Using top polarisation information to constrain resonant physics in the $t\bar{t}$ spectrum

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Based on work in 1703.05613 with Christoph Englert (supervisor), James Ferrando (DESY ATLAS)

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Rough outline

- Motivation for $t\bar{t}$ resonance searches for new physics
- Measuring the polarisation of top quarks using leptonic decays
- Introducing a benchmark model
- Combining mass spectrum and polarisation information in $t\bar{t}$ resonance searches

Motivation for $t\bar{t}$ resonances

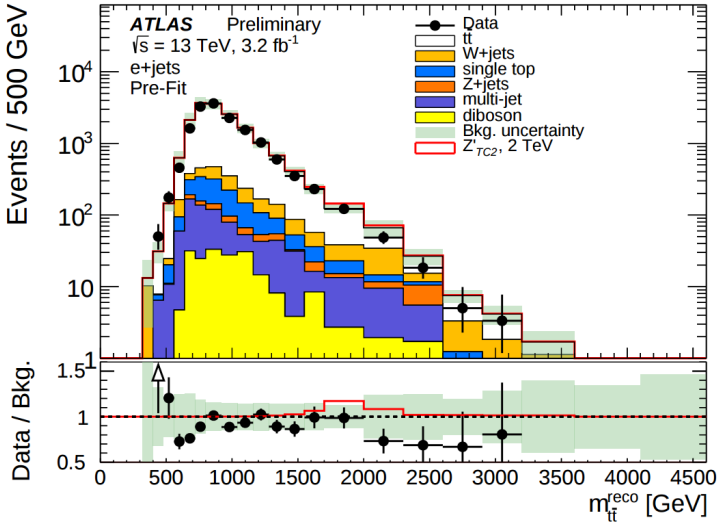
The large top quark mass ($y_t \sim 1$) suggests it could play a special role in electroweak symmetry breaking.

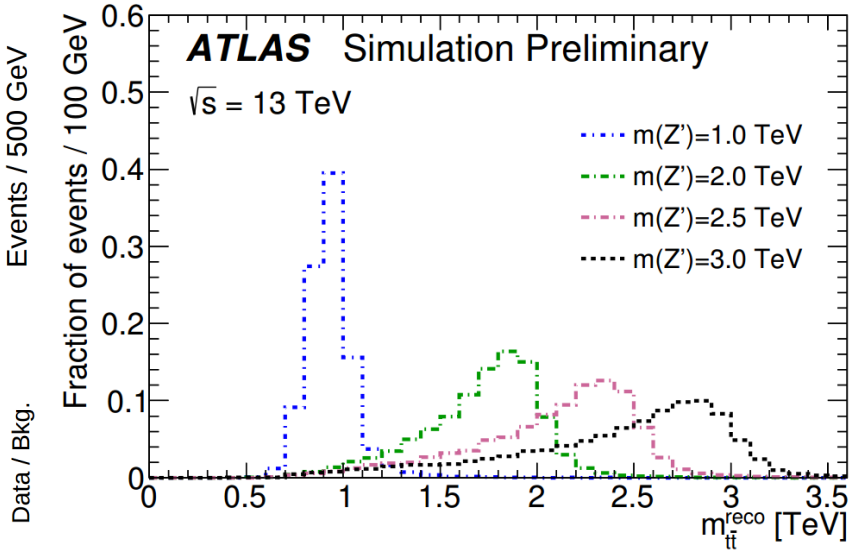
This leads to predictions of new resonances which are best discovered in the $t\bar{t}$ spectrum in many BSM models, for example:[1]

- Topcolor with leptophobic Z' induced tilting (C.T. Hill and R.M. Harris, C.T. Hill, S.J. Parke)
- Randall-Sundrum models which generate the Yukawa structure by fermion localization in the bulk (T. Gherghetta, A. Pomarol)

[1] $b\bar{b}$ resonances are also often predicted but tend to be hard to detect above SM dijet production.

Introduction to $t\bar{t}$ searches





Taken from ATLAS-CONF-2016-014.

Introduction to $t\bar{t}$ searches

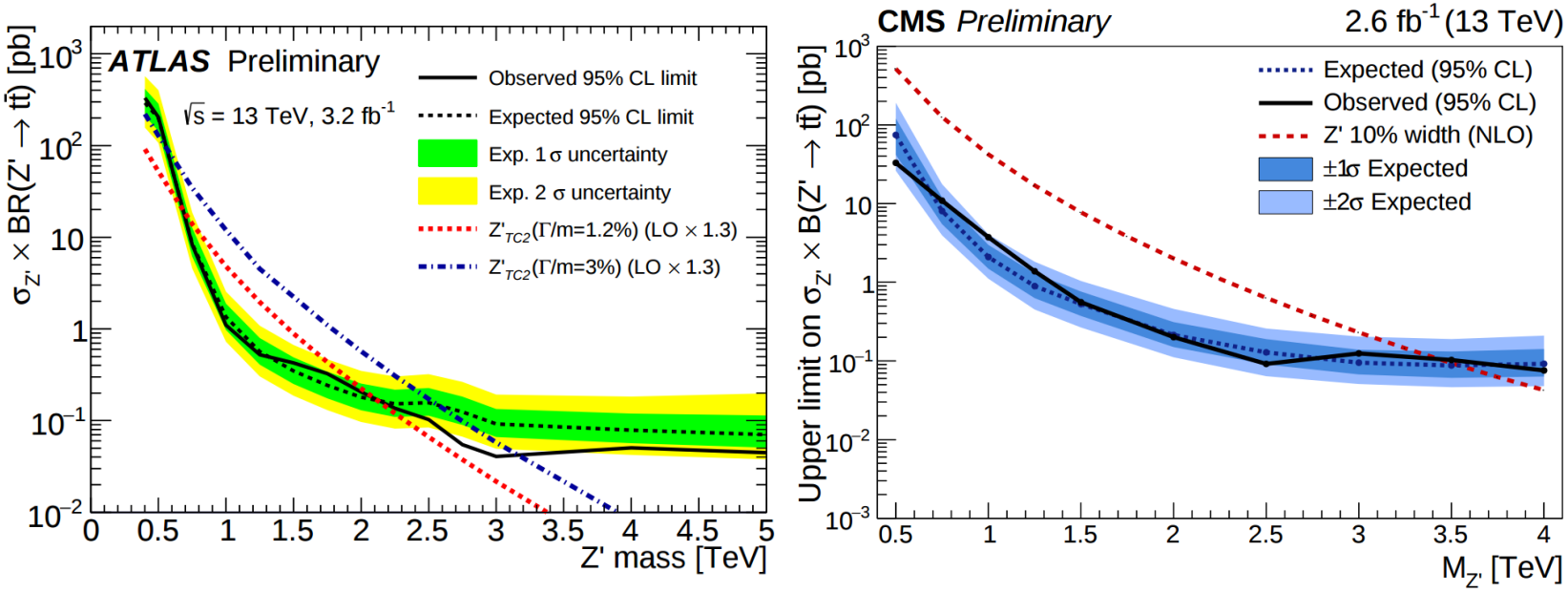
Tops decay leptonically $t \to Wb \to l\nu b$ ($P \sim 1/3$) and hadronically $t \to Wb \to jjb$ ($P \sim 2/3$) which results in three possible final states for $t\bar{t}$:

- Di-leptonic (P $\sim 1/9$) – two b jets, two leptons, missing energy
- Semi-leptonic (P $\sim 4/9$) – two b jets, two light jets, one lepton, missing energy
- All-hadronic (P $\sim 4/9$) – two b jets, four light jets

Backgrounds are mostly $V(V) + \mathrm{jets}$ production for the leptonic final states, multijets for the hadronic final state.

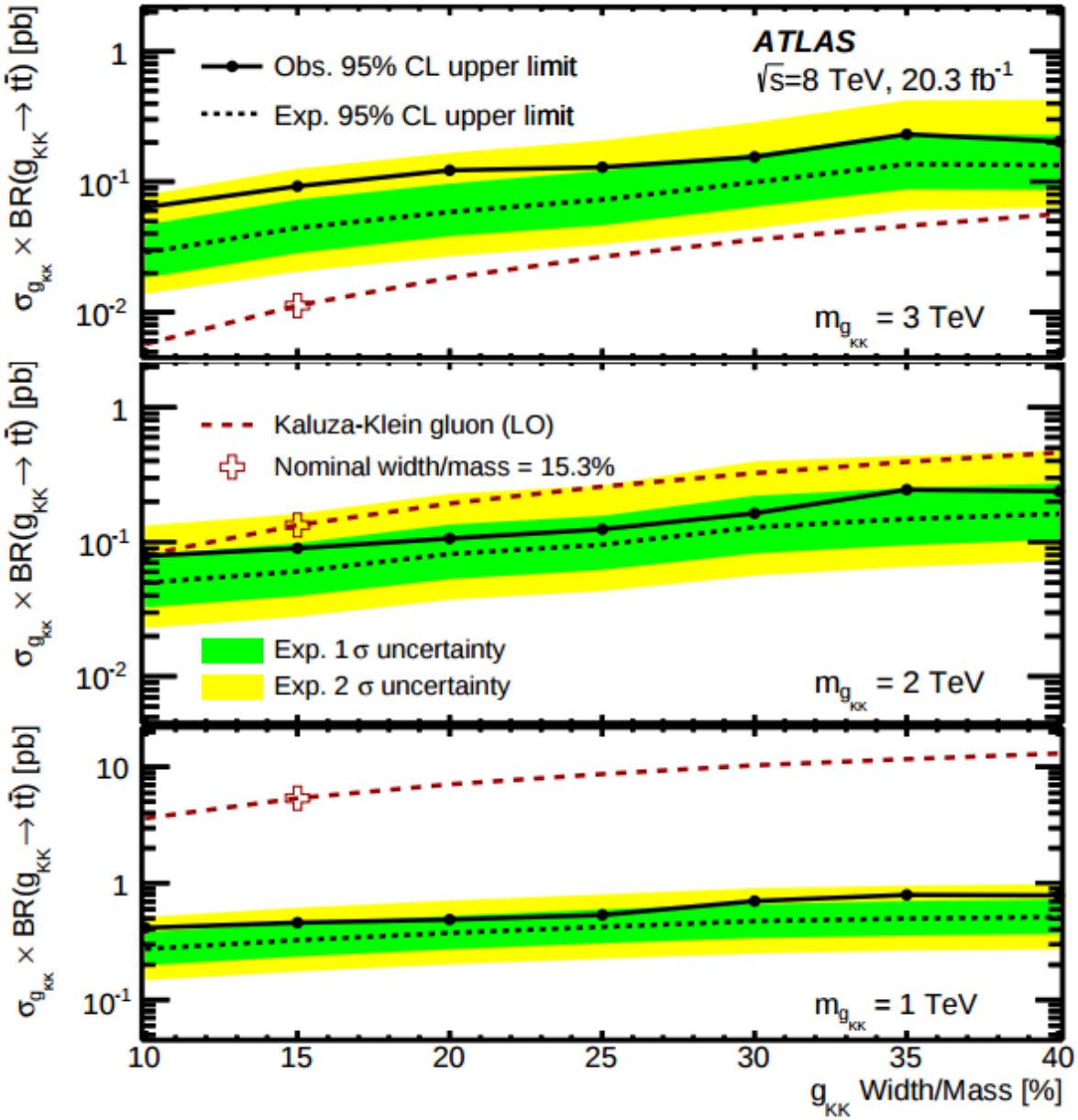
Since τ reconstruction is challenging it's typical to restrict leptonic searches to electrons and muons.

Introduction to $t\bar{t}$ searches



Using the semi-leptonic final state. Left from ATLAS-CONF-2016-014, right from CMS Top 2016 Talk.

Introduction to $t\bar{t}$ searches



Taken from
ATLAS 8 TeV search.

Moving beyond the invariant mass spectrum

Way to improve situation: include shape information from other observables that are less sensitive to width.

Spin observables are in general such observables, and in particular we will focus on the polarisation of the tops.

Thanks to decaying before hadronisation we can access polarisation information of tops through the angular distributions of its decay products.

$t\bar{t}$ production at the LHC in the Standard Model is dominated by parity-invariant QCD processes, with a sizeable contribution from weak processes creating a small preference for left-handed tops at high invariant masses.

Moving beyond the invariant mass spectrum

To analyse the polarisation we can look at the angular distributions of decay products in the top rest frame:[2]

$$\frac{1}{\Gamma_f}\frac{\mathrm{d}\Gamma_f}{\mathrm{d}\cos\theta_f} = \frac{1}{2}\left(1 + \kappa_f P_t \cos\theta_f\right) \tag{1}$$

Here P_t is the polarisation ($+1$ for right-handed) and κ_f depends on the particular decay product in question as follows (M. Jezabek, J. Kühn):

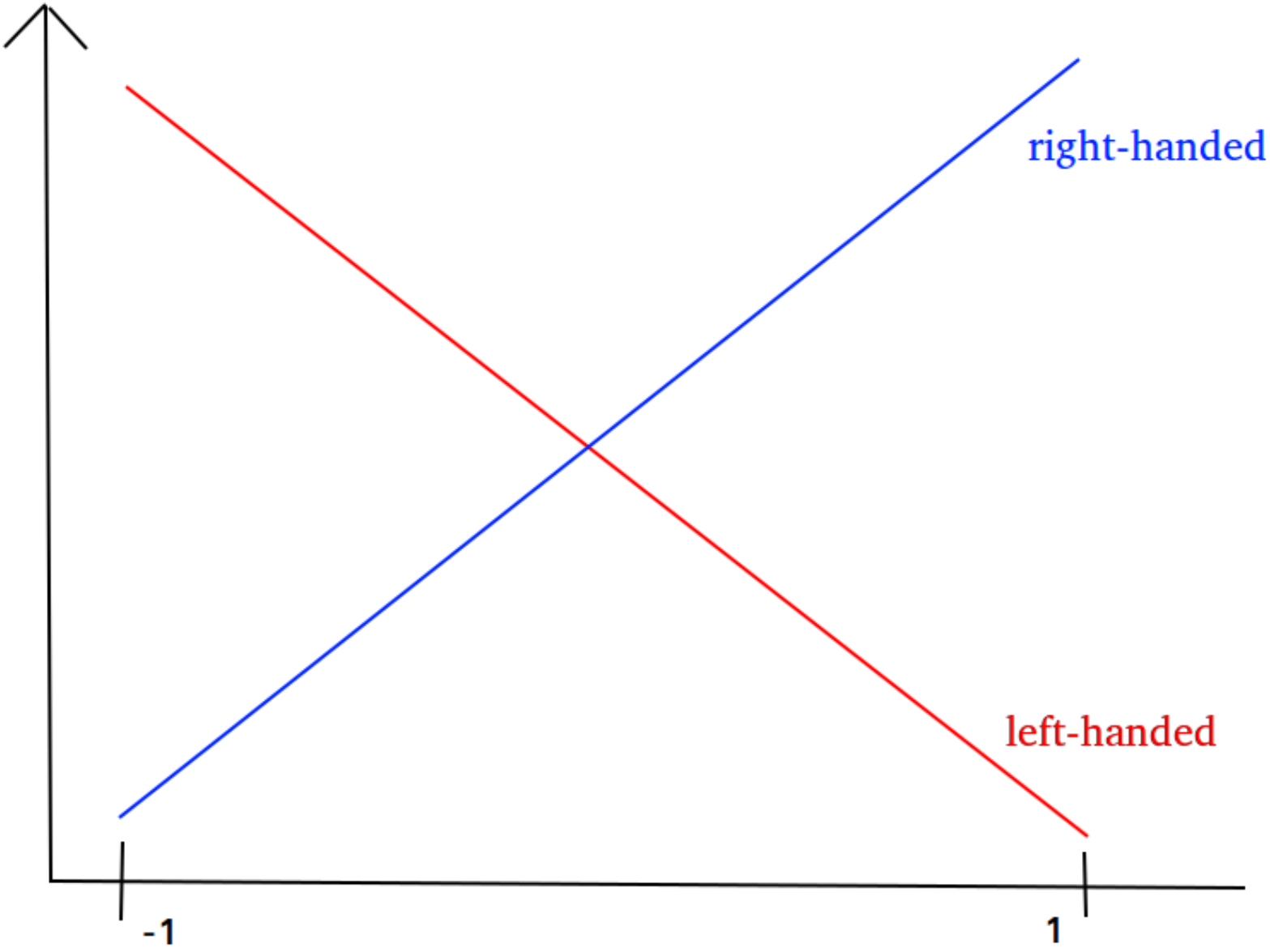
Decay product	l/d	ν/u	W	b
κ_f	1	0.3	0.39	-0.39

In general difficult to separate $u/d/b$ for boosted top decays[3] so we focus on leptonic decays.

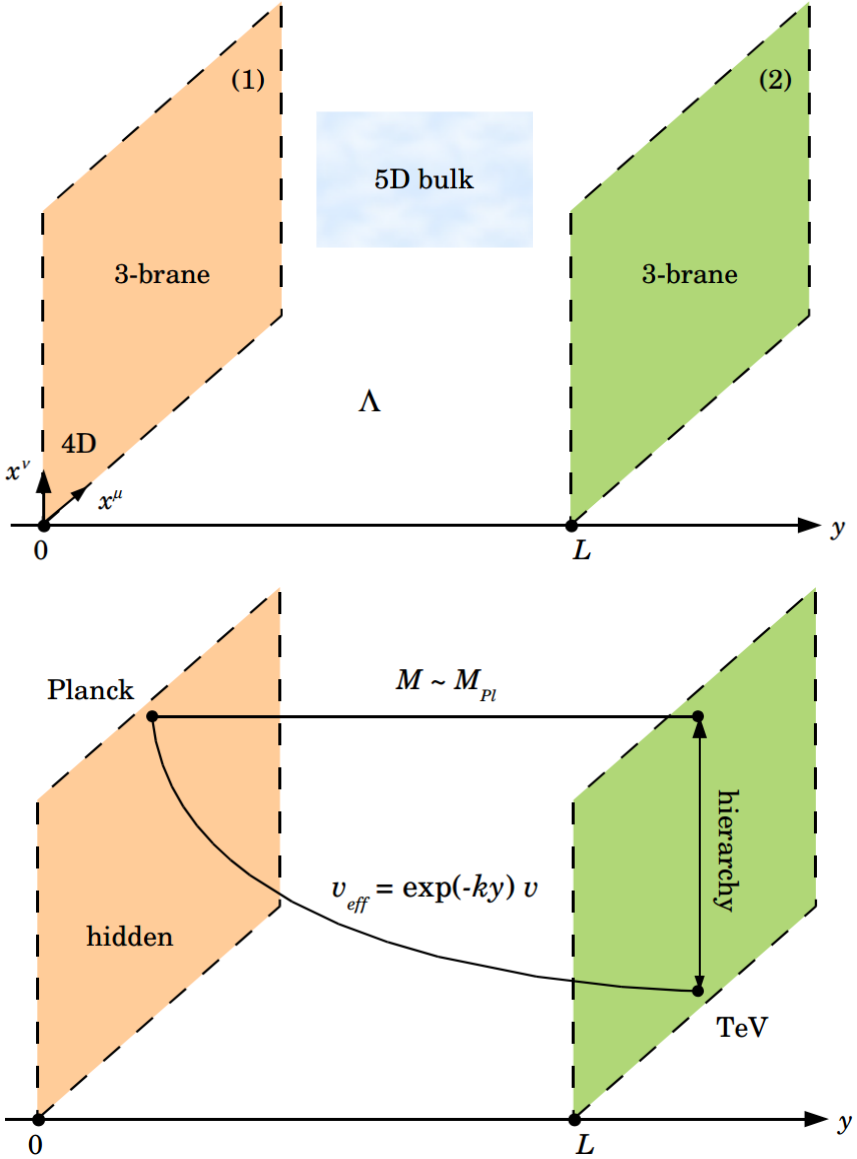
[2] Many observables are sensitive to polarisation but this dependence generally enters through the angular distributions

[3] But not impossible to measure polarisation, see e.g. D. Krohn, J. Shelton, L-T. Wang.

Moving beyond the invariant mass spectrum



The benchmark Randall-Sundrum model



Plots are taken from Maxime Gabella's excellent notes.

We consider an RS1 model (L. Randall, R. Sundrum) where the fermions are localised in the bulk.

Electroweak precision constraints on S, T, and $Z \to b\bar{b}$ and recovering the correct Yukawa structure forces particular model setups (K. Agashe, A. Delgado, M. May, R. Sundrum): lowdown is that Kaluza-Klein modes of graviton and gauge bosons couple mostly to t_R in minimal setups.

Semi-leptonic analysis and reconstruction

The semi-leptonic final state typically provides the strongest constraints:

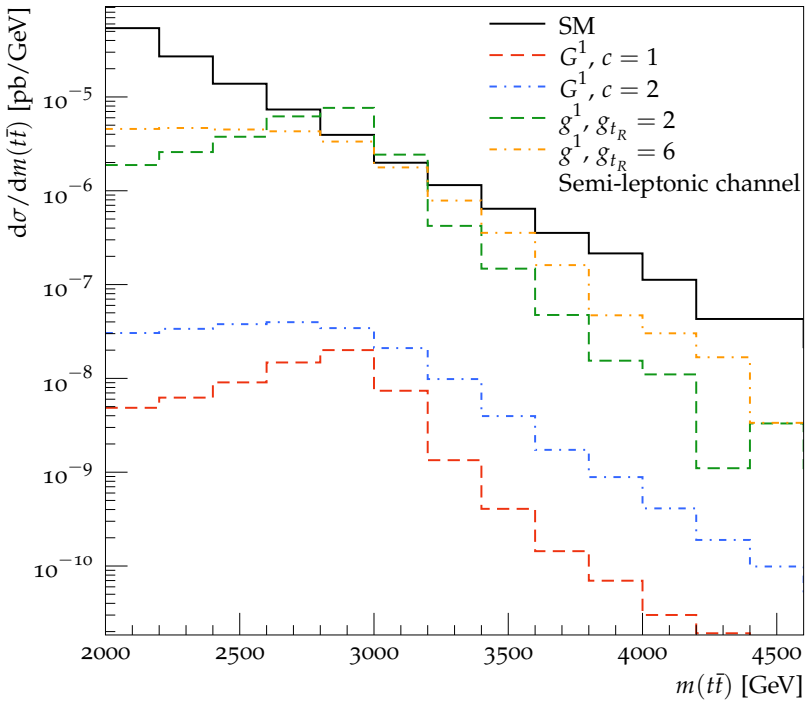
- There is a lepton in the final state which kills multijet backgrounds compared to all-hadronic
- The cross-section is six times larger than di-leptonic
- With only a single neutrino in the final state the mass resolution does not suffer from large reconstruction effects
- Hadronic top-tagging allows for small non-$t\bar{t}$ backgrounds even as the Wjj cross-section becomes sizeable

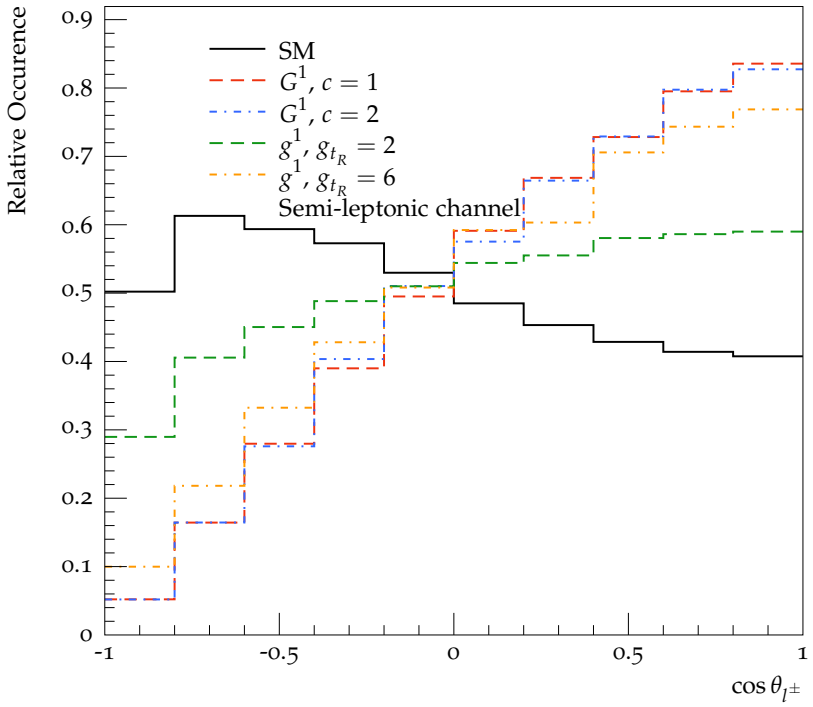
Our analysis is implemented in the Rivet framework (A. Buckley et al.) and relies on the assumption that we can drop the isolation requirement for leptons and jets on the leptonic side.[4]

[4] Realistic techniques to separate boosted leptonic top decays from QCD jets containing leptons from heavy flavor decays have been discussed in e.g. K. Rehermann, B. Tweedie.

Semi-leptonic analysis and reconstruction

All signal models have $m(g^1/G^1) = 3$ TeV here.





Di-leptonic analysis and reconstruction

The di-leptonic final state typically provides weaker constraints on BSM physics:

- The branching ratio is quite small ($\sim 4/81$)
- The two neutrinos in the final state smear out the mass resolution in resonance searches

However the two leptons provide an opportunity to access spin correlation information and spin polarisation information on both sides.

But how do we deal with reconstructing two neutrino momenta from one transverse missing momentum vector?

Di-leptonic analysis and reconstruction

Two popular approaches:[5]

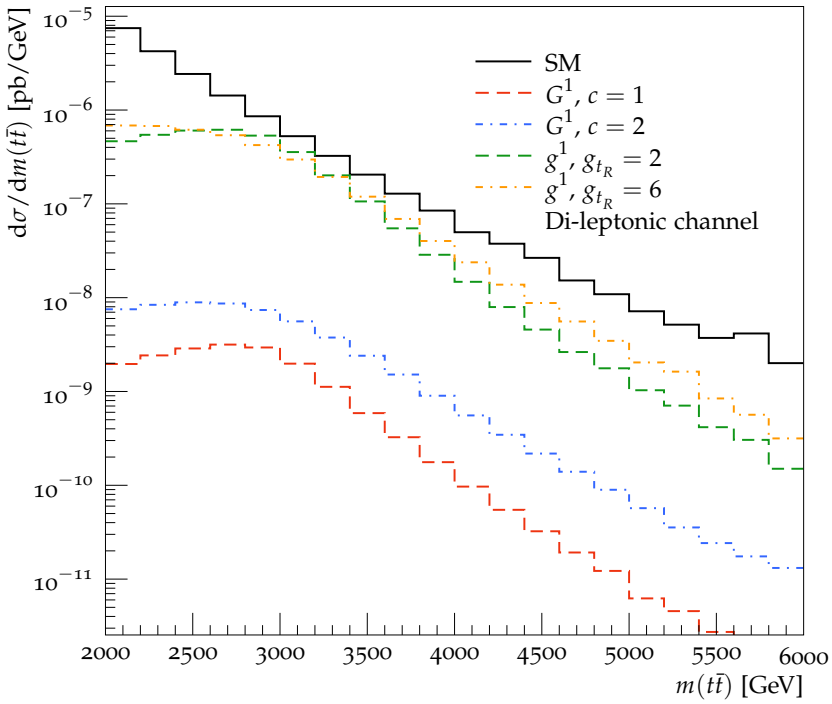
- Solve equations analytically (L. Sonnenschein) + choose among solutions using e.g. matrix element weight
- Define 'goodness of solution' weight and scan large number of proposed solutions + either use all with correct weighting or only the highest weight one (original DØ study)

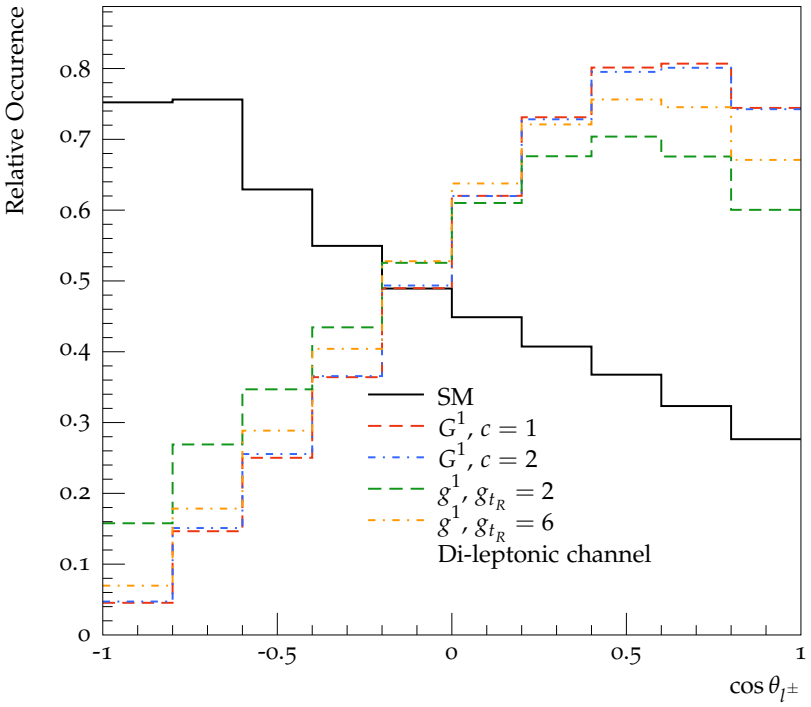
We use the so-called 'M_{T2} Assisted On-Shell' (MAOS) method of W. Cho, K. Choi, Y. Kim, C. Park.

[5] There are many possible permutations, these only outline the general ideas.

Di-leptonic analysis and reconstruction

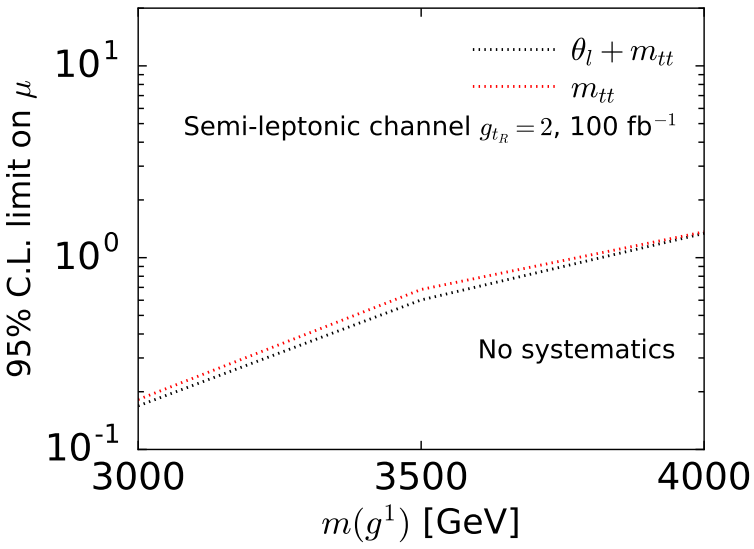
All signal models have $m(g^1/G^1) = 3$ TeV here.

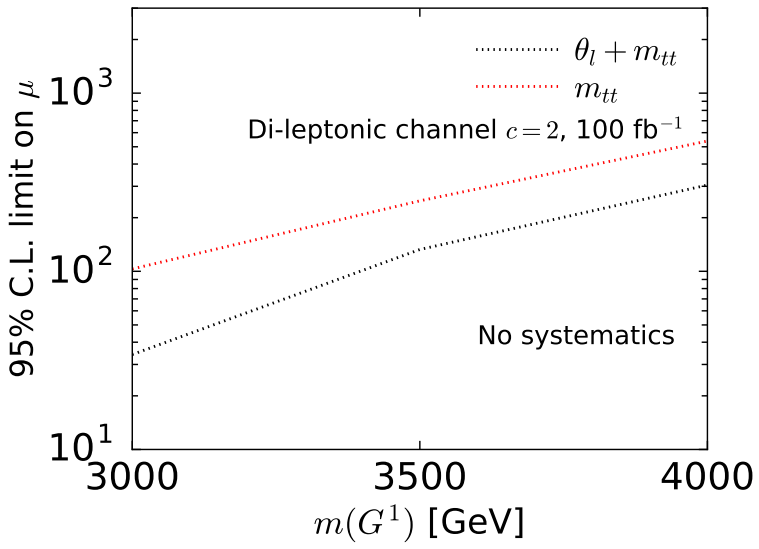




Using polarisation information

We can now calculate the expected limits for various parameters using both analyses.





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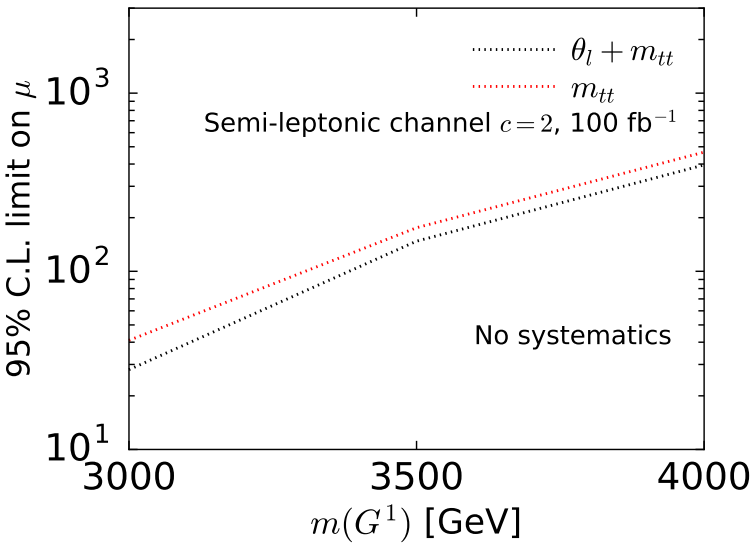
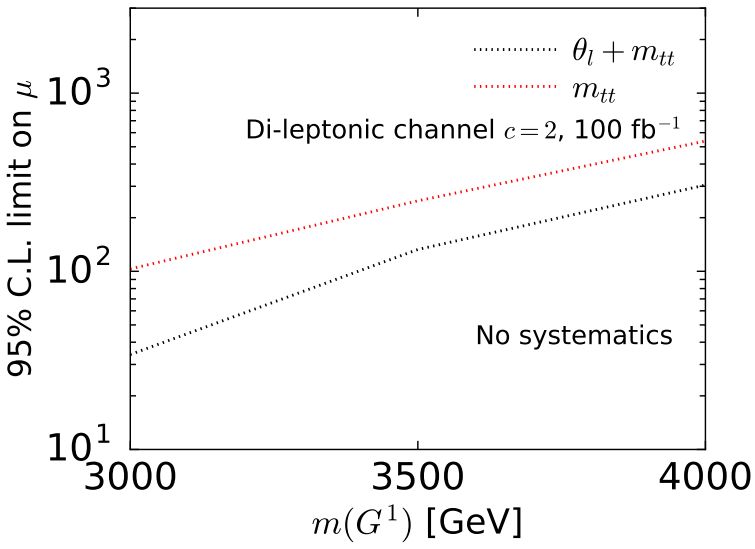
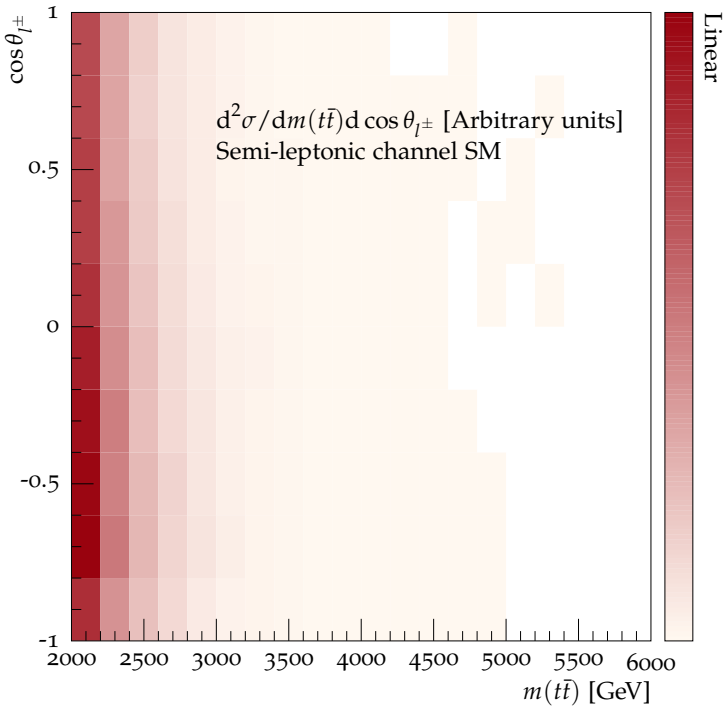


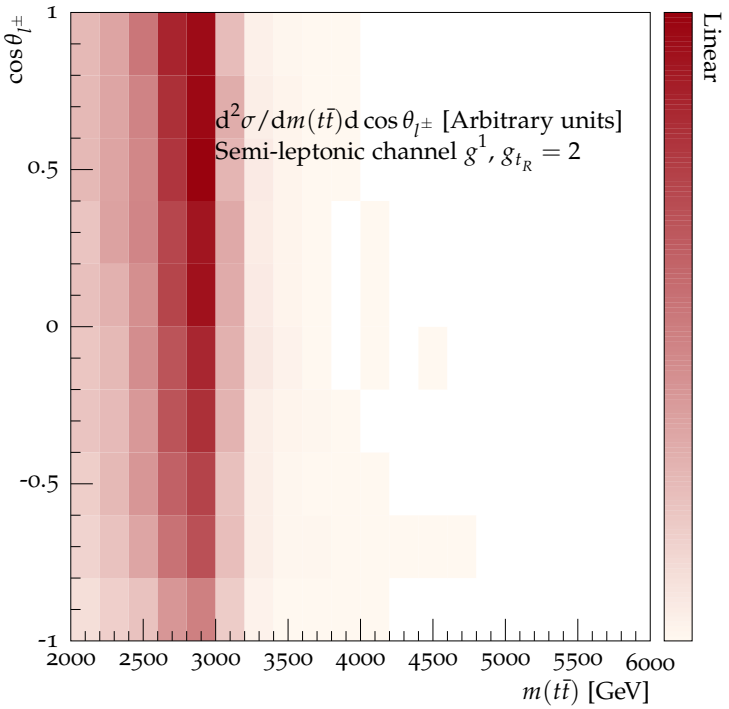


Conclusions

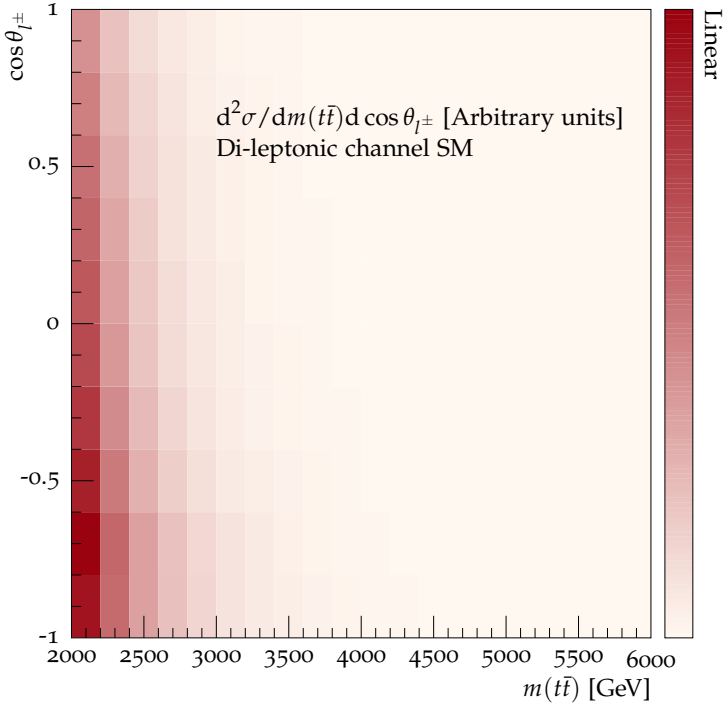
- Searching for top resonances is a well-motivated strategy for finding new physics
- Wider signals are harder to distinguish from Standard Model backgrund in $m(t\bar{t})$ spectrum
- Polarisation information is insensitive to width
- Large improvements to sensitivity can be made for wide signal models that predict polarised tops
- Di-leptonic final state can in some cases be competitive with semi-leptonic (?)

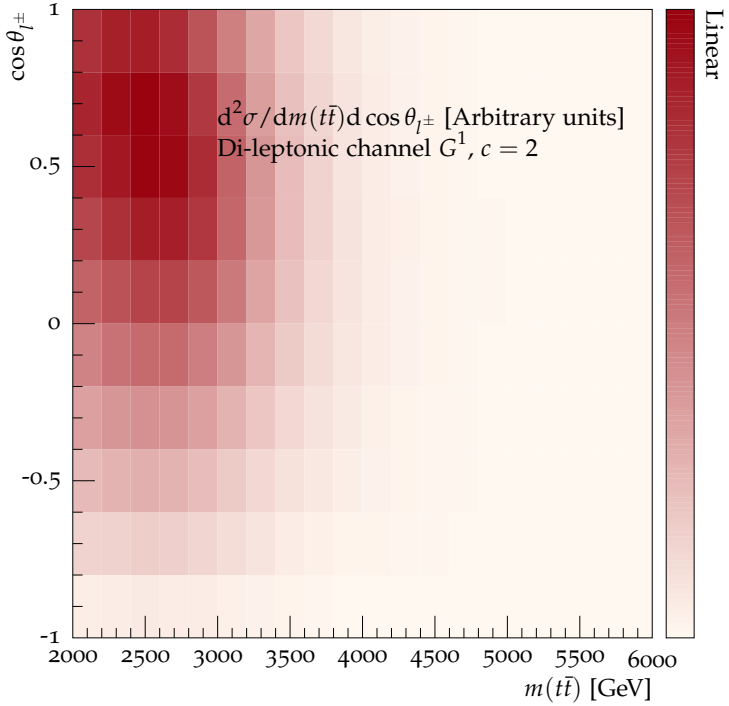
Semi-leptonic analysis, SM on left, $g_{t_R} = 2$ gluon on the right.





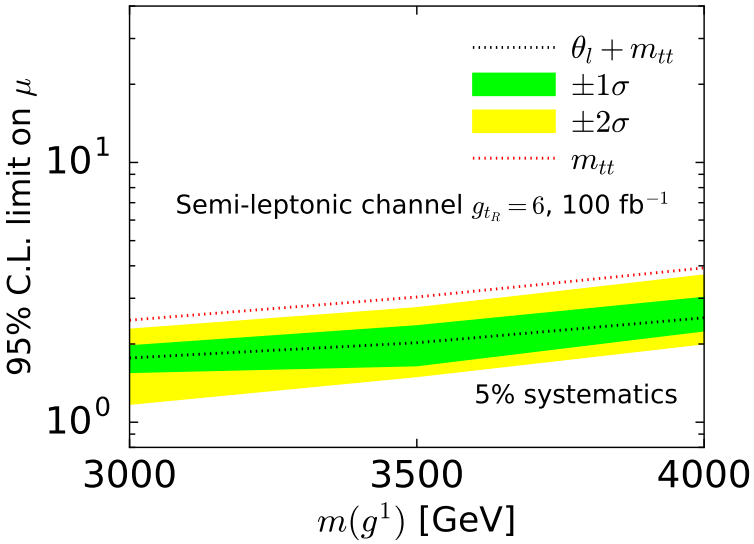
Di-leptonic analysis, SM on left, $c = 2$ graviton on the right.

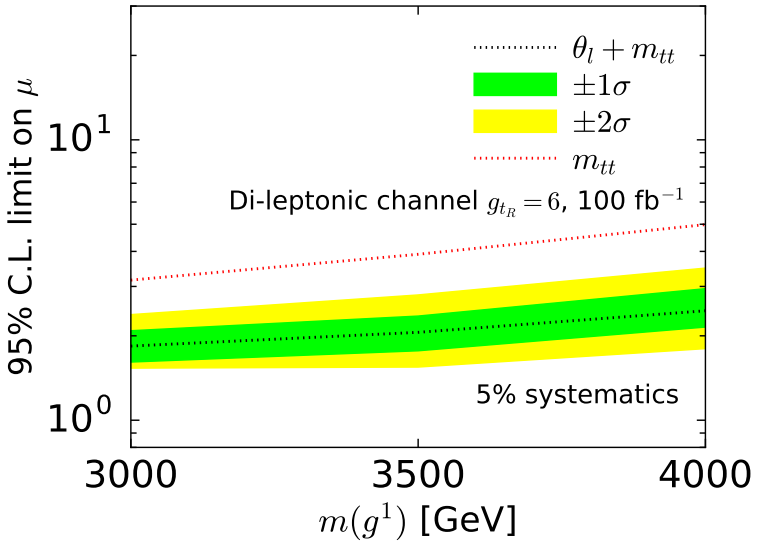




Results with systematics

. . . and add some systematics.[6]

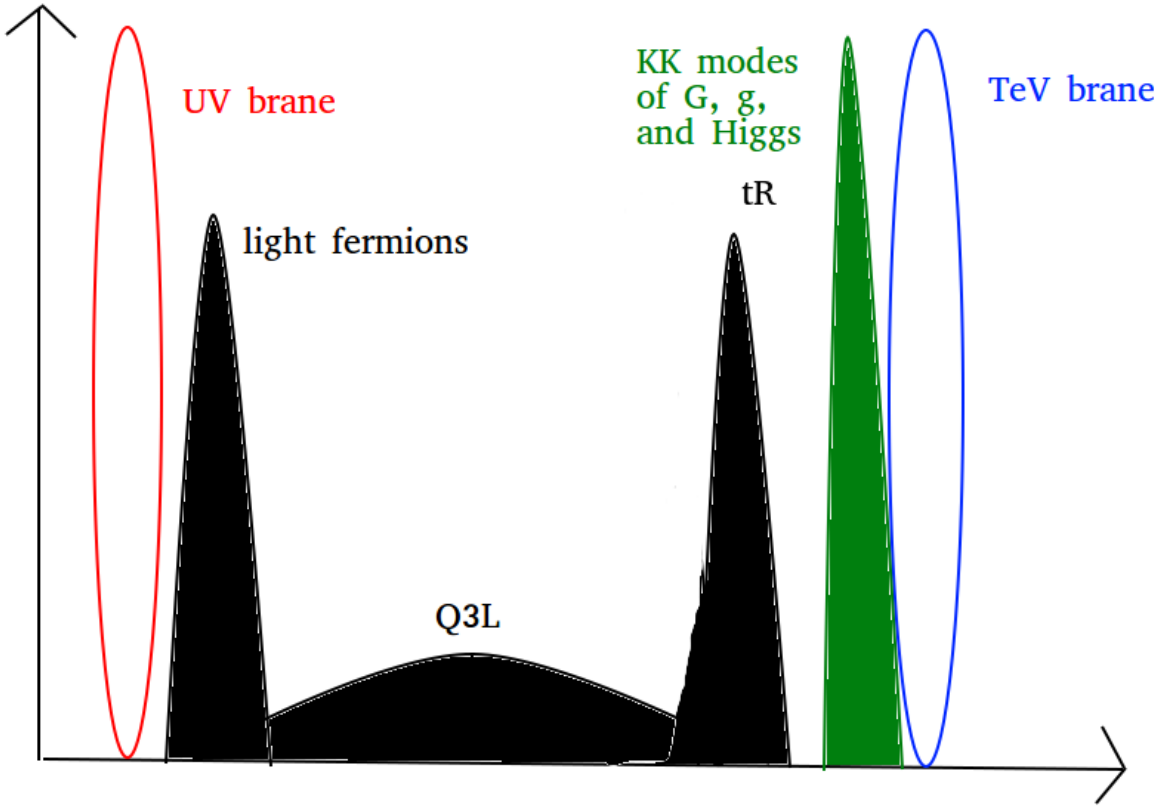




[6] How to model the systematics here is not necessarily obvious so take with grain of salt.

Model details

Yukawa structure comes about since the effective 4D couplings depend on wavefunction overlap in the 5th dimension (e.g. B. Lillie, L. Randall, L-T. Wang and L. Fitzpatrick, J. Kaplan, L. Randall, L-T. Wang)



Model details

We look for both the lightest graviton (G^1) and gluon (g^1) KK states decaying to $t\bar{t}$:

- For the graviton we set t_R on the TeV brane
- For the gluon we vary the location of t_R slightly while keeping it close to the TeV brane

In the graviton case we keep all other couplings except the ones to H heavily suppressed:[7]

$$\Gamma(G^1 \to t_R \bar{t}_R) = 9\frac{(3.83c)^2 m_{G^1}}{960\pi}\,, \tag{2}$$

$$\Gamma(G^1 \to \phi\phi) = 4\frac{(3.83c)^2 m_{G^1}}{960\pi}\,, \tag{3}$$

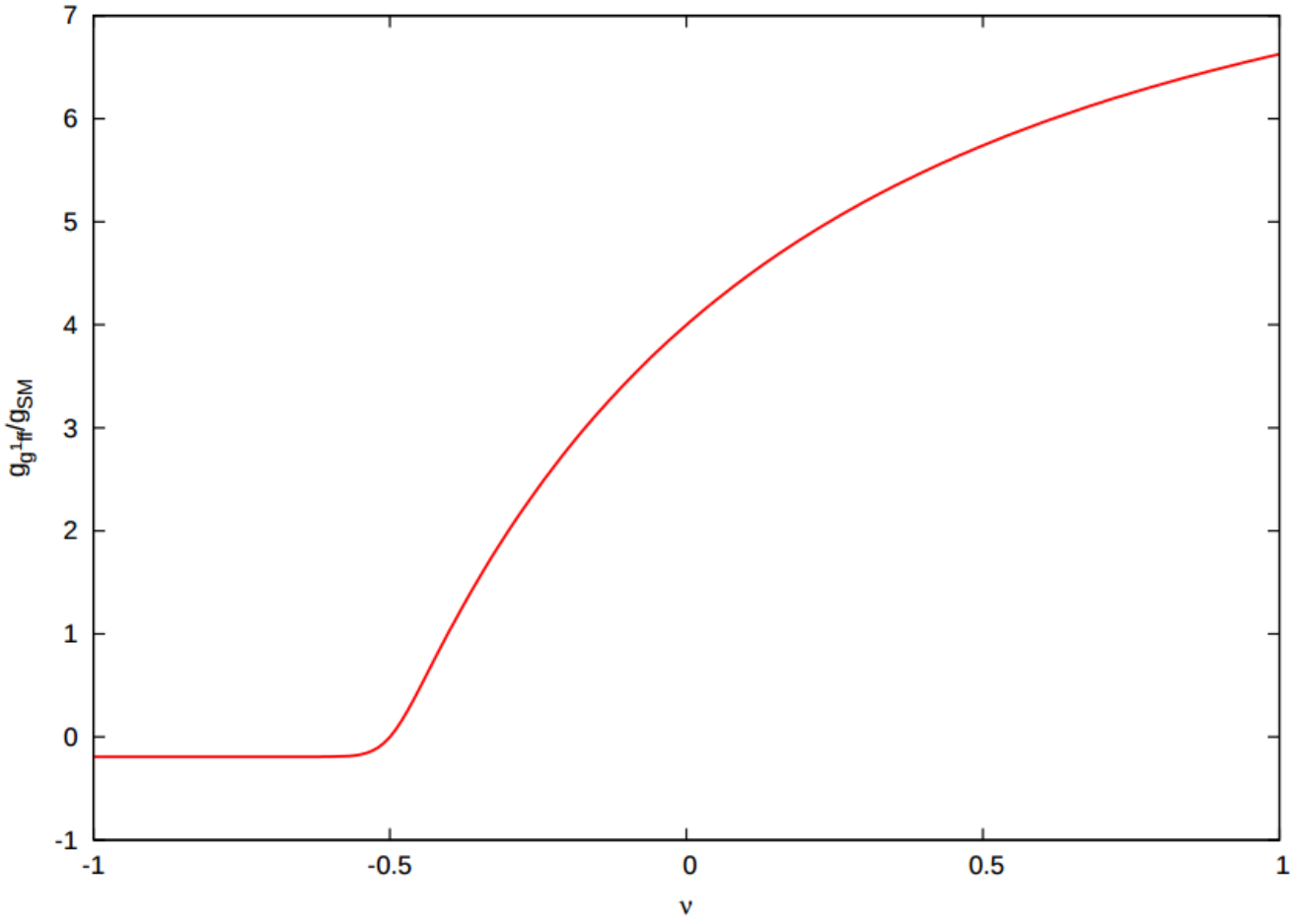
Here $c = k/M_{\mathrm{Planck}}$[8] and ϕ sums over Z_L, W_L, and h. We vary $c = \{1, 2\}$ which corresponds to $\Gamma_{G^1}/m_{G^1} = \{6.2\%, 25\%\}$.

[7] Production occurs through small couplings to gluons.

[8] $\mathcal{O}(1)$ since all mass scales generated by M_{Planck}.

Model details

The effective coupling of first gauge KK mode (taken from B. Lillie, L. Randall, L-T. Wang):



Model details

Since couplings to g^1 take an asymptotic value of $\sim 0.2 g_S$ away from the TeV brane it is efficiently produced through light quark annihilation.

Assuming $\mathcal{O}(1)$ 5D Yukawa couplings we have some freedom to vary the location of the quarks while recovering the correct 4D Yukawa structure, and we choose:

$$g_{g^1 u\bar{u}(\dots)} = 0.2 g_S, \quad g_{g^1 Q3_L \bar{Q}3_L} = g_S, \quad g_{g^1 t_R \bar{t}_R} = \{2, 6\} g_S \quad (4)$$

These give widths of $\Gamma_{g^1}/m_{g^1} = \{6.2\%, 37.5\%\}$, branching ratios to $t\bar{t} = \{78.5\%, 96.5\%\}$ and also change the overall polarisation of the $t\bar{t}$ pairs.

Semi-leptonic selections

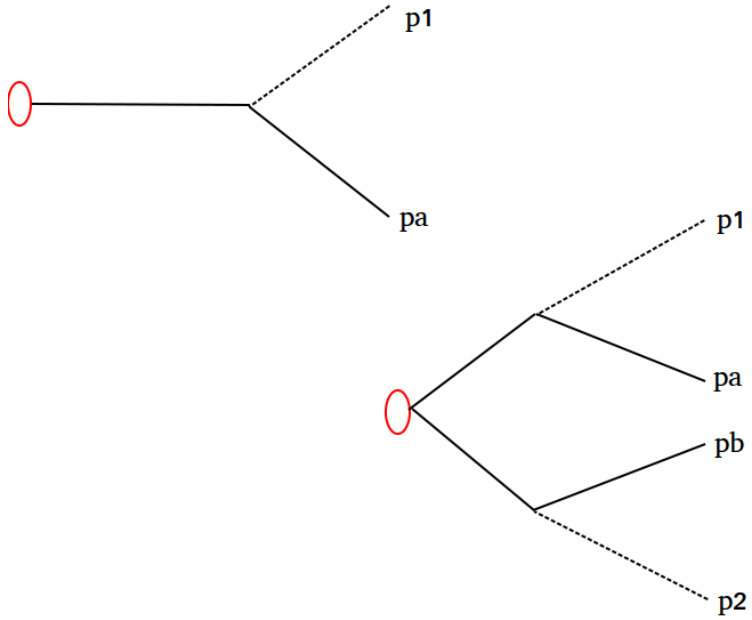
- Find muons and electrons with $p_T > 25$ GeV
- Find C/A $R = 1.2$ jets with $p_T > 250$ GeV and top tag the leading one with HEPTopTagger (G. Kasieczka, T. Plehn, T. Schell, T. Strebler, G. Salam)
- Find anti-k_T $R = 0.4$ jets with $p_T > 25$ GeV which don't overlap with the hadronic top candidate and b-tag with an efficiency of 70% and fake rate of 1% (10% for $p_T > 300$ GeV ATLAS 13 TeV b-tagging paper). Require at least one b-tag.
- Require $|\not{p}_T| > 20$ GeV and $|\not{p}_T| + m_T > 60$ GeV
- Reconstruct the leptonic top candidate by assuming the W was on-shell and choosing the $p_{\nu,z}$ solution which minimises $|m_{bl\nu} - m_t|$.
- Extract $m(t\bar{t})$ by adding the two top candidates together and $\cos\theta_l$ using the leptonic top candidate.

Di-leptonic selections

- Find muons and electrons with $p_T > 25$ GeV, require two leading ones to have opposite charge
- Find anti-k_T $R = 0.4$ jets with $p_T > 25$ GeV and b-tag with an efficiency of 70% and fake rate of 1% (10% for $p_T > 300$ GeV ATLAS 13 TeV b-tagging paper). Require at least two b-tags.
- Require $|\not{p}_T| > 60$ GeV
- Pair up the two leading b jets and leptons by choosing the combination which best corresponds to the expected m_t, m_W, and M_{T2} distributions (K. Choi, D. Guadagnoli, C. Park)
- If the selected pairing results in unphysical m_{bl} or M_{T2}, veto event
- Find neutrino solutions using MAOS method
- Extract $m(t\bar{t})$ by adding the two top candidates together and $\cos\theta_l$ from both top candidates

MAOS details

M_{T2} (C. Lester, D. Summers) is a generalisation of the standard transverse mass to case where there are two particles with invisible decay products in the final state.



Let α denote 2+1D momenta (leaving out the z component):

$$m_T^2 = (\alpha_1 + \alpha_a)^2 \quad (5)$$

$$M_{T2}^2 = \min_{\alpha_1+\alpha_2=\not{\alpha}} \max\left[m_T^2(\alpha_1, \alpha_a), m_T^2(\alpha_2, \alpha_b)\right] \quad (6)$$

MAOS details

$\Rightarrow M_{T2}$ calculation provides unique guesses for $\alpha_{1/2}$. Can calculate z component by assuming top was produced on-shell.

- Assuming no width effects and perfect detectors, should be exact solution when $M_{T2} = m_t$
- Combinatorial uncertainty only on longitudinal components

Setting limits on resonances

The inputs when perfoming limit setting using information from multiple bins i is:

- The predicted number of backgrounds events for each bin, b_i
- The observed number of events for each bin, d_i
- The predicted number of signal events for each bin, s_i
- The systematic uncertainties on the background and signal predictions for each bin, $\sigma(b_i)$, $\sigma(s_i)$

We also introduce a signal strength variable μ which rescales the signal: this allows us to find how much we need to rescale a specific signal parameter point in order to exclude it a specific confidence level.

Setting limits on resonances

A well-established approach to limit-setting when using multiple bins is to use the Poisson likelihood ratio as our test statistic X:[9]

$$X = \prod_{i}^{\text{bins}} e^{-\mu s_i} \left(1 + \frac{\mu s_i}{b_i}\right)^{d_i} \tag{7}$$

The CL_s prescription (see e.g. T. Junk) is then to calculate:

$$CL_{s+b} = P_{s+b}\left(X \leq X_{\text{obs}}\right) \tag{8}$$

$$CL_b = P_b\left(X \leq X_{\text{obs}}\right) \tag{9}$$

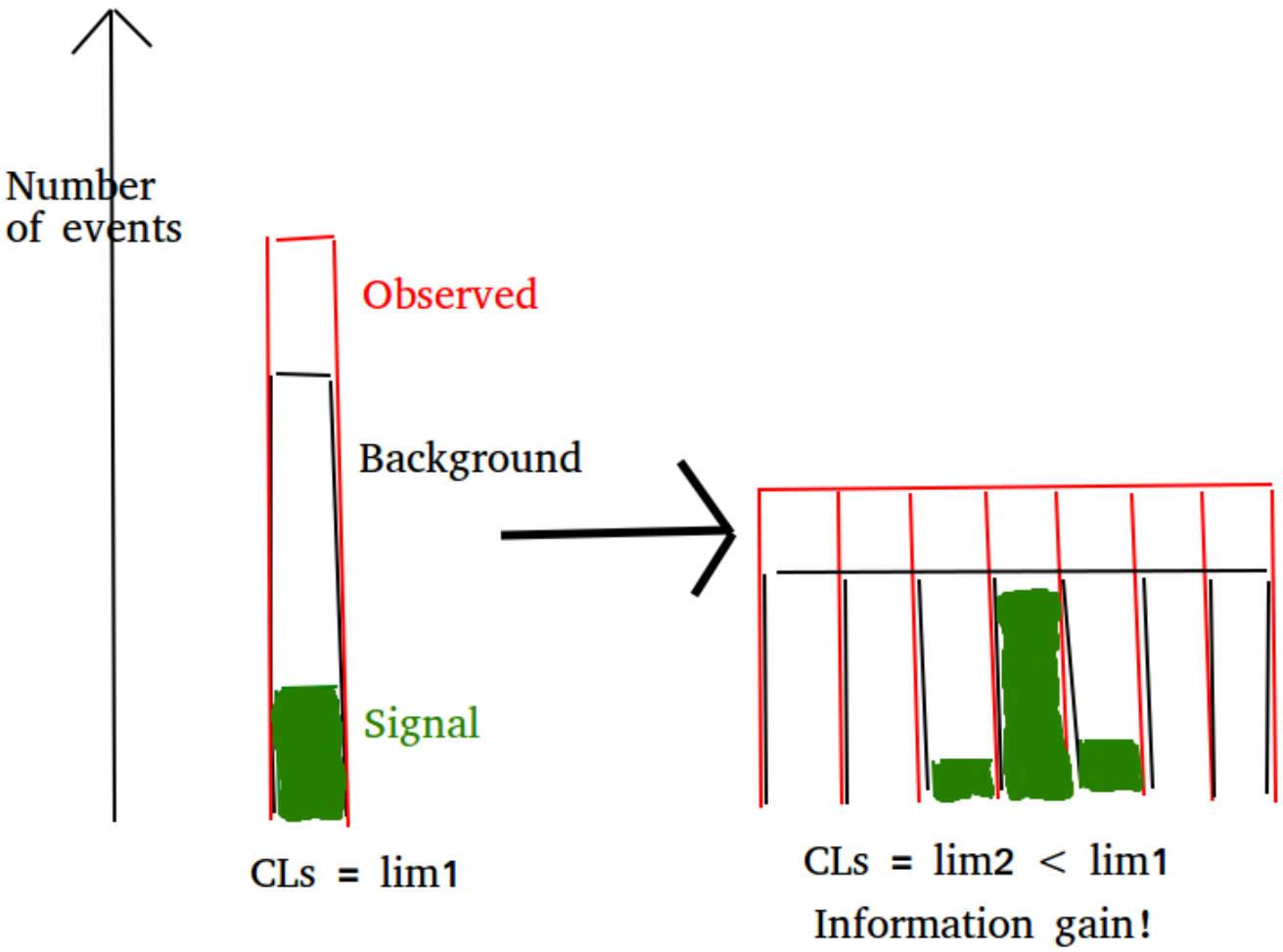
$$CL_s = CL_{s+b}/CL_b \tag{10}$$

We will in general be interested in excluding signal with 95% confidence level, which corresponds to $CL_s < 0.05$.

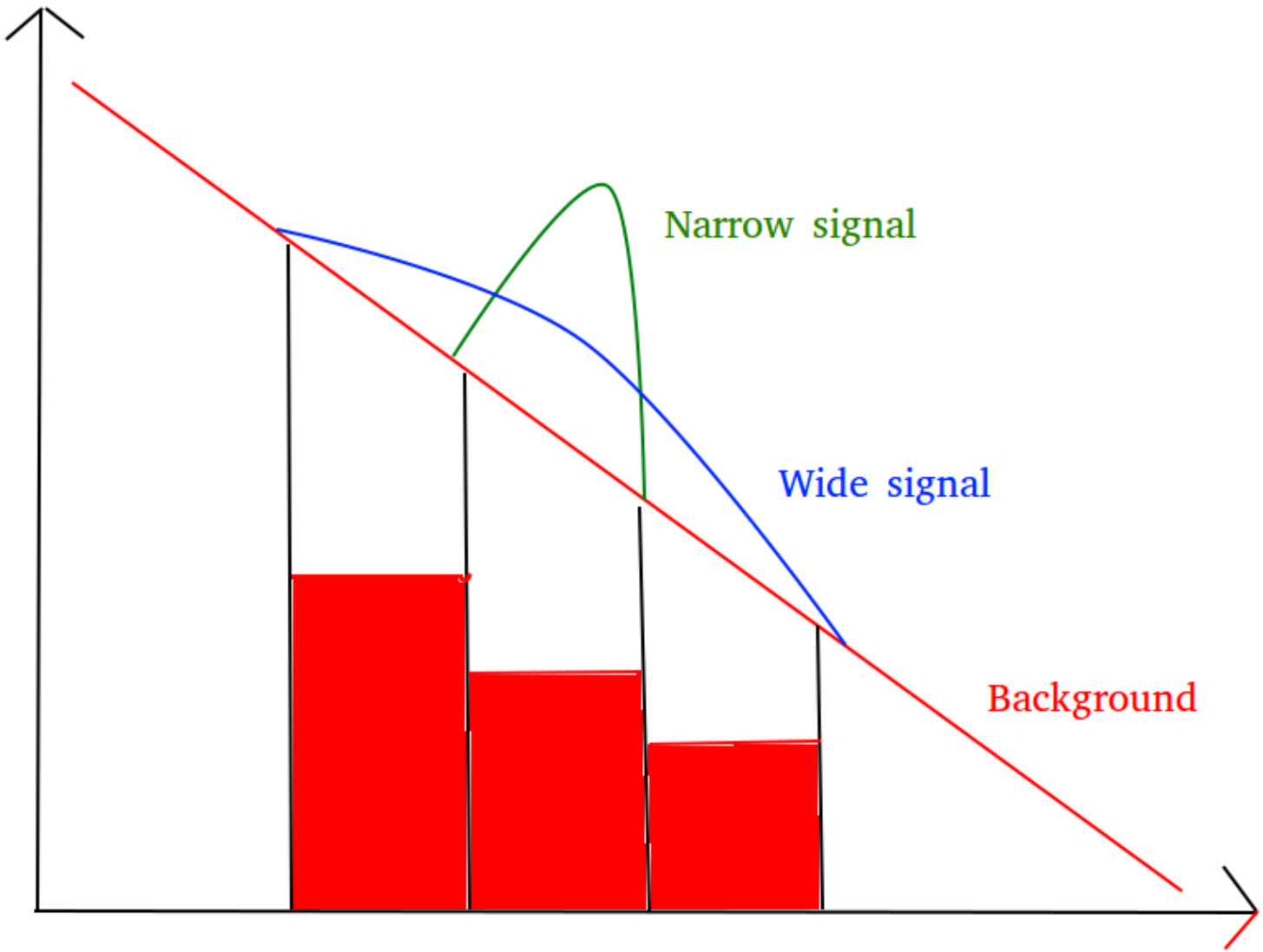
[9] We take systematic uncertainties as Gaussian uncertainties on s_i and b_i.

Setting limits on resonances

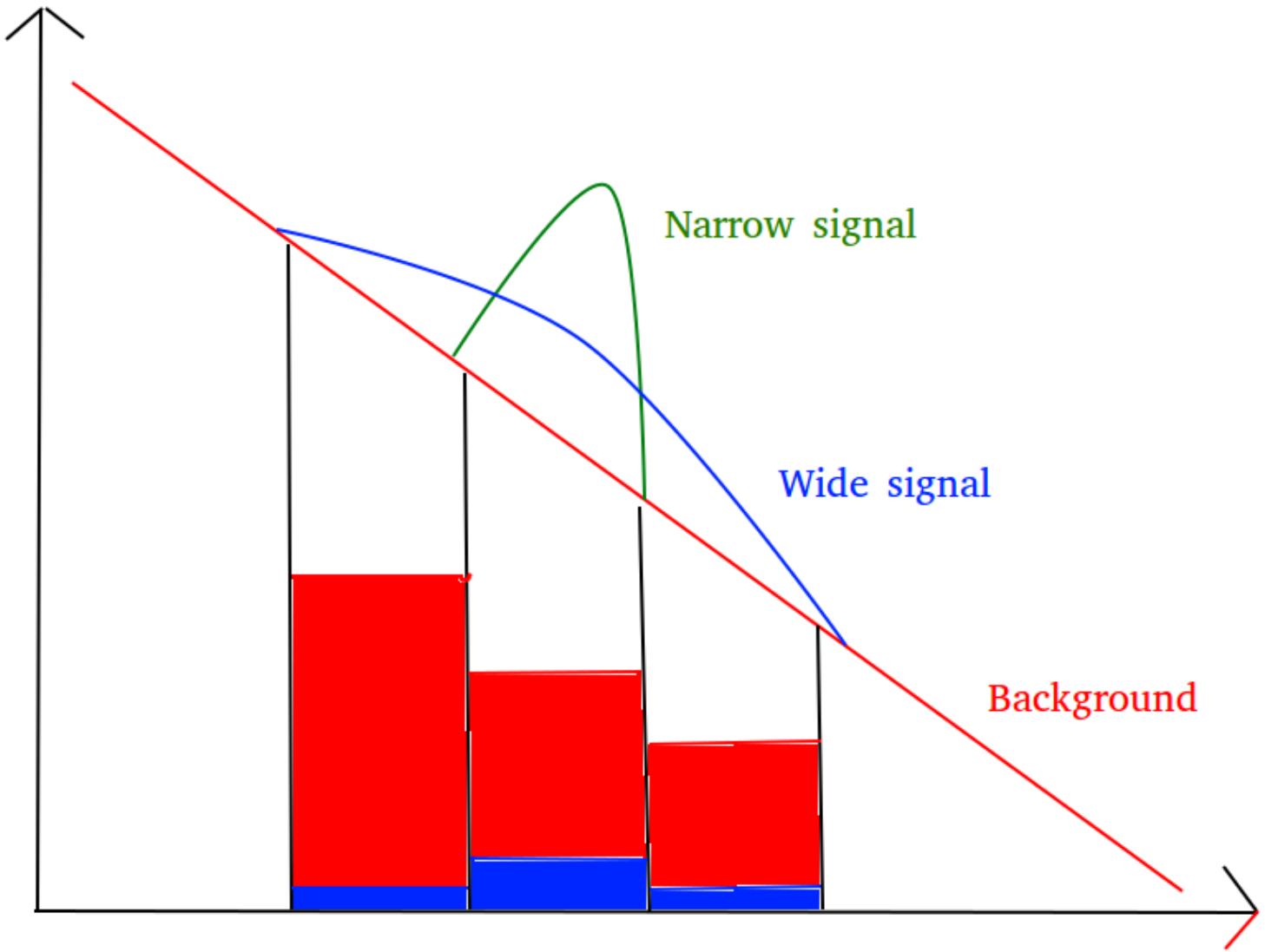
The likelihood is in general a factorising combination of normalisation and shape information: $X \sim \mathrm{I}_{\mathrm{norm}} \quad \mathrm{I}_{\mathrm{shape}}$



Setting limits on resonances



Setting limits on resonances



Setting limits on resonances