Particle Physics: A Roadmap to Discovery

Tim M.P. Tait

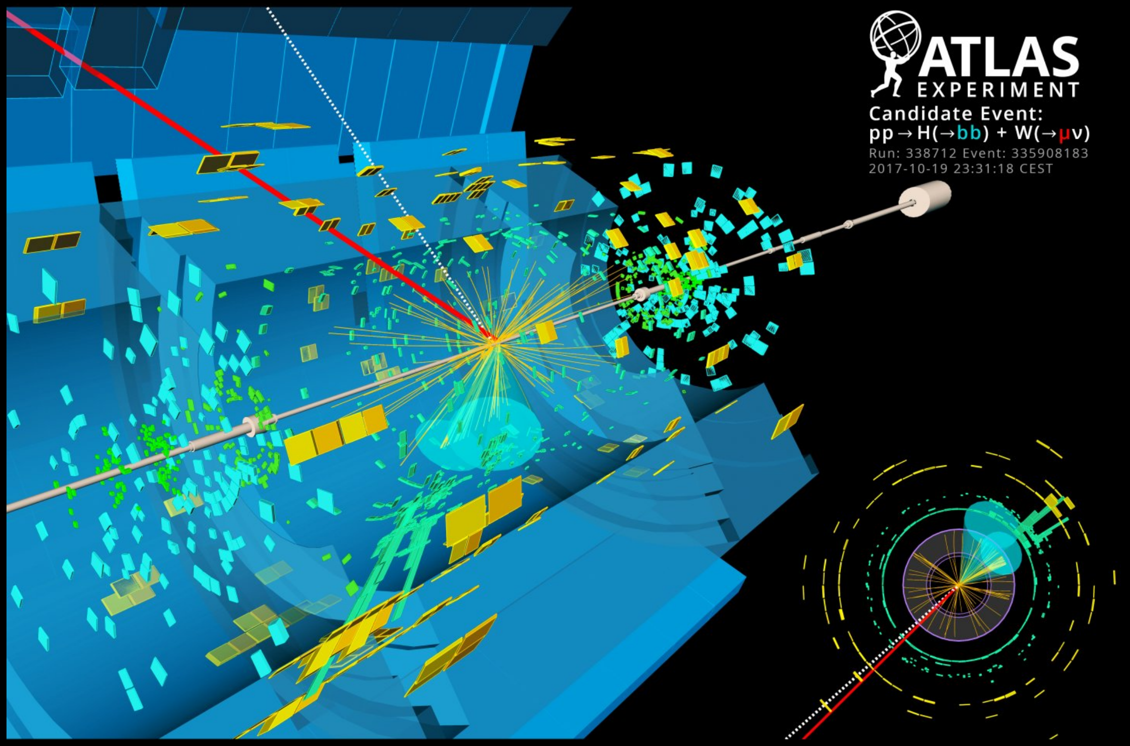
University of California, Irvine

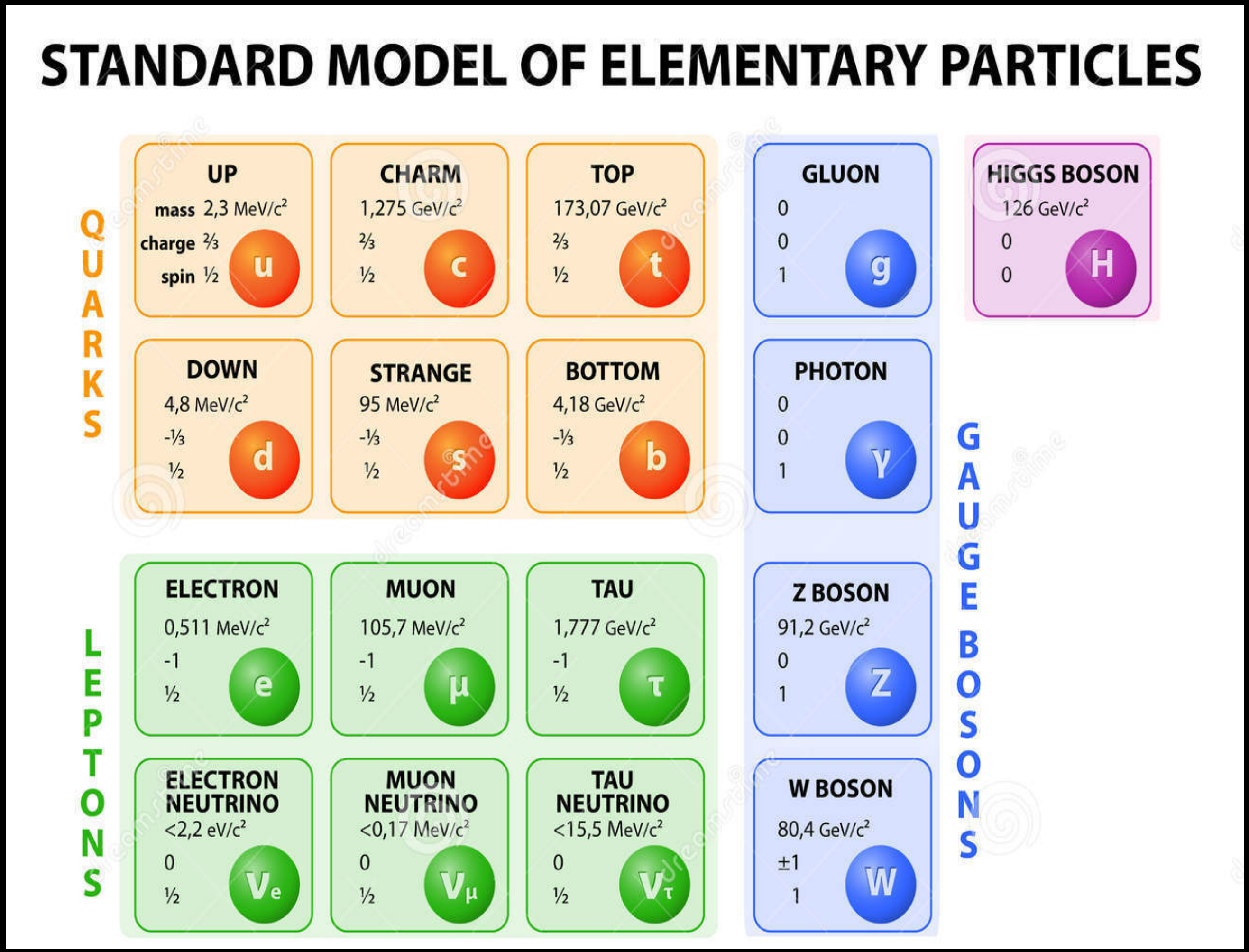
TRIUMF Science Week
August 19, 2020

Justice for Breonna Taylor
#SayHerName

The State of the SM

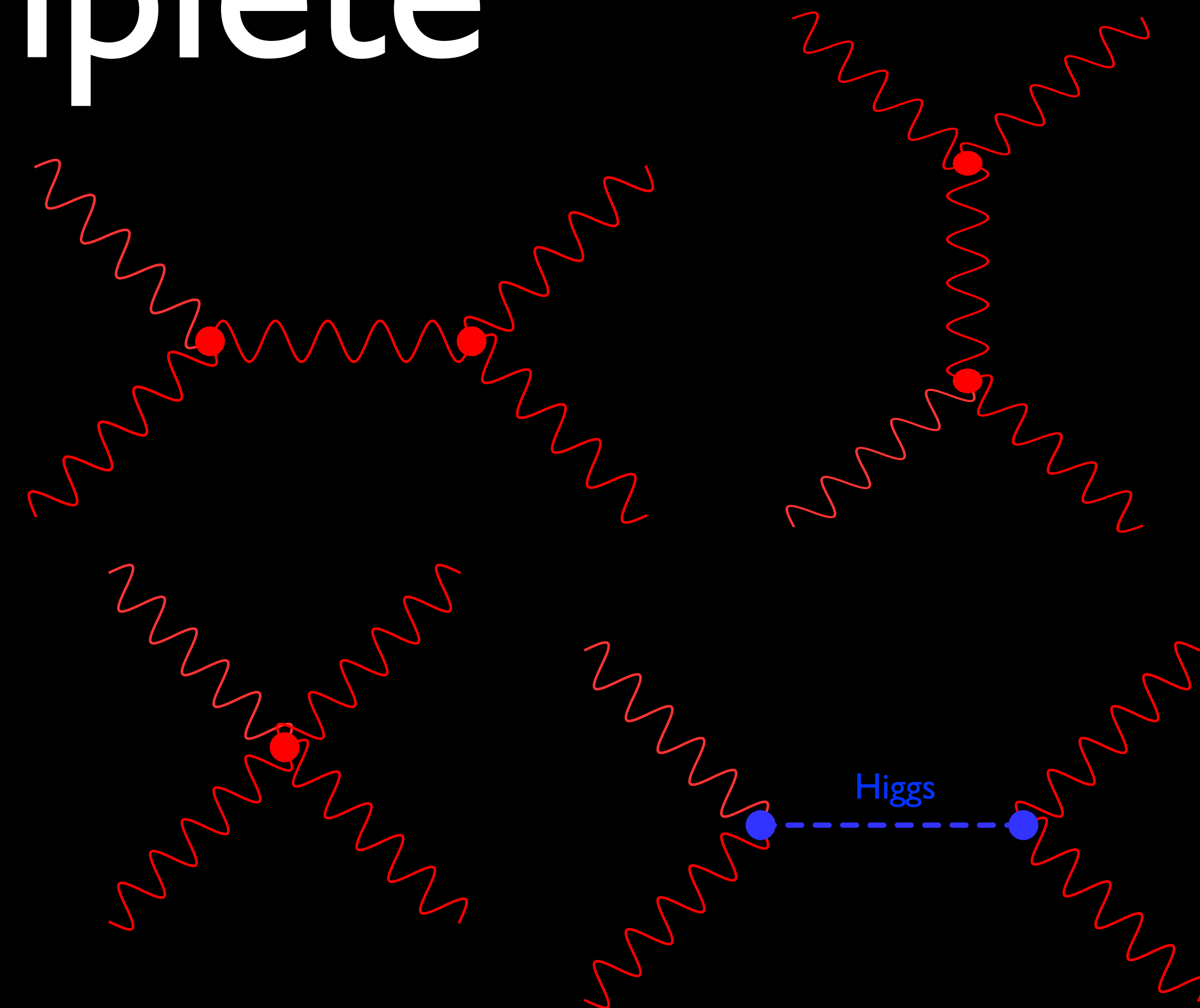
- The Higgs boson was the last missing ingredient in the Standard Model of particle physics.
- Its discovery in 2012 at the LHC was an amazing triumph of accelerator and detector design and operation, experimental search technique, and theoretical prediction.
- The Higgs is the remnant of the construction which preserves the gauge invariance that is necessary to have a consistent description of the electroweak interactions while allowing for massive particles.

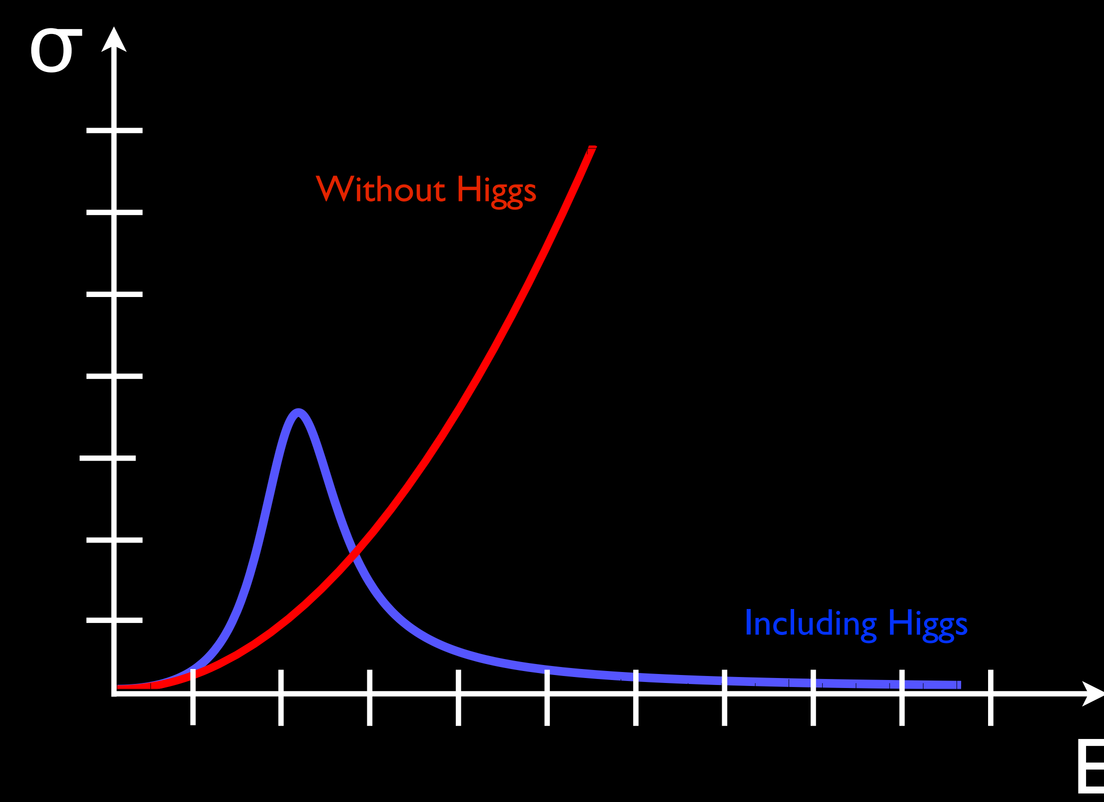




UV Complete

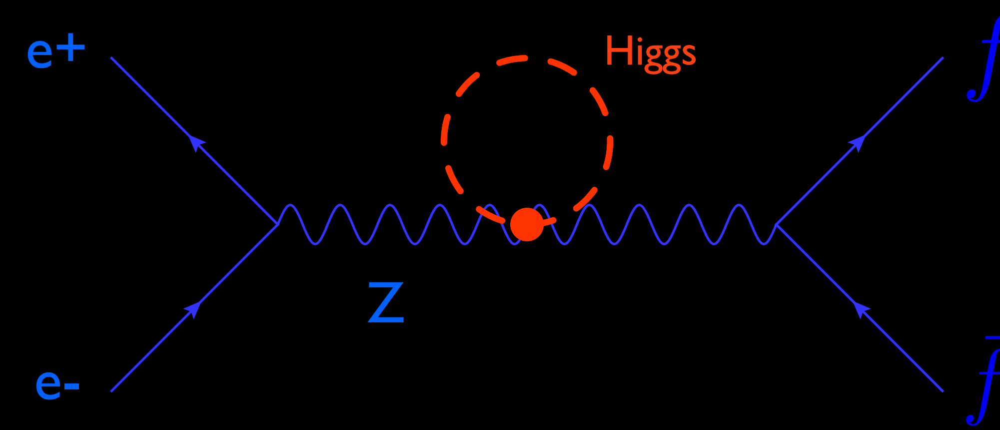
- The Higgs `UV completed' the Standard Model.
- Without it, the scattering of the weak force carriers grows with energy, and eventually becomes inconsistent with quantum mechanics because the probability of scattering ("something happening") grows larger than 100%.
- That is a clear sign that something is missing, and it tells us that the SM without the Higgs cannot be the whole story up to arbitrarily high energies.
- With the Higgs included, the rate of scattering drops at high energies, giving us a 'complete theory in the ultra-violet.'



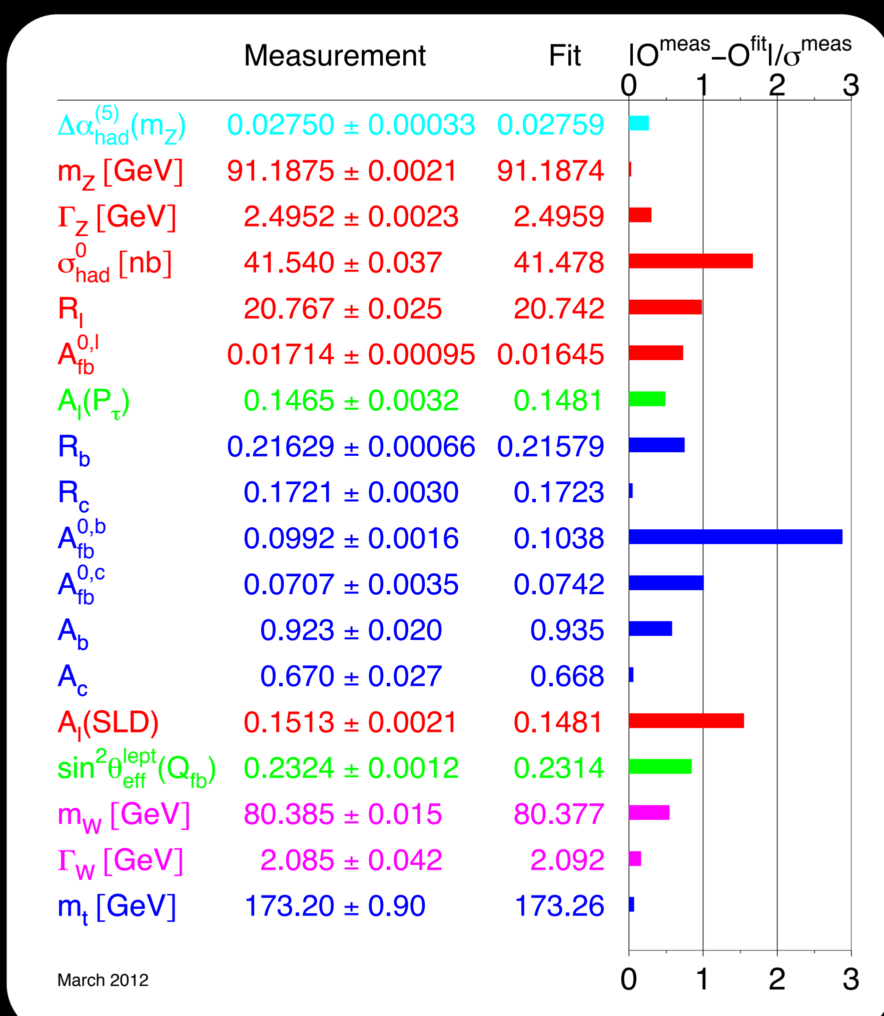


125 GeV is the right place

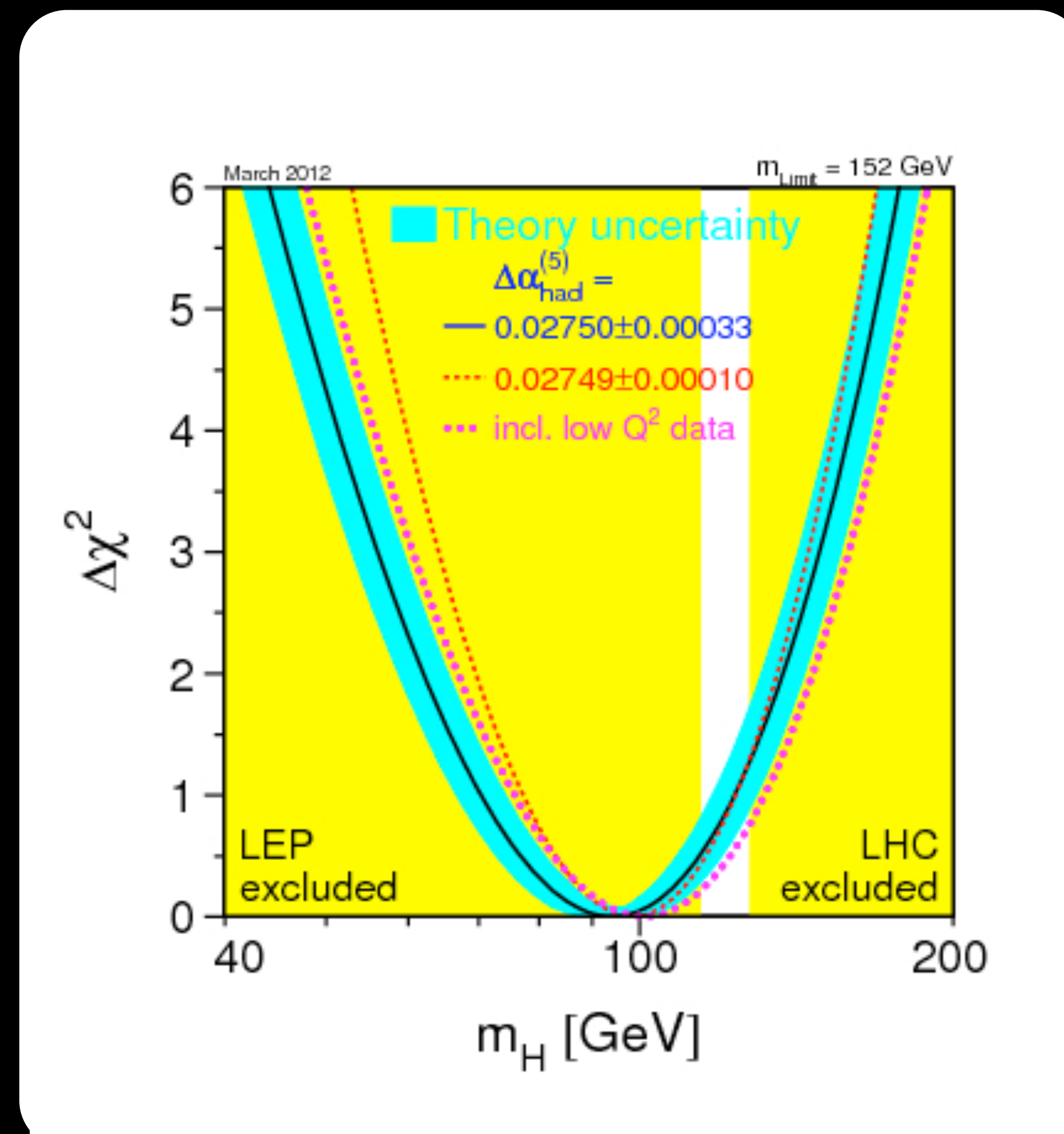
- Precision measurements of the properties of Z bosons by LEP were sensitive to virtual Higgs bosons, and as a result depended weakly on its mass.



- The combined data favored a Higgs mass between about 50 and 150 GeV.



	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02750 ± 0.00033	0.02759
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ_{had}^0 [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.385 ± 0.015	80.377
Γ_W [GeV]	2.085 ± 0.042	2.092
m_t [GeV]	173.20 ± 0.90	173.26



Some Historical Perspective

- The current situation in particle physics is reminiscent of an earlier chapter in the history of Physics.
- At the beginning of the 20th century, Lord Kelvin addressed the British Association for the Advancement of Science:

> "The beauty and clearness of the dynamical theory, which asserts heat and light to be modes of motion, is at present obscured by two clouds. I. The first came into existence with the undulatory theory of light, and was dealt with by Fresnel and Dr Thomas Young; it involved the question, How could the earth move through an elastic solid, such as essentially is the luminiferous ether? II. The second is the Maxwell-Boltzmann doctrine regarding the partition of energy."
>
> --William Thomson, April 27, 1900

- Kelvin observed that almost all of the physical phenomena of his time could be described by Newton's laws (including gravitation) and classical Electromagnetism.
- Two experimental results ("clouds") famously did not quite fit in.

Kelvin’s Clouds

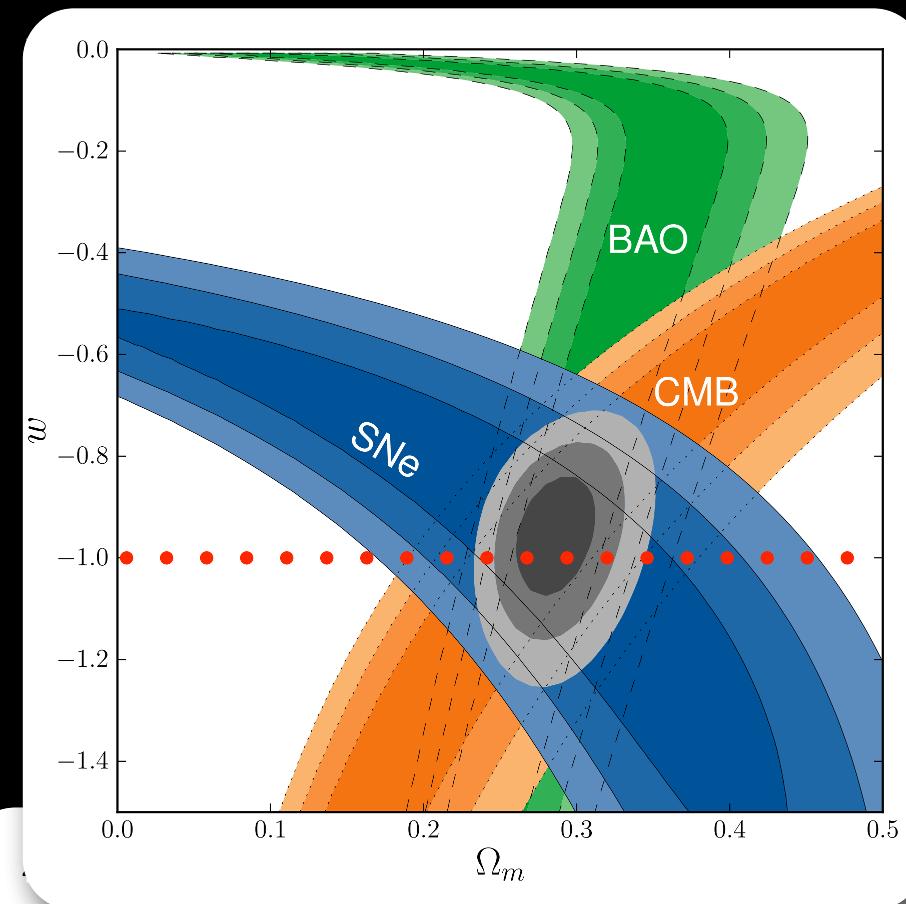
- Kelvin’s two clouds were what seemed like an inconsistency in the properties of the luminiferous ether (through which EM waves supposedly propagated) and the observed spectrum of thermal radiation from a blackbody.
- Today we know that the first was a hint leading to Einstein’s special relativity.
- The second was an initial manifestation of quantum mechanics.
- Both of these “small” hints that we did not quite have the whole picture eventually grew to redefine and subsume everything that we thought we knew.

So What Clouds Do We See?

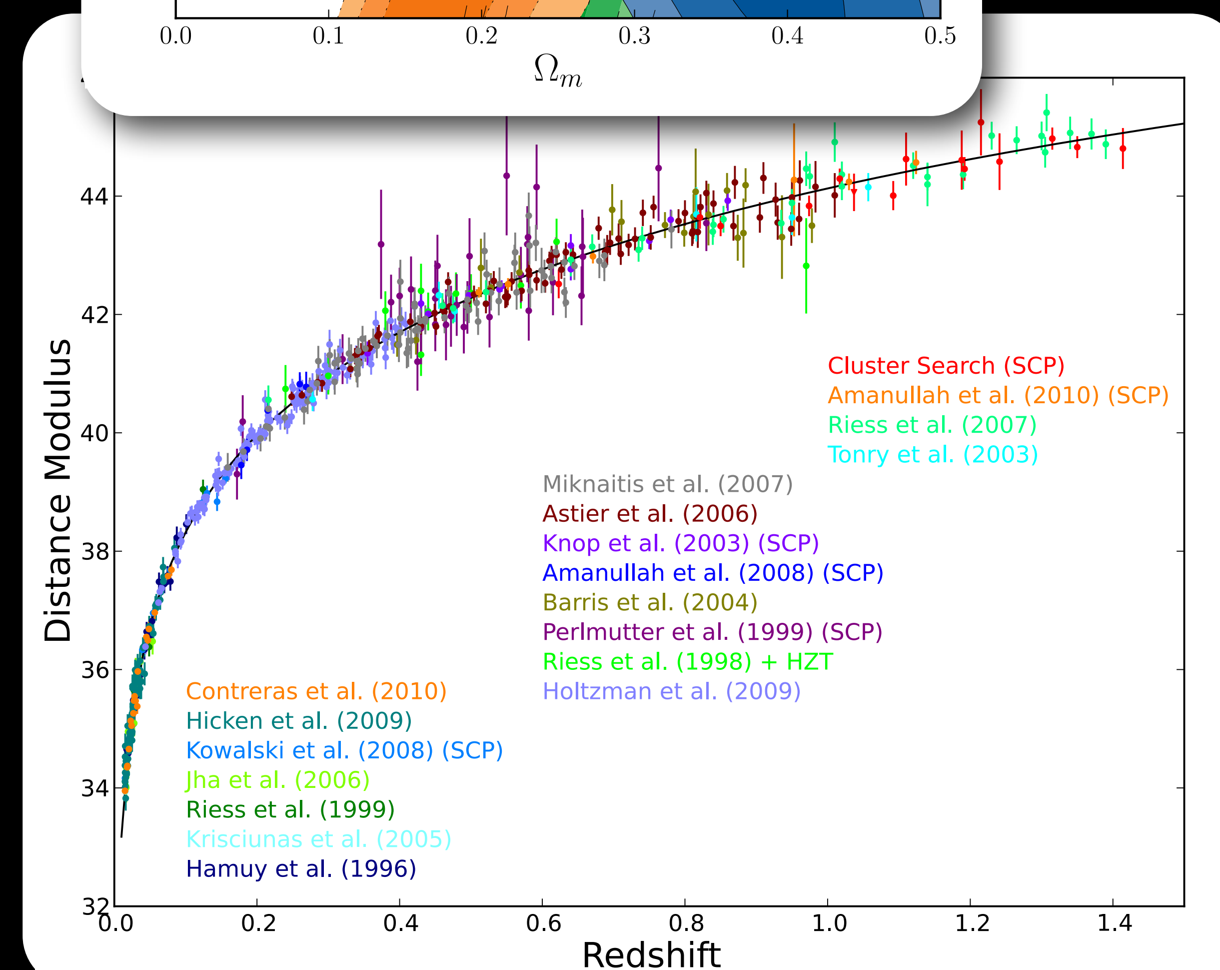
Corona Del Mar, California

Accelerating Universe

- Looking at larger scales, the Universe contains big surprises.
- Cosmological arguments based on the flatness of the Universe and the uniformity of the CMB argue that at early times, the Universe went through a period of inflation.
- Observations today from supernovae and the cosmic microwave background indicate that a large fraction of the Universe is in the form of dark energy, causing its expansion to accelerate.
    - We don't know if this represents something static like a cosmological constant, or some kind of dynamically evolving quantity.



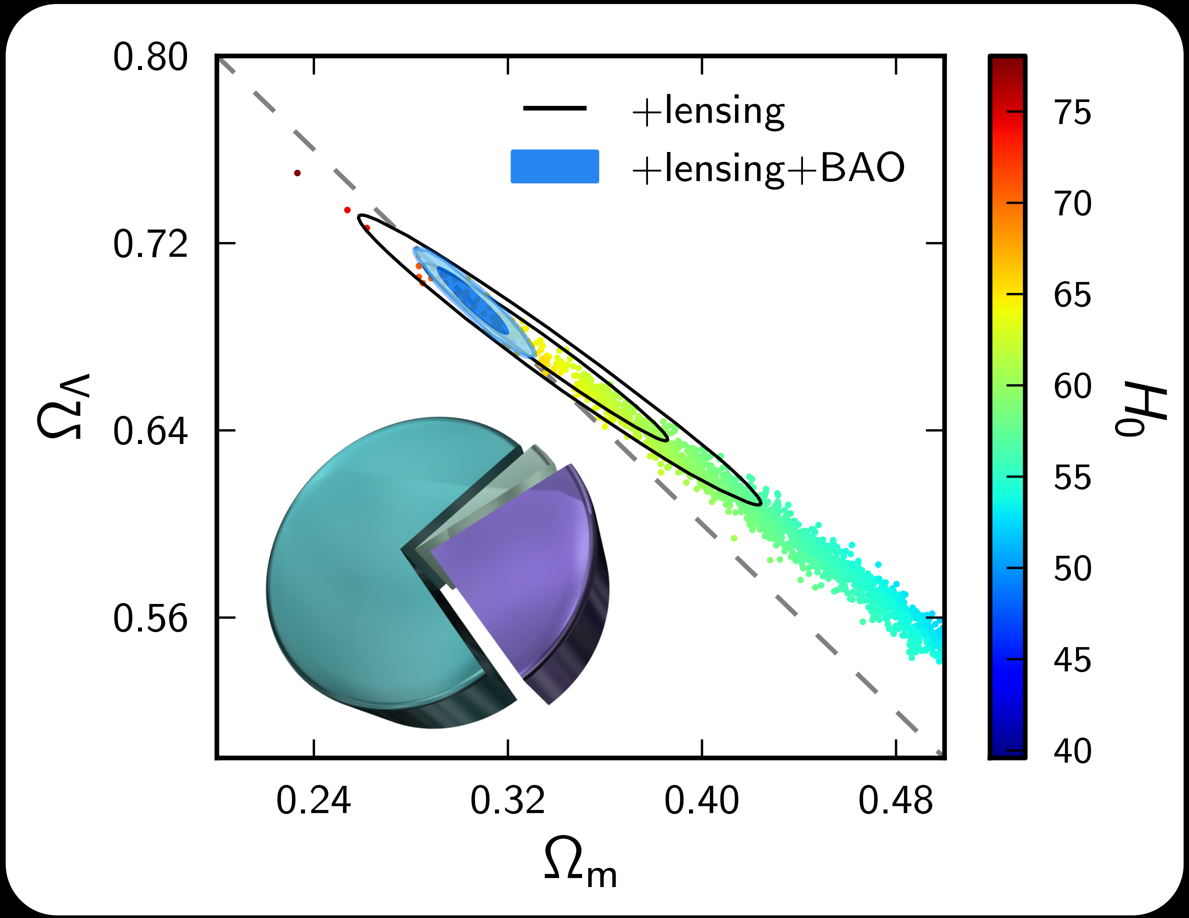
1105.3470



Dark Matter

1303.5076

- Dark energy is not the only dark component of the Universe.
- A wide range of evidence indicates most of the matter in the Universe is some kind of non-baryonic massive particle.
  - Rotation curves/Motion in clusters
  - Power spectrum of the CMB
  - Distribution of large scale structure
- Nothing in the SM has the right properties to explain the observations, arguing for the need for some kind of new particle in the theory.
  - But what particle? What are its mass and spin? Is it weak-charged? Does it have a notion of flavor?!

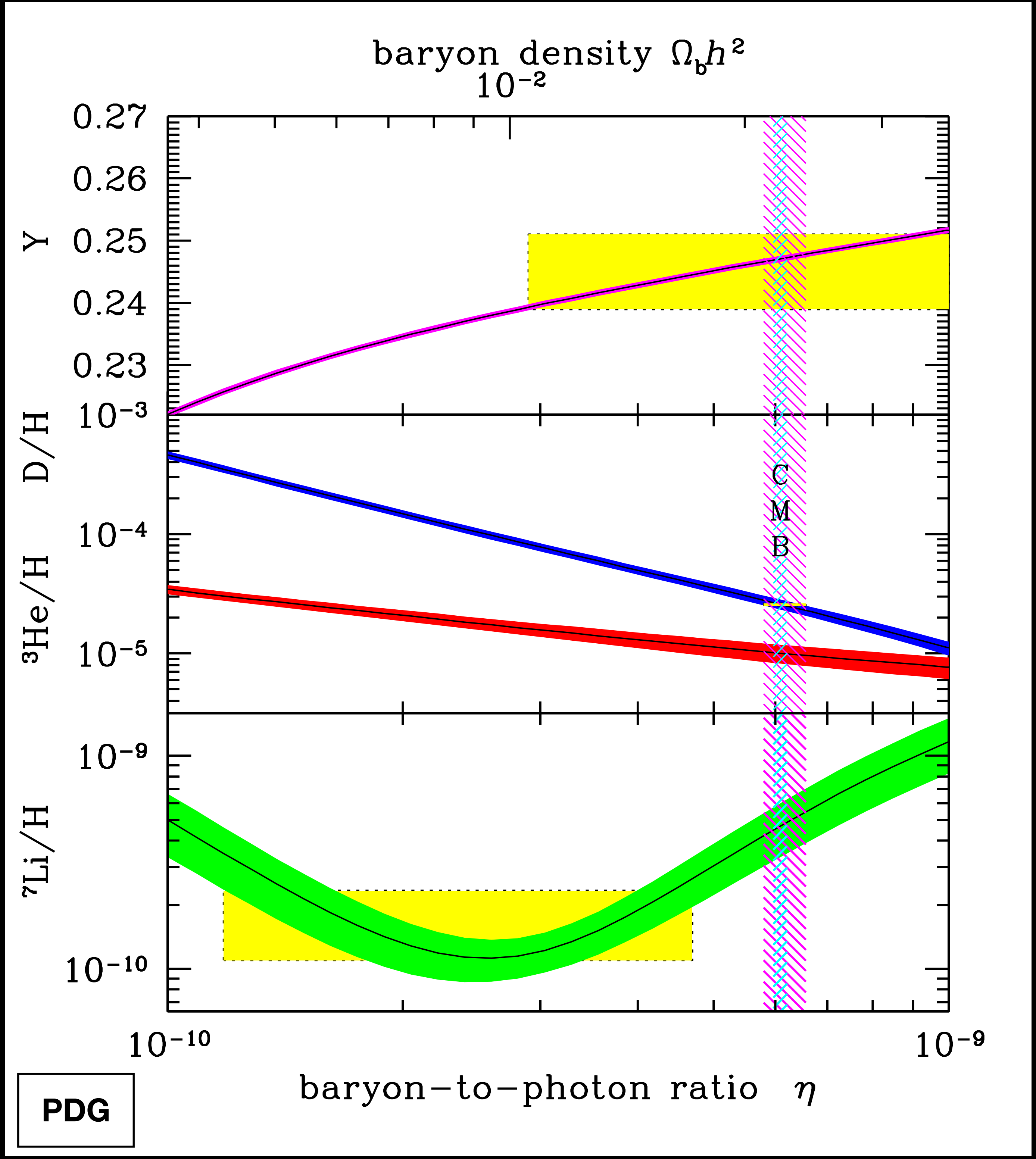


$69.99 for 20 servings

astro-ph/0608407

Baryon Asymmetry

- Even the visible sector of the Universe argues that the Standard Model is incomplete.
- Our Universe is made out of matter, and not anti-matter. This is evident from a host of observations, including:
  - Cosmic rays
  - Abundances of light primordial elements.
  - CMB
- The need for inflation argues that this is unlikely to be an initial condition of the Universe.



$$\eta_B \equiv \frac{n_B}{s} = 9.2^{+0.6}_{-0.4} \times 10^{-11}$$

Sakharov Conditions

Generating a baryon asymmetry from a baryon symmetric starting point requires very particular physics:

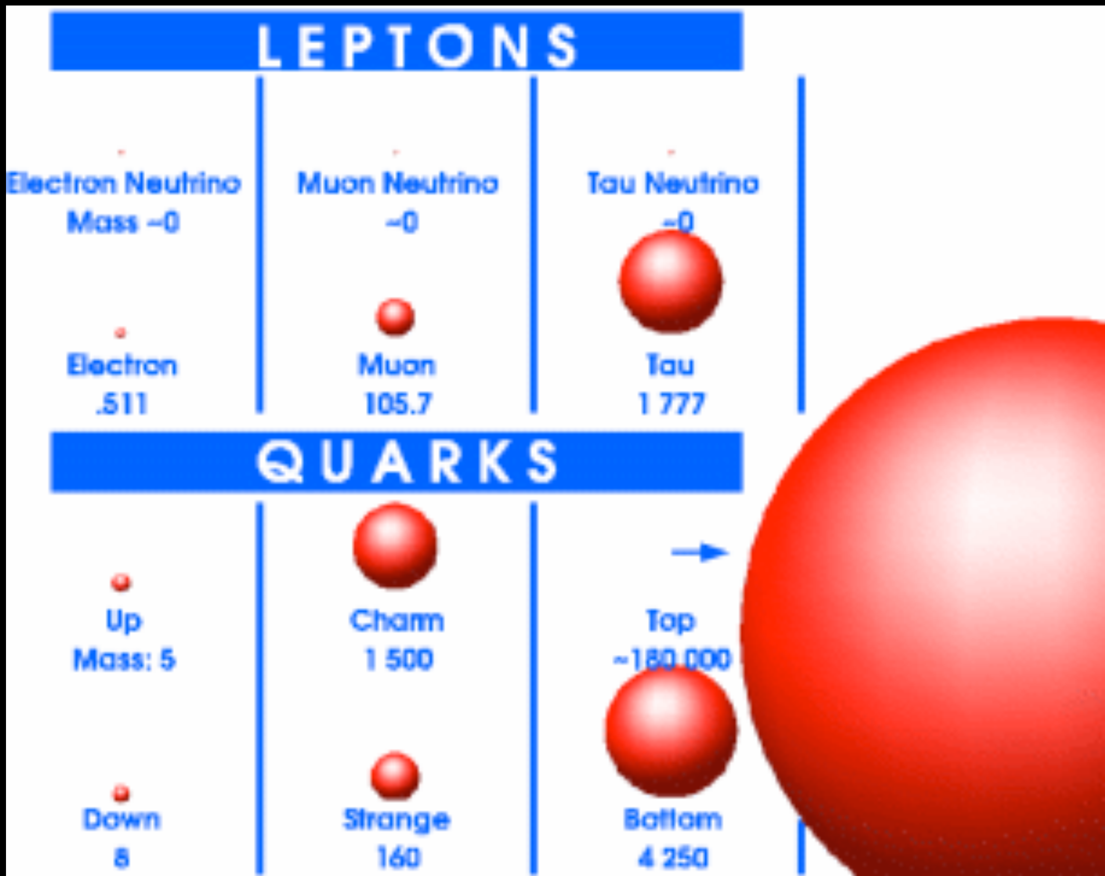
1. **B Violation:** If we can't generate baryon number ("B") through some process, we are dead in the water.
2. **C and CP Violation:** Essentially, if we don't violate C and CP, the sum of all baryon-violating processes will still result in no net baryon number.
3. **Out of Equilibrium:** If the processes which violate B are in equilibrium, the reverse processes will cancel out the B generated.

The Standard Model contains these ingredients in some measure, but cannot satisfy any of the three sufficiently to explain the asymmetry we observe.

Flavor and Neutrino Masses

- The SM has three generations of fermions, each with two quarks and two leptons.
- There is a huge variation in the masses of the fermions, ranging over many orders of magnitude and mixing to different degrees.
- So why are there three generations? What decided the pattern of masses we see and how much they mix?
- A related question is : why does the strong force seem to conserve CP? Is this a hint we need a PQ symmetry and axions?
- If there is some kind of dynamics that controls flavor, it may reveal itself as an unexpected kind of flavor violation not captured by the SM's description of mixing.

Neutrino masses are particularly mysterious -- the SM predicts that they should be zero! When we modify it to allow for them, we find two solutions which differ as to whether neutrinos are their own anti-particles : which one is correct?



More Clouds than Sky?

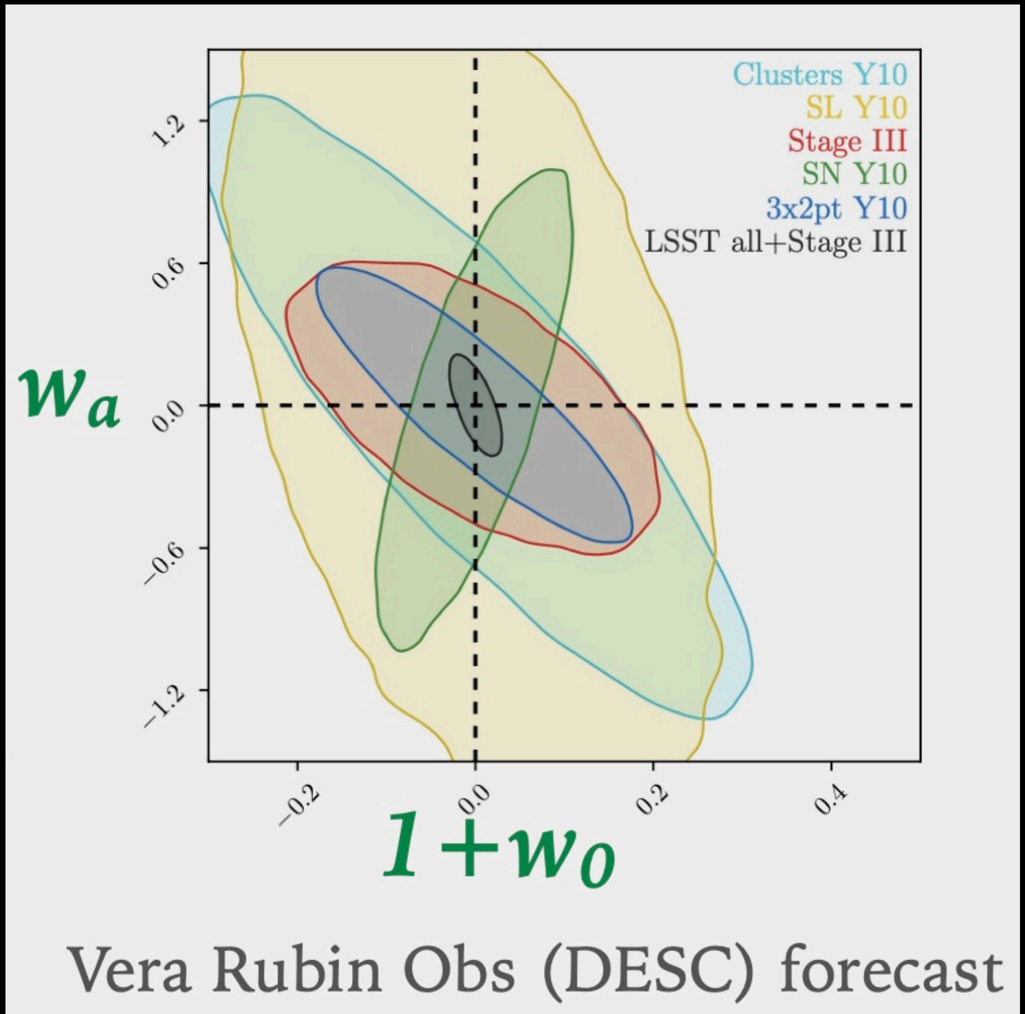
Sydney, Nova Scotia

More Clouds than Sky?

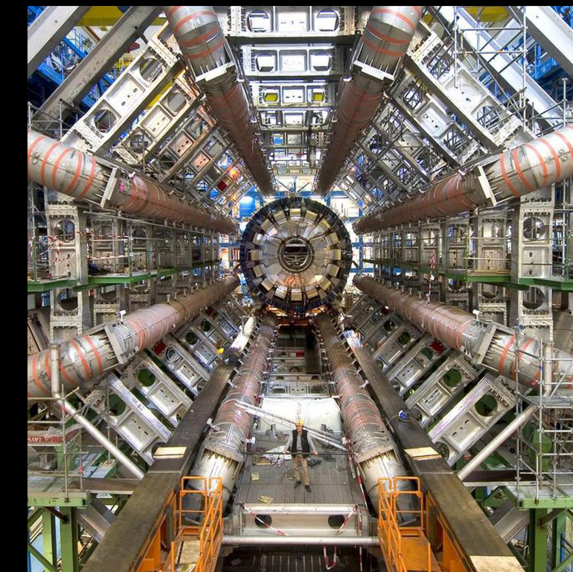
Sydney, Nova Scotia

Probing Dark Energy

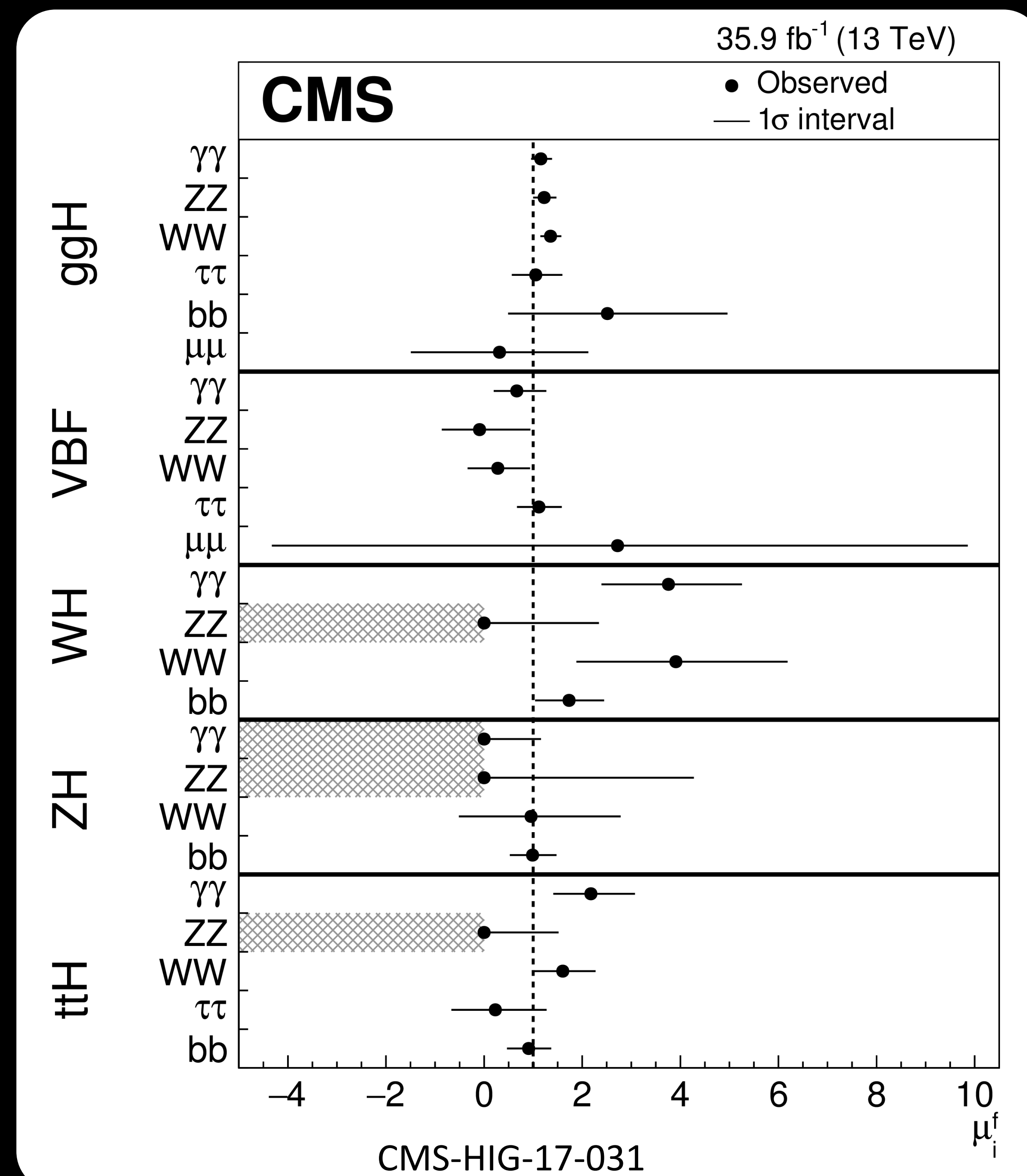
- Future observations can shed light on the nature of dark energy.
- If it is changing with time, its history can reflect itself in the formation and distribution of galaxies.
- Future telescopes are poised to lead the way to better understanding!



Higgs Properties

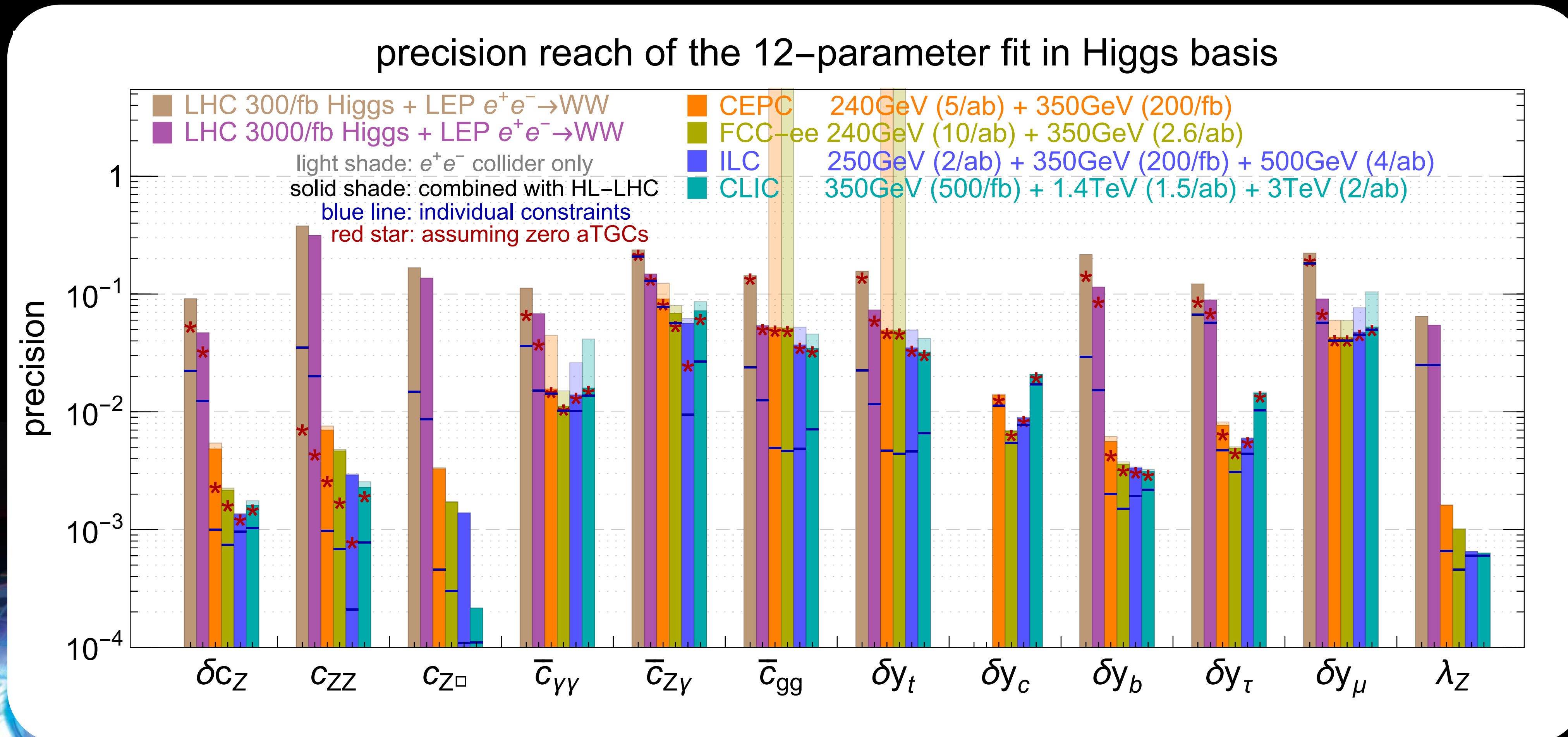


- The LHC and other future collider still have plenty to teach us about the properties of the Higgs boson.
- So far, the LHC has produced around a million Higgs bosons.
- Its high luminosity upgrade will produce more than ten times more and allow one to achieve better precision and to search for more rare processes.
- A future linear e+e- collider would provide a precision environment that could lead to unparalleled precision in determining the Higgs mass and interaction strengths.

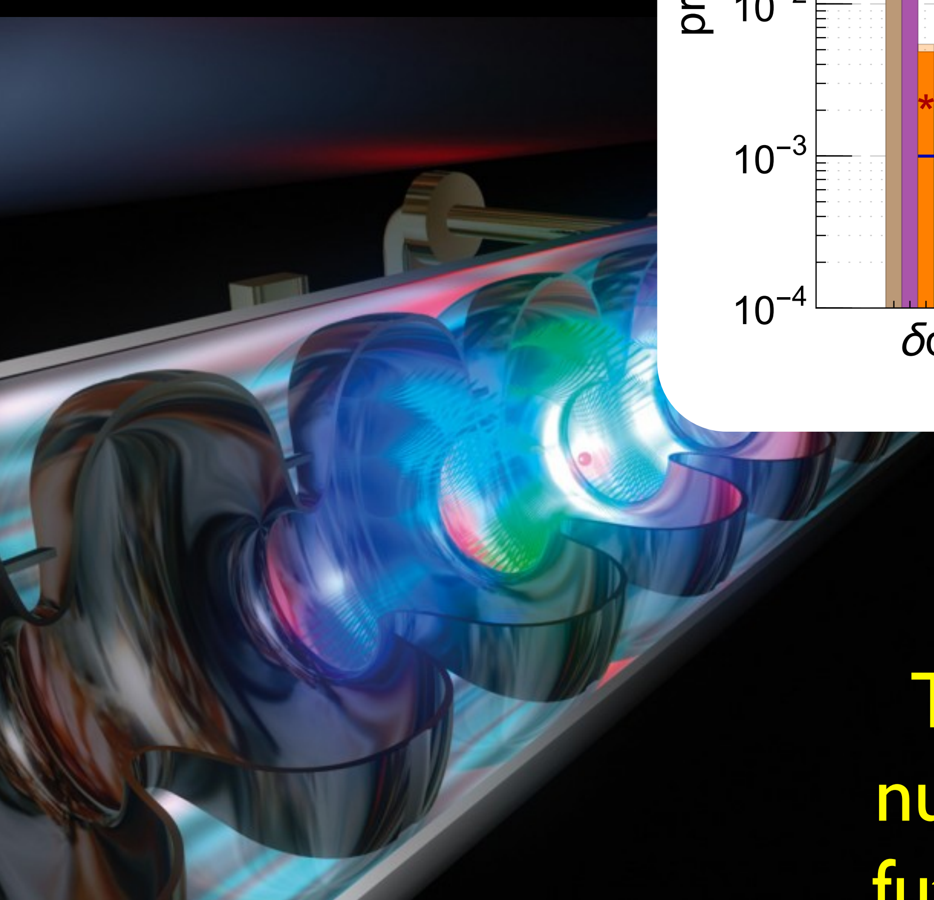


(Similar results from ATLAS)

Lepton Colliders



1704.02333

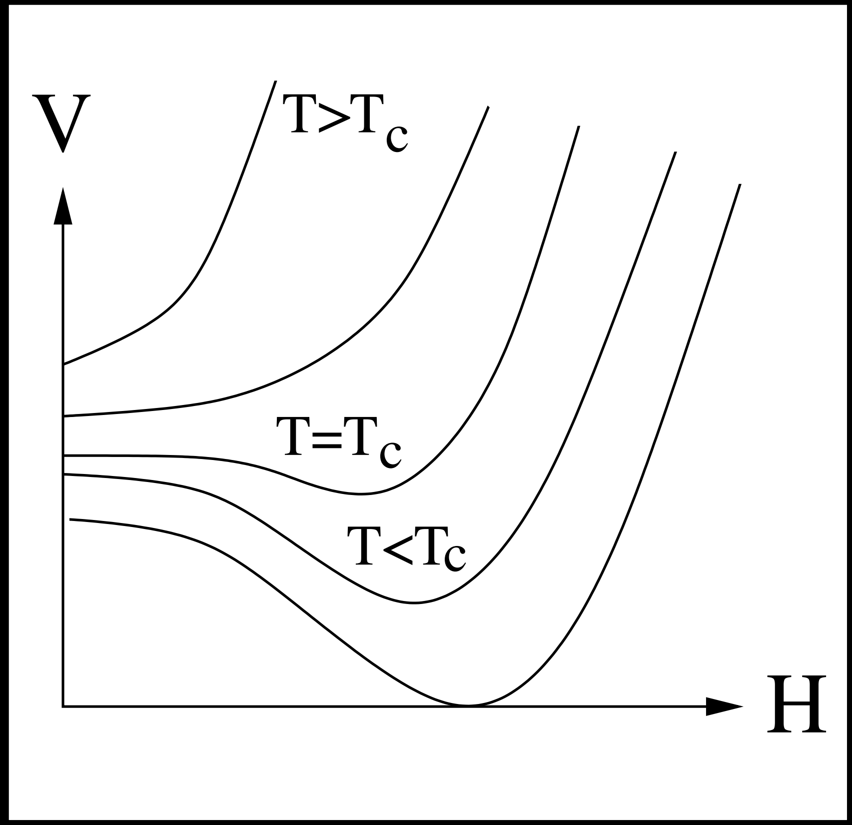


The LHC will achieve ~10% measurements of a number of key interactions of the Higgs boson. A future lepton linear collider like the ILC could get down to a few % for all of them, and to ~0.1% for some of them!

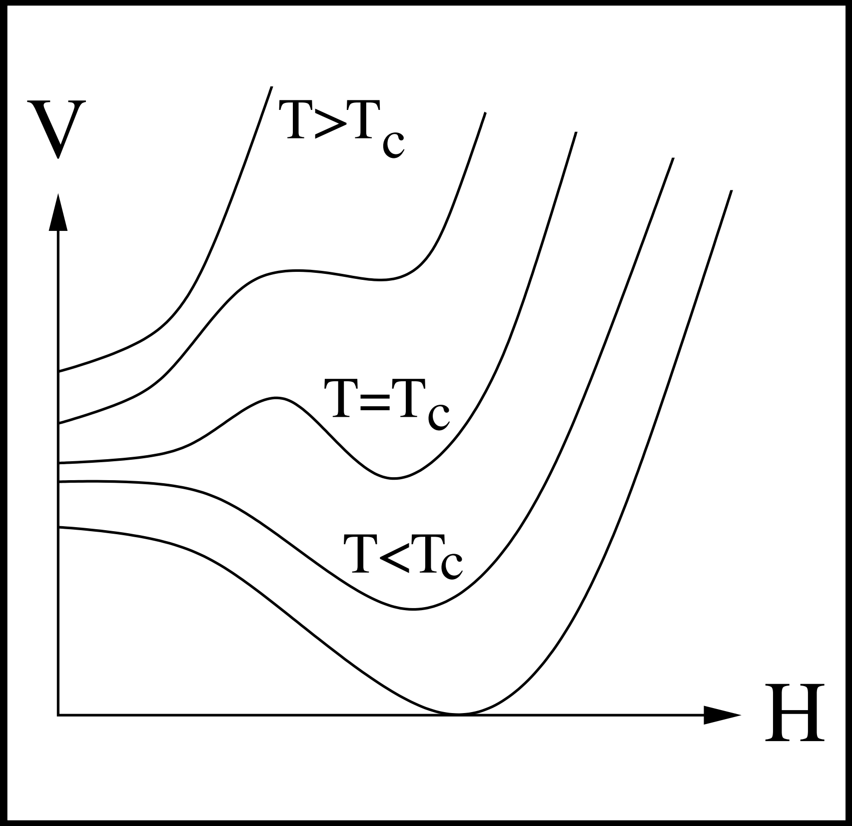
Higgs Self-Coupling

- One particular quantity of dramatic importance is the Higgs self-interaction.
- Modifications from the Standard Model impact the Higgs potential, and thus the cosmological transition from the electroweak symmetric to broken phases.
- If this phase transition is involved in baryogenesis, it should be modified from the SM prediction that it is a cross-over to one providing the out-of-equilibrium condition.
- Higgs pair production is a powerful test of modifications to these couplings, and should be visible at an upgraded LHC.

Cross-over (SM prediction)

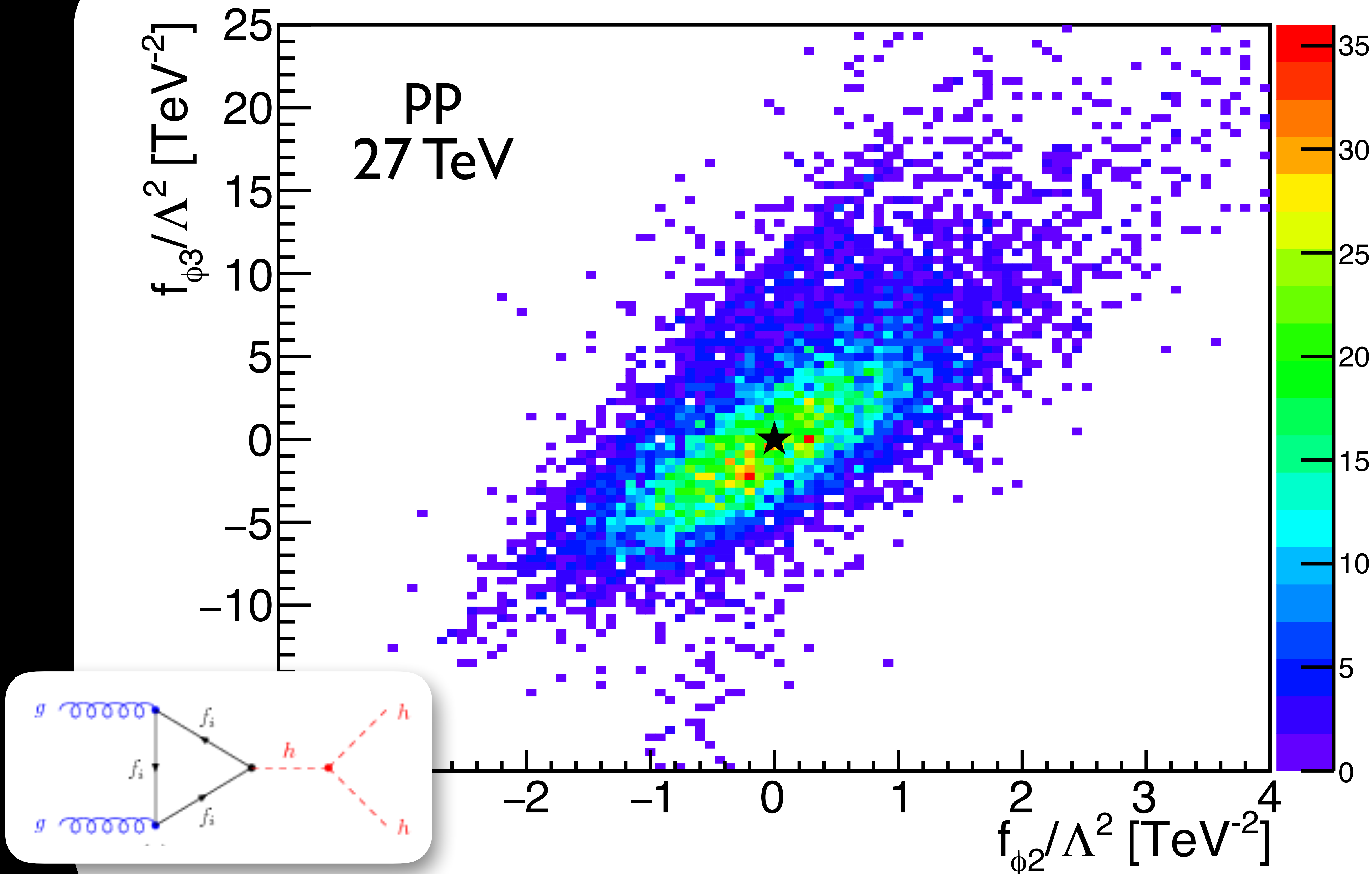


1st Order (needed for electroweak baryogenesis)

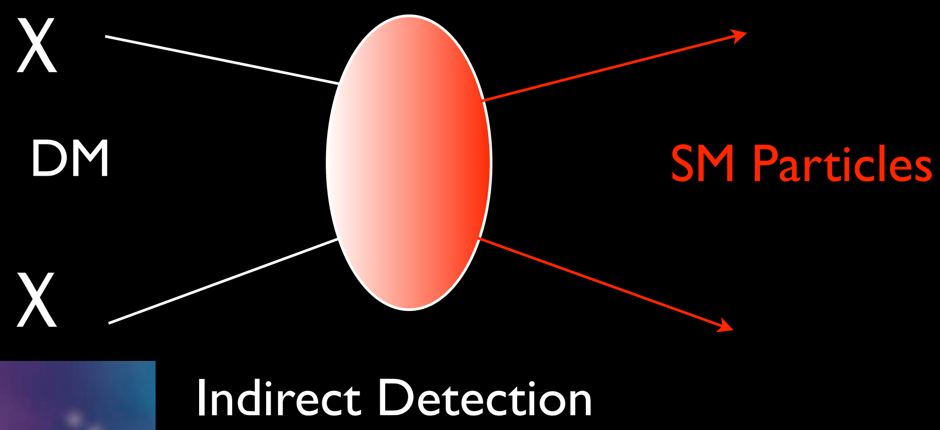


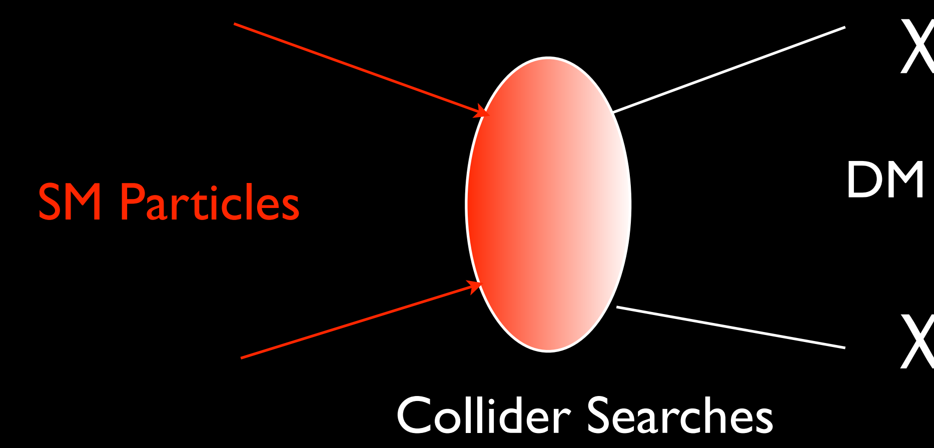
Higgs Self-Coupling

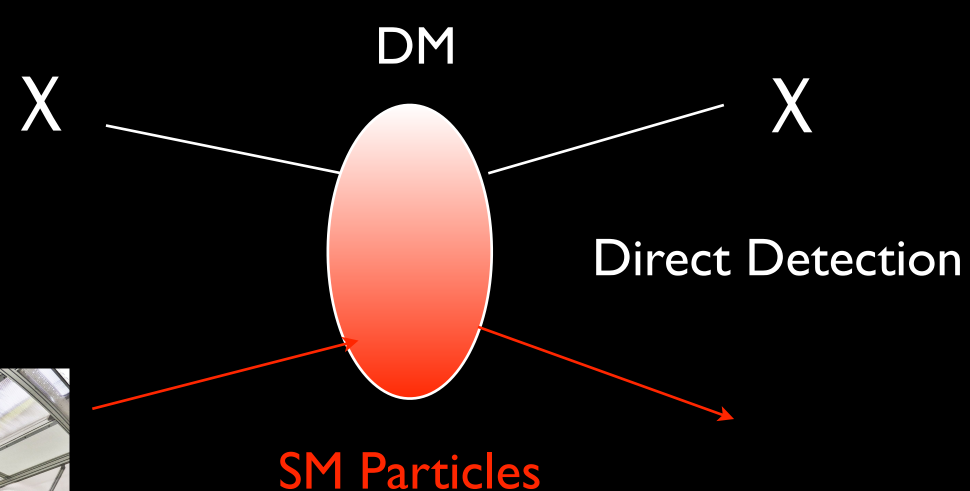
1811.08401



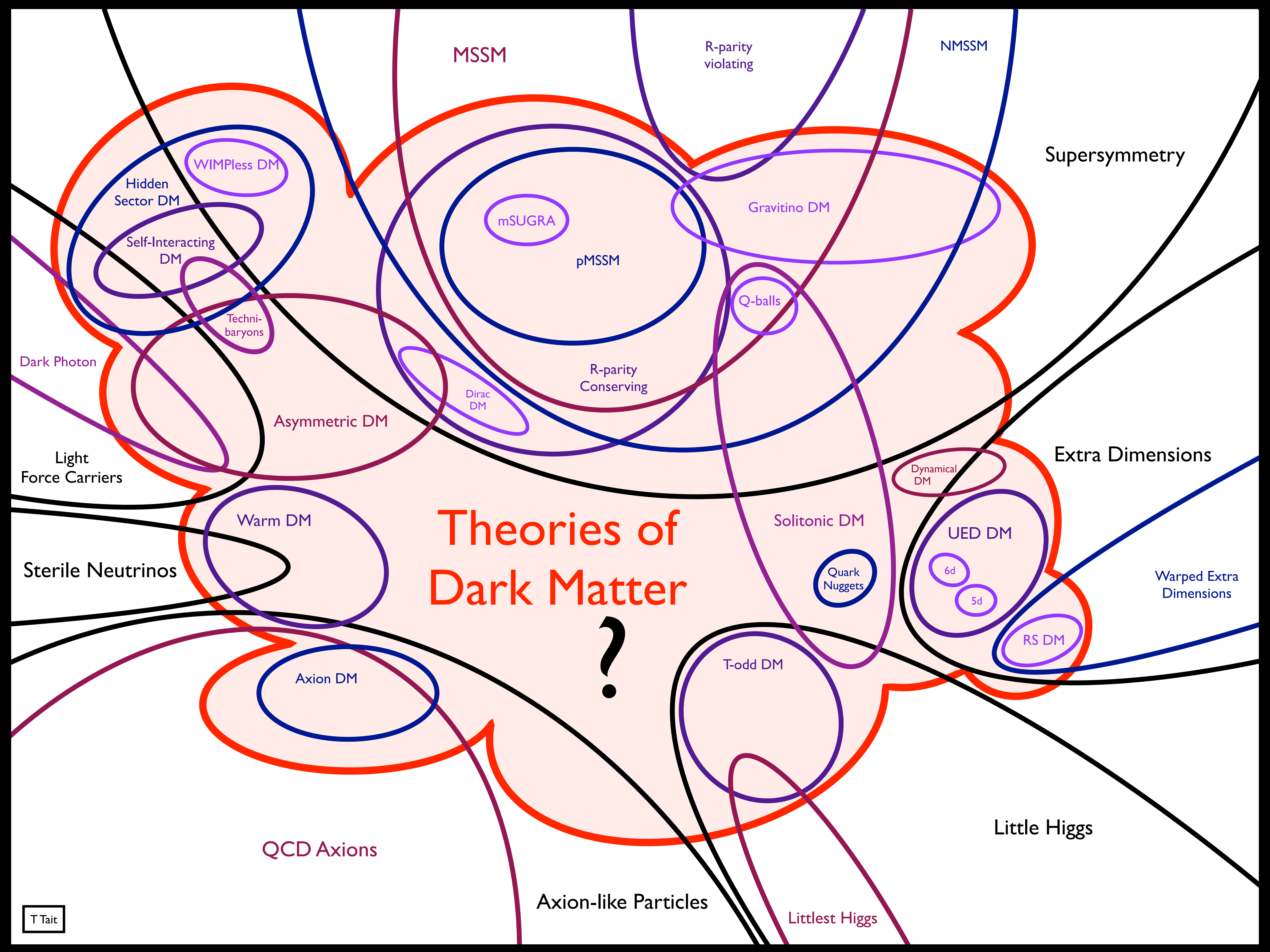
Searches for Particle Dark Matter





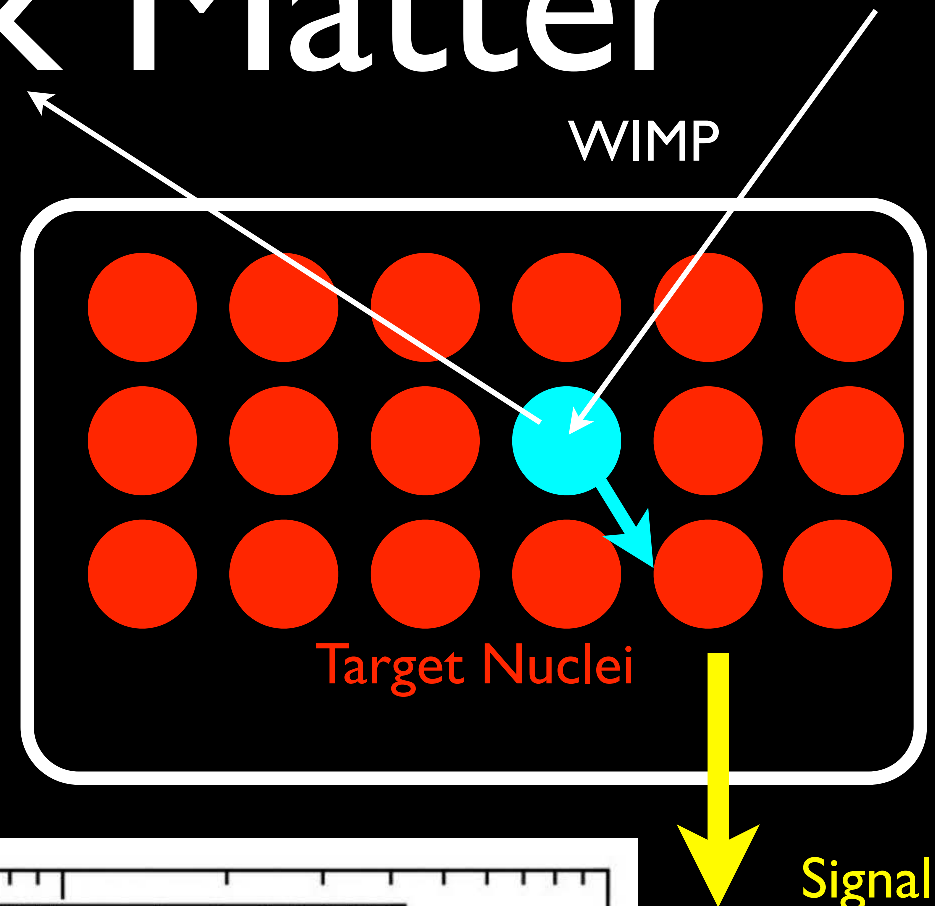


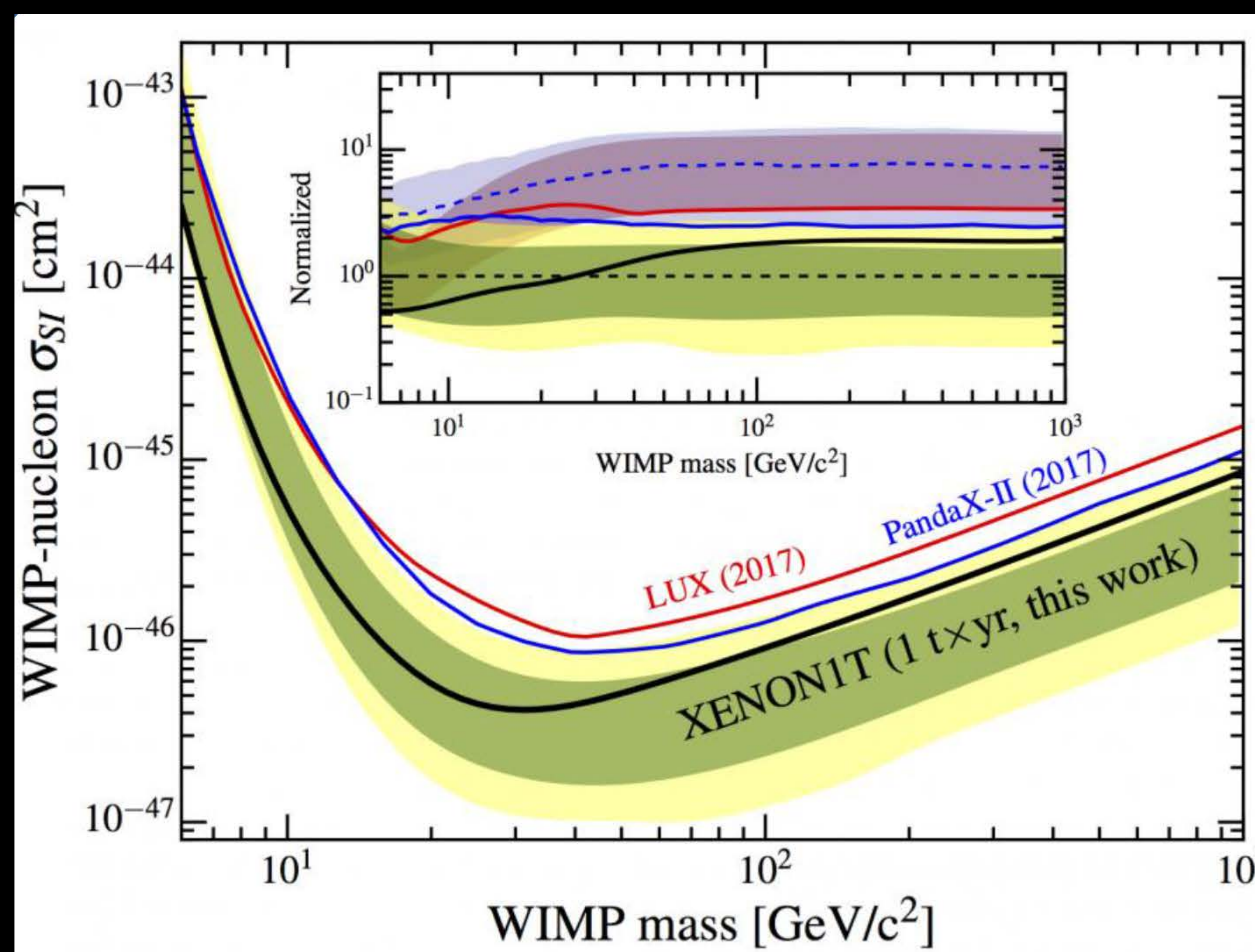
The dark matter model predicts the rates of these processes, and relates them to each other.


MSSM
R-parity
violating
NMSSM
Supersymmetry
WIMPless DM
Hidden
Sector DM
Self-Interacting
DM
Techni-
baryons
mSUGRA
pMSSM
Gravitino DM
Q-balls
Dark Photon
Dirac
DM
R-parity
Conserving
Asymmetric DM
Light
Force Carriers
Extra Dimensions
Dynamical
DM
Warm DM
Theories of
Dark Matter
?
Solitonic DM
UED DM
6d
5d
Sterile Neutrinos
Quark
Nuggets
Warped Extra
Dimensions
RS DM
Axion DM
T-odd DM
Little Higgs
QCD Axions
Axion-like Particles
Littlest Higgs
T Tait

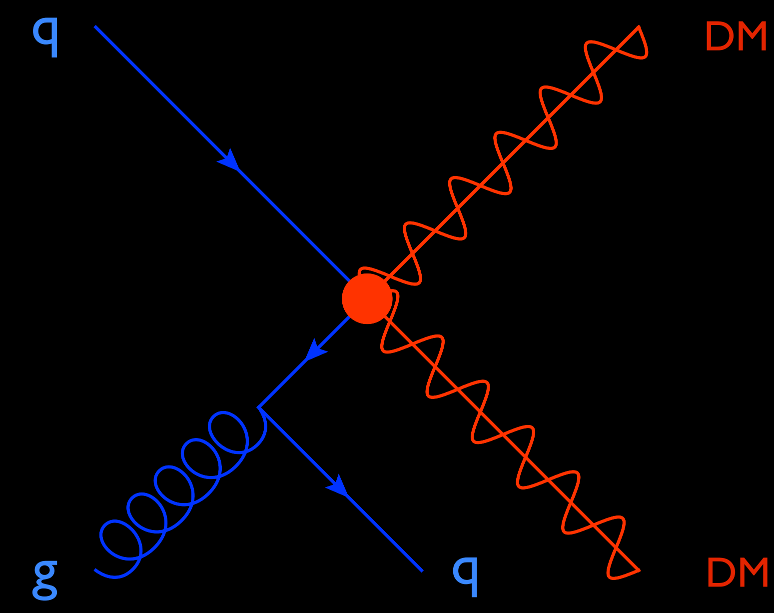
Searching for Dark Matter

- The motion of our own galaxy suggests that there should be substantial dark matter right around us.
- If it interacts with ordinary matter, it is possible that we can catch nearby dark matter particles and see them bumping into us.
- This “direct” search for dark matter uses very sensitive detectors with heavy shielding, looking for a handful of dark matter scattering events.

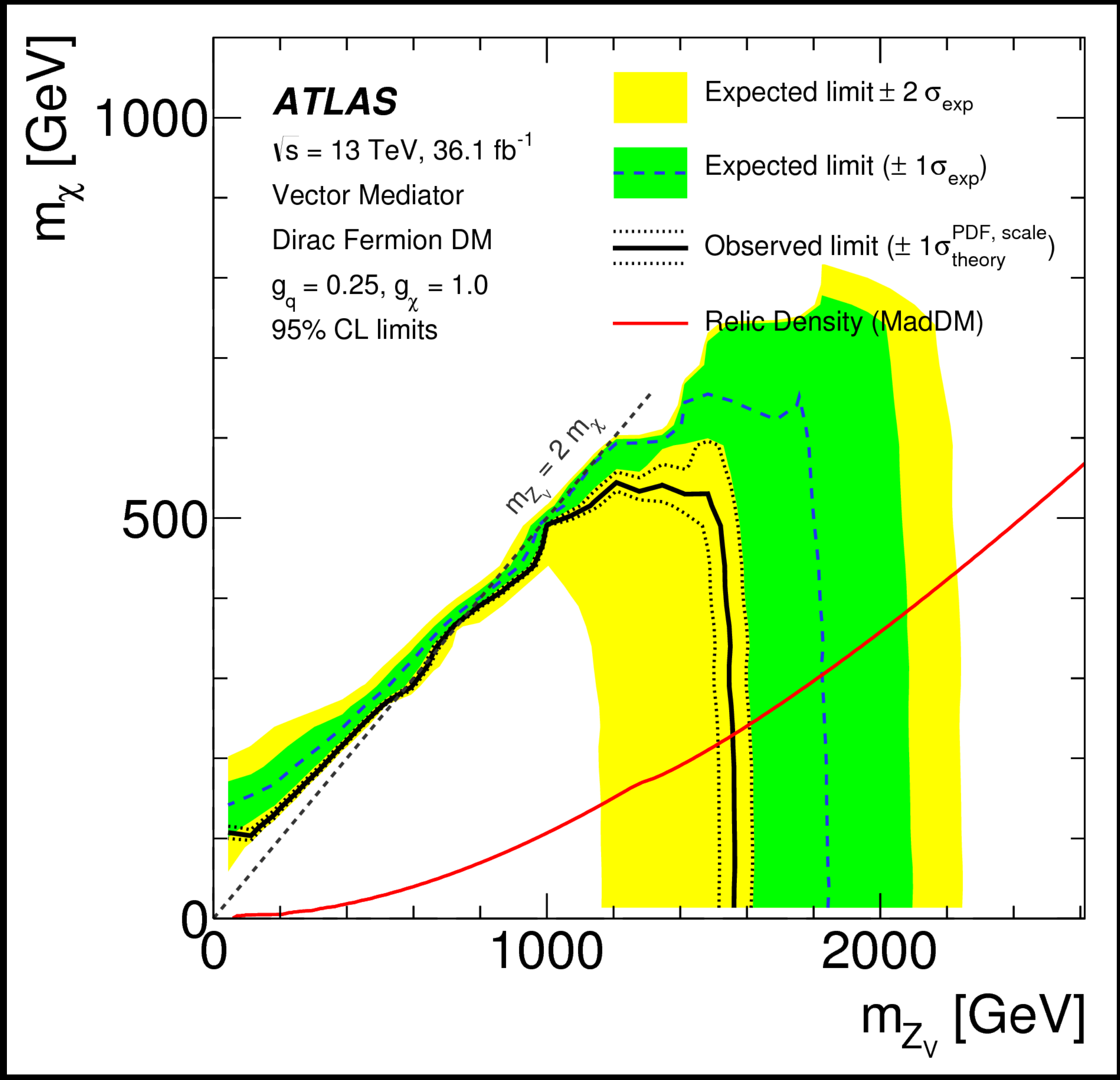




Dark Matter at Colliders?

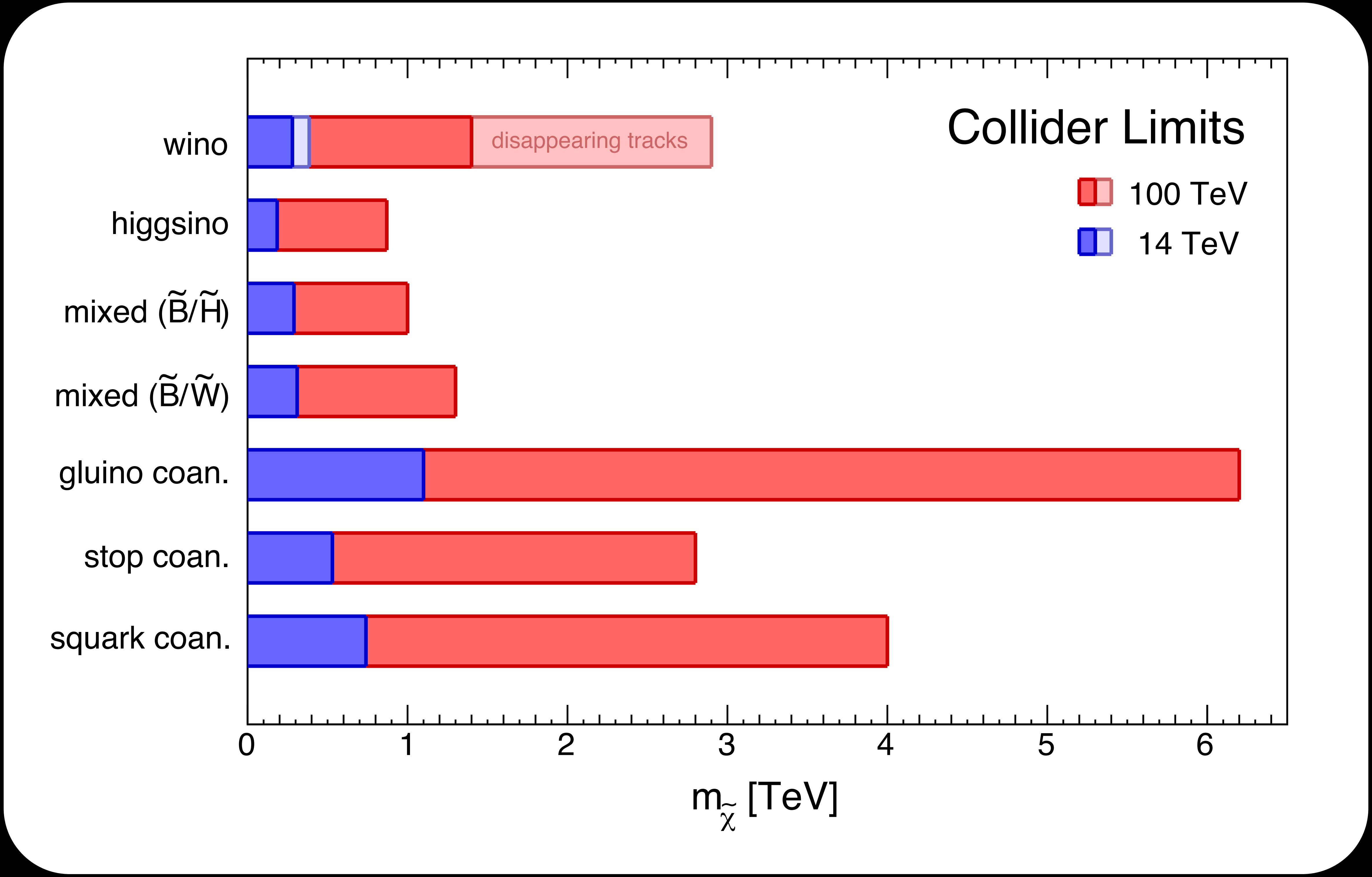


- We can also try to produce dark matter from collisions of ordinary matter, at high energy colliders.
- If dark matter interacts with quarks or gluons, we can look for a process where the dark matter is produced with some extra radiation, revealing its presence by the imbalance of momentum in the transverse direction to the beam.
- If we trace limits on the parameter space of direct detection, we see that colliders offer an interesting probe of very light dark matter.

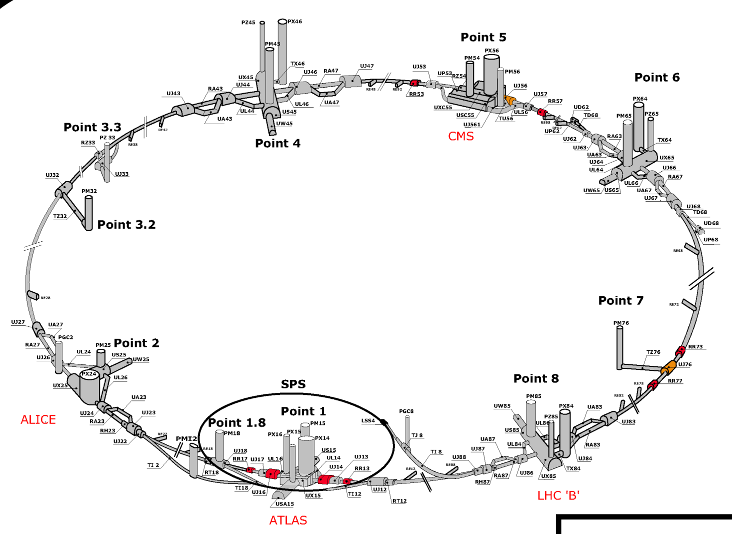


Dark Matter

1606.00947

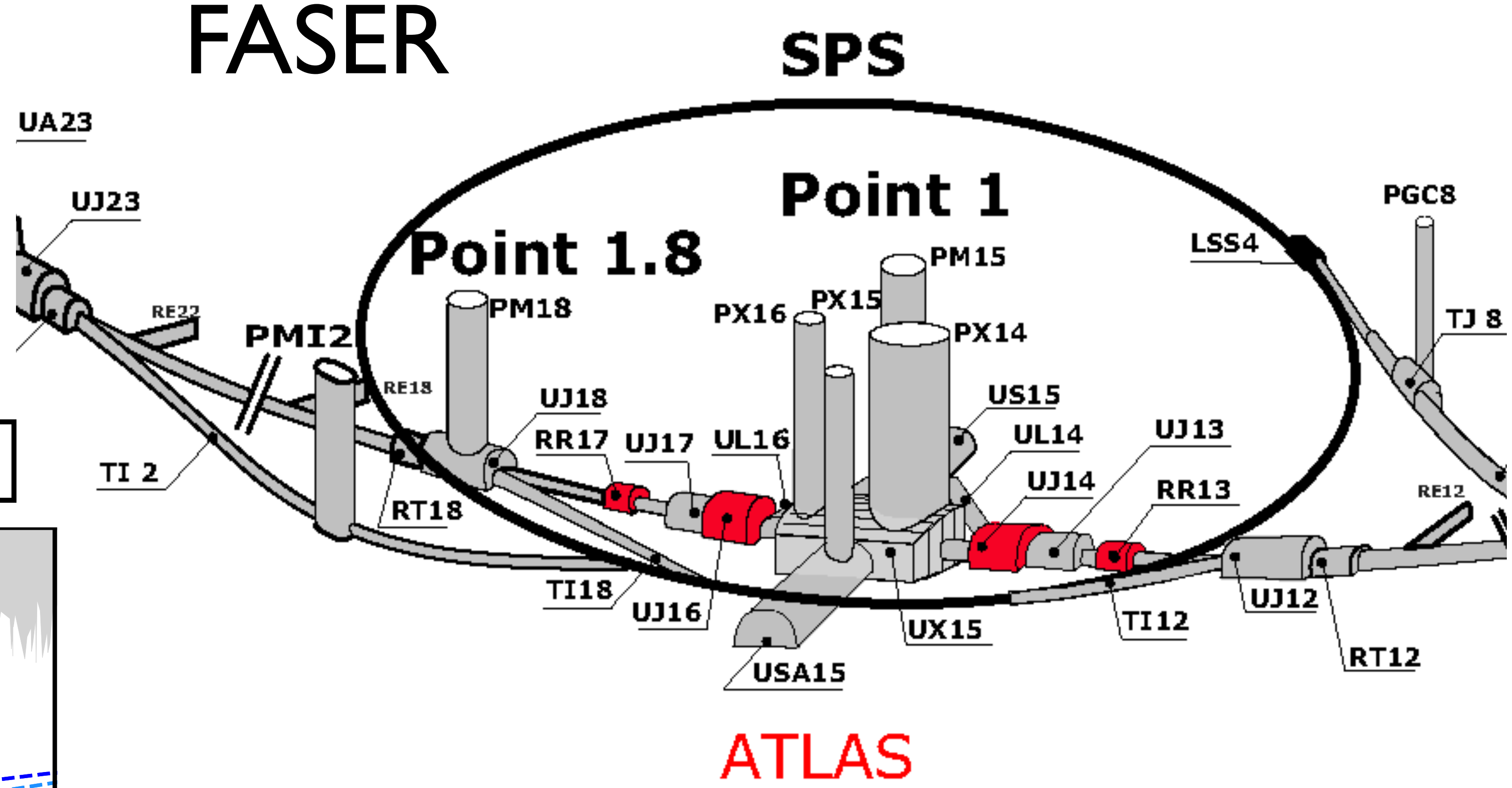


Access to the Dark Sector?

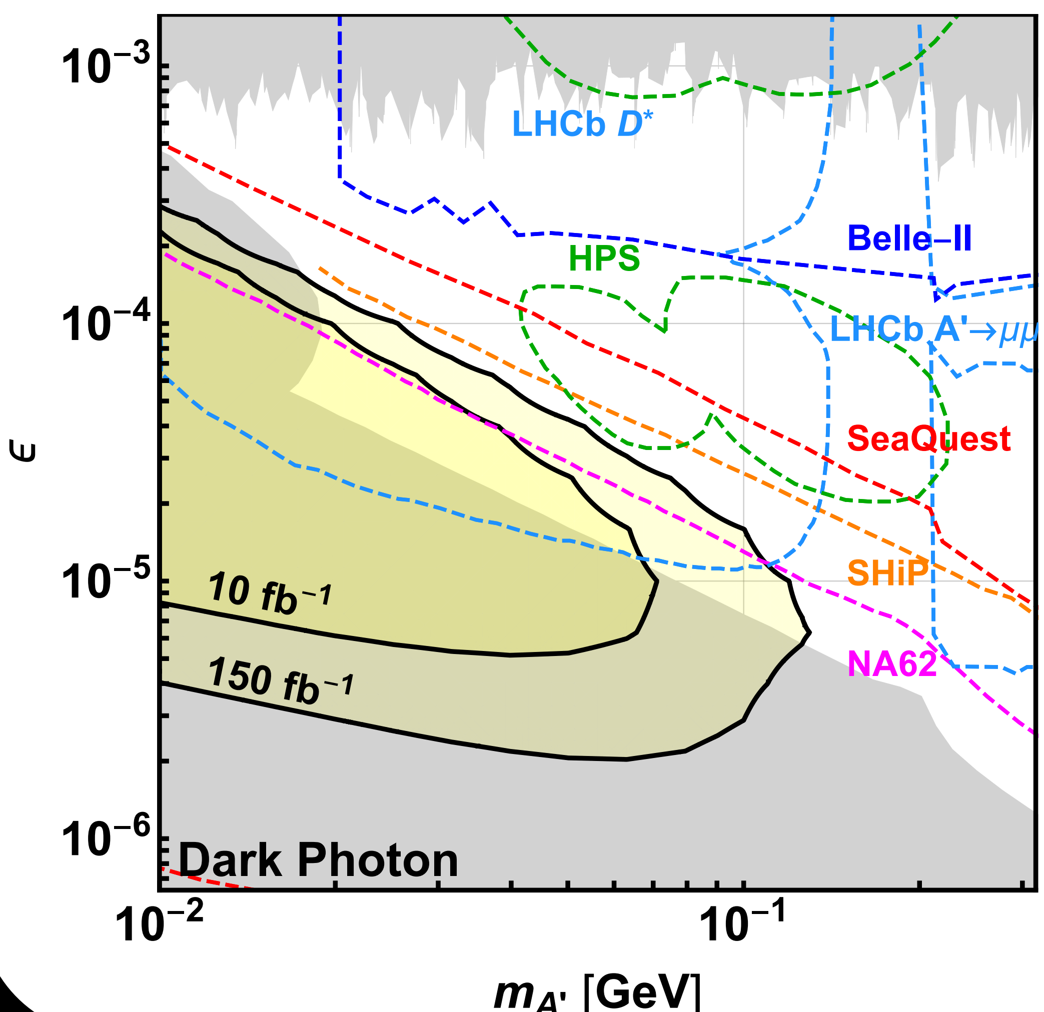


Courtesy of J Feng

FASER



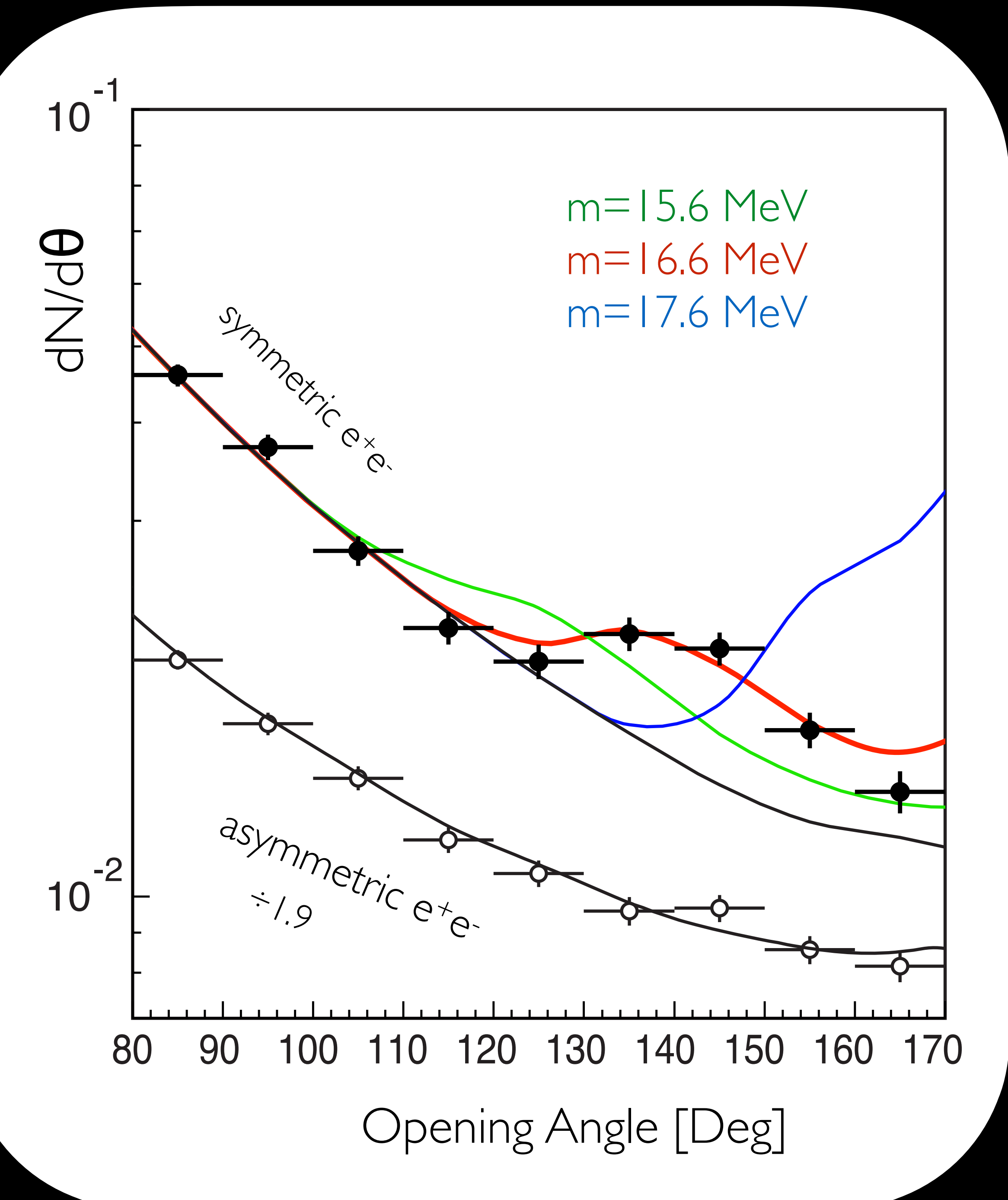
ATLAS

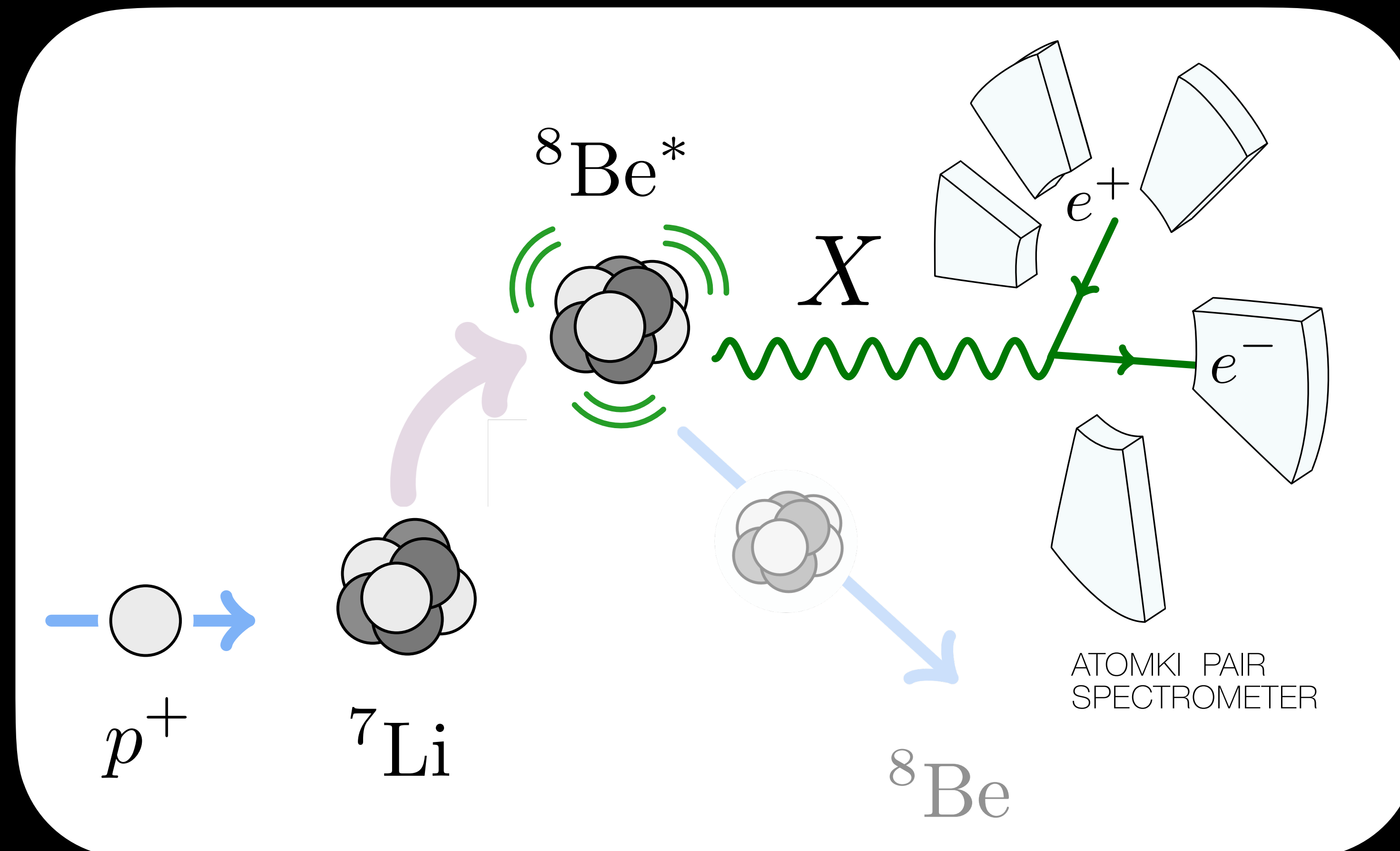


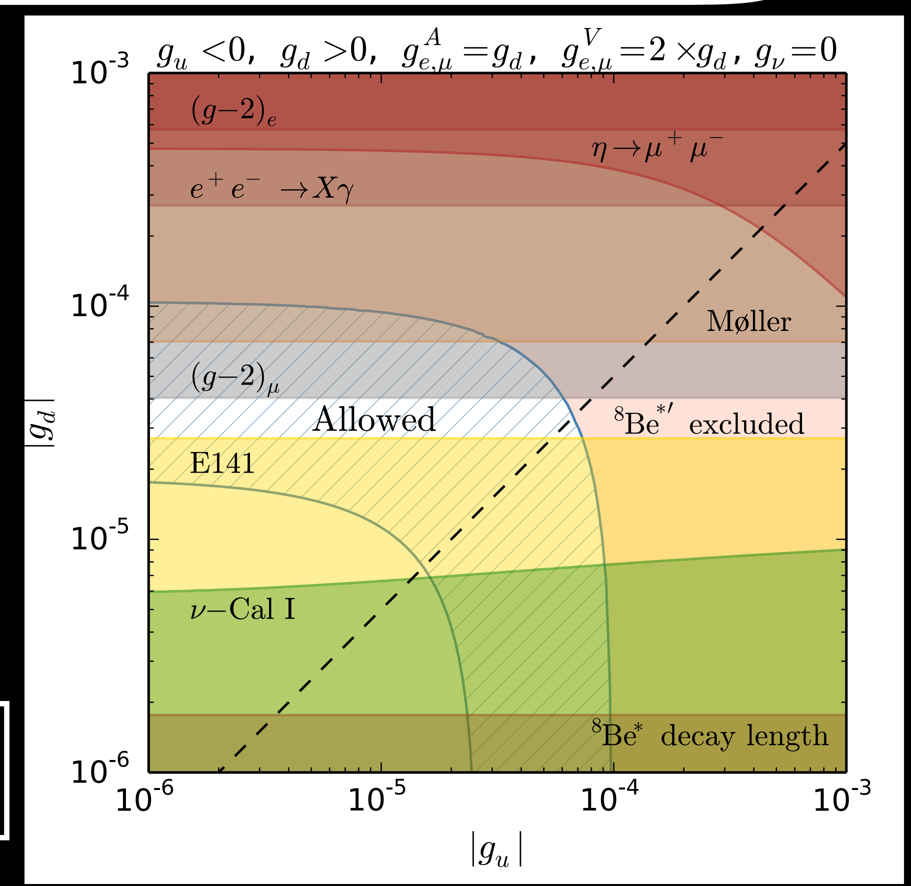
A collider can produce dark particles, which a specialized detector can hope to detect far from the interaction point.

Hints from Nuclear Processes?

A.J. Krasznahorkay, et al. PRL &1504.01527 ; 1910.10459







Kozaczuk, Morrissey, Stroberg 1612.01525

The Future Gets Brighter?

- With the discovery of the Higgs boson, the Standard Model of Particle Physics has been established as a complete theory that could in principle describe physics up to very high energies.
- Still, many questions remain:
  - The nature of dark matter and dark energy
  - The origin of the baryon asymmetry of the Universe.
  - Flavor and neutrino masses.
- Future experiments, including the high luminosity Large Hadron Collider, future observatories, and searches for dark matter offer the opportunity to shed light on these mysteries.
- The next few years offer the opportunity for great discoveries!

The Future is Bright!

Vancouver, British Columbia

Cagliari, Sardegna