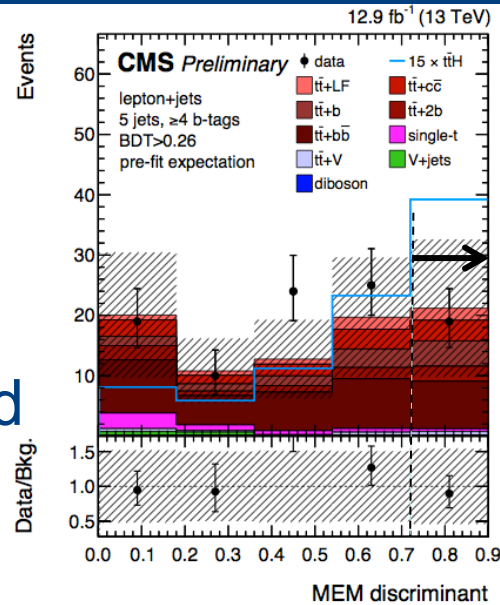
$$\mu = 2.80 \pm 1.00$$



$t\bar{t}H$, $H \rightarrow b\bar{b}$

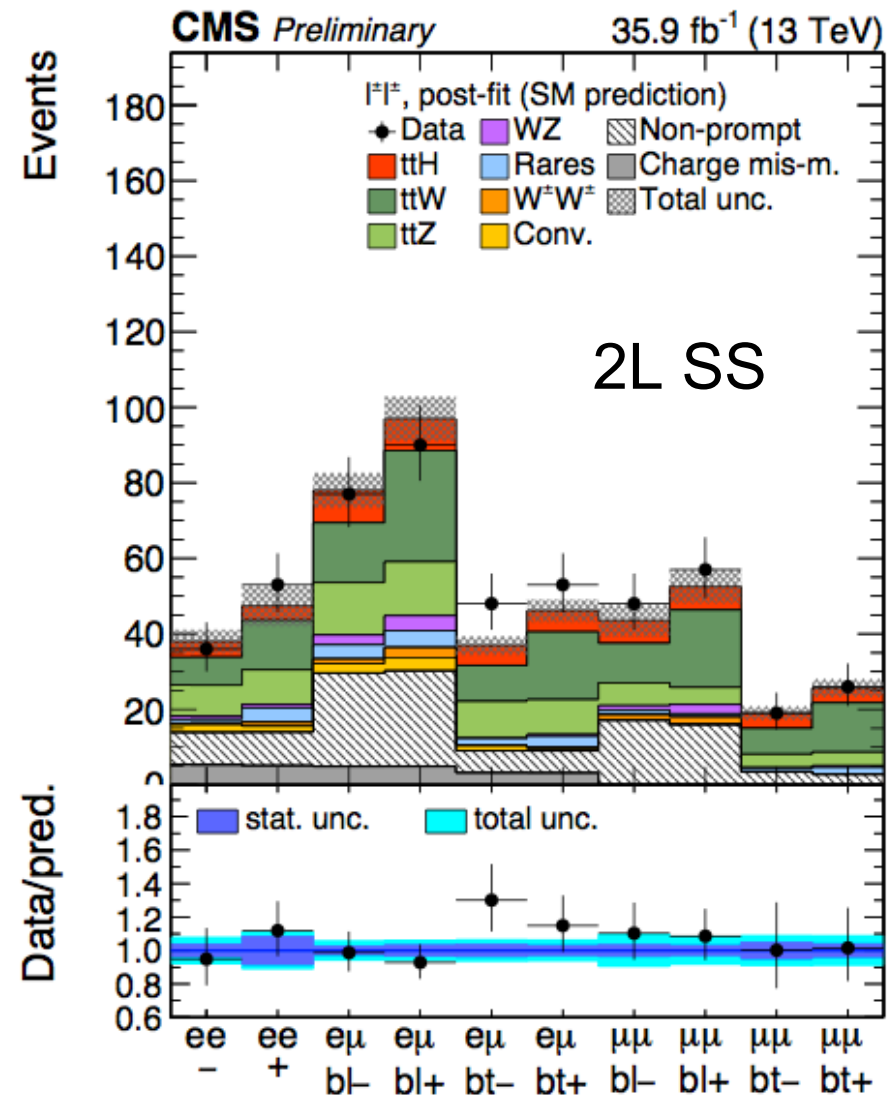
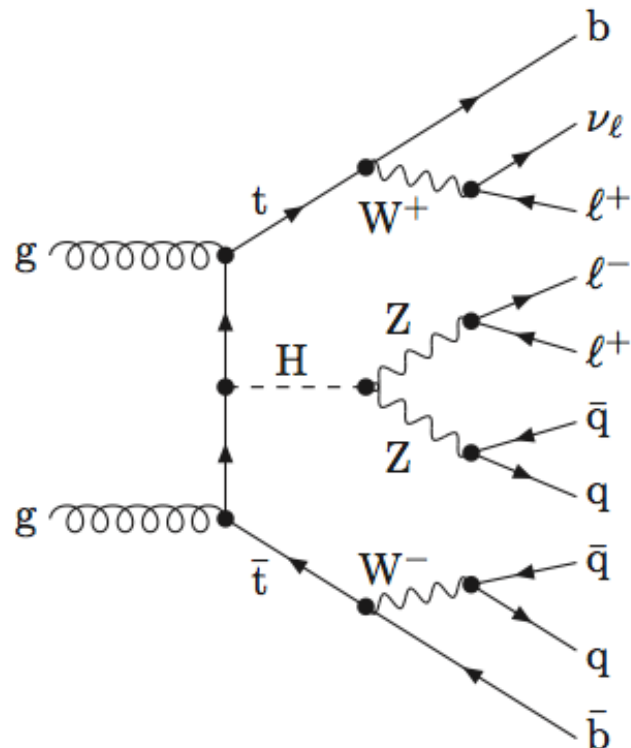
JHEP 09(2014)087, EPJC 75(2015)251, HIG-16-038

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



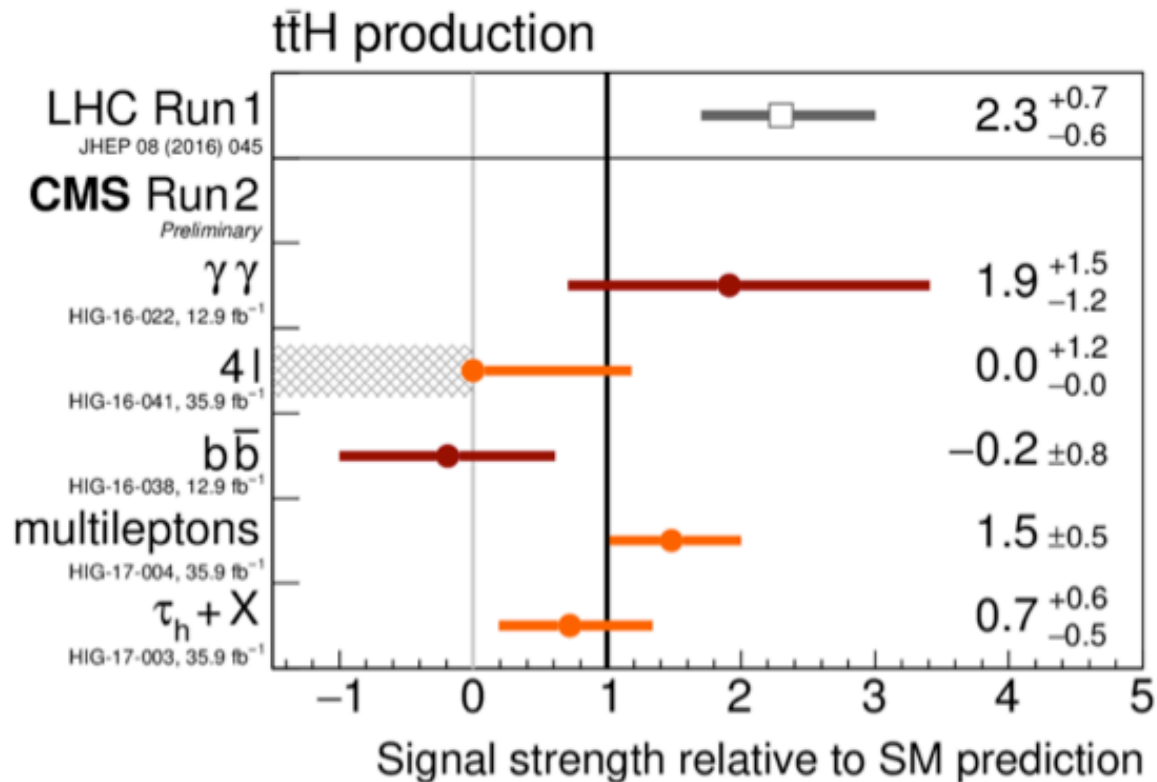
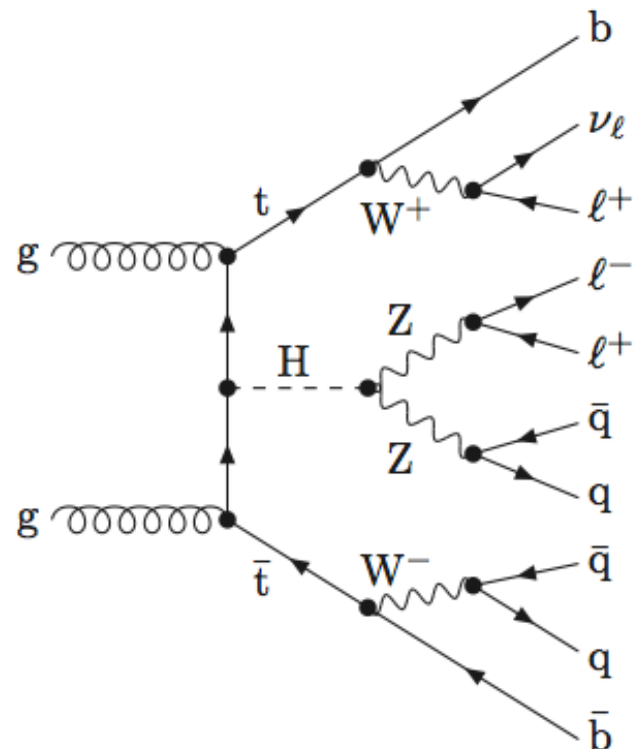
ttH: multi-leptons, $\tau\tau$

- Multi-leptons: SS, 3L and 4L
 - ttH with $H \rightarrow \tau\tau$
- \Rightarrow categories per charge, flavor



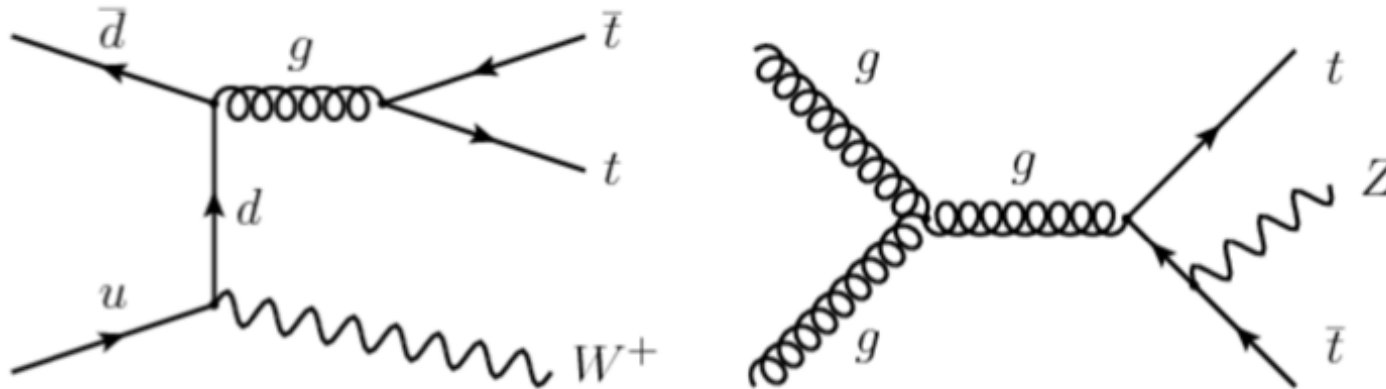
ttH: multi-leptons, $\tau\tau$

- Multi-leptons: SS, 3L and 4L
 - ttH with $H \rightarrow \tau\tau$
- \Rightarrow categories per charge, flavor



$t\bar{t}V$ production ($V=\gamma, W, Z$)

- Large datasets give access to rare $t\bar{t}+W$ and $t\bar{t}+Z$ processes
- $t\bar{t}Z$: direct probe of top- Z coupling (new physics?)
- $t\bar{t}W$: important background to NP searches

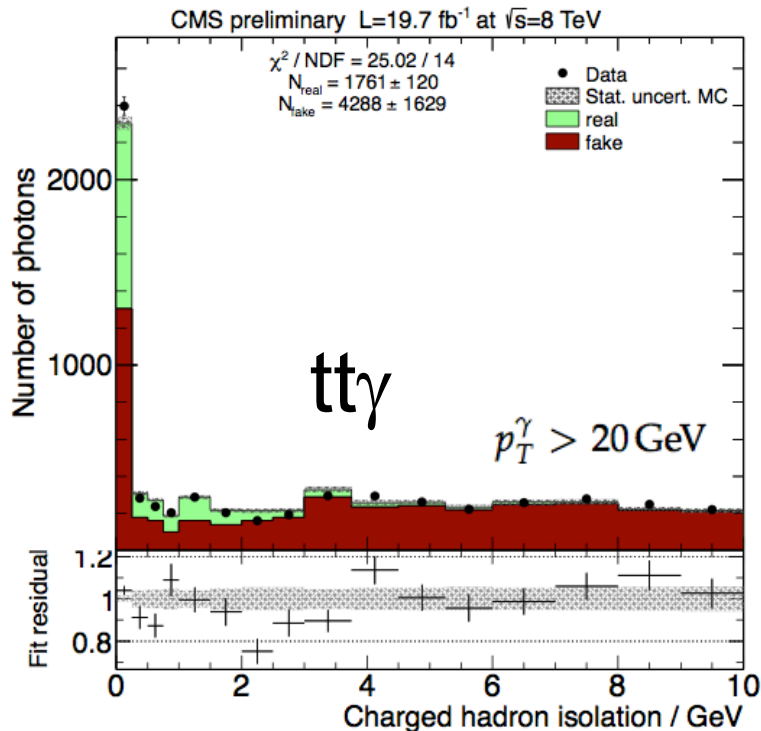


- Use multi-lepton final states
 - 2 same-sign charge leptons, 3 or 4 lepton final states

ttV production ($V=\gamma, W, Z$)

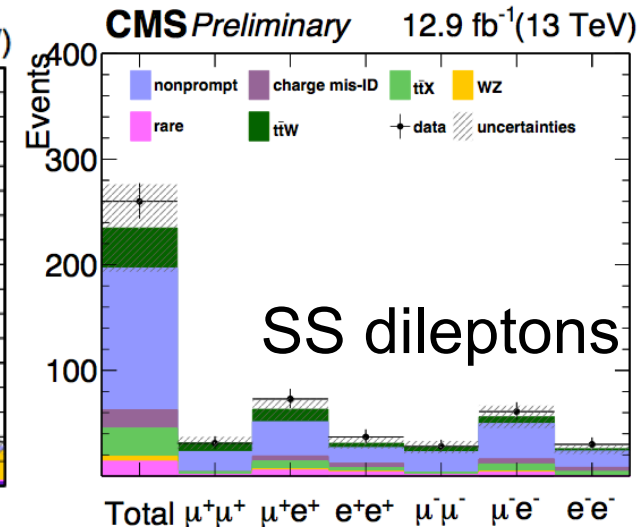
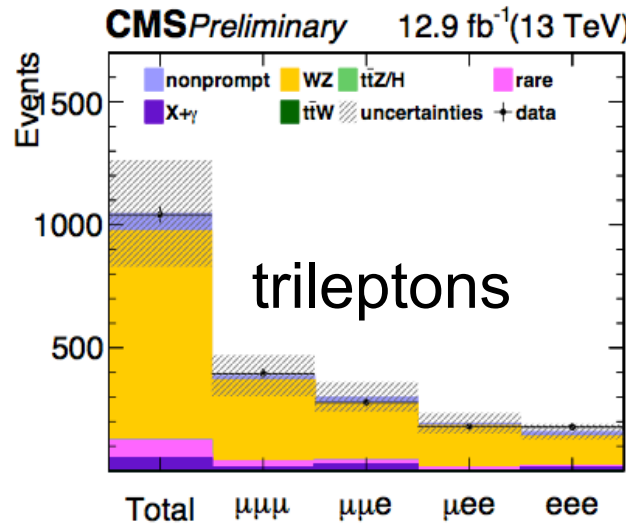
CMS-TOP-13-011, EPJC 74(2014)3060, TOP-14-008, TOP-16-017

- Measurements will give access to EW couplings of the top

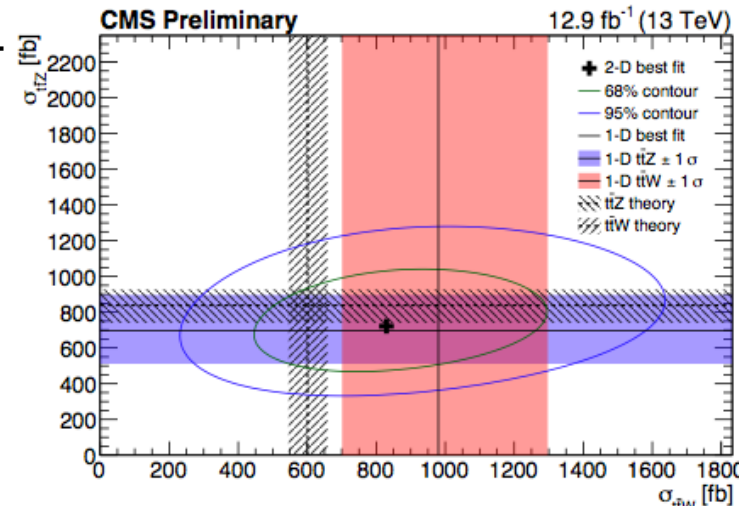


$$\sigma_{t\bar{t}\gamma} = 2.4 \pm 0.2 \text{ (stat.)} \pm 0.6 \text{ (syst.) pb.}$$

Consistent with theoretical predictions



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



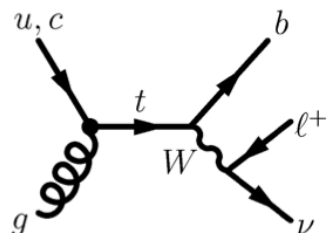
Flavor Changing Neutral Currents

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

Final states:

Wb

ATLAS



Couplings:

$t \rightarrow ug$

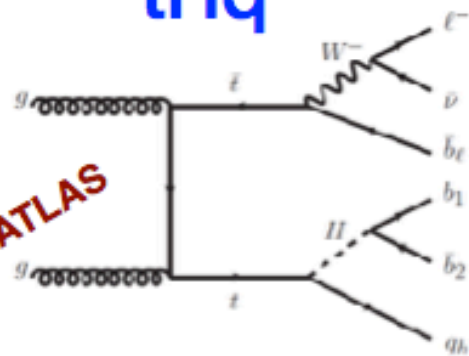
$t \rightarrow cg$

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

$$\sigma_{qg \rightarrow t} \times B(t \rightarrow Wb) < 2.9 \text{ pb}$$

tHq

ATLAS



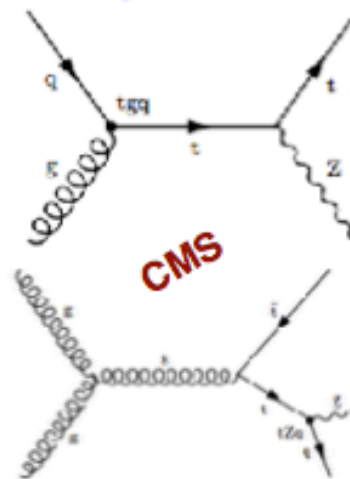
$t \rightarrow uH$

$t \rightarrow cH$

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

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

tZ



$t \rightarrow ug, t \rightarrow cg$

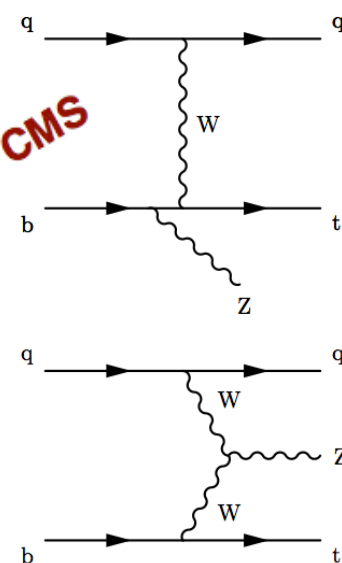
$t \rightarrow uZ, t \rightarrow cZ$

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

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

SM: tZq

CMS



$t \rightarrow tZ$

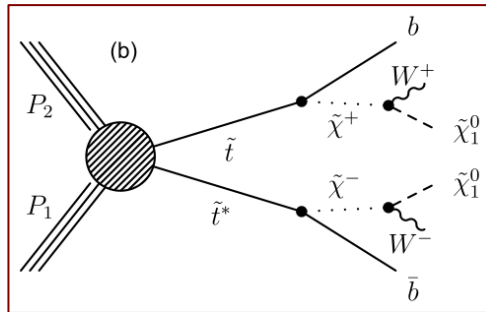
$$\text{SM } \sigma(tZq) = 10^{+8-7} \text{ fb}$$

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

- Light stop:

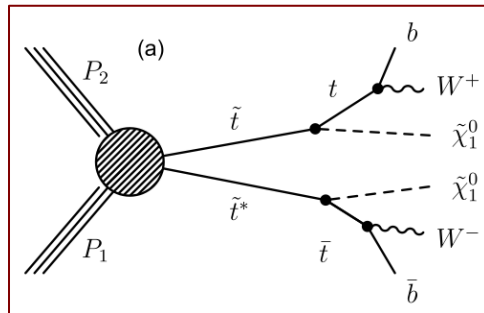
$$m_{\tilde{t}_1} \lesssim m_t$$



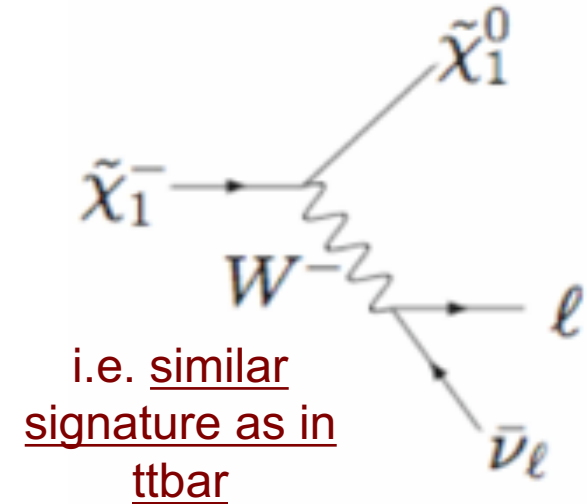
$$\tilde{t} \rightarrow b \tilde{\chi}^+ \rightarrow b W \tilde{\chi}_1^0$$

- Heavy stop:

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



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



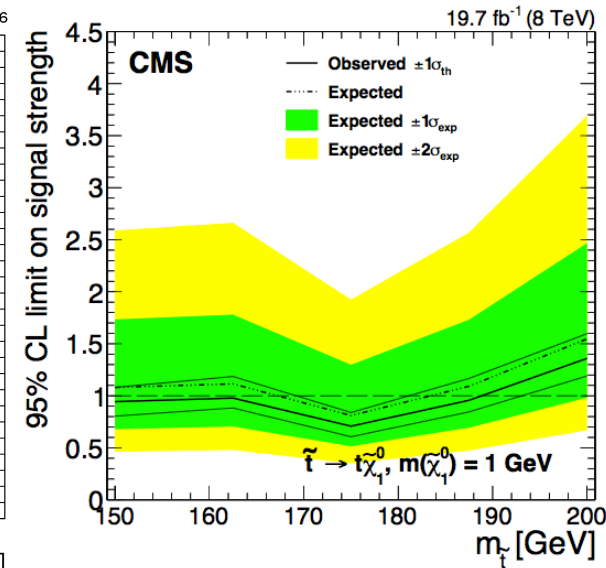
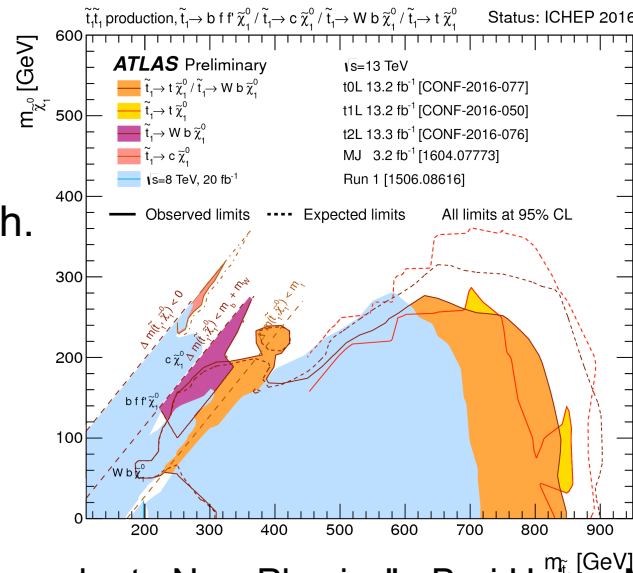
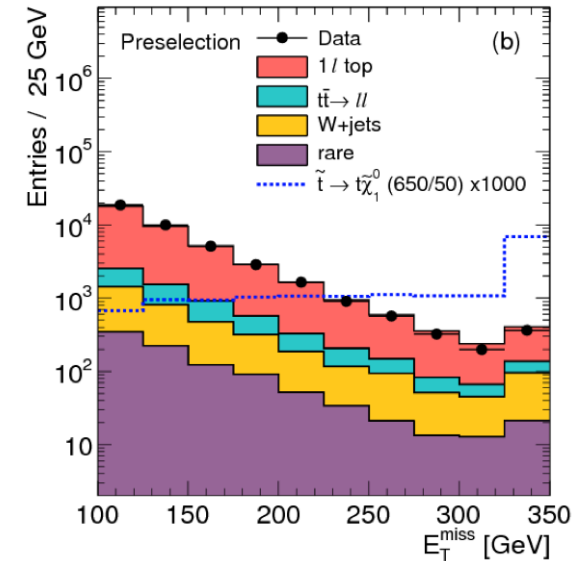
Top and SUSY

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

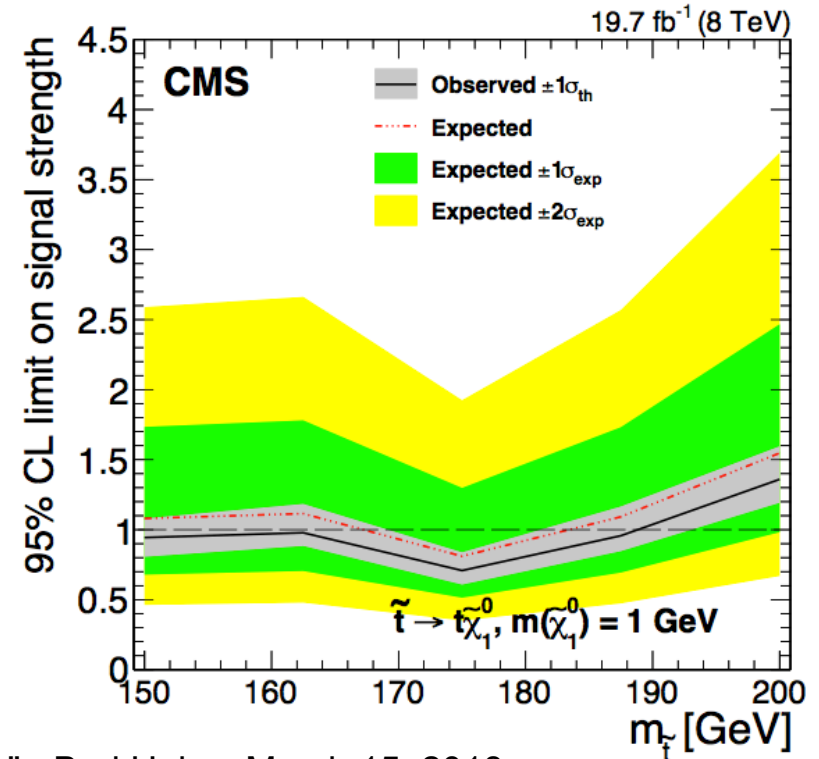
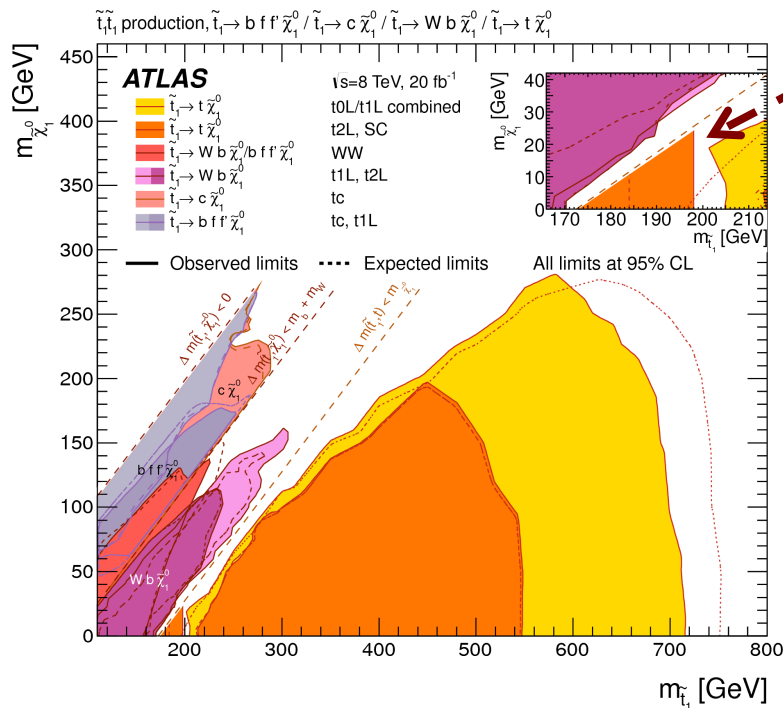
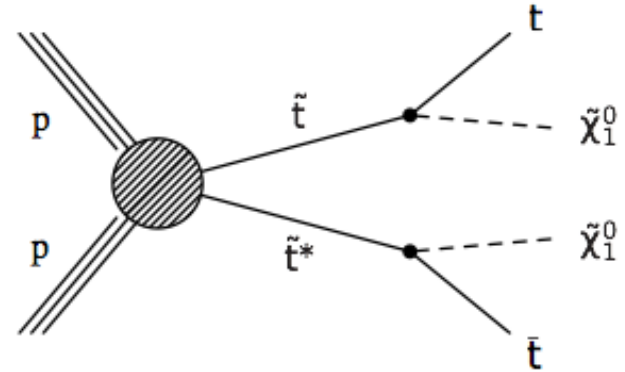
$$\begin{aligned} \tilde{t} &\rightarrow t \tilde{\chi}_1^0 \rightarrow b W \tilde{\chi}_1^0 && \text{"heavy"} \\ \tilde{t} &\rightarrow b \tilde{\chi}_1^+ \rightarrow b W \tilde{\chi}_1^0 && \text{"light"} \end{aligned}$$

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



Top cross section: dileptons

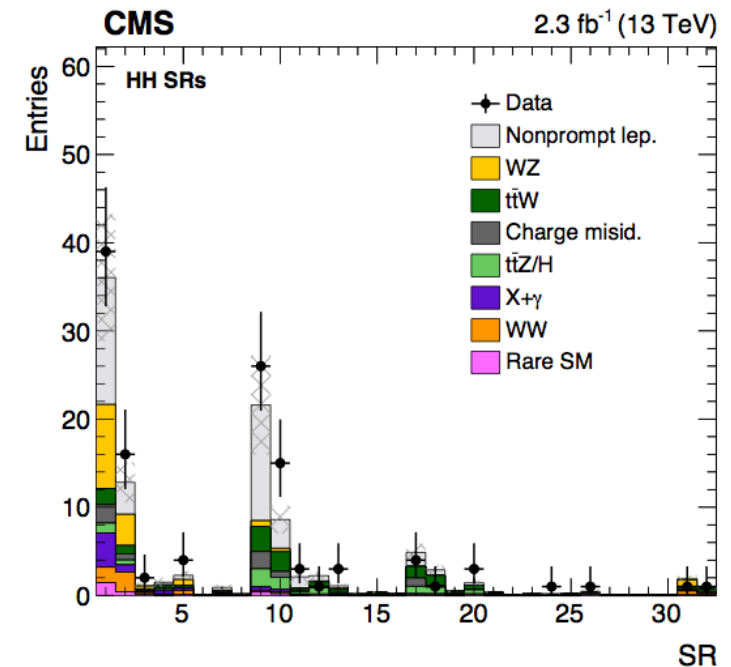
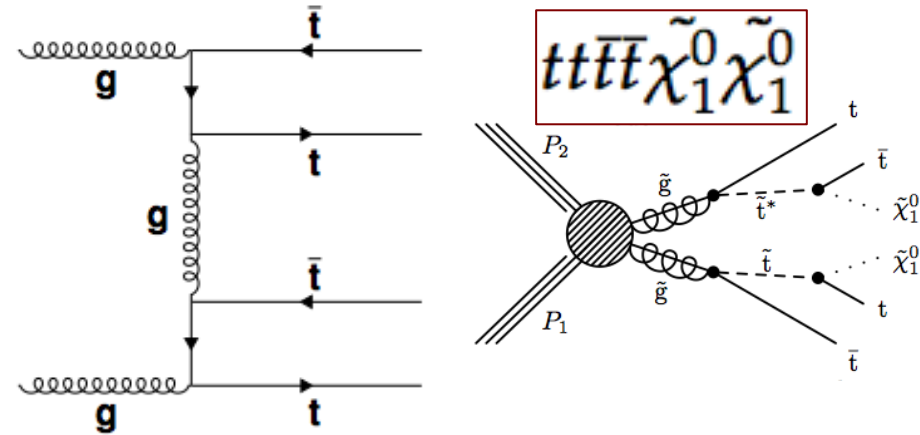
- Indirect searches
- SUSY models could produce final states very similar (with additional MET)
- For example: dilepton channel



Multi-top production

arXiv:1605.03171, TOP-16-016, 1702.06164

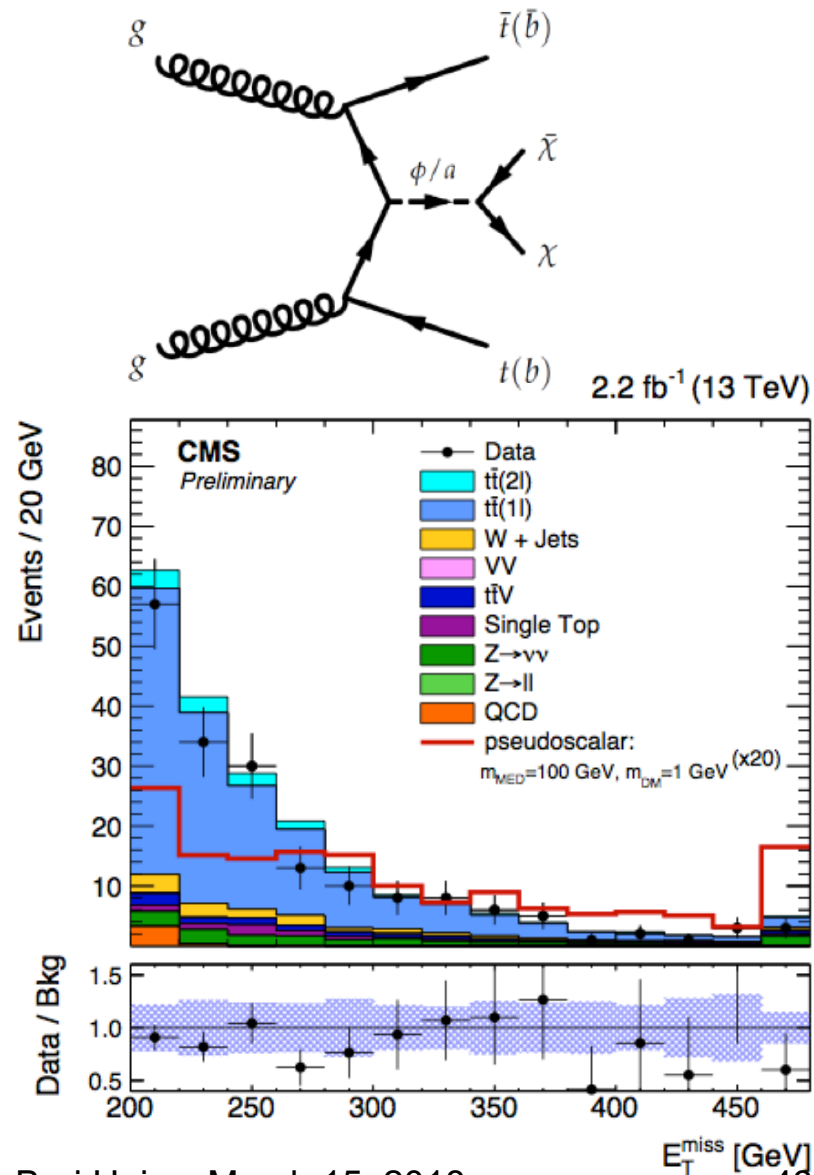
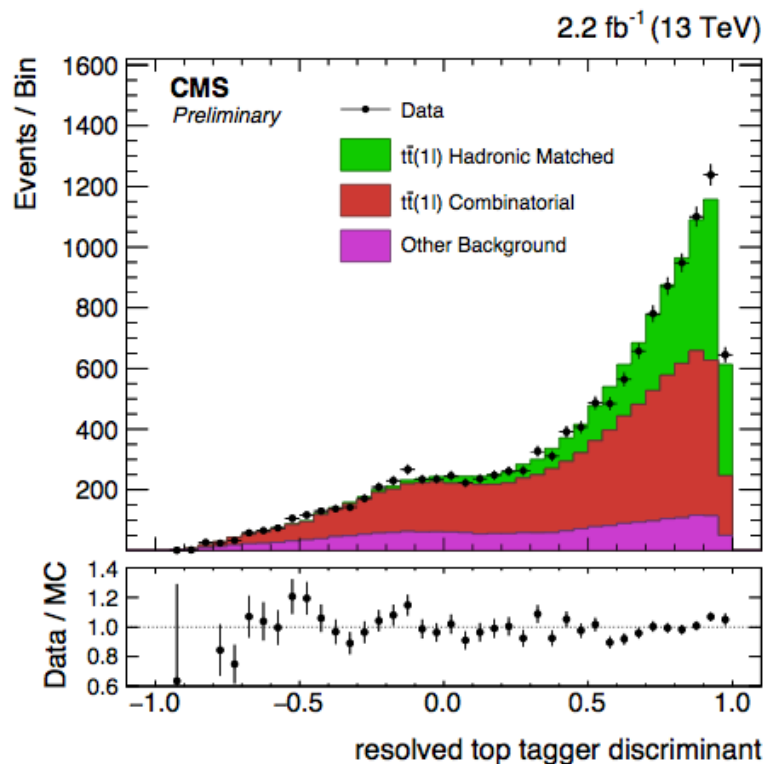
- Production of 4 tops is an attractive scenario in a number of new physics models
- The SM cross section is 9fb@13TeV
- Use lepton+jets final state
- Combination of kinematical variables and multivariate techniques
- Data are consistent with bkg expectations
- Set upper limit cross section 69fb @95%CL
- 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



Dark Matter + $t\bar{t}$

CMS-EXO-16-005

- Search for DM + $t\bar{t}$ ($\rightarrow l + \text{jets, all hadr.}$)
- Shape of MET distribution
- Signature: $t\bar{t}$ + MET
- Top-tagging categorization
- Signal events at large MET



Searches for new particles

ATLAS Exotics Searches* - 95% CL Exclusion

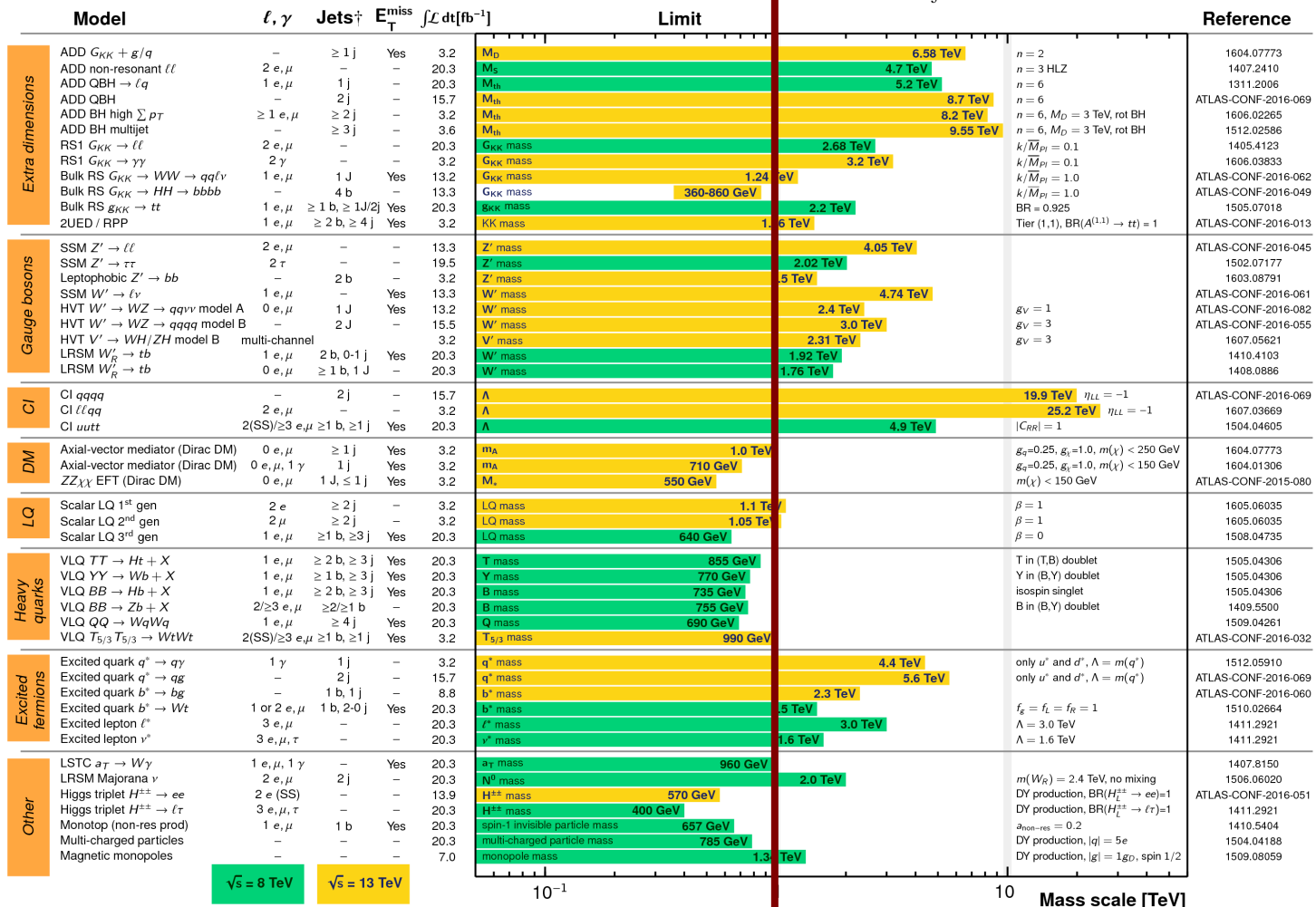
Status: August 2016

1 TeV

ATLAS Preliminary

$$\int \mathcal{L} dt = (3.2 - 20.3) \text{ fb}^{-1}$$

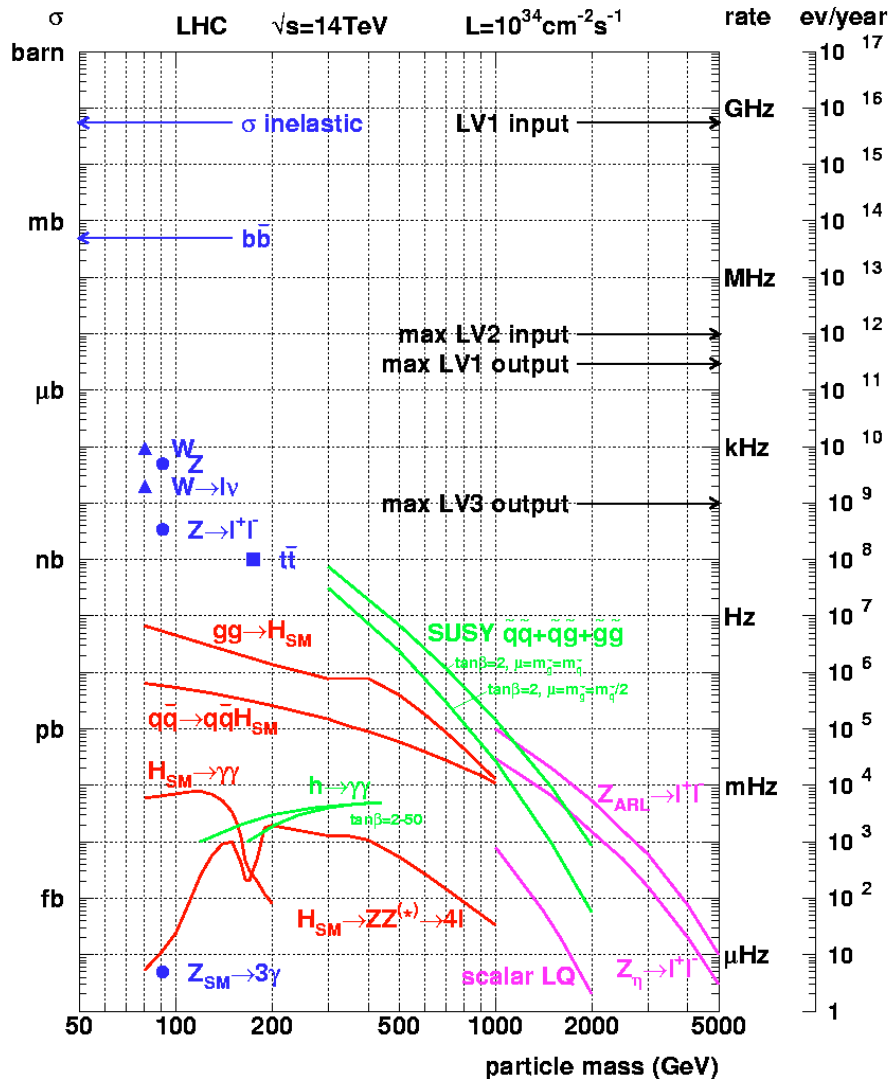
$$\sqrt{s} = 8, 13 \text{ TeV}$$



*Only a selection of the available mass limits on new states or phenomena is shown. Lower bounds are specified only when explicitly not excluded.

[†]Small-radius (large-radius) jets are denoted by the letter j (J).

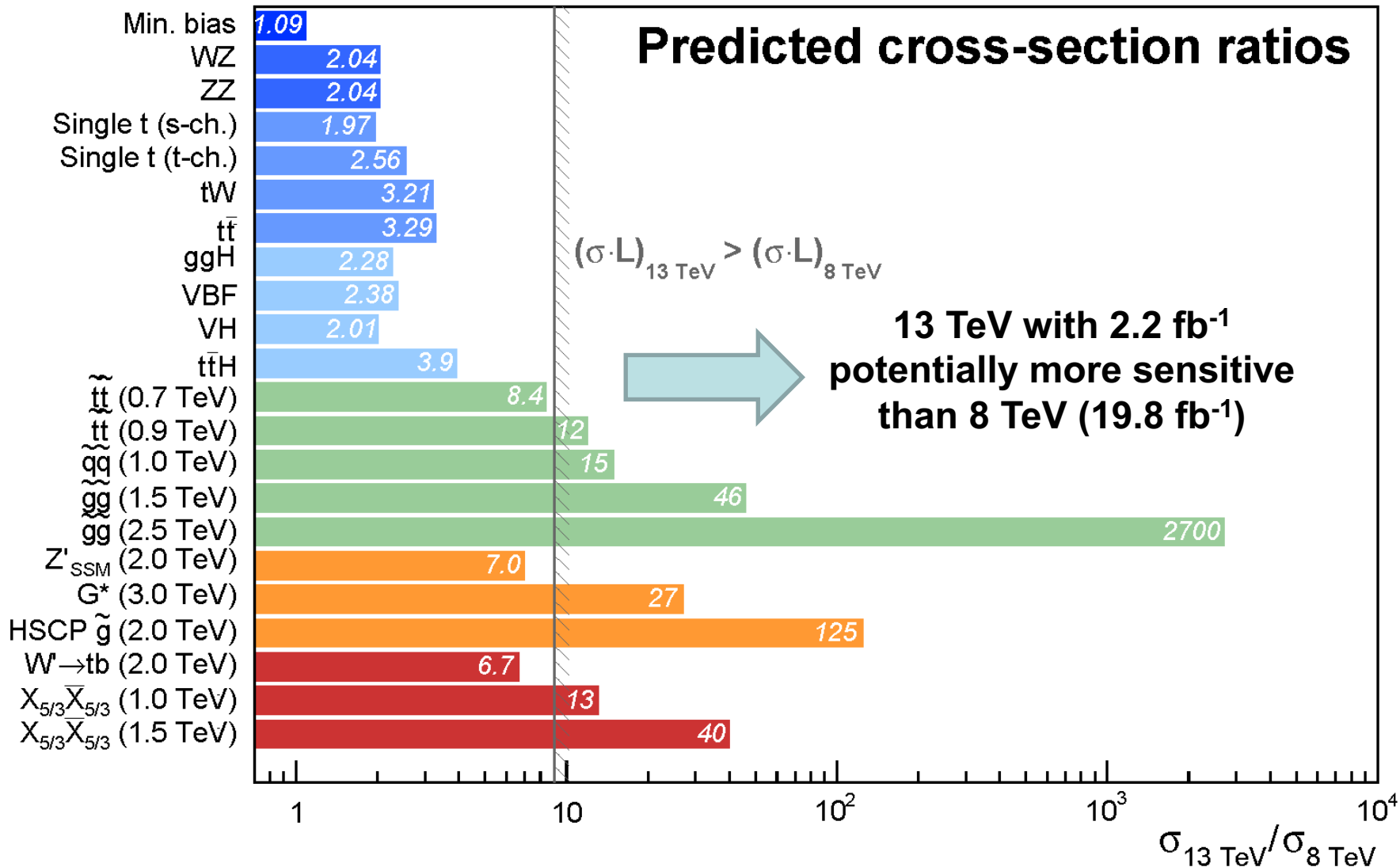
Cross sections at the LHC



“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.**