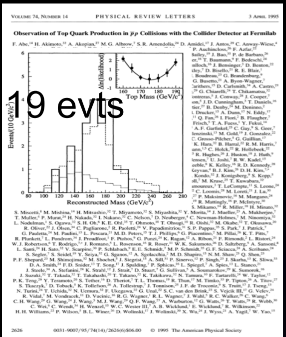
Top quark physics
cross section and mass

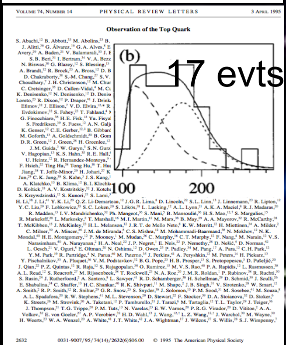
Michele Gallinaro

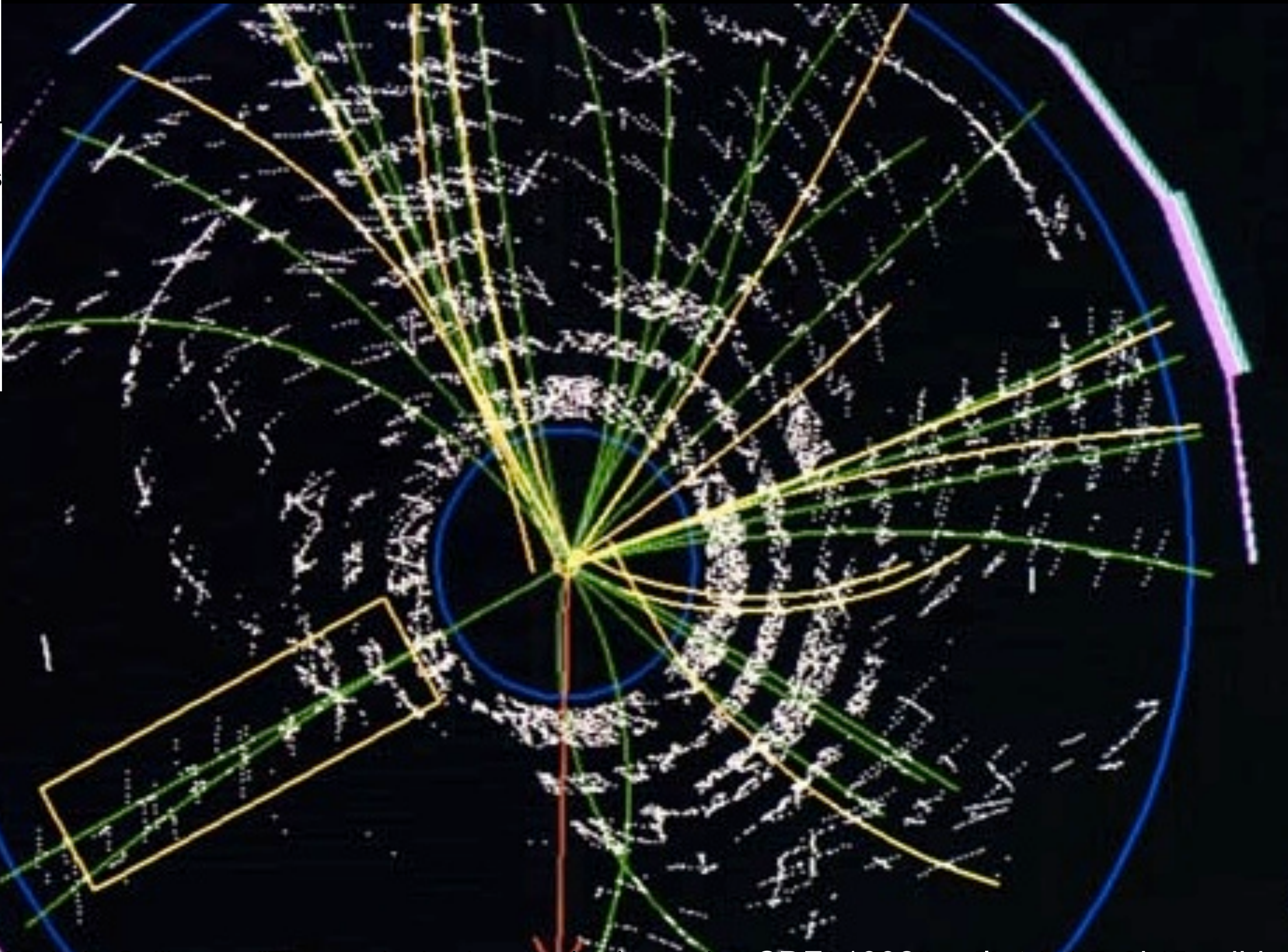
LIP Lisbon

- Introduction
- Cross section measurements
- Mass measurements

Fermilab 1995





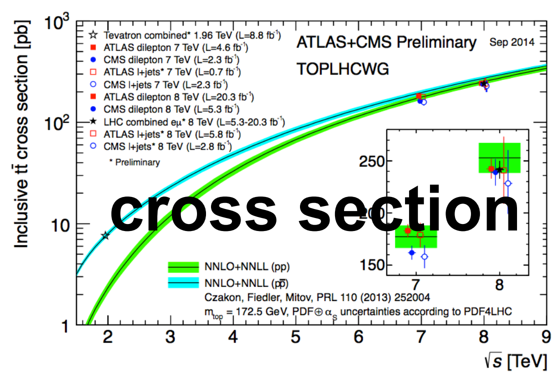


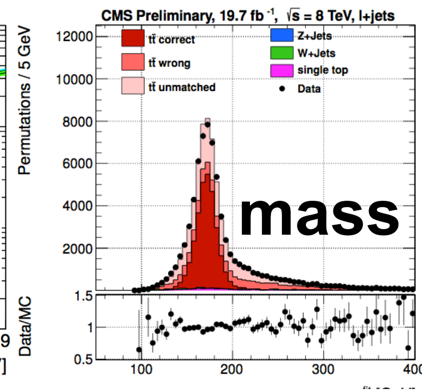
CDF, 1992: early top quark candidate event

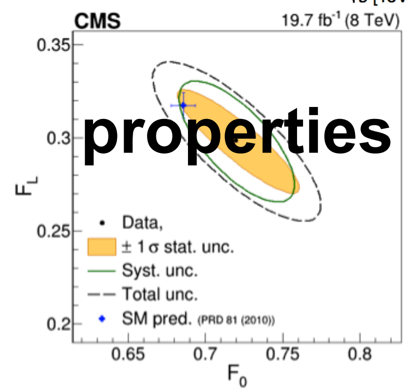
Role of top quark physics

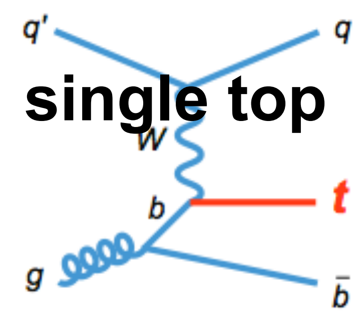
- Top quark physics after the Higgs discovery
  - Special role in EWSB mechanism?
  - Does it play a role in non-SM physics?
  - Are the couplings affected?
  - Main background for many NP searches

- Monitoring of production mechanism
- Interpretation of m_{top}: top, W, Higgs masses
- Are properties consistent with our understanding of EWSB?
- Is there any sign of NP in top production/decay?



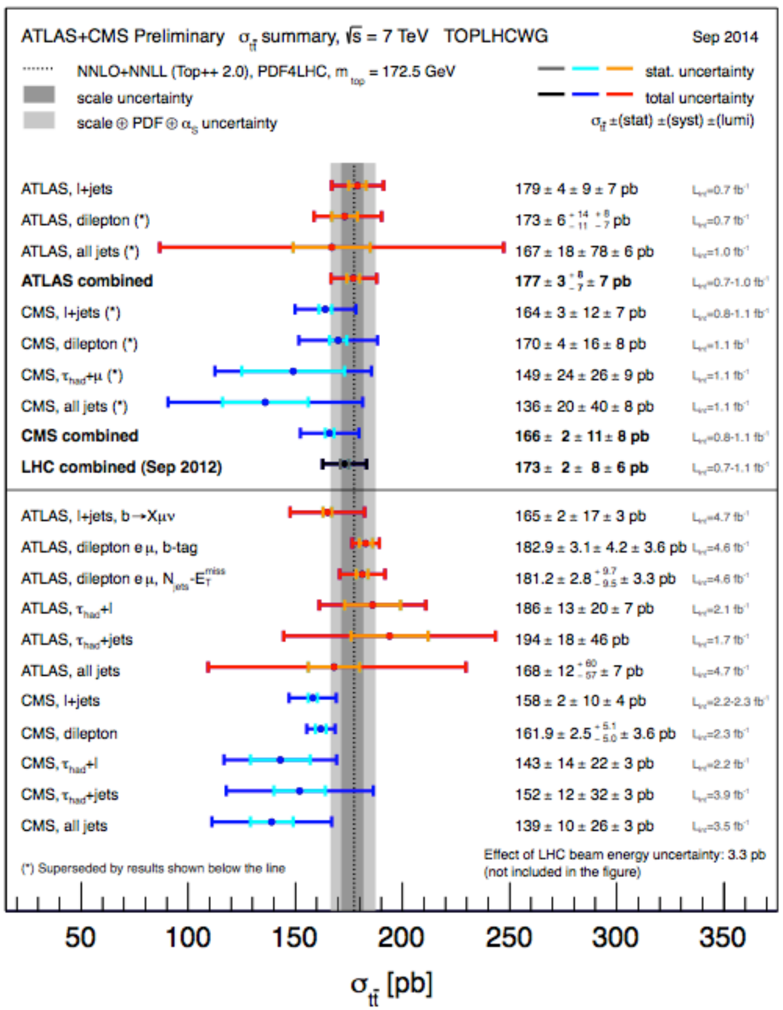




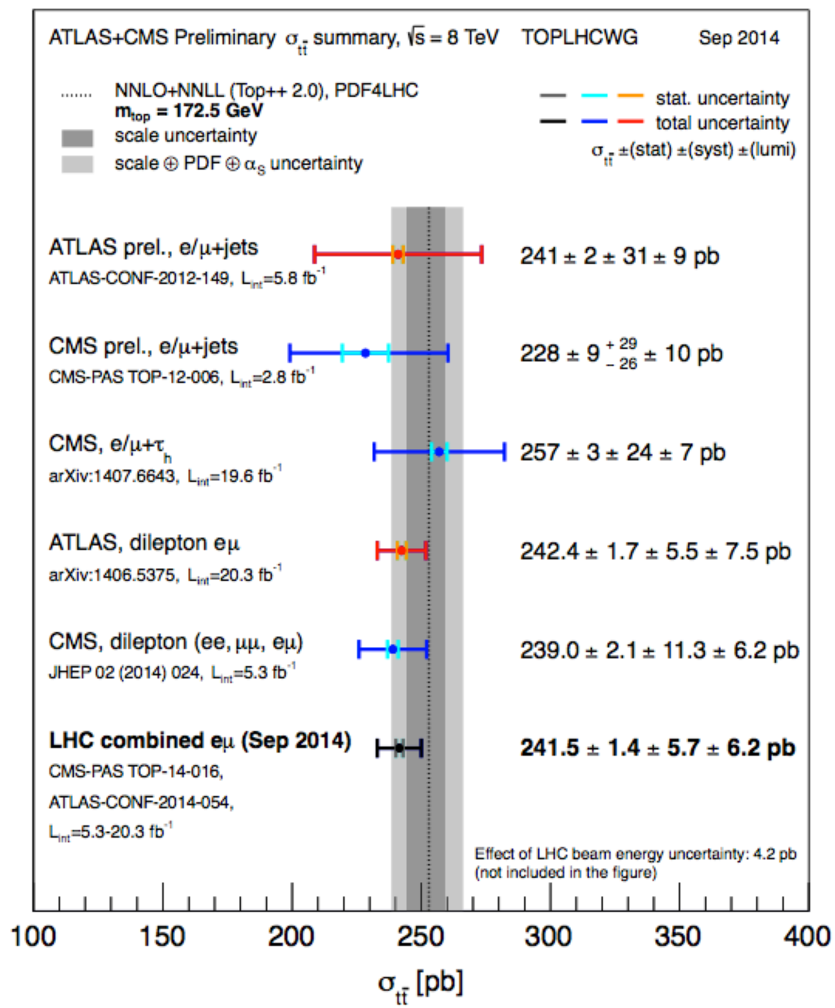


Cross section measurements

7 TeV



8 TeV

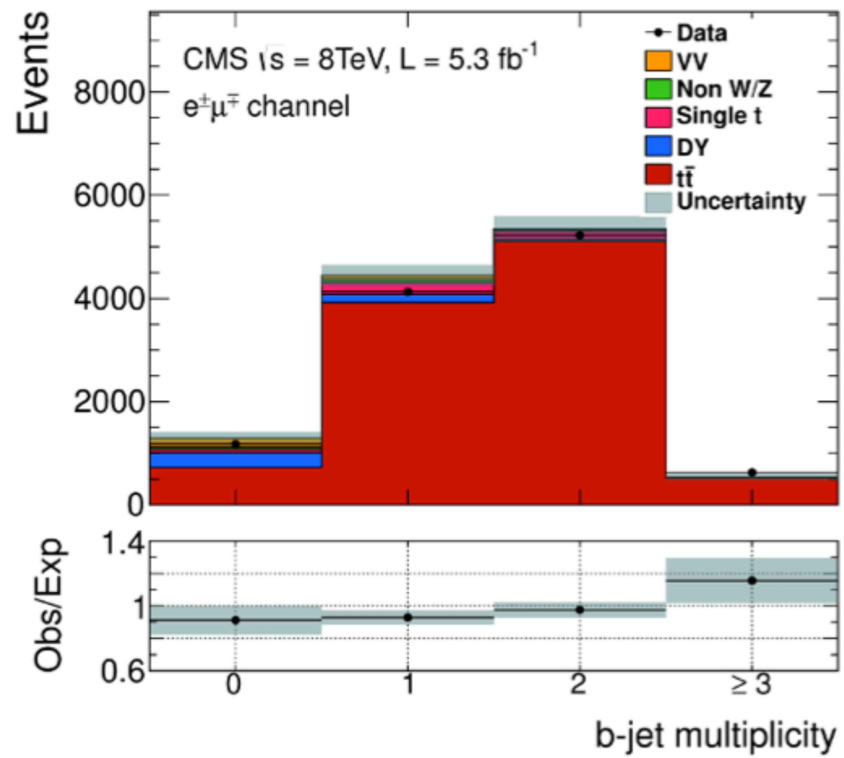


Dilepton channel

JHEP 02(2014)024

- Branching ratio (BR) ~5%
- Background: small
- Clean final state
  - two leptons + ≥2 jets + MET
  - kinematic variables

- Signal visible w/without b-tagging
- Measure cross section:
  - ee, μμ, eμ final states
  - btag (CSV): eff 85%, misID 10%
  - Cut and count
- Main systematics: JES, lepton ID, (pileup, b-tag, signal modeling)

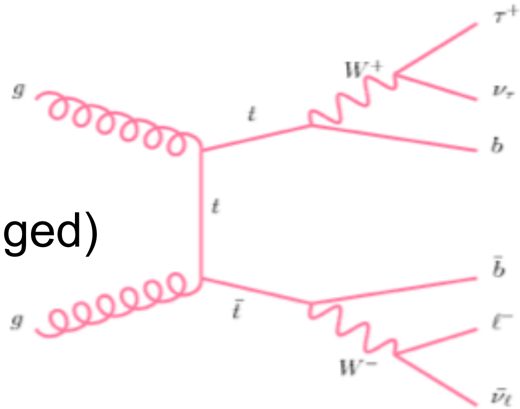


$$\sigma_{t\bar{t}} = 239 \pm 2\,(\text{stat.}) \pm 11\,(\text{syst.}) \pm 6\,(\text{lum.})\,\text{pb}$$ ±5%

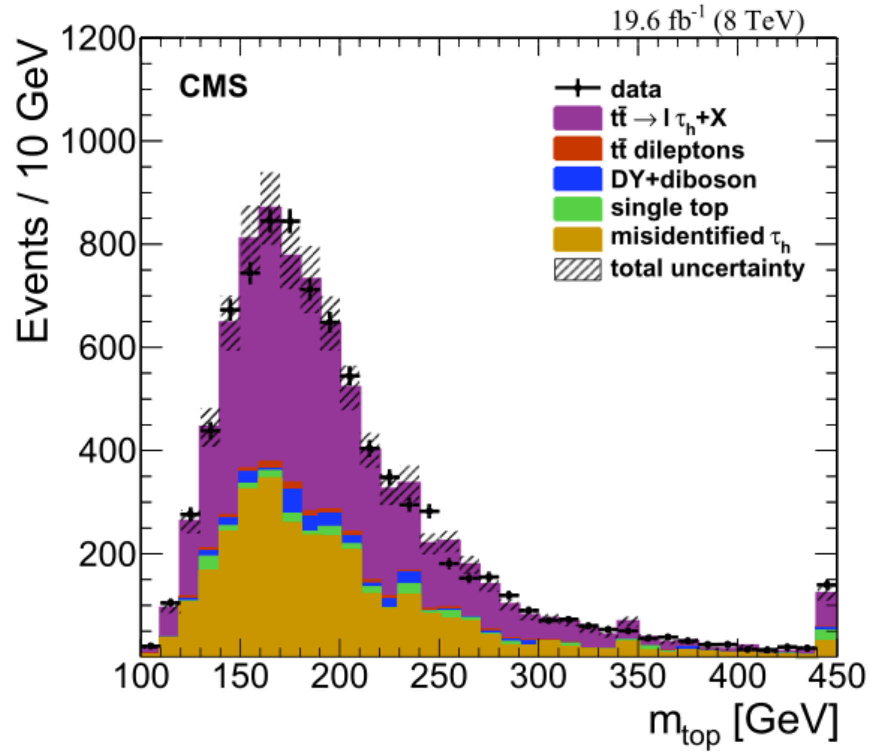
Tau$_h$+lepton final state

PLB 739(2014)23

- Selection:
  - one isolated lepton (e/μ)
  - at least two jets (one b-tagged)
  - OS tau (hadronic decay)
  - MET



- Determine τ fakes from data
  - Expected to be dominated by quark/gluon jets
  - Estimate from multi-jet/W+jets: use data



dominant syst.: τ fakes, b-tag

Good agreement between measurement and predictions

$$\sigma_{t\bar{t}}(e\tau_h) = 255 \pm 4\,(\text{stat}) \pm 24\,(\text{syst}) \pm 7\,(\text{lumi})\text{ pb};$$

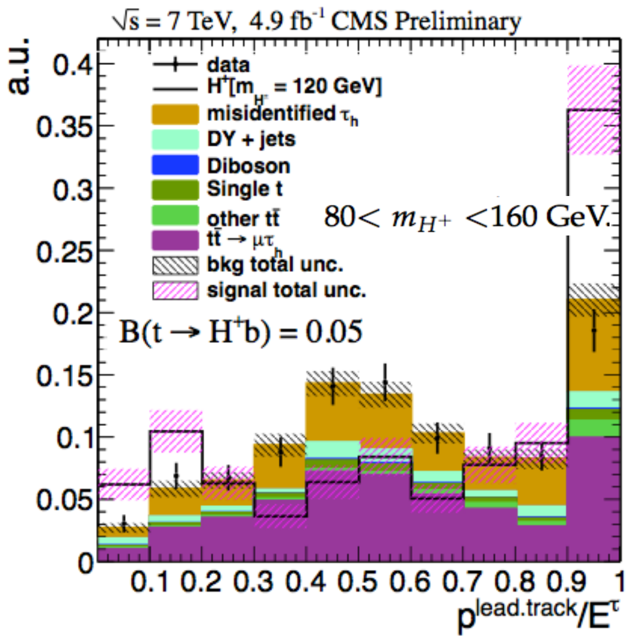
$$\sigma_{t\bar{t}}(\mu\tau_h) = 258 \pm 4\,(\text{stat}) \pm 24\,(\text{syst}) \pm 7\,(\text{lumi})\text{ pb}$$

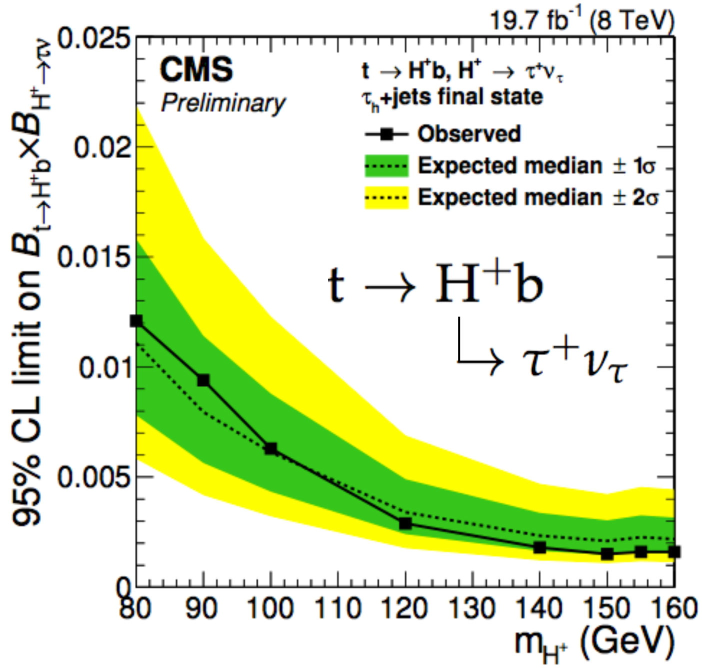
±10%

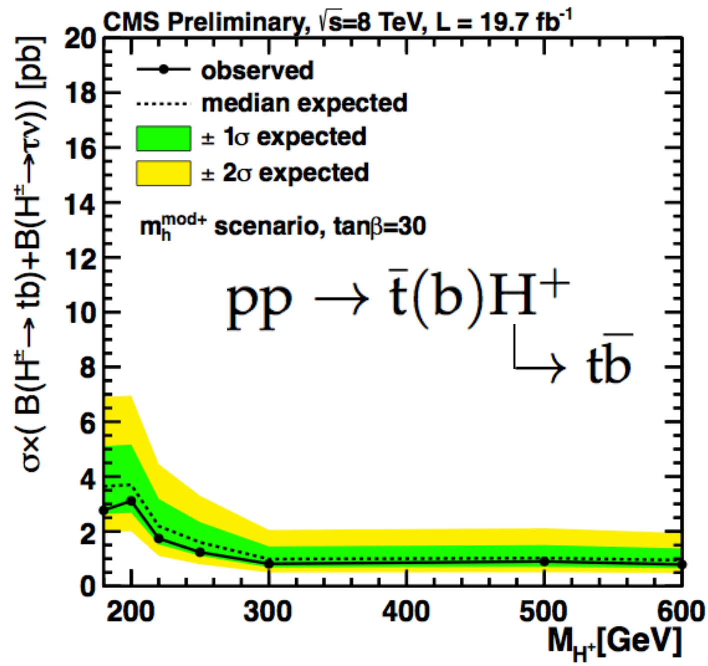
Is there a charged Higgs?

JHEP 07(2012)143, CMS-HIG-12-052, CMS-HIG-14-020, CMS-HIG-13-026

- If anomalous tau/lepton production in ttbar decays there may be contribution from charged Higgs







Yields in agreement with expectations ⇒ set limits

m_H: 80-160 GeV $\mathcal{B}(t \to bH^+)$ < 1.2-0.6%

200-600 GeV $\sigma(pp \to \bar{t}(b)H^+)$ < 4-1 pb

All-hadronic: cross section

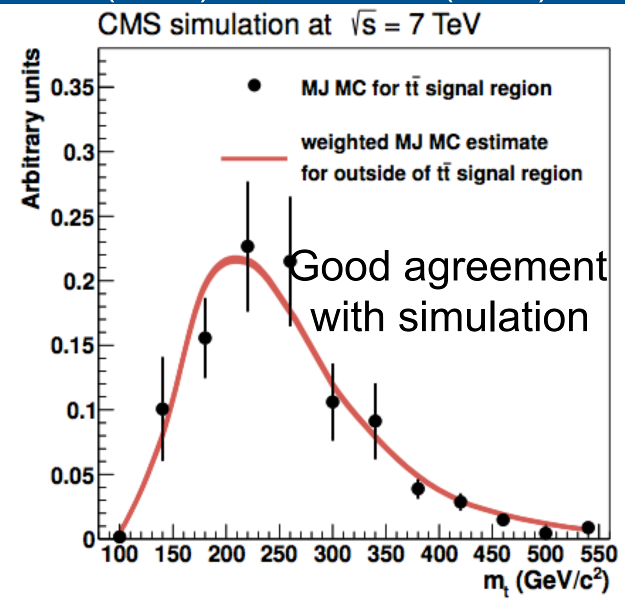
JHEP 05(2013)065. EPJC 74(2014)2758

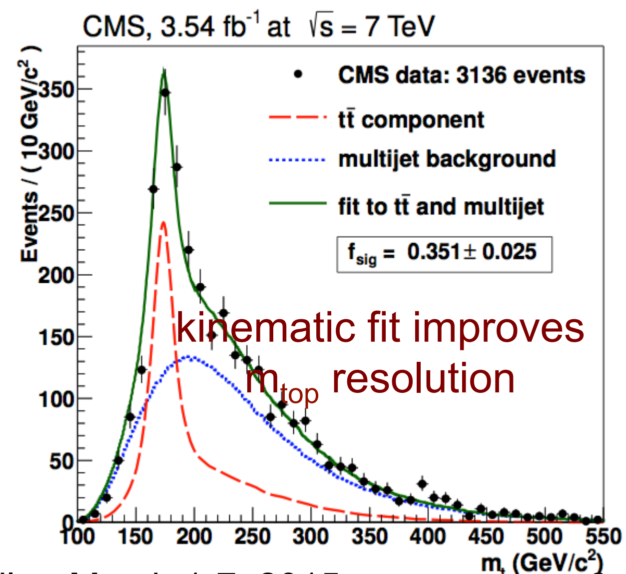
- Fully hadronic final state (BR~46%)
- Six jets and no leptons in the final state
- Reconstruct ttbar system and fit with least χ^2 method
  - reconstruct both W bosons
  - $m_{top1}=m_{top2}$ are free parameters
  - b-jets are taken as b-quark candidates
  - take permutation with smallest χ^2
- Multijet QCD is main background (from data)
  - Use same selection without b-tag req.
  - Re-weigh mass spectrum from anti-tagged sample
- Templates are inputs for likelihood fit for cross section measurement
  - Signal and background templates
  - Signal fraction is a free parameter

±20%

$$\sigma_{t\bar{t}} = 139 \pm 10\,(\text{stat.}) \pm 26\,(\text{syst.}) \pm 3\,(\text{lum.})\,\text{pb}$$

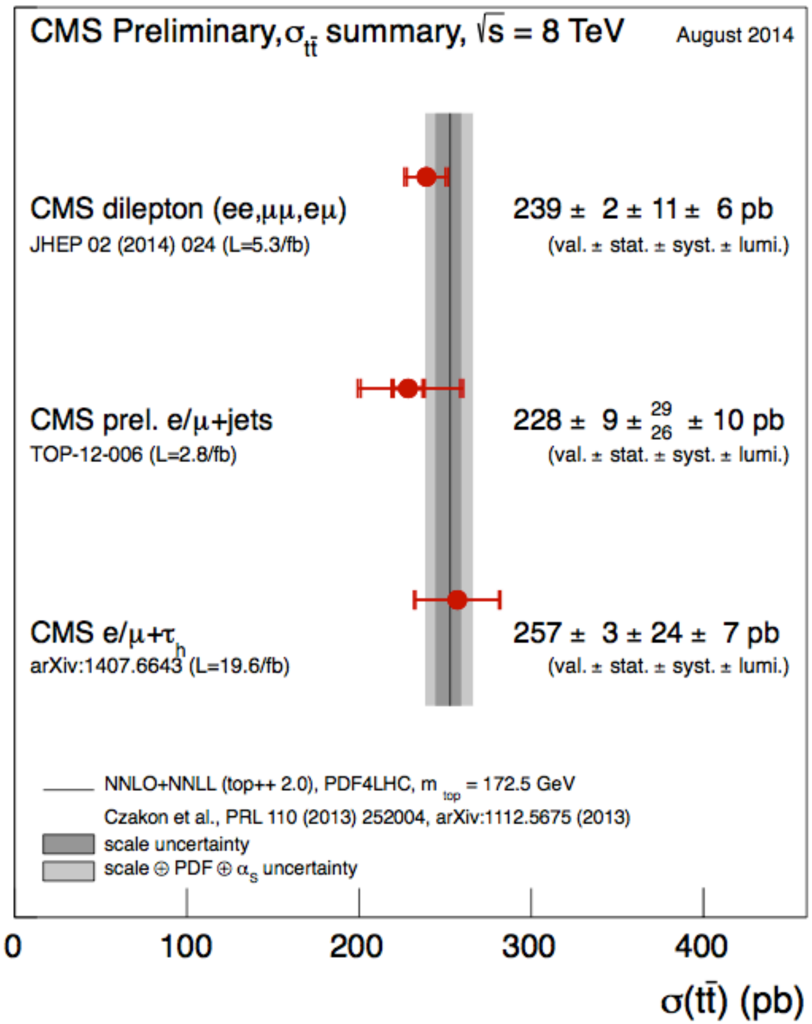
- Dominant syst.: JES, b-tag



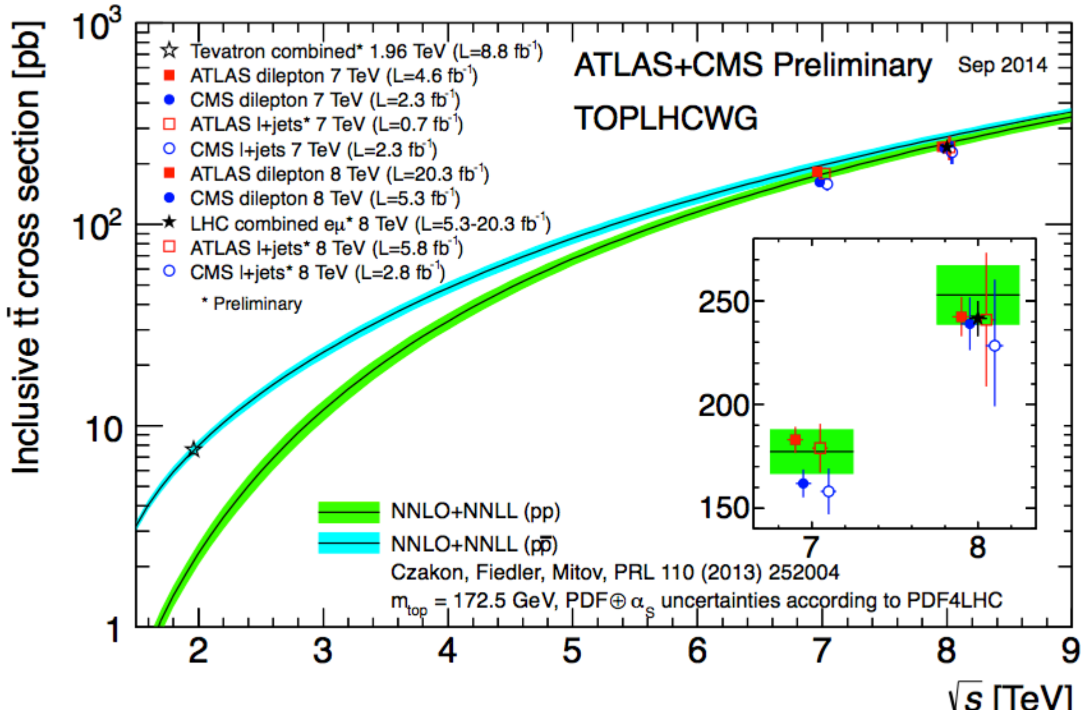


Cross sections

±5%



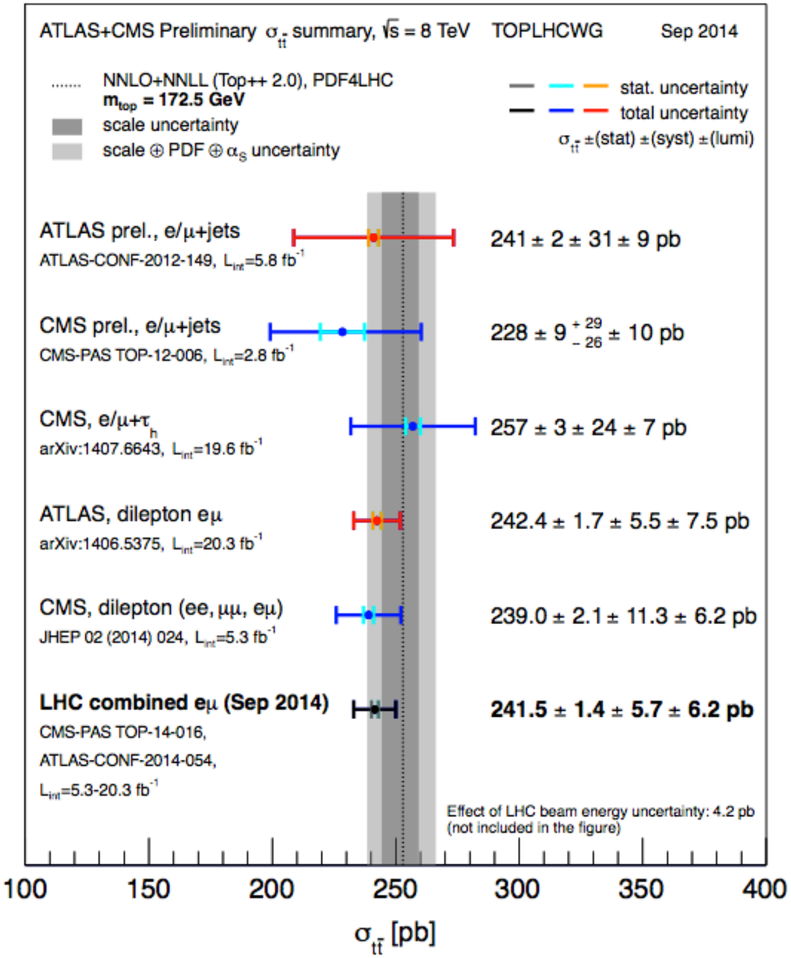
- Cross section measurements provide test of pQCD predictions
- Standard "candle":
  - ttbar is a dominant background for NP searches
- Comparison in different channels may provide constraints on BSM



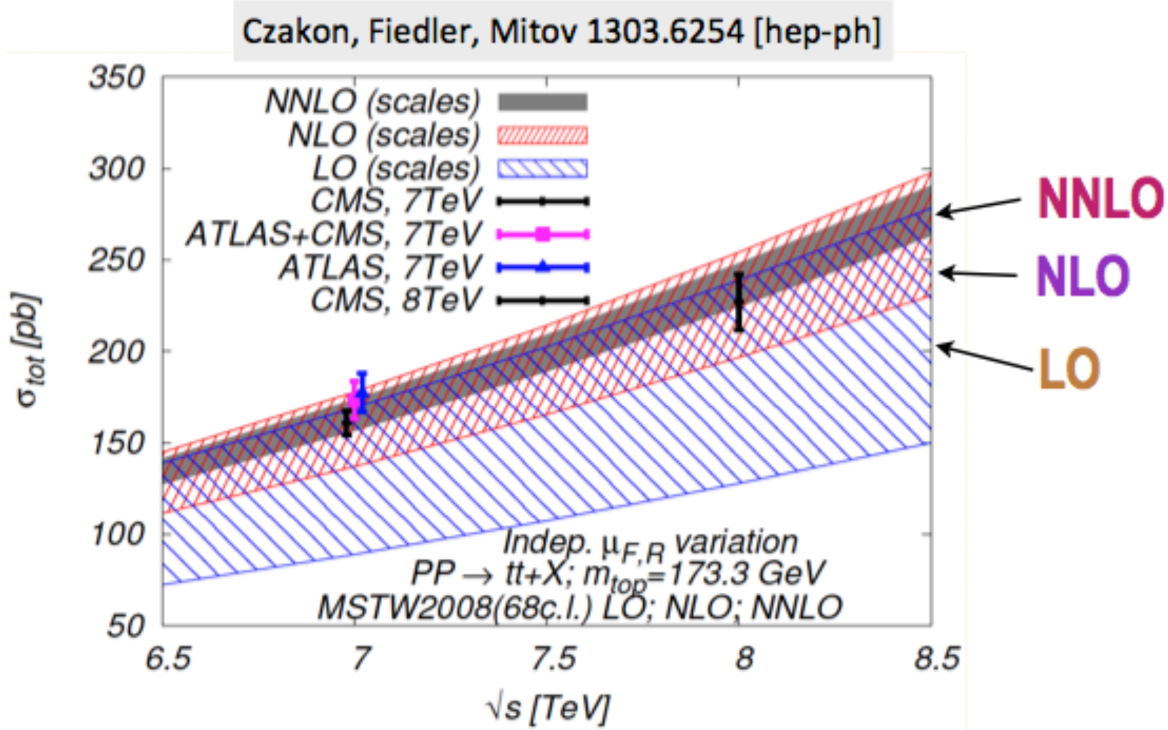
Cross sections (cont.)

CMS-TOP-14-016

±4%



⇒meas. challenging the theory



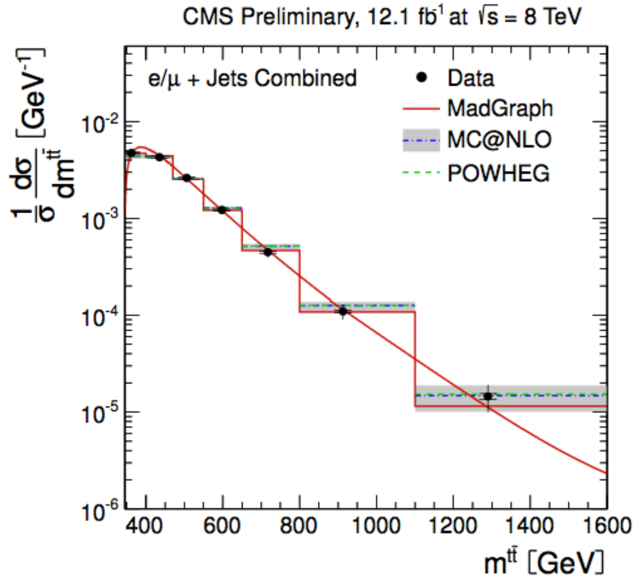
Collider	σ_{tot} [pb]	scales [pb]	pdf [pb]
Tevatron	7.164	+0.110(1.5%) −0.200(2.8%)	+0.169(2.4%) −0.122(1.7%)
LHC 7 TeV	172.0	+4.4(2.6%) −5.8(3.4%)	+4.7(2.7%) −4.8(2.8%)
LHC 8 TeV	245.8	+6.2(2.5%) −8.4(3.4%)	+6.2(2.5%) −6.4(2.6%)
LHC 14 TeV	953.6	+22.7(2.4%) −33.9(3.6%)	+16.2(1.7%) −17.8(1.9%)

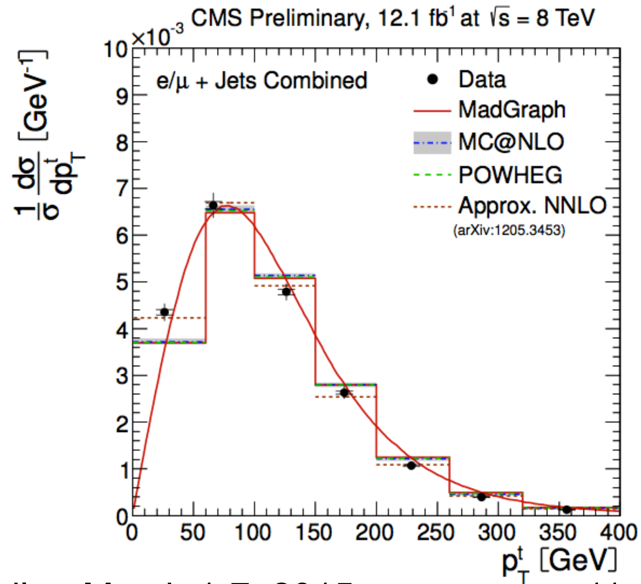
±3-5%

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





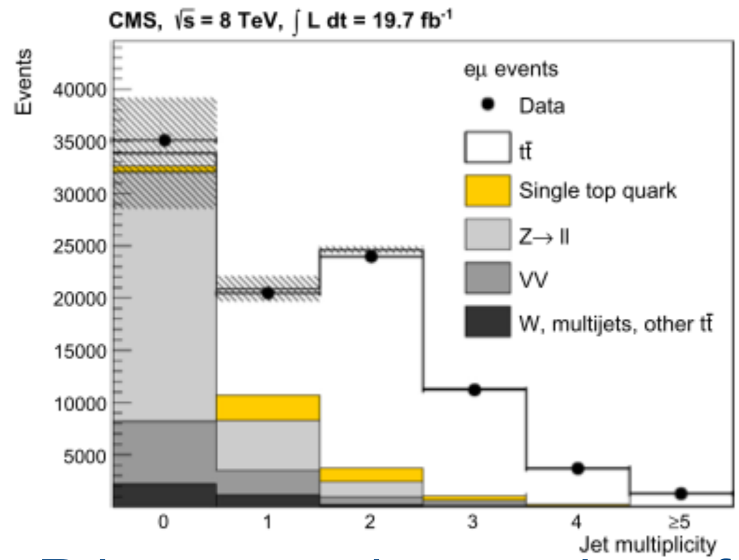
Cross section in the R measurement

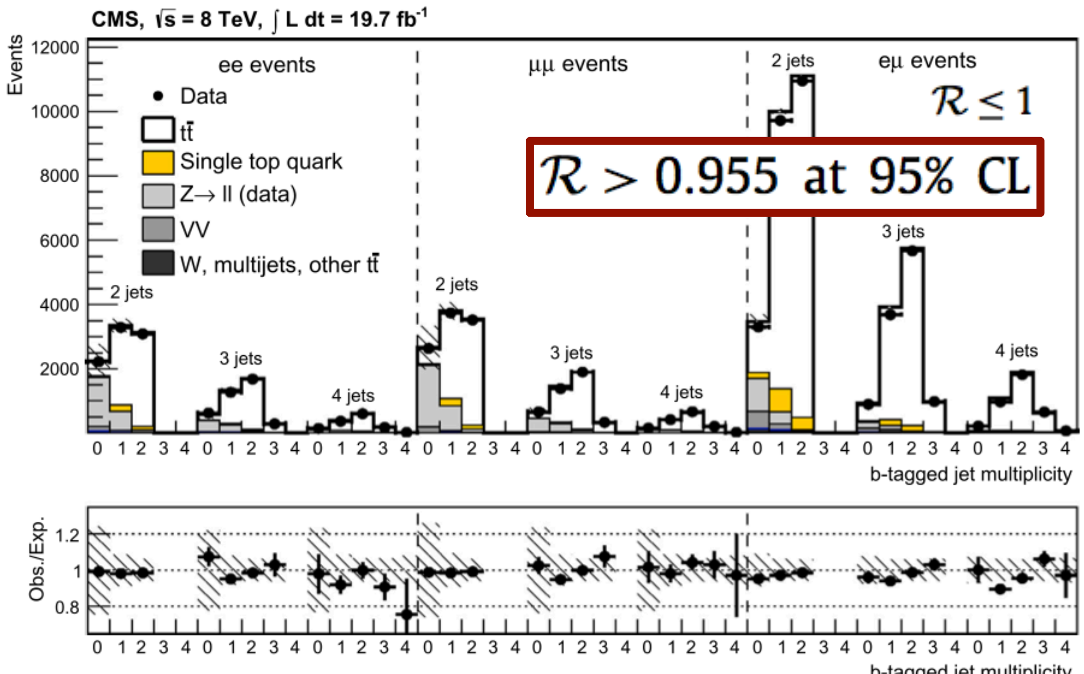
N.Cim. B125(2010)983, PLB 736(2014)33

- Focused on measurement of R:
- Dilepton final state
- Use profile likelihood
- Syst. unc.: PDF, ttbar modeling, etc.

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

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





$$\mathcal{R} > 0.955 \text{ at } 95\% \text{ CL}$$

- Measure R by comparing number of ttbar events with 0, 1 and 2 b-tags
- Fully "data-driven" background determination
  - Use wrong assignment in m_{lb} distribution
- b-tagging multiplicity vs. R, ε_b, ε_q

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

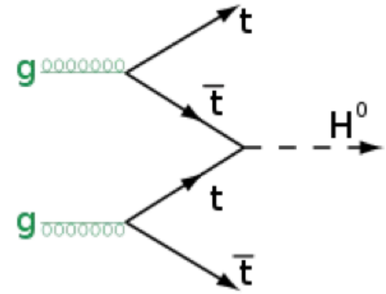
ttbar+jet cross section

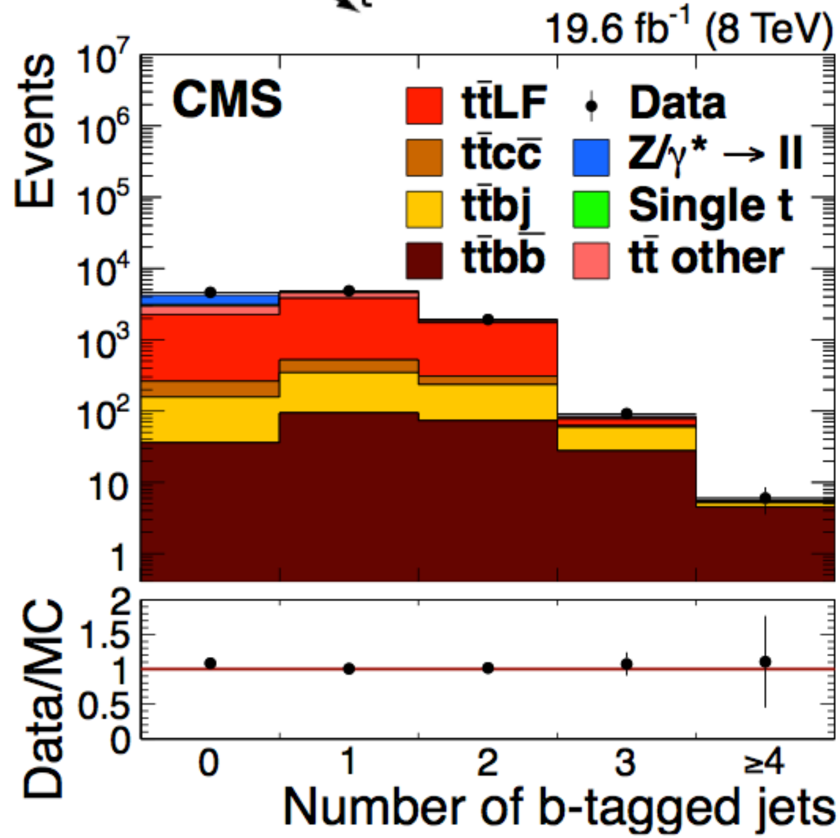
arXiv:1411.5621

- Direct measurement of typical bkg to ttH coupling
- Anomalous tt+jets could signal BSM final states
- 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)

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

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

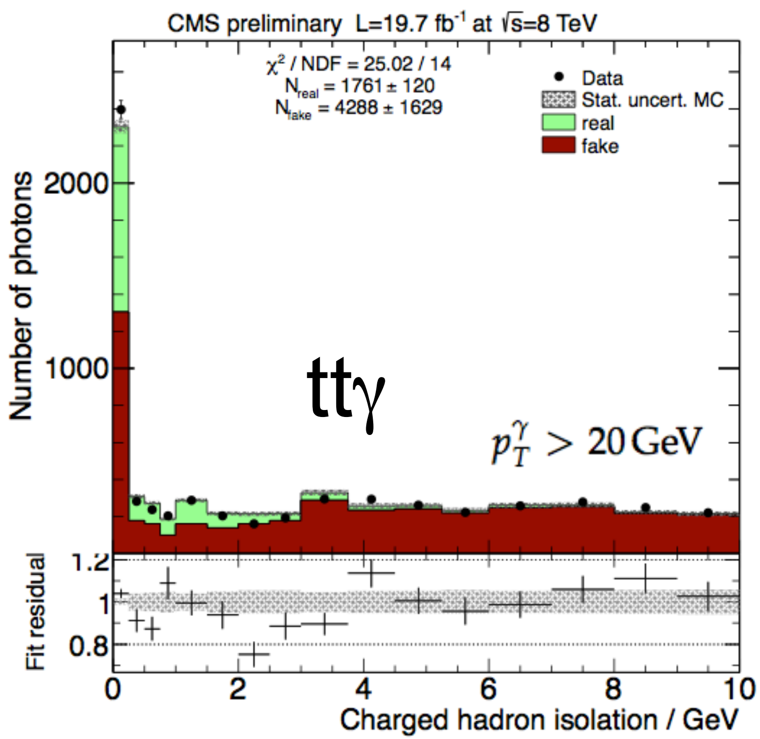




ttV (V=γ,Z,W)

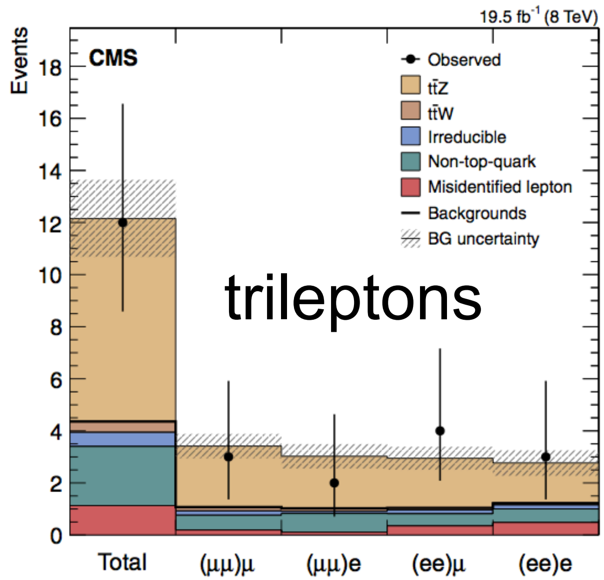
CMS-TOP-13-011, EPJC 74(2014)3060

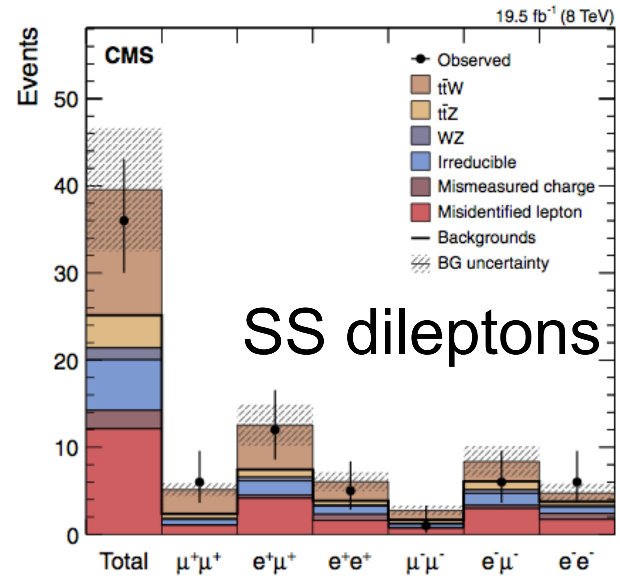
- Measurements will give access to EW couplings of the top



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

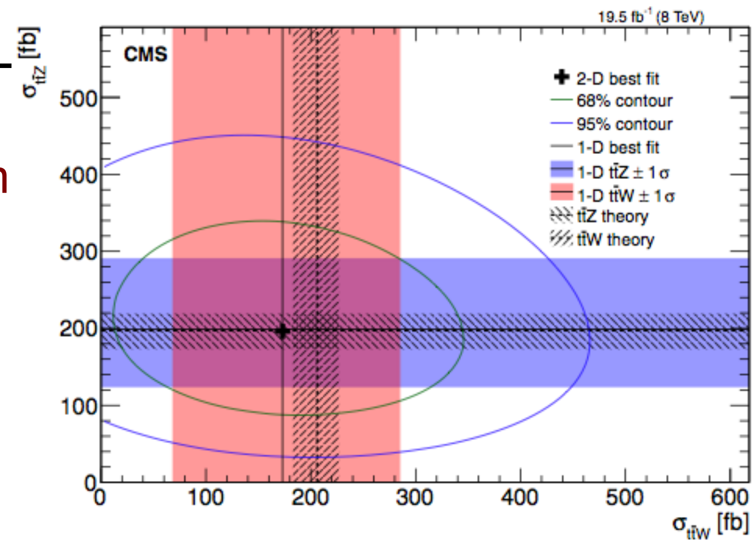
Consistent with theoretical predictions





Combine 2- 3- and 4-lepton final states

⇒ ttV xsec 3.7σ from bkg-only hypothesis



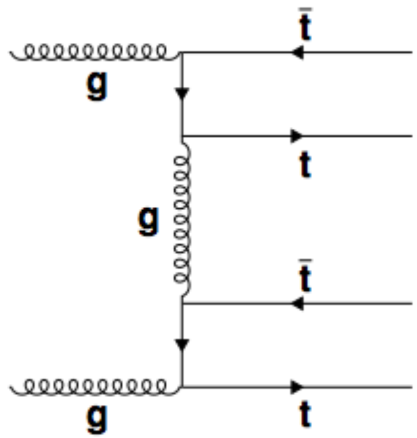
Multi-top production

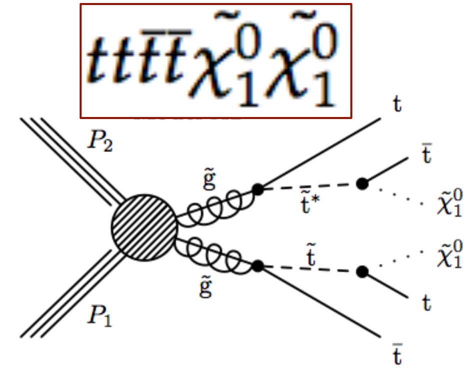
JHEP 11(2014)154, JHEP 01(2014)163

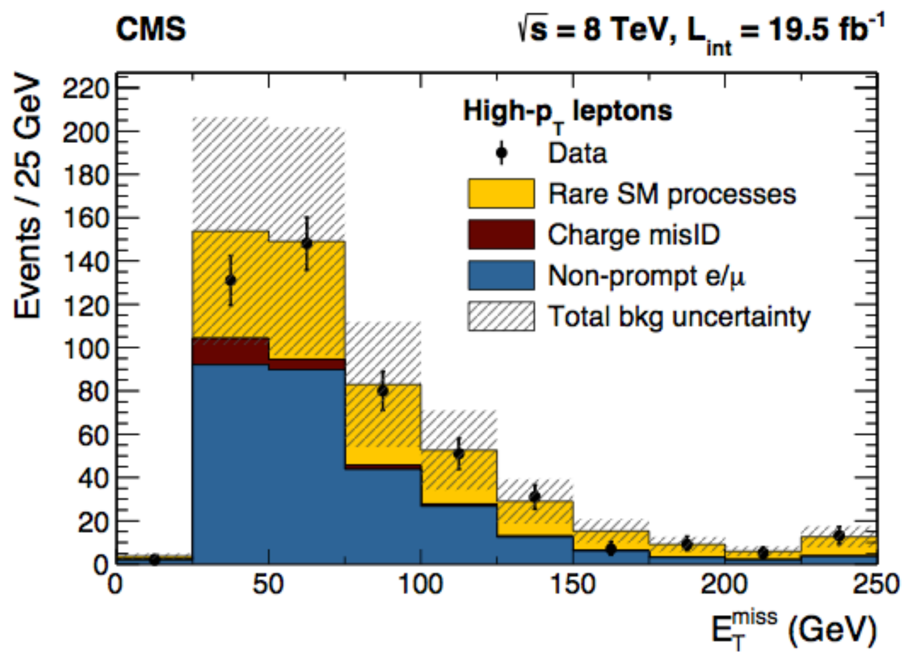
- Production of 4 tops is an attractive scenario in a number of new physics models
- The SM cross section is ~1fb

- 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





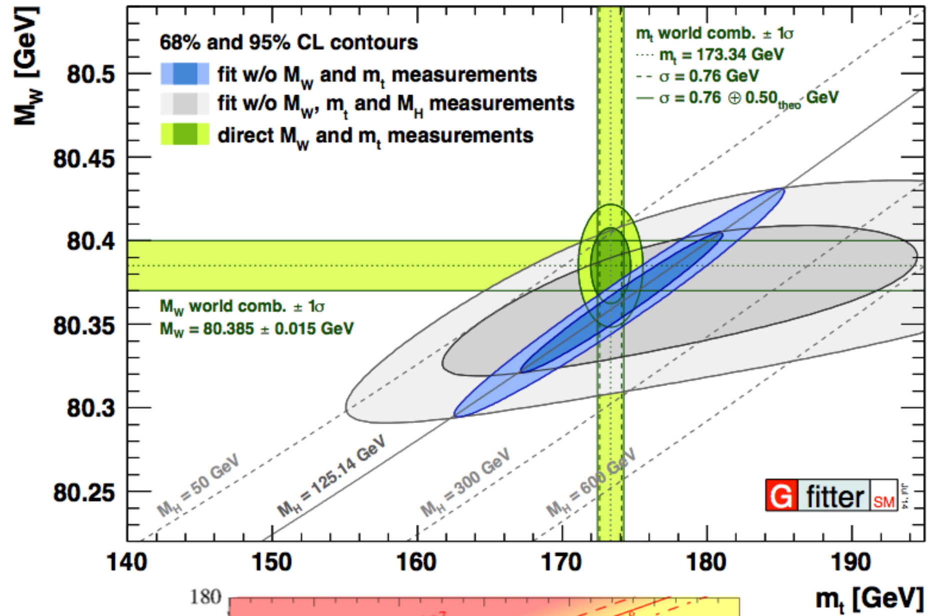


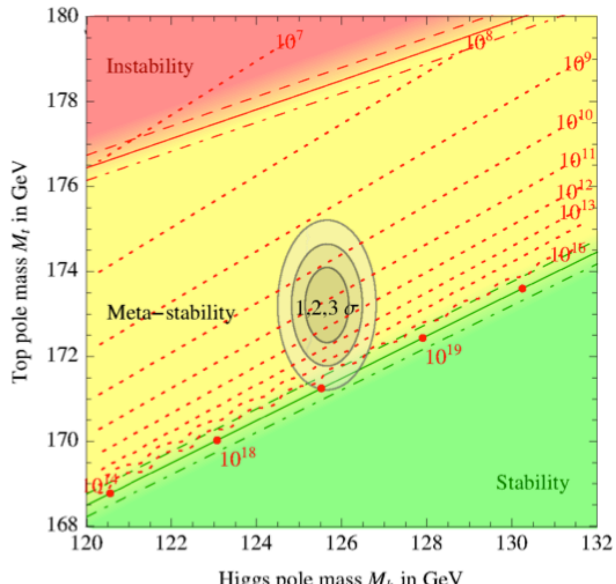
Top quark mass: why do we care?

- 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 likely allow for discrimination between SM and MSSM scenario
- The fate of the Universe might depend on Δm_{top}~1 GeV

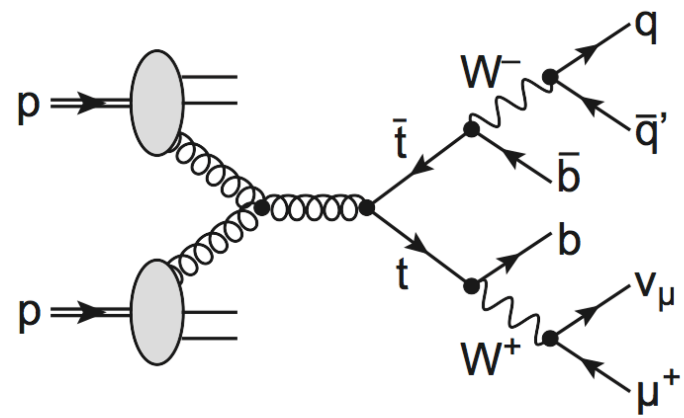


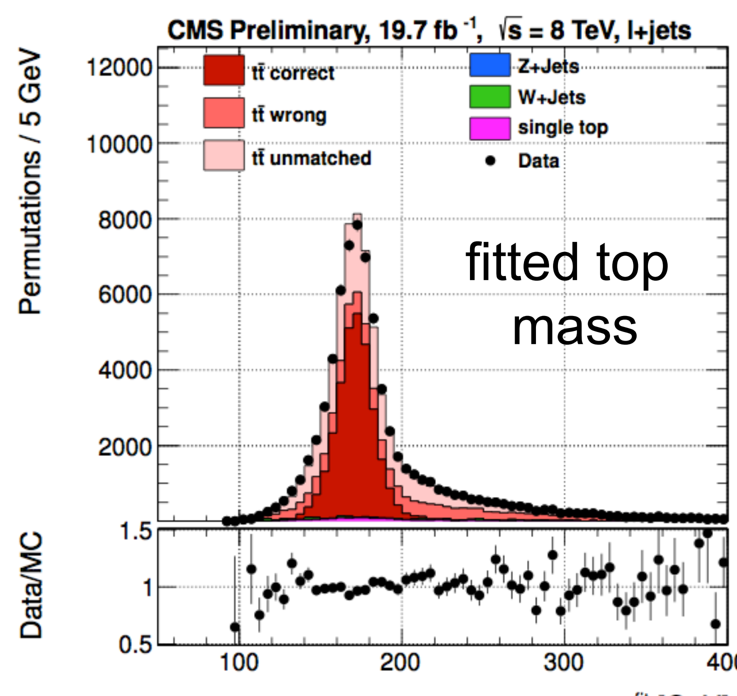


Lepton+jets final state

CMS-TOP-14-001

- Best channel to measure m_t
  - well defined final state (1 lepton, 1ν, 2b $W_{qq'}$)
- Select ttbar events, define observable
  - hadronic decays (m_t, m_W)
  - No optimization ⇒get incorrect parton-jet assignment
- Kinematic fit: constrain W mass, top-antitop masses
  - In-situ JES calibration
  - Goodness of fit
  - Event-by-event weight
  - 42% correct, 21% wrong, 37% unmatched
  - Also use info from incorrect assignments

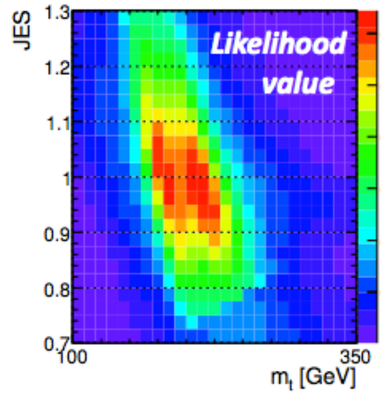




Lepton+jets final state (cont.)

CMS-TOP-14-001

- Extract top mass and JSF
- kinematic fit + "ideogram" method combine event-per-event likelihood
  - Calculate likelihood from templates and observed m_t, m_W
  - For each event (point in the m_t/JSF plane)
  - Interpret each assignment as correct/wrong/ unmatched
  - Maximize full likelihood to measure m_t and JSF
- Not one single dominant systematic uncertainty



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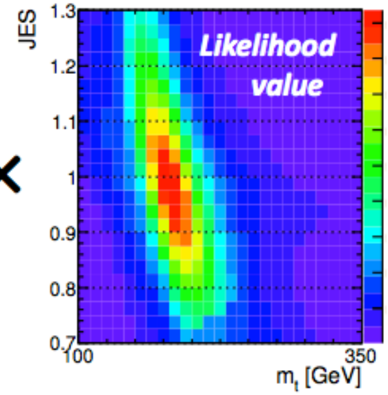

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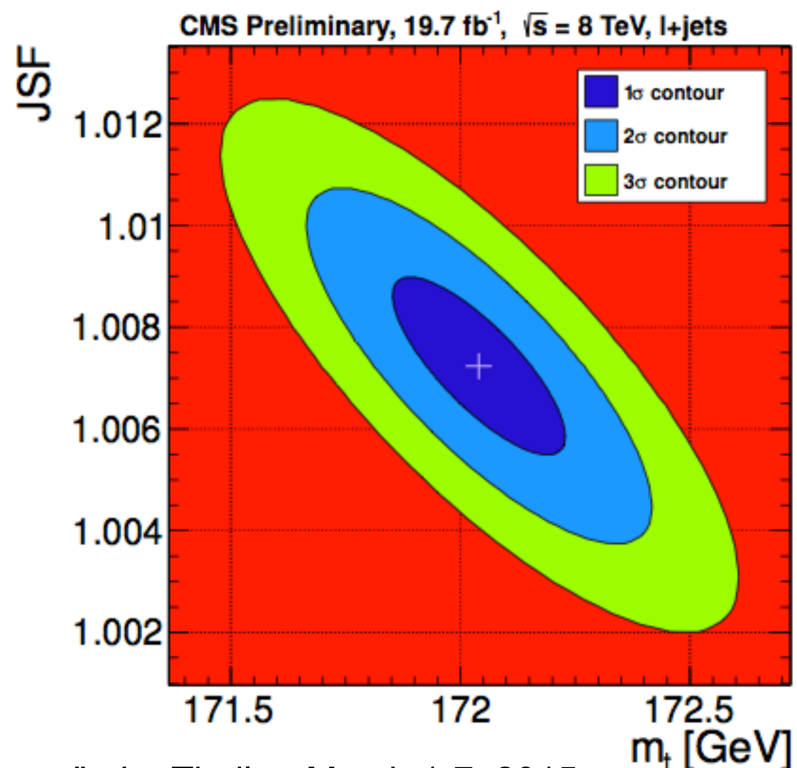


±0.4%

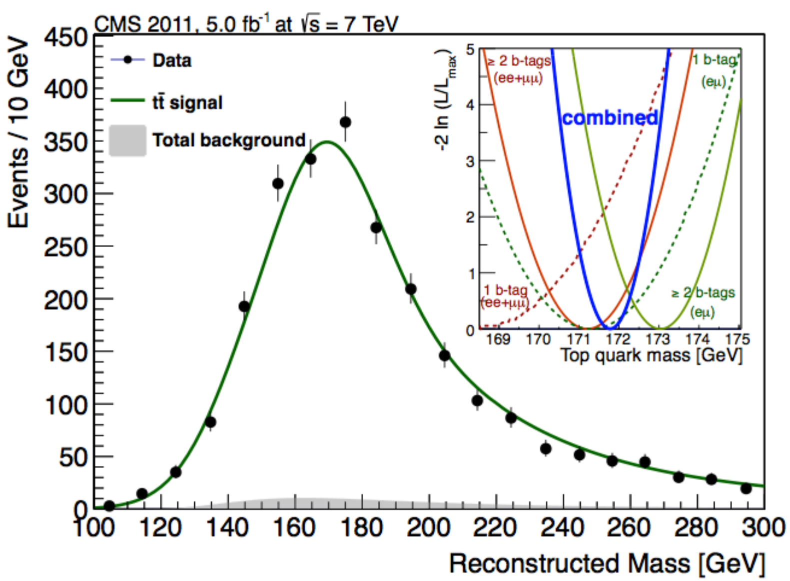
$$m_t = 172.04 \pm 0.19\,(\text{stat.+JSF}) \pm 0.75\,(\text{syst.})\,\text{GeV}$$
$$\text{JSF} = 1.007 \pm 0.002\,(\text{stat.}) \pm 0.012\,(\text{syst.}).$$

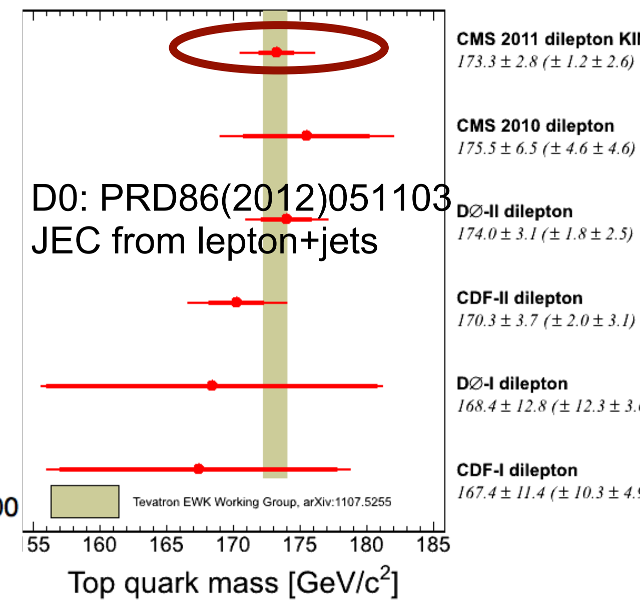
Top mass in dileptons

EPJC 72(2012)2202, TOP-14-010

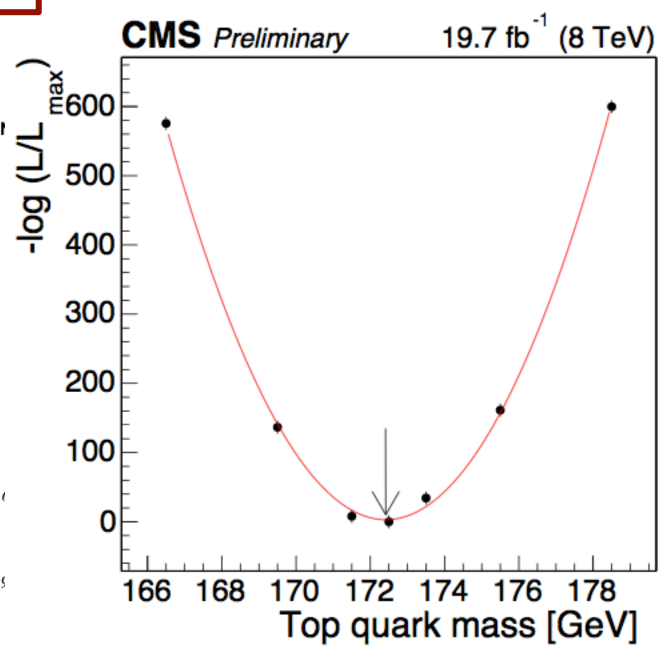
- Under-constrained system (2 neutrinos)
- Event selection similar to cross section measurement (require MET)
  - Reconstruct event kinematics with full event kinematics (KINb method)
  - Matrix element weighting (AMWT): use analytical solutions for m_{top} hypotheses
- Measurement dominated by JES uncertainty/b-fragmentation

$$m_t = 172.47 \pm 0.17(\text{stat}) \pm 1.40(\text{syst})\ \text{GeV}$$ ±0.8%





D0: PRD86(2012)051103
JEC from lepton+jets



Alternative methods: dileptons

CMS-TOP-14-014

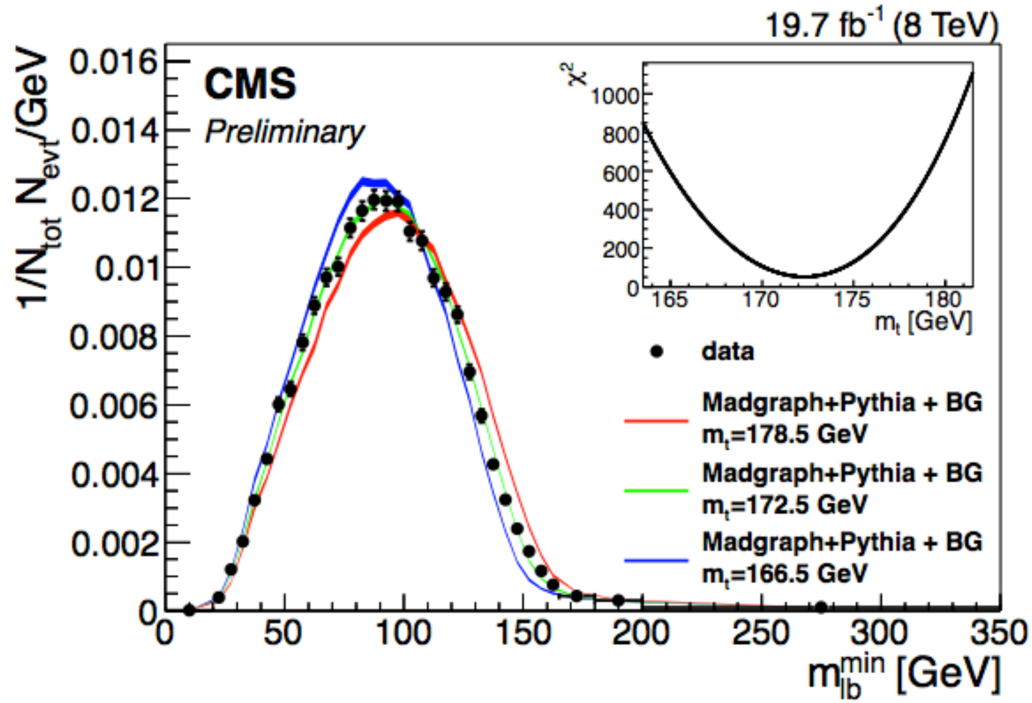
- Leptonic decays (eμ final state):
  - Expect ~92% of ttbar events

$$m_{lb}^2 = \frac{m_t^2 - m_W^2}{2}(1 - \cos\theta_{lb})$$

$$\max(m_{lb}) \approx \sqrt{m_t^2 - m_W^2}$$ ≈153GeV

- Reconstruct m_{lb} and fit event yields bin-by-bin for different m_t
  - choose permutation that minimizes m_{lb}
  - ~75-80% correct assignments
  - determine m_t by comparing yields in m_{lb} distribution for data and predictions
  - shape and/or rate of m_{lb} distr.
- Dominant uncertainties from normalization, background

⇒ m_{top}=172.3 ± 1.3 GeV ±0.8%



see J. Kieseler talk

All-hadronic: mass

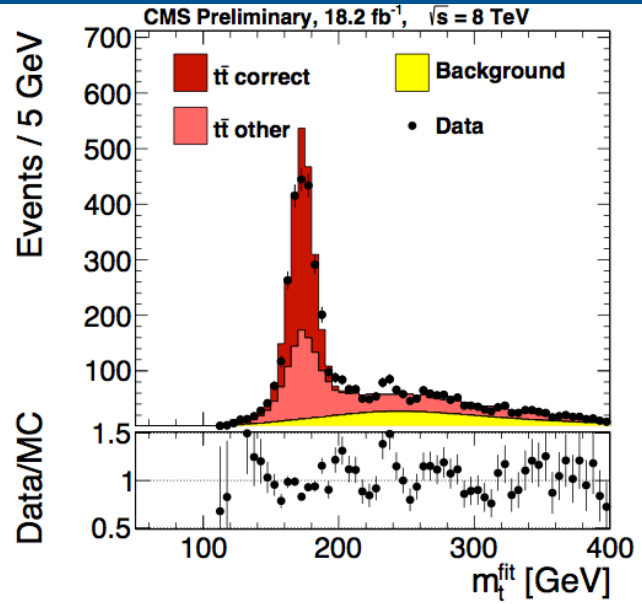
CMS-TOP-14-002

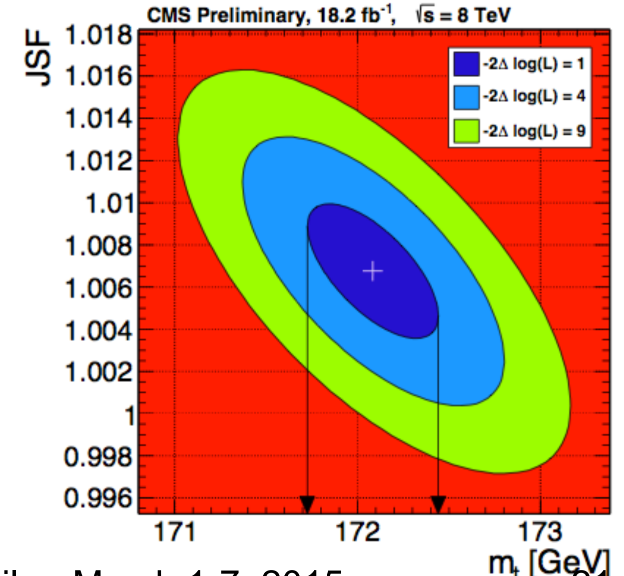
- Similar event selection as for xsection
- signal is extracted from data with a template fit on the top mass distribution
  - signal shape taken from the simulation
  - QCD multijet production is the only relevant background, **data-driven estimate**
  - kinematic fit on **zero-btag sample** (negligible signal contamination)
- Switch to 2D fit with JES scale factor
- Fit signal and correct permutation fractions
- Constrain fit to ttbar hypothesis

±0.5%

$$m_t = 172.08 \pm 0.36\,(\text{stat.+JSF}) \pm 0.83\,(\text{syst.})\,\text{GeV}$$
$$\text{JSF} = 1.007 \pm 0.003\,(\text{stat.}) \pm 0.011\,(\text{syst.}).$$

- Main systematics: JES+PU, signal modeling

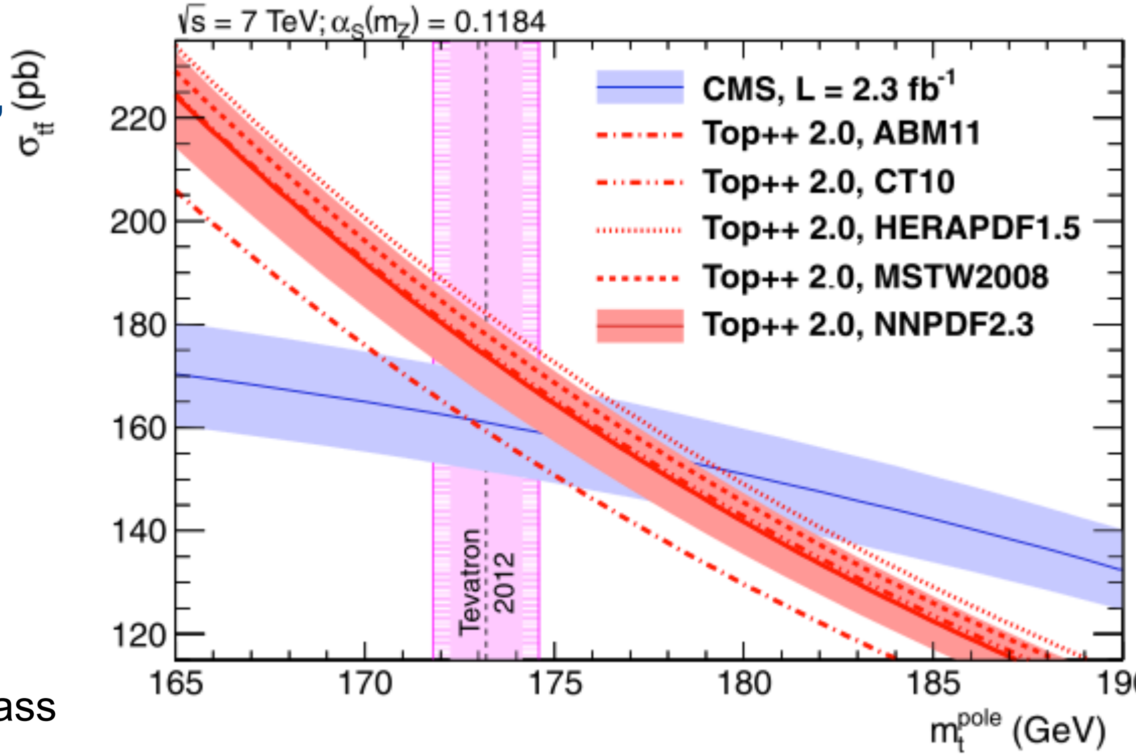




Top mass from cross section

PLB 728(2014)496

- Direct m_{top} measurements rely on details of kinematics, reconstruction, calibration
- Extract mass from cross section
  - determine top quark pole mass using the experimental ttbar production cross section
- Comparatively large systematics
- Extract mass for fixed α_S
- Results consistent with standard measurements and EWK fits
  - Constrain α_S at the scale of the Z boson mass and derive m_{top}^{pole}
  - Constrain m_{top}^{pole} to the measured value and derive α_S



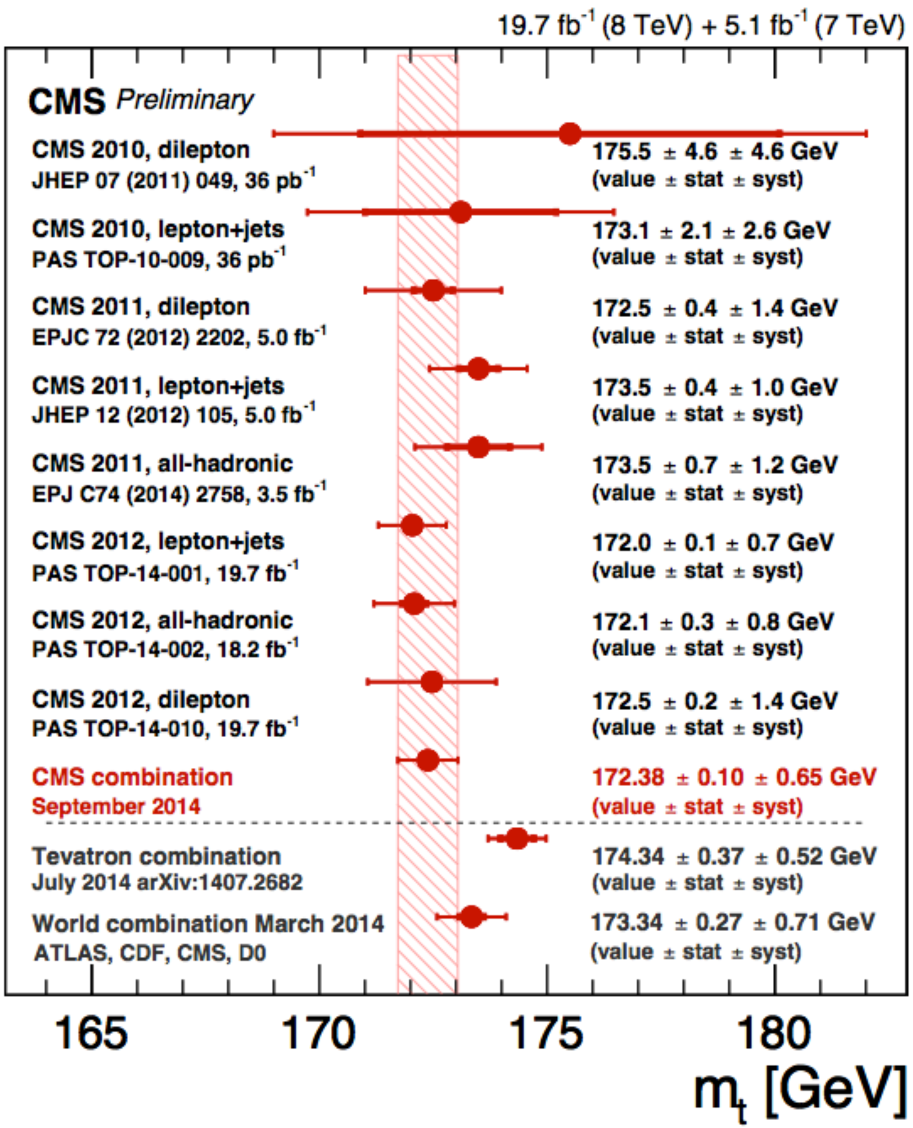
$$m_{top} = 176.7^{+3.8}_{-3.4}\ \text{GeV}$$

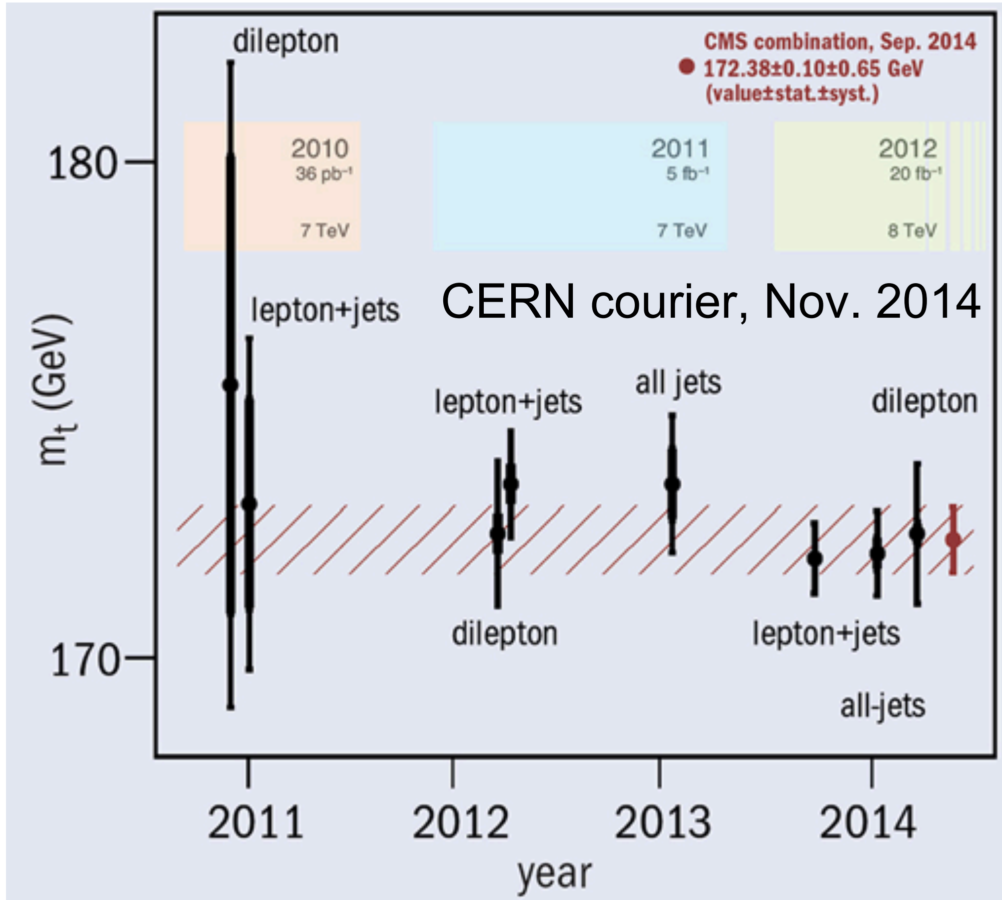
$$\alpha_S(m_Z) = 0.1151^{+0.0033}_{-0.0032}$$

⇒It works but the uncertainty is large

CMS mass combination

CMS-TOP-14-015





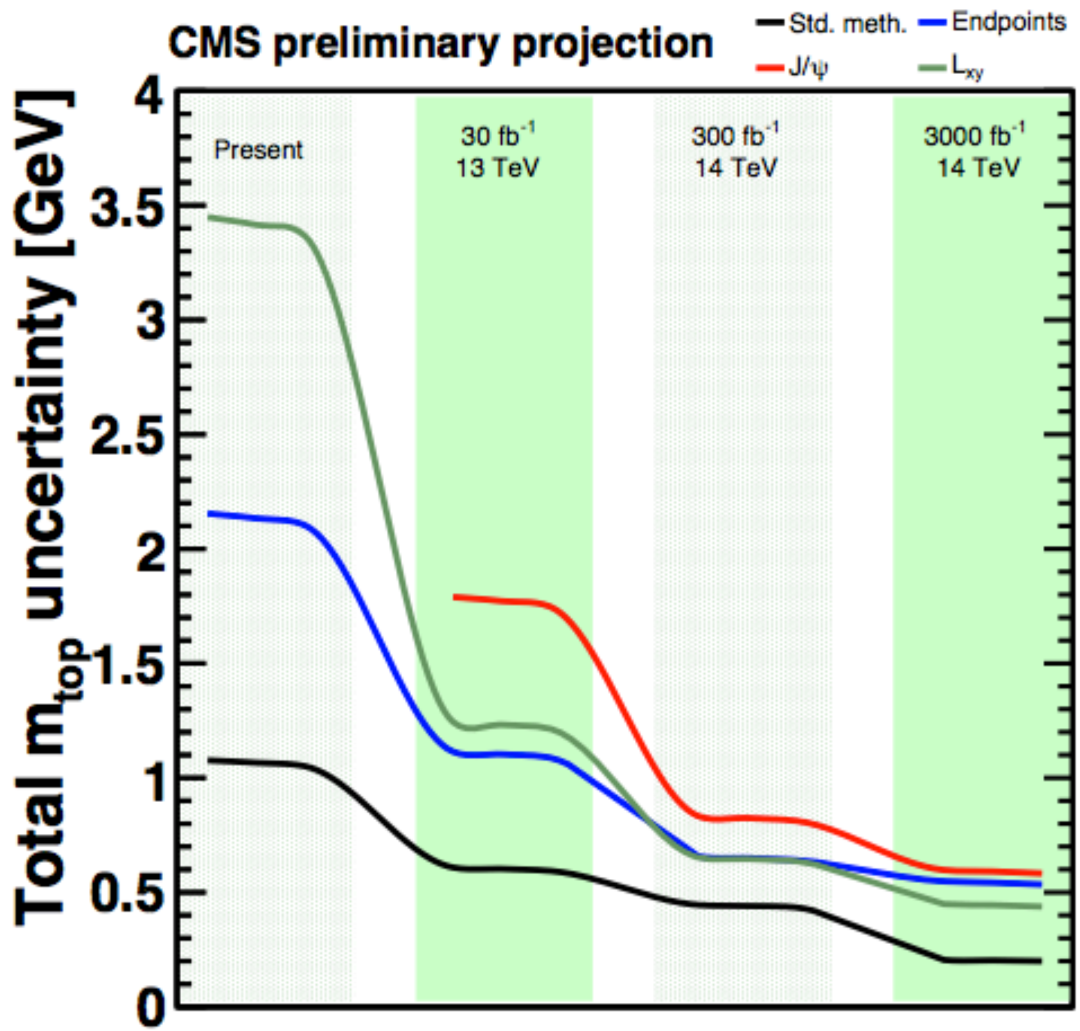
$$m_t = 172.38 \pm 0.10\,(\text{stat.}) \pm 0.65\,(\text{syst.})\,\text{GeV}$$

±0.38%

Mass: Run 2 and beyond

CMS-FTR-13-017

- Might be able to measure m_{top} with a precision of 200 MeV
- Differential study of m_{top}
- Differential cross sections with full NLO tools
- No truly dominant systematic uncertainty
- b-fragmentation studies
  - Measure in-situ in ttbar events
- Interpretation will require theory understanding improvement



Summary

- A lot of progress in understanding top quark production
- From a few events up to detailed studies
  - Improved understanding and precision
  - Uncertainties dominated by systematics
- Top quark physics plays a special role in most of BSM models
- Looking forward to future studies/13TeV data

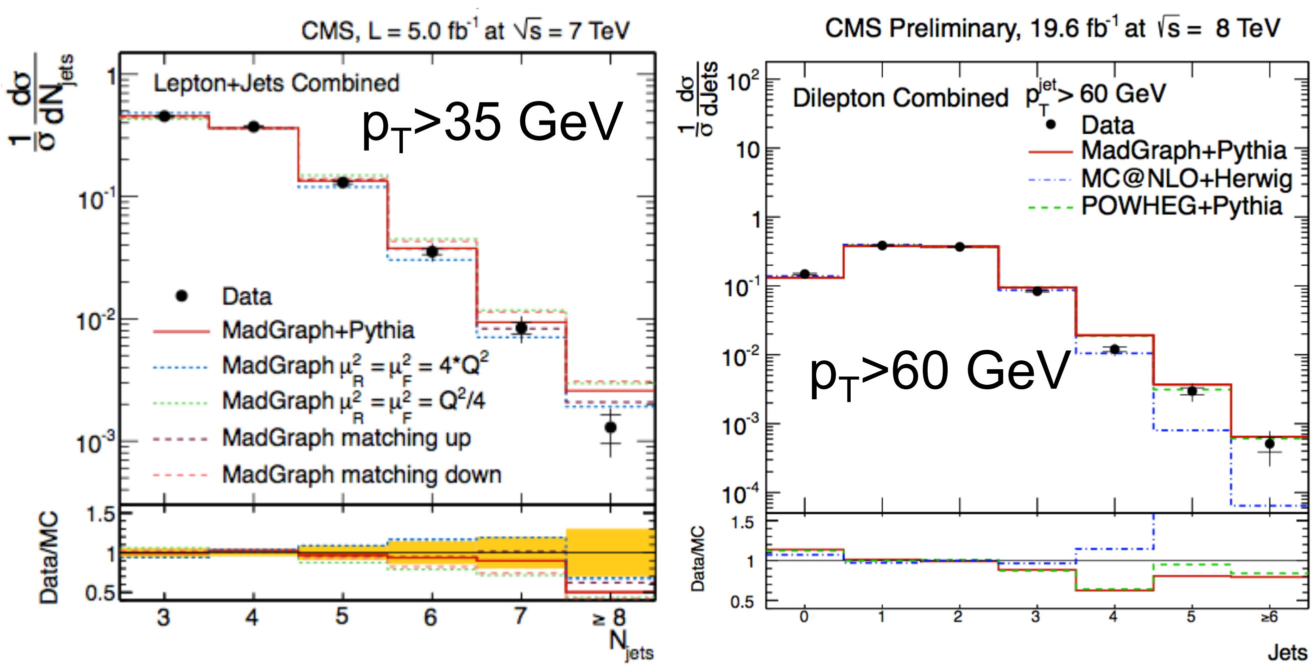
backup

Differential cross sections

CMS-TOP-12-041, arXiv:1404.3171

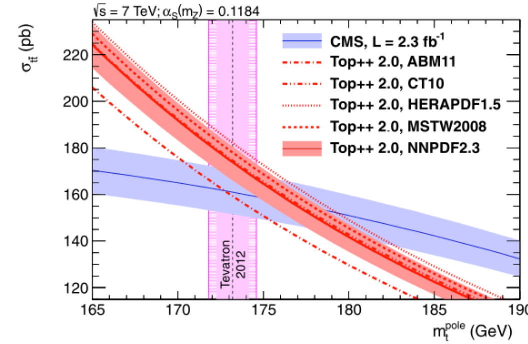
- Measurements performed in fiducial volume to minimize model dependency
- Improve ttbar modeling and reduce uncertainties
- Sensitive to BSM effects
- Correct for detector effects ("unfolding" to particle level) and acceptances
- Good agreement in dilepton and lepton+jet channels, at different energies
- Large uncertainties at high jet multiplicities dominated by JES and MC modeling

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



Alternative mass measurements

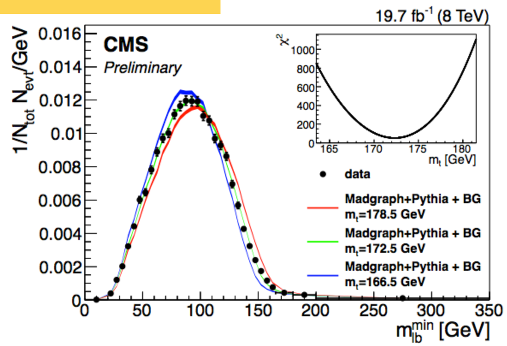
PLB 728(2014)496, CMS-TOP-14-014, EPJC 73(2013)2494,TOP-12-030

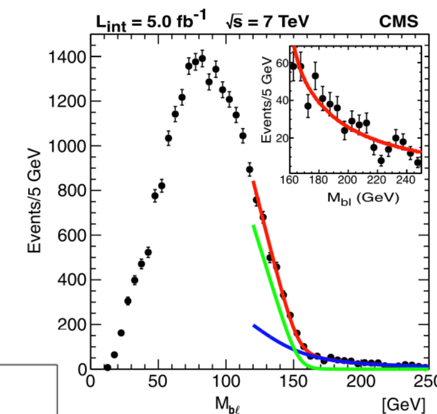


- Mass from production cross section
  - Well defined theoretical mass, relatively large uncertainties

see J. Kieseler talk

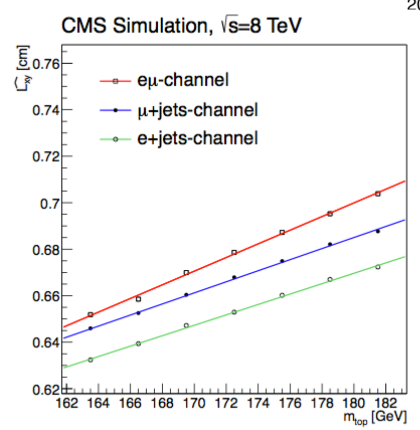
- From m_{lb} distribution
  - Potential for future applications using improved predictions





- Using kinematic endpoints
  - Completely independent of simulation

- Mass from b-hadron flight distance
  - Minimum dependence on JES
  - Depends on top p_T modeling

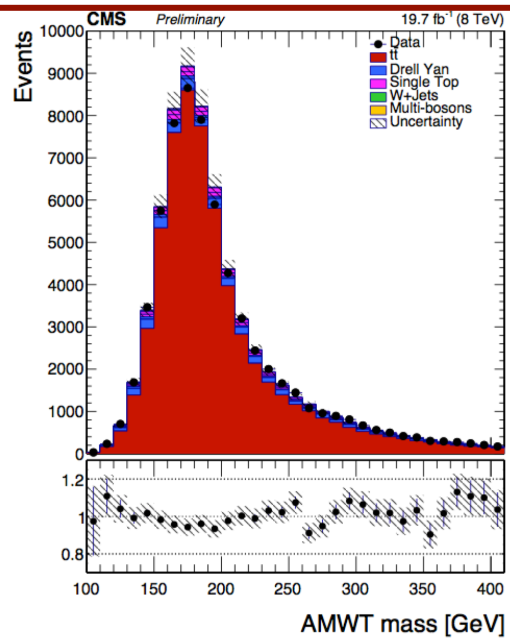


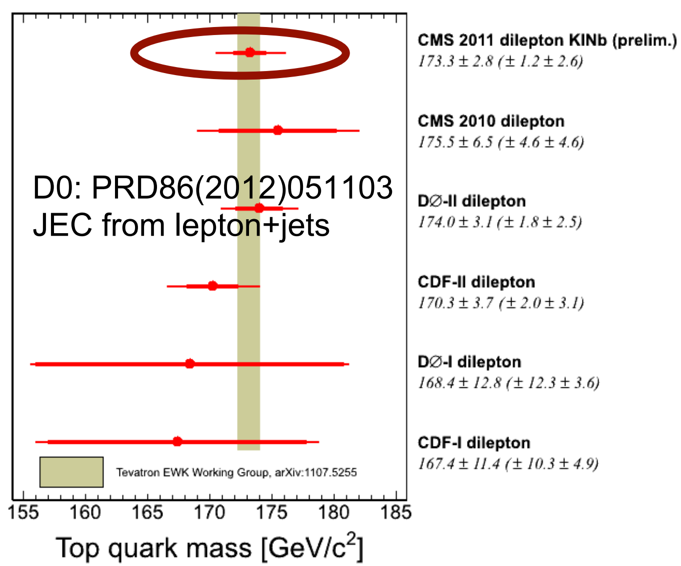
Top mass in dileptons

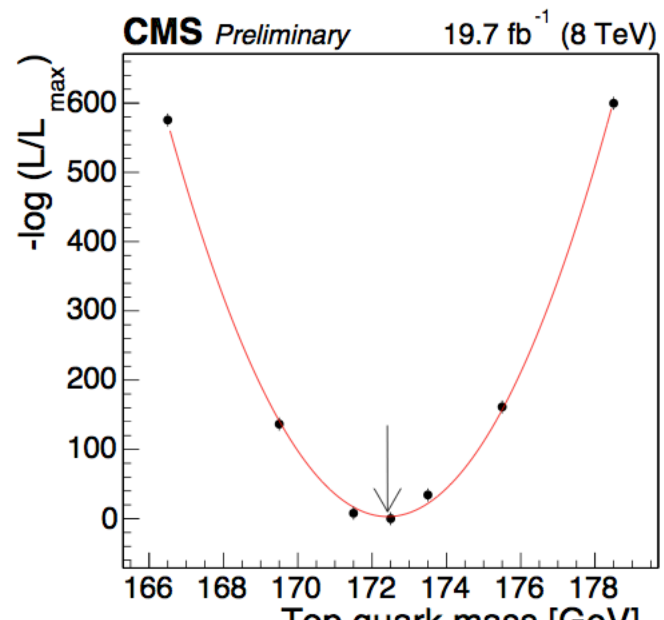
EPJC 72(2012)2202, TOP-14-010

- Under-constrained system (2 neutrinos)
- Event selection similar to cross section measurement (require MET)
- Build observable using analytical solutions for m_{top}
  - Up to 4 solutions per event per lepton-jet assignment
  - Assign weight using probability
- Measurement dominated by JES uncertainty/b-fragmentation

$$m_t = 172.47 \pm 0.17(\text{stat}) \pm 1.40(\text{syst})\ \text{GeV}$$ ±0.8%



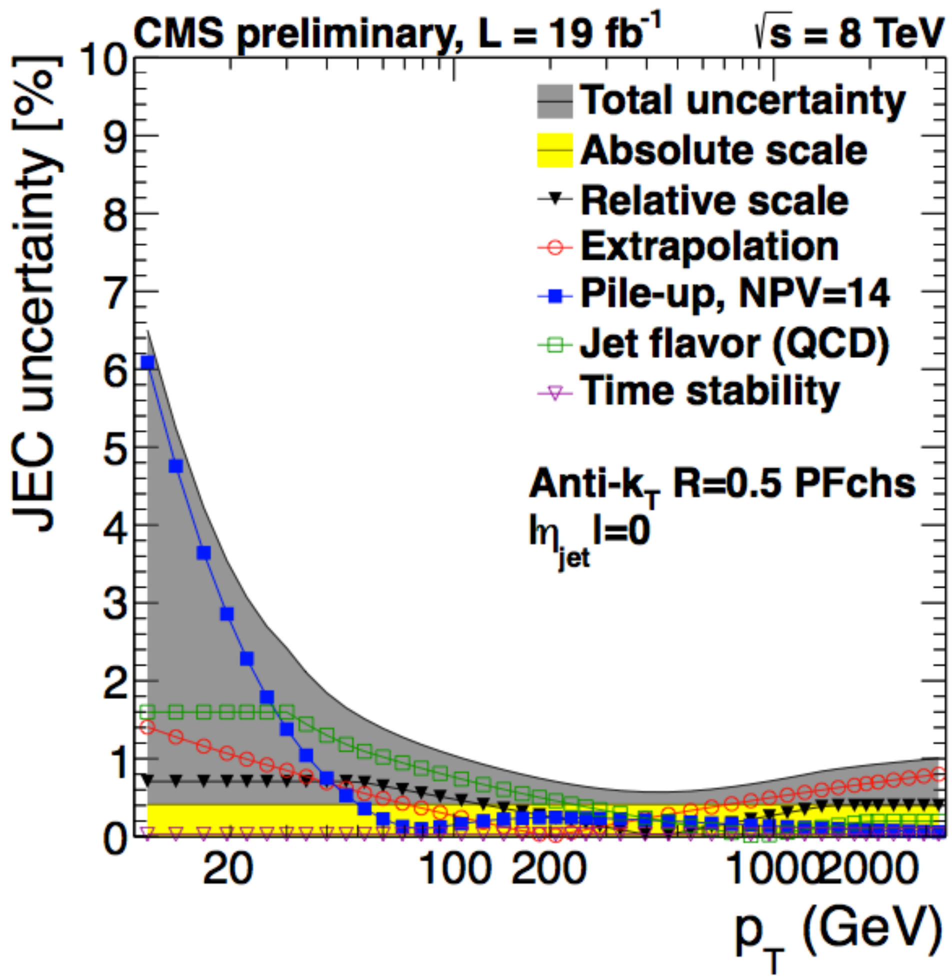




Mass: Systematic uncertainties

CMS-DP-2013/033

- Experimental
  - m_t observable based on jet momenta
  - Understanding of jet energy scale is crucial
  - p_T and η-dependent corrections
  - Jet energy resolution
- B-fragmentation/hadronization
  - Compare hadronization models (Pythia vs Herwig) separately for each jet flavor
  - Additional cross-check of b-hadronization
  - Retune Z2* to describe b-fragmentation
- Hadronization
  - Observe softer top p_T spectrum in data than simulation (Madgraph+Pythia6)
  - Quote difference as uncertainty
- Non-perturbative QCD
  - Colored final states, connect to UE

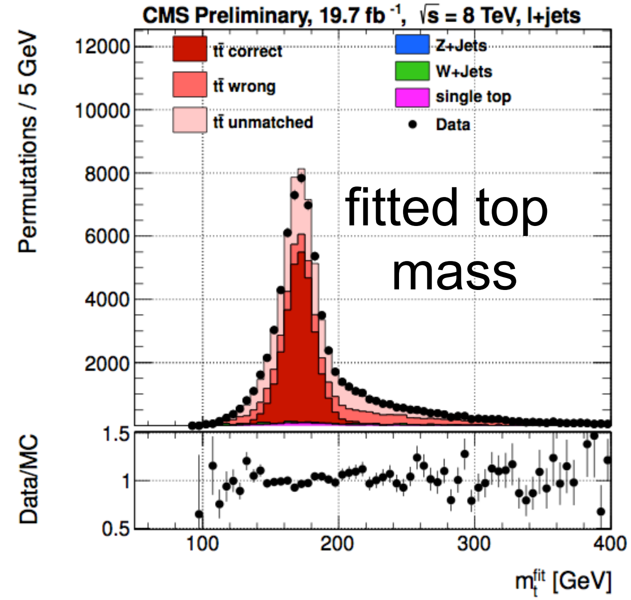


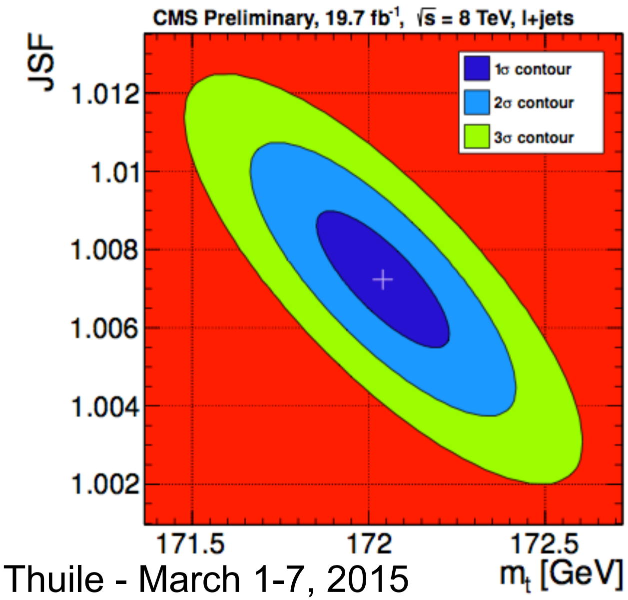
Lepton+jets final state

CMS-TOP-14-001

- Best channel to measure m_t
  - well defined final state (1 lepton, 1ν, 2b $W_{qq'}$)
- Select ttbar events, define observable
  - hadronic decays (m_t, m_W)
  - No optimization ⇒get incorrect parton-jet assignment
- Kinematic fit: constrain W mass, top-antitop masses
  - Goodness of fit
  - Event-by-event weight
  - 42% correct, 21% wrong, 37% unmatched
  - Also use info from incorrect assignments

$$m_t = 172.04 \pm 0.19\,(\text{stat.+JSF}) \pm 0.75\,(\text{syst.})\,\text{GeV}$$
$$\text{JSF} = 1.007 \pm 0.002\,(\text{stat.}) \pm 0.012\,(\text{syst.}).$$





l+jet final state: mass syst.

$$m_t = 172.38 \pm 0.10_{stat} \pm 0.65_{syst}\ \mathrm{GeV}$$

Major combined uncertainties	**Δm_t (GeV)**
Uncorrelated JES component	0.14
Jet energy resolution	0.17
Pileup	**0.20**
Flavor dependent hadronization	**0.36**
b-fragmentation / B hadron decays	0.14
Renormal. / factorization scales	0.17
ME-PS matching threshold	0.16
ME generator	0.13
Top quark p_T	0.12
Underlying Event	0.16
Color Reconnection	0.18
Total	**0.65**

dileptons: mass syst.

$m_t = 172.47 \pm 0.17_{stat} \pm 1.40_{syst}$ GeV

Major Systematics	**Δm_t (GeV)**
Jet energy scale	**0.61**
Pileup	0.15
Flavor dependent hadronization	0.28
b-fragmentation	**0.67**
B hadron decays	**0.18**
PDFs	0.18
Renormal. / factorization scales	**0.87**
ME generator	**0.37**
Color reconnection	0.16
Total	**1.40**

All-hadronic: mass syst.

Source	Relative uncertainty (%)
Jet energy scale	10.1
Background contribution	9.0
Tagging of b jets	6.0
Renormalisation and factorisation scale	5.8
Tune for underlying event	5.5
Trigger	5.0
Jet energy resolution	4.0
Matching matrix elements/parton showers	4.0
Mass of the top quark	2.1
Pileup	0.8
Total systematic	18.6
Total statistical	7.0
Luminosity	2.2
Total uncertainty	20.0

Top cross section: LHC combination

	ATLAS	CMS	Correlation	LHC combination
Cross section [pb]	242.4	239.0		241.5
Uncertainty [pb]				
Statistical	1.7	2.6	0	1.4
Detector model				
Trigger	0.4	3.6	0	1.0
Lepton scale and resolution	1.2	0.2	0	0.9
Lepton identification	1.7	4.0	0	1.6
Jet resolution	1.2	3.0	0	1.2
Jet identification	0.1	–	–	0.1
b-tagging	1.0	1.7	0	0.8
Pileup	–	2.0	–	0.5
Non-JES subtotal	2.6	6.7	0	2.6
UncorrJES	0.6	4.3	0	1.2
InsituJES	0.6	0.6	0	0.5
IntercalibJES	0.3	0.1	0.5	0.2
FlavourJES	0.9	2.9	1	1.4
bJES	0.1	–	–	0.1
JES subtotal	1.3	5.2	0.4	1.9
Class subtotal	2.9	8.5		3.2
Signal model				
Scale	0.7	5.6	0.5	1.9
Radiation	–	3.8	–	1.0
Generator and parton shower	3.0	3.3	0.5	2.7
PDF	2.7	0.5	1	2.1
Class subtotal	4.1	7.5	0.3	4.0
Background from data				
Z+jets	<0.1	1.5	0	0.4
Lepton misidentification	0.8	1.9	0	0.8
Class subtotal	0.8	2.4	0	0.9
Background from simulation				
Dibosons	0.3	0.5	1	0.4
Single top quark	2.0	2.3	1	2.1
Class subtotal	2.0	2.4	1	2.1
Luminosity				
Beam modelling	2.9	5.0	1	3.5
Luminosity determination	6.9	3.6	0	5.1
Class subtotal	7.5	6.2	0.3	6.2
Total systematic	9.3	13.4		8.4
Total	9.4	13.6		8.5