Determining the Quantum Numbers of Simplified Models in $t\bar{t}X$ production at the LHC

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Based on **Dolan, Spannowsky, Wang, ZHY, arXiv:1606.00019, PRD**

CoEPP lunch talk

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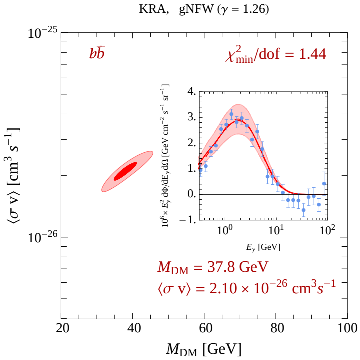
Motivation

Fermi-LAT Galactic Centre excess

- **Galactic Centre excess** of GeV diffuse γ rays can be explained by dark matter (DM) annihilation into Standard Model (SM) particles
- **DM annihilation into $b\bar{b}$** provides a particularly good fit
  $\Rightarrow$ **a light mediator X** coupled to DM and the **3rd generation quarks**?



[Cirelli *et al.*, 1407.2173]

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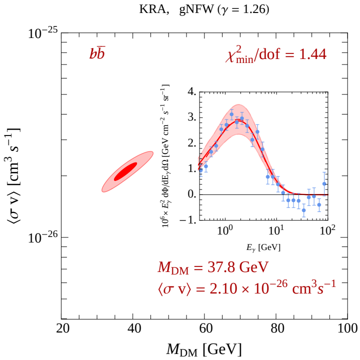
Such a light ($\lesssim 100$ GeV) **resonance X at the LHC**

- $m_X < 2m_t$: $X \to t\bar{t}$ forbidden
- $m_X < 2m_{\rm DM}$: decay into DM forbidden
- $X \to b\bar{b}$ is likely to dominate
- **LHC signature $pp \to t\bar{t}X \to t\bar{t}b\bar{b}$**
  - Easily hidden in Run 1 searches
  - Promising in 13/14 TeV searches



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Simplified Models

If such a new light resonance X is discovered at the LHC, the first priority will be the characterisation of its **spin and CP quantum numbers**

Four simplified models with a new neutral resonance which is **an eigenstate of parity and charge conjugation** are considered

$$X = S \ (J^{PC} = 0^{++}): \ \mathcal{L}_\mathrm{S} = -\sum_{q=b,t} \frac{g_q m_q}{v} S\,\bar{q}q$$

$$X = A \ (J^{PC} = 0^{-+}): \ \mathcal{L}_\mathrm{P} = -\sum_{q=b,t} \frac{g_q m_q}{v} A\bar{q}i\gamma_5 q$$

$$X = Z'^{\mu}_\mathrm{V} \ (J^{PC} = 1^{--}): \ \mathcal{L}_\mathrm{V} = -\sum_{q=b,t} g_q Z'^{\mu}_\mathrm{V}\bar{q}\gamma_\mu q$$

$$X = Z'^{\mu}_\mathrm{A} \ (J^{PC} = 1^{++}): \ \mathcal{L}_\mathrm{AV} = -\sum_{q=b,t} g_q Z'^{\mu}_\mathrm{A}\bar{q}\gamma_\mu\gamma_5 q$$

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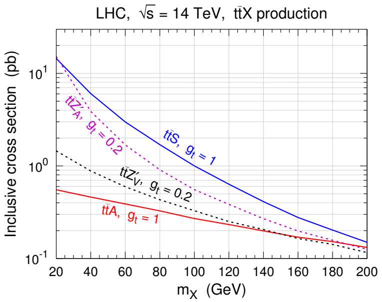
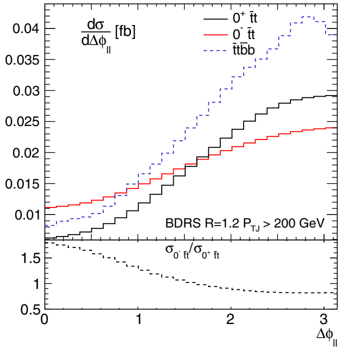


The $pp \to t\bar{t}X$ production cross section depends on g_t and m_X

Spin and Parity Discrimination

Di-leptonic top decay channel $pp \to t\bar{t}X \to b\ell\nu + b\ell\nu + bb$

- The azimuthal angle between the leptons $\Delta\phi_{\ell\ell}$ encodes the spin correlation information of the top pair, which is related to the ttX coupling structure
- Previous studies showed that $\Delta\phi_{\ell\ell}$ is useful for discriminating S (0^{++}) from A (0^{-+})



[Buckley & Gonçalves, 1407.2173, PRL]

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Semi-leptonic top decay channel

$$pp \to t\bar{t}X \to bjj + b\ell\nu + bb$$

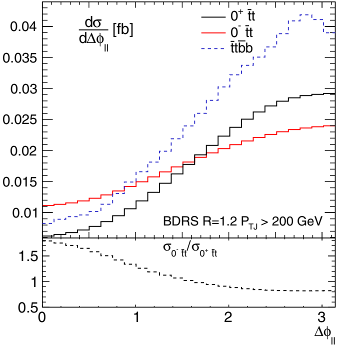
- Larger backgrounds
- The neutrino ν is the **only source** of the missing transverse momentum $\not{p}_T$

$\Downarrow$

Able to nearly fully reconstruct the two tops

$\Downarrow$

Helpful for exploring other spin and parity discriminating variables



[Buckley & Gonçalves, 1407.2173, PRL]

Parton-Level Simulation

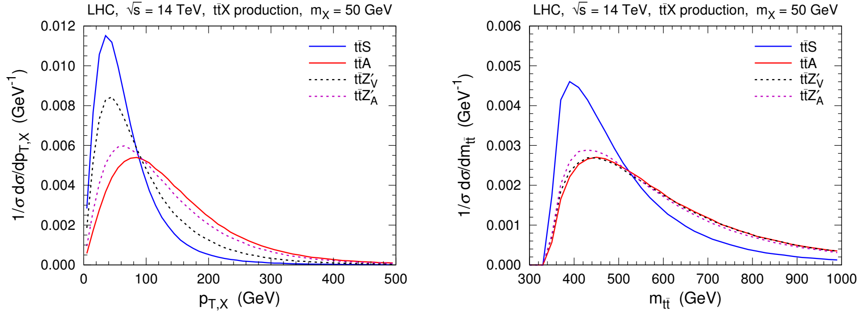
FeynRules: implementation of the simplified models

⇓ UFO format

MadGraph: parton-level simulation samples for the 14 TeV LHC

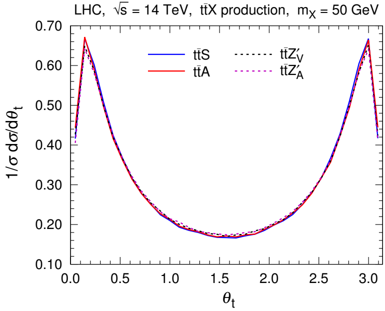
Normalised distributions of $p_{\mathrm{T},X}$ and $m_{t\bar{t}}$ for $m_X = 50$ GeV:

similar in shape; different peak positions; $t\bar{t}S$ is the softest; $t\bar{t}A$ is the hardest



Centre-of-Mass (CM) Frame: the θ_t^{CM} Variable

Distributions of θ_t (the angle between t and the beamline) in the **lab frame** show no difference



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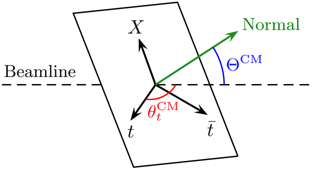
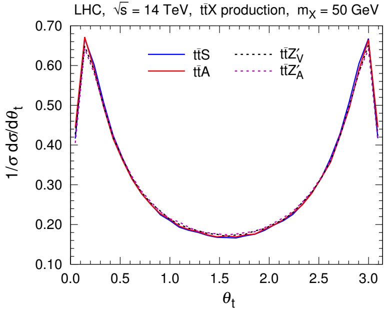


$t\bar{t}X$ CM frame

Boost to the $t\bar{t}X$ CM frame $\Rightarrow \theta_t^{\mathrm{CM}}$

- $t\bar{t}S$: a broad plateau around $\pi/2$
- Other signals: a double-peak structure



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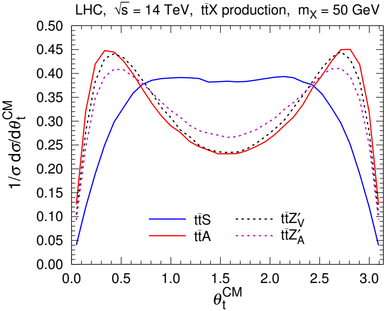
Boost



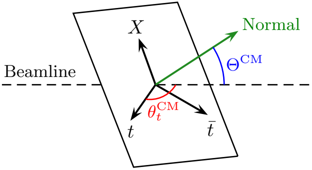
$t\bar{t}X$ CM frame

$t\bar{t}X$ CM Frame: the Θ^{CM} Variable

In the CM frame, the $t\bar{t}X$ system forms **a plane**

$\Downarrow$

Θ^{CM}: the angle between the normal vector to this plane and the beamline



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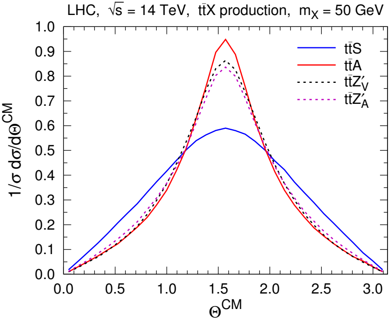


- All the signals peak at $\pi/2$
- $t\bar{t}S$ has the broadest distribution

Detector-Level Simulation

Main background: $t\bar{t}b\bar{b}$ **production**

Minor backgrounds: $t\bar{t}$ + light jets, $t\bar{t}Z$, and $t\bar{t}h$ production

Simulation: `MadGraph` + `PYTHIA` + `Delphes` (ATLAS setup)

Jet clustering algorithm: anti-k_{T} with $R = 0.4$

For $p_{\mathrm{T}} = 100$ GeV, b-**tagging efficiency** $\sim 73\%$,

misidentification rate $\sim 14\%$ for c-jets, $\sim 0.27\%$ for other light jets

Selection criteria for $pp \to t\bar{t}X \to bjj + b\ell\nu_\ell + b\bar{b}$

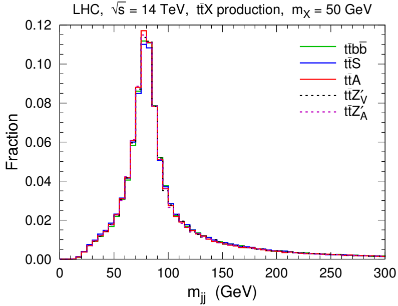
- Exactly 1 charged lepton ℓ (electron or muon) isolated from any jet with $\Delta R > 0.4$
- Exactly 4 b-tagged jets and at least 2 light jets
- The lepton and the jets should have $p_{\mathrm{T}} > 25$ GeV and $|\eta| < 2.5$

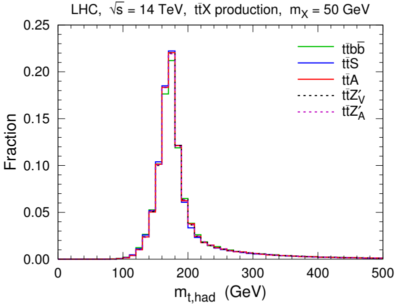
Reconstruction

Reconstruct the **hadronically decaying top** by iterating through combinations of the light jets and b-jets for minimising $\chi^2 = \frac{(m_{jj} - m_W)^2}{m_W^2} + \frac{(m_{t,\text{had}} - m_t)^2}{m_t^2}$

m_{jj}: the invariant mass of two light jets j_1 and j_2

$m_{t,\text{had}}$: the invariant mass of j_1, j_2, and a b-jets b_1



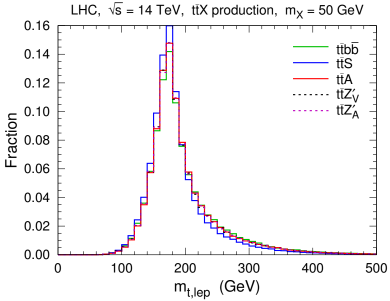


Reconstruction

Reconstruct the **leptonically decaying top** by iterating through the remaining b-jets

for minimising $\chi^2 = \frac{(m_{t,\text{lep}} - m_t)^2}{m_t^2}$

$m_{t,\text{lep}}$: the invariant mass constructed by a b-jets b_2, the lepton ℓ, and the missing transverse momentum $\not{p}_T$



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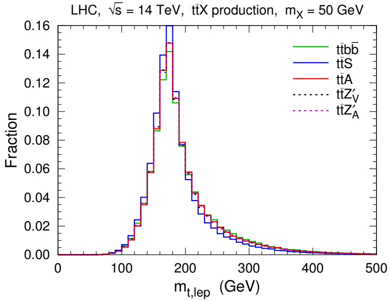
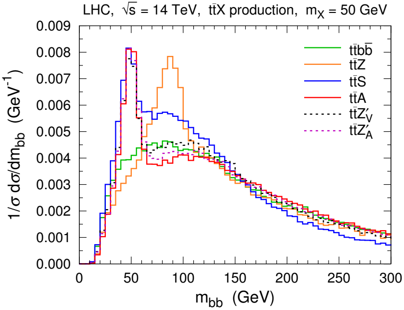




- m_{bb}: the invariant mass of the remaining b-jets b_3 and b_4; used to search for the resonance X
- A clear peak at the signal resonance position
- The Z peak from $t\bar{t}Z$ may be useful for data-driven background estimation

Cut Flow

Selection cuts for further isolating the signal (for $m_X = 50$ GeV):

$$60 \text{ GeV} < m_{jj} < 100 \text{ GeV} \qquad 120 \text{ GeV} < m_{t,\text{had}} < 200 \text{ GeV}$$
$$120 \text{ GeV} < m_{t,\text{lep}} < 220 \text{ GeV} \qquad 35 \text{ GeV} < m_{bb} < 65 \text{ GeV}$$

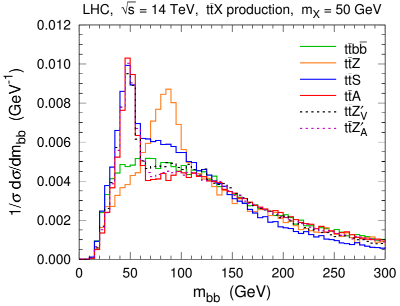
	Events per fb^{-1}				
	$t\bar{t}b\bar{b}$	$t\bar{t}S$	$t\bar{t}A$	$t\bar{t}Z'_{\text{V}}$	$t\bar{t}Z'_{\text{A}}$
No cut	24375	4211	428	714	2409
1 lepton	4612	744	80.0	132	444
4 b-tags	106	33.9	5.15	7.12	27.5
≥ 2 light jets	72.9	22.1	3.51	4.86	18.7
$m_{jj} \in (60, 100)$ GeV	42.0	12.6	2.05	2.82	10.9
$m_{t,\text{had}} \in (120, 200)$ GeV	39.1	11.9	1.92	2.64	10.2
$m_{t,\text{lep}} \in (120, 220)$ GeV	30.2	9.87	1.52	2.09	8.07
$m_{bb} \in (35, 65)$ GeV	4.35	2.33	0.333	0.450	1.78

The $t\bar{t}b\bar{b}$ background is suppressed by a factor of ~ 5000

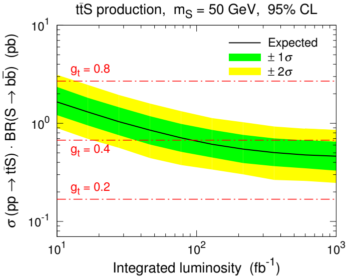
Sensitivity for Discovery

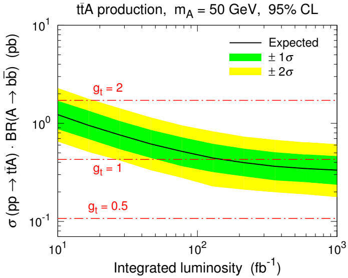
Estimation of the expected exclusion on the signal

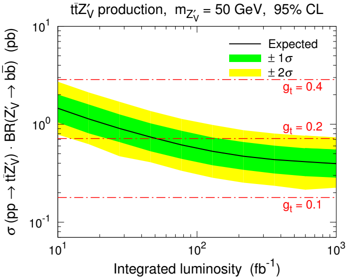
- Carry out a CL_s **hypothesis test** based on the m_{bb} distributions from 15 GeV to 200 GeV without applying the m_{bb} cut
- Scale up the $t\bar{t}b\bar{b}$ background by a factor of 1.2 in order to take into account the remaining backgrounds
- Assume a flat 10% systematic uncertainty on the total background

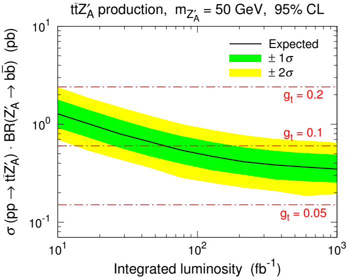


Expected Exclusion Limits on the Signal Strength









Detector-Level Discriminating Variables

The **4-momenta** of the hadronically decaying top, the leptonically decaying top, and the resonance X can be constructed from the identified jets and lepton:

$$p_{t,\text{had}} = p_{b_1} + p_{j_1} + p_{j_2}, \quad p_{t,\text{lep}} = p_{b_2} + p_\ell + \not{p}_\text{T}, \quad p_X = p_{b_3} + p_{b_4}$$

The $t\bar{t}X$ **CM frame** can be found by a Lorentz boost to the frame that satisfies

$$\mathbf{p}_{t,\text{had}} + \mathbf{p}_{t,\text{lep}} + \mathbf{p}_X = 0$$

These 4-momenta allow us to construct **detector-level** discriminating variables

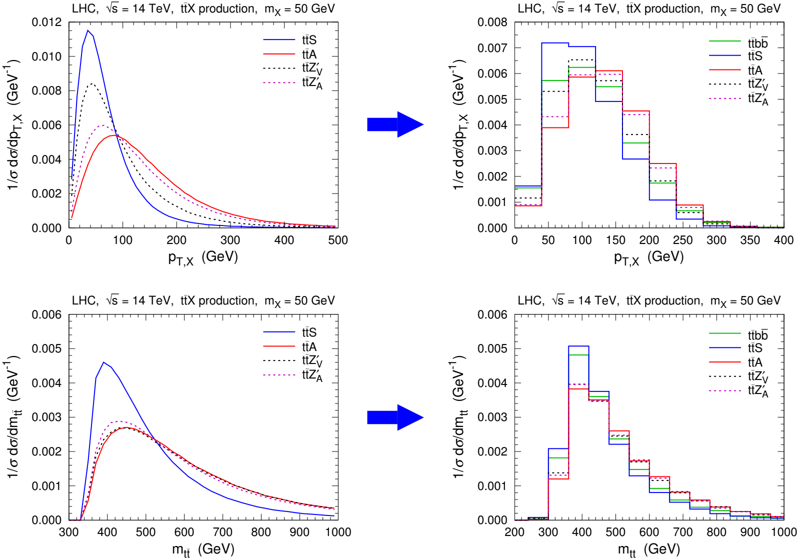
$$p_{\text{T},X}, \quad m_{tt}, \quad \theta^\text{CM}_{t,\text{had}}, \quad \text{and} \quad \Theta^\text{CM},$$

which are equivalent to the parton-level variables discussed above. Note that $m_{tt} \equiv (p_{t,\text{had}} + p_{t,\text{lep}})^2$, and $\theta^\text{CM}_{t,\text{had}}$ corresponds to the hadronically decaying top.

An analogous variable $\theta^\text{CM}_{t,\text{lep}}$ can be defined using $p_{t,\text{lep}}$, but it is less powerful than $\theta^\text{CM}_{t,\text{had}}$ for discrimination among the simplified models.

Parton Level vs Detector Level

Parton level



Detector level

Parton Level vs Detector Level

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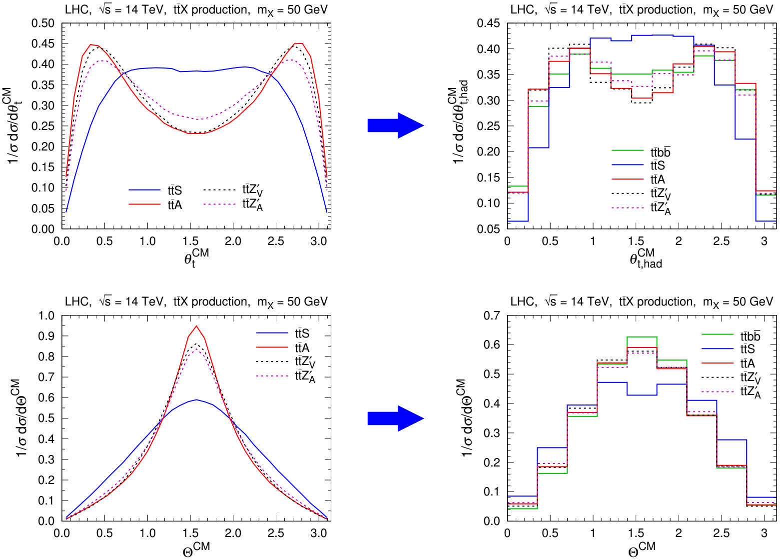


Detector level

$\mathrm{CL_s}$ Hypothesis Test for Discrimination

$\mathrm{CL_s}$ hypothesis test: study the discriminating power of each variable

Analogous to those in the CMS [1411.3441] and ATLAS [1506.05669] analyses for determining the spin and parity of the SM Higgs, the **test statistic** is defined as

$$Q = -2\ln\frac{\mathcal{L}(s_2+b)}{\mathcal{L}(s_1+b)}$$

$\mathcal{L}(s+b)$: the likelihood for the background b plus a signal hypothesis s

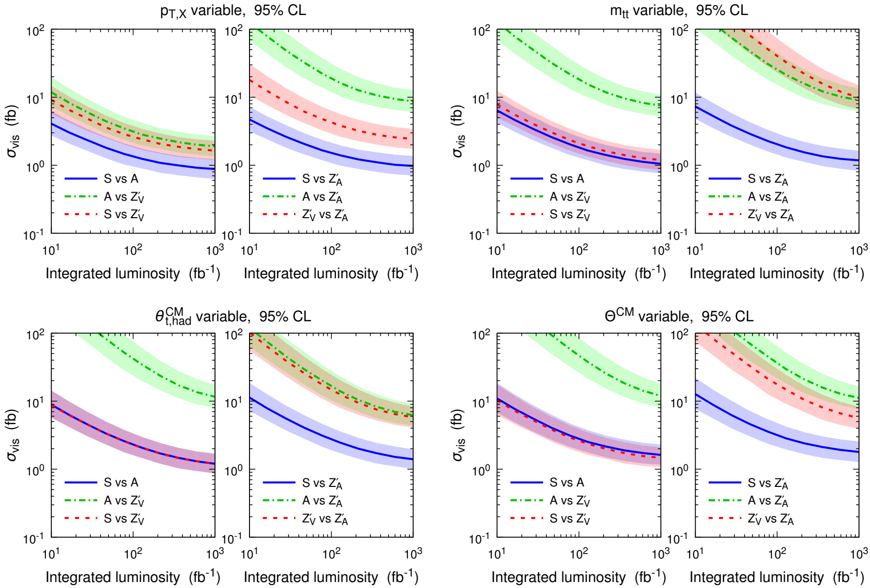
Q: used to discriminate between signal hypotheses s_1 and s_2

For an observed value Q_{obs}, the exclusion of the hypothesis s_2 in favour of the hypothesis s_1 (denoted as "s_1 vs s_2" hereafter) is evaluated in terms of the **modified confidence level**

$$\mathrm{CL_s} = \frac{P(Q \geq Q_{\mathrm{obs}}|s_2+b)}{P(Q \geq Q_{\mathrm{obs}}|s_1+b)}$$

$P(Q \geq Q_{\mathrm{obs}}|s+b)$: the probability for $Q \geq Q_{\mathrm{obs}}$ under a hypothesis $s+b$

Exclusion Limits for the Same $\sigma_{\text{vis}} \equiv \sigma \cdot \text{BR} \cdot A \cdot \epsilon$



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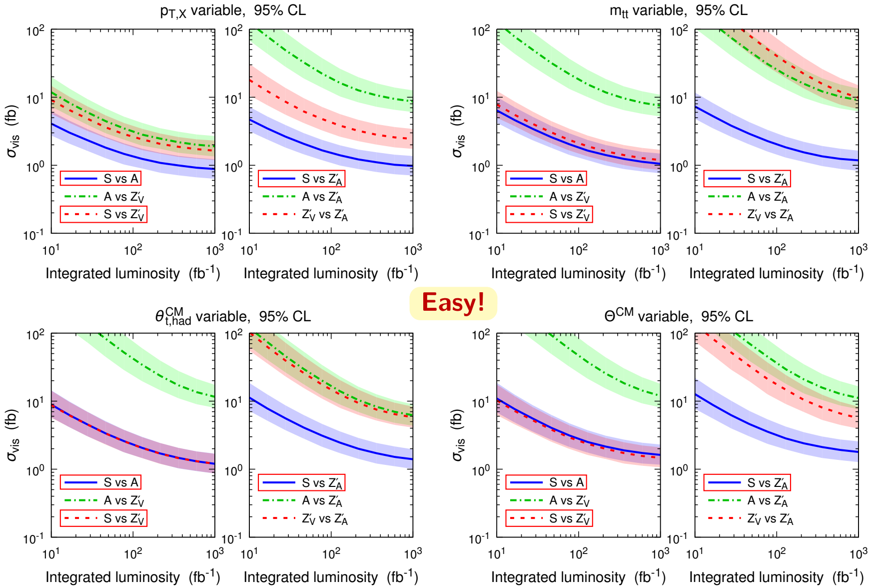

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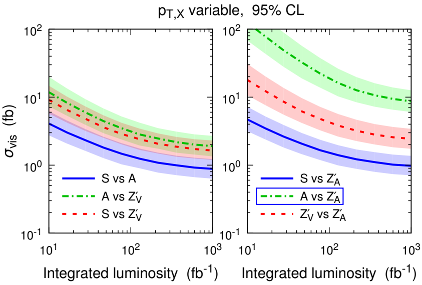
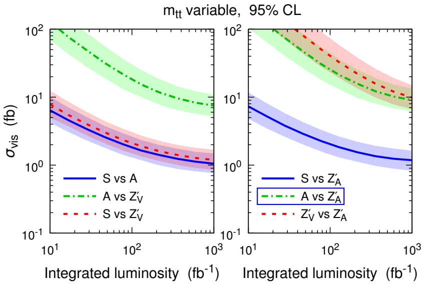
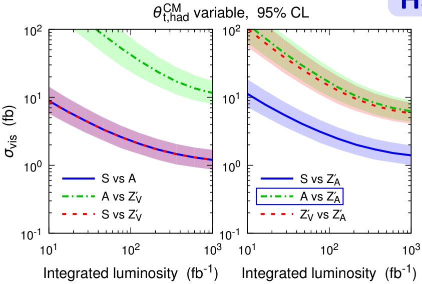
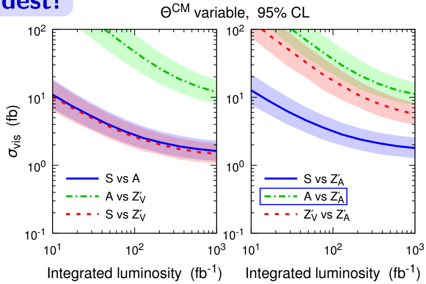


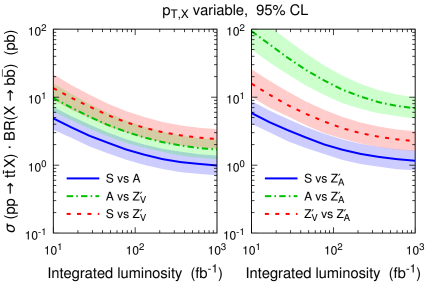


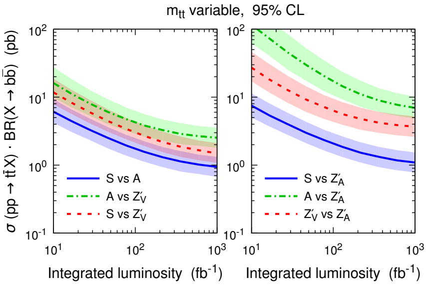
Hardest!

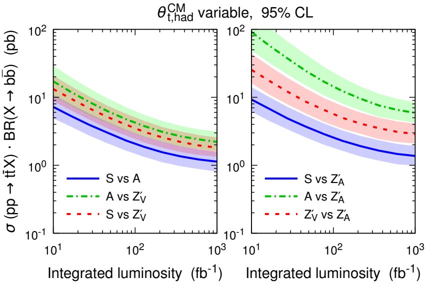


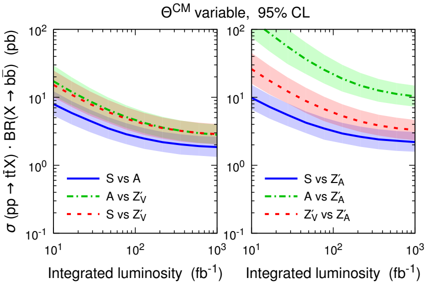


Exclusion Limits for the Same Signal Strength $\sigma \cdot \mathrm{BR}$









Conclusion

1. LHC Searches for $t\bar{t}X$ **production** are sensitive to a **new resonance** X that predominantly couples to the **third generation quarks**. If such a resonance is discovered, a further measurement of its **parity and spin** will be essential for revealing the underlying new physics.
2. We demonstrated **four kinematic variables** for discriminating different assumptions of the spin and parity in the semi-leptonic channel.
3. We found that the **scalar** is the **easiest** one to be distinguished from others, while the **hardest** case is to discriminate between the **pseudoscalar** and the **axial vector**.

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Thanks for your attention!