Broad composite resonances and their signals at the LHC

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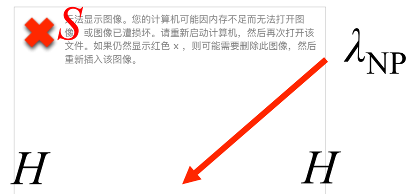
Da Liu, Lian-Tao Wang and **Ke-Pan Xie**, arXiv: 1901.01674;
Sunghoon Jung, Dongsub Lee and **Ke-Pan Xie**, arXiv: 1903.asap

➢ The hierarchy problem in Standard Model

The mass of an elementary Higgs boson is sensitive to the quantum corrections of high scale.



$$\delta M_h^2 \sim \left(\frac{\lambda_{\mathrm{NP}}}{16\pi^2}\right) \left[M_{\mathrm{NP}}^2 \frac{1}{\epsilon} + \text{finite terms}\right]$$

Hierarchy!

"Naturally" $M_h \sim M_{\mathrm{Planck}} \sim 10^{19}$ GeV

Reality M_h = **125.09** GeV!

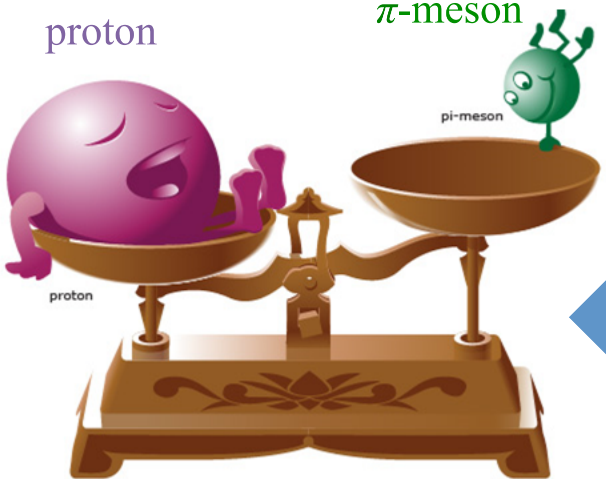
Kaplan *et al*, Phys.Lett. 136B (1984) 183-186

➢ The idea of the Composite Higgs Model

Identify the Higgs boson as the pseudo-Nambu-Goldstone boson, similar to the pions in low energy QCD !

proton

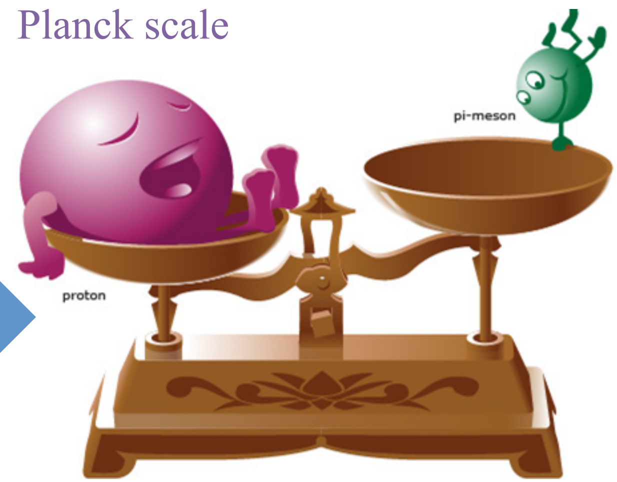
π-meson



Analogy

Planck scale

Higgs boson



Naturally $M_\pi << M_{\text{proton}}$

Naturally $M_h << M_{\text{Planck}}$

Agashe *et al*, Nucl.Phys. B719 (2005) 165-187

➢ The Minimal Composite Higgs Model

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

$$H = \begin{pmatrix} \frac{h_2 + i h_1}{\sqrt{2}} \\ \frac{h_4 - i h_3}{\sqrt{2}} \end{pmatrix}$$

Spontaneous breaking

$$SO(5) \times U(1)_X$$

$10 - 6 = 4$ NGBs

$$SO(4) \times U(1)_X$$

The strong sector (New Physics)

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

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

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

The elementary sector (SM fermions and EW bosons)

Agashe *et al*, Nucl.Phys. B719 (2005) 165-187

➢ The Minimal Composite Higgs Model

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

Explicitly break SO(5)

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

Spontaneous breaking

$$SO(5) \times U(1)_X$$

10 − 6 = 4 pNGBs

$$SO(4) \times U(1)_X$$

The strong sector (New Physics)

SM gauge coupling

Partial compositeness

$$W^{a_L}_{\mu};\ B_{\mu};$$

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

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

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➢The Minimal Composite Higgs Model

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Subgroup $SU(2)_L \times U(1)_Y$ gauged; $Y = T_R^3 + X$

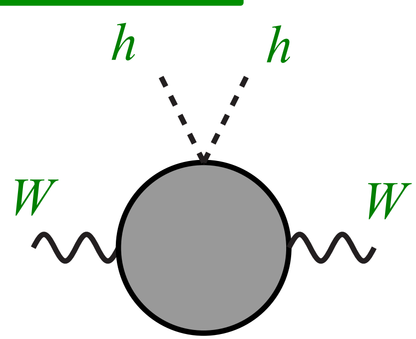
q_L and u_R fill in the incomplete representation of SO(5)

$$V_{\rm eff}(h) \approx \alpha \sin^2 \frac{h}{f} - \beta \sin^2 \frac{h}{f} \cos^2 \frac{h}{f}$$

EWSB

$$\sin^2 \frac{\langle h \rangle}{f} = \frac{\beta - \alpha}{2\beta}$$

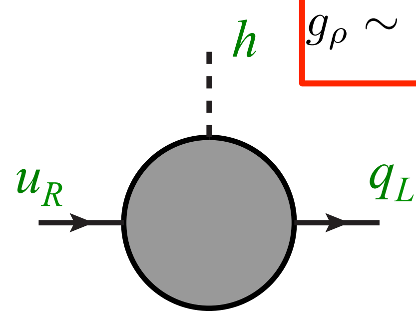
W and Z mass



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

Top mass

$$g_\rho \sim \frac{4\pi}{\sqrt{N}}$$

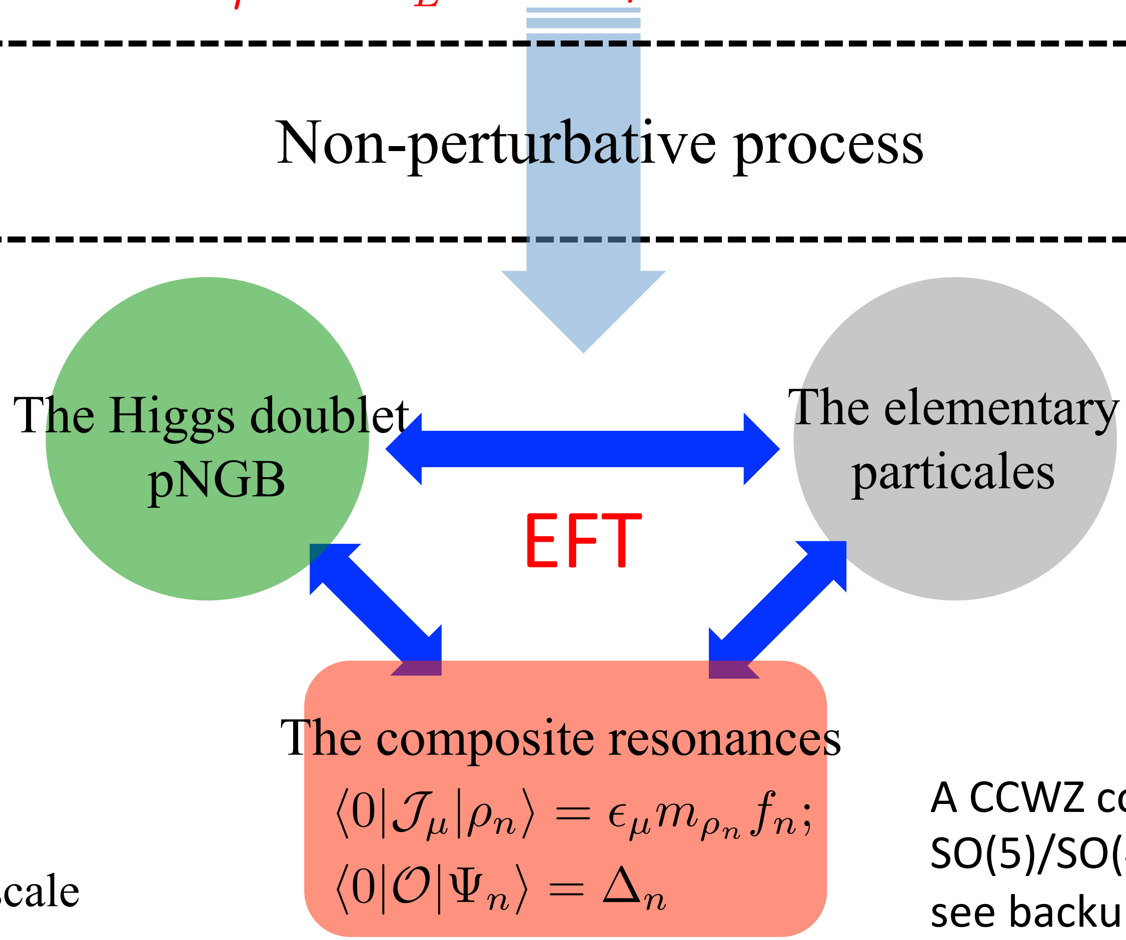


$$\langle \mathcal{O}_L \mathcal{O}_R \rangle \sim \frac{y_L y_R}{g_\rho} f \sin \frac{h}{f}$$

➢ Down to the EW scale

UV scale

$$\mathcal{L}_{\mathrm{MCHM}} = \mathcal{L}_{\mathrm{strong}} + \mathcal{L}_{\mathrm{SM}} + \mathcal{J}_{\mu}^{a_L} W_{a_L}^{\mu} + \mathcal{J}_{Y\mu} B^{\mu} + y_L \bar{q}_L \mathcal{O}_R + y_R \bar{u}_R \mathcal{O}_L$$



EW scale

A CCWZ construction of SO(5)/SO(4) Lagrangian; see backup

➢ The vector ρ resonances

SU(2)$_L$ triplet ρ resonance; robust predictions and features

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

f: SO(5)/SO(4) scale; a_ρ: the order 1 parameter; g_ρ: strong dynamics coupling

The ρ-W mixing angle

$$\sin\theta \sim \frac{g_2}{\sqrt{g_\rho^2 + g_2^2}} \approx \frac{g_2}{g_\rho}$$

The ρ-elementary quark coupling

$$g_{\rho f_L \bar{f}_L^{(\prime)}} = g_2 \sin\theta \sim \frac{g_2^2}{g_\rho}$$

The ρ-Goldstone coupling

$$\sim g_\rho \rho_\mu^{a_L} H^\dagger \frac{\sigma^{a_L}}{2} i \overleftrightarrow{D}_\mu H,$$

$$g_\rho \sim \frac{4\pi}{\sqrt{N}}$$

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$$g_\rho \sim \frac{4\pi}{\sqrt{N}}$$

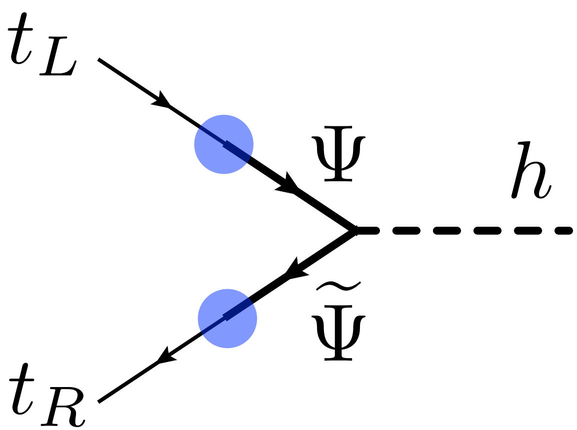
Collider phenomenology

1. Drell-Yan production;
2. Large paritial width to SM di-boson (W^+W^-, $W^\pm Z$, $W^\pm h$, Zh) channels.

➢ The fermion Ψ resonances:

top partners;
model dependent

1. Fill the representation of SO(4);
2. Giving mass to top quark: $y_L \bar{q}_L \mathcal{O}_R + y_R \bar{t}_R \mathcal{O}_L$



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

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

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

➢ The fermion Ψ resonances:

$$y_L \bar{q}_L \mathcal{O}_R \rightarrow y_L f \bar{F}_L U \Psi_R;$$

$$y_R \bar{u}_R \mathcal{O}_L \rightarrow y_R f \bar{F}'_R U \Psi_L;$$

F_L and F'_R: some multiplets of SO(5);
Ψ: some multiplets of SO(4).

top partners;
model dependent

Goldstone matrix

$$U[\vec{h}] = \exp\left\{ i \frac{\sqrt{2}}{f} h^i T^i \right\}$$

T^i: the 4 broken generators

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T^i: the 4 broken generators

The first scenario by Agashe *et al*, Nucl.Phys. B719 (2005) 165-187

$q_L = (t_L, b_L)^T$ and t_R are both embedded in **4** of SO(5):

$$q_L^{\mathbf{4}} = (t_L, b_L, 0, 0)^T; \quad t_R^{\mathbf{4}} = (0, 0, t_R, 0)^T.$$

Ψ in (**2**, **1**) of SO(4) = SU(2)$_L$ × SU(2)$_R$:

$$\Psi_{(\mathbf{2},\mathbf{1})} = (T, B)^T$$

The top quark mass

$$y_L f \bar{q}_L^{\mathbf{4}} U \Psi_R - i y_R f \bar{t}_R^{\mathbf{4}} U \Psi_L$$
$$= y_L f \bar{q}_L \Psi_R + \frac{y_R}{\sqrt{2}} \bar{t}_R \widetilde{H}^\dagger \Psi_L + \cdots,$$

$$\begin{pmatrix} t_L & T_L \end{pmatrix} \begin{pmatrix} 0 & -y_L f \\ -\frac{y_R v}{2} & M_\Psi \end{pmatrix} \begin{pmatrix} t_R \\ T_R \end{pmatrix},$$

$$\Rightarrow M_t = \frac{y_L y_R v f}{2 M_\Psi} + \cdots$$

➢ The fermion Ψ resonances:

top partners; model dependent

$$y_L \bar{q}_L \mathcal{O}_R \to y_L f \bar{F}_L U \Psi_R;$$

$$y_R \bar{u}_R \mathcal{O}_L \to y_R f \bar{F}'_R U \Psi_L;$$

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The first scenario by Agashe *et al*, Nucl.Phys. B719 (2005) 165-187

However this scenario is constrained very stringently:

$$-\frac{i}{4f^2}\bar{\Psi}\gamma^\mu\sigma^{a_L}\Psi H^\dagger \sigma^{a_L} \overleftrightarrow{D}_\mu H \to -\frac{i}{4f^2}\bar{q}_L\gamma^\mu\sigma^{a_L} q_L H^\dagger \sigma^{a_L} \overleftrightarrow{D}_\mu H \sin^2\theta_L$$

$$\sin\theta_L = \frac{y_L f}{\sqrt{M_\Psi^2 + y_L^2 f^2}}$$

Because of the EW precision test:

$$\delta g_{Zb_L\bar{b}_L} = \frac{v^2}{8f^2}\sin^2\theta_L$$

$$|\delta g_{Zb_L\bar{b}_L}| < 0.00061 \ \text{(LEP)}$$

Not favored by the experiment! See Nucl.Phys. B742 (2006) 59-85.

➢ The fermion Ψ resonances:

top partners;
model dependent

Contino *et al*, Phys.Rev. D75 (2007) 055014

$q_L = (t_L, b_L)^T$ and t_R are both embedded in **5** of SO(5):

$$q_L^{\mathbf{5}} = \frac{1}{\sqrt{2}}(ib_L, b_L, it_L, -t_L, 0)^T; \quad t_R^{\mathbf{5}} = \frac{1}{\sqrt{2}}(0,0,0,0,t_R)^T$$

Ψ in (**2**, **2**) of SO(4) = $SU(2)_L \times SU(2)_R$:

$$\Psi_{(\mathbf{2},\mathbf{2})} = \frac{1}{\sqrt{2}}\begin{pmatrix} iB - iX_{5/3} \\ B + X_{5/3} \\ iT + iX_{2/3} \\ -T + X_{2/3} \end{pmatrix}; \quad \Rightarrow \quad \Psi = \underbrace{\begin{pmatrix} T \\ B \end{pmatrix}_{1/6}}_{\text{doublet } Q} \oplus \underbrace{\begin{pmatrix} X_{5/3} \\ X_{2/3} \end{pmatrix}_{7/6}}_{\text{doublet } Q_X}$$

The top quark mass

$$y_L f \bar{q}_L^{\mathbf{5}} U \Psi_R + y_L f \bar{t}_R^{\mathbf{5}} U \Psi_L = y_L f \bar{q}_L Q_R + y_R \bar{t}_R \widetilde{H}^\dagger Q_L - y_R \bar{t}_R H^\dagger Q_{XL} + \cdots$$

$$\Rightarrow M_t = \frac{y_L f y_R v}{\sqrt{2}\sqrt{M_\Psi^2 + y_L^2 f^2}}$$

And NO Zb_Lb_L deviation at tree level!

$$\frac{1}{2}\bar{Q}\gamma^\mu Q \frac{1}{2f^2} H^\dagger i\overleftrightarrow{D}_\mu H - \bar{Q}\gamma^\mu \frac{\sigma^{a_L}}{2} Q \frac{1}{f^2} H^\dagger \frac{\sigma^{a_L}}{2} i\overleftrightarrow{D}_\mu H \Rightarrow \delta g_{Zb_L\bar{b}_L} = 0$$

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$q_L = (t_L, b_L)^T$ and t_R are both embedded in **5** of SO(5):

$$q_L^{\mathbf{5}} = \frac{1}{\sqrt{2}}(ib_L, b_L, it_L, -t_L, 0)^T; \quad t_R^{\mathbf{5}} = \frac{1}{\sqrt{2}}(0,0,0,0,t_R)^T$$

Agashe *et al*, Phys. Lett. B641, 62 (2006)

The custodial symmetry for T-parameter: $SU(2)_L \times SU(2)_R \to SU(2)_V$;

$$\Rightarrow \delta Q_V^3 \equiv \delta(T^{3_L} + T^{3_R}) = 0;$$

For $\mathbf{5}$ representation, $T^{3_L}(B) = T^{3_R}(B) = -\frac{1}{2}$;

$$\Rightarrow \delta T^{3_L}(B) = \delta T^{3_R}(B); \quad \Rightarrow \delta T^{3_L}(B) = 0;$$

$$\delta g_{ZB\bar{B}} = \frac{g}{c_W}\left(\delta T^{3_L} - \delta Q s_W^2\right) = 0;$$

Protected!

And NO Zb_Lb_L deviation at tree level!

$$\frac{1}{2}\bar{Q}\gamma^\mu Q \frac{1}{2f^2} H^\dagger i\overleftrightarrow{D}_\mu H - \bar{Q}\gamma^\mu \frac{\sigma^{a_L}}{2} Q \frac{1}{f^2} H^\dagger \frac{\sigma^{a_L}}{2} i\overleftrightarrow{D}_\mu H \Rightarrow \delta g_{Zb_L\bar{b}_L} = 0$$

– Other studied scenarios:

$q_L = (t_L, b_L)^T$ is elementary, embedded in **5** of SO(5);
t_R is a composite resonance, embedded in **1** of SO(4);

$$q_L^{\mathbf{5}} = \frac{1}{\sqrt{2}}(ib_L, b_L, it_L, -t_L, 0)^T;$$

$$y_L f q_L^{\mathbf{5}} U t_R = -y_L \bar{q}_L \widetilde{H} t_R + \cdots$$

Simone *et al*, JHEP 1304 (2013) 004

$q_L = (t_L, b_L)^T$ is elementary, embedded in **14** of SO(5);
t_R is a composite resonance, embedded in **1** of SO(4);

Simone *et al*, JHEP 1304 (2013) 004
Matsedonskyi *et al*, JHEP 1604 (2016) 003

……

➢ General features of the previous models:

The existence of triplet vector resonance ρ, and
1. Drell-Yan production;
2. <u>Strong coupling</u> to SM di-boson (W^+W^-, $W^\pm Z$, $W^\pm h$, Zh) channels.

The top partners Ψ, and
1. Give mass to top quark through mixing and EWSB;
2. t_L is elementary and $\rho t_L t_L$ interaction <u>suppressed</u> by $\sin^2\theta_L$.
3. No matter t_R is elementary or composite, it couples to ρ <u>weakly</u> because of its $SU(2)_L$ quantum number.

Universal prediction:
A Drell-Yan produced ρ from the di-boson channel!

Pappadopulo *et al*, JHEP 1409 (2014) 060

➢ General features of the previous models:

No excess!

The

1. D

2. S ... $W^{\pm}h$, Zh)

char

The

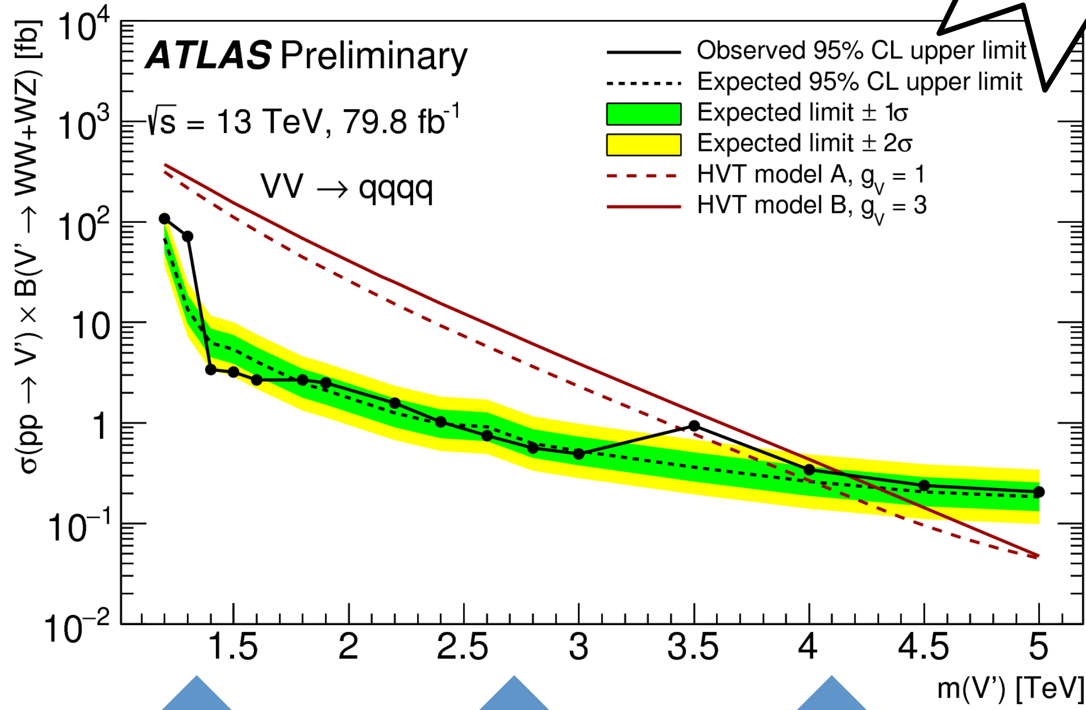
1. G ... SB;

2. t_L ... by $\sin^2\theta_L$.

3. N ... les to ρ

wea

ATLAS-CONF-2018-016



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Not necessary!

➢ A model that $q_L = (t_L, b_L)^T$ is composite

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

Composite fermion sector -- (**2**, **2**) of the SO(4):

Zb_Lb_L protected!

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

Elementary fermion sector -- **5** of the SO(5):

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

The Yukawa couplings:

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

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

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The interactions with ρ:

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

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

Without suppression!

For the pNGB modes, the interactions:

$$\sim g_\rho \rho_\mu^{a_L} H^\dagger \frac{\sigma^{a_L}}{2} i \overleftrightarrow{D}_\mu H,$$

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

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

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

Collider phenomenology

1. Drell-Yan production;
2. Doninantly decay to SM third generation quark (*tb*, *tt*, *bb*);

➢ A model that $q_L = (t_L, b$

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

The interactions with ρ:

$$\mathcal{L}_{\rm int} \supset c_1 \bar{\Psi}_L \gamma^\mu T^{a_L} \Psi_L g_\rho \rho^{a_L} =$$

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

Without suppression!

For the pNGB modes, the interactio

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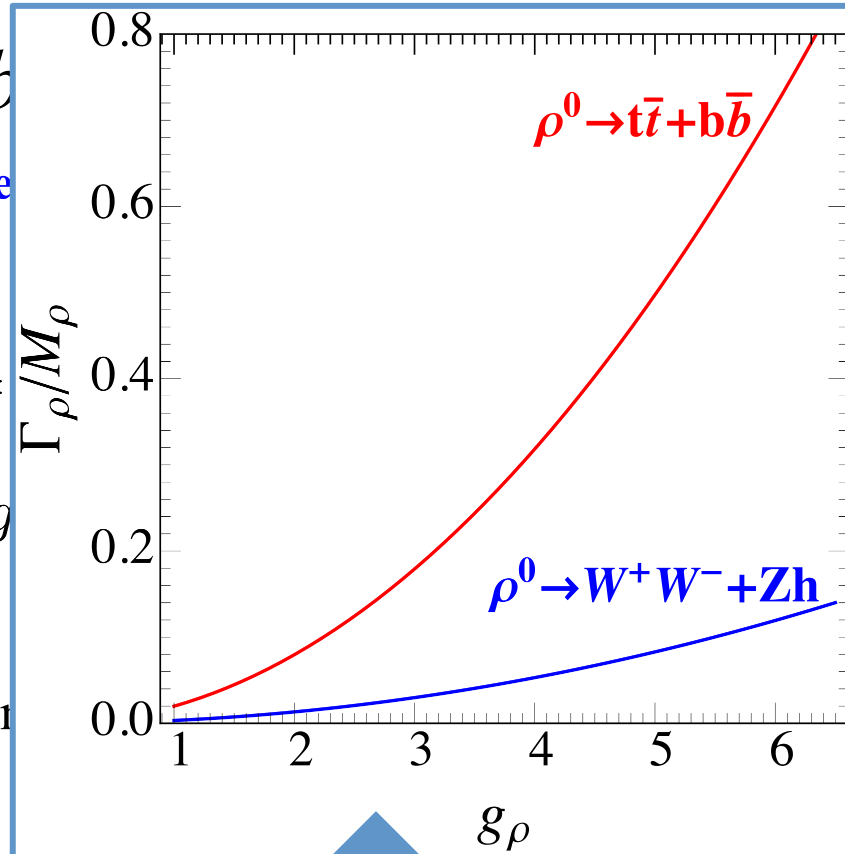

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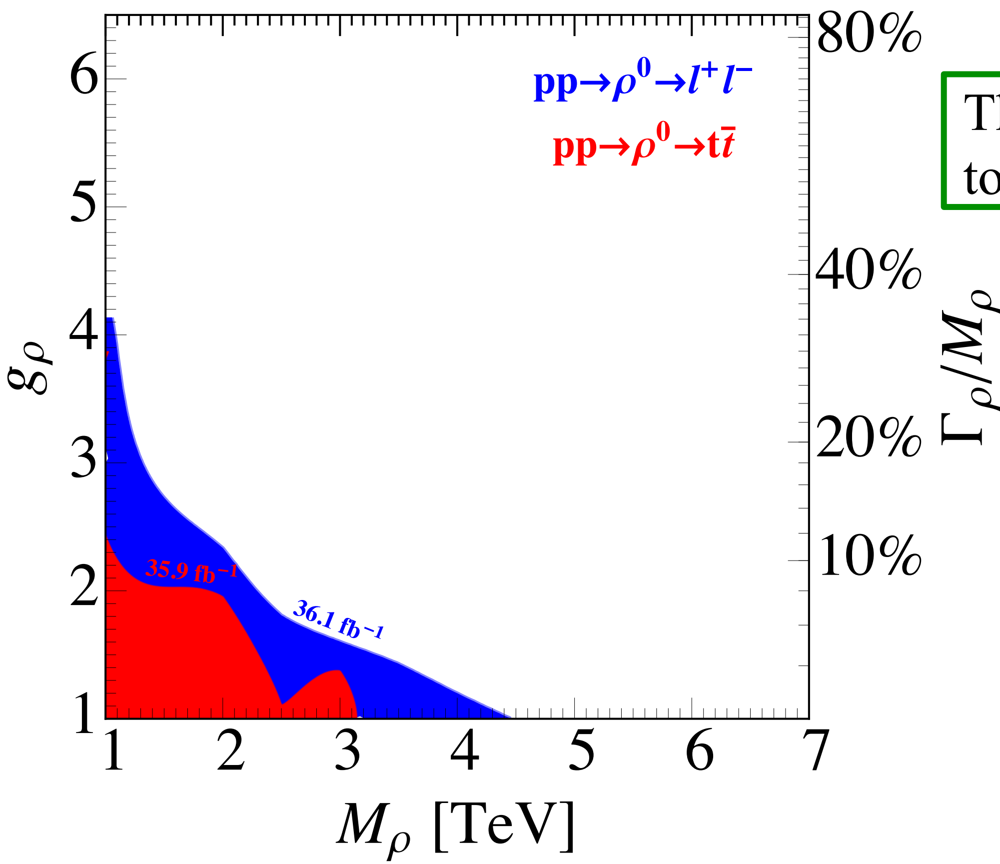
Collider phe nenology

1. Drell-Yan p luction;
2. Doninantly cay to SM third generation qu (*tb*, *tt*, *bb*);
3. Can easily be broad!

- A model that $q_L = (t_L, b_L)^T$ is composite

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

Current constraints from the experiment:



The di-boson bounds are too weak to show!

The tt constraint is from CMS 1810.05905; the l^+l^- constraint is from ATLAS 1707.02424.

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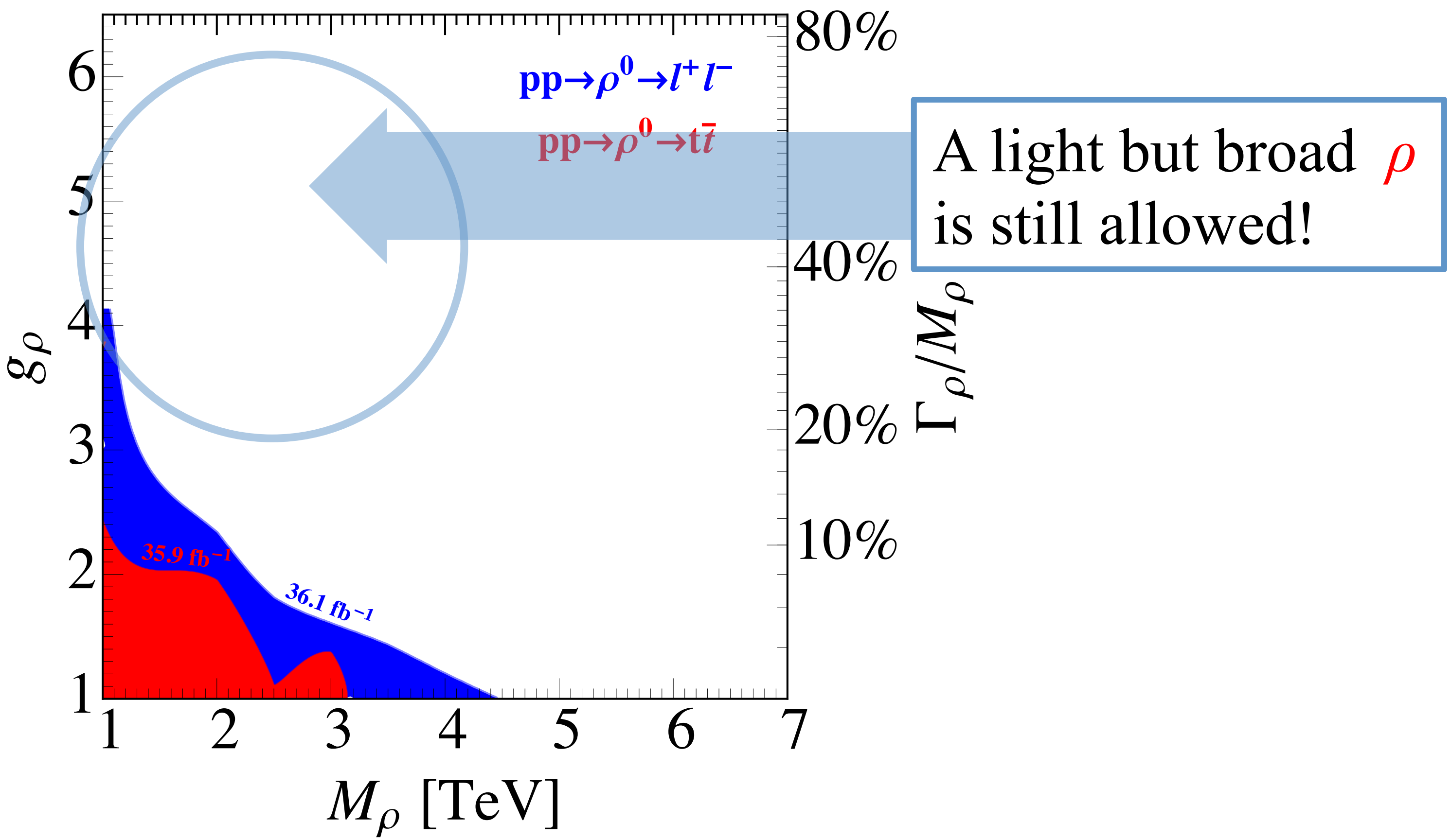
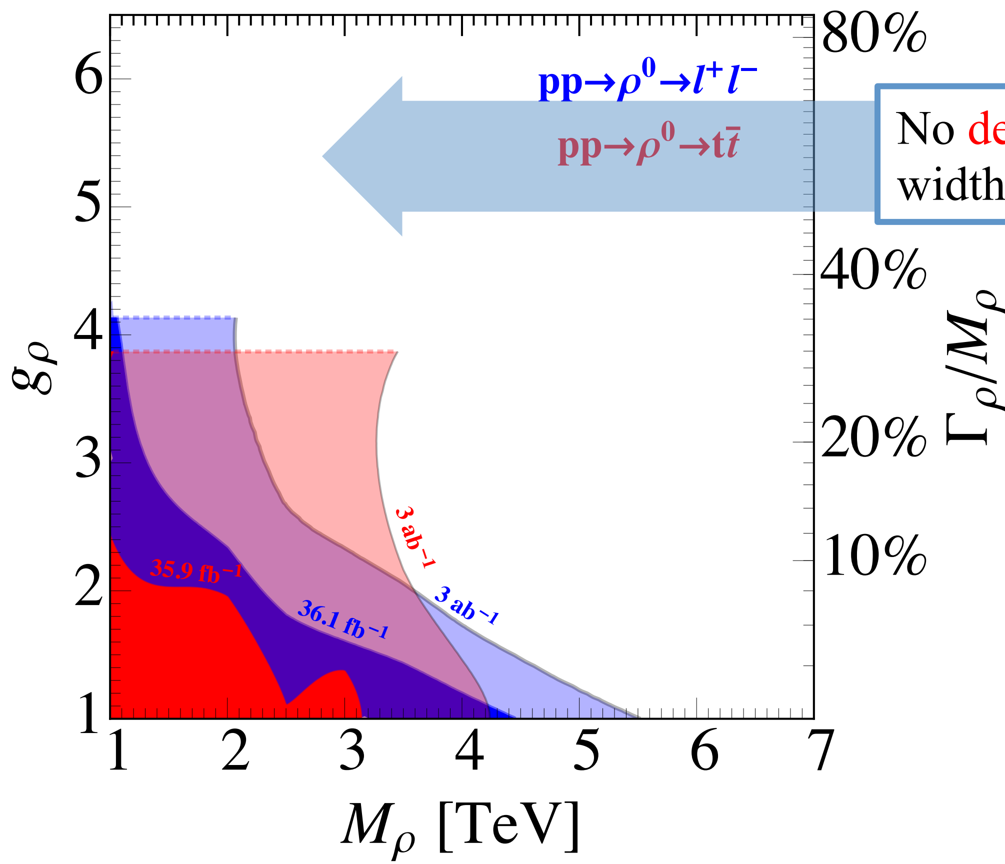


The *tt* constraint is from CMS 1810.05905; the l^+l^- constraint is from ATLAS 1707.02424.

➢ A model that $q_L = (t_L, b_L)^T$ is composite

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

Rescaling curren constraints to the **HL-LHC**:



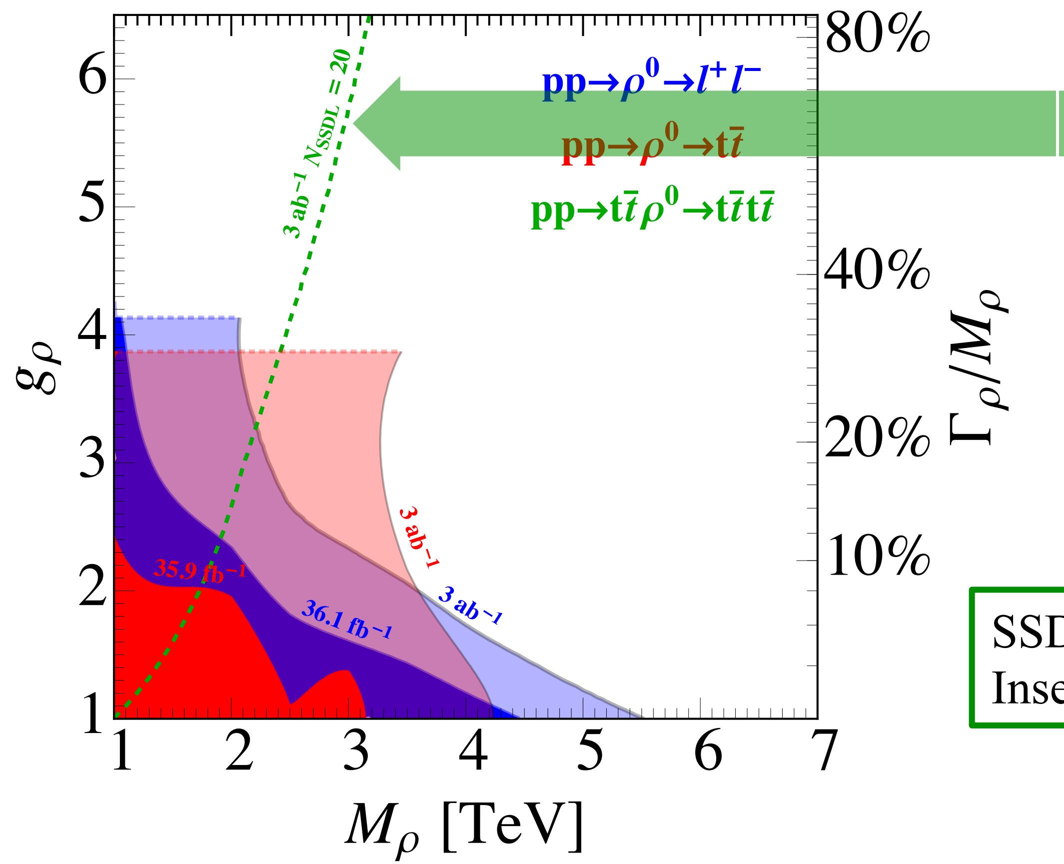
No dedicated searches for width/mass larger than ~ 40% !

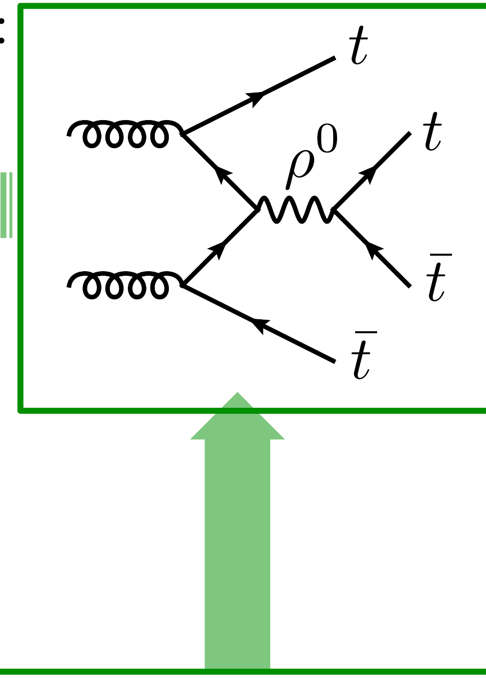
The *tt* constraint is from CMS 1810.05905; the l^+l^- constraint is from ATLAS 1707.02424.

➢ A model that $q_L = (t_L, b_L)^T$ is composite

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

The *tt* scattering process to probe large width region:



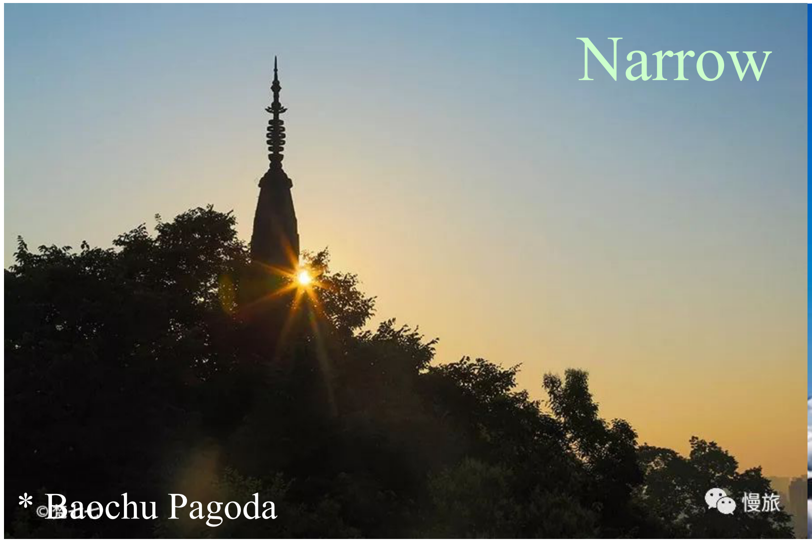


SSDL = same-sign di-lepton;
Insensitive to width!

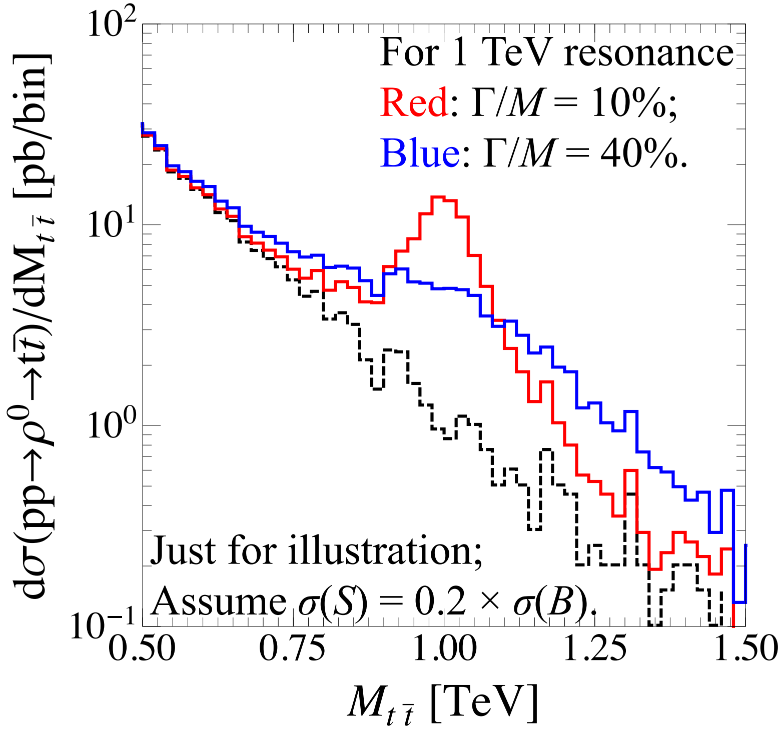
The *tt* constraint is from CMS 1810.05905; the l^+l^- constraint is from ATLAS 1707.02424.

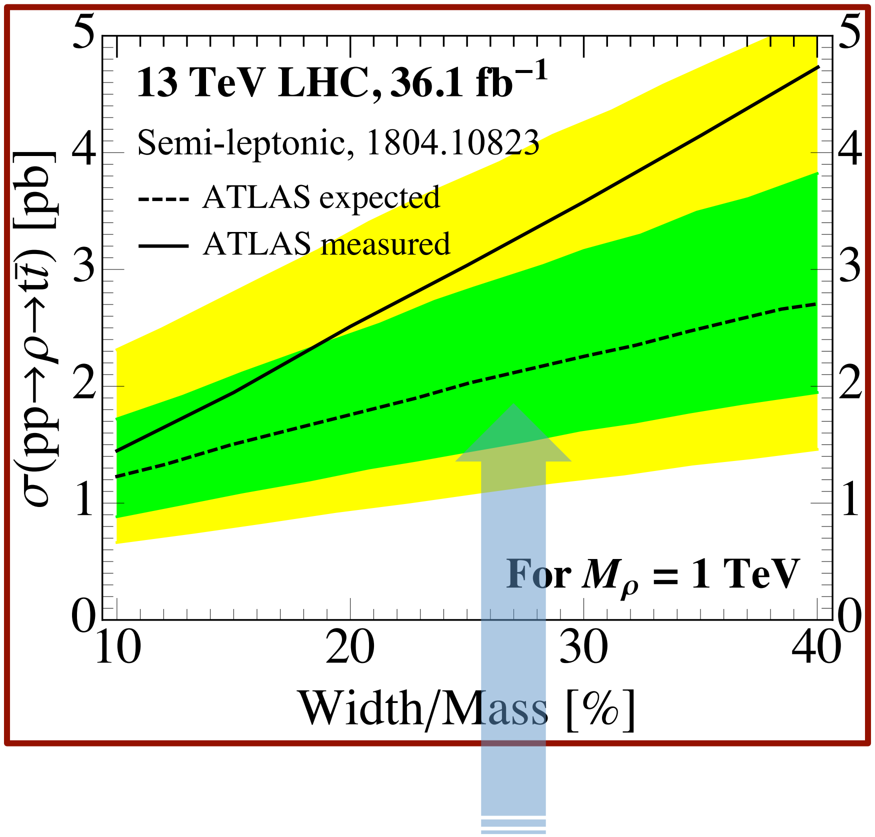
- How to search for such a broad *tt* resonance via the Drell-Yan production?

Sunghoon Jung, Dongsub Lee and **Ke-Pan Xie**, arXiv: 1903.asap;



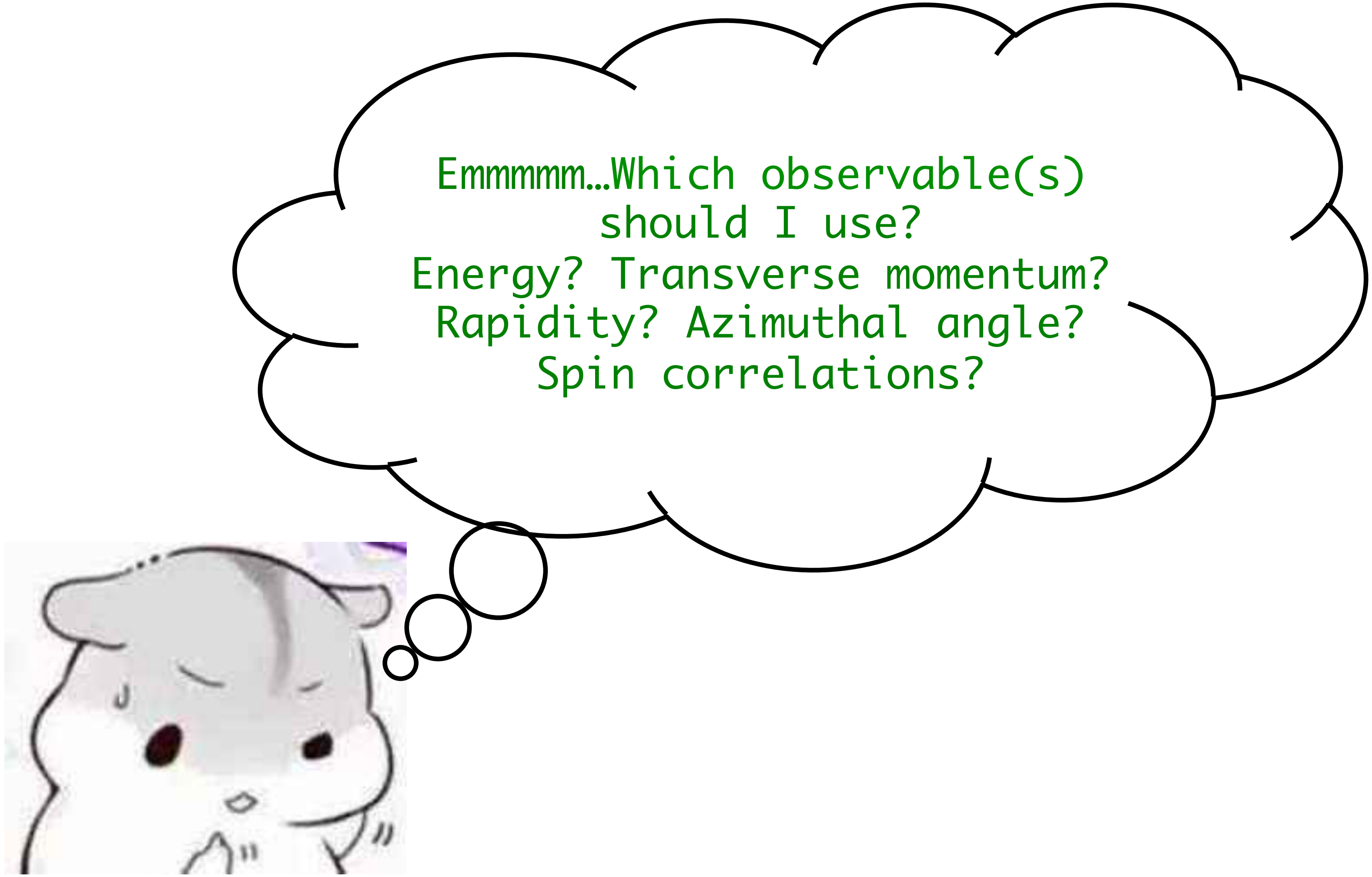
- The traditional approach: fit one observable: the invariant mass;





- The bound gets worse in large width region, as the resonant peak is smeared out.

– To improve the efficiency at large width region, more kinematic information is needed!



– To improve the efficiency at large width region, more kinematic information is needed!

Just tell me all the observables, and then I can find the answer automatically.

The Deep Neural Network

➢ The process considered in this work:

$$\text{Signal}: \; pp \to \rho^0 \to t\bar{t} \to 1\ell^{\pm} + \text{jets}$$

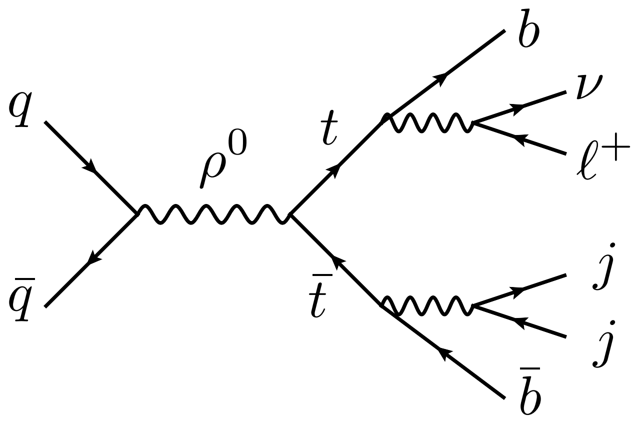
$$\text{Background}: \; \text{SM } pp \to t\bar{t} \to 1\ell^{\pm} + \text{jets}$$

– The benchmarks:

Mass M_ρ = 1 TeV;
width Γ_ρ/M_ρ = 10%, 20%, 30% and 40%;

Mass M_ρ = 5 TeV;
width Γ_ρ/M_ρ = 10%, 20%, 30% and 40%.

– We define 2 kinematic regions:



For M_ρ = 1 TeV

The resolved region:

1. $1\ell^{\pm}$ with $p_T > 30$ GeV and $|\eta| < 2.5$;
2. $\not{E}_T > 20$ GeV and $\not{E}_T + M_T > 60$ GeV;
3. 4 jets with $p_T > 25$ GeV and $|\eta| < 2.5$;

26 low-level observables can be used:

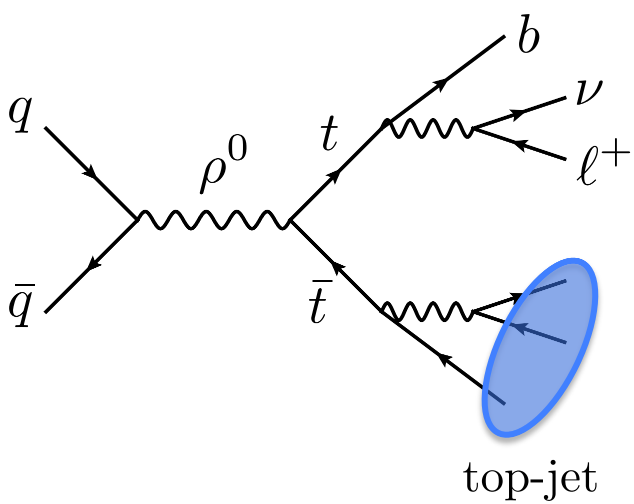
1	2	3	4	5	6	7	8	9	10	11	12	13
E^ℓ	p_T^ℓ	η^ℓ	ϕ^ℓ	$\not{E}_T$	$\phi^{\not{E}_T}$	E^{j_1}	$p_T^{j_1}$	η^{j_1}	ϕ^{j_1}	b^{j_1}	E^{j_2}	$p_T^{j_2}$

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}

* b^j: the b-tag observable, 1 for a b-tagged jet and 0 otherwise.

SM background cross section after cuts: 68.9 pb (K-factor included)

– We define 2 kinematic regions:



For M_ρ = 1 TeV and 5 TeV

The boosted region:

1. $1\ell^{\pm}$ with $p_T > 30$ GeV and $|\eta| < 2.5$;
2. $\not{E}_T > 20$ GeV and $\not{E}_T + M_T > 60$ GeV;
3. 1 top jet with $p_T > 300$ GeV and $|\eta| < 2.0$;
4. 1 selected jet with $p_T > 25$ GeV and $|\eta| < 2.5$ and $\Delta R(j, \ell) < 1.5$.

15 low-level observables can be used:

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
E^ℓ	p_T^ℓ	η^ℓ	ϕ^ℓ	$\not{E}_T$	$\phi^{\not{E}_T}$	$E^{j_{\rm sel}}$	$p_T^{j_{\rm sel}}$	$\eta^{j_{\rm sel}}$	$\phi^{j_{\rm sel}}$	$b^{j_{\rm sel}}$	$E^{j_{\rm top}}$	$p_T^{j_{\rm top}}$	$\eta^{j_{\rm top}}$	$\phi^{j_{\rm top}}$

* b^j: the b-tag observable, 1 for a b-tagged jet and 0 otherwise.

SM background cross section after cuts: 2.88 pb (K-factor included)

- DNN is a kind of machine learning technique (alternative: BDT [Boosted Decision Tree], SVM [Support Vector Machine], etc);
- It is vaguely inspired by the biological neural networks that constitute animal brains. [wikipedia]
- The basic unit of the DNN: **neuron**

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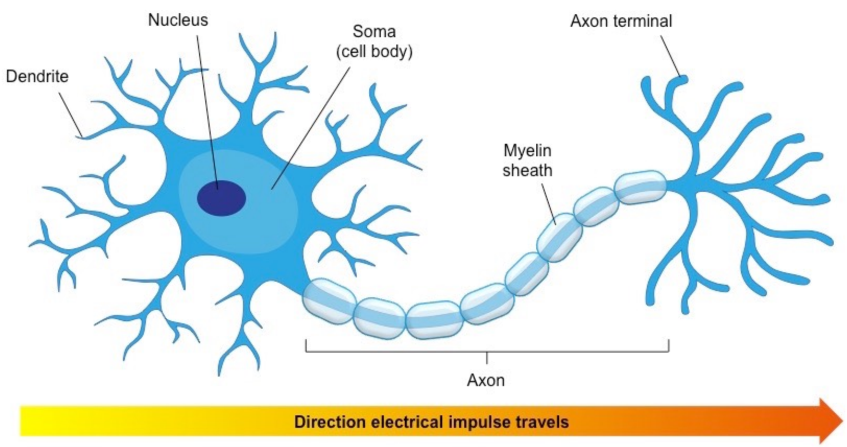

A boiological neuron

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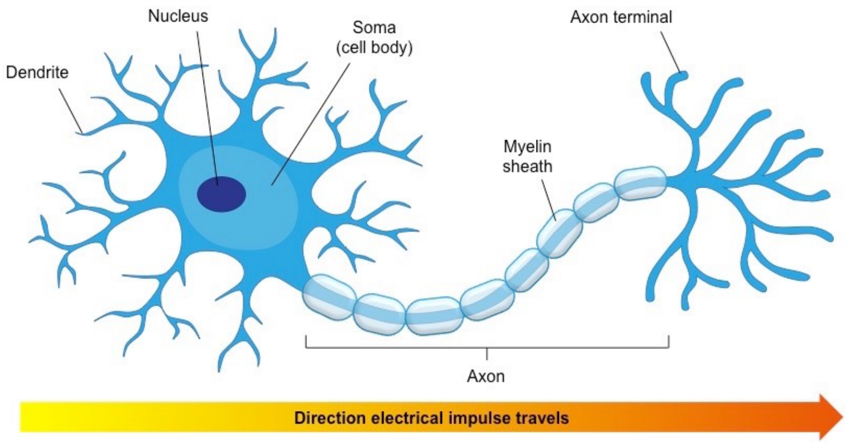
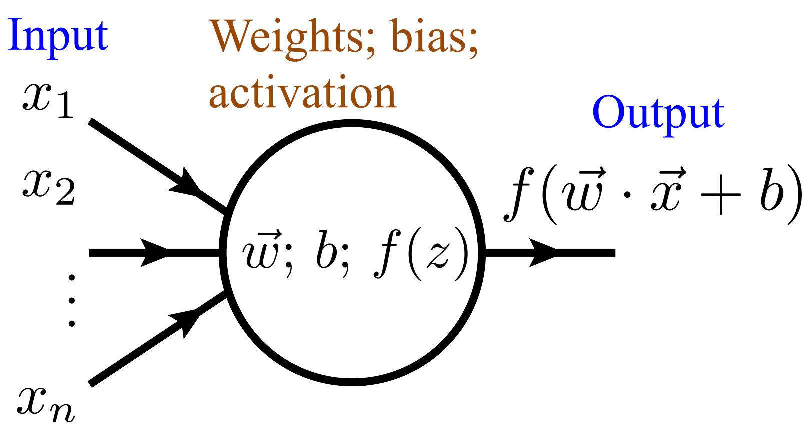
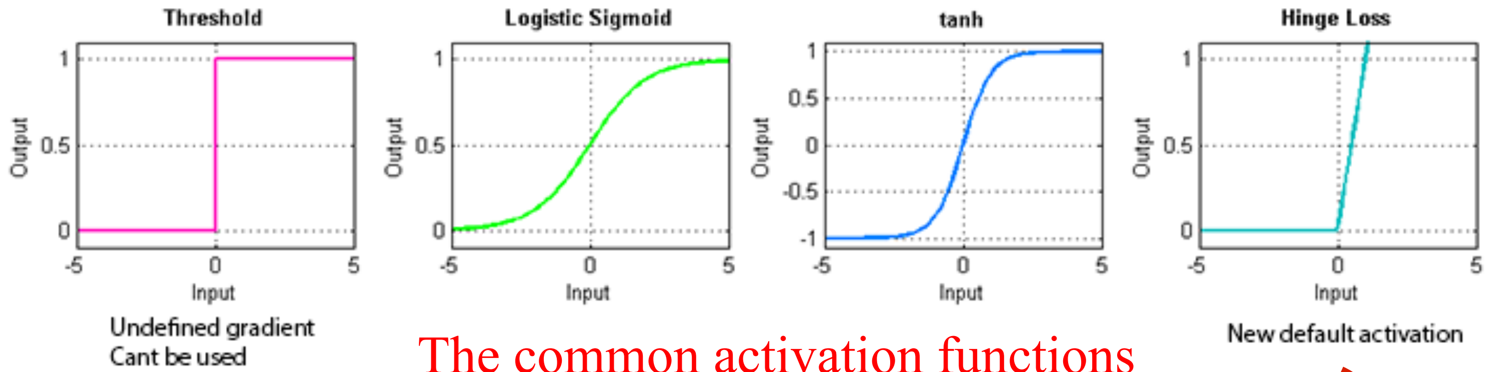


A boiological neuron



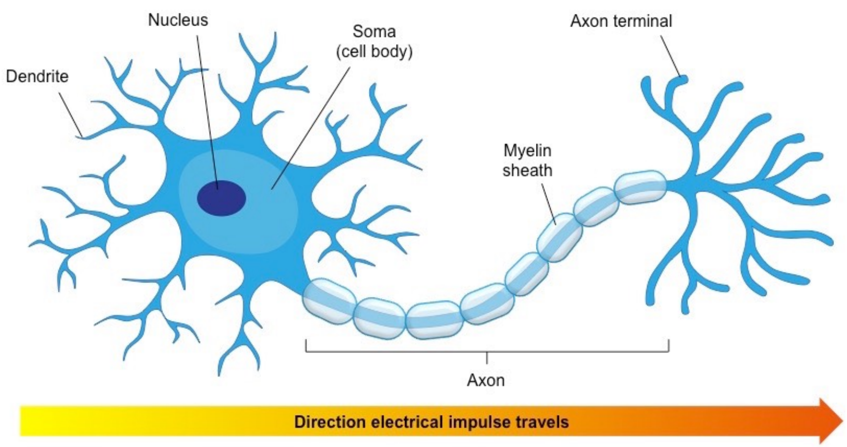
An artificial neuron

- DNN is a kind of machine learning technique

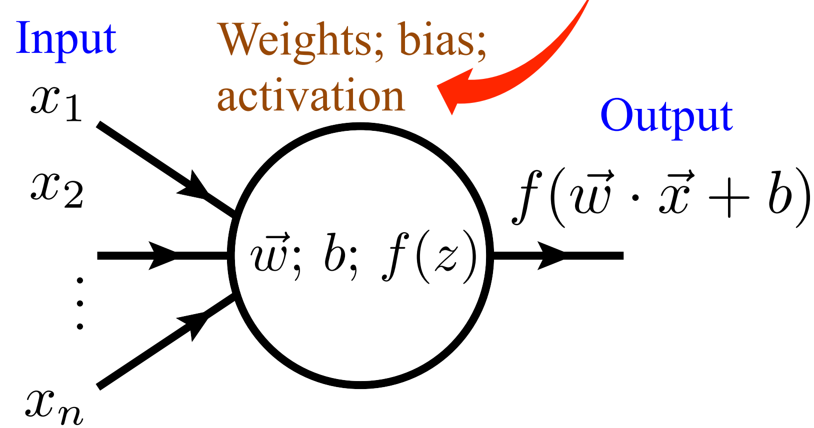


The common activation functions

- The basic unit of the DNN: **neuron**

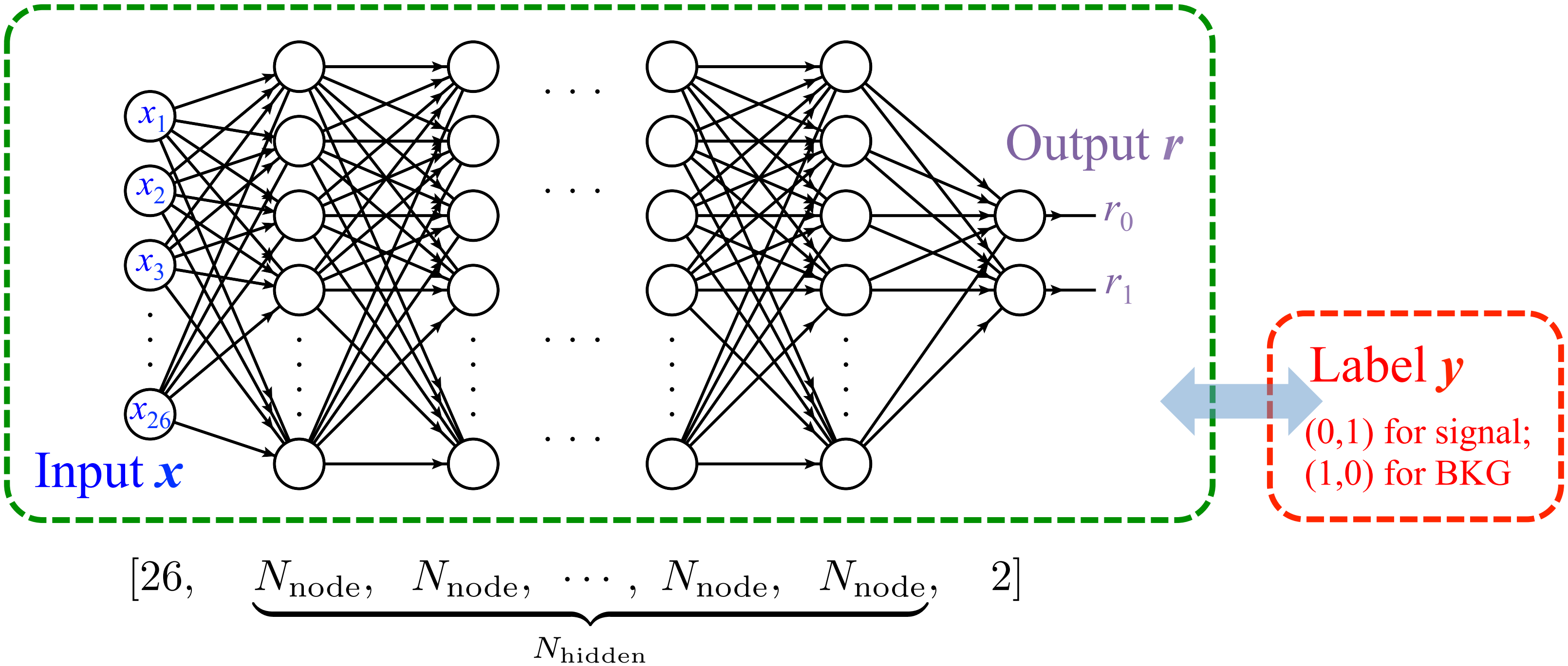


A boiological neuron



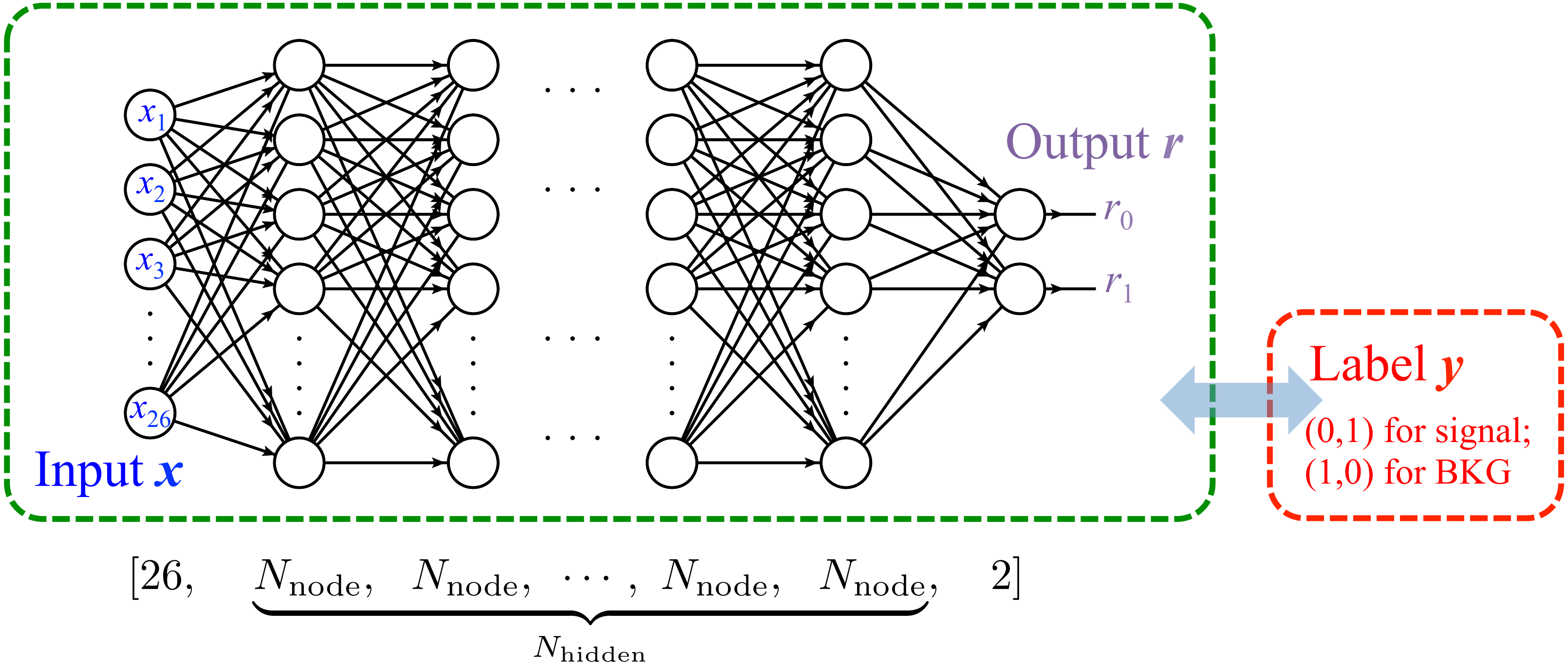
An artificial neuron

– Connecting numerous neurons to build a neural network:



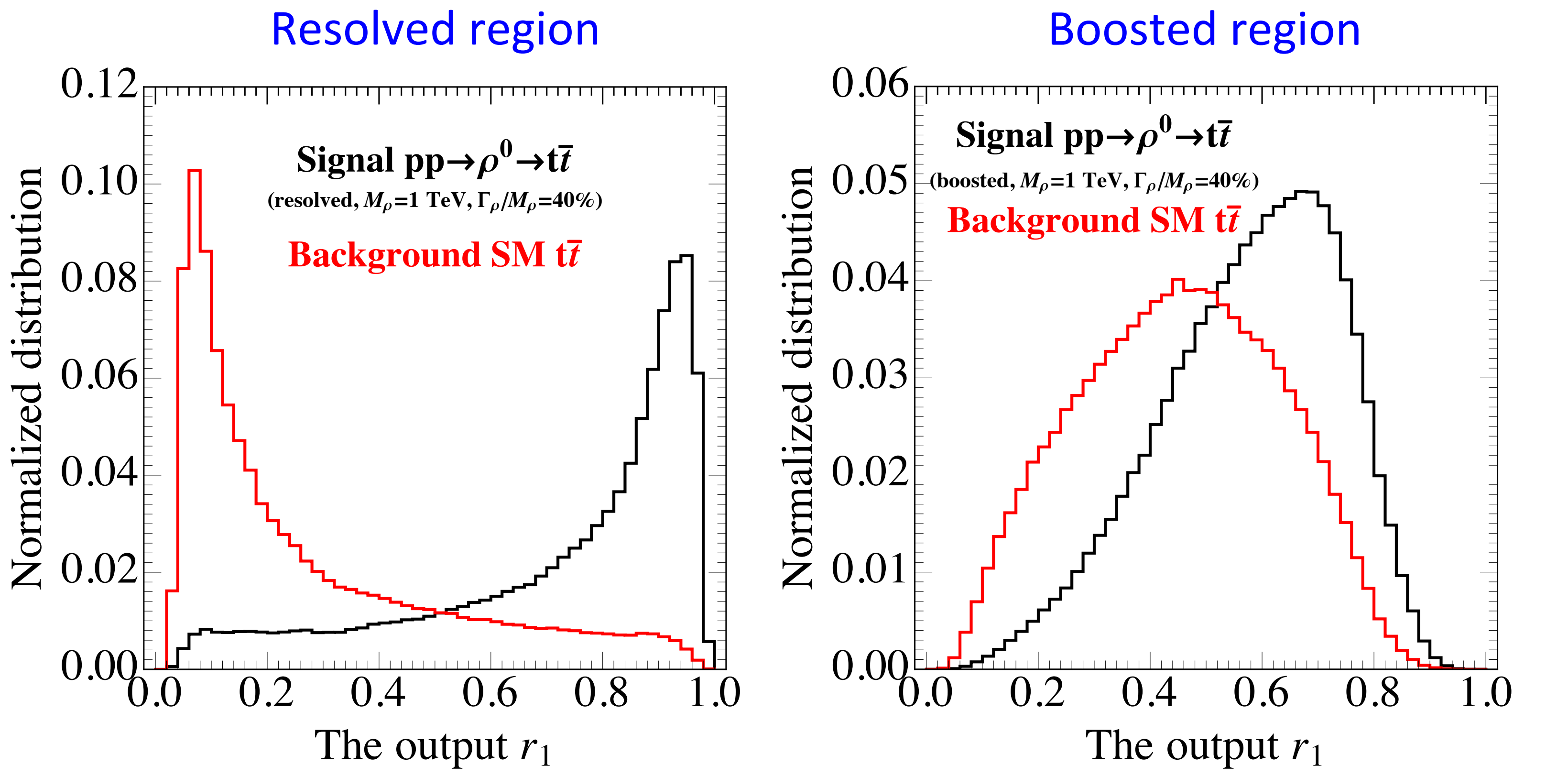
Machine learning on the DNN = Tune the w [weights] and b [biases], such that the output $\boldsymbol{r}$ and the label $\boldsymbol{y}$ are as close as possible.

– Connecting numerous neurons to build a neural network:



We tried $N_{\rm node}$ = 200 or 300, $N_{\rm hidden}$ = 4 or 5, and chose the best network configuration.

− Testing the trained network:



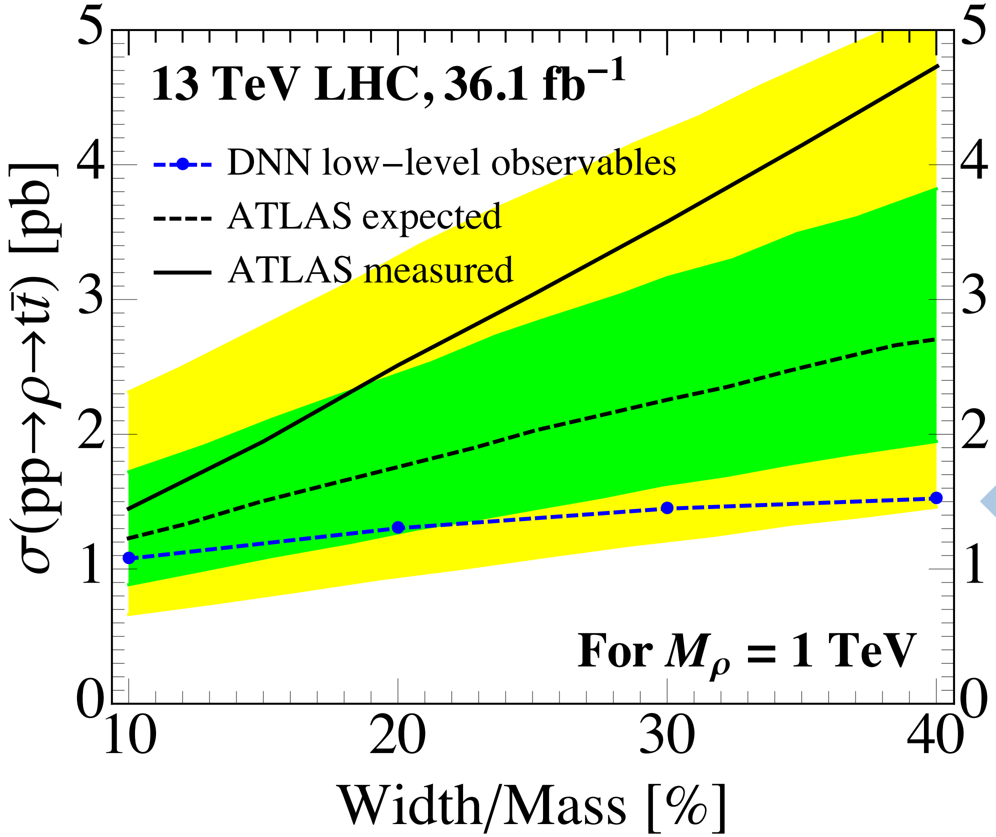
According to the given integrated luminosity, fit the neuron output to get the bounds for the signal strength!

➤ Intepret the DNN result as the cross section upper limit of the signal:

Combined resolved and boosted region; 12% systematic uncertainty for background is assumed.

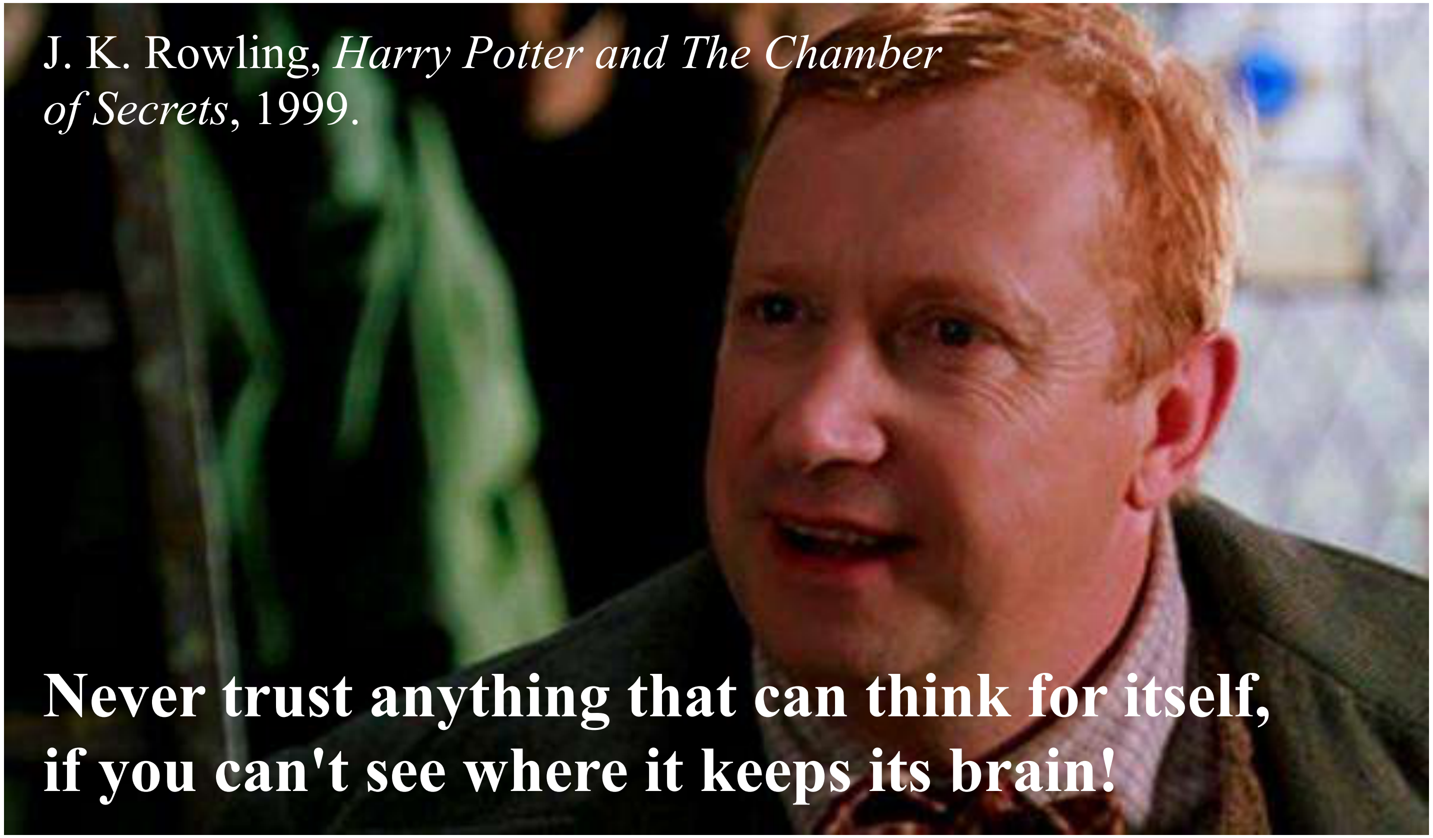
The ATLAS result: 1804.10823

The DNN result: **this work**



The DNN results are much insensitive to the width!

- We have used the DNN to learn new physics signal from SM background, and get expected result. Is that enough?
- NO! We have to figure out what it has learned.



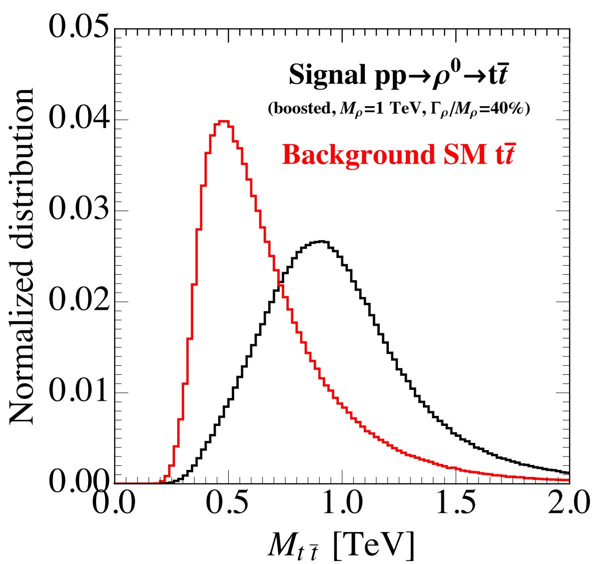
➢ Figuring out what the machine has learned

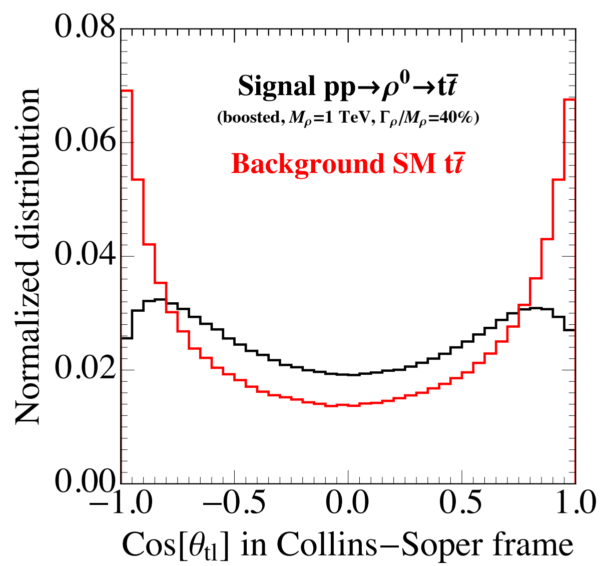
The first approach we tried: to test if the DNN learned the specific observables --

The 7 high-level observables

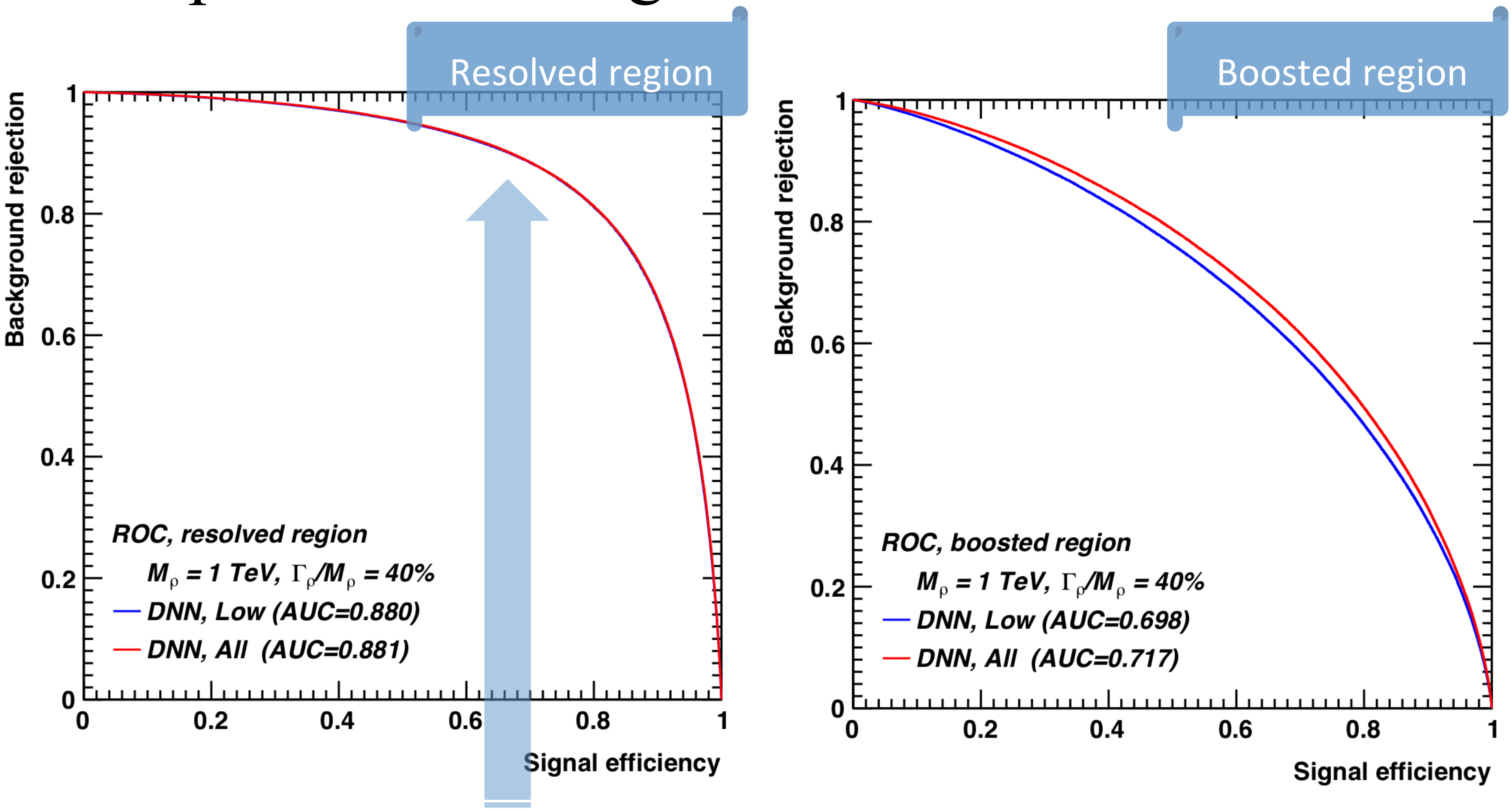
1	2	3	4	5	6	7
$M_{t\bar{t}}$	$\cos\theta_{\rm tl}^{\rm CS}$	$\cos\theta_{\rm th}^{\rm CS}$	$\phi_{\rm tl}^{\rm CS}$	$\phi_{\rm th}^{\rm CS}$	$\cos\theta_{\rm tl}^{\rm Mus.}$	$\cos\theta_{\rm th}^{\rm Mus.}$

Invariant mass   Spin correlation in the *tt* rest frame





– We define all observables = low + high, and compare the training results:



DNN can learn the high-level observables!

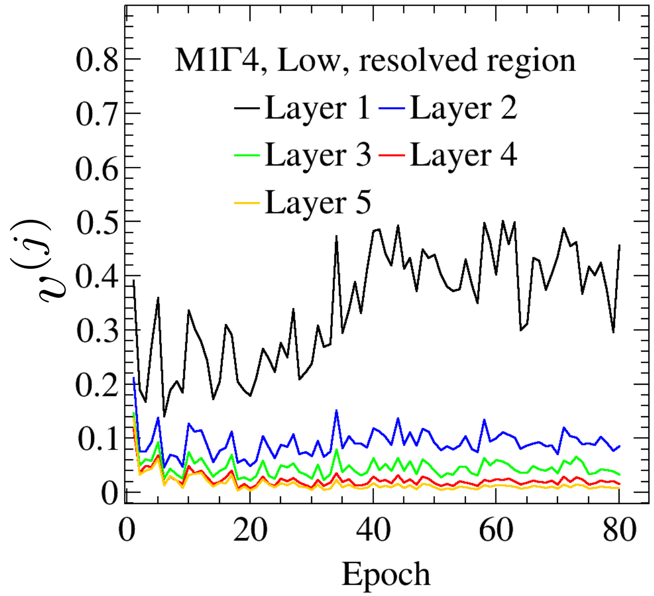
➢Figuring out what the machine has learned

The second approach we tried: disassemble the machine

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

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

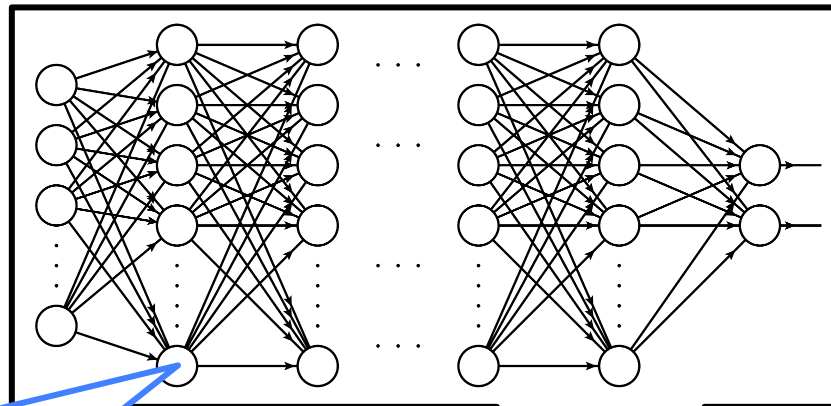
And what we found is:



The first hidden layer always has the largest learning speed!

➢Figuring out what the machine has learned

The second approach we tried: disassemble the machine

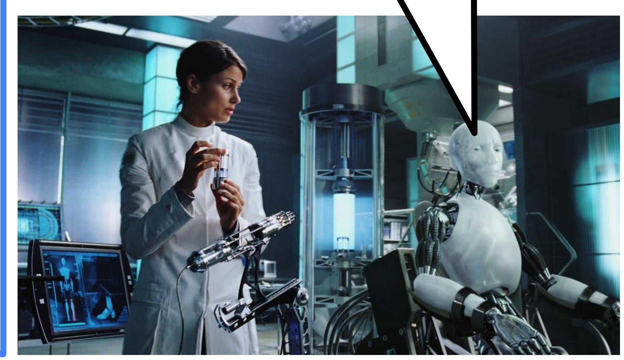


A weight W_m assigned for each input observable:

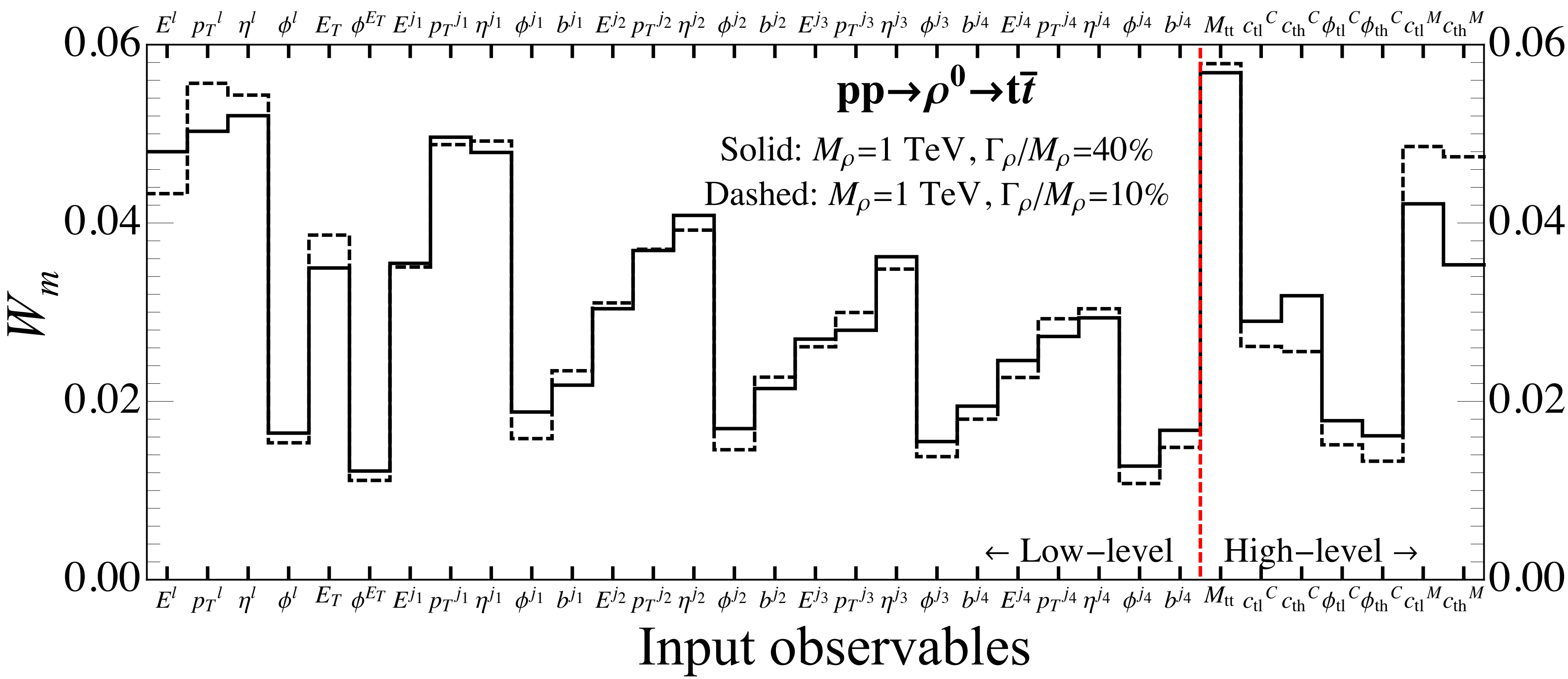
If the fist hidden layer has 200 neurons, the 1st weights $w_{mn}^{(1)}$ form a 26 × 200 matrix. Define

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

Then for each input observable we have a weight.



– Disassembling the machine



Low-level

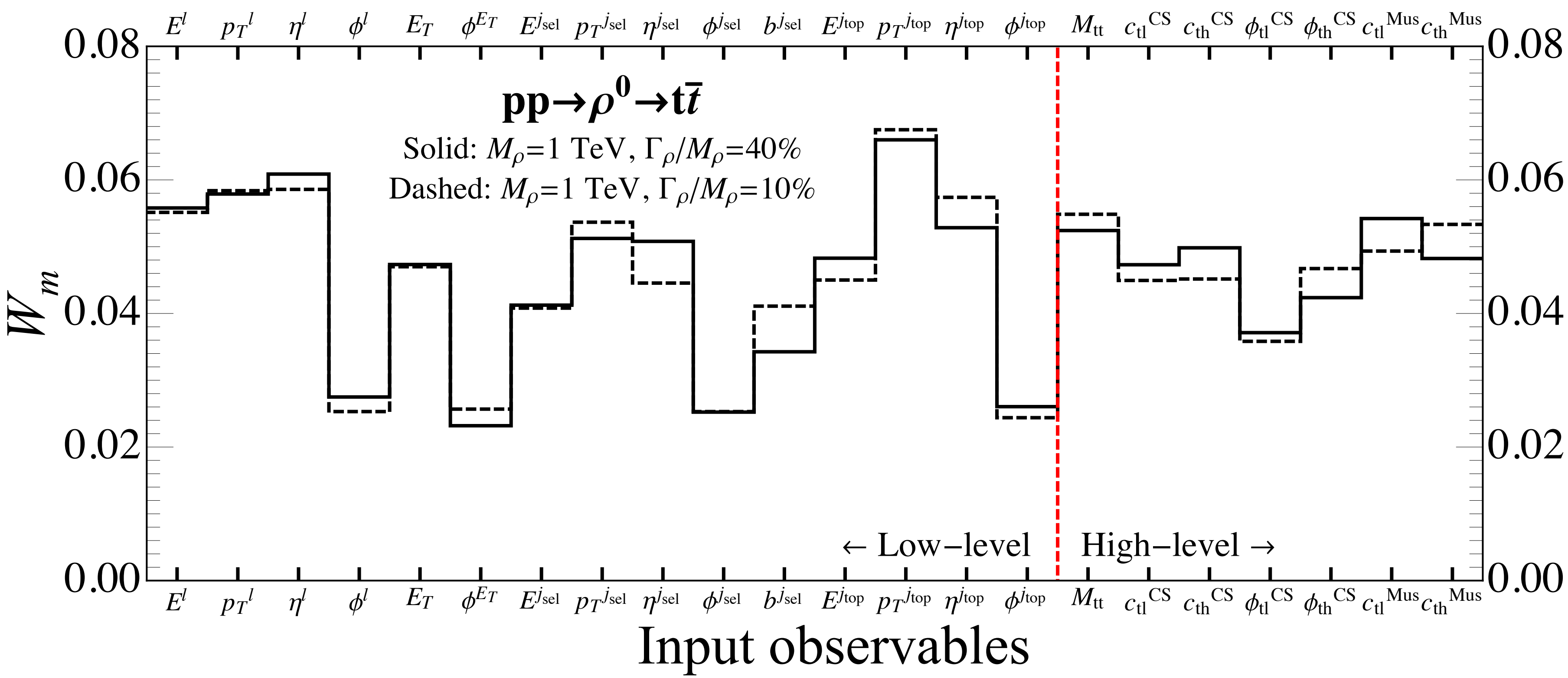
1	2	3	4	5	6	7	8	9	10	11	12	13
E^ℓ	p_T^ℓ	η^ℓ	ϕ^ℓ	$\not{E}_T$	$\phi^{\not{E}_T}$	E^{j_1}	$p_T^{j_1}$	η^{j_1}	ϕ^{j_1}	b^{j_1}	E^{j_2}	$p_T^{j_2}$

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}

High-level

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

– Disassembling the machine



Low-level

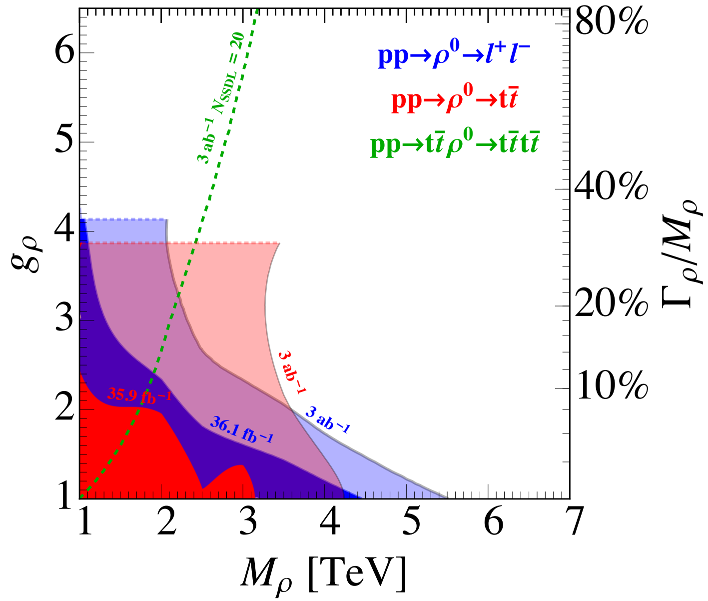
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
E^{ℓ}	p_T^{ℓ}	η^{ℓ}	ϕ^{ℓ}	$\not{E}_T$	$\phi^{\not{E}_T}$	$E^{j_{\rm sel}}$	$p_T^{j_{\rm sel}}$	$\eta^{j_{\rm sel}}$	$\phi^{j_{\rm sel}}$	$b^{j_{\rm sel}}$	$E^{j_{\rm top}}$	$p_T^{j_{\rm top}}$	$\eta^{j_{\rm top}}$	$\phi^{j_{\rm top}}$

High-level

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

➢ Conclusion

1. The composite vector ρ resonances may be hidden in their large width and the dominant *tb*, *tt* and *bb* decay channels;



2. Deep learning can help to reveal such a broad *tt* resonance at the LHC.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OF THE UNIVERSE
カブリ数物連携宇宙研究機構

Thank you!

– The CCWZ construction: $\underbrace{\{T^{a_L},\ T^{a_R},\ T^i\}}_{SO(5)} \to \underbrace{\{T^{a_L},\ T^{a_R}\}}_{SO(4)\cong SU(2)_L\times SU(2)_R}$

Pseudo NGBs h: forming the Goldstone matrix

$$U[\vec{h}] = \exp\left\{ i\frac{\sqrt{2}}{f} h^i T^i \right\}$$

$$U[\vec{h}] \to \mathcal{G} U[\vec{h}] \mathcal{H}^{-1}[\vec{h};\mathcal{G}]$$

$\mathcal{G}$: group element of SO(5)
$\mathcal{H}$: group element of SO(4)

f: SO(5)/SO(4) scale; T^i: the 4 broken generators

Elementary particales: embedded in SO(5) representation

$$t_L,\ b_L \to F_L; \qquad F_L \to \mathcal{G}_{F_L} F_L;\ \ F_R \to \mathcal{G}_{F_R} F_R;$$

$$t_R \to F_R.$$

$F_{L,R}$: some multiplet of SO(5); **model dependent**

The composite resonances: fulfill SO(4) representation

$$\rho_\mu = \rho_\mu^{a_L} T^{a_L} + \rho_\mu^{a_R} T^{a_R}; \qquad \rho_\mu \to \mathcal{H}(\rho_\mu + i\partial_\mu)\mathcal{H}^{-1};$$

$$\Psi. \qquad \Psi \to \mathcal{H}_{\mathbf{r}_\Psi} \Psi$$

– The CCWZ construction: operators

Pure bosonic interactions: construced by d and e symbols

$$U^\dagger(g_2 W_\mu^{a_L} T^{a_L} + g_1 B_\mu T^{3_R} + i\partial_\mu)U = d_\mu^i T^i + e_\mu^{a_L} T^{a_L} + e_\mu^{a_R} T^{a_R},$$

$$d_\mu \to \mathcal{H} d_\mu \mathcal{H}^{-1}, \quad e_\mu \to \mathcal{H}(e_\mu + i\partial_\mu)\mathcal{H}^{-1}$$

$$d_\mu^i = -\frac{\sqrt{2}}{f} D_\mu h_i + \cdots ,$$

$$e_\mu^{a_L} = g_2 W_\mu^{a_L} - \frac{i}{f^2} H^\dagger \frac{\sigma^{a_L}}{2} \overleftrightarrow{D}_\mu H + \cdots ,$$

$$e_\mu^{3_R} = g_1 B_\mu - \frac{i}{2f^2} H^\dagger \overleftrightarrow{D}_\mu H + \cdots$$

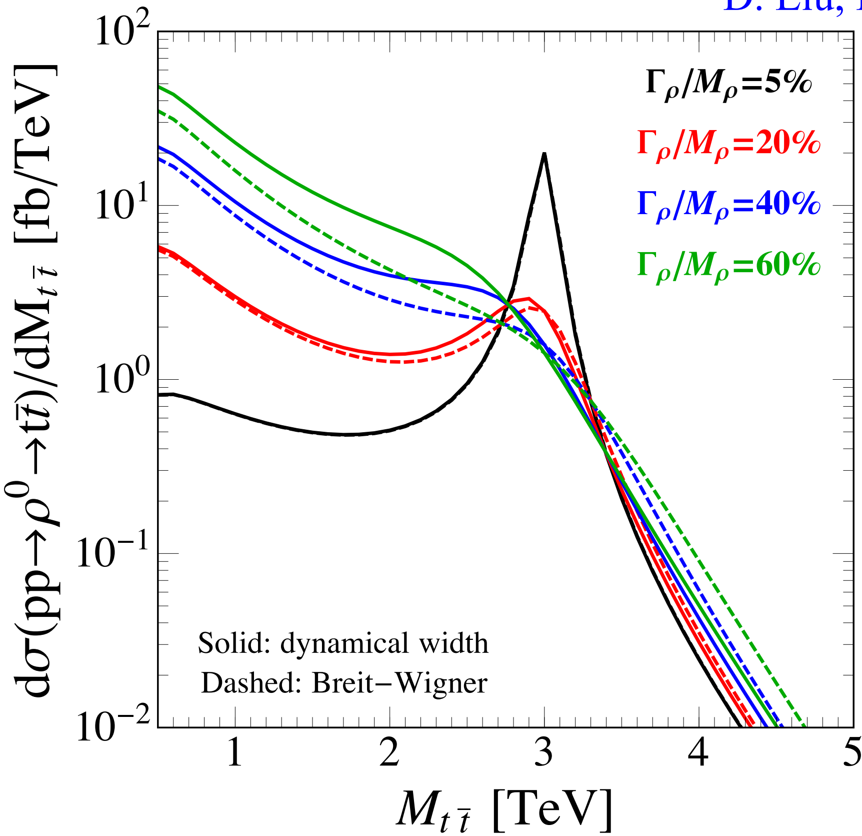
$$g_\rho \sim \frac{4\pi}{\sqrt{N}}$$

$$\frac{f^2}{4} d_\mu^i d^{i\mu} \approx \left(1 - \frac{2|H|^2}{3f^2}\right) D_\mu H^\dagger D^\mu H + \frac{1}{6f^2}(\partial_\mu |H|^2)^2,$$

$$\frac{M_\rho^2}{2g_\rho^2}\left(g_\rho \rho_\mu^{a_L} - e_\mu^{a_L}\right)^2 \approx \frac{M_\rho^2}{2g_\rho^2}\left(g_\rho \rho_\mu^{a_L} - g_2 W_\mu^{a_L} + \frac{i}{f^2} H^\dagger \frac{\sigma^{a_L}}{2} \overleftrightarrow{D}_\mu H\right)^2$$

➢ The invariant mass of a resonance

D. Liu, L.-T. Wang and K.-P. Xie, arXiv:1901.01674



$$\frac{1}{(\hat{s}-M_\rho^2)^2+M_\rho^2\Gamma_\rho^2}$$

Breit-Wigner

v.s.

dynamical width

$$\frac{1}{(\hat{s}-M_\rho^2)^2+\hat{s}^2\Gamma_\rho^2/M_\rho^2}$$

– Breit-Wigner distribution is commonly used, but a more suitable treatment is the dynamical width approach!

➢The technical details of DNN

The configurations we tried

N_{hidden}	N_{node}	Learning rate (L_r)	Dropout rate (D_r)	Batch size (B_s)
4, 5	200, 300	0.001, 0.003	0.1, 0.2, 0.3	10^3, 10^4

Table 1: The configurations we have tried when finding the best model. For each signal model we try $2 \times 2 \times 3 \times 2 \times 2 = 48$ different configurations, and choose the one with best performance.

The best networks we chose

Signal model	Kinematic region	N_{hidden}, N_{node}, L_r, D_r, B_s, N_{epochs}	Accuracy reach
M1Γ1	resolved	5, 200, 0.001, 0.2, 10^3, 150	85.2%
	boosted	5, 200, 0.001, 0.2, 10^4, 55	67.9%
M1Γ2	resolved	4, 300, 0.003, 0.2, 10^3, 35	83.2%
	boosted	5, 200, 0.001, 0.2, 10^4, 45	65.8%
M1Γ3	resolved	4, 300, 0.001, 0.2, 10^3, 30	81.6%
	boosted	4, 300, 0.003, 0.2, 10^4, 30	65.1%
M1Γ4	resolved	5, 200, 0.001, 0.2, 10^3, 80	80.8%
	boosted	4, 300, 0.001, 0.2, 10^4, 20	64.3%

Table 1: The best networks for $M_\rho = 1$ TeV. N_{epochs} is the number of epochs when we cut the training; while "accuracy reach" is the accuracy for the test data.

➢One slide for the 5 TeV case

The ATLAS result: 1804.10823

The DNN results: **this work**