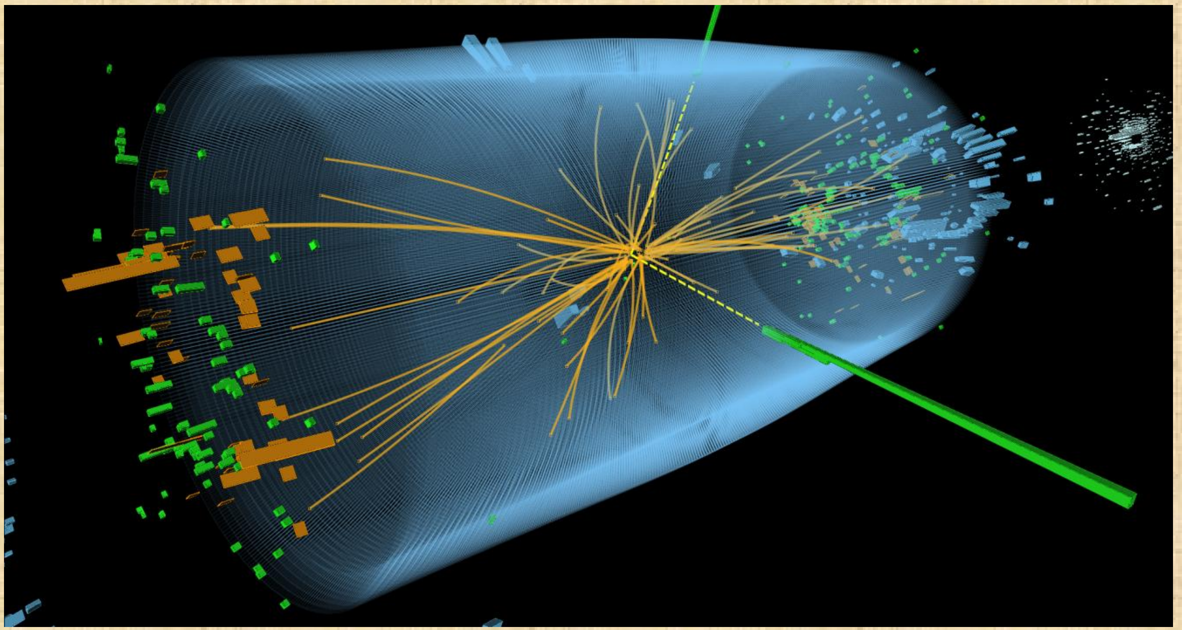
Monotops at the Large Hadron Collider



Michaël Buttignol

Tutors: J-L. Agram, J. Andrea, J-C Fontaine

IPHC/GRPHE, Strasbourg

Outline

- Experimental context
- Introduction to Monotops
- Monotop signatures at the LHC
- Pheno study at 8 TeV
- Analysis at 8 TeV
- Summary/Plan

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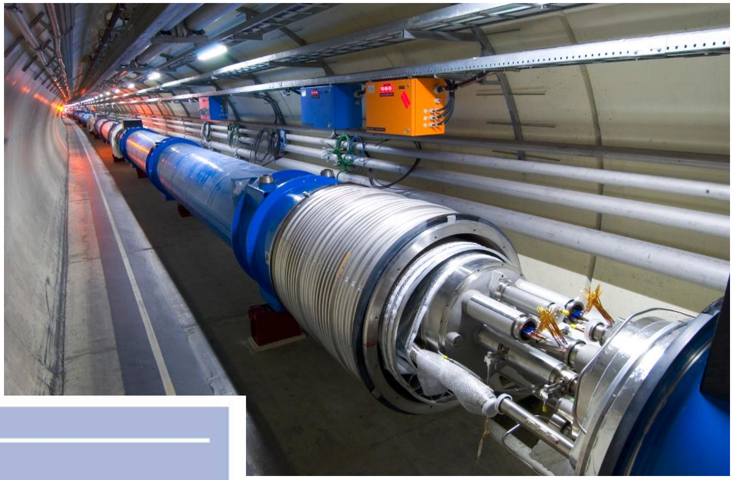
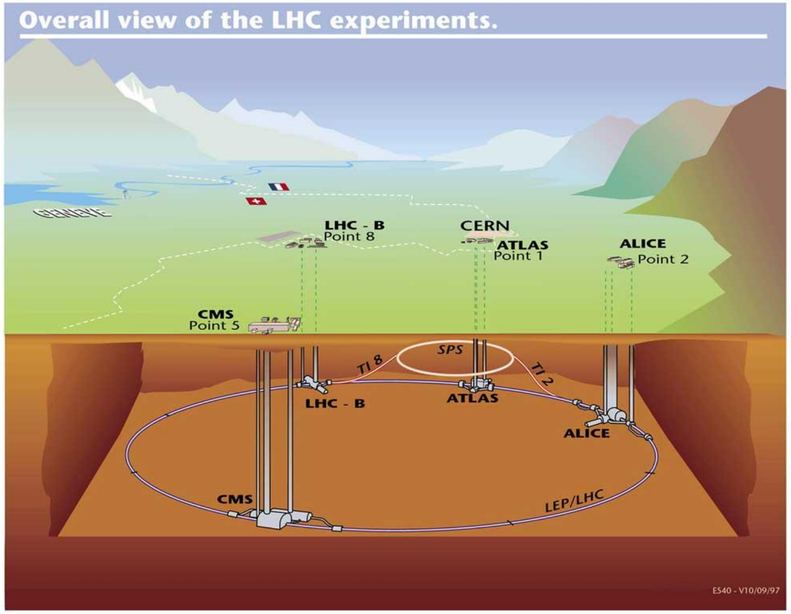
Let's build stuffs…

The **L**arge **H**adron **C**ollider



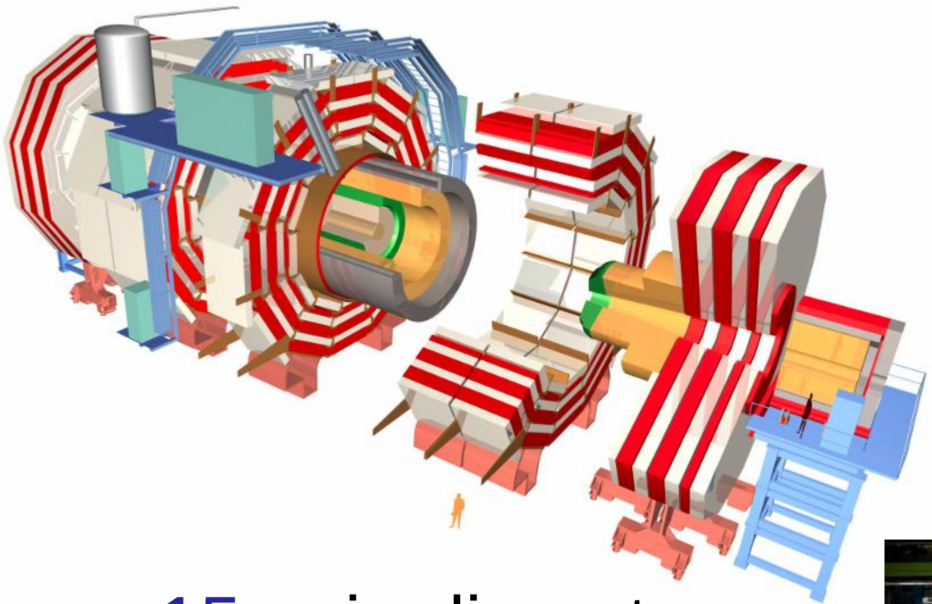
Period	Energy	Lumi
	[TeV]	[fb^{-1}]
2011	7	~5
2012-13	8	~20
2015-17	13-14	~100
2019-22	14	~300
2023-35	14	~3000

HL-LHC ? → 2023-35



- Accelerate particles (mainly protons) to very high energies
- Make them collide
- … see what happens!

Let's build stuffs…

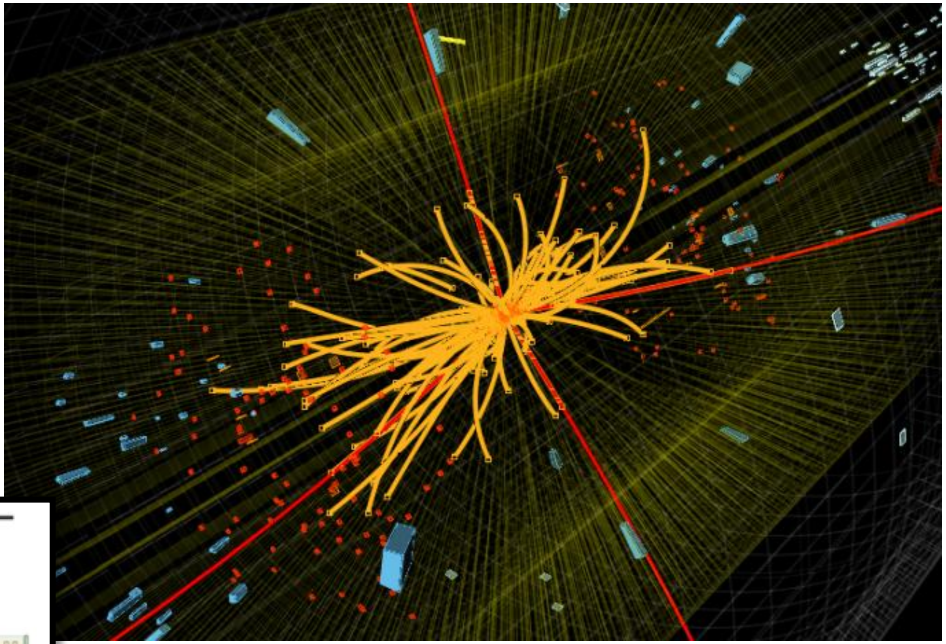


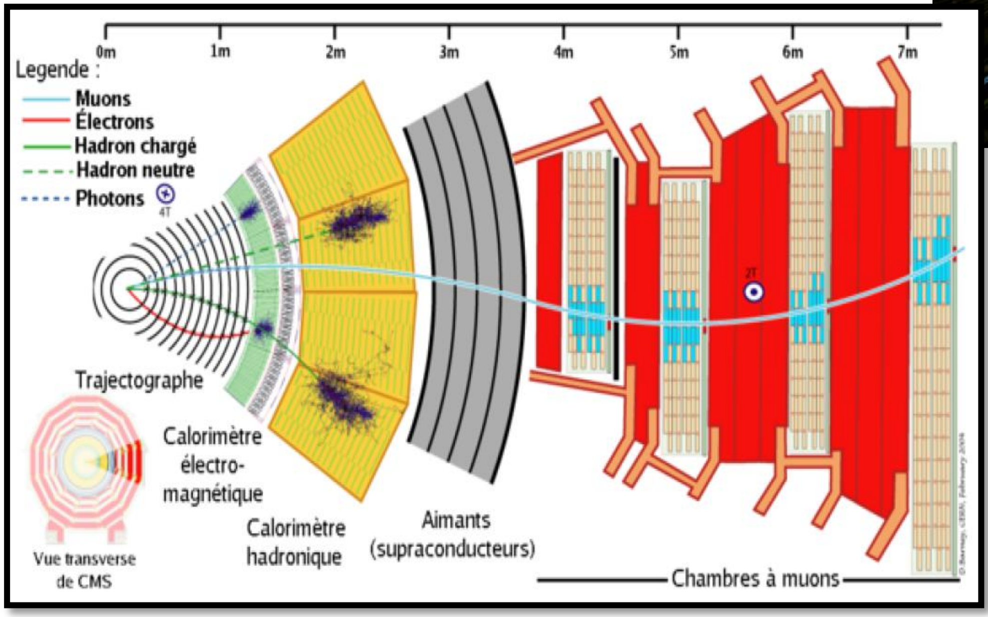
The Compact Muon Solenoid experiment

- 15 m in diameter
- 22 m long
- 12.500 tons
- 3.8 T
- ~3.000 workers

Let's build stuffs…

- « Take pictures » of p-p collisions (events)
- Try to find new physics in such a mess





- Need to reconstruct properly each particle
- Use dedicated detectors and algorithms

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Introduction to Monotops

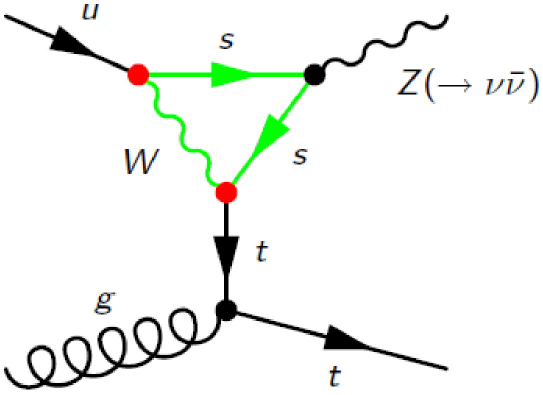
- Monotop ≡ (leptonic) top quark together with a BSM source of MET:

$$pp \to t + \not{E}_T \to bW + \not{E}_T \to b\ell + \not{E}_T$$

- **Effective theory approach:** All possible Monotop production mechanisms in a single Lagrangian → Model independent.

  (see next slides)

- Monotop in the SM:



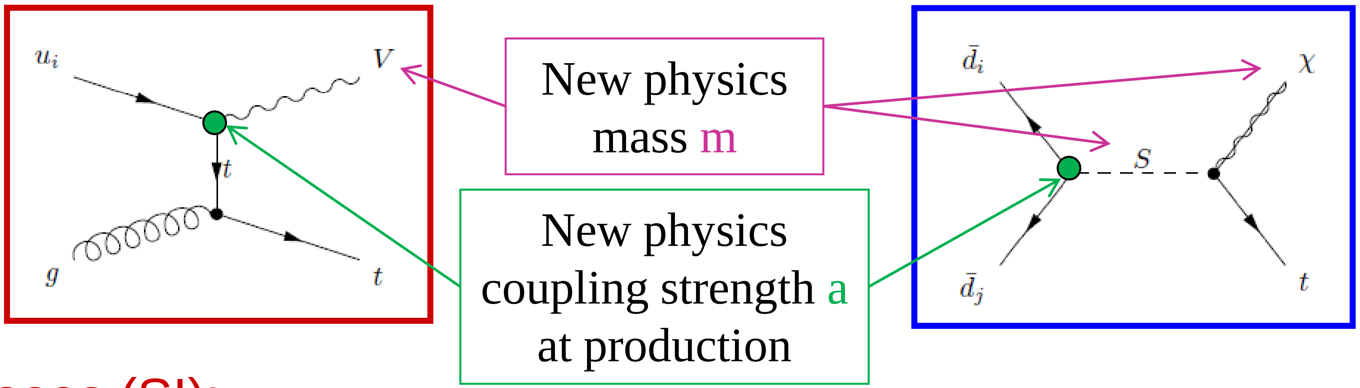
Loop + **GIM-suppressed** ➔ observing Monotop at the LHC⬄BSM physics.

Outline

- Experimental context
- Introduction to Monotops
- Monotop signatures at the LHC
  - Via a resonant production mechanism
  - Through flavor-changing interactions
  - Motivations
- Pheno study at 8 TeV
- Analysis at 8 TeV
- Summary/Plan

Monotop model

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



- FCNC cases (SI):
  - Bosonic missing energy (either scalar or vector), possibly dark matter (**DM**) candidate.
  - Only **2 free parameters** (the mass of the new particle and the coupling strength).

- Resonant cases (SII):
  - Fermionic missing energy, **DM** candidate (resonant particle being either scalar or vector).
  - Only **3 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.

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

- FCNC cases (SI):
  - Bosonic missing energy (either scalar or vector), possibly dark matter (**DM**) candidate.
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- Resonant cases (SII):
  - Fermionic missing energy, **DM** candidate (resonant particle being either scalar or vector).
  - Only **3 free parameters** (the mass of the particles of new physics and the coupling strength).

Motivations

General:

- **Top quark sector** (high mass → natural probe for BSM physics).
- **Dark matter**: one of the rare existing signs of new physics.
- Cover a resonant scenario **for the first time** at a collider.

Specific:

- **Leptonic :**
  - **Advantages :** no MET trigger → explore different phase space regions than hadronic channel.
  - **Disadvantages :** boosted regime for the top, loss of lepton selection efficiency.

- **Hadronic :** FCNC scenarii already covered at 8 TeV ***(see next slides)***
  - **Advantages :** possible top mass reconstruction, veto lepton.
  - **Disadvantages :** irreductible physical background Z→ νν + 3jets.

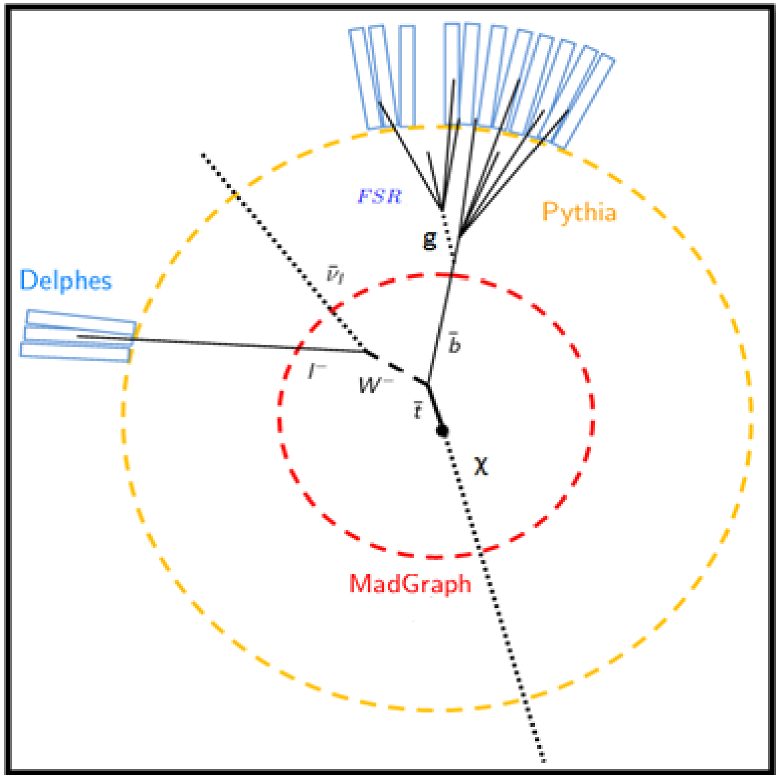
Outline

- ➢ Experimental context
- ➢ Introduction to Monotops
- ➢ Monotop signatures at the LHC
- ➢ Pheno study at 8 TeV
    - Strategies to study the hadronic/leptonic channels
    - Comparisons in terms of sensitivity
- ➢ Analysis at 8 TeV
- ➢ Summary/Plan

Pheno analysis strategy

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

- **Strategy of the pheno study :**
  - Generate MC events (signal + bkgd) with **MadGraph5** + **Pythia**.
  - Use FastSimulation (**Delphes**) of the detector.
  - Implement event selection to extract the signal from the main backgrounds (**MadAnalysis**).
  - Draw sensitivity plots for both FCNC and resonant cases.



→ **Led to an article: *Phys. Rev. D* 89 (2014) 014028**

Hadronic Monotops

(at 8 TeV with 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 → irreducible background

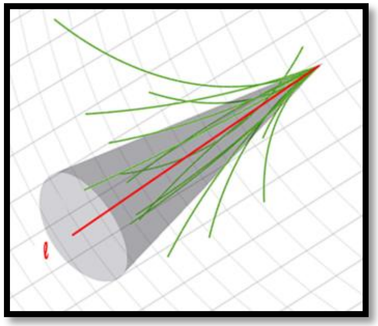
W + jets, $t\bar{t}$, diboson, single top (non- or misreconstructed leptons from W's)

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):**

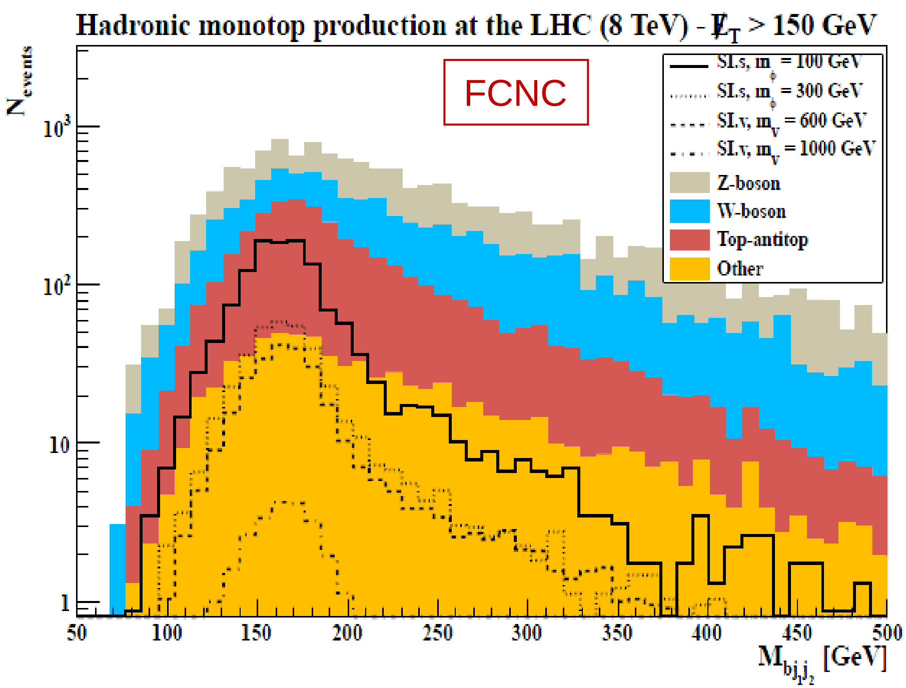
  $\Delta\varphi(\text{MPT}, p(j)) \in \,]0.5, 5.75[$

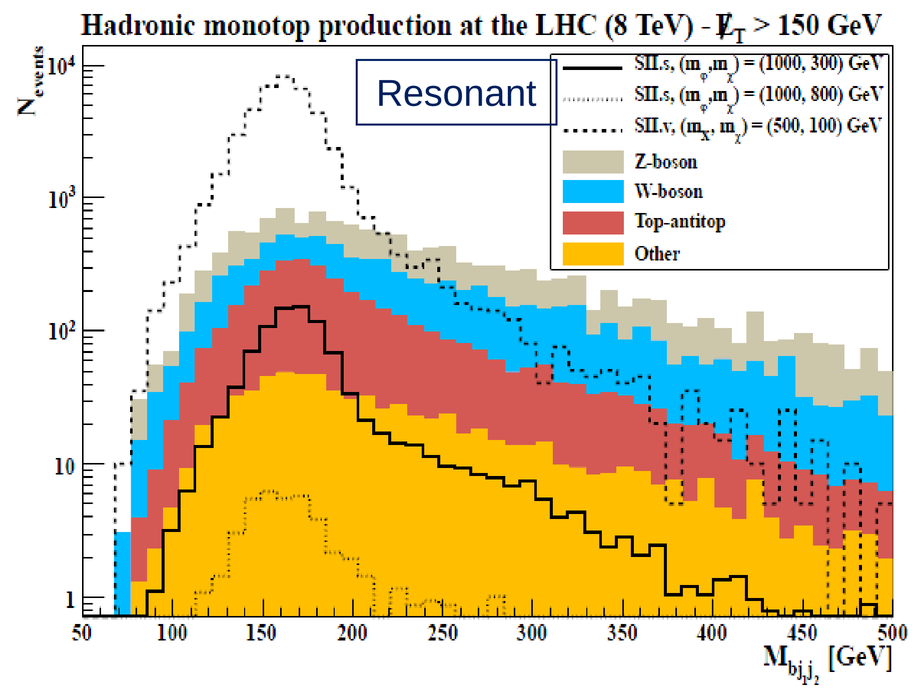
- **Transverse momentum of the reconstructed top quark required to be well separated from the MPT :**

  $\Delta\varphi(\text{MPT}, p(t)) \in \,]1, 5[$

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 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 ➔ irreducible background

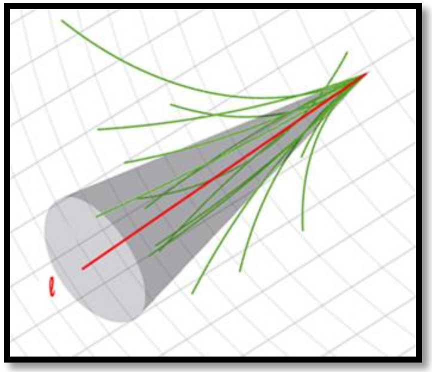
$t\bar{t}$, single top (non- or misreconstructed jet or lepton)

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)



$Cone\ of\ \Delta R = 0.3$

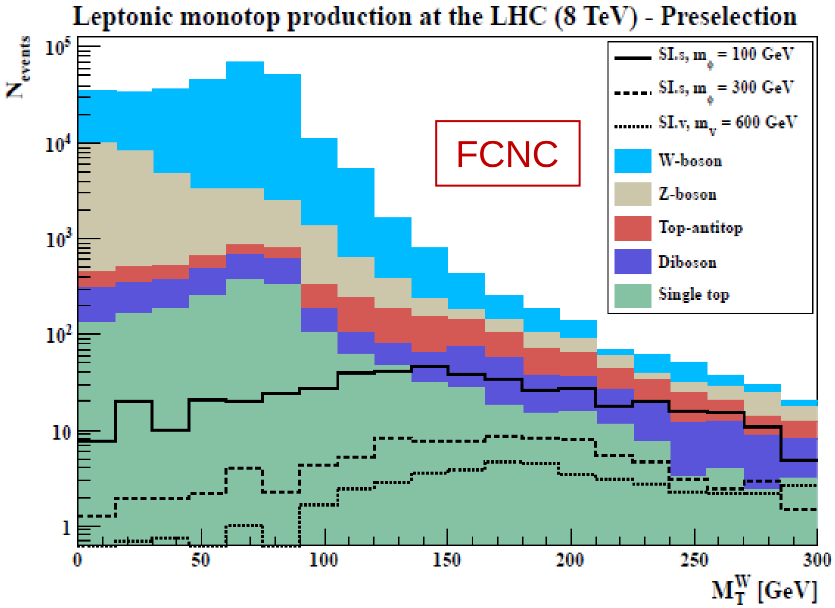
- **Exactly 1 b-tagged jet with:**
  - $|\eta| < 2.5$
  - $p_T > 75$ GeV ***(optimized)***
- **Veto on events containing any other jet with:**
  - $p_T > 20$ GeV

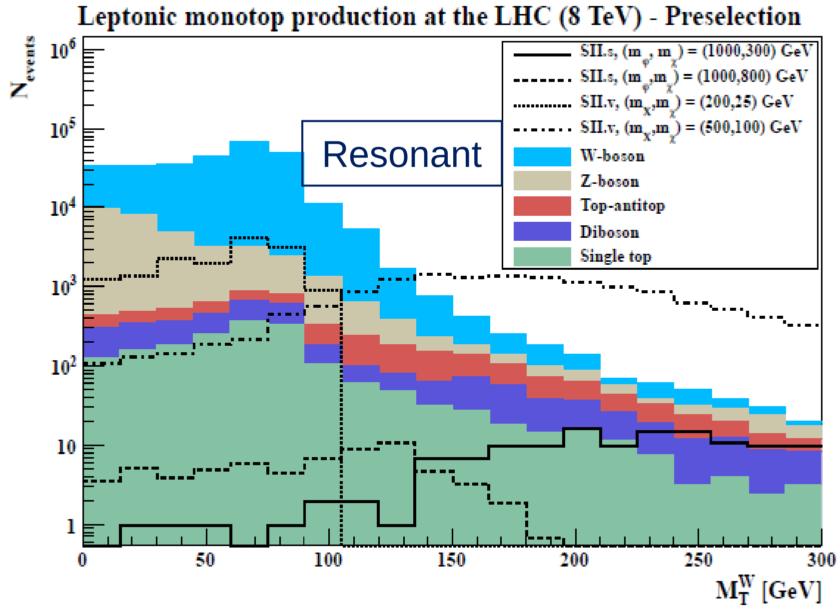
(Optimization assumption: best cut is the one who maximizes the significance)

Event selection (2/3)

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

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

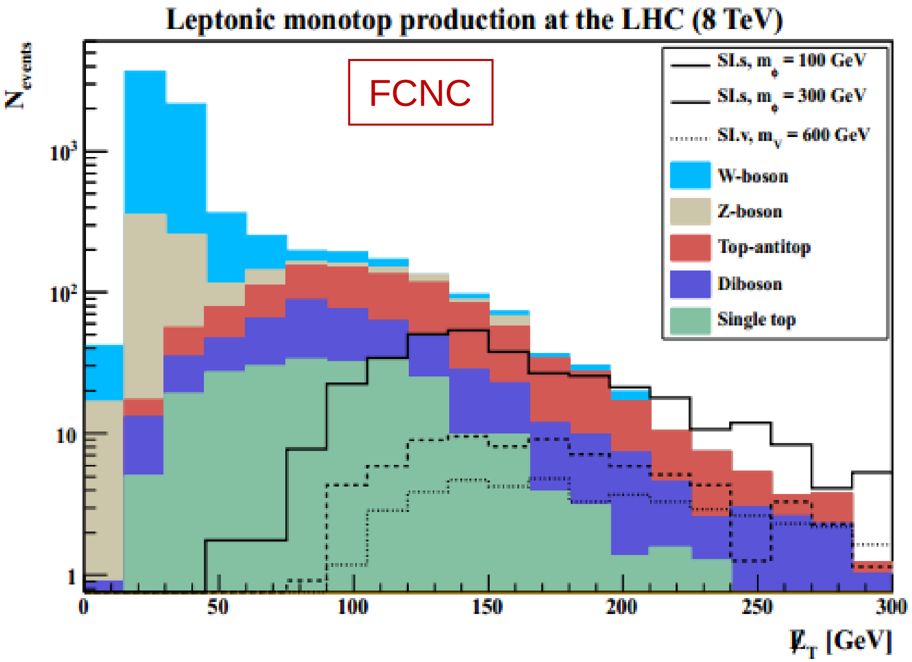


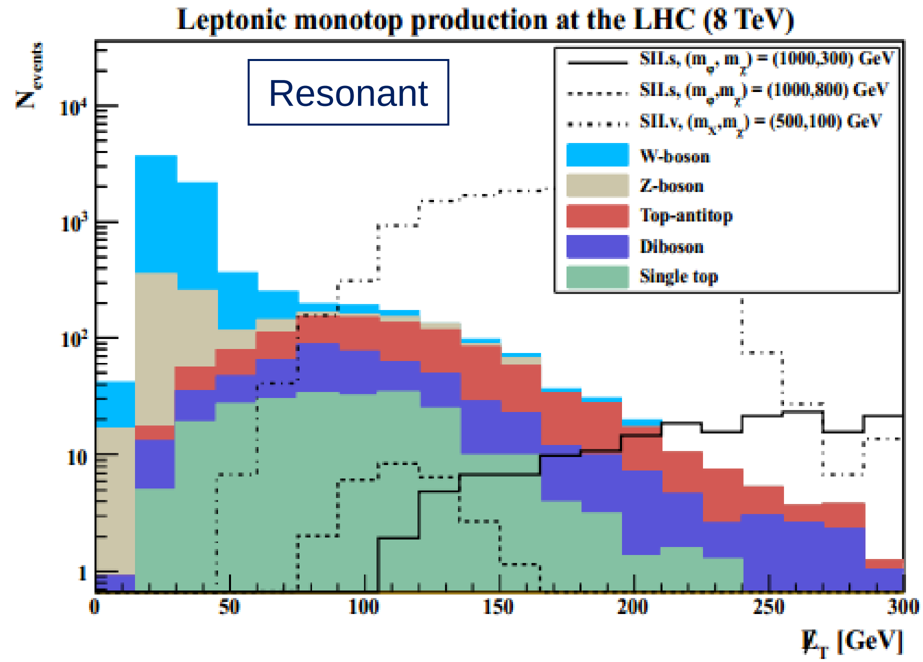


- Cut optimized for 8 different benchmark scenarios in maximizing the significance → **m_T^Wcut = 115GeV.**

Event selection (3/3)

- Distribution of the MET after all other cuts:





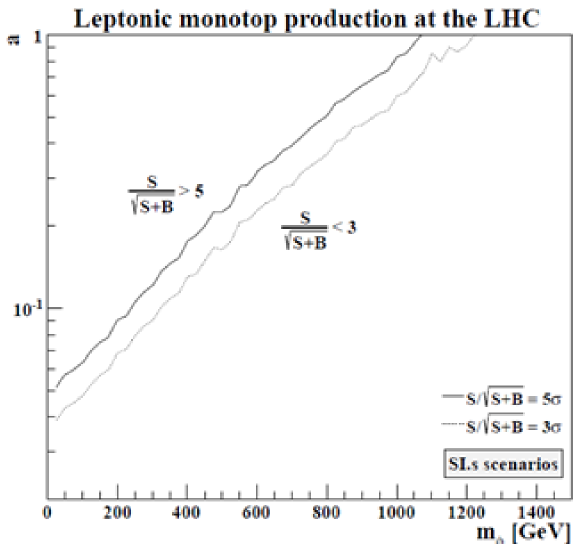
- Cut optimized for all the benchmark scenarios in maximizing the significance (**S/sqrt(S+B)**).

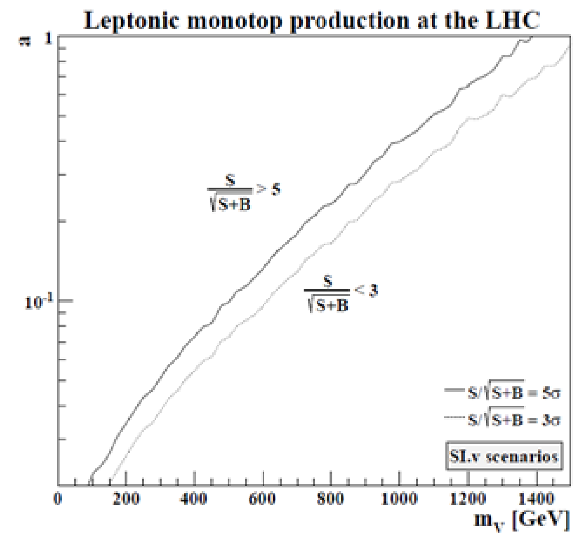
Comparison: LHC Sensitivity

FCNC

Leptonic

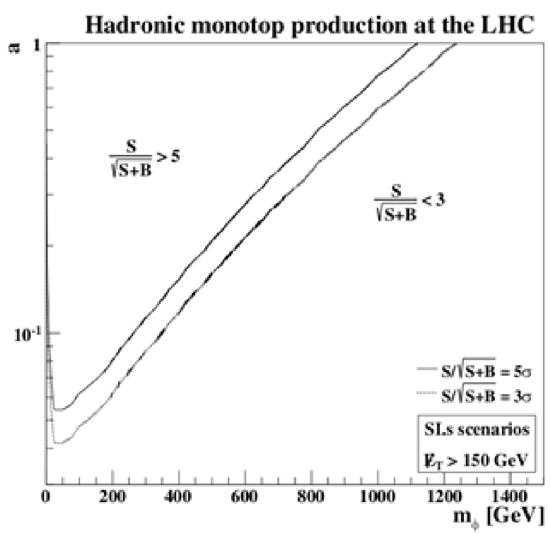
SI.s | SI.v

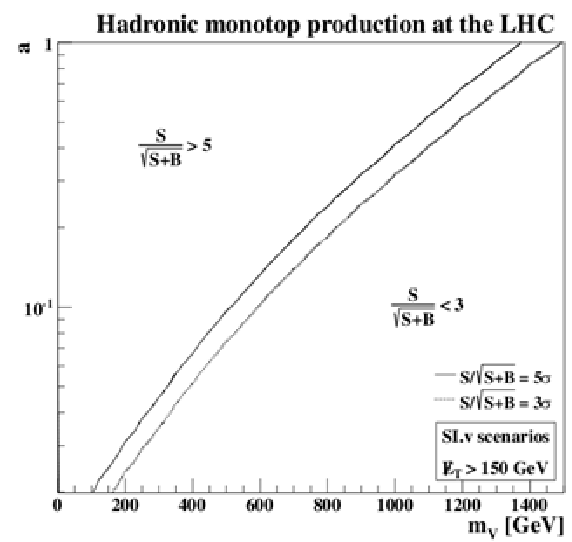




Hadronic

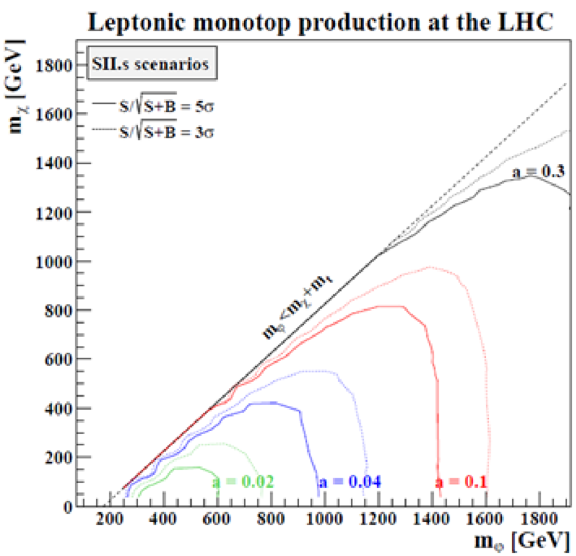
SI.s | SI.v



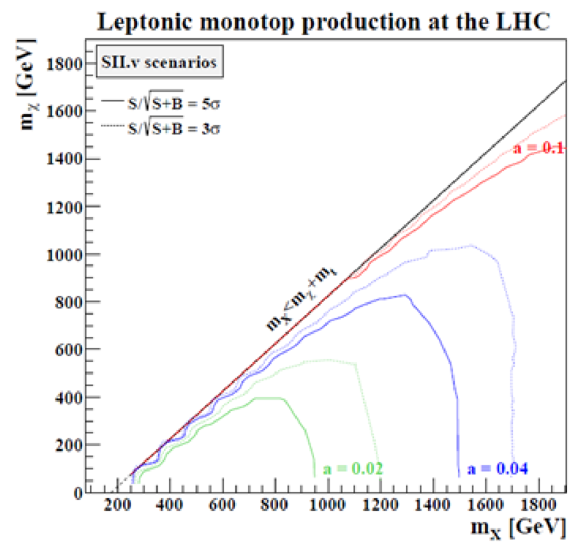


Comparison: LHC Sensitivity

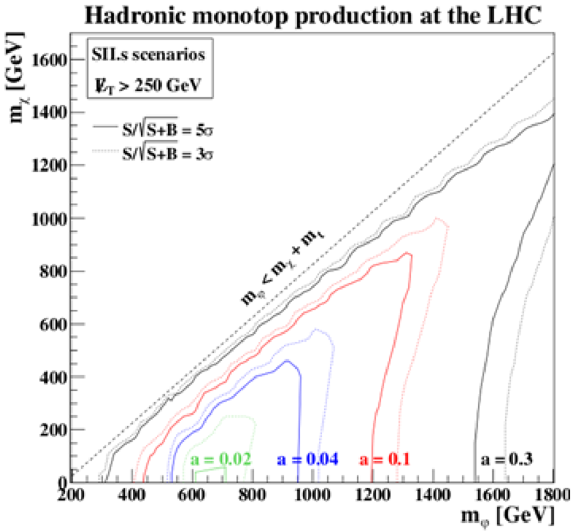
Resonant



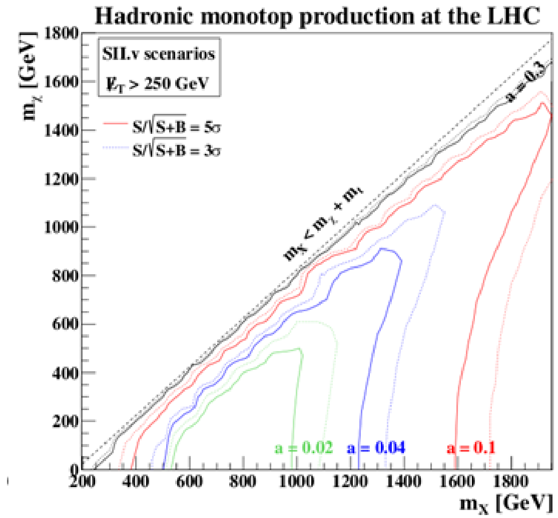
Leptonic



SII.s SII.v



Hadronic



SII.s SII.v

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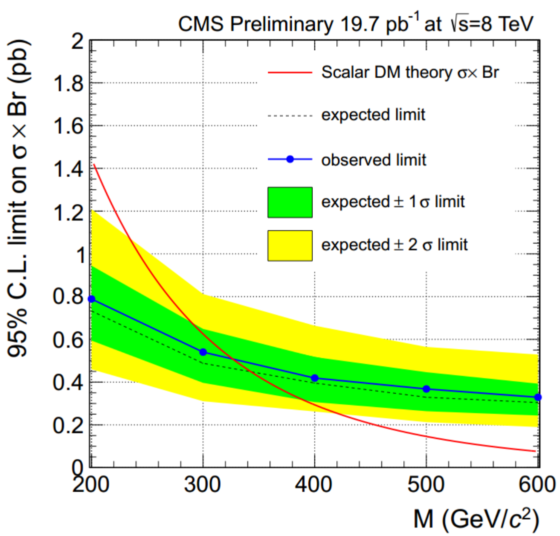
- Experimental context
- Introduction to Monotops
- Monotop signatures at the LHC
- Pheno study at 8 TeV
- **Analysis at 8 TeV**
  - Some results given by the hadronic channel
  - Strategy to study the leptonic channel
- Summary/Plan

- **Strategy of the analysis :**

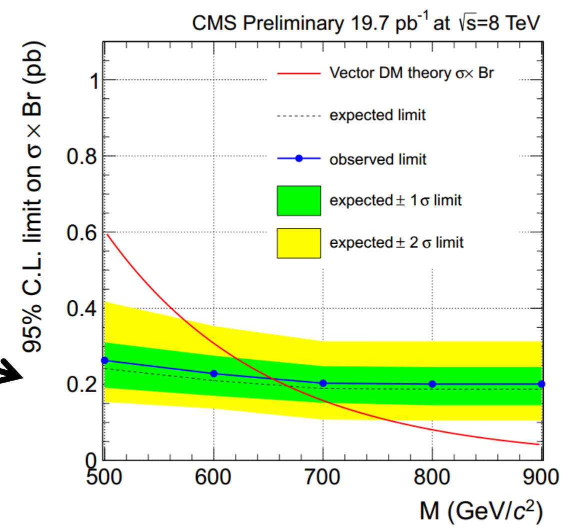
  - ✓ Study background in signal region (Z → νν + 3 jets).
  - ✓ Define signal region using pheno study results.
  - ✓ Apply corrections (JER, PU...), compute the limit.



FCNC

Scalar DM

Vector DM

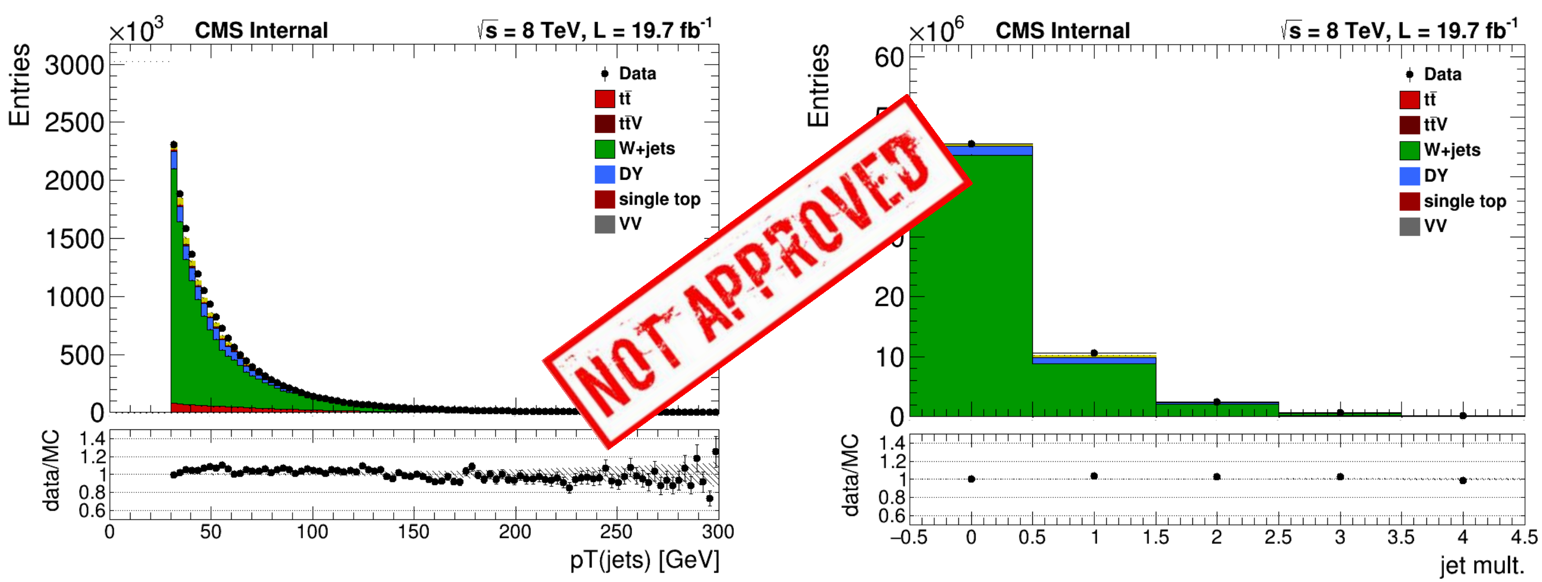


Limits at 95% CL

Paper ongoing, PAS already available (CMS PAS B2G-12-022)

Leptonic channel @8 TeV

- **Strategy of the analysis :**
  - ✓ Define control regions (QCD, Wjets, ttbar) and signal region.
  - ✓ Apply corrections (JER, pT-reweighting..).
  - ✓ Check the good agreement between data and MC.
  - ✓ Estimate the systematics uncertainties and compute the limit.



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Summary/Plan

- Monotops signatures have been described by only 2 (FCNC) or 3 (Resonant) free parameters.
- A pheno study has been performed at 8TeV showing that Monotops search is relevant, already with 8TeV data.
- Finish the 8TeV analysis with $\mathcal{L} = 19.7\ \text{fb}^{-1}$ (early 2015).
- Prepare the 13TeV collisions (Spring15).
- Be in a hurry for the restart, plan not to sleep during few months, discover Monotops, get a Nobel Prize.

Back-up

Other monotop signatures

Some classes of models yielding monotop signatures:

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

  (*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** $pp \rightarrow leptoquark \rightarrow t + \nu$

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

- **Hylogenesis scenarios** $pp \rightarrow t + composite\ state\ of\ several\ \chi$

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

- **Z' model** $pp \rightarrow t + Z' \rightarrow t + \chi\chi$

  (*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.**

Softwares references

- Generate MC events: **MadGraph5** (*Alwall et al*, JHEP ‘11).
- Hadronize hard processed particles: **Pythia** (*Sjostrand et al*, JHEP ‘06 and CPC ‘08).
- Simulate particles-detectors interactions: **Delphes** (*Ovyn et al*, 2009).
- Implement event selection: **MadAnalysis5** (*Conte et al*, CPC ’13).

Signal total cross section

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

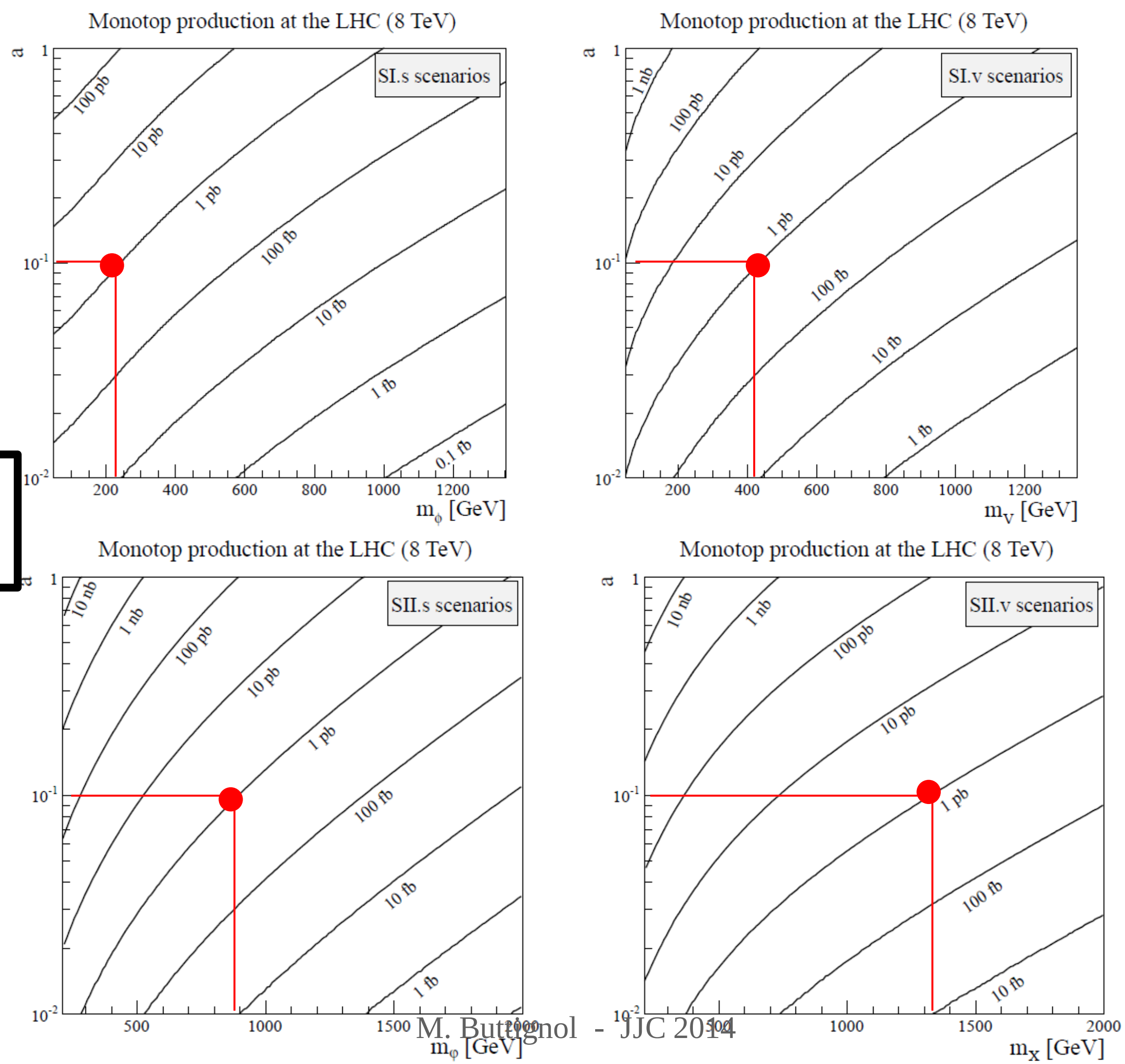
SI.s

SI.v

Calculation done with a = 0.1

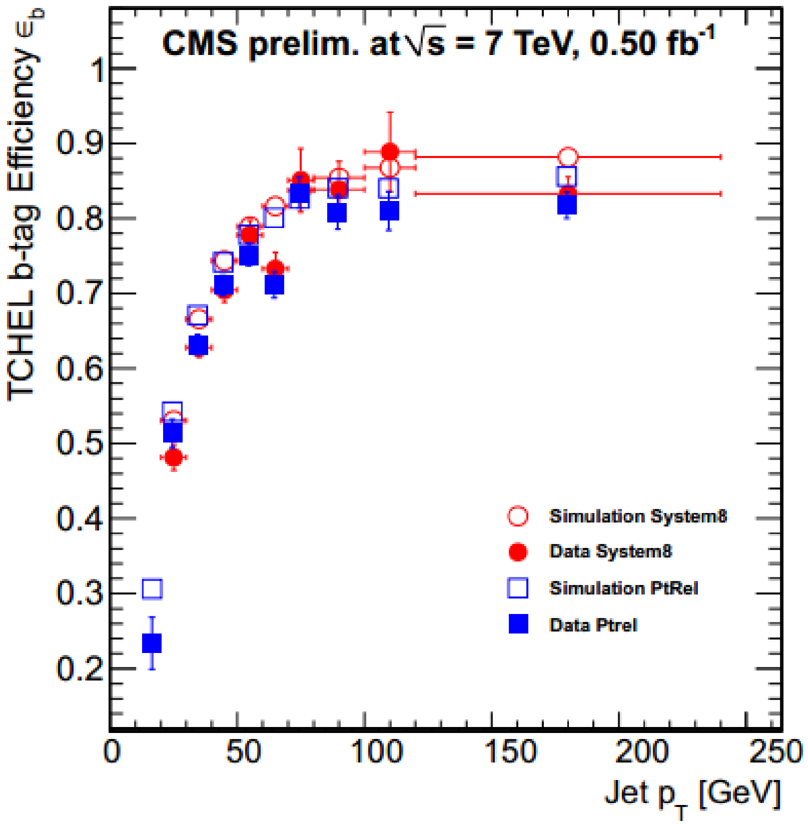
SII.s

SII.v



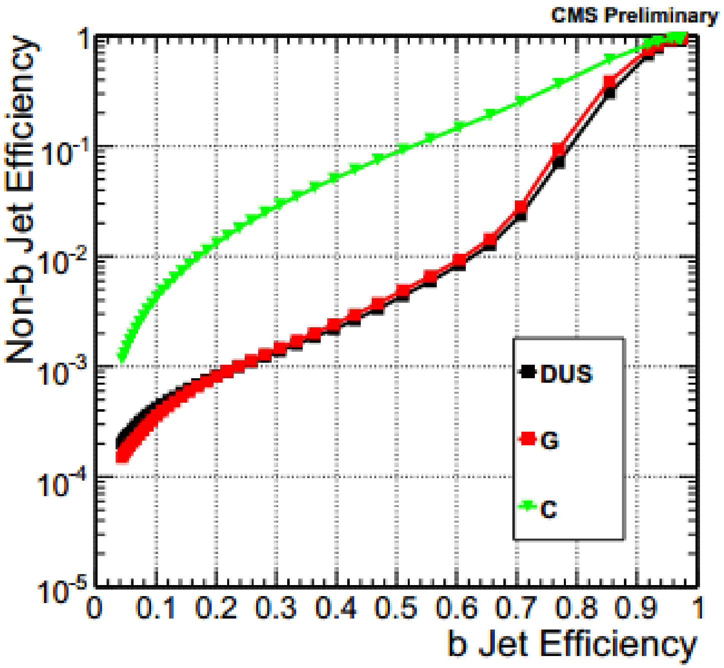
B–tagging and mistagging

- 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	σ [pb]	N
$W(\to \ell\nu)$ + jets	35678	$2.56 \cdot 10^8$
$\gamma^*/Z(\to 2\ell/2\nu)$ + jets	10319	$4 \cdot 10^7$
$t\bar{t}(\to$ 6jets)+jets	116.2	$8 \cdot 10^6$
$t\bar{t}(\to$ 4jets 1ℓ 1ν)+jets	112.4	$9 \cdot 10^6$
$t\bar{t}(\to$ 2jets 2ℓ 2ν)+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	$8 \cdot 10^5$
$t\bar{t}W$ + jets [incl.]	0.25	$3 \cdot 10^4$
$t\bar{t}Z$ + jets [incl.]	0.21	$5 \cdot 10^4$
$t/\bar{t} + Z + j$ + jets [incl.]	0.046	$3 \cdot 10^5$
$t\bar{t}WW$ + jets [incl.]	0.013	$2 \cdot 10^3$
$t\bar{t}t\bar{t}$ + jets [incl.]	$7 \cdot 10^{-4}$	10^3

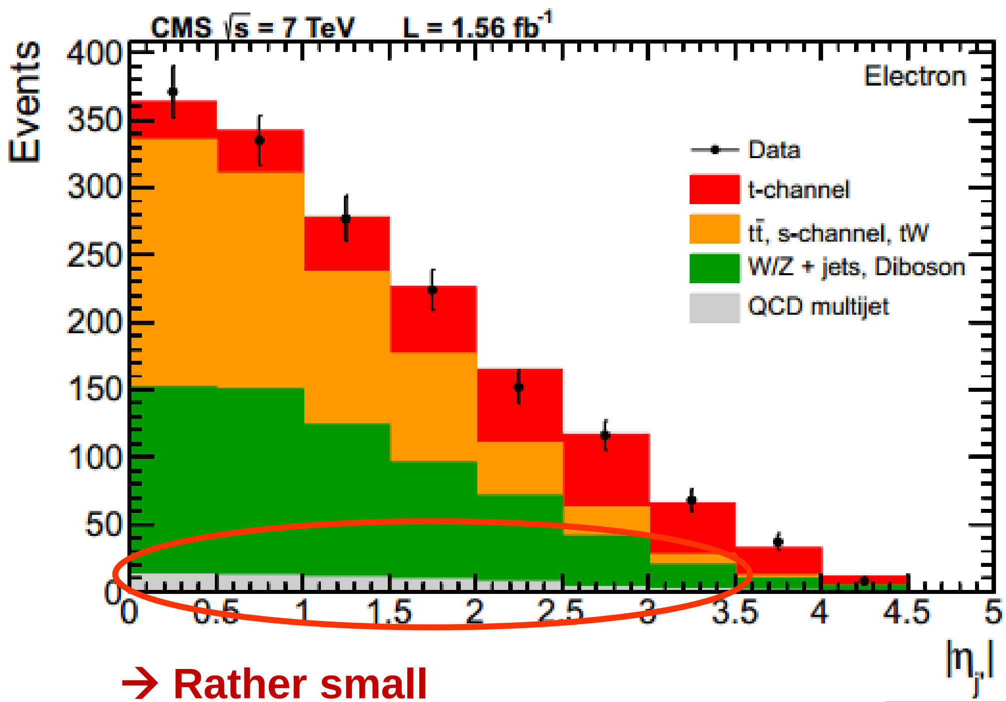
Process	σ [pb]	N
$WW(\to 1\ell$ 1ν 2jets)+jets	24.3	$3 \cdot 10^6$
$WW(\to 2\ell$ 2ν) + jets	5.87	$8 \cdot 10^5$
$WZ(\to 1\ell$ 1ν 2jets) + jets	5.03	$5 \cdot 10^5$
$WZ(\to 2\nu$ 2jets) + jets	2.98	$3 \cdot 10^5$
$WZ(\to 2\ell$ 2jets) + jets	1.58	$2 \cdot 10^5$
$WZ(\to 1\ell$ 3ν) + jets	1.44	$2 \cdot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

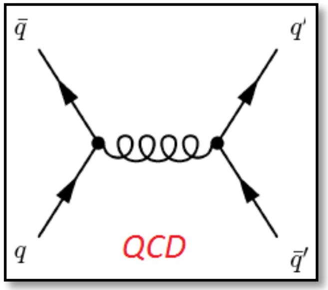
QCD Multijets

(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