Top quark: properties and beyond

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LIP Lisbon

- Mass, Vtb, taus
- Spin correlation
- Charge asymmetry
- Boosted topology
- Searches for New Physics

Contents

will use c=1

- Introduction (discovery, object ID)
- Top pair production at the Tevatron
- Top pair production at LHC
- (differential) cross section

- Mass, heavy flavor content, taus
- Search for top partners and 4th generation quarks
- Search for ttbar resonances
- Spin correlation, charge asymmetry

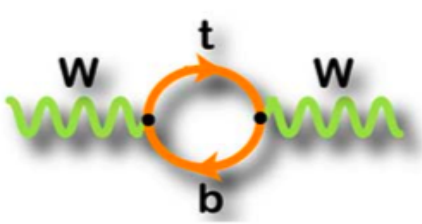
today

- Single top production
- Flavor Changing Neutral Currents (FCNC)

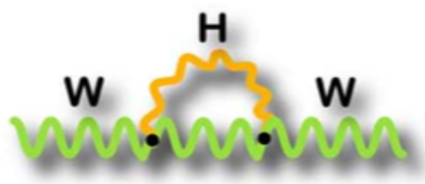
Top quark mass

Top quark mass and constraints

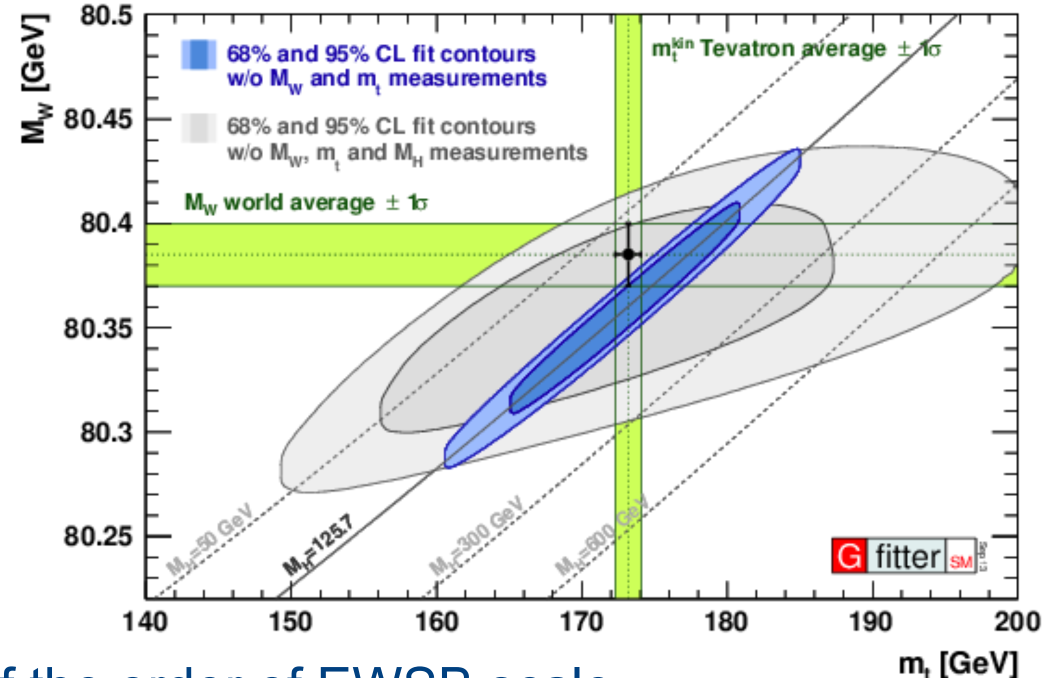
- Top quark mass is a fundamental parameter of the SM
  - Known with good accuracy from the Tevatron: 173.2±0.9 GeV (arXiv:1107.5255)
  - Indirect constraint on the Higgs boson mass via EW corrections



$\delta m_W \propto m_t^2$



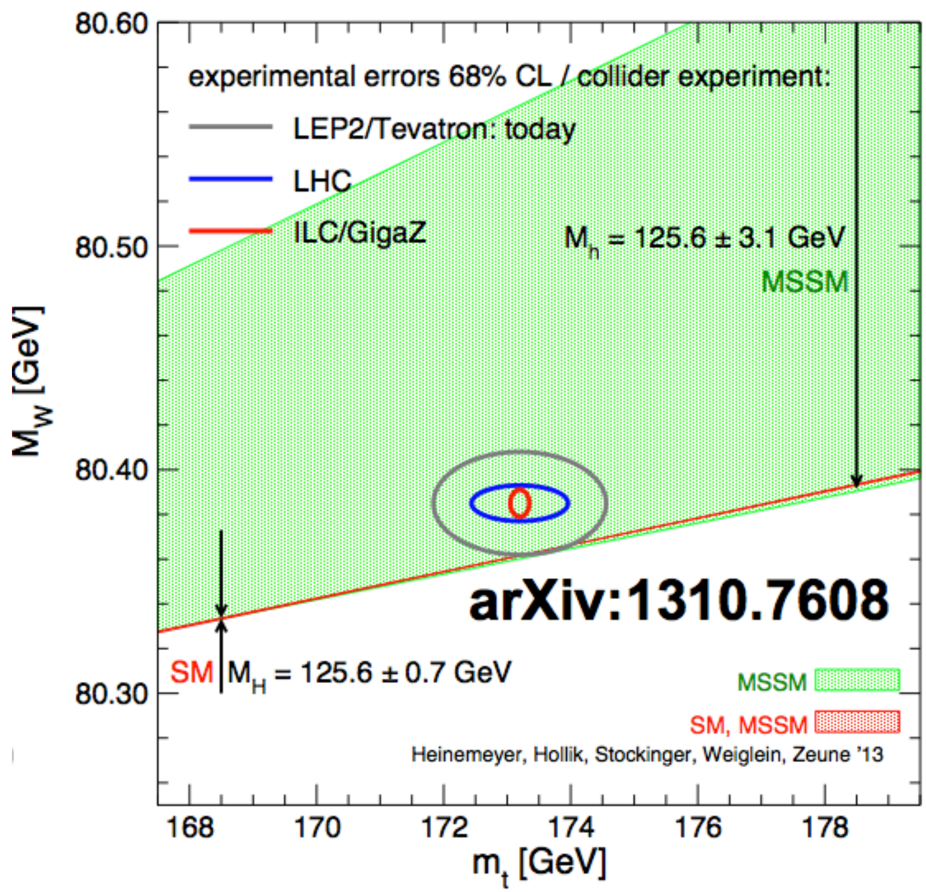
$\delta m_W \propto \log m_H$



- Top is the only fermion with the mass of the order of EWSB scale
- Measuring precisely m_W and m_{top}
  - Test consistency of SM
  - Search for new Physics

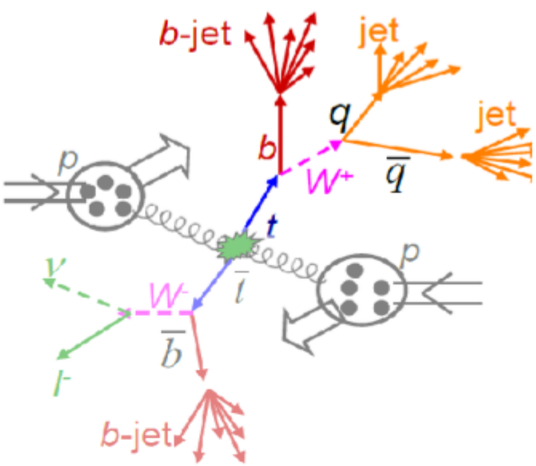
Top mass and constraints (cont.)

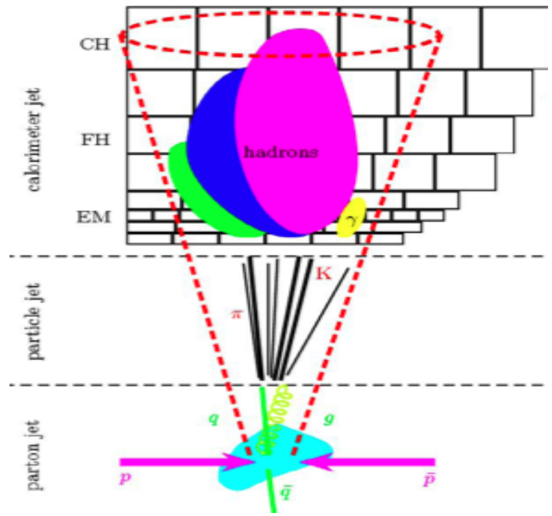
- Newly discovered Higgs boson fits well with more and more precise determinations of the W and top quark masses
  - Highly fine-tuned situation: vacuum is at the verge of being stable/metastable
  - ~1GeV in either top quark or Higgs mass is all it takes to tip the scales!
- LHC Run2 will likely allow for discrimination between SM and MSSM scenario



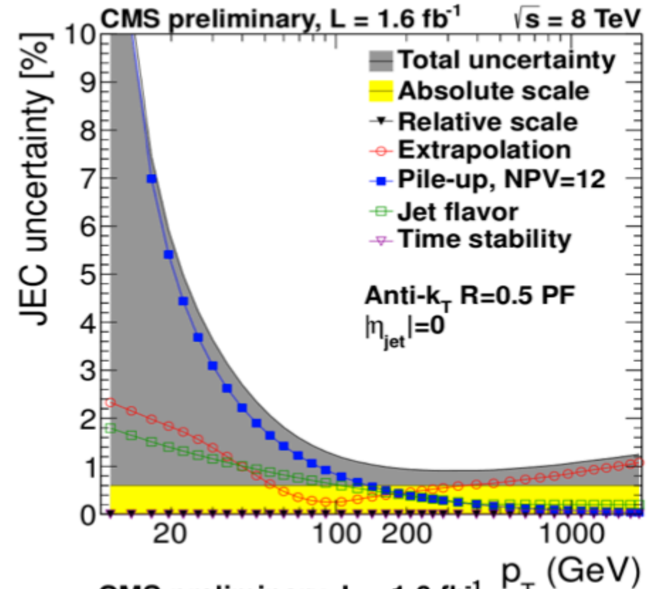
Jet reconstruction in Top events

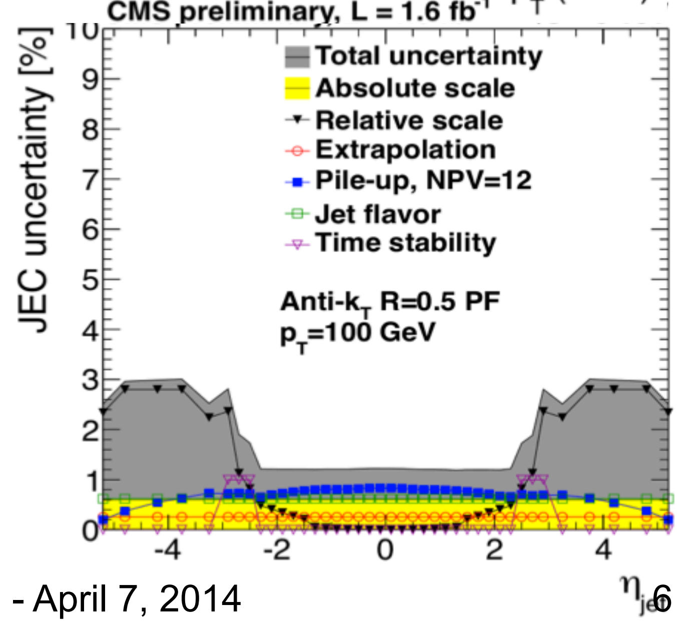
- Top mass measurement needs parton information, but we measure jets
- Use calorimeter information to correct jets to particle level





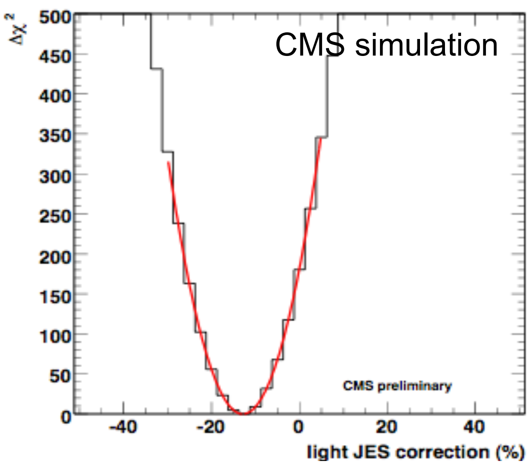
- Contribution of uncertainty sources depend on p_T, η
- Jet energy correction uncertainty:
  - Look at quantities insensitive to JES (e.g. lepton p_T)
  - "b-jet" tag helps reducing number of permutations
- JES "in-situ" calibration in ttbar events
  - Use W→jj constraint to measured W mass

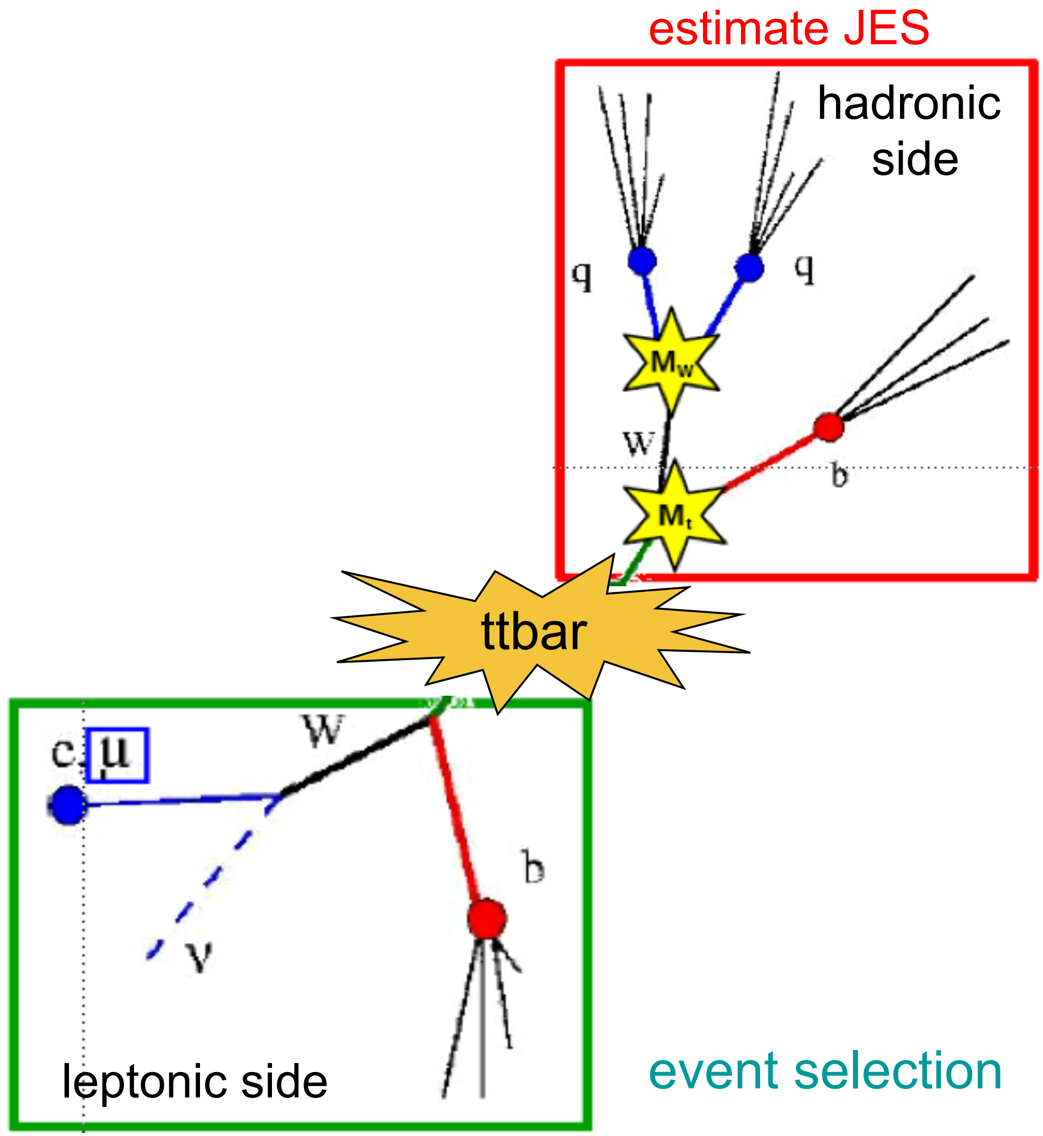




Jet energy correction from Top

- Use semi-leptonic events
  - 1 isol μ (p_T>30 GeV)+≥4 jets (40 GeV)
- Estimate jet energy corrections by applying event-by-event kinematical fit to W and Top masses
- Likelihood is used to assign jets
- Kinematical fit returns $P(\chi^2)$
- Find best JES by minimizing χ^2





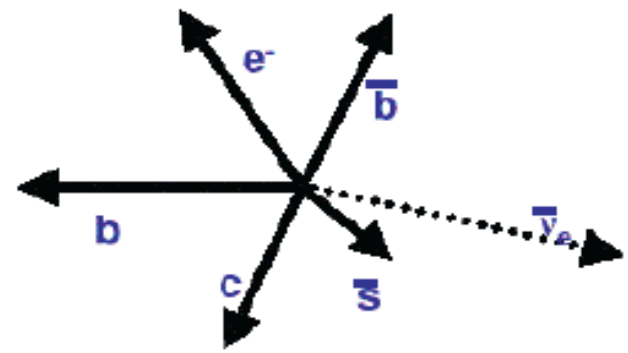
Measuring the top mass

Challenging:

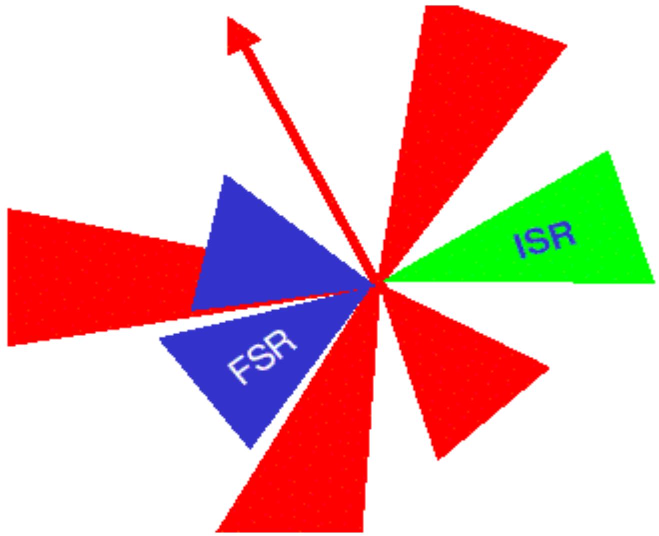
➢ **Lepton+jets**
- undetected neutrino
  - P_x and P_y from E_T conservation
  - 2 solutions for P_z from $M_W = M_{l\nu}$
- leading 4-jet combinatorics
  - 12 possible jet-parton assignments
  - 6 with 1 b-tag
  - 2 with 2 b-tags
- ISR + FSR

➢ **Dileptons**
- (less statistics)
- two undetected neutrinos
- less combinatorics: 2 jets

LO final state:

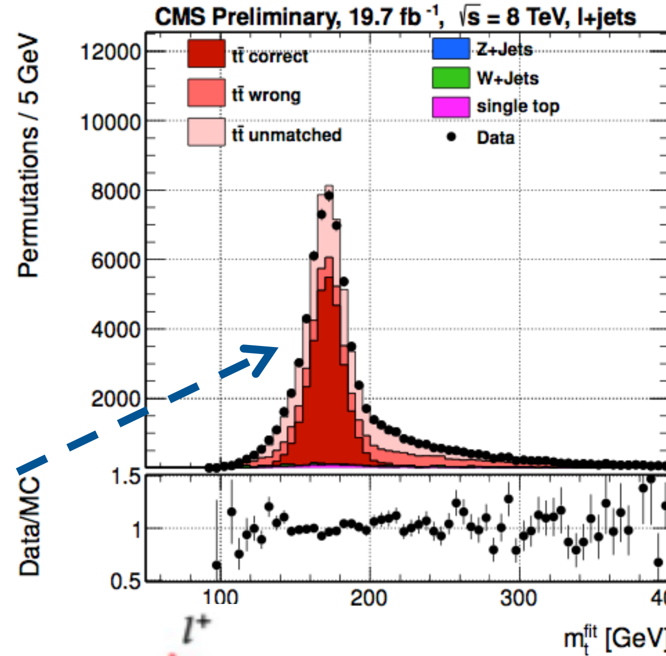


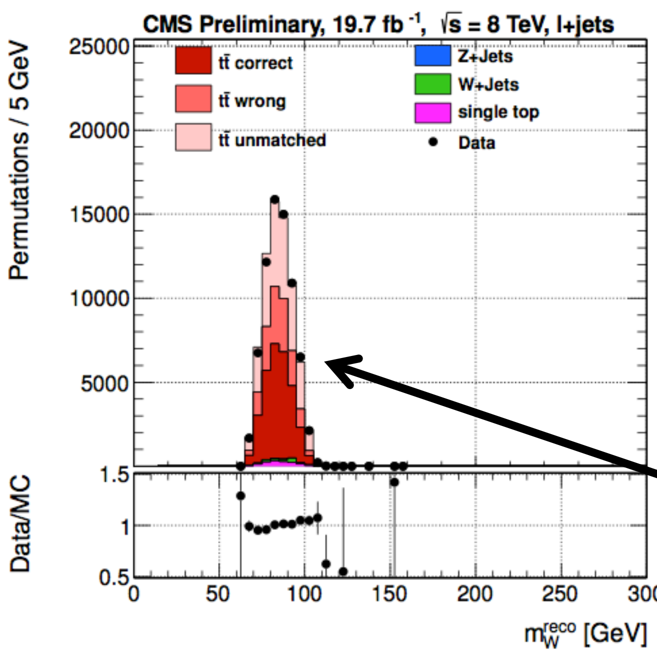
experiment sees:

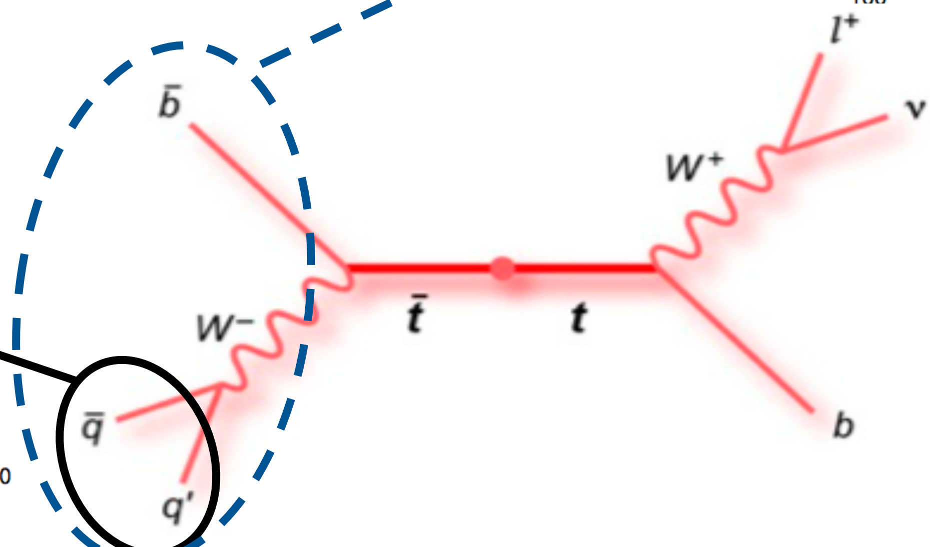


Lepton+jet channel

- Well defined final state
  - one lepton, one neutrino, 2 b-jets, W→qq ‘
- Compromise between large branching ratio (BR=30%) and a good background rejection



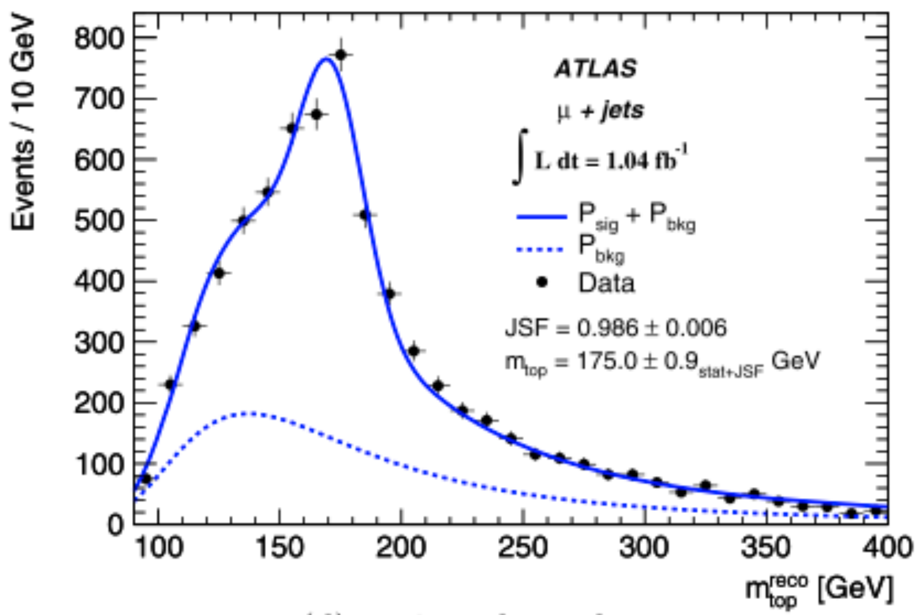




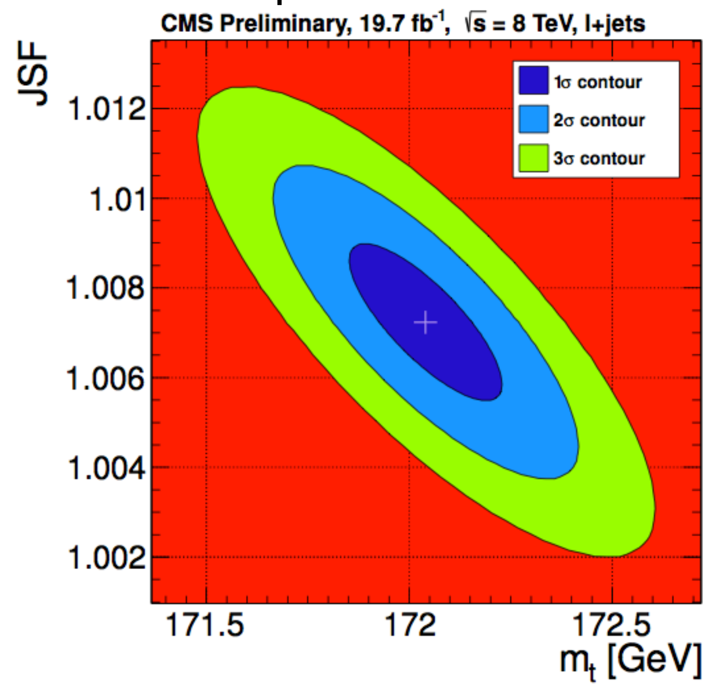
Lepton+jet channel

- in-situ calibration of the light quark JES from W→ qq'

ATLAS: template fit as function of JES and top quark mass



CMS: kinematic fit + "ideogram" method combine event-per-event likelihood



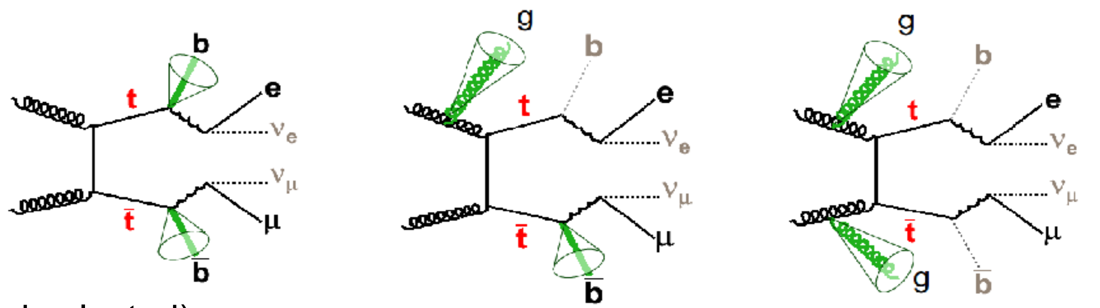
⇨m_{top}=174.4 ± 0.6 (stat) ± 2.3 (syst) GeV — EPJC C72 (2012) 2046

172.0 ± 0.2 (stat) ± 0.8 (syst) GeV — CMS PAS-TOP-14-001

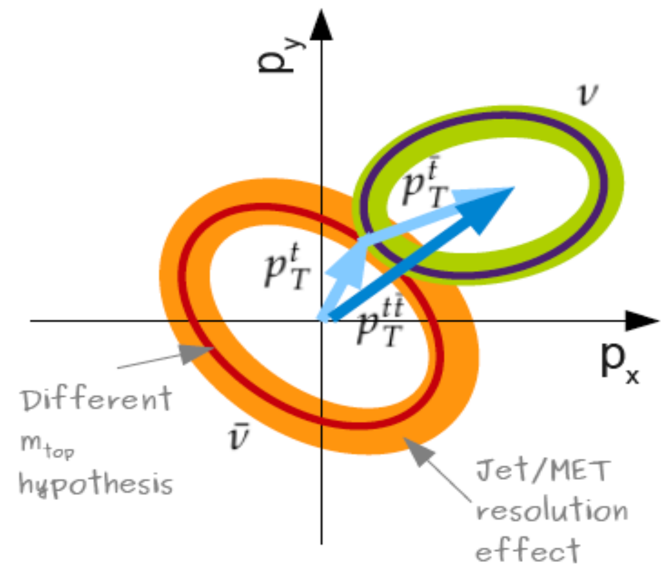
Dilepton channel: challenges

- 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 ⇒ $\vec{E}_T^{miss} = \vec{p}_T^{\nu} + \vec{p}_T^{\bar{\nu}}$



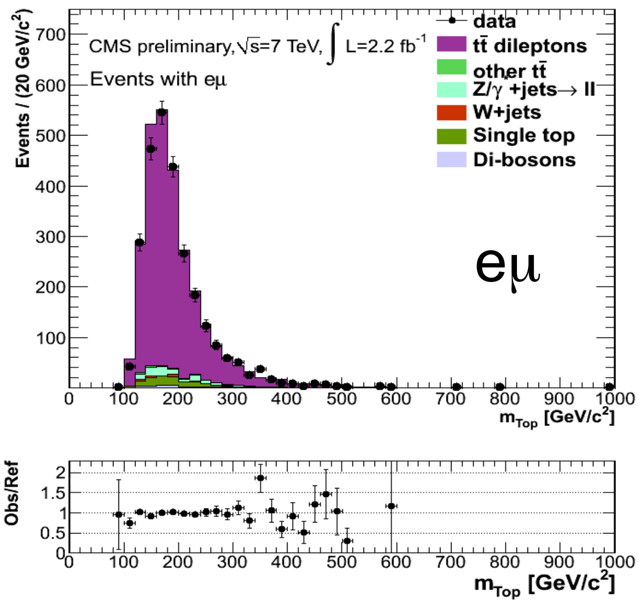
- Jet energy scale
  - m_{top} reconstruction requires measuring the parton energy
  - parton→jet affected by resolution and absolute energy scale
- Pile-up
  - Jet energy scale, MET measurement, extra jets/leptons
  - N_{pileup}≈ 6 (21) for most of data collected in 2011 (2012)

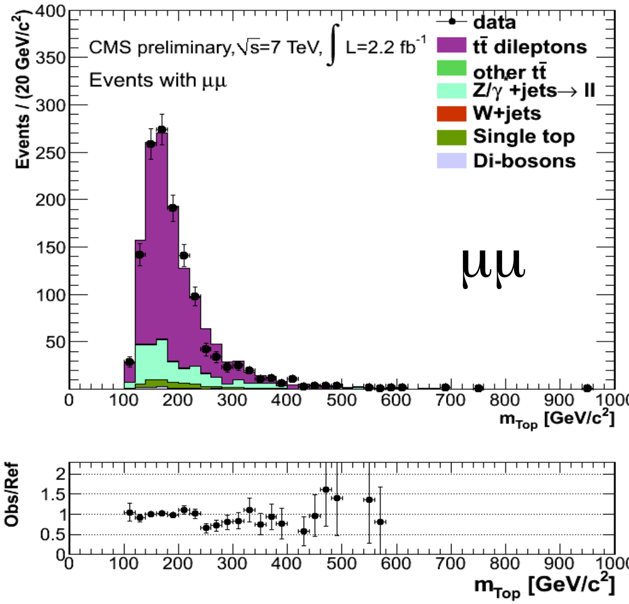
Reconstructed mass

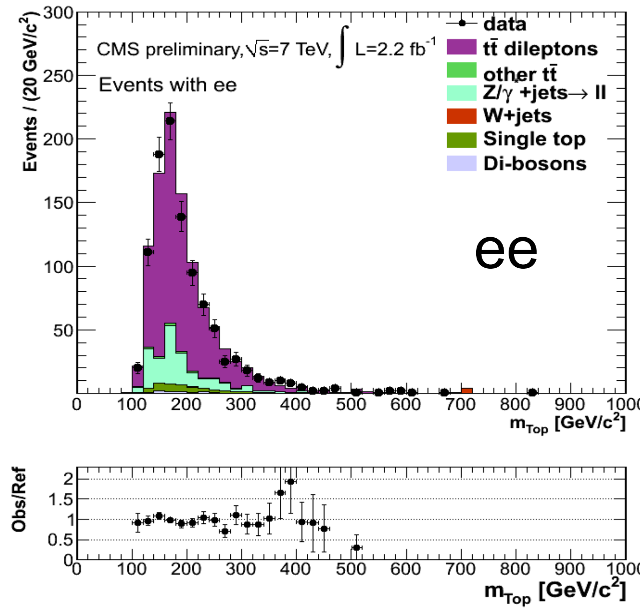
CMS-PAS-TOP-11-016

- Select events
- Reconstruct mass

Process	Pre-selection	KINb	=1 b-tag	≥ 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



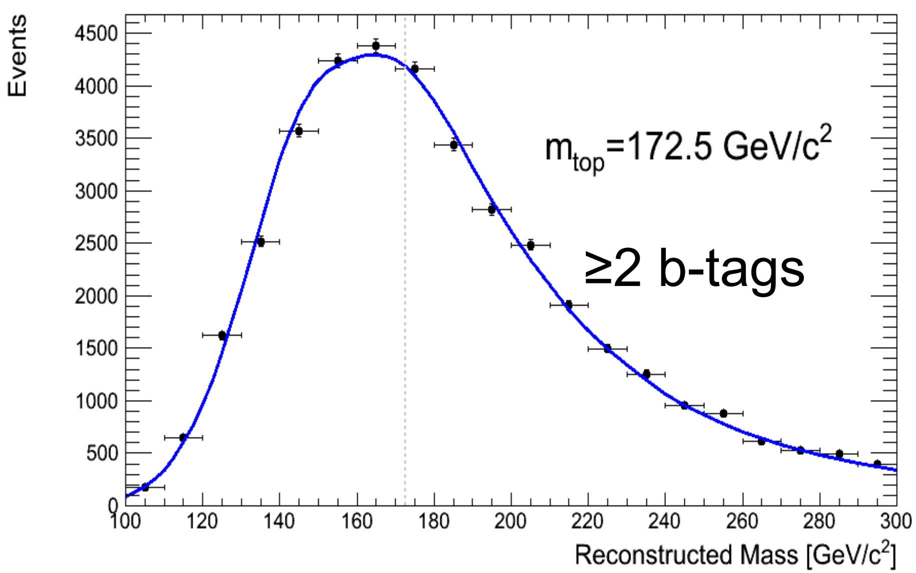


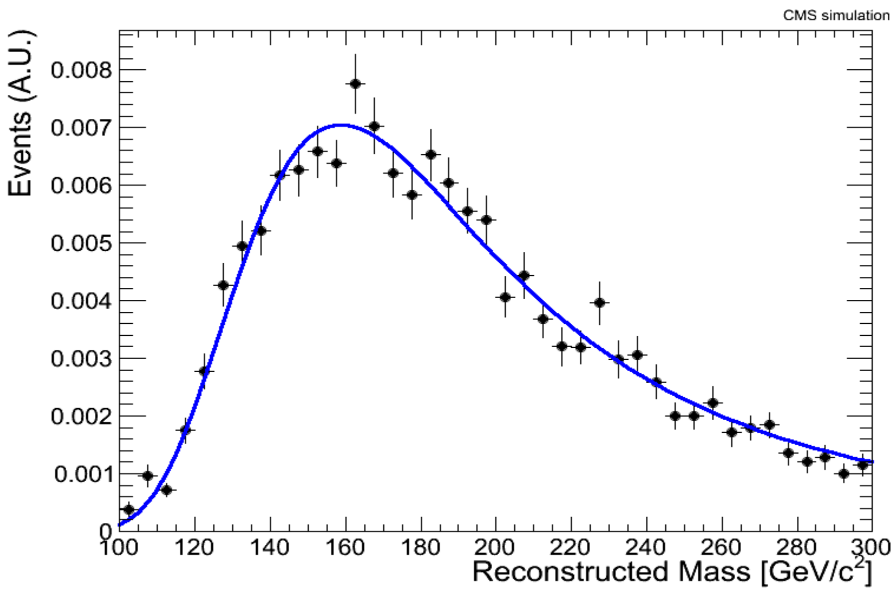


Signal and background

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

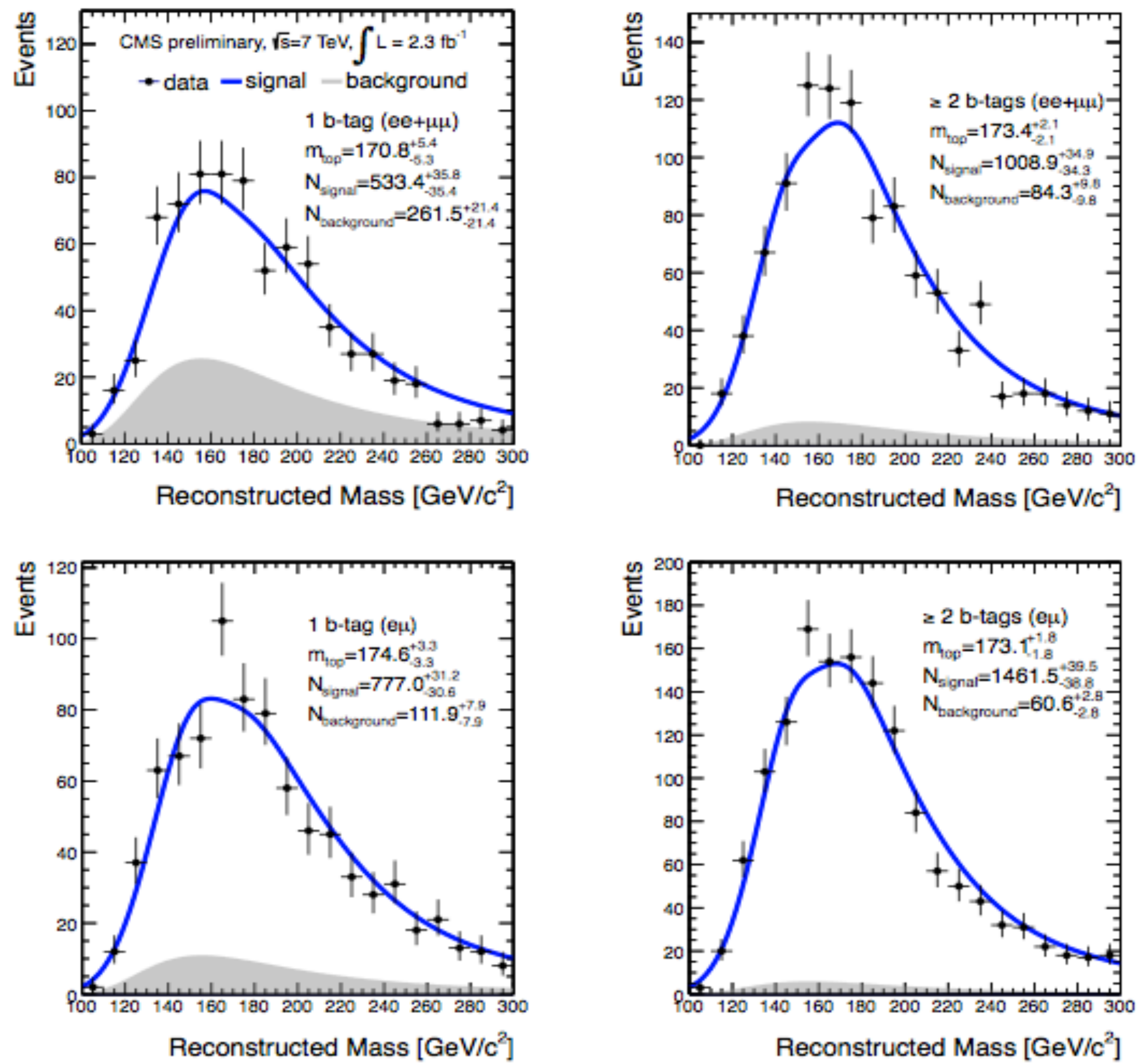
- Background component in the mass spectrum modelled with data +simulation
- Fit: Landau





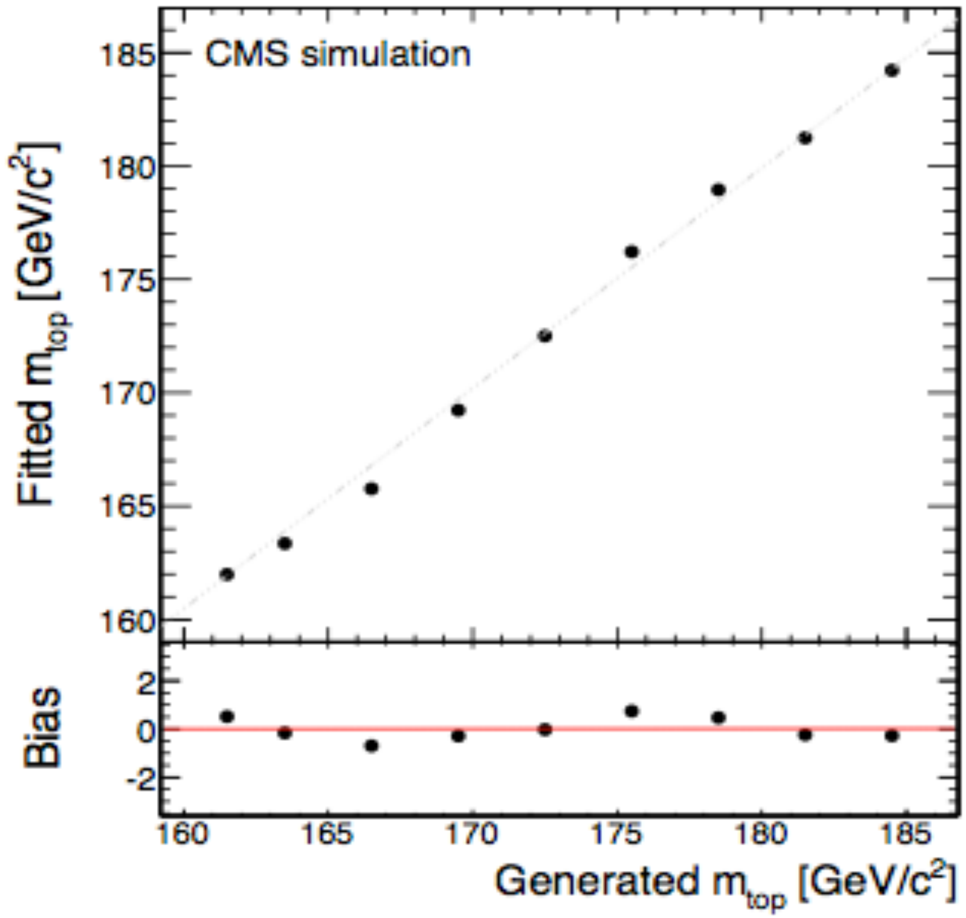
Reconstructed mass

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



Correct for the bias

- Check and correct for the bias in the measurement

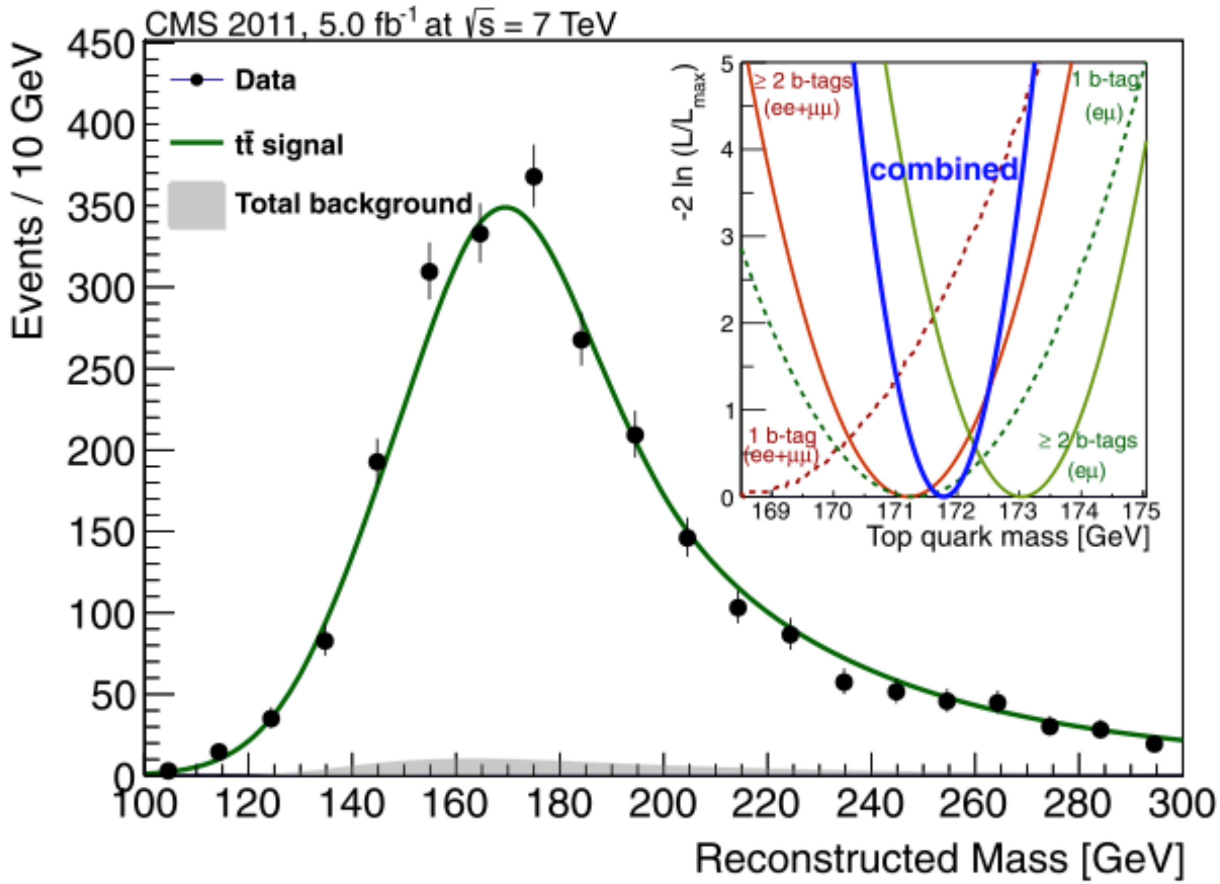


Do not forget the systematics

- 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

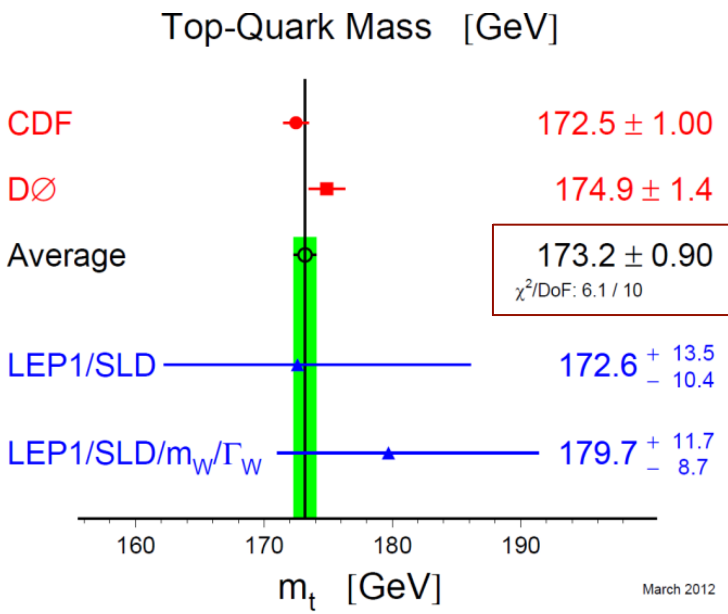
Final fit



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

EPJC C72 (2012) 2202

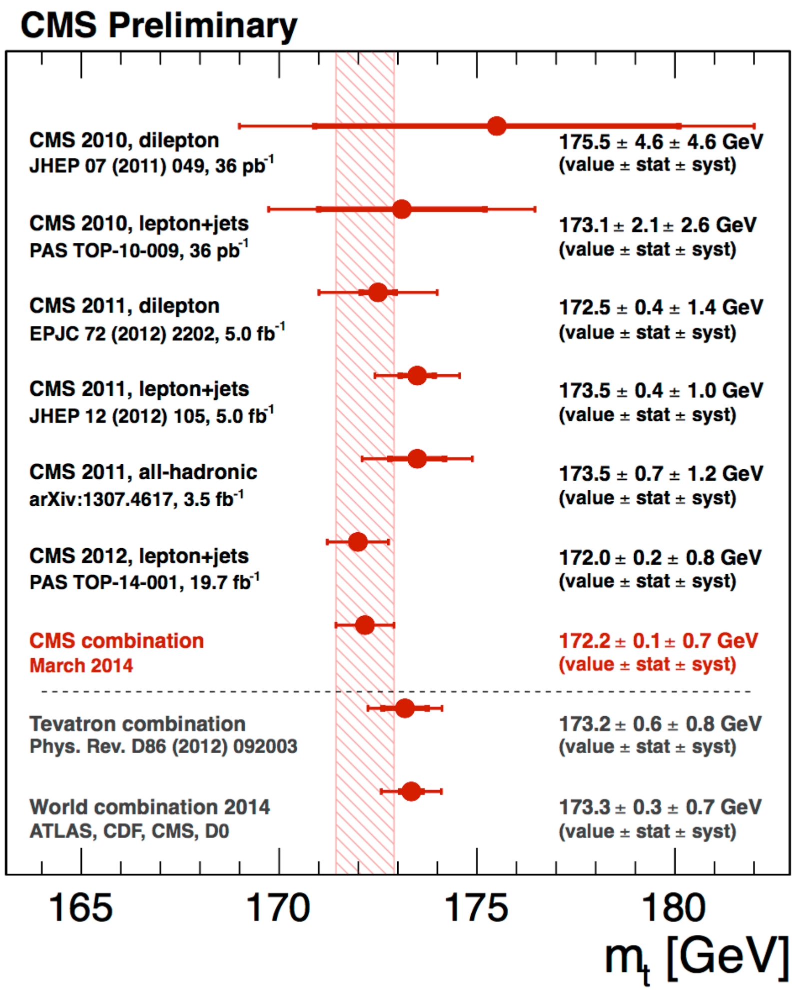
Top quark mass



arXiv:1107.5255

±0.5%

- dominated by l+jet channel

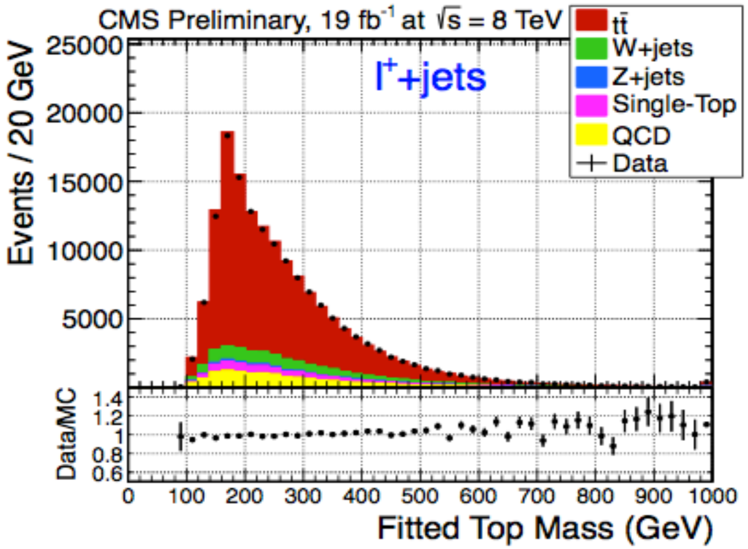


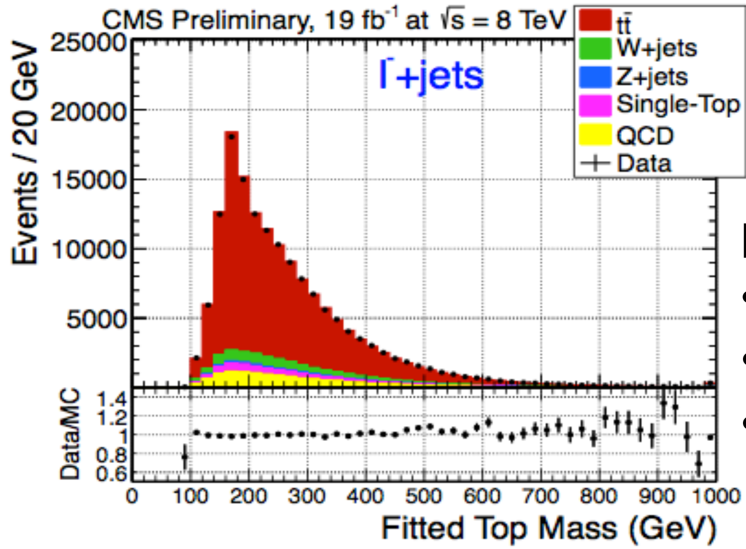
Results from LHC are rapidly improving (0.6%)

Top-antiTop mass difference

- Test of CPT invariance: particle and anti-particle have same mass
  - If masses are different →CPT violation
  - Top quark is unique because it decays before hadronizing
- use μ+jet ttbar events: positive/negative muons (L=19/fb)
  - Compare mass measured from μ^+/μ^- +jets
  - Use hadronic side

CMS-PAS-TOP-12-031





Dominant systematics:
- b vs bbar jet response
- signal fraction
- b vs bbar tagging

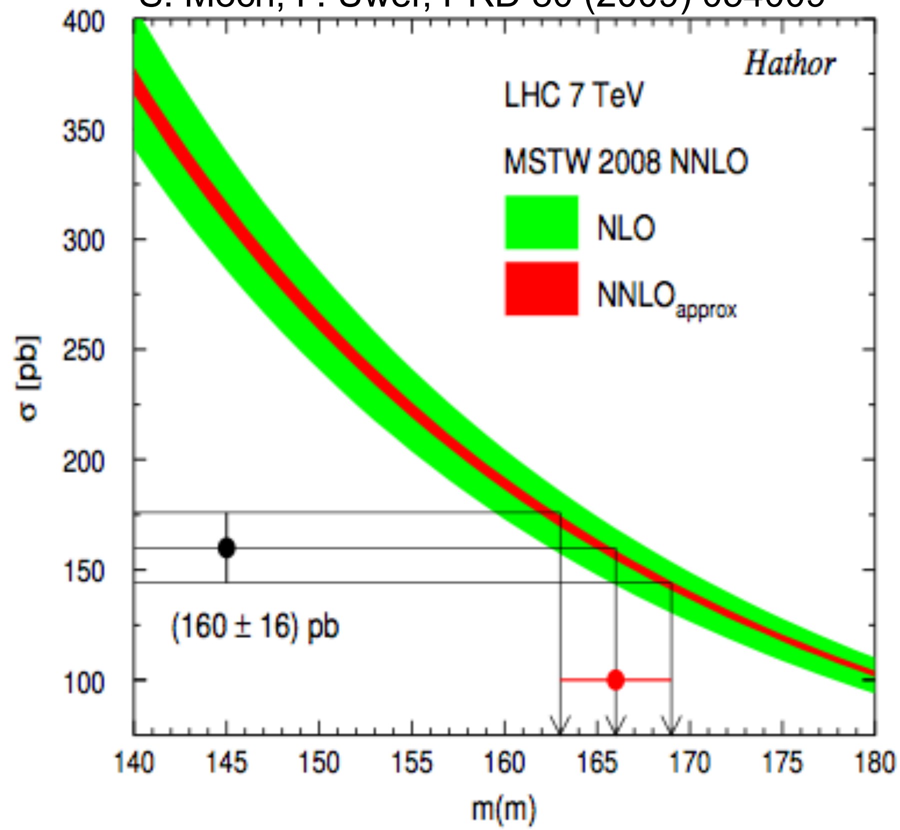
$$\Delta m_t = m_t^{had} - m_{\bar{t}}^{had} = -272 \pm 196\ (stat.) \pm 121\ (syst.)\ MeV$$

Top mass from cross section

- Direct m_{top} measurements rely on details of kinematics, reconstruction, calibration
- Experimental measurement has small uncertainty: ~0.5%
- What mass is measured?
  - Could be interpreted as pole mass

- Compare theory prediction (measured) cross section vs pole mass (=m_{top})
- Exploit relation of cross section and mass:
  - $\Delta\sigma/\sigma = -A \cdot \Delta m/m$ (A=4-5)

S. Moch, P. Uwer, PRD 80 (2009) 054009



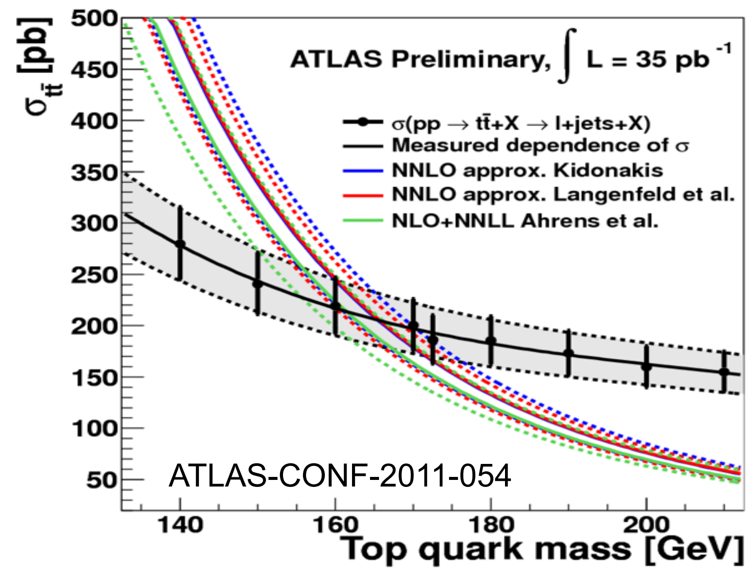
Top mass from cross section

- determine top quark pole mass using the experimental ttbar production cross section
  - from lepton+jets channel (ATLAS) with 35/pb

$$m_{top}^{pole} = (166.4\,^{+7.8}_{-7.3})\ \text{GeV}$$

  - from dilepton cross section (CMS) with 1.1/fb

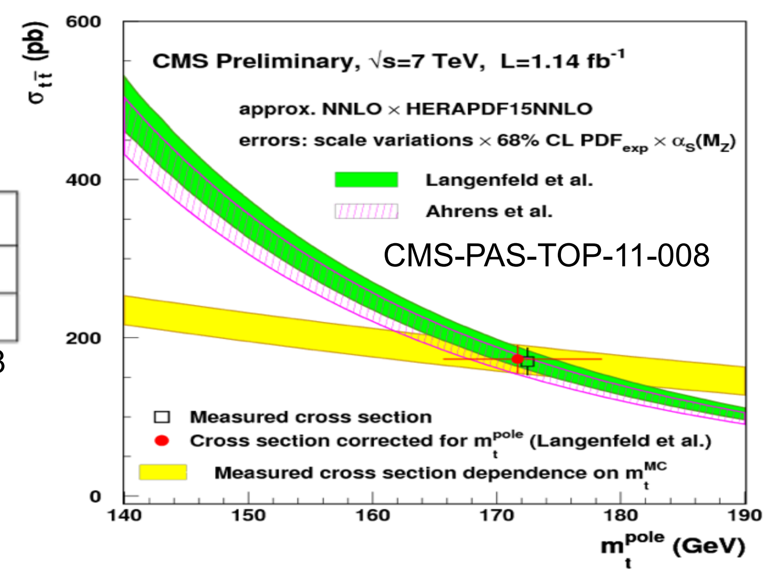
$$m_t^{pole} = 170.3^{+7.3}_{-6.7}\,\text{GeV}$$



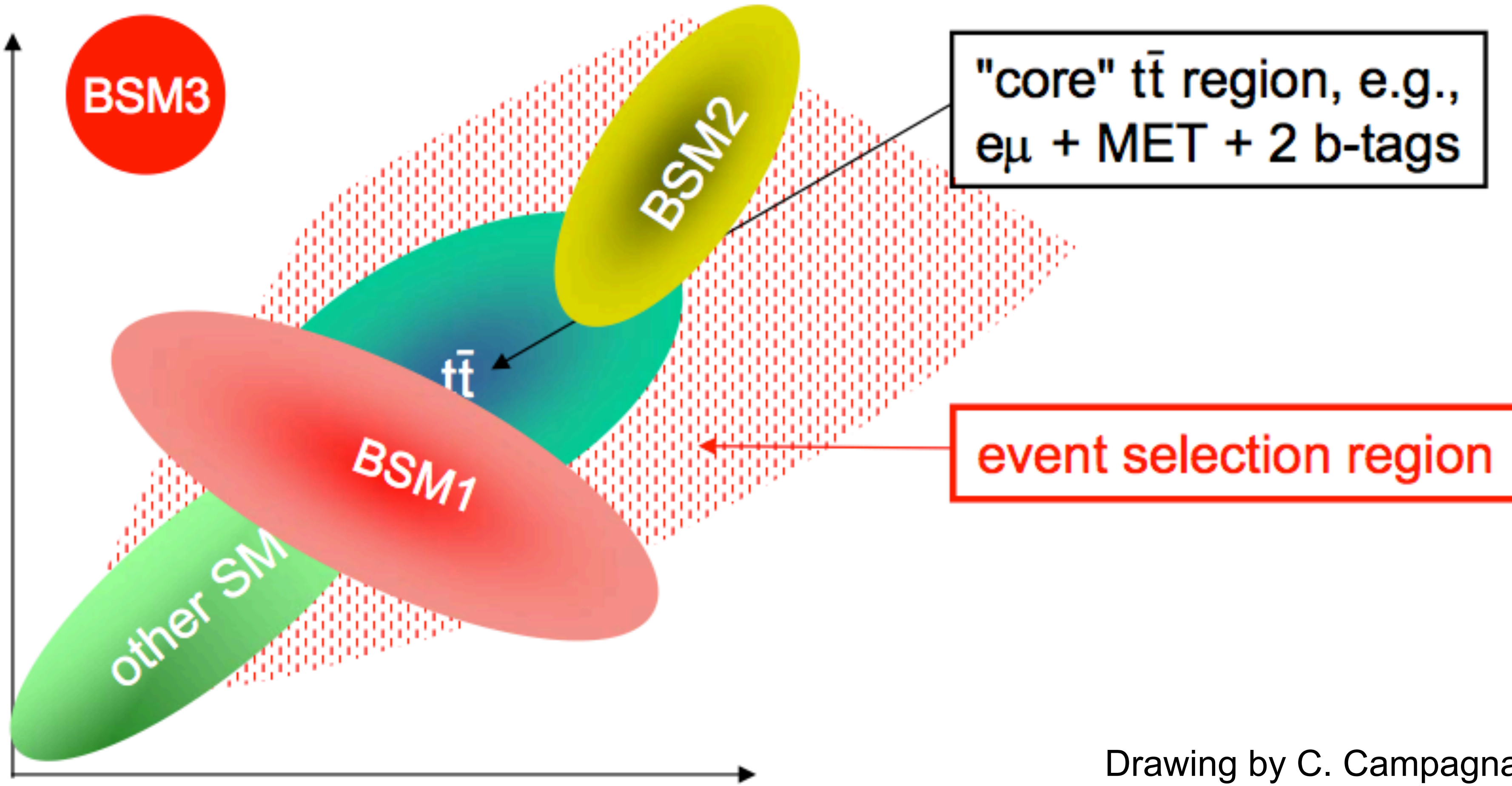
Also determine m(MSbar):

Approx. NNLO × HERAPDF15NNLO	m_t^{pole} / GeV	$m_t^{\overline{MS}}$ / GeV
Langenfeld et al. [7]	$171.7^{+6.8}_{-6.0}$	$164.3^{+6.5}_{-5.7}$
Ahrens et al. [9]	$169.1^{+6.7}_{-5.9}$	$161.0^{+6.8}_{-6.1}$

CMS-PAS-TOP-11-008

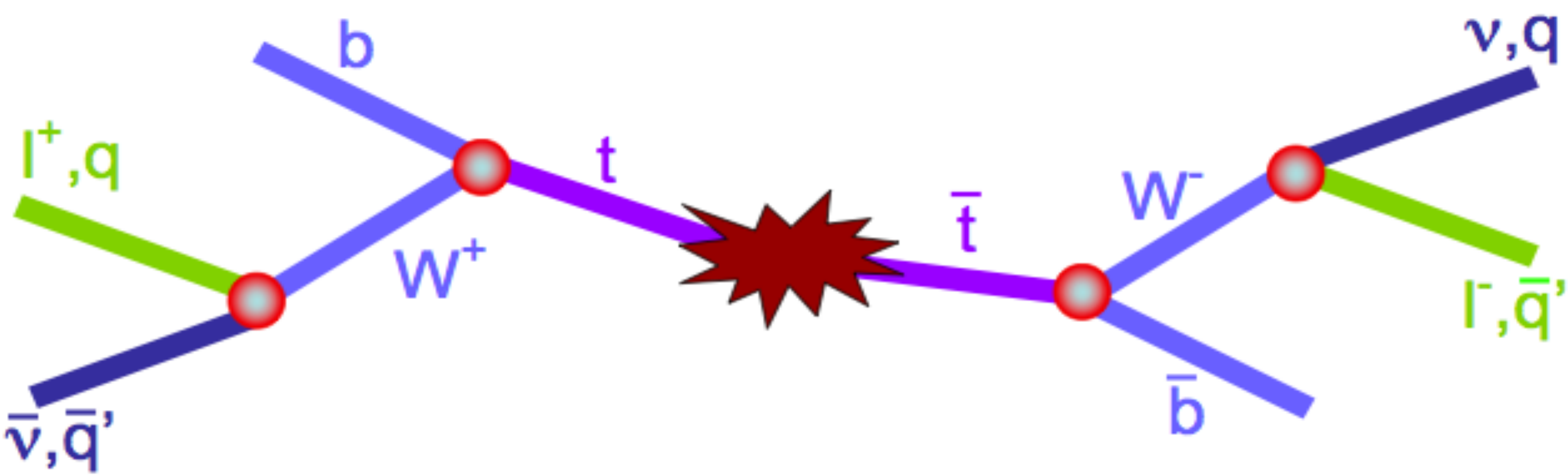


Not just cross sections



Drawing by C. Campagnari

Interesting physics with Top quark



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

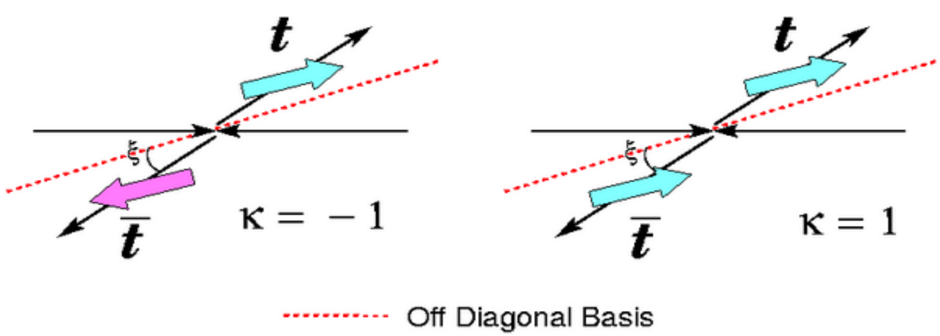
PROPERTIES
Mass
Kinematics
Charge
Lifetime and width
W helicity
Spin
...

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

Spin correlation

- Important tool for precise studies of top quark interactions
- Top quark produced are not polarized
  - …but spins between quark and anti-quark are correlated
- Top quark decays before spins decorrelate
  - Top quark decays before hadronization ($\tau \sim 10^{-25}$ sec) ⇒ spin information transmitted to the decay products (W boson, b quark)
- Spin correlation depends on the production mode

$$\kappa = \frac{n_{\pm\pm} - n_{\pm\mp}}{n_{\pm\pm} + n_{\pm\mp}}$$



$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_1 d\cos\theta_2} = \frac{1}{4}\left(1 + \kappa\cos\theta_1\cos\theta_2\right)$$

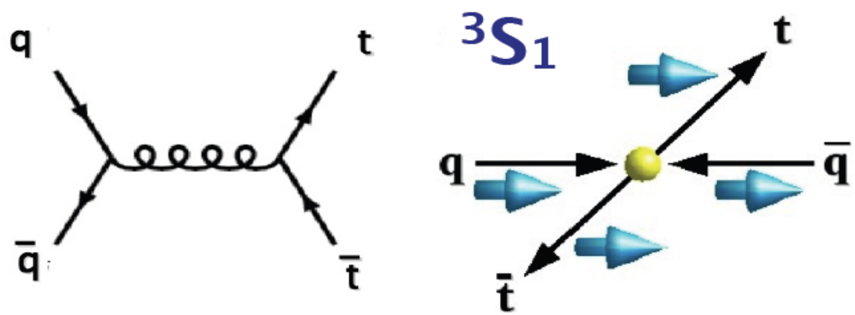
- Analyze spin using angular distributions of decay products
  - θ_1 and θ_2 are the angles of decay products wrt a "quantization axis"
  - value of κ depends on spin basis (for example, off-diagonal vs maximal)

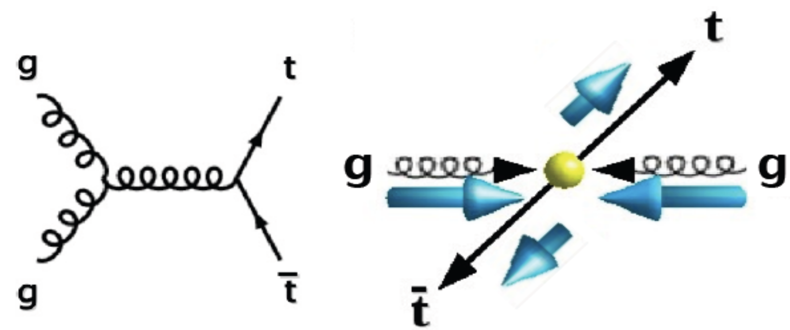
Spin correlation

- Spin correlation may differ from that expected in the SM
  - top quark decays into a charged Higgs boson and a b quark ($t \to H^+ b$)
  - Other BSM scenarios

Spin correlation: Tevatron vs LHC

$$A = \frac{N_{\uparrow\uparrow} + N_{\downarrow\downarrow} - N_{\uparrow\downarrow} - N_{\downarrow\uparrow}}{N_{\uparrow\uparrow} + N_{\downarrow\downarrow} + N_{\uparrow\downarrow} + N_{\downarrow\uparrow}}$$





Tevatron

- dominated by $q\bar{q}$ annihilation
- $t\bar{t}$ pairs close to the threshold
- beam axis as spin quantisation axis

  NLO QCD: A = 0.78

LHC

- dominated by gg fusion
- $t\bar{t}$ pairs far off the threshold
- helicity basis as spin quantisation axis

  NLO QCD: A = 0.32

Bernreuther, Brandenburg, Si, Uwer, Nucl. Phys. B690, 81 (2004)

- optimised “off-diagonal” basis
- maximal basis

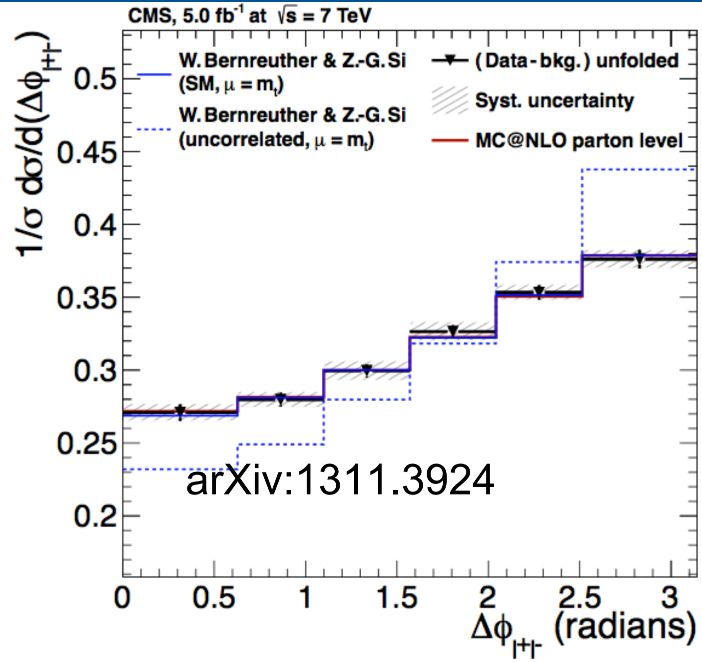
<u>complementary between Tevatron and LHC</u>

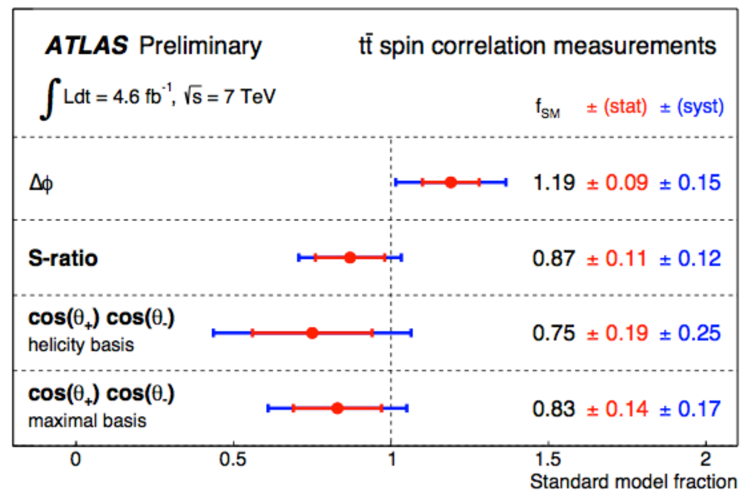
Spin correlation

- Access spin information via the angular distributions of its decay products
  - Most sensitive probes are leptons/d-type quarks
- Strategy: fit $\Delta\phi$ dilepton distribution
  - binned SM distribution and with uncorrelated spin distribution

$$A = \frac{N_{like} - N_{unlike}}{N_{like} + N_{unlike}}$$

- Translate result to maximal/helicity basis
- Main systematics: ISR/FSR and signal modelling
- Results in agreement with SM





ATLAS-CONF-2013-101

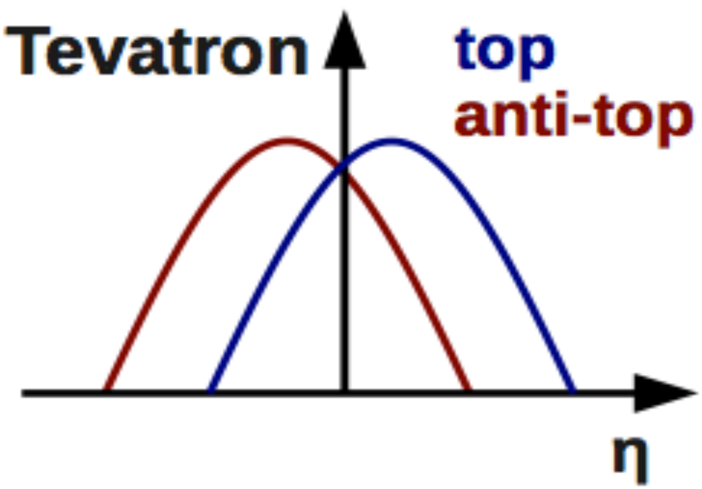
Charge asymmetry

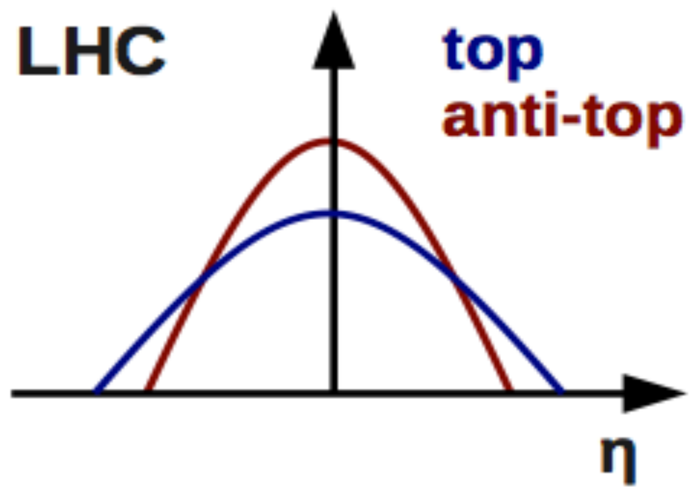
- In qqbar→ttbar (Tevatron): top quarks are emitted in the direction of the incoming quark, anti-top quarks in the direction of the incoming anti-quark
- No FB asymmetry in gg→ttbar (LHC)

SM: Only small asymmetry due to ISR/FSR

New physics: production mechanisms with new exchange bosons could enhance the charge asymmetry

At LHC quarks have larger momentum than anti-quarks (larger average momentum fraction of quarks leads to an excess of top quarks produced in the forward directions)

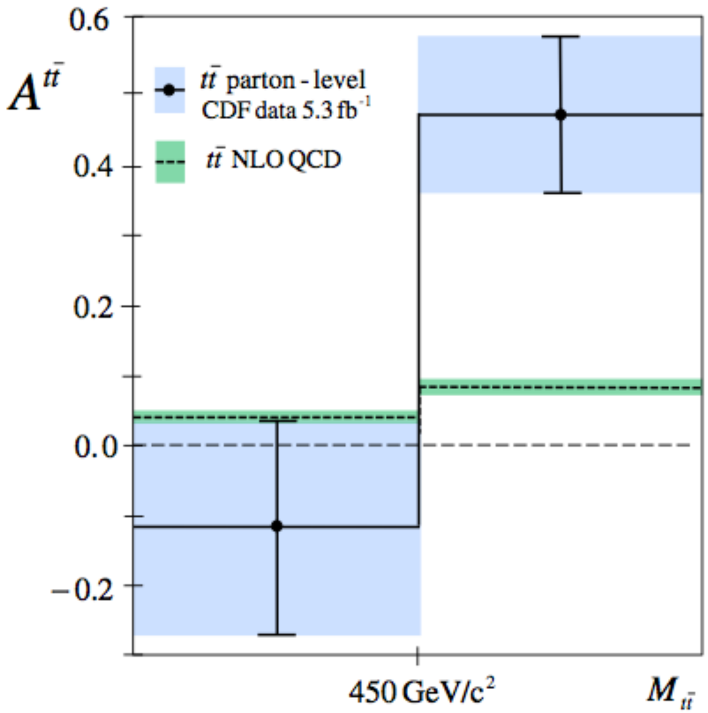




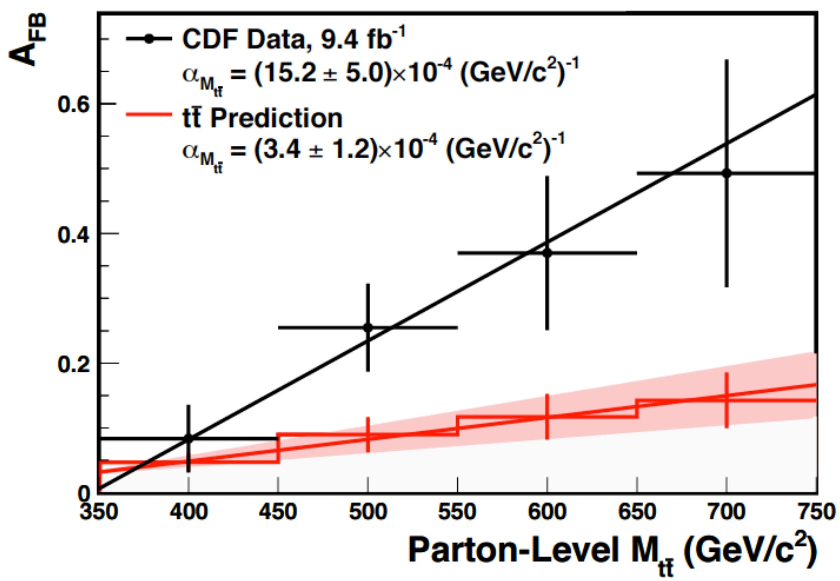
Asymmetry A_{FB} anomaly?

- Tevatron experiments observe a differential dependency on charge asymmetry
- Sign of new physics?

CDF: PRD 83(2011)112003
D0: PRL 100(2008)142002
CDF Note 10807



- At high mass, a 3σ discrepancy
- Study asymmetry vs mass of ttbar system



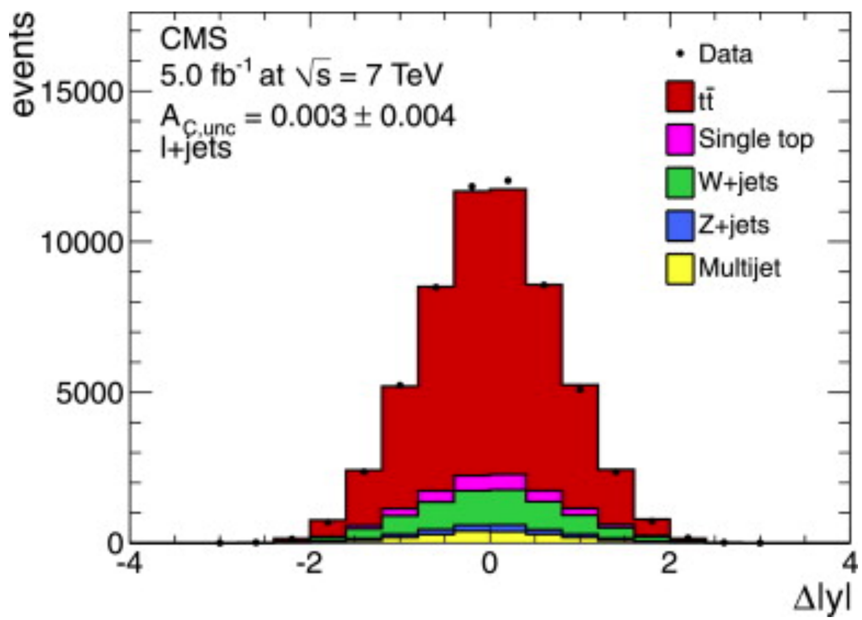
Charge asymmetry at LHC

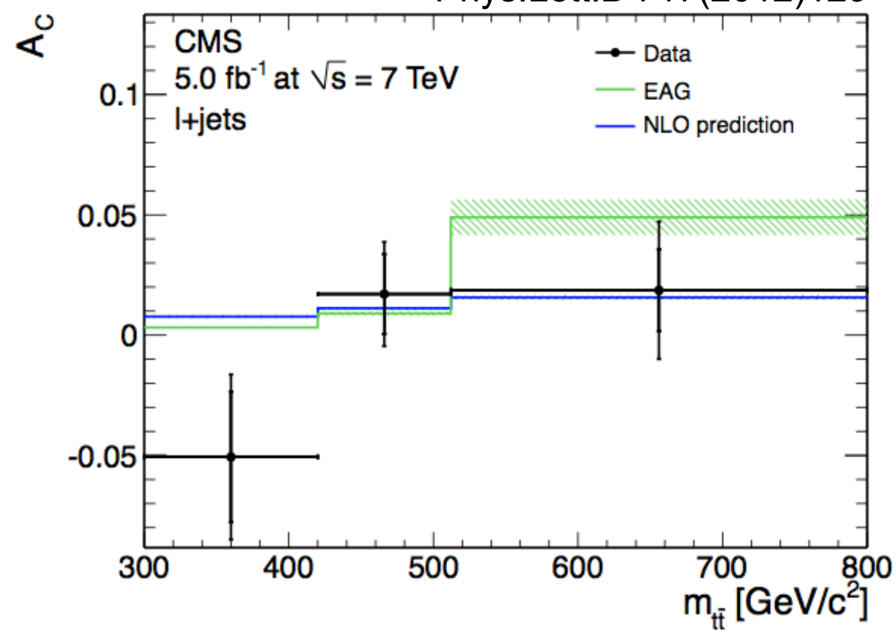
$$A_C = \frac{N^+ - N^-}{N^+ + N^-}$$

$N^+(N^-)$: number of events with positive (negative) values in the sensitive variable

Anomalous axial-vector coupling of gluons to quarks could explain the Tevatron anomaly [PRD84:054017,2011]

Phys.Lett.B 717(2012)129



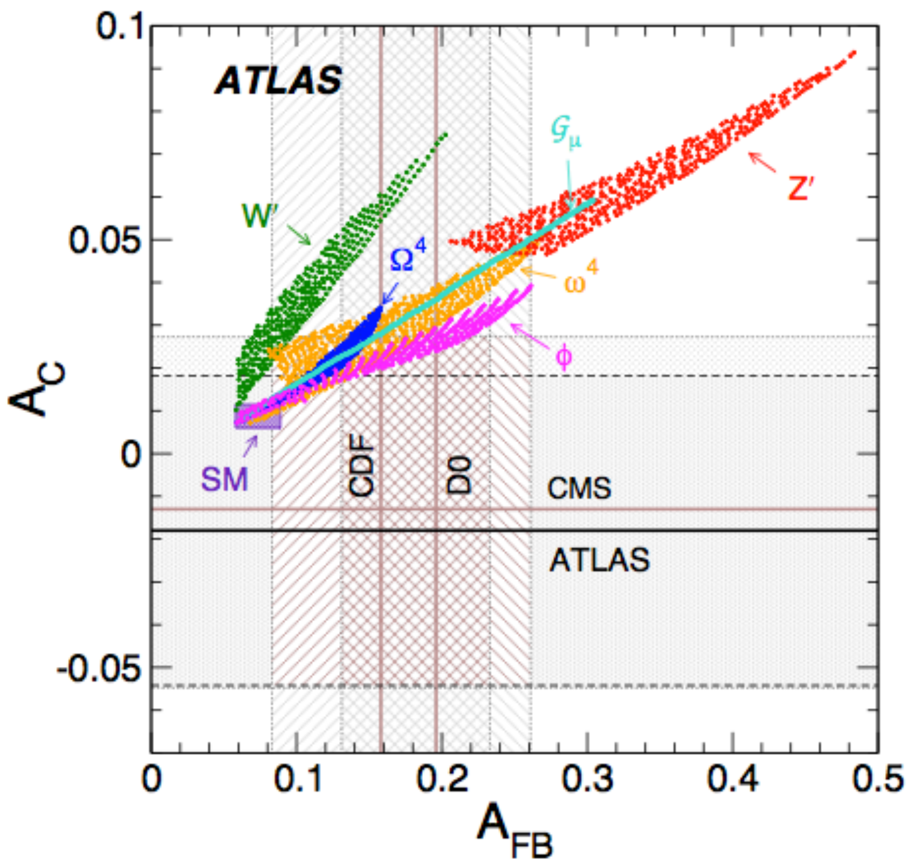


⇒Good agreement between data and SM expectations

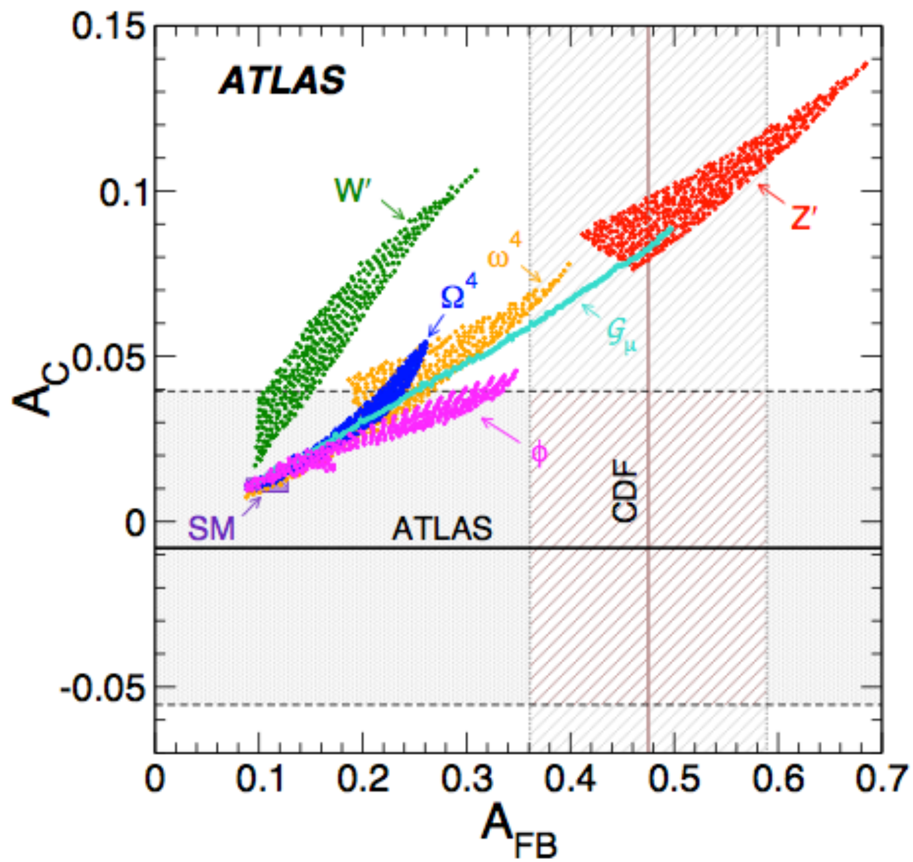
Constraints on New Physics

EPJC 72(2012)2039

Inclusive

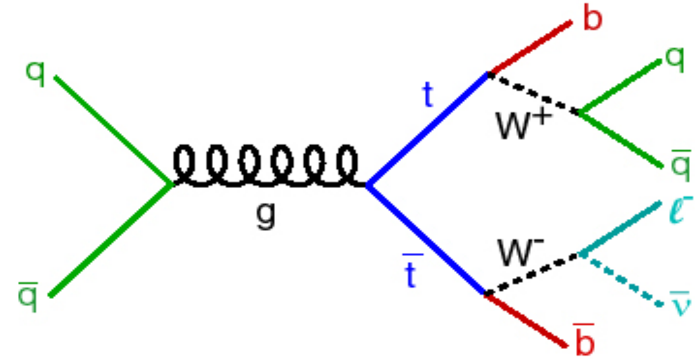


m_{tt}>450 GeV



Heavy flavor content (i.e. V_{tb})

Top quark decays



top decay t→Wb, but really 100%?

Indirect measurement using the CKM matrix:

- Elements $|V_{ub}|$ and $|V_{cb}|$ measured to be very small from decay of B mesons
- Unitarity and only three generations implies $|V_{tb}|$ is 0.998 @ 90% CL

With top quark samples we can measure it directly as "R":

$$R \equiv \frac{BR(t \to Wb)}{BR(t \to Wq)} = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2} \qquad \text{where } q = \{d, s, b\}$$

Use the ability to identify jets with a distinguished secondary vertex: b-tagging

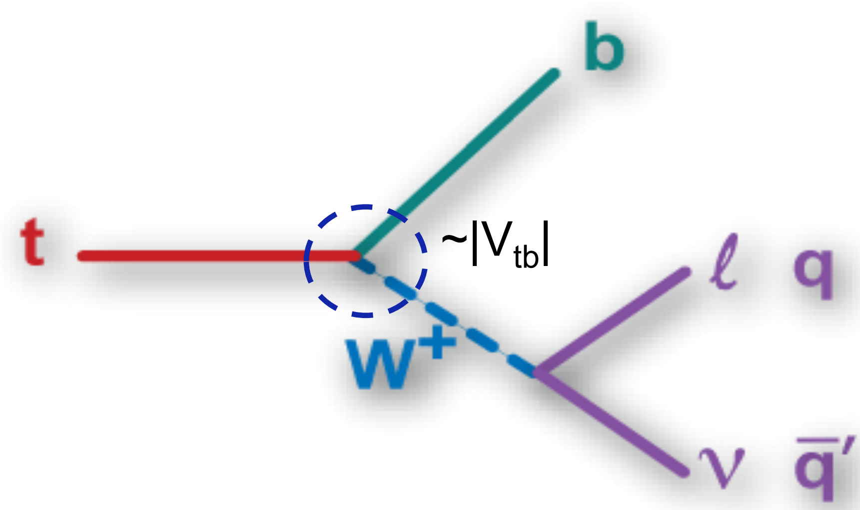
- The number of b-tagged jets depends strongly on R and b-tagging efficiency ε_b

We classify the ttbar sample based on the number of b-tagged jets

- The relative rates of events with 0/1/2 b-tags is very sensitive to R

Is BR(t→Wb)~100% ?

- In the SM, $R = \frac{BR(t \to Wb)}{BR(t \to Wq)} \approx |V_{tb}|^2$ (q=b,s,d) $0.9980 < R < 0.9984$
- measure R by comparing the number of ttbar events with 0, 1 and 2 b-tags
- SM: R=1 constrained by CKM unitarity. R<1 could indicate new physics (e.g. 4th generation hep/ph-0607115)



Measure R simultaneously with ttbar cross section:

$\sigma_{p\bar{p}\to t\bar{t}}(pb)$	7.4 ± 1.1
R	0.91 ± 0.09
$\lvert V_{tb} \rvert$	0.95 ± 0.05

CDF prelim. 7.5 fb^{-1}
lepton+jets channel

$\sigma_{t\bar{t}} = 7.74^{+0.67}_{-0.57}$ pb
R=0.90±0.04 (stat+syst)
$|V_{tb}|$=0.95±0.02 (stat+syst)
$|V_{tb}|$>0.88 @99.7% C.L.

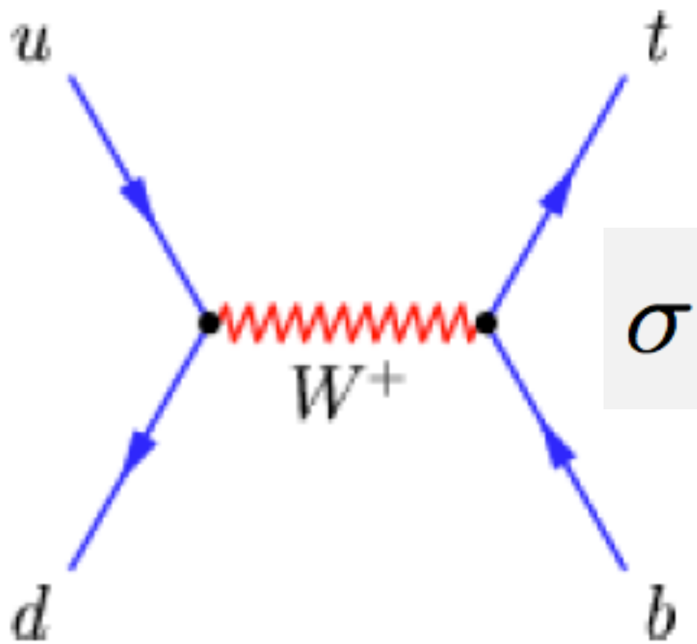
D0 5.4 fb^{-1}
l+jets & dilepton

PRL 107, 121802 (2011)

Not yet sensitive to SM

Measure of V_{tb}

- Measurement with the single top production final state
- direct measure of |Vtb|
- sensitive to non-SM phenomena (W', FCNC)



$$\sigma \approx |V_{tb}|^2$$

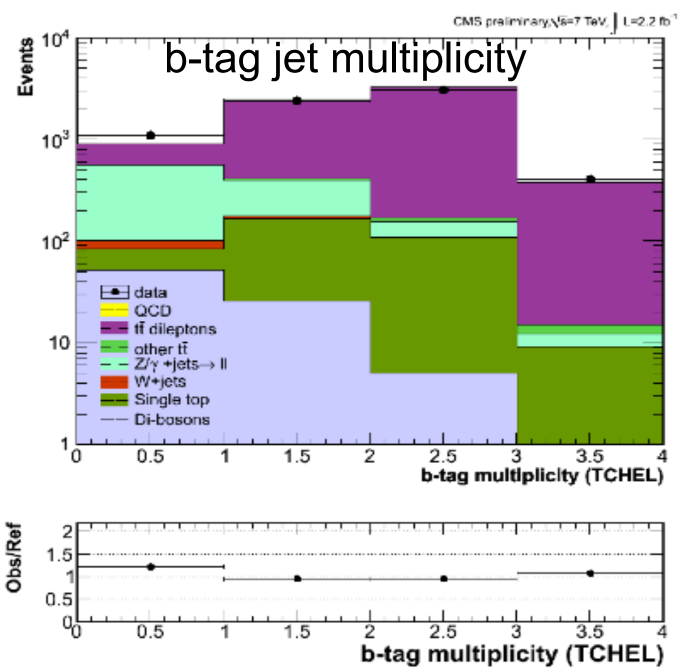
Measure R in dilepton channel

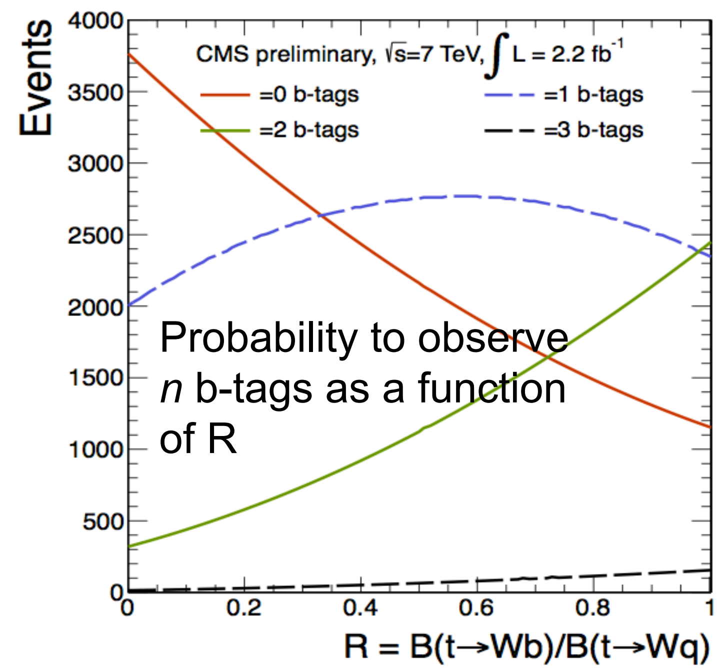
CMS TOP-11-029

- Probe heavy flavor content of ttbar events
- Use ttbar dilepton final state
- Advantages:
  - less background
- Disadvantages:
  - lower statistics
  - jet assignment

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

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

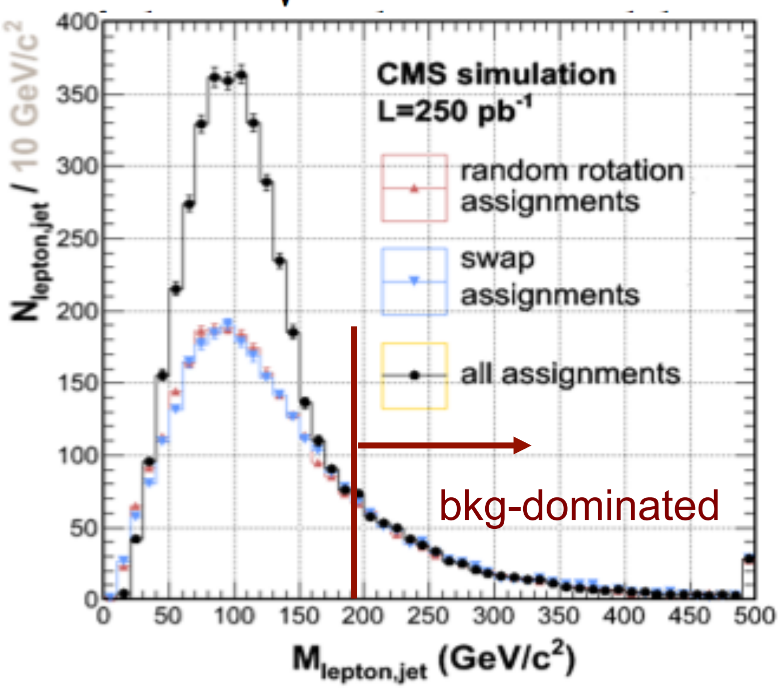


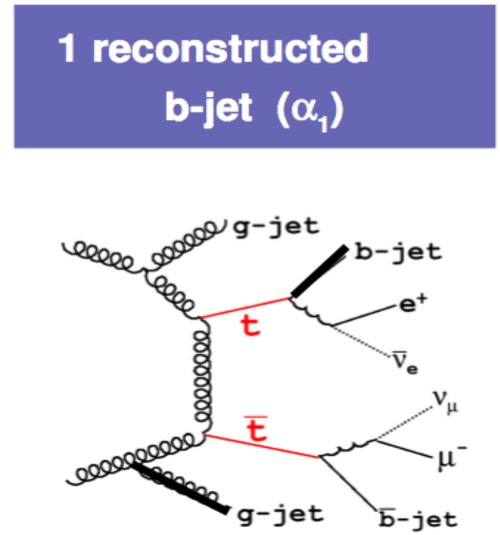


How to model the background

Events are classified in 3 cases (weight α):
1) 2 correctly assigned b-jet
2) 1 corr. ass. b-jet
3) 0 corr. ass. b-jet

$$M_{l,j} \approx \sqrt{m_t^2 - m_W^2} = 156 \ \mathrm{GeV}/c^2$$





Compute invariant mass of all lepton-jet pairs

Model background using:
- jets from different events
- rotate lepton direction

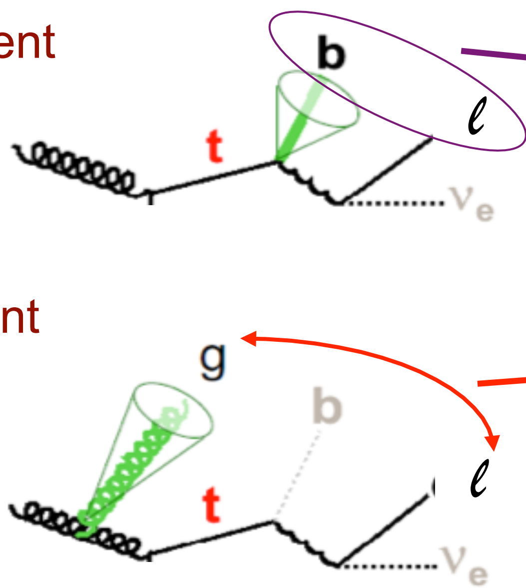
Background dominates at $M>M_{cut}$

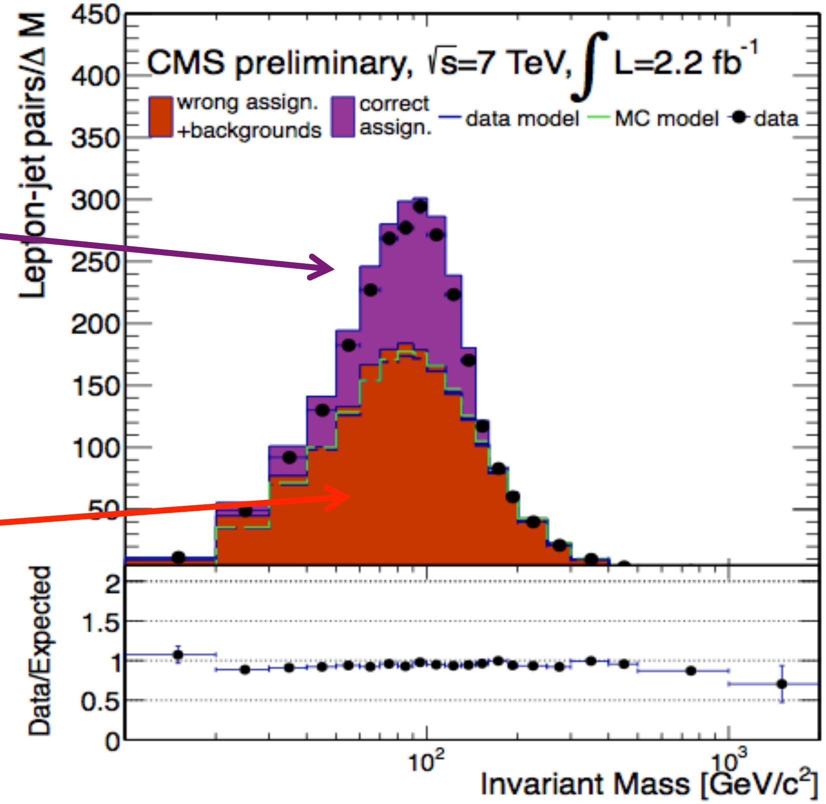
Signal or background?

CMS TOP-11-029

Data-driven determination of background

- Reconstruct lepton-jet invariant mass
  - Correct assignment
  - Wrong assignment

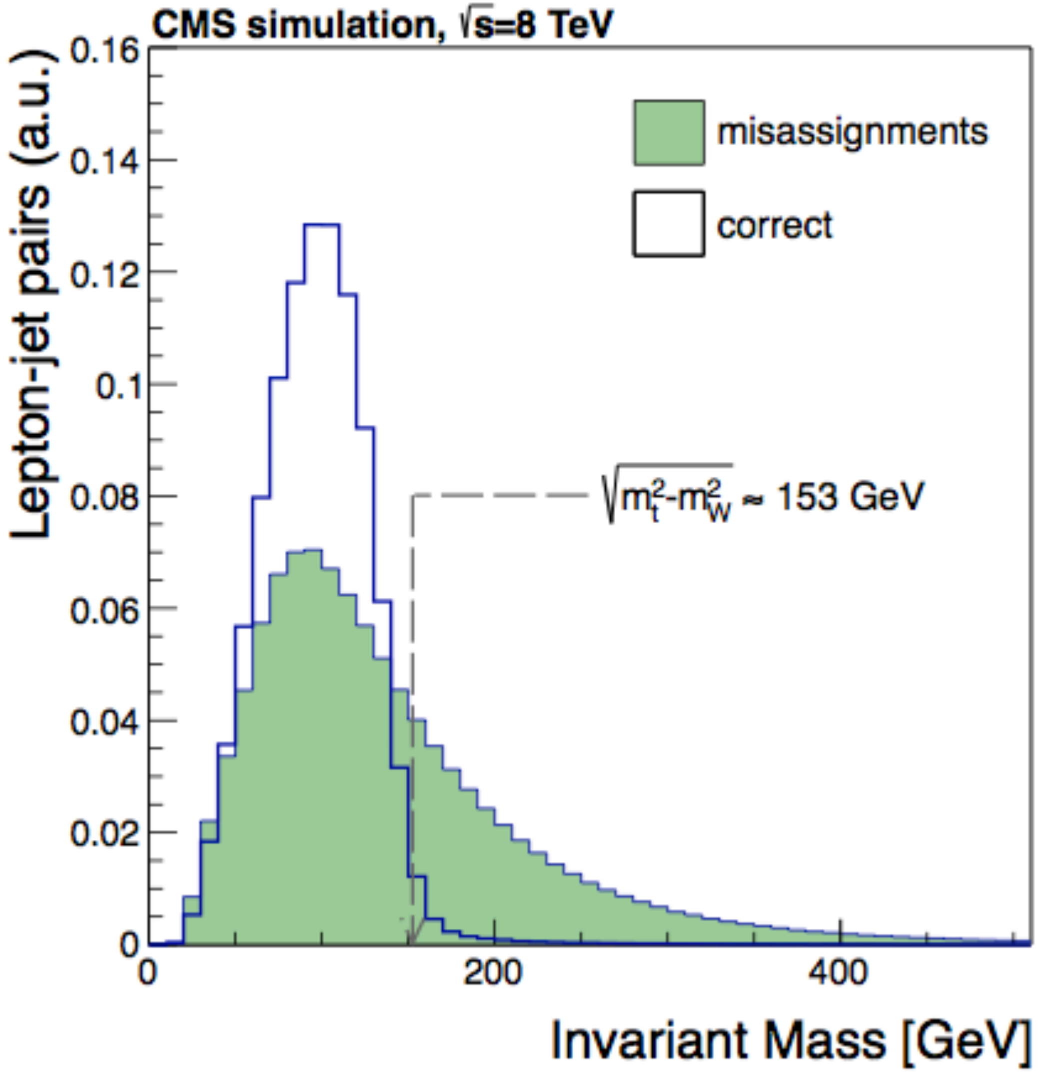




- Use tail to model background in signal region

Signal vs background

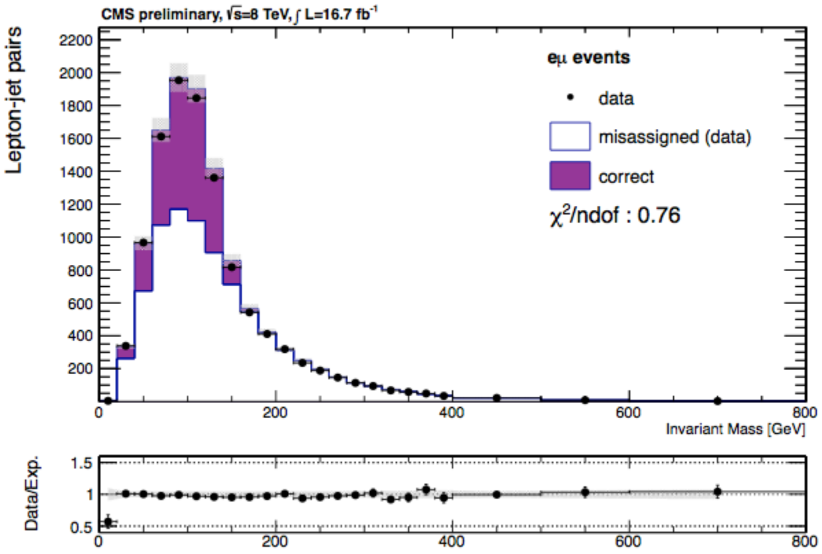
CMS TOP-12-035



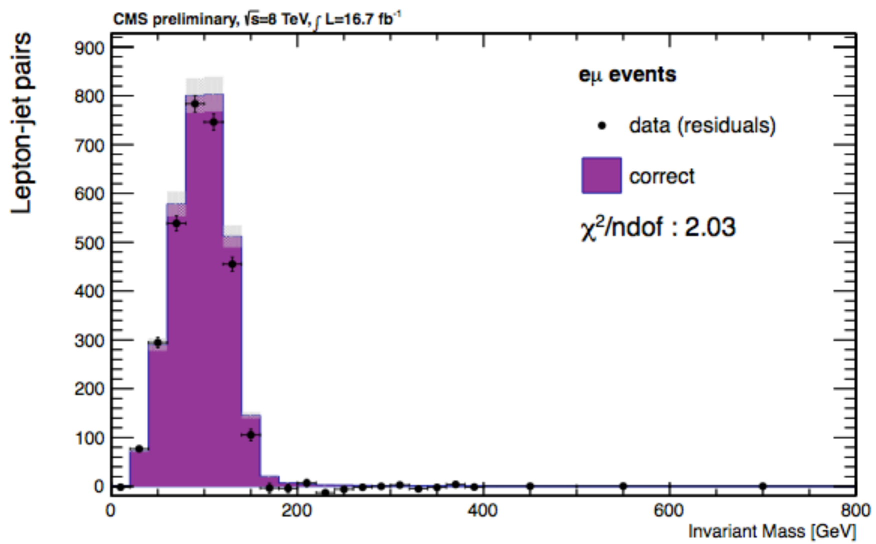
Signal or background

CMS TOP-12-035

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



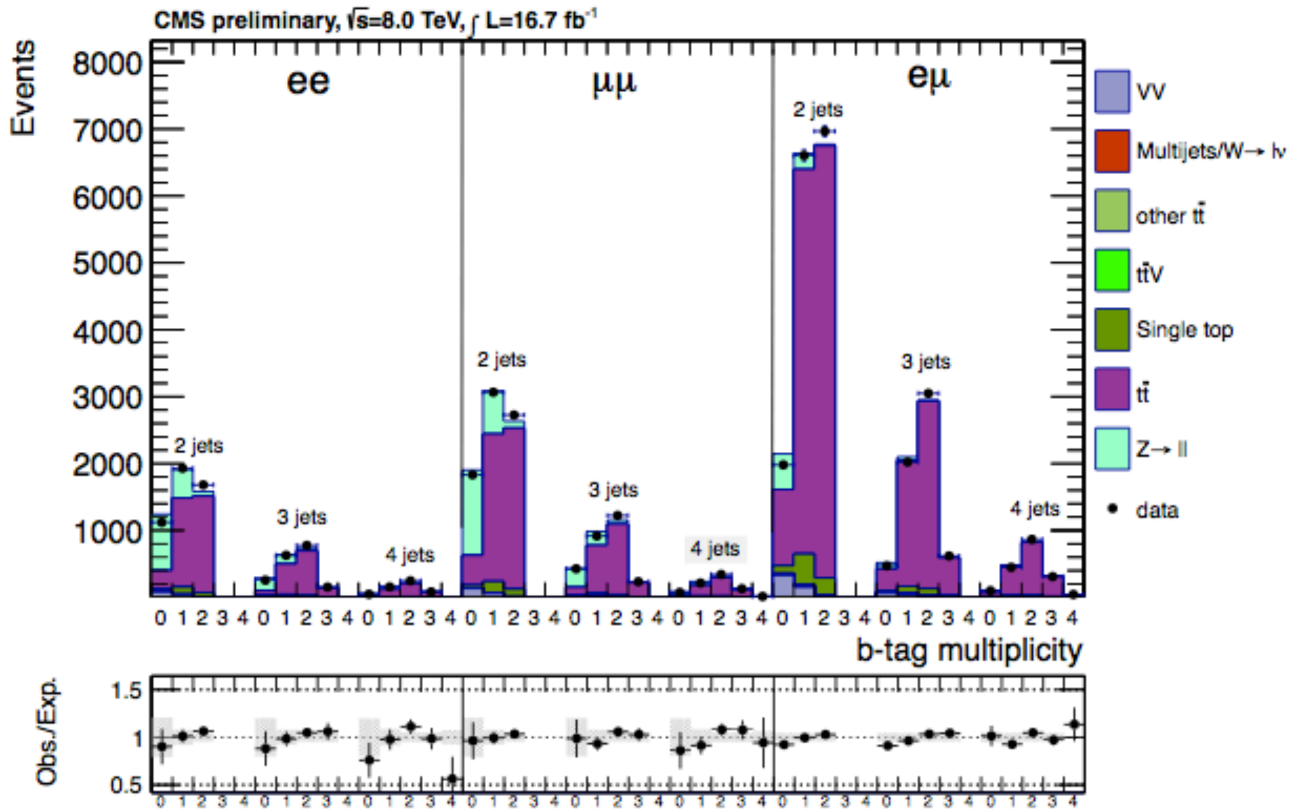
after background subtraction



Heavy flavor content

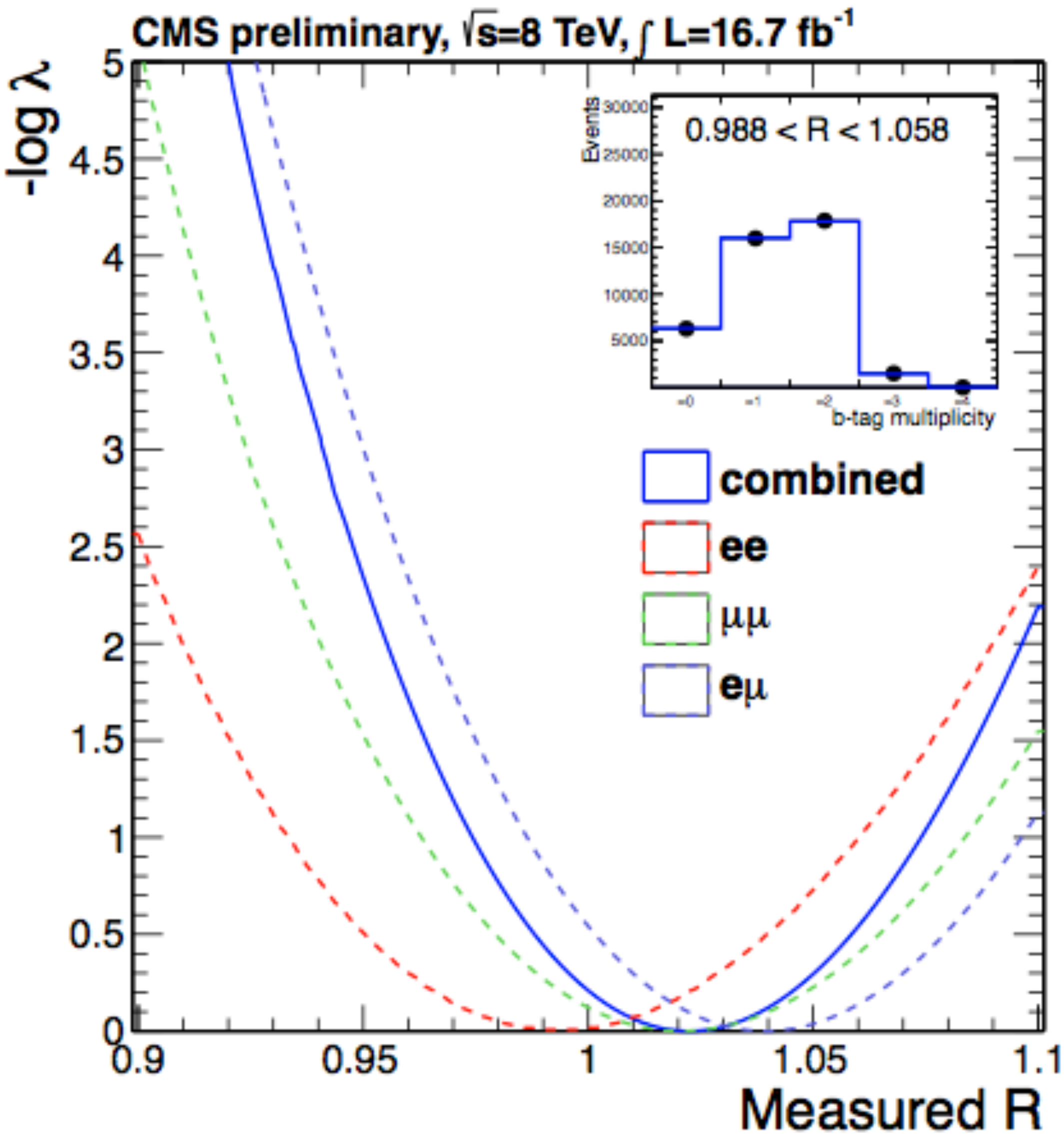
CMS TOP-12-035

- Fully data-driven measurement
  - b-tagging multiplicity parametrized as function of R ε_b, ε_q, top contribution
  - Number of reconstructed t→Wq is estimated from lepton-jet invariant mass
- R=1.02±0.04 (stat.⊕ syst.)
  - Lower boundary with confidence interval @95%CL after requiring R≤1 **⇒ R>0.945 @95%CL**



Measure R

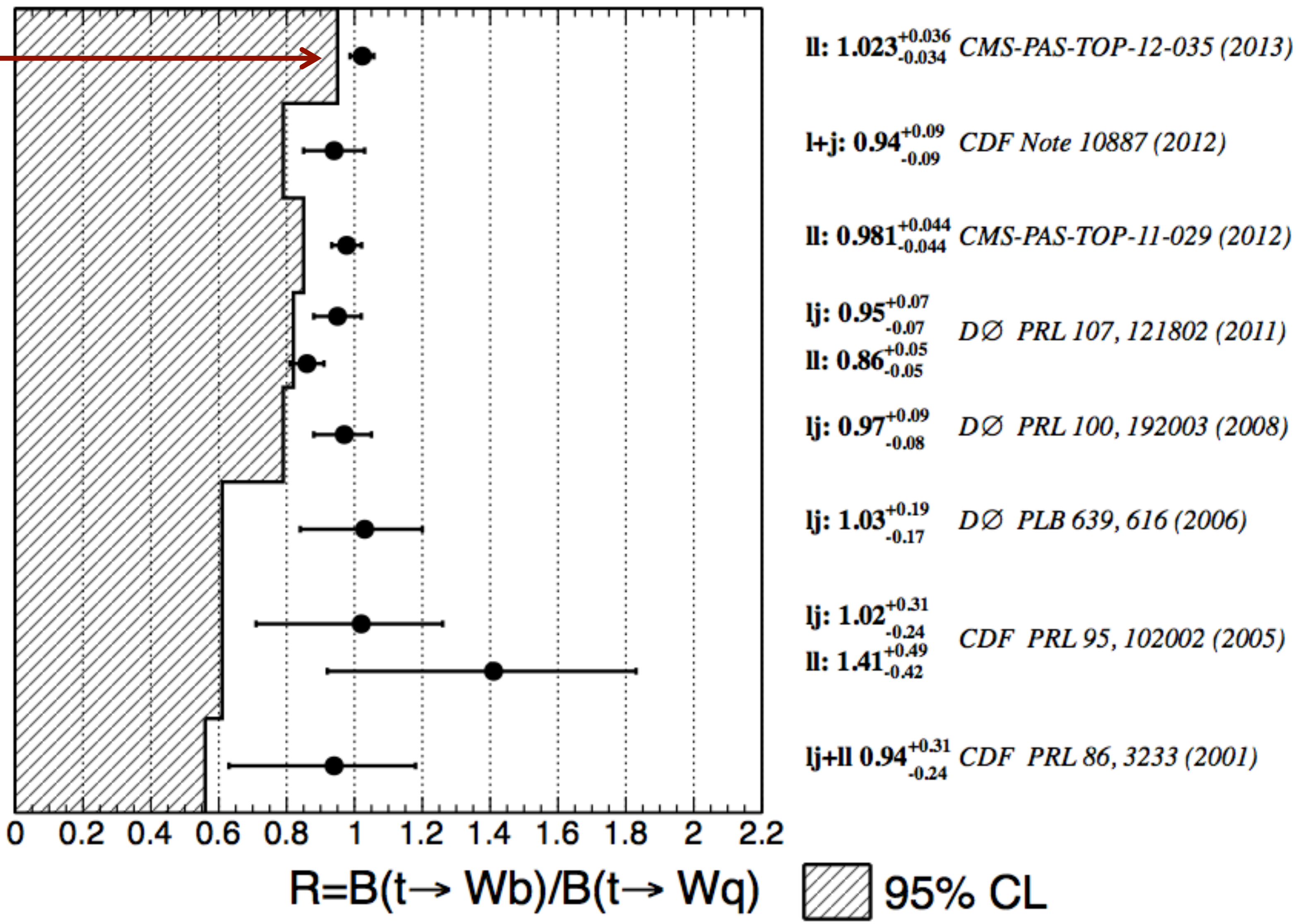
CMS TOP-12-035



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

Summary of R results

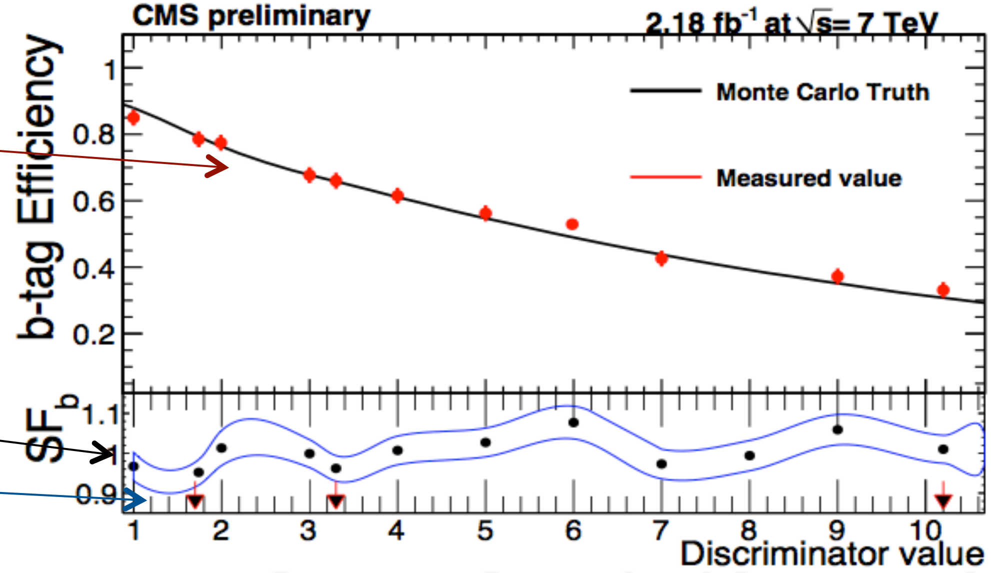
Most accurate measurement

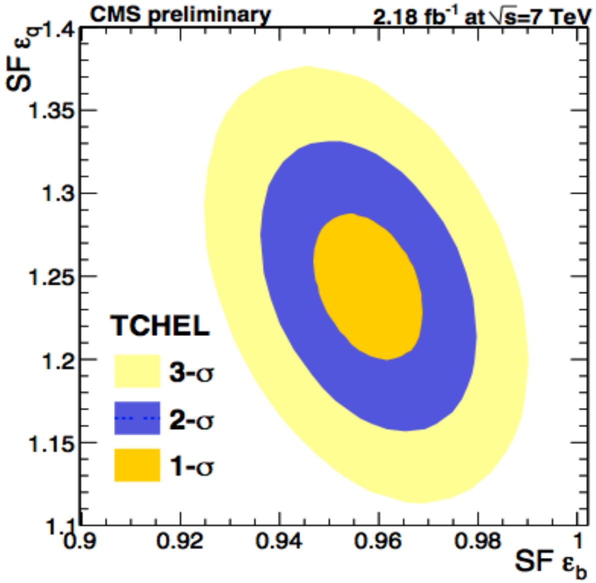


b-tagging efficiency

CMS BTV-11-003

- Can determine b-tag efficiency and/or R
- b-tagging efficiency measured
  - (assume R=1)
- absolute *b-tagging* efficiency measured from data and predicted from simulation
- Ratio of data/simulation
- Total (stat.+syst.) uncertainties





Results of the fit to the b-tagging multiplicity

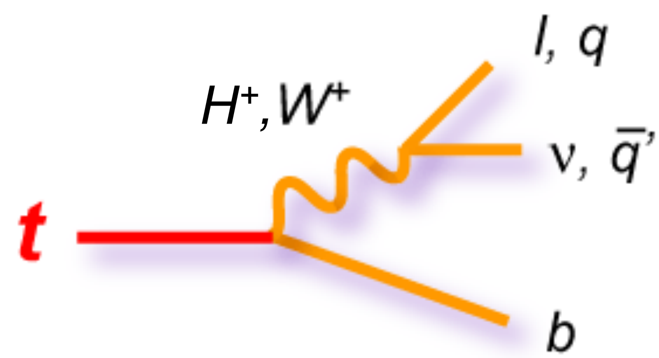
Top quark decays and taus

Probing the Wtb vertex

- Measurement of ttbar cross section with tau leptons in final state is important:
  - channel not well explored
  - Cross-check to other channels
  - increase acceptance of ttbar events
  - involves only 3rd generation leptons/quarks
  - probe non-standard physics ($t \rightarrow H^{\pm}b$, …)

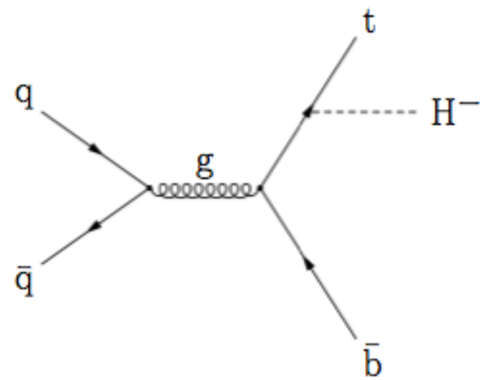
Channel	Signature	BR
Dilepton(e/μ)	*ee*,μμ,*e*μ + 2*b*-jets	4/81
Single lepton	*e*,μ + jets + 2*b*-jets	24/81
All-hadronic	jets + 2*b*-jets	36/81
Tau dilepton	*e*τ, μτ +2 *b*-jets	4/81
Tau+jets	τ + jets + 2*b*-jets	12/81

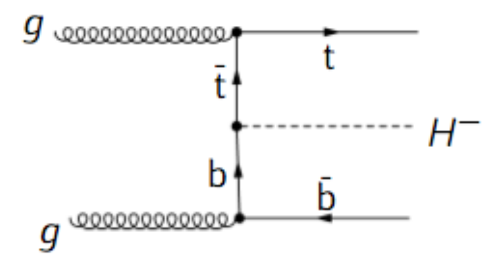
- If top quark plays special role in EWK symmetry breaking, couplings to W may change
- Charged Higgs may alter coupling to W
- Search for final states with taus

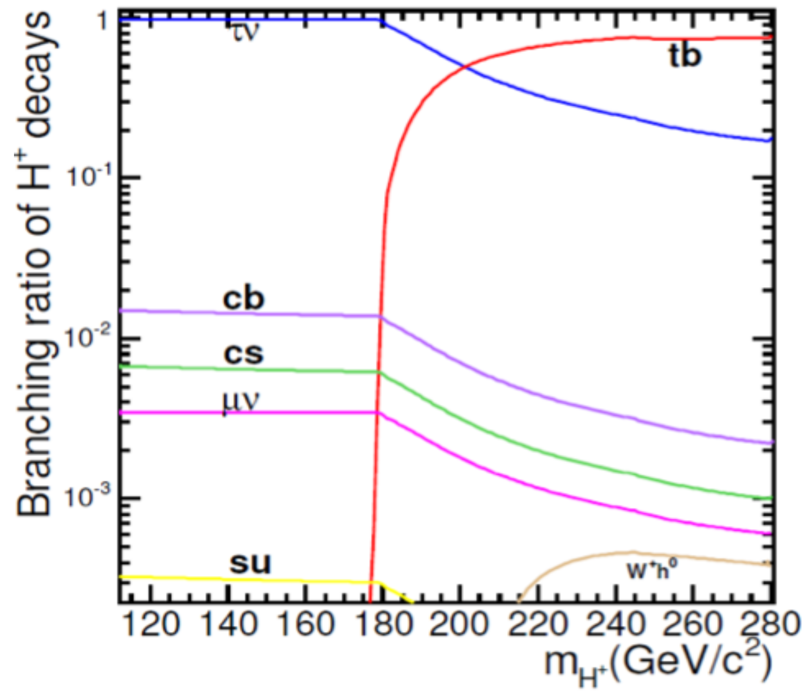


Charged Higgs

- Study non-SM Higgs in two mass regimes:
- $m_H < m_{top}$
  - Mostly produced in top quark decays
  - Large tanβ: $H^{\pm} \rightarrow \tau^{+}\nu$
  - Small tanβ (<1): $H^{+} \rightarrow cs$
- $m_H > m_{top}$
  - Produced in gluon-gluon fusion
  - Main decays: $H^{+} \rightarrow tb$, $H^{+} \rightarrow \tau^{+}\nu$
- Main backgrounds: ttbar, W+jets







Charged Higgs

- Tau dilepton channel is of particular interest as existence of charged Higgs can give rise to **anomalous** tau lepton production

If top decays: $t \rightarrow H^{+}b$ ($m_H < m_t - m_b$)

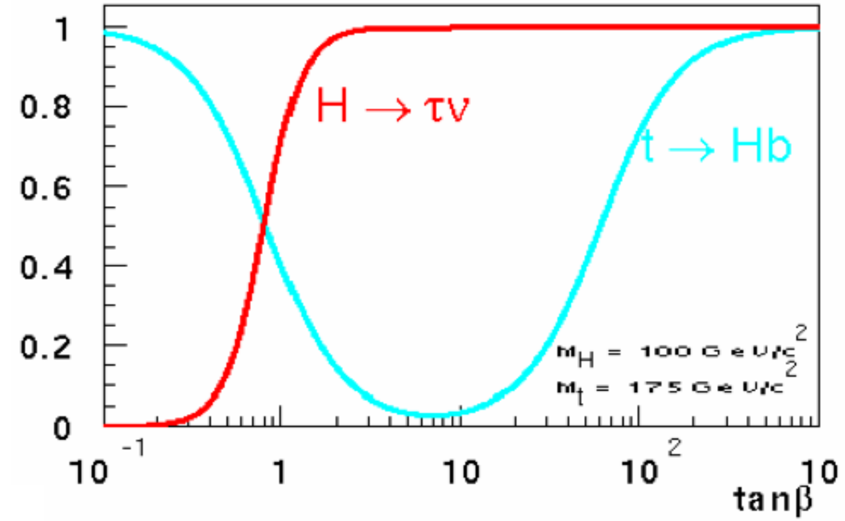
⇨directly observable in this channel

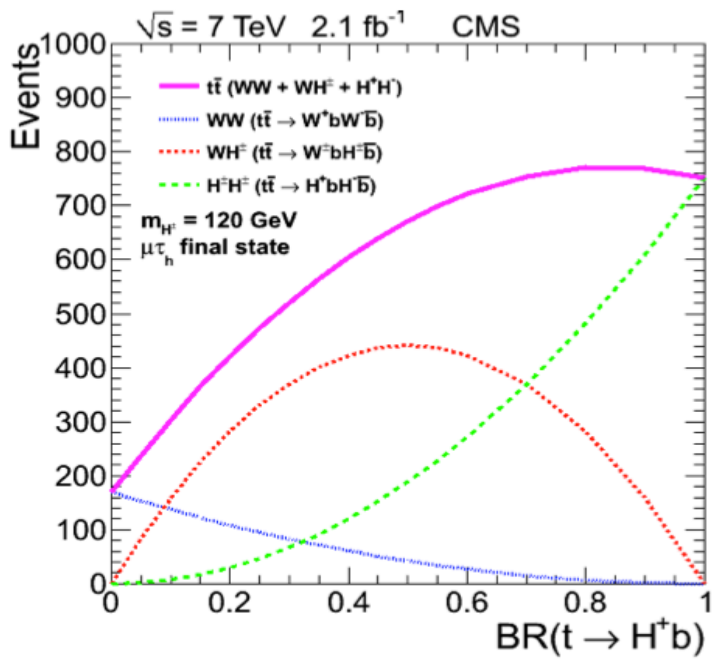
Charged Higgs

- BR($t \to H^+ b$) could be large
- $H^+ \to \tau^+ \nu_\tau$ enhanced if tanβ large

⇨ **observe more taus**

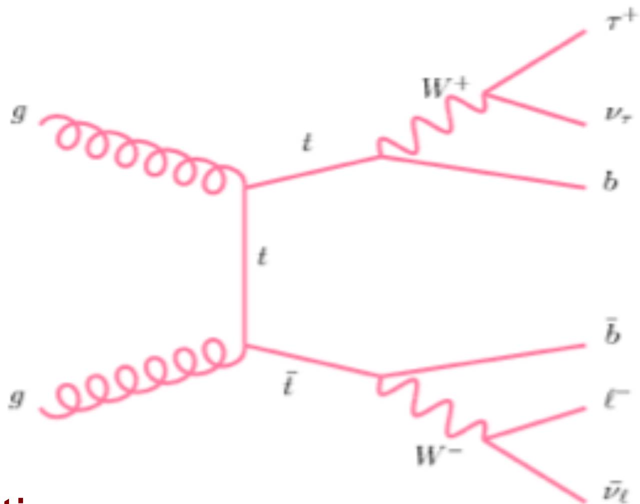
(tanβ: ratio of vacuum expectation values)

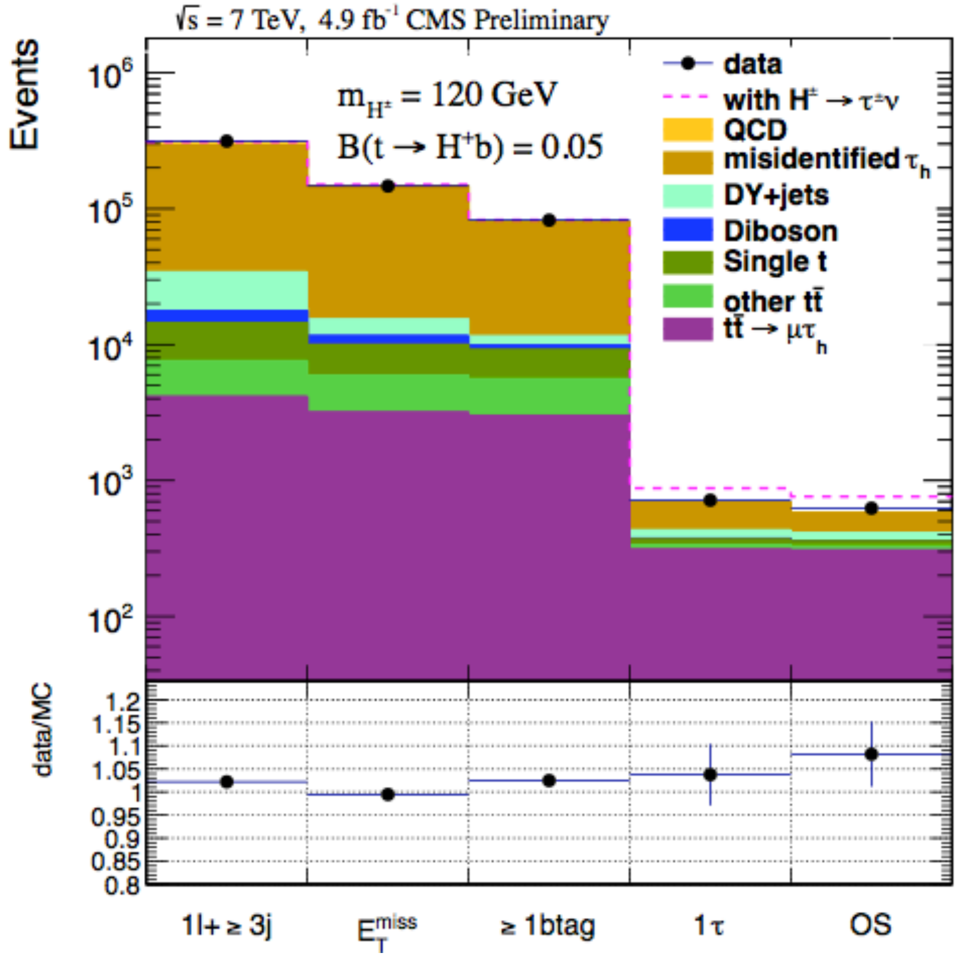




⇨number of tau dilepton events can be large

Taus in top quark decays

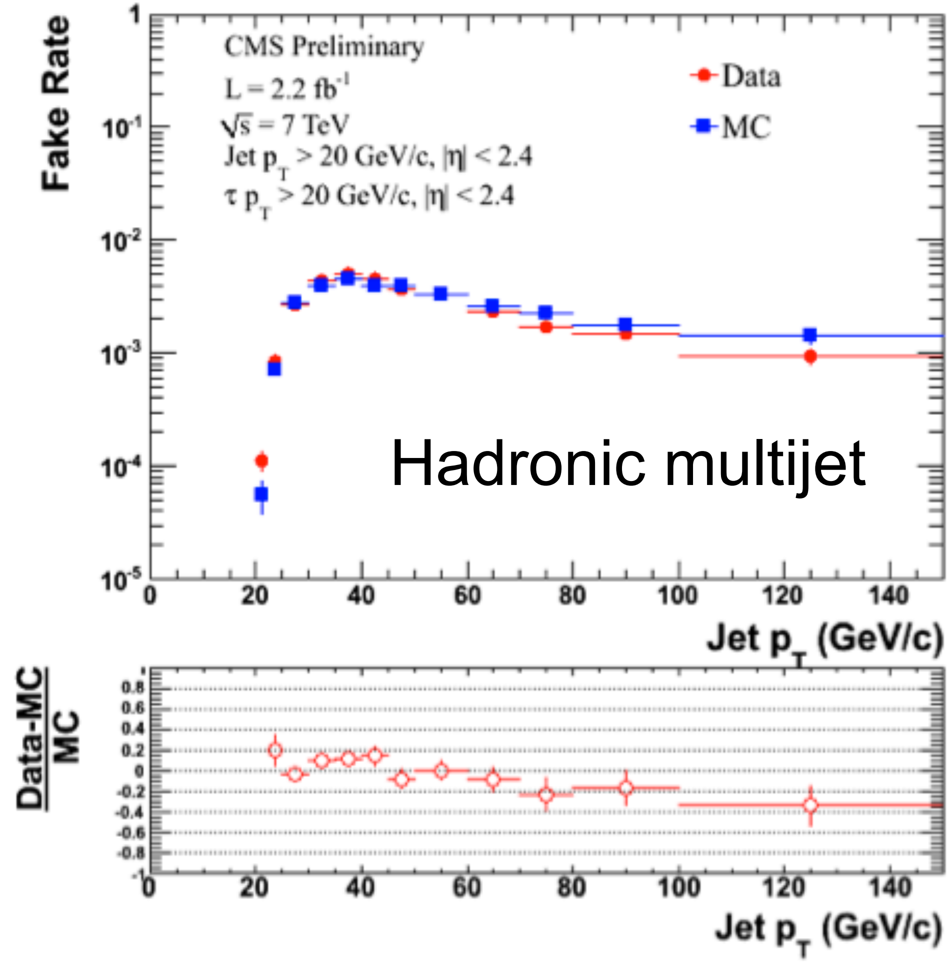




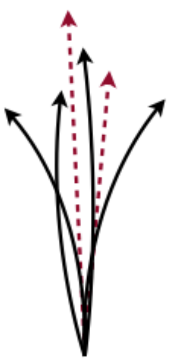
- Selection:
  - one isolated lepton (e/μ)
  - OS tau
  - at least two jets (one b-tagged)
  - MET>30 (45) GeV
- Determine τ fakes from data
  - Expected to be dominated by quark/gluon jets
  - Conservative approach: average W+jets and QCD

Tau fake rate

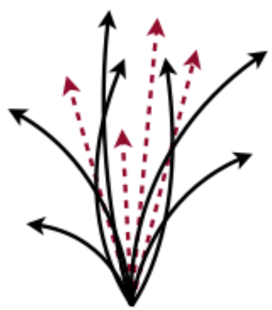
- Main background from "fake" tau jets
- Background estimated from data:
  - Select "W+≥3 jets (1 lepton+MET+≥3 jets)
  - Apply to every jet the "jet→tau probability"
  - tau fake probability evaluated from data
  - Function of p_T, η, jet width
- Good agreement with expectations



Quark jets:



Gluon jets:

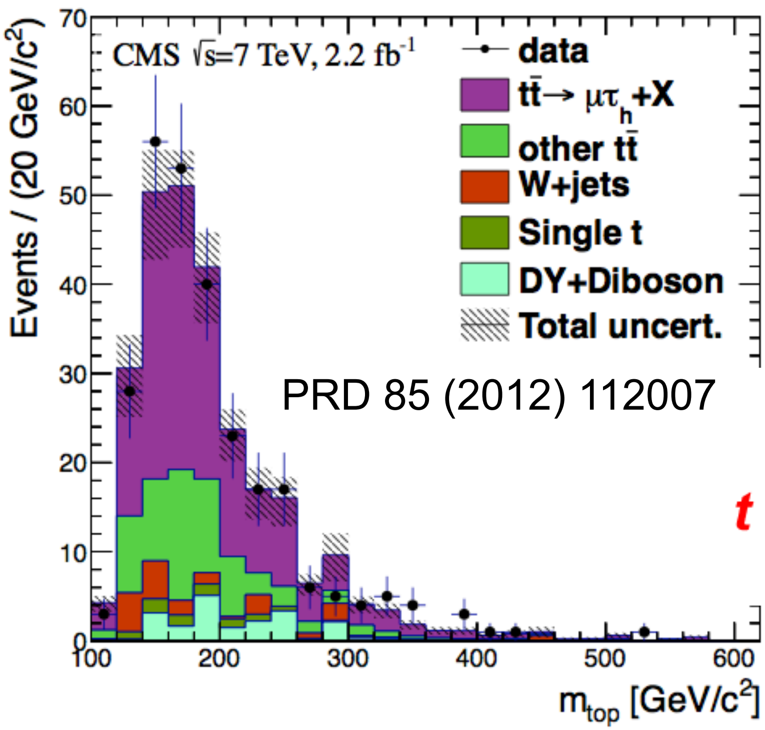


Quark vs gluon jets:

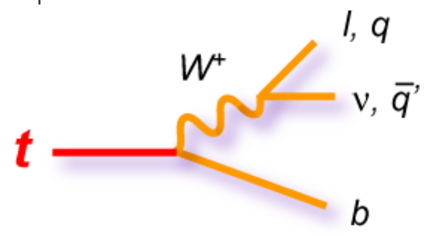
- Different coupling to strong field
- Gluon jets have higher multiplicities and softer constituents

Tau dilepton channel

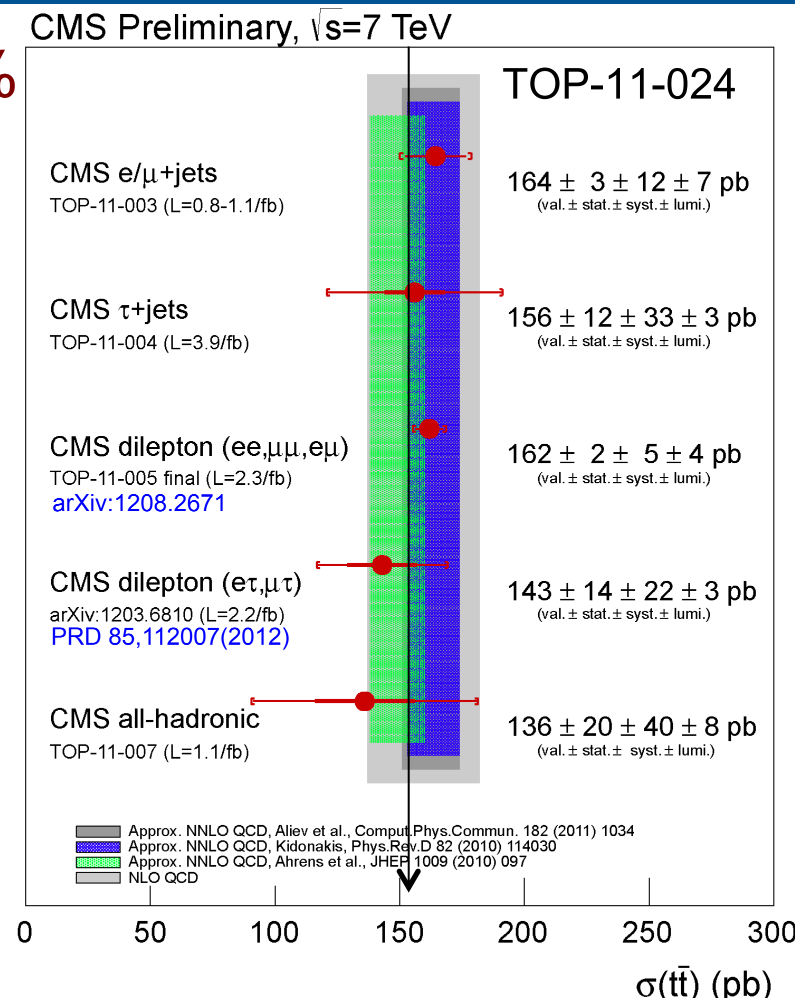
Reconstruct mass in ttbar events with taus



PRD 85 (2012) 112007



±4%



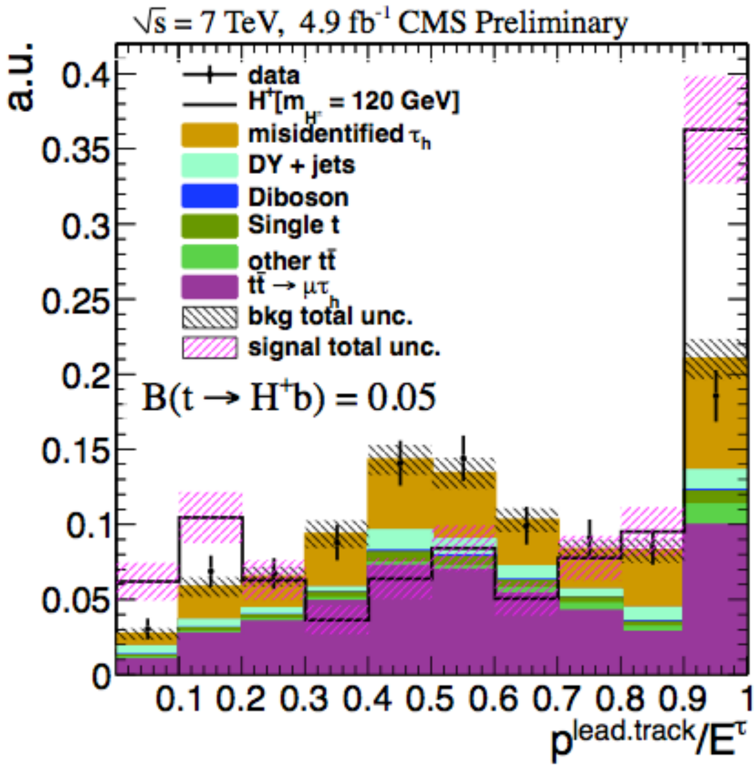
Good agreement between measurements and predictions (for all decay modes)

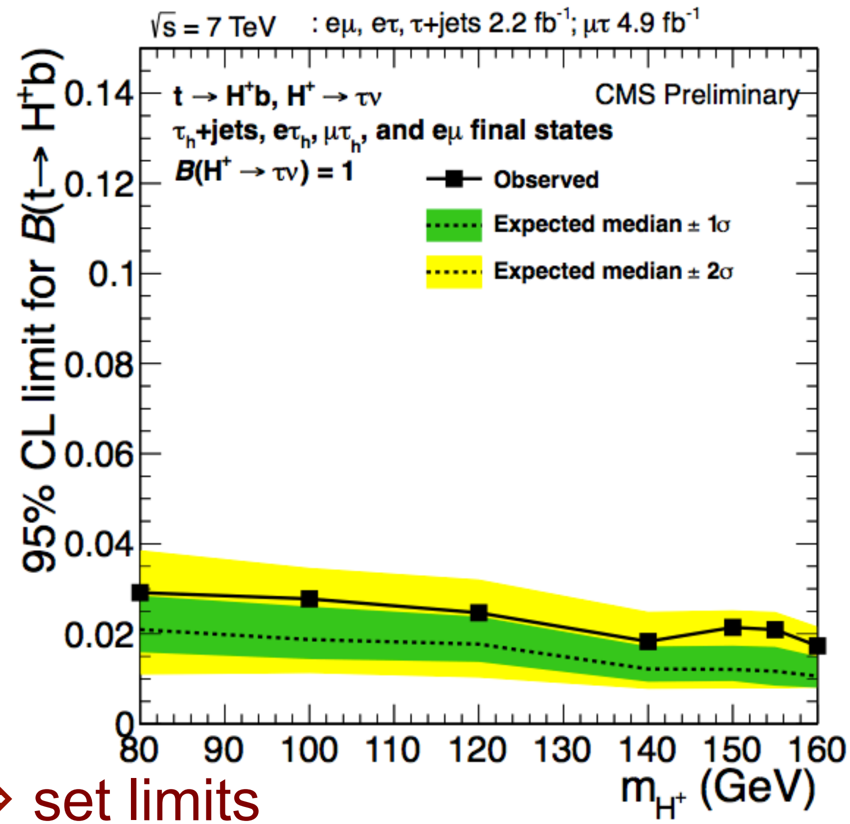
PLB 717(2012)89 $\sigma_{t\bar{t}} = 186 \pm 13\ (\text{stat.}) \pm 20\ (\text{syst.}) \pm 7(\text{lumi.})\ \text{pb}$ ATLAS ±15%

PRD85(2012)112007 $\sigma_{t\bar{t}} = 143 \pm 14(\text{stat.}) \pm 22(\text{syst.}) \pm 3(\text{lumi.})\ \text{pb}$ CMS ±16%

Is there a charged Higgs?

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





Yields in agreement with expectations ⇒ set limits

$80 < m_{H^+} < 160$ GeV. $BR(t \rightarrow H^+ b) < 2-3\%$

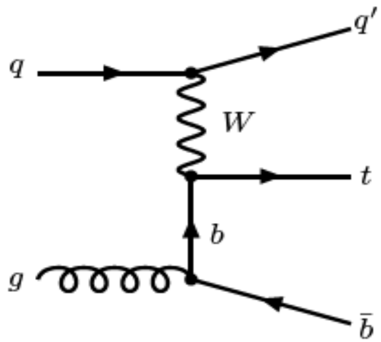
CMS HIG-11-019

ttbar resonances

How else is top produced?

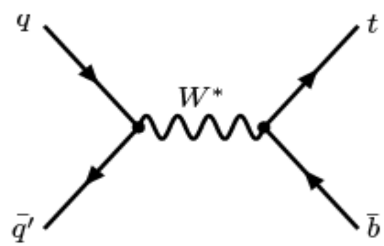
For single top: see A. Onofre, Lecture #7 May 8, 2013

Standard Model LHC Single Top Production



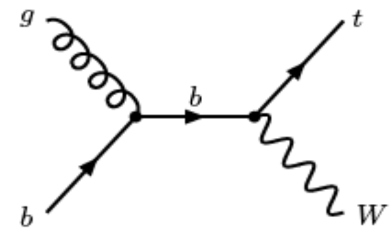
$64.57^{+2.09}_{-0.71}\ {}^{+1.51}_{-1.74}$ pb

Kidonakis,N. PRD83:091503,2011



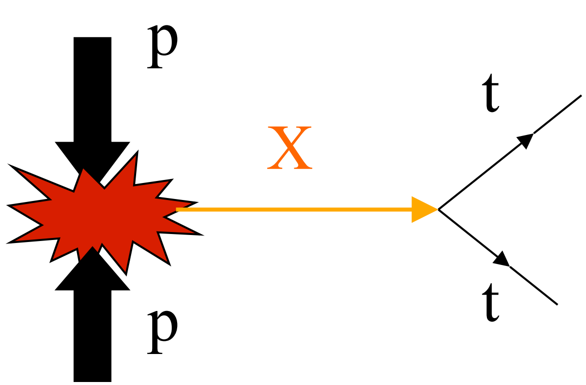
$4.63 \pm 0.07^{+0.19}_{-0.17}$ pb

Kidonakis,N. PRD81:054028,2010



$15.74 \pm 0.40^{+1.10}_{-1.14}$ pb

Kidonakis,N. PRD82:054018,2010



Resonance Production?

Top Color-Assisted Technicolor

OR

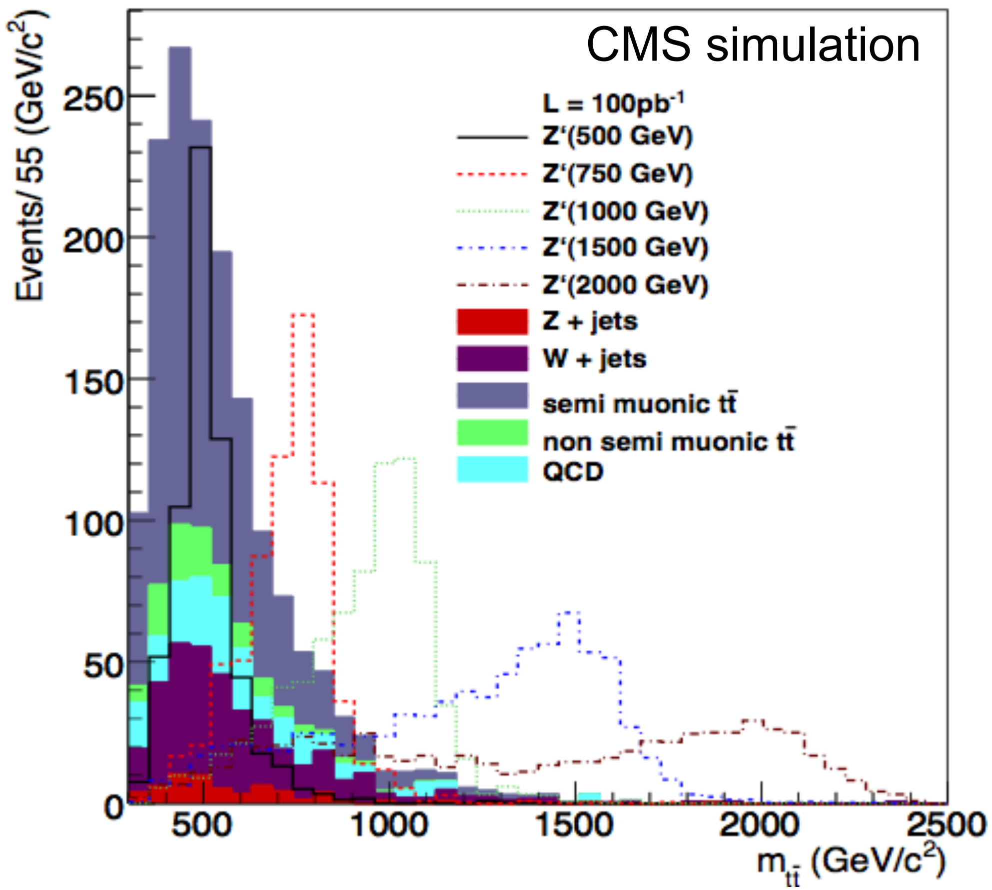
?????

Top quark pair resonance

- No resonance expected in SM
- Why is Top so heavy?
  - new physics?
  - is third generation ‘special’?
  - couples predominantly to third generation quarks
- Top is relatively unknown experimentally
- Experimental check
  - search for a bump in the invariant mass spectrum

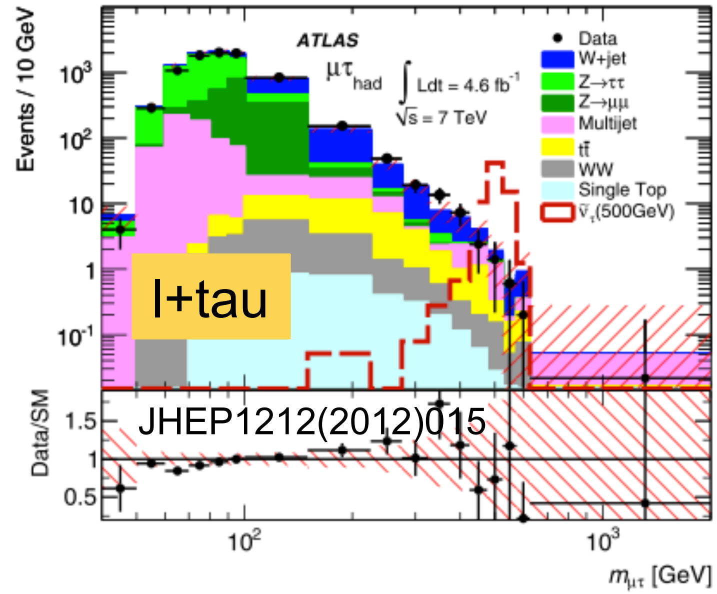
Search for resonances

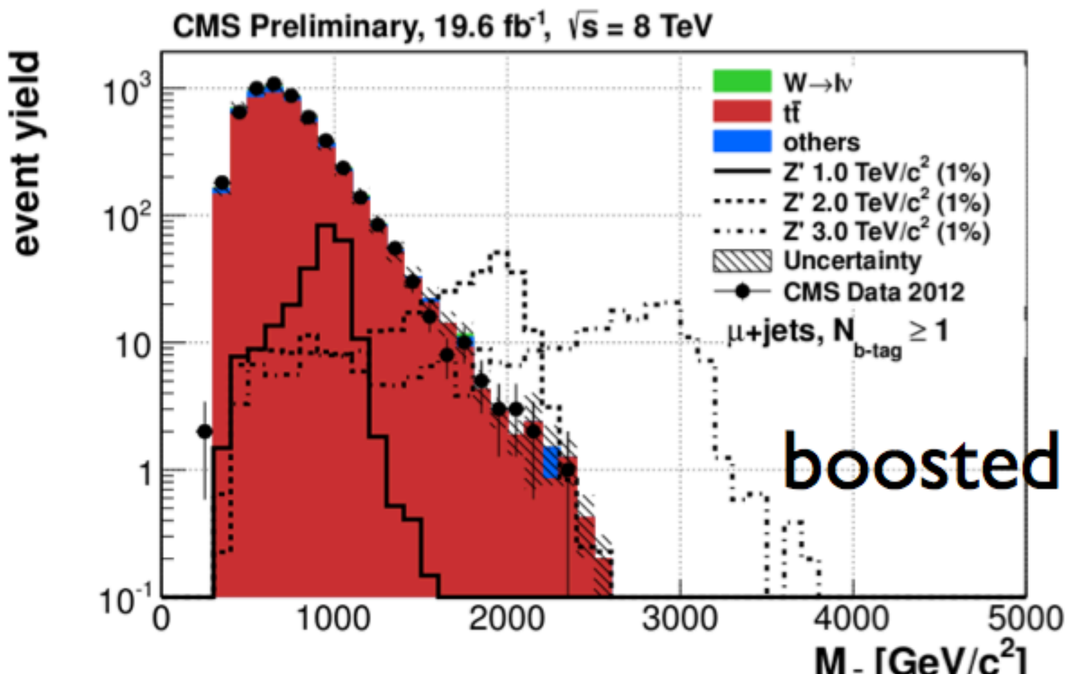
- Semi-leptonic (muon+jets) channel
- Z' → ttbar cross section normalized to SM ttbar
- Progressive loss in reconstruction ability due to jet merging

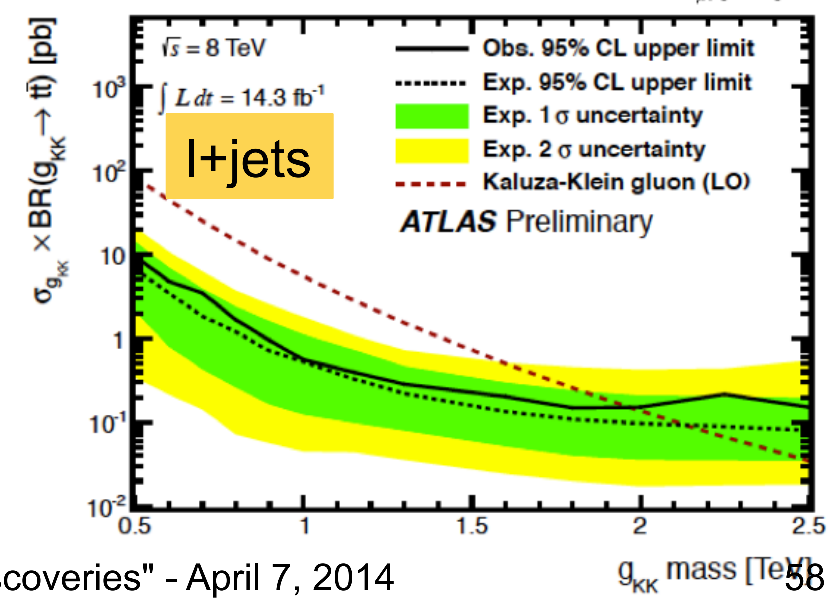


Search for heavy resonances

- search for massive neutral bosons decaying via a ttbar quark pair
- use dilepton/lepton+jet final states (electron and muon)
  - Reconstruct M_{ttbar} in different categories (e/μ, *n*-jets, *n* b-tags)
  - l+jet events: full event reconstruction
  - Dileptons: use NN approach to improve S-B separation
- systematics include shape (JES, b-tag, theory model) and rates (eff. bkg yields)



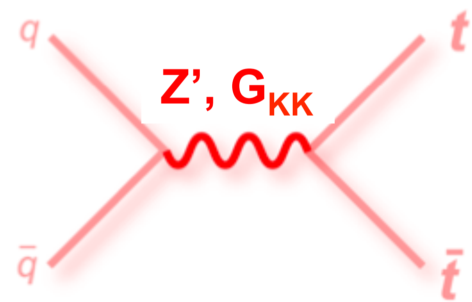


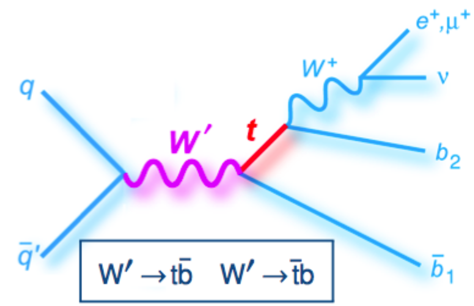


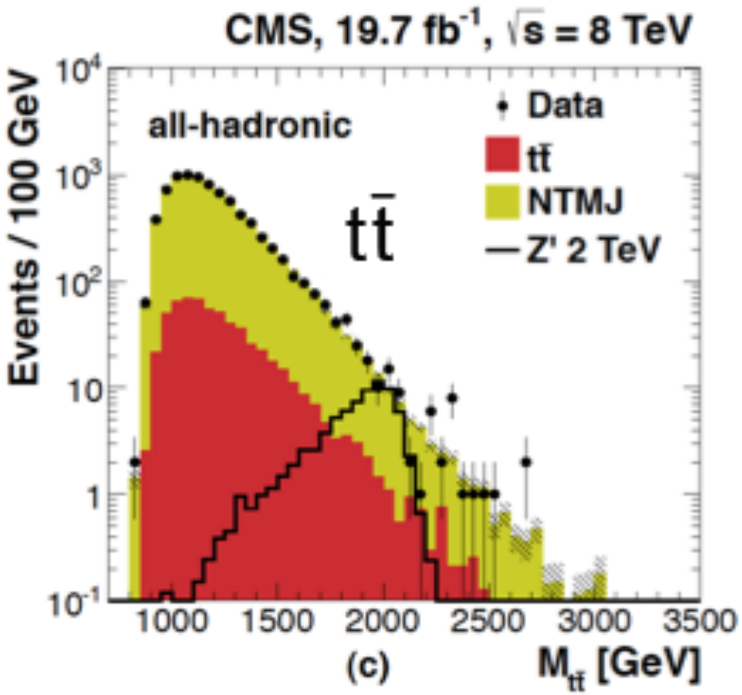
Searches for tt/tb resonances

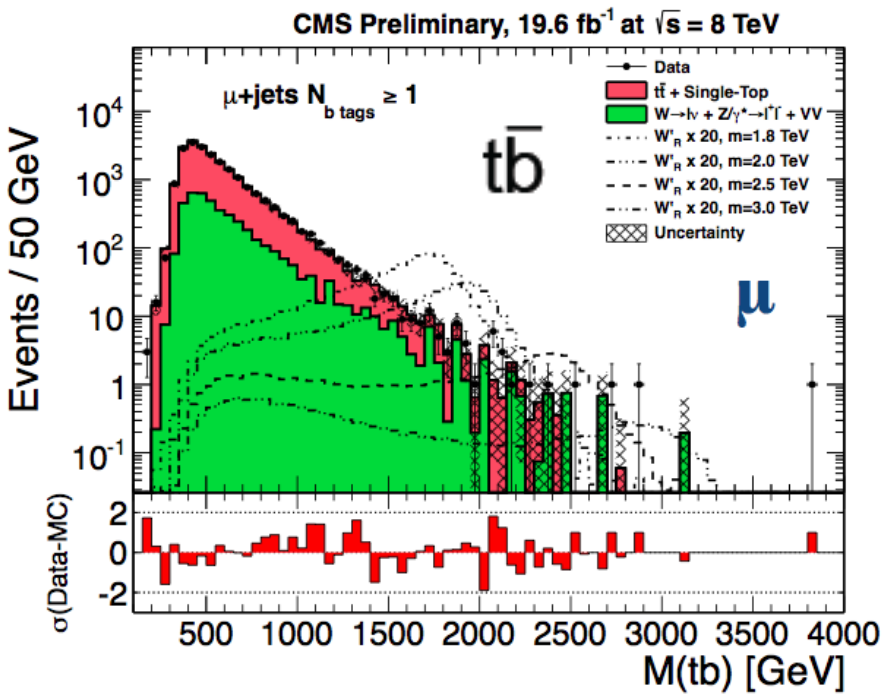
Two benchmark models considered:

- Leptophobic topcolor Z'
  ⇒ narrow resonances
- Kaluza-Klein gluons from Randall-Sundrum models
  ⇒ broad resonances

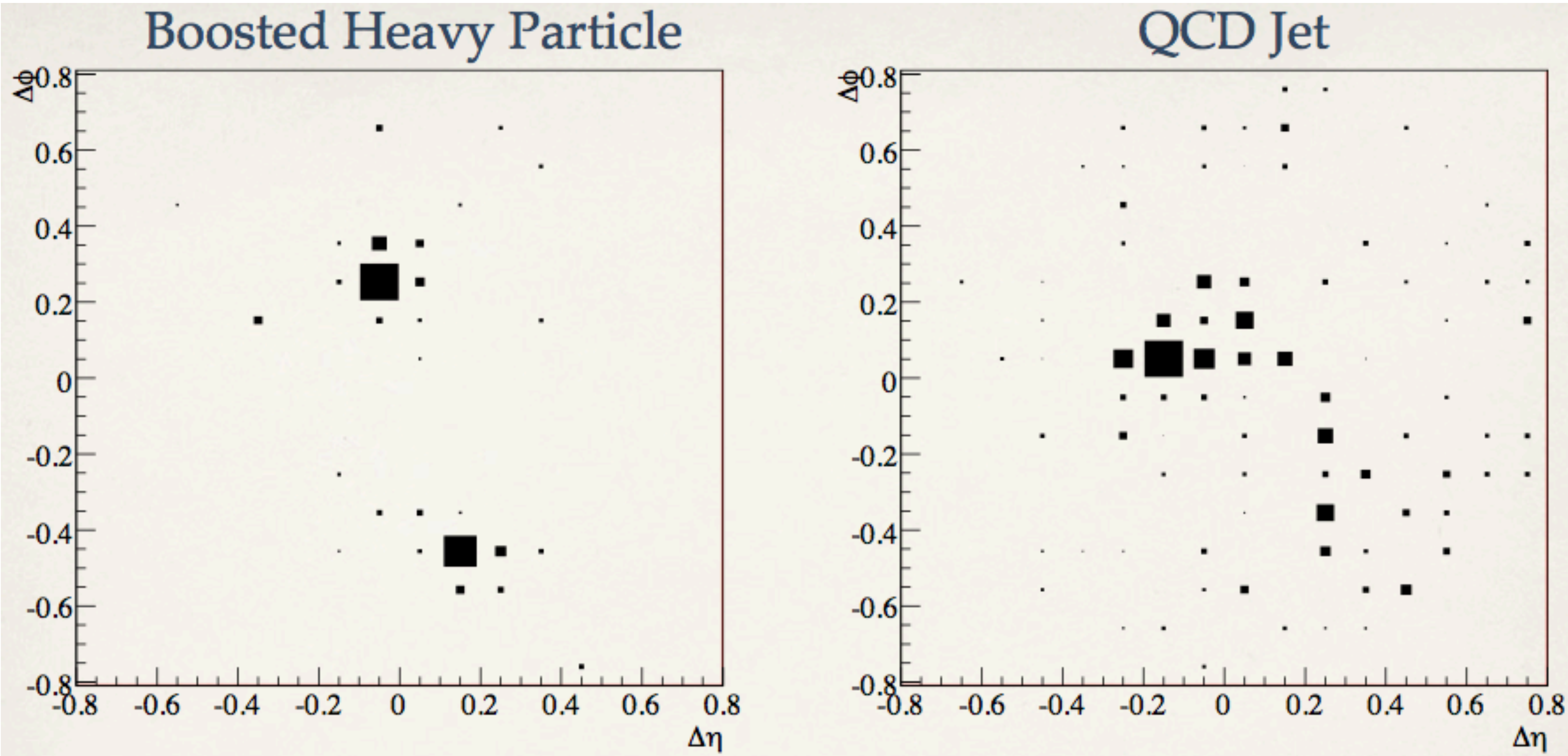




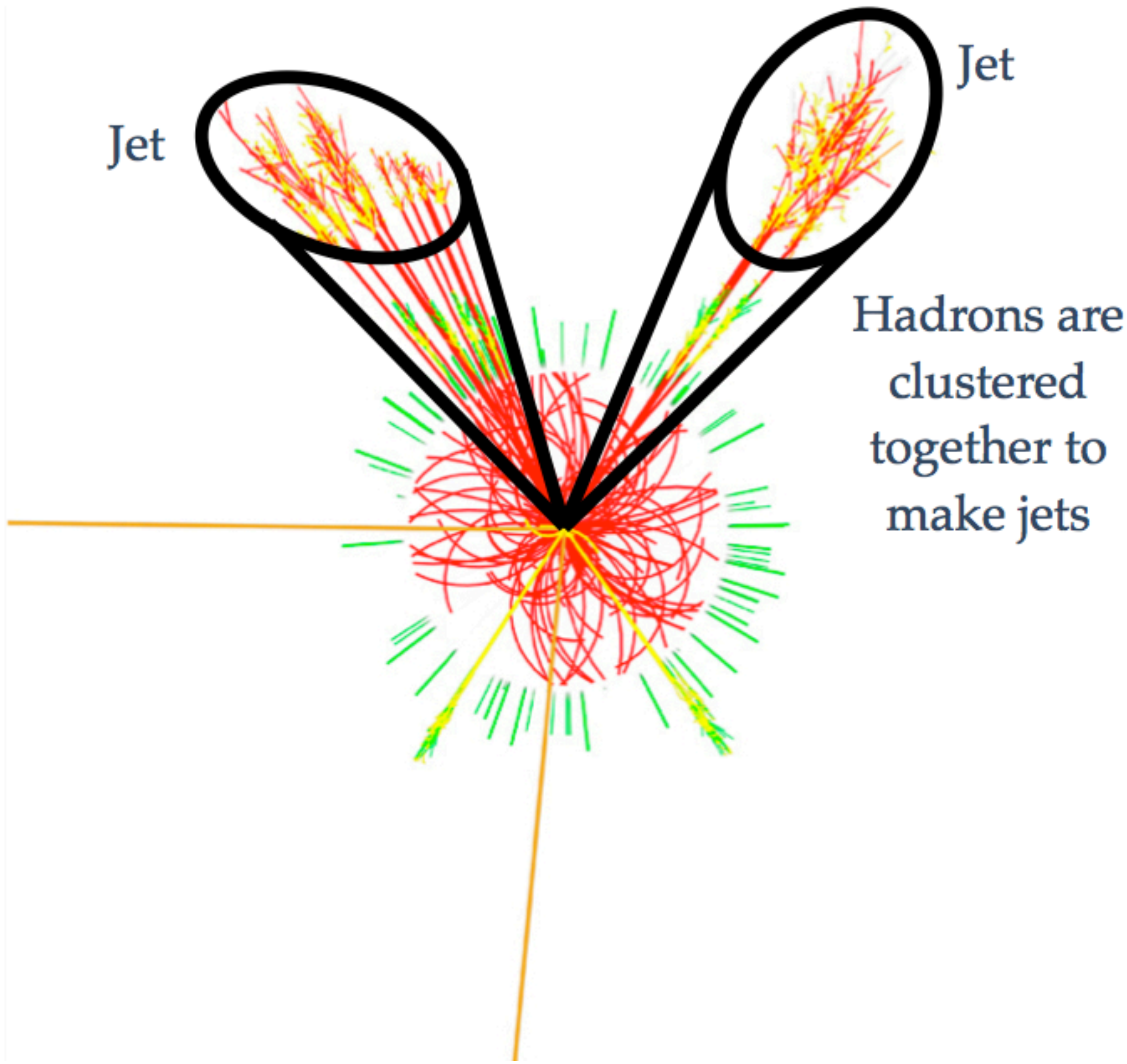




Boosted topology



Jets and boosted topology

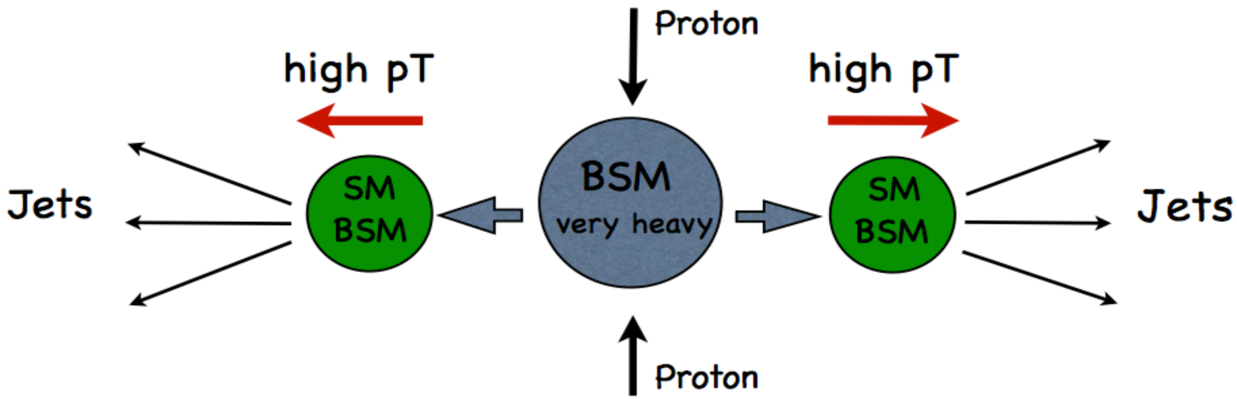


Boosted topology

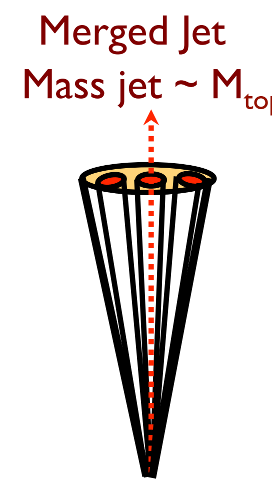
- In many models there is high potential to discover new physics in the top sector in search for heavy resonances

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

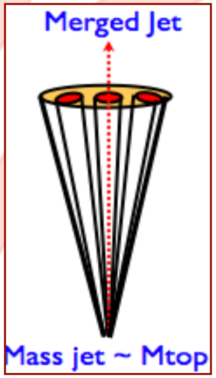
- Simple approach to merge neighboring jets

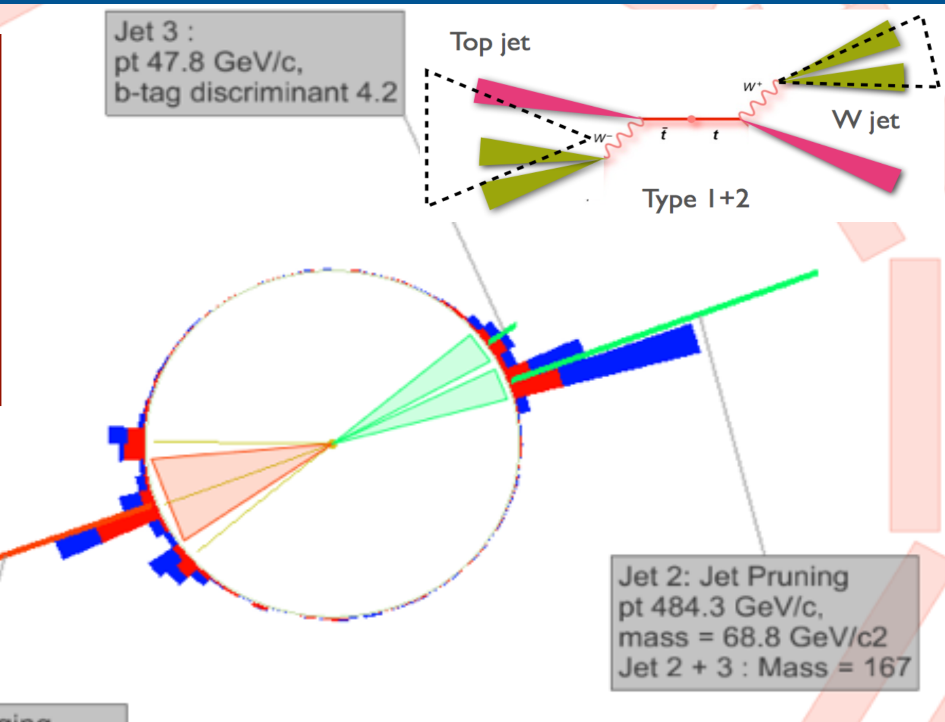


- At LHC energy, EWK scale particles produced beyond threshold
- Jets are highly collimated
- Jet-parton matching breaks down
- Decay products and FSR collected in a fat jet

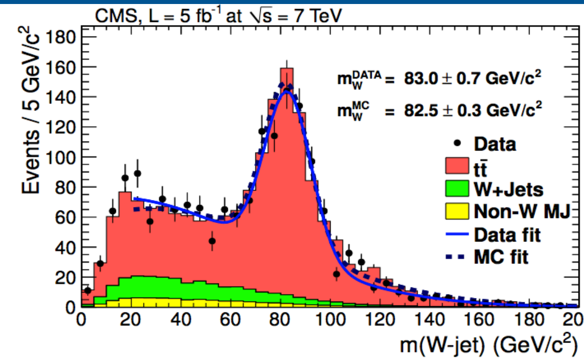


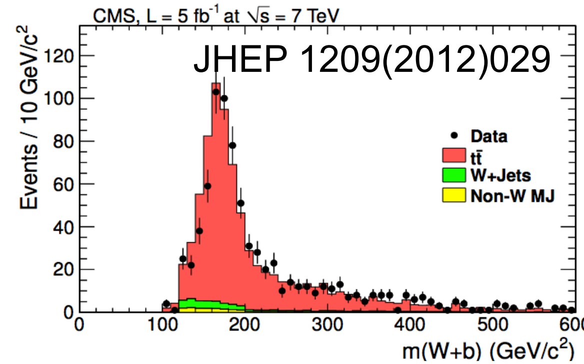
Boosted jet topology

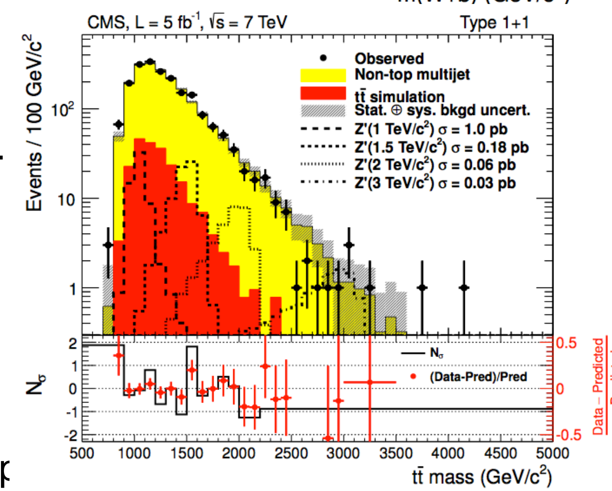




$$pp \to X \to t\bar{t}$$





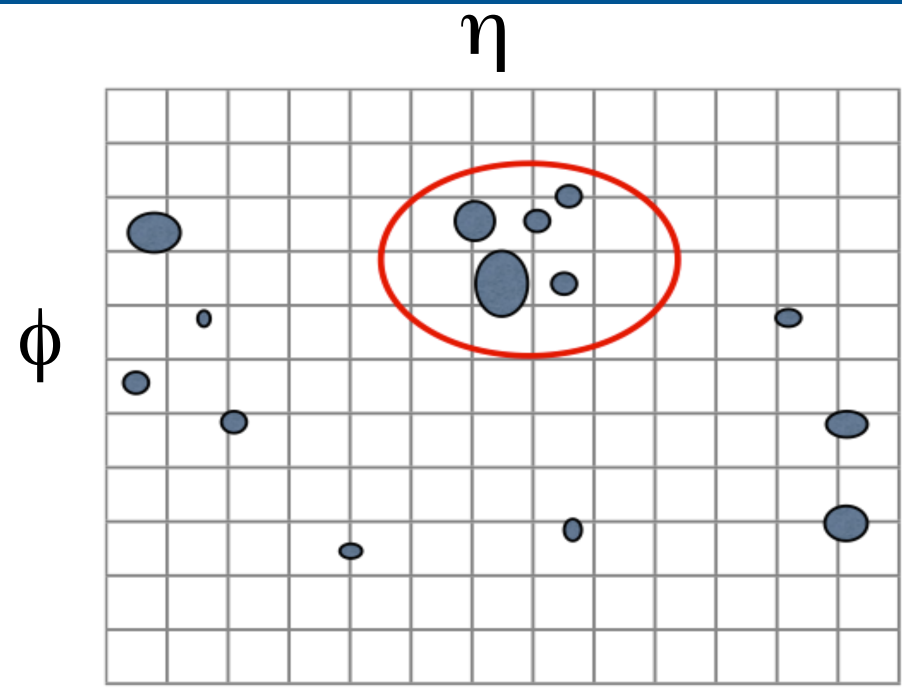


See also CDF note 10234

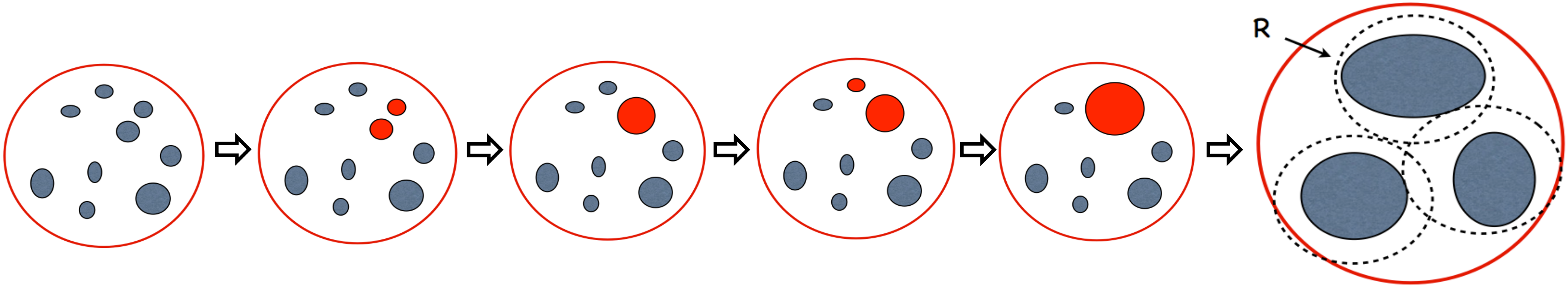
- At LHC energy, EWK scale particles produced beyond threshold
- Jets are highly collimated
- Decay products and FSR collected in a fat jet

Jet/Event selection

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

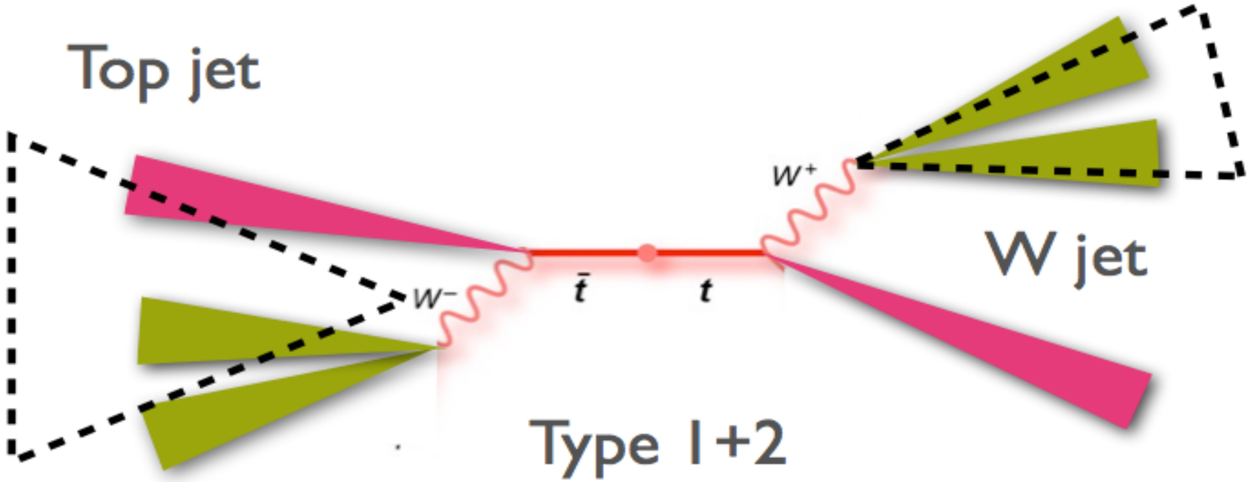


UE, ISR, Pile-up, hard interaction



Boosted top topology

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



Boosted top topology

Tested using hadronic top in semilep. tt events:

- One high-pT isolated muon from PV.
- At least two jets p_T>30 GeV with a leading jet p_T>2 GeV and at least one b-tagged jet
- Events with W tagged jets used to reconstruct the \ and the top mass of the hadronic side

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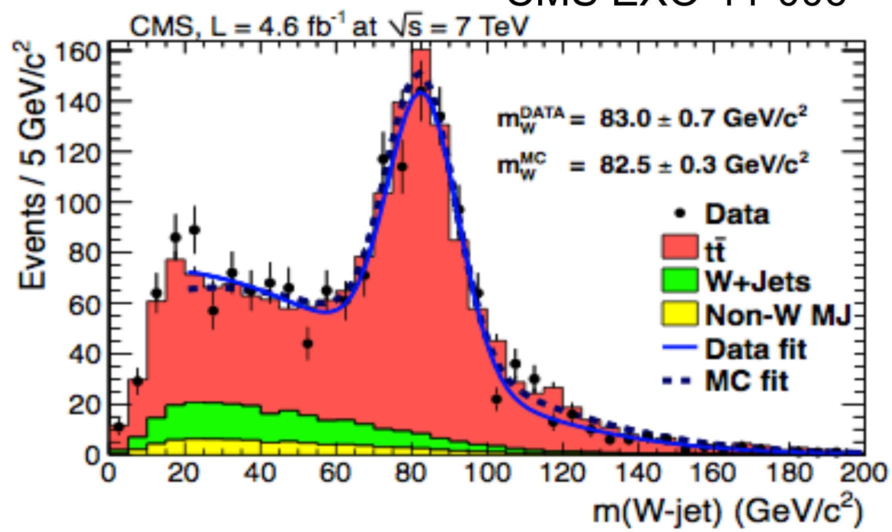
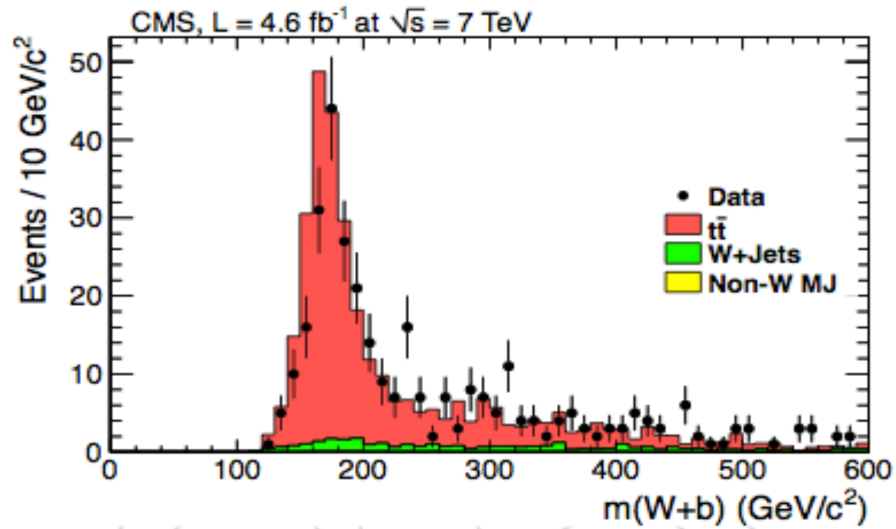
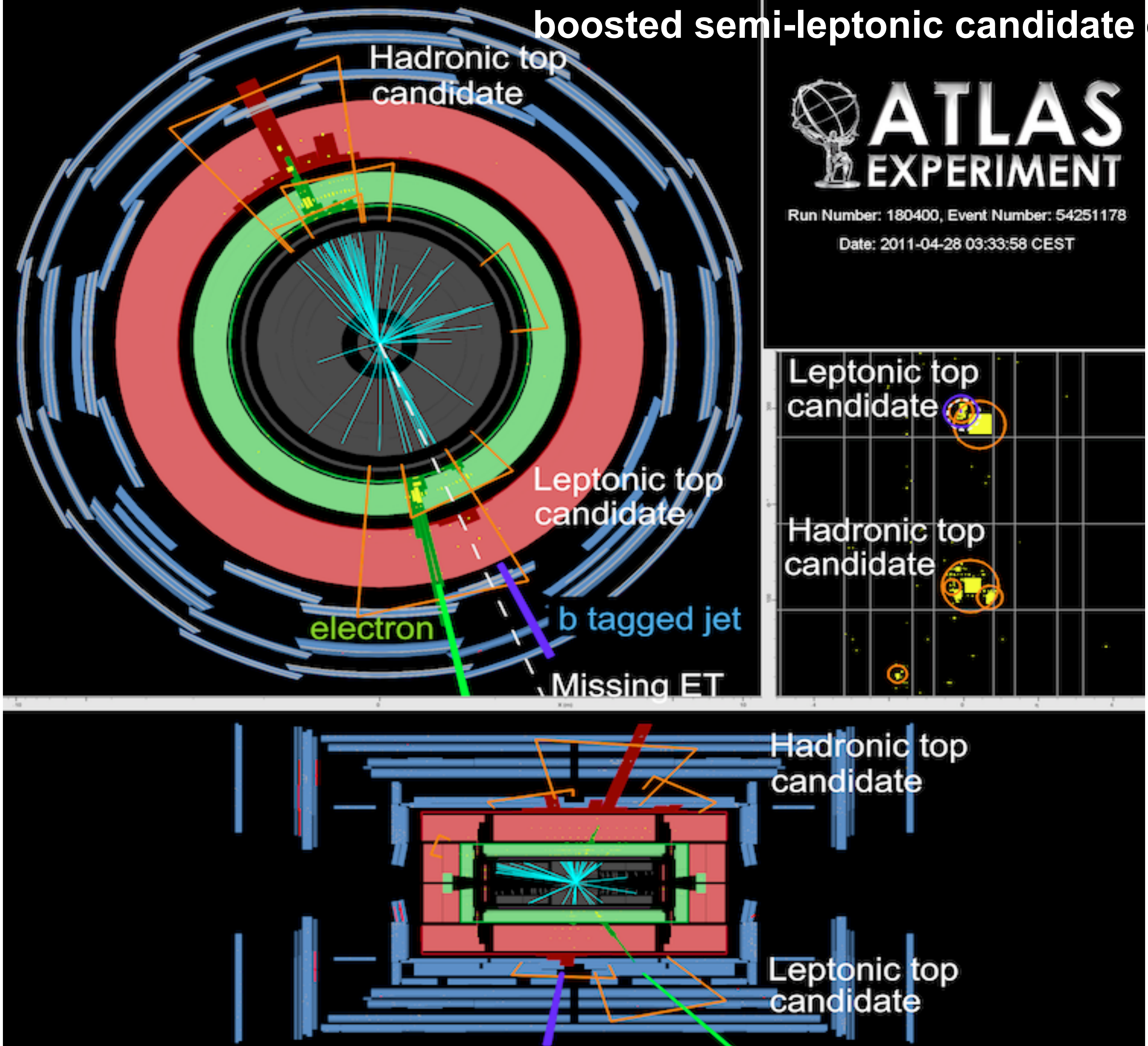


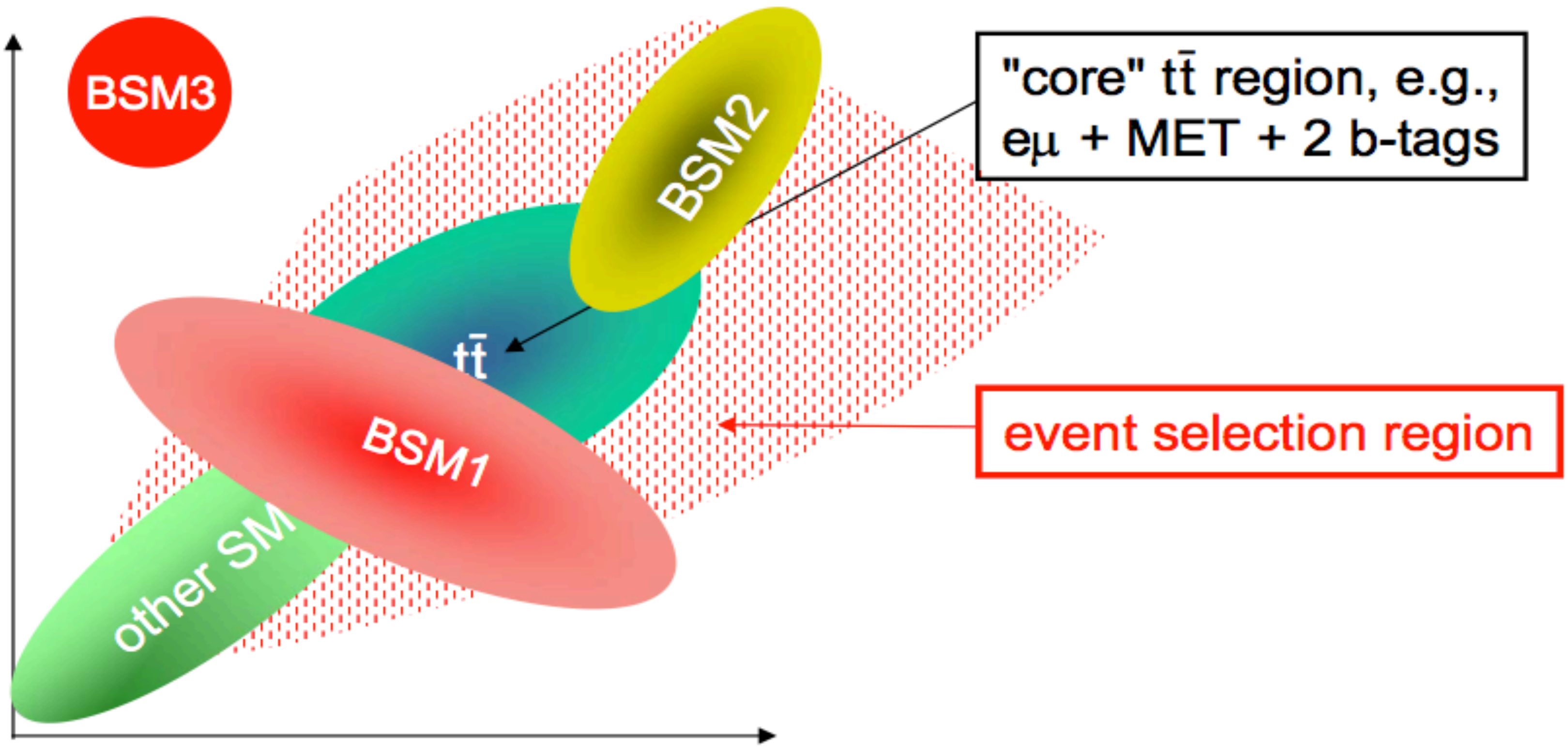


boosted semi-leptonic candidate event



Top quark and new physics

- Top quark production is main background in many searches for new physics
- Top quark sample may be contaminated by NP processes
- Is top quark sample compatible with top quark SM hypothesis?
- Need to compare distributions, gain good understanding of top sample

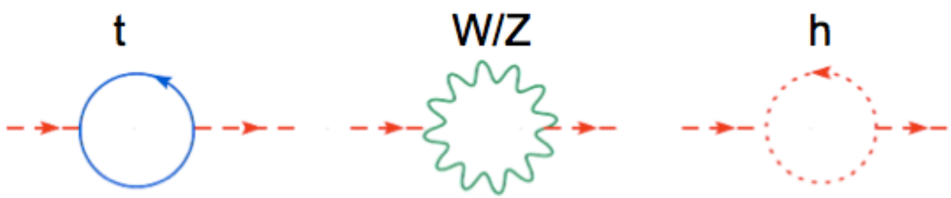


SUSY and 4th generation

Top 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?

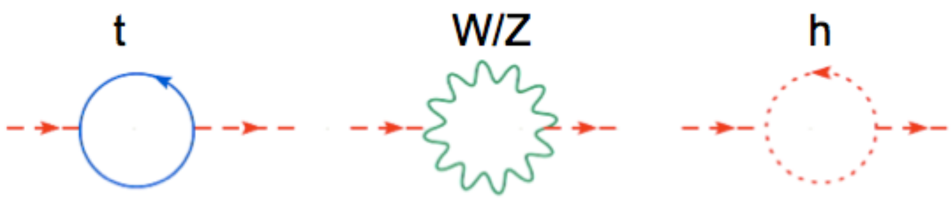
Problem:

- “low” value of Higgs mass is a problem
- Virtual SM particles in quantum loops contribute to Higgs mass
- Ad-hoc cancelations are needed to keep the Higgs mass <1 TeV

Top as window to BSM physics

Top quark affects stability of Higgs mass

Contributions grow with Λ:



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

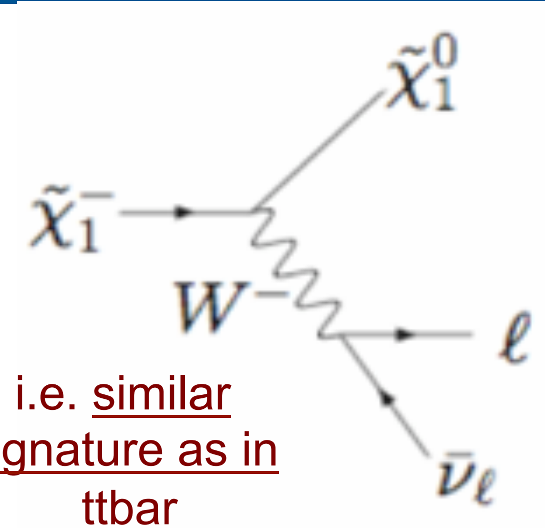
Cancellation?

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

Scalar top quark

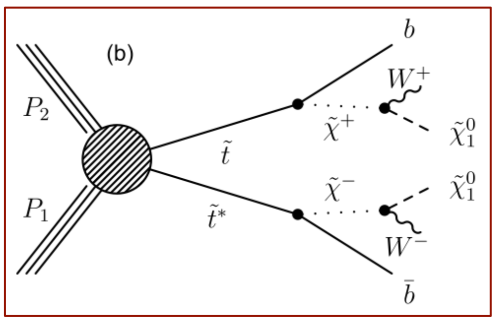
- SUSY is one plausible extension of the SM
- due to the heavy top quark, mass splitting between $\tilde{t}_1$ and $\tilde{t}_2$ can be large, such that the lighter stop $\tilde{t}_1$ can be even lighter than the top quark
- Decays dictated by mass spectrum of other SUSY particles



i.e. similar signature as in ttbar

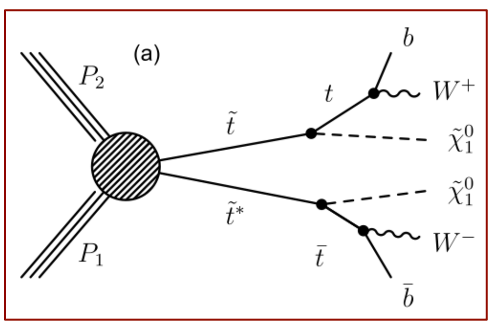
- Light stop:

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



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

- Heavy stop:

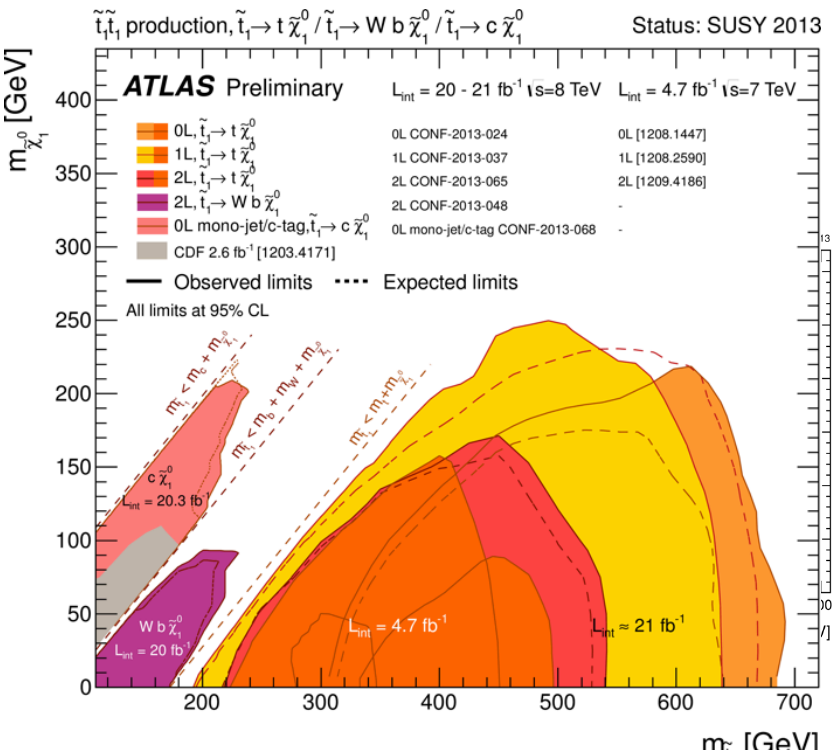


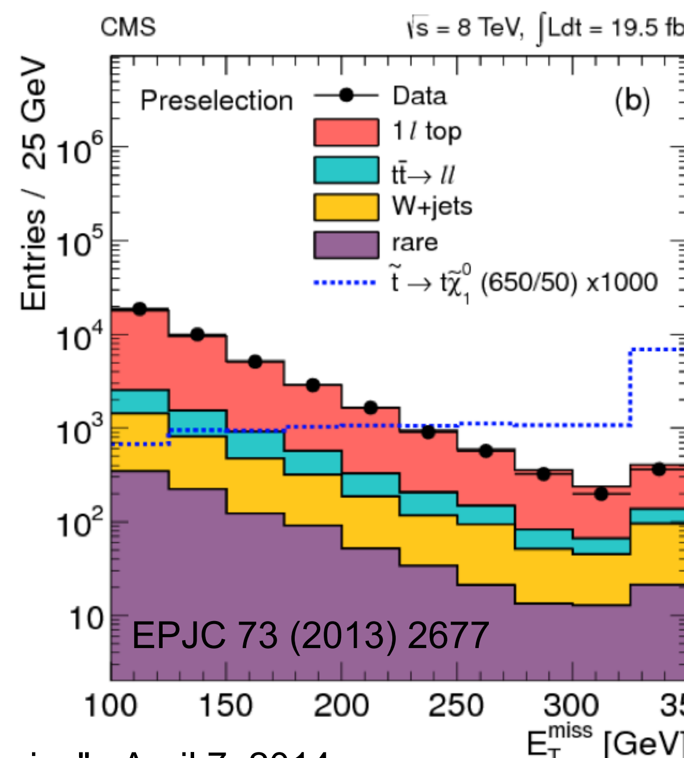
$$\tilde{t} \rightarrow t\tilde{\chi}_1^0 \rightarrow bW\tilde{\chi}_1^0$$

Top and SUSY

- Due to the large top mass, the scalar top quark can be lighter than the top quark
- Direct stop production
- 1st and 2nd generation squarks can be very heavy
- Similar to ttbar lepton+jet and dilepton final states

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

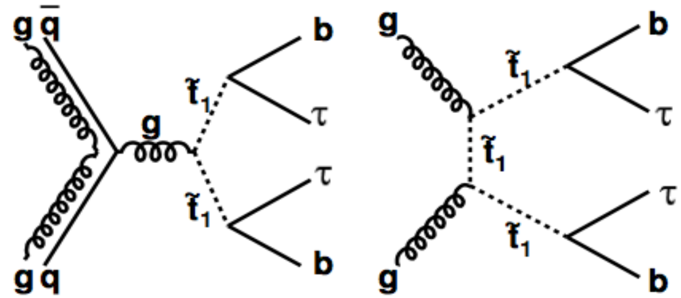




Taus

- Assume each stop decays to tau and b (R-parity violation)

$$\tilde{t}_1\bar{\tilde{t}}_1 \rightarrow \tau^+\tau^- b\bar{b}$$



- Similar final state as in ttbar dilepton with taus
- Look for e/μ+ ≥2 jets + MET
- Define 6 regions in: m_T(l,MET) vs N_{jet} plane
- Find 2 evts in signal region (2.2 expected)

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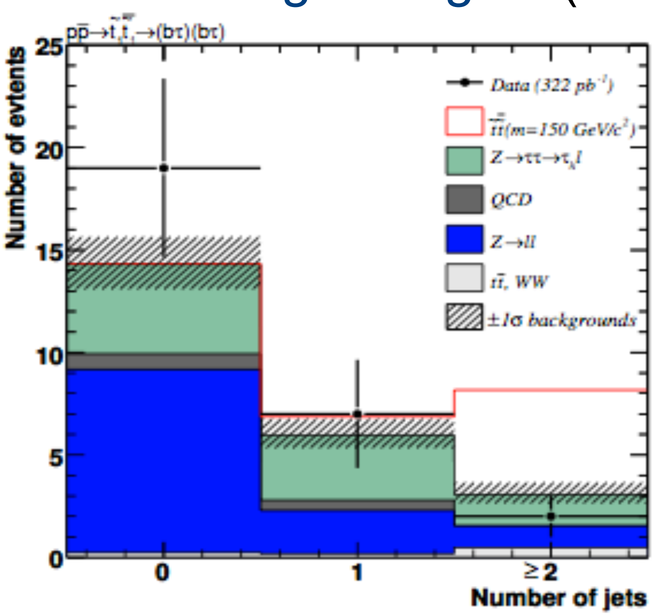
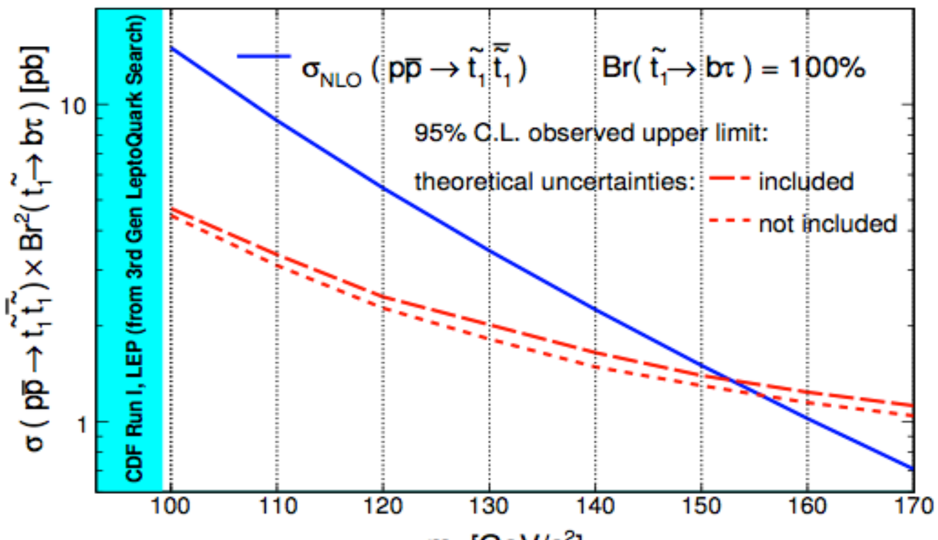
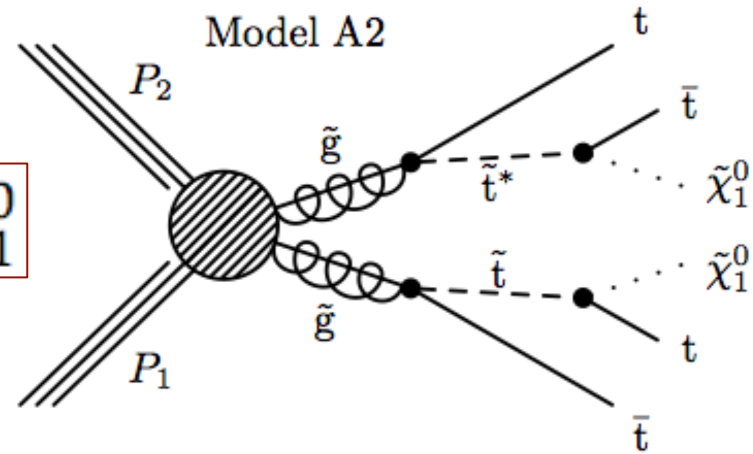




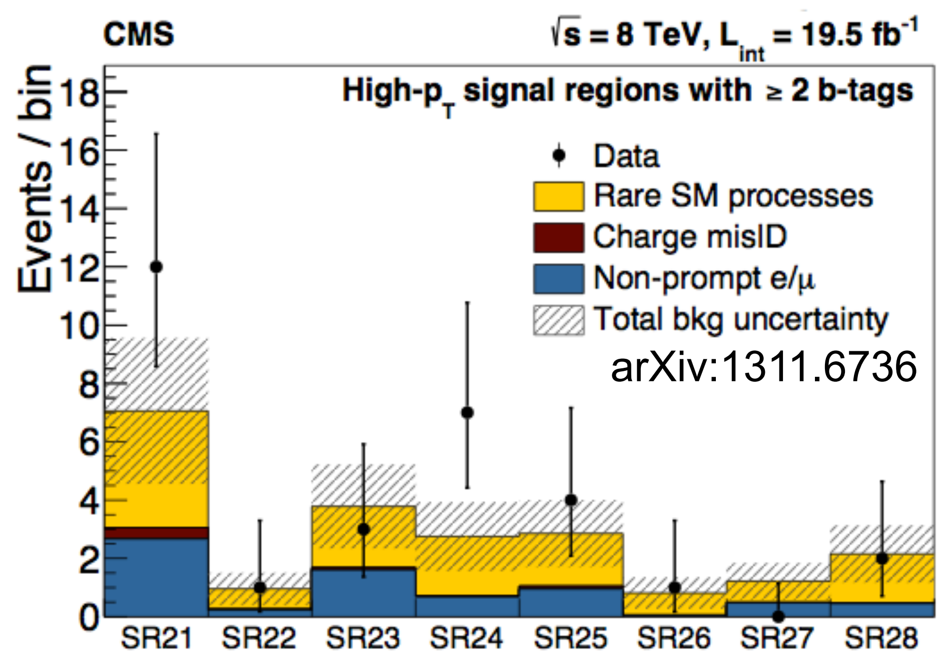
Multi-top production

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

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

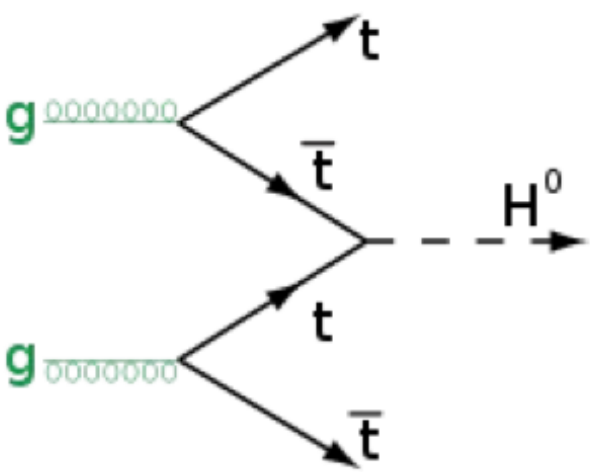


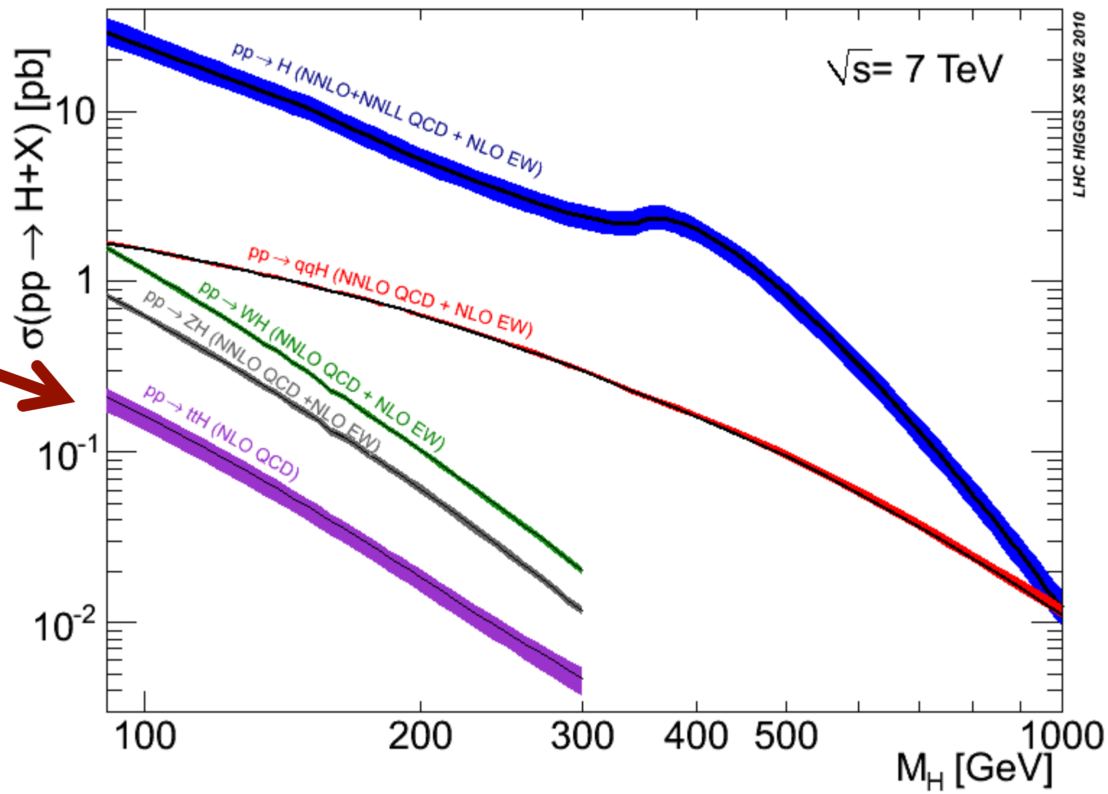
- Search for same-sign dileptons
- Several models studied
- consider multiple search regions defined by MET, hadronic energy, number of (b-) jets, and transverse momenta of the leptons in the events



ttbar+Higgs

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

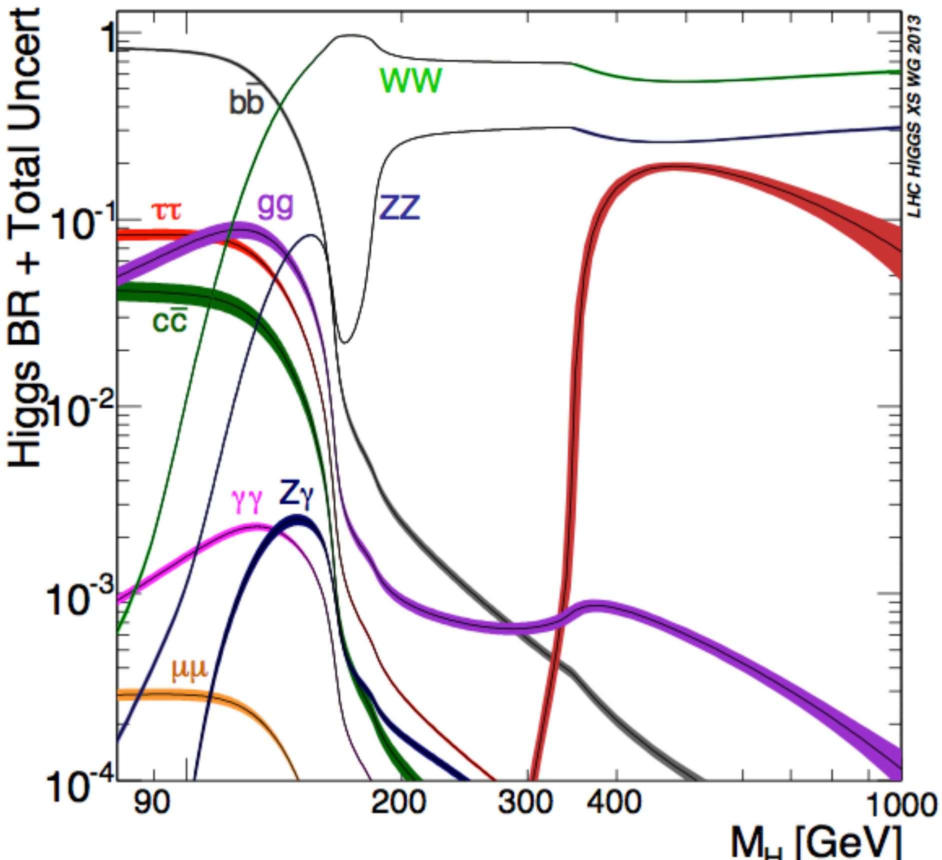


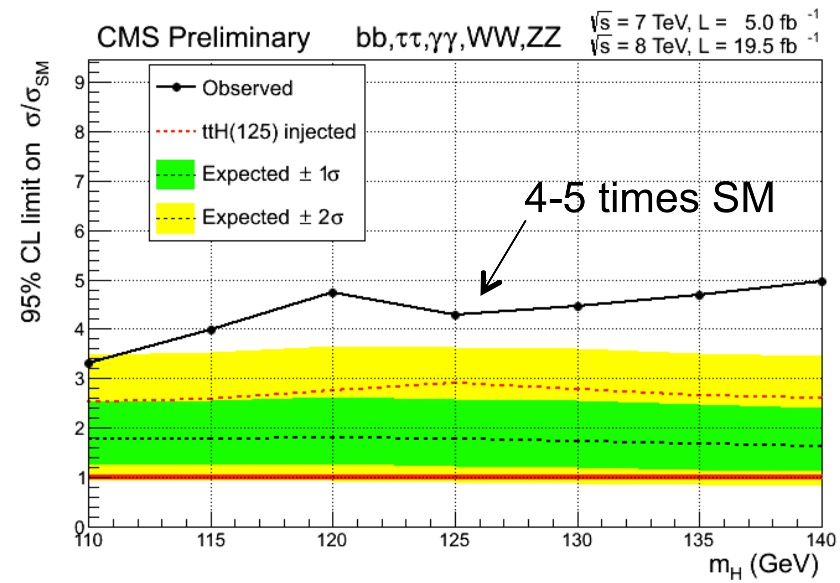


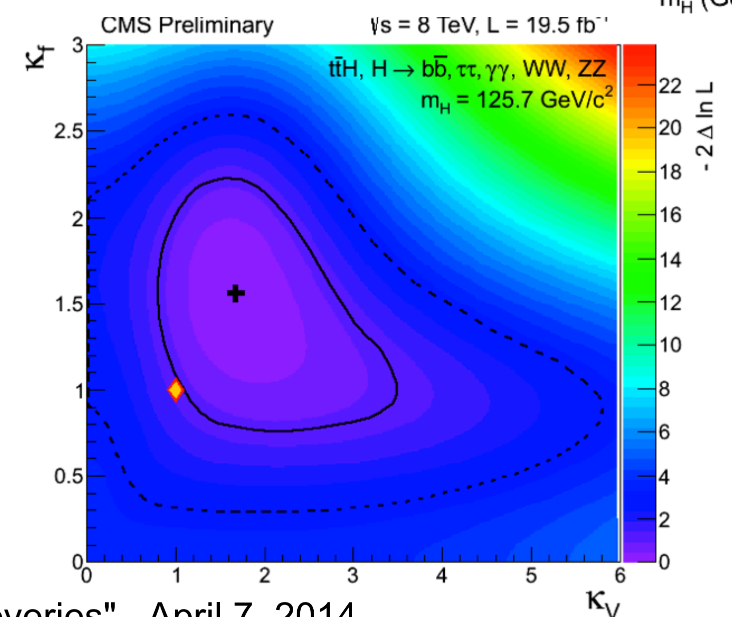
Cross section for $t\bar{t}H$ at the LHC:
0.13 pb (8 TeV)
0.61 pb (14 TeV)

ttbar+Higgs (cont.)

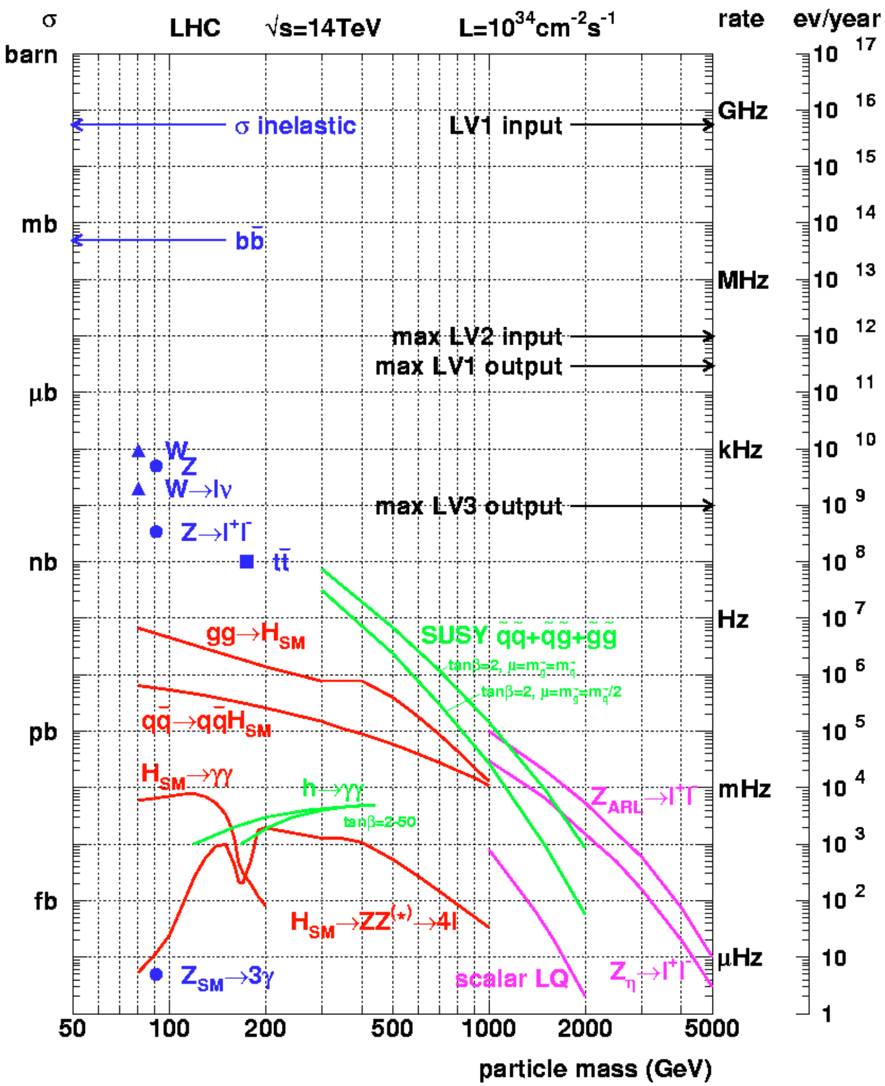
- Search for associated SM Higgs production: ttH
  - Both “dilepton” and “l+jets” channels
- Simultaneous fit for S and B fractions
  - different categories: jet and b-jet multiplicity.







Cross sections at the LHC



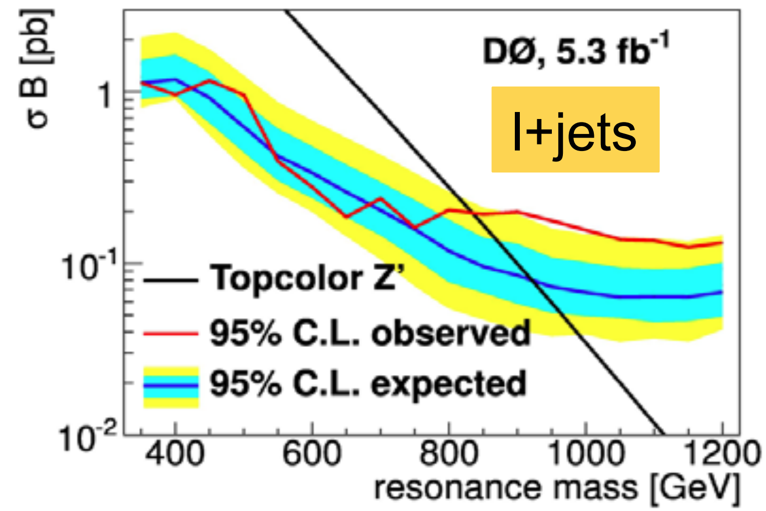
"Well known" processes, don't need to keep all of them …

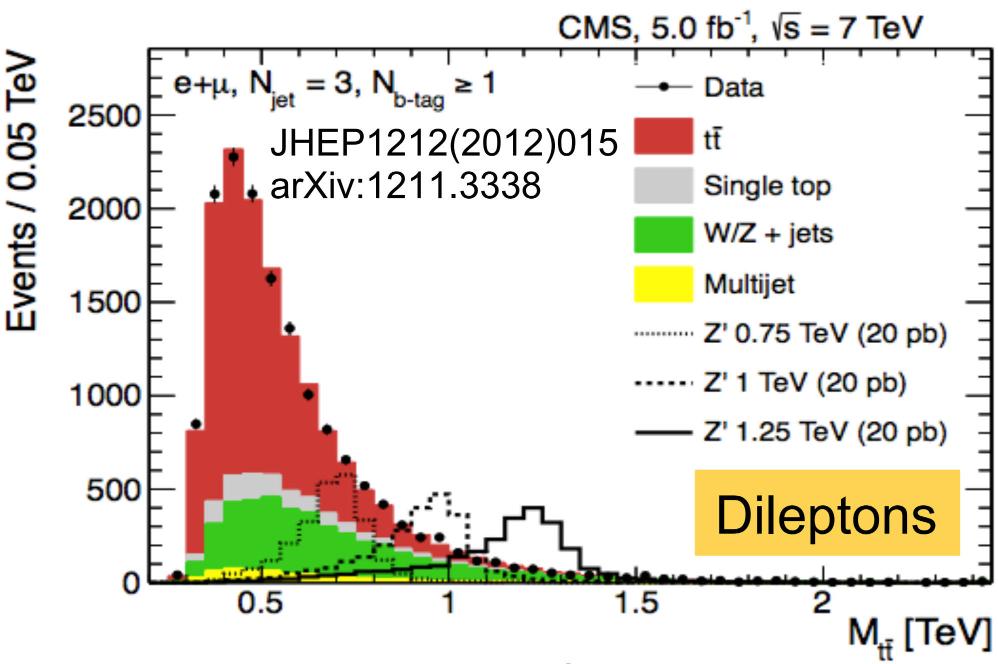
New Physics!!
we want to keep those!

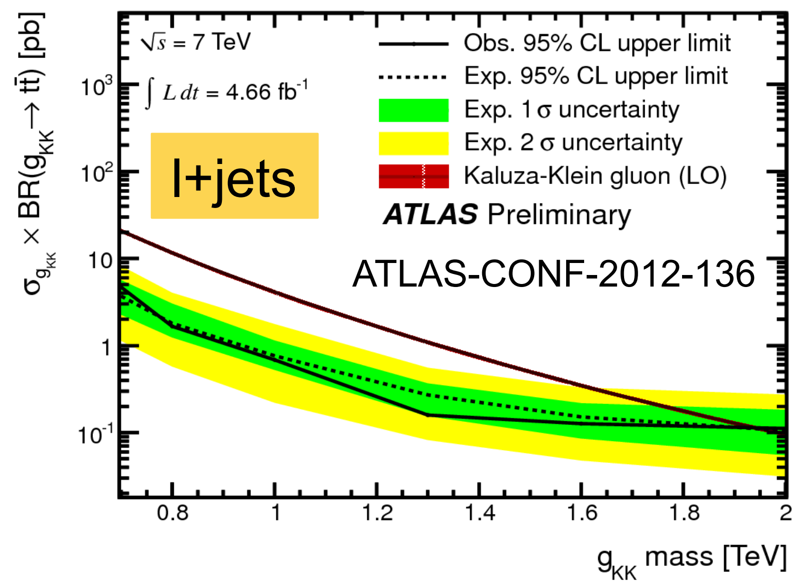
end

Search for heavy resonances

- search for massive neutral bosons decaying via a ttbar quark pair
- use dilepton/lepton+jet final states (electron and muon)
  - Reconstruct M_{ttbar} in different categories (e/μ, *n*-jets, *n* b-tags)
  - l+jet events: full event reconstruction
  - Dileptons: use NN approach to improve S-B separation
- systematics include shape (JES, b-tag, theory model) and rates (eff. bkg yields)







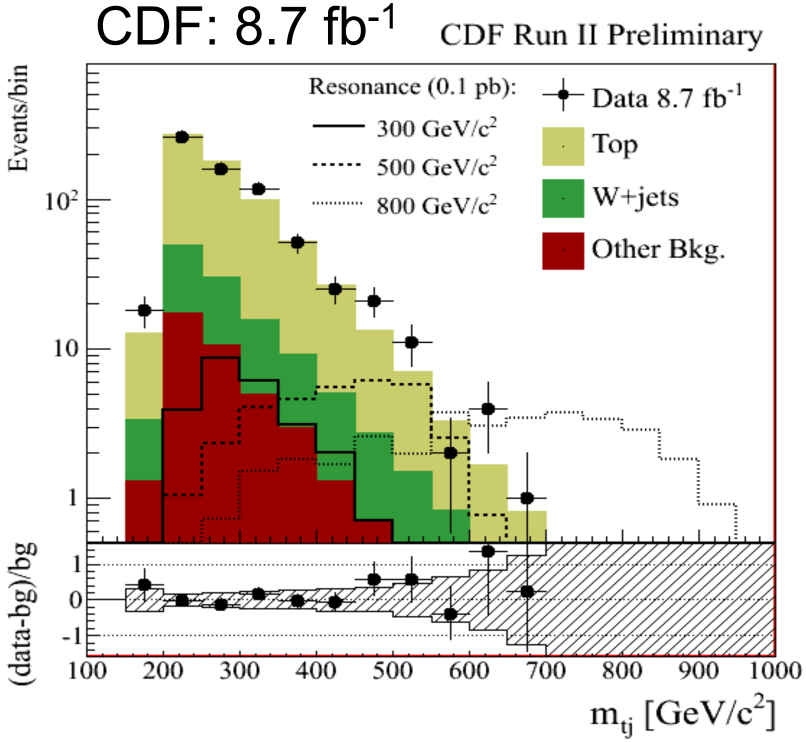
Search for ttbar+jet resonance

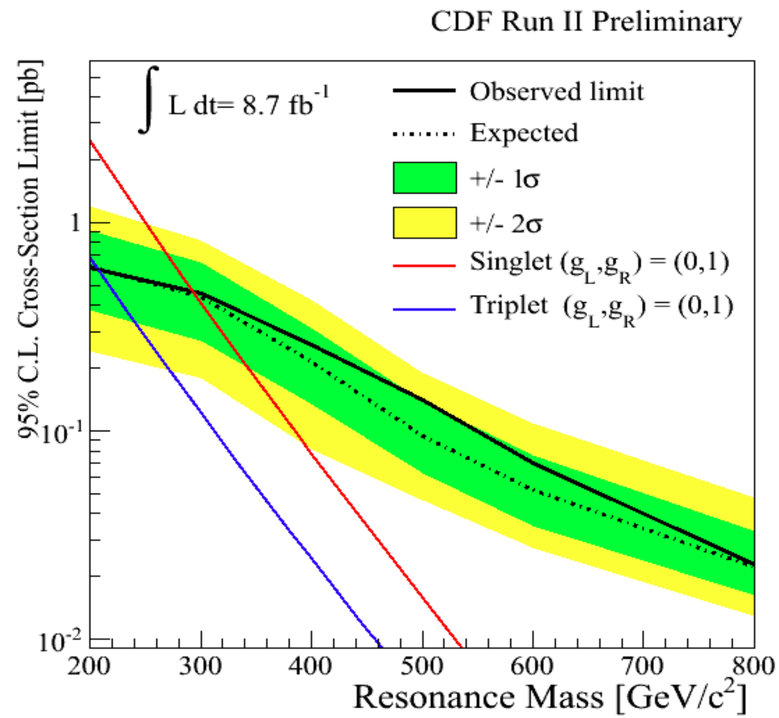
- Search for a heavy new particle M produced in association with a top quark:

$$p\bar{p} \rightarrow Mt \rightarrow \bar{t}qt$$

- Resonance in the system t+jets ot ttbar+jets
- Select events in lepton+jets channel with at least 5 jets and 1 b-tag

CDF: 8.7 fb^{-1}

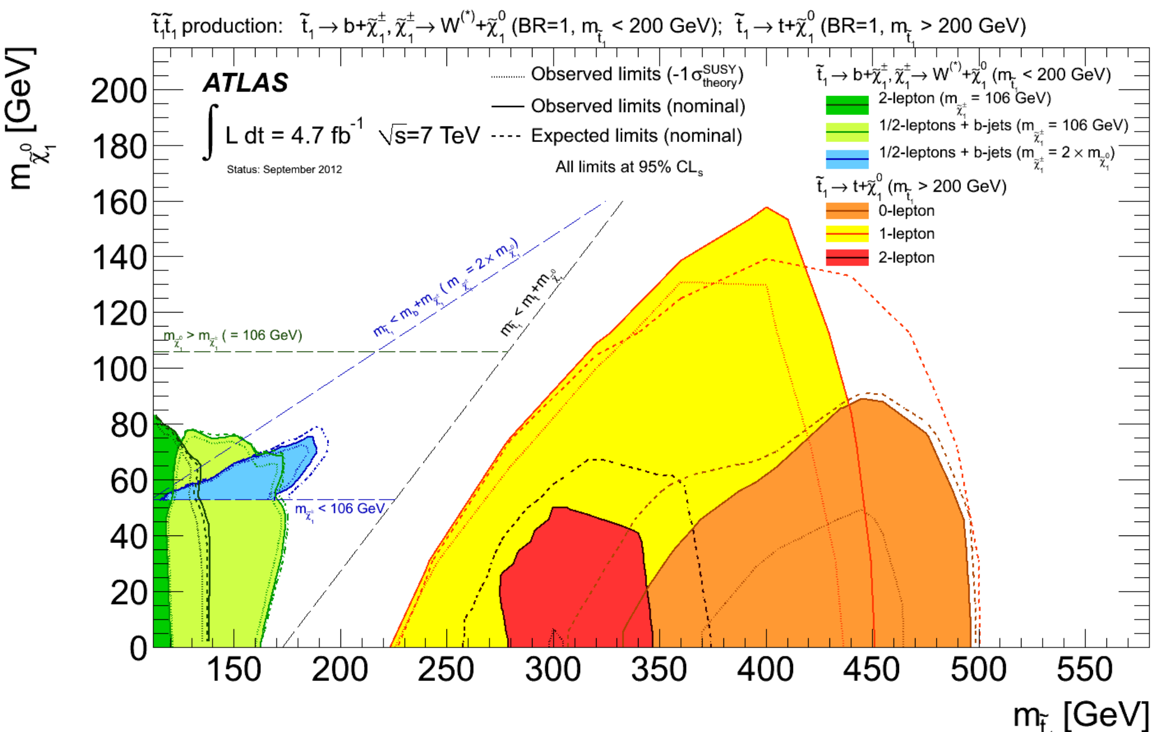


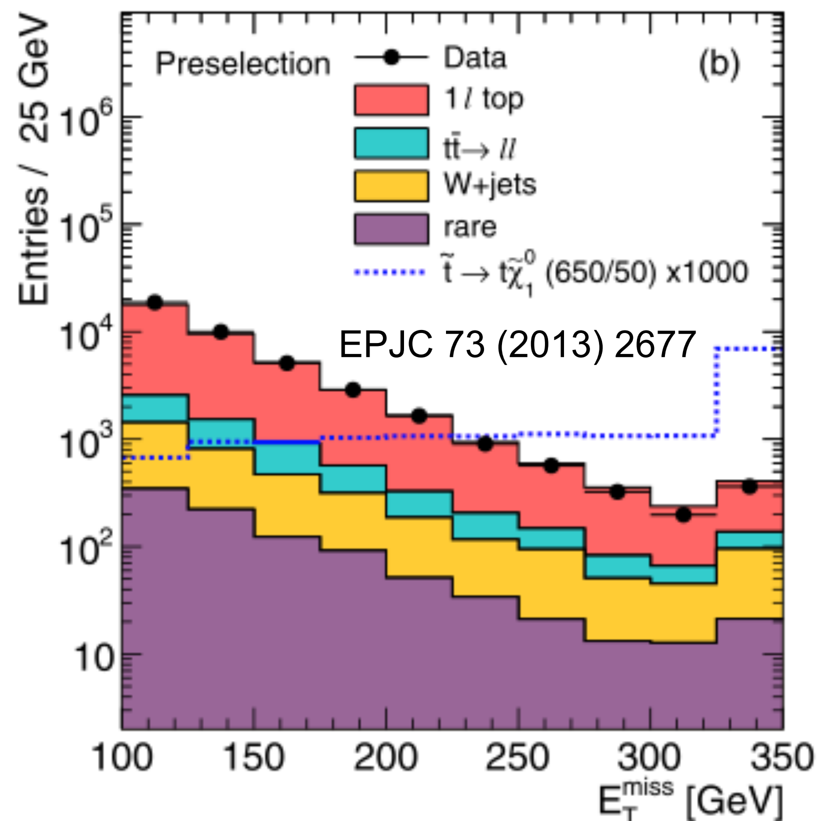


SUSY: direct stop production

- Due to the large top mass, the scalar top quark can be lighter than the top quark
- 1st and 2nd generation squarks can be very heavy
- Direct stop production:

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

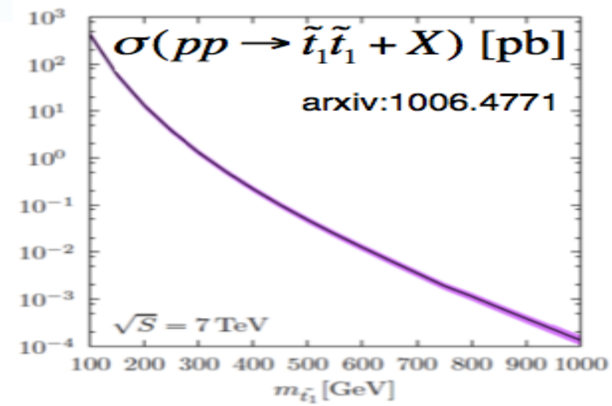


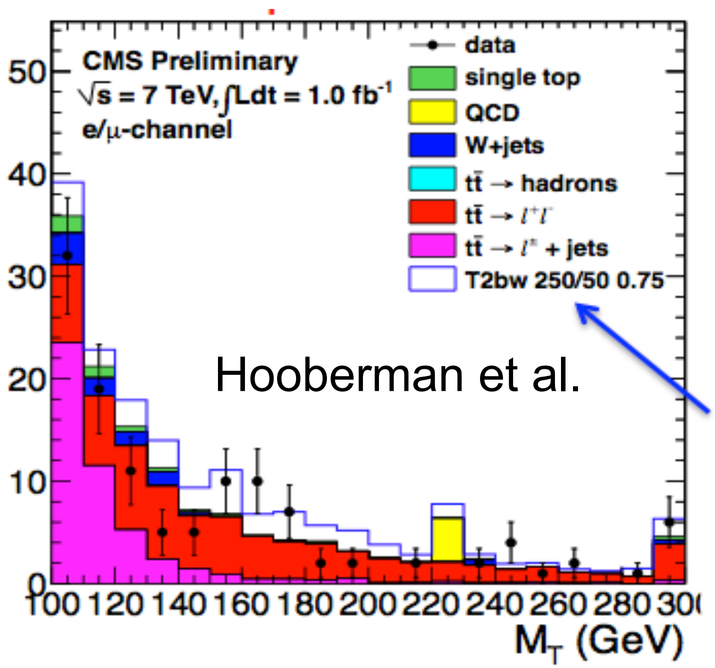


SUSY: search for scalar top

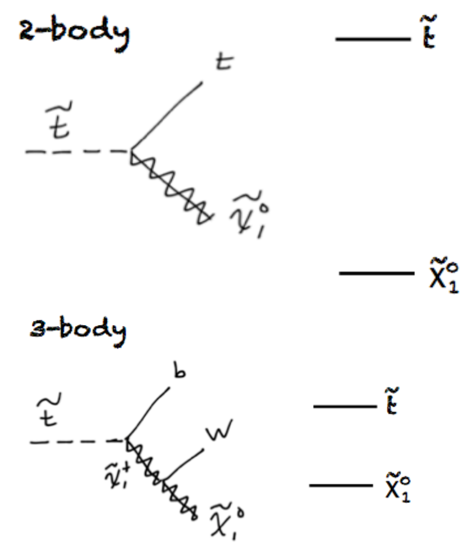
$$\tilde{t}\tilde{t} \rightarrow t\bar{t}\chi^0\chi^0 \qquad \tilde{t}\tilde{t} \rightarrow b\bar{b}\chi^+\chi^- \rightarrow b\bar{b}W^+W^-\chi^0\chi^0$$

- Status:
  - Final state: both dileptons and 1lepton+MET +2jets+2b jets
  - limitations due to small xsec, large ttbar background



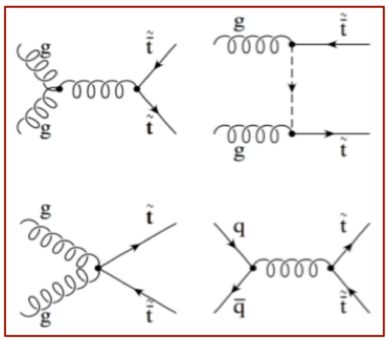


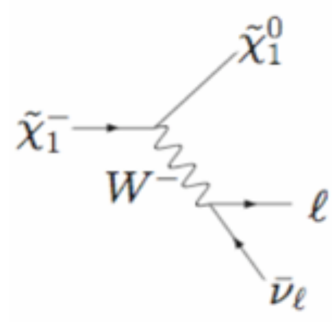
example signal:
stop(250) → b χ±
m(χ⁰) = 50 GeV
x = 0.75



Scalar top quark

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





i.e. similar signature as in ttbar

- Light stop:

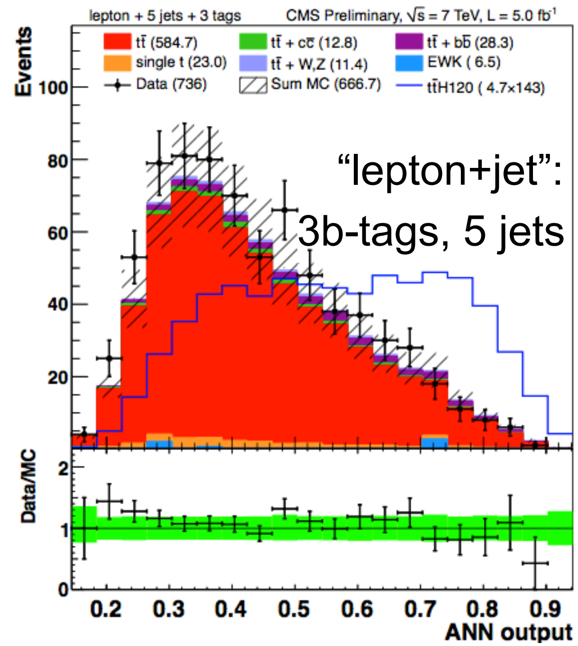
$$m_{\tilde{t}_1} \lesssim m_t \qquad \tilde{t}_1 \to b + \tilde{\chi}_1^\pm \to b + \tilde{\chi}_1^0 + \nu + \ell$$

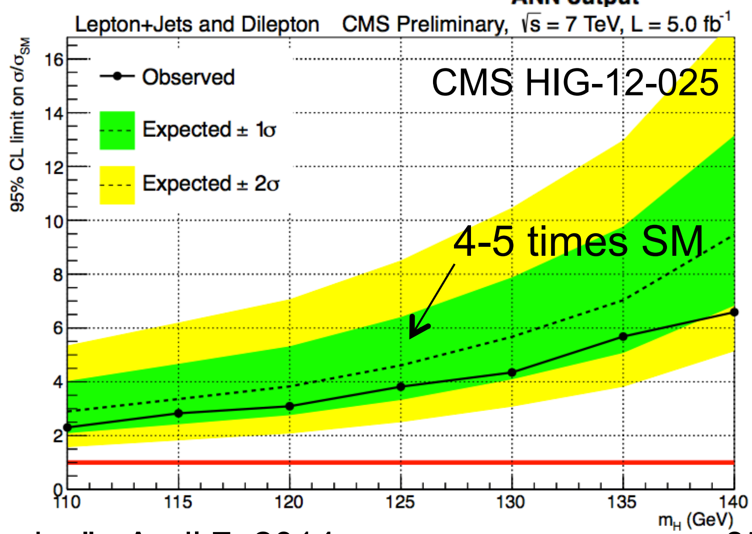
- Heavy stop:

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

ttbar+Higgs (cont.)

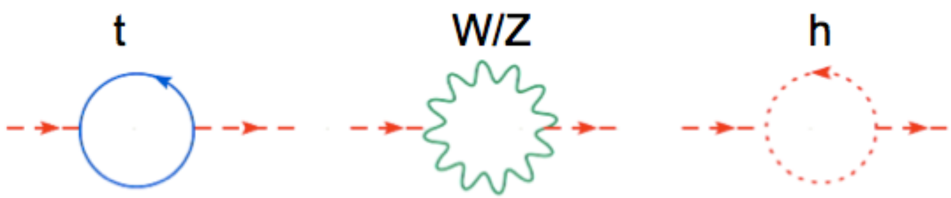
- Search for associated SM Higgs production: ttH(→bbar)
- Both “dilepton” and “l+jets” channels
  - ATLAS results only for l+jets (~11 x SM)
- Simultaneous fit for S and B fractions
  - different categories: jet and b-jet multiplicity
- Use ANN to discriminate S and B
  - b-tagging information provides best discrimin.
- Main background: ttbar(+bbar), Z+jets





Top 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:

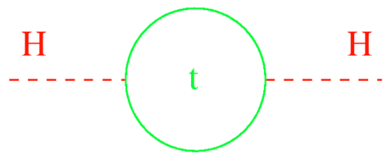
- Naturalness: There is no problem
- Weakly-coupled model at TeV scale
  - New particles to cancel SM divergences
  - Top partners: new scalar/vectors coupled to top, exotic top decays
- Strongly-coupled model at TeV scale
  - ttbar resonances, bound states, 4-top production, etc.
- New space-time structure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

Beyond the Higgs boson

- “low” value of Higgs mass is a problem
- Virtual SM particles in quantum loops contribute to the Higgs mass
- Contributions grow with Λ (upper scale validity of the SM)
- Λ could be huge, i.e. the Plank scale (10^{19} GeV)
- Ad-hoc cancelations are needed to keep the Higgs mass below <1 TeV

“Naturalness” problem:

– Radiative corrections



$\delta m_H^2 \sim \Lambda^2 \Rightarrow$ diverge for large Λ

$\Rightarrow$fine tuning!

“Hierarchy” problem: why $M_{EW}/M_{Pl} \sim 10^{-17}$?

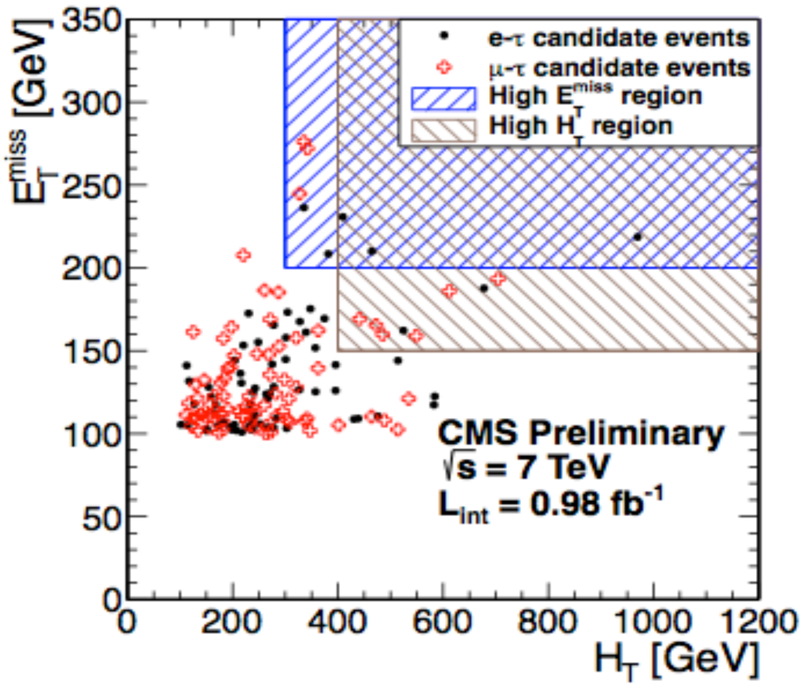
Beyond the Higgs:

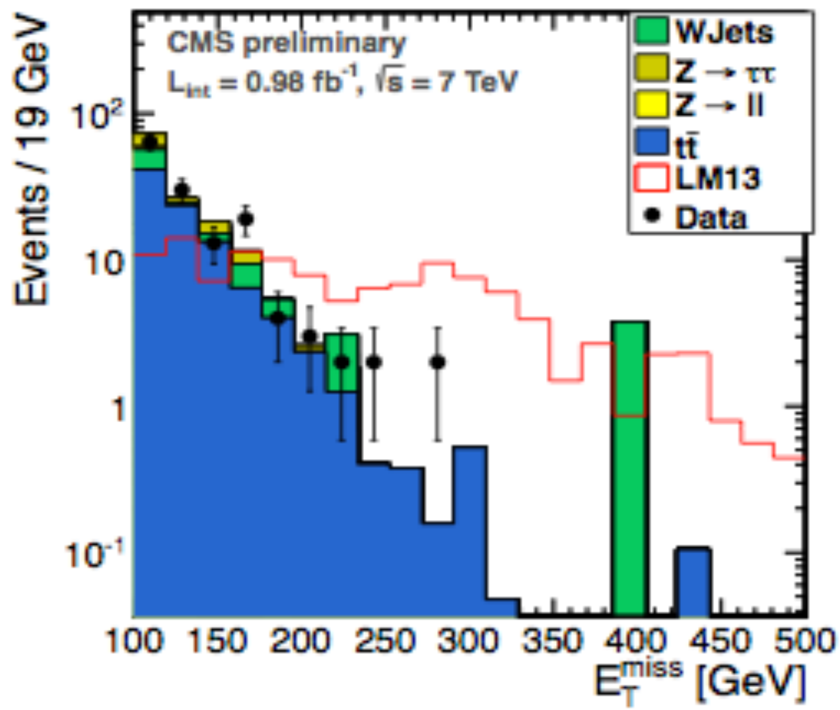
New physics beyond the Standard Model is very likely Supersymmetry, hidden dimensions of space-time, ...

Search for Dark Matter with taus

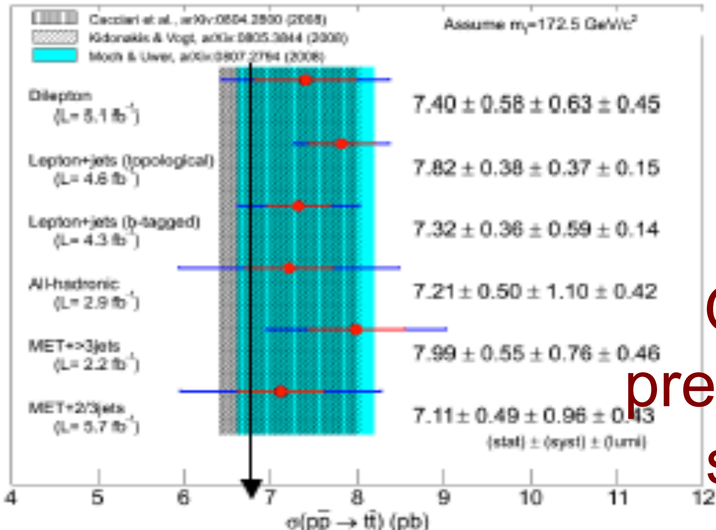
CMS SUS-11-007

- search concentrates on heavy BSM particle production
  - astrophysical evidence for dark matter points to the existence of weakly-interacting massive particles (WIMPs) at EWSB scale
  - These particles escape detection ⇒ large MET
- Not constrained to a specific theory
  - general BSM search in events with jets, MET, and OS dileptons (at least one tau)
  - $e\tau_h$, $\mu\tau_h$, $\tau_h\,\tau_h$ final states



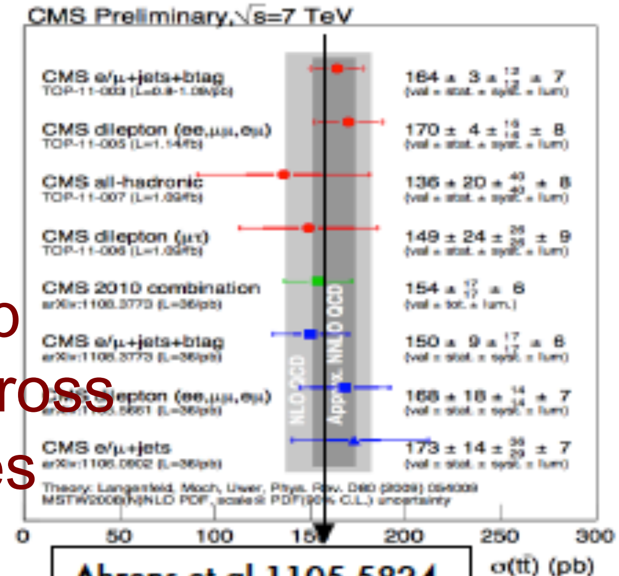


Cross section measurements

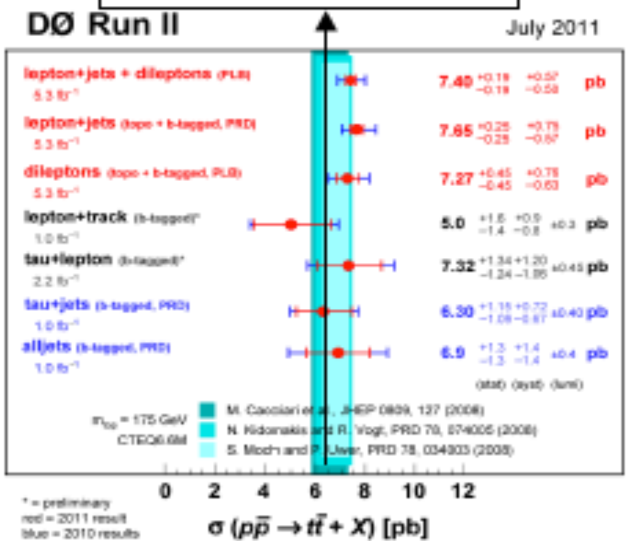


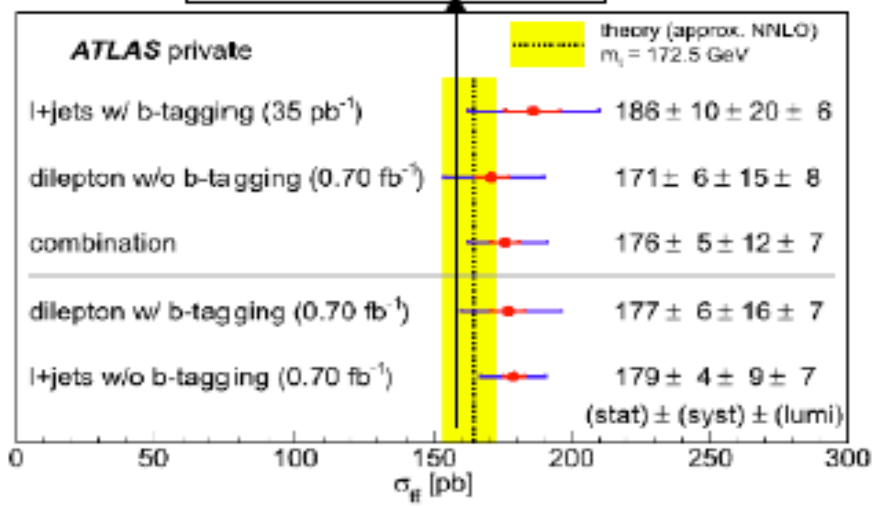
Ahrens et al 1105.5824

One th. group predicts lower cross section values



Ahrens et al 1105.5824

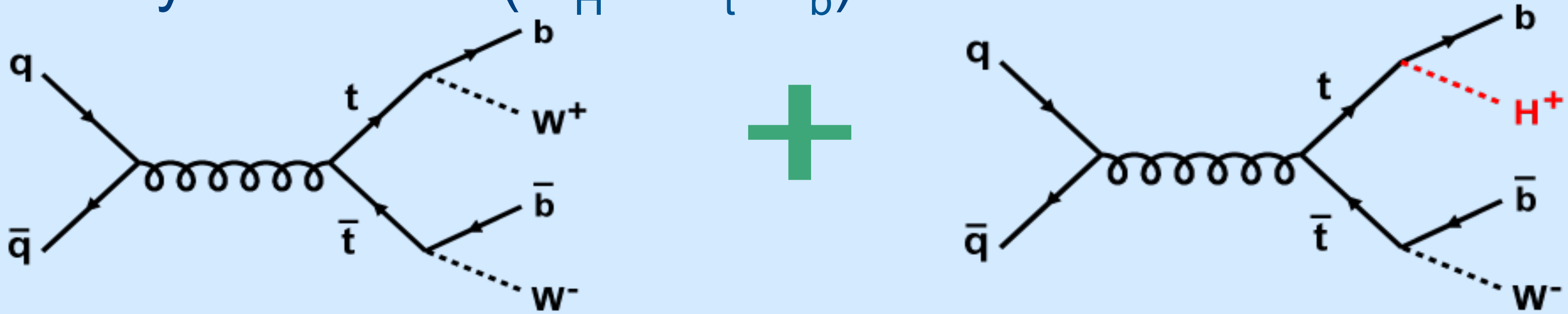




Charged Higgs

This study focuses on the mass range $100 \leq \mathrm{H}^{+} \leq 160\,\mathrm{GeV/c^2}$, where we may observe an anomalous excess of events in the τ dilepton channel when compared to the SM decay of
$t\bar{t} \to W^{+}W^{-}b\bar{b} \to \tau\nu_{\tau}l\nu_{l}b\bar{b}, \qquad l = e, \mu.$

If top decays: $t \to H^{+}b$ $(m_H < m_t - m_b)$

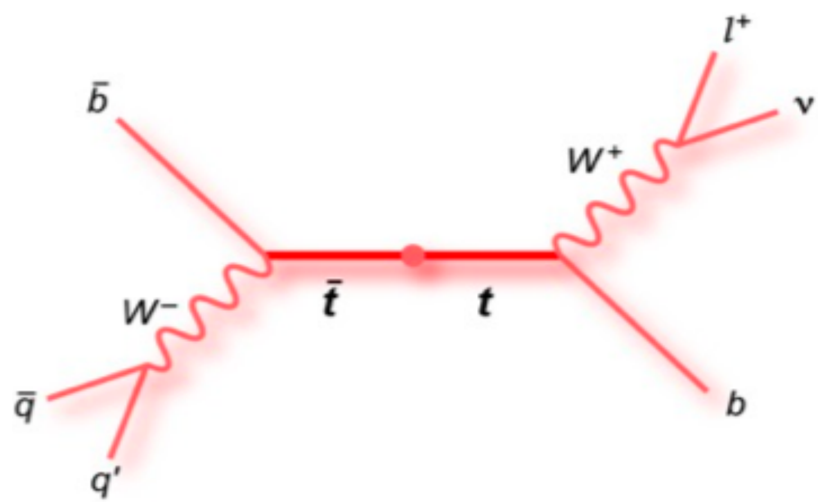


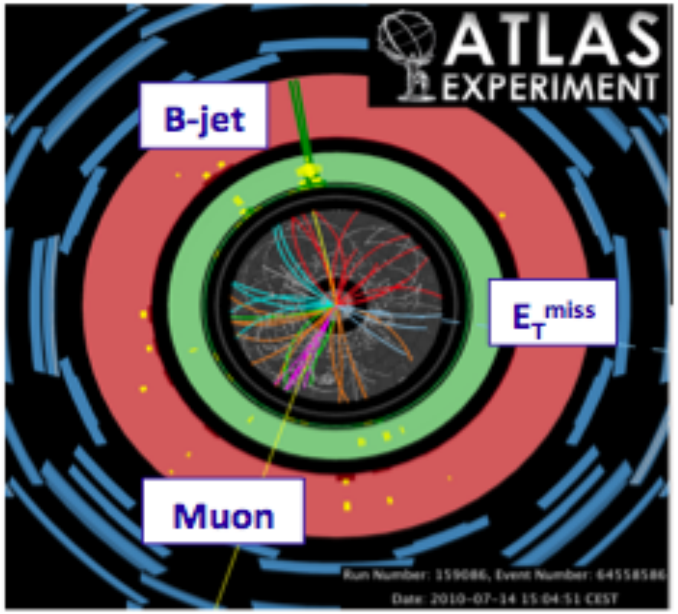
Implies a larger measured cross section (see MG, Lecture #6)

⇨probe non-standard physics ($t \to H^{\pm}b$, …)

Lepton+jet channel

- Best channel (for now) to measure top quark mass
- Compromise between large branching ratio (BR=30%) and a good background rejection
- Well defined final state (1 lepton, one neutrino, 2 b-jets, W→qq')

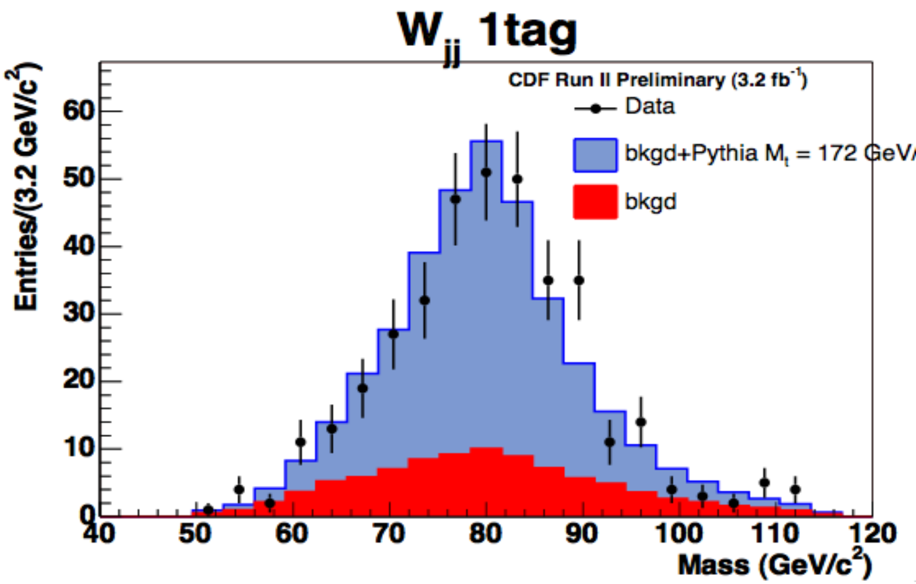




Top as a calibration tool

- Top quarks can be used as calibration tool
  - Top mass, W mass, b/q jets
- can determine:
  - b-tagging efficiency
  - jet energy scale

…or alternatively…



- use b-tag as a probe
  - compare rates in different b-tag multiplicity bins
  - is the signal, ttbar or not?
- BSM may appear in the sample and “distort” the distribution