Probing the SM: Top quarks and beyond

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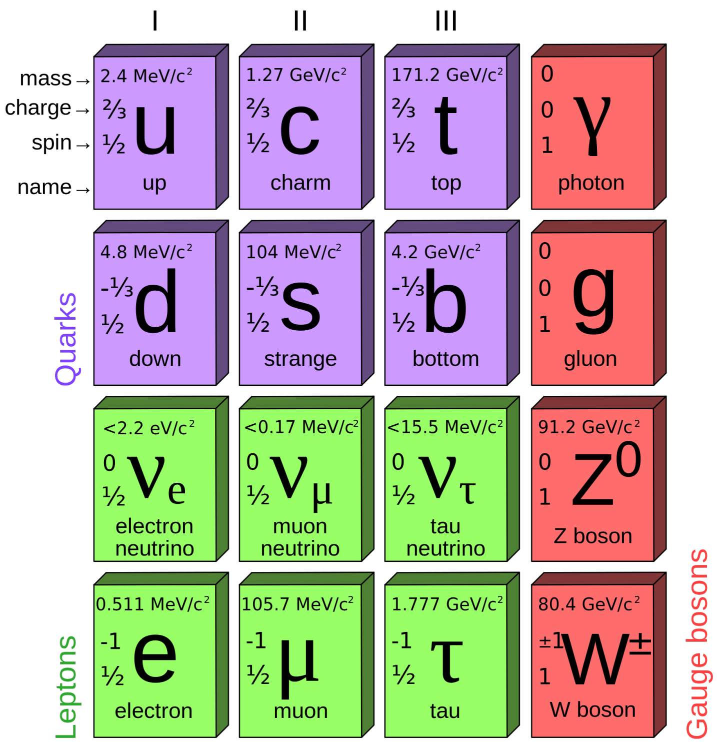
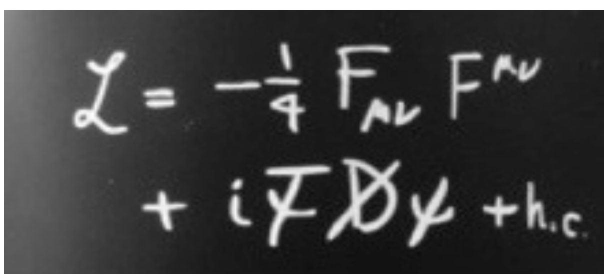
LIP Lisbon

April 4, 2016

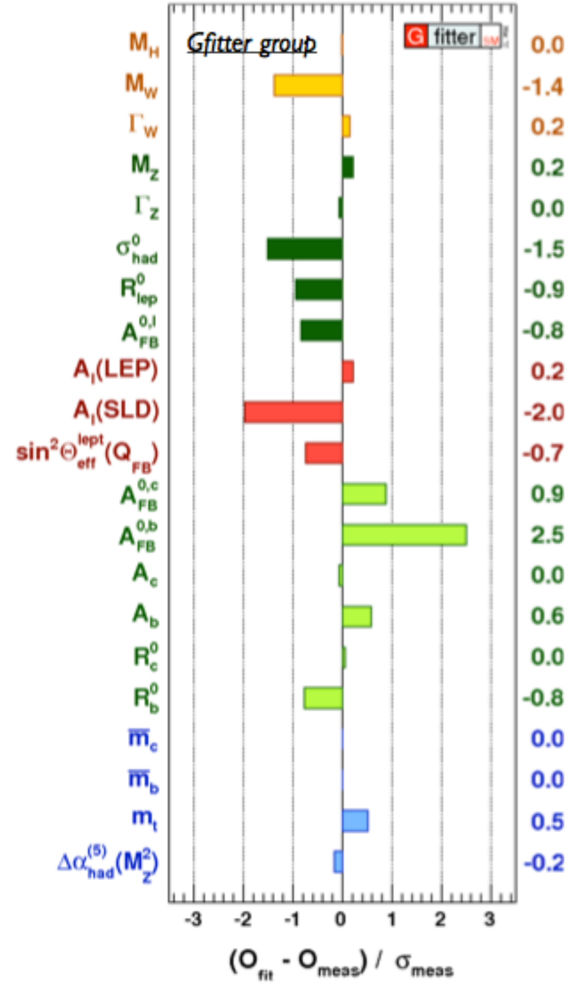
- ✓ Top quarks as window to New Physics
- ✓ Top-Higgs associated production
- ✓ Top quark signatures in SUSY
- ✓ Higgs and Dark Matter

SM confirmed by the data





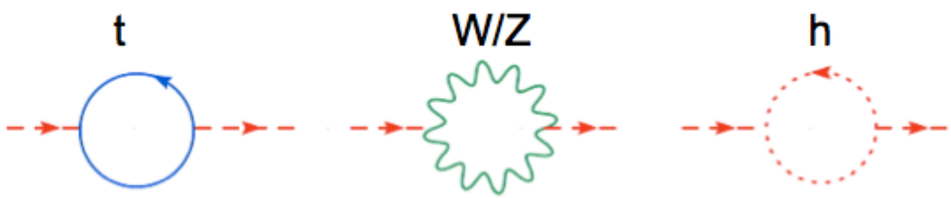
Standard model of elementary particles



Excellent agreement with all experimental results

Top quarks as window to BSM physics

Top quark affects stability of Higgs mass



Contributions grow with Λ:

$$m^2 = m_0^2 + g^2\Lambda^2$$

Cancellation?

Solutions:

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

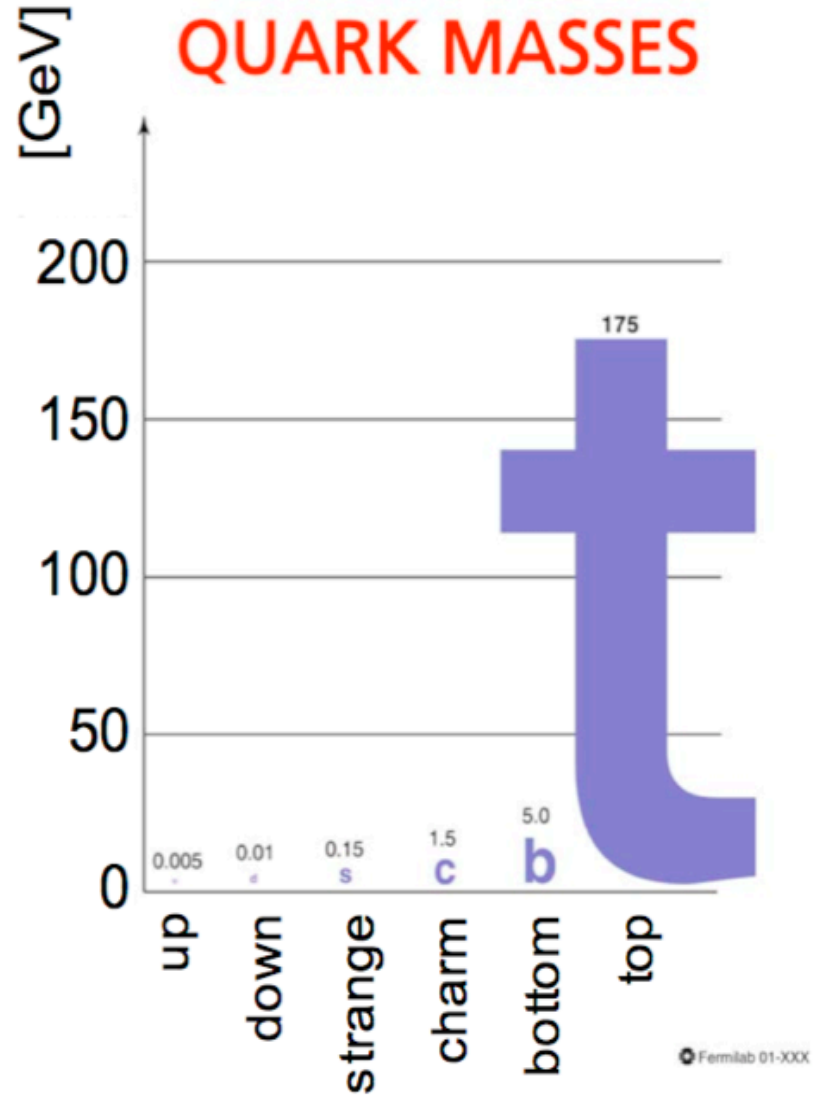
The top quark

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

τ=0.4x10^{-24} sec

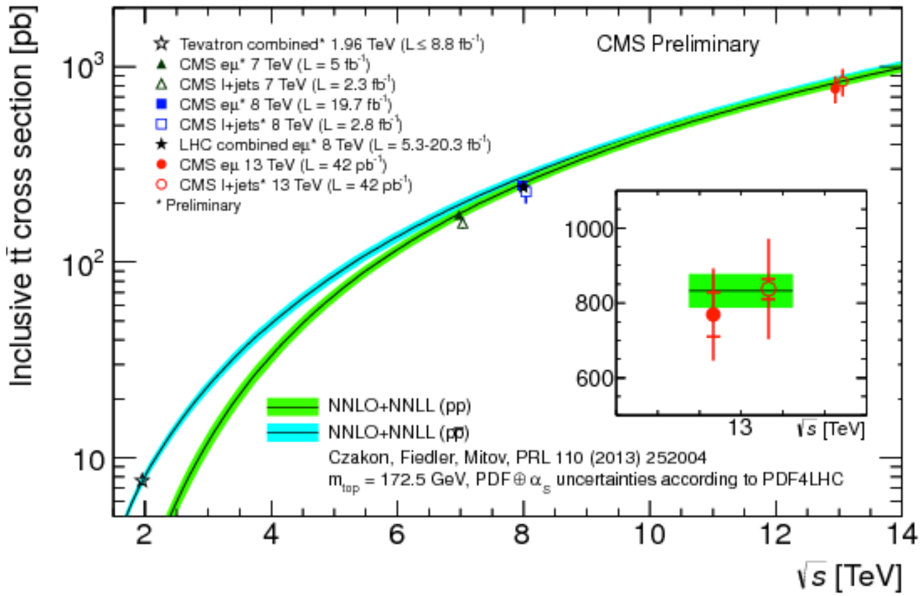
  - for m_{top}=175 GeV$\Rightarrow\Gamma$=1.4 GeV $\Rightarrow$no hadronization
  - large contributions to EWK corrections ~$G_F m_{top}^2$
  - very short lifetime $\Rightarrow$ bound states are not formed
    $\Rightarrow$ opportunity to study a free quark

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

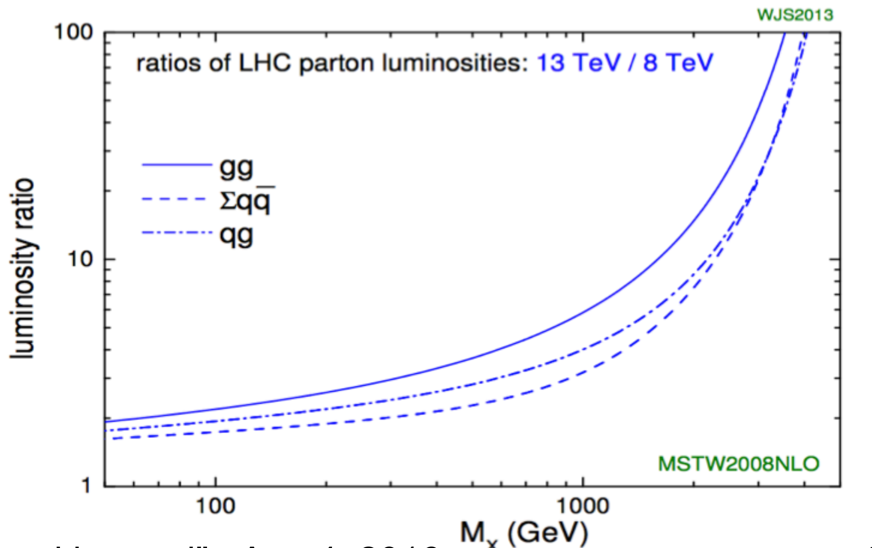


Role of top quark physics

- 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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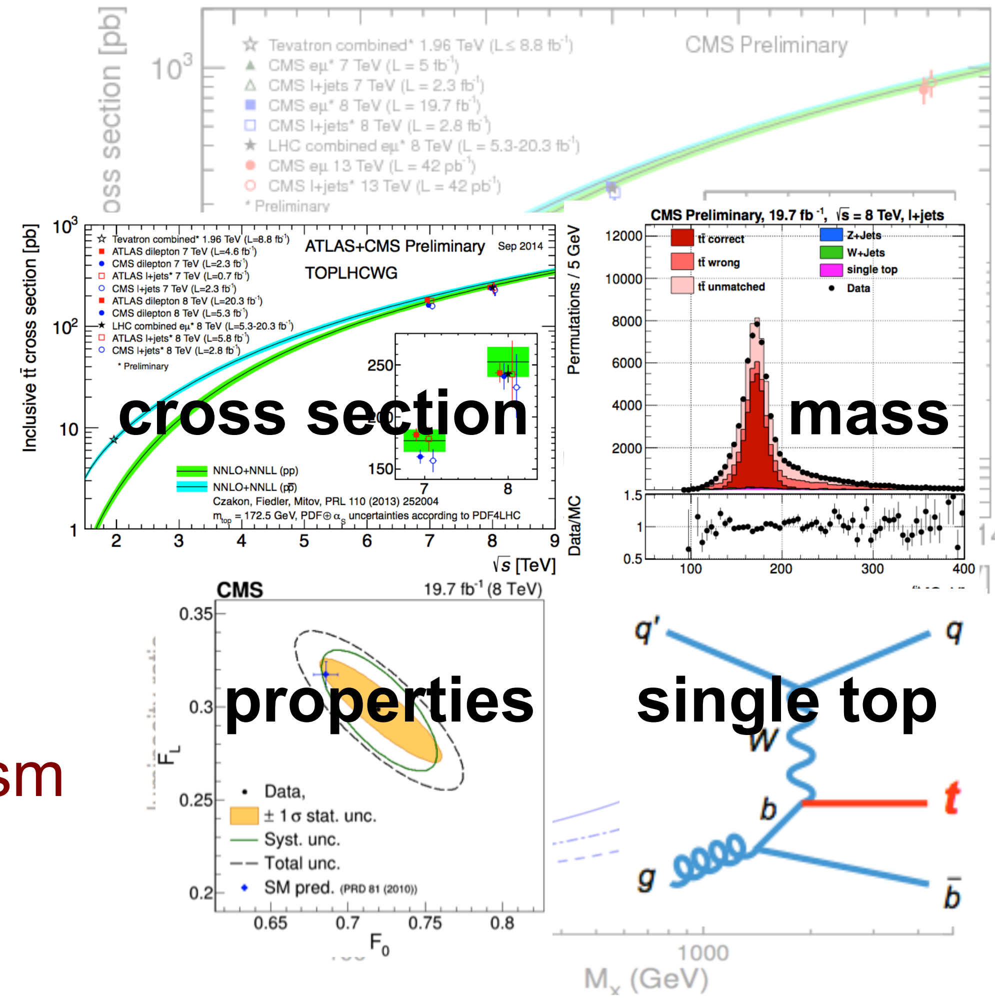
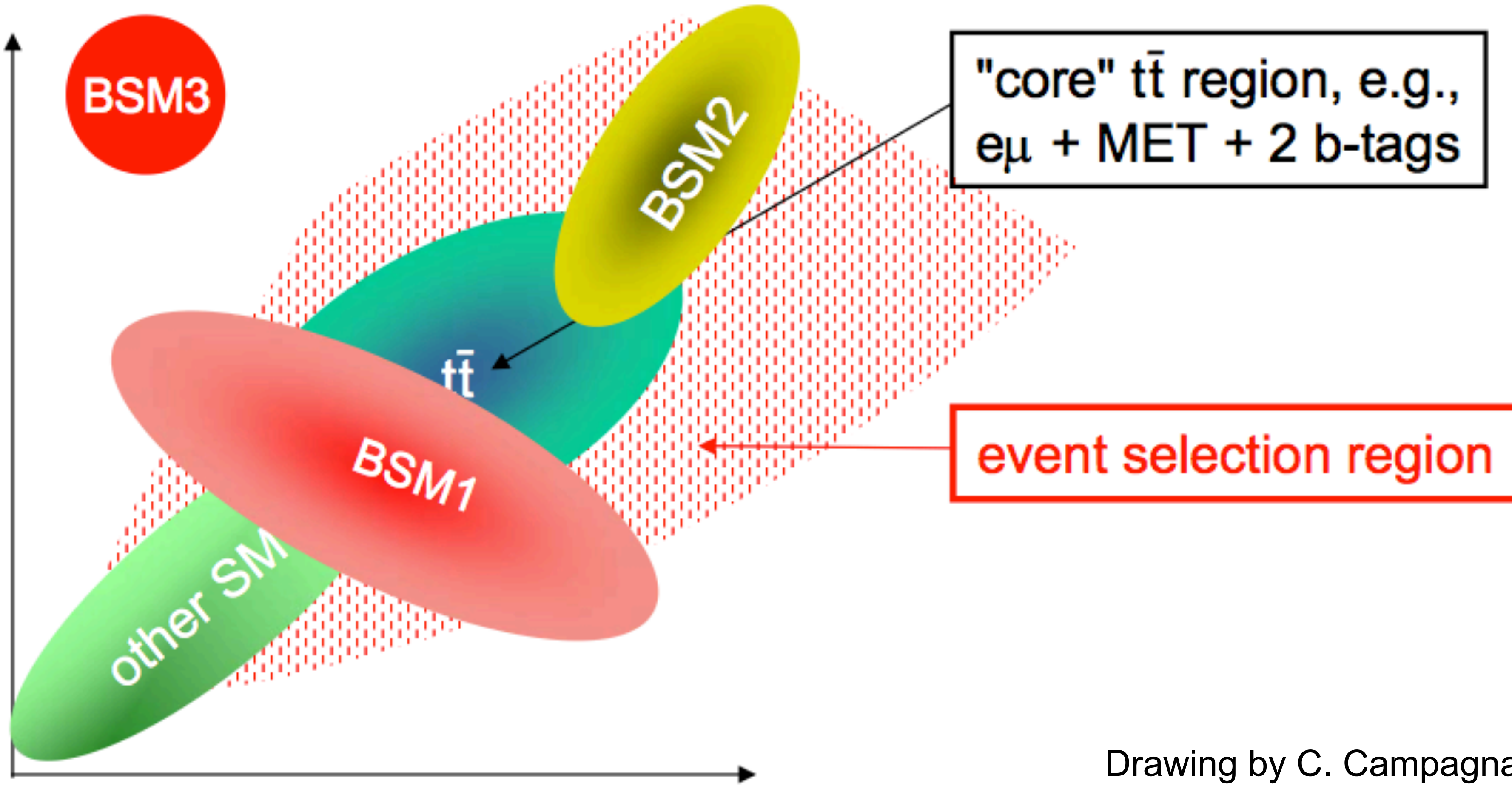


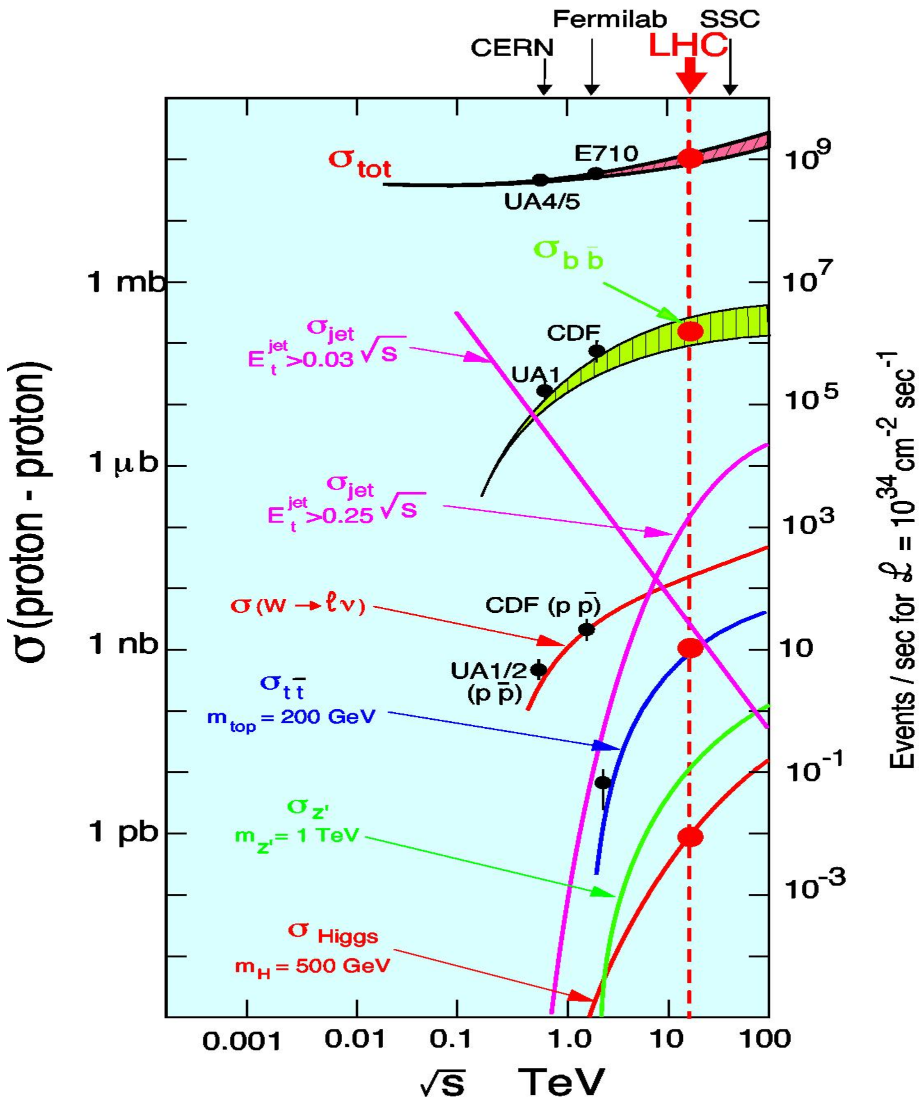
Study characteristics



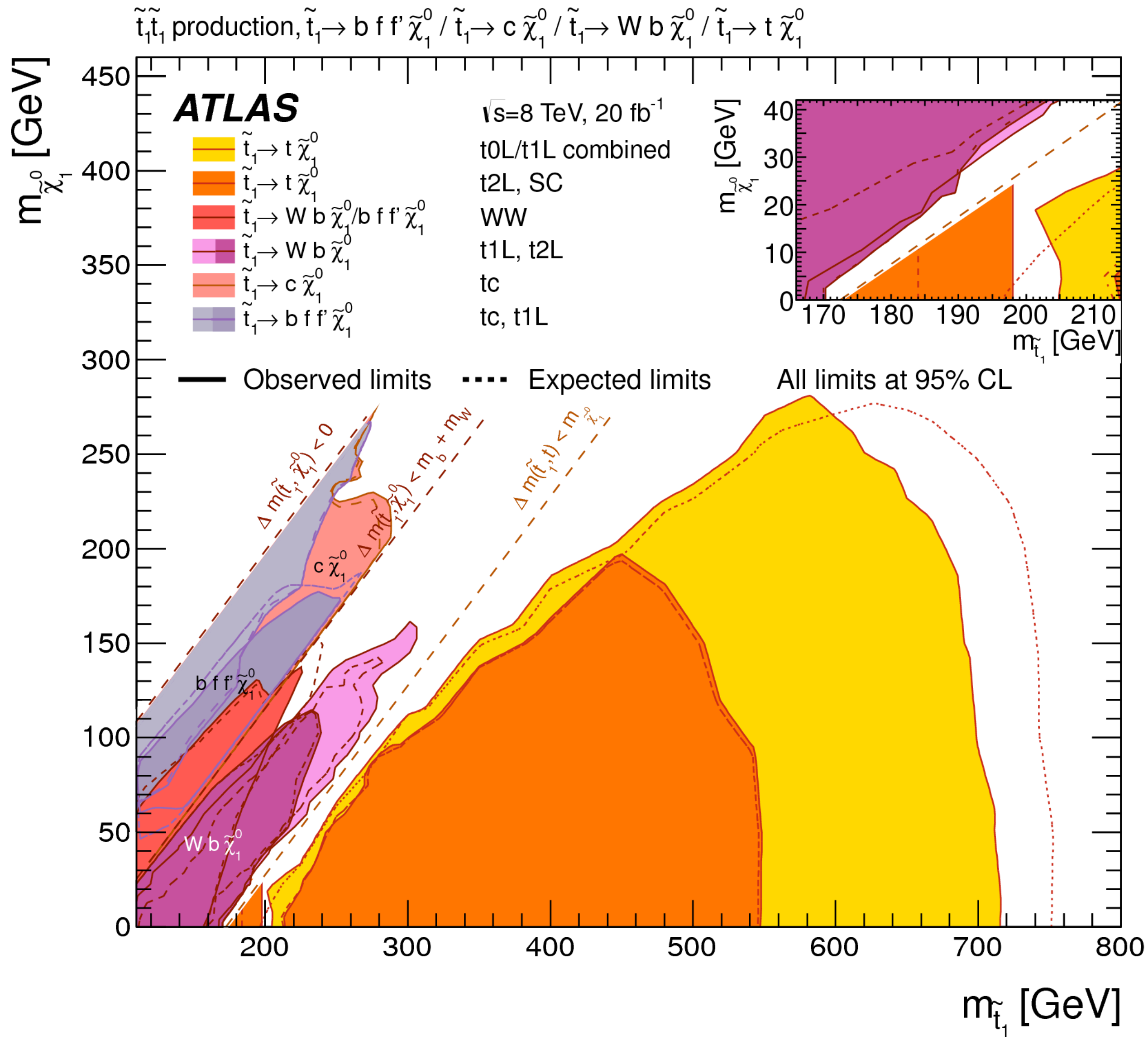
Drawing by C. Campagnari

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 cross section drops by factor of ~5:
  - Cacciari,Frixione, Mangano, Nason, Ridolfi: arXiv: 0804.2800
  - Czakon, Mitov: arXiv:1112.5675
  - top σ(7TeV) = 174 pb
  - top σ(8TeV) = 248 pb
  - top σ(13TeV)= 816 pb
- Background is more “flat”

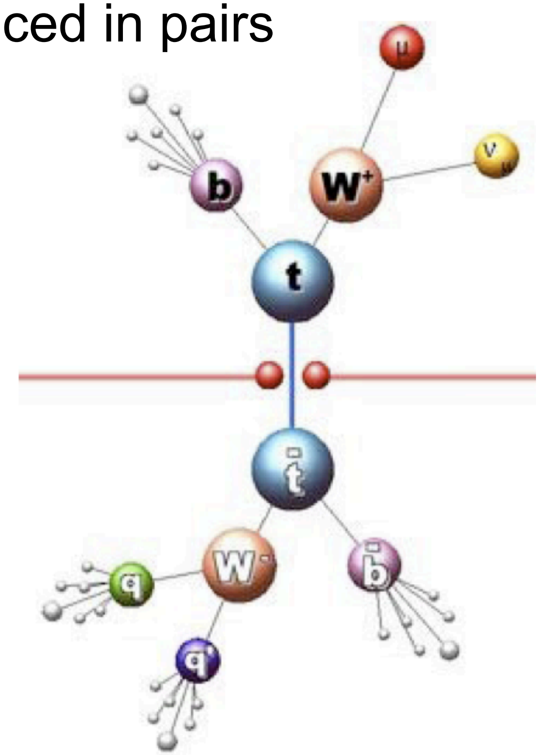


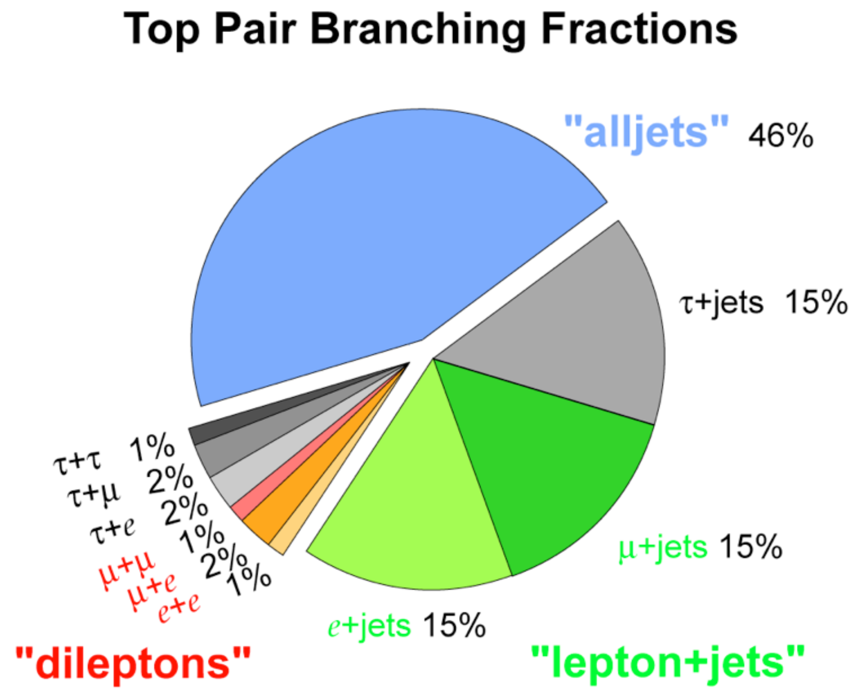
Regions hard to explore



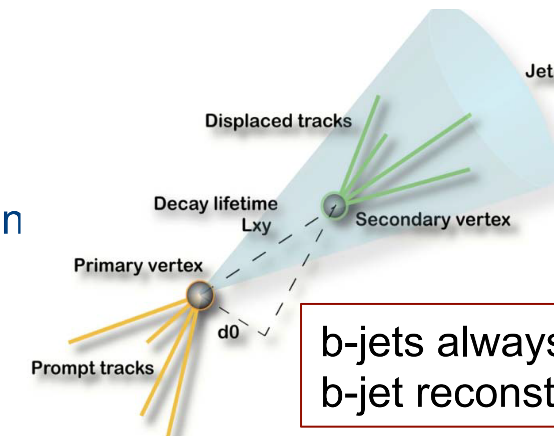
Top quark decays

Top quarks (mostly) produced in pairs





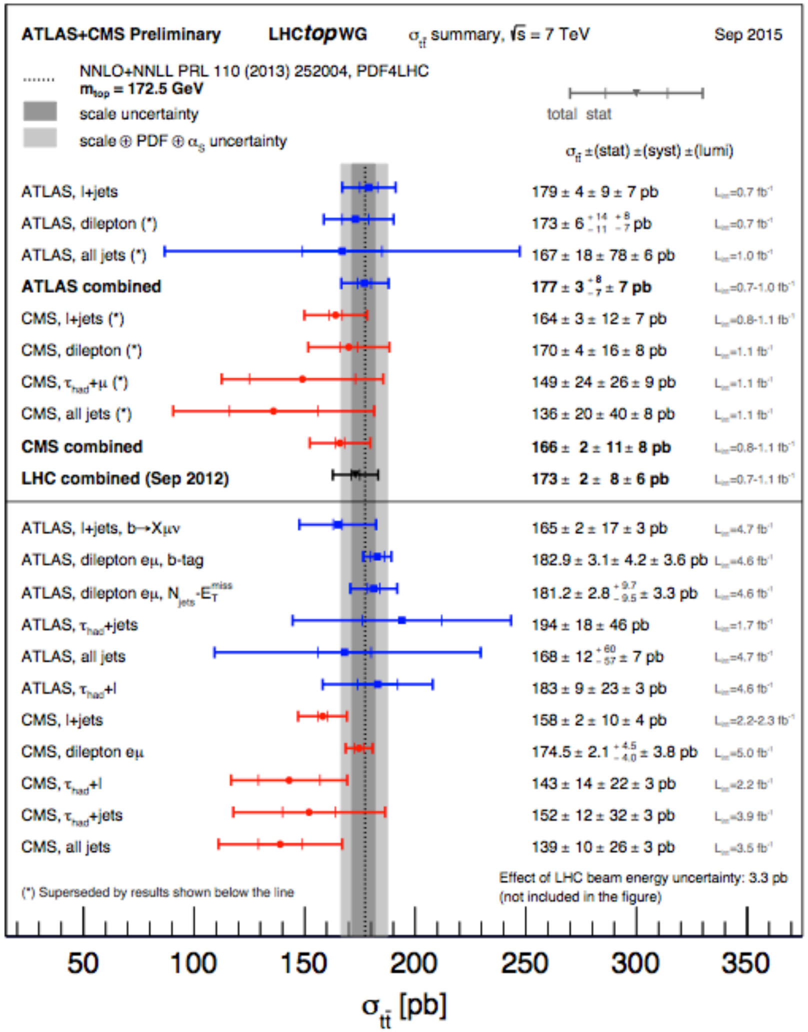
- Dilepton (ee, μμ, eμ):
  - BR~5%, 2 leptons+2 b-jets+2 neutrinos
- Lepton (e or μ) + jets
  - BR~30%, one lepton+4jets (2 from b)+1 n
- All hadronic
  - BR~44%, 6 jets (2 from b), no neutrinos



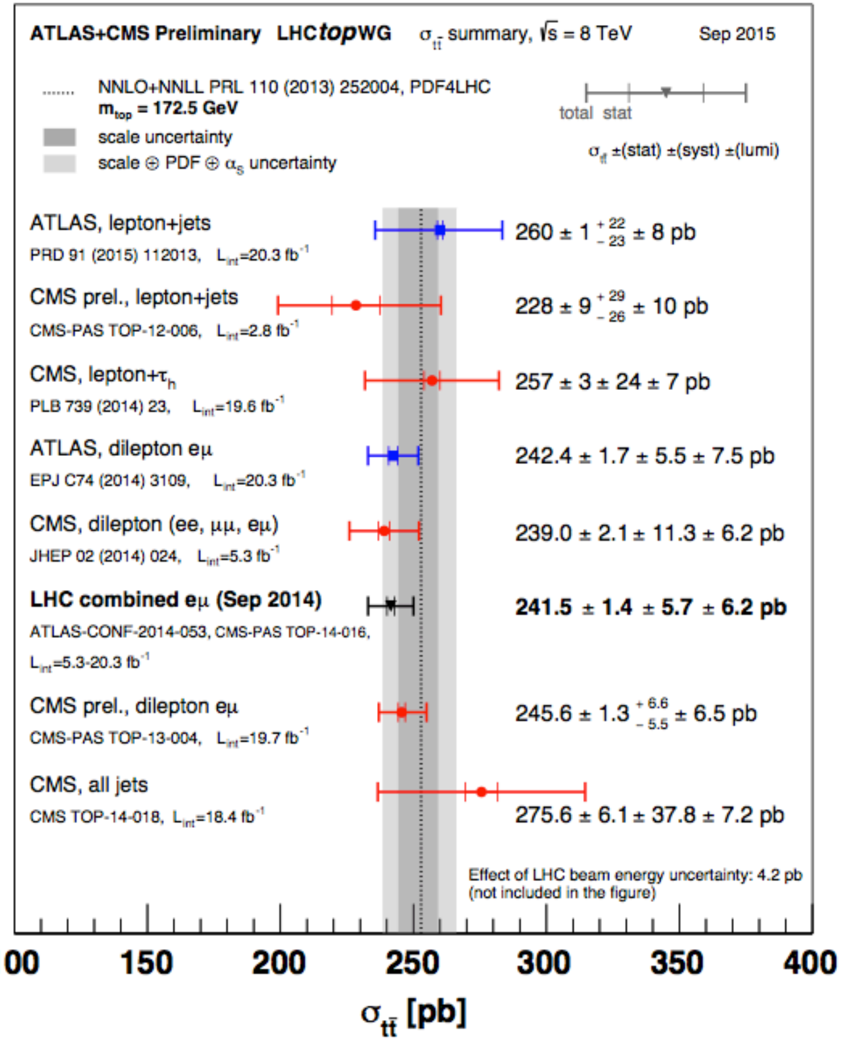
b-jets always present
b-jet reconstruction plays important role

Cross sections

7 TeV



8 TeV



Cross section measurement

Number of observed events

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

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

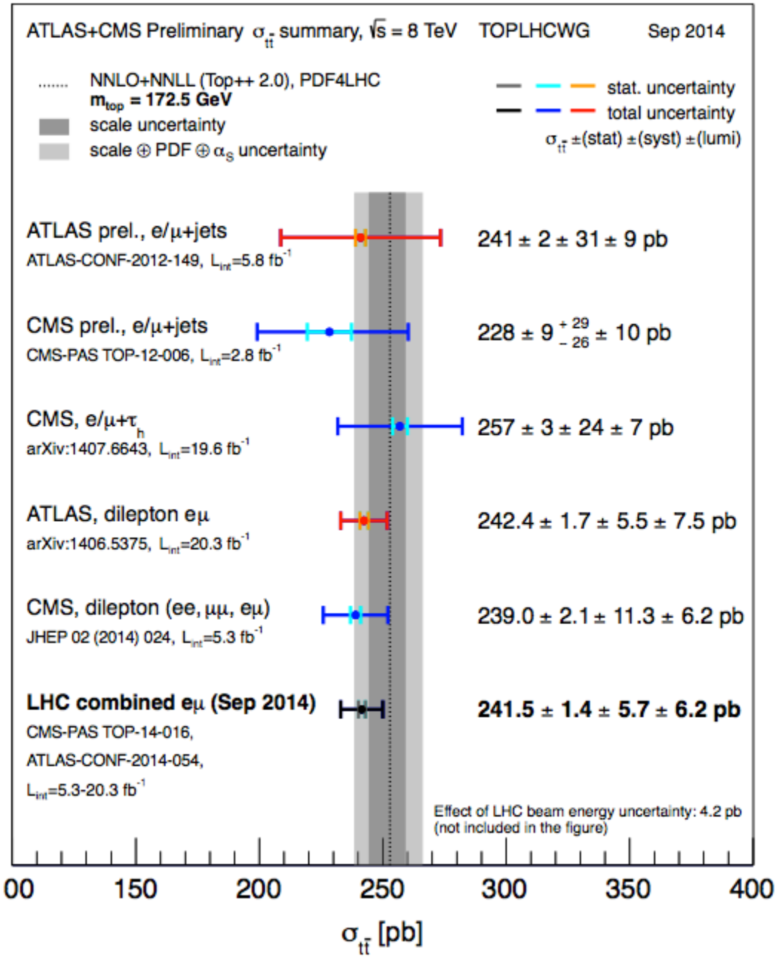
Acceptance *(experimental: detector, efficiencies)*

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

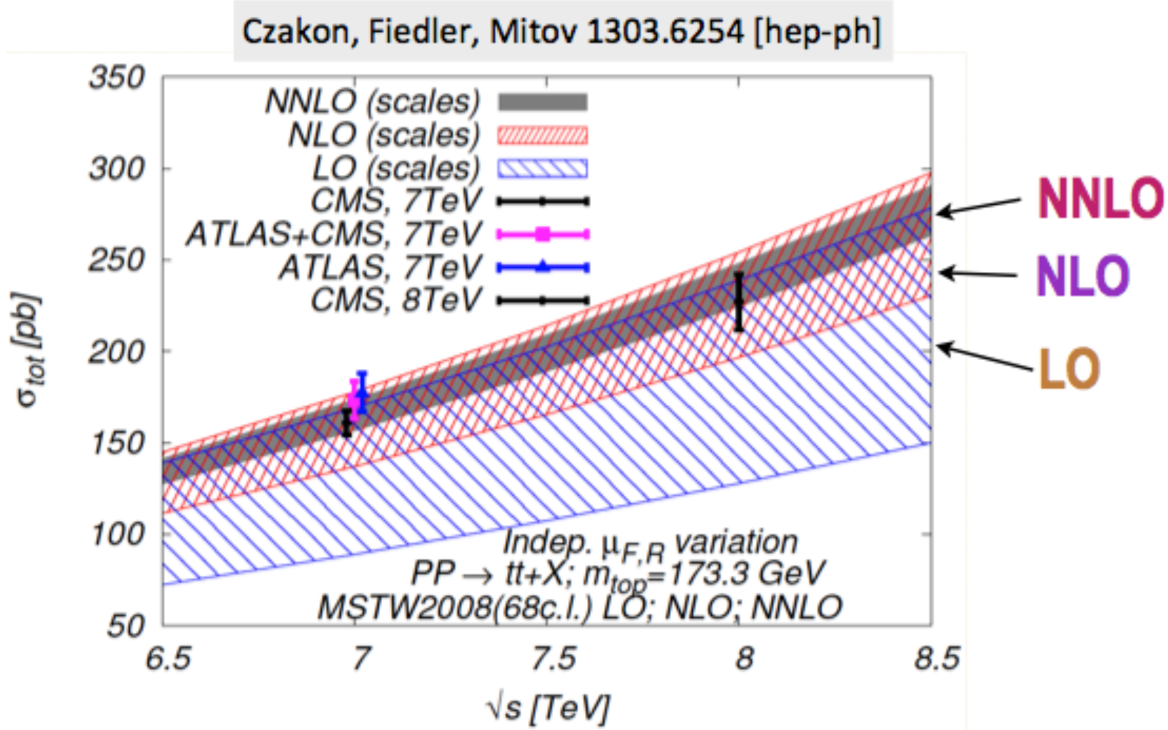
Cross sections (cont.)

CMS-TOP-14-016

±4%



⇒meas. challenging the theory



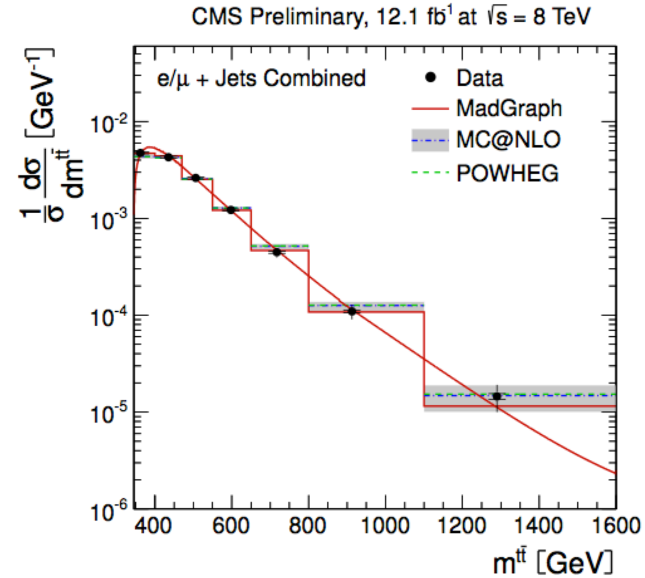
Collider	σ_{tot} [pb]	scales [pb]	pdf [pb]
Tevatron	7.164	+0.110(1.5%) −0.200(2.8%)	+0.169(2.4%) −0.122(1.7%)
LHC 7 TeV	172.0	+4.4(2.6%) −5.8(3.4%)	+4.7(2.7%) −4.8(2.8%)
LHC 8 TeV	245.8	+6.2(2.5%) −8.4(3.4%)	+6.2(2.5%) −6.4(2.6%)
LHC 14 TeV	953.6	+22.7(2.4%) −33.9(3.6%)	+16.2(1.7%) −17.8(1.9%)

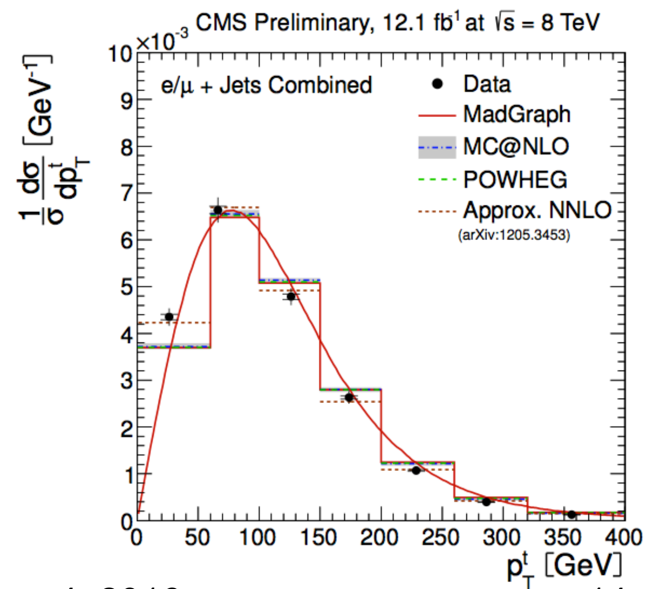
±3-5%

Differential cross sections

EPJC 73(2013) 2339, CMS-TOP-12-027

- Measure differential cross section
  - Test perturbative QCD
  - Test BSM scenarios (Z' decays, etc) with narrow resonance
  - Improve ttbar modeling and reduce uncertainties
- Correct for detector effects and acceptances
- CMS sees softer top p_T in data, agreement with ATLAS at high p_T
  - Due to momentum reshuffling, P. Nason, indico.cern.ch/event/301787
  - FSR shower changes mass of final state partons. Light parton shower can build sizeable mass, and t/tbar do not radiate (reduced momenta to conserve energy)
- NNLO might be able to solve issue
- Short term solution: consider difference as uncertainty

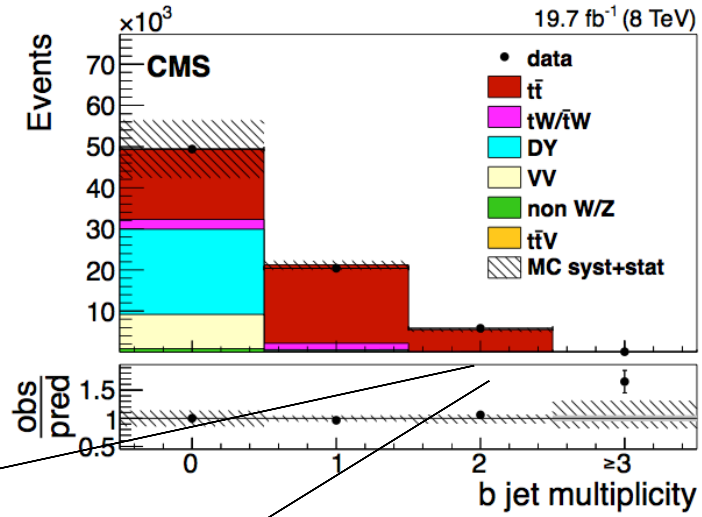


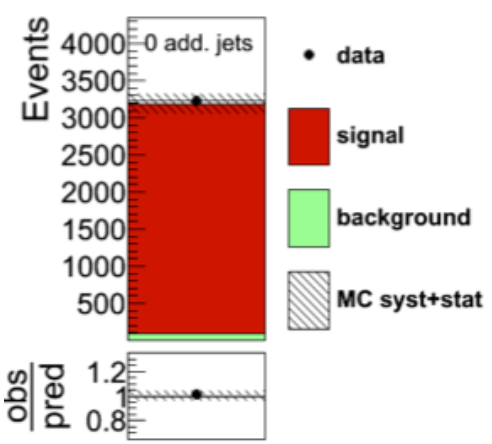


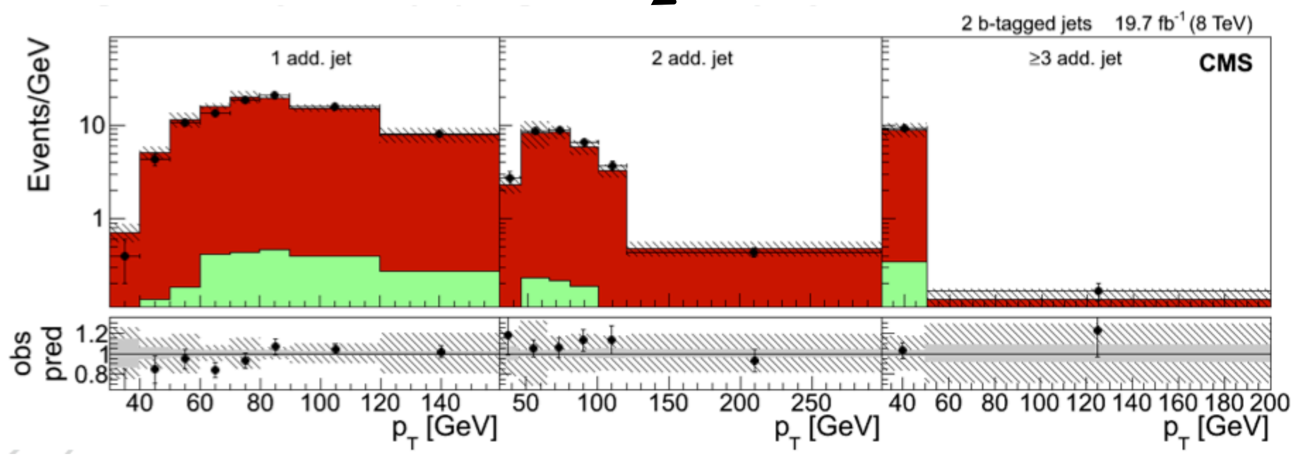
Cross section: multi-dimensional fit

CMS-TOP-13-004

- Look into finer details
- Keep selection as inclusive as possible
- Re-calibrate in-situ (ε_b, …)
- Categorize: high-purity vs background dominated
- Constrain systematics (JES, ISR/FSR, modeling, etc)





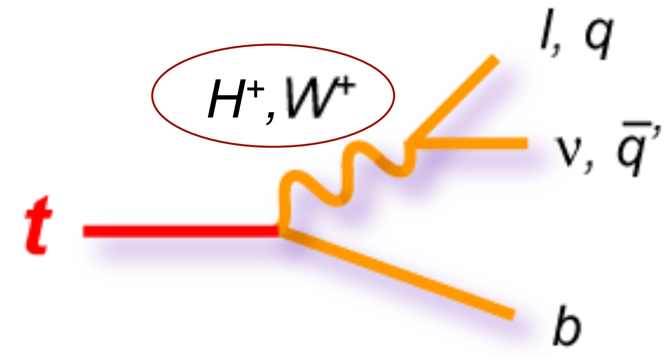


Probing the Wtb vertex

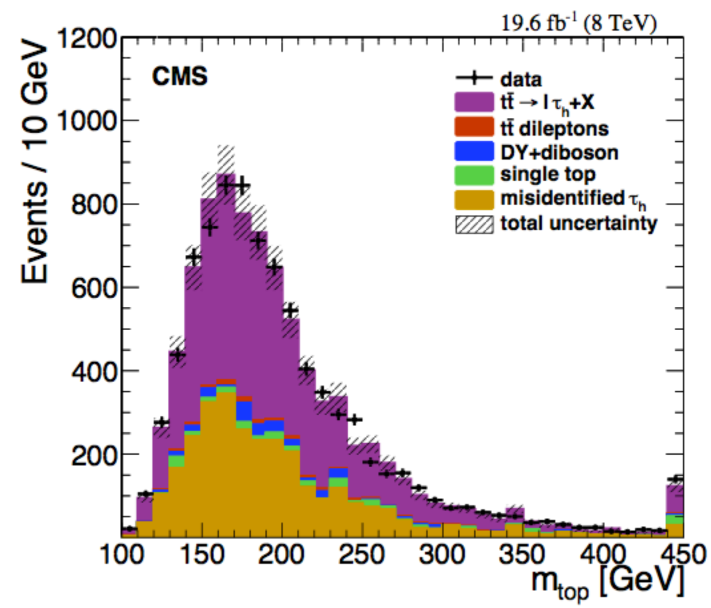
PRD 85 (2012) 112007, PLB 739 (2014) 23

Dileptons with taus

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

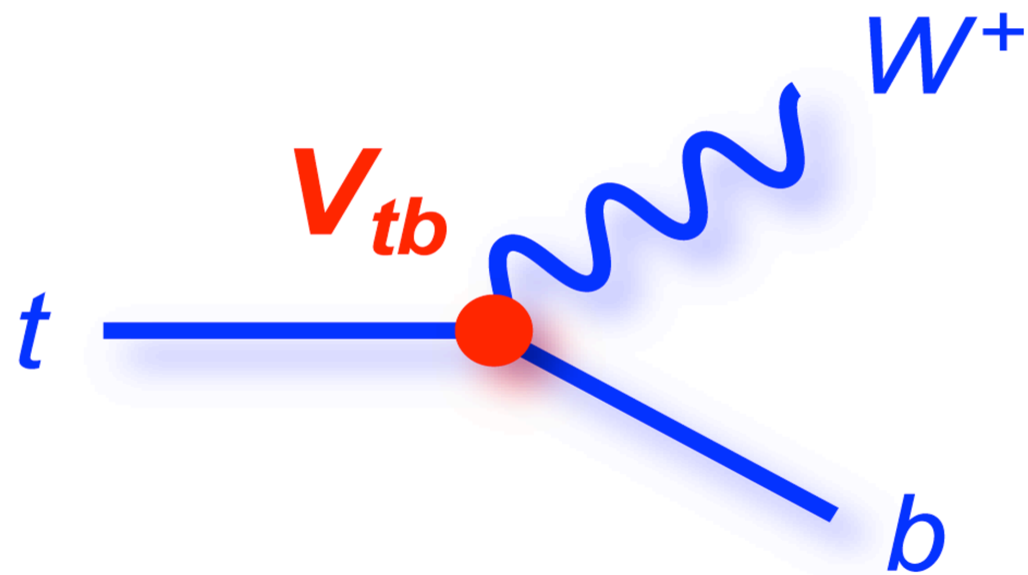


Channel	Signature	BR
Dilepton(e/μ)	*ee*,μμ,*e*μ + 2*b*-jets	4/81
Single lepton	*e*,μ + jets + 2*b*-jets	24/81
All-hadronic	jets + 2*b*-jets	36/81
Tau dilepton	*e*τ, μτ +2 *b*-jets	4/81
Tau+jets	τ + jets + 2*b*-jets	12/81



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

How does a top quark decay?



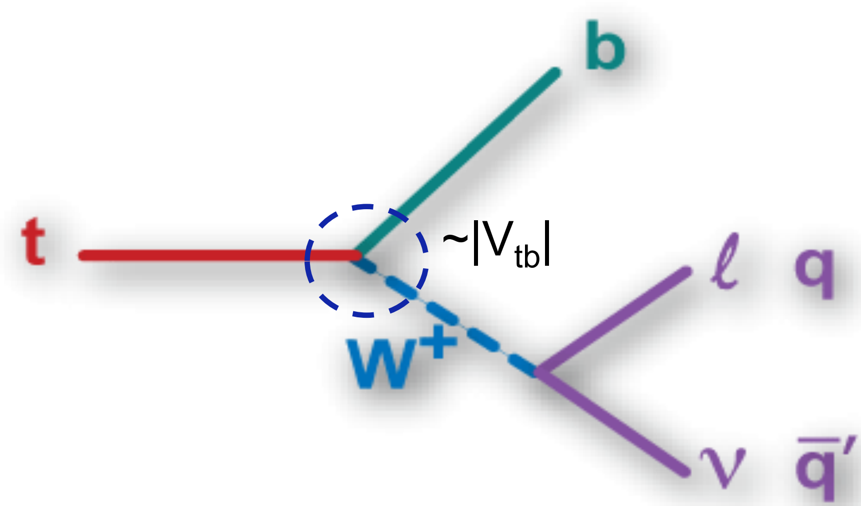
- almost always $t \rightarrow Wb$ (i.e. $V_{tb} \sim 1$)
- lifetime is short, and it decays before hadronizing
- the W is real:
  - can decay $W \rightarrow l\nu$ ($l = e, \mu, \tau$), BR~1/9 per lepton
  - can decay $W \rightarrow qq$, BR~2/3

Measure R in dilepton channel

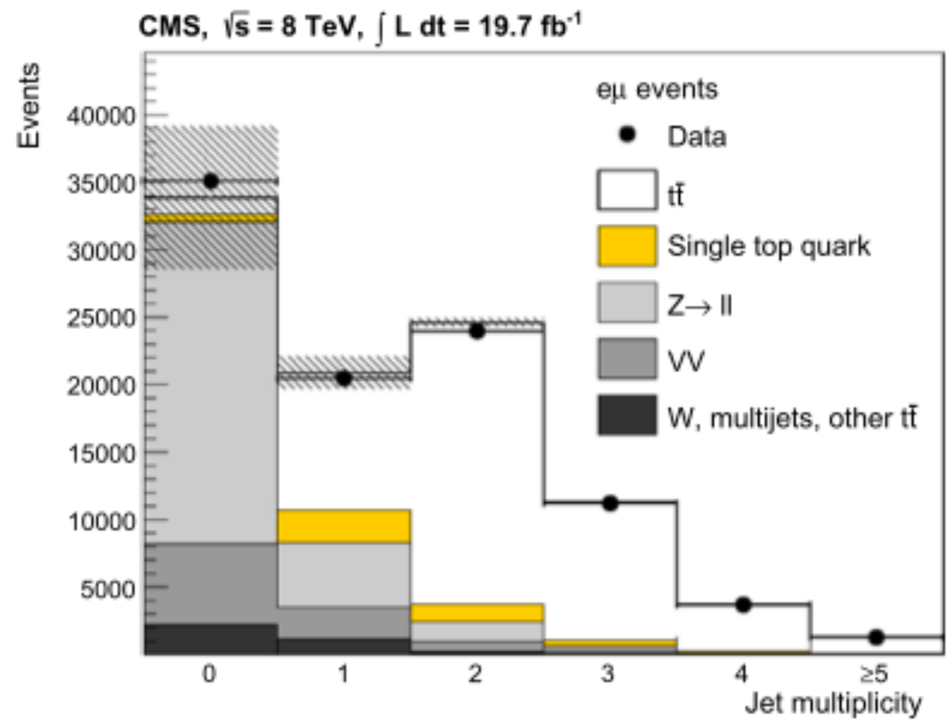
N.Cim. B125(2010)983, PLB 736(2014)33

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

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



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

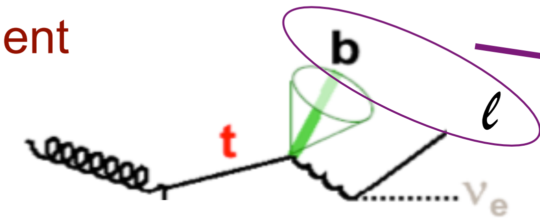


Signal or background?

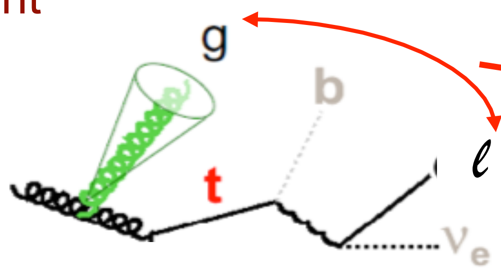
N.Cim. B125(2010)983, PLB 736(2014)33

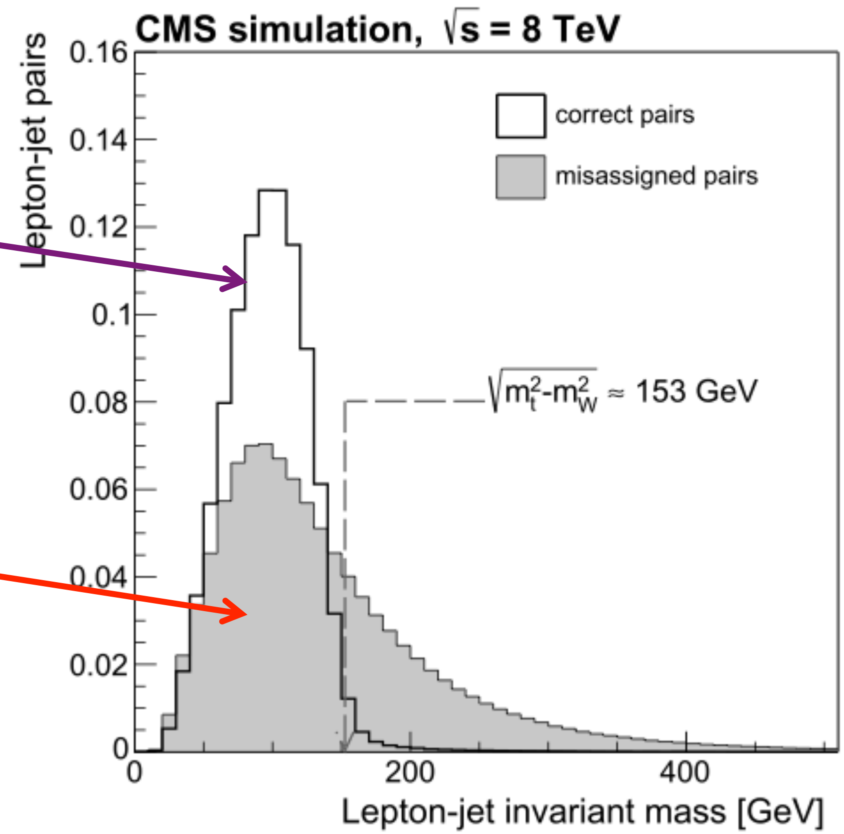
Data-driven determination of background

- Reconstruct lepton-jet invariant mass
  - Correct assignment



  - Wrong assignment



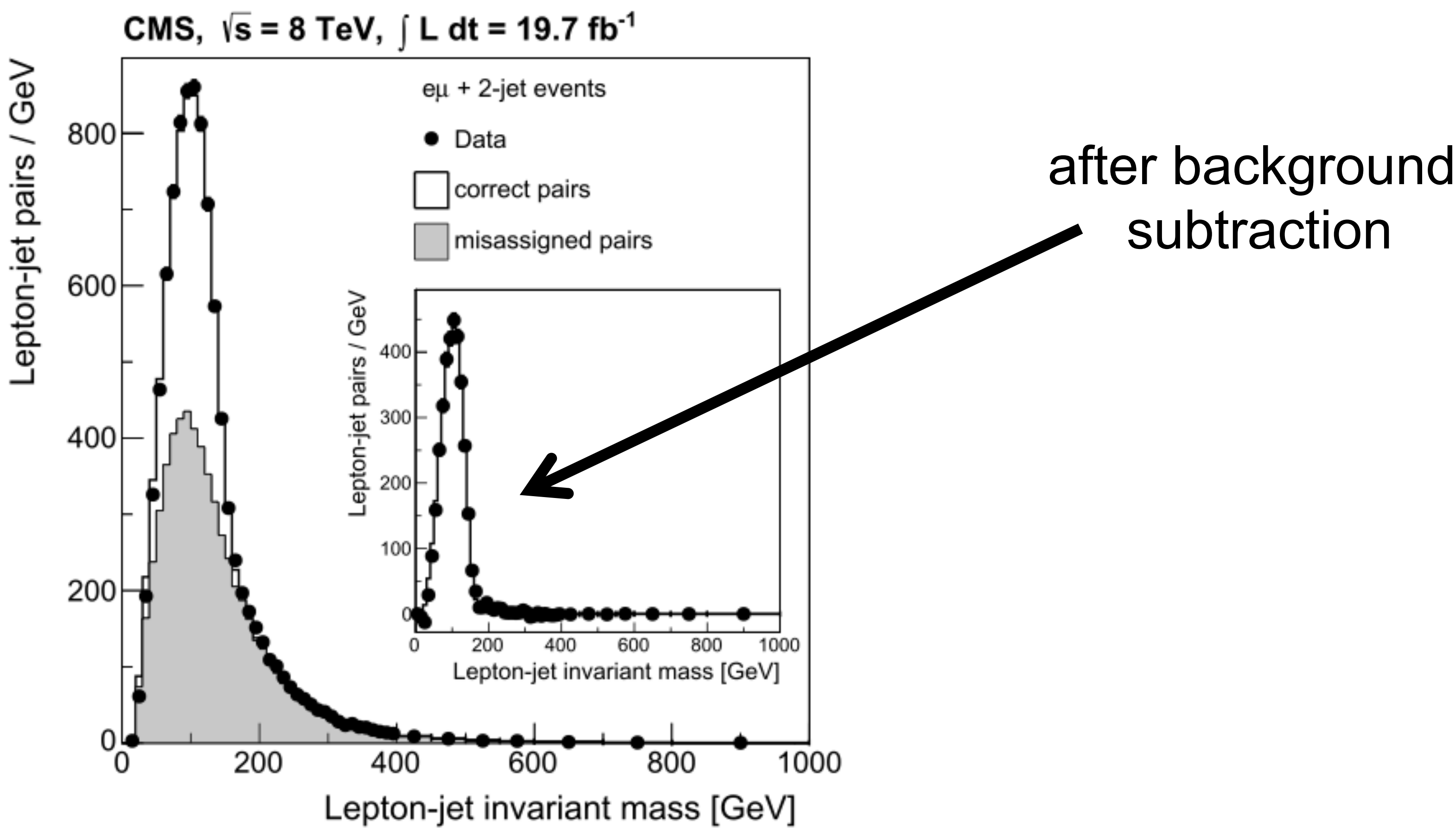


- Use tail to model background in signal region

Signal vs. background

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

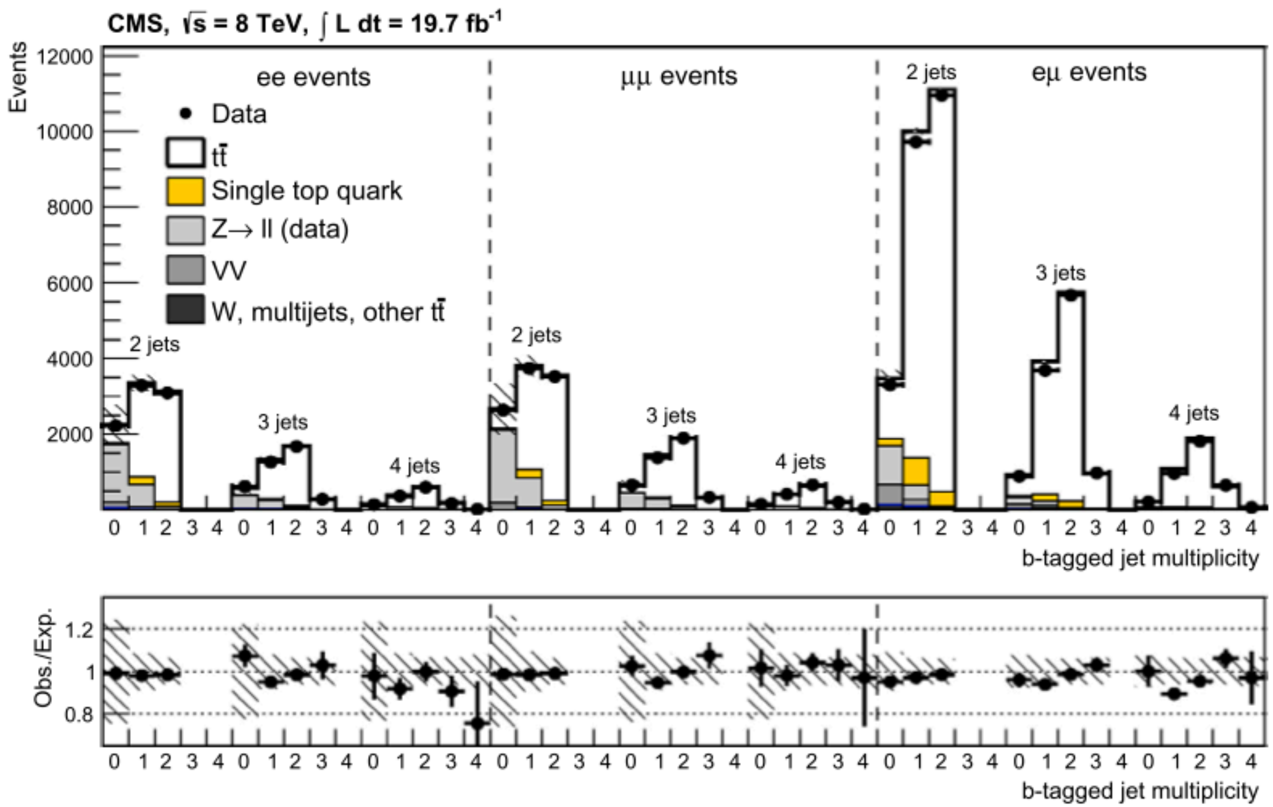
Scale shape to match spectrum observed with M_{lj}>180 GeV



Heavy flavor content

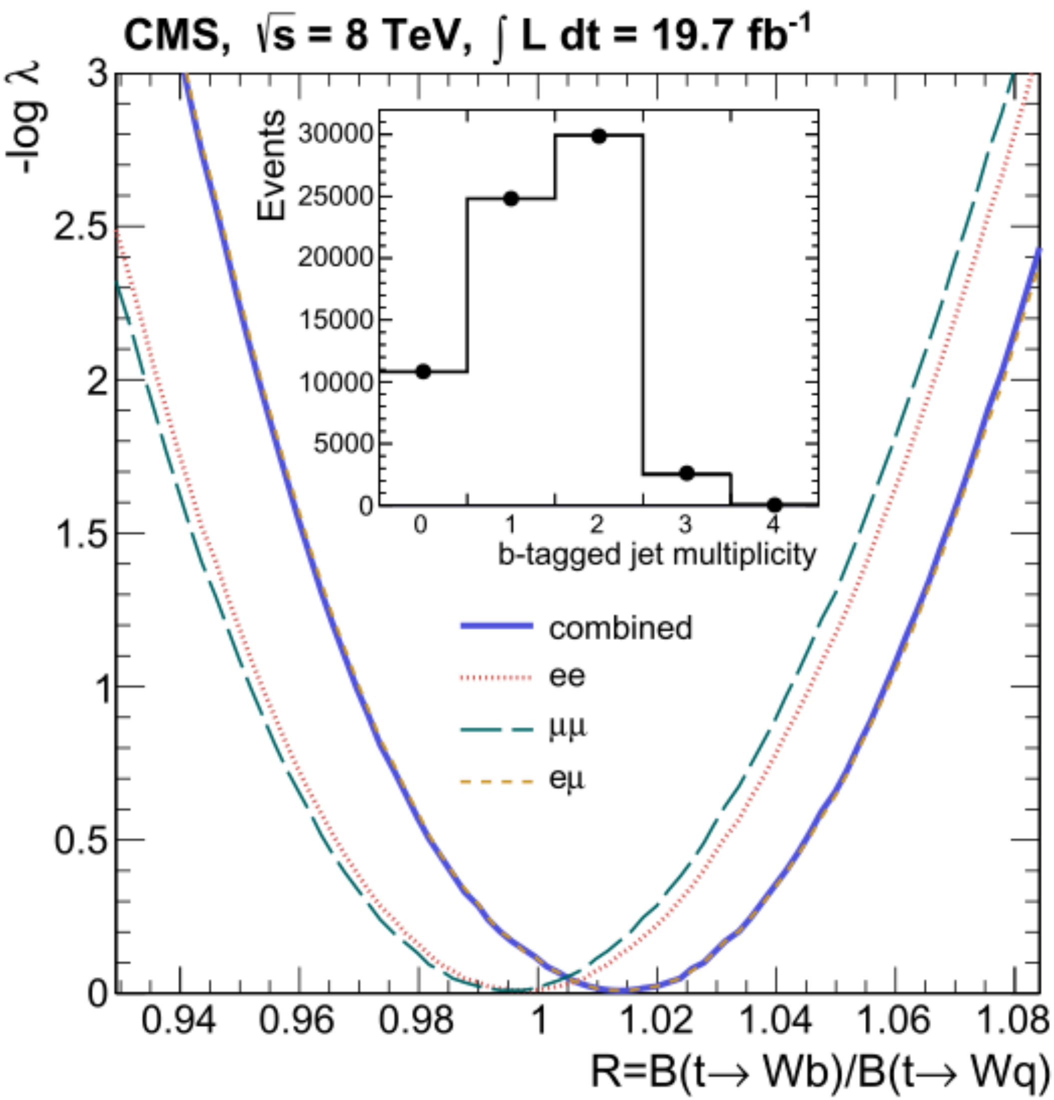
N.Cim. B125(2010)983, PLB 736(2014)33

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



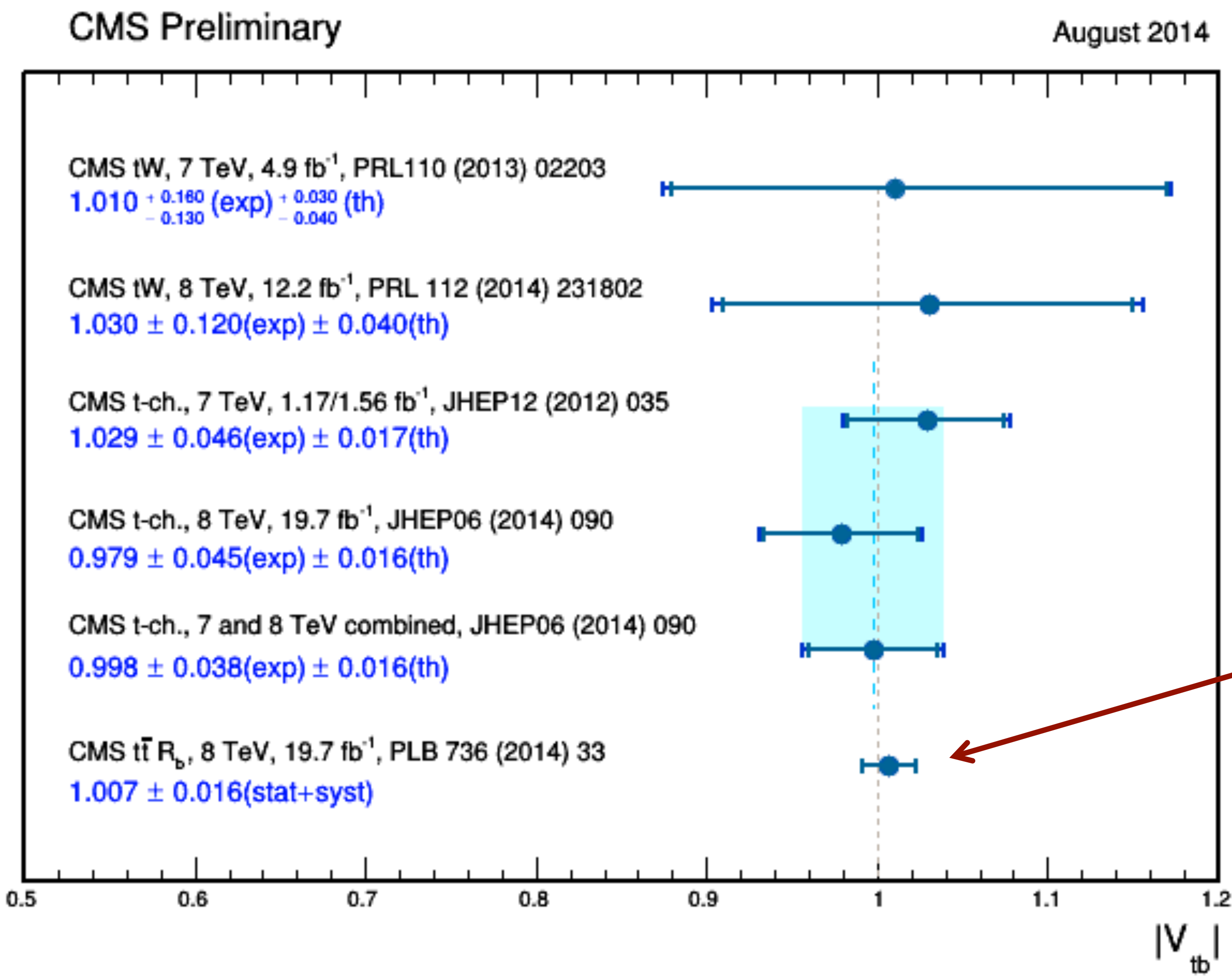
Measure R

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



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

Summary of R results



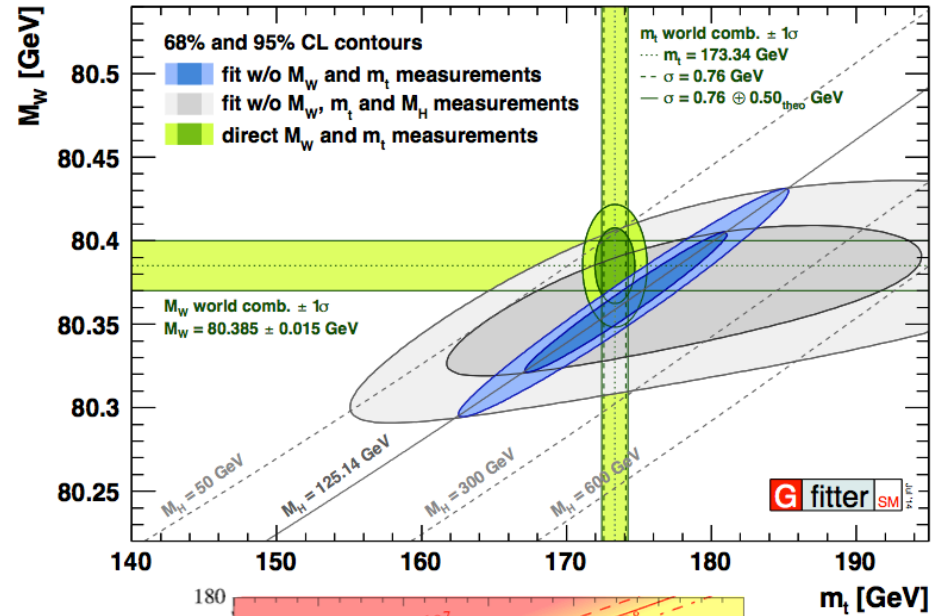
Most accurate measurement

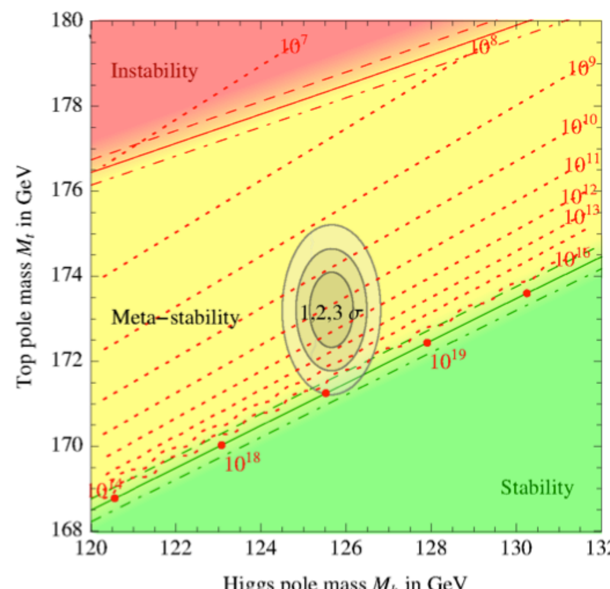
Top quark mass: why do we care?

- Top quark mass is a fundamental parameter of the SM

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

- Top is the only fermion with the mass of the order of EWSB scale
- Discovered Higgs boson fits well with precise determinations of m_W and m_{top}
  - Highly fine-tuned situation
  - ~1GeV is all it takes to tip the scales
- Run2 will allow for discrimination between SM and MSSM scenario (?)
- The fate of the Universe might depend on Δm_{top}~1 GeV

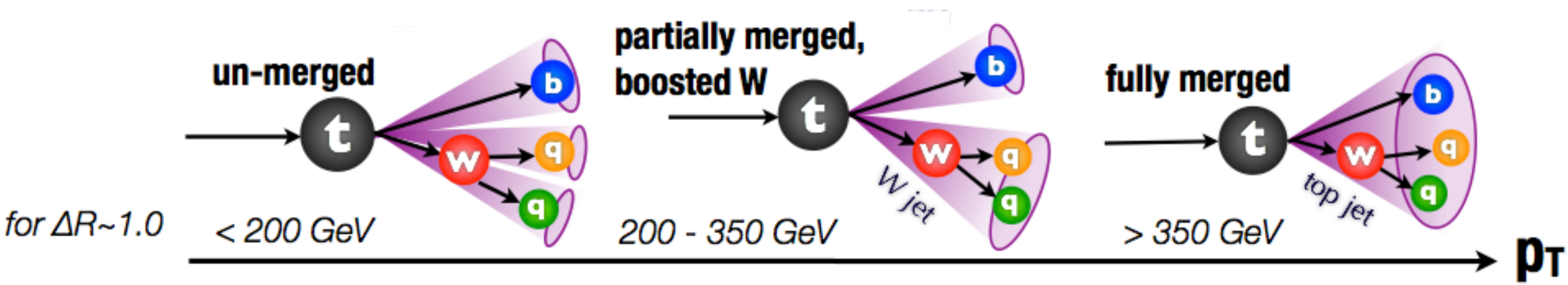




Probing top quark production

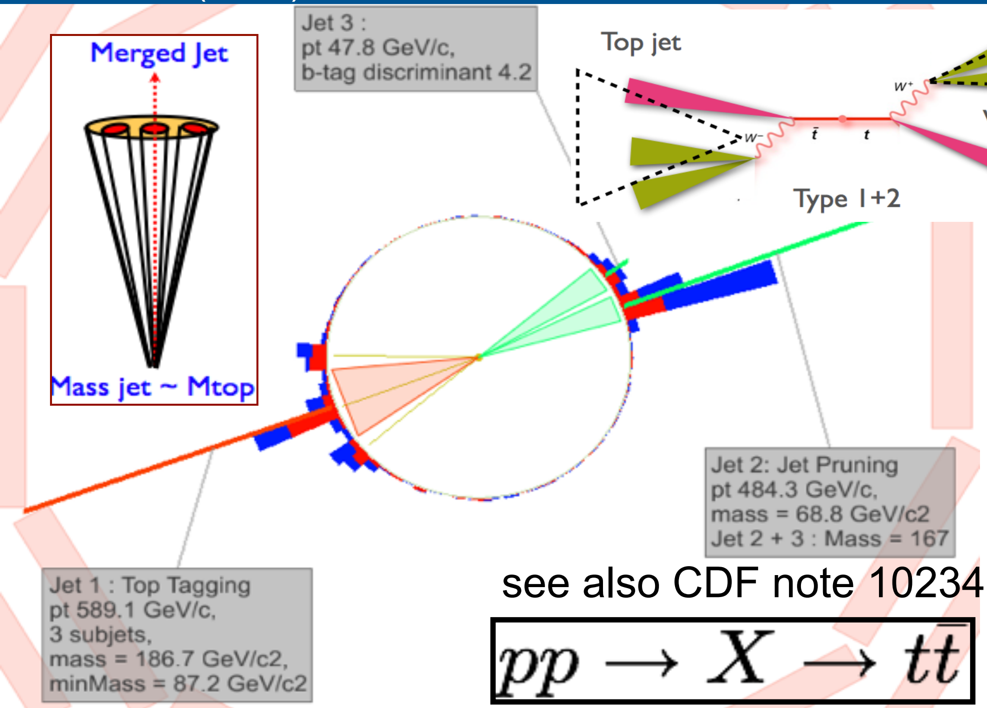
- Differential measurements
  - Testing QCD, measuring properties, searching for new physics, …
  - Function of kinematics, global variables, associated production
- Increased sensitivity: top quark pairs produced at rest
  - σ (M_{tt}>1 TeV at 13 TeV) =8 x σ(M_{tt}>1 at 8 TeV)

⇒Unique opportunity to probe boosted production at 13 TeV



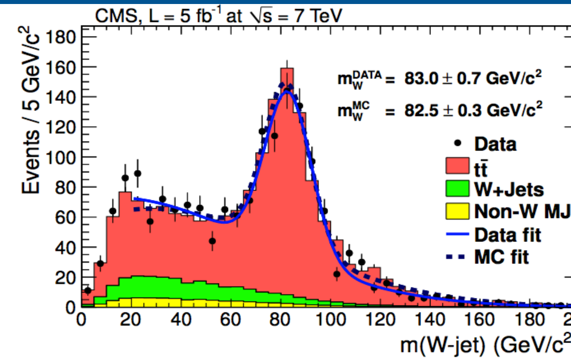
Boosted topology

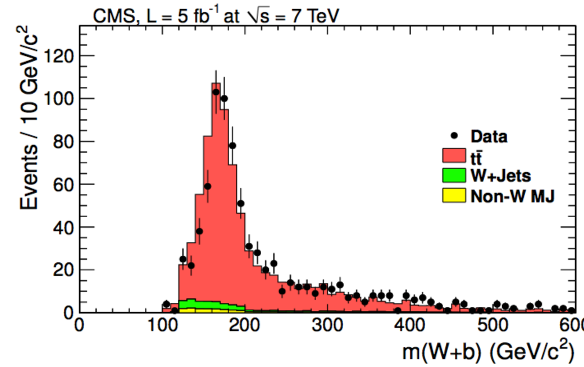
JHEP 1209(2012)029

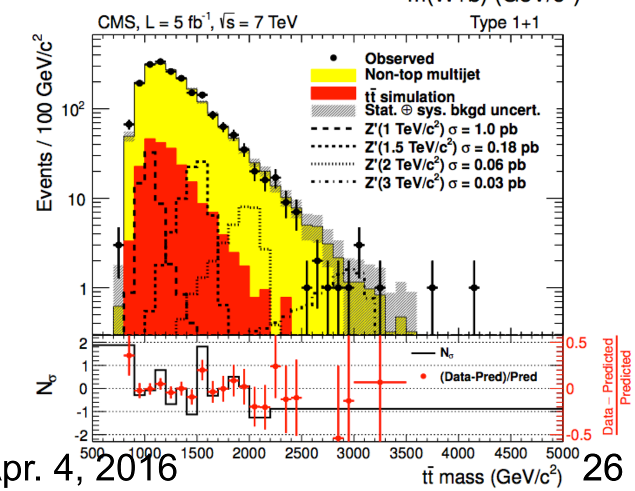


see also CDF note 10234

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







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

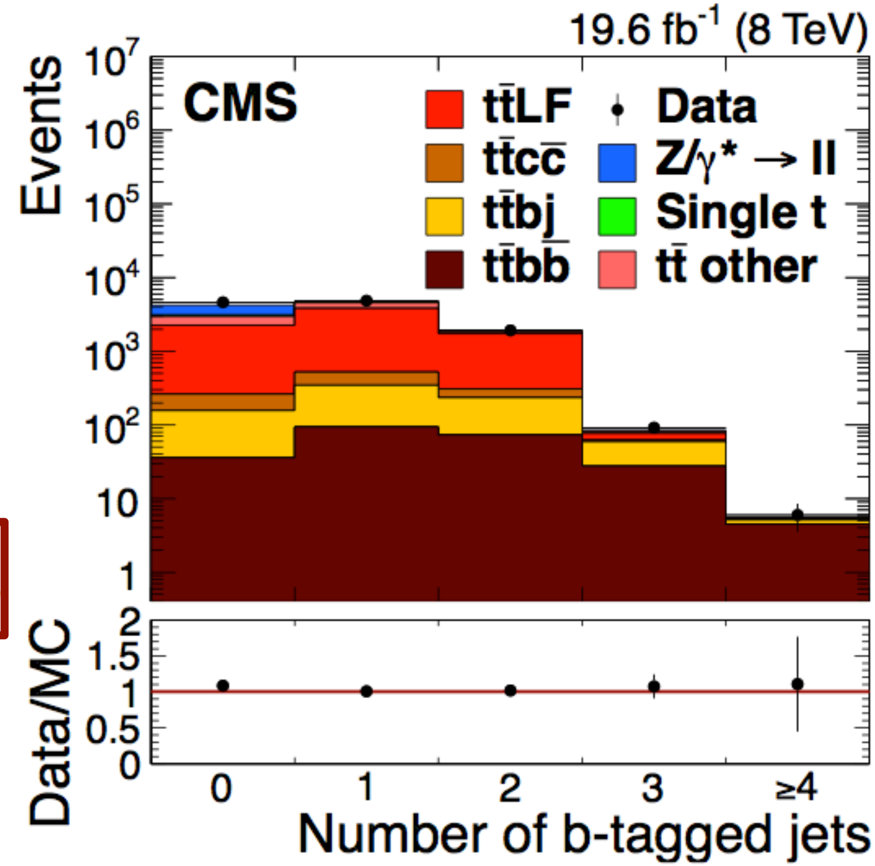
ttbar+jet cross section

arXiv:1411.5621

- Study ttbar with associated jet production
  - Dilepton events (≥4 jets, at least 2 b-jets)
  - Order jets by b-tag discriminator value
  - Ratio of number of events obtained from data by fitting the b-tagging discriminator distributions
  - Cross section measured in the visible (full) phase space (p_T>20,40 GeV)

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

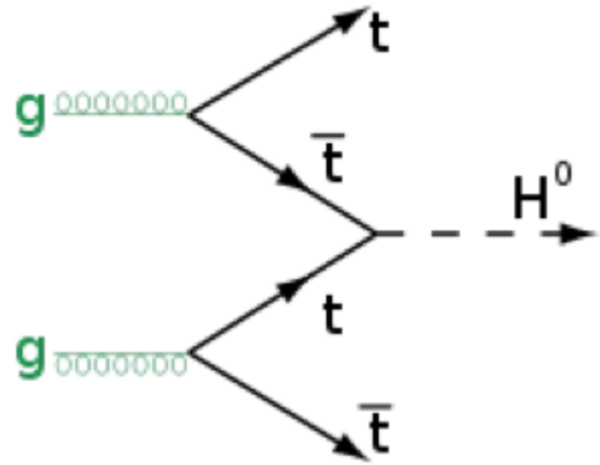
- Measured value higher but compatible (1.6σ) with NLO calculation
- Dominant systematics (ttbar modeling and JES) cancel in the ratio
  - Remaining uncertainties from b-(mis)tag rate



ttbar+heavy flavour

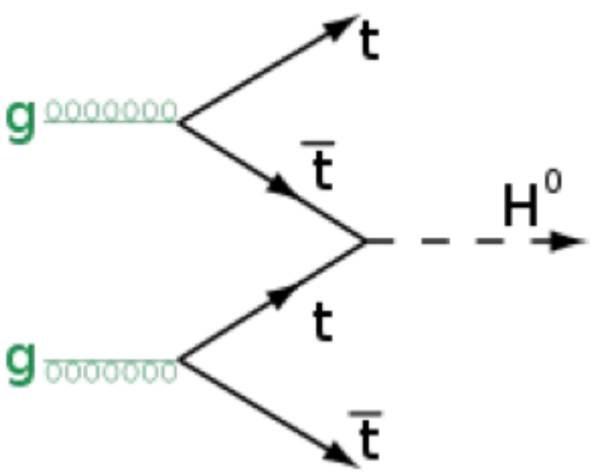
- Study rate of ttbb: $\boxed{\sigma(t\bar{t}b\bar{b})/\sigma(t\bar{t}jj)}$

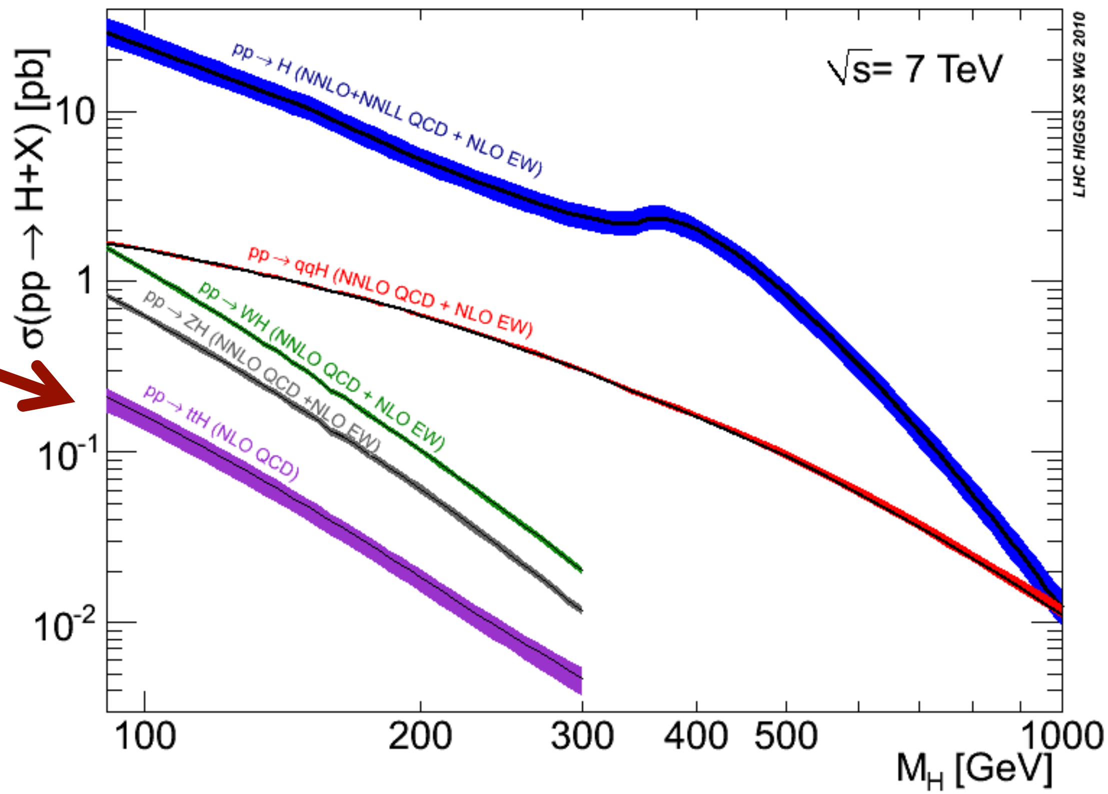
- Anomalous tt+jets could signal BSM final states
- First direct measurement of typical bkg to top-Higgs coupling
  - Irreducible non-resonant bkg from ttbb
- Improved theoretical understanding of ttH(bb) crucial to ttH and NP searches



ttbar+Higgs

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



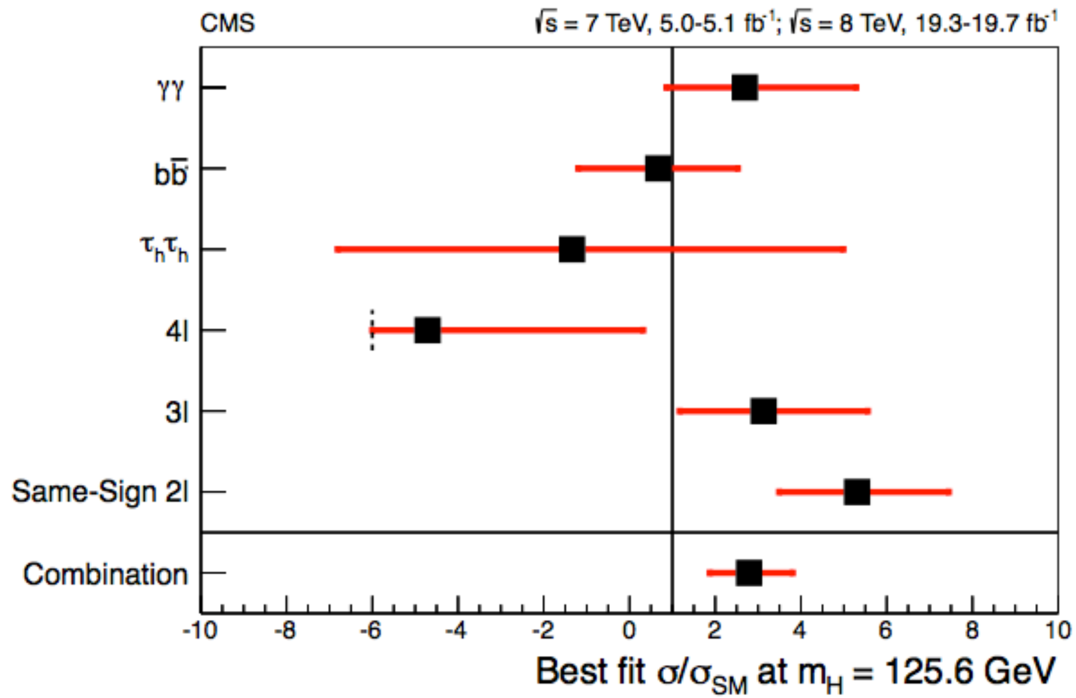


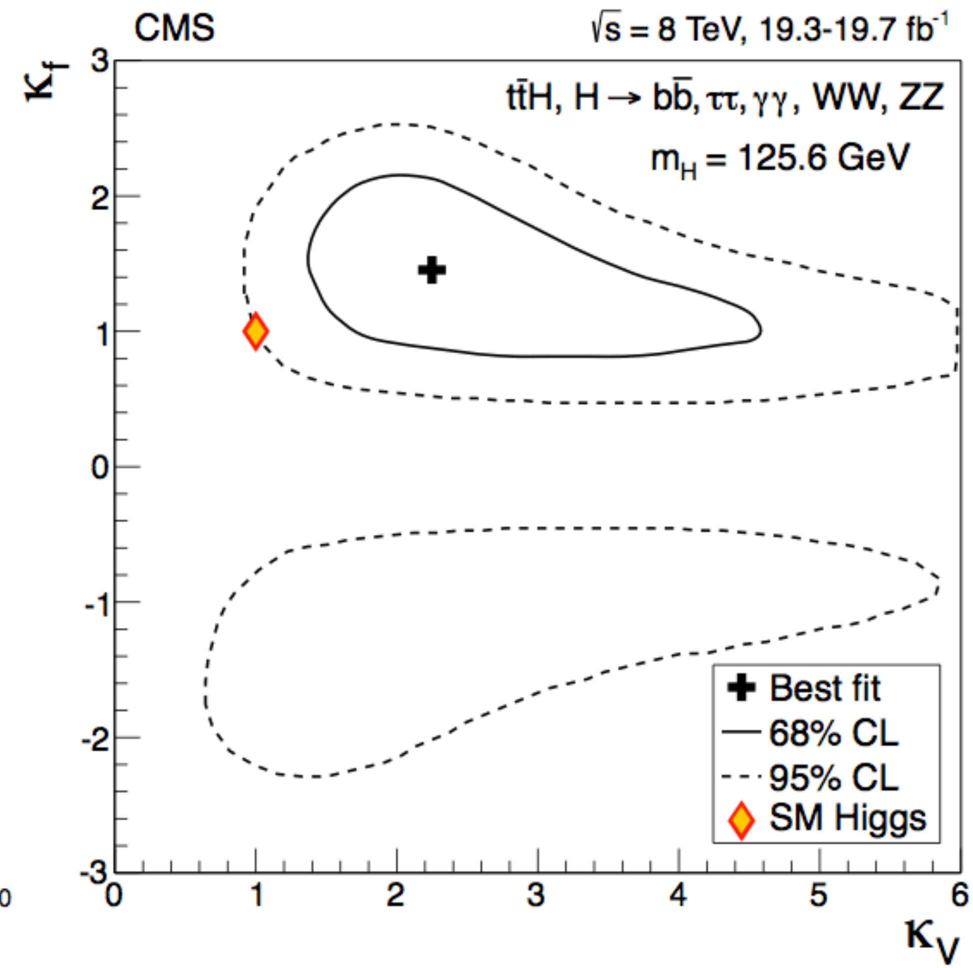
Cross section for $t\bar{t}H$ at the LHC:
0.13 pb (8 TeV)
0.61 pb (14 TeV)

ttbar+Higgs (cont.)

arXiv:1408.1682

- Search for associated SM Higgs production: ttH
  - Both “dilepton” and “l+jets” channels
- Study bb, tt, gg, WW, ZZ final states
- Simultaneous fit for S and B fractions
  - different categories: jet and b-jet multiplicity

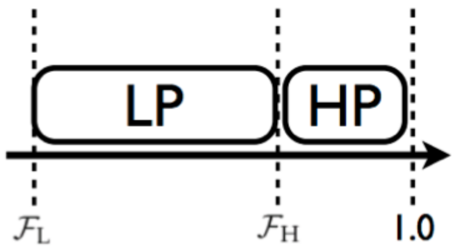


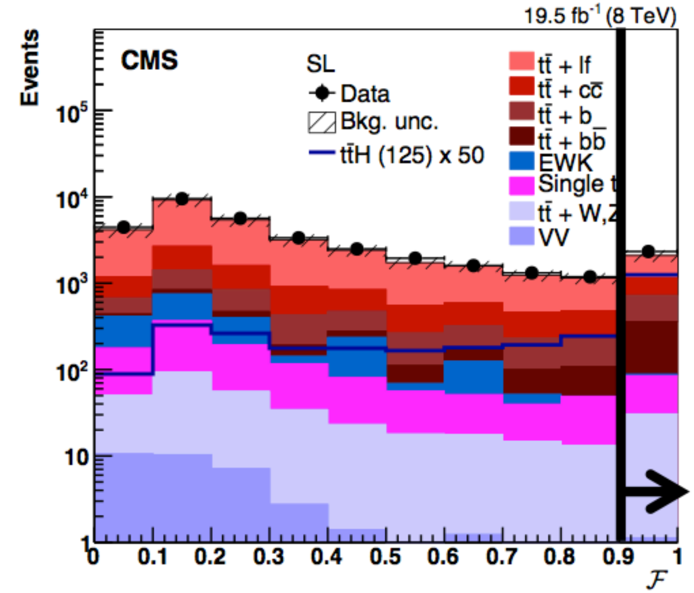


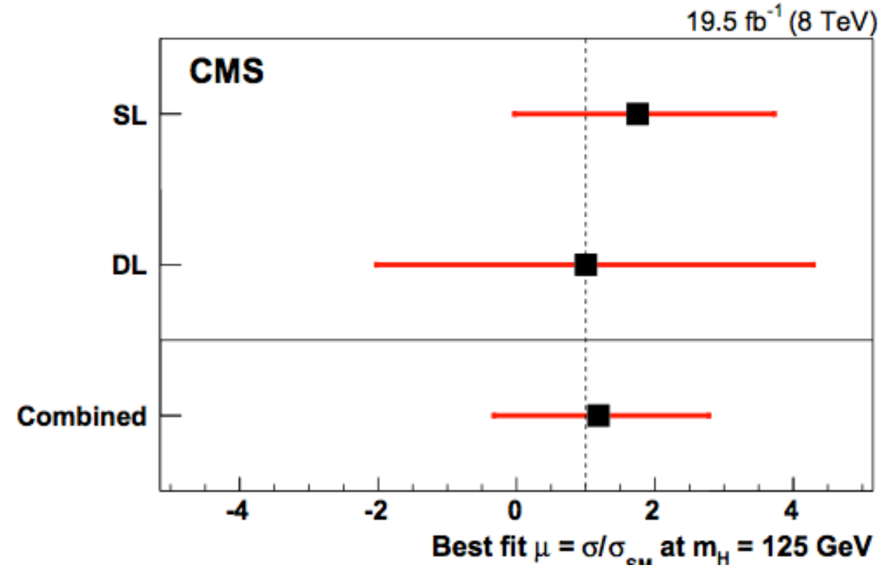
ttH, H→bb

JHEP 09(2014)087, EPJC 75(2015)251

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



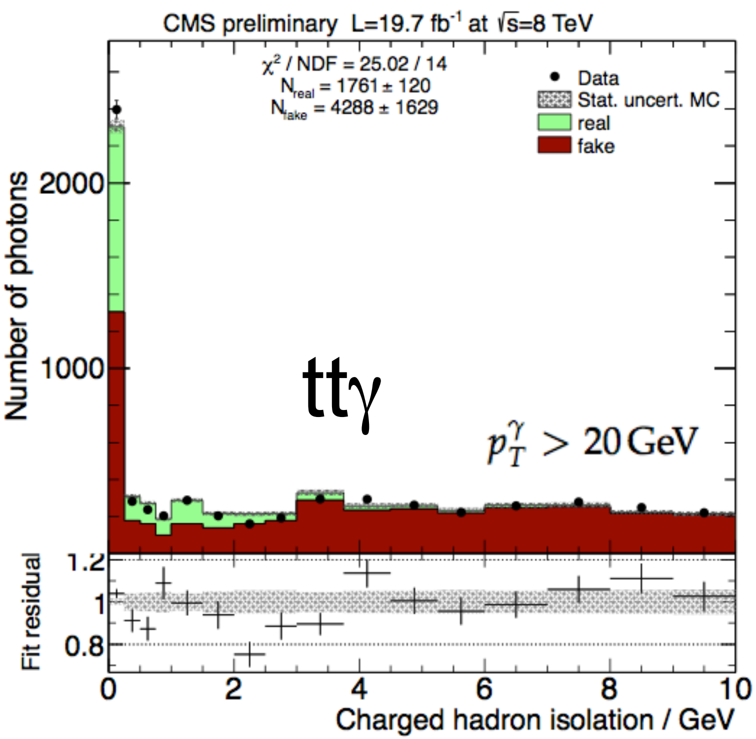




ttV (V=γ,Z,W)

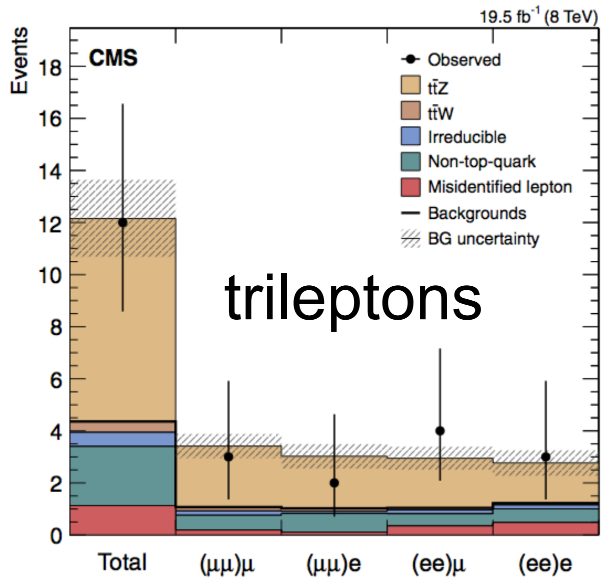
CMS-TOP-13-011, EPJC 74(2014)3060

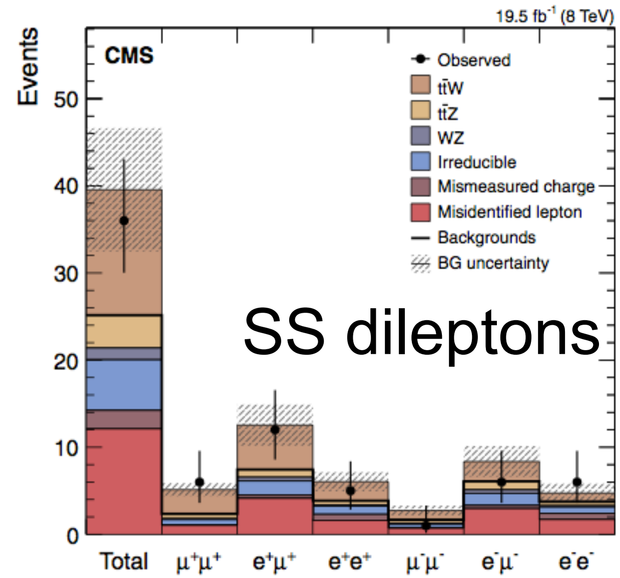
- Measurements will give access to EW couplings of the top



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

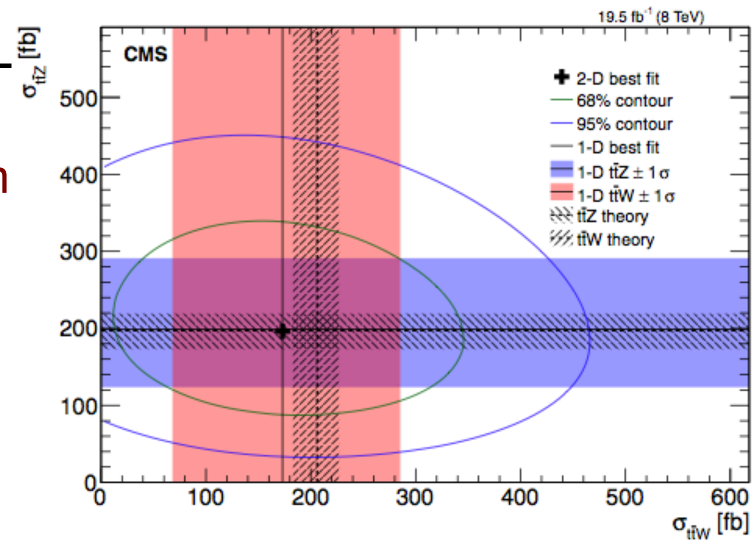
Consistent with theoretical predictions





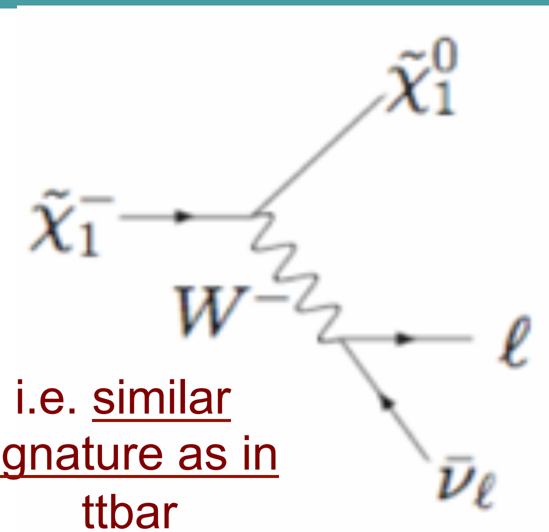
Combine 2- 3- and 4-lepton final states

⇒ ttV xsec 3.7σ from bkg-only hypothesis



Scalar top quark

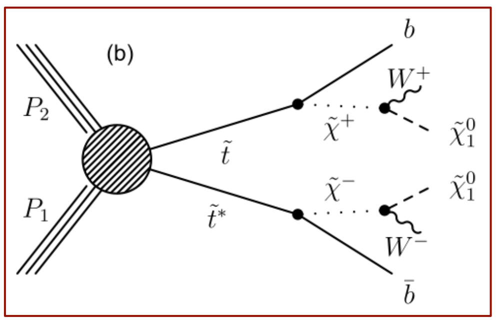
- SUSY is one plausible extension of the SM
- due to the heavy top quark, mass splitting between $\tilde{t}_1$ and $\tilde{t}_2$ can be large, such that the lighter stop $\tilde{t}_1$ can be even lighter than the top quark
- Decays dictated by mass spectrum of other SUSY particles



i.e. similar signature as in ttbar

- Light stop:

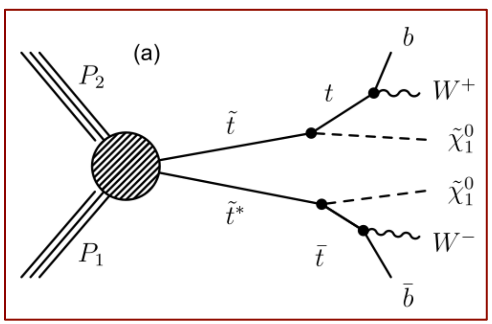
$$\boxed{m_{\tilde{t}_1} \lesssim m_t}$$



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

- Heavy stop:

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

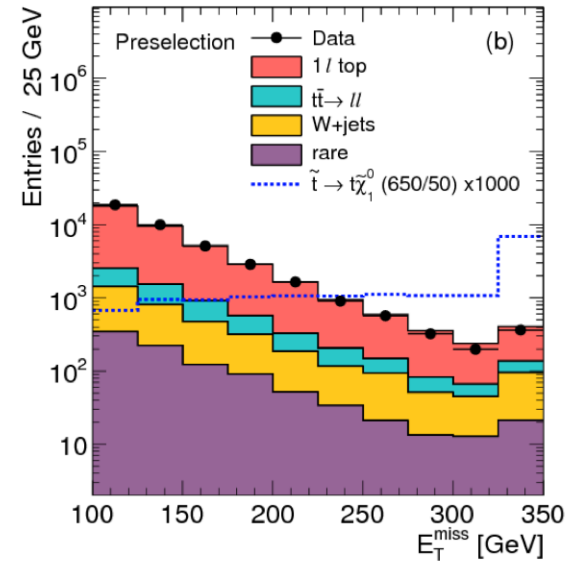


$$\tilde{t} \to t\tilde{\chi}_1^0 \to bW\tilde{\chi}_1^0$$

Top and SUSY

EPJC 74 (2014) 3109, TOP-13-004

- 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

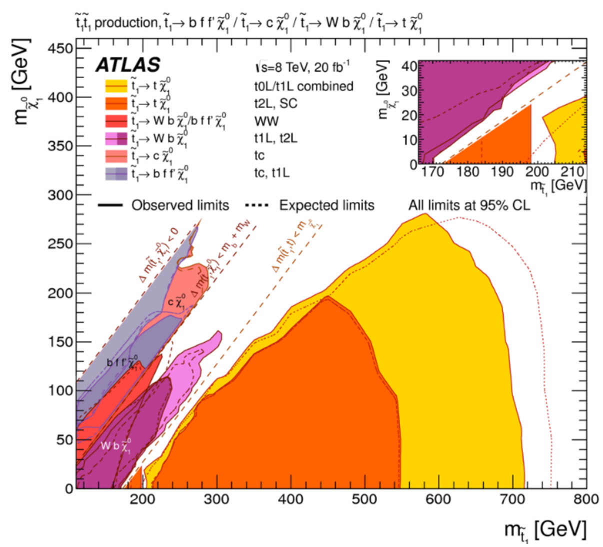


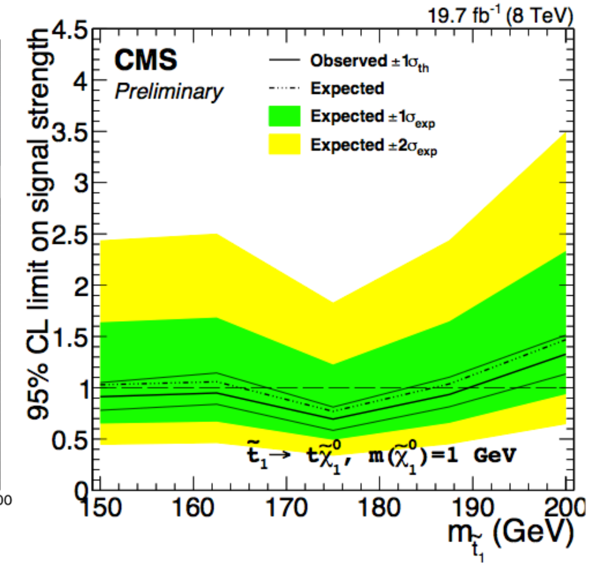
$$\boxed{\begin{array}{l}\tilde{t} \to t\tilde{\chi}_1^0 \to bW\tilde{\chi}_1^0 \\ \tilde{t} \to b\tilde{\chi}_1^+ \to bW\tilde{\chi}_1^0\end{array}}$$

"heavy"

"light"

- Small predicted xsection
  - 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
- increase in ttbar cross section





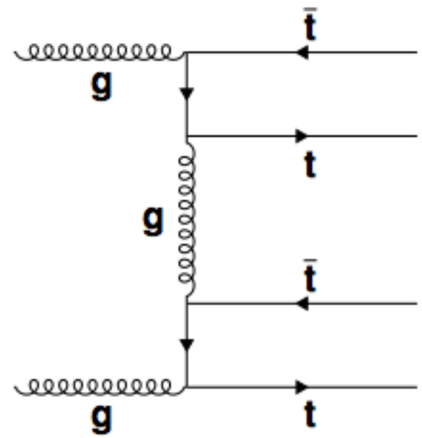
Multi-top production

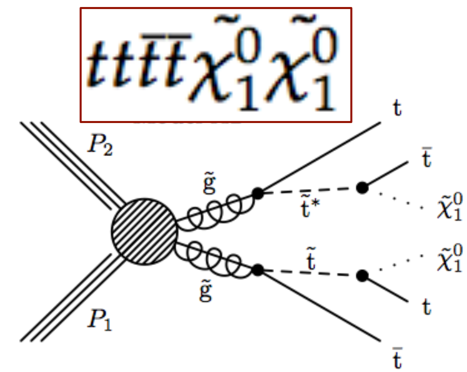
JHEP 11(2014)154, JHEP 01(2014)163

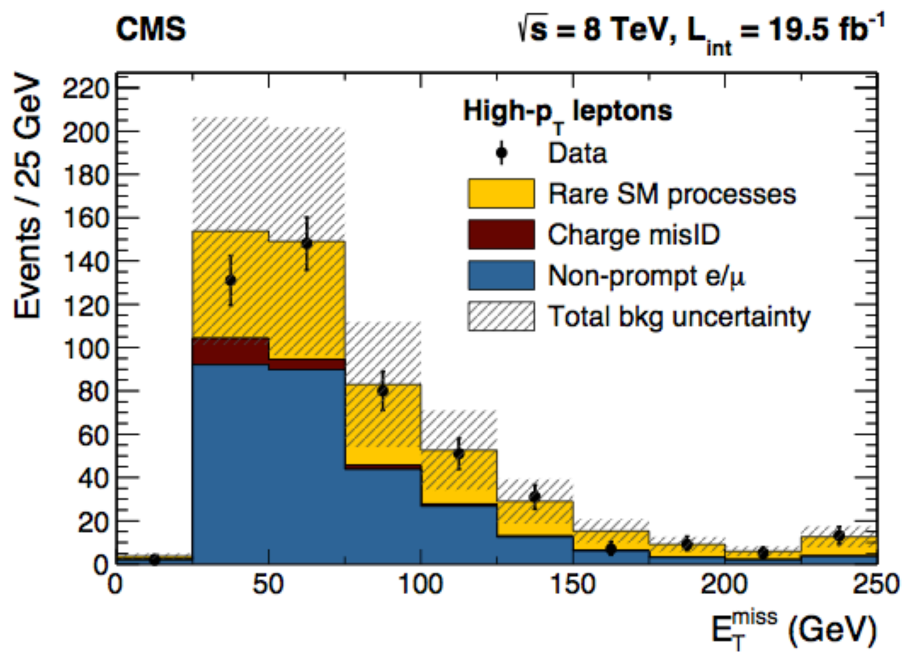
- Production of 4 tops is an attractive scenario in a number of new physics models
- The SM cross section is ~1fb

- Use lepton+jets final state
- Combination of kinematical variables and multivariate techniques
- Data are consistent with bkg expectations
- Set upper limit cross section 32fb @95%CL

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



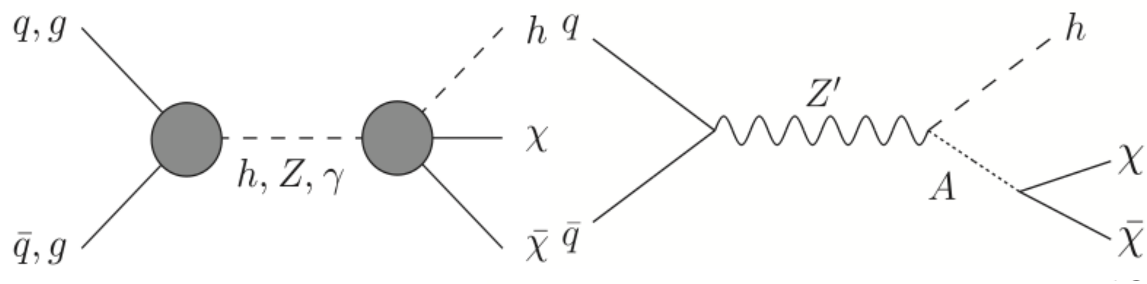




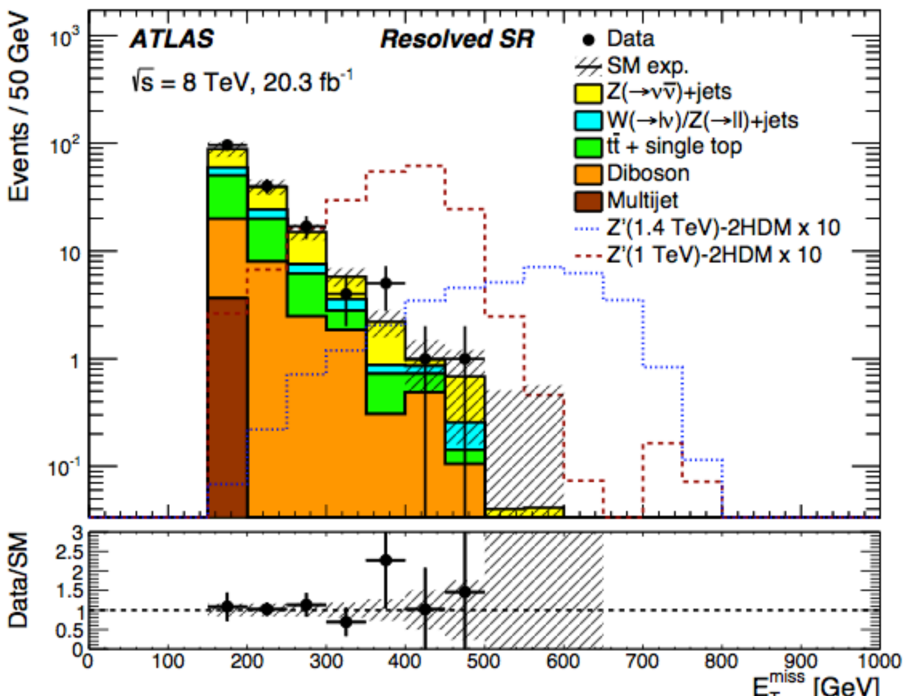
Dark Matter+ Higgs

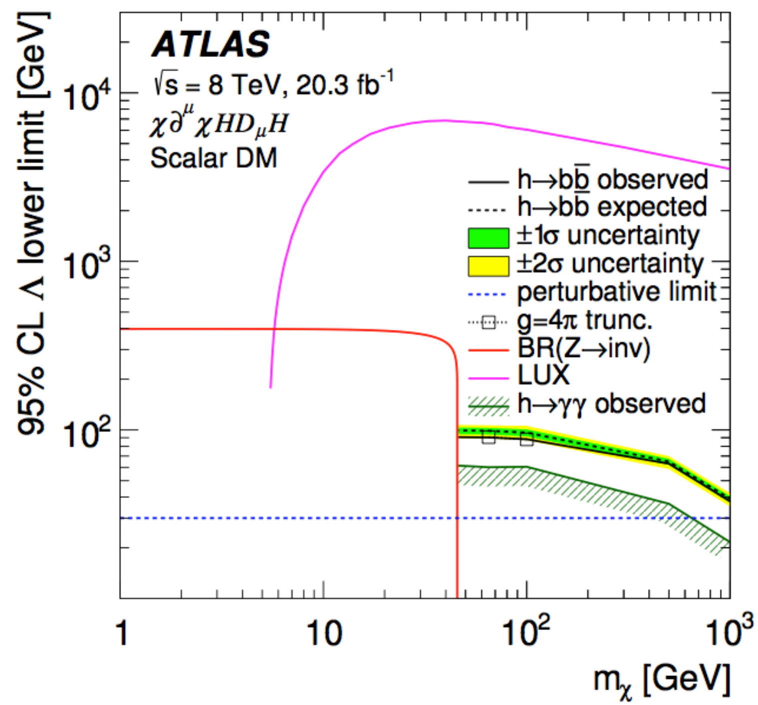
arXiv:1510.06218, arXiv:1506.01081

- Search for DM + h(→bb)
- Model-independent search
- Signature: h(→bb/γγ)+MET
- Simplified model with Z' or pseudo-scalar Higgs A(→χχ)
- Signal events at large MET

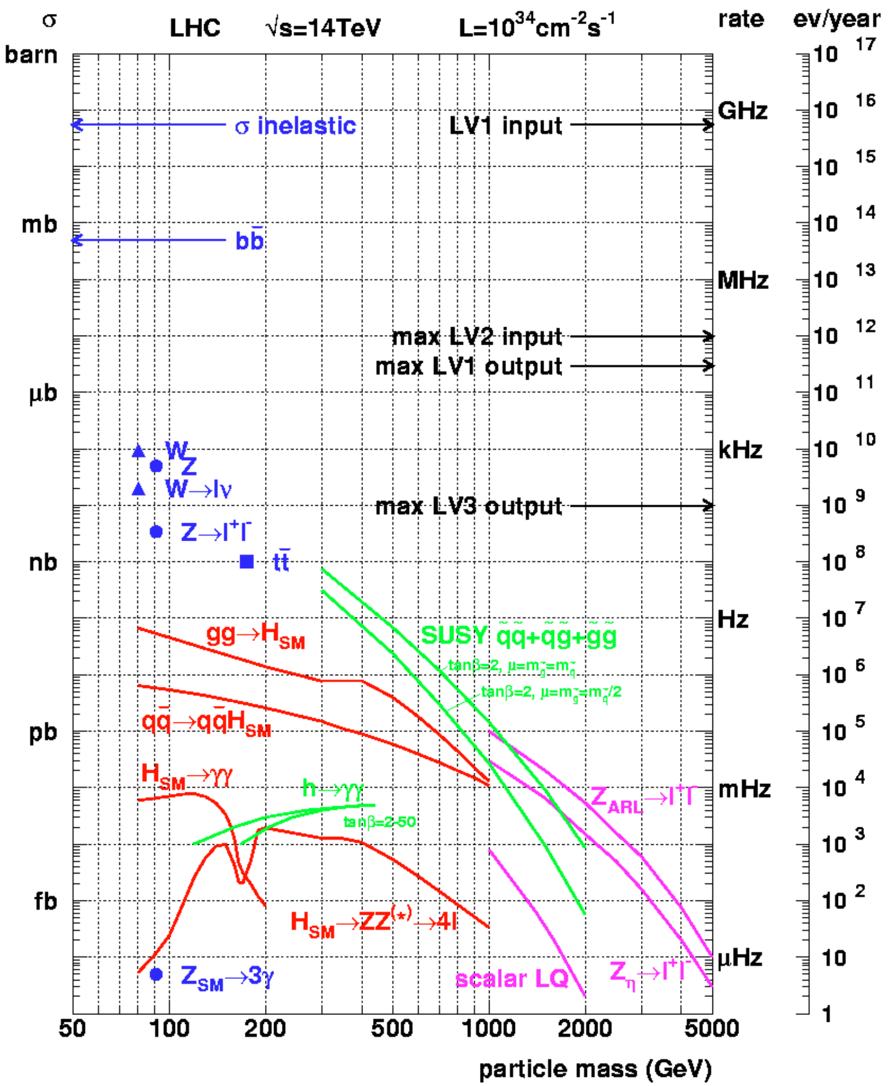


DM particle (χ): can be scalar or fermion
Pseudo-scalar Higgs A





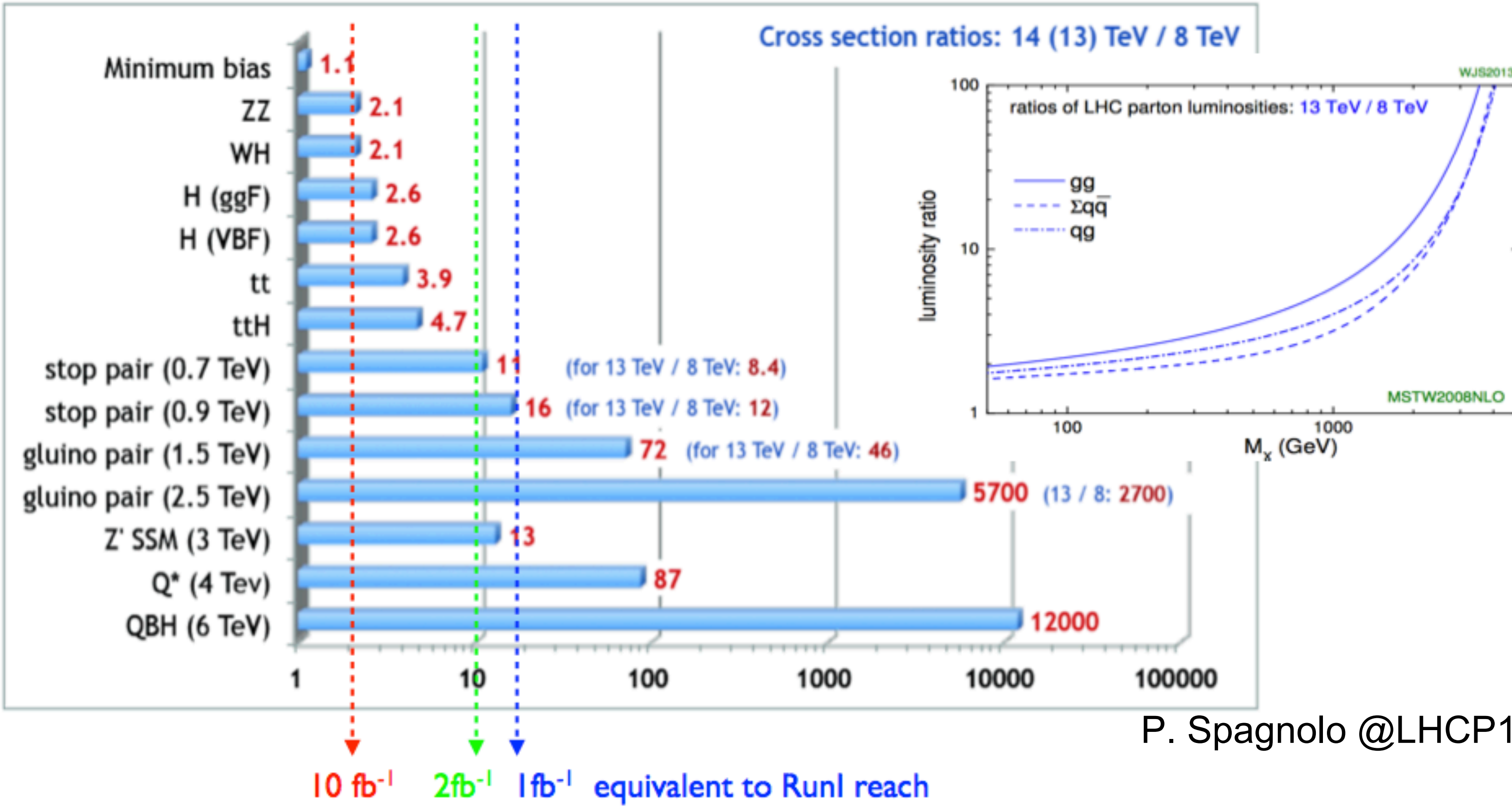
Cross sections at the LHC



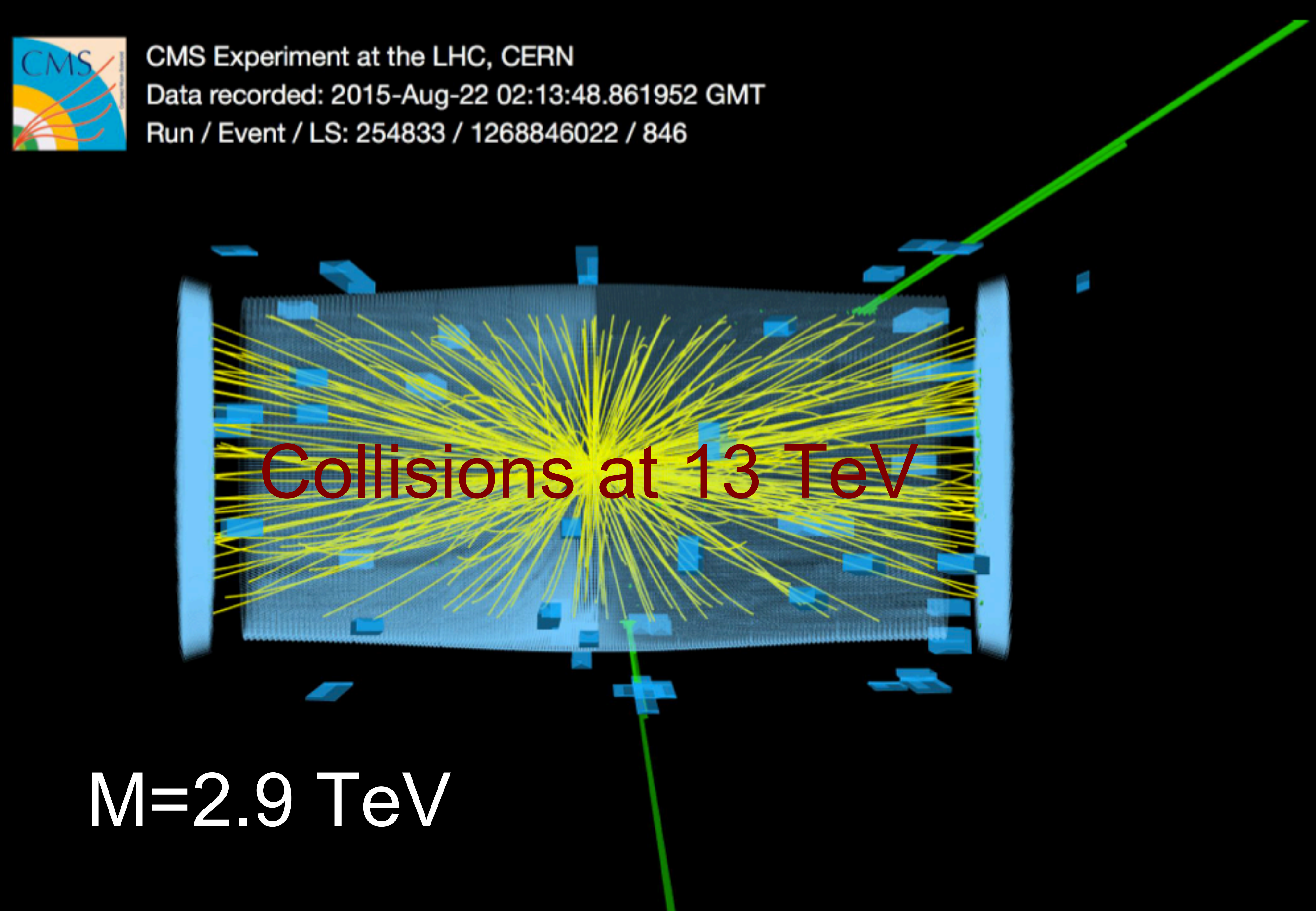
"Well known" processes, don't need to keep all of them …

New Physics!!
This is where to look

Prospects at 13 TeV



P. Spagnolo @LHCP15


CMS Experiment at the LHC, CERN
Data recorded: 2015-Aug-22 02:13:48.861952 GMT
Run / Event / LS: 254833 / 1268846022 / 846
Collisions at 13 TeV
M=2.9 TeV

Summary

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

The end

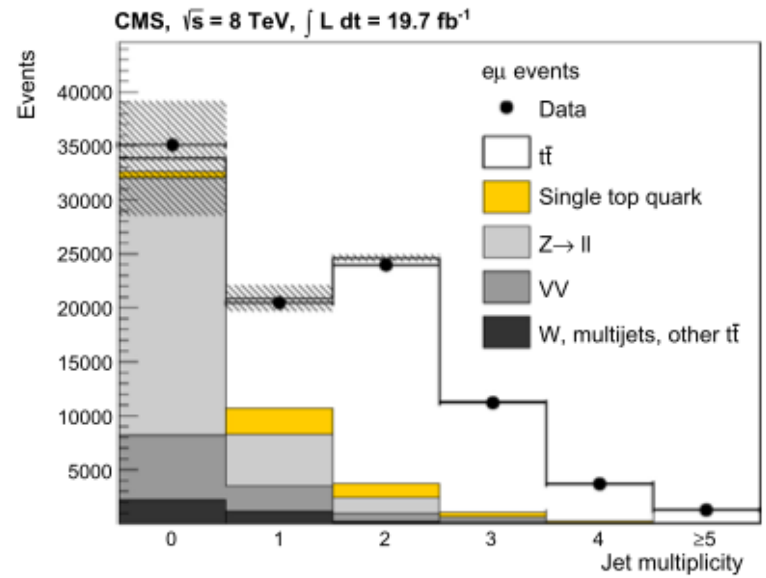
Cross section in the R measurement

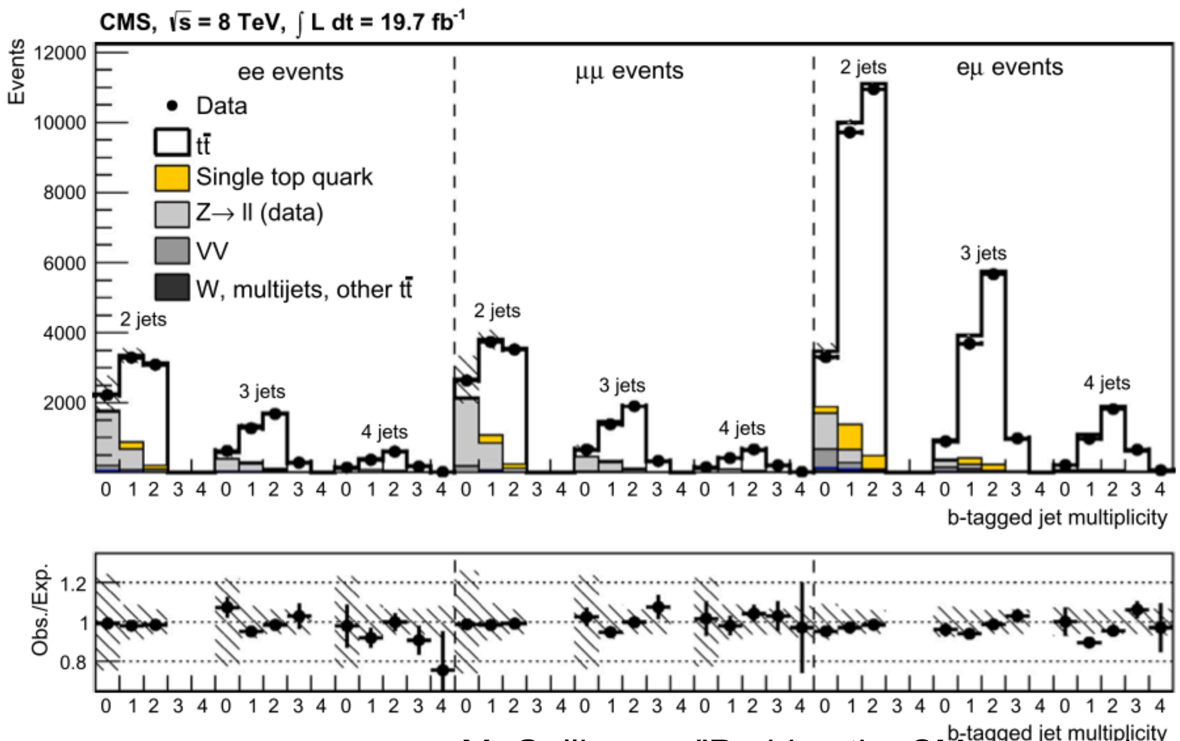
N.Cim. B125(2010)983, PLB 736(2014)33

- Measure R:
- Dilepton final state

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

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





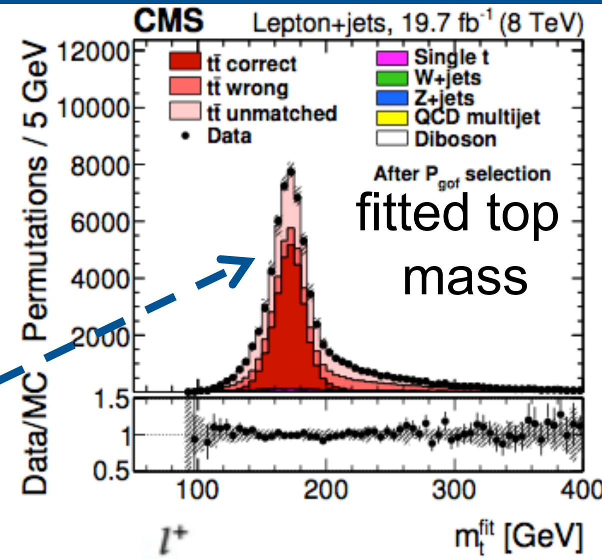
- Measure R by comparing number of ttbar events with 0, 1 and 2 b-tags

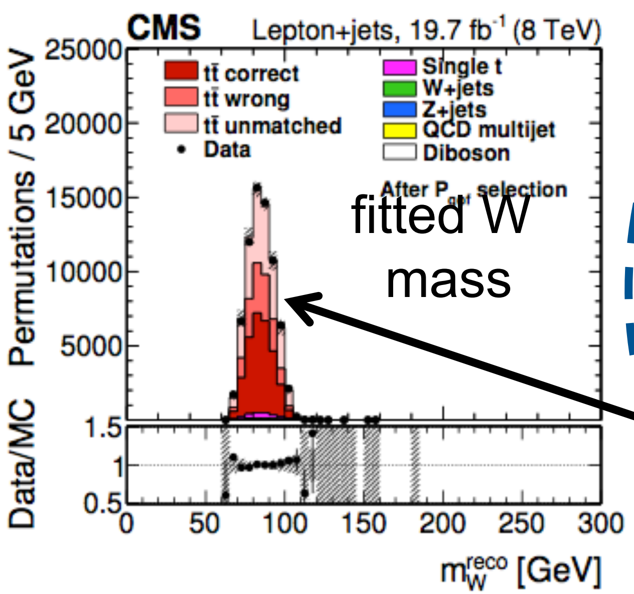
$$|V_{tb}| > 0.975 \text{ at } 95\% \text{ CL}$$

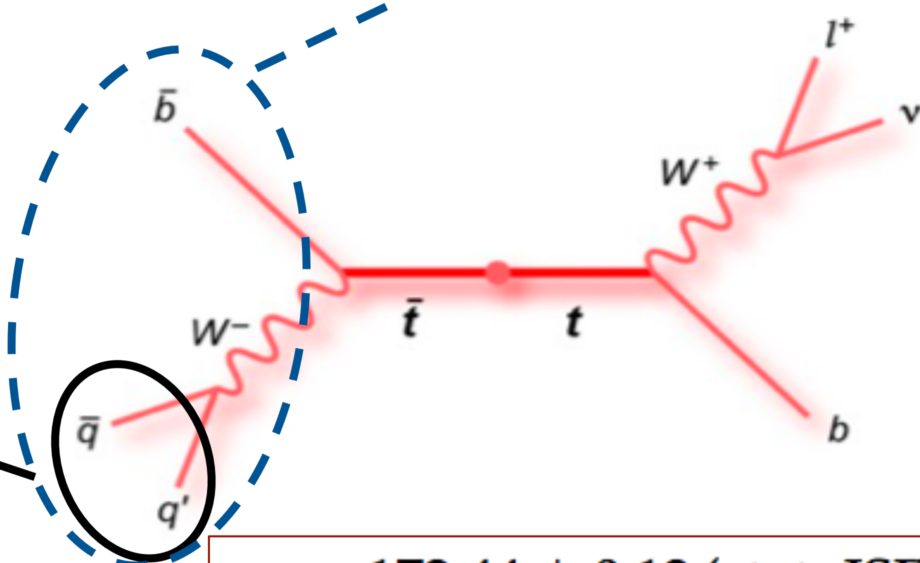
Precise mass measurement

arXiv:1509.04044

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



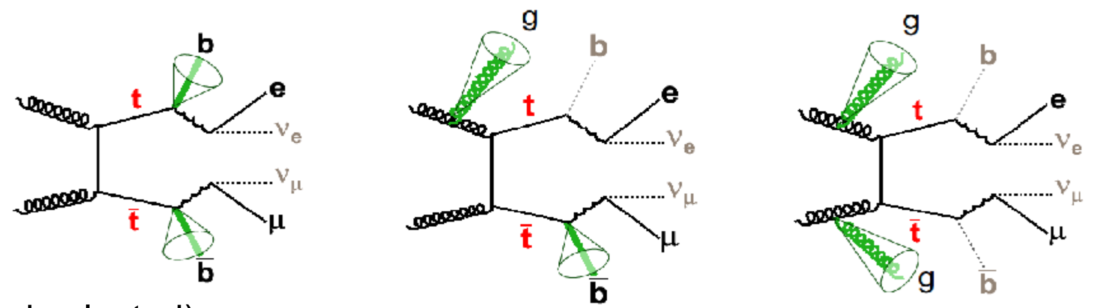




±0.3%

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

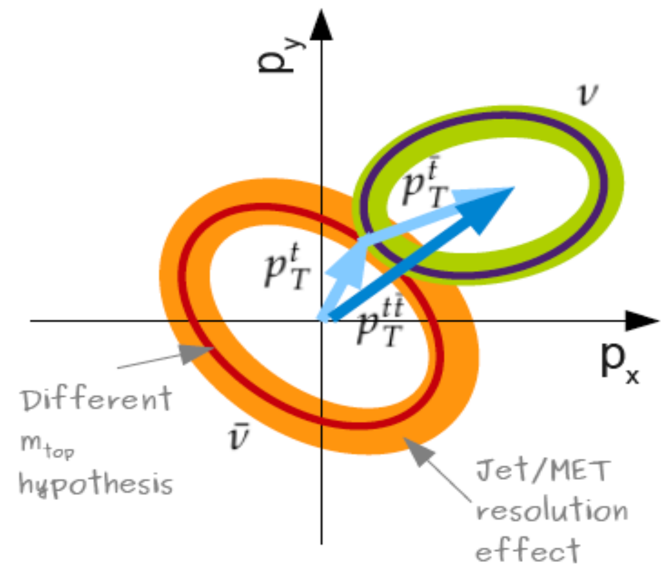
Case study: the dilepton channel



- Combinatorics
  - Identify top quark decay products
  - Ambiguity
  - ISR/FSR introduces further complexity for selection

  (~70% of the events have both b-jets reconstructed and selected)

- Missing transverse energy
  - Constrains the contribution from undetected particles
  - In the dilepton channel: 2 neutrinos ⇒ $\vec{E}_T^{miss} = \vec{p}_T^{\nu} + \vec{p}_T^{\bar{\nu}}$



- Jet energy scale
  - m_{top} reconstruction requires measuring the parton energy
  - parton→jet affected by resolution and absolute energy scale

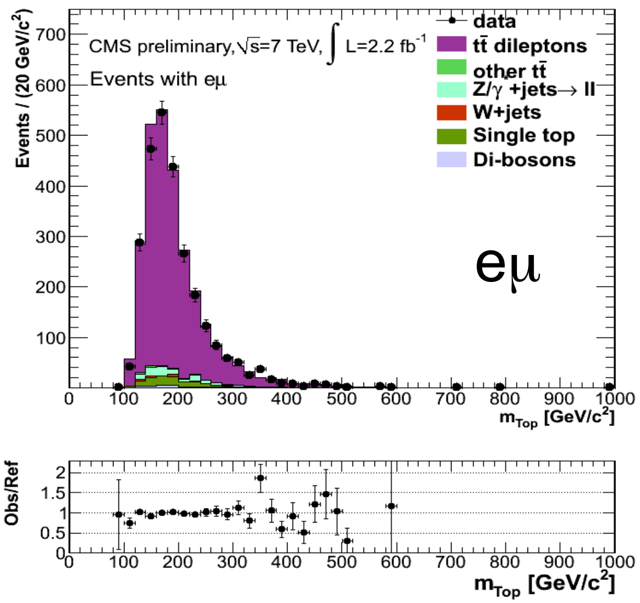
- Pile-up
  - Jet energy scale, MET measurement, extra jets/leptons
  - N_{pileup}≈ 6 (21) for most of data collected in 2011 (2012)

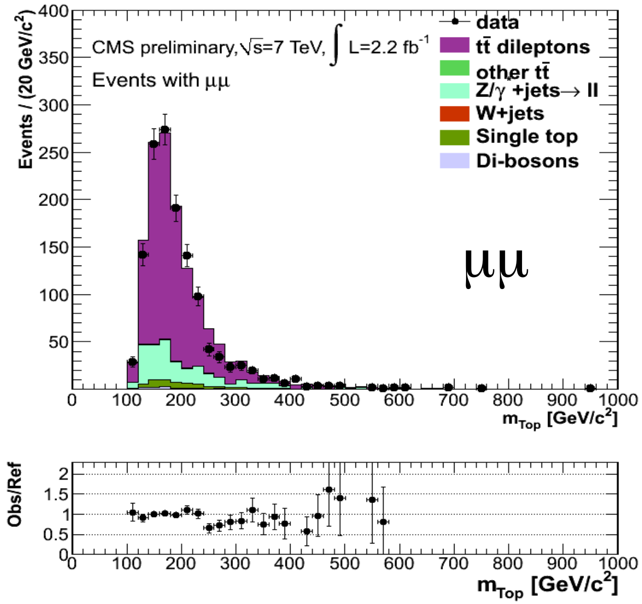
Top mass: Event selection

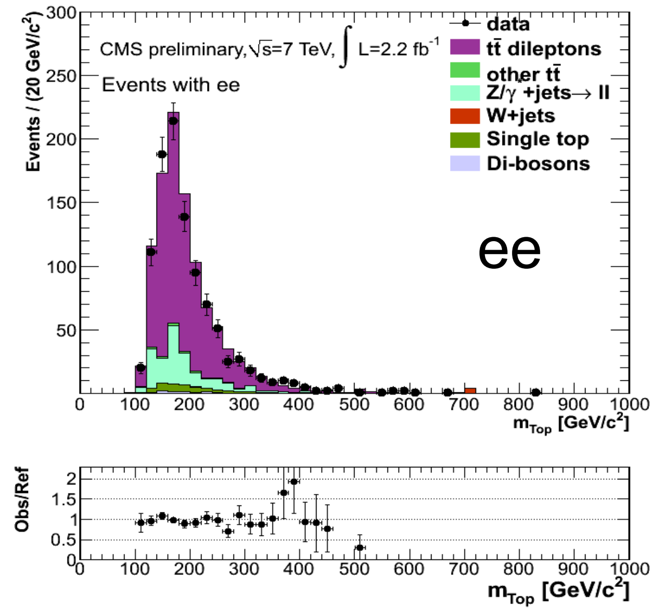
EPJC C72 (2012) 2202

- Select events
- Reconstruct mass

Process	Pre-selection	KINb	=1 b-tag	$\geq$ 2 b-tags
Di-bosons	73 ± 14	55 ± 10	18 ± 4	4 ± 1
Single top	247 ± 92	182 ± 68	88 ± 33	76 ± 29
W+jets	22 ± 10	16 ± 8	8 ± 6	-
$Z/\gamma^* \to \ell\ell$	1091 ± 97	756 ± 71	238 ± 29	47 ± 11
other $t\bar{t}$	32 ± 4	28 ± 3	11 ± 2	14 ± 2
$t\bar{t}$ dileptons	5057 ± 463	4209 ± 385	1379 ± 127	2623 ± 240
total expected	6522 ± 482	5246 ± 398	1742 ± 134	2765 ± 242
data	6358	5047	1692	2620



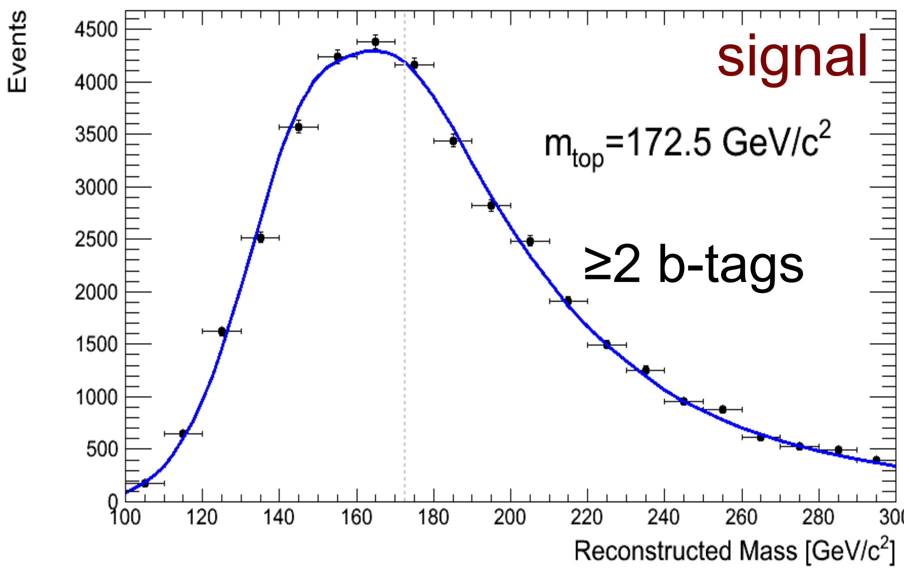


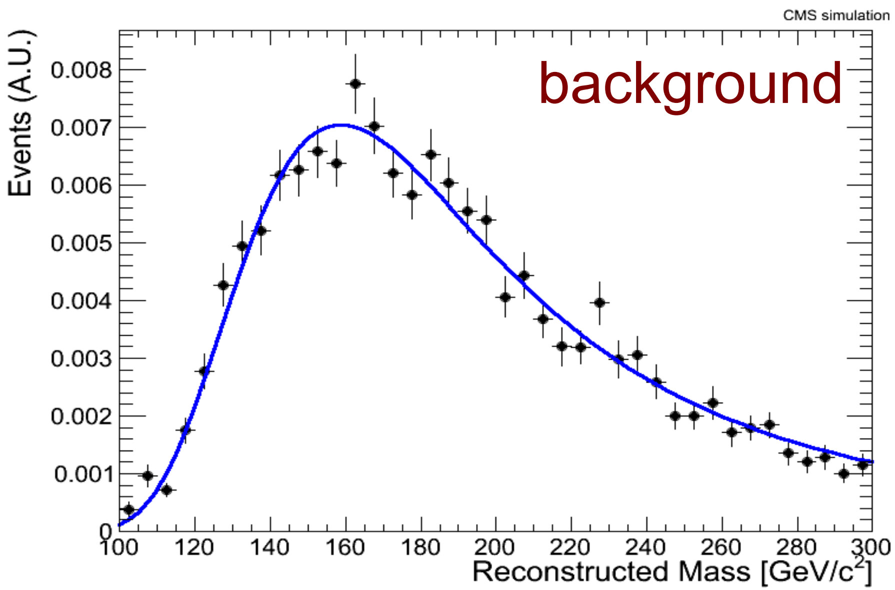


Top mass: Signal and background

- Signal component in the mass spectrum modelled: simulation
- Fit: Landau+Gaussian
- Categories: =1 and ≥2 b-tags

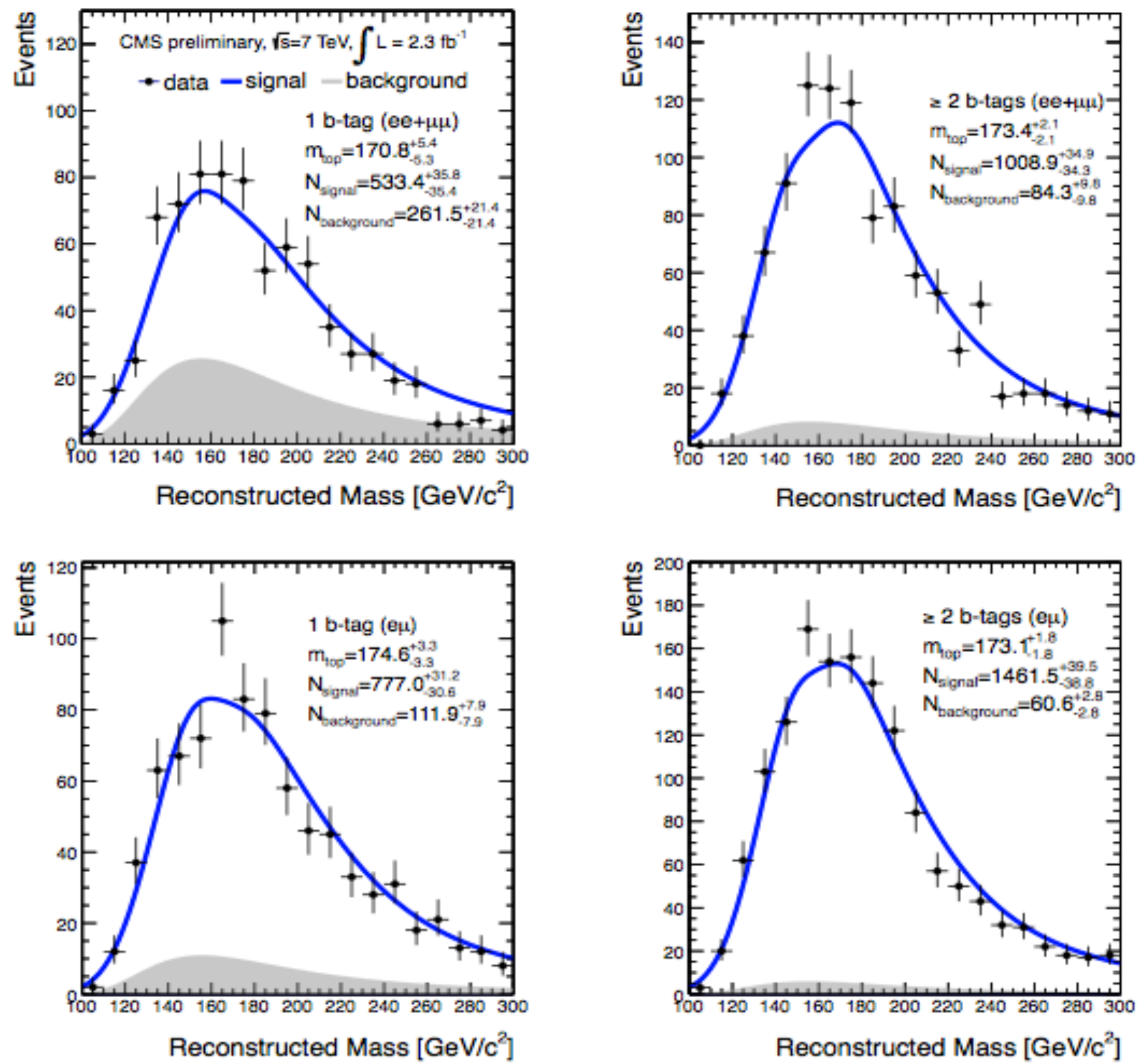
- Background component in the mass spectrum modelled with data +simulation
- Fit: Landau





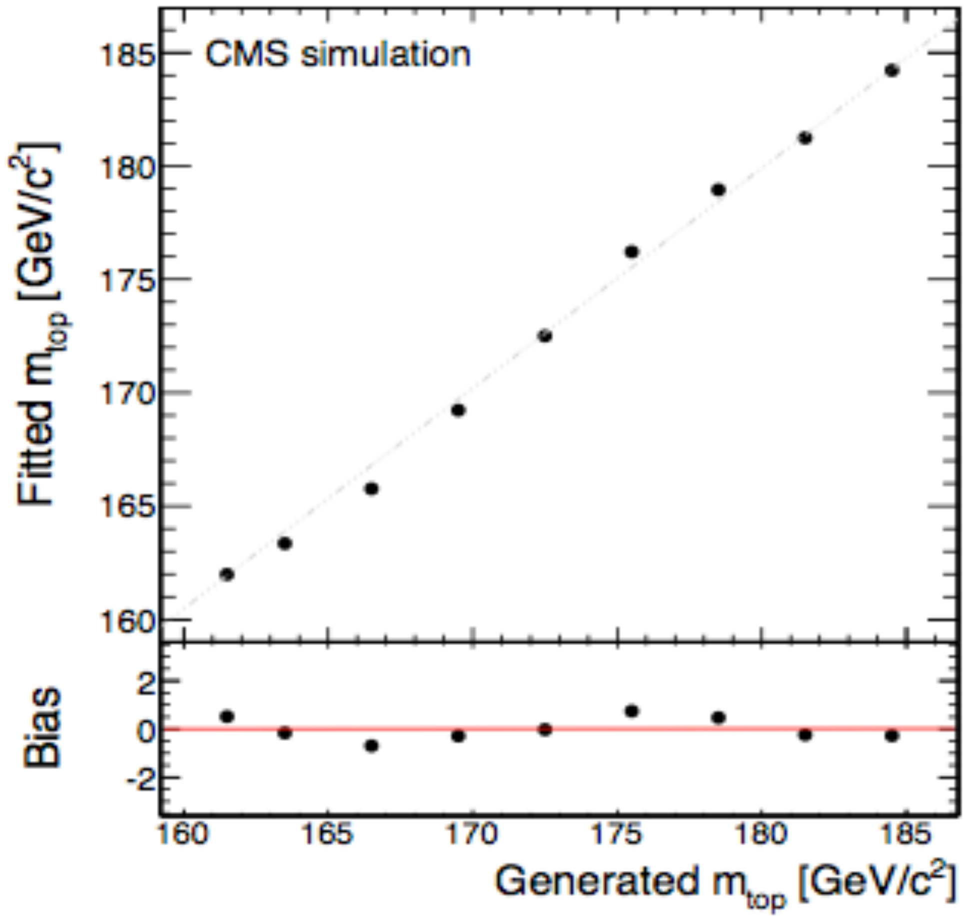
Top mass: Reconstructed mass

- Top quark mass is reconstructed in different categories
- Signal and background shapes



Top mass: Correct for the bias

- Check and correct for the bias in the measurement



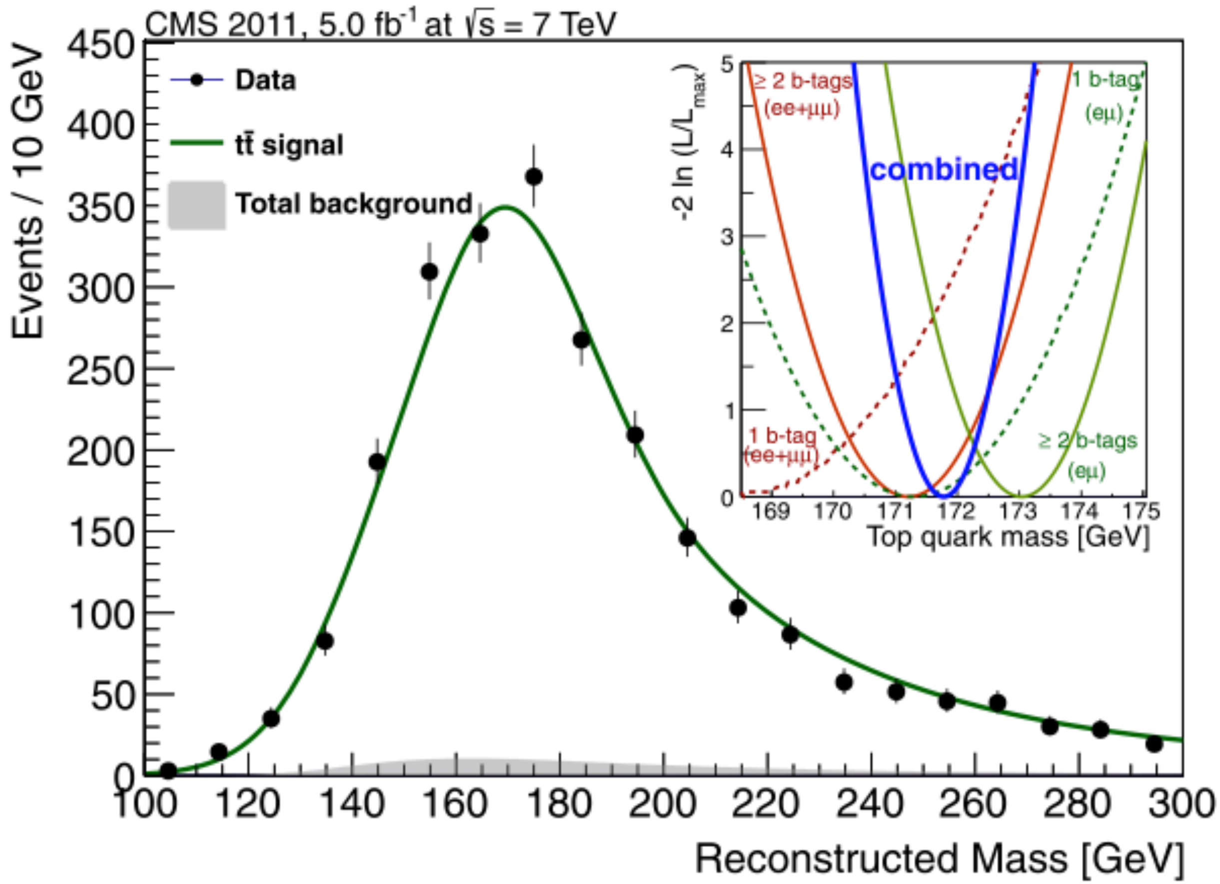
Do not forget the systematics

- Jet energy scale (JES) is the largest unc.
  - JES is varied up and down and difference in m_{top} is accounted for as systematics
  - Flavor (b) specific uncertainty added in quadrature
- Other systematics:
  - Difference with respect to reference sample used for signal
  - MC: compare Alpgen and Powheg with Madgraph
  - Vary factorization/matching scale, ISR/FSR

Source	Δm_t (GeV)
Jet energy scale	$^{+0.90}_{-0.97}$
b-jet energy scale	$^{+0.76}_{-0.66}$
Jet energy resolution	± 0.14
Lepton energy scale	± 0.14
Unclustered E_T^{miss}	± 0.12
b-tagging efficiency	± 0.05
Mistag rate	± 0.08
Fit calibration	± 0.40
Background normalization	± 0.05
Matching scale	± 0.19
Renormalisation and factorisation scale	± 0.55
Pileup	± 0.11
PDFs	± 0.09
Underlying event	± 0.26
Colour reconnection	± 0.13
Monte Carlo generator	± 0.04
Total	± 1.48

Top mass: Final fit

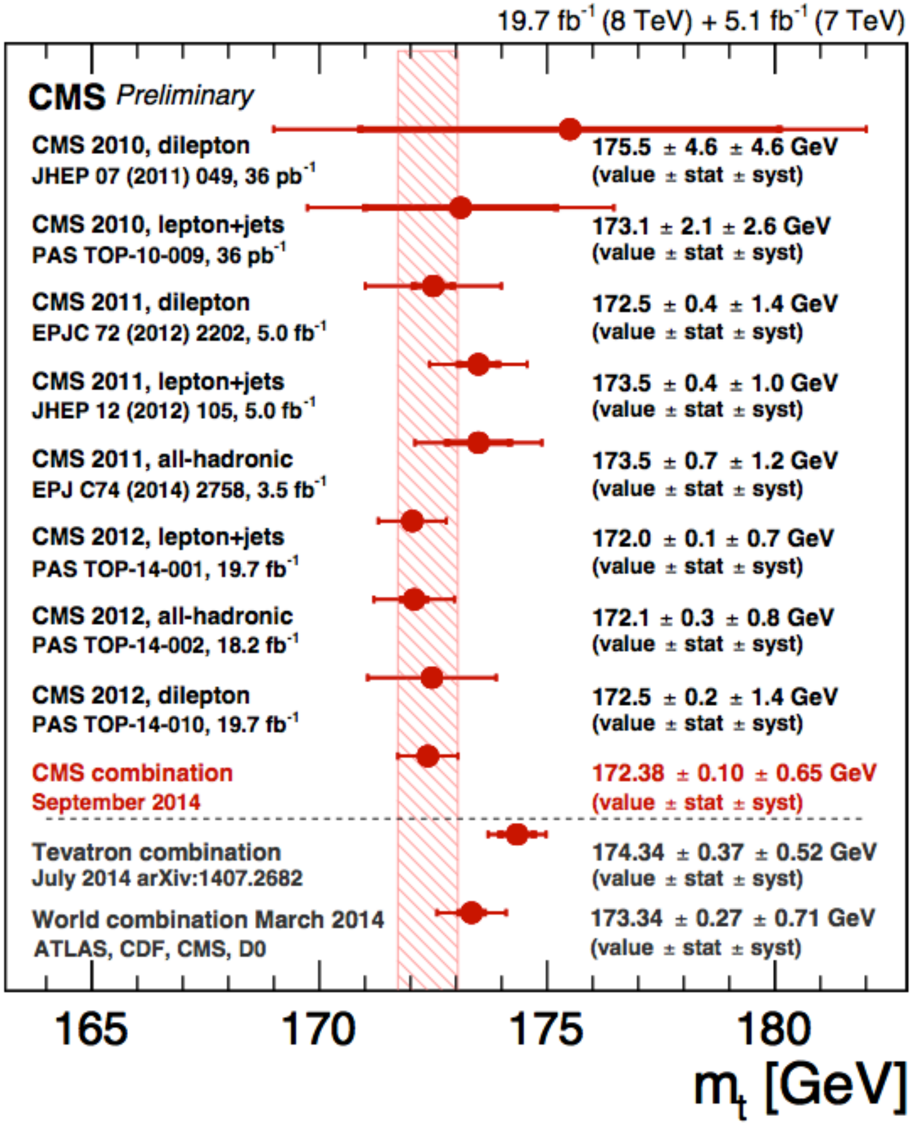
EPJC C72 (2012) 2202

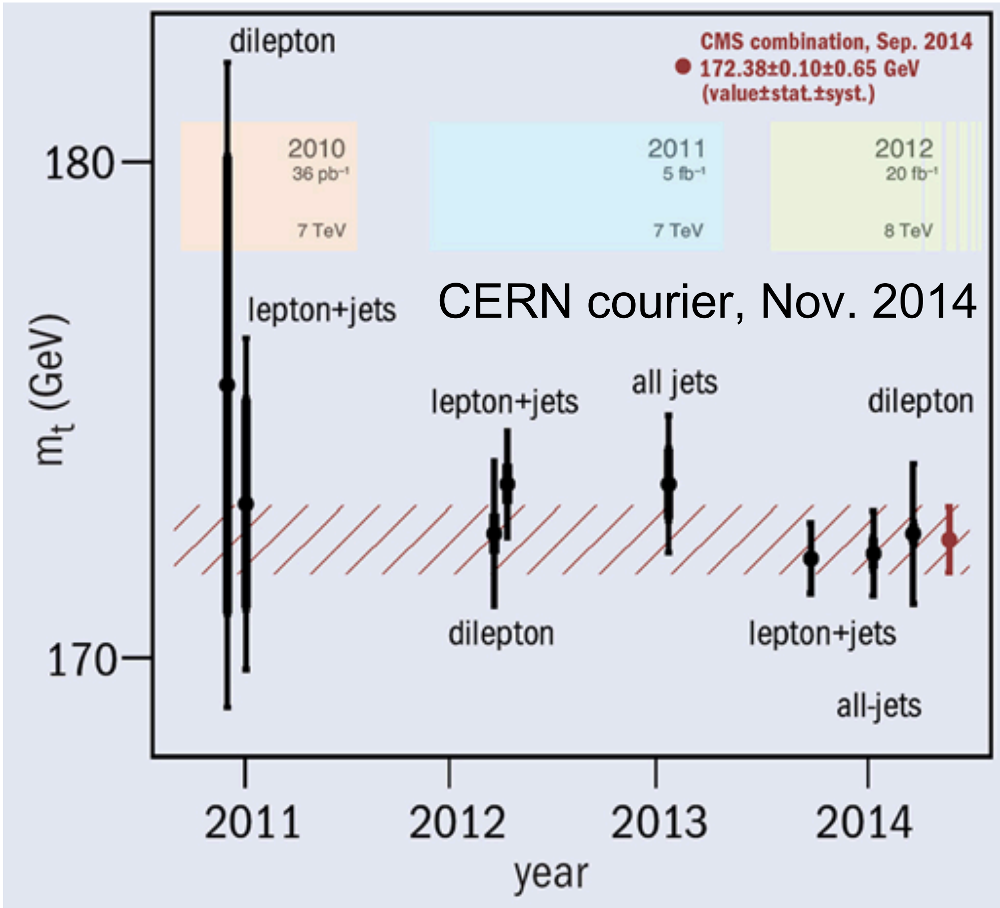


$$m_t = 172.5 \pm 0.4\ \text{(stat.)} \pm 1.5\ \text{(syst.)}\ \text{GeV}$$

CMS mass combination

CMS-TOP-14-015





$$\boxed{m_t = 172.38 \pm 0.10\,(\mathrm{stat.}) \pm 0.65\,(\mathrm{syst.})\,\mathrm{GeV}}$$

±0.38%