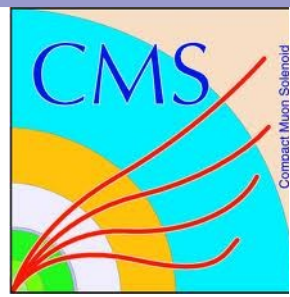


Searches for New Physics with top quarks at CMS

Viola Sordini , IPNLyon

On behalf of the CMS collaboration – B2G group

Outline of the presentation

- Set the scene : New Physics searches in CMS with top quarks
- Get the ingredients : CMS 2012 performance
- Basics of search analyses and common tools
- Review of searches (all on 2012 data) for :
  - resonances decaying to top pair
  - resonances decaying to tb
  - excited top quarks
  - vector-like top partners
  - baryon number violation in top decays
- Conclusions

New Physics in the top quark sector

➔ Top quark provides various handles on new physics
- after the discovery of a particle consistent with a 126 GeV Higgs boson, the hierarchy problem remains a puzzling question
- top quark has a special role because of its large mass

- LHC is a top factory
  - top quarks abundantly produced at the LHC (top pair production cross-section at 8TeV ~225 pb)
- Dedicated New Physics searches (complementary to top quark properties precision measurements) :
  - unusual production modes, exotic top-like particles
  - Rare top quark decays

- CMS B2G group dedicated to non-SUSY new physics searches involving quarks beyond the second generation (close contact with TOP, EXOTICS, SUSY)

Phenomenology of (non-SUSY) new physics connected to top quarks

- Heavy bosons Z', W'
  - Massive Z/W-like bosons in extended gauge theories
  - Kaluza Klein excited states
  - Axigluons
  - Colorons
  - Topcolor models
  - Little Higgs
- 4th generation
- Vector-like heavy quarks (GUT theories)
- Excited top quarks (compositness)
- Rare decays (baryon number violation)
- Many more...

Phenomenology of (non-SUSY) new physics connected to top quarks

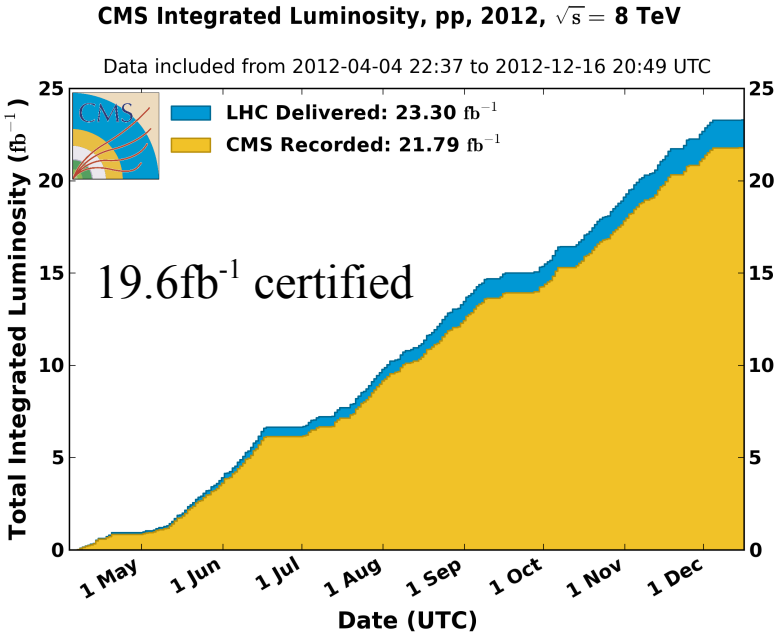
NP in production

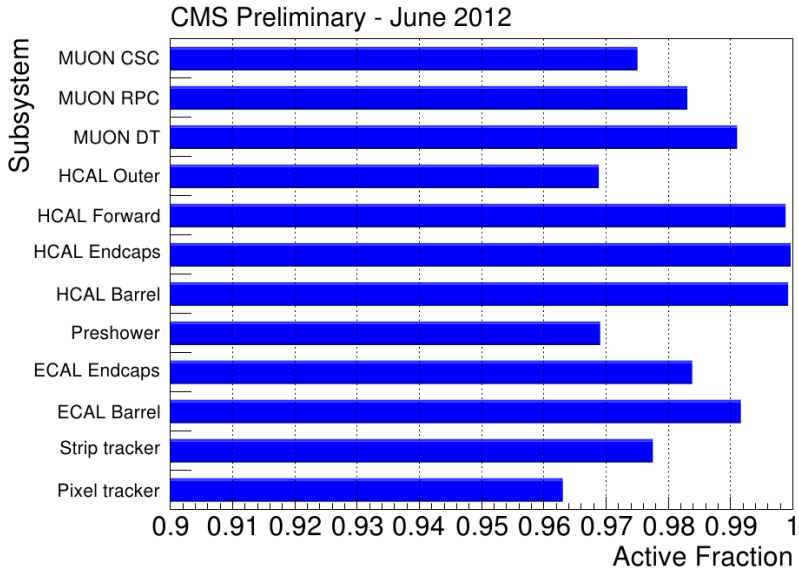
- Heavy bosons Z', W'
  - Massive Z/W-like bosons in extended gauge theories
  - Kaluza Klein excited states
  - Axigluons
  - Colorons
  - Topcolor models
  - Little HIggs
- 4th generation
- Vector-like heavy quarks (GUT theories)
- Excited top quarks (compositness)
- Rare decays (baryon number violation) ← NP in decay
- Many more...

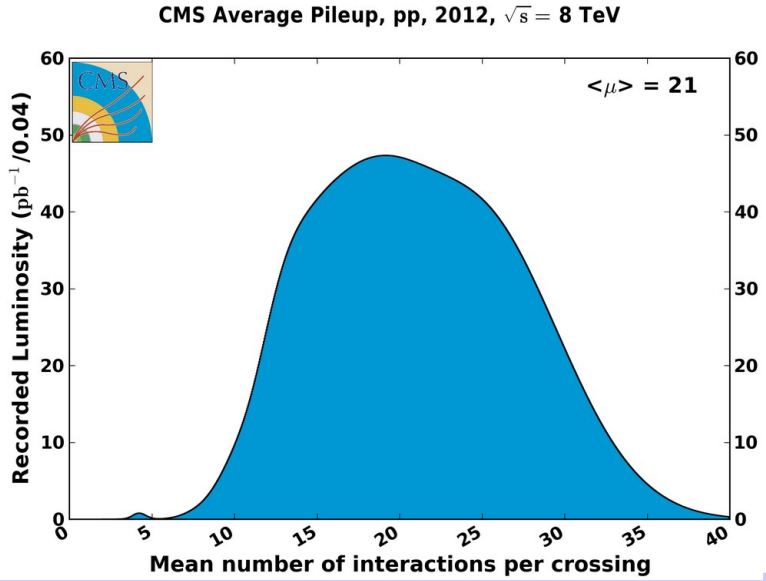
All B2G public results on : https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G

CMS performance

- Basic common selection : certified data, one good PV







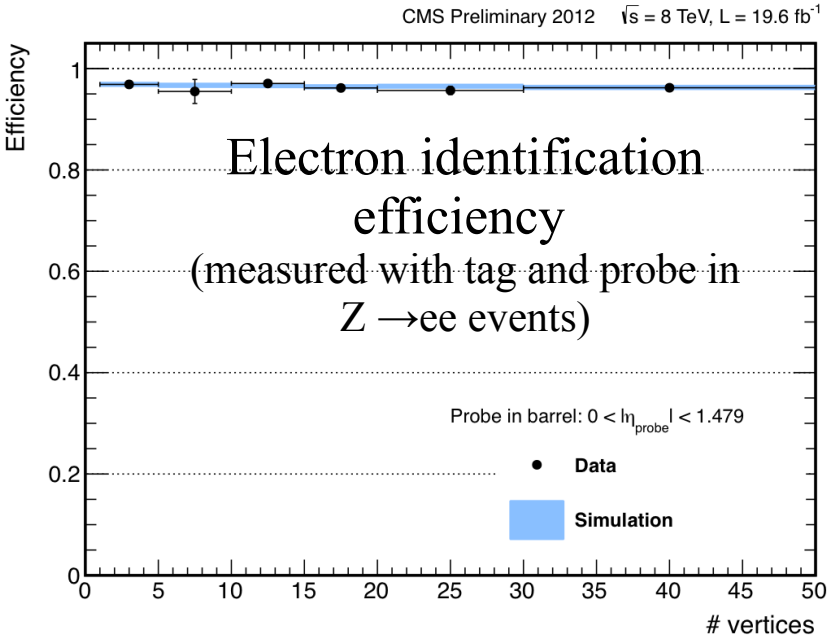
- **Particle Flow** reconstruction : global event description exploiting all subdetectors information
- Contributions from PU vertices are removed from the event

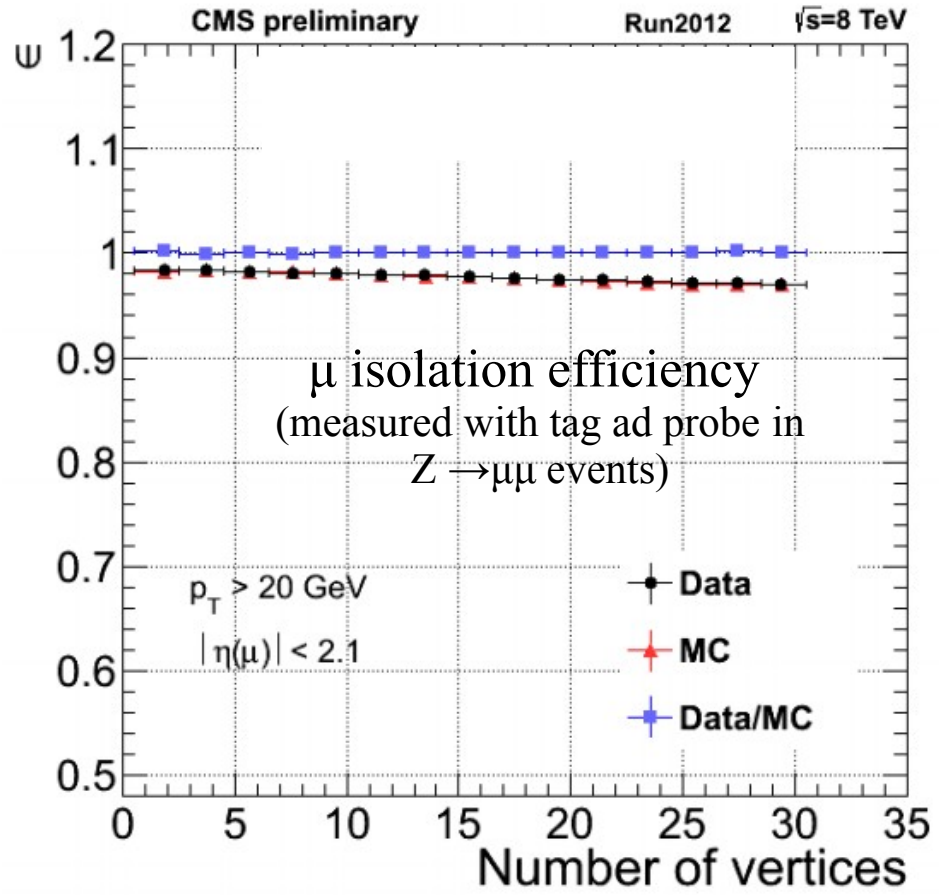
- Central standard selections, with performances and uncertainties
- PU distribution on MC matches data

CMS performance

All physics object reconstruction optimised to
- maximise the performances
- minimise the PU dependence

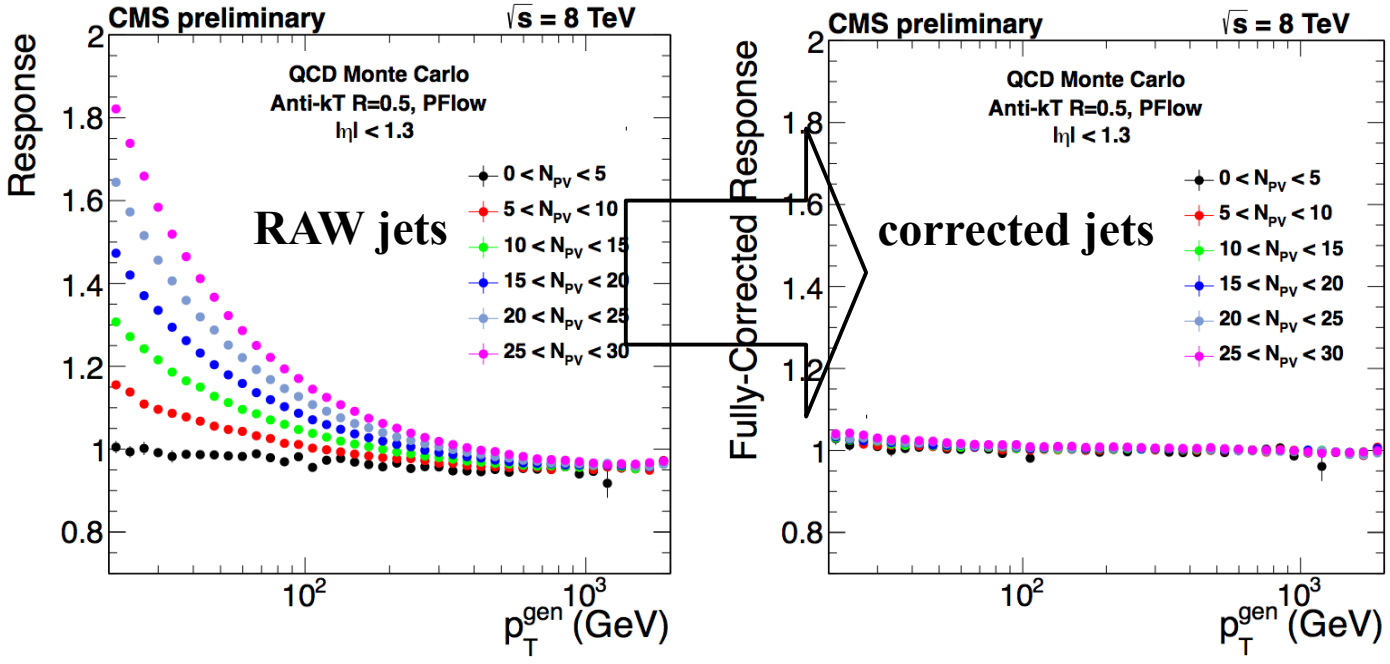
Lepton reconstruction
- well simulated on MC
- very stable as a function of n_{PV}



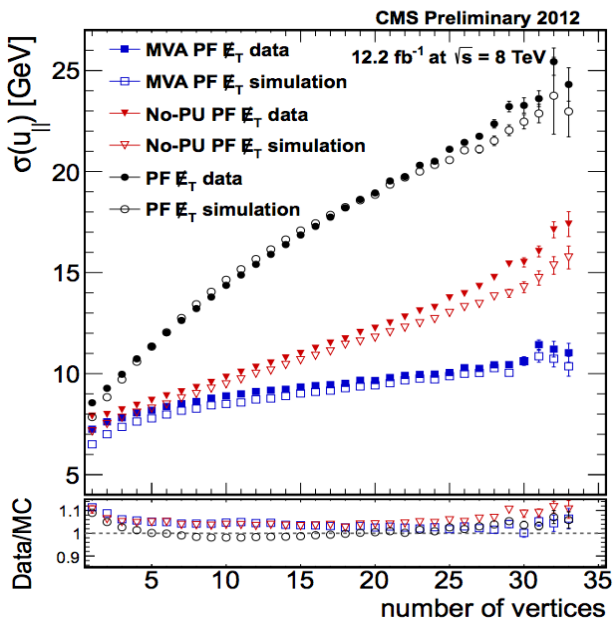


CMS performance

Jets and **MET** undergo several level of cleaning and correction
- jet energy response and resolution well under control
- MET cleaning very effective and resolution well understood



MET resolution
(studied in Z →μμ events)

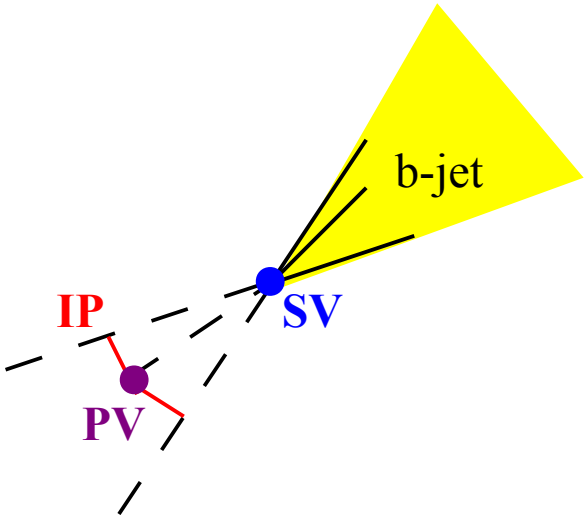


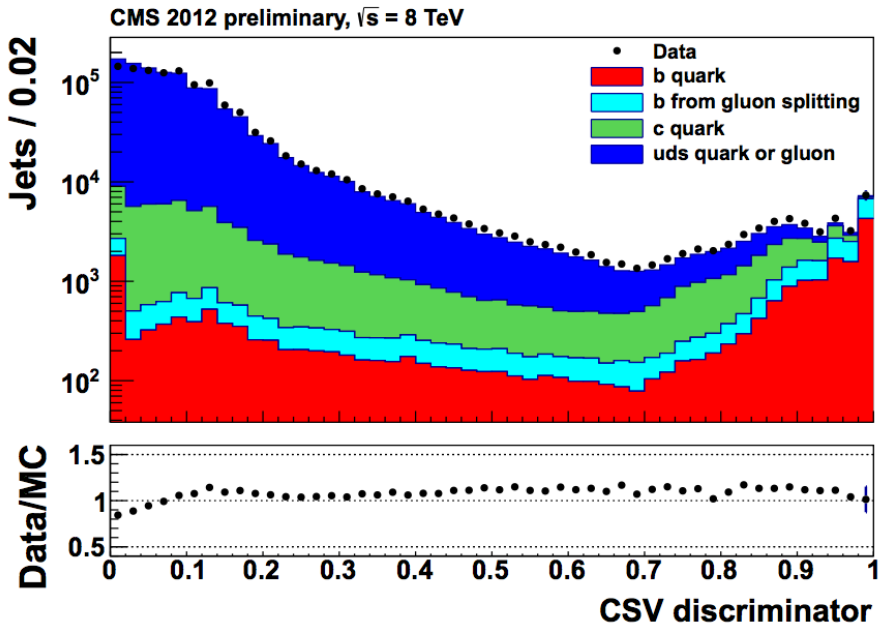
Many improvements since 7TeV data, and more ongoing work in view of next run !

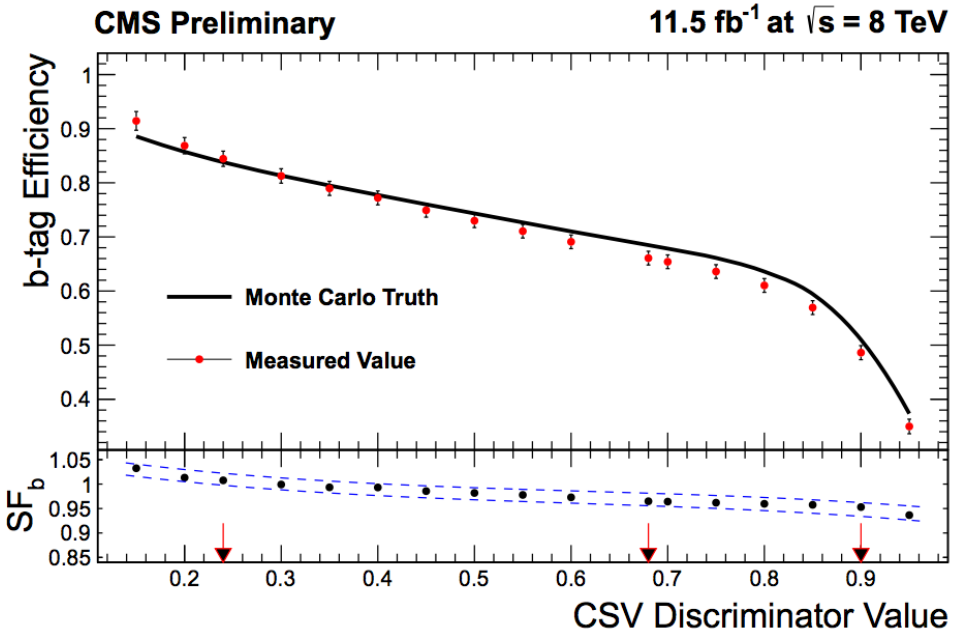
CMS performance

B-tagging
- well simulated and under control
- several algorithms
- today will show Combined Secondary Vertex (**CSV**)

based on secondary vertex and track-based information (IP)



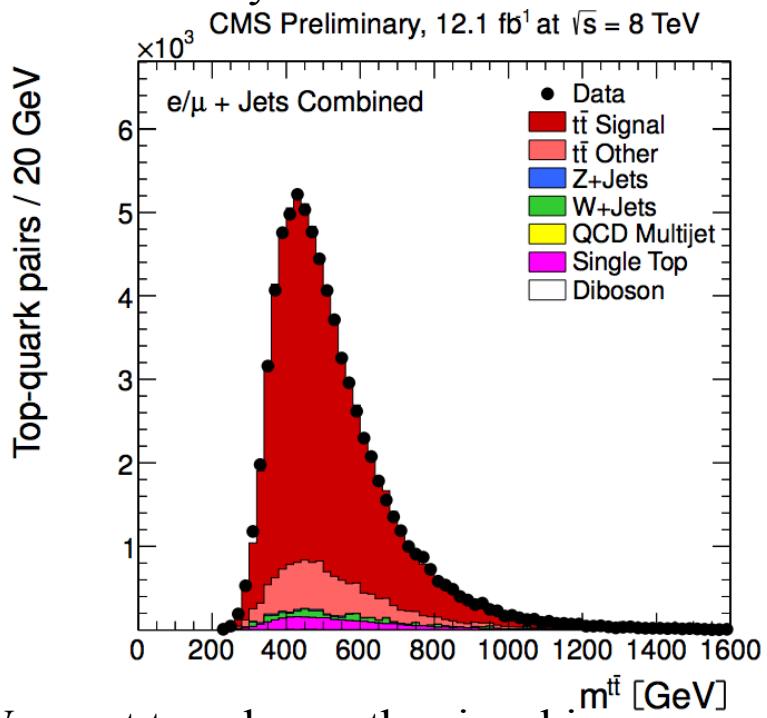


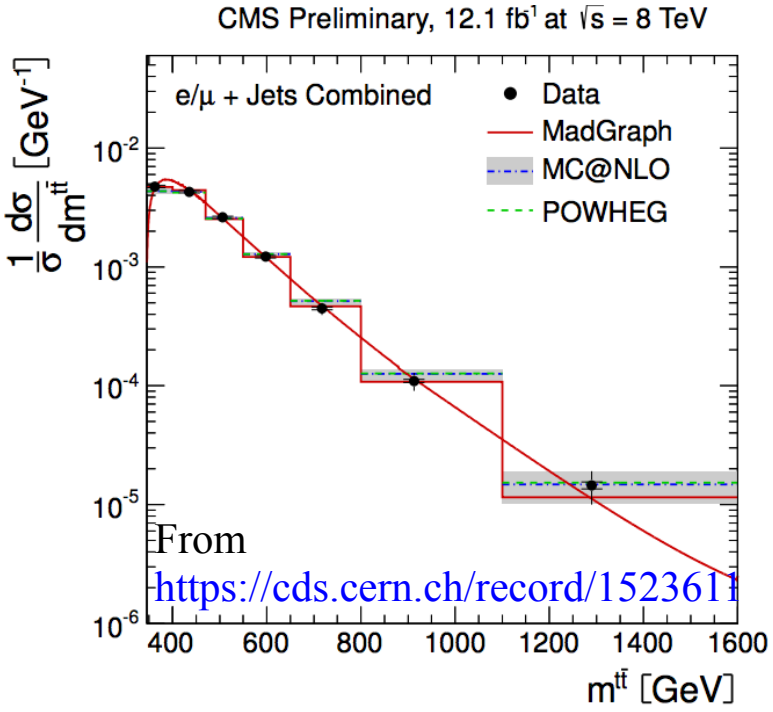


Common procedures : strategy

We look for excesses over a known background

- How well do we know the background from simulation ?
- Can we constrain the background from data ?
  - ➔ Different systematics





From https://cds.cern.ch/record/1523611

- We want to enhance the signal in our sample
- We want to control well our efficiency on signal to set limits
- Depends on what exactly we generate as a signal (selection choices, efficiency evaluation)
  - ➔ In most of the cases results hold in specific models
  - ➔ Whenever we can, we try to be as model independent as possible (general enhancement studies, not depend on BRs, couplings..)

Common procedures : samples and uncertainties

Generators :
Background samples
Ttbar : MadGraph/POWHEG + PYTHIA 6 (Z2*)
Single t : MadGraph/POWHEG +PYTHIA
W/Z+jets, ttW, ttZ : MadGraph + PYTHIA
WW/WZ/ZZ, ttH : PYTHIA

Signal samples (depending on the channel) :
MadGraph/COMPHEP interfaced with PYTHIA/PYTHIA

With some reweighting from data control samples

HLT paths:
- Single lepton / dilepton , Lepton + 3 central Pfjets, HT
- All efficiencies studied on MC and data, selection tuned to be on the plateau

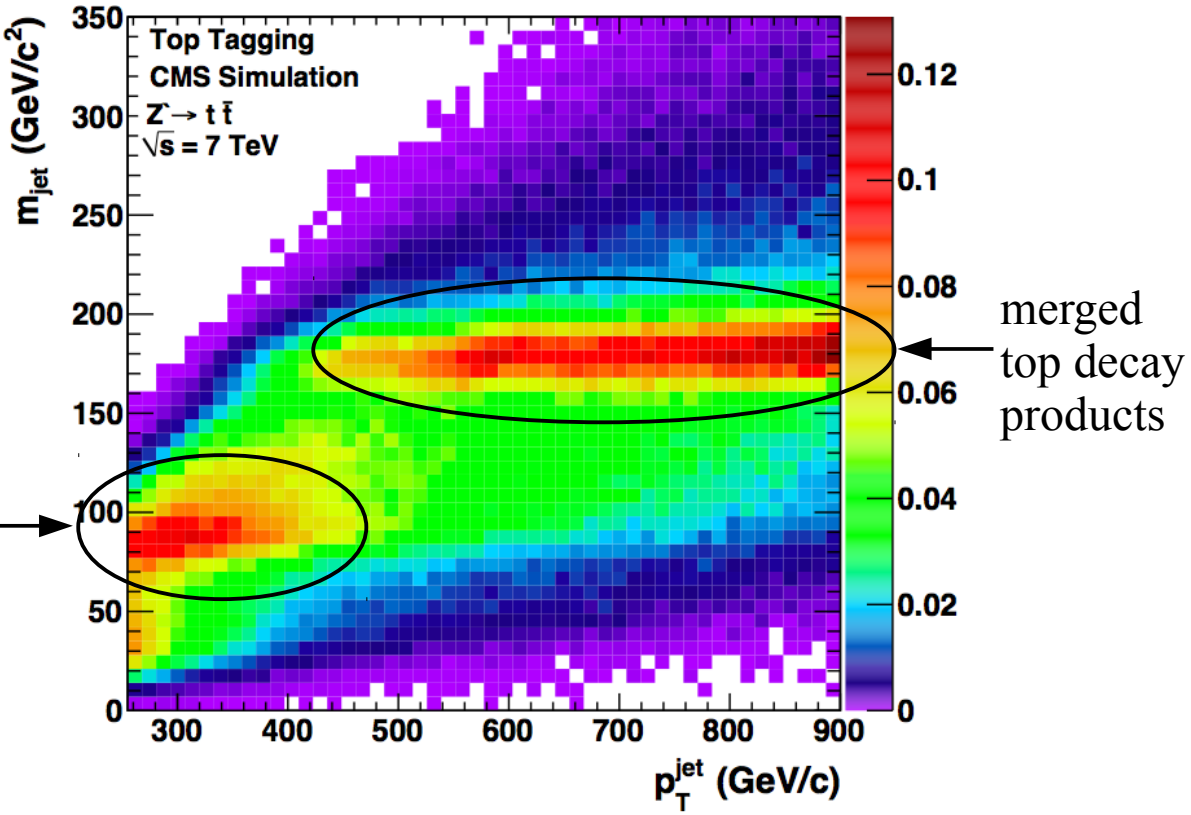
Systematics
- all HLT, reconstruction and selection efficiencies and data/MC differences
- luminosity (4.4%)
- JES (~5% eta and pT dependent), JER
- whenever we rely on MC : factorization and renormalisation scale, jet-parton matching scale, dedicated systematic samples
- when data driven estimation of backgrounds uncertainties of the methods, data/MC, closure tests
- analysis specific

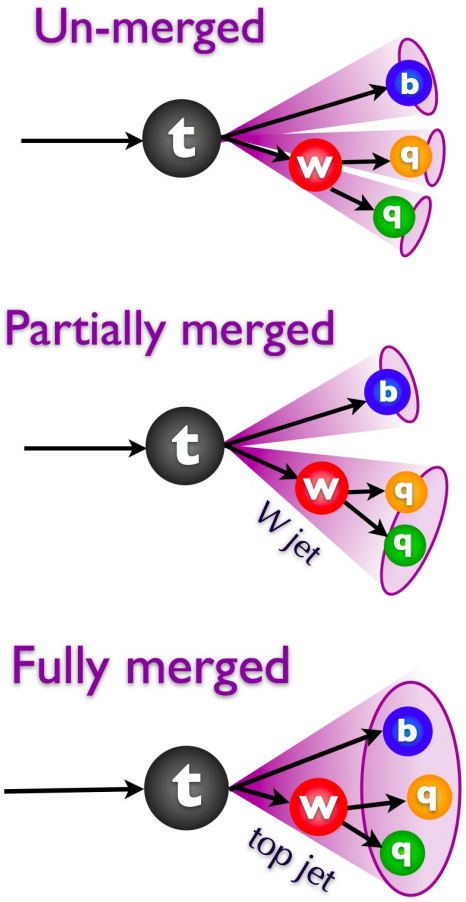
Common tools : boosted top

The New Physics searches often imply to look for massive objects

- boosted decay products, fat, merged jets
- need for non standard, dedicated reconstruction techniques

Example $Z' \rightarrow t\bar{t}$





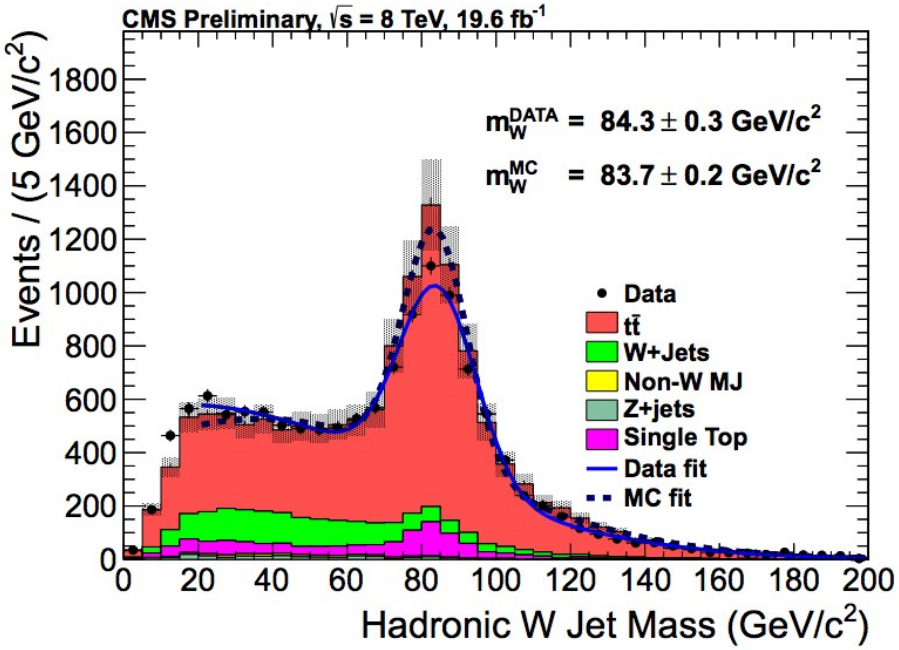
- standard jet reconstruction with Anti-kt clustering algorithm, distance parameter 0.5 (ak5)
- fat jets tagging algorithms developed for Cambridge/Aachen jet clustering algorithm, with distance parameter 0.8 (CA8)

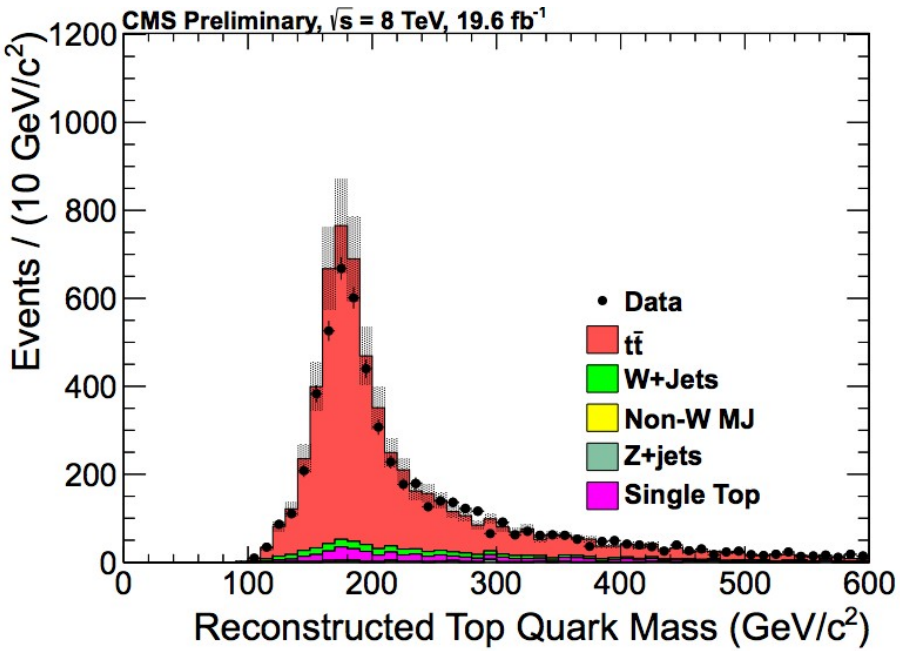
Common tools : W tagging

W tagging pruning algo http://arxiv.org/abs/0912.0033
Reclusters the jet from its constituents removing soft and wide angle radiation.

W selection :
$N_{subjets} = 2$
$60\ GeV < m_{jet} < 130\ GeV$

Validated on semileptonic tt events (leptonic and hadronic legs are tag and probe)



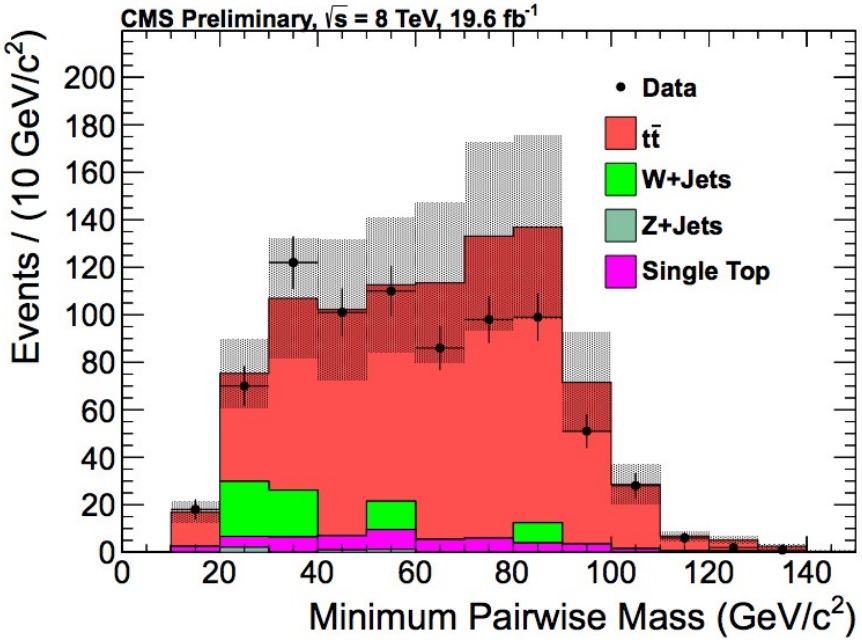


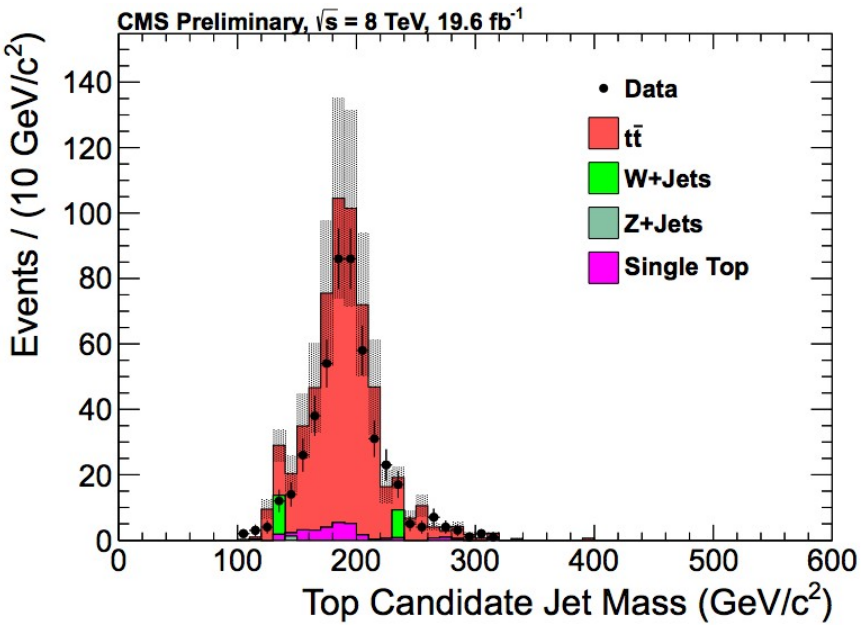
Common tools : top tagging

Top tagging Johns Hopkins University algorithm http://arxiv.org/abs/0806.0848
Inverts last steps of CA algo removing soft objects.

Top selection :
$N_{subjets} \geq 3$
$140\ GeV < m_{jet} < 250\ GeV$
$m_{min} > 50\ GeV$

Validated on semileptonic tt events (leptonic and hadronic legs are tag and probe)

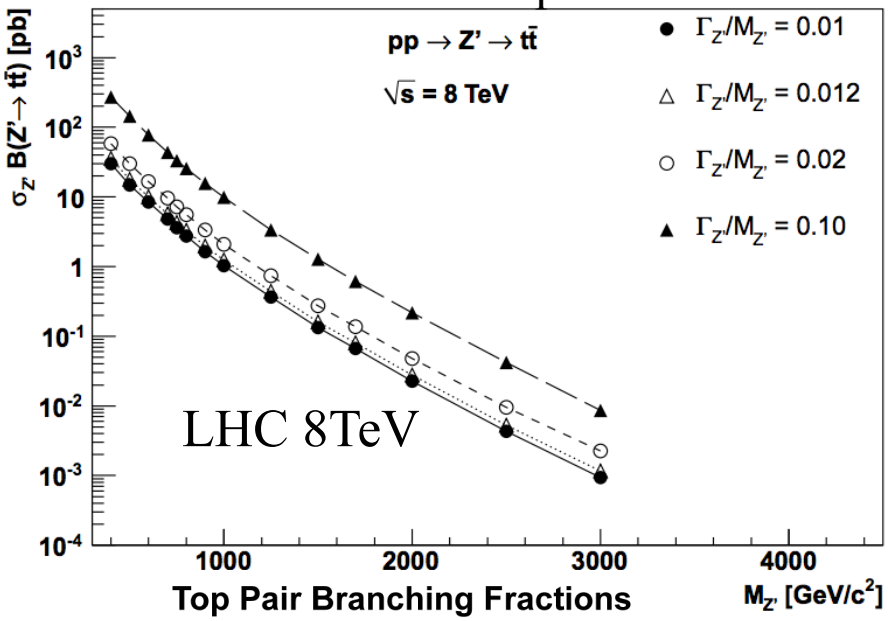




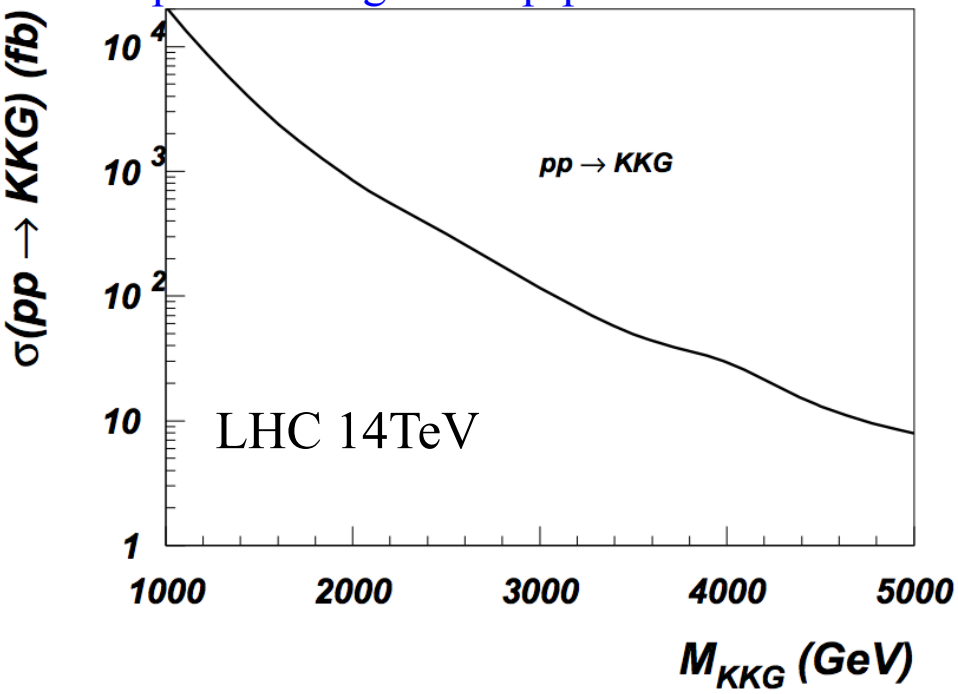
Analyses review

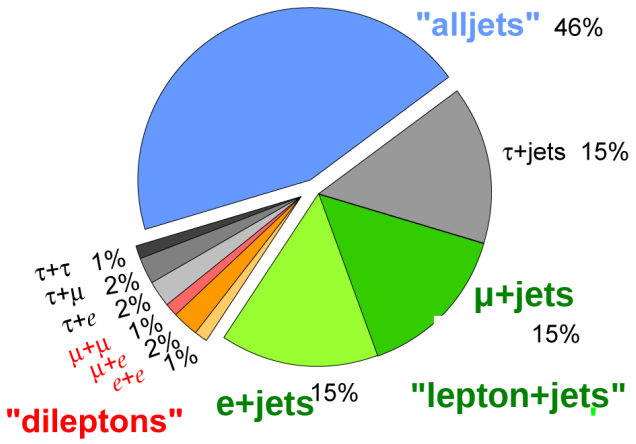
Top pair resonances

Leptophobic Z' in topcolor model
R.Harris, S.Jain http://arxiv.org/abs/1112.4928
1% and 10% widths explored



Randall Sundrum 1 framework (RS1) of warped extra dimensions, K.Agashe et al.
http://arxiv.org/abs/hep-ph/0612015





Searches for resonances top pair final state

- over wide mass range (500 GeV to 3 TeV)
- different final states :
  - all-jets
  - lepton+jets

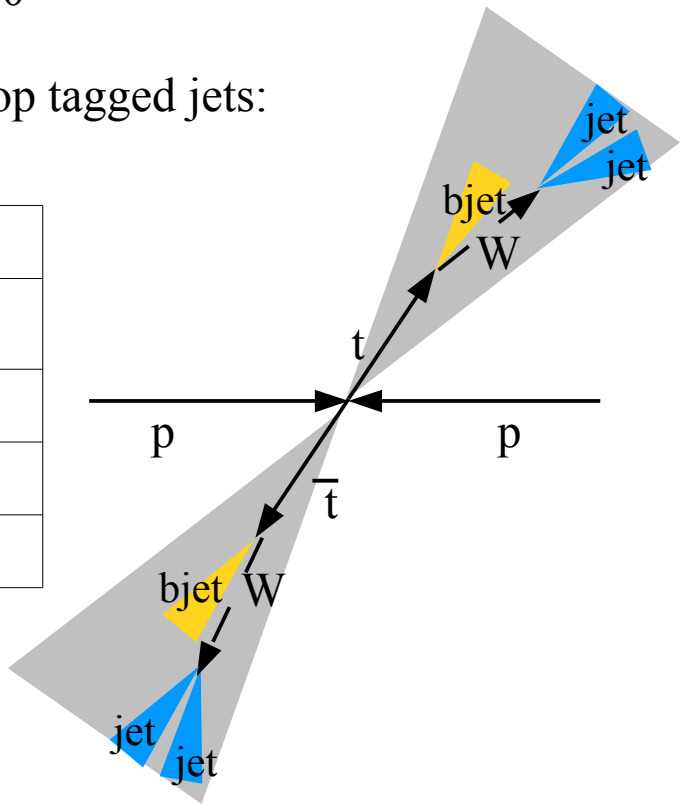
Top pair resonances – all-jets

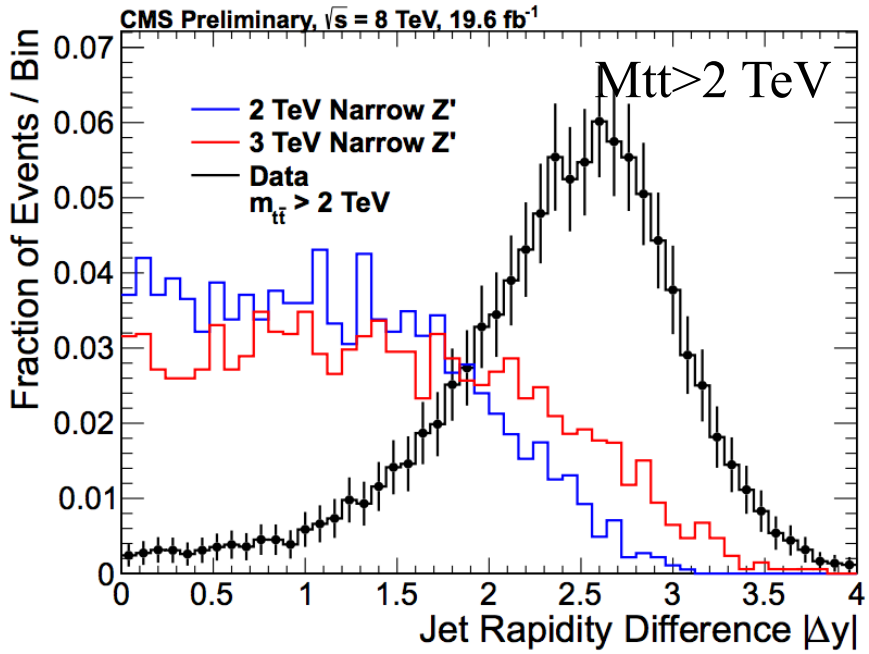
https://cds.cern.ch/record/1545285

Trigger path HT_750

Dijet selection for top tagged jets:

>= 2 CA8 jets
p_T >400, 350 GeV/c^2
Top-tagged
$\Delta\varphi>\pi/2$
$\lvert\Delta y\rvert<1$

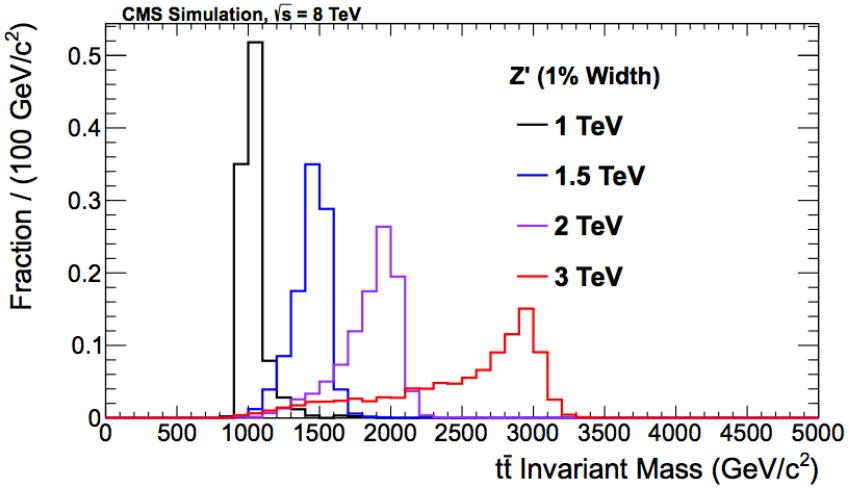


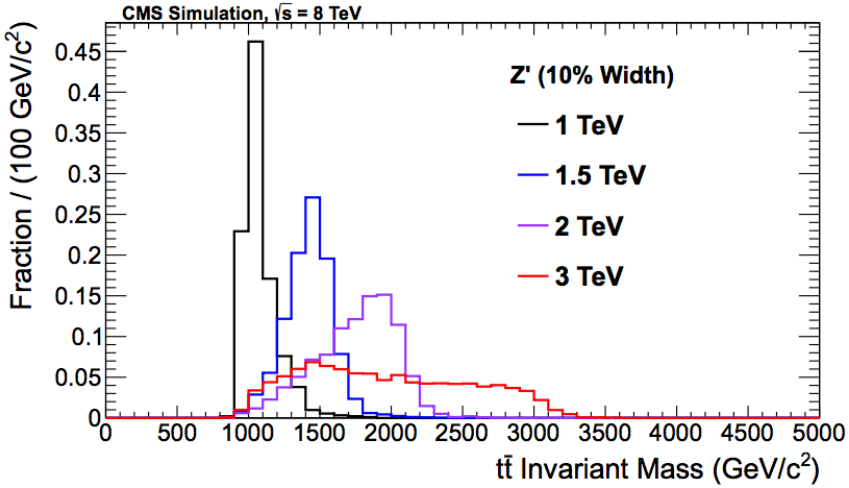


Control region lepton+jets top pair events to determine :

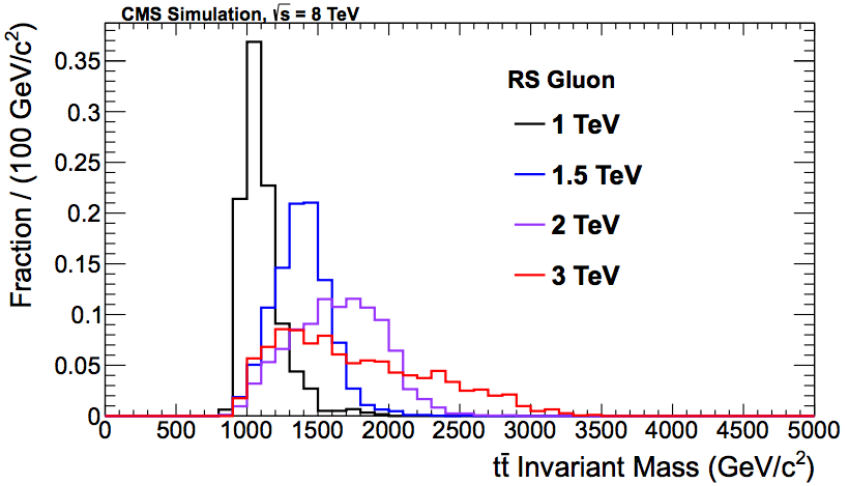
- the data/MC SF for top-tagging (0.926 ± 0.039)
- the subjet energy scale by comparing the W mass reconstructed in data and MC
- no significant dependence on p_T

Top pair resonances – all-jets signal





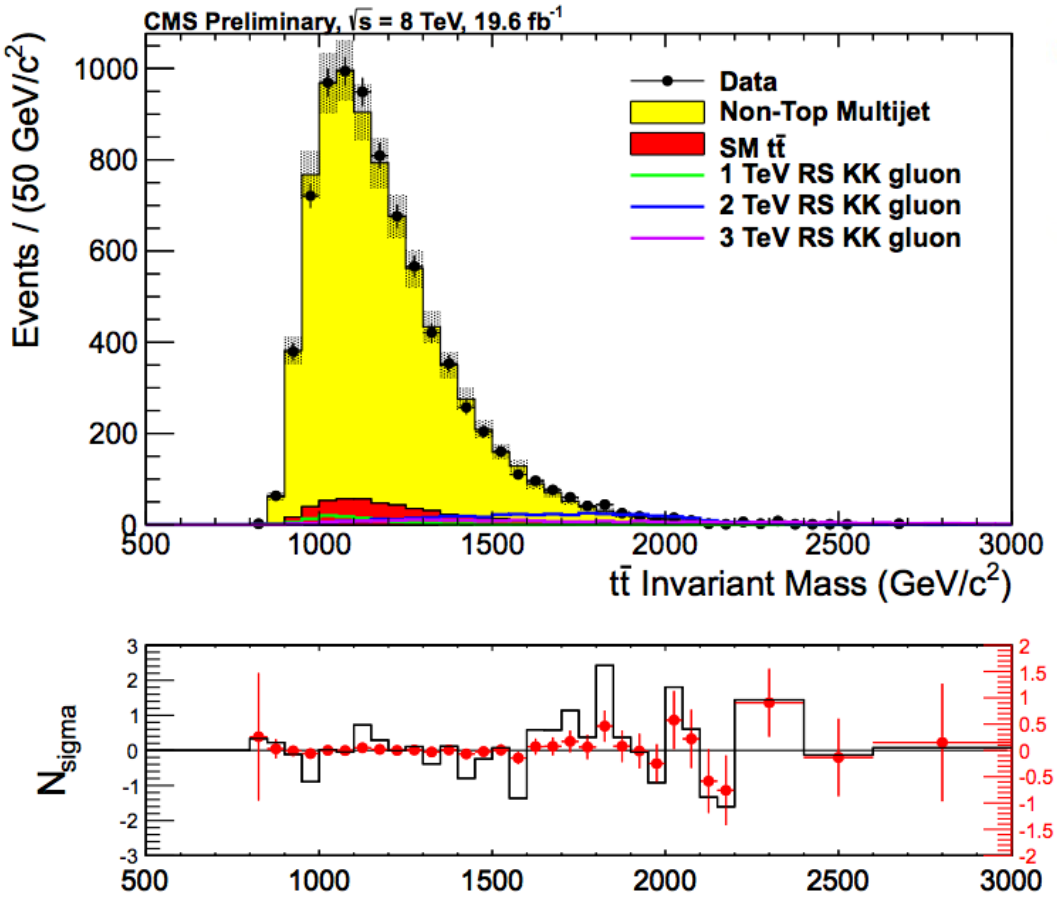
Signal - Z' samples (generic spin-1 Z' boson, with same fermion couplings as the SM Z ,1% and 10% width) :
MADGRAPH 4 + PYTHIA 6 (Z2*)

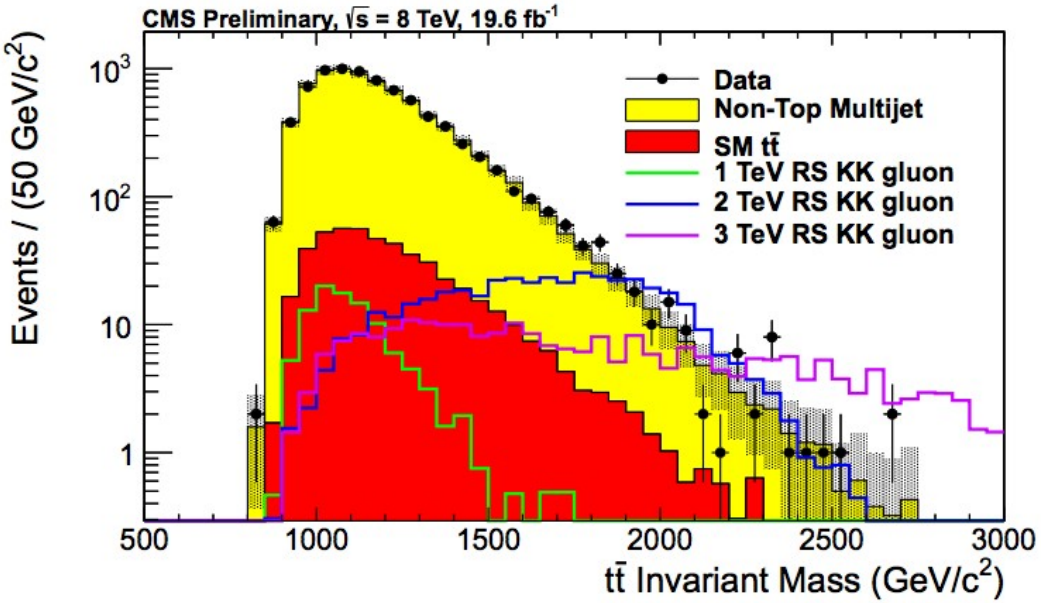


Signal - RS KK gluon samples :
PYTHIA 8 (4c)

Top pair resonances – all-jets selected data-background

- non-top multijet background (main background) estimated from data
- SM top pair production estimated from MC
- no data excess over expected background is observed



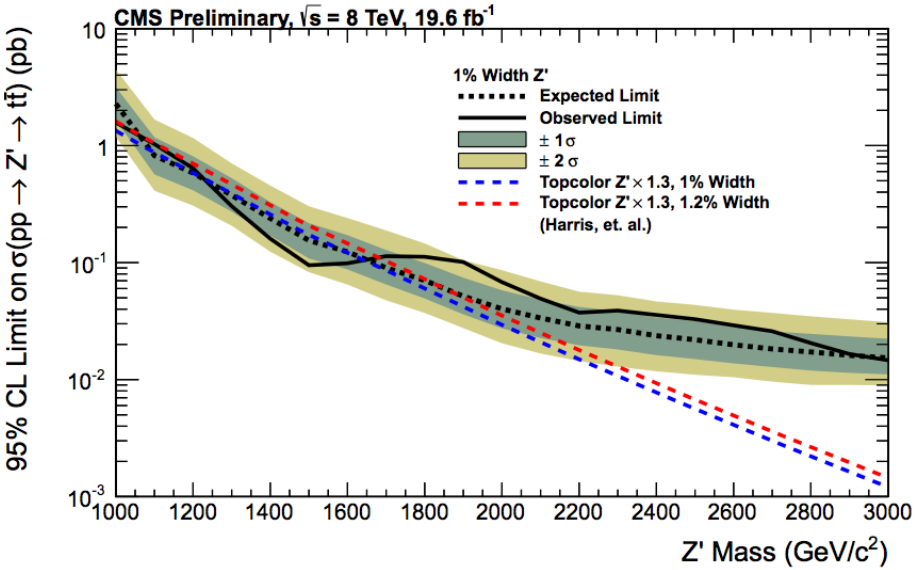


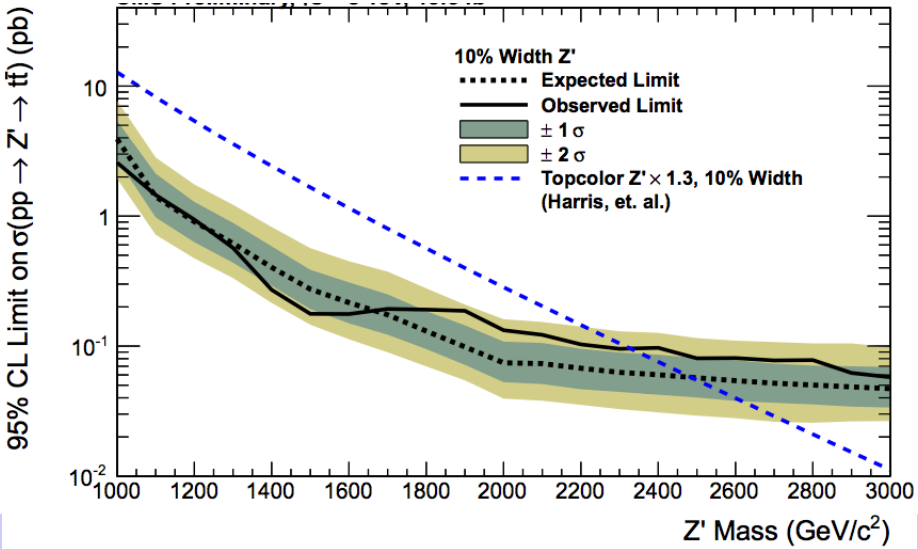
Process	Events
SM $t\bar{t}$	580 ± 305
Non-Top Multijet	7807 ± 855
Total Background	8387 ± 908
Observed Data	8052

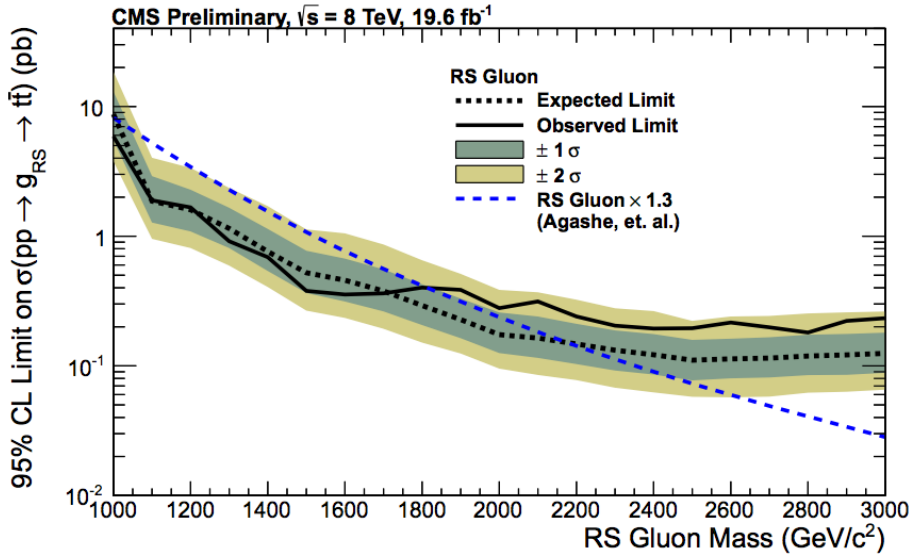
Top pair resonances – all-jets limits

Template based m_{tt} shape analysis

Limit setting with a Bayesian procedure, all uncertainties as nuisance parameters







New resonances excluded for masses below :

- 1.7 TeV for narrow Z'
- 2.35 TeV for wide Z'
- 1.8 TeV for RS KK gluons

Simple counting experiment (m_{tt}>1TeV) excludes models predicting more than 1.79 the SM $t\bar{t}$ rate.

Only available result on 8 TeV data.

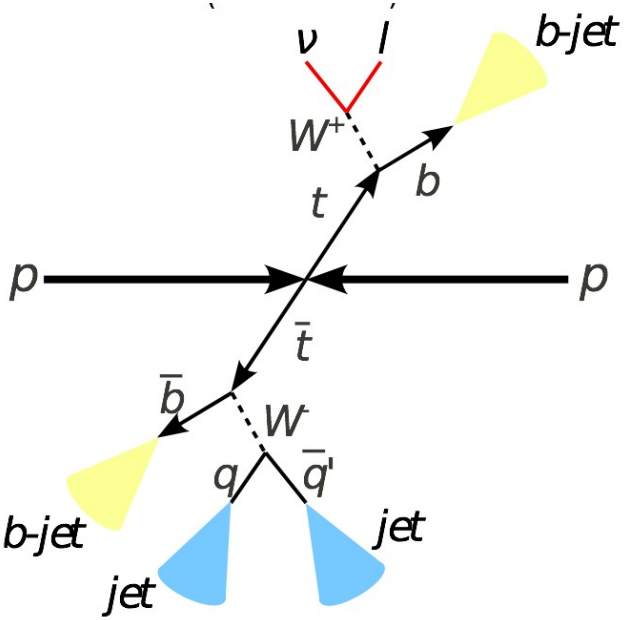
Top pair resonances - lepton+jets

http://cds.cern.ch/record/1543467

Two separate analyses for different topologies in different mass ranges

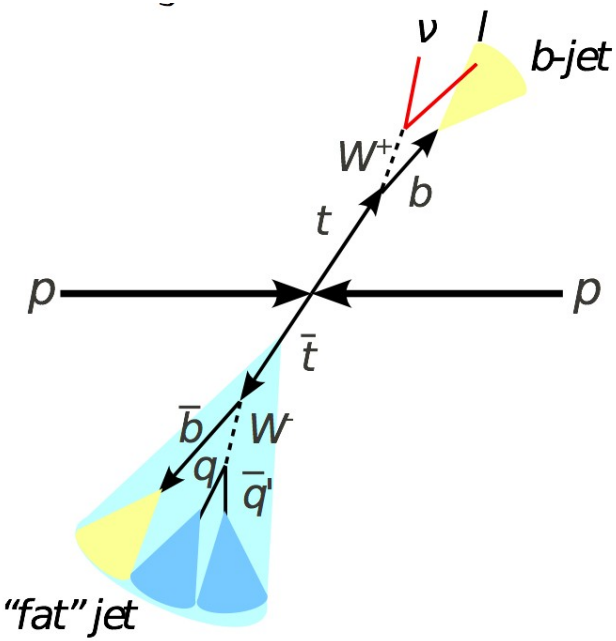
Resolved ttbar (m_{tt} < 1 TeV)

- isolated lepton
- 4 distinguishable jets



Boosted (m_{tt} > 1 TeV)

- non isolated lepton
- (partially) merged jets



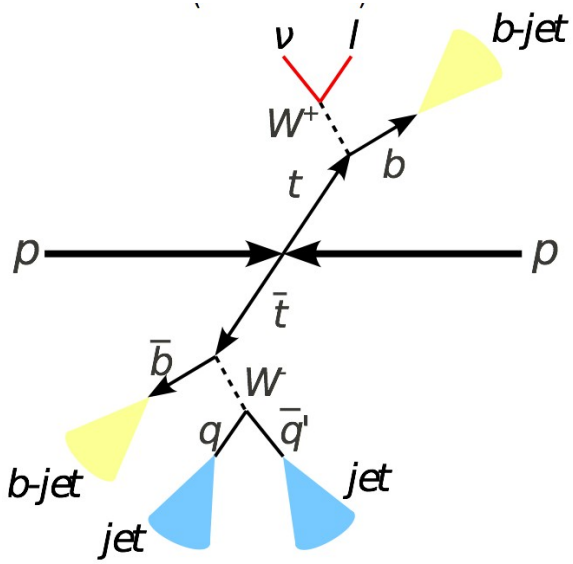
Different selections and analysis strategies

Top pair resonances – lepton+jets resolved selection

Selection :

HLT lepton+3jets

Exactly one good isolated lepton (e, mu)
>=4 jets (p_T>70, 50, 30, 30) GeV
MET > 20 GeV
At least one b-tagged jet



Mass reconstruction and pairing :

- neutrino momentum calculated from lepton momentum and MET with a W mass constraint
- jet assignment to leptonic or hadronic leg from minimization of χ^2 (m^{HAD}_t, m^{LEP}_t, m_W, p_T^{tt})

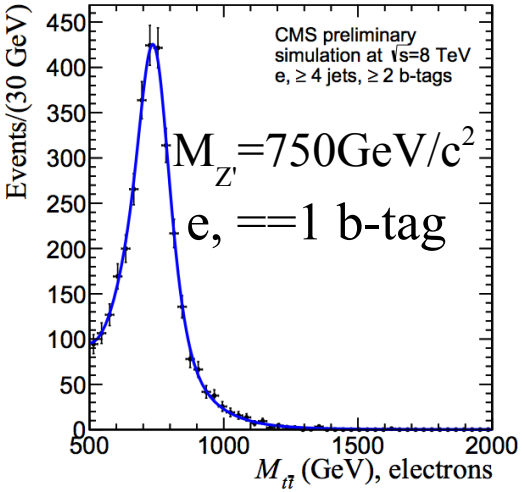
Events split in 4 categories for further treatment

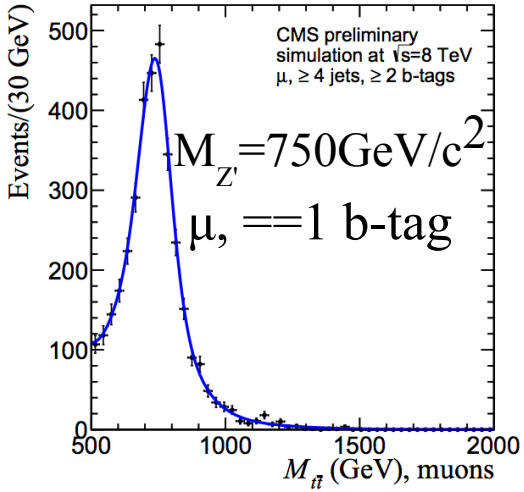
muon	x	==1 btagged jet
electron		>=2 btagged jets

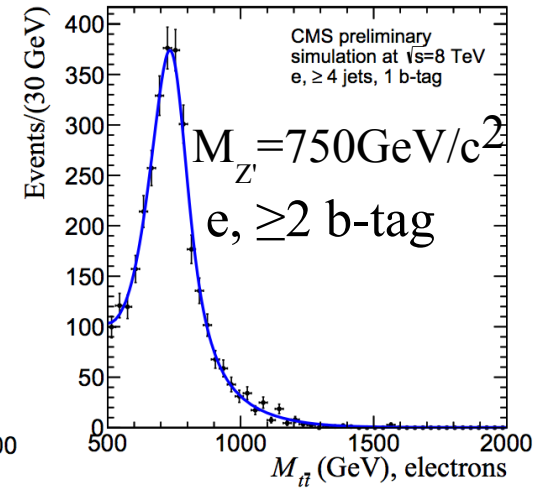
Top pair resonances – lepton+jets resolved - signal extraction

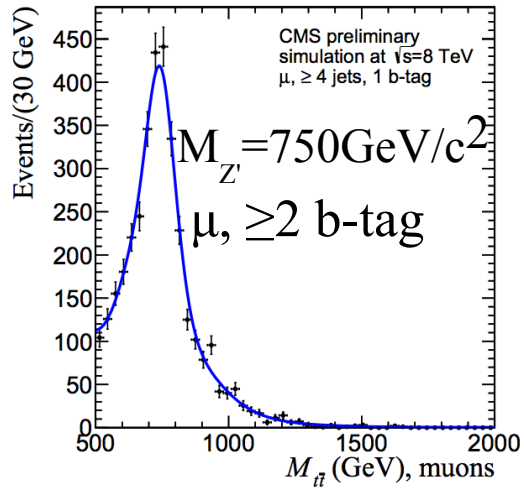
Signal extracted from a binned maximum likelihood fit to data.
The 4 categories are exploited simultaneously.

Signal parametrised with a Gaussian kernel estimation :









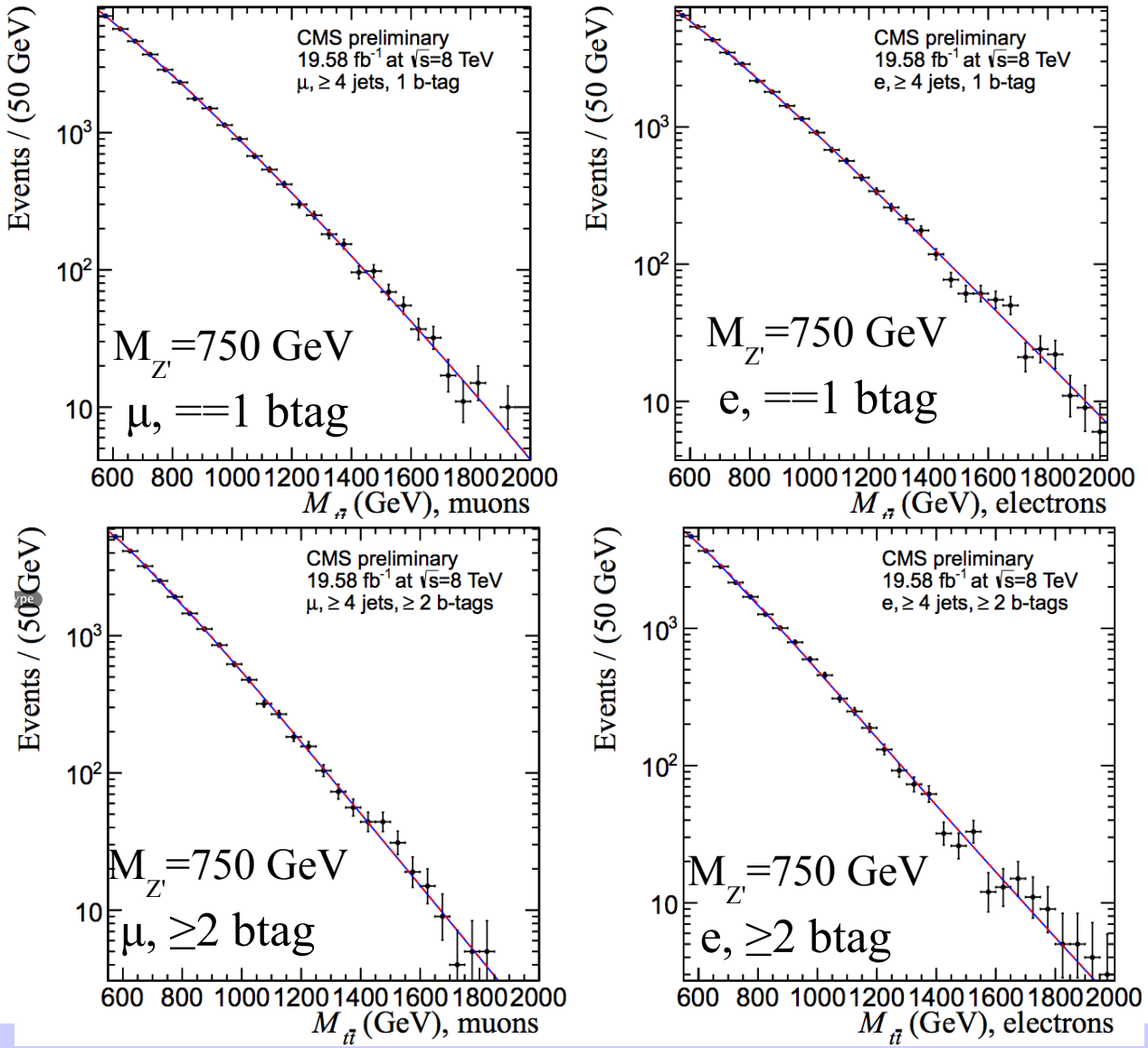
Background parametrised directly on data with a falling functional form inspired by parton density distributions

- several forms tried out
- optimised from studies on simulated events
- motivated from existing analyses
- no bias in the signal extraction

$$f_{bkg}(m) = \frac{\left(1-\frac{m}{\sqrt{s}}\right)^{c_1}}{\left(\frac{m}{\sqrt{s}}\right)^{c_2+c_3\ln\frac{m}{\sqrt{s}}}}$$

Top pair resonances – lepton+jets resolved - signal extraction

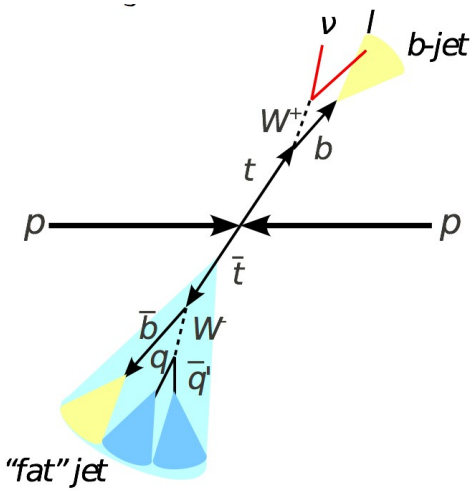
Signal PDF fixed during the fit, background parameters floating.
No evidence of the signal is found.



Top pair resonances – lepton+jets boosted selection

Selection :
HLT single lepton

Exactly one good lepton (e, mu) – no isolation requirement
>=2 jets (p_T > 150, 50) GeV
MET > 50 GeV
MET+p_T(lepton) > 150 GeV



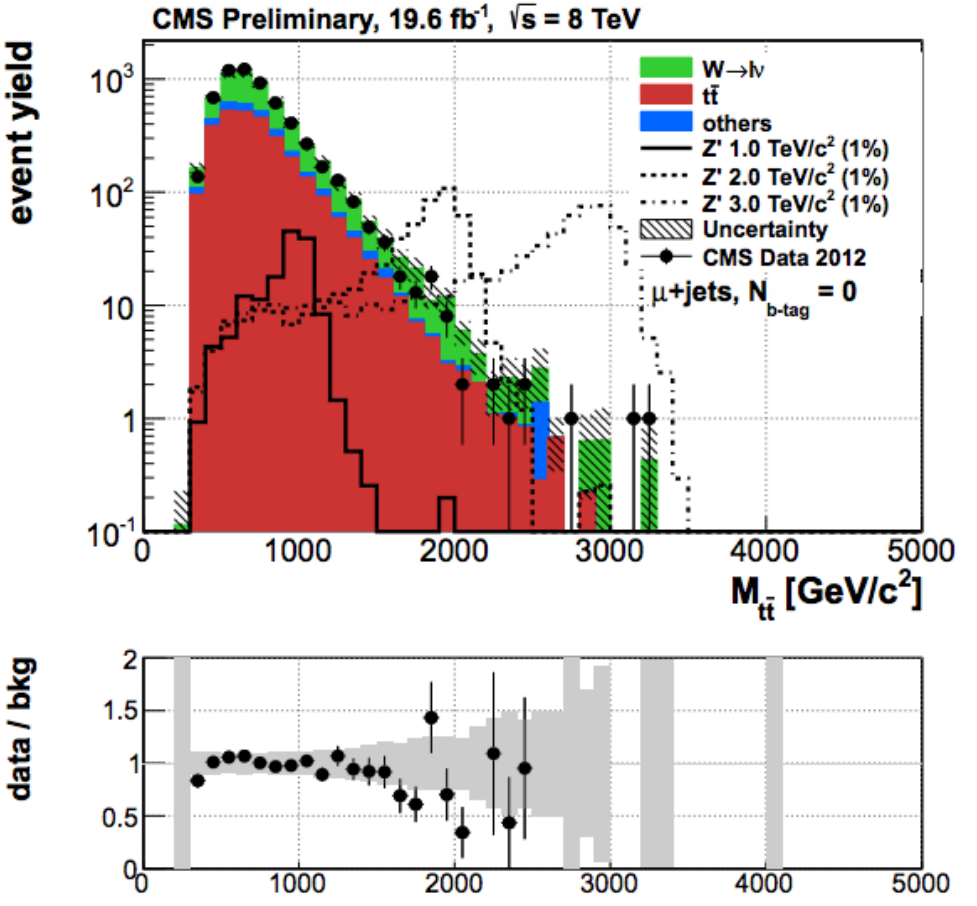
Mass reconstruction and pairing :
- Neutrino momentum calculated from lepton momentum and MET with a W mass constraint
- One jet assigned to leptonic leg, one or more to hadronic leg , minimization of χ^2 (m^{HAD}_t, m^{LEP}_t)

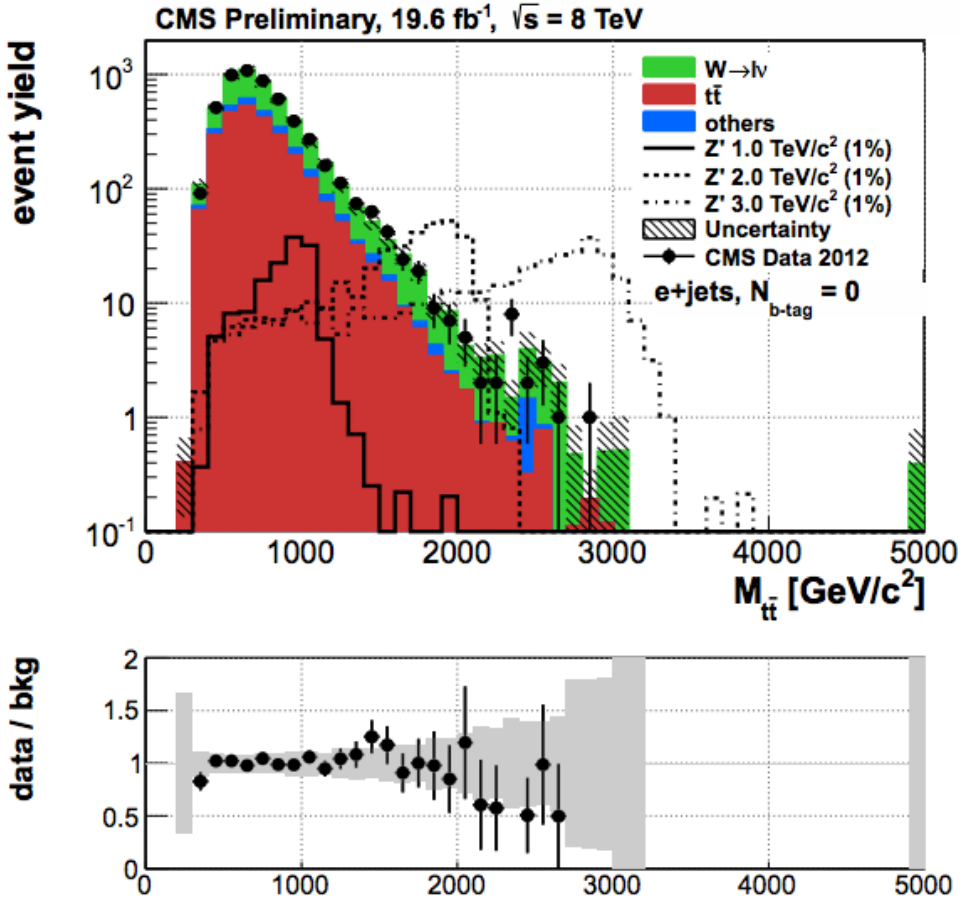
Events split in 4 categories for further treatment

muon	x	==0 btagged jet
electron		>=1 btagged jets

Top pair resonances – lepton+jets boosted signal extraction

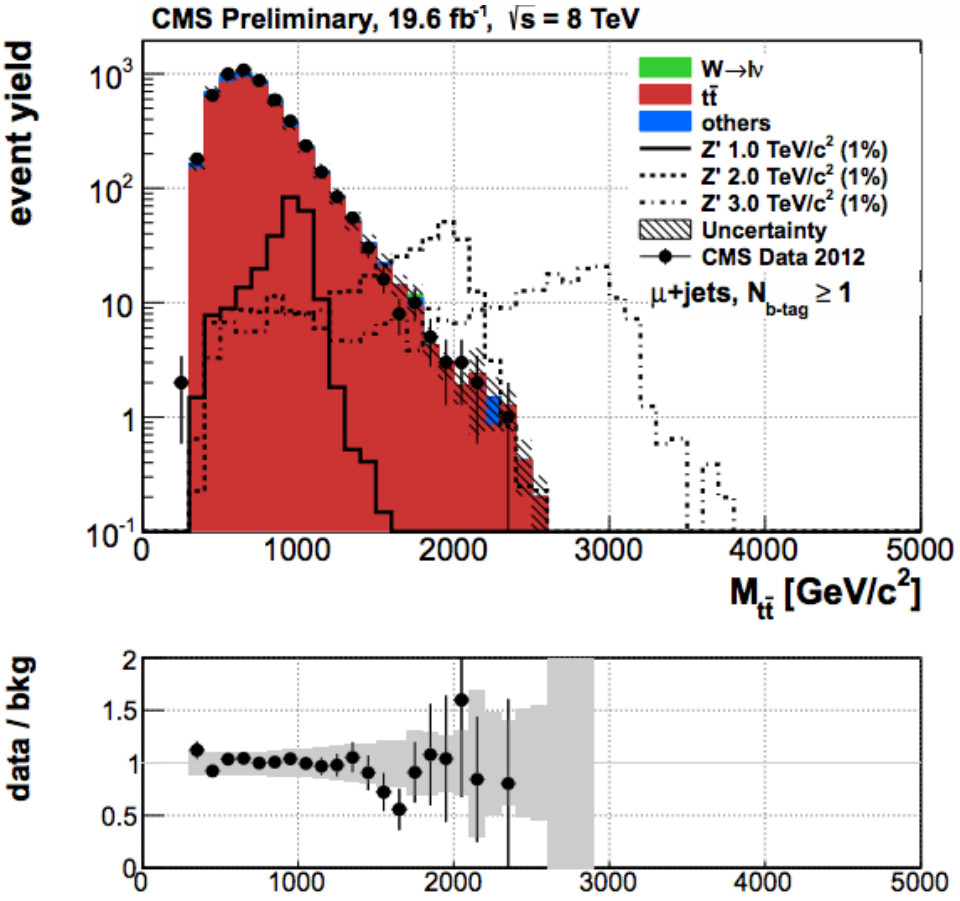
- both background and signal taken from MC (templates).
- binned likelihood fit to the m_{tt} distribution.
- the 4 categories are exploited simultaneously

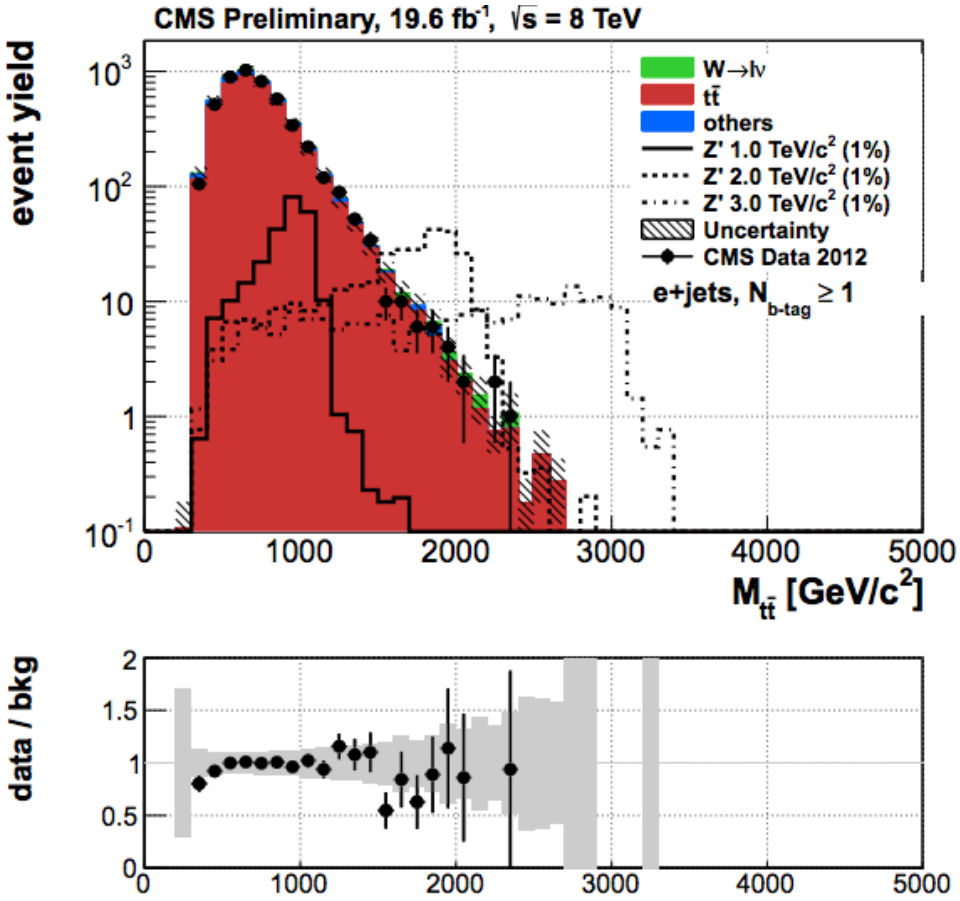




Top pair resonances – lepton+jets boosted signal extraction

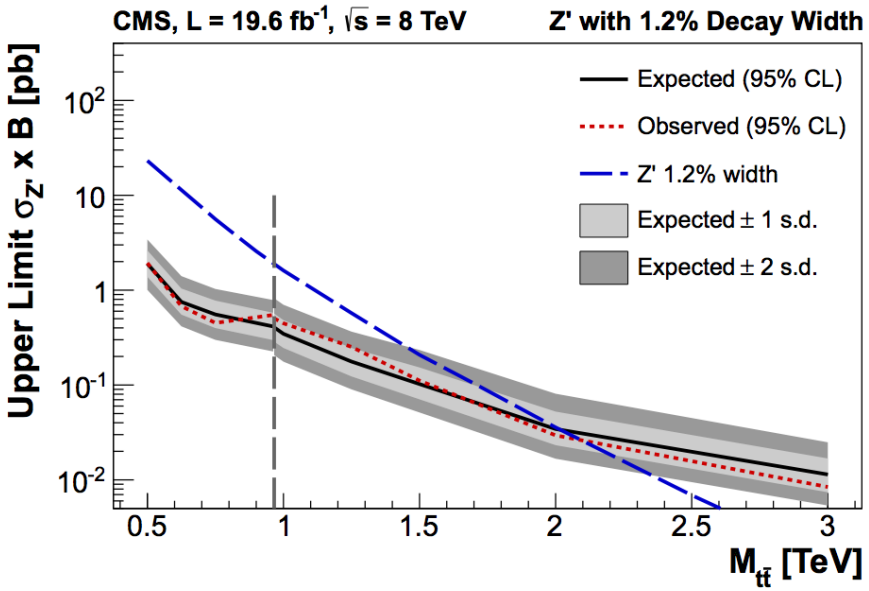
- both background and signal taken from MC (templates).
- binned likelihood fit to the m_{tt} distribution.
- the 4 categories are exploited simultaneously

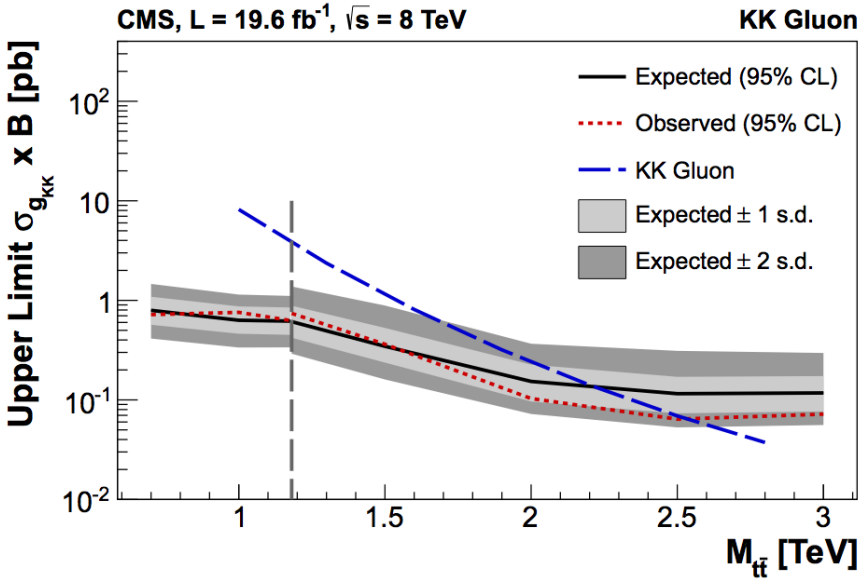


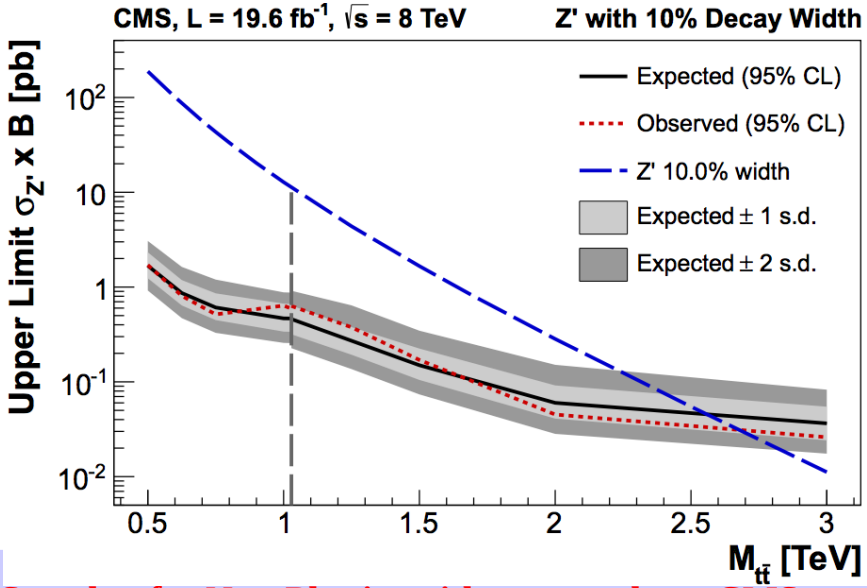


Top pair resonances – semileptonic limits

Limits extracted with Bayesian procedure







New resonances excluded for masses below :

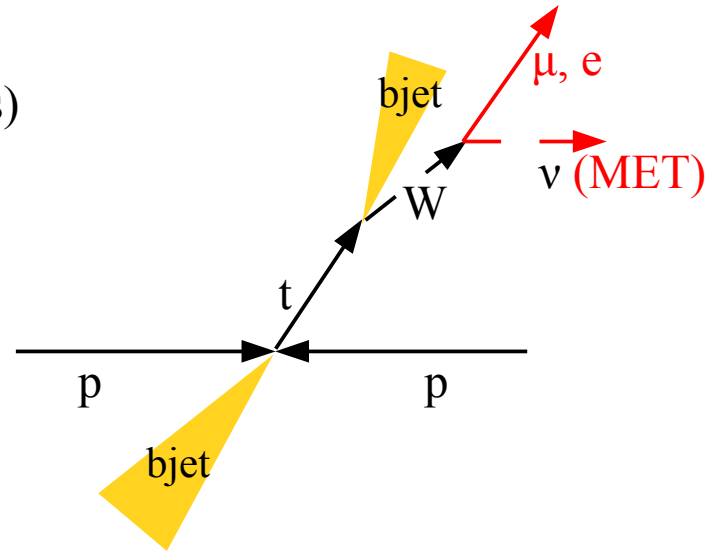
- 2.1 TeV for narrow Z'
- 2.68 TeV for wide Z'
- 2.54 TeV for RS KK gluons

Best available limits !

tb resonances

http://cds.cern.ch/record/1525924

Generic massive gauge boson W' , with arbitrary vector and axial couplings according to http://arxiv.org/abs/hep-ph/0207290
Signal samples generated in COMPHEP :
- W' right handed couplings to fermions
- SM+W' left handed couplings to fermions (with interferences)
- SM+W' mixed (with interferences for left handed)



Selection :
HLT single lepton

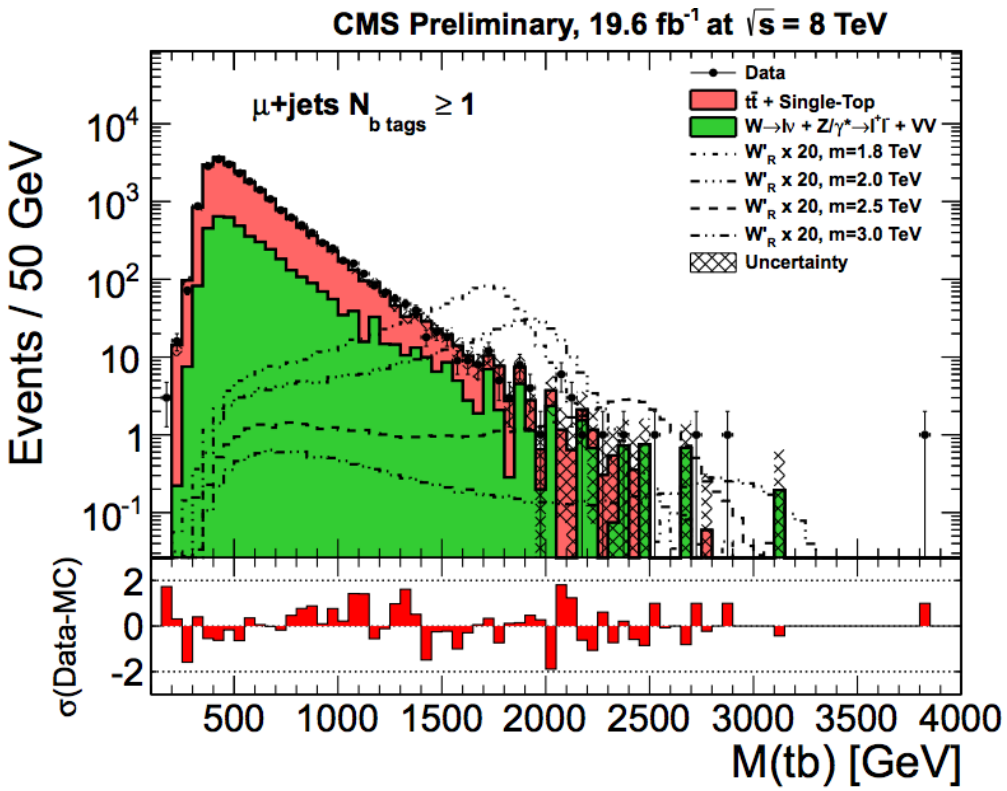
Exactly one good isolated lepton
>= 2 jets (p_T>120, 40 GeV)
>=1 b-tagged jet
MET>20 GeV

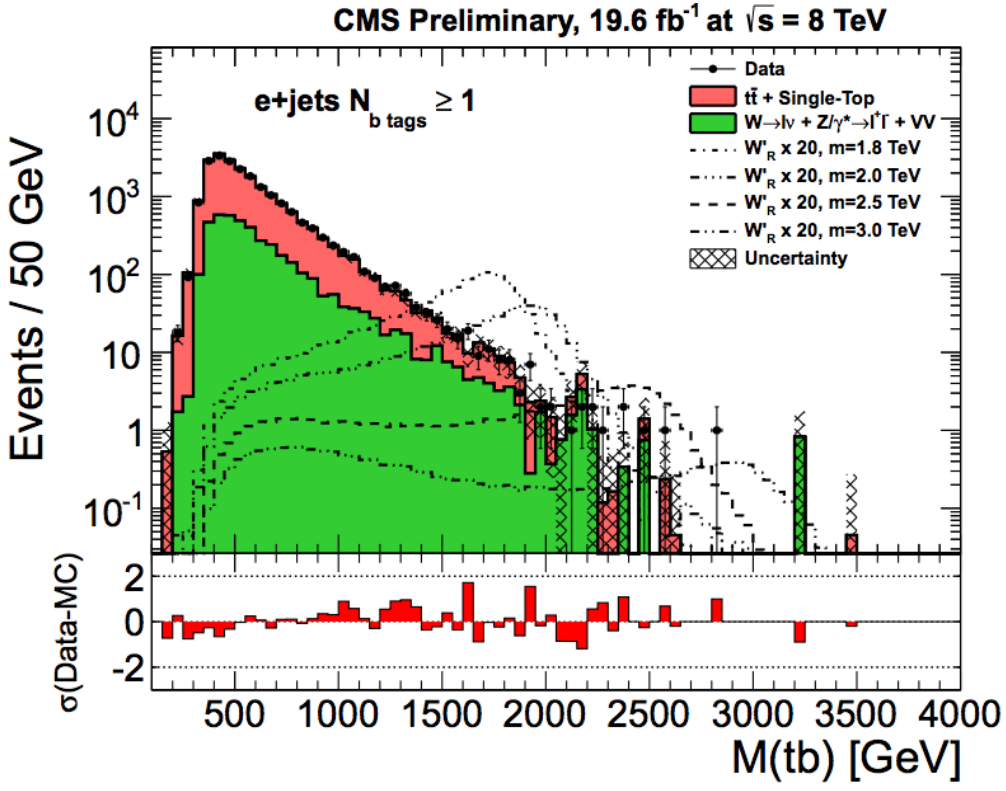
Mass reconstruction and pairing :
- Neutrino momentum calculated from lepton momentum and MET with a W mass constraint
- Within selected jets, it is assigned to the top the one that gives the best top mass
- Next hardest jet assigned to the b

p_T^t>85 GeV
Sum p_T selected jets > 140 GeV
130 GeV< m_{top} < 210 GeV

tb resonances selection

- backgrounds determined on MC with input from data
- taken into account in systematic uncertainties

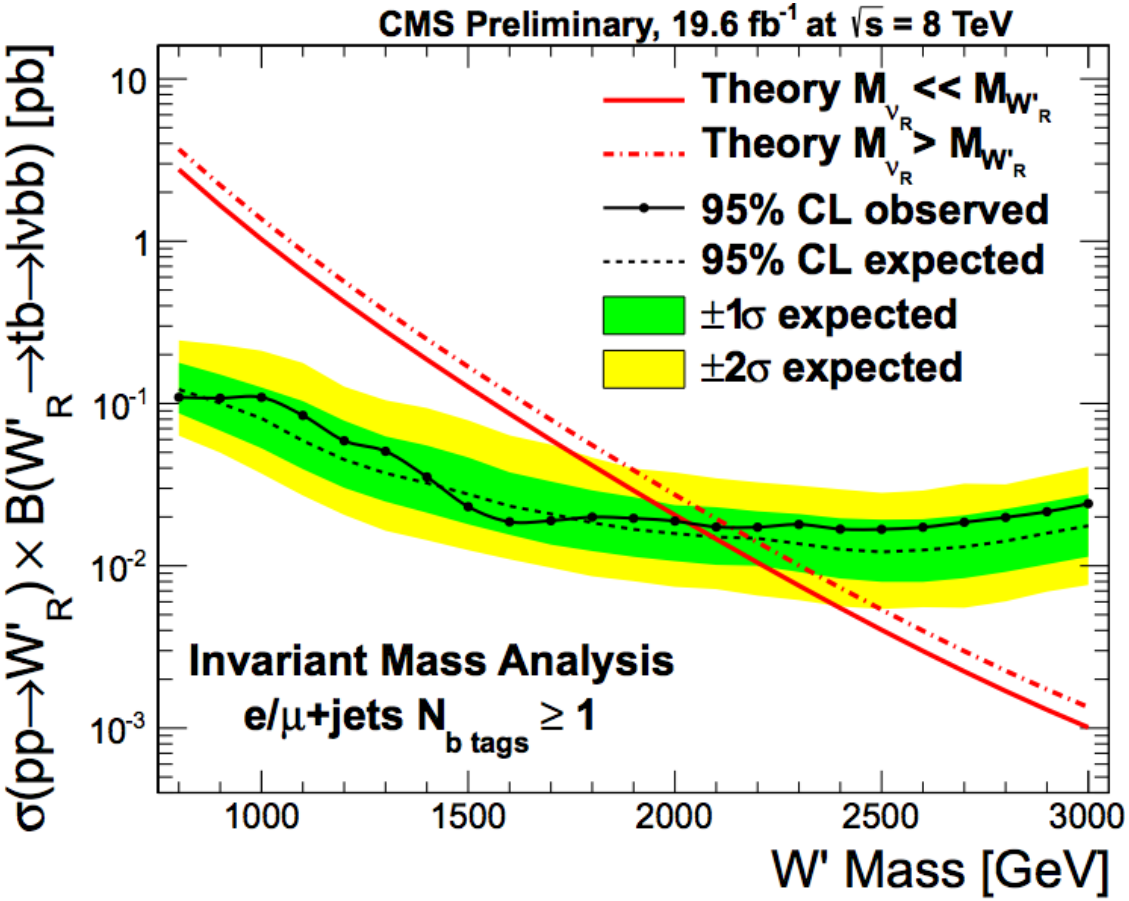




No excess over expected background is observed

tb resonances limits

• binned maximum likelihood fit on M(tb) distribution on data using MC templates for background and signal.
• limits extracted with a Bayesian procedure, all systematics taken into account as nuisance parameters

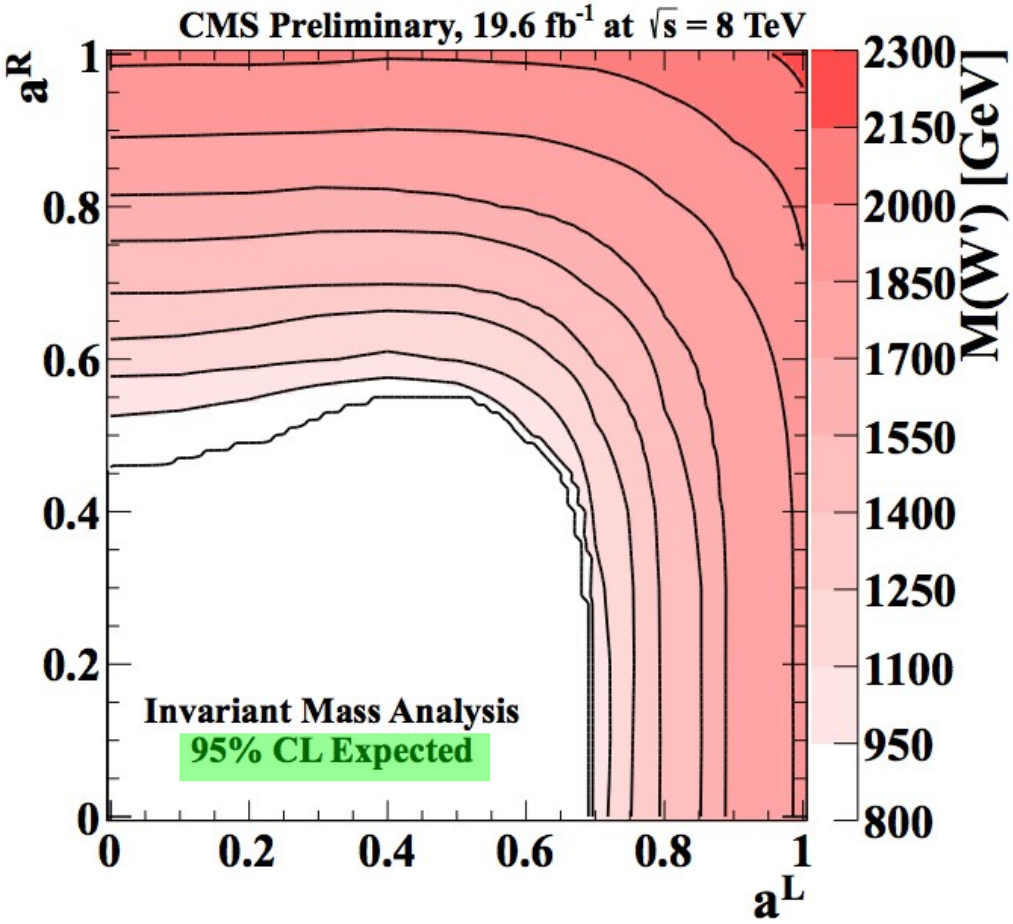


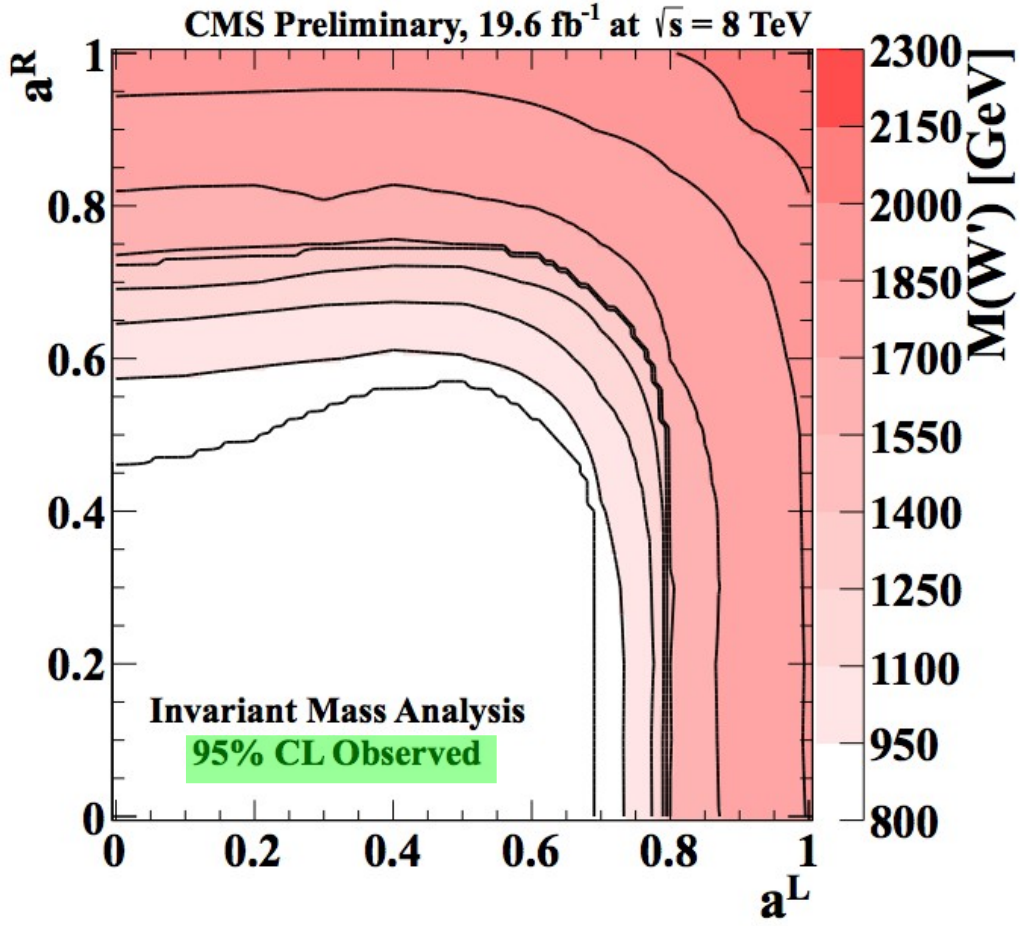
Best available limit !

Right handed W' (or left handed W' with no interference with the SM) of masses below 2.03 TeV are excluded

tb resonances limits

- mixed signal samples used to constrain (from the M(tb) distributuion), as a function of $M_{W'}$, the left and right handed W' couplings a_L, a_R.
- shaded regions are where the cross-section limit equals the theory predicted one





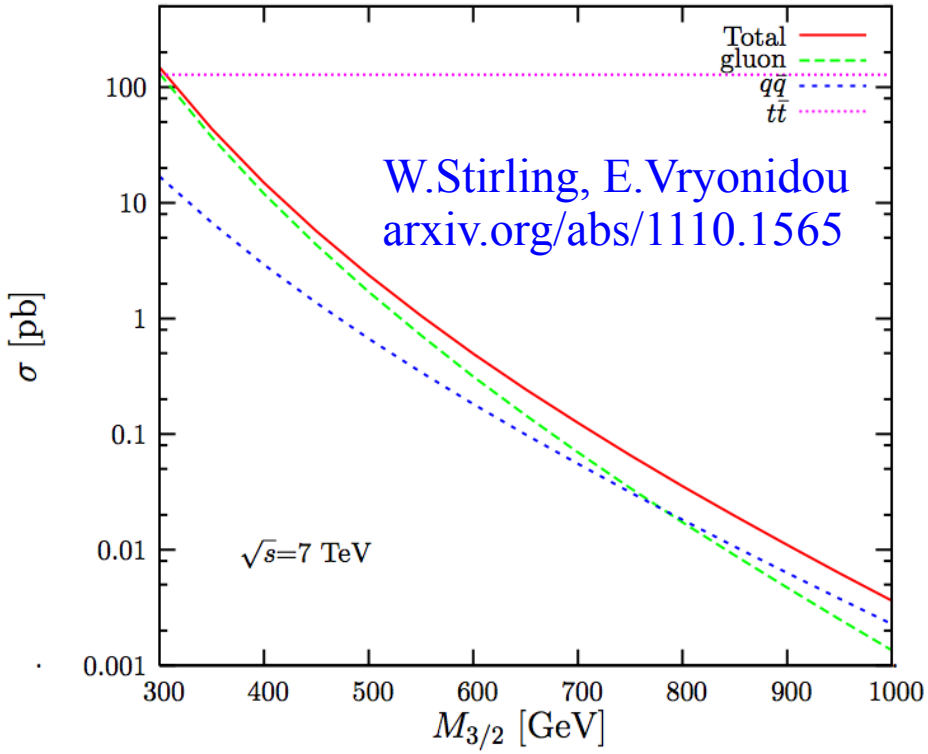
Excited tops

NEW !

https://cds.cern.ch/record/1528573

Several models for composite top quarks

- Search for pair produced spin 3/2 t*, decaying into top gluon
- Final state ttjj
- **First dedicated analysis**
- Similar searches for spin ½ q* → qg single production in dijet channels

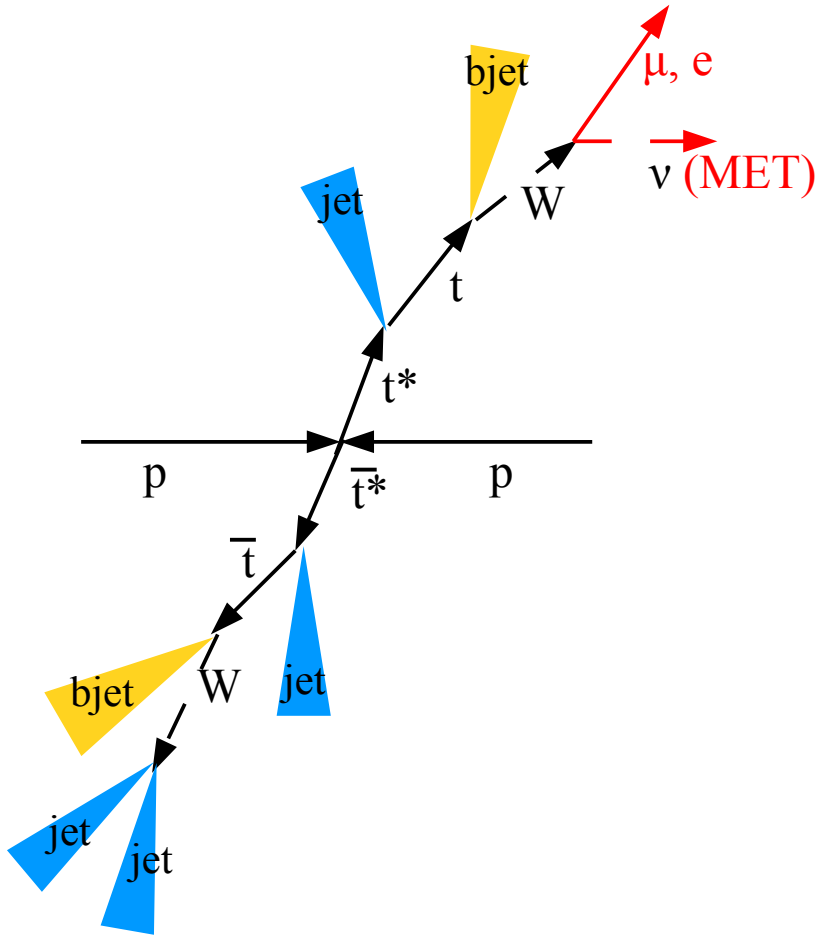


Signal : t*' samples : MADGRAPH+PYTHIA 6

Excited tops selection

Selection :
HLT isolated lepton + 3 jets
Semileptonic ttbar selection with two additonal jets

Exactly one isolated lepton
>=6 jets
>=1 b-tagged jets



Mass reconstruction and pairing :

- neutrino momentum calculated from lepton momentum and MET with a W mass constraint
- jet assignment from kinematic fit with η, φ and p_T free to vary within their resolution and constraints on m_t and m_W values and $m^{LEP}_{t^*}=m^{HAD}_{t^*}$

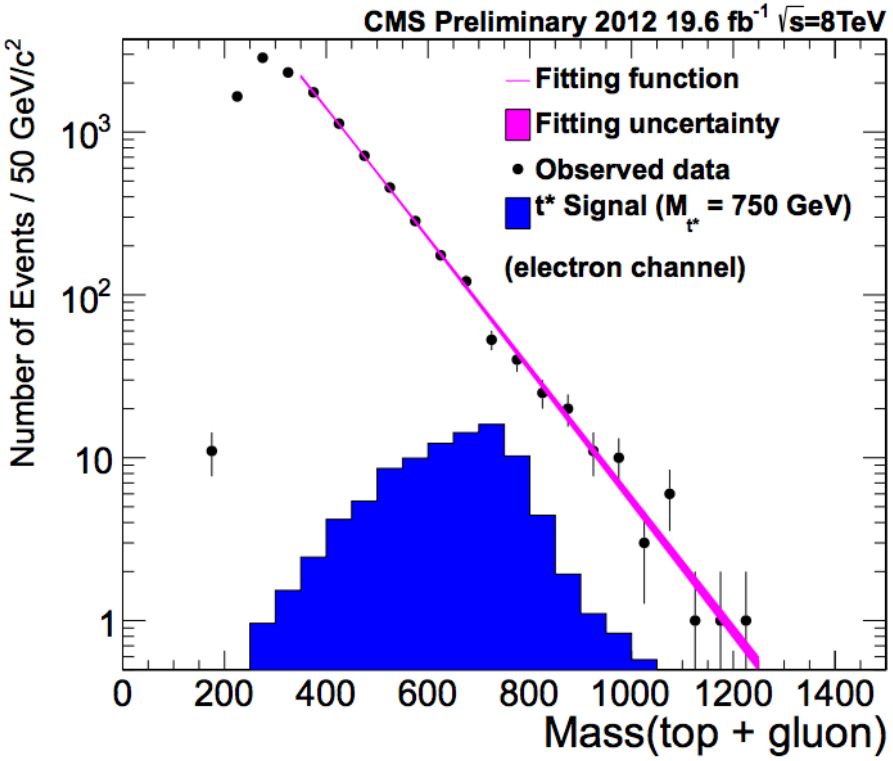
Excited tops
signal extraction

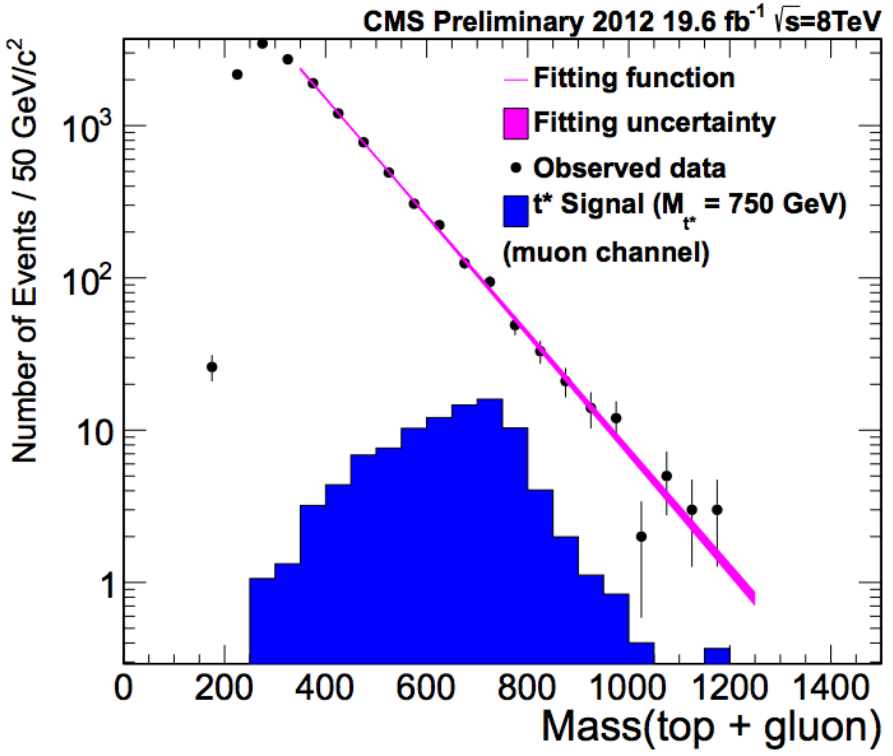
Signal extracted from a binned maximum likelihood fit on data
- signal parametrised with templates from MC

- background parametrised directly on data with a falling functional form
  - no bias in the signal extraction
  - accounted for in systematics

$$f_{bkg}(m) = \frac{a}{1 + \frac{e^{m-b}}{c}}$$

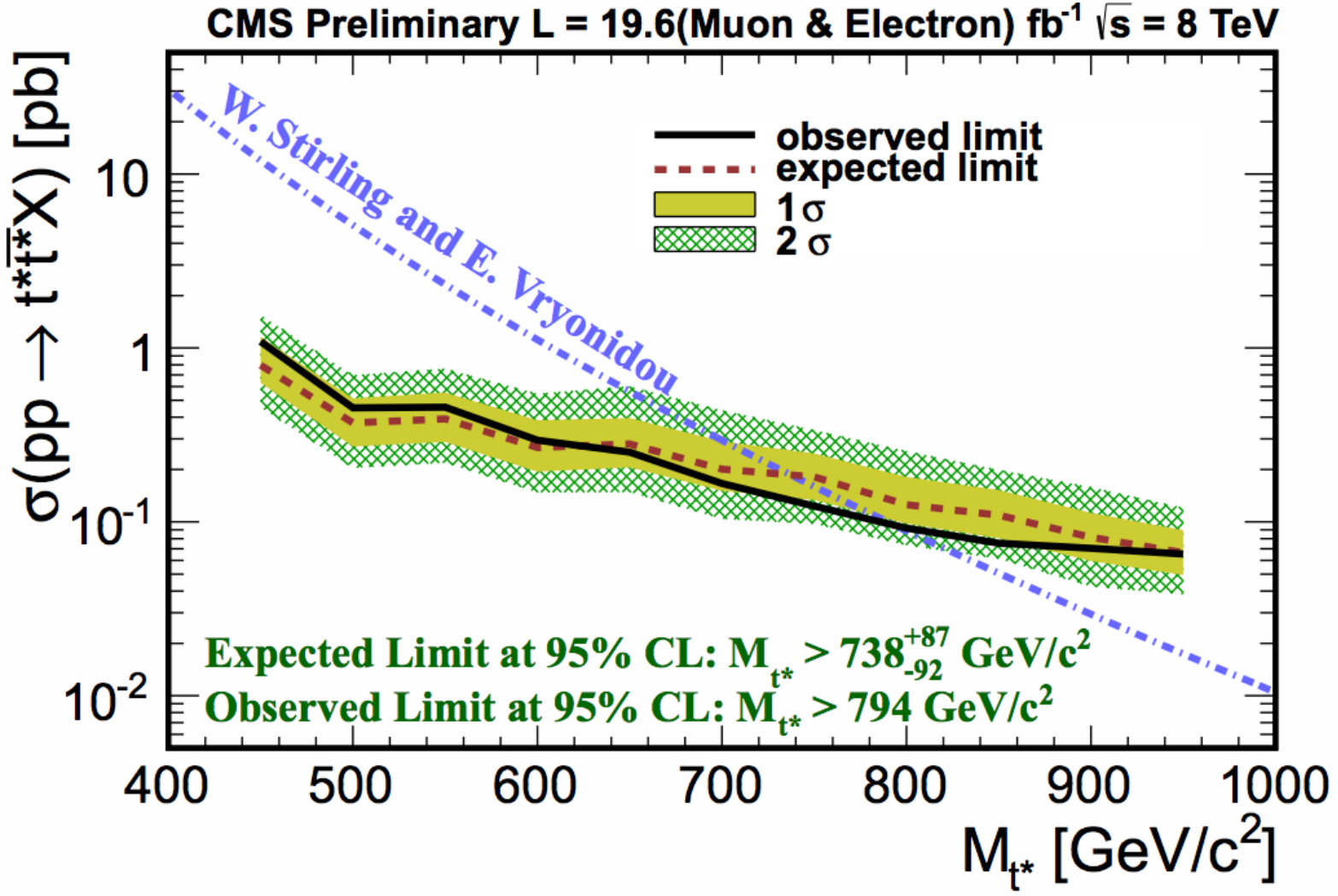
- several cross-checks with alternative methods





Excited tops limits

Limit setting with a Bayesian procedure, all uncertainties as nuisance parameters



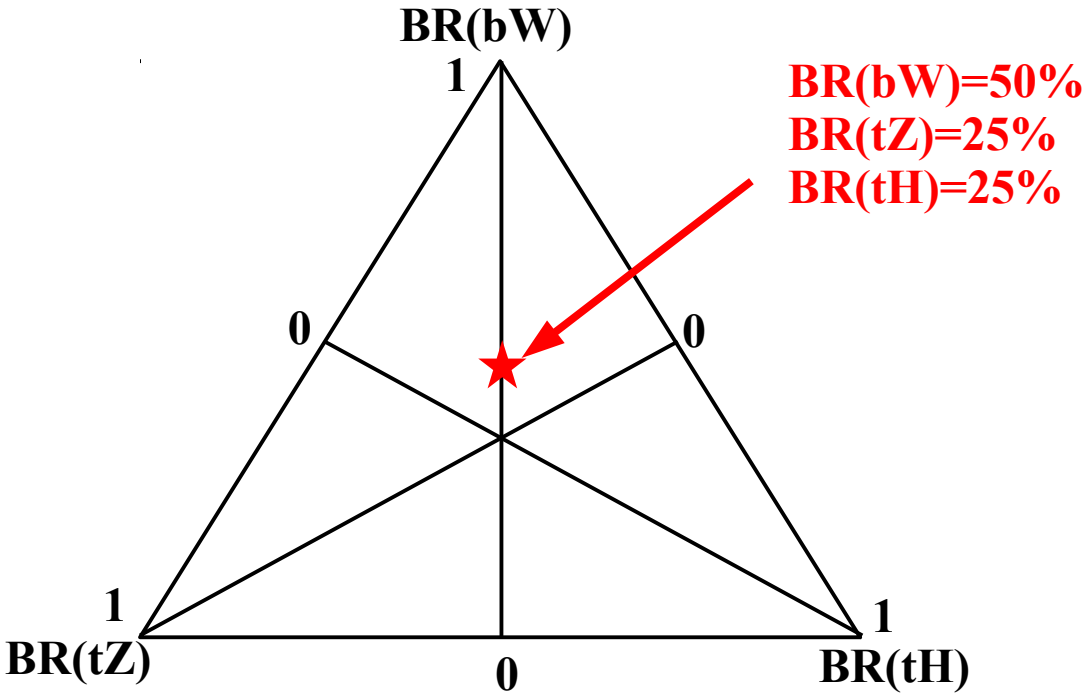
3/2 spin excited tops decaying to top+gluon of masses below 790 GeV are excluded.

Top partner T2/3

http://cds.cern.ch/record/1557571

Search for pair produced top partners

- T of charge 2/3, electro-weak singlet and only vector couplings with W and Z
- T → bW, tZ, tH search independent on BR
- Possible final states : bWbW, bWtH, bWtZ, tHtH, tHtZ, and tZtZ
  - single lepton signatures
  - multilepton (2 or 3) signatures



Top partners – T2/3
single lepton selection

Single lepton with W	Single lepton W veto
One isolated lepton (e, μ)	
MET > 20 GeV	
>= 3 jets (ak5) (p_T>120, 90, 50 GeV)	>= 4 jets
W tagged jet (CA8)	no Wtagged

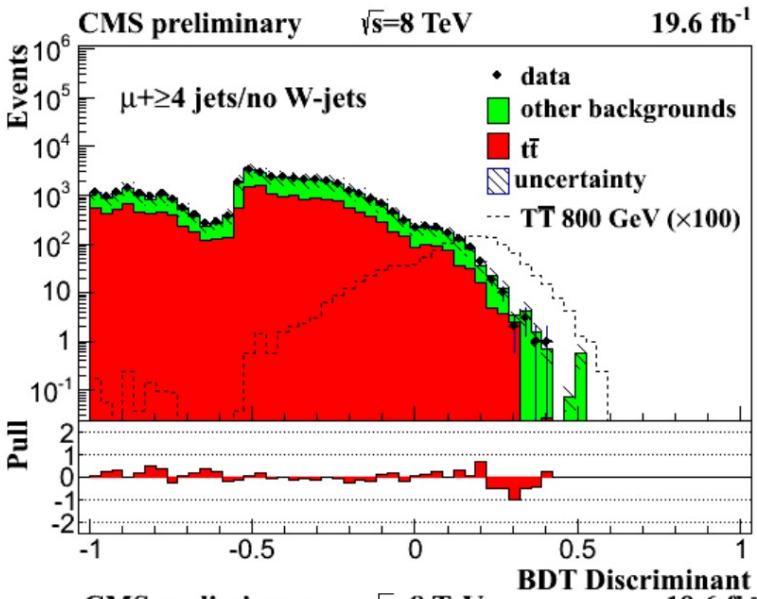
Boosted Decision Tree

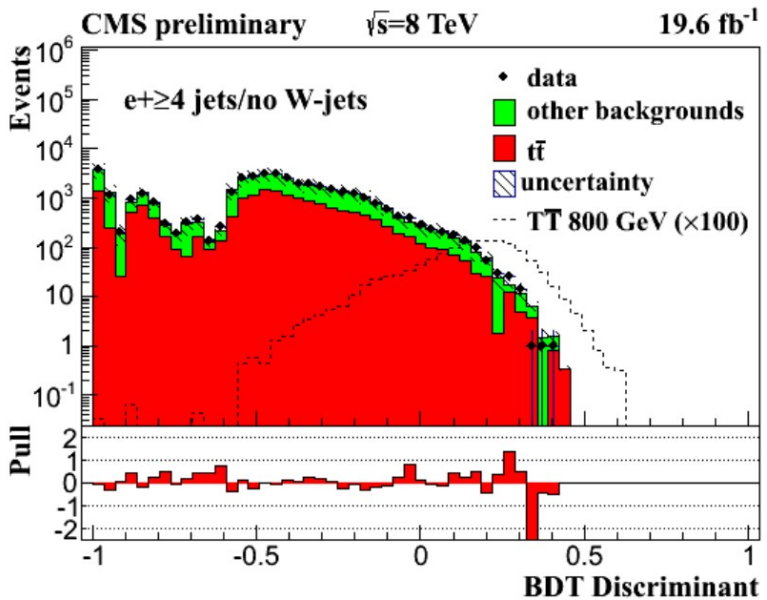
- variables with discrimination power and not highly correlated
- one BDT for all combinations of BR

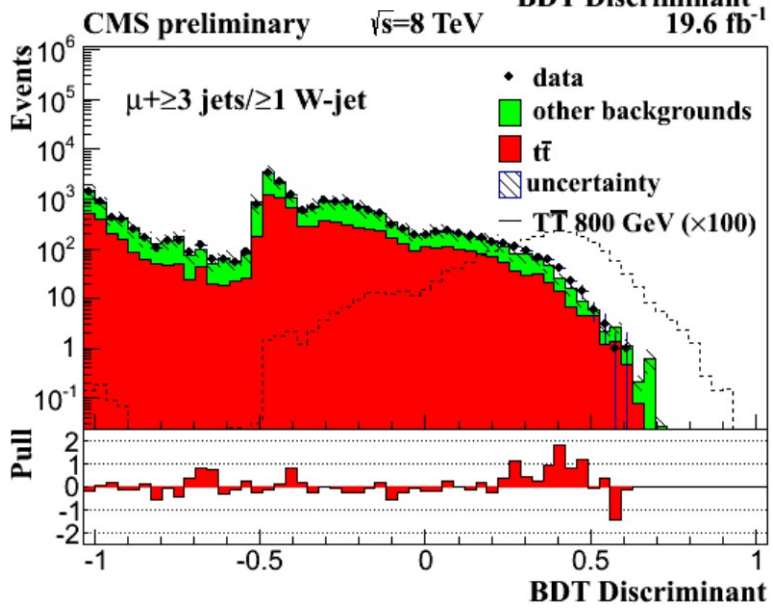
N_{jets} $N_{b\text{-}jets}$ HT (all jets) MET lepton p_T p_T^{j3} , p_T^{j4}	N_{jets} N_{bjets} HT (all jets) MET lepton p_T p_T^{j3} , p_T^{j4}
$N_{W\text{-}jets}$, $p_{TW\text{-}jets}$, $N_{t\text{-}jets}$	

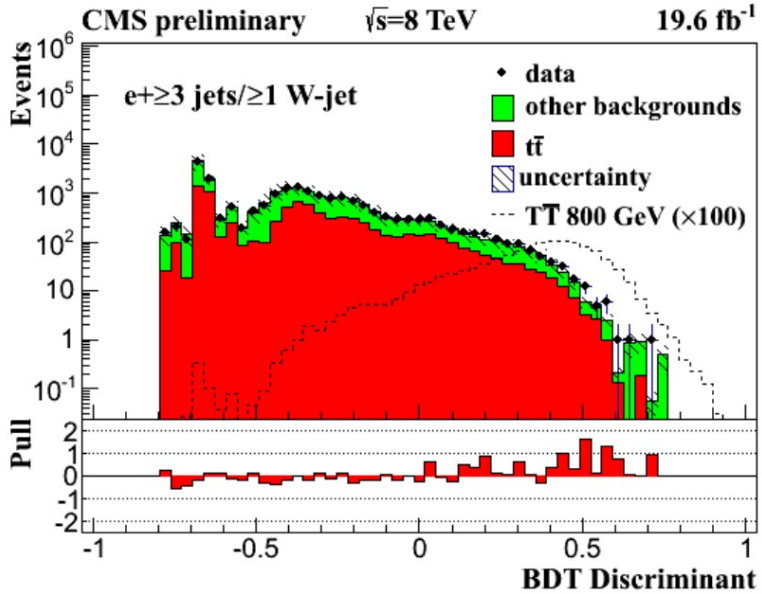
W+jets constrained on a data control sample
Additional information on W+light/heavy from independent analysis. Accounted for in systematics.

Top partners – T2/3
Data/MC for BDT output









BDT data/MC agreement validated on sidebands (0 btag)

Top partners – T2/3 multilepton selection

2 OS leptons
≥5 jets, HT>500 GeV
ST>1 TeV (jets+leptons+MET)

2 OS leptons, Z veto
2 or 3 jets, HT>300 GeV
ST>900 GeV (jets+leptons+MET)
m(lepton b-jet) > 170 GeV

2 SS leptons
≥3 jets, HT>500 GeV
ST > 700 GeV (jets+leptons+MET)

3 leptons
≥3 jets, HT>500 GeV
ST>700 GeV (jets+leptons+MET)

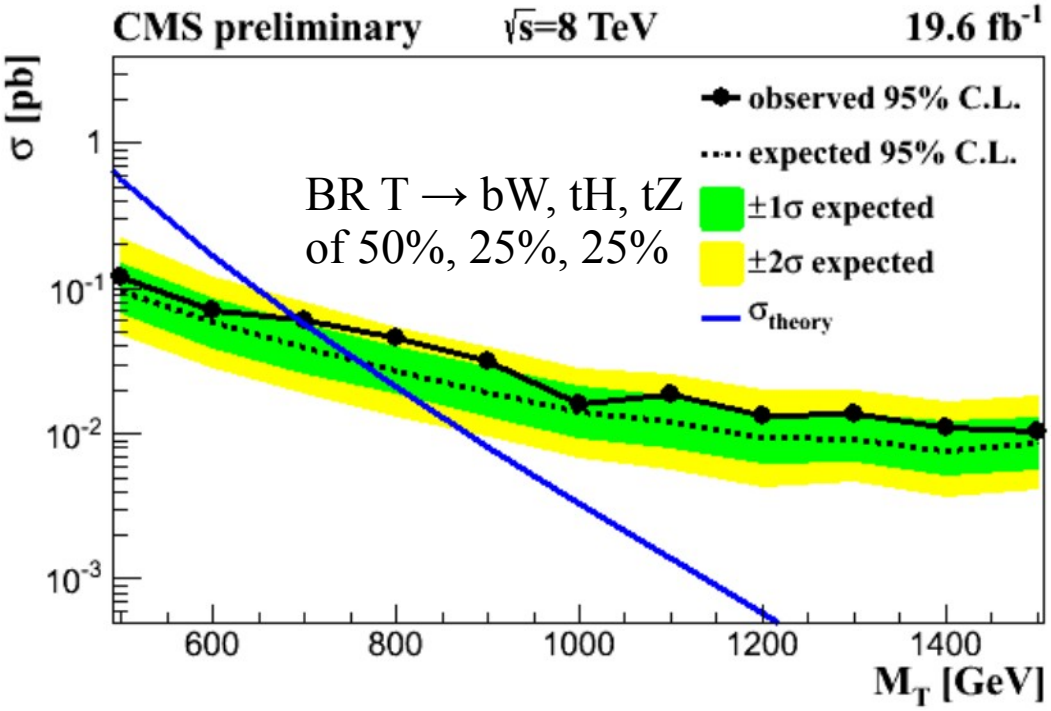
channel	OS1	OS2	SS	trileptons
$t\bar{t}$	5.2±1.9	80 ±12	-	-
single top	2.5±1.3	2.0±1.0	-	-
Z	9.7±2.9	2.5±1.9	-	-
$t\bar{t}W$	-	-	5.8 ±1.9	0.25±0.11
$t\bar{t}Z$	-	-	1.83±0.93	1.84±0.94
WW	-	-	0.53±0.29	-
WZ	-	-	0.34±0.08	0.40±0.21
ZZ	-	-	0.03±0.00	0.07±0.01
WWW/WWZ/ZZZ/WZZ	-	-	0.13±0.07	0.08±0.04
$t\bar{t}WW$	-	-	-	0.05±0.03
charge mis-ID	-	-	0.01±0.00	-
non-prompt	-	-	7.9 ±4.3	0.99±0.90
total background	17.4±3.7	84 ±12	16.5 ±4.8	3.7 ±1.3
data	20	86	18	2

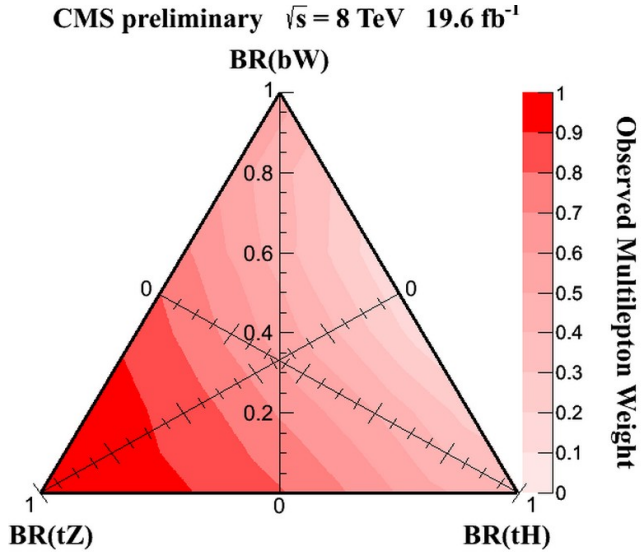
ee	eee
μμ	μμμ
eμ	eμμ/eeμ

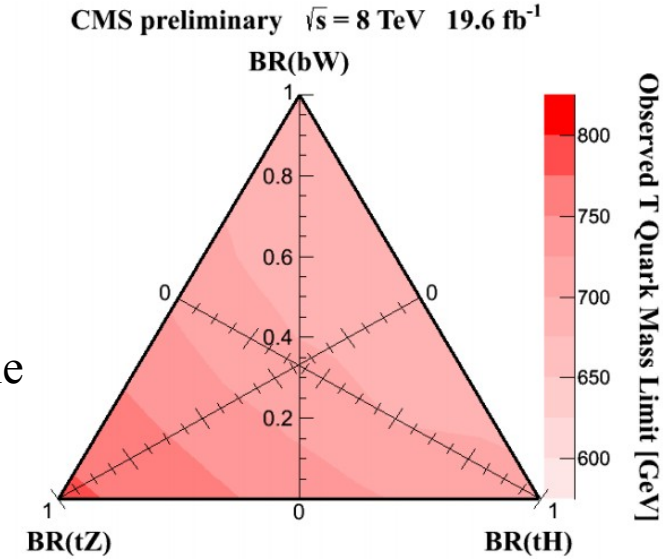
total of 12 categories

Top partners – T2/3 systematics

Bayesian limit calculation, all uncertainties nuisance parameters
- Single lepton limits set from the BDT distribution
- Multilepton limits from number of events in the 12 categories



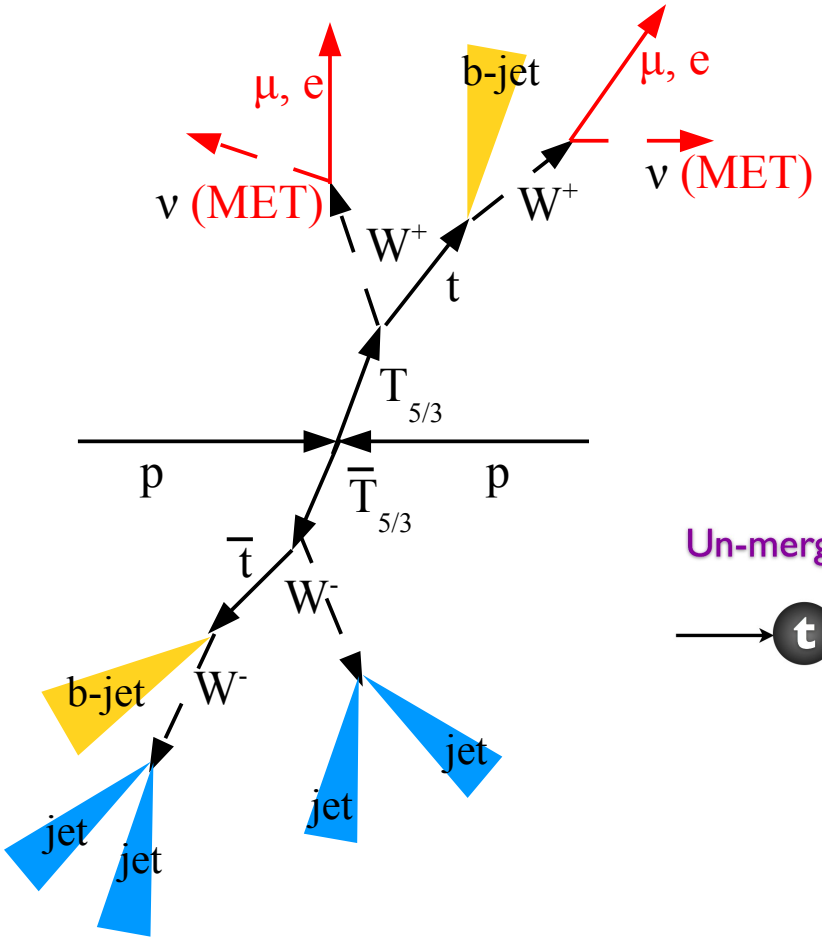




Limits for the T quark mass between **687 and 782 GeV** for all possible values of the branching fractions into the three different final states. Comparable with the expected limits.

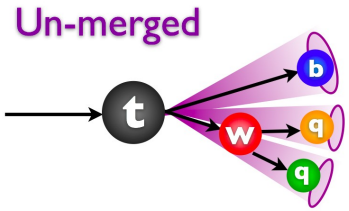
Top partners – T5/3

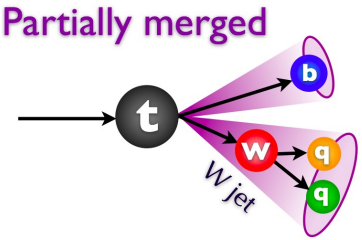
http://cds.cern.ch/record/1524087

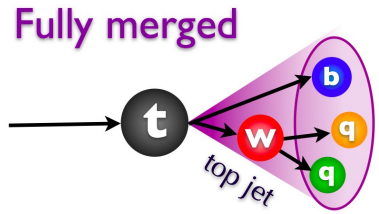


Search for pair produced top partners

- T of charge 5/3
- T → tW 100%







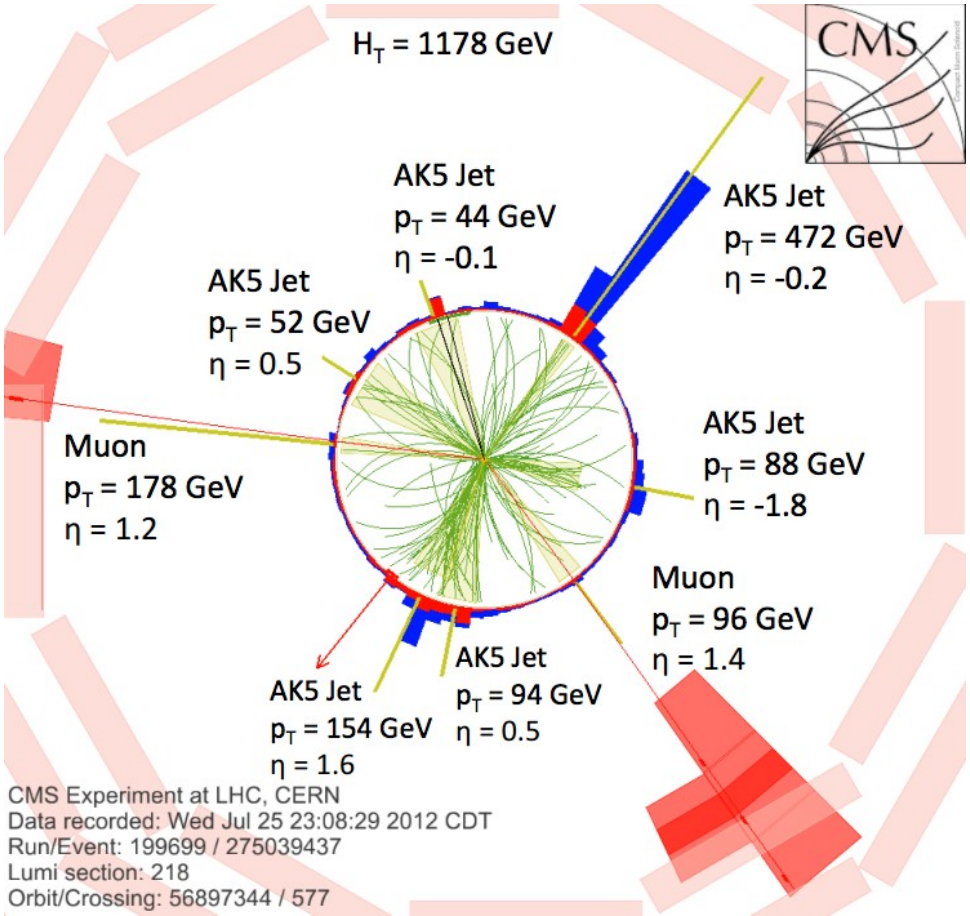
HLT dilepton trigger

- Jets reconstructed with both ak5 and CA8 algos
- One ak5 jet counts as 1 constituent
- One W-tagged CA8 jet counts as 2 constituents
- One top-tagged CA8 jet counts as 3 constituents

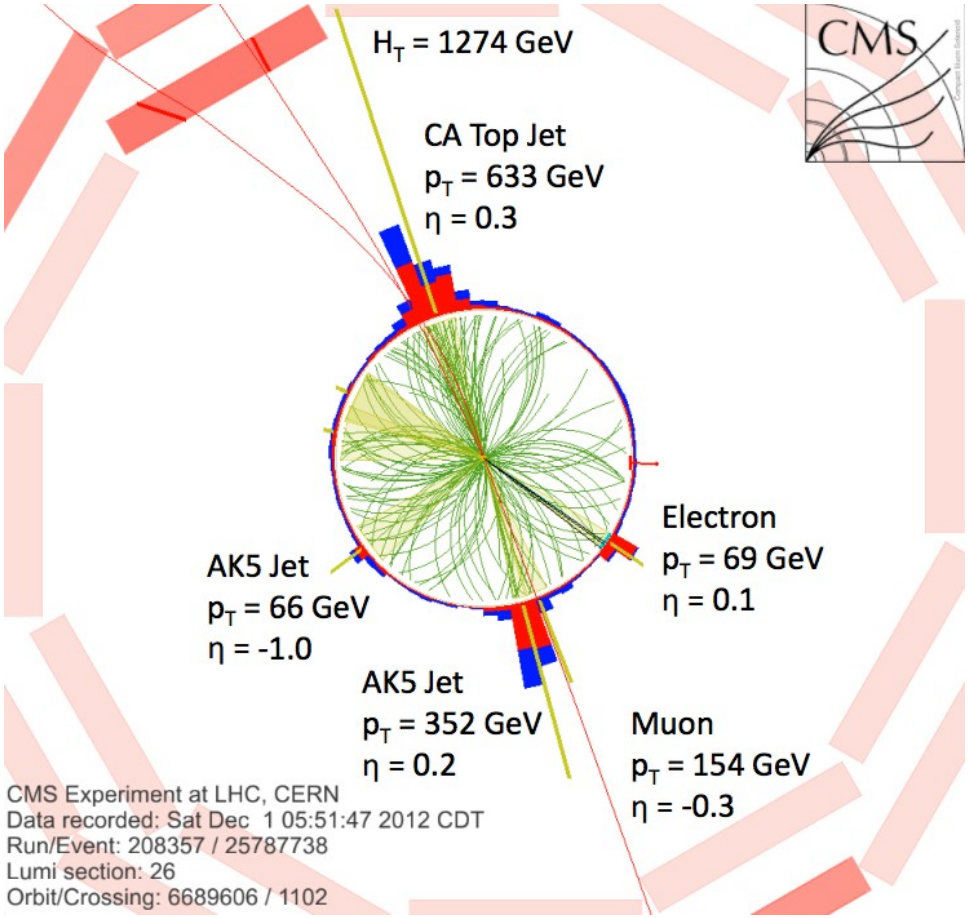
2 SS isolated leptons
2 dilepton and 3 lepton Z veto
HT>900 GeV (jets+leptons)
≥ 5 constituents

Top partners – T5/3

6 ak5 jets + 2 μ



1 (top-tagged) CA8 + 2 ak5 jets + μ + e



Top partners – T5/3

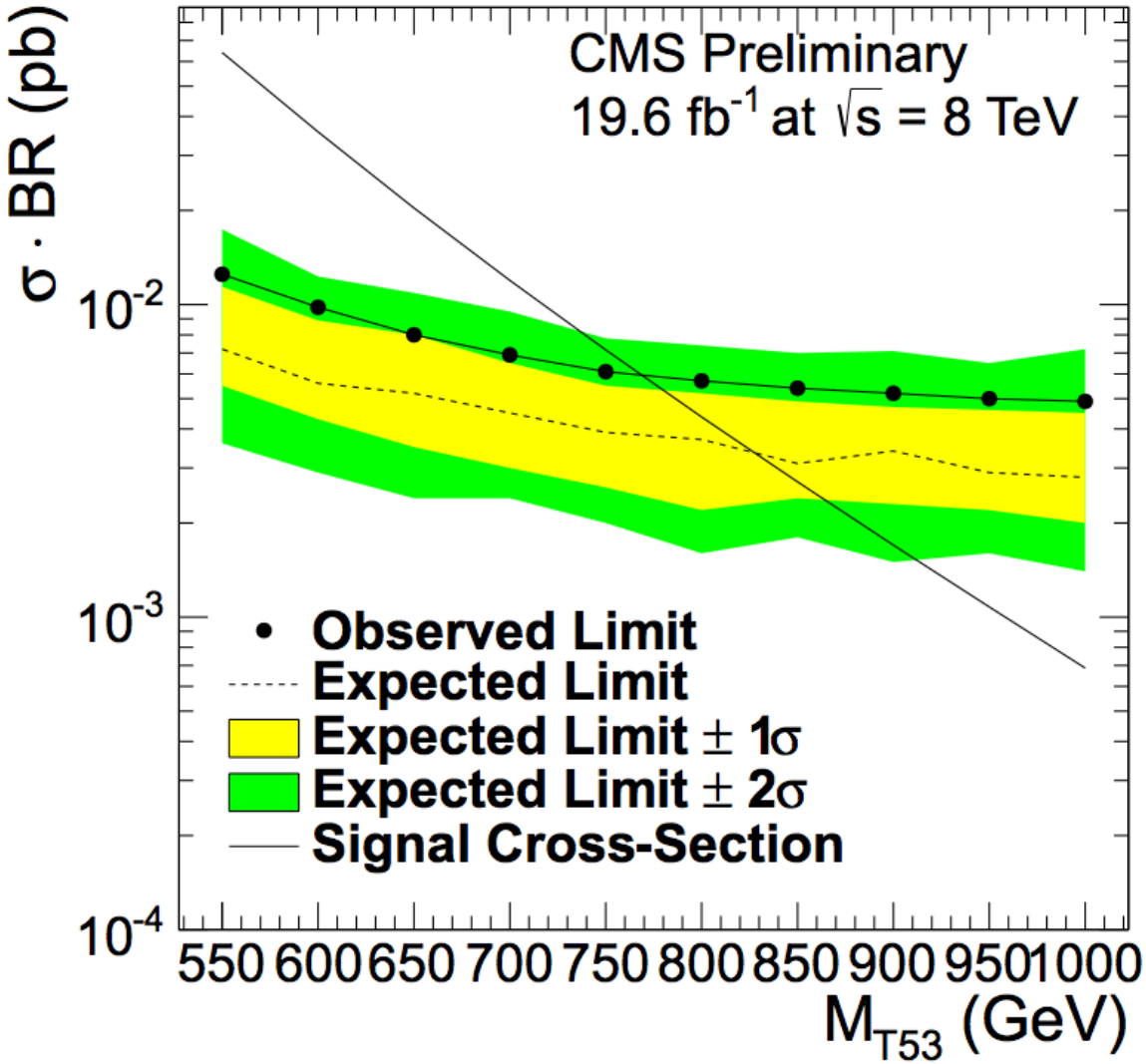
Backgrounds :

- **SS prompt leptons** from diboson or ttW/Z/H estimated from MC
- **SS from non-prompt leptons** (HF decays, decays in flight, conversions) estimated from data sideband enriched in non-prompt (m_T and Z veto) with tight-to-loose method. Cross-checked on MC and data, 50% uncertainty on the background estimation.
- **OS prompt leptons** from charge misID estimated on data (η dependent misID probability extracted from Z+jets enriched sample)

	PSS MC	Non-Prompt	Charge Mis-ID	Total Expected	Observed
ee	0.7 ± 0.2	1.9 ± 1.2	0.06 ± 0.02	2.6 ± 1.3	0
eμ	1.9 ± 0.4	0.6 ± 0.9	0.05 ± 0.01	2.5 ± 1.0	6
$\mu\mu$	1.3 ± 0.3	0.2 ± 0.6	-	1.5 ± 0.7	5
All	3.9 ± 0.8	2.6 ± 1.8	0.1 ± 0.02	6.6 ± 2.0	11

Top partners – T5/3 selection

- number of events in all categories are used for a Bayesian limit calculation
- $T_{5/3}$ for masses below 770 GeV are excluded
- only available result ob 8 TeV data



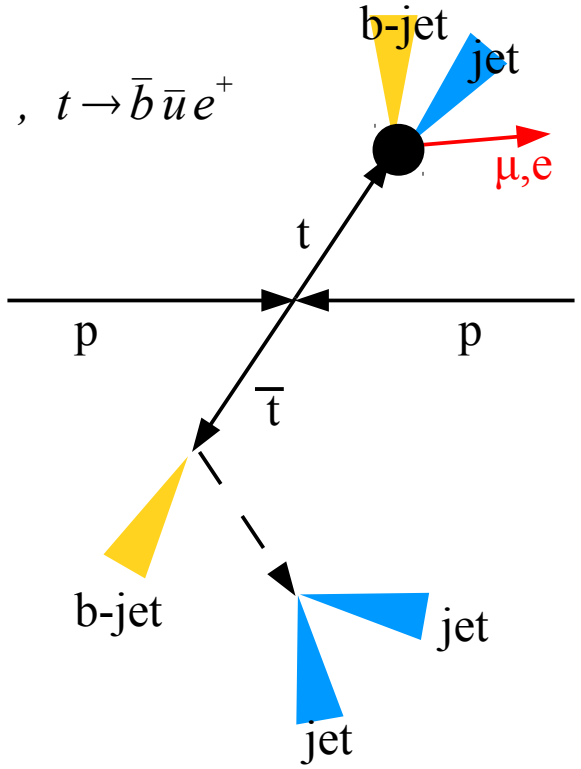
Baryon number violation in top decays

http://cds.cern.ch/record/1550330

- Baryon Number Violation possible in several models of New Physics (SUSY, GUTs..)
- BNV tested in nucleons, τ decays, heavy mesons, Z^0

- search for top pairs where one top decays SM, the other
- signature : Isolated lepton ; 5 jets ; no MET

$t \to \bar{b}\,\bar{c}\,\mu^+$, $t \to \bar{b}\,\bar{u}\,e^+$



HLT lepton + 3 central jets

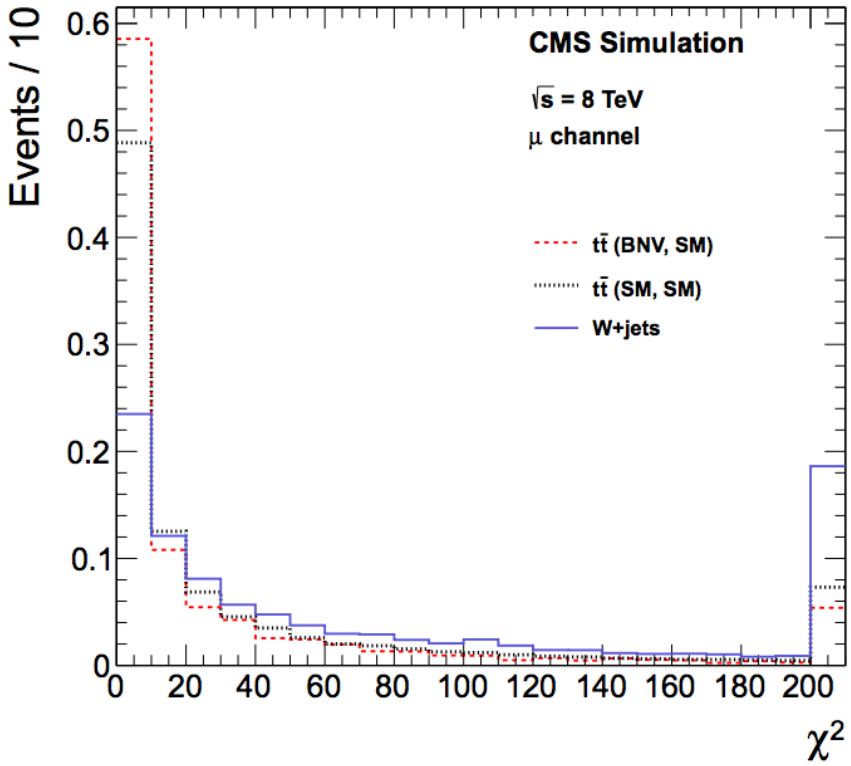
Exactly one good isolated lepton
≥5 jets (p_T > 70,55,40,30,30 GeV)
One b-tagged jet
MET < 20 GeV

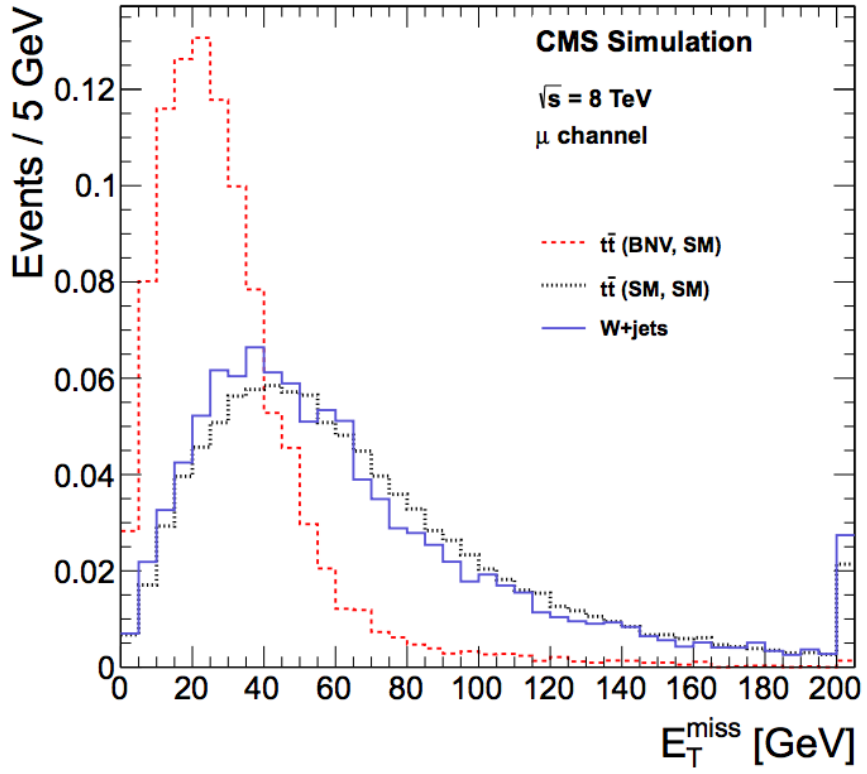
Signal samples for ttbar (one top BNV) and single (BNV) top
MADGRAPH 5+PYTHIA 6

Baryon number violation in top decays reconstruction

Mass reconstruction via χ^2 minimization, constraints on
- hadronic W mass
- hadronic top mass
- BNV top mass

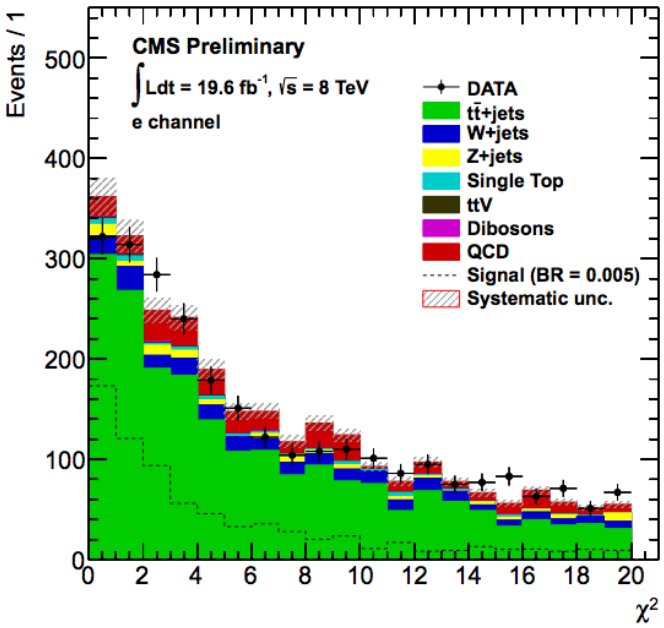
Minimal χ^2 <20

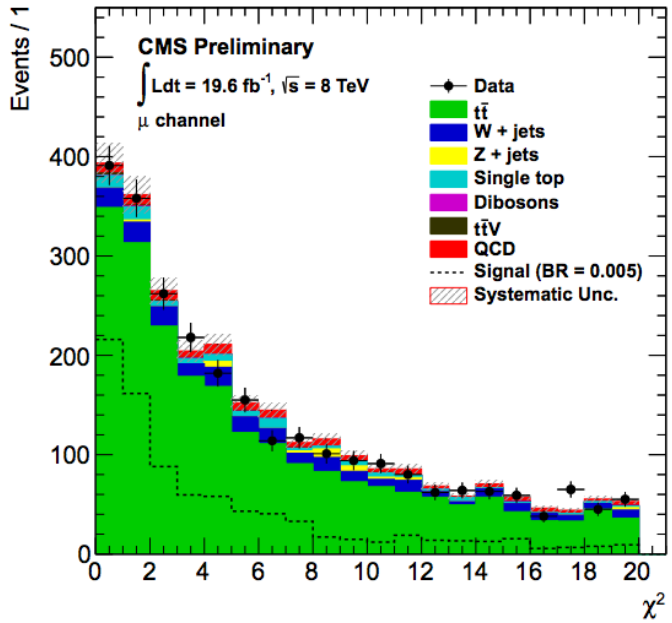




Baryon number violation in top decays signal extraction

Backgrounds determined from MC and data





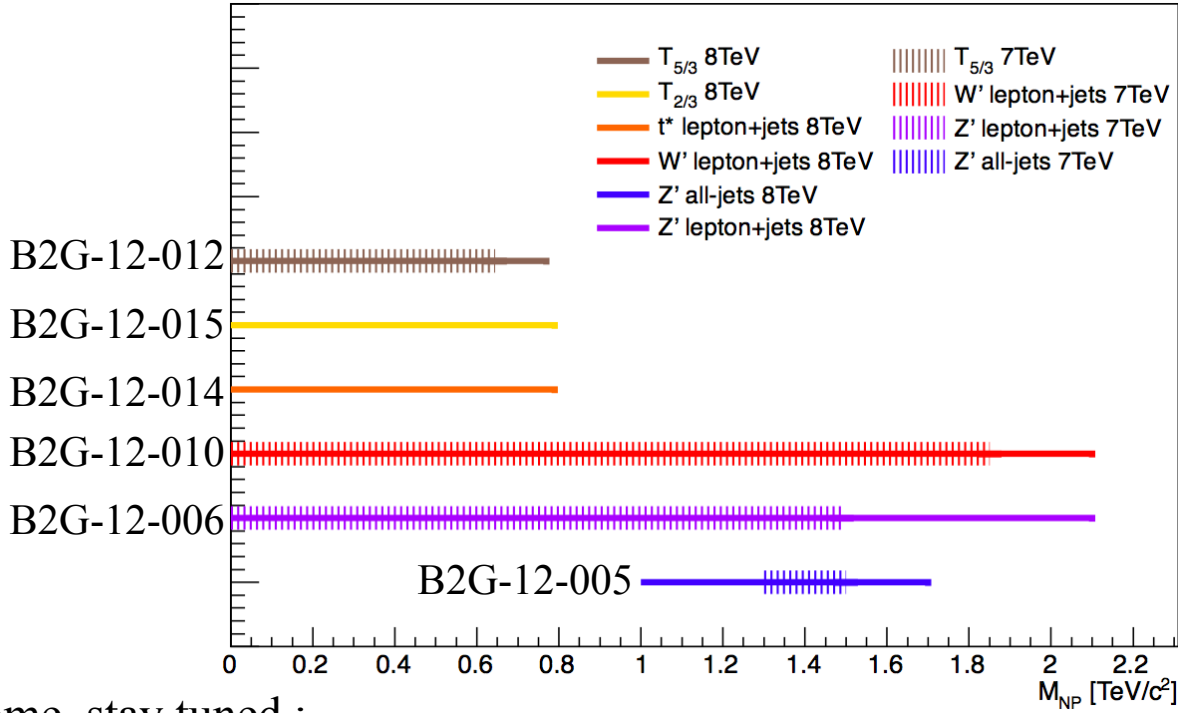
No sifgnificant excess over expected background.
Product of e and μ channels likelihood functions maximised (assuming same BR for the two channels). Upper limit on BR at 95% CL obtained with the Feldman-Cousins approach.
Only available result on 8 TeV data.

	95% CL Upp. lim.	Exp. lim.	68% exp. lim. range
Muon ch.	0.0016	0.0029	[0.0017, 0.0042]
Electron ch.	0.0017	0.0031	[0.0018, 0.0045]
Combined	0.0015	0.0029	[0.0016, 0.0042]

Conclusions

- Top quark production and decay a handle on many BSM models
- LHC as a top factory : precision measurements, playground for searches of new physics

- The B2G group in CMS is very actively pursuing the search program in the top sector
- Many interesting analyses, (for the moment) more and more stringent limits
- Exploiting the very high performance of CMS operations, reconstruction and analysis expertise
- Pioneer in new reconstruction techniques

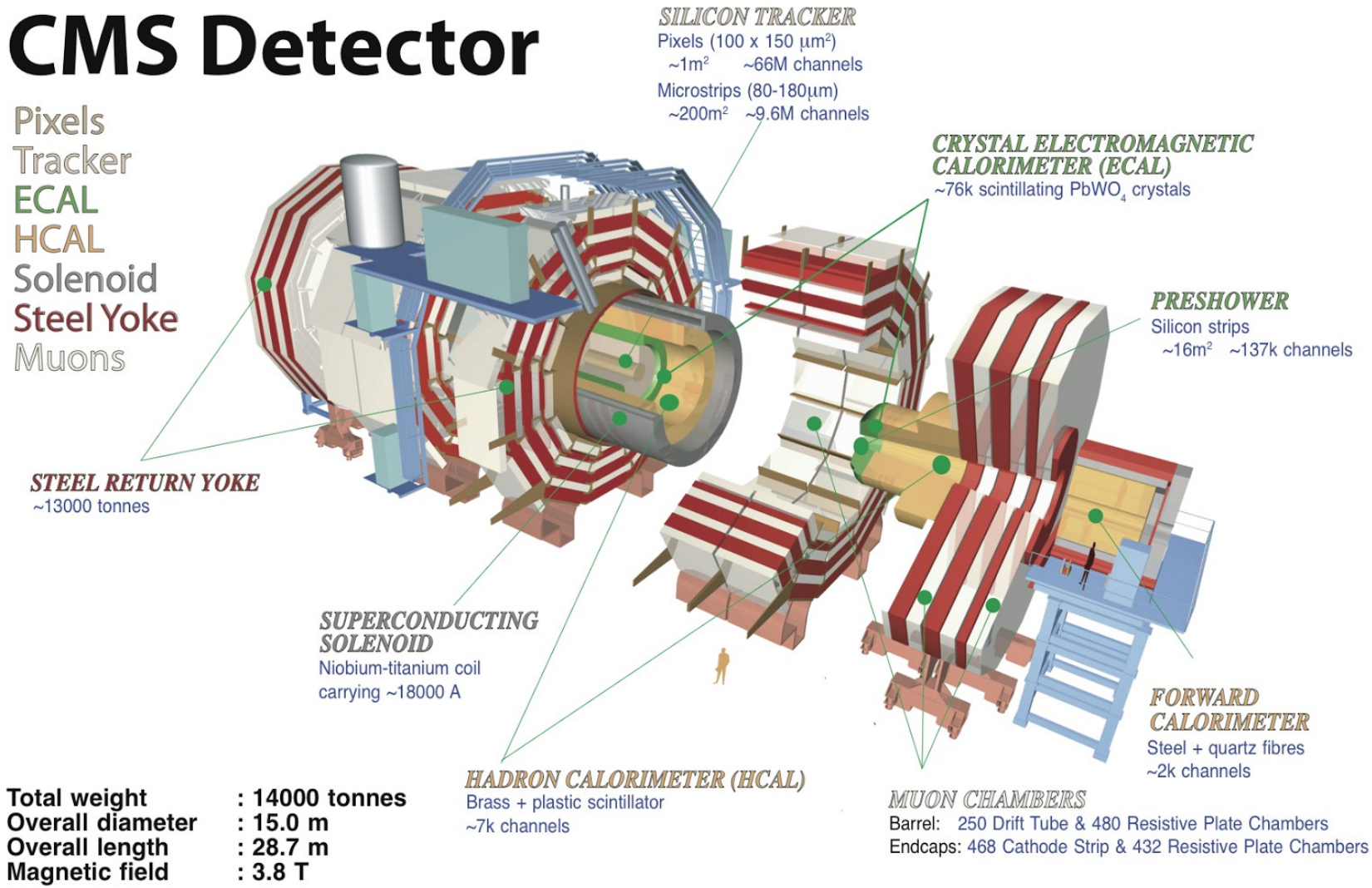


- More results to come, stay tuned :
  https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G
- Getting ready for more data at higher energy !

Backup

The CMS detector

All analyses presented today are **on the full 2012 dataset**



Ttbar resonances – lepton+jets systematics

All systematics taken as nuisance parameters in the fit procedure (lognormal priors)

Systematic uncertainty	threshold analysis signal	threshold analysis background	boosted analysis signal	boosted analysis background
event pileup	×	×	×	×
luminosity	×		×	×
lepton ID and trigger	×		×	×
jet energy scale and resolution	×		×	×
signal probability density function	×			
background probability density function		×		
background cross section				×
parton distribution functions	○		×	×
background modelling				×

Top tagging
minimum pairwise mass

https://cds.cern.ch/record/1333700