

# HEAVY QUARKS SEARCHES AT THE LHC EXPERIMENTS



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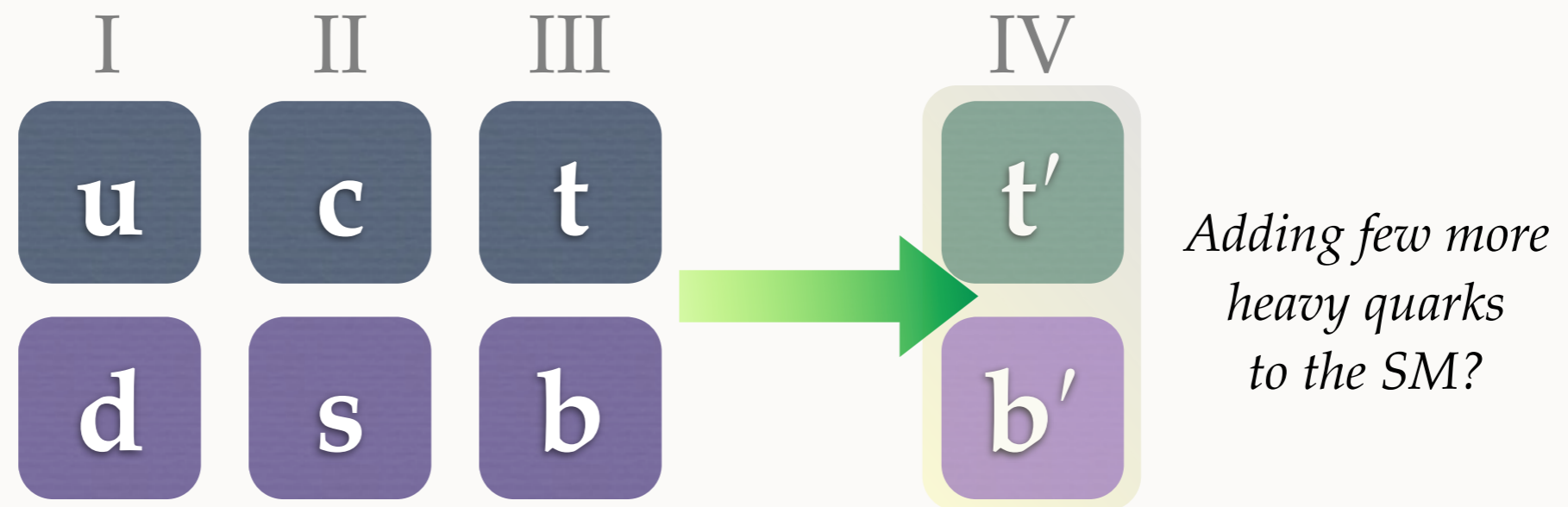
Workshop on Very Heavy Quark Searches  
January 19<sup>th</sup>, 2012

# TODAY'S MENU



- A brief introduction
- Summary of LHC heavy quark searches
  - Sequential 4th generations
  - Vector-like and exotic heavy quarks
- Results reinterpreting:
  - The sensitivity at the end of 2012?
  - A challenge to the 100% assumption.
  - Adding two quarks together?

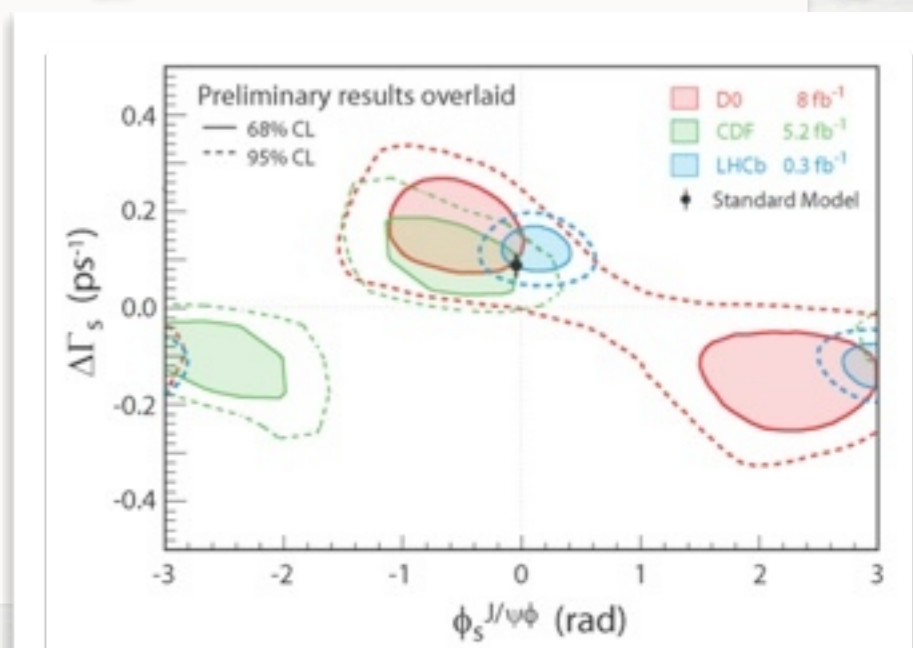
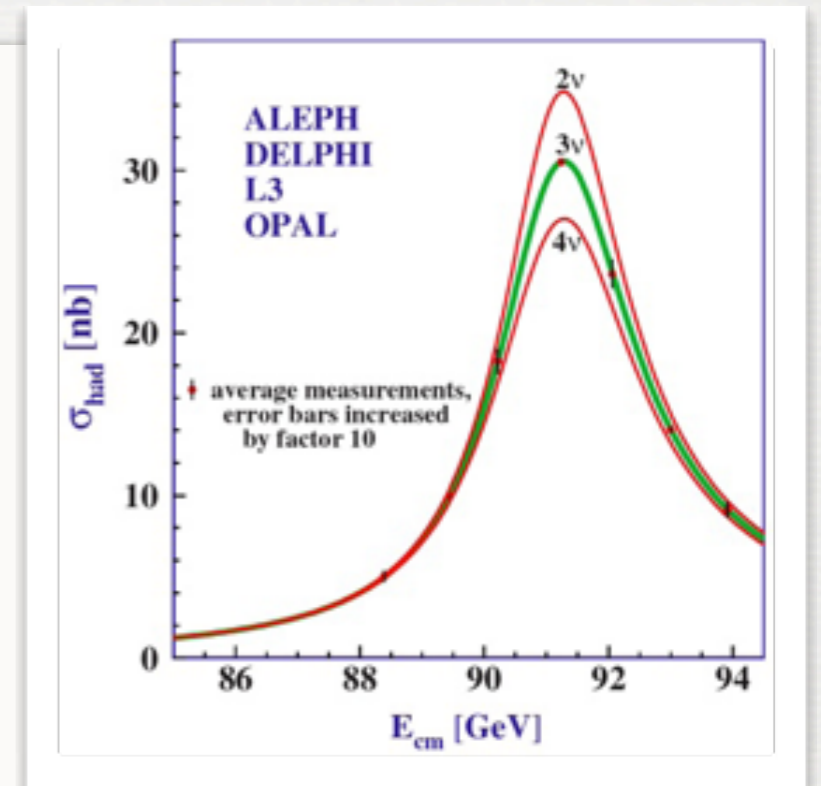
# INTRODUCTION



- Adding one more generation of quarks is an obvious extension to the SM, and is not really excluded by the EWK precision data.
- Small mass splitting between  $b'$  and  $t'$  is preferred:  $|M_{t'} - M_{b'}| < M_W$ .
- Flavor physics data for unitarity triangle provide some information regarding the “CKM4” matrix, but it is only weakly constrained due to the uncertainties.

# ADDING 4G TO THE WORLD

- The direct measurement of invisible Z width from LEP:  $N\nu = 2.92 \pm 0.05$ , but it does not guarantee that  $N(\text{gen}) = 3$  exactly, e.g. heavy neutrino with mass  $> 0.5 M_Z$ .
- Adding 4th generation quarks will pull down the  $\sin 2\Phi_{B_s}$  value from the SM. It resolves some “old” tension from Tevatron data. (*But the tension was relaxed with new LHCb result.*)
- Due to the heaviness of 4G quarks, the CP violation in the universe can be boosted by a huge factor; it might resolve the issue of BAU in a single shoot.

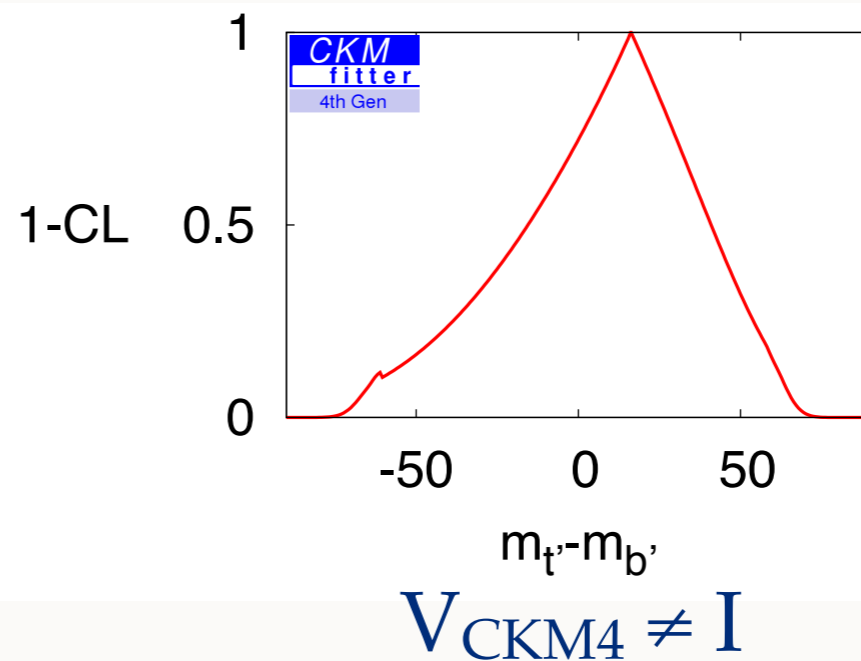
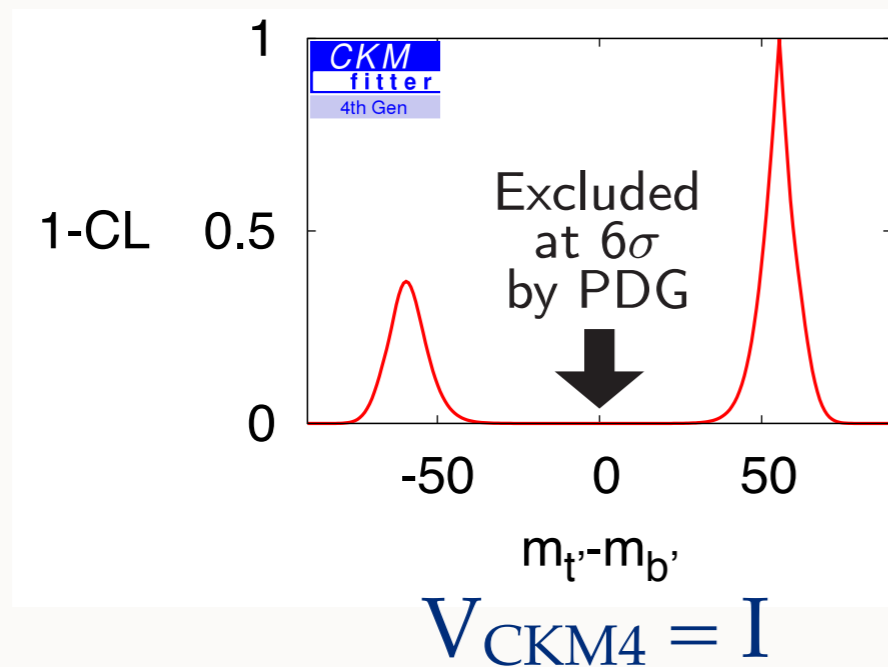


# ADDING 4G TO THE WORLD

- In PDG, the “inaccurate” statement for the exclusion of 4G is based on electroweak constraints on the oblique parameter S.

$$\delta S = \frac{2}{3\pi} - \frac{1}{3\pi} \left[ \log \frac{m_{t'}}{m_{b'}} - \log \frac{m_{\nu_{\tau}'}}{m_{\tau'}} \right]$$

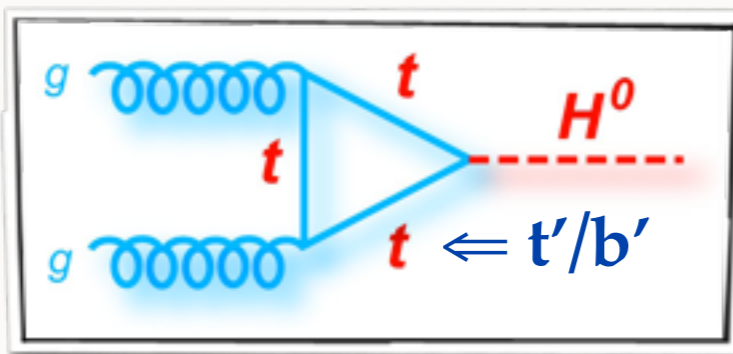
This exclusion only works with **degenerate 4G** and **unity CKM4**:



Not a real  
constraint  
any more...

# ADDING 4G TO THE WORLD

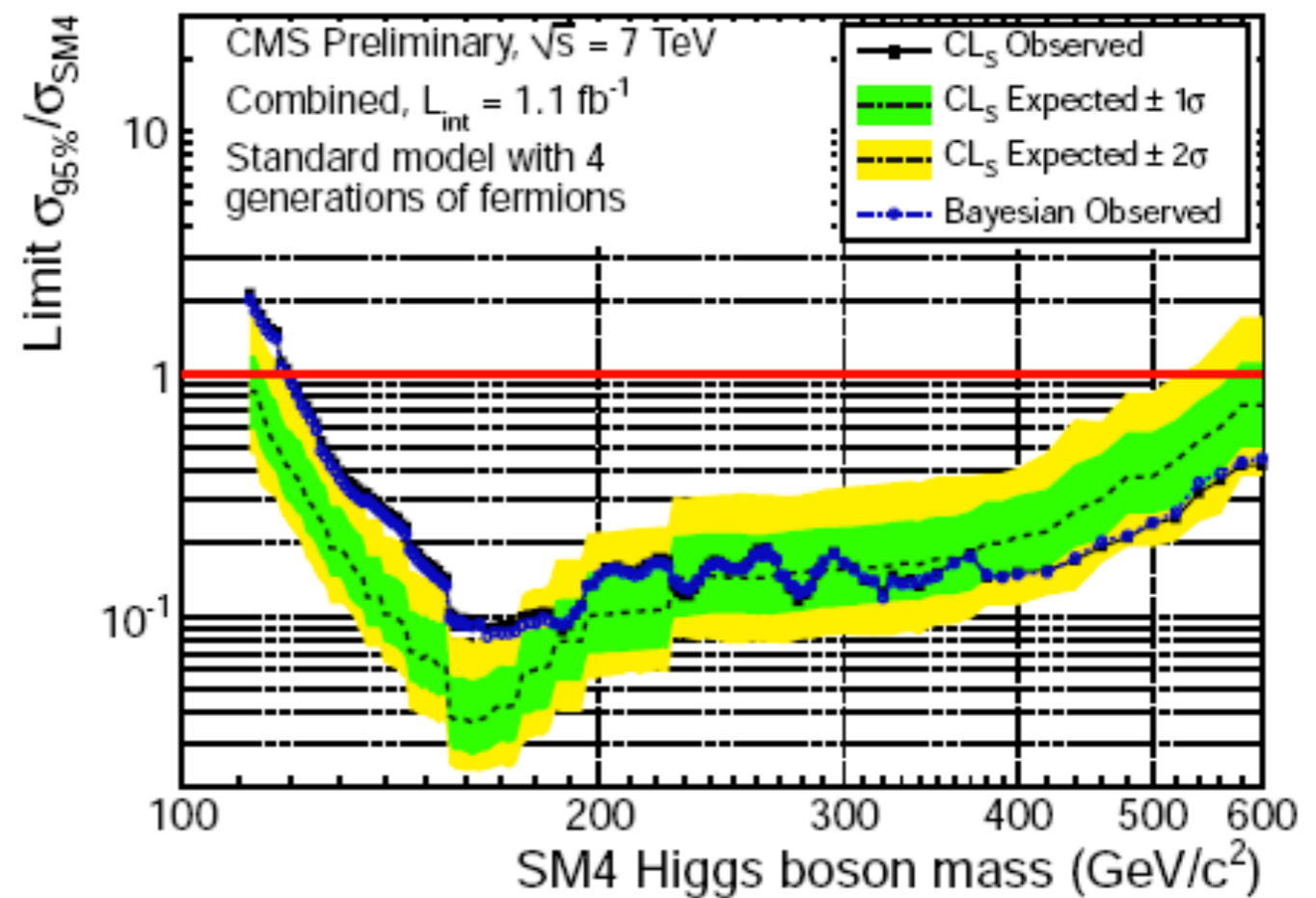
- Since the new quarks are supposed to be heavy (at least heavier than the top quark). Large impact on the Higgs sector is expected:



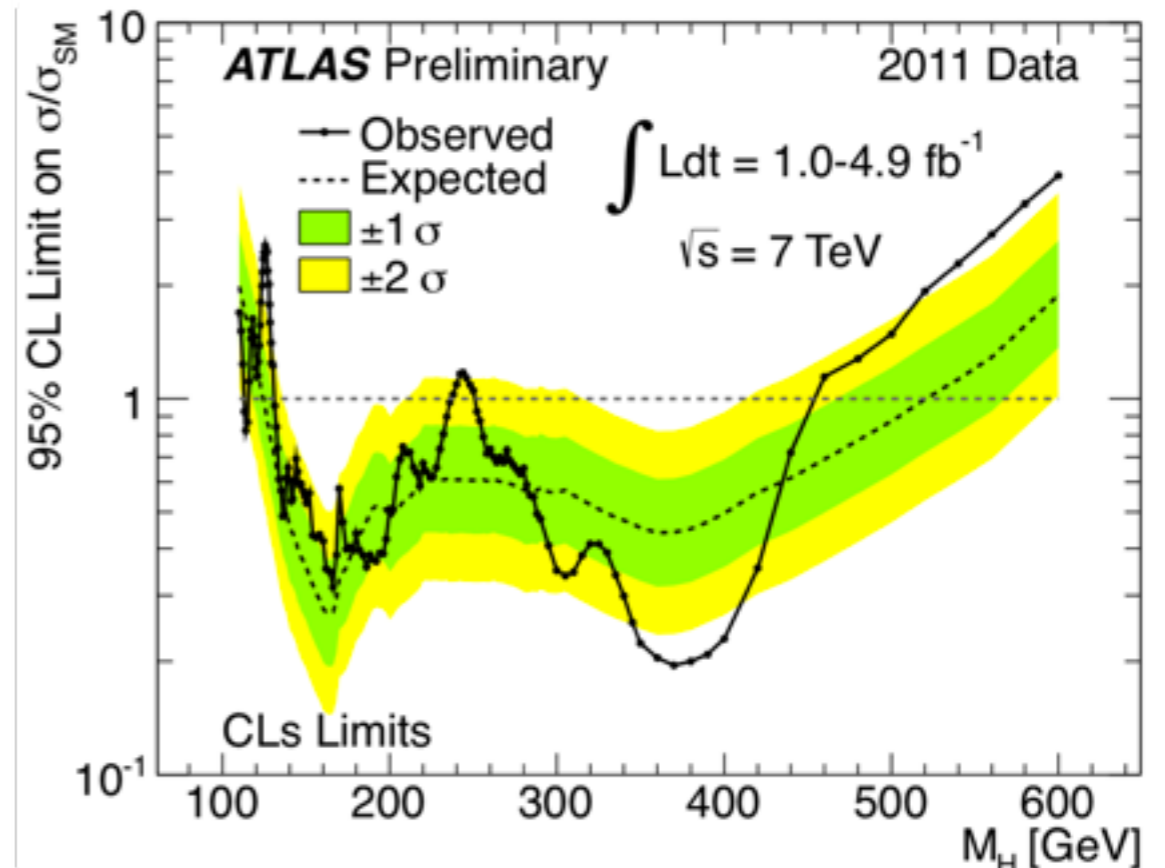
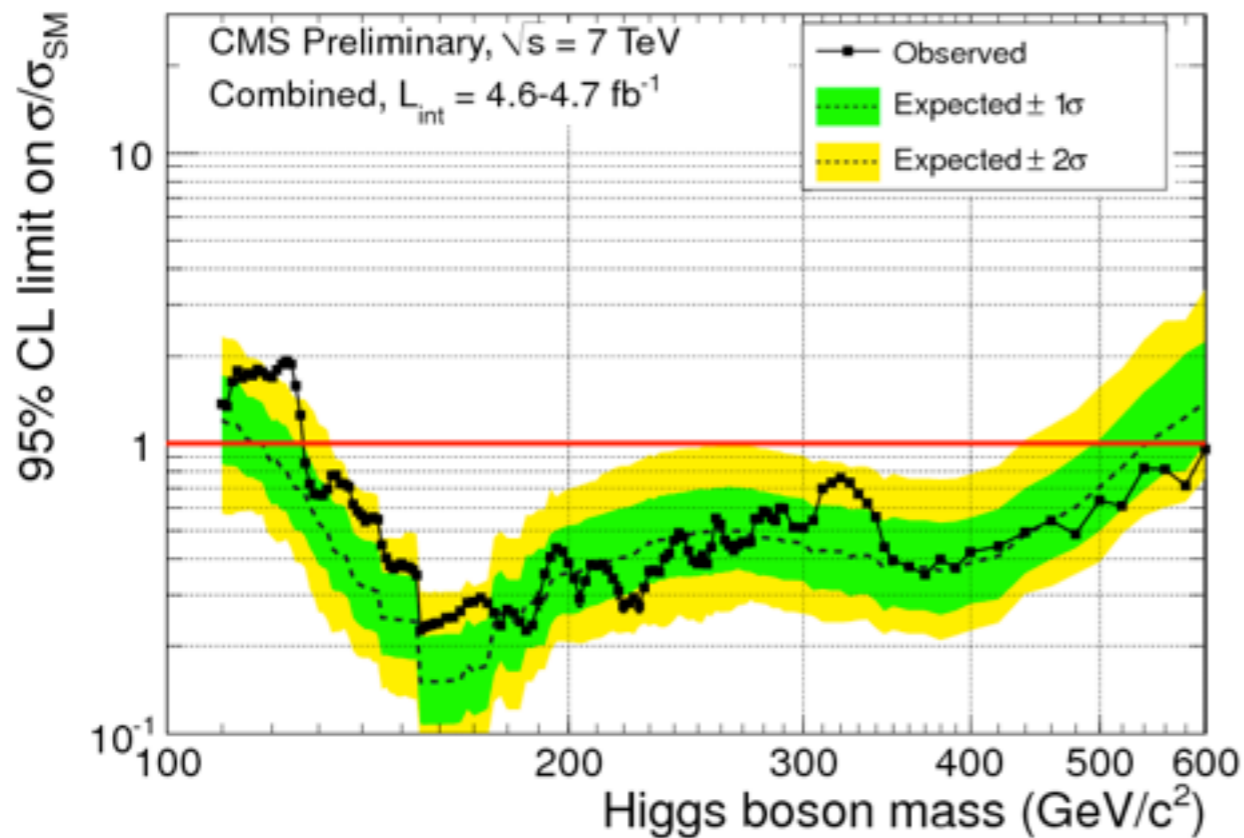
Enlarge the Higgs production rate by a factor 4~9

If 4G fermions exist, the SM Higgs boson has been fully excluded since summer:

Pure 4G  $\Leftrightarrow$  SM Higgs cannot coexist.



# FRESH AND HOT HIGGS RESULTS



New SM Higgs results released on Dec/13 –

- 1) Most of the spaces are excluded already.
- 2) Mild hints around 124, 126 GeV from individual experiments.
- 3) Need more data to fully kill/observe the SM Higgs...

4G?



iPhone 4



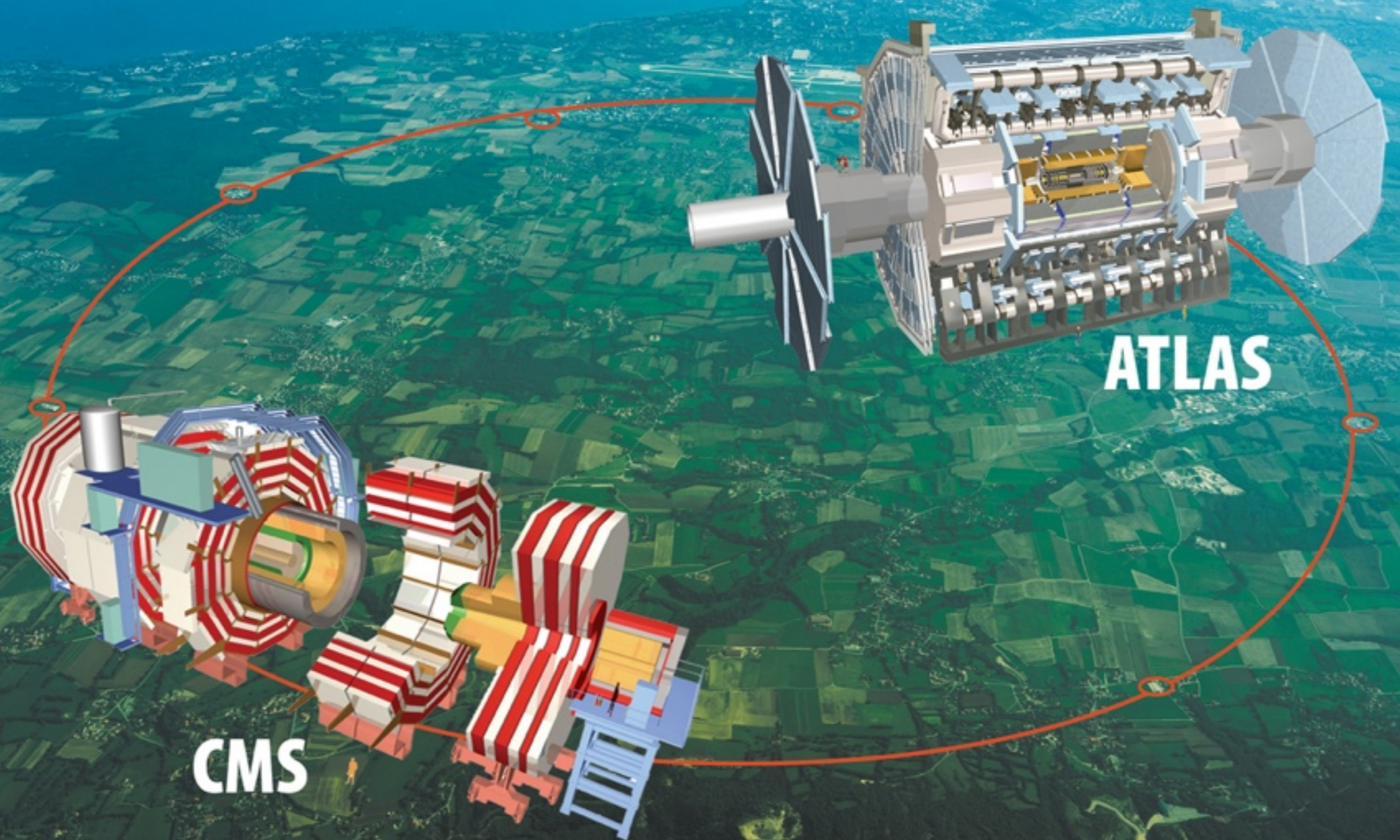
iPhone 4S

not just  
4G?

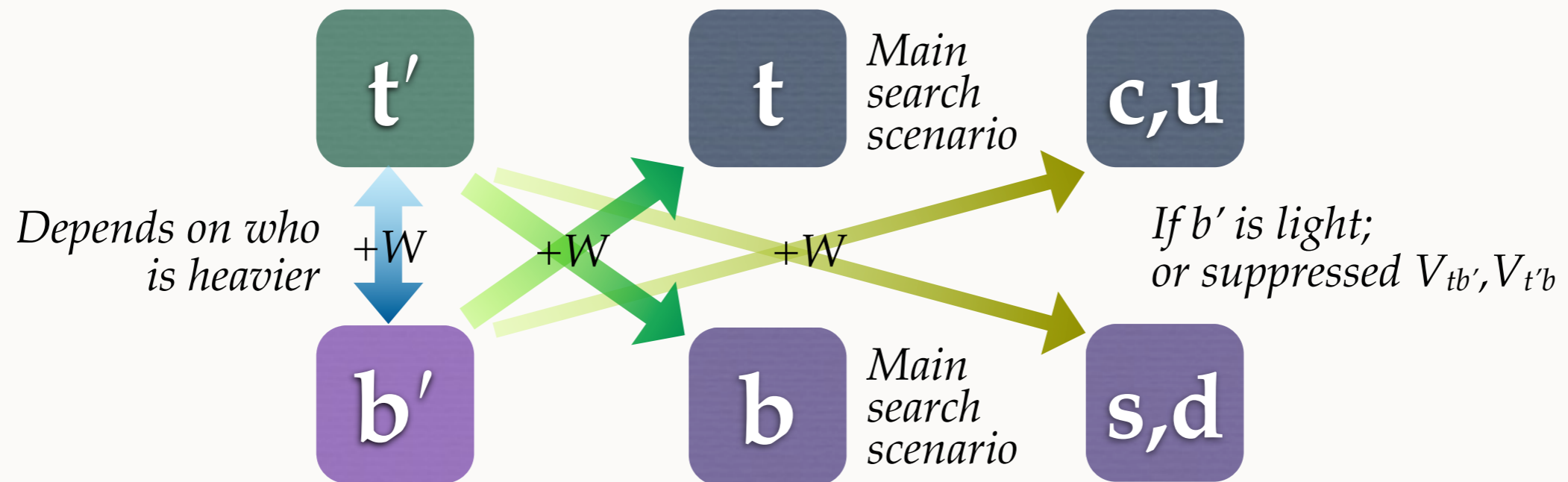
- Search for heavy quarks is one of the “must done” topics at the LHC.
- Sequential 4th generation quarks are constrained with EWK precision data, but not fully excluded yet.
- Other new quarks (such as vector-like quarks, exotic quarks) do not have the same dependence.



Results from **Atlas** and **CMS** are summarized.



# SIGNATURES OF NEW HEAVY QUARKS

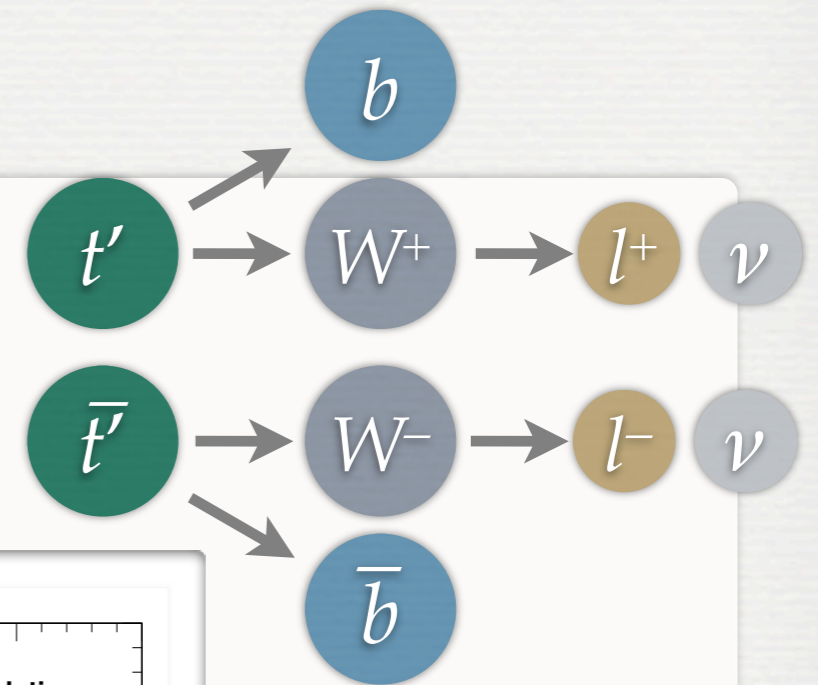


Main decay signatures for direct searches:

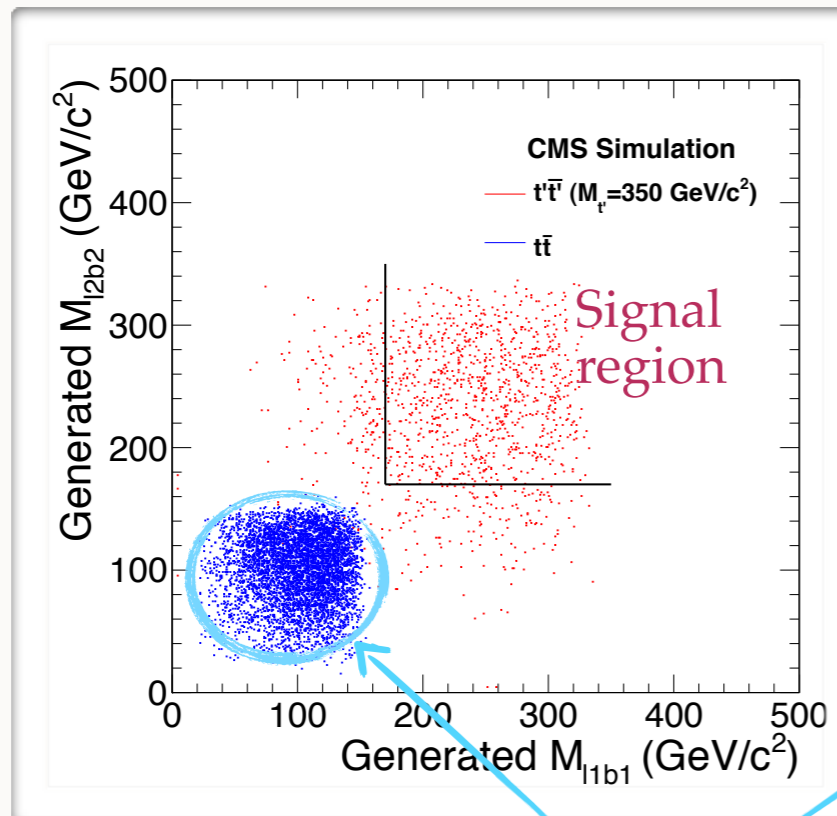
- $t' \rightarrow bW, t' \rightarrow qW$  : not really different from a heavy top.
- $b' \rightarrow tW(\rightarrow bWW)$  : complex signature,  $b' \rightarrow qW$  : heavy top.
- $t' \rightarrow b'W$  &  $b' \rightarrow t'W$  : should be seen after the above two.

# SEARCHES FOR $t' \rightarrow bW$ (dilepton)

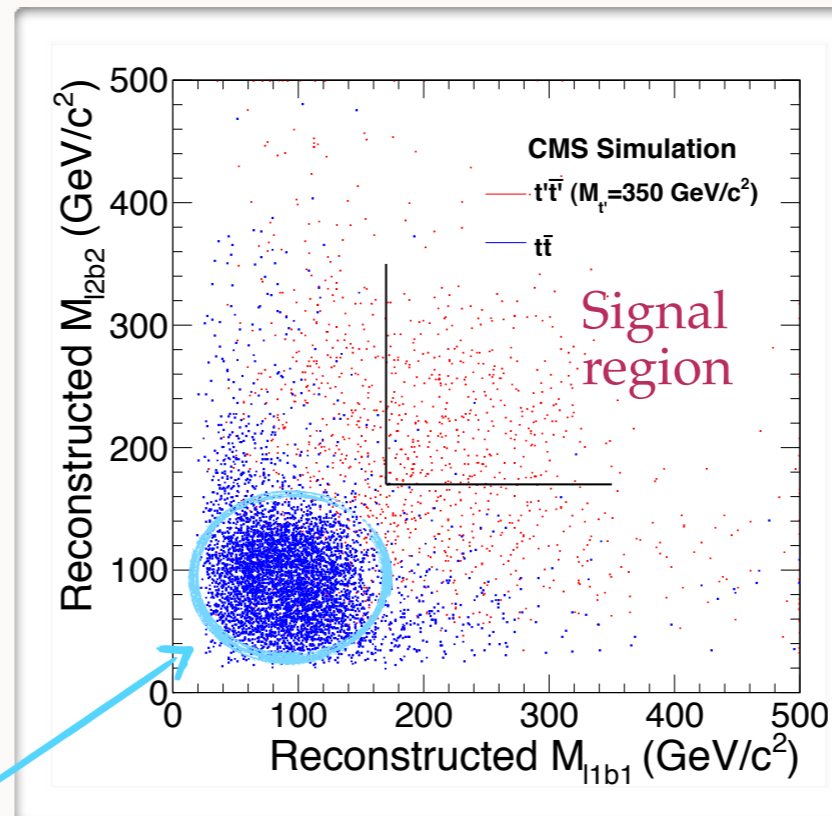
- Look for **dilepton events** + jets.
- Reconstruct two “b-jet+lepton” masses:



Generator level



Reconstruction level



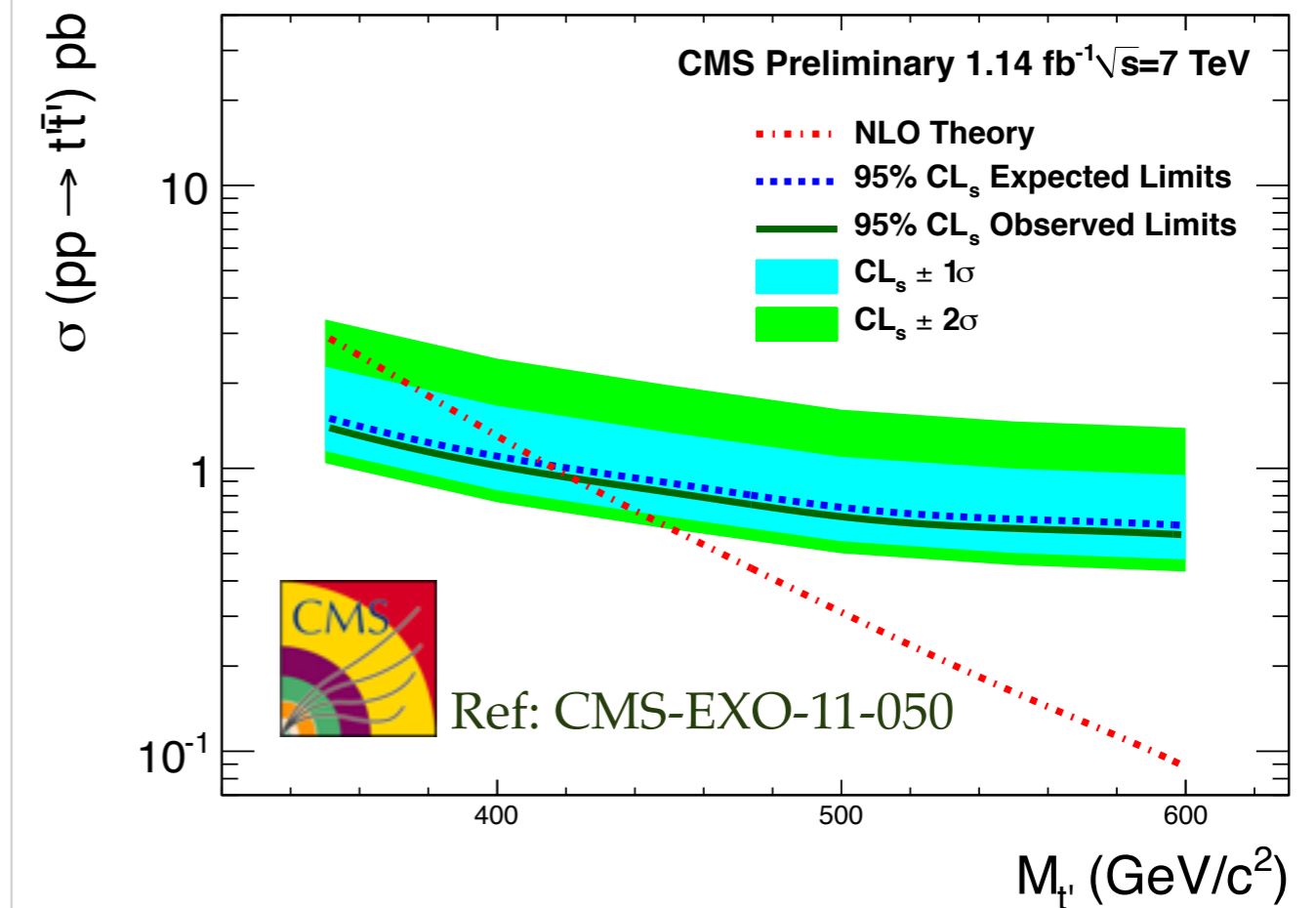
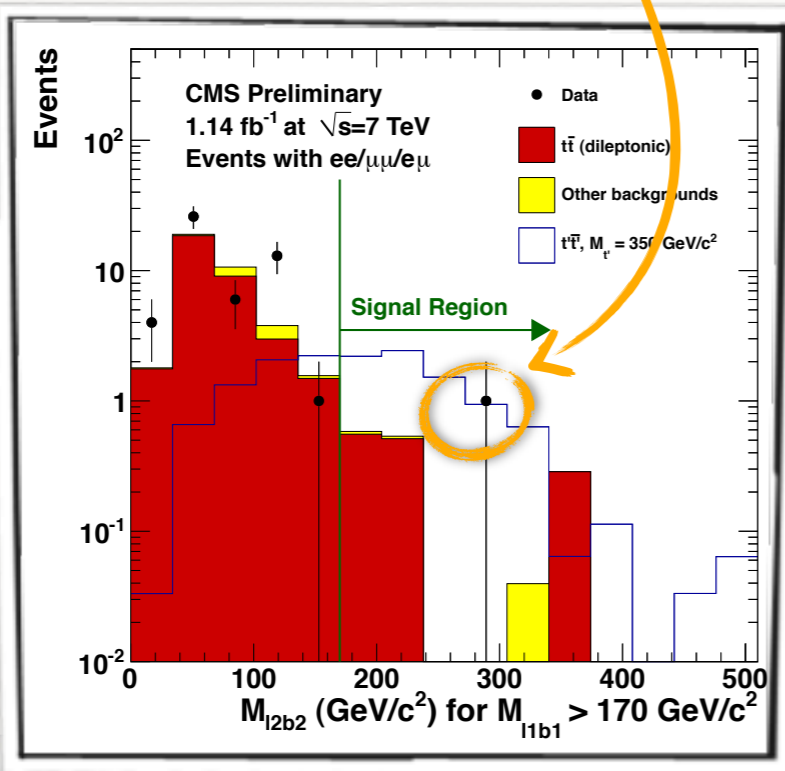
Signal lost due to the resolution, but it (still) keeps the background away.

*Optimize the b-lepton pairing to keep top background outside of the signal region*

# SEARCHES FOR $t' \rightarrow bW$ (dilepton)

A simple counting analysis

	Yield
$t't'(350 \text{ GeV}/c^2)$	11.8
Estimated background	$1.62^{+0.80}_{-0.70}$
data	1

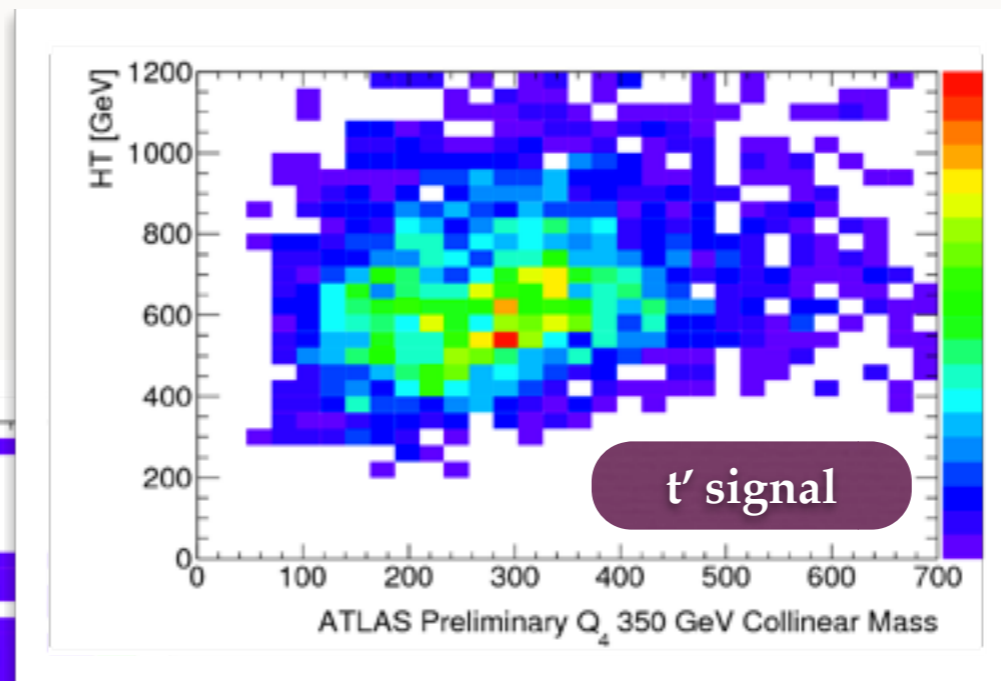
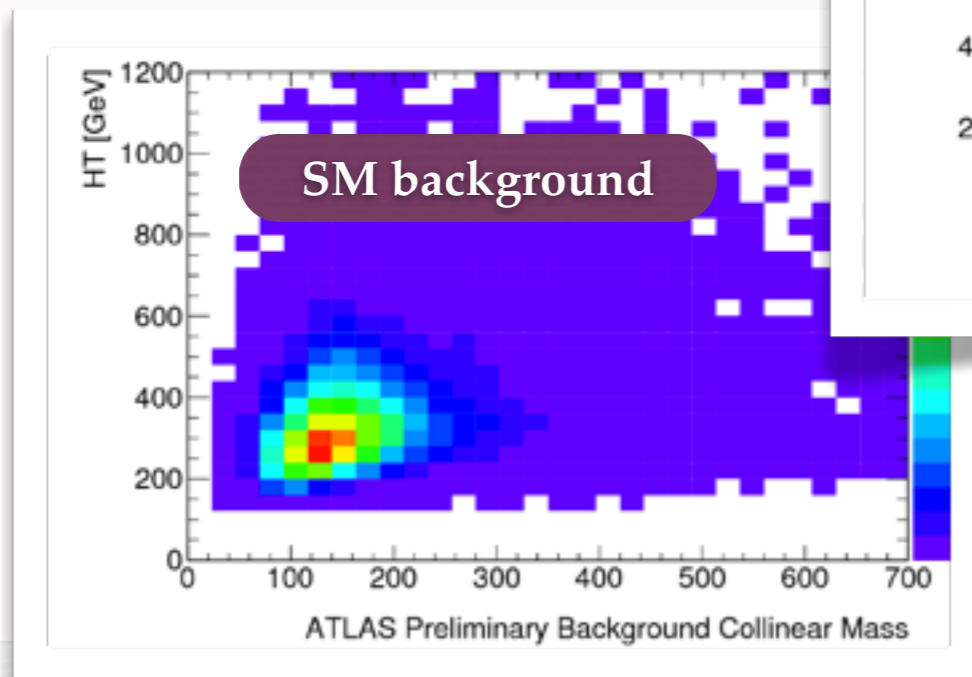
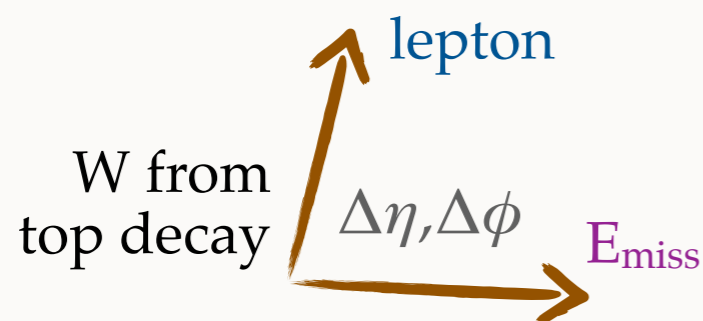


For  $t' \rightarrow bW$  decays,  
 $M(t') > 422 \text{ GeV}$  at 95% C.L.

# ATLAS SEARCH FOR

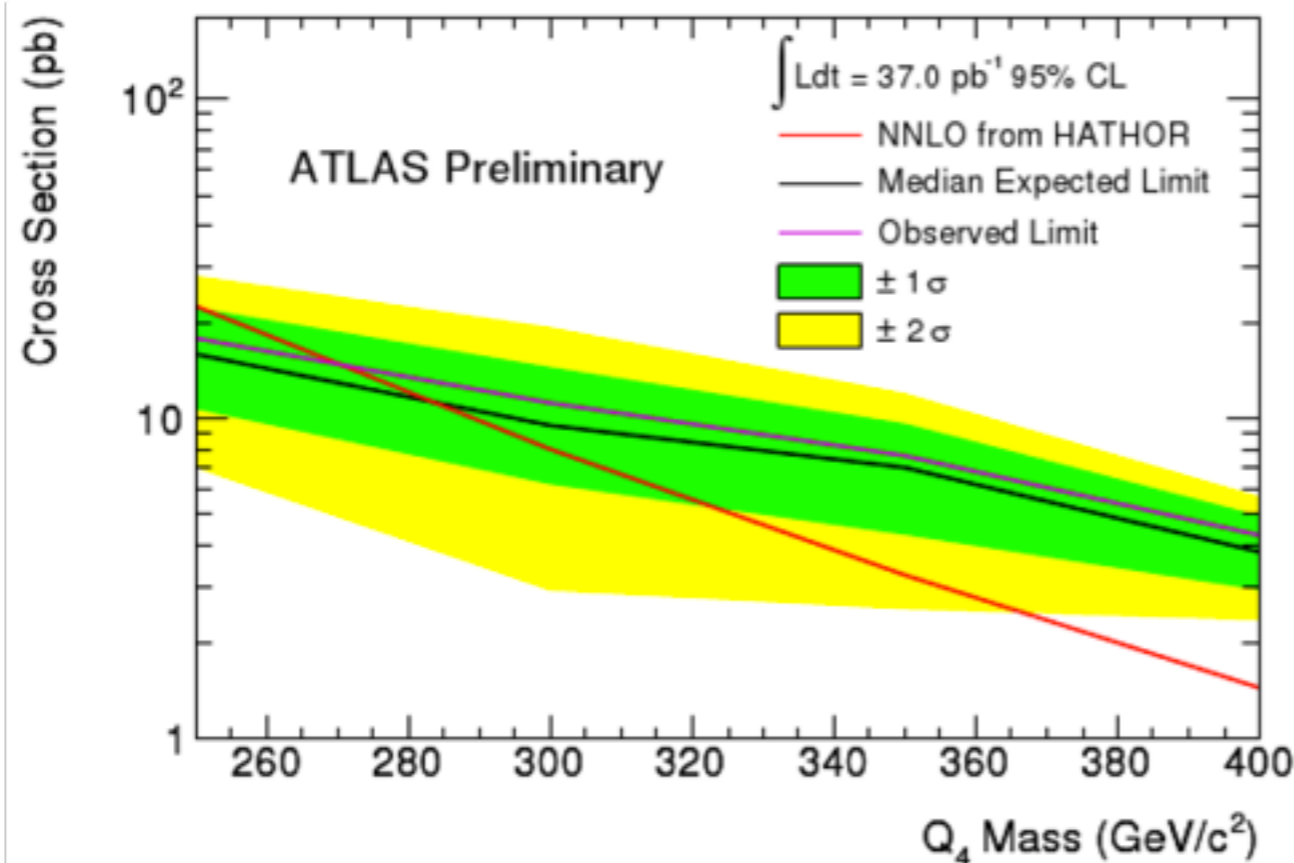
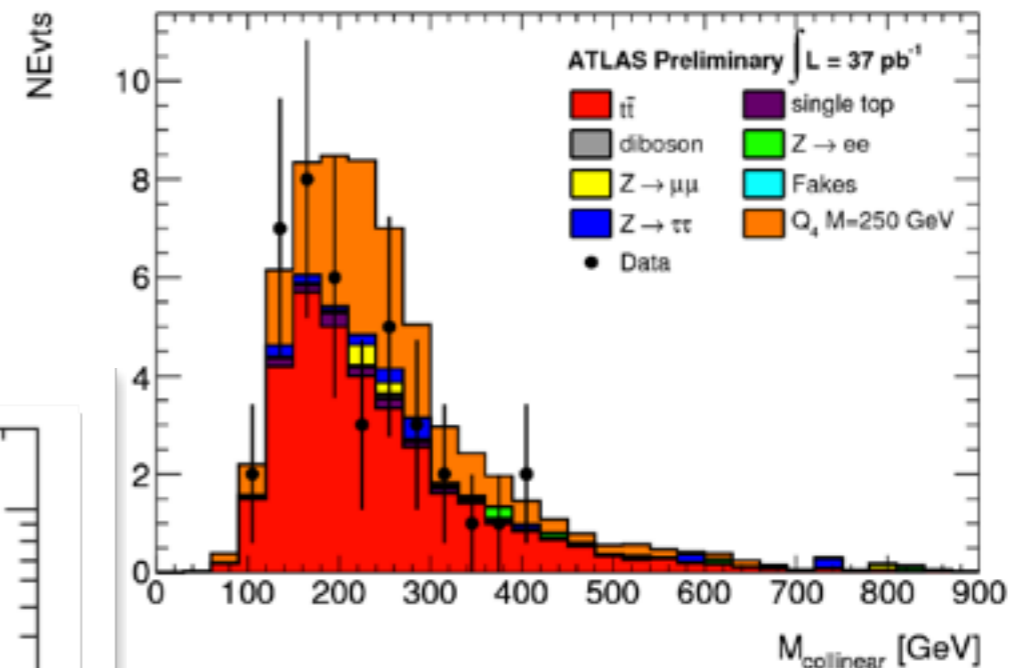
## $t' \rightarrow qW$

- Look for **dilepton events**;  $H_T$  and  $M_{\text{collinear}}$  are used as a discriminant against the SM background (e.g. top pair events).
- “Collinear Mass”: find the best  $\Delta\eta, \Delta\phi$  for each  $lv$  pair, to minimize the difference between in the two reconstructed quark masses ( $= M_{\text{collinear}}$ )



# ATLAS SEARCH FOR $t' \rightarrow qW$

- No hint of signal found in 2010 data ( $37 \text{ pb}^{-1}$ ).
- Exclusion limit obtained by fits to  $H_T$  and  $M_{\text{collinear}}$ .

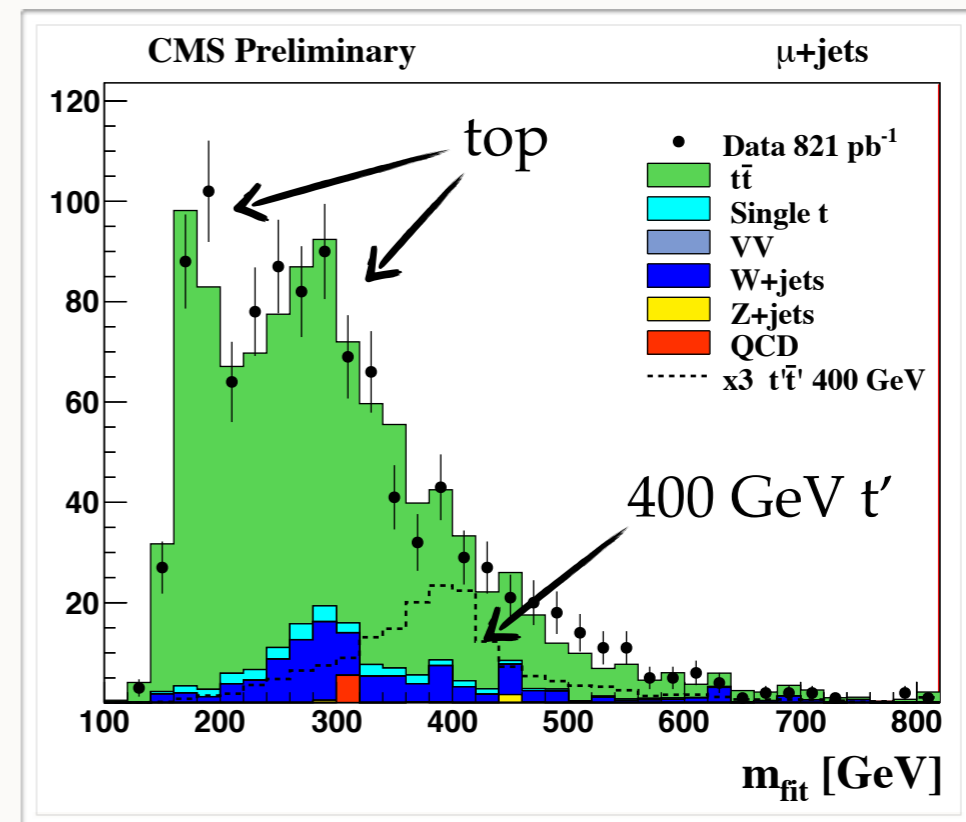
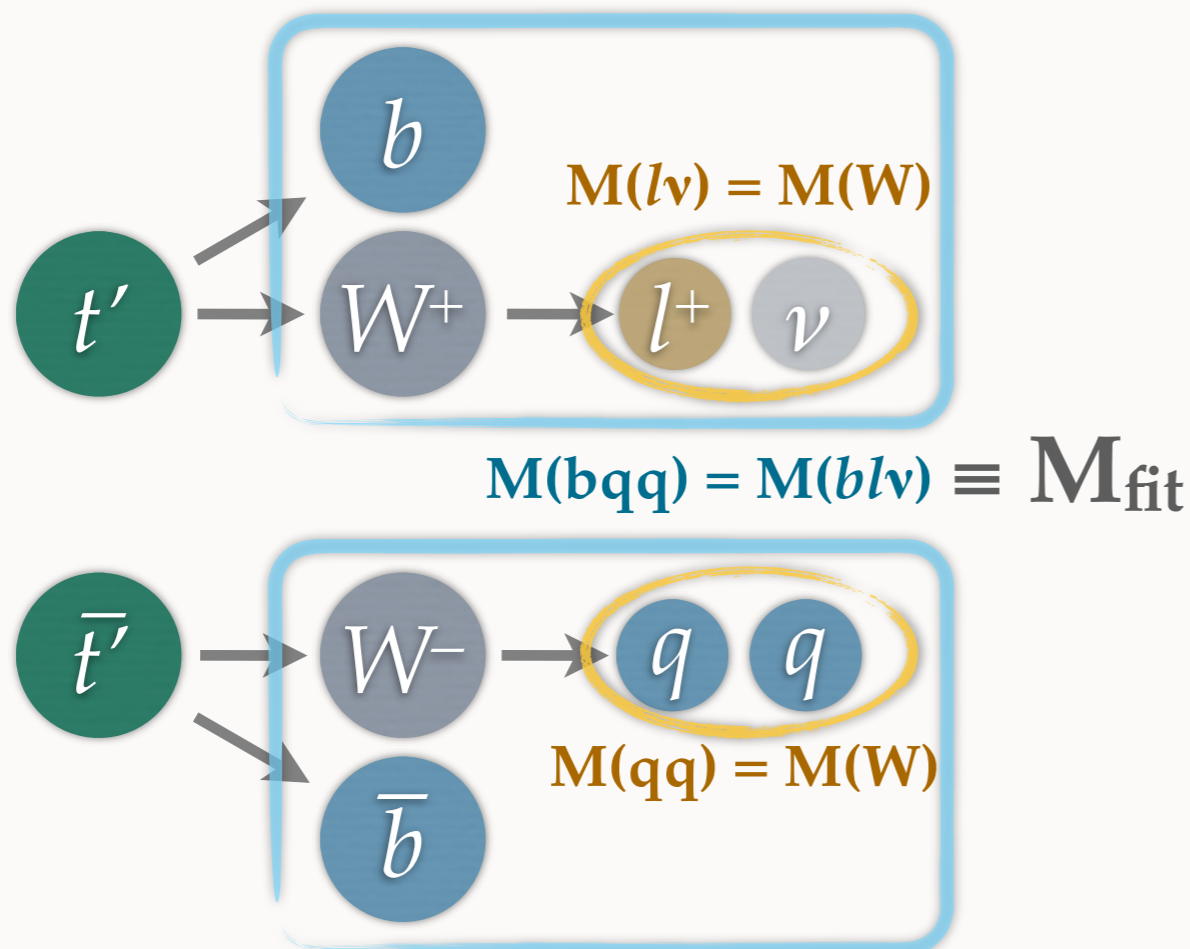


For  $t'(b') \rightarrow qW$ ,  
 $M(Q_4) > 270 \text{ GeV}$  at 95% C.L.

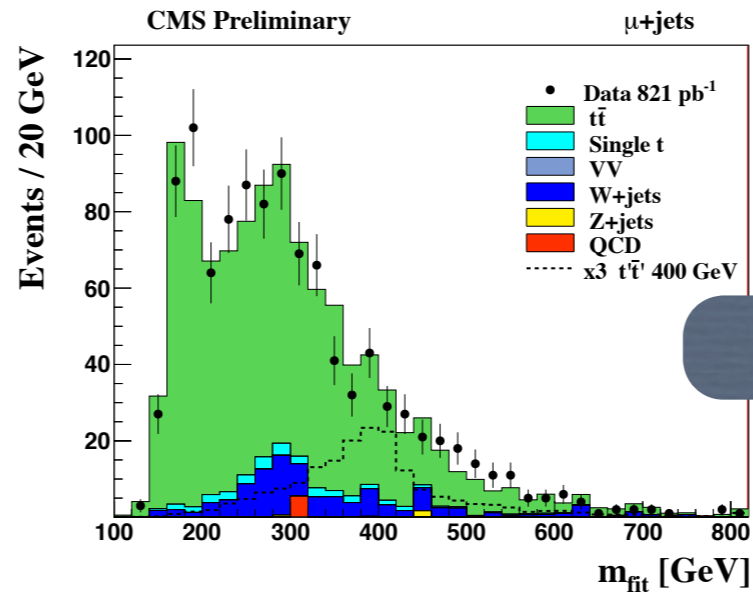
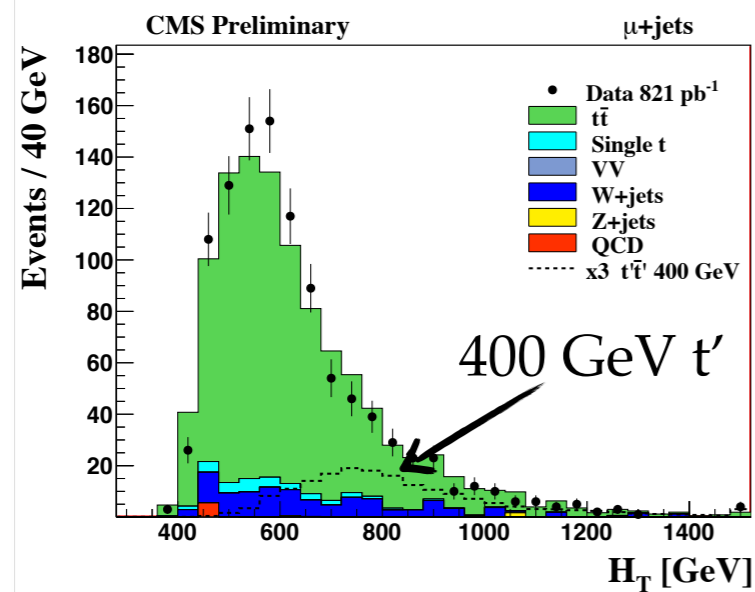
Ref: ATLAS-CONF-2011-022

# SEARCHES FOR $t' \rightarrow bW$ (lepton+jets)

- Reconstruct a pair of “Heavy Top” in lepton+jets channel.
- Select an electron or a muon,  $\geq 4$  high  $p_T$  jets, missing energy, at last one b-tagged jet.
- Kinematic fit applied for the mass reconstruction:



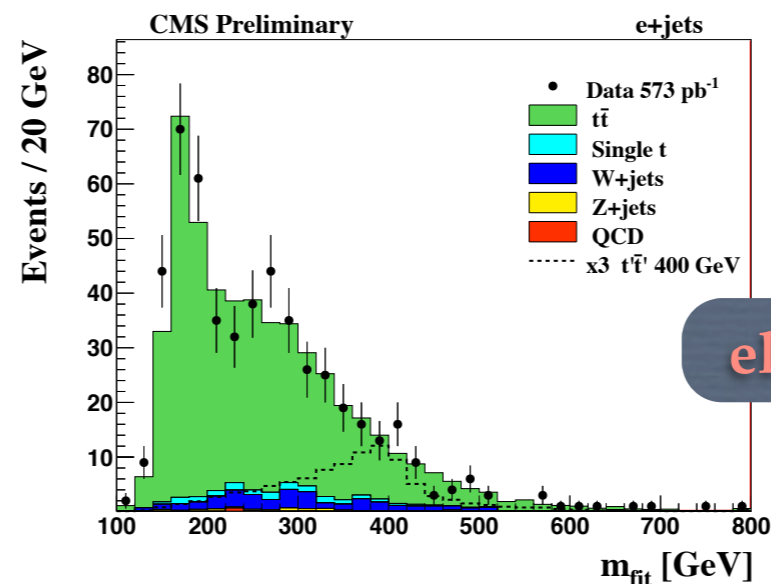
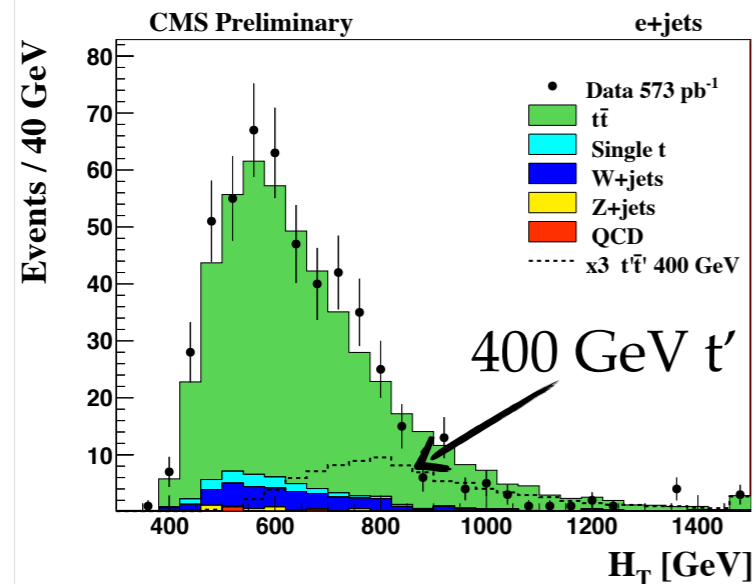
# SEARCHES FOR $t' \rightarrow bW$ (lepton+jets)



muon+jets

$M_{fit}$  and  $H_T$  are both reconstructed.

$$H_T = \sum p_T(\text{jets}) + \sum p_T(\text{leptons}) + \text{MET}$$

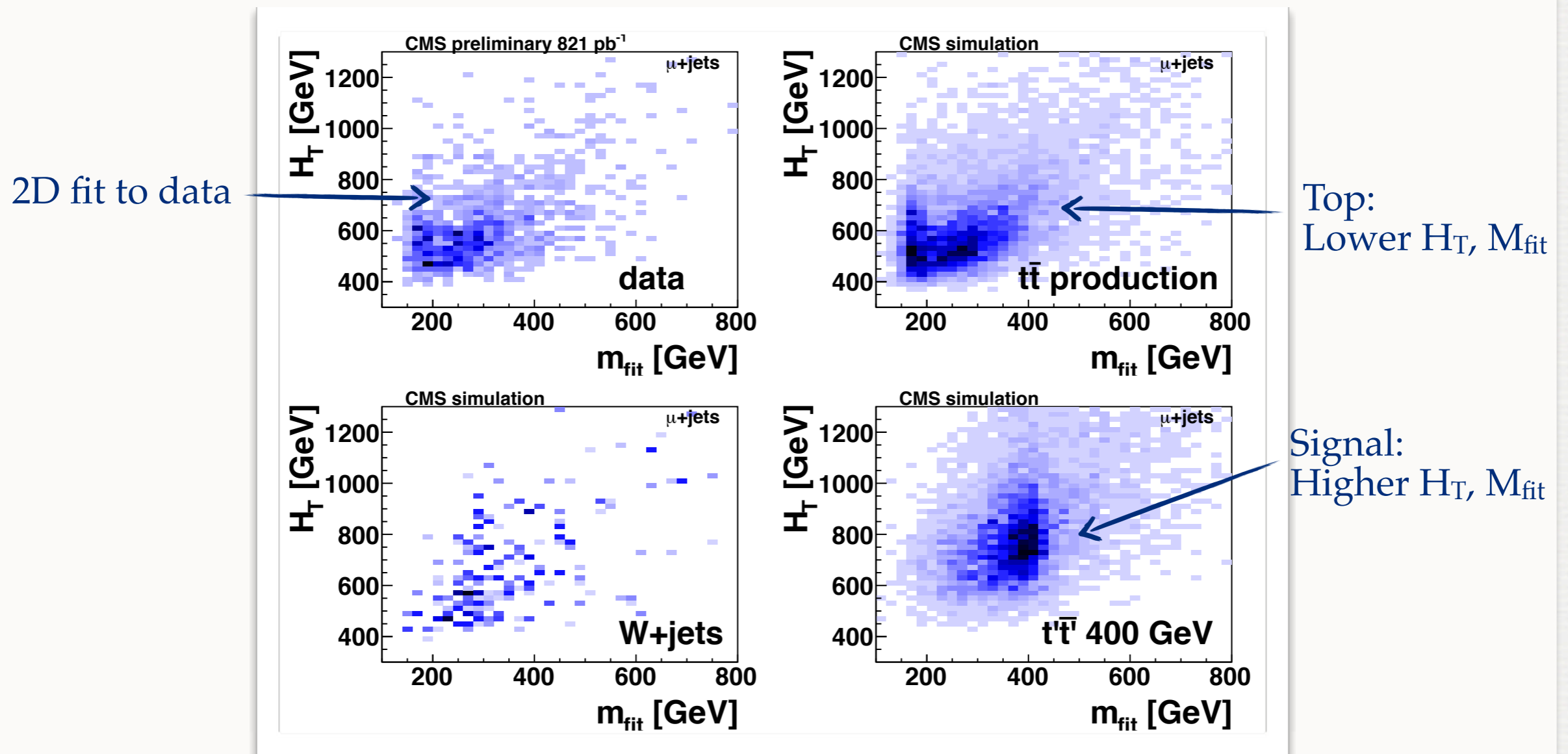


electron+jets



# SEARCHES FOR $t' \rightarrow bW$ (lepton+jets)

- Limit are extracted by 2D fits to  $H_T$  and  $M_{fit}$  including the correlations:



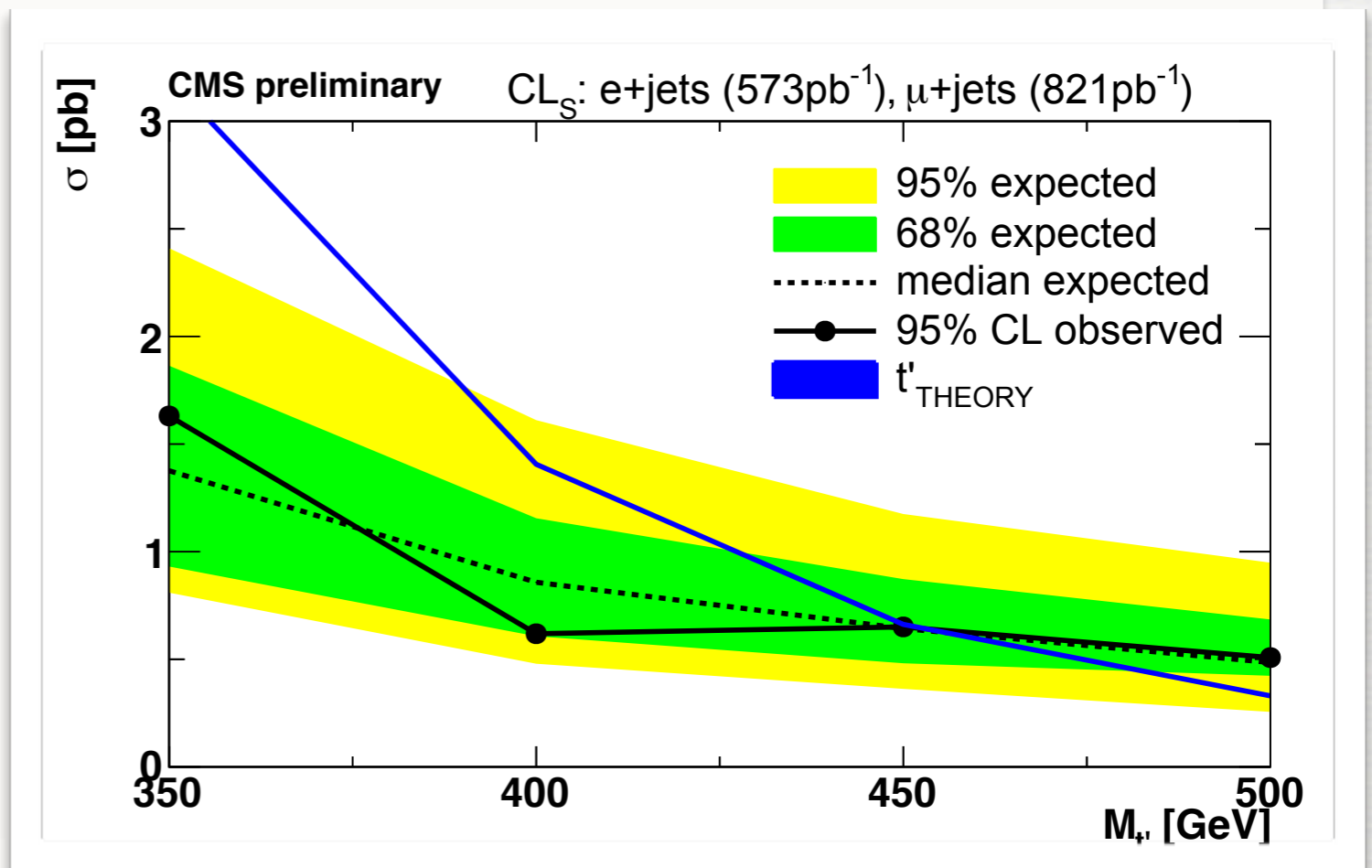
# SEARCHES FOR $t' \rightarrow bW$ (lepton+jets)

- No excess found above the SM background.
- The combined limit is determined with the CLs method.

Channel	e+jets	$\mu$ +jets
Luminosity	573 pb <sup>-1</sup>	821 pb <sup>-1</sup>
Total background	510 ± 103	1054 ± 145
Data	520	1054



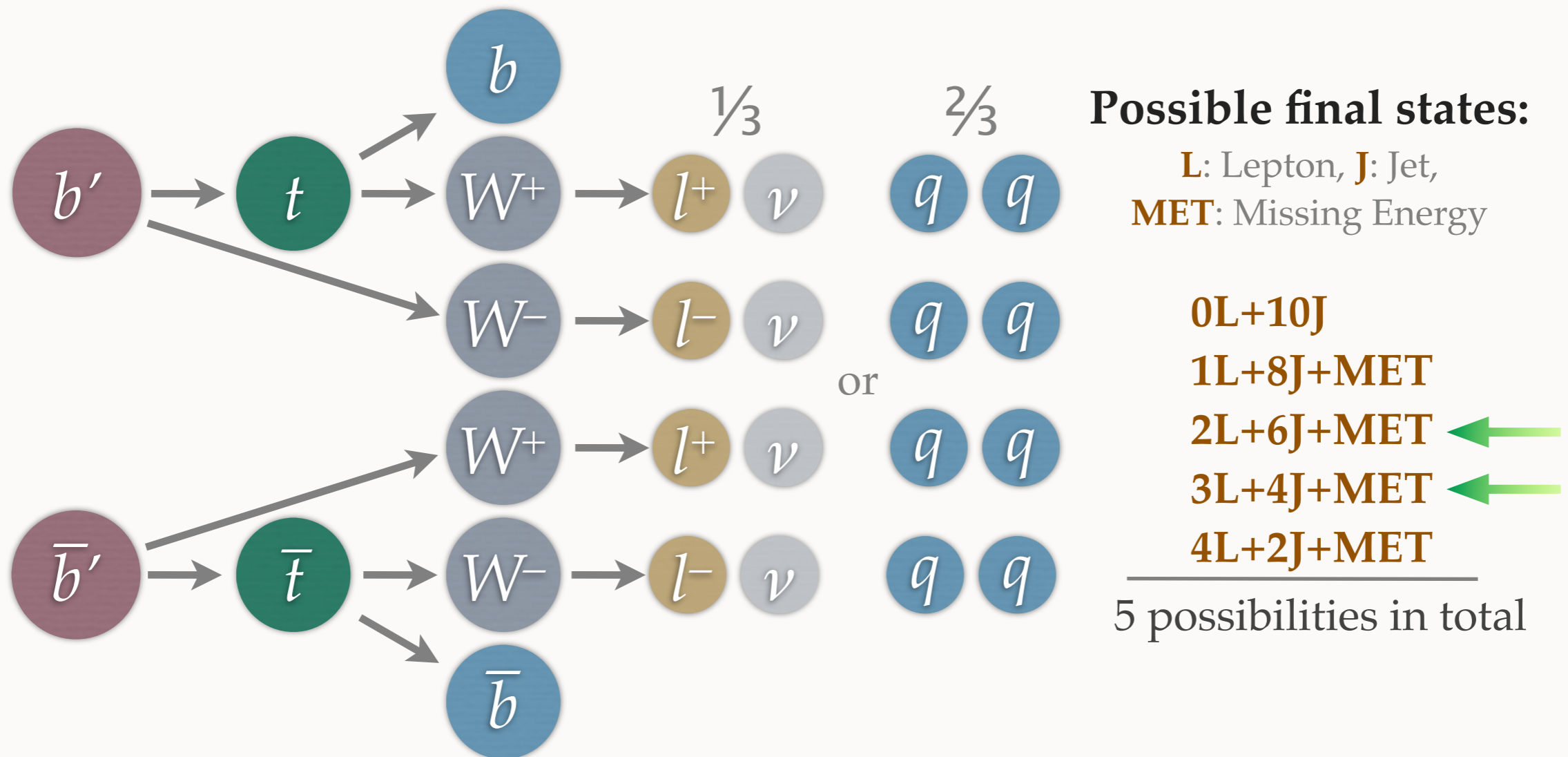
Ref: CMS-EXO-11-051



For  $t' \rightarrow bW$ ,  
 $M(t') > 450$  GeV at 95% C.L.

# SEARCHES FOR $b' \rightarrow tW$

The full decay chain:  $b'b' \rightarrow tWtW \rightarrow bbW^+W^-W^+W^-$  (4 W-bosons + 2 b-jets)



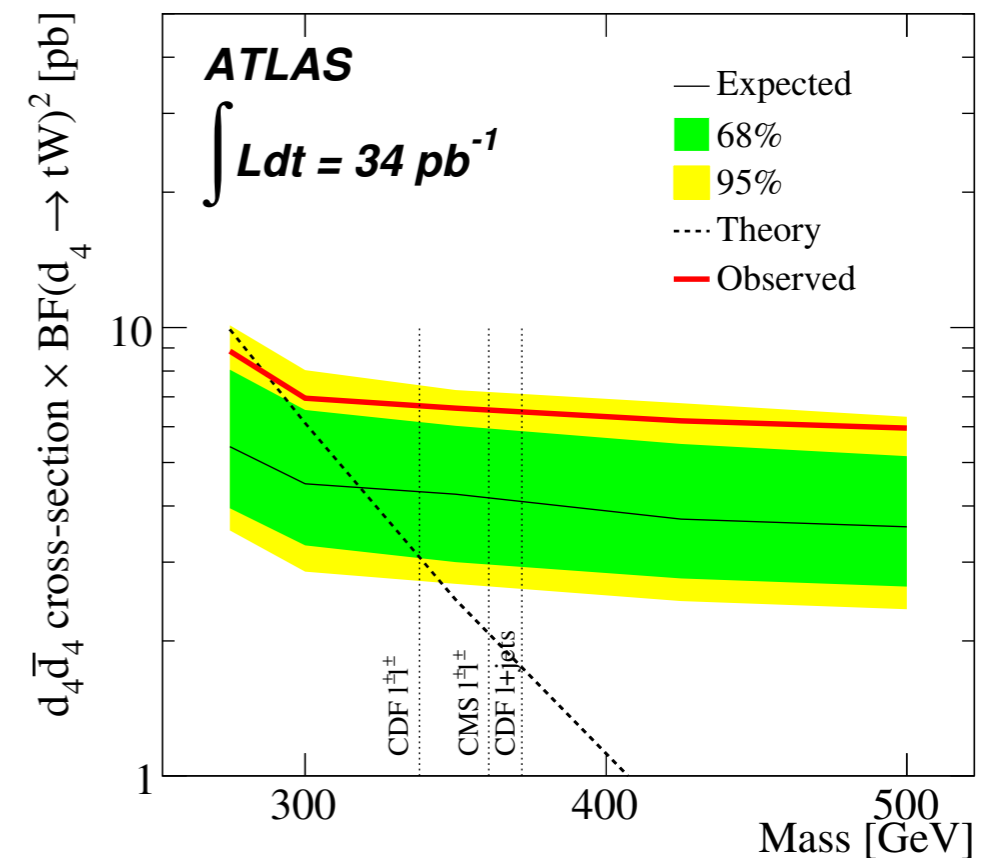
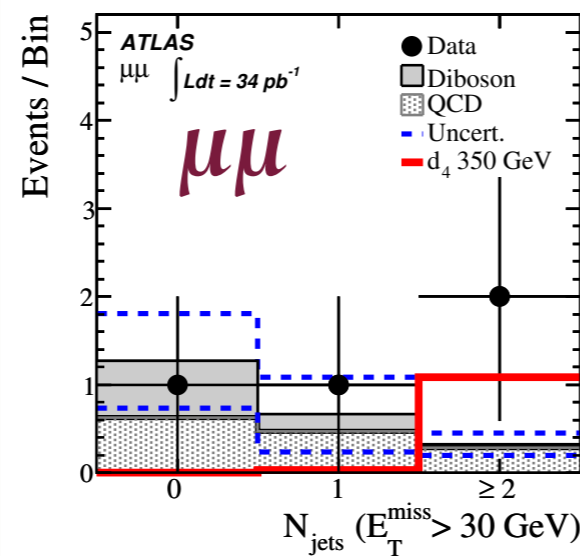
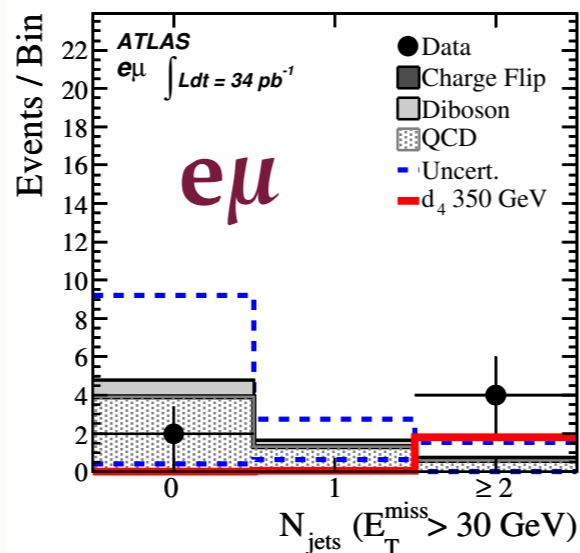
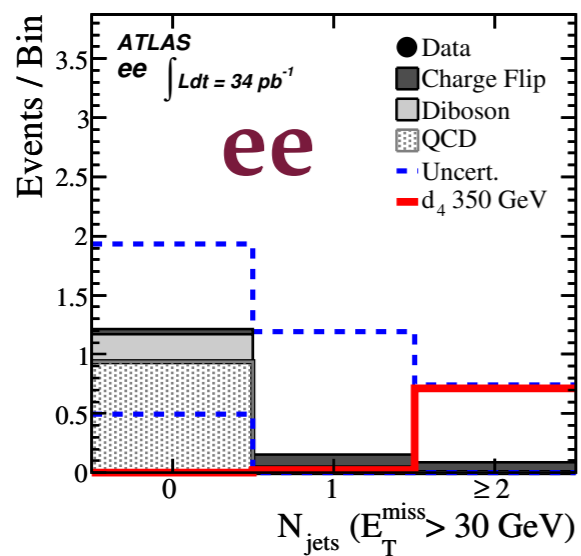
Look for clean signatures: **trilepton** and **same-sign dilepton** events.

# ATLAS SEARCHES FOR $b' \rightarrow tW$

- Generic same-sign dilepton + MET signature searches:

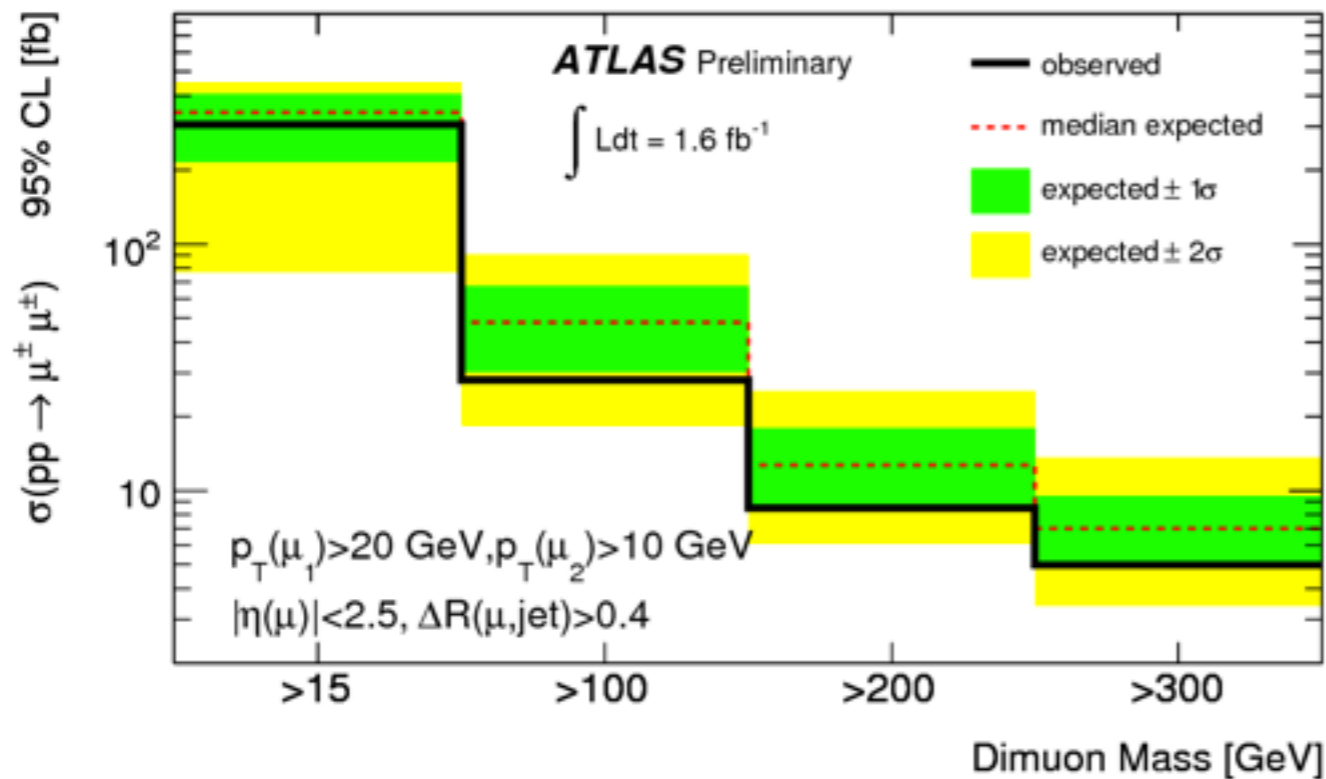


Ref: arXiv: 1108.0366



For  $b' \rightarrow tW$  decays,  
 $M(b') > 290$  GeV at 95% C.L.

# ATLAS SEARCHES FOR SAME-SIGN DIMUON



ATLAS-CONF-2011-126

Mass range [GeV]	95% C.L. limit on dimuon pair $\sigma$ [fb]	
	expected	observed
$m_{\mu\mu} > 15 \text{ GeV}$	$341^{+67}_{-125}$	304
$m_{\mu\mu} > 100 \text{ GeV}$	$48^{+20}_{-18}$	28
$m_{\mu\mu} > 200 \text{ GeV}$	$12.6^{+5.3}_{-4.2}$	8.5
$m_{\mu\mu} > 300 \text{ GeV}$	$7.0^{+2.5}_{-2.0}$	5.0

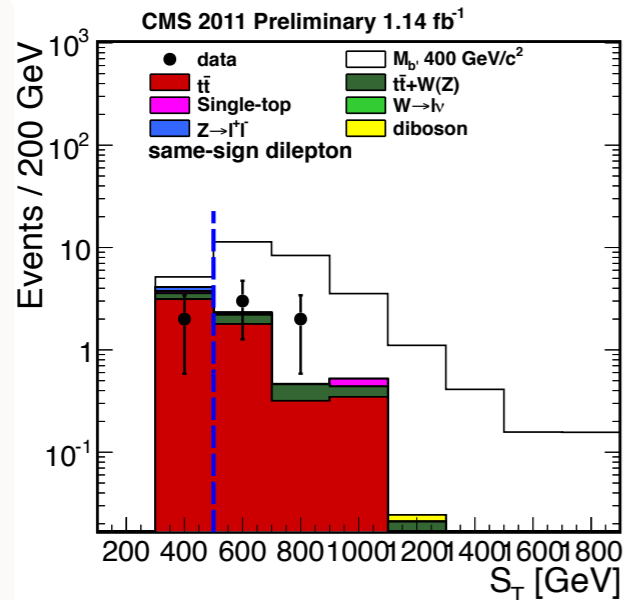
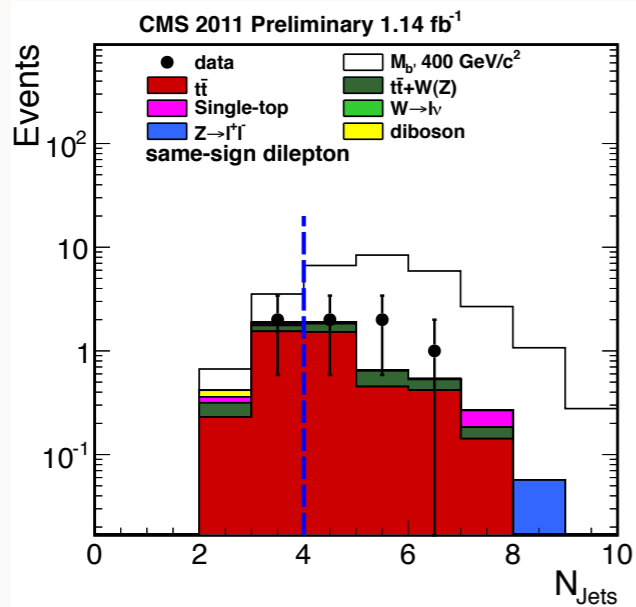
*(no excess found...)*

- A generic same-sign dimuon searches.
- Scan over dimuon mass, and set limits on the dimuon cross sections.

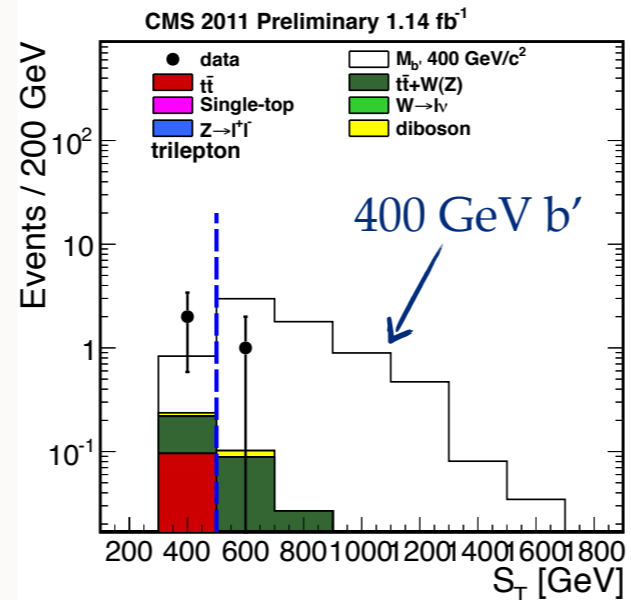
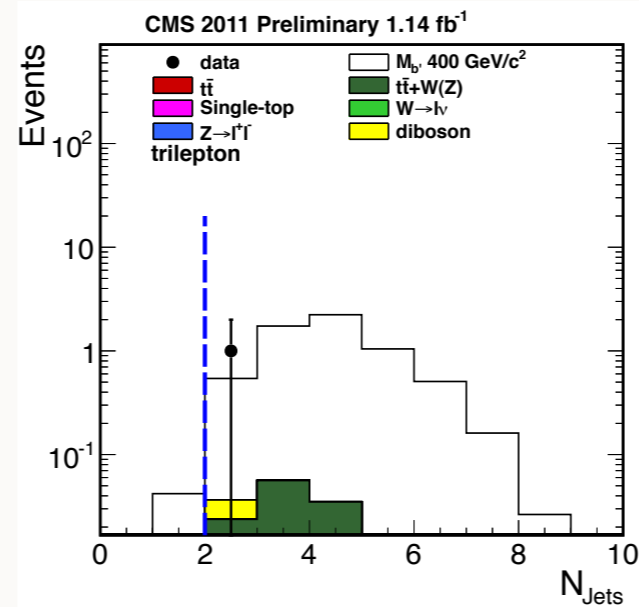
One may convert these limits to the mass of 4G, or some SUSY signatures, etc.

# CMS SEARCH FOR $b' \rightarrow tW$

*same-sign 2L +  $\geq 4$  jets*



*3L +  $\geq 2$  jets*



- Select “trilepton + jets” & “same-sign dilepton + jets” events.
- At least 1 b-jet.
- Very clean signature; almost no SM background.
- Reconstruct  $S_T$ :

$$S_T = \sum p_T(\text{jets}) + \sum p_T(\text{leptons}) + \text{MET}$$

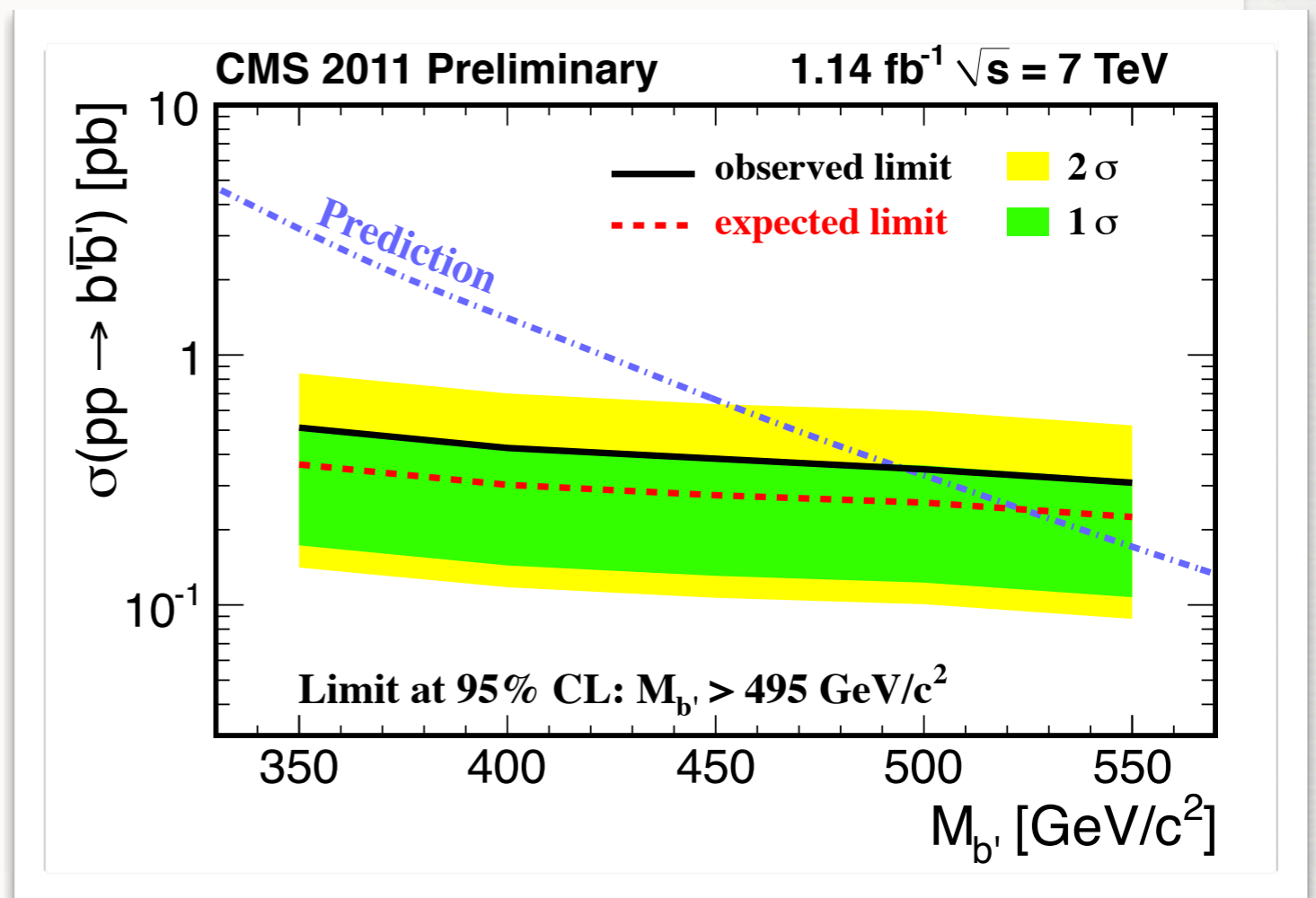
# CMS SEARCH FOR $b' \rightarrow tW$

- Simple counting analysis.
- Exclusion limit is obtained with a Bayesian method.

Channel	SS2L	3L
$b'(400 \text{ GeV}/c^2)$	22	6.7
Estimated background	$4.4 \pm 1.4$	$0.16 \pm 0.09$
Data	5	1



Ref: CMS-EXO-11-036



For  $b' \rightarrow tW$  decays,  
 $M(b') > 495 \text{ GeV}$  at 95% C.L.

# CMS INCLUSIVE b'/t' SEARCHES

- Addressing the following points:
  - Why not looking for b' / t' at the same time, since they should show up together?
  - How about the single productions?
- We can only scan for two parameters at once.

Assumptions have to be made:

- Degenerate 4G:  $M(t') = M(b')$ , no  $t' \leftrightarrow b'$  transitions.
- Simplify  $V_{CKM4}$ , with only one free parameter  $A = |V_{tb}|^2 = |V_{t'b'}|^2$ .

$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & \sqrt{A} & \sqrt{1-A} \\ 0 & 0 & \sqrt{1-A} & \sqrt{A} \end{pmatrix}$$

Scanning parameters:

$$M_{t'}=M_{b'}, A$$

This will produce the following processes:

$$bt' \rightarrow bbW$$

$$b't \rightarrow tWbW \rightarrow bbWWW$$

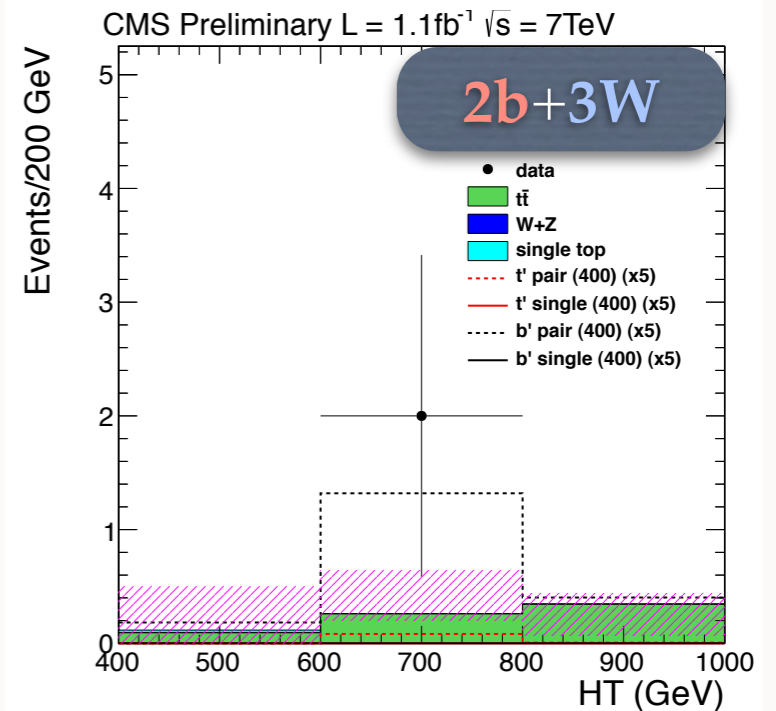
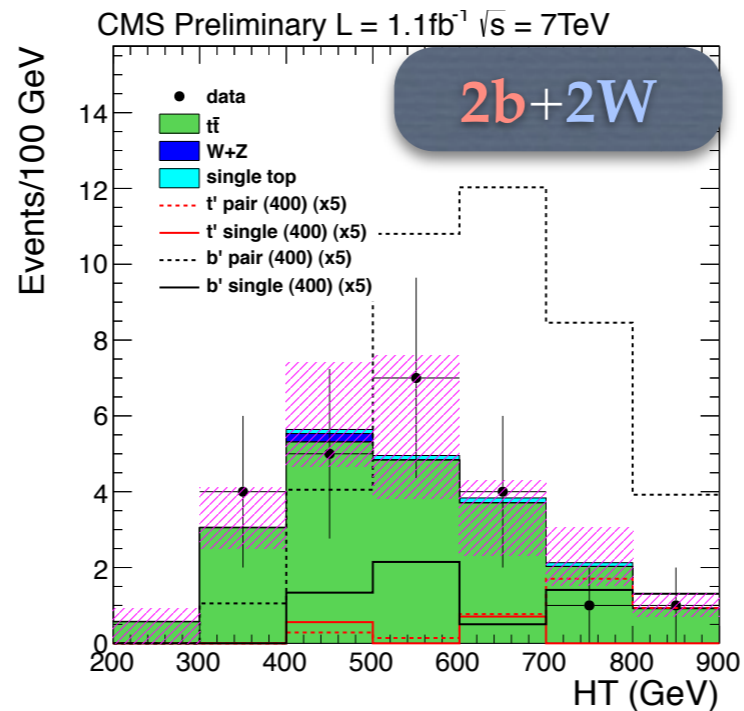
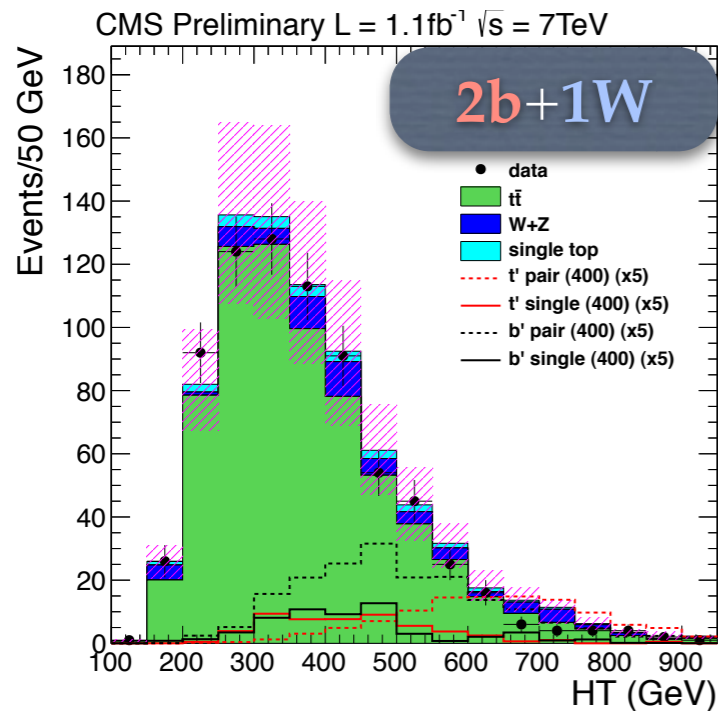
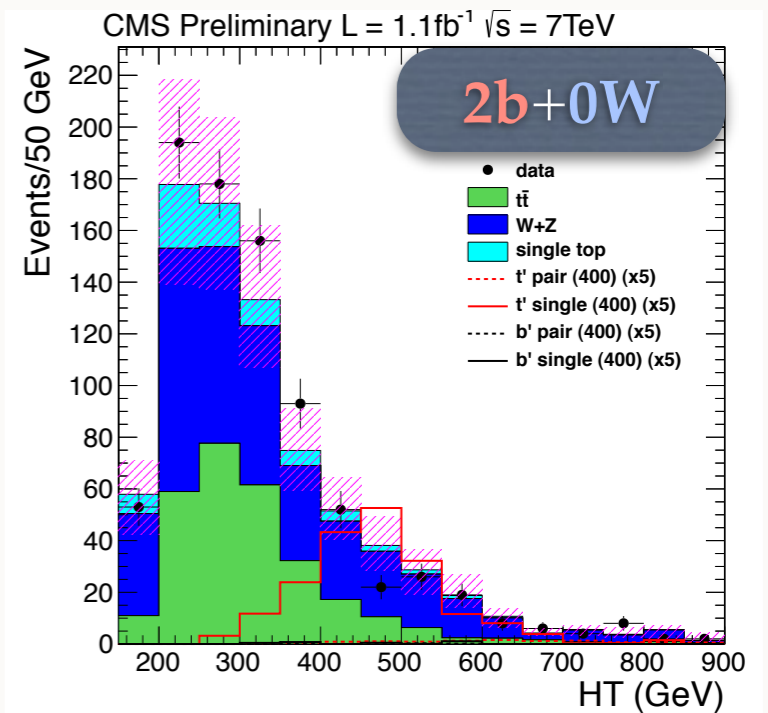
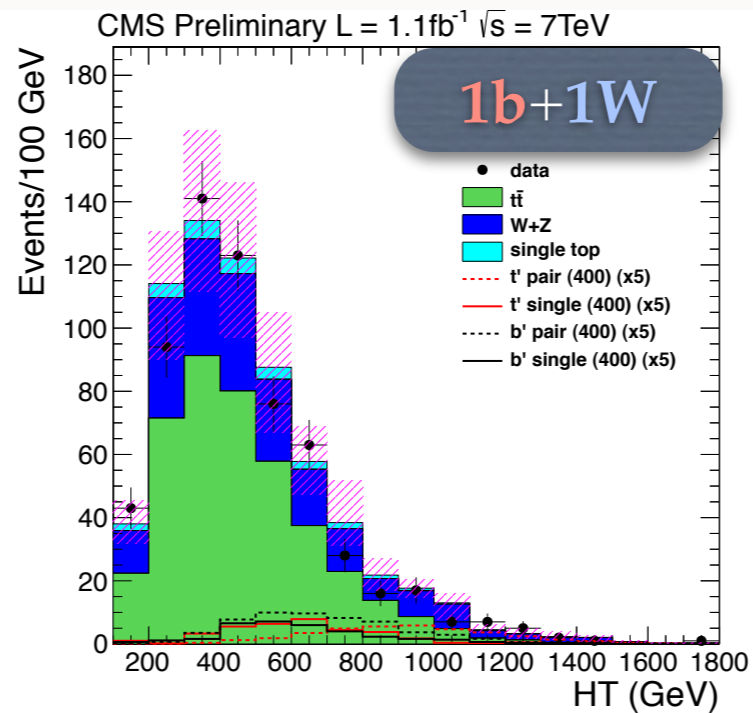
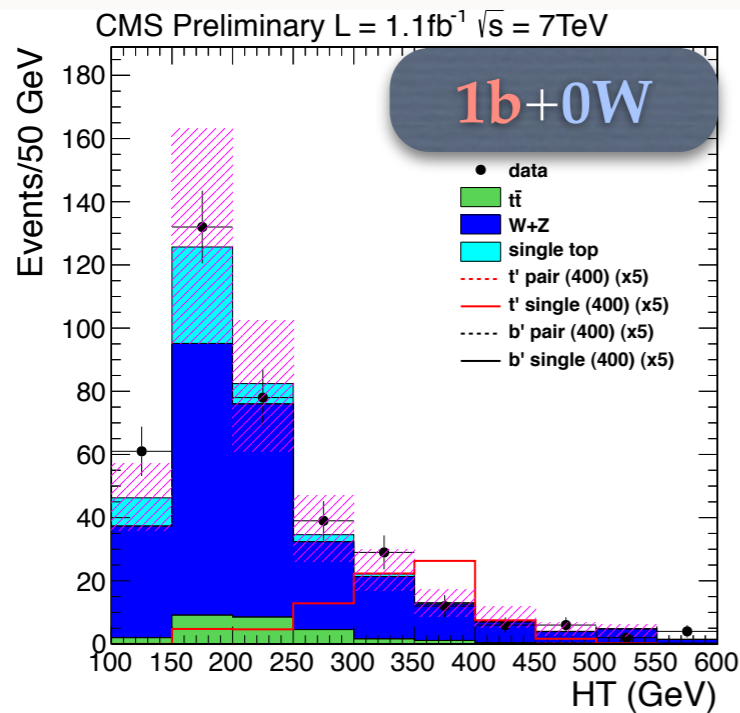
$$t't' \rightarrow bbWW$$

$$b'b' \rightarrow tWtW \rightarrow bbWWWW$$

reconstruct whatever  $bb+1\sim 4W$ 's

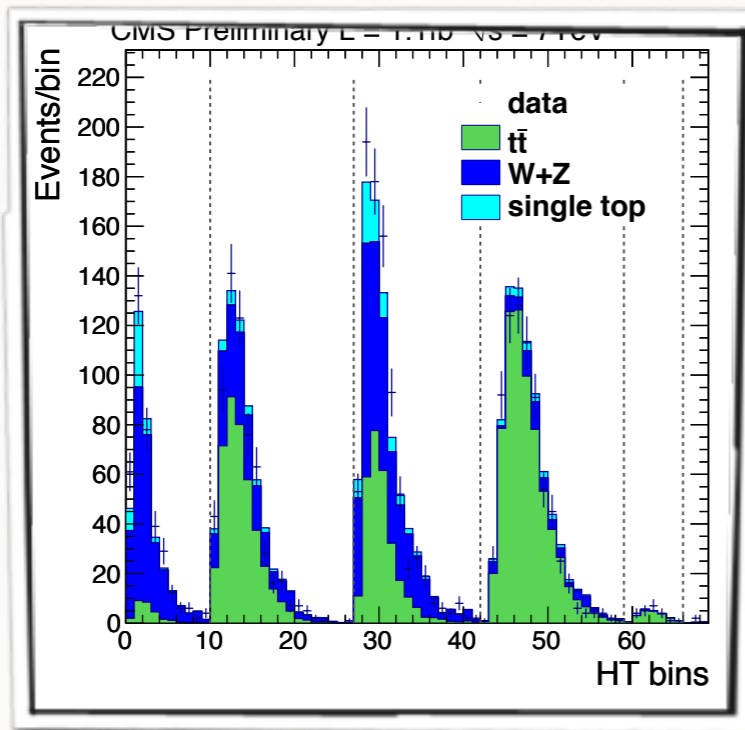


- Select one muon (from the  $W \rightarrow \mu\nu$  decays) + jets.
- Categorize events according to # of b-jets and # of hadronic W:

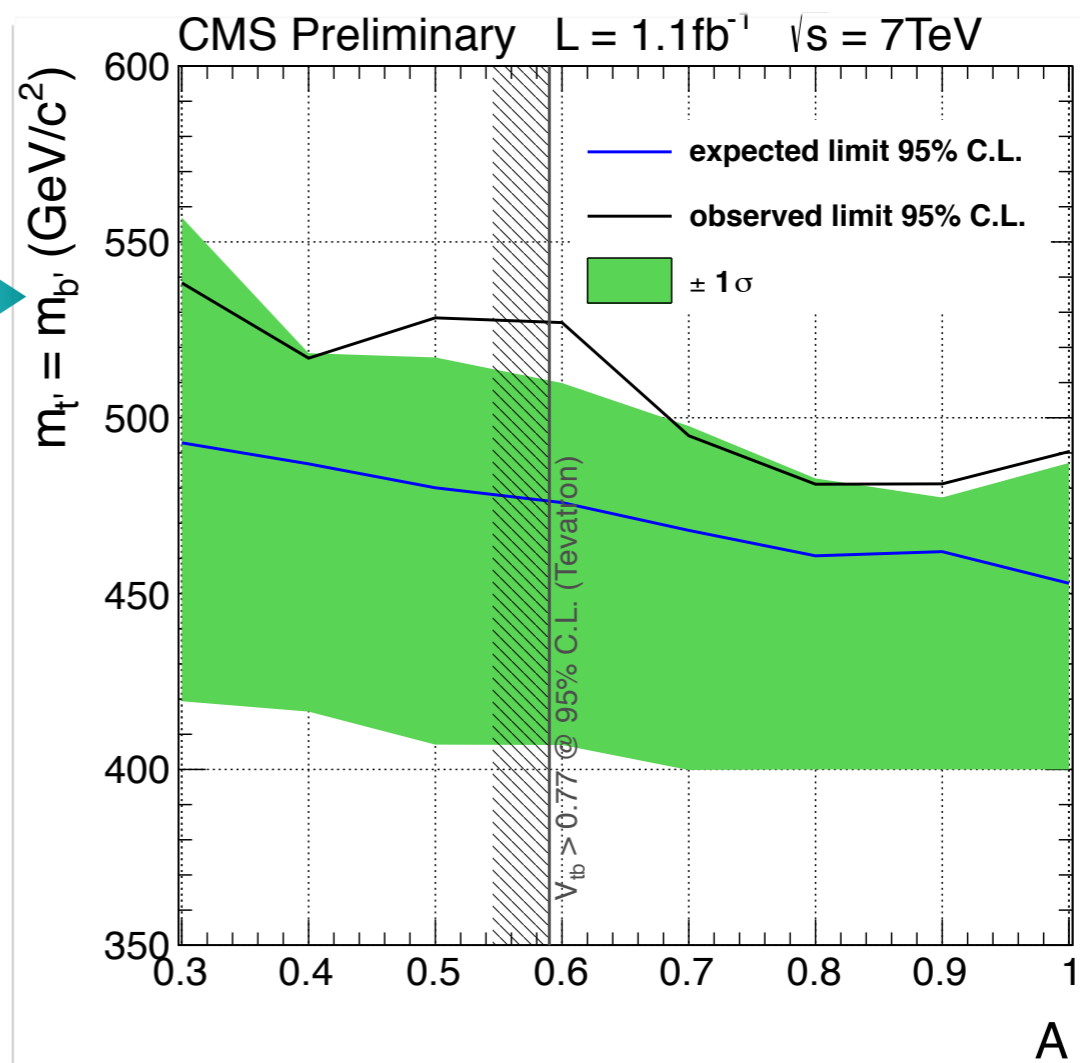


# CMS INCLUSIVE $b'/t'$ SEARCHES

- Fit to binned HT templates;
- Scan the mass limit as a function of A.



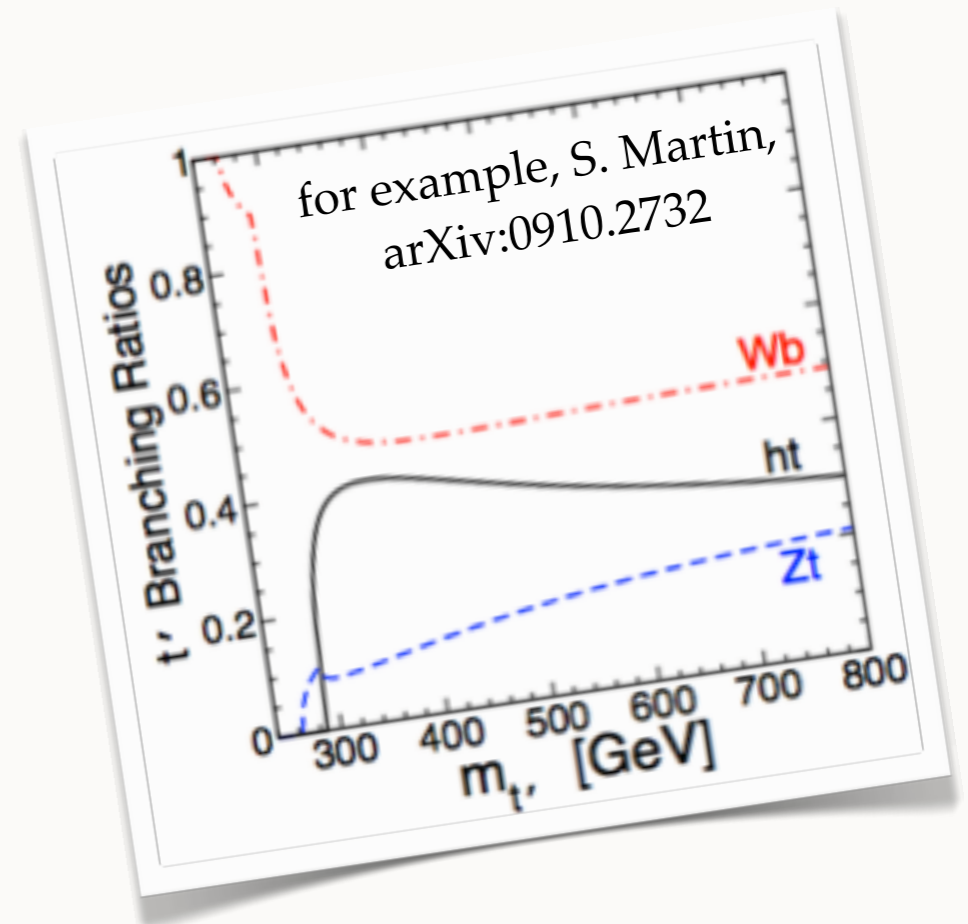
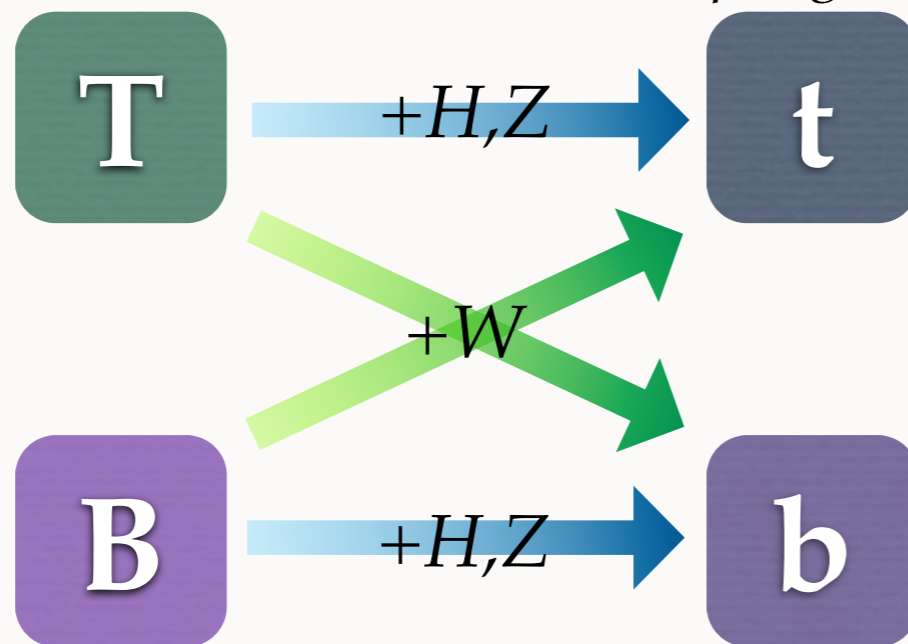
Ref: CMS-EXO-11-054



For  $M(b')=M(t')$  and  $A=|V_{tb}|^2=|V_{t'b'}|^2 \sim 1$ ,  
 $M > 490 \text{ GeV}$  at 95% C.L.

# SIGNATURES OF VECTOR-LIKE QUARKS

*FCNC or vector-like quark  
with H/Z tree-level coupling*



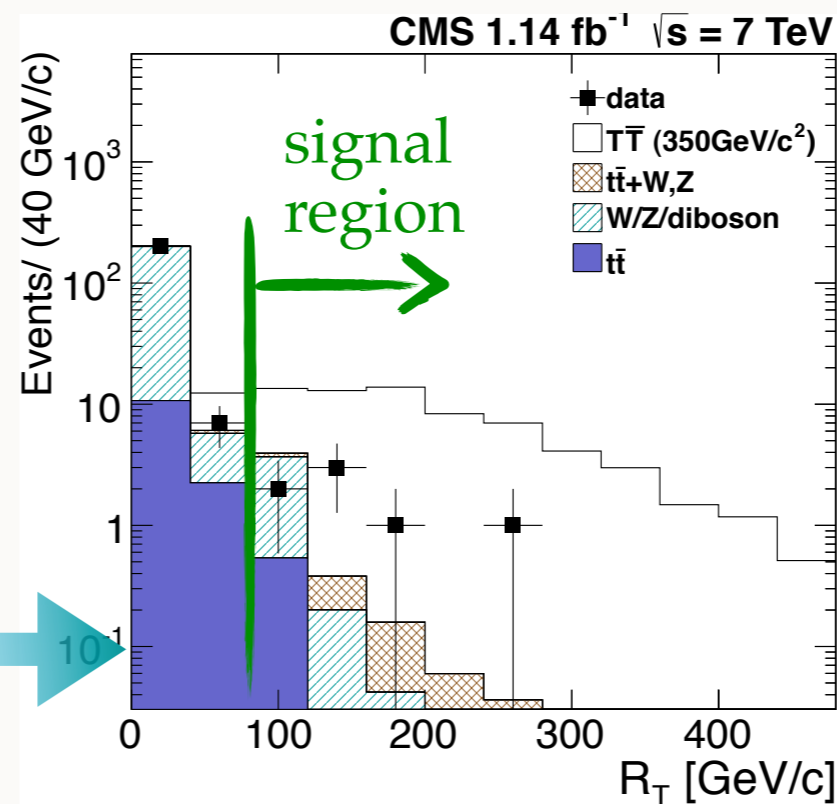
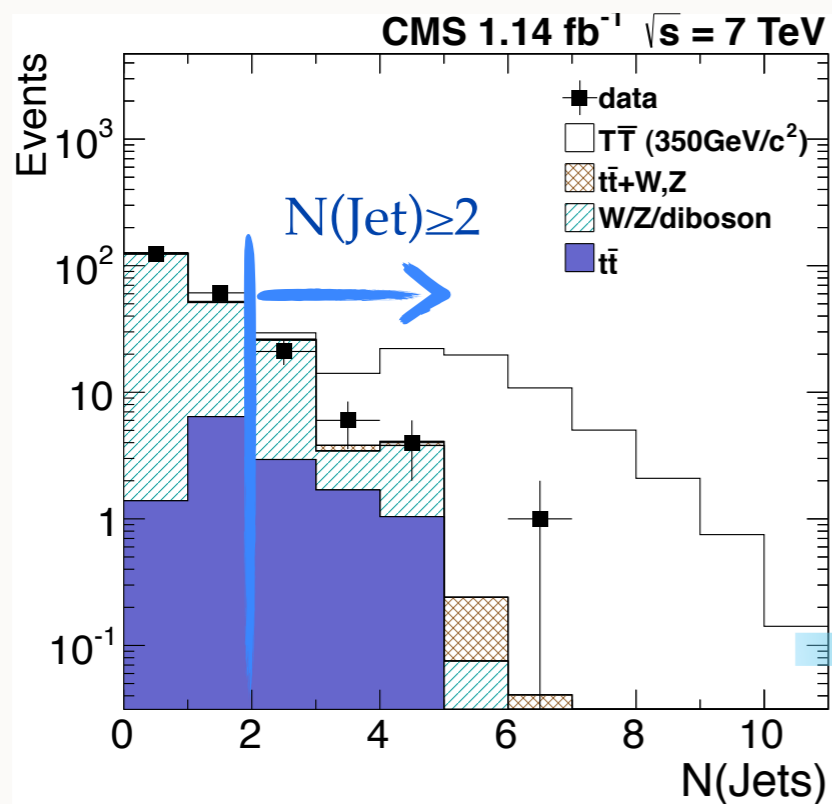
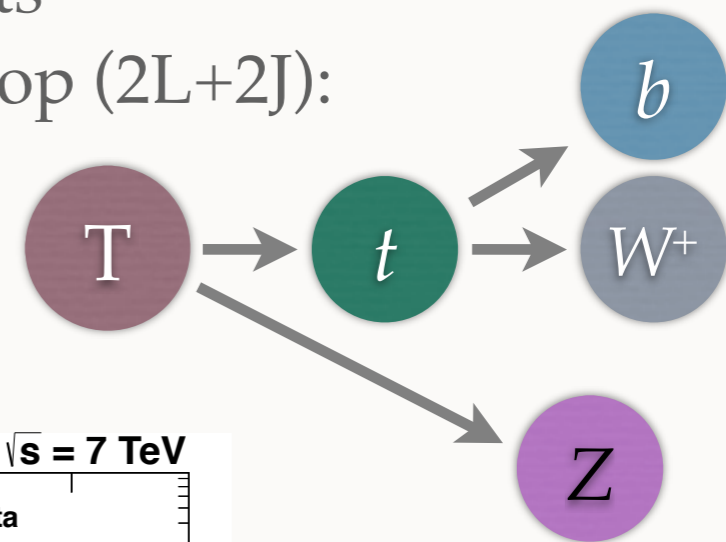
Decay signatures for direct searches:

- **T/B  $\rightarrow$  bW, tW :**  
not really different from the sequential 4G quark searches.
- **T  $\rightarrow$  tH, tZ / B  $\rightarrow$  bH, bZ :** FCNC decays from sequential 4G quarks, or vector-like quark with enhanced branching fractions.

# CMS SEARCH FOR VECTOR-LIKE QUARK

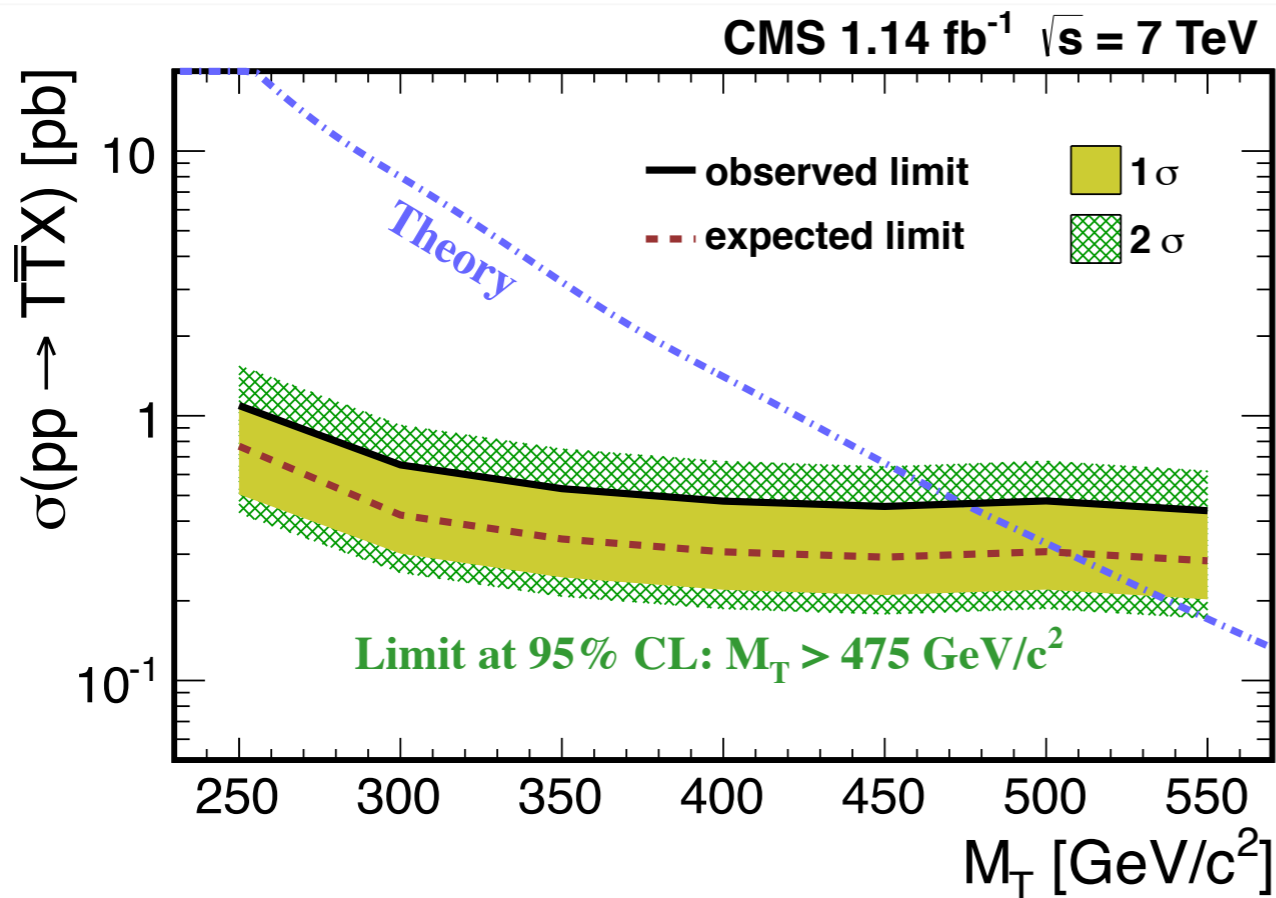
- Tag a  $Z(\rightarrow l^+l^-)$  + another isolated lepton + 2 jets
- Reconstruct a special variable to concentrate top (2L+2J):

$$R_T = \sum p_T(\text{jets, excluding leading 2}) + \sum p_T(\text{leptons, excluding leading 2})$$



*keep top background close to lower residual  $S_T$ .*

# CMS SEARCH FOR VECTOR-LIKE QUARK



- No real excess observed.
- Limited determined by the Bayesian approach assuming a 100% branching fraction.

	Yield
T(350 GeV / c <sup>2</sup> )	58
Estimated background	4.6 ± 1.0
Data	7

For 100%  $T \rightarrow tZ$  decays,  
 $M(T) > 475$  GeV at 95% C.L.



arXiv:1109.4985  
 accepted by PRL

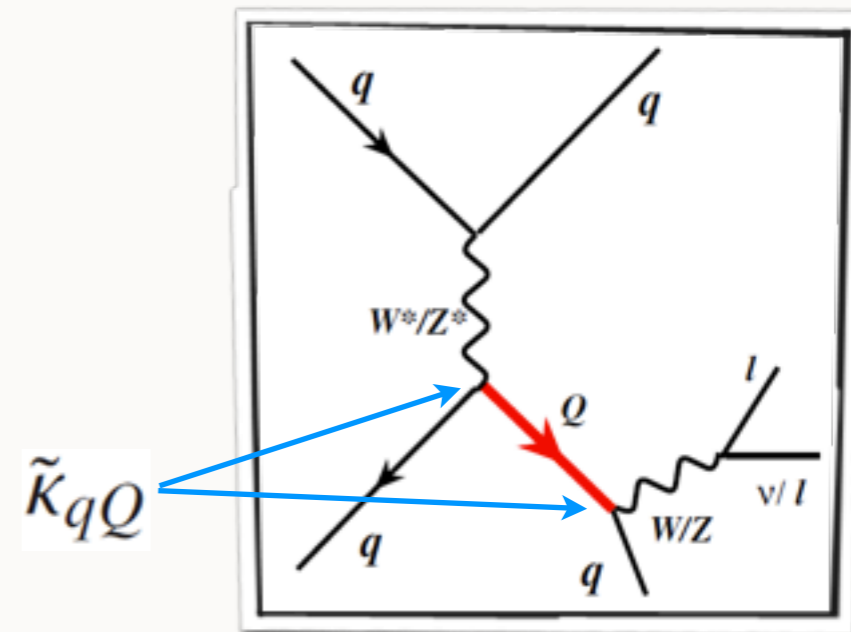
# ATLAS SEARCH FOR VECTOR-LIKE QUARK

- In some extra-dimension models, the vector-like quarks could (strongly) couple to the light generation quarks, leading to a sizable signal at the LHC:

The most promising channel could be the single production (mostly t-channel)

$$qq \rightarrow (W^*, Z^*) \rightarrow qQ,$$
$$\text{and } Q \rightarrow qW, qZ$$

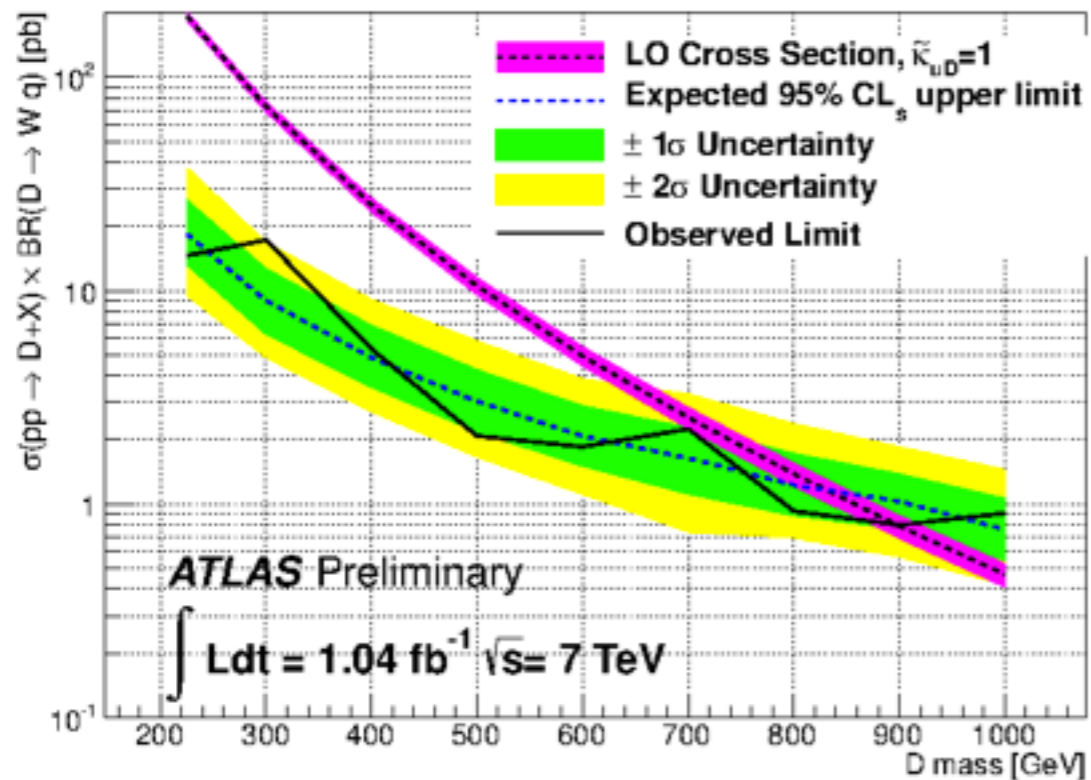
assuming  $\tilde{K}_{qQ} = 1$



- Assuming strong coupling + 100% branching fractions.
- Select a  $W(\rightarrow l\nu)$  or  $Z(\rightarrow ll)$  plus 2 jets, and reconstruct the corresponding quark mass.

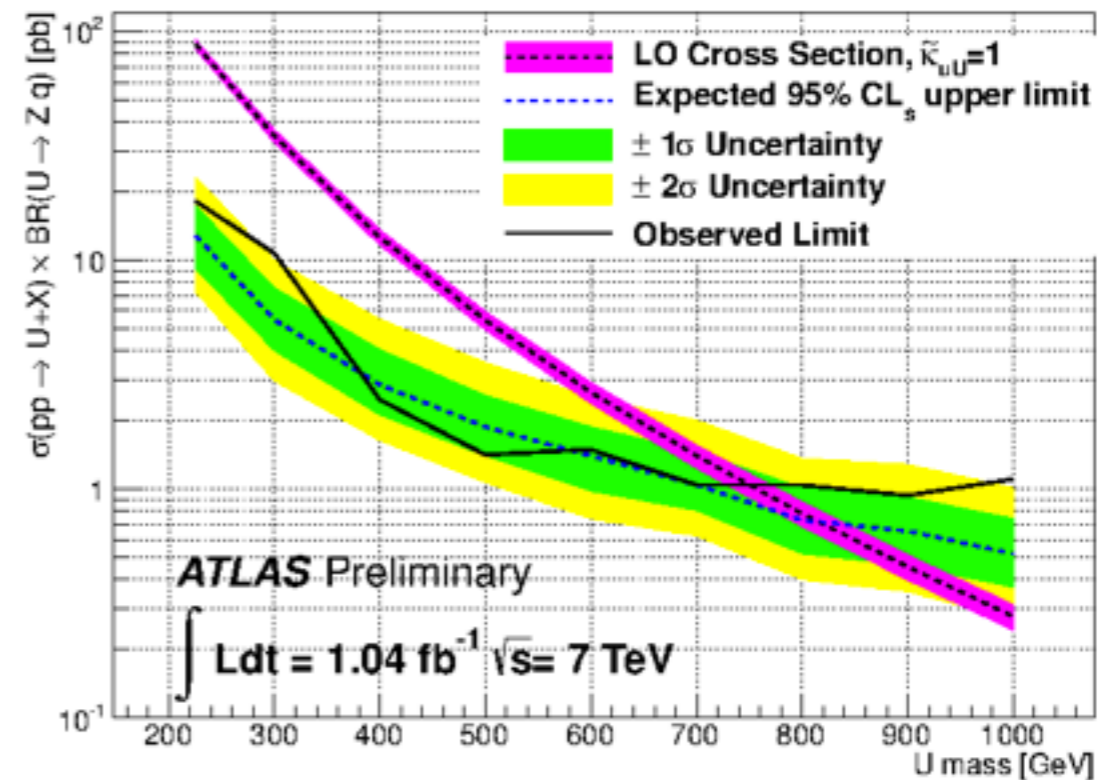
# ATLAS SEARCH FOR VECTOR-LIKE QUARK

## Charge Current (Wj)



For 100%  $D \rightarrow Wq$  decays,  
 $M(D) > 900$  GeV at 95% C.L.

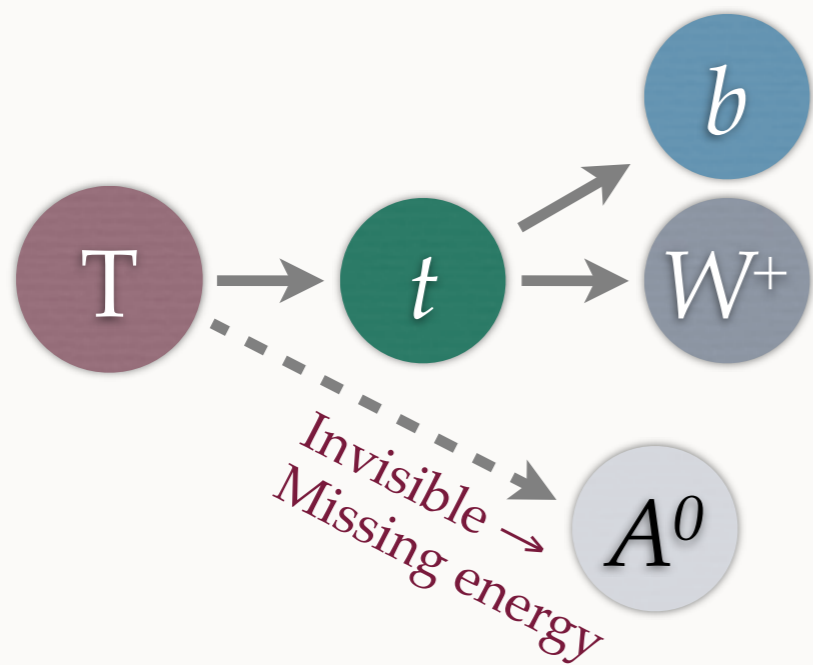
## Neutral Current (Zj)



For 100%  $U \rightarrow Zq$  decays,  
 $M(U) > 760$  GeV at 95% C.L.

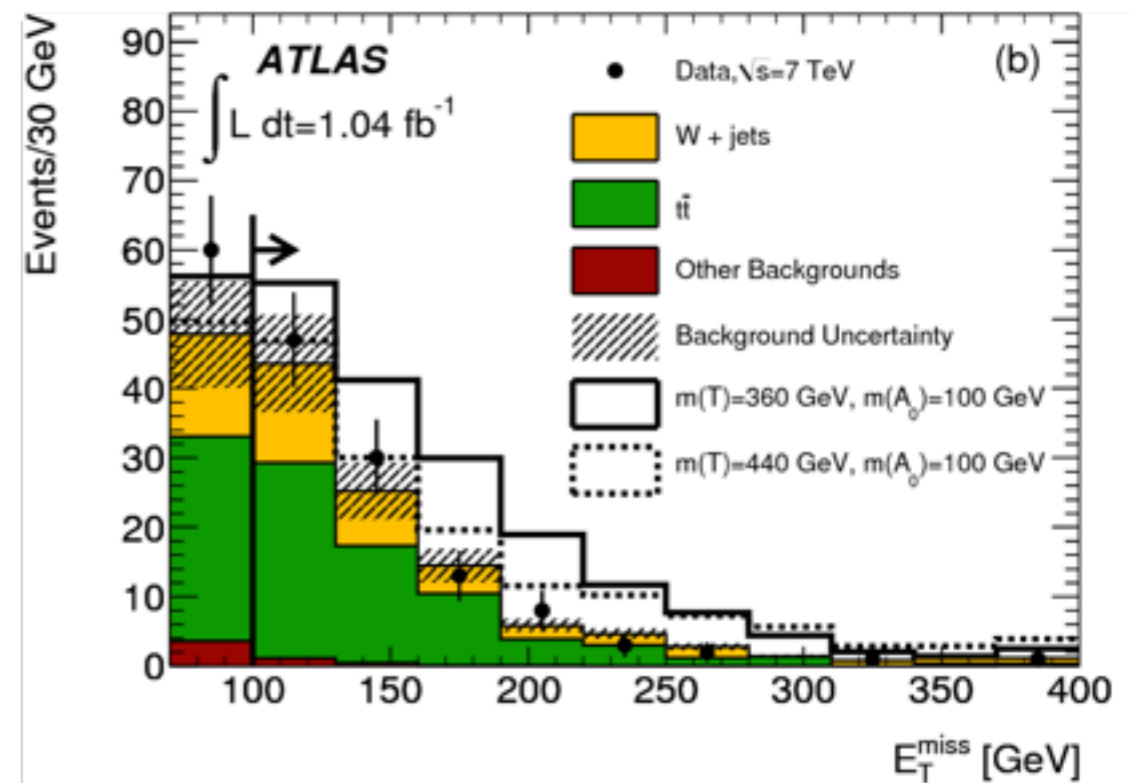
*Obtained strong limit if  $\tilde{K}_{qQ} = 1$  and 100% branching fractions!*

# ATLAS SEARCH FOR EXOTIC HEAVY QUARK



- Could be exotic 4<sup>th</sup> generation  $T \rightarrow tX$ , where  $X$  is a dark matter candidate (e.g. J. Alwall et al, arXiv: 1002.3366).
- SUSY scenario: stop  $\rightarrow t +$  neutralino.
- Other possibilities: little Higgs, 3<sup>rd</sup> generation leptoquarks, etc.

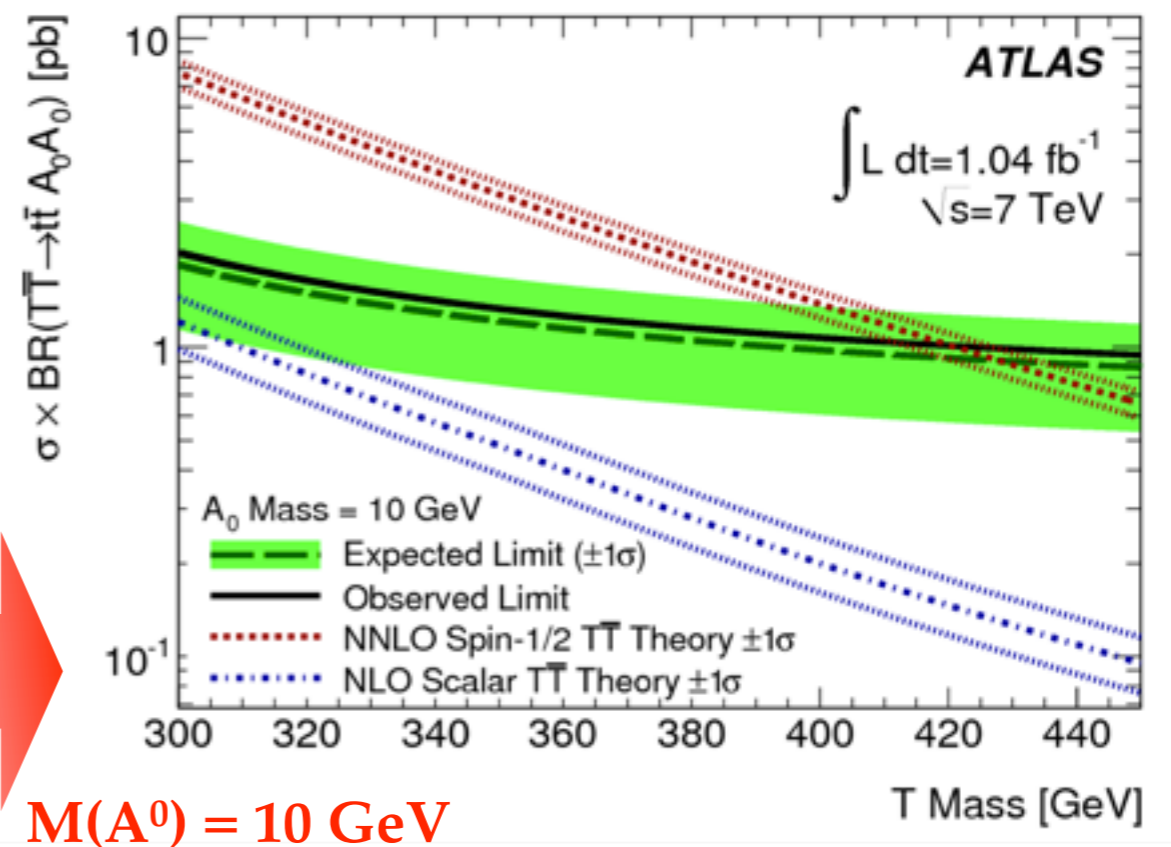
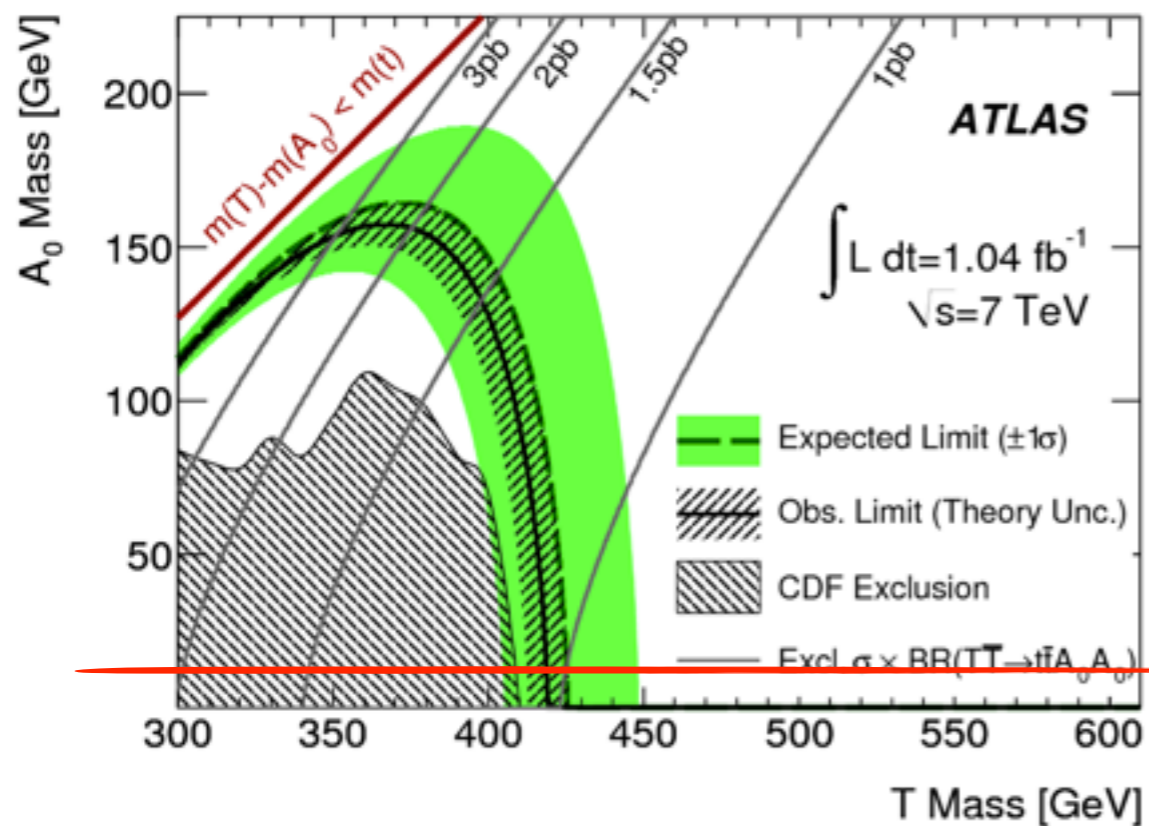
- Signature: simply a top-pair:  $TT \rightarrow tt + A^0A^0$
- Reconstruct a semileptonic top pair, and examine if there is **(extra-)large missing  $E_T$** .





# ATLAS SEARCH FOR EXOTIC HEAVY QUARK

↓ Limit should be calculated as a function of  $M(A^0)$  and  $M(T)$



arXiv:1109.4725

For 100%  $T \rightarrow tA_0$  decays and  $M(A^0) = 10 \text{ GeV}$ ,  
 $M(T) > 420 \text{ GeV}$  at 95% C.L.

# WHAT HAVE BEEN SEARCHED FOR

- Public results that have been shown today:
  - $t' \rightarrow bW$  pair: lepton+jet (CMS), dilepton (CMS)
  - $t' \rightarrow bW, qW$  pair: dilepton (Atlas)
  - $b' \rightarrow tW$  pair: trilepton+same-sign dilepton (CMS), same-sign dilepton (Atlas)
  - $b'/t'$  pair+single: inclusive multi-W with mu+jets (CMS)
  - $T \rightarrow tZ$  pair: Z+lepton (CMS)
  - $D \rightarrow qW, U \rightarrow qZ$  single: Z+jet and W+jet (Atlas)
  - $T \rightarrow tA^0$ : ttbar+extra MET (Atlas)
- Issues:
  - What will be the sensitivity with more data (w/ 2012 full sample)?
  - Some of the analysis (e.g.  $T \rightarrow tZ$ ) is carried out with a strong assumption of 100% branching fraction. What will happen if we relax it?

➡ *To be addressed in the next part of this talk.*



What I'm going to show is not a part of "CMS official result".

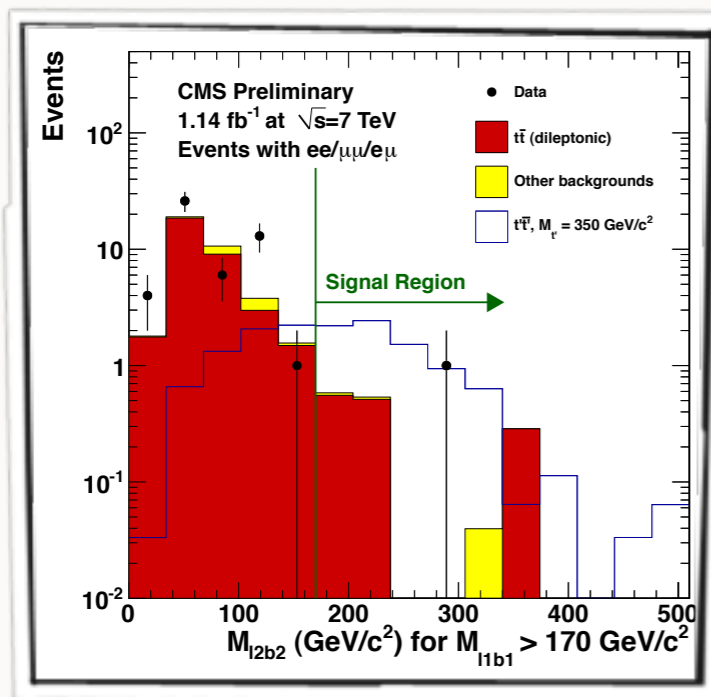
I will only use public documents, numbers and tools.

These results are generally underestimating the power of analysis.

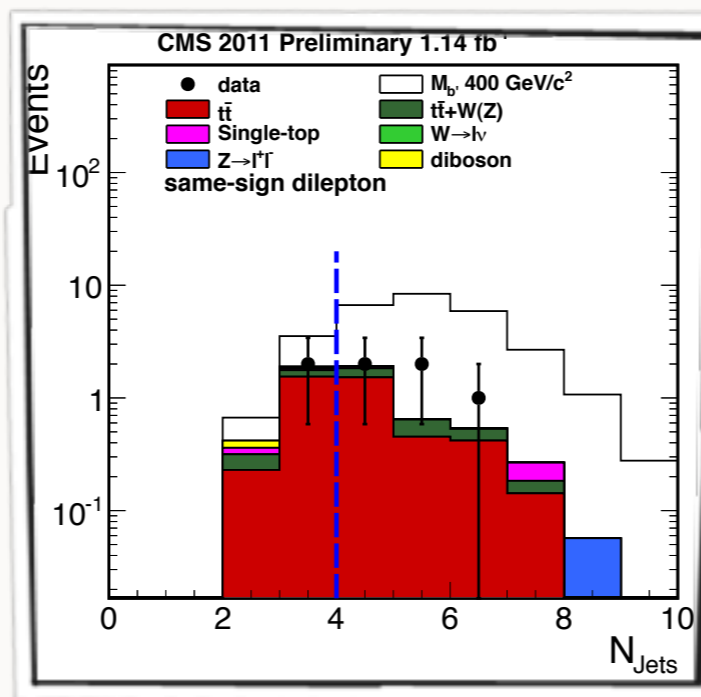
Please treat them as a "minimum naive guesstimation".

# REINTERPRET RESULTS

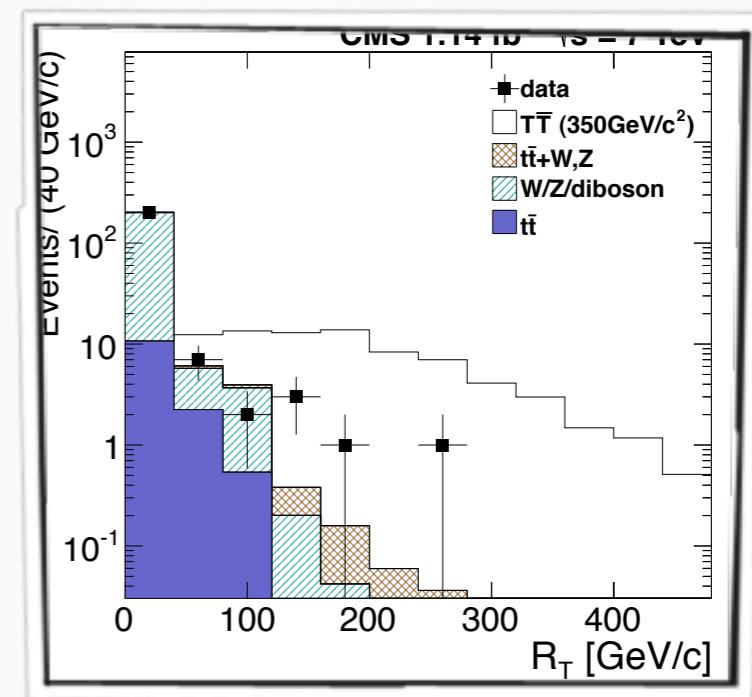
- Use 3 CMS summer results as the basis (all counting experiments):



$t' \rightarrow bW$  (dilepton)



$b' \rightarrow tW$  (3L + same-sign 2L)

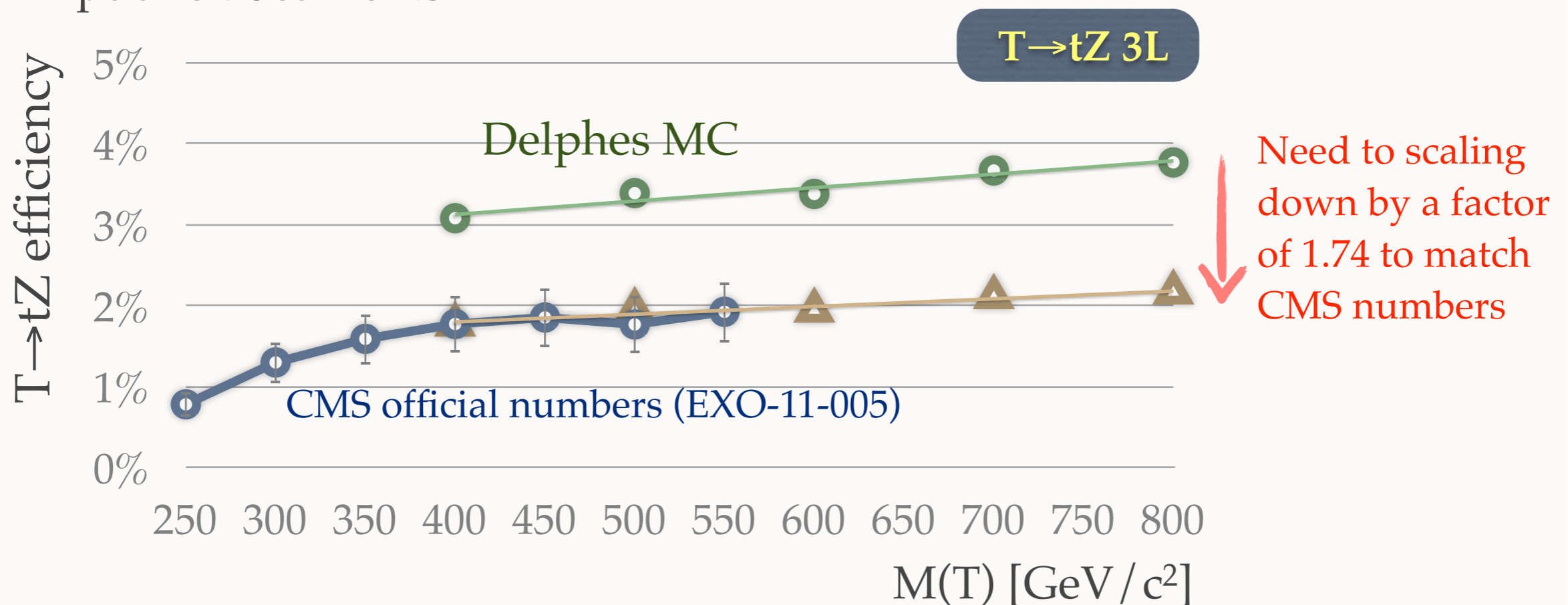


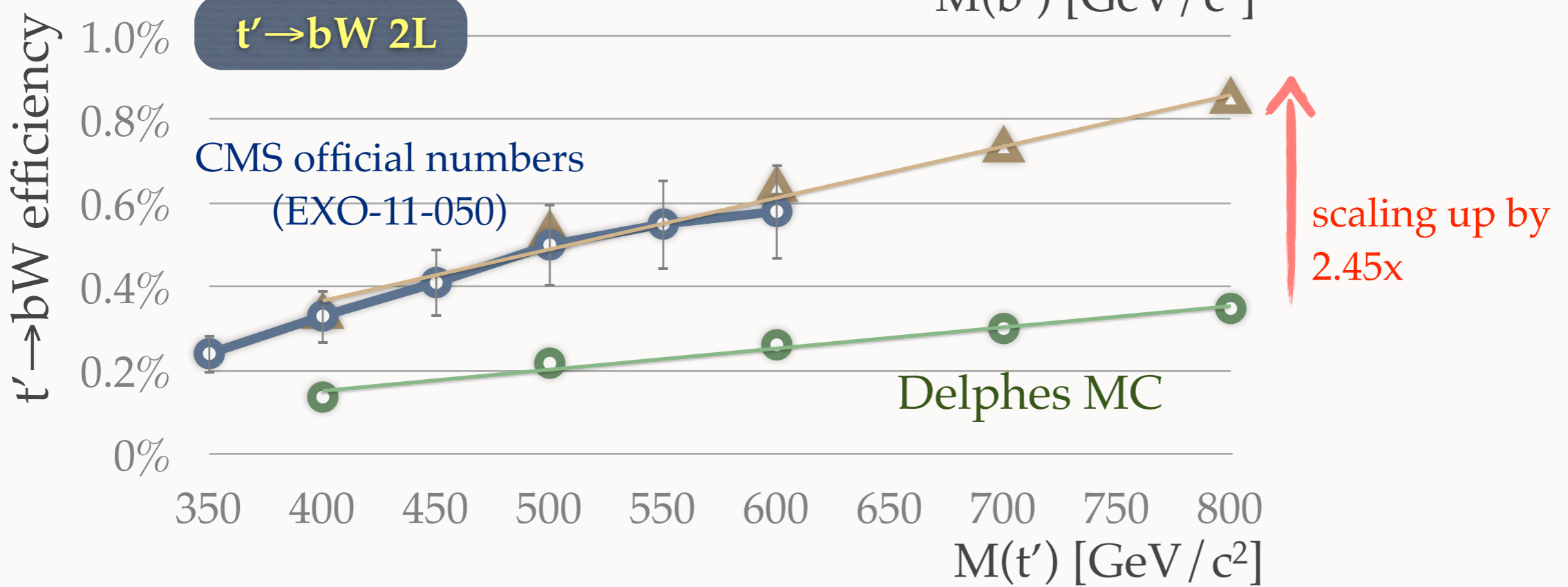
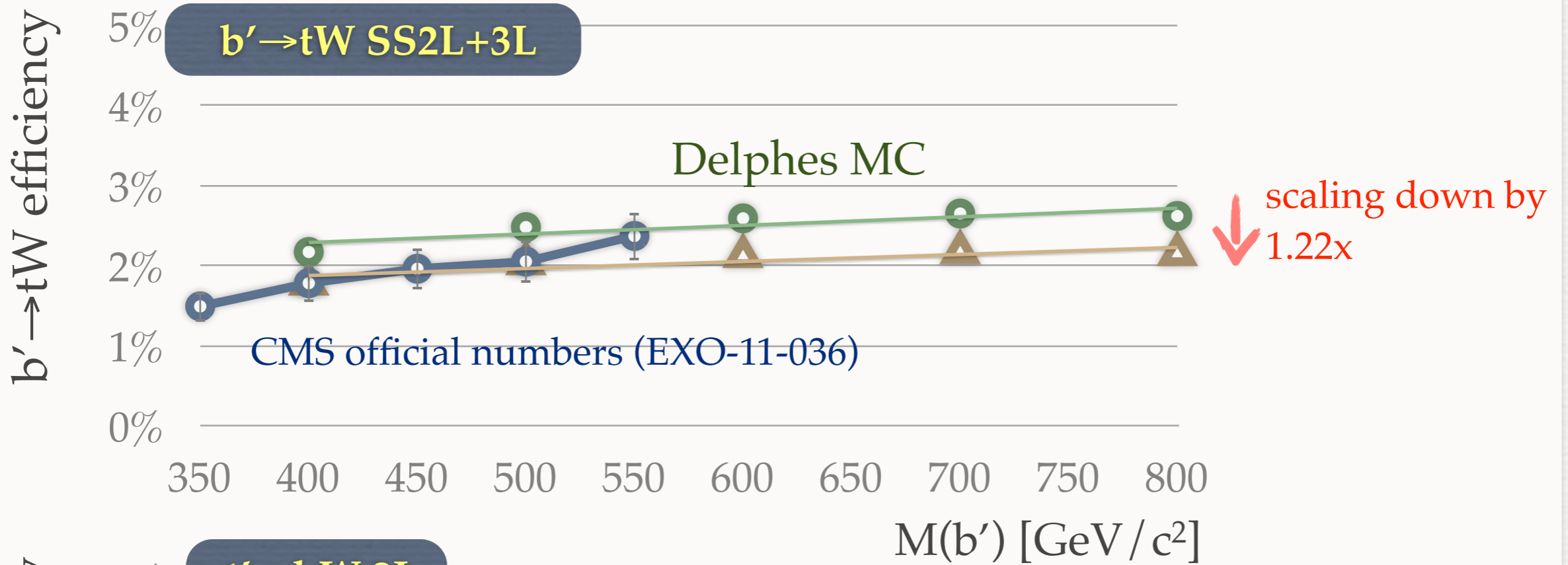
$T \rightarrow tZ$  (3L)

- ➔ Assuming no improvement on analysis themselves: easy to scale the background and its uncertainty.
- ➔ The only missing part is the efficiency with different assumption.

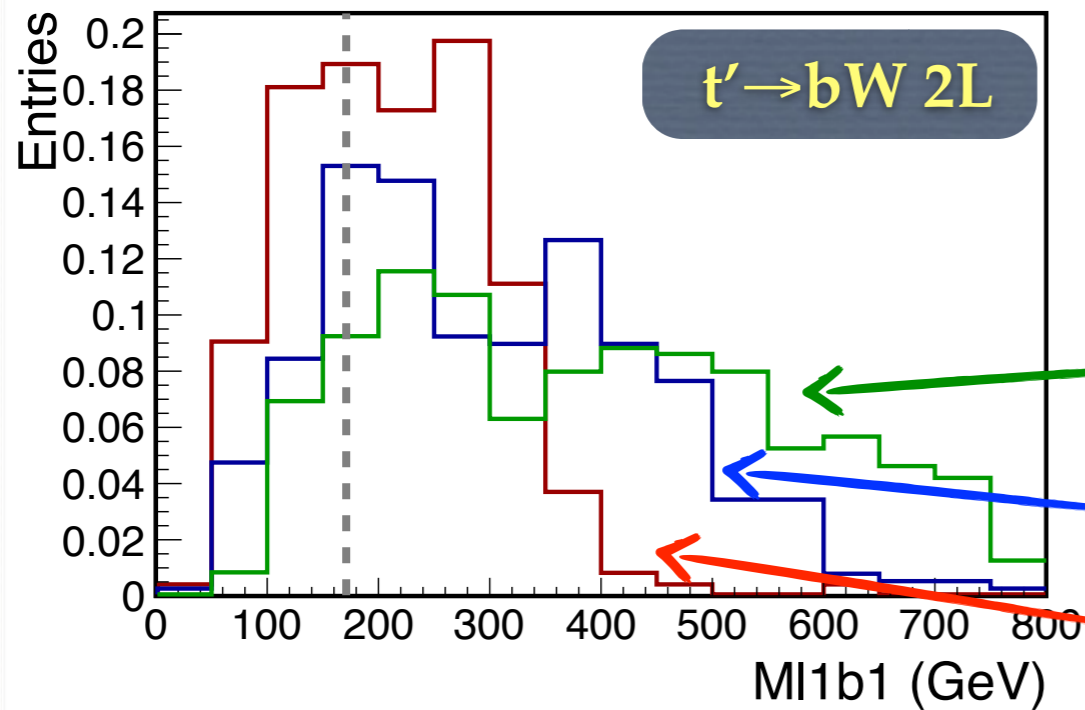
# REINTERPRET RESULTS

- The missing efficiencies are estimated with Delphes fast simulation (so anyone can do it, no dependence on CMS official Monte Carlo) plus some naive selection criteria to mimic the CMS analysis.
- Apply a “correction” from a known reference point give by the CMS public documents.





analysis threshold

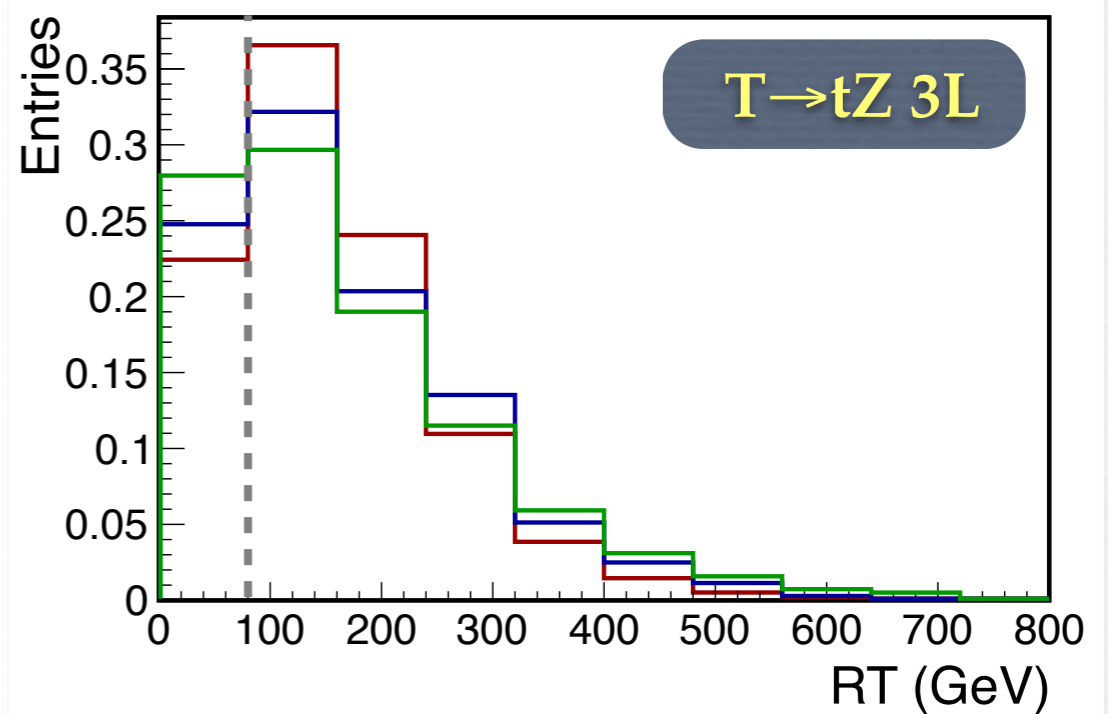
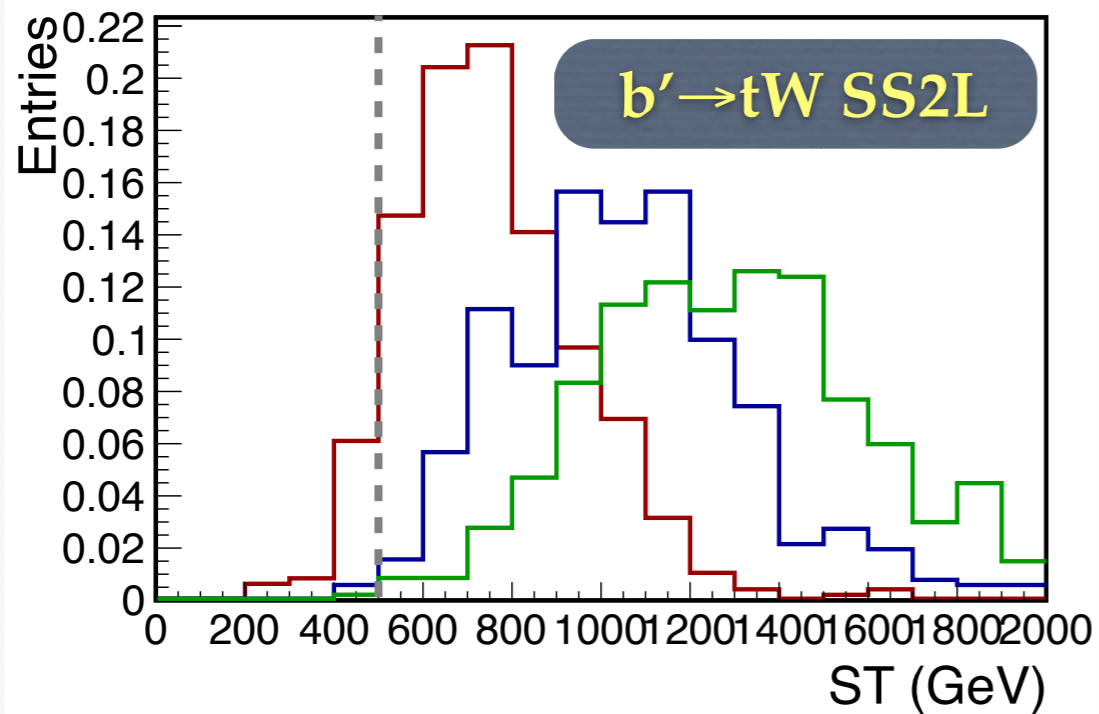


# KINETIC DISTRIBUTIONS

$M(t') = 800 \text{ GeV}/c^2$

$M(t') = 600 \text{ GeV}/c^2$

$M(t') = 400 \text{ GeV}/c^2$

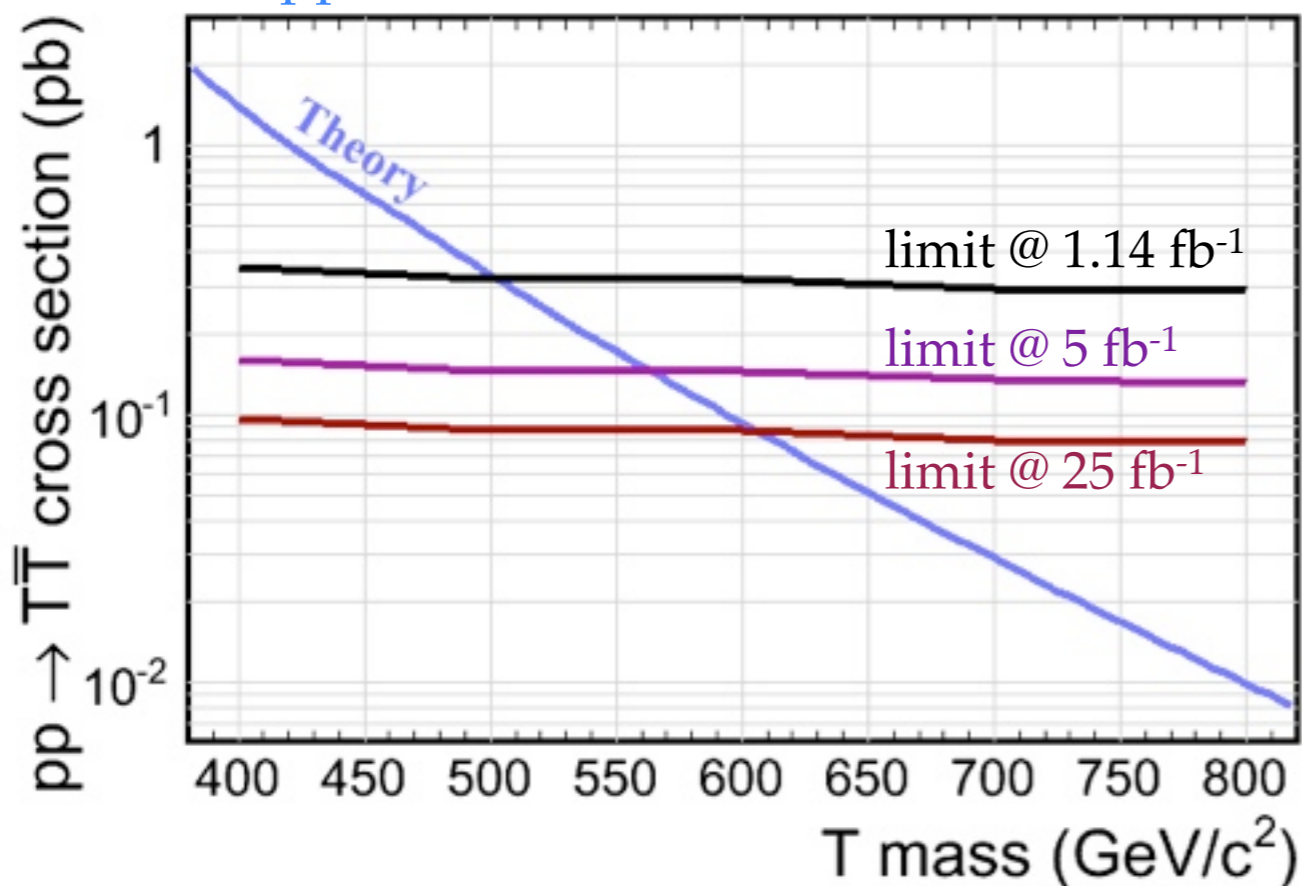


# EXPECTED LIMITS @ 1 fb<sup>-1</sup>/5 fb<sup>-1</sup>/25 fb<sup>-1</sup>

**T → tZ, 100% BF**

Luminosity	1.14 fb <sup>-1</sup>	5 fb <sup>-1</sup>	25 fb <sup>-1</sup>
Background yield	4.6 ± 1.0	20 ± 4	101 ± 22
Expected limit	>502 GeV	>565 GeV	>606 GeV

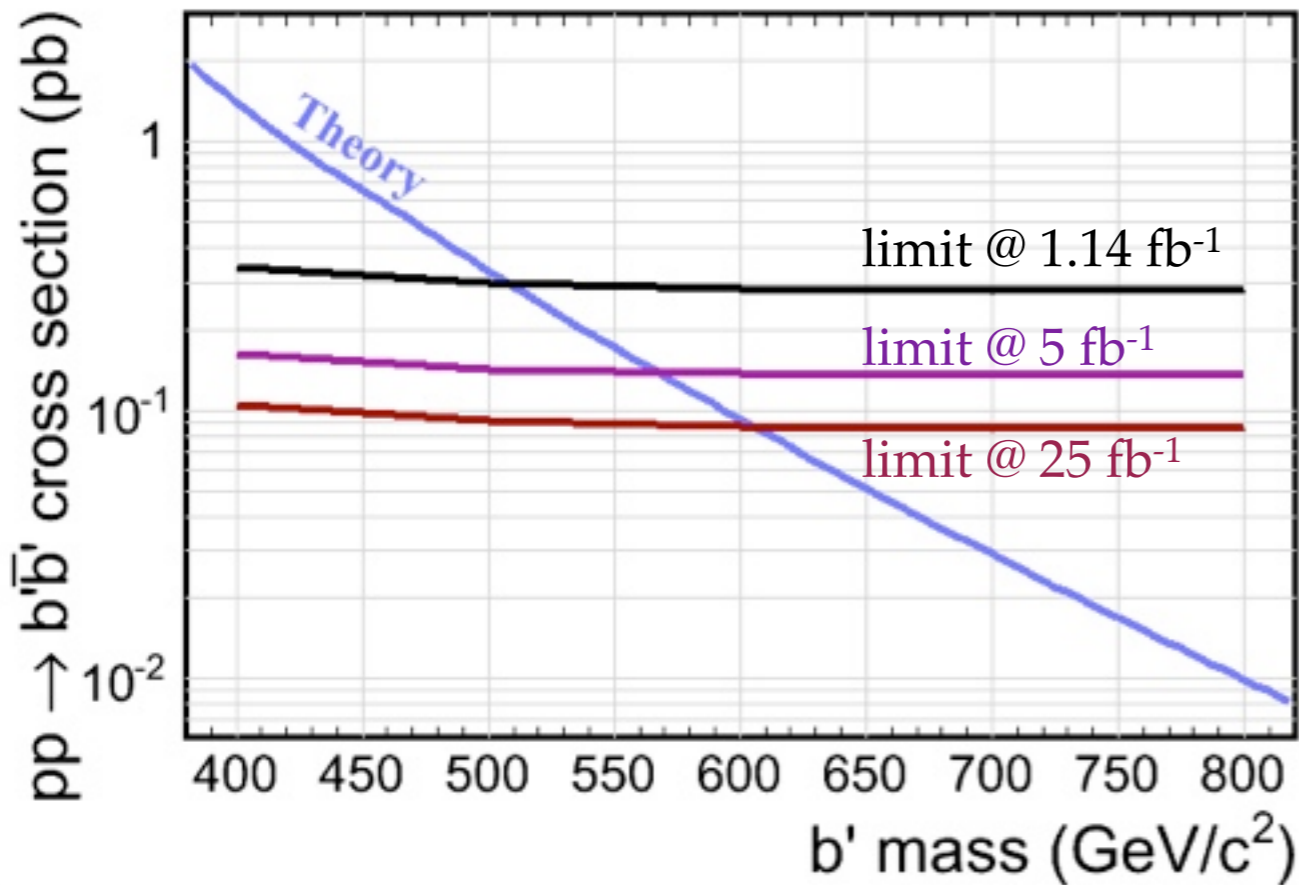
↓ approx. NNLO cross section



→  
*Getting saturated with high luminosity if no improvement on the analysis itself.*

- Direct copy of performance numbers from the paper:
  - Efficiency uncertainty = 20%
  - S/N is the same.
  - Background error = 22%  
*(ignoring the statistical improvement on the background estimation)*





### $b' \rightarrow tW, 100\% \text{ BF}$

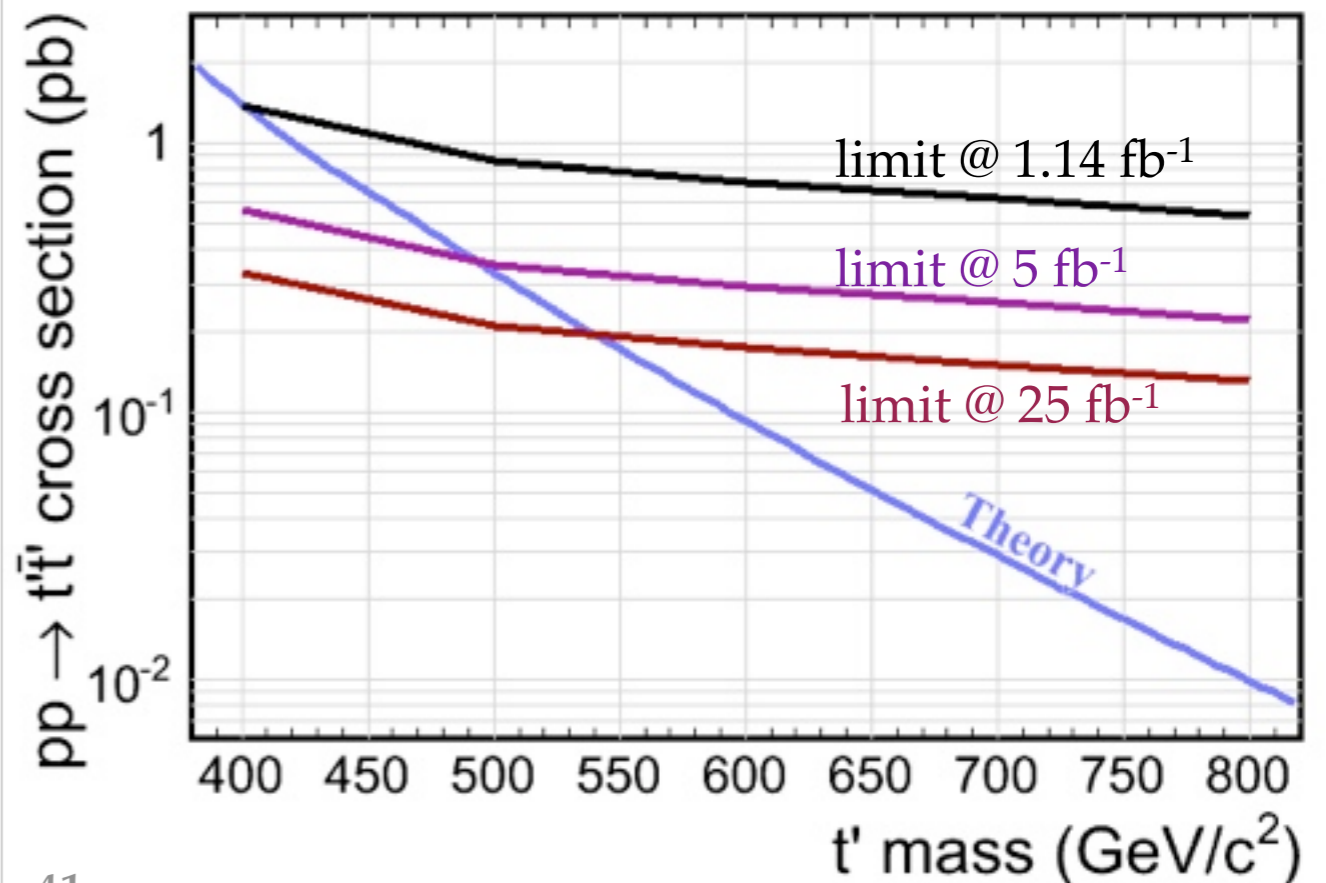
*remark: statistical improvement on the background estimation is ignored.*

Luminosity	1.14 fb <sup>-1</sup>	5 fb <sup>-1</sup>	25 fb <sup>-1</sup>
Background yield	4.6 ± 1.4	20 ± 6	100 ± 31
Expected limit	>509 GeV	>568 GeV	>605 GeV

### $t' \rightarrow bW, 100\% \text{ BF}$

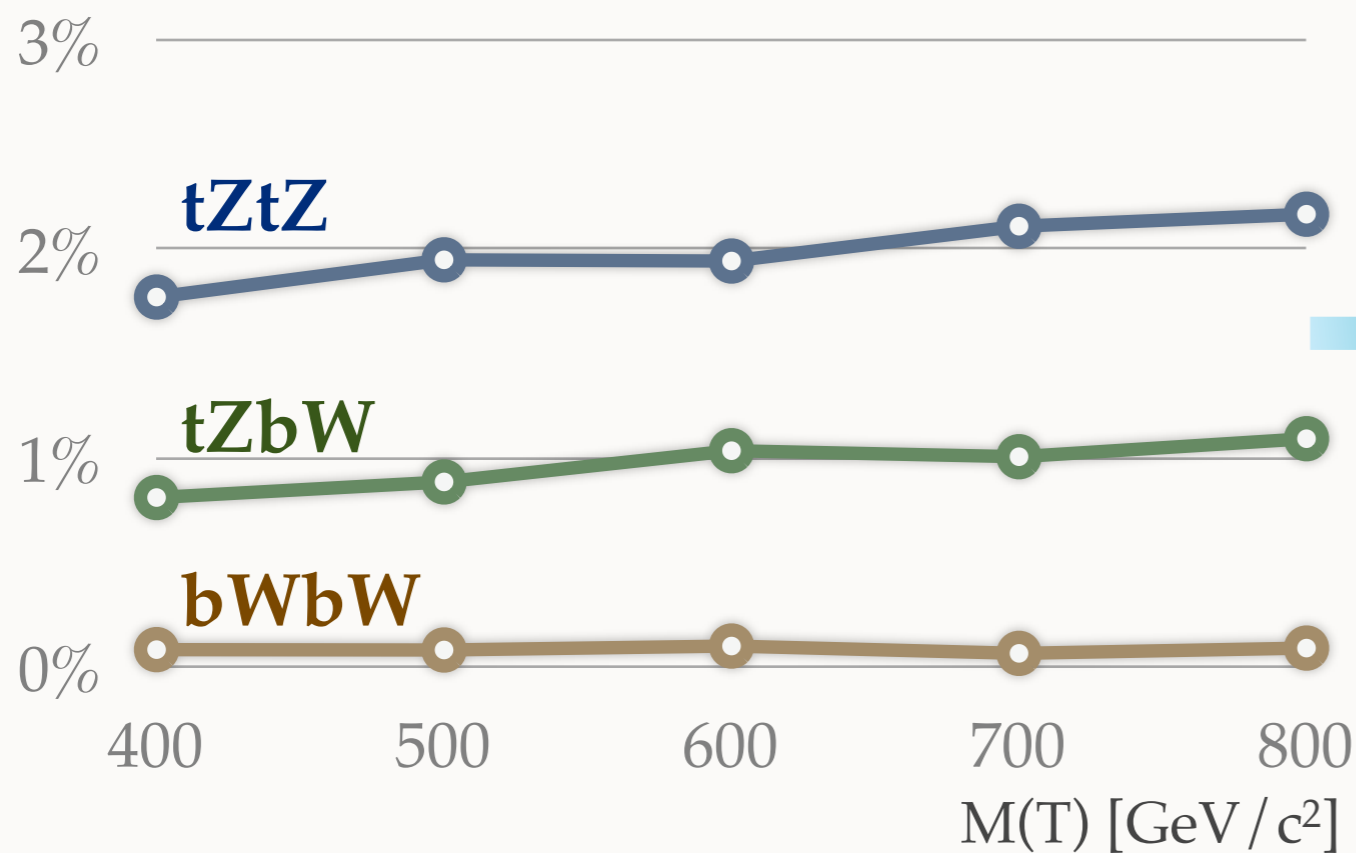
*remark: this is not the channel with the best sensitivity.*

Luminosity	1.14 fb <sup>-1</sup>	5 fb <sup>-1</sup>	25 fb <sup>-1</sup>
Background yield	1.62 ± 0.80	7.1 ± 3.5	36 ± 18
Expected limit	>401 GeV	>492 GeV	>542 GeV



# IF THE BRANCHING FRACTION IS $<100\%$

- Estimate the selection efficiency with 3 different final states:  
 $tZtZ$ ,  $tZbW$ ,  $bWbW$ :

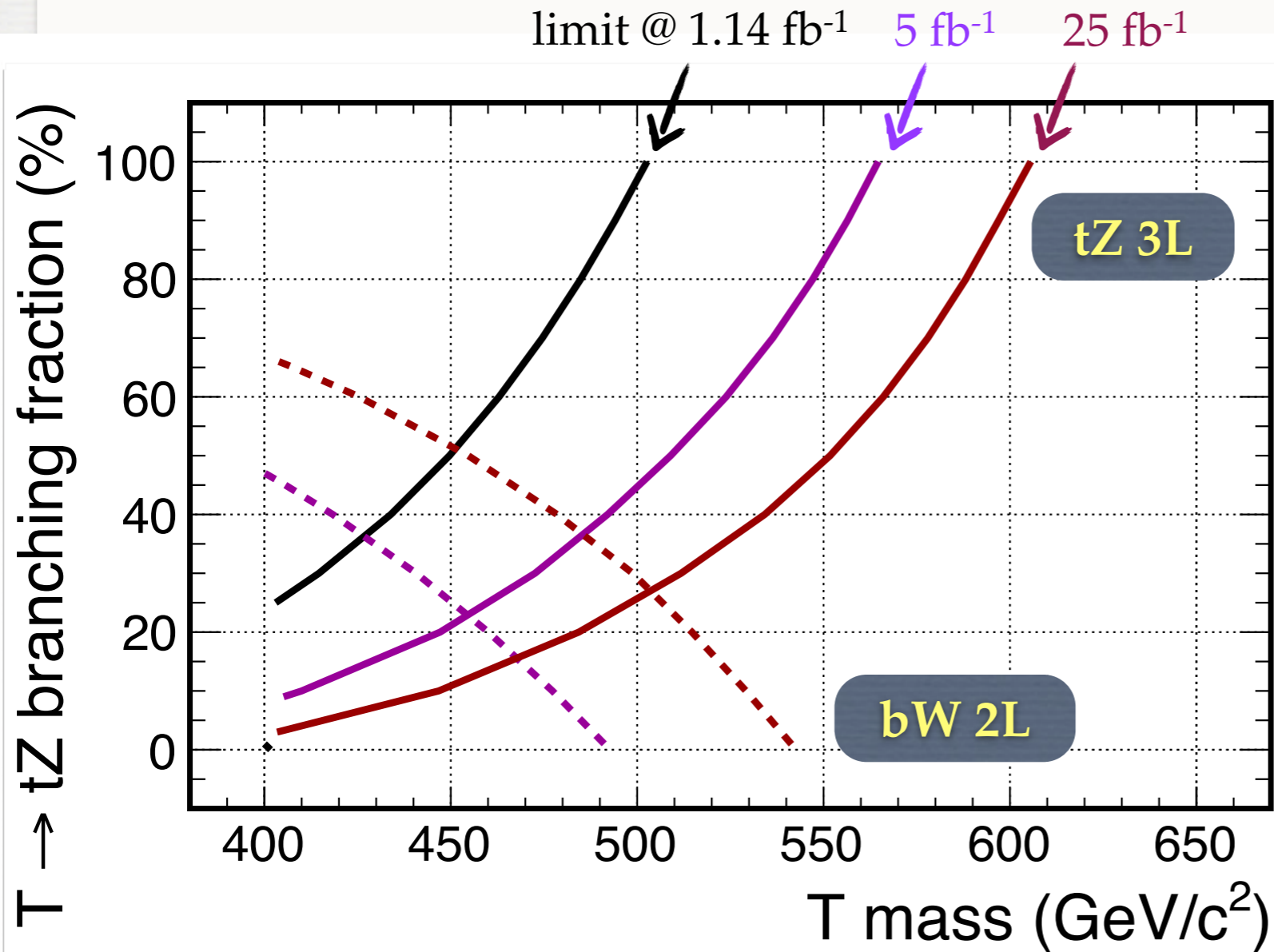


The effective efficiency can be calculated for different  $BF(T \rightarrow tZ)$ :

tZ BF	Efficiency (500 GeV)
100%	1.95%
80%	1.53%
60%	1.14%
40%	0.77%
20%	0.41%
0%	0.08%

Then, re-do the limit calculation with different branching fraction assumptions.

# IF THE BRANCHING FRACTION IS <100%

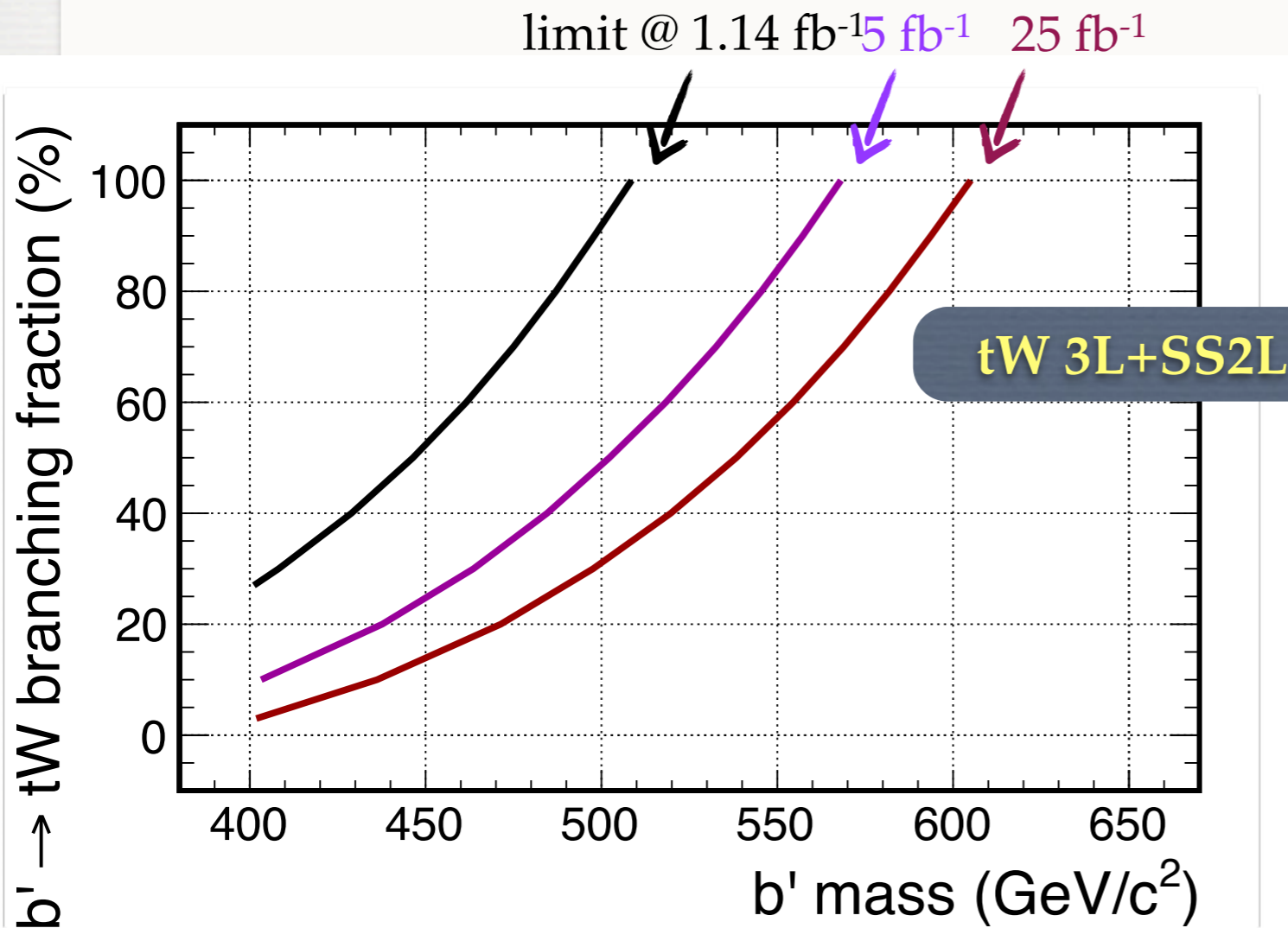


Determine the limit as a function of BF and T mass.

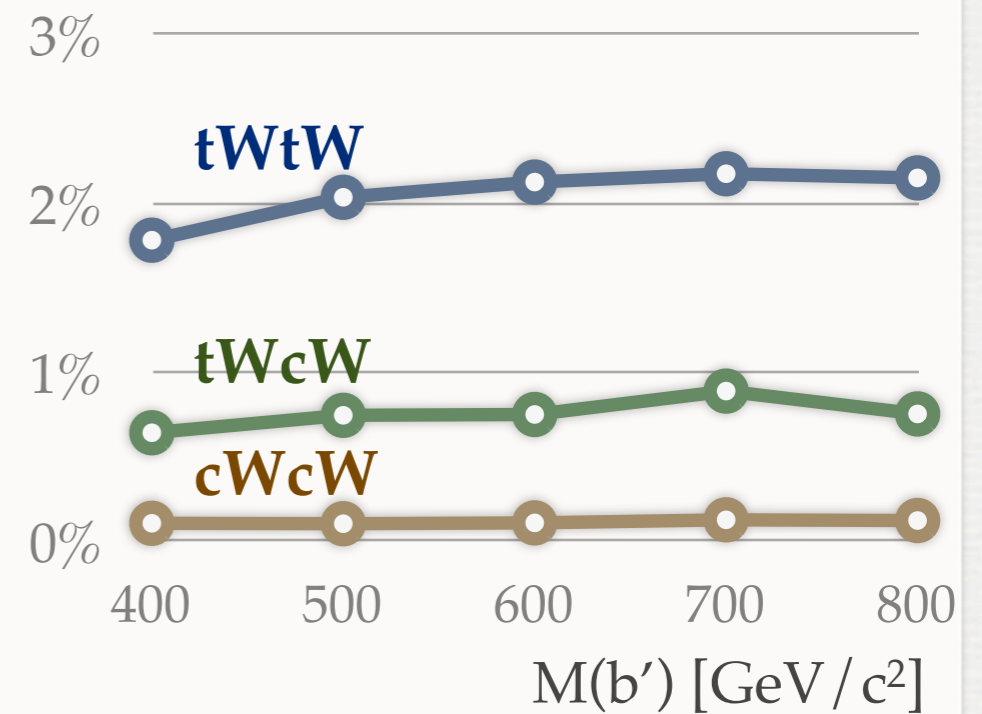
Low BF part (=bW dominance) can be covered by  $t' \rightarrow bW$  analysis.

**A combined analysis may give a better limit.**

# IF THE BRANCHING FRACTION IS <100%

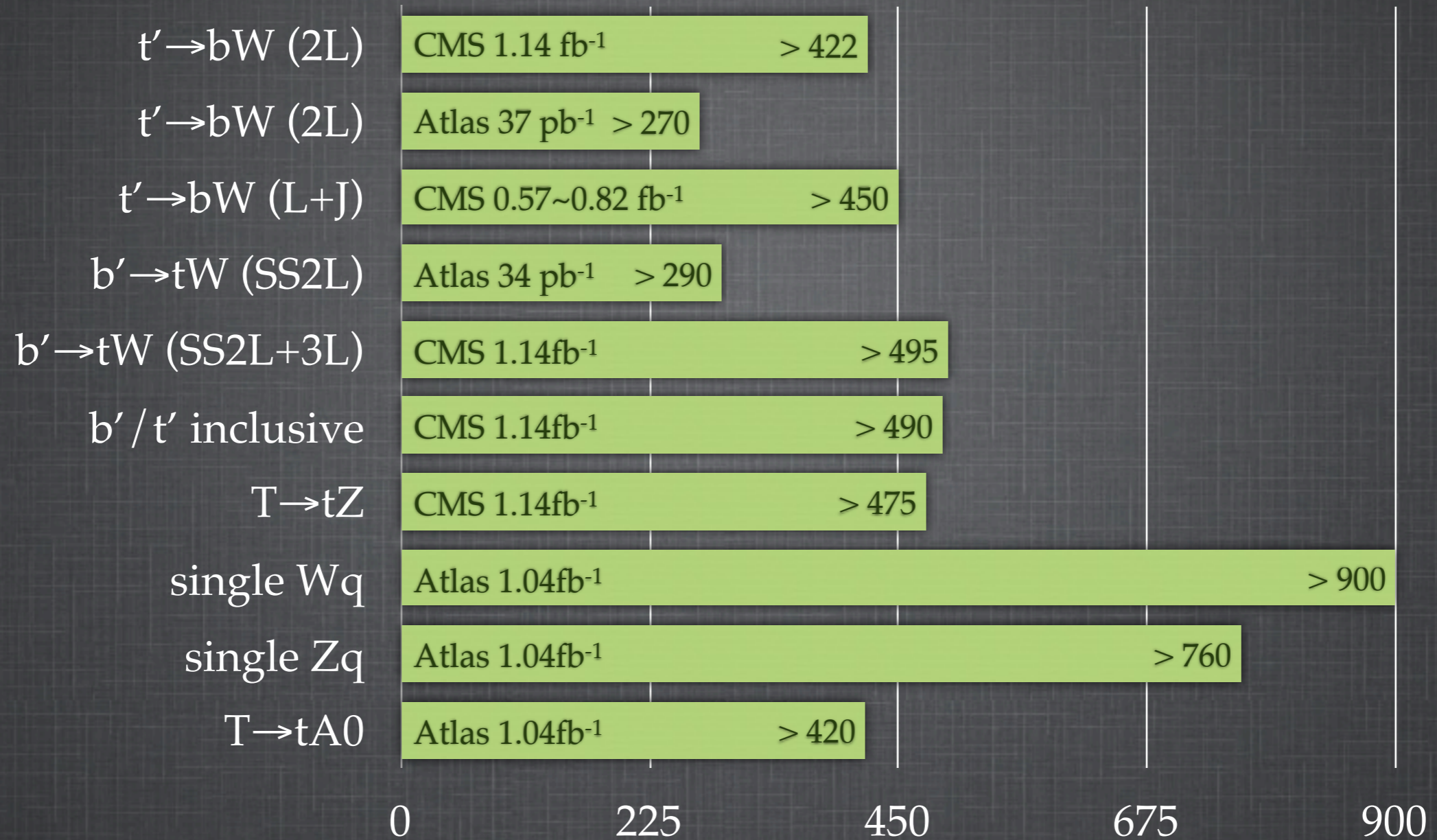


■ Estimate the selection efficiency with 3 different final states as well:



Need a "cW" analysis to patch the phase space.

# SUMMARY



Some ongoing extensions:

- $t' \rightarrow bW$  with full hadronic,  $b' \rightarrow tW$  with lepton+jets.
- Adding  $t' \rightarrow b' / b' \rightarrow t'$  in the inclusive analysis.
- Top partner  $T_{5/3}$ ,  $T \rightarrow tH$ ,  $b \rightarrow bZ$ , etc.

# DISCUSSION ITEMS

- **Extend analysis works to any uncovered signatures:**
  - $t' / b' \rightarrow qW$  (no b-tagging or anti b-tagging)
  - heavy quark resonances?
  - long lived heavy quark?
  - anything else (your beloved model?)
- **What if we see something?**
  - How could we identify this is heavy quark, not a contributions of something else (SUSY, etc...)
  - Mass reconstruction, property tests (charge, spin, etc?)
- **Sensitivity / coverage maximizing (if we see nothing)**
  - How could we extend the searches to cover a wider parameter space?
  - How to add  $t' \rightarrow b' / b' \rightarrow t'$  and any other mixture in an effective way?
  - A global constraint on  $M(t')$ ,  $M(b')$ ,  $V_{CKM4}$ , etc?



# BACKUP SLIDES

# IF WE ADD $t' \leftrightarrow b'$

Hypothesis	$b'(600) \rightarrow tW$ only	$b'(600) \rightarrow tW +$ $t'(650) \rightarrow b'W$	$b'(600) \rightarrow tW +$ $t'(700) \rightarrow b'W$	$b'(600) \rightarrow tW +$ $t'(800) \rightarrow b'W$
Yields @ 5 fb <sup>-1</sup> for $b' \rightarrow tW$ (SS2L+3L) analysis	9.8	9.8 + 11.4	9.8 + 6.6	9.8 + 2.4

Hypothesis	$t'(600) \rightarrow bW$ only	$t'(600) \rightarrow bW +$ $b'(650) \rightarrow t'W$	$t'(600) \rightarrow bW +$ $b'(700) \rightarrow t'W$	$t'(600) \rightarrow bW +$ $b'(800) \rightarrow t'W$
Yields @ 5 fb <sup>-1</sup> for $t' \rightarrow bW$ (2L) analysis	2.9	2.9 + 2.2	2.9 + 1.4	2.9 + 0.6
Yields @ 5 fb <sup>-1</sup> for $b' \rightarrow tW$ (SS2L+3L) analysis		8.4	5.3	1.9

**Unable to convert this to a (2D) limit; need some more studies.**