Search for Fourth Generation Quarks at CMS

The CMS Collaboration
Speaker: Michael Luk[1]

[1]Department of Physics
Brown University

DPF2011 - 09AUG11

General Information

Searches for fourth generation quarks at the CMS detector.

Analyses look at:

- $b' \to t + W$
- $t' \to t + Z$
- $t' \to b + W$

Assume:

- is strongly pair produced
- has mass greater than top quark
- decays promptly

Motivation

Our searches are not limited to fourth generation chiral quarks - can be extended to BSM model with the same decay products.

- Natural extension of Standard Model: 3 $\to$ 4 fermion generations
- Is consistent with precision electroweak measurements
- Heavy top-like quark can resolve the naturalness problem (Higgs predicted to be light).

Constraints

Constraints on the pair produced b' mass:

- $m_{b'} > 2m_t + 2m_w$ favoured

  CDF 'Search for New Bottomlike Quark Pair Decays $QQ \to (tW)(tW)$ in Same-Charge Dilepton Events', Phys. Rev. Lett. 104 (2010) 091801

  $m_{b'} > 375 GeV$ direct search
  (CDF arXiv:1101.5728)

Constraints on the pair produced t' mass:

- $m_{t'} > 358 GeV$ direct search

  CDF conference note 10395, D0 arXiv:1104.4522

- $m_{t'} - m_{b'} < 50 GeV$ from precision electroweak measurements
  (Kribs, PRD 76 075016 (2007) Eberhardt, Lenz, Rohrwild, PRD 82 095006 (2010))

Events

Final state of events:
$b'\bar{b}' \to tWtW \to bWWbWW$

- Ws decay to two same sign charged leptons or three isolated leptons (i.e. dilepton and trilepton - has small SM bg and large B.R.)

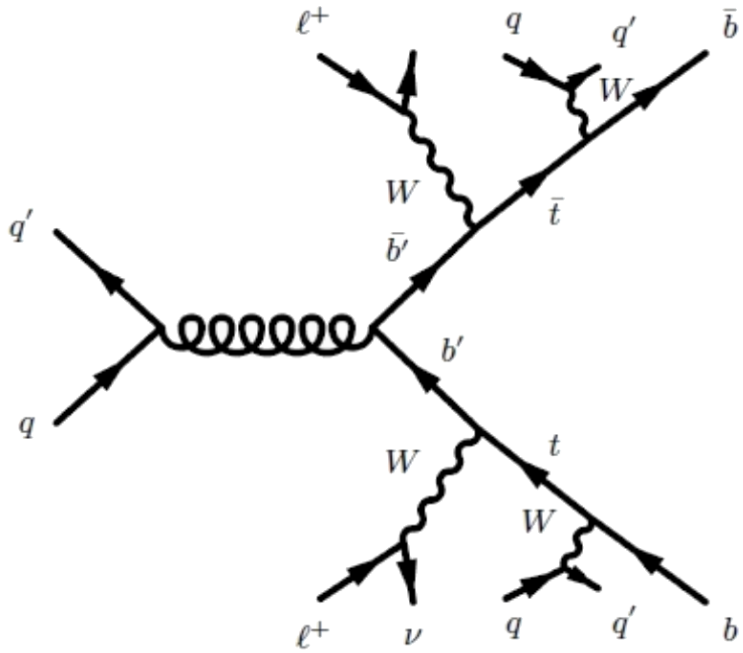
$t'\bar{t}' \to tZtZ \to bbWWZZ$:

- $Z \to l^+l^-$ and one W decays to isolated lepton i.e. trilepton decay.

$t'\bar{t}' \to bbWW$:

- one W decays leptonically, the other hadronically i.e. 4 jets + lepton

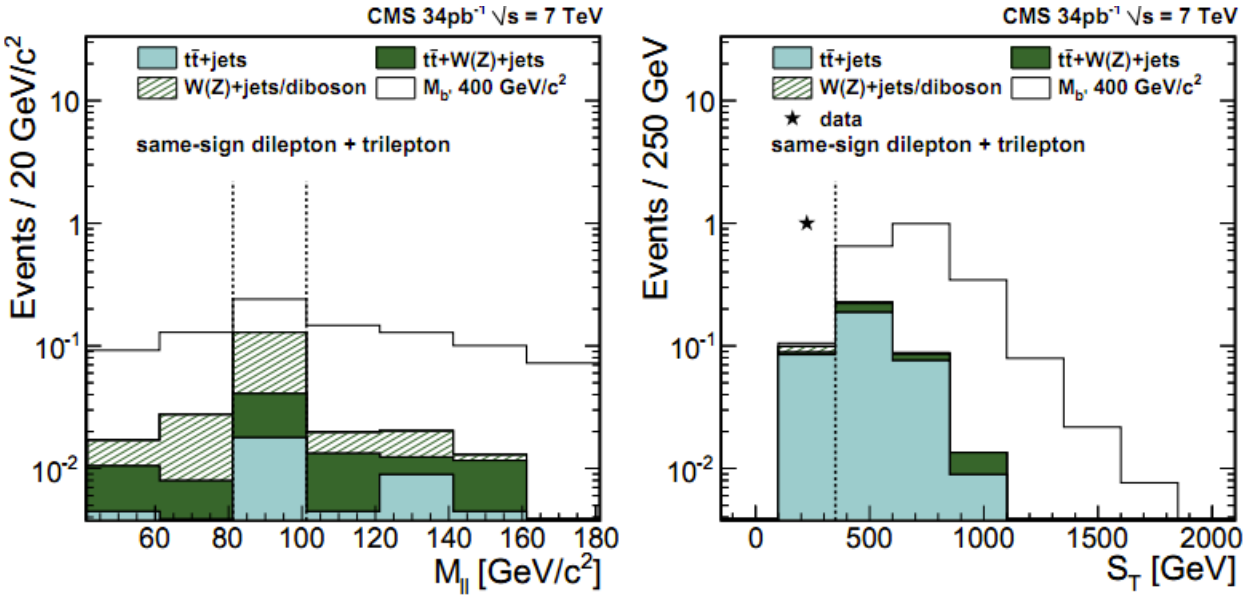
$b'\bar{b}' \to tWtW \to bWWbWW$



Relevant final state:

- 4/6 Jets from:
  - 1/2 $W \to qq$ (or not into jets as $W \to l\nu$)
  - 2 b-jets
- 3/2 visible leptons from:
  - 3/2 $W \to l\nu$

b' selections @34ipb

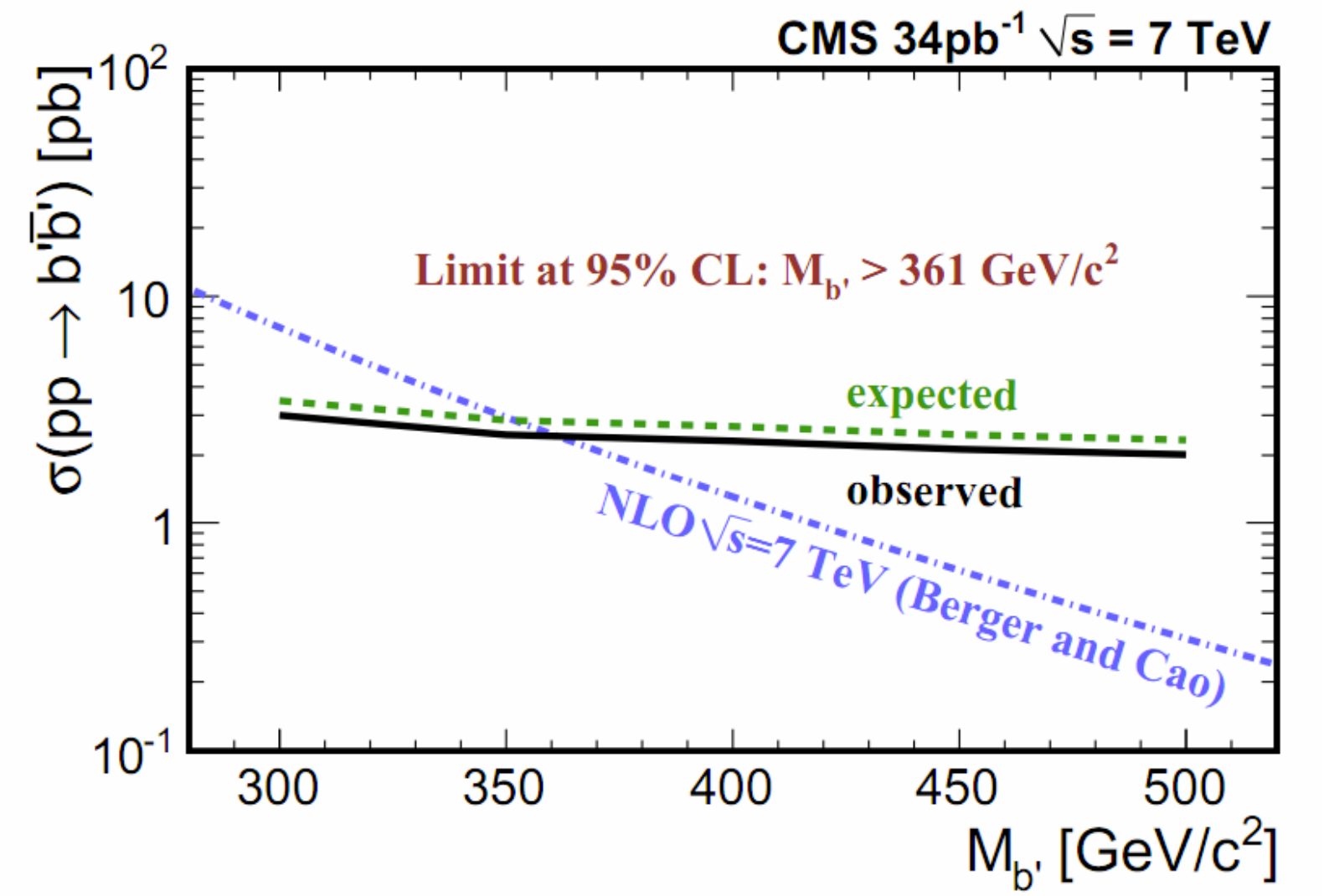


- Likesigned dilepton (trilepton) events with less than four(two) jets discarded
- $|M_{l^+l^-} - M_Z| < 10 GeV$ veto -suppresses SM Z decay.
- $S_T = \sum p_T(jets, leptons) + \not{E}_T \quad > 350 GeV$ required

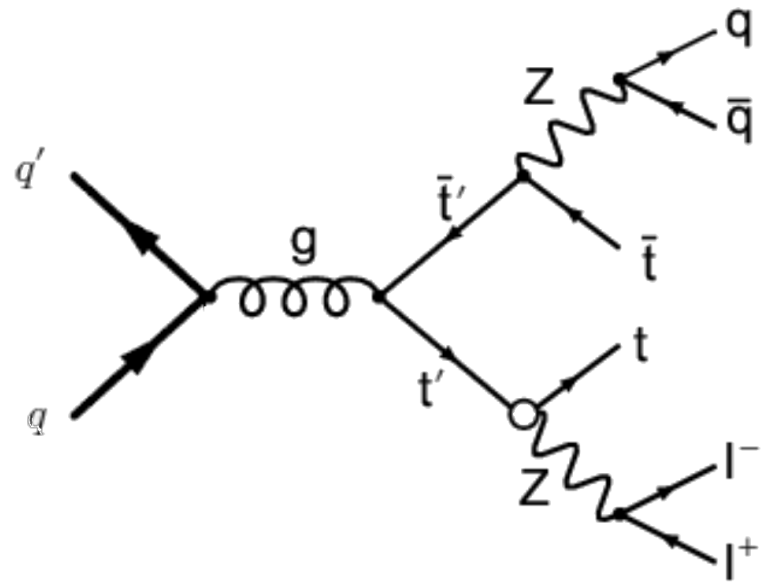
b' event yield @34ipb

Process	Cross section	ϵ [%]	Yield
$b'\bar{b}'$, $M_{b'} = 300\ \mathrm{GeV}/c^2$	7.29 pb (NLO)	3.08	7.7
$b'\bar{b}'$, $M_{b'} = 350\ \mathrm{GeV}/c^2$	2.94 pb (NLO)	3.75	3.8
$b'\bar{b}'$, $M_{b'} = 400\ \mathrm{GeV}/c^2$	1.30 pb (NLO)	3.99	1.8
$b'\bar{b}'$, $M_{b'} = 450\ \mathrm{GeV}/c^2$	0.617 pb (NLO)	4.34	0.91
$b'\bar{b}'$, $M_{b'} = 500\ \mathrm{GeV}/c^2$	0.310 pb (NLO)	4.58	0.49
$t\bar{t}$ + jets	1.9×10^2 pb (CMS)	4.1×10^{-3}	0.27
$t\bar{t}$ + W + jets	0.144 pb (LO)	0.67	0.033
$t\bar{t}$ + Z + jets	0.094 pb (LO)	0.50	0.016
W + jets	3.0×10^4 pb (CMS)	$< 1.0 \times 10^{-5}$	< 0.11
Z + jets	2.9×10^3 pb (CMS)	$< 9.2 \times 10^{-5}$	< 0.09
WW	43 pb (NLO)	$< 8.2 \times 10^{-4}$	< 0.012
WZ	18 pb (NLO)	$< 8.1 \times 10^{-4}$	< 0.005
ZZ	5.9 pb (NLO)	3.0×10^{-3}	0.006
Same-sign WW + jj	0.15 pb (LO)	3.9×10^{-2}	0.002
Background sum	-	-	0.33
Data-driven background yield	-	-	0.32
Observed yield in data	-	-	0

b' limit setting @34ipb



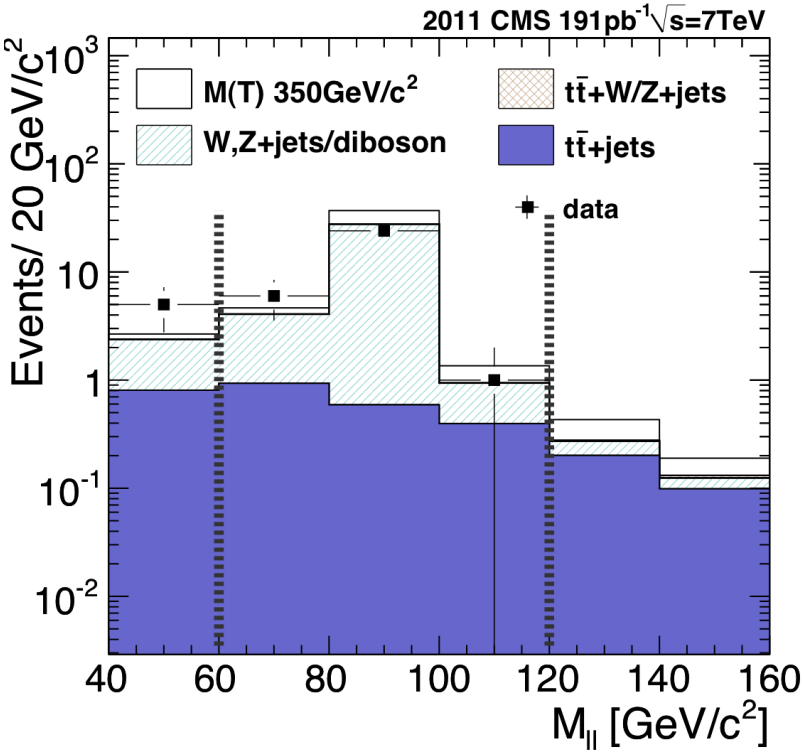
$t'\bar{t}' \to tZtZ \to bbWWZZ$

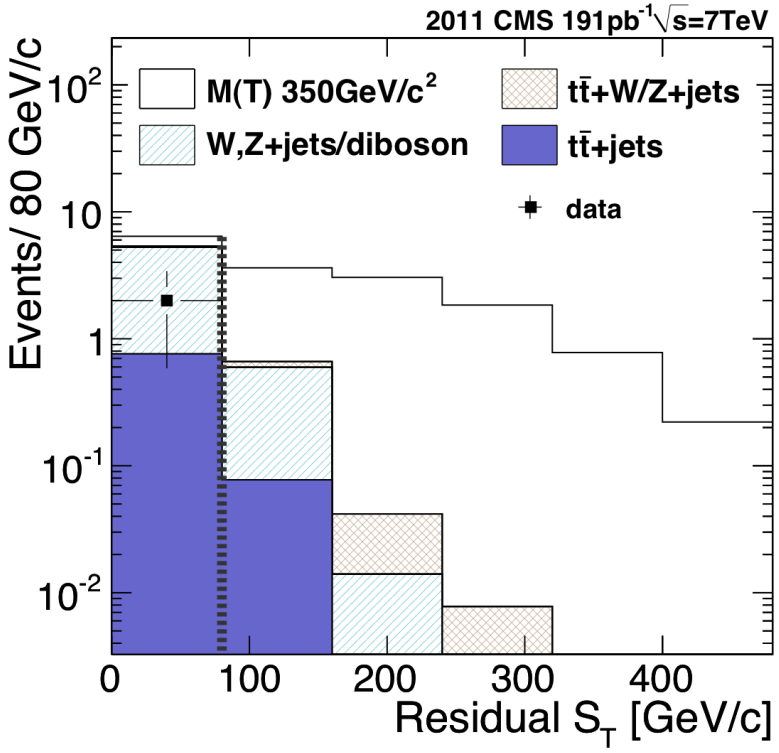


Relevant final state:

- $\geq$ 2 Jets from:
  - $W \to qq$ (not jet decay $W \to l\nu$)
  - $Z \to q\bar{q}$ (not jet decay $Z \to \nu\nu$)
  - 2 b-jets
- 3 visible leptons from:
  - $Z \to l^+l^-$
  - $W \to l\nu$

$t' \to tZ$ Selection @191ipb



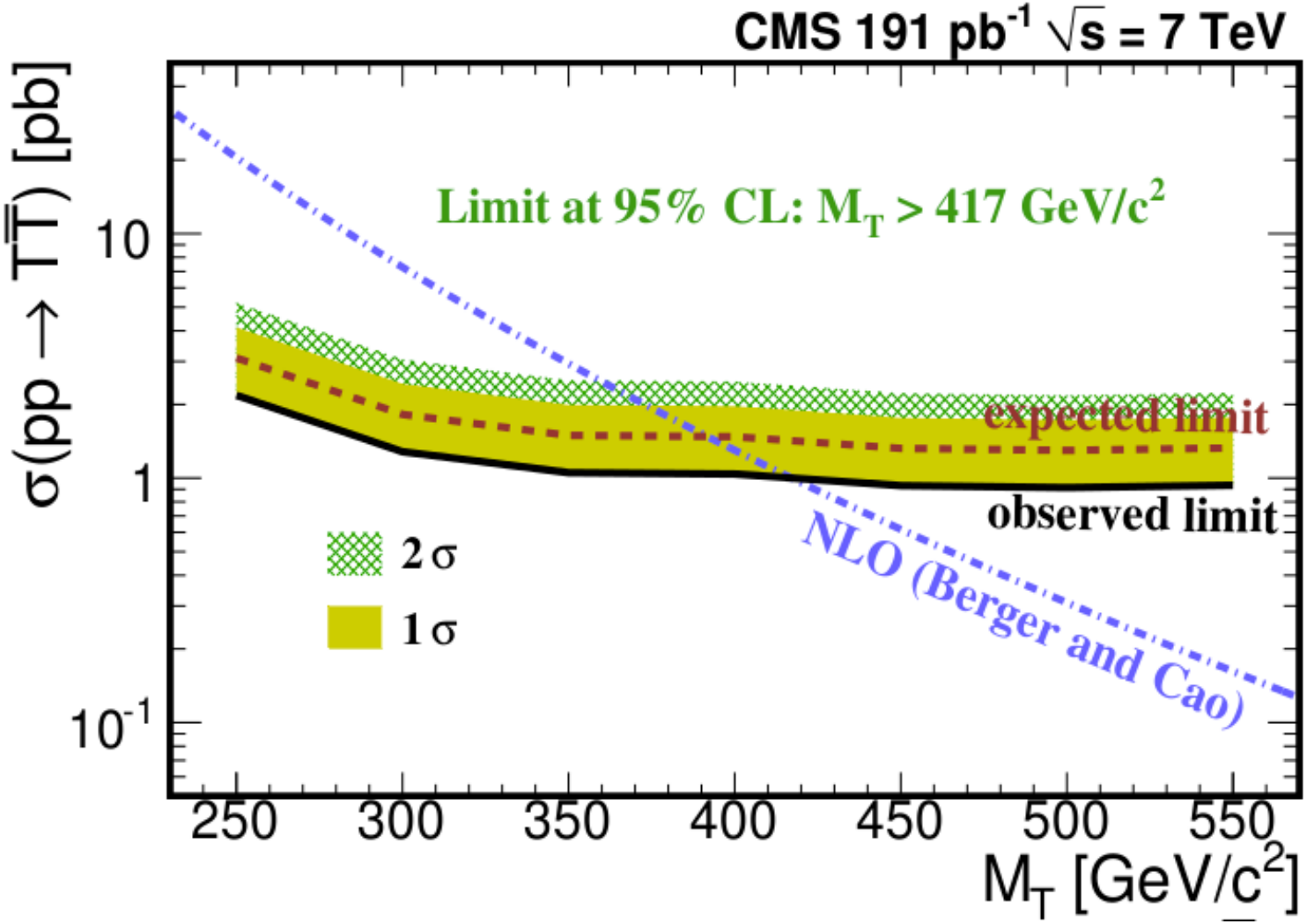


- $60 < M_{l^+l^-} < 120 GeV$ Z veto
- Residual $S_T = \sum p_T(jets) + \sum p_T(lepton) \quad > 80 GeV$ required

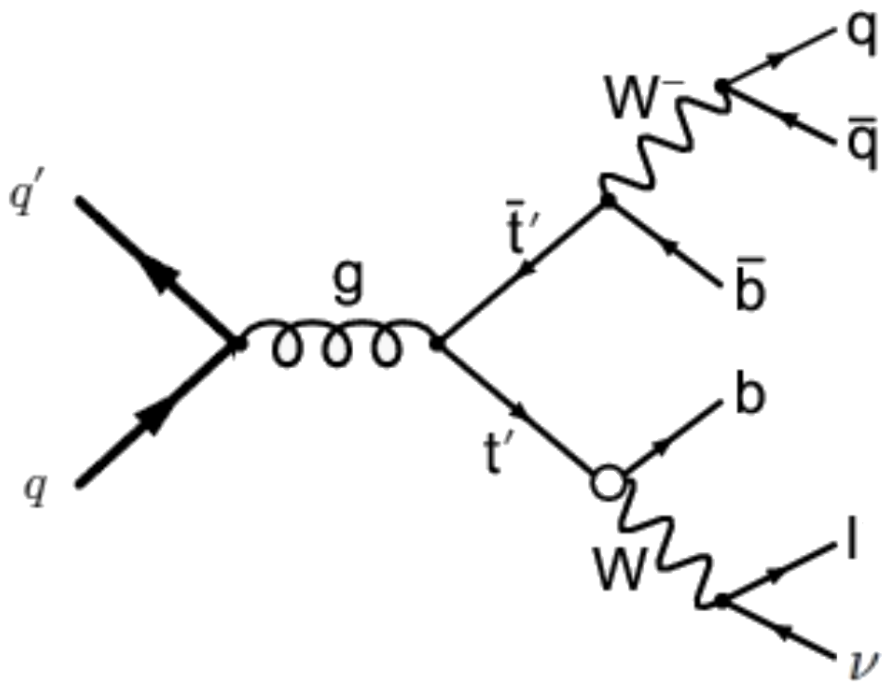
$t' \to tZ$ yield @191 ipb

Process	Cross-section (pb)	ϵ[%]	Yield
$T\bar{T}$, $M(T) = 250$ GeV/c^2	20.5 (NLO)	14.5 ± 3.0	30.4
$T\bar{T}$, $M(T) = 300$ GeV/c^2	7.29 (NLO)	24.6 ± 5.0	18.4
$T\bar{T}$, $M(T) = 350$ GeV/c^2	2.94 (NLO)	29.9 ± 6.8	8.99
$T\bar{T}$, $M(T) = 400$ GeV/c^2	1.30 (NLO)	30.3 ± 6.9	4.03
$T\bar{T}$, $M(T) = 450$ GeV/c^2	0.617 (NLO)	33.8 ± 7.7	2.13
$T\bar{T}$, $M(T) = 500$ GeV/c^2	0.310 (NLO)	34.4 ± 7.9	1.09
$T\bar{T}$, $M(T) = 550$ GeV/c^2	0.162 (NLO)	33.6 ± 7.9	0.56
$t\bar{t}$ + jets	158 (CMS)	$(2.6 \pm 2.0) \times 10^{-4}$	0.08
Z + jets	2.9×10^3 (CMS)	$(6.3 \pm 5.4) \times 10^{-5}$	0.35
WZ inclusive	18.0 (NLO)	$(3.3 \pm 0.5) \times 10^{-3}$	0.12
ZZ inclusive	5.9 (NLO)	$(5.9 \pm 0.6) \times 10^{-3}$	0.07
$t\bar{t}$ + W + jet	0.144 (LO)	$(1.3 \pm 1.3) \times 10^{-2}$	0.004
$t\bar{t}$ + Z + jet	0.094 (LO)	$(5.4 \pm 1.3) \times 10^{-1}$	0.10
Expected background from simulated samples			0.71
Background with two real leptons (data-driven)			0.45 ± 0.28
Background with three real leptons (simulated)			0.28 ± 0.11
Sum (estimated background)			0.73 ± 0.31
Data (191 pb^{-1})			0

$t' \to tZ$ limits setting @191*ipb*



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



Relevant final state:

- 4 Jets from:
  - 2 $W \to qq$
  - 2 b-jets
- 1 visible lepton from:
  - $W \to l\nu$

$t' \to bW$ Event Reconstruction

We use a kinematic fitter to 'fit' to mass constraints:

- $M(W_{had} \to q\bar{q}) = M_W = M(W_{lep} \to l\nu)$
- $M(W + b) = M_{fit}$

Unknowns:

- t' mass
- ν has p_T (calculated) and 2 $p_{//}$ solutions
- 4Jets from $b, \bar{b}, W_{had}$ $(4!/2 \times 2 = 24$ combos)

Then pick 'best' combination (currently minχ^2) that reconstructs the event.

Backgrounds:

- $t\bar{t}$ production - irreducible
- single top production
- W+jets/Z+jets/diboson production
- multijets

Selection criteria - channel: l + jets

Selection chosen to maximise $n_s/\sqrt{n_b}$ in accepted signal sample for a $400GeV$ t'.

- primary vertex
  - $|z| < 24cm, |r| < 2cm$
- lepton
  - $pT > 30/35/45GeV$ to match trigger threshold ($30GeV$ for e)
  - pseudorapidity $|\eta| < 2.5$ (2.1 for e)
  - impact paramter of matched track $|dxy| < 0.02cm, |dz| < 1cm$
  - missing $p_T > 20GeV$
- at least 4 jets with
  - $pT > 120, 90, 35, 35GeV$ && $|\eta| < 2.4$
  - $\Delta R(l, jets) = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} < 0.3$ veto - avoids double counting leptonic jets
  - ≥ 1 jet is btagged

Event Yield: e + *jets*@573*ipb* & μ + *jets*@821*ipb*

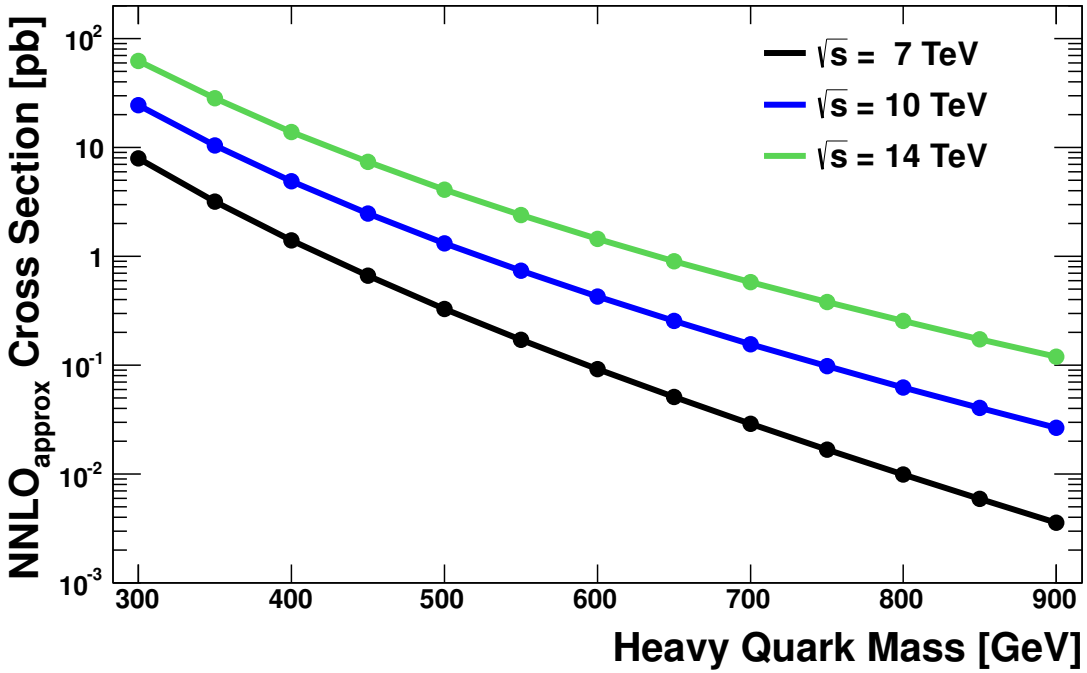
process	cross section	e+jets events	μ+jets events
$\mathcal{L}$		573 pb^{-1}	821 pb^{-1}
data		520	1054
$t\bar{t}$	158 pb	456 ± 91	907 ± 114
single t	33 pb	14.5 ± 3.5	30 ± 6
W+jets	30 μb	33.3 ± 8.2	106 ± 25
Z+jets	2.9 μb	4.5 ± 1.2	2.6 ± 2.6
WW,WZ,ZZ	67 pb		2.1 ± 0.6
multijets		2.5 ± 1.2	5.7 ± 5.5
total background		510 ± 103	1054 ± 145

CMS preliminary

Selection Efficiencies of Signal

process	cross section	e+jets eff.	μ+jets eff.
$t'\bar{t}'$			
$m_{t'} = 350$ GeV	3.20 pb	$3.7 \pm 0.4\%$	$4.5 \pm 0.3\%$
$m_{t'} = 400$ GeV	1.41 pb	$4.3 \pm 0.4\%$	$5.2 \pm 0.4\%$
$m_{t'} = 450$ GeV	0.66 pb	$4.8 \pm 0.4\%$	$5.6 \pm 0.4\%$
$m_{t'} = 500$ GeV	0.33 pb	$5.0 \pm 0.4\%$	$5.8 \pm 0.4\%$
CMS simulation			

M. Aliev et al 'HATHOR - HAdronic Top and Heavy quarks crOss section calculatoR', Comput. Phys. Commun 182(2011)1034 – 1046



Event Reconstruction

Measurements:

- Lepton momentum
- Neutrino p_T
- Jet momentum

Unknowns:

- z component of neutrino momentum

Constraints:

- $M(l\nu) = m(qq) = M_W$
- $M(l\nu b) = m(qqb) = M_{t,t'}$

Fit and minimise χ^2 - get one χ^2 value for each combination.

Using kinematic fit we reconstruct the fitted mass.

- $t\bar{t}$ background is irreducible - but use mass to discriminate against $t'\bar{t}'$ signal.

Mass Reconstruction

Final state: $4Jets + l\nu$ but can have ISR,FSR etc.
Number of ways jets can be assigned to partons:

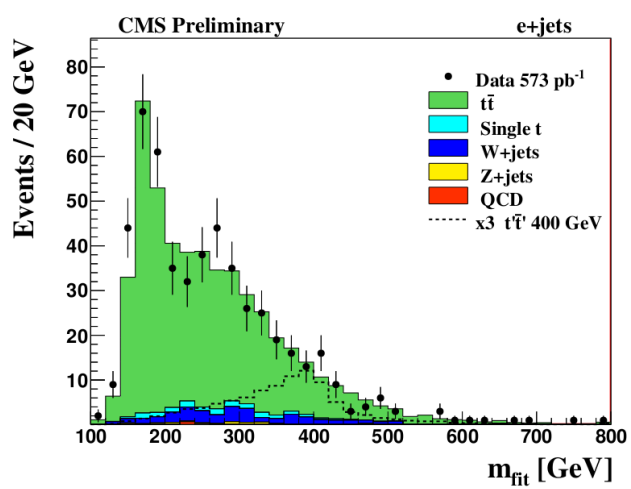
no of jets	combinations
4	12
5	60
6	180

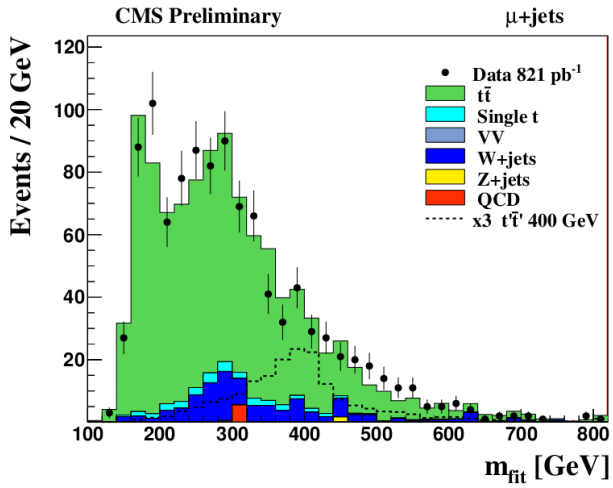
We take Minχ^2 combination with:

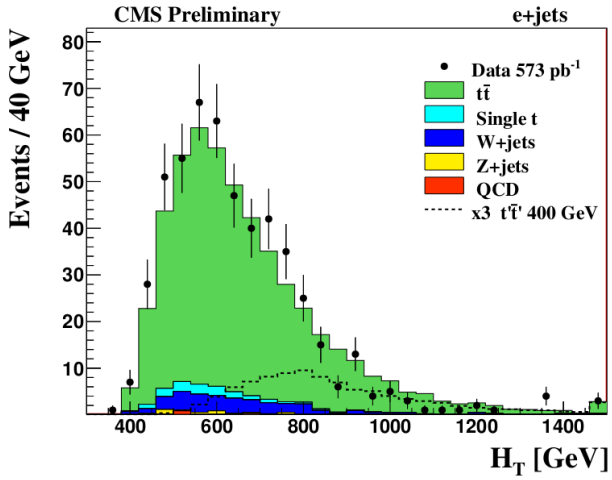
- e + *jets*: try all 4-jet combs out of the leading 5 jets
- μ + *jets*: use 4 leading jets. If 5th jet has highest b-tagging discriminant use it instead of 4th jet

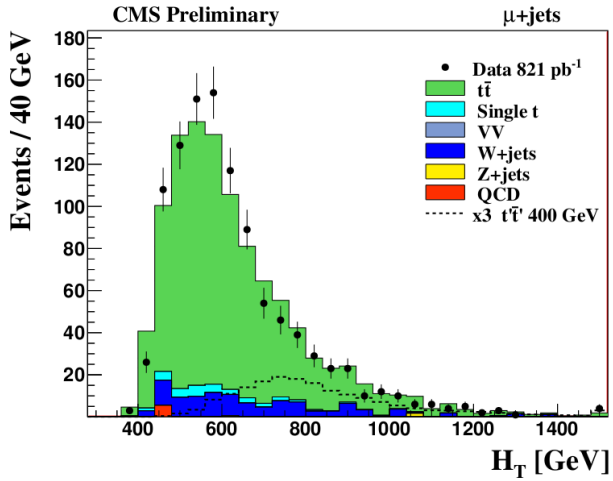
Studied 4,5,6 leading jets - considering 5jets best (significant improvement).

M_{fit} & H_{fit}: e + jets@573ipb & μ + jets@821ipb









2D Plots - channel: e + *jets*

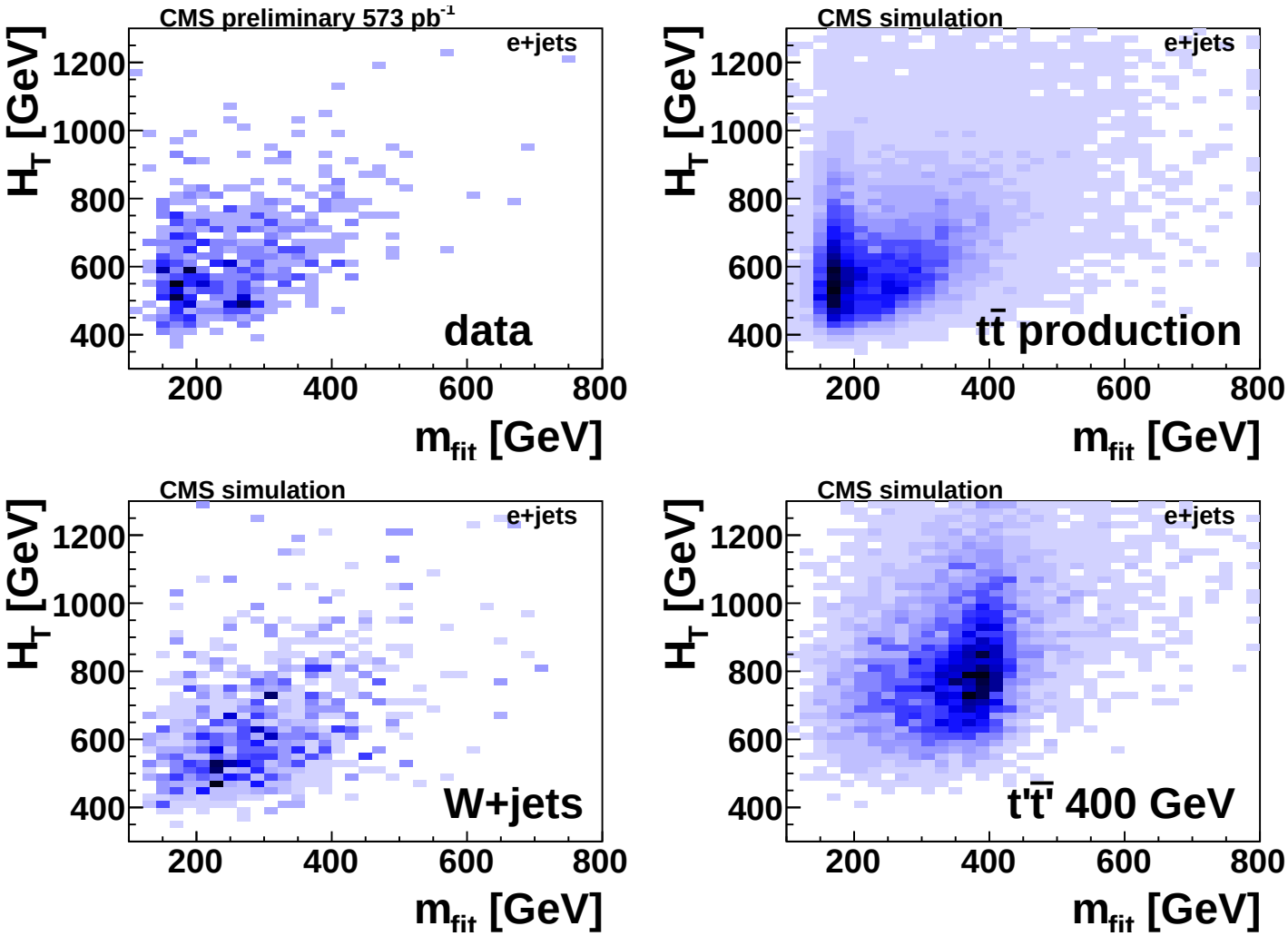


Figure: e + *jets* 2D (HTvsMfit) plots using $\int \mathcal{L} = 573 pb^{-1}$ data.

2D Plots - channel: μ + *jets*

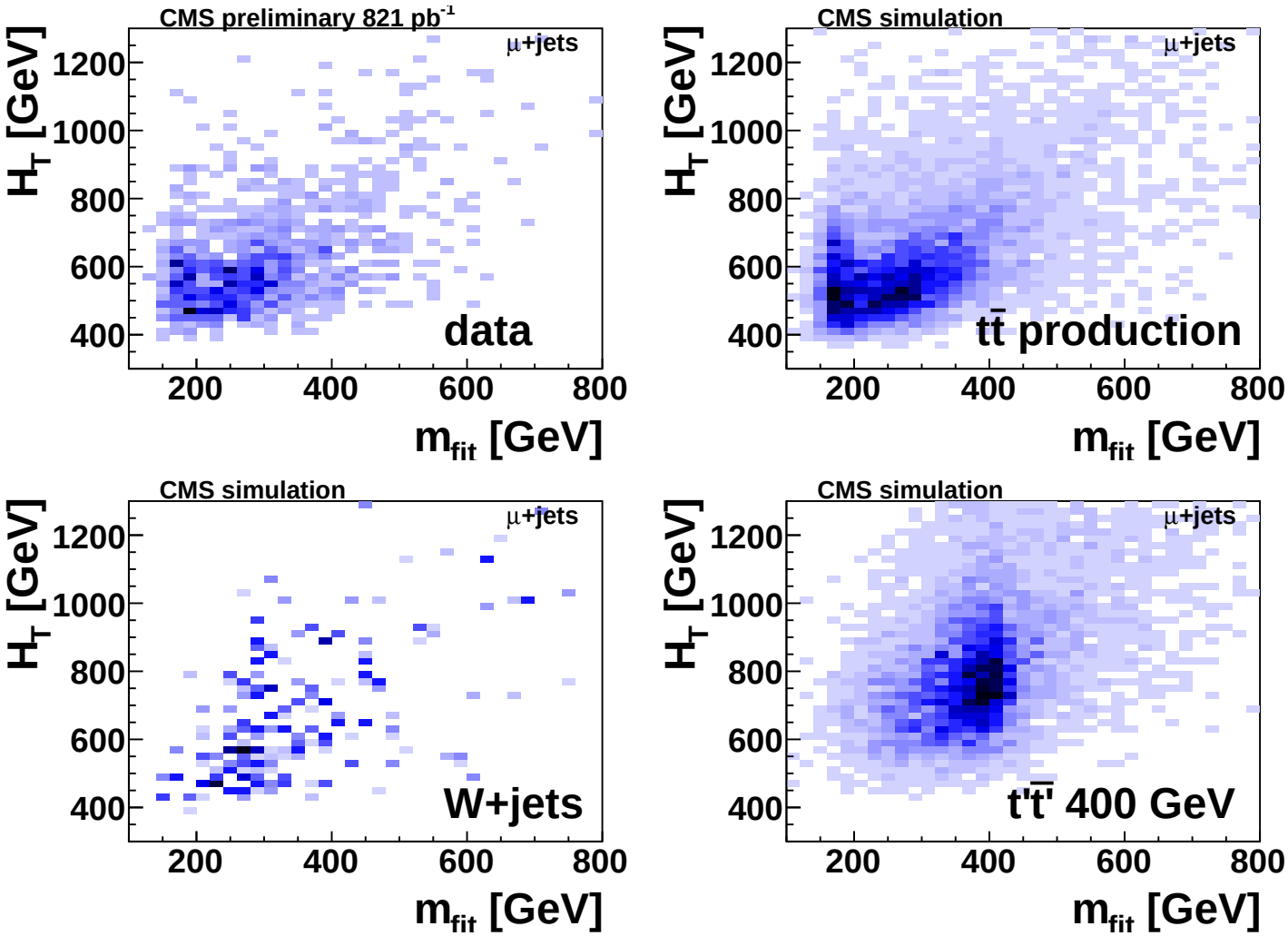


Figure: μ + *jets* 2D (HTvsMfit) plots using $\int \mathcal{L} = 821 pb^{-1}$ data.

Limit Computation

- compare observed distribution to predicted dist. from MC simulation of signal and background
- use
  - m_{fit} = reconstructed mass from kinematic fitter
  - H_T = sum of transverse energies of reconstructed objects

Each bin is then compared to data by limit calculator HistFactory.
The model likelihood is defined by:

$$L = \prod_{m \in bins} P\left(n_m \mid \nu_m\left(\mu, \{\alpha_i\}\right)\right) \prod_{i \in syst} N\left(a_i \mid \alpha_i\right)$$

- lognormal constraints on nuisance parameters
- nuisance parameters
- parameter of interest
- number of events expected in bin m
- number of events observed in bin m
- Poisson probability

Model Parameters

Nuisance Parameters:

- $\sigma_{t\bar{t}}$ - constrained to CMS measured value of $158pb \pm 11\%$
- $N_{ewk}^{e,\mu}$ - number of other background events (constrained to prediction with 50% precision)
- α_{jes} - jet energy scale calibration. This affects shape and norm of dist. Distributions are determined for the nominal jes and $\pm 1\sigma$ variations. Intermediate are obtained by vertical morphing.
- $\epsilon_{e,\mu}$- selection efficiency for e/μevents - constrained to 3%
- ϵ_b - btagging eff 5%
- $\int \mathcal{L}$ - uncertainty $\pm 6\%$

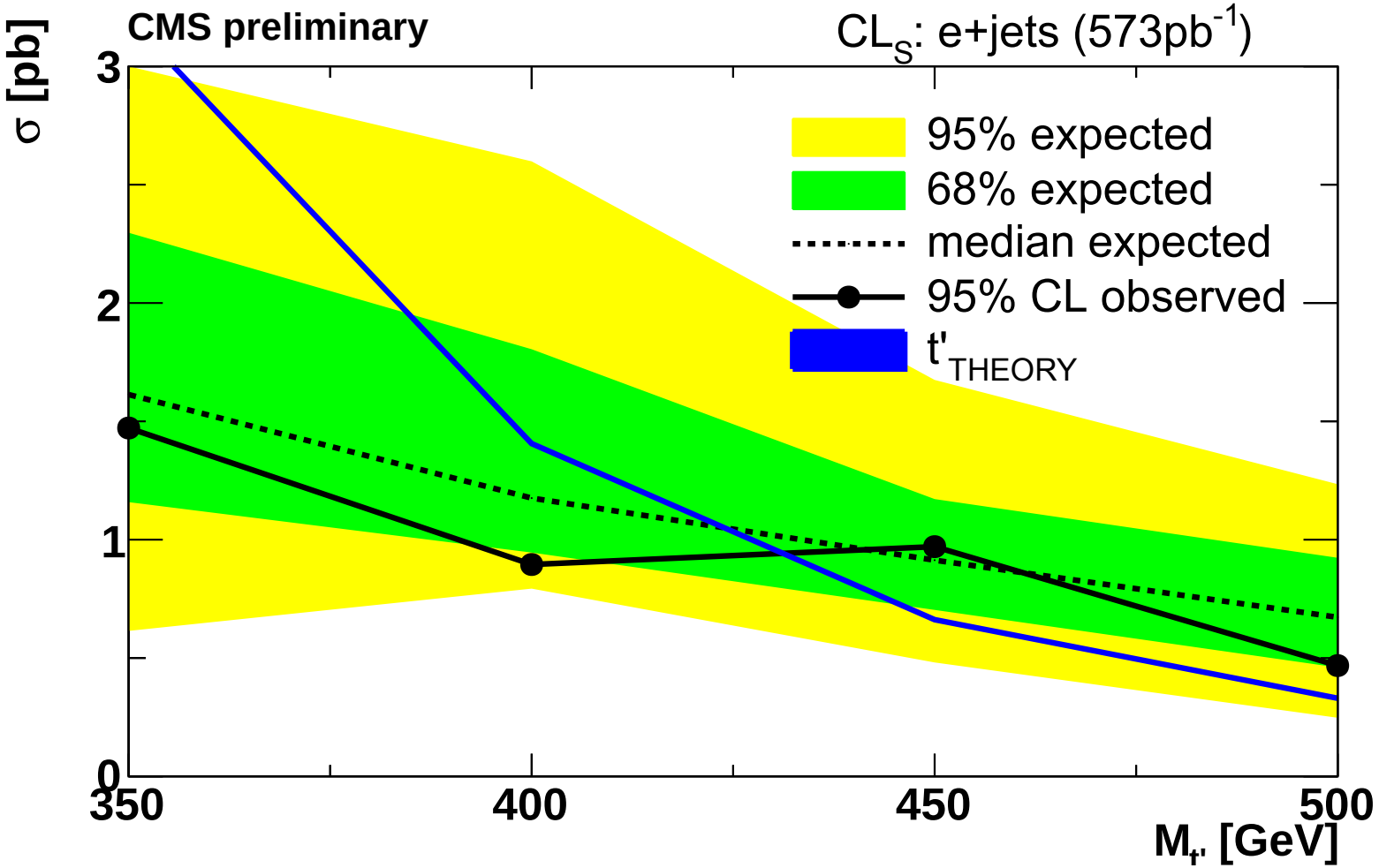
Limit Computation -CLs

- for each t' mass value perform two fits:
  - maximise likelihood wrt parameters $(\mu, \{\alpha\})$
  - background-only hypothesis $(\mu = 0) \to L_b$
  - signal + background hypothesis$\to L_{s+b}$
- likelihood ratio $L = L_{s+b}/L_b$
- prob for $L > L_{obs}$
  - for background only $\to CL_b$
  - for signal+background $\to CL_{s+b}$ (depends on signal cross section)
- the 95% CL limit is the signal cross section for which:

$$1 - \frac{CL_{s+b}}{CL_b} = 1 - CL_s = 0.95 \quad (1)$$

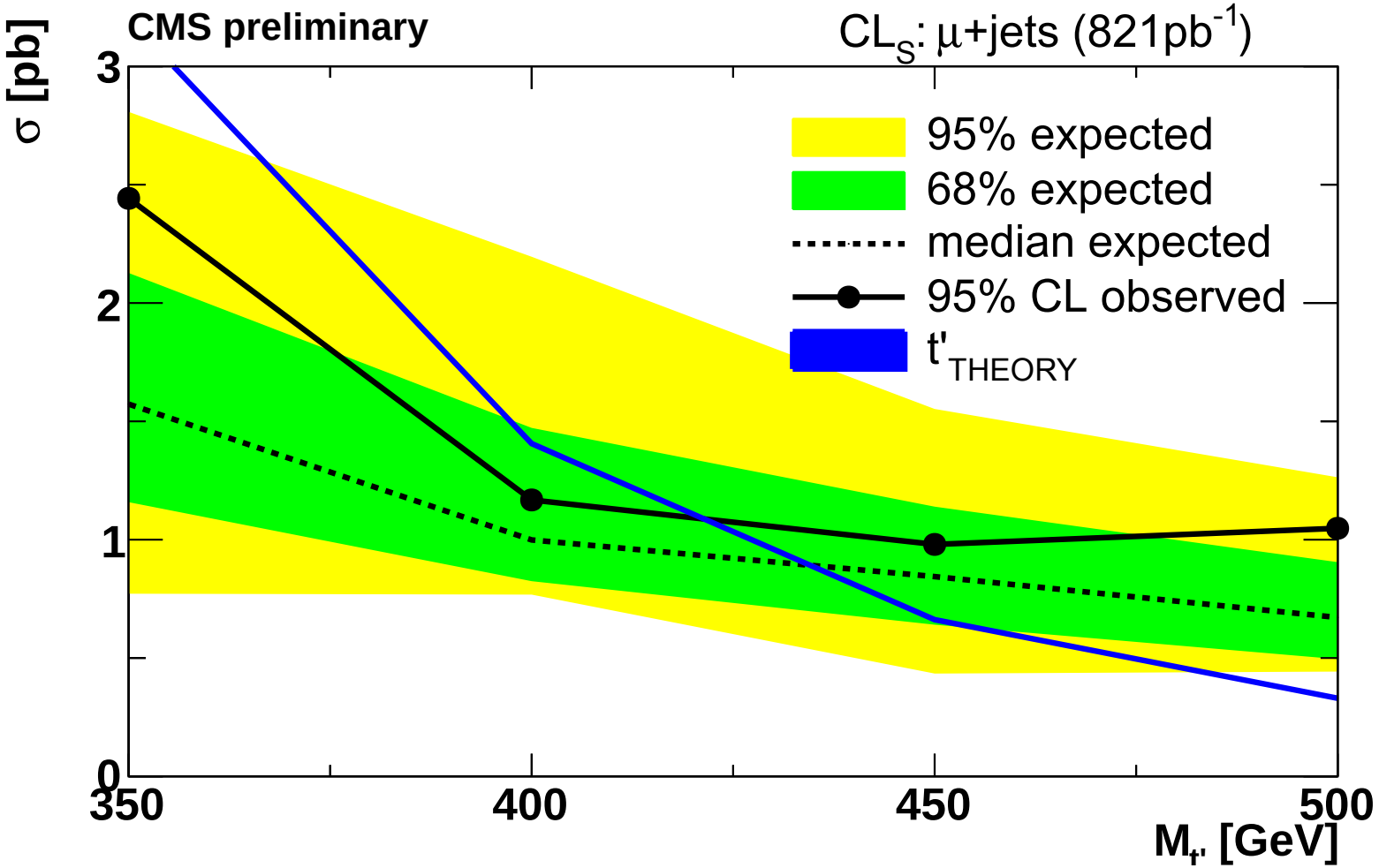
Expected limit is determined using pseudoexperiments.

Results - channel: e + *jets*@573*ipb*



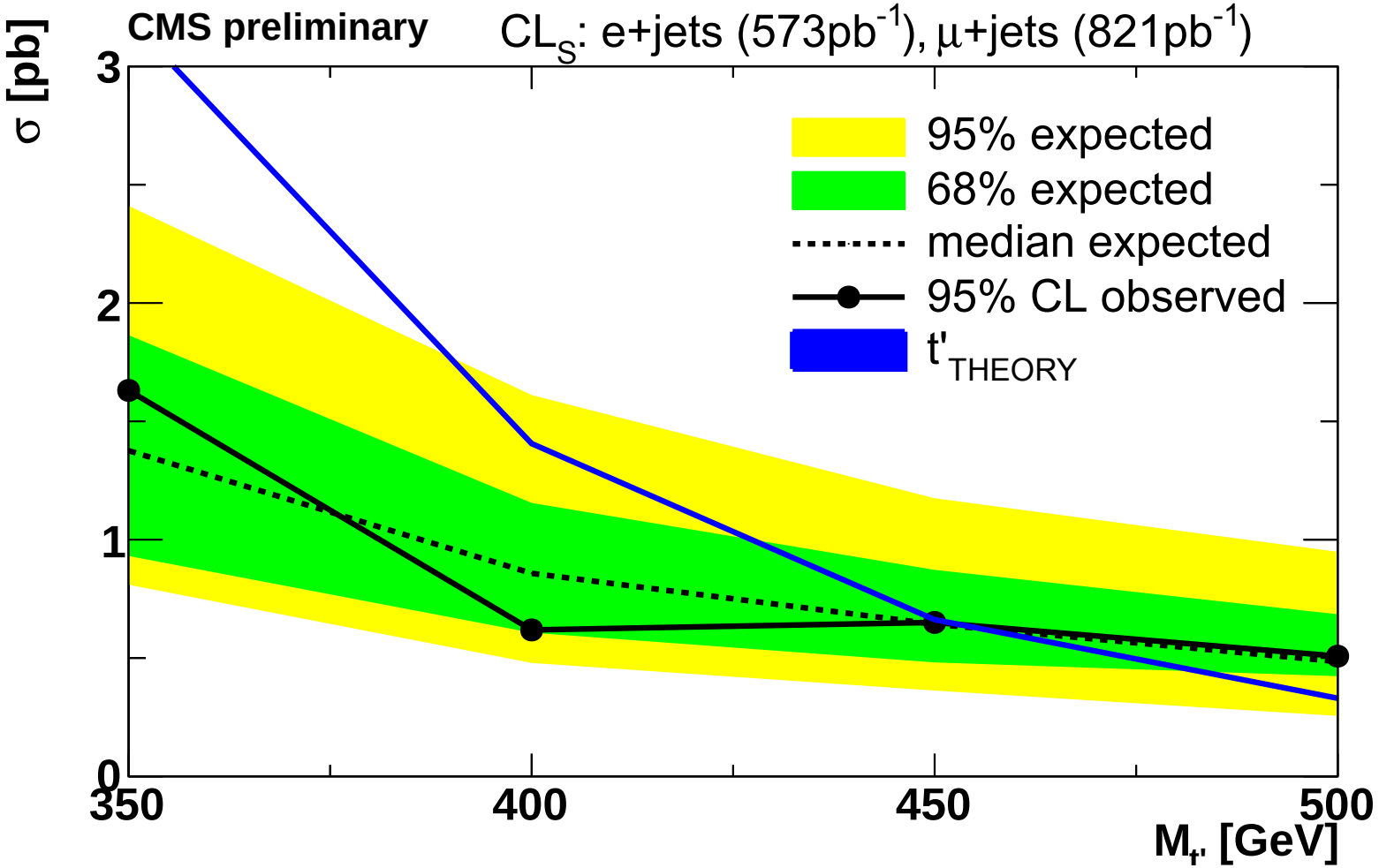
observed limit: $m_{t'} > 431 GeV@95\% CL$ (expected $424 GeV$)

Results - channel: $\mu + jets@821ipb$



observed limit: $m_{t'} > 422GeV@95\%CL$ (expected $435GeV$)

Results - channel: *combined* for e + *jets*@573*ipb* and μ + *jets*@821*ipb*



observed limit: $m_{t'} > 450 GeV$@95%CL (expected $450 GeV$)

Summary

- Searched for pair produced $b' \to tW$ in trilepton channel.
  - used $34 pb^{-1}$
  - $m_{b'} > 361 GeV$ observed limit with 95% CL
- Searched for pair produced $t' \to tZ$ in dilepton and trilepton channel.
  - used $191 pb^{-1}$
  - $m_{t'} > 417 GeV$ observed limit with 95% CL
- Searched for $t' \to bW$ pair production in the lepton+jets channel
  - assumed strong pair production
  - exclusive decay $t' \to Wb$
  - used $573 pb^{-1}$ in $e + jets$ and $821 pb^{-1}$ in $\mu + jets$ channel
  - $m_{t'} > 450 GeV$ observed limit with 95% CL

t' limits are best in the world (b' limit to be updated soon).
$\to$ no excess over SM seen.