University of Glasgow

Christoph Englert

Dark Energy at the LHC

Patras Workshop Jeju

20.06.2016

[Brax, Burrage, CE `15]
[Brax, Burrage, CE, Spannowsky `16]

"What can the Large Hadron Collider contribute to the search for dark energy?"

laboratory
looking into large momentum transfers

screening mechanisms
effective field theory
[Horndeski `74]

DE interpretation?

similarity with wimpy / wispy DM

Dark Energy at the LHC

☛ search strategies depend on the form of interactions

shift symmetry conserving

e.g. $\mathcal{L}_1 = \frac{\partial_\mu \phi \partial^\mu \phi}{M^4} T^\nu_{\ \nu}$

$\mathcal{L}_2 = \frac{\partial_\mu \phi \partial_\nu \phi}{M^4} T^{\mu\nu}$

[Bekenstein `93]

dark energy scalars pair produced, stable on collider scales

shift symmetry violating

e.g. $\mathcal{L}_{10,n} = \left(\frac{\phi}{N}\right)^n T^\mu_{\ \mu}$

dark energy scalar singly produced, rapid decay depending on mass

scalar is assumed to be light compared to collider energy scales

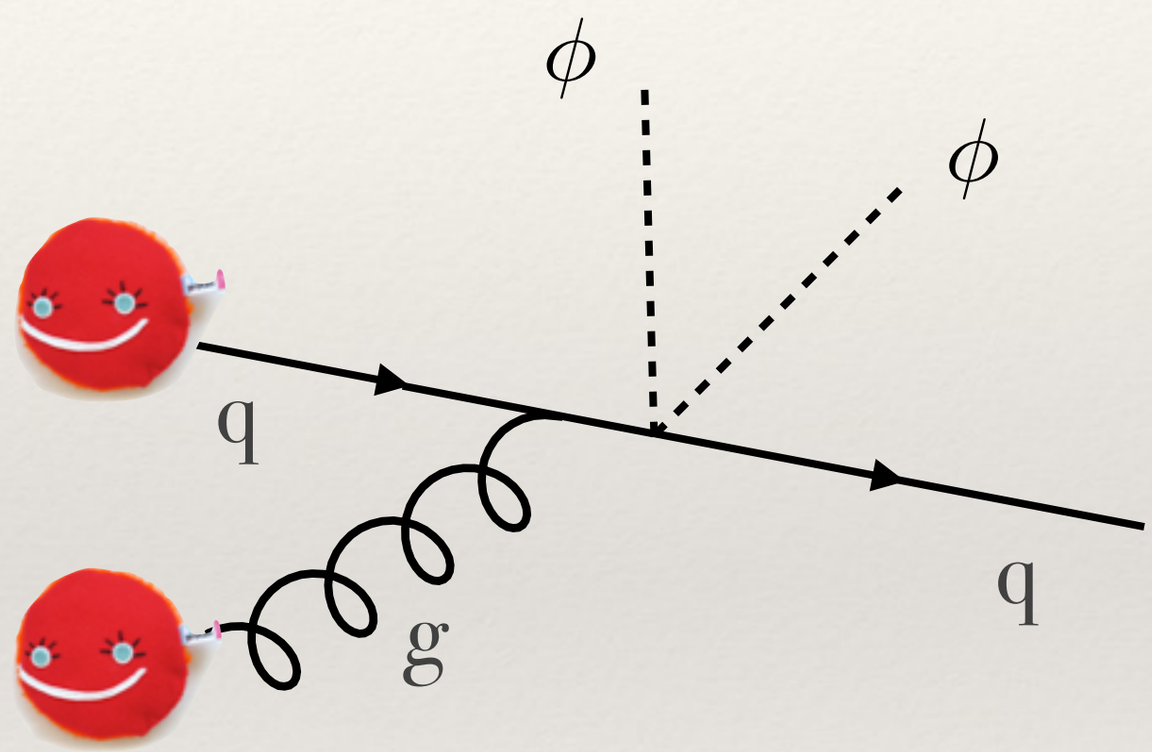
dominant phenomenology

- typical effective interactions

conformal anomaly: explicit mass terms

$$\mathcal{L}_1 = \frac{\partial_\mu \phi \partial^\mu \phi}{M^4} T^\nu_\nu$$

$$\mathcal{L}_2 = \frac{\partial_\mu \phi \partial_\nu \phi}{M^4} T^{\mu\nu}$$

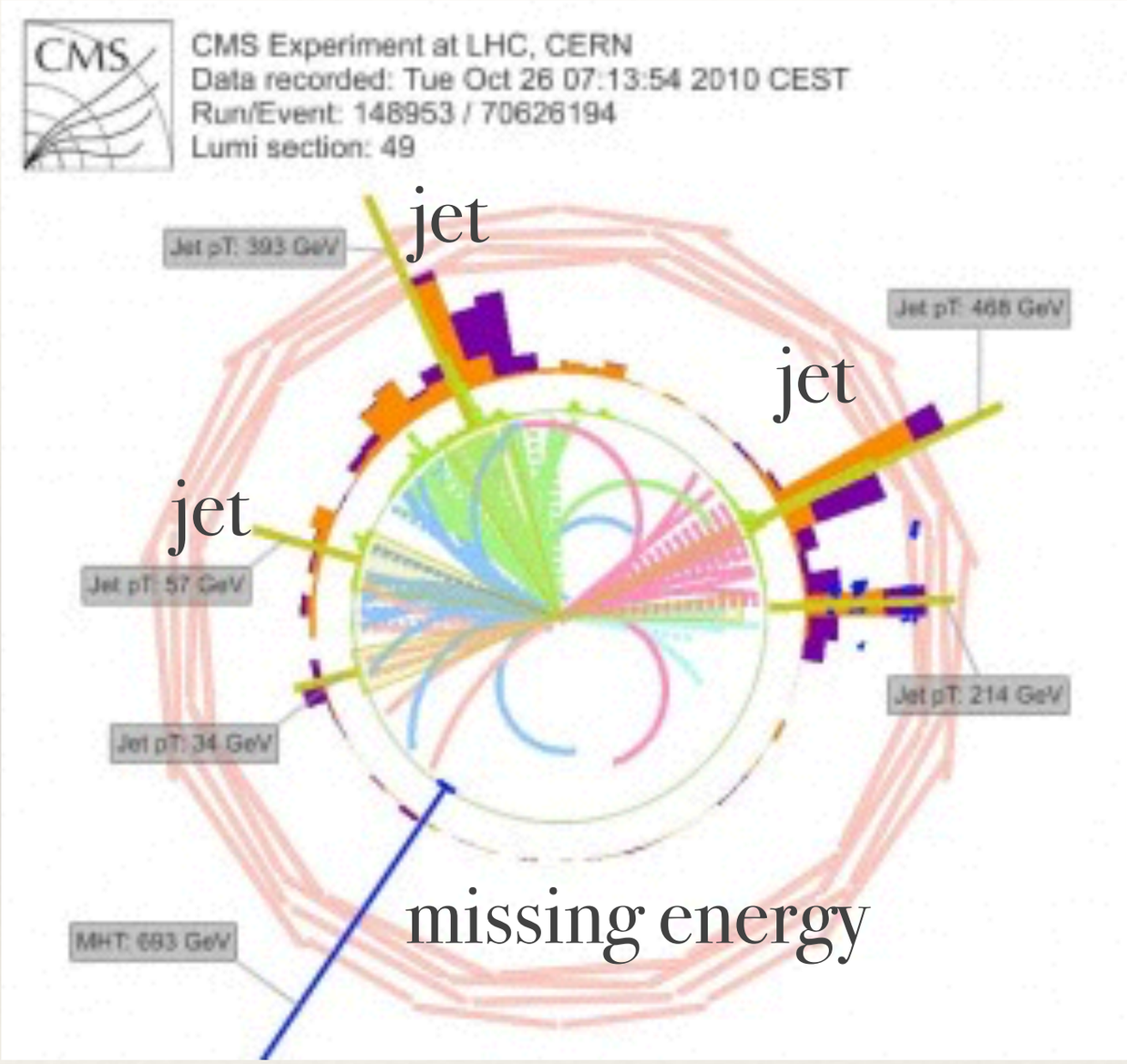


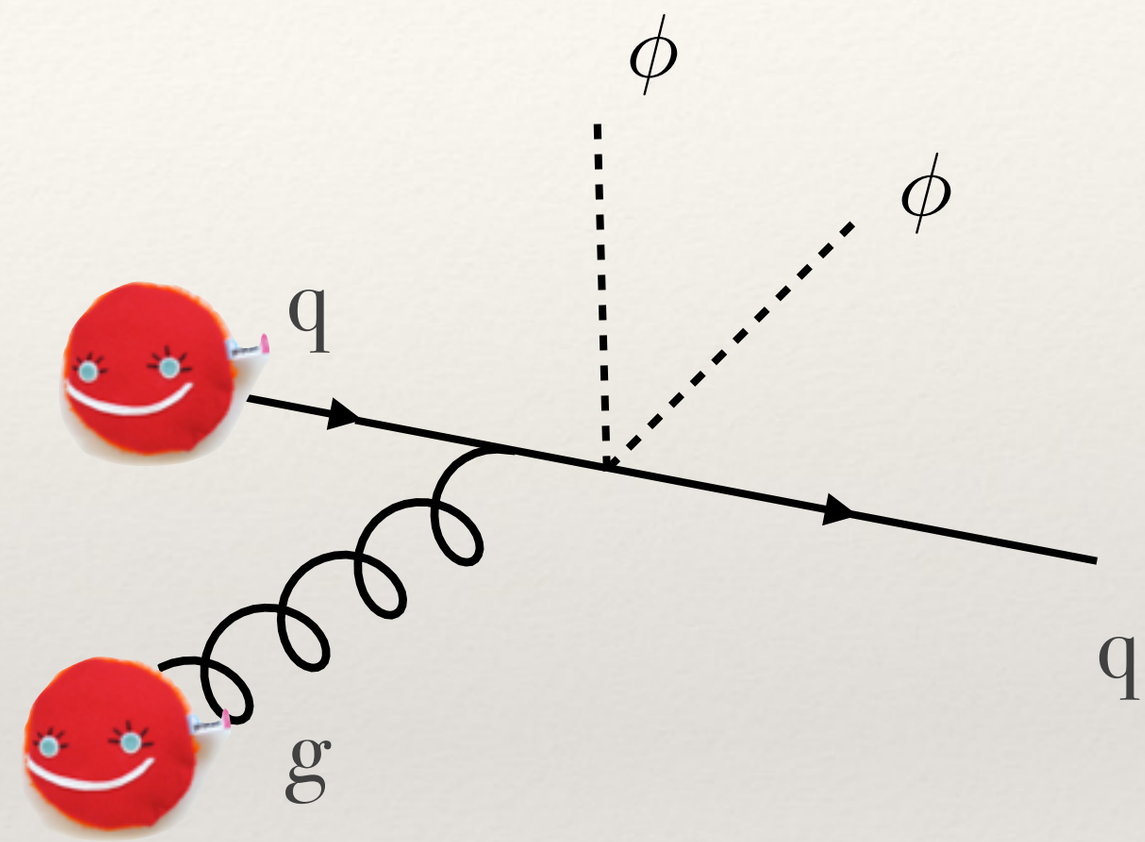
momentum dependence

- a (heavy) quark recoils against nothing in the detector

dominant phenomenology

- typical interactions





- a (heavy) quark recoils against nothing in the detector

  jets + missing energy signal

dominant phenomenology

- typical interactions

need large mass: top quark pair production + missing energy

$$\mathcal{L}_1 = \frac{\partial_\mu \phi \partial^\mu \phi}{M^4} T^\nu_\nu$$

$$\mathcal{L}_2 = \frac{\partial_\mu \phi \partial_\nu \phi}{M^4} T^{\mu\nu}$$

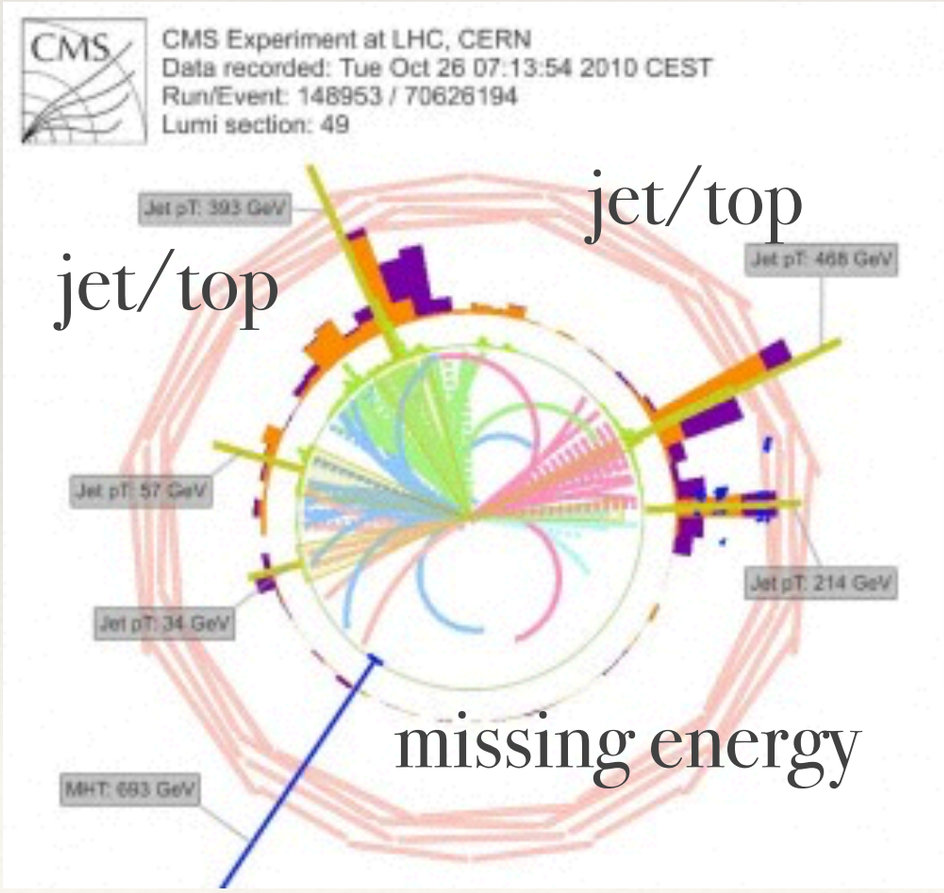
large momentum transfers with large statistics: jets + missing energy

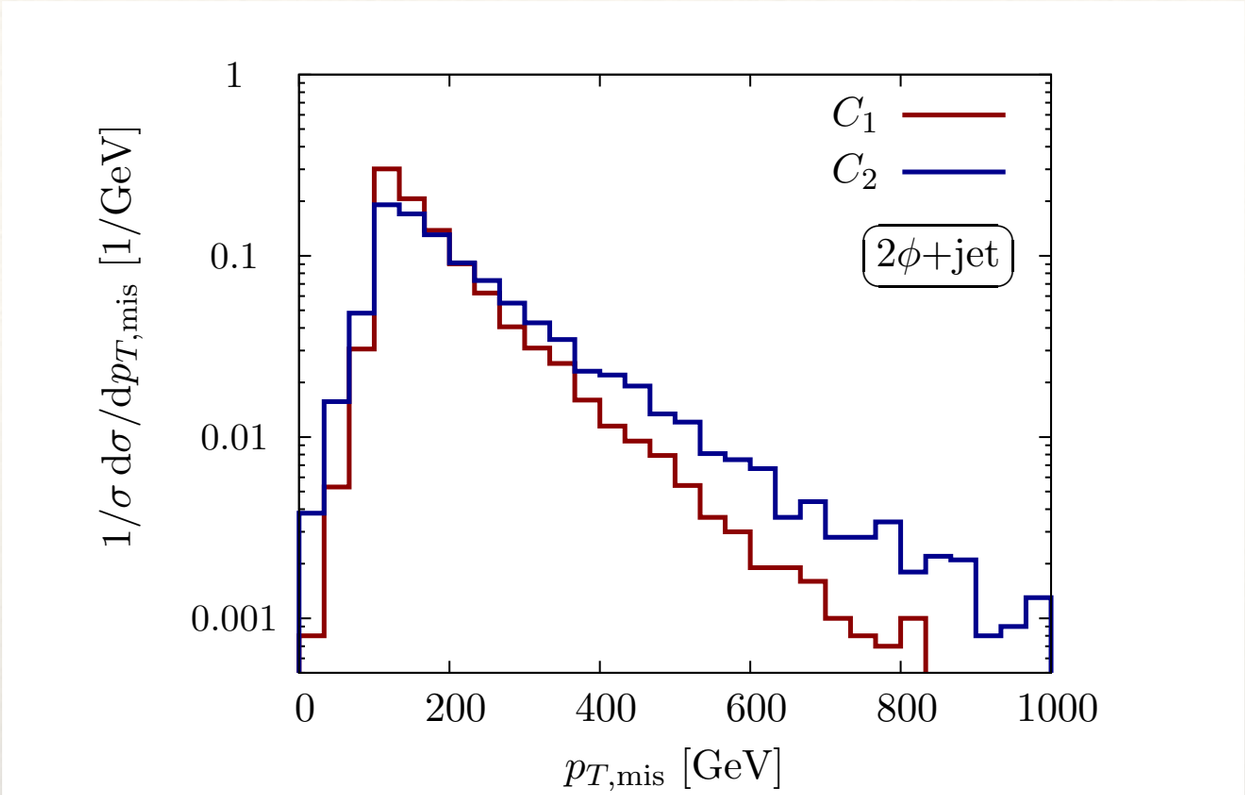
dominant phenomenology

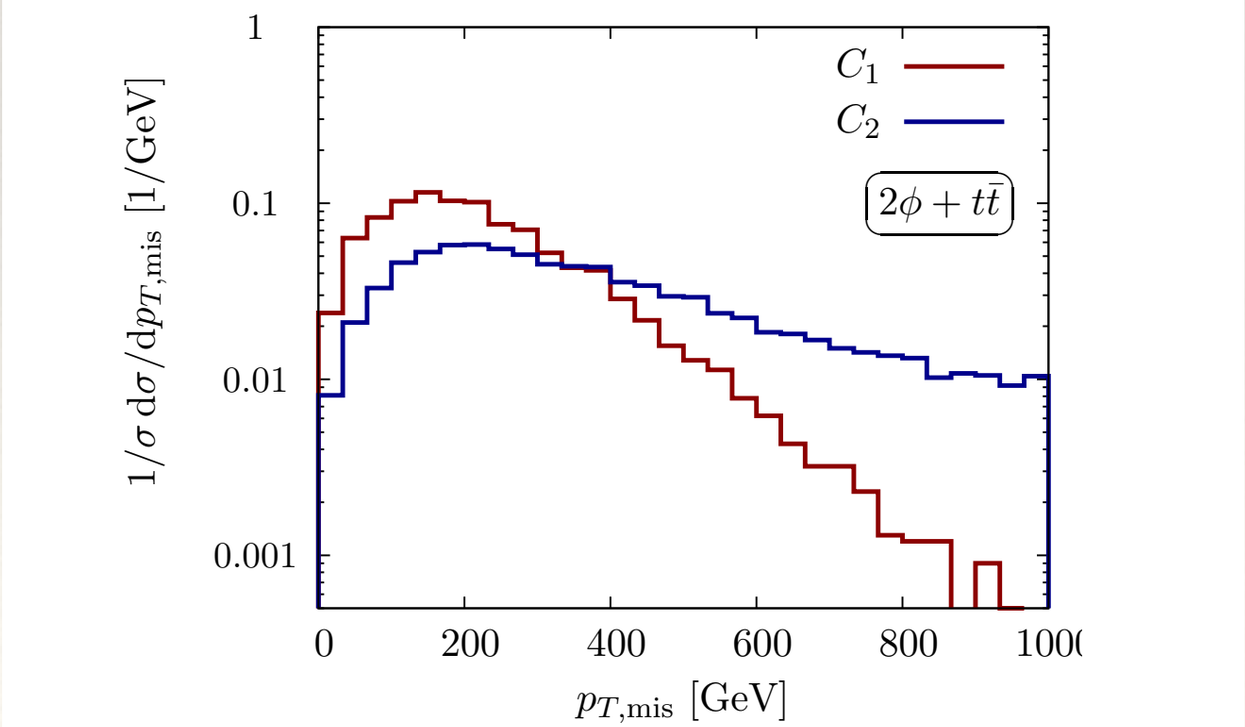
- typical interactions

$$\mathcal{L}_1 = \frac{\partial_\mu \phi \partial^\mu \phi}{M^4} T^\nu_{\ \nu}$$

$$\mathcal{L}_2 = \frac{\partial_\mu \phi \partial_\nu \phi}{M^4} T^{\mu\nu}$$





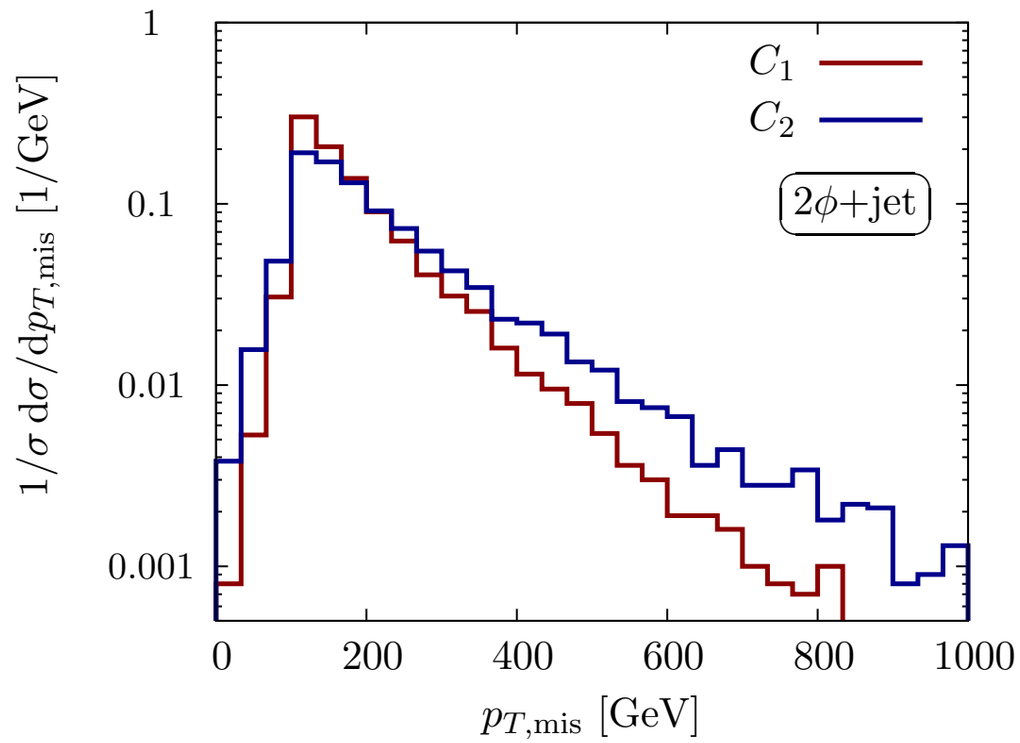


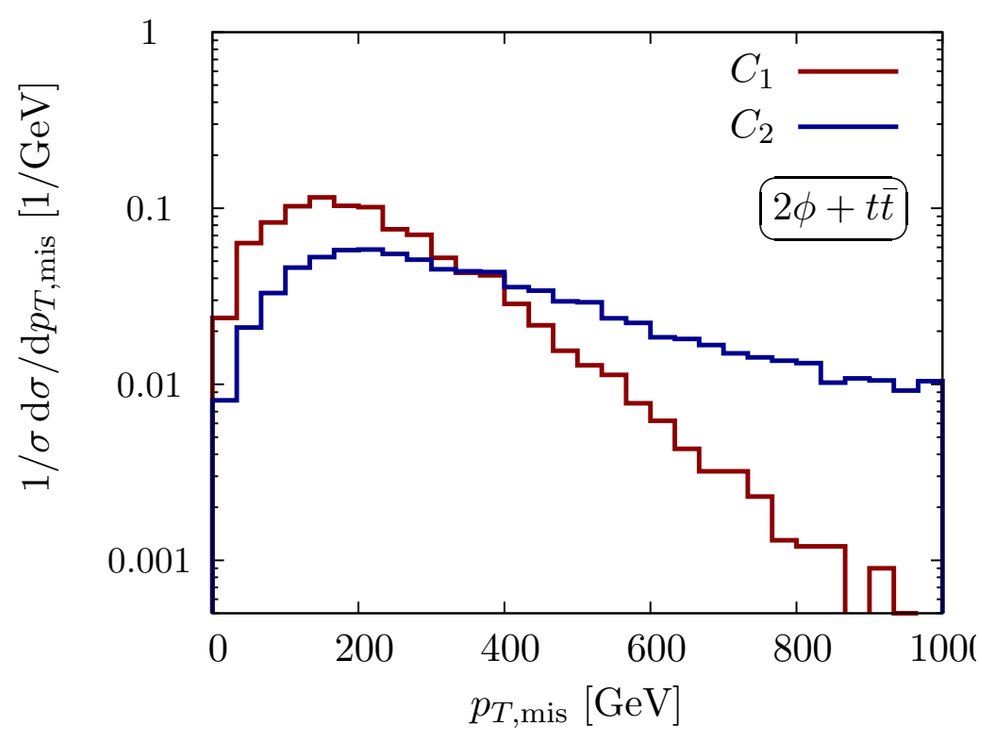
dominant phenomenology

- most stringent constraints from SUSY searches during run 1 (8 TeV)

$\mathcal{L}_1$	$M \gtrsim 75.4$ GeV	(ATLAS)
$2\phi + \text{jet}$	$M \gtrsim 66.5$ GeV	(CMS)
$\mathcal{L}_1$	$M \gtrsim 237.4$ GeV	(ATLAS)
$2\phi + t\bar{t}$	$M \gtrsim 192.8$ GeV	(CMS)

$\mathcal{L}_2$	$M \gtrsim 693.9$ GeV	(ATLAS)
$2\phi + \text{jet}$	$M \gtrsim 822.8$ GeV	(CMS)
$\mathcal{L}_2$	$M \gtrsim 461.2$ GeV	(ATLAS)
$2\phi + t\bar{t}$	$M \gtrsim 399.8$ GeV	(CMS)



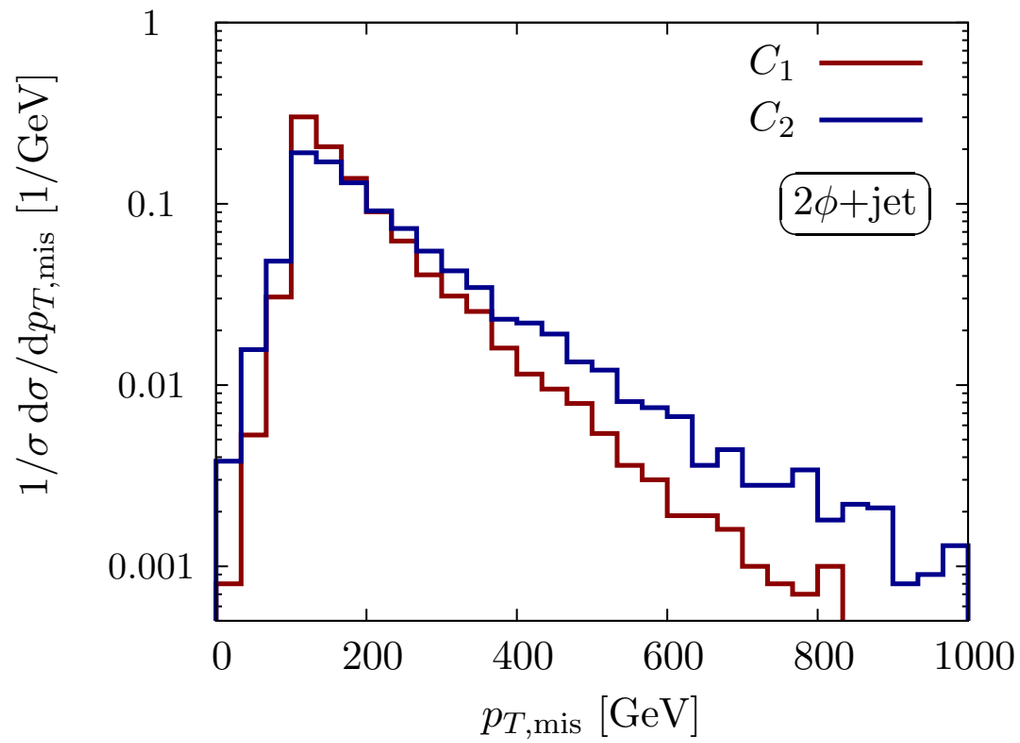


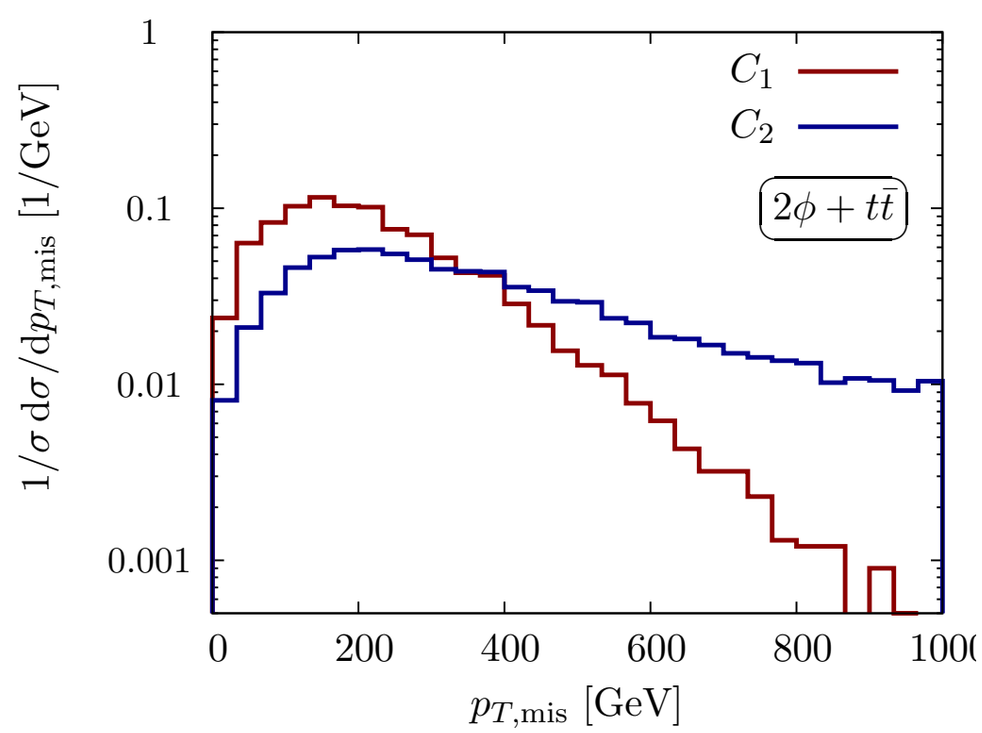
inverse problem?

In case of a signal: does this point to dark energy?

$\mathcal{L}_1$	$M \gtrsim 75.4$ GeV	(ATLAS)
$2\phi + \text{jet}$	$M \gtrsim 66.5$ GeV	(CMS)
$\mathcal{L}_1$	$M \gtrsim 237.4$ GeV	(ATLAS)
$2\phi + t\bar{t}$	$M \gtrsim 192.8$ GeV	(CMS)

$\mathcal{L}_2$	$M \gtrsim 693.9$ GeV	(ATLAS)
$2\phi + \text{jet}$	$M \gtrsim 822.8$ GeV	(CMS)
$\mathcal{L}_2$	$M \gtrsim 461.2$ GeV	(ATLAS)
$2\phi + t\bar{t}$	$M \gtrsim 399.8$ GeV	(CMS)



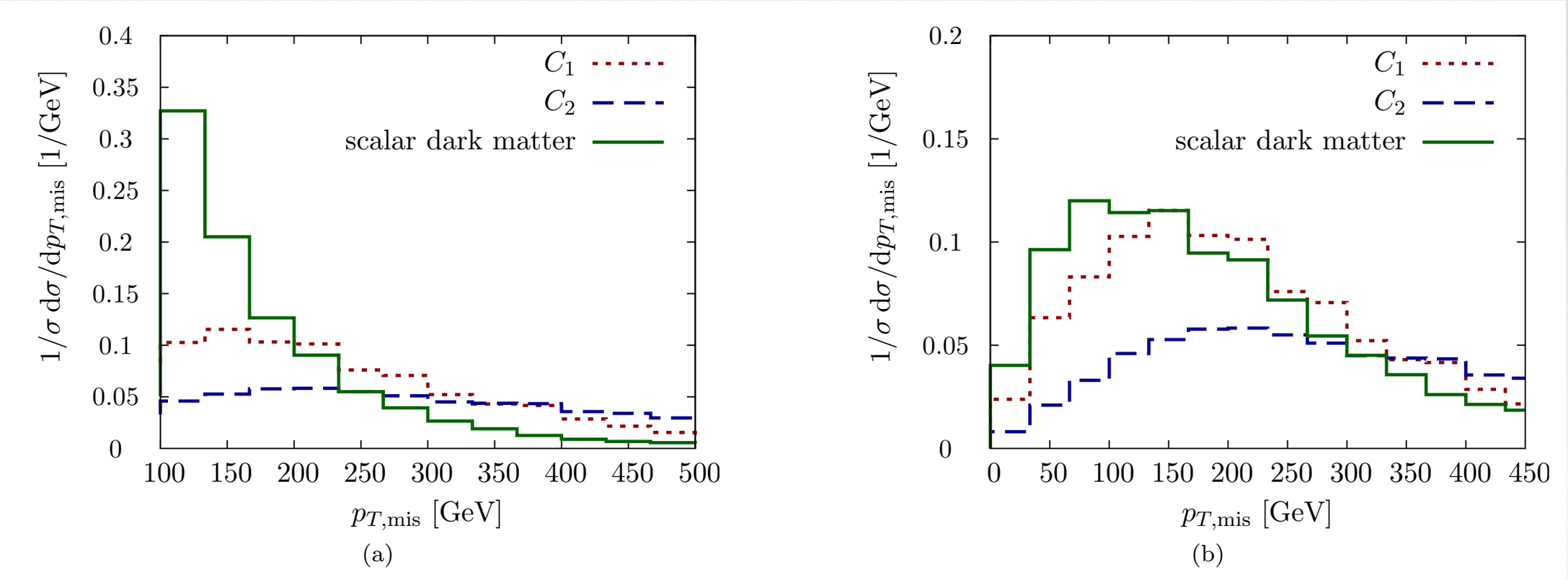


inverse problem?

In case of a signal: does this point to dark energy?

- is there a significant deviation in the missing energy distribution?

YES! New class of LHC-relevant interations!



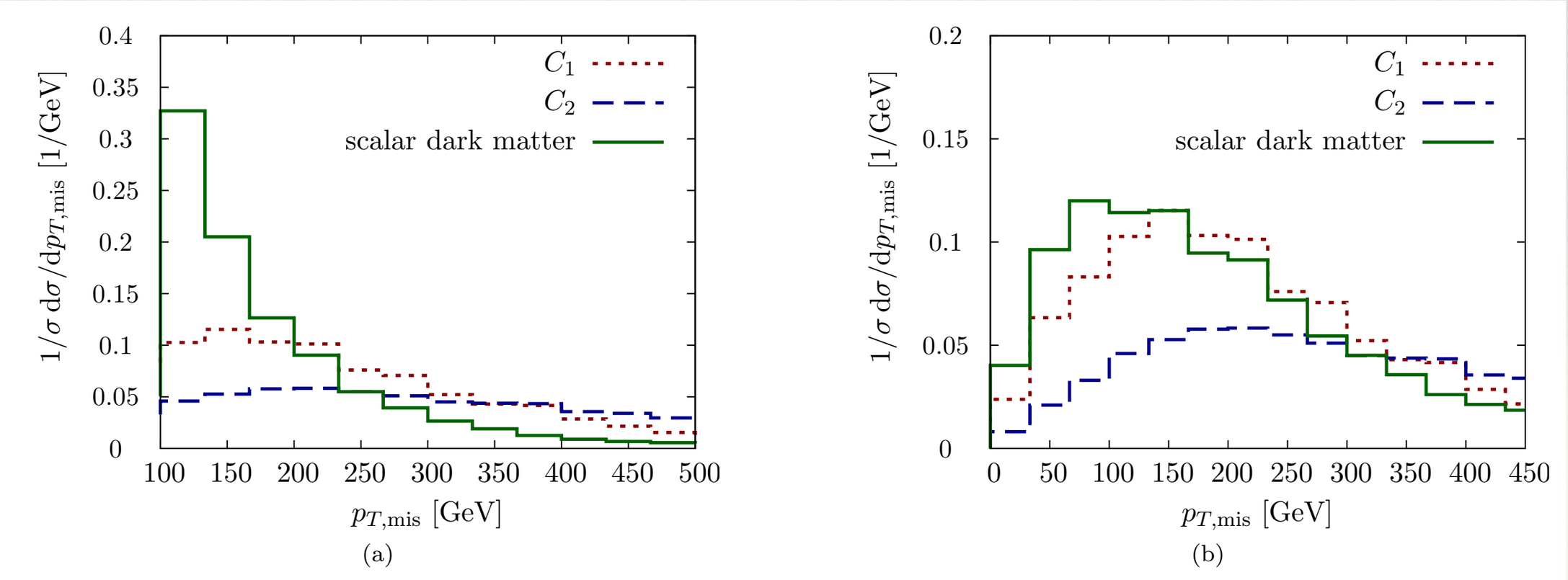
inverse problem?

In case of a signal: does this point to dark energy?

- is there a significant deviation in the missing energy distribution?

YES! New class of LHC-relevant interations!

- expect significant improvements through targeted analyses



What about higher order interactions?

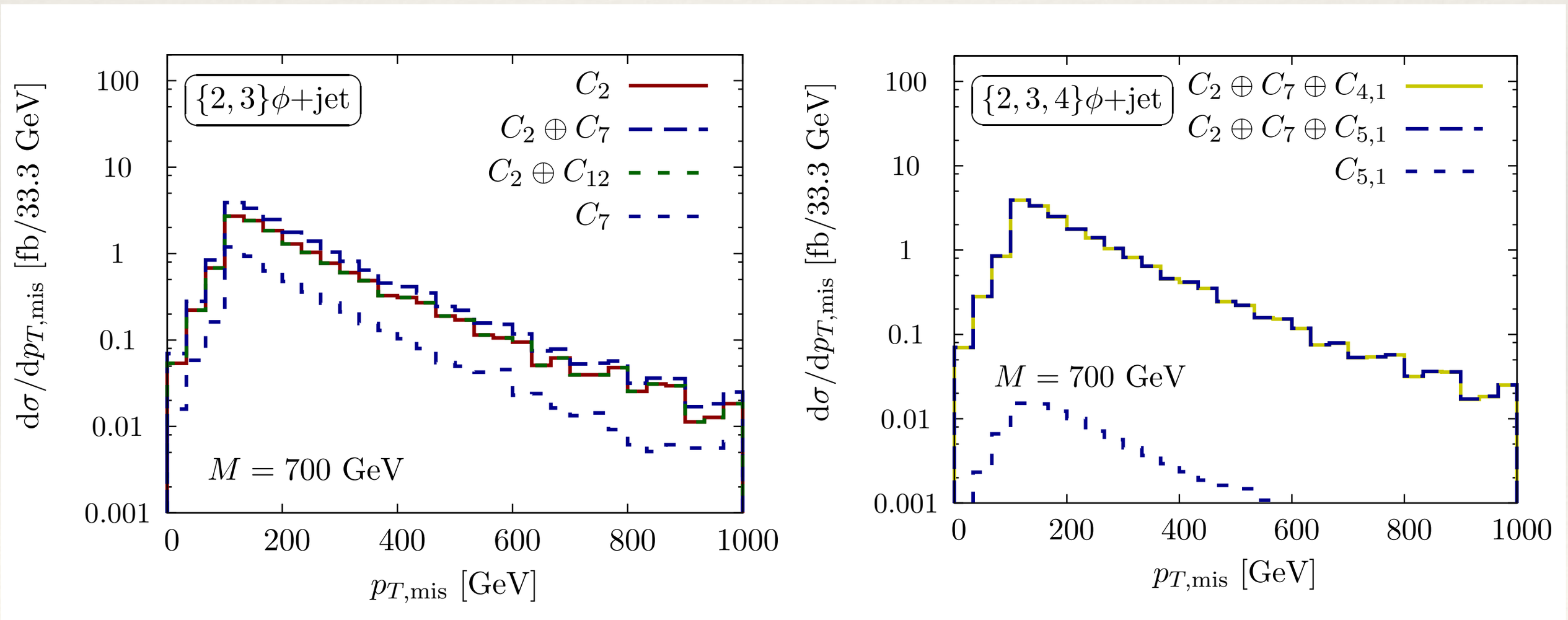
...or asked differently: can we make a meaning of these limits?

- consider higher terms

chosen equal

scaling is determined by # of EFT insertions and multiplicity

$$\mathcal{L}_{\rm BSM} = \mathcal{L}_{\rm SM} + \sum_i C_i \mathcal{L}_i$$



What about higher order interactions?

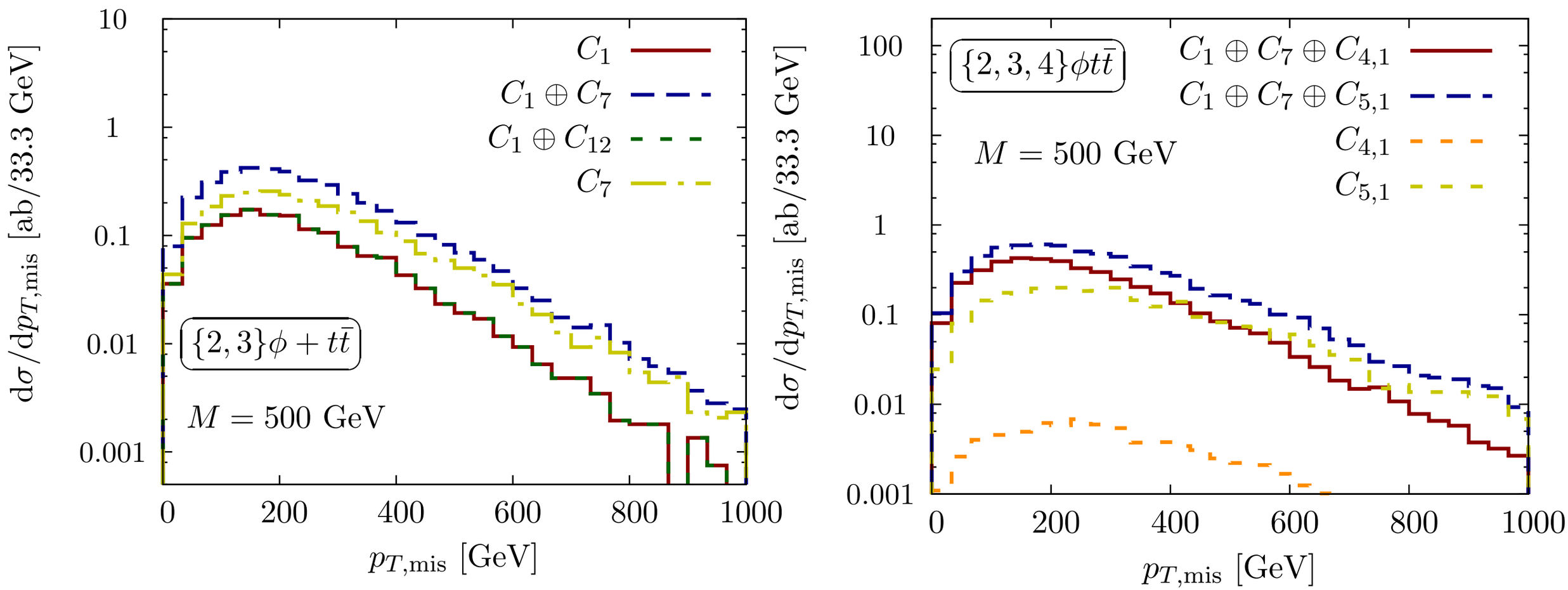
...or asked differently: can we make a meaning of these limits?

- consider higher terms

chosen equal

scaling is determined by # of EFT insertions and multiplicity

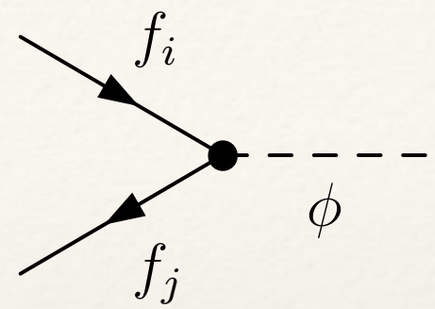
$$\mathcal{L}_{\rm BSM} = \mathcal{L}_{\rm SM} + \sum_i C_i \mathcal{L}_i$$



some comments shift symmetry breaking operators

- introduce interactions very similar to dilaton scenarios

$$\mathcal{L}_{10,n} = \left(\frac{\phi}{N}\right)^n T^\mu_\mu \quad :$$



$$= \frac{4iC_{10}}{N} m_{f_i} \delta_{ji} \, .$$

scalar dark energy mass becomes a crucial parameter for the search strategies.

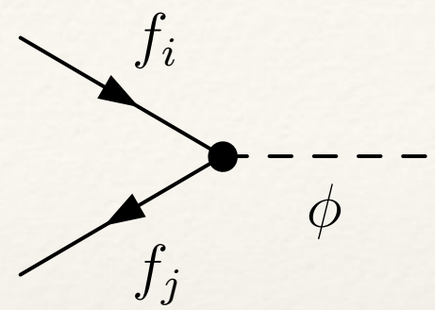
LIGHT scalars: spectacular signatures depending on parameters

HEAVY scalars: Higgs searches are directly applicable

some comments shift symmetry breaking operators

- introduce interactions very similar to dilaton scenarios

$$\mathcal{L}_{10,n} = \left(\frac{\phi}{N}\right)^n T^\mu_\mu \quad :$$



$$= \frac{4iC_{10}}{N} m_{f_i} \delta_{ji} \, .$$

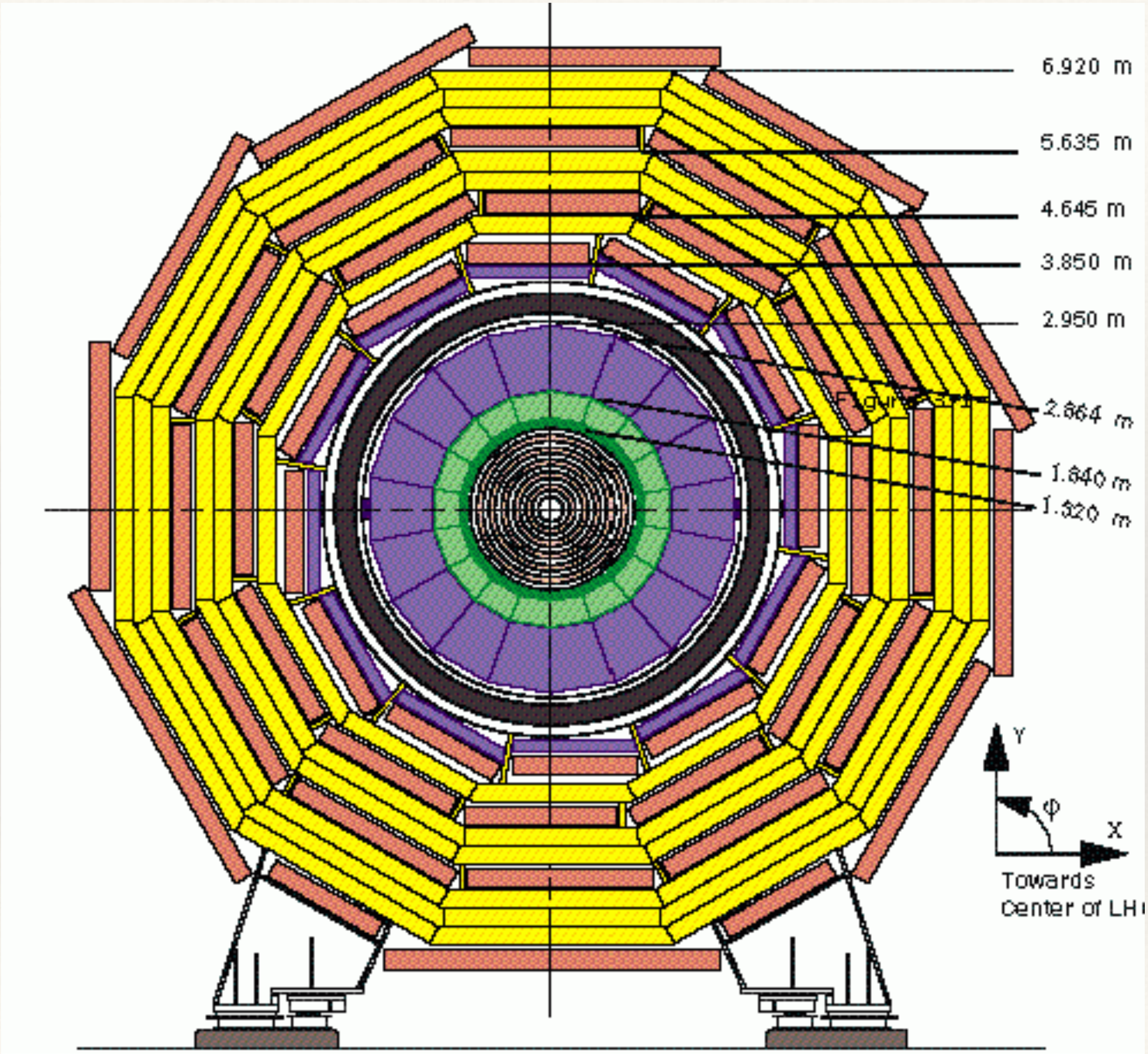
scalar dark energy mass becomes a crucial parameter for the search strategies.

$$\Gamma(\phi \to f\bar{f}) = \frac{2}{\pi} C_{10}^2 \frac{m_f^2}{N^2} \frac{(m_\phi^2 - 4m_f^2)^{3/2}}{m_\phi^2}$$

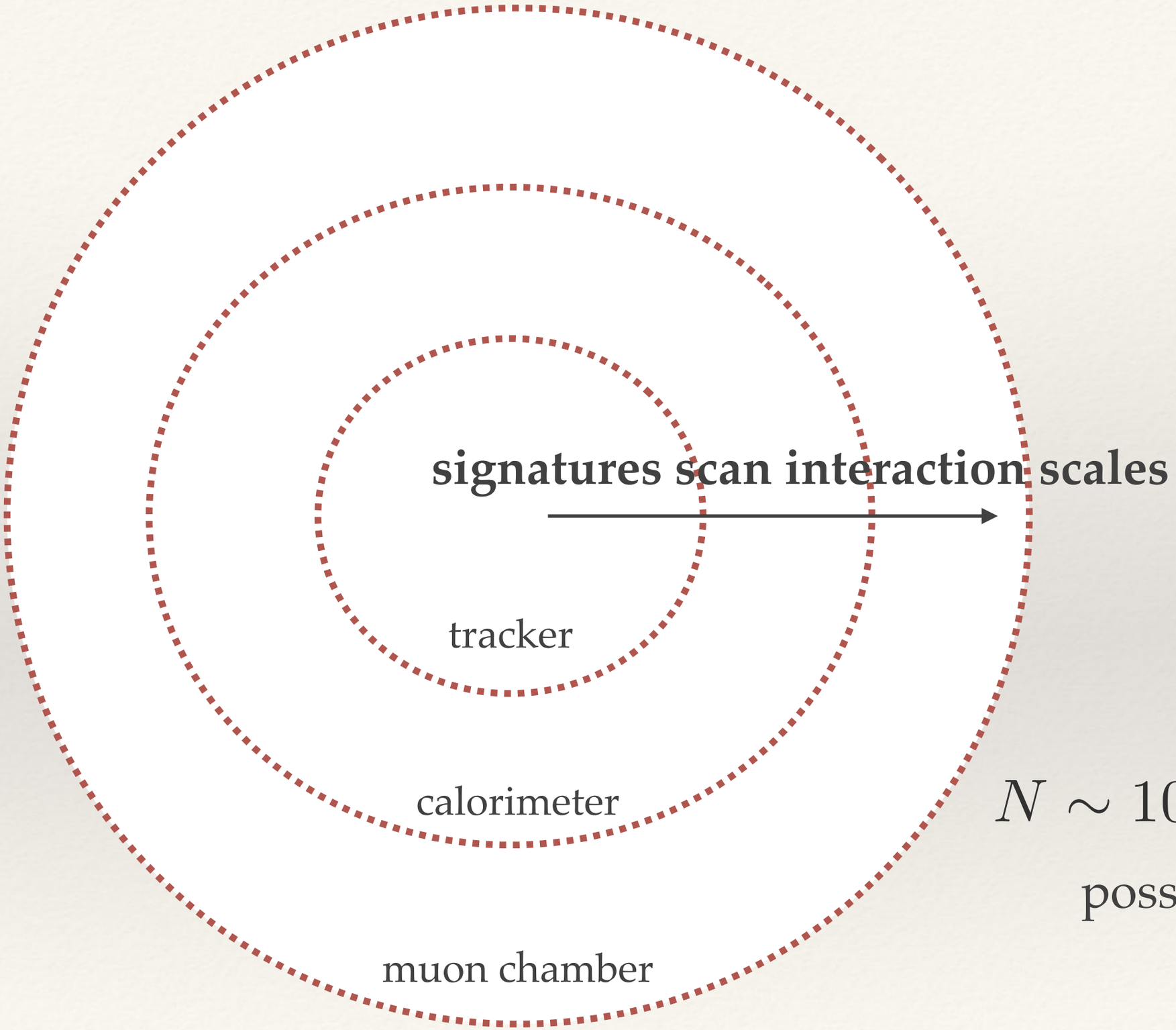
- decay width^{-1} ~ lifetime ~ traveled distance from interaction point *directly accesses scale N/C_{10}*
- displaced vertices, emergent particles....

LIGHT scalars: spectacular signatures depending on parameters

some comments shift symmetry breaking operators



some comments shift symmetry breaking operators



$N \sim 10^8 \mathrm{GeV}$

possible

Summary

- Dark Energy searches at colliders can provide complementary information

novel signatures

room for improvement!

- range of validity depends on interpretation as high momentum transfers are sampled with high statistics, yet sensitivity can be small
- displaced vertices and emergent structures provide a window to high scale physics at the price of lost sensitivity to shift symmetry conserving operators
- interest in ATLAS to pursue these searches

BACKUP

shift symmetry conserving operators

- typical effective interactions

$$\mathcal{L}_1 = \frac{\partial_\mu \phi \partial^\mu \phi}{M^4} T^\nu_{\ \nu}$$

$$\mathcal{L}_2 = \frac{\partial_\mu \phi \partial_\nu \phi}{M^4} T^{\mu\nu}$$

$$\mathcal{L}_{3,n} = \left(\frac{\partial_\mu \phi \partial^\mu \phi}{M^4} \right)^n T^\nu_{\ \nu}$$

$$\mathcal{L}_{4,n} = \left(\frac{\partial_\alpha \phi \partial^\alpha \phi}{M^4} \right)^n \frac{\partial_\mu \phi \partial_\nu \phi}{M^4} T^{\mu\nu}$$

$$\mathcal{L}_{5,n-1} = \frac{1}{M^{4n}} \partial_{\alpha_1} \phi \partial_{\beta_1} \phi \ldots \partial_{\alpha_n} \phi \partial_{\beta_n} \phi \frac{2^{n-1}}{\sqrt{-g}} \frac{\partial^{n-1} (\sqrt{-g} T^{\alpha_1 \beta_1})}{\partial g_{\alpha_2 \beta_2} \ldots \partial g_{\alpha_n \beta_n}}$$

$$\mathcal{L}_{6,n} = \frac{(\partial_\mu \phi \partial^\mu \phi)^n}{M^{4(n-1)}} \qquad \ldots\ldots\ldots\ldots$$

$$\mathcal{L}_7 = \frac{1}{M^3} \partial_\mu \phi \partial^\mu \phi \Box \phi \qquad \ldots\ldots\ldots\ldots$$

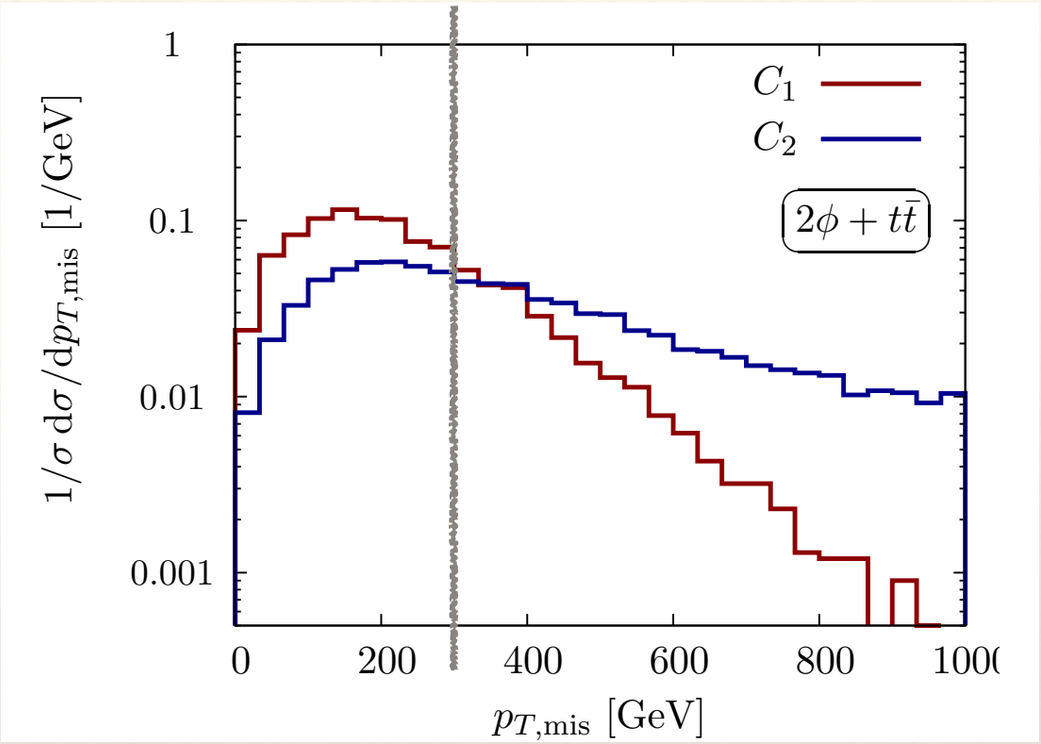
What about higher order interactions?

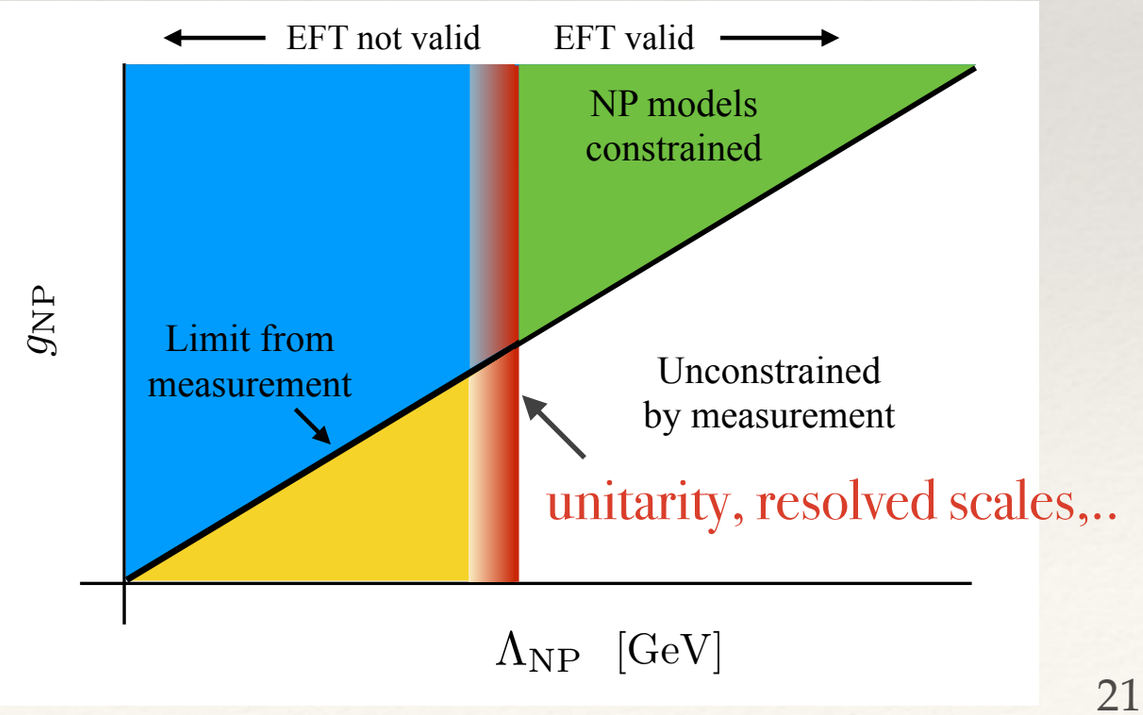
...or asked differently: can we make a meaning of these limits?

- we are not constraining a physical scale, but a ratio (e.g. Fermi theory)

$\mathcal{L}_1$	$M \gtrsim 75.4$ GeV	(ATLAS)
$2\phi + \text{jet}$	$M \gtrsim 66.5$ GeV	(CMS)
$\mathcal{L}_1$	$M \gtrsim 237.4$ GeV	(ATLAS)
$2\phi + t\bar{t}$	$M \gtrsim 192.8$ GeV	(CMS)

$\mathcal{L}_2$	$M \gtrsim 693.9$ GeV	(ATLAS)
$2\phi + \text{jet}$	$M \gtrsim 822.8$ GeV	(CMS)
$\mathcal{L}_2$	$M \gtrsim 461.2$ GeV	(ATLAS)
$2\phi + t\bar{t}$	$M \gtrsim 399.8$ GeV	(CMS)





What about higher order interactions?

...or asked differently: can we make a meaning of these limits?

- but does the EFT expansion still make sense?

$\mathcal{L}_1$	$M \gtrsim 75.4$ GeV	(ATLAS)
$2\phi + \text{jet}$	$M \gtrsim 66.5$ GeV	(CMS)
$\mathcal{L}_1$	$M \gtrsim 237.4$ GeV	(ATLAS)
$2\phi + t\bar{t}$	$M \gtrsim 192.8$ GeV	(CMS)

$\mathcal{L}_2$	$M \gtrsim 693.9$ GeV	(ATLAS)
$2\phi + \text{jet}$	$M \gtrsim 822.8$ GeV	(CMS)
$\mathcal{L}_2$	$M \gtrsim 461.2$ GeV	(ATLAS)
$2\phi + t\bar{t}$	$M \gtrsim 399.8$ GeV	(CMS)

$$\mathcal{L}_{3,n} = \left(\frac{\partial_\mu \phi \partial^\mu \phi}{M^4}\right)^n T^\nu_\nu$$

$$\mathcal{L}_{4,n} = \left(\frac{\partial_\alpha \phi \partial^\alpha \phi}{M^4}\right)^n \frac{\partial_\mu \phi \partial_\nu \phi}{M^4} T^{\mu\nu}$$

different multiplicity, same signature

- optical theorem connects different loop orders with different final state multiplicities
- if say 4ϕ production dominates over 2ϕ we can't trust the limit **unless** there is a symmetry reason