SEARCH for Heavy Partners of the Top-quark at CMS experiment

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DESY seminar

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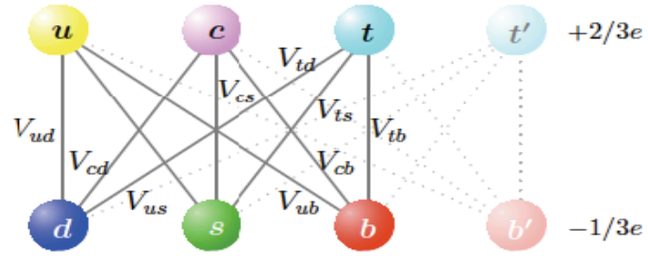
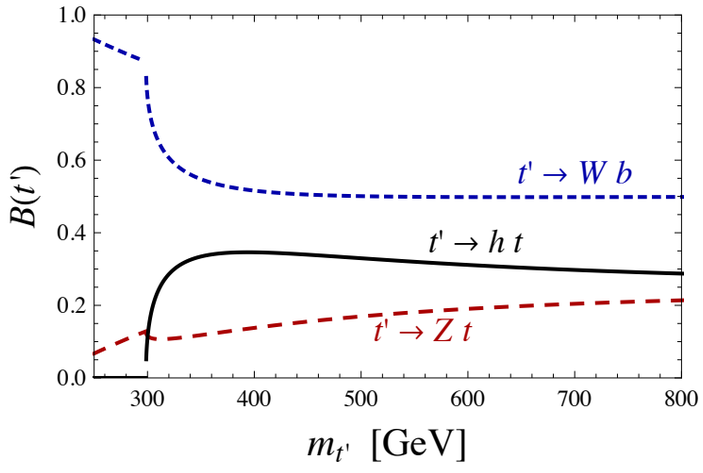
Heavy Partner of the Top

- Can be divided into two main categories
  - Sequential Fourth fermion generation (SM4)
    - A simplest extension of the SM3, adding another fermion generation
    - Direct limits on t´/b´ production
    - M. S. Paul H. Frampton, P.Q. Hung Phys. Rep. 330 (2000) 263

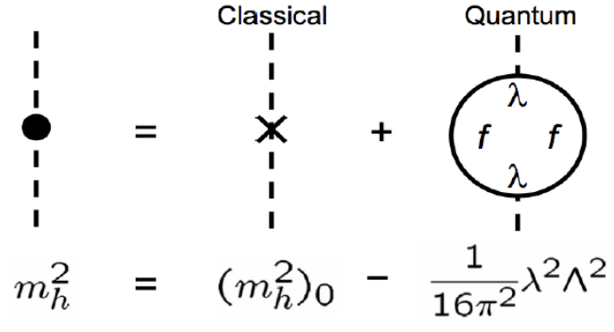


  - Vector-like quarks
    - Transforms as $(3,1,+2/3)$ under $SU(3)_c \times SU(2)_W \times U(1)_Y$ would mix with the top quark
    - Rakhi Mahbubani et.el, JHEP 0906:001 (2009)

Branching fractions of t':
($M_h = 125$ GeV, $\sin\theta_L = 0.1$)



- We need new physics at TeV scale to stabilize its mass
  - T quark cancels the top loop



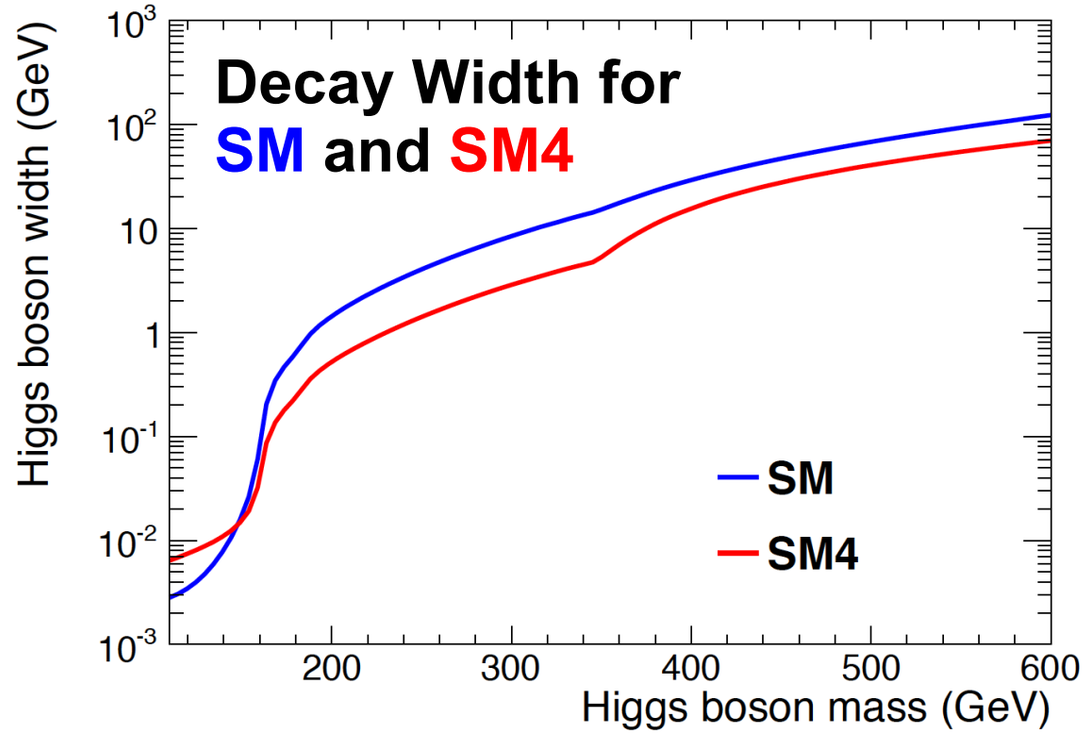
4th Generation

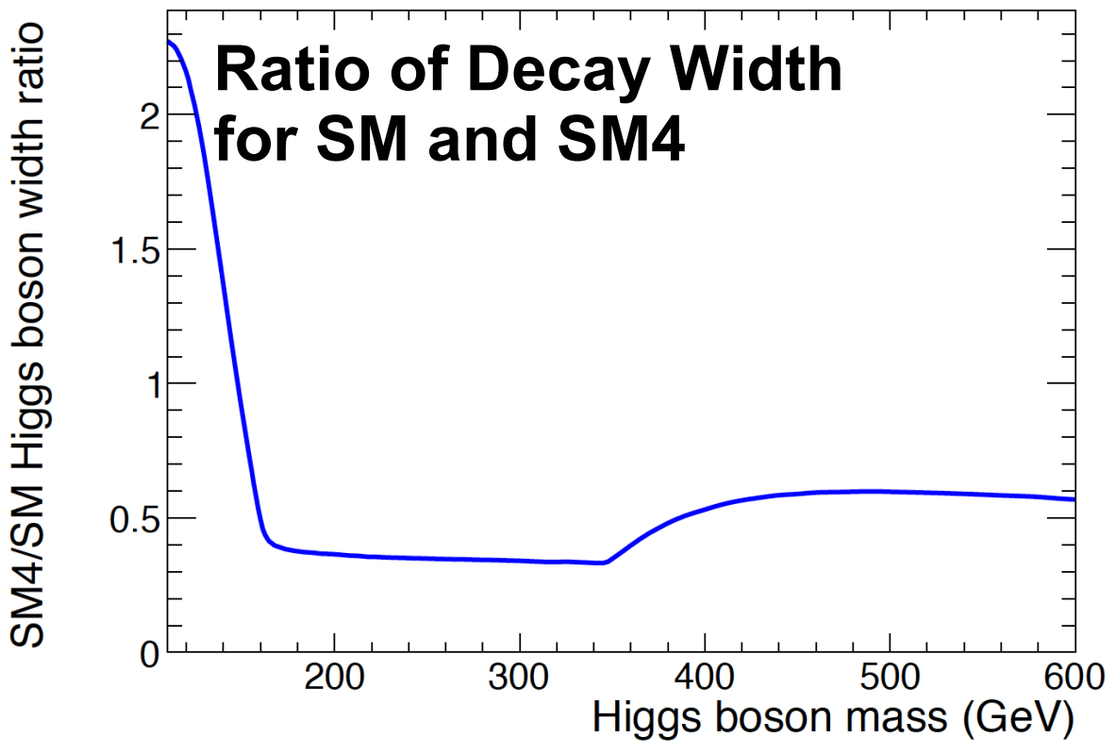
- A sequential family of the heavy quarks and leptons has been an important topic - G. D. Kribs, T. Plehn, M. Spannowsky and T. Tait, PRD 76, 075016(2007); P. Q. Hung and M. Sher, PRD 77, 037302 (2008); H. He, N. Polonsky and S. Su, PRD 64, 053004 (2001); M. Chanowitz, PRL 87, 231802 (2001) V. A. Novikov, L. B. Okun, A. N. Rozanov and M. I. Vysotsky, PLB 529 (2002);... B. Holdom, PLB 686(2010); J. Erler, P. Langacker, PRL 105,031801 (2010), ...
- If exist,
  - 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)
  - It can induce a heavy neutrino as a candidate for dark matter
  - expect small mass splitting between the t′ and b′ masses - M.Baak et al., arXiv:1107.0975

$$\left|m_{t'} - m_{b'}\right| < m_W$$

4th Generation

- However, sequential 4th generation would enhance Higgs boson cross section by a factor ~5
  - Change of couplings: $H \to \tau\tau$ are largely enhanced, $H \to \gamma\gamma$ strongly suppressed
  - Having found some new state mostly showing up in $H \to gg$ is not a direct exclusion criterion.
  - If the resonance does not show up in $H \to \tau\tau$ this is a killer for this kind of models.





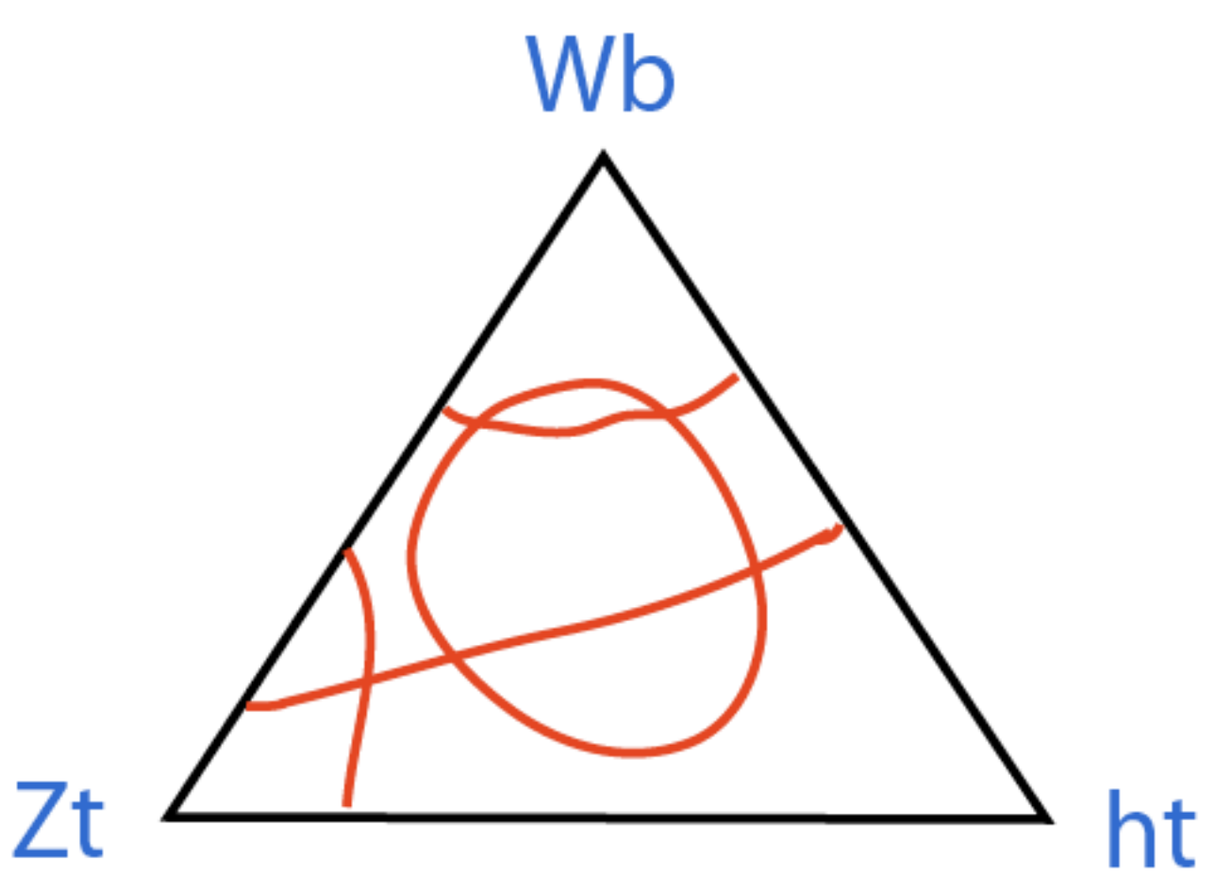
Vector-like Quark

- 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
- Production: pp→TT, BB --- pair produced
- pp→Tt, Bb --- singly produced
- Decays: T→bW or B→tW as in the 4th Gen case, but also flavor changing neutral current (FCNC) decays as
  - T→tZ, tH or B→bZ, bH where **H couples to fermions and bosons**, but with **non SM couplings**
    - heavy Higgs is not excluded (weaker couplings than in SM case)
    - more Higgs-like bosons are possible (one light, one heavy...)
- Different final states are possible:
  - Pair production: **TT→ bWbW, bWtZ, bWtH, tZtZ, tHtH, tZtH**
  - Singly produced: **Tt →bWt, ttZ, ttH**

Vector-like Quark

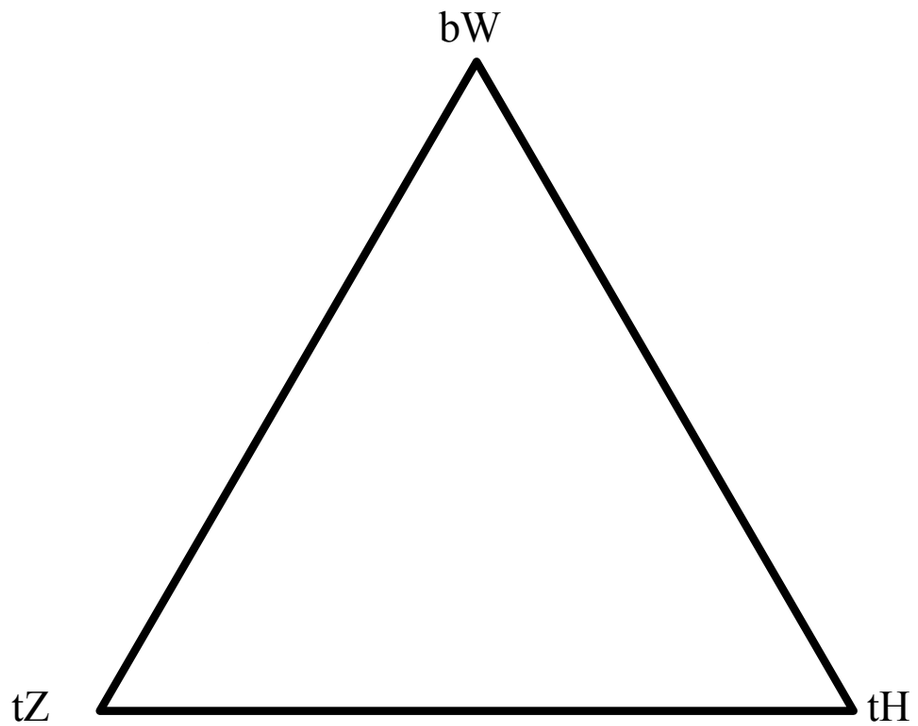
- At 7 TeV most heavy quark, Q searches assume 100% BR for a given channel
- Michael Peskin's slogan #2
  - Exclude Triangles not Points, a vector-like heavy quark would have the following decay modes

https://indico.fnal.gov/getFile.py/access?contribId=49&resId=0&materialId=slides&confId=5256



Vector-like Quark

- What does it mean?
  - T decays into different final states
    - $T \rightarrow bW$
    - $T \rightarrow tZ$
    - $T \rightarrow tH$
  - There is one triangle for every T mass
  - Every point in the triangle corresponds to a different set of these branching fractions



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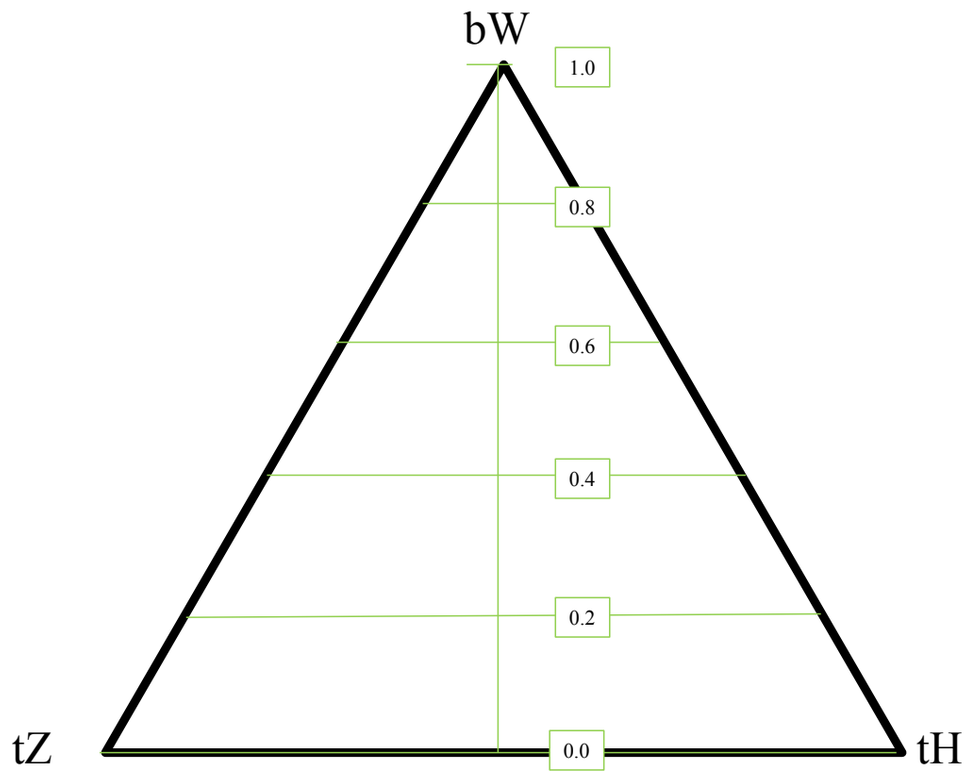

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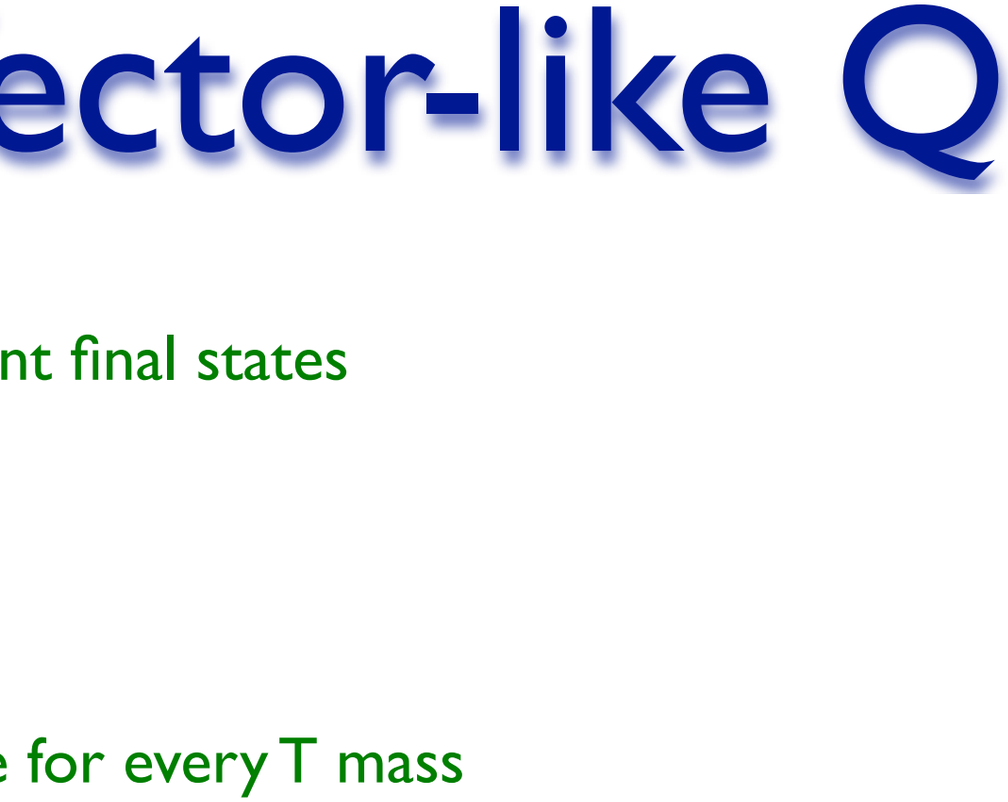

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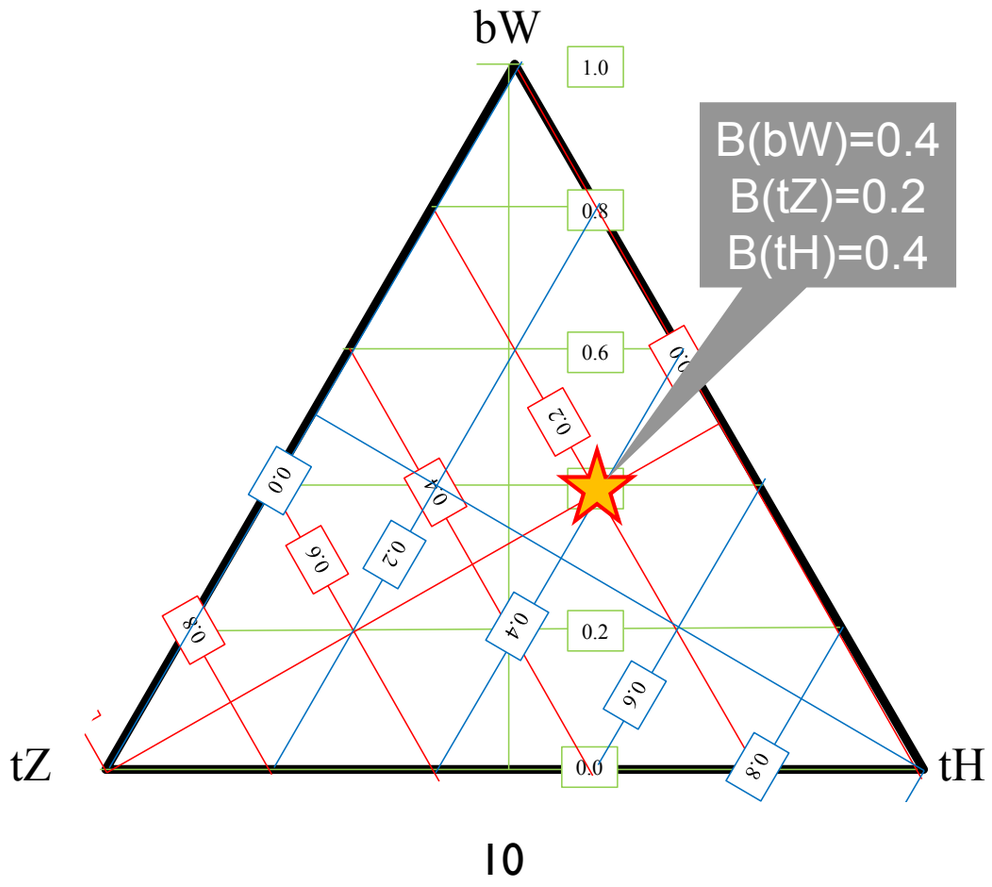


Status @ 7 TeV

- CMS 4th generation searches @7 TeV

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO

- t´ pair search
  - lepton+jets channel
  - dilepton channel

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

PLB.2012.10.038, EXO-11-099

PLB.2012.07.959, EXO-11-050

- b´ search
  - lepton+jets channel
  - same sign dilepton + trilepton channel

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

arXiv:1210.7471 (accept by JHEP), B2G-12--004

arXiv:1204.1088 (sub to JHEP)

- Inclusive t´ and b´ search
  - singly produced
  - pair produced

$t'b \to bWb$
$b't \to tWbW \to bWWbW$

$b't' \to tWbW \to bWWbW$
$t'\bar{t}' \to bWbW$
$b'\bar{b}' \to tWtW \to bWWbWW$

arXiv:1209.1062 (accept by PRD)

- T vector like pair
  - lepton+jets
  - trilepton channel

$T\bar{T} \to tZ\bar{t}Z \to b\bar{b}WWZZ$

arXiv:1210.7471 (accept by JHEP), B2G-12--004

PRL.107.271802
EXO-11-005

- B vector-like pair

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

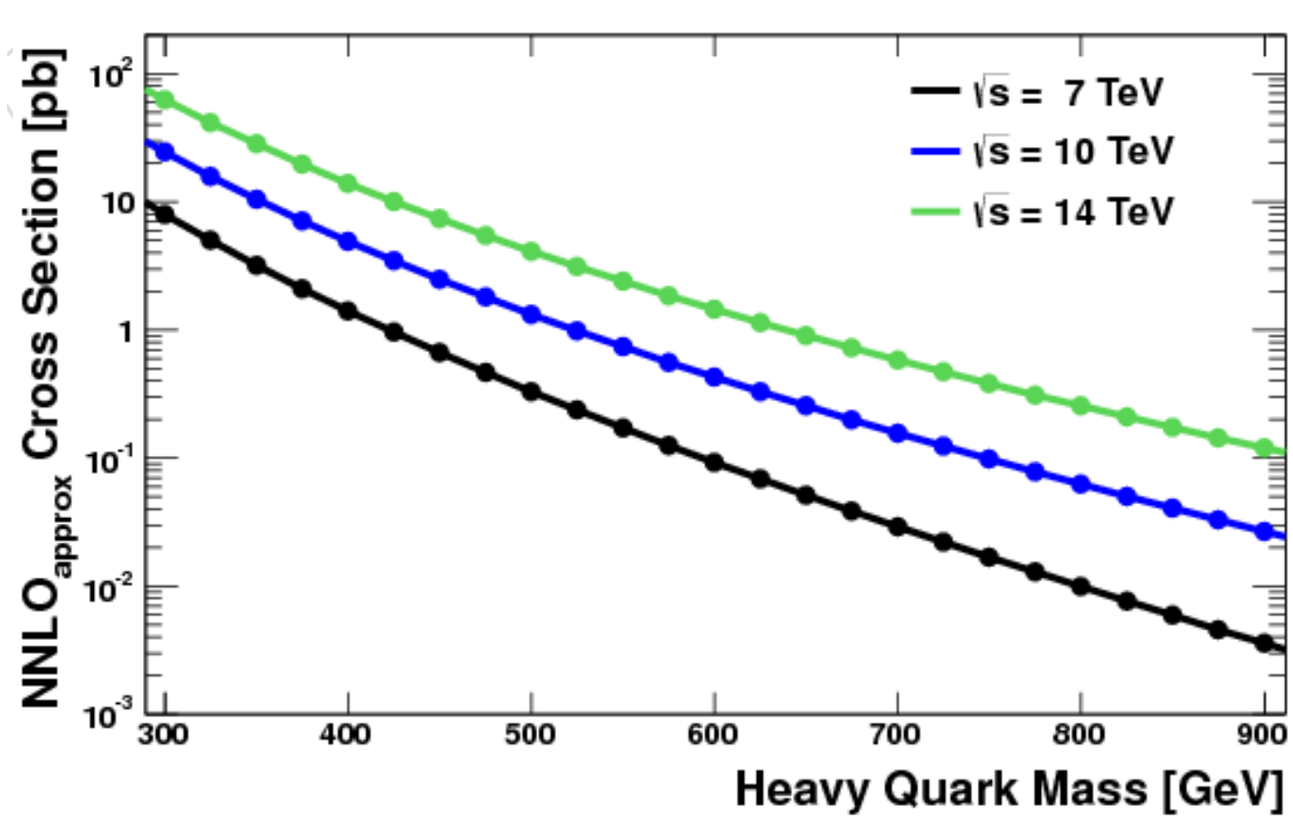
CMS-PAS-EXO-11-066

Theory Cross sections

- Use HATHOR (HAdronic Top and Heavy quarks crOss section calculatoR) http://arxiv.org/abs/1007.1327

7 TeV

$M_{t'}$ (GeV)	Cross section (pb)
400	1.41
425	0.96
450	0.66
475	0.46
500	0.33
525	0.24
550	0.17
575	0.13
600	0.092
625	0.069



Where are we now?

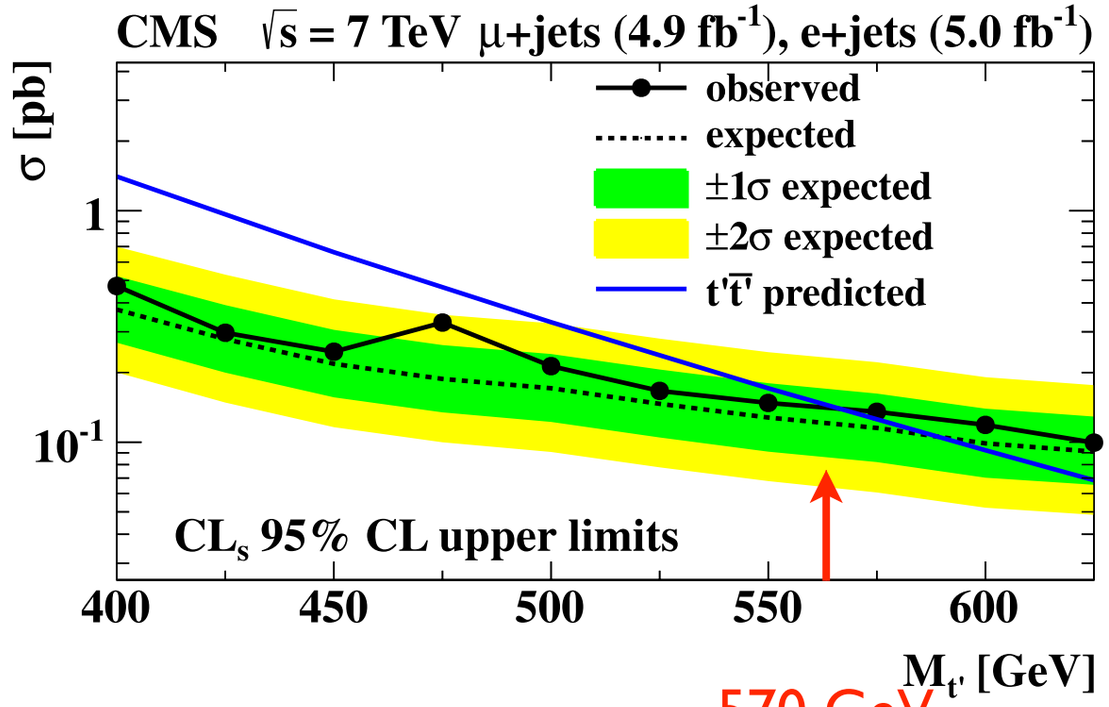
$$TT \to bWbW$$

PLB.2012.10.038, EXO-11-099

$$t'\bar{t}' \to l + jets$$

PLB.2012.07.959, EXO-11-050

$$t'\bar{t}' \to dileptons$$



570 GeV

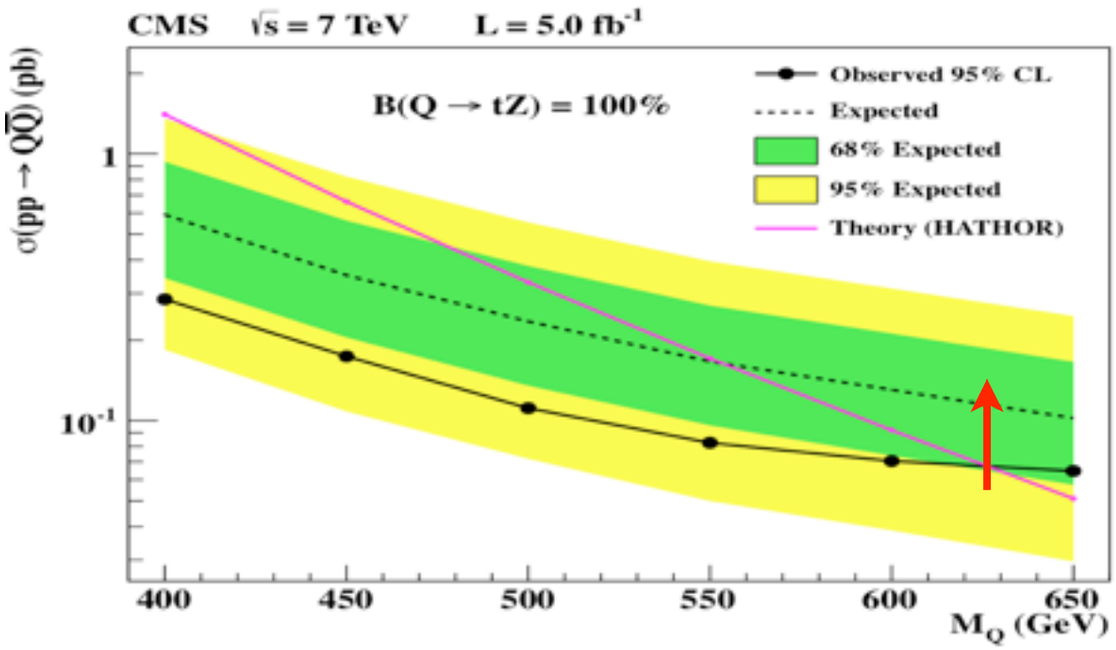
$$TT \to tZtZ$$

arXiv:1210.7471, B2G-12--004

$$t'\bar{t}' \to l + jets$$

PRL.107.271802, EXO-11-005

$$t'\bar{t}' \to trileptons$$



625 GeV

Limits on Branching Fractions

$$max(B) = \sqrt{\frac{\max(\sigma)}{\langle\sigma\rangle}}$$

T mass	TT xsec	bW $max(\sigma)$	$max(B)$	tZ $max(\sigma)$	$max(B)$
400 GeV	1.406 pb	0.473 pb	0.58	0.48 pb	0.58
450 GeV	0.662 pb	0.246 pb	0.61	0.45 pb	0.82
500 GeV	0.330 pb	0.213 pb	0.80	0.48 pb	---
550 GeV	0.171 pb	0.148 pb	0.93	0.44 pb	---

PLB.2012.10.038, EXO-11-099

$t'\bar{t}' \rightarrow l + jets$

PRL.107.271802, EXO-11-005

$t'\bar{t}' \rightarrow trileptons$

For T mass = 450 GeV

$$TT \to bWbW$$

PLB.2012.10.038, EXO-11-099

$t'\bar{t}' \to l + jets$

PLB.2012.07.959, EXO-11-050

$t'\bar{t}' \to dileptons$

$$TT \to tZtZ$$

arXiv:1210.7471, B2G-12--004

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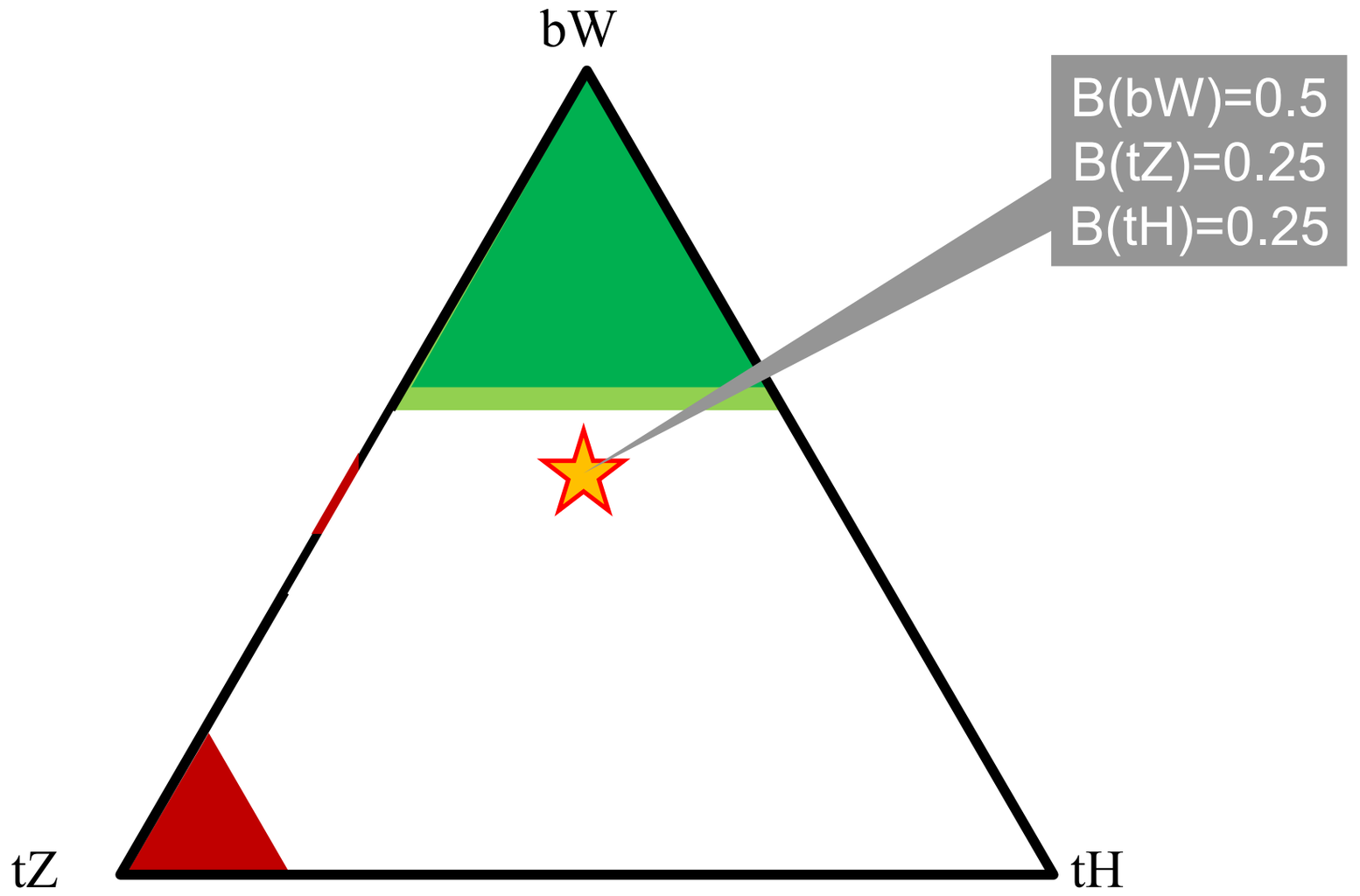
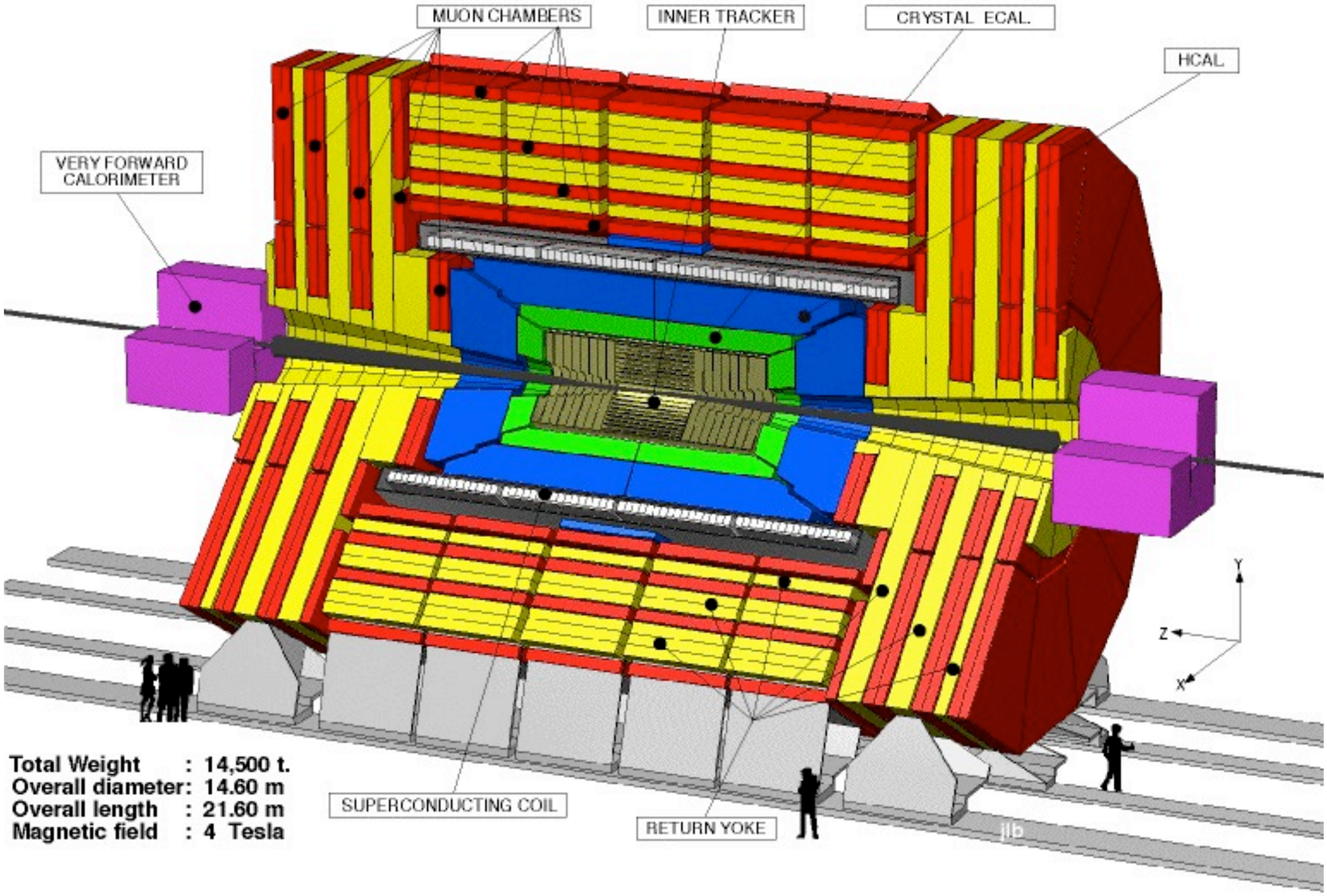


CMS Detector



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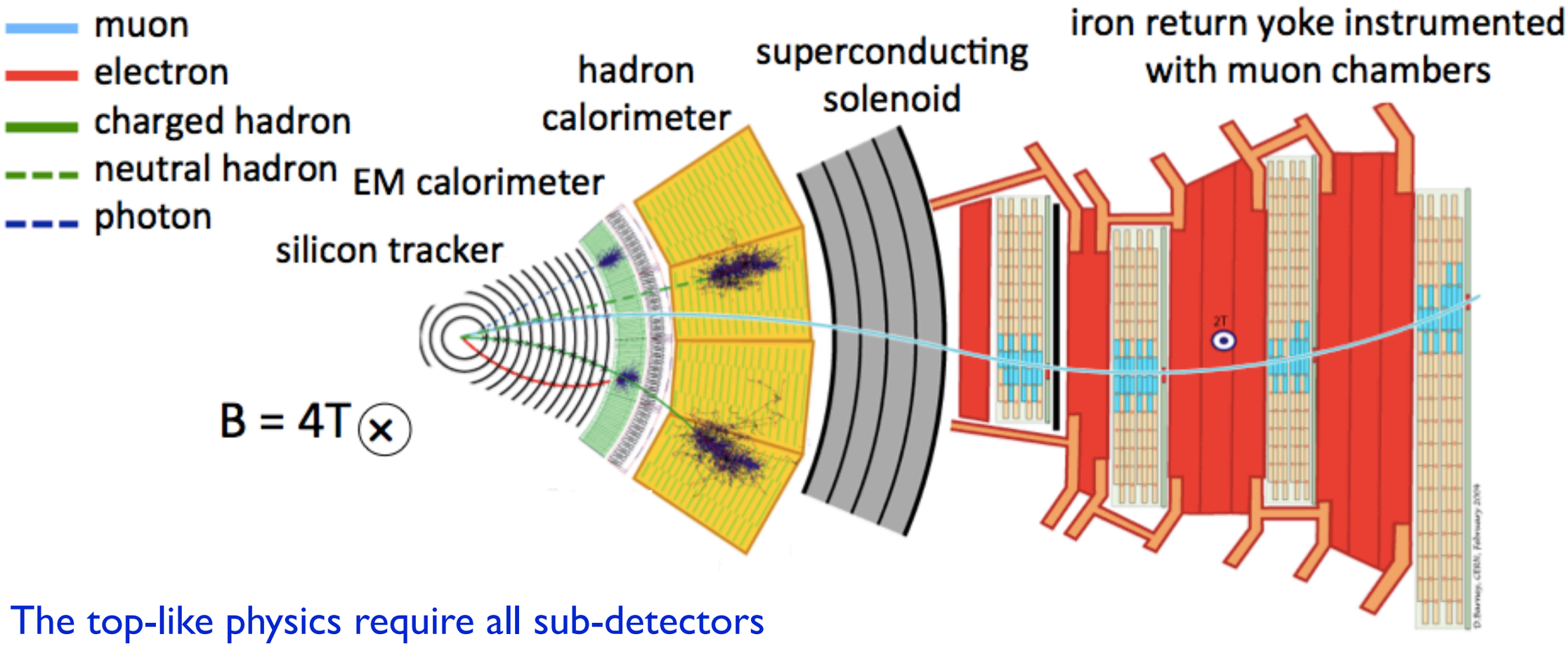


- The top-like physics require all sub-detectors
- Significant improvement due to Particle Flow Algorithm that uses information from all sub-detectors, starting from particle traces in each sub detector to
  - muons, electrons, photons, charged and neutral hadrons
  - the list is used to reconstruct higher level objects like jets, MET
    - **electrons**: tracks matched to clusters in EM calorimeter
    - **muons**: minimum ionizing tracks, penetrate deep into muon system
    - **jets / H_T**: constructed with combined tracking + calo info
    - **MET**: constructed with combined tracking + calo info, hermetic detector

Particle Flow overview (PFT-10-003)

Particle-Flow Based Reconstruction
- Can be done on the AOD
- Can be tuned to the analysis

Taus
b jets
Particle tagging
Jets
Jet clustering
MET
$\overrightarrow{MET} = -\sum_i \overrightarrow{E_{T,i}}$
import from RECO

Iso. γ
Iso. e
Iso. μ
Particle Isolation
integrated in RECO

Particle-Flow reconstruction
- Done in RECO

Particles
ECAL rechits
HCAL rechits
Tracks
μ

Selected Analysis

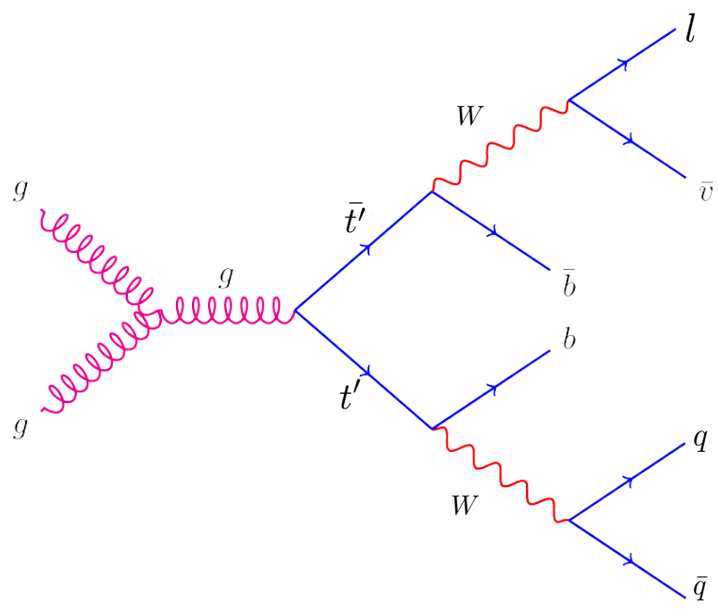
Search for t′→bW(l+jets)

PLB.2012.10.038, EXO-11-099

Selection

- A lepton e/μ with p_T >30 GeV
- ≥ 4 jets, ≥ 1b-tagged jet
- Missing E_T > 20 GeV

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

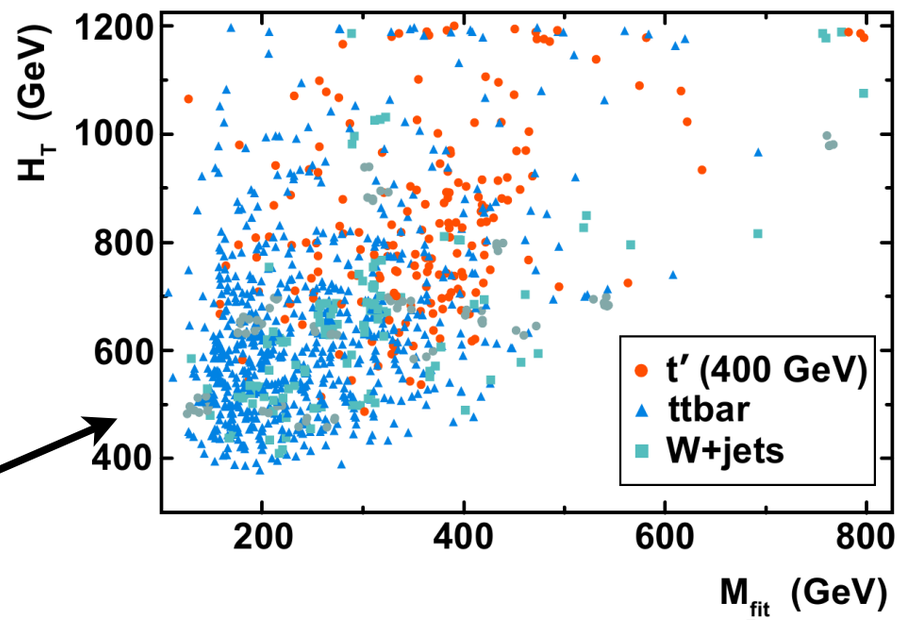


Strategy

- Apply kinematic fit for mass reconstruction (M_{fit}) with constraints
  - m(lν) = m(qq) = M_W
  - m(lνb) = m(qqb)
  - 2-C fit → minimize χ^2
- Define H_T (scalar sum of transverse energies of the fitted final objects)

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

- Look at the H_T and M_{fit} of the tt→lνbqqb event tails for signs of a massive quark decay
- Dominant backgrounds: ttbar and W+jets



Discriminators

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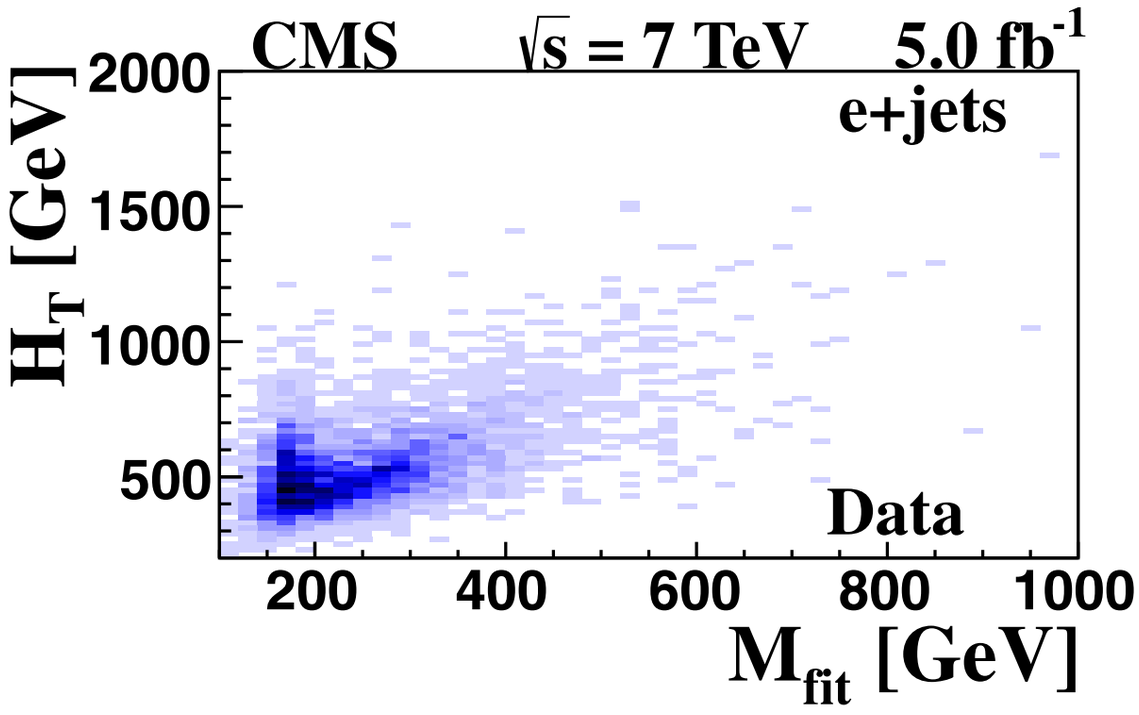
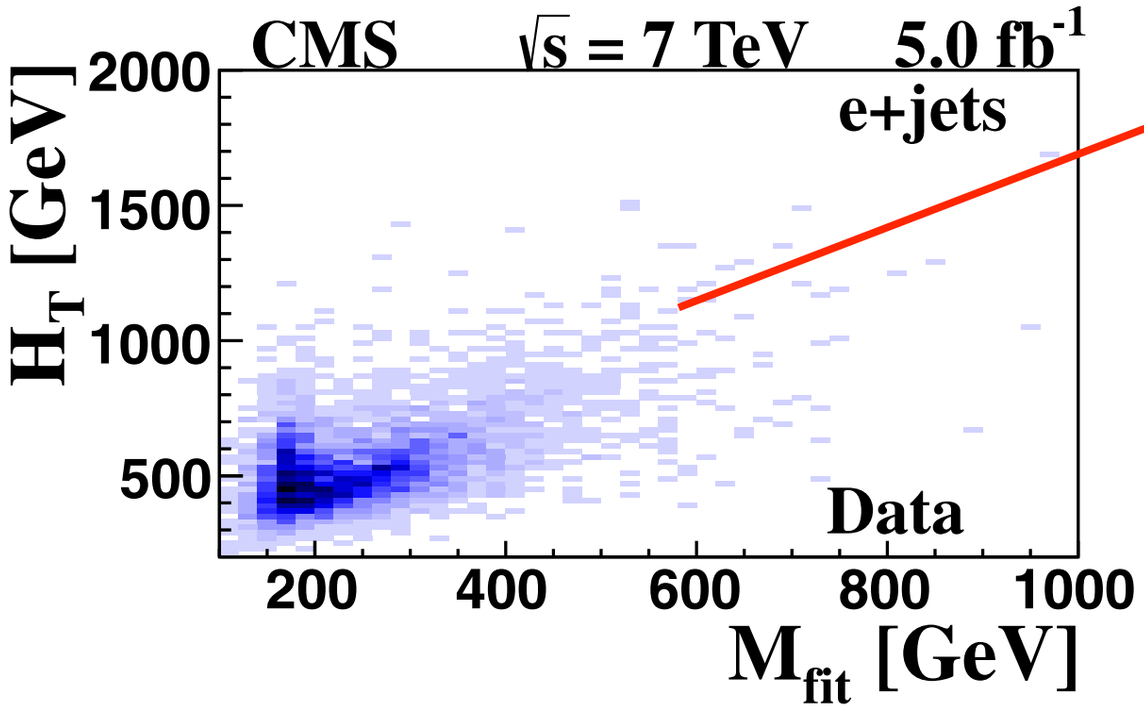
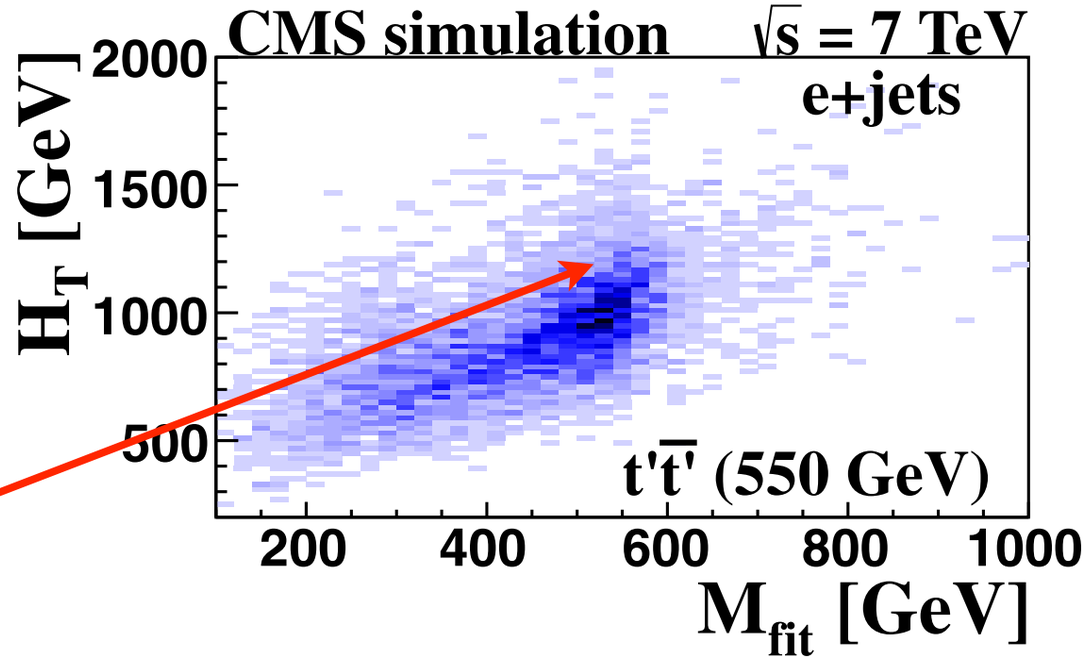


Discriminators

PLB.2012.10.038, EXO-11-099

Signal towards high H_T, M_{fit}





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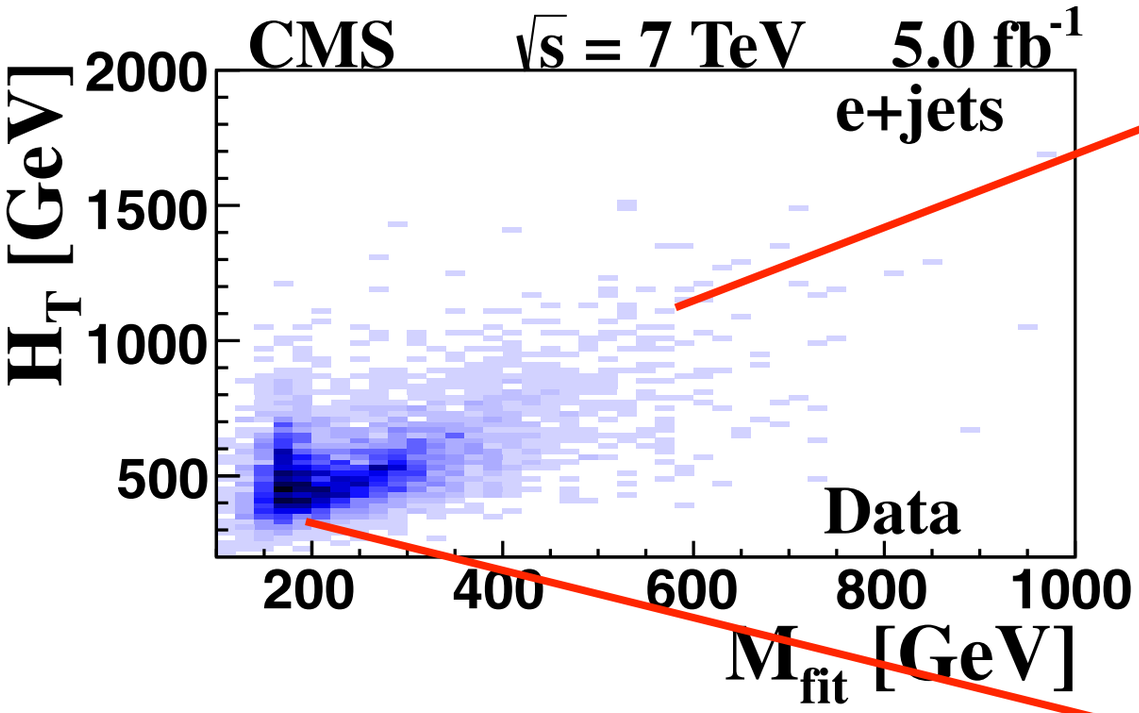
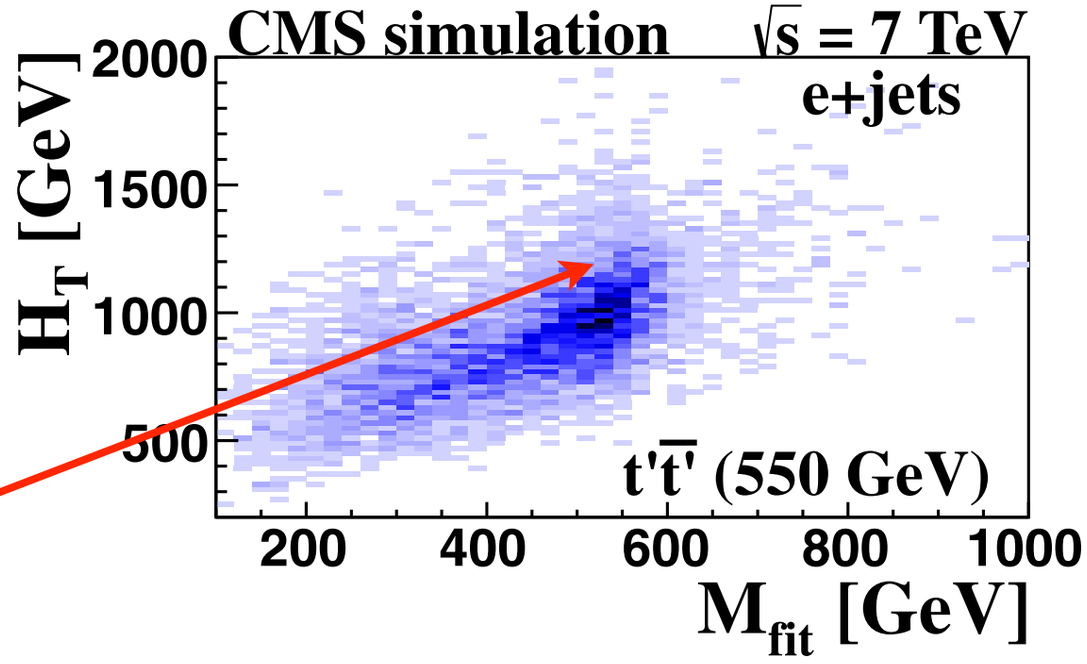
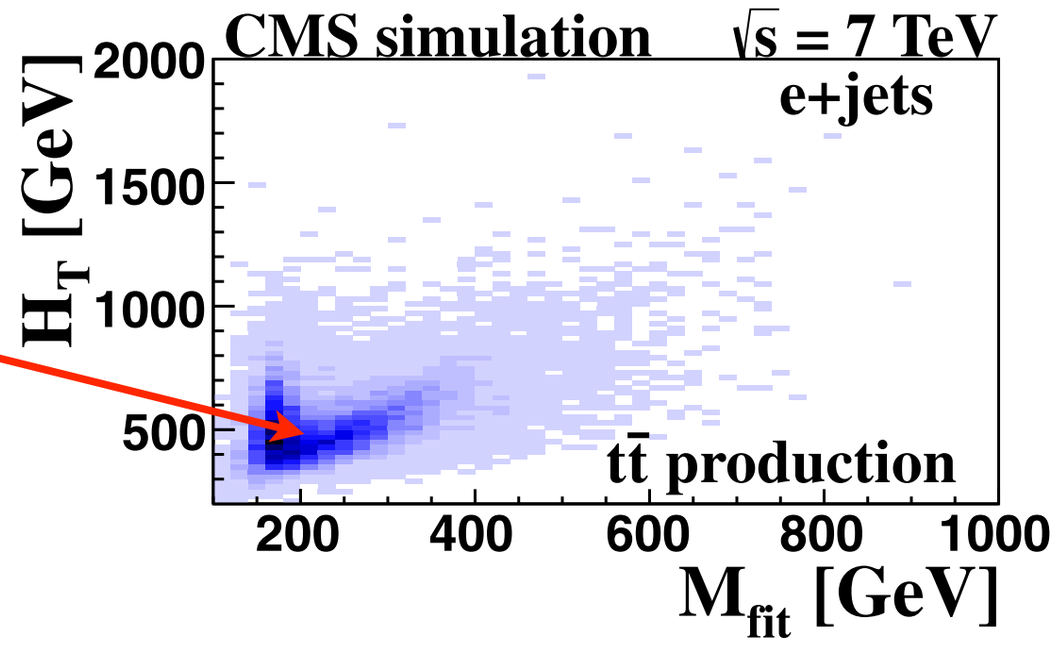




top towards lower H_T, M_{fit}



Discriminators

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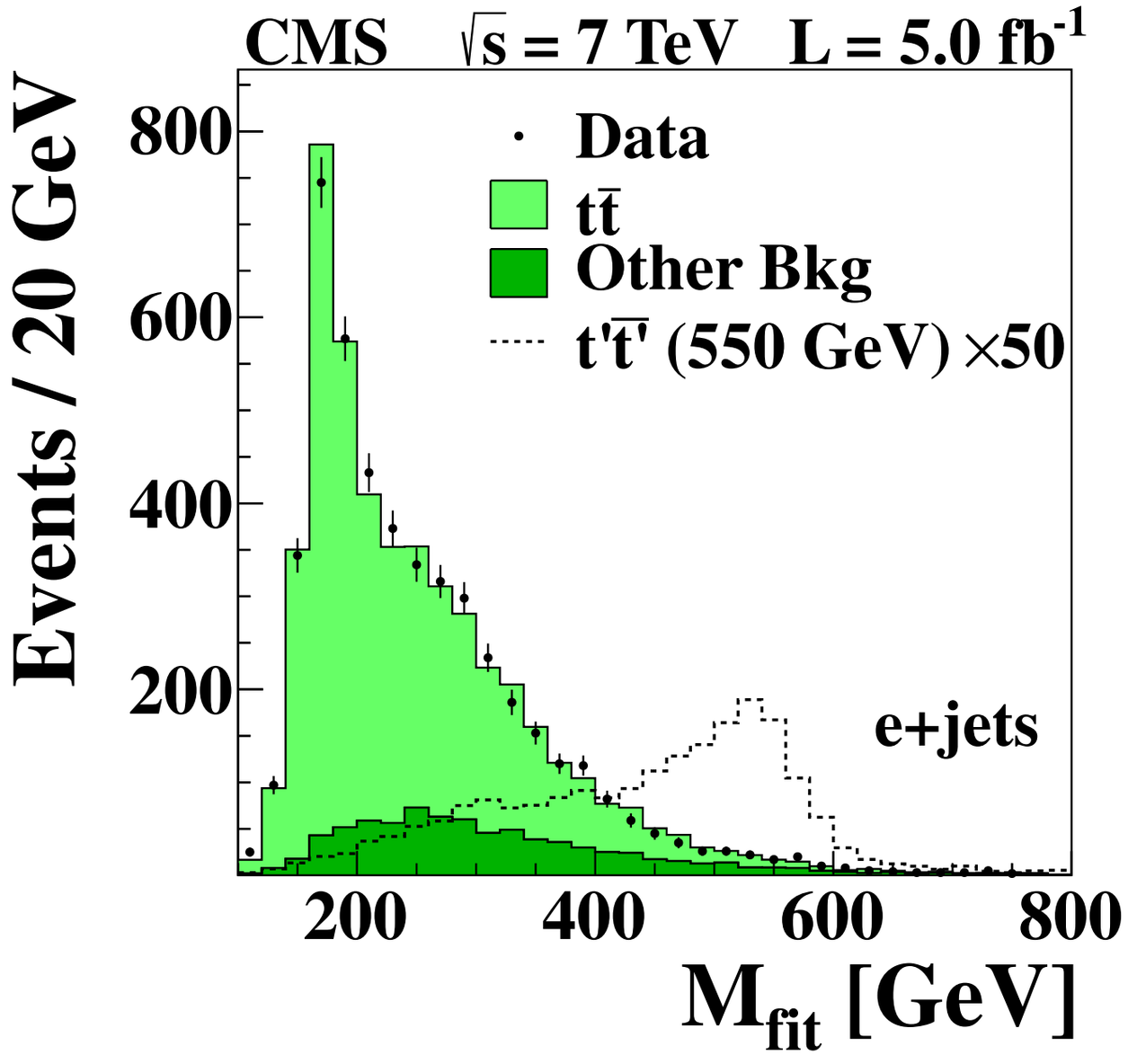
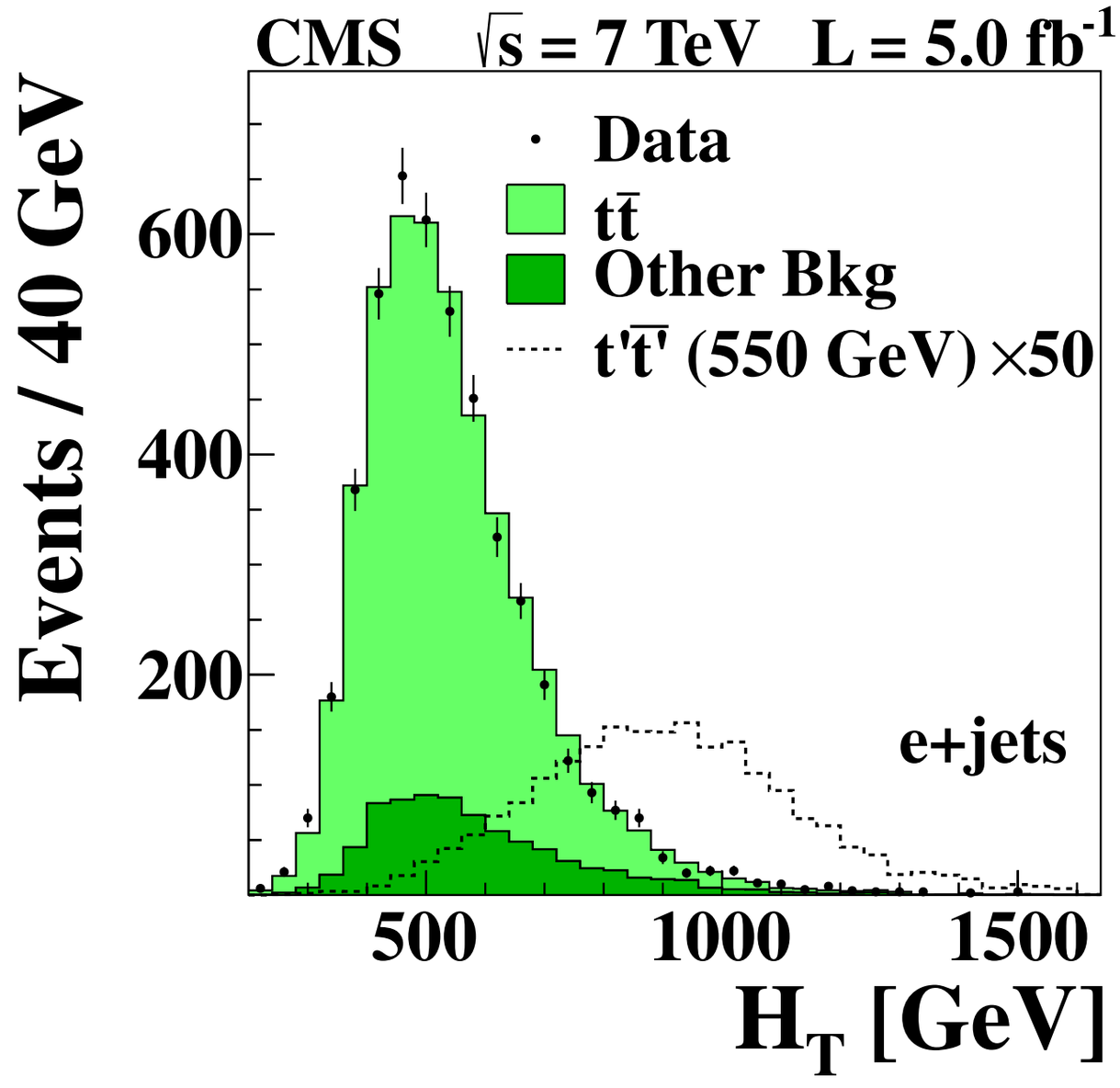
e+jets





2D→1D Rebinning

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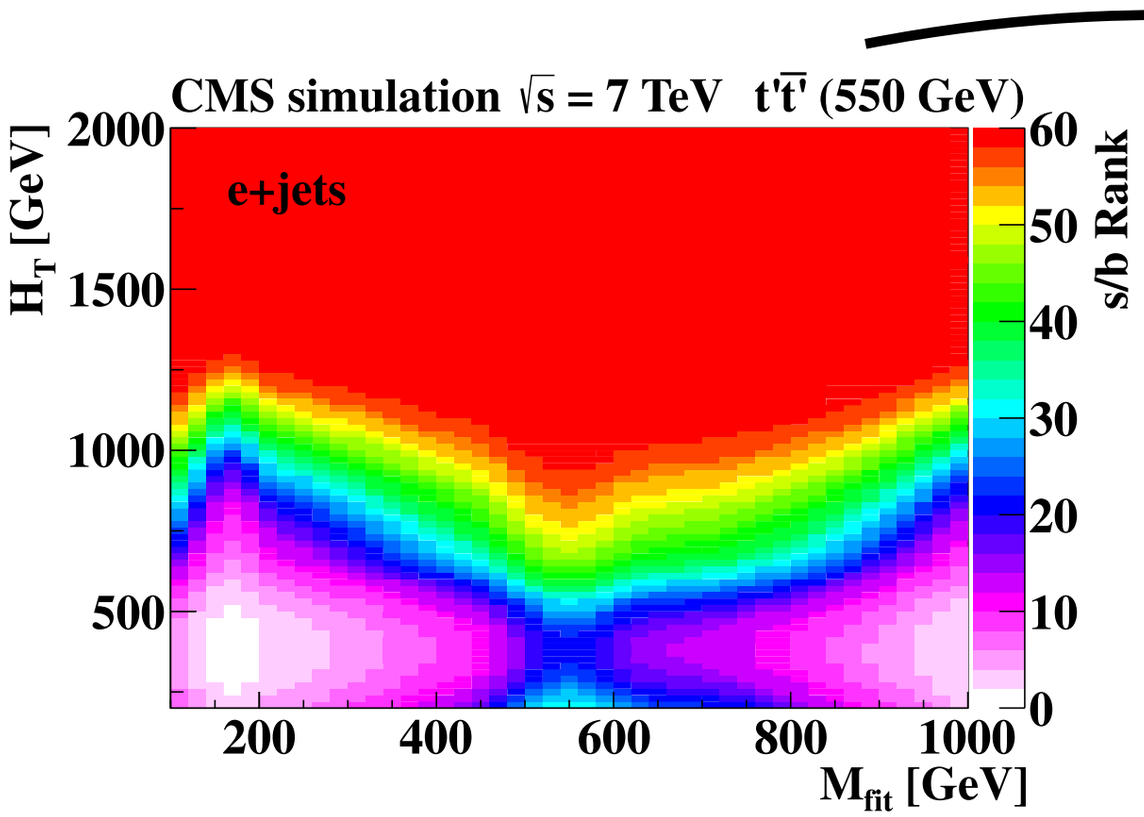
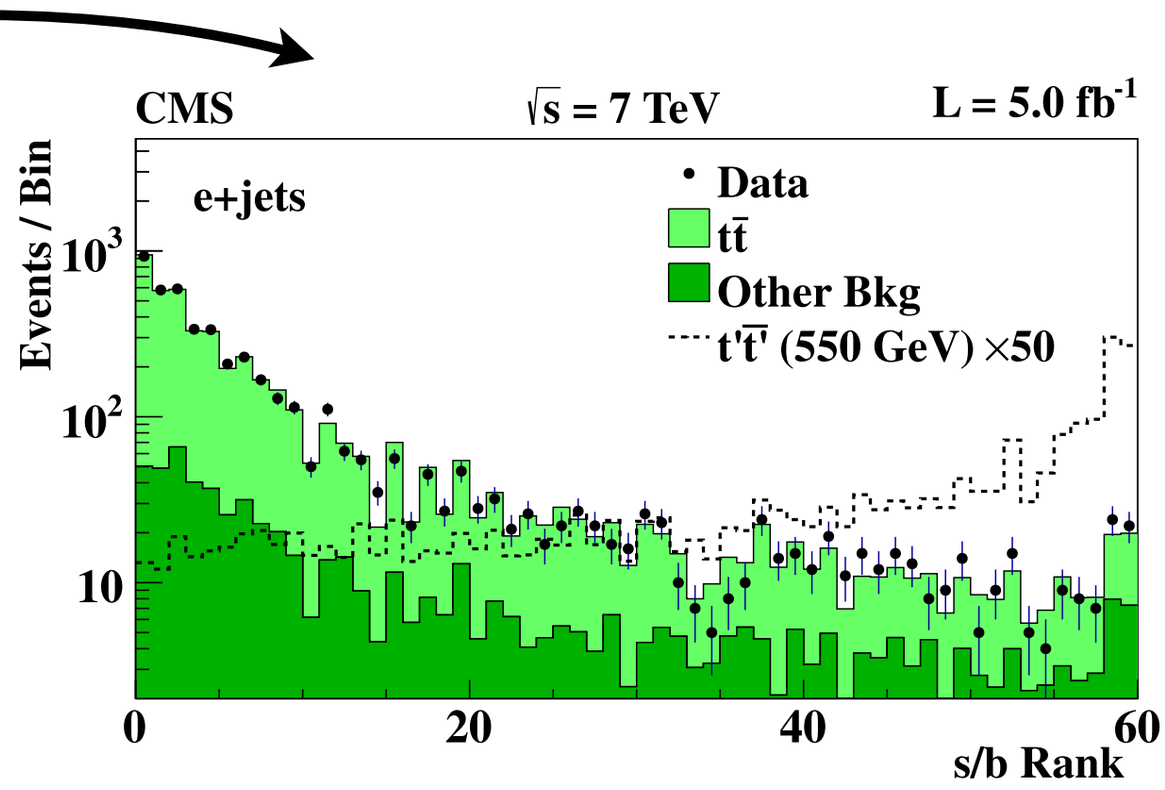
- The 2D H_T vs M_{fit} histograms have empty or low occupancy bins
  - incorrect statistical inferences
- Rebin the 2D H_T vs M_{fit} histograms
  - Project 2D histograms into a 1D by ordering the bins in descending S/B ratio
  - Merge neighboring bins into 1D histogram until fractional uncertainty in the combined bin falls below 20% for both the background and signal events





- Each color becomes a single bin in the 1D template
- Same procedure for every simulated t´ mass point

Result

PLB.2012.10.038, EXO-11-099

Sources	Syst. Unct
background normalization	50%
Luminosity	2.2%
lepton Trigger/ID	3%
Q2 (renorm. and fact. scale)	±σ(nom)
Matrix-element to parton matching	±σ(nom)
ISR/FSR	±σ(nom)
Jet Energy Scale	±σ(nom)
Jet Energy Resolution	±σ(nom)

Systematic Uncertainties

Result

PLB.2012.10.038, EXO-11-099

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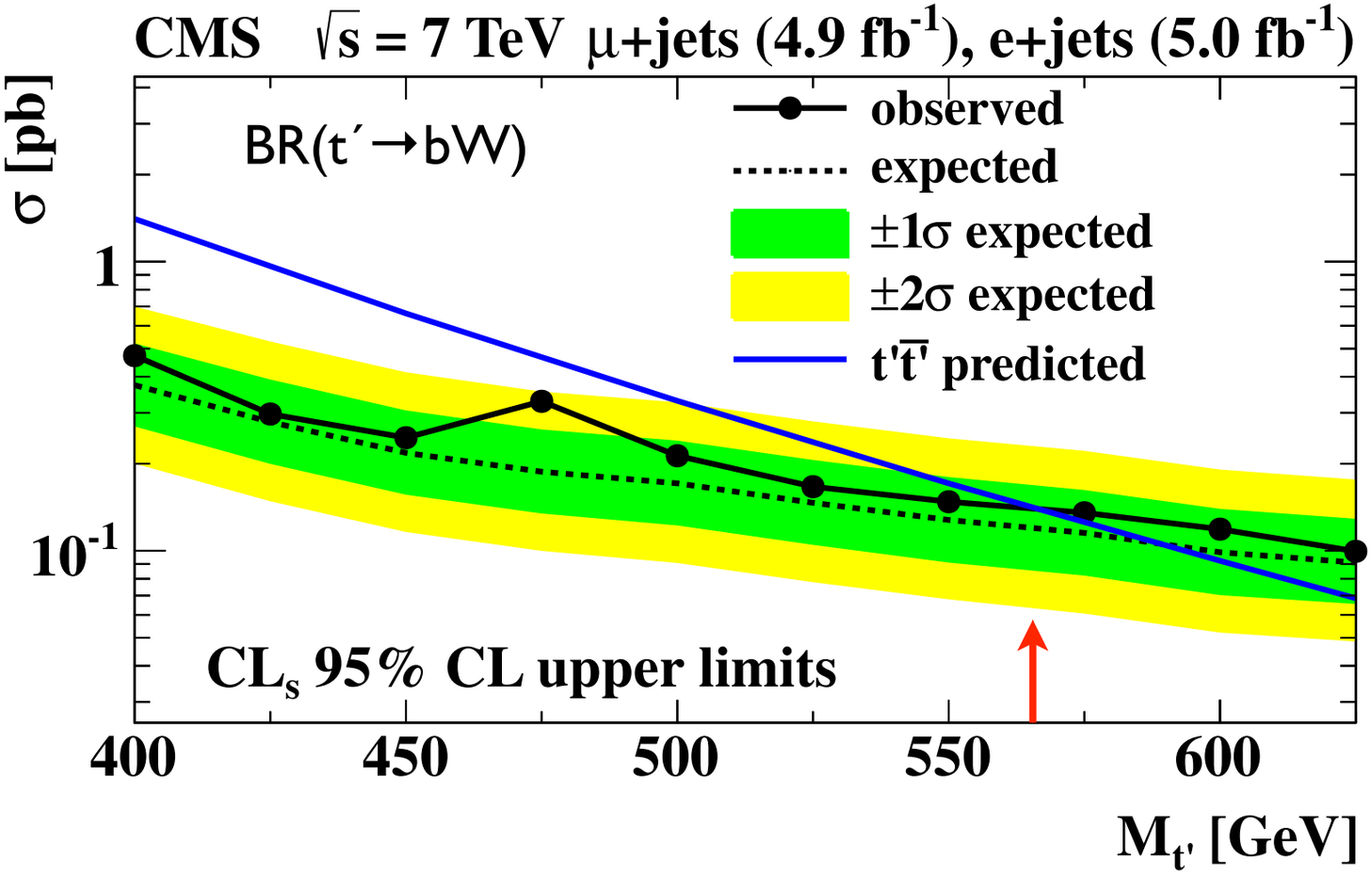


Observed limit: $m_{t'} > 570$ GeV/c^2 @ 95% CL

Search for t′→bW(dilepton)

Selection

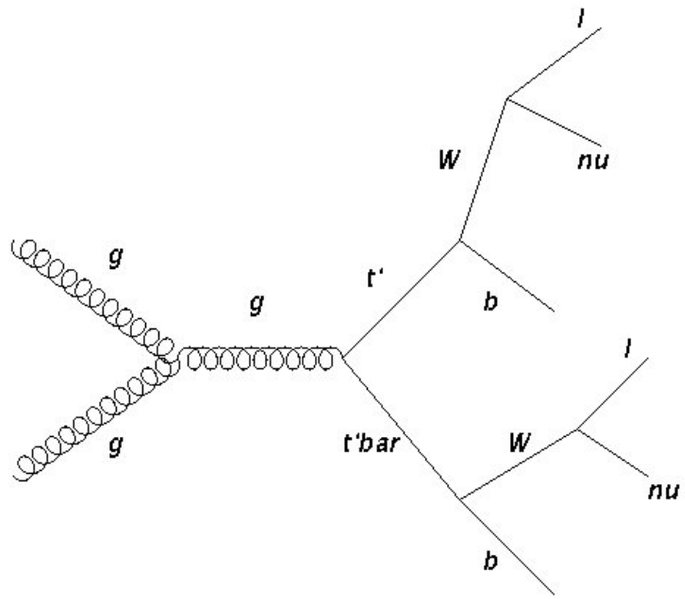
PLB.2012.07.959, EXO-11-050

- 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:

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



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

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

Search for t′→bW(dilepton)

PLB.2012.07.959, EXO-11-050

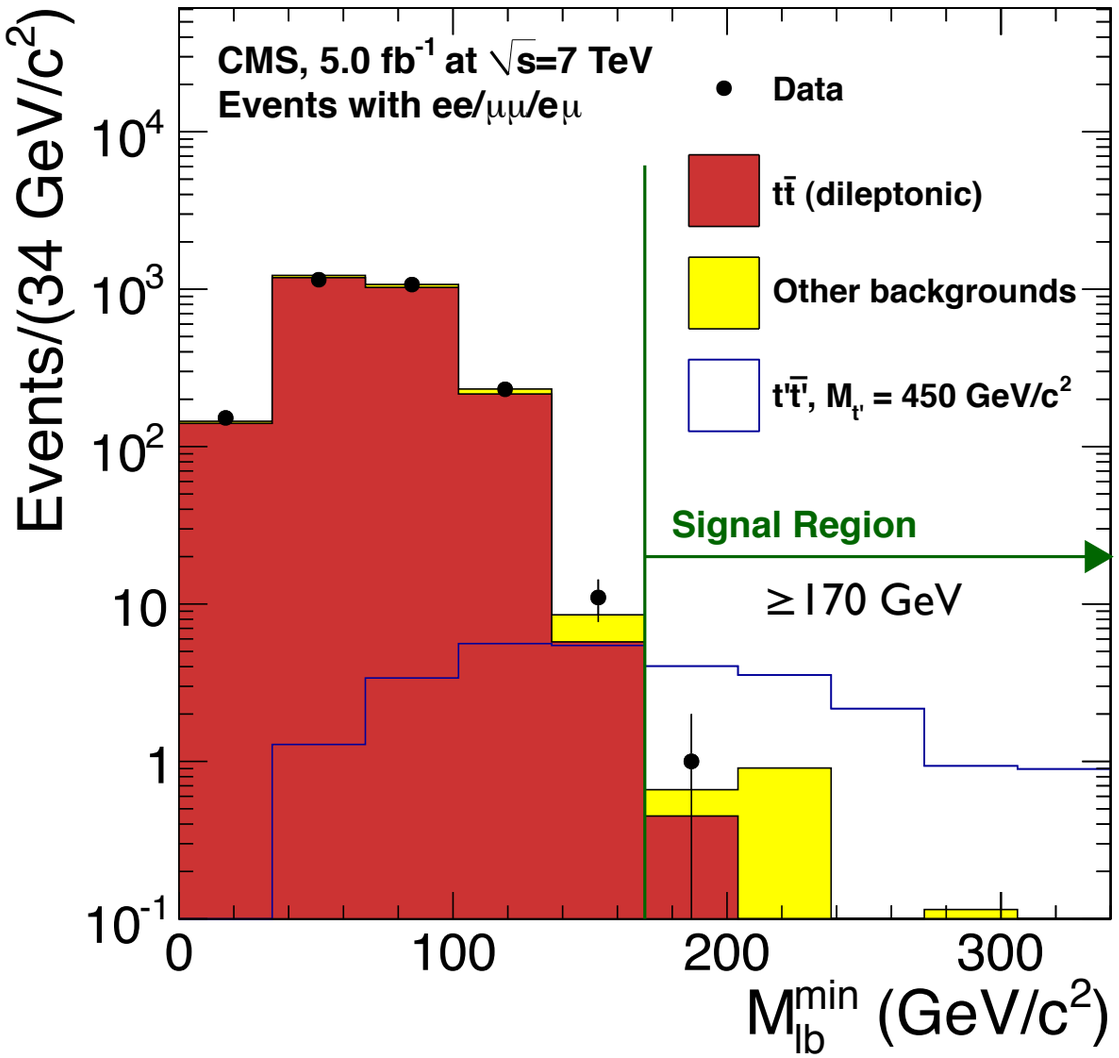
Backgrounds

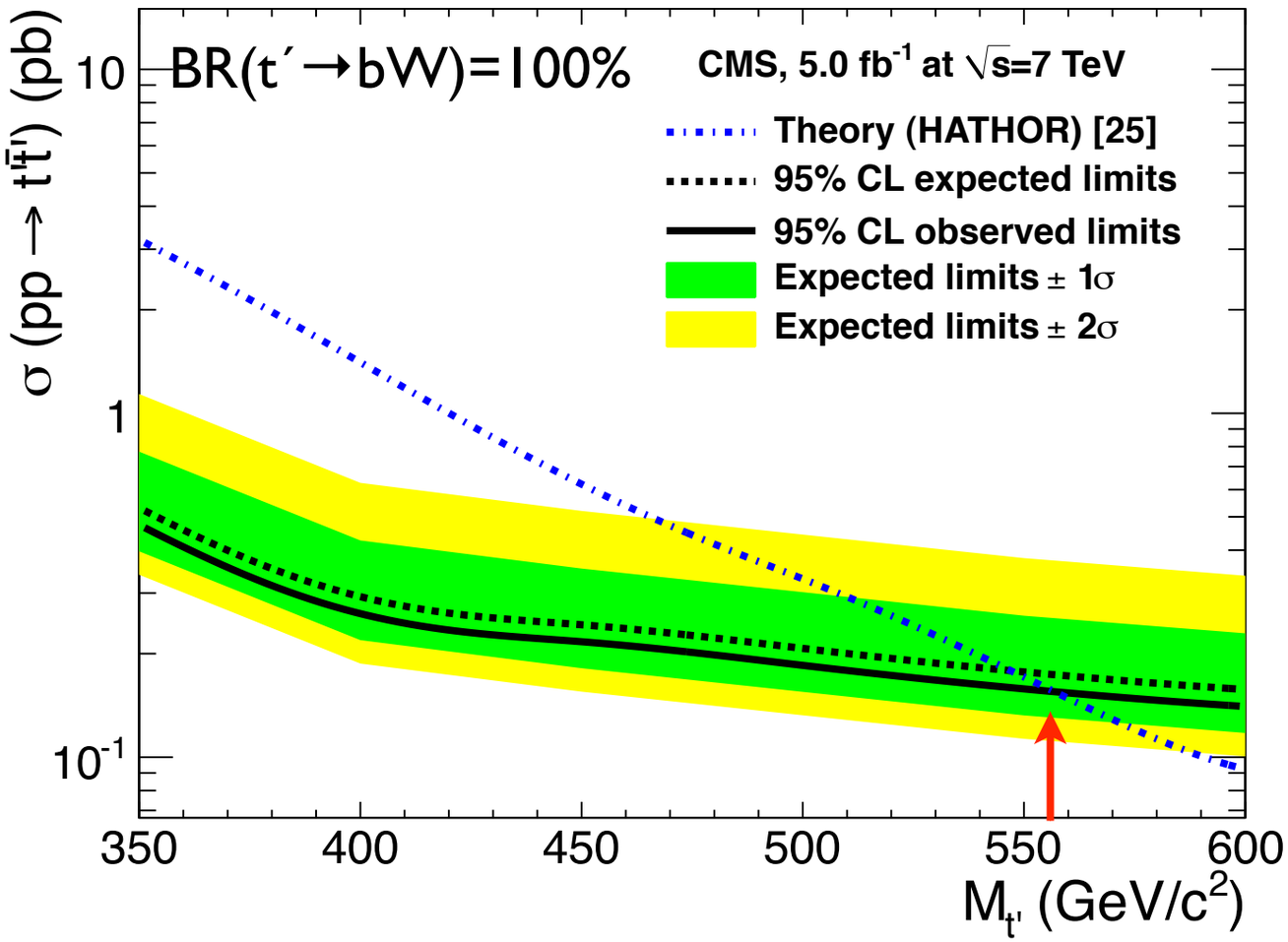
Samples	Yield
Misidentified b-jet(s) and prompt lepton (from data)	0.7±0.8
Fake lepton(s) and real b-tagged jet(s) (from data)	$0.0^{+0.4}_{-0.0}$
2 real b-tagged jets and 2 real leptons (from MC)	1.0±0.7
Misidentified b-jet(s) and fake lepon	0.0+0.0
Total predicted	1.8±1.1
Data	1.0

Search for t′→bW(dilepton)

PLB.2012.07.959, EXO-11-050

Result



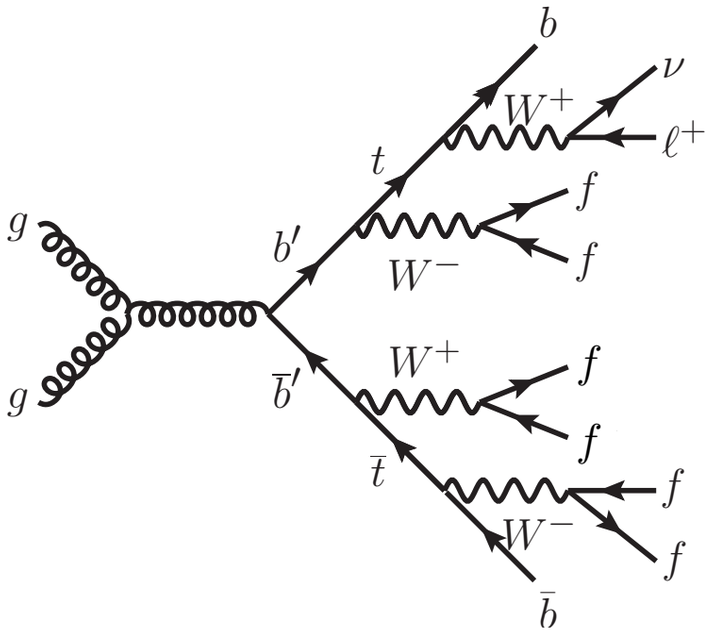


Exclude $m_{t'}$ < 557 GeV @ 95% C.L. on the production cross section

Search for Q→tV (l+jets)

arXiv:1210.7471, accepted by JHEP

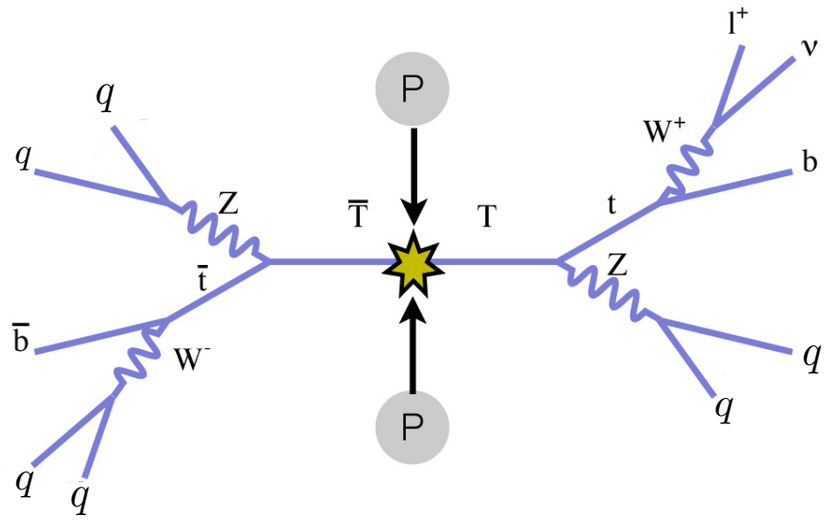
b´→tW



$$b'\bar{b}' \to WtW\bar{t} \to WWbWW\bar{b} \to l\nu qqbqqqqb$$

- one isolated lepton (muon or electron)
- ≥4 jets (accounting for jets merged and out of our fiducial acceptance)

T→tZ



$$T\bar{T} \to tZ\bar{t}Z \to Wbqq W\bar{b}qq \to l\nu bqqqqbqq$$

- We have similar N_{Jets} in the final state and therefore our selection is also sensitive to it

Search for Q→tV (l+jets)

arXiv:1210.7471, accepted by JHEP

Selection

- A lepton e/μ with p_T >30 GeV
- ≥ 4 jets, ≥ 1b-tagged jet
- Jet E_T thresholds 100, 60, 50, 35 GeV
- Missing E_T : PFMET > 20.0 GeV
- Dilepton Veto

SM Backgrounds

- ttbar+jets
- non-ttbar+jets
  - W+jets
  - Single top quark
  - Z+jets
  - Diboson (WW/WZ/ZZ)
  - QCD Multijets

Strategy

$$S_T = p_T^l + \Sigma p_T^{jet} + E_T^{miss}$$

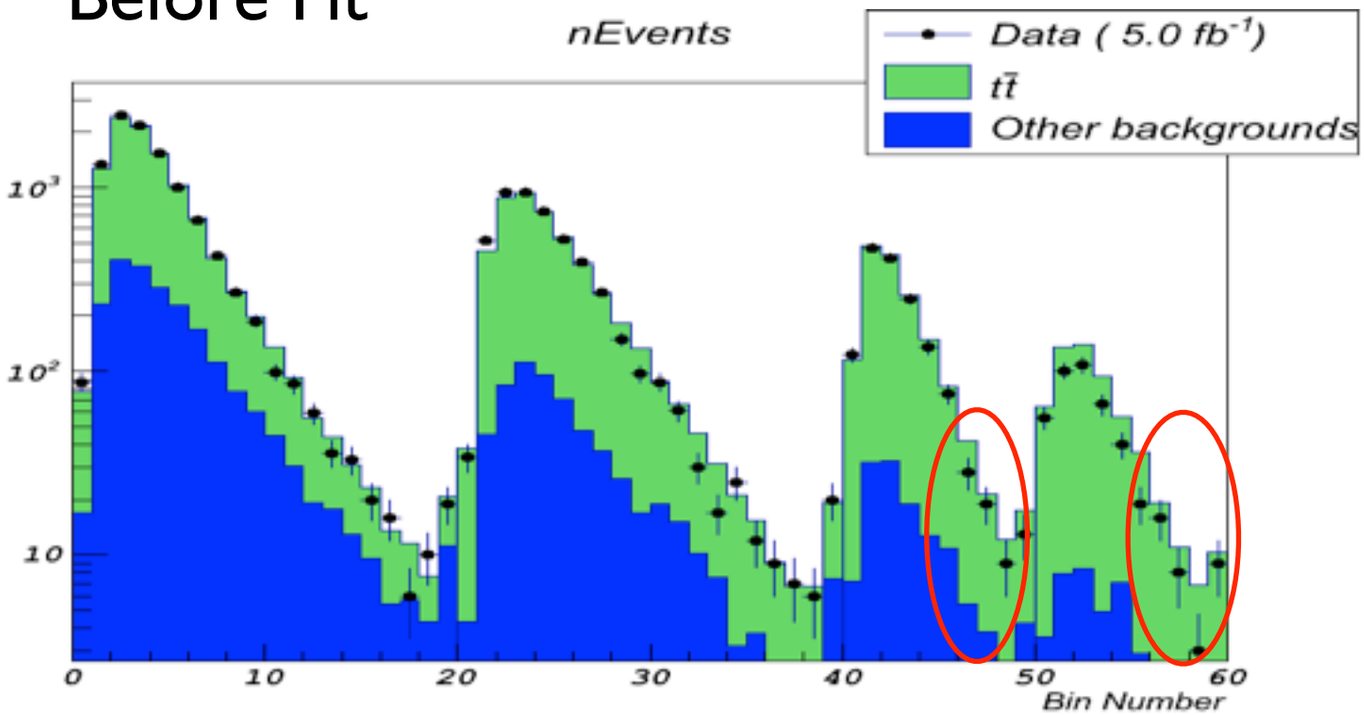
- The signal features events with high S_T and N_{Jets}
- Perform fit on S_T distributions for different jet multiplicities (N_{Jets} = 4,5,6,≥7) to search for a fourth generation massive quark Q

Search for Q→tV (l+jets)

arXiv:1210.7471, accepted by JHEP

- Extremely important to model the backgrounds accurately in the high tails of the S_T

Before Fit



Systematic Uncertainty

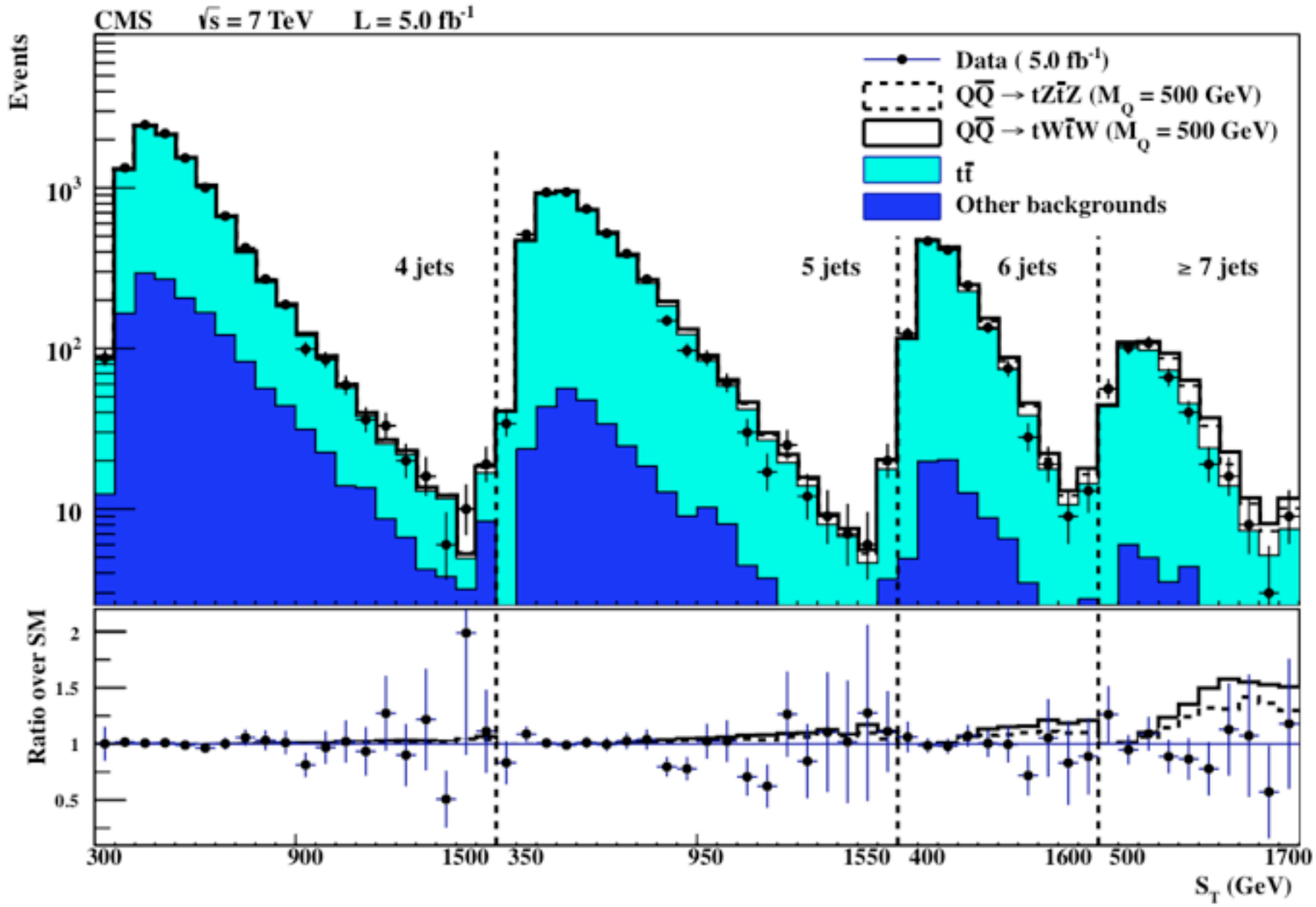
Parameter type	Source	Uncertainty (%)
Distribution	Q^2 scales for $t\bar{t}$+jet	8.7
	Matching partons	5.8
	Jet energy scale	5.4
	b-tagging efficiency	5.1
Normalization	Lepton ID/reco/trigger	3.5
	Luminosity	2.2
	$t\bar{t}$ cross section	12
	$N_{jets} = 4$	3.5
	$N_{jets} = 5$	16
	$N_{jets} = 6$	23
	$N_{jets} \geq 7$	22
	Other backgrounds	50

- The shape parameters are quoted based on their effect on the acceptance only
- Due to the correlation between the fit parameters, the combined number is not the sum of the squares of the contribution

Search for Q→tV (l+jets)

arXiv:1210.7471, accepted by JHEP

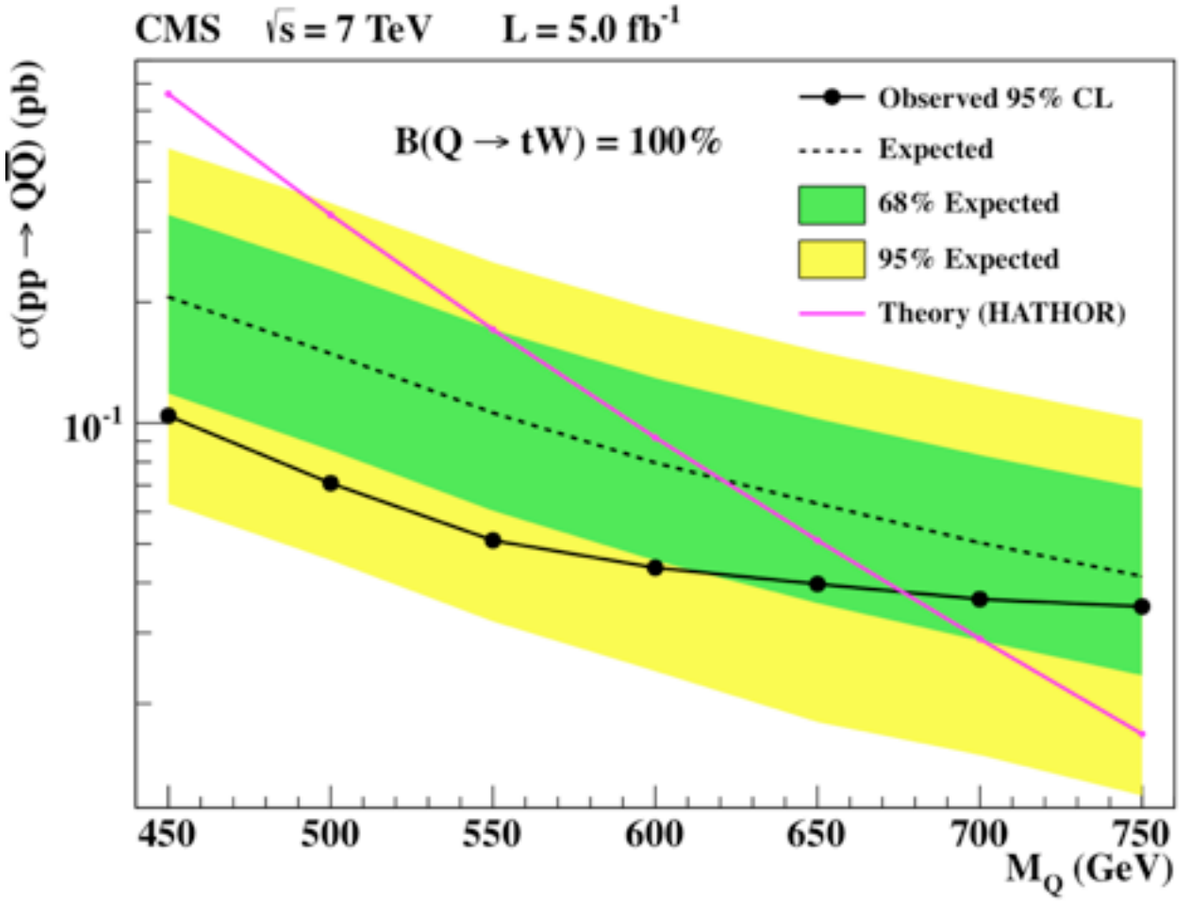
After Fit



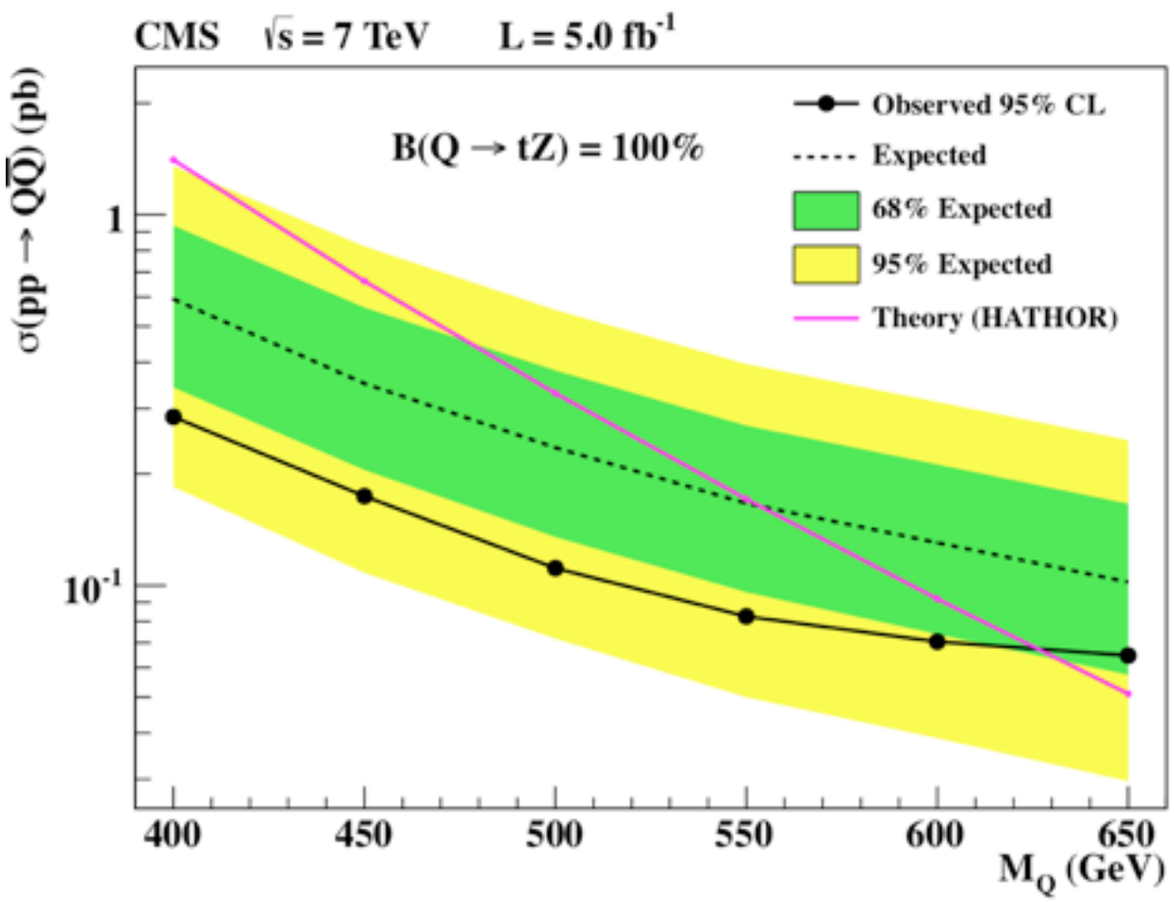
Results

arXiv:1210.7471, accepted by JHEP

Combine $b' \to tW$



Combine $T \to tZ$



- We exclude at 95% C.L, $m_{b' \to tW} < 675$ GeV/c^2 and for $m_{T \to tZ} < 625$ GeV/c^2

Theorist Excitement!

arXiv:1210.7471, accepted by JHEP

- As soon as this result was public, theorist get excited to claim the method! :)

Blog by Matt. Strassler(Rutgers, US) during HCP

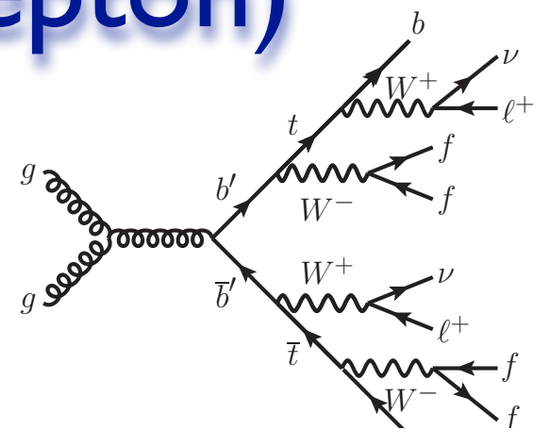
> [NOTE ADDED: Not So! in another talk at HCP, the following search by CMS was briefly mentioned: http://arxiv.org/pdf/1210.7471v1.pdf . See in particular Figure 1; this is almost exactly the method that we recommended. This search needs to be more widely studied and interpreted; it rules out many more variants of many more theories than the ones analyzed in the paper.]

http://profmattstrassler.com/2012/11/13/theory-killers-at-the-hcp-conference/#more-4928

- Requests are made to provide limits in light of vector quark-like models for an inclusive search for T and B decays (expected for Moriond)
- The method is very suitable for low Missing E_T natural SUSY !

arXiv:1204.1088, submitted to JHEP
EXO-11-036

Search for b´→tW(di/tri-lepton)



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

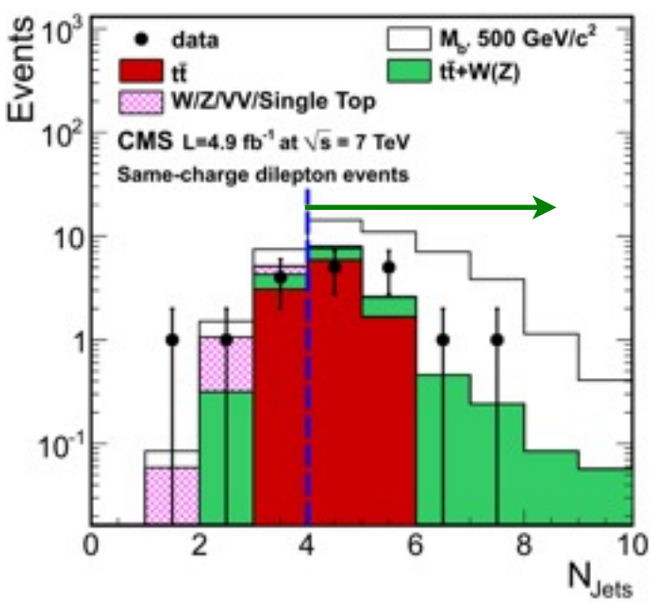
Strategy

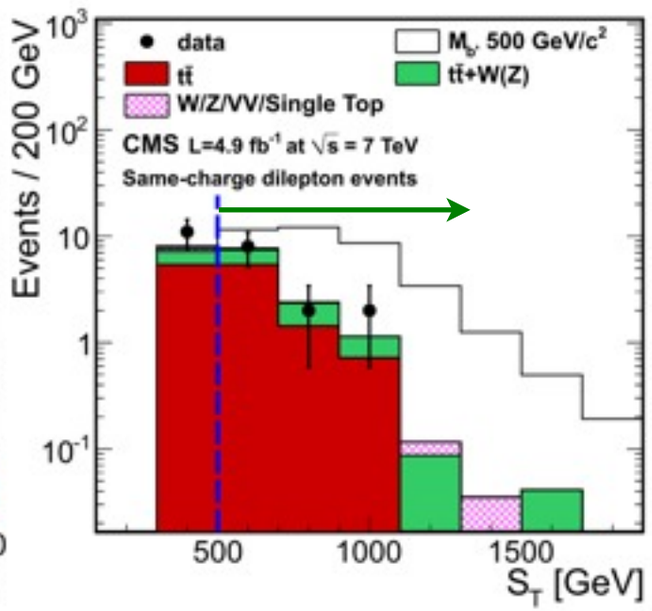
- For each event scalar quantity, S_T is determined

$$S_T = |E_T^{miss}| + \sum |p_T^l| + \sum |p_T^{jet}|$$

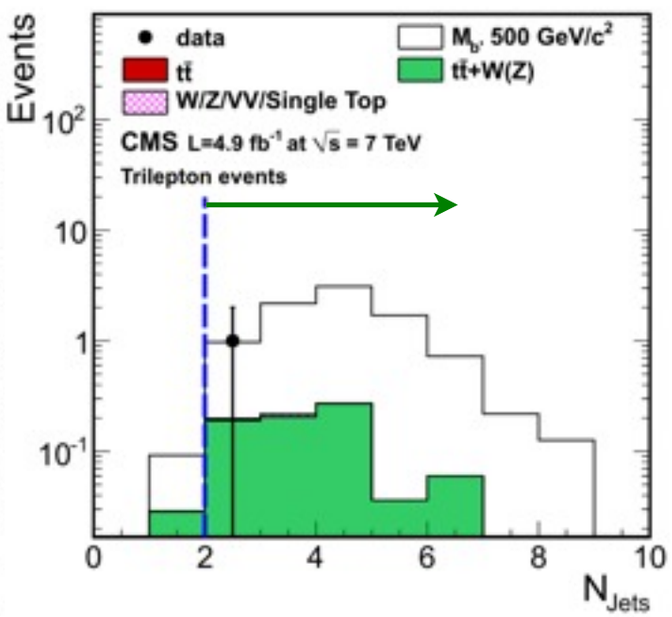
- S_T > 500 GeV

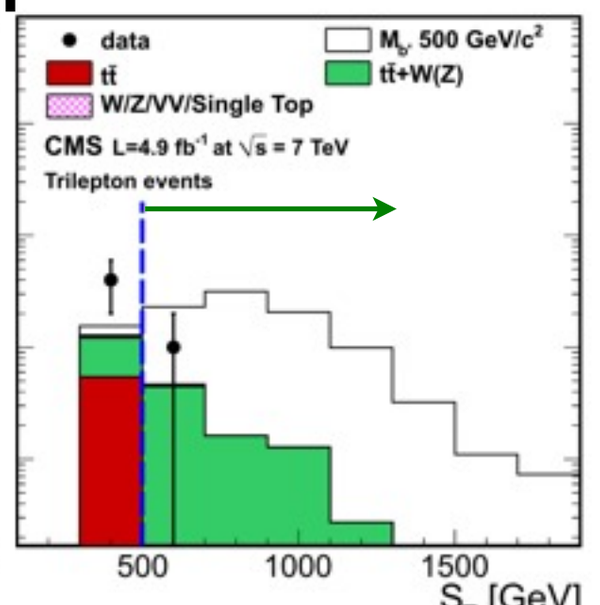
dilepton





trilepton



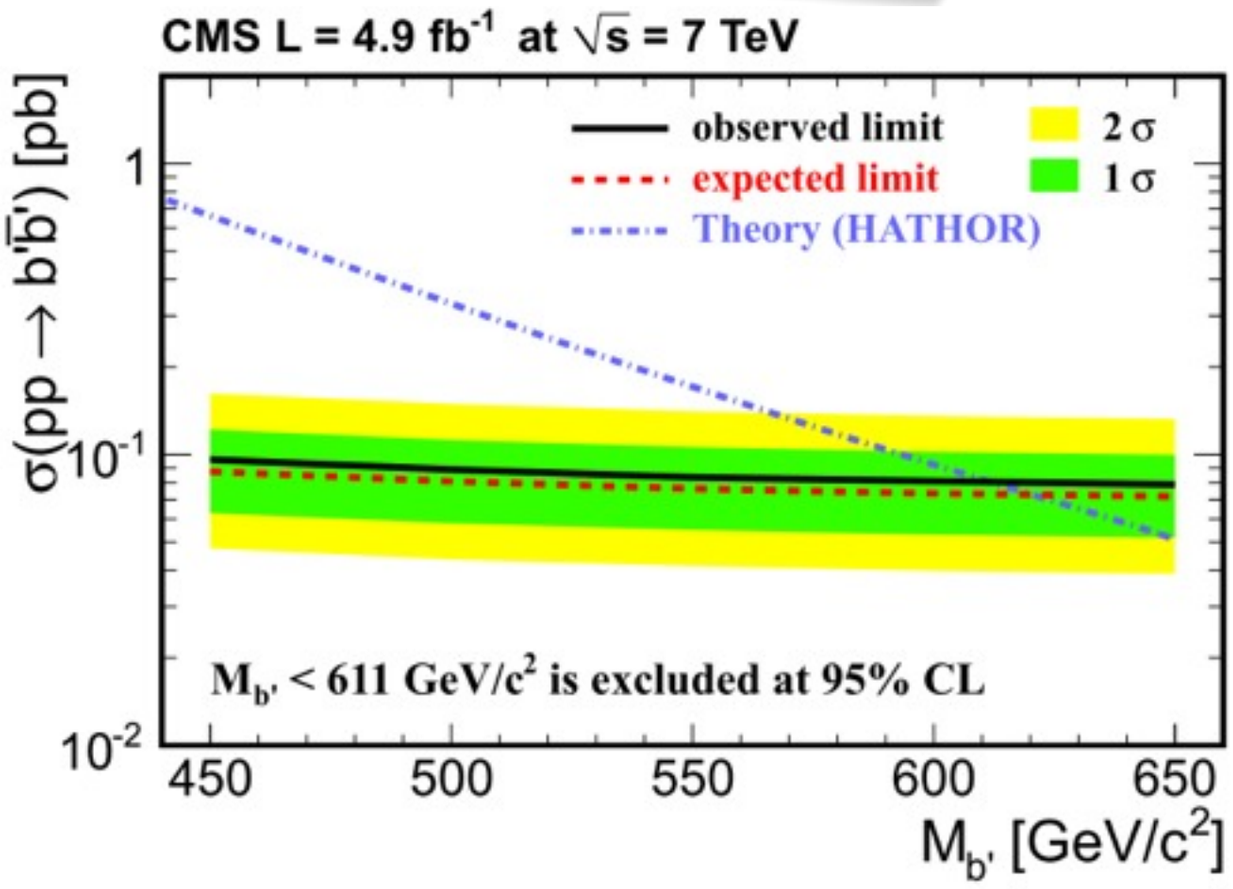


arXiv:1204.1088, submitted to JHEP
EXO-11-036

Search for b´→tW(di/tri-lepton)

- 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 inclusive b′/t′ production

arXiv:1209.1062 (accept by PRD)

- Why not look for b′/t′ at the same time? What about single productions?
- Assuming degenerate states: $m_{t'} = m_{b'} = m_{q'}$
- Simplifying CKM4 with one free parameter: $\mathrm{A} = |\mathrm{V_{tb}}|^2 = |\mathrm{V_{t'b'}}|^2$

$$\mathrm{CKM4} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} & V_{ub'} \\ V_{cd} & V_{cs} & V_{cb} & V_{cb'} \\ V_{td} & V_{ts} & V_{tb} & V_{tb'} \\ V_{t'd} & V_{t's} & V_{t'b} & V_{t'b'} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & \sqrt{A} & \sqrt{1-A} \\ 0 & 0 & \sqrt{1-A} & \sqrt{A} \end{pmatrix}$$

- Assuming the branching fractions to be ~100% $\nearrow b' \to tW$ $\searrow t' \to bW$

Selection and Classification

arXiv:1209.1062 (accept by PRD)

- 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
- Final state topologies contains
  - 1-4 W bosons (≥ 1 W decay leptonically)
  - 2 b-quarks
- Search is performed
  - Single lepton(e/μ) + jets
  - Same-sign dilepton + jets
  - Trilepton + jets

- $t'b \to bWb$
- $t'\bar{t}' \to bWbW$
- $b't \to tWbW \to bWWbW$
- $b't' \to tWbW \to bWWbW$
- $b'\bar{b}' \to tWtW \to bWWbWW$

The events can be categorized according to number of W bosons

1W	2W	3W	4W
t´b	t´t´	b´t + b´t´	b´b´

arXiv:1209.1062 (accept by PRD)

Search for inclusive b´/t´ production

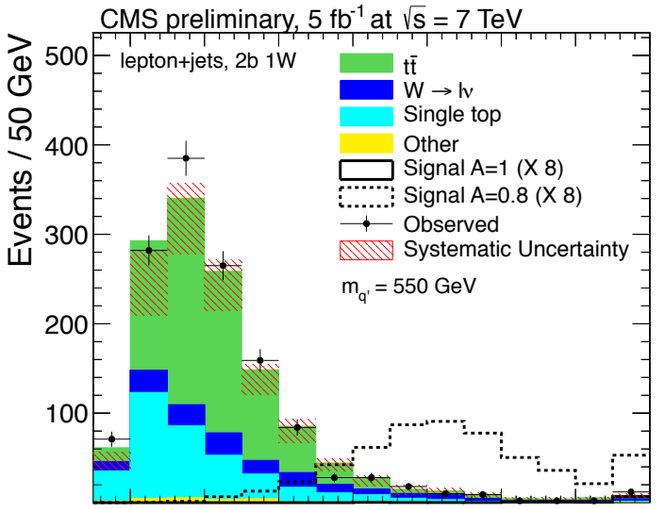
Discriminator: Scalar sum of reconstructed objects (S_T) and hadronic top mass (m_{bW})

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

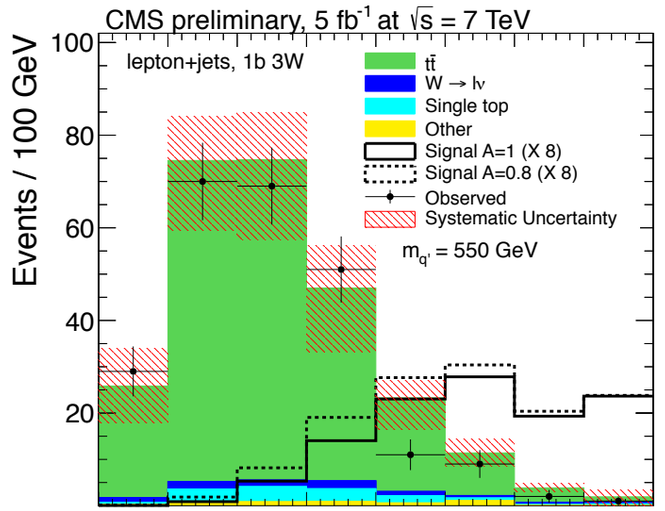
- $\not{E}_T$ + p_T^l: lepton p_T
- p_T^b: b-jet p_T
- p_T^j: p_T of 2nd b-jet or jet not from W_{had}
- $p_T^{W^i_{q\bar{q}}}$: p_T of W_{had}

- 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

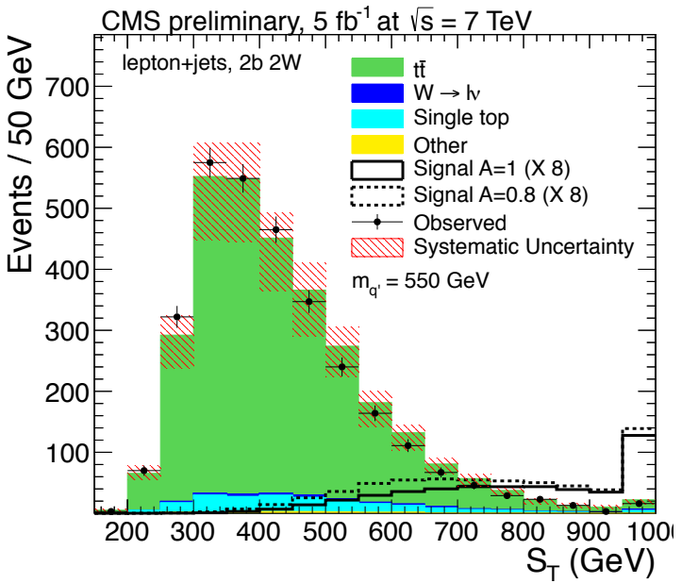
2b1W



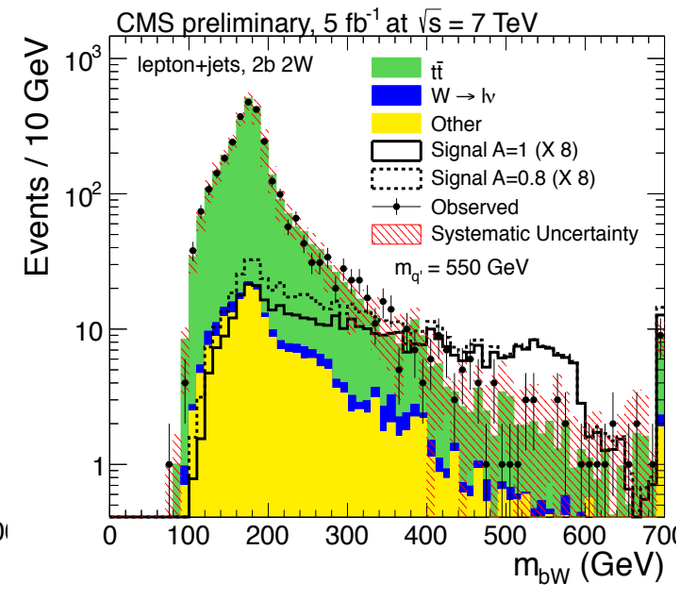
1b3W



2b2W



2b2W

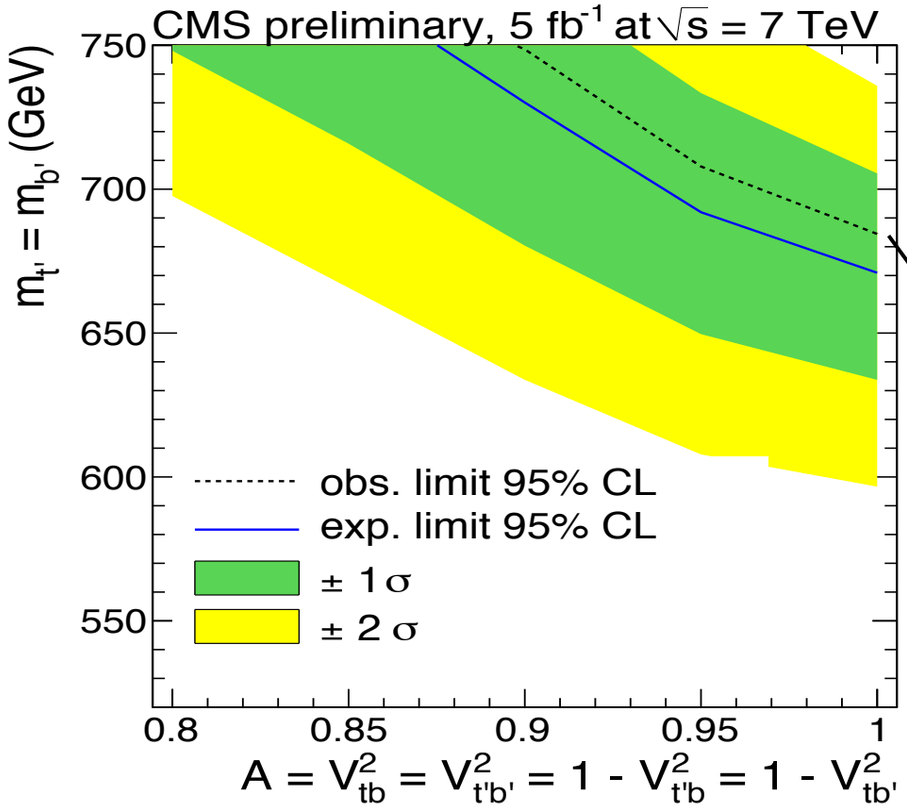


2nd discriminating variable

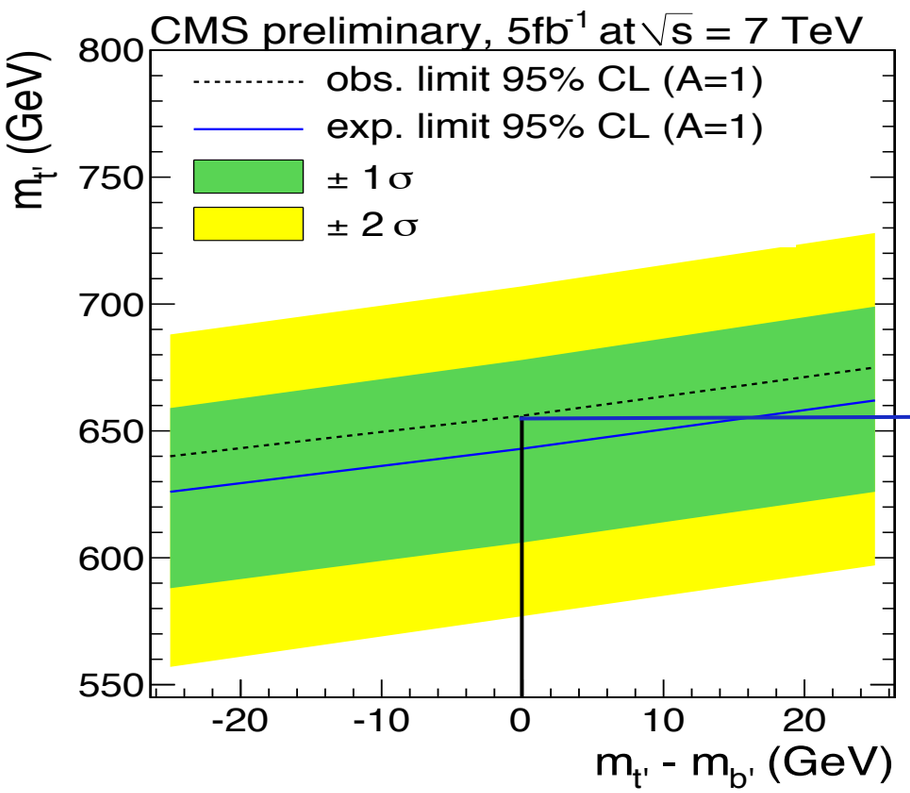
arXiv:1209.1062 (accept by PRD)

Search for inclusive b′/t′ production

EXO-11-098



- 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 $m_{t'} = m_{b'}$

Future Aspects

- On going analysis at 8 TeV
  - T pair search (bWbW, bWtZ, bWtH, tZtZ, tHtH, tHtH)
  - B pair search (tWtW, tWbZ, tWbH, bZbH, bZbZ, bHbH)
  - Single T and B search
  - Inclusive search to extract couplings and branching ratios

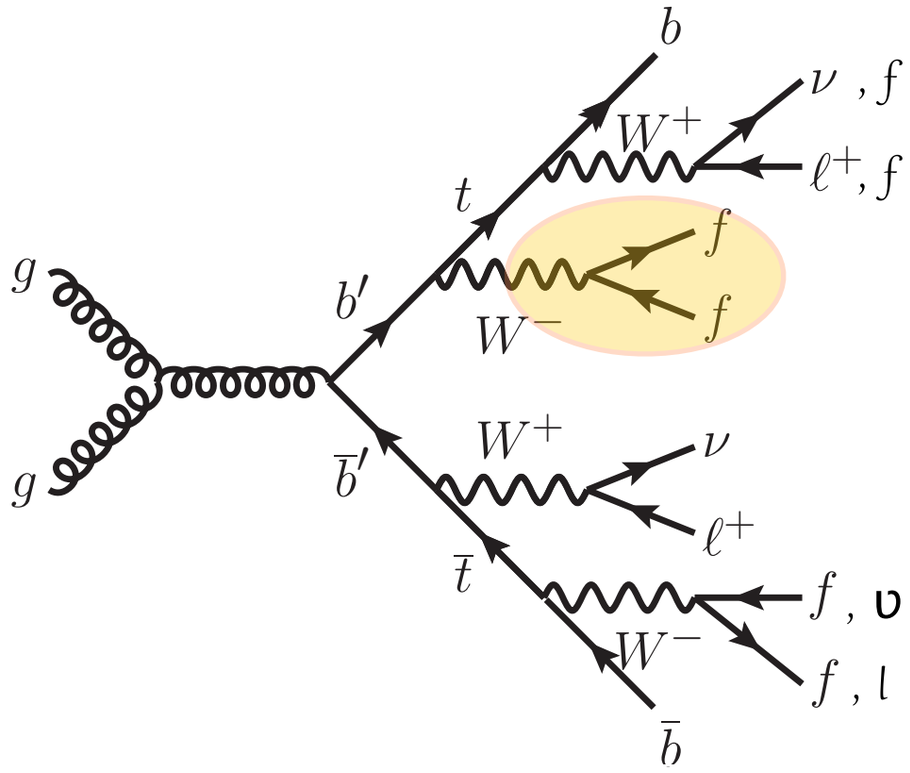
Search for Vector-like B quark (l+jets)

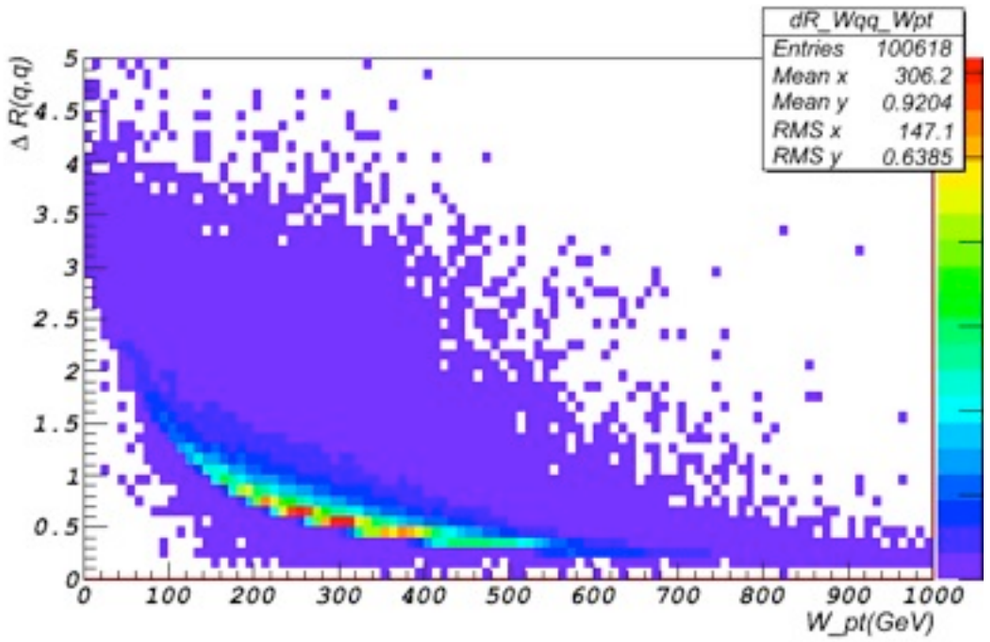
On going analysis at 8 TeV

- Need new strategies to gain sensitivity, since we have excluded the heavy quark masses so high.
- Exploiting boosted topologies
  - BB→tWtW, tWbZ, tWbH, bHbZ, bHbH, bZbZ
  - The decay products being highly boosted will be collimated and clustered into single jet
  - Categorize events based on b-jets and number of bosons (V-tagging)
    - Use CA Algorithm to tag a W/Z/H

Search for Vector-like B quark (l+jets)

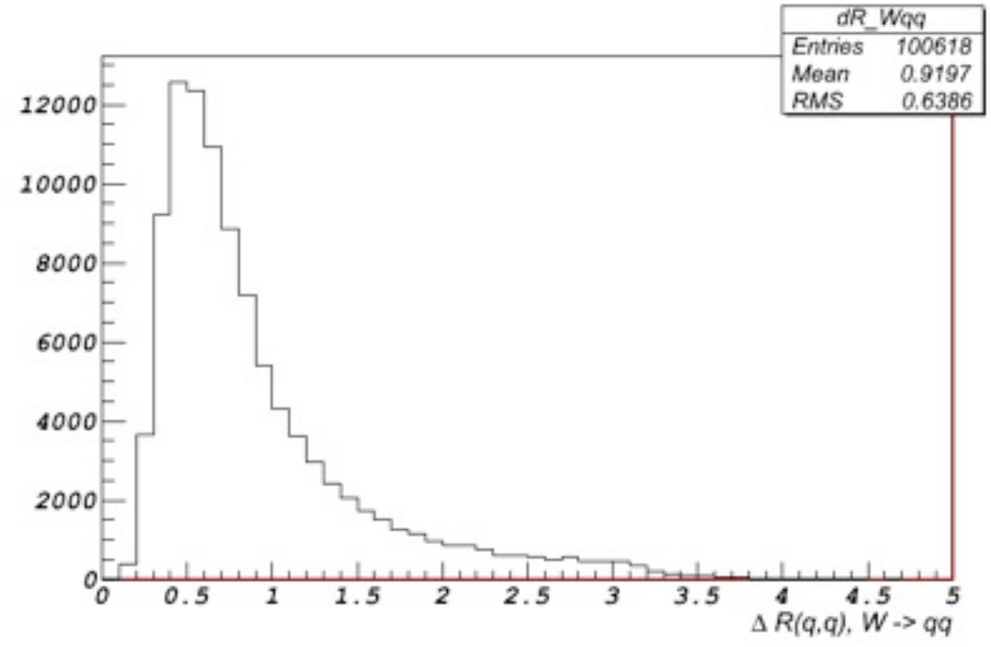
On going analysis at 8 TeV





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

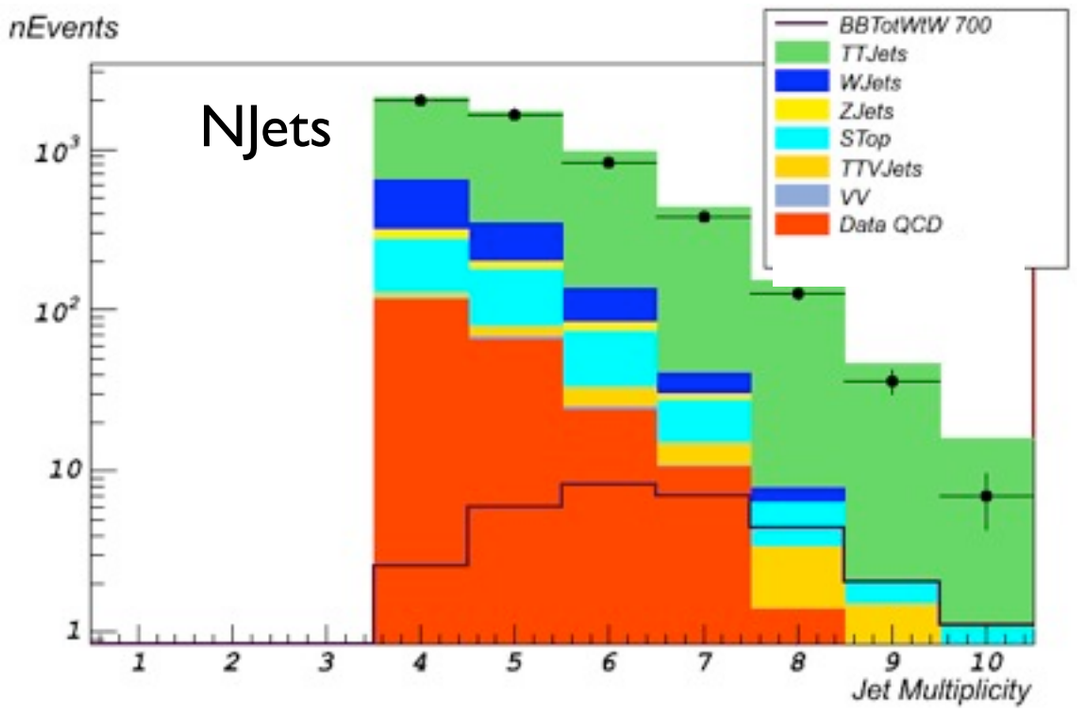
$$b' = 700 \text{ GeV}$$

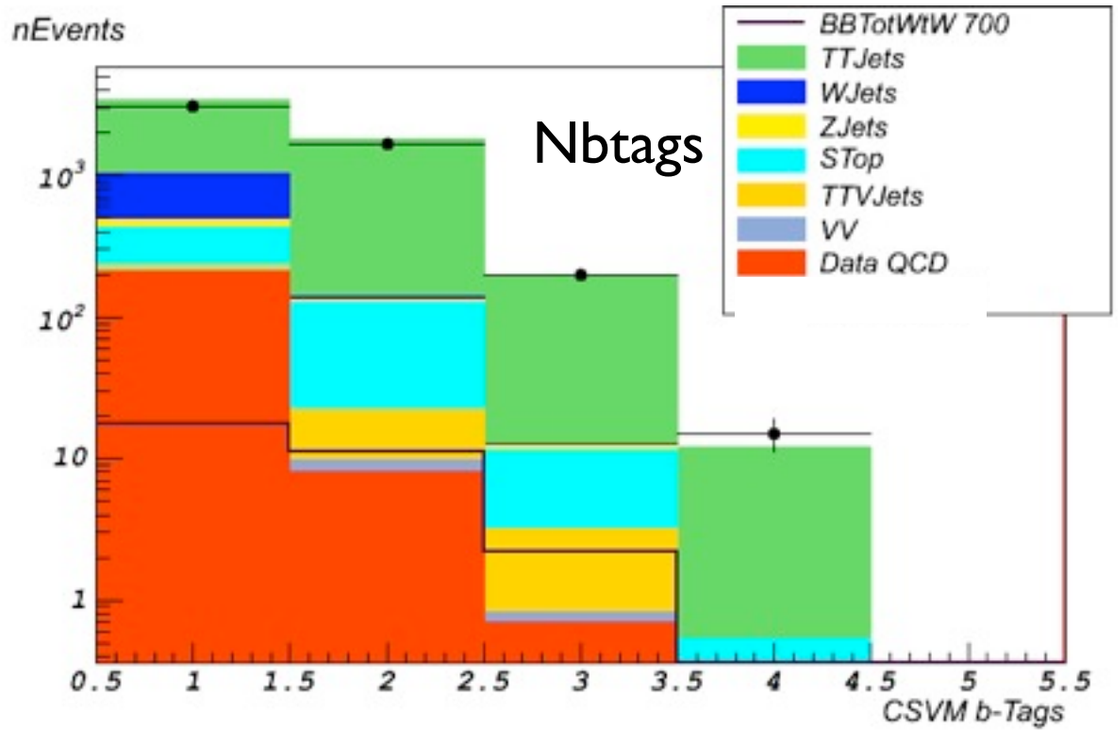


Search for Vector-like B quark (l+jets)

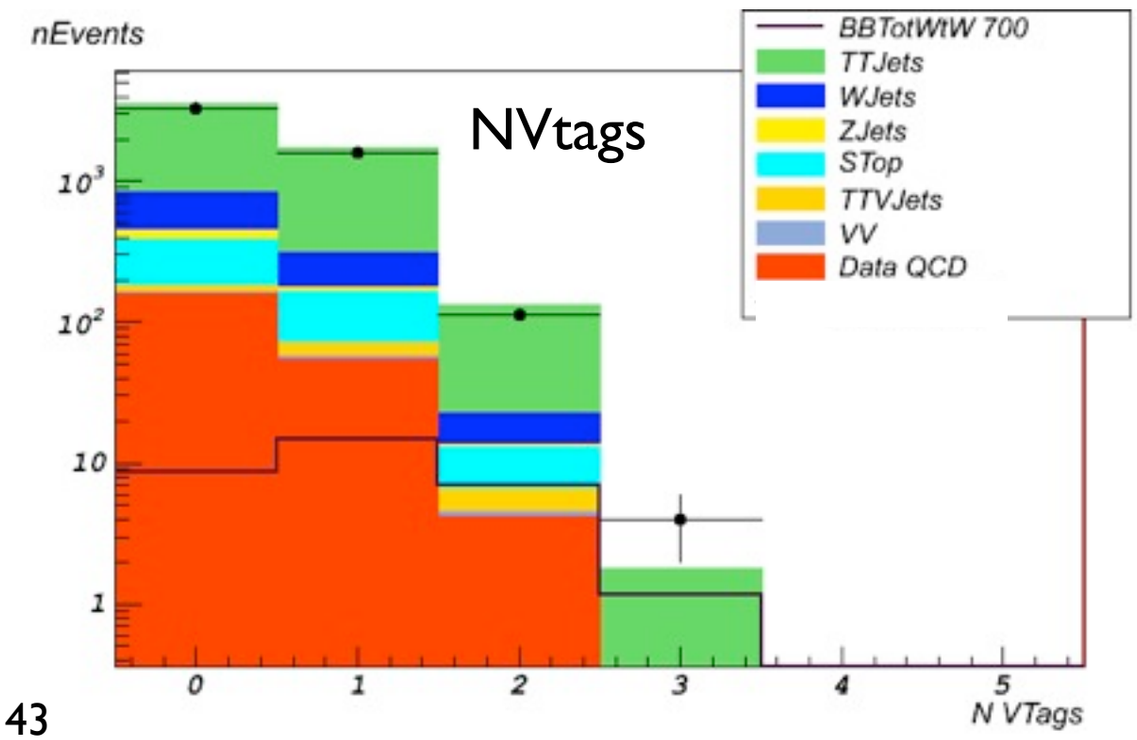
$$b'\bar{b}' \rightarrow WtW\bar{t} \rightarrow bWWbWW$$

On going analysis at 8 TeV





- Using Multidimensional fit using N_{Jets}, $N_{b\text{-}tags}$ and N_{Vtags} gives sensitivities to high mass signal region



Summary (7 TeV)

Search	Channel	Lower mass limit
t′→bW pair	lepton+jets	570 GeV/c^2
	dileptons	557 GeV/c^2
b′→tW pair	lepton+jets	675 GeV/c^2
	trilepton and same-sign dilepton	611 GeV/c^2
T→tZ pair	lepton+jets	625 GeV/c^2
	trileptons	475 GeV/c^2
B→bZ pair	two leptons	550 GeV/c^2
Model-Dependent t′/b′	lepton(s)+jets	685 GeV/c^2

Conclusions

- 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)
- Many interesting analysis are awaited for Moriond exploring the territories that were not explored before!
  - overlap with top Physics
  - overlap with SUSY

Thank you!

Extra material

Backgrounds

EXO-11-050

5 fb^{-1}

- Backgrounds (mostly data driven)
  - Category I - misidentified b-jet(s) and prompt leptons
    - use data control regions for events passing all but b-tag jet requirement.
      - $N_{1mistag}$ → with1 b-tag, weight each untagged jet by mistag rate (r_i)
        - No untagged jets passes M_{lbmin} selection →event weight=0
        - For each untagged jet passing M_{lbmin} selection → event weight is increased by r_i / (r_i -1)
      - $N_{2mistag}$ →weigth each untagged jet by r_i / (r_i -1) * r_j / (r_j -1)
      - $N_{mistag} = N_{1mistag} - N_{2mistag}$
  - Category II - fake lepton(s) and real b-tagged jet(s)
    - use data control region of lepton passing loose selection of electron ID
      - Fraction of loosly identified electron passing the event ref selection = 0
  - Category III - 2 real b-tagged jets and 2 real leptons (obtained from MC)
    - require to match the jets and leptons at generator level particles
  - Category IV - misidentified b-jet(s) and fake lepton(s) (negligible)
    - no double counting possible as shown by Category II

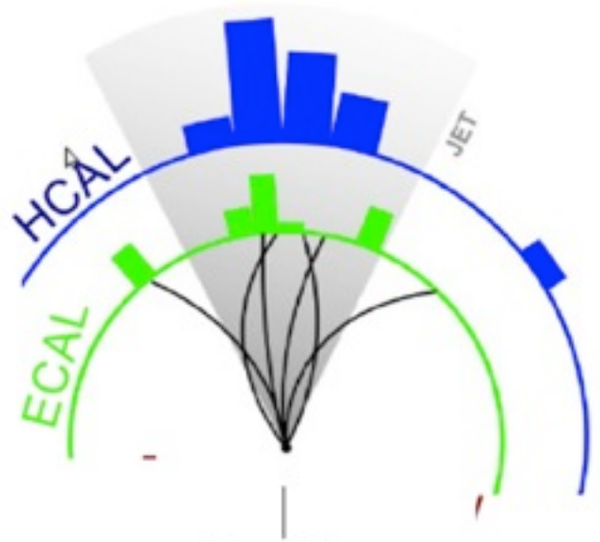
Sample	Yield
Category I (from data)	0.7 ± 0.8
Category II (from data)	$0.0^{+0.4}_{-0.0}$
Category III (simulated)	1.0 ± 0.7
Total prediction	1.8 ± 1.1
Data	1

Global Event Description

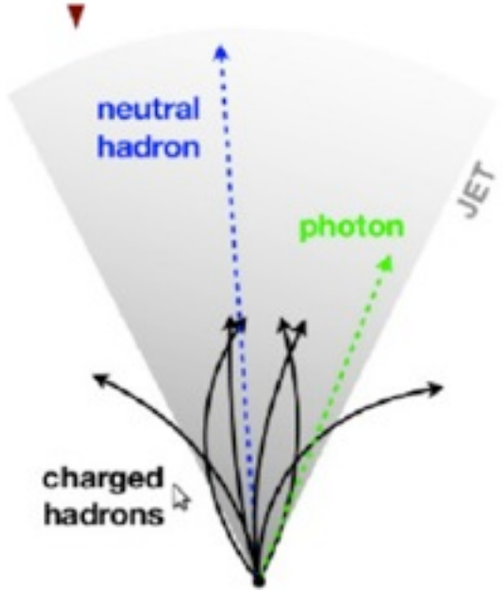
P. Silva
CERN PH-LHC Seminar

- Charged-based separation of components making best use of
  - field integral $B \times R = 4.9\ \mathrm{T \cdot m}$
  - calorimeter granularity $\Delta\eta \times \Delta\phi|_{\mathrm{ECAL}} \sim 0.017^2$

    $\Delta\eta \times \Delta\phi|_{\mathrm{HCAL}} \sim (5 \cdot \Delta\eta) \times (5 \cdot \Delta\phi)|_{\mathrm{ECAL}}$
  - iterative tracking(progressively relaxing constrains/removing hits)
  - linking algorithm yields blocks sub-detector elements called **particle candidates**
- Particle flow provides a global description of each event
- A reconstructed jet is "again" a cluster of particles



Algorithm	Calorimeter-based	Particle Flow		
Composition	Towers	Charged Hadrons	Photons	Neutral hadro
Energy fraction	100%	65%	25%	10%
Energy	$E_{HCAL} + E_{ECAL}$		$\sum_{k=h^\pm,h^0,\gamma,\ell} E_k$	
Resolution (σ)	120% $\sqrt{E}$	1% p_T	1% $\sqrt{E}$	120% $\sqrt{E}$
Direction	biased by $\vec{B}$	vertex-based	good resolution	-



- crucial for b-jets (e.g. reduce material budget uncertainty on energy scale)
- crucial for missing transverse energy $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}} = -\sum_{k=h^\pm,h^0,\gamma,\ell} \vec{p}_{\mathrm{T},k}$

Search for vector-like T→tZ(trilepton)

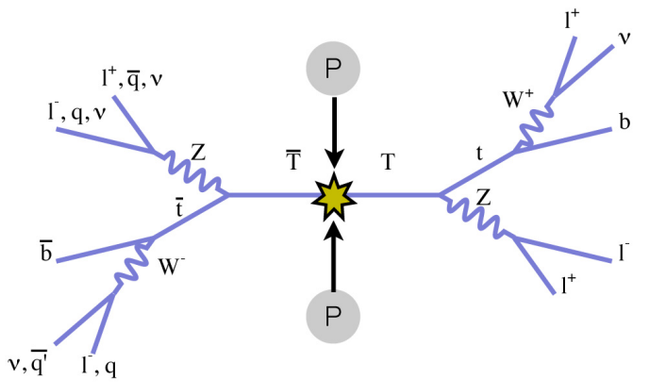
1.14 fb^{-1}

PRL. 107, 271802(2011)

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

B.F = 5.4% for (e/μ)

Decay mode	BF
3L+4-6J (1Wlν+1Zll)	72/900
4L+2-4J (2Wlν+1Zll)	18/900
4L+6J (2Zll)	4/900
5L+4J (1Wlν+2Zll)	4/900
6L+2J (2Wlν+2Zll)	1/900

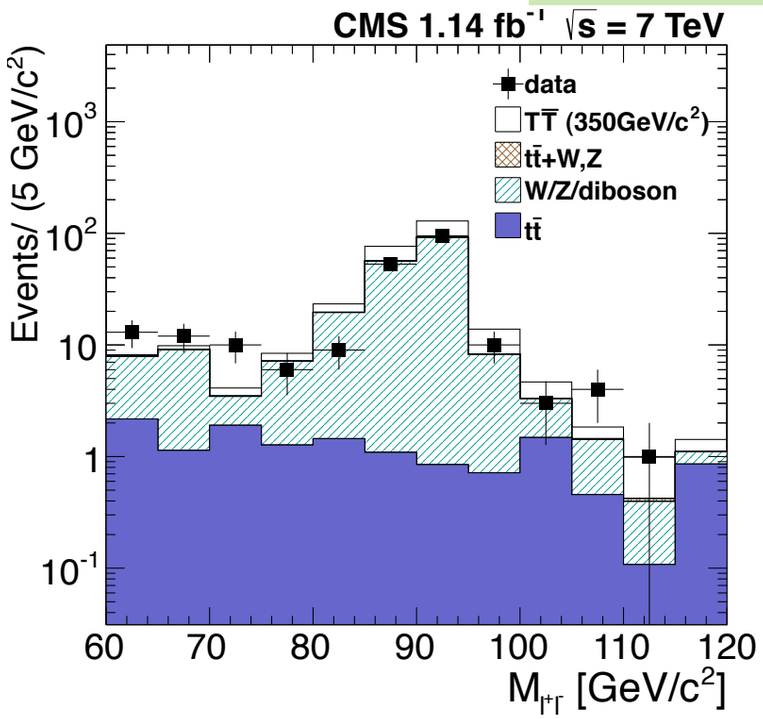


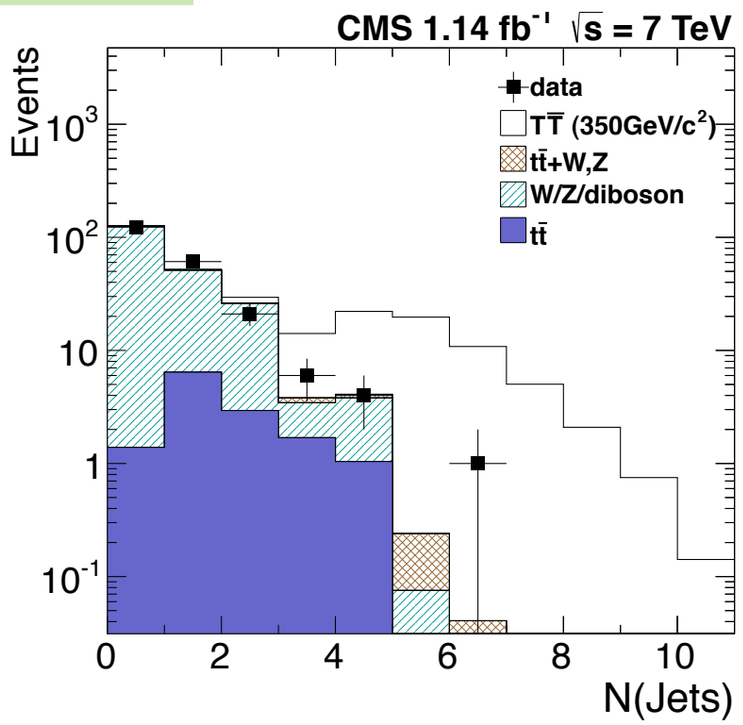
$T\bar{T} \rightarrow tZ\bar{t}Z \rightarrow b\bar{b}W^+W^-ZZ$

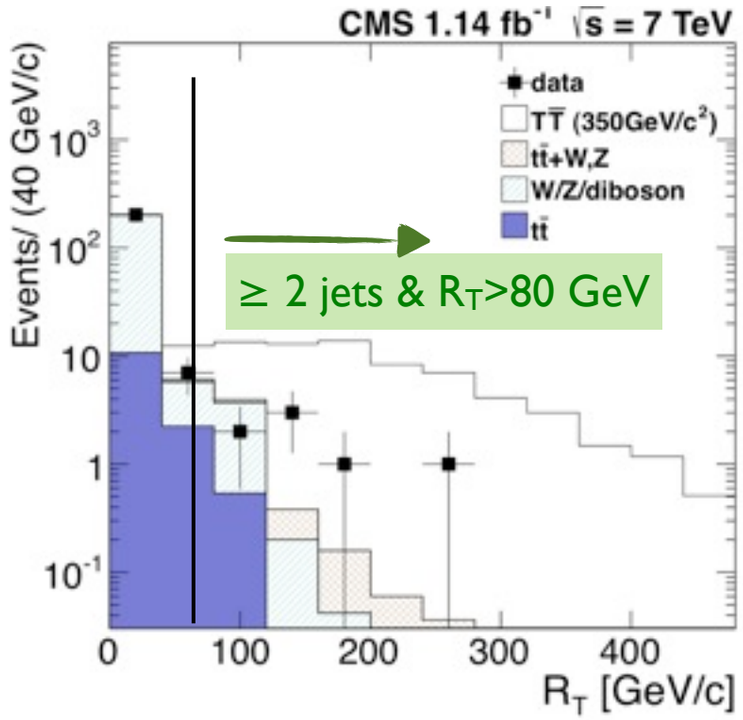
Strategy

- Construct the variable $R_T = (\sum p_T^{\text{leptons}} + \sum p_T^{\text{jets}}) - (\sum p_T^{\text{two leading leptons}} + \sum p_T^{\text{two leading jets}})$ > 80 GeV

~~≥ 2 jets & R_T>80 GeV~~







Search for vector-like T→tZ(trilepton)

1.14 fb^{-1}

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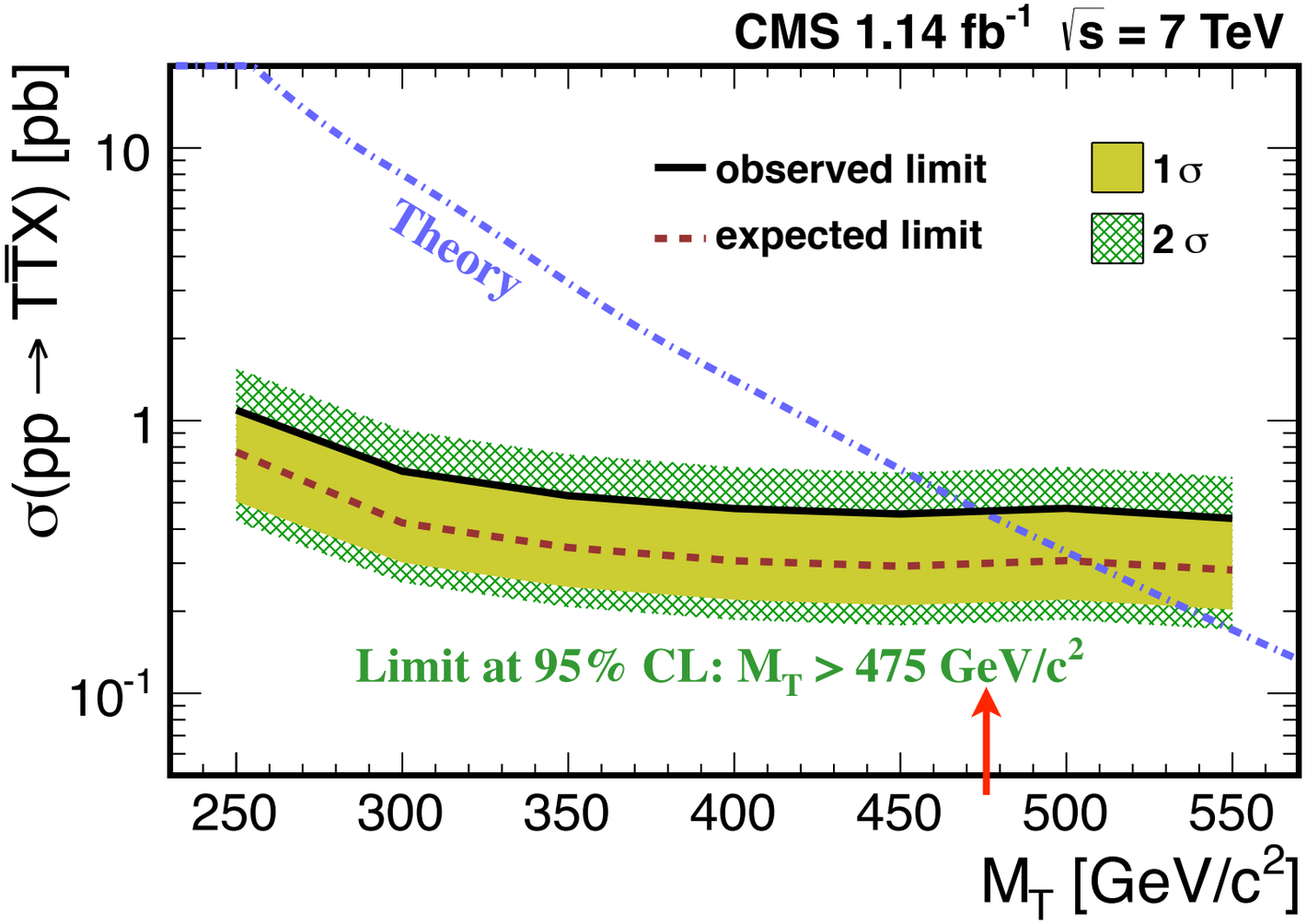
Yields

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

Assuming a branching fraction of 100% T→tZ



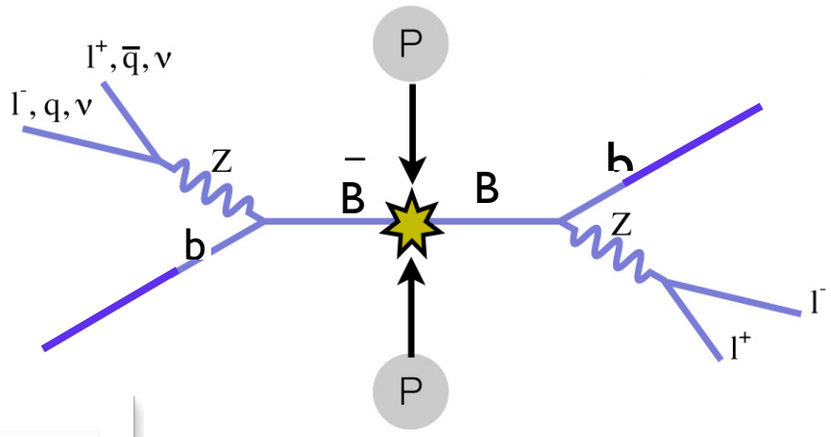
- With the observed upper limit at 95% CL on the production cross section, we excludes a T quark with a mass < 475 GeV

Search for vector-like B→bZ(dilepton)

5 fb^{-1}

EXO-11-066

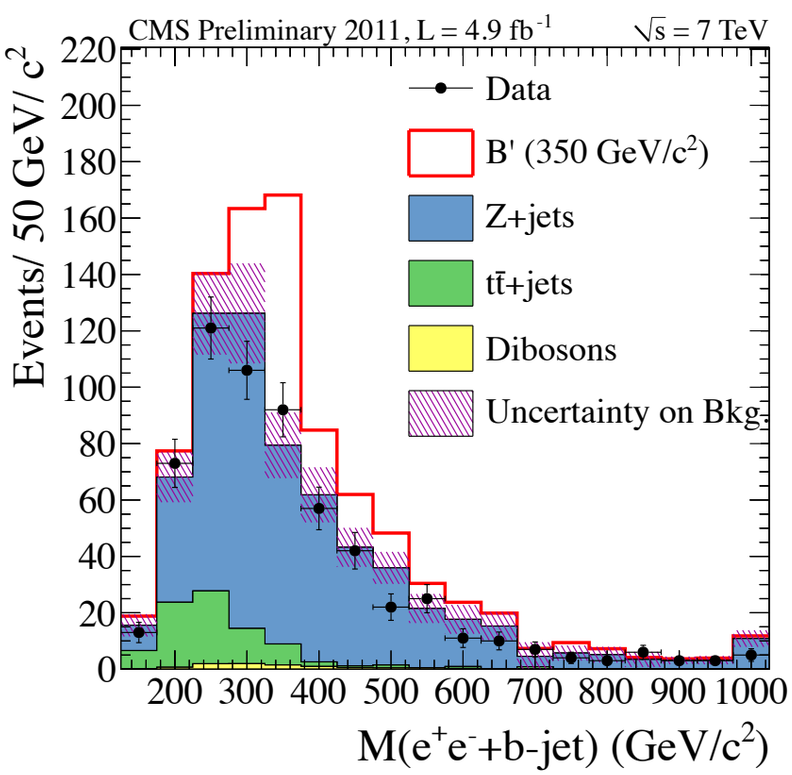
- Clean signature includes
  - ≥ 2 jets, ≥ 1 b-tag (p_T > 65 GeV)
  - Z Cand: (60 < m_{ll} <120) GeV, p_T > 95 GeV

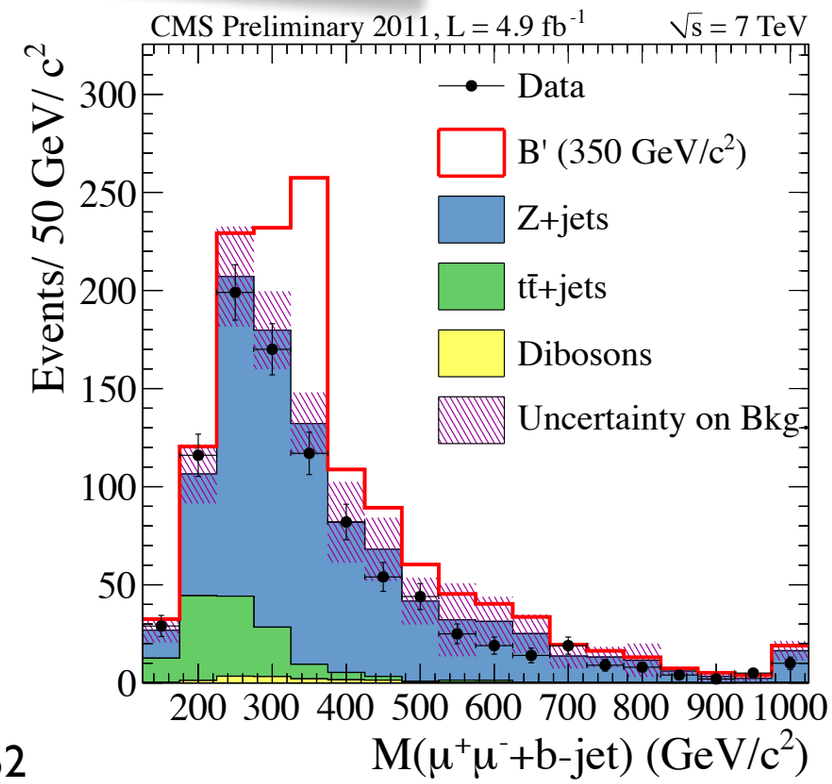


$B\bar{B} \rightarrow bZ\bar{b}Z$

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)

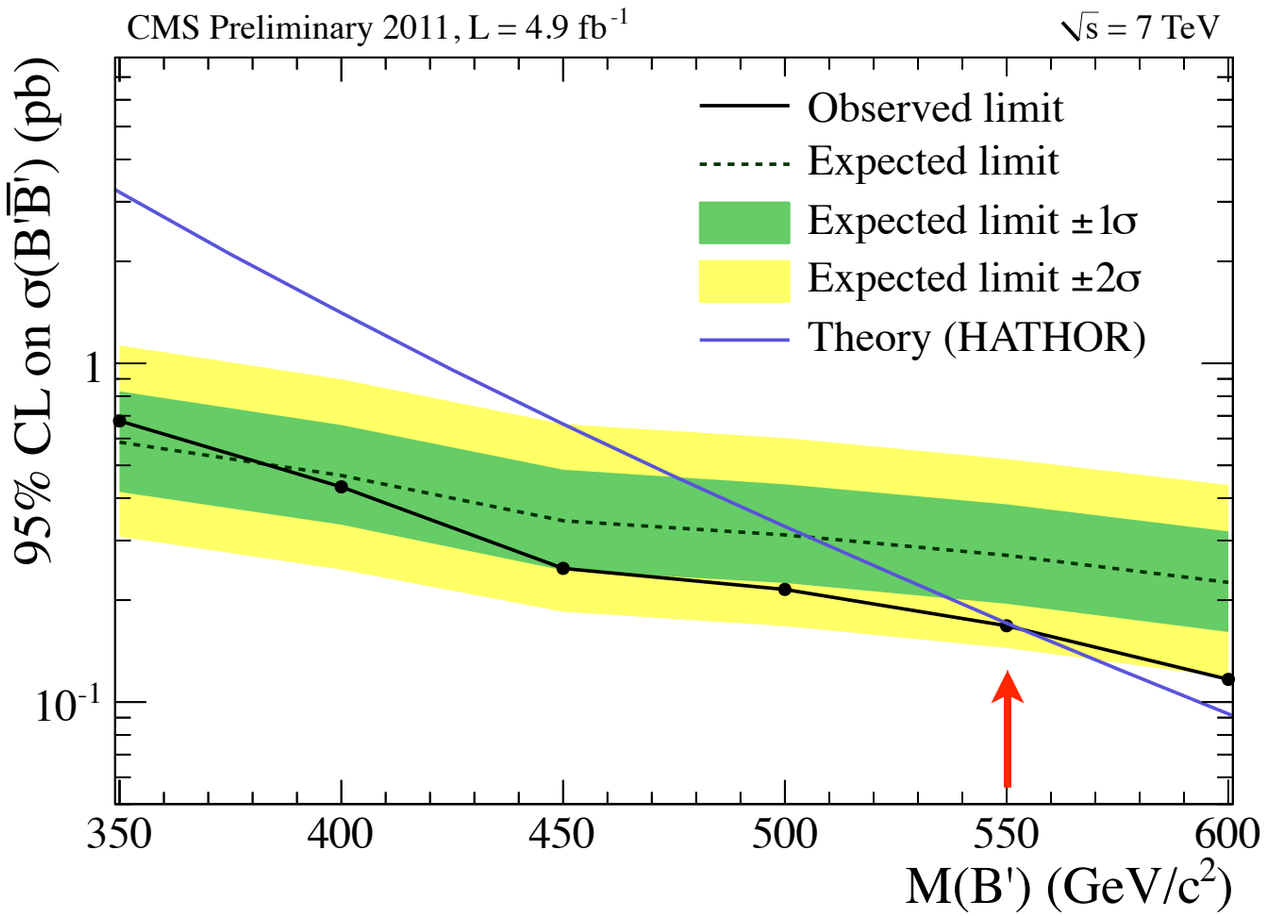
5 fb^{-1}

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 excludes a B´quark with a mass < 550 GeV