Discussion on the physics of Four Tops, February 19th 2021 @ CERN

Topping-up multilepton plus b-jets anomalies at the LHC with a Z' boson

Ezequiel Alvarez[a], Aurelio Juste[b,c], **Manuel Szewc**[a] , Tamara Vazquez Schroeder[d]

Based on arxiv:2011.06514

(a) ICAS) UNSAM & CONICET (b) IFAE, Universitat Autonoma de Barcelona (c) ICREA (d) CERN

In this talk:

We propose a purely phenomenological BSM model, where a Z' spin-1 boson with mass below 1 TeV is responsible for reported discrepancies in $t\bar{t}H$ and four-top-quarks searches.

We design this model with a particular coupling structure as it is able to provide both charge asymmetry and high b-jet multiplicity, key ingredients to accommodate the different experimental signatures.

We explore how a global search which encompasses both regions could probe this model (and distinguish between different BSM hypotheses).

Four Tops: a potential BSM window (one of the few!)

An increasingly sensitive SM benchmark to be explored at the LHC, with huge experimental effort and impressive results (see S. Berlendis and E. Usai's talks)

Correspondingly, state of the art calculations and improvement of SM predictions (see R. Frederix's talk)

A theoretically well motivated (but perhaps more importantly, still allowed) window to BSM effects (see T. Theil, K. Mimasu and L. Darmé's talks).

But let’s take a detour: $t\bar{t}W^{\pm}$

$t\bar{t}W^{\pm}$ is an irreducible background in four-top-quarks searches,

There has been a consistent tension in $t\bar{t}W^{\pm}$ signal strength:

- In direct measurements: e.g. arXiv:1901.03584, arXiv:1711.02547
- As an irreducible background in $t\bar{t}H$ multilepton searches: e.g. https://cds.cern.ch/record/2693930, arXiv:2011.03652.
- Also an important background in four-top-quarks searches where $t\bar{t}W^{\pm}$ + heavy-flavour is irreducible: e.g. arXiv:2007.14858, arXiv:1908.06463

It could be a mixture of missing theoretical uncertainties and statistical fluctuations

But let's take a detour: $t\bar{t}W^{\pm}$

YR4: cross-section reported in arXiv:1610.07922. It's 600.8 fb

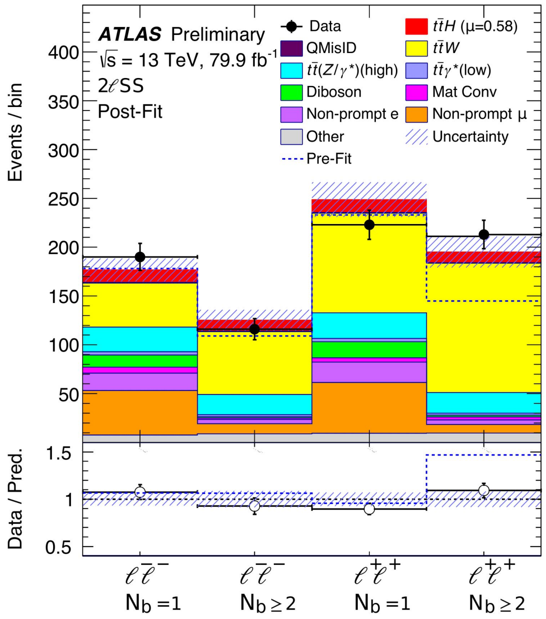
Search	$\mathcal{L}$ [fb^{-1}]	σ_{ref} [pb]	μ or NF	μ_{YR4} or NF$_{YR4}$
$t\bar{t}W$ ATLAS	36.1	0.60±0.07	1.44±0.32	1.44±0.32
$t\bar{t}W$ CMS	35.9	0.628±0.082	$1.23^{+0.3}_{-0.28}$	$1.29^{+0.31}_{-0.29}$
$t\bar{t}H$ ATLAS	80	0.727±0.092	$1.39^{+0.17}_{-0.16}$	$1.68^{+0.21}_{-0.19}$
$t\bar{t}H$ CMS	137	0.650	1.43±0.21	1.55±0.23
4-tops ATLAS	139	0.601	1.6±0.3	1.6±0.3
4-tops CMS	137	0.610	1.3±0.2	1.3±0.2

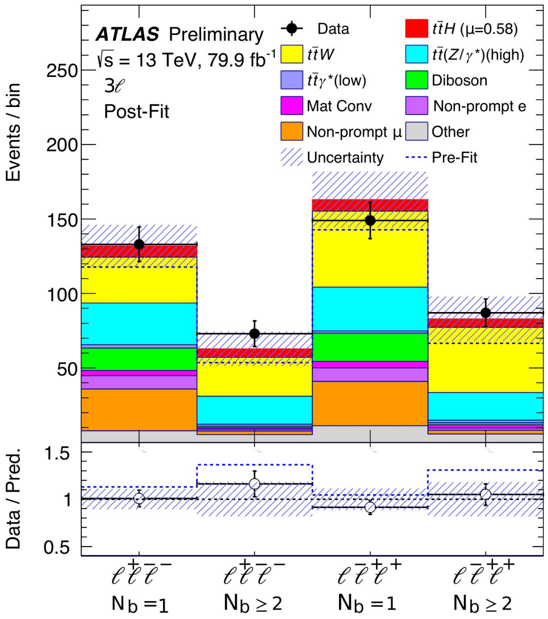
But let's take a detour: $t\bar{t}W^{\pm}$

It's all multilepton with high b-jet multiplicity!

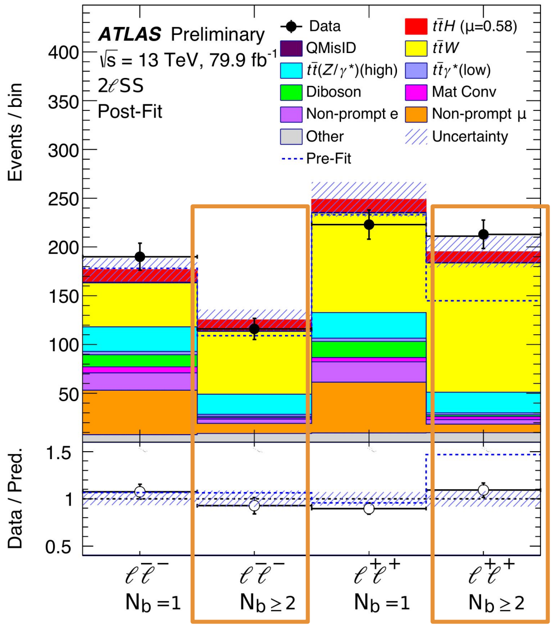
Search	$\mathcal{L}$ [fb^{-1}]	σ_{ref} [pb]	μ or NF	μ_{YR4} or NF_{YR4}
$t\bar{t}W$ ATLAS	36.1	0.60±0.07	1.44±0.32	1.44±0.32
$t\bar{t}W$ CMS	35.9	0.628±0.082	$1.23^{+0.3}_{-0.28}$	$1.29^{+0.31}_{-0.29}$
$t\bar{t}H$ ATLAS	80	0.727±0.092	$1.39^{+0.17}_{-0.16}$	$1.68^{+0.21}_{-0.19}$
$t\bar{t}H$ CMS	137	0.650	1.43±0.21	1.55±0.23
4-tops ATLAS	139	0.601	1.6±0.3	1.6±0.3
4-tops CMS	137	0.610	1.3±0.2	1.3±0.2

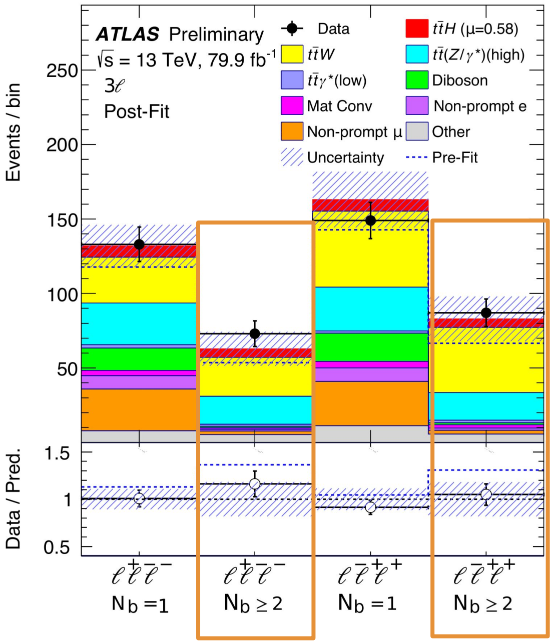
$t\bar{t}$H ATLAS search:





tt̄H ATLAS search:





What if... BSM?

To mimic $t\bar{t}W^{\pm}$, a BSM signal would need to have:

- Charge asymmetry
- High b-jet multiplicity

And such a signal could be present in four-top-quarks final states depending on the available production diagrams. The ATLAS search reports

$$N_{\mathrm{obs}}^{\text{four-tops}} / N_{SM}^{\text{four-tops}} = 2.0^{+0.8}_{-0.6}$$

Our BSM Model: A purely phenomenological FCNC Z'

We consider a top-philic neutral boson with $M_{Z'} > m_t$ with the interaction Lagrangian:

$$\mathcal{L}_{int} \supseteq Z'_\mu \left(g_{ut}\, \bar{t}_R \gamma^\mu u_R + g_{ct}\, \bar{t}_R \gamma^\mu c_R + g_{tt}\, \bar{t}_R \gamma^\mu t_R\right) + \mathrm{h.c.}$$

Our BSM Model: A purely phenomenological FCNC Z’

We consider a top-philic neutral boson with $M_{Z'} > m_t$ with the interaction Lagrangian:

$$\mathcal{L}_{int} \supseteq Z'_\mu \left(g_{ut}\, \bar{t}_R \gamma^\mu u_R + g_{ct}\, \bar{t}_R \gamma^\mu c_R + g_{tt}\, \bar{t}_R \gamma^\mu t_R \right) + \text{h.c.}$$

Charge asymmetric production due to pdf imbalance

Our BSM Model: A purely phenomenological FCNC Z'

We consider a top-philic neutral boson with $M_{Z'} > m_t$ with the interaction Lagrangian:

$$\mathcal{L}_{int} \supseteq Z'_\mu \left(g_{ut}\, \bar{t}_R \gamma^\mu u_R + g_{ct}\, \bar{t}_R \gamma^\mu c_R + g_{tt}\, \bar{t}_R \gamma^\mu t_R \right) + \text{h.c.}$$

Charge symmetric production

Our BSM Model: A purely phenomenological FCNC Z'

We consider a top-philic neutral boson with $M_{Z'} > m_t$ with the interaction Lagrangian:

$$\mathcal{L}_{int} \supseteq Z'_\mu \left(g_{ut}\, \bar{t}_R \gamma^\mu u_R + g_{ct}\, \bar{t}_R \gamma^\mu c_R + g_{tt}\, \bar{t}_R \gamma^\mu t_R \right) + \text{h.c.}$$

Allows four-top-quarks final states and, in conjunction with non-zero g_{ut}/g_{ct}, three-top-quarks final states.

Our BSM Model: A purely phenomenological FCNC Z'

We consider a top-philic neutral boson with $M_{Z'} > m_t$ with the interaction Lagrangian:

$$\mathcal{L}_{int} \supseteq Z'_\mu \left(g_{ut}\, \bar{t}_R \gamma^\mu u_R + g_{ct}\, \bar{t}_R \gamma^\mu c_R + g_{tt}\, \bar{t}_R \gamma^\mu t_R \right) + \text{h.c.}$$

A $t\bar{t}W^{\pm}$-like phenomenology will need g_{ut} for charge asymmetric production. But we also require g_{tt} for high b-jet multiplicity

Our BSM Model: A purely phenomenological FCNC Z'

We consider a top-philic neutral boson with $M_{Z'} > m_t$ with the interaction Lagrangian:

$$\mathcal{L}_{int} \supseteq Z'_\mu \left(g_{ut}\, \bar{t}_R \gamma^\mu u_R + g_{ct}\, \bar{t}_R \gamma^\mu c_R + g_{tt}\, \bar{t}_R \gamma^\mu t_R \right) + \text{h.c.}$$

$g_{ut}, g_{ct} \ll g_{tt}$

Are we dead on arrival due to existing constraints?

We consider $0.0 \leq g_{ut} \leq 0.1$, $0.0 \leq g_{ct} \leq 0.1$ and $0.0 \leq g_{tt} \leq 1.0$. This allows us to evade existing limits:

- Rare top branching ratios are below current limits due to the value of the couplings and the chiral structure.
- The absence of g_{uu} and g_{cc} implies no Z' resonant production
- $t\bar{t}$ non-resonant effects are below experimental uncertainty
- Same-sign top pair production, both prompt and with an associated jet, are suppressed due to our couplings (and that they are optimized for heavier $M_{Z'}$)
- Z' mediated $tj+\bar{t}j$ production is absent due to absent g_{uu}, g_{cc}. Moreover, radiative $tZ'j+\bar{t}Z'j$ production is suppressed due to non-existent left-handed couplings.

Are we dead on arrival due to existing constraints?

D-meson mixing is shown to constrain our parameter space.

Although we do not have an exact SM calculation to use, we ask that the BSM effect is smaller than the experimental uncertainty. We thus find that

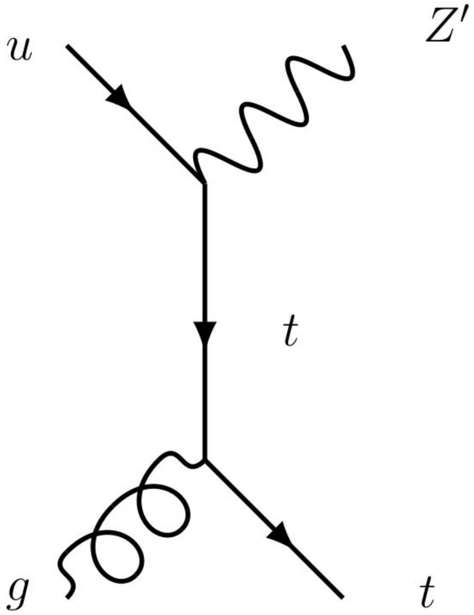
$$g_{ut}\, g_{ct} < 2.0 \times 10^{-3} \text{ to } 4.5 \times 10^{-3}$$

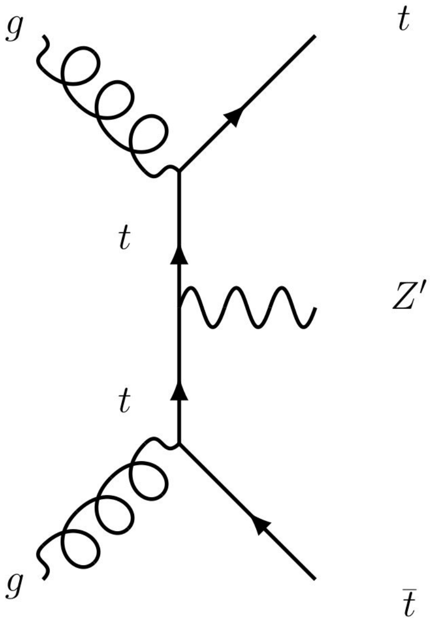
Production cross-sections

We consider two processes: tZ’ and $t\bar{t}$Z’.

- tZ’ will be the main culprit for $t\bar{t}W^{\pm}$ measurements. It is charge asymmetric, driven by g_{ut} and, through the three-top final state, possesses high b-jet multiplicity.
- $t\bar{t}$Z’ populates even higher jet and b-jet multiplicities and is charge symmetric. It will be more important to the four-top final state and is driven by g_{tt}.

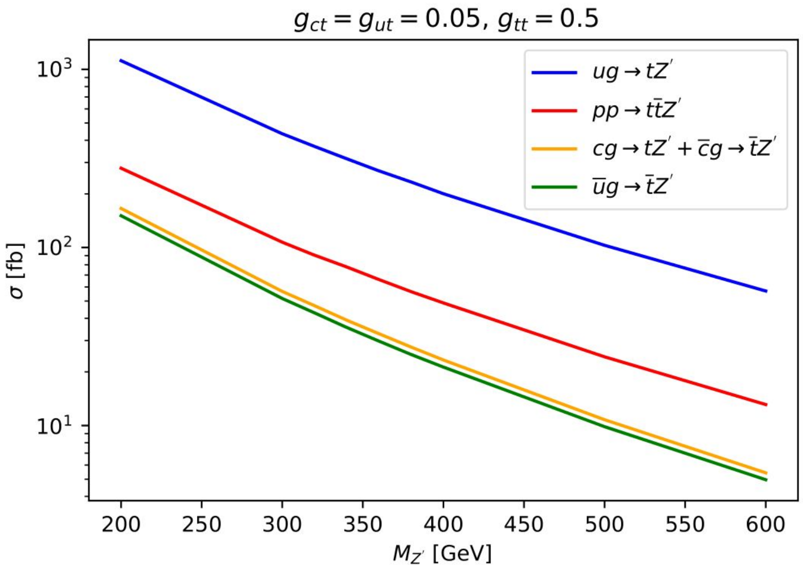
Production cross-sections





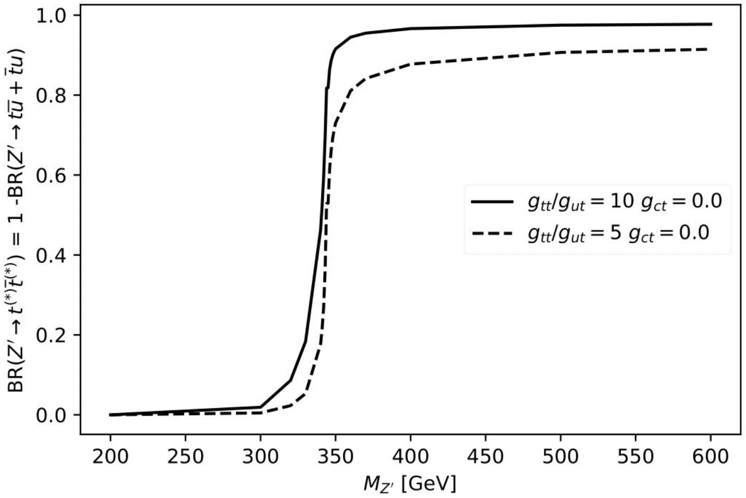
Production cross-sections

Charge asymmetric production dominates even with a large coupling difference due to pdf imbalance and kinematic requirements.



Branching Ratios

Even when $M_{Z'} < 2m_t$, a large enough coupling hierarchy allows three- and four-top-quarks production, ensuring high b-jet multiplicity.



$t\bar{t}W^{\pm}$ region:

We focus on $t\bar{t}H$ searches because they have a higher luminosity than the dedicated $t\bar{t}W^{\pm}$ measurements and the signal region is similar.

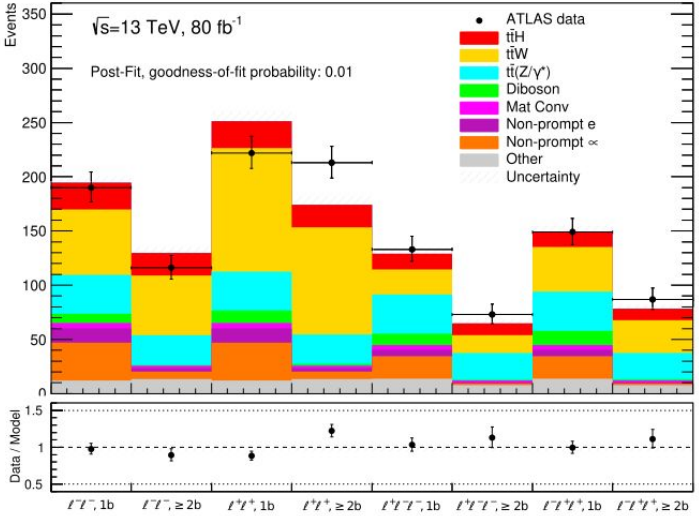
Between both searches, we choose ATLAS in particular because $t\bar{t}H$ ATLAS provides complete information on the multilepton discrepancies observed as a function of the total lepton charge and the b-jet multiplicity of the event

We focus on 2LSS and 3L with no hadronic taus.

tt̄H ATLAS:

The tt̄H ATLAS search provides us with useful data in Fig. 2. The goal is to obtain the point in (g_{ut}, g_{ct}, g_{tt}, $M_{Z'}$) parameter space that best fits the data.

Here we show the SM-only case where we fit the SM Nuisance Parameters to the data.



Four-top-quarks searches

Four-top-quarks searches are sensitive to three- and four-top-quarks final states. Both tZ' and tt̄Z' are important.

From our simulation, we obtain two relevant numbers

$$N_{SM+BSM}^{\text{four-tops}} / N_{SM}^{\text{four-tops}}$$

The event ratio, to be compared to the reported results

$$r(4t) = \frac{N_{SM+BSM}^{\text{four-tops},Q>0}}{N_{SM+BSM}^{\text{four-tops},Q<0}} \frac{N_{SM}^{\text{four-tops},Q<0}}{N_{SM}^{\text{four-tops},Q>0}}$$

The charge imbalance in the estimated events that pass the four-top-quarks analysis selection cuts.

Four-top-quarks searches

Relevant because four-top analyses are currently not able to distinguish between genuine three- and four- top events (the former can be charge asymmetric in our model)

SM: $t\bar{t}t\bar{t}$, BSM: $t\bar{t}t$, $t\bar{t}tj$, $t\bar{t}\bar{t}j$, $t\bar{t}t\bar{t}$

$$r(4t) = \frac{N^{\text{four-tops},Q>0}_{SM+BSM}}{N^{\text{four-tops},Q<0}_{SM+BSM}} \frac{N^{\text{four-tops},Q<0}_{SM}}{N^{\text{four-tops},Q>0}_{SM}}$$

How do we calculate the BSM signal contribution?

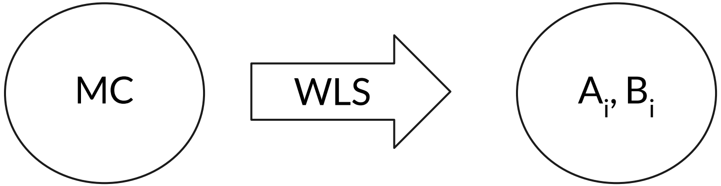
For each $M_{Z'}$ we parametrize the expected events for a given channel (which can be a bin in Fig. 2 of tt̄H ATLAS or the four-tops event yield with positive or negative total charge) as:

$$
\begin{aligned}
N_{tZ'}^{\rm ch} =& A_1^{\rm ch} \cdot BR(Z' \to t\bar{u} + \bar{t}u) \cdot (g_{ut})^2 + A_2^{\rm ch} \cdot BR(Z' \to t\bar{c} + \bar{t}c) \cdot (g_{ut})^2 \\
&+ A_3^{\rm ch} \cdot BR(Z' \to t\bar{t}) \cdot (g_{ut})^2 + A_4^{\rm ch} \cdot BR(Z' \to t\bar{u} + \bar{t}u) \cdot (g_{ct})^2 \\
&+ A_5^{\rm ch} \cdot BR(Z' \to t\bar{c} + \bar{t}c) \cdot (g_{ct})^2 + A_6^{\rm ch} \cdot BR(Z' \to t\bar{t}) \cdot (g_{ct})^2, \\
N_{t\bar{t}Z'}^{\rm ch} =& B_1^{\rm ch} \cdot BR(Z' \to t\bar{u} + \bar{t}u) \cdot (g_{tt})^2 + B_2^{\rm ch} \cdot BR(Z' \to t\bar{c} + \bar{t}c) \cdot (g_{tt})^2 \\
&+ B_3^{\rm ch} \cdot BR(Z' \to t\bar{t}) \cdot (g_{tt})^2,
\end{aligned}
$$

Where A_i, B_i are functions of $M_{Z'}$ and absorb the acceptance of the channel and the cross-section for the specific process normalized to the corresponding coupling set to unity

How do we calculate the BSM signal contribution?

Using this parametrization, we can use a relatively small set of points in (g_{ut}, g_{ct}, g_{tt}) parameter space and obtain the A_i and B_i coefficients using a Weighted Least Squares that takes into account the MC finite sampling.



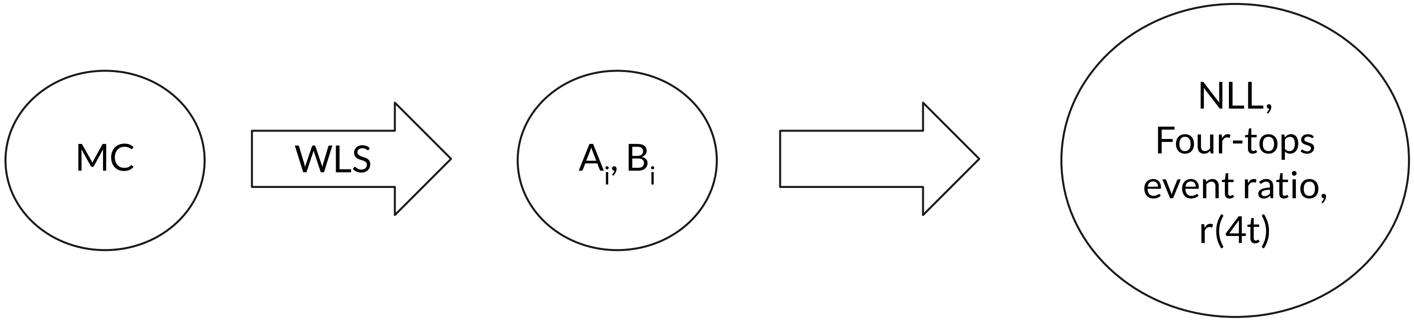
How do we perform the fit?

Once we have the A_i, B_i coefficients, we generate a grid in parameter space and obtain the Negative Log-Likelihood for the eight bins of $t\bar{t}H$ data, the four-tops event ratio and four-tops charge imbalance.

We consider NLL alone and in combination with the four-tops event ratio as:

$$\mathrm{NLL}(t\bar{t}H) + \frac{(N_{SM+BSM}^{\text{four-tops}}/N_{SM}^{\text{four-tops}} - N_{\text{obs}}^{\text{four-tops}}/N_{SM}^{\text{four-tops}})^2}{\sigma^2}$$

How do we perform the fit?

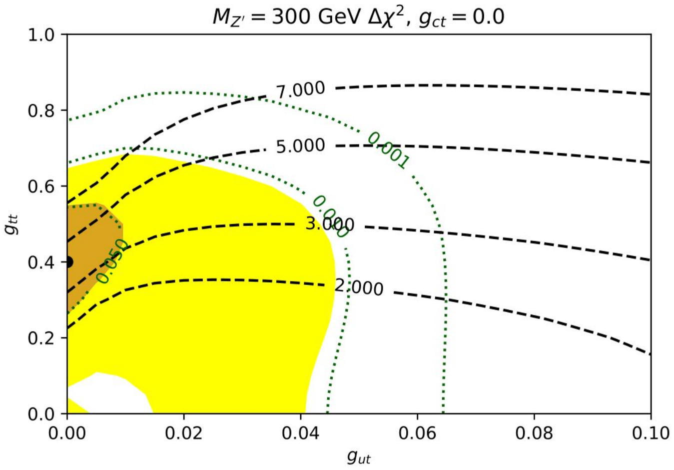


How do we perform the fit?

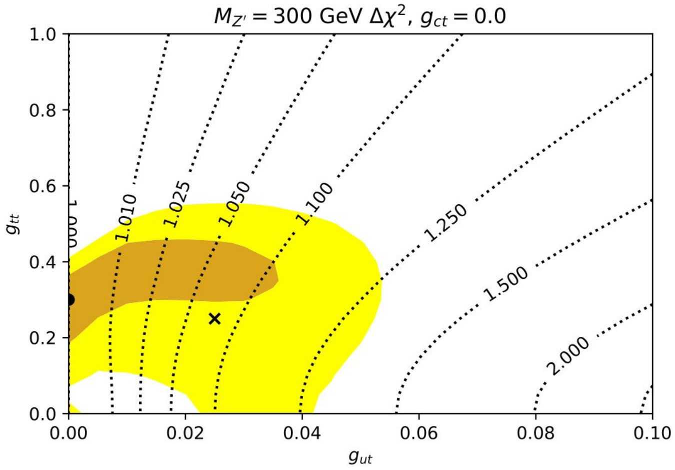
We consider $M_{Z'}$ = 200, 300, 400, 500 and 600 GeV.

As we are interested in charge asymmetry with high b-jet multiplicity, we first study the case with $g_{ct} = 0$ and then explore g_{ct} for a fixed g_{tt}.

Plots

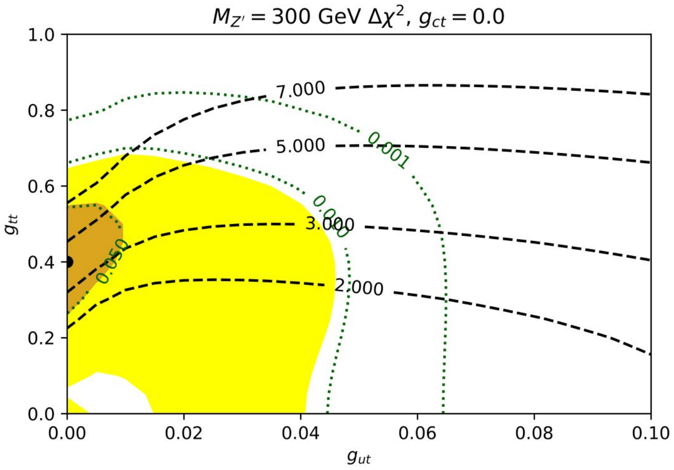


$M_{Z'} = 300$ GeV $\Delta\chi^2$, $g_{ct} = 0.0$
7.000
5.000
3.000
2.000
0.001
0.000
0.050
g_{tt}
g_{ut}



$M_{Z'} = 300$ GeV $\Delta\chi^2$, $g_{ct} = 0.0$
1.010
1.025
1.050
1.100
1.250
1.500
2.000
g_{tt}
g_{ut}

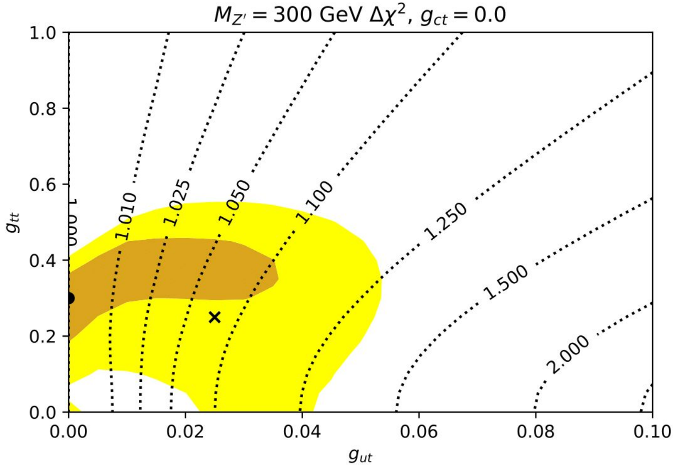
Plots



- black dot is NLL($t\bar{t}H$) minimum.
- Gold (yellow) region is the 1 (2) s.d. from the minimum
- Green dotted curve is the goodness-of-fit
- Black dashed curve is the four tops event ratio

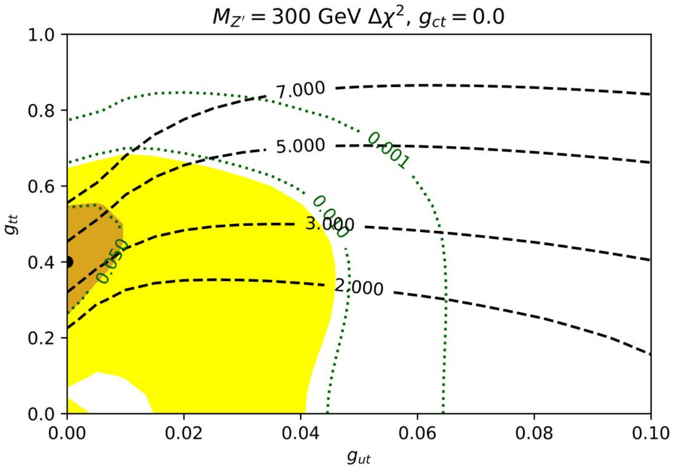
Plots

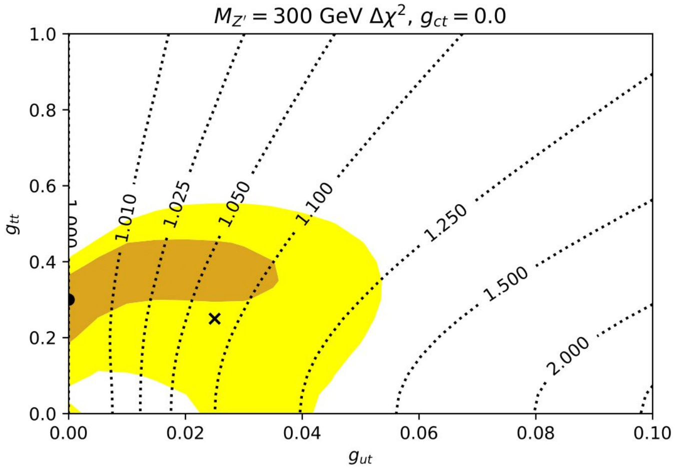
- black dot is NLL($t\bar{t}H$)+ATLAS four-top-quarks minimum
- Gold (yellow) region is the 1 (2) s.d. from the minimum
- black cross is NLL($t\bar{t}H$)+ATLAS and CMS combination four-top-quarks minimum.
- Black dotted curve is the four tops charge imbalance r(4t)



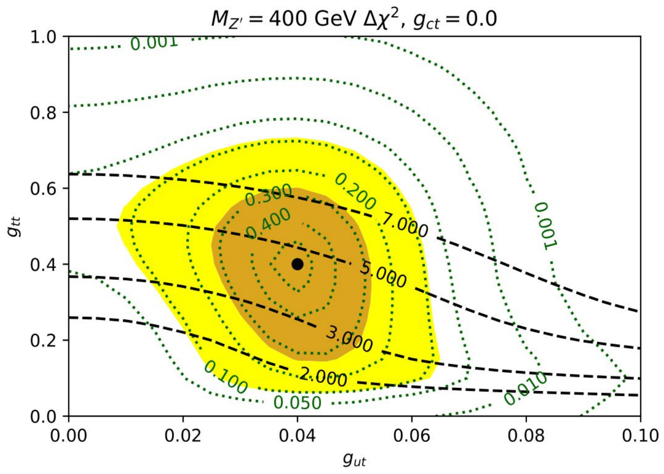
Plots

For $M_{Z'} < 2m_t$, the fit is compatible with no charge asymmetry.

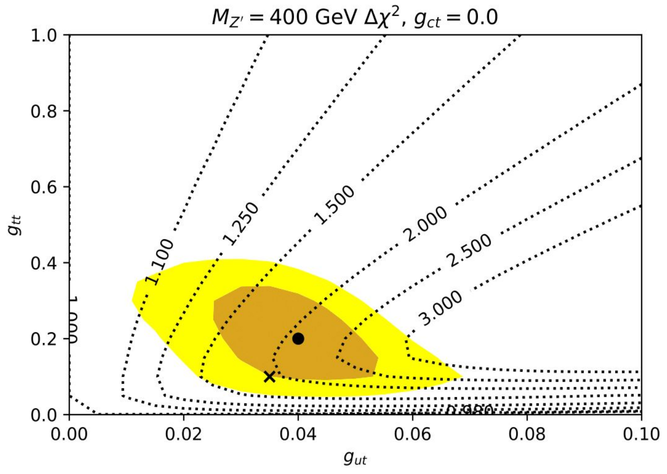




Plots



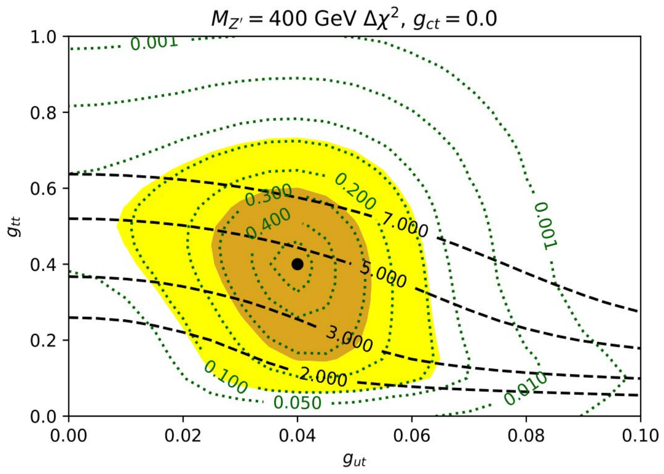
$M_{Z'} = 400$ GeV $\Delta\chi^2$, $g_{ct} = 0.0$
g_{tt}
g_{ut}
0.001
0.200
0.300
0.400
7.000
5.000
3.000
2.000
0.100
0.050
0.010

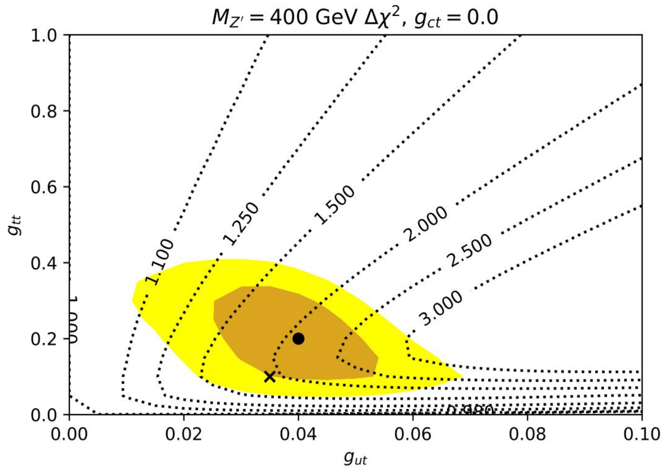


$M_{Z'} = 400$ GeV $\Delta\chi^2$, $g_{ct} = 0.0$
g_{tt}
g_{ut}
1.100
1.250
1.500
2.000
2.500
3.000

Plots

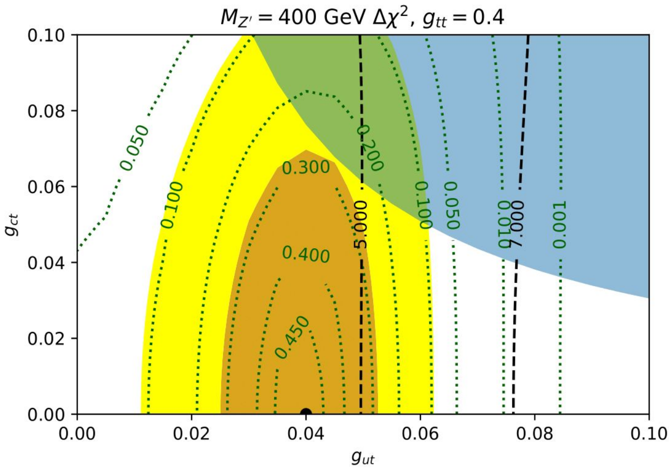
For $M_{Z'} > 2m_t$, the fit is much better. Four-top-quarks mostly constrain g_{tt}. r(4t) would be a very useful handle!

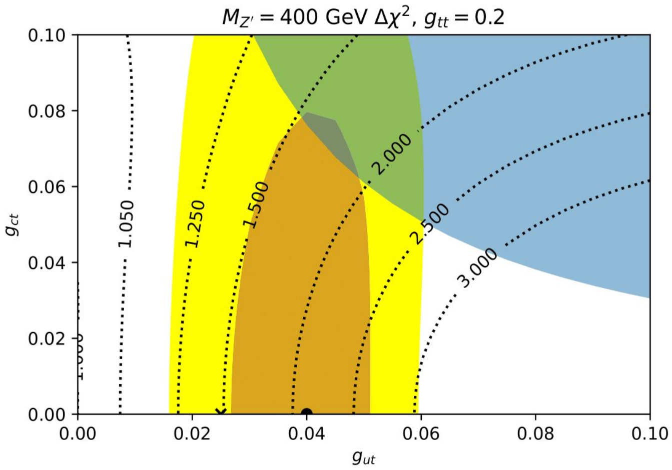




Plots

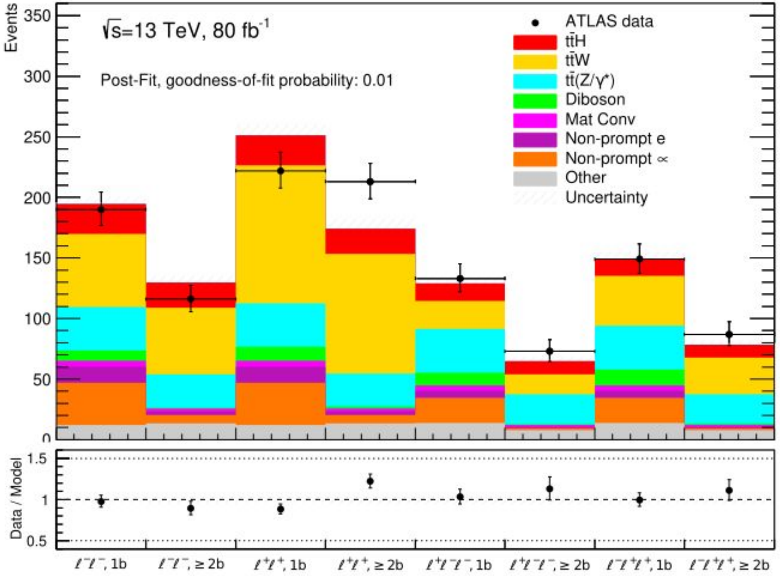
Exploring $g_{ct} > 0$ worsens the fit (although data is compatible with $g_{ct} \sim g_{ut}$), as it reduces both charge asymmetry and b-jet multiplicity. We also risk running into meson mixing constraints.



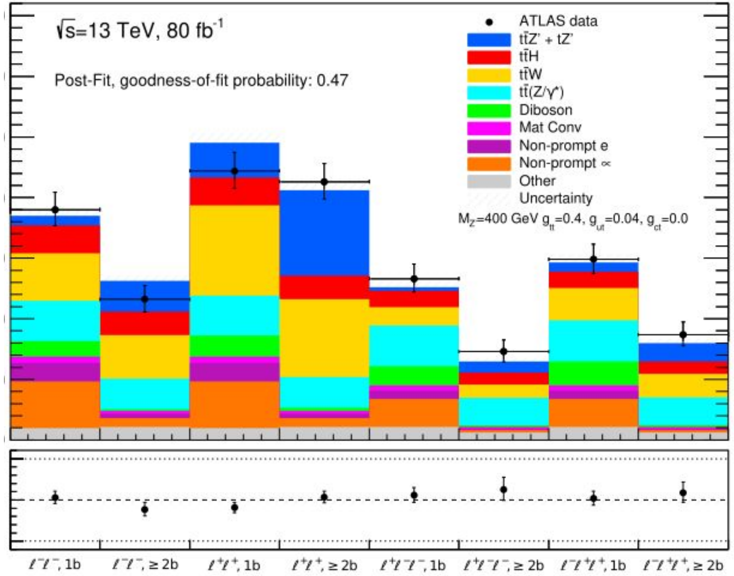


Taking the best fit point for $t\bar{t}H$

SM



SM+BSM



So...

We have showed how a relatively light resonance between 400 and 500 GeV could easily hide in $t\bar{t}W^{\pm}$, $t\bar{t}H$ and four-top-quarks searches.

This light resonance could be confused with the need of scaling up the SM processes.

We can go further!

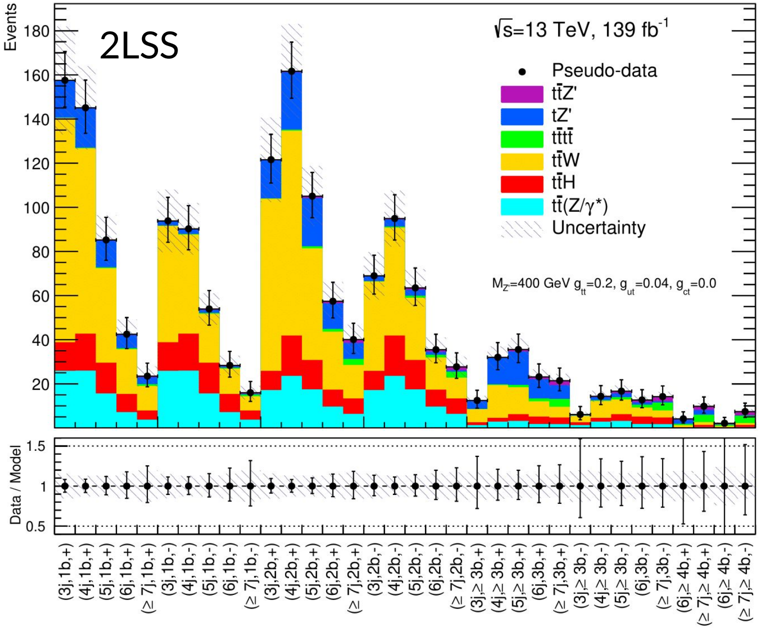
A global search, which encompasses $t\bar{t}W^{\pm}$ and four-top-quarks regions could provide a greater clarity. We use N_j, N_b and Q_{lep} to define bins in a global search both for 2LSS and 3L

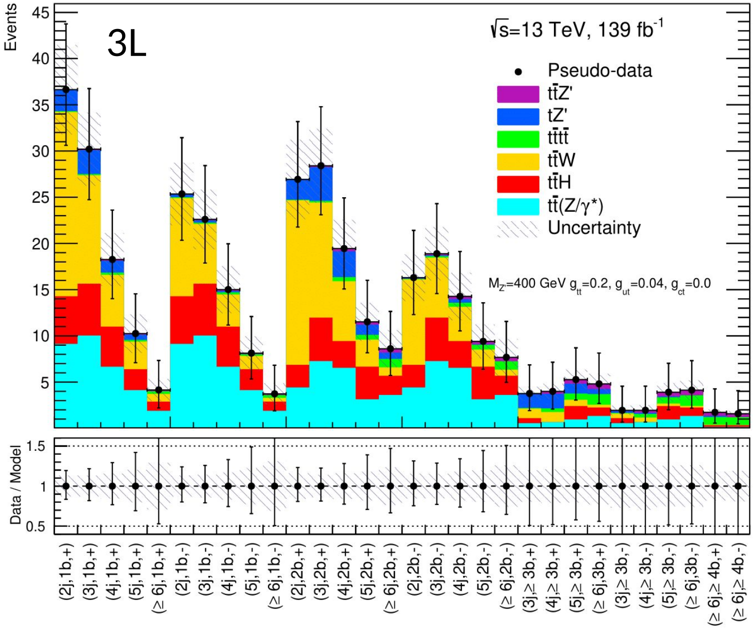
2LSS: Two same-sign leptons, at least 3 jets and at least 1 b-jet

3L: (Exactly) Three leptons, at least 2 jets and at least 1 b-jet

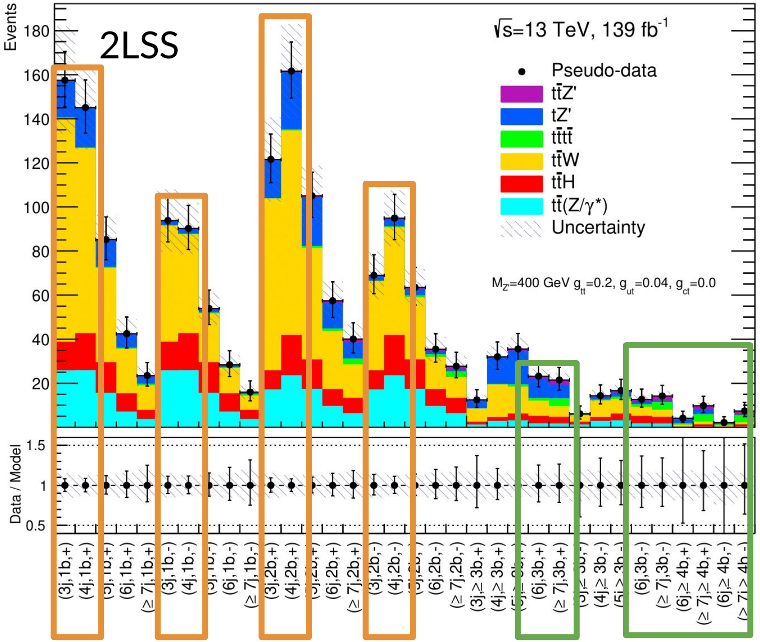
No H_T cuts

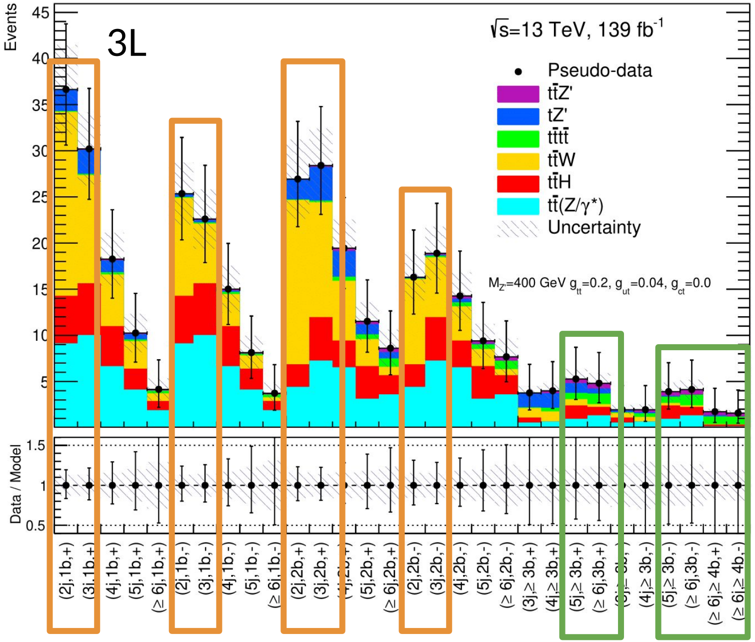
A global picture





A global picture



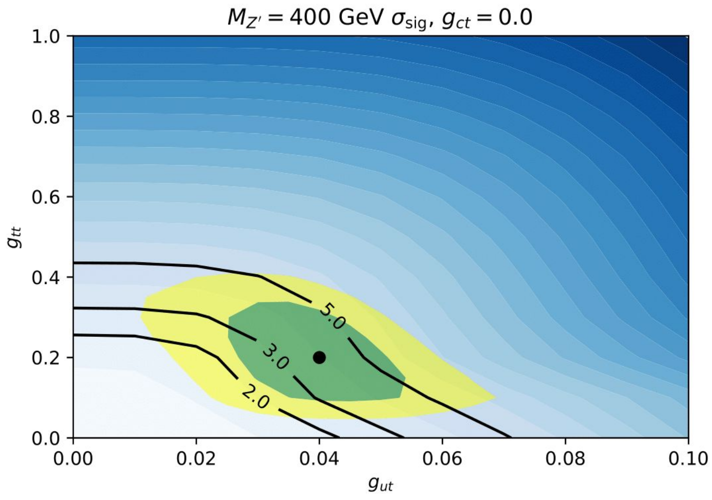


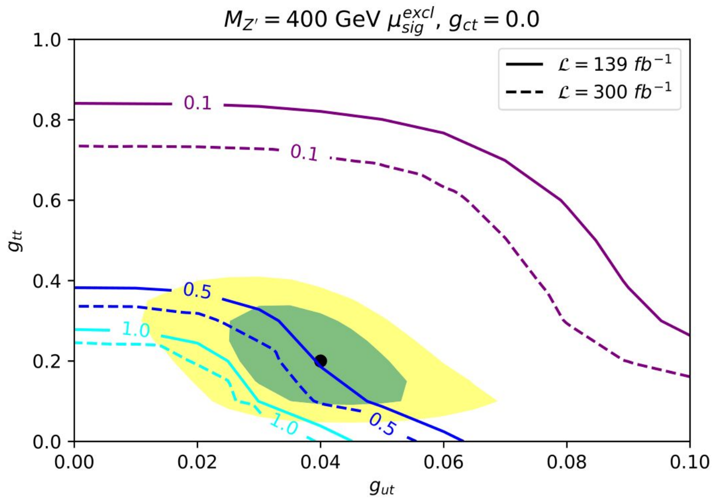
A global picture

We see how tZ' can "hide" in $t\bar{t}W^{\pm}$ and $t\bar{t}Z'$ can "hide" in four-top-quarks, but there are other bins which can be useful to disentangle the different processes involved.

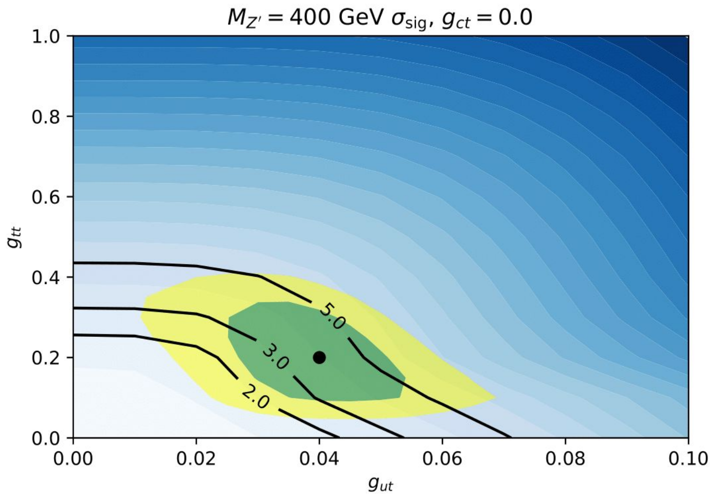
We generate arbitrary points in parameter space for $M_{Z'}$= 400 GeV and g_{ct} = 0.0 as before and, with the help of an Asimov dataset, we can obtain the expected significance and the expected exclusion limits. We consider the integrated luminosity for the full Run-2 dataset (139 fb^{-1}) and the expected Run-2 + Run-3 datasets (300 fb^{-1})

A global picture





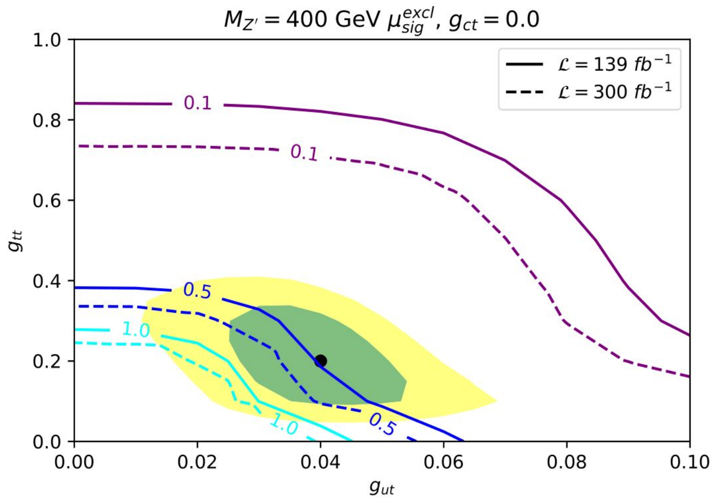
A global picture



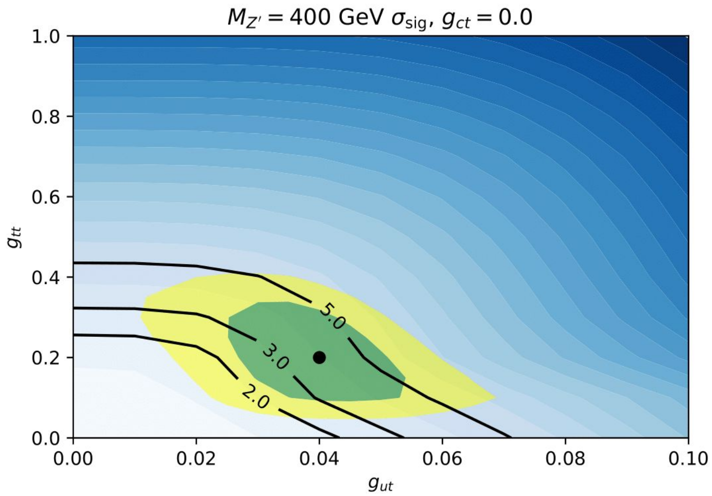
Expected significance using global bins for 139 fb^{-1}. Underlying we show the $t\bar{t}H$ + ATLAS four-top-quarks 1 and 2 s.d. regions.

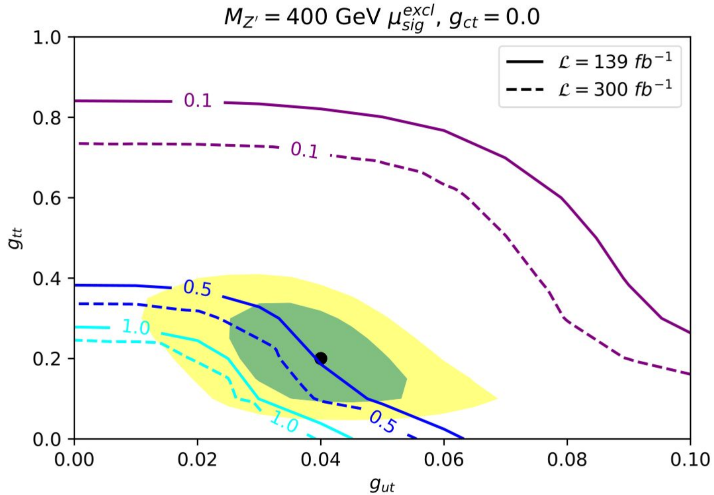
A global picture

Expected exclusion limits on μ using global bins. Solid (dashed) lines are limits set with 139 fb^{-1} (300 fb^{-1}). Underlying we show the $t\bar{t}H$ + ATLAS four-top-quarks 1 and 2 s.d. regions.



A global picture





A global picture

We can define two signal enriched regions:

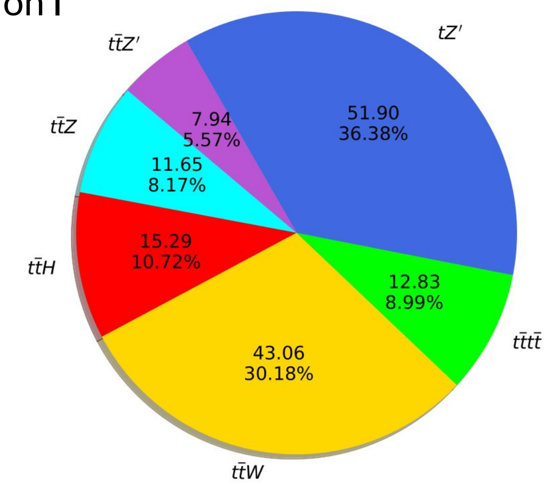
Region I, 2LSS (3L): $N_j \geq 4(3)$, $N_b \geq 3$ and $Q_{lep} = +2(+1)$,

Region II, 2LSS (3L): $N_j \geq 7(5)$, $N_b \geq 3$ and $Q_{lep} = \pm 2(\pm 1)$.

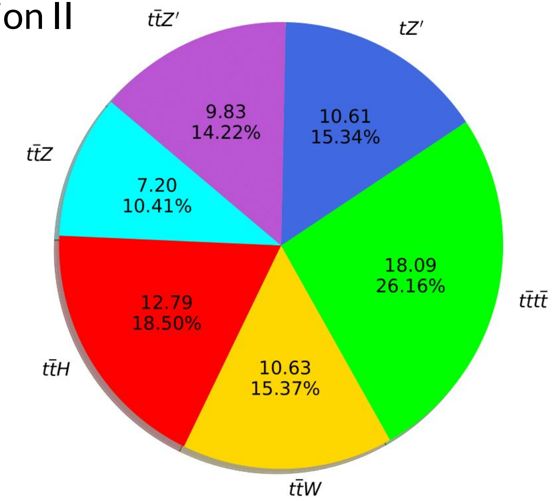
Region I is more sensitive to tZ' while Region II is more sensitive to $t\bar{t}$Z'.

A global picture

Region I



Region II



A global picture

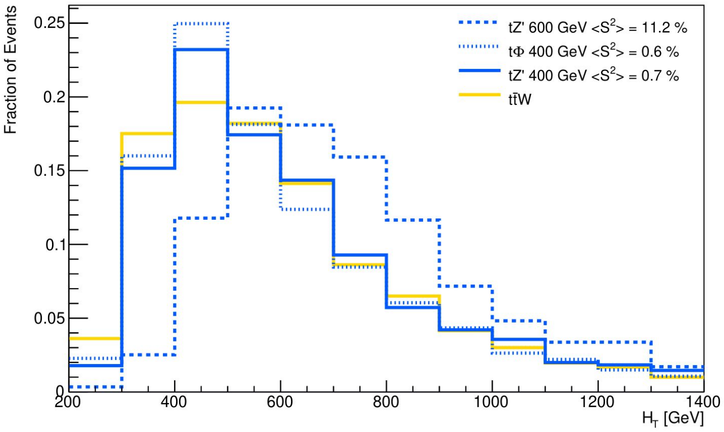
For these Regions we study the different kinematical variables and their densities for each process.

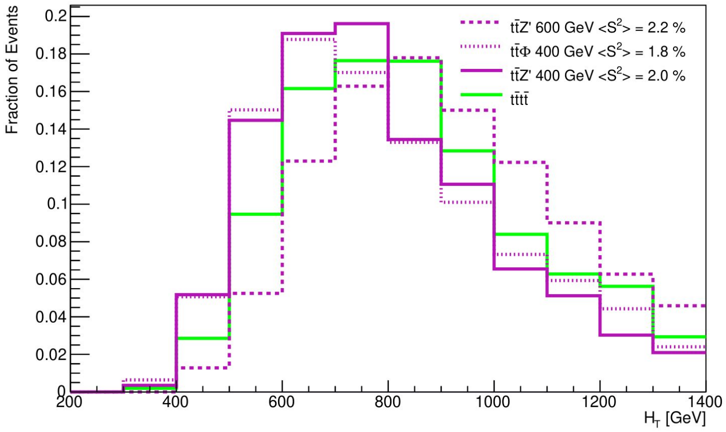
We include also a scalar boson with same mass and coupling values to see how the observables can also tell apart different BSM hypotheses.

We compute the separation power of the variables we could use with:

$$\text{Separation} = \langle S^2 \rangle = \frac{1}{2} \sum_{i=1}^{N_{\text{bins}}} \frac{\left(f_i^{\text{sig}} - f_i^{\text{bkg}} \right)^2}{f_i^{\text{sig}} + f_i^{\text{bkg}}}$$

H_T distribution in Regions I and II





A nice variable to tell things apart: MaxMin(ℓ,b)

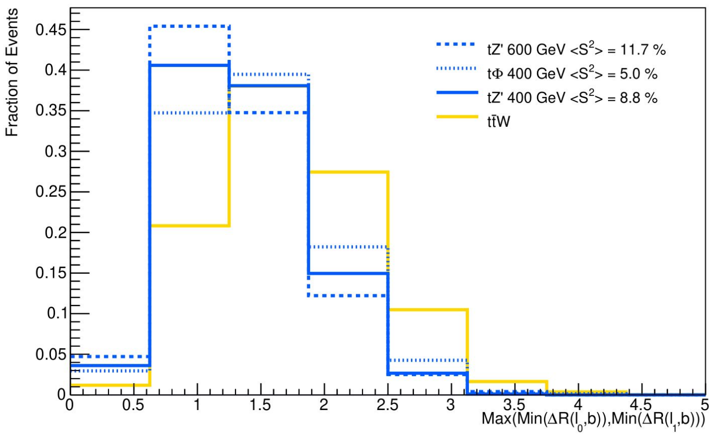
MaxMin(ℓ, b) = The maximum of the minimum ΔR-distances between the same-sign leptons and a b-jet.

We expect it to discriminate between tZ’ and $t\bar{t}W^{\pm}$. In tZ’ all leptons come from top quarks while in $t\bar{t}W^{\pm}$ there is a lepton coming from a prompt $W^{\pm}$ boson and which should not be associated with a b-jet.

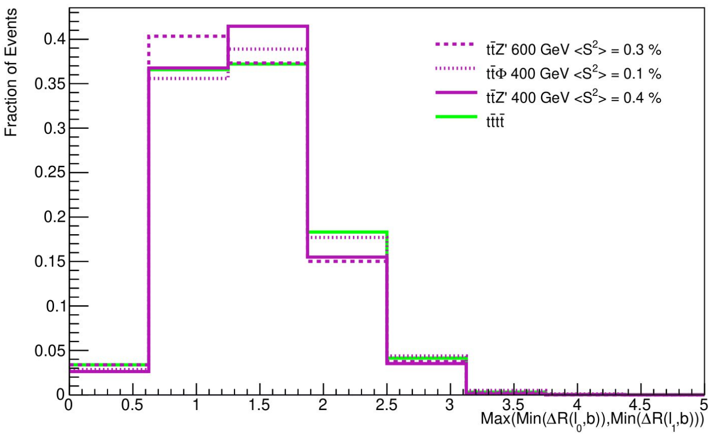
A nice variable to tell things apart: MaxMin(ℓ,b)

MaxMin(ℓ, b) = The maximum of the minimum ΔR-distances between the same-sign leptons and a b-jet.

Region I



Region II



Conclusions:

We have proposed a phenomenological FCNC Z’ model that couples hierarchically to the up-type right-handed quarks to explain LHC discrepancies in multilepton plus b-jet final states.

We have found regions in parameter space that fit the data better than the SM and proposed different ways to explore the data to test the BSM Z’ model.

We find that a more inclusive experimental search, along the lines of our proposed global analysis could in the near future shed light on the existence of such a BSM scenario


Thank you!
©QUINO

Extra slides

$t\bar{t}$H: ATLAS vs CMS selection differences

$t\bar{t}H$	ATLAS		CMS	
	2LSS	3L	2LSS	3L
Total lepton charge	± 2	± 1	± 2	± 1
Lepton p_T [GeV]	20/20	15/15/10	25/15	25/15/10
Number of jets	≥ 2		≥ 3	≥ 2
Number of b-jets	≥ 1 (70% eff.)		≥ 1 (70% eff.) OR ≥ 2 (84% eff.)	
$\lvert m_{\ell\ell}\rvert$ (2LSS) or $\lvert m_{OSSF}\rvert$ (3L) [GeV]	> 12			
$\lvert m_{e^\pm e^\pm} - m_Z\rvert$ (2LSS) or $\lvert m_{OSSF} - m_Z\rvert$ (3L) [GeV]	-	> 10		
Other		$\lvert m_{\ell\ell\ell} - m_Z\rvert > 10$ GeV	Missing transverse momentum cuts	

$t\bar{t}H$: ATLAS vs CMS selection differences

- Different fake estimation techniques (simultaneous prole likelihood template fit in ATLAS vs misidentification probability method in CMS)
- Different analysis strategies (jet multiplicity, total lepton charge and BDT categorisation in ATLAS vs Deep Neural Networks in CMS)

Fit to Fig. 2 $t\bar{t}H$ ATLAS:

There is no free-floating NF for $t\bar{t}W^{\pm}$. We fix the $t\bar{t}W^{\pm}$ normalization to the reported cross-section and consider Nuissance parameters to account for systematic uncertainties in on the overall normalization of each process.

We consider 20% uncertainty for $t\bar{t}W^{\pm}$, $t\bar{t}Z$, $t\bar{t}H$ and signal and 50% uncertainty for diboson.

The various fake lepton components have uncertainties assigned corresponding to the normalisation factor precision reported in the ATLAS result.

Four-top-quarks: ATLAS vs CMS selection differences

four-top-quarks	ATLAS		CMS	
	2LSS	$\geq$ 3L	2LSS	$\geq$ 3L
Total lepton charge	± 2	-	± 2	-
Lepton p_T [GeV]	28 (all ℓ)		$25/20$	$25/20/20(/20)$
Number of jets and b-jets	$\geq$ 6j $\geq$ 2bj (77% eff.)		$\geq$ 6j $\geq$ 2bj OR 5j $\geq$ 3bj (55-70% eff.)	$\geq$ 5j $\geq$ 2bj OR 4j $\geq$ 3bj (55-70% eff.)
H_T [GeV]	> 500		> 300	
$\lvert m_{e^\pm e^\pm}\rvert$ (2LSS) or $\lvert m_{OSSF}\rvert$ (3L) [GeV]	> 15	-	> 12	
$\lvert m_{e^\pm e^\pm} - m_Z\rvert$ (2LSS) or $\lvert m_{OSSF} - m_Z\rvert$ (3L) [GeV]	> 10		-	> 15
Other			Missing transverse momentum cuts	

How do we calculate the BSM signal contribution?

A_i, B_i are functions of $M_{Z'}$ and absorb the acceptance of the channel and the cross-section for the specific process normalized to the corresponding coupling set to unity

$$
\begin{aligned}
N^{\mathrm{ch}}_{tZ'} =& A^{\mathrm{ch}}_1 \cdot BR(Z' \to t\bar{u} + \bar{t}u) \cdot (g_{ut})^2 + A^{\mathrm{ch}}_2 \cdot BR(Z' \to t\bar{c} + \bar{t}c) \cdot (g_{ut})^2 \\
&+ A^{\mathrm{ch}}_3 \cdot BR(Z' \to t\bar{t}) \cdot (g_{ut})^2 + A^{\mathrm{ch}}_4 \cdot BR(Z' \to t\bar{u} + \bar{t}u) \cdot (g_{ct})^2 \\
&+ A^{\mathrm{ch}}_5 \cdot BR(Z' \to t\bar{c} + \bar{t}c) \cdot (g_{ct})^2 + A^{\mathrm{ch}}_6 \cdot BR(Z' \to t\bar{t}) \cdot (g_{ct})^2, \\
N^{\mathrm{ch}}_{t\bar{t}Z'} =& B^{\mathrm{ch}}_1 \cdot BR(Z' \to t\bar{u} + \bar{t}u) \cdot (g_{tt})^2 + B^{\mathrm{ch}}_2 \cdot BR(Z' \to t\bar{c} + \bar{t}c) \cdot (g_{tt})^2 \\
&+ B^{\mathrm{ch}}_3 \cdot BR(Z' \to t\bar{t}) \cdot (g_{tt})^2,
\end{aligned}
$$

Charge asymmetric

How do we calculate the BSM signal contribution?

A_i, B_i are functions of $M_{Z'}$ and absorb the acceptance of the channel and the cross-section for the specific process normalized to the corresponding coupling set to unity

$$\begin{aligned}
N^{\text{ch}}_{tZ'} =& A^{\text{ch}}_1 \cdot BR(Z' \to t\bar{u} + \bar{t}u) \cdot (g_{ut})^2 + A^{\text{ch}}_2 \cdot BR(Z' \to t\bar{c} + \bar{t}c) \cdot (g_{ut})^2 \\
&+ A^{\text{ch}}_3 \cdot BR(Z' \to t\bar{t}) \cdot (g_{ut})^2 + A^{\text{ch}}_4 \cdot BR(Z' \to t\bar{u} + \bar{t}u) \cdot (g_{ct})^2 \\
&+ A^{\text{ch}}_5 \cdot BR(Z' \to t\bar{c} + \bar{t}c) \cdot (g_{ct})^2 + A^{\text{ch}}_6 \cdot BR(Z' \to t\bar{t}) \cdot (g_{ct})^2, \\
N^{\text{ch}}_{t\bar{t}Z'} =& B^{\text{ch}}_1 \cdot BR(Z' \to t\bar{u} + \bar{t}u) \cdot (g_{tt})^2 + B^{\text{ch}}_2 \cdot BR(Z' \to t\bar{c} + \bar{t}c) \cdot (g_{tt})^2 \\
&+ B^{\text{ch}}_3 \cdot BR(Z' \to t\bar{t}) \cdot (g_{tt})^2,
\end{aligned}$$

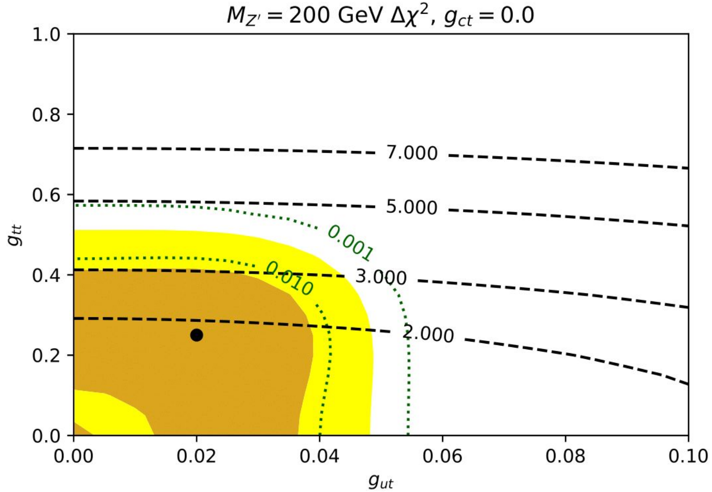
High b-jet multiplicity

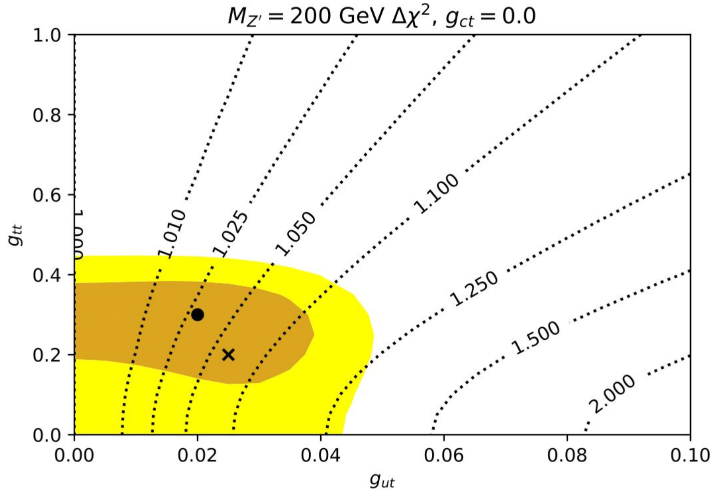
How do we calculate the BSM signal contribution?

Parameter specific production and decay

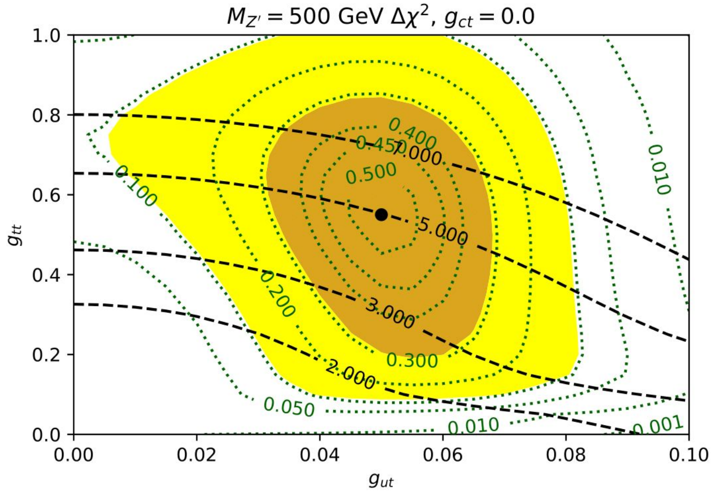
$$
\begin{aligned}
N^{\text{ch}}_{tZ'} =& A^{\text{ch}}_1 \cdot BR(Z' \to t\bar{u} + \bar{t}u) \cdot (g_{ut})^2 + A^{\text{ch}}_2 \cdot BR(Z' \to t\bar{c} + \bar{t}c) \cdot (g_{ut})^2 \\
&+ A^{\text{ch}}_3 \cdot BR(Z' \to t\bar{t}) \cdot (g_{ut})^2 + A^{\text{ch}}_4 \cdot BR(Z' \to t\bar{u} + \bar{t}u) \cdot (g_{ct})^2 \\
&+ A^{\text{ch}}_5 \cdot BR(Z' \to t\bar{c} + \bar{t}c) \cdot (g_{ct})^2 + A^{\text{ch}}_6 \cdot BR(Z' \to t\bar{t}) \cdot (g_{ct})^2, \\
N^{\text{ch}}_{t\bar{t}Z'} =& B^{\text{ch}}_1 \cdot BR(Z' \to t\bar{u} + \bar{t}u) \cdot (g_{tt})^2 + B^{\text{ch}}_2 \cdot BR(Z' \to t\bar{c} + \bar{t}c) \cdot (g_{tt})^2 \\
&+ B^{\text{ch}}_3 \cdot BR(Z' \to t\bar{t}) \cdot (g_{tt})^2,
\end{aligned}
$$

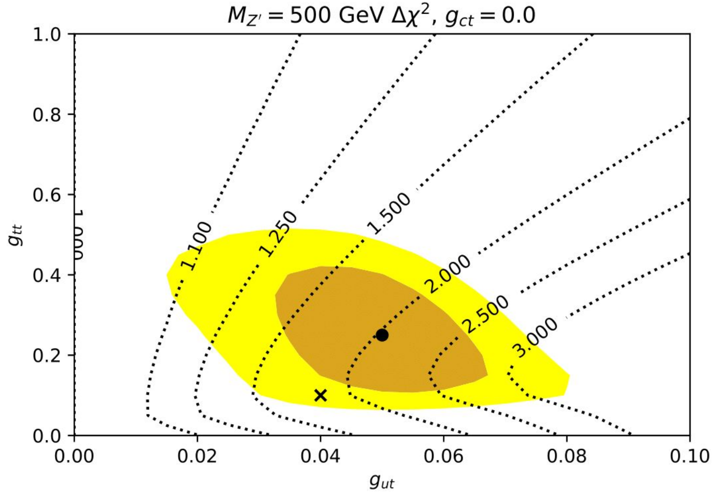
The other masses:



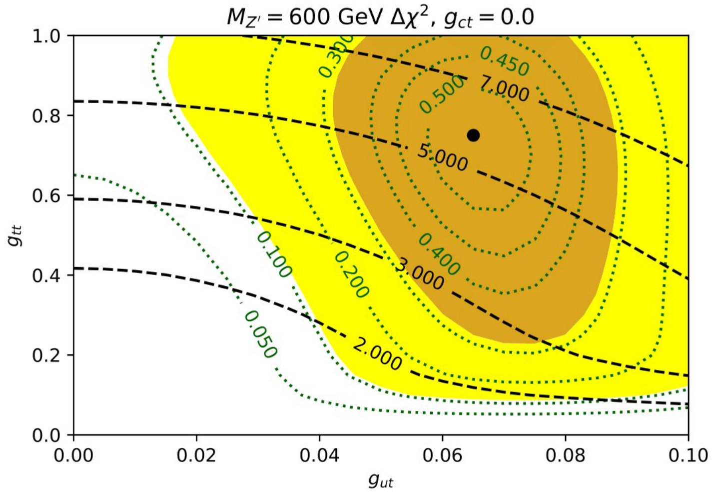


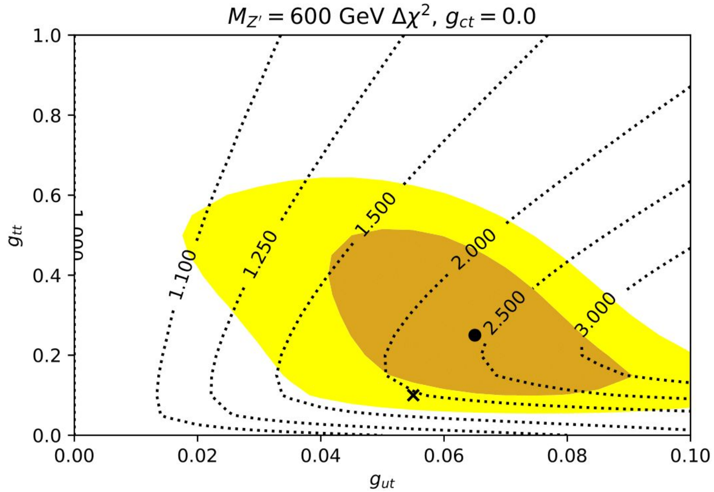
The other masses:



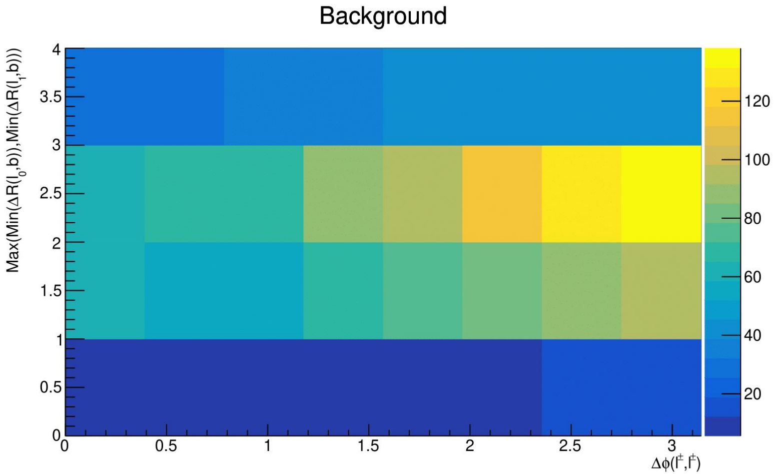


The other masses:

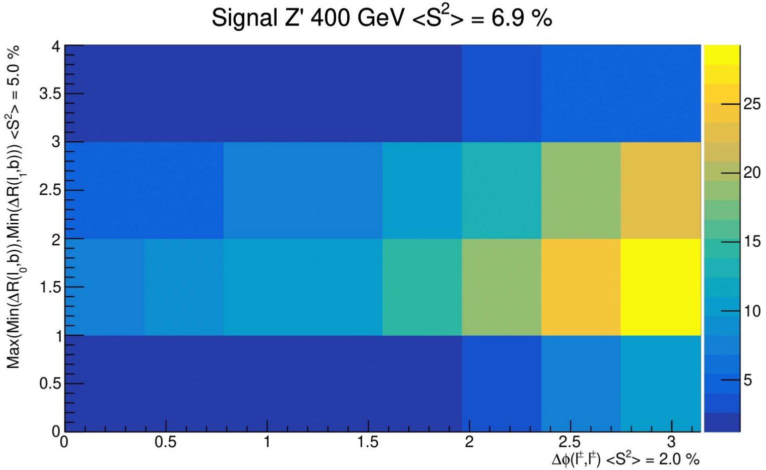




And... a 2d plot



Background
Max(Min(ΔR(l_0,b)),Min(ΔR(l_1,b)))
Δϕ(l±,l±)



Signal Z' 400 GeV <S²> = 6.9 %
Max(Min(ΔR(l_0,b)),Min(ΔR(l_1,b))) <S²> = 5.0 %
Δϕ(l±,l±) <S²> = 2.0 %