Monotops at the LHC

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March 17, 2015

Outline

- Main features
- Classifying monotop signatures
- Baryogenesis
- A minimal model
- Monotop+MET with top quark channels
- Signal and background descriptions
- Monotop searches at the LHC
  - Hadronic and leptonic monotops at 7, 8 and 13 TeV
- Baseline cuts (initial proposal)

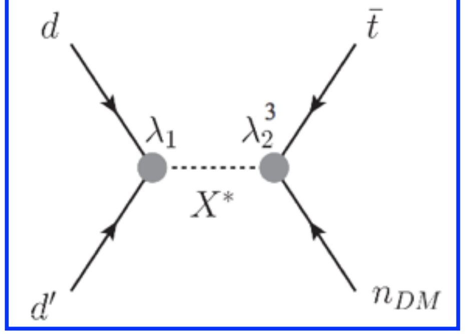
Main features

- Bottom-up strategy
  - Start from a final state signature

top + missing energy

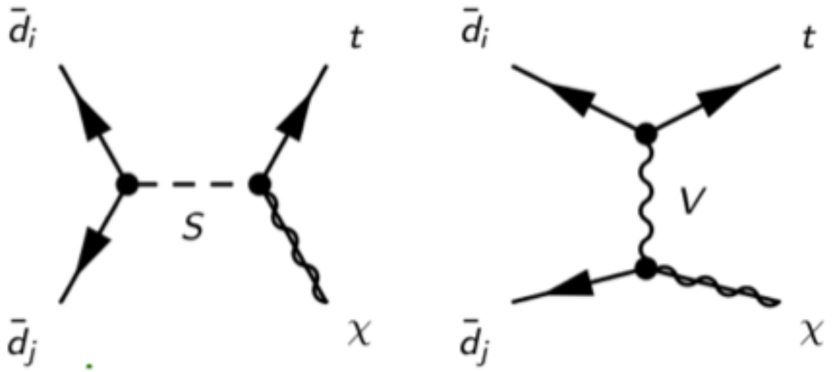
- Key features
  - **Missing energy (DM candidates)**
    - Bosonic or fermionic state / One-particle or n-particle state
    - Neutral, weakly-interacting, long-lived/stable/invisible
  - **One single top quark**
  - **Enhanced coupling between the 3rd generation and the others**
  - **Initial state: two possibilities**
    - **A down-type (anti) quark pair → baryon-number-violating process**
    - An up-type quark / gluon associated → flavor-changing neutral interactions

s-channel resonant case



Monotop signatures (I)

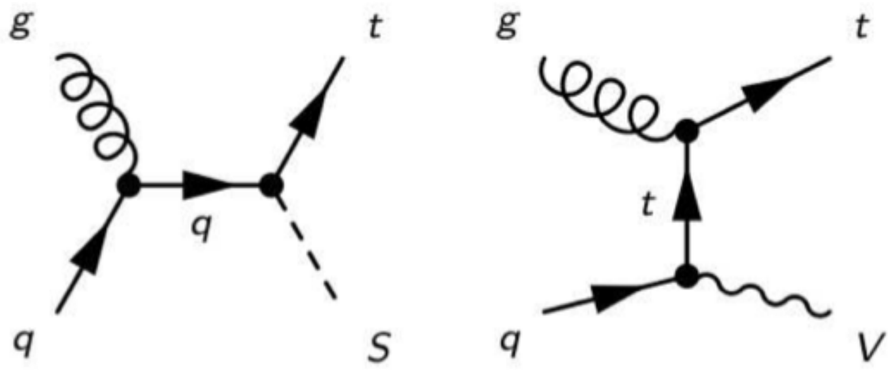
- MET is a fermion χ (or n_{DM})
- Monotop produced via (resonant or not) exchange of a new bosonic state



- Examples
  - *R*-parity-violating SUSY ($\bar{d}\bar{s} \to \tilde{u}_i \to t\tilde{\chi}^0_1$, S=squark, χ=lightest neutralino)
  - *SU*(5) theories ($\bar{d}\bar{d} \to V \to t\bar{\nu}$, V=leptoquark, χ=neutrino)
  - Four-fermion interactions (very heavy S or V), $\chi \equiv$ spin 3/2 excitations, Etc.

Monotop signatures (II)

- MET is a boson S or V
- Monotop produced via flavor-changing interactions (top-charm or top-up)



- Examples
  - *R*-parity conserving SUSY: $ug \rightarrow \tilde{u}_i \tilde{\chi}_1^0 \rightarrow t \tilde{\chi}_1^0 \tilde{\chi}_1^0$
  - Compressed spectrum, Flavor-violating graviton couplings (spin 2), Etc.

$ug \rightarrow tS \ , \ tV \quad \text{or} \quad tG$

Motivation: baryogenesis

Probing Light Nonthermal Dark Matter at the LHC, PRD 89, 096009 (2014)

- A minimal extensions to SM with ~TeV color-triplet scalars (*X*) and one singlet fermion (n_{DM})
- Baryon-number-violating interaction mediated by heavy scalars *X*

$$\mathcal{L}_{int} = \lambda_1^{\alpha,\rho\delta} \epsilon^{ijk} X_{\alpha,i} \bar{d}^c_{\rho,j} \mathbf{P}_R d_{\delta,k} + \lambda_2^{\alpha,\rho} X^*_\alpha \bar{n}_{\mathrm{DM}\rho} \mathbf{P}_R u + \mathrm{C.C.}$$

X index α =1, 2 for a minimal case with two *X* fields, required for successful baryogenesis

Quark generation indices ρ,δ={1,2,3} and SU(3) color indices i,j,k={1,2,3}

- *X* couples to two *d*-quarks or one *u*-quark + DM
- DM couples to light fermions since it isn't protected by a a parity

$|m_{DM} - m_{proton}| < m_{electron}$ $\lambda_2 \sim 0.1$ and $m_X \sim$ TeV

A minimal model

- New interaction terms and production mechanism are implemented within the FeynRules package and interfaced with the MadGraph 5 event generator

$$\mathcal{L}_{int} = \lambda_1^{\alpha,\rho\delta}\epsilon^{ijk} X_{\alpha,i}\bar{d}^c_{\rho,j}\mathbf{P}_R d_{\delta,k} + \lambda_2^{\alpha,\rho} X^*_\alpha \bar{n}_{DM}\mathbf{P}_R u_\rho + C.C.$$

$$\lambda_1^{\alpha,\rho\delta} = \lambda_1 \times \lambda_{1X}^{\alpha} \times \lambda_{1R}^{\rho\delta} \qquad \lambda_2^{\alpha,\rho} = \lambda_2 \times \lambda_{2X}^{\alpha} \times \lambda_{2R}^{\rho}$$

Our focus:

☑ $\lambda_{2R}^{\rho} = (1, 1, 1)$ allows to probe the coupling to top quark

light jets

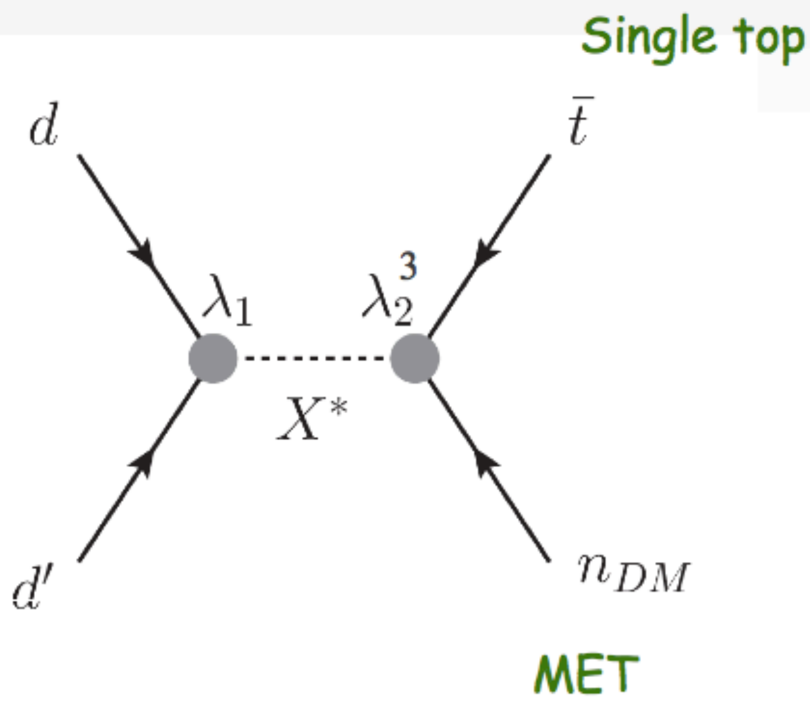
top

☑ Suppose X_1 be lighter then X_2

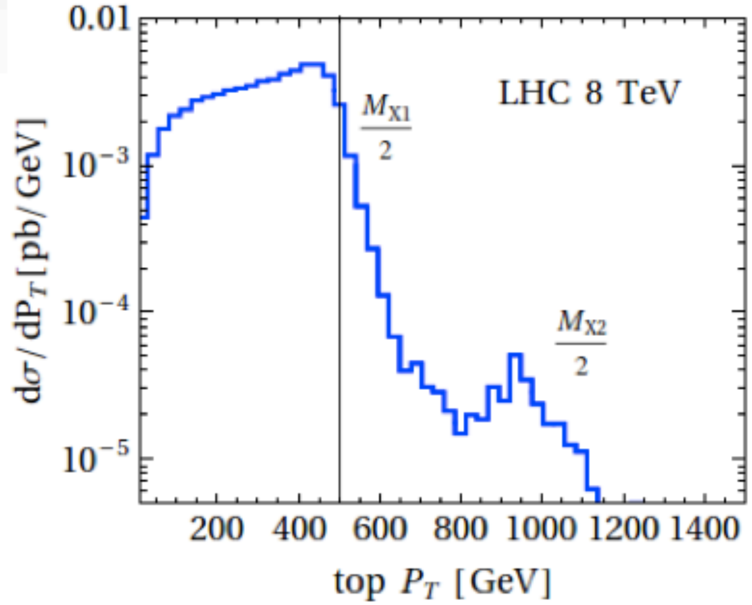
☑ Make a flavor-blind coupling structure for simplicity

From the slide by Mykhailo and Youngdo

Monotop + MET



assumed $M_{X2} = 2M_{X1}$



M_{X1} = 1 TeV

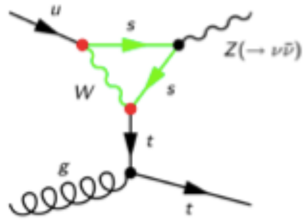
Top-quark decay modes determine the sub-channels:

- $t \to Wb \to \ell \nu b$, where $\ell = e, \mu, \tau$
- $t \to Wb \to jets$

Signal description

- Hadronic top decay
  - 2 light jets + 1 b jet + missing energy
  - **Top reconstruction possible**
- Leptonic top decay
  - 1 lepton + 1 b jet + missing energy
  - **No top mass reconstruction**
  - Challenging due to two different invisible particles

Background



$Z \rightarrow \nu\nu$ + 3 jets	Irreducible

	Fake missing energy
QCD multijet	mis-reconstructed jet
W+jets ttbar diboson	non-reconstructed leptons from W
Single top	non- or mis-reconstructed leptons

A first prospective parton-level study done at 7 TeV (1 fb^{-1})

→ Learning the key features necessary for a full analysis

Monotops with 1 fb^{-1} of 7 TeV (I)

CMS and ATLAS

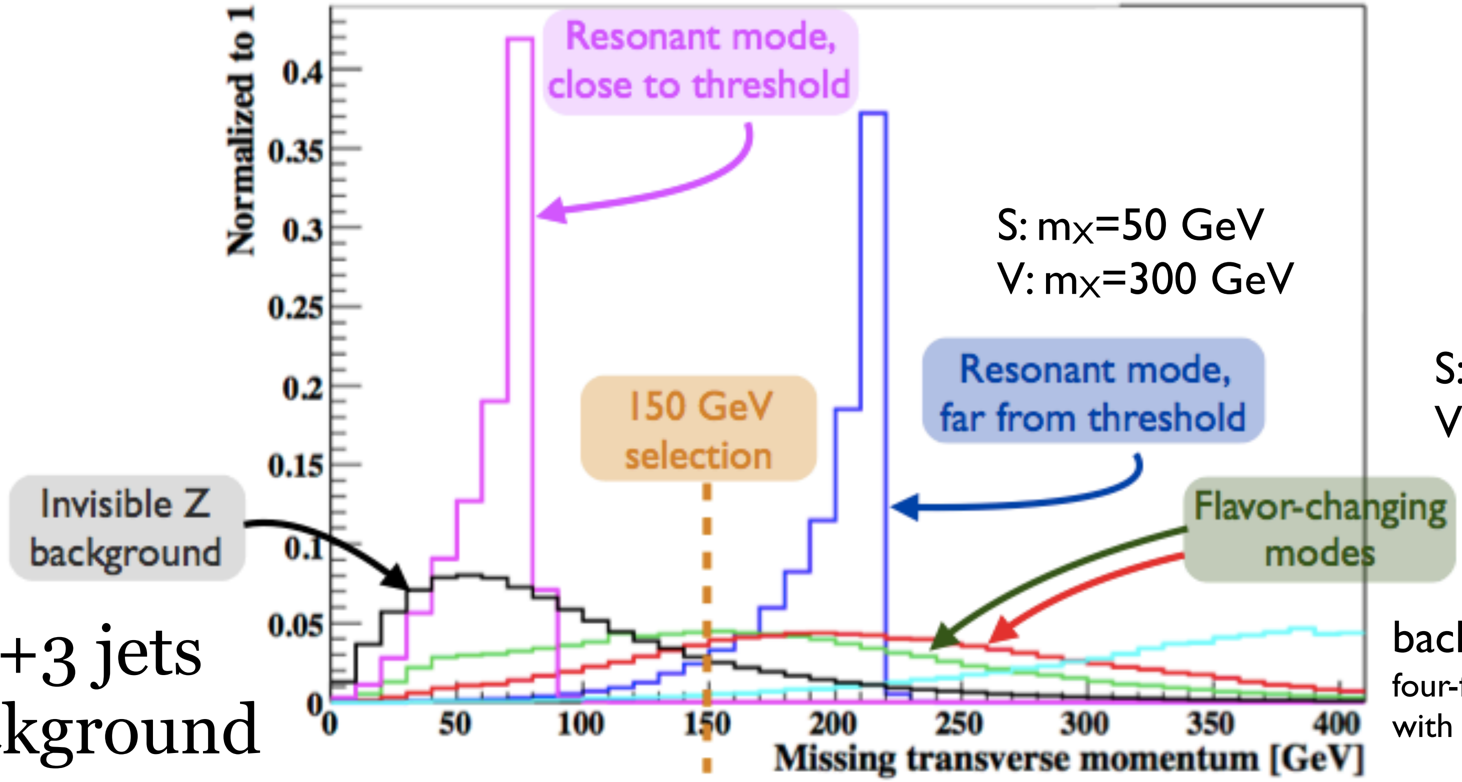
- Analysis strategy
  - Large missing energy, three high-quality hard jets, large hadronic activity
- Effects on the background
  - Comparable amount of multijet, ttbar, Drell-Yan and W+jets events
  - Single top and diboson contributions highly reduced
- Additional specific monotop search strategy
  - Exactly one top → exactly 3 jets with one b tag
  - Lepton veto
  - The two light jets from a W boson (m_W)
  - The three jets from a top quark (m_{top})

Simple selection	
MET	> 150 GeV
top p_T	> 50 GeV
SET(3 jets)	> 300 GeV

Monotops with 1 fb^{-1} of 7 TeV (II)

Results based on a parton-level simulation for the signal and background

- The key selection: the missing energy
  - Resonant and non-resonant production have different missing energy spectra



Z+3 jets background

background in cyon:
four-fermion interactions
with a massless invisible state

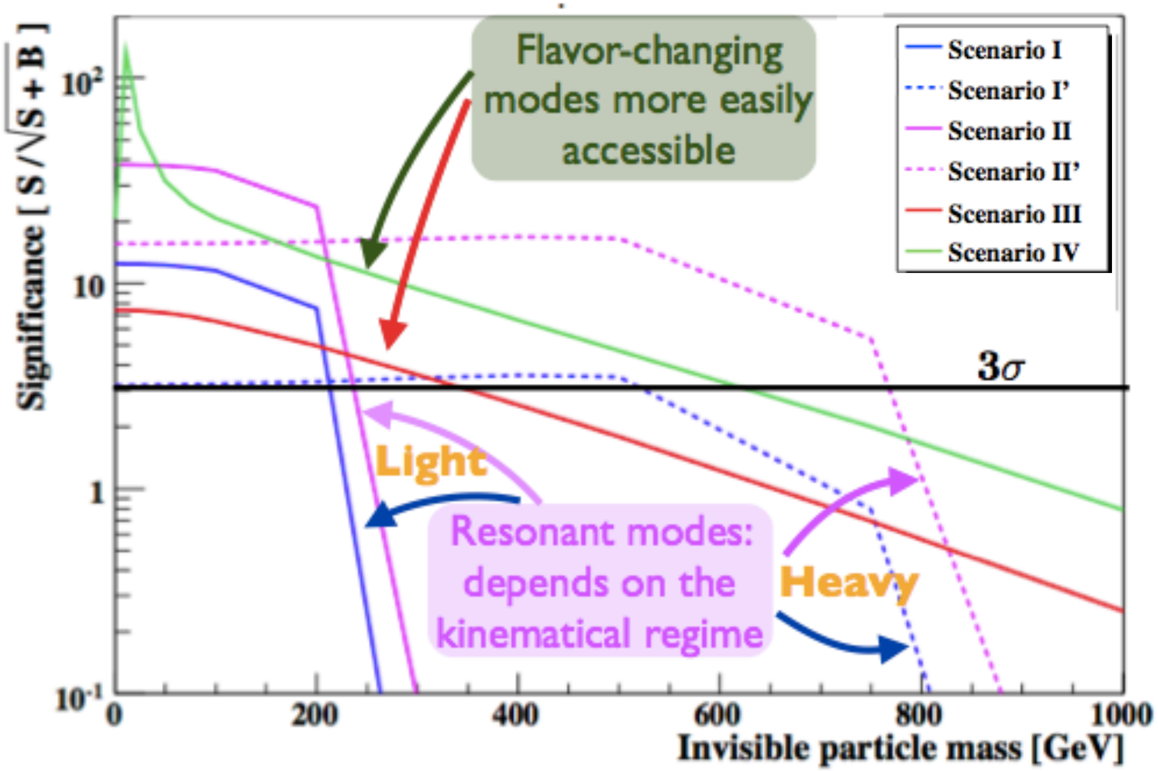
This selection criterion drives the sensitivity to the different modes

IPHC-PHENO-11-03
arXiv:1106.6199

Monotops with 1 fb^{-1} of 7 TeV (III)

Scenario	$\not{E}_T$ cut [GeV]	$\sigma(t+\bar{t})$ [pb]	a_{min}
I	150	3.99	0.042
II	65	32.1	0.043
III	150	0.322	0.14
IV	150	24.3	0.017
V	250	$1.08 \cdot 10^{-4}$	4.9

- Analysis strategy: detailed specifications
  - $\not{E}_T$ > 150 GeV (hard to detect light resonances)
  - W-boson reconstruction: 20 GeV window
  - Top reconstruction: 30 GeV window
  - b-tagging efficiency: 60 % (10% c-mistagging and 1% light jet-mistagging)

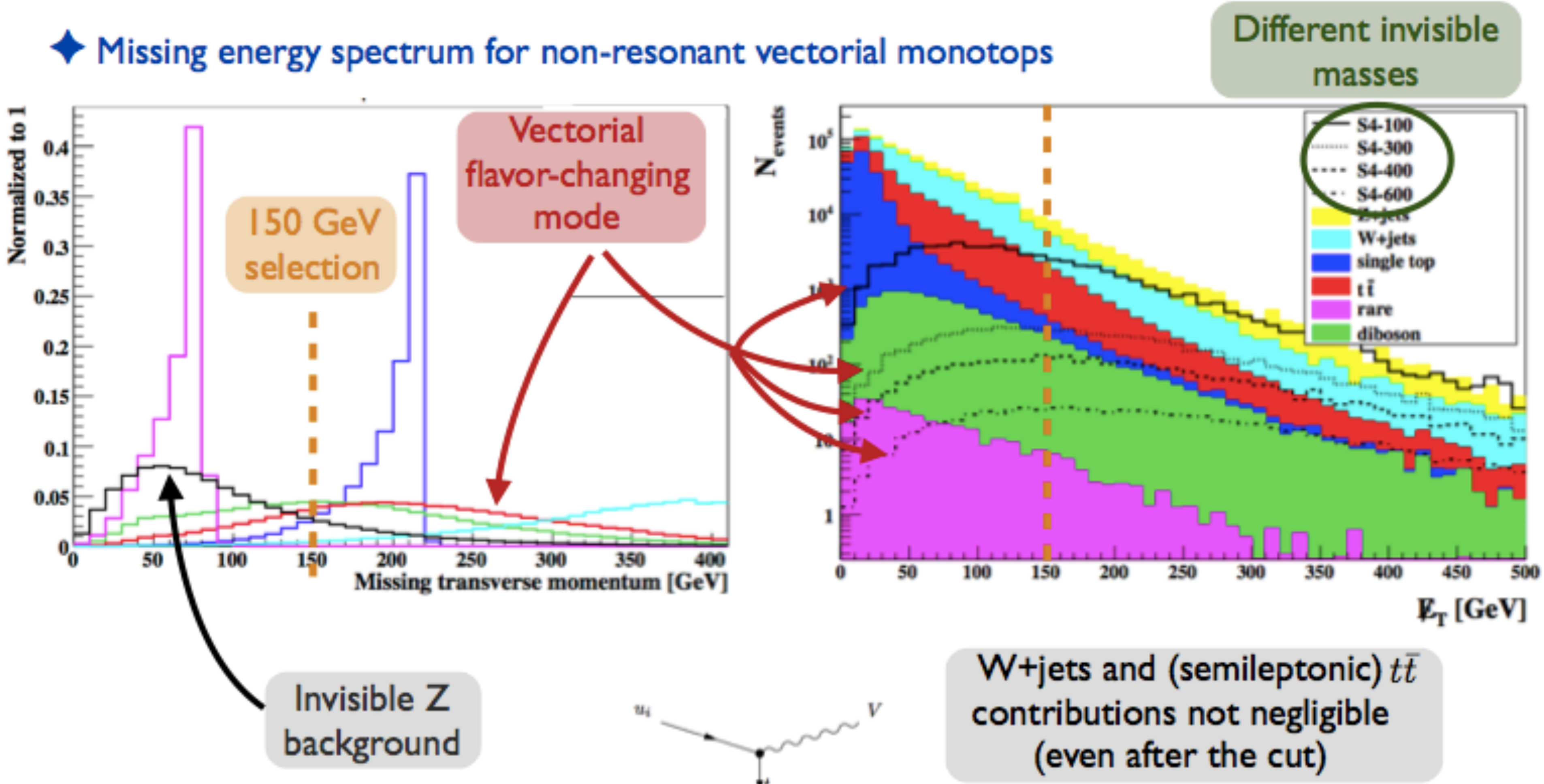


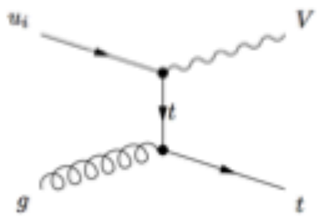
⇒ Light monotops are reachable in all production modes

⇒ Heavier monotops are only visible in specific channels

Monotops with 20 fb^{-1} of 8 TeV (I)

- Missing energy spectrum for non-resonant vectorial monotops





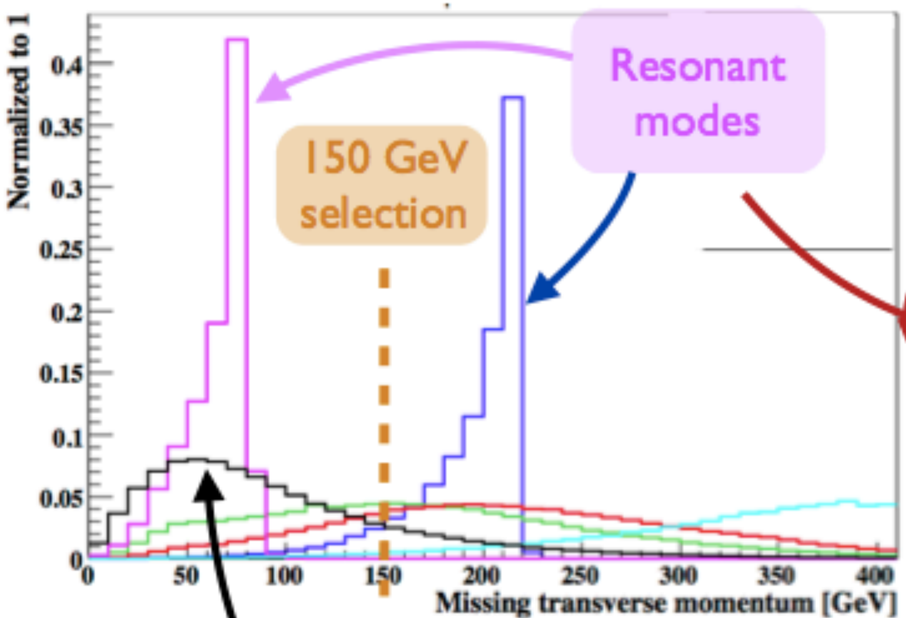
7 TeV, parton-level

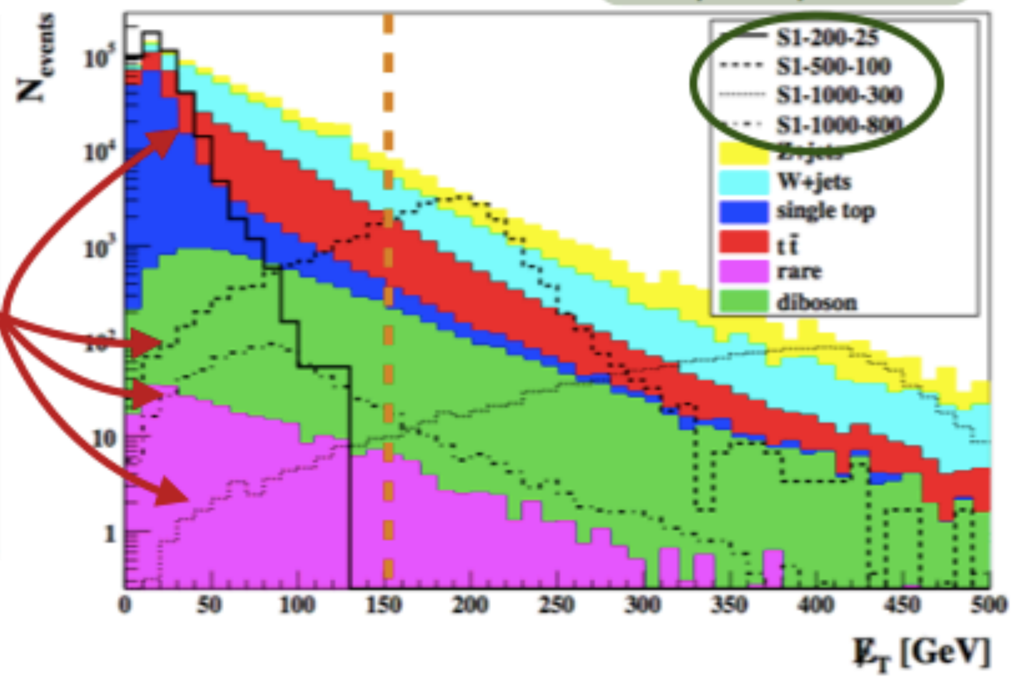
8 TeV, reconstructed-level

Monotops with 20 fb^{-1} of 8 TeV (II)

✦ Missing energy spectrum for scalar resonant monotops

Kinematics drives the peak position

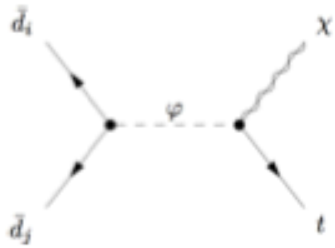




Resonant modes

150 GeV selection

Invisible Z background



W+jets and (semileptonic) $t\bar{t}$ contributions not negligible (even after the cut)

7 TeV, parton-level

8 TeV, reconstructed-level

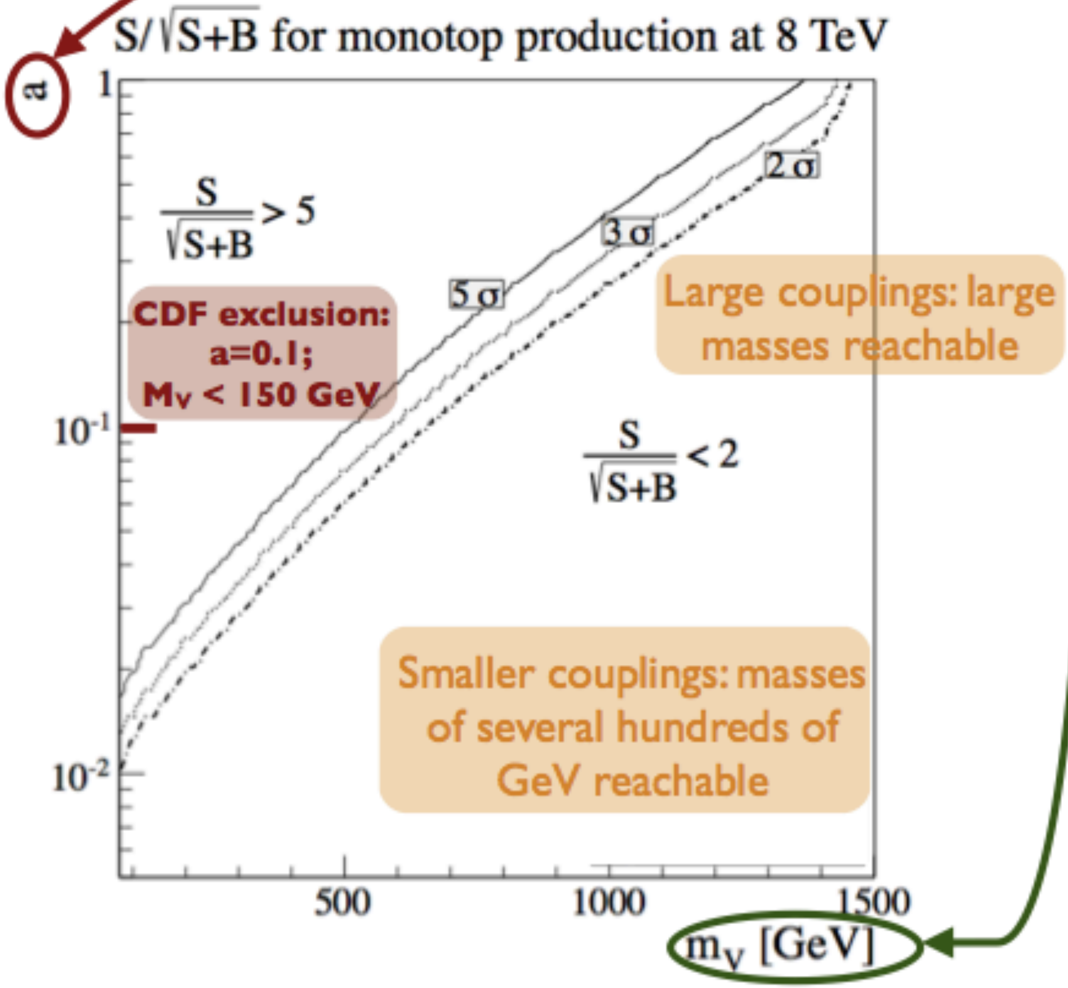
Monotops with 20 fb^{-1} of 8 TeV (III)

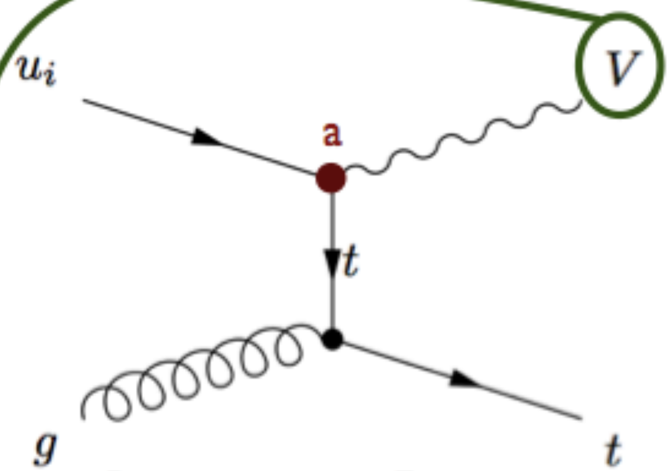
$$\mathcal{L} = V_\mu \bar{u} a^1_{FC} \gamma^\mu u + \dots$$

Only non-zero couplings: top-up

$$(a^1_{FC})_{13} = (a^1_{FC})_{31} = a$$

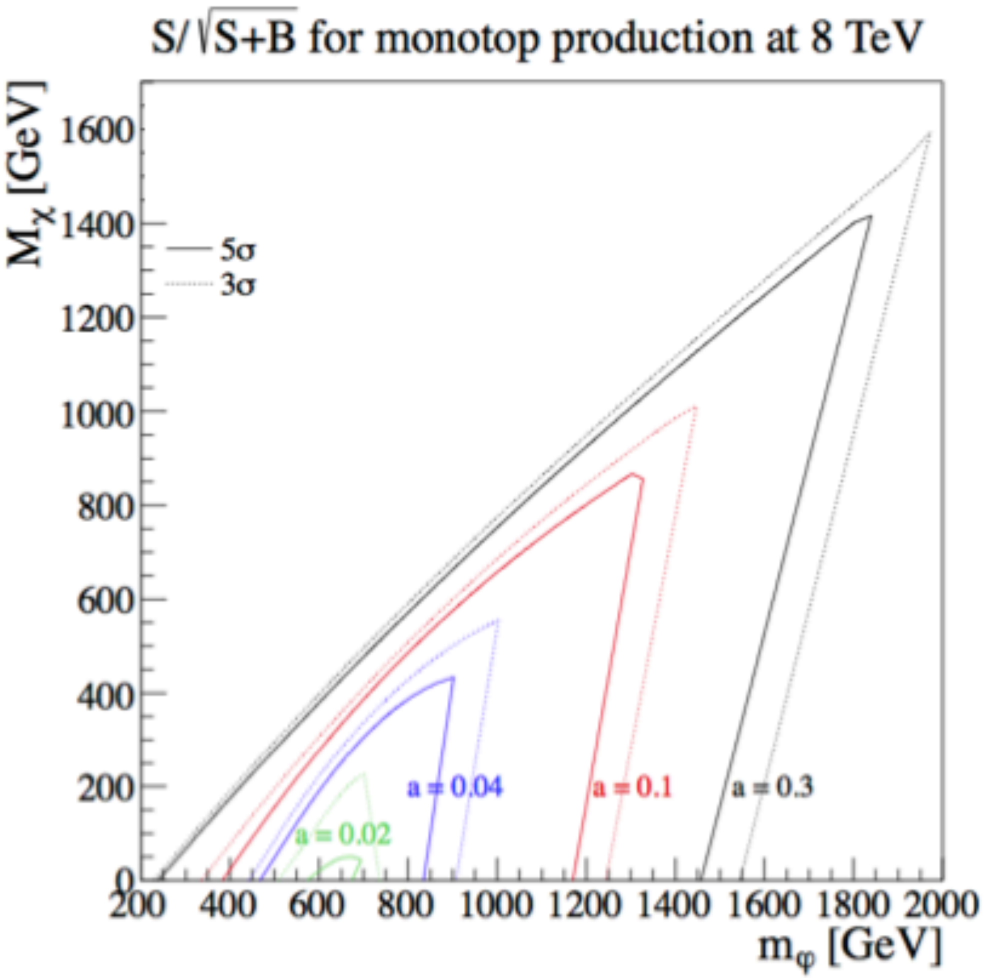
Only two free parameters





Representative Feynman diagram

Monotops with 20 fb^{-1} of 8 TeV (IV)



The sensitivity highly depends on the mass difference (as well as on the total rate)

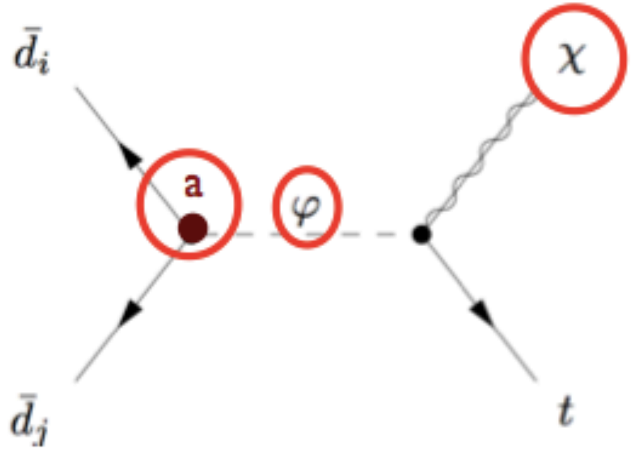
$$\mathcal{L} = \epsilon^{ijk}\varphi_i \bar{d}^c_j a^q_{SR} d_k + \varphi_i \bar{u}^i a^{1/2}_{SR}\chi + \ldots$$

$$(a^q_{SR})_{12} = -(a^q_{SR})_{21} = a$$

BR($\varphi \rightarrow u\chi$) = 100%

→ total rate independent of $a^{1/2}_{SR}$ and of m_χ .

Only three free parameters

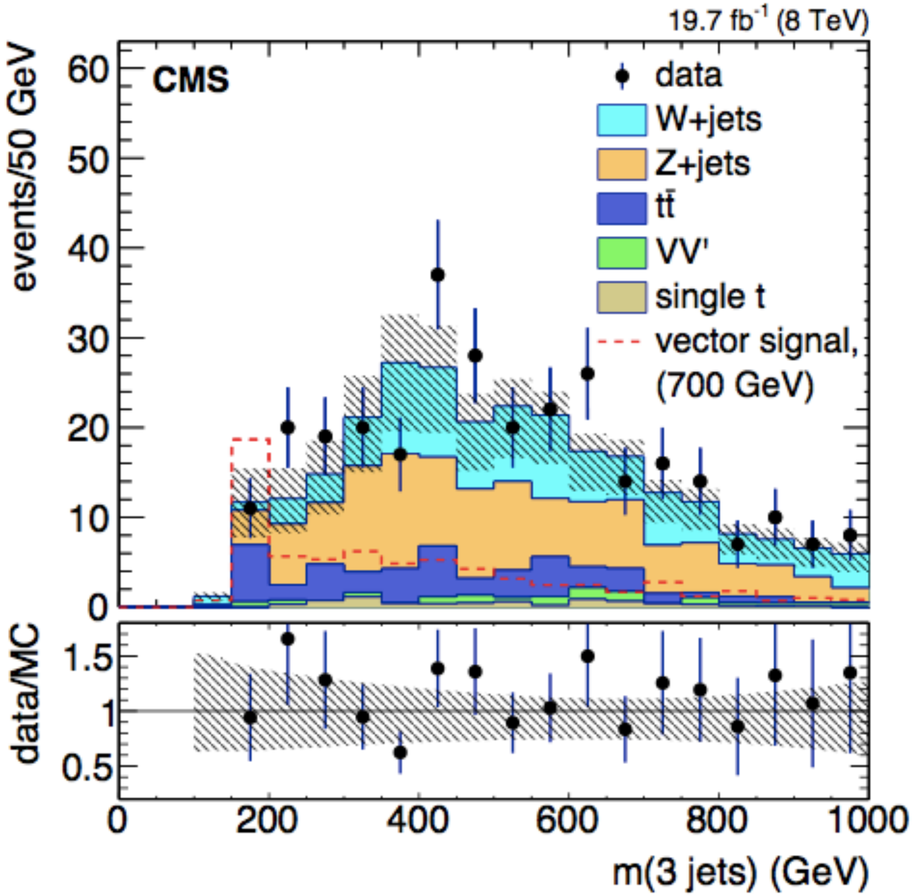


Representative Feynman diagram

CMS-B2G-12-022
CERN-PH-EP-2014-225
arXiv:1410.1149
Accepted by PRL

CMS monotop at 8 TeV

20 fb^{-1} of 8 TeV



Baseline selection	
jet p_T > 35 GeV and $|\eta|$ < 2.4	
leading jets p_T	> 60, 60, 40 GeV
Number of jets = 3	
veto events w/ any additional jets	
MET	> 350 GeV
m_{jjb} cut	(see next page)
b tagging efficiency ≈ 70%	
mistag rate: 1-4 %	

Figure 1: The invariant mass of the three jets prior to the selection on their mass to be less than 250 GeV, for events with one b-tagged jet. Data are compared to the simulated backgrounds. The expectation from a model for an invisible vector particle with a mass of 700 GeV is represented by the dashed line.

CMS-B2G-12-022
CERN-PH-EP-2014-225
arXiv:1410.1149
Accepted by PRL

Number of events

20 fb^{-1} of 8 TeV

Table 1: Total number of selected events in data compared to the background prediction. The background yields are given with statistical (first) and systematic (second) uncertainties. The multijet background is calculated using all the other backgrounds and therefore its uncertainty is not included in the quadratic sum of background uncertainties.

	No b tag	One b tag
$t\bar{t}$	6±0±5	12±0±12
W+jets	18±9±7	3±1±2
Z+jets	103±33±9	11±10±1
single top	2±1±1	1±1±1
VV'	5±0±0	0±0±0
multijet	6(±39)	1(±9)
total bkgd	140±36	28±16
data	143	30

Baseline selection

jet p_T > 35 GeV and $|\eta|$ < 2.4

leading jets p_T > 60, 60, 40 GeV

Number of jets = 3

veto events w/ any additional jets

MET > 350 GeV

m_{jjb} < 250 GeV

b tagging efficiency ≈ 70%

mistag rate: 1-4 %

CMS-B2G-12-022
CERN-PH-EP-2014-225
arXiv:1410.1149
Accepted by PRL

Lower limits on mass

20 fb^{-1} of 8 TeV

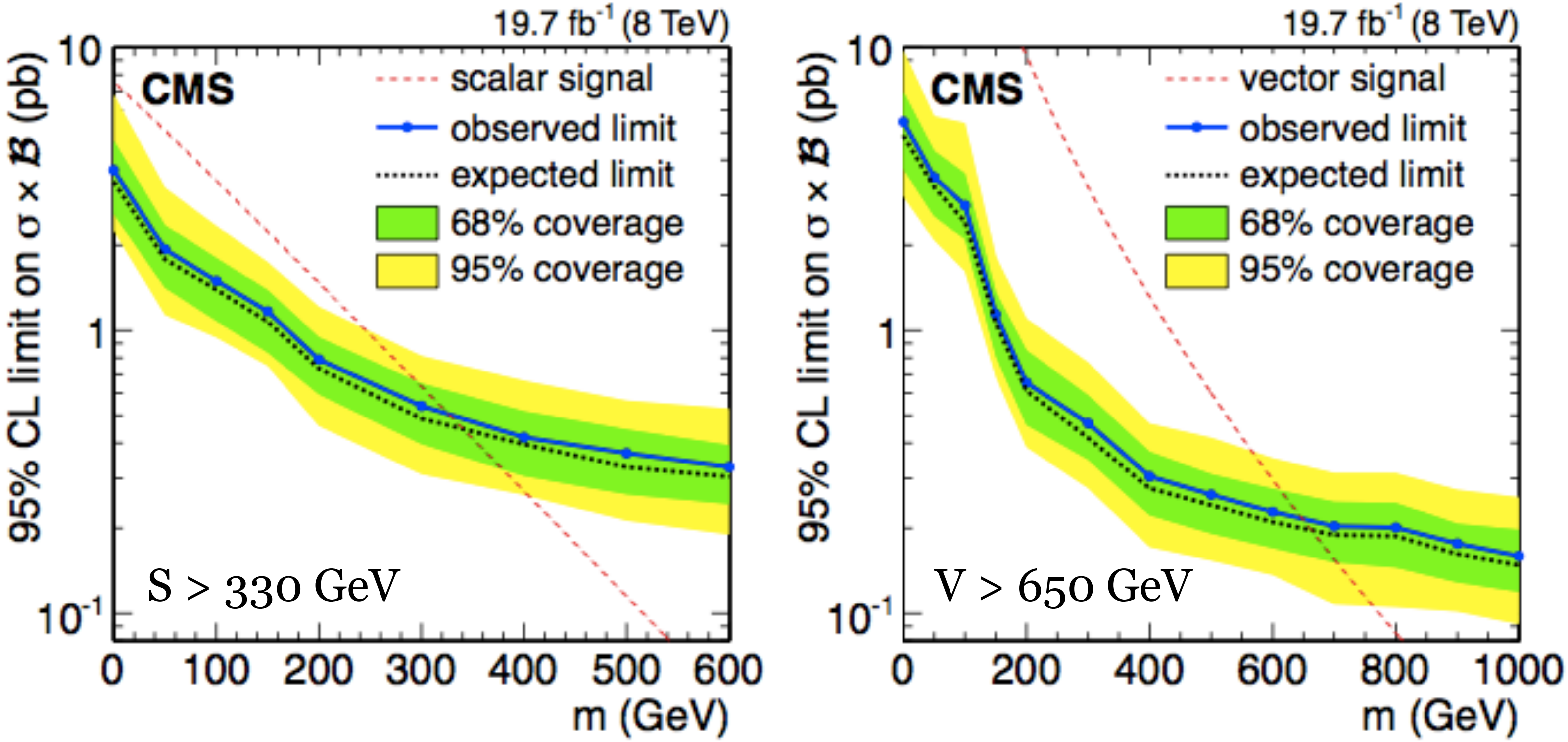
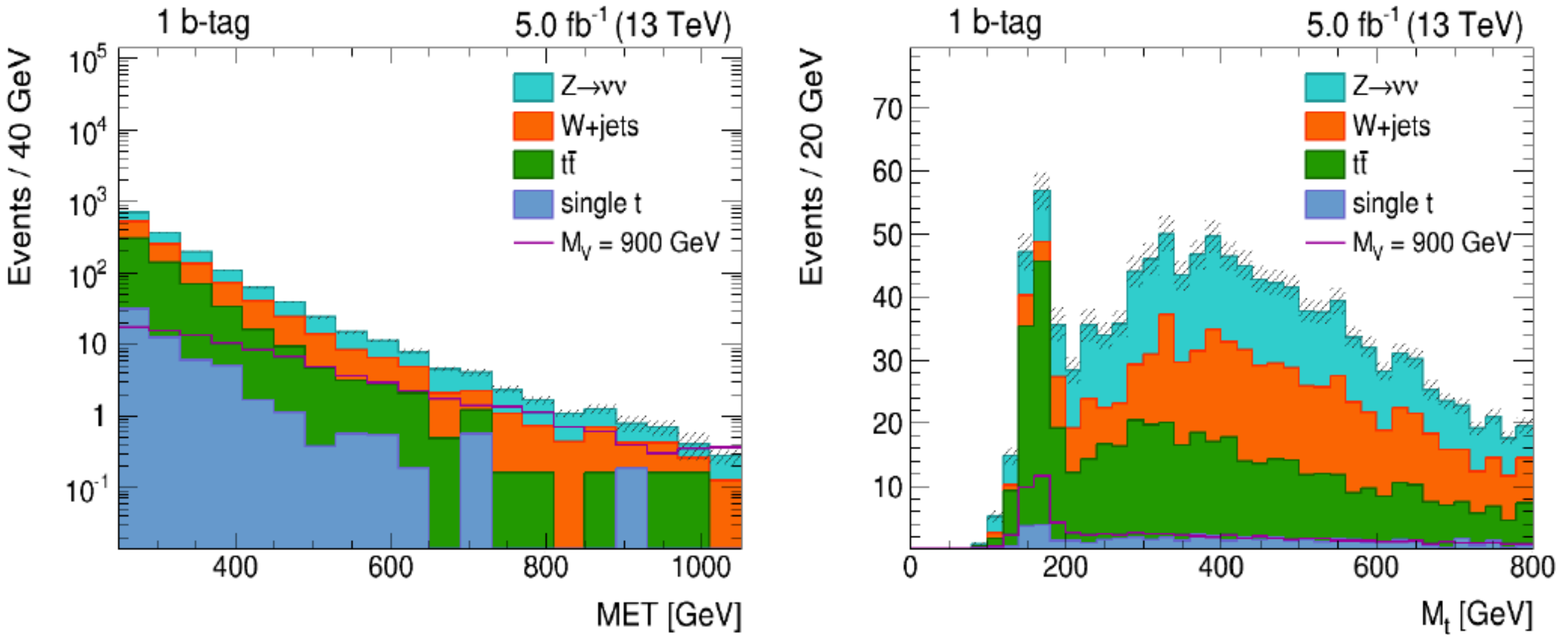


Figure 2: The 95% CL expected and observed CL_s limits as functions of the mass of a scalar (left) and vector (right) invisible particle. The expected magnitude of a signal as a function of mass, calculated at leading order, is shown by the dashed curve. The confidence intervals for the expected limit are given at 68% and 95% coverage probability.

Expected yields for 5 fb^{-1} at 13 TeV

DM+mono top (hadronic)

K. Sung



- Expected yields for 5 fb^{-1} after signal selection:

Process	Z(νν)	W+jets	tt̄	Single t	**Total Bkg**	mS=300	mS=600	mV=900	mV=1200
0 b-tags	74.58	38.28	6.18	0.73	**119.77**	13.48	5.24	8.46	2.73
1 b-tag	10.85	5.81	12.83	1.10	**30.59**	27.25	9.44	16.13	4.77

Leptonic monotop at 8 TeV (AN-14-279)

Event selection

Institut Pluridisciplinaire Hubert CURIEN STRASBOURG

- Single muon trigger (**HLT_IsoMu24_eta2p1_v***) (with SF)
- Exactly **1 isolated muon** with :(with SF)
  - RelIso < 0.12
  - |eta| < 2.1
  - pT > 33 GeV
- No other isolated lepton (electron or muon) with p_T > 10 geV and |η| < 2.4 (RelIso = 0.20 for muons and 0.15 for electrons)
- **Jet selection :** p_T > 30 GeV, |η| < 2.4, jet ID loose, correction of jet energy resolution,
- **Btag selection :** Medium WP, Btag CSV reshapes using data efficiencies,
- **MET** Type1, corrected for JER,
- Main backgrounds : W+jets, ttbar, single top.

same backgrounds to hadronic monotop!

Leptonic monotop at 8 TeV (AN-14-279)

Analysis strategy

1) We define a W+jets enriched (1j0t) CR, a TTbar enriched (4j2t) CR and a Signal Region (1j1t).

2) We produce m_T(W)-templates for signal and control regions accounting for all backgrounds and systematics.

3) We fit the three regions (W+jets, TTbar, Signal) at the same time to better constrain the backgrounds. The fit is proceeded assuming a background-only hypothesis. All systematics are treated as nuisance parameters.

4) We use the theta framework (using Bayesian techniques, will be cross-checked with CLs) to compute the exclusion limits at 95 % CL using each signal.

Summary of the previous talk

- QCD fully data-driven from an « isolation inverted » region (iso > 0.4).
- Split the W+jets sample depending on the flavour (b, c, light).

13/02/15 **leptonic-monotop / M. Buttignol** 4

Leptonic monotop at 8 TeV (AN-14-279)

Considered signals

Resonant benchmarks (scalar mediator – S1):

- mRes = 1000 GeV, mInv = 800 GeV σ = 0.24 pb
- mRes = 1000 GeV, mInv = 100 GeV σ = 0.24 pb
- mRes = 500 GeV, mInv = 100 GeV σ = 5.58 pb (covered by ATLAS)

ATLAS : σ = 1.00 pb

FCNC benchmarks (vector DM – S4) :

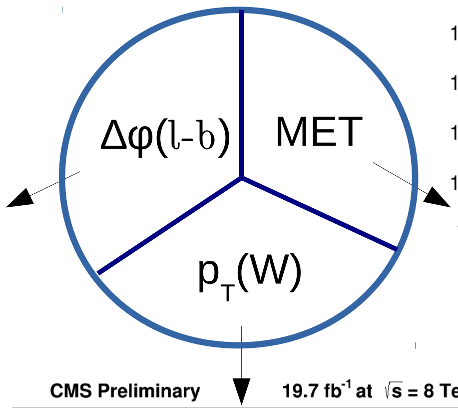
		ATLAS
mInv = 400 GeV σ = 0.60 pb	(covered by ATLAS and CMS)	σ = 1.37 pb
mInv = 600 GeV σ = 0.14 pb	(covered by ATLAS and CMS)	σ = 0.32 pb
mInv = 700 GeV σ = 0.074 pb	(covered by ATLAS and CMS)	σ = 0.17 pb

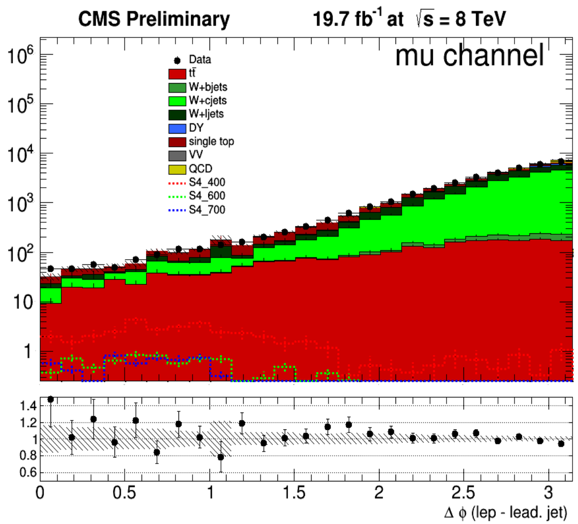
Note : σ is given here considering the leptonic decay and under these conventions (CMS).

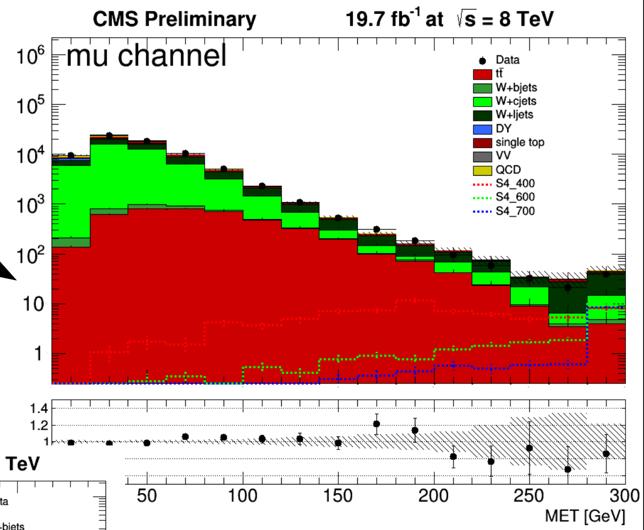
Leptonic monotop at 8 TeV (AN-14-279)

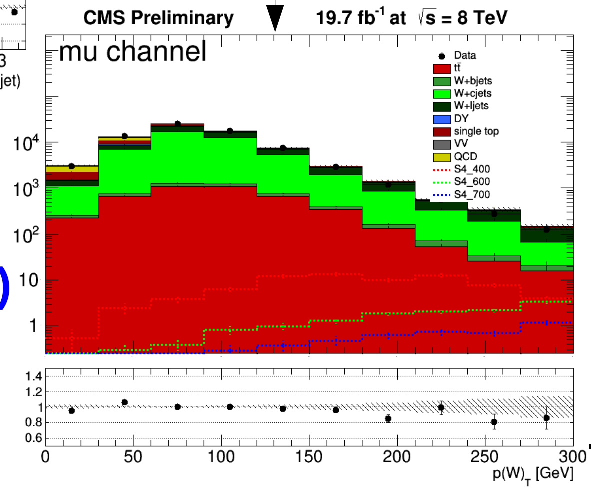
Focusing more on FCNC...

Signal Region









→ $\Delta\varphi(l\text{-}b) < 1.7$

Adding $\Delta\varphi(l\text{-}b)$ templates in the fit.

→ MET > 100 GeV

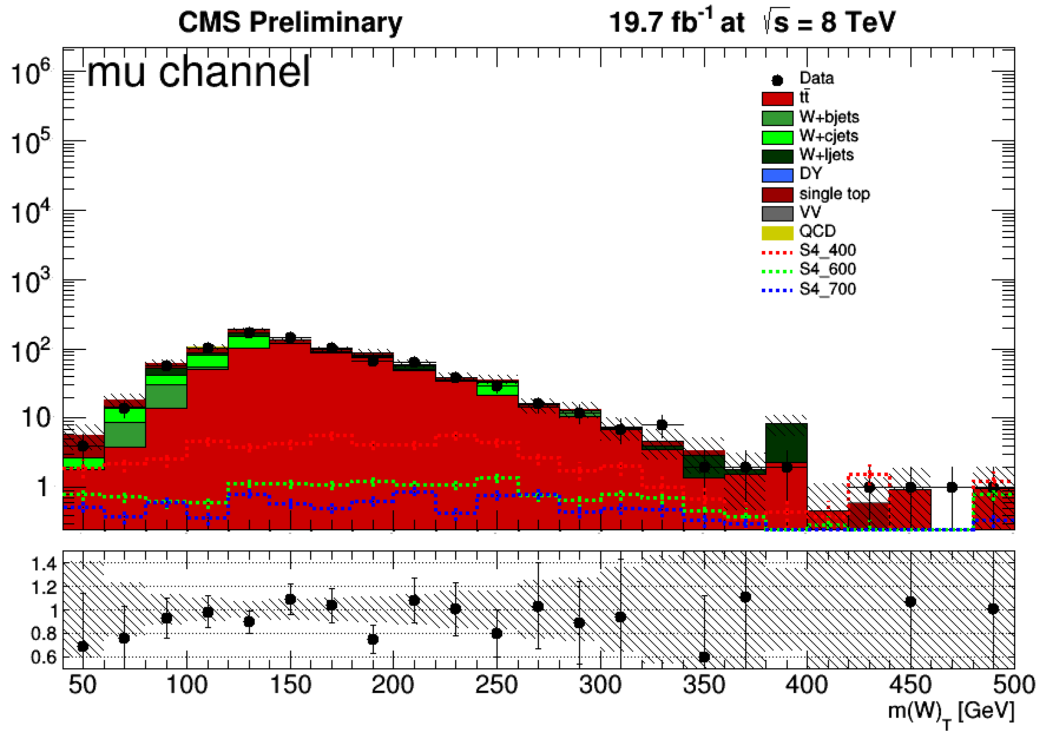
Adding MET templates in the fit.

→ $p_T(W) > 50$ GeV

Leptonic monotop at 8 TeV (AN-14-279)

Signal Region postFit

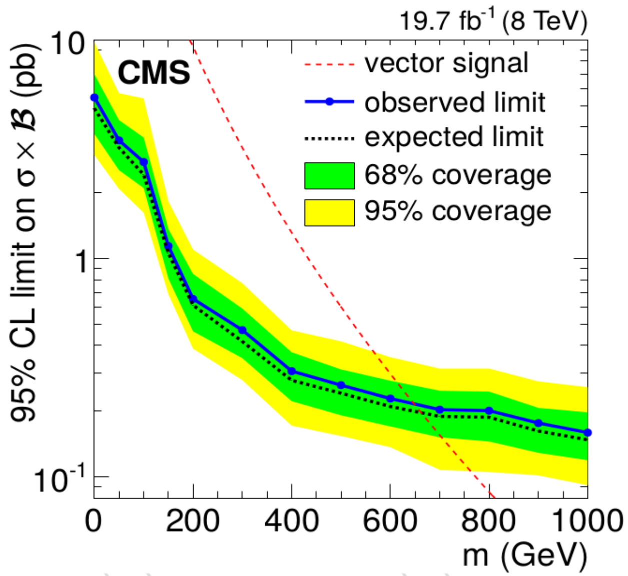
- $M_T(W)$ > 40 GeV
- MET > 100 GeV
- $P_T(W)$ > 50 GeV
- $\Delta\varphi$(l-b) < 1.7



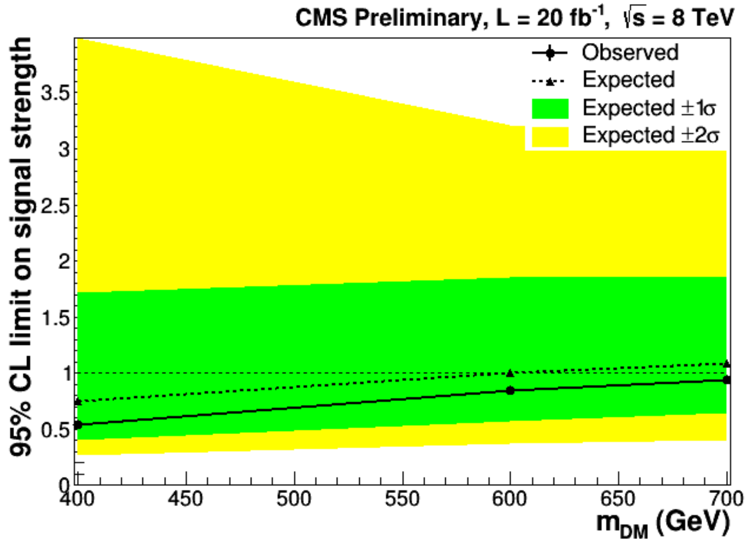
Lack of statistics especially in the very end of the tail but reasonable agreement.

Leptonic monotop at 8 TeV (AN-14-279)

Limits (FCNC) – Had. CMS



CMS Hadronic results



Our Leptonic results

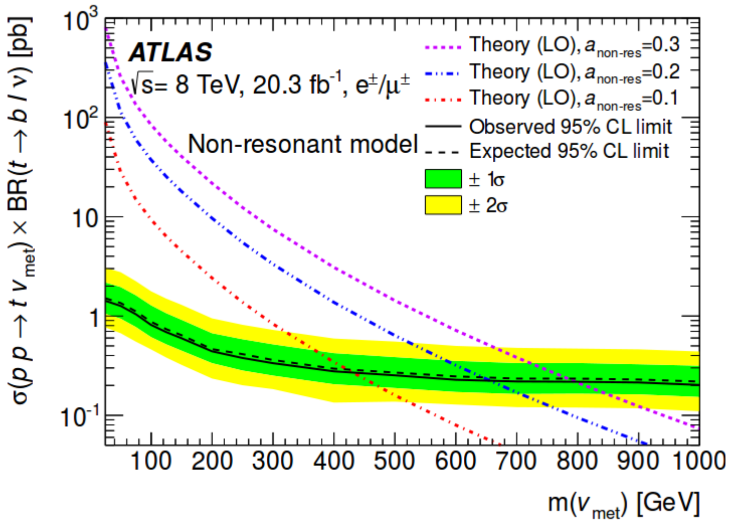
Excluded range : **M(Inv) < 660 GeV**

Excluded range : **M(Inv) < ~700 GeV**

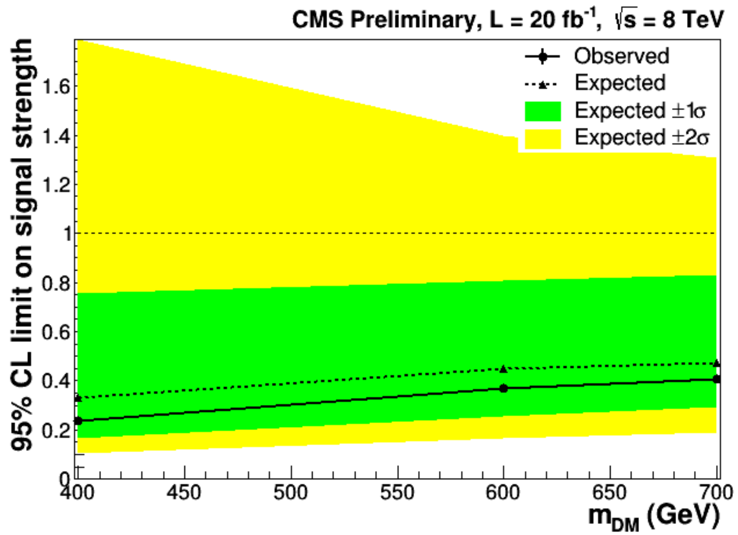
We plan to present the results the same way as for the hadronic channel.

Leptonic monotop at 8 TeV (AN-14-279)

Limits (FCNC) – Lep. ATLAS



ATLAS results



Our results

Excluded range : **M(Inv) < ~650 GeV**

Excluded range : **Comparable to ATLAS**

When rescaling to the same xsection (see ATLAS, $a_{non-res}$ = 0.2)

--> Scan more benchmarks !

Expected yields for 5 fb^{-1} at 13 TeV (con't)

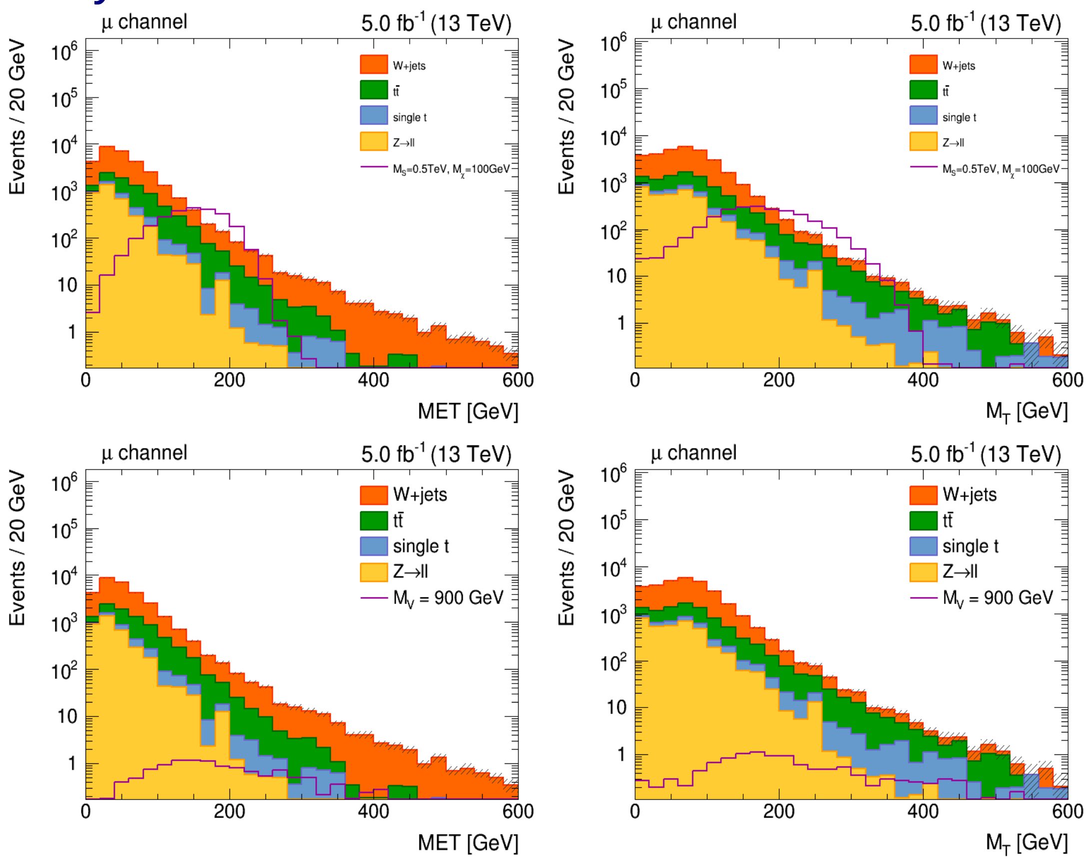
K. Sung, M. Buttignol, J. Andrea
NORTHWESTERN UNIVERSITY

Mono-top (lep) Selection

- MET and M_T distributions in muon channel
- Given bkg tails are longer, should consider M_T window for a cut-and-count analysis

Resonant model with M_S = 0.5 TeV and M_χ = 100 GeV

Vector non-resonant model with M_V = 0.9 TeV



Initial proposal (not yet electron channel)

Baseline cuts with a good vertex

Hadronic monotop

MET trigger (HLT_PFMET150)

veto events with isolated μ (e) p_T > 10 (20) GeV

jet p_T > 35 GeV and |η| < 2.4

leading jets p_T	> 60, 60, 40 GeV

number of jets = 3 jets (0 or 1 b-tagged jet)

veto events w/ any additional jets p_T > 35 GeV

(caveat: zero b jets at low working point = b veto)

P_T (top)	> 50 GeV
MET Type1	> 350 GeV
Δφ(j,j)	< 2.8
m_{jjb}	< 250 GeV

CSVM b tagging efficiency ≈ 70%

mistag rate: 1-4 %

Leptonic monotop

Single muon trigger (HLT_IsoMu24_eta2p1)

muon p_T > 30 GeV, |η| < 2.1, Rel.Iso < 0.12

veto events w/ other isolated μ (e) p_T > 10 (20) GeV

jet p_T > 30 GeV and |η| < 2.4

leading jet p_T	> 70 GeV

number of jets = 1 b-tagged jet

veto events w/ any additional jets p_T > 30 GeV

Mt (W)	> 40 GeV
P_T (W)	> 50 GeV
MET Type1	> 100 GeV
Δφ(l,b)	< 1.7

CSVM b tagging efficiency: TBC

mistag rate: TBC

Summary

In case that we are missing some signature not predicted by any model (and not investigated before)

- Bottom-up approach:
  - Start from the signature
  - Construct an appropriate effective theory and study at colliders
- Monotop production at the LHC:
  - Search for hadronic/leptonic top in association with missing energy
  - Provide initial proposal of baseline cuts

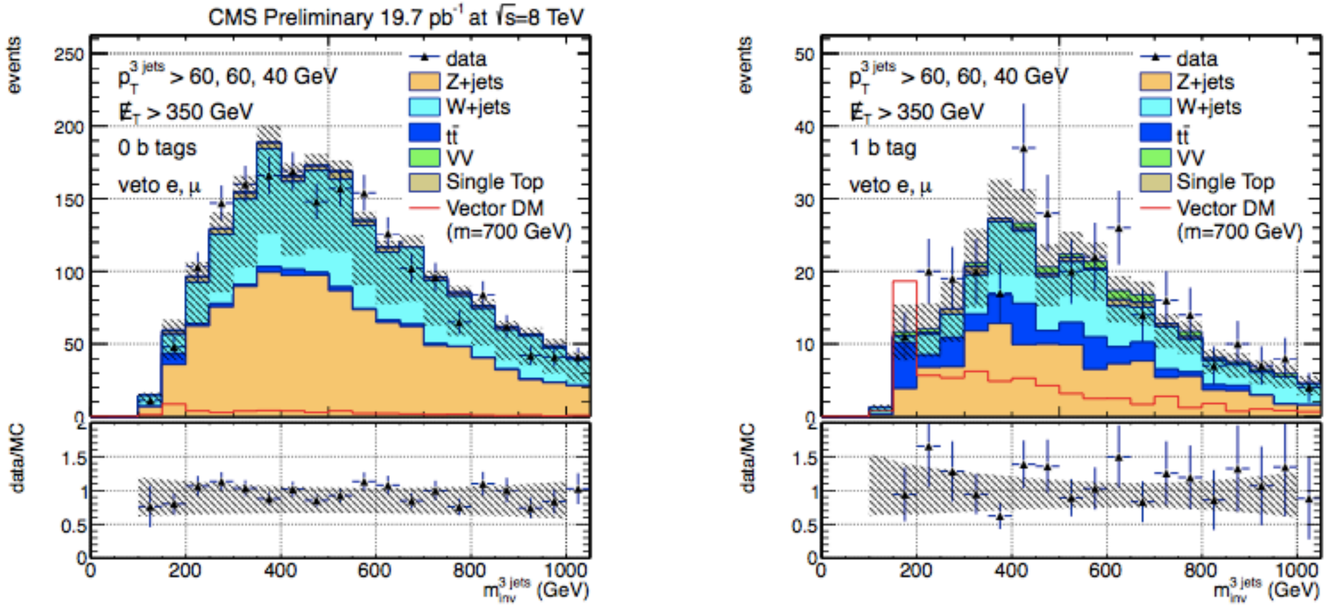
Backup

CMS monotop at 8 TeV

CMS-B2G-12-022
CERN-PH-EP-2014-225
arXiv:1410.1149
Accepted by PRL

Zero b tags

One b tag



(a) (b)

Baseline selection

jet p_T > 35 GeV and $|\eta|$ < 2.4

leading jets p_T > 60, 60, 40 GeV

Number of jets = 3

veto events w/ any additional jets

MET > 350 GeV

b tagging efficiency ≈ 70%

mistag rate: 1-4 %

Figure 2: The invariant mass of the three leading jets. In panels: (a) — zero b tags, (b) — one b tag. Measured distribution (points) are compared to the simulated backgrounds (stacked histograms) and one of the signal models (solid line) scaled to 19.7 fb^{-1}. The shaded area represents the square sum of the systematic uncertainties related to the renormalization and factorization scales for the $t\bar{t}$ and V+jets backgrounds.

Missing E_T distribution

CMS-B2G-12-022
CERN-PH-EP-2014-225
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a b tag veto to enrich V+jets | Two b tags to enrich ttbar events

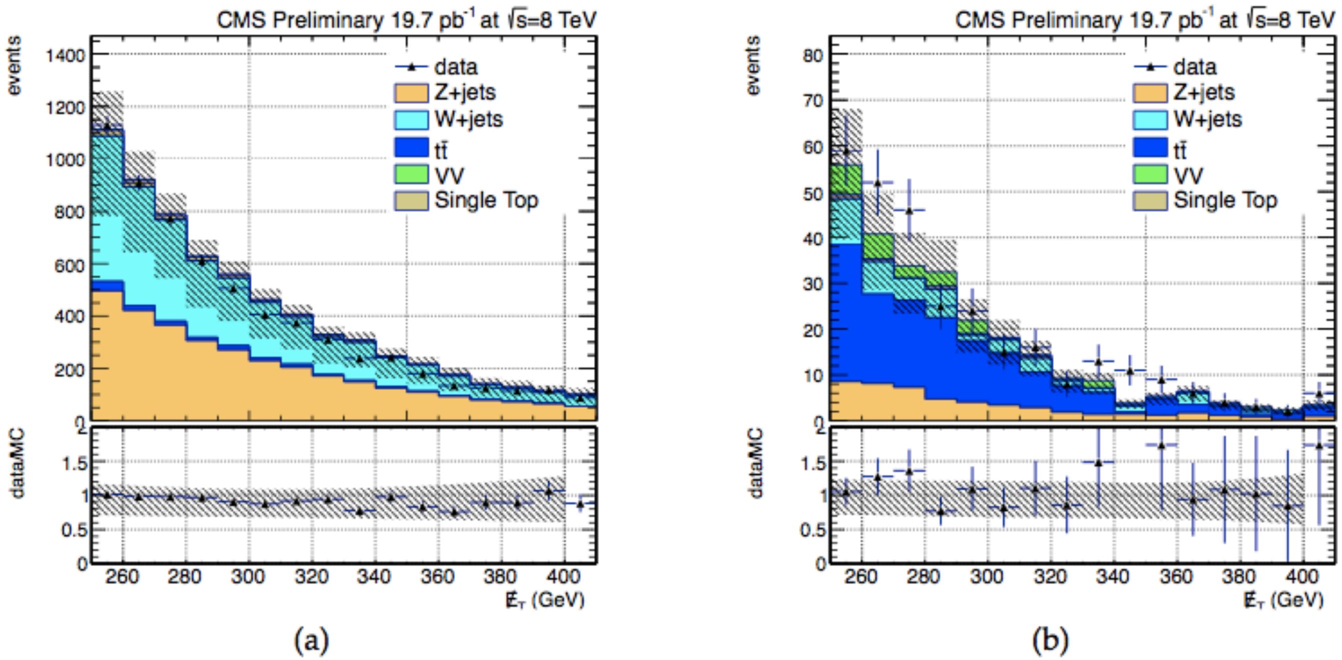

Figure 3: E_T^{miss} distribution in events after the signal selection with the modified b tag requirement. In panel (a) we use a b tag veto so as to enrich the sample with the V+jets events. In panel (b) we require two b tags so as to enrich the sample with $t\bar{t}$ events. The shaded area represents the square sum of the systematic uncertainties related to the renormalization and factorization scales for the $t\bar{t}$ and V+jets backgrounds.

Number of events

20 fb^{-1} of 8 TeV

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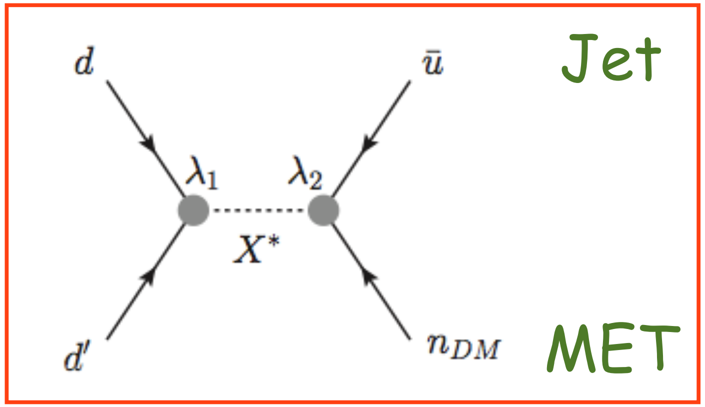
Table 5: Total number of selected events in data compared to the background prediction for E_T^{miss} >350 GeV. The background yields are given with statistical (first) and systematic (second) uncertainties. Uncertainty on the simulated backgrounds ($t\bar{t}$, single top, and VV) are presented as a square sum of the uncertainties from all of the sources. The QCD background is calculated using all of the other backgrounds and data in Eq. 4. Uncertainty on the QCD background is 100% correlated with uncertainties on other backgrounds and therefore is dismissed. The final uncertainty on the sum of all backgrounds is the squre sum of uncertainties on all but QCD backgrounds.

# of b tags	Zero CSVm b tag	One CSVm b tag
$t\bar{t}$	6±0±5	12±0±12
W+jets	18±9±7	3±1±2
Z+jets	103±33±9	11±10±1
Single top	2±1±1	1±1±1
VV	5±0±0	0±0±0
QCD	6	1
sum	140±36	28±16
Data	143	30

Collider phenomenology



Mx1 = 1 TeV

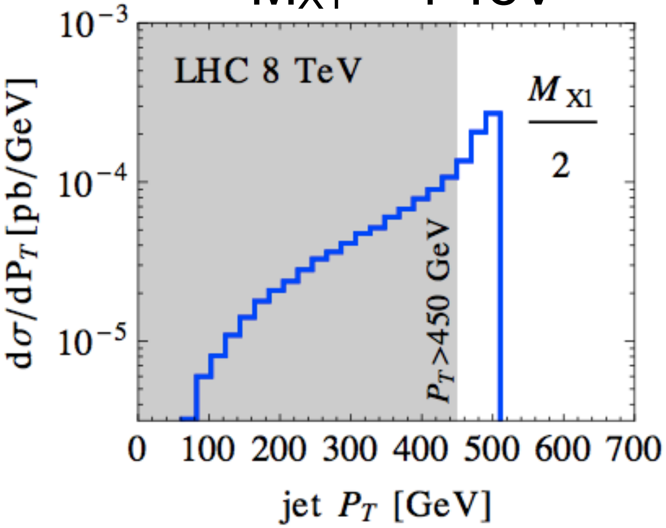


FIG. 4. Monojet p_T distribution for M_{X1}=1 TeV. Among all the p_T cuts in Ref. [20], the 450 GeV cut is the closest to $M_{X1}/2$ and gives the most stringent constraint.

Single-X channel: X → u + n

Single-X channel: $X \rightarrow u + n_{DM}$

- *The monojet channel occurs via an s-channel X resonance*
- *The jet recoils against the missing particle n_{DM}, and its p_T peaks near one half of the resonance energy M_{X1} ()*
- *The interaction terms are described by two scalar couplings and the masses of two X fields*

High p_T jet signature

- *The signal requires a high p_T cut in monojet searches*
- *In contrast, in models where DM must be pair produced, monojet events arise from initial state radiation, and the jet p_T would peak at low energy due to infrared and collinear divergences*