Prospects for a Search for gluon mediated FCNC in top quark production at the FCC-hh

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FCC-hh physics analysis meeting
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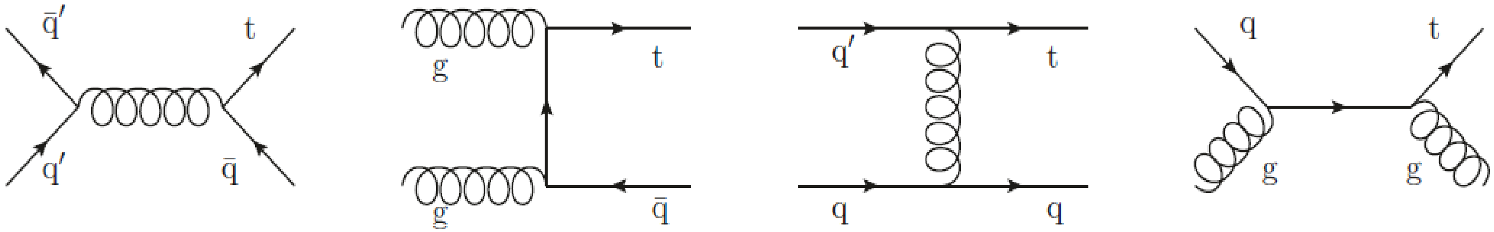
Gluon mediated FCNC top quark production

Effective Lagrangian:

$$g_s \frac{\kappa_{tug}}{\Lambda}\ \bar{u}\ \sigma^{\mu\nu} \frac{\lambda^a}{2} t\ G^a_{\mu\nu} + g_s \frac{\kappa_{tcg}}{\Lambda}\ \bar{c}\ \sigma^{\mu\nu} \frac{\lambda^a}{2} t\ G^a_{\mu\nu} +\ h.c.$$

Representative diagrams of pp->tq->Wbj channel:



There are no direct correspondence of the couplings to EFT opearators for FCNC [Phys. Rev. D 91, 074017 (2015)]

$$g_s \frac{\kappa^g_{tq}}{\Lambda} \quad \bar{t}\sigma^{\mu\nu} T^A (f^g_{tq} + i h^g_{tq} \gamma_5) q \quad G^A_{\mu\nu} \qquad g_s \frac{\kappa^g_{tq}}{\Lambda} \begin{cases} f^g_{tq} \\ i h^g_{tq} \end{cases} = g_s \frac{m_t}{\Lambda} \left[C^{(3a)}_{uG} \pm C^{(a3)*}_{uG} \right]$$

$$|f_{tq}|^2 + |h_{tq}|^2 = 1$$

Simulation

Signal samples:

CompHEP 4.5.2

FCNC tgu

FCNC tgc

Fast simulation with Parametric DELPHI 3.4.2 using the reference FCC-hh detector parameters

Background samples:

MG5_MC@NLO 2.5.2 + PYTHIA 8.230

Single Top	7.5×10^3 pb
$t\bar{t}$	4.3×10^4 pb
W+jets	1.6×10^6 pb
Z+jets	5.1×10^5 pb

Energy, TeV	FCNC "tug" CompHEP LO CS [pb]	FCNC "tcg" CompHEP LO CS [pb]
7	33.2	4.9
8	41.7	6.7
13	91.6	18.5
14	102.8	21.4
27	268.6	71.1
100	1720	575

κ/Λ=0.03 TeV^{-1}

NLO CS = K* LO CS
K (tgu) = 1.52
K (tgc) = 1.4
(Phys.Rev. D72 (2005) 074018)

Event Selection

Muon and Electron channel:

Exactly one lepton with

- p_T > 26 GeV/c ,
- $|\eta|$ < 2.8,
- *RelIso* < 0.15

Lepton veto:

No more any additional muons or electrons with

- "**loose**" ID passes**,**
- p_T > 10 GeV/c ,
- $|\eta|$ < 2.8,
- *RelIso* < 0.25

Jet Selection:

Two or three jets with

- anti-kt reconstruction algorithm R=0.4**,**
- p_T > 30 GeV/c ,
- $|\eta|$ < 4.7,
- ΔR_{lep} > 0.4

B-Tagging:

- **Exactly one of the jets is b-tagged**

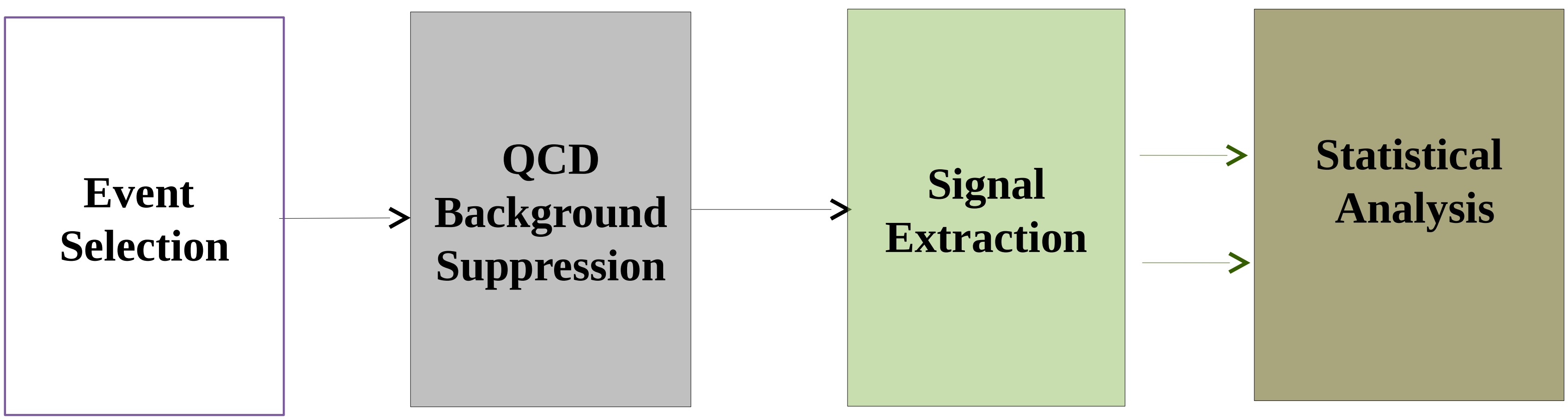
Expected event yields at 30 ab^{-1} and $k/\Lambda = 3x10^{-5}$ TeV^{-1}

Process	Basic selections	$m_T(W) > 40$ GeV
FCNC tgc	3,036,000,000	2,320,000,000
FCNC tgu	7,710,000,000	5,560,000,000
Single Top	10,223,000,000	7,934,000,000
$t\bar{t}$	39,517,000,000	30,617,000,000
$W + jets$	28,709,000,000	23,588,000,000
$Z/\gamma^* + jets$	2,591,000,000	1,031,000,000

Analysis Pipeline

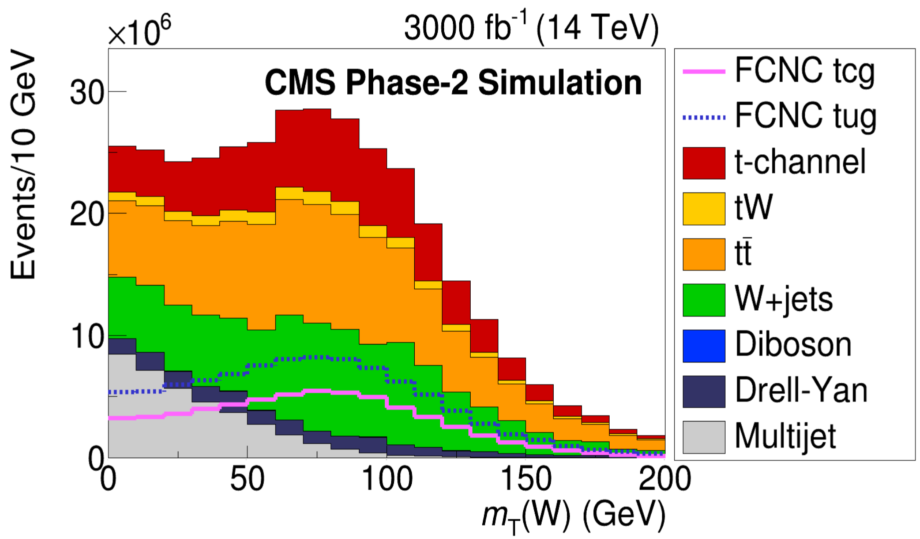
General analysis scheme in 4 steps:

1) Basic event selection. The QCD background use modified event selection.
2) QCD background rejection using a specialized Bayesian Neural Network (BNN).
3) Training BNNs or Deep Learning Neural Networks (DNN) to extract the signal.
4) Statistical analysis via Theta package: fitting the BNN/DNN discriminant distributions with prior systematic uncertainty to estimate upper limits to FCNC couplings.



Description of the previous analysis could be found in CMS-PAS-FTR-18-004 (HL-LHC), CMS 7&8 TeV analysis JHEP 1702 (2017) 028

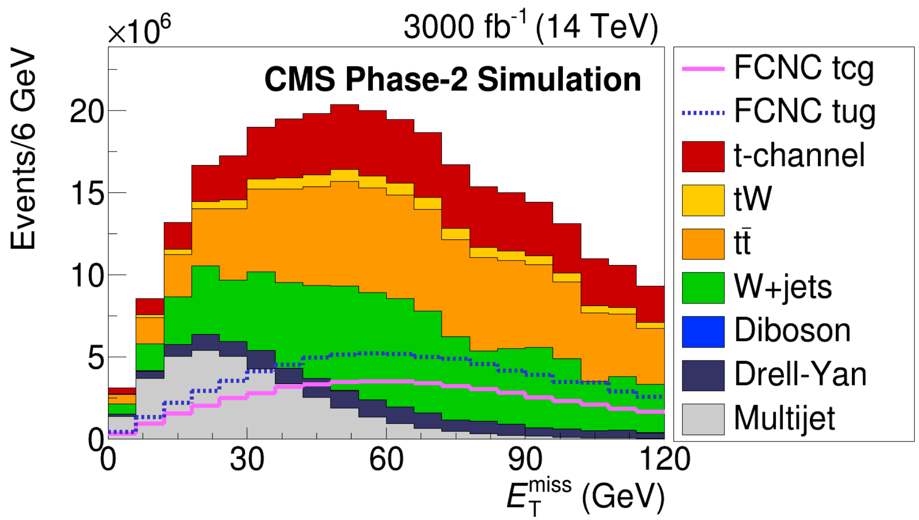
Multijet Background Suppression at HL-LHC

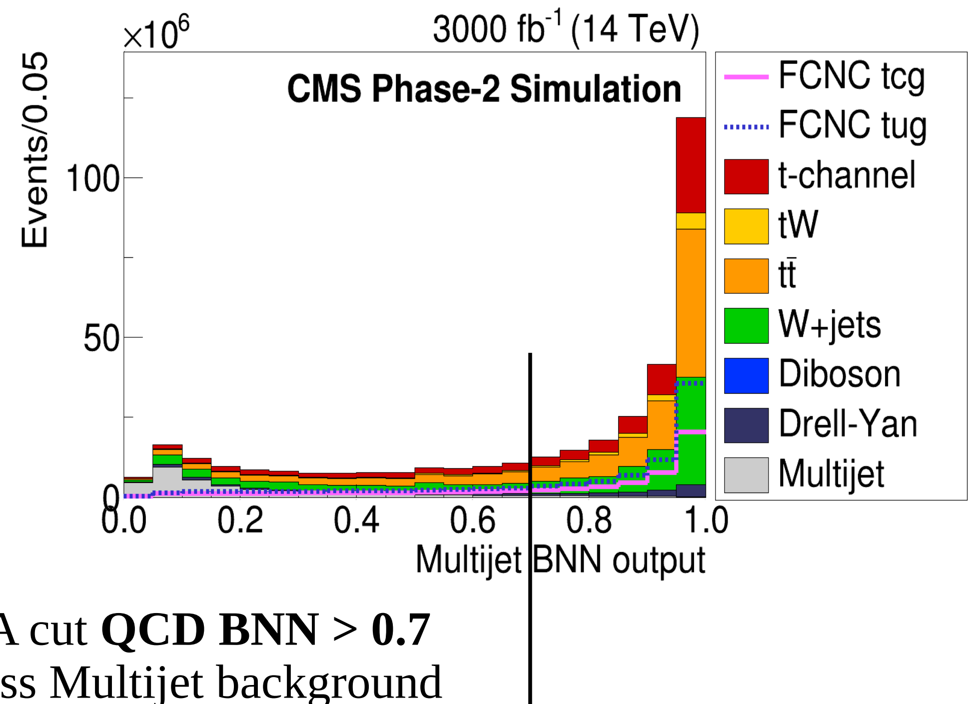


CMS-PAS-FTR-18-004

QCD BNN input variables:

- $M_t(W)$
- $P_t(Lep)$
- Dphi(Lep,Nu)
- MET





A cut **QCD BNN > 0.7**
is applied to suppress Multijet background

Expected event yields at HL-LHC

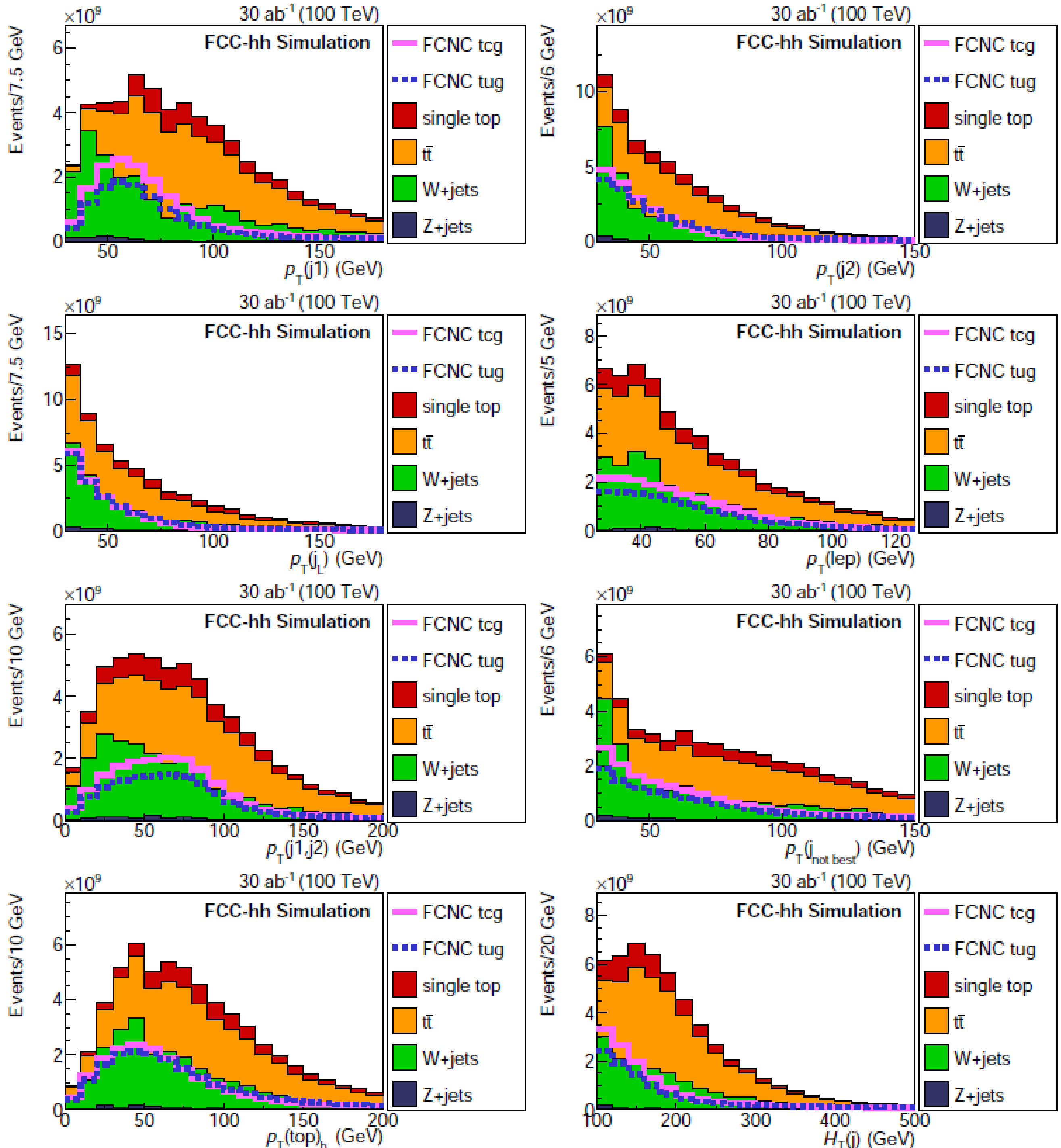
Process	Basic selections	Multijet BNN > 0.7
FCNC tcg	646,000	434,000
FCNC tug	2,190,000	1,510,000
t channel	7,420,000	5,270,000
tW channel	1,190,000	846,000
$t\bar{t}$	11,000,000	7,970,000
W+jets	9,690,000	6,380,000
Dibosons	97,500	58,000
Drell–Yan	1,600,000	870,000
Multijets	3,680,000	226,000

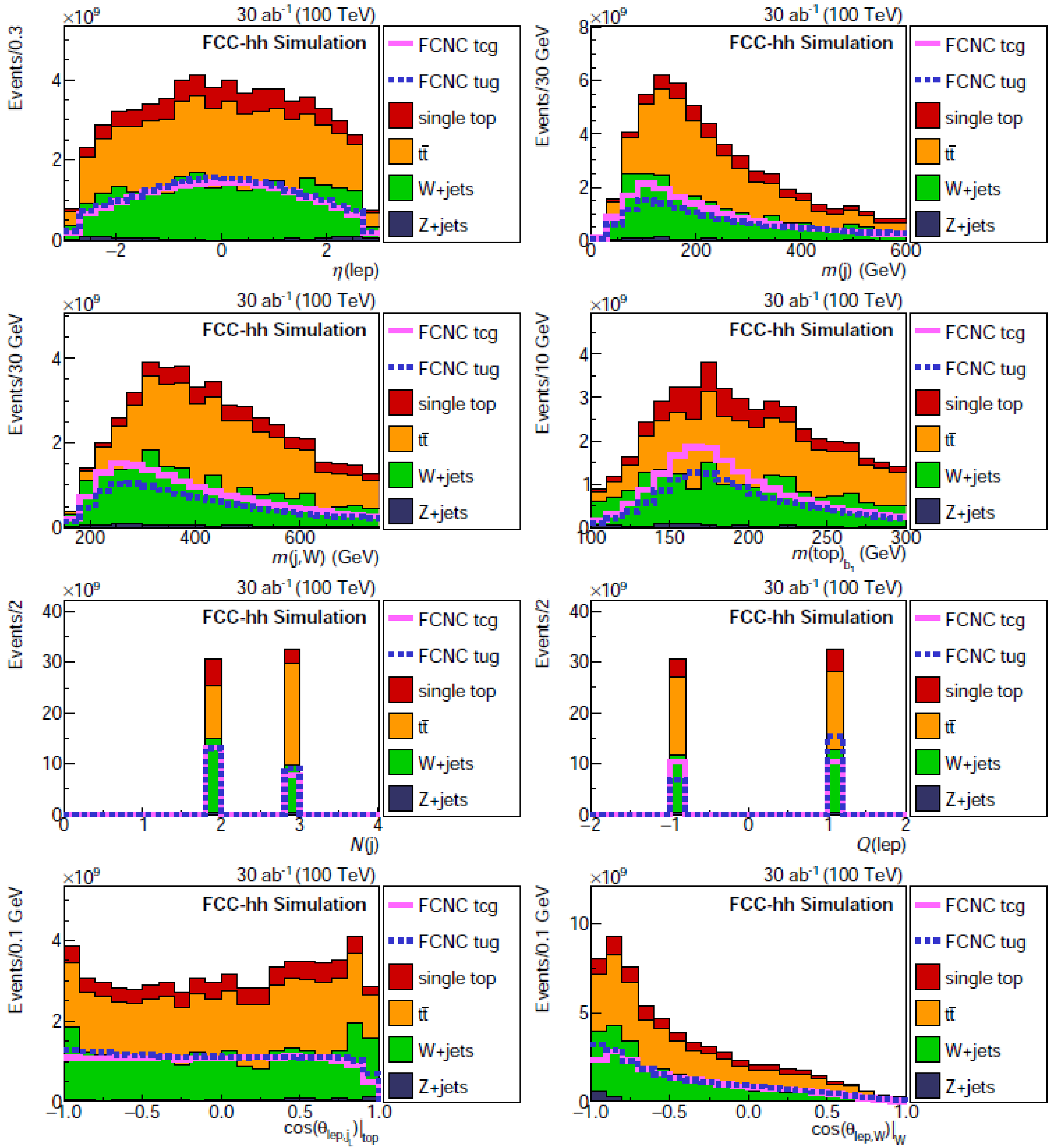
[CMS-PAS-FTR-18-004]

$|\kappa_{tug}|/\Lambda = 0.03$ and $|\kappa_{tcg}|/\Lambda = 0.03\ \text{TeV}^{-1}$

Input Vars. For Bayesian Neural Networks

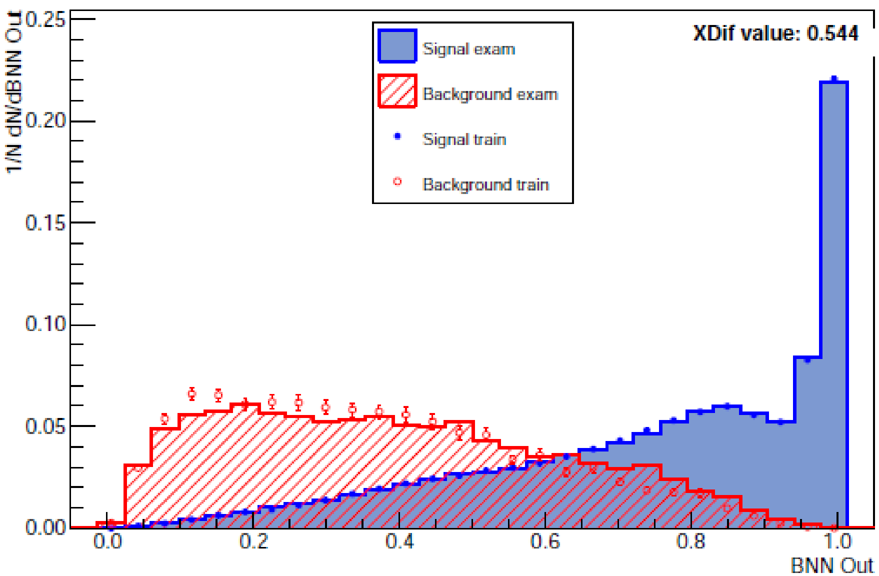
Variable	Description	tug FCNC BNN	tcg FCNC BNN
$P_T\ (j_1)$	P_T of the leading jet	X	X
$P_T\ (j_2)$	P_T of the leading jet	X	X
$P_T\ (j_1, j_2)$	vector sum of the P_T of the leading and the next-to-leading jet	X	X
$P_T\ (j_L)$	P_T of the light-flavour jet (untagged jet with the highest value of $\|\eta\|$)	X	X
$P_T\ (j_{not\ best})$	P_T of the all jets without one, best to reconstruct the top quark	X	X
P_T (lep)	P_T of the lepton	X	X
$P_T\ (\text{top})_{b_1}$	P_T of the top quark reconstructed with leading c jet (the b-tagged jet with the highest P_T)	X	X
$H_T(j)$	scalar sum of the P_T of the all jets	X	X
$\eta(lep)$	η of the lepton	X	X
$\eta(j_L)$	η of the light-flavour jet	X	X
$m(j)$	the invariant mass of the all jets	X	X
$m(j,W)$	the invariant mass of the W boson and all jets	X	X
$m(top)_{b_1}$	the invariant mass of the top quark reconstructed with leading c jet	X	X
$N(j)$	the number of the selected jets	X	X
$\cos(\theta_{lep,j_L})\|_{top}$	the cosine of the angle between the lepton and the light-flavour jet in the top quark rest frame, for top quark reconstructed with the leading c jet [36]	X	X
$\cos(\theta_{lep,W})\|_{W}$	the cosine of the angle between the lepton momentum in the W boson rest frame and the direction of the W boson boost vector [37]	X	X
$Q(lep)$	charge of the lepton	X	


30 ab⁻¹ (100 TeV)
FCC-hh Simulation
FCNC tcg
FCNC tug
single top
tt̄
W+jets
Z+jets
Events/7.5 GeV
Events/6 GeV
Events/5 GeV
Events/10 GeV
Events/20 GeV
×10⁹
p_T(j1) (GeV)
p_T(j2) (GeV)
p_T(j_L) (GeV)
p_T(lep) (GeV)
p_T(j1,j2) (GeV)
p_T(j_not best) (GeV)
p_T(top)_{b_1} (GeV)
H_T(j) (GeV)

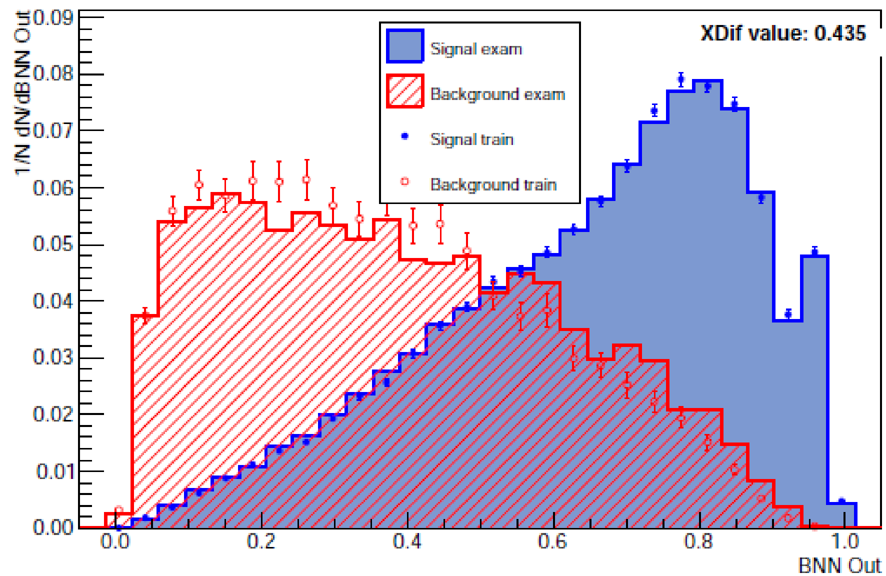

30 ab⁻¹ (100 TeV)
FCC-hh Simulation
FCNC tcg
FCNC tug
single top
tt̄
W+jets
Z+jets
Events/0.3
η(lep)
Events/30 GeV
m(j) (GeV)
Events/30 GeV
m(j,W) (GeV)
Events/10 GeV
m(top)_{b_1} (GeV)
Events/2
N(j)
Events/2
Q(lep)
Events/0.1 GeV
cos(θ_{lep,j_1})|_{top}
Events/0.1 GeV
cos(θ_{lep,W})|_W
×10⁹

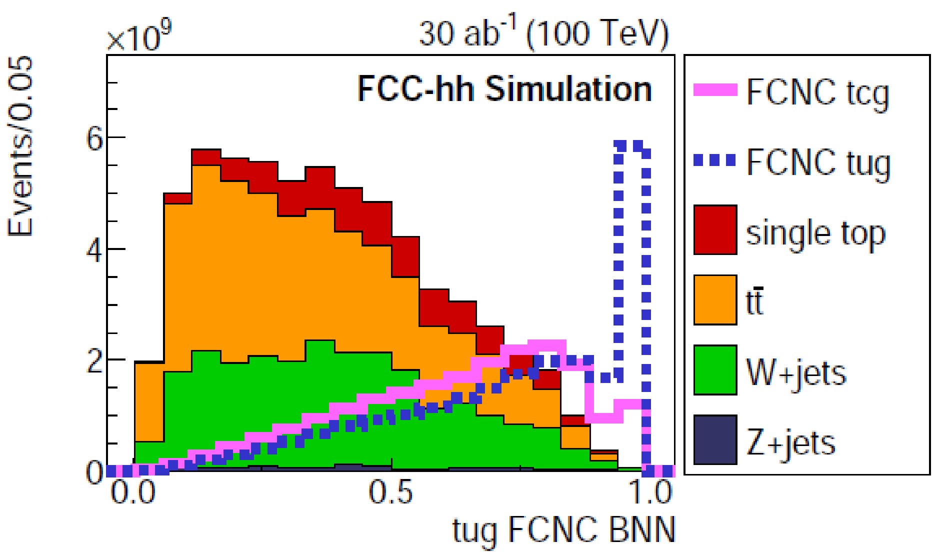
FCNC BNNs

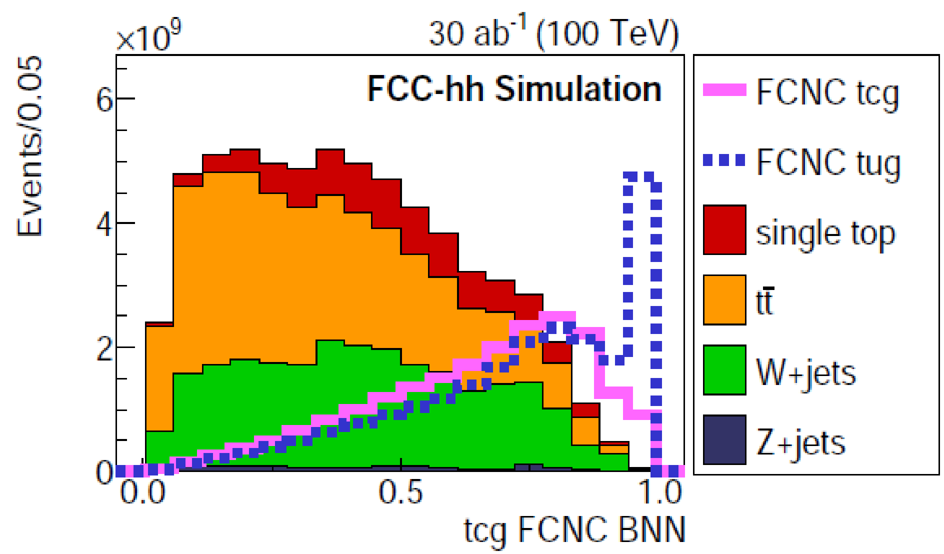
Distributions of training and testing events for FCNC tug BNN



Distributions of training and testing events for FCNC tcg BNN







Statistical Analysis

The Bayesian inference is used to derive posterior probability using the **Theta** package.

$$p(\vec{\mu}_s|d) = \int p(d|\vec{\mu}_s, \vec{\mu}_b, \vec{\theta}) \frac{\pi(\vec{\mu}_s)\pi(\vec{\mu}_b)\pi(\vec{\theta})}{\pi(d)} \mathrm{d}\vec{\mu}_b \mathrm{d}\,\vec{\theta}$$

Sources of systematic uncertainties:

- Single and pair top quark production cross section (prior 15%)
- W + jets (prior 50%)
- Z + jets (prior 30%)
- Additional general Gaussian blur 15% to simulate experimental uncertainties
- Finite MC statistics via Barlow-Beeston method

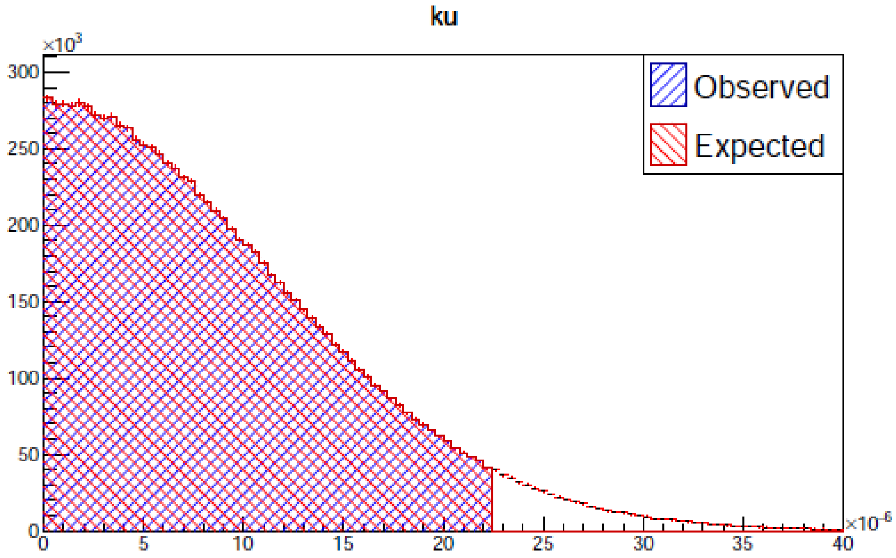
Three fitting scenarios:

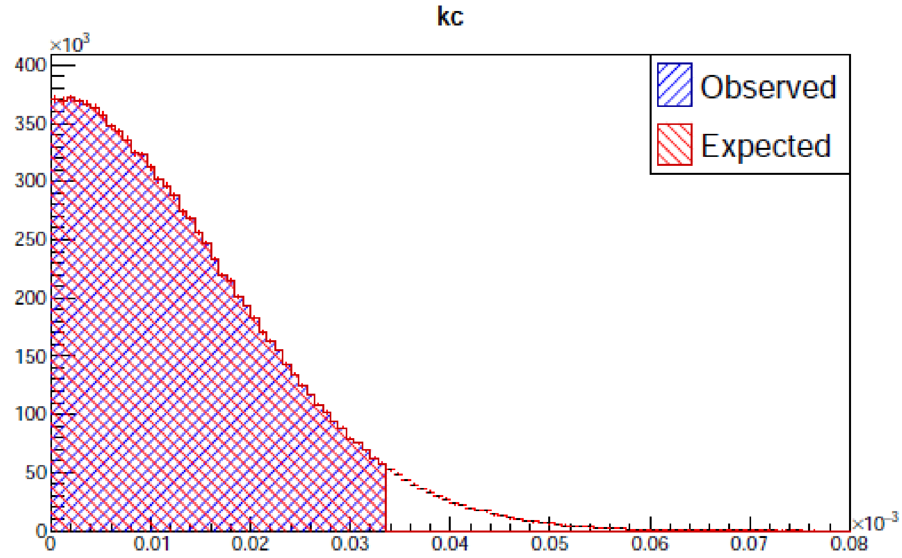
1) 1D tug FCNC

2) 1D tcg FCNC

3) 2D tug and tcg FCNC couplings

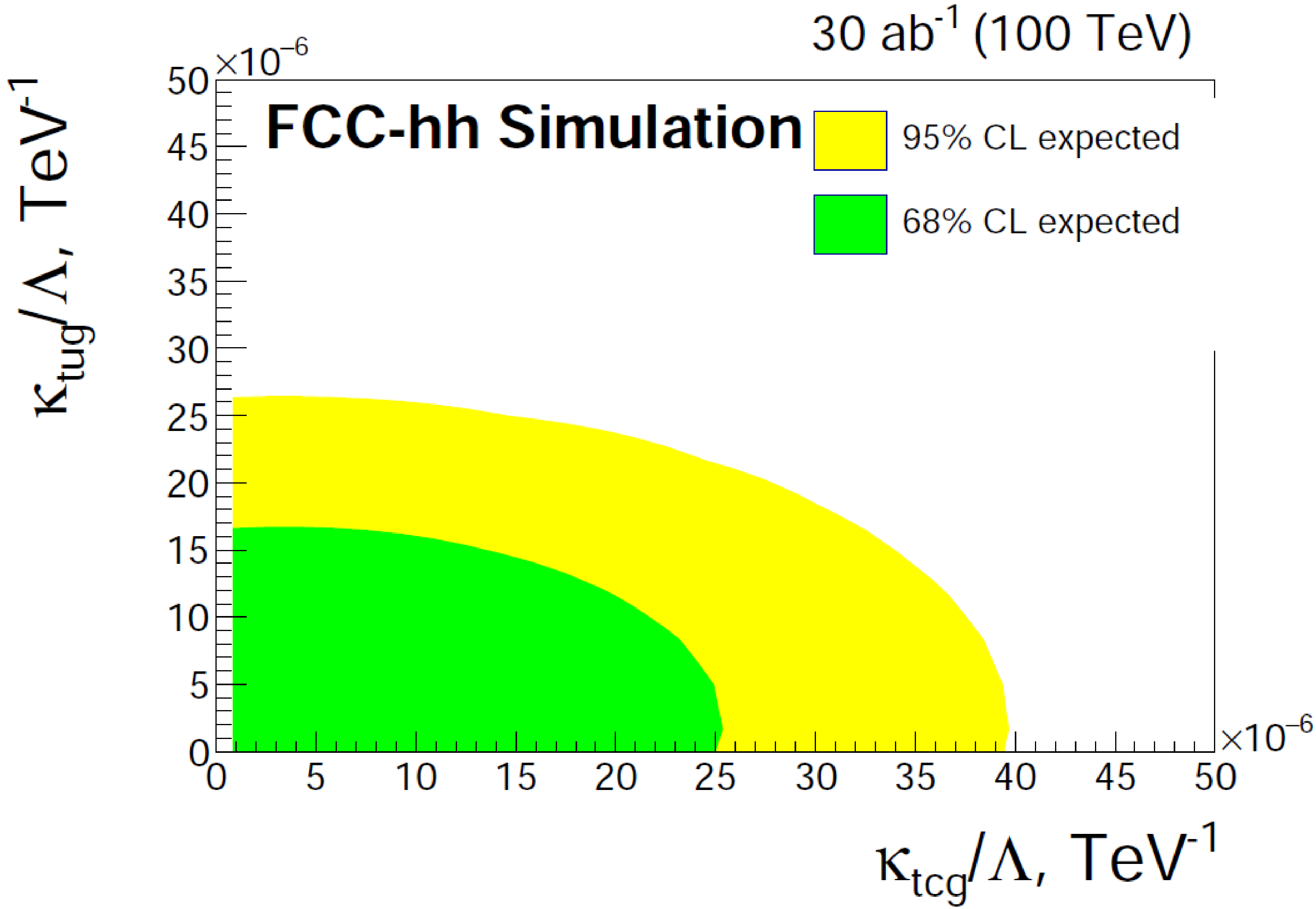
1D FCNC Upper Limits





$$\kappa_{tgu}/\Lambda < 2.2\times10^{-5}\ \mathrm{TeV}^{-1},\ \kappa_{tgc}/\Lambda < 3.3\times10^{-5}\ \mathrm{TeV}^{-1}$$
$$\mathrm{Br}(\mathrm{t} \to gu) < 5.8 \cdot 10^{-10}, Br(t \to gc) < 1.3 \cdot 10^{-9}$$

2D FCNC Upper Limits

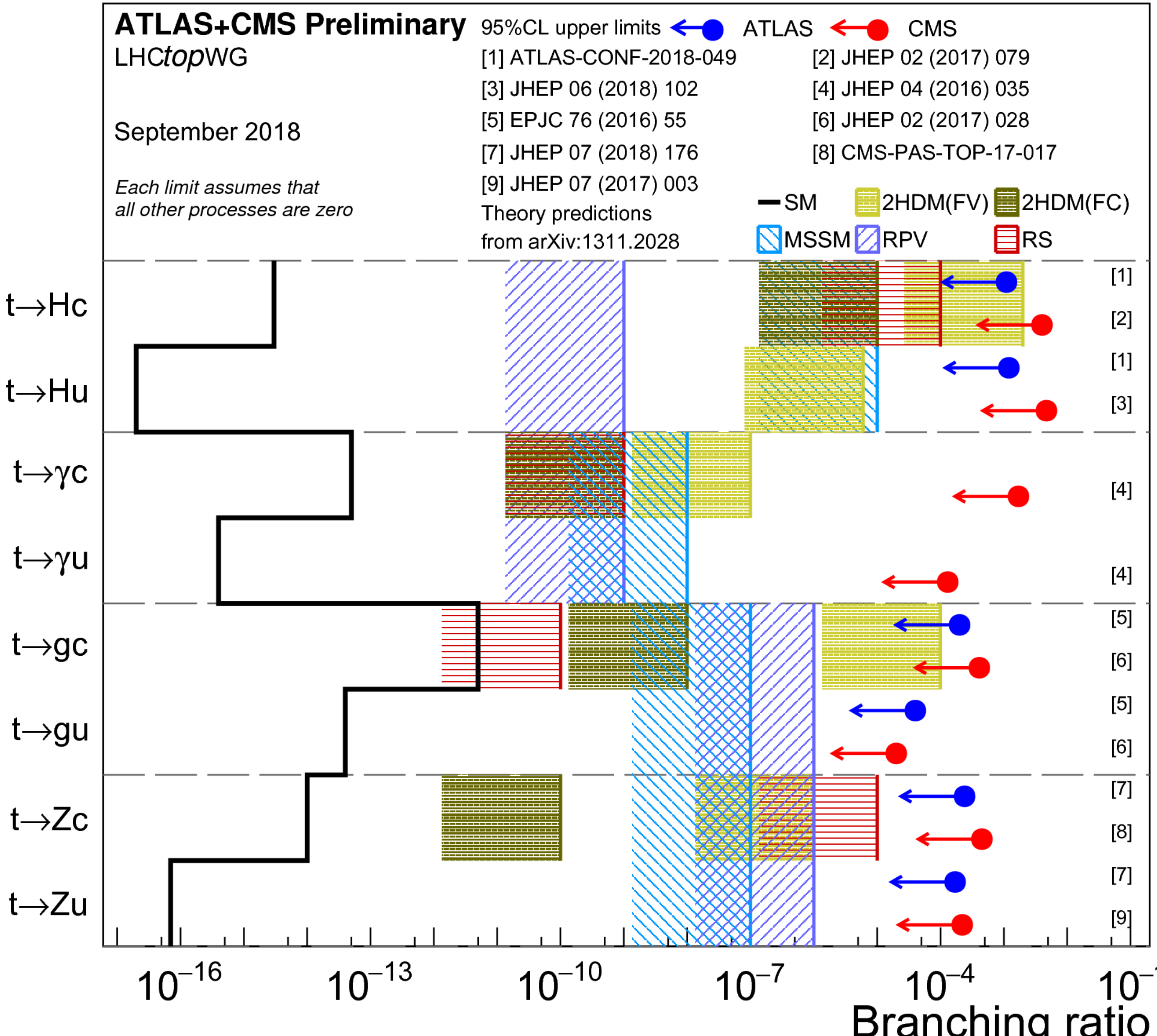


Simple extrapolation to compare

$$\frac{|\kappa^{\text{exp}}_{100\ \text{TeV}}|}{\Lambda} = \frac{|\kappa^{\text{obs}}_{14\ \text{TeV}}|}{\Lambda}\sqrt{\frac{\mathcal{L}_{14\ \text{TeV}}}{\mathcal{L}_{100\ \text{TeV}}}}\sqrt{\frac{\sigma_{14\ \text{TeV}}}{\sigma_{100\ \text{TeV}}}}$$

$\lvert\kappa_{tgu}^{8\ obs}\rvert/\Lambda$	$\lvert\kappa_{tgu}^{100\ obs}\rvert/\Lambda$	$\lvert\kappa_{tgu}^{100\ exp}\rvert/\Lambda$	$\frac{\lvert\kappa_{tgu}^{100\ obs}\rvert}{\Lambda}/\frac{\lvert\kappa_{tgu}^{100\ exp}\rvert}{\Lambda}$
4.1×10^{-3}	2.2×10^{-5}	2.0×10^{-5}	0.91
$\lvert\kappa_{tgu}^{14\ obs}\rvert/\Lambda$	$\lvert\kappa_{tgu}^{100\ obs}\rvert/\Lambda$	$\lvert\kappa_{tgu}^{100\ exp}\rvert/\Lambda$	$\frac{\lvert\kappa_{tgu}^{100\ obs}\rvert}{\Lambda}/\frac{\lvert\kappa_{tgu}^{100\ exp}\rvert}{\Lambda}$
1.8×10^{-3}	2.2×10^{-5}	1.4×10^{-4}	0.16
$\lvert\kappa_{tgu}^{8\ obs}\rvert/\Lambda$	$\lvert\kappa_{tgu}^{14\ obs}\rvert/\Lambda$	$\lvert\kappa_{tgu}^{14\ exp}\rvert/\Lambda$	$\frac{\lvert\kappa_{tgu}^{14\ obs}\rvert}{\Lambda}/\frac{\lvert\kappa_{tgu}^{14\ exp}\rvert}{\Lambda}$
4.1×10^{-3}	1.8×10^{-3}	2.6×10^{-4}	0.14
$\lvert\kappa_{tgu}^{14;\ 3/ab\ obs}\rvert/\Lambda$	$\lvert\kappa_{tgu}^{14;\ 15/ab\ obs}\rvert/\Lambda$	$\lvert\kappa_{tgu}^{14;\ 15/ab\ exp}\rvert/\Lambda$	$\frac{\lvert\kappa_{tgu}^{14;\ 15/ab\ obs}\rvert}{\Lambda}/\frac{\lvert\kappa_{tgu}^{14;\ 15/ab\ exp}\rvert}{\Lambda}$
1.8×10^{-3}	1.1×10^{-3}	0.8×10^{-3}	0.73

Present top quark FCNC upper limits



Summary

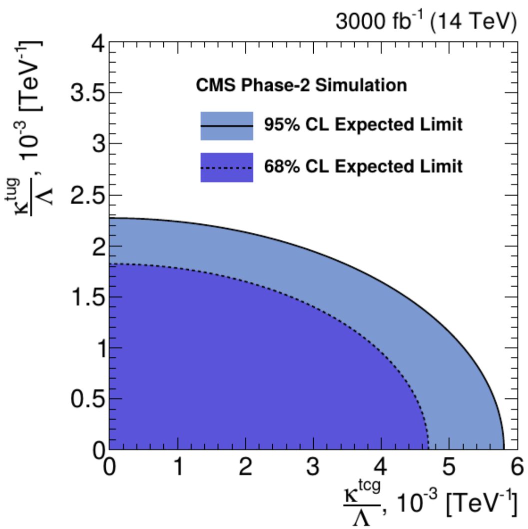
14 TeV expected 95% CL upper limits:

$\kappa^u/\Lambda < 1.8 * 10^{-3}\ \text{TeV}^{-1}$

$\kappa^c/\Lambda < 5.2 * 10^{-3}\ \text{TeV}^{-1}$

$Br(t \to ug) < 3.8 * 10^{-6}$

$Br(t \to cg) < 3.2 * 10^{-5}$



$\sqrt{s}=27\ TeV,\ \ L=15\ ab^{-1}$:

$|\kappa_{tug}|/\Lambda < 5.3\times10^{-4}\,TeV^{-1}\,,\ |\kappa_{tcg}|/\Lambda < 7.4\times10^{-4}\,TeV^{-1}$

$B(t\to ug) < 3.3\times10^{-7}\,,\ B(t\to cg) < 6.6\times10^{-7}$

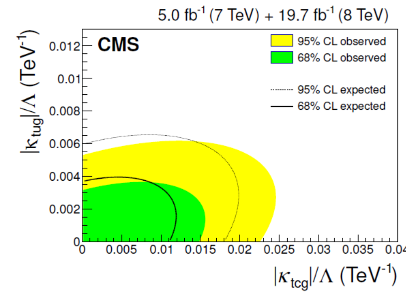
CMS combined 7+8 TeV observed (expected) 95% CL upper limits:

$\kappa^u/\Lambda < 4.1\ (4.8) * 10^{-3}\ \text{TeV}^{-1}$

$\kappa^c/\Lambda < 18.4\ (15.2) * 10^{-3}\ \text{TeV}^{-1}$

$Br(t \to ug) < 2.0\ (2.8) * 10^{-5}$

$Br(t \to cg) < 40.5\ (27.6) * 10^{-5}$



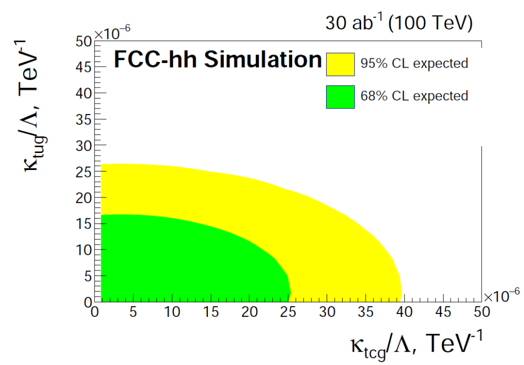
FCC-hh 100 TeV, 30 ab^{-1} expected 95% CL upper limits:

$\kappa^u/\Lambda < 2.2 * 10^{-5}\ \text{TeV}^{-1}$

$\kappa^c/\Lambda < 3.3 * 10^{-5}\ \text{TeV}^{-1}$

$Br(t \to ug) < 5.8 * 10^{-10}$

$Br(t \to cg) < 1.3 * 10^{-9}$



Back Up Slides

Statistical Analysis

The Bayesian inference is used to calculate the expected upper limits on Br(t → cg) and Br(t → ug) using the **Theta** package. The posterior probabilities are obtained on Asimov data set of background-only model.

Sources of systematic uncertainties (YR18):

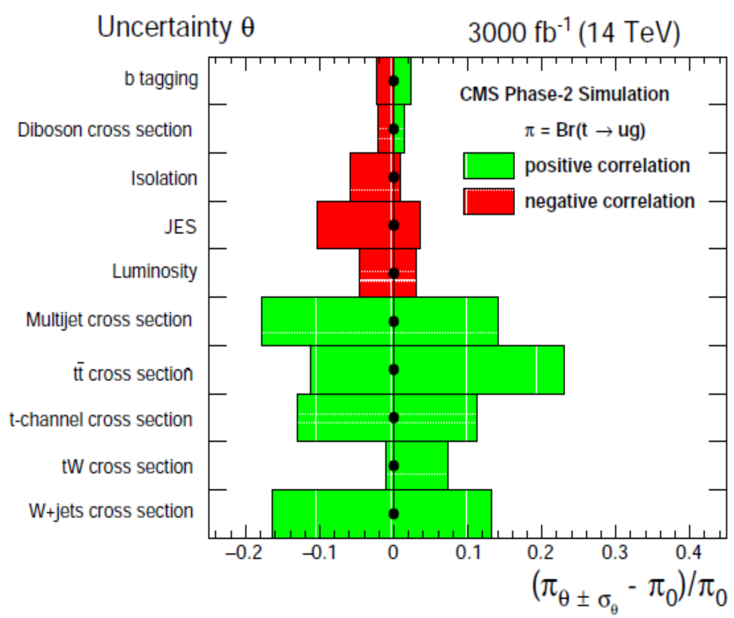
[CMS-PAS-FTR-18-004]

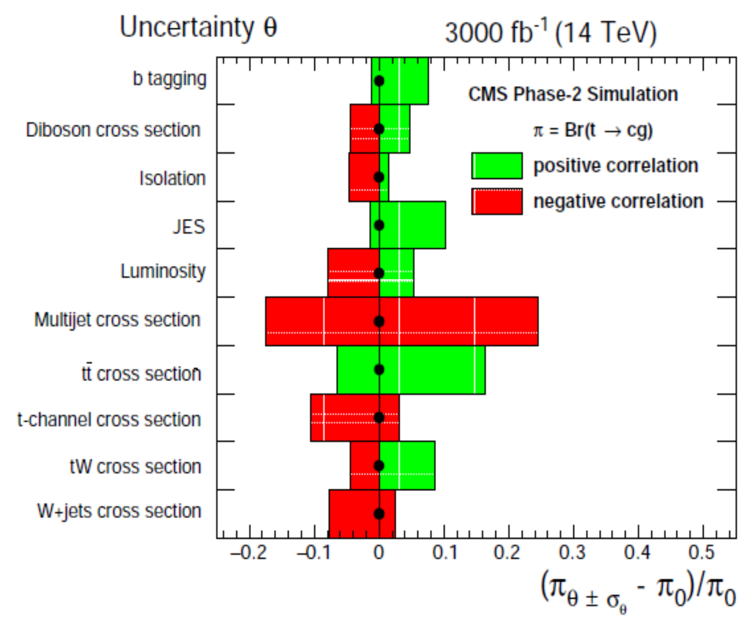
- Luminosity (1%)
- JES (1%)
- Lepton Id/Iso (0.5-1%)
- B-tag (1% for b-jets, 2% for c-jets and 15% for light jets)
- Renormalization and factorization scales
- Finite MC statistics via Barlow-Beeston method

As prior normalization uncertainties for ttbar is taken 6%, for the data-driven QCD background is taken 50%, for remaining background sources, the cross section is varied through their scale uncertainties.

Three fitting scenarios:

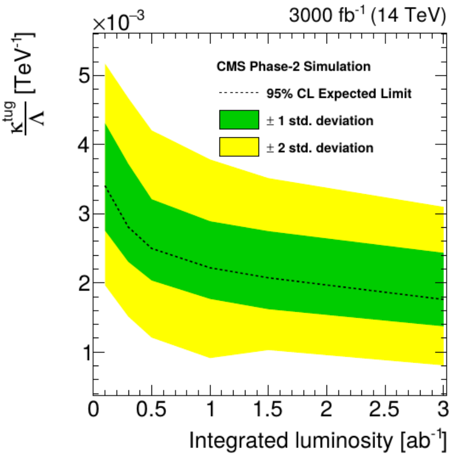
1) 1D tug FCNC
2) 1D tcg FCNC
3) 2D tug and tcg FCNC couplings

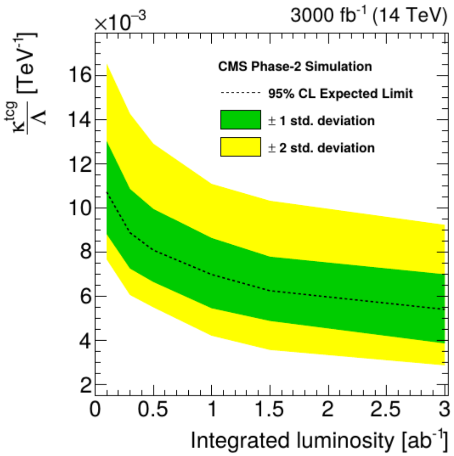


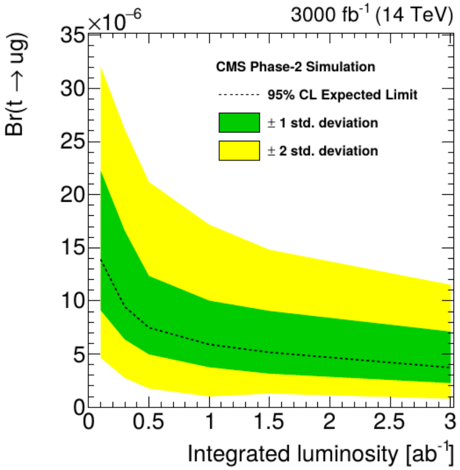


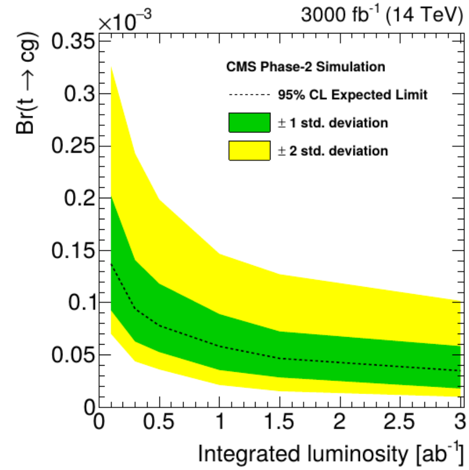
HL-LHC Results: 1D Limits

[CMS-PAS-FTR-18-004]









14 TeV expected 95% CL upper limits:

(**couplings to branching translation**)

Integrated luminosity	$\mathcal{B}(t \to ug)$	$\lvert\kappa_{tug}\rvert/\Lambda$	$\mathcal{B}(t \to cg)$	$\lvert\kappa_{tcg}\rvert/\Lambda$
$300\ \mathrm{fb}^{-1}$	$9.8 \cdot 10^{-6}$	$0.0029\ \mathrm{TeV}^{-1}$	$99 \cdot 10^{-6}$	$0.0091\ \mathrm{TeV}^{-1}$
$3000\ \mathrm{fb}^{-1}$	$3.8 \cdot 10^{-6}$	$0.0018\ \mathrm{TeV}^{-1}$	$32 \cdot 10^{-6}$	$0.0052\ \mathrm{TeV}^{-1}$
$3000\ \mathrm{fb}^{-1}$ Stat. only	$1.0 \cdot 10^{-6}$	$0.0009\ \mathrm{TeV}^{-1}$	$4.9 \cdot 10^{-6}$	$0.0020\ \mathrm{TeV}^{-1}$

Combined CMS 7+8 TeV observed (expected) 95% CL upper limits:

Br(t→ug) $< 2.0(2.8) \times 10^{-5}$ **κ^u /Λ <** $4.1\ (4.8) \times 10^{-3}$ TeV^{-1}

Br(t→cg) $< 40.5(27.6) \times 10^{-5}$ **κ^c /Λ <** $18.4\ (15.2) \times 10^{-3}$ TeV^{-1}