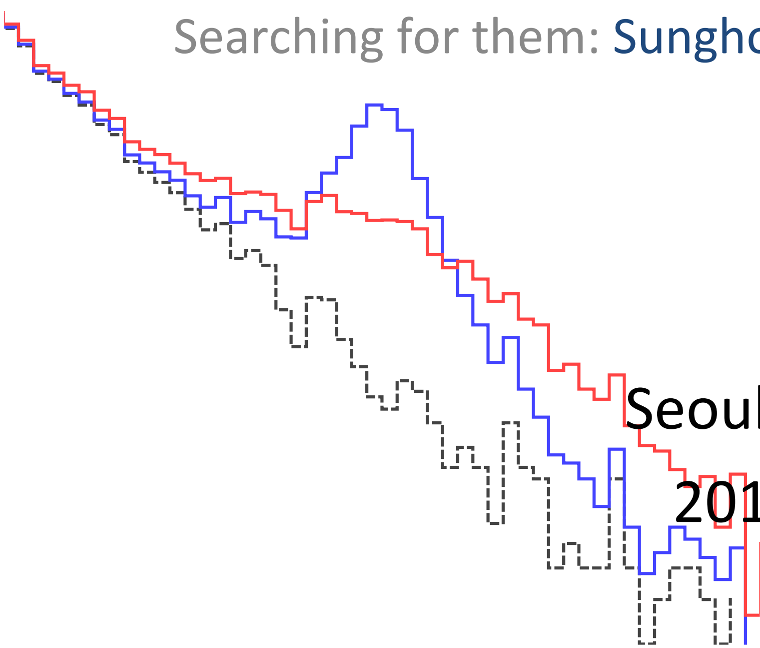
Broad composite resonances and their signals at the LHC

Why they exist: Da Liu, Lian-Tao Wang and **KPX**, 1901.01674;

Searching for them: Sunghoon Jung, Dongsub Lee and **KPX**, 1906.02810.



Ke-Pan Xie

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2019.7.16 KAIST-KAIX

The composite Higgs models

Kaplan *et al*, Phys.Lett. 136B (1984) 183-186
Agashe *et al*, Nucl.Phys. B719 (2005) 165-187

- Two sectors

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm strong}$$

$W_\mu^{a_L};\ B_\mu;$

$q_L = \begin{pmatrix} t_L \\ b_L \end{pmatrix};\ t_R;\ b_R;\ \cdots$

$\ell_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix};\ e_R;\ \cdots$

Contain the Higgs doublet

Global symmetry breaking $\mathcal{G} \to \mathcal{H}$

Nambu-Goldstone Bosons

The elementary sector
(SM fermions and EW bosons)

The strong sector
(new physics)

- Interactions between two sectors

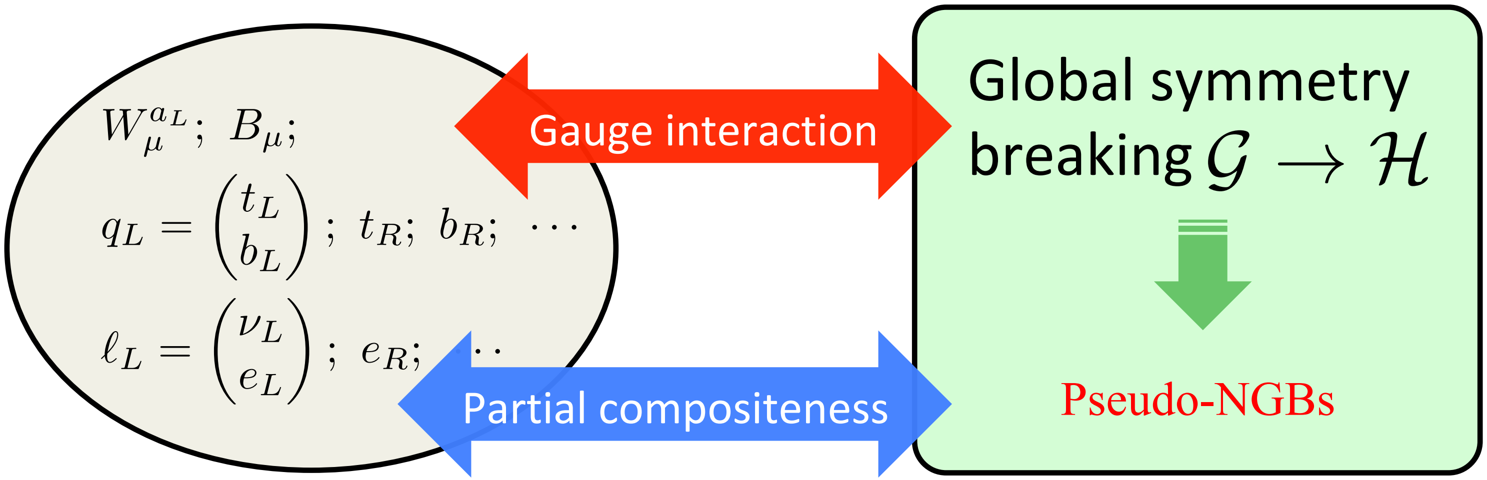
$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm strong}$$

Kaplan *et al* (1984) and Agashe *et al* (2005)

$$+ \mathcal{J}^a_\mu W^\mu_a + \mathcal{J}_{Y\mu} B^\mu + y_L \bar{q}_L \mathcal{O}_R + y_R \bar{t}_R \mathcal{O}_L$$

EW gauge coupling:
Subgroup $SU(2)_L \times U(1)_Y$ gauged

Partial compositeness:
q_L and u_R fill in the incomplete representation of $\mathcal{G}$



The elementary sector
(SM fermions and EW bosons)

The strong sector
(new physics)

- Interactions between two sectors triggering EWSB

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm strong}$$

Kaplan *et al* (1984) and Agashe *et al* (2005)

$$+\, \mathcal{J}^a_\mu W^\mu_a + \mathcal{J}_{Y\mu} B^\mu + y_L \bar{q}_L \mathcal{O}_R + y_R \bar{t}_R \mathcal{O}_L$$

EW gauge coupling:
Subgroup $SU(2)_L \times U(1)_Y$ gauged

Partial compositeness:
q_L and u_R fill in the incomplete representation of $\mathcal{G}$

Explicitly break $\mathcal{G}$!!

Higgs potential generated; EWSB triggered

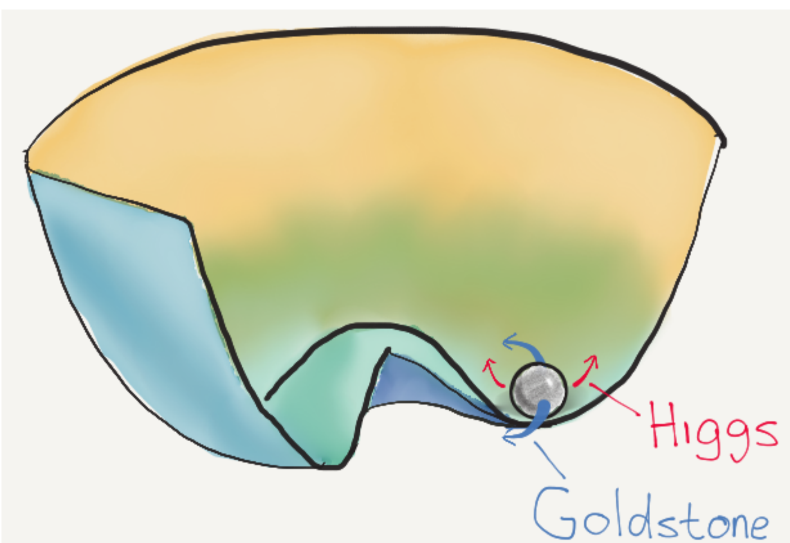
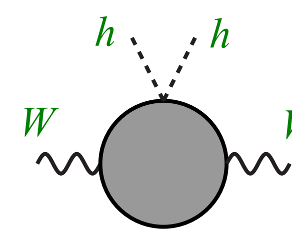


Figure from https://freethoughtblogs.com

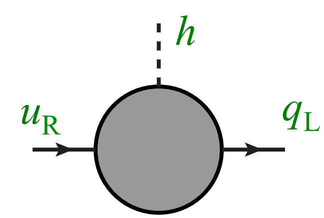
W and *Z* mass

$$\langle \mathcal{J}\mathcal{J} \rangle \sim g^2 f^2 \sin^2 \frac{h}{f}$$



Top mass

$$\langle \mathcal{O}_L \mathcal{O}_R \rangle \sim \frac{y_L y_R}{g_\rho} f \sin \frac{h}{f}$$



• Composite Higgs zoo

$\mathcal{G}/\mathcal{H}$: the scalar sector	q_L & t_R embedding	Relevant references
SO(5)/SO(4): Higgs doublet [known as minimal composite Higgs model]	4+4	Agashe *et al*, Nucl.Phys. B719 (2005) 165-187
	5+5	Contino *et al*, Phys. Rev. D75, 055014 (2007)
	10+10, 14+1, ...	Panico *et al*, JHEP 1303 (2013) 051
	5+5, 14+1	Matsedonskyi *et al*, JHEP 1604 (2016) 003
	......	......
SO(6)/SO(5): Higgs doublet + 1 singlet	6+6	Gripaios *et al*, JHEP 0904 (2009) 070
	6+6, 15+6, 20+1, ...	Banerjee *et al*, JHEP 1803 (2018) 062
	......	......
SU(5)/SO(5): Higgs doublet + 2 triplets + 1 singlet	1, 10, 15, 24, ...	Agugliaro *et al*, JHEP 1902 (2019) 089
SO(8)/SO(7): twin Higgs	8+1	Barbieri *et al*, JHEP 1508 (2015) 161
......	......	......

The collider phenomenology

- Robust prediction: the $\rho^{\pm,0}$ resonances

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm strong}$$
$$+ \mathcal{J}^a_\mu W^\mu_a + \mathcal{J}_{Y\,\mu} B^\mu + y_L \bar{q}_L \mathcal{O}_R + y_R \bar{t}_R \mathcal{O}_L$$

$$\mathcal{J}^{a_L}_\mu W^\mu_{a_L} \to -a_\rho^2 f^2 g_\rho \rho^{a_L}_\mu \left(g_2 W^{a_L}_\mu - \frac{i}{f^2} H^\dagger \frac{\sigma^{a_L}}{2} \overleftrightarrow{D}_\mu H \right) + \cdots ,$$

f: $\mathcal{G}/\mathcal{H}$ scale; a_ρ: the order 1 parameter; g_ρ: strong dynamics coupling >> g_2

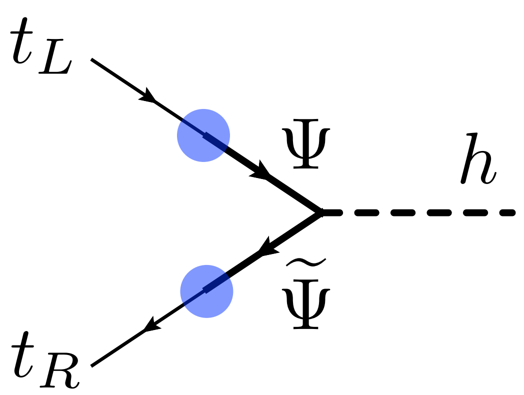
The ρ-W mixing: $\sin\vartheta \approx g_2/g_\rho$
➔ The ρ-elementary quark coupling ≈ $g_2 \sin\vartheta$
➔ Can be produced by Drell-Yan process

The ρ-Goldstone coupling: $g_\rho >> g_2$
➔ Large paritial width to SM di-boson ($W^\pm Z$, $W^\pm h$, W^+W^-, Zh) channels.

- Robust prediction: the Ψ resonances (top partners)

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm strong}$$
$$+ \mathcal{J}^a_\mu W^\mu_a + \mathcal{J}_{Y\mu} B^\mu + y_L \bar{q}_L \mathcal{O}_R + y_R \bar{t}_R \mathcal{O}_L$$

1. Giving mass to top quark:



$$y_t \sim \frac{M_\Psi}{f} \sin\theta_L \sin\theta_R$$

ϑ_L and ϑ_R: mixing angles

2. Interactions with the ρ resonances:

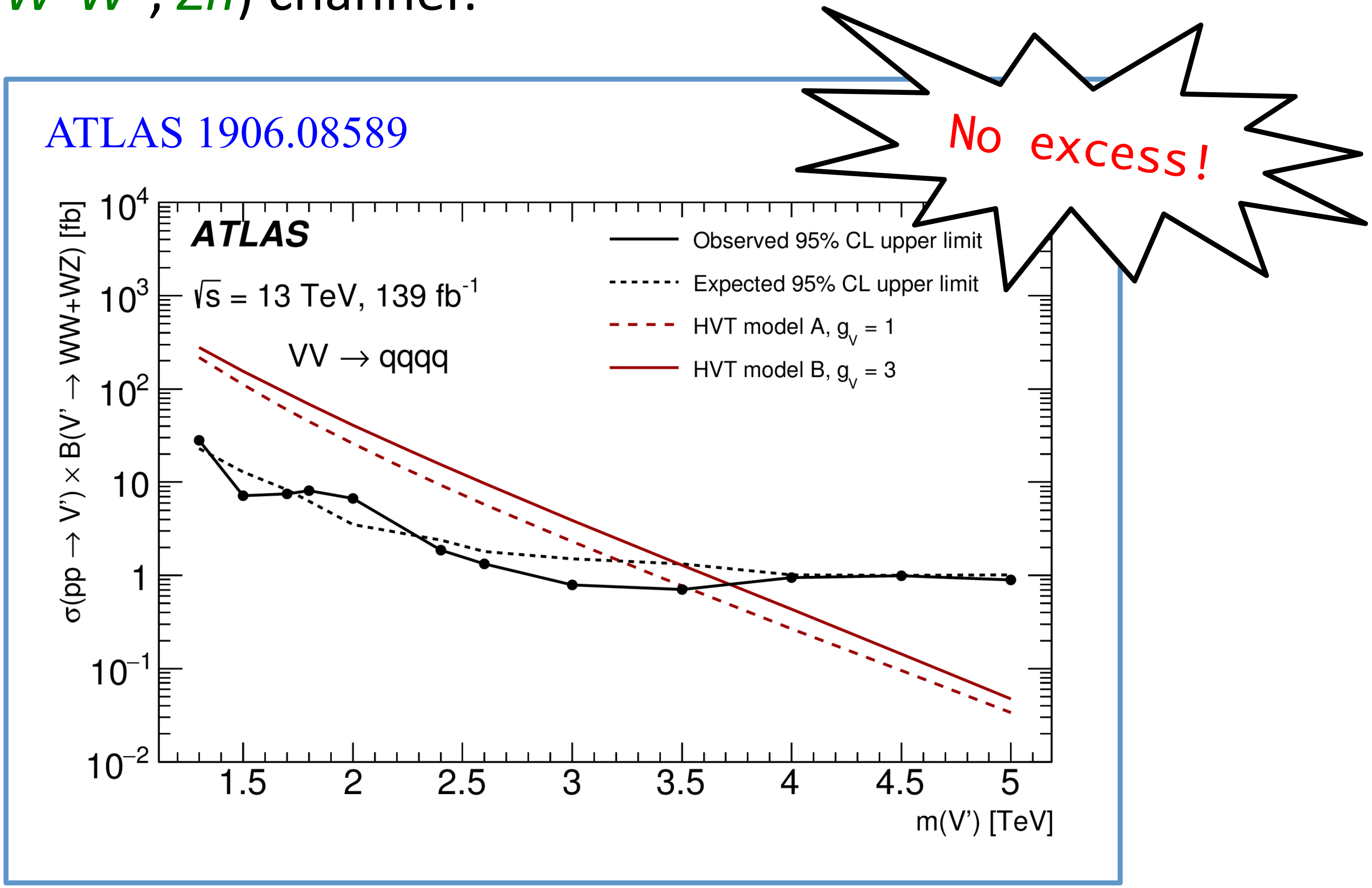
$$\mathcal{L}_{\rm int} \sim c_1 g_\rho \rho_\mu \bar{\Psi}\gamma^\mu\Psi; \quad c_1 \sim \mathcal{O}(1).$$

$$\Rightarrow \quad g_{\rho\Psi\bar{\Psi}} \sim g_\rho, \quad g_{\rho q_L \bar{q}_L} \sim g_\rho \sin^2\theta_L$$

t_L-ρ, b_L-ρ interactions are suppressed by mixing angle;
t_R-ρ interaction is tiny because of quantum number.

- General predictions of previous scenario:

An SU(2) triplet vector resonance $\rho^{\pm,0}$, can be Drell-Yan produced, and decays dominantly to SM di-boson ($W^{\pm}Z$, $W^{\pm}h$, $W^{+}W^{-}$, Zh) channel!



- Why? Two possibilities:

1. The ρ resonances are much heavier than expected.

- Why? Two possibilities:

1. The ρ resonances are much heavier than expected.

2. The $\rho^{\pm,0}$s are not that heavy, but hidden in some unexpected channels.

Our work: what happen if SM 3rd generation quark $q_L = (t_L, b_L)^T$ itself is a strong dynamics bound state from new physics?

Da Liu, Lian-Tao Wang and **Ke-Pan Xie**, 1901.01674

$q_L = (t_L, b_L)^T$ as new physics bound states

Da Liu, Lian-Tao Wang and **Ke-Pan Xie**, 1901.01674

- Symmetry group: SO(5)/SO(4)

The "minimal composite Higgs scenario";
Scalar sector: one Higgs doublet.

- Fermion embedding: q_L in (2,2) while t_R in 5

$$\Psi_L = \frac{1}{\sqrt{2}}\begin{pmatrix} ib_L - iX_L \\ b_L + X_L \\ it_L + iT_L \\ -t_L + T_L \end{pmatrix} = \underbrace{\begin{pmatrix} t_L \\ b_L \end{pmatrix}_{1/6}}_{q_L} \oplus \underbrace{\begin{pmatrix} X_L \\ T_L \end{pmatrix}_{7/6}}_{q_L^X}$$

$$t_R^{\mathbf{5}} = (0,0,0,0,t_R)^T, \quad q_R^{X\mathbf{5}} = \frac{1}{\sqrt{2}}(-iX_R, X_R, iT_R, T_R, 0)^T.$$

$q^X = (T, X)^T$, top partner: q_L^X is composite; q_R^X is elementary

- More details about the fermion sector

1. Why q_L in (2,2)?

$$\bar{\Psi}_L \gamma^\mu (i\partial_\mu + e_\mu)\Psi_L \to$$

$$-\frac{i}{4f^2}\bar{q}_L\gamma^\mu\sigma^a q_L H^\dagger\sigma^a \overleftrightarrow{D}_\mu H + \frac{i}{4f^2}\bar{q}_L\gamma^\mu q_L H^\dagger \overleftrightarrow{D}_\mu H$$

$$iH^\dagger \overleftrightarrow{D}_\mu H \to -\frac{\langle h\rangle^2}{2}\left(g_2 W_\mu^3 - g_1 B_\mu\right); \quad iH^\dagger\sigma^a \overleftrightarrow{D}_\mu H \to \frac{\langle h\rangle^2}{2}\left(g_2 W_\mu^a - g_1\delta^{a3}B_\mu\right)$$

Zb_Lb_L vertex protected. Consequence of the P_{LR} symmetry.

For P_{LR}, see Contino *et al*, Phys.Rev. D75 (2007) 055014

2. Why introduce q^X?

$$-y_{1R}f\bar{q}_R^{X\mathbf{5}}U\Psi_L - y_{2R}f\bar{t}_R^{\mathbf{5}}U\Psi_L$$

$$= \underbrace{-y_{1R}f\bar{q}_R^X q_L^X}_{\text{top partner mass}} - y_{2R}(\underbrace{\bar{t}_R\widetilde{H}^\dagger q_L}_{\text{top mass}} - \bar{t}_R H^\dagger q_L^X) + \cdots$$

To fulfill the SO(4) representation and give masses.

- Interactions

1. Most remarkable coupling

$$\mathcal{L}_{\rm int} \supset c_1 \bar{\Psi}_L \gamma^\mu T^{a_L} \Psi_L g_\rho \rho^{a_L} = c_1 g_\rho \rho_\mu^{a_L} \bar{q}_L \gamma^\mu \frac{\sigma^{a_L}}{2} q_L + \cdots$$

$$g_{\rho^- t_L \bar{b}_L} = \frac{g_\rho}{\sqrt{2}}; \quad g_{\rho^0 t_L \bar{t}_L} = -g_{\rho^0 b_L \bar{b}_L} = \frac{g_\rho}{2},$$

$\rho t_L t_L$, $\rho b_L b_L$ and $\rho t_L b_L$ vertices strong couple without suppression!

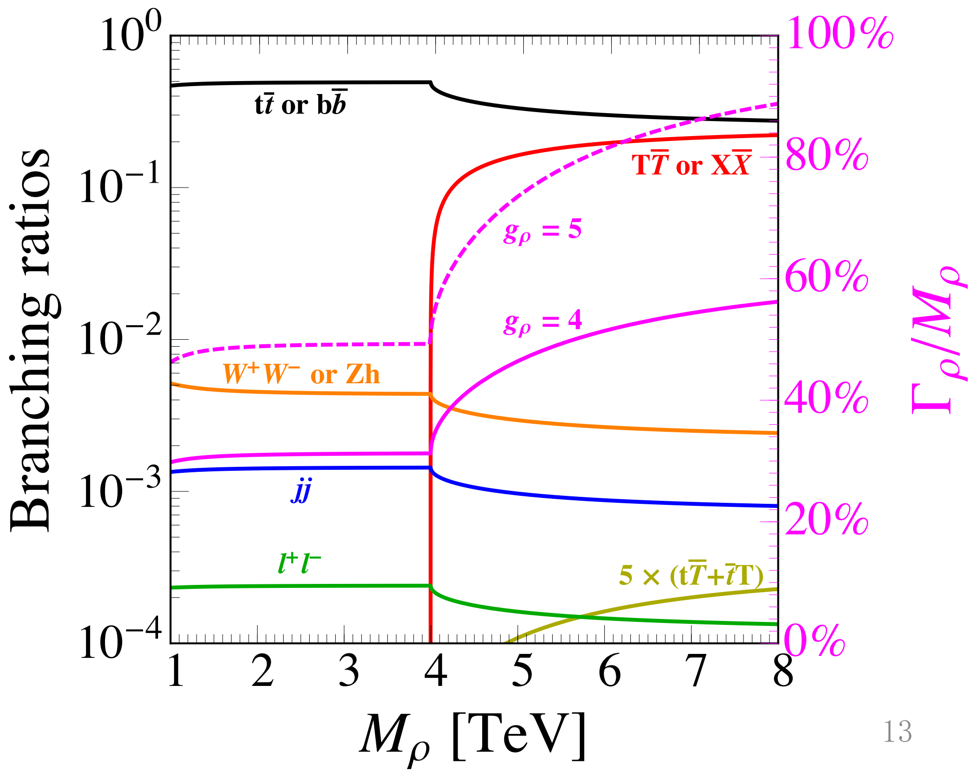
2. The decay of $\rho^{\pm,0}$

Di-fermion dominates di-boson;

$$\frac{\Gamma_{\rho^0 \to W^+ W^-}}{M_\rho} = \frac{g_\rho^2}{192\pi};$$

$$\frac{\Gamma_{\rho^0 \to t\bar{t}}}{M_\rho} = \frac{N_c g_\rho^2}{96\pi};$$

$$\frac{\Gamma_{\rho^0 \to t\bar{t}}}{\Gamma_{\rho^0 \to W^+ W^-}} = 2N_c = 6.$$



- Interactions

1. Most remarkable coupling

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$\rho t_L t_L$, $\rho b_L b_L$ and $\rho t_L b_L$ vertices strong couple without suppression!

2. The decay of $\rho^{\pm,0}$

Can easily be broad!

$$\frac{\Gamma_{\rho^0 \to W^+ W^-}}{M_\rho} = \frac{g_\rho^2}{192\pi};$$

$$\frac{\Gamma_{\rho^0 \to t\bar{t}}}{M_\rho} = \frac{N_c g_\rho^2}{96\pi};$$

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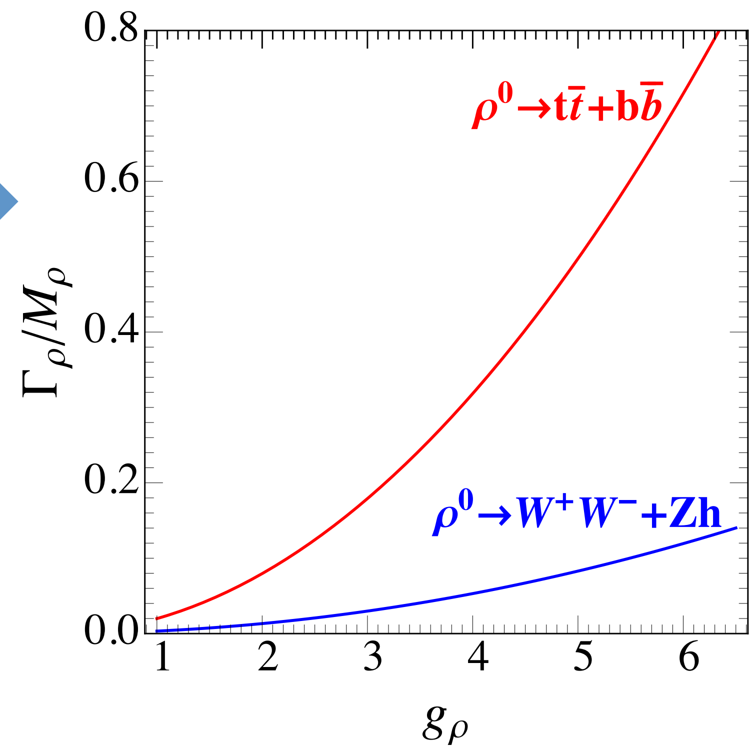
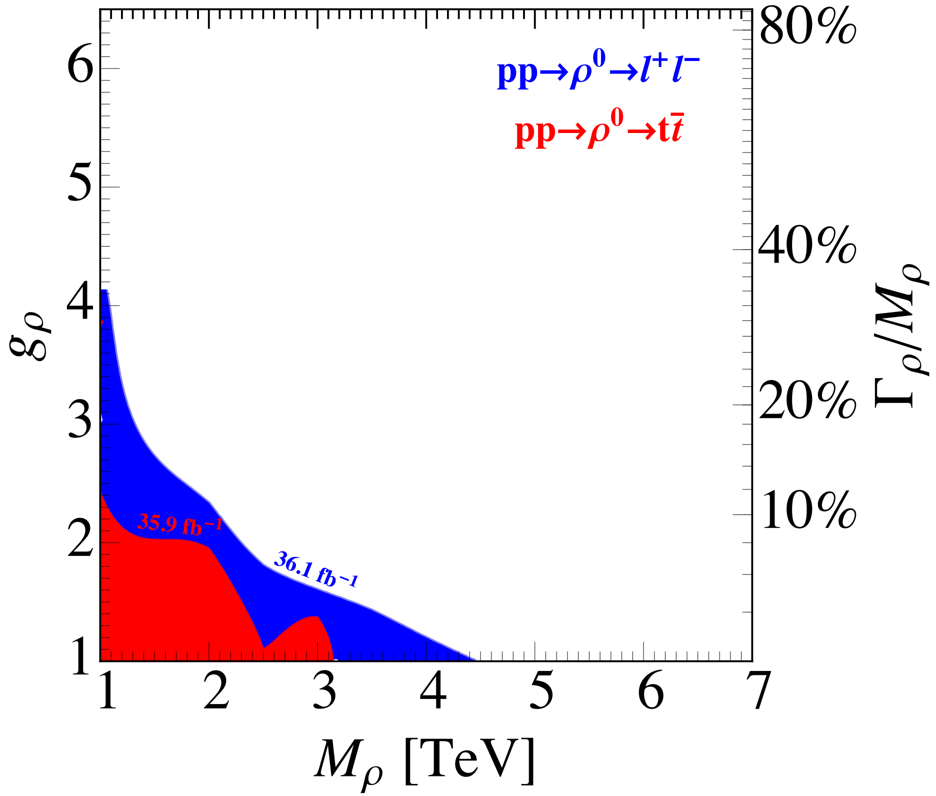


- Collider phenomenology

Current constraints from the experiment (the di-boson bounds are too weak to show):



A light but broad ρ is still allowed!

- Collider phenomenology

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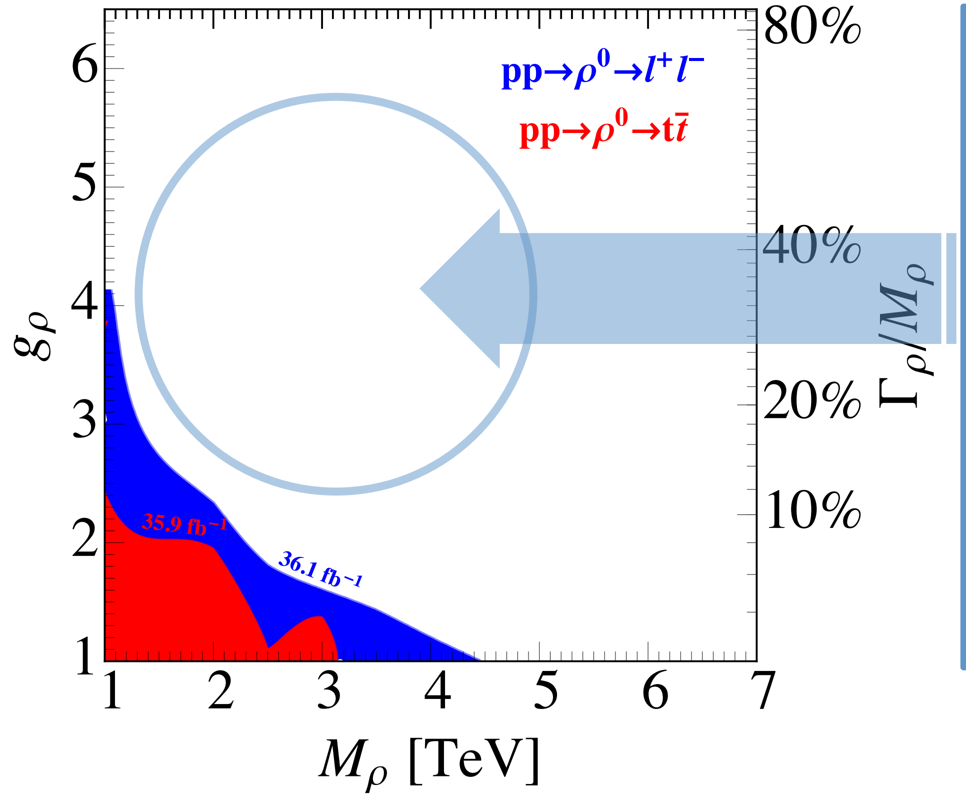
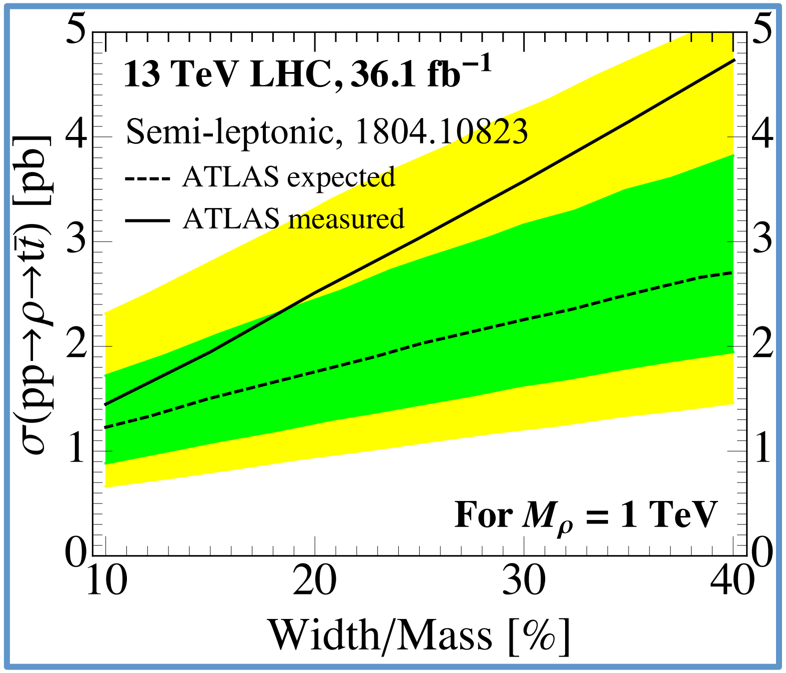
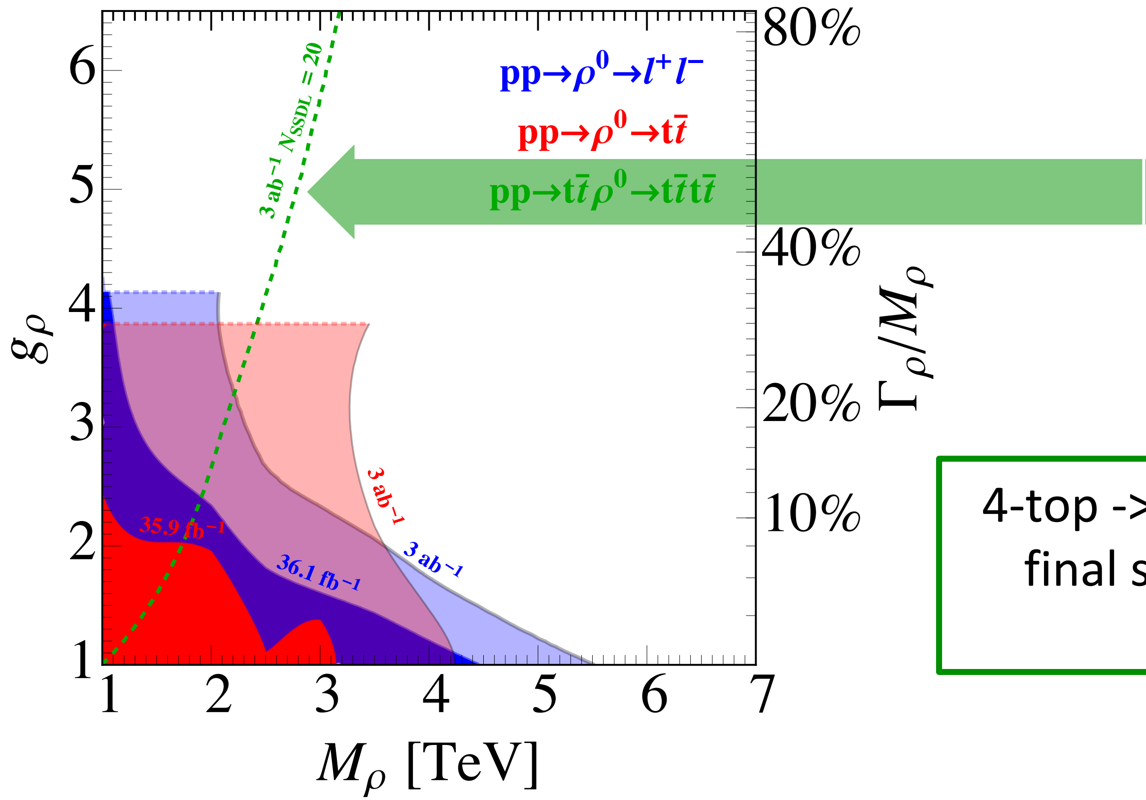


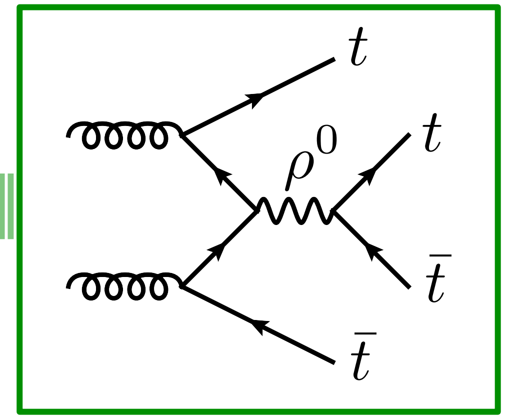


A light but broad ρ is still allowed!

- Collider phenomenology

Projections for the HL-LHC: *tt*, *ll*, and the *tttt* channels.





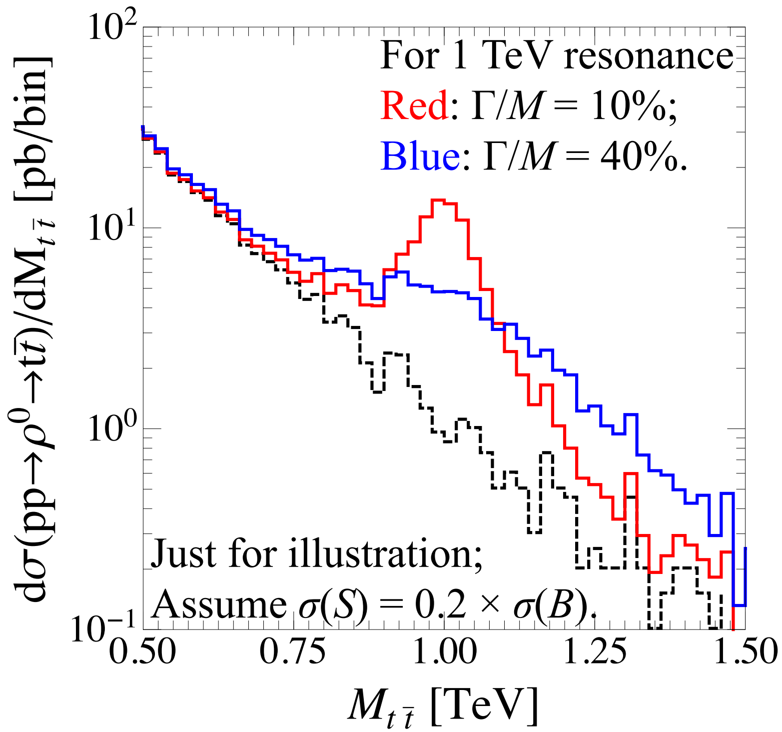
4-top -> same-sign di-lepton final state, insensitive to width!

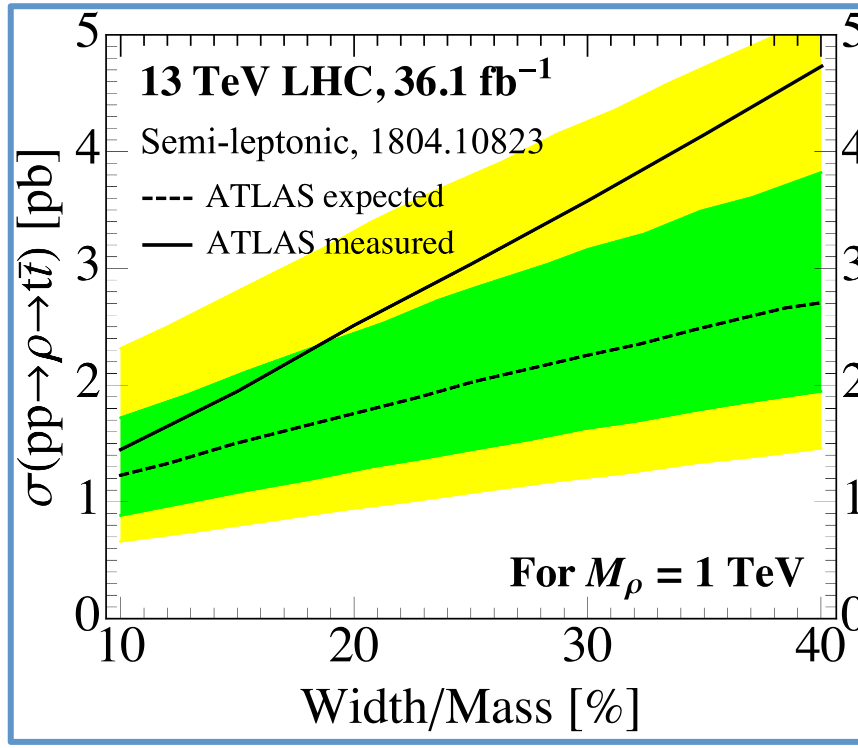
More dedicated searches are needed!

Searching for a broad *tt* resonance

Sunghoon Jung, Dongsub Lee and **Ke-Pan Xie**, 1906.02810

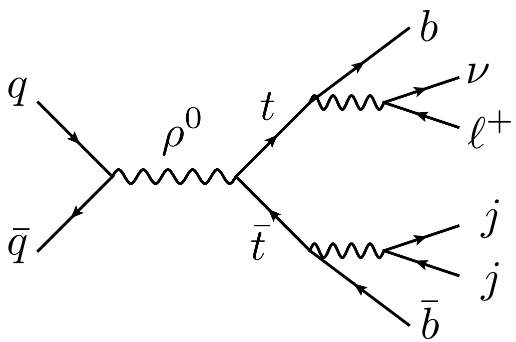
- The traditional search: only fit M_{tt}





The bound gets worse when the resonant peak is smeared out.

- Our approach: input all the kinematic features

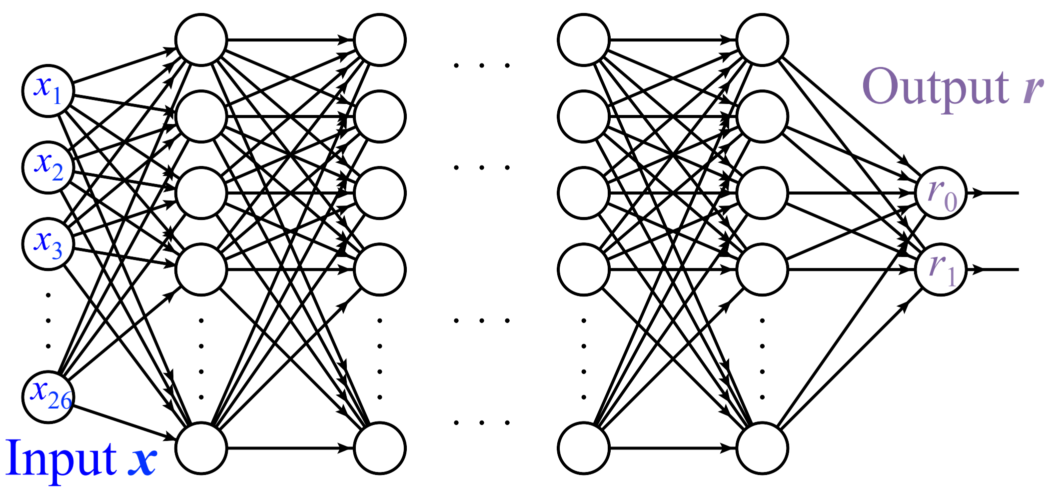


Input low-level observables:
Four momenta of 1 lepton + MET + 4 jets

1	2	3	4	5	6	7	8	9	10	11	12	13
E^ℓ	p_T^ℓ	η^ℓ	ϕ^ℓ	$\not{E}_T$	$\phi^{\not{E}_T}$	E^{j_1}	$p_T^{j_1}$	η^{j_1}	ϕ^{j_1}	b^{j_1}	E^{j_2}	$p_T^{j_2}$

14	15	16	17	18	19	20	21	22	23	24	25	26
η^{j_2}	ϕ^{j_2}	b^{j_2}	E^{j_3}	$p_T^{j_3}$	η^{j_3}	ϕ^{j_3}	b^{j_3}	E^{j_4}	$p_T^{j_4}$	η^{j_4}	ϕ^{j_4}	b^{j_4}

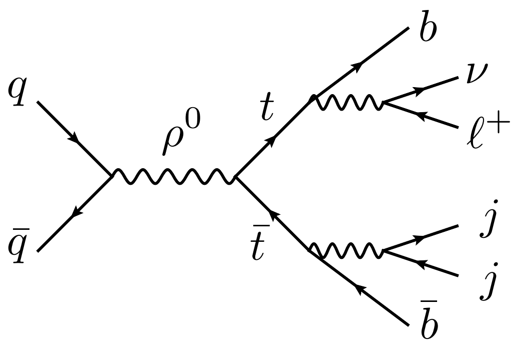
Main background: SM ttbar



Label $\boldsymbol{y}$ (0,1) for signal; (1,0) for BKG

Machine learning on the DNN: Tune the *w* [weights] and *b* [biases], such that the output ***r*** and the label ***y*** are as closed as possible.

- Our approach: input all the kinematic features



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η^{j_2}	ϕ^{j_2}	b^{j_2}	E^{j_3}	$p_T^{j_3}$	η^{j_3}	ϕ^{j_3}	b^{j_3}	E^{j_4}	$p_T^{j_4}$	η^{j_4}	ϕ^{j_4}	b^{j_4}

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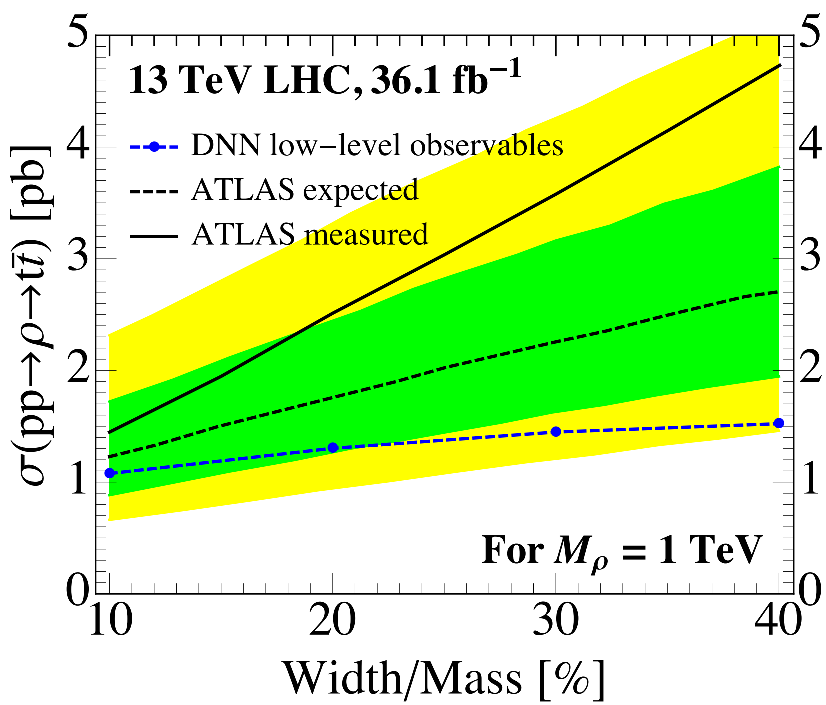


The ATLAS result: 1804.10823
The DNN result: **this work**

The DNN results are much insensitive to the width!

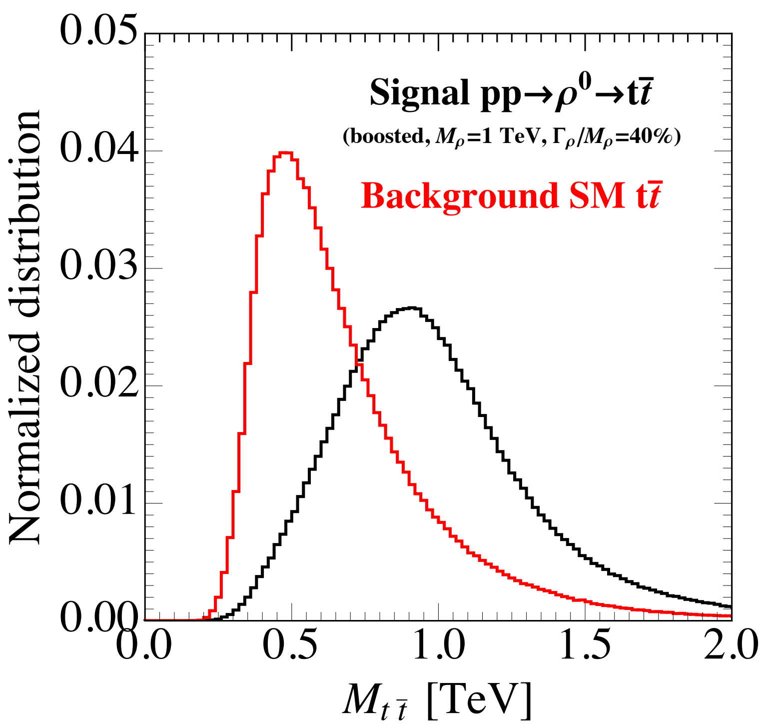
- What information dose the DNN make use of?

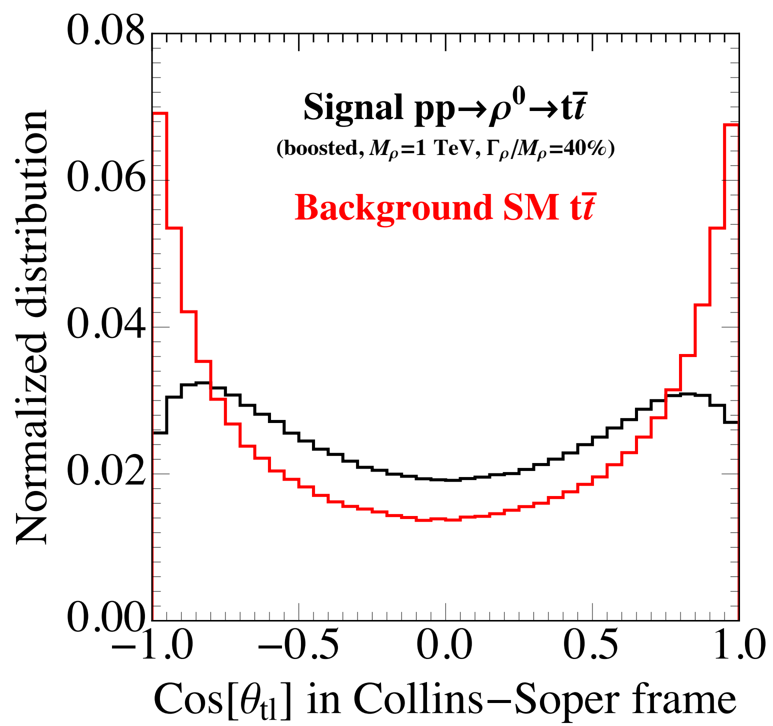
Adding high-level observables and test

1	2	3	4	5	6	7
$M_{t\bar{t}}$	$\cos\theta_{\rm tl}^{\rm CS}$	$\cos\theta_{\rm th}^{\rm CS}$	$\phi_{\rm tl}^{\rm CS}$	$\phi_{\rm th}^{\rm CS}$	$\cos\theta_{\rm tl}^{\rm Mus.}$	$\cos\theta_{\rm th}^{\rm Mus.}$

Invariant mass

Spin correlation in the *tt* rest frame





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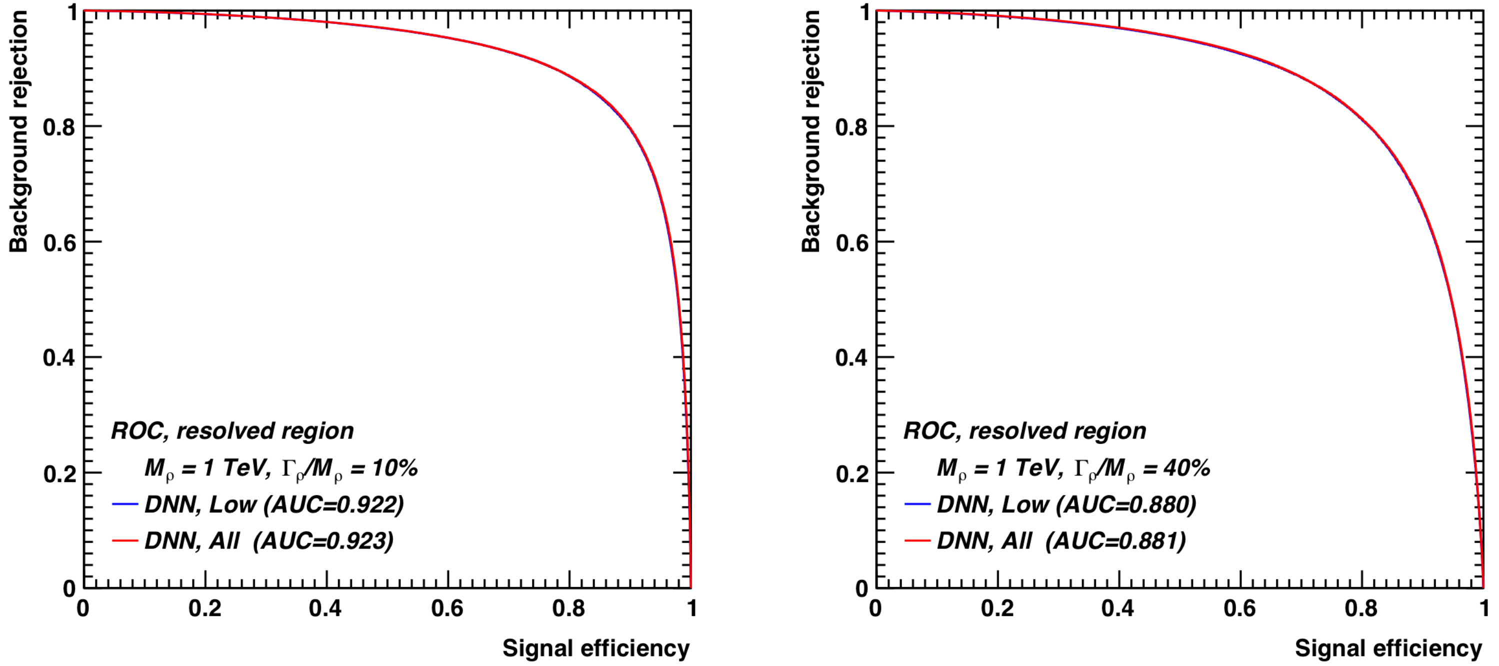
The receiver operating characteristic curves (ROC)



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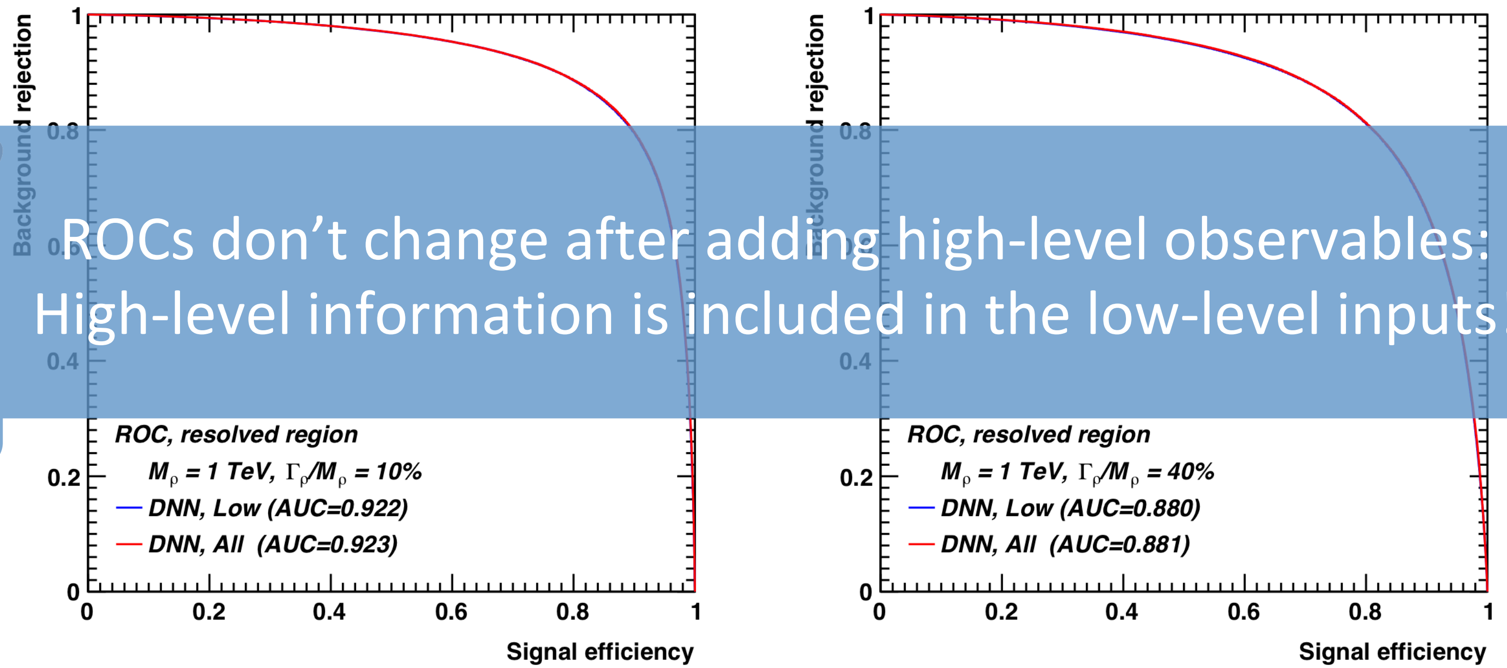


ROCs don't change after adding high-level observables:
High-level information is included in the low-level inputs!

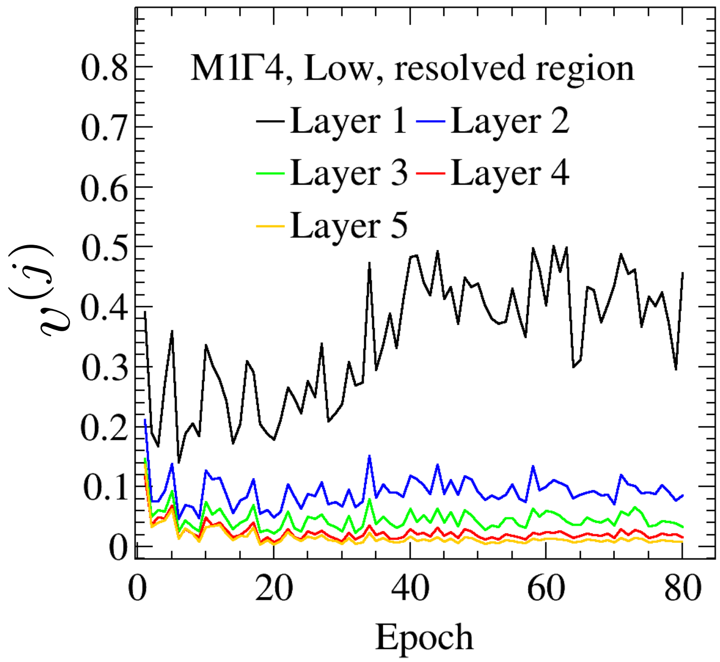
- What information dose the DNN make use of?

Ranking the importance of inputs

We define the learning speed of the *j*-th hidden layer as

$$v^{(j)} = \left| \frac{\partial \mathcal{L}_{\text{loss}}(w, b)}{\partial \vec{b}^{(j)}} \right|,$$

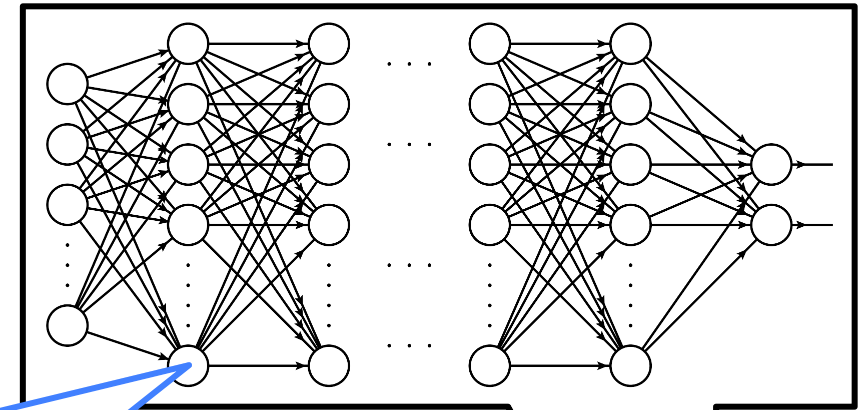
And what we found is:



The first hidden layer always has the largest learning speed!

- What information dose the DNN make use of?

Ranking the importance of inputs

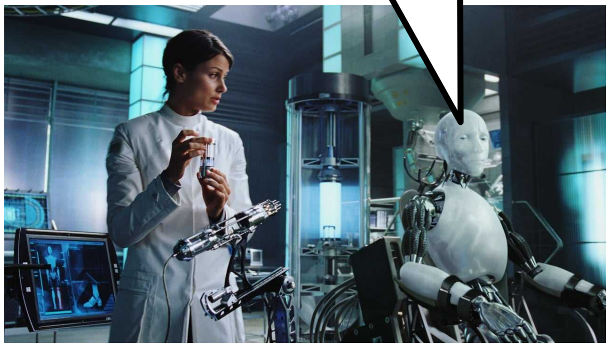


A weight W_m assigned for each input observable:

If the fist hidden layer has 200 neurons, the 1st weights $w_{mn}^{(1)}$ form a 26 × 200 matrix. Define

$$W_m \propto \sqrt{\sum_{n=1}^{200} \left(w_{mn}^{(1)}\right)^2},$$

Then for each input observable we have a weight.



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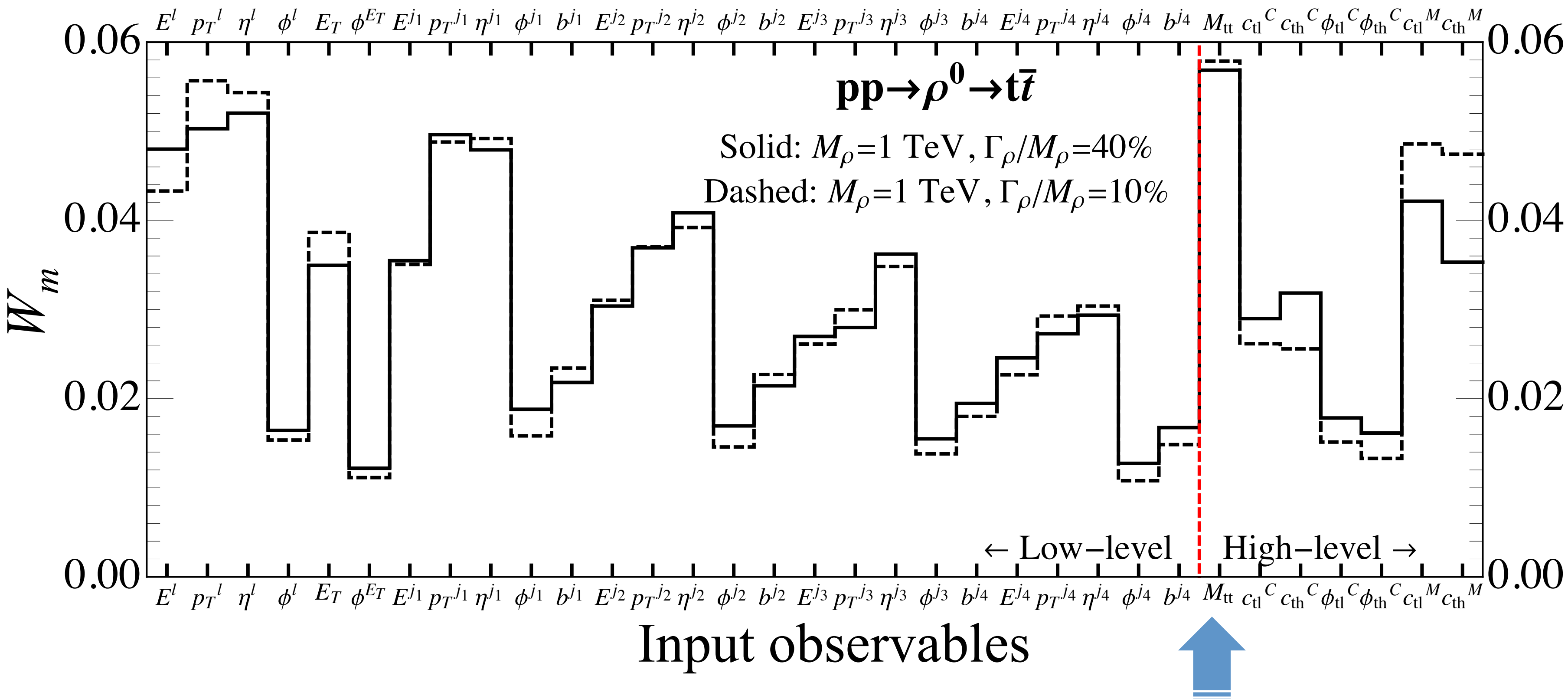
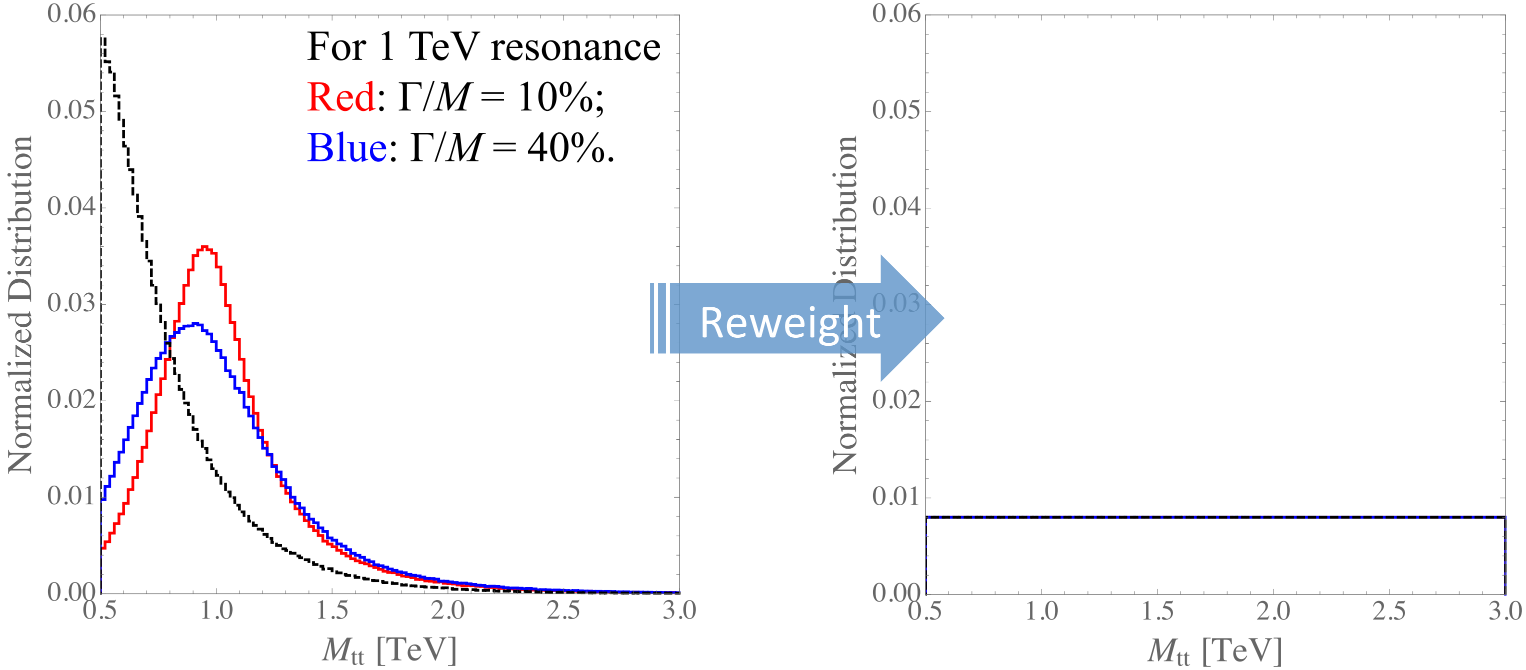


Unsurprisingly the invariant mass M_{tt} is still the most important observable, even for a broad resonance!

- What information dose the DNN make use of?

Subtracting the information of M_{tt} from input

"Data planing", see Chang *et al*, Phys. Rev. D97, 056009 (2018)



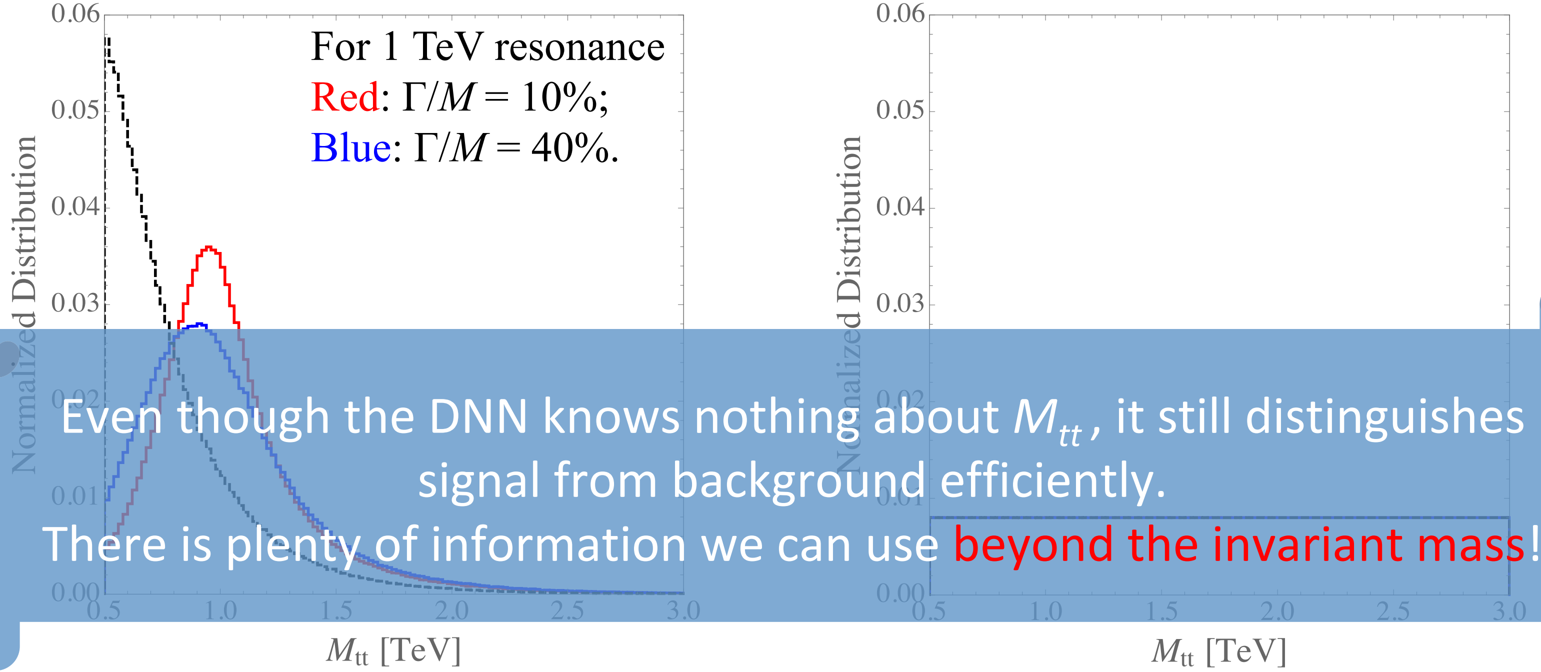
The distinguish accuracy reach:

Widths	$\Gamma_\rho/M_\rho = 10\%$	$\Gamma_\rho/M_\rho = 20\%$	$\Gamma_\rho/M_\rho = 30\%$	$\Gamma_\rho/M_\rho = 40\%$
Low-level input	85.2%	83.2%	81.6%	80.8%
Planing away $M_{t\bar{t}}$	76.8%	75.3%	74.1%	73.0%

- # What information dose the DNN make use of?

Subtracting the information of M_{tt} from input

"Data planing", see Chang *et al*, Phys. Rev. D97, 056009 (2018)



Even though the DNN knows nothing about M_{tt}, it still distinguishes signal from background efficiently.
There is plenty of information we can use beyond the invariant mass!

The distinguish accuracy reach:

Widths	$\Gamma_\rho/M_\rho = 10\%$	$\Gamma_\rho/M_\rho = 20\%$	$\Gamma_\rho/M_\rho = 30\%$	$\Gamma_\rho/M_\rho = 40\%$
Low-level input	85.2%	83.2%	81.6%	80.8%
Planing away $M_{t\bar{t}}$	76.8%	75.3%	74.1%	73.0%

Conclusion

- The composite vector ρ resonances may be hidden in their large width and the dominant *tb*, *tt* and *bb* decay channels; Da Liu, Lian-Tao Wang and **Ke-Pan Xie**, 1901.01674

- Deep learning can help to reveal such a broad tt resonance at the LHC.

Sunghoon Jung, Dongsub Lee and **Ke-Pan Xie**, 1906.02810

Thank you!