Probing the SM: Top quarks and beyond

Michele Gallinaro

LIP Lisbon

March 26, 2024

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

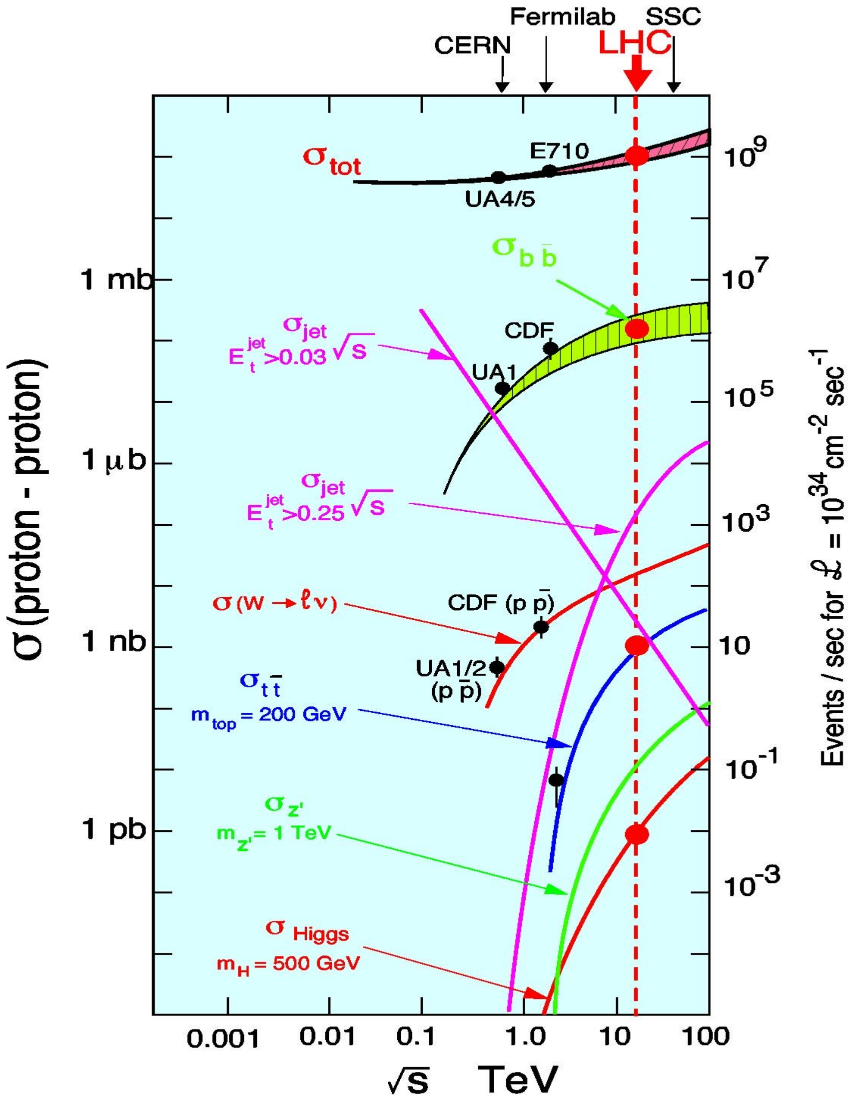
Theory cross sections: TeV vs LHC

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	$+22.7(2.4\%)$ $-33.9(3.6\%)$	$+16.2(1.7\%)$ $-17.8(1.9\%)$

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

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

Number of observed events

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

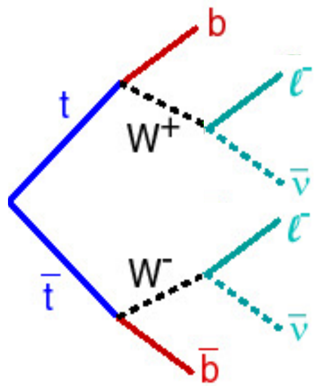
$$\sigma_{t\bar{t}} = \frac{N_{obs} - N_{bgd}}{\varepsilon_{t\bar{t}} \cdot \int L dt}$$

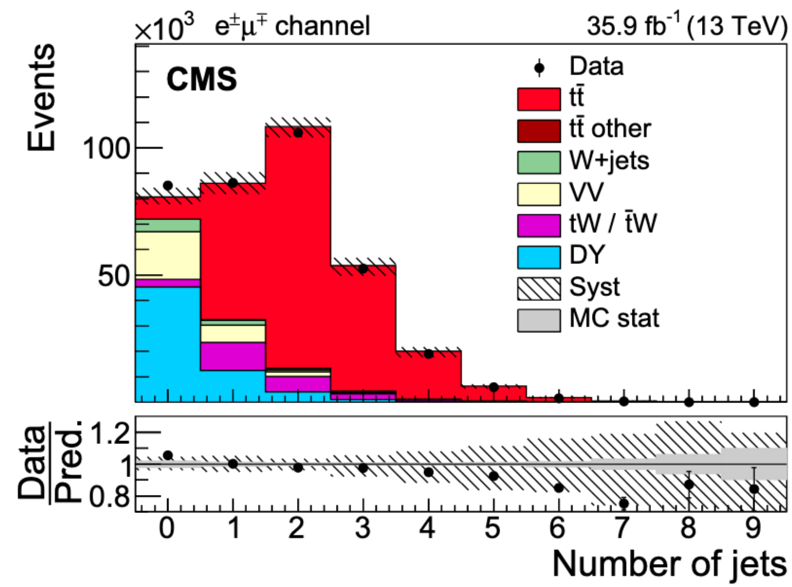
Acceptance *(experimental: detector, efficiencies)*

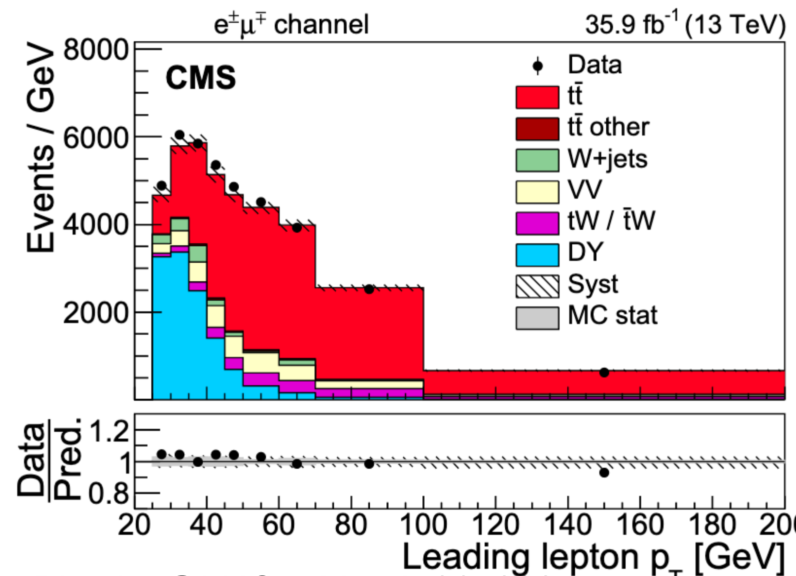
Luminosity *(determined by amount of data, accelerator, triggers, etc)*

Dilepton channel

EPJC 79(2019)368





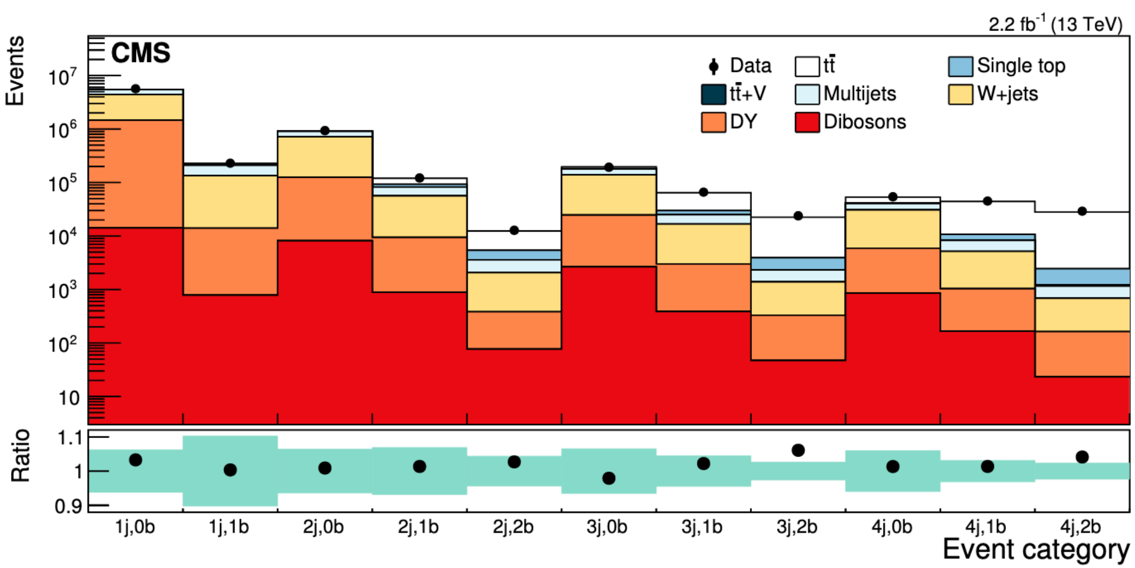


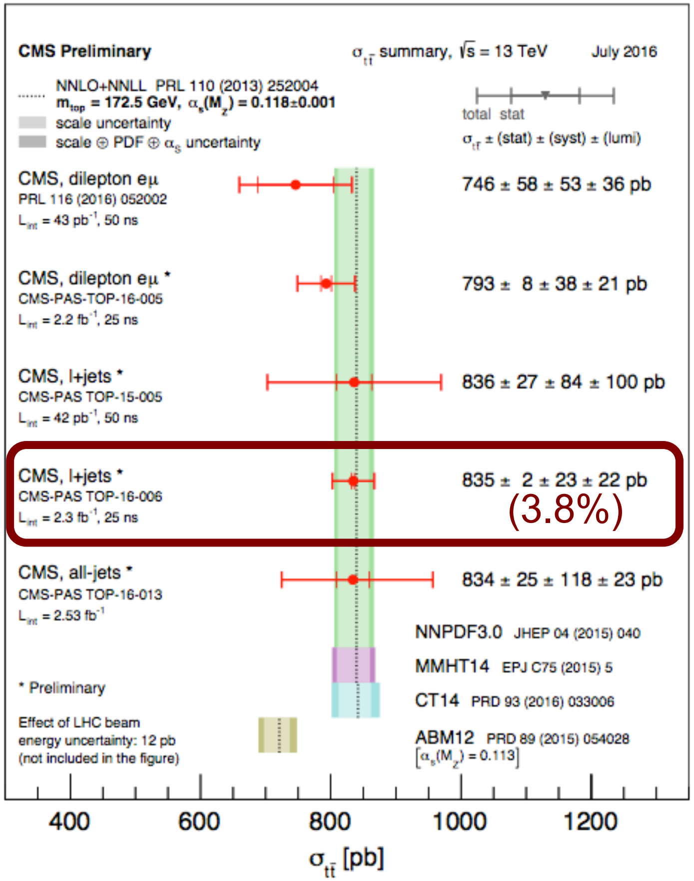
- Branching ratio (BR) ~5%
- Background: small
- Clean final state
  - two leptons + ≥2 jets + MET
  - kinematic variables
- Signal visible w/without b-tagging
- Main systematics: JES, lepton ID, (pileup, b-tag, signal modeling)

Cross section: multi-dimensional fit

JHEP 09(2017)051

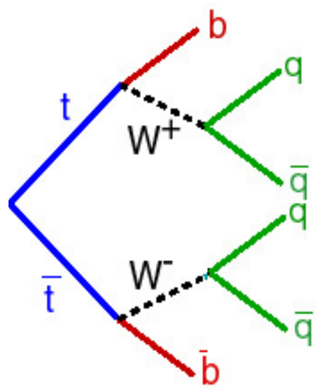
- Lepton+jet final state
- Keep selection as inclusive as possible
- Categorize events according to (b-) jet multiplicity
  - high-purity vs background dominated
  - Constrain systematics (JES, ISR/FSR, modeling, etc)
- Combined fit of M_{lb} to signal and backgrounds
- Precise cross section measurement

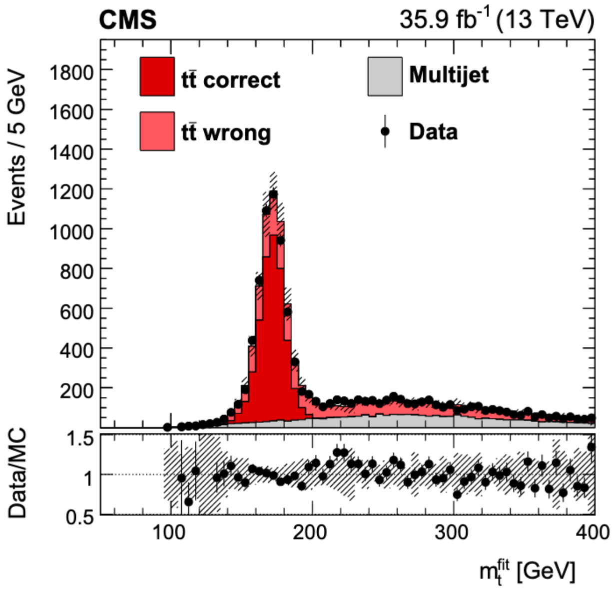


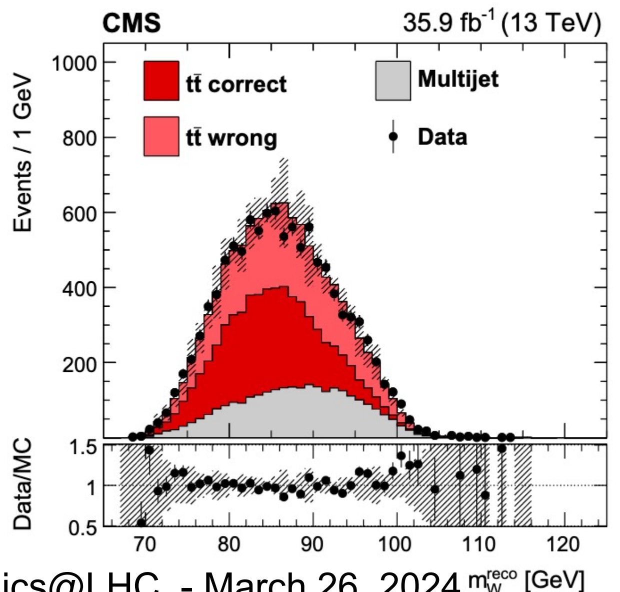


All hadronic

EPJC 79(2019)313





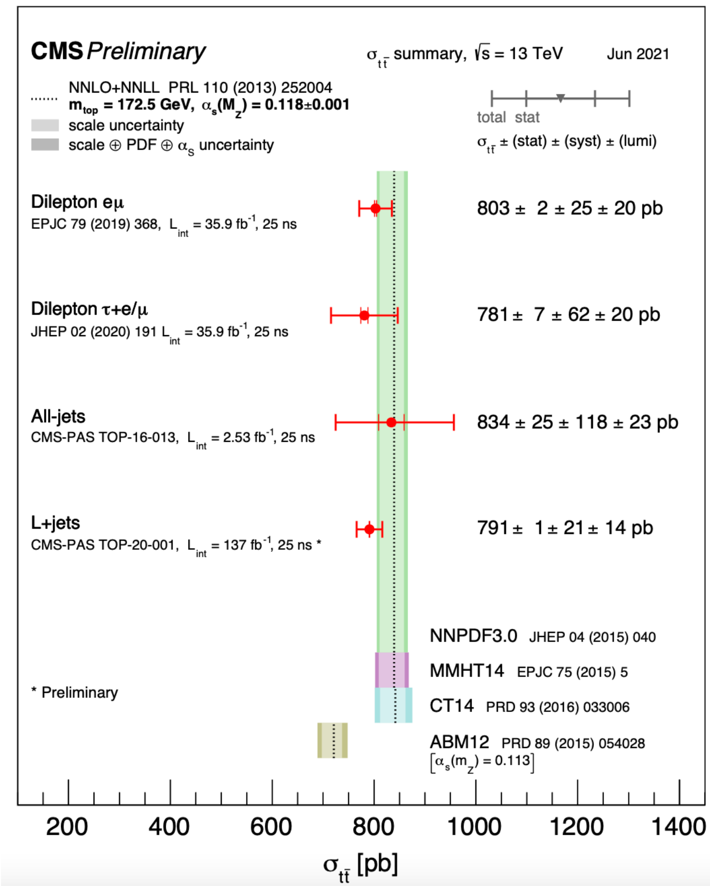


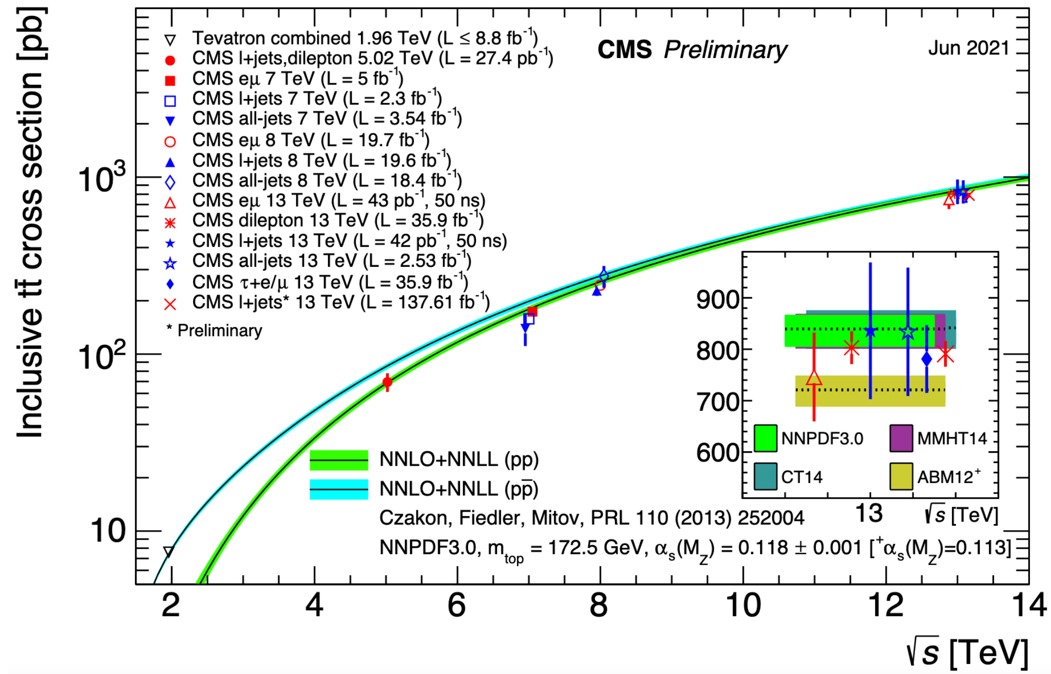
- BR ~46%
- Background: large

- Selection:
  - ≥6 jets + kinematical selection
  - require 2 b-tags
- Main backgrounds:
  - hadronic multi-jet
  - same selection without b-tag

Cross sections

±4%





⇒measurements challenging theory

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	$+22.7(2.4\%)$ $-33.9(3.6\%)$	$+16.2(1.7\%)$ $-17.8(1.9\%)$

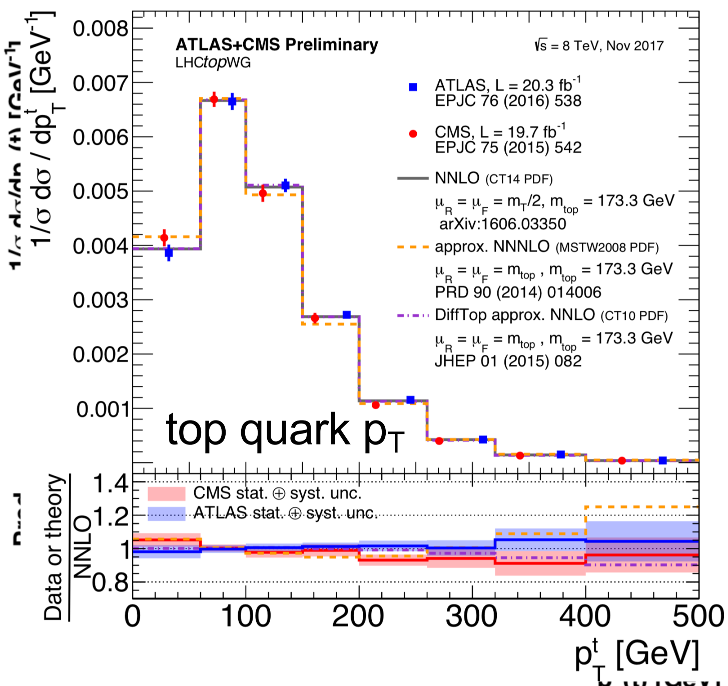
±3-5%

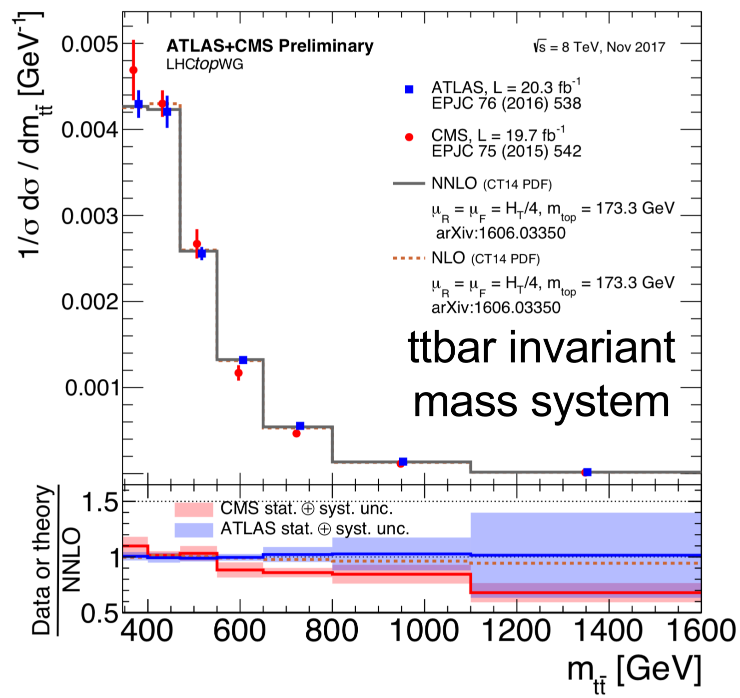
Differential cross section

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

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

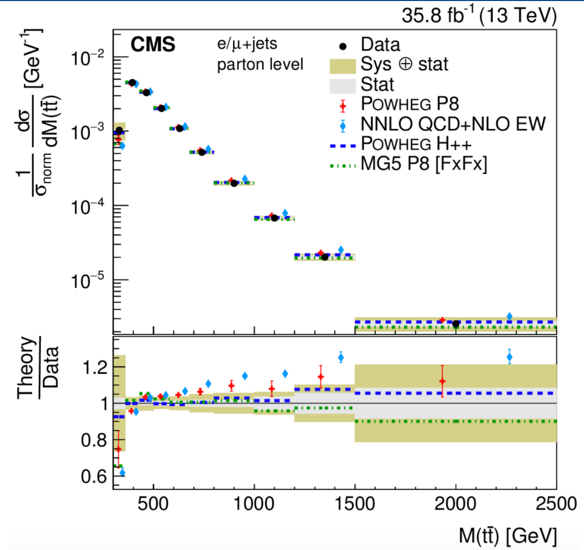
- Measure differential cross section
  - Test perturbative QCD
  - Test BSM scenarios (Z' decays, etc)
- Cross sections measured as a function of p_T, η, invariant mass of the final state leptons, top quarks, ttbar system, etc.
- Good agreement with expectations



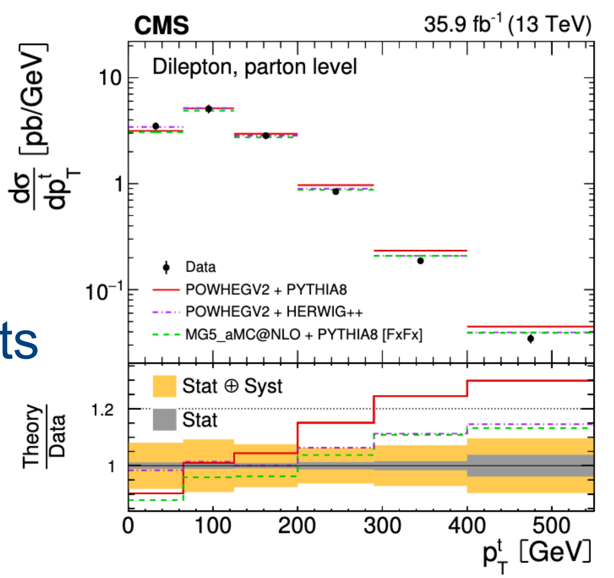


Differential cross section (cont.)

PRD 97(2018)112003, JHEP 02(2019)149



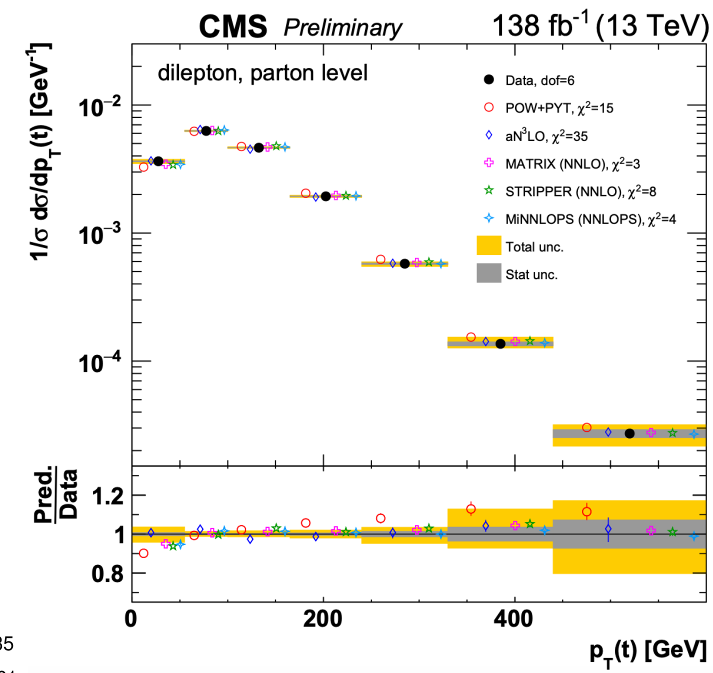
- Correct for detector effects and acceptances
- Softer top p_T (CMS), agreement in ATLAS at high p_T
  - Due to momentum reshuffling, P.Nason, cern.ch/event/301787
  - FSR shower changes mass of final state partons. light partons can build sizeable mass, and t/tbar do not radiate
  - short term solution: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

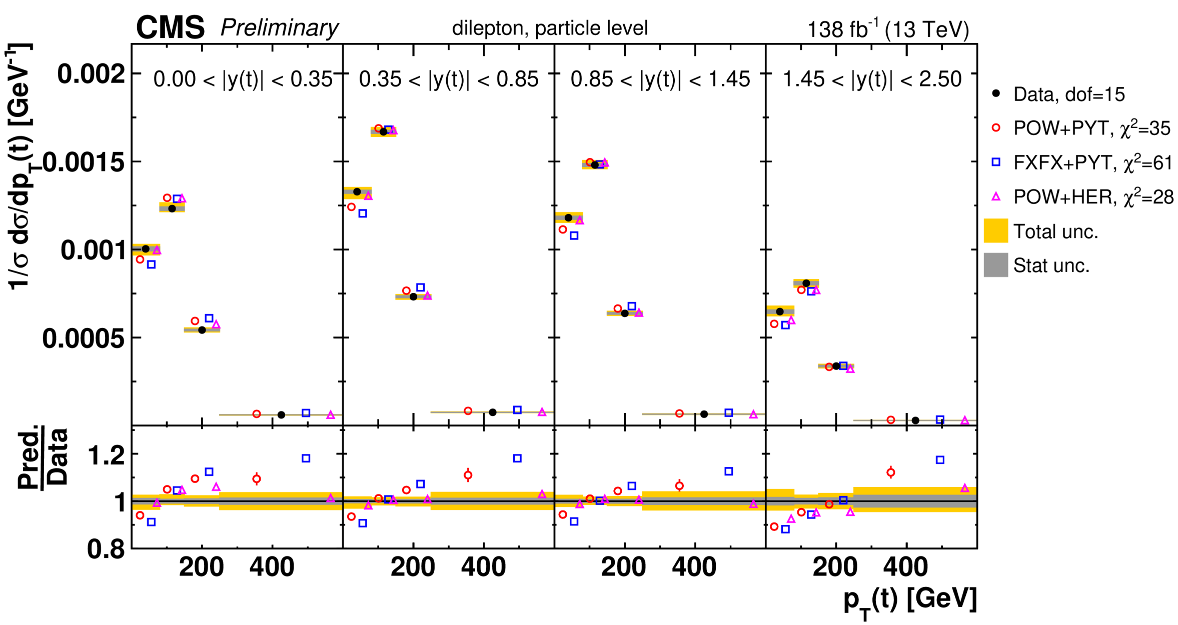


Multi-differential cross section

TOP-20-006

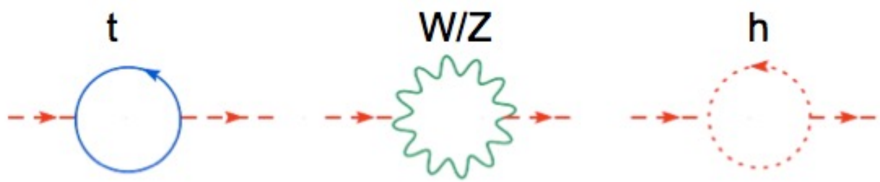
- Multi-differential cross section as a function of top and ttbar kinematics, decay products and additional jets
- Sensitive to SM parameters m_t and α_S
- Total uncertainty reduced by a factor of ~2 wrt previous analyses





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?

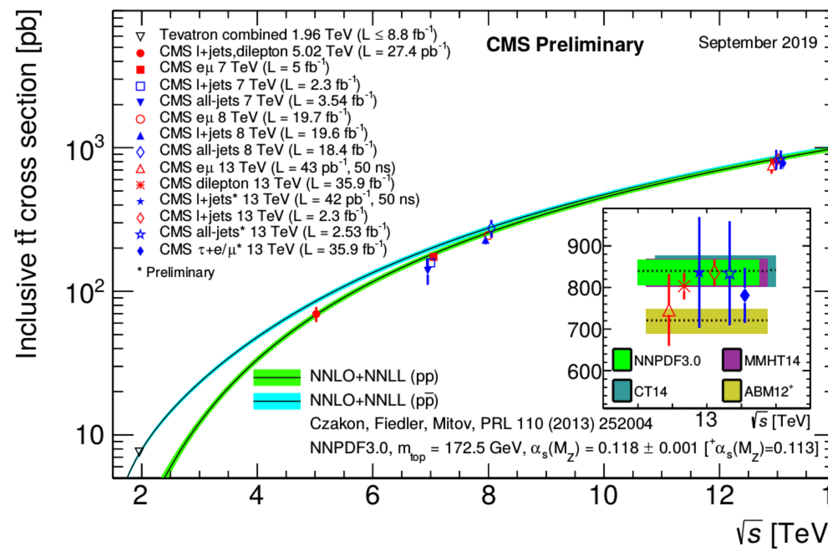
Solutions:

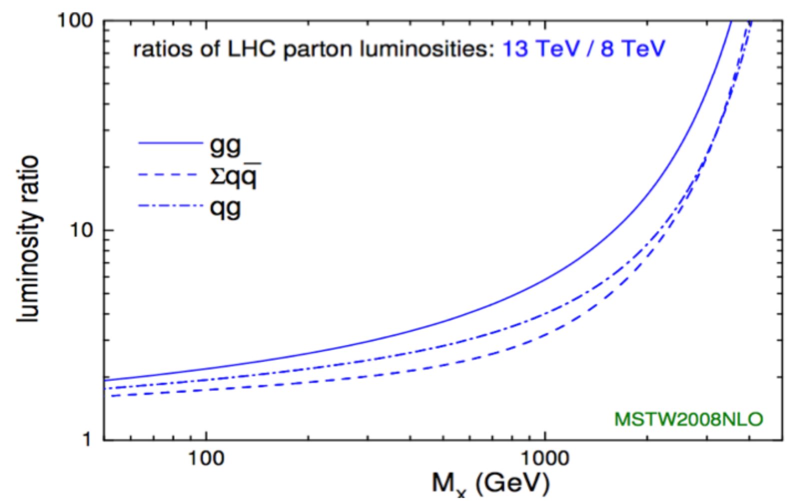
- Naturalness: There is no problem
- Weakly-coupled model at TeV scale
  - New particles to cancel SM divergences
  - Top partners: new scalar/vectors coupled to top, exotic top decays
- Strongly-coupled model at TeV scale
  - ttbar resonances, bound states, 4-top production, etc.
- New space-time structure
  - Introduce extra space dimensions to lower Planck scale cutoff to ~1TeV
  - KK excitations

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?

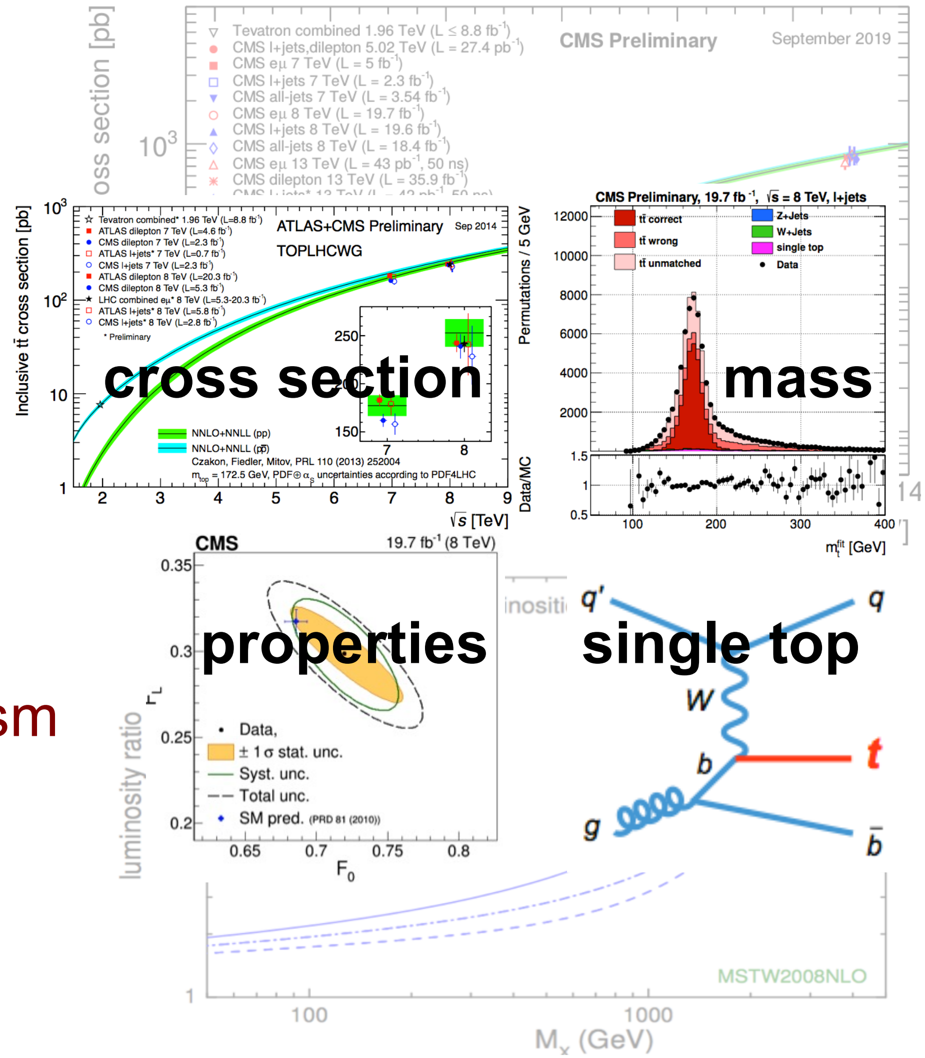




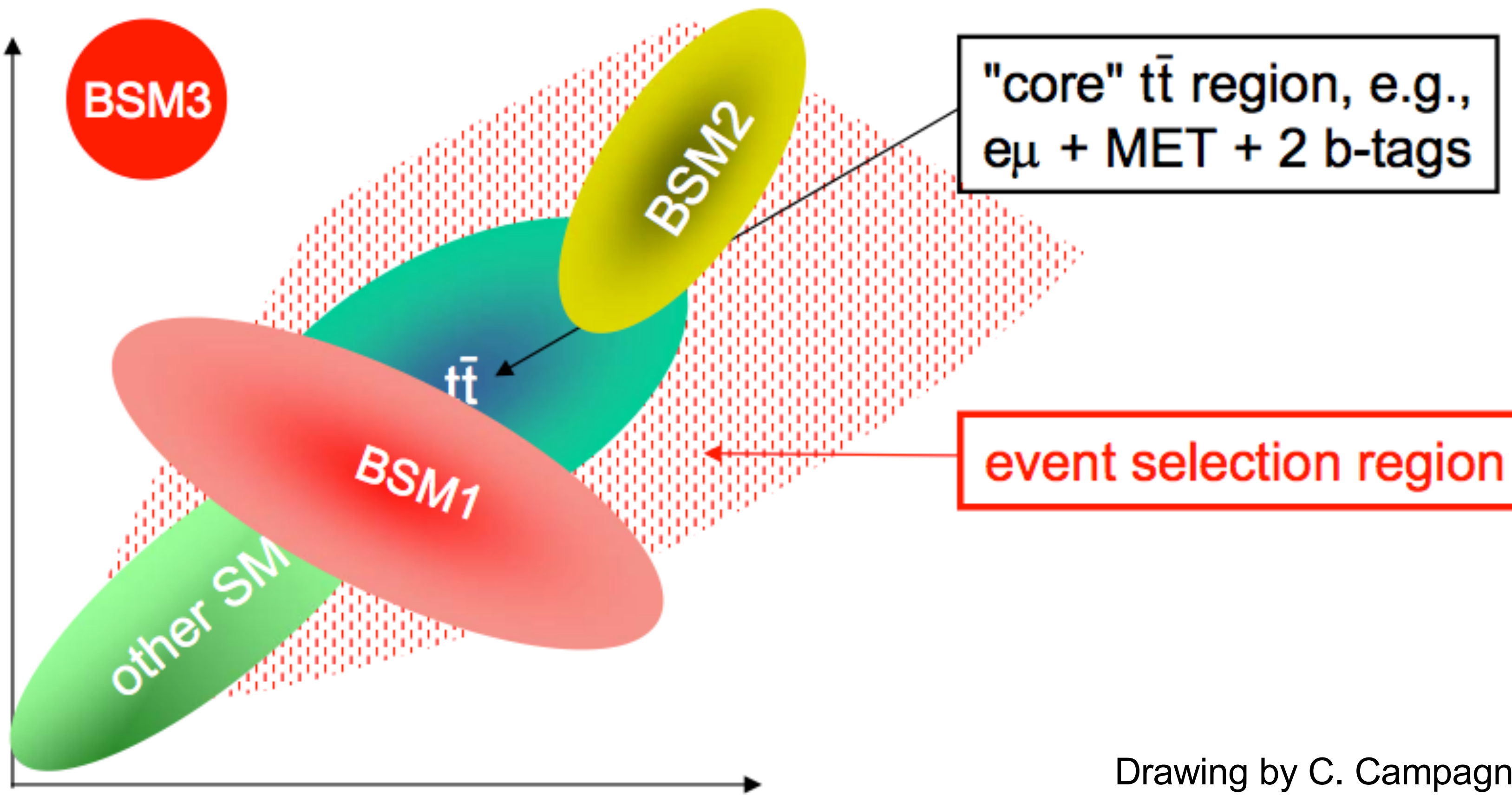
Role of top quark physics

- 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?

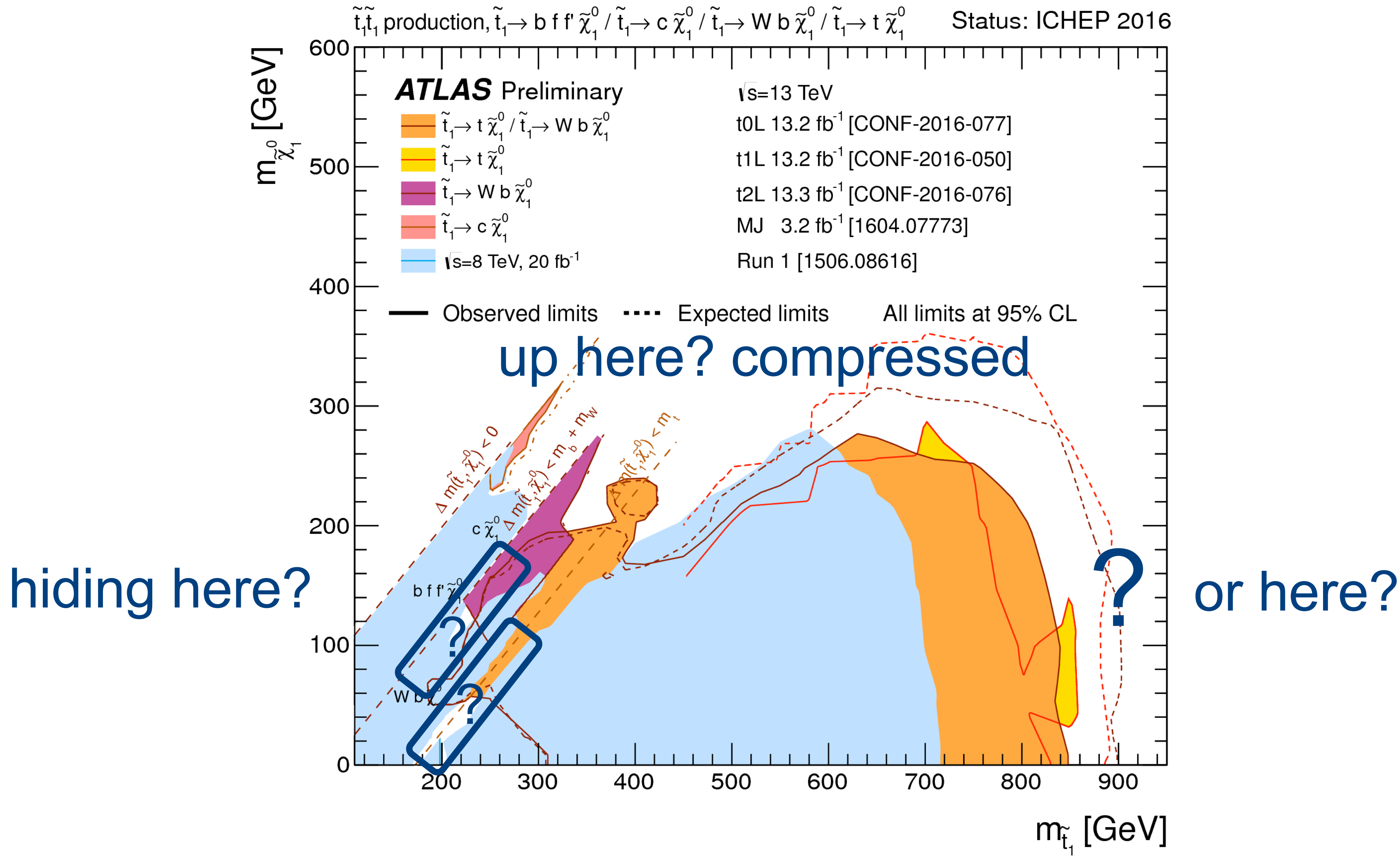


Study characteristics



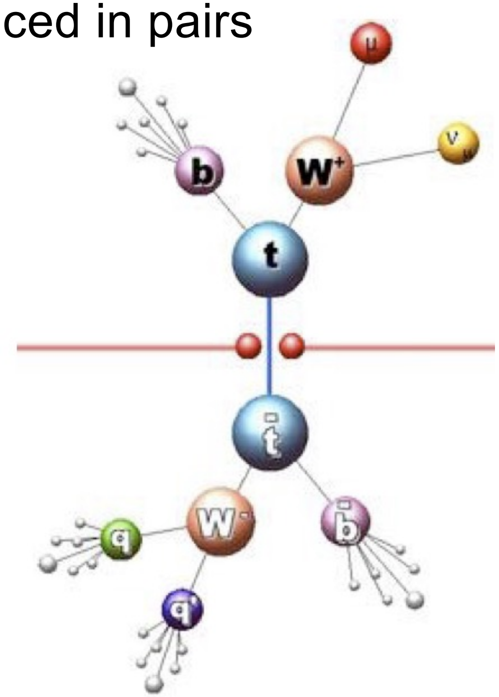
Drawing by C. Campagnari

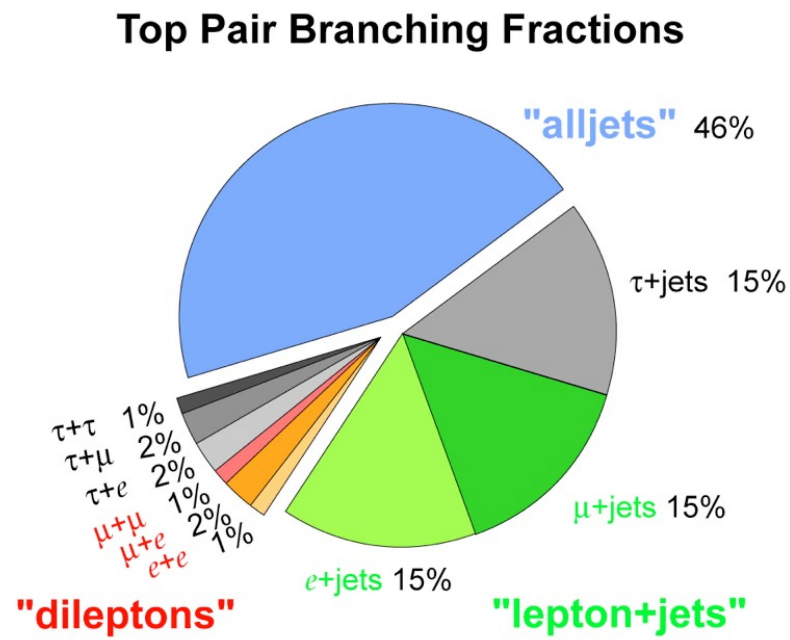
Regions hard to explore



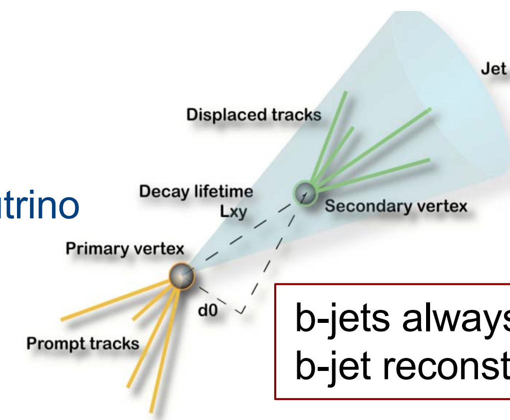
Top quark decays

Top quarks (mostly) produced in pairs





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



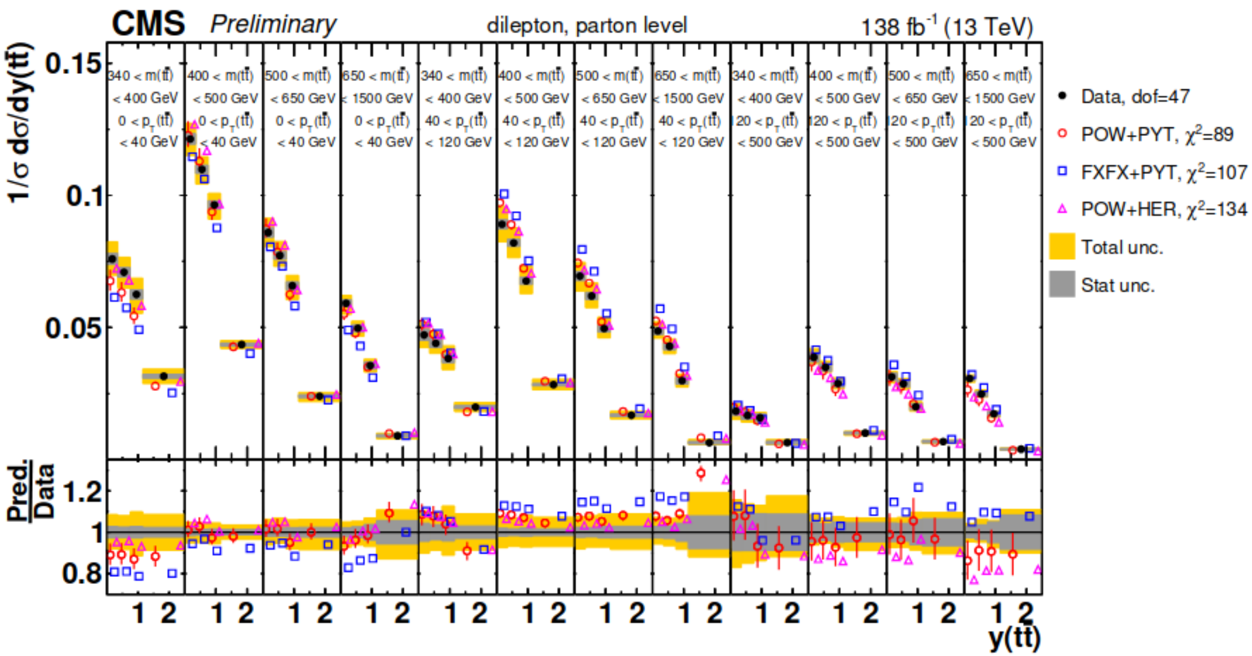
b-jets always present
b-jet reconstruction plays important role

Differential cross section

CMS-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

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

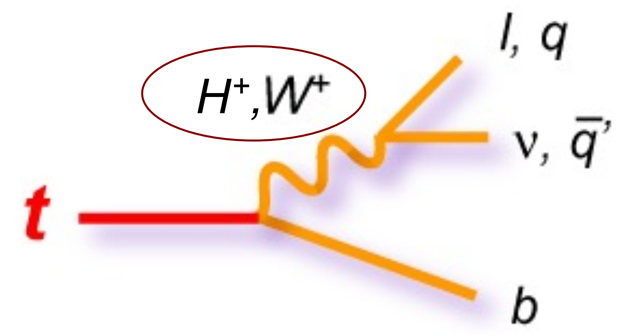


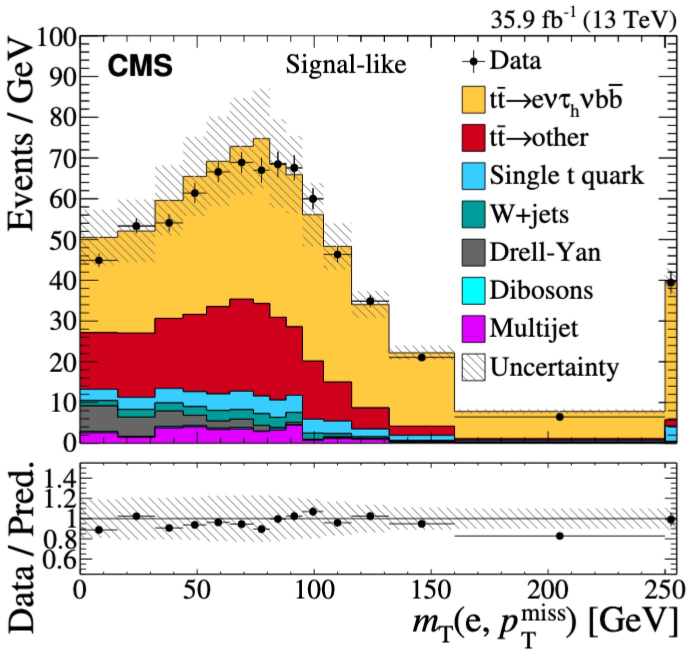
Probing the Wtb vertex

Dileptons with taus

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

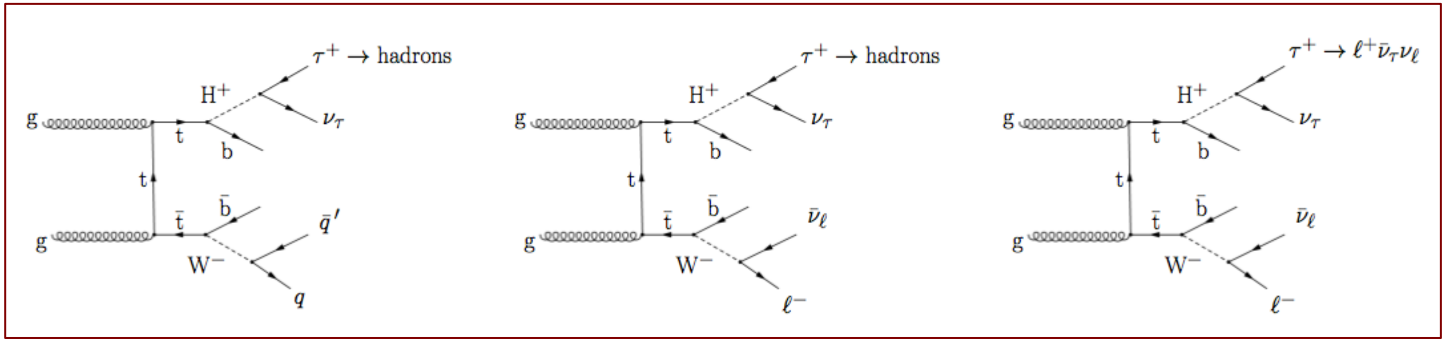
Channel	Signature	BR
Dilepton(e/μ)	*ee*,$\mu\mu$,*e*μ + 2*b*-jets	4/81
Single lepton	*e*,μ + jets + 2*b*-jets	24/81
All-hadronic	jets + 2*b*-jets	36/81
Tau dilepton	*e*τ, $\mu\tau$ +2 *b*-jets	4/81
Tau+jets	τ + jets + 2*b*-jets	12/81



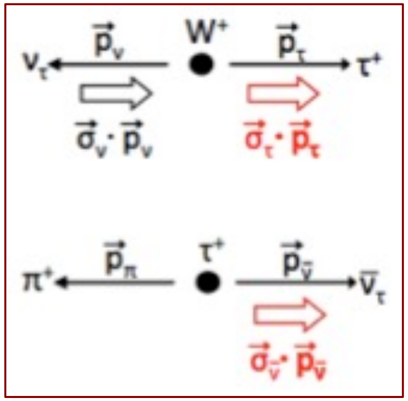


- If top quark plays special role in EWK symmetry breaking, couplings to W may change
- Charged Higgs may alter coupling to W
- Search for final states with taus: charged Higgs

Looking at tau decays

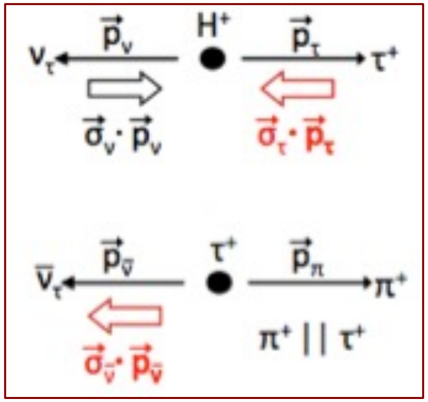


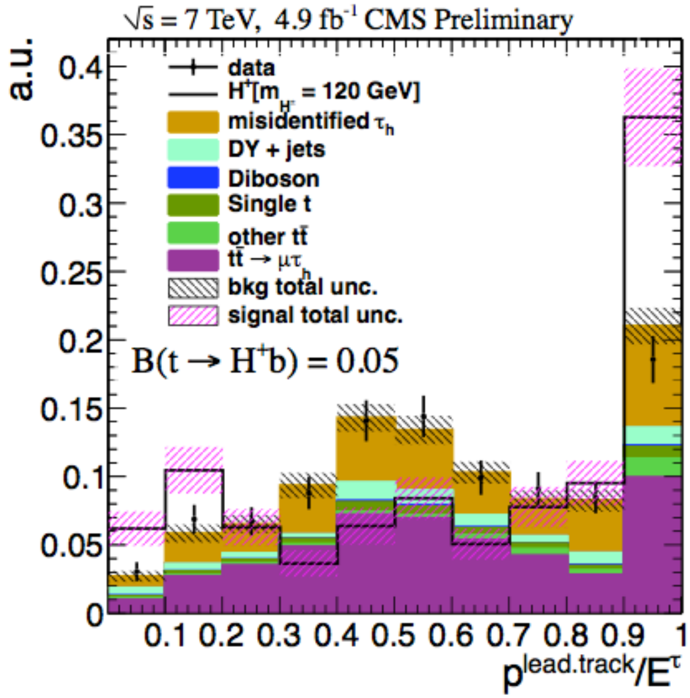
SM



vs

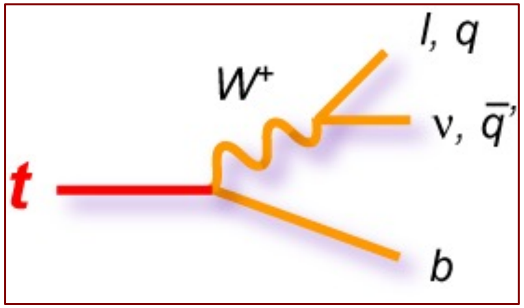
BSM



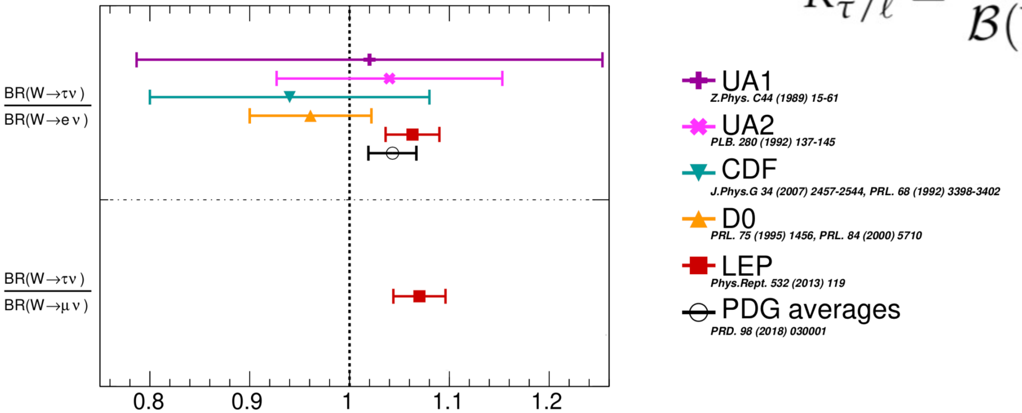


W boson branching fractions

- 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



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



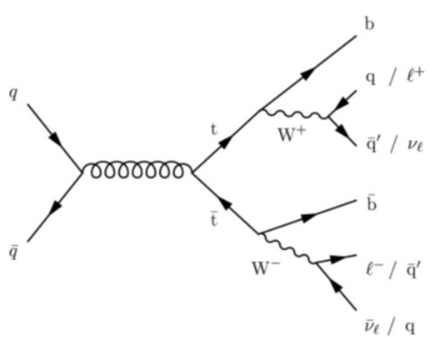
Lepton Flavour Universality

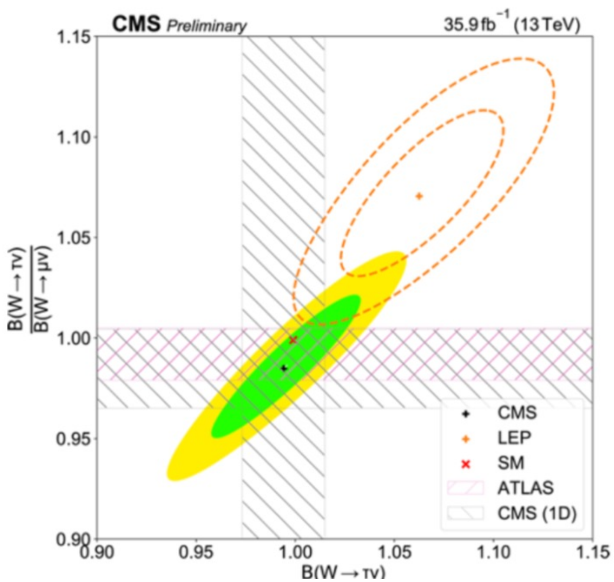
Resolving an old discrepancy from LEP

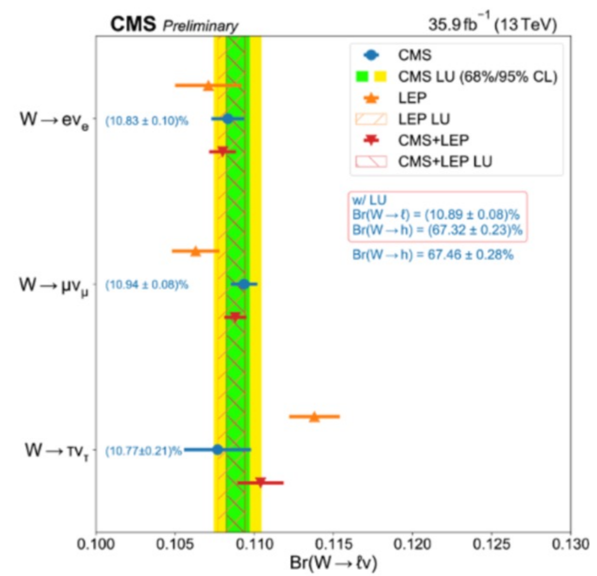
Strategy :
Use W bosons from top quarks

Many more Ws than at LEP

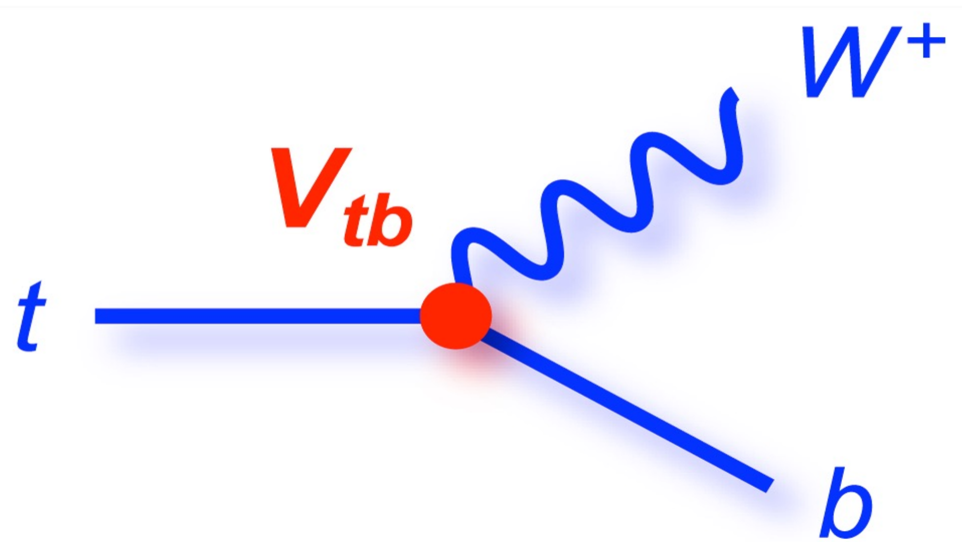
	CMS	LEP
$\mathcal{B}(W \to e\overline{\nu}_e)$	$(10.83 \pm 0.01 \pm 0.10)\%$	$(10.71 \pm 0.14 \pm 0.07)\ \%$
$\mathcal{B}(W \to \mu\overline{\nu}_\mu)$	$(10.94 \pm 0.01 \pm 0.08)\%$	$(10.63 \pm 0.13 \pm 0.07)\ \%$
$\mathcal{B}(W \to \tau\overline{\nu}_\tau)$	$(10.77 \pm 0.05 \pm 0.21)\%$	$(11.38 \pm 0.17 \pm 0.11)\ \%$
$\mathcal{B}(W \to h)$	$(67.46 \pm 0.04 \pm 0.28)\%$	
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?



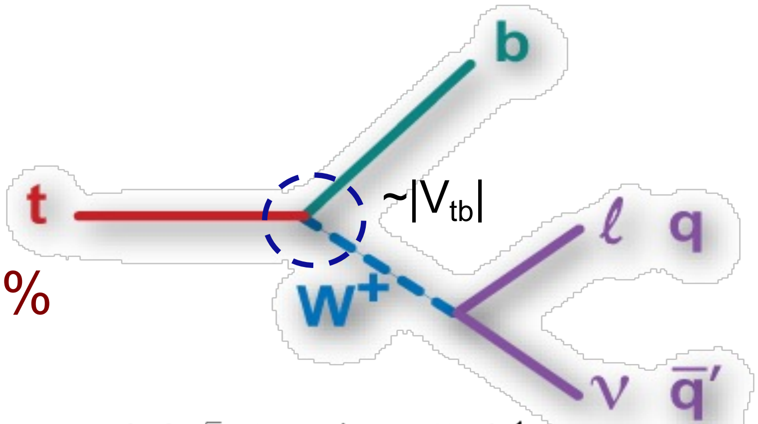
- almost always $t \rightarrow Wb$ (i.e. $V_{tb} \sim 1$)
- lifetime is short, and it decays before hadronizing
- the W is real:
  - can decay $W \rightarrow l\nu$ ($l = e, \mu, \tau$), BR~1/9 per lepton
  - can decay $W \rightarrow qq$, BR~2/3

Cross section in the R measurement

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

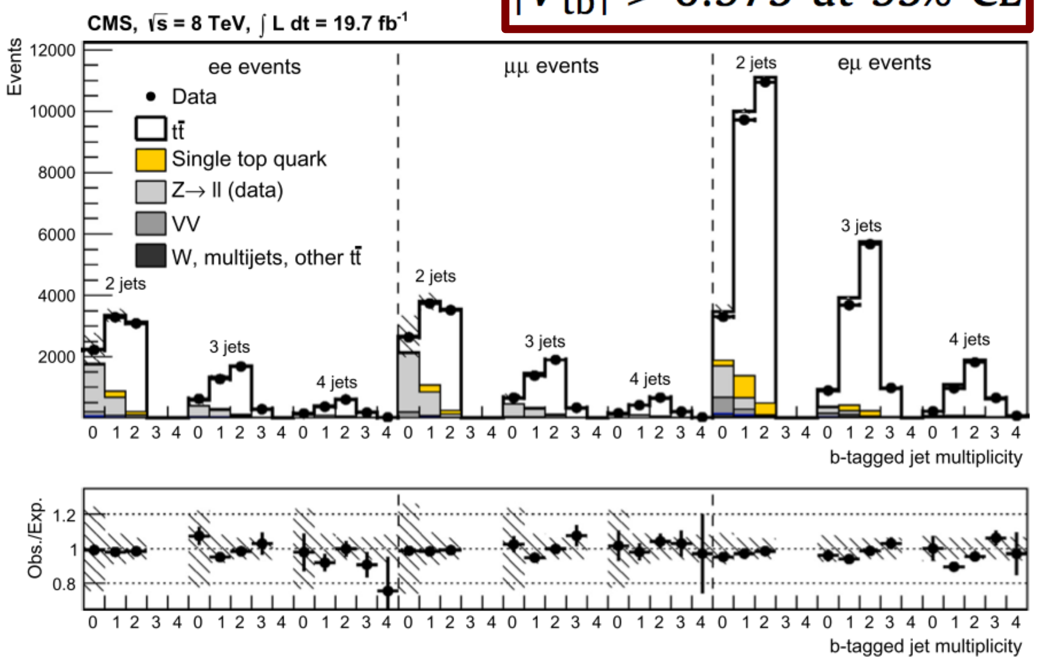
- Measure R:
- Dilepton final state

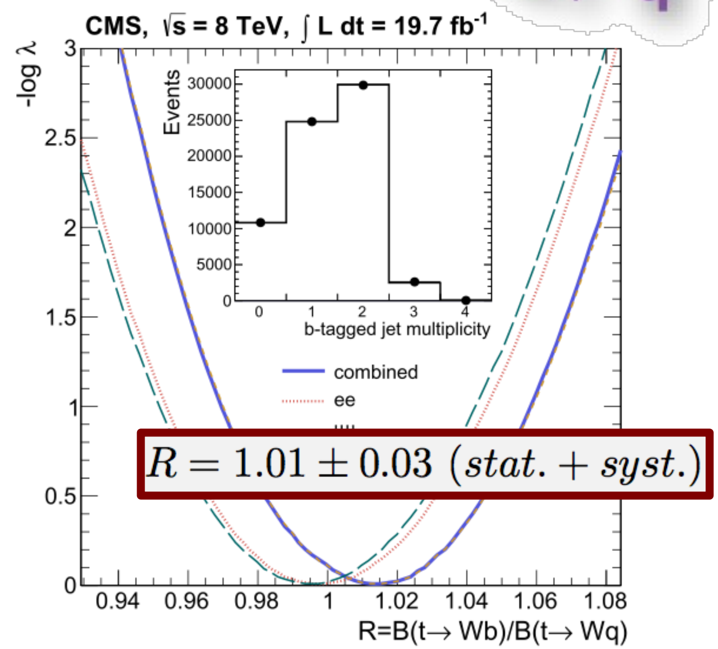
$$R \equiv \frac{BR(t \to Wb)}{BR(t \to Wq)} \approx |V_{tb}|^2$$



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

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



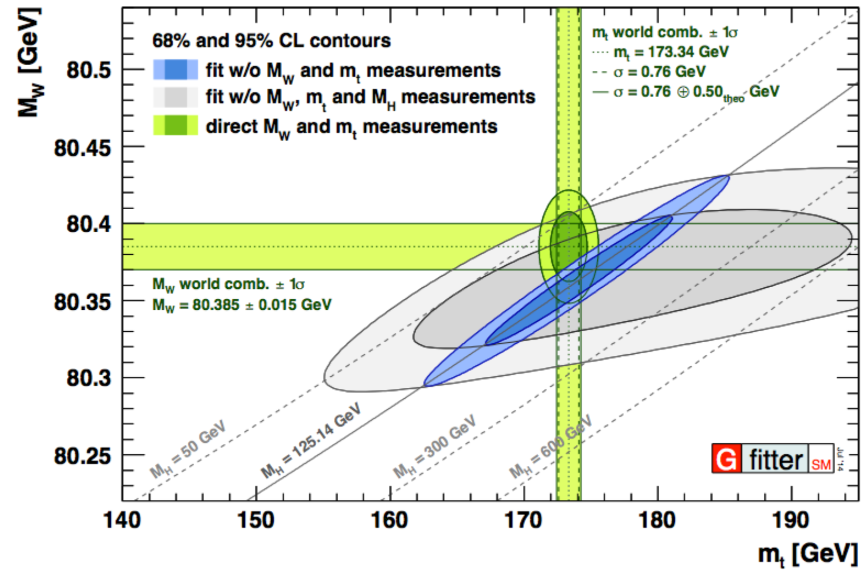


$$\boxed{R = 1.01 \pm 0.03\ (stat. + syst.)}$$

Top quark mass

- Top quark mass is a fundamental parameter of the SM

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



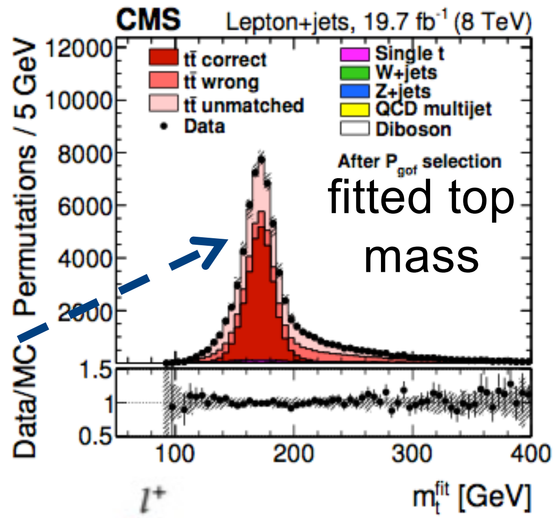
- Precise measurement needed for checking consistency of the SM

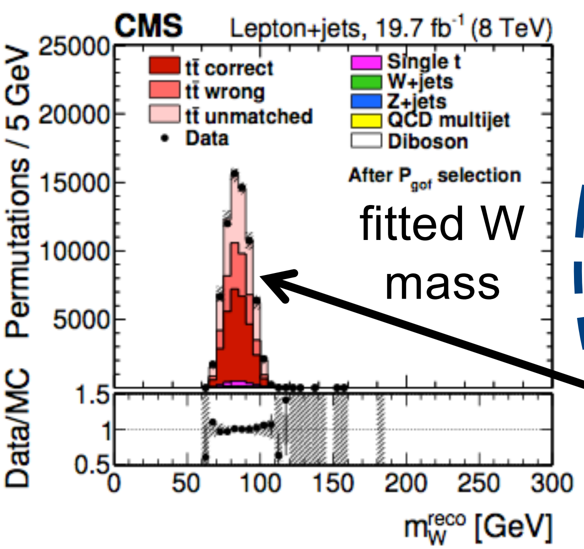
- Top is the only fermion with the mass of the order of EWSB scale
- Discovered Higgs boson fits well with precise determinations of m_W and m_{top}
- Other properties (EWK coupling, production asymmetries, etc.) are predicted by SM
- Precise measurements could reveal breakdown of SM

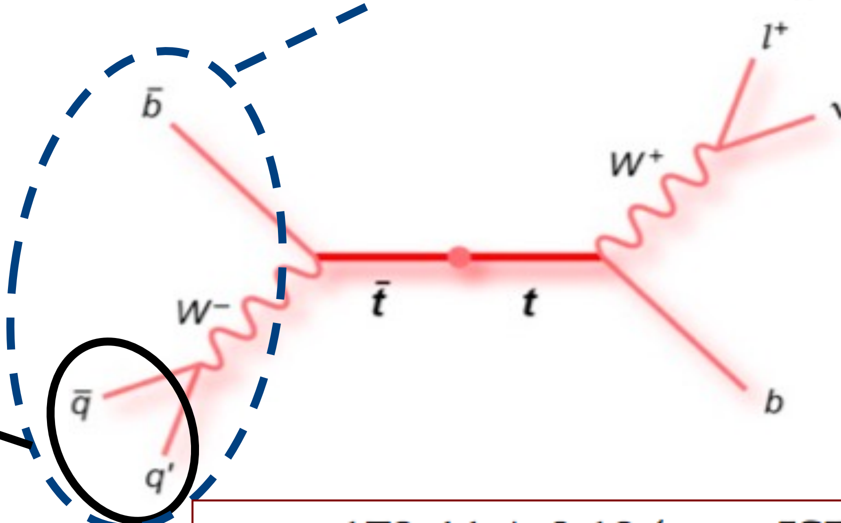
Precise mass measurement

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







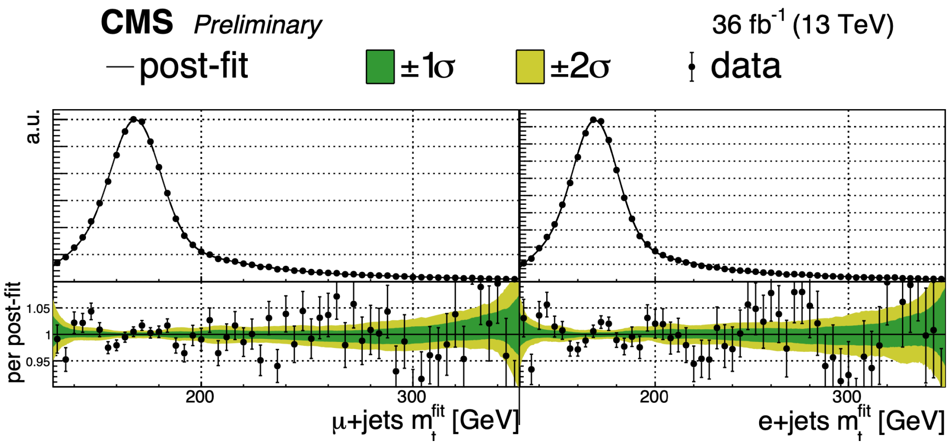
±0.3%

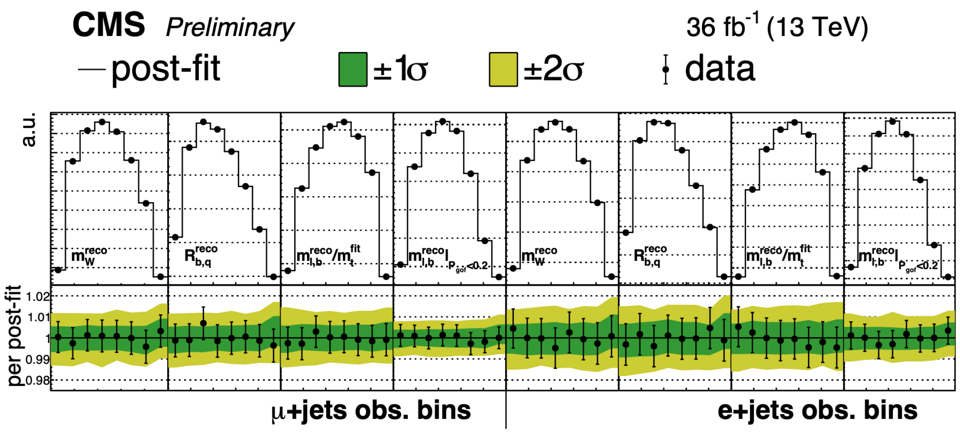
$$m_t = 172.44 \pm 0.13\,(\text{stat+JSF}) \pm 0.47\,(\text{syst})\ \text{GeV}$$

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





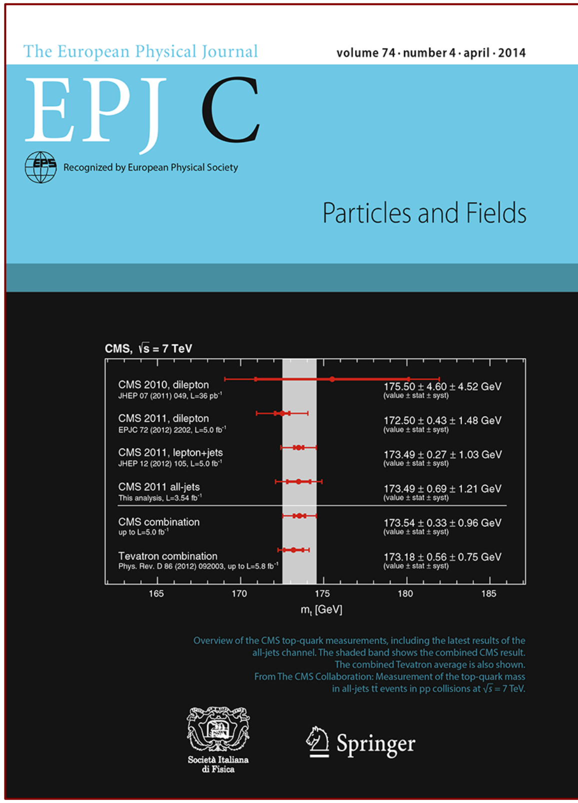
$$\boxed{m_t = 171.77 \pm 0.38\ \mathrm{GeV}}$$

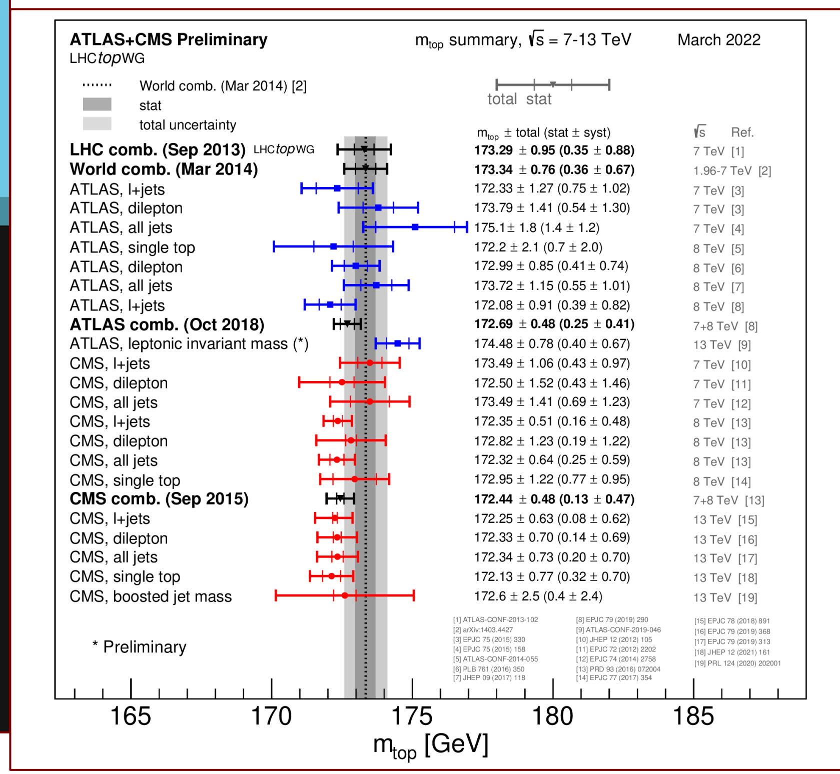
±0.22%

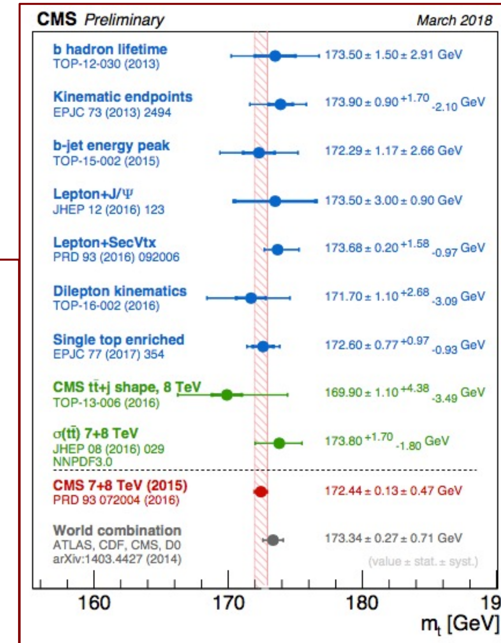
⇒ most precise measurement to date

Top quark mass results

- accurate (~0.3%) measurement



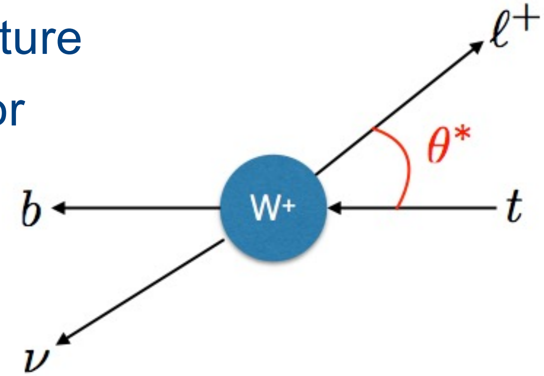


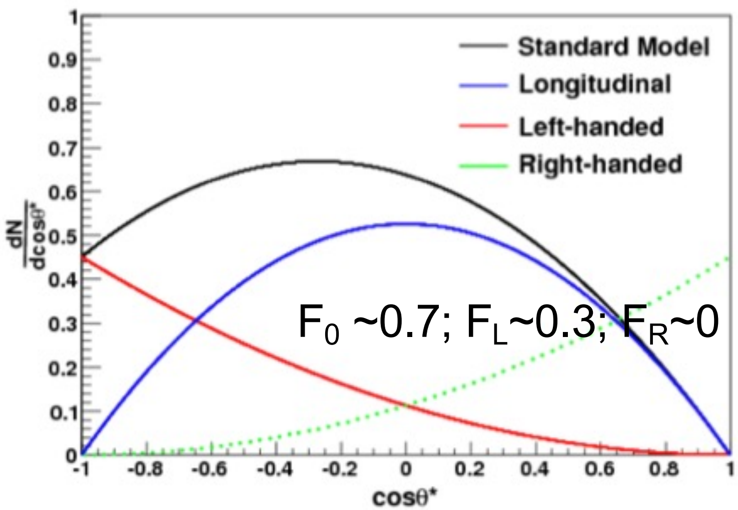


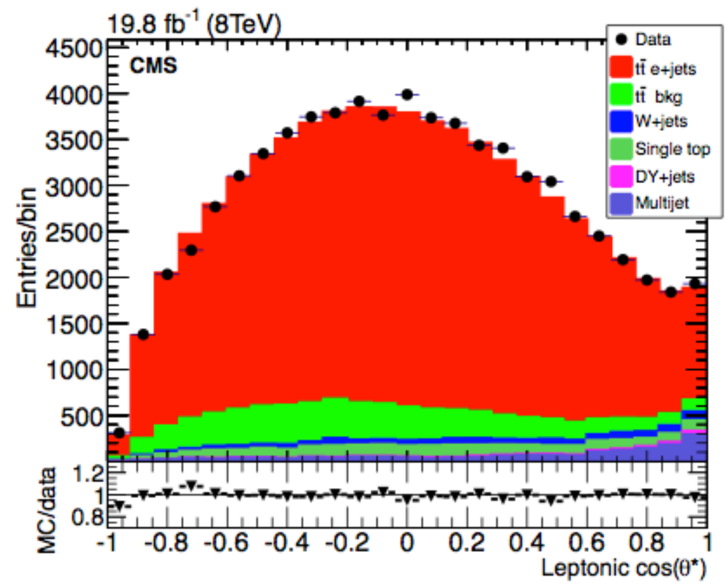
W boson polarization

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



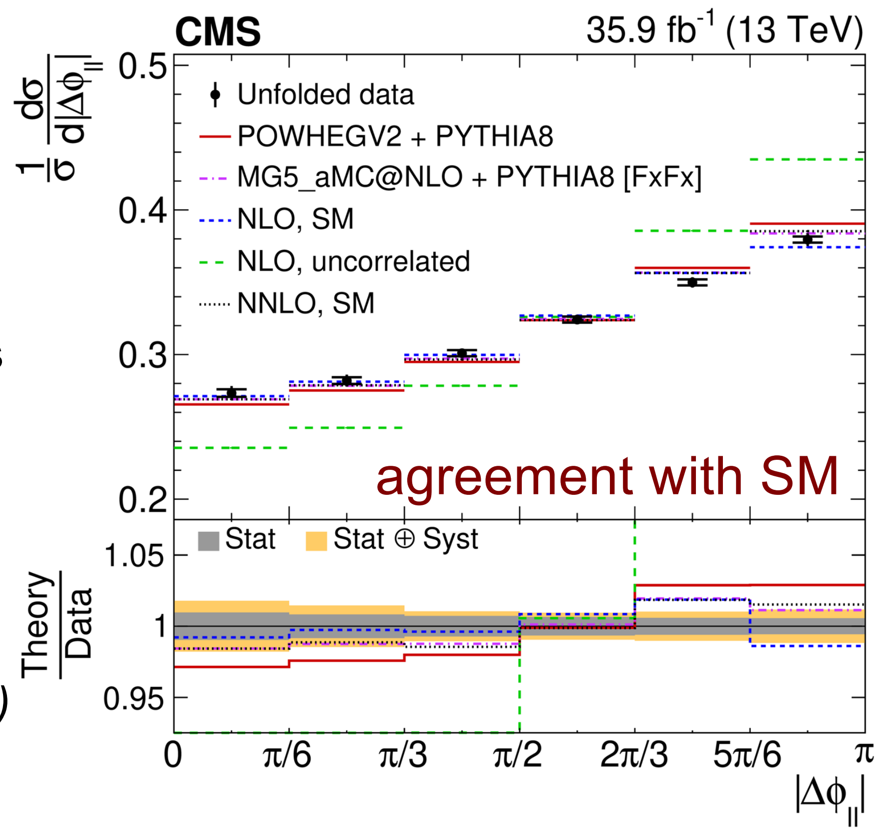




Spin correlation

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

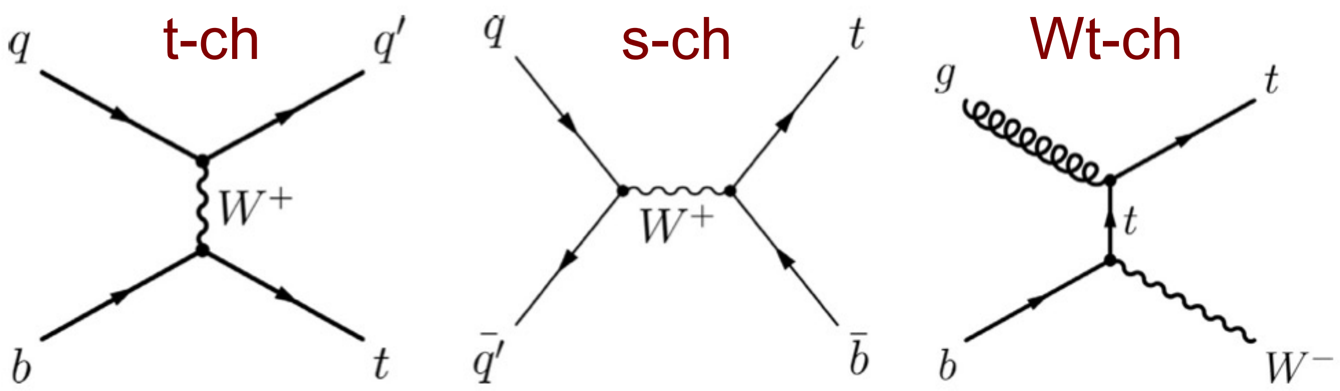
- Top quark produced are not polarized
  - …but spins between quark and anti-quark are correlated
- Top quark decays before spins decorrelate
  - It decays before hadronization ($\tau \sim 10^{-25}$ s) $\Rightarrow$ spin information transmitted to decay products
  - No need to reconstruct full ttbar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



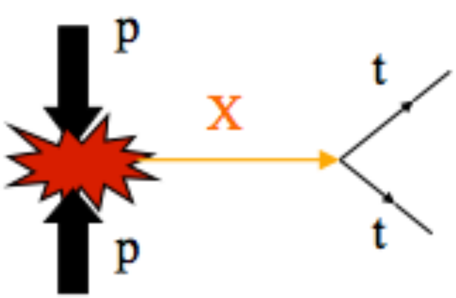
How else is Top produced?

PRD102(2009)182003, PRD81(2010)054028

- Single top quark production



σ(13TeV) = 217 pb 10 pb 72 pb

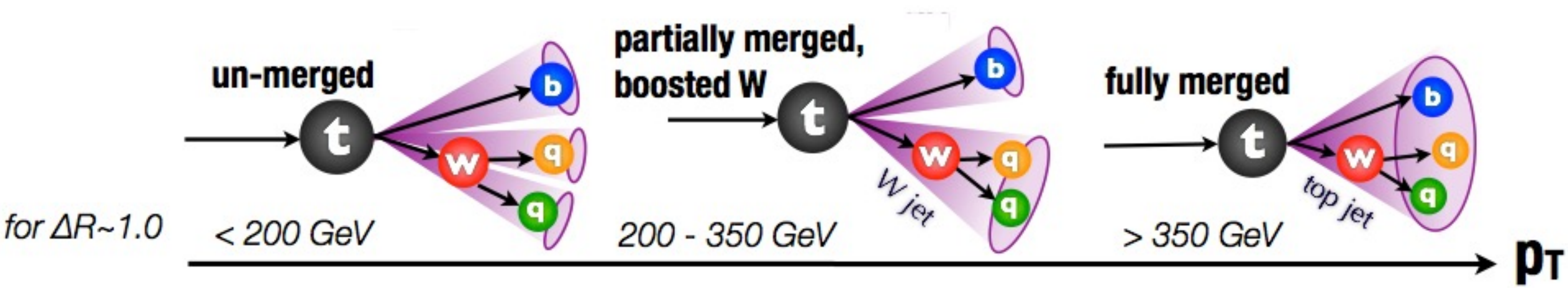


Resonance Production?
Top Color-Assisted Technicolor
OR
?????

Probing top quark production

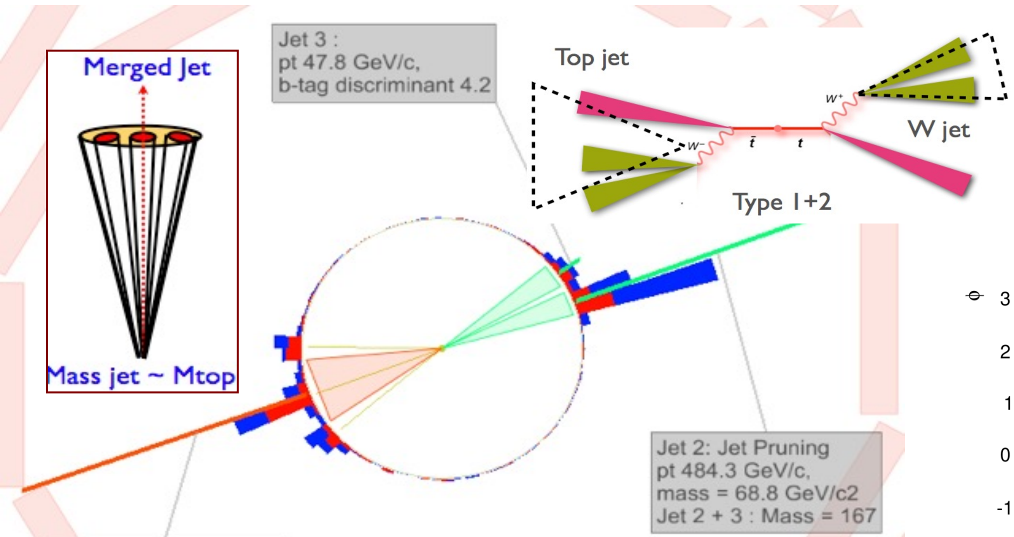
- Differential measurements
  - Testing QCD, measuring properties, searching for new physics, …
  - Function of kinematics, global variables, associated production
- Increased sensitivity: top quark pairs produced at rest
  - σ (M_{tt}>1 TeV at 13 TeV) =8 x σ(M_{tt}>1 at 8 TeV)

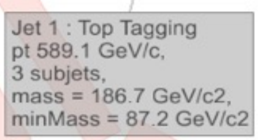
⇒Unique opportunity to probe boosted production at 13 TeV



Boosted topology

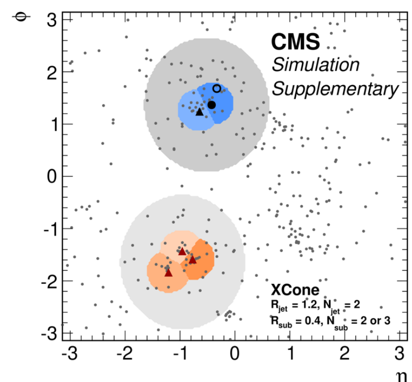
JHEP 1209(2012)029, TOP-16-013, PRL 124(2020) 202001

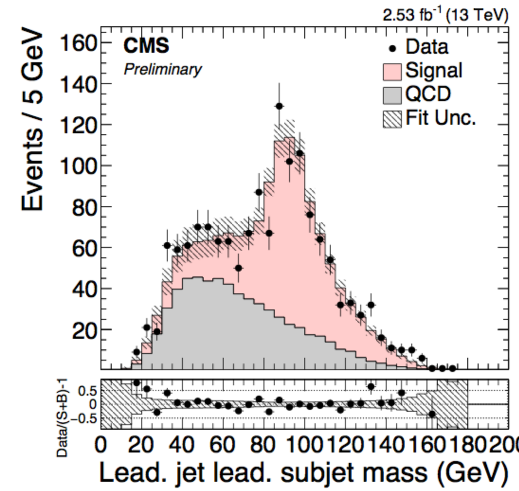


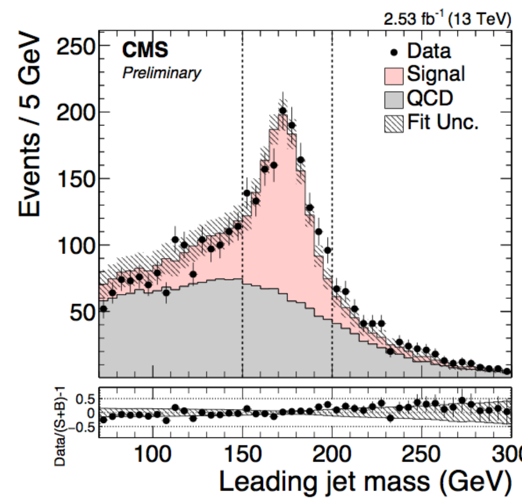


see also CDF note 10234

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







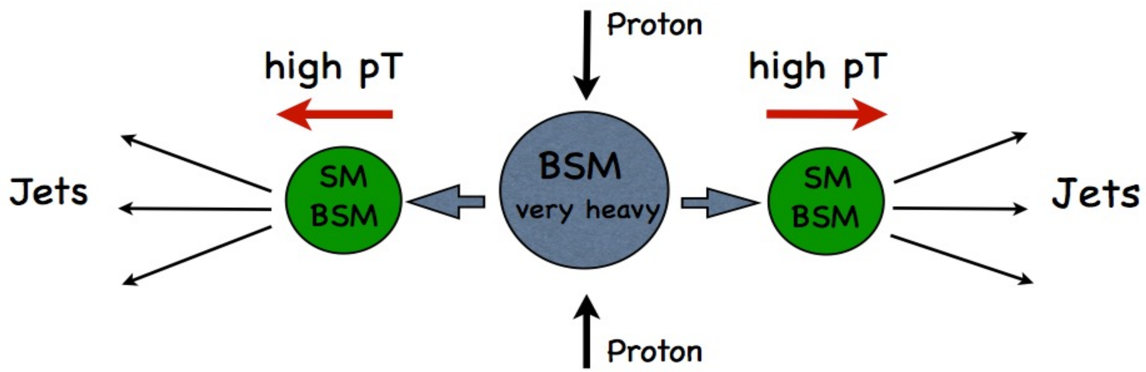
- At high energy, particles produced beyond threshold
- All-hadronic topology
  - Top p_T boosted, jets are collimated
  - Decay products and FSR collected in a “fat” jet
- Look at jet substructure
- Measure mass (no neutrinos)

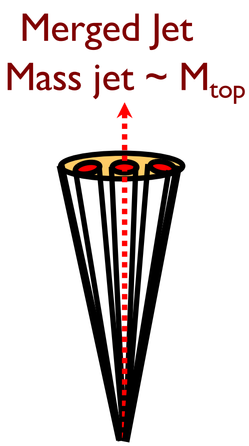
Boosted topology

- 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

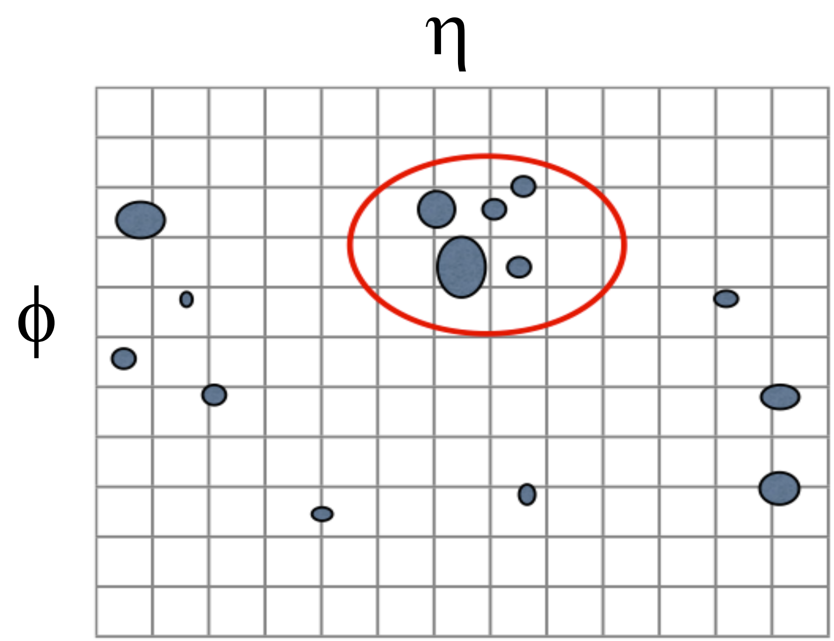




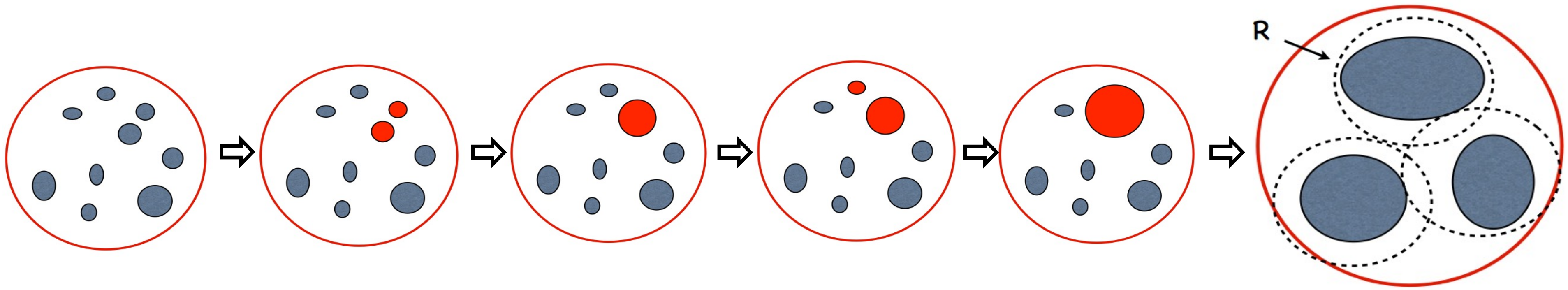
- At LHC energy, EWK scale particles produced beyond threshold
- Jets are highly collimated
- Decay products and FSR collected in a fat jet

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



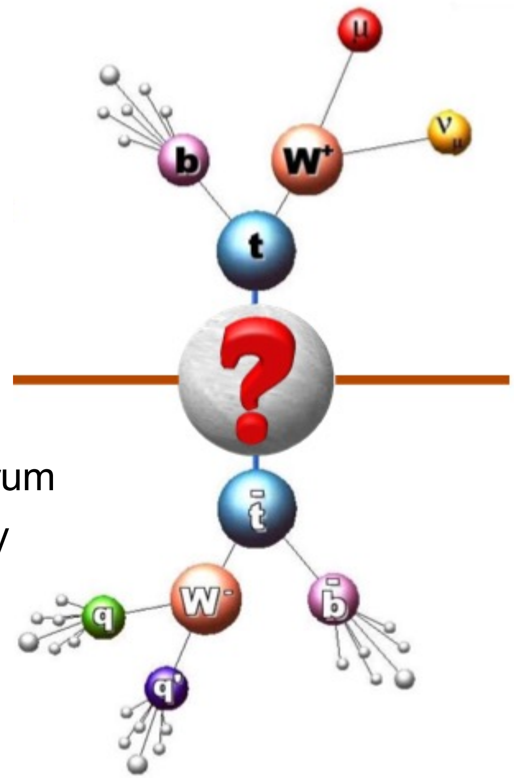
UE, ISR, Pile-up, hard interaction

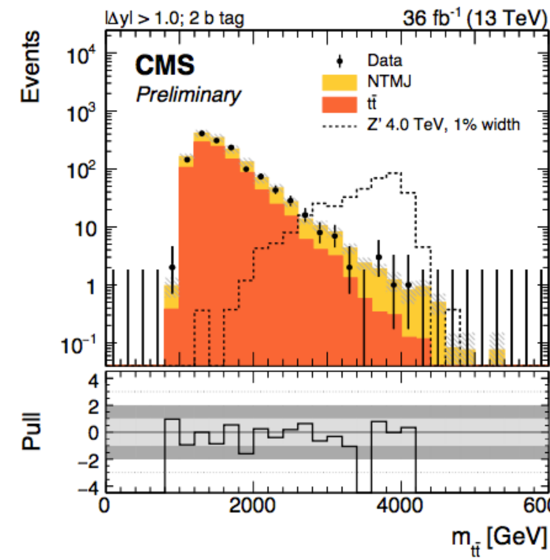


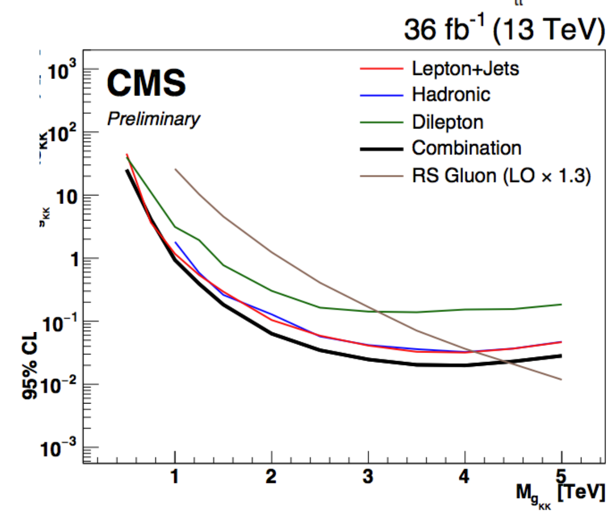
Top quark pair resonance

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

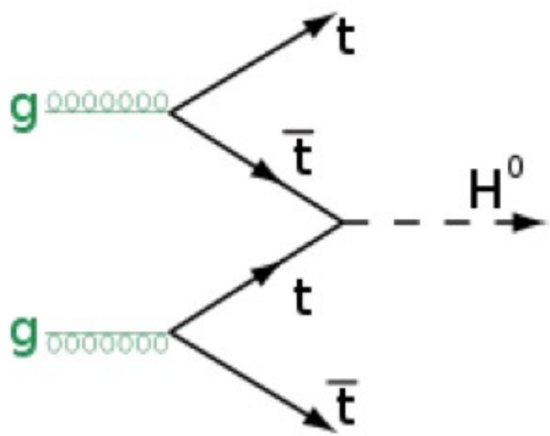




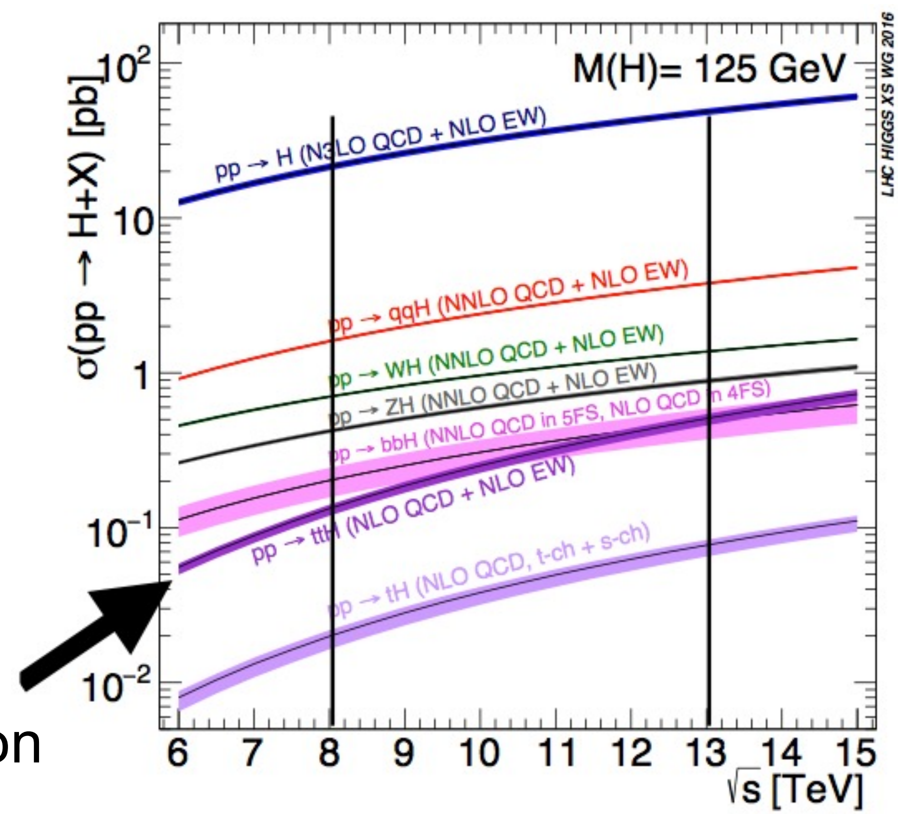


ttbar+Higgs

- ttbar produced in association with H
  - ttbar is a “clean” tag
- direct measurement of Higgs couplings



Cross section for tt̄H at the LHC:
0.13 pb (8 TeV)
0.61 pb (14 TeV)



ttH ~1% of total Higgs cross section

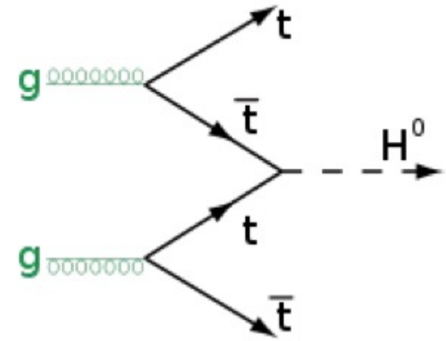
ttbar+heavy flavour

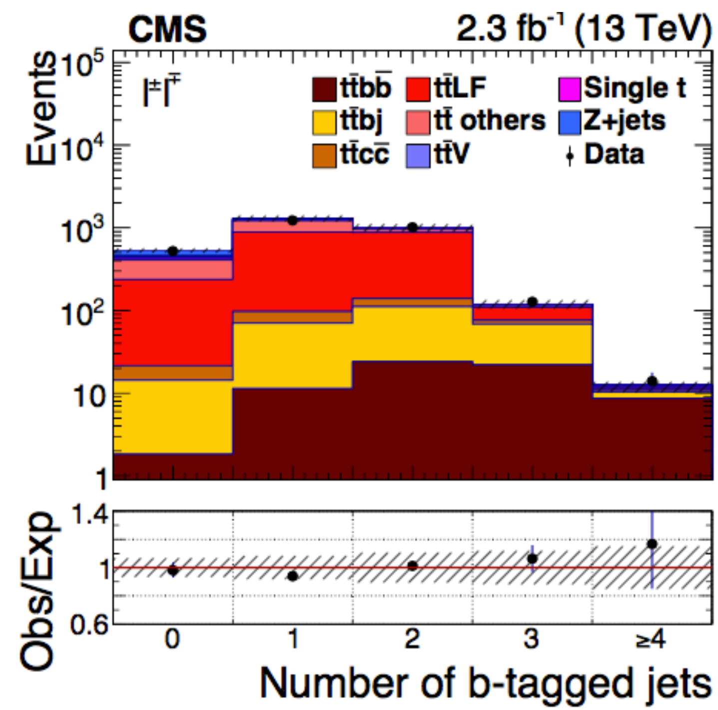
arXiv:1411.5621, PLB776(2018)355

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

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

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

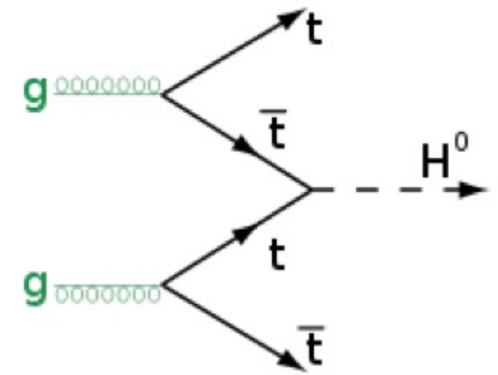


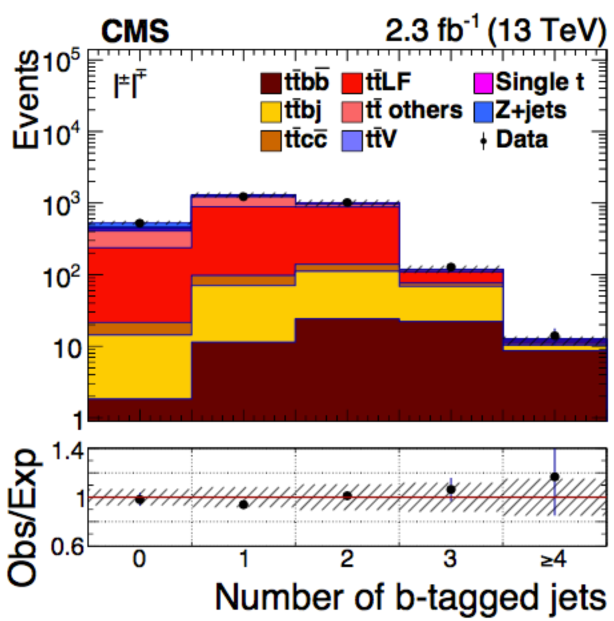


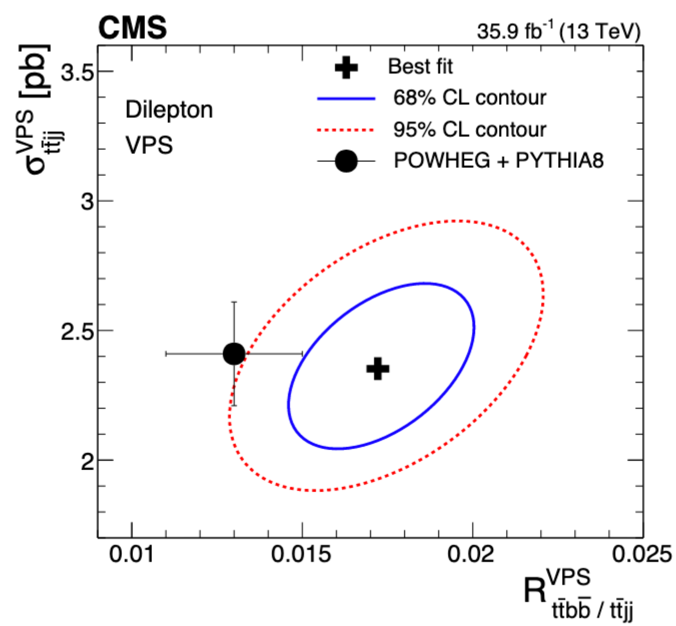
ttbar+heavy flavour

arXiv:1411.5621, PLB776(2018)355

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



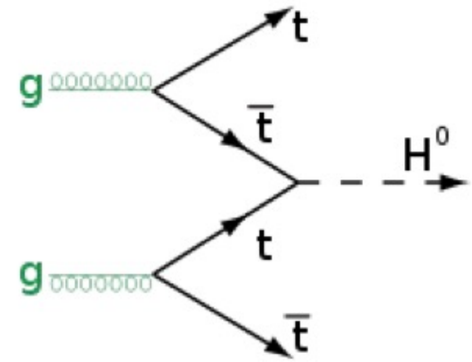


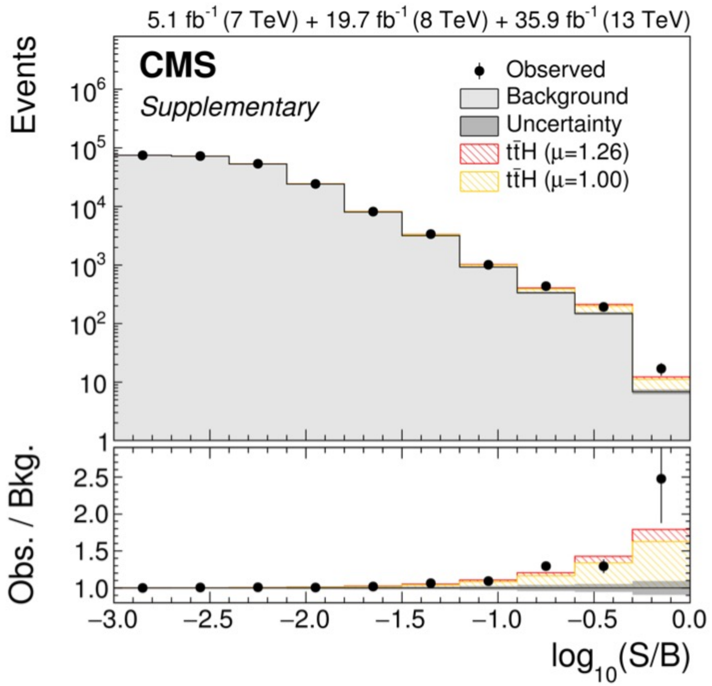


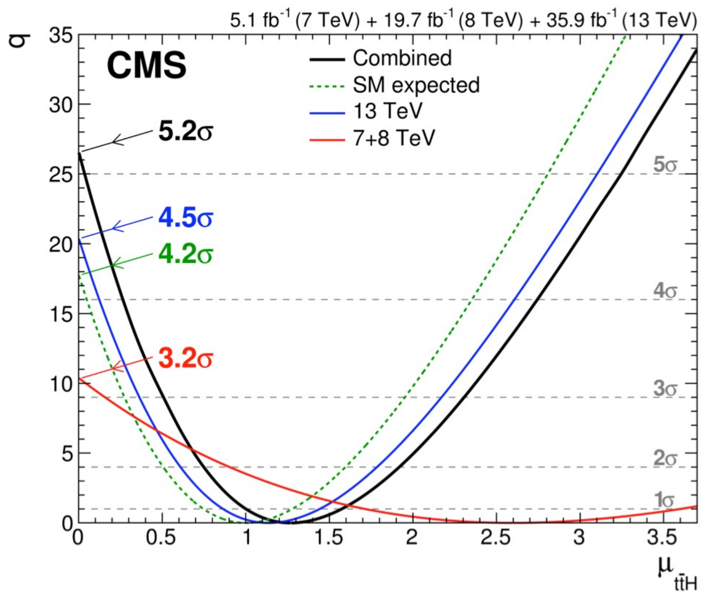
Higgs couplings to top quarks

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)

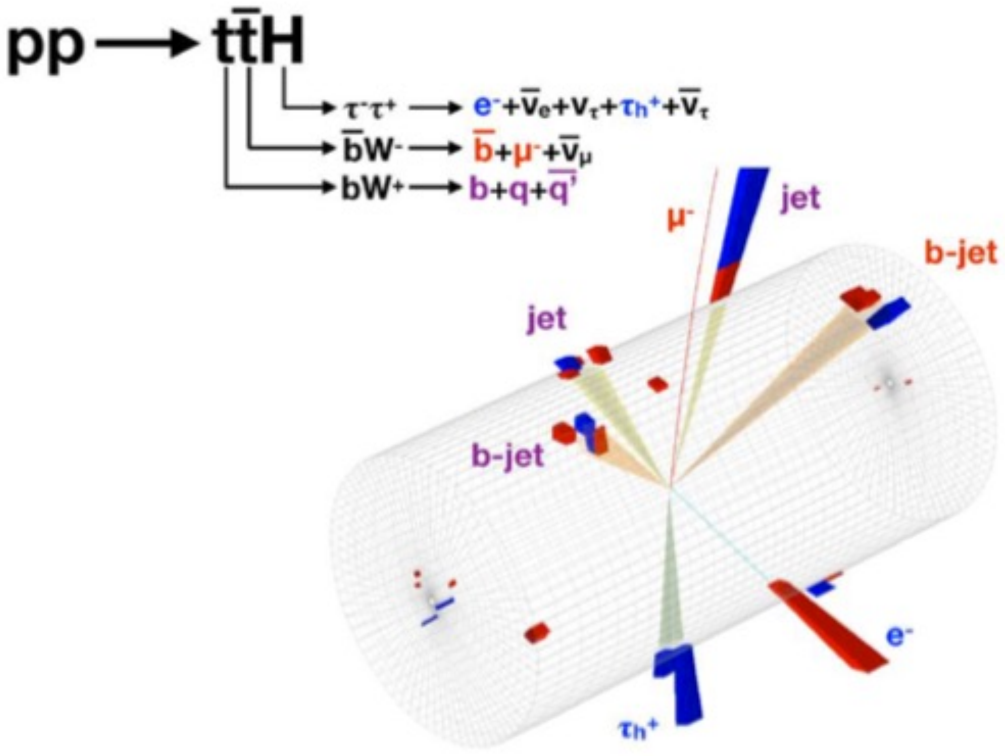






Event selection

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

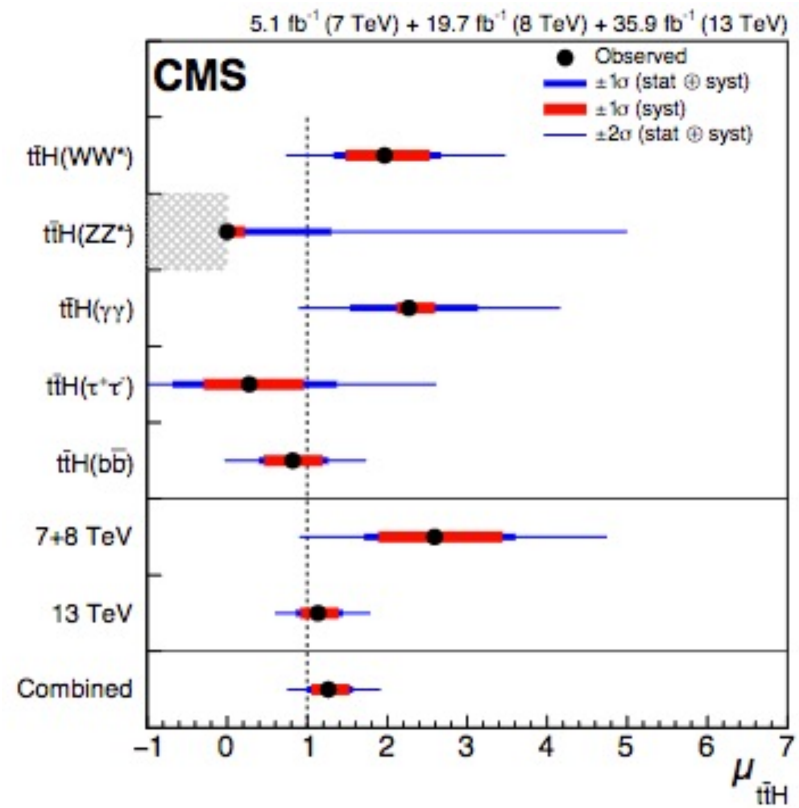


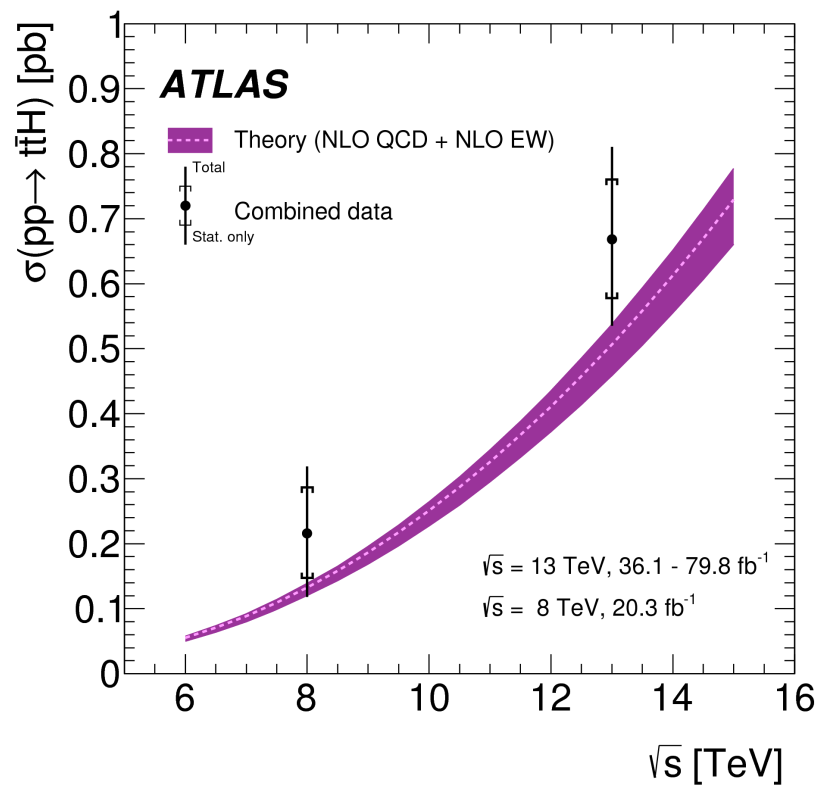
Observation of ttH

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

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

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



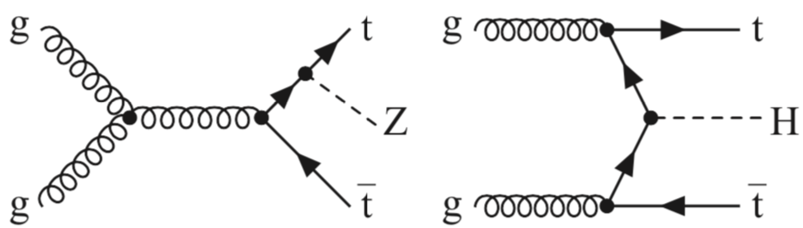


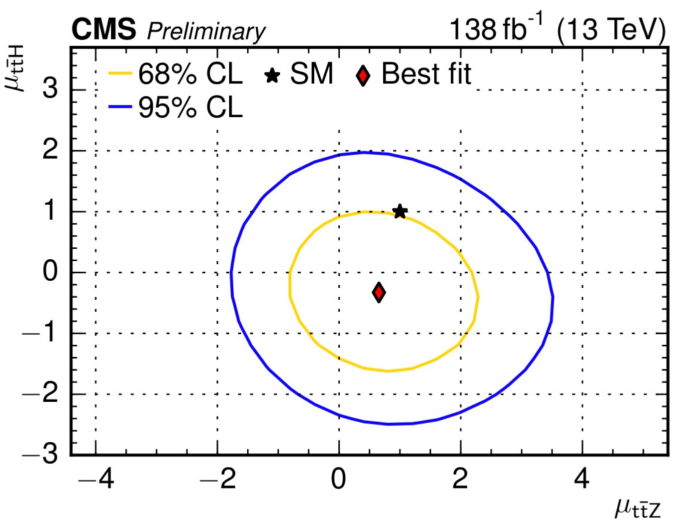
ttH/Z with boosted Z/H

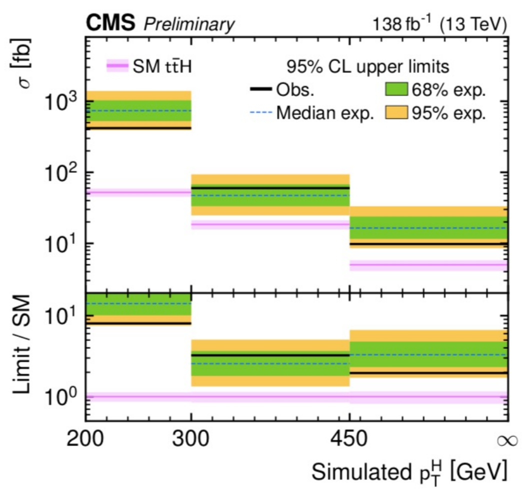
CMS-TOP-21-003

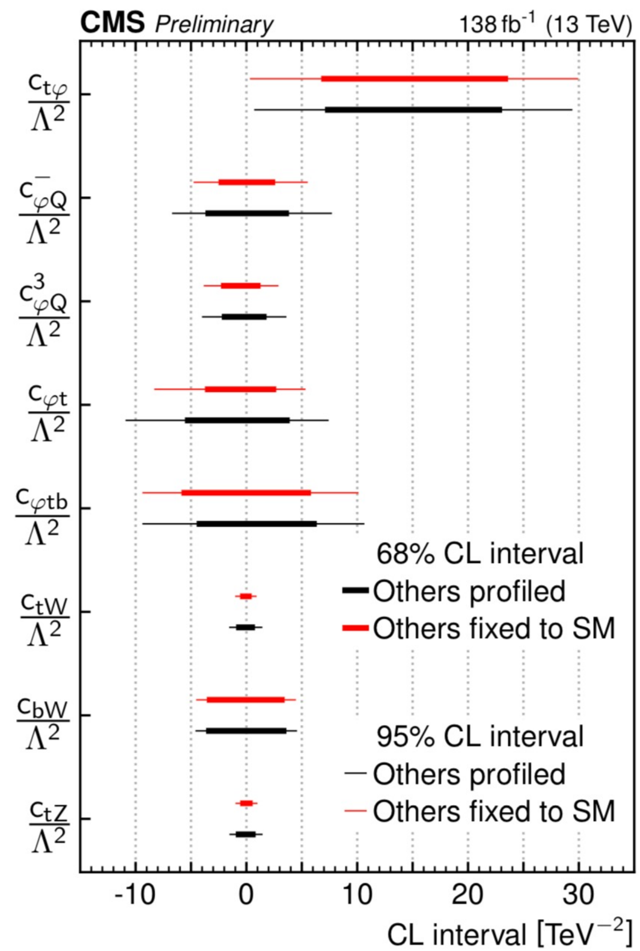
Search for tt+ boosted Z/H⟶bb

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



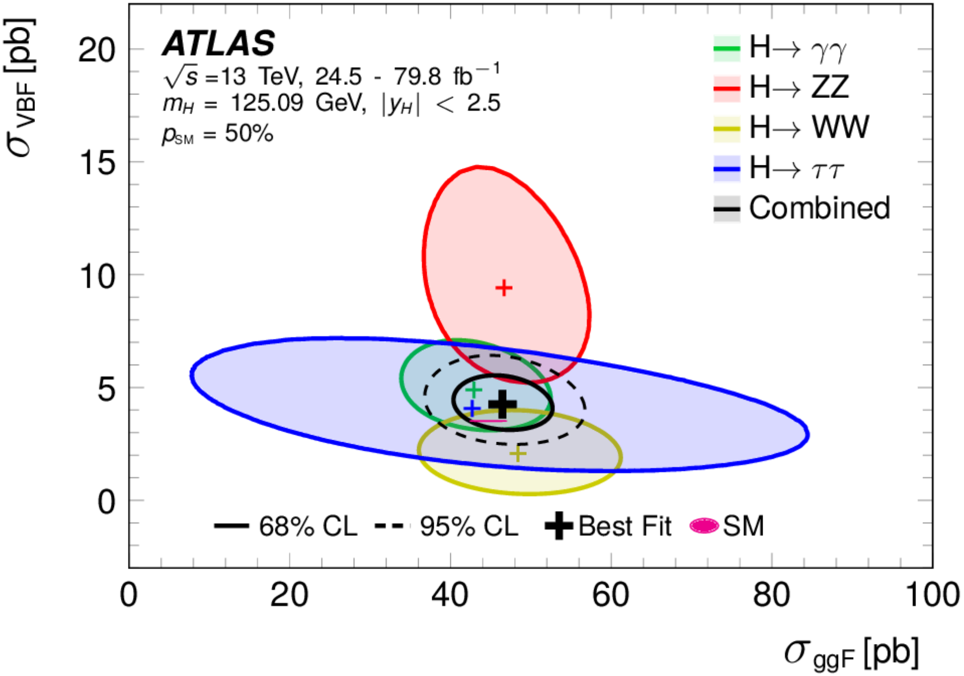


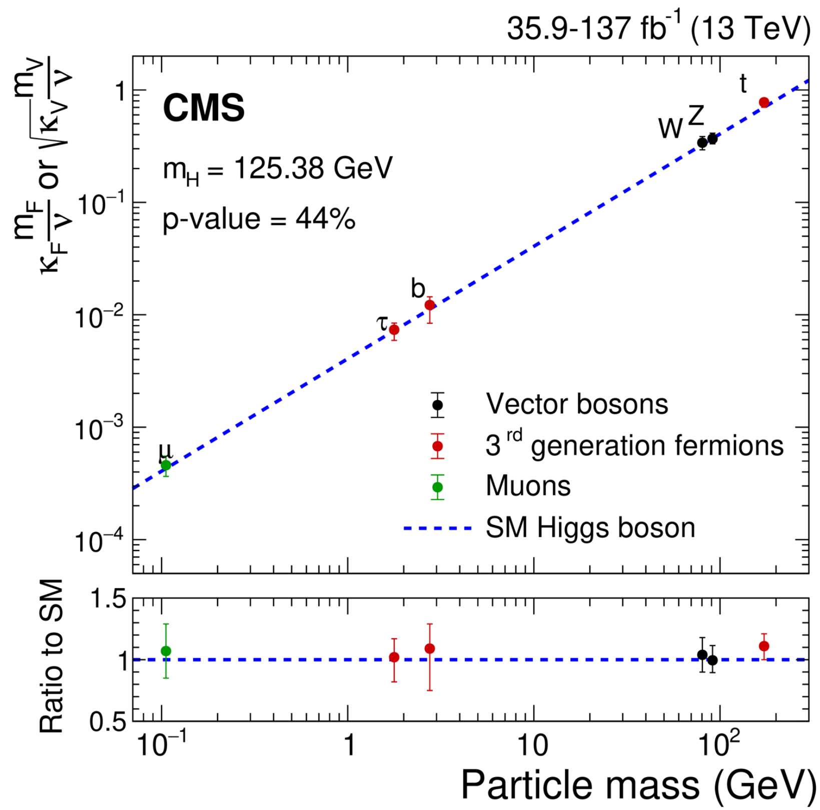




Consistency with SM

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

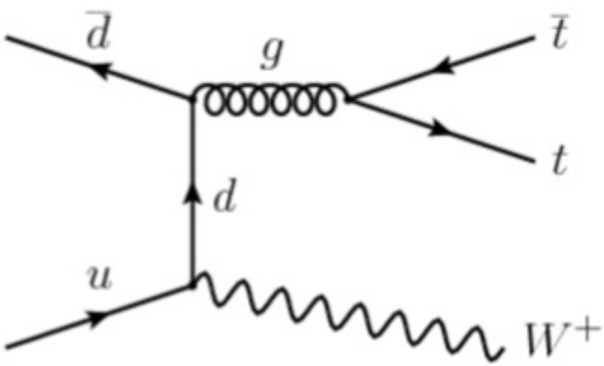


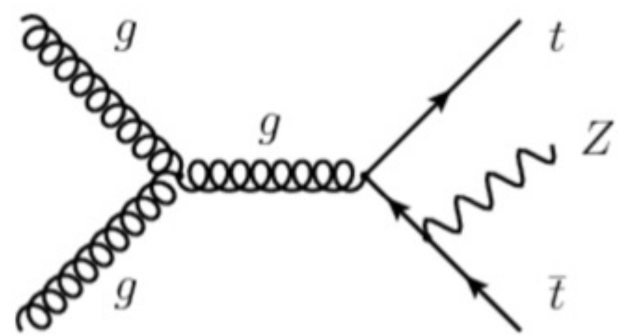


VBF+VH: boson in production
ggF+ttH: fermions in production

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



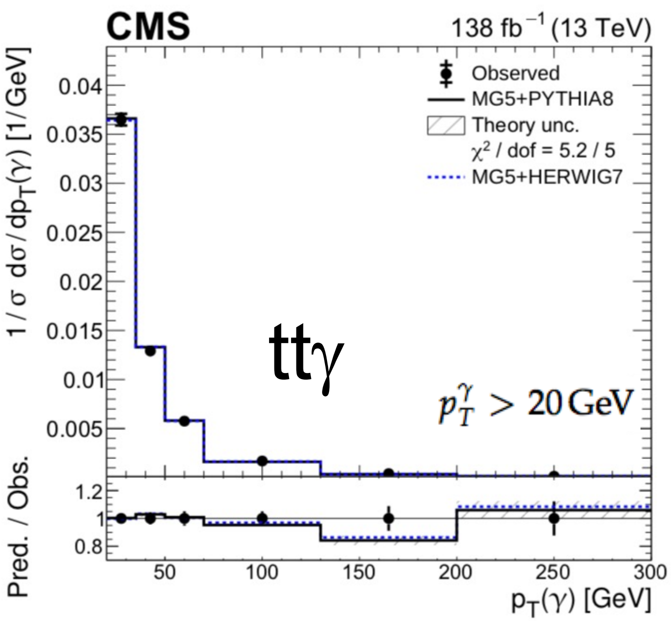


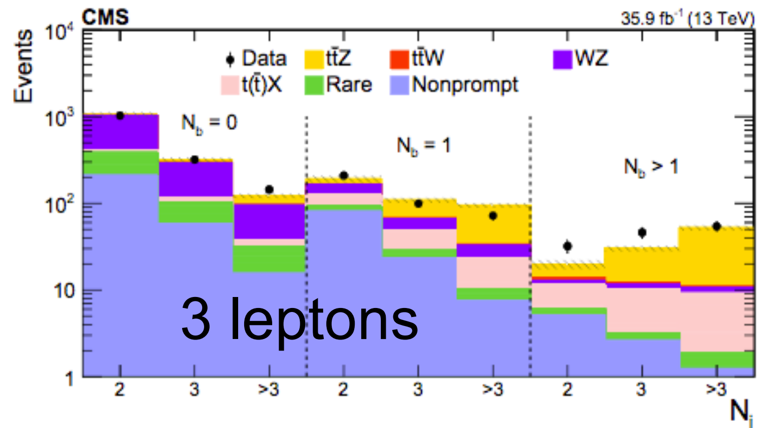
- Use multi-lepton final states
  - 2 same-sign charge leptons, 3 or 4 lepton final states

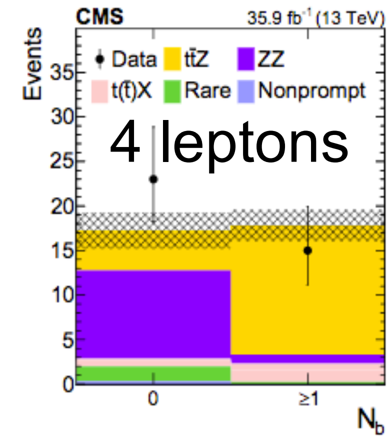
ttV production (V=γ,W,Z)

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

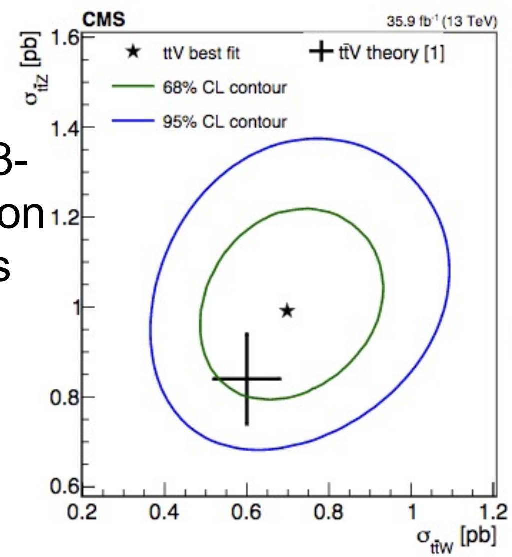
- Measurements gives access to EW couplings of the top

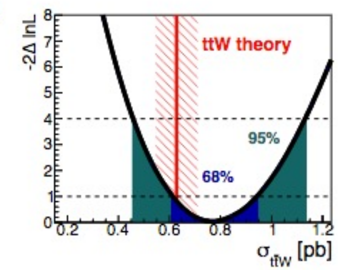


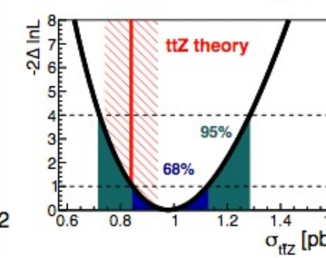




Combine 3- and 4-lepton final states







Measure:

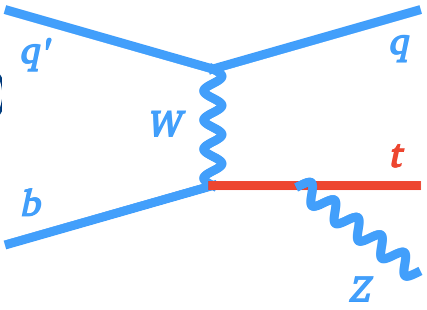
$$\sigma_{\text{fid}}(\text{pp} \to t\bar{t}\gamma) = 173.5 \pm 2.5\,(\text{stat}) \pm 6.3\,(\text{syst})\ \text{fb}$$

⇒ Consistent with SM predictions

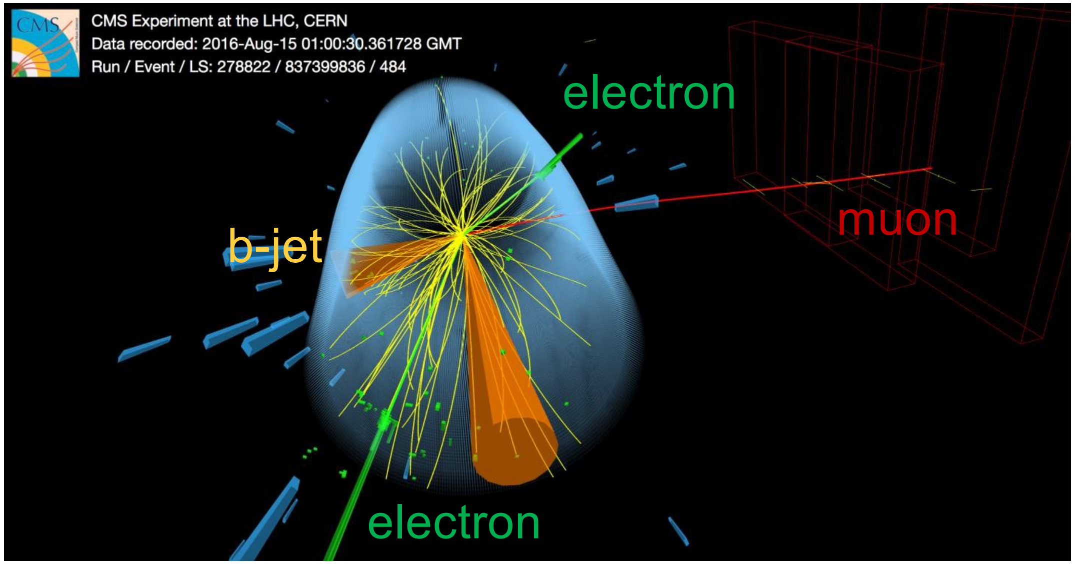
Top-Z coupling

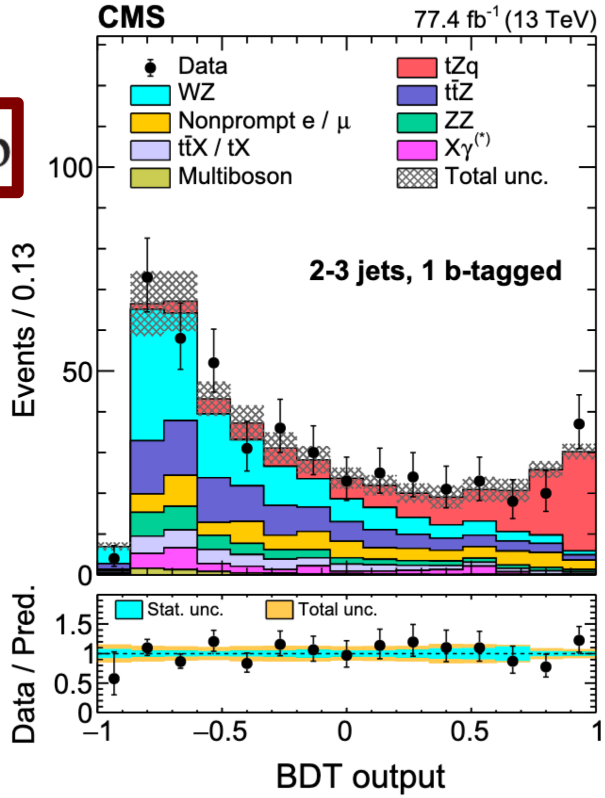
PRL 122(2019)132003

- 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

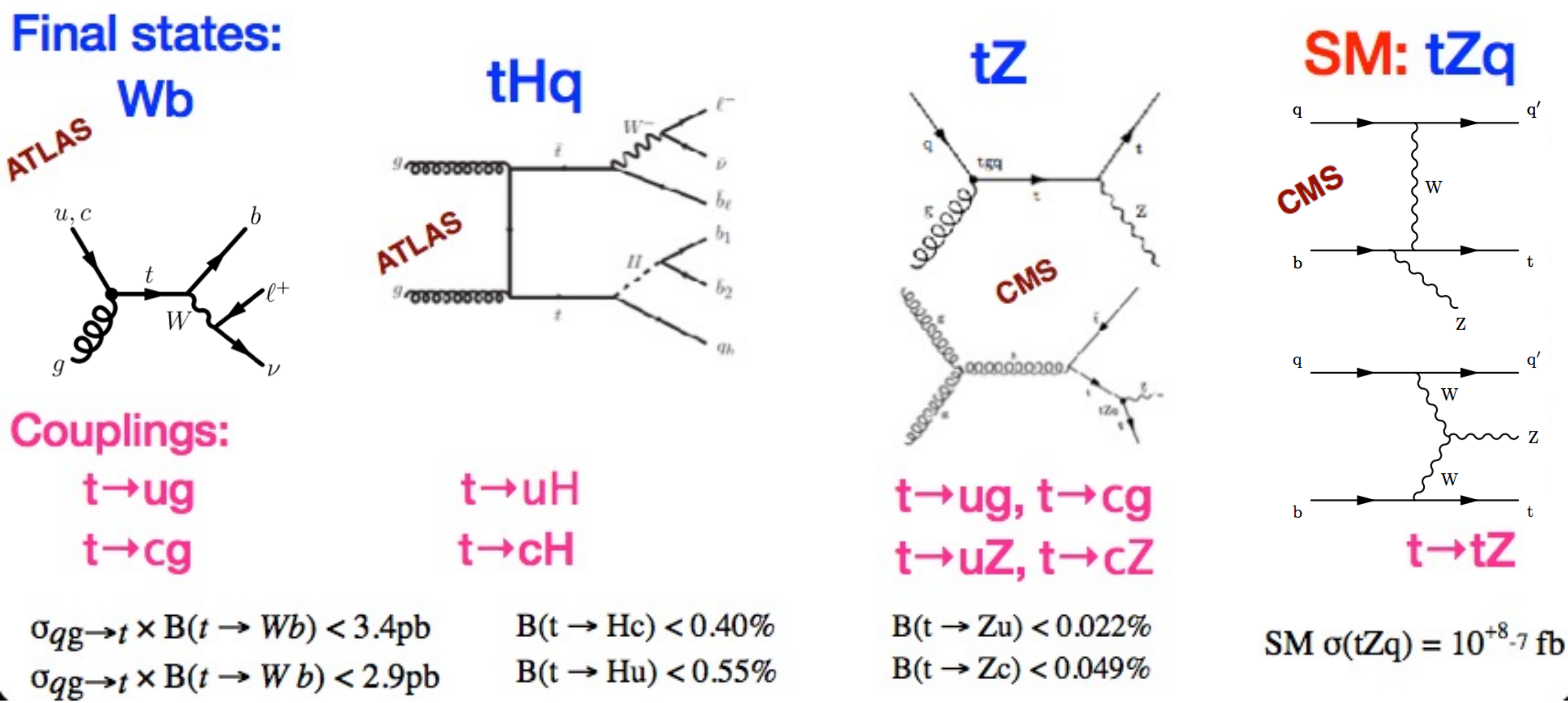
- FCNC: top couples to light quarks (u/c) and neutral bosons (γ,Z,H,g)
- Forbidden at tree level in SM
- Very small rates predicted
- Deviations would give hint for NP

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

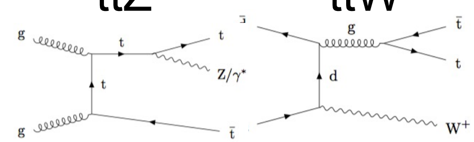


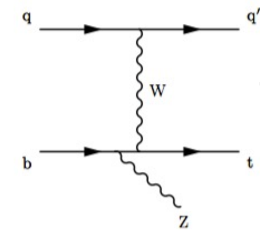
Top quarks and rare decays

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

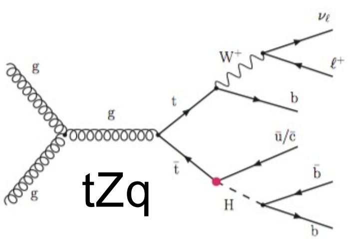
- Heaviest fundamental particle
- Study naked quark, decays before hadronization
- Strongly interacting with EWK sector and Higgs
- Anomalous couplings: Wtb vertex may include BSM terms

ttZ ttW

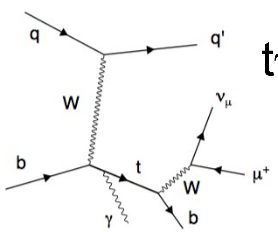




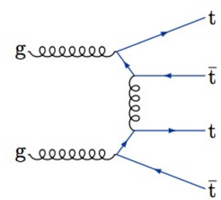
tZ



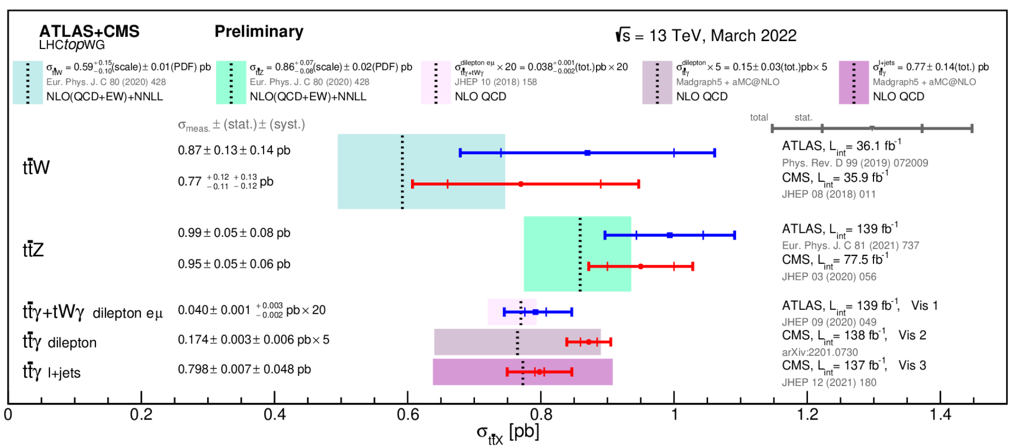
tZq

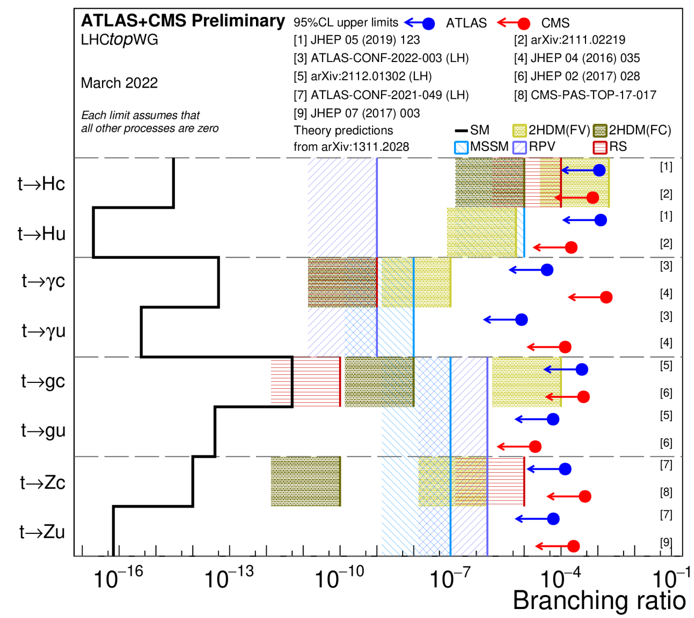


tγ



tttt

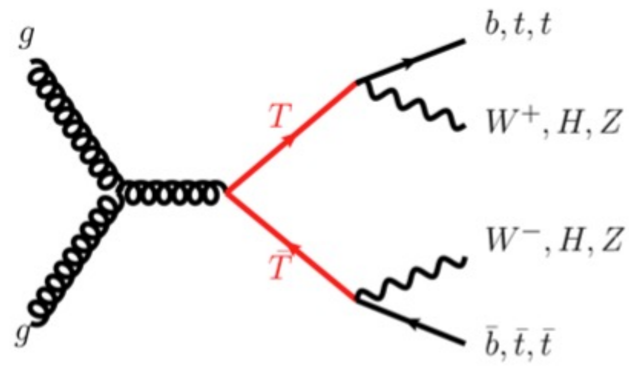


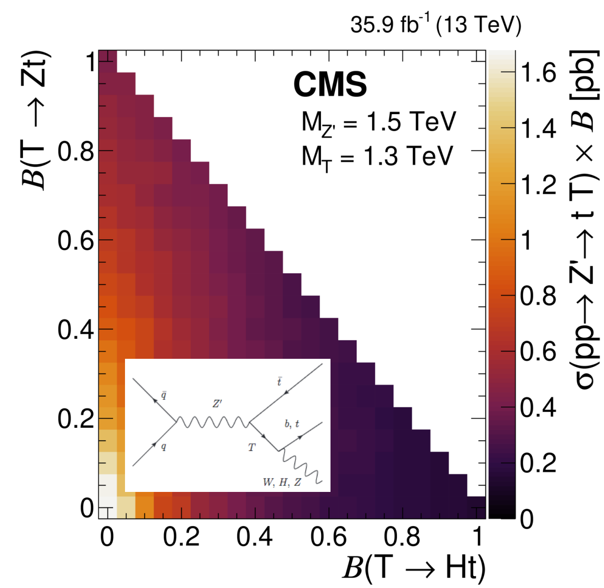


Vector-like quarks

EPJC79(2019)364

- Predicted in many BSM models, aim to solve the hierarchy problem
  - Produced through strong interactions
  - left- and right-handed components 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)
  - FCNC decays
- Busy events, a lot of top quarks, bottom quarks, leptons and jets in final state
  - Example: 2 tops in final state
  - use top/H/W/Z taggers to find hadronic decays

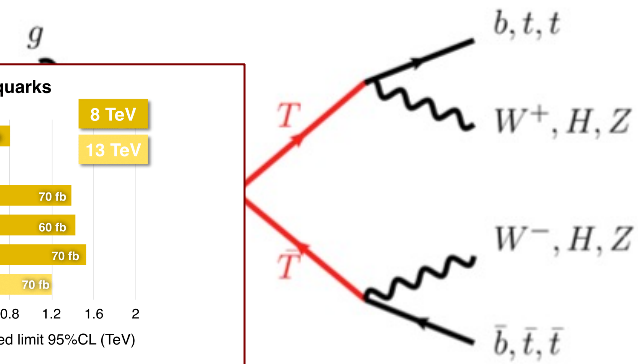


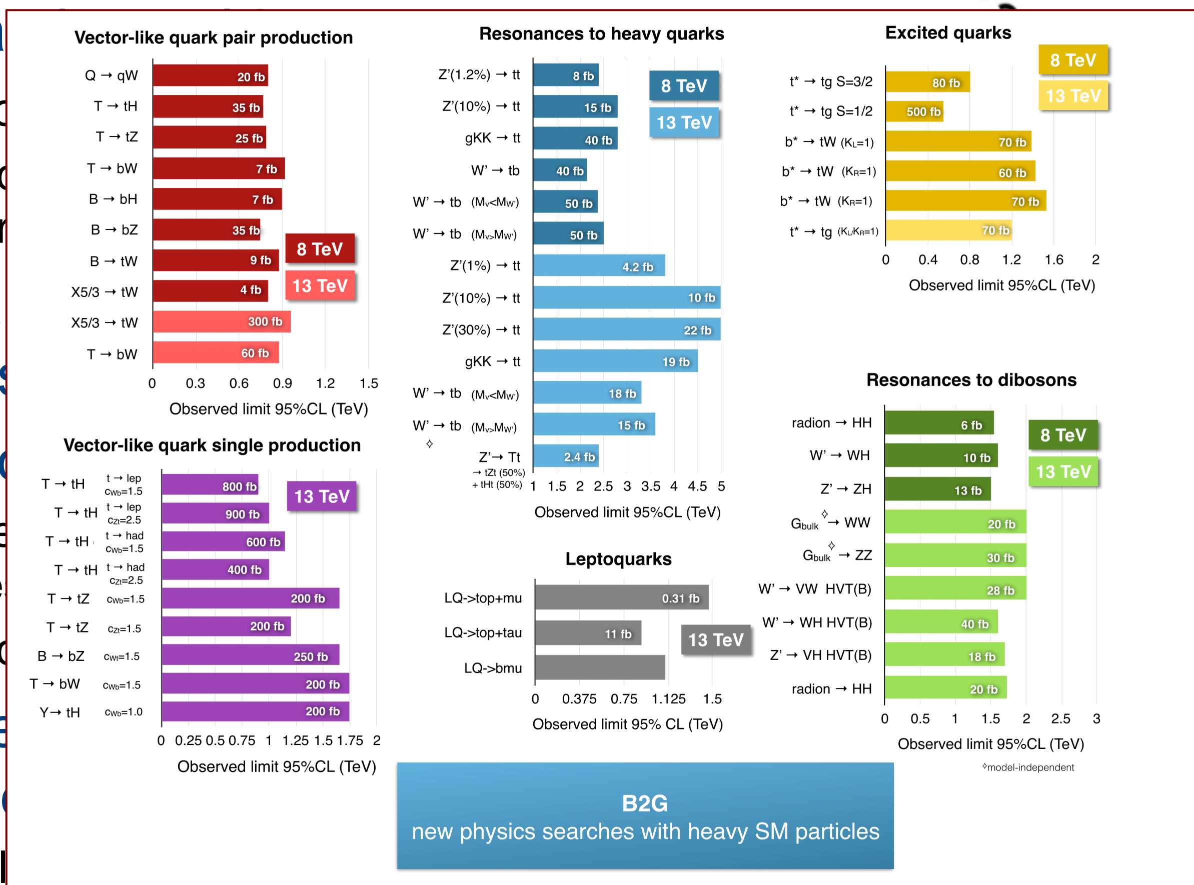


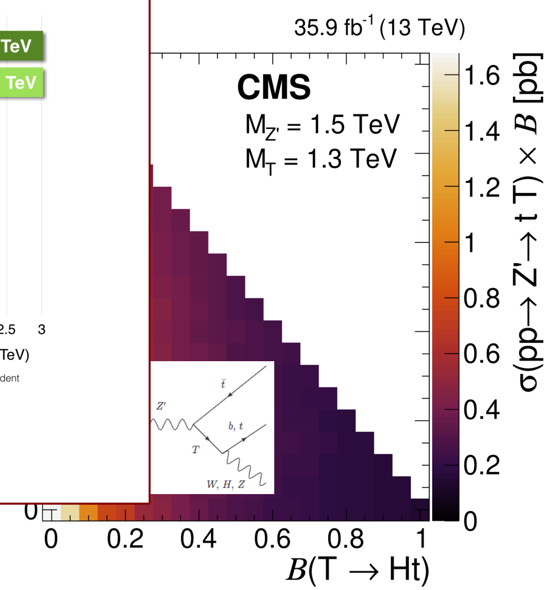
Vector-like quarks

EPJC79(2019)364

- Predicted in many BSM models, aim to solve the hiera
  - Produc
  - left- an number
- VLQs ca couplings
- Search f
  - Most se particle
  - FCNC
- Busy eve quarks, l
  - Exampl
  - use top/H/W/Z taggers to find hadronic decays

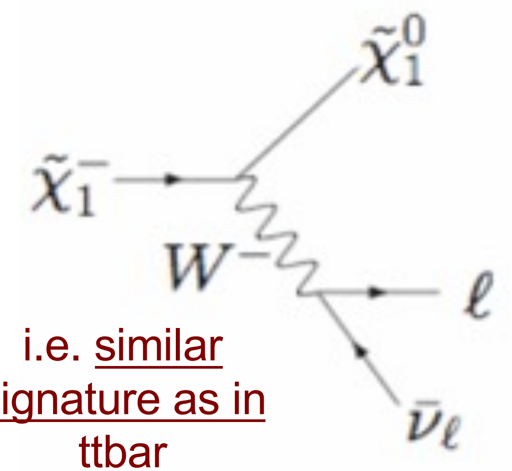






Scalar top quark

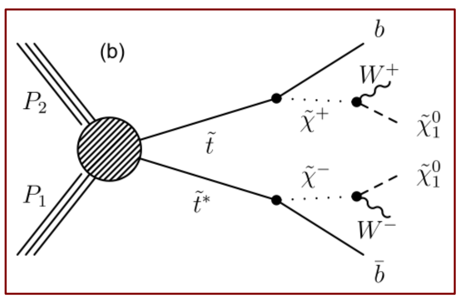
- SUSY is one plausible extension of the SM
- due to the heavy top quark, mass splitting between $\tilde{t}_1$ and $\tilde{t}_2$ can be large, such that the lighter stop $\tilde{t}_1$ can be even lighter than the top quark
- Decays dictated by mass spectrum of other SUSY particles



i.e. similar signature as in ttbar

- Light stop:

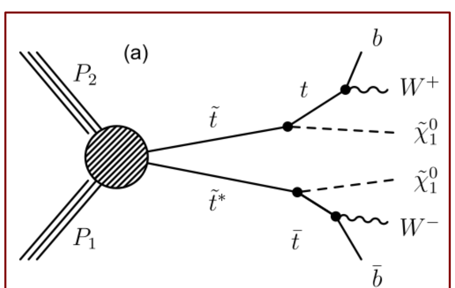
$\boxed{m_{\tilde{t}_1} \lesssim m_t}$



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

- Heavy stop:

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



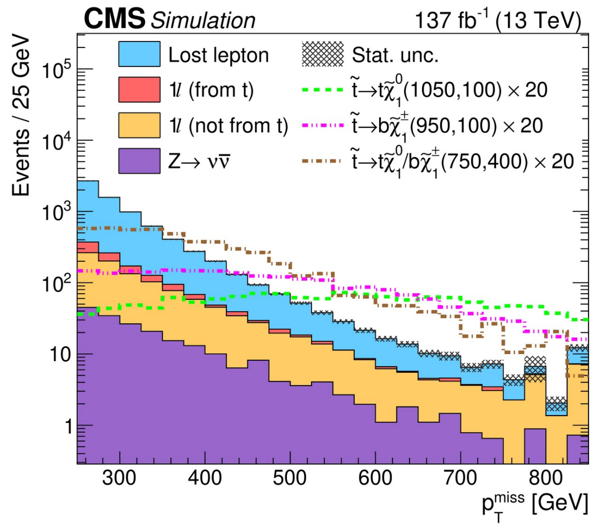
$$\tilde{t} \to t\tilde{\chi}_1^0 \to bW\tilde{\chi}_1^0$$

Top and SUSY

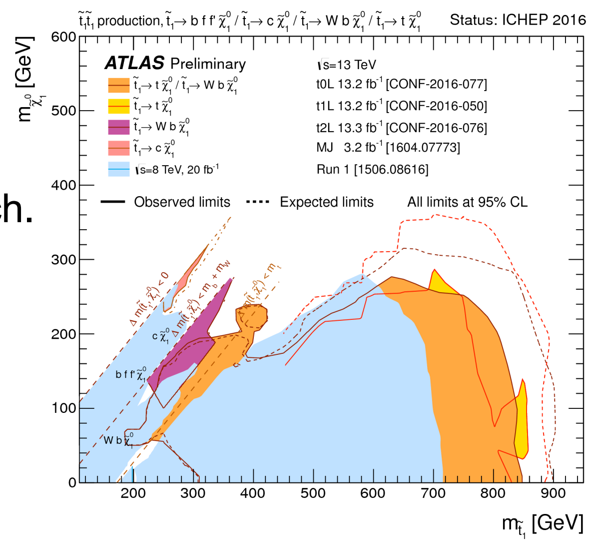
arXiv:1603.02303, JHEP05(2020)032

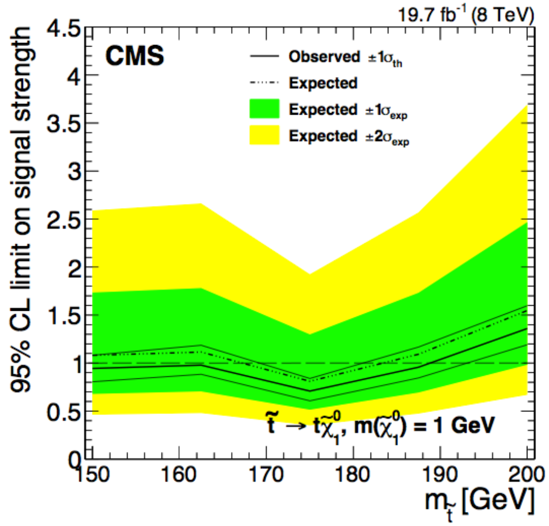
- If SUSY exists and is responsible for solution of hierarchy problem, naturalness arguments suggest that SUSY partners of top quark (*stop*) may have mass close to m_{top} to cancel top quark loop contributions to Higgs mass

$$\boxed{\begin{array}{l}\tilde{t} \to t\tilde{\chi}_1^0 \to bW\tilde{\chi}_1^0 \\ \tilde{t} \to b\tilde{\chi}_1^+ \to bW\tilde{\chi}_1^0\end{array}}$$ "heavy" / "light"



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





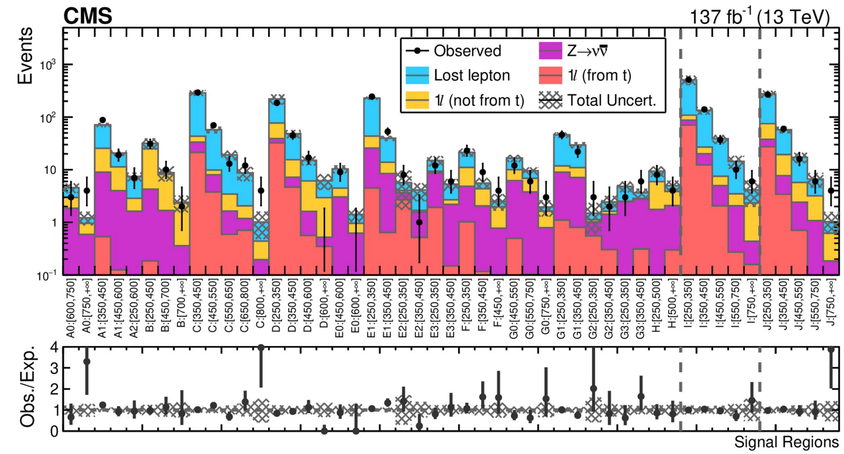
Top and SUSY

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

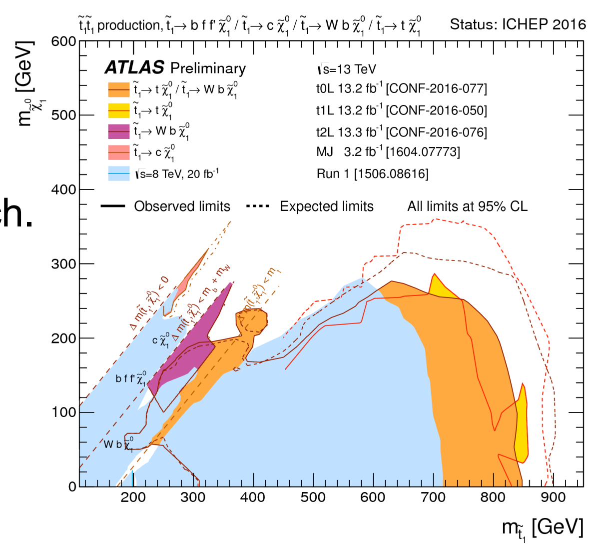
- If SUSY exists and is responsible for solution of hierarchy problem, naturalness arguments suggest that SUSY partners of top quark (*stop*) may have mass close to m_{top} to cancel top quark loop contributions to Higgs mass

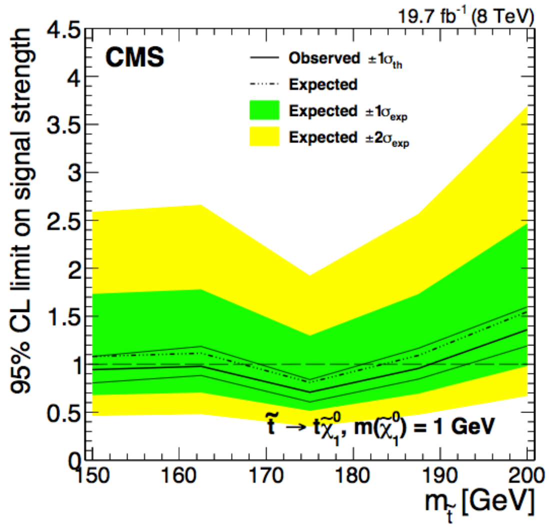
$$\boxed{\begin{array}{l} \tilde{t} \to t\tilde{\chi}_1^0 \to bW\tilde{\chi}_1^0 \\ \tilde{t} \to b\tilde{\chi}_1^+ \to bW\tilde{\chi}_1^0 \end{array}}$$

"heavy"
"light"



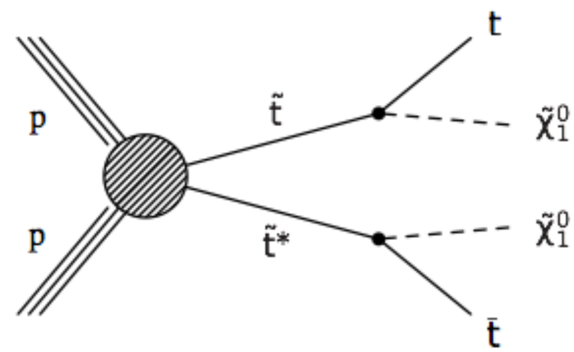
- Small predicted cross section
  - for 175GeV: 40pb@8TeV
- Stop pair production: $\boxed{t\bar{t}\tilde{\chi}_1^0\tilde{\chi}_1^0}$
  - similar to ttbar lepton+jet and dilepton ch.
  - additional MET from neutralinos
- change in ttbar cross section

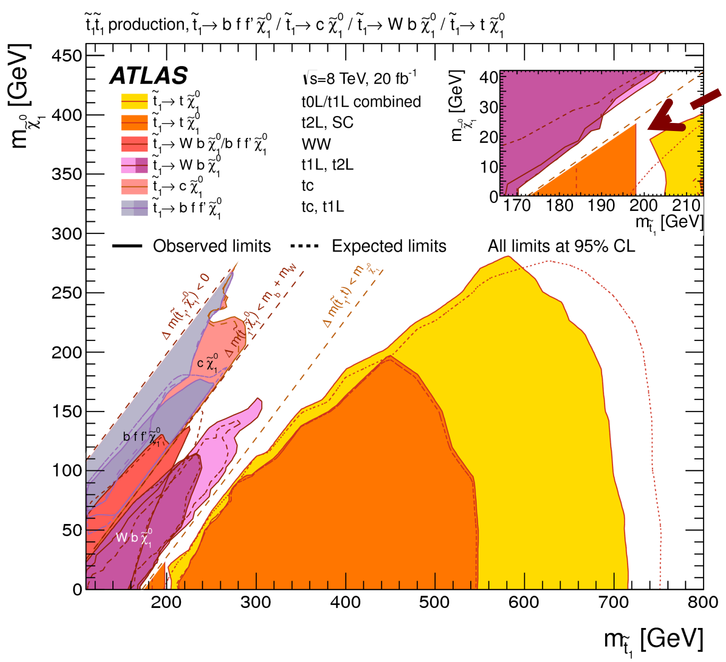


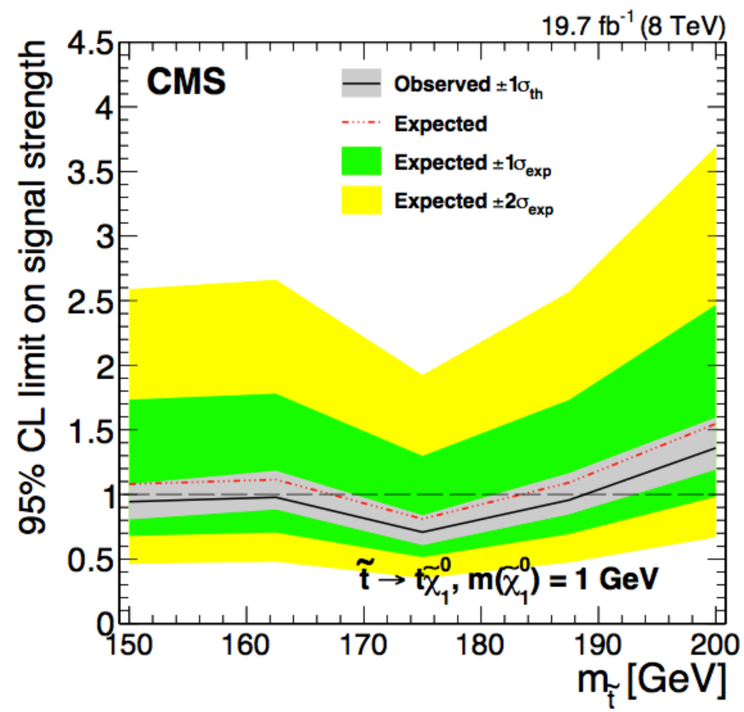


Top cross section: dileptons

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



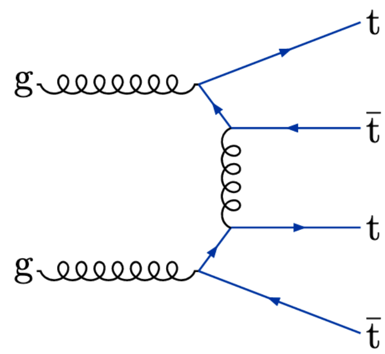


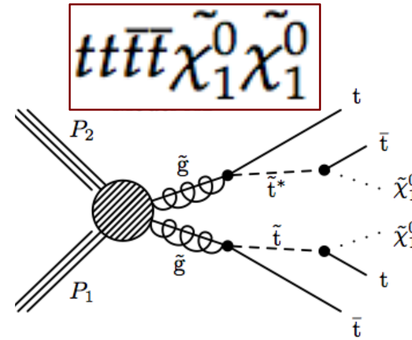


Multi-top production

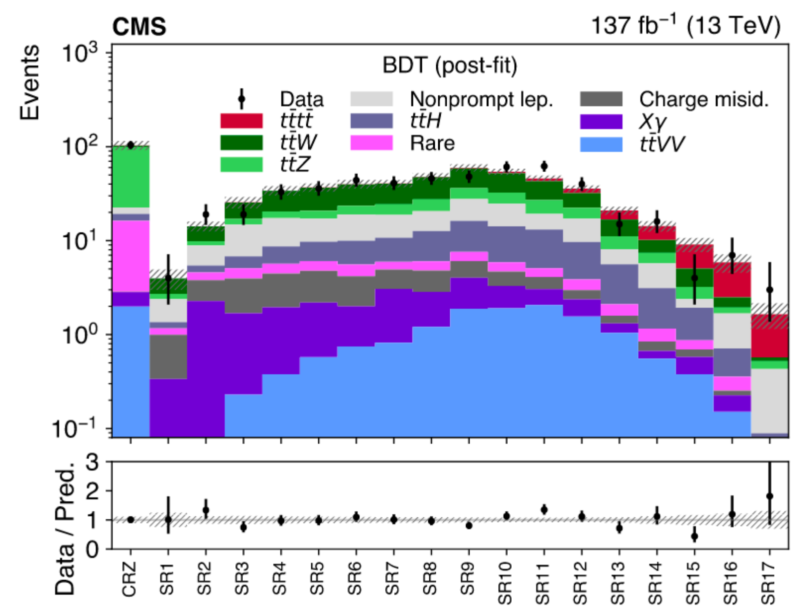
arXiv:1605.03171, EPJC 80(2020)75, JHEP11(2021)118

- 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

Multi-top production

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

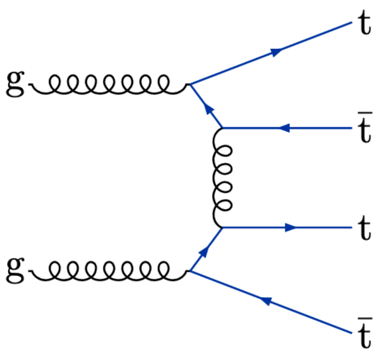
- Production of 4 tops is an attractive scenario in a number of new physics models
- The SM cross section is 12fb@13TeV

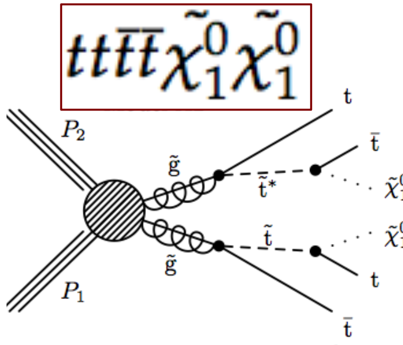
- Use dilepton and lepton+jets final states
- Combination of kinematical variables and BDT
- Search for same-sign dileptons, or >2 leptons

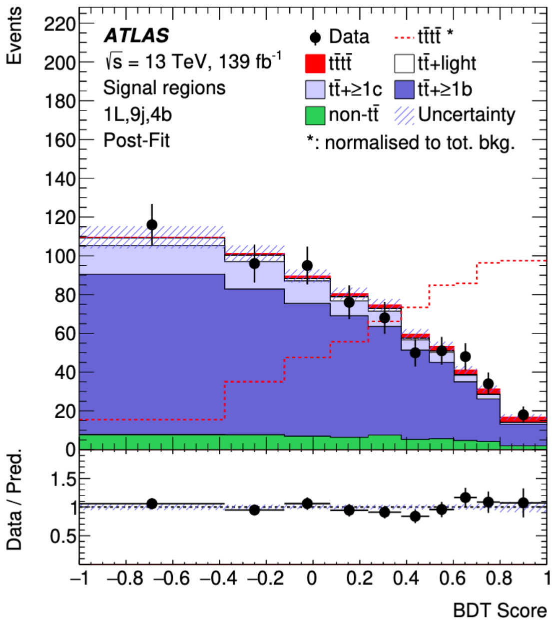
- Consider multiple control- and search-regions defined by MET, hadronic energy, number of (b-) jets, and p_T of the leptons in the events

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

- Limits on Yukawa couplings: $|y_t/y_t^{SM}| < 1.7$



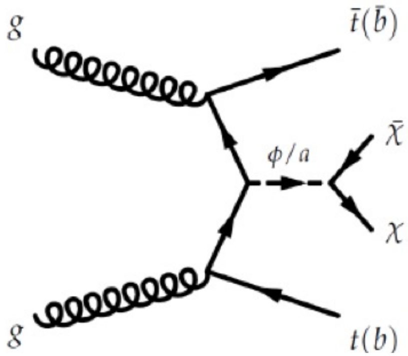


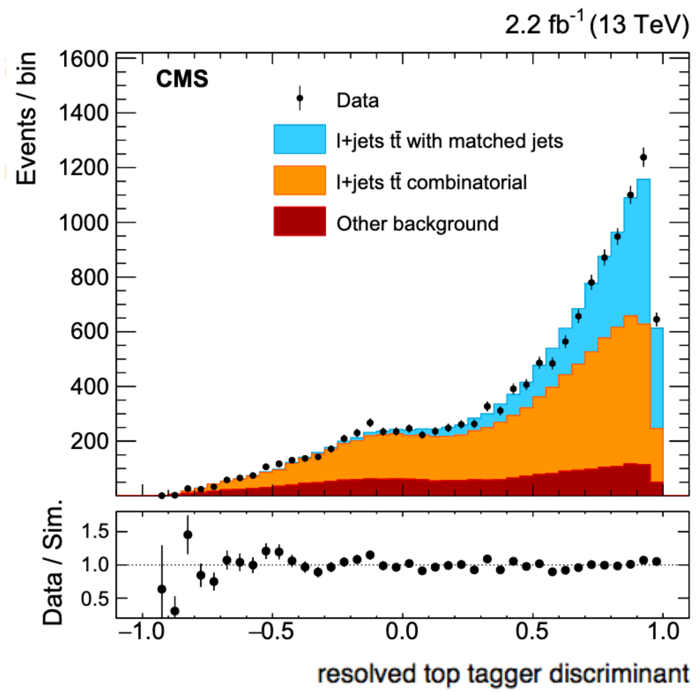


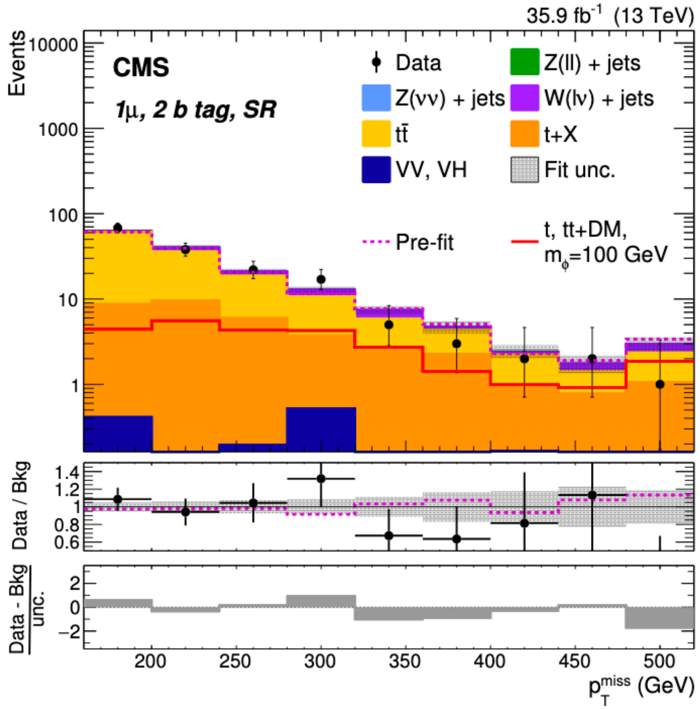
Dark Matter + ttbar

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

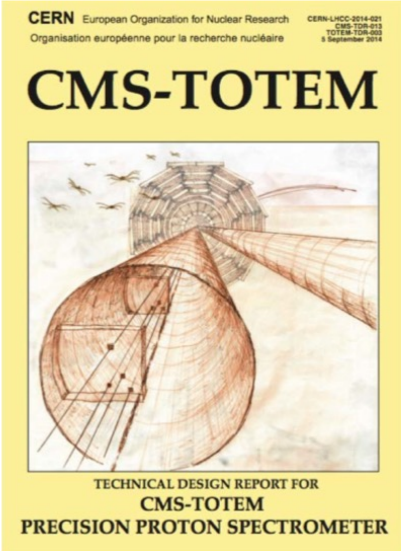




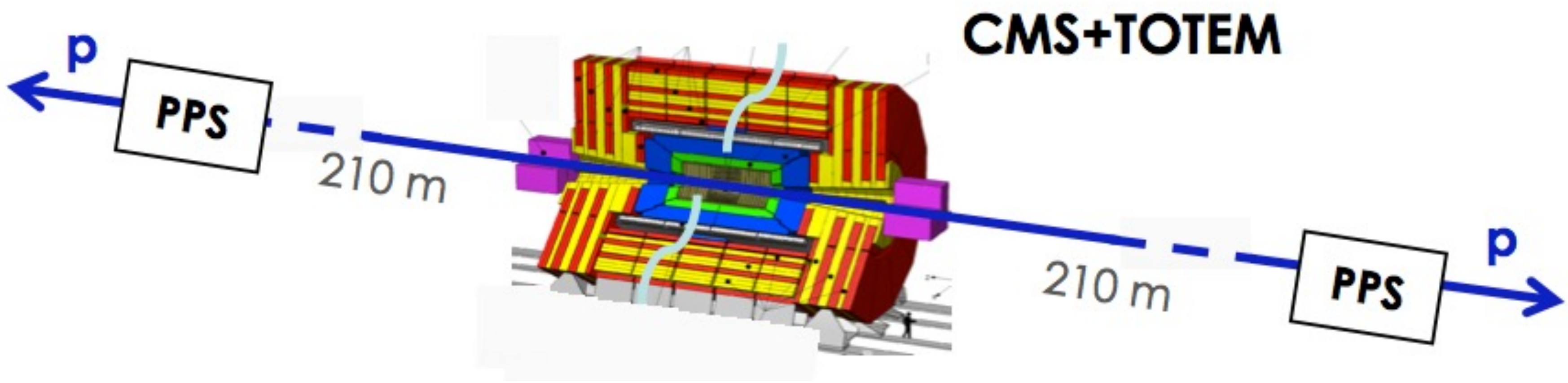


Precision Proton Spectrometer

- 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

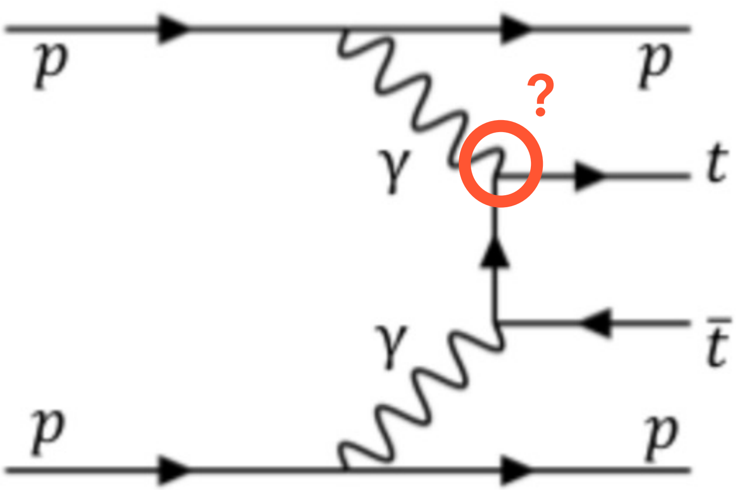


CERN-LHC-2014-021



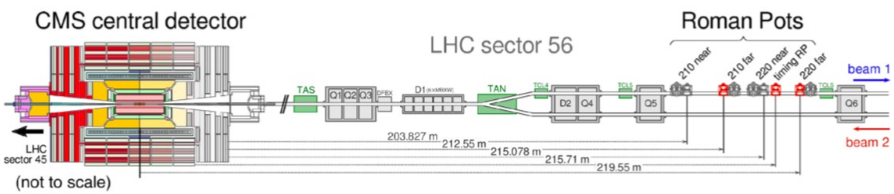
Exclusive top quark production

- 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



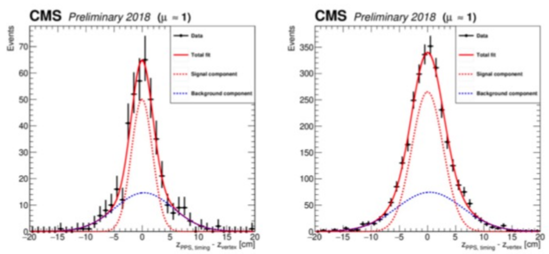
- Couplings of top quark to photons are small
- Process expected to be very sensitive to top quark anomalous couplings with the photon
- Anomalous production cross section or kinematical properties would provide hints for New Physics

Physics with forward protons



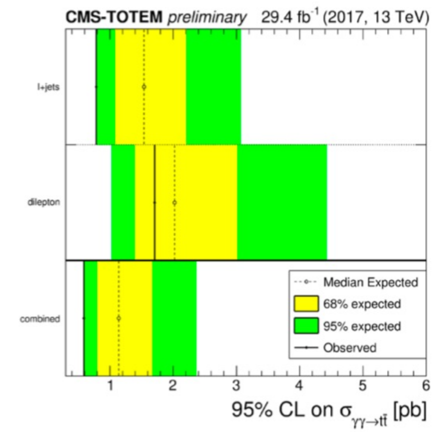
[CMS-PAS-PRO-21-001]

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



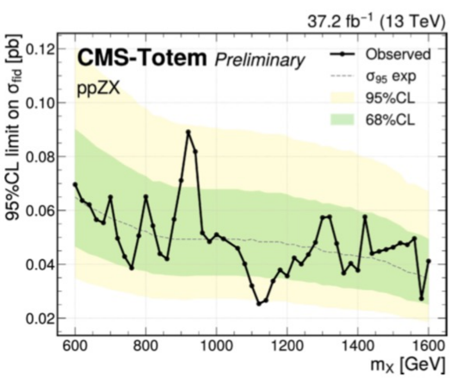
[CMS-PAS-TOP-21-007]

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



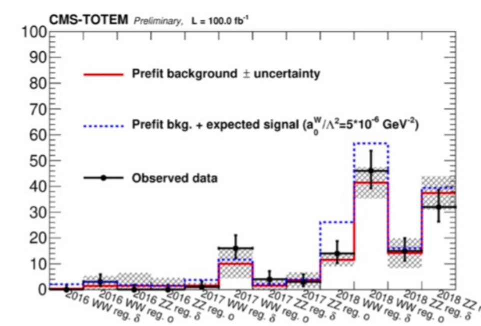
[CMS-PAS-EXO-19-009]

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



[CMS-PAS-SMP-21-014]

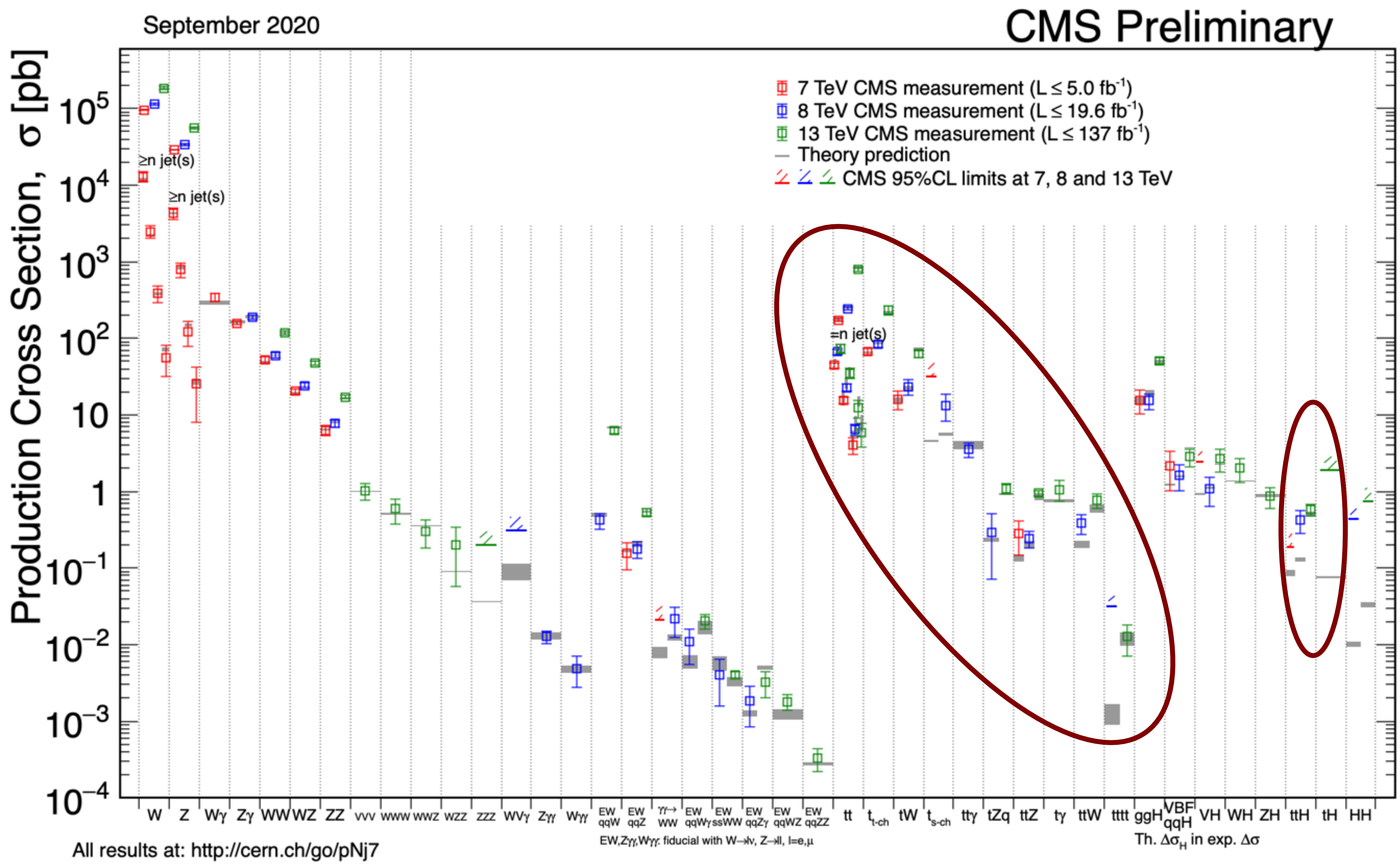
Search for anomalous high-mass γγ → WW and ZZ with forward protons



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.