Searching for Dark Energy with the LHC

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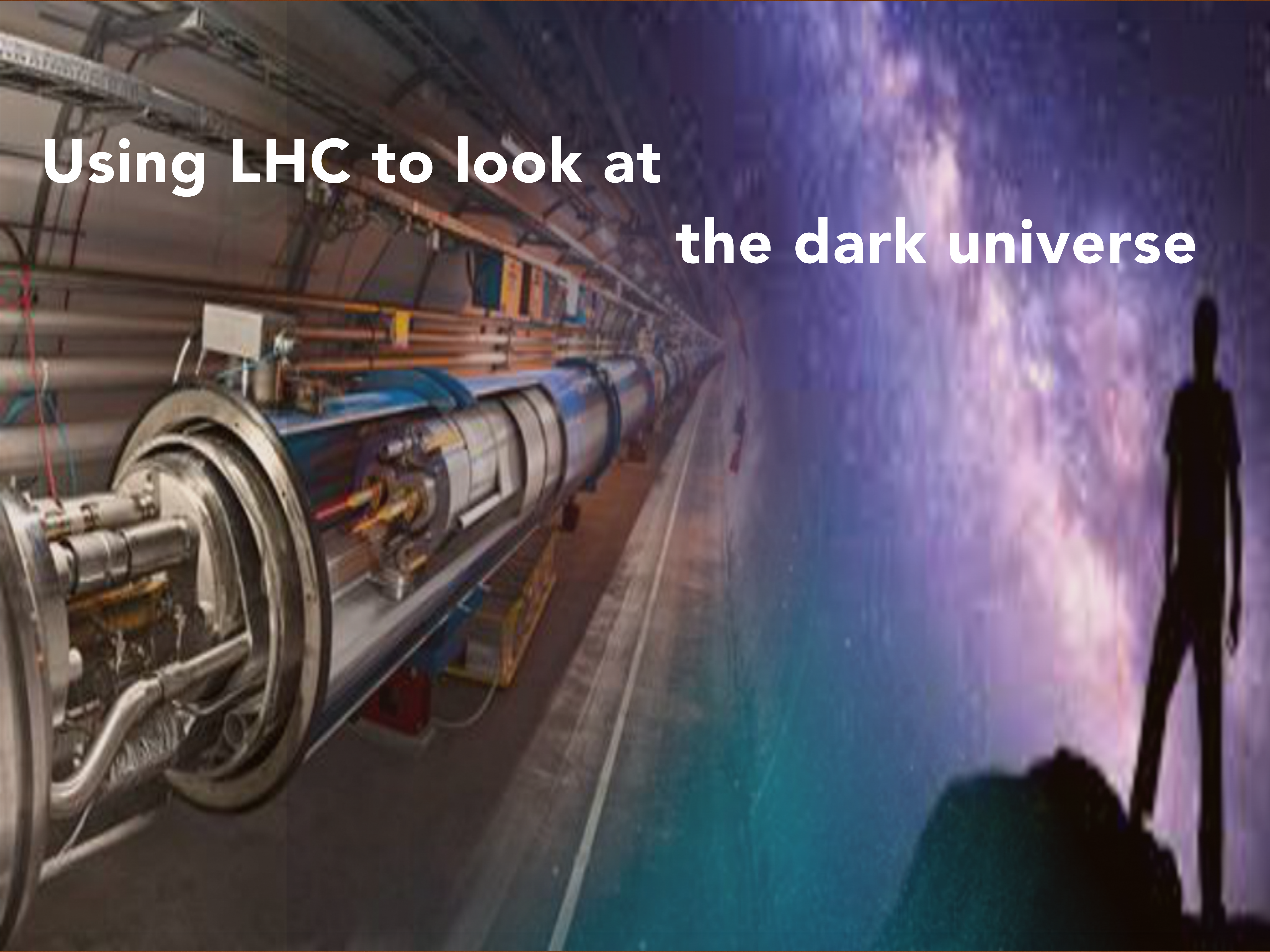

Using LHC to look at
the dark universe

Big open problems

Dark Energy

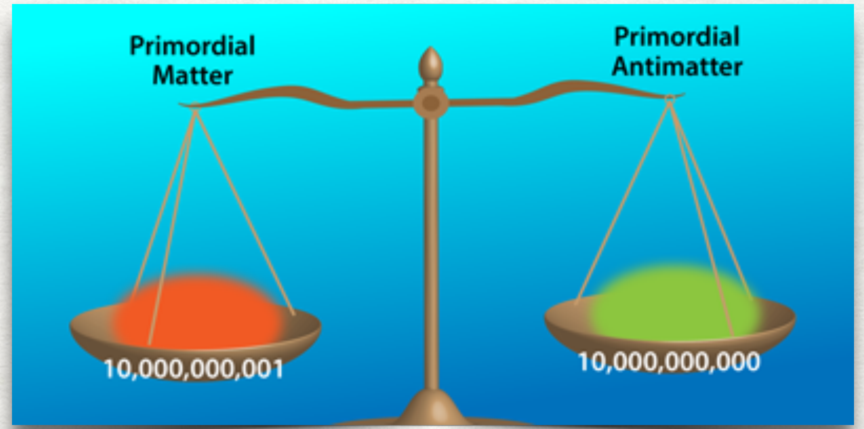
The universe accelerates

Dark Matter

Galaxies have more matter than what we see

Baryon asymmetry

We don't see anti-matter in the universe



➡ Can the LHC tell us anything about these problems?

Outline

Introduction

- cosmology & dark energy
- theory & experiment landscape
- why to search for DE at colliders

The DE model

- details of the model
- relation to other benchmark models

The ATLAS search for DE

- experimental analysis
- results
- interpretation

Next steps

The Higgs connection

- DE, DM and baryogenesis

INTRODUCTION

Cosmology = metric + General Relativity

Cosmology

observations

the universe is isotropic (CMB)

assumptions

cosmological principle: universe is everywhere isotropic (homogeneous)

Metric

FLRW: $$g_{\mu\nu} = a^2(d\tau^2)\ \mathrm{diag}\left[-1, \frac{1}{1-Kr^2}, r^2, r^2\sin^2\theta\right]$$

Three important quantities:

- **scale factor a:** size of universe relative to a_0=1
- **Hubble parameter:** $H(t) \equiv \dot{a}(t)/a(t)$
- **curvature:** shape (closed K>0, flat K=0, open K<0)

Cosmology = metric + General Relativity

Cosmology

Metric + **General Relativity**

$$g_{\mu\nu} = a^2(d\tau^2)\ \mathrm{diag}\left[-1, \frac{1}{1-Kr^2}, r^2, r^2\sin^2\theta\right]$$

$$G_{\mu\nu} = 8\pi G\ T_{\mu\nu}$$

$$G_{\mu\nu} = G(g, g', g'')$$

$$T_{\mu\nu} = -\frac{2}{\sqrt{-g}}\frac{\delta S}{\delta g^{\mu\nu}} = diag[\rho, p, p, p]$$

Friedmann equation: $$H^2 = \frac{8\pi G}{3}\rho$$

➡ **How does the universe evolve with time?**

- matter determines expansion of universe
- important quantity: w=p/ρ

Cosmic expansion

$$H^2 = \frac{8\pi G}{3}\rho \qquad \Rightarrow a(t) = \left(\frac{t}{t_0}\right)^{2/3(1+w)}$$

$$\rho = \rho_0 a^{-3(1+w)}$$

- different evolution for different types of matter

Type of matter	Behaviour of scale factor
Relativistic (e.g. photons)	$w = 1/3 \Rightarrow a \propto t^{1/2} \Rightarrow \ddot{a} < 0$
Non-relativistic (e.g. DM, baryons)	$w = 0 \Rightarrow a \propto t^{2/3} \Rightarrow \ddot{a} < 0$
Curvature	$w = -1/3 \Rightarrow a \propto t \Rightarrow \ddot{a} = 0$
Violating SEC (e.g. scalar field)	$w < -1/3 \Rightarrow \ddot{a} > 0$

➡ ***so what is dark energy?***

What is "Dark Energy"?

"Dark Energy": matter which leads to an accelerated expansion

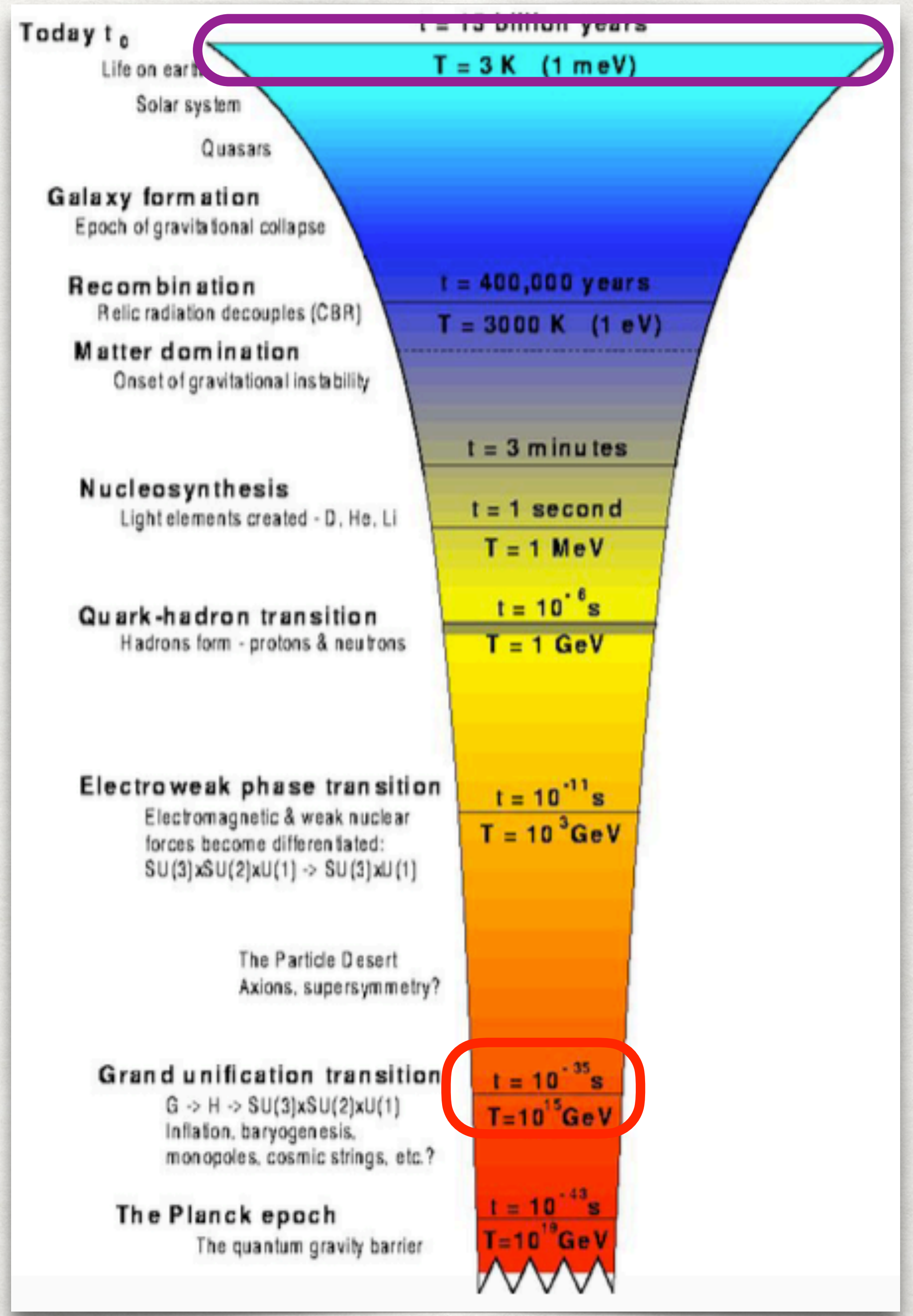
- Two prototypical models:
  - scalar field
  - cosmological constant Λ (constant energy density)

$$\rho \propto a^{-3(1+w)} \Rightarrow w = -1 \Rightarrow \rho_\Lambda \equiv \frac{\Lambda}{8\pi G}$$

$$a(t) \propto \mathrm{e}^{\sqrt{\Lambda/3}t} \Rightarrow \ddot{a} \propto \mathrm{e}^{\sqrt{\Lambda/3}t}$$

- **Λ ⇒ exponentially accelerated expansion**

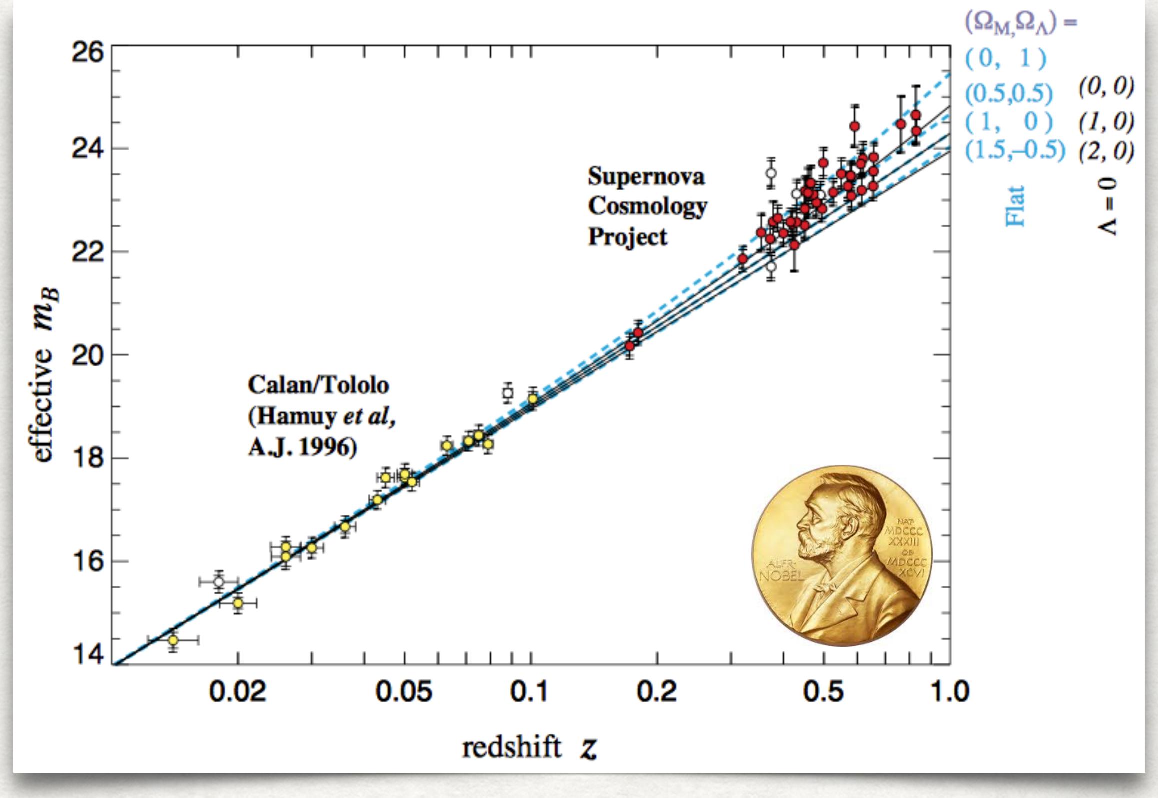
- Two periods of accelerating expansion in the history of the universe:
  - early time: inflation (slowly rolling inflaton)
  - late time: "dark energy"



How we know it exists

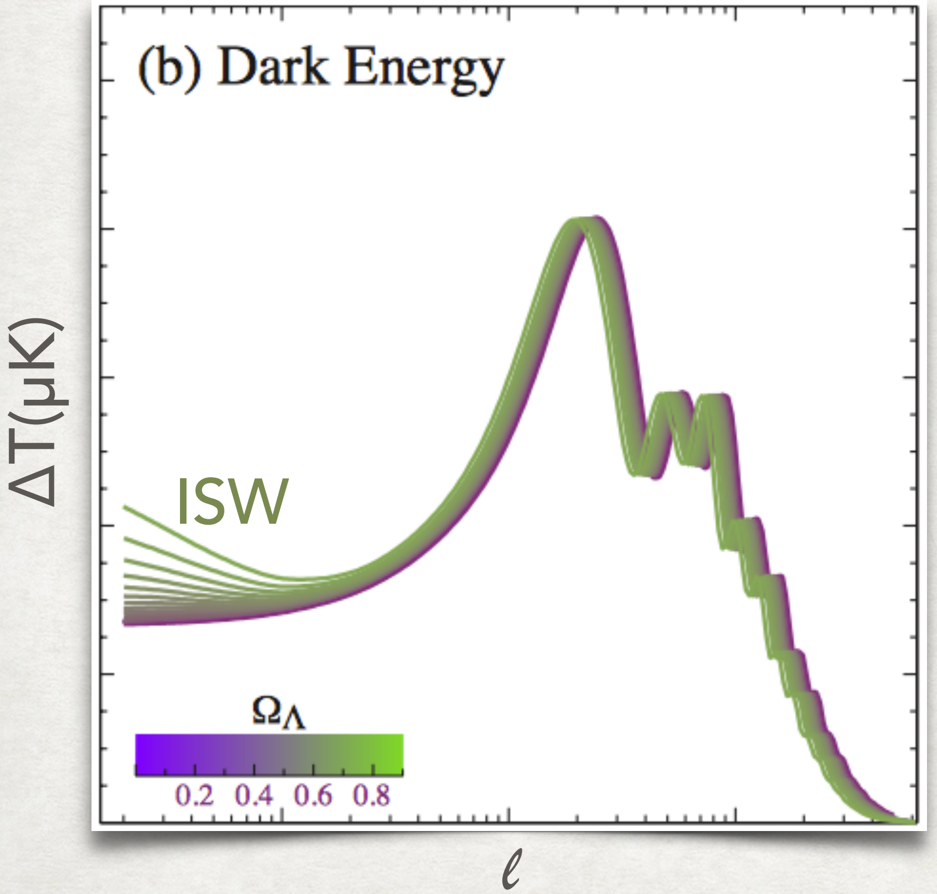
- distance measurements
  - SN farther than expected
- age of globular clusters
  - without DE: $t_{universe} \sim 10$ Gyr while age oldest clusters >11 Gyr

DE = higher distance at higher redshifts



Perlmutter et al, Astrophys.J.517:565-586,1999

Effect of DE on CMB



- CMB
  - position of acoustic peaks
  - late-time ISW effect
- BAO
  - angular distance vs redshift
- Large Scale Structure
  - structure formation slows down

Hu, Dodeldson, Ann.Rev.Astron.Astrophys.40:171-216,2002

What DE really is

- We don't really know!
- Measurements point towards a cosmological constant w = -1.03 ± 0.03

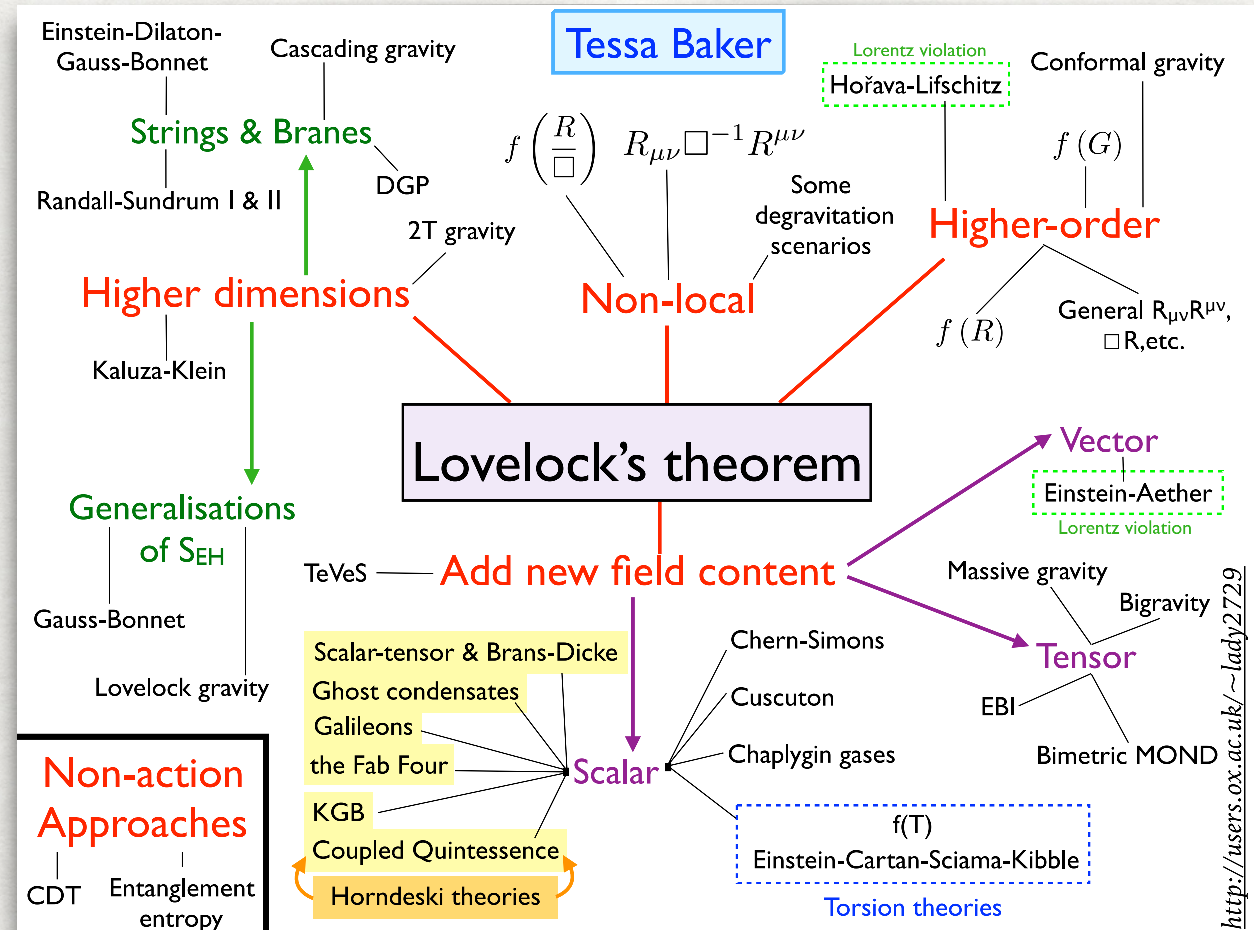
[Planck 2018]

- The "cosmological constant problem"
  - from measurements: $\rho_\Lambda \simeq 10^{-48}$ GeV^4
  - from QFT: $\rho_{vac} \sim \Lambda_{cut}{}^4$ GeV$^4 \gtrsim 10^{12}$ GeV^4

➡ *60 orders of magnitude off*

- New physics: $G_{\mu\nu} = 8\pi G\, T_{\mu\nu}$
  - Modified gravity:
    - higher order: e.g. f(R)
    - higher dimensions: e.g. brane-world models
  - Modified matter content:
    - scalar: e.g. Horndeski
    - vector: e.g. Proca
    - tensor: e.g. e.g. massive gravity

Theory & experiment landscape



Schematic from here

Laboratory:

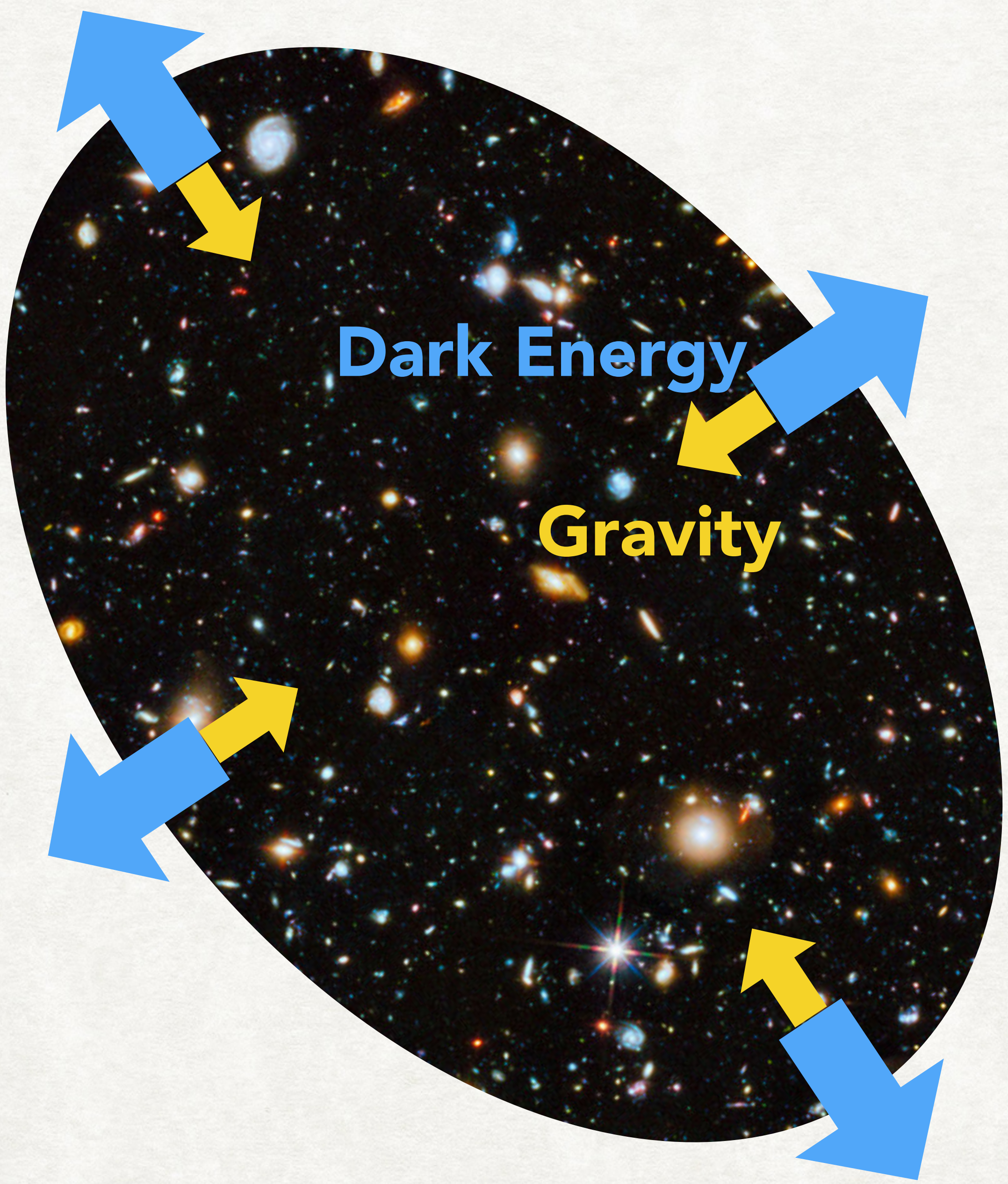
- torsion balance: Eöt-Wash [9,11]
- Casimir forces [9,11]
- Interferometry [9,11]
- Coupling to photons: CAST, CHASE [12,13]

Cosmology/Astro:

- SN/BAO (distance/redshift relations) [14]
- Structure growth [14]
- Lensing [14]
- Stellar burning [9]
- Multi-messenger signals with GW (new!) [10]

- **The landscape of viable models is enormous!**
- **Need multiple experiments to provide as much information as possible**
- **BUT many questions remain open …**

Dark Energy = accelerated expansion of the universe



- The biggest unanswered question in cosmology and particle physics
  - new particle or modified gravity?
  - constant or dynamic?
  - interacting or not?
  - microscopic nature?
- Vast landscape of models with no leading candidate theory

Why to search for DE at colliders

- Interaction of DE with SM particles arises naturally in many models
  - Screening of 5th forces: escape detection at high density regions $\rightarrow$ DE must "feel" the density of SM matter $\rightarrow$ non-zero DE/SM interaction

  $\Rightarrow$ DE can be produced and constrained at colliders [1]

- Dark degeneracy
  - modified gravity models can lead to same phenomenology as DE

$$\tilde{G}_{\mu\nu} = 8\pi G \, \tilde{T}_{\mu\nu}$$

  $\Rightarrow$ need particle physics to distinguish modified gravity from dark energy [2]

- Complementarity with non-collider experiments

  $\Rightarrow$ collider experiments sensitive to multitude of signatures

  $\Rightarrow$ access different parts of parameter space

  $\Rightarrow$ investigate microscopic nature of DE

So far no direct search by collider experiments

AN EFT MODEL OF SCALAR DE

The model

- New model based on Effective Field Theory [Brax, Burrage, Englert, Spannowsky - 3]
- Using framework of **Horndeski theories**
  (most general theories with scalar field with 2nd order eq. of motion)
  ⇒ **assumption: DE couples to matter**

  ⇒ independent of microscopic models - offers **general framework to study DE**

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{M^{d-4}} \mathcal{O}^{(d)} + \frac{1}{2} m^2 \phi^2$$

- **Idea**: extend SM Lagrangian with extra operators suppressed by
  new physics scale M
  ⇒ **measure M - translate to the parameters of UV models**

EFT operators

- **2 classes of operators:**
  ⇒ shift symmetry invariant

  ⇒ shift symmetry breaking (φ can decay to SM fields - not considered here)

- **9 shift-symmetric operators:**
  - kinetic conformal couplings
  - disformal couplings
  - kinetic term for DE field
  - Galileons

⇒ studied here

- **Combination of these operators appear in cosmological/non-collider searches**
  - Gravitational waves/CMB [5] $\mathcal{L}_7, \mathcal{L}_8$
  - Atom interferometers/Chameleon search [6] $\frac{1}{2}\mathcal{L}_{6,1} + \mathcal{L}_{10,1} + \mathcal{L}_{11,1}$
  - Torsion pendulum search for symmetron DE [7] $-\frac{1}{2}\mathcal{L}_{6,1} - \frac{1}{2}\mathcal{L}_{10,2} + \frac{1}{2}\mathcal{L}_{11,2} - \frac{1}{4!}\mathcal{L}_{11,4}$

Conformal & disformal couplings - signatures

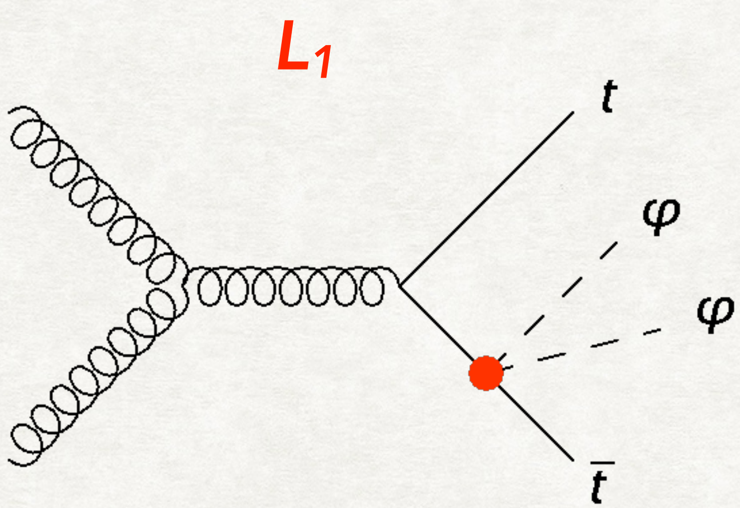
- Study two lowest-dimension operators:

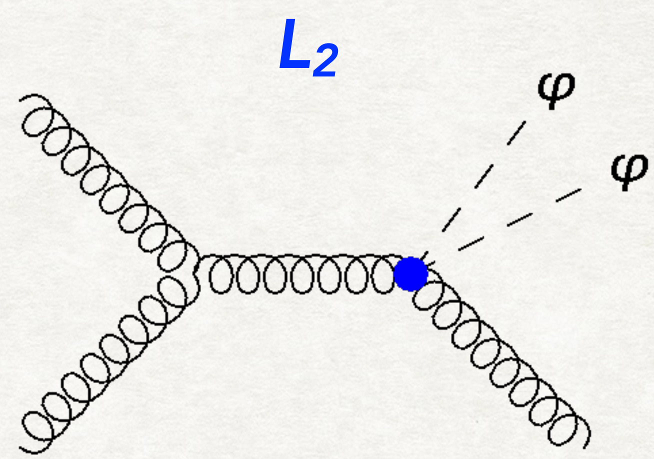
$$\mathcal{L}_1 = \frac{\partial_\mu \phi \partial^\mu \phi}{M^4} T^\nu_\nu$$

(kinetic) conformal coupling
⇒ enhanced for heavy final states

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

disformal coupling
⇒ enhanced for high momentum





- Top final states: enhanced sensitivity to L_1 due to high top mass
- Mono-jet final states: enhanced sensitivity to L_2 due to high momentum transfers
- DE particle φ stable ⇒ missing energy

⇒ Signatures: tt+ E_T^{miss} , jet+ E_T^{miss}

THE SEARCH

ATL-PHYS-PUB-2018-008

DE signal simulation

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i}{M^{d-4}} \mathcal{O}^{(d)} + \frac{1}{2} m^2 \phi^2$$

- Set c_i=1 for one operator at a time
  ⇒ express constraints only as a function of M

- m_φ must be small to get correct equation of state
  ⇒ set m_φ=0.1 GeV (negligible wrt LHC scales)

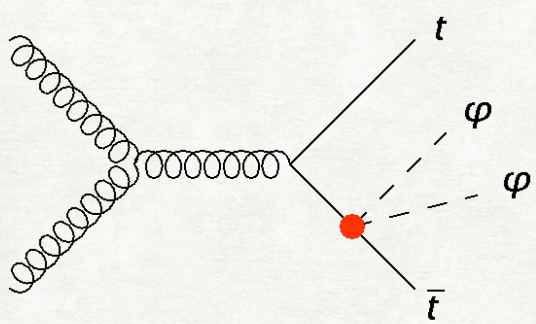
  ⇒ kinematics and cross-section independent of m_φ

- **LO approximation**: single insertion of EFT operator
  ⇒ kinematics independent of M

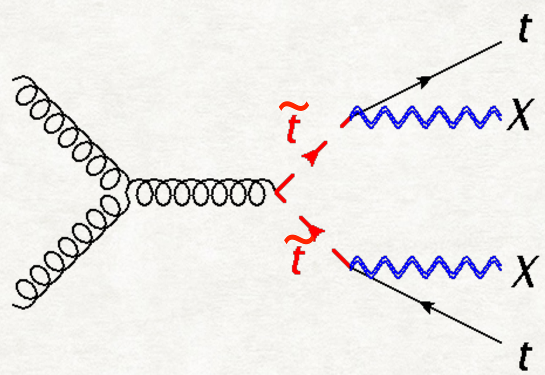
  ⇒ M only affects normalisation

How signal events look like

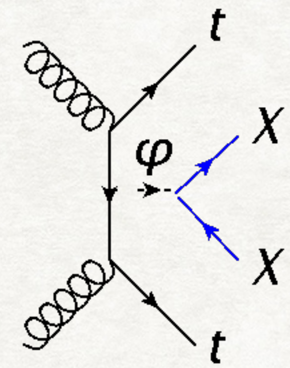
tt+DE



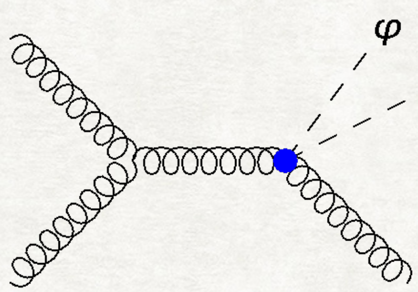
stop



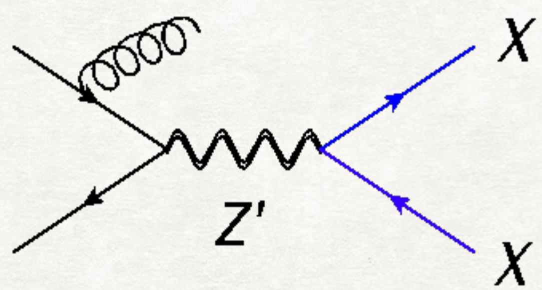
tt+DM



jet+DE

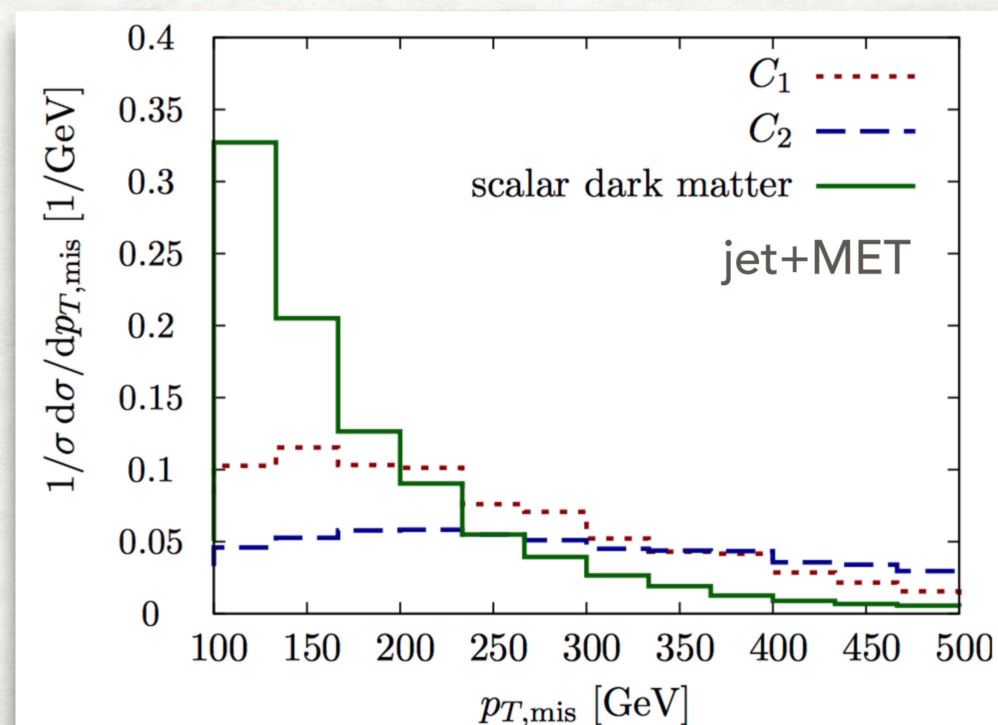


jet+DM



- **Same signatures as DM searches** (both DM and DE give MET signature)
- tt+MET: also same signature as stop search - more sensitive than tt+DM

- **Much higher MET in general than DM**
- Re-interpret results of:
  - L_1: stop search *[ATLAS, JHEP 12 (2017) 085]*
  - L_2: mono-jet DM search *[ATLAS, JHEP 01 (2018) 126]*

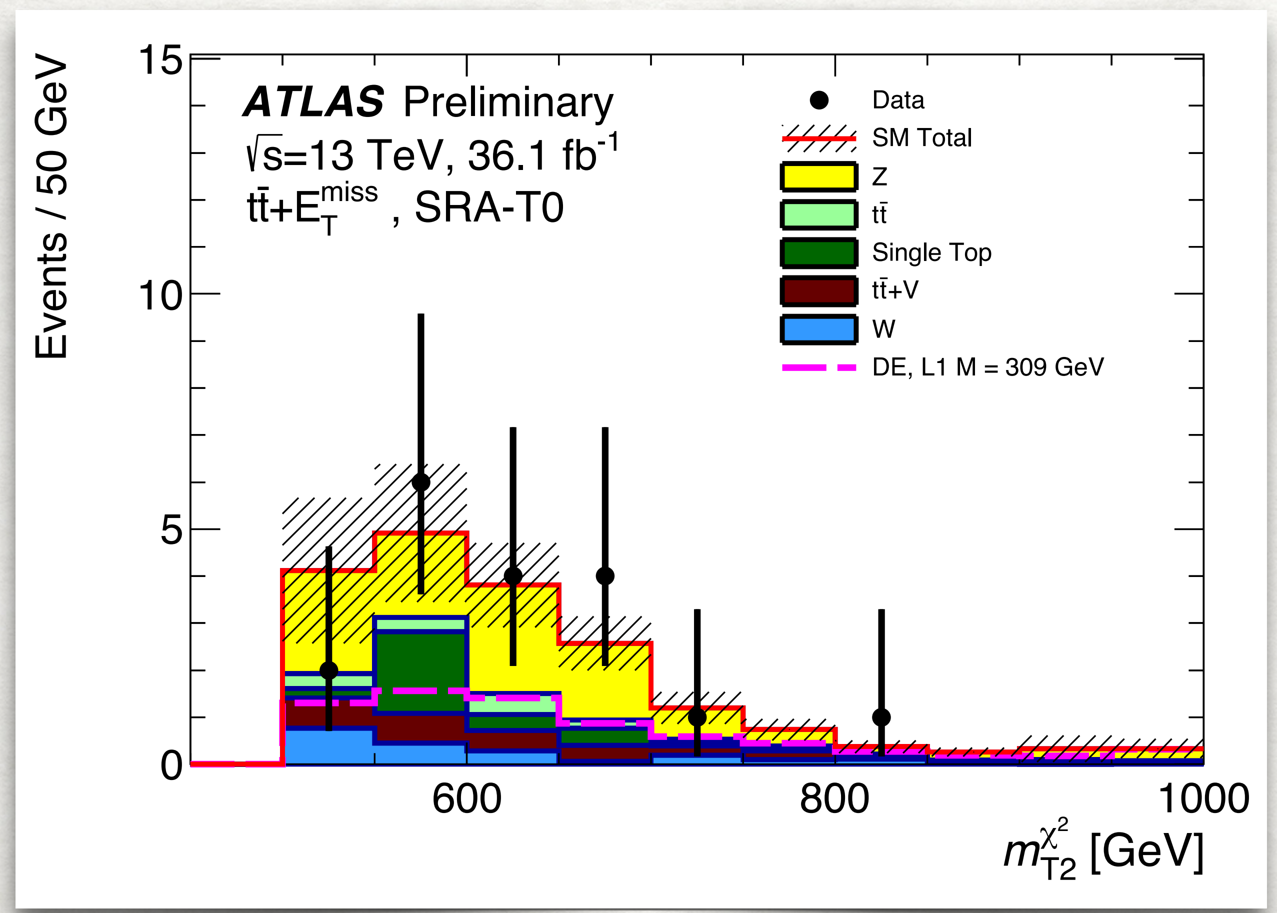


Brax et al., Phys. Rev. D 94, 084054 (2016)

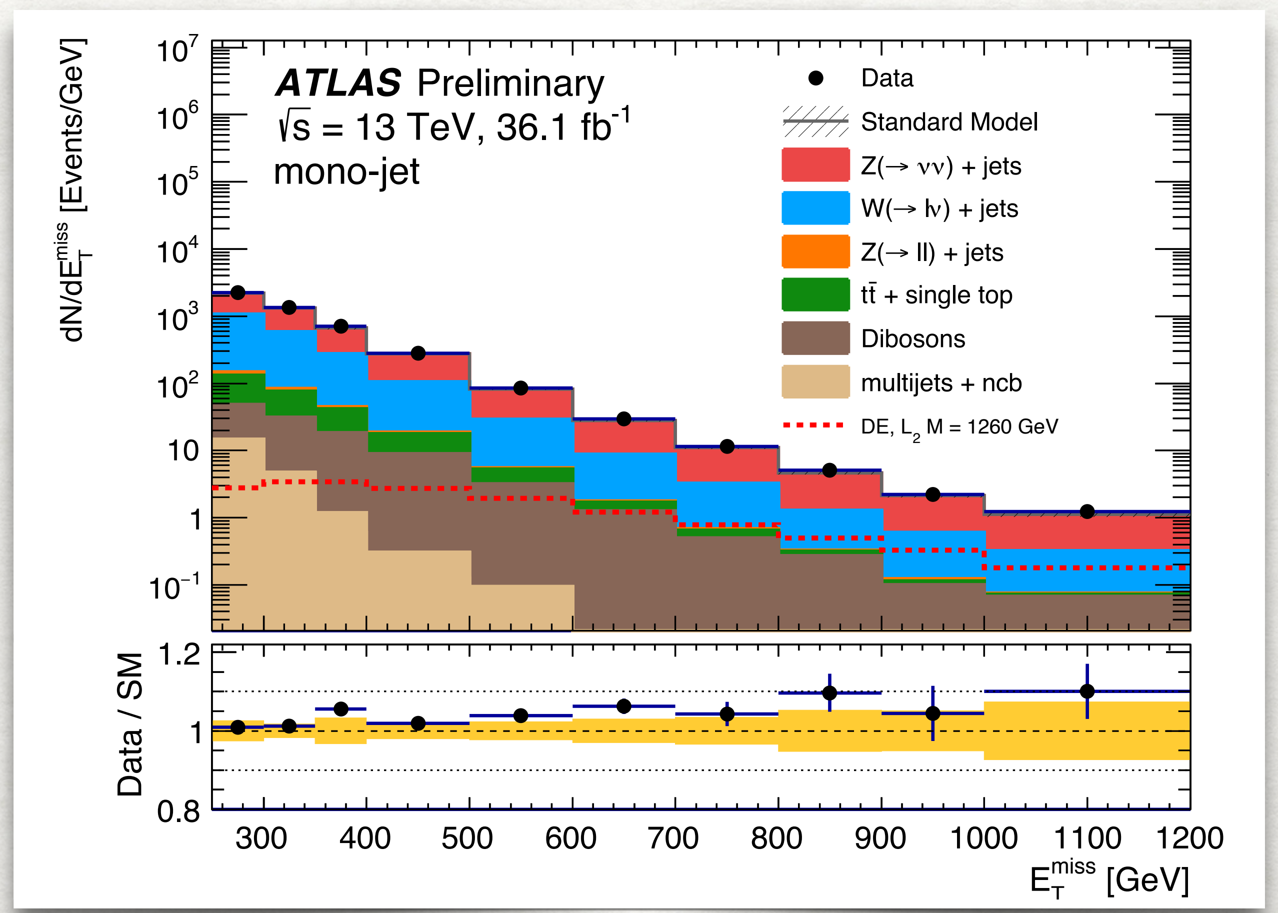
Analysis

- Dataset: 36 fb^{-1} of pp collisions , $\sqrt{s}$ = 13 TeV
- tt+ E_T^{miss}
  - 3 channels studied (0/1/2L) - 0L found to be the most sensitive
  - all hadronic top decays: b-jets, 0 leptons, high E_T^{miss} - 3 signal regions
- mono-jet
  - high p_T jet + high E_T^{miss}
- Background + signal normalisation determined by a likelihood fit to data

Stransverse mass in tt+E_T^{miss} analysis



E_T^{miss} in mono-jet analysis

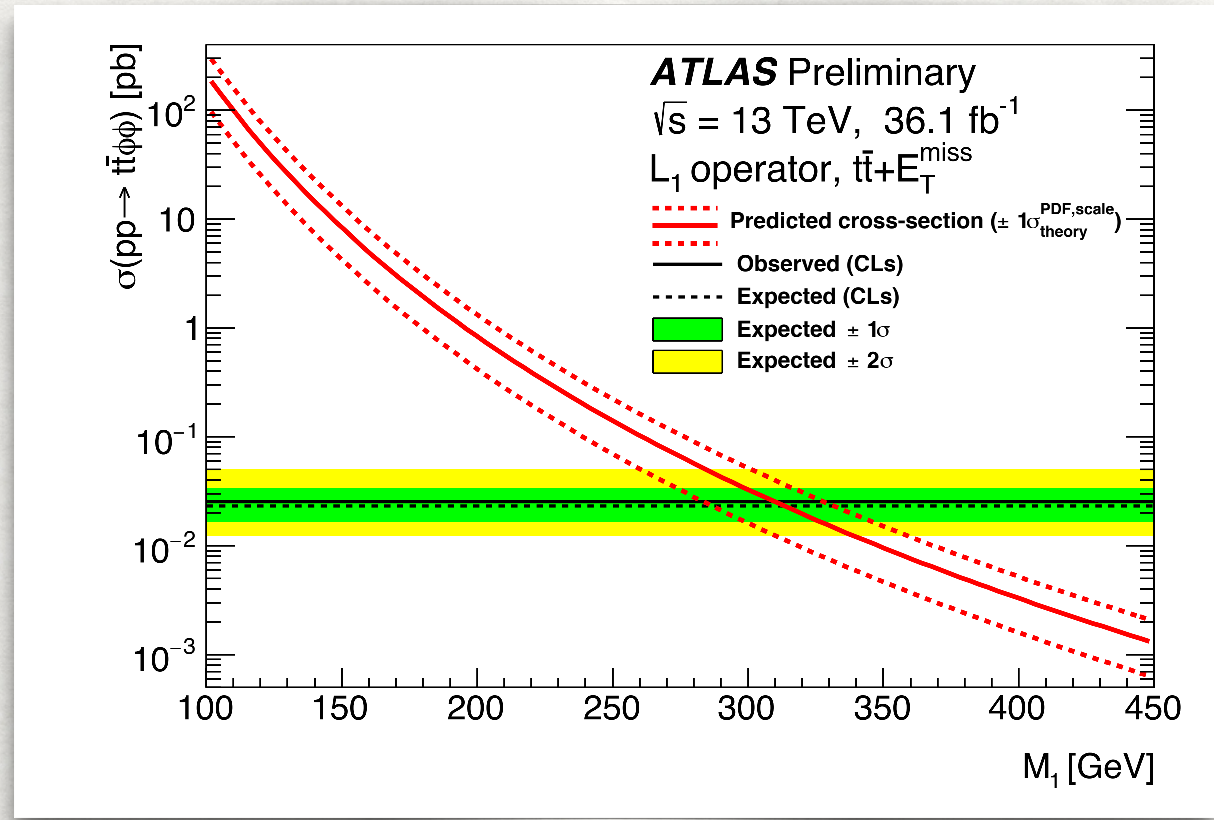


Limits on DE production

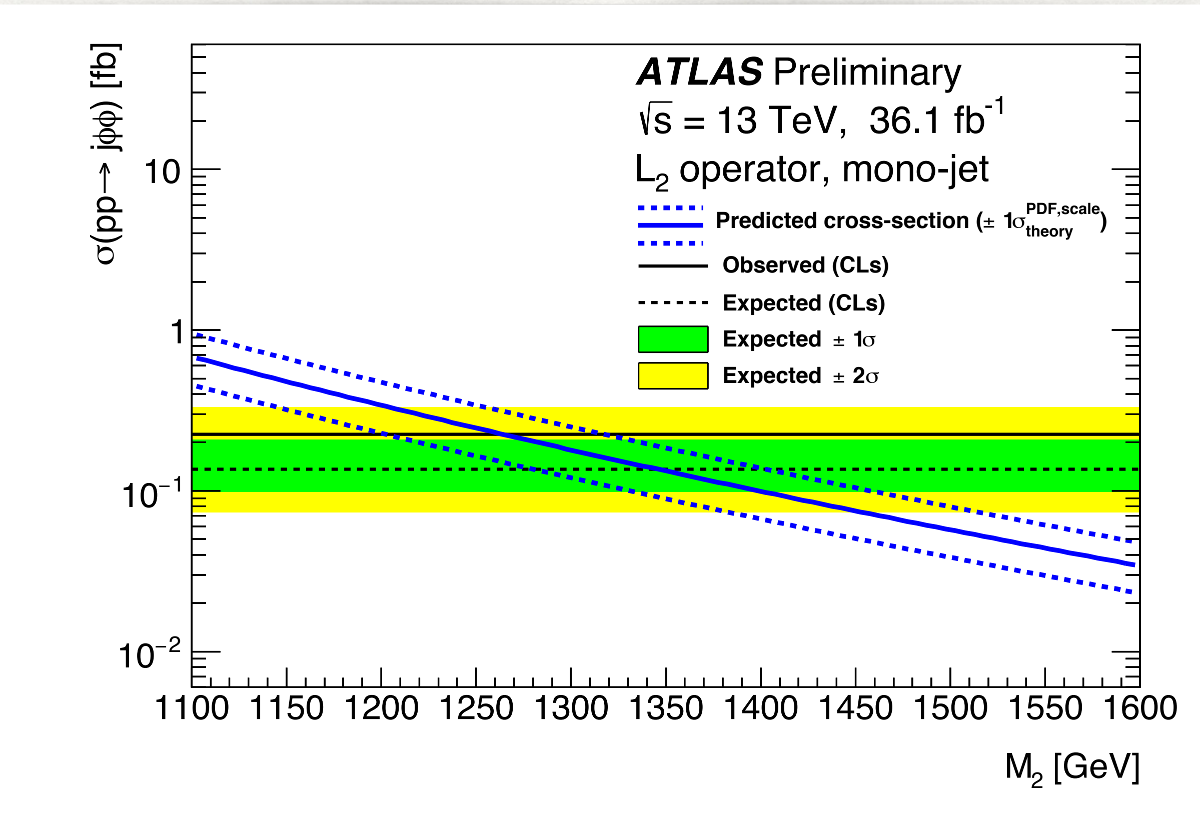
- No signal excess ⇒ set upper limit on production cross-section for L_1, L_2

Channel	Operator	Lower limits on M [GeV]					
		Observed	Expected	$+2\sigma$	$+1\sigma$	-1σ	-2σ
$t\bar{t} + E_T^{miss}$	$\mathcal{L}_1$	309^{+19}_{-24}	313	284	299	326	338
Mono-jet	$\mathcal{L}_2$	1260^{+50}_{-60}	1350	1200	1280	1400	1450

Upper limit on cross-section for L_1



Upper limit on cross-section for L_2



INTERPRETATION

Validity of EFT model

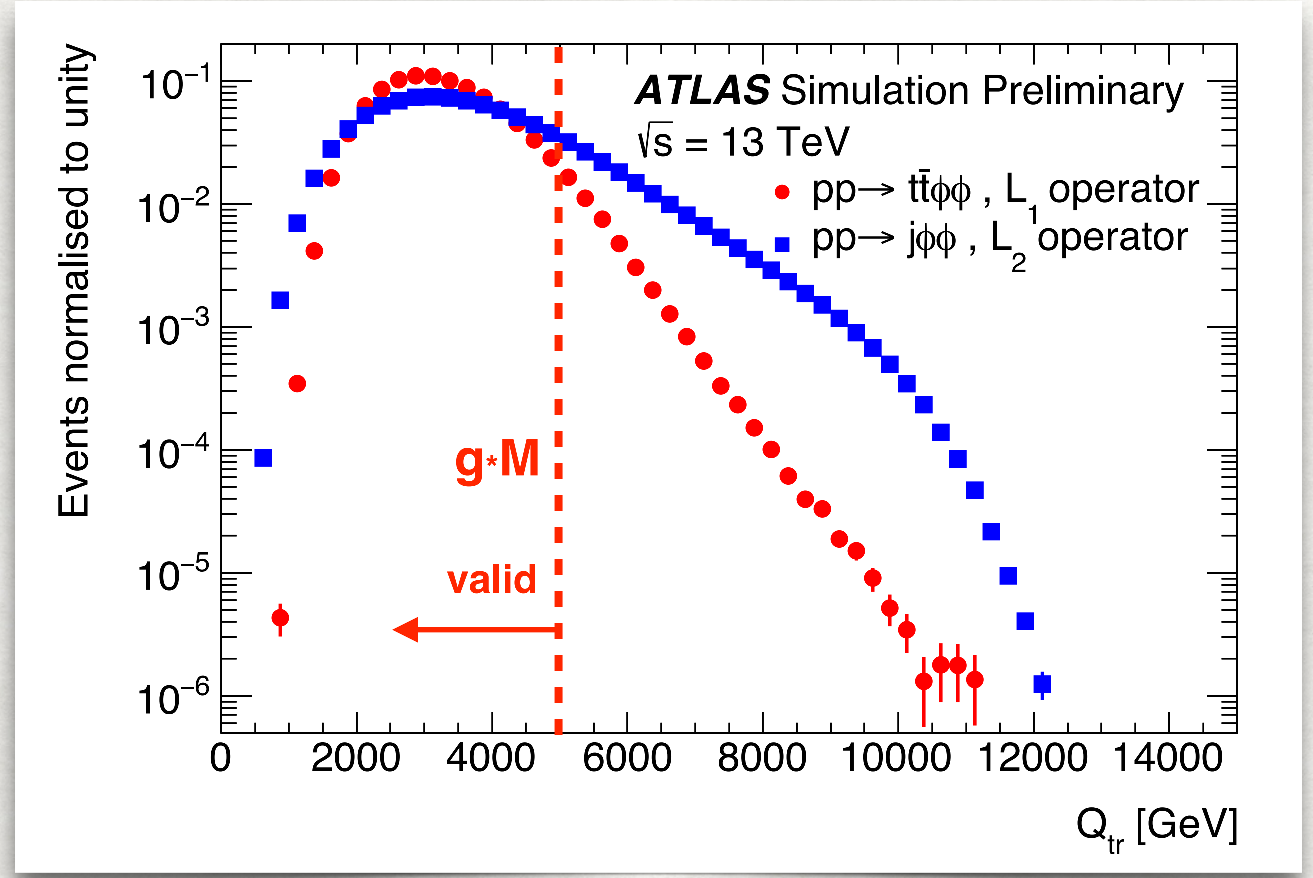
- EFT approximation valid when momentum transfer not enough to resolve the interaction: $Q_{tr} \ll M$
- In practice use

$$Q_{\rm tr} < g_* M$$

$g_\star$: effective coupling related to UV completion of EFT ($g_\star < 4\pi$)

M : lower limit on EFT suppression scale

Momentum transfer

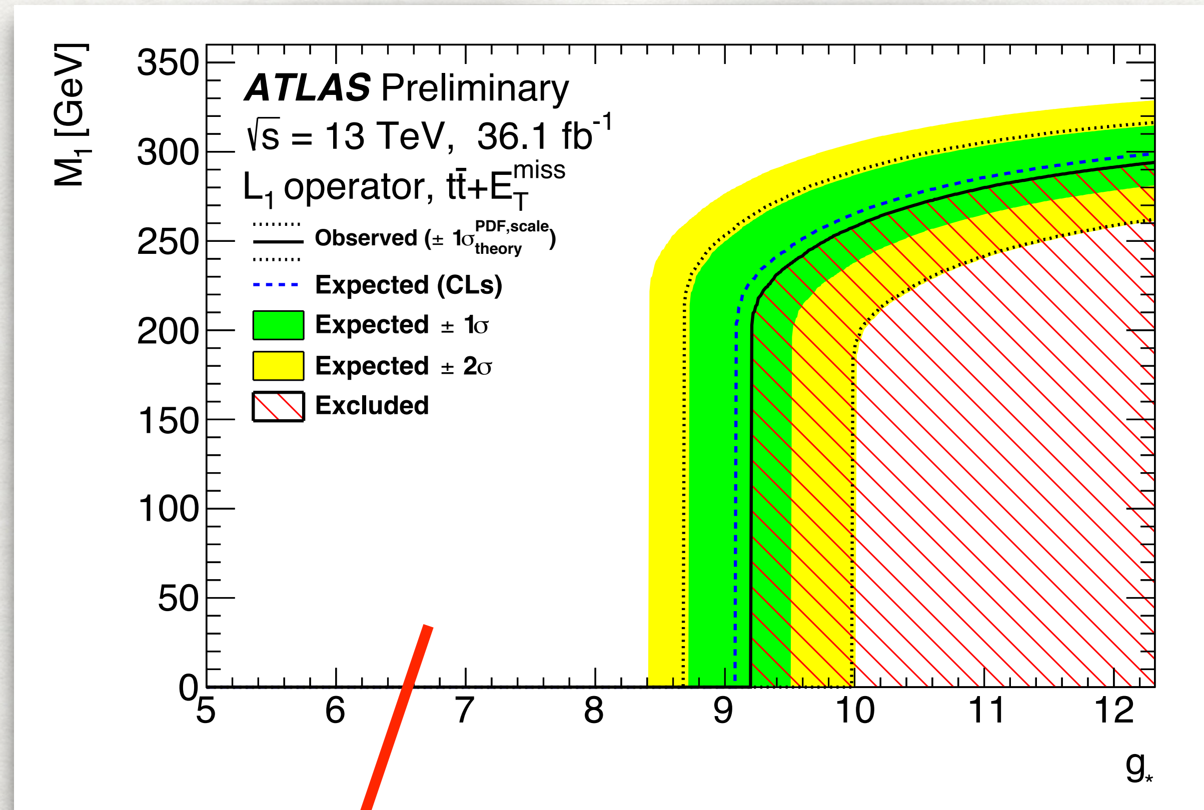


- UV completion unknown ⇒ use partonic c.o.m. energy
- Scan $g_\star$ and evaluate R: fraction of events that satisfy validity criterion
- Rescale limit using (dim-8 operators)

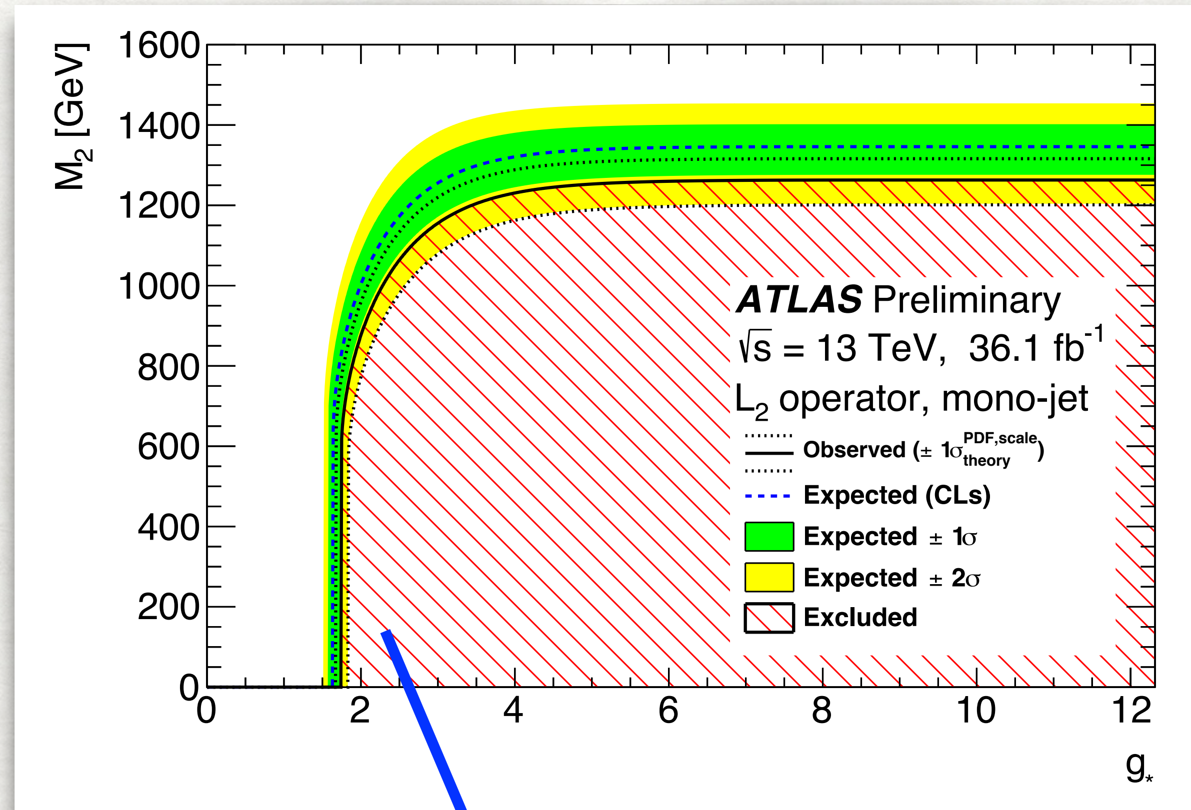
$$M_{\rm resc} = R^{1/8} M$$

Interpretation

Exclusion limit vs coupling for L_1



Exclusion limit vs coupling for L_2



No sensitivity yet to weakly coupled models for L_1:

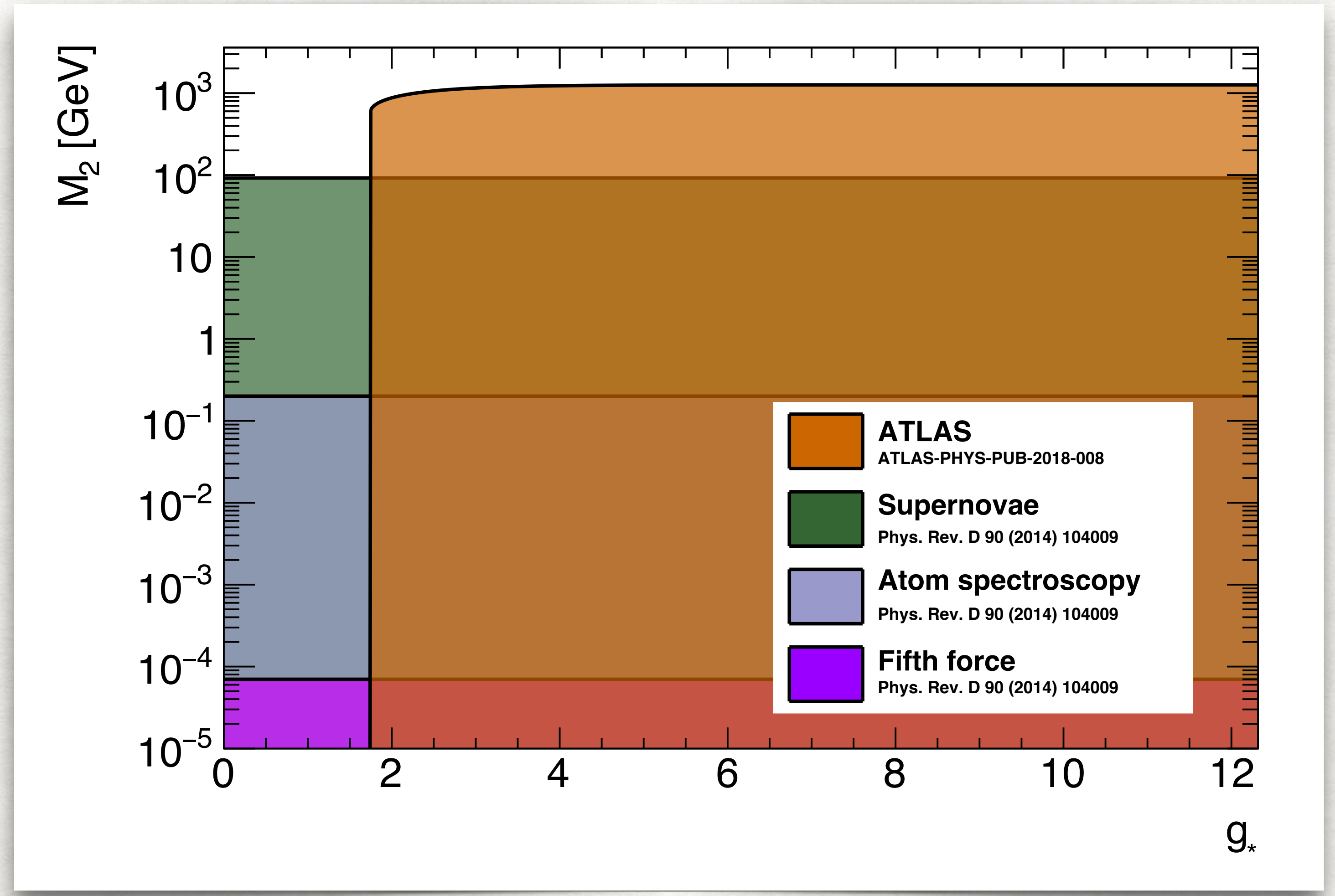
- very high momentum transfers due to high top mass
- should improve with higher data/more sensitive search

Sensitivity extends to lower couplings for L_2:

- higher limit
- lower momentum transfers wrt tt+E_T^{miss}

Comparison with other experiments

- Disformal coupling analysis already performed for non-collider probes [9]
  - supernovae, atom spectroscopy, fifth force experiments
- Momentum transfers in these processes are small so we can assume that EFT limit is completely valid and compare the limits:



own compilation based on [9[

➡ ***Colliders several orders of magnitude more sensitive to disformal couplings!***

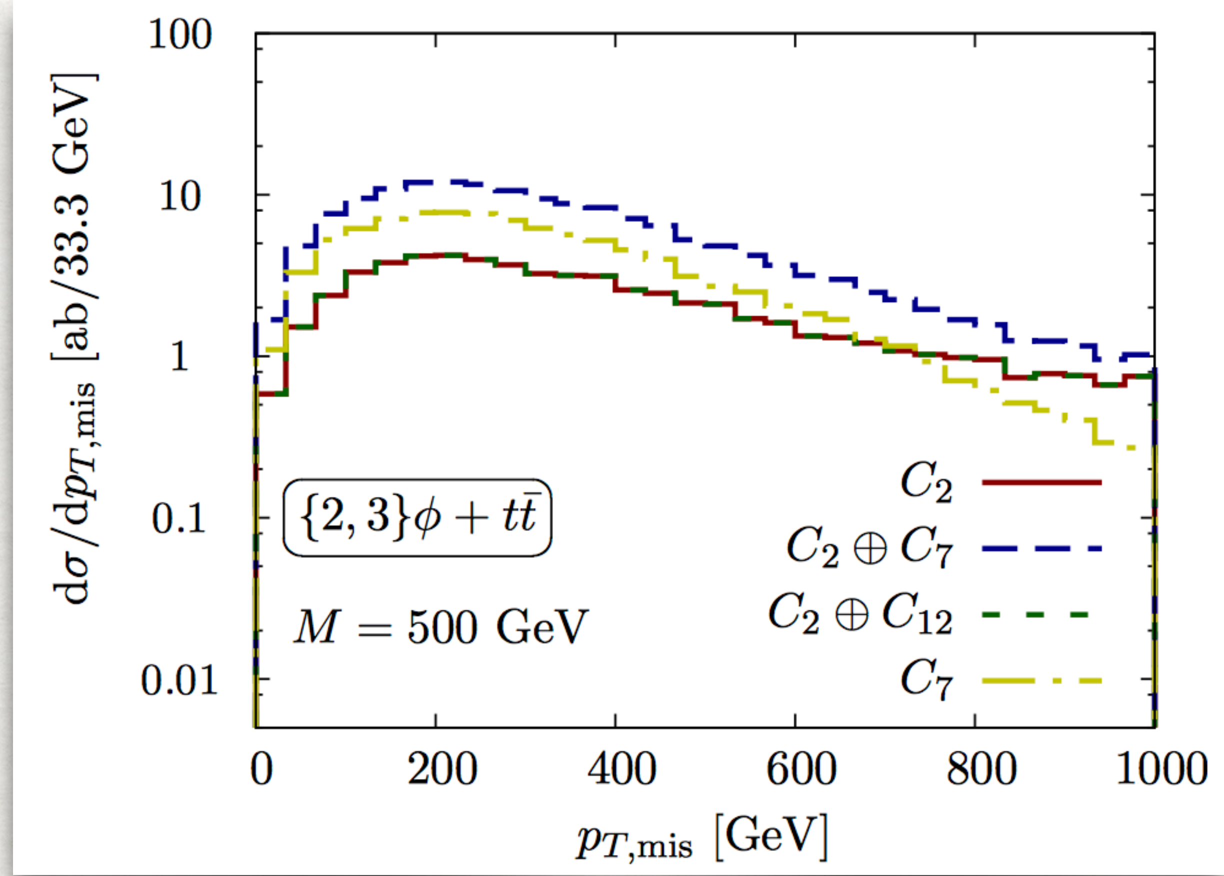
NEXT STEPS

Things for the future

- **optimise search strategy** (e.g. adding dedicated selections)
- **probe more final states** ⇒ stronger constraints / enlarged EFT validity

- **more operators**:
  - additional operators can alter E_T^{miss} shape
  - complementary with non-collider searches?
- **theorists**:
  - any signatures that we are missing?
  - translate constraints into specific benchmark models (?)
  - simplified UV models (?)

Effect of additional operators



Brax et al., Phys. Rev. D 94, 084054 (2016)

THE HIGGS CONNECTION

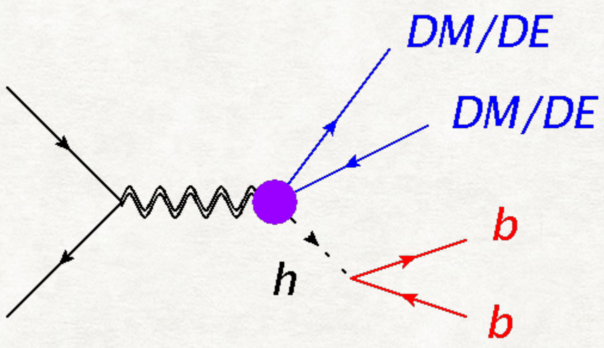
Why final states with Higgs bosons are interesting

One final state with many interpretations:

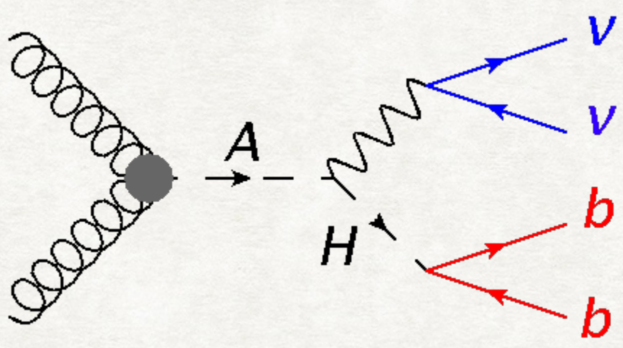
Higgs + MET (Z→νν, DM, DE)

- High mass ⇒ enhanced conformal coupling
- Scalar - might play special role in cosmology (Higgs potential) [15]
- Smoking gun signal for electroweak baryogenesis (Higgs potential) [16]
- New particle - portal to hidden sector
  - Rich phenomenology in terms of DM/DE models [17]

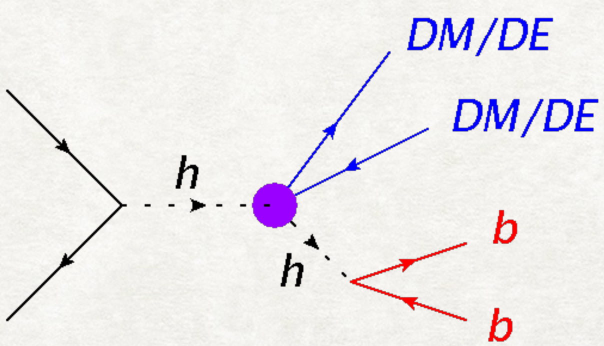
Higgs + DM/DE



EW baryogenesis



Higgs portal



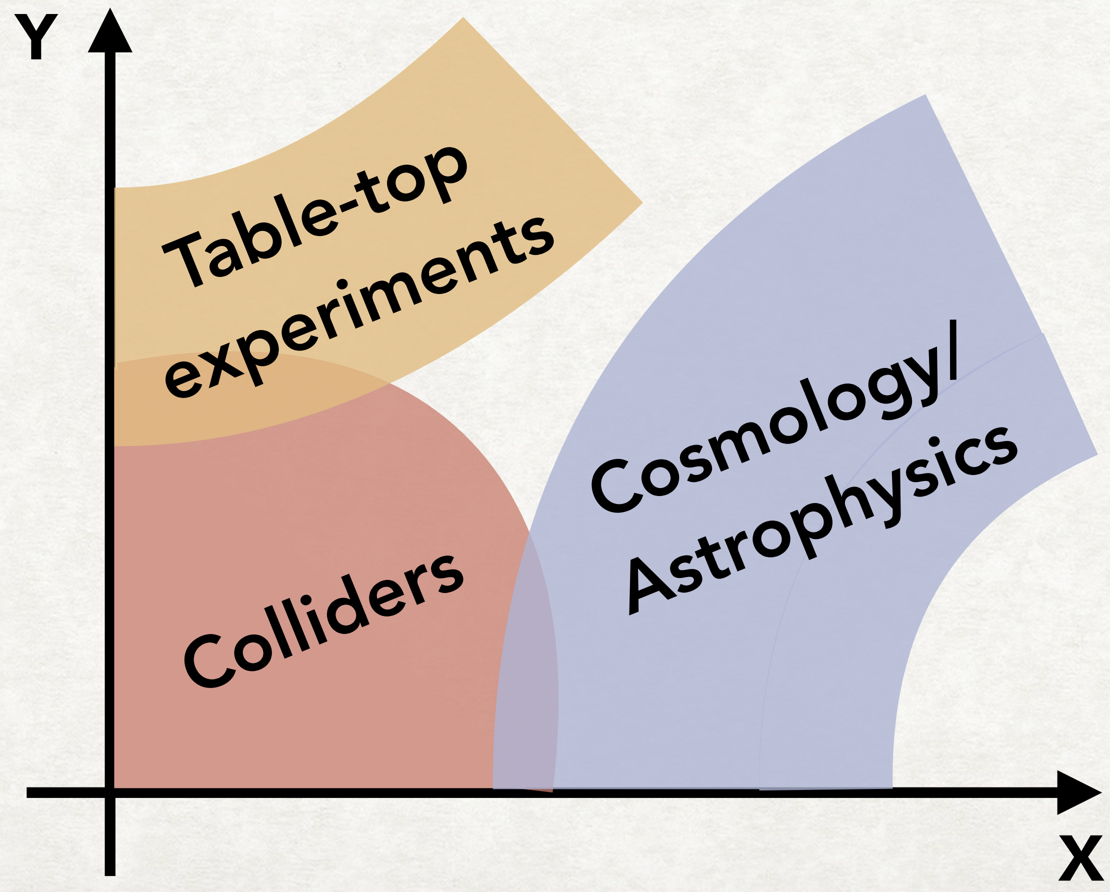
Final words

- ✓ strong motivation for DE search @ colliders
- ✓ first time experimental collaboration sets limits on DE using collider data
- ✓ colliders more sensitive than other experiments for certain couplings

Dark Energy might be more than 1 particle or more than 1 effect

or even something completely unexpected

The best approach to understand it is to have multiple approaches…



BACKUP

References

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[16] Dorsch et al, Phys. Rev. Lett. 113 (2014) 211802, ATLAS PLB 783 (2018) 392

[17] Burrage et al., arXiv:1804.07180

Shift symmetric models [4]

- Nearly massless field needed for cosmic acceleration
  - model with complex scalar field **Φ** with global U(1) symmetry
  - Goldstone mode **φ** below symmetry breaking scale f (**φ** plays role of DE)

$$S = \int d^4x \sqrt{-\tilde{g}}[-\tilde{g}^{\mu\nu}\partial_\mu \bar{\Phi}\partial_\nu \Phi - V(|\Phi|^2)]$$

$$\Phi = f e^{i\phi/(\sqrt{2}f)}$$

- Residual symmetry in the broken phase ⇒ shift symmetry
  - forbids Yukawa interactions of DE field with SM matter

Event selection

tt+E_T^{miss}

Variable	Region		
	SRA_TT	SRA_TW	SRA_T0
N^{jet}	$\geq$ 4 within $\lvert\eta\rvert$ < 2.7		
$N^{\text{b-jet}}$	≥ 2		
P_T^{jet}	> 80, 80, 40, 40 GeV		
$m^0_{\text{jet},R=1.2}$	> 120 GeV		
$m^1_{\text{jet},R=1.2}$	> 120 GeV	[60, 120] GeV	< 60 GeV
$m_T^{b,\text{min}}$	> 200 GeV		
$N_{b-\text{jet}}$	≥ 2		
τ-veto	yes		
$\lvert\Delta\phi(\text{jet}^{0,1,2}, \mathbf{p}_T^{\text{miss}})\rvert$	> 0.4		
$m^0_{\text{jet},R=0.8}$	> 60 GeV		
$\Delta R(b, b)$	> 1	-	
$m_{T2}^{\chi^2}$	> 400 GeV	> 400 GeV	> 500 GeV
$E_{\text{T}}^{\text{miss}}$	> 400 GeV	> 500 GeV	> 550 GeV

Mono-jet

$E_{\text{T}}^{\text{miss}}$ > 250 GeV
leading jet p_T > 250 GeV and $\lvert\eta\rvert$ < 2.4
$\leq$ 4 selected jets with P_T > 30 GeV and $\lvert\eta\rvert$ < 2.8
$\Delta\phi\left(jet, \vec{p}_T^{miss}\right)$ > 0.4 for all selected jets
no identified electron with p_T > 20 GeV
no identified muon with p_T > 10 GeV

Iterative limit rescaling

- Taken from ATL-PHYS-PUB-2014-007
- Start with nominal expected limit assuming 100% validity
- Until $R_i = 1$ or 0
  - Calculate $Q_{tr}^{max}(i) = 4\pi M_{in}(i) = 4\pi\ M_{out}(i\text{-}1)$
  - Calculate $R_i = N(Q_{tr} < Q_{tr}^{max}(i))/N(Qtr < Q_{tr}^{max}(i\text{-}1))$
  - Evaluate $M_{out}(i) = R_{tot}^{1/8} \cdot M_{in}(i)$
- Determine $M_{resc} = (\prod R_i)^{1/8} \cdot M_{in}$

Example for L_2 with $g_\star=4$				
M_{in}	$Q_{tr}^{max}(i)$	$Q_{tr}^{max}(i\text{-}1)$	R_i	M_{out}
1263	5052	13000	0.83	1234
1234	4937	5052	0.98	1231
1231	4924	4937	1	**1231**

Operators

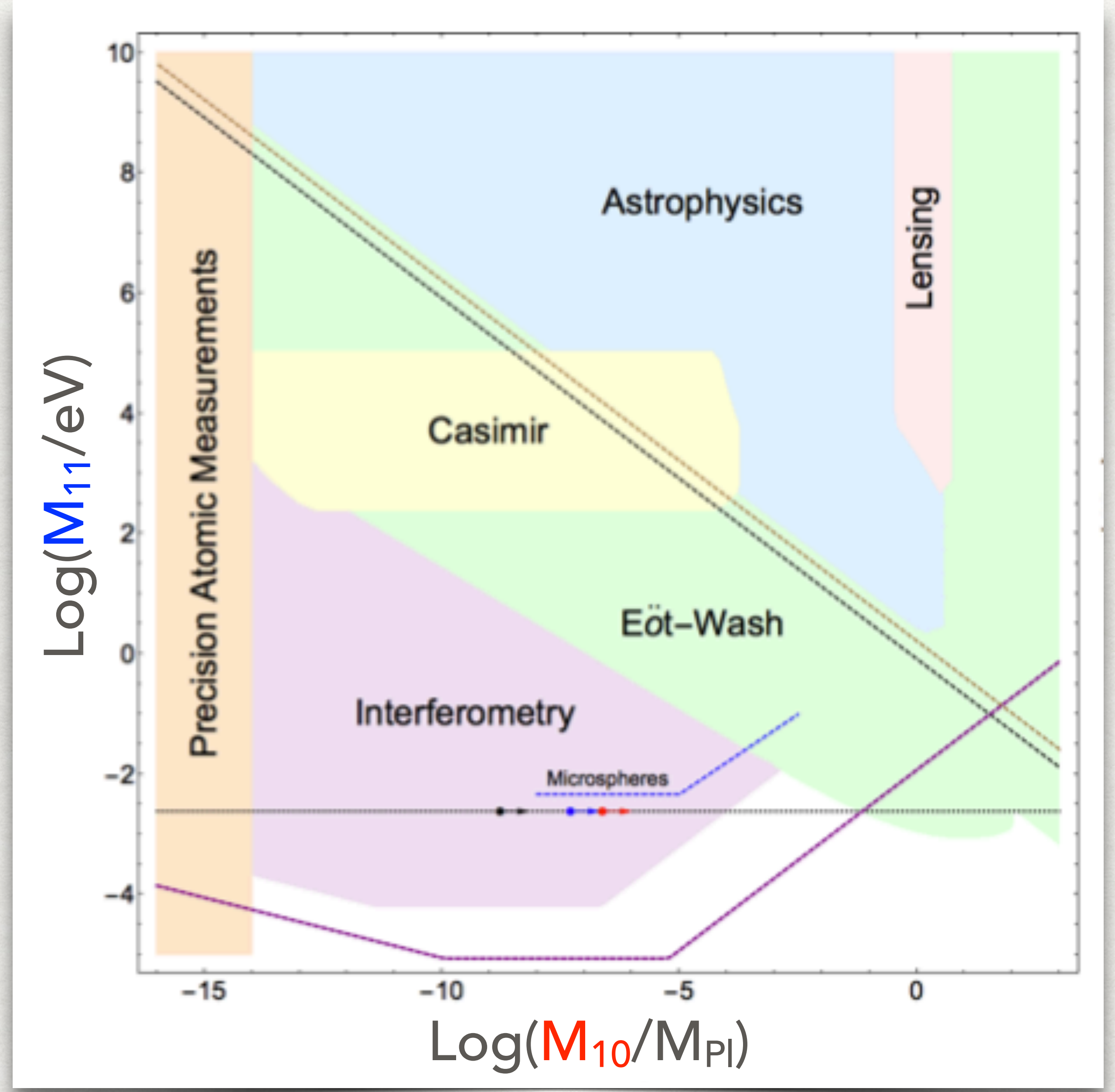
Kinetic conformal couplings	$\mathcal{L}_1 = \frac{\partial_\mu\phi\partial^\mu\phi}{M^4} T^\nu_\nu$
	$\mathcal{L}_{3,n} = \left(\frac{\partial_\mu\phi\partial^\mu\phi}{M^4}\right)^n T^\nu_\nu$
Disformal couplings	$\mathcal{L}_2 = \frac{\partial_\mu\phi\partial_\nu\phi}{M^4} T^{\mu\nu}$
	$\mathcal{L}_{4,n} = \left(\frac{\partial_\alpha\phi\partial^\alpha\phi}{M^4}\right)^n \frac{\partial_\mu\phi\partial_\nu\phi}{M^4} T^{\mu\nu}$
	$\mathcal{L}_{5,n-1} = \frac{1}{M^{4n}}\partial_{\alpha_1}\phi\partial_{\beta_1}\phi\cdots\partial_{\alpha_n}\phi\partial_{\beta_n}\phi\frac{2^{n-1}}{\sqrt{-g}}\frac{\partial^{n-1}(\sqrt{-g}T^{\alpha_1\beta_1})}{\partial g_{\alpha_2\beta_2}\cdots\partial g_{\alpha_n\beta_n}}$
DE kinetic term	$\mathcal{L}_{6,n} = \frac{(\partial_\mu\phi\partial^\mu\phi)^n}{M^{4(n-1)}}$
Galileons	$\mathcal{L}_7 = \frac{1}{M^3}\partial_\mu\phi\partial^\mu\phi\Box\phi$
	$\mathcal{L}_8 = \frac{1}{M^6}\partial_\mu\phi\partial^\mu\phi[2(\Box\phi)^2 - 2D_\alpha D_\beta\phi D^\beta D^\alpha\phi]$
	$\mathcal{L}_9 = \frac{1}{M^9}\partial_\mu\phi\partial^\mu\phi[(\Box\phi)^3 - 3(\Box\phi)D_\alpha D_\beta\phi D^\beta D^\alpha\phi + 2D_\alpha D^\beta\phi D_\beta D^\gamma\phi D_\gamma D^\alpha\phi]$

Limits on disformal coupling from other sources

Source of bound	Lower bound on M in GeV	Environment	Discussed in Section
Unitarity at the LHC	30	Lab. vac.	3
CMS mono-lepton	120	Lab. vac.	3
CMS mono-photon	490	Lab. vac.	3
Torsion Balance	7×10^{-5}	Lab. vac.	4.1
Casimir effect	0.1	Lab. vac.	5.1
Hydrogen spectroscopy	0.2	Lab. vac.	6
Neutron scattering	0.03	Lab. vac.	7
Bremsstrahlung	4×10^{-2}	Sun	8.3
	0.18	Horizontal Branch	8.3
Compton Scattering	0.24	Sun	8.4
	0.81	Horizontal Branch	8.4
Primakov	4×10^{-2}	Sun	8.5
	0.35	Horizontal Branch	8.5
Pion exchange	~ 92	SN1987a	8.6

Brax, Burrage, Phys. Rev. D 90, 104009 (2014)

Comparing limits



Burrage, Sakstein JCAP 11 (2016) 045

- plot here shows constraints on chameleons:

$$\mathcal{L} = \frac{1}{2}\mathcal{L}_{6,1} + \mathcal{L}_{10,1} + \mathcal{L}_{11,-n}$$

$$= \frac{1}{2}\partial_\mu\phi\partial^\mu\phi + \frac{{M_{11}}^{4+n}}{\phi^n} + \frac{\phi T^\mu_\mu}{M_{10}}$$

- does it make sense to have something similar for M_1, M_2 including collider and non-collider experiments?