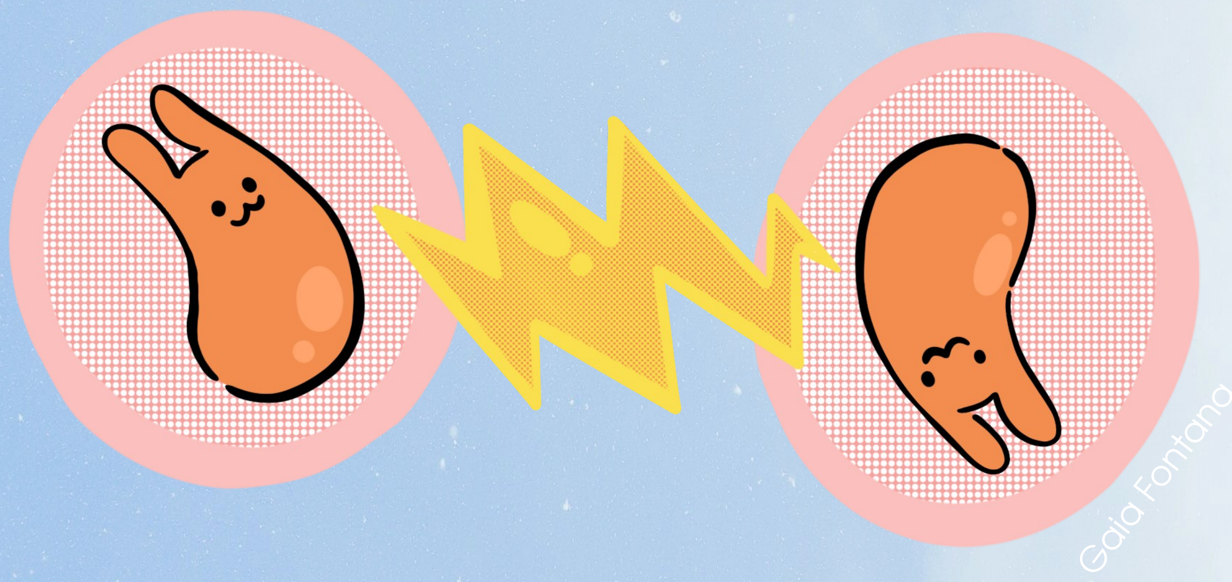
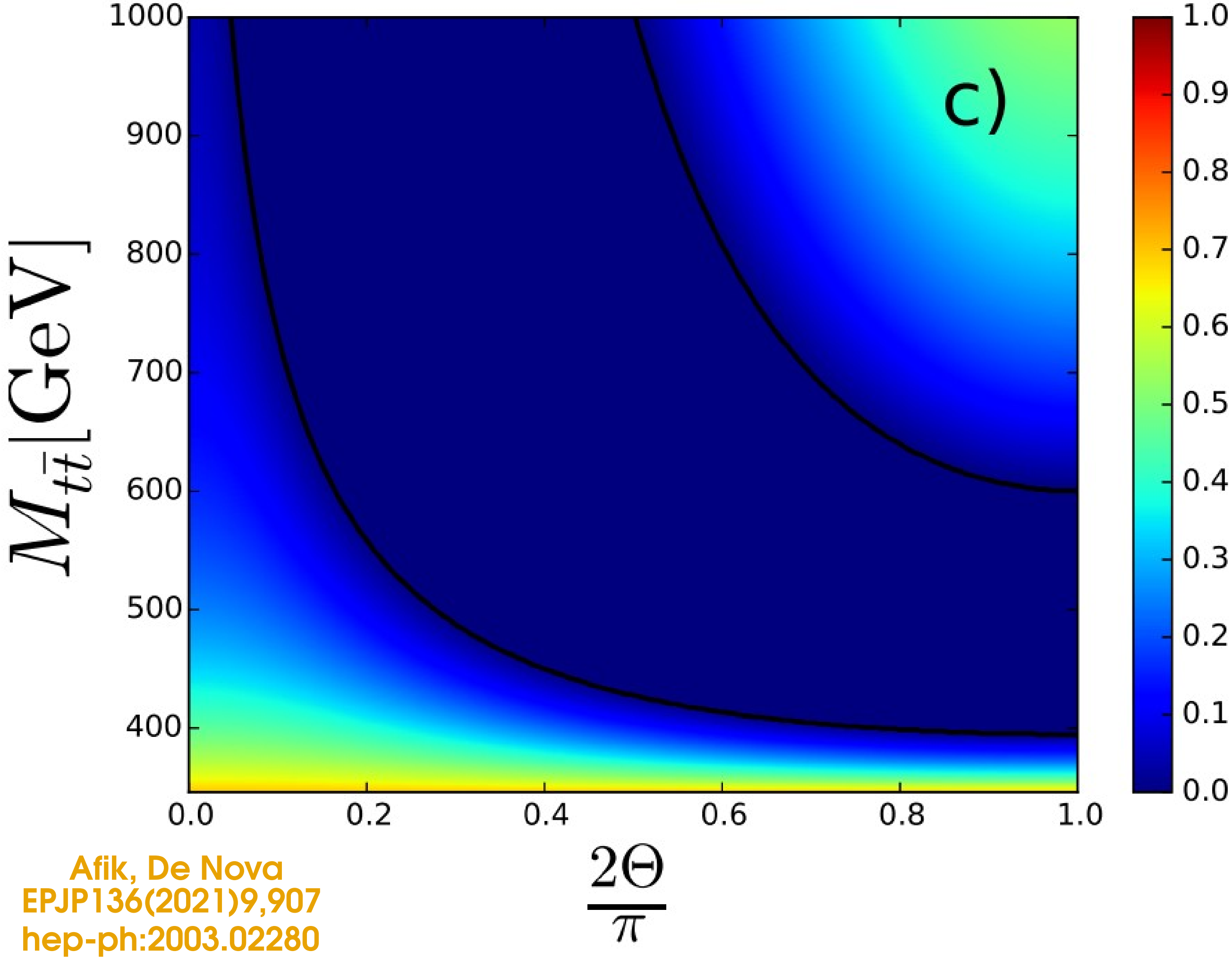
Searches for new physics with quantum observables



2110.10112 Degli Esposti, Maltoni, Sioli, CS
2210.09330 CS, Vryonidou
in preparation Maltoni, CS, Tentori, Vryonidou

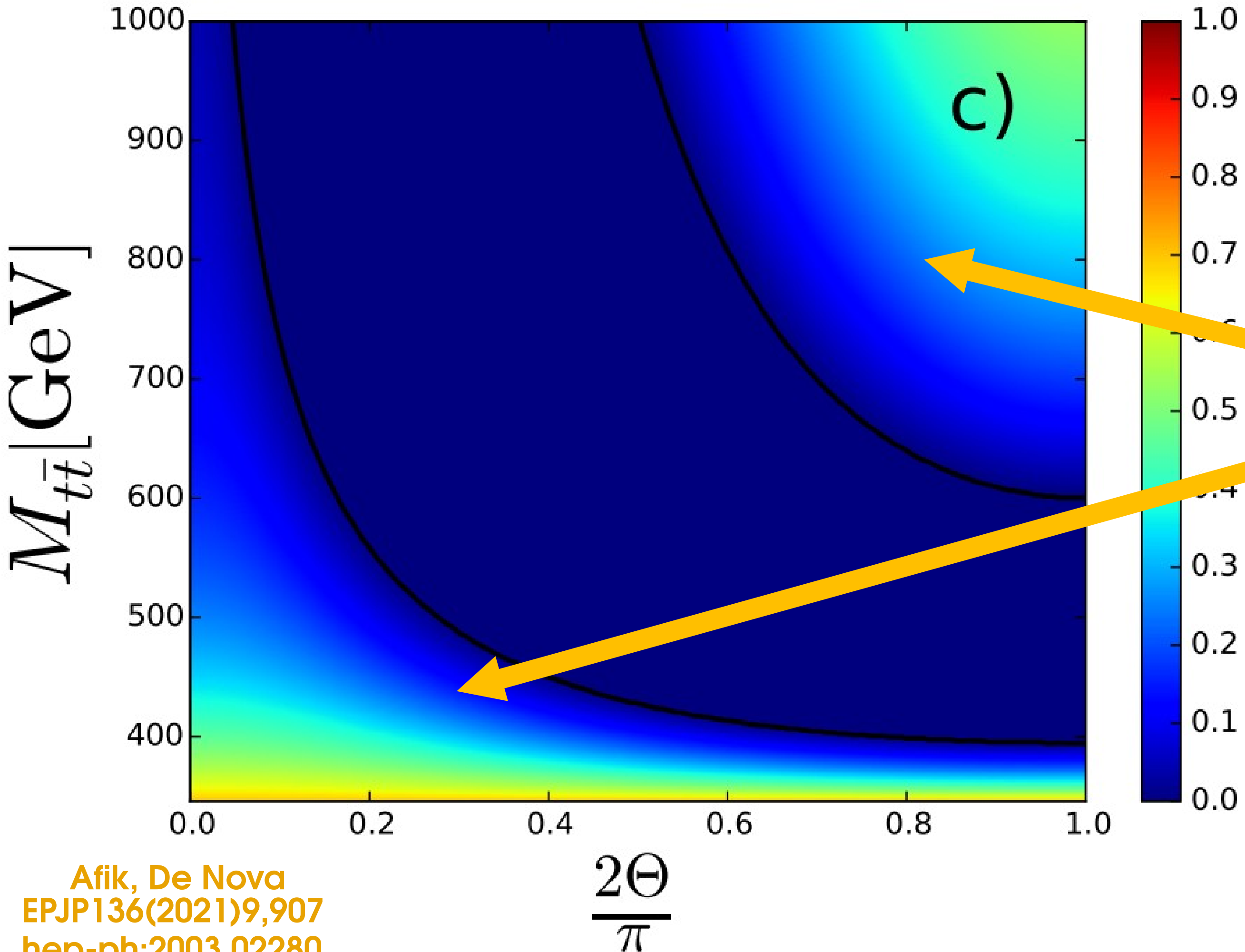
9/28/23 Claudio Severi - U. Manchester - TOP23

The Standard Model produces top pairs with correlated spin. Sometimes spin correlations are so strong they can not be explained classically:



Afik, De Nova
EPJP136(2021)9,907
hep-ph:2003.02280

The Standard Model produces top pairs with correlated spin. Sometimes spin correlations are so strong they can not be explained classically:



Afik, De Nova
EPJP136(2021)9,907
hep-ph:2003.02280

Entangled regions

1. High p_T
2. Threshold & forward (zero p_T)

There are four maximally entangled states:

$$|\Phi^{\pm}\rangle = \frac{1}{\sqrt{2}}\big(|\uparrow\uparrow\rangle \pm |\downarrow\downarrow\rangle\big),$$
$$|\Psi^{\pm}\rangle = \frac{1}{\sqrt{2}}\big(|\uparrow\downarrow\rangle \pm |\downarrow\uparrow\rangle\big).$$

There are four maximally entangled states:

$$|\Phi^{\pm}\rangle = \frac{1}{\sqrt{2}}\big(|\uparrow\uparrow\rangle \pm |\downarrow\downarrow\rangle\big),$$
$$|\Psi^{\pm}\rangle = \frac{1}{\sqrt{2}}\big(|\uparrow\downarrow\rangle \pm |\downarrow\uparrow\rangle\big).$$

The singlet state is Ψ^-, the triplet is $(\Phi^+ - \Phi^-,\ \Psi^+,\ \Phi^+ + \Phi^-)$.

There are four maximally entangled states:

$$|\Phi^{\pm}\rangle = \frac{1}{\sqrt{2}}\big(|\uparrow\uparrow\rangle \pm |\downarrow\downarrow\rangle\big),$$
$$|\Psi^{\pm}\rangle = \frac{1}{\sqrt{2}}\big(|\uparrow\downarrow\rangle \pm |\downarrow\uparrow\rangle\big).$$

The singlet state is Ψ^-, the triplet is (Φ^+-Φ^-, Ψ^+, Φ^++Φ^-).

The spin correlation matrix,

$$\langle S_i \bar{S}_j \rangle = C_{ij}$$

parametrizes the quantum state, and is measurable experimentally. Entanglement is present when:

$$C_{11} + C_{22} - C_{33} > 1\,,$$
$$-C_{11} - C_{22} - C_{33} > 1\,,$$
$$C_{11} - C_{22} + C_{33} > 1\,,$$
$$-C_{11} + C_{22} + C_{33} > 1\,.$$

There are four maximally entangled states:

$$|\Phi^{\pm}\rangle = \frac{1}{\sqrt{2}}\big(|\uparrow\uparrow\rangle \pm |\downarrow\downarrow\rangle\big),$$
$$|\Psi^{\pm}\rangle = \frac{1}{\sqrt{2}}\big(|\uparrow\downarrow\rangle \pm |\downarrow\uparrow\rangle\big).$$

The singlet state is Ψ^-, the triplet is (Φ^+-Φ^-, Ψ^+, Φ^++Φ^-).

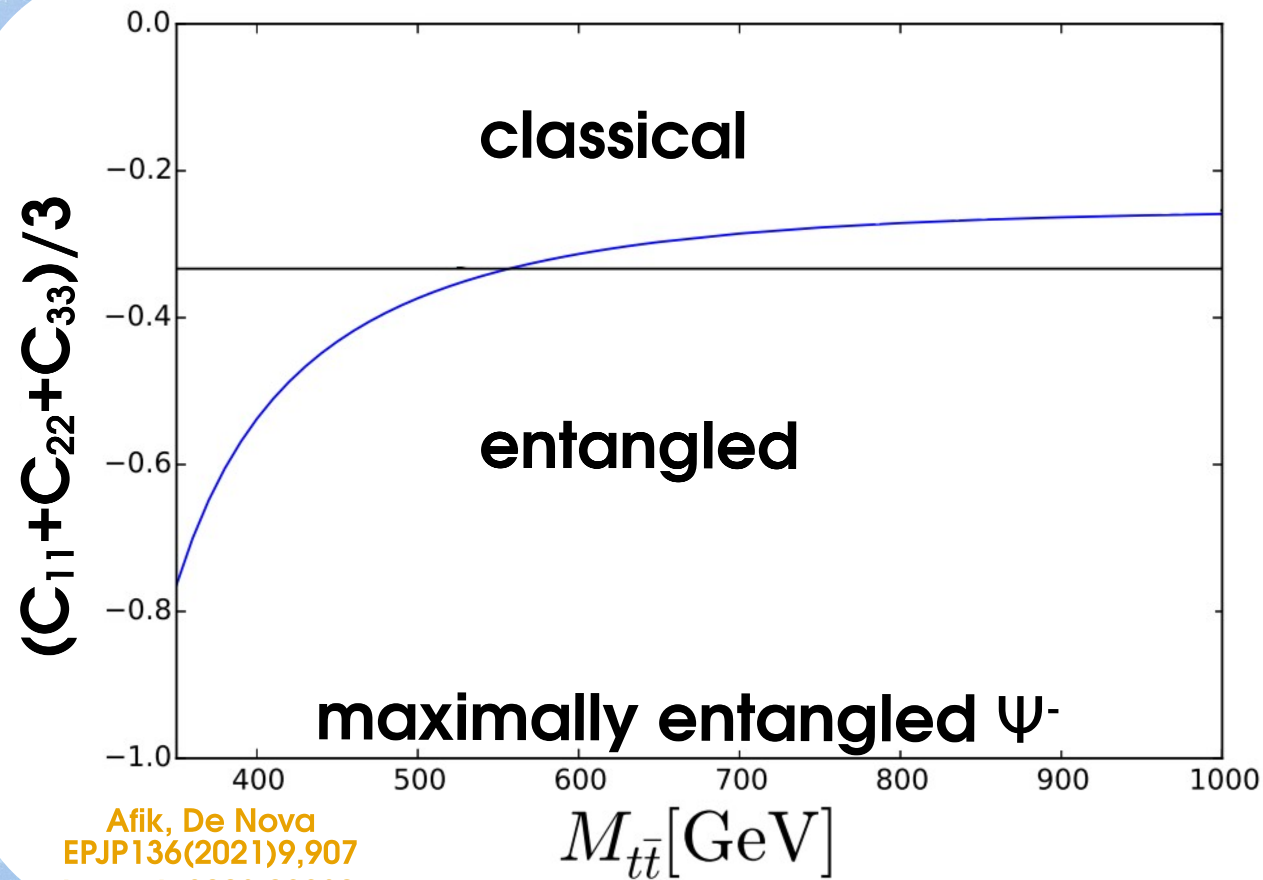
The spin correlation matrix,

$$\langle S_i \bar{S}_j \rangle = C_{ij}$$

parametrizes the quantum state, and is measurable experimentally. Entanglement is present when:

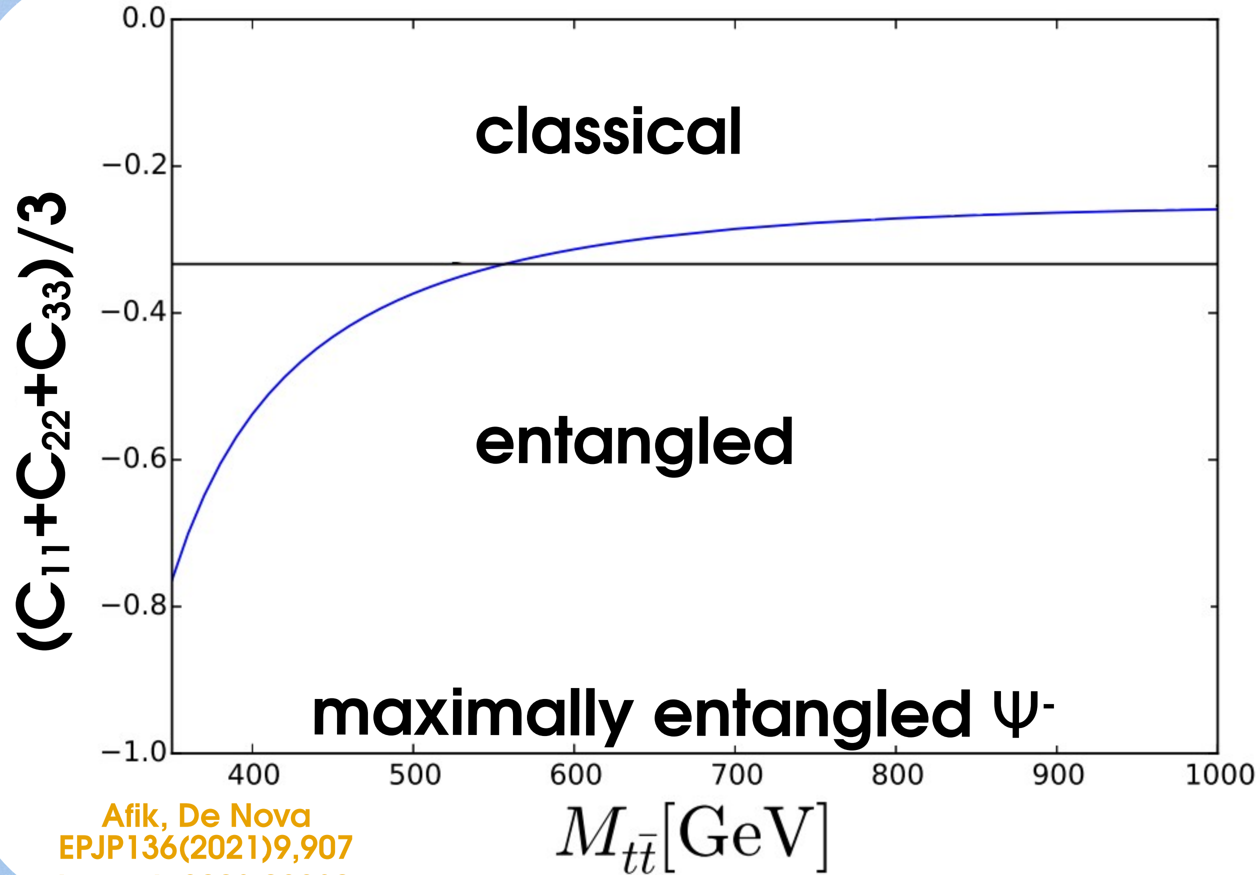
$$C_{11} + C_{22} - C_{33} > 1\,, \rightarrow \Psi^+$$
$$-C_{11} - C_{22} - C_{33} > 1\,, \rightarrow \Psi^-$$
$$C_{11} - C_{22} + C_{33} > 1\,, \rightarrow \Phi^+$$
$$-C_{11} + C_{22} + C_{33} > 1\,. \rightarrow \Phi^-$$

The SM produces Ψ^- at threshold,
so $-C_{11}-C_{22}-C_{33} > 1$ is the inequality to use:



Afik, De Nova
EPJP136(2021)9,907
hep-ph:2003.02280

The SM produces Ψ^- at threshold,
so $-C_{11}-C_{22}-C_{33} > 1$ is the inequality to use:



Afik, De Nova
EPJP136(2021)9,907
hep-ph:2003.02280

At large p_T the SM produces Ψ^+,
so a similar plot can be made for $C_{11}+C_{22}-C_{33} > 1$.

New physics in spin correlations

Spin correlations provide a novel window on top physics, whose exploration only started recently.

Several new physics scenarios predict different spin correlations, while keeping the more conventional observables within experimental bounds.

New physics in spin correlations

Spin correlations provide a novel window on top physics, whose exploration only started recently.

Several new physics scenarios predict different spin correlations, while keeping the more conventional observables within experimental bounds.

We explored examples of resonant and heavy new physics in the top sector.

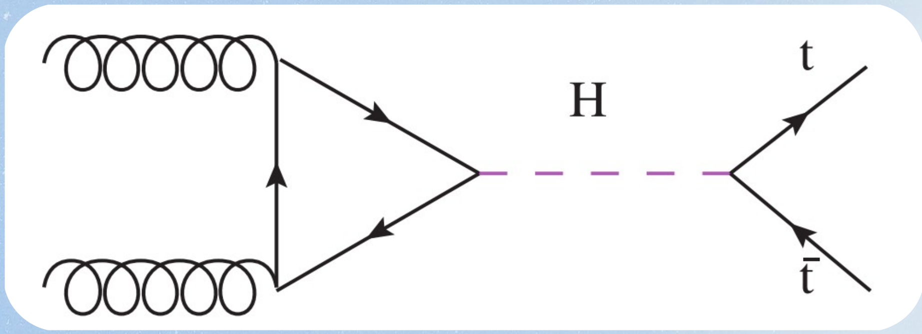
Resonant new physics

There is still room for resonant new physics in the top sector.

Resonant new physics

There is still room for resonant new physics in the top sector.

A (pseudo)scalar heavier than $2m_t$ is particularly interesting, and challenging to detect in m_{tt} resonance searches.

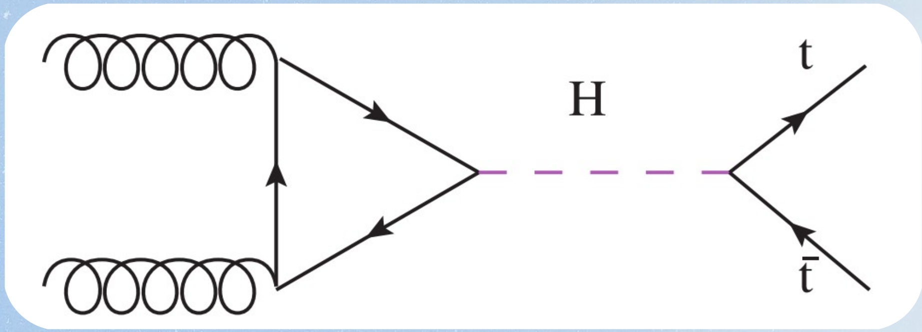


At the same time, the quantum state reached by this production channel is <u>always</u> Φ^- for a scalar and Ψ^- for a pseudoscalar.

Resonant new physics

There is still room for resonant new physics in the top sector.

A (pseudo)scalar heavier than $2m_t$ is particularly interesting, and challenging to detect in m_{tt} resonance searches.



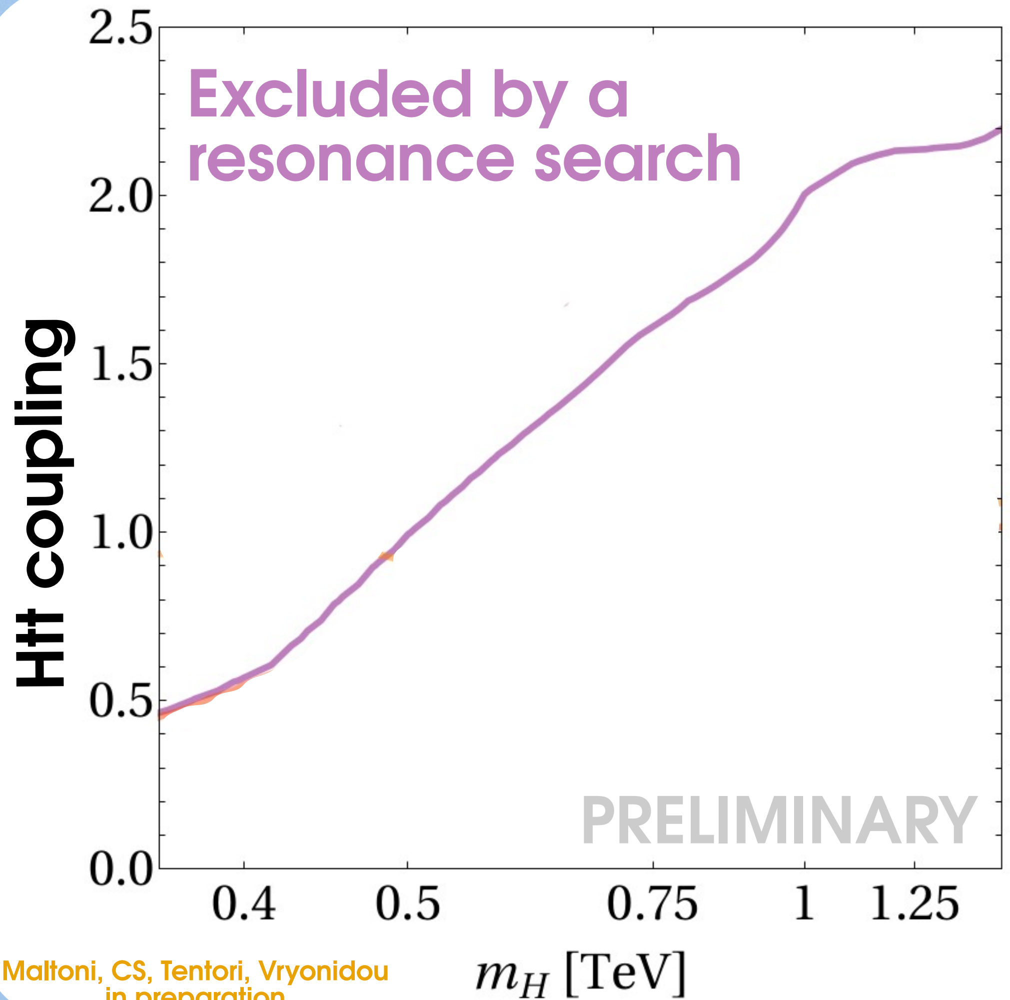
At the same time, the quantum state reached by this production channel is <u>always</u> Φ^- for a scalar and Ψ^- for a pseudoscalar.

Can an “entanglement search” be more sensitive than a normal resonance search?

Yes!

Yes!

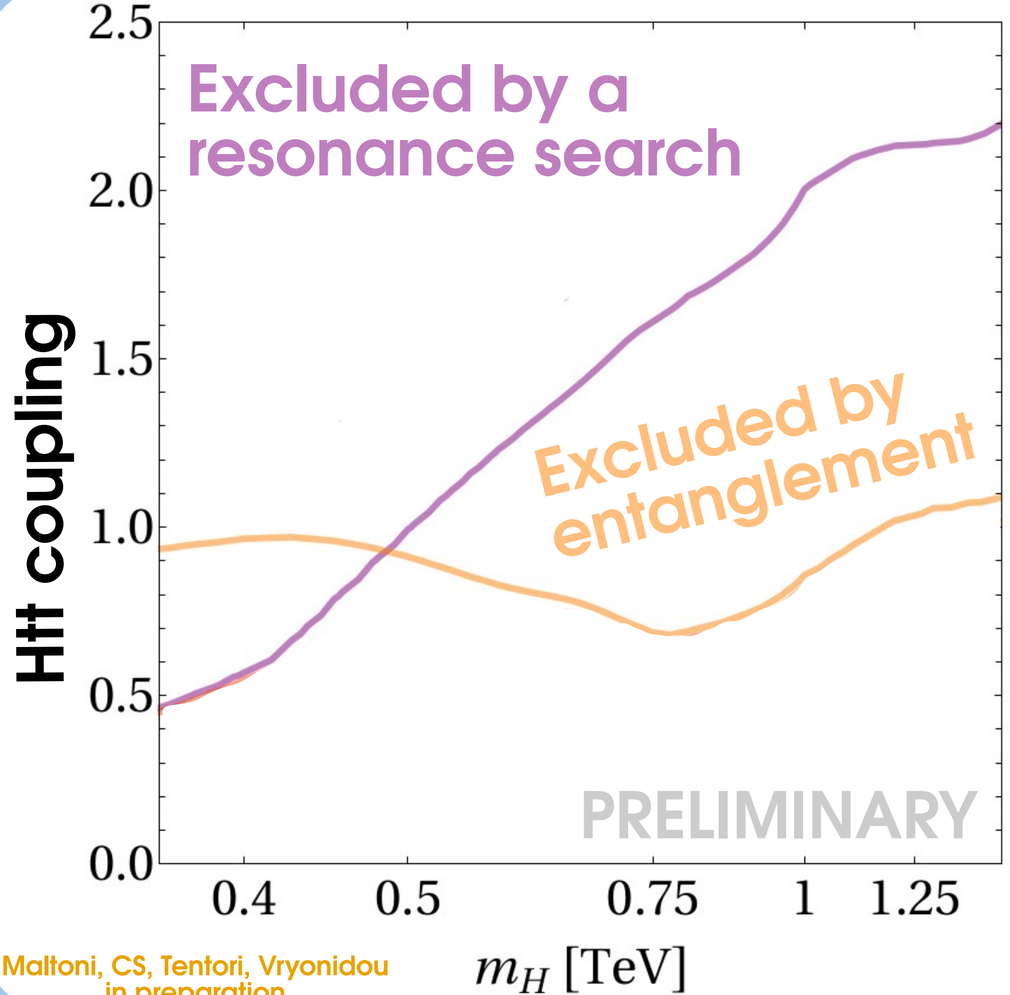
There are regions of parameter space that result in a signal invisible under a normal resonance search, but visible with a measurement of spin entanglement.



Maltoni, CS, Tentori, Vryonidou in preparation

Yes!

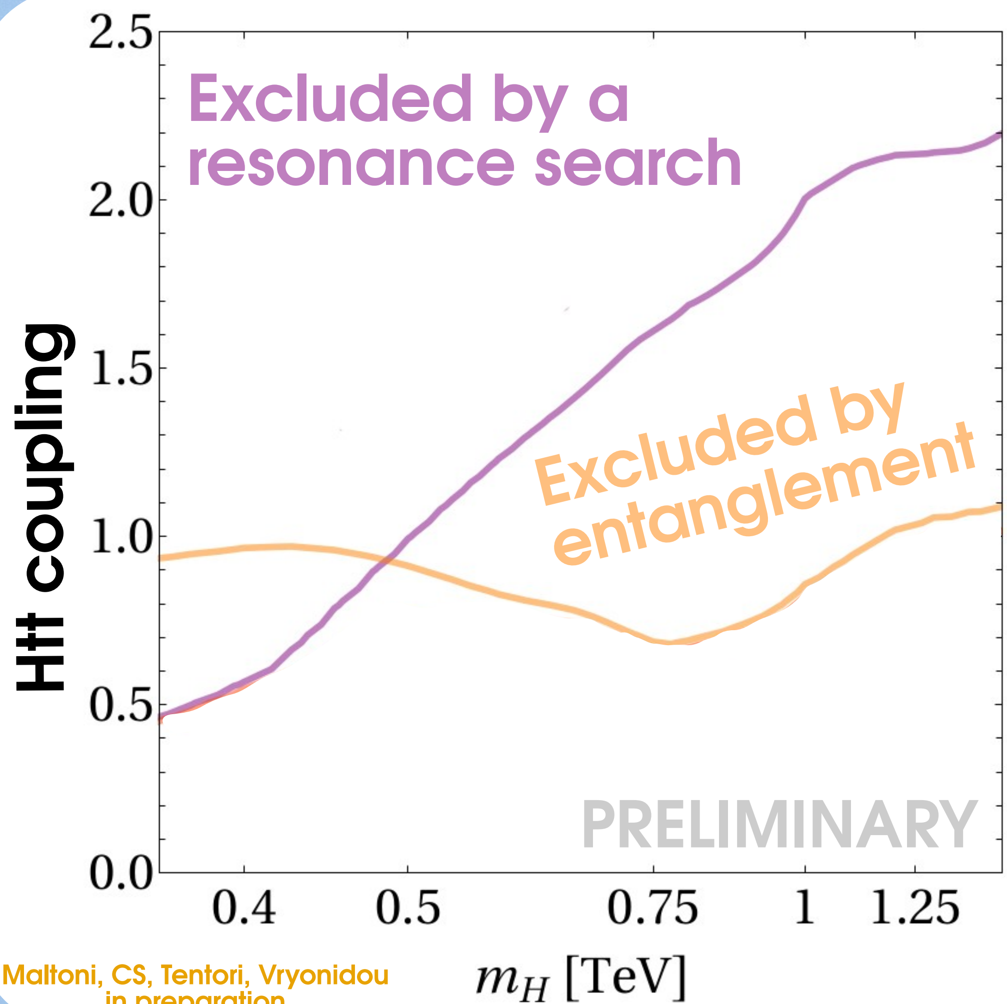
There are regions of parameter space that result in a signal invisible under a normal resonance search, but visible with a measurement of spin entanglement.



Maltoni, CS, Tentori, Vryonidou in preparation

Yes!

There are regions of parameter space that result in a signal invisible under a normal resonance search, but visible with a measurement of spin entanglement.

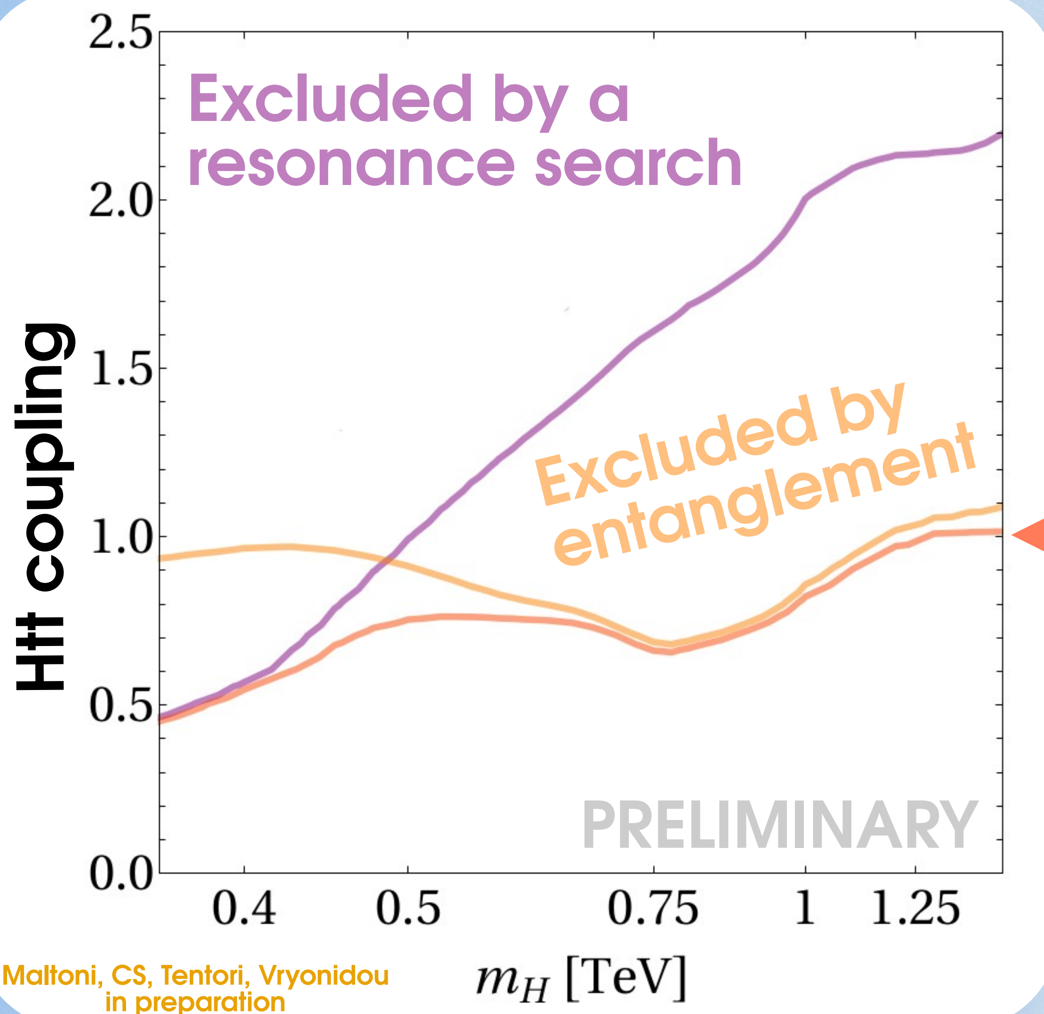


Maltoni, CS, Tentori, Vryonidou in preparation

The entanglement exclusion is worse at threshold, as the SM is also maximally entangled

Yes!

There are regions of parameter space that result in a signal invisible under a normal resonance search, but visible with a measurement of spin entanglement.

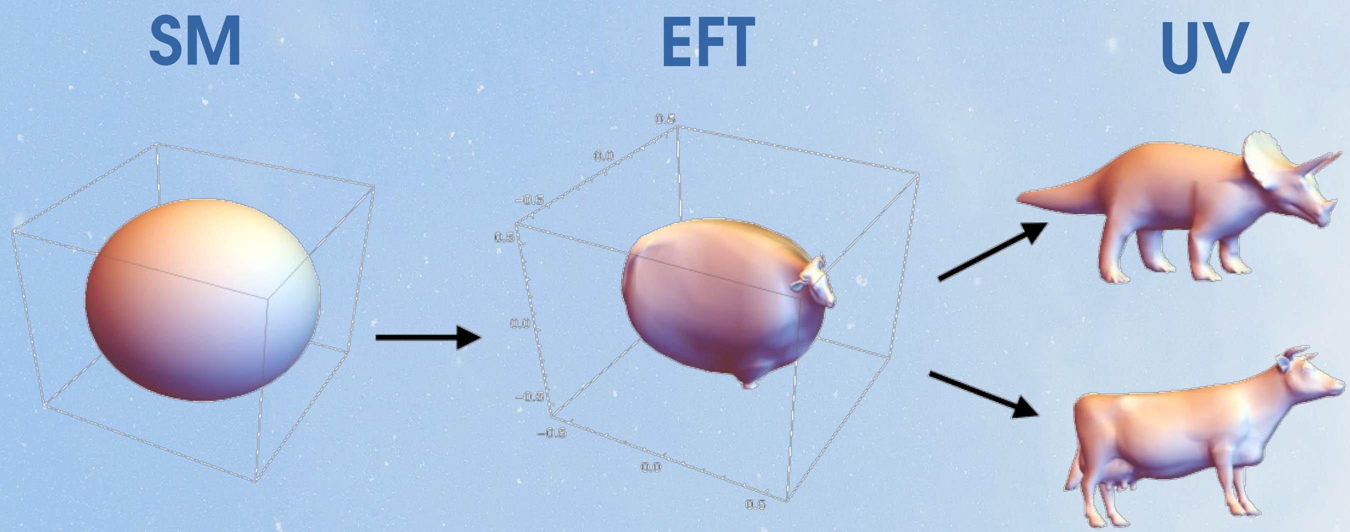


Maltoni, CS, Tentori, Vryonidou in preparation

The entanglement exclusion is worse at threshold, as the SM is also maximally entangled

Past 600GeV, the combination is heavily driven by the spin measurement.

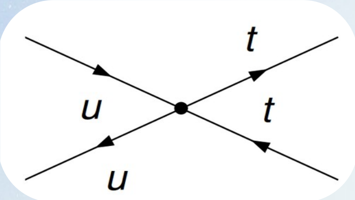
Heavy new physics (SMEFT)



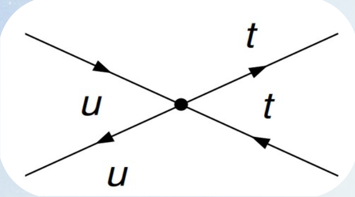
There are 15 dimension 6 operators entering spin correlations: 14 four-quark operators and the top chromo dipole O_{tG}.

Remarkably, SMEFT operators do not affect the spin analyzing power of leptons at dimension 6.

Example:
contact interaction between light quarks and tops.

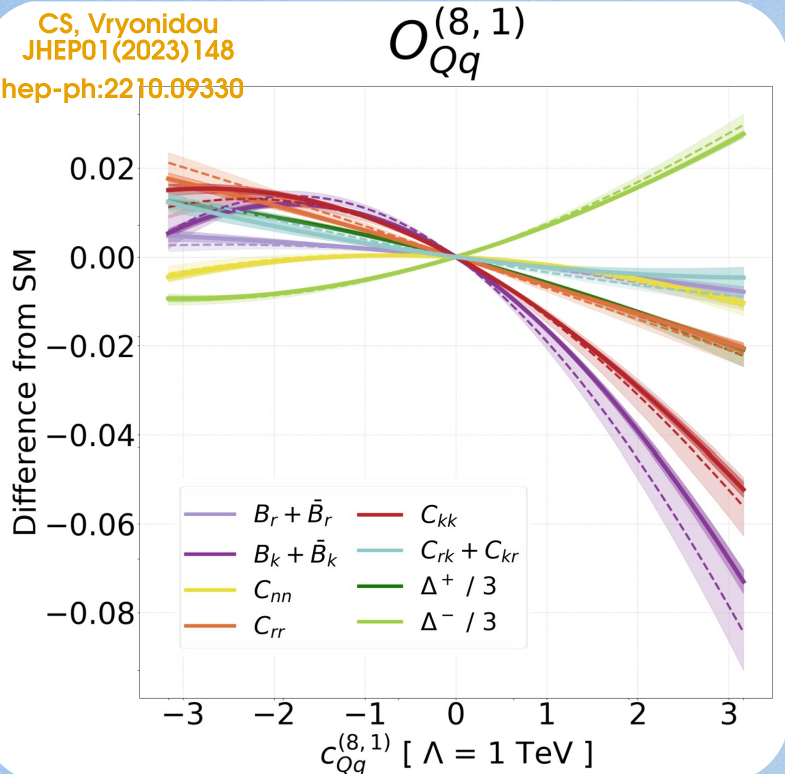


Example:
contact interaction between light quarks and tops.

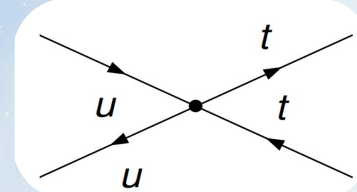


Inclusive measurement

CS, Vryonidou
JHEP01(2023)148
hep-ph:2210.09330

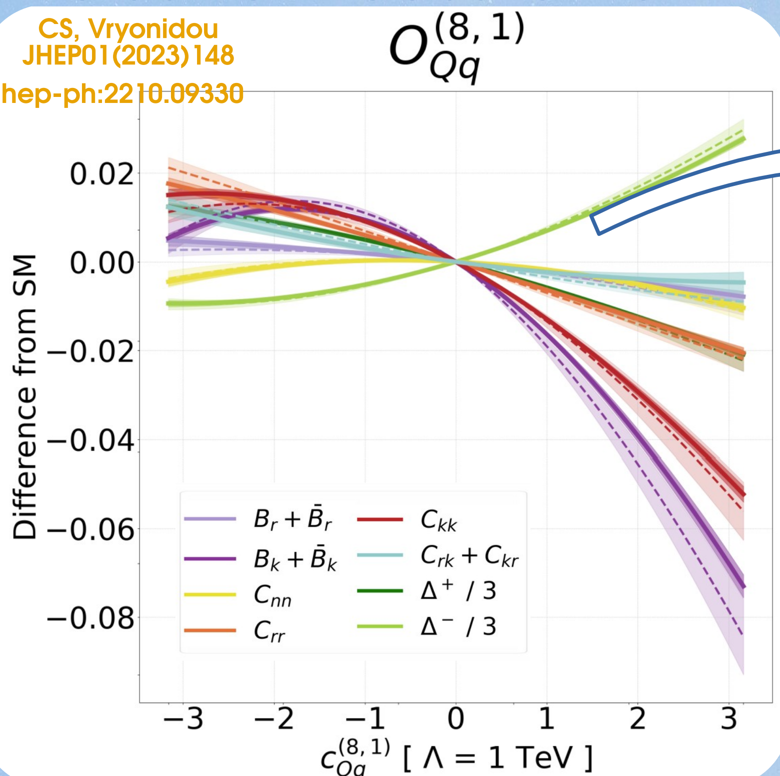


Example:
contact interaction between light quarks and tops.

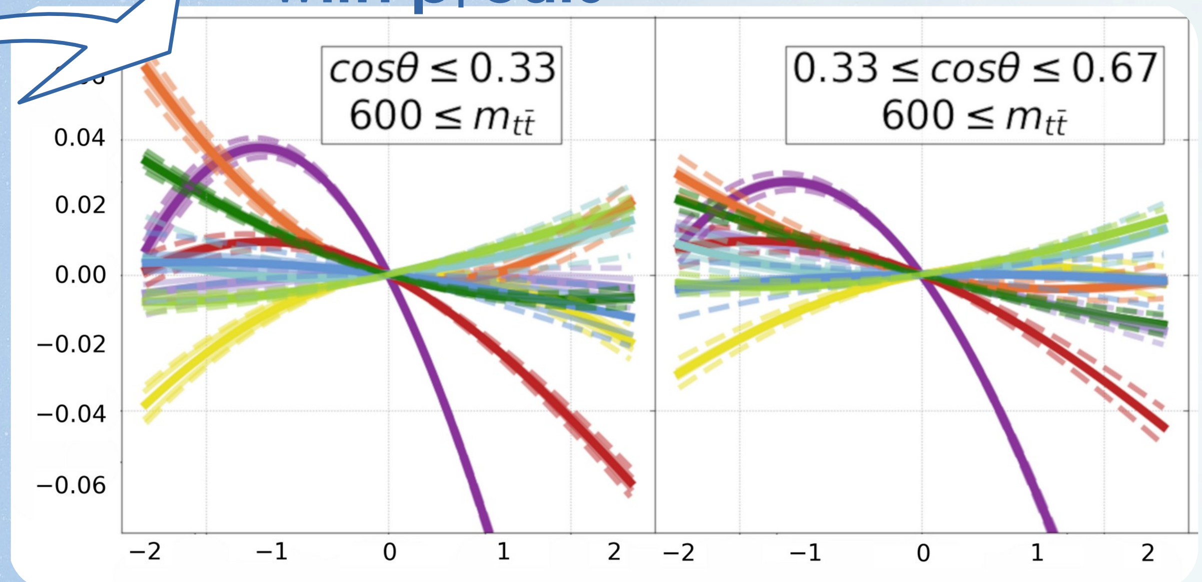


Inclusive measurement

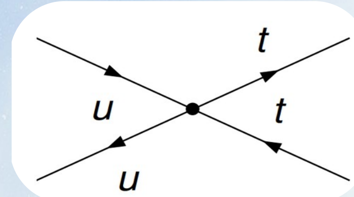
CS, Vryonidou
JHEP01(2023)148
hep-ph:2210.09330



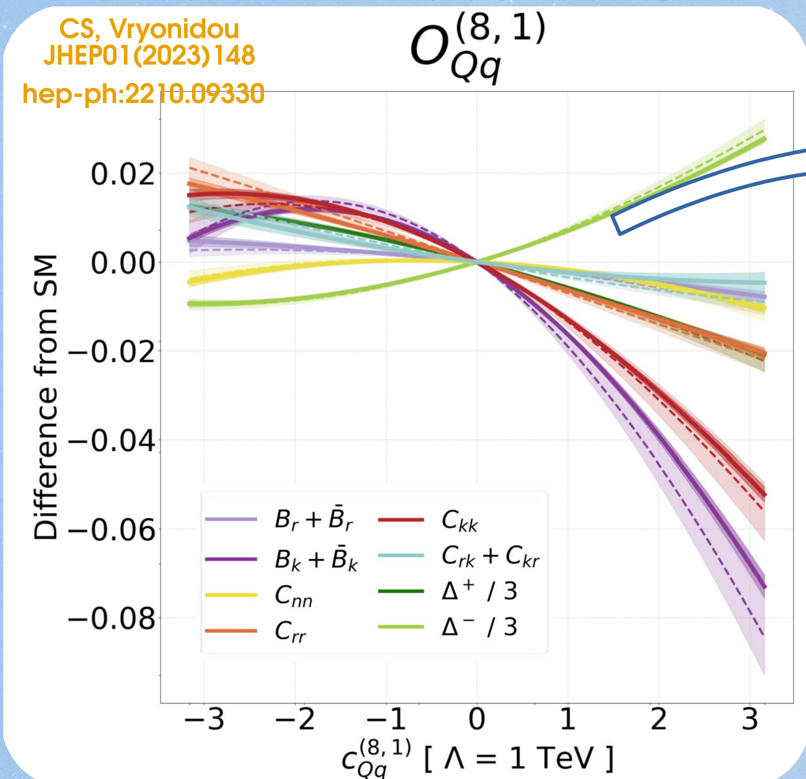
Measurement with p_T cuts



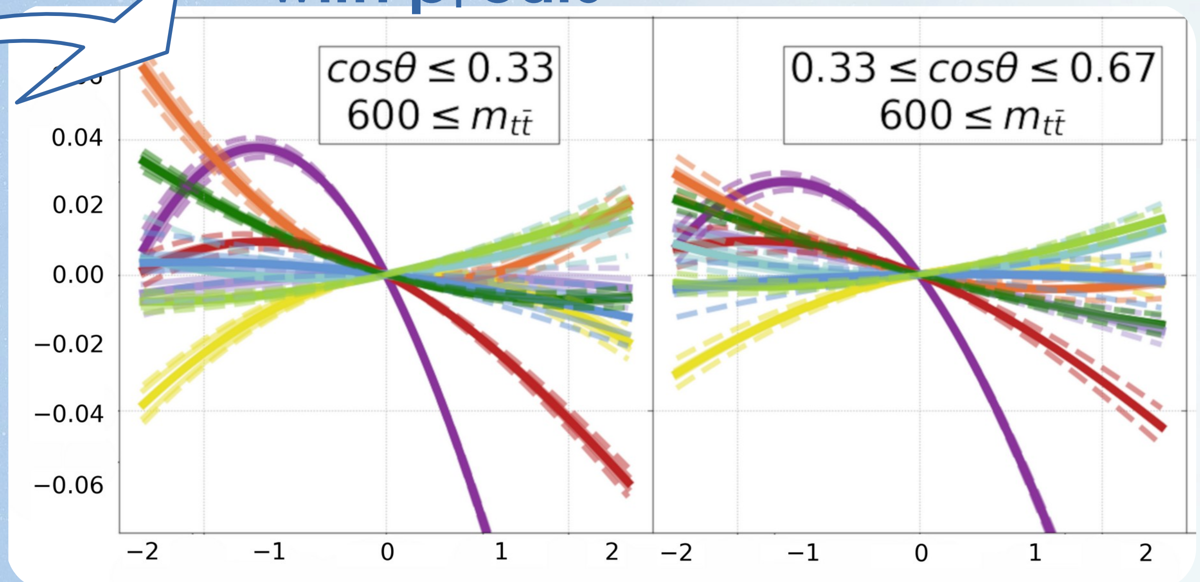
Example:
contact interaction between light quarks and tops.



Inclusive measurement



Measurement with p_T cuts

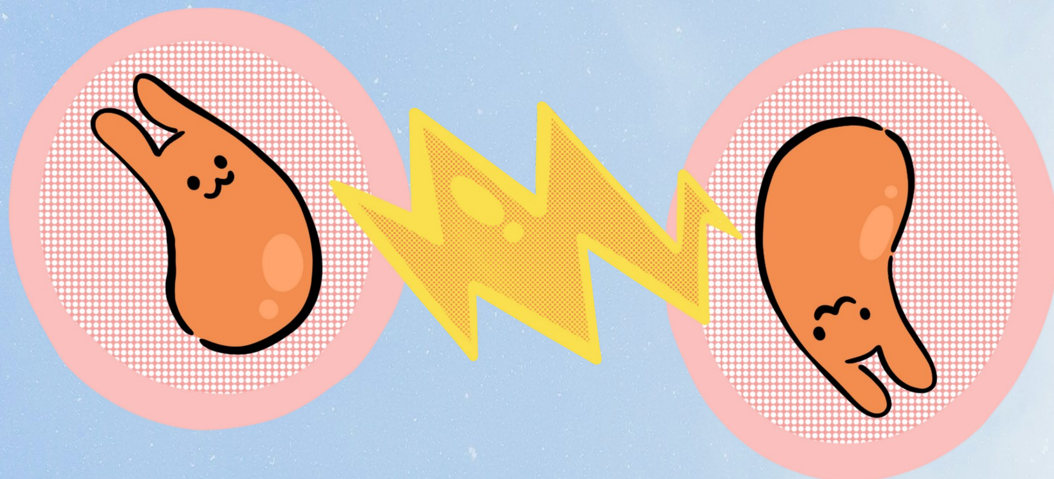


Operator	Run III Projection 300 fb^{-1} Differential	Current Global Fit
$\mathcal{O}_{Qu}^{8}$	$[-0.7, 0.6]$	$[-1.0, 0.5]$
$\mathcal{O}_{Qd}^{8}$	$[-0.9, 0.8]$	$[-1.6, 0.9]$
$\mathcal{O}_{Qq}^{(1,8)}$	$[-0.4, 0.3]$	$[-0.4, 0.3]$
$\mathcal{O}_{Qq}^{(3,8)}$	$[-1.1, 0.8]$	$[-0.5, 0.4]$

Our simulations show that one differential measurement will be competitive with the global fits to all top data.

Conclusions

The era of quantum tops has just began.



There are many spin/entanglement observables, of different theoretical cleanliness and experimental accessibility.

They explore new corners of top physics, and carry a remarkable discovery potential.