Probing the SM: Top quarks and beyond

Michele Gallinaro

LIP Lisbon

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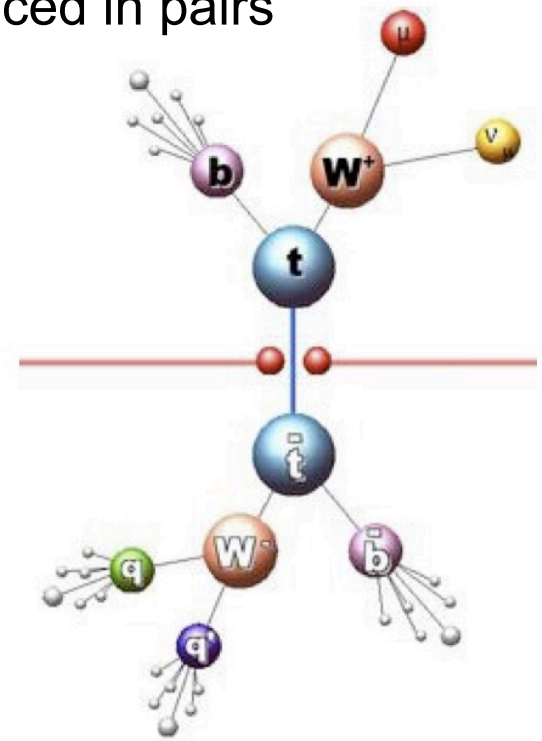
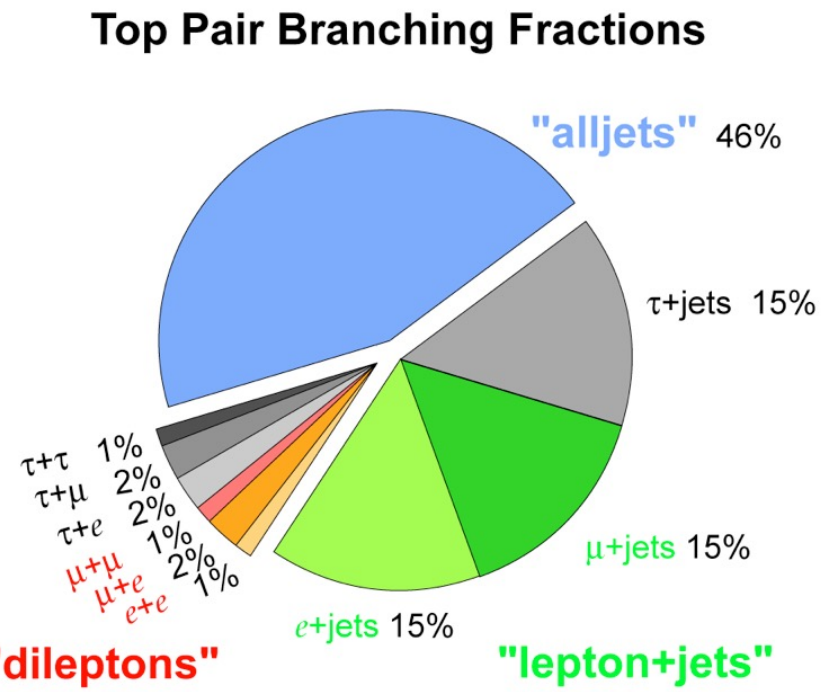
- ✓ Top quarks: cross section and properties
- ✓ Top as a window to New Physics
- ✓ Top-Higgs associated production
- ✓ Top quark signatures in SUSY
- ✓ Top and Dark Matter

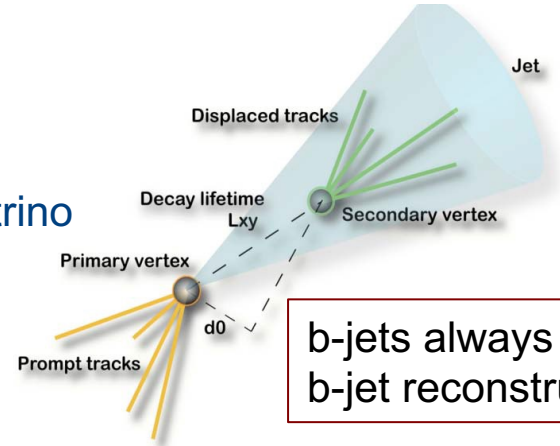
Top quark decays

Top quarks (mostly) produced in pairs



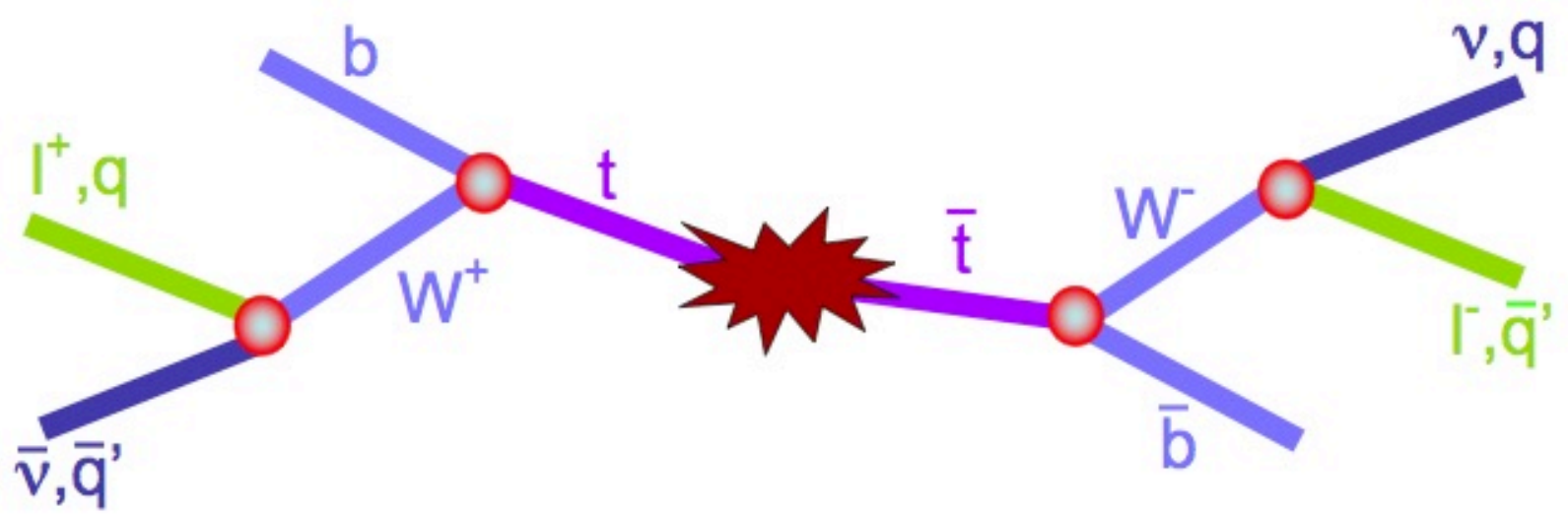


- Dilepton (ee, μμ, eμ):
  - BR~5%, 2 leptons+2 b-jets+2 neutrinos
- Lepton (e or μ) + jets
  - BR~30%, one lepton+4jets (2 from b)+1 neutrino
- All hadronic
  - BR~44%, 6 jets (2 from b), no neutrinos



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

Interesting physics with Top quark



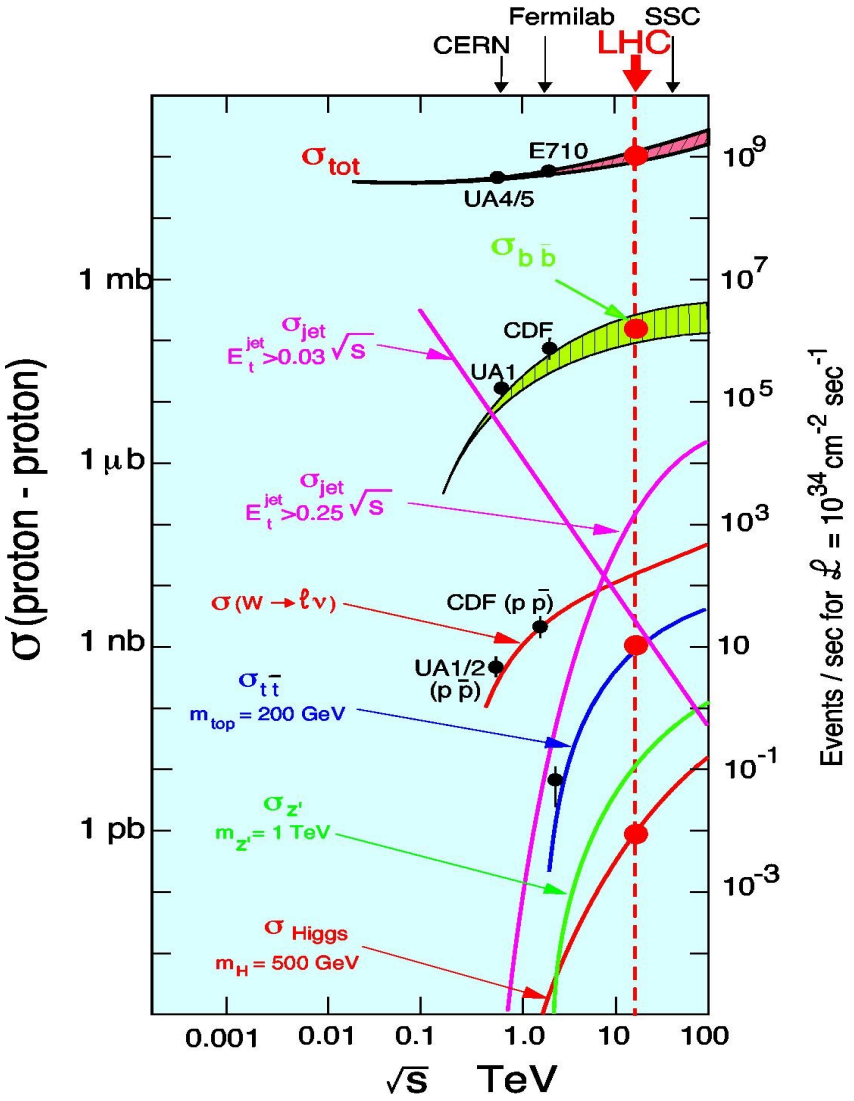
PRODUCTION
Cross section
Resonances X→tt
Fourth generation t'
Spin-correlations
New physics (SUSY)
Flavour physics (FCNC)
...

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

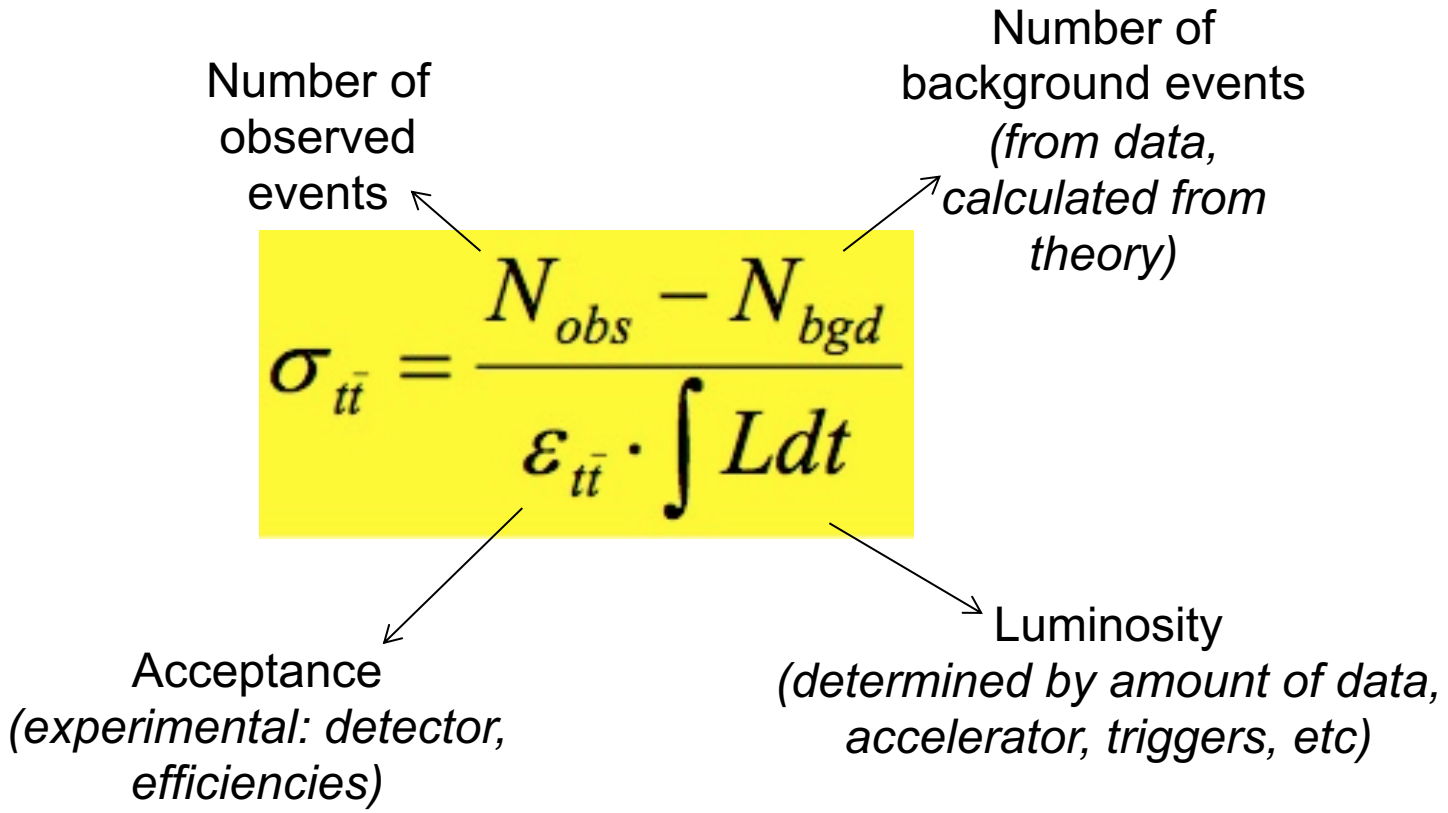
DECAY
Branching ratios
Charged Higgs (non-SM)
Anomalous couplings
Rare decays
CKM matrix elements
Calibration sample @LHC
...

Top cross section at 7/8 vs 13 TeV

- LHC collisions started at 7/8 TeV
- LHC design is at 14 TeV
- Top cross section drops faster than background processes at lower sqrt{s}
  - top σ(7TeV) = 172 pb
  - top σ(8TeV) = 246 pb
  - top σ(13TeV)= 832 pb
- Background is more “flat”

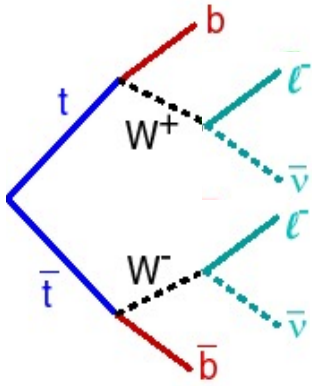


Cross section measurement



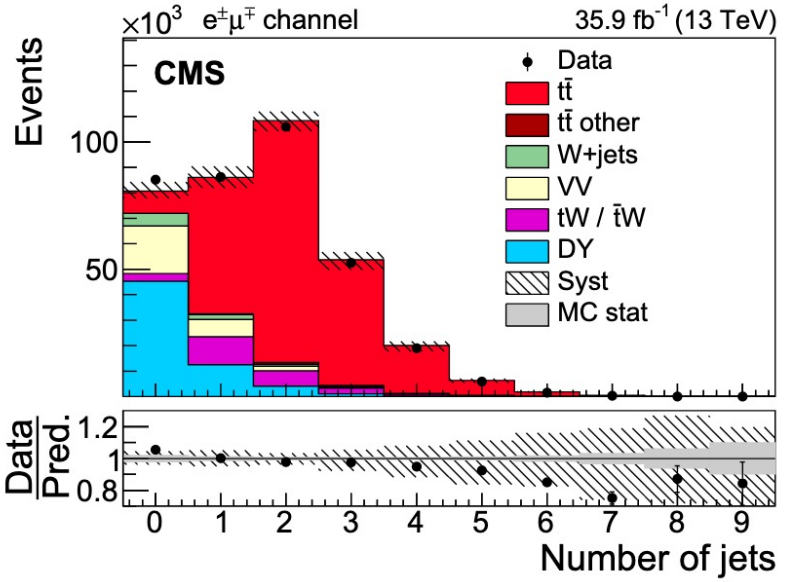
Dilepton channel

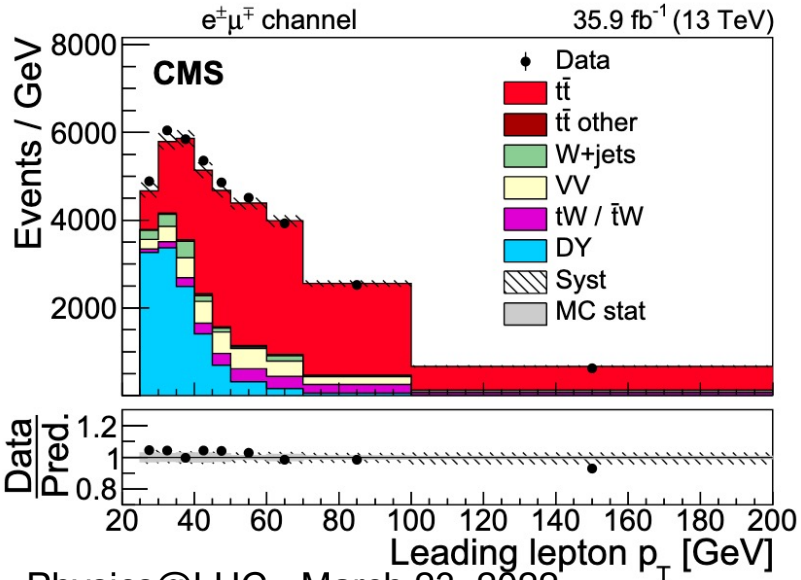
EPJC 79(2019)368



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

- Clean final state
  - two leptons + ≥2 jets + MET
  - kinematic variables
- Signal visible w/without b-tagging
- Main systematics: JES, lepton ID, (pileup, b-tag, signal modeling)

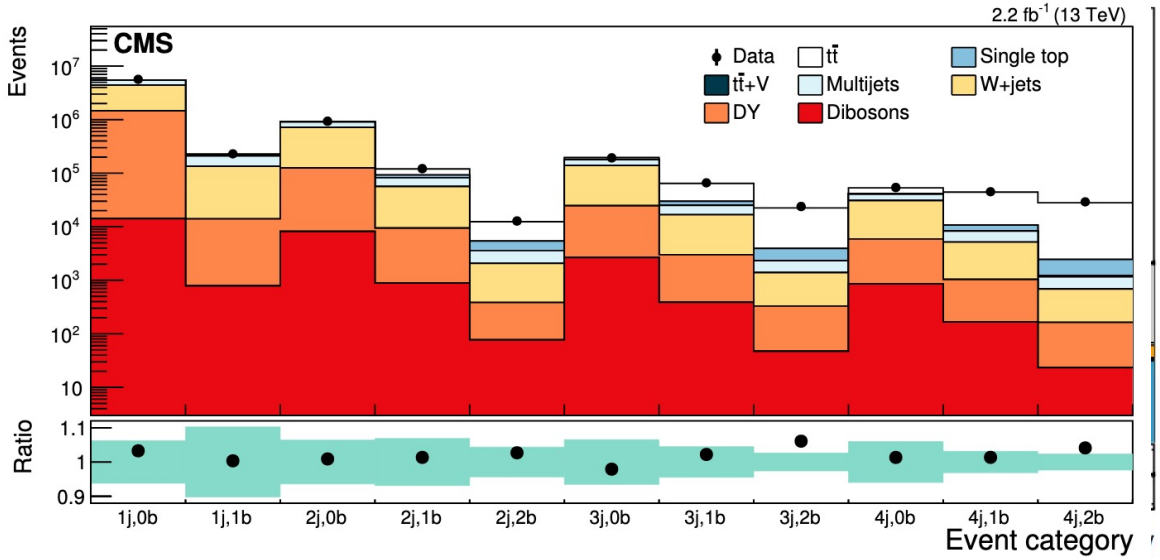


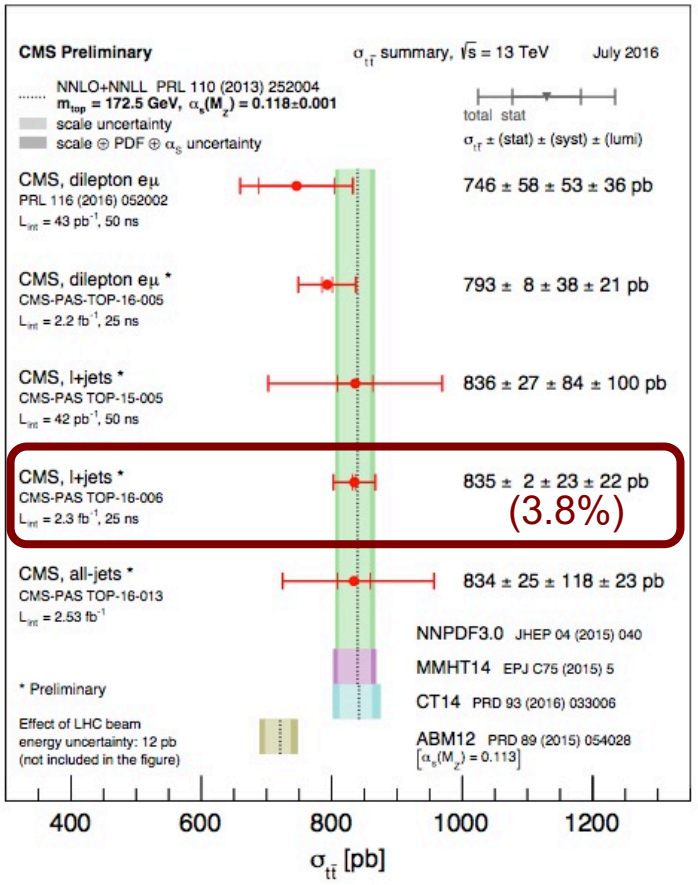


Cross section: multi-dimensional fit

JHEP 09(2017)051

- Lepton+jet final state
- Keep selection as inclusive as possible
- Categorize events according to (b-) jet multiplicity
  - high-purity vs background dominated
  - Constrain systematics (JES, ISR/FSR, modeling, etc)
- Combined fit of M_{lb} to signal and backgrounds
- Precise cross section measurement





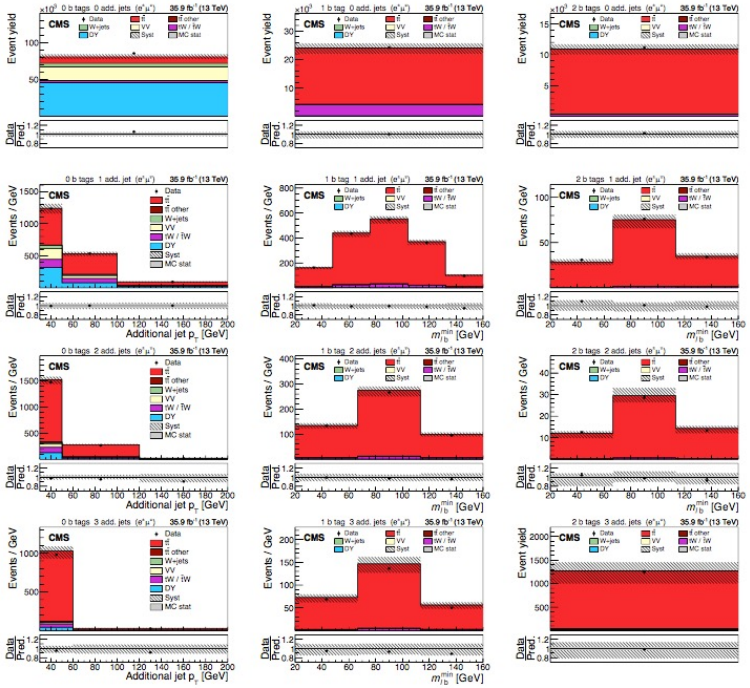
Cross section: multi-dimensional fit

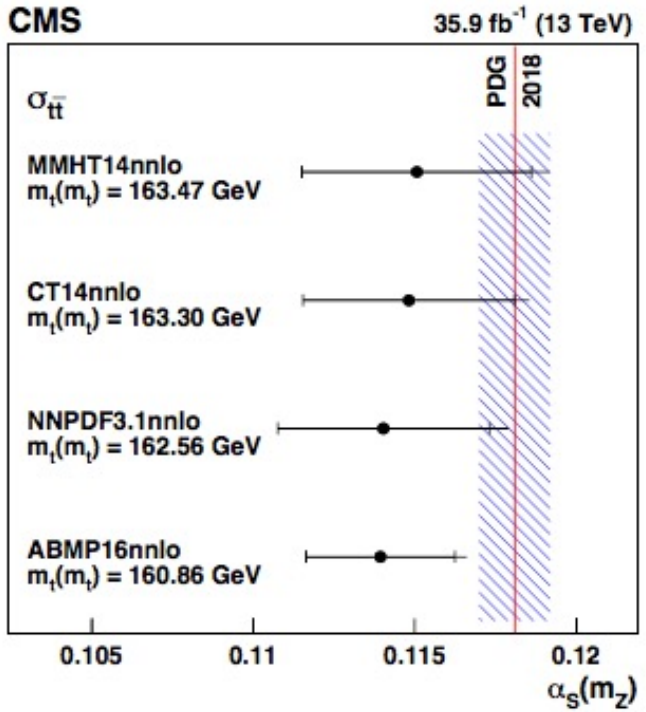
- Dilepton final state
- Simultaneous fit in ($N_{\text{additional jet}}$,$N_{\text{b-jet}}$) categories
- Fit of σ_{ttbar} and m(top)

(~4%)

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

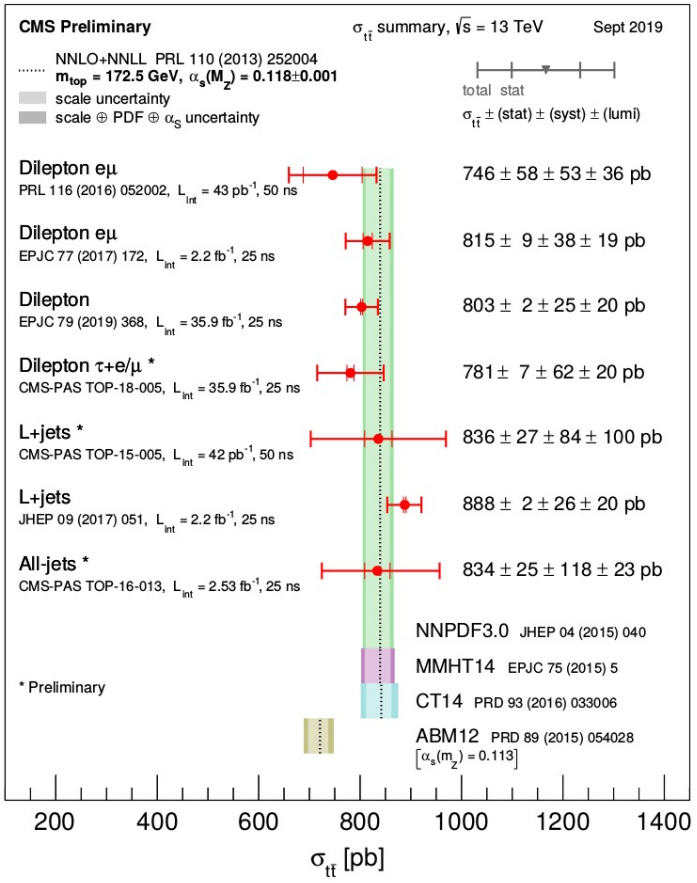
$$m_t^{\text{MC}} = 172.33 \pm 0.14\,(\text{stat})\ ^{+0.66}_{-0.72}\,(\text{syst})\ \text{GeV}$$

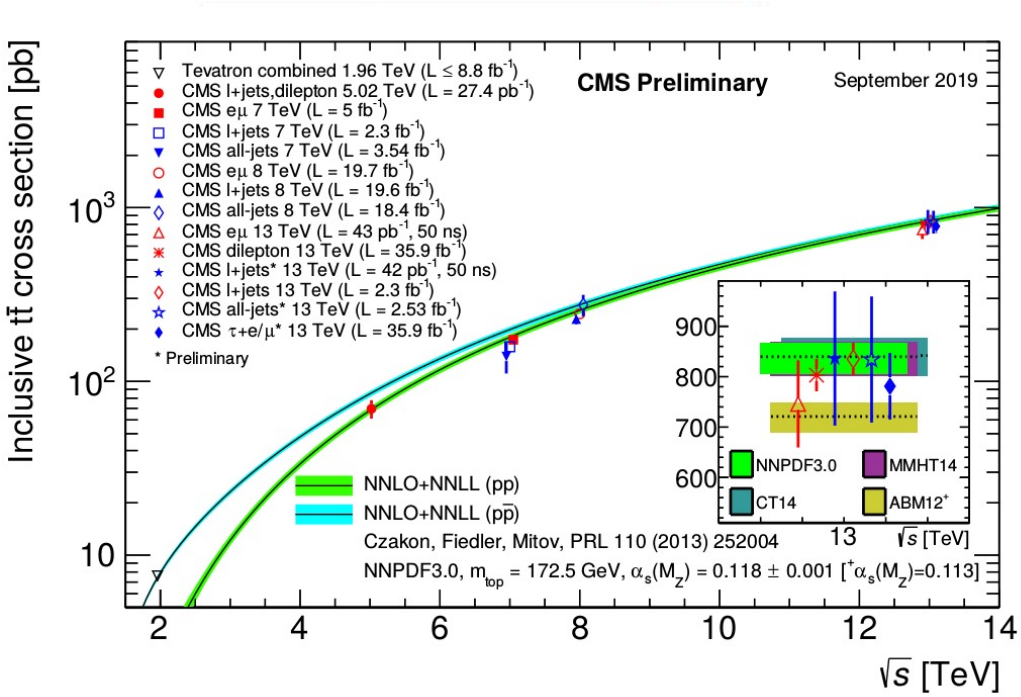




Cross sections

±4%





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

±3-5%

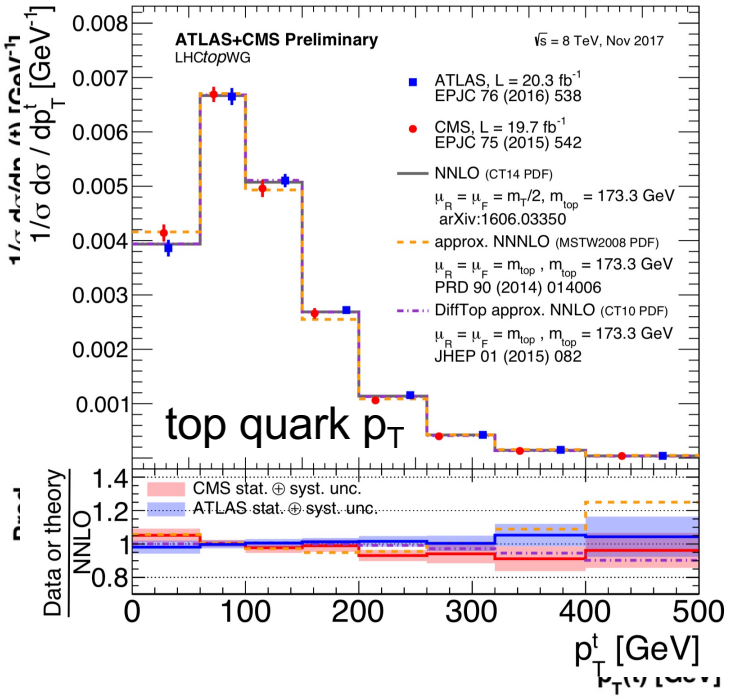
⇒measurements challenging theory

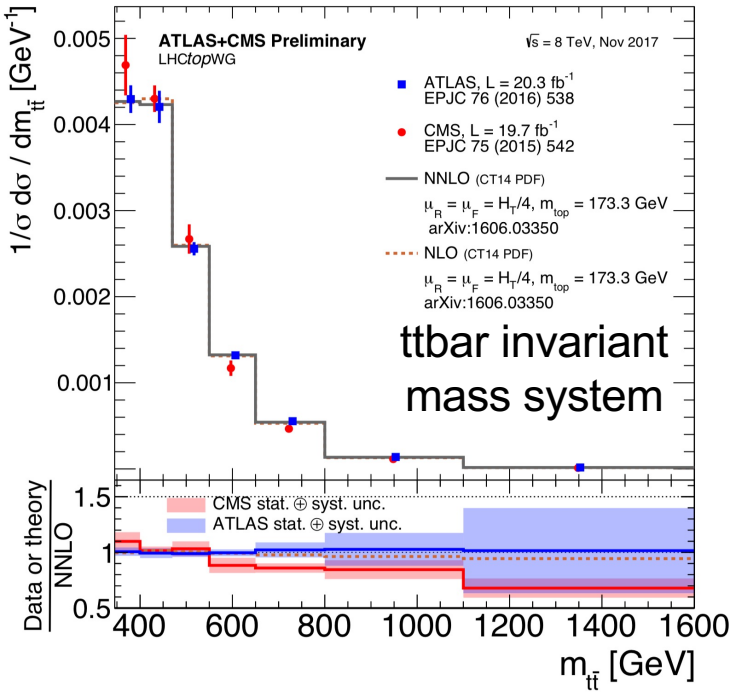
Differential cross section

EPJC 73(2013) 2339, arXiv:1610.04191, TOP-20-001, TOP-20-006

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

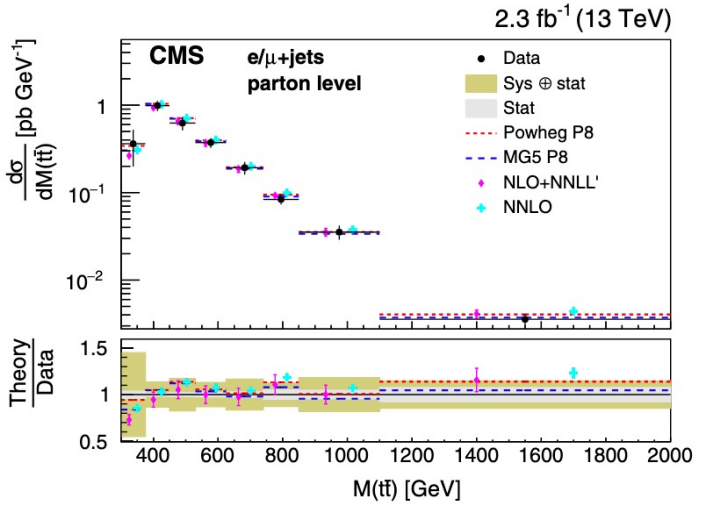
$$\frac{1}{\sigma_{t\bar{t}}}\frac{d\sigma_{t\bar{t}}}{dX}$$



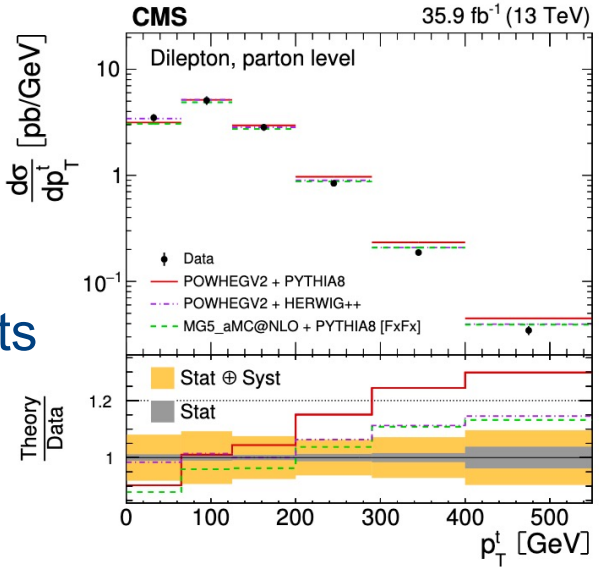


Differential cross section (cont.)

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



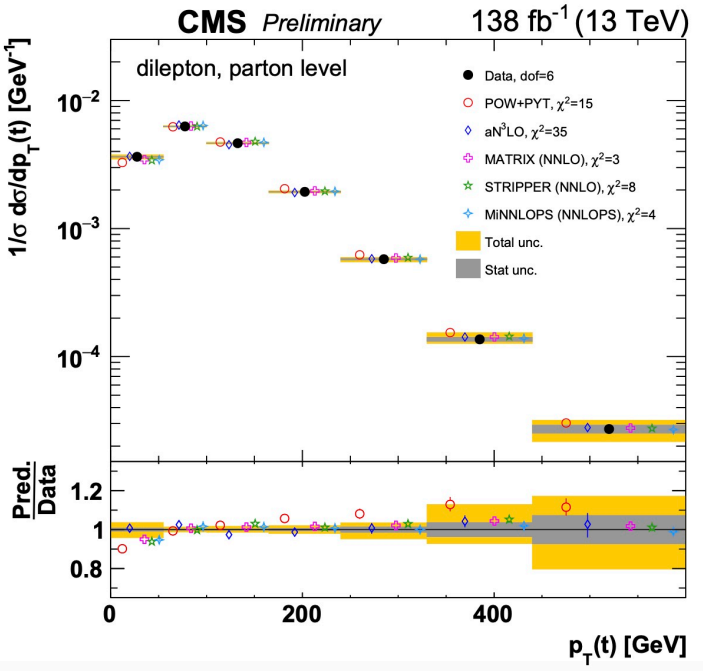
- Correct for detector effects and acceptances
- Softer top p_T (CMS), agreement in ATLAS at high p_T
  - Due to momentum reshuffling, P.Nason, cern.ch/event/301787
  - FSR shower changes mass of final state partons. light partons can build sizeable mass, and t/tbar do not radiate
  - short term solution: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

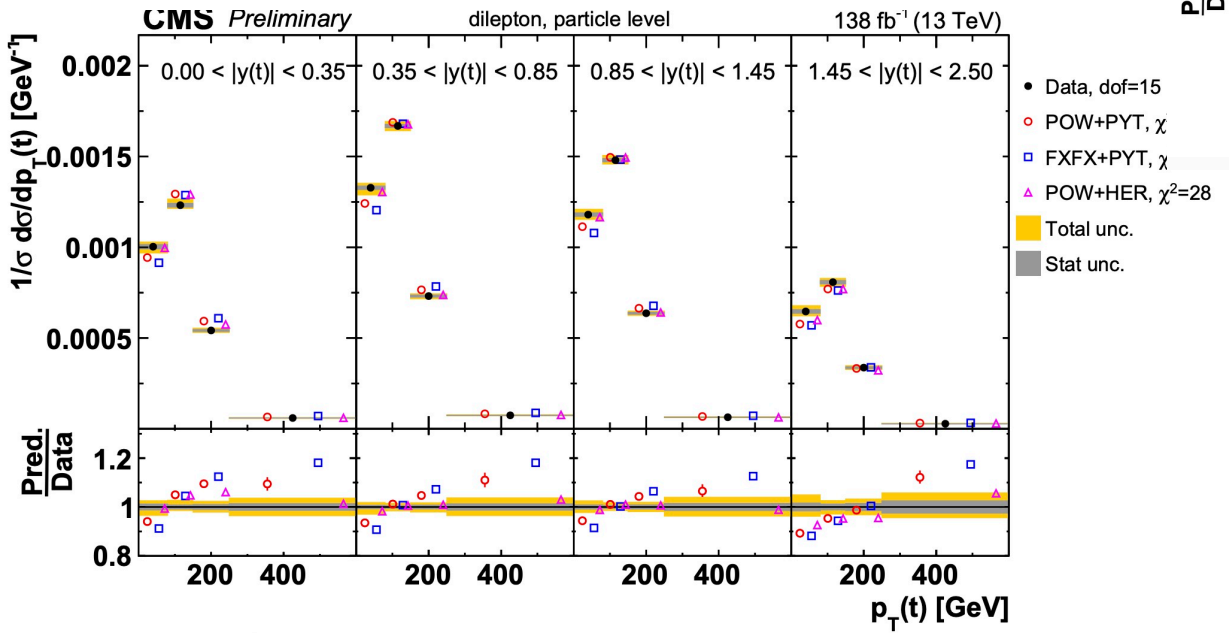


Multi-differential cross section

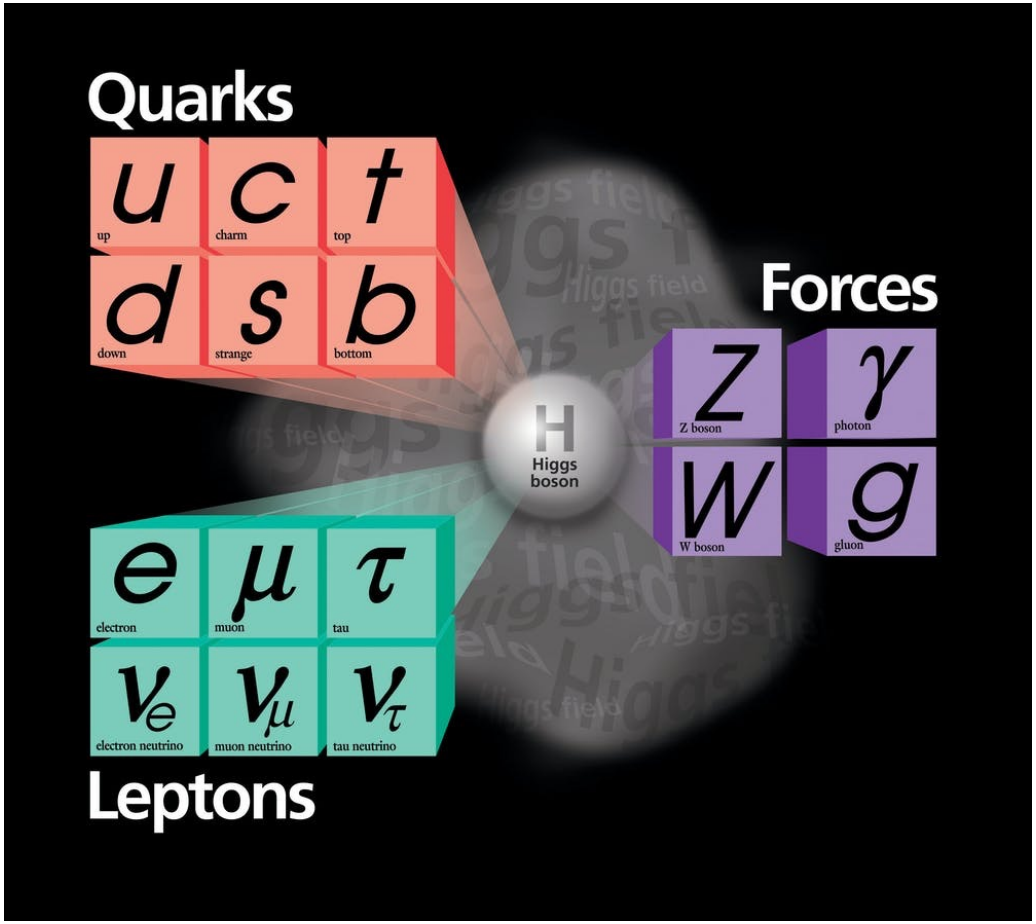
TOP-20-006

- Multi-differential cross section as a function of top and ttbar kinematics, decay products and additional jets
- Sensitive to SM parameters m_t and α_S
- Total uncertainty reduced by a factor of ~2 wrt previous analyses

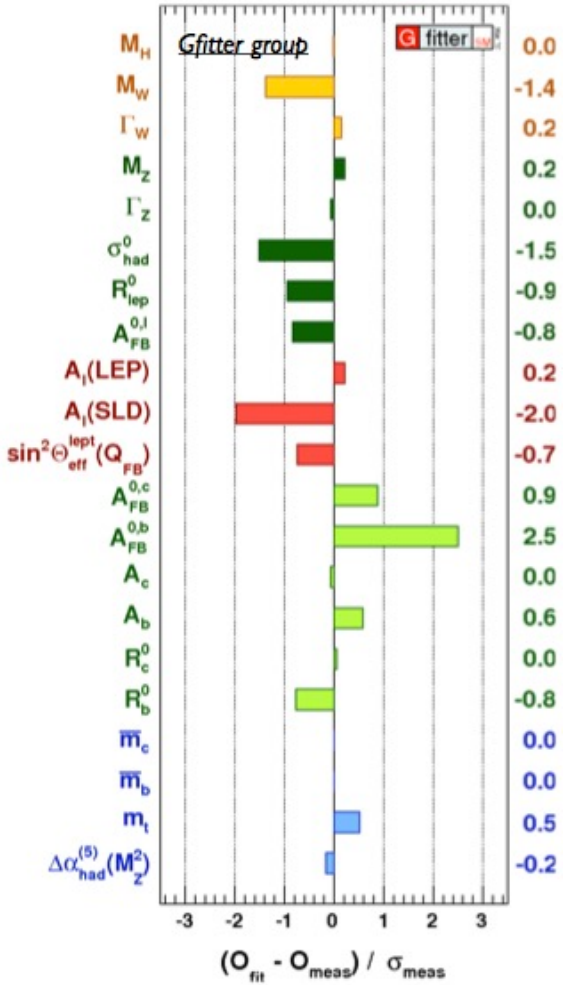




SM confirmed by the data



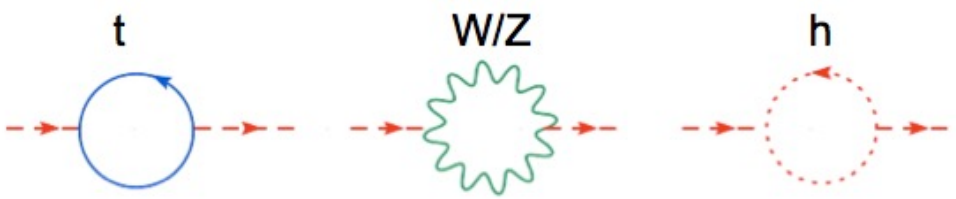
Standard model of elementary particles



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

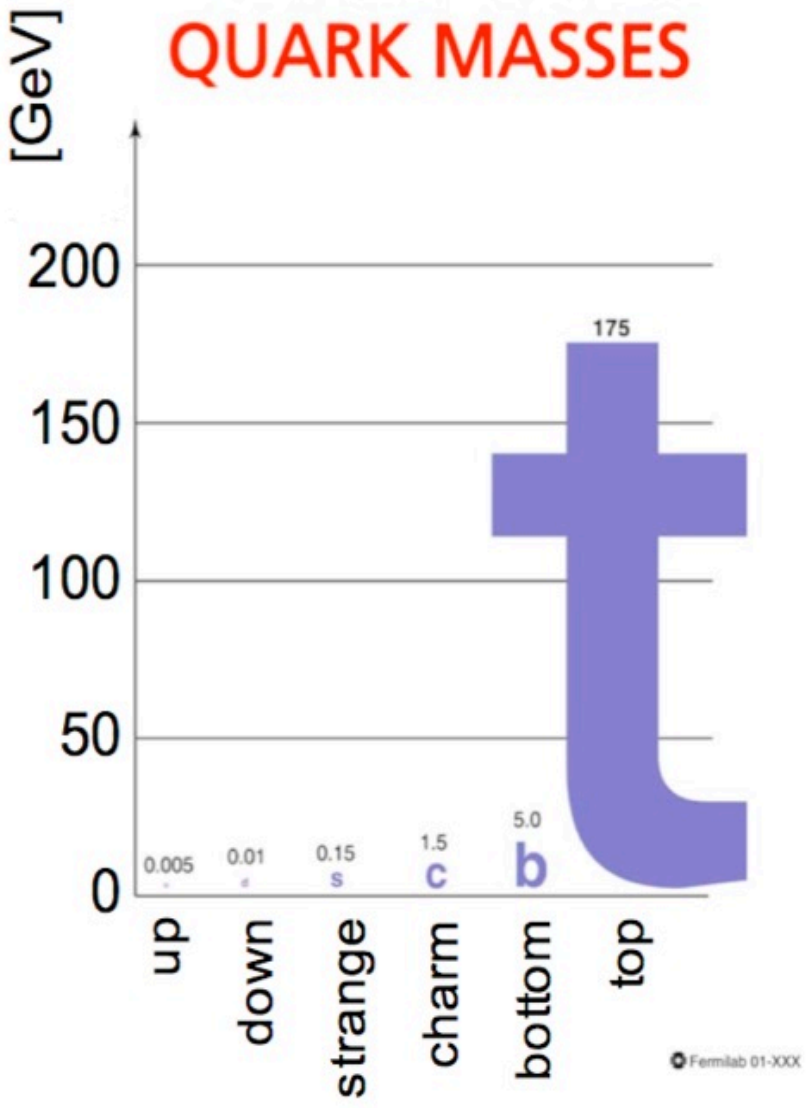
The top quark

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

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

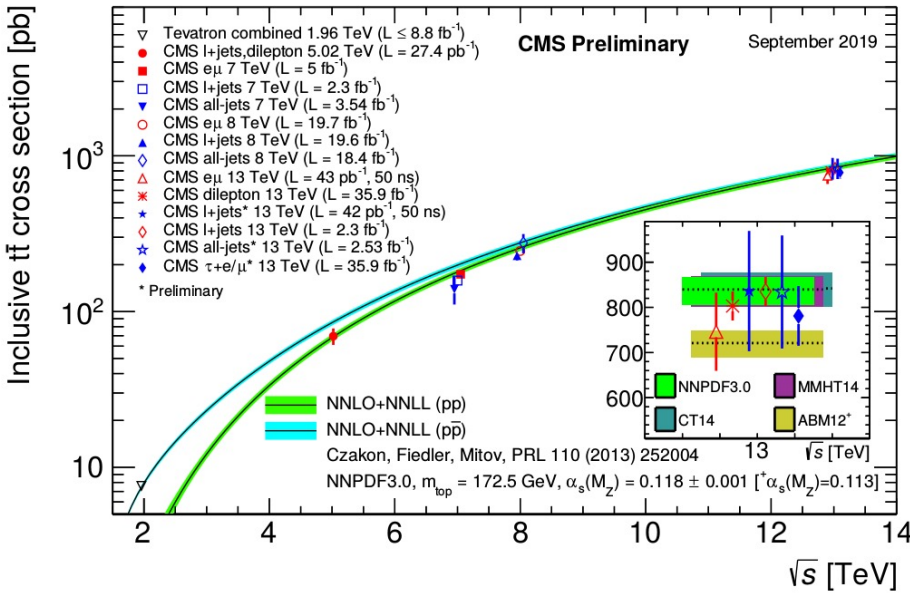
- Large samples of top quarks available
- Top quarks are main background for many New Physics searches
- Precision measurements may provide insight into physics beyond SM

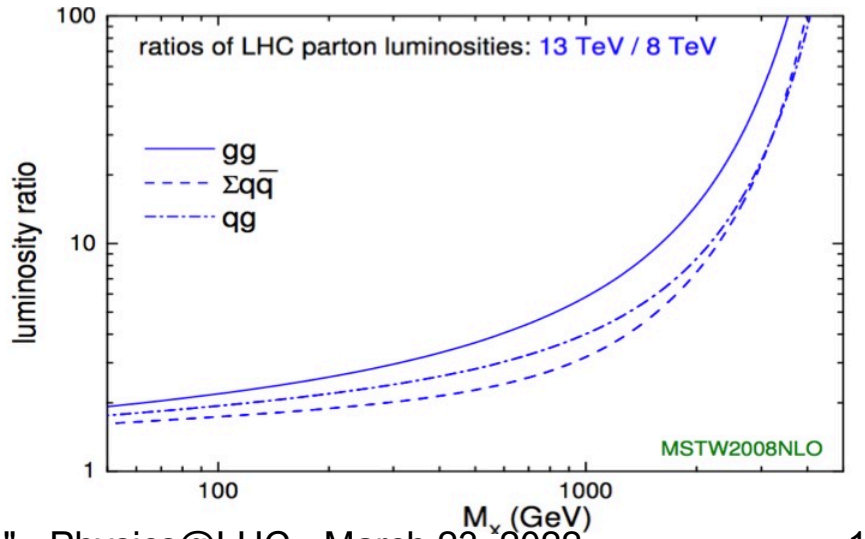


Role of top quark physics

- 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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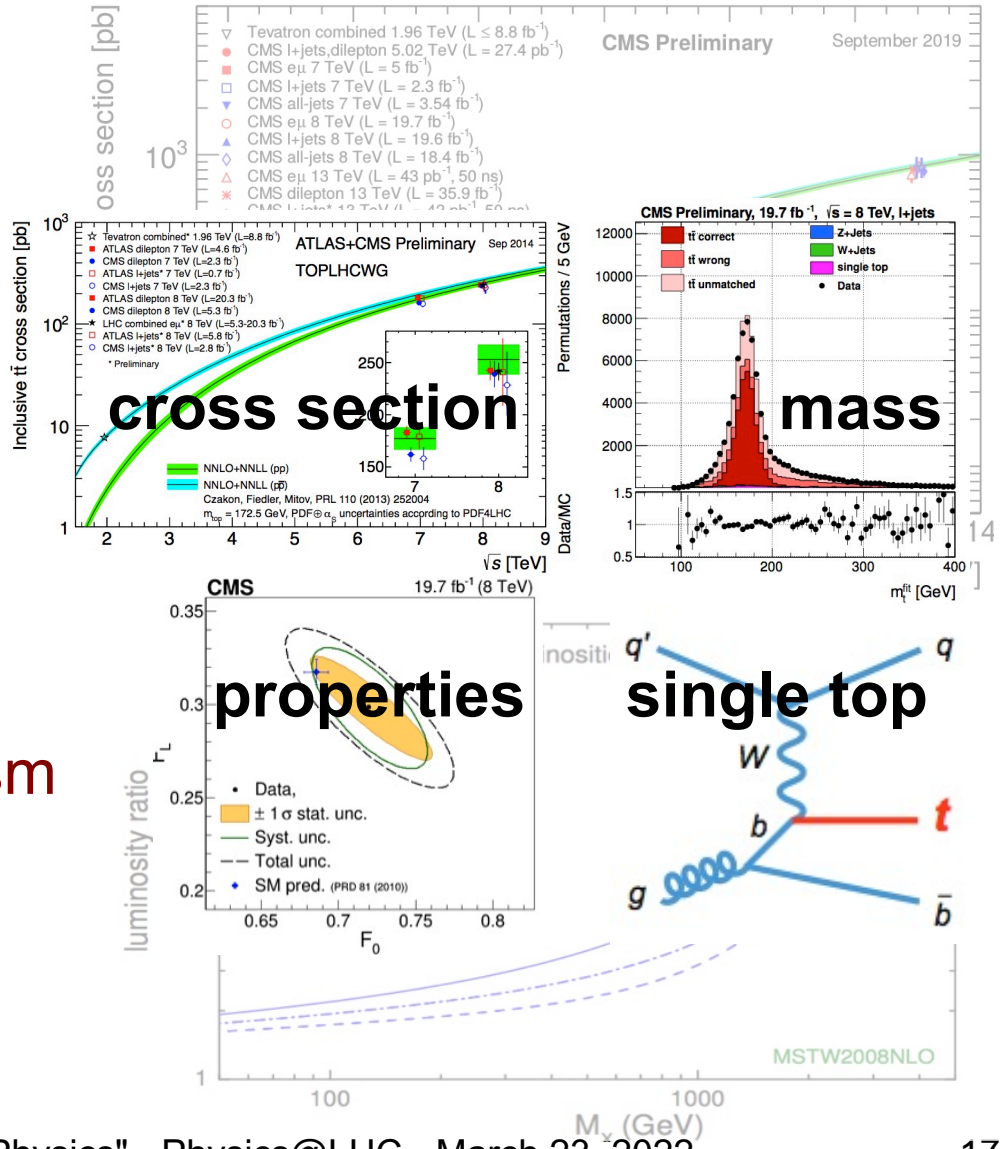
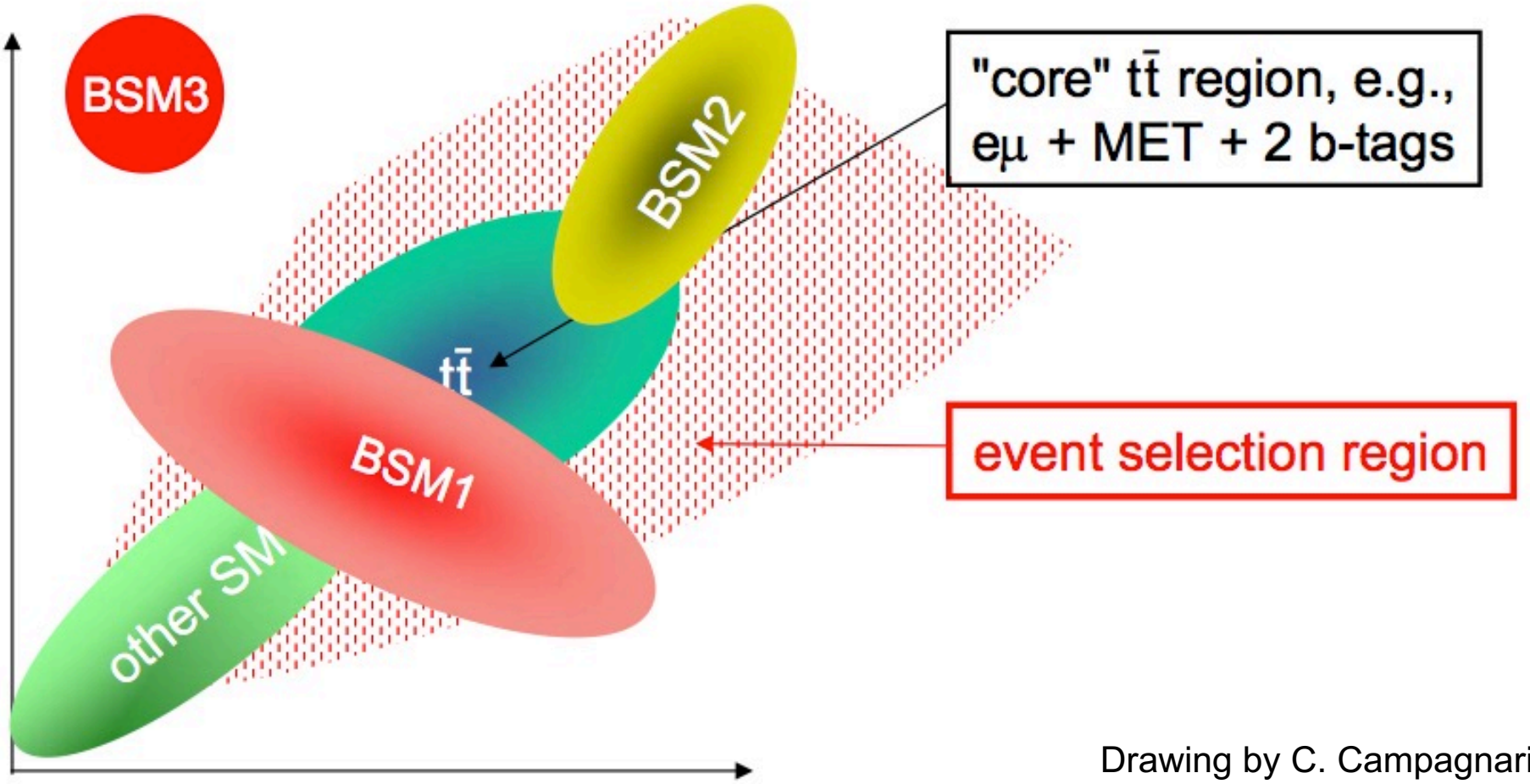
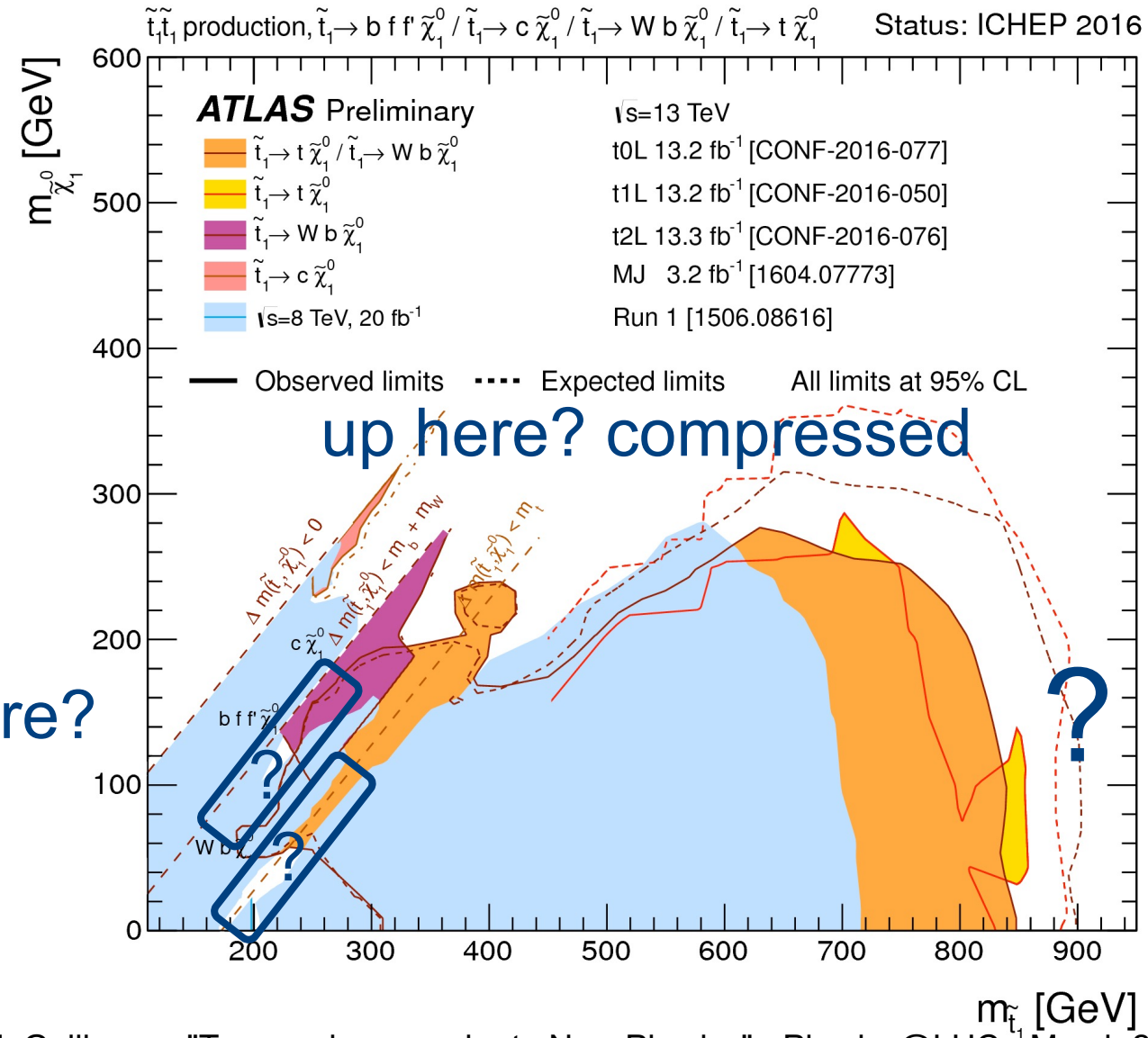


Study characteristics



Drawing by C. Campagnari

Regions hard to explore



hiding here?

or here?

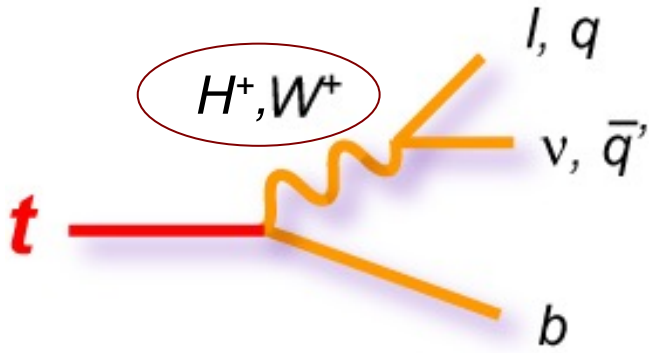
Probing the Wtb vertex

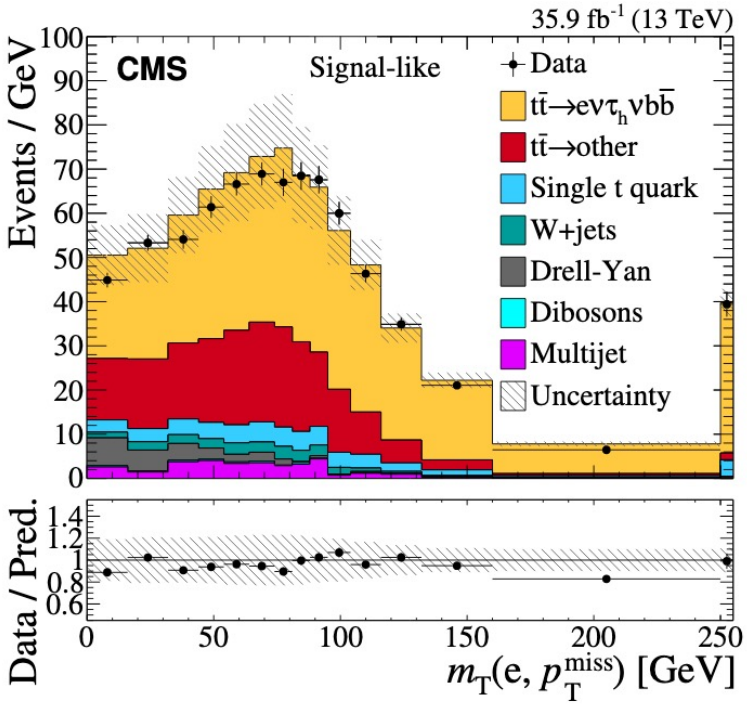
PRD 85(2012)112007, PLB 739(2014)23, JHEP 02(2020)191

Dileptons with taus

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

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

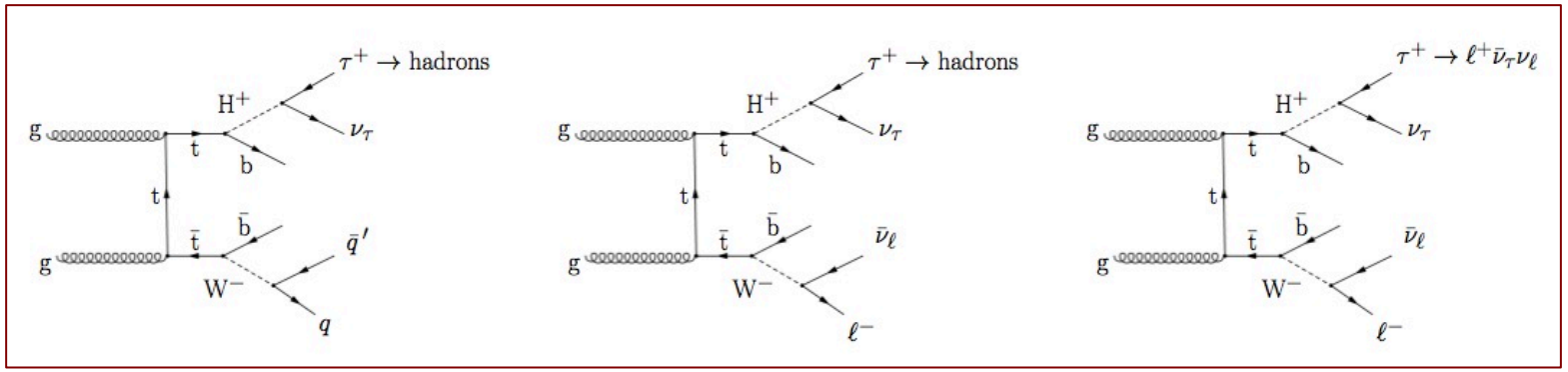




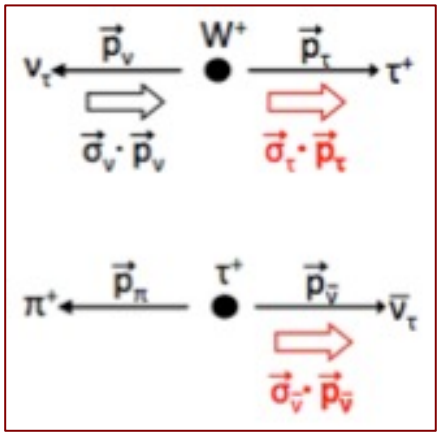
- If top quark plays special role in EWK symmetry breaking, couplings to W may change
- Charged Higgs may alter coupling to W
- Search for final states with taus: charged Higgs

Looking at tau decays

CMS-HIG-12-052

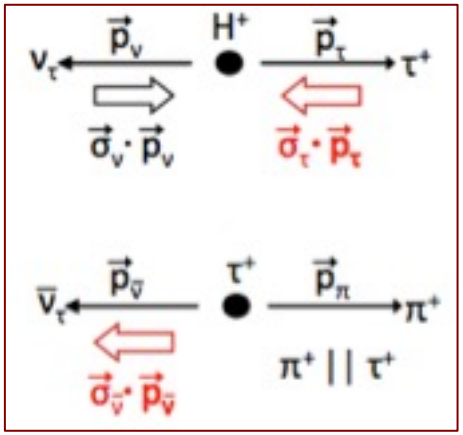


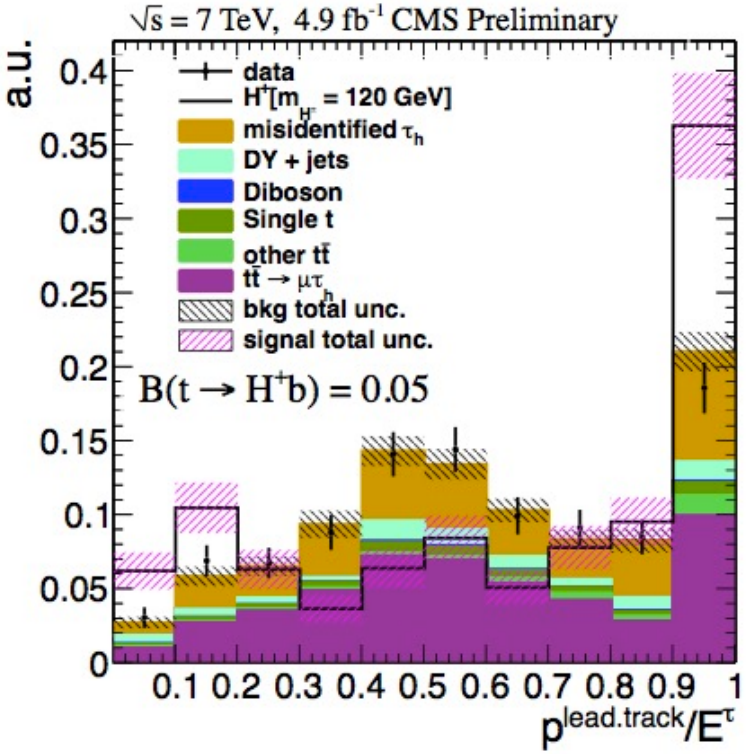
SM



vs

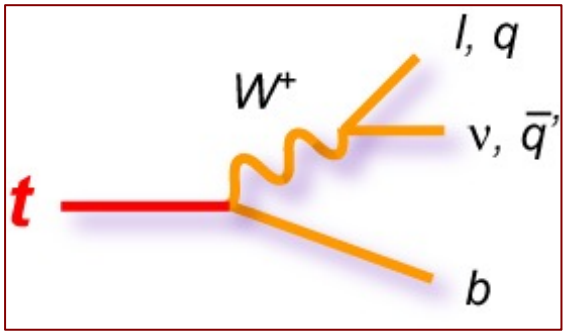
BSM



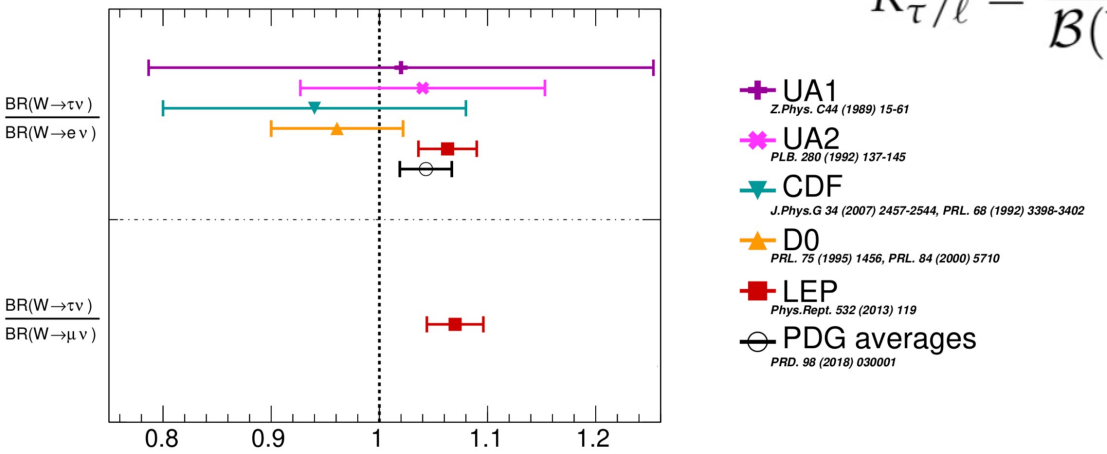


W boson branching fractions

- Precise measurement of the W boson BRs (electrons, muons, taus)
  - Use events with WW and W+jets
  - Multiple categories used
  - Maximum likelihood simultaneous fitting of templates to data in each category
- Most precise determination of B(W⟶lν) from LEP has 2.6σ deviation from LFU



$$R_{\tau/\ell} = \frac{2\,\mathcal{B}(\mathrm{W} \to \tau\bar{\nu}_\tau)}{\mathcal{B}(\mathrm{W} \to \mathrm{e}\bar{\nu}_\mathrm{e}) + \mathcal{B}(\mathrm{W} \to \mu\bar{\nu}_\mu)} = 1.066 \pm 0.025$$



Lepton Flavour Universality

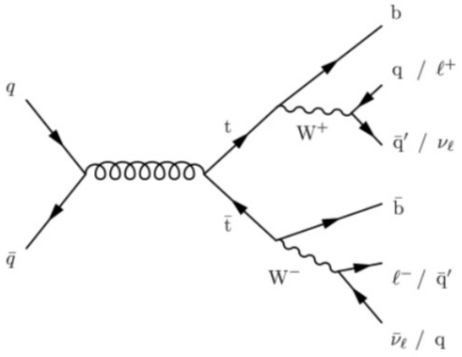
arXiv:2007.14040, arXiv:2201.07861

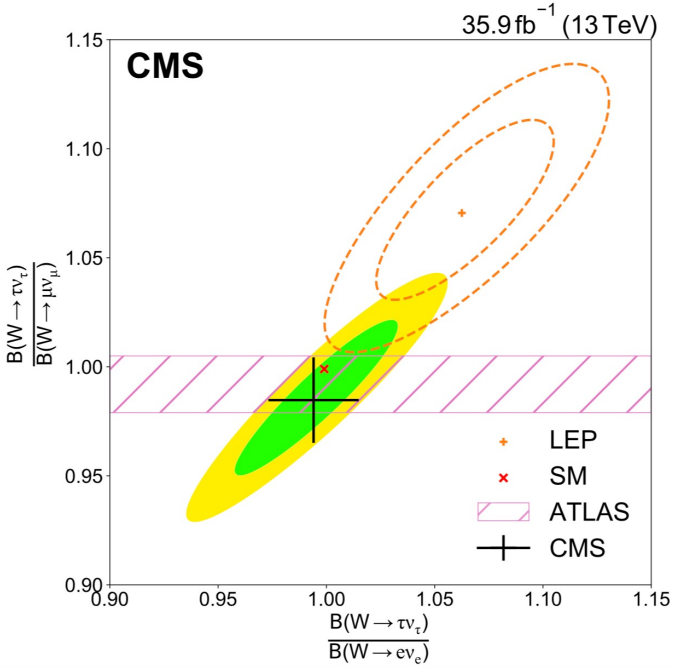
Strategy: use W bosons from top quarks

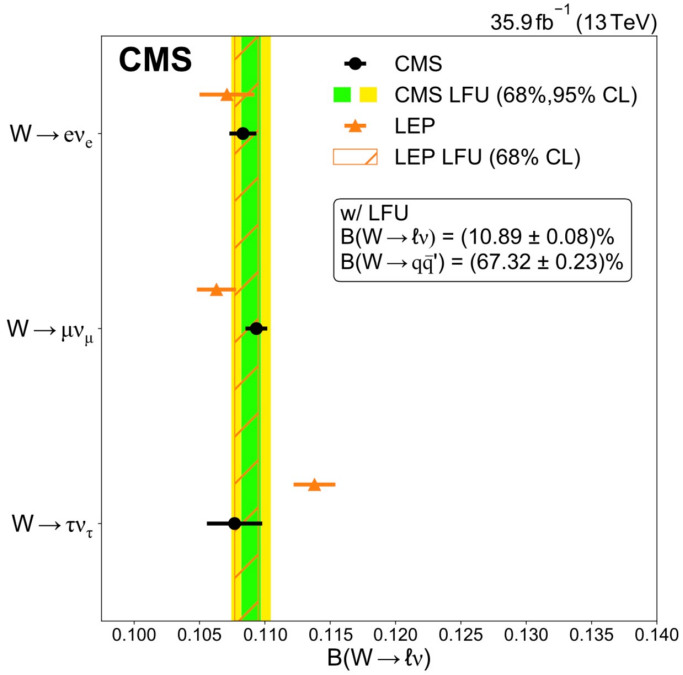
Results consistent with LFU hypothesis

- Extract V_{cs} and $\alpha_S(m_W^2)$

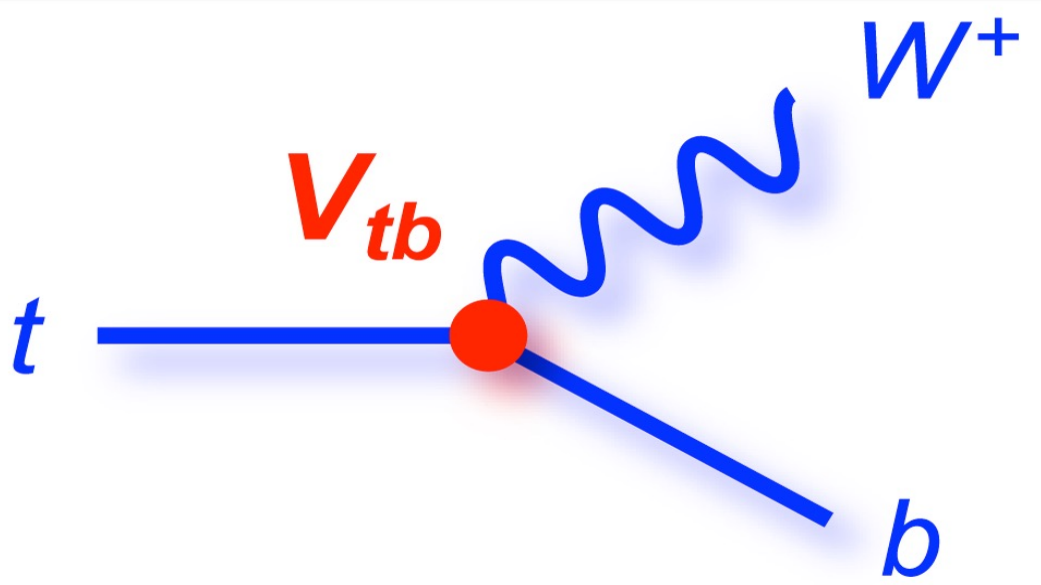
	CMS	LEP
$\mathcal{B}(W \to e\overline{\nu}_e)$	$(10.83 \pm 0.01 \pm 0.10)\%$	$(10.71 \pm 0.14 \pm 0.07)\ \%$
$\mathcal{B}(W \to \mu\overline{\nu}_\mu)$	$(10.94 \pm 0.01 \pm 0.08)\%$	$(10.63 \pm 0.13 \pm 0.07)\ \%$
$\mathcal{B}(W \to \tau\overline{\nu}_\tau)$	$(10.77 \pm 0.05 \pm 0.21)\%$	$(11.38 \pm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







How does a top quark decay?



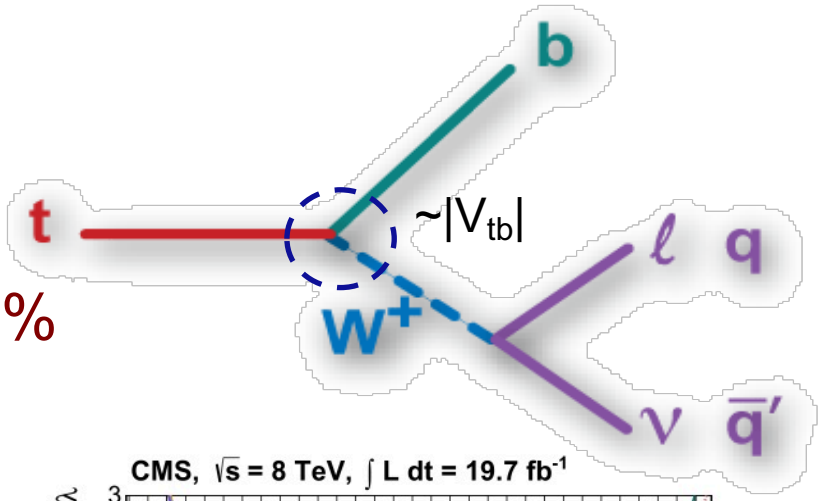
- almost always t→Wb (i.e. V_{tb}~1)
- lifetime is short, and it decays before hadronizing
- the W is real:
  - can decay W→lν (l=e,μ,τ), BR~1/9 per lepton
  - can decay W→qq, BR~2/3

Cross section in the R measurement

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

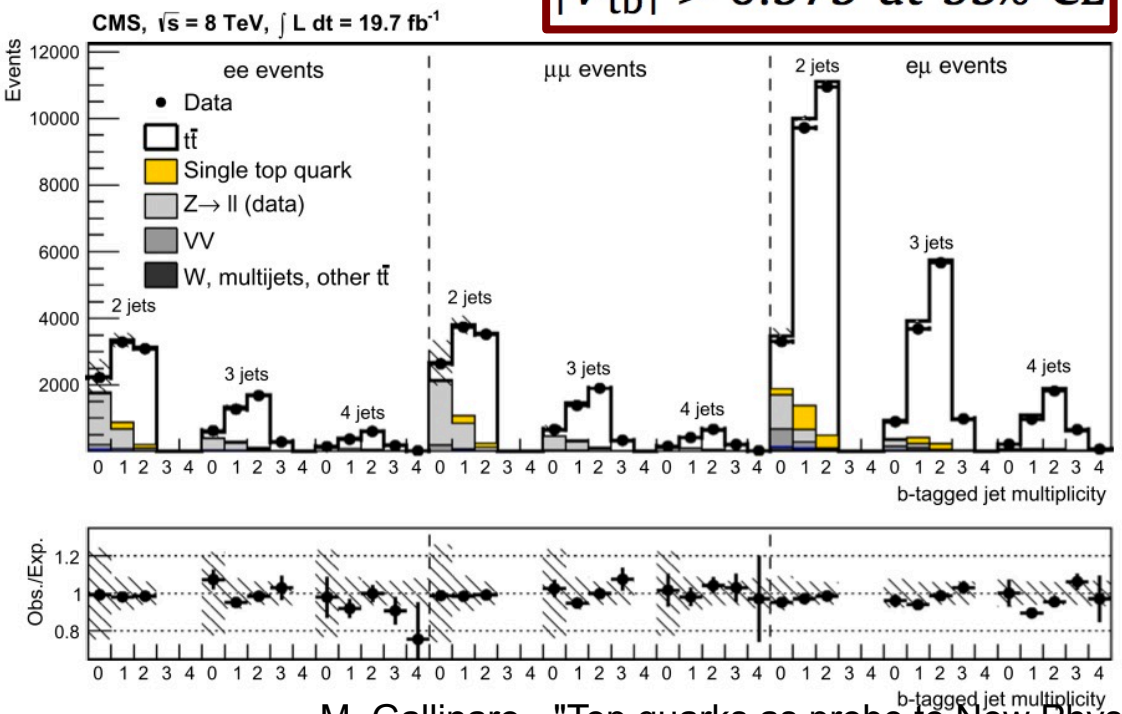
- Measure R:
- Dilepton final state

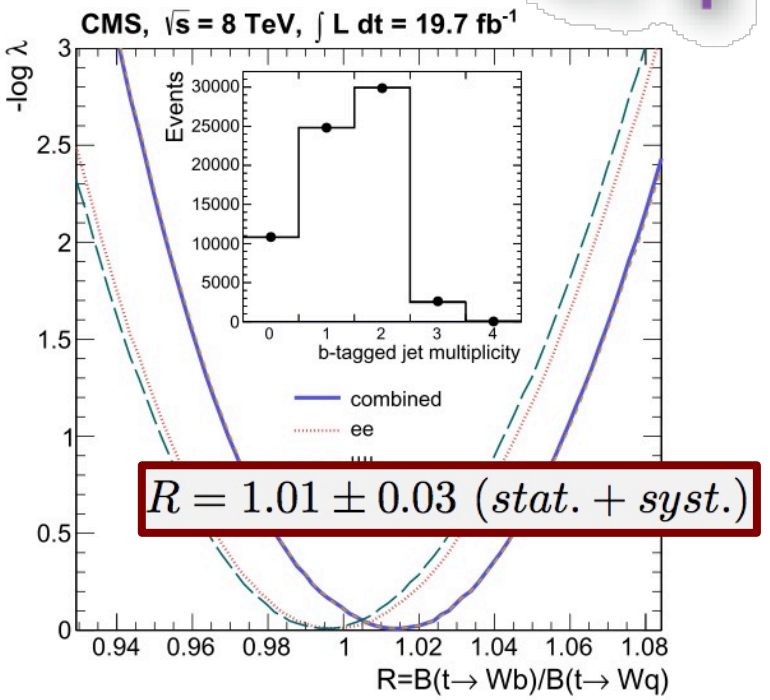
$$R \equiv \frac{BR(t \to Wb)}{BR(t \to Wq)} \approx |V_{tb}|^2$$



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

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

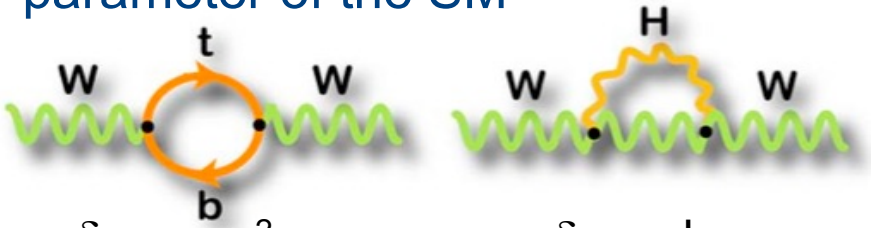




$$R = 1.01 \pm 0.03\ (stat. + syst.)$$

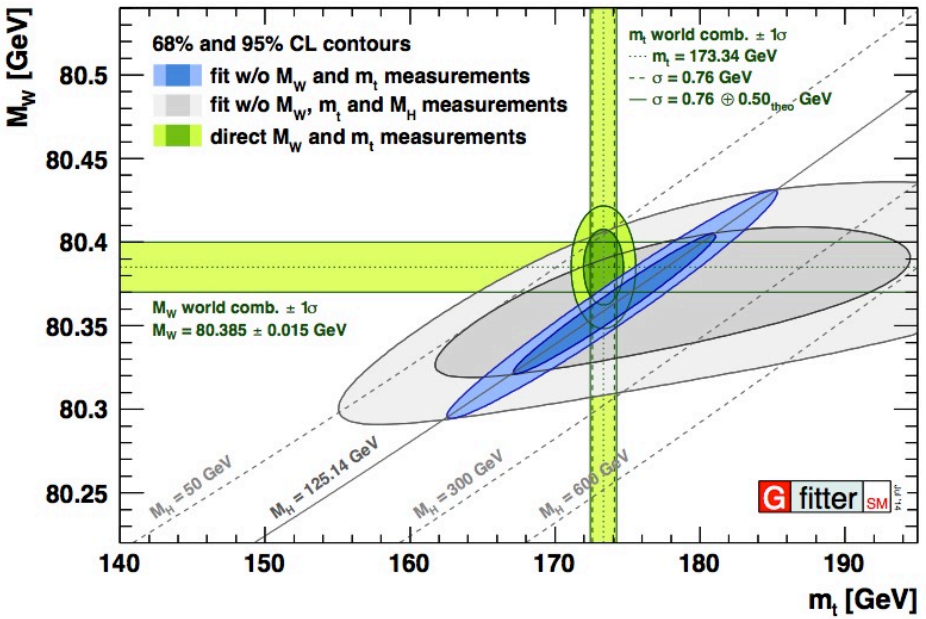
Top quark mass

- Top quark mass is a fundamental parameter of the SM



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

- Precise measurement needed for checking consistency of the SM

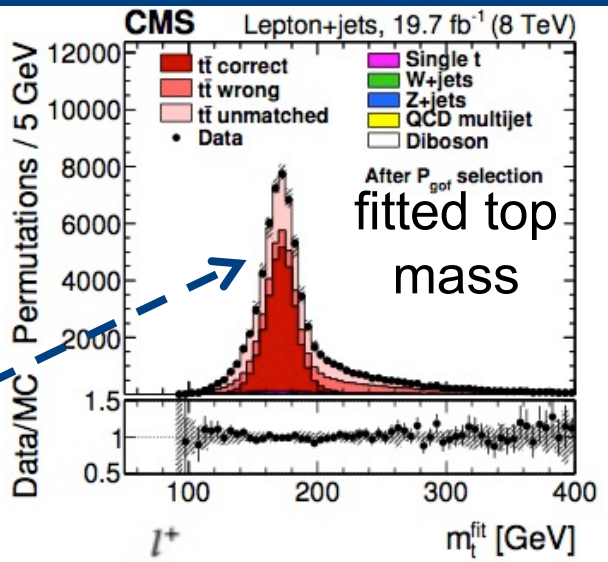


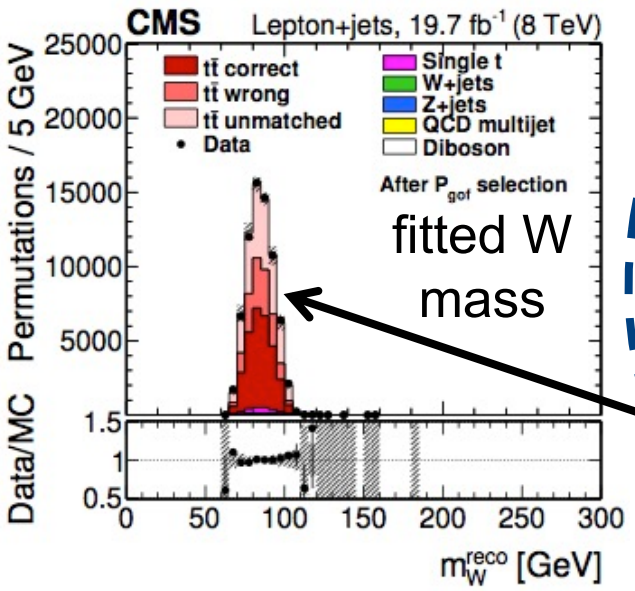
- Top is the only fermion with the mass of the order of EWSB scale
- Discovered Higgs boson fits well with precise determinations of m_W and m_{top}
- Other properties (EWK coupling, production asymmetries, etc.) are predicted by SM
- Precise measurements could reveal breakdown of SM

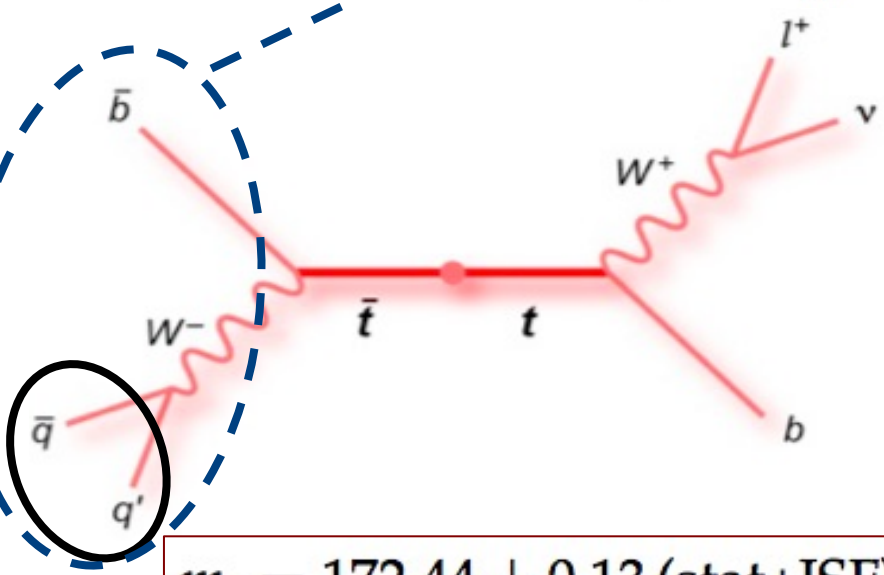
Precise mass measurement

arXiv:1509.04044, EPJC78(2018)891

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







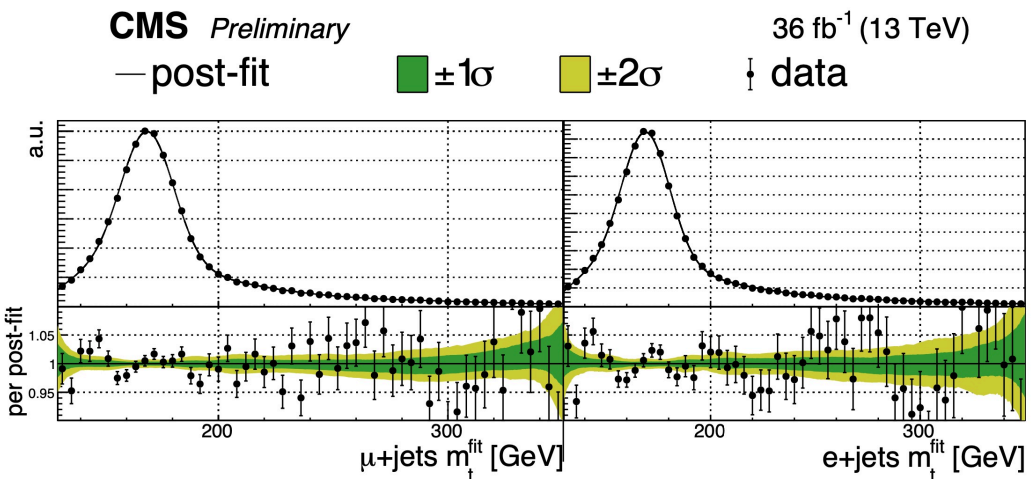
$\pm 0.3\%$

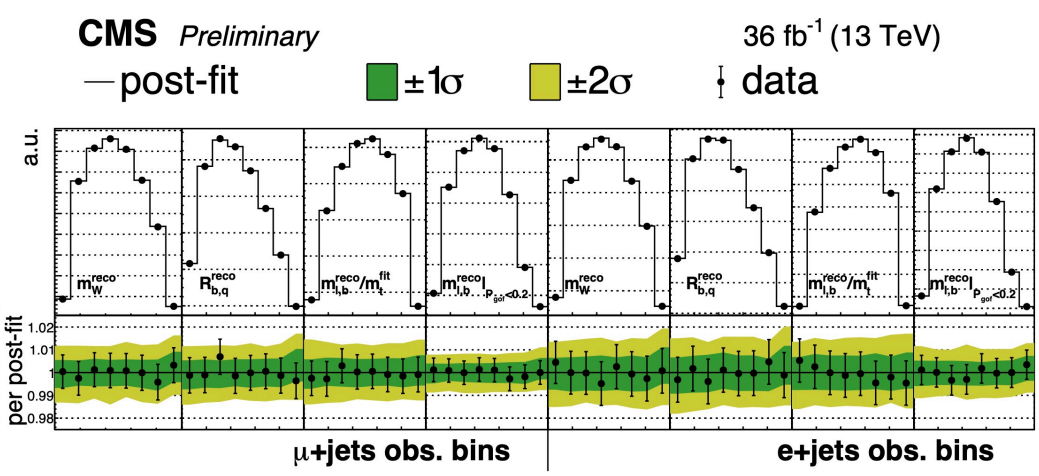
$$m_t = 172.44 \pm 0.13\,(\text{stat+JSF}) \pm 0.47\,(\text{syst})\,\text{GeV}$$

Top quark mass

CMS-TOP-20-008

- Updated measurement (l+jets ch.)
- Likelihood method (m_t^{fit}, m_W^{reco},m_{lb}^{reco}/m_t^{fit}, R_{bq}^{reco})
- In-situ constraints via nuisance parameters
- Main systematics: b-flavour component of JEC, FSR



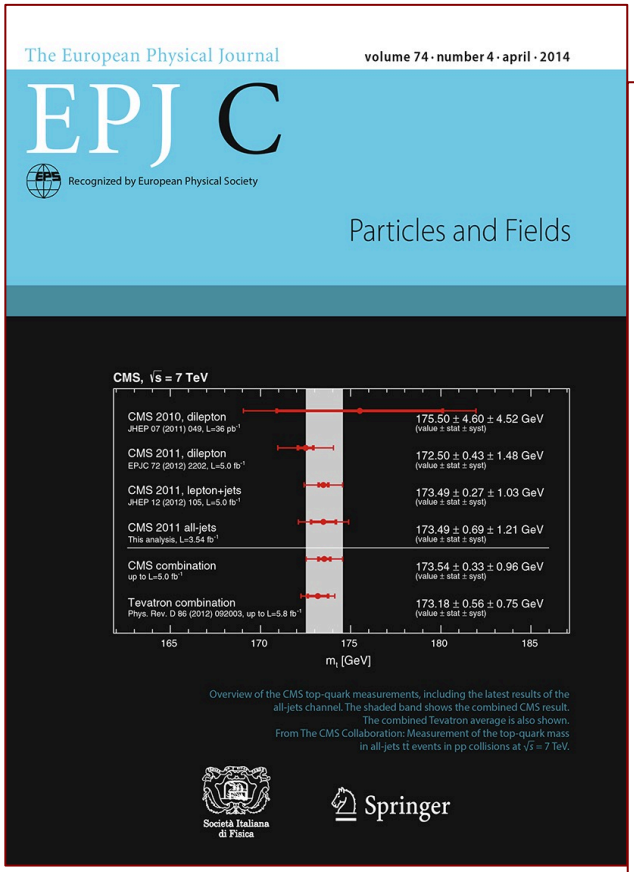


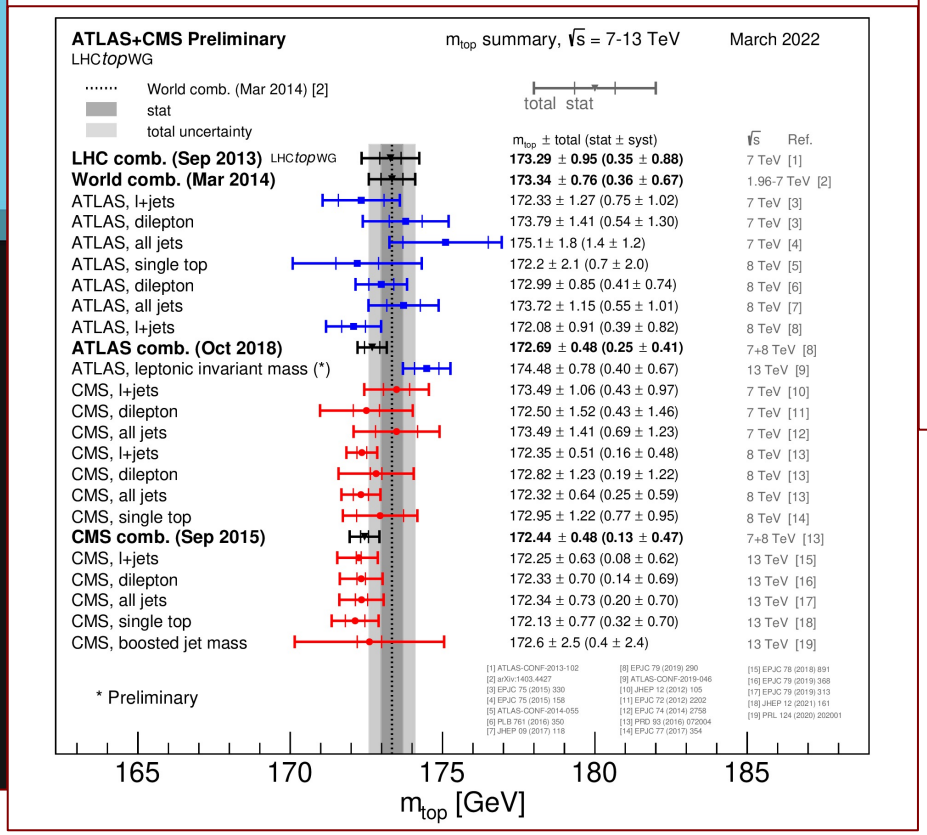
$$m_t = 171.77 \pm 0.38\ GeV$$

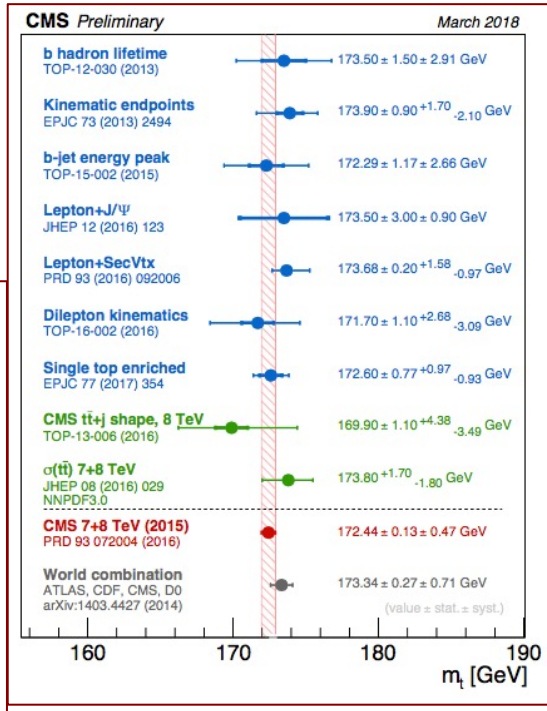
⇒ most precise measurement to date

Top quark mass results

- accurate (~0.3%) measurement



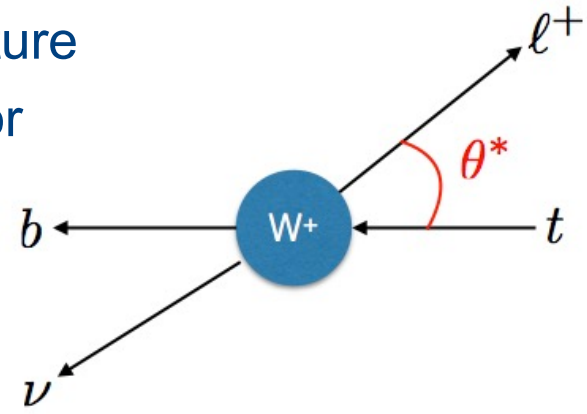


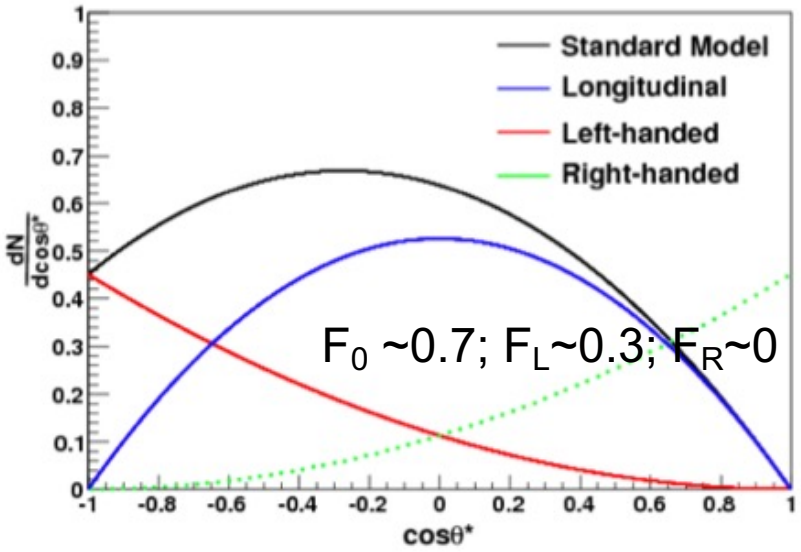


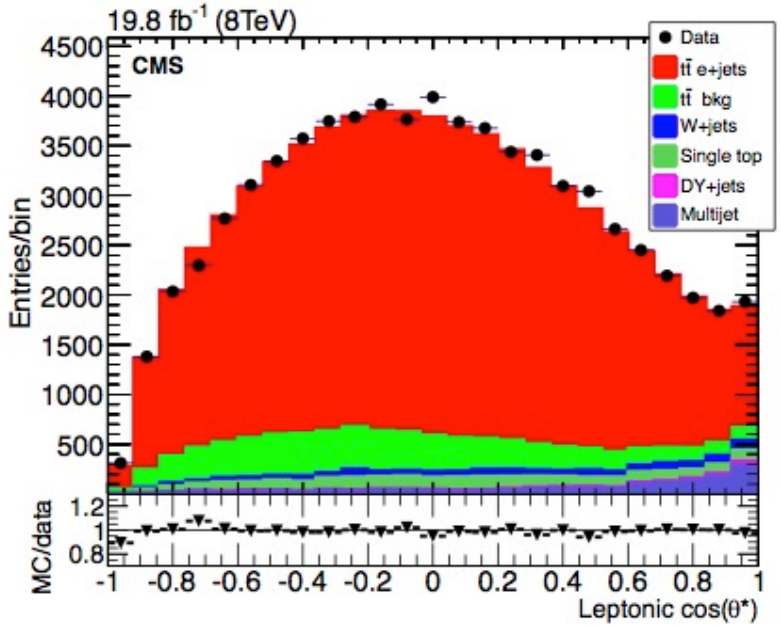
W boson polarization

arXiv:1612.02577, PRD 93(2016)052007

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



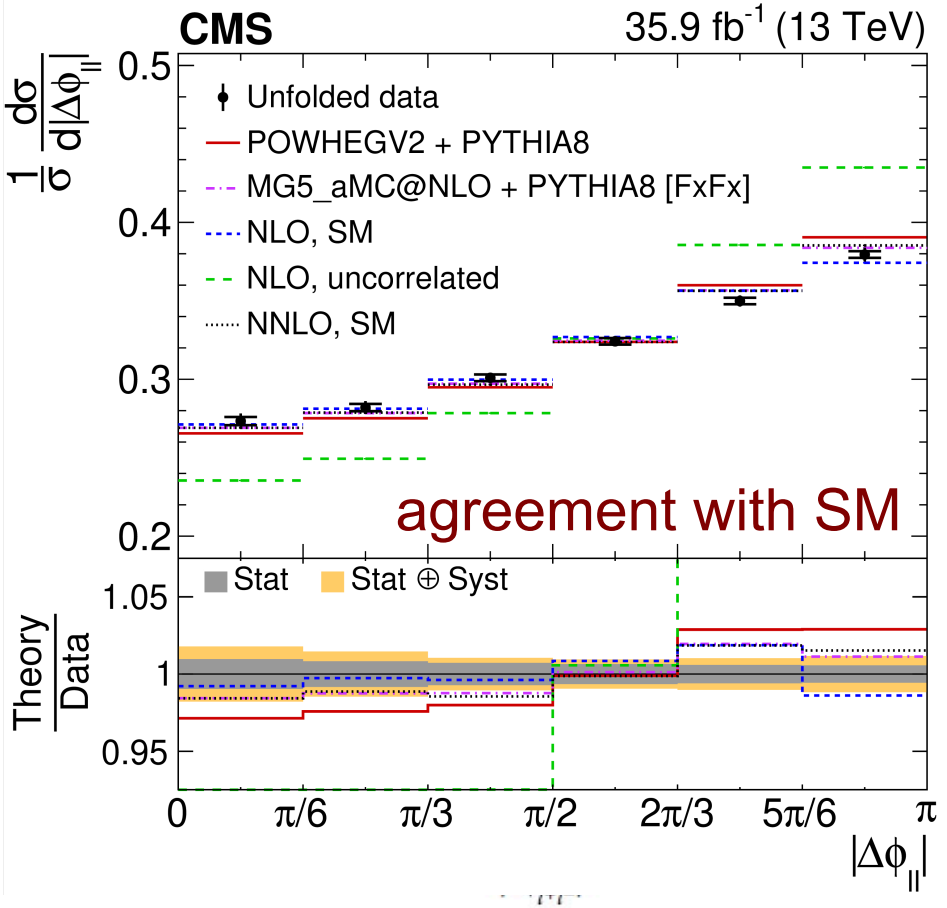




Spin correlation

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

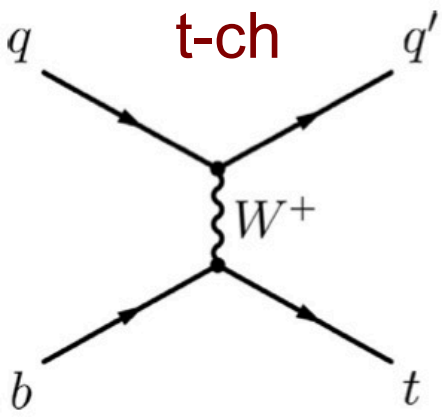
- Top quark produced are not polarized
  - …but spins between quark and anti-quark are correlated
- Top quark decays before spins decorrelate
  - It decays before hadronization ($\tau \sim 10^{-25}$ s) ⇒ spin information transmitted to decay products
  - No need to reconstruct full ttbar system
- Spin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



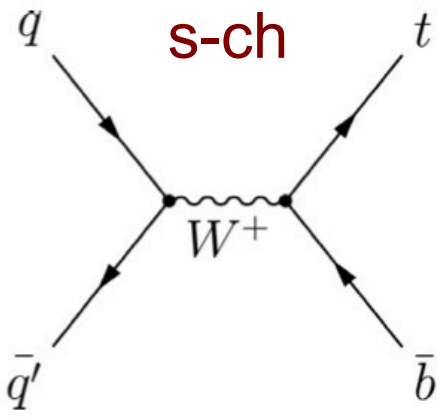
How else is Top produced?

PRD102(2009)182003, PRD81(2010)054028

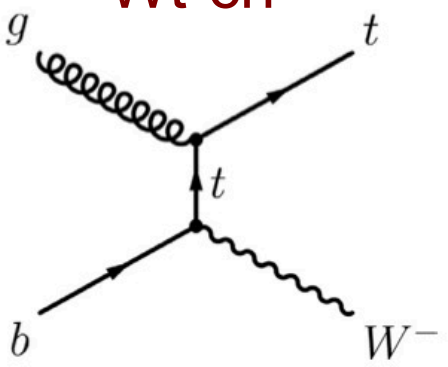
- Single top quark production



t-ch



s-ch

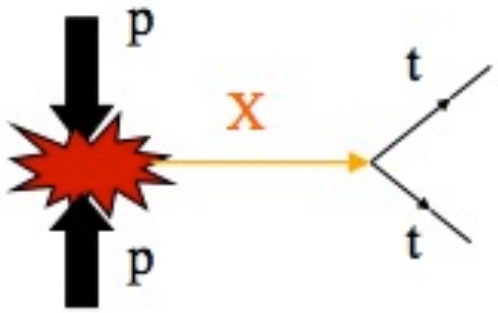


Wt-ch

σ(13TeV) = 217 pb

10 pb

72 pb

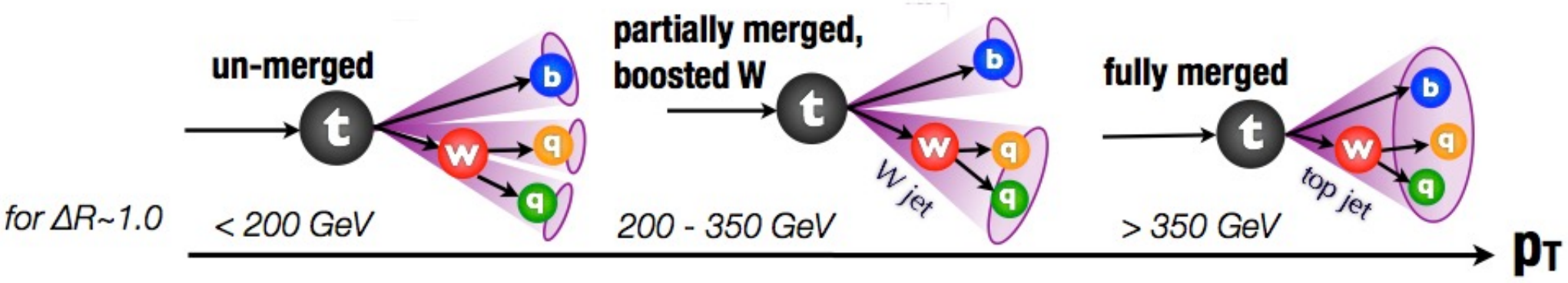


Resonance Production?
Top Color-Assisted Technicolor
OR
?????

Probing top quark production

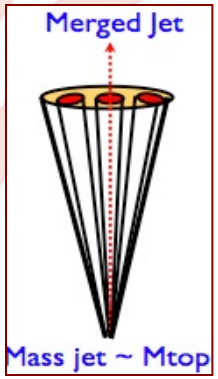
- Differential measurements
  - Testing QCD, measuring properties, searching for new physics, …
  - Function of kinematics, global variables, associated production
- Increased sensitivity: top quark pairs produced at rest
  - σ (M_{tt}>1 TeV at 13 TeV) =8 x σ(M_{tt}>1 at 8 TeV)

⇒Unique opportunity to probe boosted production at 13 TeV



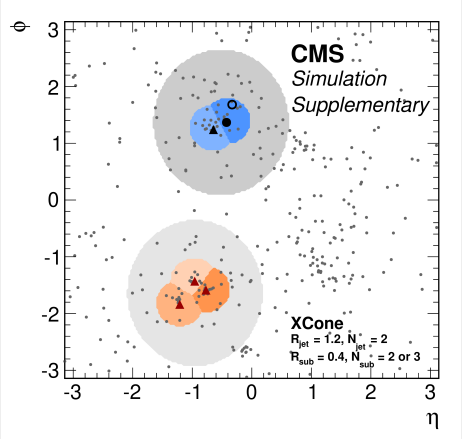
Boosted topology

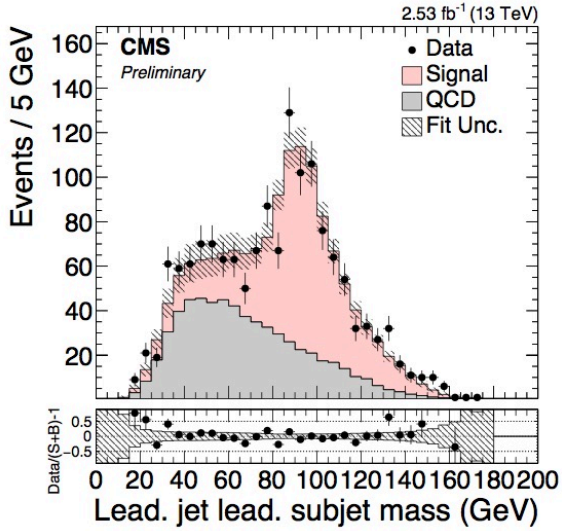
JHEP 1209(2012)029, TOP-16-013, PRL 124(2020) 202001

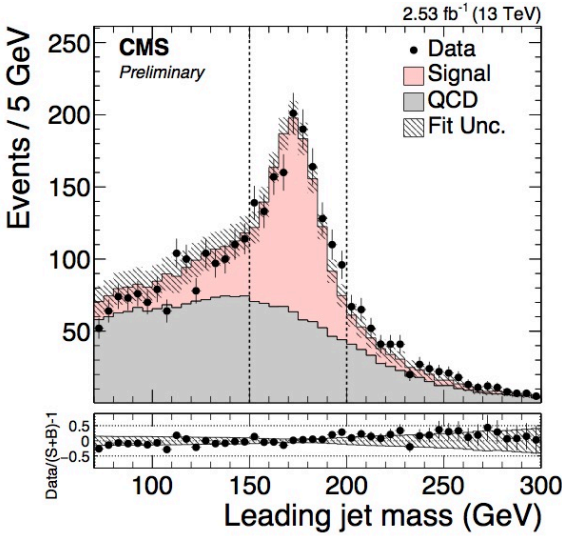


see also CDF note 10234

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







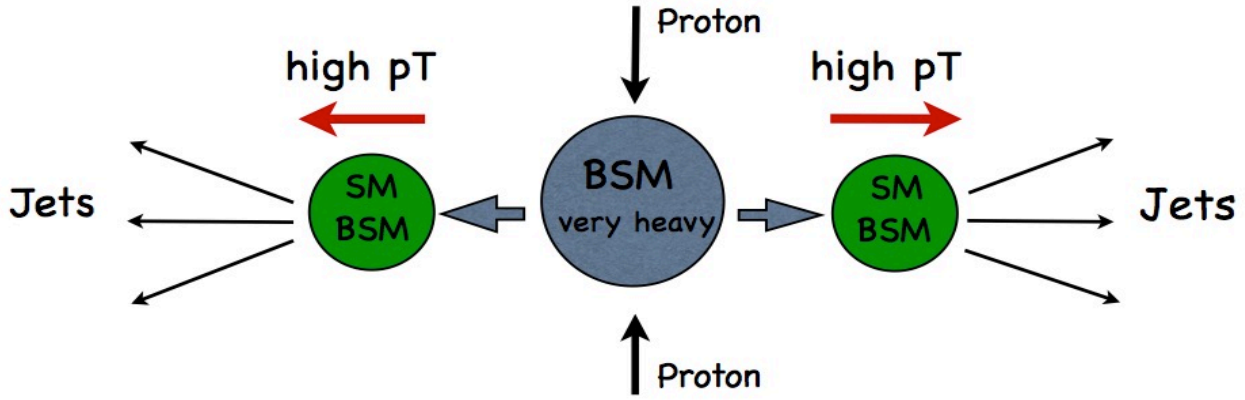
- At high energy, particles produced beyond threshold
- All-hadronic topology
  - Top p_T boosted, jets are collimated
  - Decay products and FSR collected in a “fat” jet
- Look at jet substructure
- Measure mass (no neutrinos)

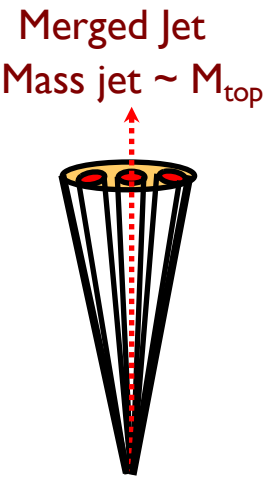
Boosted topology

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

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

- Simple approach to merge neighboring jets

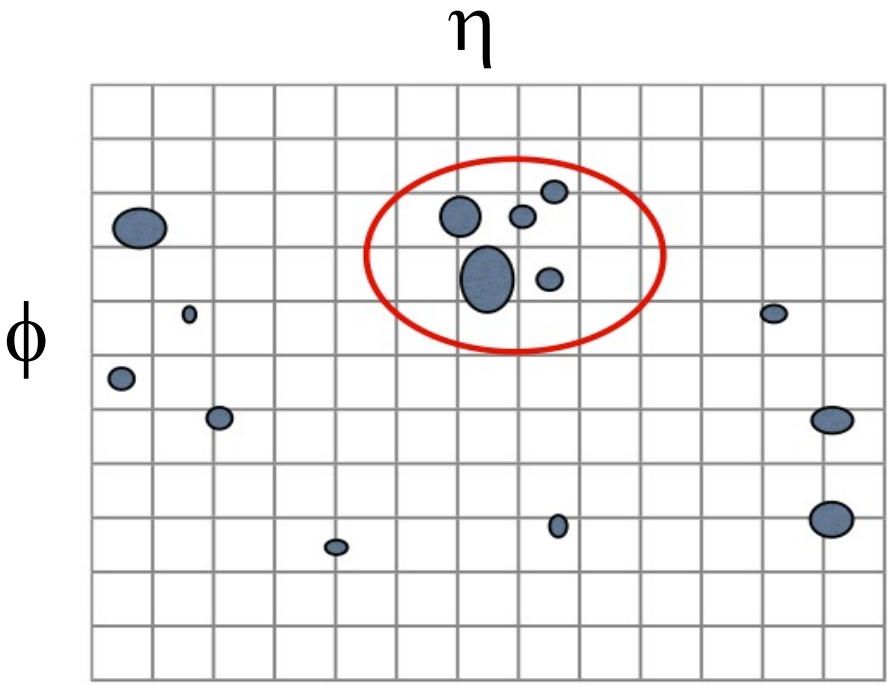




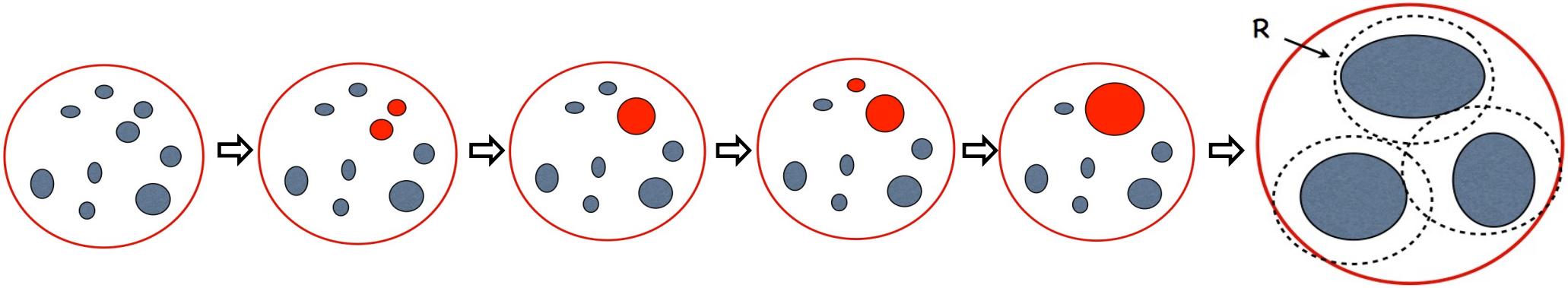
- At LHC energy, EWK scale particles produced beyond threshold
- Jets are highly collimated
- Decay products and FSR collected in a fat jet

Jet/Event selection

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



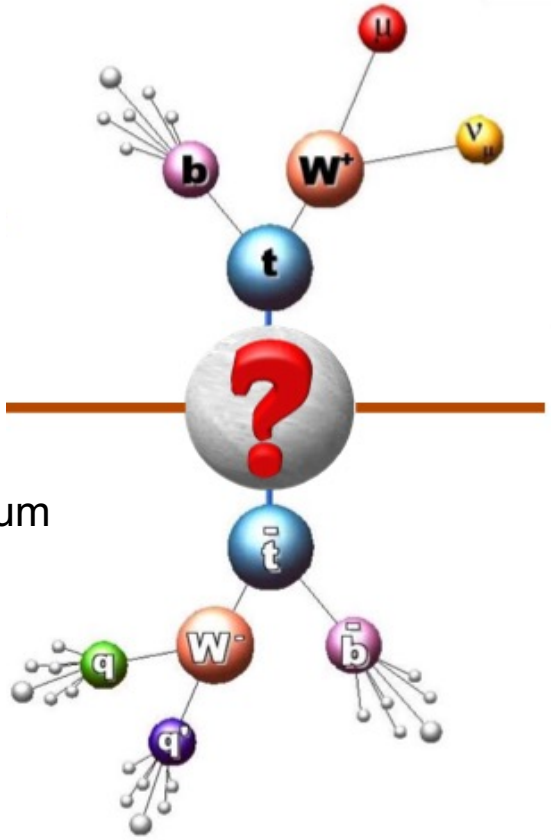
UE, ISR, Pile-up, hard interaction

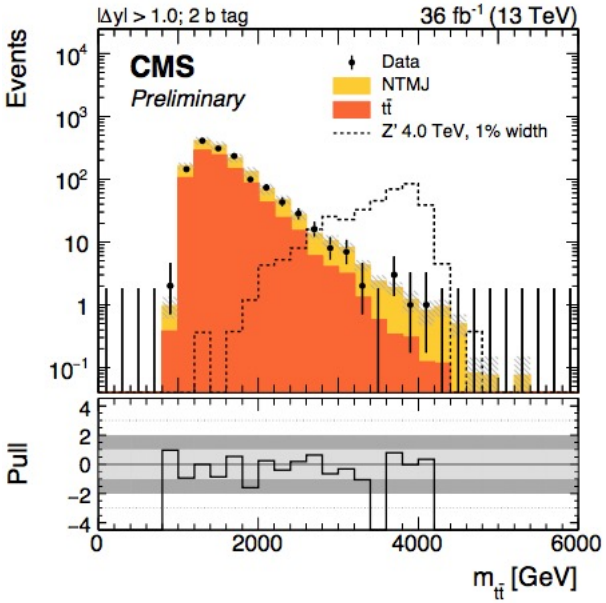


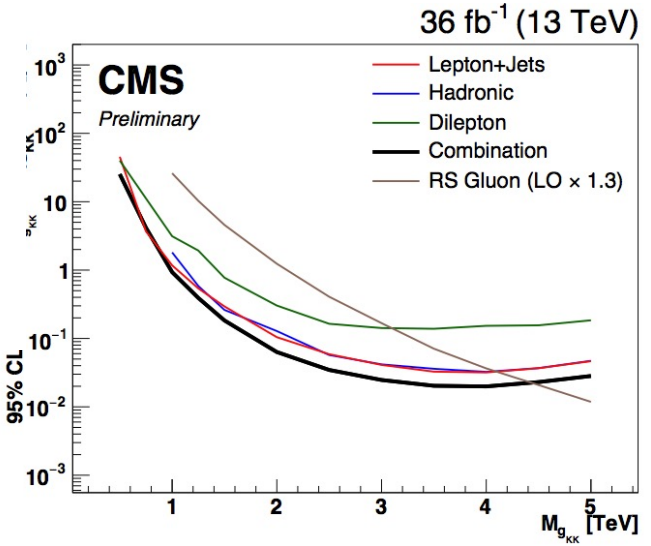
Top quark pair resonance

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

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

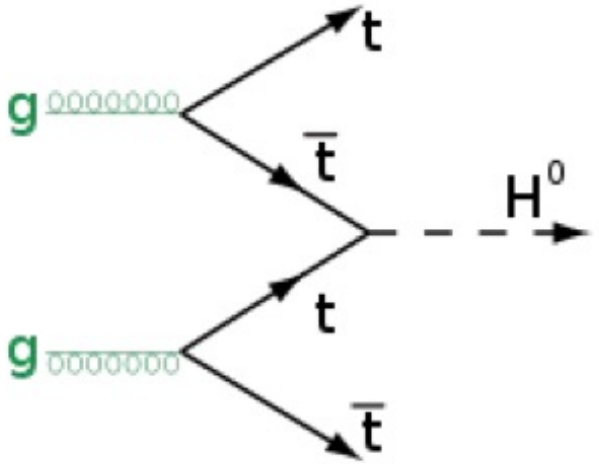




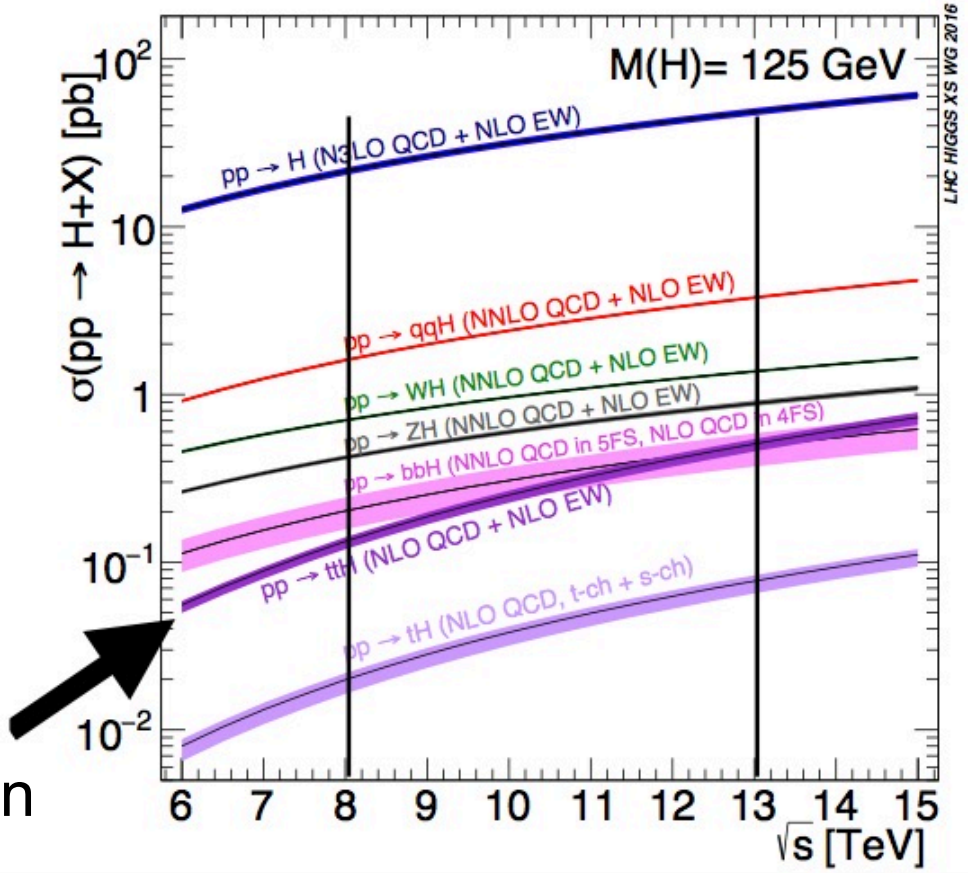


ttbar+Higgs

- 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

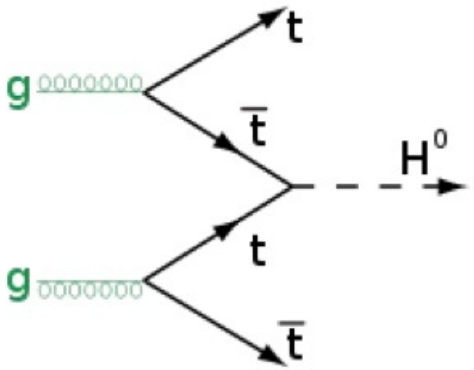
ttbar+heavy flavour

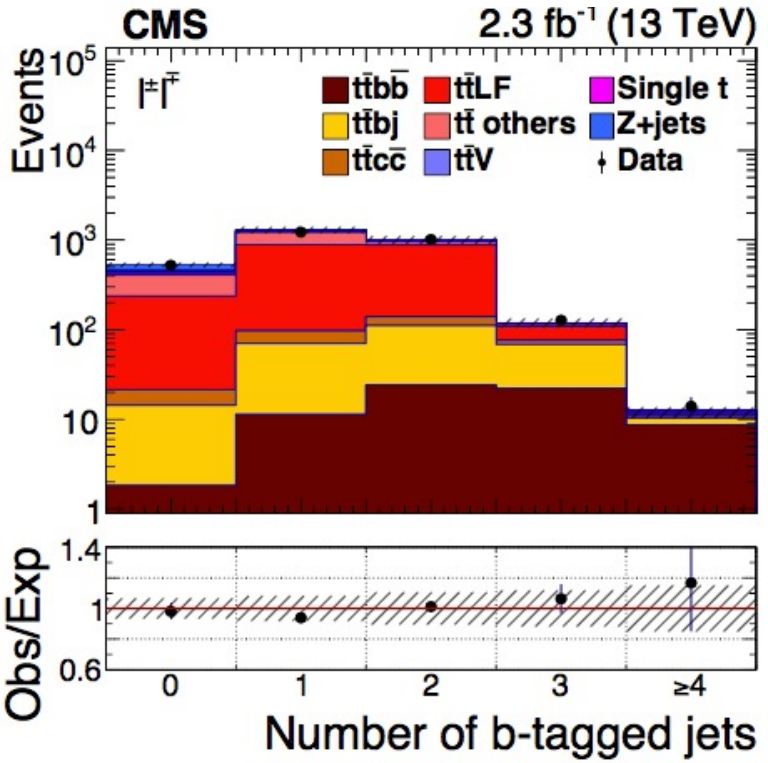
arXiv:1411.5621, PLB776(2018)355

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

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

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

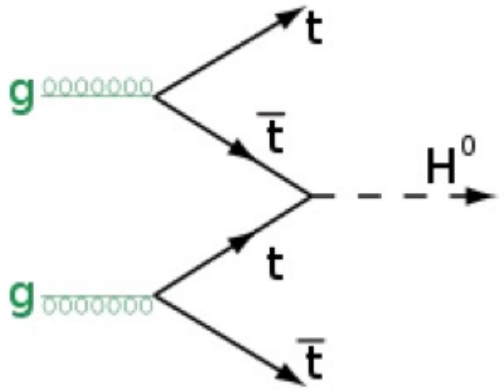


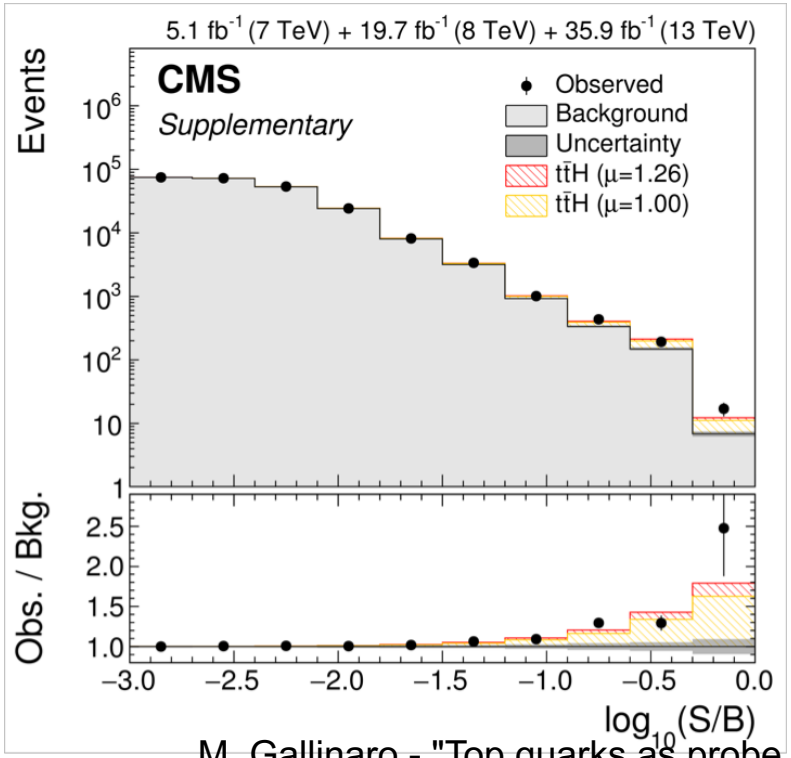


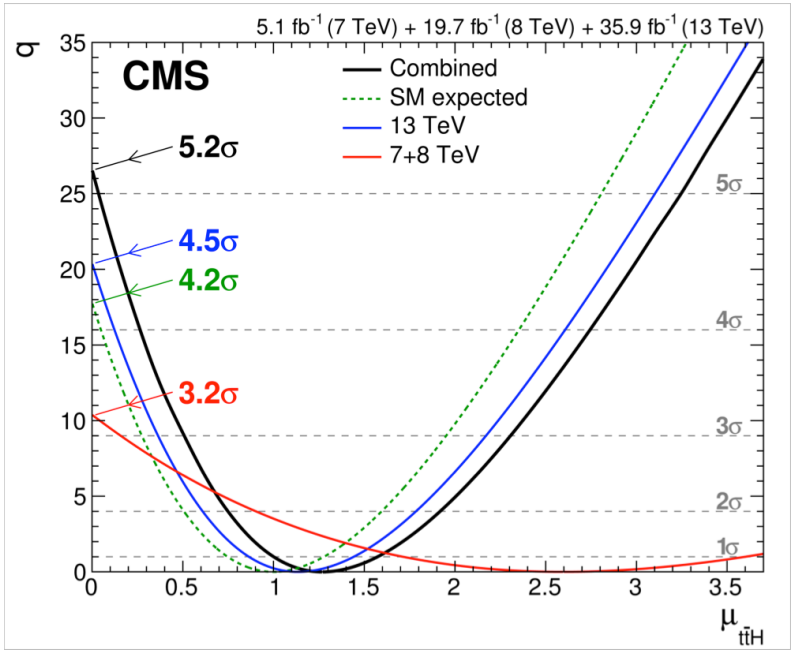
Higgs couplings to top quarks

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

- Direct study of Top-Higgs Yukawa coupling
- Explore all accessible Higgs decay modes
- Independent analysis of different final states (WW, ZZ, $\gamma\gamma$, $\tau\tau$, bb)

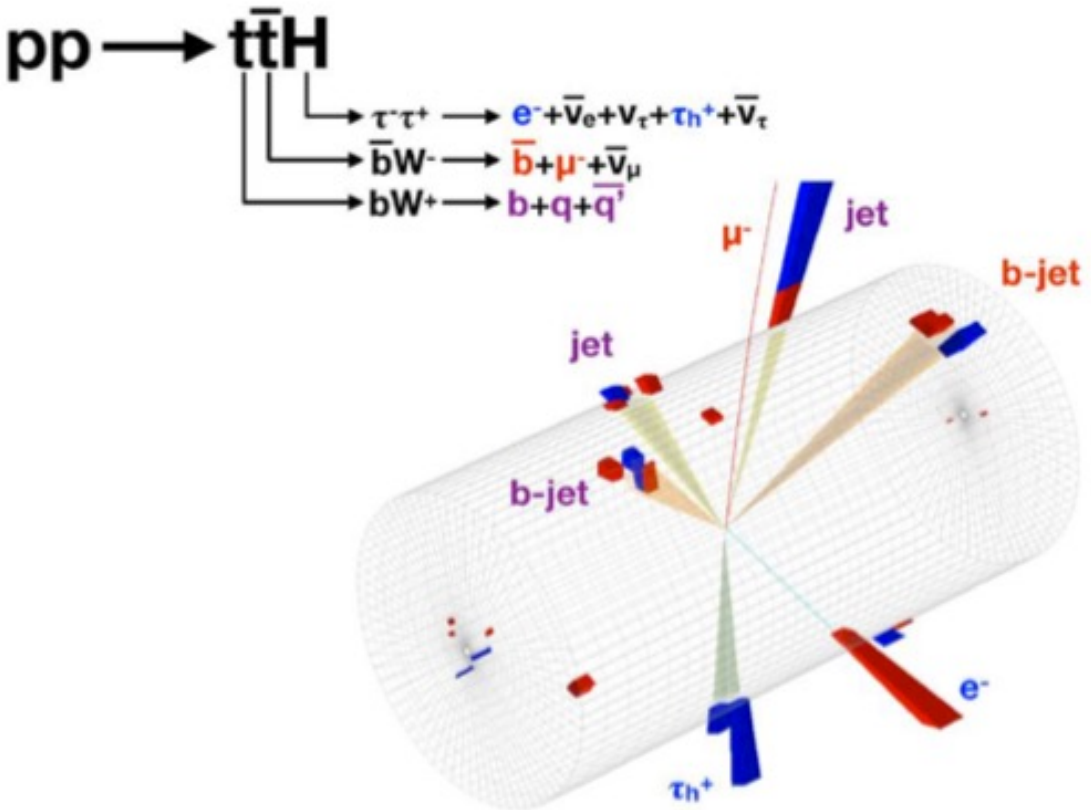






Event selection

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

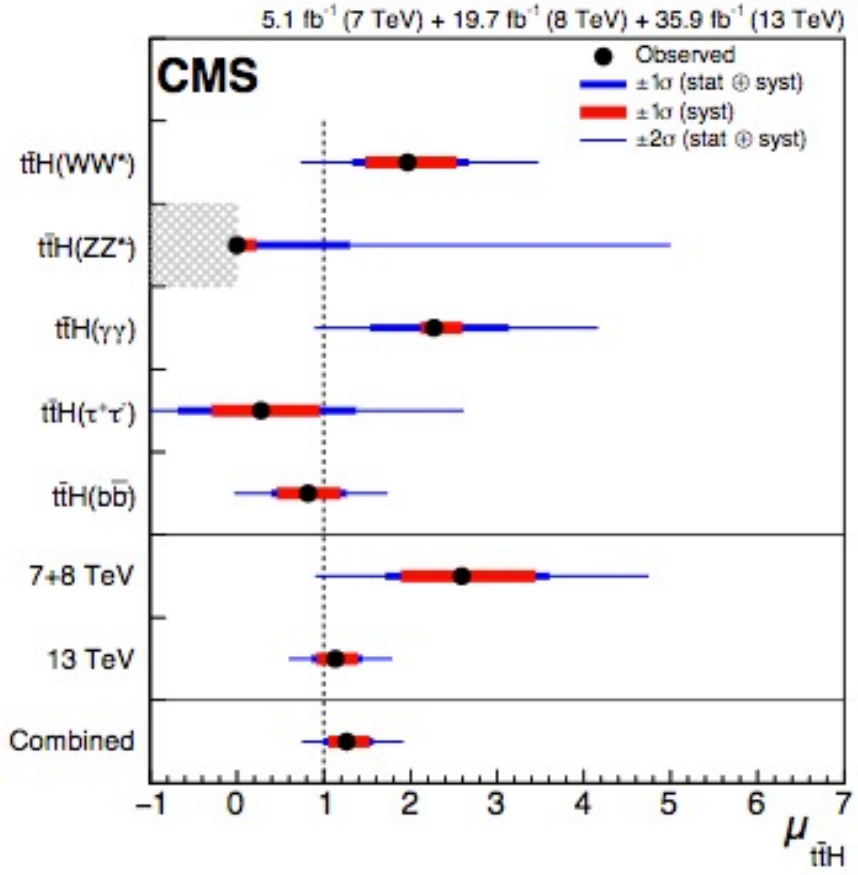


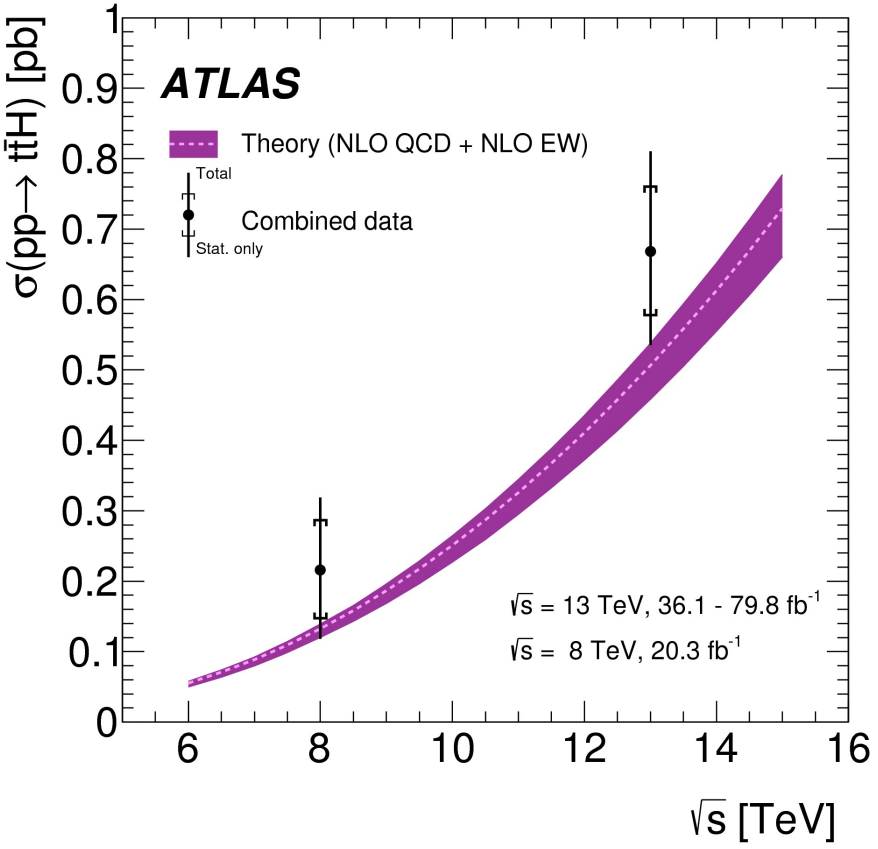
Observation of ttH

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

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

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



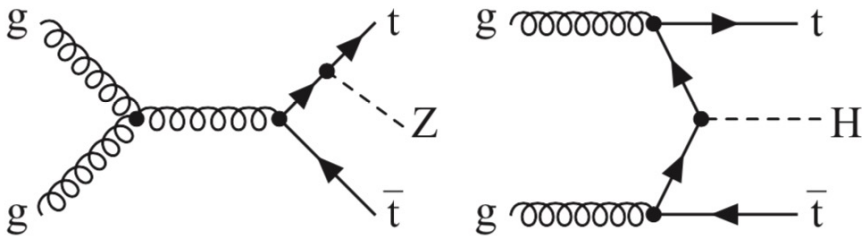


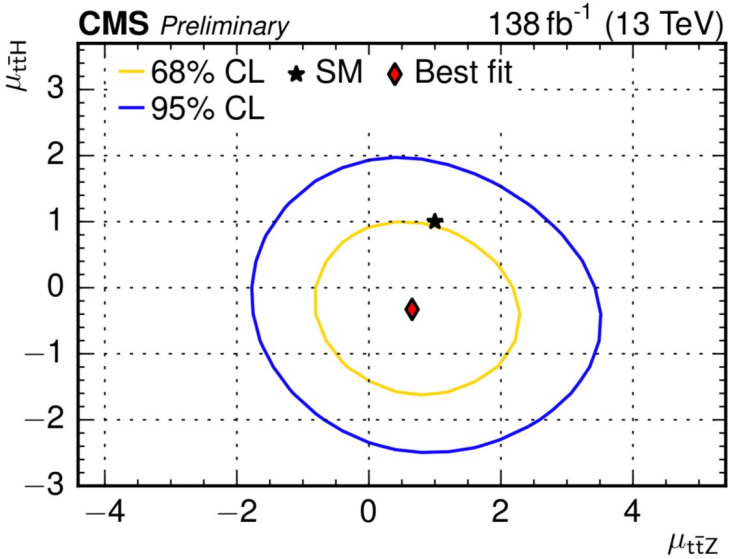
ttH/Z with boosted Z/H

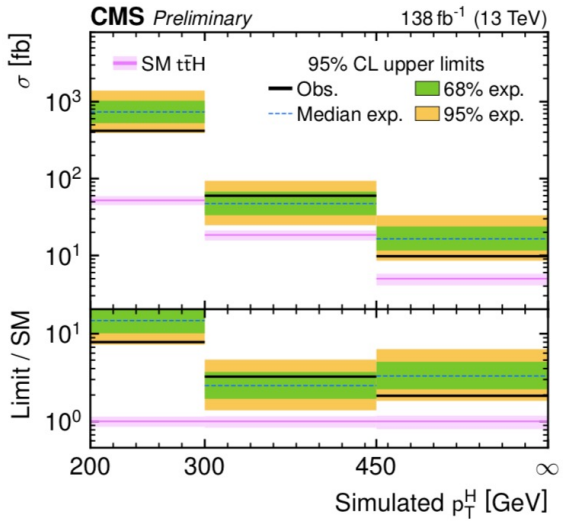
CMS-TOP-21-003

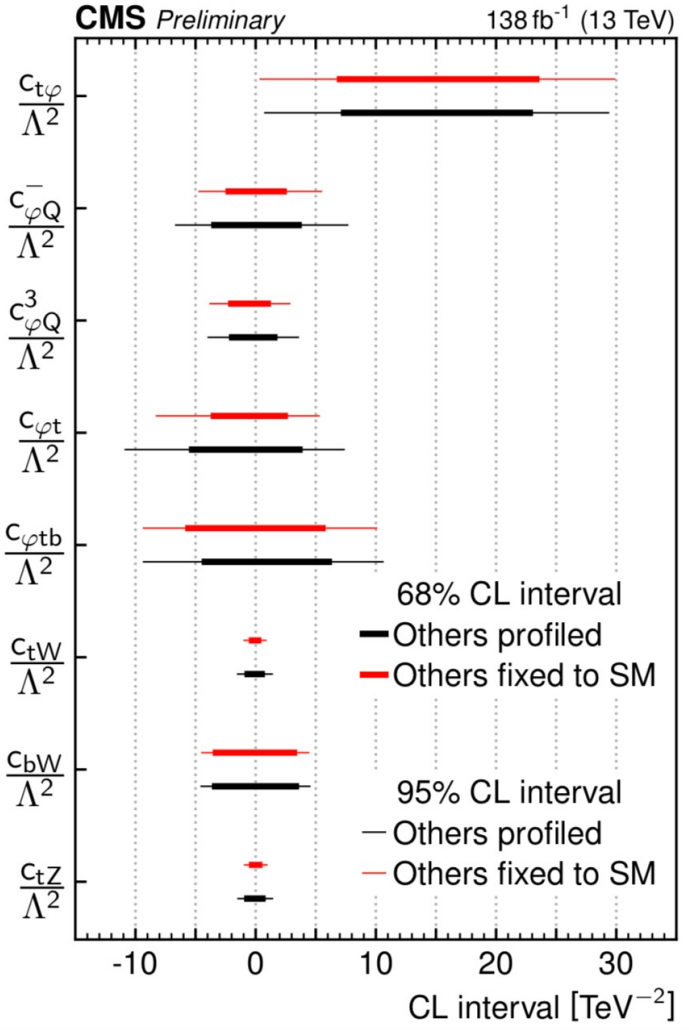
Search for tt+ boosted Z/H→bb

- ~~Direct access to top~~-Z and top-H couplings
- Signal strengths and differential cross section
- Search for EFT effects



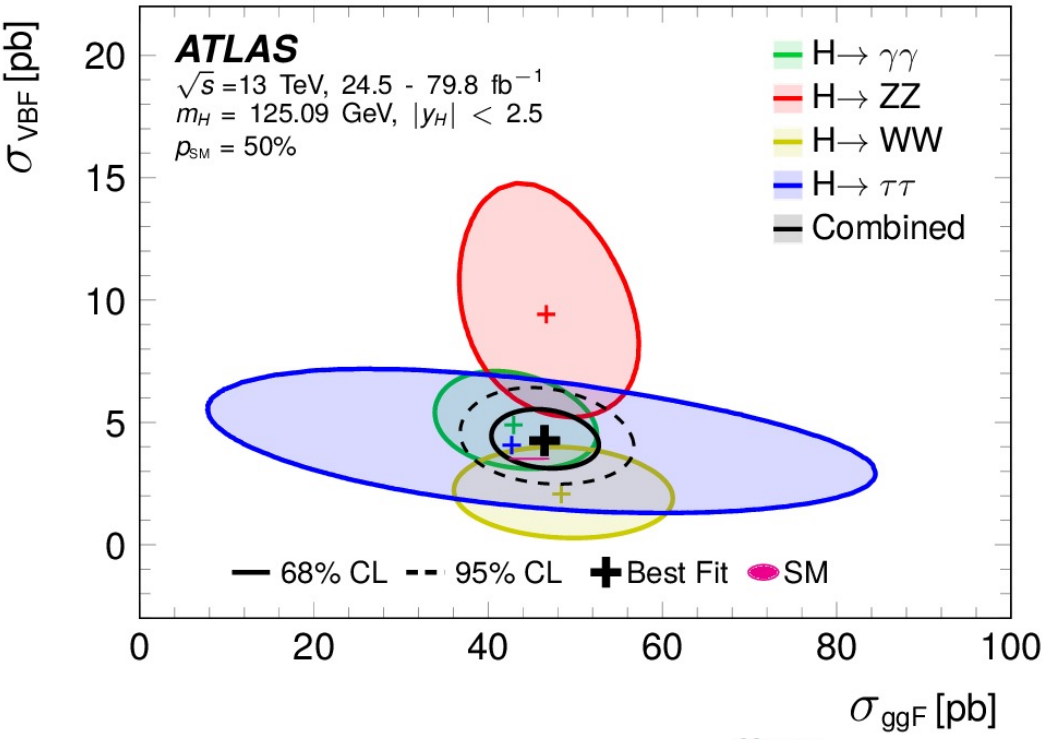


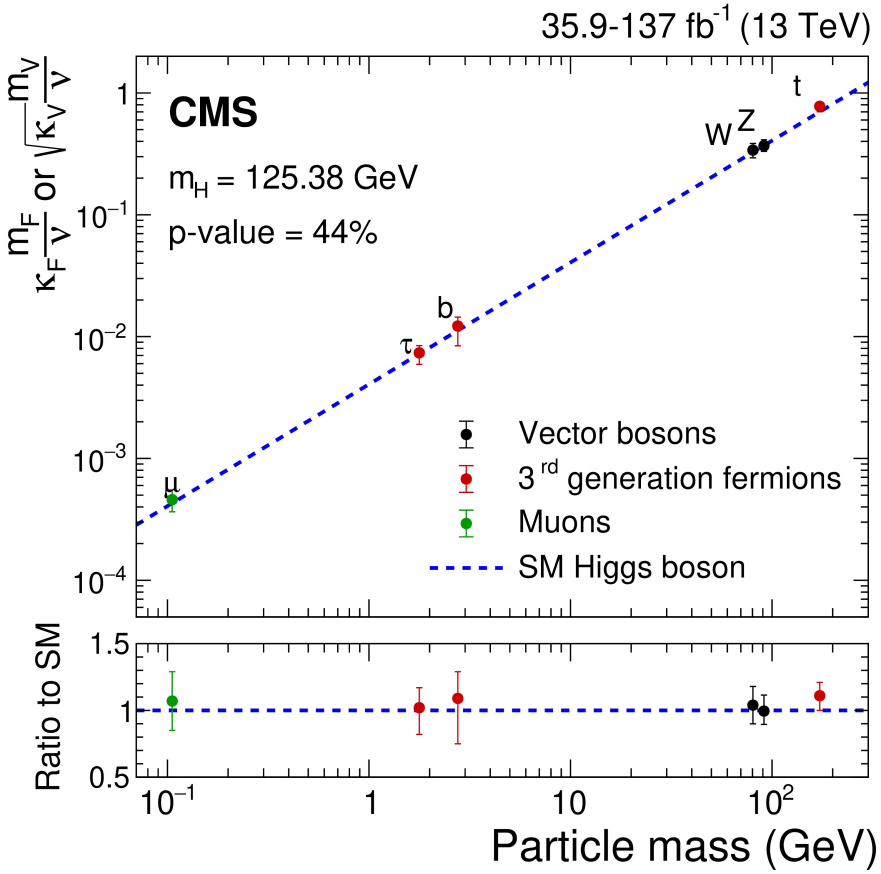




Consistency with SM

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

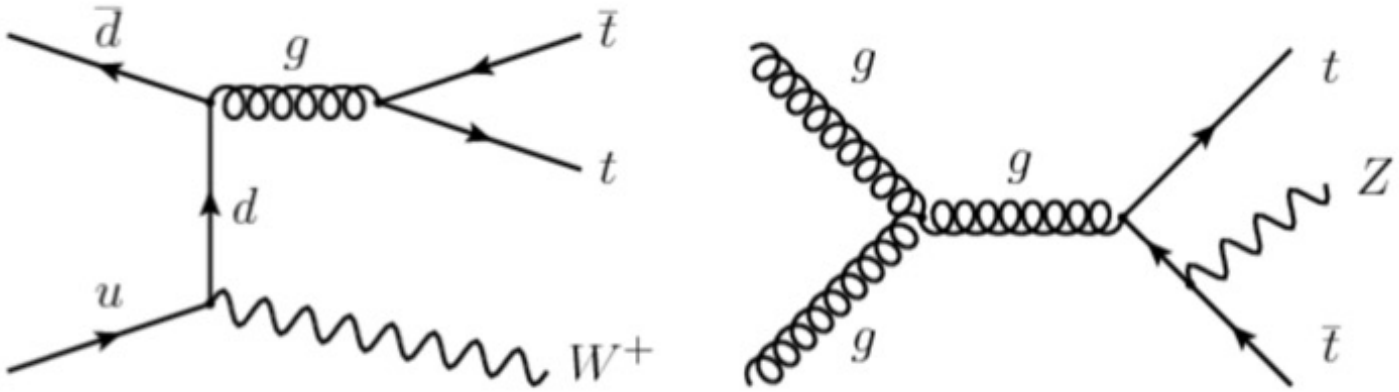




VBF+VH: boson in production
ggF+ttH: fermions in production

ttV production (V=γ,W,Z)

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

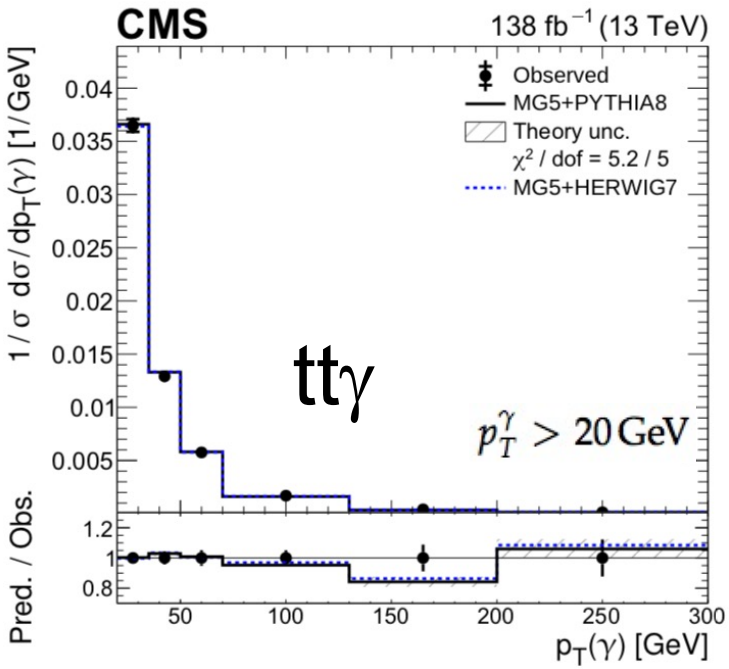


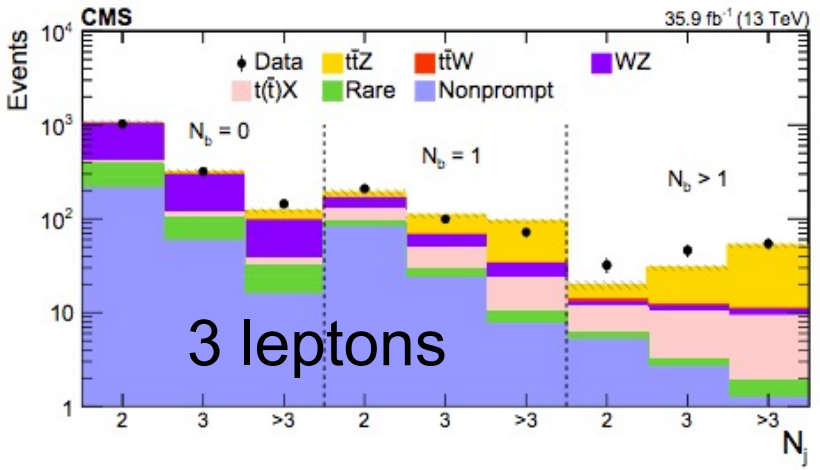
- Use multi-lepton final states
  - 2 same-sign charge leptons, 3 or 4 lepton final states

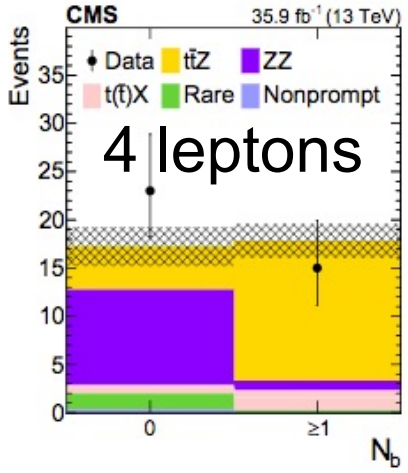
ttV production (V=γ,W,Z)

arXiv:1808.02913, JHEP08(2018)011, arXiv:2201.07301

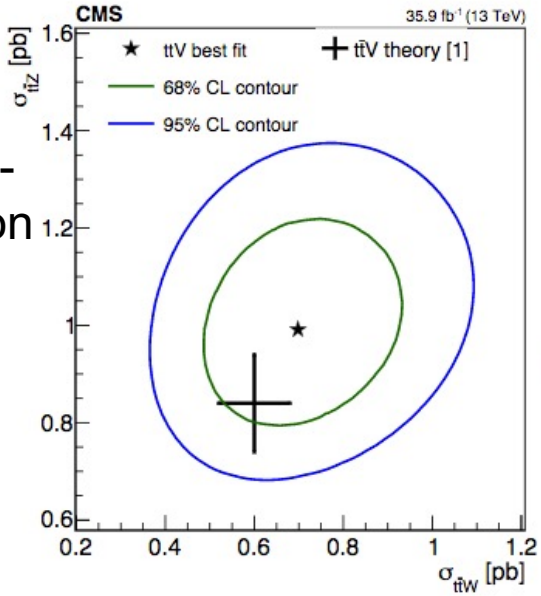
- Measurements gives access to EW couplings of the top

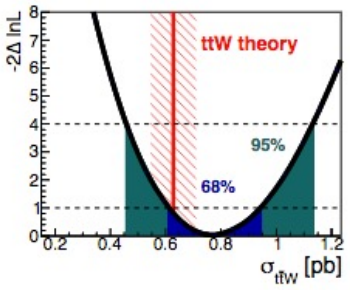


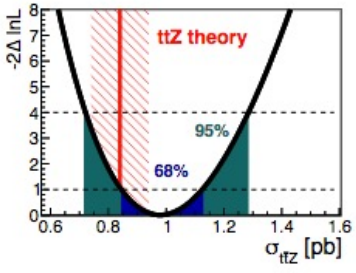




Combine 3- and 4-lepton final states







Measure:

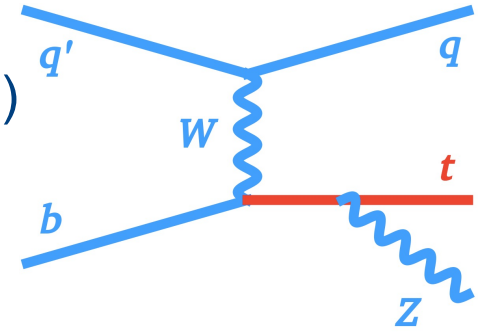
$$\sigma_{\text{fid}}(\text{pp} \to \text{t}\bar{\text{t}}\gamma) = 173.5 \pm 2.5\,(\text{stat}) \pm 6.3\,(\text{syst})\ \text{fb}$$

⇒ Consistent with SM predictions

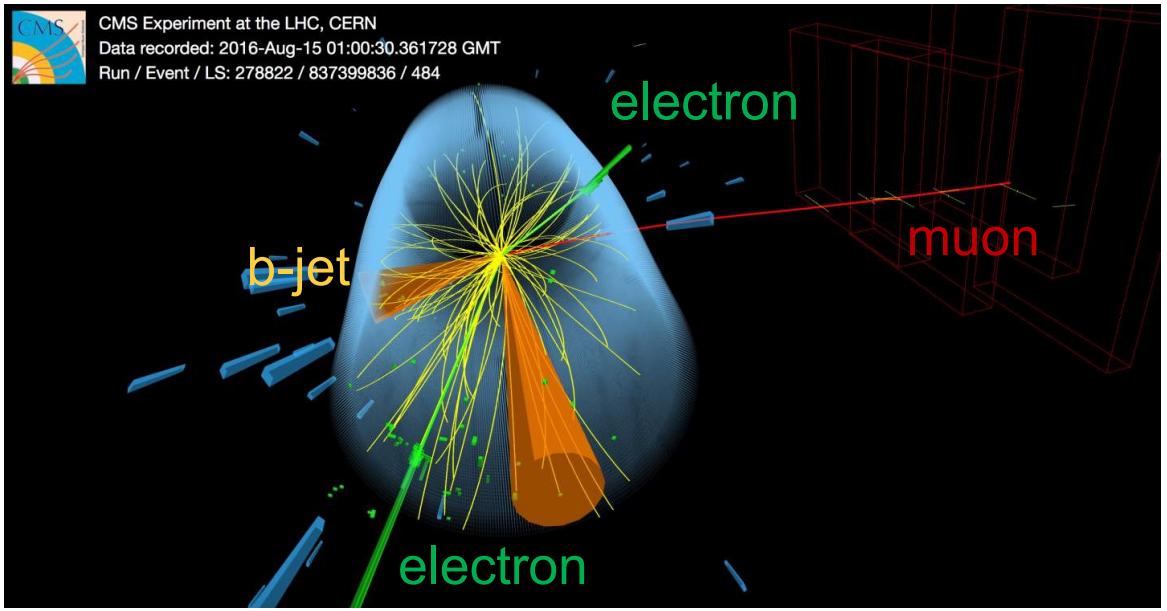
Top-Z coupling

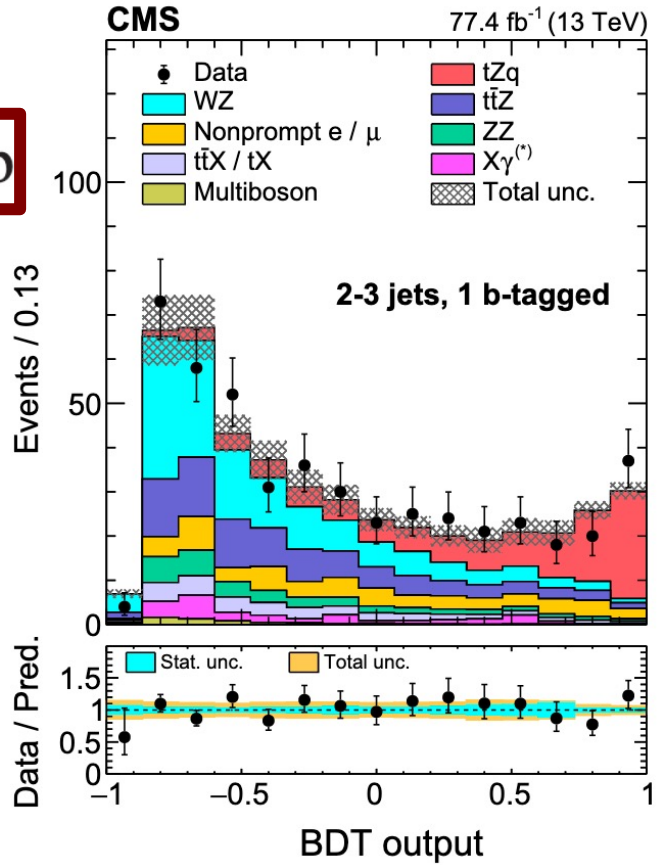
PRL 122(2019)132003

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



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





Flavor Changing Neutral Currents

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

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

Flavor Changing Neutral Currents

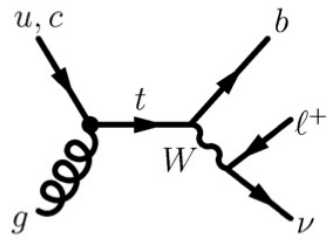
- Expect small signal from SM

…but signal may be large in BSM models

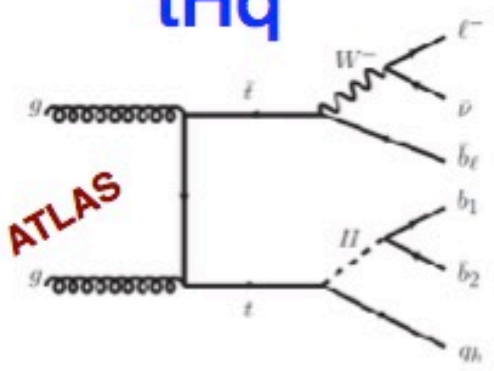
Final states:

Wb

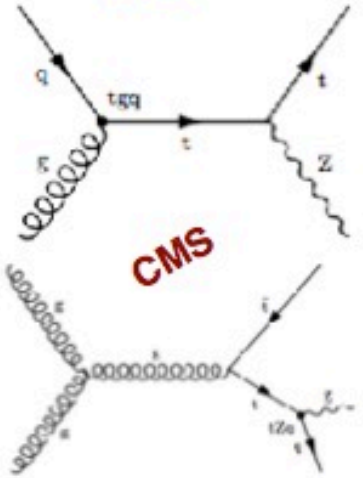
ATLAS



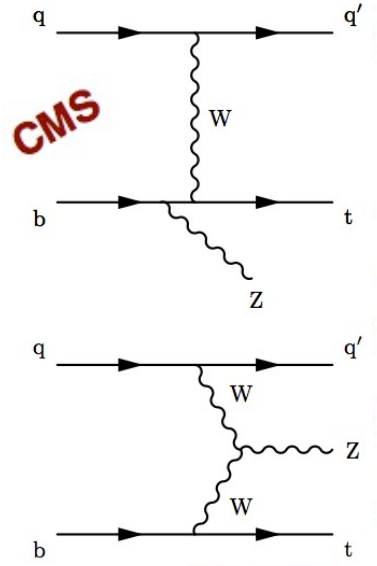
tHq



tZ



SM: tZq



Couplings:

t→ug	t→uH	t→ug, t→cg	t→tZ
t→cg	t→cH	t→uZ, t→cZ	

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

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

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

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

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

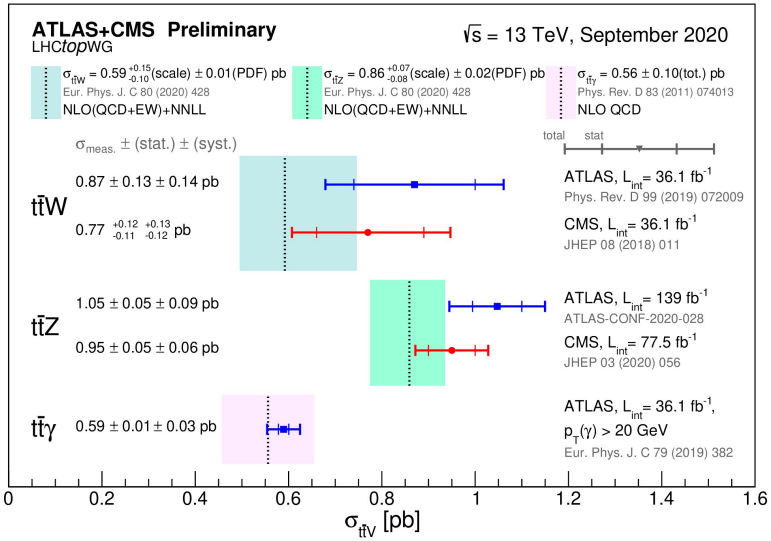
$B(t \to Zc) < 0.049\%$

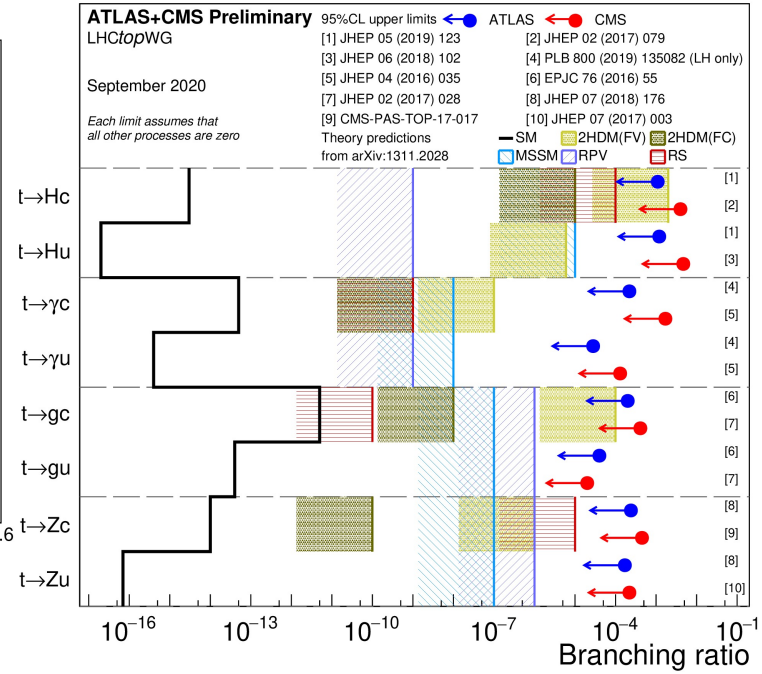
SM $\sigma(tZq) = 10^{+8}_{-7}$ fb

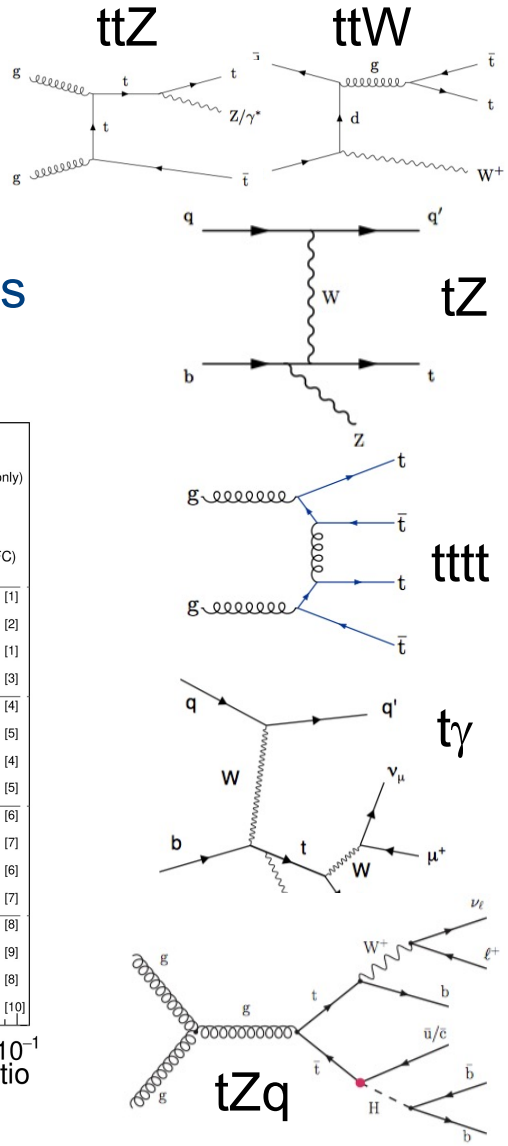
Top quarks and rare decays

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

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

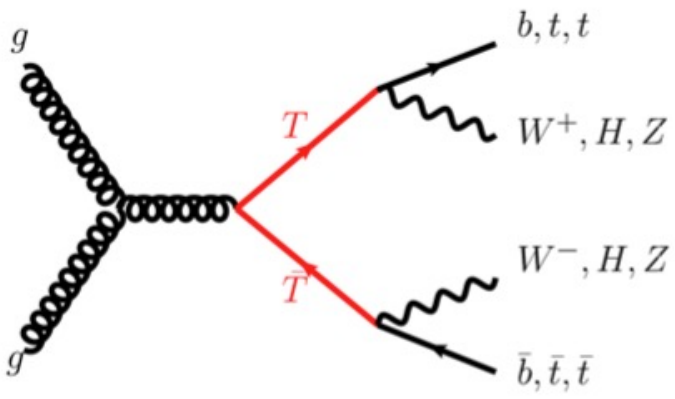


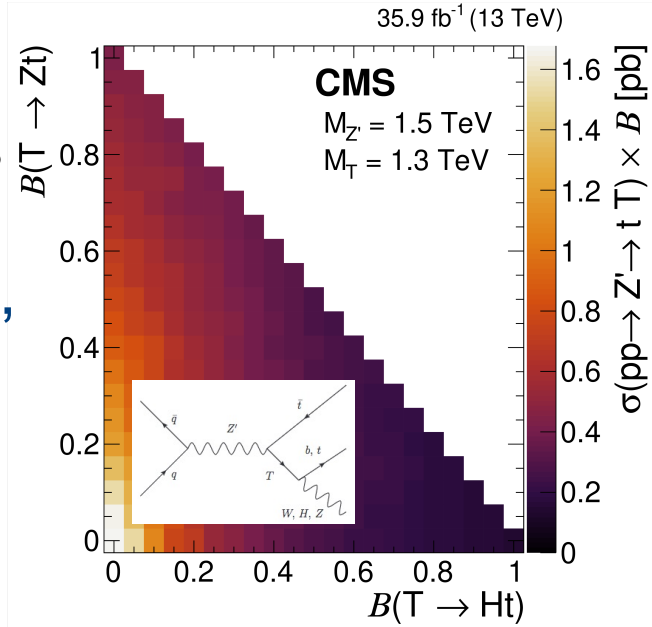




Vector-like quarks

- Predicted in many BSM models, aim to solve the hierarchy problem
  - in multiplets: singlet, doublet, triplet
  - left- and right-handed component with same quantum numbers
- VLQs can mix with SM quarks and modify the couplings to the Z/W/Higgs bosons
- Search for VLQ single and pair production
  - Most searches assume VLQs couple/decay to SM particles (bosons and 3rd generation quarks)
- Busy events, a lot of top quarks, bottom quarks, leptons and jets in final state
  - Example: 2 tops in final state, look for resolved/merged top quark decays
  - use top/H/W/Z taggers to find hadronic decays





Vector-like quarks

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  - in multip
  - left- and numbers
- VLQs car couplings
- Search fo
  - Most se (bosons
- Busy eve leptons a
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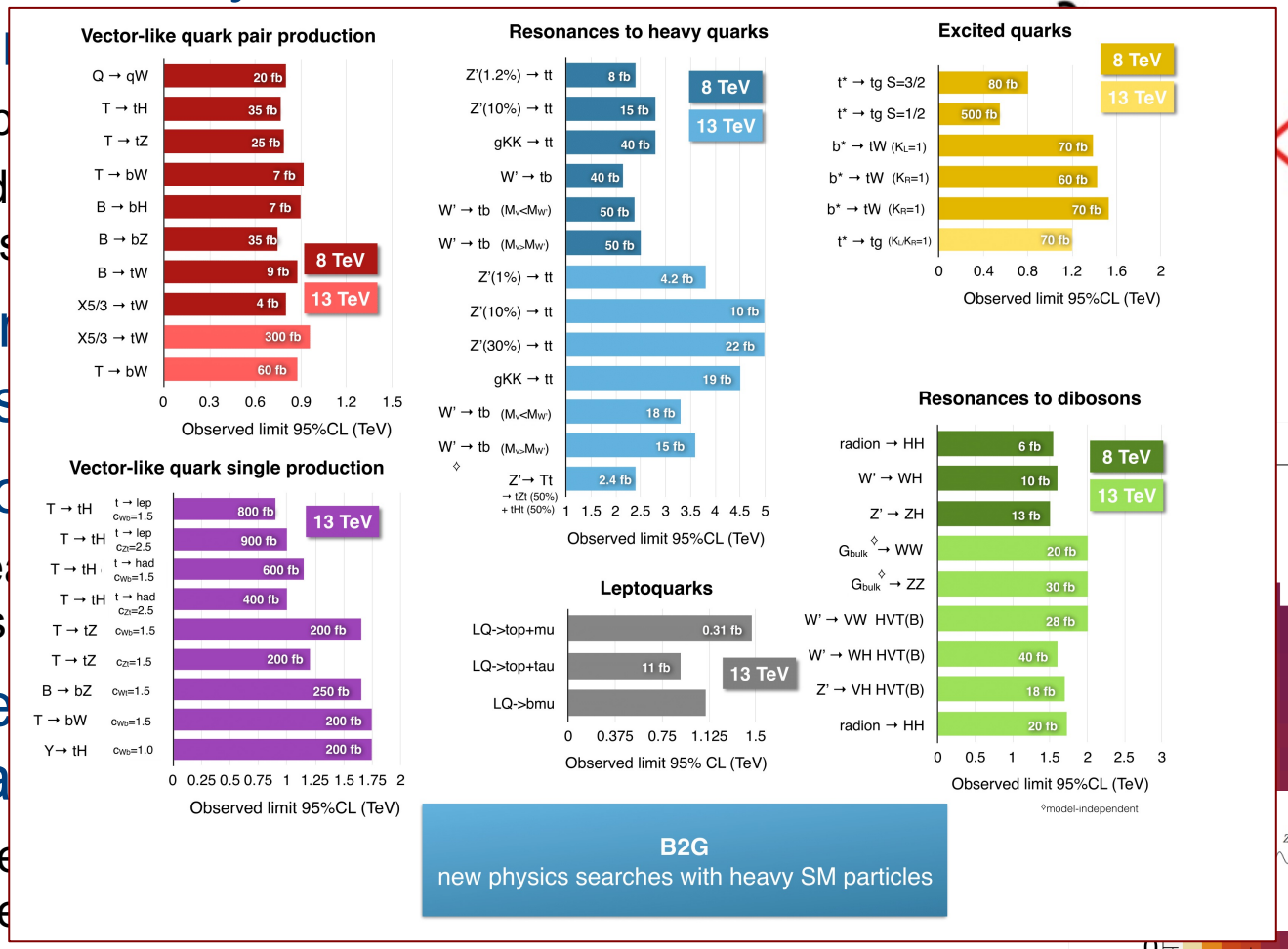
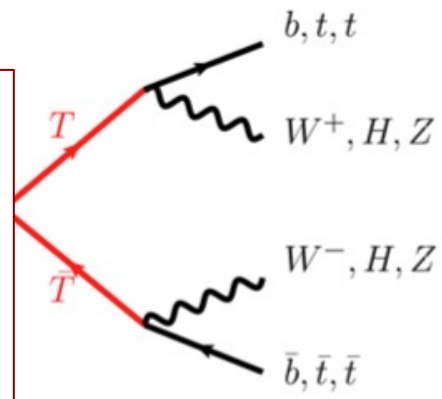
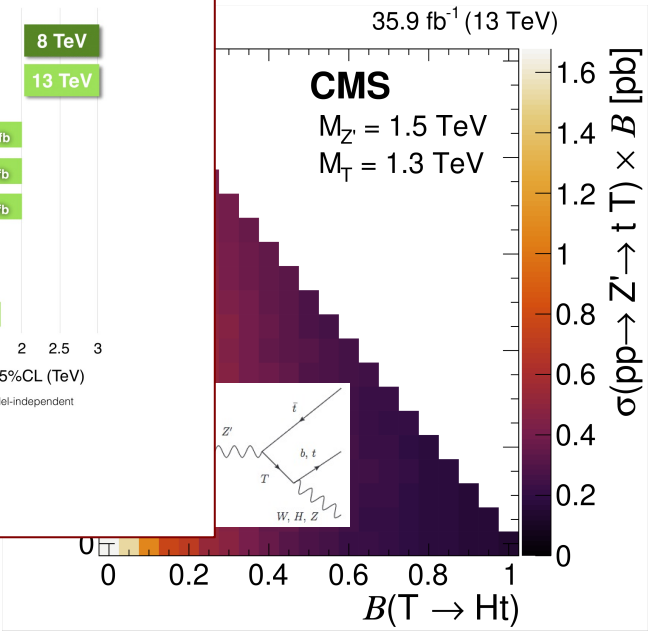
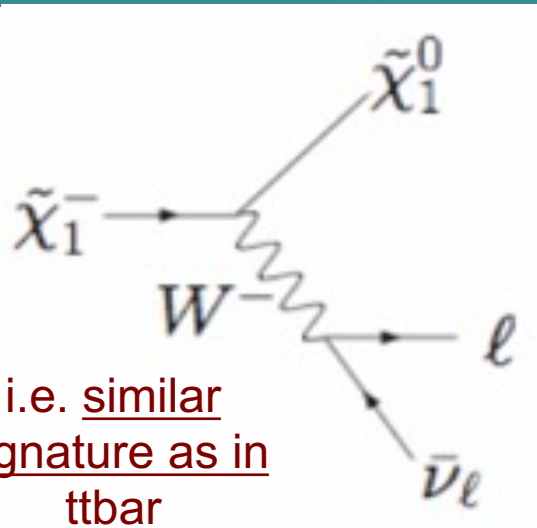






Scalar top quark

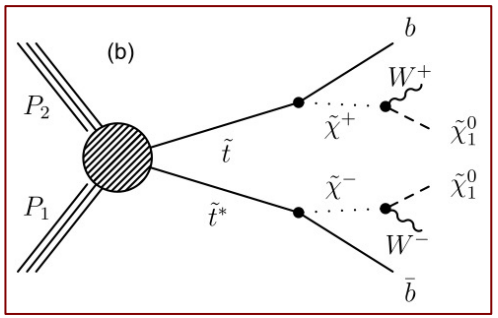
- SUSY is one plausible extension of the SM
- due to the heavy top quark, mass splitting between $\tilde{t}_1$ and $\tilde{t}_2$ can be large, such that the lighter stop $\tilde{t}_1$ can be even lighter than the top quark
- Decays dictated by mass spectrum of other SUSY particles



i.e. similar signature as in ttbar

- Light stop:

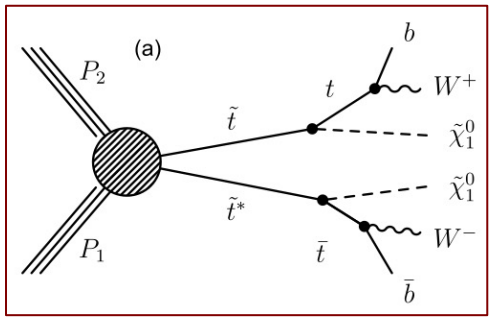
$$m_{\tilde{t}_1} \lesssim m_t$$



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

- Heavy stop:

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



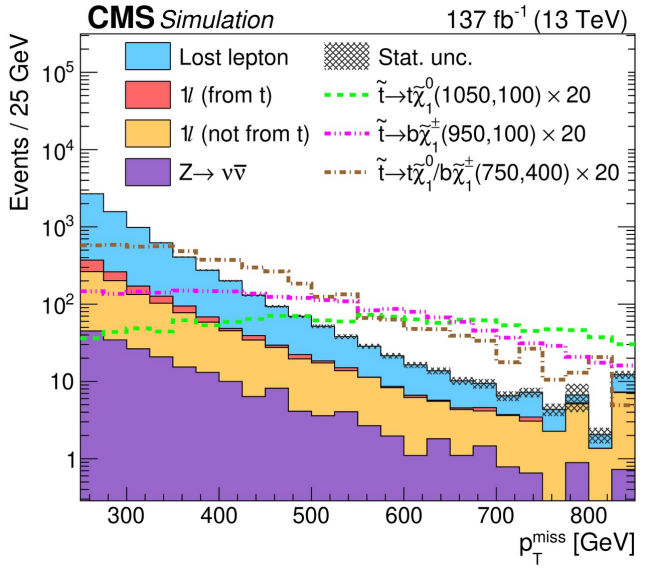
$$\tilde{t} \to t\tilde{\chi}_1^0 \to bW\tilde{\chi}_1^0$$

Top and SUSY

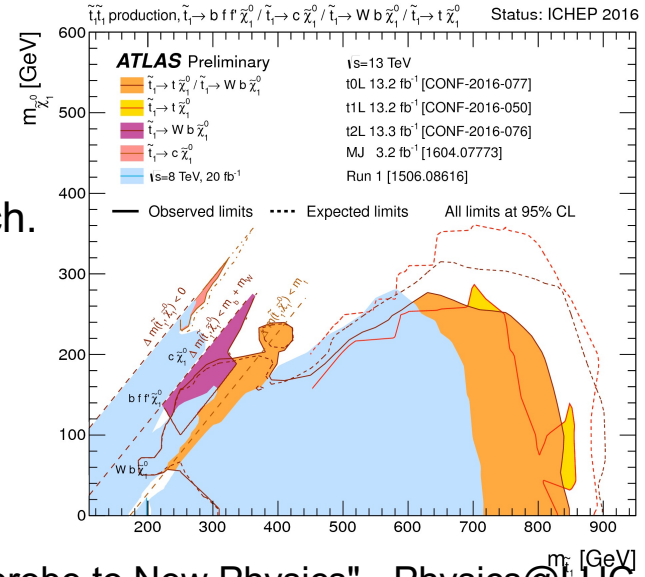
arXiv:1603.02303, JHEP05(2020)032

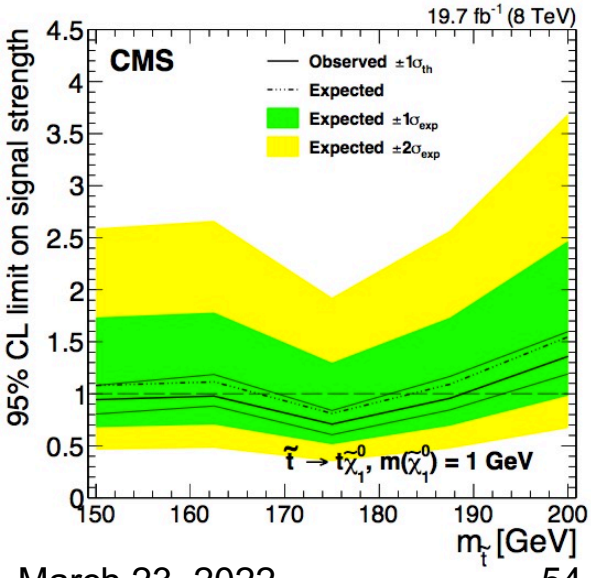
- If SUSY exists and is responsible for solution of hierarchy problem, naturalness arguments suggest that SUSY partners of top quark (*stop*) may have mass close to m_{top} to cancel top quark loop contributions to Higgs mass

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



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





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EPJC 74 (2014) 3109, arXiv:1603.02303, JHEP05(2020)032

- 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

$$\tilde{t} \to t\tilde{\chi}_1^0 \to bW\tilde{\chi}_1^0 \quad \text{“heavy”}$$
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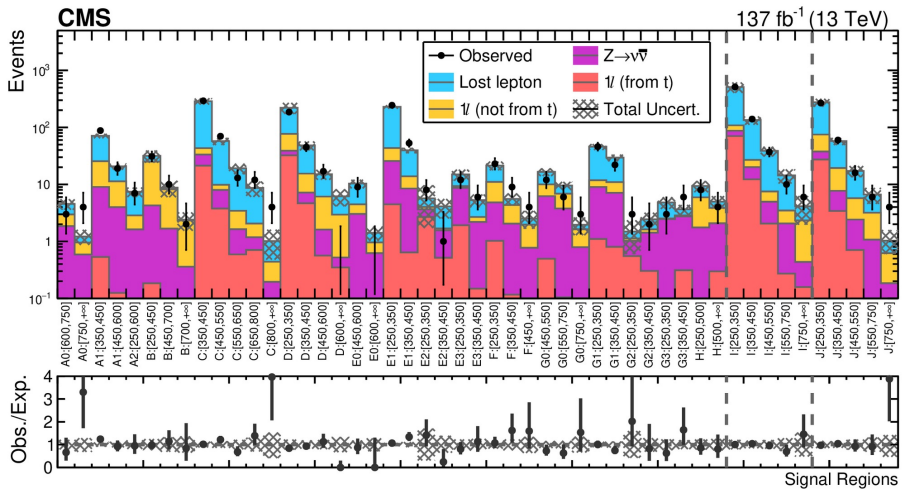

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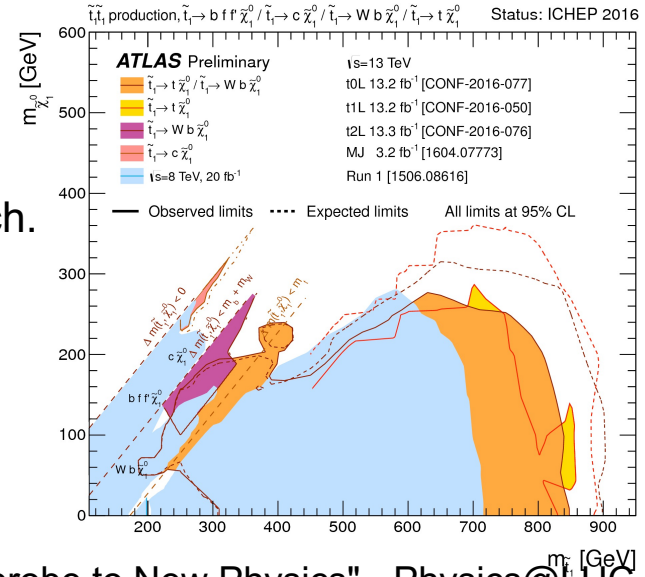
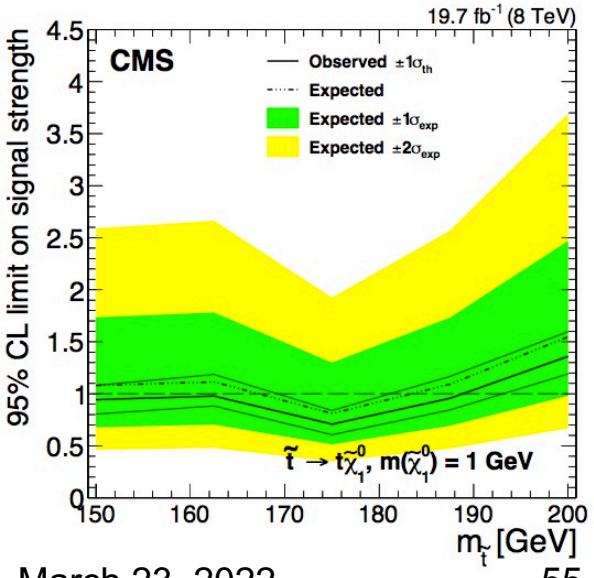
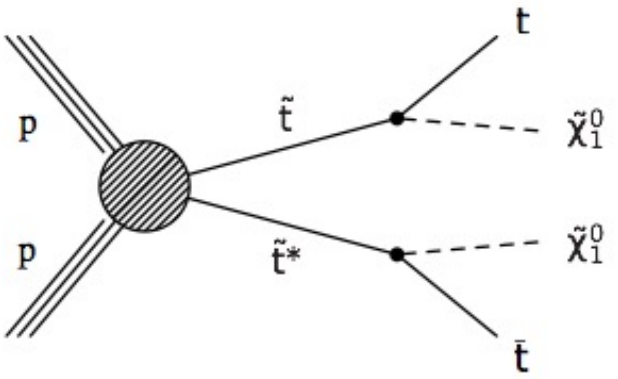


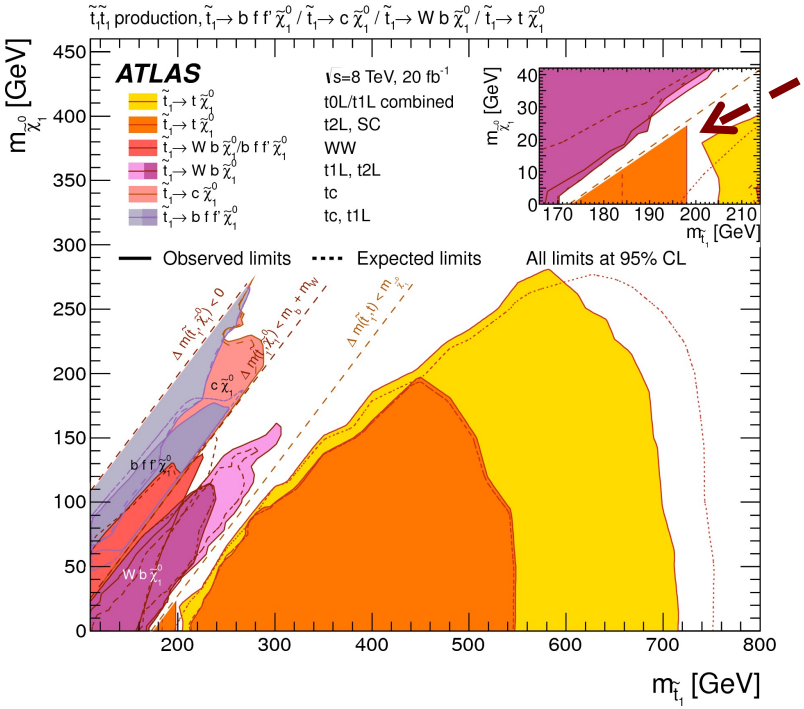


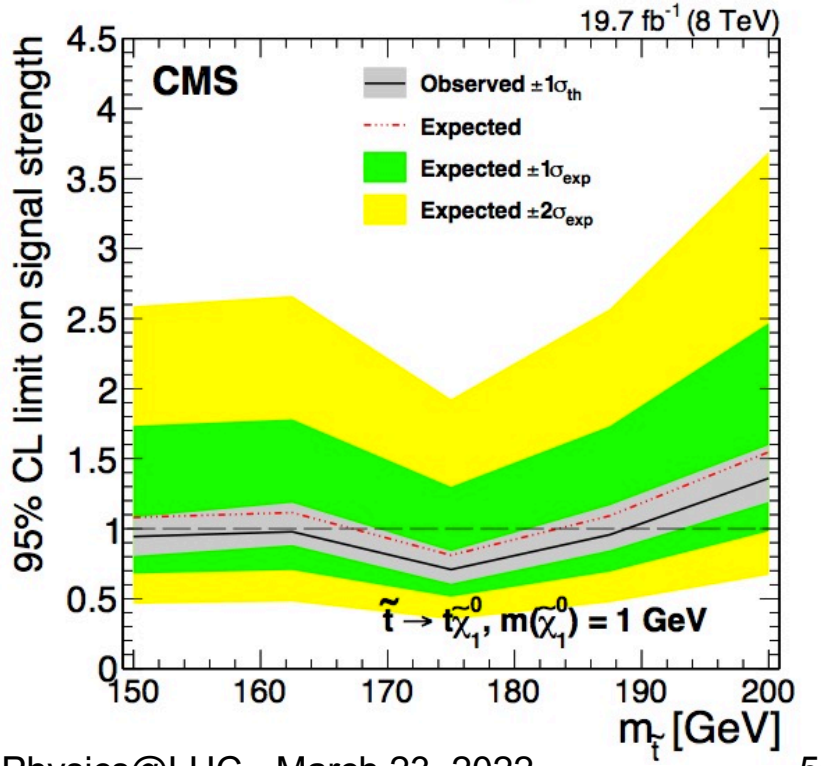
Top cross section: dileptons

EPJC 74 (2014) 3109, arXiv:1603.02303, JHEP05(2020)032

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



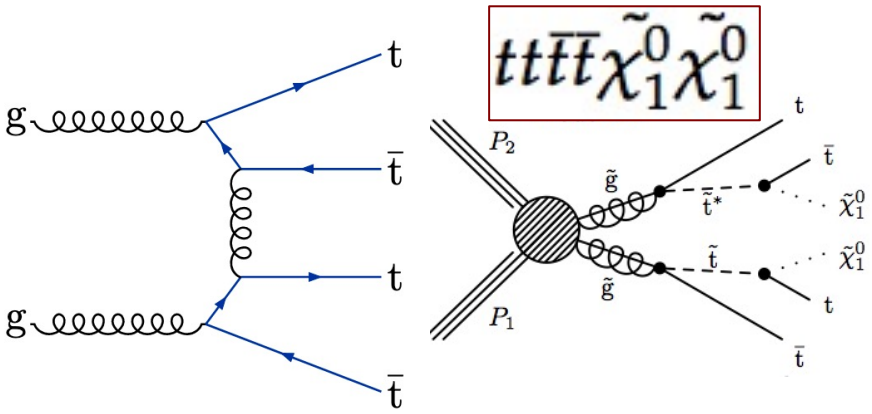




Multi-top production

arXiv:1605.03171, EPJC 80(2020)75, JHEP11(2021)118

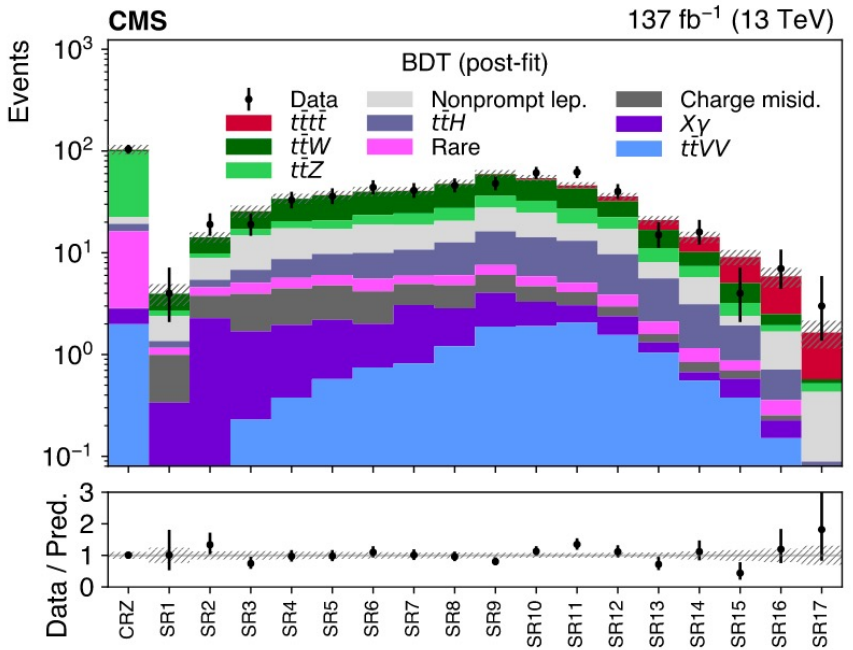
- Production of 4 tops is an attractive scenario in a number of new physics models
- The SM cross section is 12fb@13TeV



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

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

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



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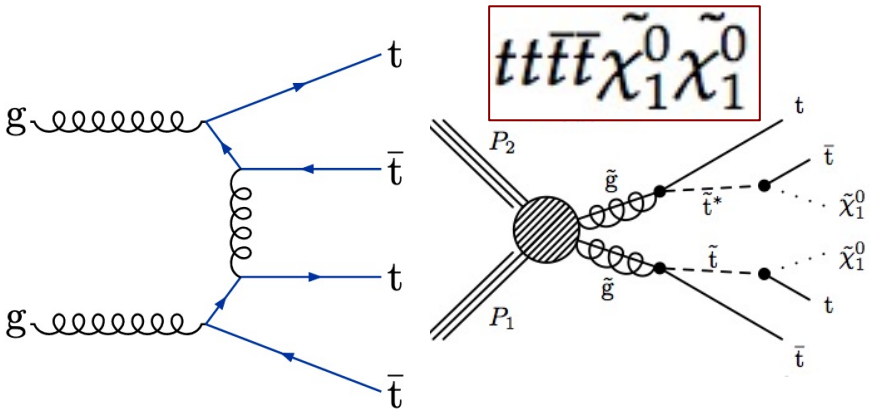

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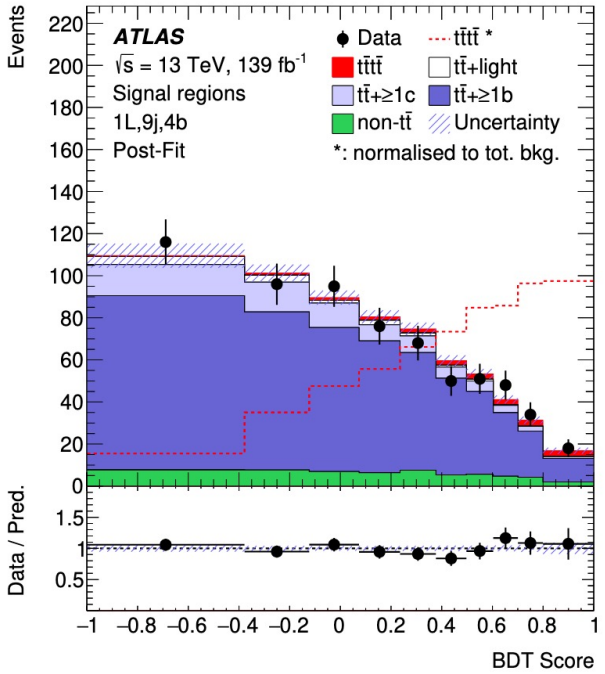
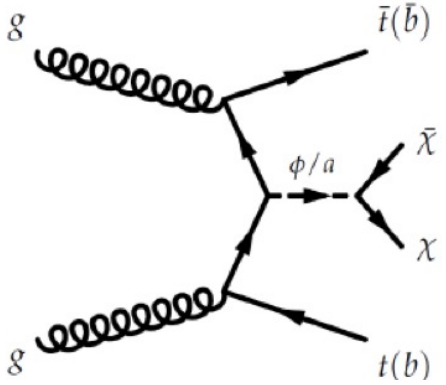


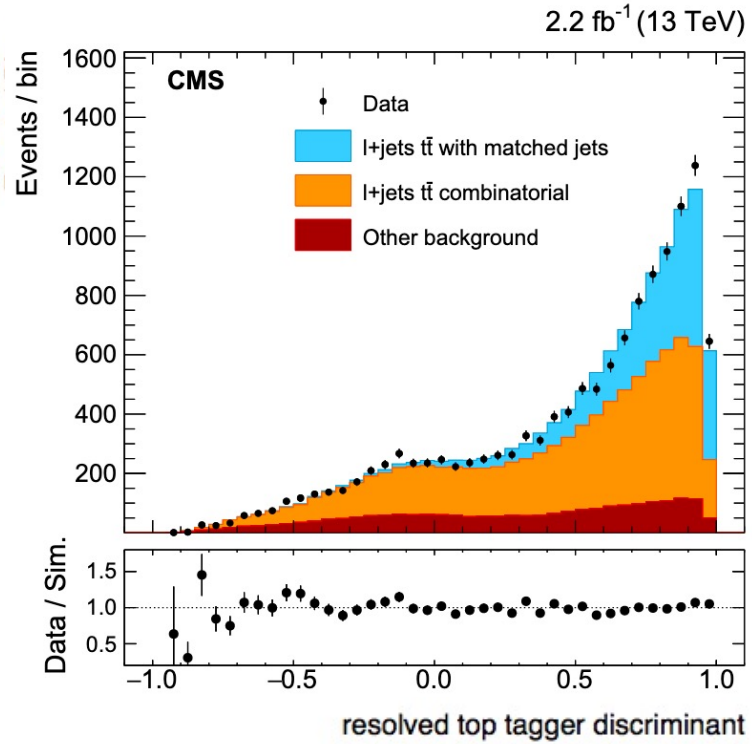
- Measure cross section: $\sigma = 12.6^{+5.8}_{-5.2}$ fb
- Limits on Yukawa couplings: $|y_t/y_t^{SM}| < 1.7$

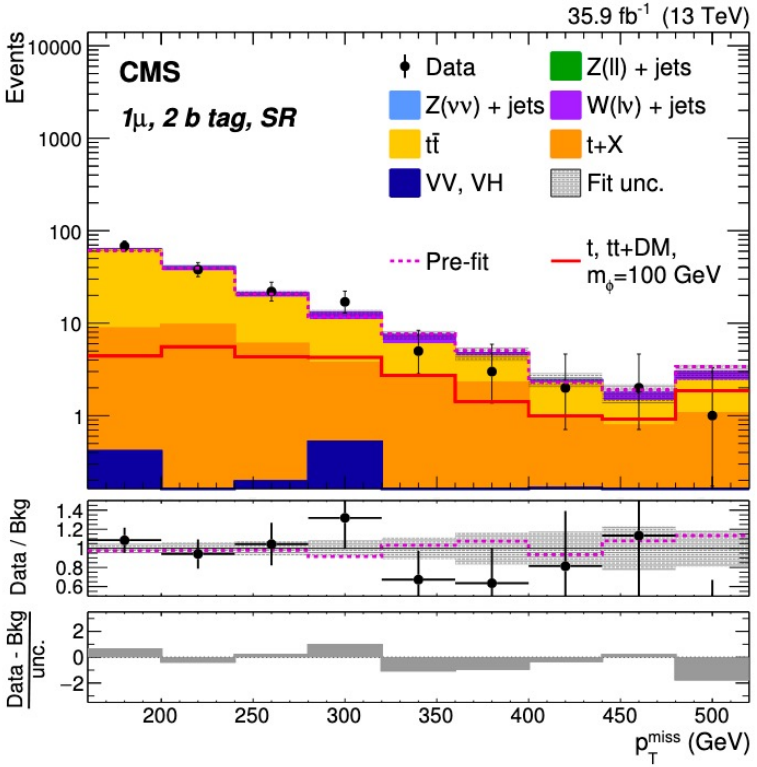
Dark Matter + ttbar

EPJC 77(2017)845, JHEP 03(2019)141

- Search for DM + ttbar(→l+jets,all hadr.)
- Shape of MET distribution
- Signature: ttbar+MET
- Top-tagging categorization
- Signal events at large MET

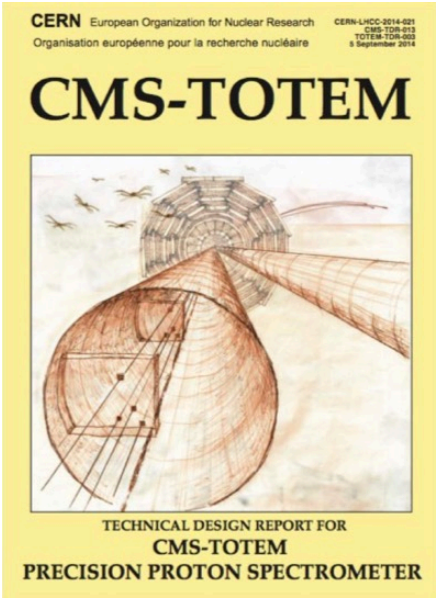




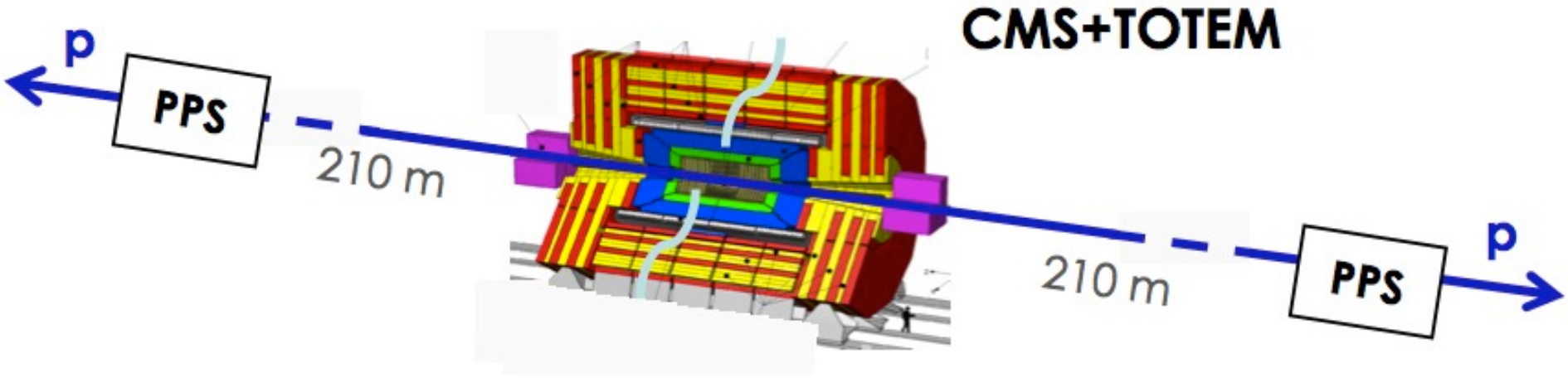


Precision Proton Spectrometer

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

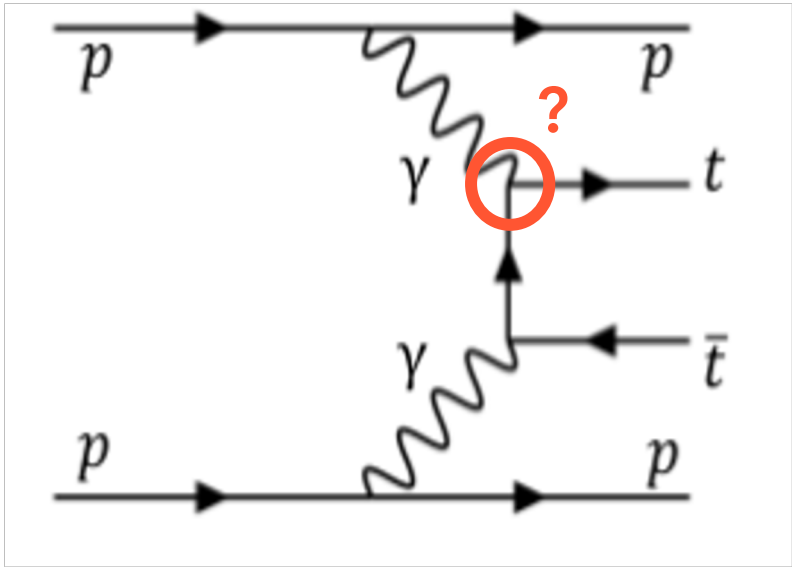


CERN-LHC-2014-021



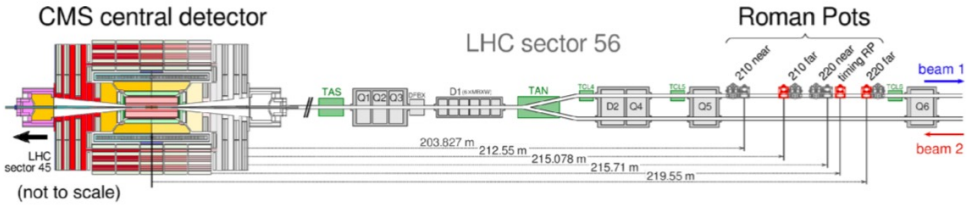
Exclusive top quark production

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



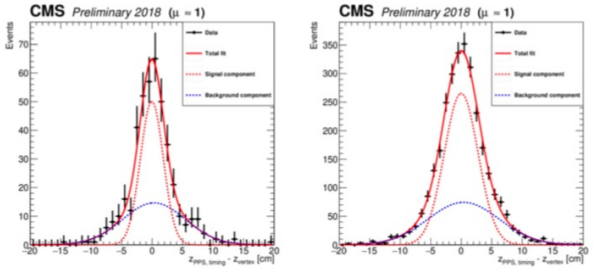
- Couplings of top quark to photons are small
- Process expected to be very sensitive to top quark anomalous couplings with the photon
- Anomalous production cross section or kinematical properties would provide hints for New Physics

Physics with forward protons



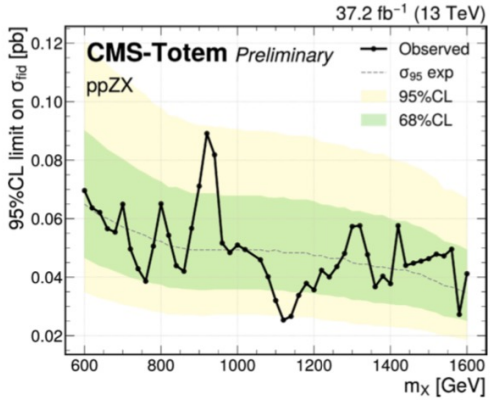
[CMS-PAS-PRO-21-001]

CT-PPS collected more than 110 fb^{-1} of data during Run-2



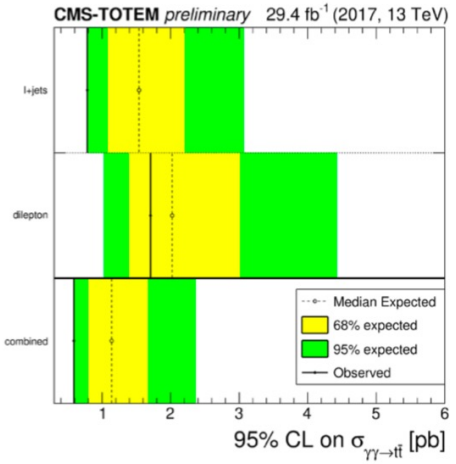
[CMS-PAS-EXO-19-009]

Search for anomalous Z/γ* central production with CT-PPS 2017 data (2% resolution on the missing mass)



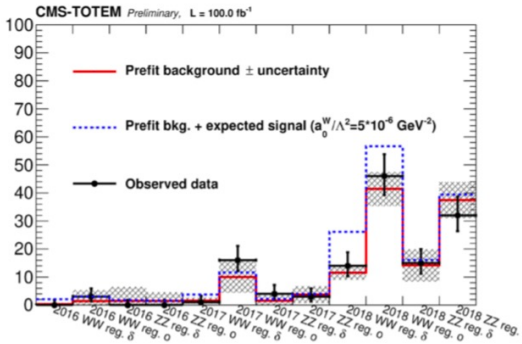
[CMS-PAS-TOP-21-007]

Search for central exclusive production of top quark-antiquark pairs in proton-proton interactions (with tagged protons)

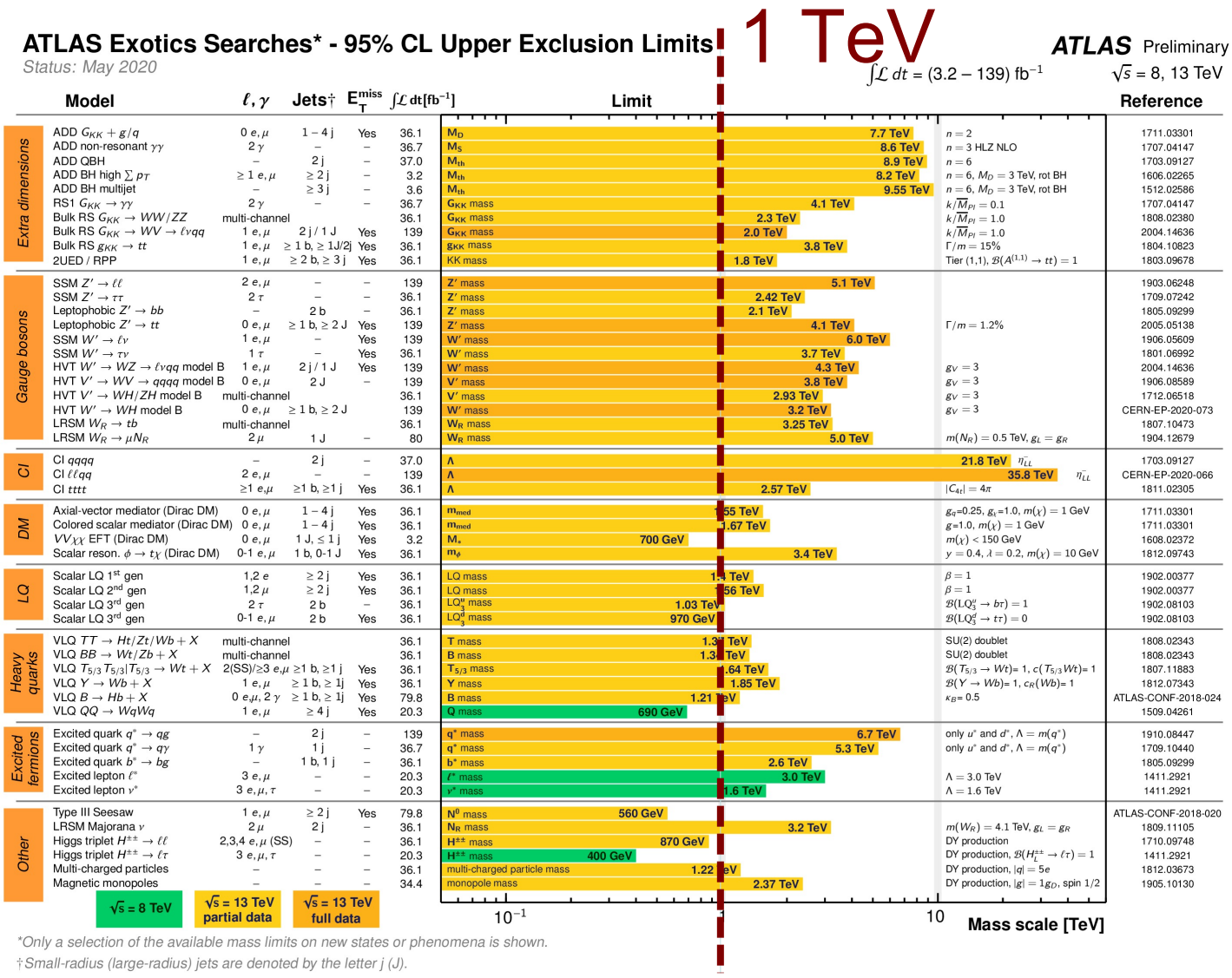


[CMS-PAS-SMP-21-014]

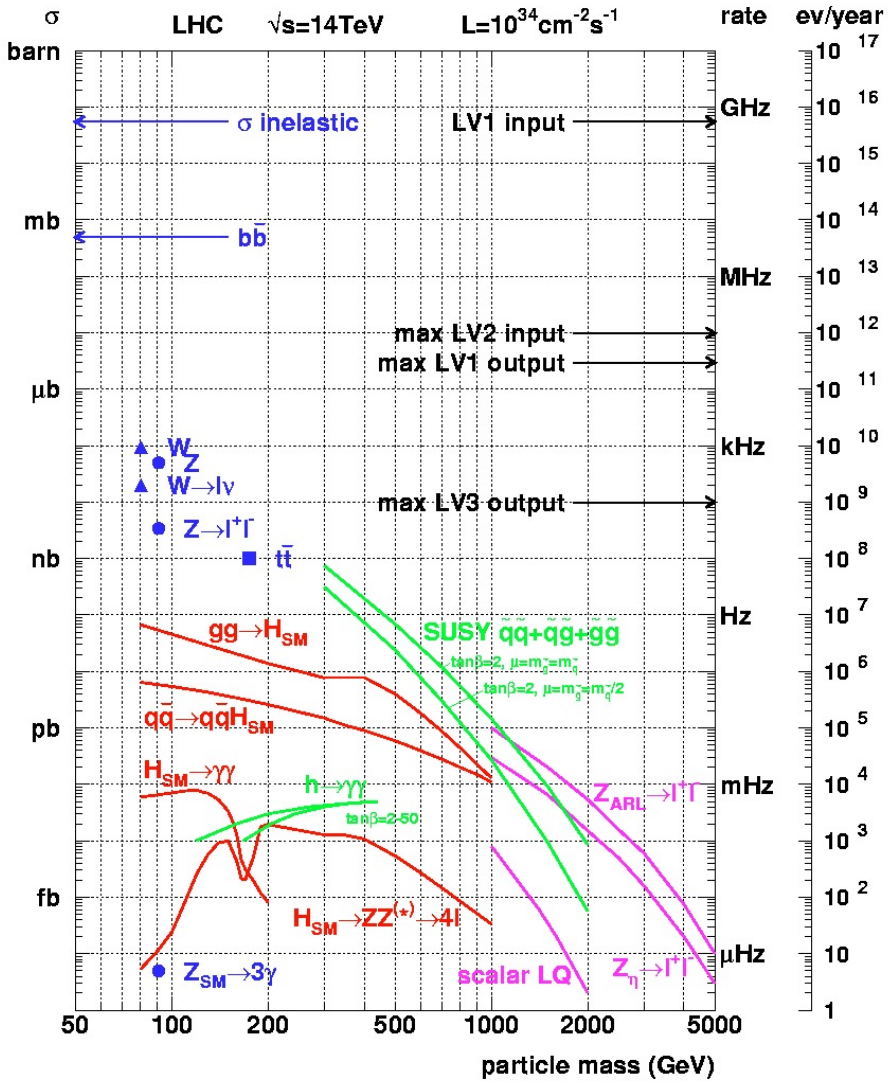
Search for anomalous high-mass γγ → WW and ZZ with forward protons



Searches for new particles



Cross sections at the LHC



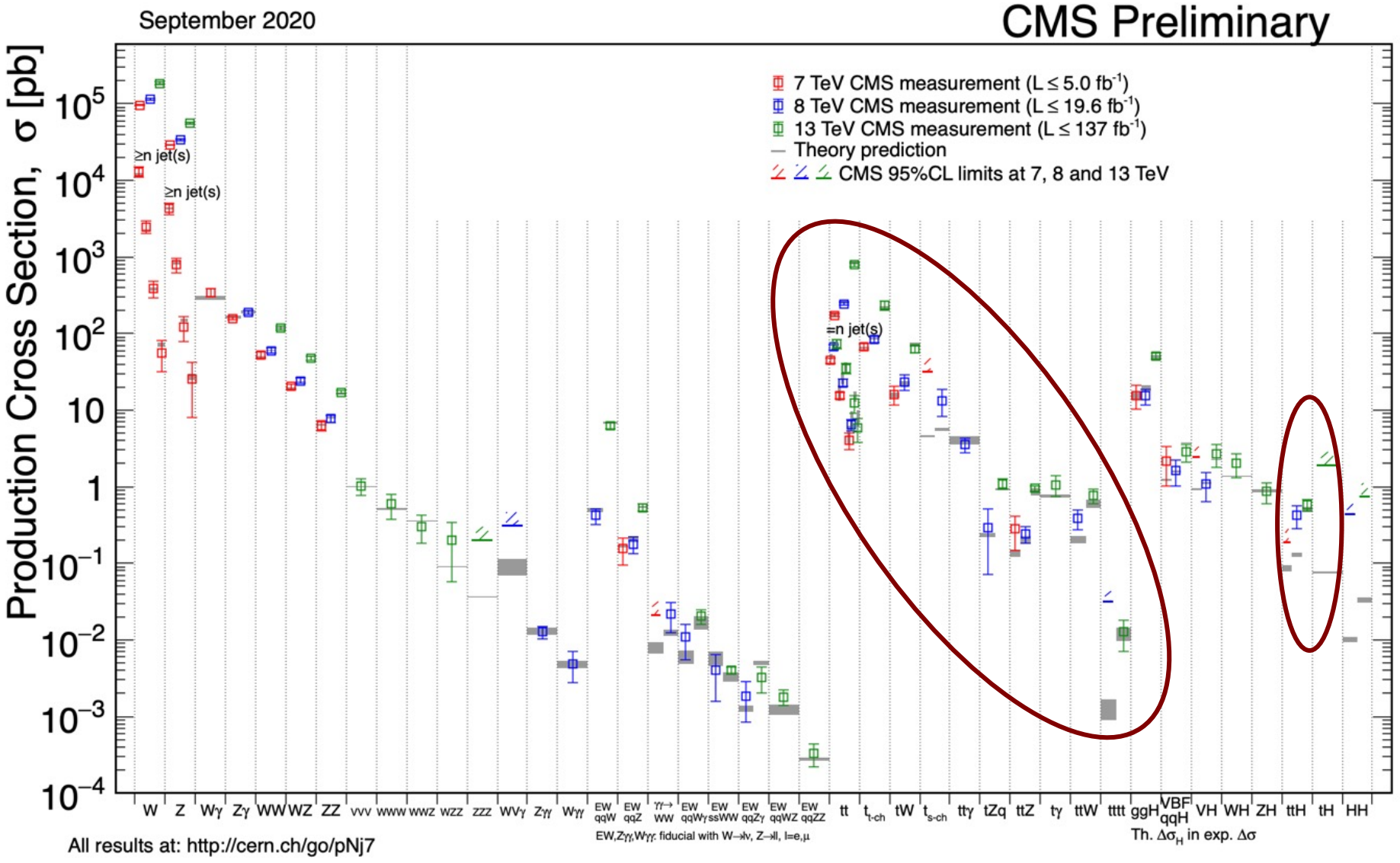
"Well known" processes, don't need to keep all of them …

New Physics!!
This is where to look

LHC: from searches to precision

- A hadron collider at full throttle
  - Reaching the energy limit
  - In Run3 (2022+), collisions at 13.6 TeV (?)
  - Large datasets (~300/fb expected in Run3)
- Moving from searches to precision measurements and rare processes
  - Top quarks and rare decays
  - Higgs couplings and rare decays
  - Anomalous couplings etc.
- Preparing for High-Luminosity (2028 and beyond) with improved detectors
  - Several technological challenges ahead as complexity increases

Rich and extensive set of results



Summary

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

Exotic searches