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Measurements of the top quark properties at decay with CMS

On behalf of the CMS collaboration

Top quark precision physics

The increasing accuracy of the measurement of top properties challenges SM theory predictions

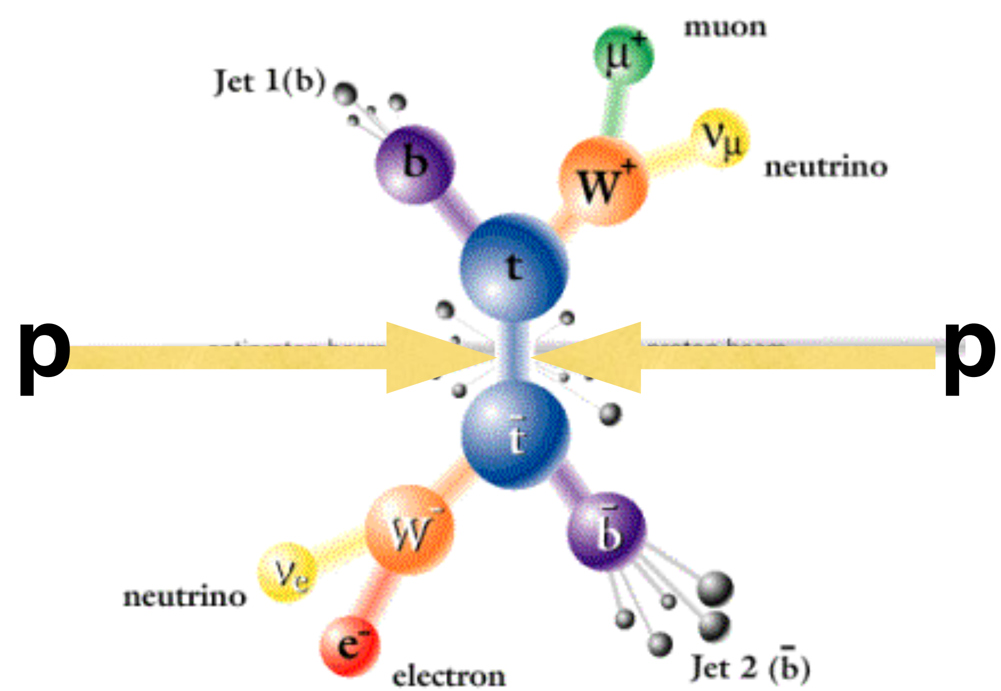
Top quark properties

Intrinsic:

- mass
- charge
- spin & polarization

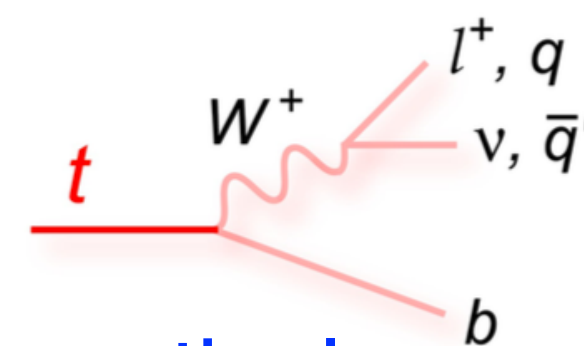
@ production:

- cross sections
- asymmetries
- spin correlations



@ decay:

- widths
- branching ratios
- W helicity
- anomalous couplings
- rare decays



Any significant deviation found w.r.t. theoretical expectations would be a hint of new physics BSM (for instance SUSY, multiple Higgs, composite top)

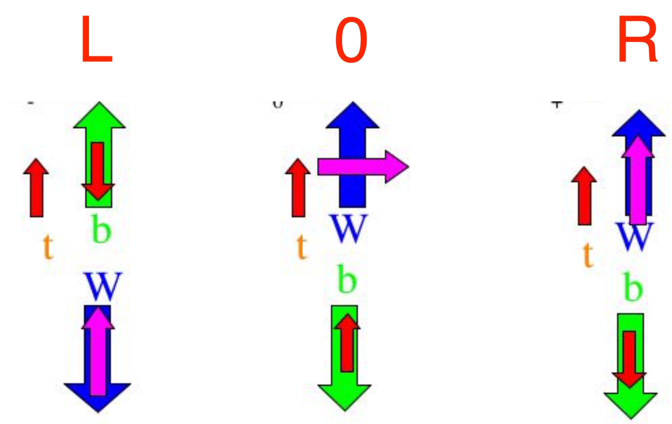
Top properties @ decay

There are several measurements made by CMS so far at 7 and 8 TeV

Will discuss here only the most recent ones (2012 @ 8 TeV):

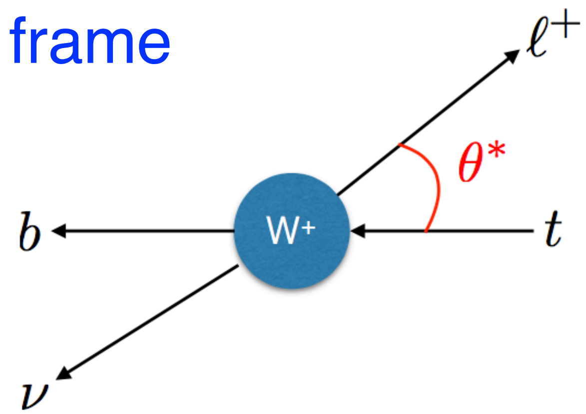
1) **W**-helicity from top decays (sensitive to **Wtb** vertex structure)
2) anomalous couplings (i.e. other than V–A **Wtb**)
3) FCNC rare decays (**t→Zq**, **t→Hq**)

1. W helicity



W-helicity fractions: defined as $F_{L,R,0}=\Gamma_{L,R,0}/\Gamma_{total}$ for left-handed, right-handed and longitudinal **W** polarization

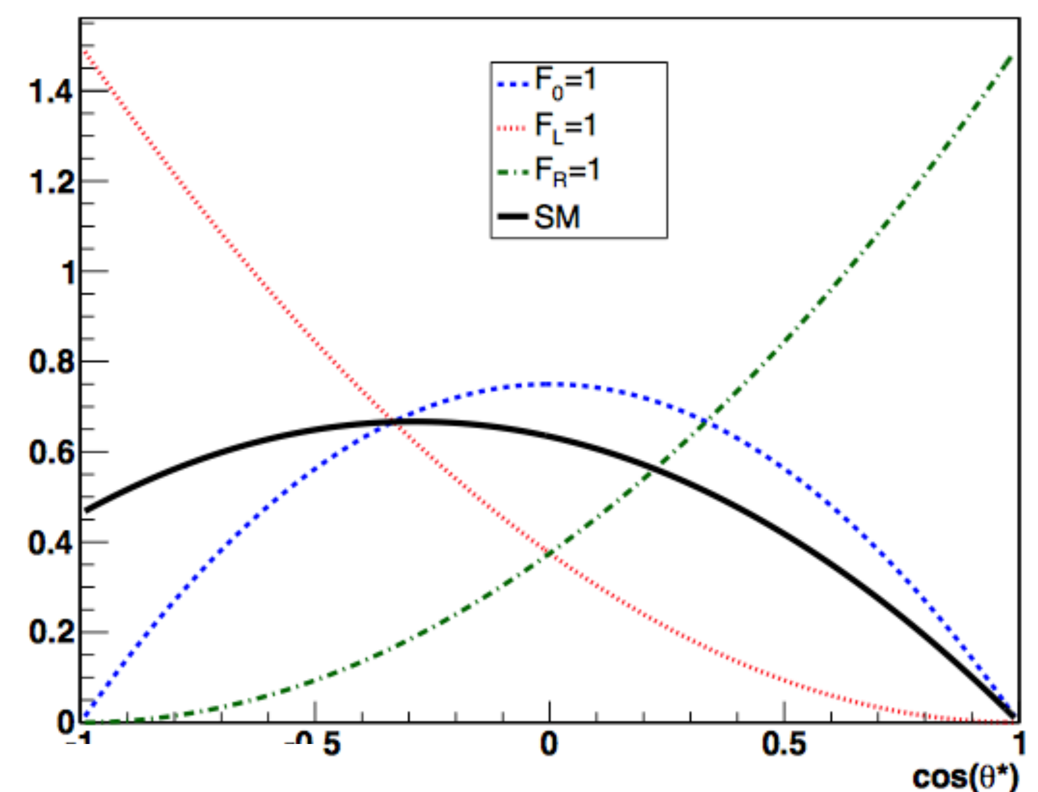
Helicity angle θ* defined as the angle between the charged lepton/down-type q and the **t**, in the **W** rest frame



SM predictions @NNLO, m_t=172.8 GeV

PRD 81 (2010) 111503

F_0=0.687±0.005, *F_L=0.311±0.005,* *F_R=0.0017±0.0001*



θ* distributions

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta^*} = \frac{3}{8}(1-\cos\theta^*)^2 F_L + \frac{3}{4}(\sin\theta^*)^2 F_0 + \frac{3}{8}(1+\cos\theta^*)^2 F_R.$$

W helicity (8 TeV, 19.7 fb^{-1})

Fit method:

- maximize a binned Poisson likelihood using the cosθ* distributions expected from the 3 helicities
- reweight each bin by a factor (one for each branch)

$$w = \frac{\frac{3}{8}F_L(1-\cos\theta^*_{gen})^2 + \frac{3}{4}F_0\sin^2\theta_{gen} + \frac{3}{8}F_R(1+\cos\theta^*_{gen})^2}{\frac{3}{8}F_L^{SM}(1-\cos\theta^*_{gen})^2 + \frac{3}{4}F_0^{SM}\sin^2\theta_{gen} + \frac{3}{8}F_R^{SM}(1+\cos\theta^*_{gen})^2}$$

where θ^*_{gen} is the helicity angle at generator level

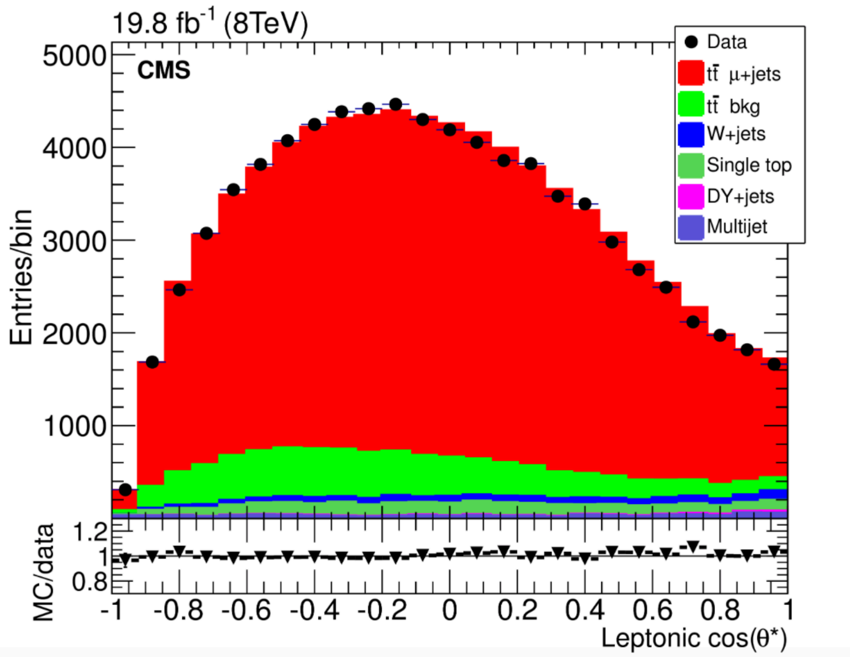
- the separate **e**+jets and **μ**+jets measurements are combined accounting for correlations
- **μ**+jets events weigh more than double than **e**+jets events
- unitarity constraint $F_L+F_0+F_R=1$

W helicity (8 TeV, 19.7 fb^{-1})

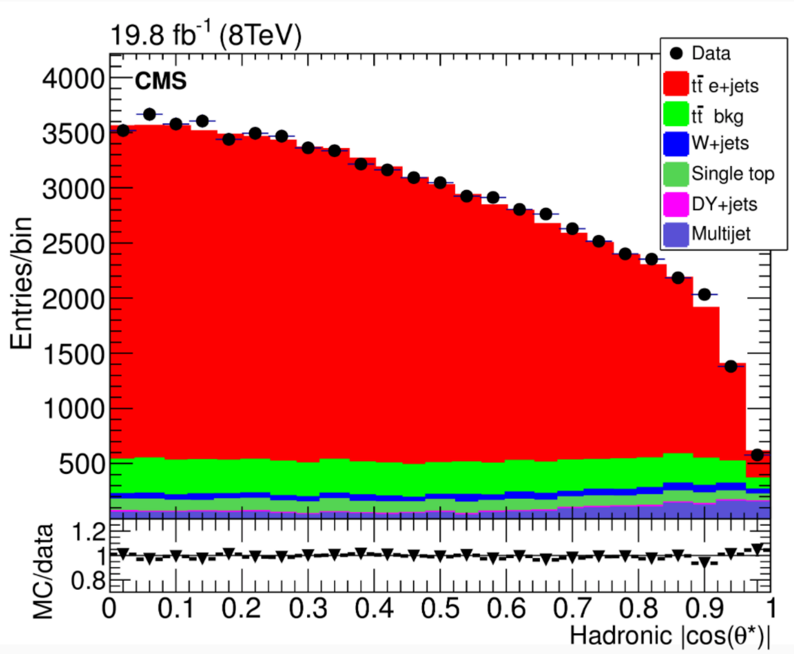
$t\bar{t}$: lepton+jets

[PLB 762 (2016) 512]

Selection: 1 **e** or **μ**, ≥4 jets (2 b-tagged)



leptonic branch
μ+jets



hadronic branch
e+jets

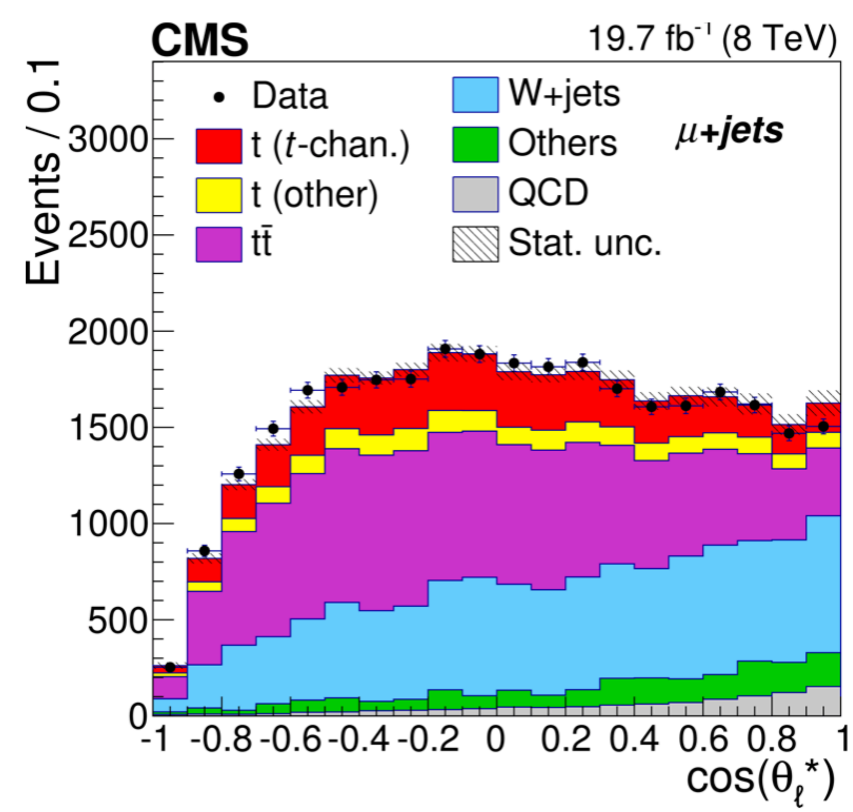
up/down-type
ambiguity ⇒ not used

single top:
1 lepton+2jets

[JHEP 1501 (2015) 053]

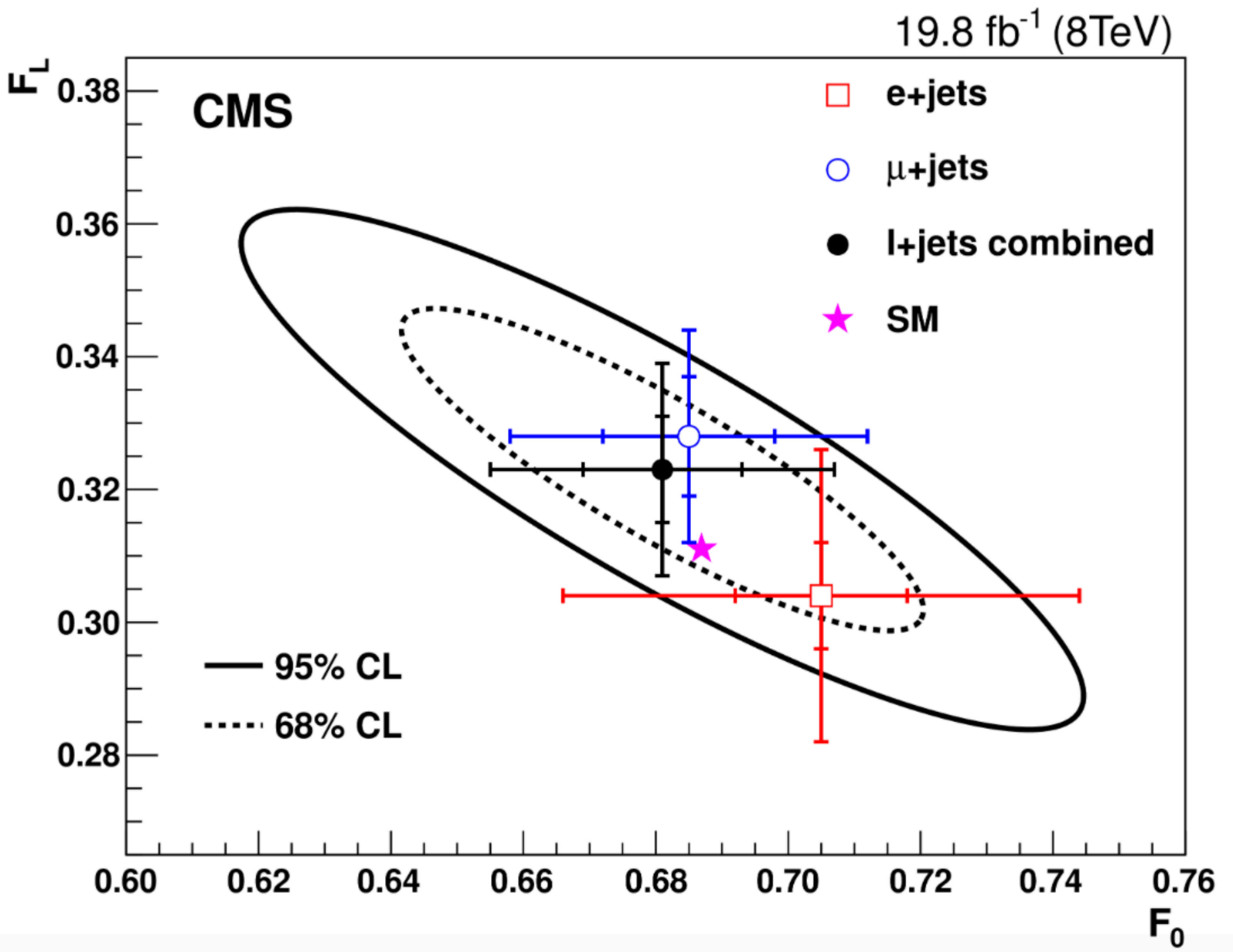
Selection: 1 **e** or **μ**, 2 jets (1 b-tagged)

leptonic branch
μ+jets

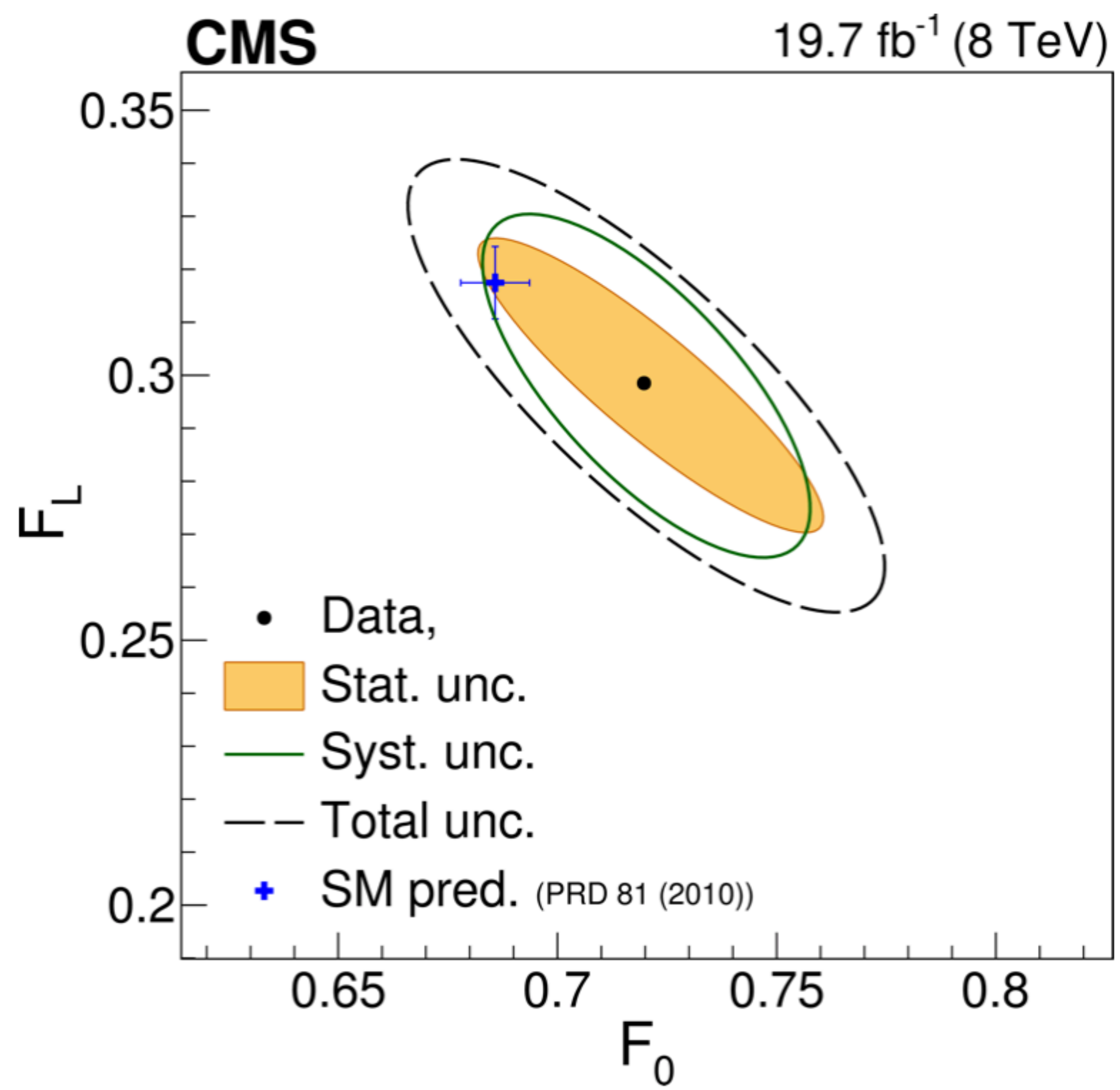


W helicity (8 TeV, 19.7 fb^{-1})

$t\bar{t}$: lepton+jets



single top:
1 lepton+2jets



W helicity (8 TeV, 19.7 fb^{-1})

$t\bar{t}$: lepton+jets

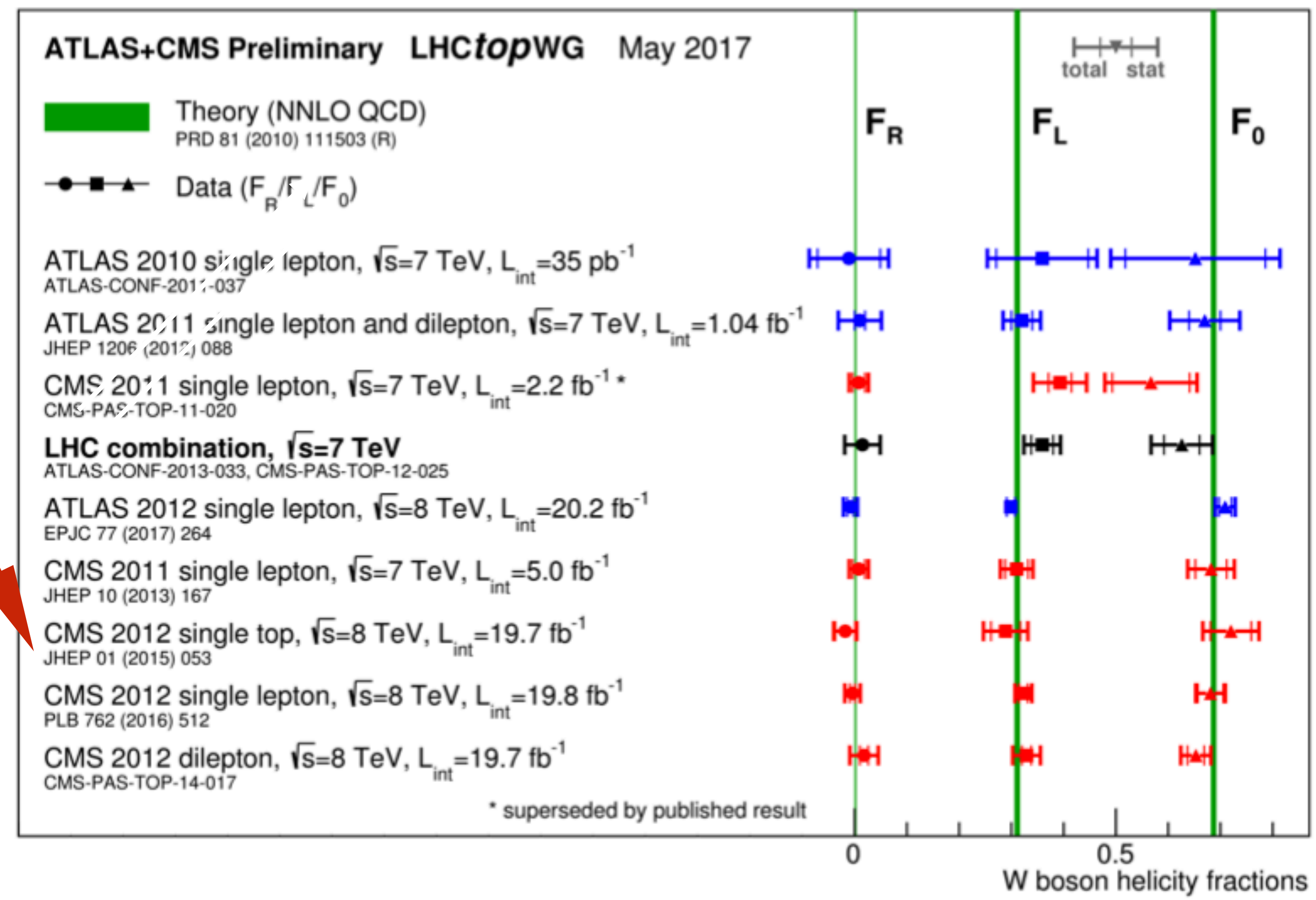
Channel	$F_0 \pm$ (stat) $\pm$ (syst)	$F_L \pm$ (stat) $\pm$ (syst)	$F_R \pm$ (stat) $\pm$ (syst)	$\rho_{0,L}$
e+jets	0.705 ±0.013±0.037	0.304±0.009±0.020	−0.009 ± 0.005±0.021	−0.950
μ+jets	0.685 ±0.013±0.024	0.328±0.009±0.014	−0.013 ± 0.005±0.017	−0.957
ℓ+jets	0.681 ±0.012±0.023	0.323±0.008±0.014	−0.004 ± 0.005±0.014	−0.959

anticorrelated because of unitarity constr.

single top: 1 lepton+2jets

$$F_L = 0.298 \pm 0.028\,(\text{stat}) \pm 0.032\,(\text{syst}),$$
$$F_0 = 0.720 \pm 0.039\,(\text{stat}) \pm 0.037\,(\text{syst}),$$
$$F_R = -0.018 \pm 0.019\,(\text{stat}) \pm 0.011\,(\text{syst}),$$

$\rho_{0,L}$=–0.8



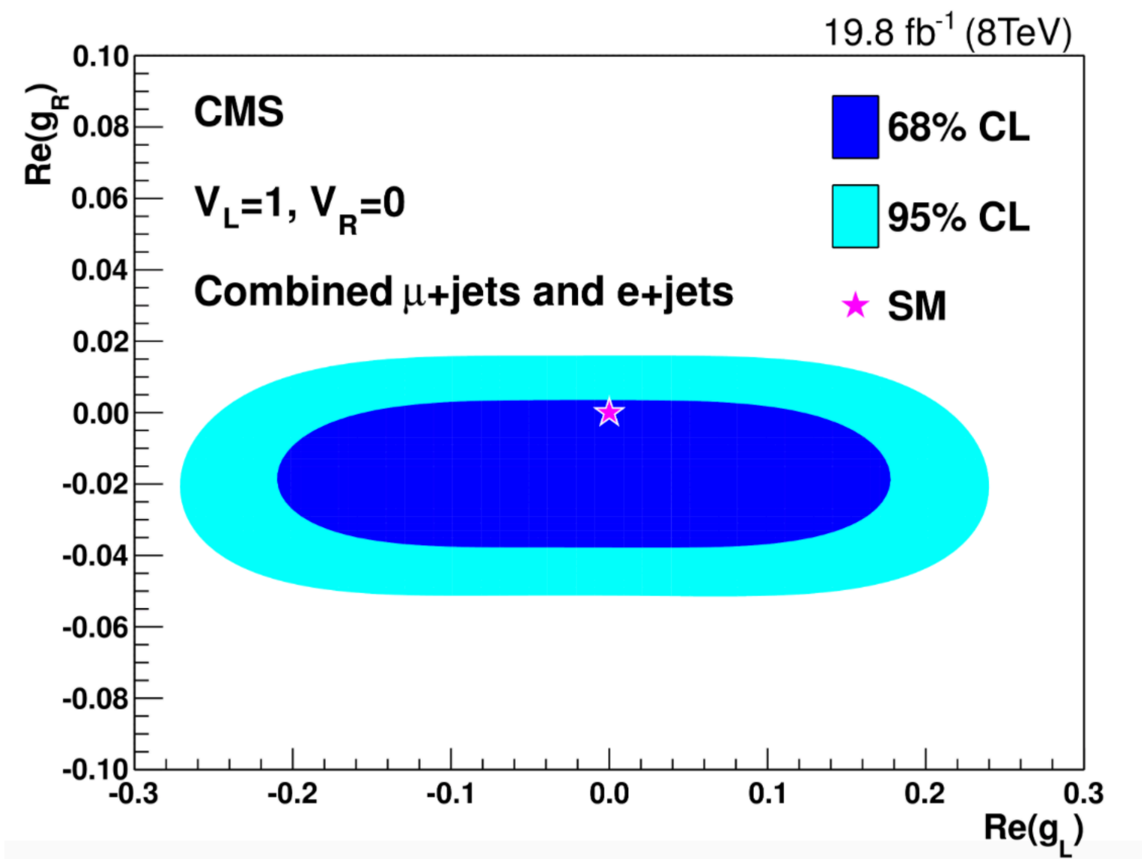
W helicity (8 TeV, 19.7 fb^{-1})

Structure of **Wtb** vertex expressed as:

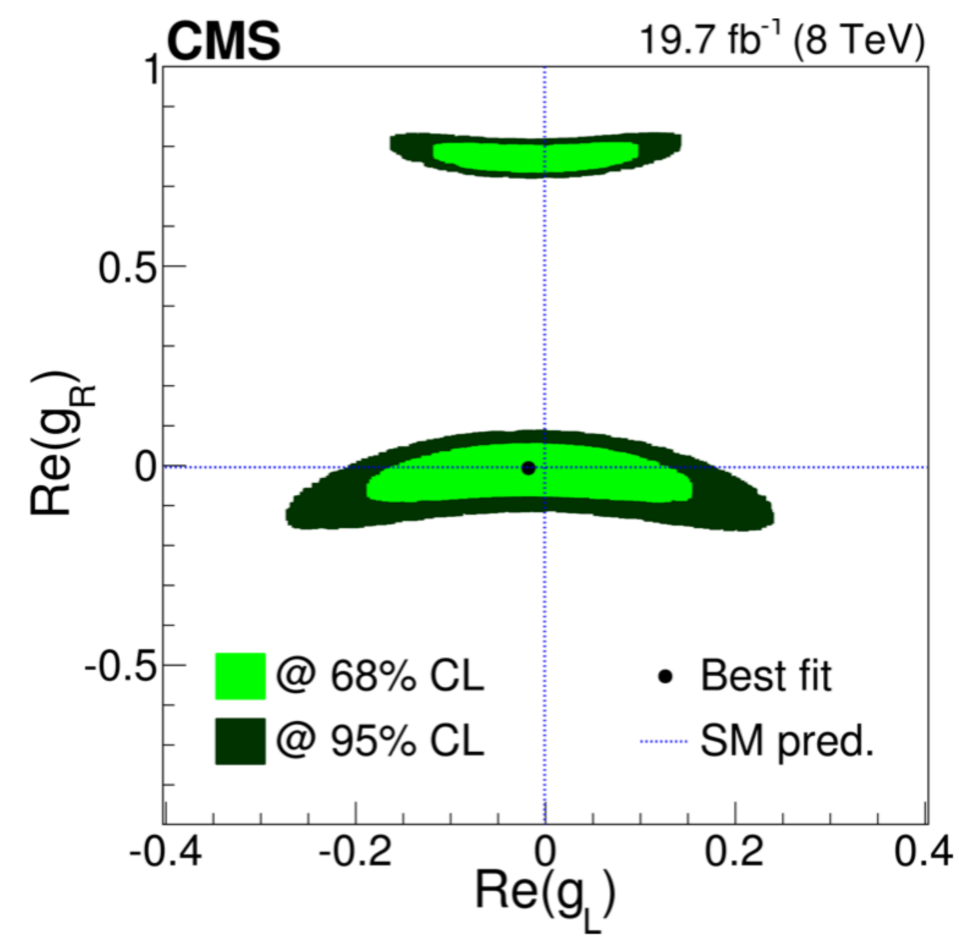
$$\mathcal{L}_{\mathrm{Wtb}} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}(V_{\mathrm{L}}P_{\mathrm{L}} + V_{\mathrm{R}}P_{\mathrm{R}})tW_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{M_{\mathrm{W}}}(g_{\mathrm{L}}P_{\mathrm{L}} + g_{\mathrm{R}}P_{\mathrm{R}})\,t\,W_{\mu}^{-} + \mathrm{h.c.},$$

Setting limits on anomalous tensor couplings (fixing V_L=1, V_R=0 as in SM):

$t\bar{t}$: lepton+jets



single top:
1 lepton+2jets



2. Anomalous couplings

JHEP 1702 (2017) 028

In the SM the **Wtb** vertex has V–A structure

FCNC currents are absent at LO and suppressed by GIM mechanism at higher orders, but can be enhanced in SM extensions

Single top events with t-channel production (→ a light forward jet) are sensitive to these deviations ⟹ events with one μ and 2 or 3 jets (w. one b-tagged)

Signal and background are discriminated with a multijet Bayesian Neural Network
The most general CP-conserving Lagrangian for the **Wtb** vertex is

$$\mathfrak{L} = \frac{g}{\sqrt{2}}\bar{\mathrm{b}}\gamma^{\mu}\left(f_{\mathrm{V}}^{\mathrm{L}}P_{\mathrm{L}} + f_{\mathrm{V}}^{\mathrm{R}}P_{\mathrm{R}}\right)\mathrm{t}\mathrm{W}_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{\mathrm{b}}\frac{\sigma^{\mu\nu}\partial_{\nu}\mathrm{W}_{\mu}^{-}}{M_{\mathrm{W}}}\left(f_{\mathrm{T}}^{\mathrm{L}}P_{\mathrm{L}} + f_{\mathrm{T}}^{\mathrm{R}}P_{\mathrm{R}}\right)\mathrm{t} + \mathrm{h.c.},$$

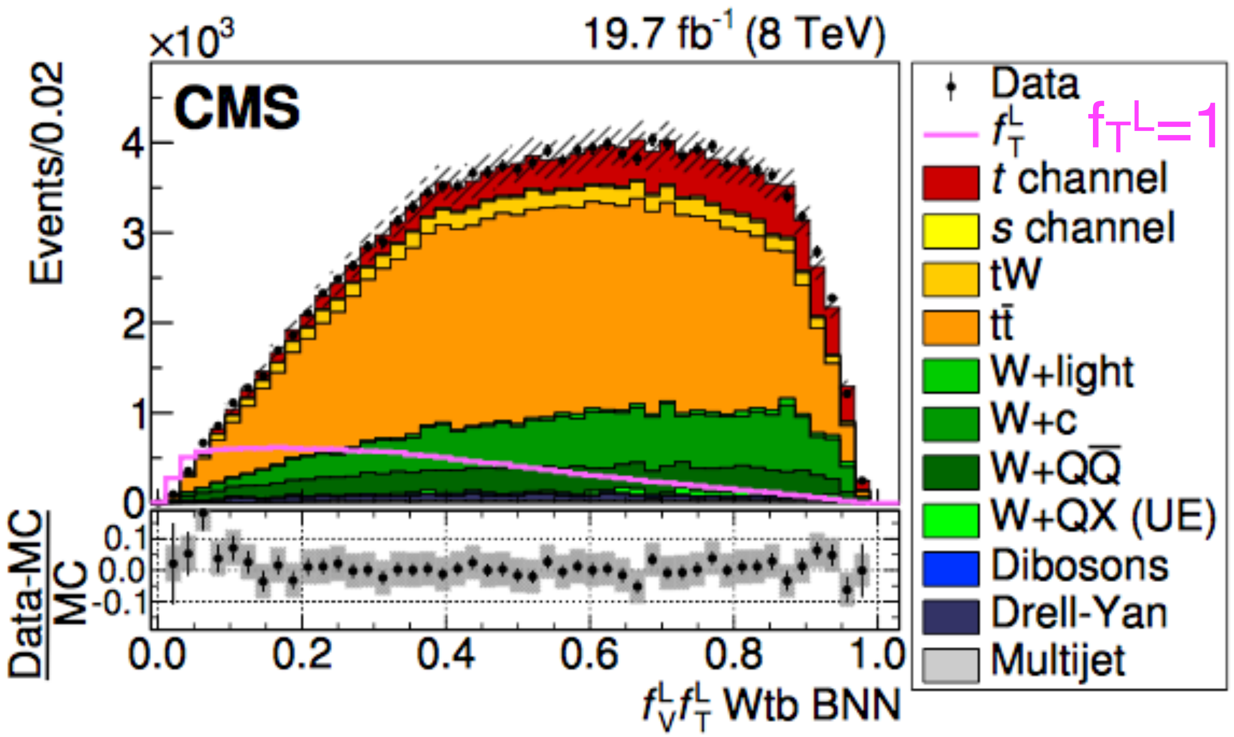
for the SM the form factors are: $f_{\mathrm{V}}^{\mathrm{L}} = V_{\mathrm{tb}}, f_{\mathrm{V}}^{\mathrm{R}} = f_{\mathrm{T}}^{\mathrm{L}} = f_{\mathrm{T}}^{\mathrm{R}} = 0.$

Limits on **Wtb** and FCNC anomalous couplings are derived using specific BNN’s

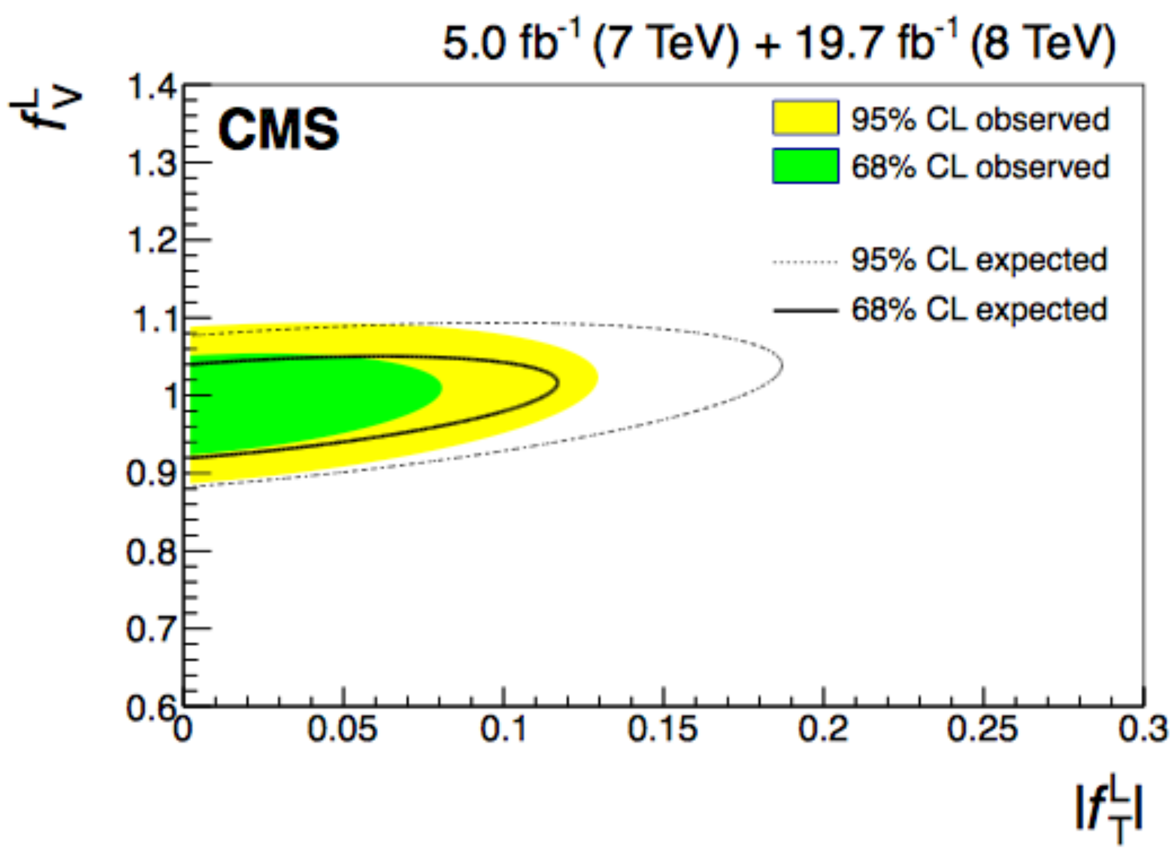
Anomalous couplings

A specific **Wtb** BNN is trained for each coupling

In this case it's trained to separate the contribution Vector-Left from that Tensor-Left



A 2D fit of **Wtb** BNN and SM BNN gives exclusion limits



Similar exclusion limits for

- Vector-Left vs Vector-Right
- Vector-Left vs Tensor-Right

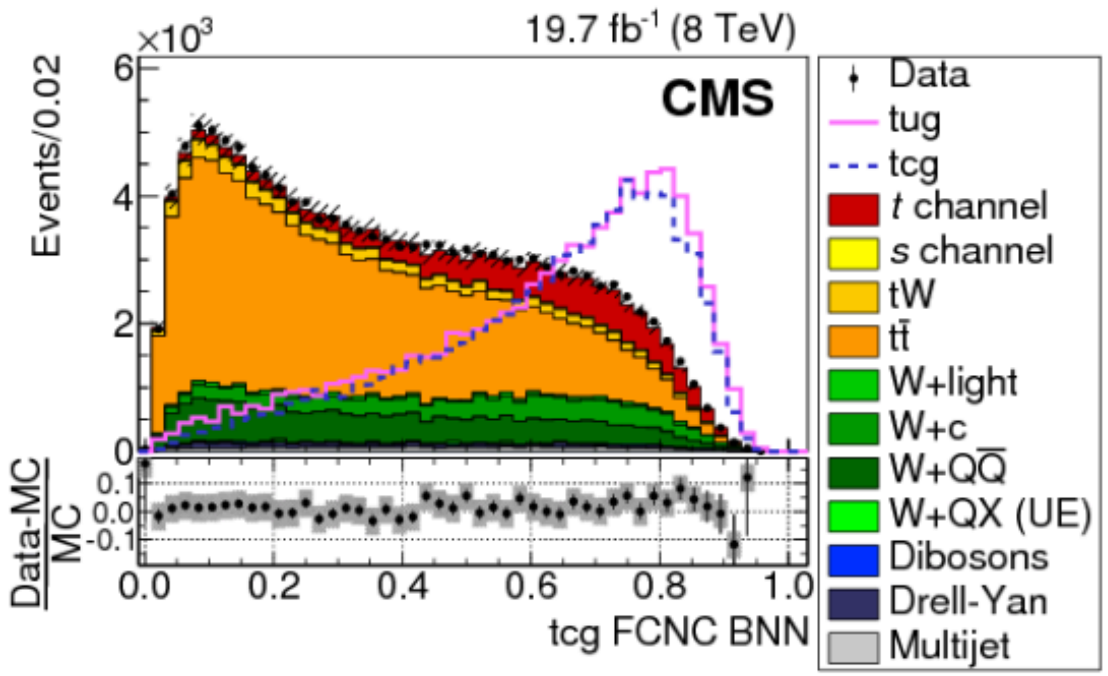
Anomalous couplings

The FCNC **tcg** and **tug** interactions can be expressed by the effective Lagrangian

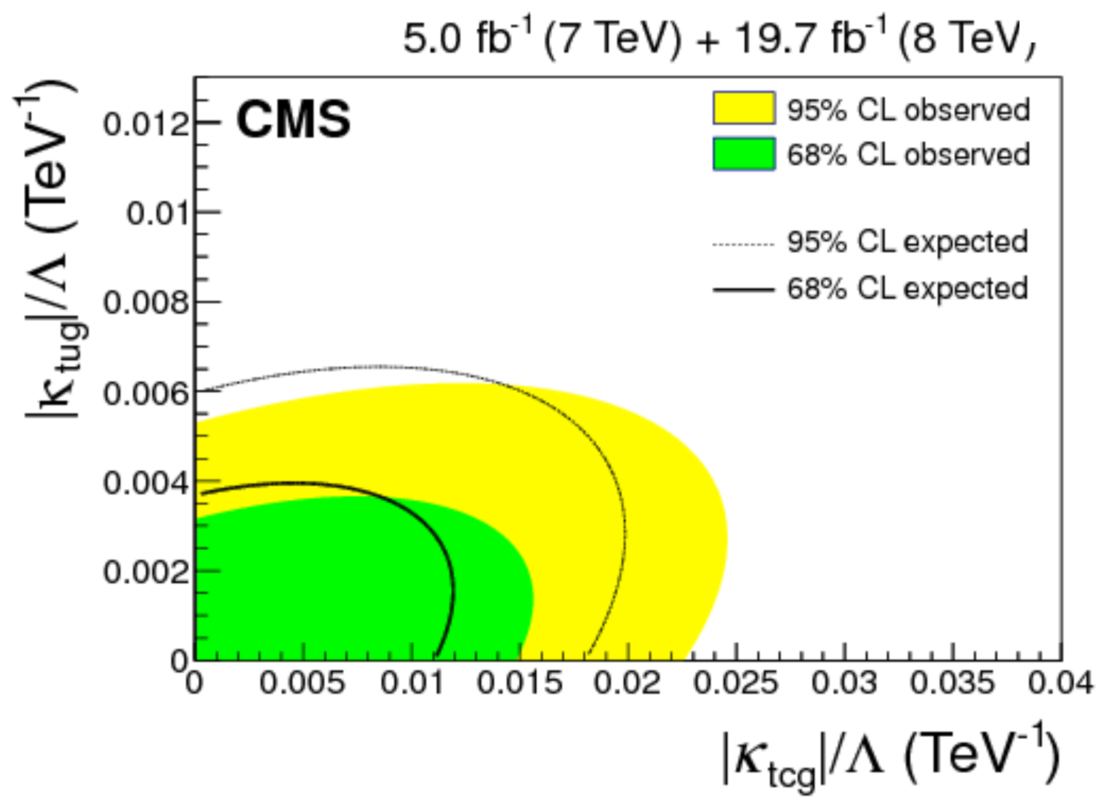
$$\mathscr{L} = \frac{\kappa_{tqg}}{\Lambda} g_s \bar{q} \sigma^{\mu\nu} \frac{\lambda^a}{2} t G^a_{\mu\nu} \qquad (\Lambda \approx 1 \text{ TeV})$$

A specific BNN is trained for each coupling

$|\kappa_{tug}|/\Lambda=0.06$
$|\kappa_{tcg}|/\Lambda=0.12$



Limits on the couplings are set from the posterior prob. distr. of $\frac{|\kappa_{tqg}|}{\Lambda}$



Limits on couplings and branching fractions (7 + 8 TeV)

$\lvert\kappa_{tug}\rvert/\Lambda$ (TeV^{-1})	$\mathcal{B}(t\to ug)$	$\lvert\kappa_{tcg}\rvert/\Lambda$ (TeV^{-1})	$\mathcal{B}(t\to cg)$
4.1 (4.8) $\times 10^{-3}$	2.0 (2.8) $\times 10^{-5}$	1.8 (1.5) $\times 10^{-2}$	4.1 (2.8) $\times 10^{-4}$

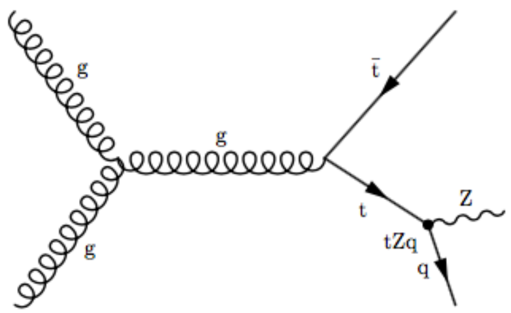
3. Rare decays -1

https://inspirehep.net/record/1512295

accepted by JHEP

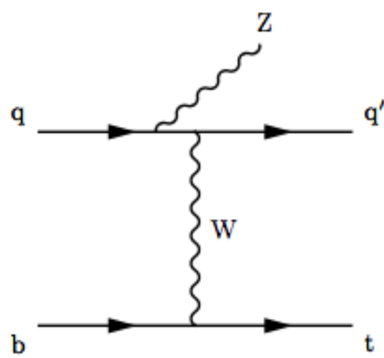
One rare decay sought for is **$t \to Zq$**: $BR_{SM} = O(10^{-15} \div 10^{-14})$

In models beyond SM : $BR_{BSM} \sim O(10^{-4}) \Longrightarrow$ within reach

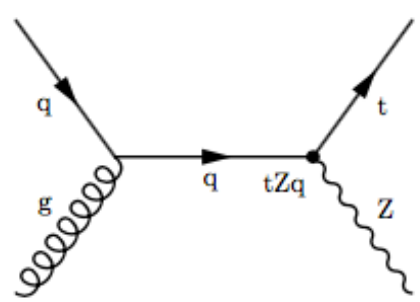


Decay can be found in the FCNC production mode **$gg \to t\bar{t} \to tZq$** $\Longrightarrow$

which needs to be distinguished from SM (for instance $\Longrightarrow$)



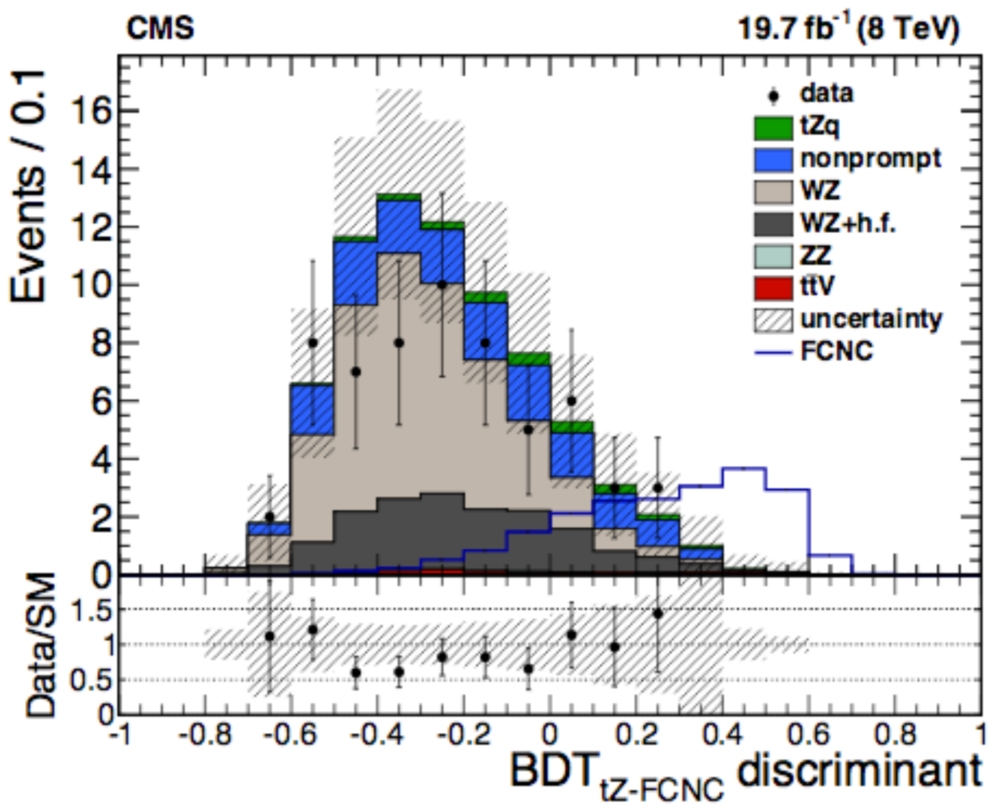
and the suppressed FCNC production of **tZ** (for instance $\Longrightarrow$)

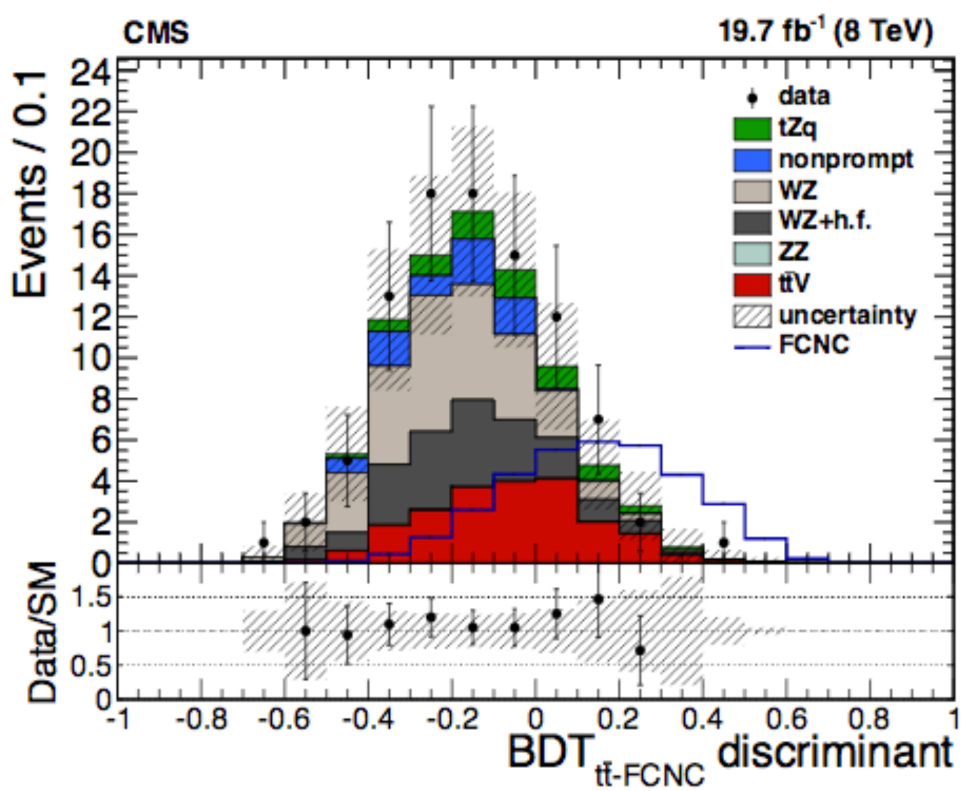


The 3 cases produce a distinctive trilepton final state:
eee, **eeμ**, **eμμ**, **μμμ**

(see J. Andrea's talk)

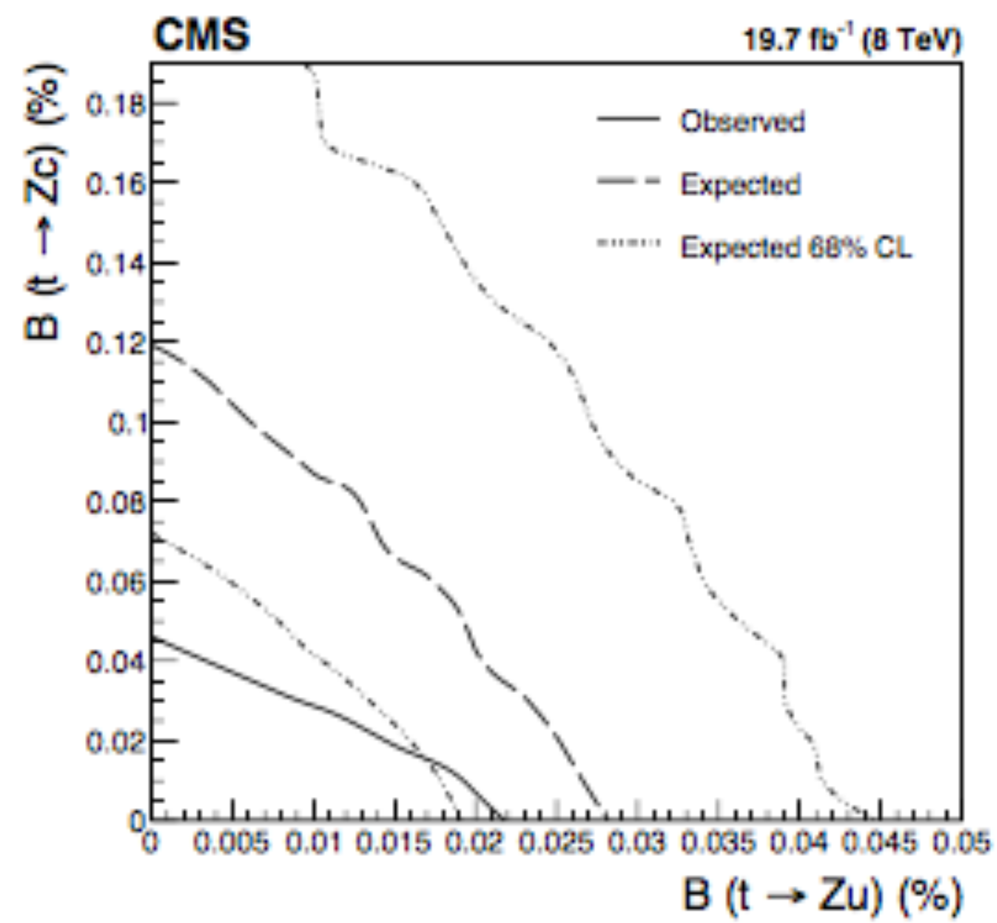
Rare decays -1





B(t→Zu)=0.1%

No excess found ⟹
95% CL exclusion limits



$$\mathcal{B}(t \to Zc) < 0.049\% \ @ \ 95\%CL \ (0.118\% \ exp.)$$

$$\mathcal{B}(t \to Zu) < 0.022\% \ @ \ 95\%CL \ (0.027\% \ exp.)$$

Rare decays -2

JHEP 02 (2017) 079

Another rare decay is **$t \to Hq$** (**$t \to Hu$** or **$t \to Hc$**): $BR_{SM} = O(10^{-15} \div 10^{-14})$

In models beyond SM (like the 2HDM): $BR_{BSM} = O(10^{-5} \div 10^{-3}) \Longrightarrow$ within reach!

Searched for in **$t\bar{t} \to Wb\ Hq$** events:

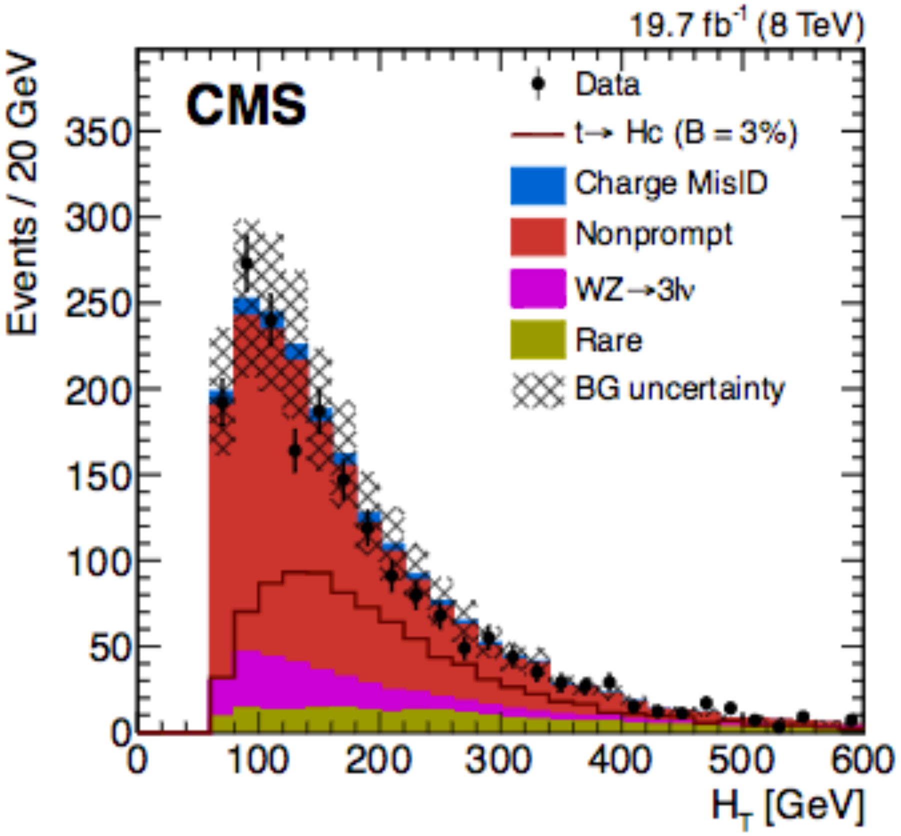
- with **W** decaying leptonically or hadronically
- with **H** decaying to 2 bosons or 2 fermions

Three independent analyses/selections which are then combined:

1. multilepton analysis: two SS leptons, or 3 leptons (**e** or **μ**) (for **$H \to WW,ZZ$**$,\tau\tau$)
2. diphoton + **W** (leptonic or hadronic) + btag (for **$H \to$**$\gamma\gamma$)
3. 3 btagged jet + leptonic **W** + additional jet (for **$H \to b\bar{b}$**)

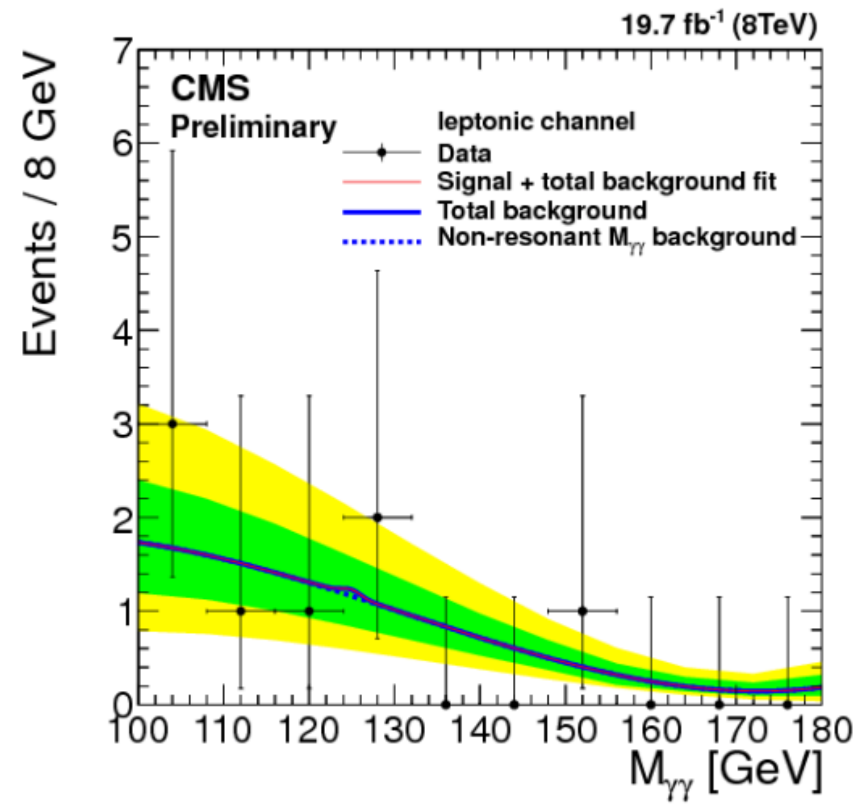
Rare decays -2

1. Selection on E_T^{miss} and H_T



SS

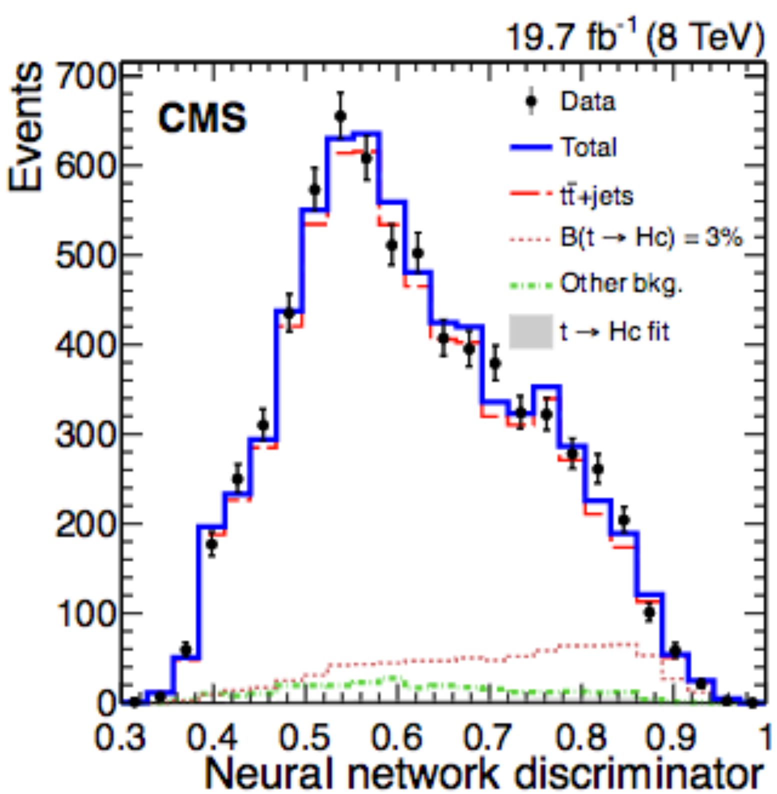
2. $M_{\gamma\gamma}$ fits



leptonic channel

(similar for the hadronic channel)

3. NN discriminator fit



No excess found ⟹ 95% CL exclusion limits on BR (combined channels)

$$\mathcal{B}(t \rightarrow Hc) < 0.40\% \ @ \ 95\%CL \ (0.43\% \ exp)$$

$$\mathcal{B}(t \rightarrow Hu) < 0.55\% \ @ \ 95\%CL \ (0.40\% \ exp)$$

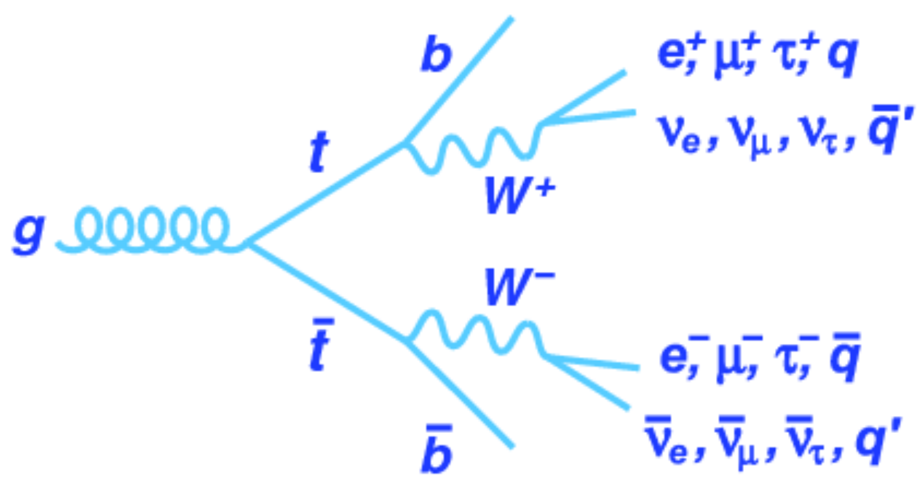
Conclusions

- LHC is a top factory which enables precision measurements which can challenge the Standard Model
- Extensions of the SM affect the **Wtb** vertex coupling and the top quark decay BR's
- No significant deviation found *so far* w.r.t. theoretical expectations …
- … but the search continues increasing statistics (Run 2) and attacking systematic uncertainties *(see E. Yazgan's talk)*

Backup

The top quark at LHC

$pp \rightarrow t\bar{t} \rightarrow W^+ b W^- \bar{b}$



Physics objects:

- isolated energetic e or μ
- energetic jets
- b-tagged jets
- momentum imbalance (MET)

- **LHC is a top factory**
  - ≈5 million pairs per experiment in 2012, ≈30 million in 2016, each **t** decays ≈100% to **W+b**
  - single top EWK production ($\sigma_t \sim \sigma_{tt}/3$)

- **Characterized by W decays**

  – lepton + jets (LJ, BR(LJ)≈30%, golden channel, good yield and good S/B)

  – dilepton (DIL, BR(DIL)≈5%, low yield, better S/B)

  – all-jets (AJ, BR(AJ)≈45%, max yield, large bkgd)

All of them useful for completeness and with (some) uncorrelated systematics