THEORY IN THE LHC ERA

2017 ICFA Seminar

Ottawa, Canada

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8 November 2017

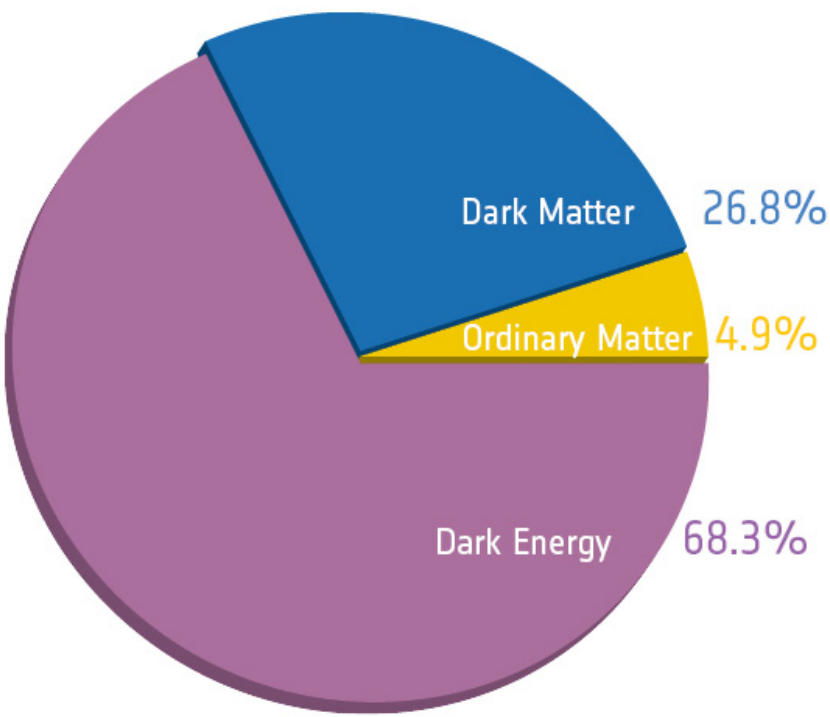
NEWTON AND NATURALNESS

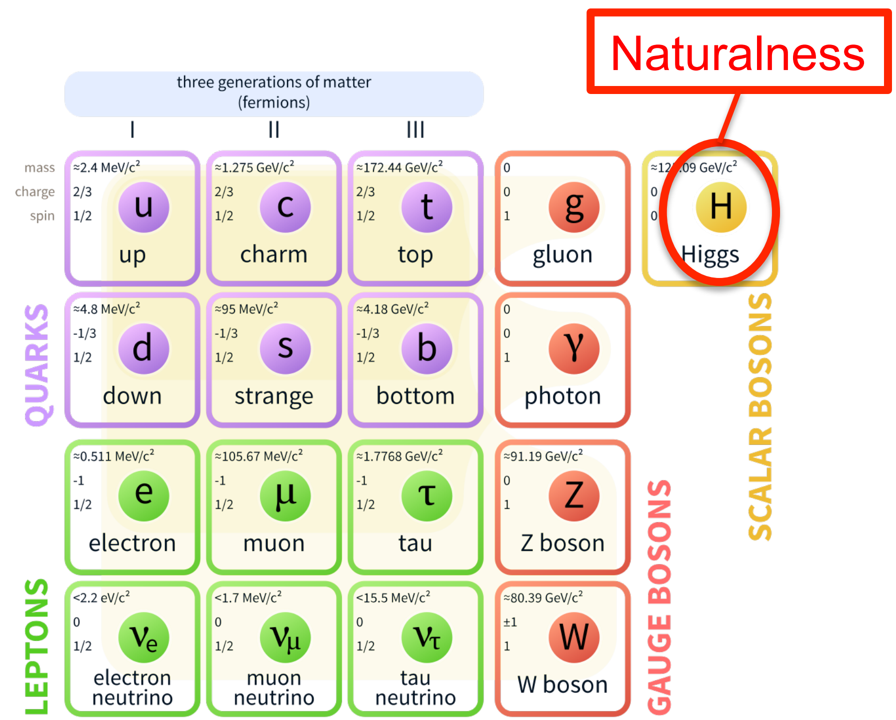
- In 1687, Isaac Newton published the *Principia*. 5 years later, a clergyman, Robert Bentley, asked him how the law of universal gravitation could be consistent with a static universe.

- Newton's rueful reply: "That there should be a central particle, so accurately placed in the middle, as to be always equally attracted on all sides, and thereby continue without motion, seems to me a supposition fully as hard as to make the sharpest needle stand upright on its point upon a looking-glass."

THE PRESENT

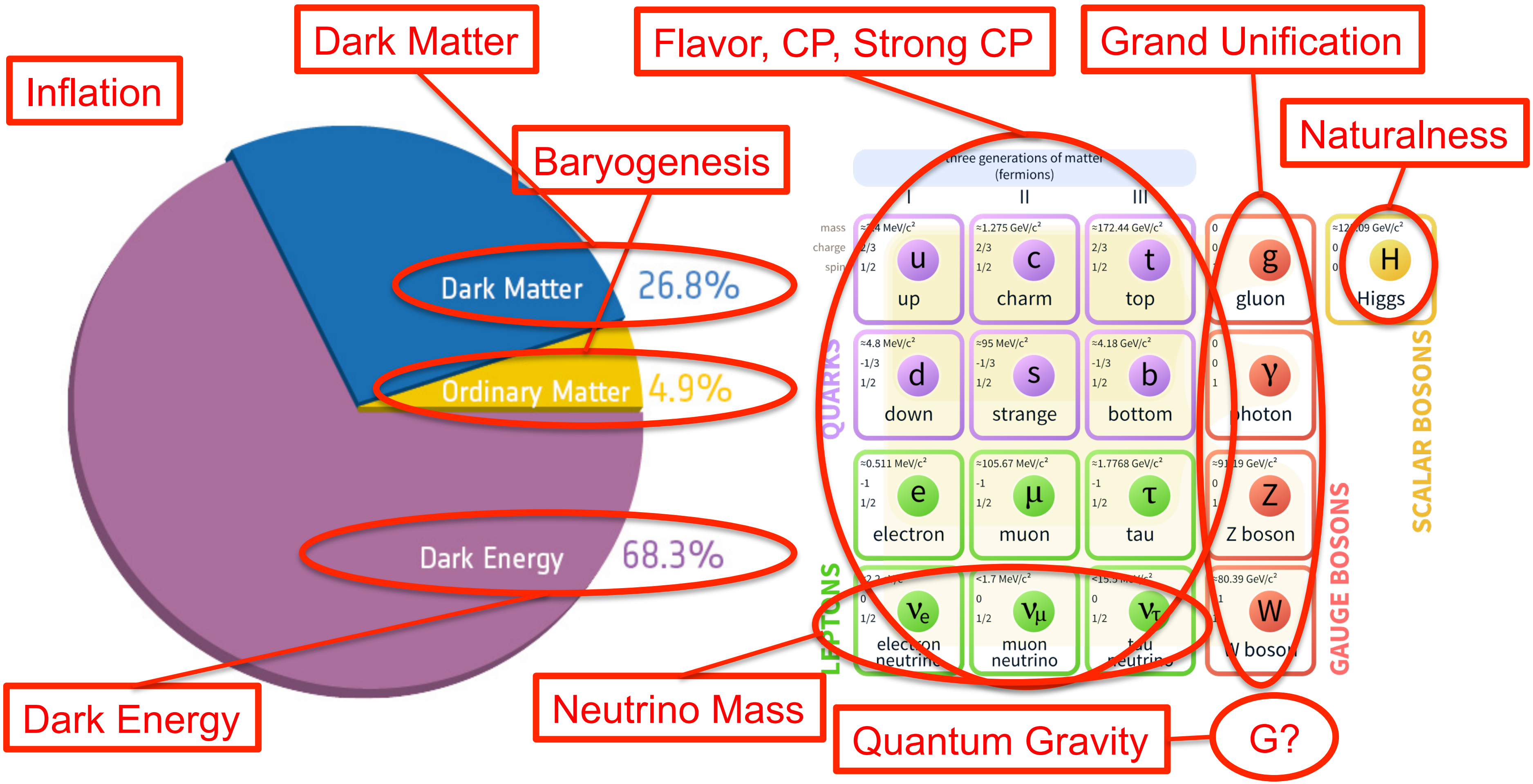
- Like Newton, we have just completed a monumental achievement, the completion of the standard models of cosmology and particle physics, and 5 years later, we also have a naturalness problem





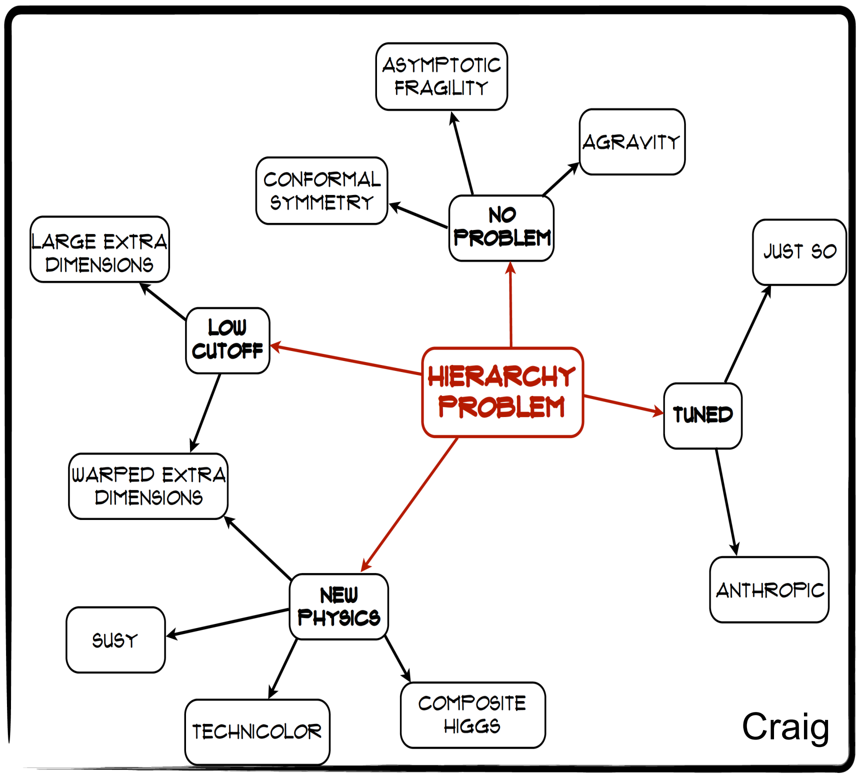
OUTSTANDING PROBLEMS

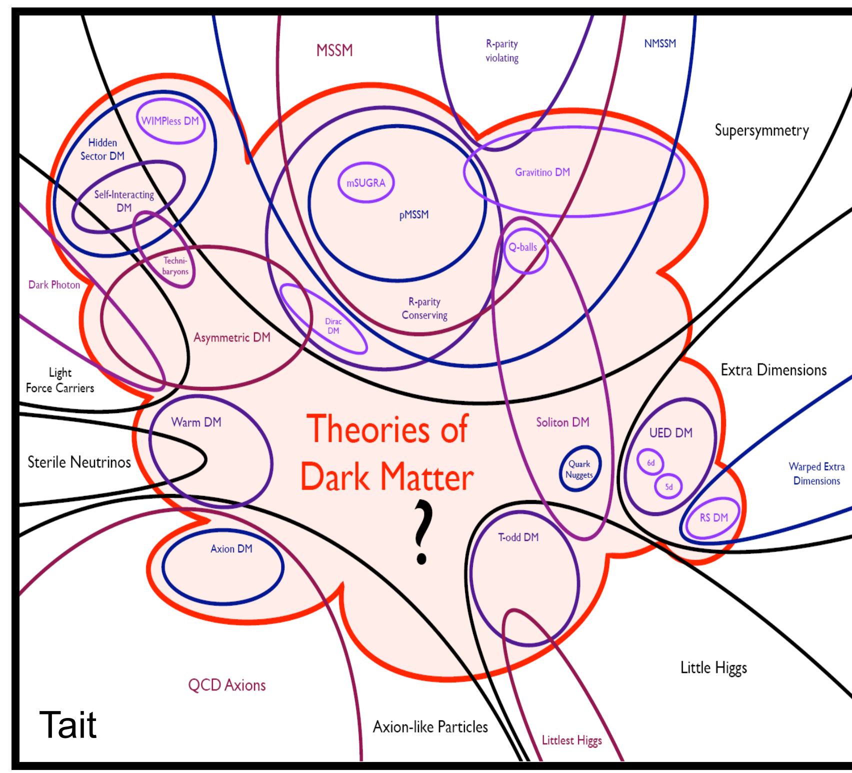
- Actually, we have an embarrassment of riches: naturalness is just one of the many deep and interesting puzzles we have the privilege to think about



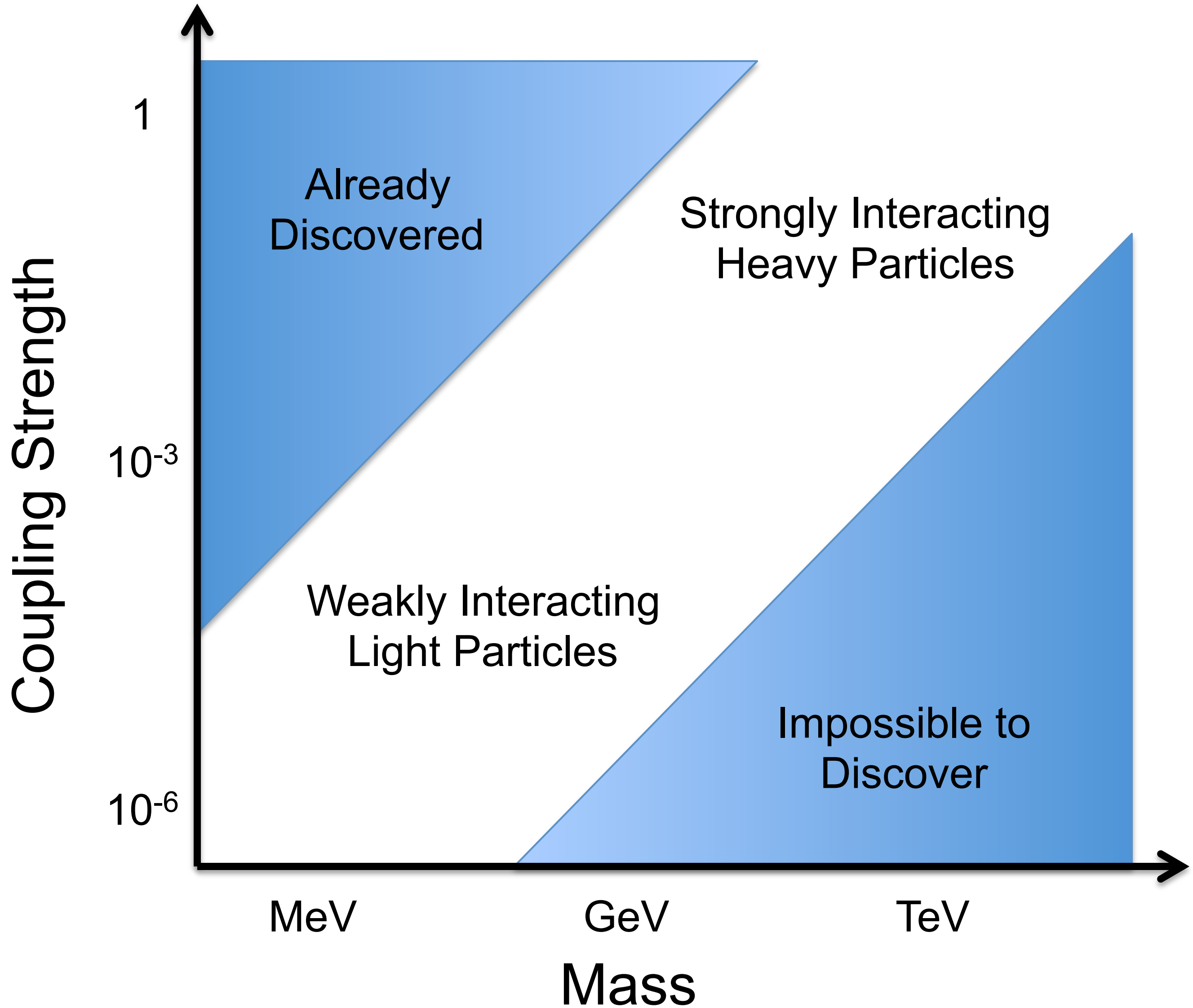
OUTSTANDING OPPORTUNITIES

- In particle theory, this is a time of great creativity, new ideas, and best of all, new proposals for experiments and connections to other fields (cosmology, astrophysics, nuclear physics, condensed matter, atomic physics, ...)





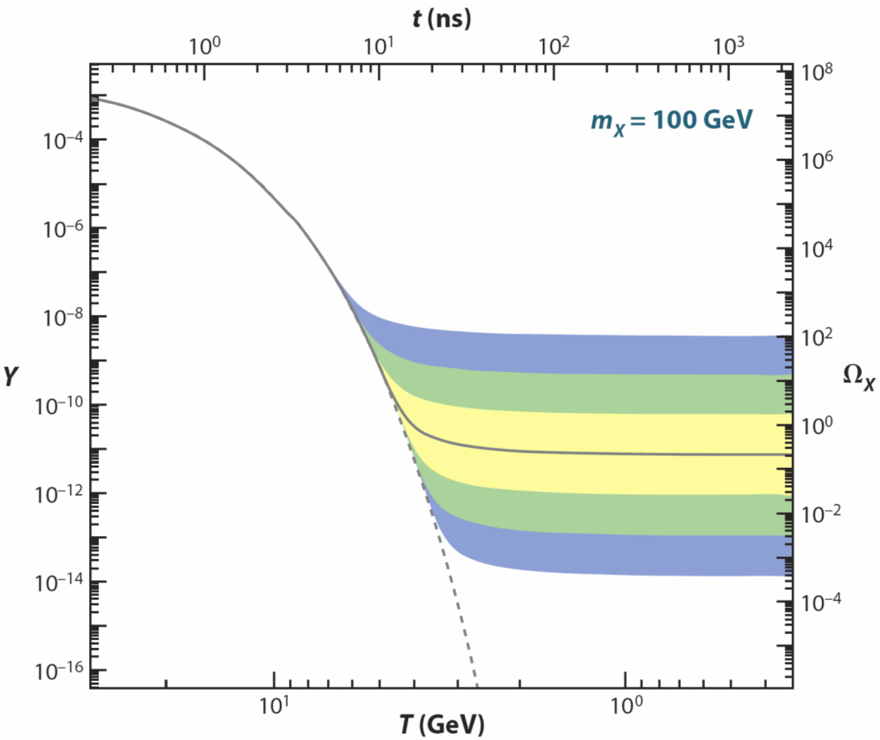
LOOKING UNDER THE LAMPPOST



STRONGLY INTERACTING, HEAVY PARTICLES

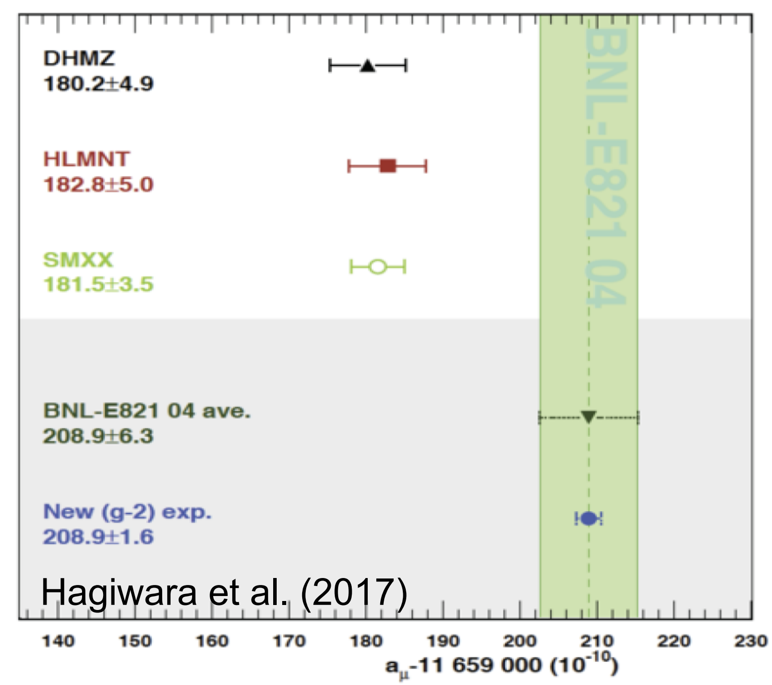
- The traditional target for new physics searches, with strong motivations

- WIMP Miracle



~TeV particles with O(1) couplings have the right thermal relic densities to be dark matter

- Anomalies

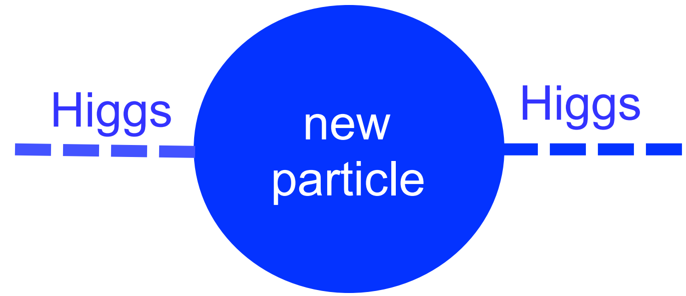


~TeV particles with O(1) couplings can explain the ~3.5σ discrepancy in the muon anomalous magnetic moment

STRONGLY INTERACTING, HEAVY PARTICLES

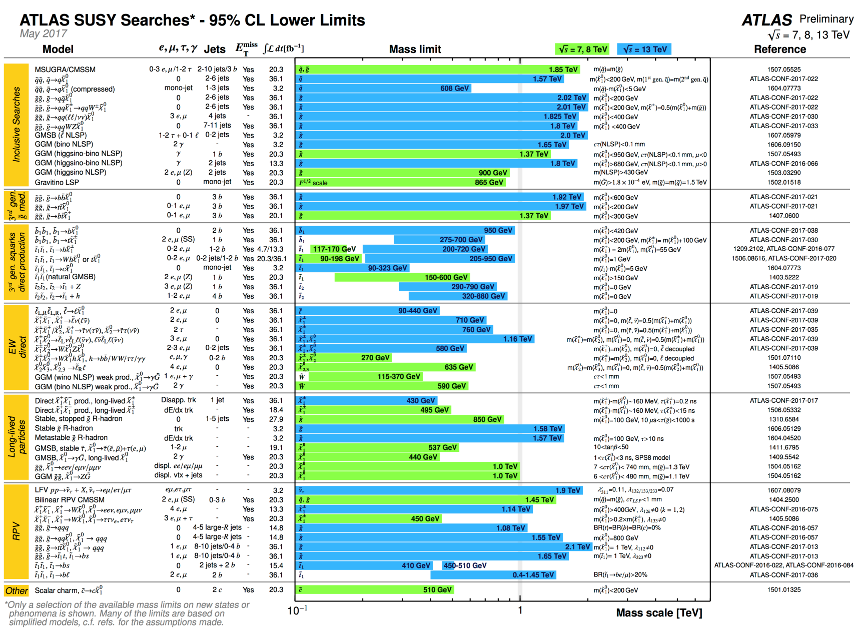
- Naturalness

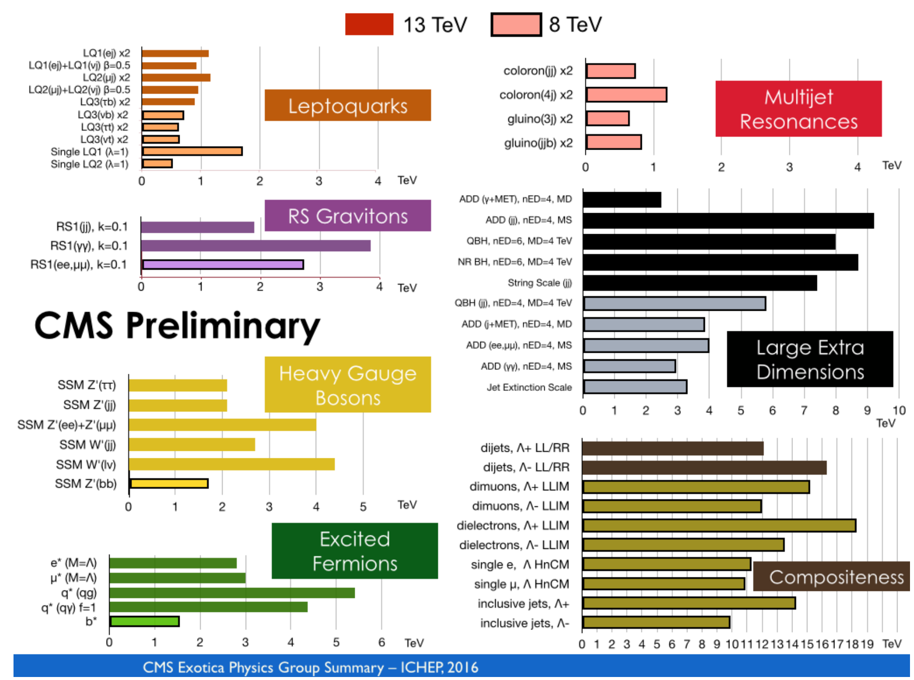
~TeV particles with O(1) couplings can explain why $m_h << M_{Pl}$



- Is this motivation spoiled by the lack of new particles at the LHC so far?

E.g., “gluino mass > 2 TeV >> m_h , fine tuning > 100, 1000...”





QUANTIFYING NATURALNESS

- Quantifying fine tuning is fraught with subjective choices. E.g., SUSY

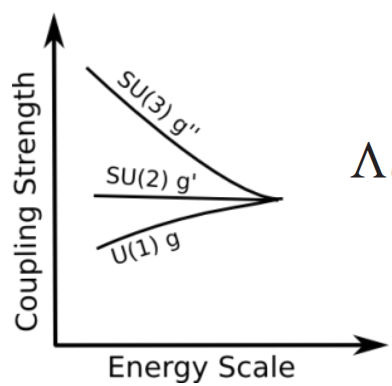
Step	Systematic Error
Choose a framework with some fundamental parameters a_i	~10
Define sensitivity coefficients and combine them	~10
Normalize to average fine tuning	~10

$$m_Z^2 \approx -2m_{H_u}^2 - 2\mu^2$$

$$\begin{aligned}
-2m_{H_u}^2(m_{\rm weak}) = {} & 3.84M_3^2 + 0.32M_3M_2 + 0.047M_1M_3 - 0.42M_2^2 \\
& +0.011M_2M_1 - 0.012M_1^2 - 0.65M_3A_t - 0.15M_2A_t \\
& -0.025M_1A_t + 0.22A_t^2 + 0.0040M_3A_b \\
& -1.27m_{H_u}^2 - 0.053m_{H_d}^2 \\
& +0.73m_{Q_3}^2 + 0.57m_{U_3}^2 + 0.049m_{D_3}^2 - 0.052m_{L_3}^2 + 0.053m_{E_3}^2 \\
& +0.051m_{Q_2}^2 - 0.110m_{U_2}^2 + 0.051m_{D_2}^2 - 0.052m_{L_2}^2 + 0.053m_{E_2}^2 \\
& +0.051m_{Q_1}^2 - 0.110m_{U_1}^2 + 0.051m_{D_1}^2 - 0.052m_{L_1}^2 + 0.053m_{E_1}^2,
\end{aligned}$$

$$\mathcal{N}_i \equiv \left| \frac{\partial \ln m_Z^2}{\partial \ln a_i^2} \right| = \left| \frac{a_i^2}{m_Z^2} \frac{\partial m_Z^2}{\partial a_i^2} \right| \qquad \mathcal{N} \equiv \max(\mathcal{N}_i)$$

Ellis, Enqvist, Nanopoulos, Zwirner (1986)
Barbieri, Giudice (1988)



$$\Lambda_{\rm QCD} \approx M_{\rm Pl} e^{-c/g^2}$$

De Carlos, Casas (1993)
Anderson, Castano (1995)

A NATURAL, VIABLE EXAMPLE: MSSM4G

- Naturalness suggests light stops and sbottoms, m_h = 125 GeV suggests heavy stops and sbottoms

- A resolution: introduce a 4th generation of particles to raise the Higgs mass

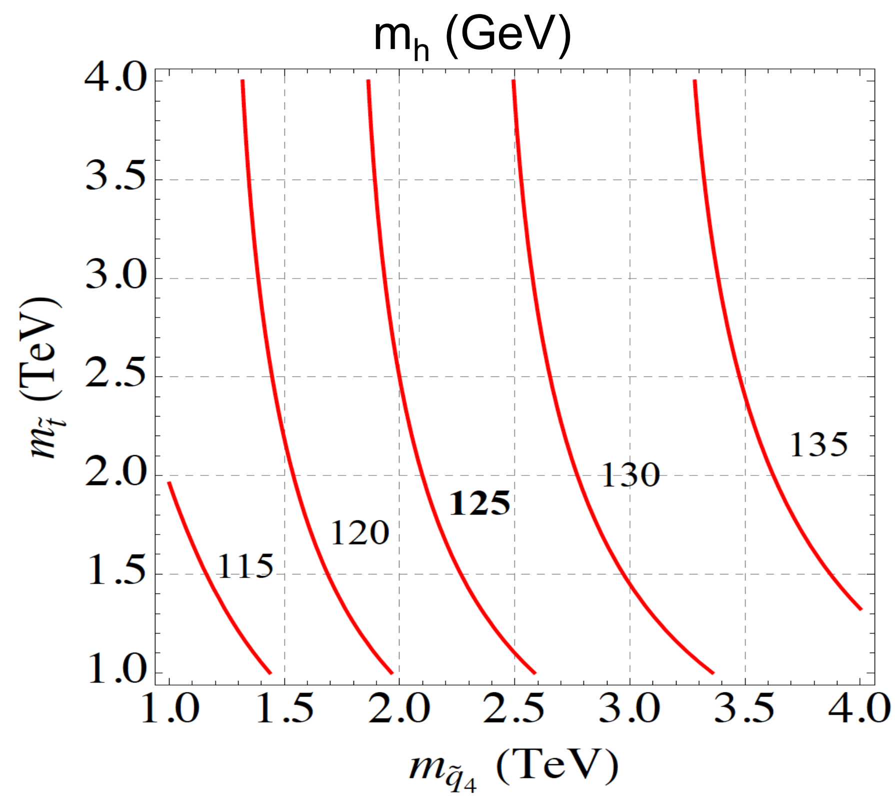
Moroi, Okada (1992)

- Chiral 4th generation particles are highly constrained. Instead, add vector-like 4th generation particles. For example, add a 10 of SU(5) consistent with gauge coupling unification:

Dirac fermions: T_4, B_4, t_4, τ_4

Complex scalars: $\tilde{T}_{4L}, \tilde{T}_{4R}, \tilde{B}_{4L}, \tilde{B}_{4R}, \tilde{t}_{4L}, \tilde{t}_{4R}, \tilde{\tau}_{4L}, \tilde{\tau}_{4R}$

Martin (2010)



MSSM4G AT THE LHC

- MSSM4G models imply a wealth of signals at the LHC
- 4^{th} generation particles must decay, but can decay to any of the 1^{st} three generations with a variety of lifetimes. Possible signals:
  - Quarks, squarks, gluinos in the 1-3 TeV range, cascading down to MET signatures
  - $\tau_4 \tau_4$ Drell-Yan production, followed by decays $\tau_4 \rightarrow \tau Z$, νW, τh, etc.
  - $\tilde{\tau}_4 \tilde{\tau}_4$ Drell-Yan production, followed by decays $\tilde{\tau}_4 \rightarrow e \chi$, $\mu \chi$, $\tau \chi$
  - $\tilde{\tau}_4 \tilde{\tau}_4$ Drell-Yan production, leading to long-lived charged particles, displaced vertices

Parameter	QUE (GeV)
$M_{\tilde{B}}$	$200 - 540$
$m_{\tilde{q}_4}$	$1000 - 4000$
$m_{\tilde{\ell}_4}$	$350 - 550$
m_{q_4}	$1000 - 2000$
m_{ℓ_4}	$170 - 450$
$m_{\tilde{t}}$	$1000 - 4000$

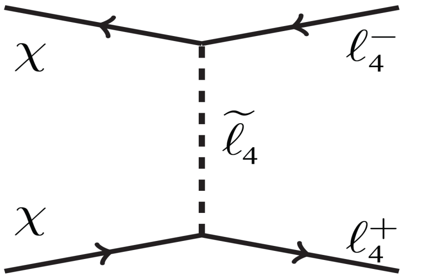
Kumar, Martin (2015); Abdullah, Feng, Iwamoto, Lillard (2016)

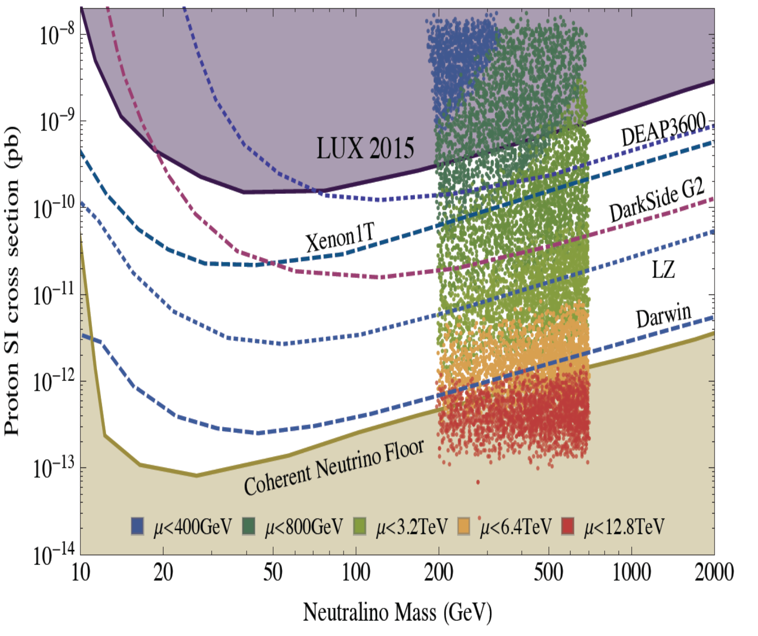
MSSM4G DARK MATTER

- MSSM4G predicts heavy neutralino dark matter that freezes out with the right thermal relic density through $\chi\chi \rightarrow \tau_4\tau_4$

- Direct detection cross sections naturally fall between current bounds and the neutrino floor

- Interesting signals for indirect detection also (CTA)



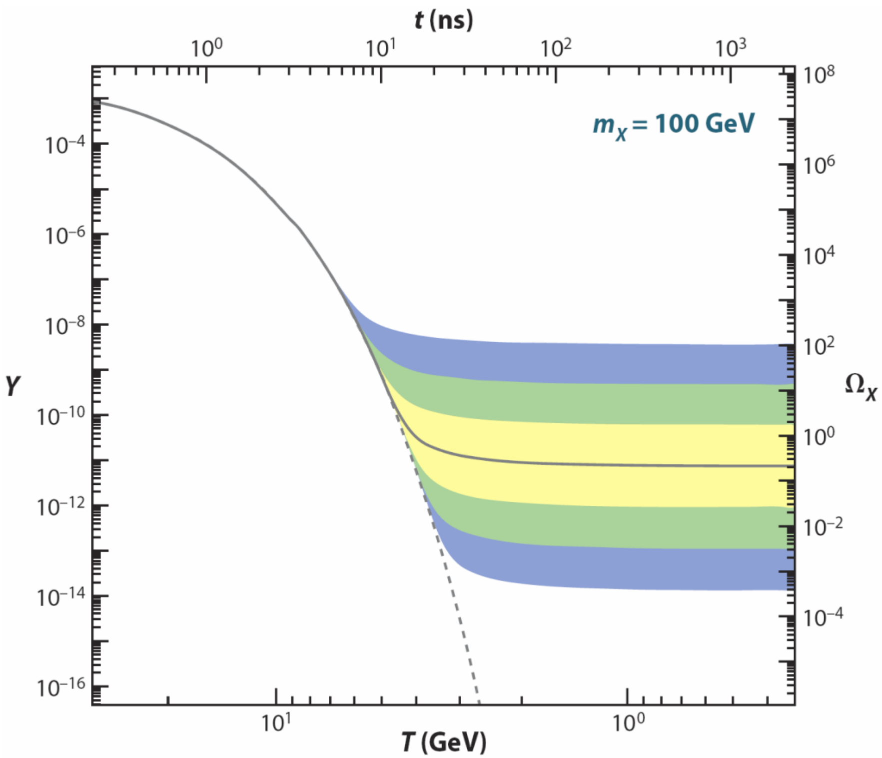


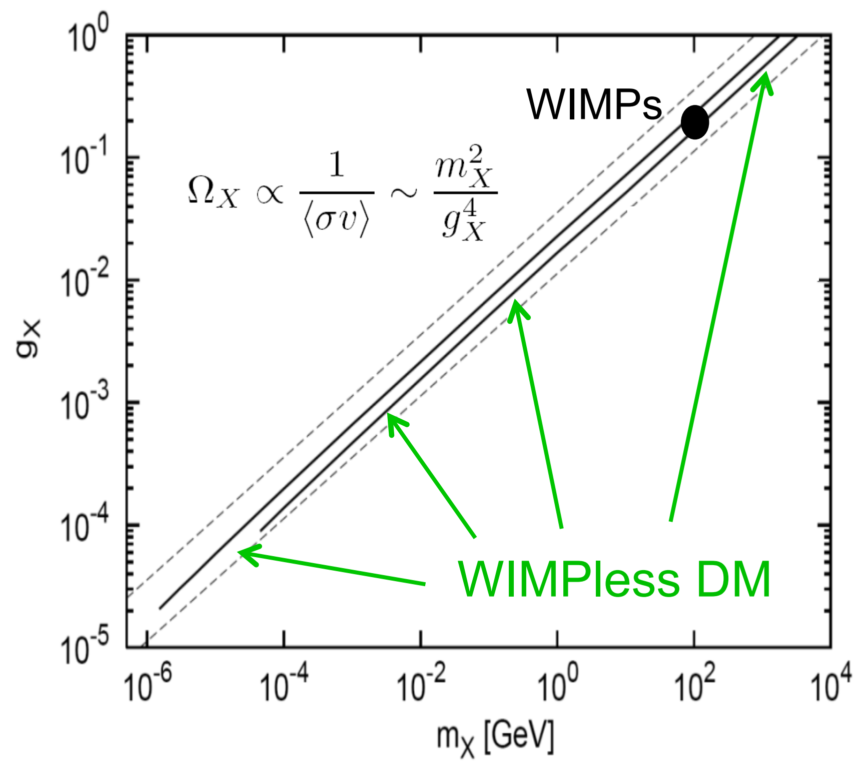
Models like these have strong theoretical motivations and promise an exciting program of discovery for DM searches, the LHC, and future colliders

WEAKLY INTERACTING, LIGHT PARTICLES

- A new target for new physics searches, but with similarly strong motivations

- WIMPless Miracle



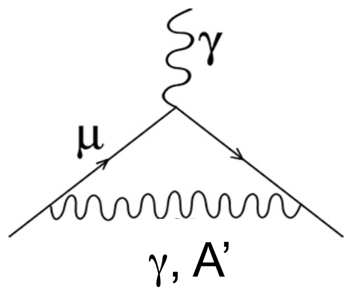


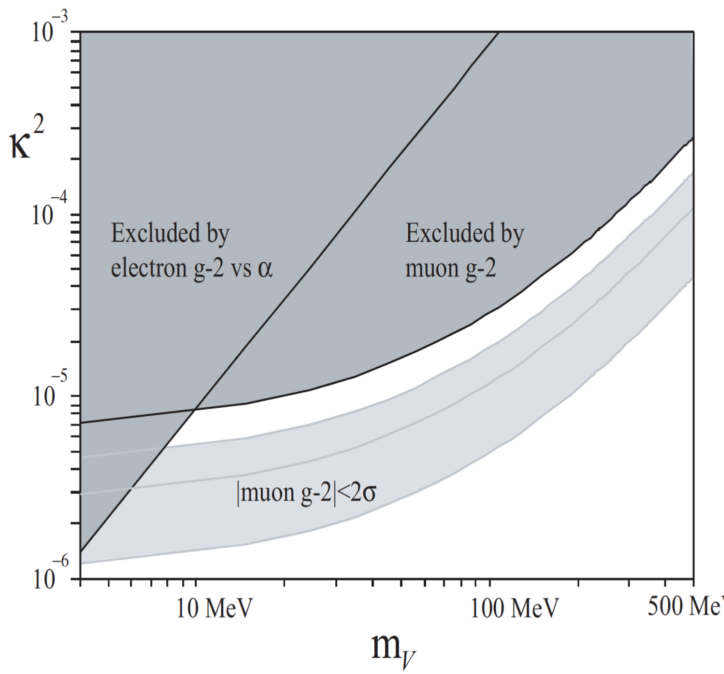
- Weakly interacting, light particles can be thermal relic dark matter and open connections to the intensity frontier, nuclear, AMO, and CM physics

WEAKLY INTERACTING, LIGHT PARTICLES

- Anomalies

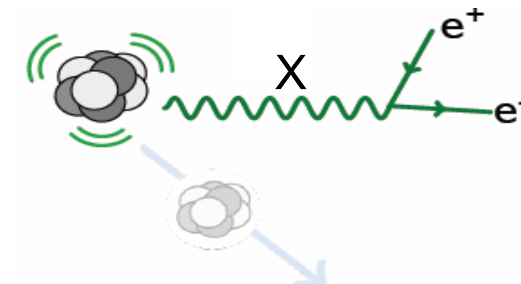
Muon g-2





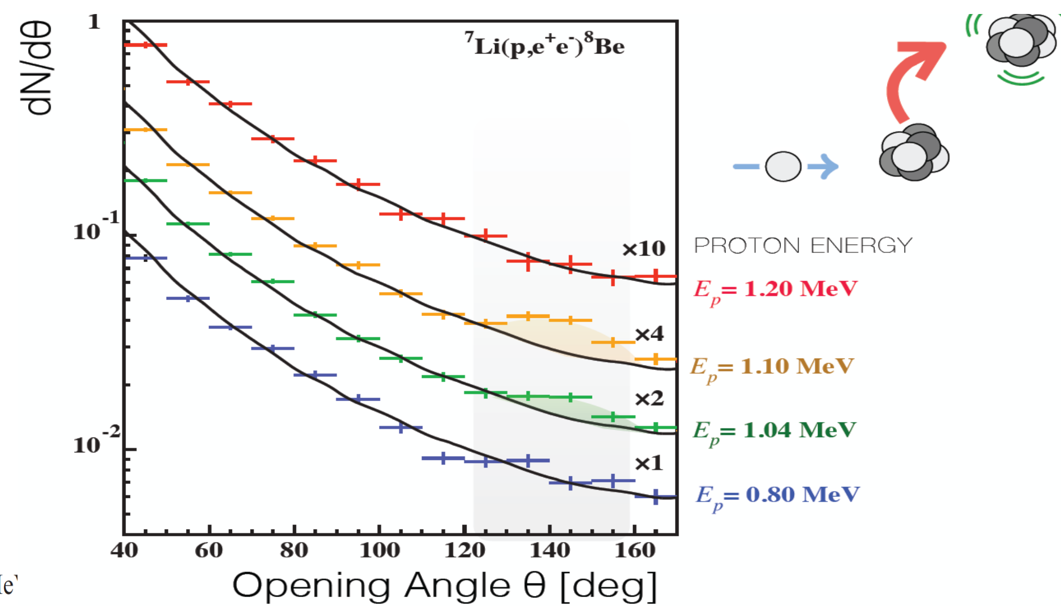
Fayet (2007), Pospelov (2008)

^{8}Be



6.8σ anomaly now seen in two decays

→ milli-charged, 17 MeV boson



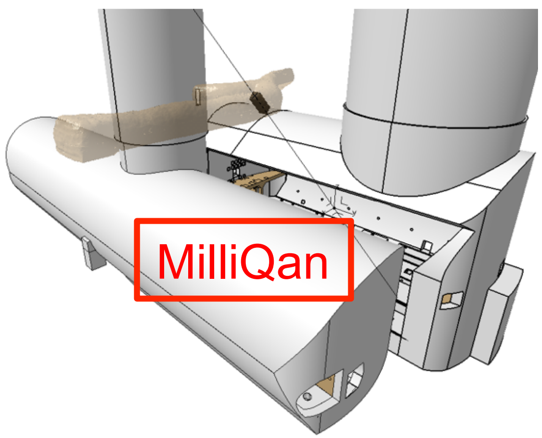
Krasznahorkay et al. (2015, 2017)

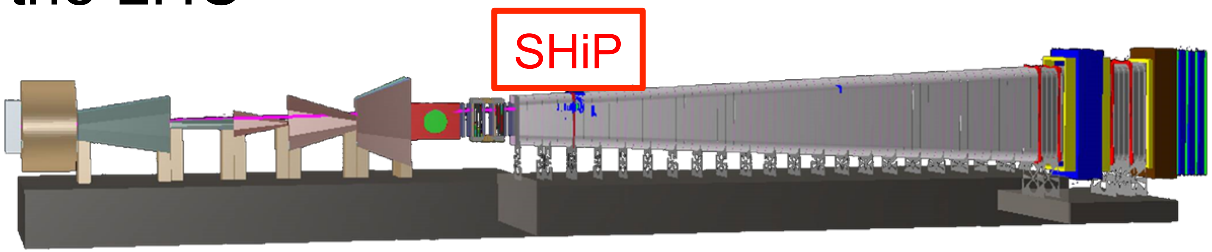
WEAKLY INTERACTING LIGHT PARTICLES AT LHC

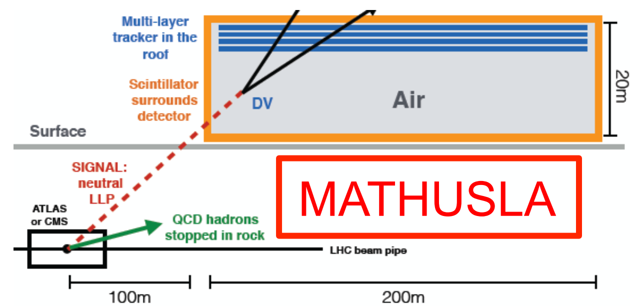
- Weakly interacting light particles, produce striking signals

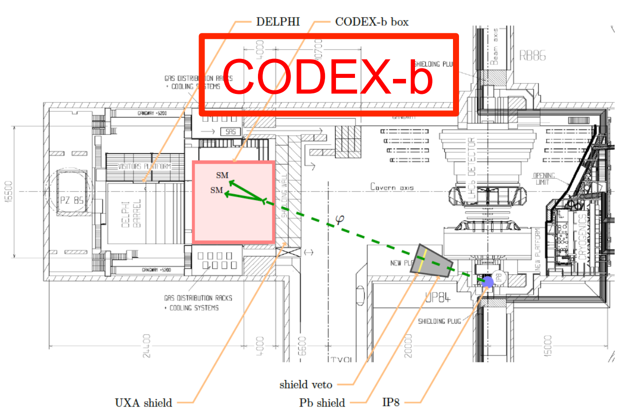
$$pp \to A' X \,, \quad A' \text{ travels } \sim \mathcal{O}(100)\text{ m}\,, \quad A' \to e^+e^-,\, \mu^+\mu^-$$

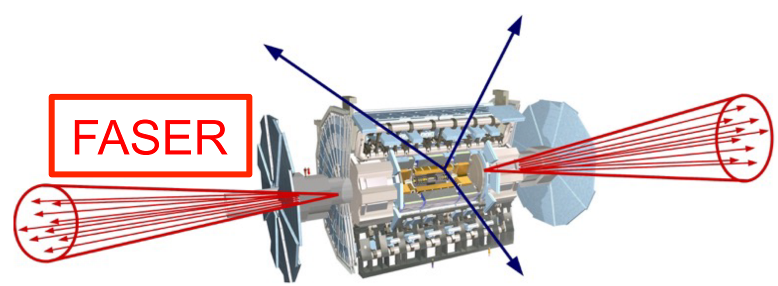
- These have motivated many new proposals for experiments, including some for the LHC







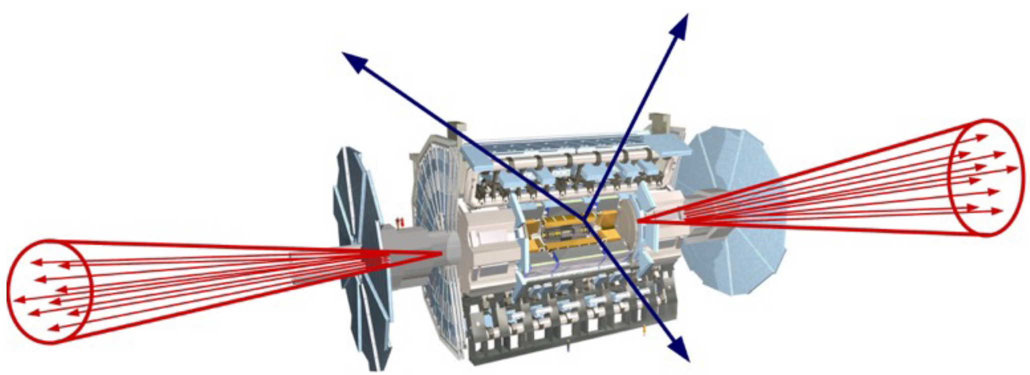




FASER: FORWARD SEARCH EXPERIMENT

Feng, Galon, Kling, Trojanowski (2017)

- New physics searches at ATLAS, CMS focus on high p_T. This is appropriate for strongly interacting, heavy particles
  - σ ~ fb to pb → N ~ 10^3 – 10^6, produced ~isotropically
- However, if new particles are weakly interacting and light, they are predominantly produced at low p_T (e.g., in π, K, B decay), better to look in the forward region
  - σ_{inel} ~ 100 mb → N ~ 10^{17}, $\theta \sim \Lambda_{QCD}$ / E ~ 250 MeV / TeV ~ mrad

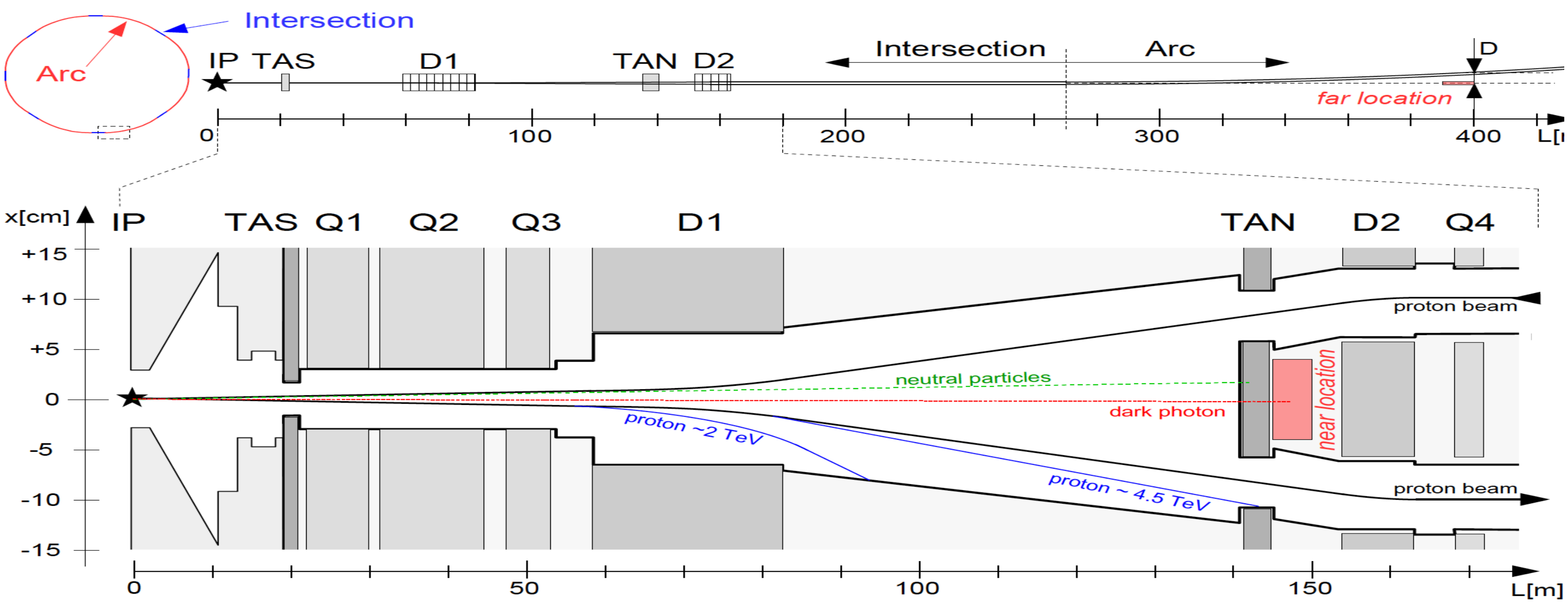


FASER: FORWARD SEARCH EXPERIMENT

- A small, inexpensive detector, appropriately placed, could have great reach. Two "extremes":

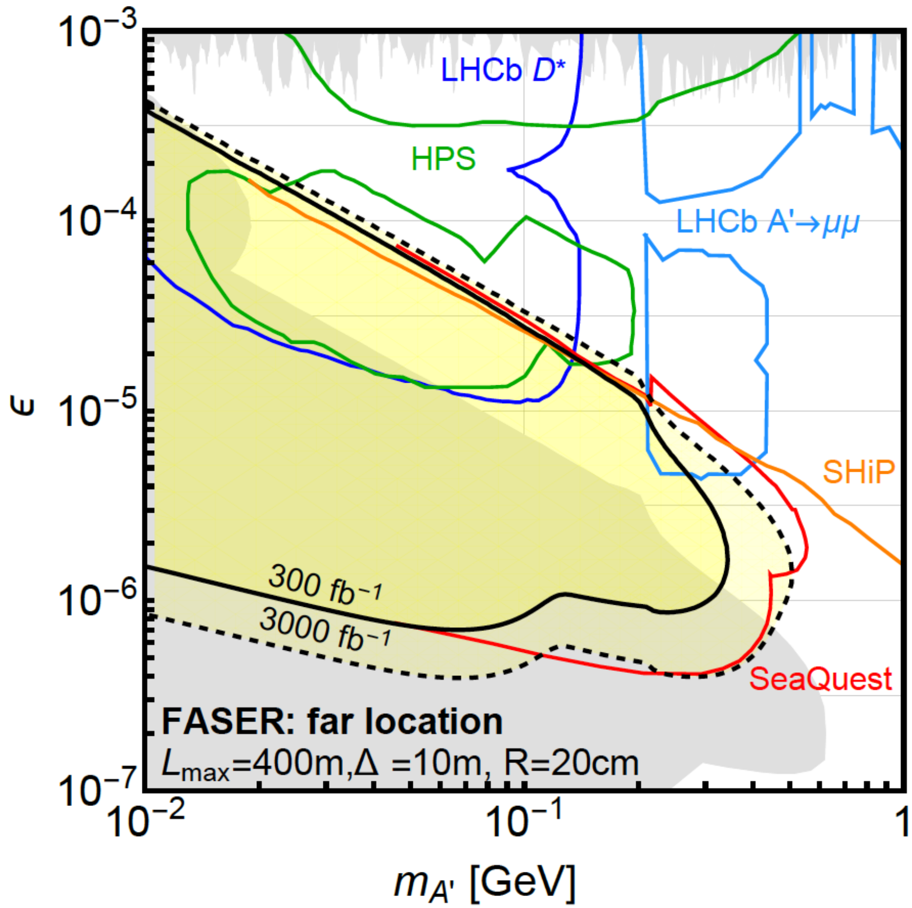
  Near location: 150 m downstream, between the beams

  Far location: 400 m downstream, after the beam curves

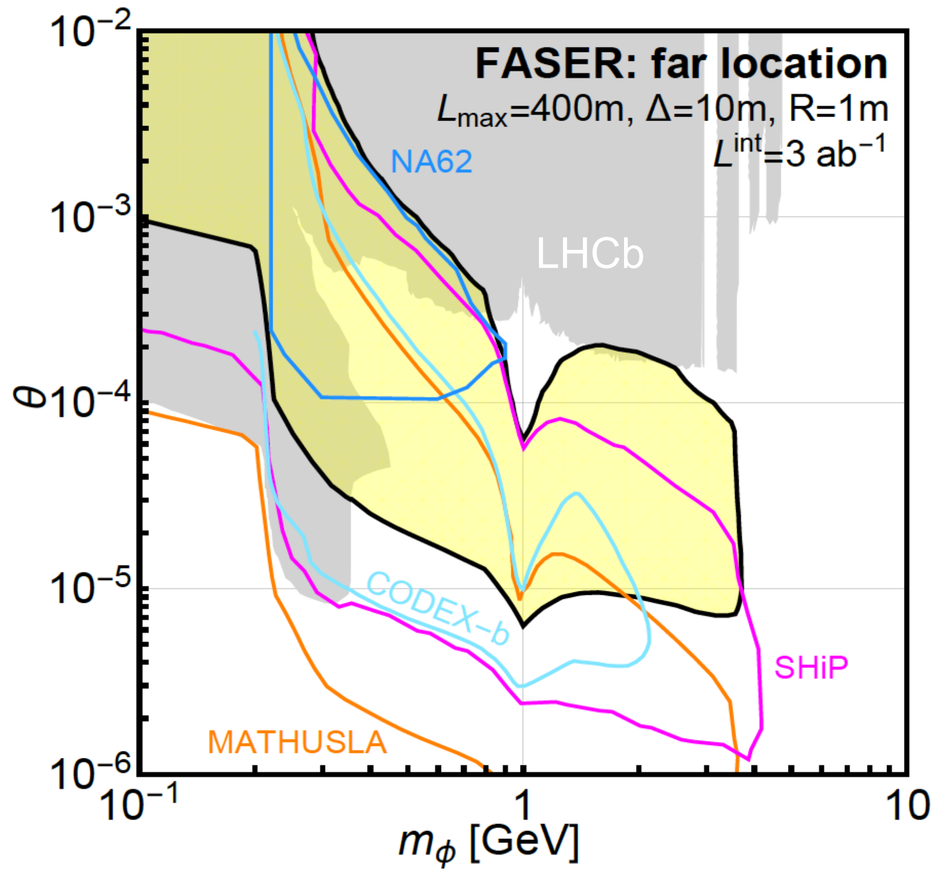


DISCOVERY POTENTIAL

- Dark Photons

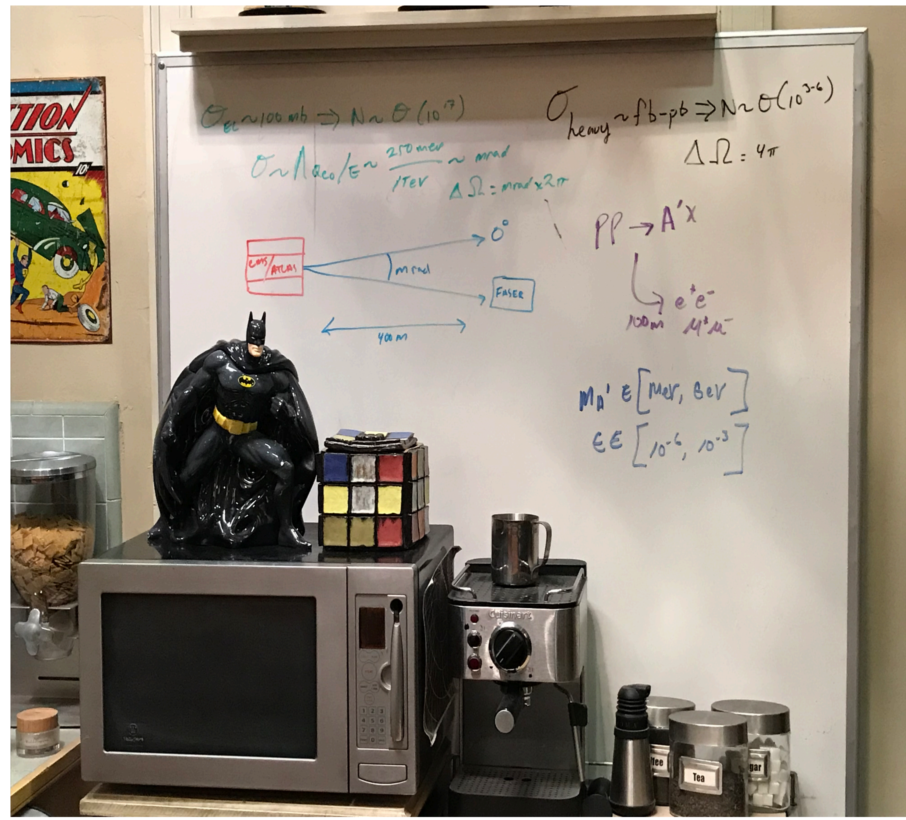


- Dark Higgs Bosons



WEAKLY INTERACTING, LIGHT PARTICLES

- These experiments will significantly extend the discovery potential of the LHC program in the HL-LHC era and they are already attracting the attention of some of the world's best known physicists



Leonard and Sheldon from "The Big Bang Theory" !

CONCLUSIONS

- We have many deep and important problems
- The current lack of one dominant paradigm for their solution is leading to a flowering of creative theoretical ideas
- Many new connections between theory and experiment
- Many new connections to other fields