# Monotops at the Large Hadron Collider

Michaël Buttignol

**Based on arXiv:1311.6478v1 (accepted by PRD)**

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# Outline

- Introduction
- Monotop signatures at the LHC
  - Via a resonance production mechanism
  - Through flavor-changing interactions
- LHC Sensitivity to monotops at 8 TeV
  - Hadronic monotop
  - Leptonic monotop
  - Comparison
- Summary/Plan

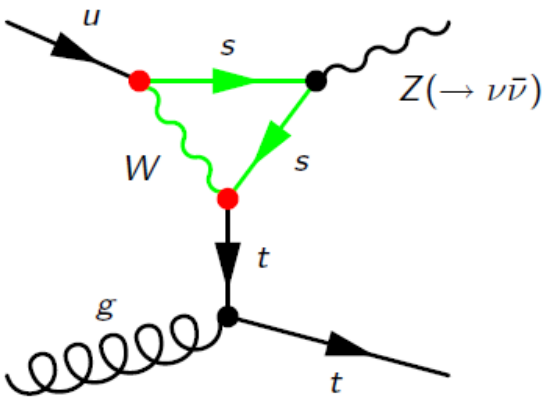
# Introduction

- Monotop ≡ top quark together with a BSM source of MET:

$$pp \to t + \not{E}_T$$

- **Motivations:** - top quark sector (high mass → natural probe for BSM physics)
  - dark matter: one of the rare existing signs of new physics
- **Effective theory approach:** All possible Monotop production mechanisms in a single Lagrangian → Model independent.

  ***(see next slides)***
- Monotop in the SM:




**Loop + GIM-suppressed** → observing Monotops at the LHC⇔BSM physics.

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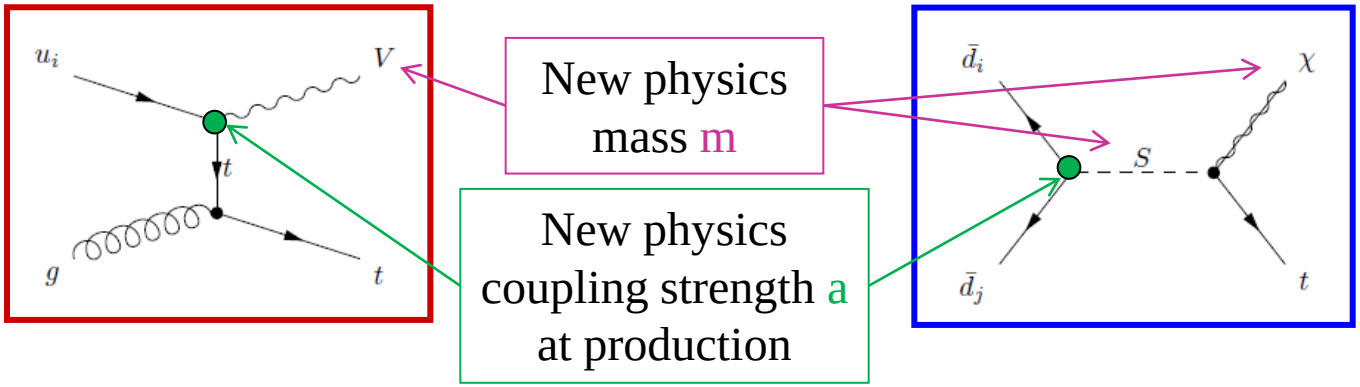
# Monotop model

- Monotop signatures : either produced via FCNC or resonant diagrams.




- FCNC cases (SI):
  - Bosonic missing energy (either scalar SI.s or vector SI.v), possibly dark matter (DM) candidate.
  - Only two free parameters (the mass of the new particle and the coupling strength).

- Resonant cases (SII):
  - Fermionic missing energy, possibly DM candidate (resonant particle being either scalar SII.s or vector SII.v).
  - BR into a monotop state taken to 100%.
  - Only three free parameters (the mass of the particles of new physics and the coupling strength).

# Monotop model

- Monotop signatures : either produced via FCNC or resonant diagrams.

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm kin} + \phi\bar{u}\left[a^0_{FC}+b^0_{FC}\gamma_5\right]u + V_\mu\bar{u}\gamma^\mu\left[a^1_{FC}+b^1_{FC}\gamma_5\right]u$$
$$+\varphi\bar{d}^c\left[a^q_{SR}+b^q_{SR}\gamma_5\right]d+\varphi\bar{u}\left[a^{1/2}_{SR}+b^{1/2}_{SR}\gamma_5\right]\chi$$
$$+X_\mu\bar{d}^c\gamma^\mu\left[a^q_{VR}+b^q_{VR}\gamma_5\right]d+X_\mu\bar{u}\gamma^\mu\left[a^{1/2}_{VR}+b^{1/2}_{VR}\gamma_5\right]\chi+\text{h.c.}\Big] \ .$$

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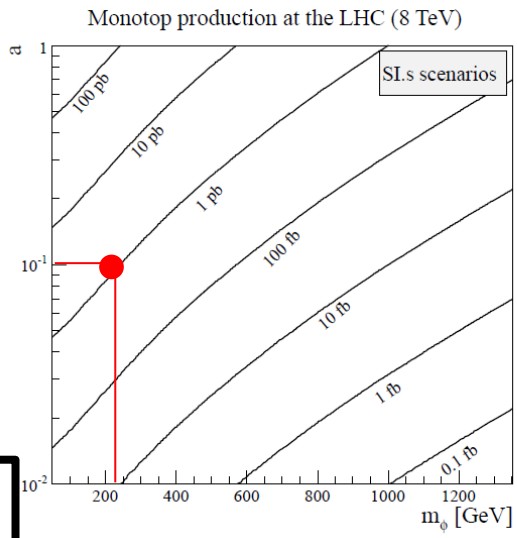
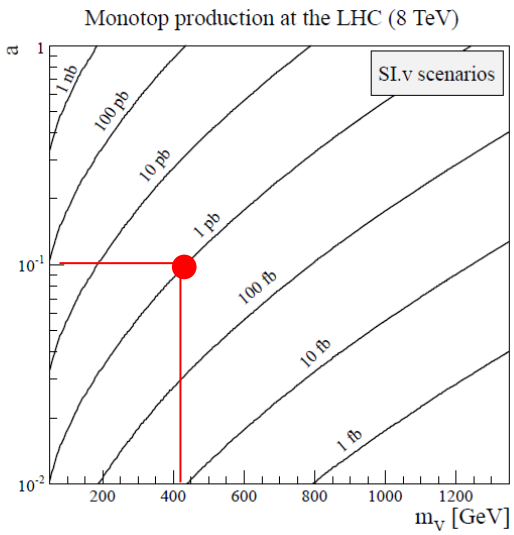
  - BR into a monotop state taken to 100%.
  - Only three free parameters (the mass of the particles of new physics and the coupling strength).

# Signal total cross section

- Total cross section evolves as $a^2$ (coupling strength) and $m^{-4}$ (mass).

SI.s

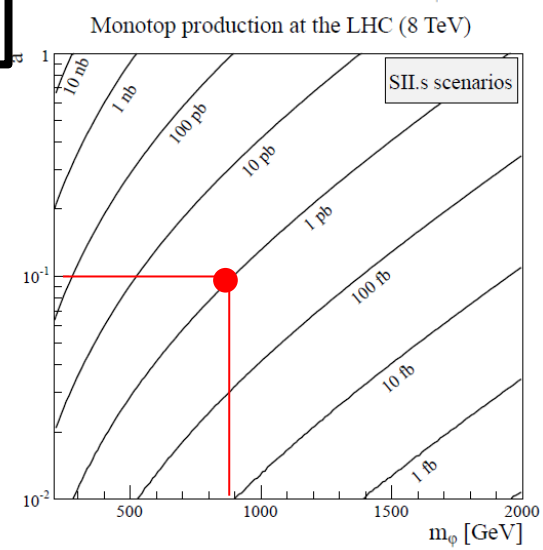


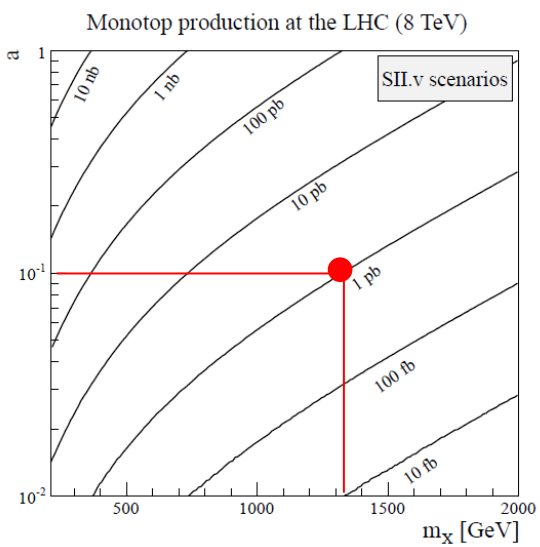




SI.v

Calculation done with a = 0.1

SII.s




SII.v

# Other monotop signatures

Some classes of models yielding monotop signatures:

- **R-parity-violating supersymmetry** $\boxed{pp \to \tilde{t} \to t + \tilde{\chi}^0}$

  (*E. Berger et al.* , Phys.Rev.Lett. 83, 4472-4475 (1999), Phys.Rev. D63, 115001 (2001)

  *N. Desai et al.* , JHEP 1010, 060 (2010) )

- **Leptoquark theories** $\boxed{pp \to leptoquark \to t + \nu}$

  (*A. Kumar et al.* , Phys.Rev D88, 075012 (2013) )

- **Hylogenesis scenarios** $\boxed{pp \to t + composite\ state\ of\ several\ \chi}$

  (*H. Davoudiasl et al.* , Phys.Rev. D84, 096008 (2011) )

- **Z' model** $\boxed{pp \to t + Z' \to t + \chi\chi}$

  (*J. Kamenik et al.* , Phys.Rev. D84, 111502 (2011)

  *E. Alvarez et al.* , arXiv:1310.7600 (2013) )

- **Etc…**

# Monotop bibliography

- Various theoretical (pheno) papers :

  - *J. Andrea, B. Fuks, and F. Maltoni*, "Monotops at the LHC" Phys.Rev. D84, 074025 (2011), arXiv:1106.6199 [hep-ph].
  - *J. Wang et al.*, "Search for the signal of monotop production at the early LHC" Phys.Rev. D86, 034008 (2012), arXiv:1109.5963 [hep-ph]
  - *B.Fuks*, "Beyond the Minimal Supersymmetric Standard Model: from theory to phenomenology", Int. J. Mod. Phys. A 27 (2012) 1230007, arXiv:1202.4769 [hep-ph]
  - *E. Alvarez et al.*, "Leptonic Monotops at LHC"(2013), arXiv:1310.7600 [hep-ph].
  - ***J-L Agram, J. Andrea, M. Buttignol, E. Conte, B. Fuks*, "Monotop phenomenology at the LHC" (2013), arXiv:1311.6478v1 [hep-ph], accepted by PRD.**

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# Pheno analysis strategy

- **Goal of pheno study :** can we search for monotops with the 8TeV data at the LHC?

- **Strategy of the pheno study :**

  – Generate MC events (signal + background) with **MadGraph5** (*Alwall et al*, JHEP '11)+ **Pythia** (*Sjostrand et al*, JHEP '06 and CPC '08).

  – Use FastSimulation (**Delphes** – *Ovyn et al*, 2009) of the detector.

  – Implement event selection (with optimization) to extract the signal from the main backgrounds (**MadAnalysis5** – *Conte et al*, CPC '13).

  – Determine the significance (S/sqrt(S+B)) for different "benchmarks":

    - **FCNC case** : coupling strength vs DM candidate mass
    - **Resonant case** : DM candidate mass vs res mass for different coupling strengths.

  – Sensitivity plots for both the FCNC and resonant cases.

# Hadronic Monotops

(at 8 TeV with $\mathcal{L}$ = 20 fb$^{-1}$)

**Signal description**

2 light jets from the W boson, 1 b-jet and missing transverse energy

**Possible** top mass reconstruction

**Main backgrounds**

Z → νν + 3 jets ➔ irreductible background

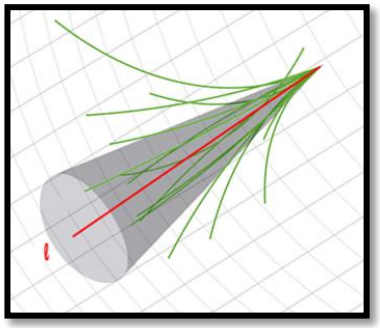
W + jets, $t\bar{t}$, diboson, single top (non- or misreconstructed leptons from W's )

QCD multijet neglected because can only be correctly estimated from data

# Event selection (1/3)

***WARNING*: Delphes does not simulate any trigger!**

- **Jets required to have:**
  - $|\eta| < 2.5$
  - $p_T > 50$ GeV ***(b-tagged jet)***
  - $p_T > 30$ GeV ***(2 or 3 light-tagged jets)***
  - $H_{cal}/E_{cal} > 30$ %
- **Veto on event containing any isolated muon or electron with:**
  - $|\eta| < 2.5$
  - $p_T > 10$ GeV
  - **Isolation:** $\Sigma(p_T^{cone})/p_T^{lep} < 0.2$



*Cone of* $\Delta R = 0.4$

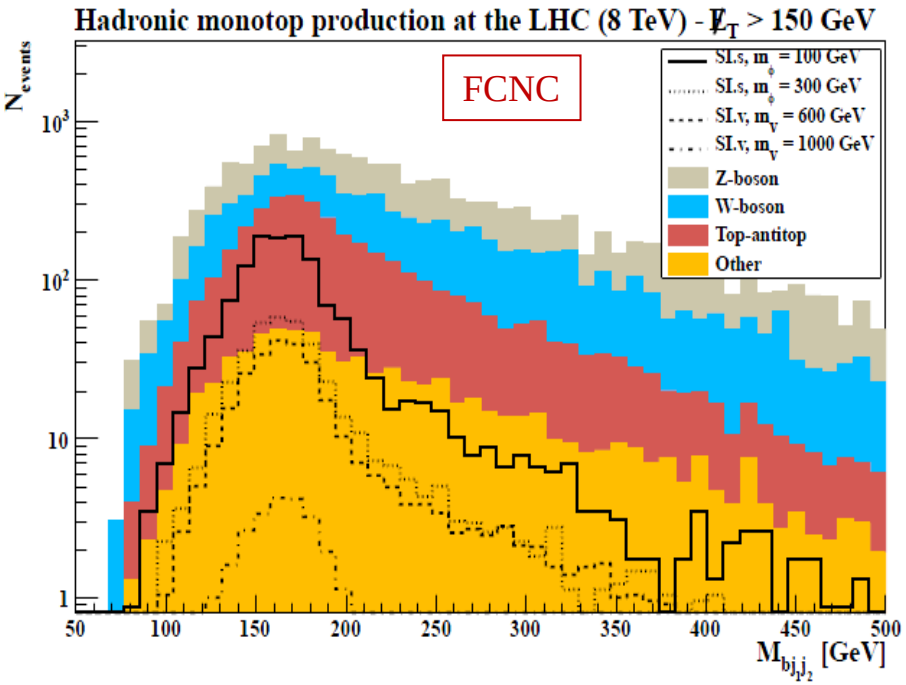
- **Missing Transverse Energy :** MET > 150 GeV

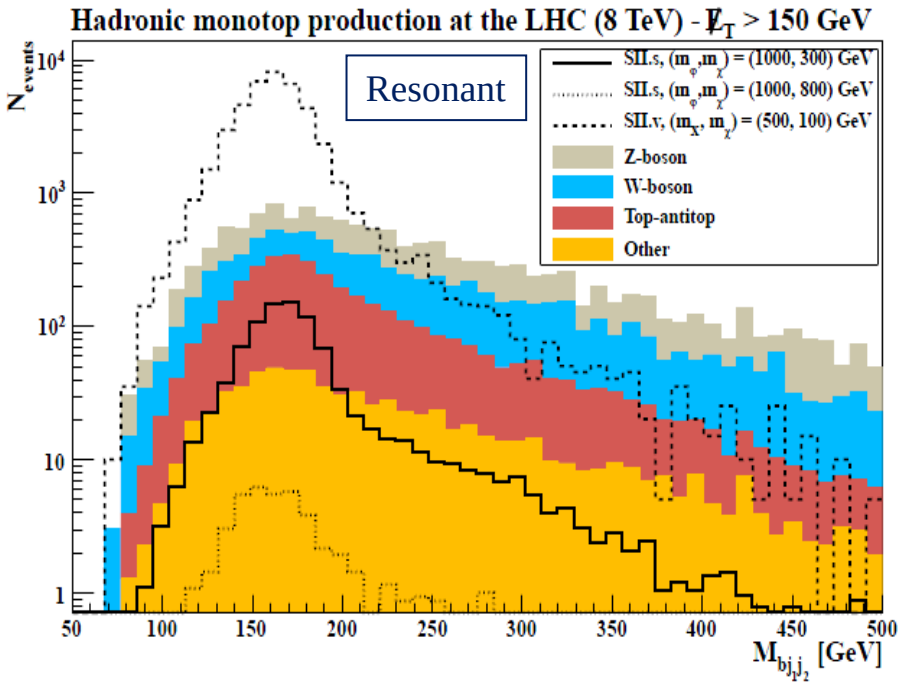
# Event selection (2/3)

- **Light jets required to have a transverse mass compatible with the mass of a W boson:**
  - $M_{j_1 j_2} \in ]50;105[$ GeV
- **Transverse momentum of the leading light jet required to be non-collinear with the MPT (missing transverse momentum):**
  - $\Delta\varphi(\text{MPT}, p(j)) \in ]0.5, 5.75[$
- **Transverse momentum of the reconstructed top quark required to be well separated from the MPT :**
  - $\Delta\varphi(\text{MPT}, p(t)) \in ]1, 5[$

# Event selection (3/3)

- Invariant mass distribution of the reconstructed top quark after all other requirements:




- We enforced: $M_{bj_1j_2} \in ]140,195[$ GeV.

# Leptonic Monotops

## (at 8 TeV with $\mathcal{L}$ = 20 fb$^{-1}$)

**Signal description**

1 lepton from the W boson, 1 b-jet and missing transverse energy

**No possible** top mass reconstruction

**Main backgrounds**

W → lν + 1jet, WZ → lν + νν + 1 jet ➔ irreductible background

$t\bar{t}$, single top (non- or misreconstructed jet or lepton)

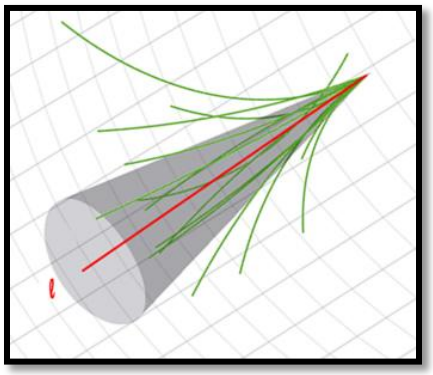
QCD multijet neglected because can only be correctly estimated from data

# Event selection (1/3)

***WARNING*: Delphes does not simulate any trigger!**

- **Exactly 1 isolated muon or electron with:**
  - $|\eta| < 2.5$
  - $p_T > 30$ GeV
  - **Isolation:** $\Sigma(p_T^{cone})/p_T^{lep} < 0.18$ (electrons)

    ***(optimized)*** $\Sigma(p_T^{cone})/p_T^{lep} < 0.06$ (muons)



*Cone of* $\Delta R = 0.3$

- **Exactly 1 b-tagged jet with:**
  - $|\eta| < 2.5$
  - $p_T > 75$ GeV ***(optimized)***
- **Veto on events containing any other jet with:**
  - $p_T > 20$ GeV

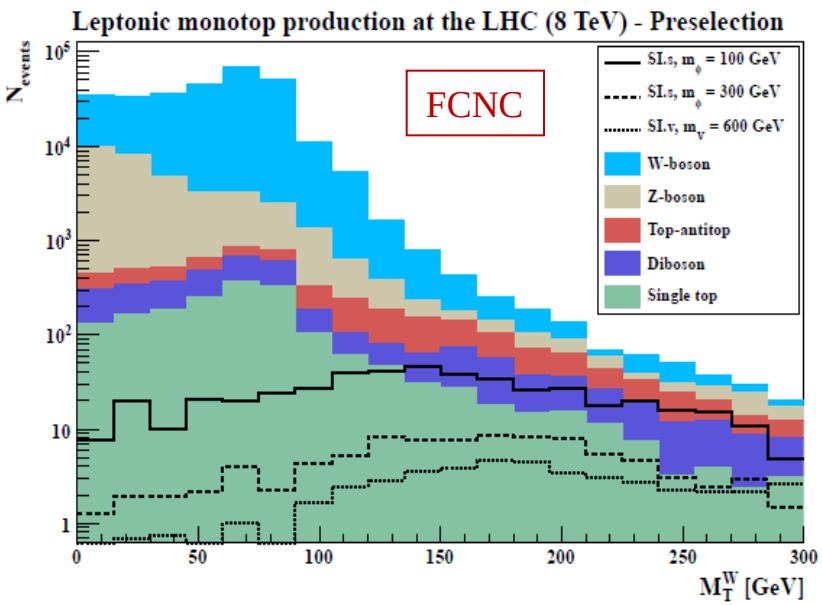
***(Optimization assumption: best cut is the one who maximizes the significance)***

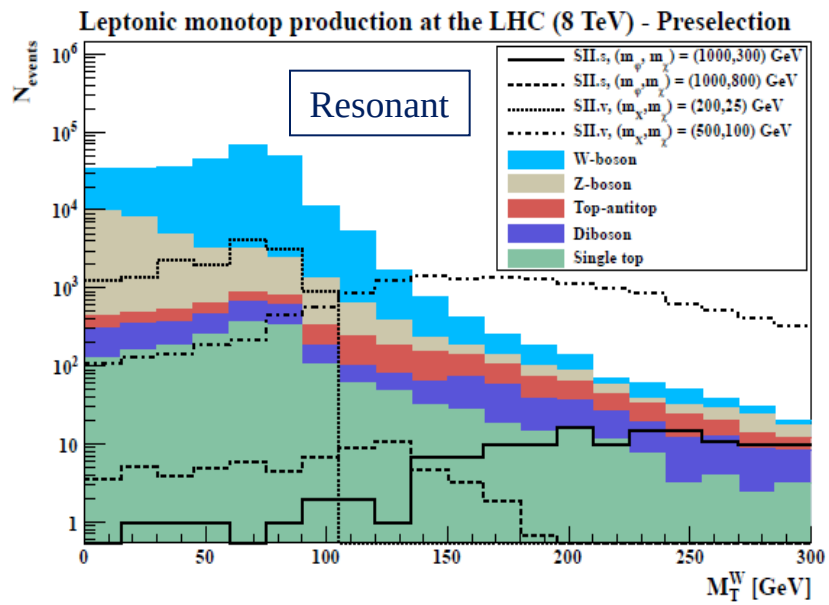
# Event selection (2/3)

- Reconstruction of the transverse mass of the W-boson in the case all the MET is assumed issued from a W-boson:

$$M_T^W = \sqrt{2p_T^\ell \not{E}_T \left[1 - \cos\Delta\phi_{\ell,\not{E}_T}\right]}$$

where $\Delta\phi_{\ell,\not{E}_T}$ stands for the angular distance, in the azimuthal direction with respect to the beam, between the lepton and the MET.

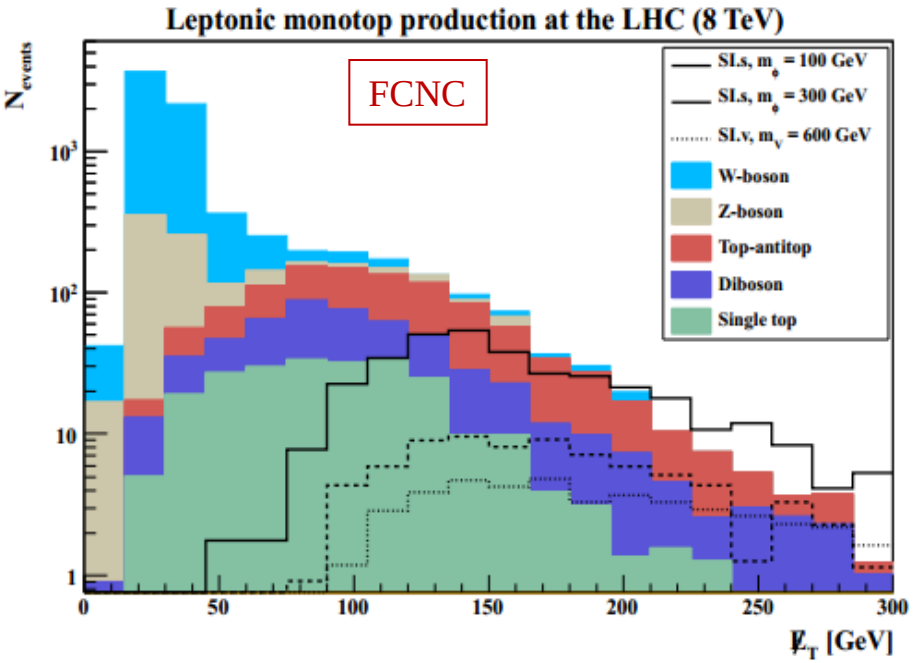


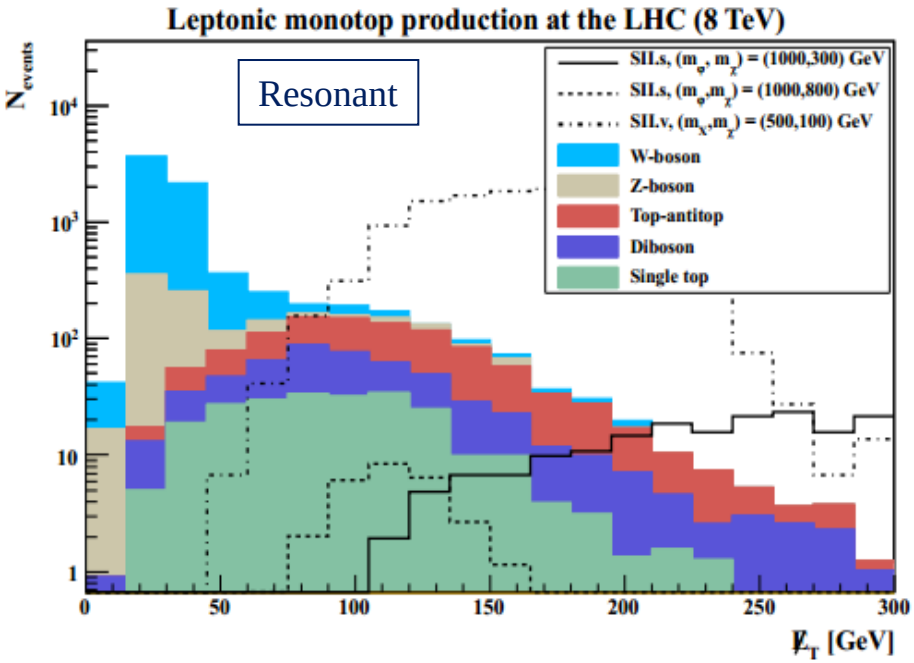




- Cut optimized for 8 different benchmark scenarios in maximizing the significance → **$m_T^W$cut = 115GeV.**

# Event selection (3/3)

- Distribution of the MET after all other cuts:




- Cut optimized for all the benchmark scenarios in maximizing the significance (S/sqrt(S+B)).

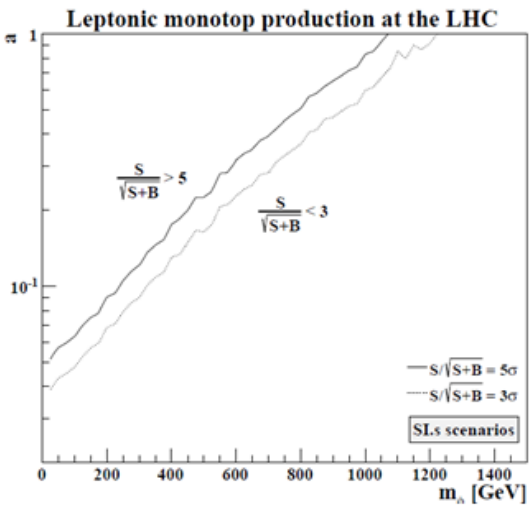
# Comparison between the two channels (pheno study at 8 TeV with $\mathcal{L}$ = 20 fb$^{-1}$)

# Sensitivity at the LHC

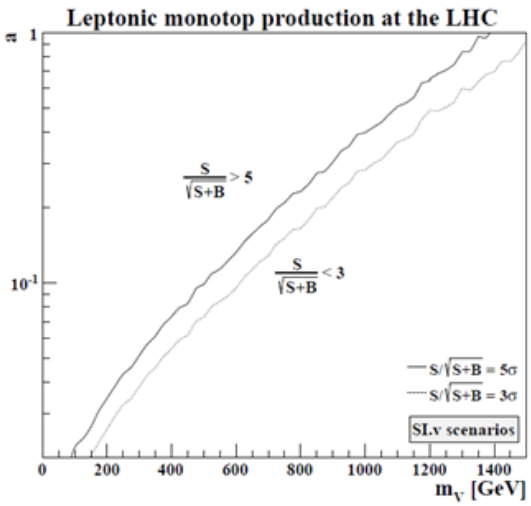
FCNC

*Leptonic*

SI.s

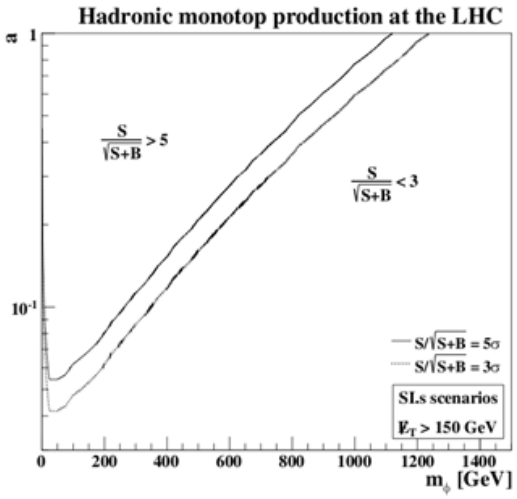



SI.v

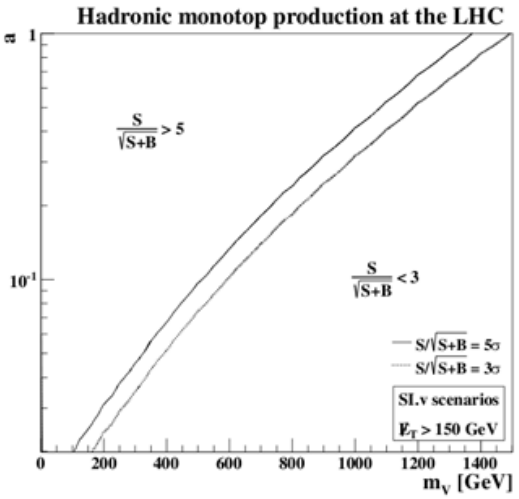



*Hadronic*

SI.s




SI.v

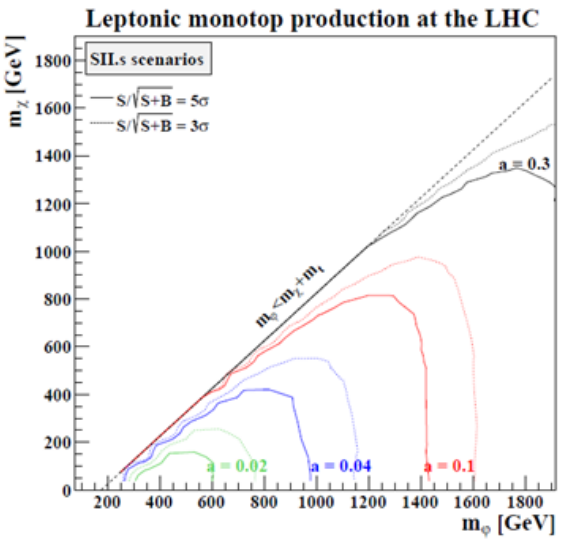


# Sensitivity at the LHC

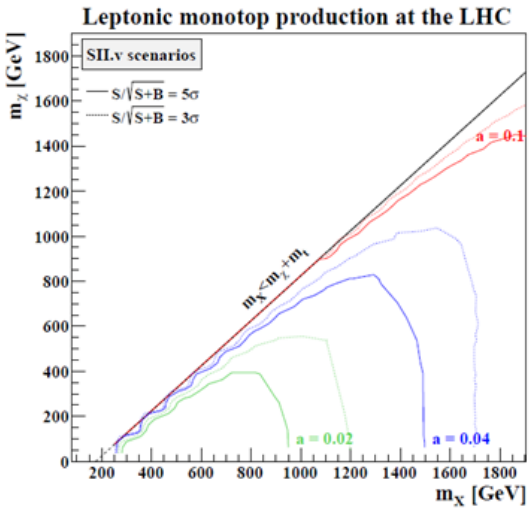
## Resonant

*Leptonic*

SII.s

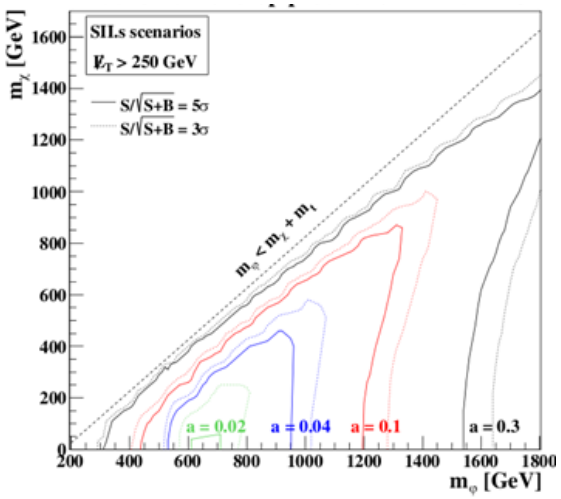



SII.v

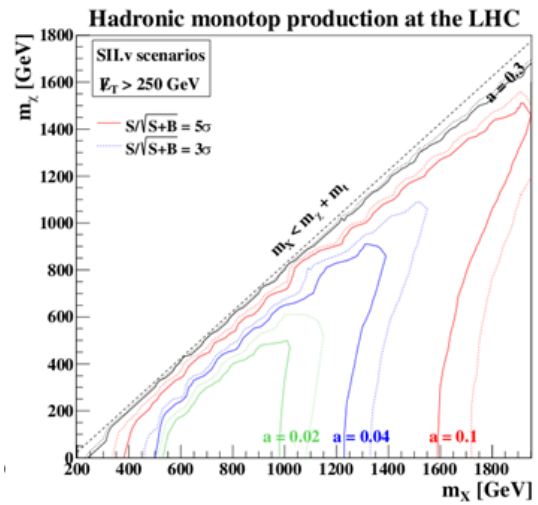



*Hadronic*

SII.s




SII.v



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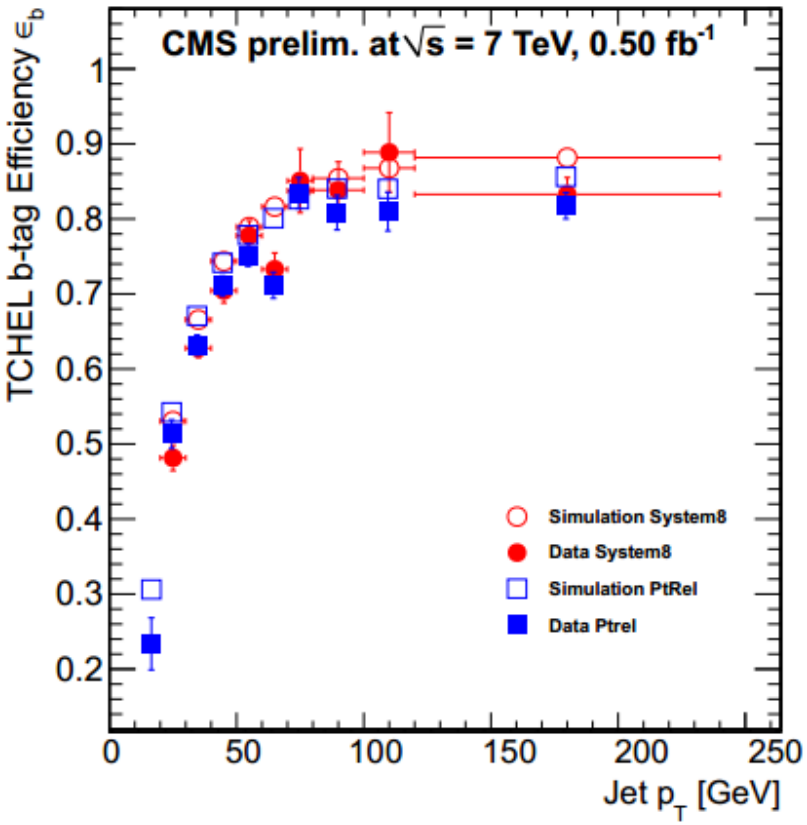
# Summary/Plan

- We described the monotop signatures by only 2 (FCNC) or 3 (Resonant) free parameters.
- We performed a pheno study at 8 TeV with $\mathcal{L}$ = 20 $fb^{-1}$ using MadGraph and a FastSim (Delphes) analyzed in the MadAnalysis framework.
- Through sensitivity plots, we found that monotop search is relevant, already with 8TeV data.
- We will do the analysis on the 8 TeV data and prepare the 13/14 TeV collisions.

# Back-up

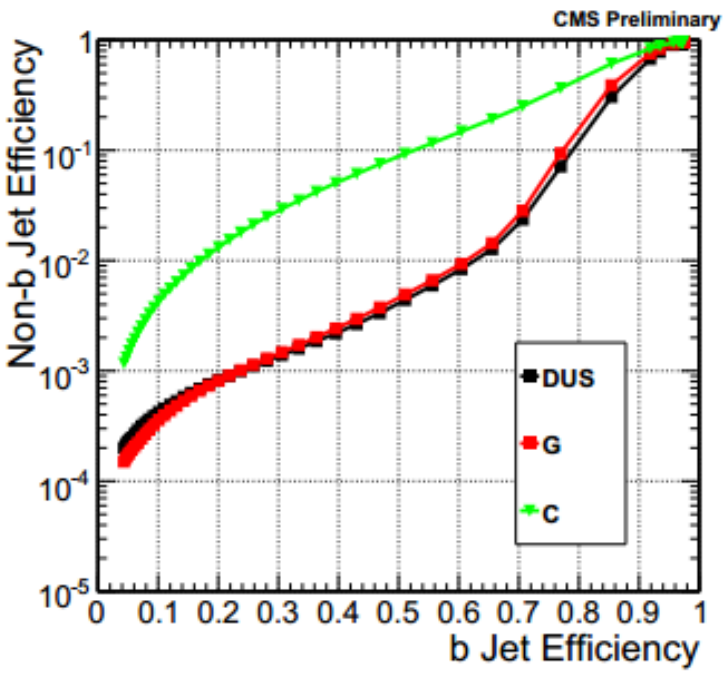
# B-tagging and mistagging

- Btag: $p_T$ dependant




**TCHEL algorithm**

- Charm/light mistag: also $p_T$ dependant




**Refs**

CMS Collaboration, CMS-BTV-11-001 (left)

CMS Collaboration, CMS-BTV-09-001 (right)

# Considered backgrounds

| Process | $\sigma$ [pb] | $N$ |
|---|---|---|
| $W(\to \ell\nu) + \text{jets}$ | 35678 | $2.56 \cdot 10^8$ |
| $\gamma^*/Z(\to 2\ell/2\nu) + \text{jets}$ | 10319 | $4 \cdot 10^7$ |
| $t\bar{t}(\to 6\text{jets}) + \text{jets}$ | 116.2 | $8 \cdot 10^6$ |
| $t\bar{t}(\to 4\text{jets } 1\ell\ 1\nu) + \text{jets}$ | 112.4 | $9 \cdot 10^6$ |
| $t\bar{t}(\to 2\text{jets } 2\ell\ 2\nu) + \text{jets}$ | 27.2 | $3 \cdot 10^6$ |
| Single top + jets [$t$-channel, incl.] | 87.2 | $6 \cdot 10^6$ |
| Single top + jets [$tW$-channel, incl.] | 22.2 | $1 \cdot 10^6$ |
| Single top + jets [$s$-channel, incl.] | 5.55 | $8 \cdot 10^5$ |
| $t\bar{t}W + \text{jets}$ [incl.] | 0.25 | $3 \cdot 10^4$ |
| $t\bar{t}Z + \text{jets}$ [incl.] | 0.21 | $5 \cdot 10^4$ |
| $t/\bar{t} + Z + j + \text{jets}$ [incl.] | 0.046 | $3 \cdot 10^5$ |
| $t\bar{t}WW + \text{jets}$ [incl.] | 0.013 | $2 \cdot 10^3$ |
| $t\bar{t}t\bar{t} + \text{jets}$ [incl.] | $7 \cdot 10^{-4}$ | $10^3$ |

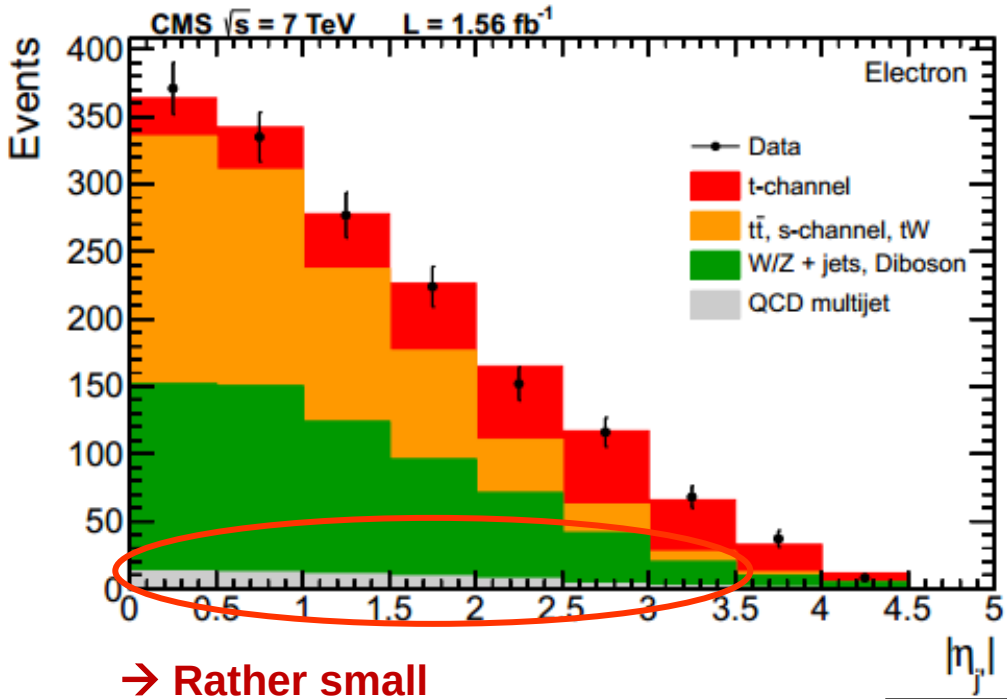
| Process | $\sigma$ [pb] | $N$ |
|---|---|---|
| $WW(\to 1\ell\ 1\nu\ 2\text{jets}) + \text{jets}$ | 24.3 | $3 \cdot 10^6$ |
| $WW(\to 2\ell\ 2\nu) + \text{jets}$ | 5.87 | $8 \cdot 10^5$ |
| $WZ(\to 1\ell\ 1\nu\ 2\text{jets}) + \text{jets}$ | 5.03 | $5 \cdot 10^5$ |
| $WZ(\to 2\nu\ 2\text{jets}) + \text{jets}$ | 2.98 | $3 \cdot 10^5$ |
| $WZ(\to 2\ell\ 2\text{jets}) + \text{jets}$ | 1.58 | $2 \cdot 10^5$ |
| $WZ(\to 1\ell\ 3\nu) + \text{jets}$ | 1.44 | $2 \cdot 10^5$ |
| $WZ(\to 3\ell\ 1\nu) + \text{jets}$ | 0.76 | $2 \cdot 10^6$ |
| $ZZ(\to 2\nu\ 2\text{jets}) + \text{jets}$ | 2.21 | $3 \cdot 10^5$ |
| $ZZ(\to 2\ell\ 2\text{jets}) + \text{jets}$ | 1.18 | $1.5 \cdot 10^4$ |
| $ZZ(\to 4\nu) + \text{jets}$ | 0.63 | $1 \cdot 10^5$ |
| $ZZ(\to 2\nu\ 2\ell) + \text{jets}$ | 0.32 | $4 \cdot 10^4$ |
| $ZZ(\to 4\ell) + \text{jets}$ | 0.17 | $4 \cdot 10^4$ |

# QCD Multijets

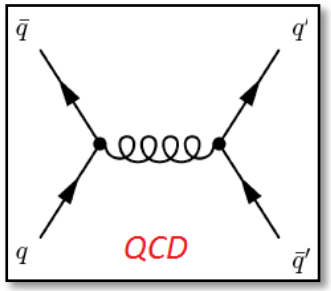
## (NEGLECTED)

**Non reliable description of fake leptons in Delphes.**

→ Cross-checked with SingleTop in CMS/ATLAS papers (data) where similar event selection, even looser, was done.




→ **Rather small**




| | |
|---|---|
| ATLAS: | Physics Letters B 717 (2012) 330-350 |
| CMS: | JHEP 12 (2012) 035 |