Top quark: properties and beyond

Michele Gallinaro

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

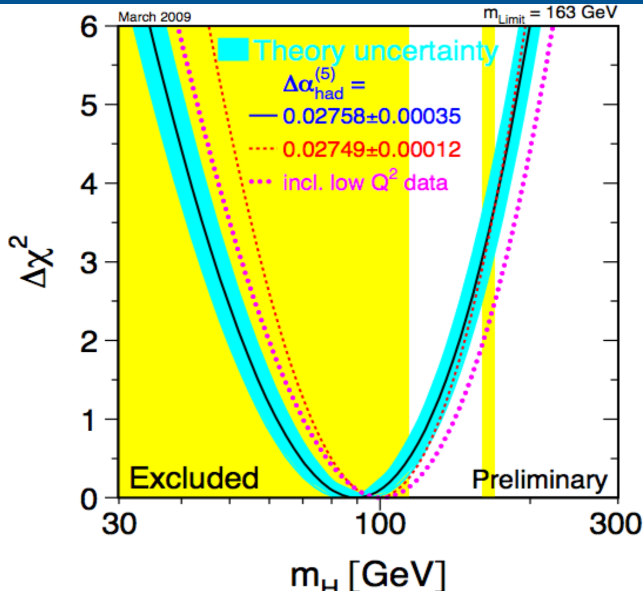
- Single top production
- Flavor Changing Neutral Currents (FCNC)

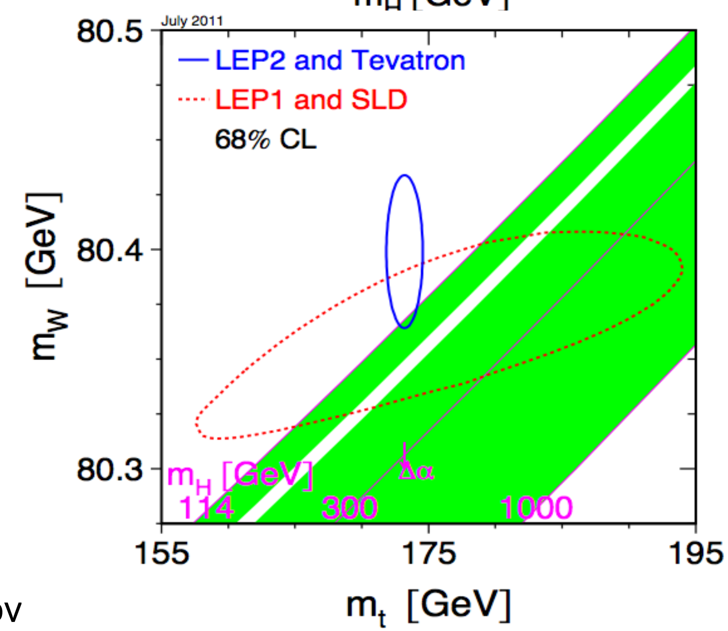
Top quark mass

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
  - ⇒ $m_H = 92^{+34}_{-26}$ GeV or <161 GeV

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





- 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

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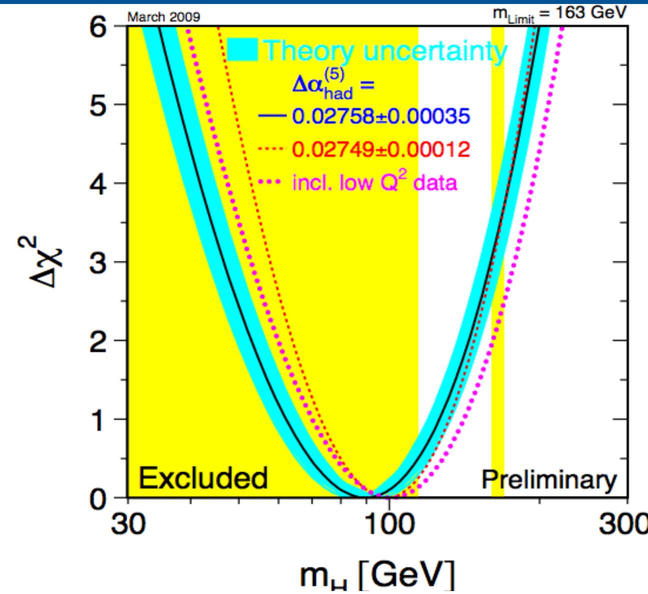

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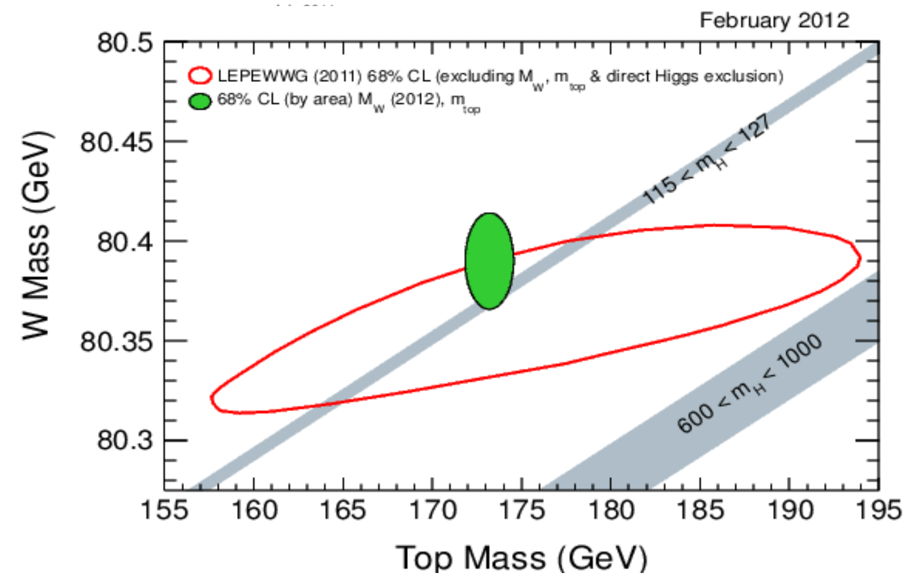
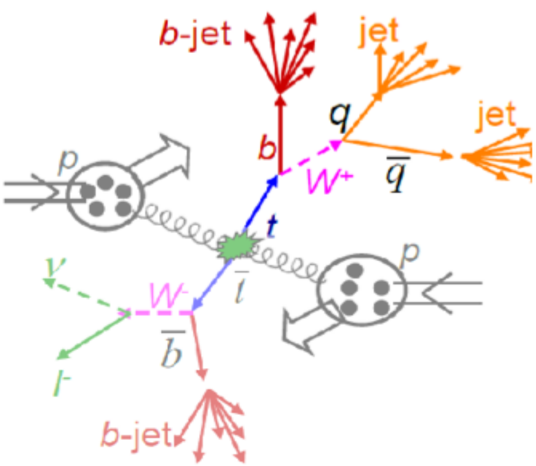
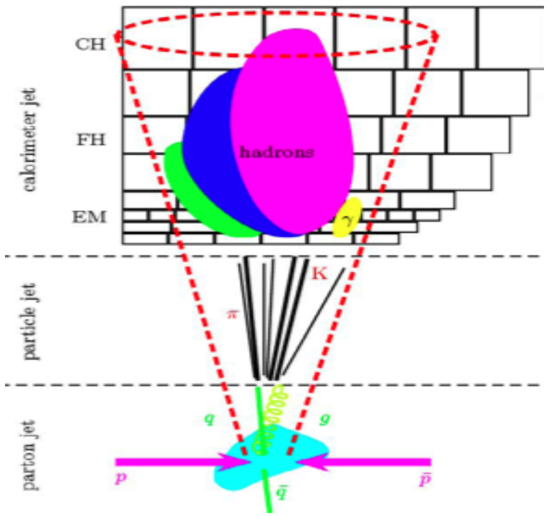


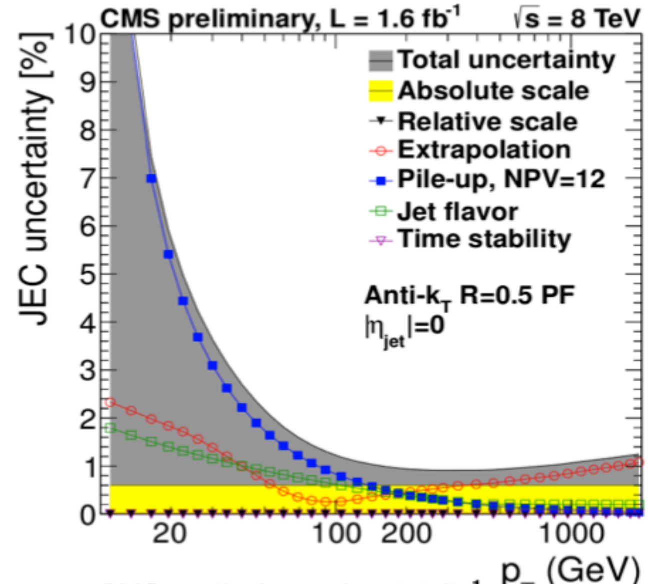
m_t [GeV]

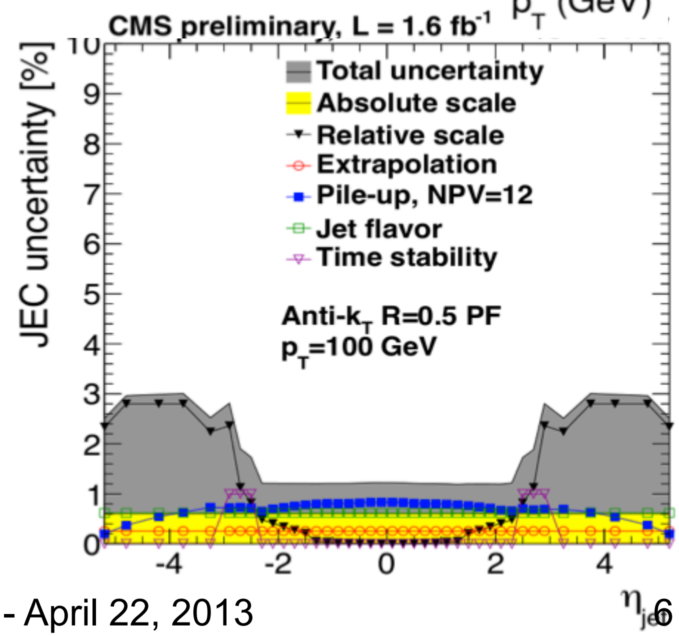
Jet reconstruction in Top events

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





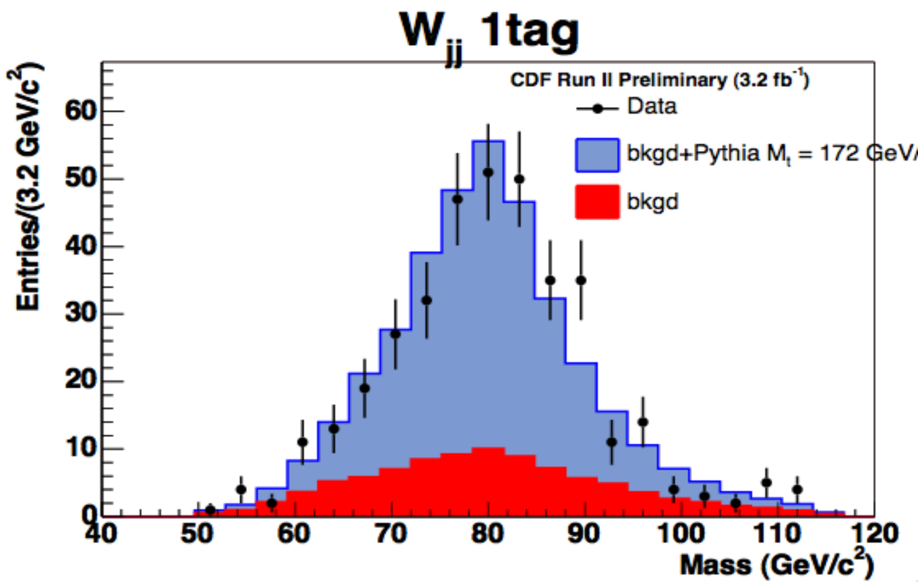




- Contribution of uncertainty sources depend on p_T, η
- Jet energy correction uncertainty:
  - Look at quantities insensitive to JES (e.g. lepton p_T)
  - “b-jet” tag helps reducing number of permutations
- JES “in-situ” calibration in ttbar events
  - Use $W \rightarrow jj$ constraint to measured W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

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

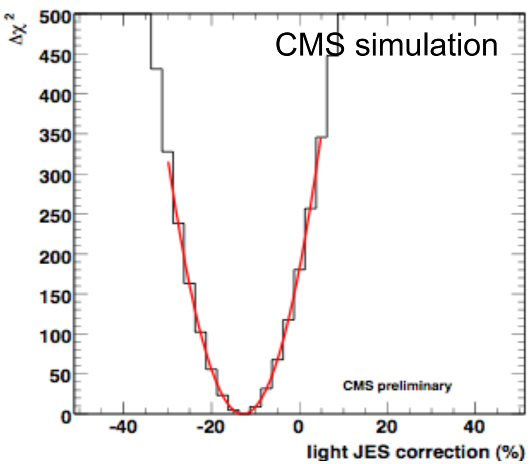


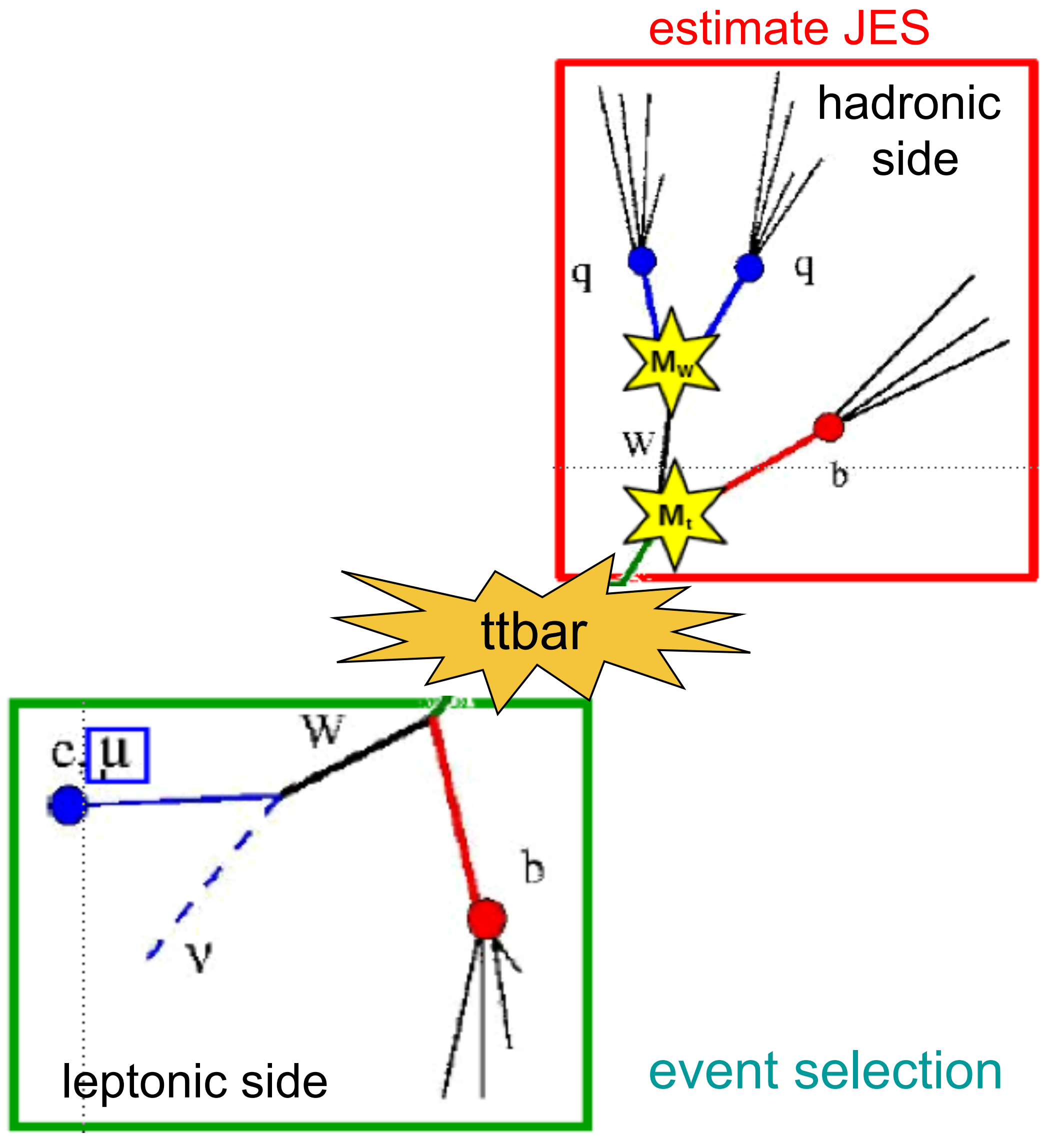
…or alternatively…

- 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

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





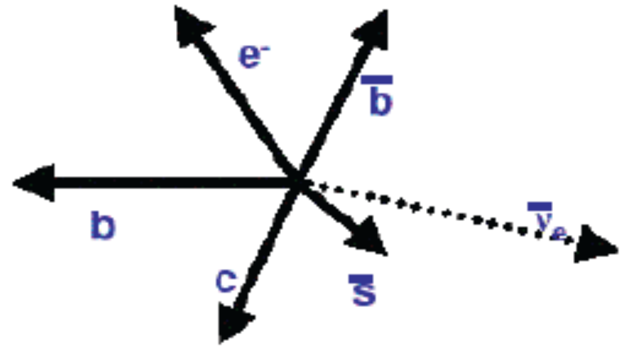
Measuring the top mass

Challenging:

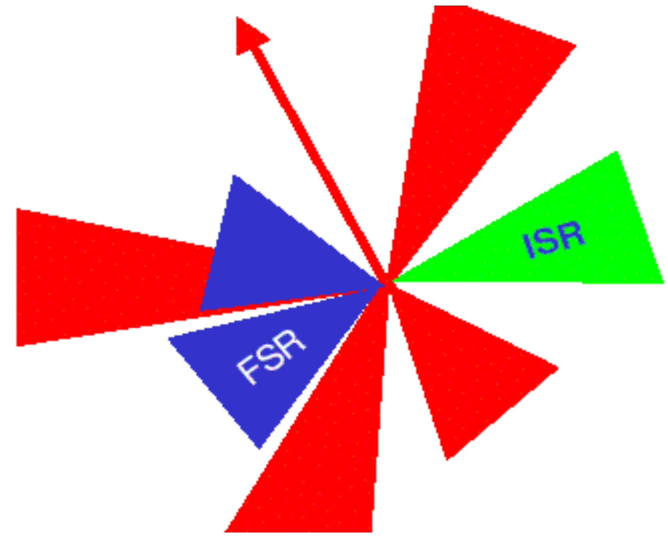
➢ **Lepton+jets**
- undetected neutrino
  - P_x and P_y from E_T conservation
  - 2 solutions for P_z from $M_W = M_{l\nu}$
- leading 4-jet combinatorics
  - 12 possible jet-parton assignments
  - 6 with 1 b-tag
  - 2 with 2 b-tags
- ISR + FSR

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

LO final state:

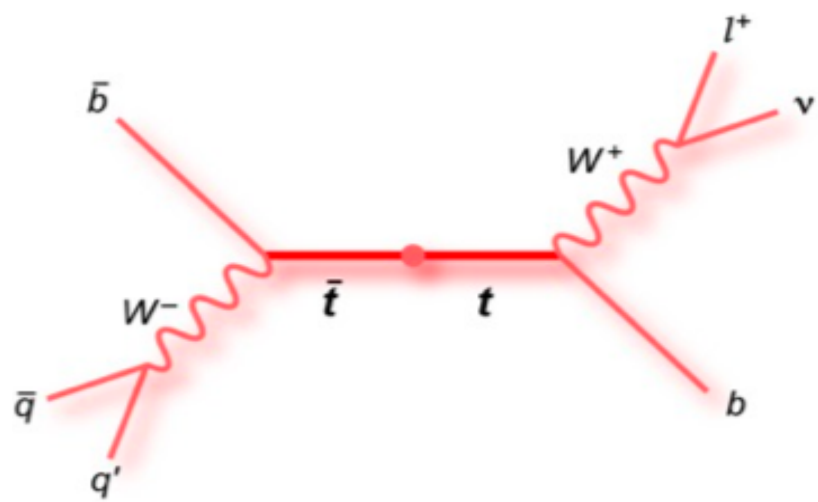


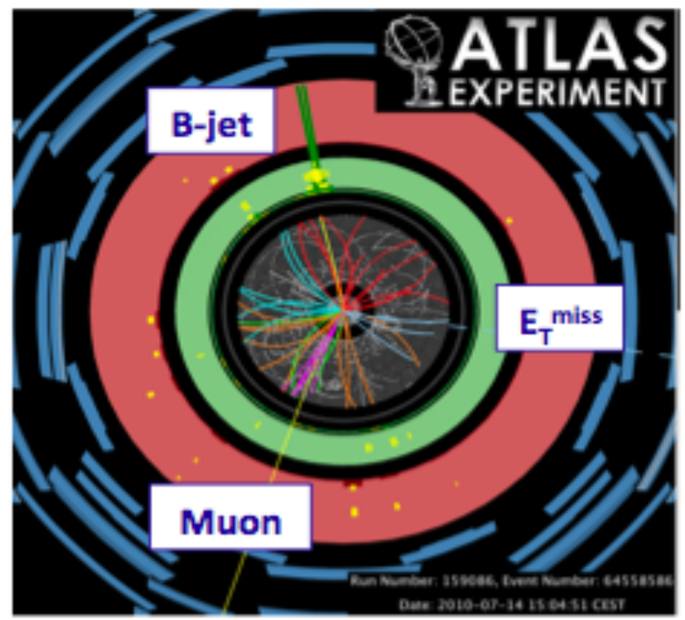
experiment sees:



Lepton+jet channel

- 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')

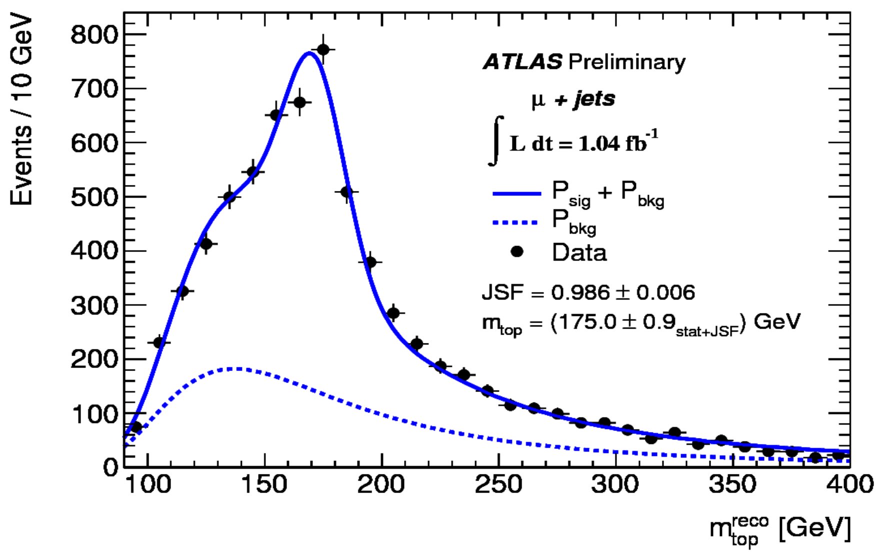




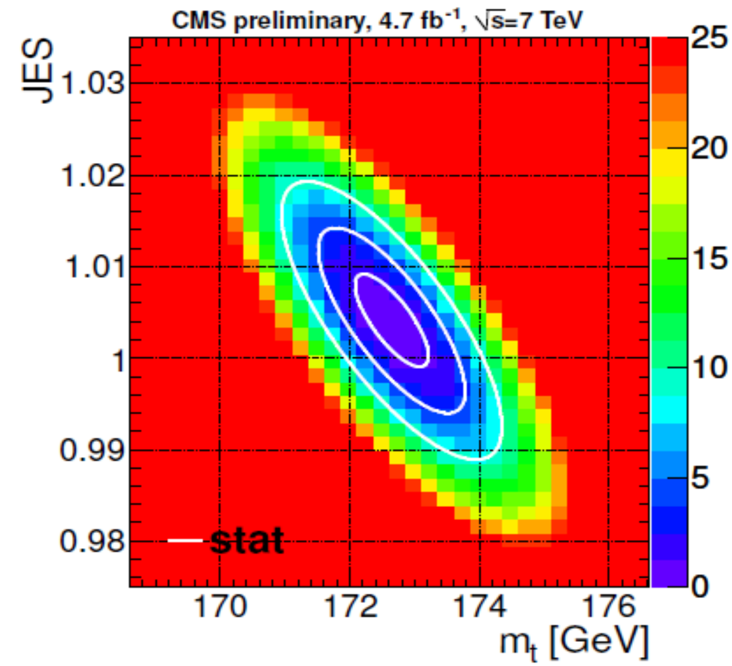
Lepton+jet channel

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

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



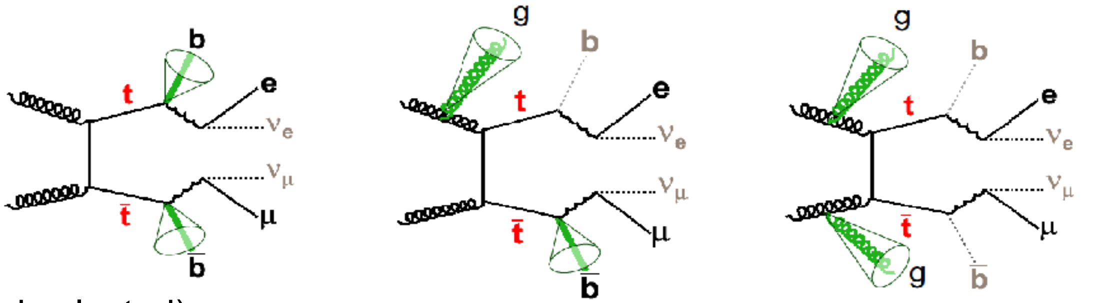
CMS: kinematic fit + "ideogram" method combine event-per-event likelihood



⇨m_{top}=174.4 ± 0.6 (stat) ± 2.3 (syst) GeV — ATLAS CONF-2011-120

172.6 ± 0.6 (stat) ± 1.2 (syst) GeV — CMS PAS-11-015

Dilepton channel: challenges

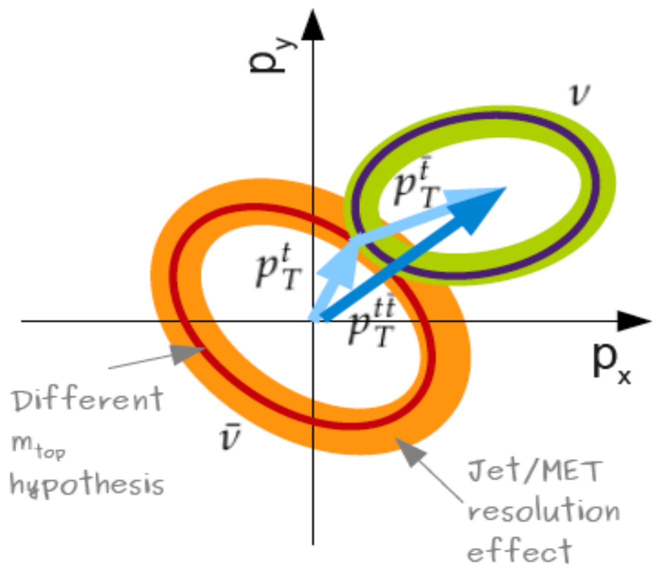


- Combinatorics
  - Identify top quark decay products
  - Ambiguity
  - ISR/FSR introduces further complexity for selection

  (~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



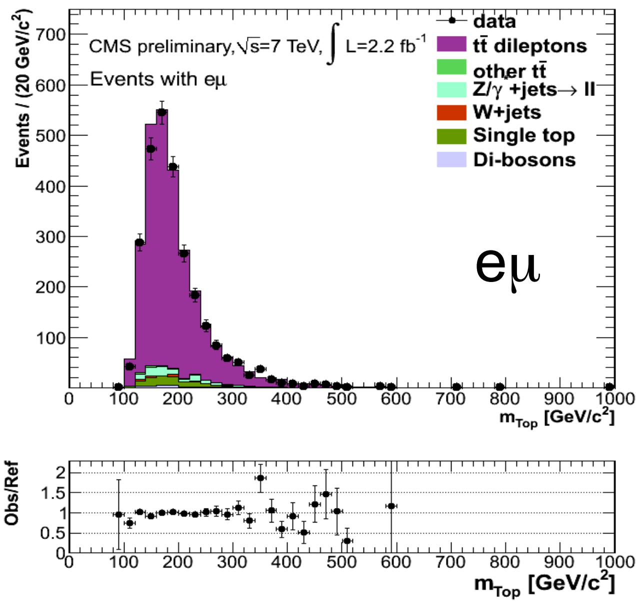
- Pile-up
  - Jet energy scale, MET measurement, extra jets/leptons
  - $N_{pileup} \approx$ 6 (21) for most of data collected in 2011 (2012)

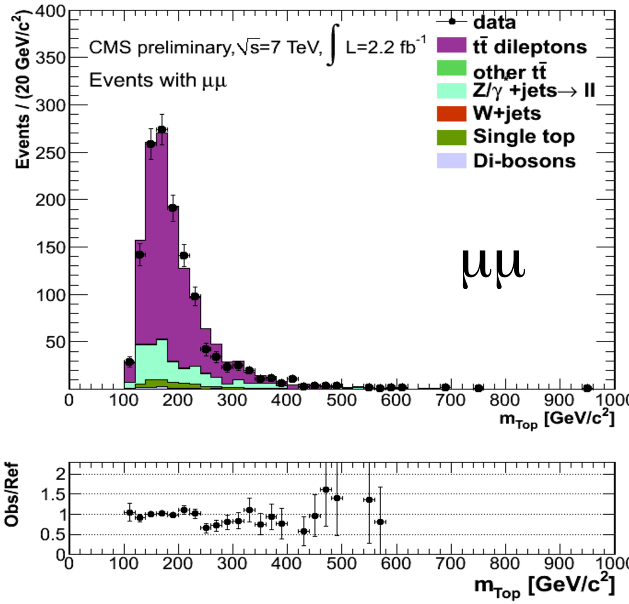
Reconstructed mass

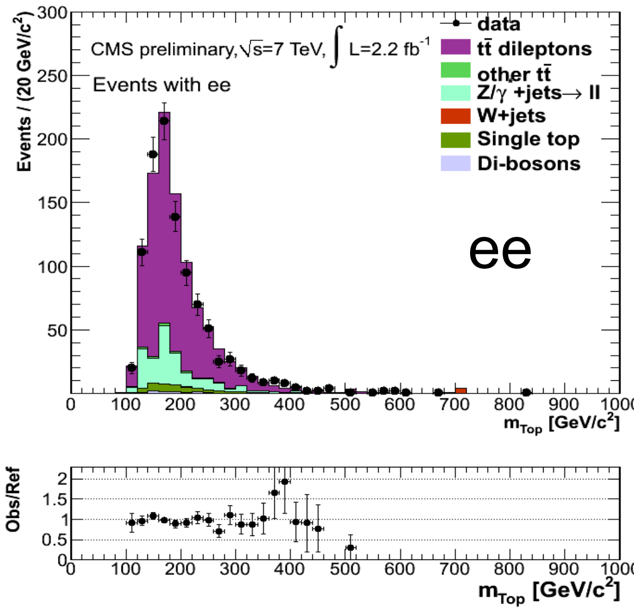
CMS-PAS-TOP-11-016

- Select events
- Reconstruct mass

Process	Pre-selection	KINb	=1 b-tag	$\geq$ 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	-
$Z/\gamma^* \rightarrow \ell\ell$	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



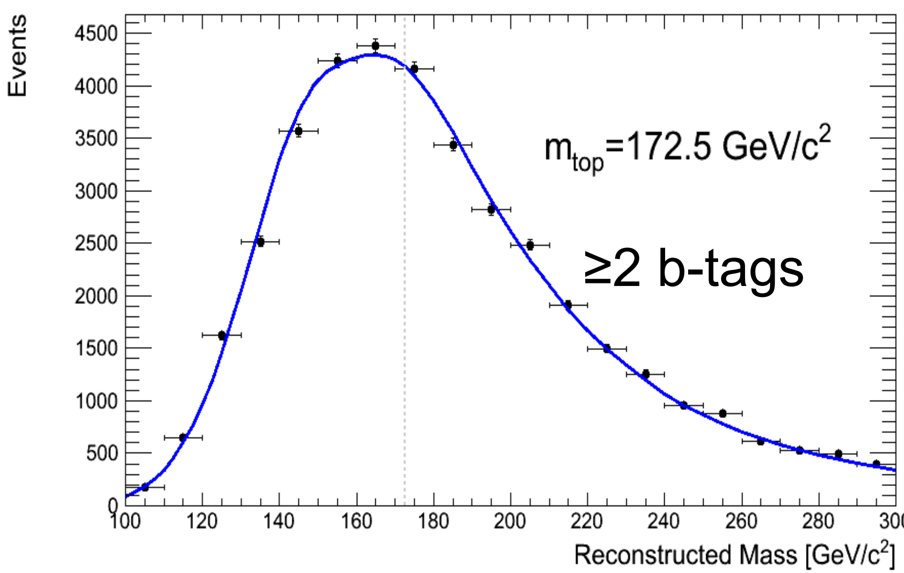


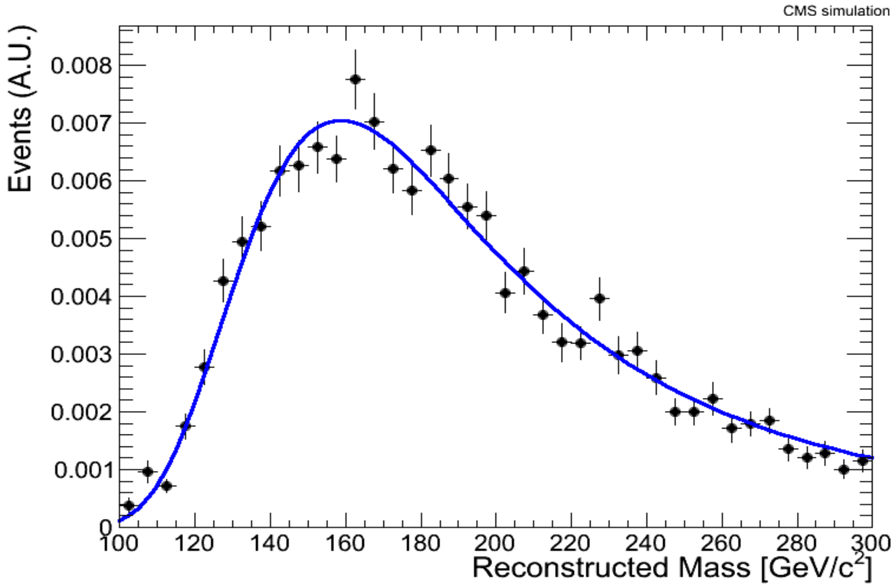


Signal and background

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

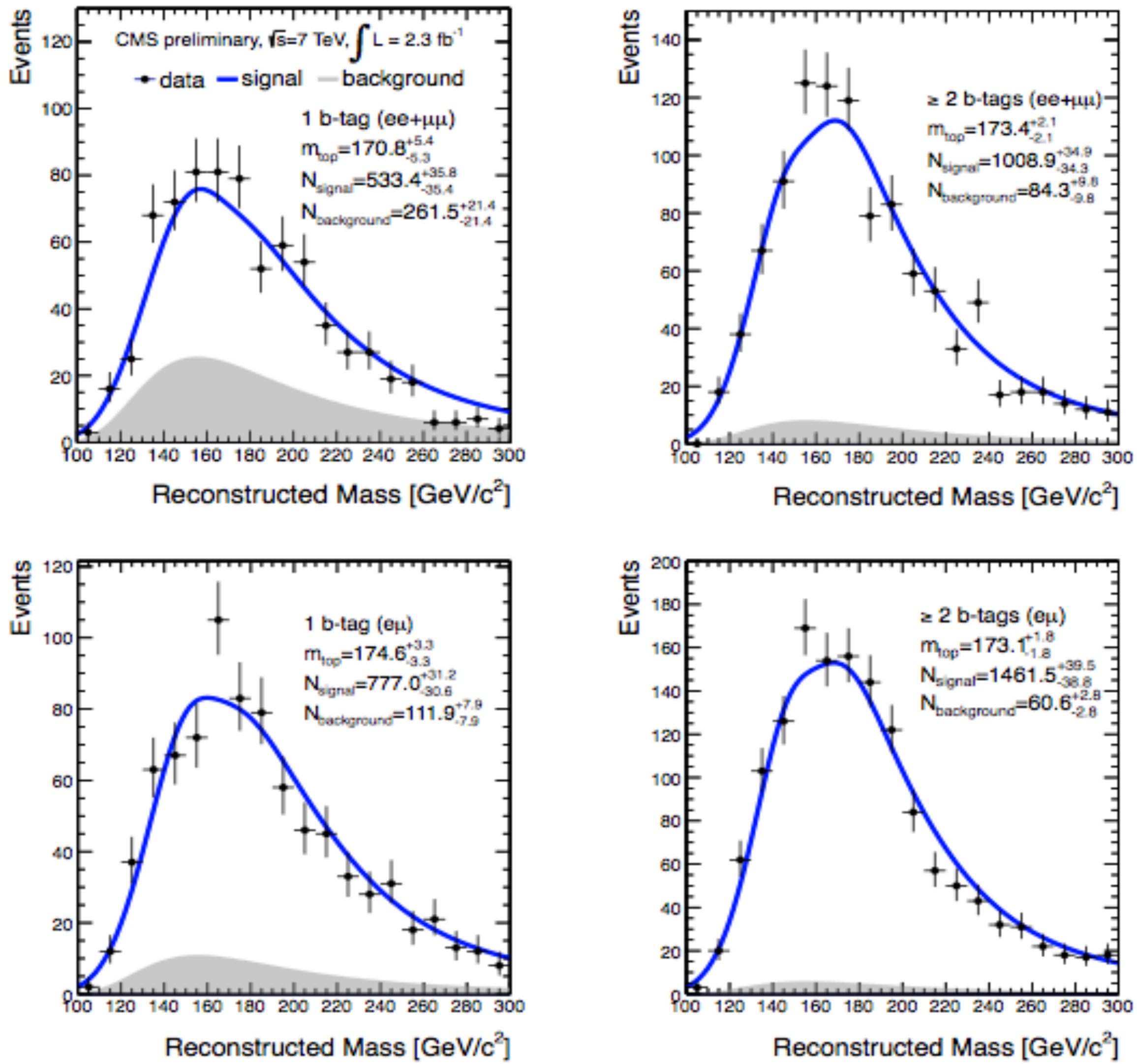
- Background component in the mass spectrum modelled with data +simulation
- Fit: Landau





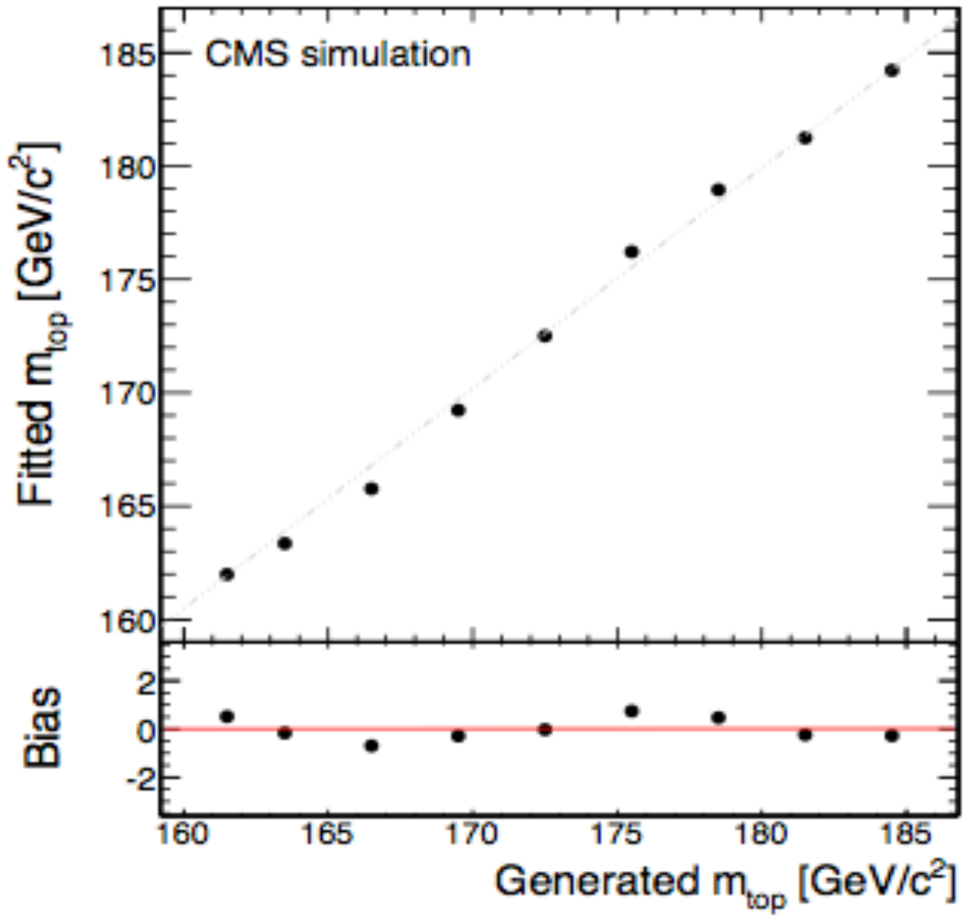
Reconstructed mass

- 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

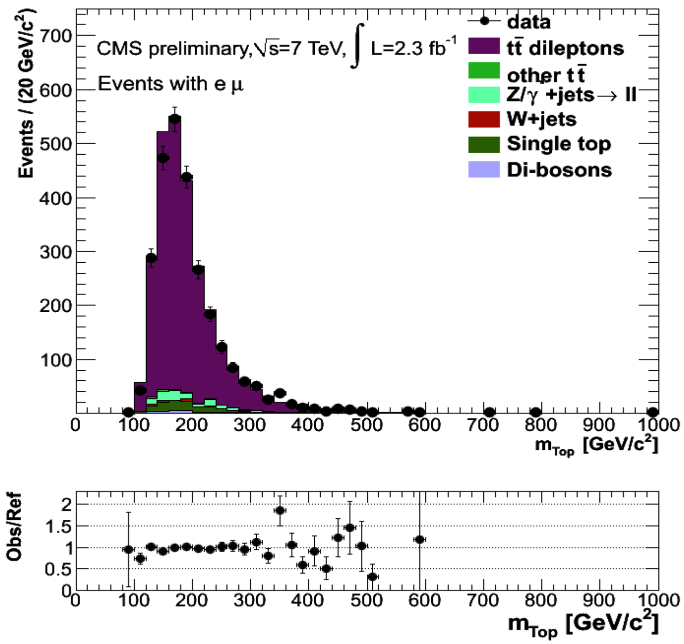


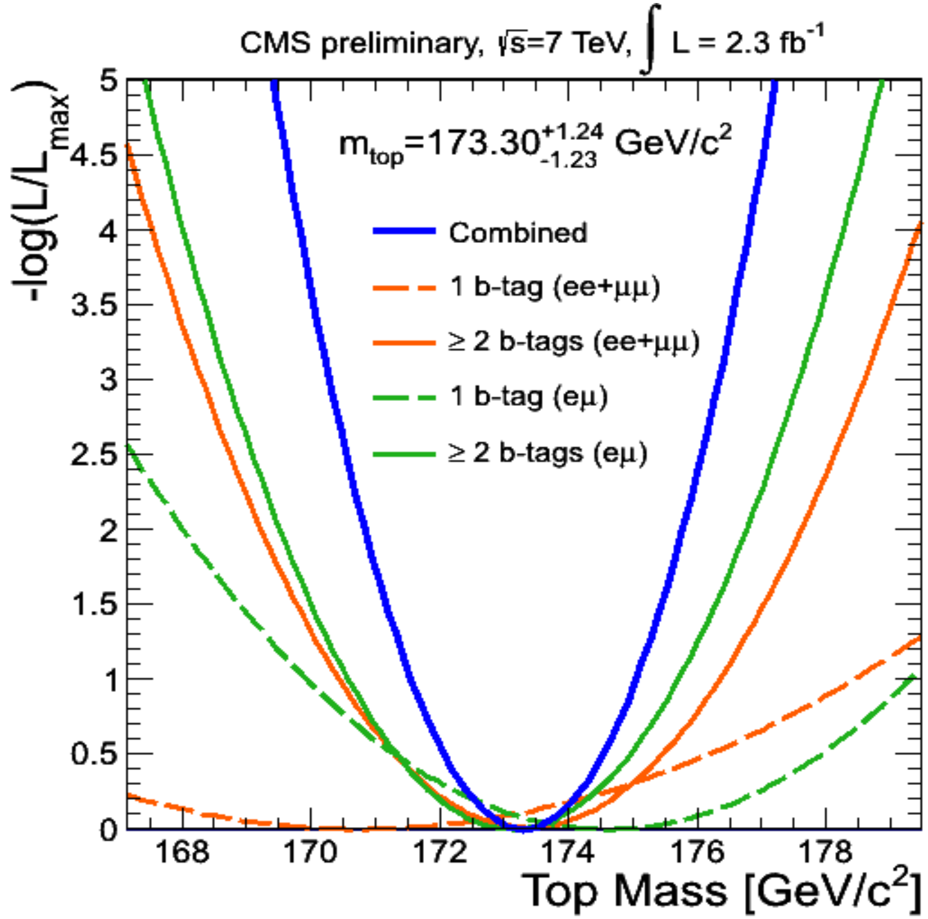
Do not forget the systematics

- 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_{top} (GeV/c^2)
JES	$^{+1.90}_{-2.00}$
flavor-JES	$^{+1.08}_{-1.13}$
JER	$\pm$ 0.30
LES	$^{+0.12}_{-0.18}$
Unclustered E_T^{miss}	$\pm$ 0.43
Fit calibration	$\pm$ 0.40
DY normalization	$\pm$ 0.40
Factorization scale	$\pm$ 0.41
Jet parton matching scale	$\pm$ 0.65
Pile-up	$\pm$ 0.19
b-tagging uncertainty	$\pm$ 0.30
mis-tagging uncertainty	$\pm$ 0.43
MC generator	$\pm$ 0.14
PDF uncertainty	$\pm$ 0.39
Total	$^{+2.52}_{-2.63}$

Final fit

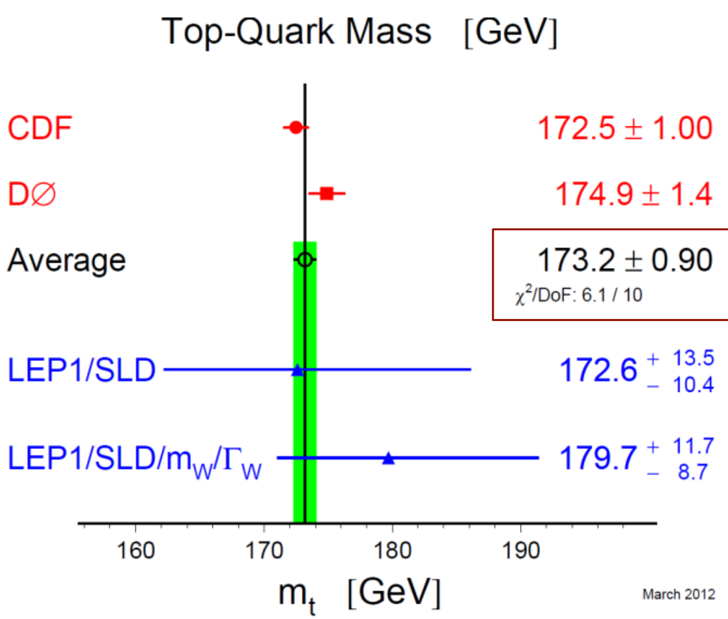




$$m_{\rm top} = 173.3 \pm 1.2({\rm stat.})^{+2.5}_{-2.6}({\rm syst.})\ {\rm GeV}/c^2$$

CMS TOP-11-016

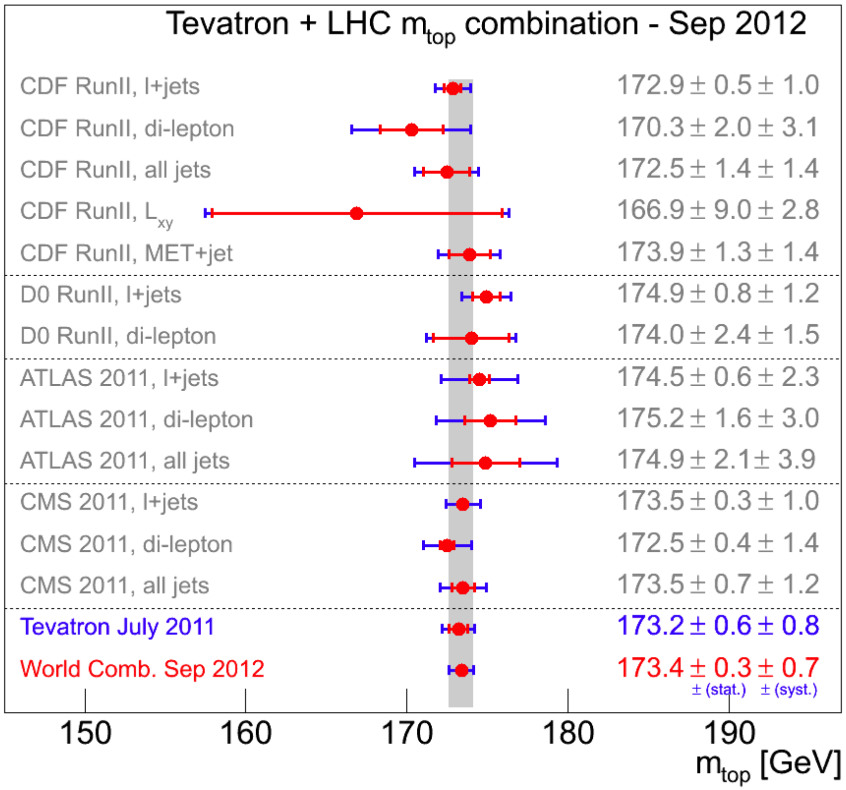
Top quark mass



arXiv:1107.5255

±0.5%

- dominated by l+jet channel
- Towards LHC and global combination

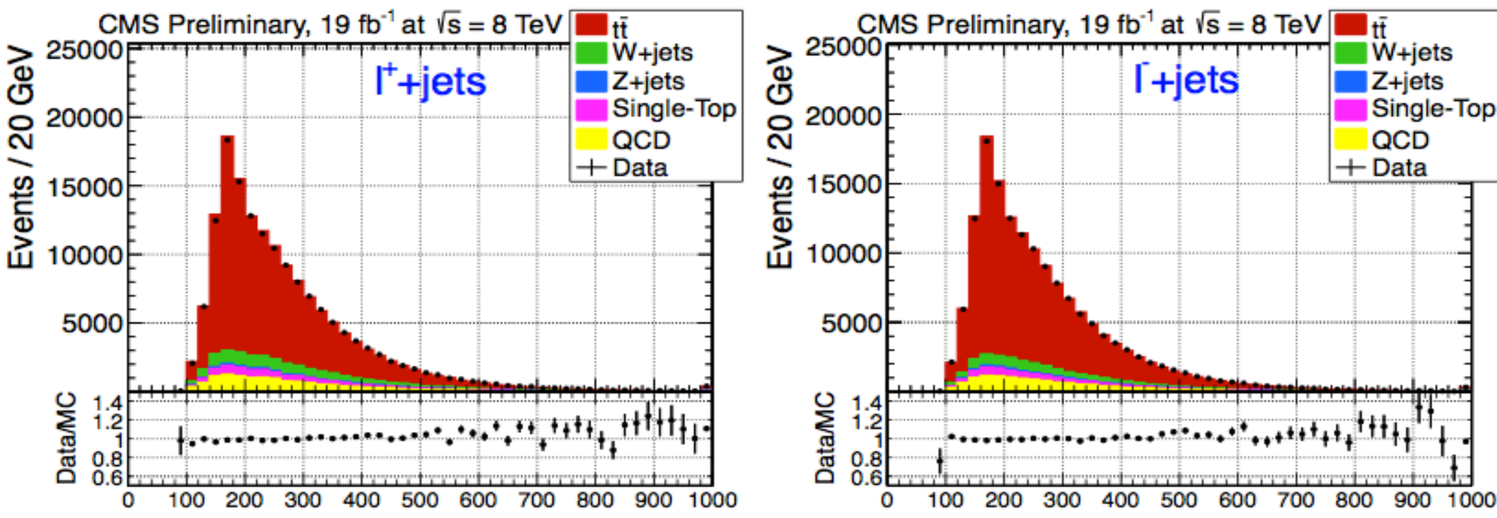


Results from LHC are rapidly improving (0.6%)

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=1.1/fb)
  - Compare mass measured from μ^+/μ^- +jets
  - Use hadronic side

CMS-PAS-TOP-12-028



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

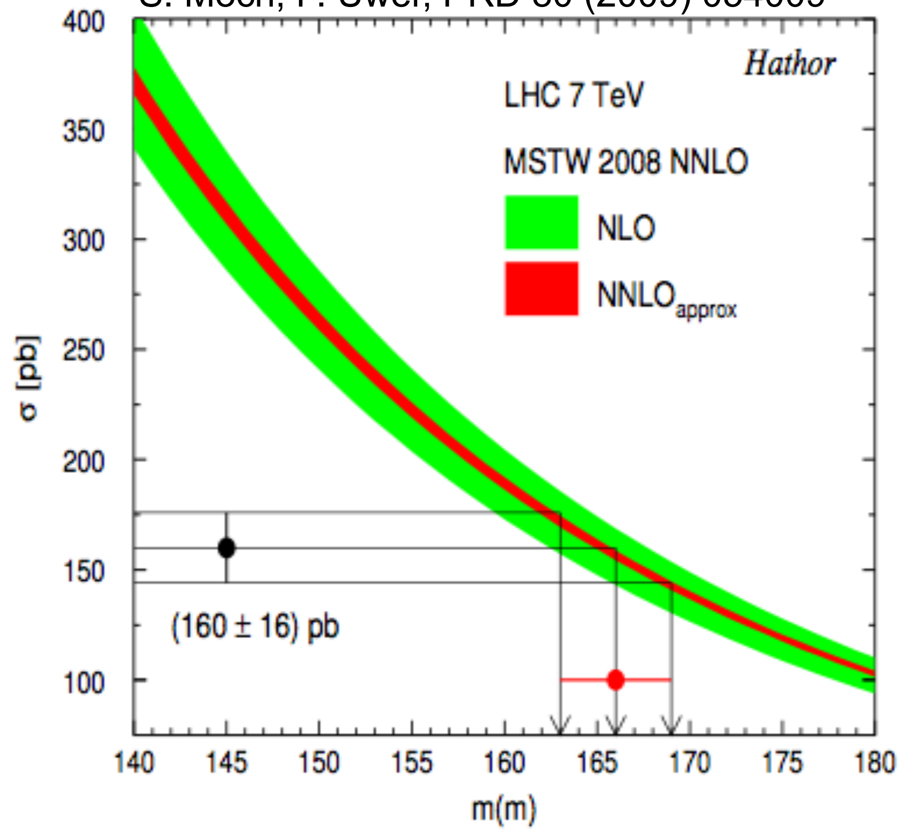
$$\Delta m_t = m_t^{had} - m_{\bar{t}}^{had} = -272 \pm 196\ (stat.) \pm 121\ (syst.)\ MeV$$

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

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

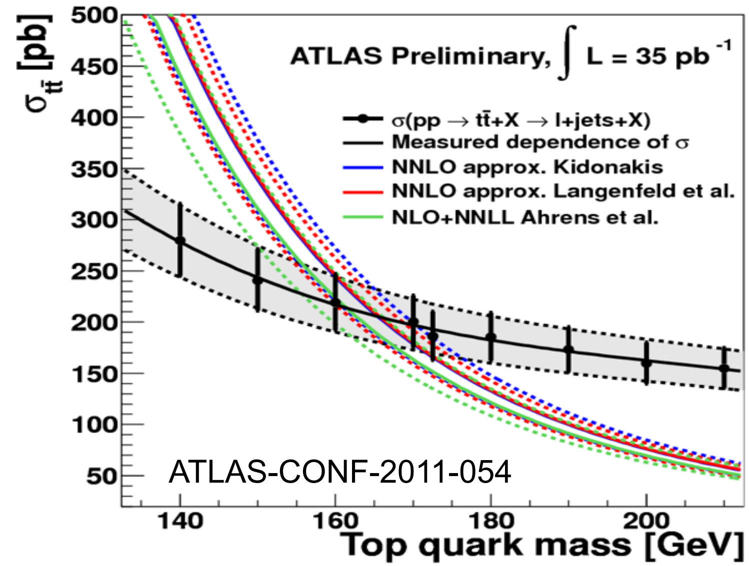
  - from dilepton cross section (CMS) with 1.1/fb

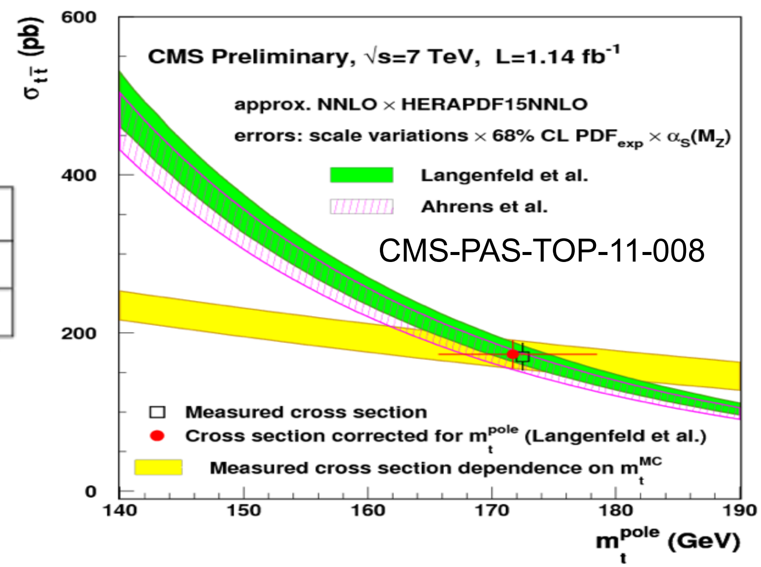
$$m_t^{pole} = 170.3^{+7.3}_{-6.7}\,\text{GeV}$$

Also determine m(MSbar):

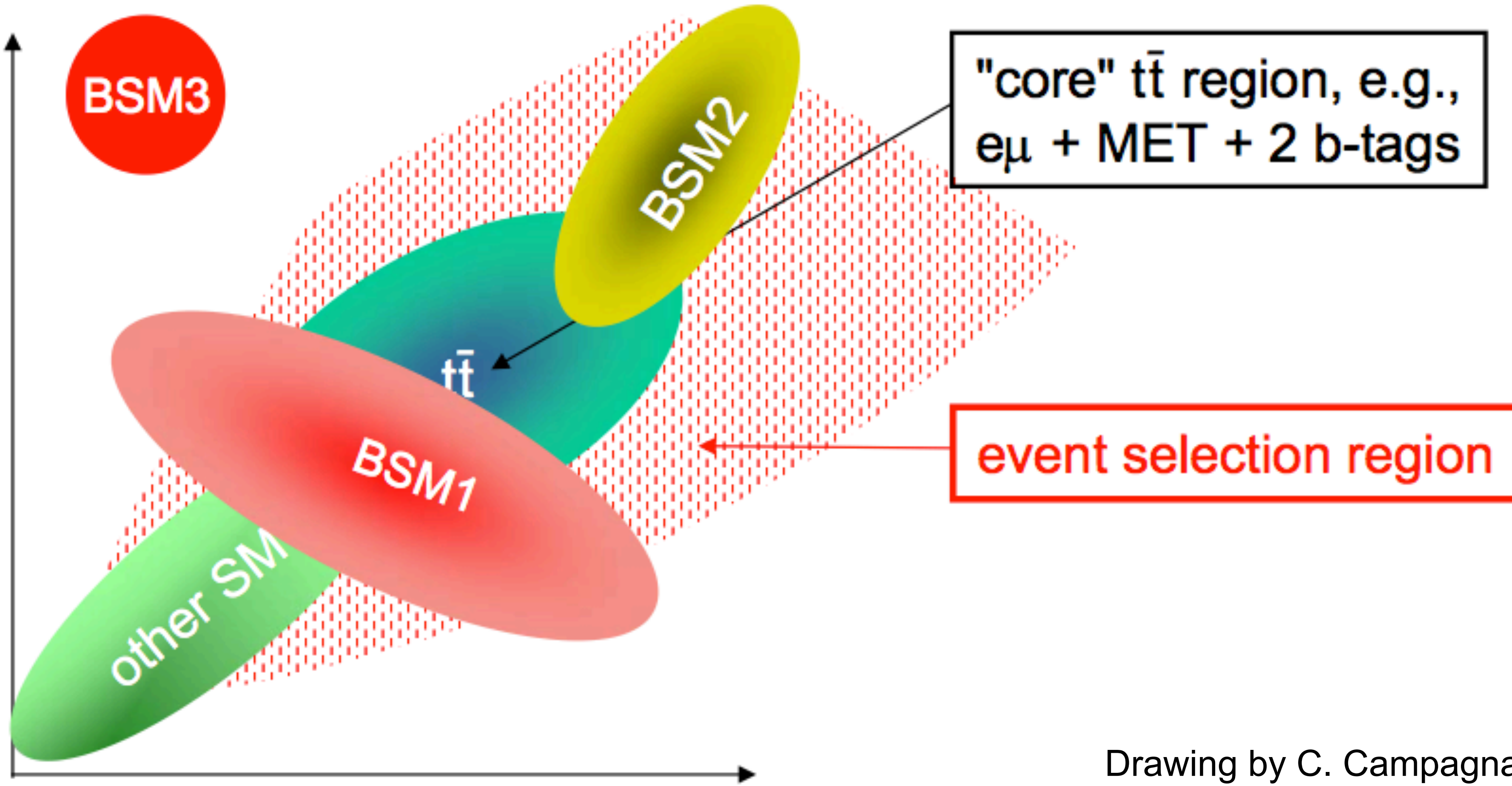
Approx. NNLO × HERAPDF15NNLO	m_t^{pole} / GeV	$m_t^{\overline{\text{MS}}}$ / GeV
Langenfeld et al. [7]	$171.7^{+6.8}_{-6.0}$	$164.3^{+6.5}_{-5.7}$
Ahrens et al. [9]	$169.1^{+6.7}_{-5.9}$	$161.0^{+6.8}_{-6.1}$

CMS-PAS-TOP-11-008



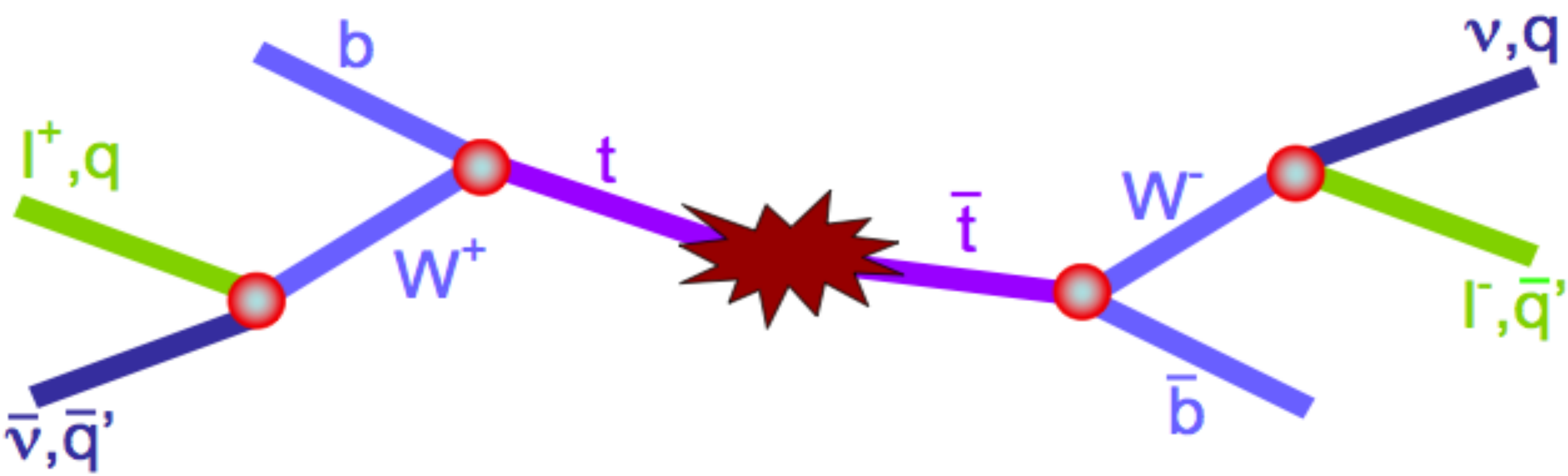


Not just cross sections



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)
...

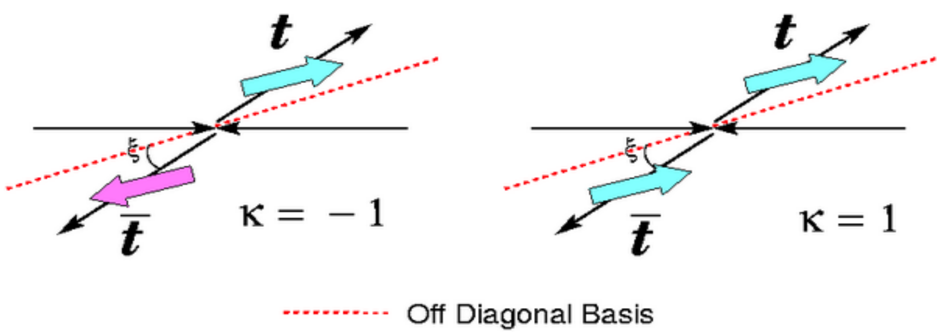
PROPERTIES
Mass
Kinematics
Charge
Lifetime and width
W helicity
Spin
...

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) $\Rightarrow$ spin information transmitted to the decay products (W boson, b quark)
- Spin correlation depends on the production mode

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



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

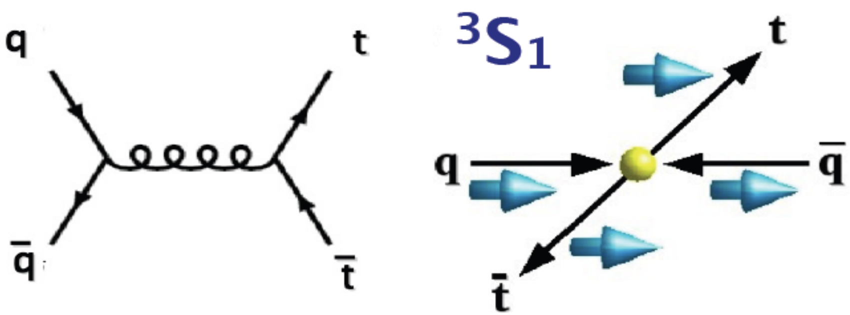
- Analyze spin using angular distributions of decay products
  - θ_1 and θ_2 are the angles of decay products wrt a "quantization axis"
  - value of κ depends on spin basis (for example, off-diagonal vs maximal)

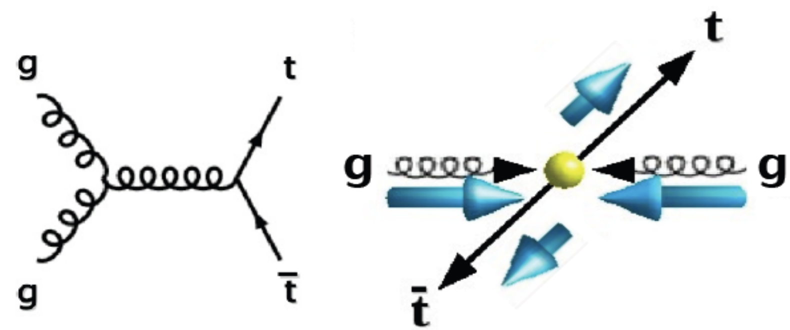
Spin correlation

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

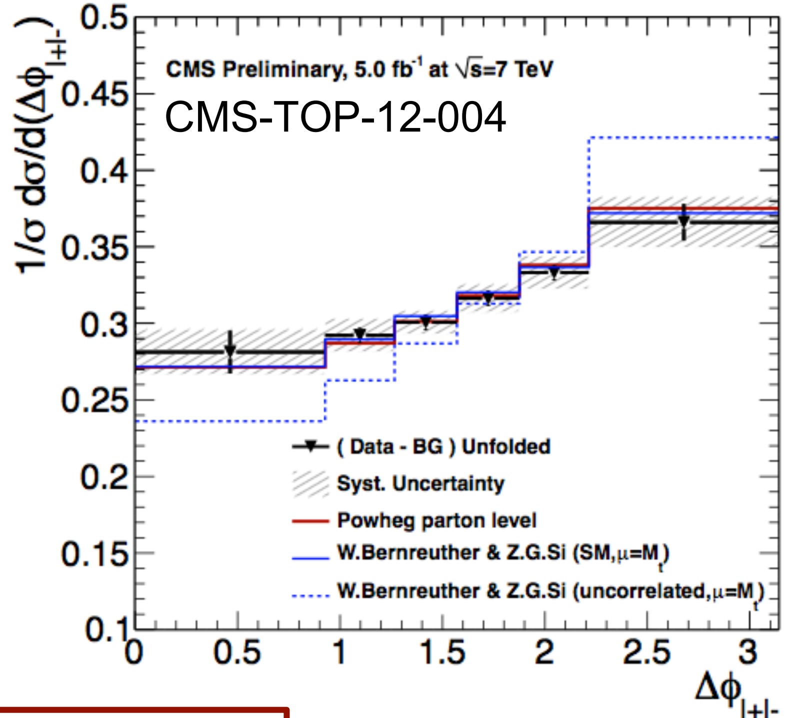
- optimised "off-diagonal" basis
- maximal basis

complementary between Tevatron and LHC

Spin correlation

- Access spin information via the angular distributions of its decay products
- Most sensitive probes are leptons and d-type quarks
- Strategy: fit Δϕ dilepton distribution with binned SM distribution and in the case with uncorrelated spin distribution
- Translate result to maximal/helicity basis
- Main systematics: ISR/FSR and signal modelling
- Results in agreement with SM:

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



$$A_{\text{helicity}} = 0.34 \pm 0.07_{\text{stat}}\ {}^{+0.13}_{-0.09}\ \text{syst} \qquad A^{\text{SM}}_{\text{helicity}} = 0.32$$

$$A_{\text{maximal}} = 0.47 \pm 0.09_{\text{stat}}\ {}^{+0.18}_{-0.12}\ \text{syst} \qquad A^{\text{SM}}_{\text{maximal}} = 0.44$$

ATLAS-CONF-2011-117

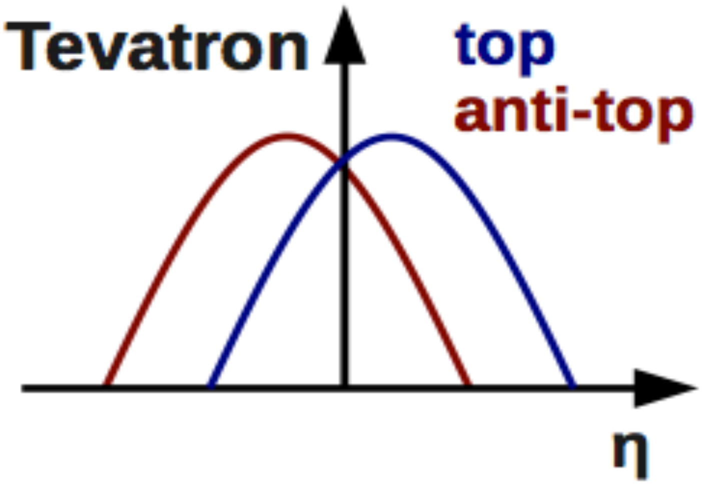
Charge asymmetry

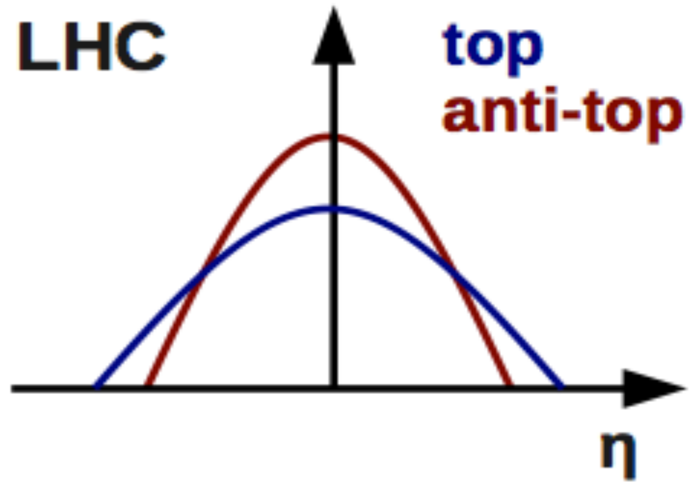
- In qqbar→ttbar (Tevatron): top quarks are emitted in the direction of the incoming quark, anti-top quarks in the direction of the incoming anti-quark
- No FB asymmetry in gg→ttbar (LHC)

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)

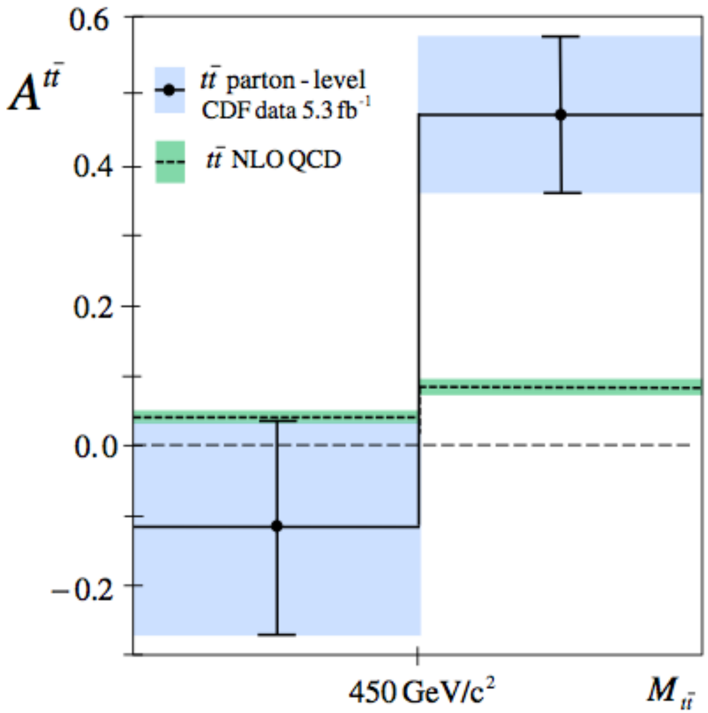




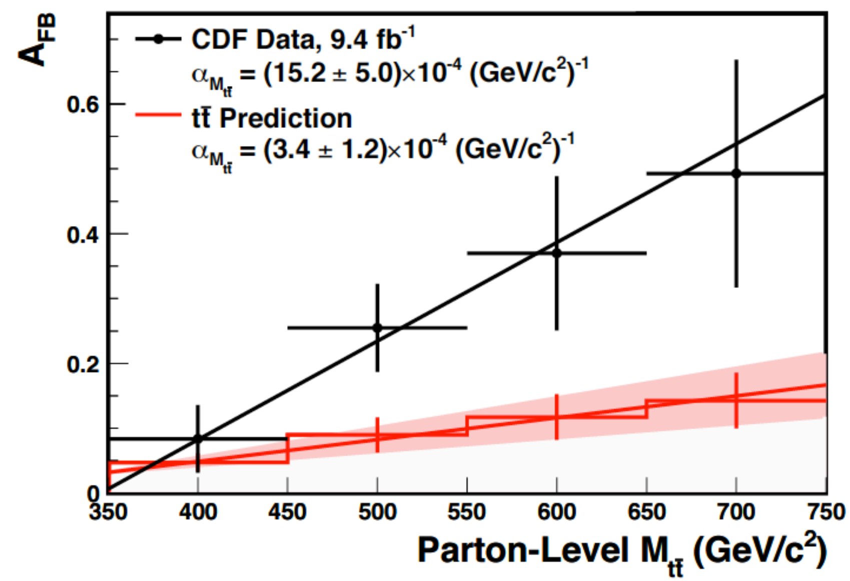
Asymmetry A_{FB} anomaly?

- 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



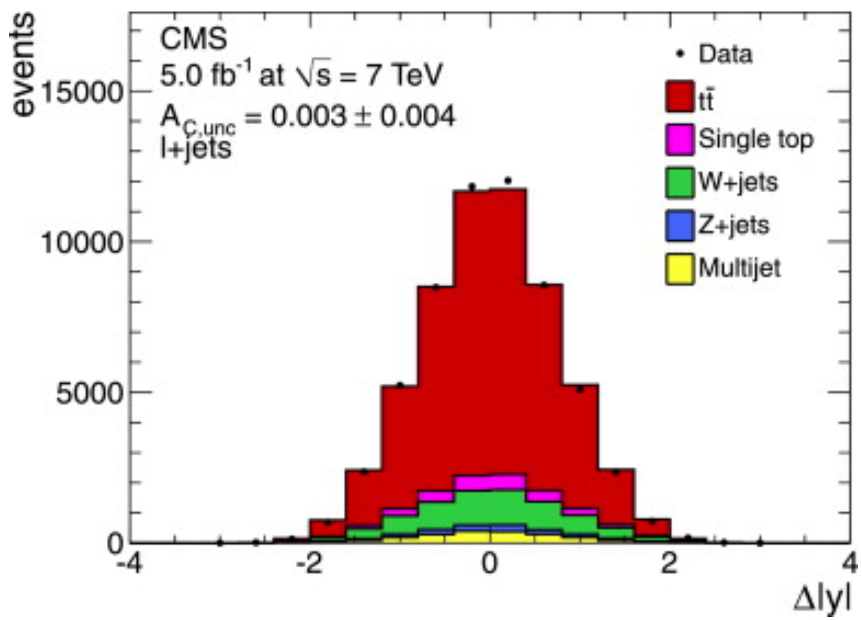
Charge asymmetry at LHC

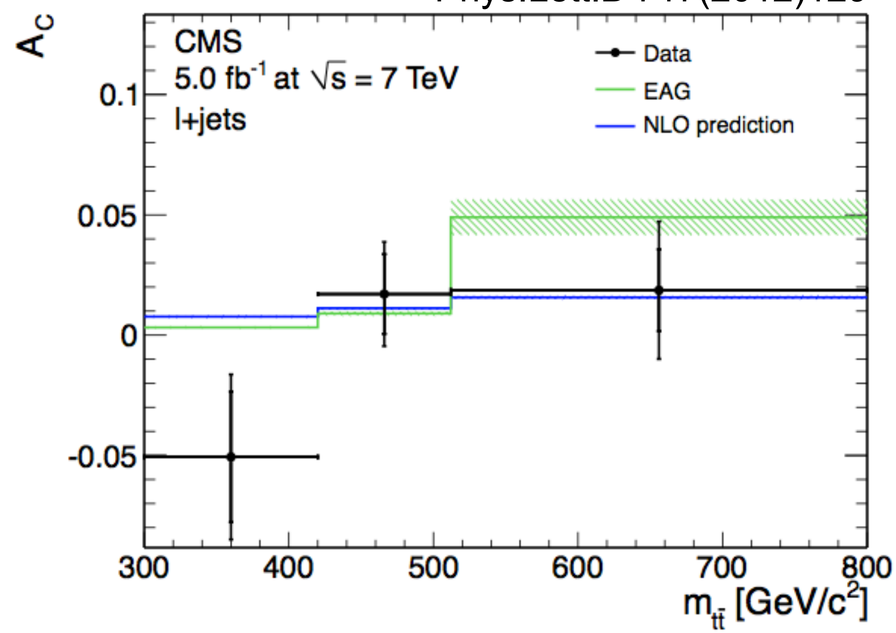
$$A_C = \frac{N^+ - N^-}{N^+ + N^-}$$

$N^+(N^-)$: 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



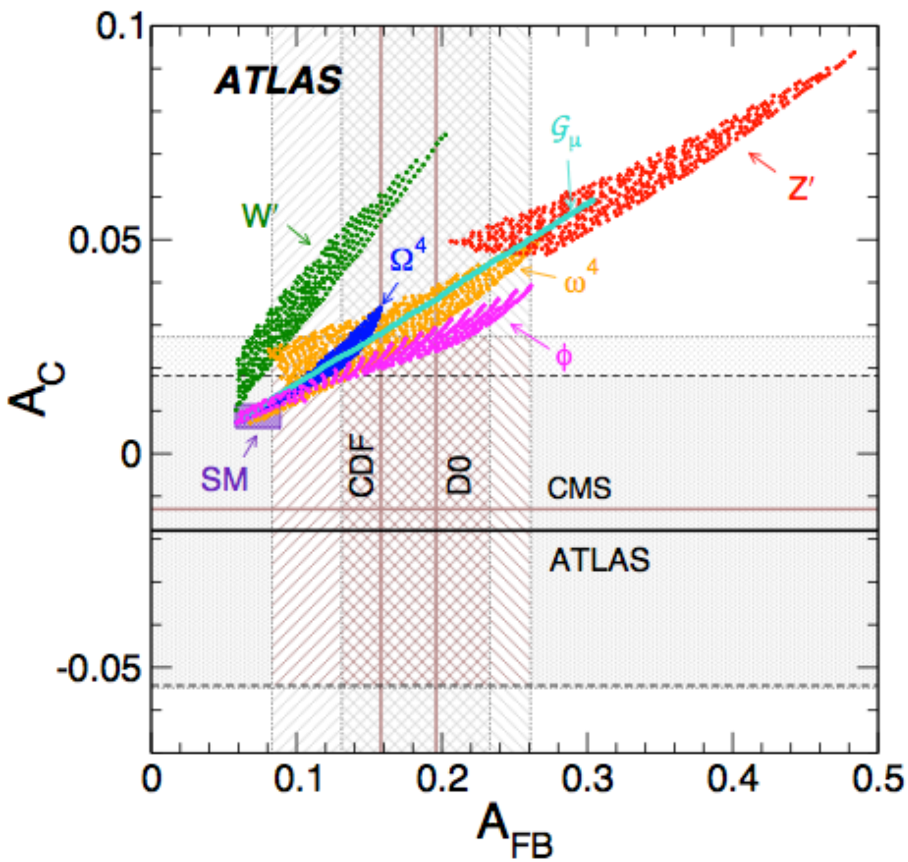


⇒Good agreement between data and SM expectations

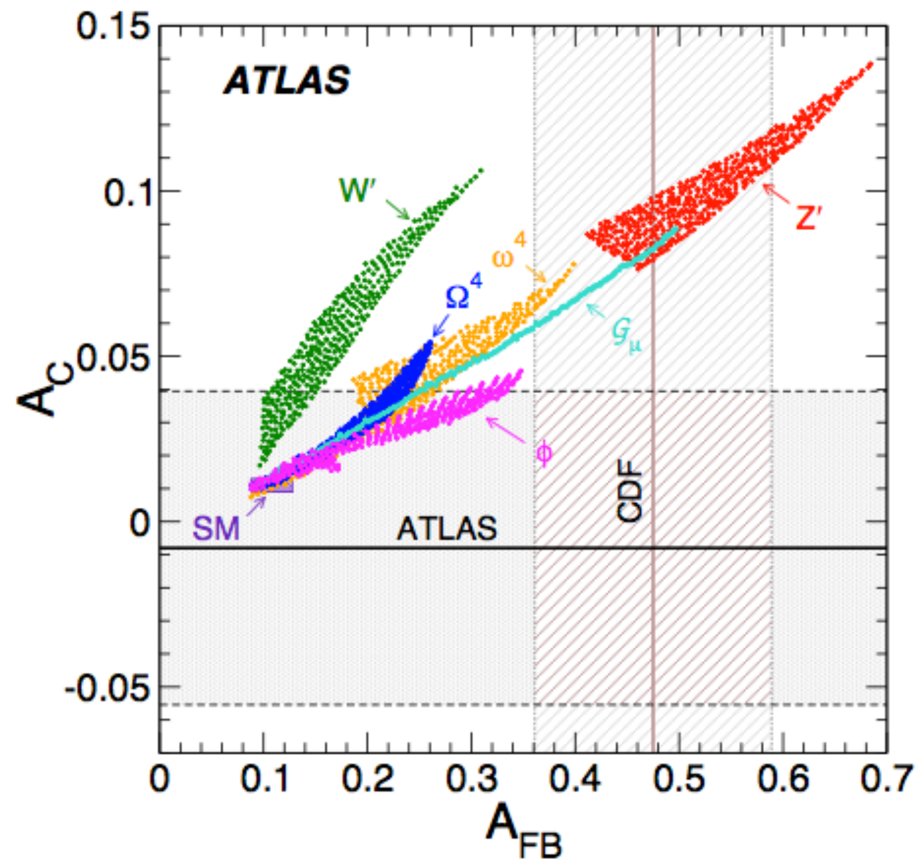
Constraints on New Physics

EPJC 72(2012)2039

Inclusive



m_{tt}>450 GeV



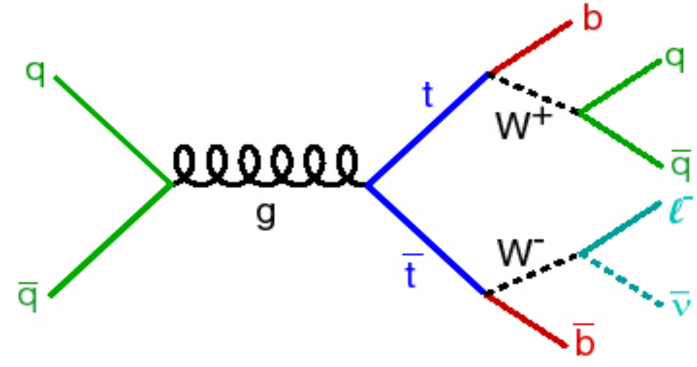
Heavy flavor content (i.e. V_{tb})

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

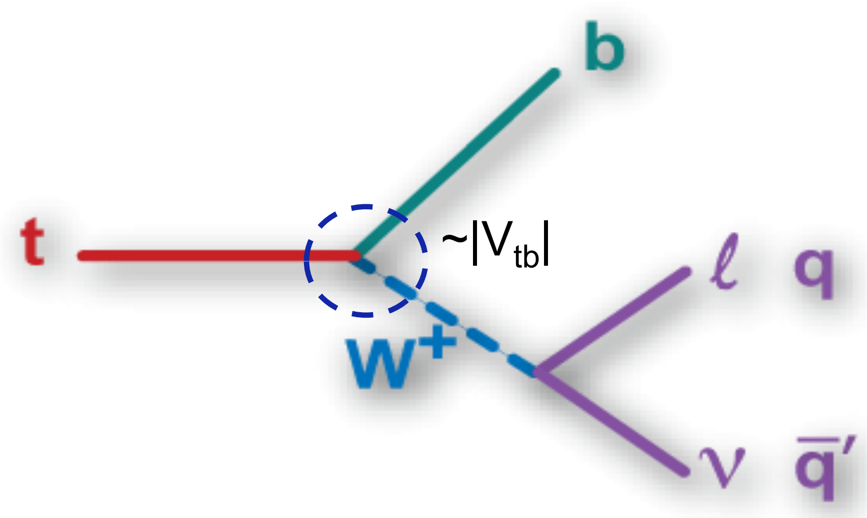
We classify the ttbar sample based on the number of b-tagged jets

- 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
$\vert V_{tb}\vert$	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.

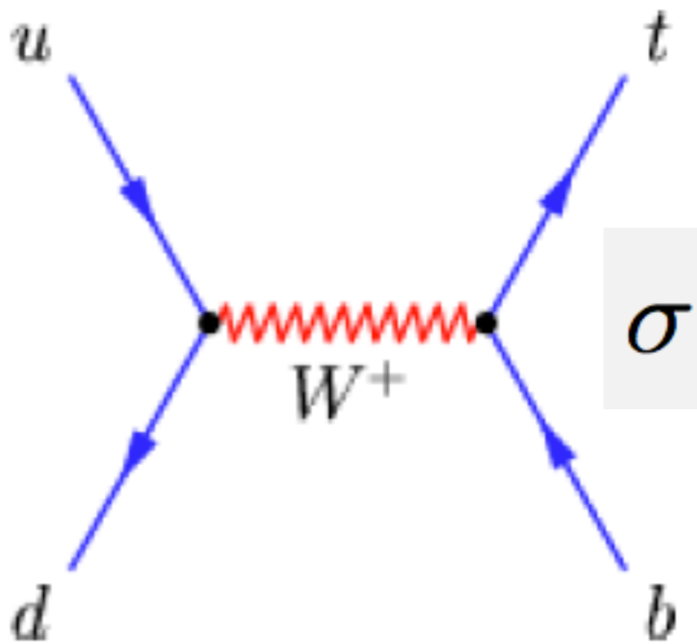
D0 5.4 fb^{-1}
l+jets & dilepton

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)



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

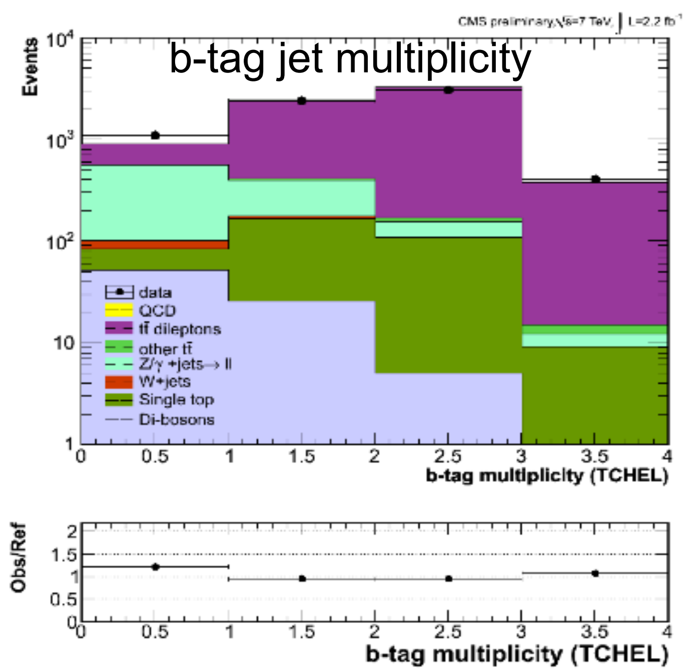
Measure R in dilepton channel

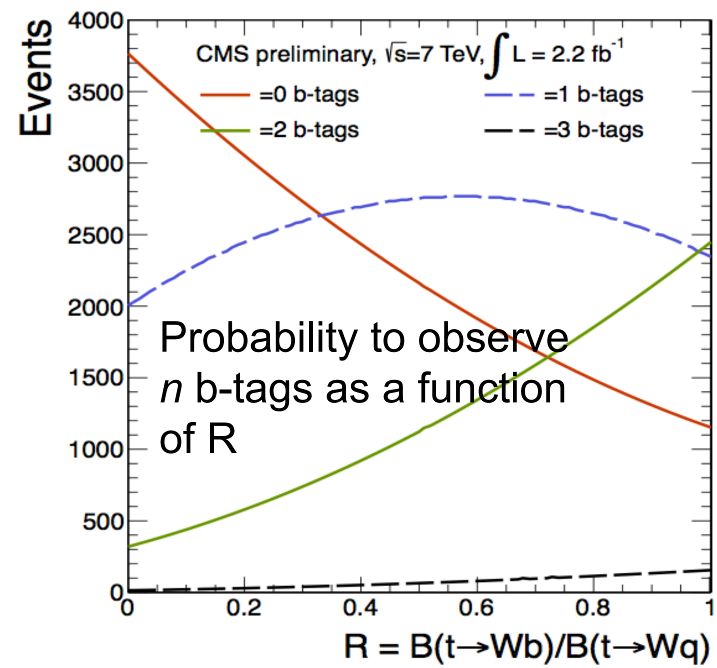
CMS TOP-11-029

- 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 ε(b) and R

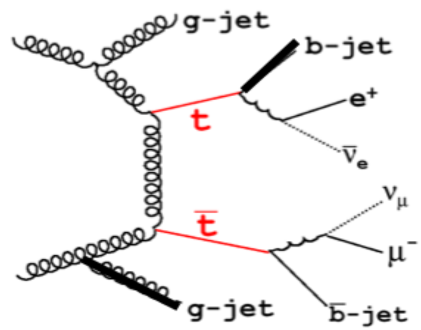




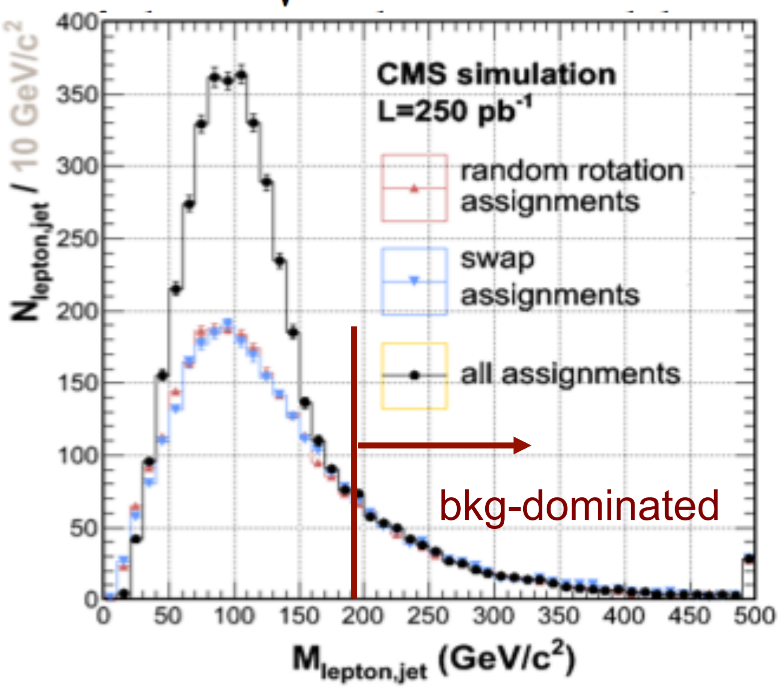
How to model the background

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

1 reconstructed b-jet (α_1)



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



Compute invariant mass of all lepton-jet pairs

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

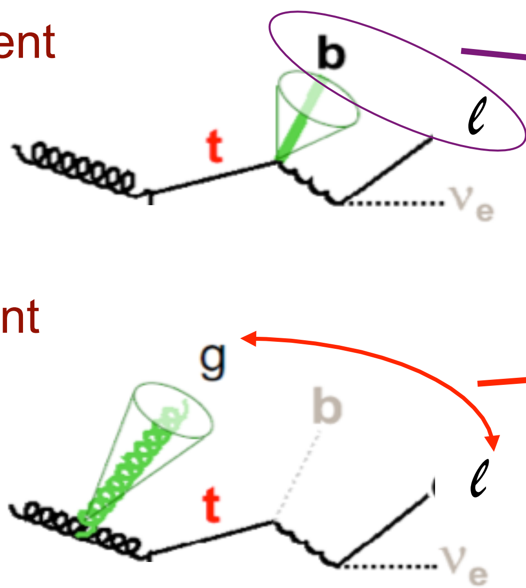
Background dominates at $M>M_{cut}$

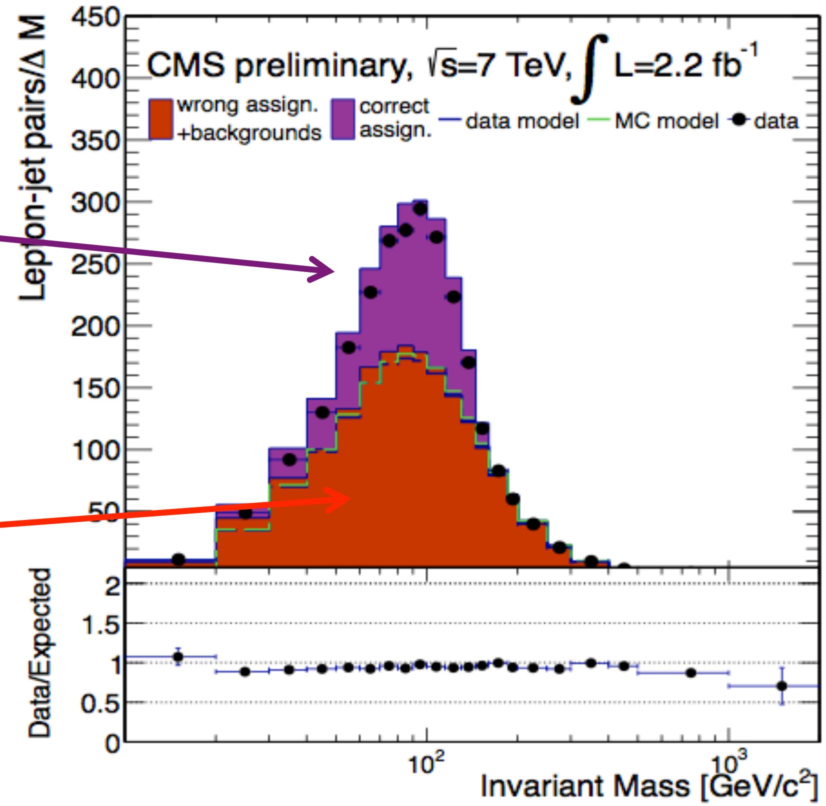
Signal or background?

CMS TOP-11-029

Data-driven determination of background

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

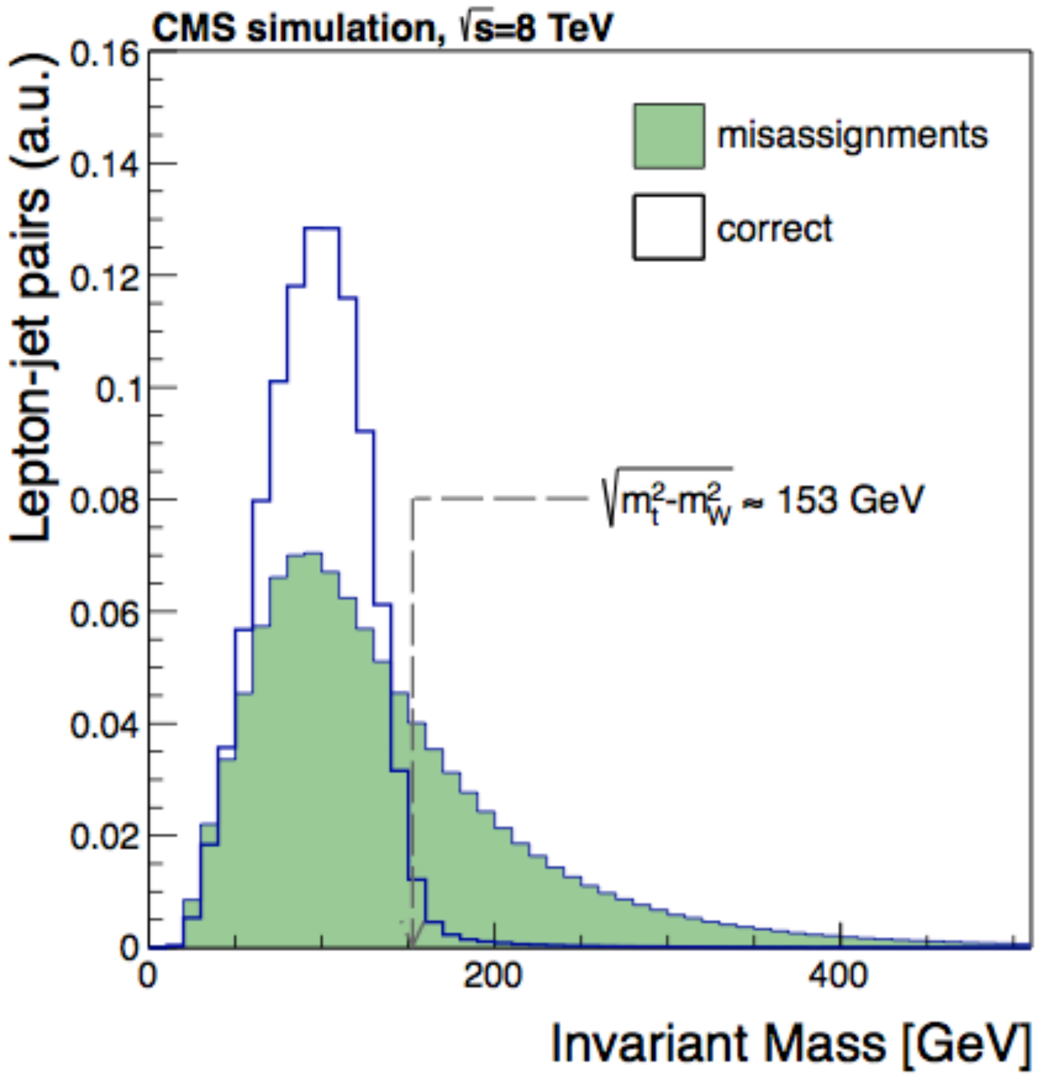




- Use tail to model background in signal region

Signal vs background

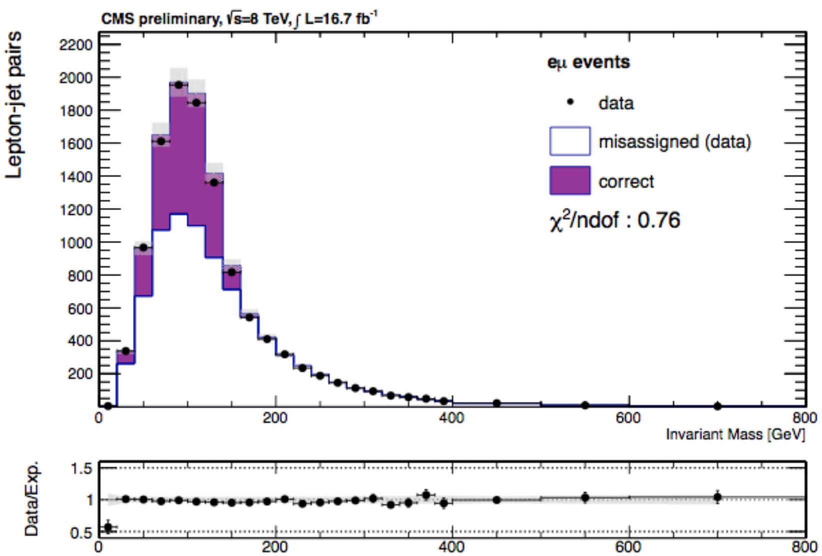
CMS TOP-12-035



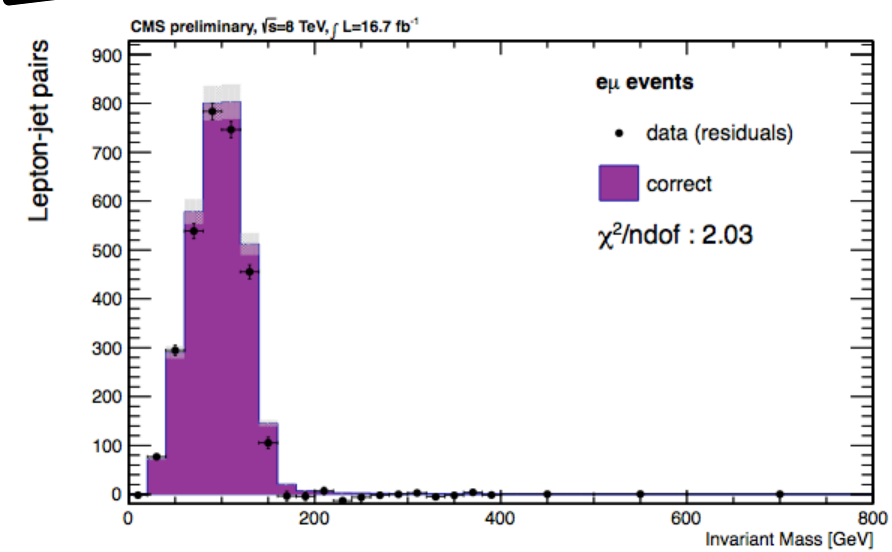
Signal or background

CMS TOP-12-035

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



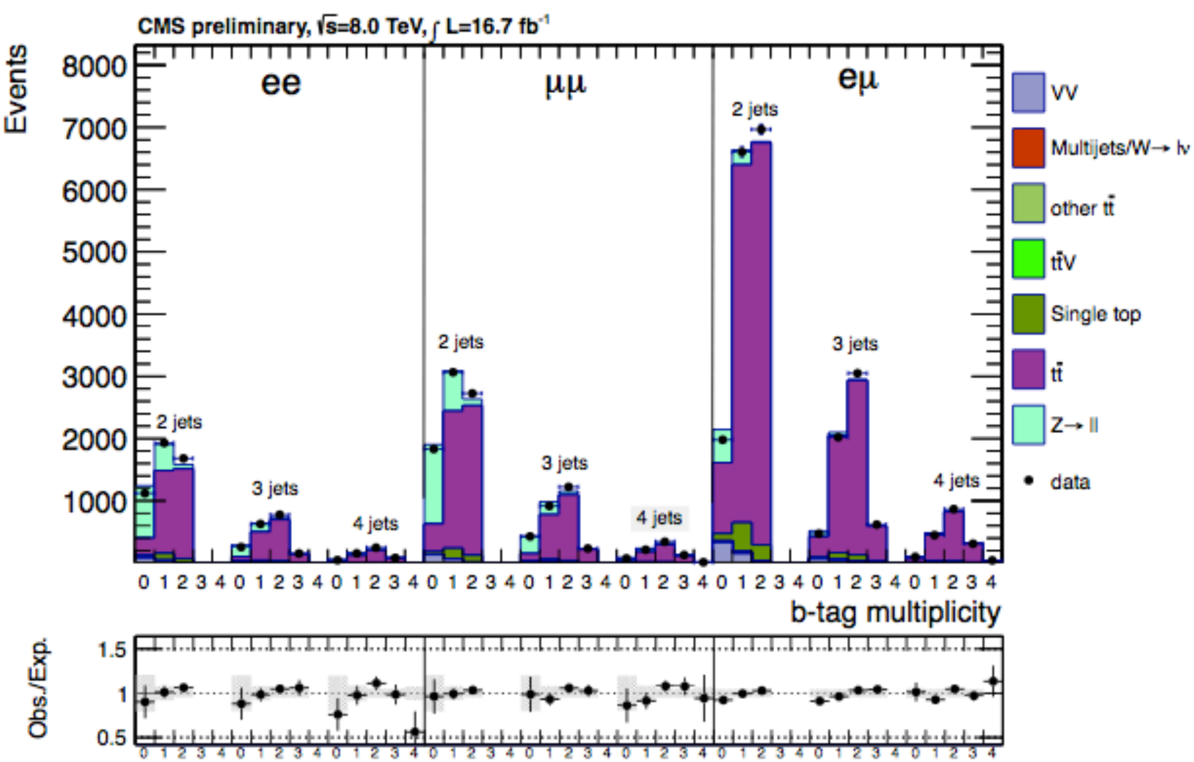
after background subtraction

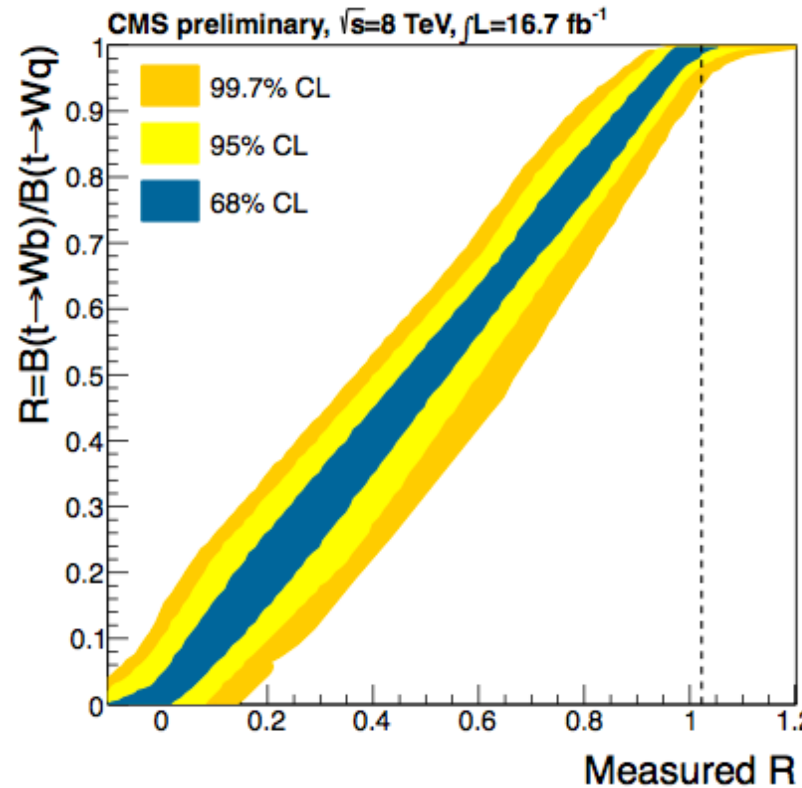


Heavy flavor content

CMS TOP-12-035

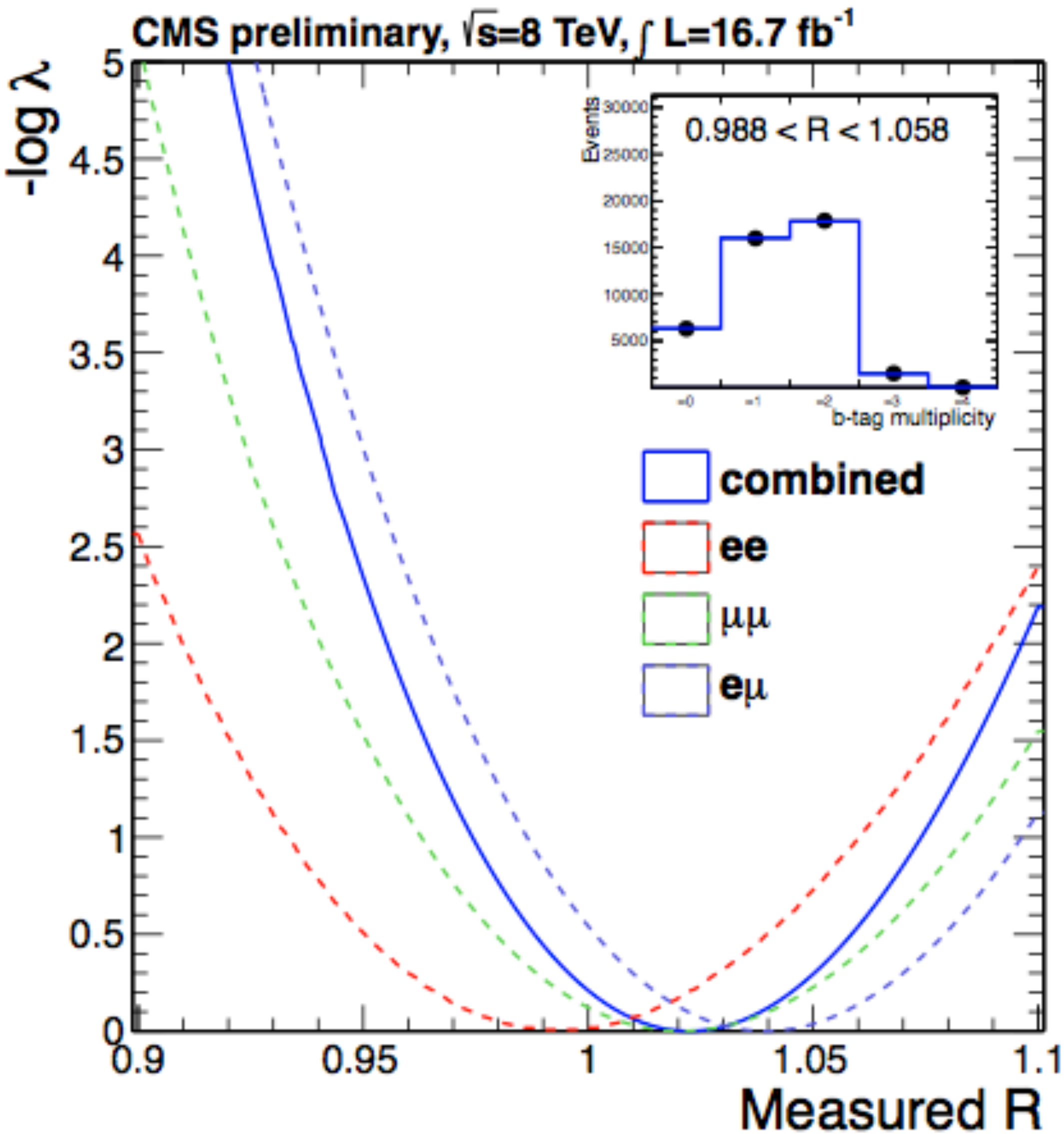
- Fully data-driven measurement
  - b-tagging multiplicity parametrized as function of R ε_b, ε_q, top contribution
  - Number of reconstructed t→Wq is estimated from lepton-jet invariant mass
- R=1.02±0.04 (stat.⊕ syst.)
  - Lower boundary with confidence interval @95%CL after requiring R≤1 ⇒ **R>0.945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





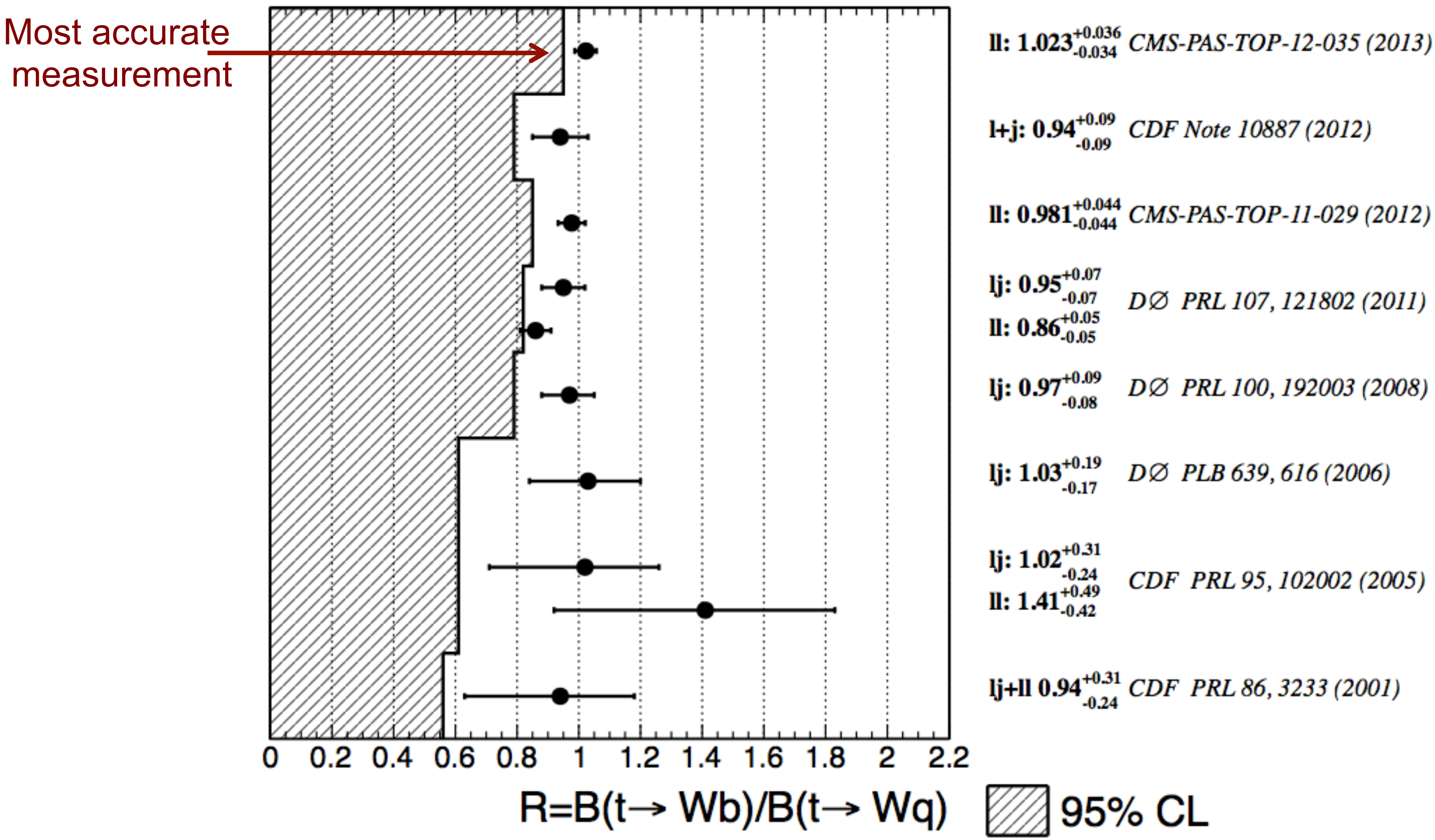
Measure R

CMS TOP-12-035



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

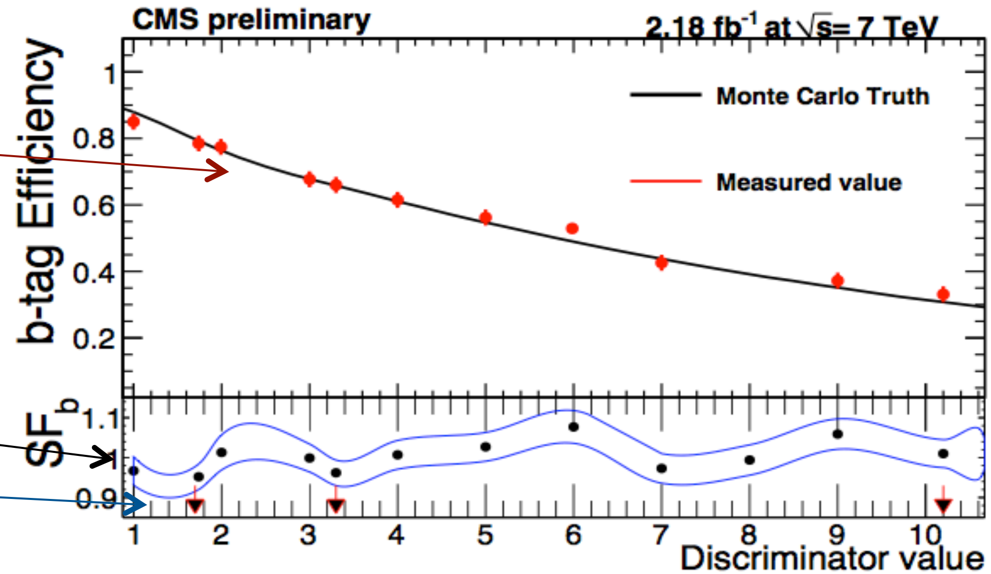
Summary of R results

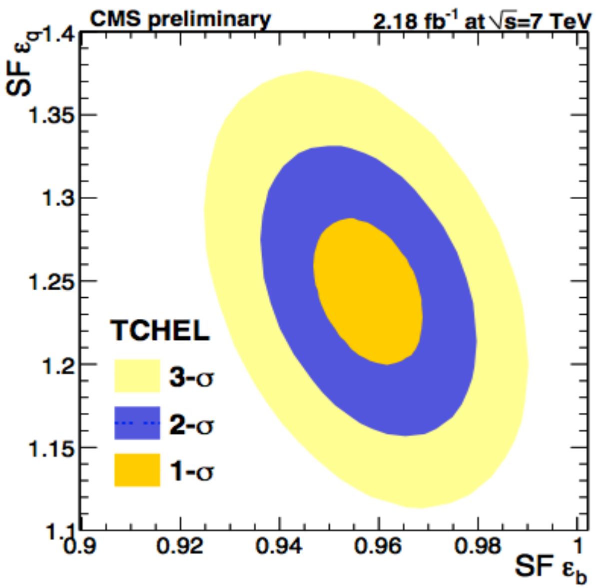


b-tagging efficiency

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

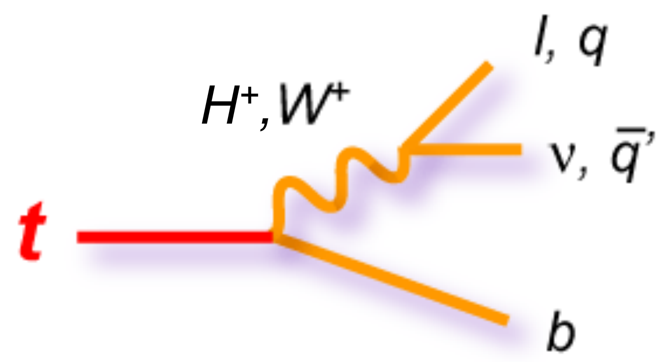
Top quark decays and taus

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)	$ee, \mu\mu, e\mu$ + 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	$e\tau$, $\mu\tau$ +2 *b*-jets	4/81
Tau+jets	τ + jets + 2*b*-jets	12/81

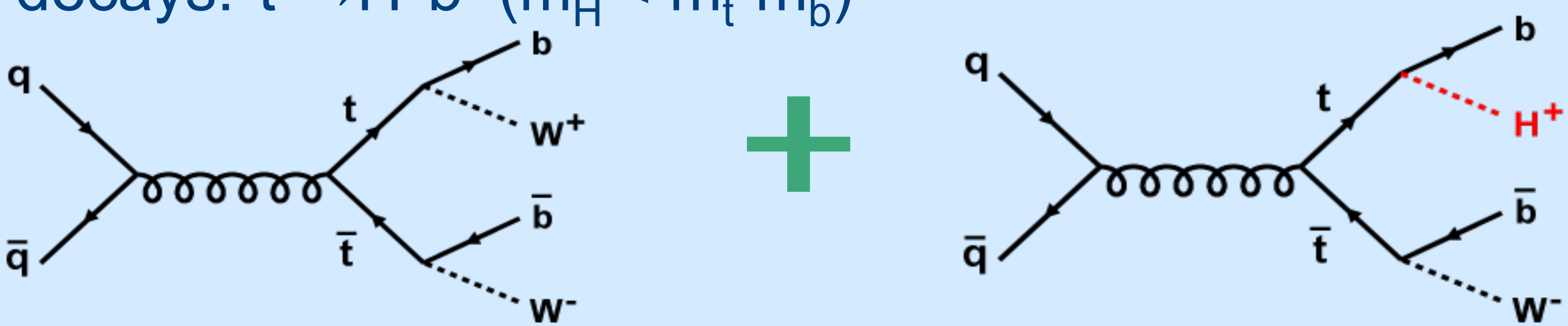
- If top quark plays special role in EWK symmetry breaking, couplings to W may change
- Charged Higgs may alter coupling to W
- Search for final states with taus



Charged Higgs

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

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



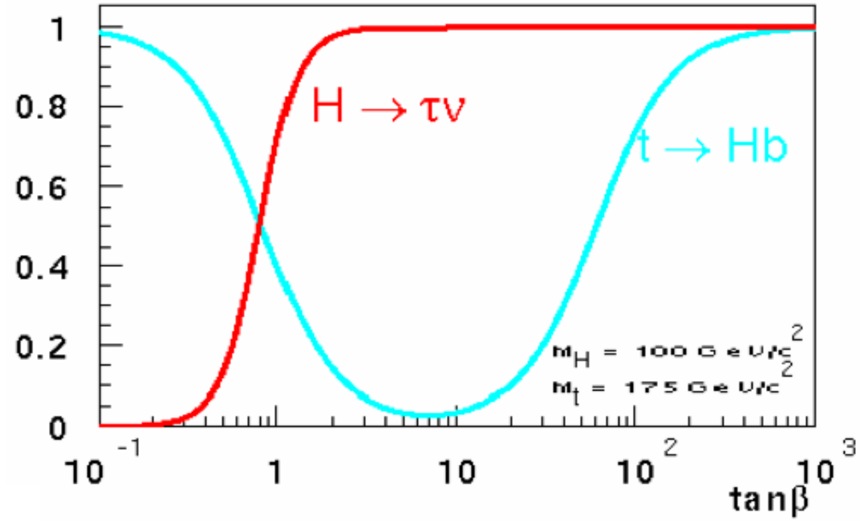
⇨directly observable in this channel

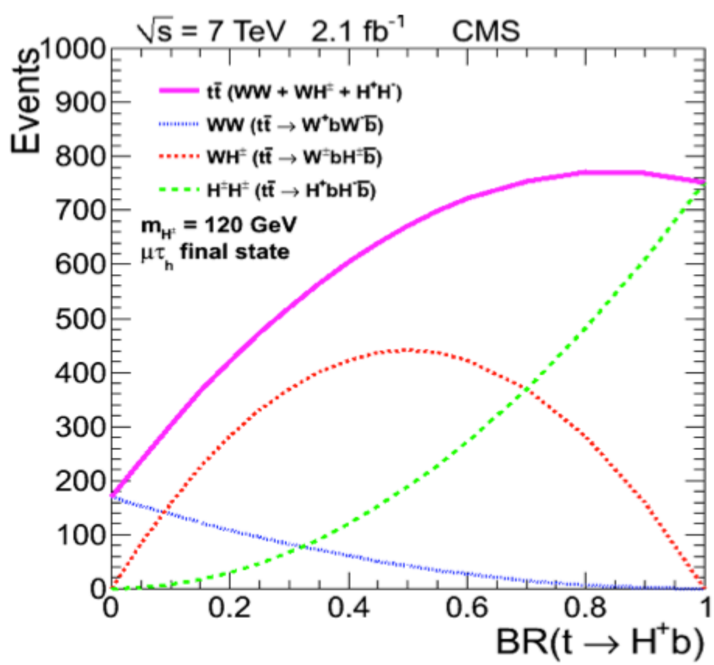
Charged Higgs

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

⇨observe more taus

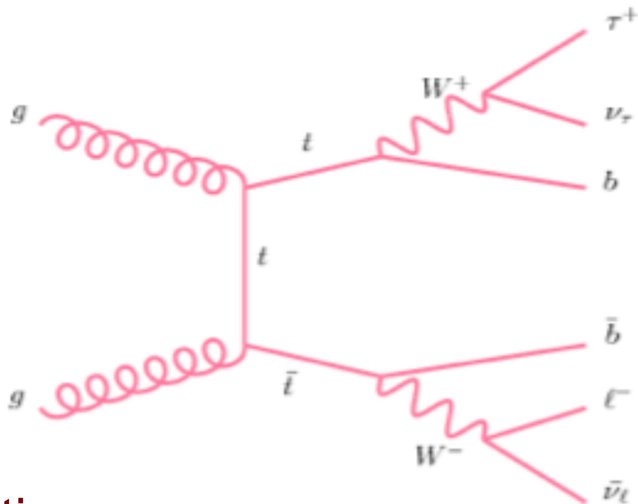
(tanβ: ratio of vacuum expectation values)



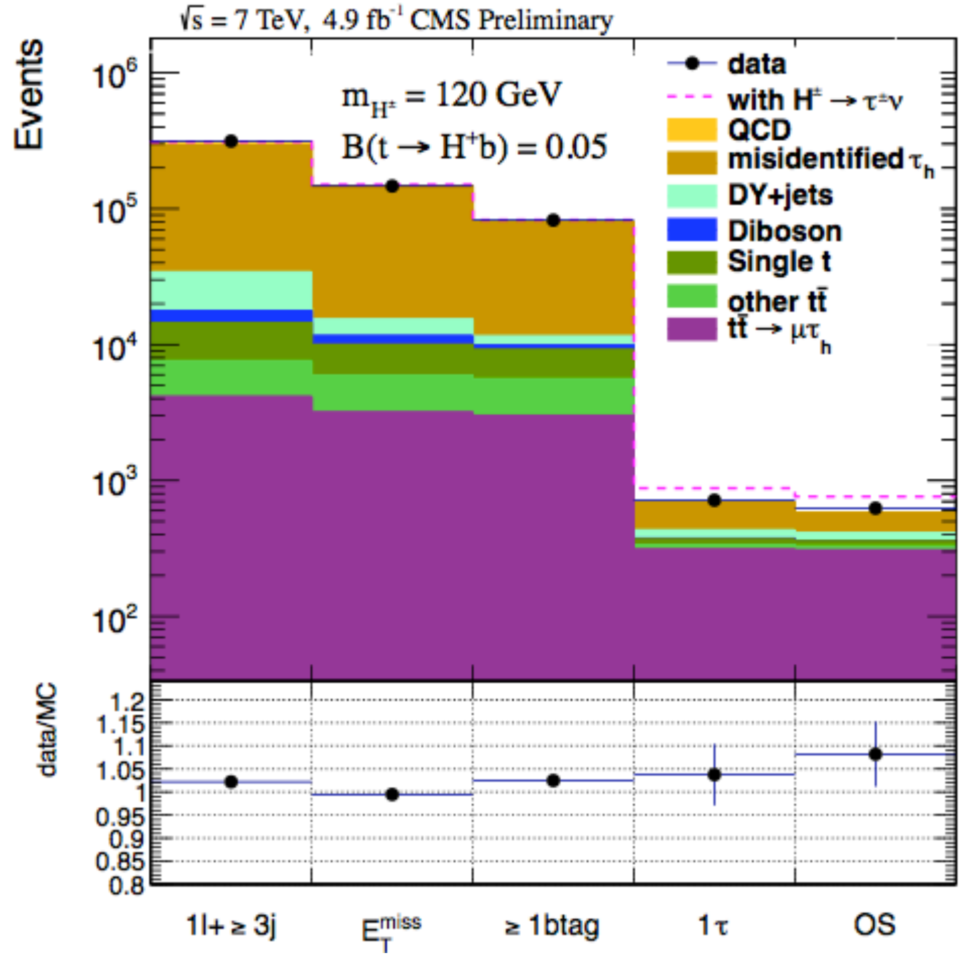


⇨number of tau dilepton events can be large

Taus in top quark decays

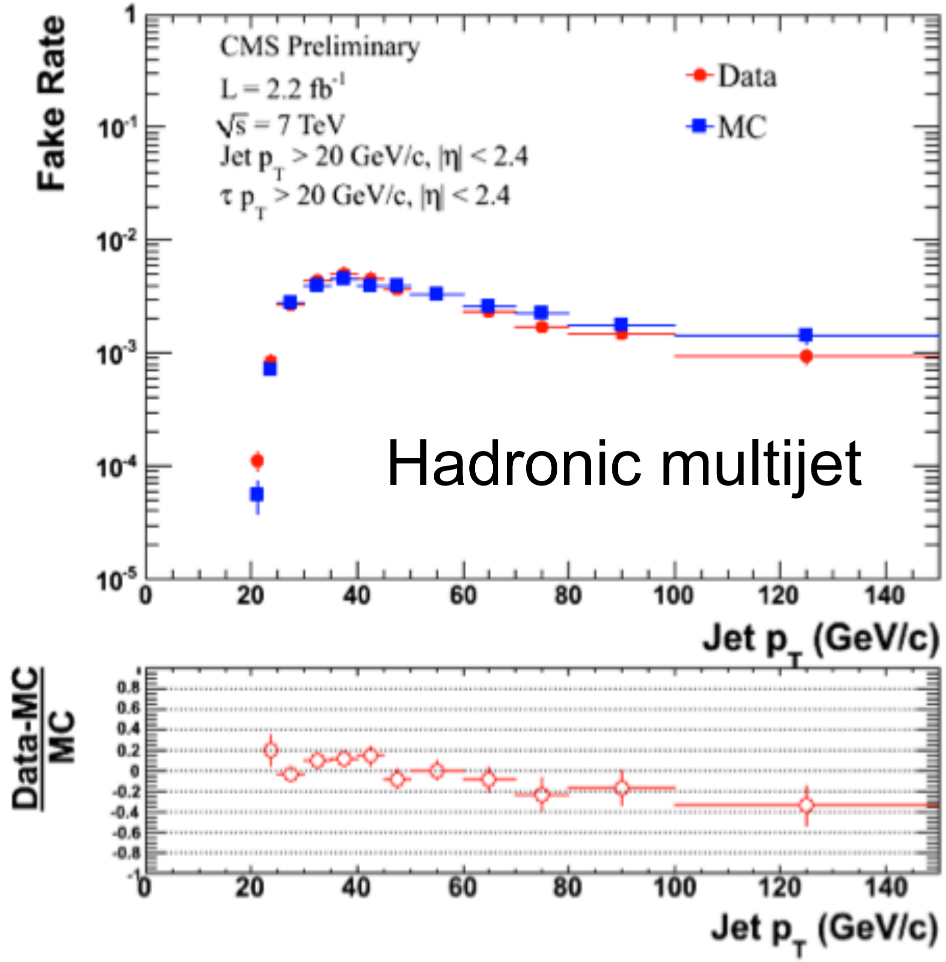


- Selection:
  - one isolated lepton (e/μ)
  - OS tau
  - at least two jets (one b-tagged)
  - MET>30 (45) GeV
- Determine τ fakes from data
  - Expected to be dominated by quark/gluon jets
  - Conservative approach: average W+jets and QCD



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

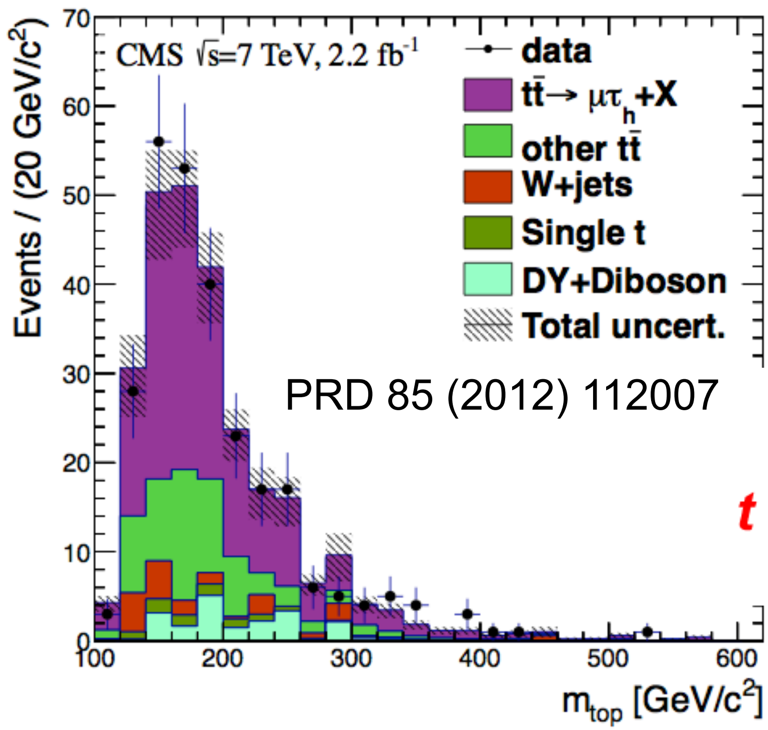


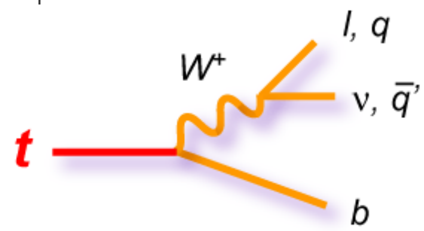
Quark vs gluon jets:

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

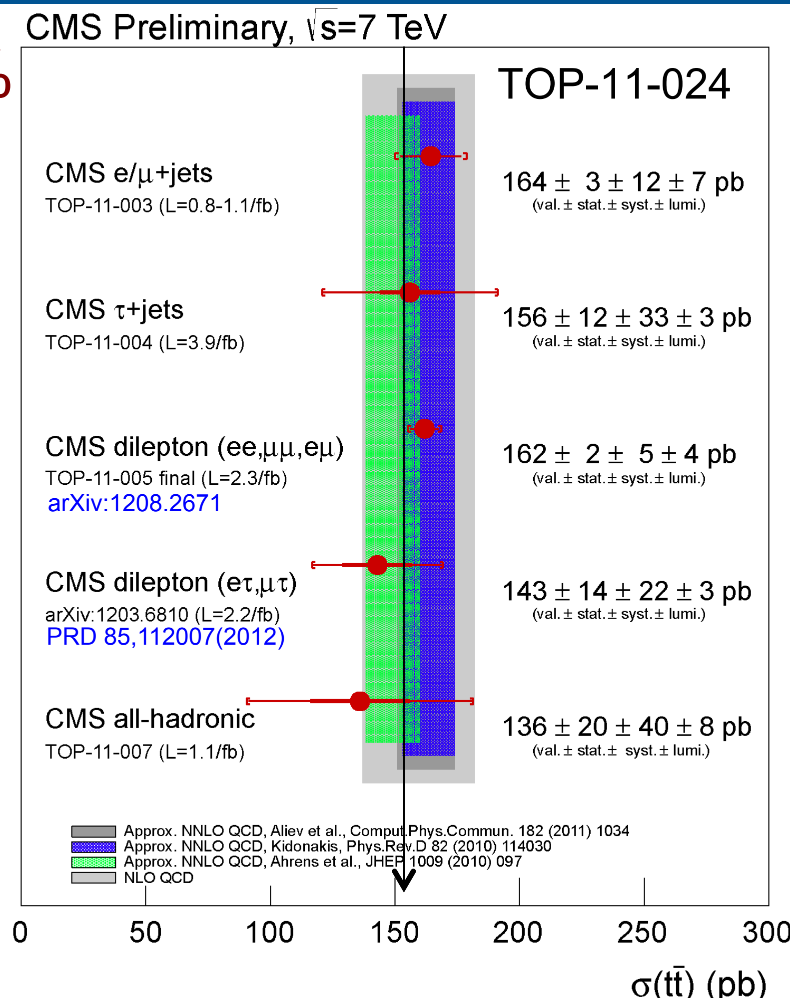
Tau dilepton channel

Reconstruct mass in ttbar events with taus





±4%



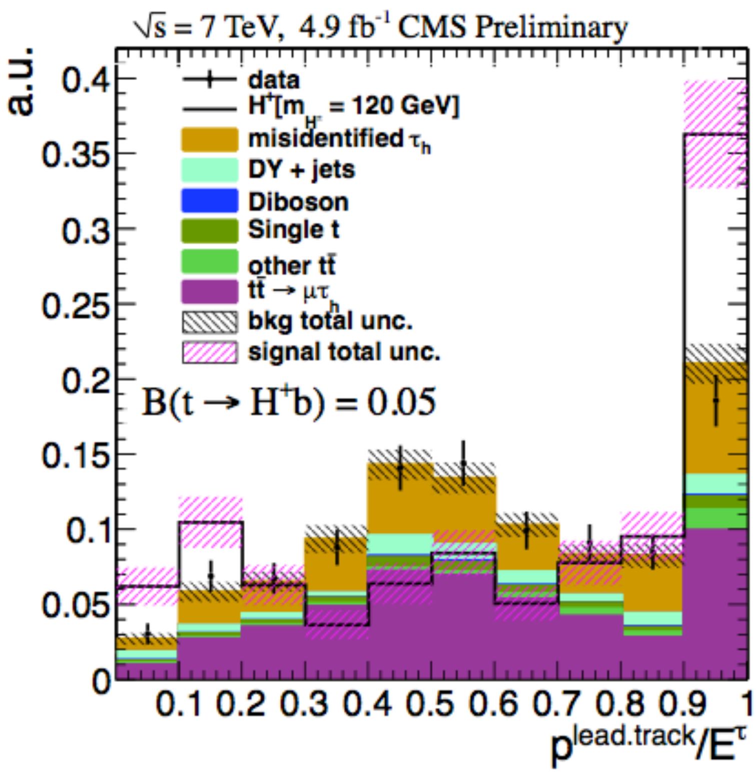
Good agreement between measurements and predictions (for all decay modes)

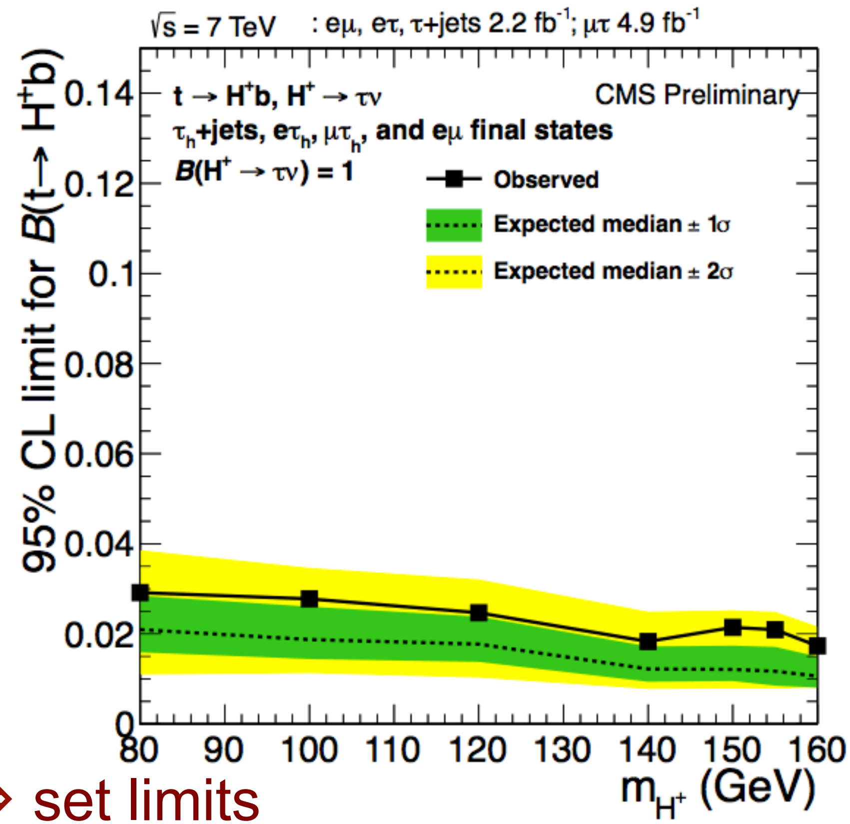
PLB 717(2012)89 $$\sigma_{t\bar{t}} = 186 \pm 13\ (\text{stat.}) \pm 20\ (\text{syst.}) \pm 7(\text{lumi.})\ \text{pb}$$ ATLAS ±15%

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. $BR(t \to H^+b) < 2-3\%$

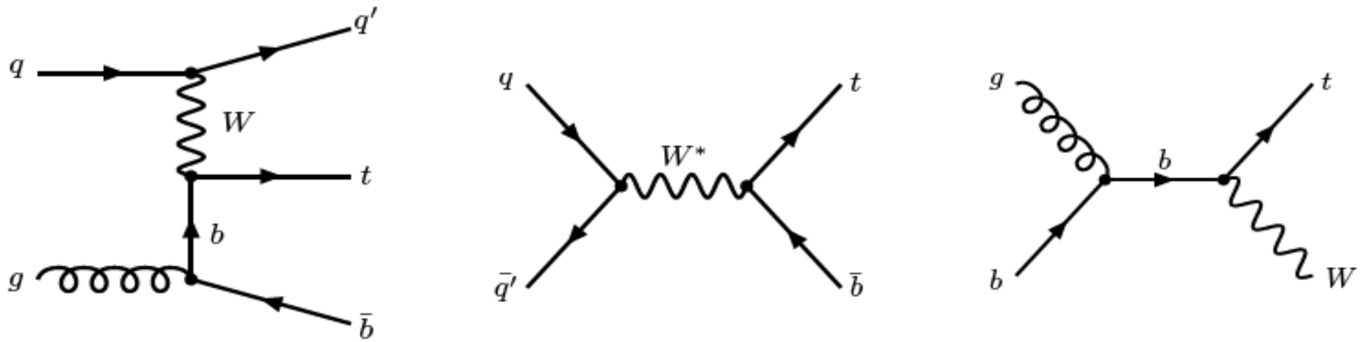
CMS HIG-11-019

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

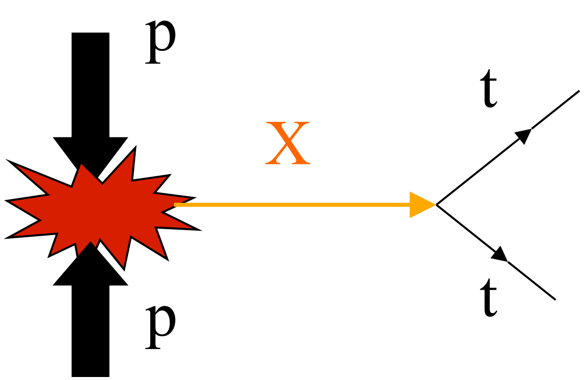
Kidonakis,N. PRD83:091503,2011

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

Kidonakis,N. PRD81:054028,2010

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

Kidonakis,N. PRD82:054018,2010



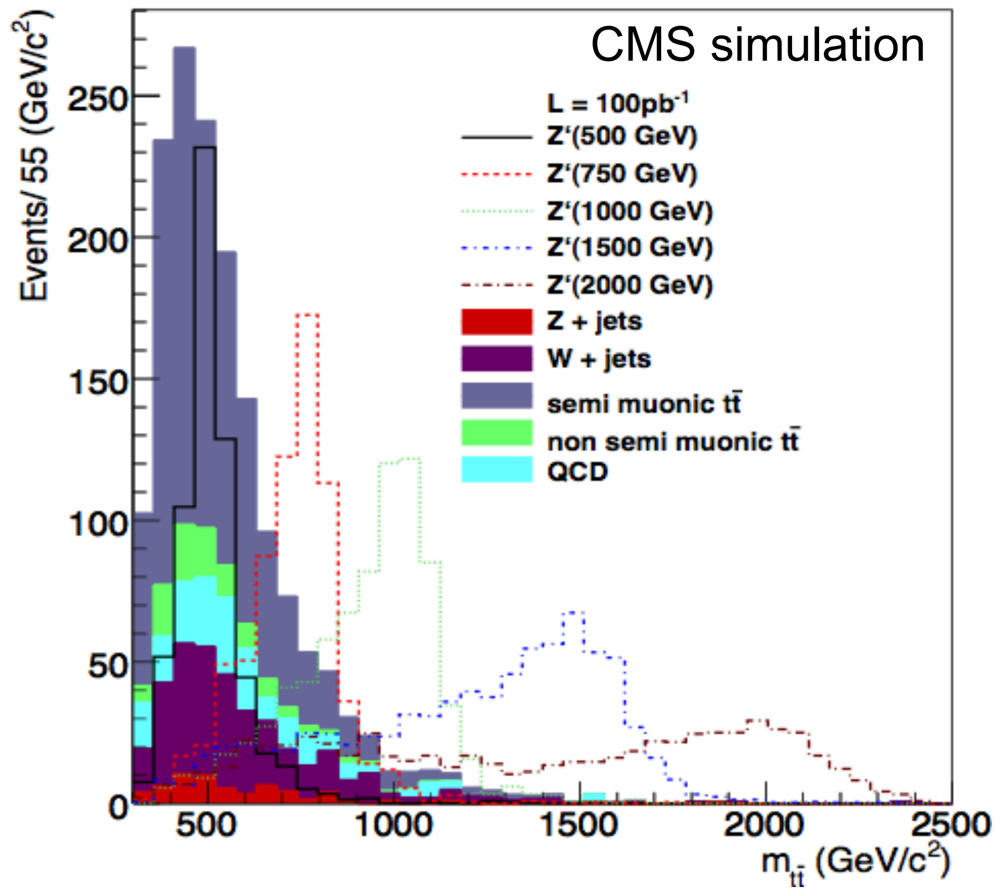
Resonance Production?
Top Color-Assisted Technicolor
OR
?????

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

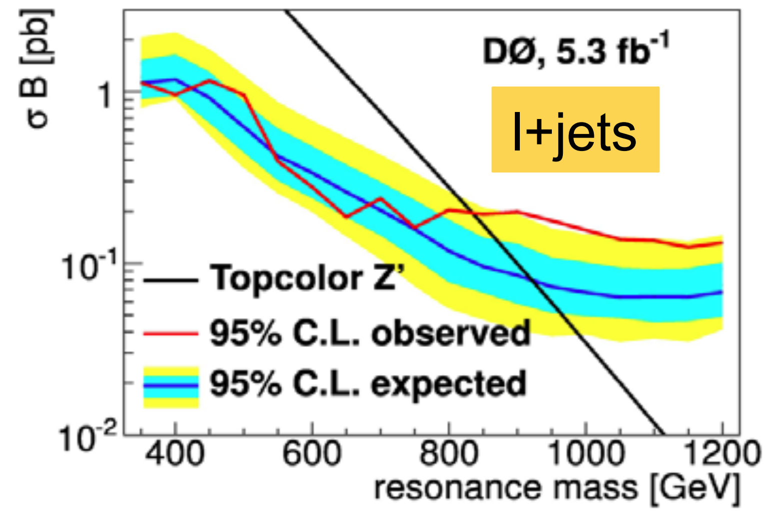
Search for resonances

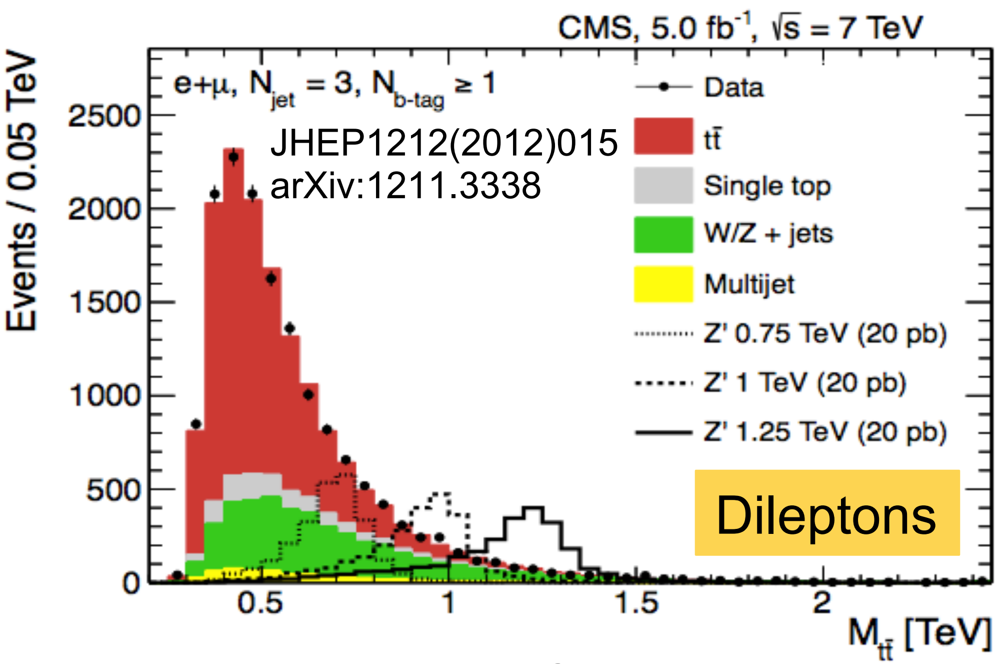
- Semi-leptonic (muon+jets) channel
- Z' → ttbar cross section normalized to SM ttbar
- Progressive loss in reconstruction ability due to jet merging

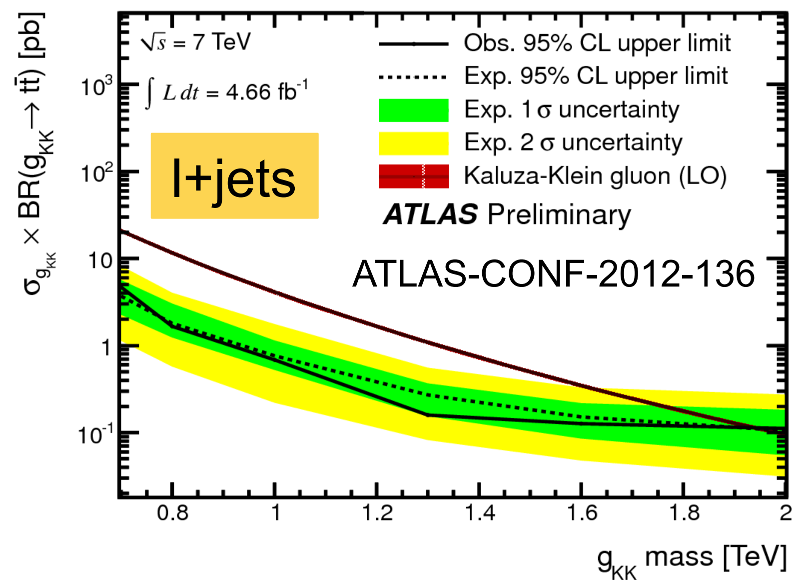


Search for heavy resonances

- 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)







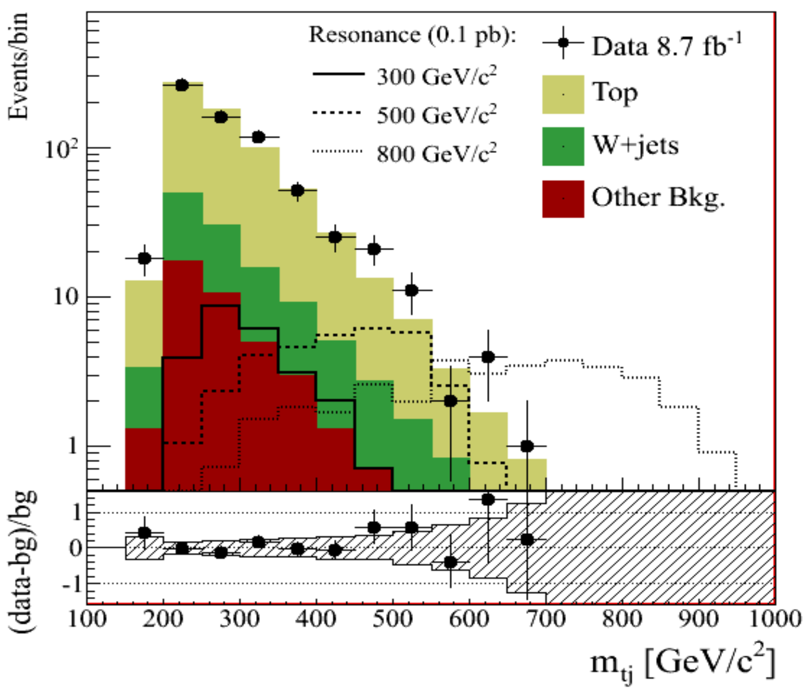
Search for ttbar+jet resonance

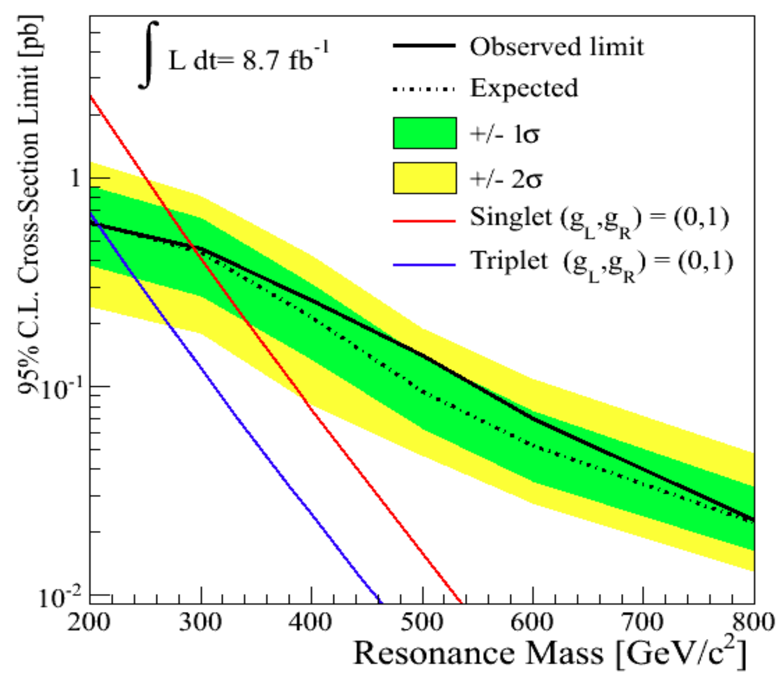
- Search for a heavy new particle M produced in association with a top quark:

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

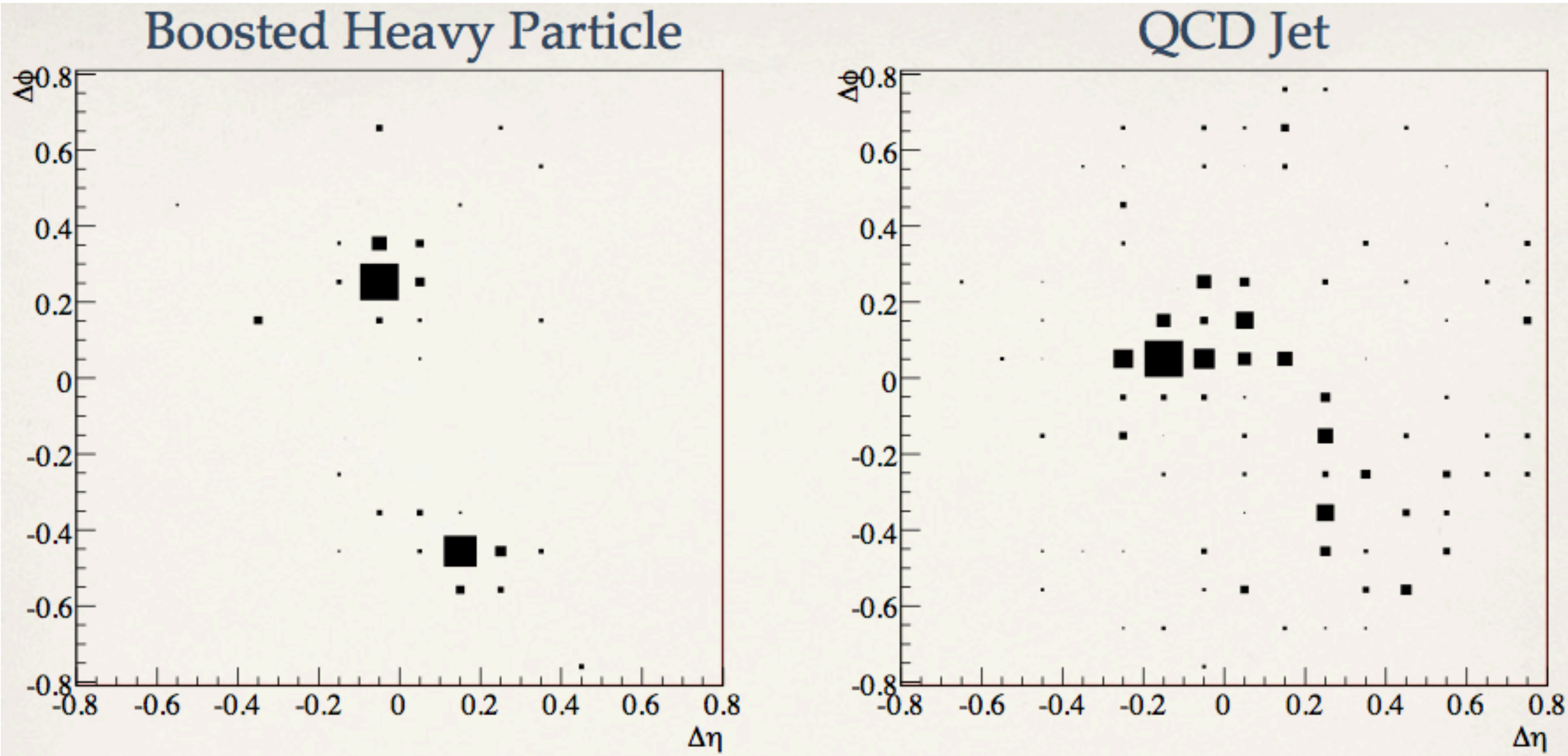
- Resonance in the system t+jets ot ttbar+jets
- Select events in lepton+jets channel with at least 5 jets and 1 b-tag

CDF: 8.7 fb^{-1}

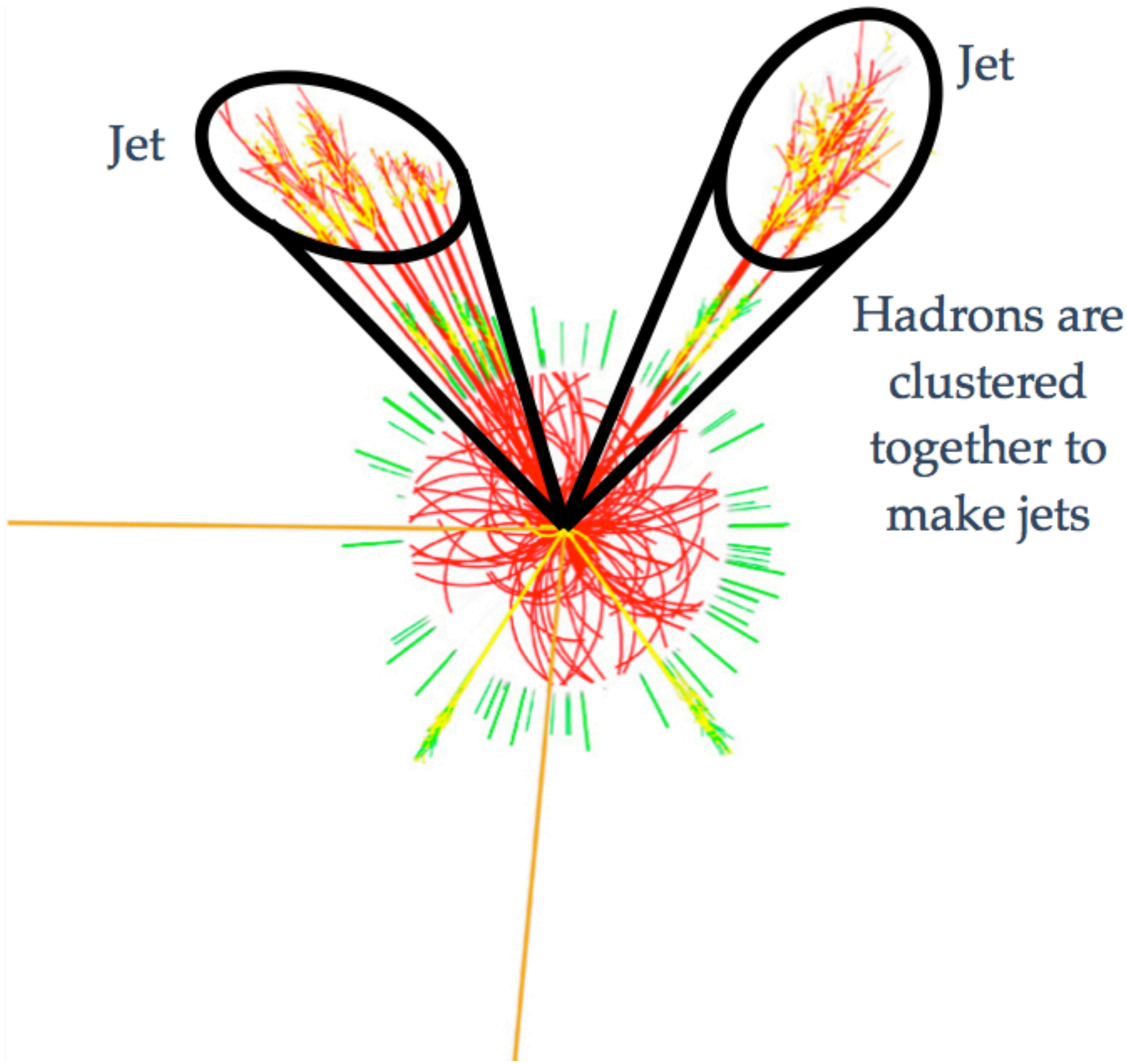




Boosted topology



Jets and boosted topology

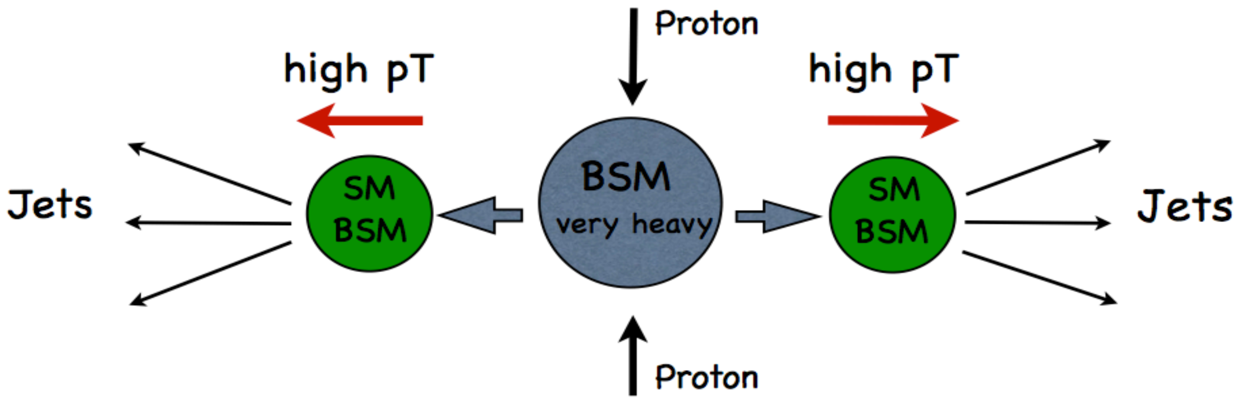


Boosted topology

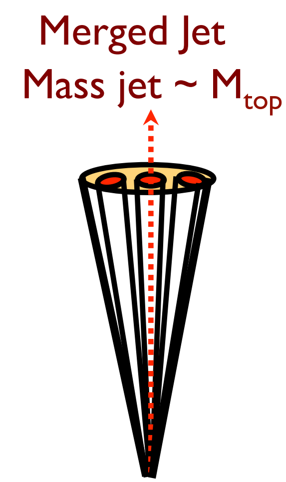
- In many models there is high potential to discover new physics in the top sector in search for heavy resonances

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

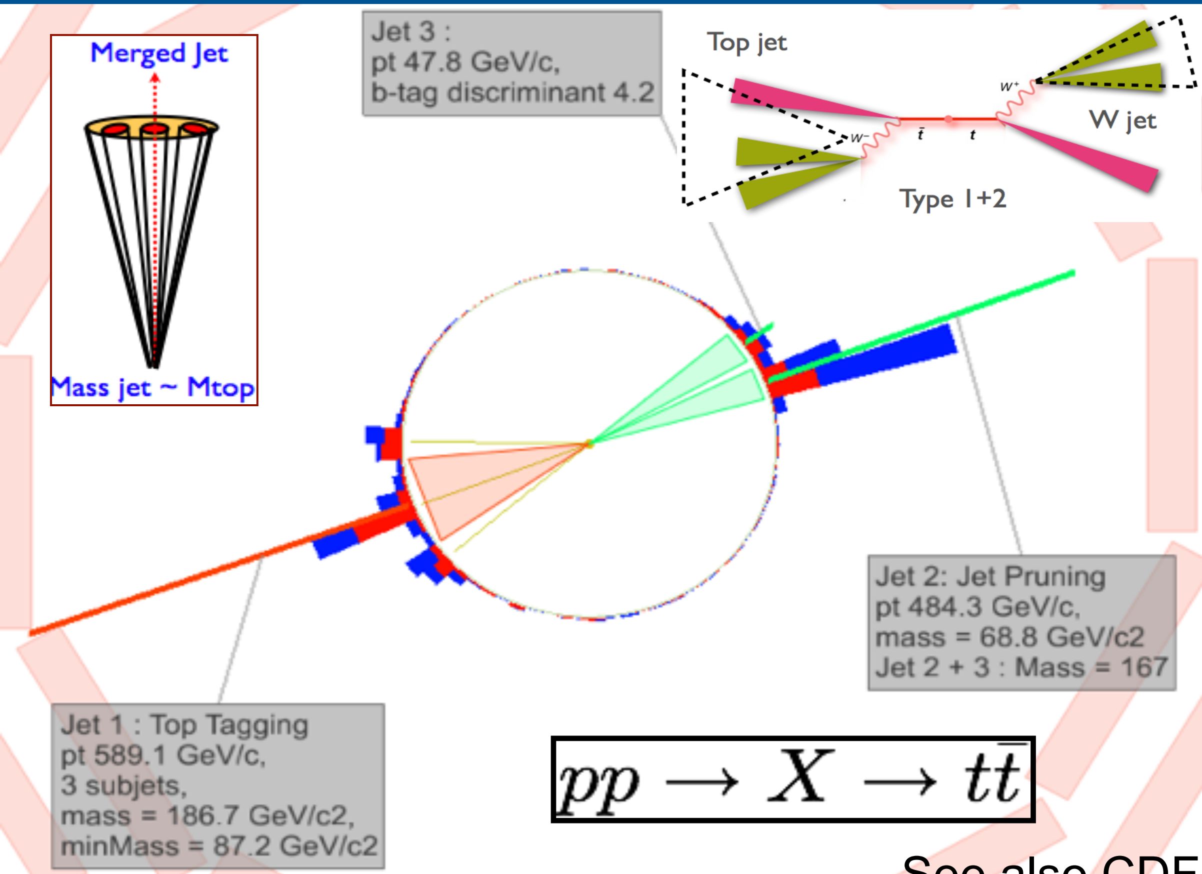
- Simple approach to merge neighboring jets



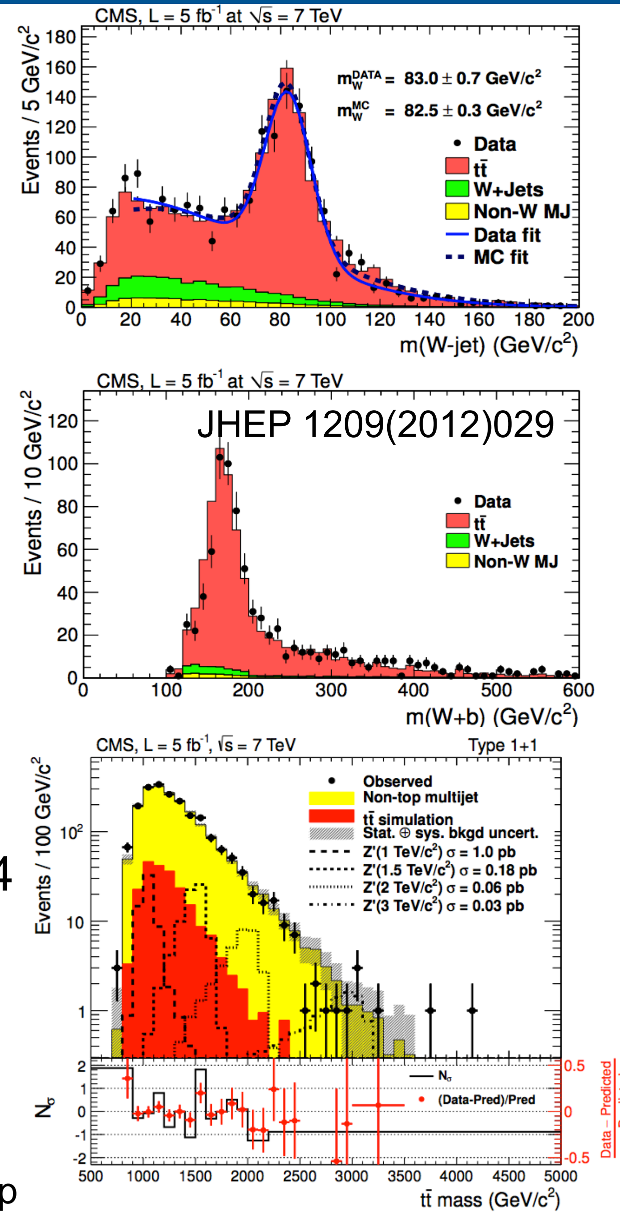
- At LHC energy, EWK scale particles produced beyond threshold
- Jets are highly collimated
- Jet-parton matching breaks down
- Decay products and FSR collected in a fat jet



Boosted jet topology



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

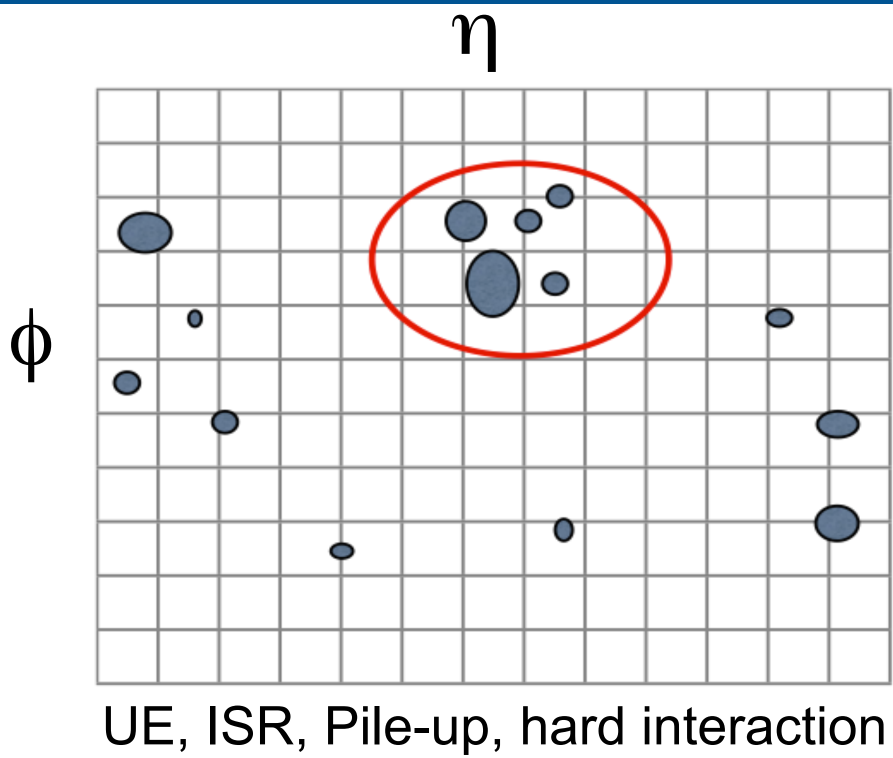


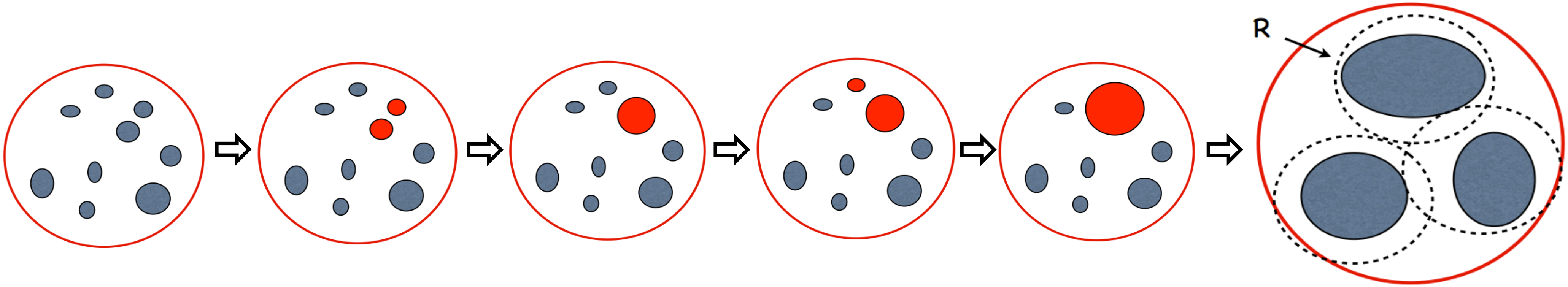
See also CDF note 10234

- 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

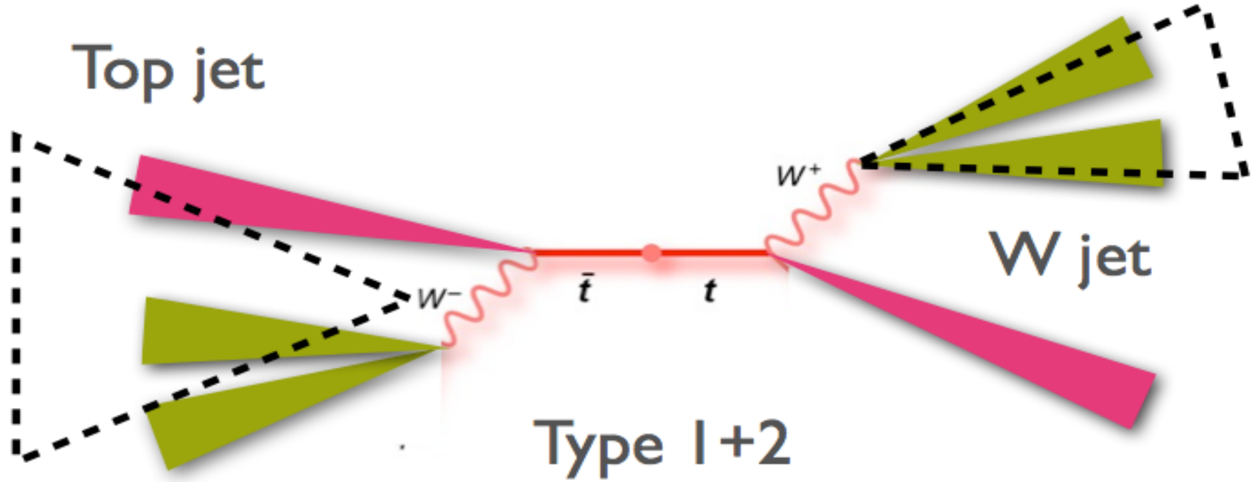
- Locate hadronic energy deposit in detector by choosing initial jet finding algorithm
- Impose jet selection cuts on fat jet
  - Recombine jet constituents with new algorithm
  - Filtering: recombine n sub-jets min d(i,j)
  - Trimming: recombine sub-jets with min p_T
- Minimum distance between jets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





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

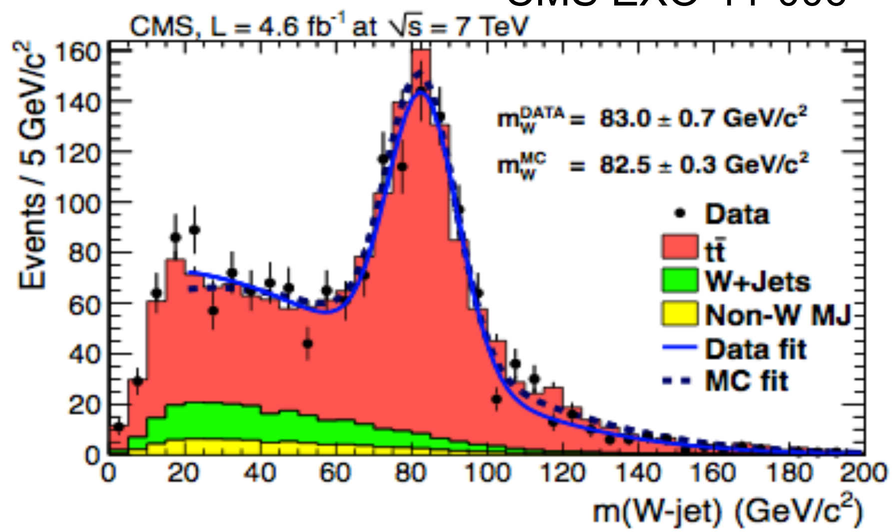


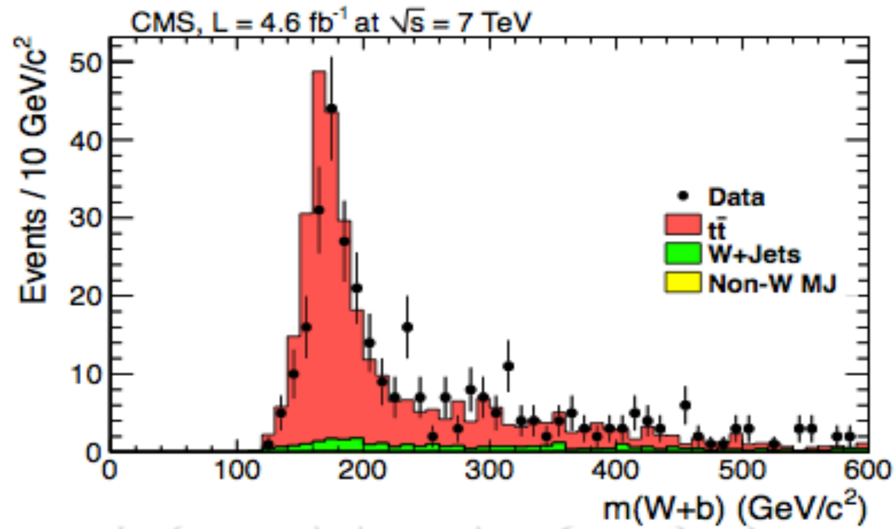
Boosted top topology

Tested using hadronic top in semilep. tt events:

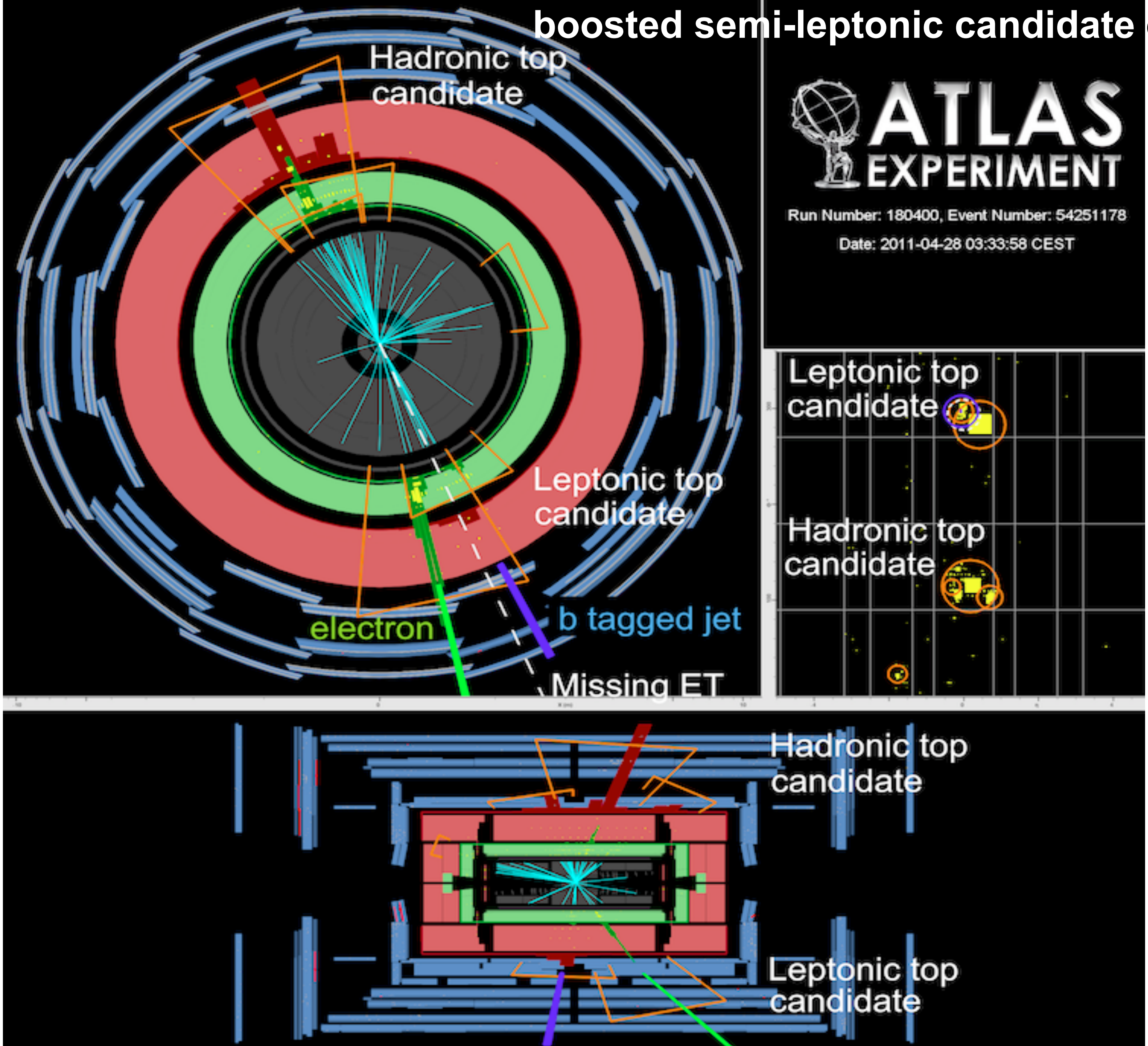
- One high-pT isolated muon from PV.
- At least two jets p_T>30 GeV with a leading jet p_T>2 GeV and at least one b-tagged jet
- Events with W tagged jets used to reconstruct the \ and the top mass of the hadronic side

CMS EXO-11-006



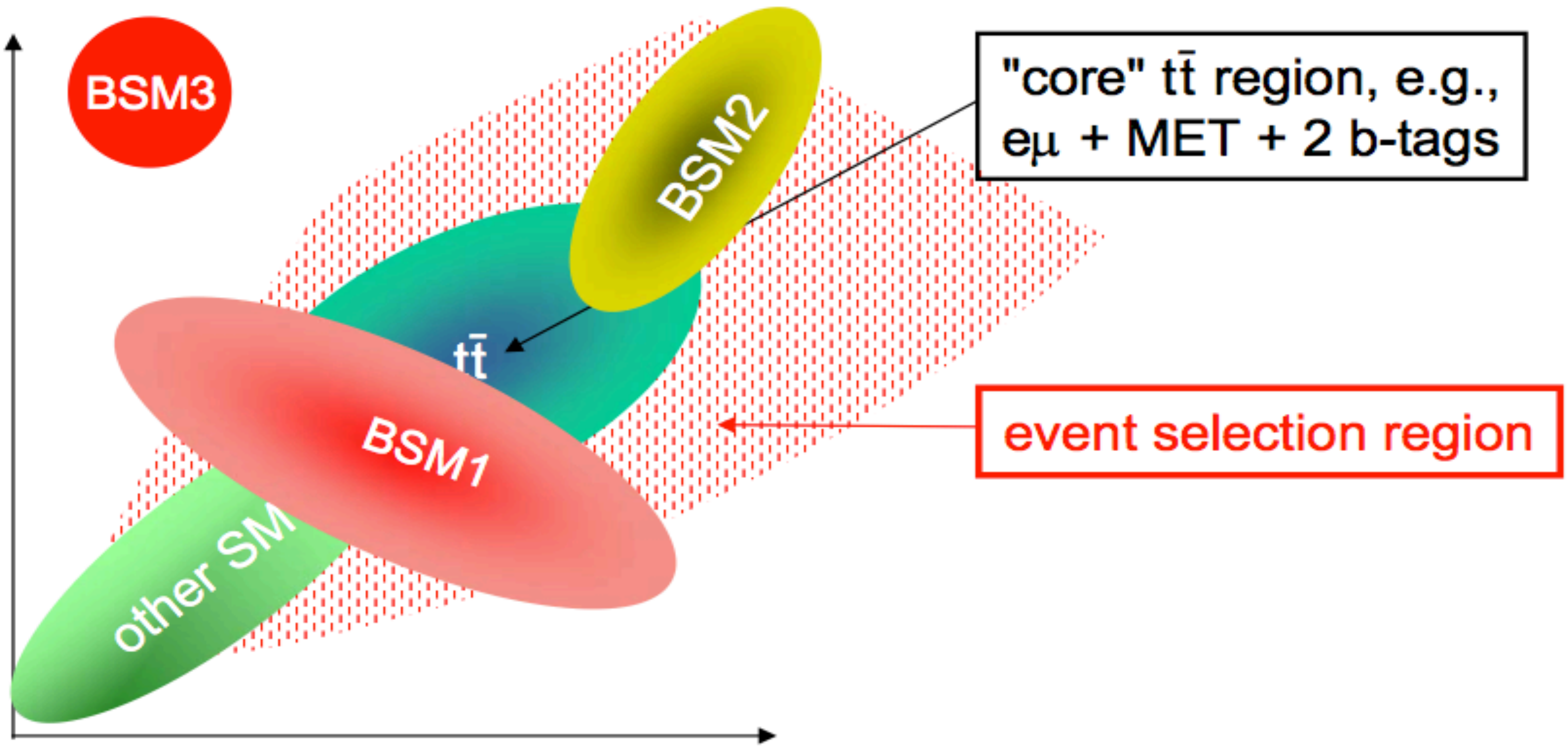


boosted semi-leptonic candidate event



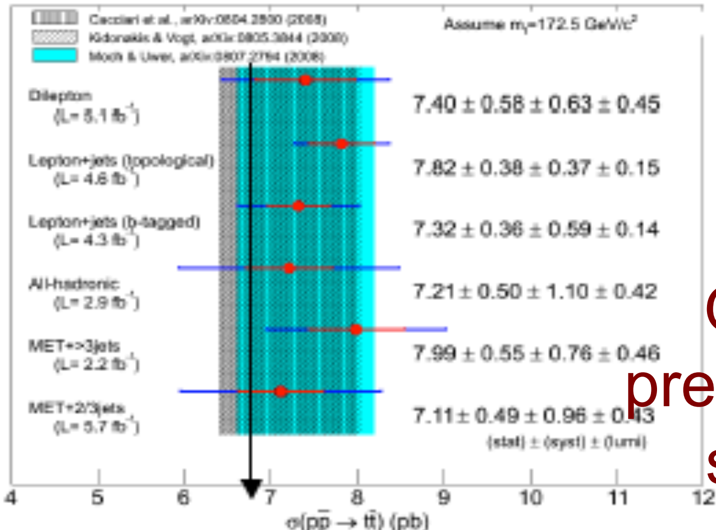
Top quark and new physics

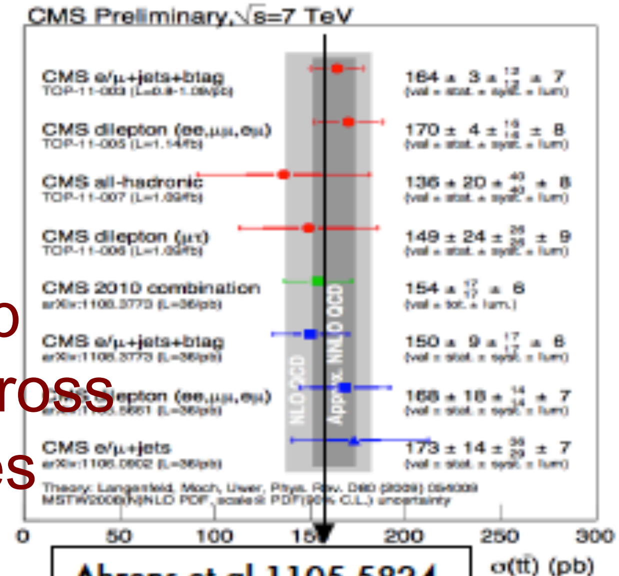
- Top quark production is main background in many searches for new physics
- Top quark sample may be contaminated by NP processes
- Is top quark sample compatible with top quark SM hypothesis?
- Need to compare distributions, gain good understanding of top sample



SUSY and 4th generation

Cross section measurements

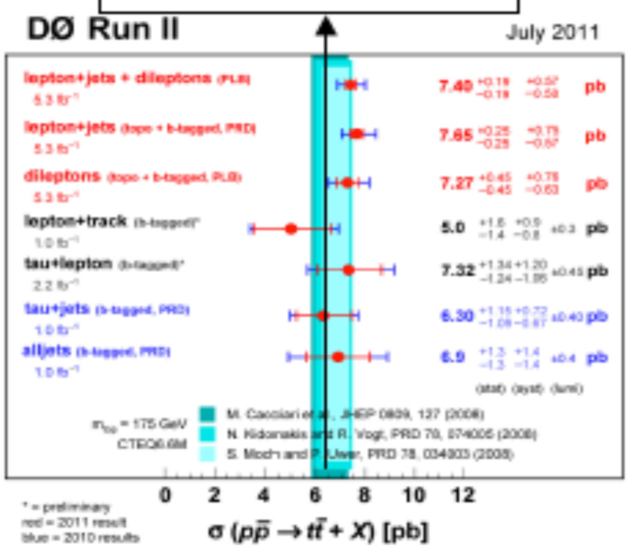


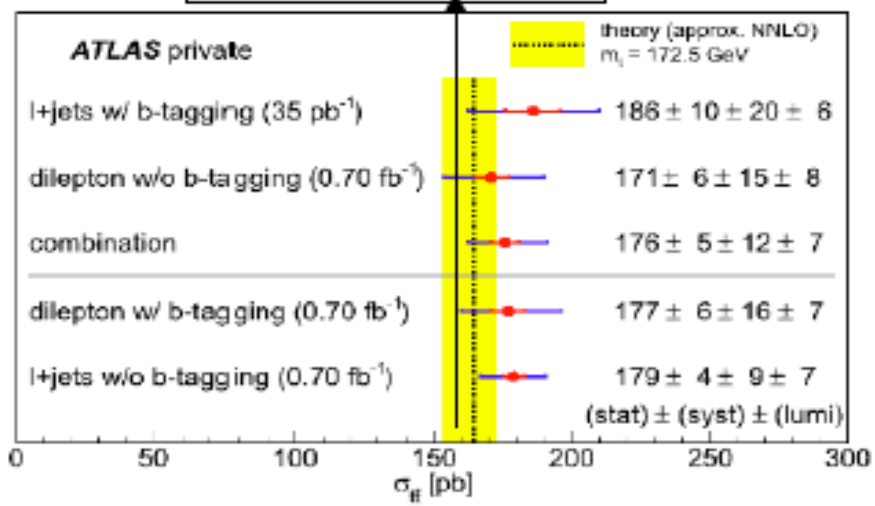


One th. group predicts lower cross section values

Ahrens et al 1105.5824

Ahrens et al 1105.5824

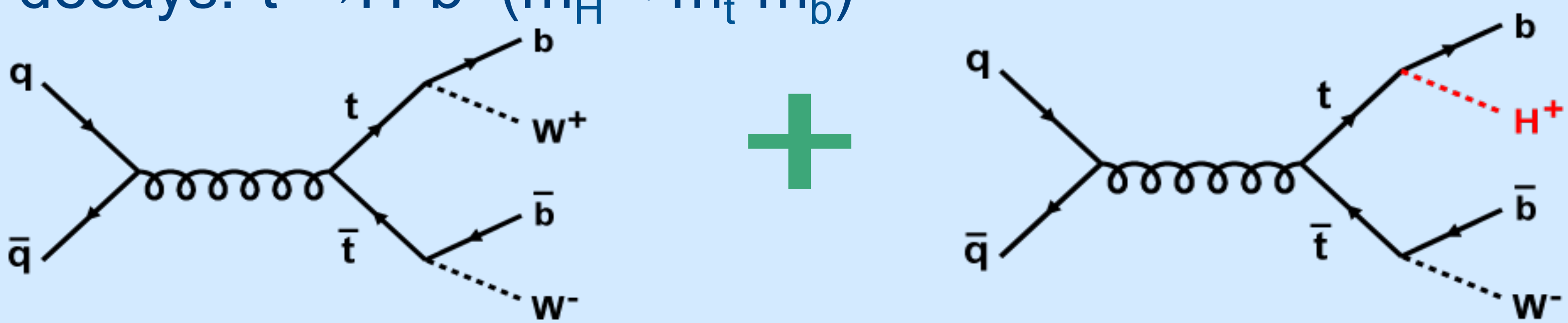




Charged Higgs

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
$t\bar{t} \rightarrow W^+W^-b\bar{b} \rightarrow \tau\nu_\tau l\nu_l b\bar{b}, \qquad l = e, \mu.$

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

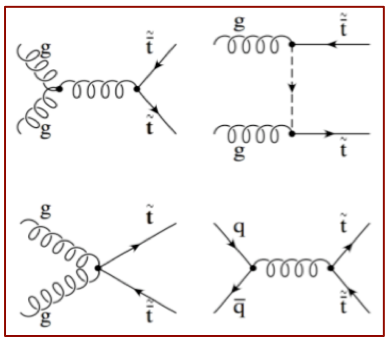


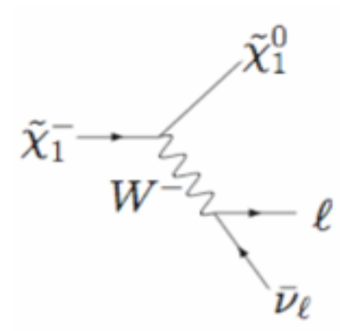
Implies a larger measured cross section (see MG, Lecture #6)

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

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:

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

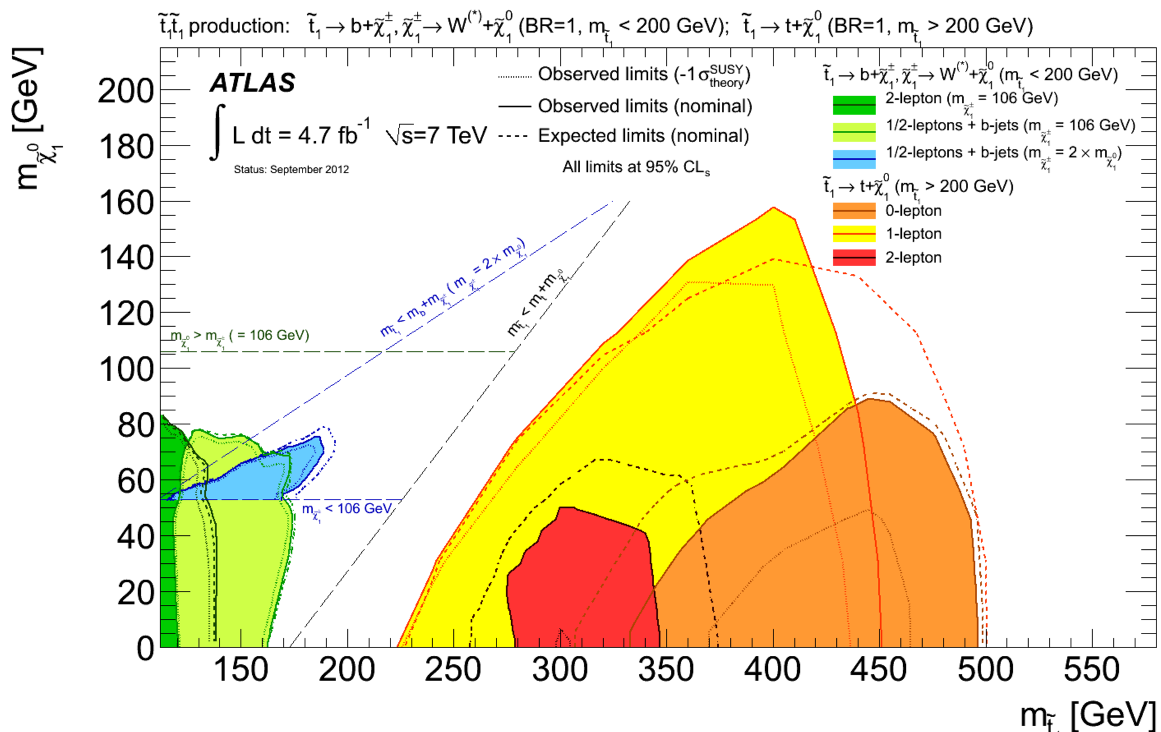
- Heavy stop:

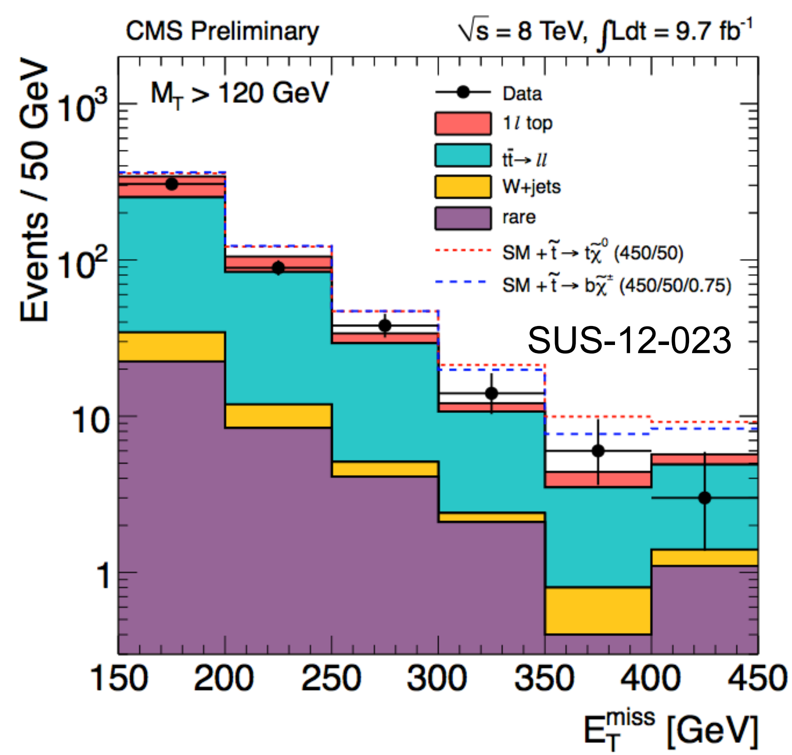
$$\tilde{t} \rightarrow t\tilde{\chi}^0$$

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:

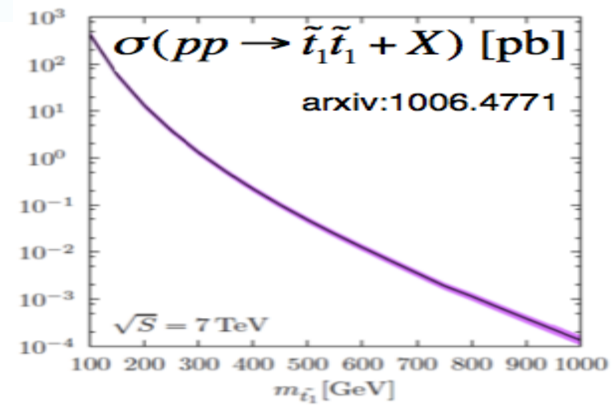
$$\tilde{t} \rightarrow t\tilde{\chi}_1^0 \rightarrow bW\tilde{\chi}_1^0$$
$$\tilde{t} \rightarrow b\tilde{\chi}_1^+ \rightarrow bW\tilde{\chi}_1^0$$



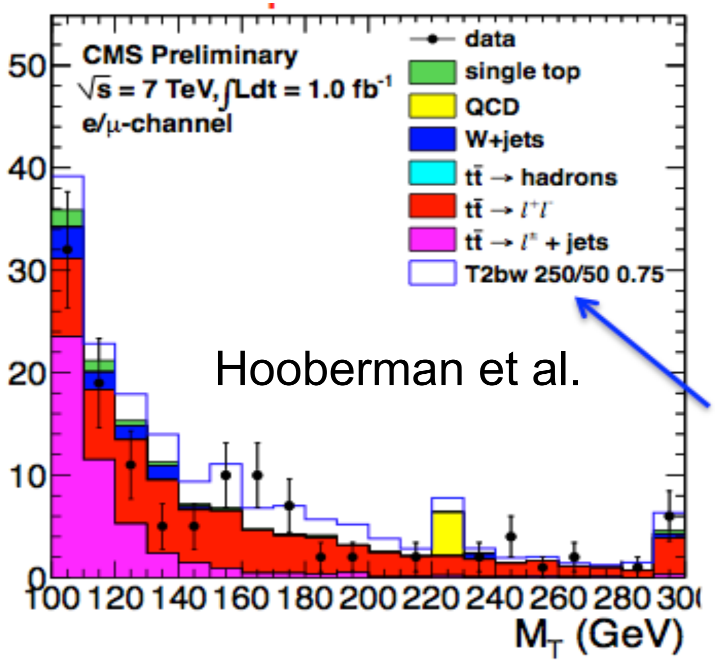


SUSY: search for scalar top

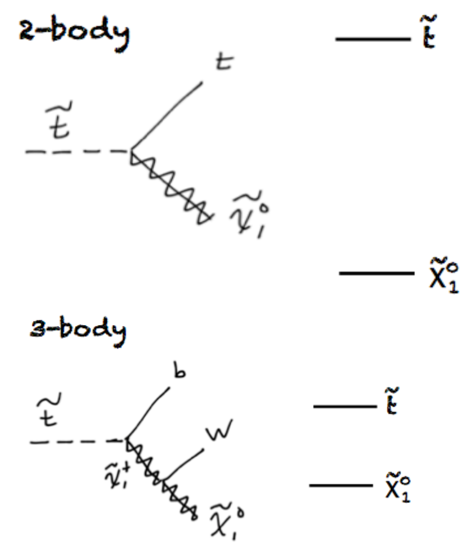
$$\tilde{t}\bar{\tilde{t}} \rightarrow t\bar{t}\chi^0\chi^0 \qquad \tilde{t}\bar{\tilde{t}} \rightarrow b\bar{b}\chi^+\chi^- \rightarrow b\bar{b}W^+W^-\chi^0\chi^0$$



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



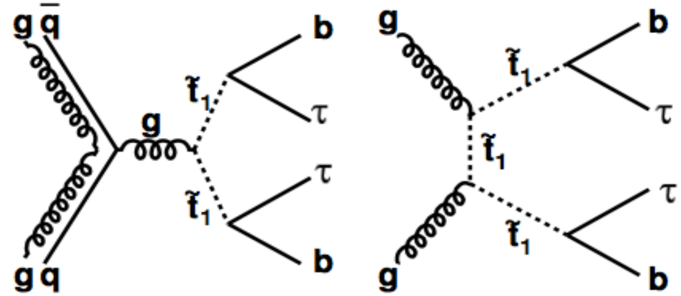
example signal:
stop(250) → b χ±
m(χ⁰) = 50 GeV
x = 0.75



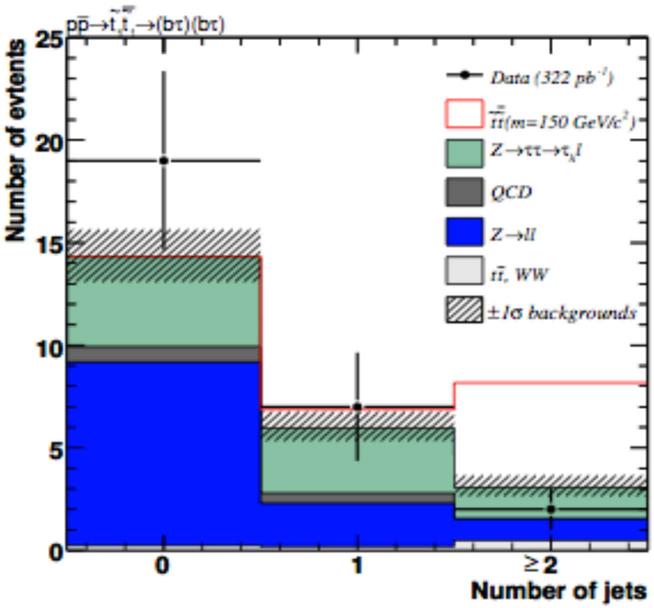
Taus

- 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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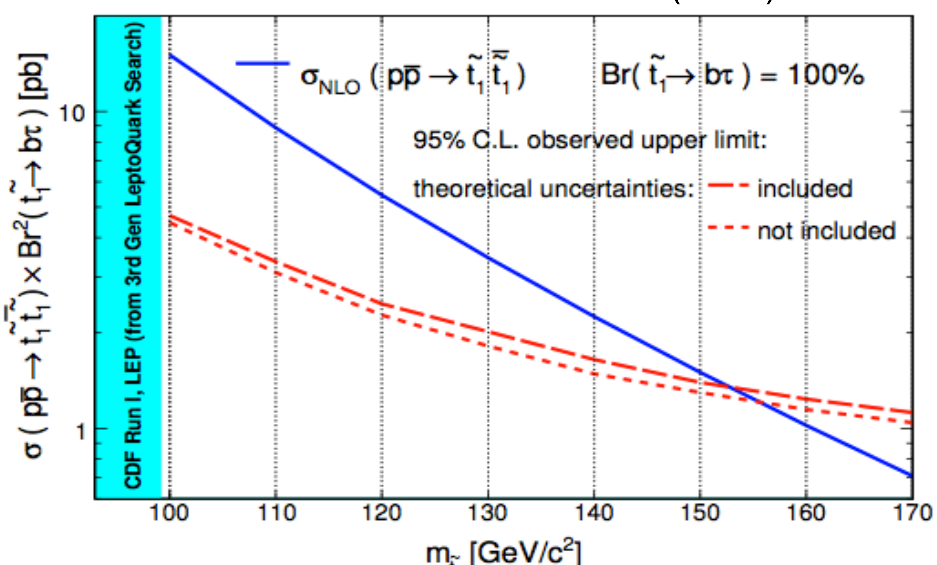
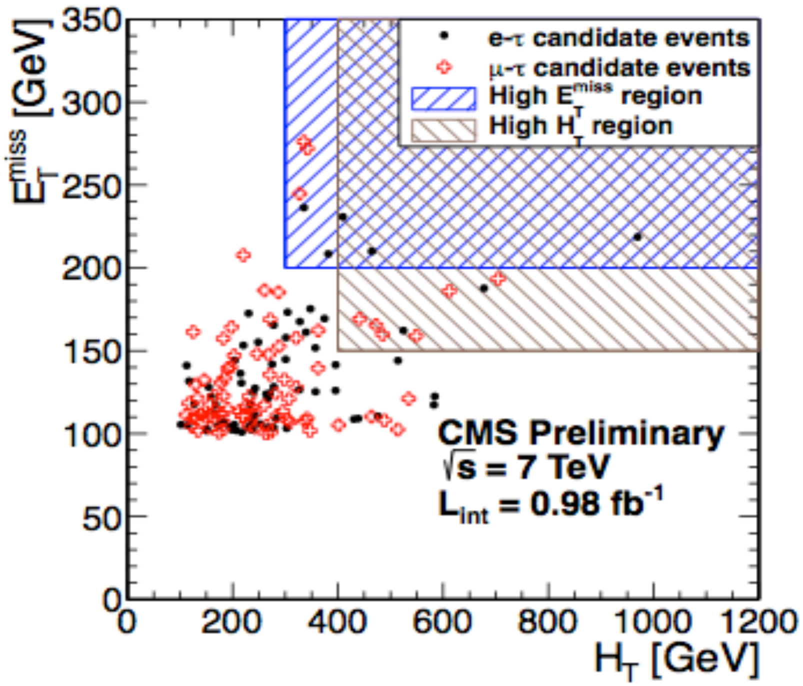
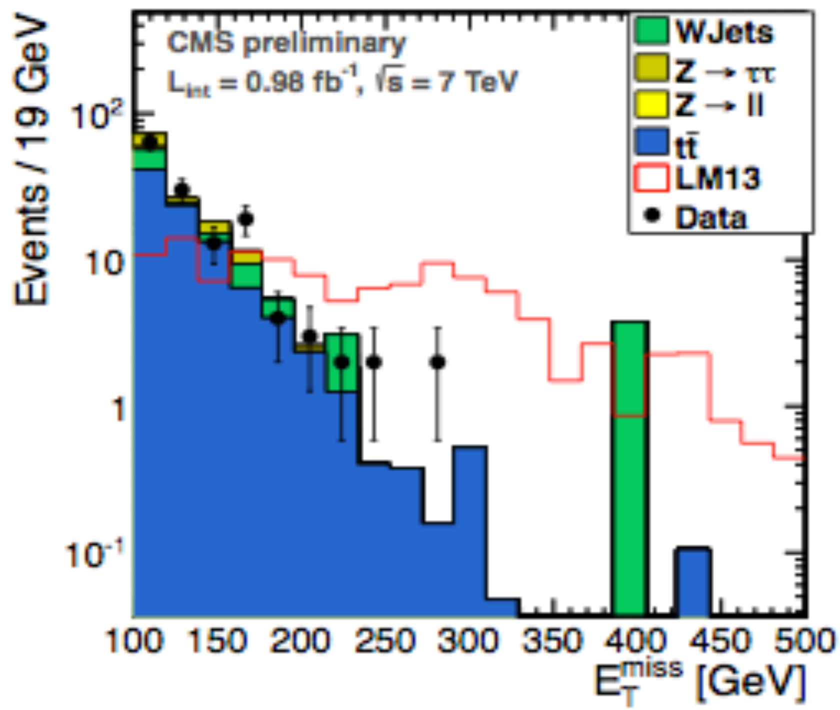


Search for Dark Matter with taus

CMS SUS-11-007

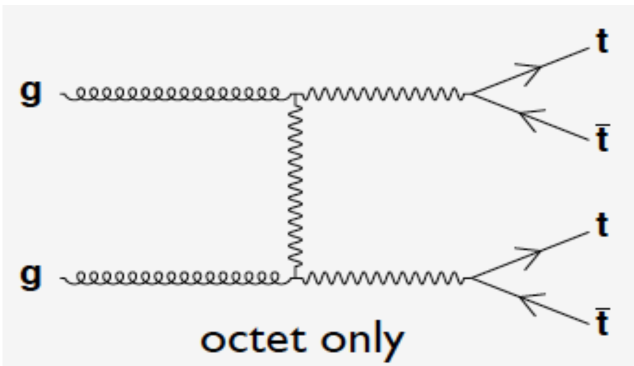
- search concentrates on heavy BSM particle production
  - astrophysical evidence for dark matter points to the existence of weakly-interacting massive particles (WIMPs) at EWSB scale
  - These particles escape detection ⇒ large MET
- Not constrained to a specific theory
  - general BSM search in events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

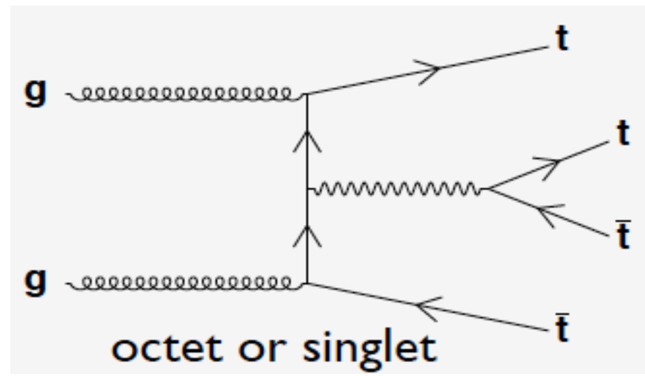




Multi-top production

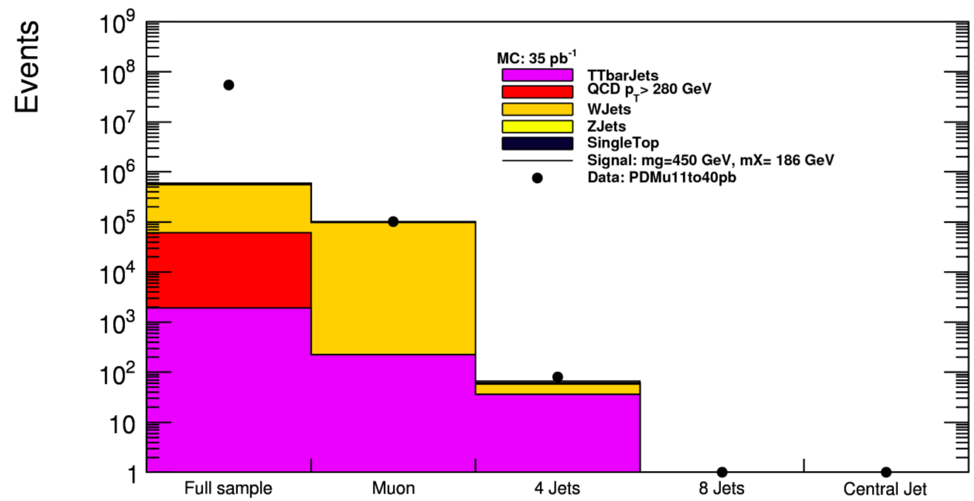
- Production of 4 tops is an attractive scenario in a number of new physics models (SUSY, compositeness, resonances strongly coupled to top, etc.)
- The SM cross section is a few fb





Multi-top in SUSY? $\tilde{g}\tilde{g} \rightarrow t\bar{t}t\bar{t}\chi_0\chi_0$

- Example: require one muon, at least 8 jets (one central)
- Yields in 30 fb^{-1} (gluino mass 450 GeV):
  - 330 signal events, 120 ttbar+jets, 30 W+jets



Multi-top production

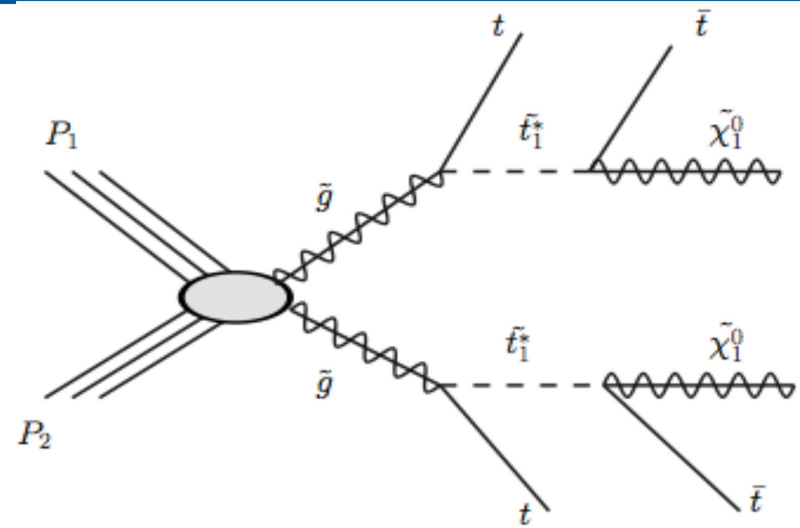
CMS SUS-11-020

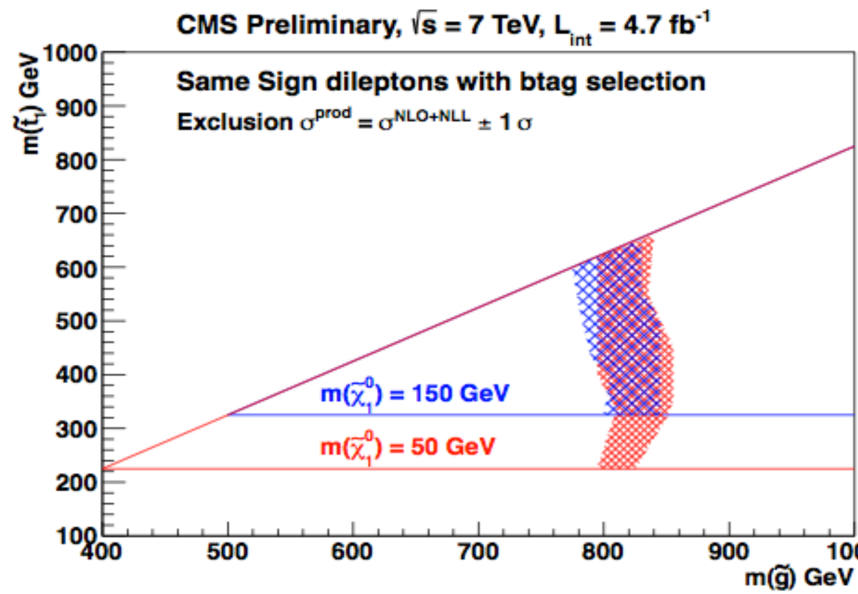
- SUSY models with four top quarks
- Consider models of gluino pair production

$$\text{Type A1}: \quad \tilde{g} \to t\bar{t}\tilde{\chi}_1^0$$
$$\text{Type A2}: \quad \tilde{g} \to \tilde{t}_1\bar{t}, \quad \tilde{t}_1 \to t\tilde{\chi}_1^0$$ (stop on-shell)

- Fina

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





Multi-top production

CMS SUS-11-020

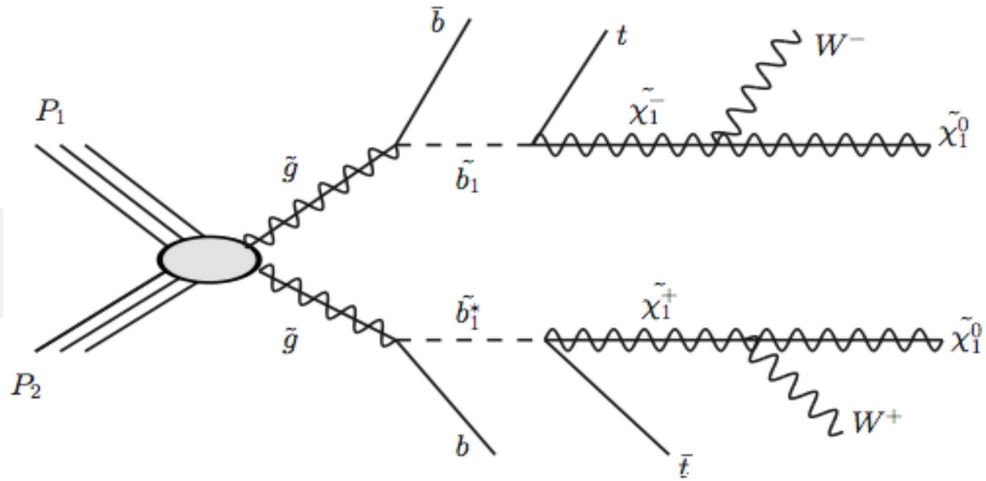
- Study of SUSY signal with pairs of sbottom quarks

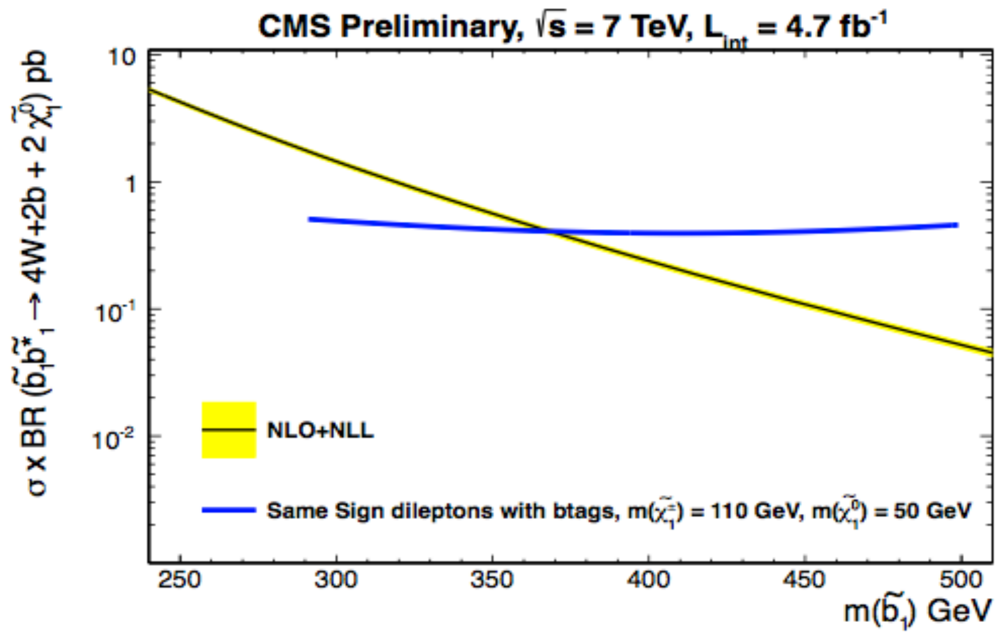
$$\tilde{b}_1 \to t\tilde{\chi}^-$$

$$\text{Type B1}: \quad pp \to \tilde{b}_1\tilde{b}_1^*$$
$$\text{Type B2}: \quad pp \to \tilde{g}\bar{\tilde{b}}_1, \quad \tilde{g} \to \tilde{b}_1\bar{b}$$

- Final states with up to 4 isolated leptons

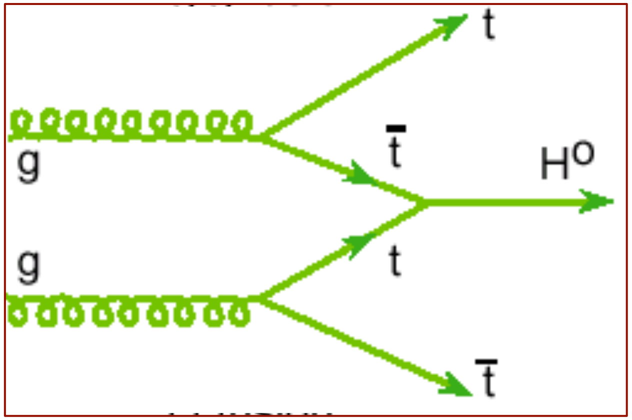
$$m(\tilde{b}_1) > 380 \text{ GeV } @95\%C.L.$$

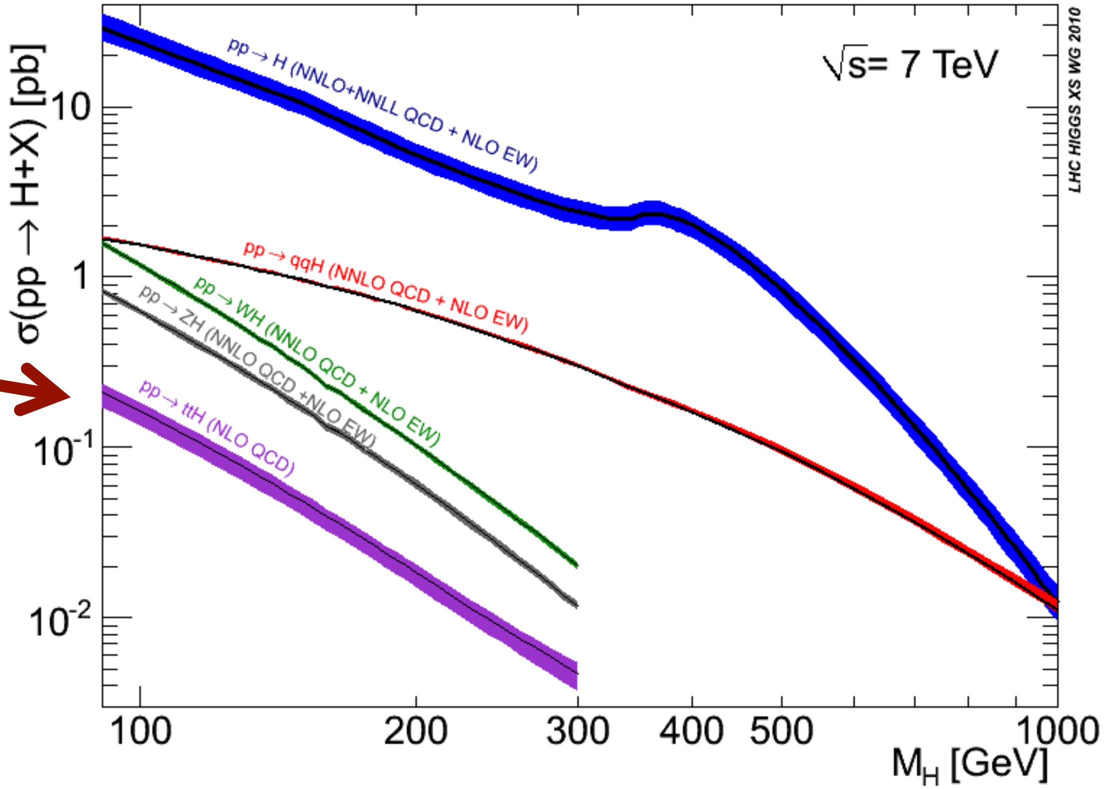




ttbar+Higgs

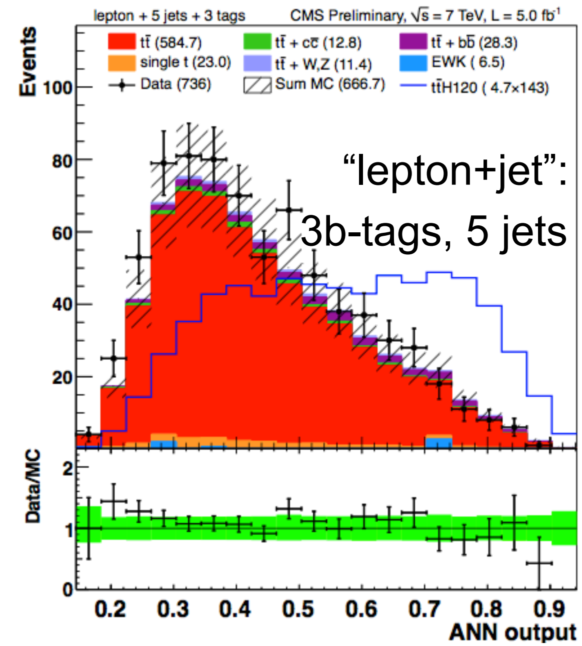
- ttbar produced in association with H
  - ttbar is a “clean” tag
- direct measurement of H couplings

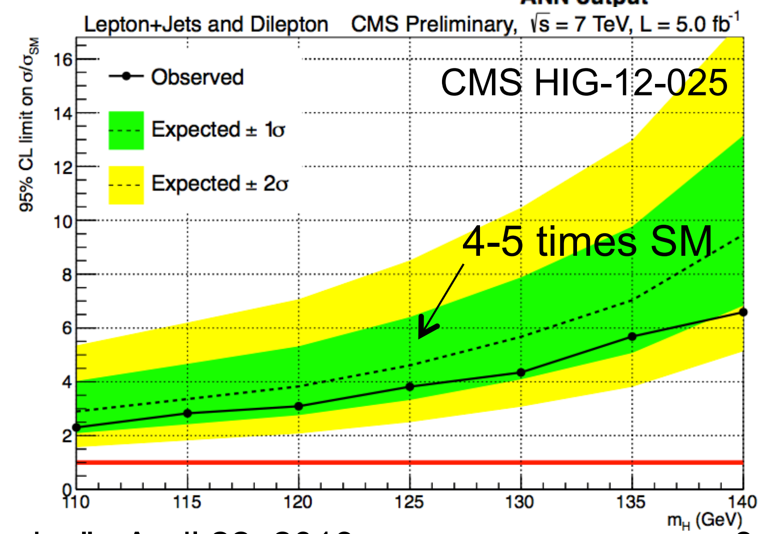




ttbar+Higgs (cont.)

- 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





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