Flavour changing neutral currents of top quarks at the LHC, a probe for new physics

Isis Van Parijs
Vrije Universiteit Brussel
IIHE – CMS – CERN
BPS Meeting
18 May 2016

Beyond the SM

In the quest for new physics, FCNCs provide a model independent look into BSM without the need for new heavy particles

The Large Hadron Collider

Home to e.g. CMS and ATLAS.
Experiments that study proton collisions at 7 TeV, 8 TeV and 13 TeV

A 27-kilometre ring of superconducting magnets and accelerating structures

FCNCs with top quarks

Flavour changing neutral current transitions are interaction processes where a fermion undergoes a change of flavour without the alternation of its charge.

arXiv:hep-ph/0409342	SM	2HDM	MSSM
$t \to cZ$	1×10^{-14}	$\sim 10^{-7}$	2×10^{-6}
$t \to c\gamma$	4.6×10^{-14}	$\sim 10^{-6}$	2×10^{-6}
$t \to cg$	4.6×10^{-12}	$\sim 10^{-4}$	8×10^{-5}
$t \to cH$	3×10^{-15}	1.5×10^{-3}	10^{-5}

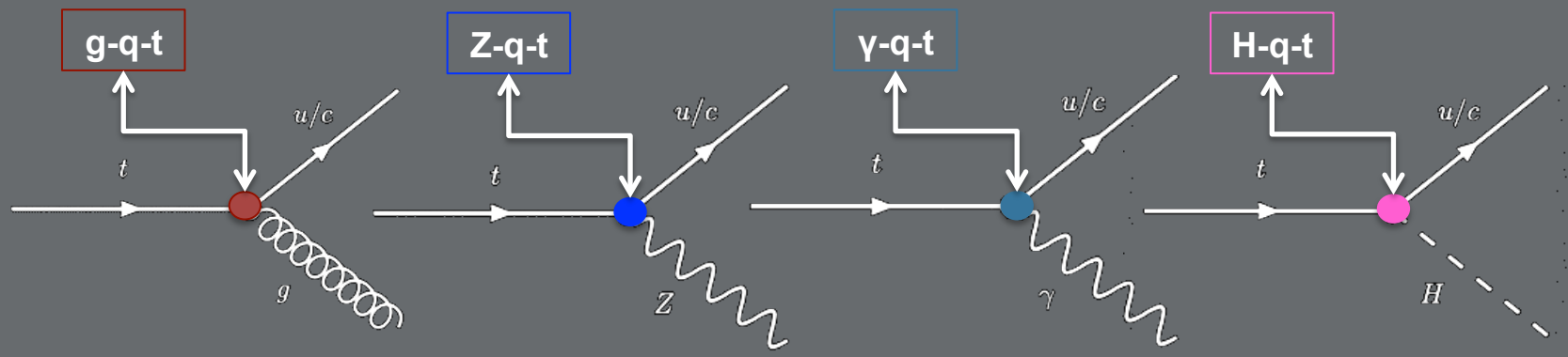
Extensions of the SM can increase the BR up O(12) !

There is a whole landscape of FCNC searches at CMS

q = u / c	Single top (at production)	Top pair (at decays)	Reference
tgq	$B(t \to gc) < 3.44\ 10^{-3}$ $B(t \to gu) < 3.55\ 10^{-4}$	N/A	CMS-PAS-TOP-14-007
tZq	$B(t \to uZ) < 0.51\ 10^{-2}$ $B(t \to cZ) < 11.4\ 10^{-2}$	$B(t \to Zq) < 0.05\ 10^{-2}$	CMS-PAS-TOP-12-021 arXiv:1312.4194
tγq	$B(t \to u\gamma) < 1.3\ 10^{-4}$ $B(t \to u\gamma) < 1.7\ 10^{-3}$	N/A	CMS-TOP-14-003 ; CERN-PH-EP-2015-287
tHq	N/A	$B(t \to uH) < 0.71\ 10^{-2}$ $B(t \to cH) < 0.47\ 10^{-2}$ $B(t \to uH) < 1.92\ 10^{-2}$ $B(t \to cH) < 1.16\ 10^{-2}$ $B(t \to qH) < 0.93\ 10^{-2}$	CMS-PAS-TOP-14-019 (diphoton) CMS-PAS-TOP-14-020 (bbar) CMS-PAS-TOP-13-017 (WW/ZZ/ττ)

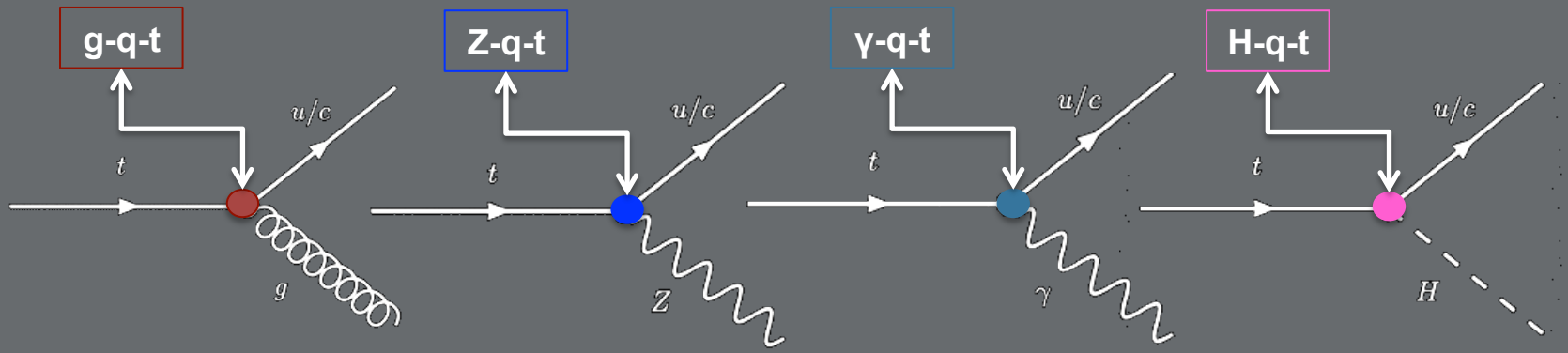
There is a whole landscape of FCNC searches

$$
\begin{aligned}
\mathcal{L} \;=\; & \sum_{q=u,c} \Big[\sqrt{2}\, g_s \frac{\kappa_{gqt}}{\Lambda} \bar{t}\, \sigma^{\mu\nu}\, T_a (f^L_{Gq} P_L + f^R_{Gq} P_R)\, q\, G^a_{\mu\nu} \\
& + \frac{g}{\sqrt{2} c_W} \frac{\kappa_{zqt}}{\Lambda} \bar{t} \sigma^{\mu\nu}\, (f^L_{Zq} P_L + f^R_{Zq} P_R)\, q\, Z_{\mu\nu} \\
& - e \frac{\kappa_{\gamma qt}}{\Lambda} \bar{t}\, \sigma^{\mu\nu}\, (f^L_{\gamma q} P_L + f^R_{\gamma q} P_R)\, q\, A_{\mu\nu} \\
& + \frac{g}{\sqrt{2}} \bar{t} \kappa_{Hqt} (f^L_{Hq} P_L + f^R_{Hq} P_R)\, q\, H \Big] + \text{h.c.}
\end{aligned}
$$



Only most stringent CMS limits are discussed as a roadmap into FCNC

FCNC t-g-q single top → FCNC t-Z-q top pair → FCNC t-γ-q single top → FCNC t-H-q top pair



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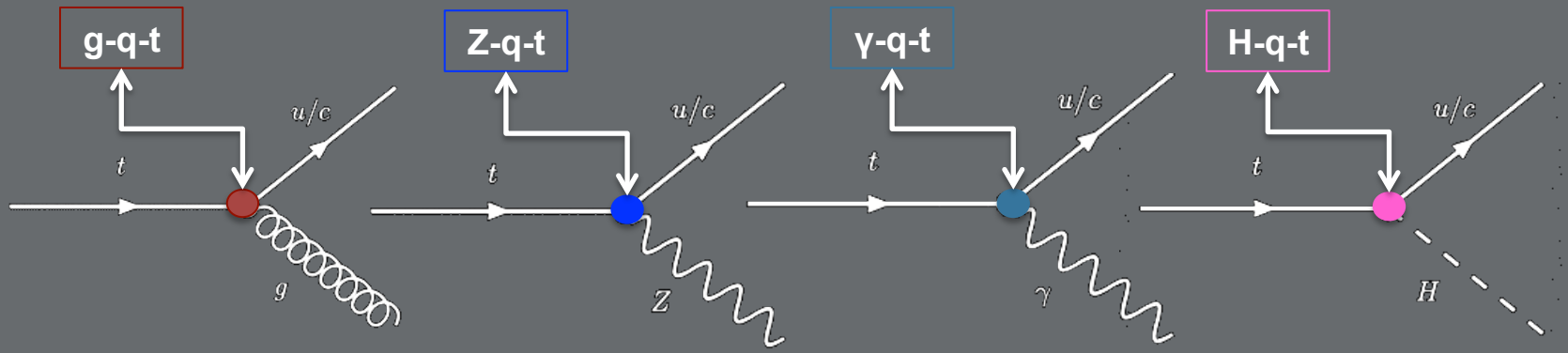
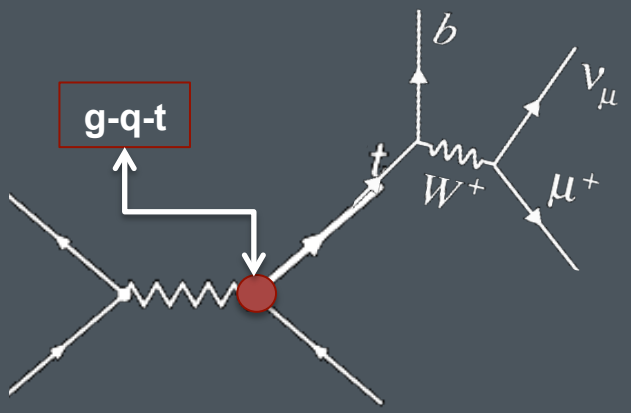


FCNCs: a top, a gluon and a quark

7 TeV pp collision data
Luminosity of 5 fb^{-1}
single top

tgq



$q\bar{q} \rightarrow t\bar{c}$

- ✘ t → qg not possible due to multi-jet QCD background
- ✘ Look at qg → t → Wb → lν b
- ✘ Muonic decay channel: muon + jets
- ✘ Signature:
  1 muon, MET, ≥ 2 jets with ≥ 1 b jet

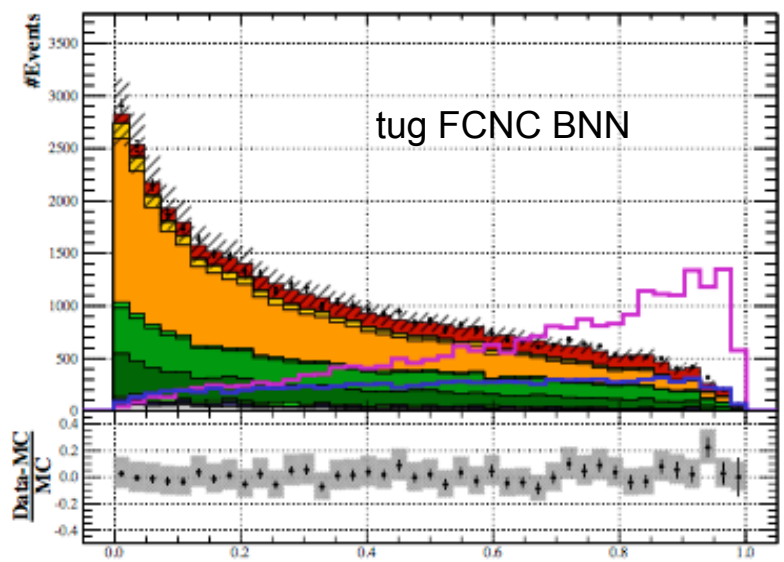
$B(t \rightarrow ug) < 3.55\ 10^{-4}$
$B(t \rightarrow cg) < 3.44\ 10^{-3}$

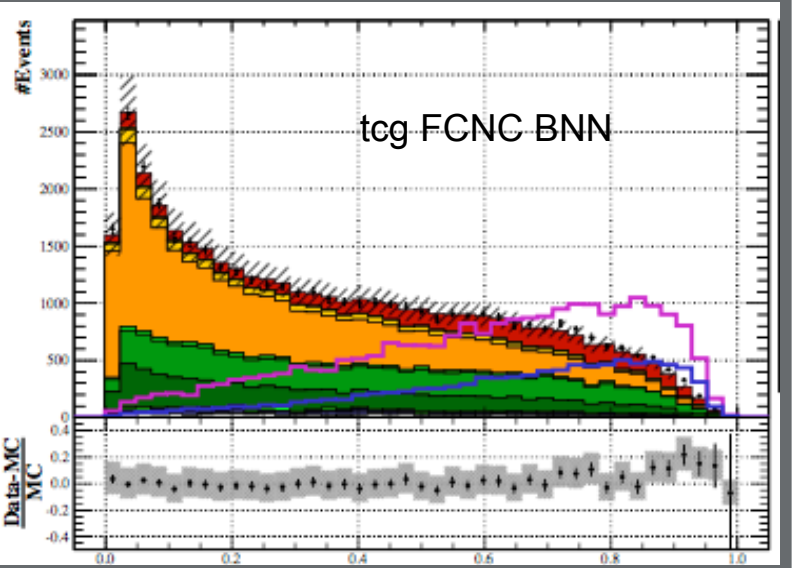
- ✘ Main backgrounds:
  Single top, top quark pair, W+jets, diboson, Drell Yann multi-jet QCD
- ✘ Multi-jet background estimated from data using Bayesian Neural Network template fit

Bayesian Neural Network classifier to differentiate signal from background

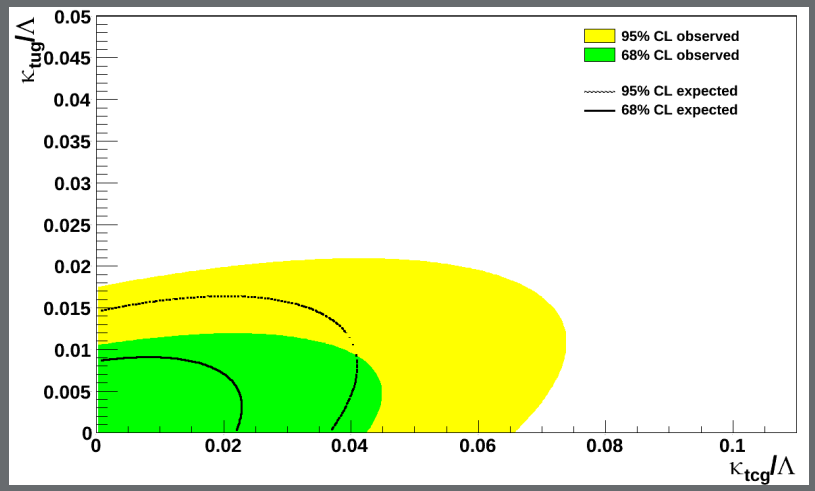
- Separate BNN for tug and tcg
- Used simultaneously in statistical analysis

tgq





$\kappa_{tug}/\Lambda < 1.8\ 10^{-2}\ TeV^{-1}$
$\kappa_{tcg}/\Lambda < 5.6\ 10^{-2}\ TeV^{-1}$



$B(t \rightarrow ug) < 0.036\ \%$
$B(t \rightarrow cg) < 0.34\ \%$

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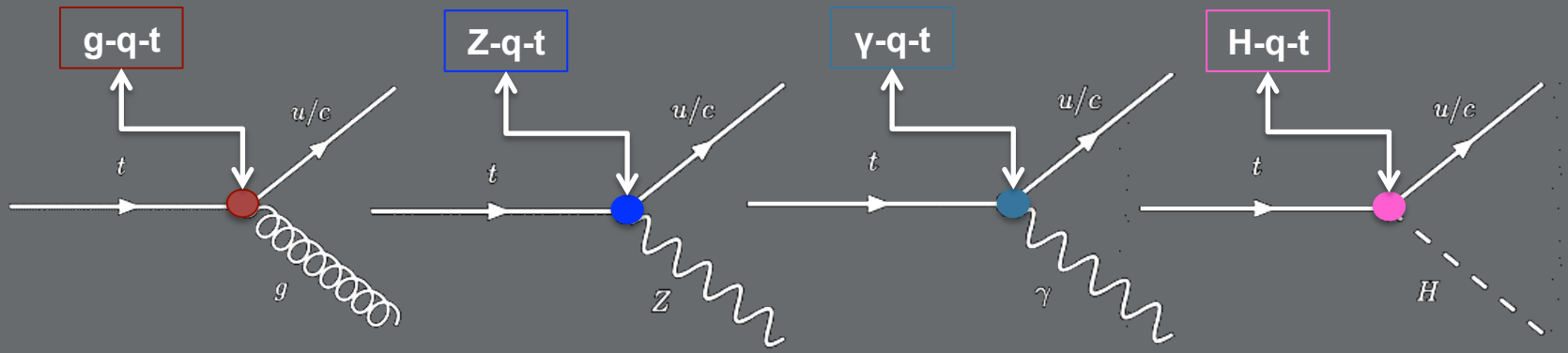
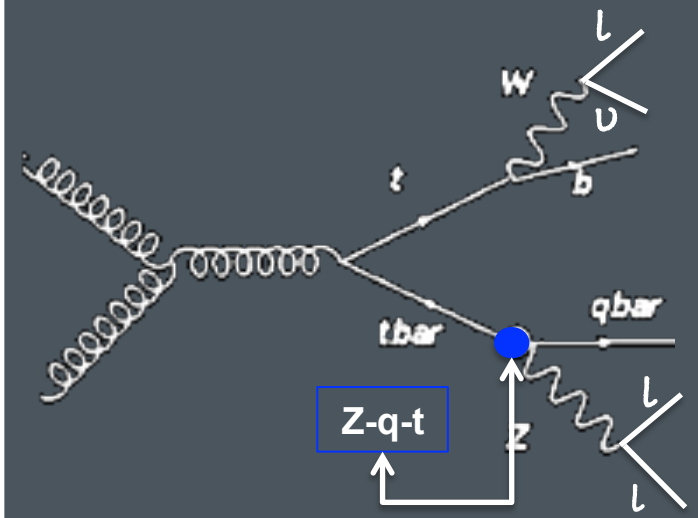


FCNCs: a top, a Z boson and a quark

7+8 TeV pp collision data
Luminosity of 19.7 fb^{-1}
top pair



B(t→Zq) < 0.05 %

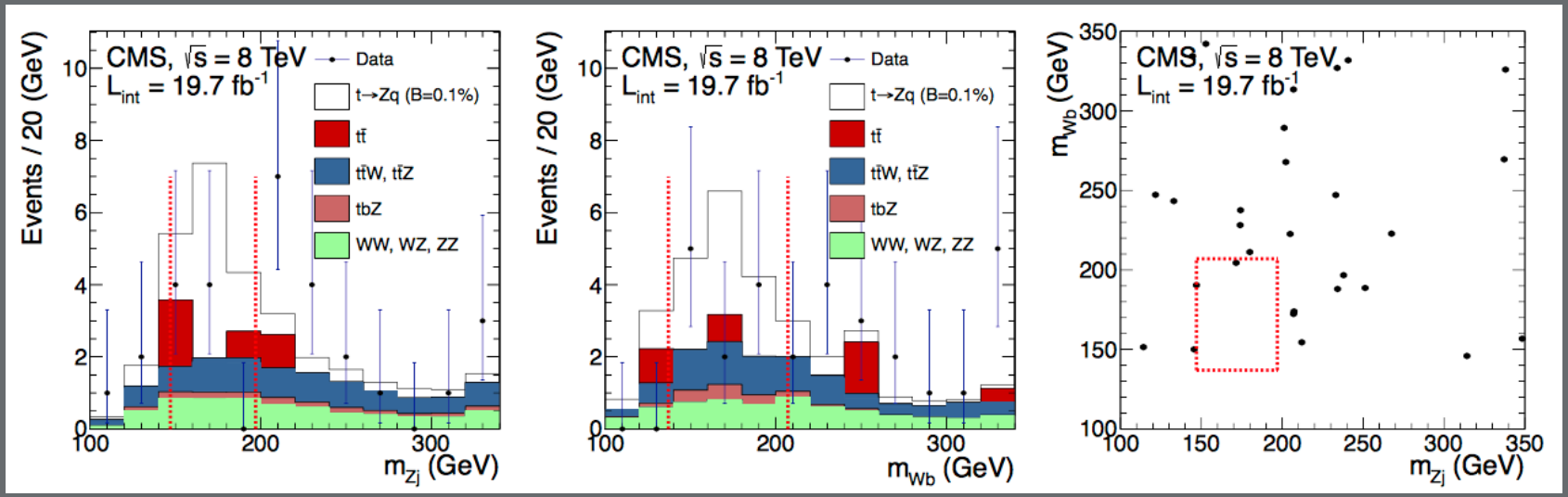
- tt → Zq + Wb → llq + vl b
- Signature:
  3 leptons, MET, ≥ 2 jets with ≥ 1 b jet

- Main backgrounds:
  diboson+jets, ttbar + X,
  Drell Yann; top pair, tZq
- Bkgds are estimated from data

arXiv:1312.4194

Limits extracted using a modified frequentist (CLs) likelihood method

3 regions used:
- diboson and Drell Yann: 0 b jets
- signal: 1 b jet
- ttX and tt : > 1 b jet



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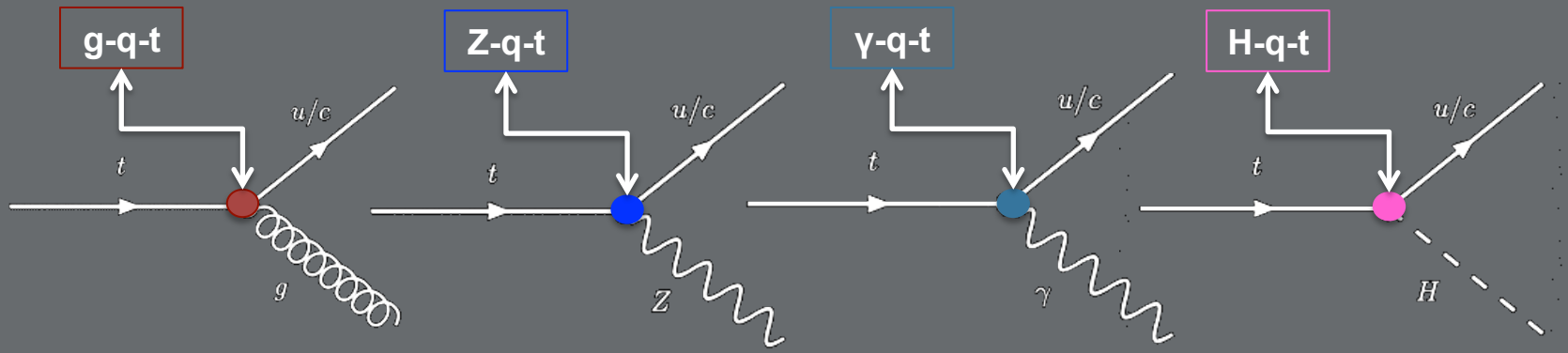
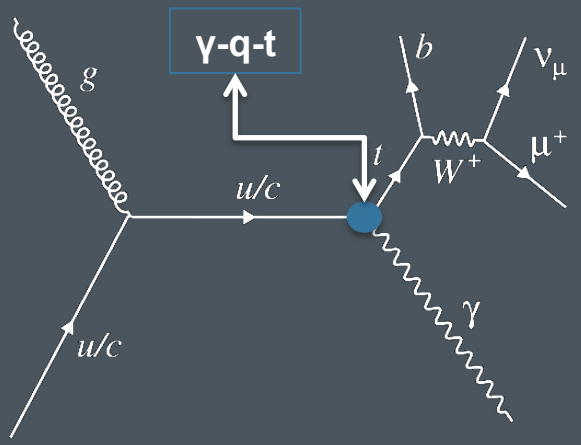


FCNCs: a top, a photon and a quark

8 TeV pp collision data
Luminosity of 19.8 fb^{-1}
single top



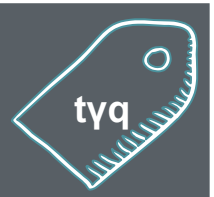
- ✘ q → t γ → Wb γ → νμ b γ
- ✘ Signature
  1 muon, 1 photon, MET, 1 b jet

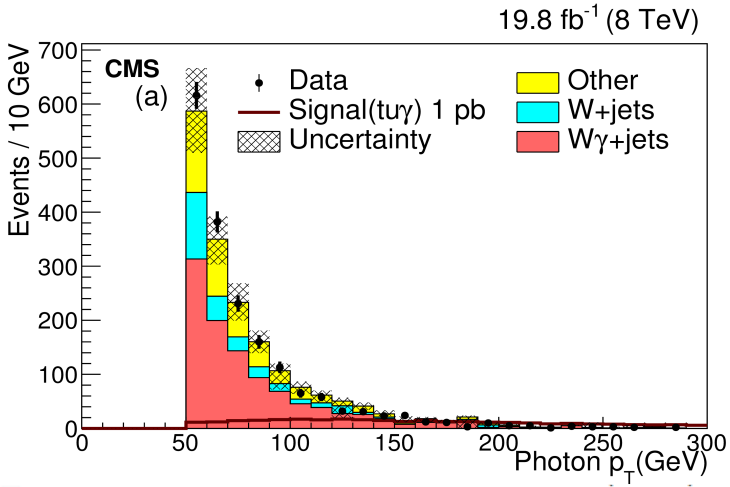
- ✘ Main backgrounds:
  W(γ)+jets, Z(γ)+jets, top pair (+ γ), diboson (+ γ) production
- ✘ W(γ) + jets background estimated from NN in data with e.g. cos(W,γ)

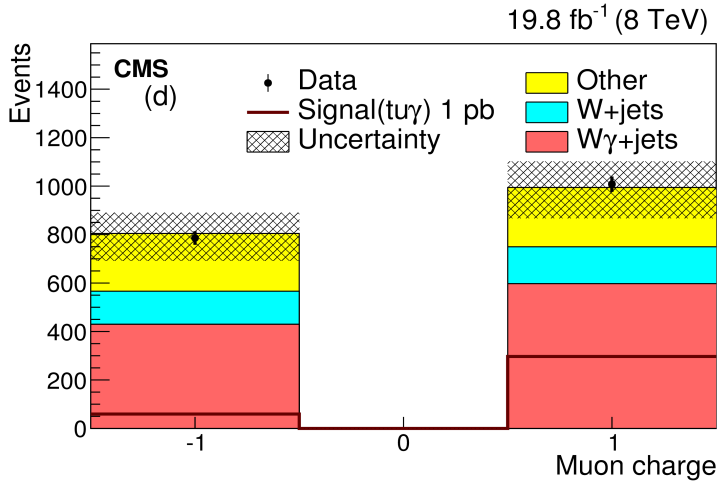
$B(t \rightarrow u\gamma) < 1.3\ 10^{-4}$
$B(t \rightarrow c\gamma) < 1.7\ 10^{-3}$

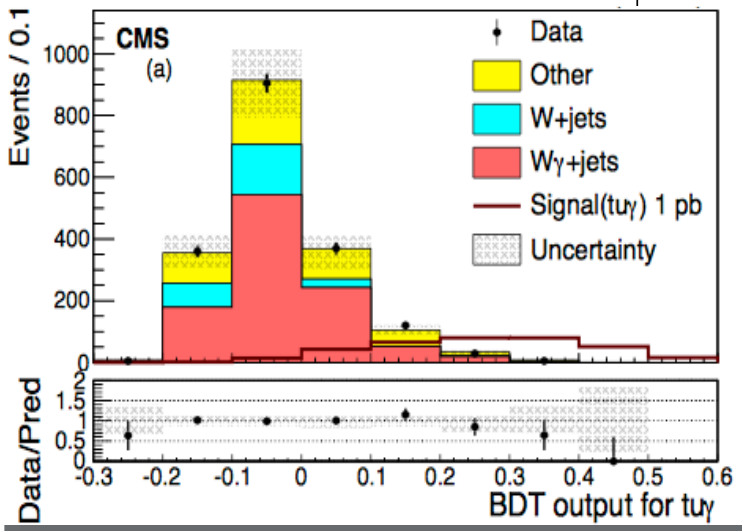
Binned MLM on a BDT classifier with 8 variables based on several differences e.g.

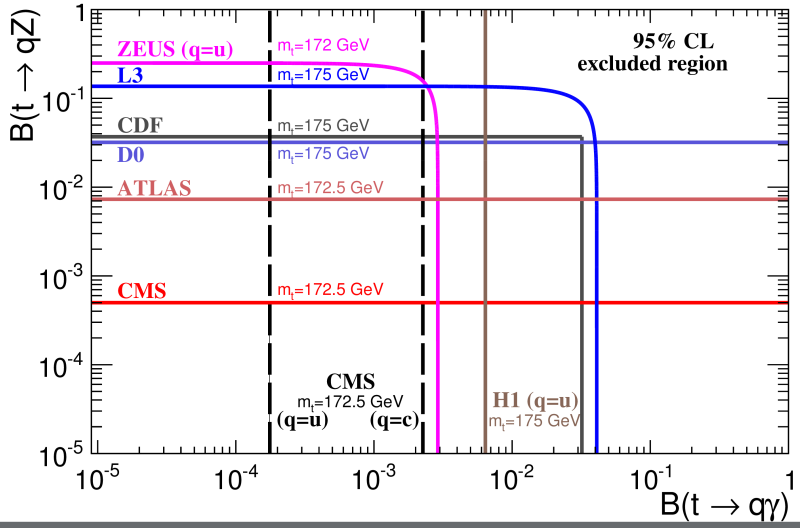
1. Pt photon is harder in FCNC
   → W and b are back to back ≠ SM top
2. Top quark charge asymmetry differs in uγt channel
   → use lepton charge











$B(t \to u\gamma) < 1.3\ 10^{-4}$

$B(t \to c\gamma) < 1.7\ 10^{-3}$

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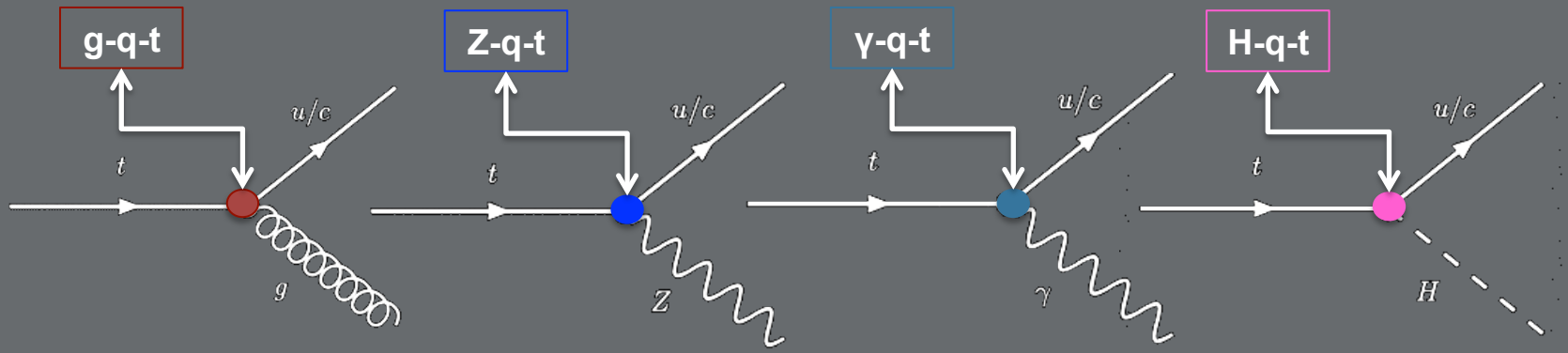
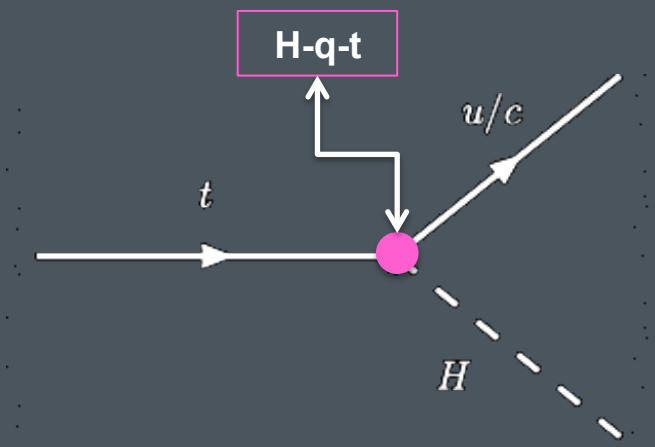


FCNCs: a top, a H boson and a quark
- FCNH -



Best limit from H →γγ
B(t → uH) < 0.42%
B(t → cH) < 0.47%

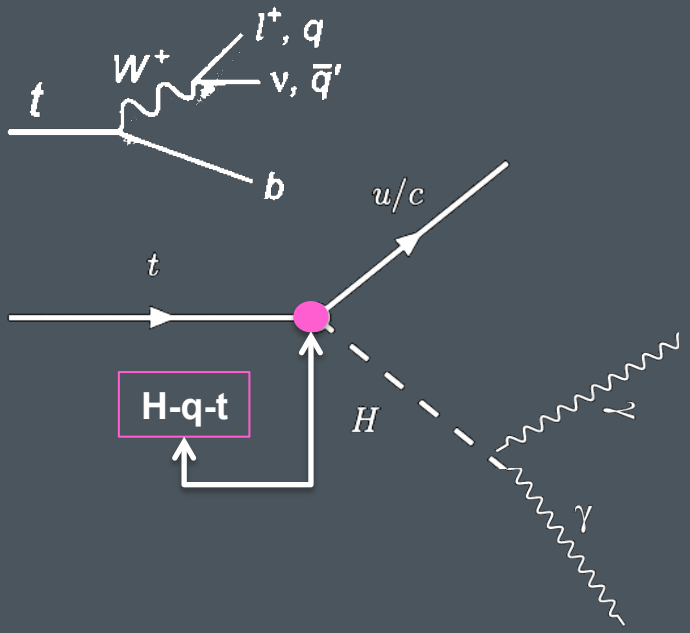
Different final states based on decay of the H boson:

- H → WW/ZZ/ττ
  - CMS-PAS-TOP-13-017
  - multi-lepton final states, easy to ID, small bkgd
- H → γγ
  - CMS-PAS-TOP-14-019
  - low BR, but very clean, excellent mass resolution
- H → bbar
  - CMS-PAS-TOP-14-020
  - high BR, suffers from multi-jet bkgd

FCNCs: a top, a H boson and a quark

8 TeV pp collision data
Luminosity of 19.7 fb^{-1}
Top pair

tHq

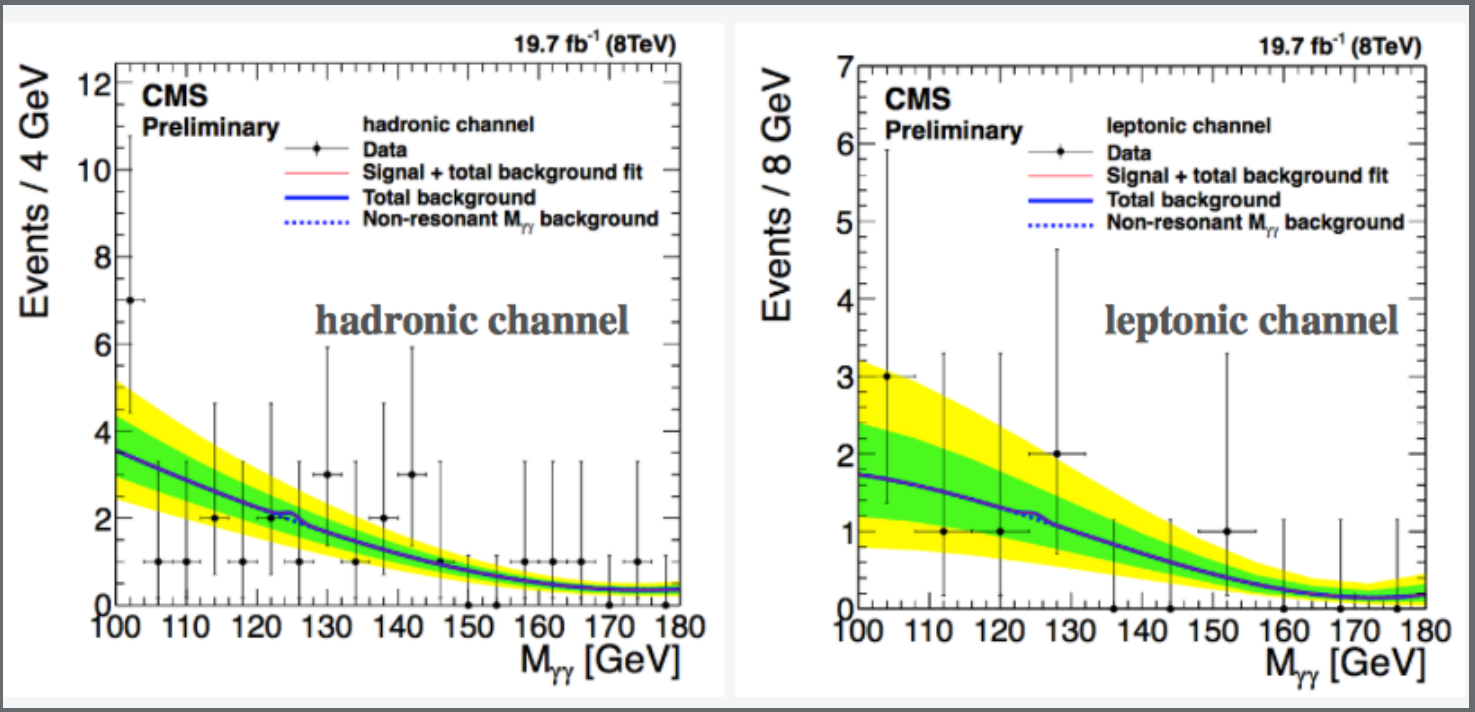


- ✘ tt → bW + qH with H → γγ
- ✘ Signature hadronic channel:
  2 photons, ≥ 4 jets from which 1 b jet
- ✘ Signature leptonic channel:
  2 photons, ≥ 1 lepton, MET, ≥ 2 jets from which 1 b jet

B(t → uH) < 0.42%
B(t → cH) < 0.47%

- ✘ Main backgrounds:
  γγ+ jets,W+jets, ttbar + γγ, ttH
- ✘ Non resonant γγ background (non higgs) estimated from data

Fit of the diphoton spectrum to data with bkgd-only and bkgd + signal in the hadronic and leptonic channel



B(t → uH) < 0.42%
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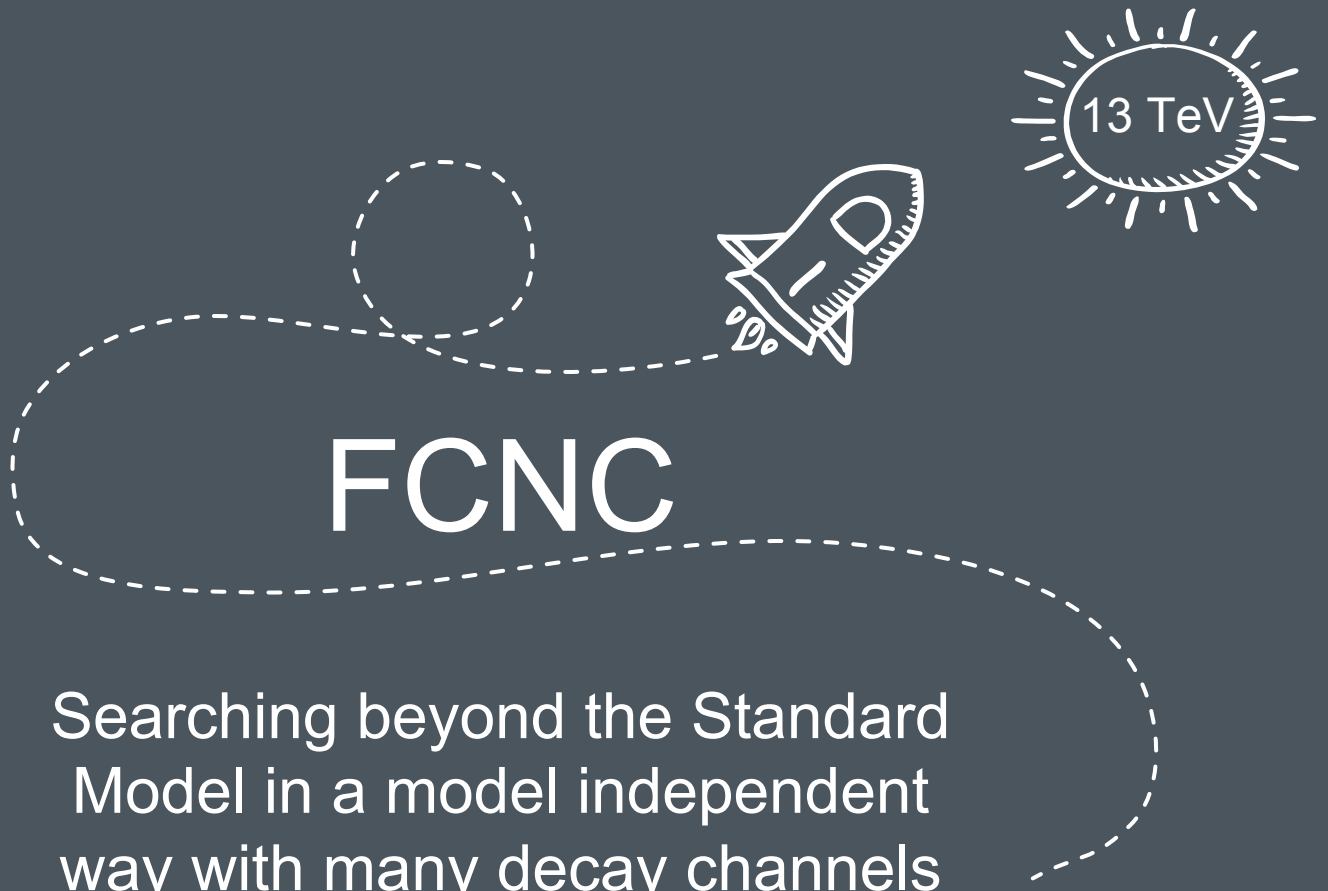


FCNC

Searching beyond the Standard Model in a model independent way with many decay channels

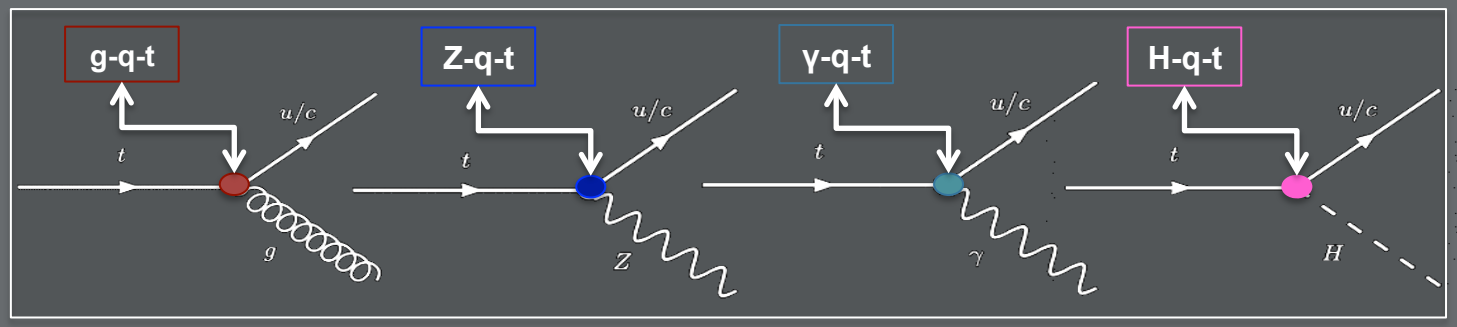
The key elements of the FCNC searches at 13 TeV

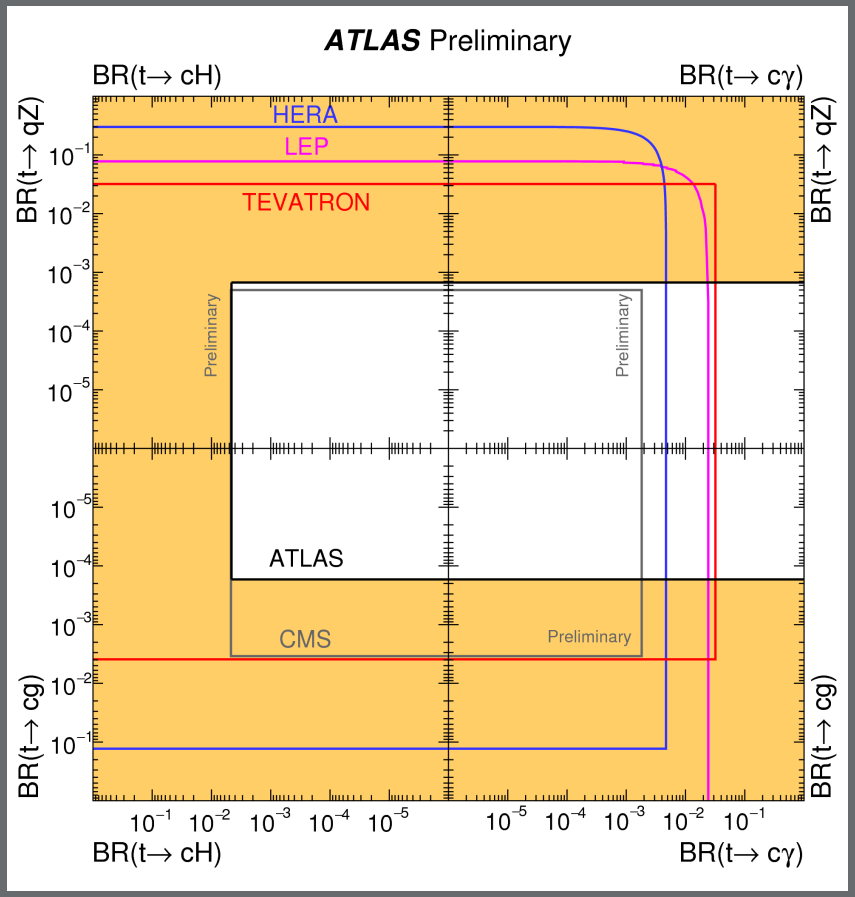
E.g. jet identification
- b jet ID
  see poster by Kevin Deroover
- c jet ID
  see poster by Seth Moortgat

In CMS, an FCNC working group has been formed, e.g. SM/FCNC tZ(q) in dilepton and multilepton final states

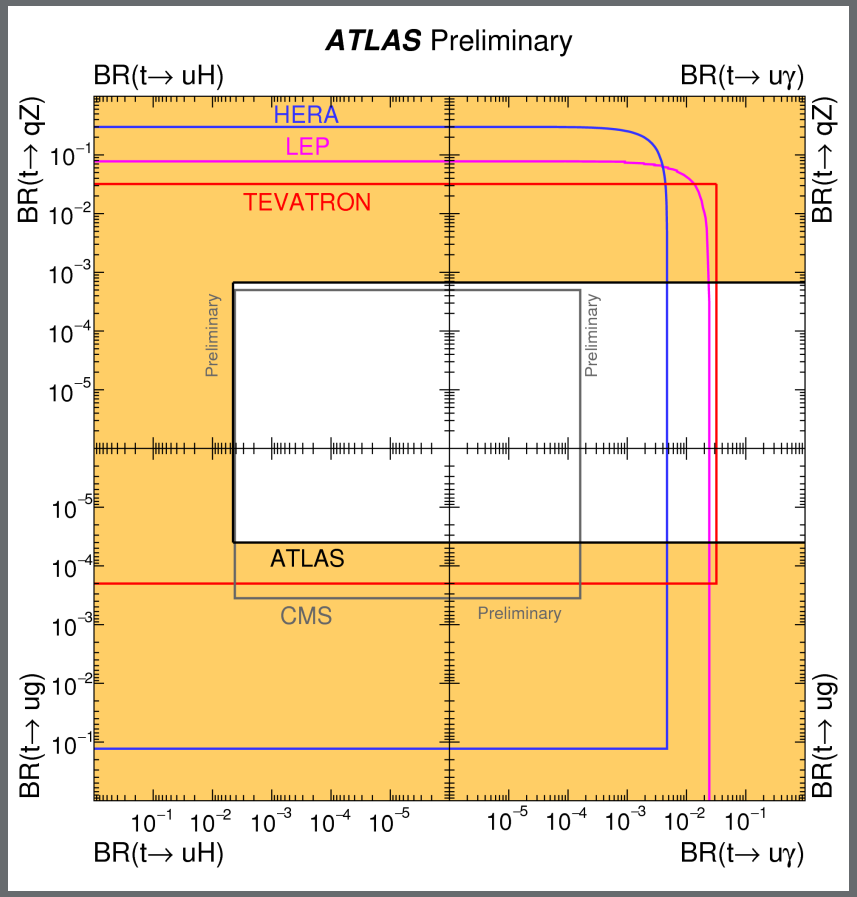
Effective field theory
- Only dim-6 gauge invariant operators
- Aguilar-Saavedra's way: minimal set of couplings
- Only top trilinear couplings considered

In summary:
FCNC at the LHC


g-q-t
Z-q-t
γ-q-t
H-q-t
u/c
t
g
Z
γ
H


ATLAS Preliminary
BR(t→ cH)
BR(t→ cγ)
BR(t→ qZ)
BR(t→ cg)
HERA
LEP
TEVATRON
ATLAS
CMS
Preliminary

q = c


ATLAS Preliminary
BR(t→ uH)
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Preliminary

q = u

FCNCs are closing in on excluding certain BSM models and are a clear way of searching for any new physics in various final states

Isis Van Parijs
Vrije Universiteit Brussel
IIHE – CMS – CERN
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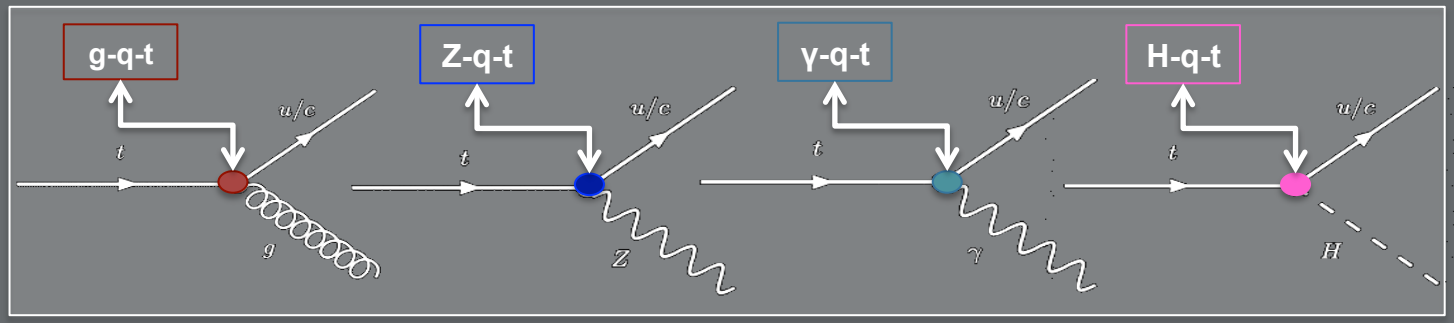
Back up slides

FCNCs are closing in on excluding certain BSM models and are a clear way of searching for any new physics in various final states

q = u / c	Current best limit	Prediction for 2HDM and MSSM	Reference
tgq	B(t→ug) < 0.004 % (ATLAS) B(t→cg) < 0.020 % (ATLAS)	~10^{-4} (2HDM), 8 10^{-5} (MSSM)	arXiv:1509.00294v1
tZq	B(t → Zq) < 0.05 % (CMS)	~10^{-7} (2HDM), 2 10^{-6} (MSSM)	arXiv:1312.4194
tγq	B(t → uγ) < 0.013 % (CMS) B(t → uγ) < 0.17 % (CMS)	~10^{-6} (2HDM), 2 10^{-6} (MSSM)	arXiv:1509.00294
tHq	B(t→uH) < 0.42 % (CMS) B(t→cH) < 0.46 % (ATLAS)	1.5 10^{-7} (2HDM), 10^{-5} (MSSM)	arXiv:CMS-PAS-TOP-14-019 arXiv:1509.06047


Run II analysis are on the way !


Summary of FCNC at the LHC



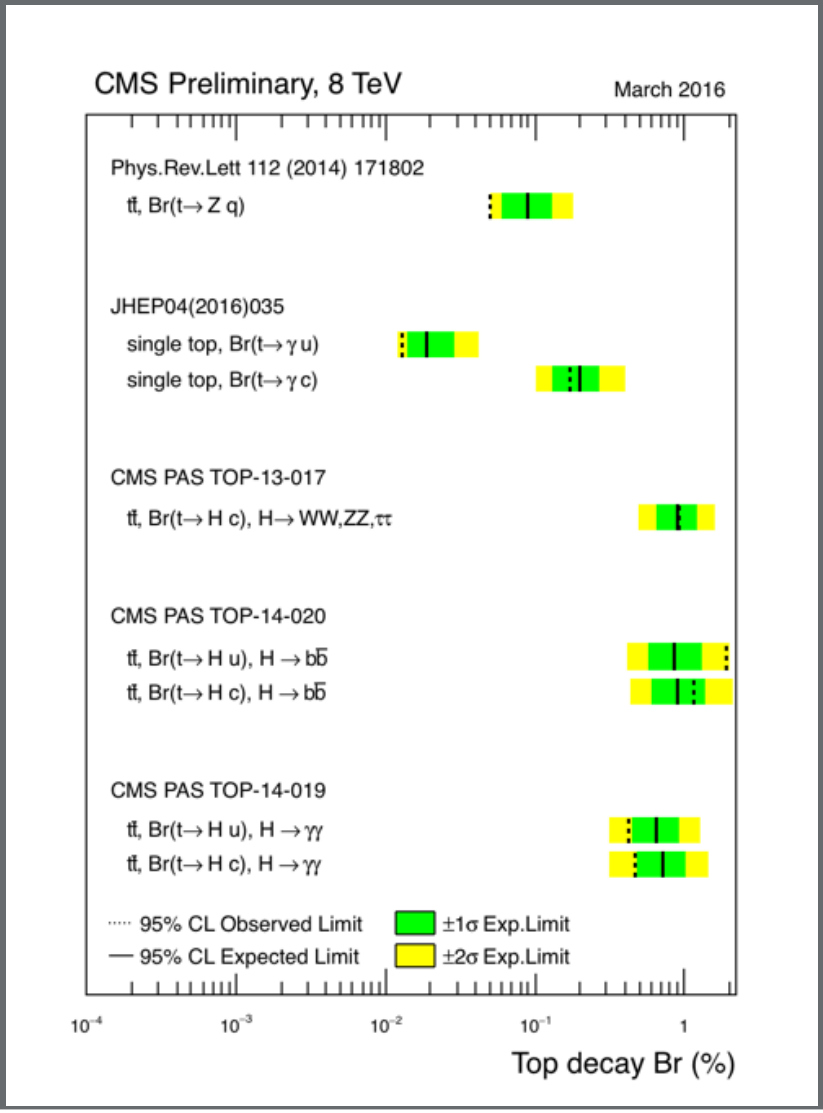
Experiment	BR(t→ug)	BR(t→cg)	Reference
ATLAS	0.004 %	0.017 %	arXiv: 1509.00294v1
CMS	0.036 %	0.34 %	CMS-PAS-TOP-14-007

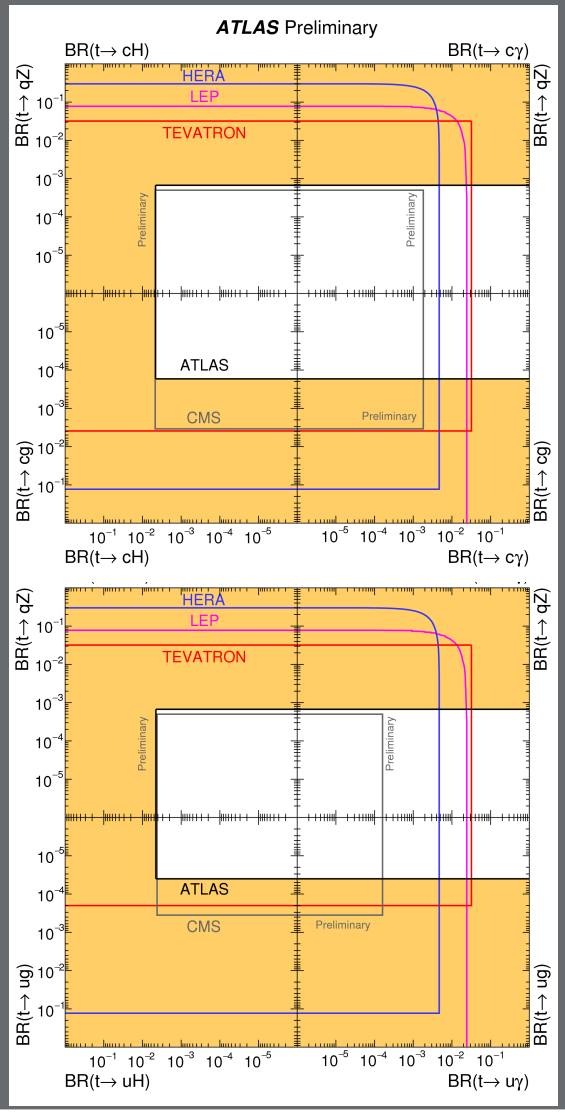
Experiment	BR(t→uZ)	BR(t→cZ)	Reference
ATLAS	0.07 %		arXiv: 1508.05796
CMS	0.05 %		Phys. Rev. Lett. 112 (2014) 171802

Experiment	BR(t→uγ)	BR(t→cγ)	Reference
CMS	0.013 %	0.17 %	CMS-PAS-TOP-14-003

Experiment	BR(t→uH)	BR(t→cH)	Reference
ATLAS	0.45 %	0.46 %	arXiv: 1509.06047
CMS	0.42 %	0.47 %	CMS-PAS-TOP-14-019

Summary of FCNC at the LHC





ATLAS LIMITS

FCNC t-g-q single top

FCNC t-Z-q top pair

FCNC t-γ-q single top

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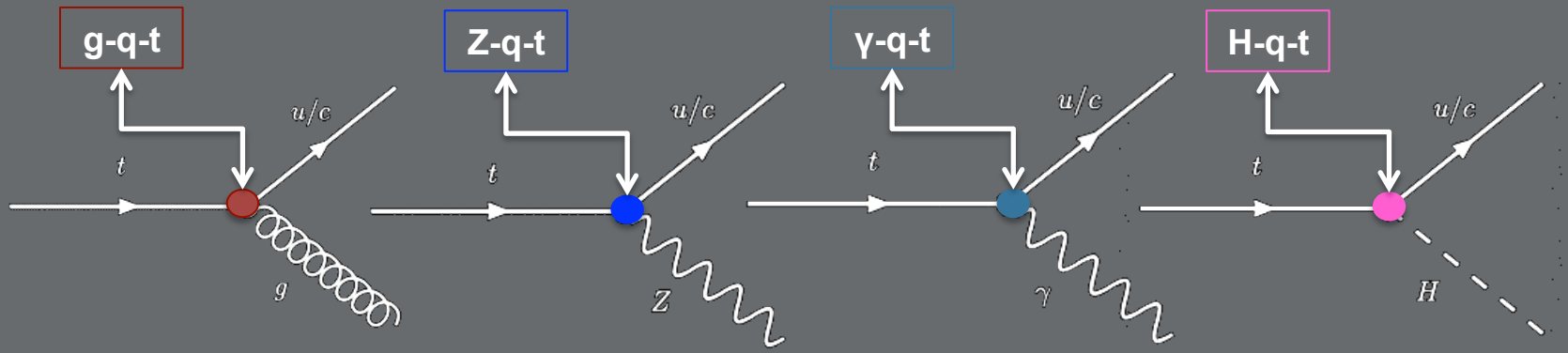

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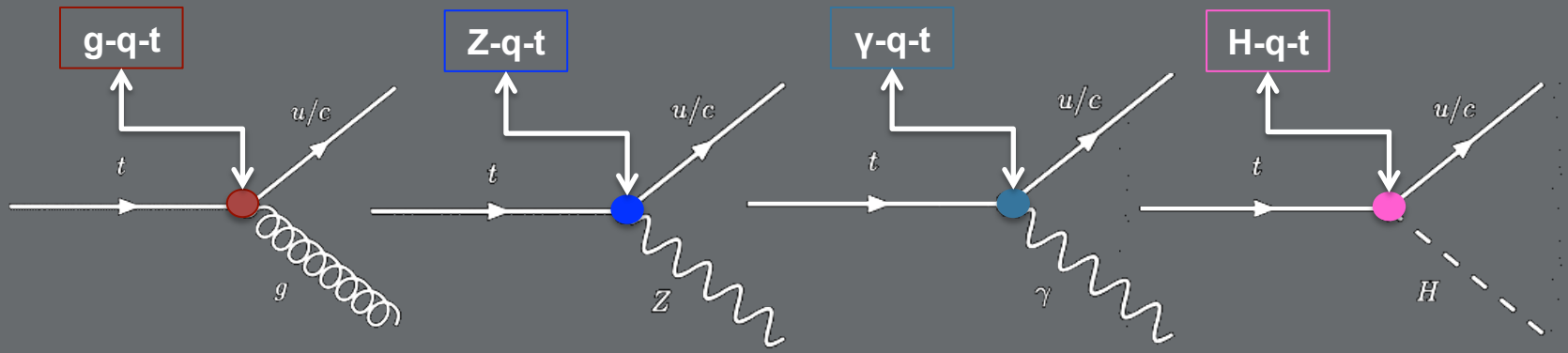

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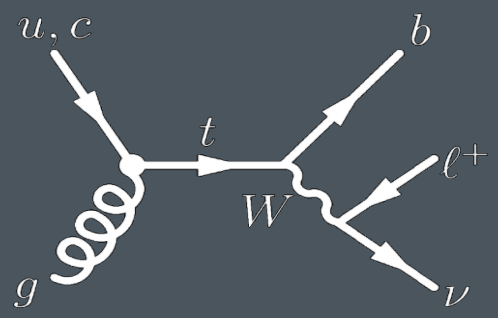
ATLAS



- ✘ t → qg not possible due to multi-jet QCD background
  ➔ look at qg → t → Wb → lν b
- ✘ Signature:
  1 lepton, MET, 1 b jet

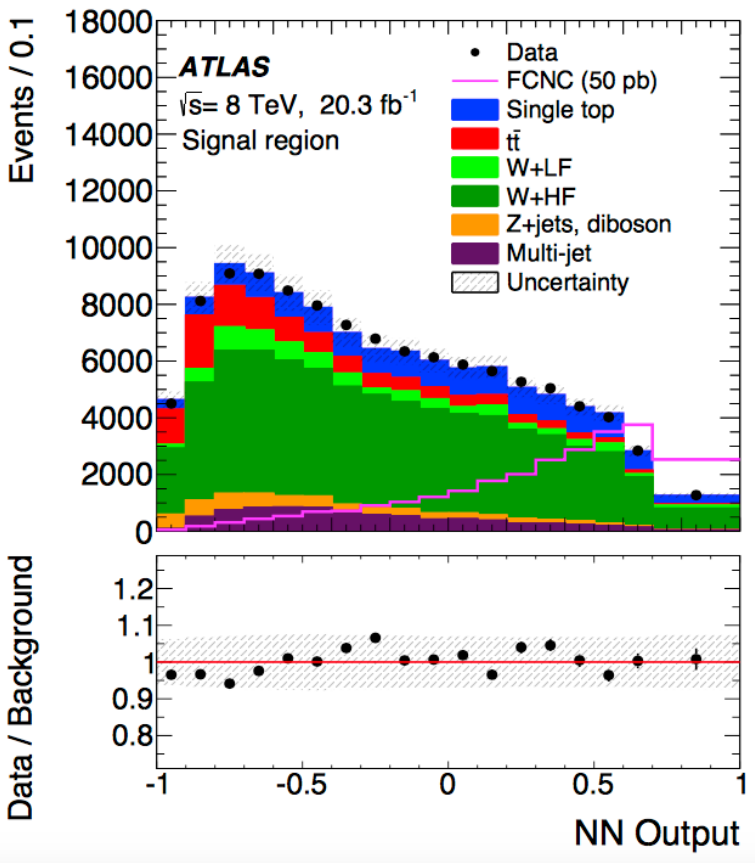
$B(t \to ug) < 4\ 10^{-5}$
$B(t \to cg) < 20\ 10^{-5}$

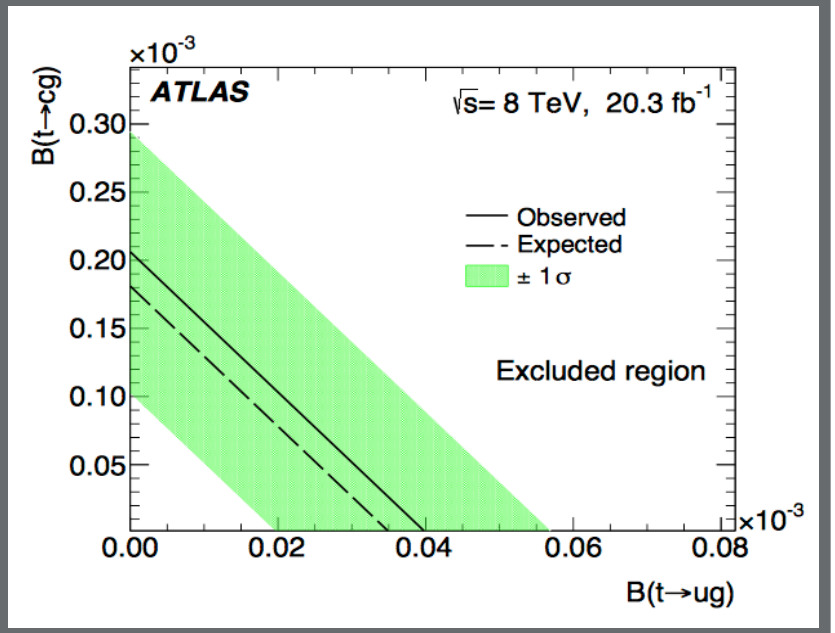
- ✘ Main backgrounds:
  V+jets, SM top quark production, diboson production, multi-jet QCD
- ✘ Multi-jet background estimated with a fit of the MET from data

arXiv:1509.00294

Neural Network classifier with 13 variables based on several differences

1. Pt top quark is softer in FCNC
   → W and b are back to back ≠ SM top
2. Pt W boson is high in FCNC
   → small angles for lν ≠ diboson, W/Z + jets
3. Top quark charge asymmetry differs in ugt channel
   → FCNC production of top = 4 x anti top
   SM top = 2 x anti top

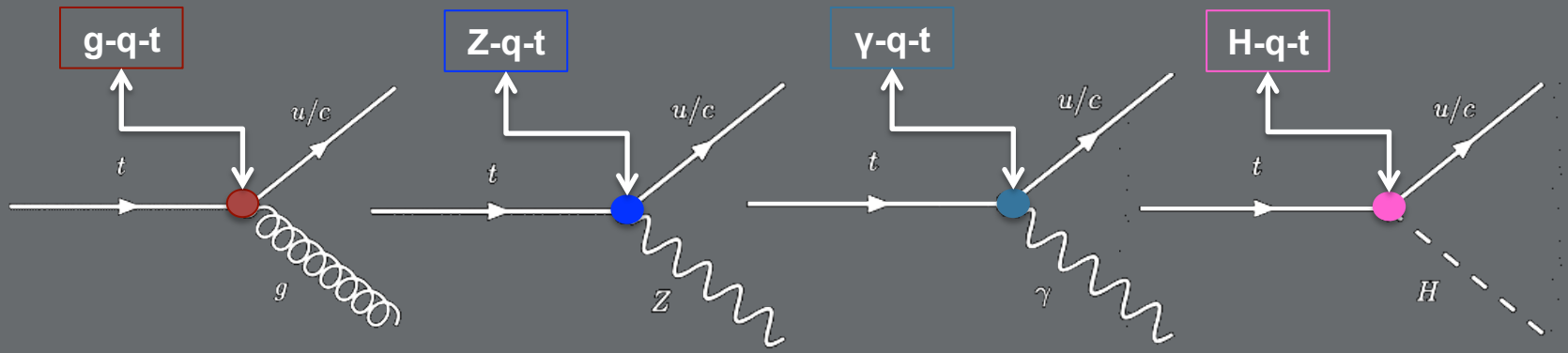




$B(t \to ug) < 4\ 10^{-5}$
$B(t \to cg) < 20\ 10^{-5}$

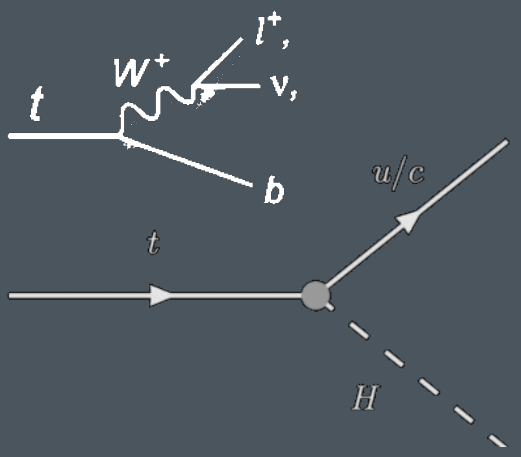
ATLAS LIMITS

FCNC t-g-q single top → FCNC t-Z-q top pair → FCNC t-γ-q single top → FCNC t-H-q top pair



FCNCs: a top, a H boson and a charm quark

8 TeV pp collision data
Luminosity of 20.3 fb^{-1}
ATLAS



B(t→ cH) < 0.46 %

Combination paper
tt → bW + c(u)H
with
H → γγ / WW* / bb / ττ

- ✘ bbar search
  ≥ 1 lepton, MET, ≥ 4 jets where ≥ 2 b jets
- ✘ Recast of SM ttH multilepton search
  2-3 leptons, ≥ 3 jets where ≥ 1 b jet
- ✘ Diphoton search
  2 photons, 1 lep, ≥ 3 jets where ≥ 1 b jet
  or
  2 photons, ≥ 4 jets where ≥ 1 b jet

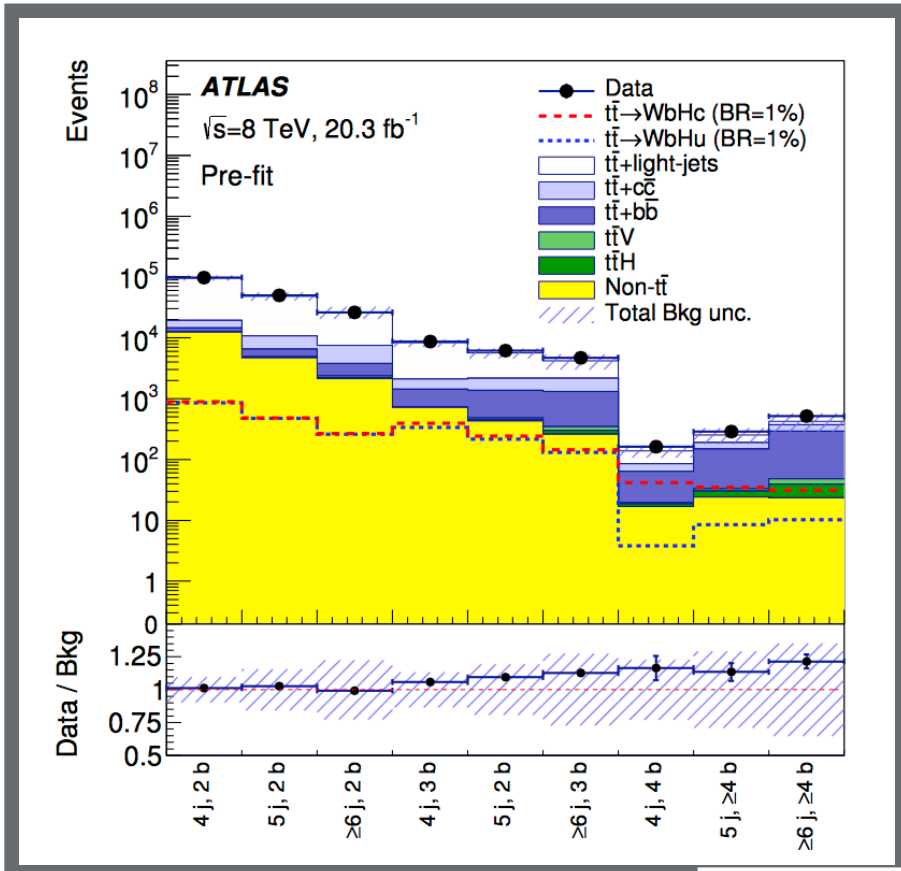
- ✘ Main backgrounds for bb search:
  tt + jets, single top, W+jets, multi-jet, Z +jets, diboson, ttV, ttH
  → tt+jets estimated with data

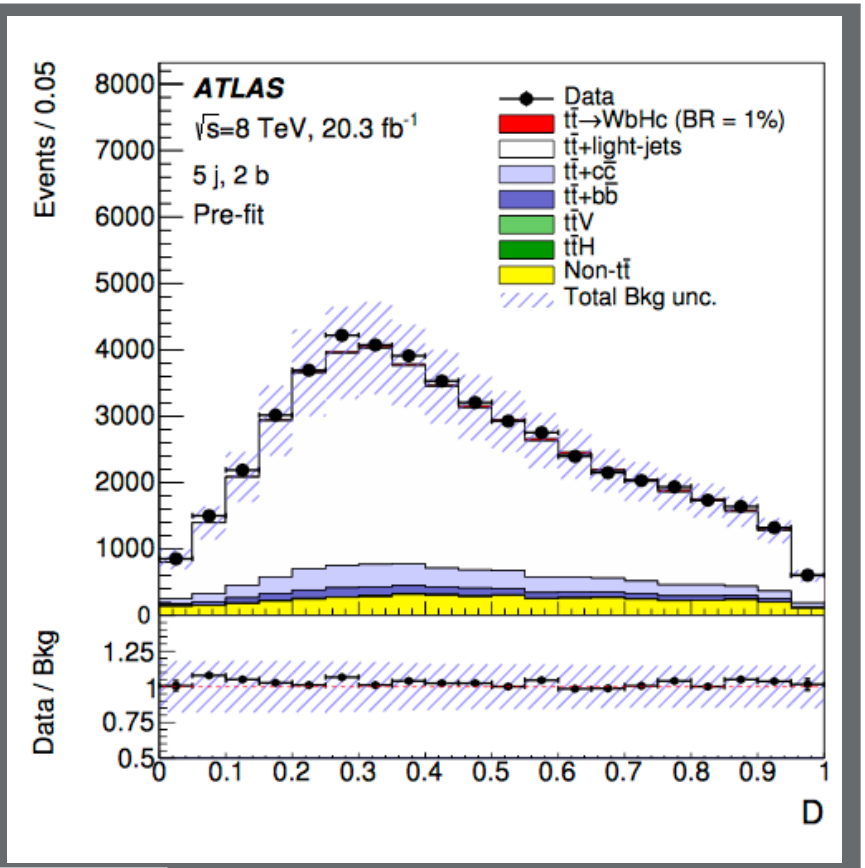
- ✘ Main backgrounds for H → WW* / ττ:
  top pair, single top, ttW, ttZ, ttH, diboson
  → non-prompt lepton contributions estimated from data

arXiv:1509.06047

tt → bW + c(u)H → b lν + c(u) bb
→ Large b multiplicity helps against top pair background

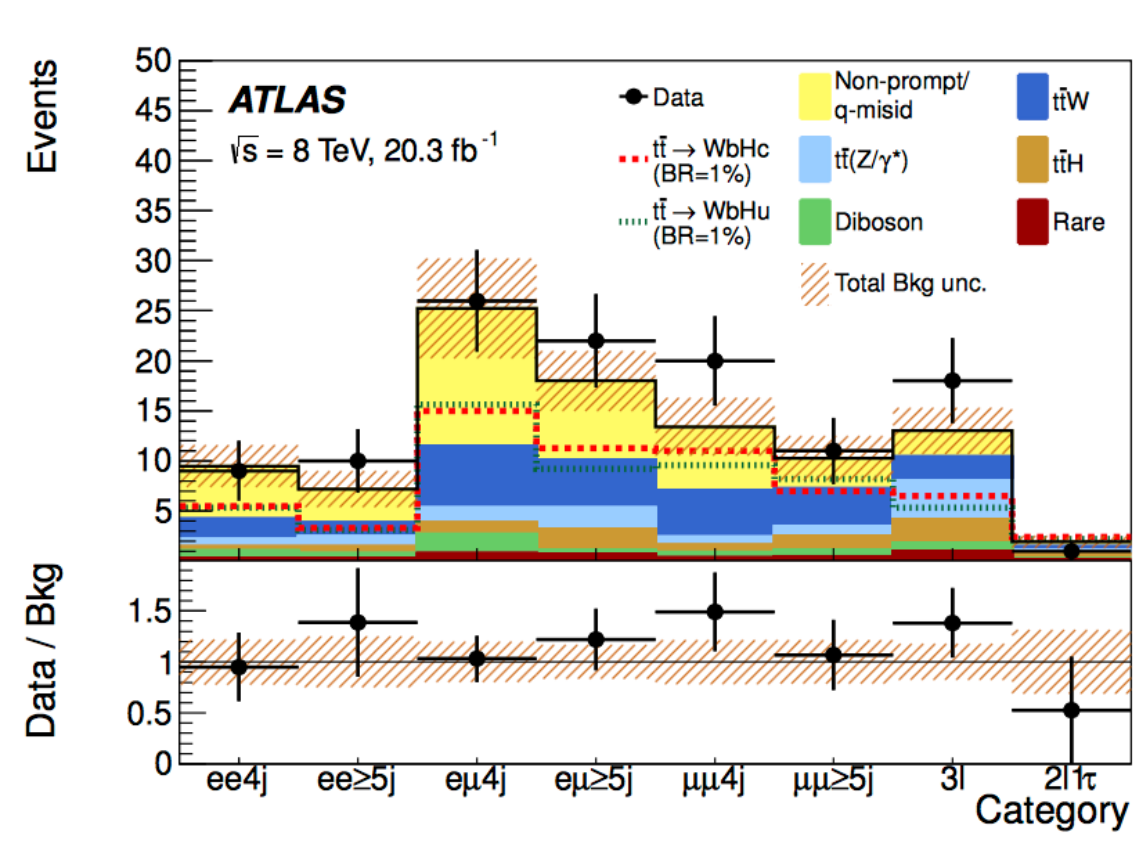
Categorization based on nb of b-jets (2,3, >3)
→ CLs likelihood





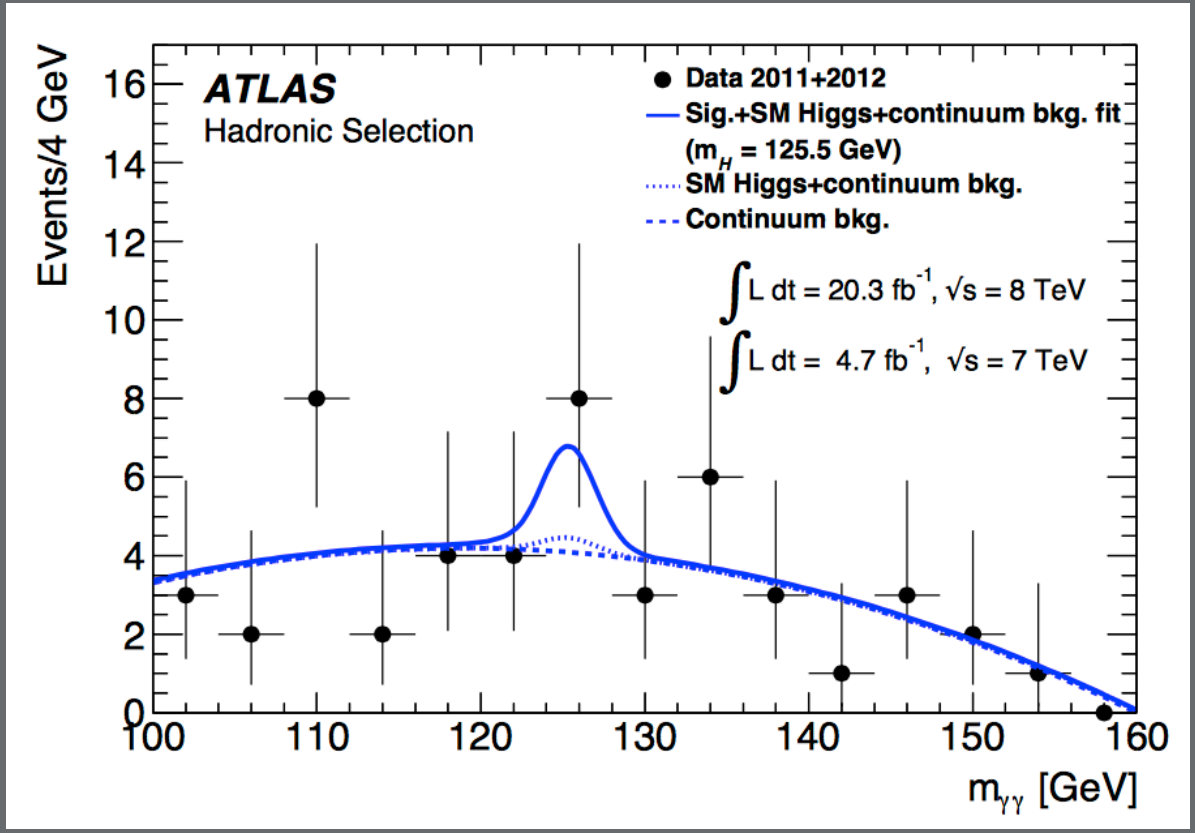
B(t→ cH) < 0.56 %

tt → bW + c(u)H →bW + c(u) WW* (ττ) multilepton final state
3 event categories based on reconstructed electrons, muons, taus
→ CLs likelihood

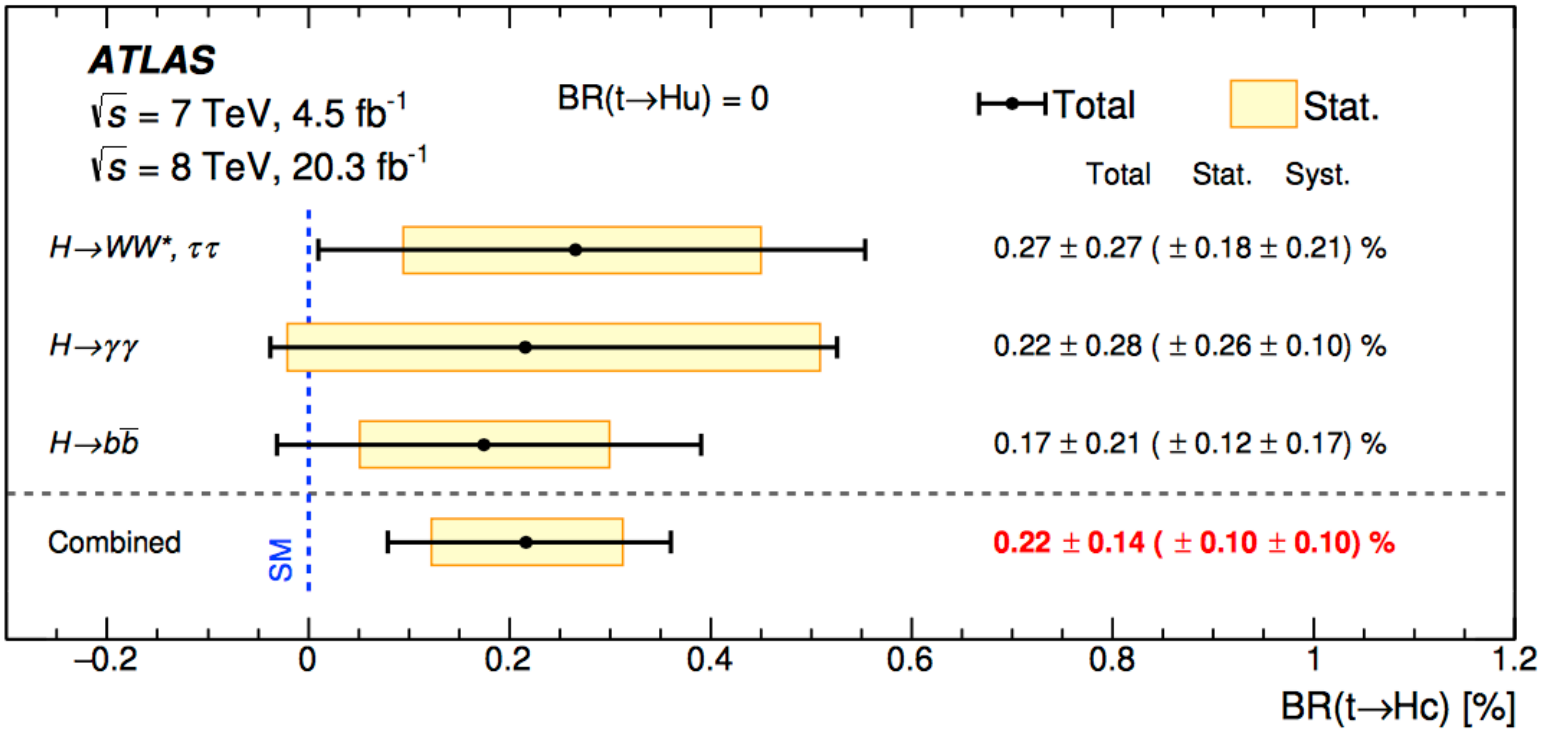


B(t→ cH) < 0.79 %

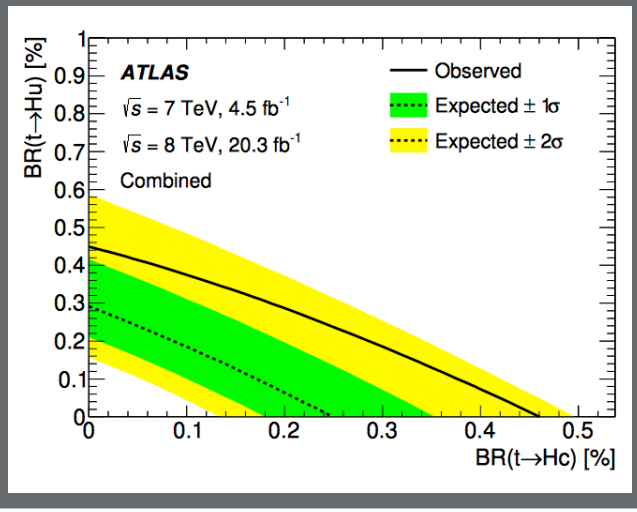
tt → bW + c(u)H →bW + c(u) γγ
Fit of the diphoton mass spectrum



B(t→ qH) < 0.79 %


ATLAS
√s = 7 TeV, 4.5 fb-1
√s = 8 TeV, 20.3 fb-1
BR(t→Hu) = 0
Total
Stat.
Total Stat. Syst.
H→WW*, ττ
0.27 ± 0.27 (± 0.18 ± 0.21) %
H→γγ
0.22 ± 0.28 (± 0.26 ± 0.10) %
H→bb̄
0.17 ± 0.21 (± 0.12 ± 0.17) %
Combined
0.22 ± 0.14 (± 0.10 ± 0.10) %
SM
–0.2
0
0.2
0.4
0.6
0.8
1
1.2
BR(t→Hc) [%]

B(t→ cH) < 0.46 %


ATLAS
√s = 7 TeV, 4.5 fb-1
√s = 8 TeV, 20.3 fb-1
Combined
Observed
Expected ± 1σ
Expected ± 2σ
BR(t→Hu) [%]
BR(t→Hc) [%]
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

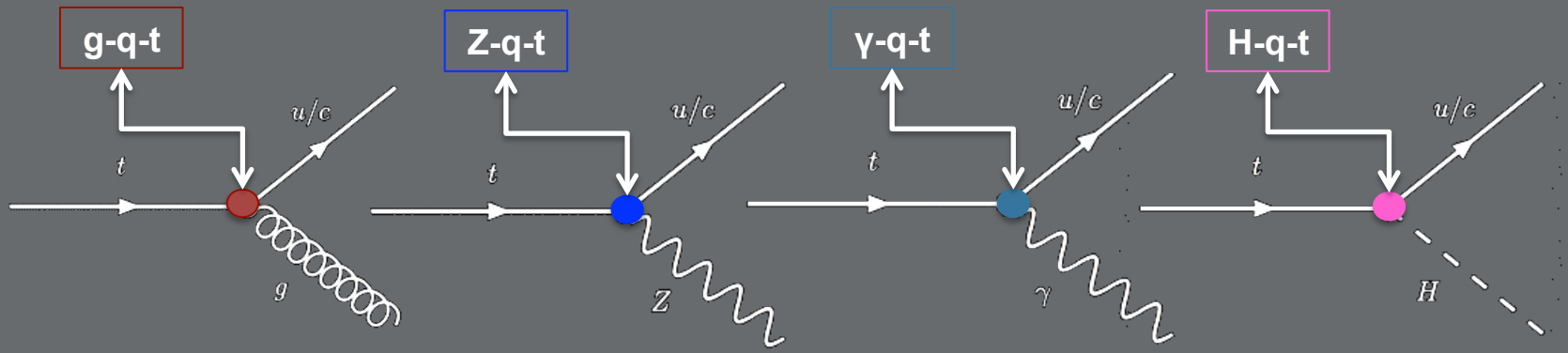
CMS LIMITS

FCNC t-g-q single top

FCNC t-Z-q top pair

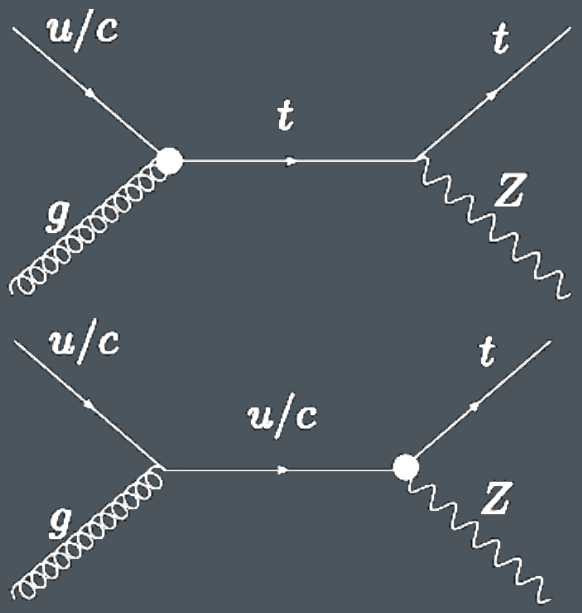
FCNC t-γ-q single top

FCNC t-H-q top pair



FCNCs: a top, a Z boson and a quark

7 TeV pp collision data
Luminosity of 5 fb^{-1}
single top

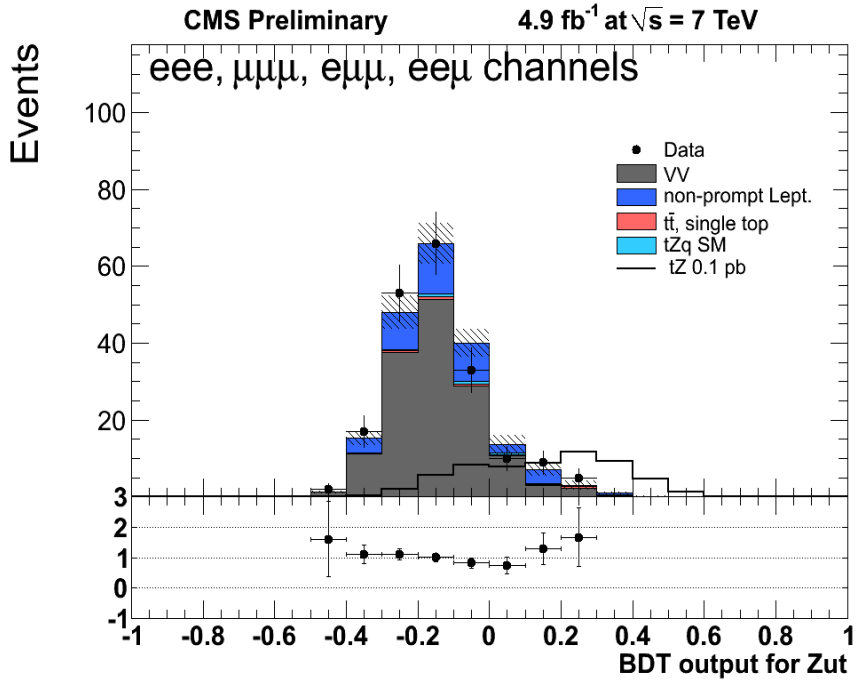


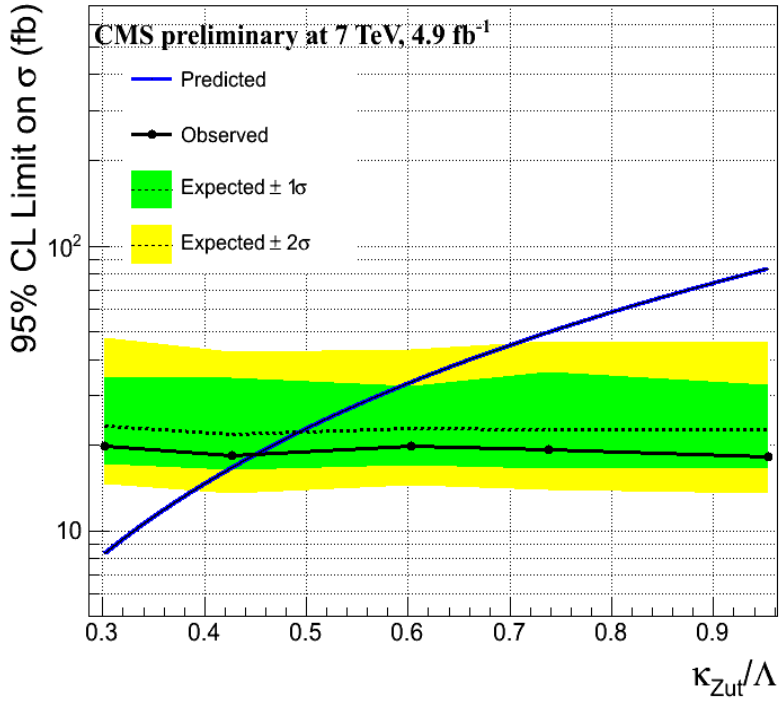
- ✘ qg → t → tZ → llq + vl b
- ✘ Signature:
  3 leptons, MET, ≥ 1 b jet

B(t→Zu) < 0.51 %
B(t→ Zc) < 11 %

- ✘ Main backgrounds:
  WZ/ZZ + jets, fake leptons
- ✘ VV and fake lepton measured from m_T(W) template fit in data

BDT to discriminate signal and background
→ Kinematic variables and b-tag information used
Profile likelihood method with Theta





B(t→Zu) < 0.51 %
B(t→ Zc) < 11 %

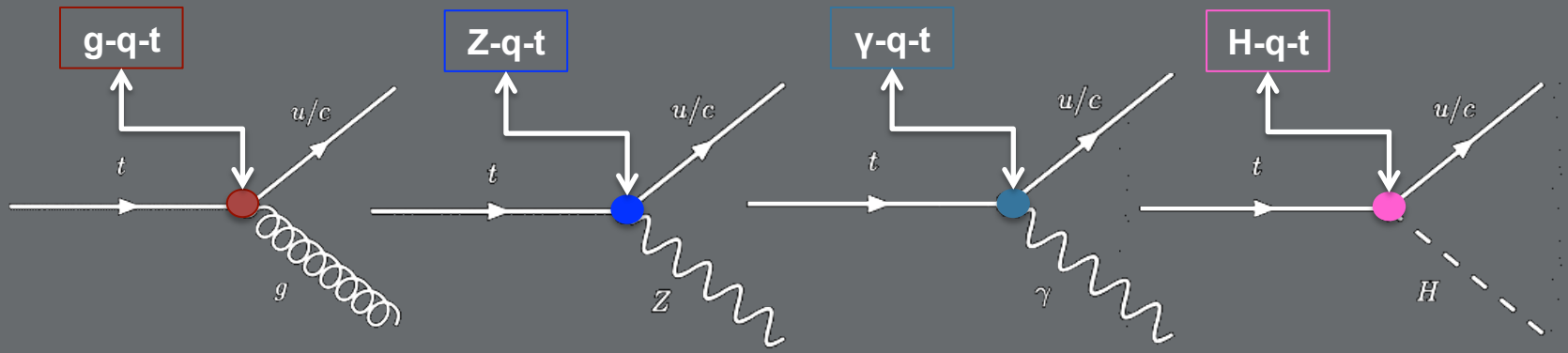
CMS LIMITS

FCNC t-g-q single top

FCNC t-Z-q top pair

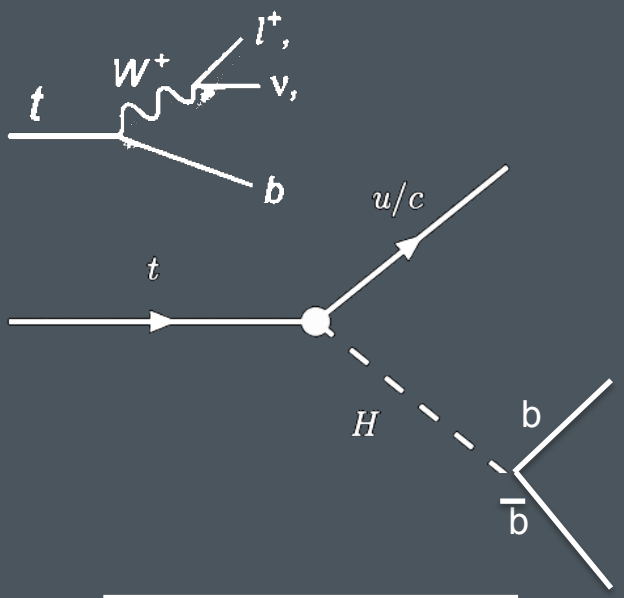
FCNC t-γ-q single top

FCNC t-H-q top pair



FCNCs: a top, a H boson and a quark

8 TeV pp collision data
Luminosity of 19.8 fb^{-1}
Top pair



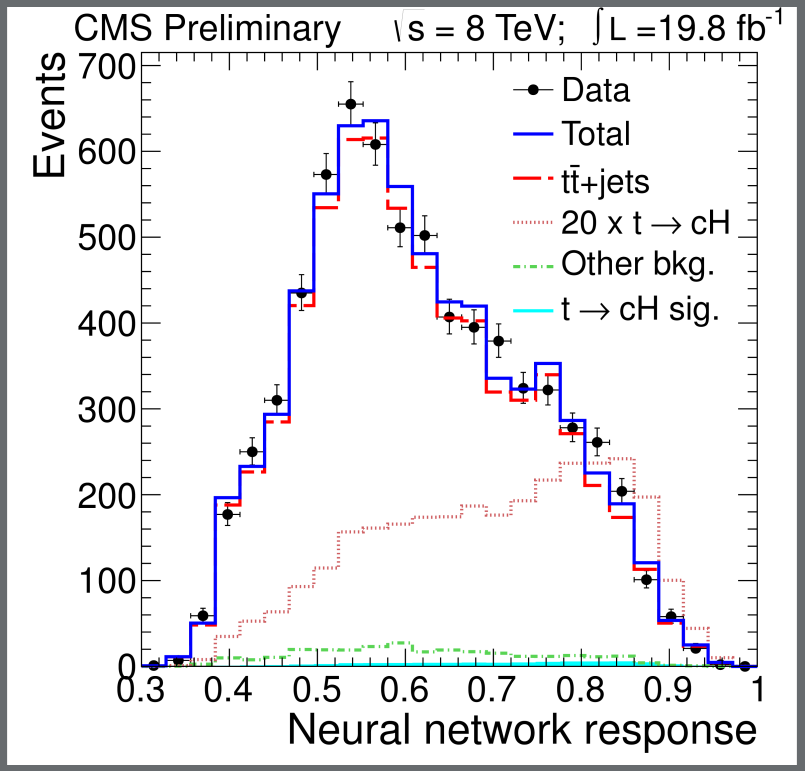
- ✘ tt → bW + qH with H → bbar
- ✘ Signature:
  1 lepton, MET, ≥ 4 jets with 3 b jets

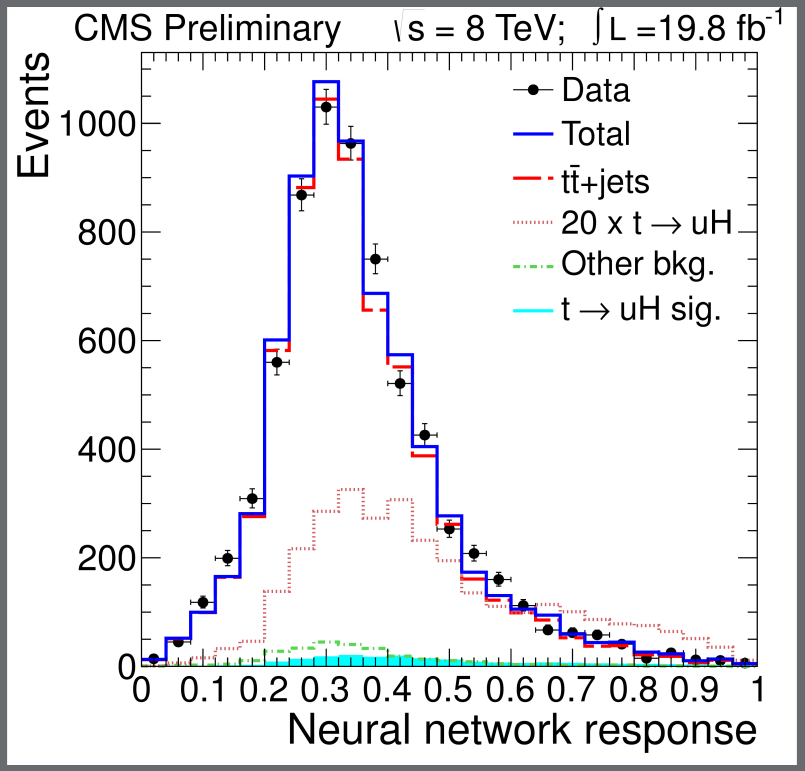
B(t → uH) < 1.92%
B(t → cH) < 1.16%

- ✘ Main backgrounds:
  ttbar, single top, W+bbar, ttH
- ✘ BDT to reconstruct top candidates, same for tuH and tcH

Template fit on an artificial neural network with 2 input variables:

1. **Invariant mass Higgs candidate**
2. **Distribution CSV discriminant**

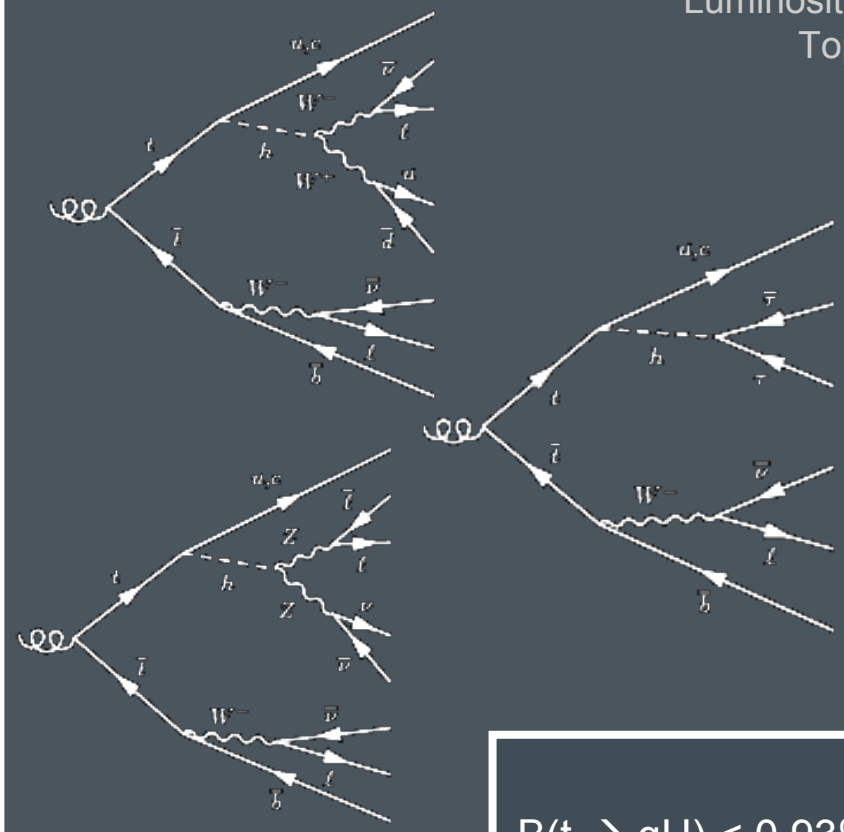




B(t → uH) < 1.92%
B(t → cH) < 1.16%

FCNCs: a top, a H boson and a quark

8 TeV pp collision data
Luminosity of 19.7 fb^{-1}
Top pair

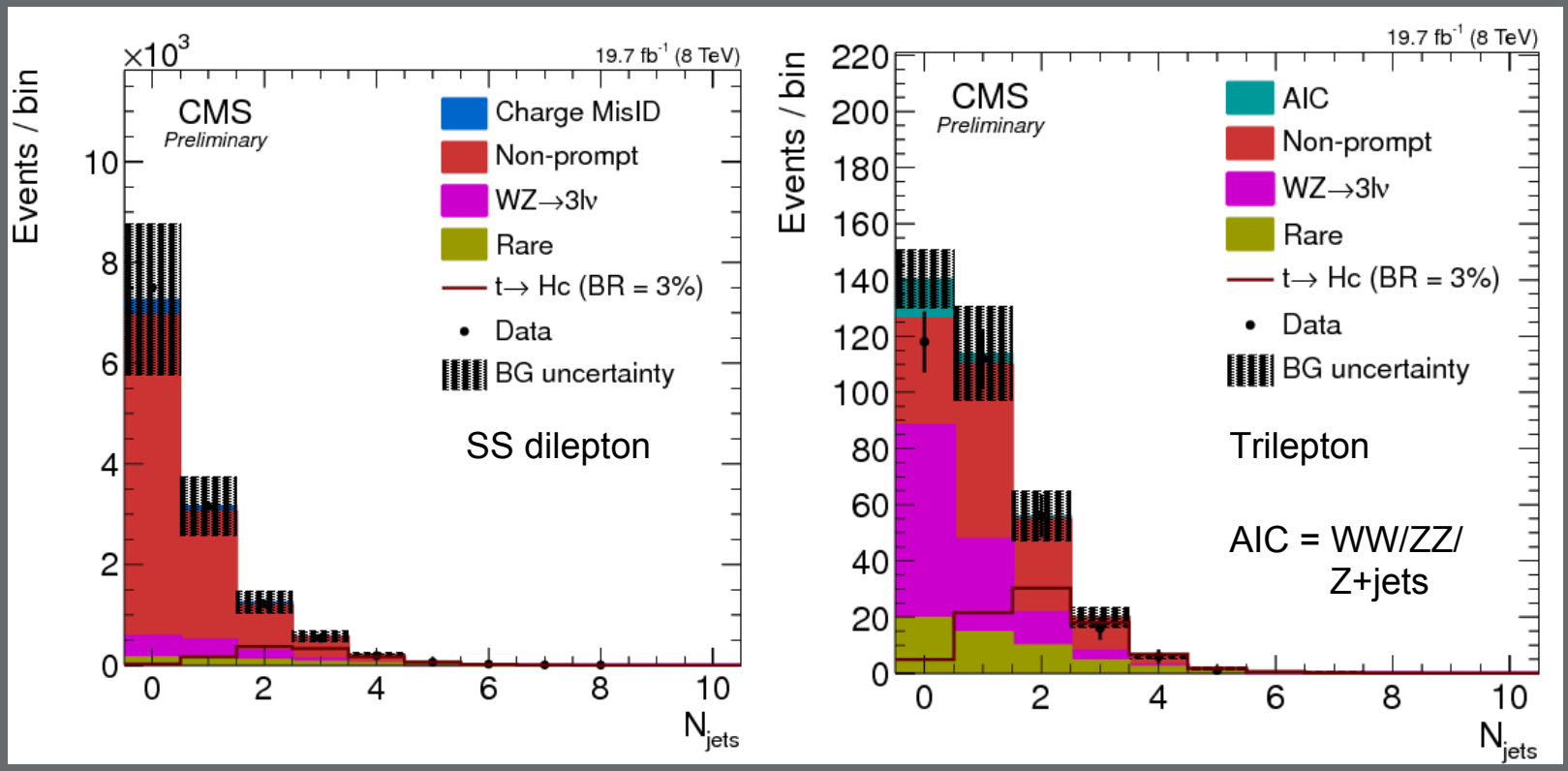


B(t → qH) < 0.93%

- ✘ tt → bW + qH
  with H → WW/ZZ/ττ
- ✘ Signature:
  same sign dilepton or trilepton
  and ≥ 2 jets with 1 b jet, MET

- ✘ Main backgrounds:
  WZ,ZZ, triboson, WW, ttX, DY,
  ttbar, W/Z+jets
- ✘ Fake lepton and charge mis ID
  estimated from data

Cut based analysis in SS dilepton and trilepton final state, CLs method



B(t → qH) < 0.93%

CMS INFO

Charm tagging at CMS