“Search for Large Extra Dimensions, Leptoquarks and Heavy Quarks at CMS”

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Outline

- ✦ Brief introduction and search for large extra dimensions (LED) at CMS:
  - ✤ Di-photon, di-electron and di-muon production
  - ✤ Photon+MET and jet+MET final states
- ✦ Introduction and searches for leptoquarks
- ✦ Heavy quark searches:
  - ✤ Di, tri-lepton and lepton+jet channel
  - ✤ t'/b' inclusive searches and
  - ✤ vector-like quark production
- ✦ Summary and future prospects

Results in this talk are also available as public results of CMS at the following link:

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

Large Extra Dimension(LED)

- ADD model for large extra dimenions proposed by Arkani-Hamed, Dimopolous and Dvali in 1990s [Phys. Lett. B 429(1998) 263]

- Large extra dimensions can explains the large difference between the Plank and electroweak scale, the so-called *hierarchy problem*

- Gravity could propagate in these extra dimensions while SM particles in 4D space-time

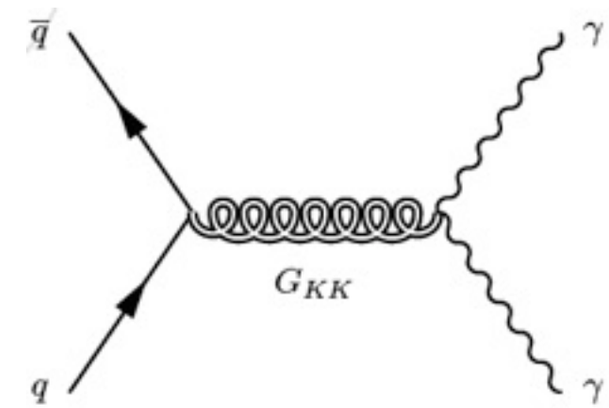
- Introduce a new scale M_D: $$M_{Pl}^2 = M_D^{n+2} R^n$$

- At $M_D \sim M_W$, the observed large value of M_{Pl} is only a consequence of large R and it depends on n extra dimensions

Di-photon Search :LED

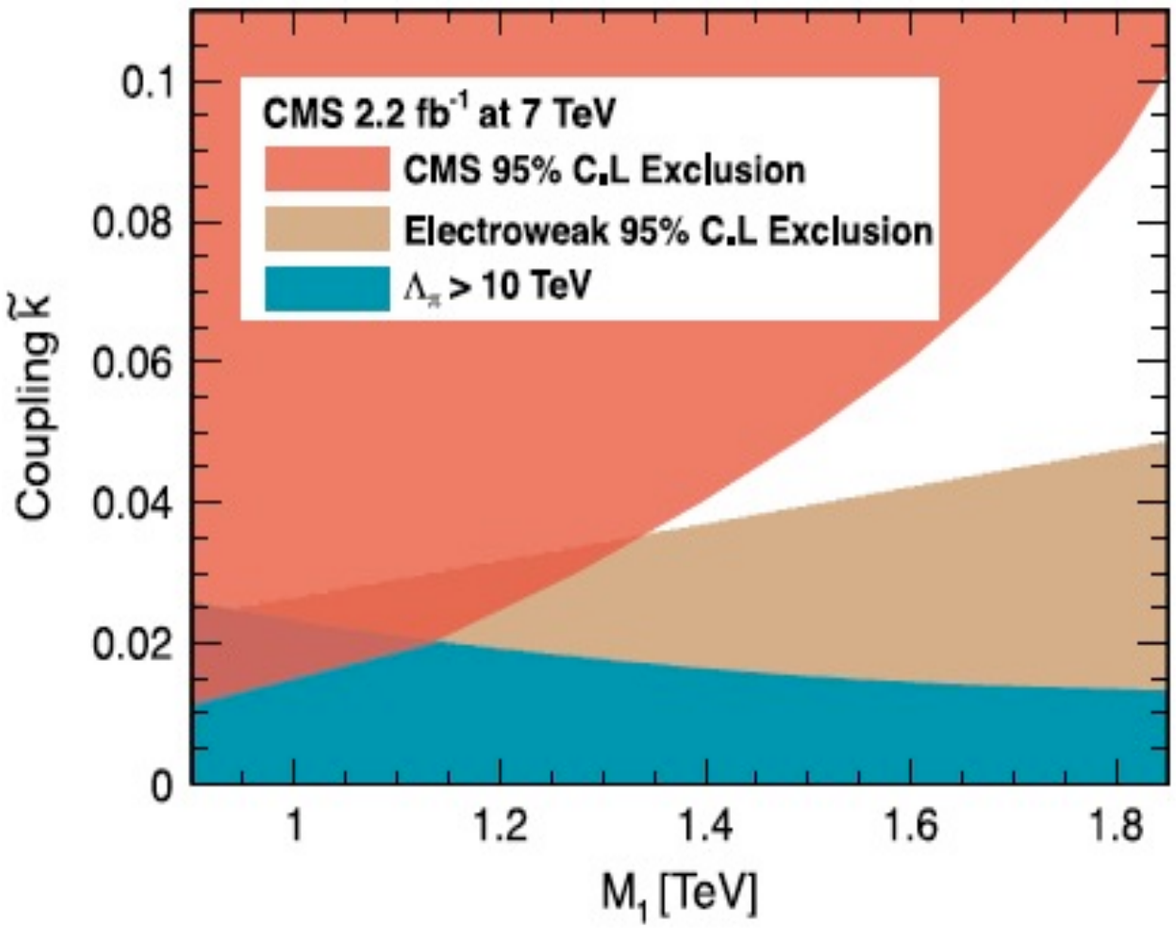
CMS Search in 2.2fb $^{-1}$

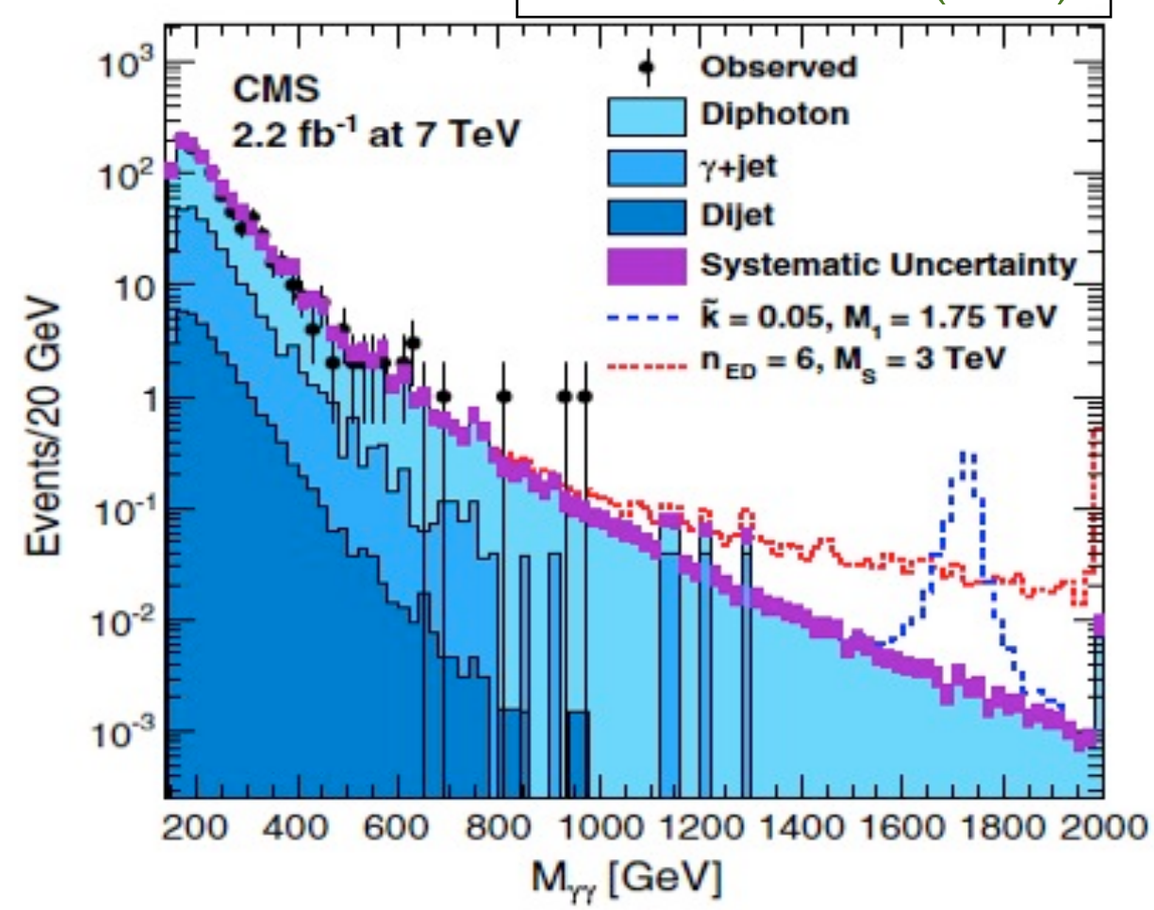
- The visible signal is two high P_T isolated photons with modest backgrounds
  - Look for excess of events in diphoton invariant mass for ADD



- **ADD Limits: M_s > 2.3-3.8 TeV**

PRL 108, 111801(2012)

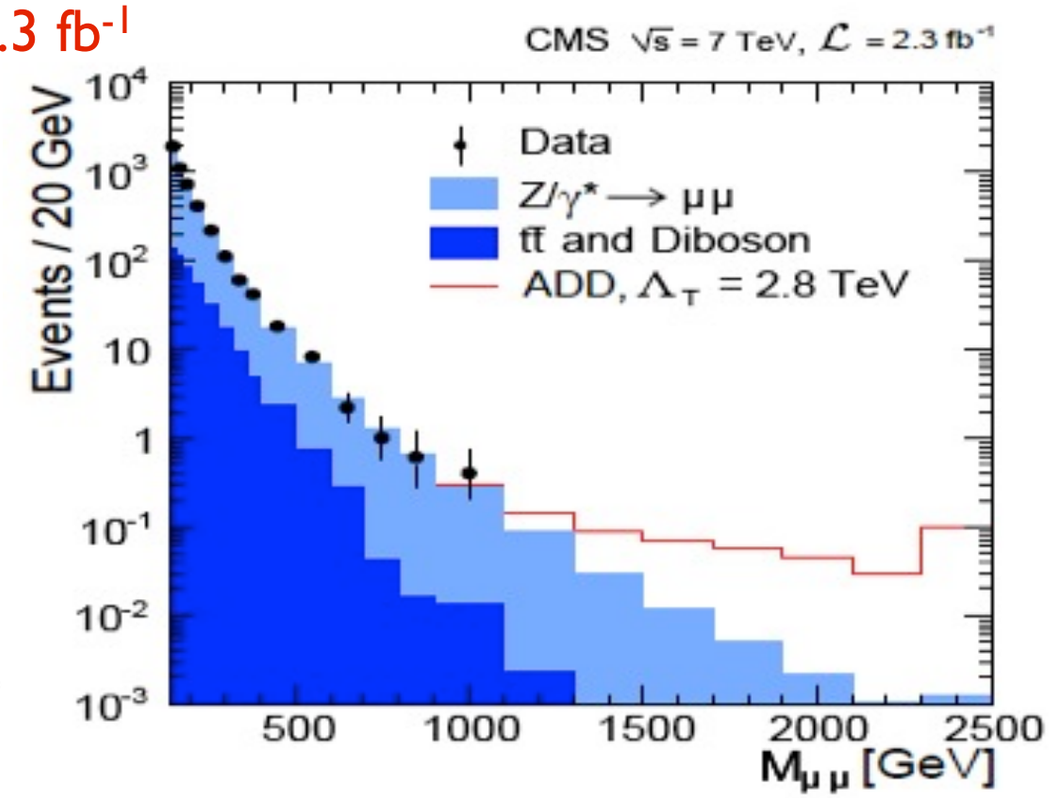


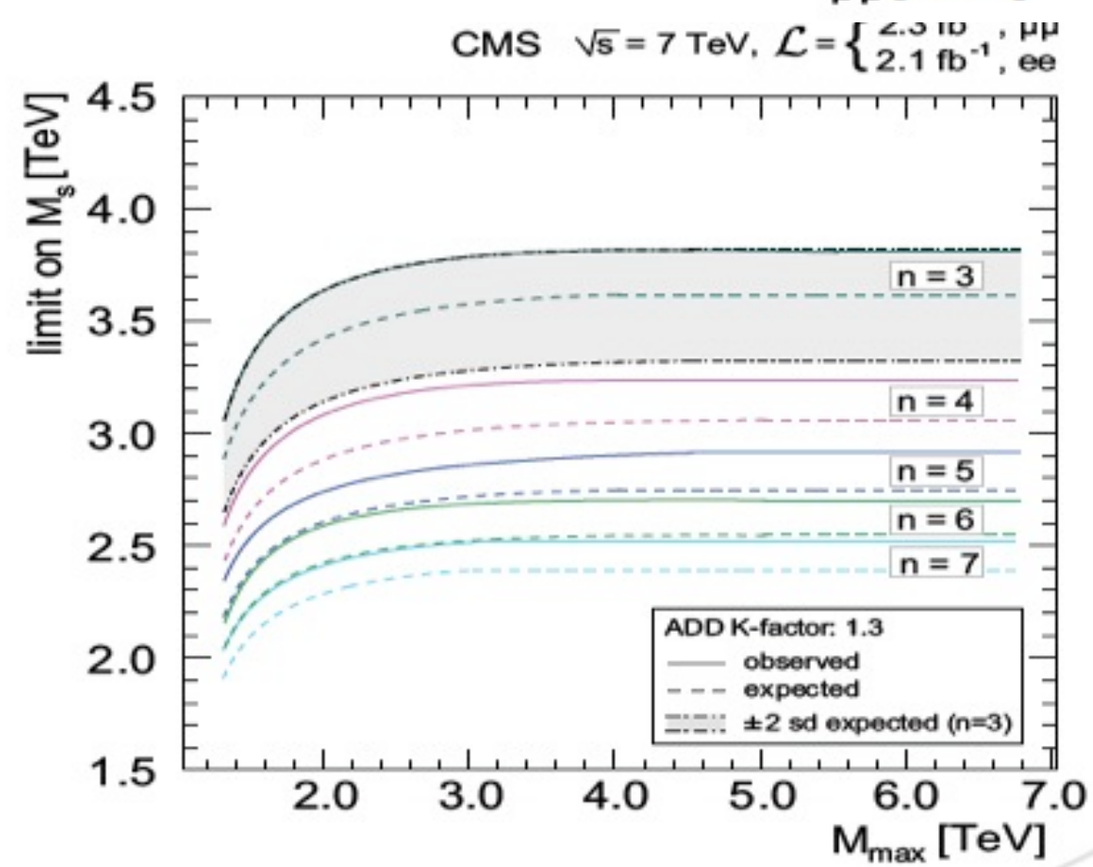


Di-lepton Search :LED

CMS Search in 2.3 fb^{-1}

- ✦ Isolated muons and electrons
  - ✤ for di-electron: Opposite charges and at least one barrel electron
  - ✤ for muon channel no such requirement
- ✦ Non-DY background contributions are small and include: ttbar, γ+jet, W+jet etc..
- ✦ For DY simulated background the correction factors are estimated in the signal region:
  - ✤ Radiation effect, QCD correction(NNLO)
- ✦ Main source of systematic uncertainty :PDF and higher orders for DY



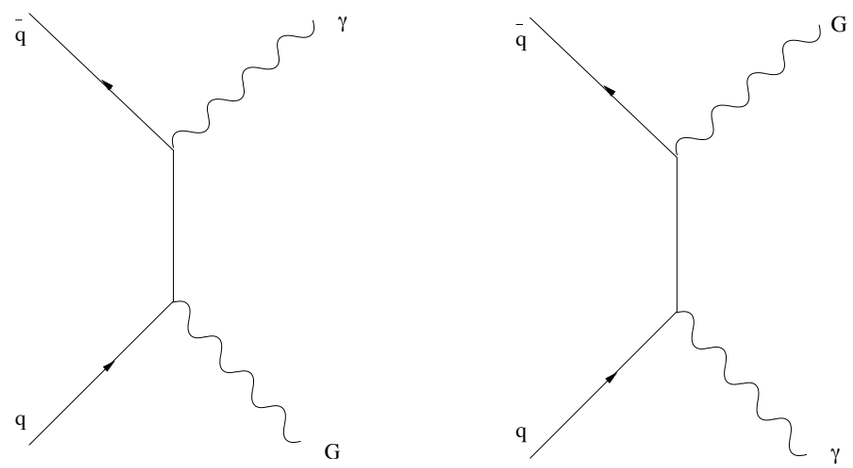


ADD limits: M_s > 2.5-3.8 TeV

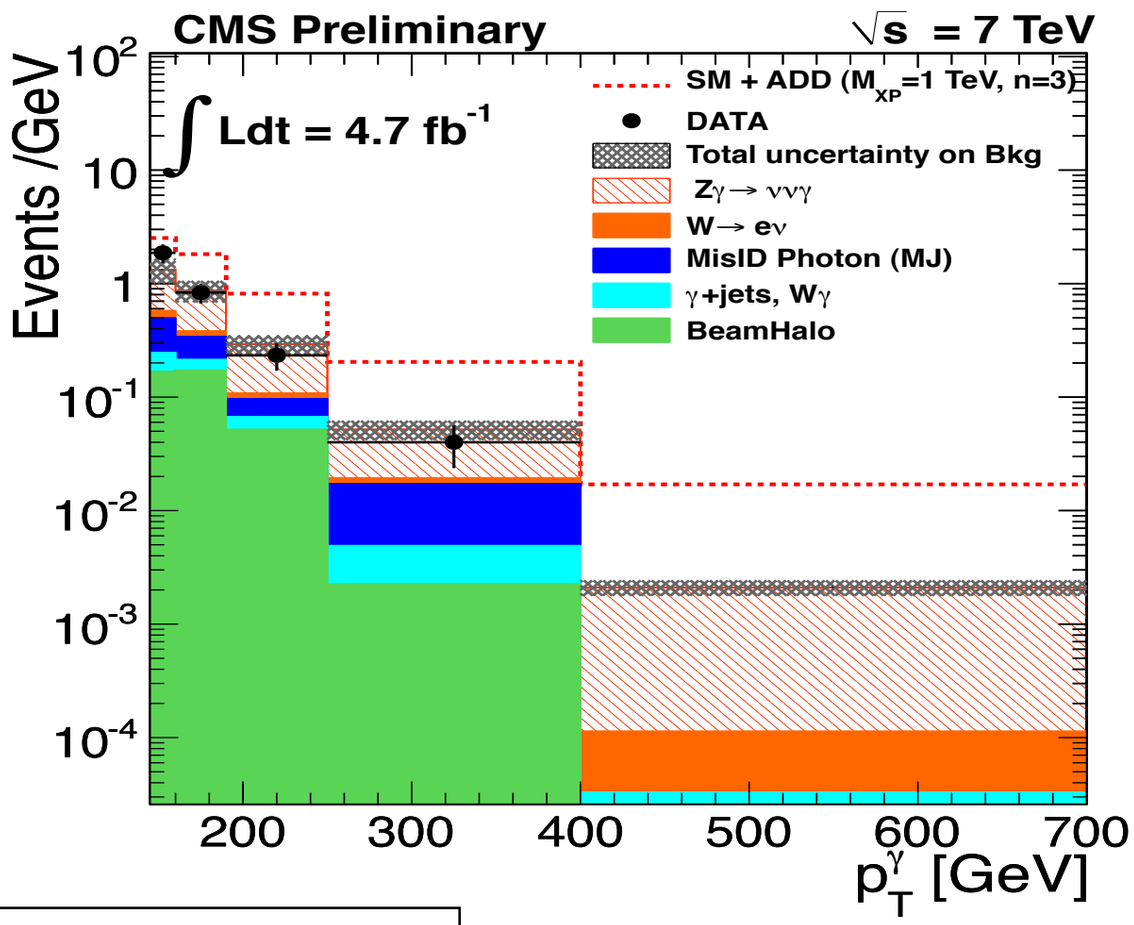
CMS EXO-11-087, Accepted by PLB

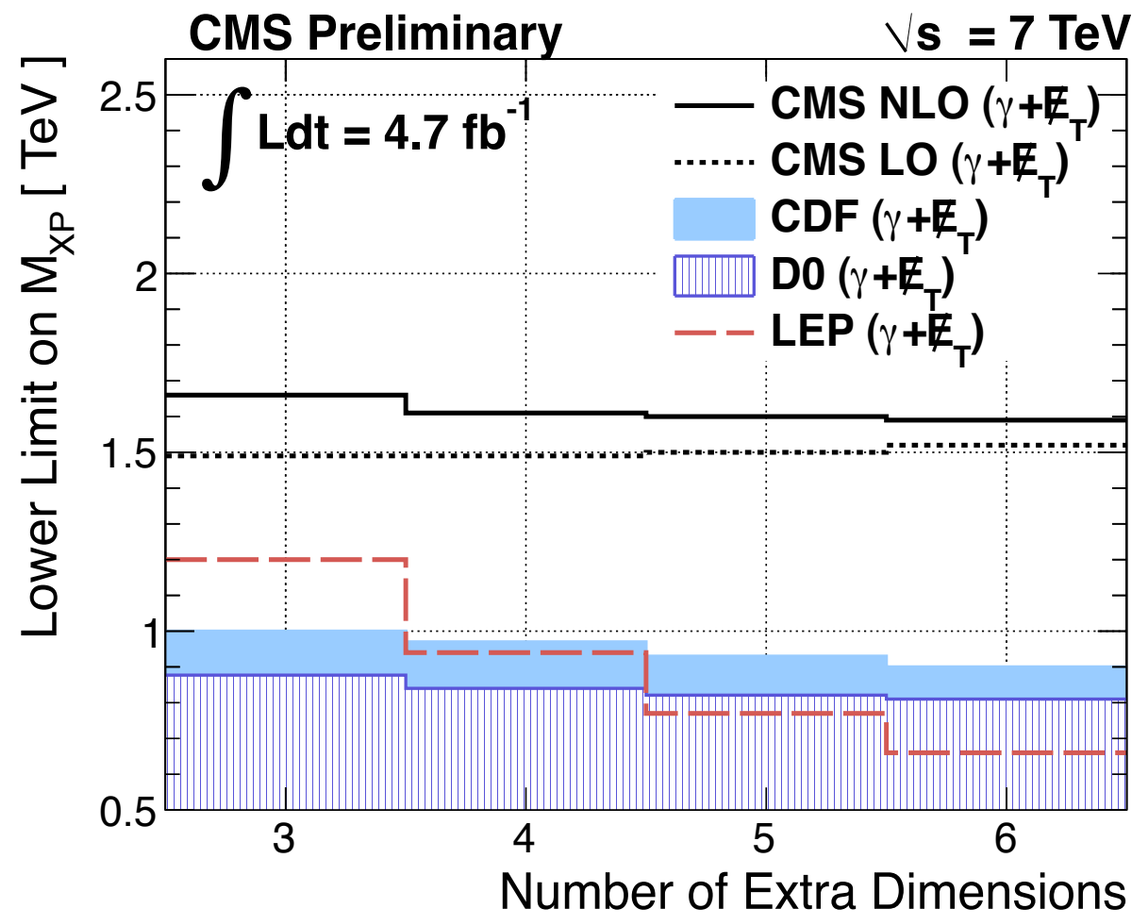
Photon+MET :LED

CMS Search in 4.7 fb $^{-1}$



- Clean signal with P_T high photon and large missing-E_T
  - qqbar→γG
- Event counting to look for an excess in P_T or Missing-E_T
- SM Z(νν)γ production is main background, rest comes from QCD, non-collision sources





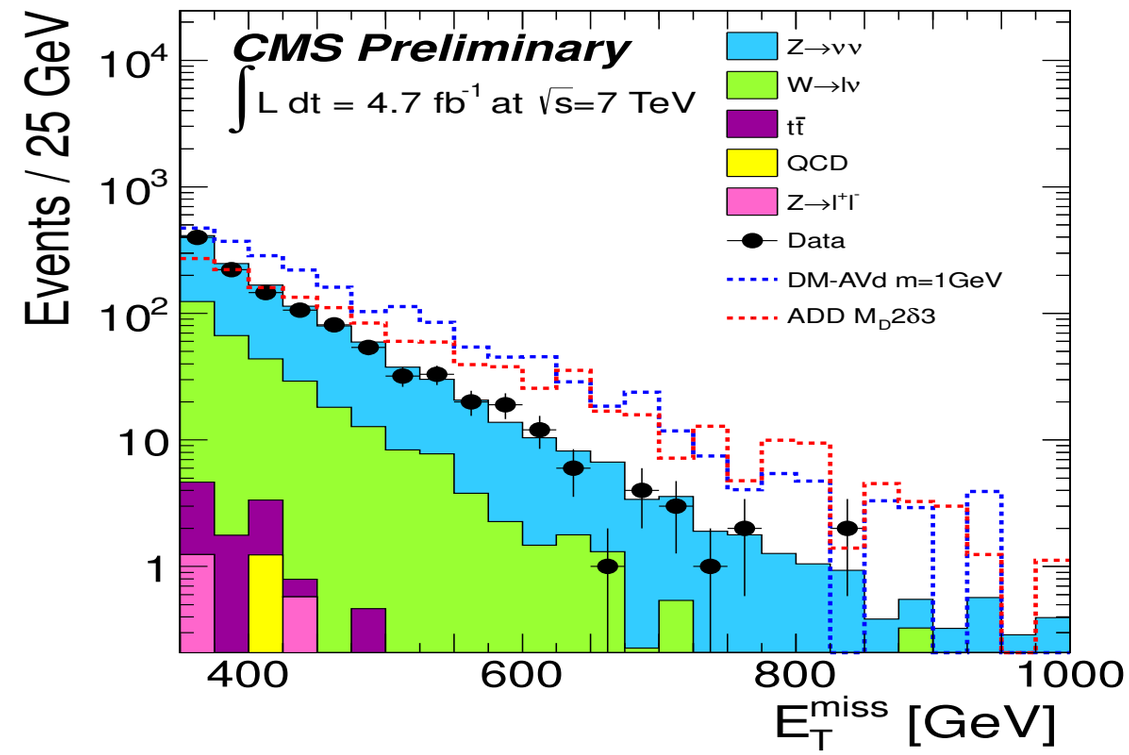
- $M_D \gtrsim$ 1.59-1.66 TeV for $3 \leq n_{ED} \leq 6$

CMS EXO-11-096

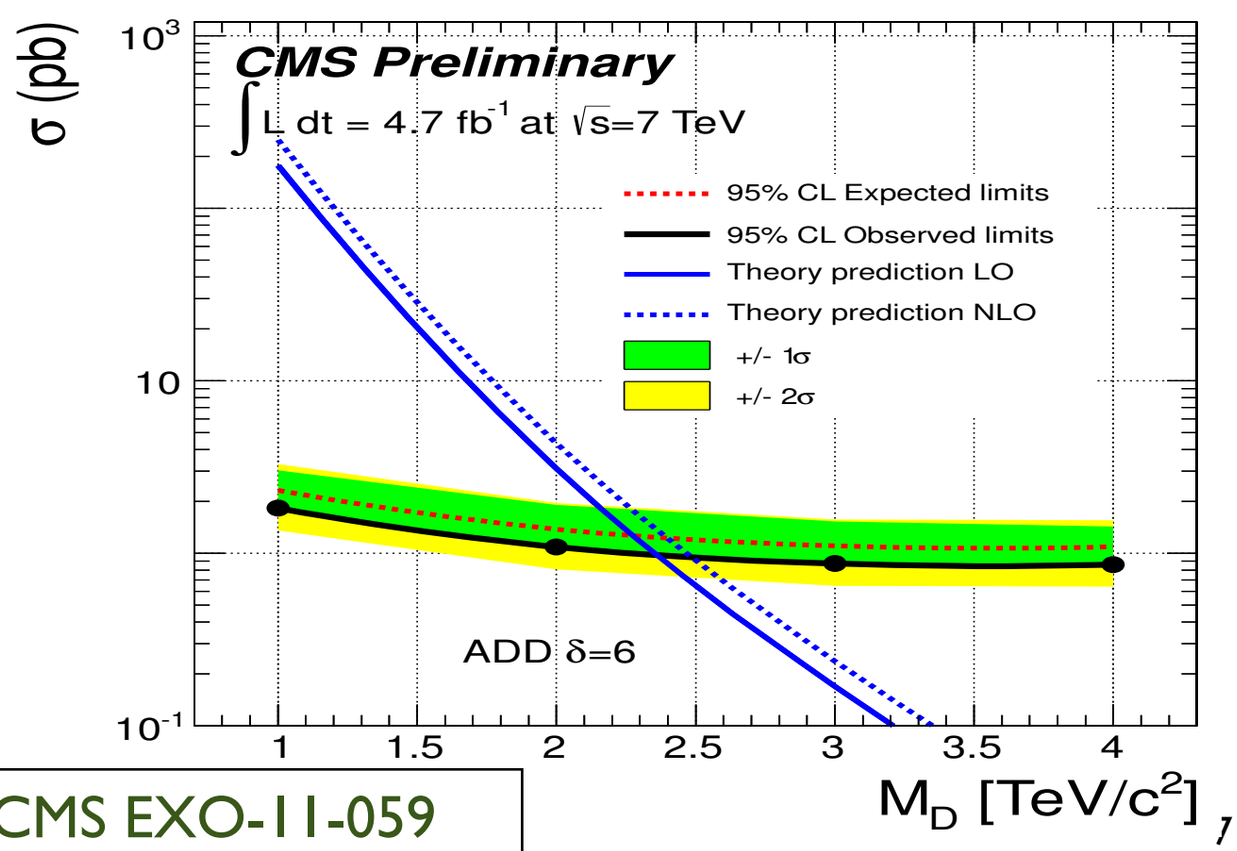
Jet+ MET : LED

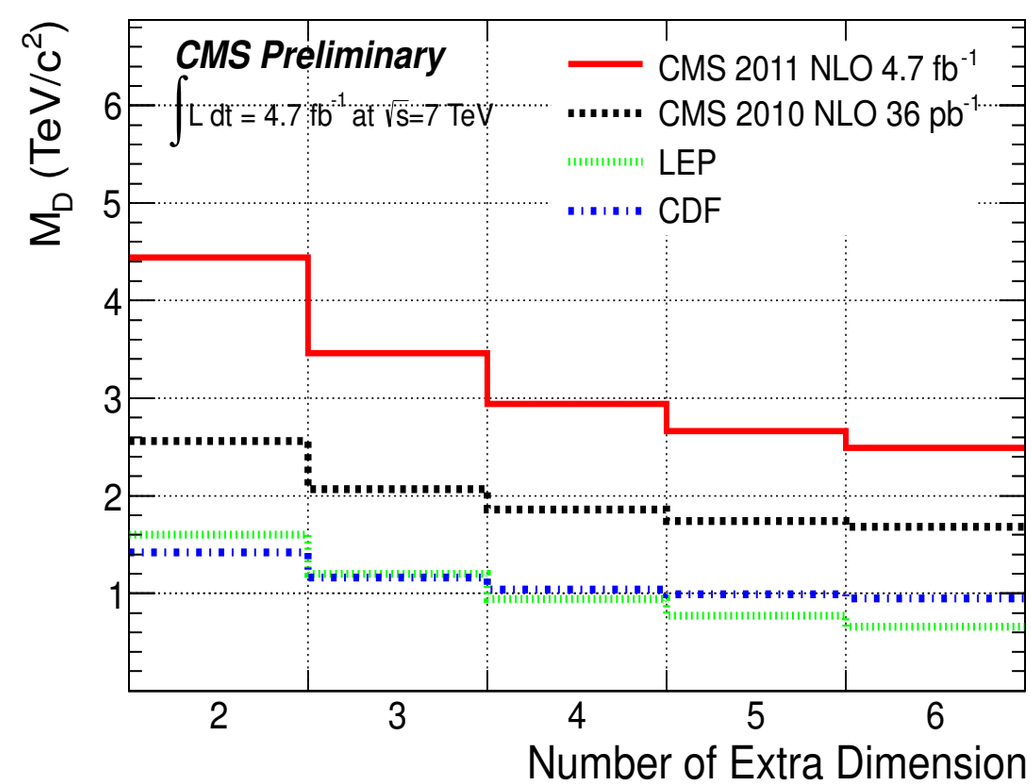
CMS Search in 4.7fb $^{-1}$

- Relatively large production and clean final state with high P_T jet and large missing-E_T
  - qq→gG, qg→qG, gg→Gg
- Main background: Z→νν and W+jets



- **M_D > 2.49 - 4.44 TeV for n_{ED} = 2-6**



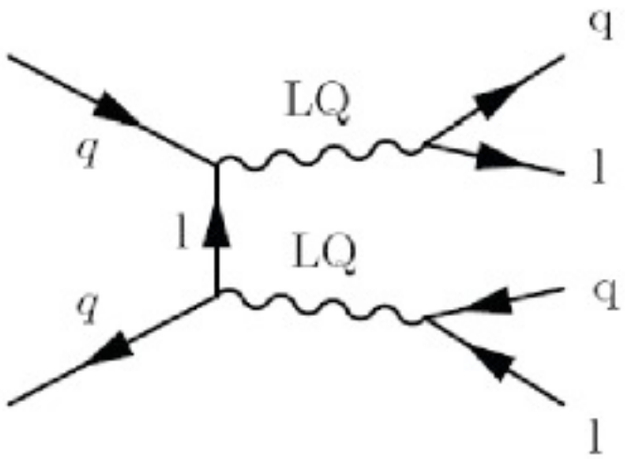


CMS EXO-11-059

Leptoquark Searches at CMS

- Possibility of a fundamental relationship between quarks and leptons through leptoquarks
  - they are colored and have fractional charge
  - couples to quarks and leptons with coupling λ
  - branching fractions are denoted as: $\beta(lq)$ and $1-\beta\ (\nu q)$

- **CMS searched for all 3 generation of leptoquarks with following final states:**
  - *llqq* (β =1) where $l = e, \mu$
  - *lvqq* (β =0.5)
  - *bbvv*

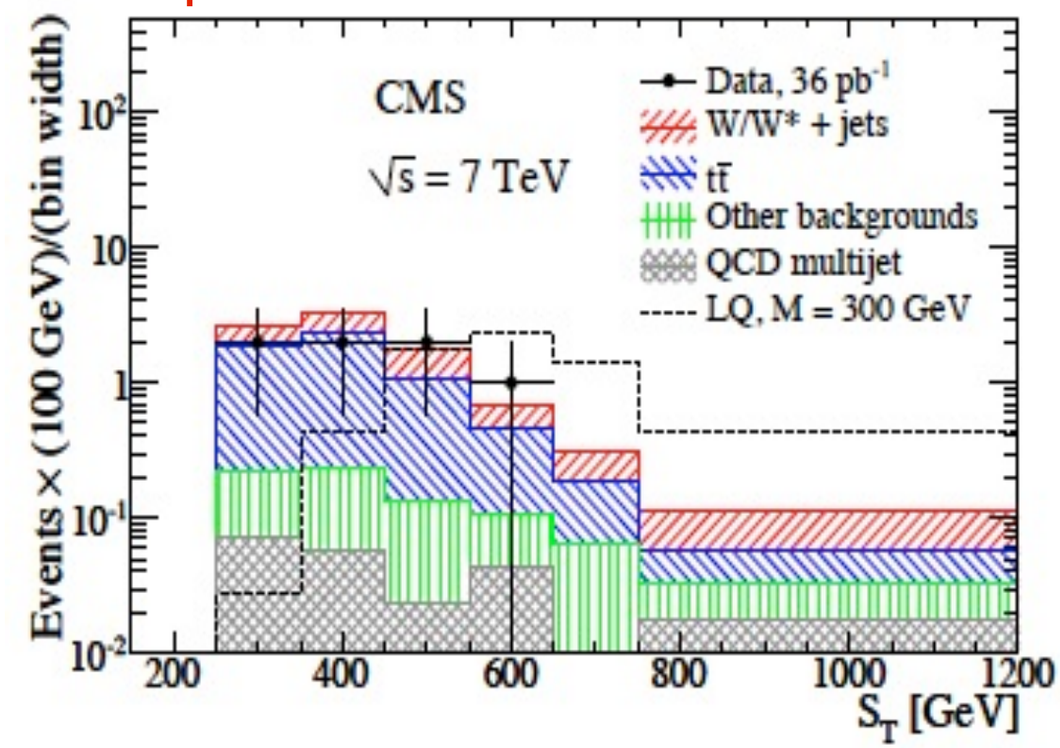


- **Limits are set on mass of leptoquarks (M_{LQ})**

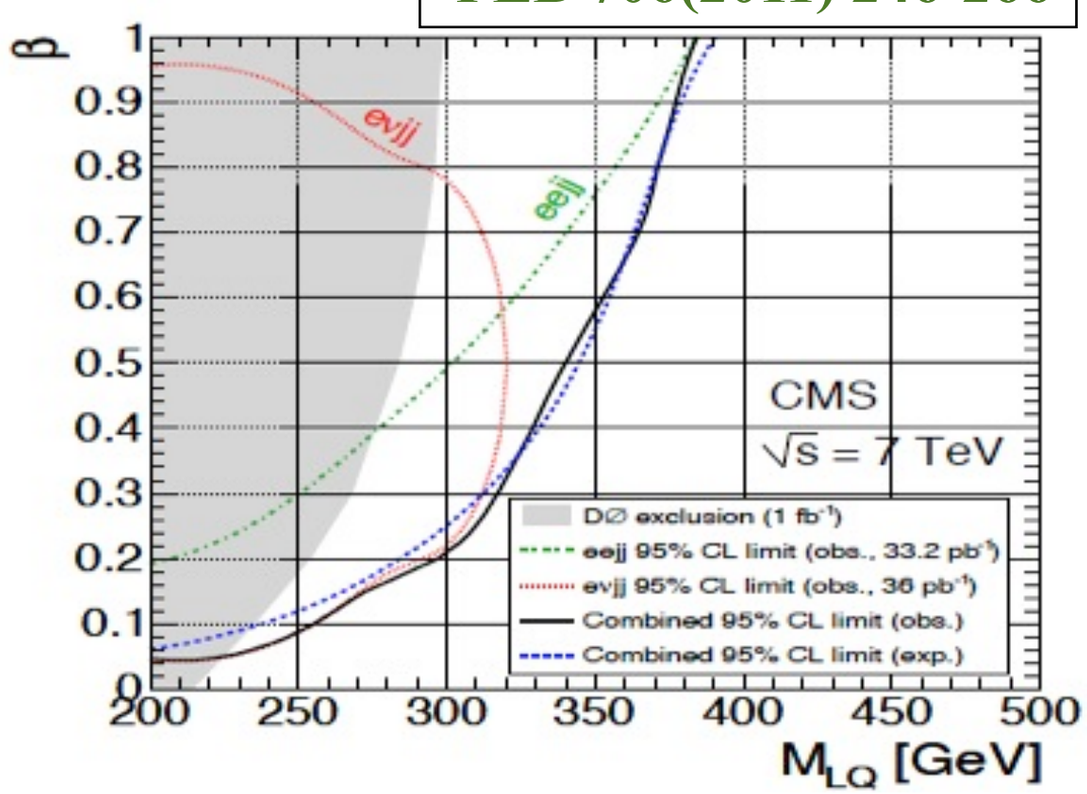
1st Generation Scalar Leptoquarks

CMS Search in 36 pb $^{-1}$

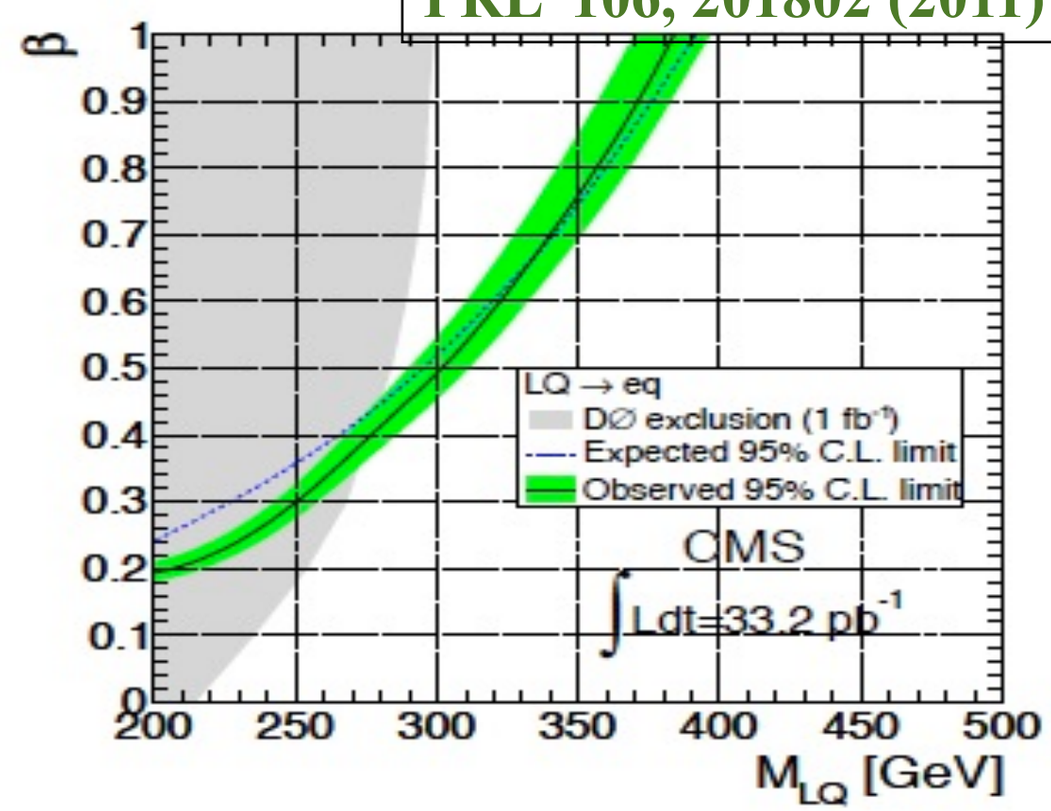
- ✦ Isolated electron + missing-E_T
- ✦ Main bkg: ttbar, W+jets (for evqq)
  ttbar, Z+jets (for *eeqq*)
- ✦ $S_T = P_T(l_1) + P_T(l_2) + P_T(j_1) + P_T(j_2)$
- ★ **Limits : M_{LQ} > 339 GeV(384 GeV) for *evqq* (*eeqq*)**



PLB 706(2011) 246-266



PRL 106, 201802 (2011)



2nd Generation Scalar Leptoquarks

CMS Search in 2.0 fb $^{-1}$

Final state: $\mu\mu qq$ and $\mu\nu qq$

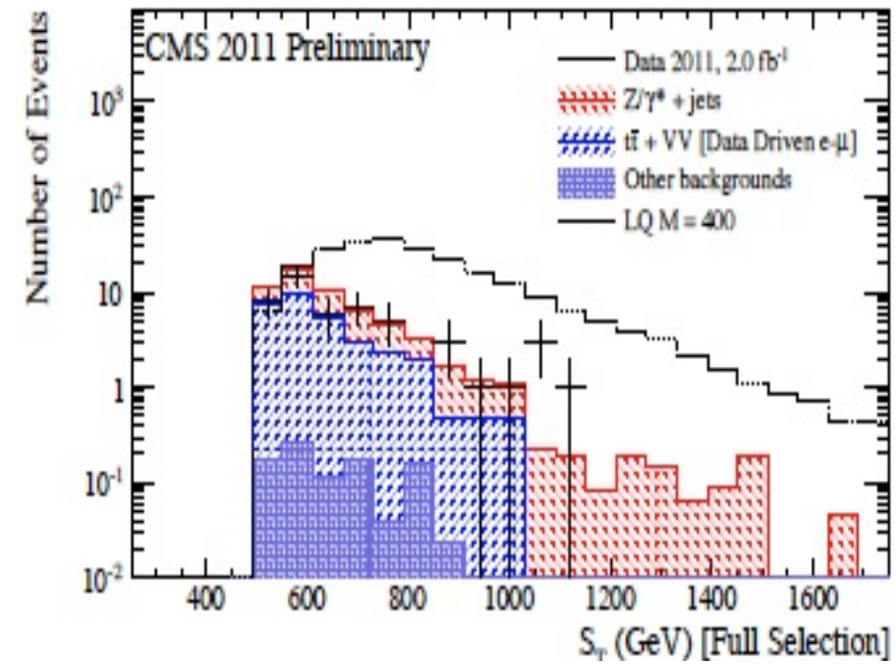
- $P_T(\mu)$> 40 GeV, P_T(jets)> 30 GeV

In addition for $\mu\nu qq$ channel:

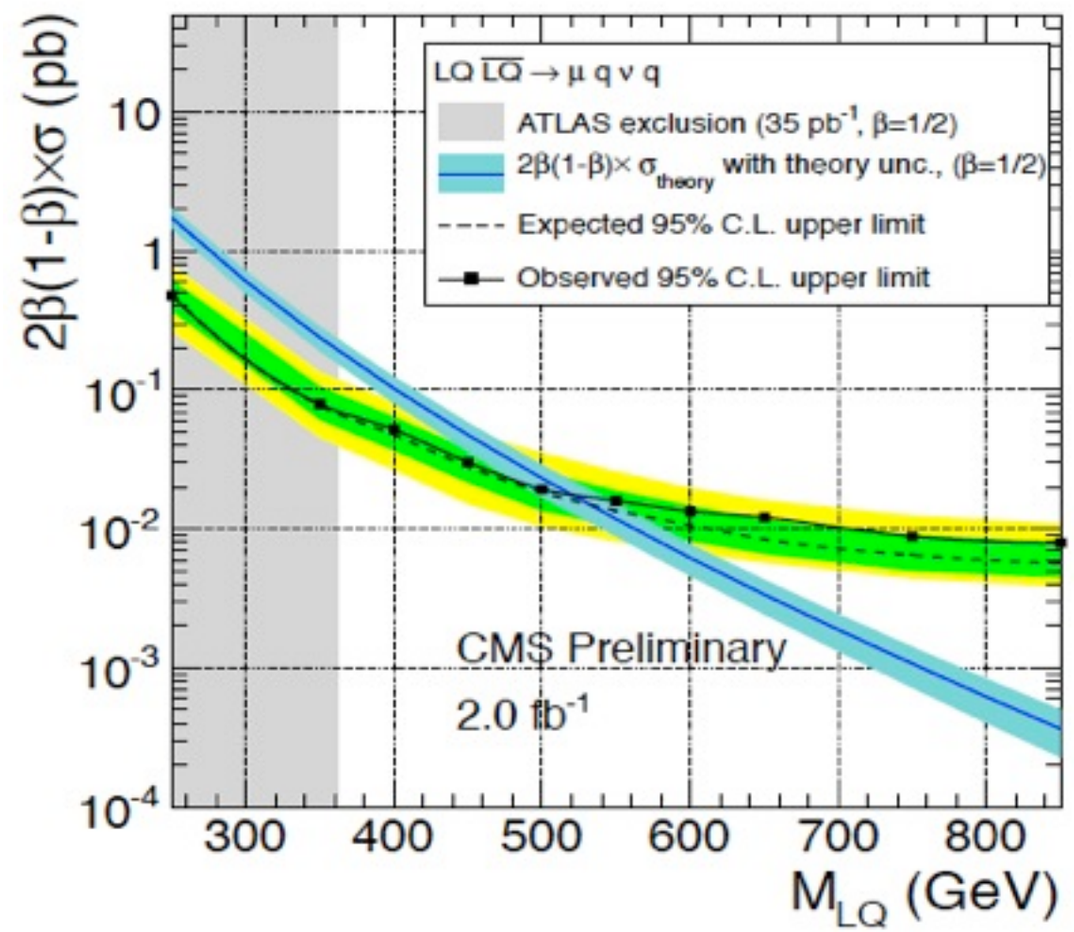
- Veto on 2nd muon and 3rd jet and electron
- missing-E_T > 45 GeV

- The dominant backgrounds are estimated from data

- Multi-jet QCD background is negligible in both final states



- **Limits:**
  - **M_{LQ} > 632 GeV for β=1.0**
  - **M_{LQ} > 523 GeV for β=0.5**



CMS EXO-11-028

3rd Generation Scalar Leptoquarks

Final state: bbνν

CMS Search in 1.8 fb $^{-1}$

- Used *razor* variable $R \equiv \frac{M_T^R}{M_R}$

$$M_R \equiv \sqrt{(E_{j_1} + E_{j_2})^2 - (p_z^{j_1} + p_z^{j_2})^2}$$

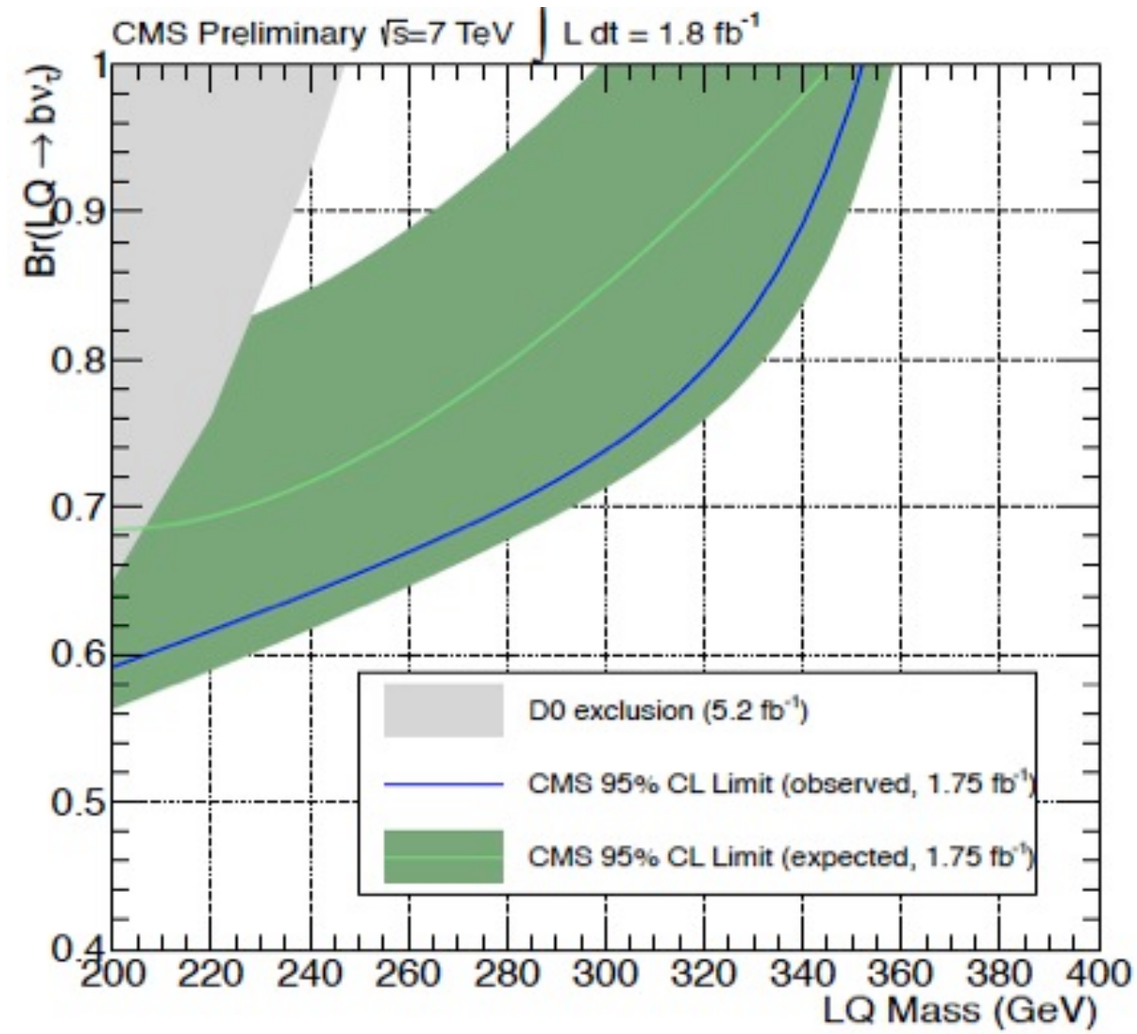
$$M_T^R \equiv \sqrt{\frac{\not{E}_T(p_T^{j1} + p_T^{j2}) - \vec{\not{E}}_T \cdot (\vec{p}_T^{j1} + \vec{p}_T^{j2})}{2}}$$

  - Designed to search for a pair of "heavy particles"

- 2 b-tagged jets

- Main Bkg: 1) Heavy Flavor (HF) Multi-jet
  2) ttbar+jets and W/Z+HF jets

- Systematics: background shape and b-tagging efficiency



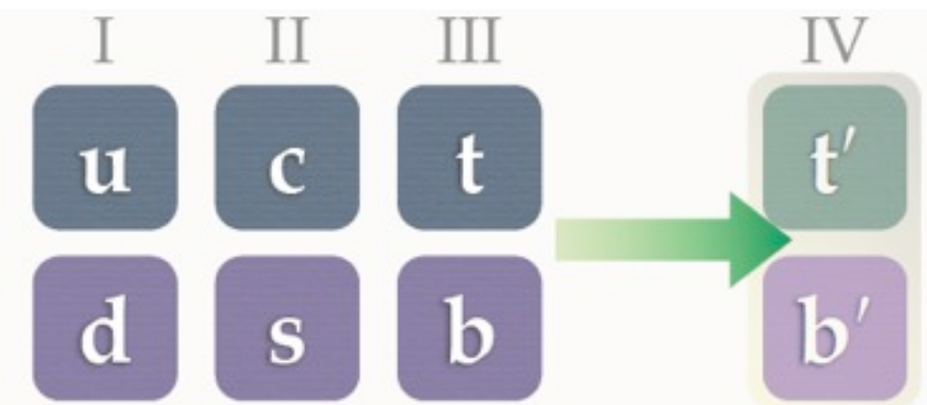
- **Limit: M_{LQ} >350 @ 95%CL**

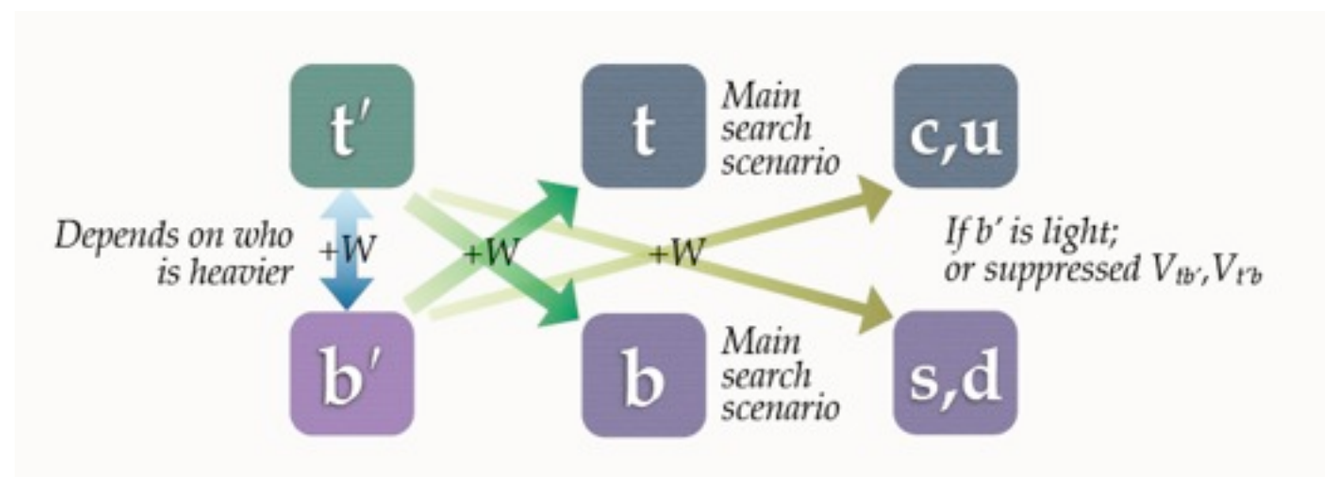
CMS EXO-11-030

Heavy Quarks

- SM Extension?: Adding one more generation of quarks is an obvious extension of SM and is also not fully excluded by electroweak precision data

- Due to heaviness of this new generation of quarks the CP violation can be boosted by large factor and could resolve the matter-antimatter asymmetry in the universe





Decay signatures for direct searches:

- $t' \to bW$, $b' \to tW(bWW)$: complex final state, $b' \to qW$
- With small mass splitting: $|M_{t'} - M_{b'}| < M_W$

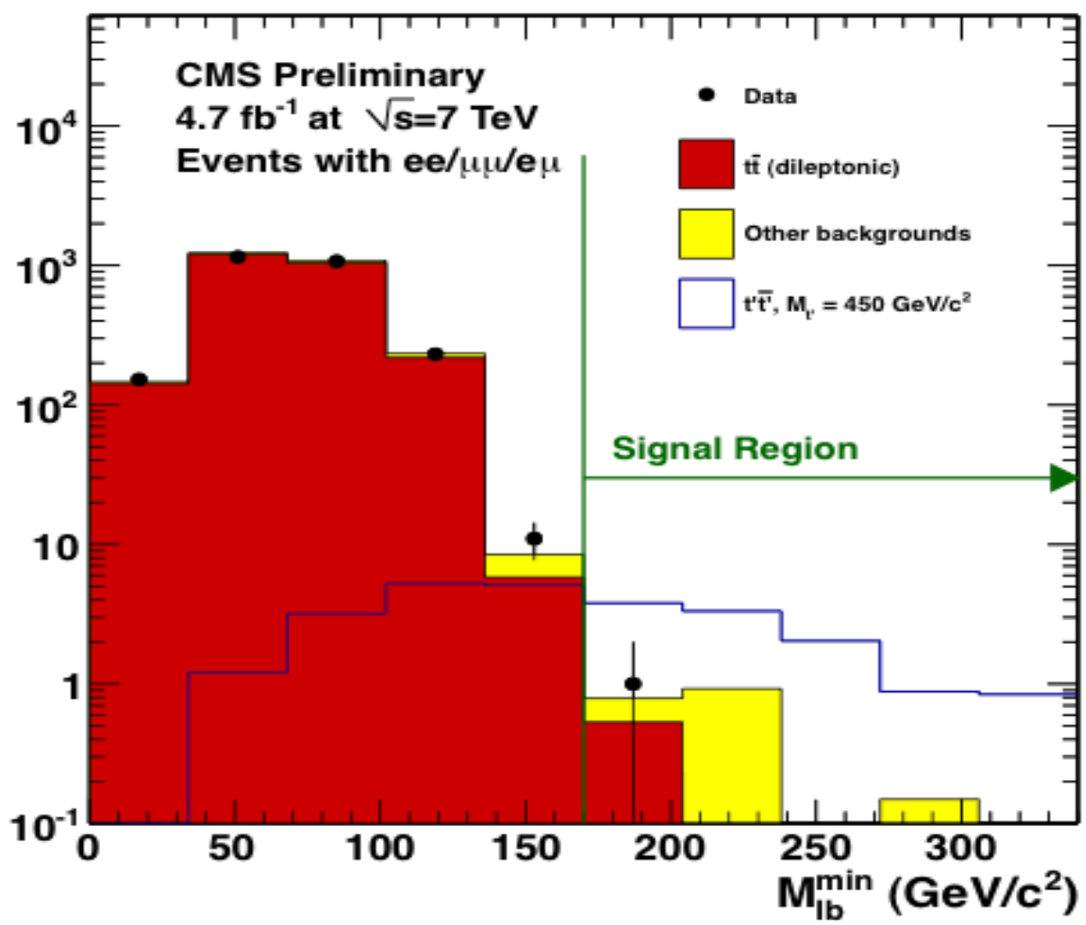
t′ →bW (di-lepton)

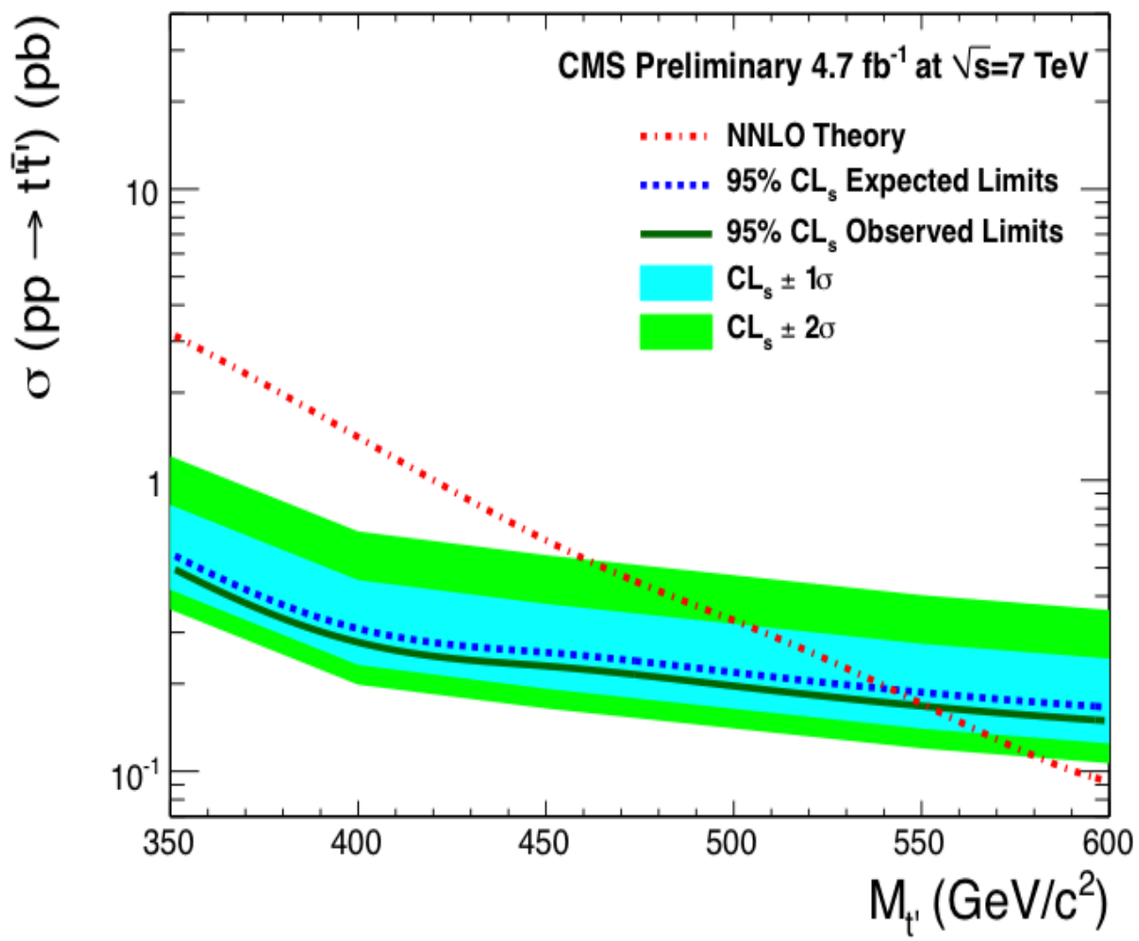
CMS Search in 4.7 fb $^{-1}$

$$t'\bar{t}' \to W^+bW^-\bar{b} \to l^+\nu bl^-\bar{\nu}\bar{b}$$

- Signal: 2 leptons + 2 b-jets + missing-E_T
- Reconstruct "*b-jet* + *lepton*" masses

$M_{t'}$ > 552 GeV @95% CL





CMS EXO-11-050

t′ →bW (leptons+jets)

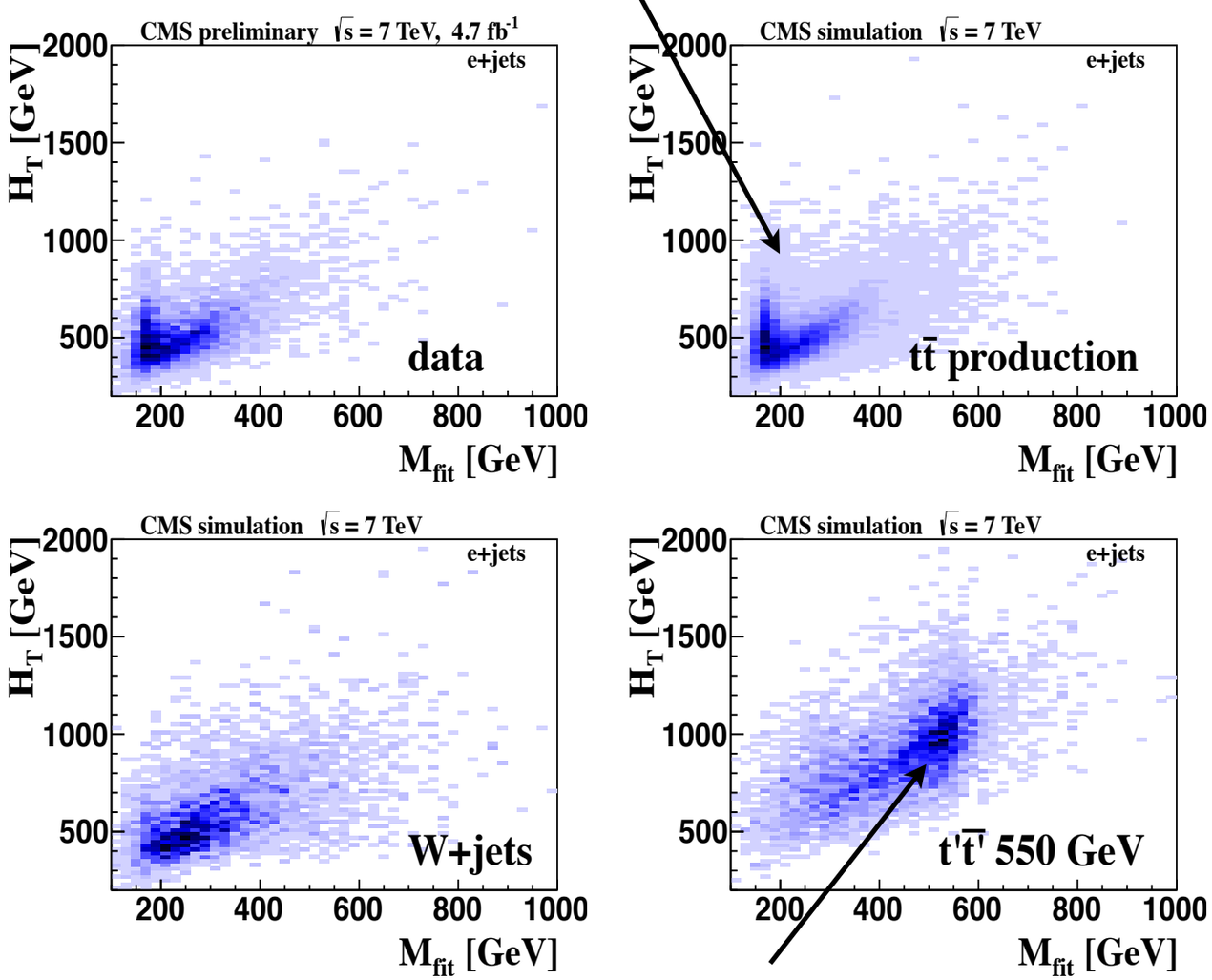
CMS Search in 4.7 fb $^{-1}$

- ✦ Reconstruction of a pair of "*heavy tops*":
  - ✤ 1 lepton + 4 jets + at least 1 b-jet + missing-E_T

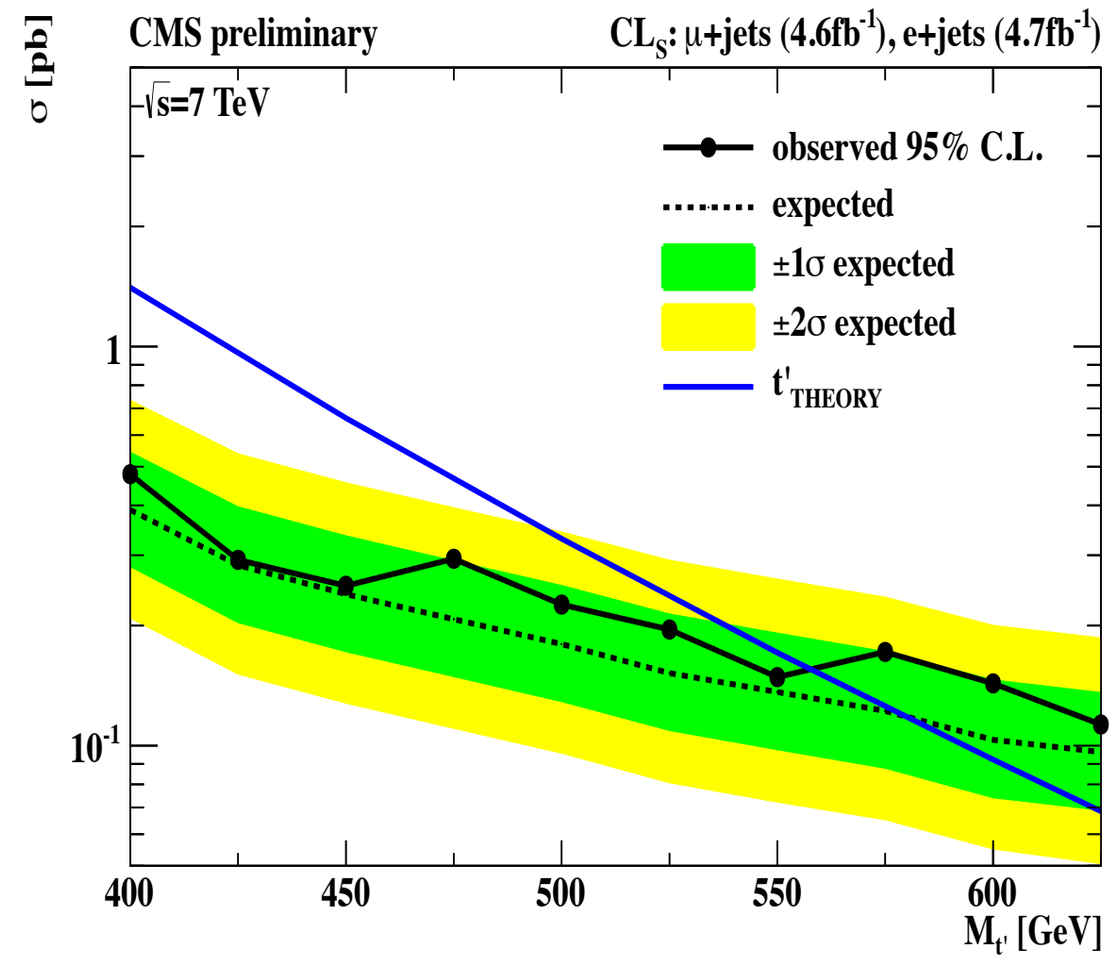
★ **Kinematic fit is applied for mass reconstruction (M_{fit}) and look for H_T and reconstructed mass tail for signal**

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

Top towards lower H_T and M_{fit}

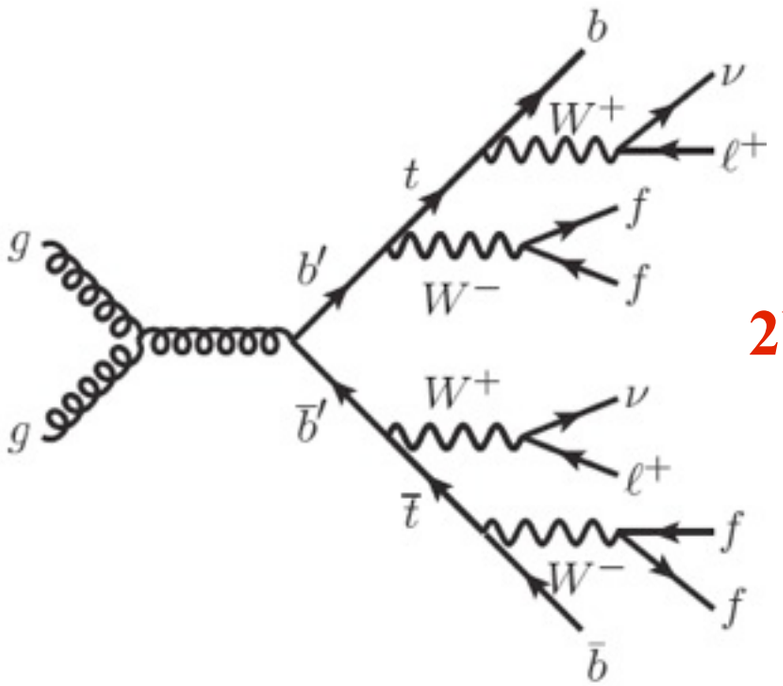


Signal towards higher H_T and M_{fit}



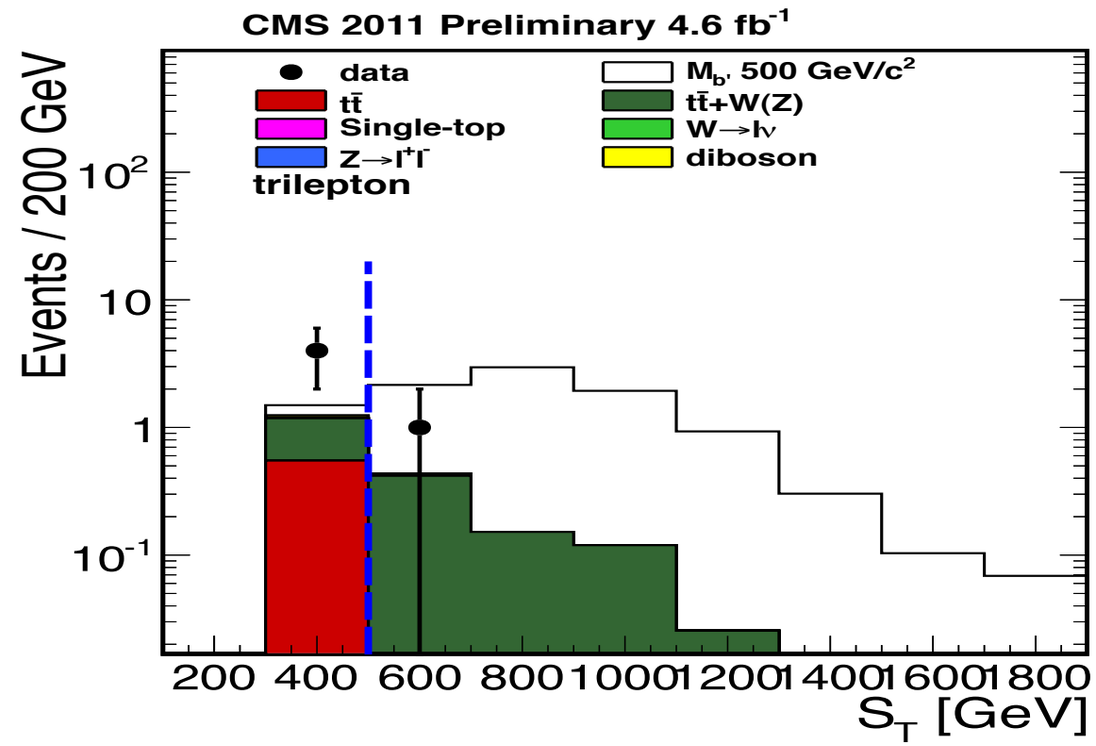
✦ **$M_{t'}$ > 560 GeV @95% CL**

b′ Search (di-lepton, tri-lepton)



2b-jet + 4Ws

CMS Search in 4.6 fb $^{-1}$

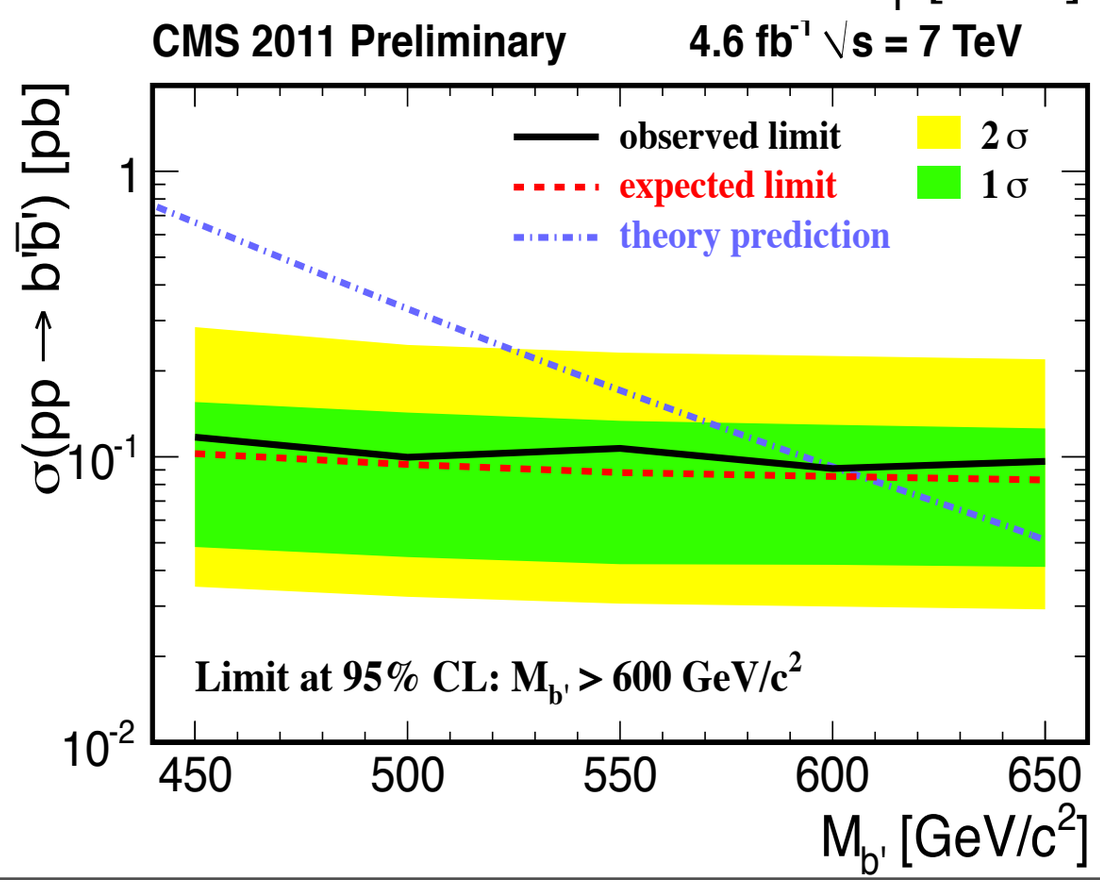


- ✦ 3 leptons + 2jets OR 2 same sign leptons + 4jets
  - ✤ at least 1 b-jet, missing-E_T
- ✦ $S_T > 500$ GeV where,

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

- ✦ Almost no background

$M_{b'}$ > 600 GeV @ 95% CL



CMS EXO-11-036

b′/t′ Inclusive Search(1)

Why not look for b′ and t′ at the same time with a single production?

- For simplicity degenerate masses are assumed and no $t' \leftrightarrow b'$ transition
- A convenient way to express the CKM4 matrix is to express it in terms of free parameter A where $A = |V_{tb}|^2 = |V_{t'b'}|^2$

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

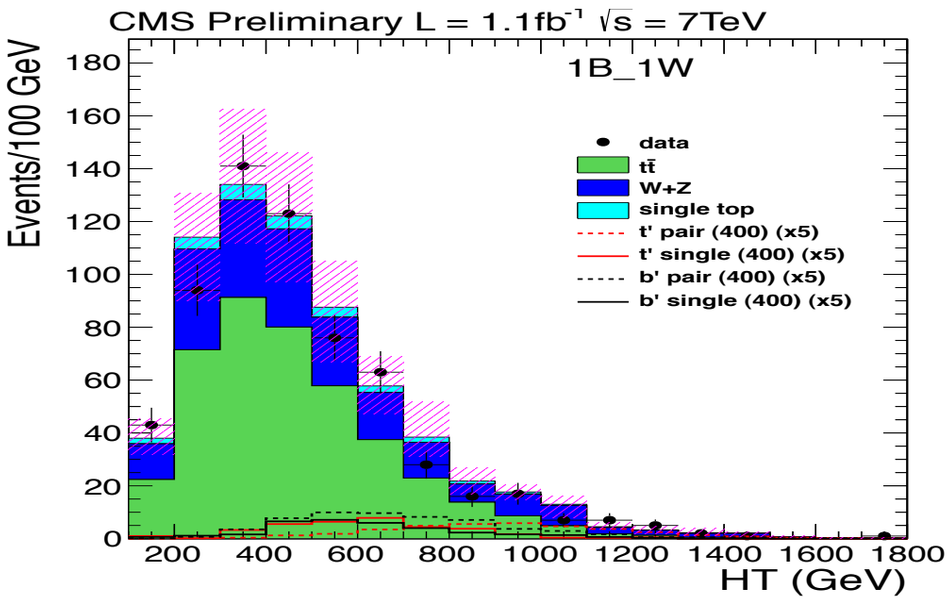
These channels will be possible:

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

- Look for 1 isolated muon ($W \to \mu\nu$) , missing-E_T and at least one jet with P_T(jets) > 30 GeV

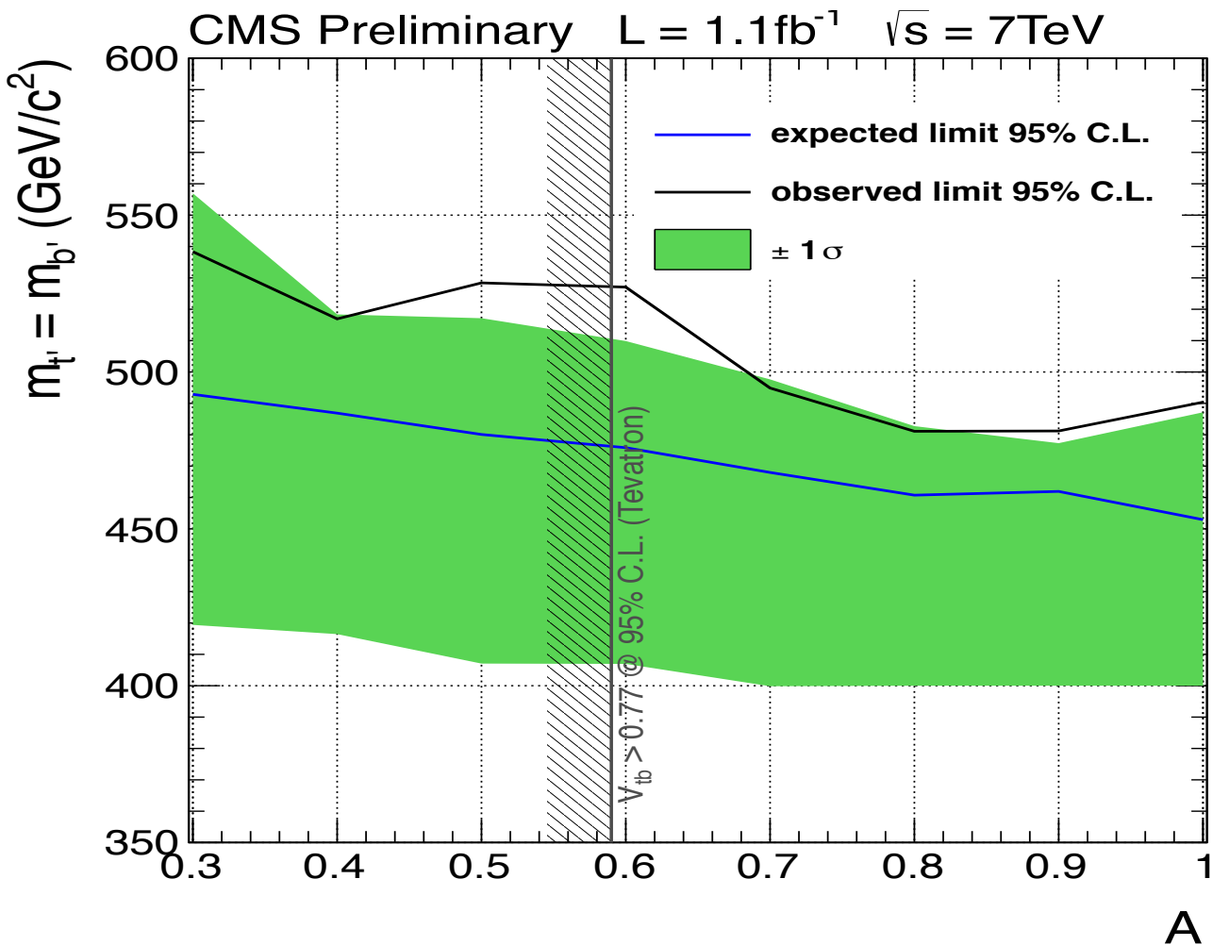
- Classify events by number of b-jets and W multiplicity

b′/t′ Inclusive Search (2)

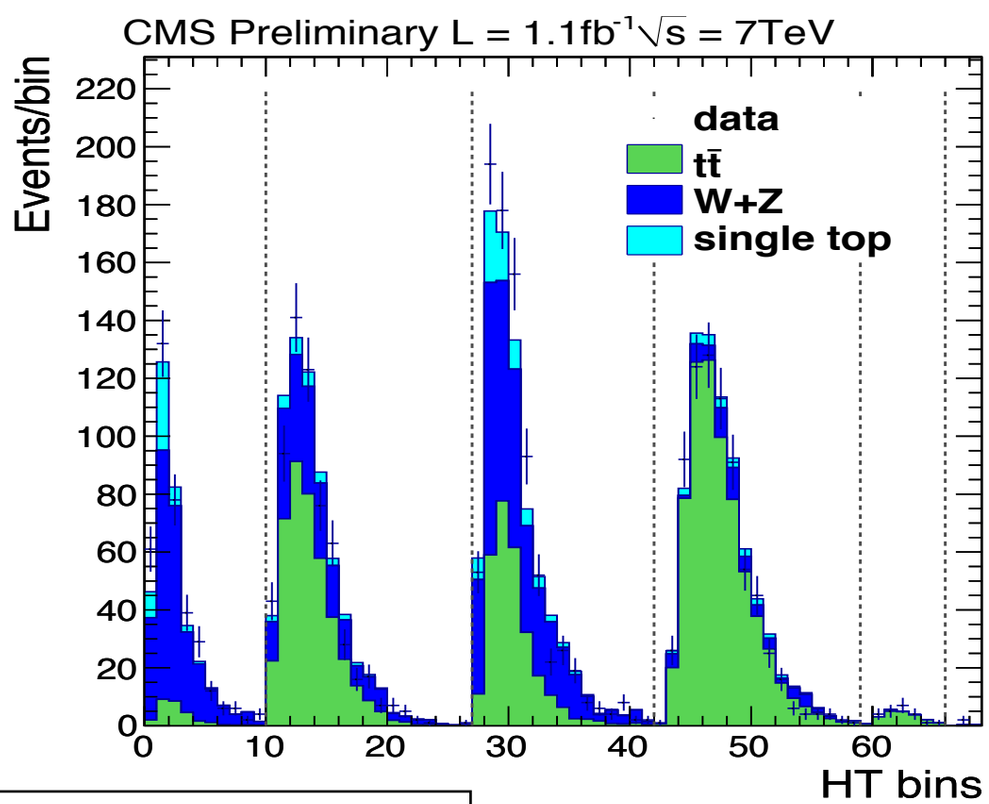


$$H_T = p_T^l + \sum p_T^{jet} + E_T^{miss}$$

Scanning of mass limit as a function of A



Fits are done in binned HT templates

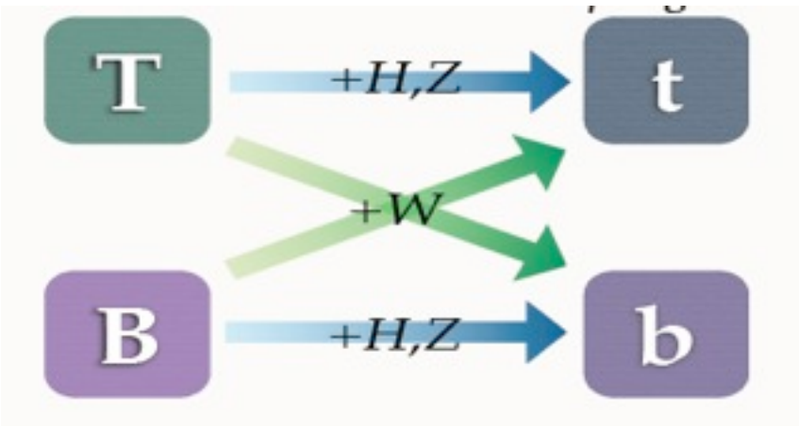


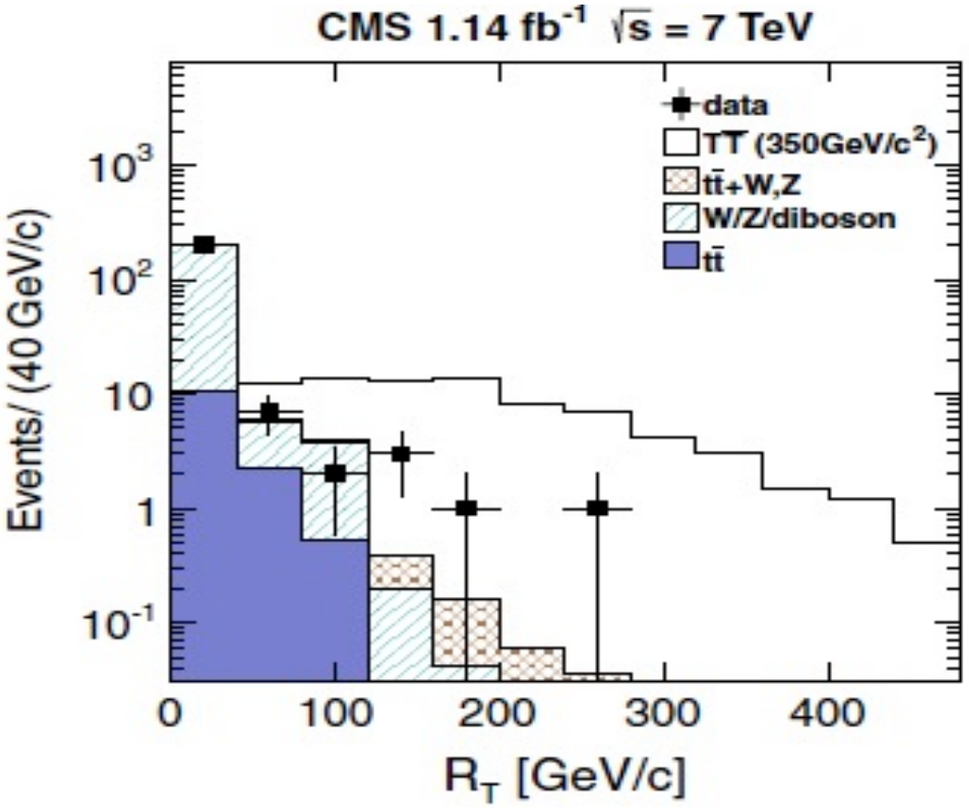
$M_{b'} = M_{t'} >$ 590 GeV @ 95% CL

CMS EXO-11-054

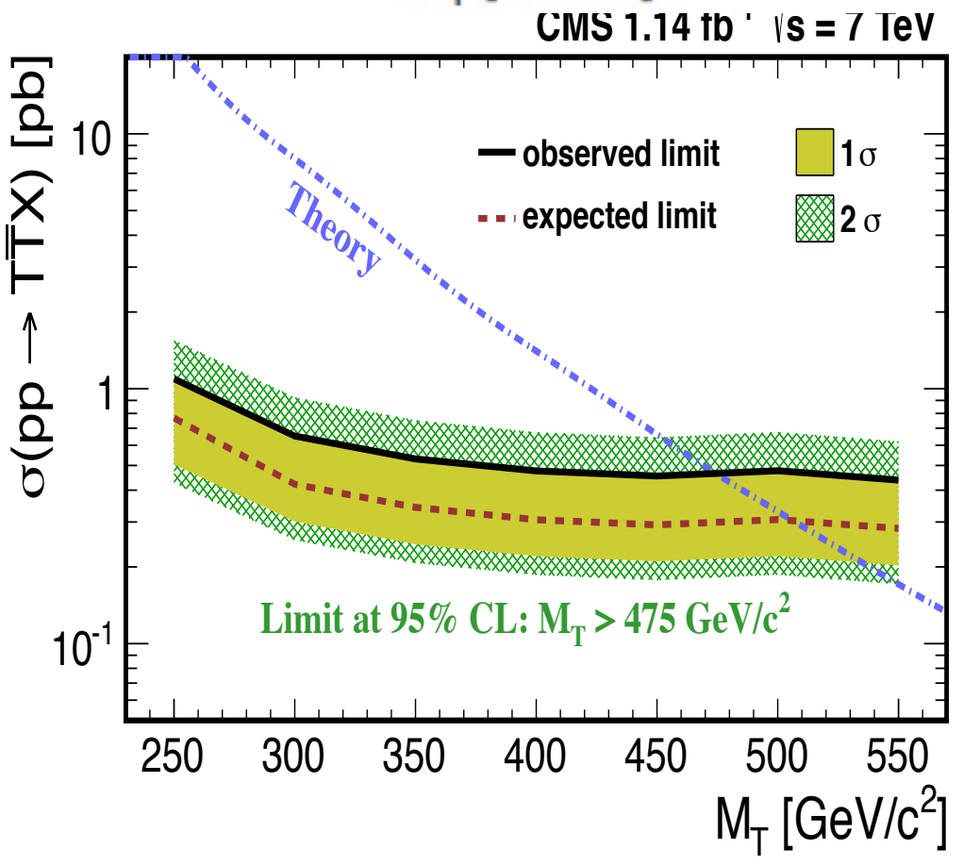
Vector-like Heavy Quarks: T→tZ

CMS Search in 1.14 fb $^{-1}$





- ✦ Pair production of T→ tZ
  - ✤ tag a Z(ll) + an isolated lepton + ≥ 2 jets
  - ✤ Define: $\mathbf{R_T}$ = ∑pT (jets, excluding leading two) + ∑pT (leptons, excluding leading two)



- ✦ Assuming 100% branching fraction
- ✤ **M_T > 475 GeV @ 95% CL**

PRL 107, 271802 (2011)

Summary

- 2011 data taking at CMS was very successful. Many analyses with different final states have set the most stringent limits. In a nutshell:

  - for LED the limits are extend up to **M_D > 2.49 - 4.44 TeV for n_{ED} = 2- 6**

  - for leptoquarks the lower limits on mass are set to **M_{LQ} > 632(523) GeV for β=1.0(0.5)** from 2nd generation searches

  - the limits on heavy quark masses are extended to **$M_{t'}$ >560 GeV and $M_{b'}$ > 600 GeV** from pair production searches

Future Prospects

- Analyses to cover a wider parameter space
- Combine limits from many different final states to improve sensitivity
- Some heavy quark analyses based on 100% branching fraction, what if we relax this assumption?
  - e.g., for $T \rightarrow tZ$ determine limits as function of BF and T mass and low BF could be cover with $t' \rightarrow bW$
  - a combined limit

- If we see signal then how to discriminate it from similar signatures e.g, SUSY etc.

Thank you!

Backup Slides

Di-lepton:LED

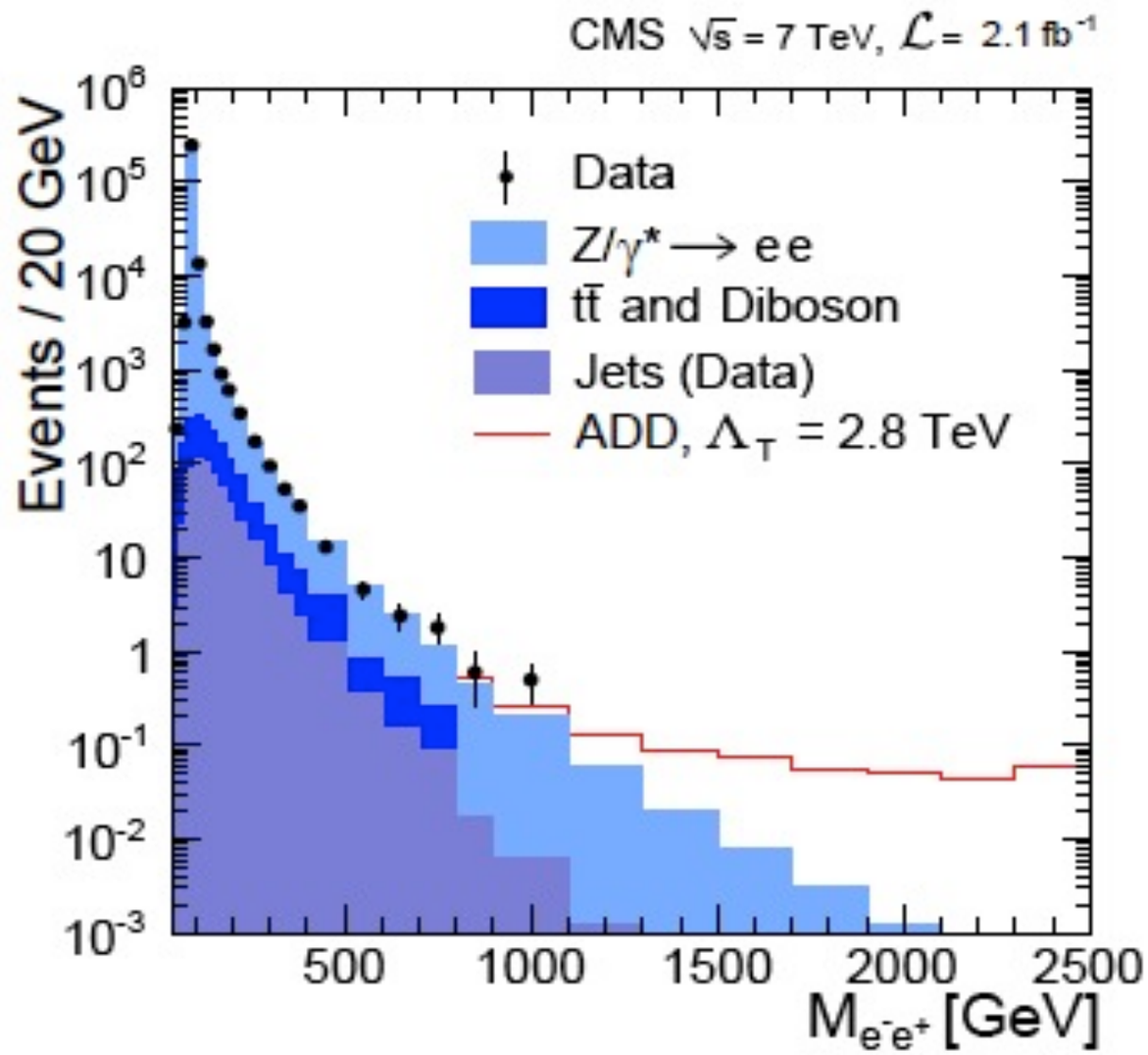
Selection for muon and electron:

- ✦ Isolated muons and electrons
- ✦ $P_T(\mu) > 45$ GeV, $|\eta| < 2.1$
- ✦ $P_T(e) > 35$ GeV(45GeV) for barrel(endcap)
  - ✤ opposite charge and at least one barrel electron

The main source of systematic uncertainty

- ✦ Trigger and reconstruction efficiency: Signal: ~3-4%,
  Background:~ 3%

- ✦ Electron energy scale: 1-3 %
- ✦ PDF and higher order (for DY):
  - ✤ Background:~10-13 %



Di-lepton:LED

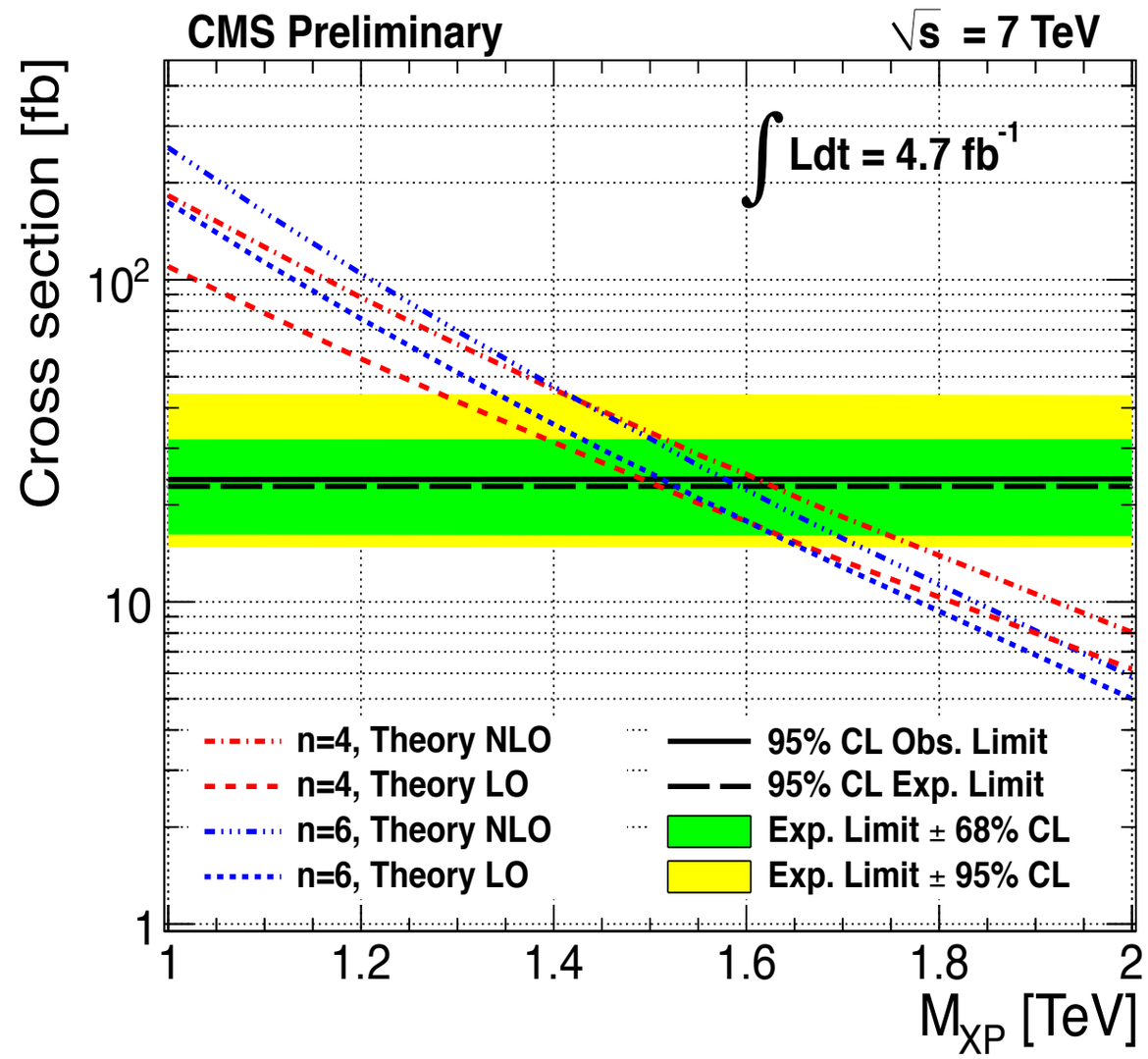
Table 2: Comparison of the observed and expected number of events in control and signal regions for the dimuon and dielectron mass distributions. Expected signal contributions are shown for $\Lambda_T = 2.8$ TeV (ADD K-factor 1.0, signal truncation at $M_{max} = \Lambda_T$).

$\mu\mu$, $\mathcal{L} = 2.3\,\mathrm{fb}^{-1}$				ee, $\mathcal{L} = 2.1\,\mathrm{fb}^{-1}$			
Mass region [TeV]	N_{obs}	Background expectation	Signal exp. $\Lambda_T = 2.8$ TeV	Mass region [TeV]	N_{obs}	Background expectation	Signal exp. $\Lambda_T = 2.8$ TeV
Control regions				Control regions			
0.14–0.20	3723	3690±300	-	0.12–0.20	6592	6598±530	-
0.20–0.40	1674	1605±160	-	0.20–0.40	1413	1301±120	-
0.40–0.60	131	122±13	-	0.40–0.60	88	103±11	-
0.60–0.80	16	21±3	-	0.60–0.80	21	18±3	-
0.80–1.10	8	5±1	0.8	0.80–1.10	7	6±1	0.6
Signal region				Signal region			
> 1.10	0	1.0±0.2	3.2	> 1.10	0	1.3±0.2	2.7

Photon+MET :LED

CMS Search in 4.7fb $^{-1}$

Source	Estimate	Uncertainty
Beam Halo	11.1	5.6
Jet Fakes Photon	11.2	2.8
Electron Fakes Photon	4.1	2.4
$W\gamma$	2.8	0.9
γ+jet	0.5	0.2
$\gamma\gamma$	0.5	0.3
$Z(\nu\bar{\nu})+\gamma$	42.4	6.3
Total Background	72.5	9.2



✦ $M_D \gtrsim 1.59\text{-}1.66$ TeV for $3 \leq n_{ED} \leq 6$

CMS EXO-11-096

Jet+ MET: LED

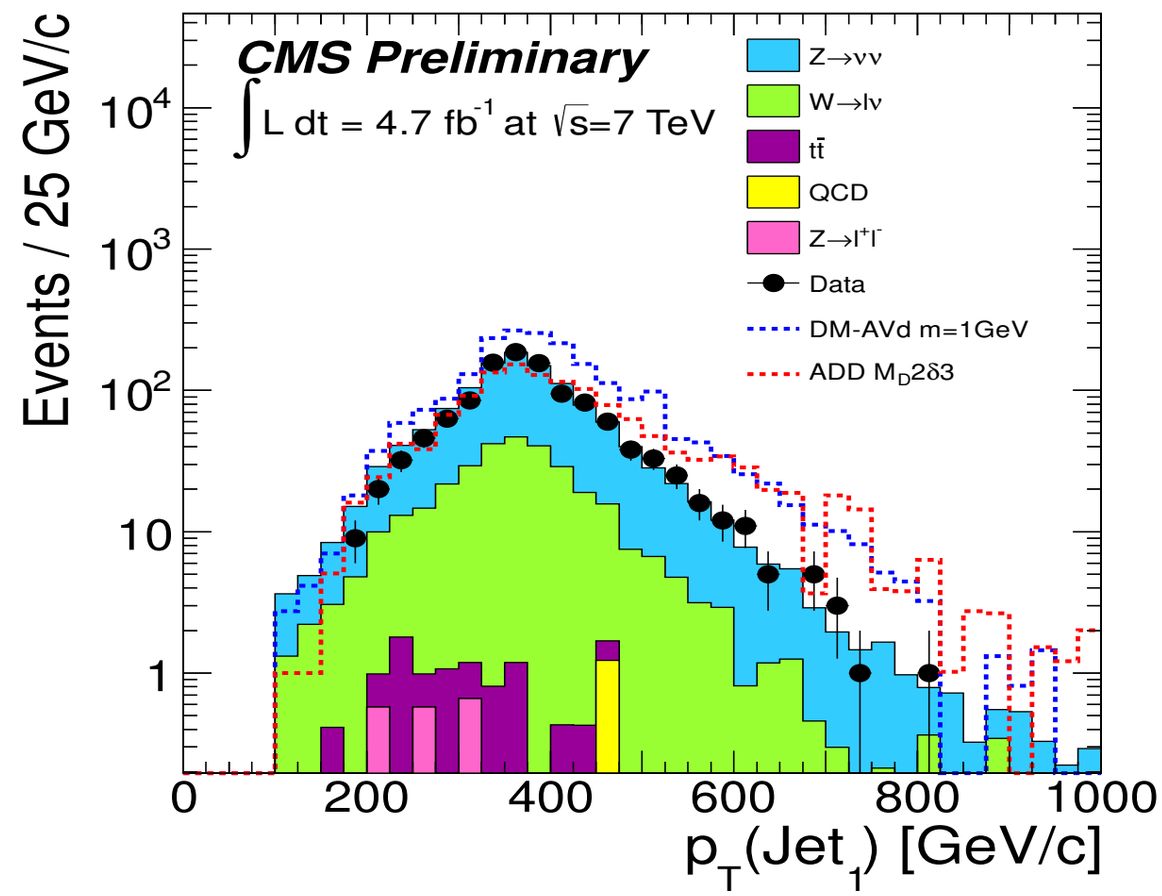
- Relatively large production and clean final state with high pT jet and large Missing-E_T
  - $qq \to gG$, $qg \to qG$, $gg \to Gg$

CMS Search in 4.7 fb^{-1}

- Main background: $Z \to \nu\nu$ and W+jets

- Limits are set on M_D, the Planck scale M_s for extra dimensions n_{ED}

Background process	Events
$Z \to \nu\bar{\nu}$	900 ± 94
W+jets	312 ± 35
$t\bar{t}$	8 ± 8
$Z(\ell\ell)$+jets	2 ± 2
QCD multijet	1 ± 1
Single t	1 ± 1
Total background	1224 ± 101
Observed in data	1142



CMS EXO-11-059

1st and 2nd Generation Scalar Leptoquarks

Selection:1st generation

- ✦ $P_T(e) > 35$ GeV, $P_T(\text{jets}) > 30$ GeV and
- ✦ Missing-$E_T > 45$ GeV

- ✦ Main bkg: ttbar, W+jets
- ✦ Main systematic from W+Jet bkg shape

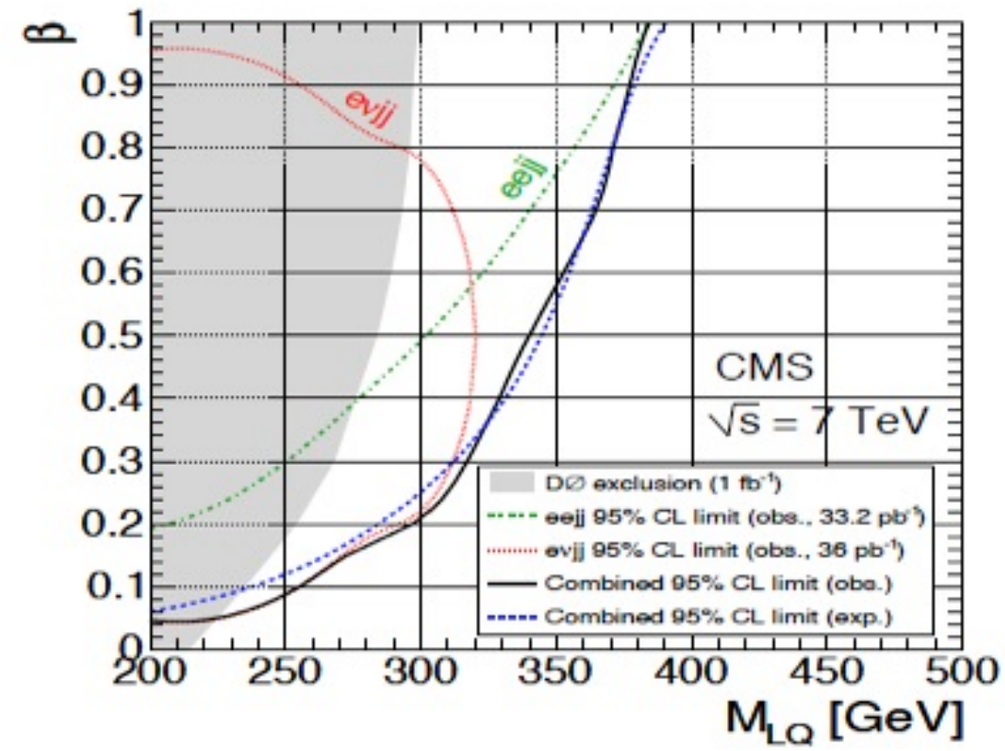
Selection: 2nd Generation

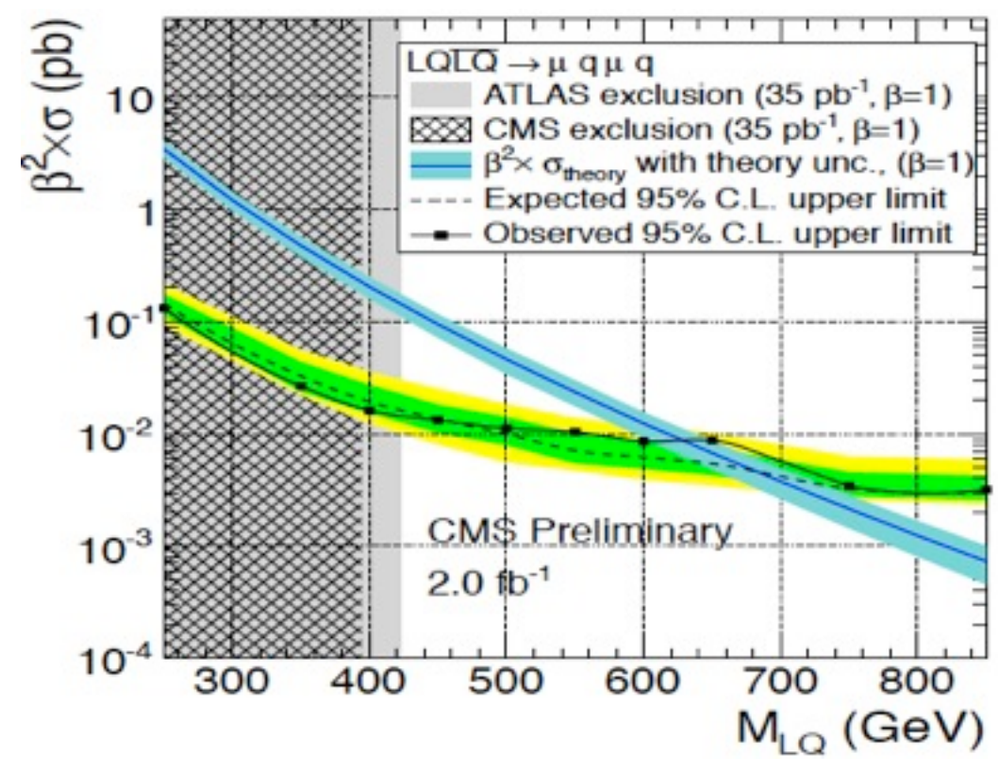
- ✦ $P_T(\mu) > 40$ GeV, $P_T(\text{jets}) > 30$ GeV
- ✦ $\Delta R(\mu\text{-}\mu) > 0.3$
- ✦ $S_T > 250$ GeV (at preselection level)

In addition for $\mu\nu qq$ channel:

- ✦ Veto on 2nd muon and 3rd Jet(and electron) with $P_T > 15$, 25 GeV(25 GeV) respectively
- ✦ Missing-$E_T > 45$ GeV
- ✦ $\Delta\phi$(MET-jet) and $\Delta\phi$(MET-μ) >0.5

CMS Search in 36 pb





PLB 706(2011) 246-266, CMS EXO-11-028

3rd Generation Scalar Leptoquarks

✦The analysis is designed to kinematically discriminate the pair production of heavy particle from SM background with making strong assumption about missing-E_T

✦Force every event to *dijet-topology* by combining all jets in the event into two *mega jets* and defined Razor variable as

Razor Variable: $$R \equiv \frac{M_T^R}{M_R}$$

Where,

$$M_R \equiv \sqrt{(E_{j_1} + E_{j_2})^2 - (p_z^{j_1} + p_z^{j_2})^2}$$

$$M_T^R \equiv \sqrt{\frac{\not{E}_T(p_T^{j1} + p_T^{j2}) - \vec{\not{E}}_T \cdot (\vec{p}_T^{j1} + \vec{p}_T^{j2})}{2}}$$

Peaks at leptoquark mass

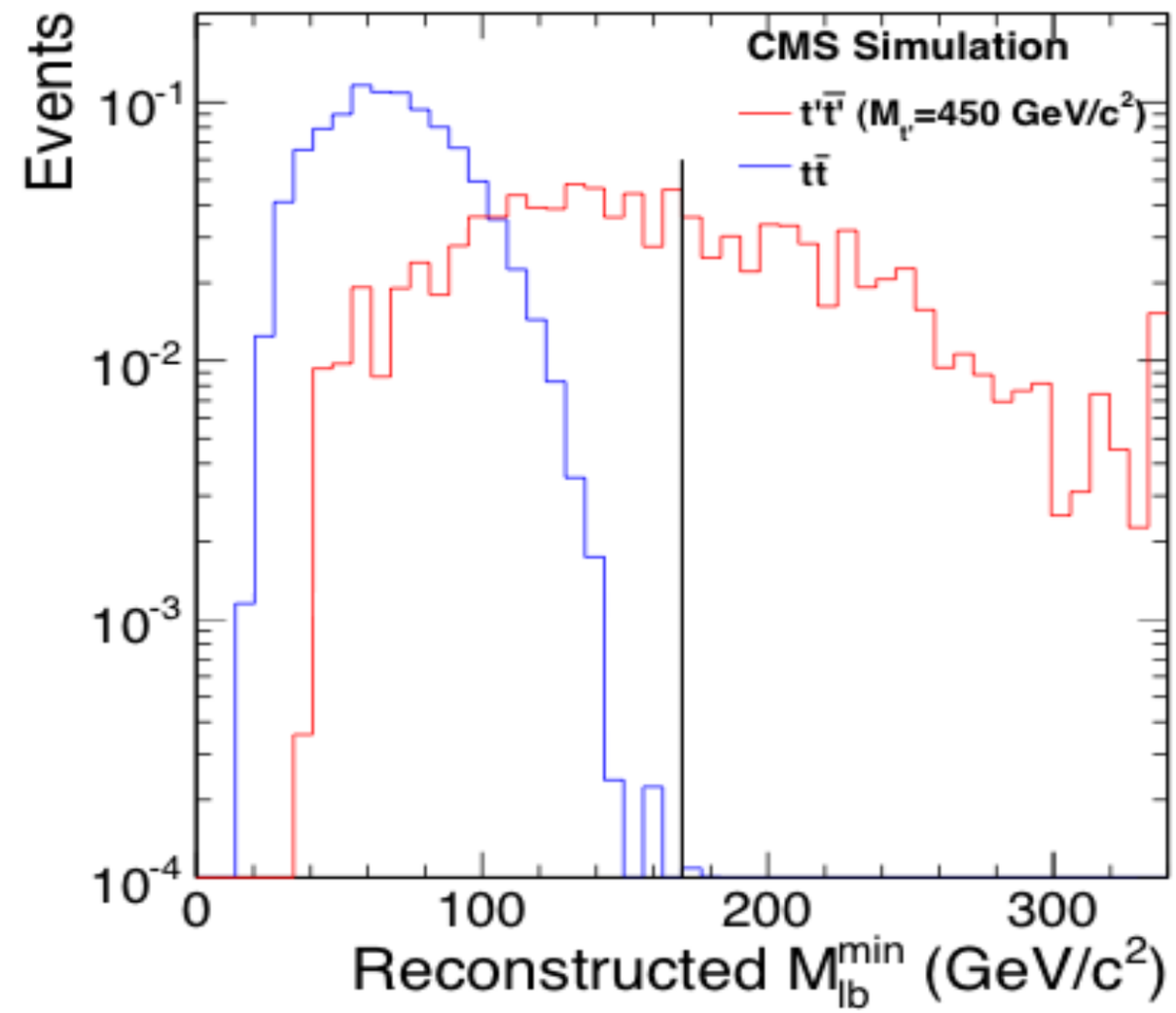
CMS EXO-11-030

t′ →bW (di-lepton)

CMS Search in 4.7 fb $^{-1}$

- Signal: 2 leptons+ Jets+ Missing-E_T
- Reconstruct "*b-jet+ lepton*" masses

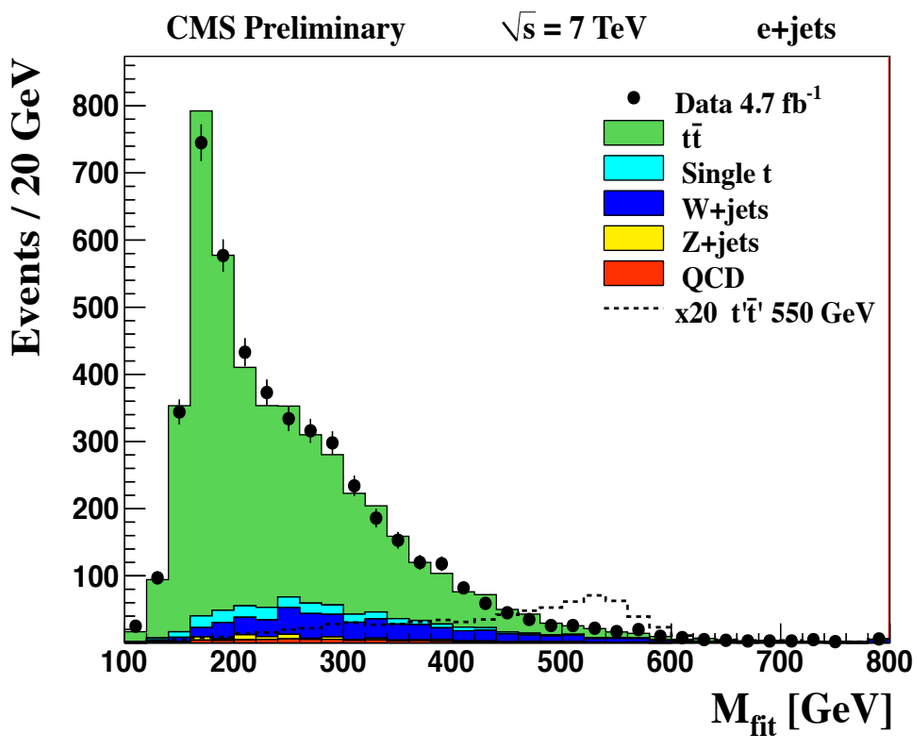
Limit: $M_{t'}$ > 552 GeV @95% CL

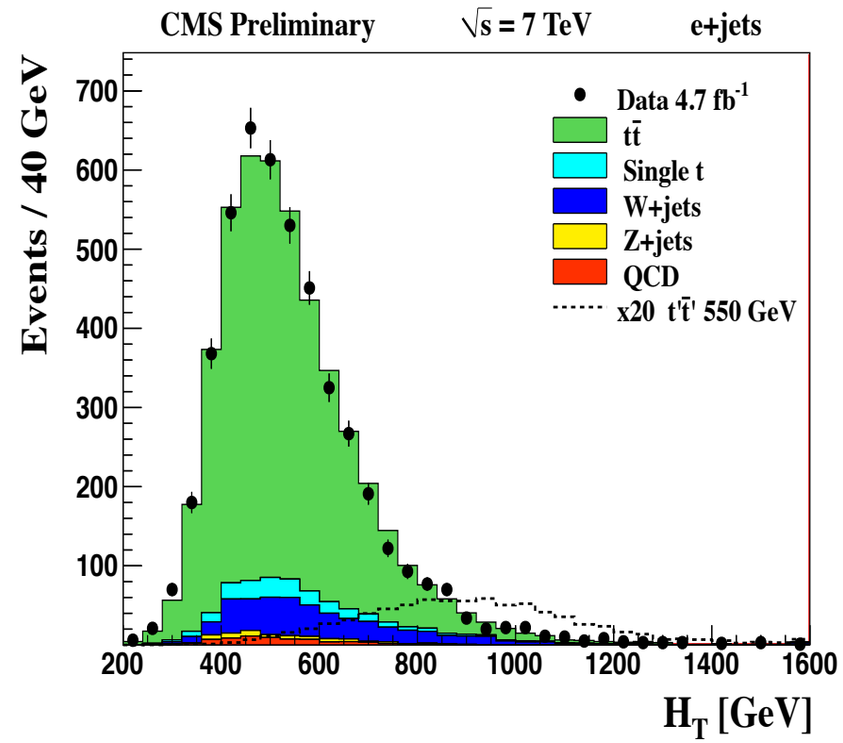


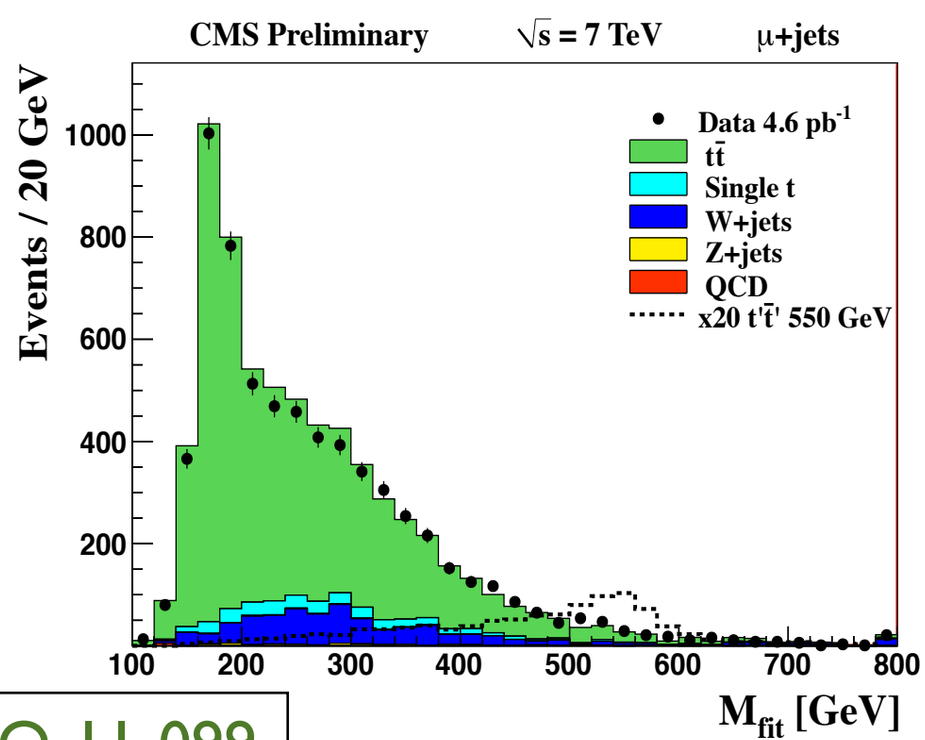
CMS EXO-11-050

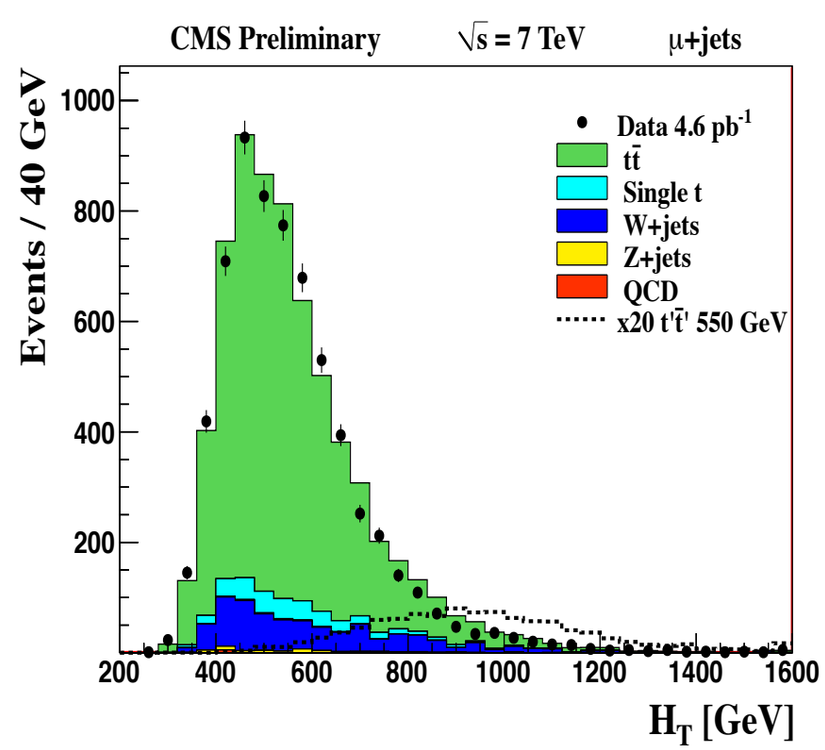
t′ →bW (leptons+jets)

CMS Search in 4.7 fb $^{-1}$





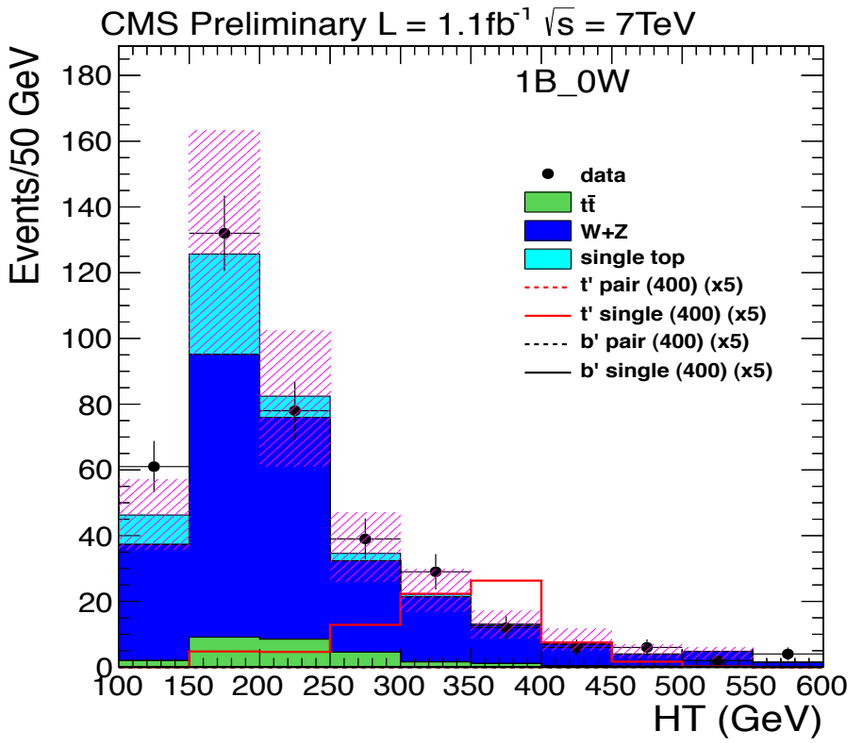


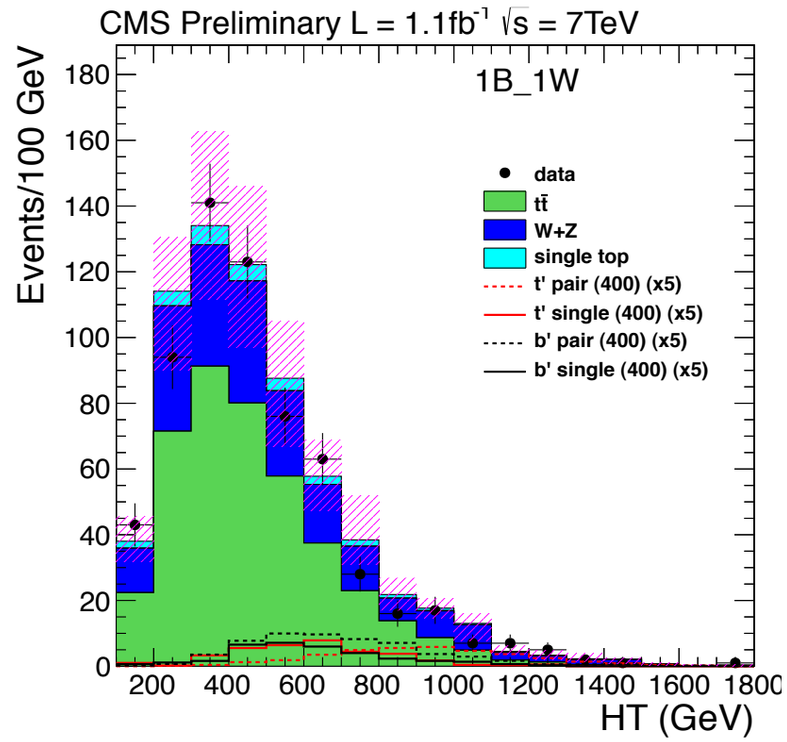


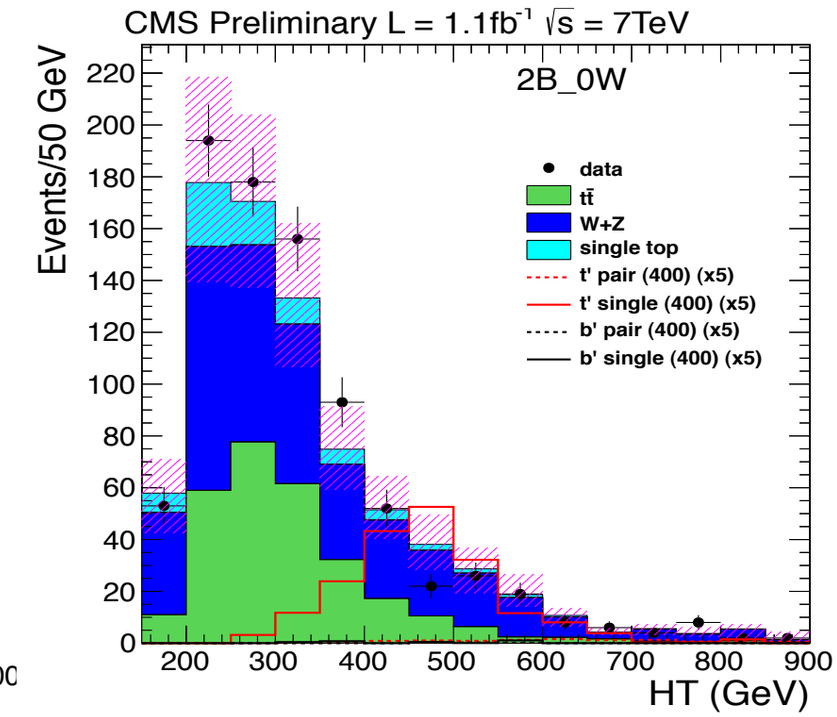
CMS EXO-11-099

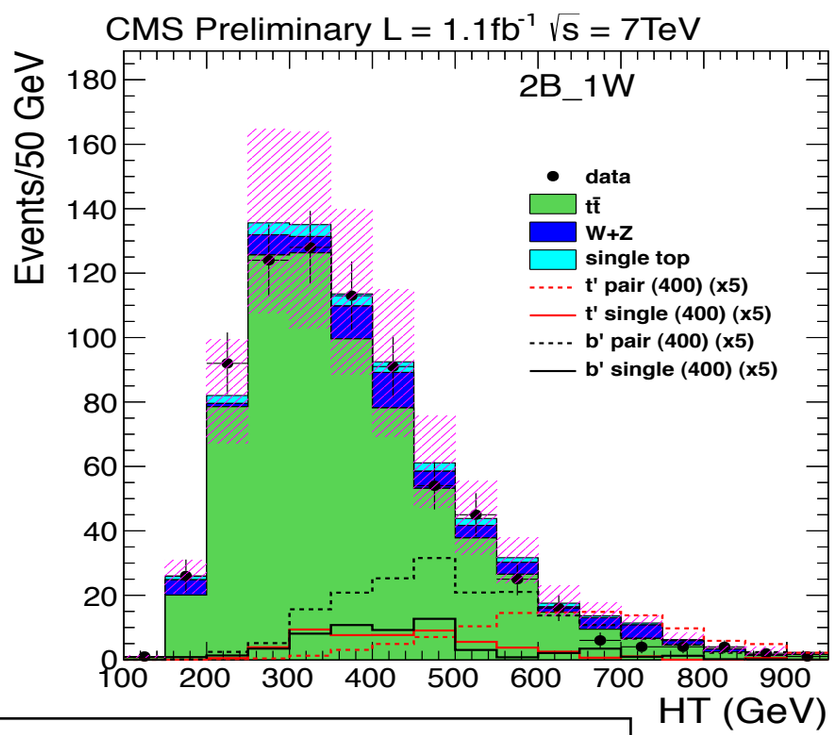
b′/t′ Inclusive Search: Classification

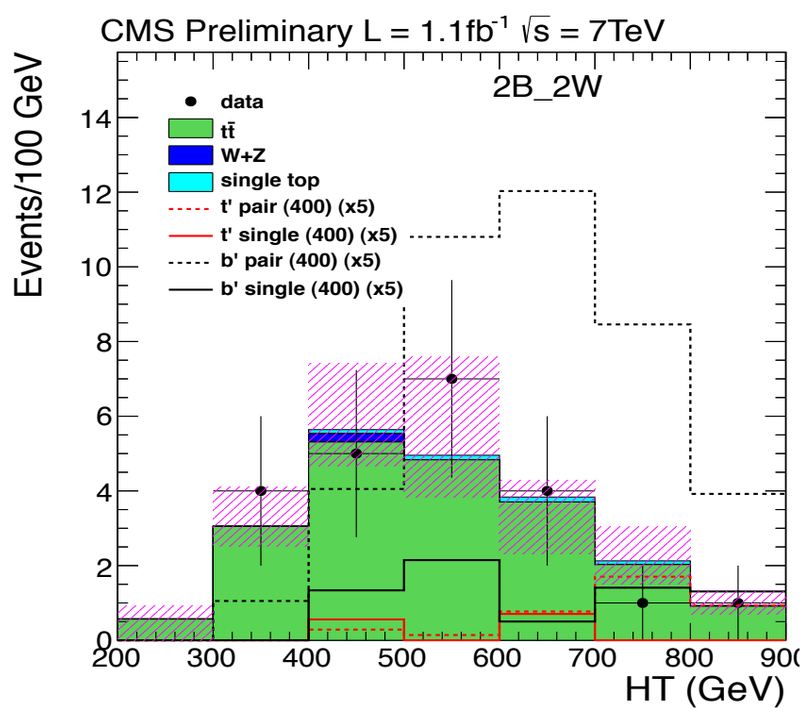
CMS Search in 1.1 fb $^{-1}$

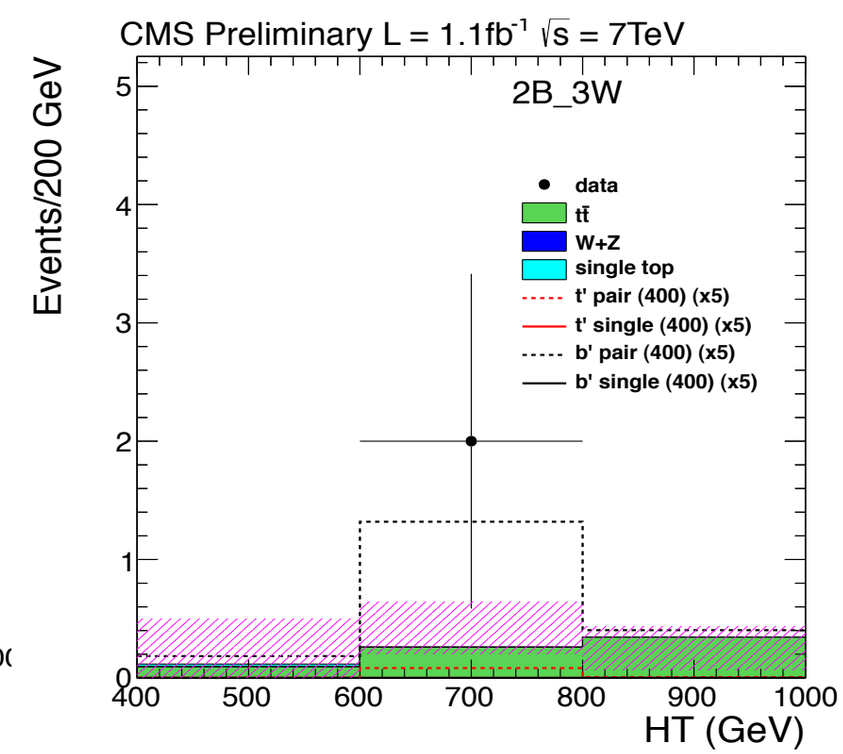








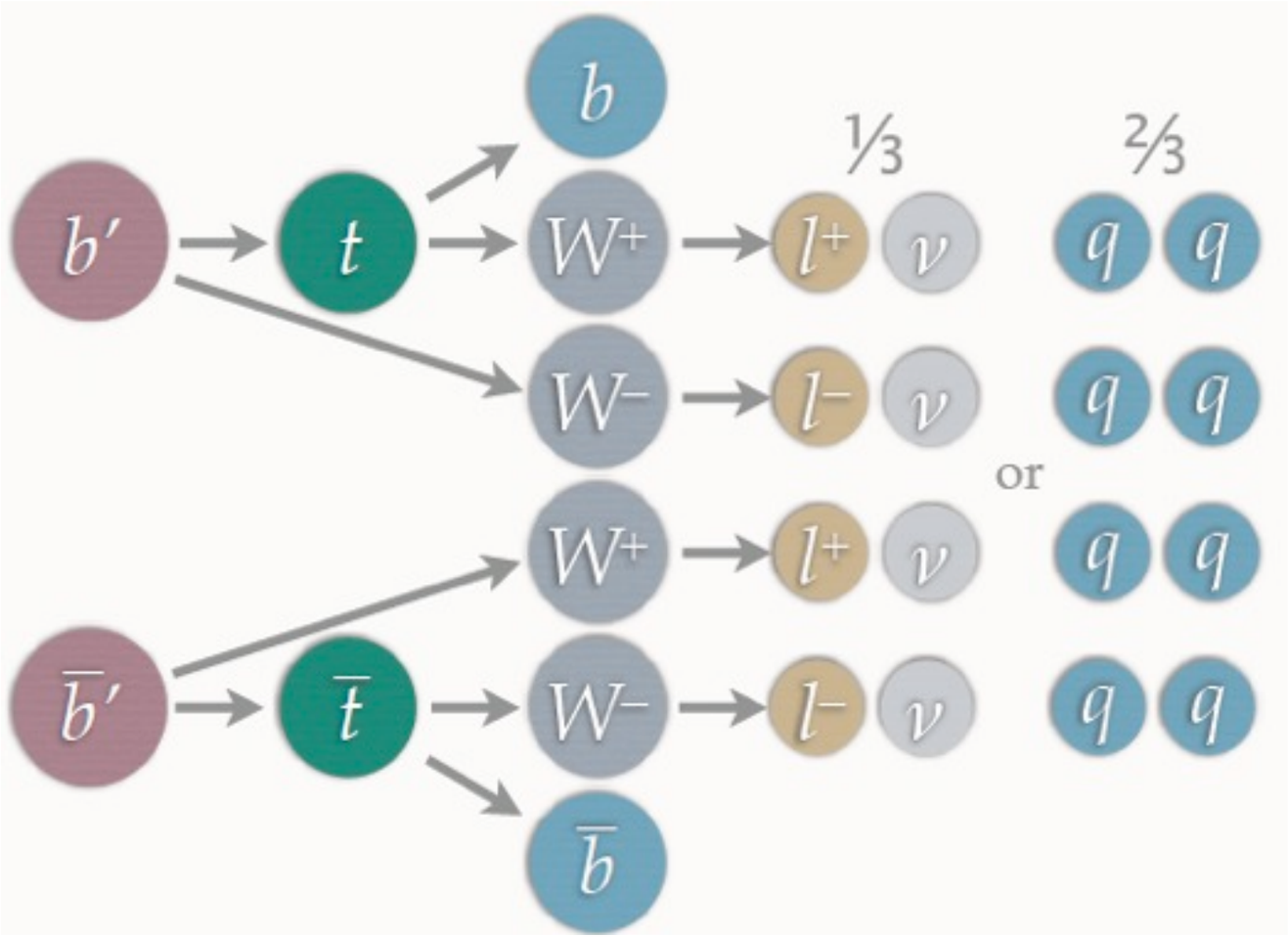




CMS PAS EXO-11-054

b′ Search

Full decay chain: b′b′ → tWtW → bWWbWW: 2 b-jets+ 4 Ws



Possible channels:

1L + 8Jet + MET
2L + 6jet + MET
3L + 4jet + MET
4L + 2jet + MET

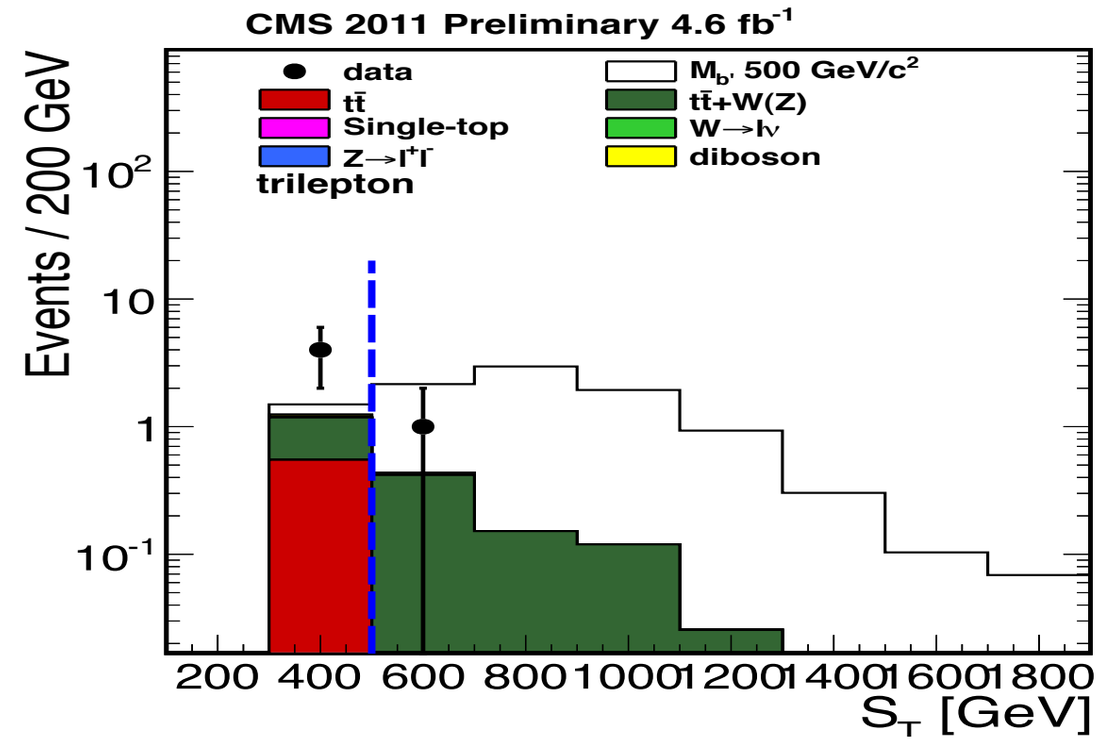
Clean signatures: tri-leptons and opposite signe di-lepton events

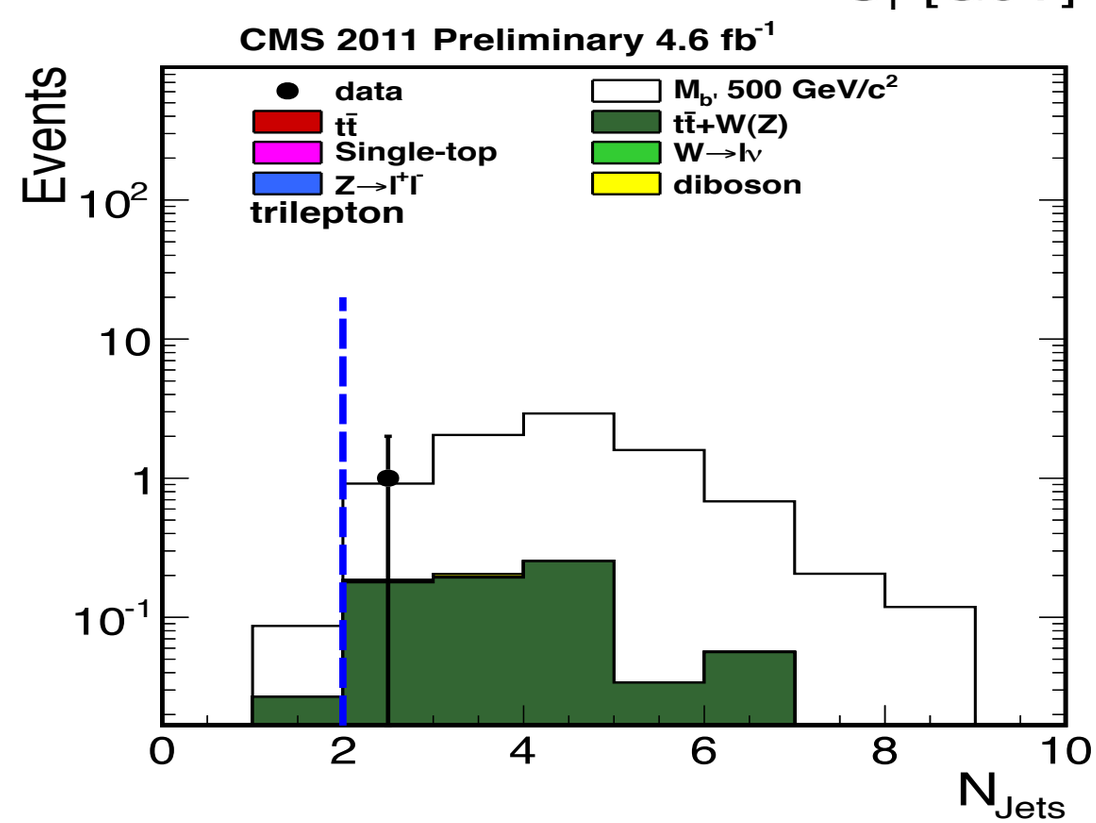
b′ Search (di-lepton, tri-lepton)

CMS Search in 4.7 fb $^{-1}$

Full decay chain: b′b′ → 2 b-jets+ 4 Ws

- **Clean signal:** 3 leptons+ 2jets
  OR 2 same sign leptons + 4jets
  - at least 1 b-jet, Missing-E_T
- $P_T(e, \mu) > 20$ GeV and P_T(each jet) > 25 GeV, $S_T > 500$ GeV
- Very less or almost no backgrounds





$M_{b'}$ > 600 GeV @ 95% CL

CMS EXO-11-036

T→tZ: Decay Modes

2W bosons+ 2 Z bosons + 2 jets

BF 5.4 % for e, μ

Clean signature, includes 3 leptons (two coming from Z) and at least 2 jets

Decay Mode	BF
1L+4-8J (1Wlν)	324/900
2L+2-6J (2Wlν)	81/900
2L+6-8J (1Zll)	72/900
3L+4-6J (lWlν+ 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**