SEARCH for Heavy 4th generation quarks at CMS

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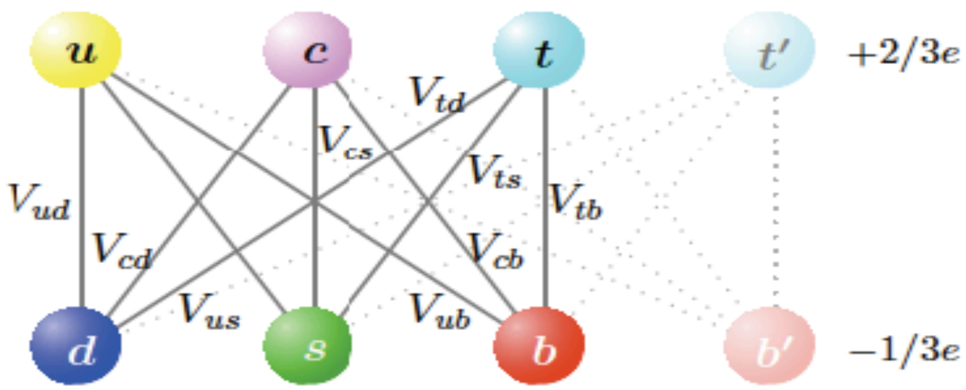
On behalf of the CMS Collaboration
ICHEP 2012
July 4-12, 2012 - Melbourne, Australia

4th Generation



- A simplest extension of the SM3, adding another fermion generation
- It is not excluded by Electroweak precision measurements
  - G. Kribs, T. Plehn, M. Spannowsky, T. Tait PRD 76 (2007) 075016
- It allows indirect bounds on the Higgs boson mass to be relaxed
  - P. Q. Hung and M. Sher. PRD 77, 037302 (2008)
- It can enhance CP violation significantly to explain the matter anti-matter asymmetry in the Universe
  - W. Hou, F.Lee, C. Ma PRD 79, 07302 (2009)
- If SM4 exists we expect small mass splitting between the t´ and b´ masses: $|m_{t'} - m_{b'}| < m_W$
  - M.Baak et al., arXiv:1107.0975

4th Gen: Vector-like Quark

- Vector-like fermions (non-chiral fermions) can be found in models like:
  - Little Higgs model
    - Nucl.Phys.Proc.Suppl.117 (2003)40
  - Warped extra dimensions
    - Phys.Rev.Lett.83:3370-3373,1999
- These models provide an explanation to the large difference between the Plank and the electroweak scale, the so called hierarchy problem in the SM
- **T´→tH, tZ or B´→bH, bZ** -- flavor changing neutral current (FCNC) decays enhance branching fractions

Outline

- CMS 4th generation searches @7 TeV https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO
  - t´ pair search
    - dilepton channel $t'\bar{t}' \to WbW\bar{b} \to l\nu bl\bar{\nu}\bar{b}$ arXiv:1203.5410, submitted to PLB
    - lepton+jets channel $t'\bar{t}' \to WbW\bar{b} \to l\nu b\bar{b}q\bar{q}$ CMS-PAS- EXO-11-099
  - b´ search $b'\bar{b}' \to WtW\bar{t} \to bWWbWW$ arXiv:1204.1088, submitted to JHEP
    - trilepton channel
    - same sign dilepton channel
  - Inclusive t´ and b´ search CMS-PAS- EXO-11-098
    - singly produced
      $t'b \to bWb$
      $b't \to tWbW \to bWWbW$
    - pair produced
      $b't' \to tWbW \to bWWbW$
      $t'\bar{t}' \to bWbW$
      $b'\bar{b}' \to tWtW \to bWWbWW$
  - T´vector like pair $T\bar{T} \to tZ\bar{t}Z \to b\bar{b}WWZZ$ 10.1103/PhysRevLett.107.271802
  - B´ vector-like pair $B\bar{B} \to bZ\bar{b}Z$ CMS-PAS-EXO-11-066

Search for t′→bW(l+jets)

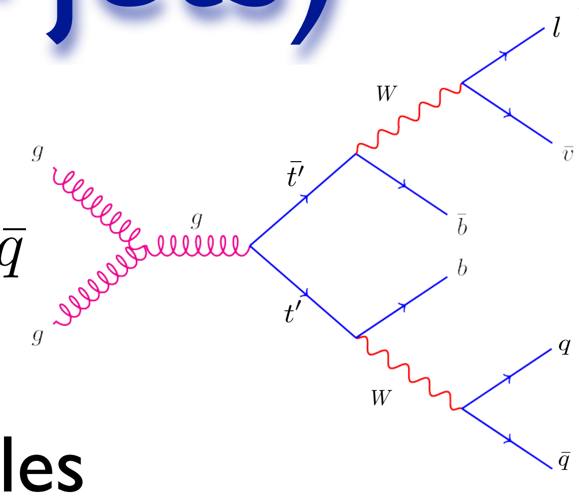
EXO-11-099

5 fb^{-1}

Selection

- A lepton e(μ) with p_T > 35 GeV
- ≥ 4 jets of p_T > 35, ≥1b-tagged jet
- Missing E_T > 20 GeV

$$t'\bar{t}' \to WbW\bar{b} \to l\nu b\bar{b}q\bar{q}$$

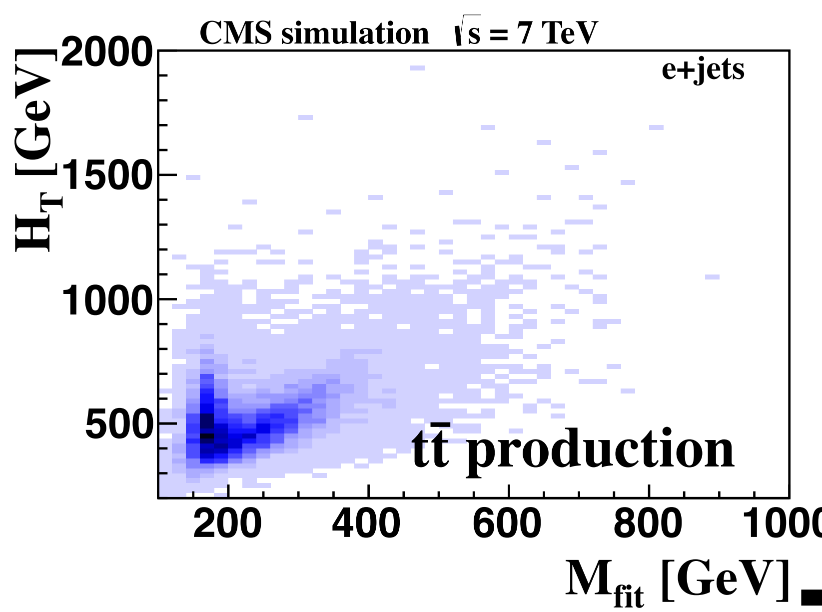


Strategy

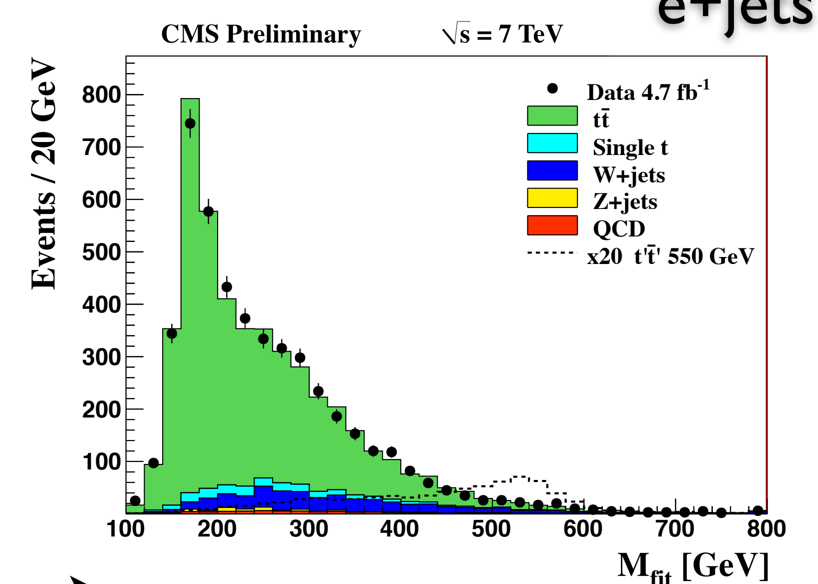
- Apply kinematic fit for mass reconstruction (M_{fit}) with constraints
  - m(lν) = m(qq) = M_W
  - m(lνb) = m(qqb)
- Look in the H_T and M_{fit} tails for signs of a massive quark decay

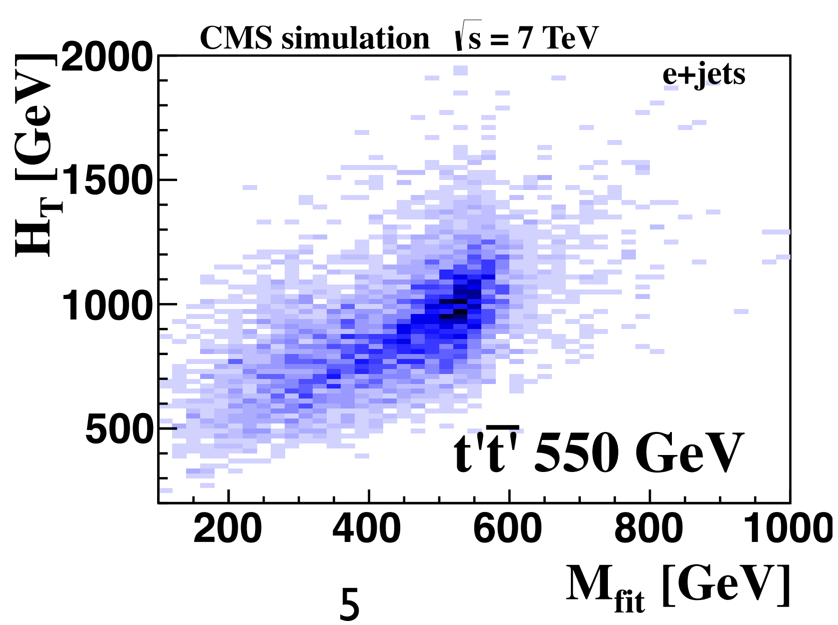
$$H_T = p_T^{lepton} + p_T^{miss} + \sum p_T^{jets}$$

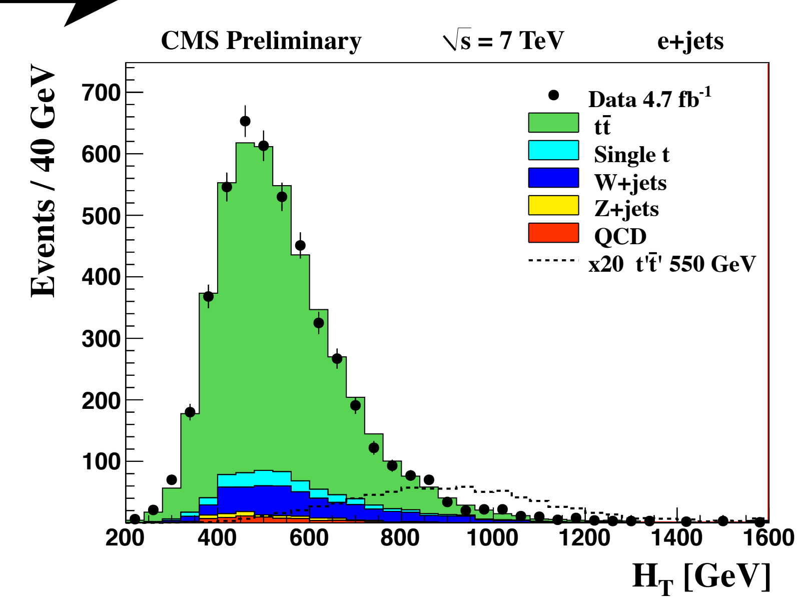
Discriminating variables



e+jets





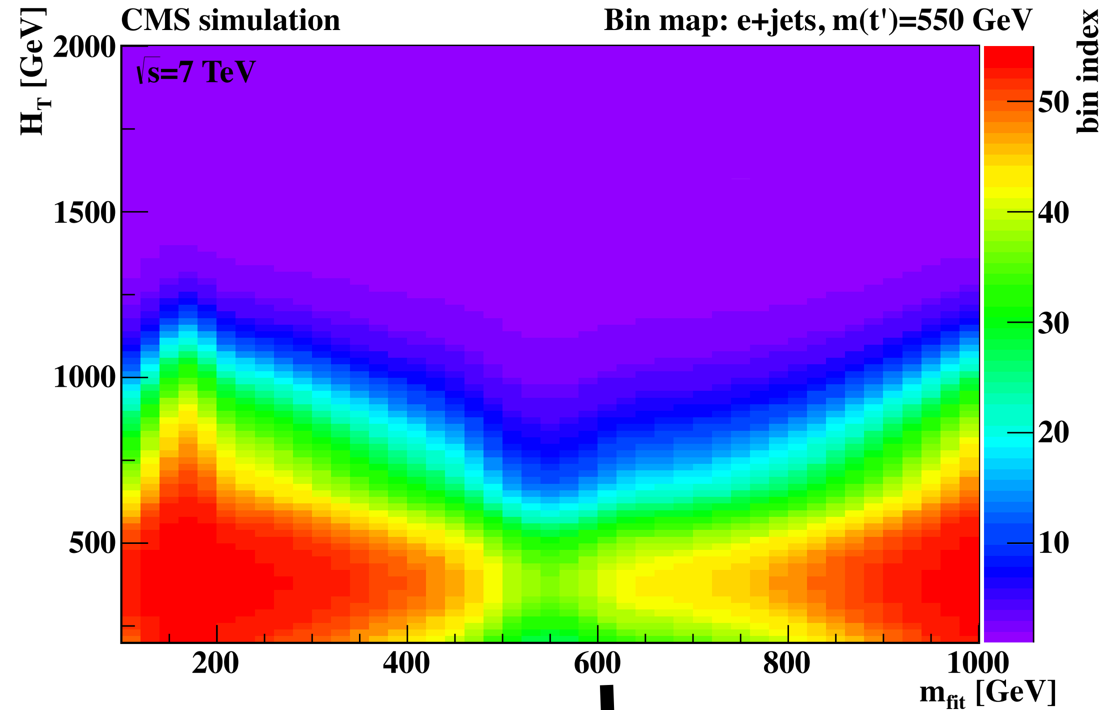


Search for t′→bW(l+jets)

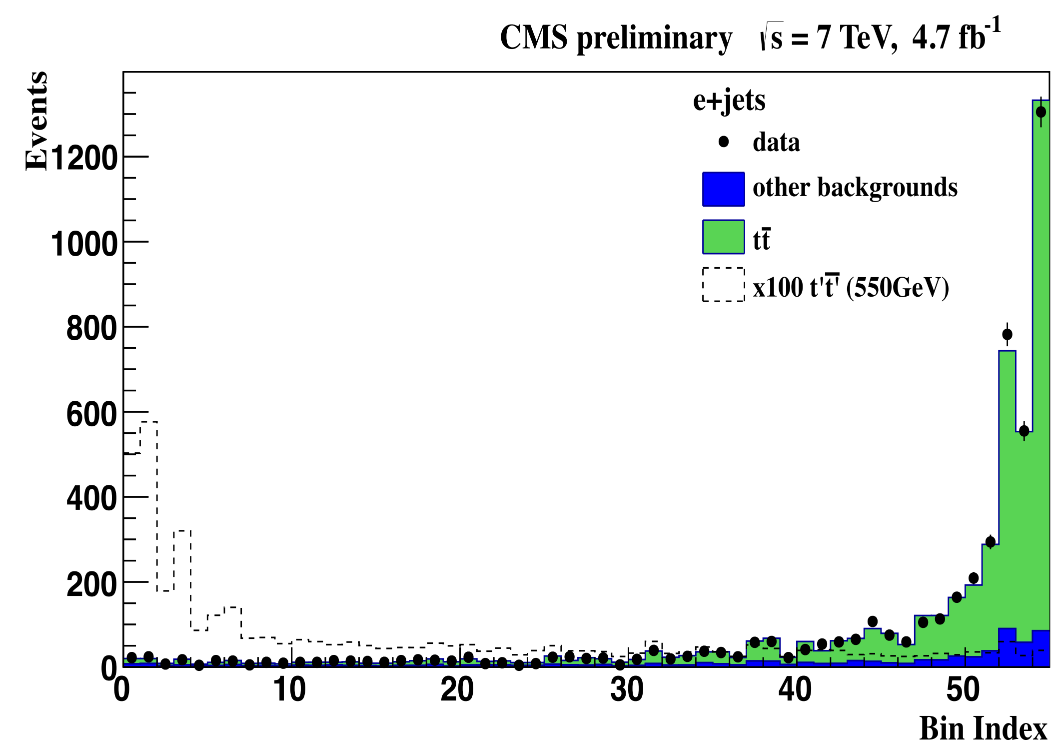
EXO-11-099

4.7 fb^{-1}

- The 2D H_T vs M_{fit} histograms have few empty or low occupancy bins
- Rebin them to extract the correct statistical inferences
  - Project 2D histograms into 1D profiled with analytic functions
  - Sort by ordering the bins in descending S/B ratio
  - Merge neighboring bins into 1D histogram until a minimum precision in the expected number of background and signal events is achieved



Each color becomes a single bin in the 1D template



Low index values corresponds to high S/B ratio

Search for t′→bW(l+jets)

EXO-11-099

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- Compute the t′ pair cross section using CLs method
  - Likelihood ratio is used as a test statistics for an observable x, parameter of interest σ and nuisance parameters α

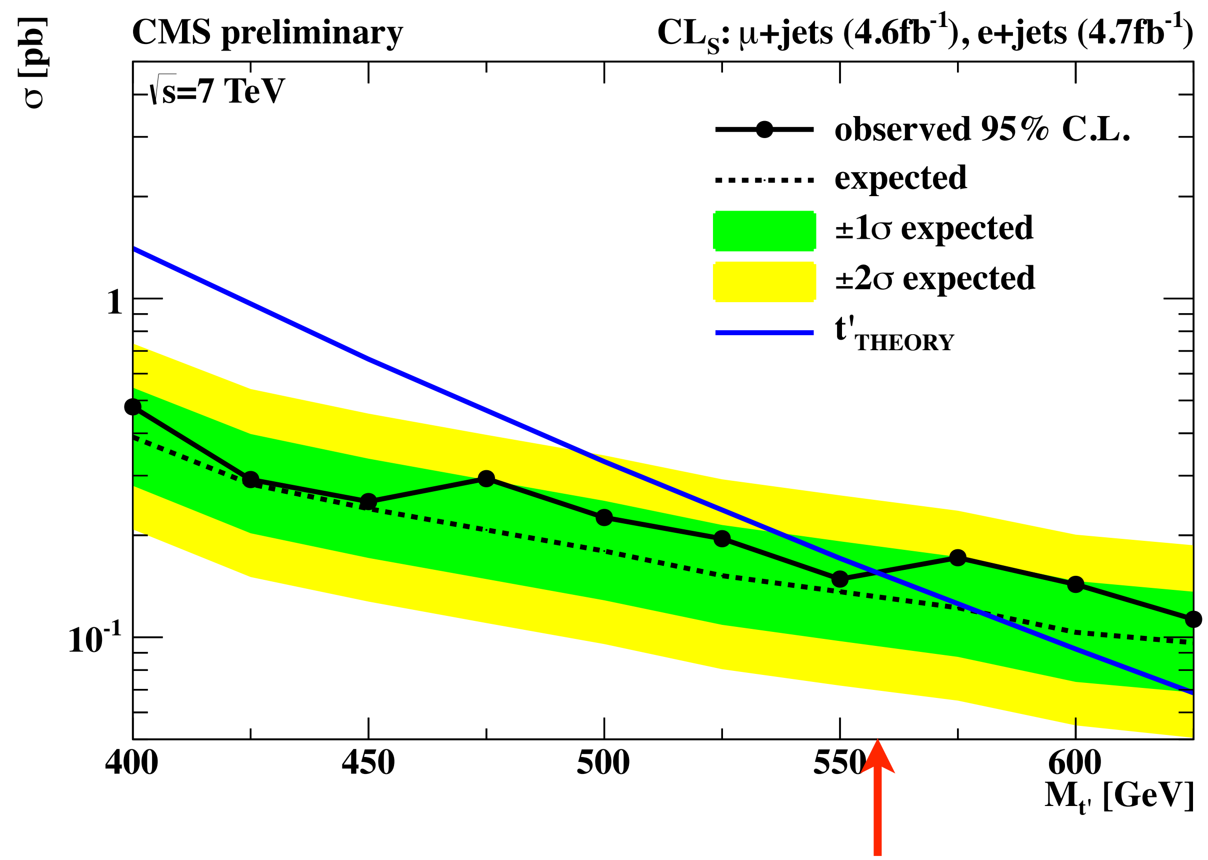
$$t(x|\sigma) = \begin{cases} L(x|\sigma,\hat{\alpha}_\sigma)/L(x|\hat{\sigma},\hat{\alpha}) & \text{if } \sigma > \hat{\sigma} \\ 1 & \text{if } \sigma \leq \hat{\sigma}. \end{cases}$$

  - 95% C.L. upper limit corresponds to

$$CL_s = \frac{CL_{s+b}}{CL_b} = 0.05.$$

- The nuisance parameters includes
  - Normalization of electroweak and ttbar backgrounds
  - Jet energy scale
  - Integrated luminosity
  - Lepton efficiency
  - Parton shower matching threshold .....

Result



Observed limit: $m_{t'}$ > 560 GeV/c^2 @ 95% CL

Search for inclusive b′/t′ production

EXO-11-098

5 fb^{-1}

- Simplify CKM4 with one free parameter: $A = |V_{tb}|^2 = |V_{t'b'}|^2$
  - A > 0.66 (|Vtb| > 0.81 @ 95% C.L.) from Tevatron

$$V_{CKM}^{4\times4} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} & V_{ub'} \\ V_{cd} & V_{cs} & V_{cb} & V_{cb'} \\ V_{td} & V_{ts} & V_{tb} & V_{tb'} \\ V_{t'd} & V_{t's} & V_{t'b} & V_{t'b'} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & \sqrt{A} & \sqrt{1-A} \\ 0 & 0 & -\sqrt{1-A} & \sqrt{A} \end{pmatrix}$$

- Assume degenerate states: $m_{t'} = m_{b'} = m_{q'}$
  - Assume the branching fractions to be ~100%
- Baseline selection
  - Lepton (e/μ) with p_T > 40 GeV
  - ≥ 1 jet of p_T > 30 GeV and ≥ 1 b-tagged
  - Missing E_T > 40 GeV

Process	
$t'b \to bWb$	max for A = 0
$t'\bar{t}' \to bWbW$	independent of A
$b't \to tWbW \to bWWbW$	max for A = 0
$b't' \to tWbW \to bWWbW$	max for A = 1
$b'\bar{b}' \to tWtW \to bWWbWW$	independent of A

- Final state topologies contains
  - 1-4 W bosons (≥ 1 W decay leptonically)
  - 2 b-quarks

1W	2W	3W	4W
t′b	t′t′	b′t + b′t′	b′b′

- Search is performed
  - Single $\underbrace{\text{lepton}}_{\text{sensitivity to all signal process}}$(e/μ) / Same-sign $\underbrace{\text{dilepton}}_{\text{sensitivity to signal with 1 or 2 b′ process}}$ / Trilepton + jets

Search for inclusive b′/t′ production

EXO-11-098

5 fb^{-1}

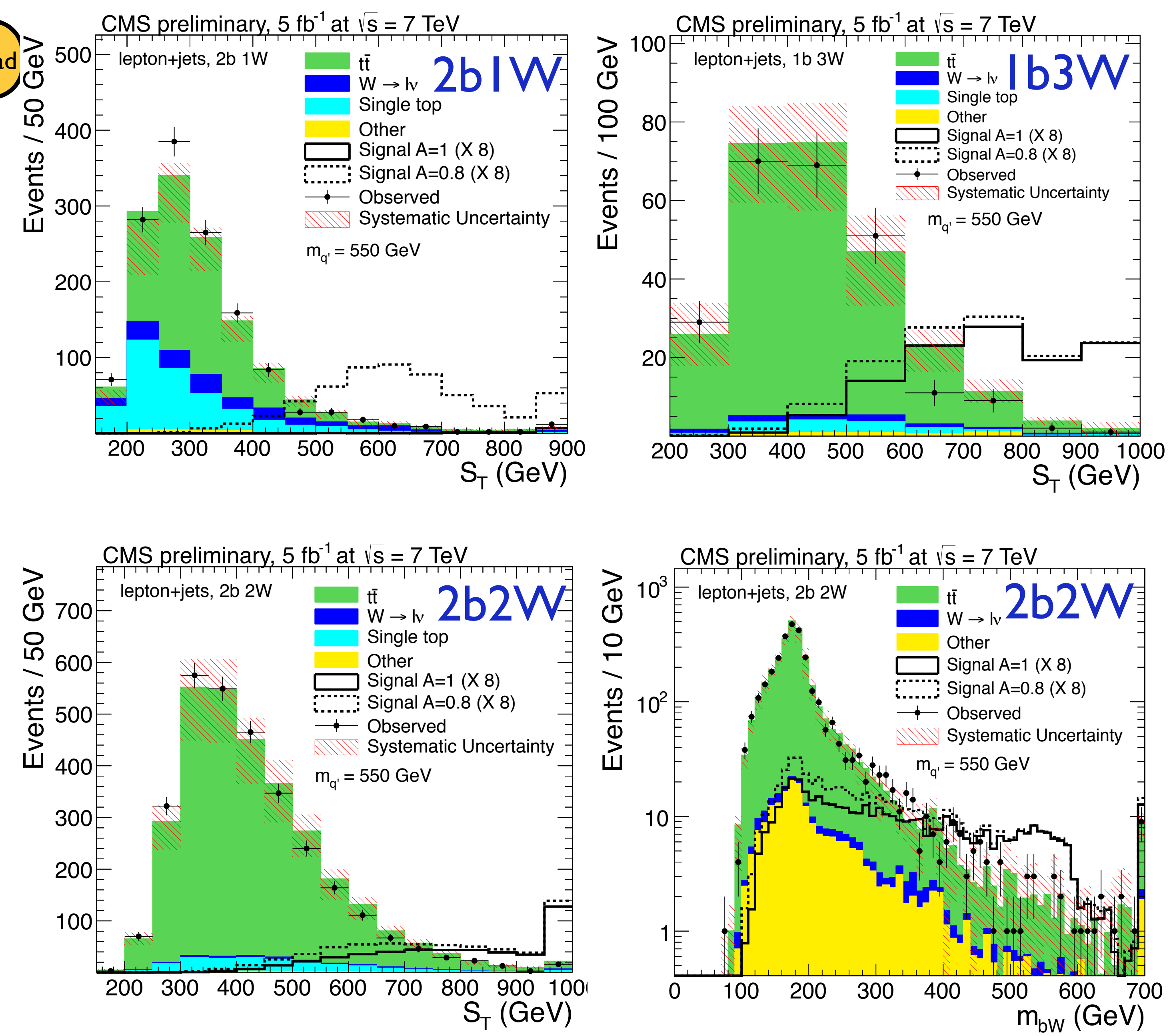
Discriminator: Scalar sum of reconstructed objects (S_T) and hadronic top mass (m_{bW})

$$S_T = \not{E}_T + p_T^l + p_T^b + p_T^j + \sum_{i=0}^{N} p_T^{W^i_{q\bar{q}}},$$

lepton p_T | b-jet p_T | p_T of 2nd b-jet or jet not from W_{had} | p_T of W_{had}

- 2b1W box : single t′
  - exactly 2 b-tagged jet
- 1b2W box (2b2W box): t′t′
  - exactly 1 (2) b-tagged jet(s)
  - exactly 1 hadronically decaying W
- 1b3W box (2b3W box): single b′
  - exactly 1 (2) b-tagged jet(s)
  - exactly 2 hadronically decaying W
- 1b4W box (2b4W box): b′b′
  - exactly 1 (2) b-tagged jet(s)
  - at least 3 hadronically decaying W

Single lepton channel



2nd discriminating variable

Search for inclusive b′/t′ production

EXO-11-098

5 fb^{-1}

multilepton channel

- Same-sign dilepton channel
  - ≥2 leptons (charge ++ or --), ≥ 4 jets
  - Backgrounds
    - Wrong-sign lepton(e.g, Z or dilepton events)
    - Fake leptons (single top, semileptonic ttbar, W)
    - Irreducible background (WZ, ZZ, ttV, $W^{\pm} W^{\pm}$)

  } Data-driven
- Trilepton channel
  - ≥3 leptons (charge ++- or +--), ≥ 2 jets
  - Background (WZ, ZZ, ttV) estimate from simulation
- Suppress Z events, $|M_{ll}-M_{Z}| > 10$ GeV

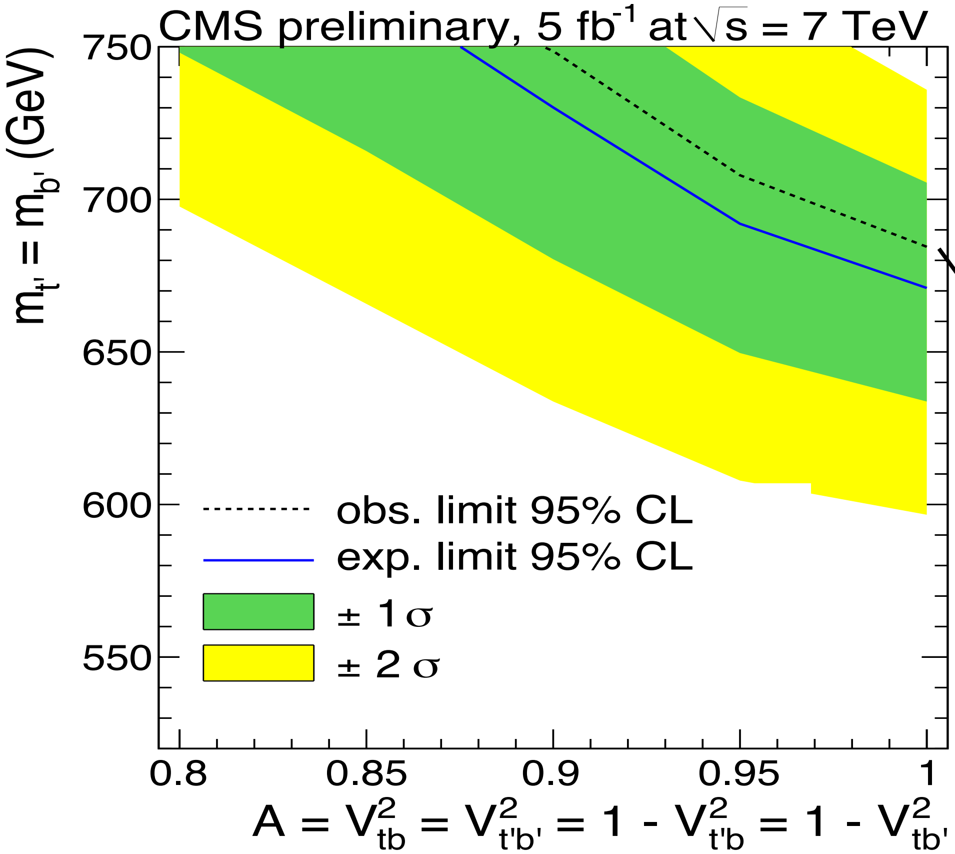
type	2 muons	2 electrons	electron+muon	trilepton
Observed	2	2	2	1
Background	0.83 ± 0.11	1.36 ± 0.19	2.27 ± 0.22	0.96 ± 0.12
Signal ($A = 1$, $m_{q'} = 550\,\mathrm{GeV}$)	3.31 ± 0.15	2.03 ± 0.36	5.29 ± 0.19	3.37 ± 0.16
Signal ($A = 0.8$, $m_{q'} = 550\,\mathrm{GeV}$)	3.79 ± 0.15	2.29 ± 0.36	6.00 ± 0.19	3.65 ± 0.16

These event counts are used in the limit calculation

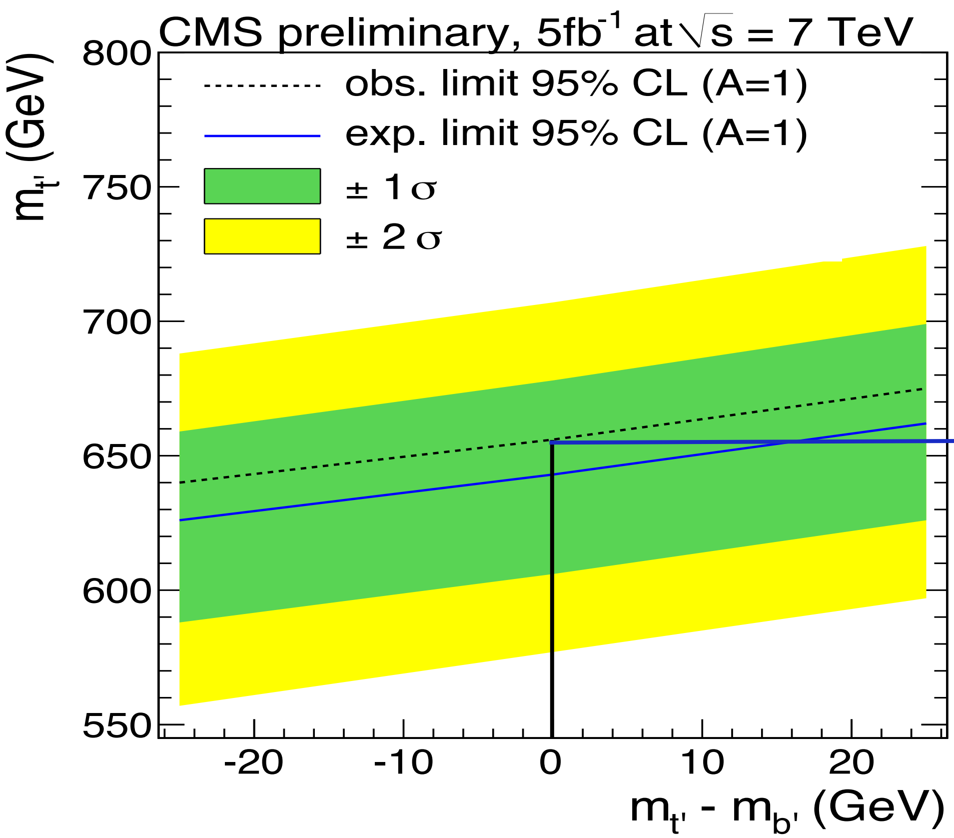
Search for inclusive b´/t´ production

EXO-11-098

$5\ \mathrm{fb}^{-1}$



- Model-dependent exclusion limit on $m_{t'} = m_{b'}$ as a function of A
  - t´b´ production ∝ A
  - t´b and t b´ production ∝ 1- A
  - $m_{q'}$ < 685 GeV excluded at 95% CL



- Effect of mass diff: $m_{t'} - m_{b'}$ = 25 GeV is studied
  - Limit shifts about 20 GeV
- The electroweak t´b´ process is omitted
  - Less stringent limit for $m_{t'} = m_{b'}$

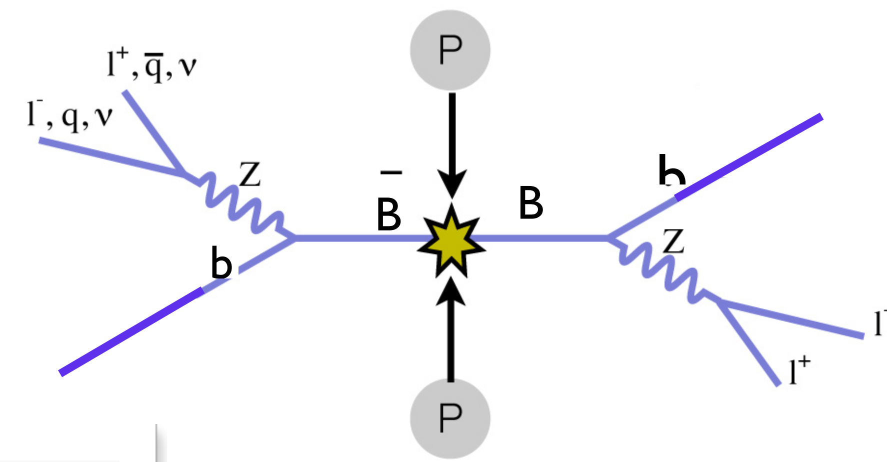
Search for vector-like B´→bZ(dilepton)

5 fb^{-1}

EXO-11-066

Event Selection

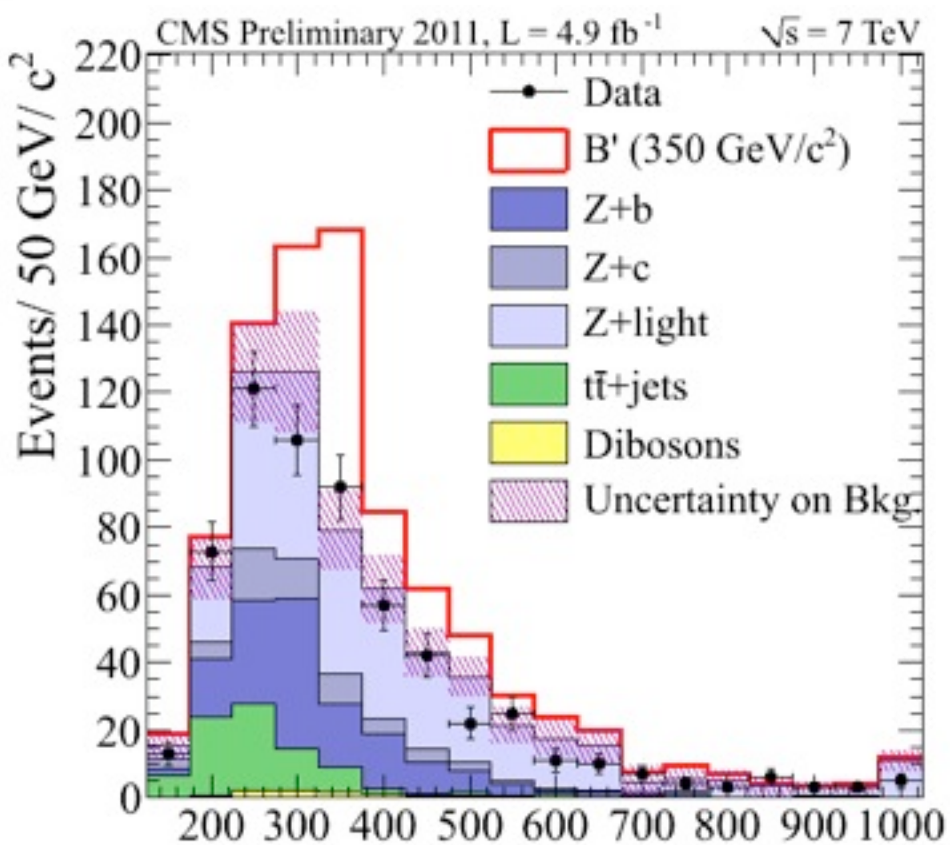
- Clean signature includes
  - ≥ 2 jets, ≥ 1 b-tag (p_T > 65 GeV)
  - Z Cand: (60 < m_{ll} <120) GeV, p_T > 95 GeV

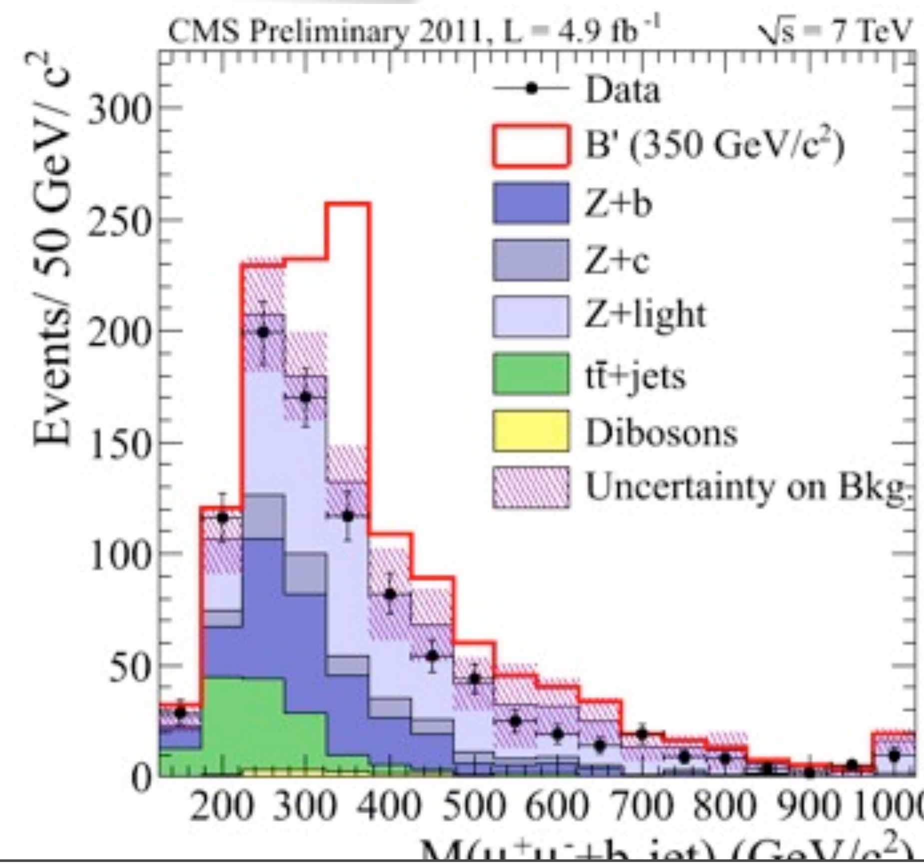


$$B\bar{B} \to bZ\bar{b}Z$$

Strategy

- Search for resonance peak of mass spectrum of the bZ candidate
  - Reconstruct B´ candidate using leading p_T Z boson and the leading p_T b-tagged jet





Search for vector-like B´→bZ(dilepton)

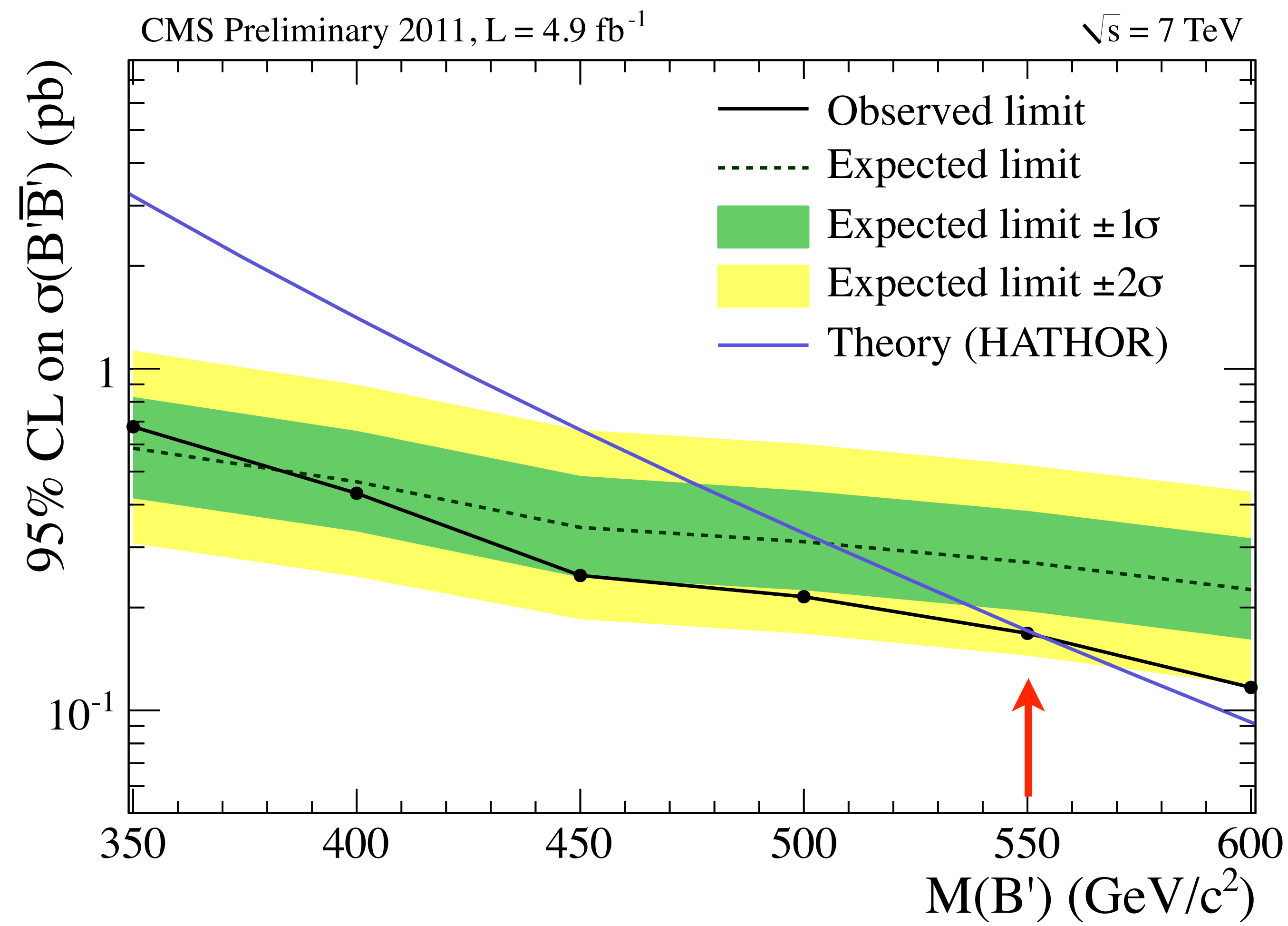
5 fb^{-1}

EXO-11-066

Yields

	Z→ee	Z→μμ
B´(350 GeV)	222±6	345±9
Total Pred	648±15	999±26
DATA	604±24	928±30

Assuming a branching fraction of 100% B´→bZ



- With the observed upper limit at 95% CL on the production cross section, we exclude a B´quark with a mass < 550 GeV
- **See details by Kai-Yi Kao in poster session**

Conclusions

Search	Channel	Lower mass limit
$t' \to bW$ pair	dileptons	557 GeV/c^2
$t' \to bW$ pair	lepton+jets	560 GeV/c^2
$b' \to tW$ pair	trilepton and same-sign dilepton	611 GeV/c^2
$T' \to tZ$ pair	three leptons	475 GeV/c^2
$B' \to bZ$ pair	two leptons	550 GeV/c^2
Model-Dependent t'/b'	lepton(s)+jets	685 GeV/c^2

- CMS has the most stringent limits on the existence of 4th generation quarks
- We have reached the critical mass of ~550 GeV/c^2 at which fermion's weak interactions become non-perturbative

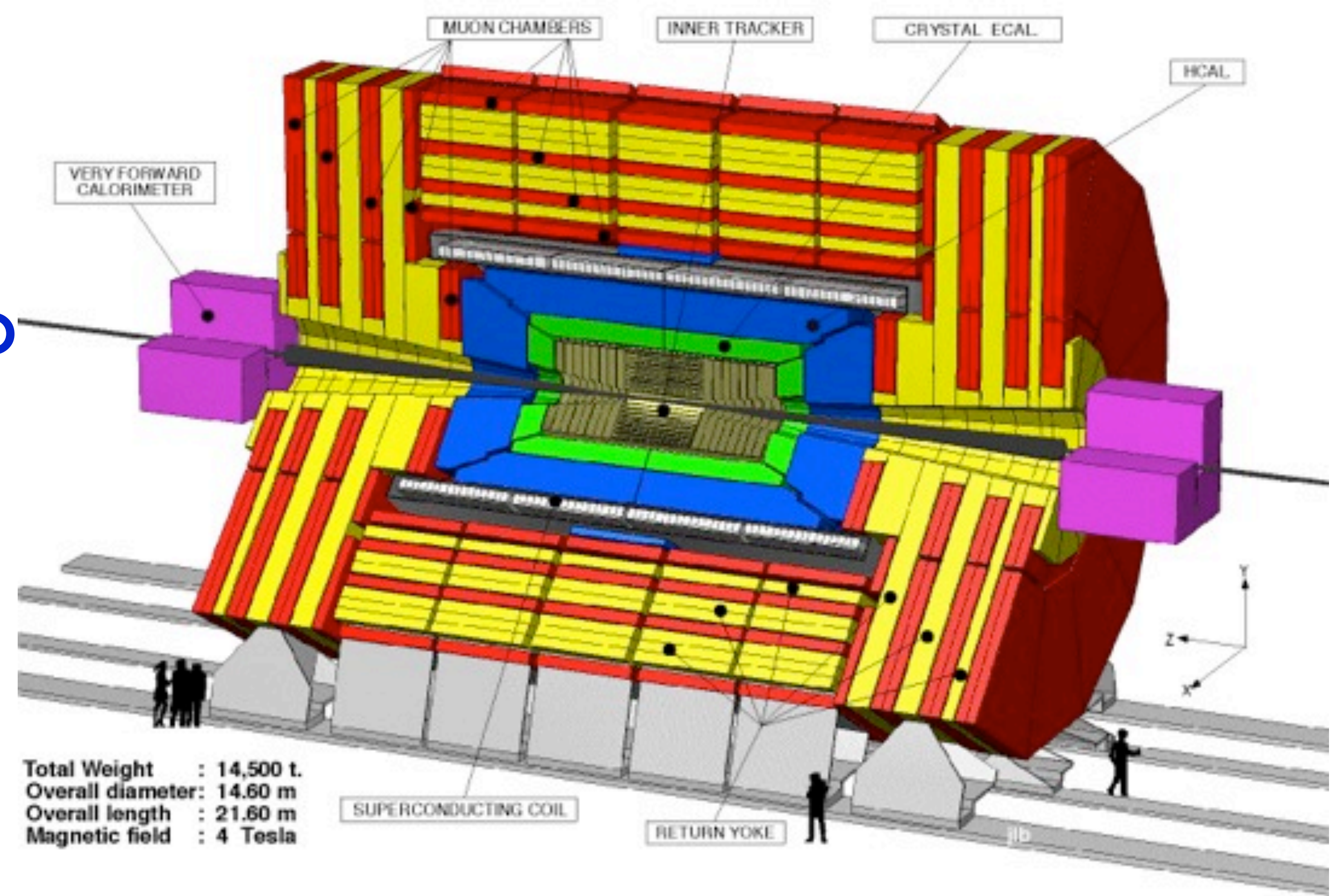
M.S. Chanowitz, M.A. Furman, I. Hinchcliffe, Phys. Lett.B78, 285 (1978)

Thank you!

Extra material

Particle Flow Algorithm

- Provides a list of observable particles that describe the event
    - muons, electrons, photon, charged and neutral hadrons
- It combines the information from all CMS sub-detectors to achieve this
- This list is used to reconstruct higher level objects like jets, MET



Search for inclusive b′/t′ production

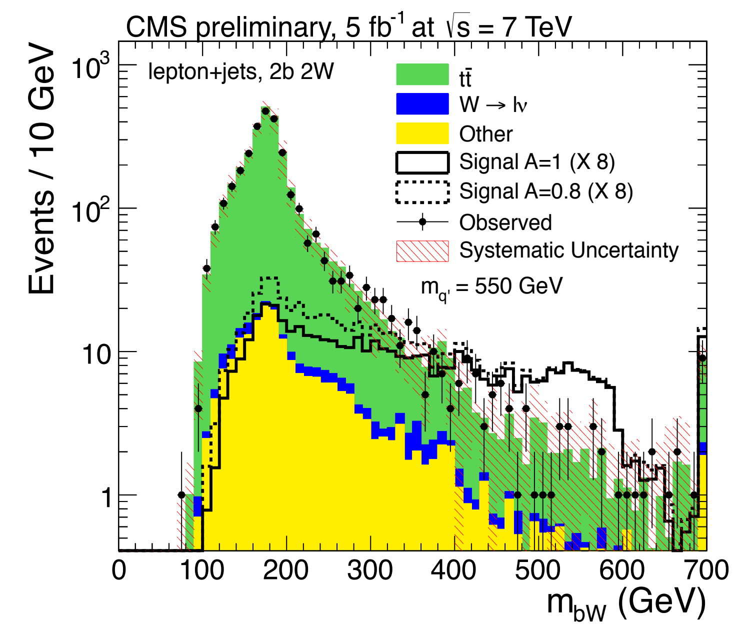
EXO-11-098

5 fb^{-1}

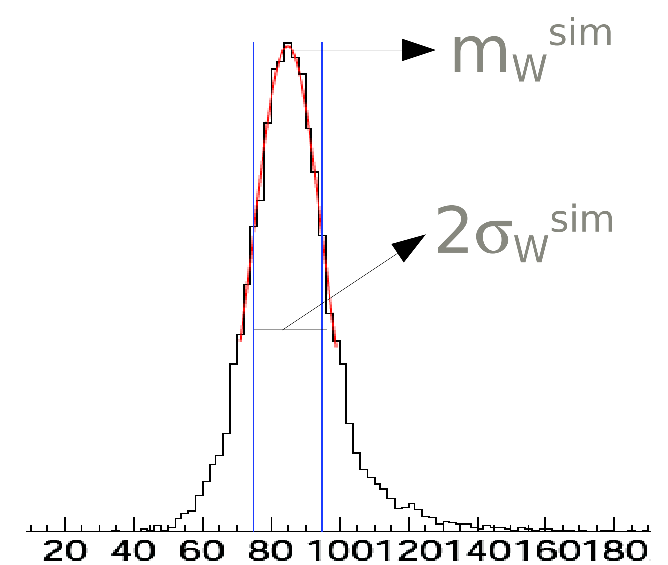
Subsamples with 2 W bosons

2b2W

- Reconstruct hadronic top mass (m_{bW})
  - Likelihood ratio (LH) with 7 observables (angles, W mass, b-tag discriminator values, p_T of the top quark candidate)
  - Use the jet combination with the largest LR value



- W→qq counting procedure
  - remove the 1or 2 b-tag jets
  - Choose the jet pair that minimizes $|m_{j1j2} - m_W^{sim}|$
  - If $|m_{j1j2} - m_W^{sim}| < \sigma_W^{sim}$, a W→qq event is found
  - Remove the jet pair that formed the W→qq
  - Repeat the procedure until no hadronically decaying W are found



Search for inclusive b′/t′ production

EXO-11-098

5 fb^{-1}

Backgrounds for same-sign dilepton channel

- Wrong-sign lepton(e.g, Z or dilepton events)
  - Missing E_T < 20 GeV, M_T < 25 GeV
  - Require two electrons within a 10 GeV window around Z mass
  - Charge misidentification ratio, $R = N_{SS}/2N_{OS}$
  - Rescale the events passing all selections except the same-sign requirement
- Non-prompt leptons (single top, semileptonic ttbar, W)
  - Missing E_T < 20 GeV, M_T < 25 GeV
  - Veto events with $|M_{ll}-M_z| < 20$ GeV
  - Count #loose (N_L) and tight (N_T) leptons with p_T < 35 GeV
  - Probability that a loose lepton passes the tight cuts: $\epsilon_{fl} = N_T/N_L$
  - Require the events to pass selection criteria except
    - One tight lepton
    - One loose but not tight lepton
  - Scale the data yields by $R_{fl} = \epsilon_{fl}(1-\epsilon_{fl})$

Search for t′→bW(dilepton)

arXiv:1203.5410

5 fb^{-1}

Selection

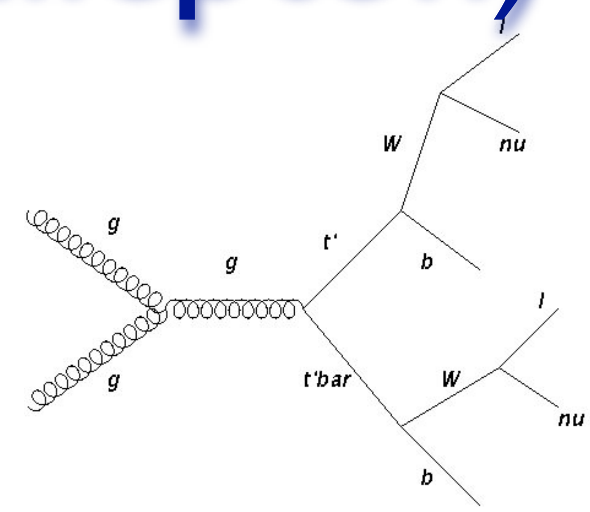
- Two opposite sign high p_T leptons (ee, eμ,μμ)
- Z/Υ→ee/μμ veto
- ≥ 2 jets, ≥ 1b-tagged jet
- Missing E_T > 50 GeV

Strategy

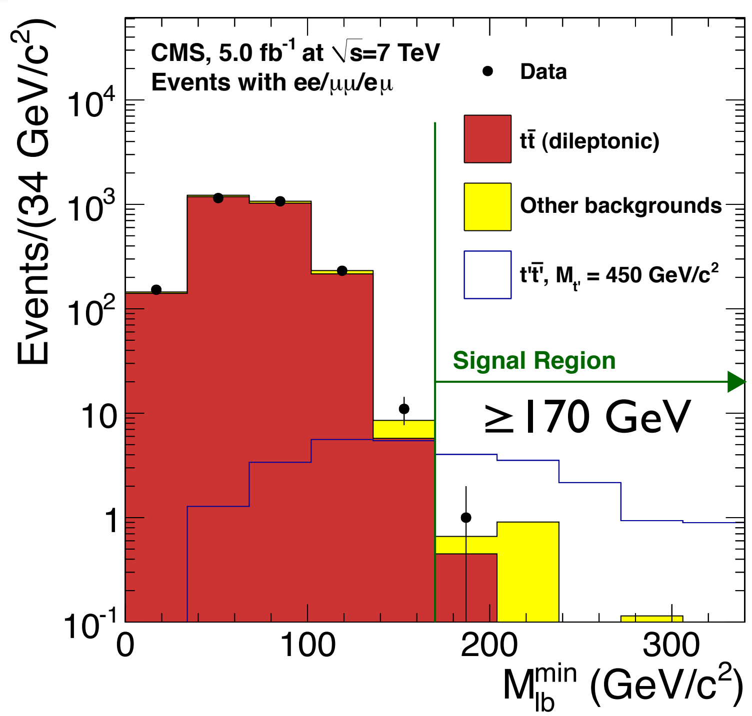
- Invariant mass of the lepton and the b-tagged jets:

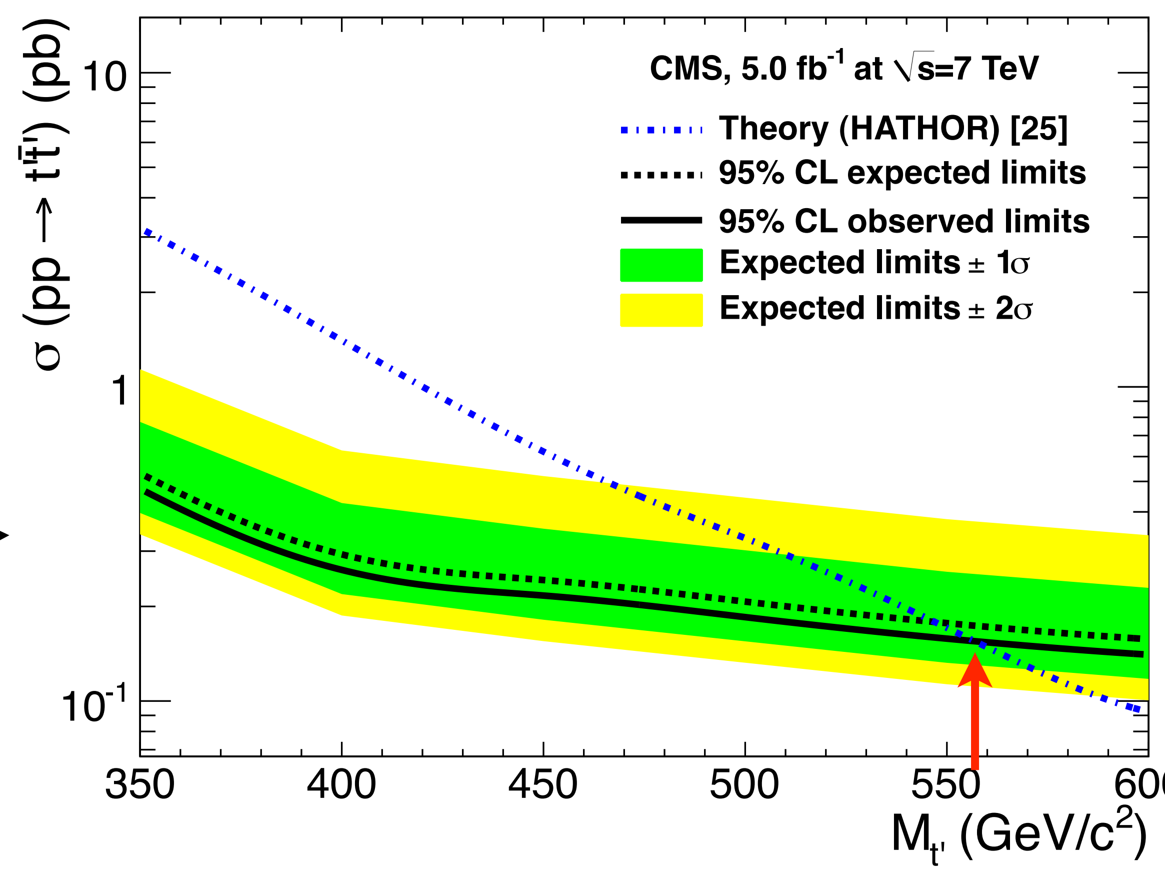
$$M_{lb} = \sqrt{(E_l + E_b)^2 - |\vec{p}_l + \vec{p}_b|^2}$$

- Combine the two leptons and two b-tagged jets
  - 4 possible values of M_{lb}
  - Choose the minimum M_{lb}^{min}
  - For a top decay $M_{lb}^2 < M_t^2 - M_W^2$



$$t'\bar{t}' \rightarrow WbW\bar{b} \rightarrow l\nu bl\bar{\nu}\bar{b}$$





Exclude $m_{t'}$ < 557 GeV @ 95% C.L. on the production cross section

Search for t′→bW(dilepton)

arXiv:1203.5410

5 fb^{-1}

- Backgrounds (mostly data driven)
  - Category I - b-mistagged jet(s) and prompt leptons
  - Category II - fake lepton(s) and real b-tagged jet(s)
  - Category III - b-mistagged jet(s) and fake lepton(s) (negligible)
  - Category IV - 2 real b-tagged jets and 2 real leptons (obtained from MC)

Sample	Yield
Category I (from data)	0.7 ± 0.8
Category II (from data)	$0.0^{+0.4}_{-0.0}$
Category III (simulated)	1.0 ± 0.7
Total prediction	1.8 ± 1.1
Data	1

arXiv:1204.1088

Search for b′→tW(di/tri-lepton)

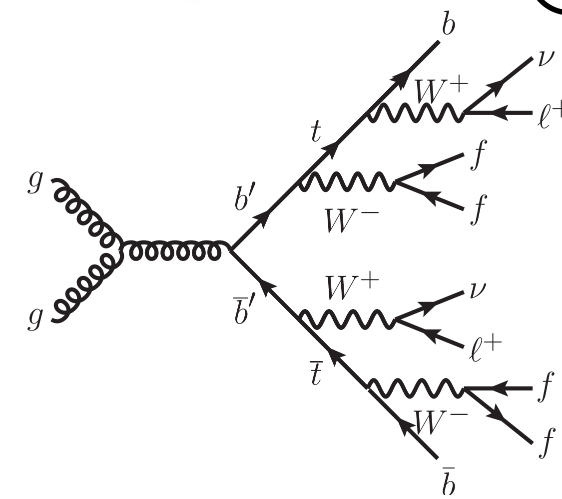
5 fb^{-1}

Selection

- Leptons (e/μ) with p_T > 20 GeV
- Suppress Z events, $|M_{ll}-M_Z|$ > 10 GeV
- Reject events with
  - < 4 jets for the same-sign dilepton
  - < 2 jets for trilepton channel
- ≥1 b-tagged jets

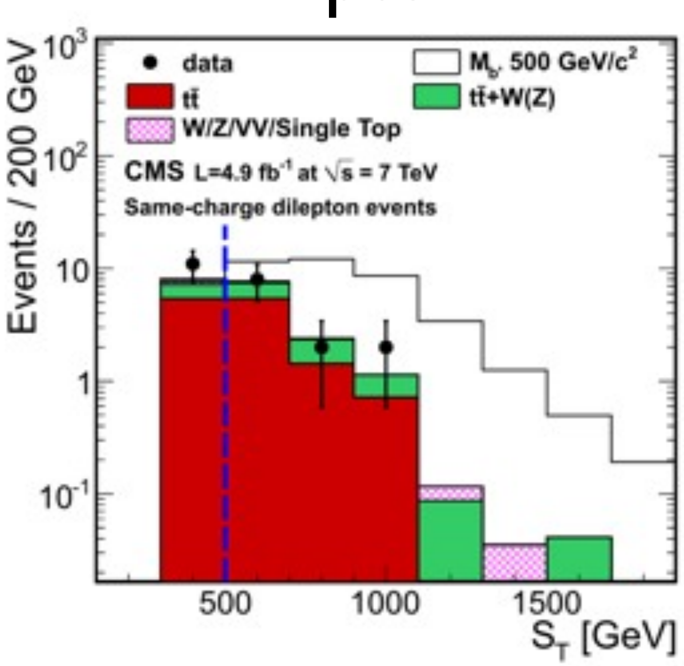
Strategy

- Construct scalar quantity, S_T > 500 GeV
- $S_T = |E_T^{miss}| + \sum |p_T^l| + \sum |p_T^{jet}|$

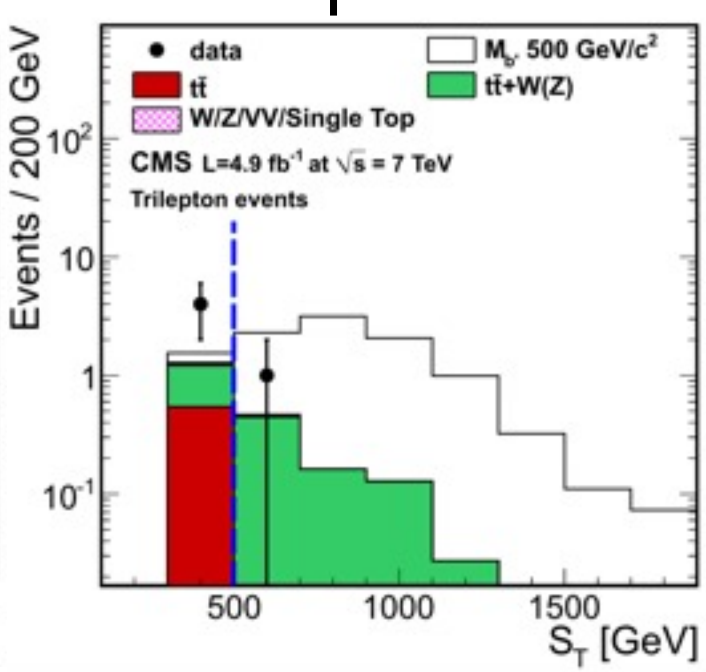


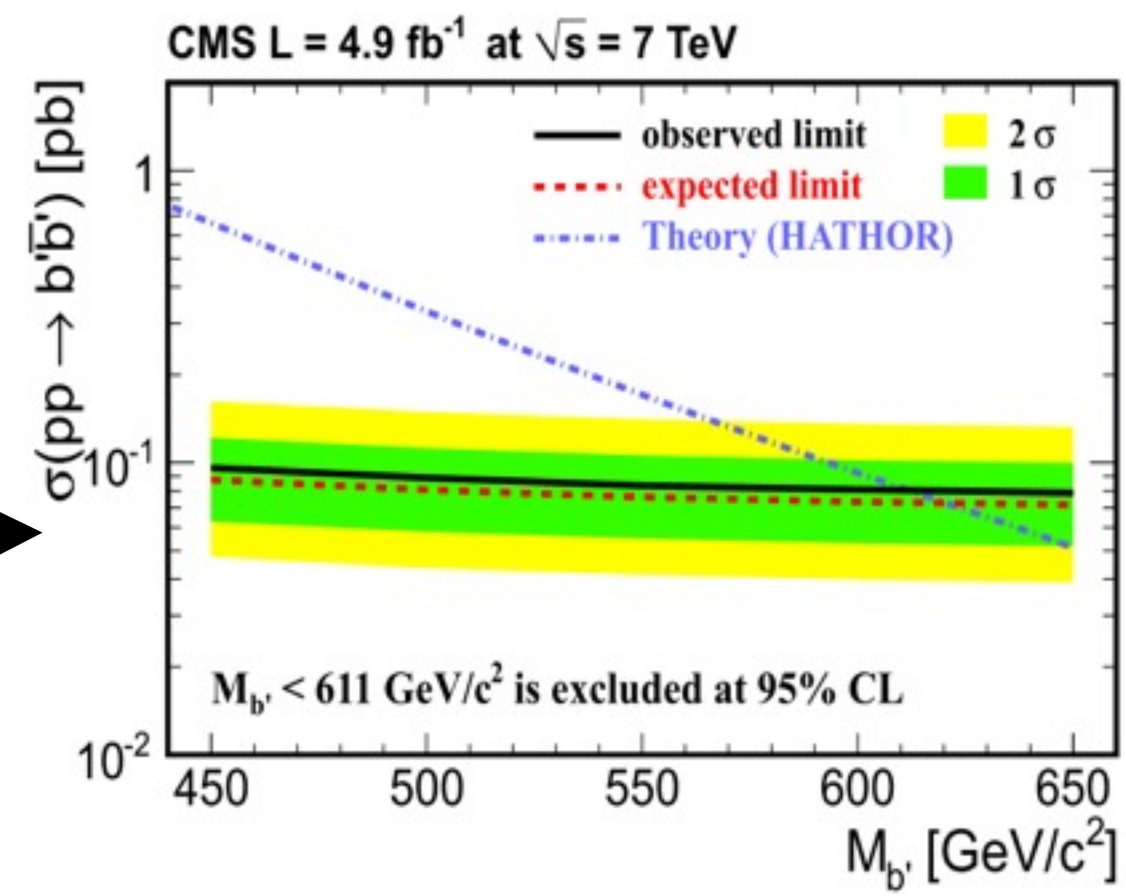
$$b'\bar{b}' \to WtW\bar{t} \to bWWbWW$$

dilepton



trilepton





Search for $b' \rightarrow tW$(di/tri-lepton)

arXiv:1204.1088

4.9 fb^{-1}

- Backgrounds (mostly from ttbar)
  - Sources for same sign dilepton channel
    - Type I (data driven) -- Fake lepton
    - Type II (data driven)-- Charge Misidentification
    - Type III (from MC) -- Prompt dileptons
  - Sources for trilepton channel
    - Dominated by 3 prompt leptons events (ttW)

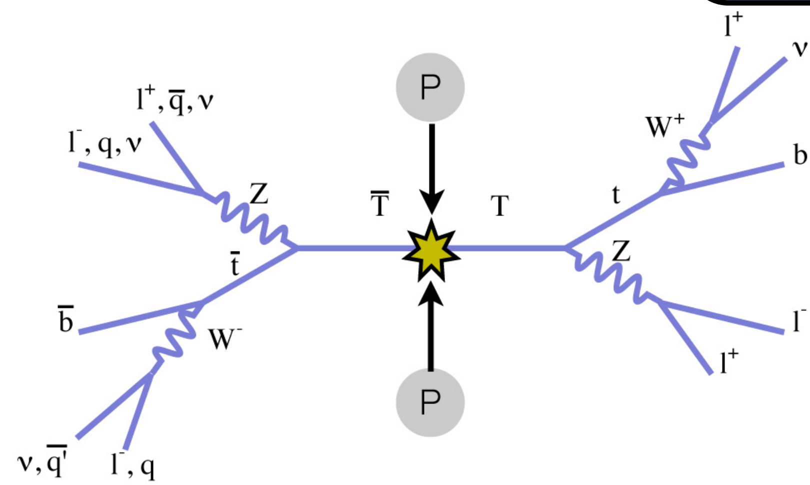
Sources	Same-charge	Trilepton
TypeI+TypeII	7.8 ± 2.8	
TypeIII	3.6 ± 0.6	0.78 ± 0.21
Background sum	11.4 ± 2.9	0.78 ± 0.21
Observed yield	12	1

Search for vector-like $T' \rightarrow tZ$(trilepton)

1.14 fb^{-1}

PRL. 107, 271802(2011)

- Clean signature includes
  - $\geq$ 3 leptons (e/μ)
  - $\geq$ 2 jets
  - (60 < m_{ll} <120) GeV



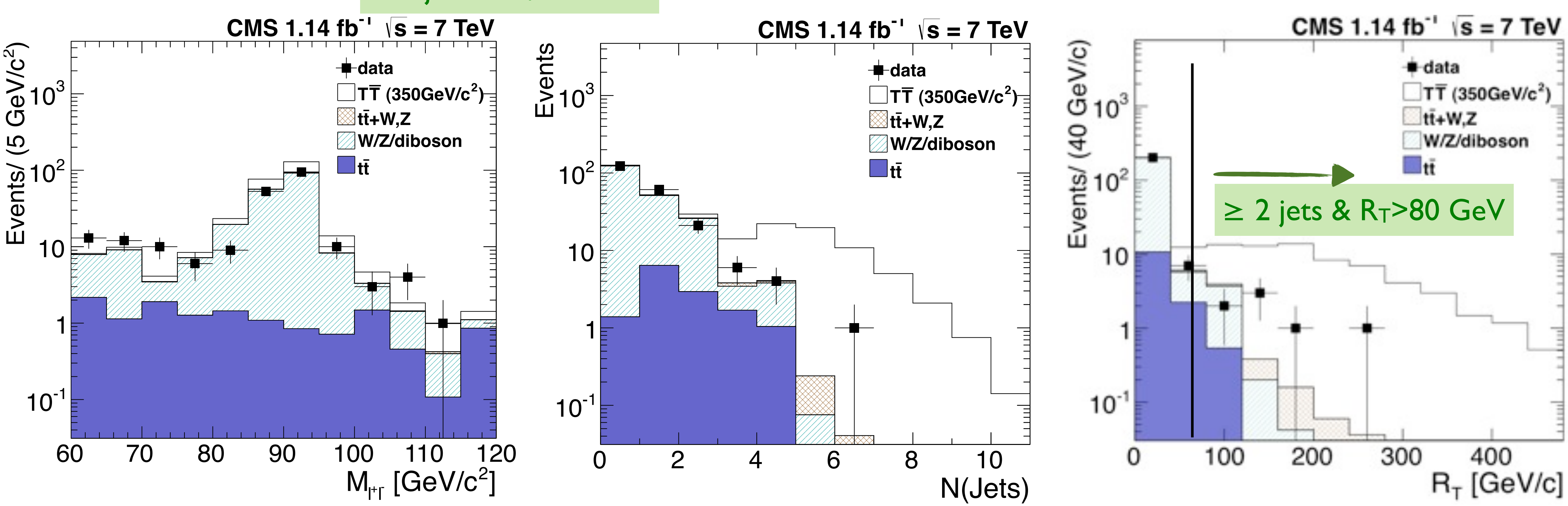
$$T\bar{T} \rightarrow tZ\bar{t}Z \rightarrow b\bar{b}W^+W^-ZZ$$

Strategy

- Construct the variable R_T > 80 GeV

$$R_T = (\sum p_T^{\mathrm{leptons}} + \sum p_T^{\mathrm{jets}}) - (\sum p_T^{\mathrm{two\ leading\ leptons}} + \sum p_T^{\mathrm{two\ leading\ jets}})$$

~~$\geq$ 2 jets & R_T>80 GeV~~



Search for vector-like T′→tZ(trilepton)

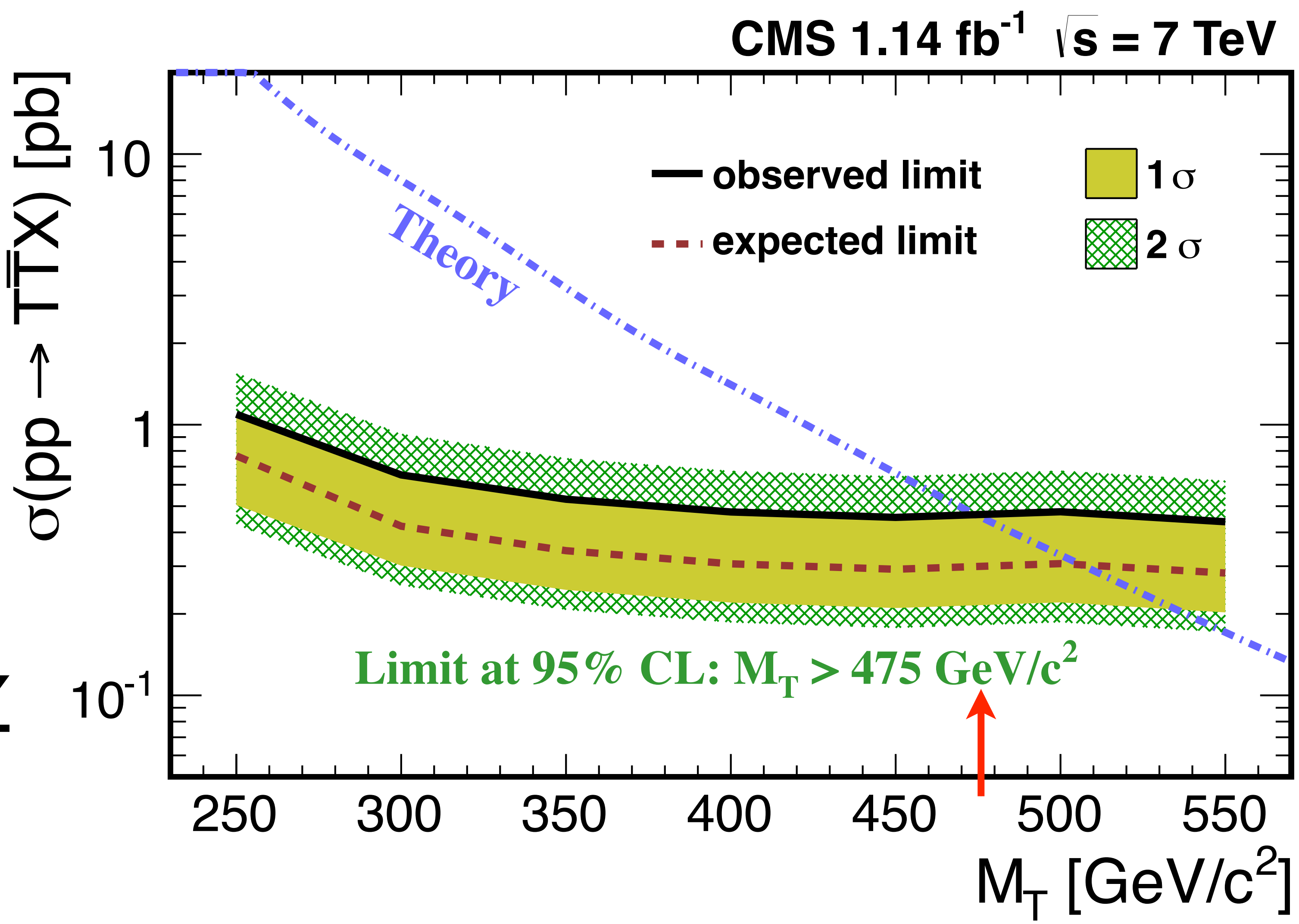
1.14 fb^{-1}

PRL. 107, 271802(2011)

Yields

T′(350 GeV)	57.8±11.0
Background	4.60±1.04
DATA	7

Assuming a branching fraction of 100% T′→tZ



- With the observed upper limit at 95% CL on the production cross section, we excludes a T′quark with a mass < 475 GeV